PINGU - Resolving the Neutrino Mass Hierarchy at the South Pole

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New Directions in Neutrino Physics
Aspen Center for Physics
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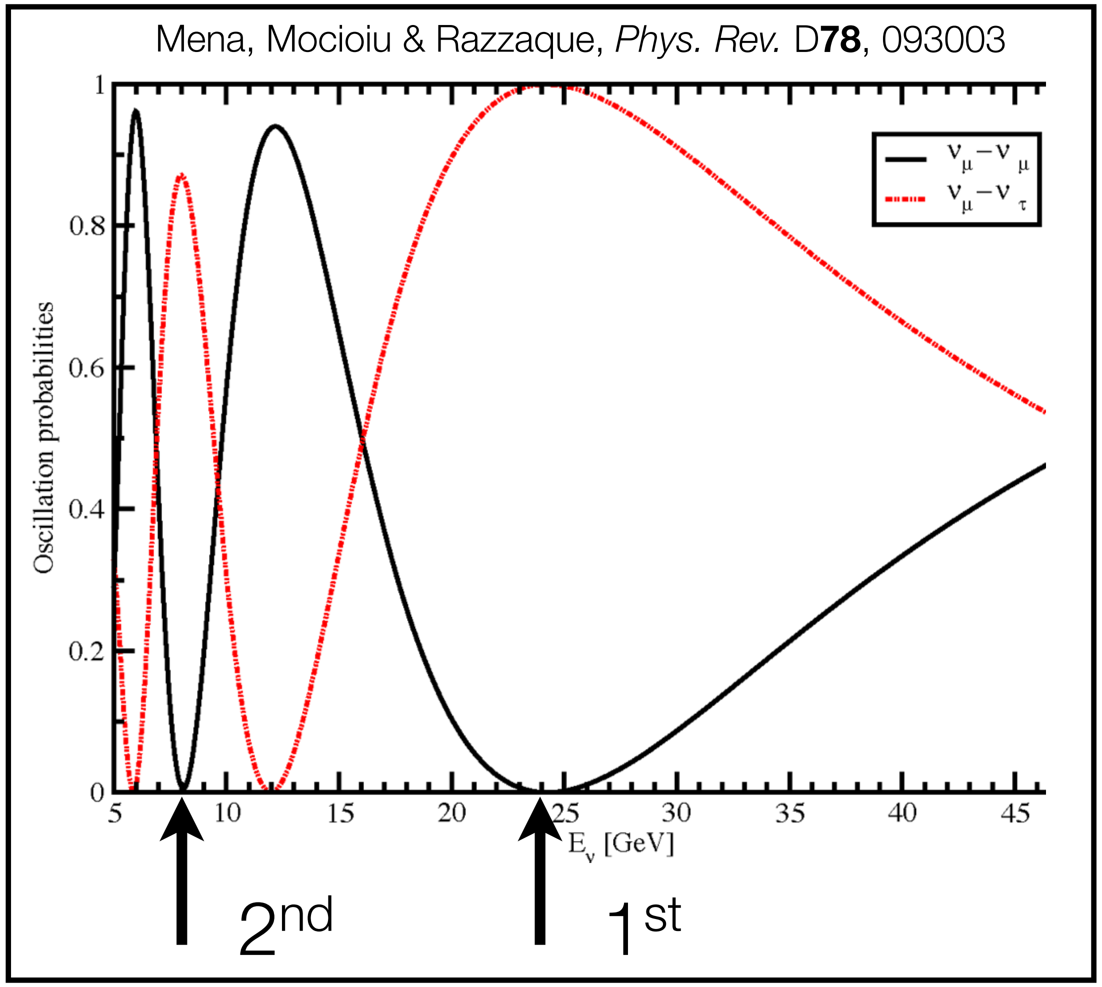
PINGU Intro/Goals

- **P**recision **I**ceCube **N**ext **G**eneration **U**pgrade (PINGU)
- Physics goals
- Drive neutrino energy reach down to few GeV at multi-megaton scale size by infilling IceCube/DeepCore
- South Pole is an attractive option for a GeV-scale energy neutrino detector

Physics Beyond DeepCore

- Enhance/extend ongoing oscillation analyses - see E. Resconi



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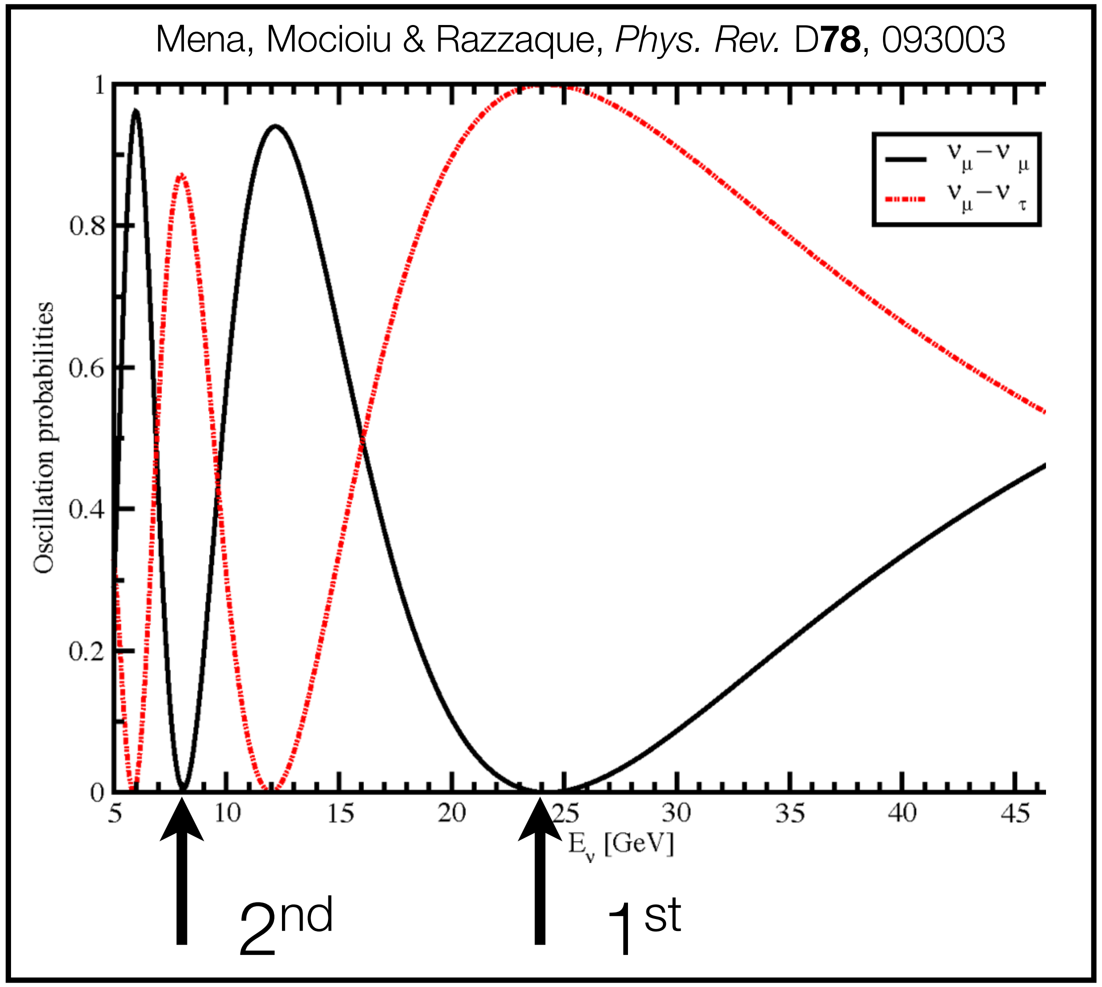

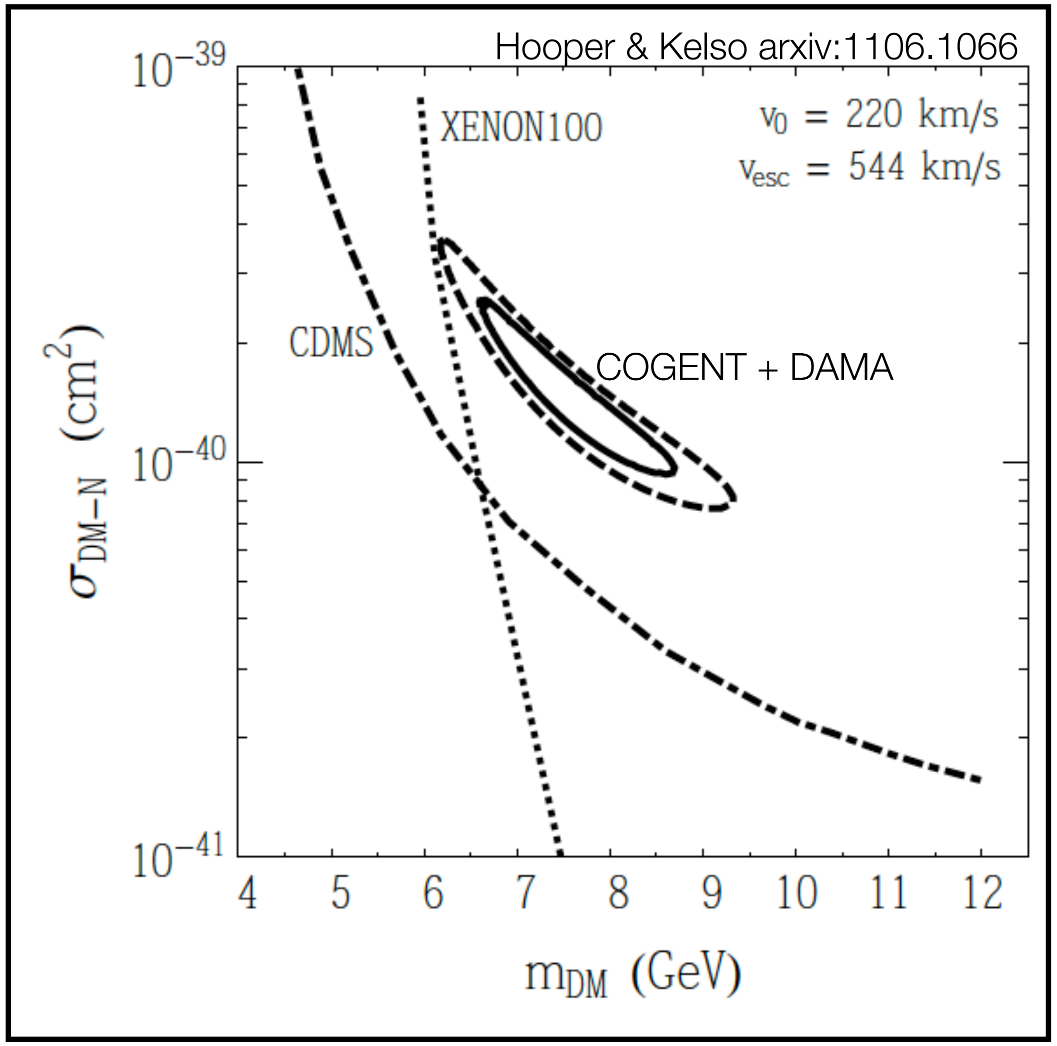

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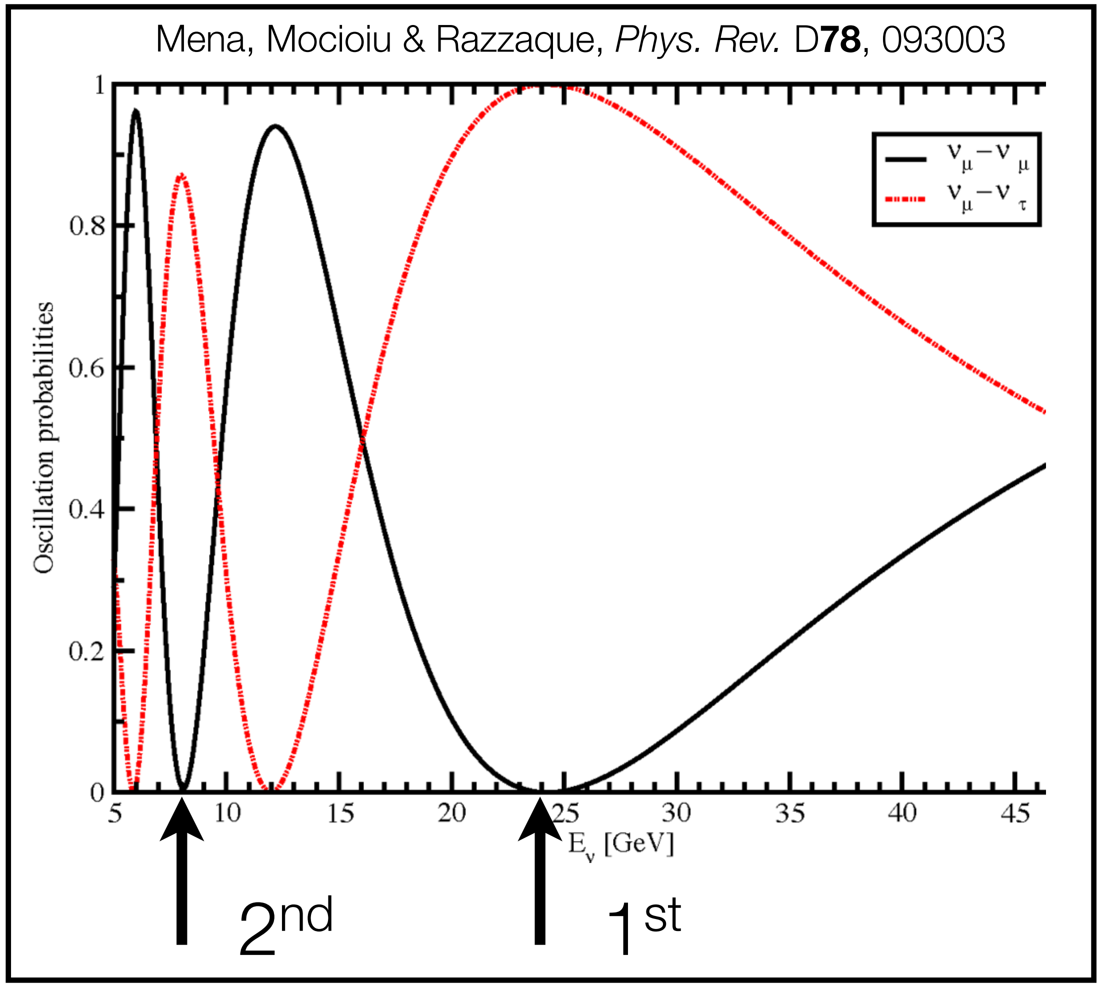
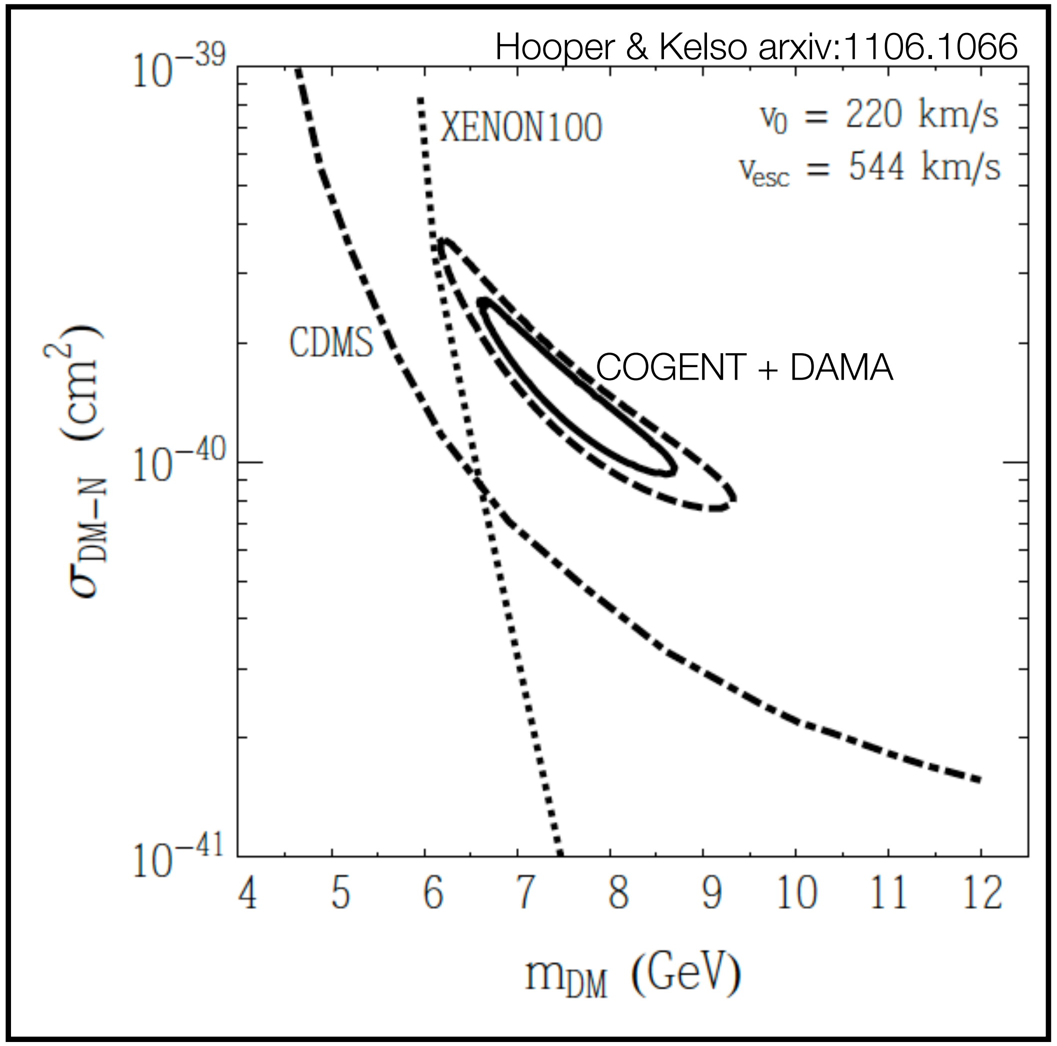
- GeV Dark Matter - see C. Rott
- θ_{23} maximal mixing (end of talk)





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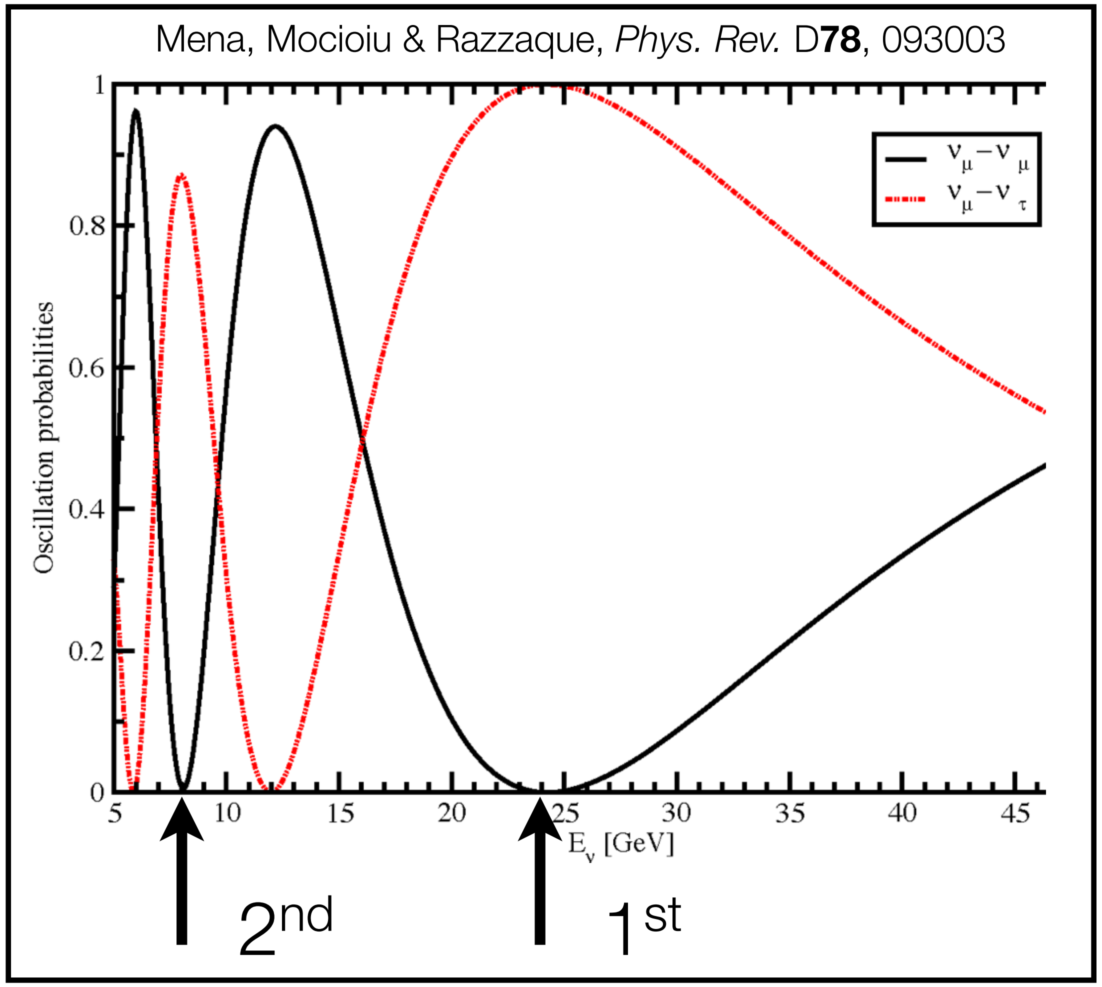
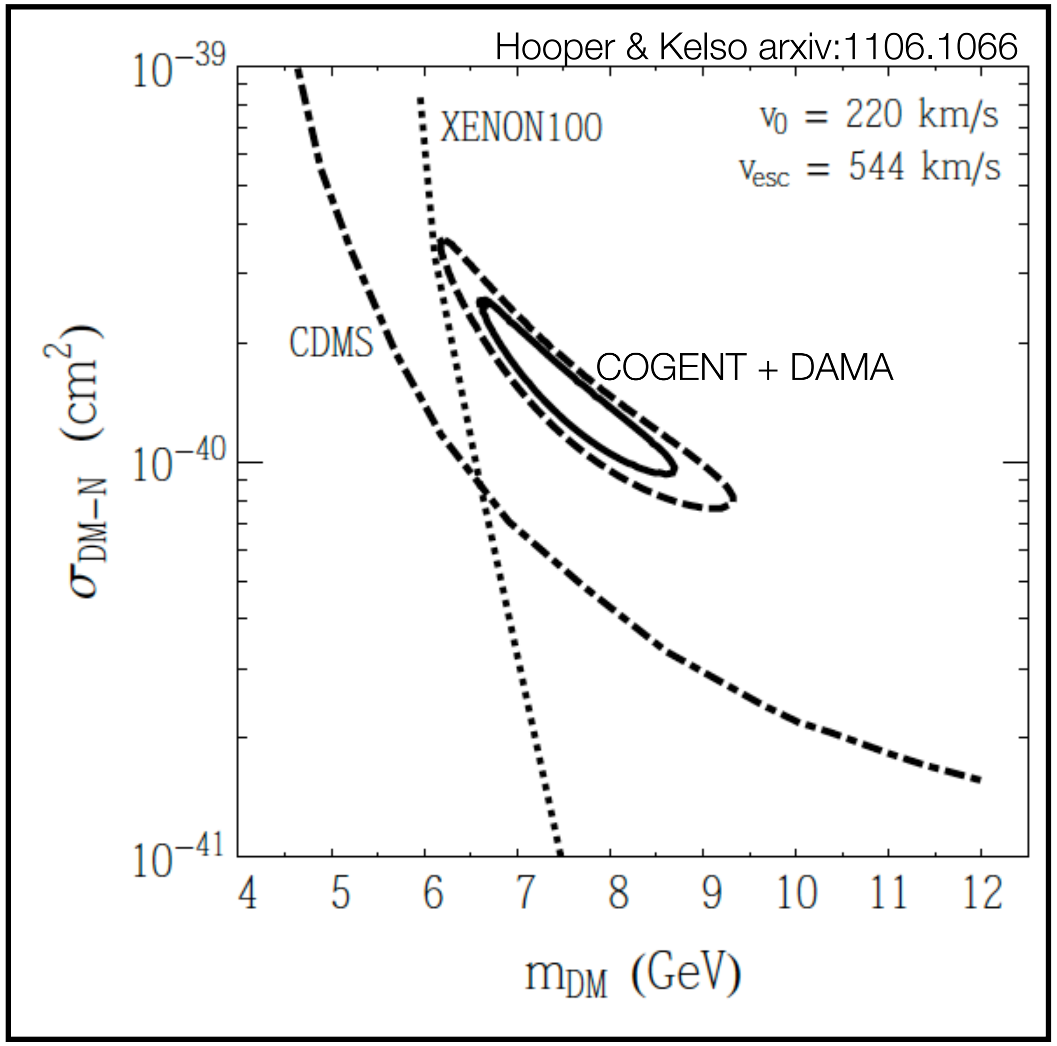
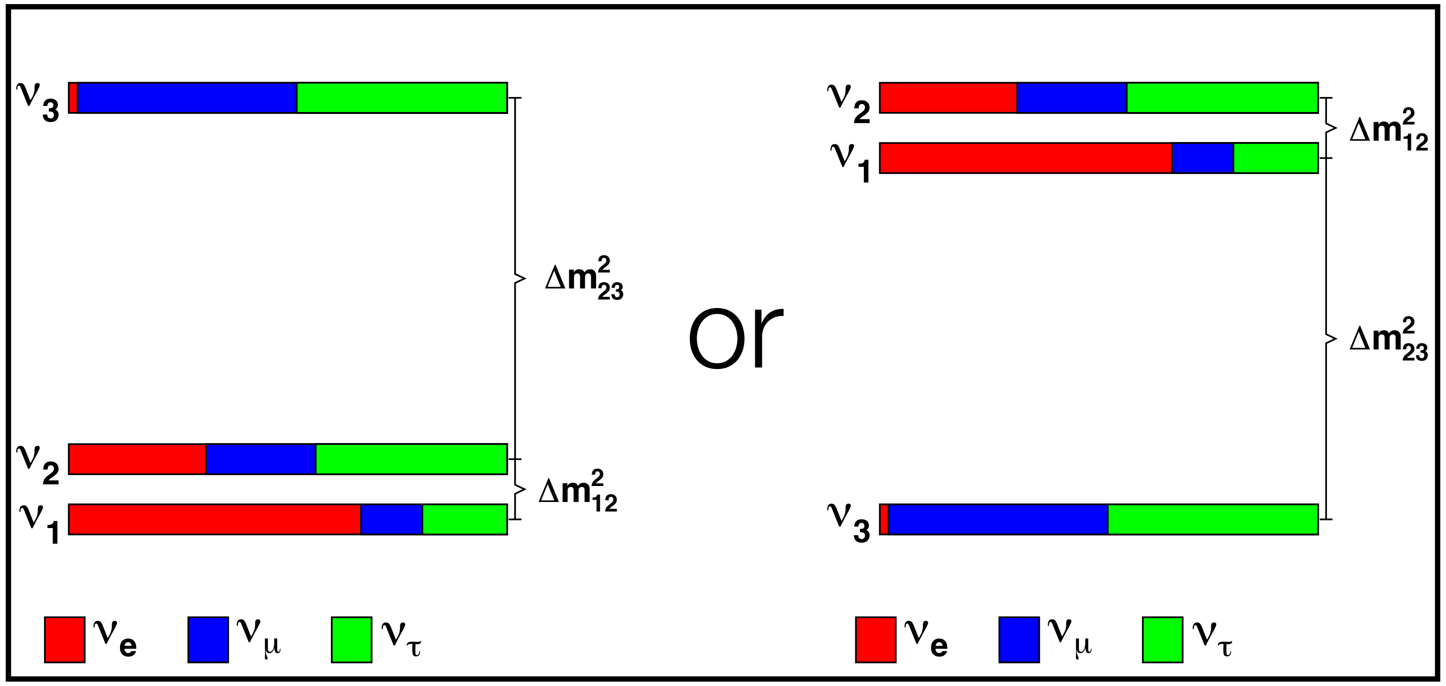
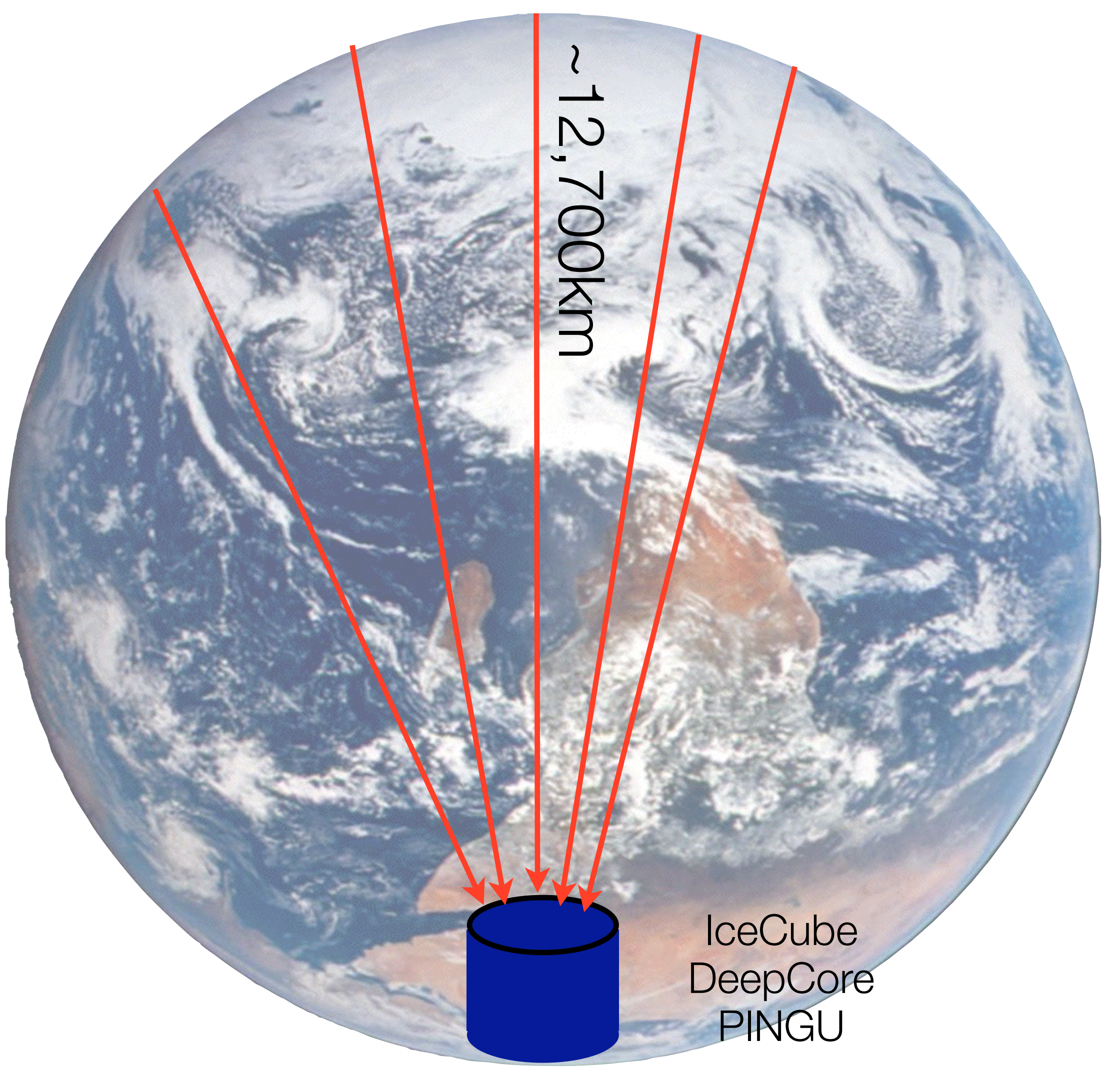
 Neutrino Hierarchy

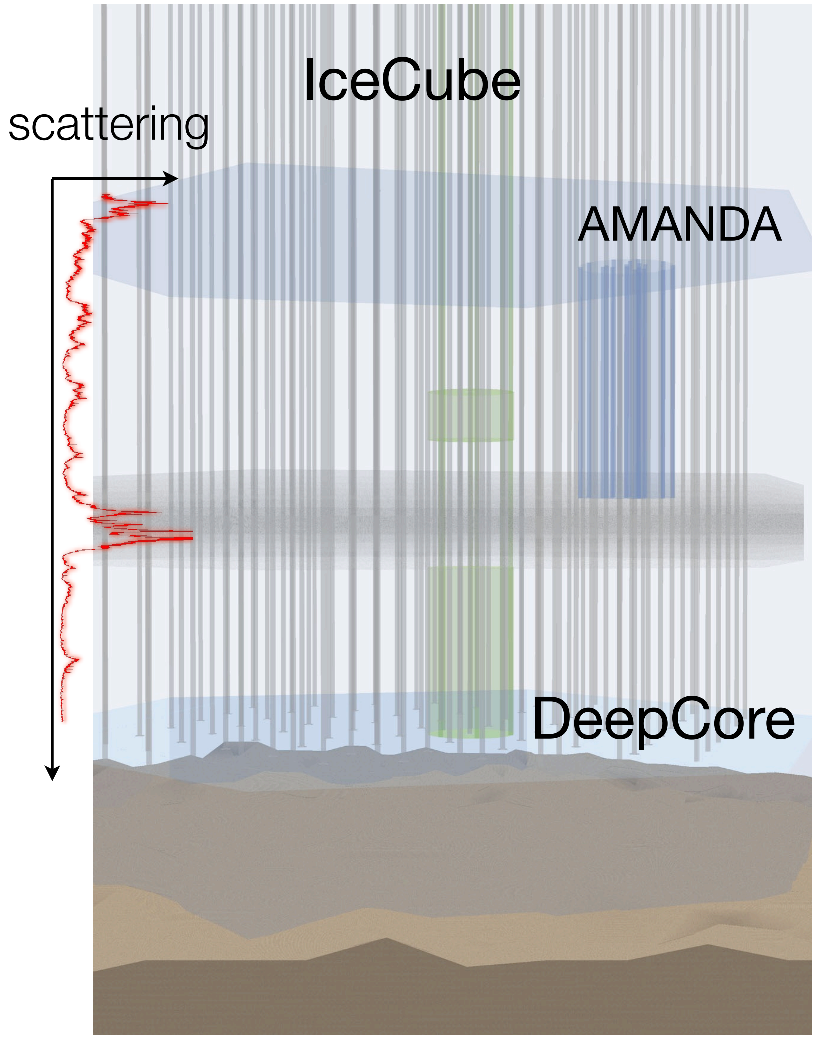






- Free/cheap stuff is the best stuff
  - Atmospheric neutrino “beam” covers all baselines up to 12,700km and a large energy region (MeV - TeV+)
  - More clear ice than you can shake a stick at, just needs instrumentation
  - Gigaton veto (IceTop/IceCube/DeepCore) already built and operational

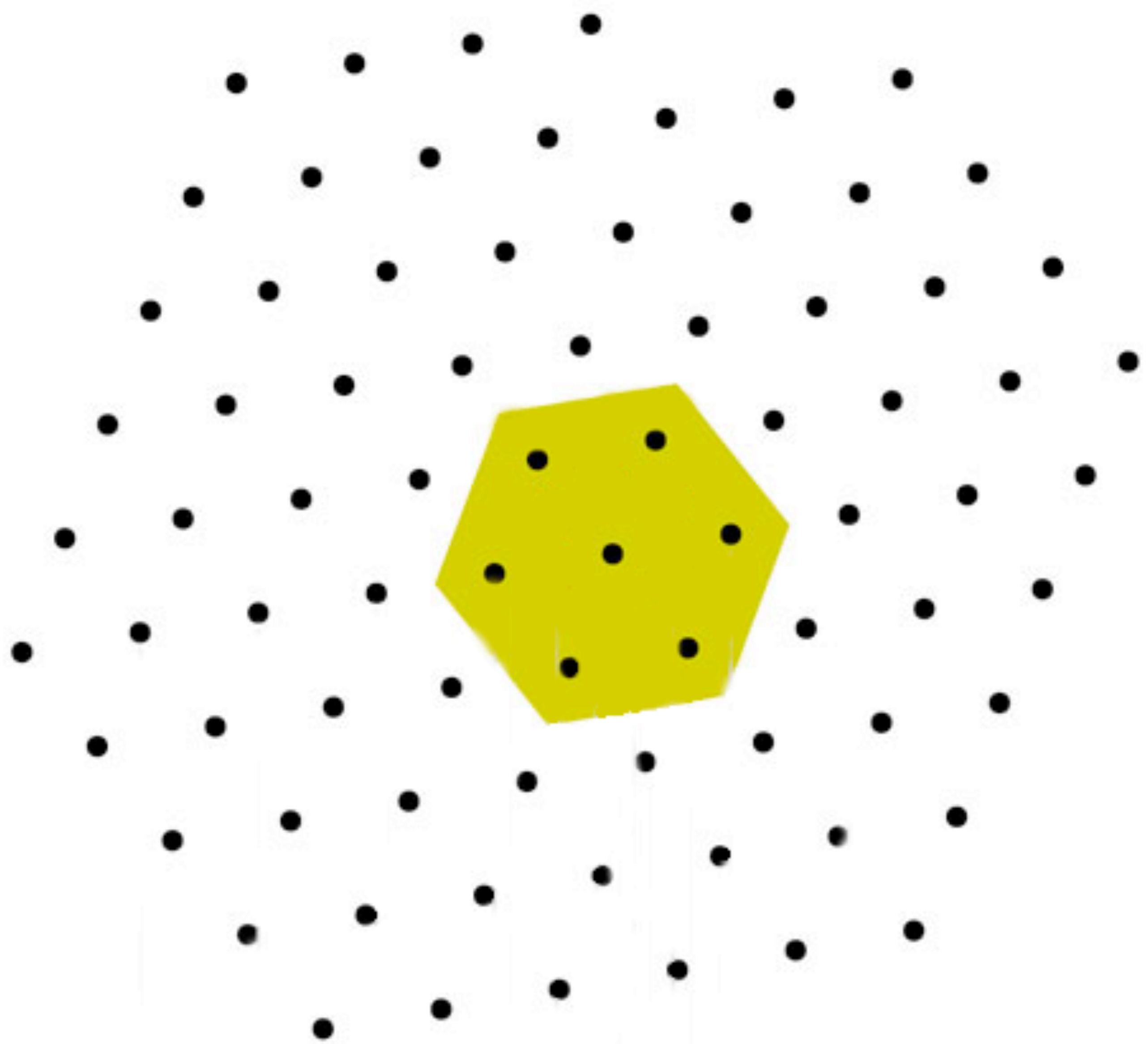




PINGU Detector

- Additional strings within IceCube/DeepCore volume
  - Number of strings, string-string spacing, DOM-DOM spacing, etc... under investigation
  - 10 different simulated geometries already
- Shorter DOM-DOM spacing than DeepCore
- R & D for future water/ice cerenkov detectors
- 1.5 year procurement/ shipping + 2-3 year deployment

Top View



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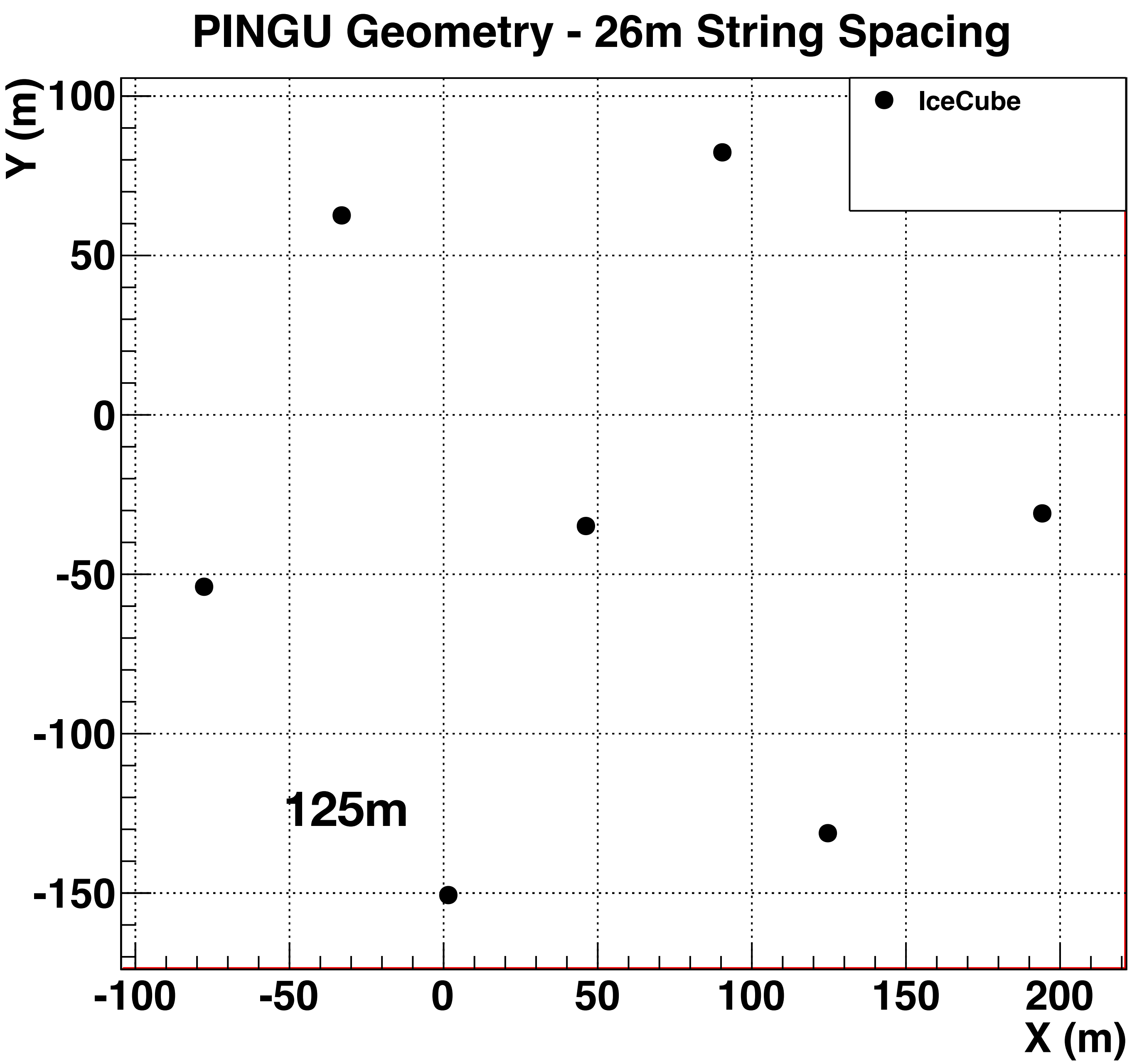

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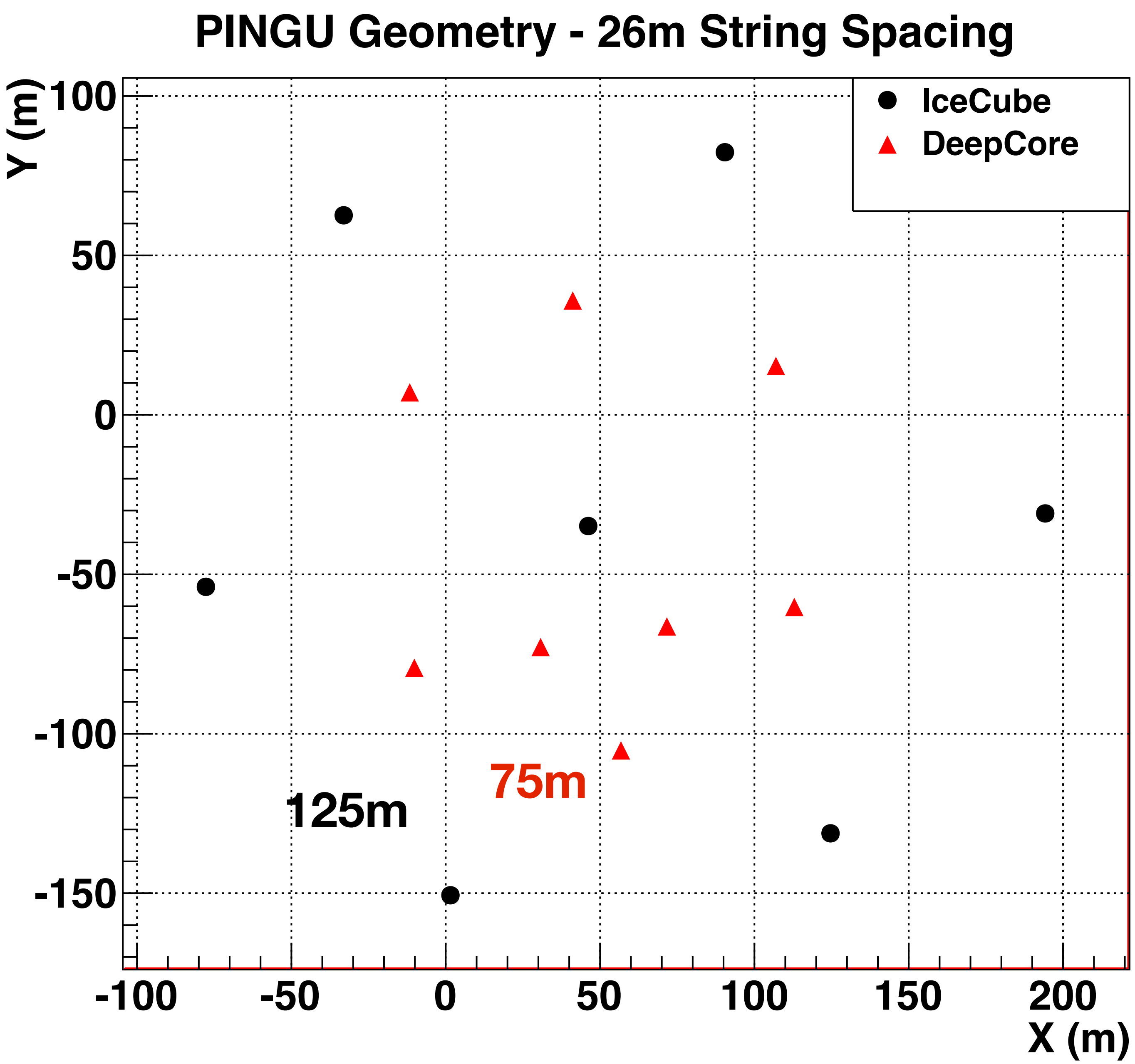

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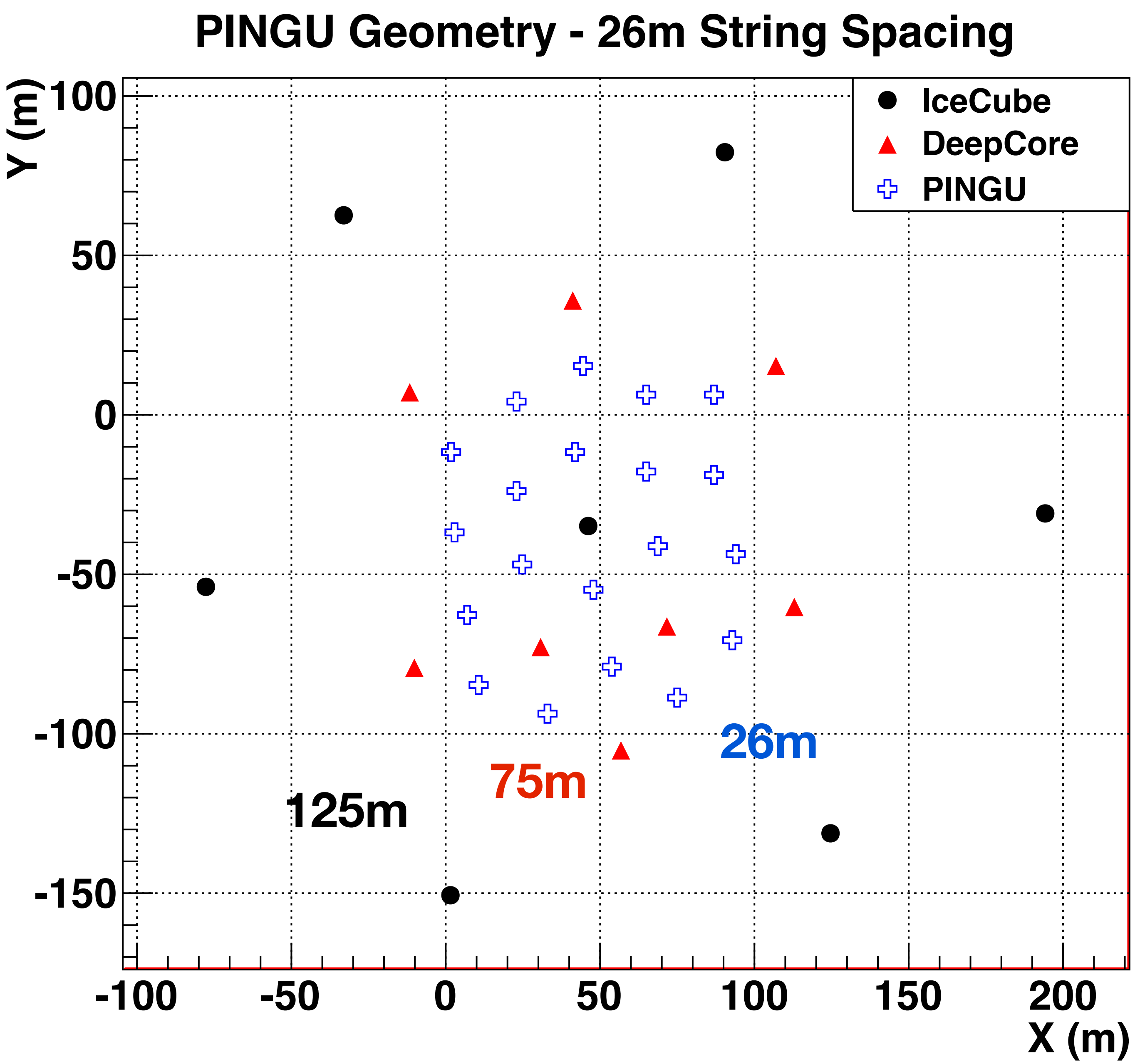
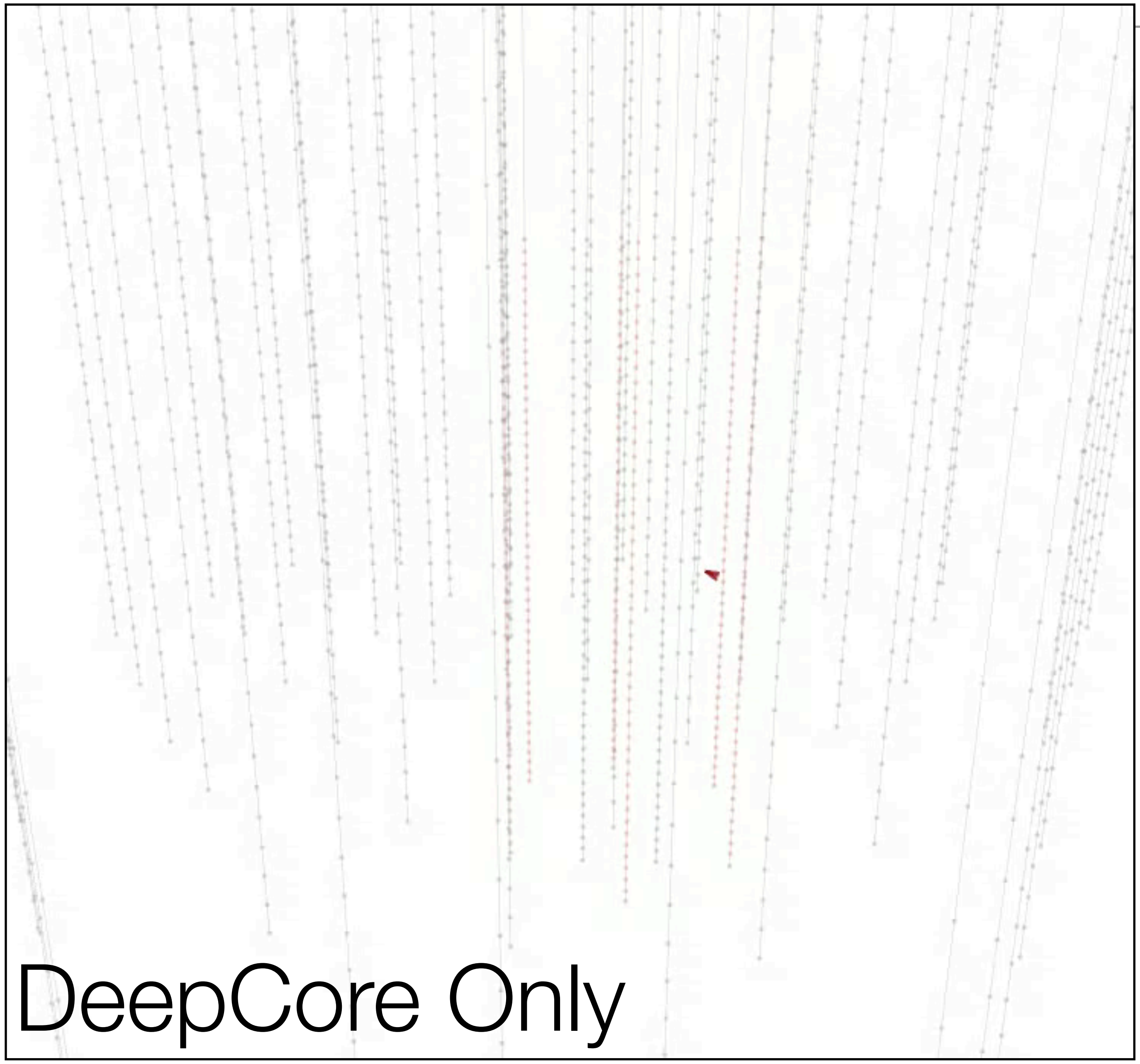


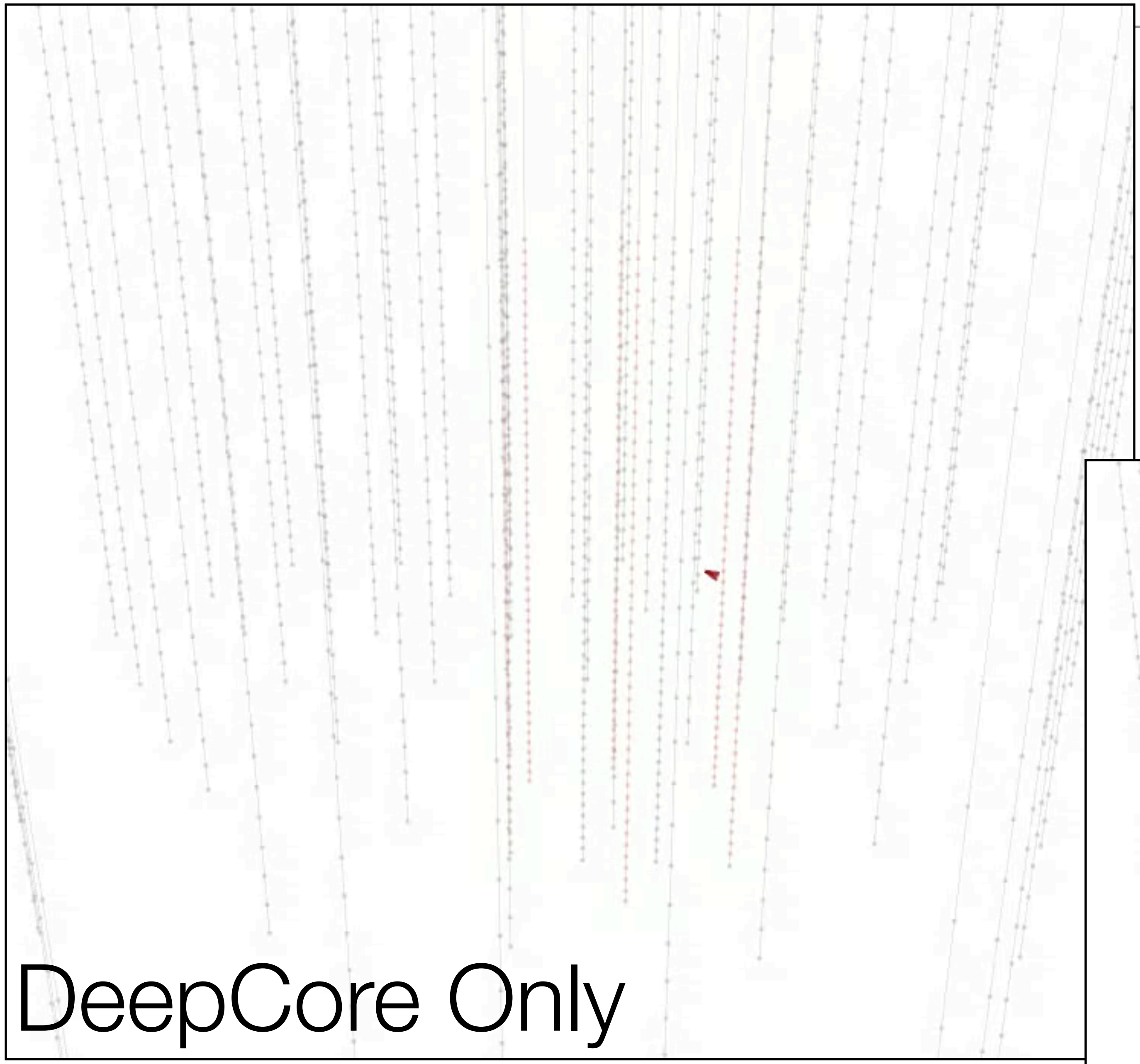
All following plots use V6 Geometry

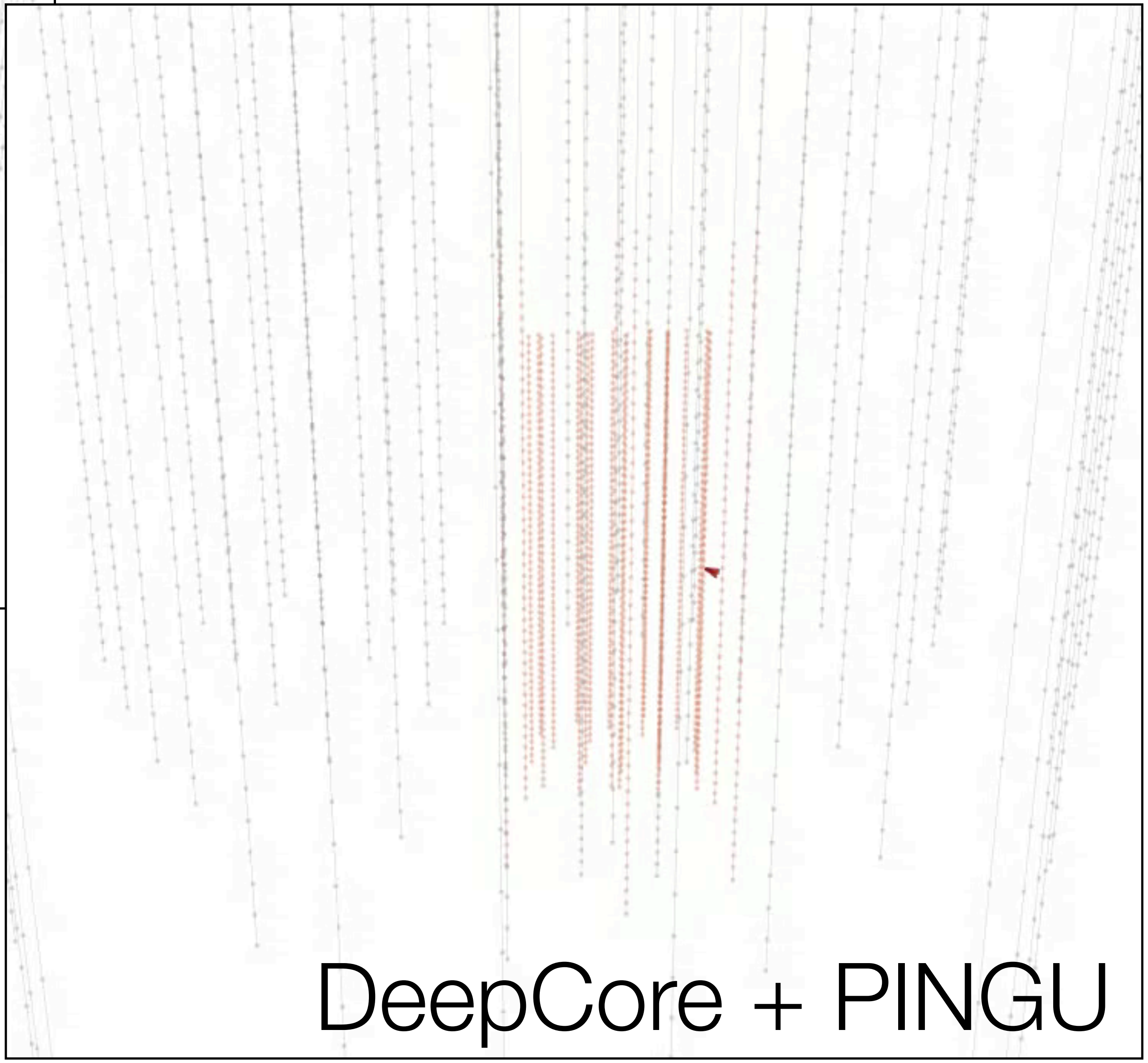
V6 = 20 strings w/ 60 DOMs/string @ 26m string-string spacing, 5m DOM-DOM



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

Event Movies





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- ~20 vs. ~50 Hit Modules

Resolving the Mass Hierarchy

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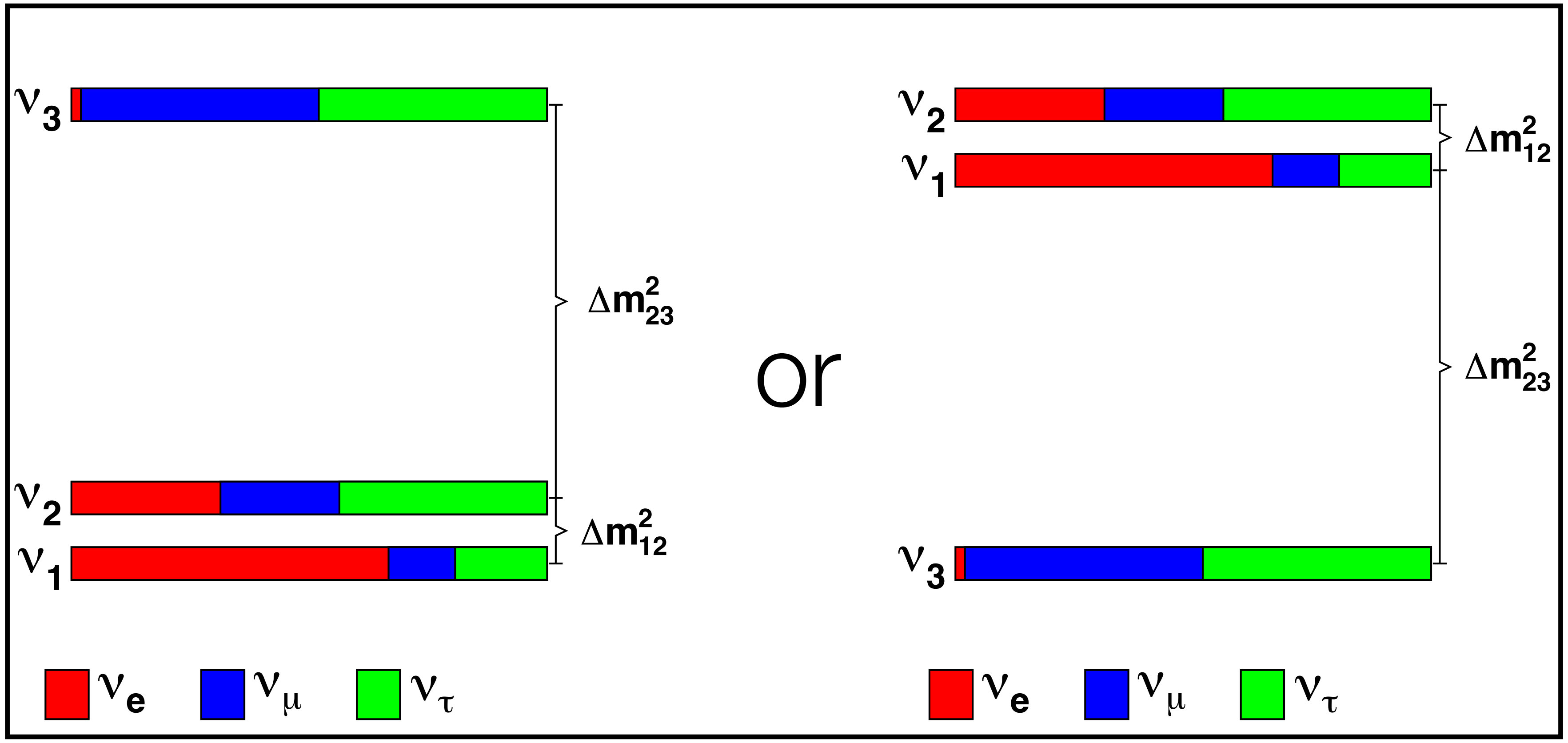
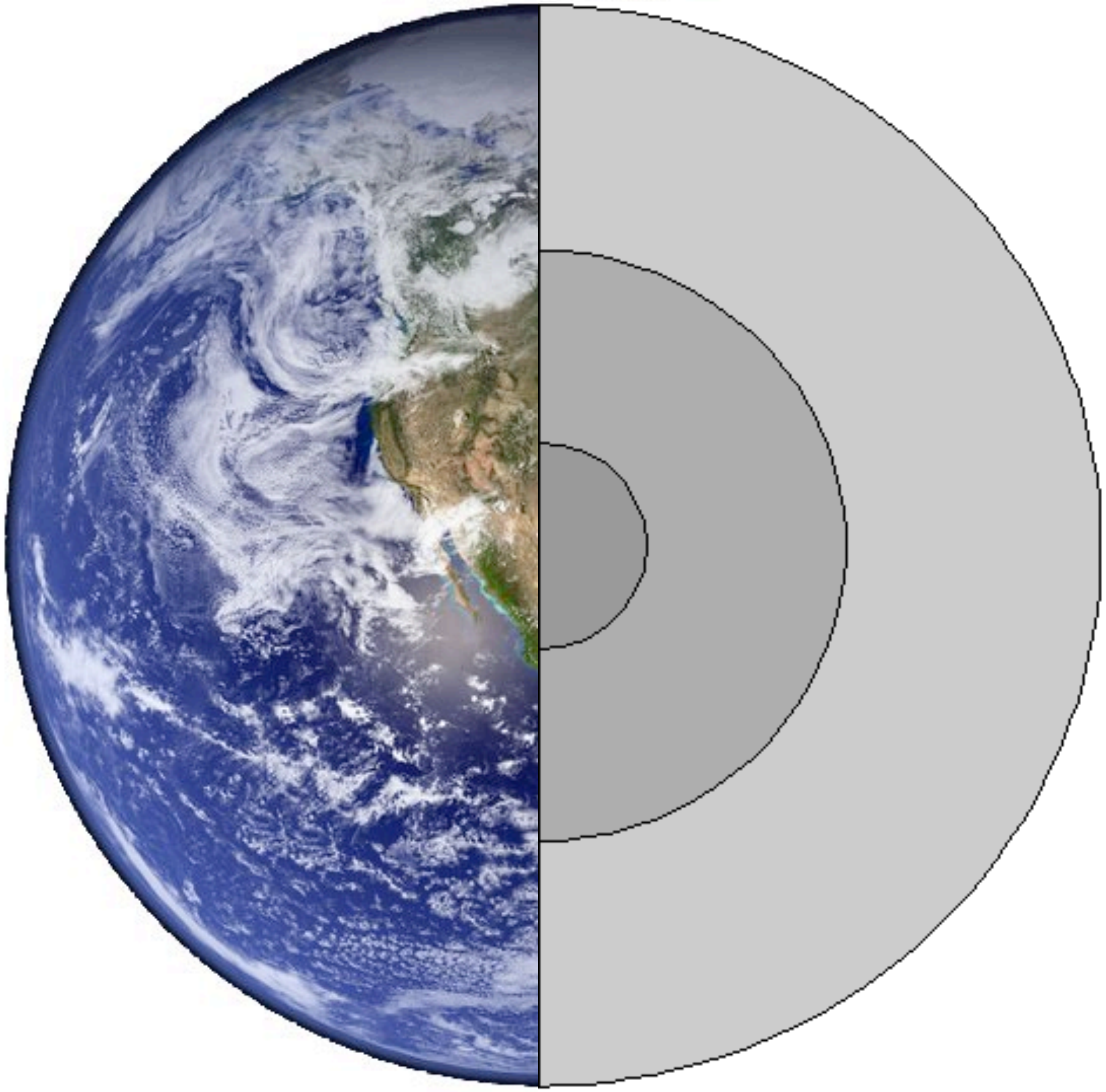
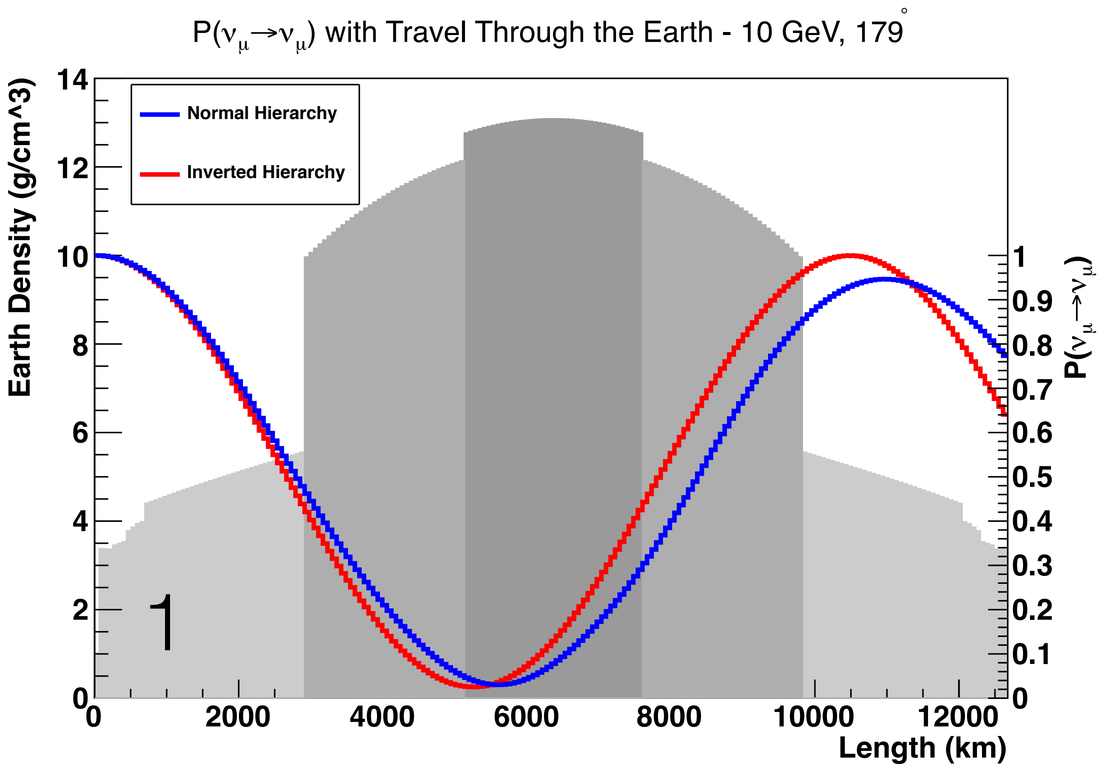
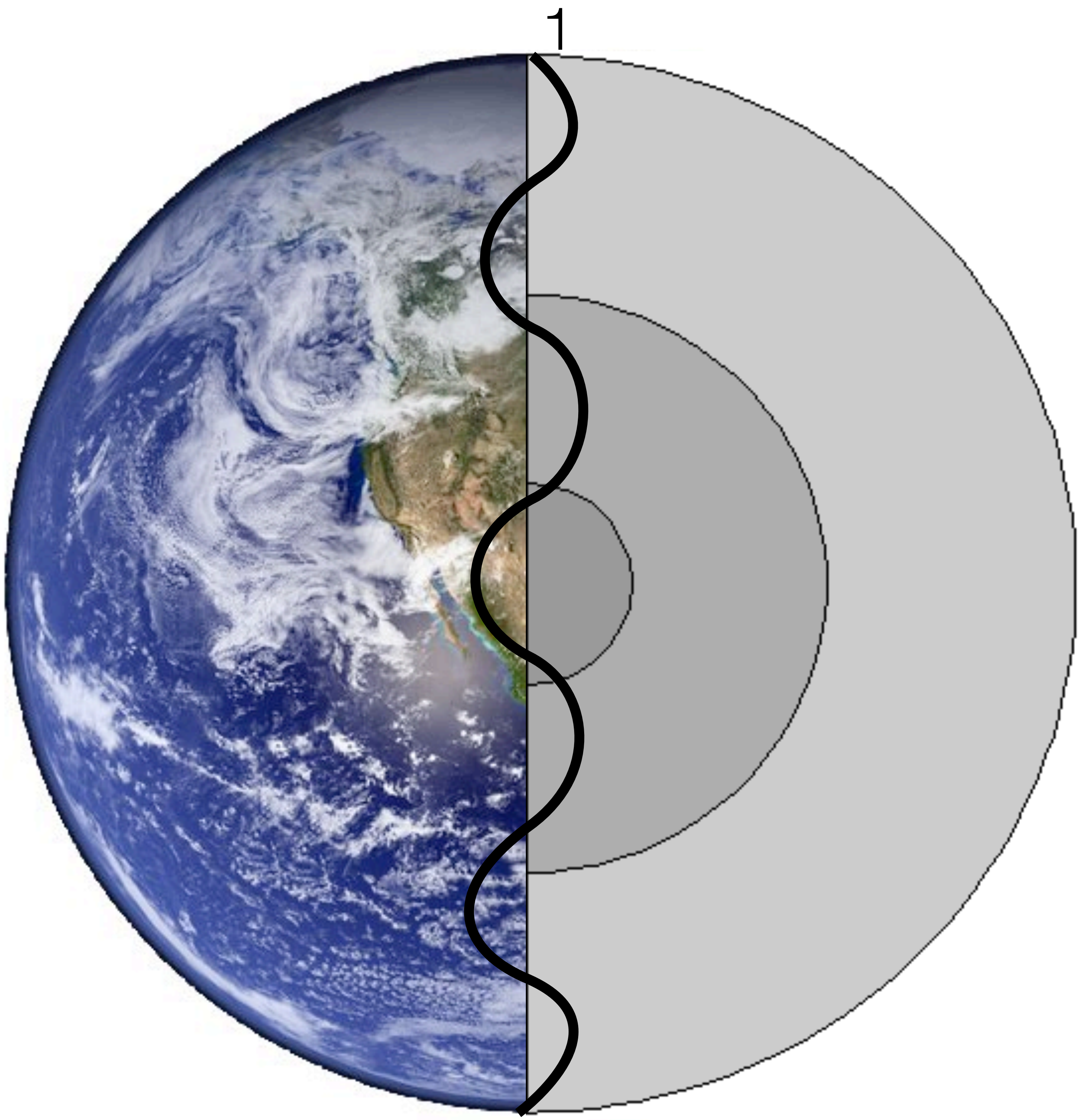




Matter Effects & Neutrino Hierarchy





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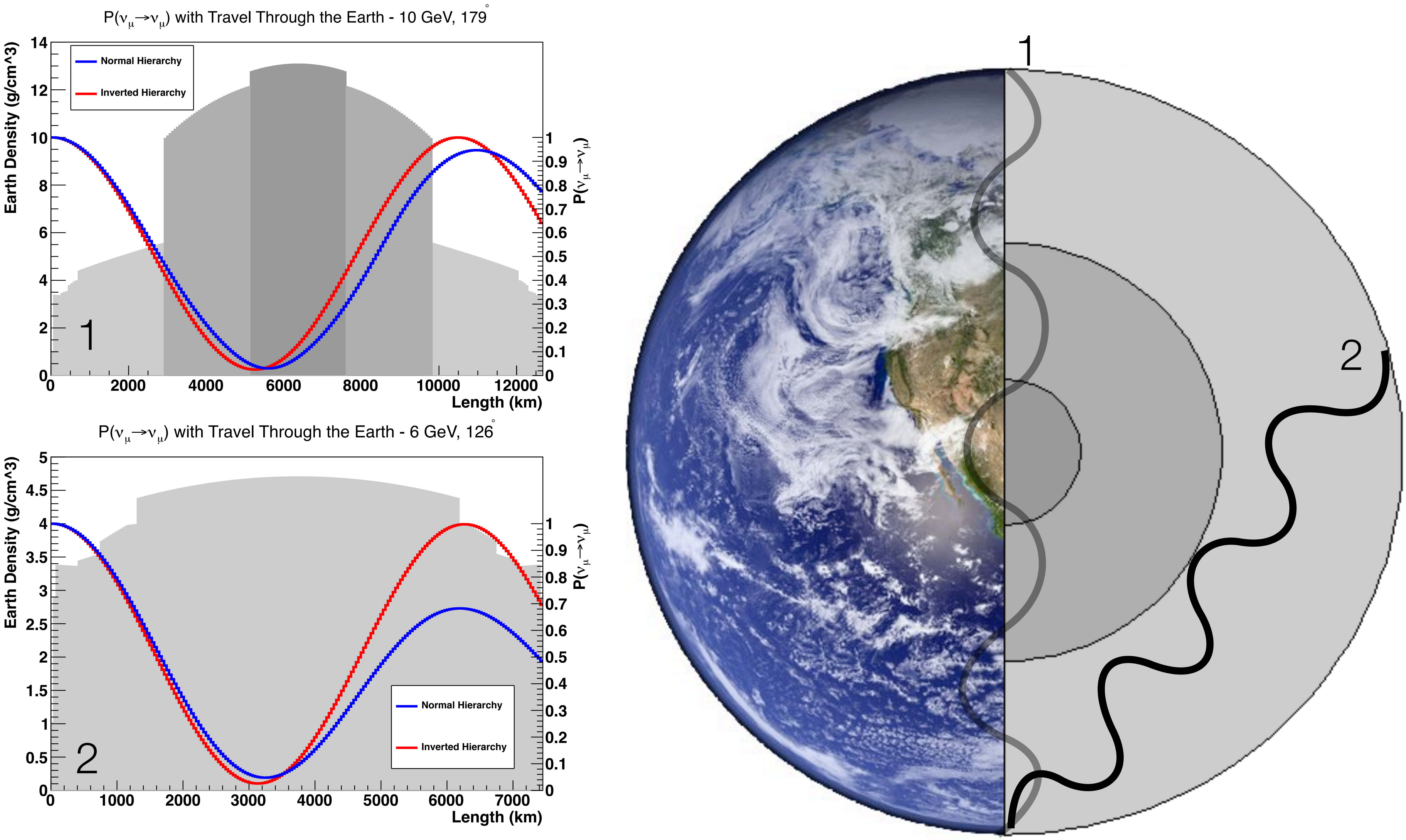

- Inverted/Normal hierarchy has up to a 20% difference in ν_μ oscillation probability for specific energies and zenith angles (baselines)

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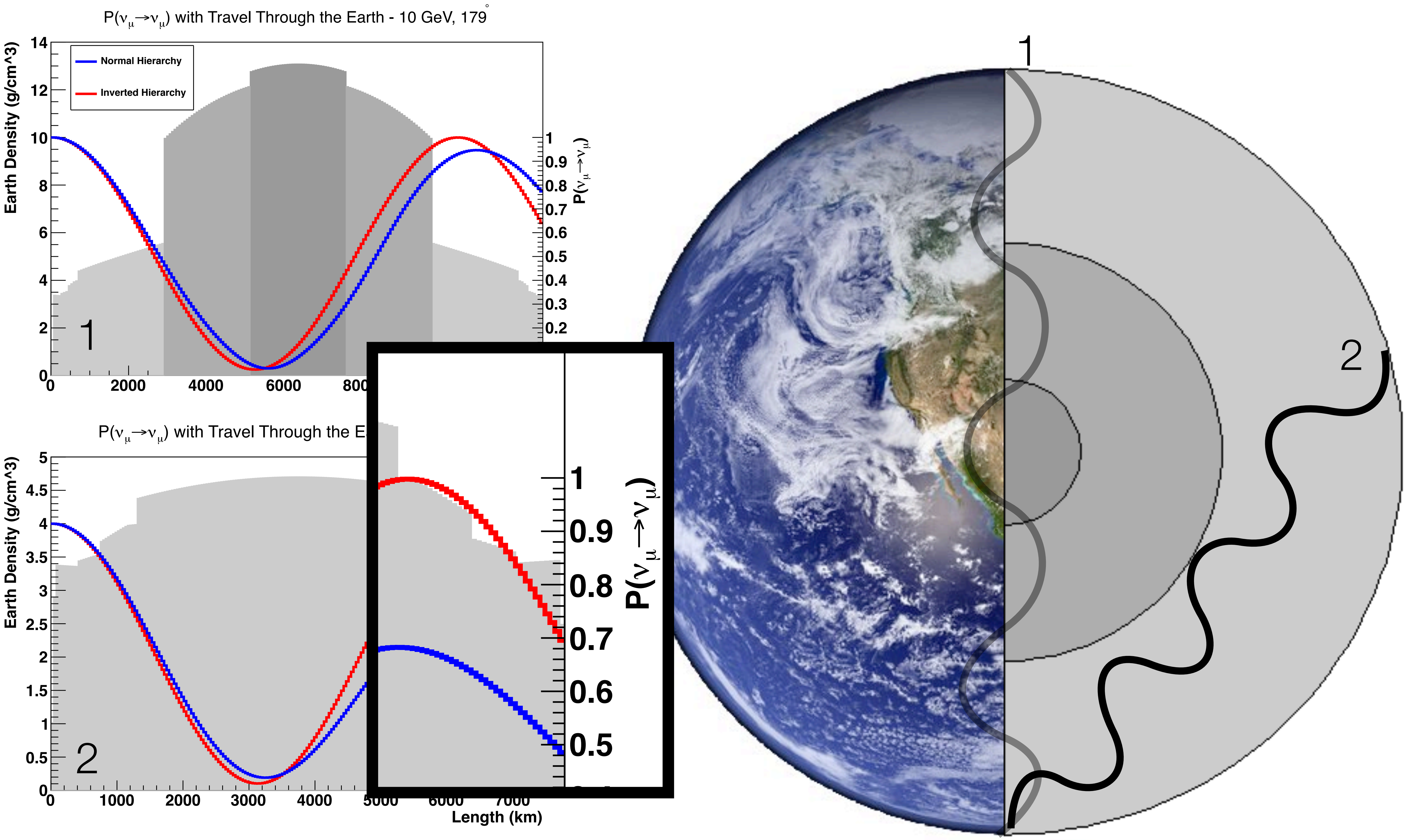


- Inverted/Normal hierarchy has up to a 20% difference in ν_μ oscillation probability for specific energies and zenith angles (baselines)

- Use method outlined in Akhmedov, Razzaque, Smirnov - arXiv:1205.7071

$$S_{tot} = \sqrt{\Sigma_{ij} \frac{(N_{ij}^{IH} - N_{ij}^{NH})^2}{N_{ij}^{NH}}}$$

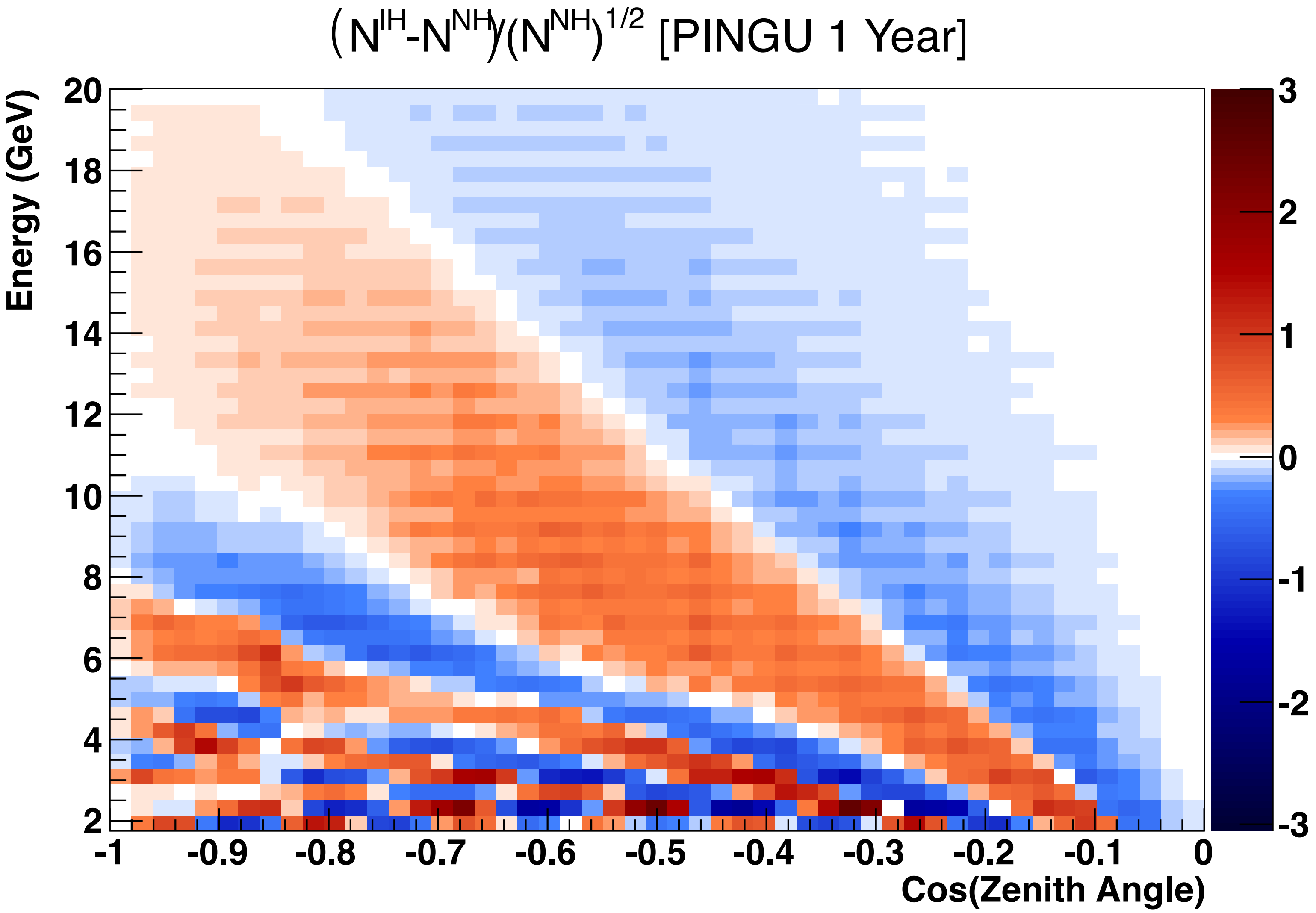
$$\begin{aligned} i &= \cos(zenith) \\ j &= energy \\ V^{eff} &= effective\ volume \end{aligned}$$

$$N_{i,j}^{NH} = P(\nu_\mu)_{i,j}^{NH} * \Phi(\nu_\mu)_{i,j} * \sigma(\nu_\mu)_j * V_{i,j}^{eff} + P^{NH}(\overline{\nu_\mu})_{ij} * \Phi(\overline{\nu_\mu})_{i,j} * \sigma(\overline{\nu_\mu})_j * V_{i,j}^{eff}$$

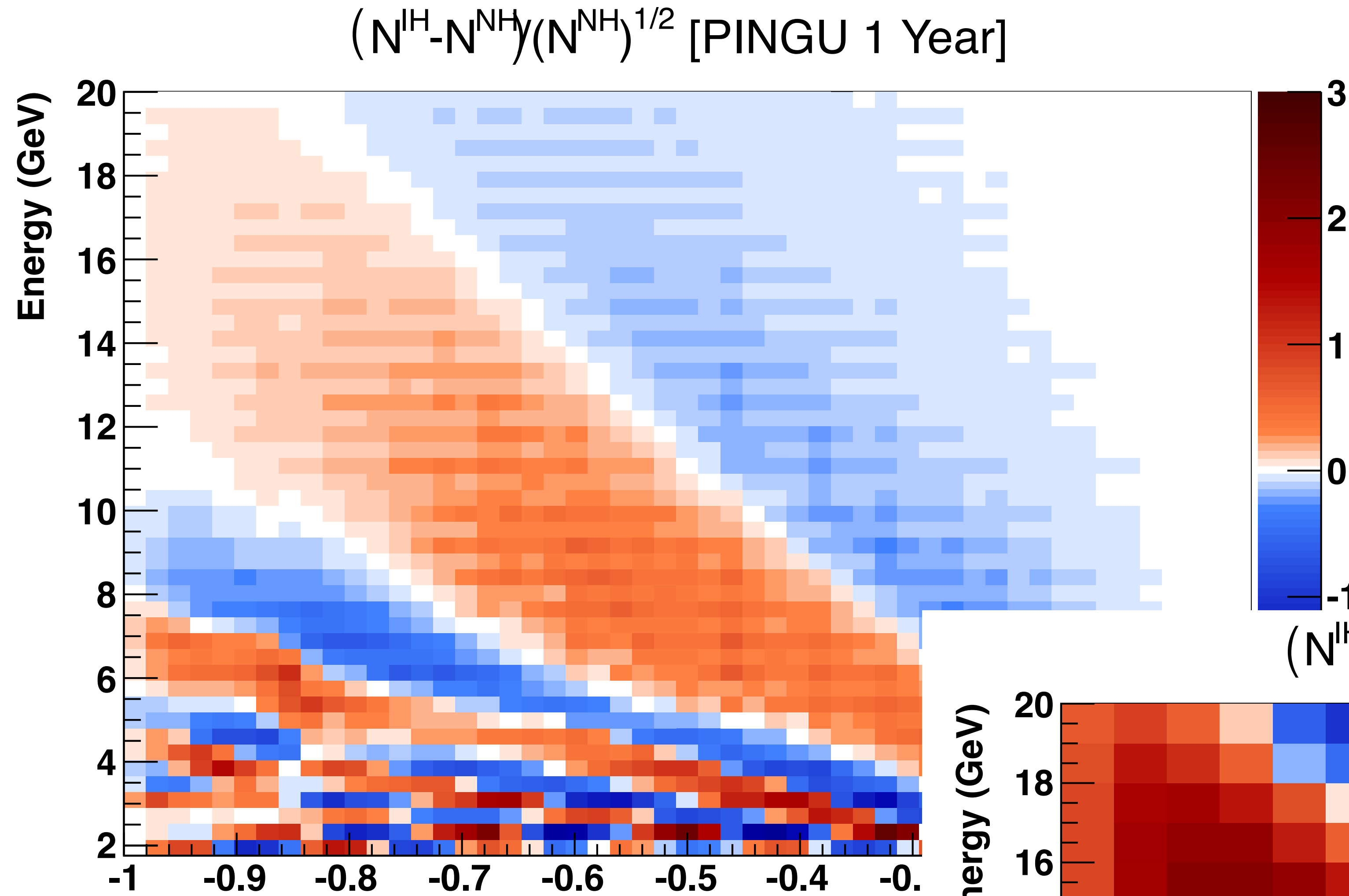
- Essentially bin, sum, and subtract one hierarchy from the other. It works because:

$$\begin{aligned} Probability &: P(\nu_\mu)^{IH} + P(\overline{\nu_\mu})^{IH} \neq P(\nu_\mu)^{NH} + P(\overline{\nu_\mu})^{NH} \\ Flux &: \Phi(\nu_\mu) > \Phi(\overline{\nu_\mu}) \\ Cross - Section &: \sigma(\nu_\mu) > \sigma(\overline{\nu_\mu}) \end{aligned}$$

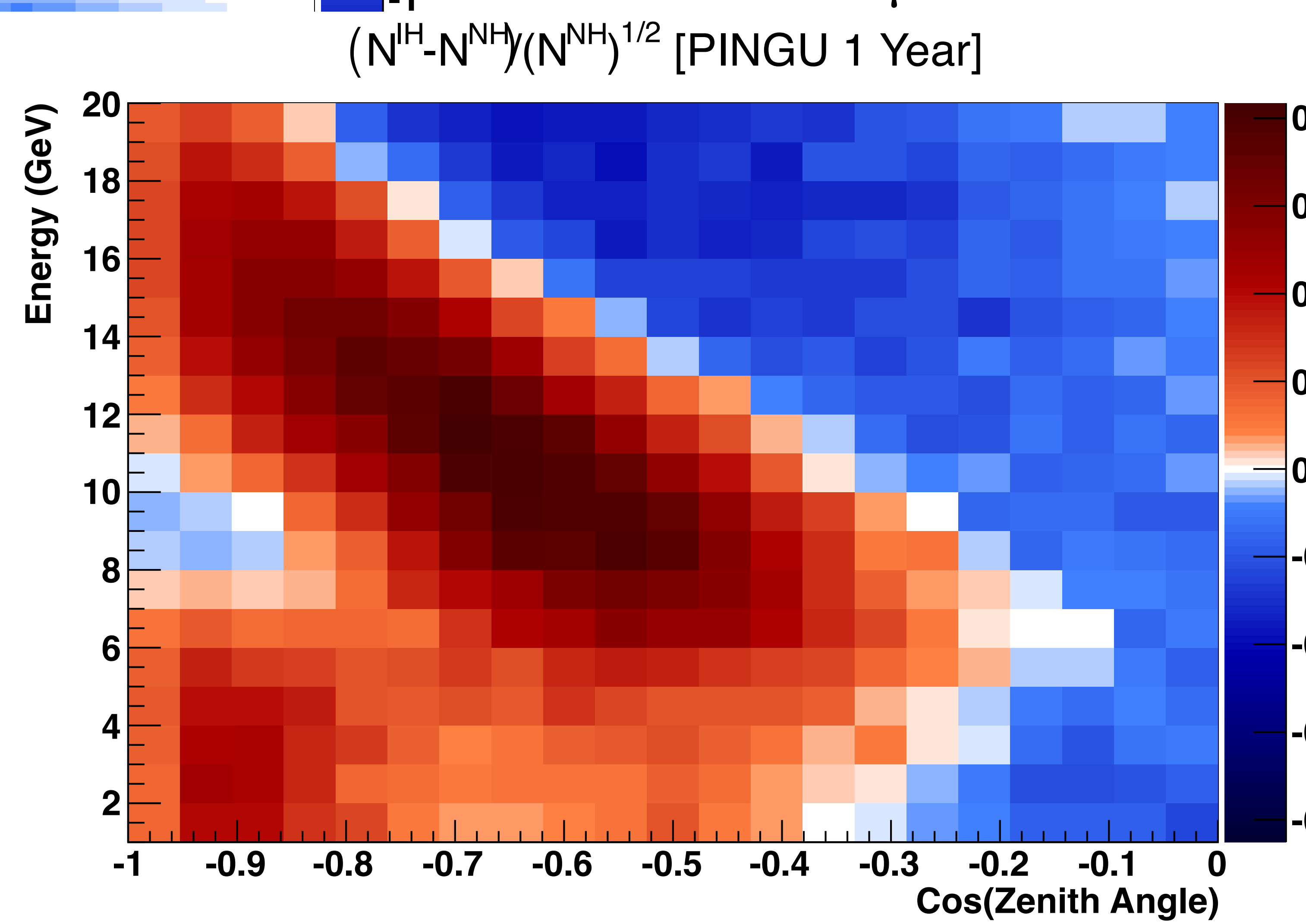
Hierarchy



- **Idealized case** w/ perfect event ID, 100% event selection efficiency, no quality cuts and no background
- Detector response (ice modeling, DOM efficiency) may play a major role in final sensitivity
- Evaluations of angular and energy resolution are ongoing



smeared: 3 GeV in ν_μ energy and 11.25° in μ zenith resolution



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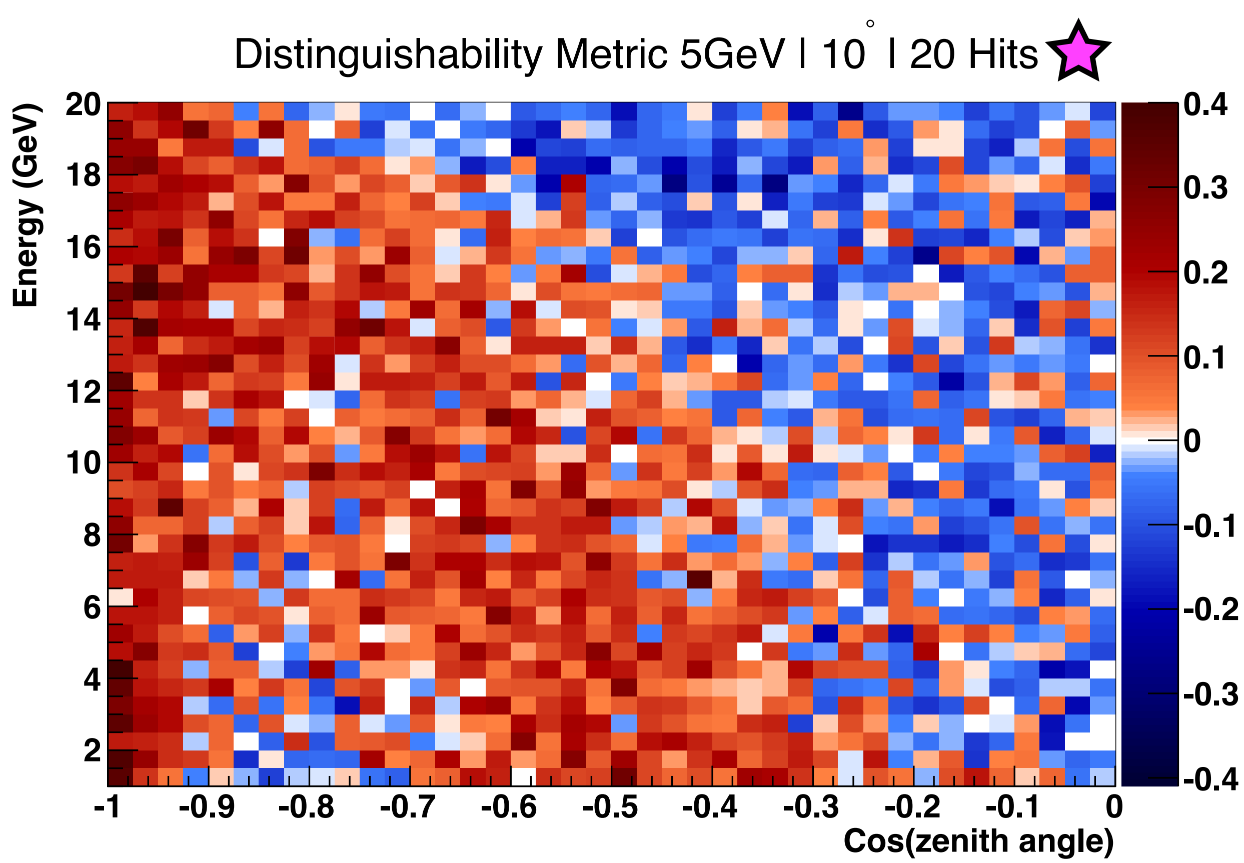
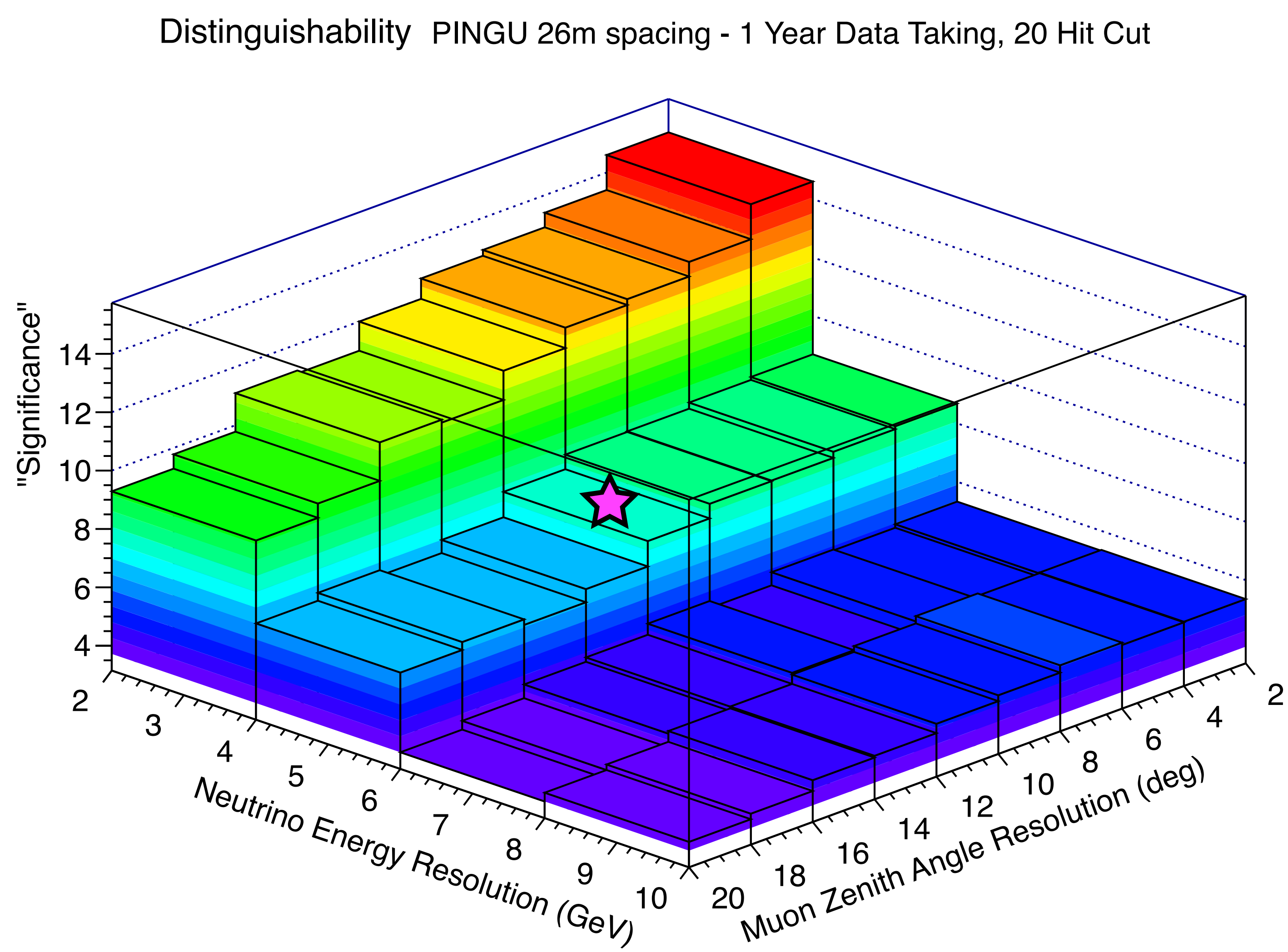
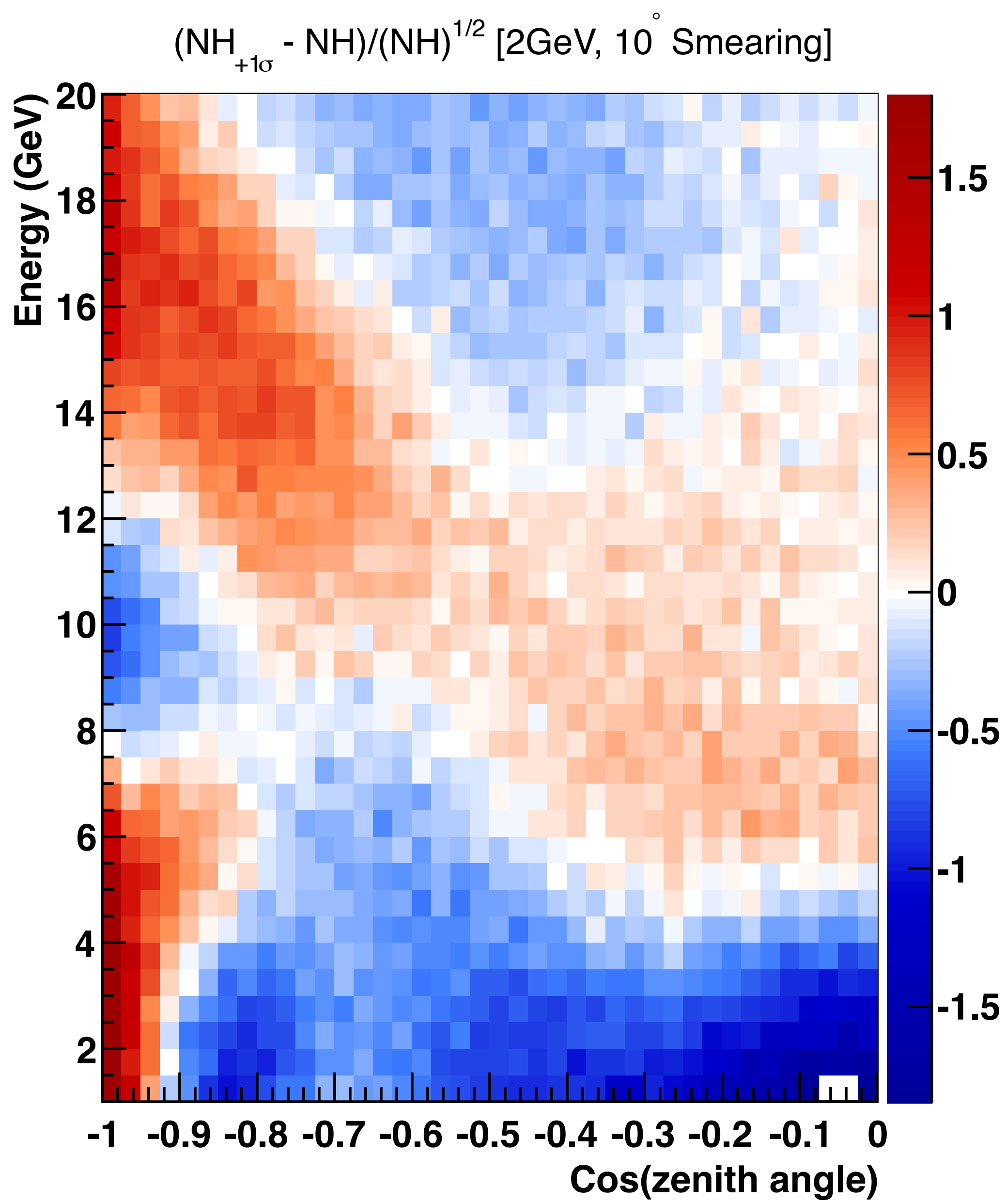
Detector/Reconstruction Issues

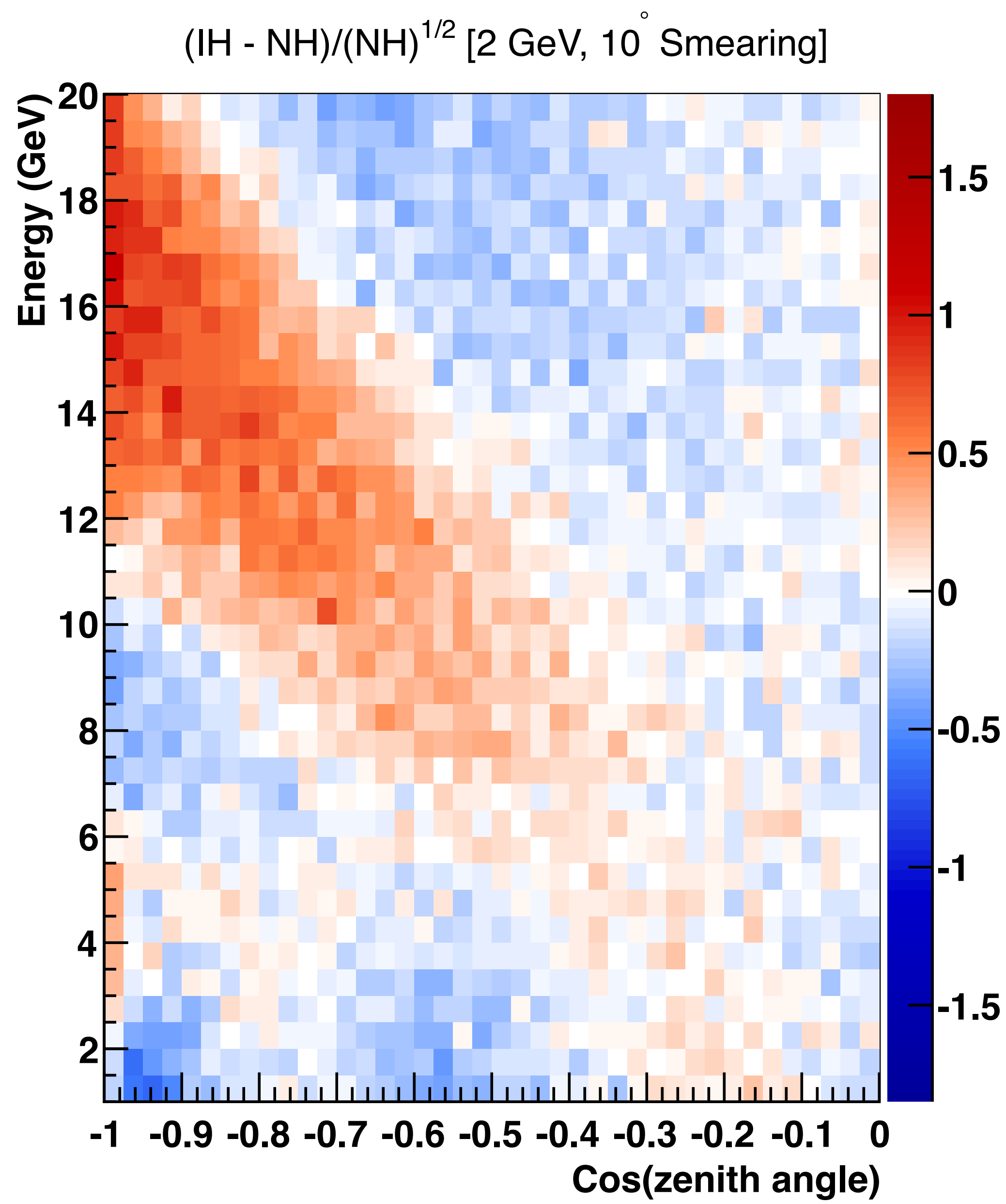
- There are benchmarks that relate hierarchy distinguishability to reconstruction uncertainties
  - A cut on 20 hits represents a reconstruction efficiency
  - Provide targets for ongoing reconstruction effort





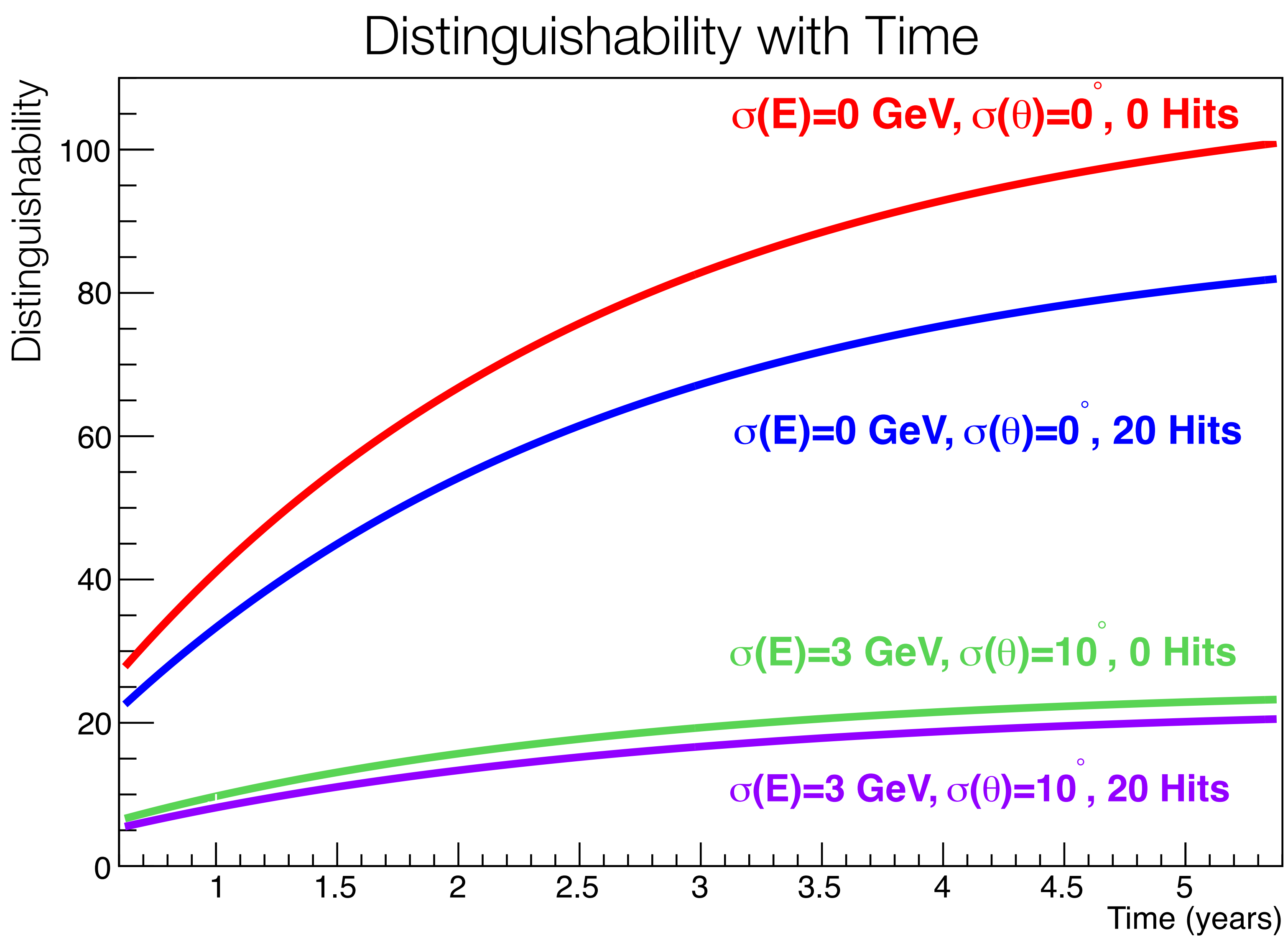
- Uncertainty in global Δm^2_{31} creates some degeneracy in the distinguishability metric
  - Plots have perfect event ID and 100% selection efficiency, but include energy and angle smearing





Time to Distinguishing

- The statistical power of PINGU makes systematics a critical factor sooner rather than later for hierarchy
  - PINGU specific - angular reco, energy reco, ice modeling...
  - Neutrino field at large - MC neutrino generators, cross-sections, atmospheric flux...



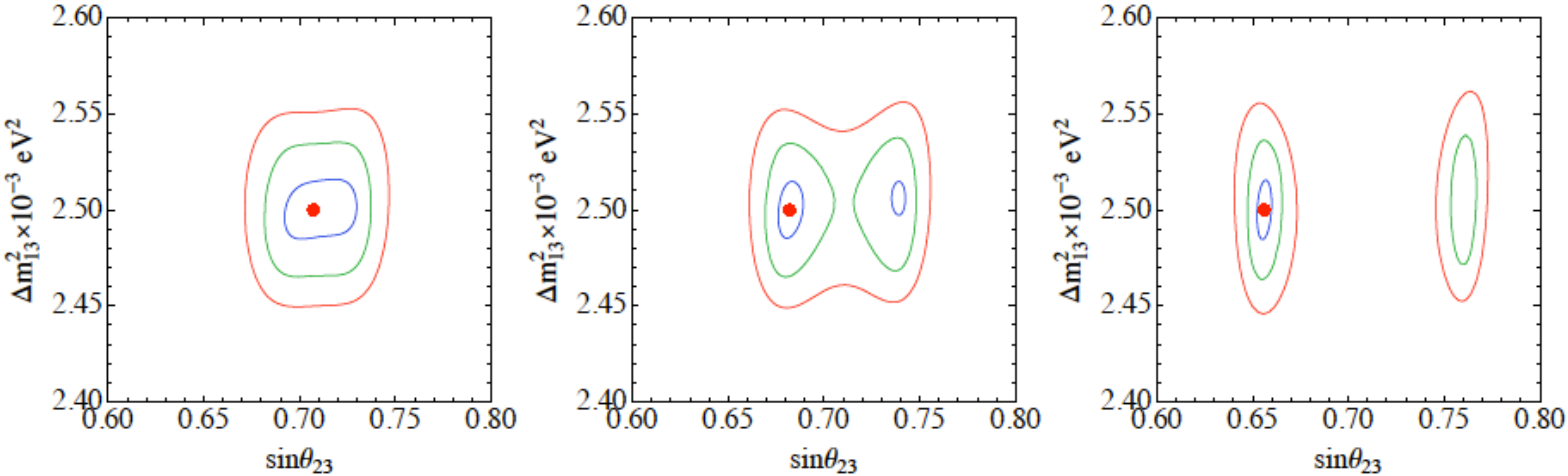
V6 Geometry

Leaving Feasible and
Moving on to Ambitious

θ_{23} Maximal? Octant?

- Instead of fitting $\sin^2 2\theta_{23}$ fit $\sin\theta_{23}$
- Requires lots and lots of events
  - Plots below are 10 years of DeepCore exposure w/ ambitious reco assumptions
  - But, the requirements are similar to what is necessary for resolving the hierarchy in PINGU

Observable energies of 5 to 50 GeV
10 energy bins, 4 angular bins
vs.
1st energy bin, 1 angular bin +
9 energy bins, 4 angular bins
vs.
Exclude first 2 energy bins:
8 energy bins, 4 angular bins



Fernandez-Martinez, Giordano, Mena, Mocioiu, PhysRevD.82.093011

PINGU Maximal Mixing

- Precision of atm. oscillation fit parameters will improve drastically the more minima/maxima can be resolved
- Trigger efficiency is much higher at lower energies for PINGU versus DeepCore
- PINGU/DeepCore covers all zeniths (baselines), while the oscillation minimum is at ~25 GeV @12700km, the minimum shifts to lower energies for decreasing baselines

$\sin^2(2\theta_{13})=0.1$

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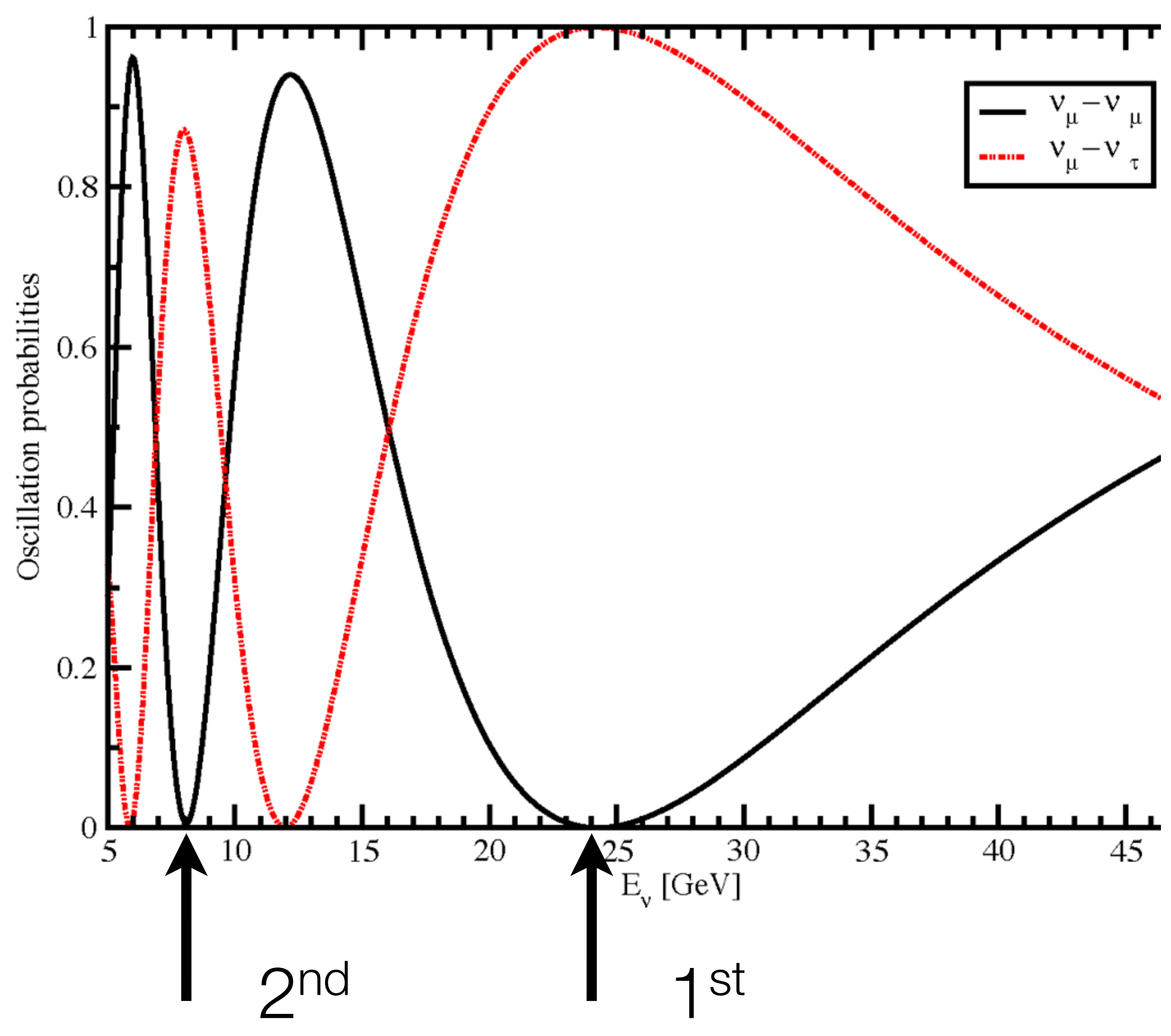
Mena, Mocioiu & Razzaque, *Phys. Rev.* D**78**, 093003



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Leaving Ambitious and Moving onto...

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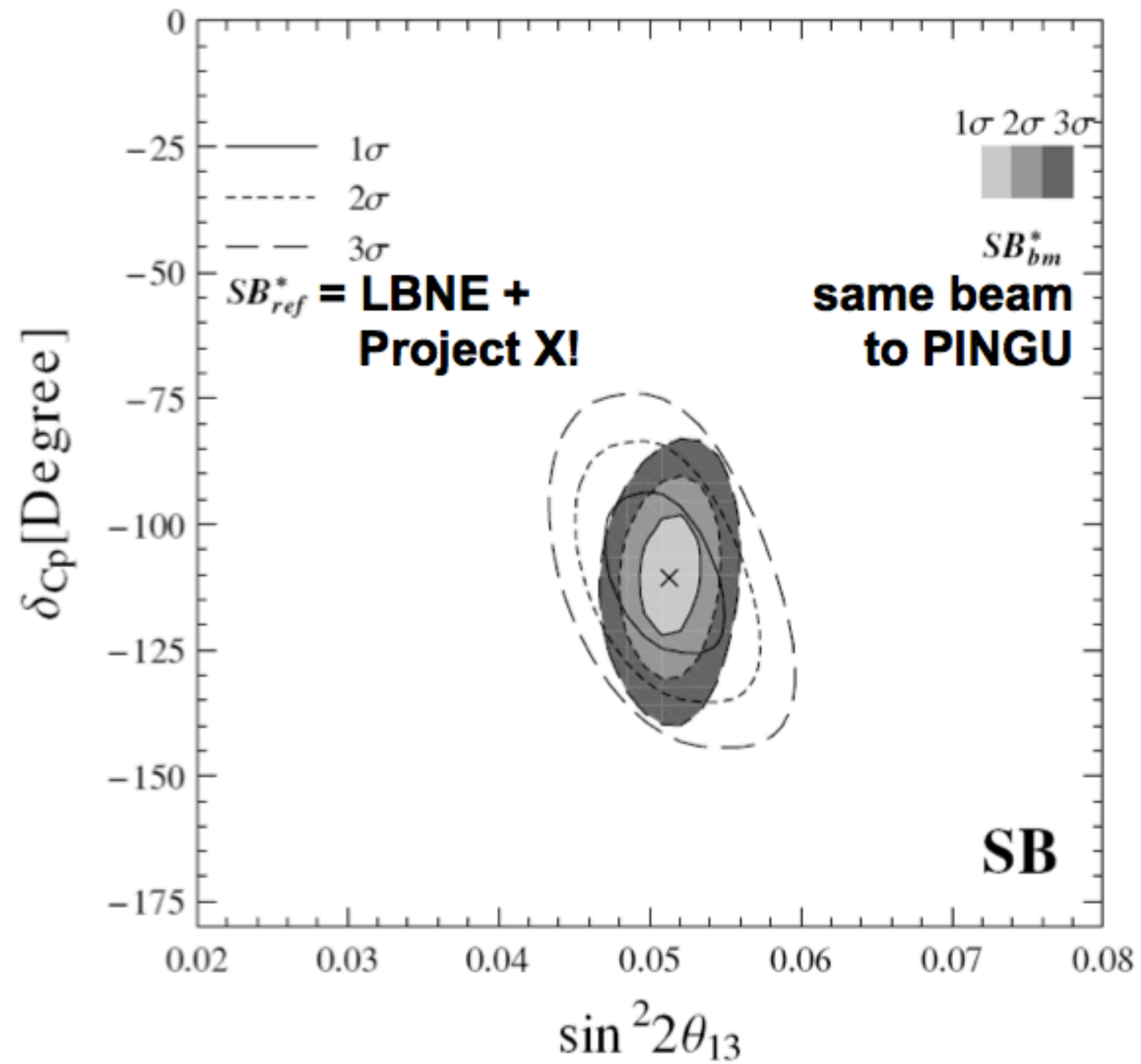
Beam?

"Superbeam FNAL-PINGU?", W. Winter

Julius-Maximilians-
UNIVERSITÄT WÜRZBURG

Upgrade path towards δ_{CP}?

- Measurement of δ_{CP} in principle possible, but challenging
- Requires:
  - Electromagnetic shower ID (here: 1% mis-ID)
  - Energy resolution (here: 20% x E)
  - Maybe: volume upgrade (here: ~ factor two)
  - Project X
- Performance and optimization of PINGU, and possible upgrades (MICA, …) require further study



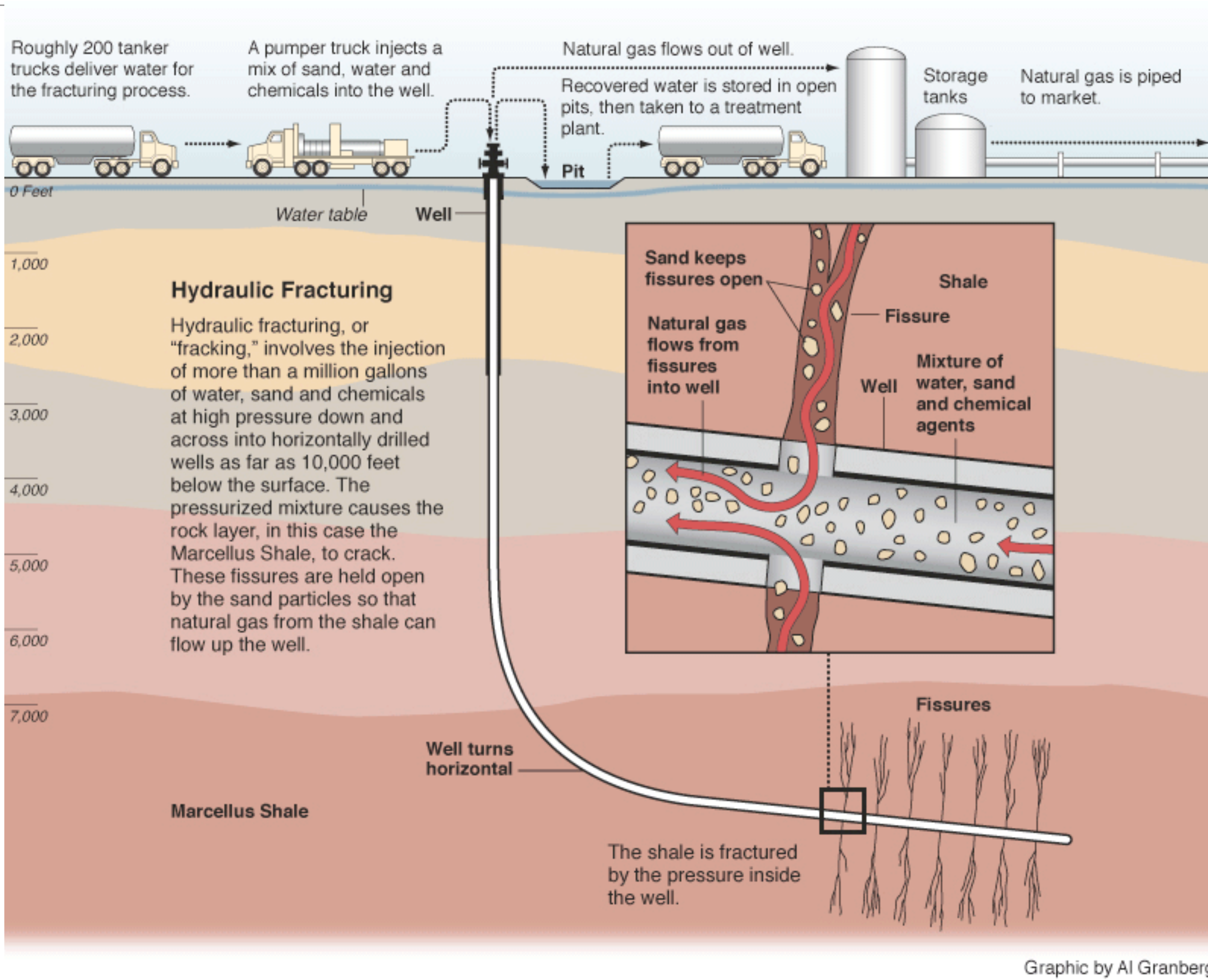
(Tang, Winter, JHEP 1202 (2012) 028)

15

- PINGU and MICA physics portfolio makes us of natural neutrino sources. Adding a beam will strengthen the diversity.
- Beam construction more of a headache than detector
  - 11620 baseline has a tilt angle of 65.8^{o} from FNAL (similar for CERN)
  - Hydraulic fracturing drills *may* provide help

‘Frakking’

- Maximal Mixing
- Beam?



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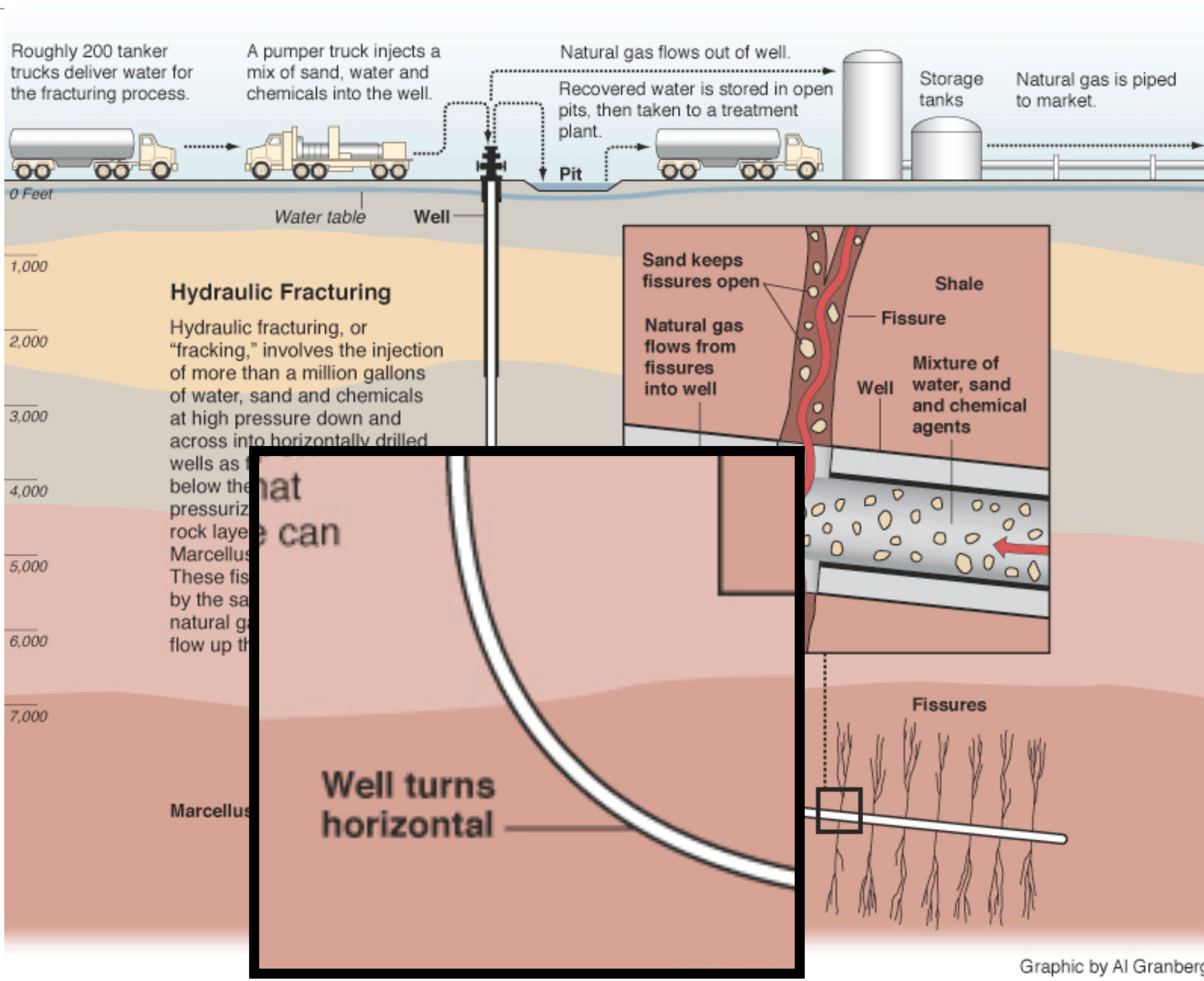

Future

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- Beam construction more of a headache than detector
  - 11620 baseline has a tilt angle of 65.8^{o} from FNAL (similar for CERN)
  - Hydraulic fracturing drills *may* provide help
- Melting ice is cheaper than excavating rock
  - Going bigger underground gets non-linearly expensive for civil construction (in a bad way)
  - Whereas, the difficulty of in-ice deployment is going smaller

PINGU Advantages

- Relatively quick, cost effective, huge and unique
  - 2-3 season deployment w/ additional ~1.5 year procurement/shipping
  - ~10M$ start up and ~1.25M$/string based on IceCube experience
  - Megaton size at GeV energies
  - Samples many angle, many baselines and crosses the earth core
- Enhance on-going DeepCore physics
  - muon disappearance
  - tau appearance
- Gains sensitivity to additional neutrino oscillation features
  - 2nd oscillation minima/maxima
  - Maximal θ_{23}
  - Neutrino hierarchy over all possible values of δ_{cp}
  - Maximal mixing and beam option

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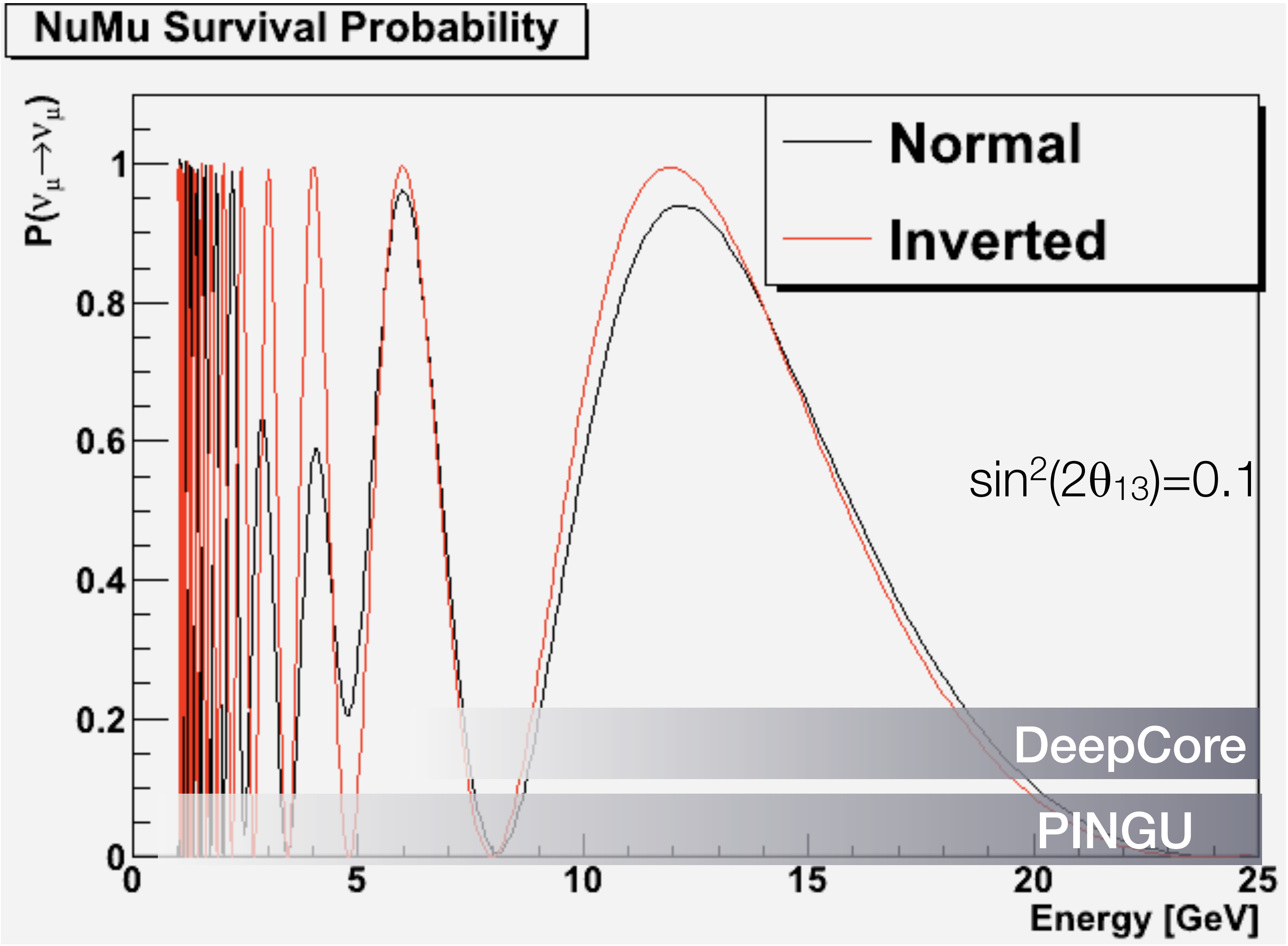
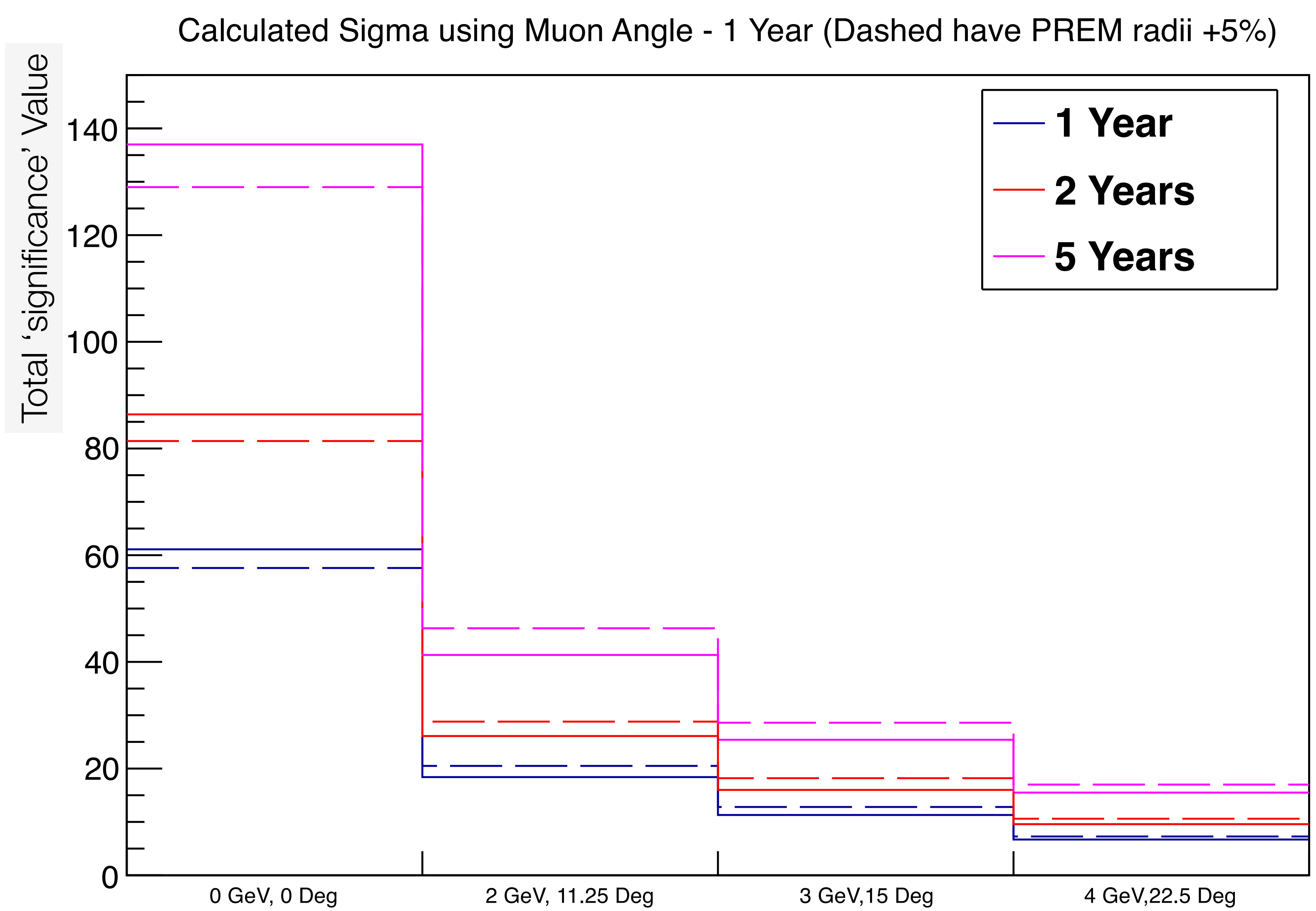
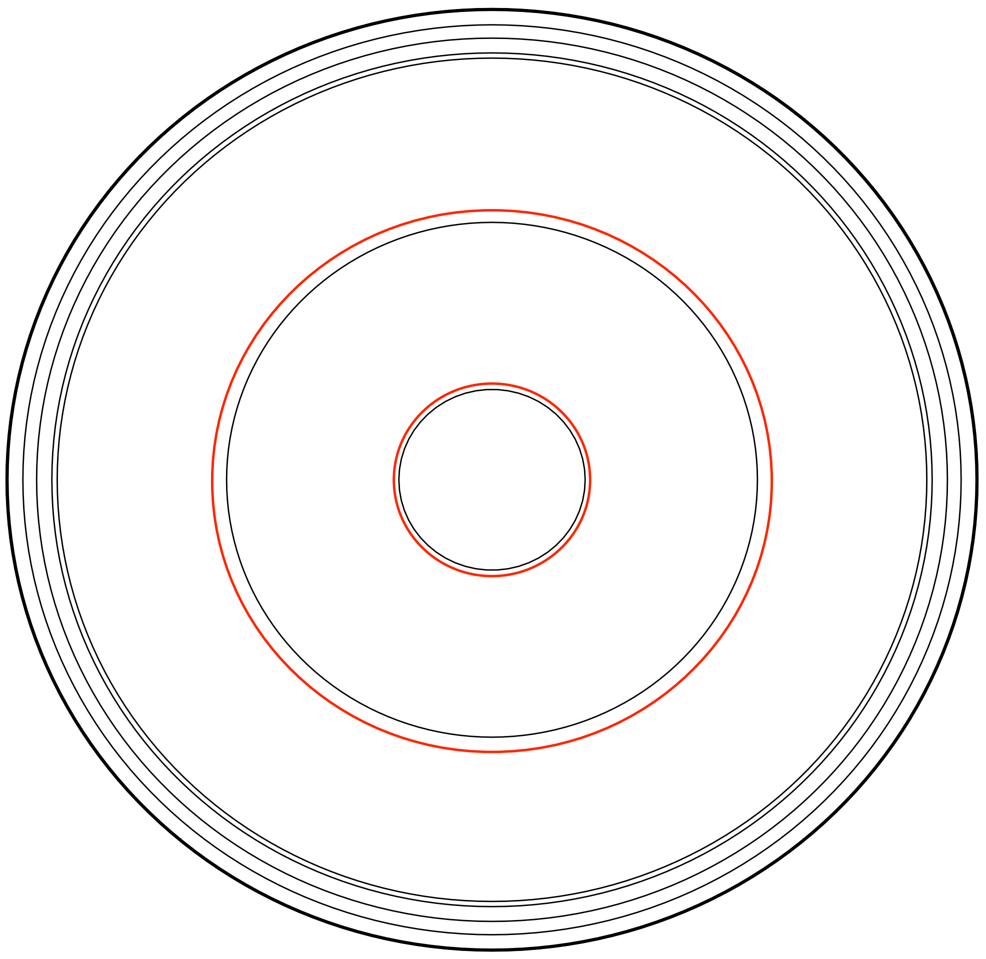
Backup

- Qualitative comparison of DeepCore to PINGU energy region

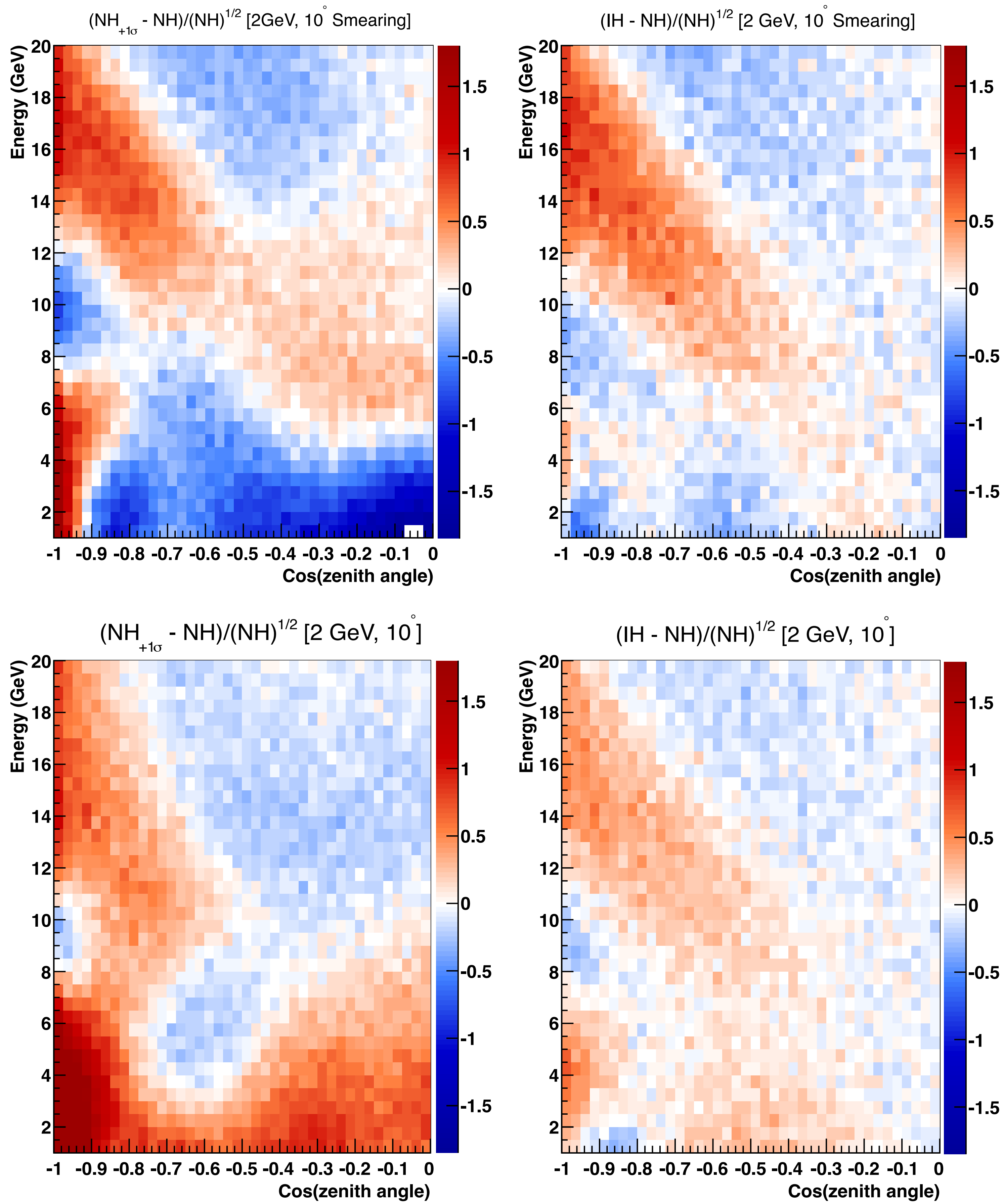


- Change the earth layers within the PREM model radii +5%
- Distinguishability is largely unaffected by PREM model uncertainty





- Including a 20 >= hit cut (bottom row) still shows some degeneracy between hierarchy ordering and uncertainty in Δm^2_{31}
- Event selection and analysis techniques can be used to reduce the degeneracy
  - Optimize for inelastic event selection
  - Likelihood analysis instead of a chi-squared like test



- In-situ cameras show that refrozen hole ice has a central column of 'cloudy' ice
- Degassing filters can be included on the hot water drill to reduce the addition of bubbles