PINGU: Neutrino Hierarchy Determination at the South Pole

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Intensity Frontier Department Physics Discussions
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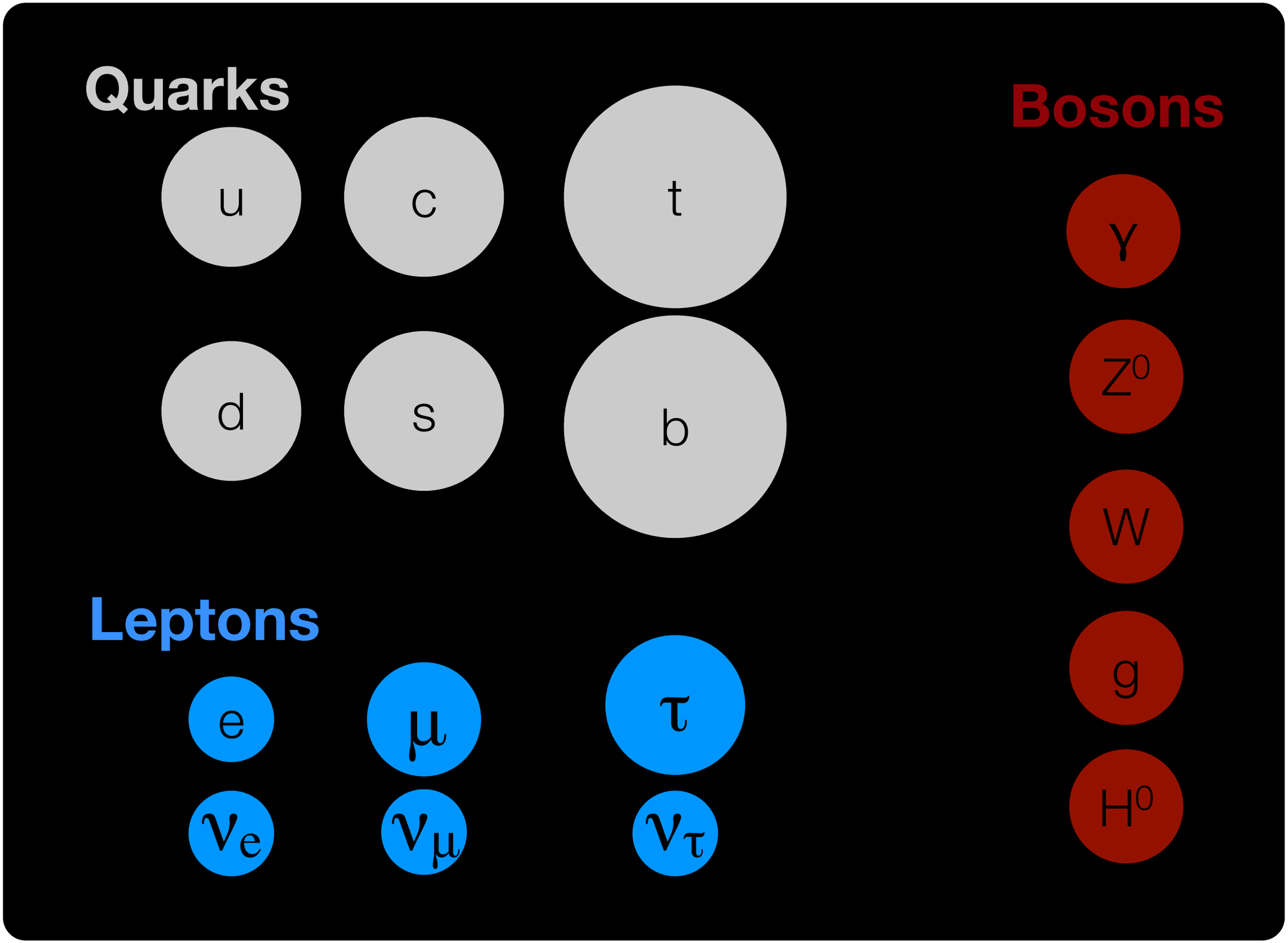
Why Neutrinos?

Standard Model



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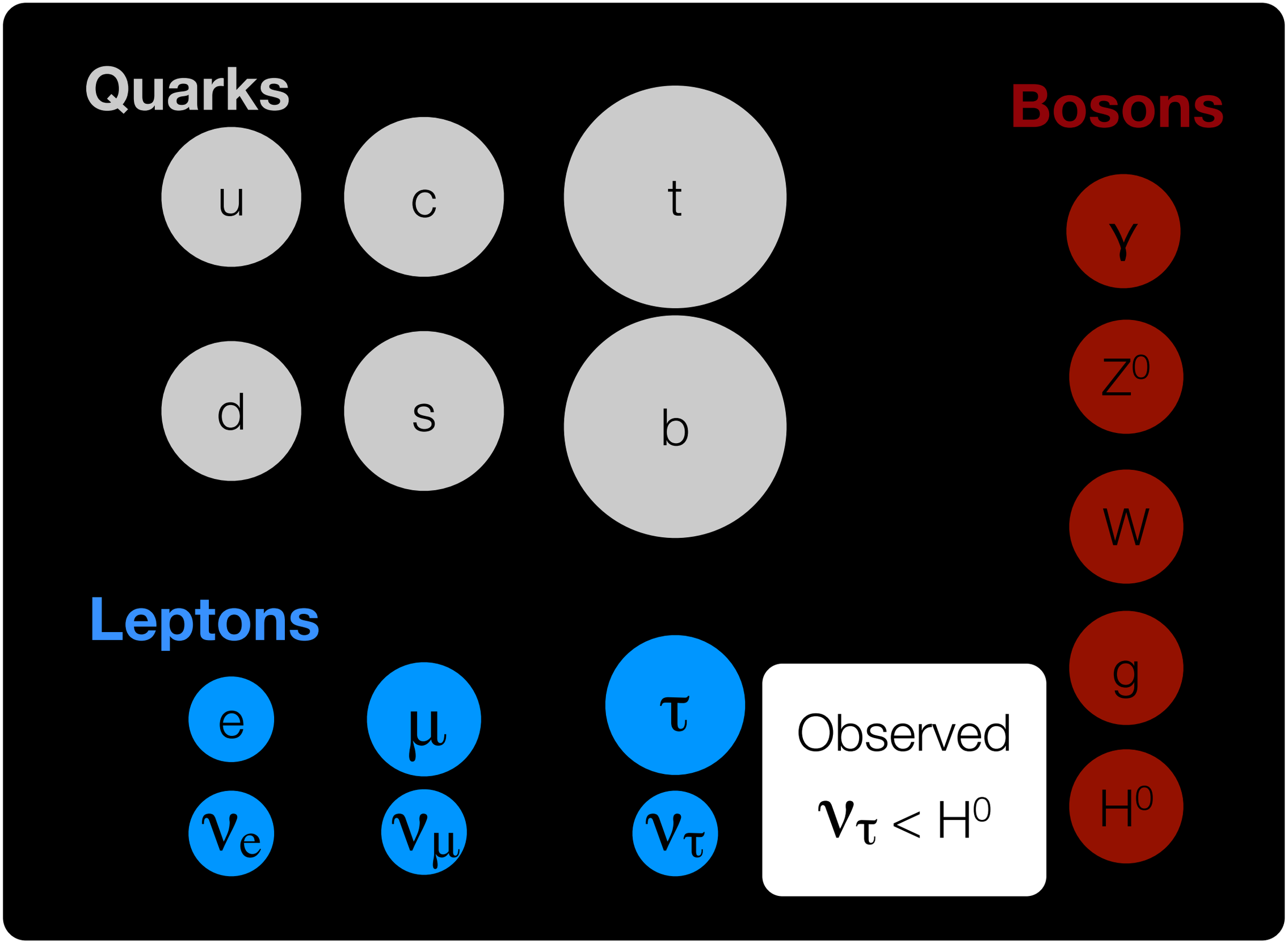


Neutrino Oscillation

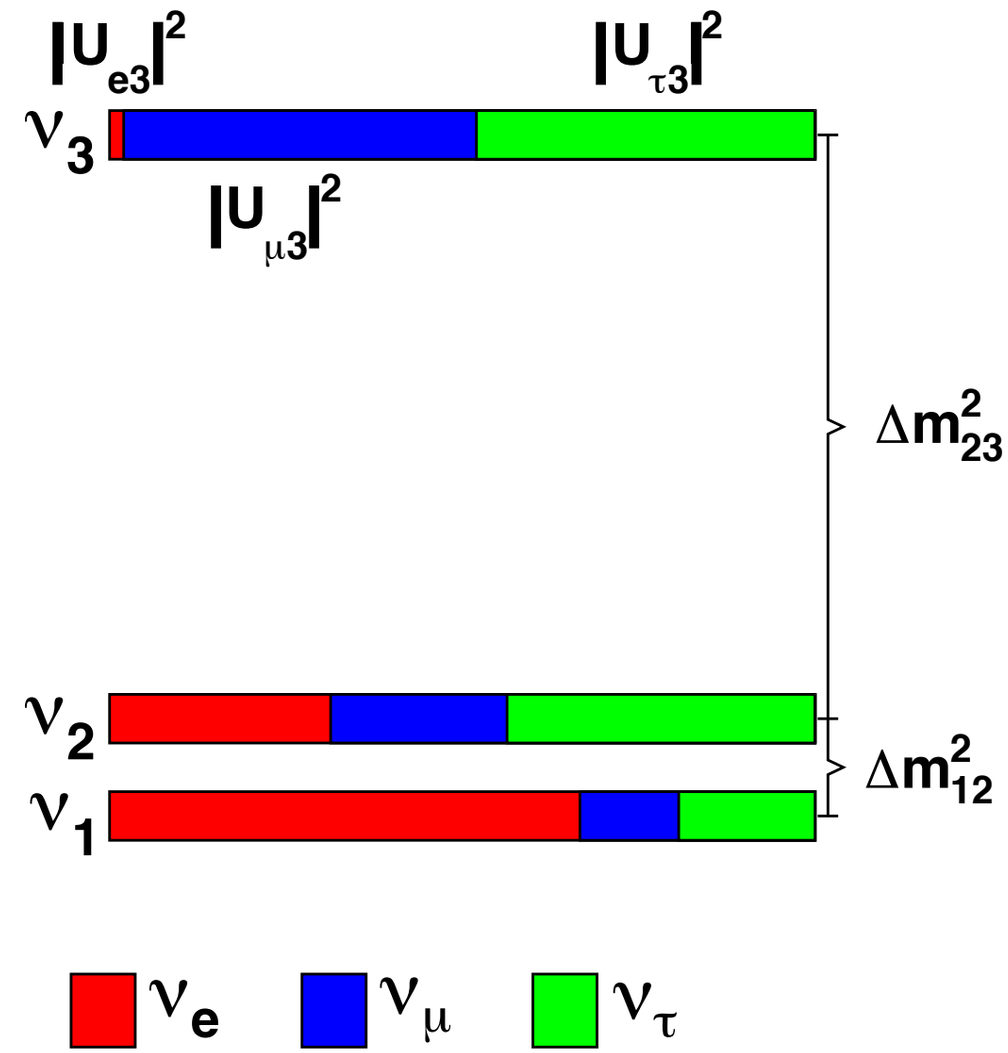
Flavor Eigenstate | Mass Eigenstate

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \mathcal{U}_{\mathrm{PMNS}} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- Neutrino flavor eigenstates are related to mass eigenstates via the PMNS Unitary mixing matrix

Neutrino Mixing Diagram



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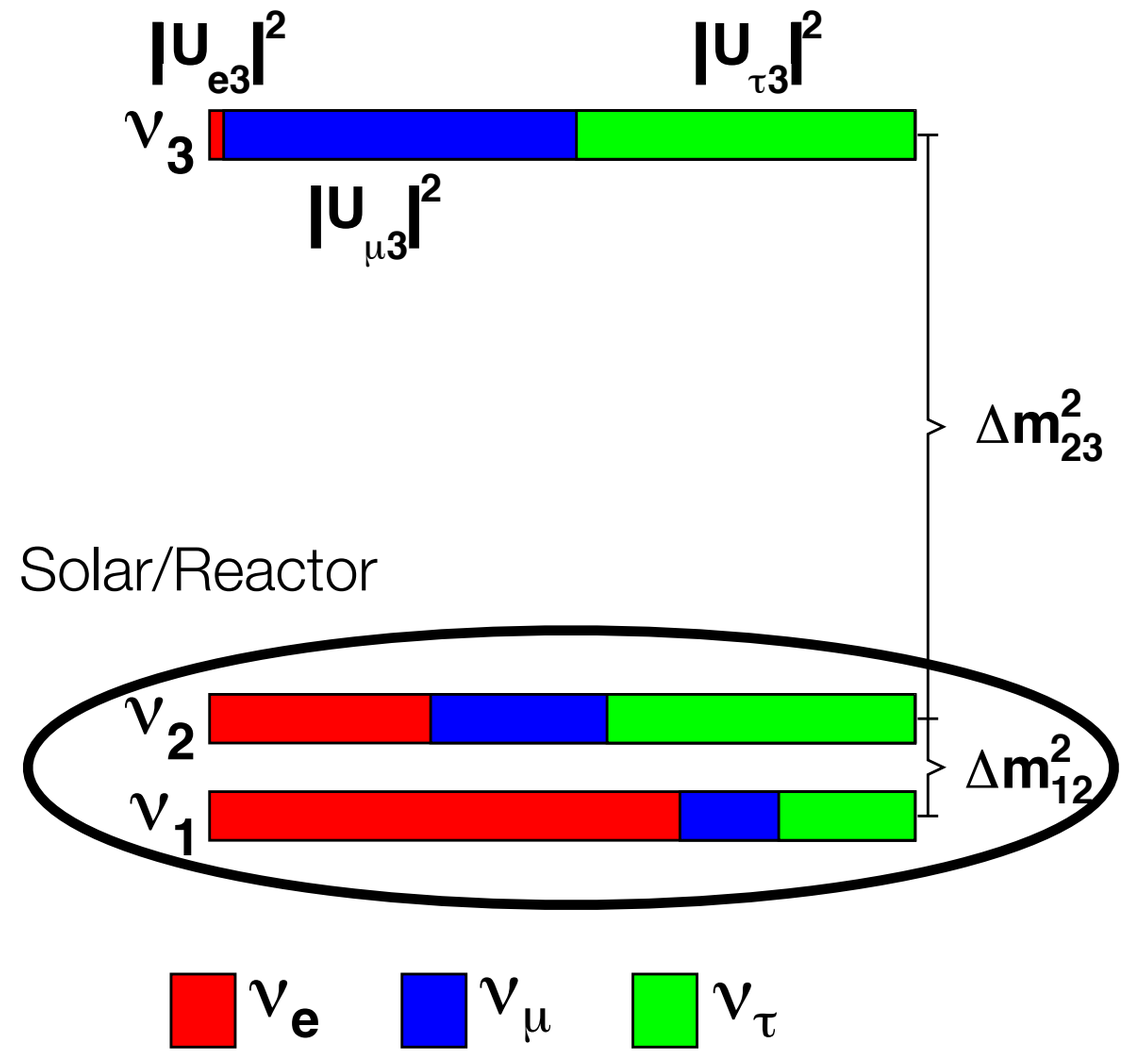
Neutrino Mixing Diagram

Experiment type	Oscillation Channel
Solar & Reactor	$(\nu_e \rightarrow \nu_\mu)$



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Neutrino Mixing Diagram

Experiment type	Oscillation Channel
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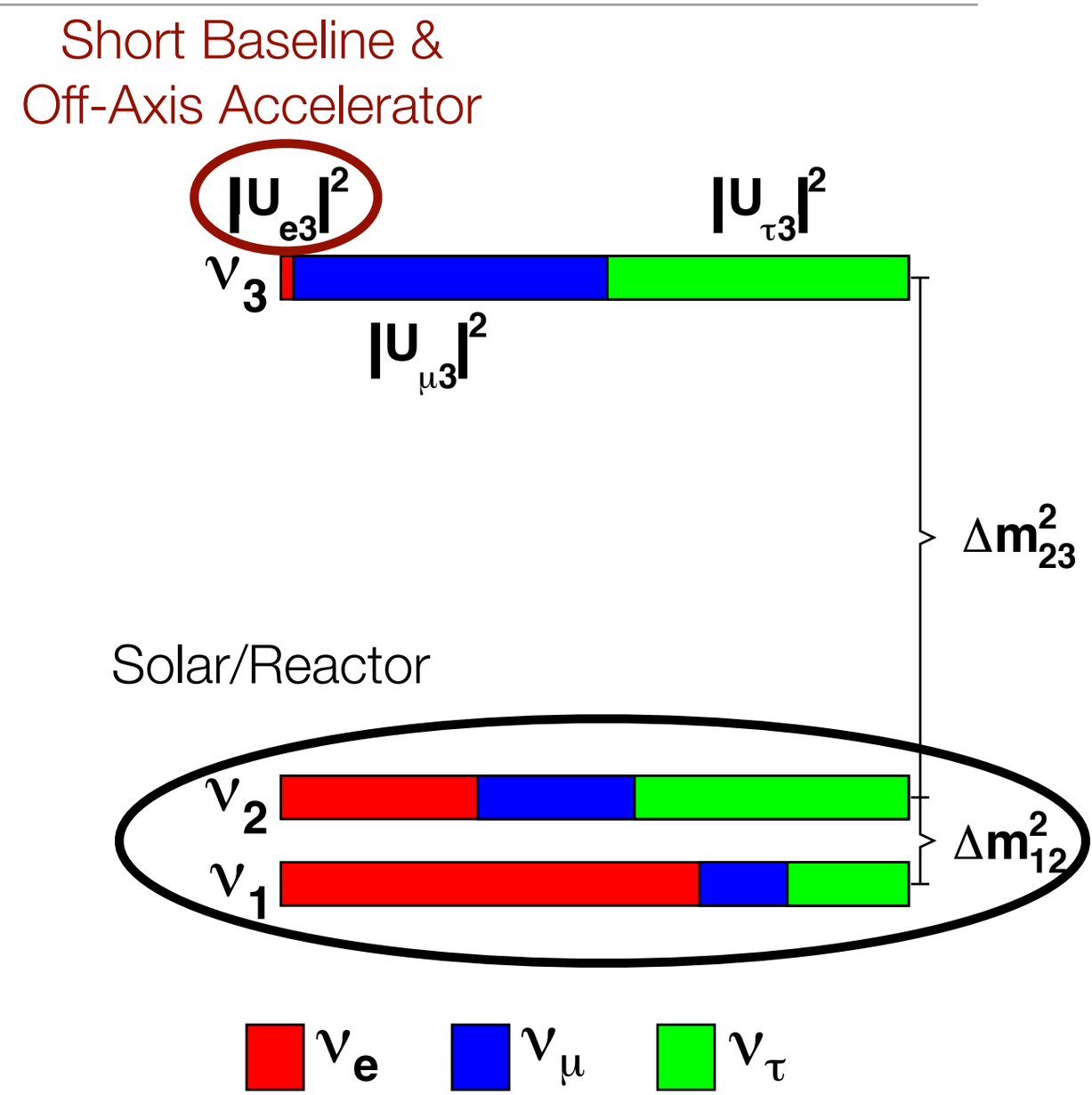
Short Baseline (SBL) & Off-Axis	$(\nu_e \rightarrow \nu_e)$ $(\nu_\mu \rightarrow \nu_e)$



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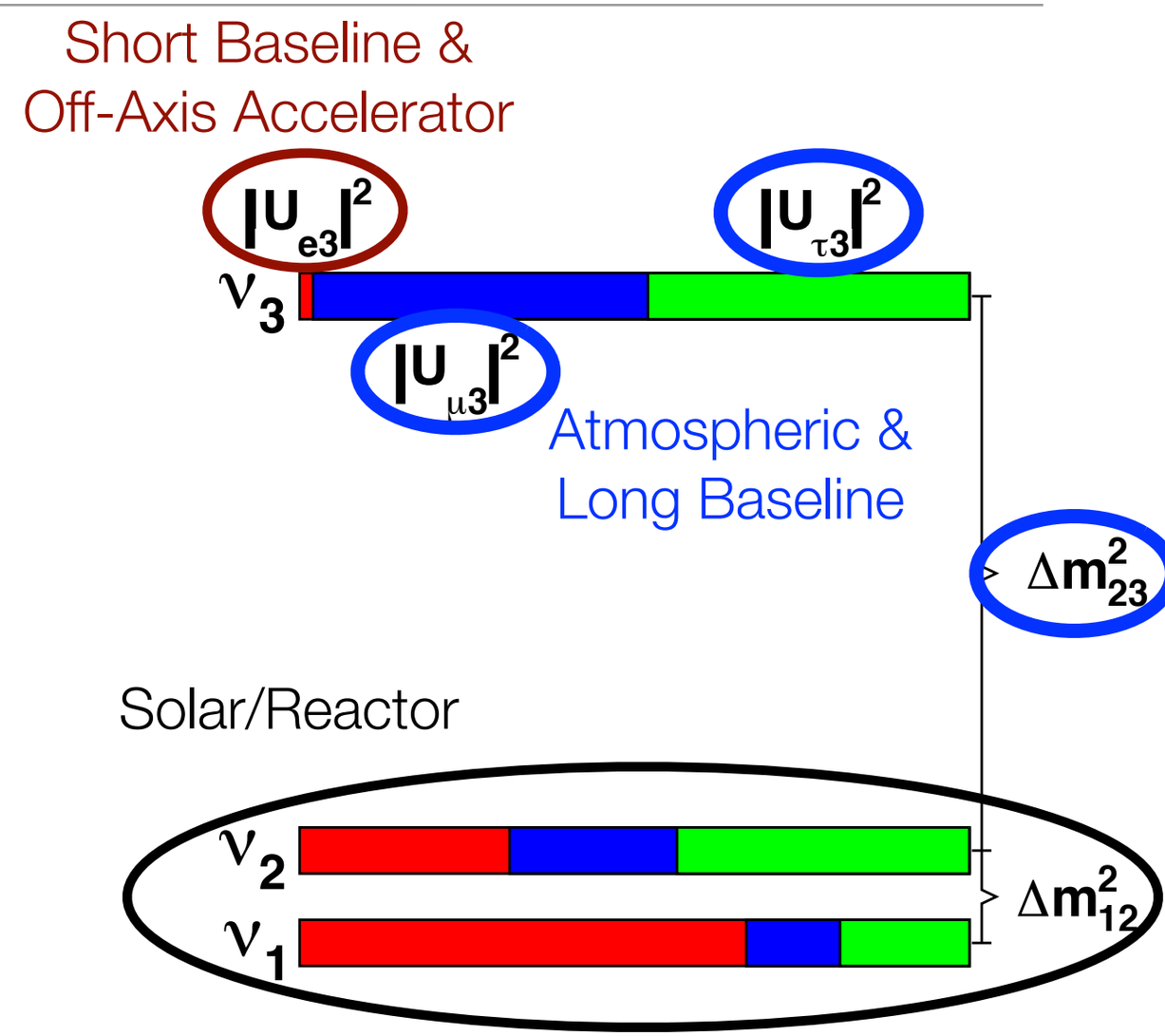
Neutrino Mixing Diagram

Experiment type	Oscillation Channel
Solar & Reactor	$(\nu_e \rightarrow \nu_\mu)$
Short Baseline (SBL) & Off-Axis	$(\nu_e \rightarrow \nu_e)$ $(\nu_\mu \rightarrow \nu_e)$
Atmospheric & Long Baseline	$(\nu_\mu \rightarrow \nu_\mu)$ $(\nu_\mu \rightarrow \nu_\tau)$



ν_e ν_μ ν_τ

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Focus

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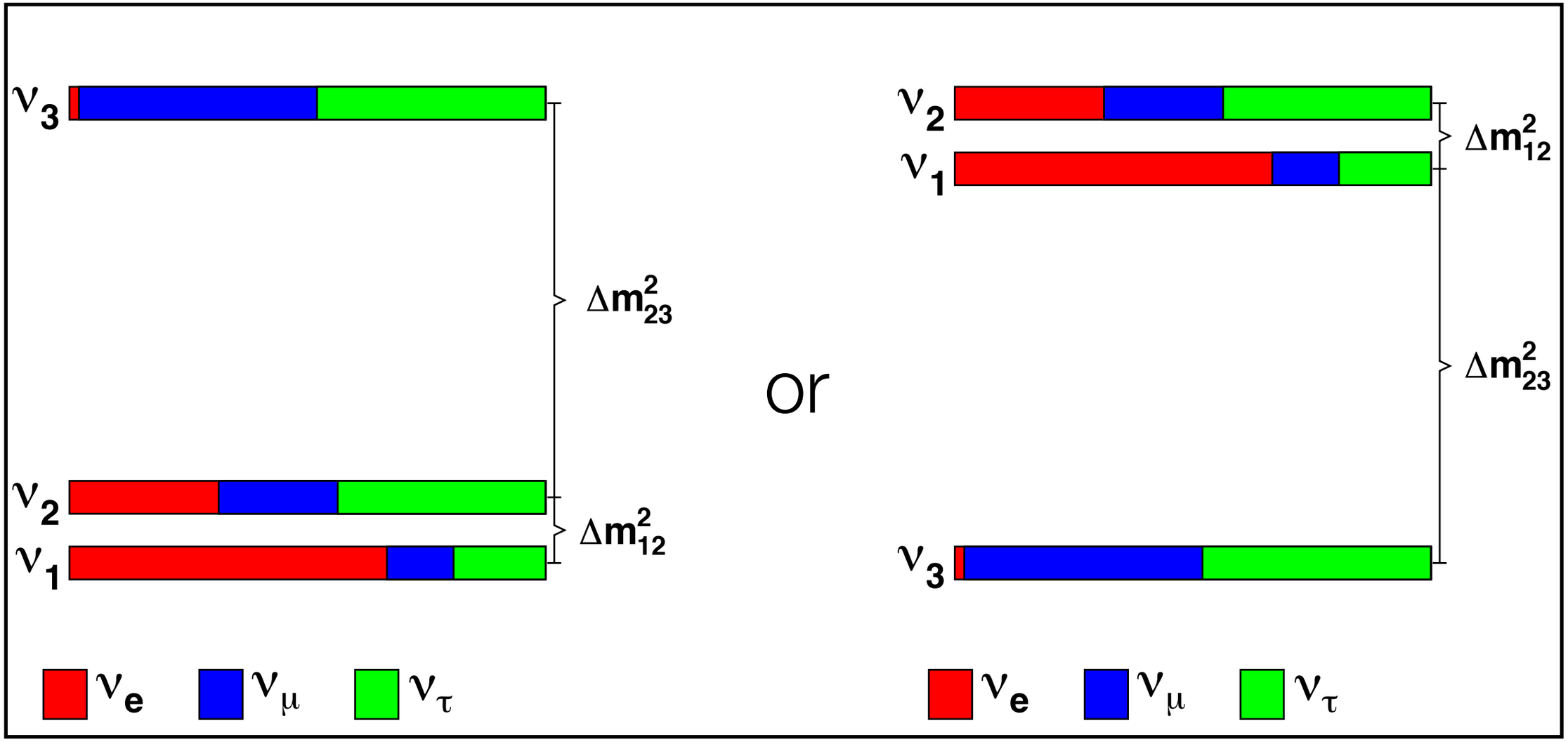
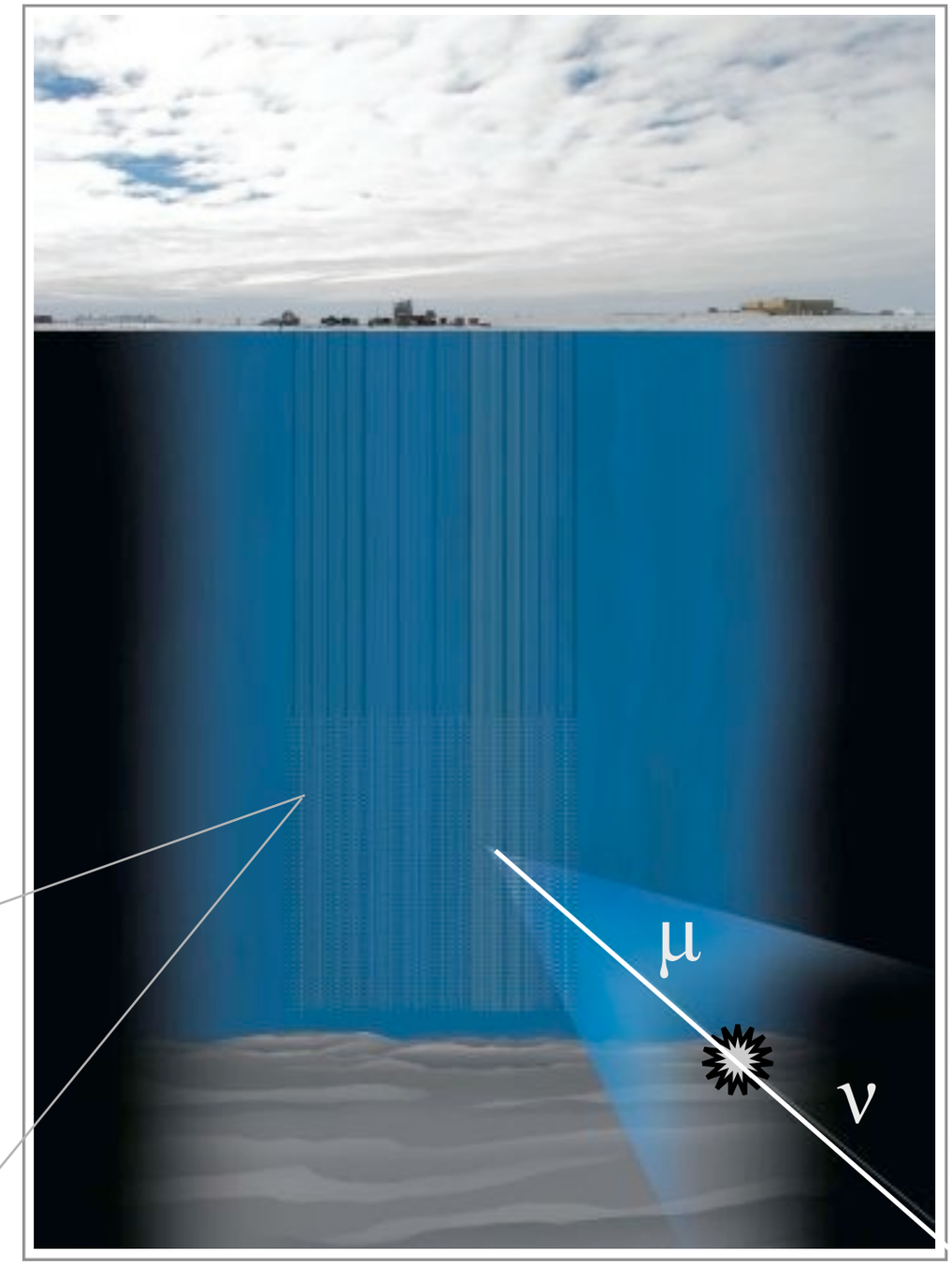
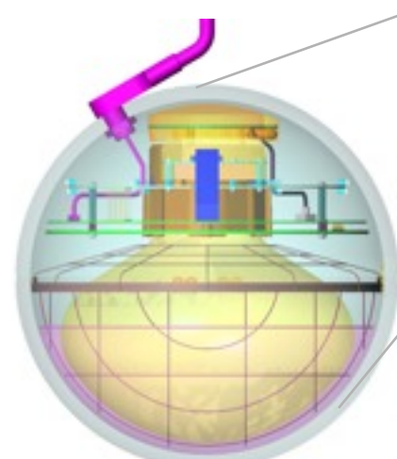

ν_3
ν_2
ν_1
Δm^2_{23}
Δm^2_{12}
or
ν_2
ν_1
Δm^2_{12}
Δm^2_{23}
ν_3
ν_e ν_μ ν_τ
ν_e ν_μ ν_τ

South Pole Setup

IceCube

- ~1km^3 of instrumented ice
- Uses 5160 Digital Optical Modules (DOMs) across 86 vertical strings to detect Cherenkov radiation
- 160 Cherenkov tank surface array (IceTop)
- Deployed 1.5 - 2.5km below the surface





IceCube DOM

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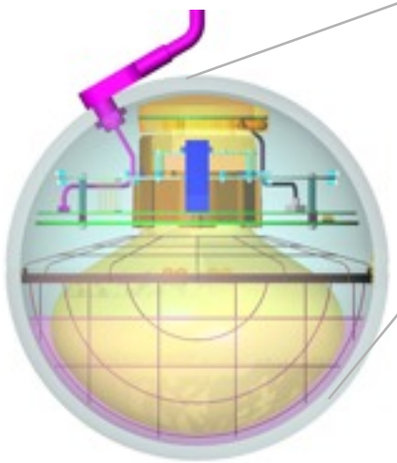

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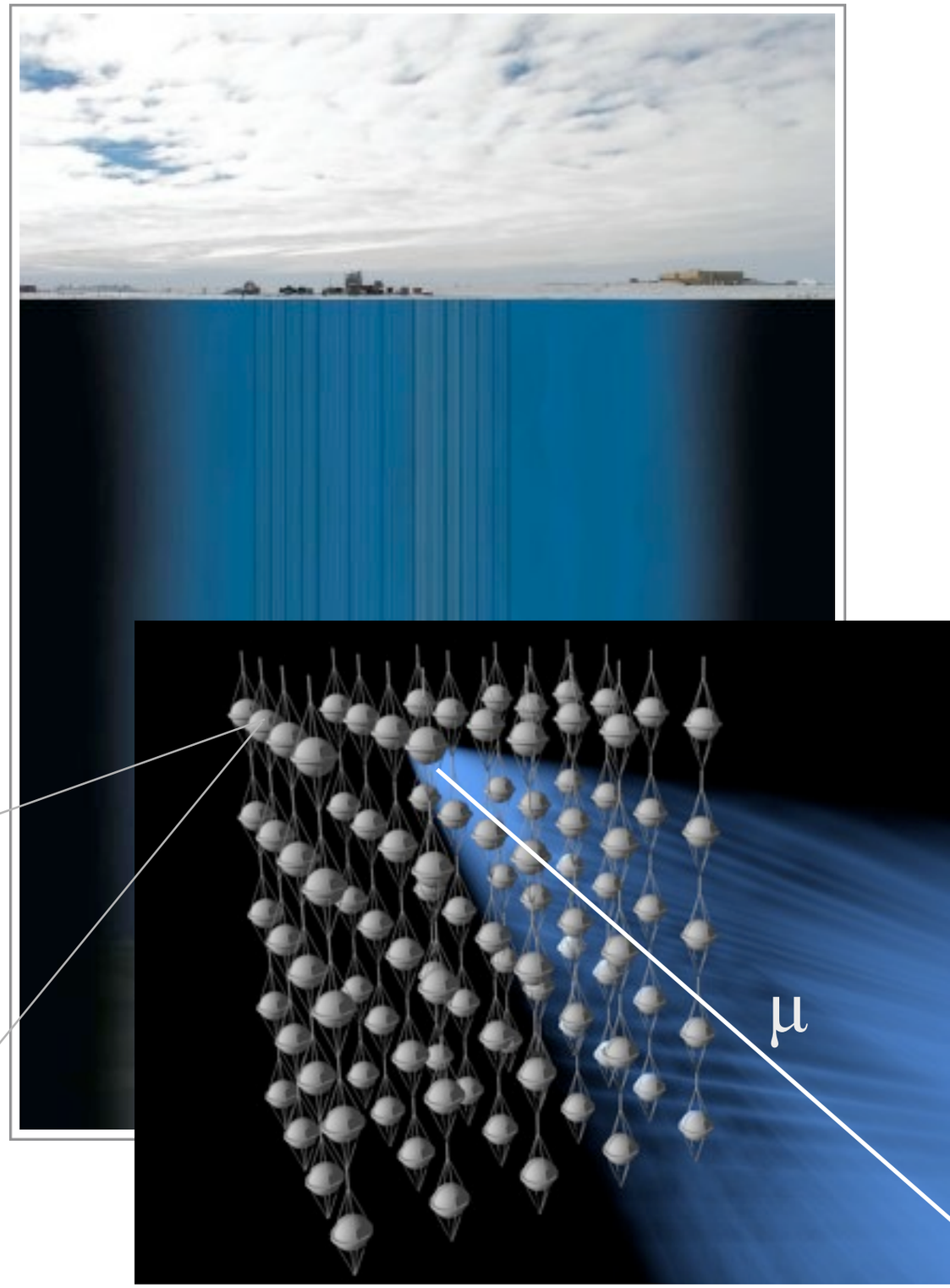


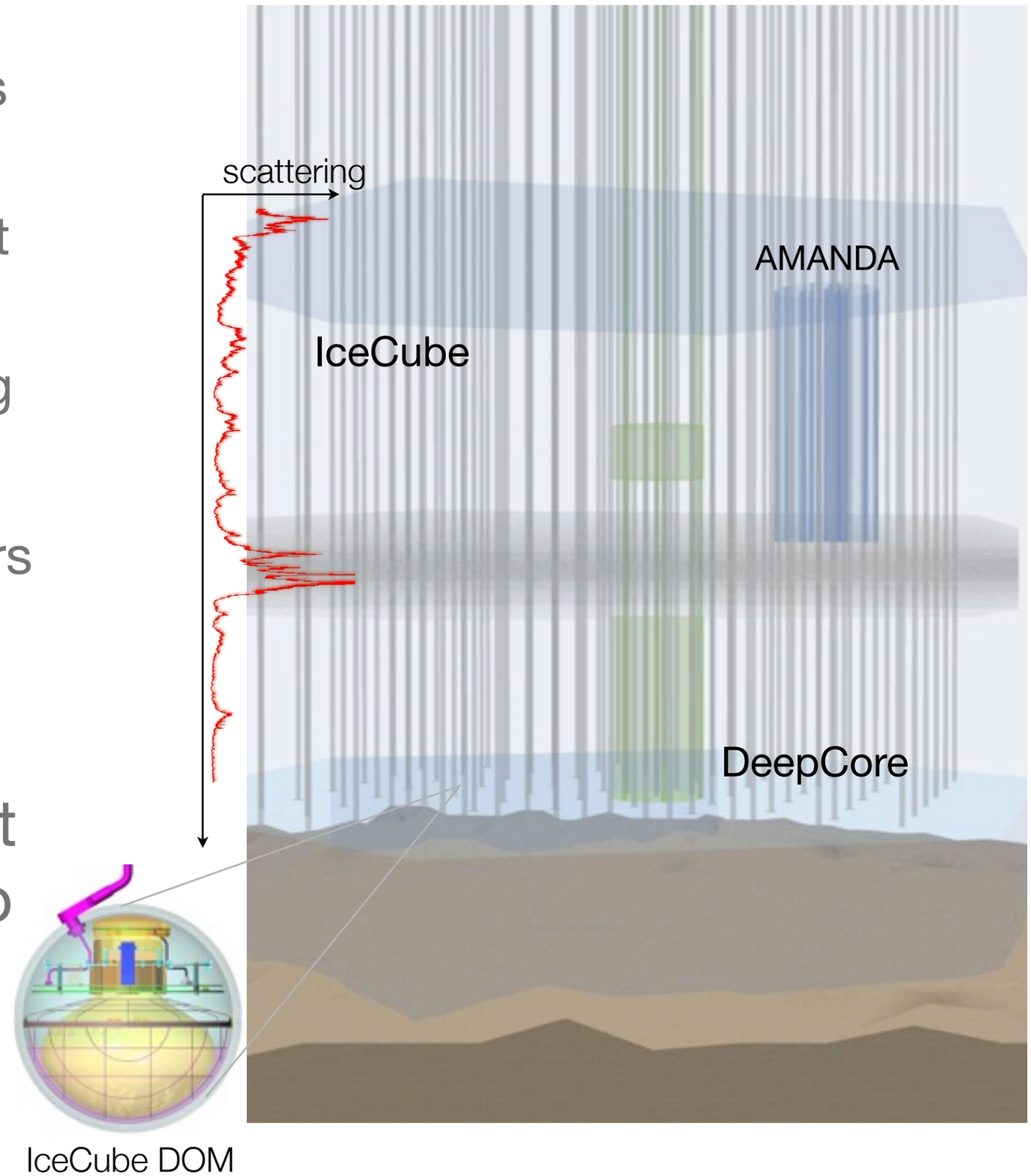
Collaboration

The IceCube Collaboration

~36 institutions - 4 continents - ~250 Collaborators

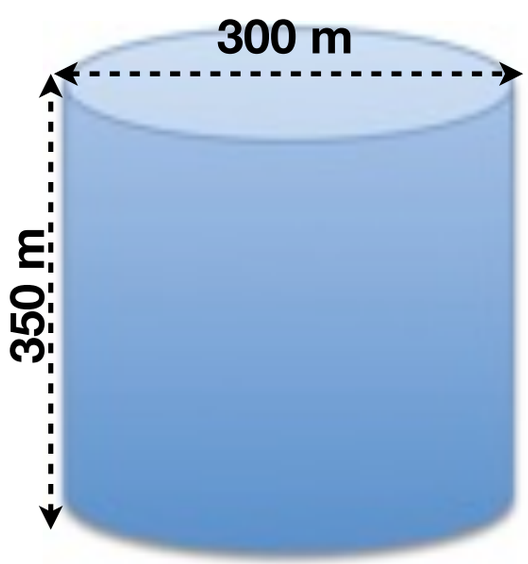
IceCube + DeepCore

- DeepCore
  - Increased sensitivity at energies < 100-200 GeV
  - 8 special strings plus 12 closest IceCube-standard strings
  - Denser DOM and string spacing
  - Deepest and clearest Ice
  - Higher efficiency photon sensors
  - Lower trigger threshold
- IceCube is not only a high energy neutrino detector, but also a cosmic ray muon veto for any inner detectors

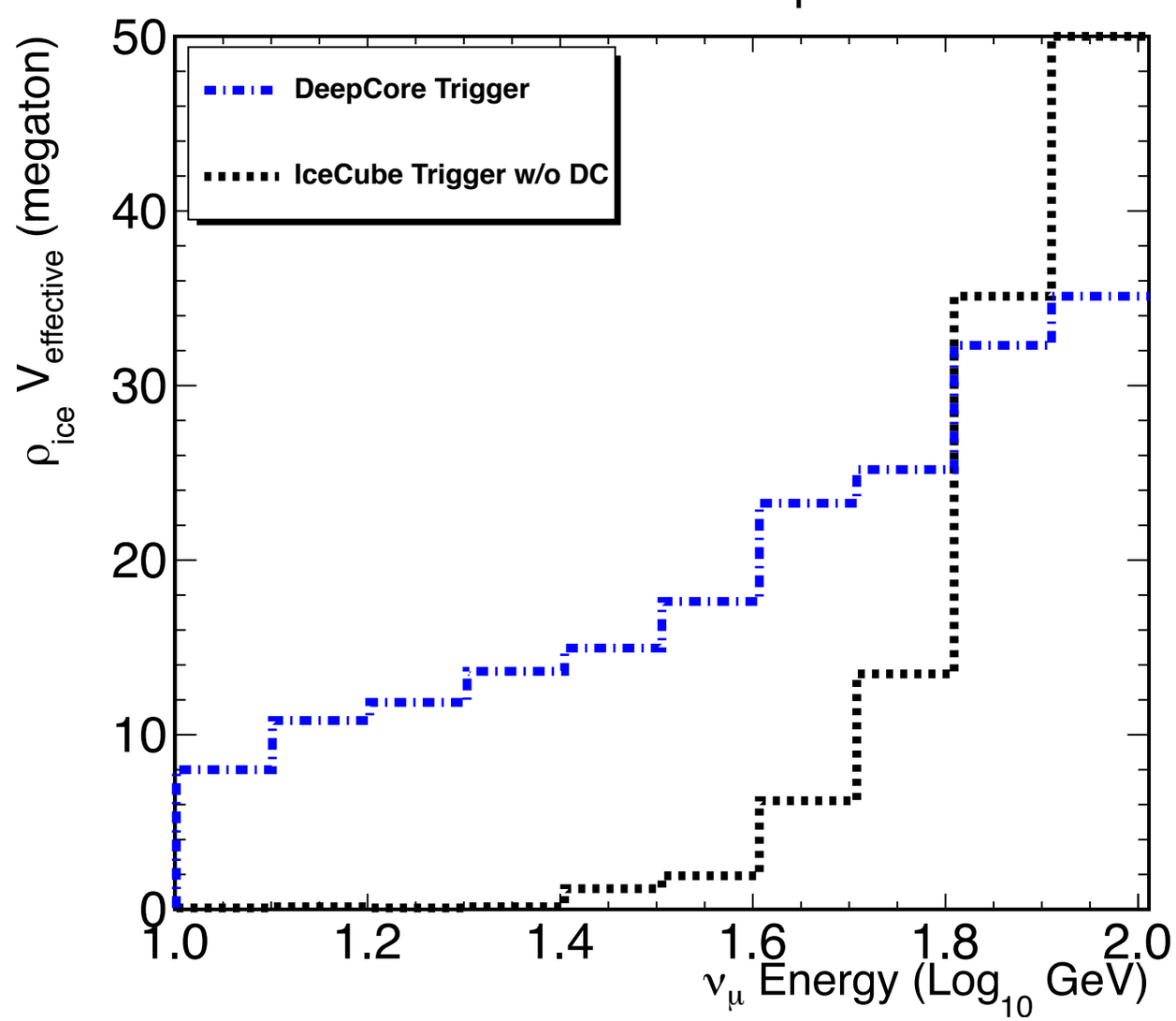


Size Matters

- IceCube gains a dramatic improvement at trigger-level sensitivity to neutrinos < 100 GeV with DeepCore



Effective volume for muon neutrinos in IceCube w/ and w/o DeepCore



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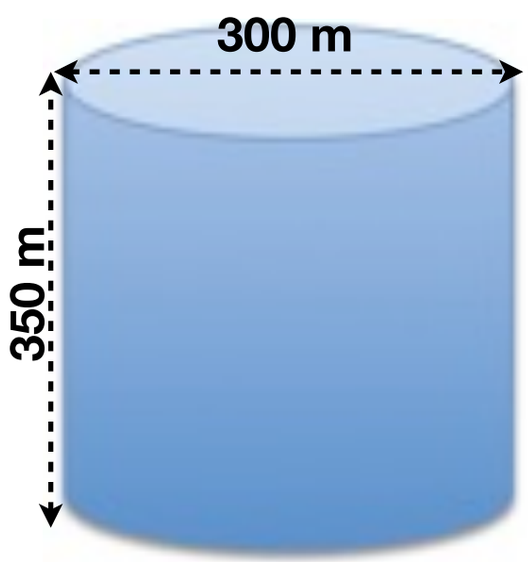

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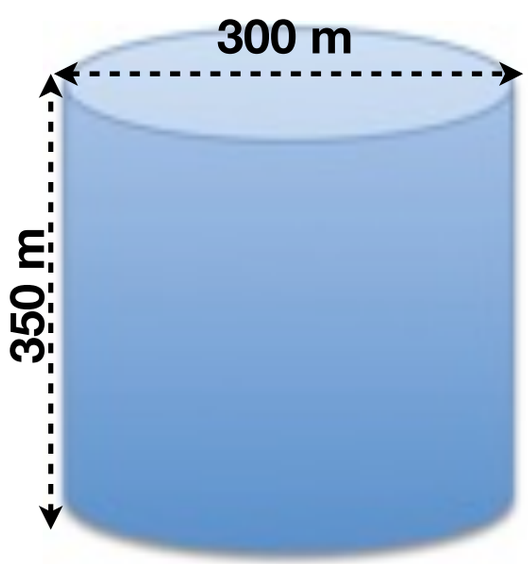

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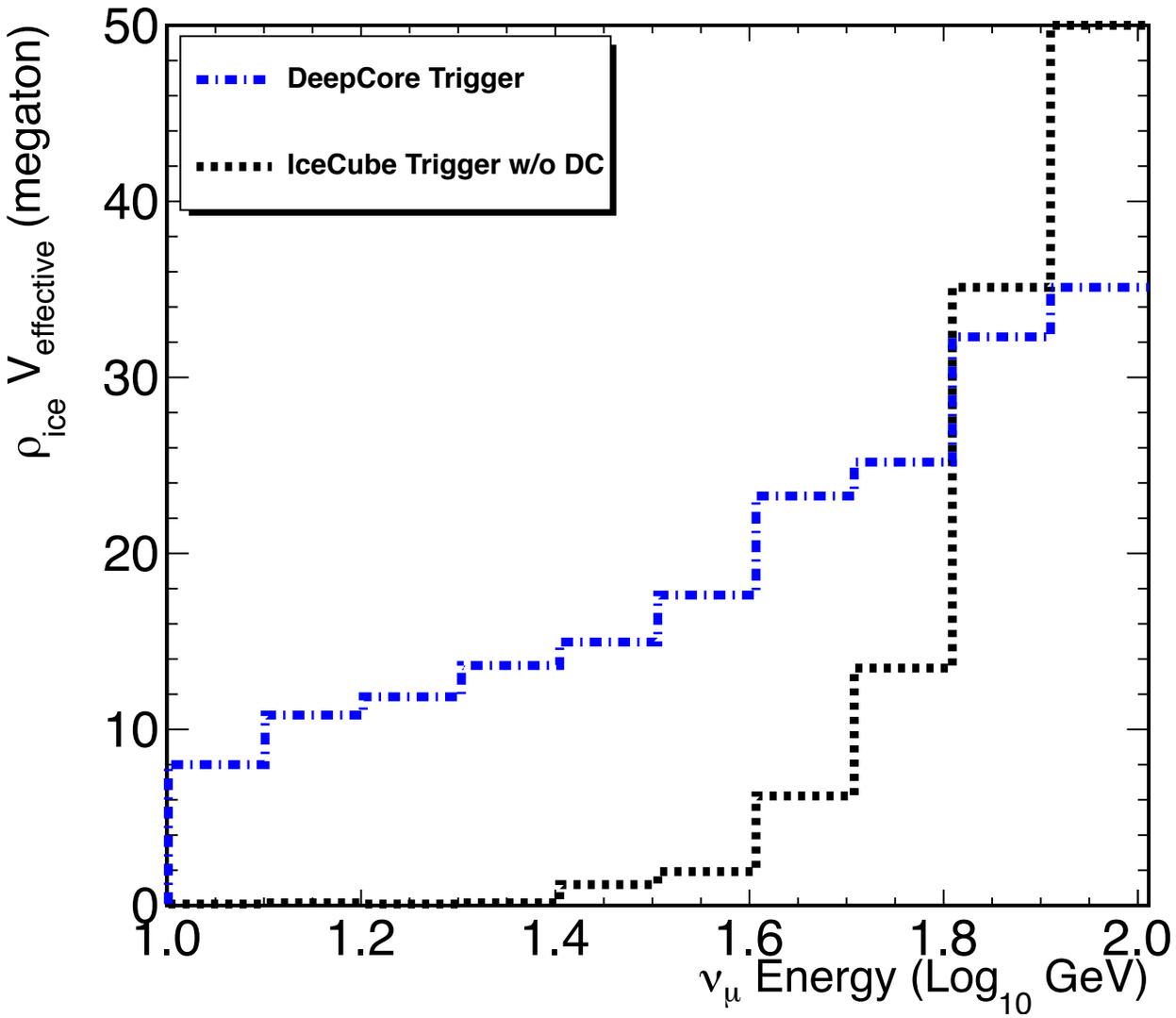


Extended Topics

- Extensive array of physics that are outside the scope of this talk
- IceCube ‘high’ energy
  - Limits on neutrino emission from Gamma Ray Bursts
  - Astrophysical point sources
  - Cosmic ray muon anisotropy
  - Very high energy (PeV+) neutrino excess
- DeepCore ‘low’ energy
  - numu disappearance
  - nutau appearance
  - WIMP dark matter searches
  - Kaluza-Klein dark matter searches
  - Atmospheric nue measurement

IceCube

IceCube

DeepCore

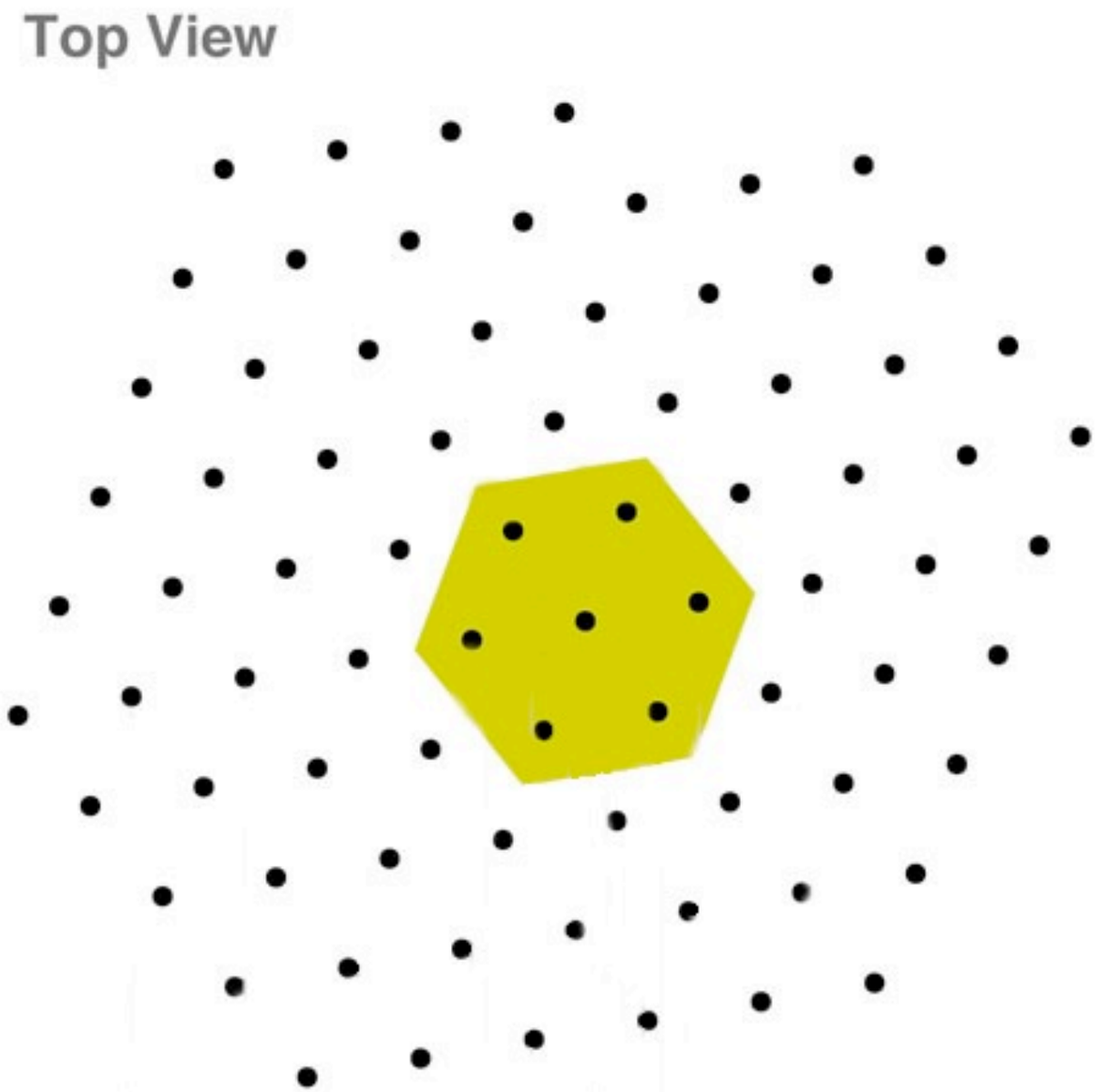
IceCube
DeepCore
PINGU

PINGU Idea

- Using existing and familiar technology (hot water drill, HQE PMT DOMs) infill DeepCore with additional Strings
- Drive neutrino energy reach down to few GeV while maintaining multi-megaton scale size
- **P**recision **I**ceCube **N**ext **G**eneration **U**pgrade (PINGU)

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



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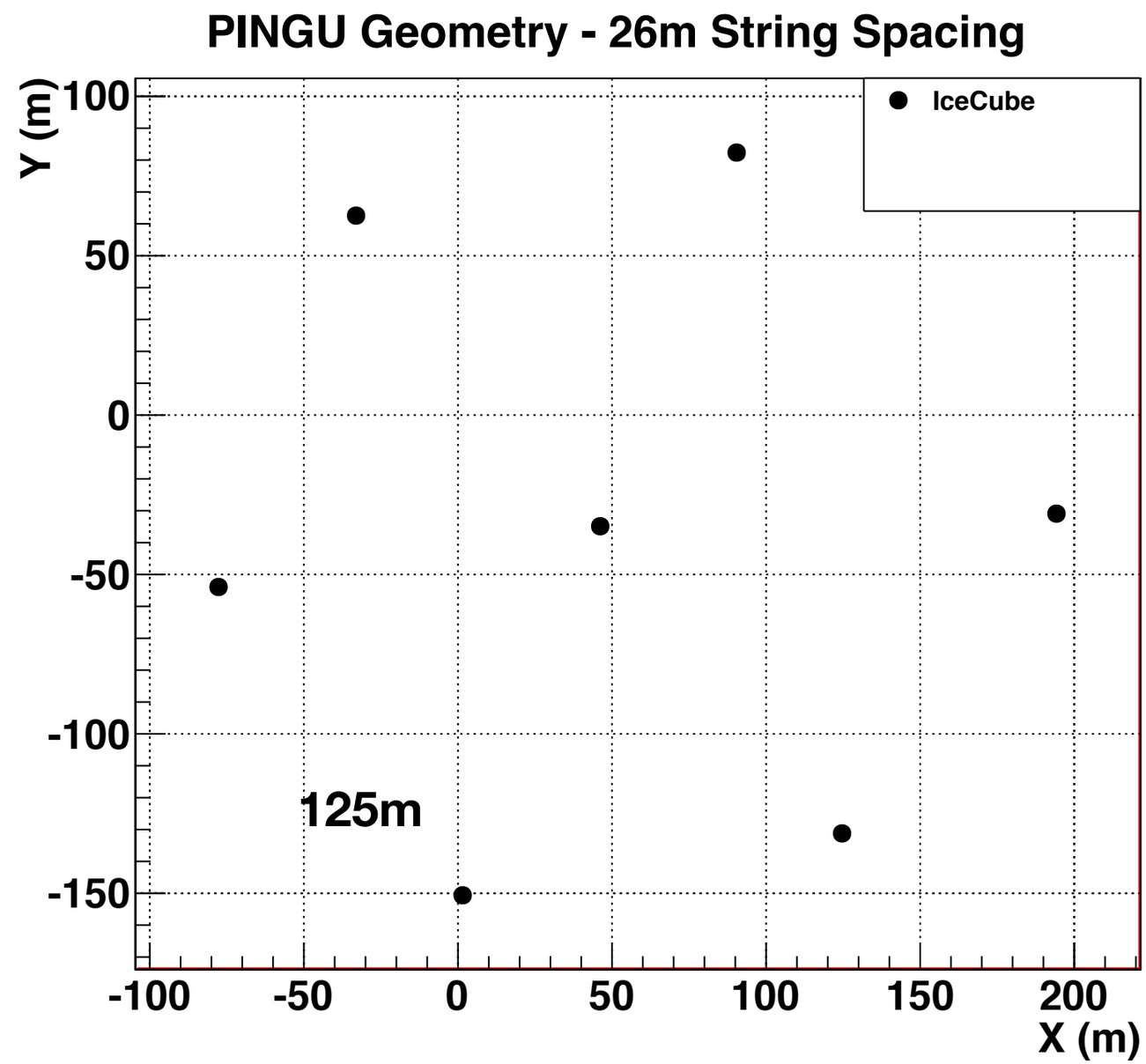

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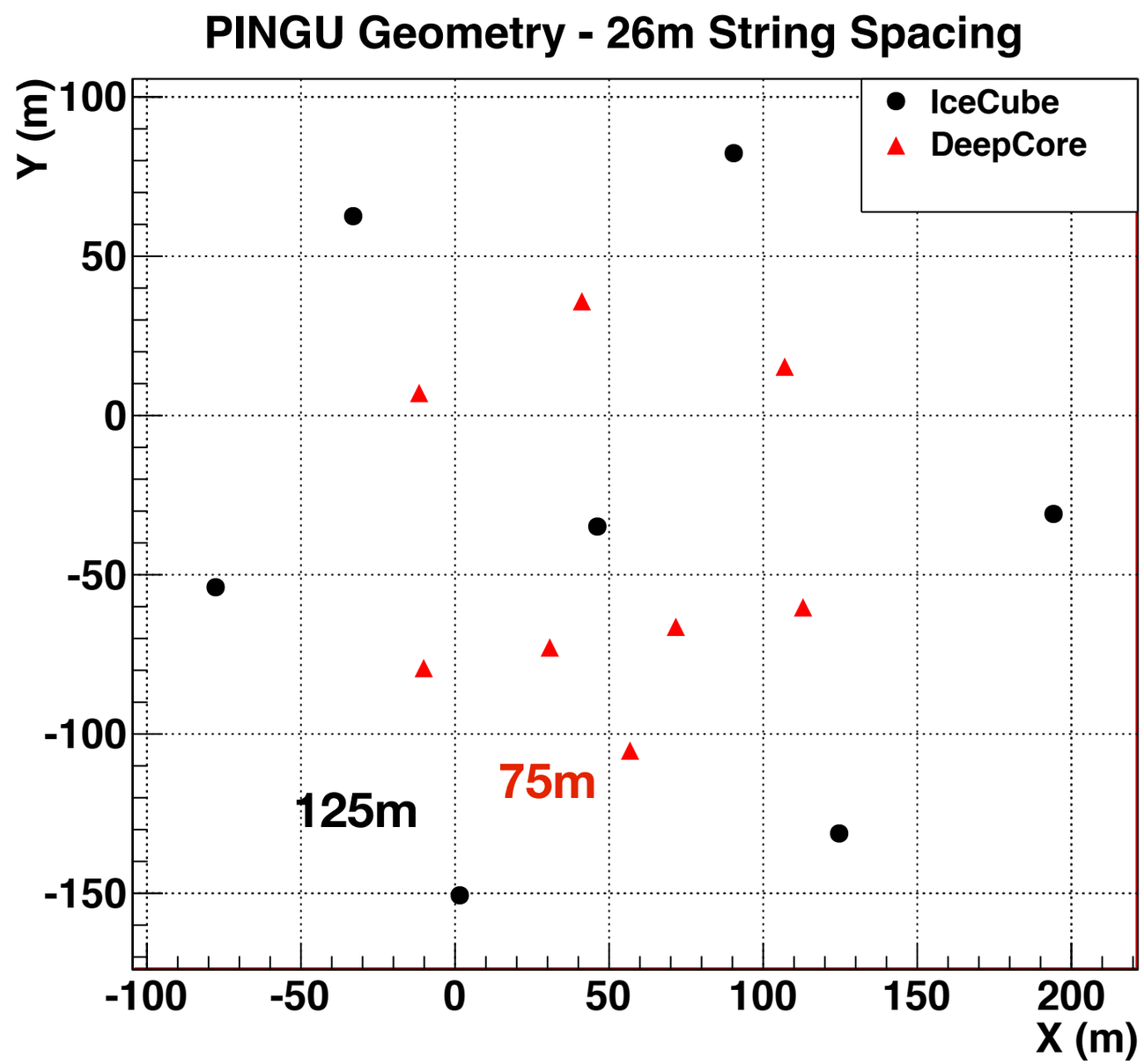

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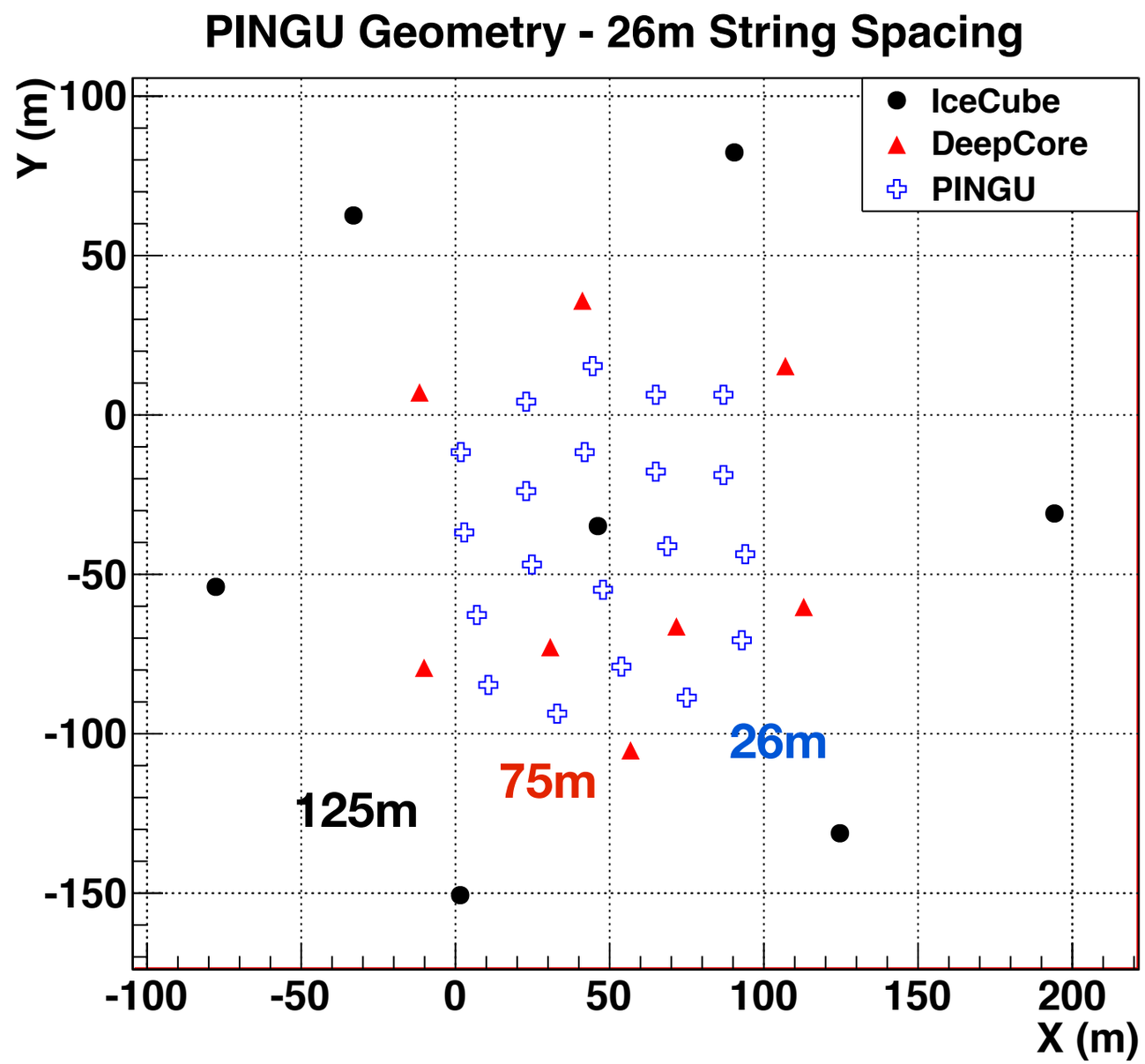
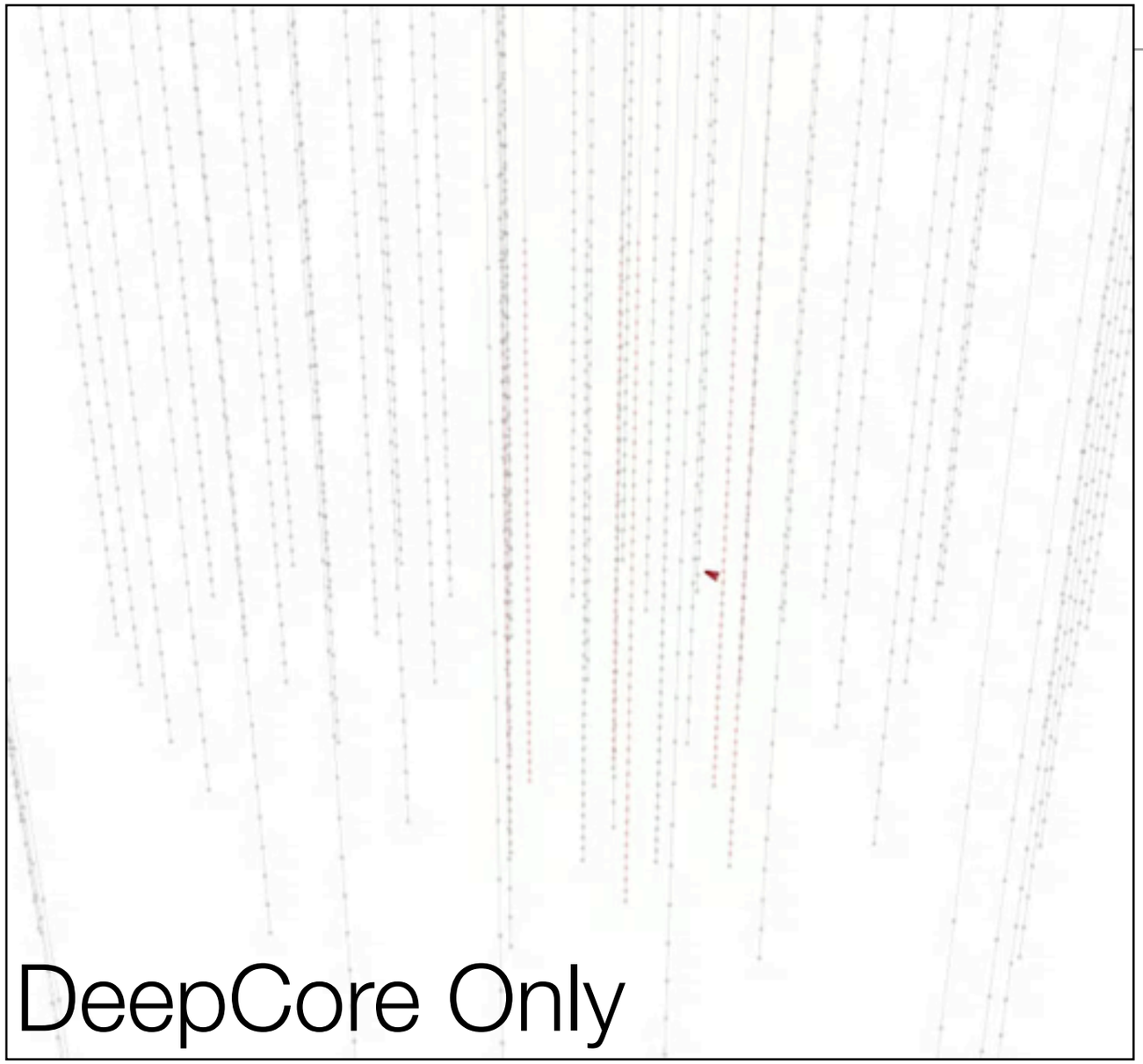


All following plots use V6 Geometry

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

PINGU Simulation Events



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

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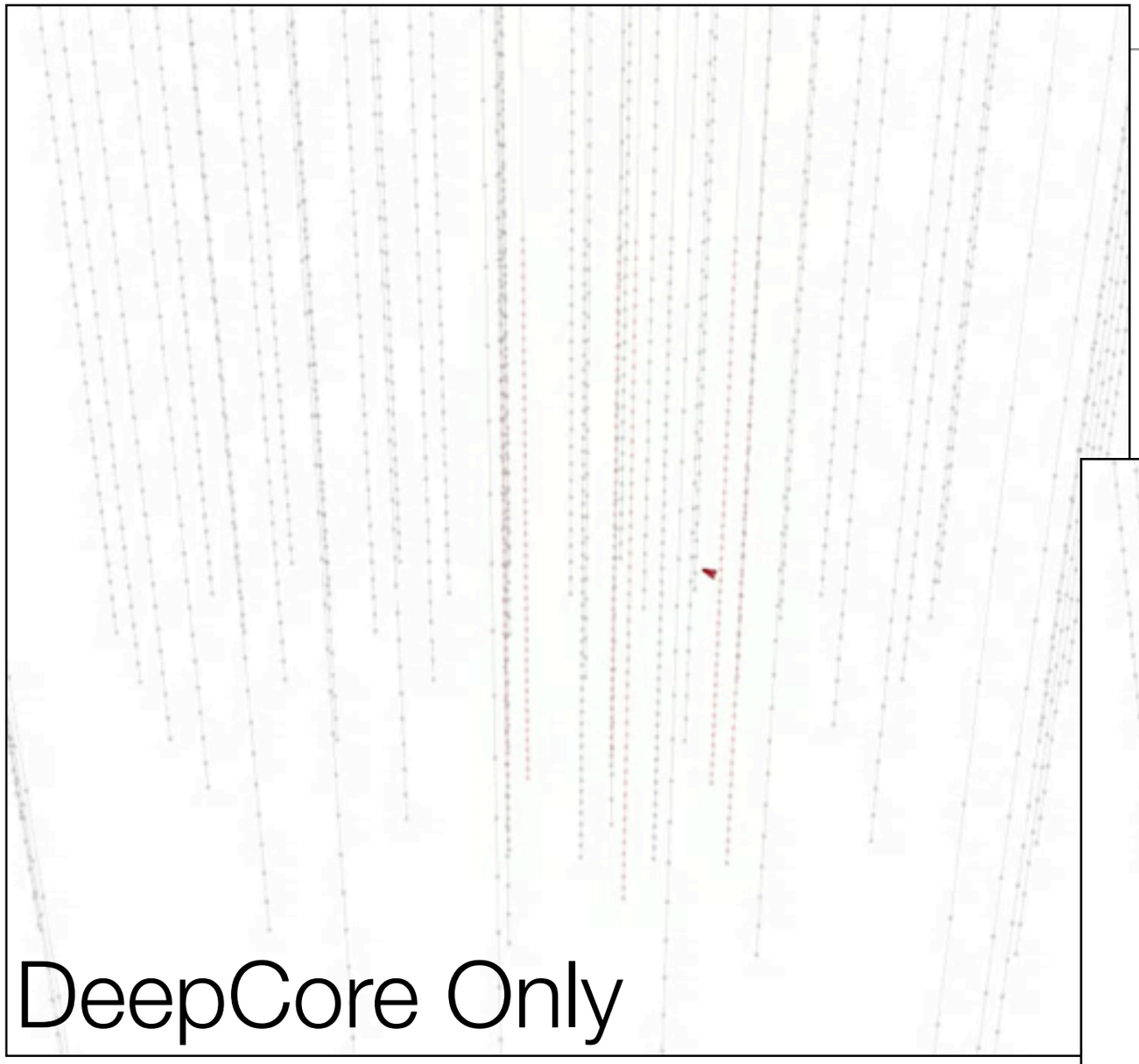

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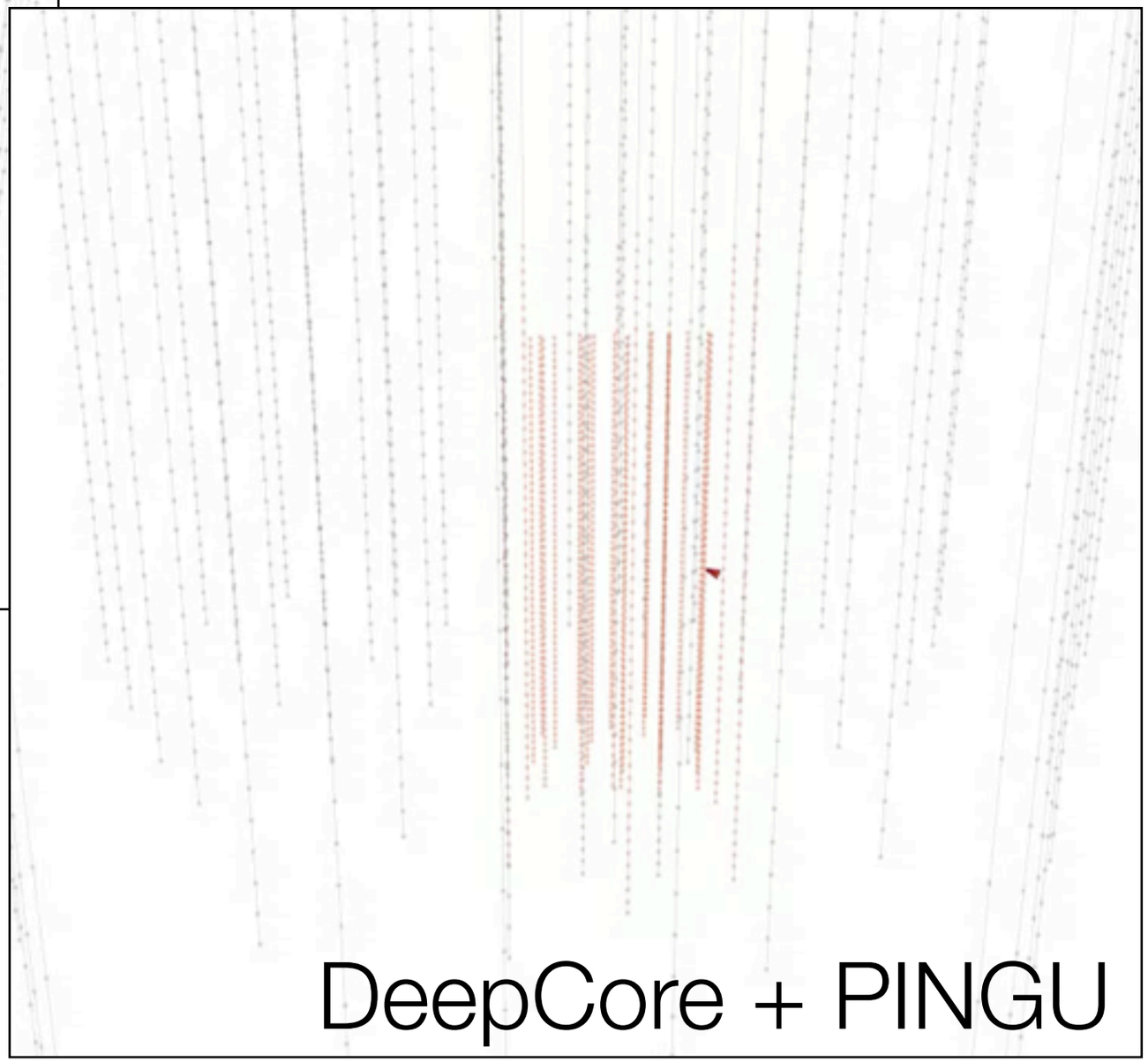
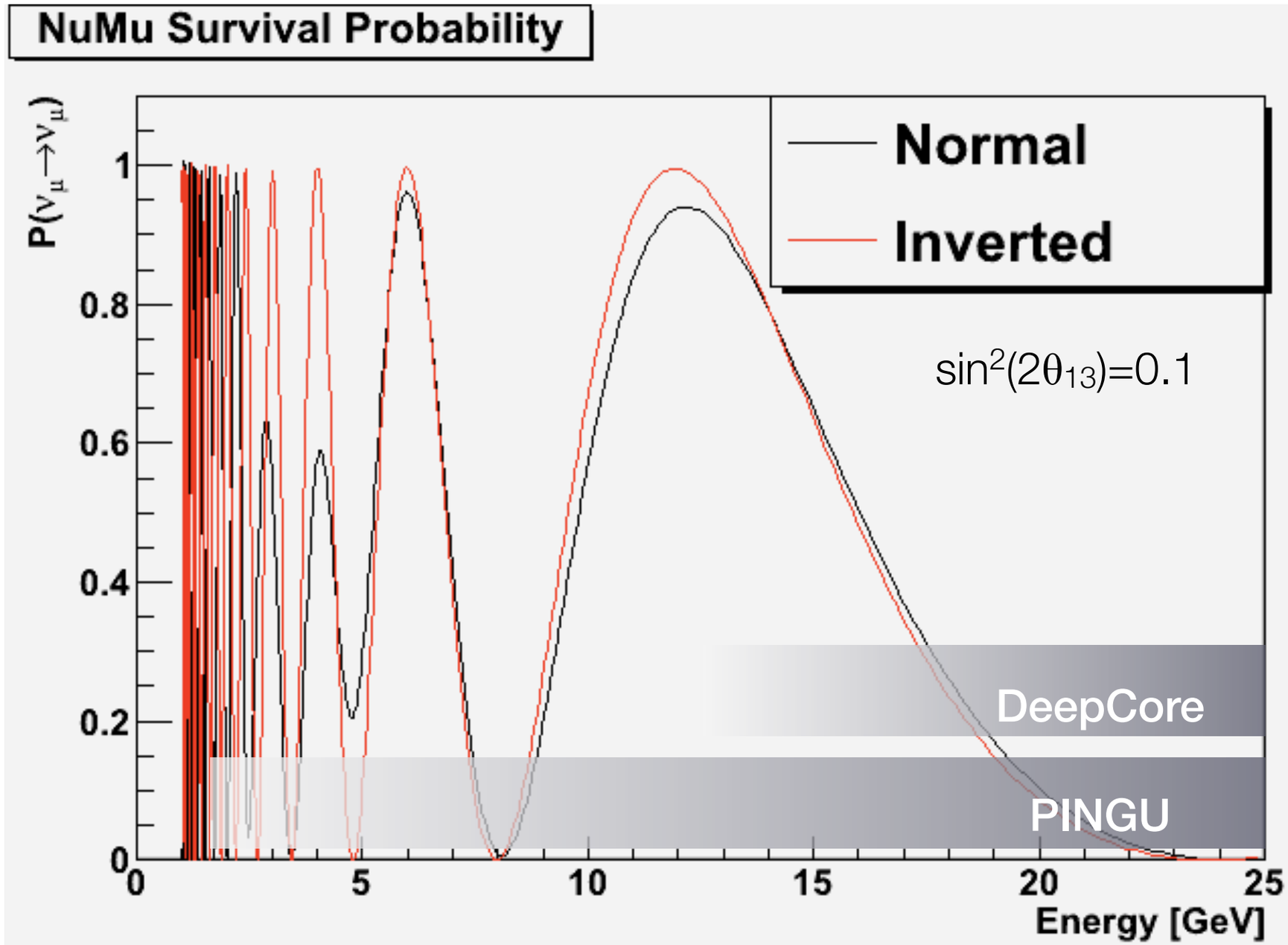
- ~20 vs. ~50 Hit Modules

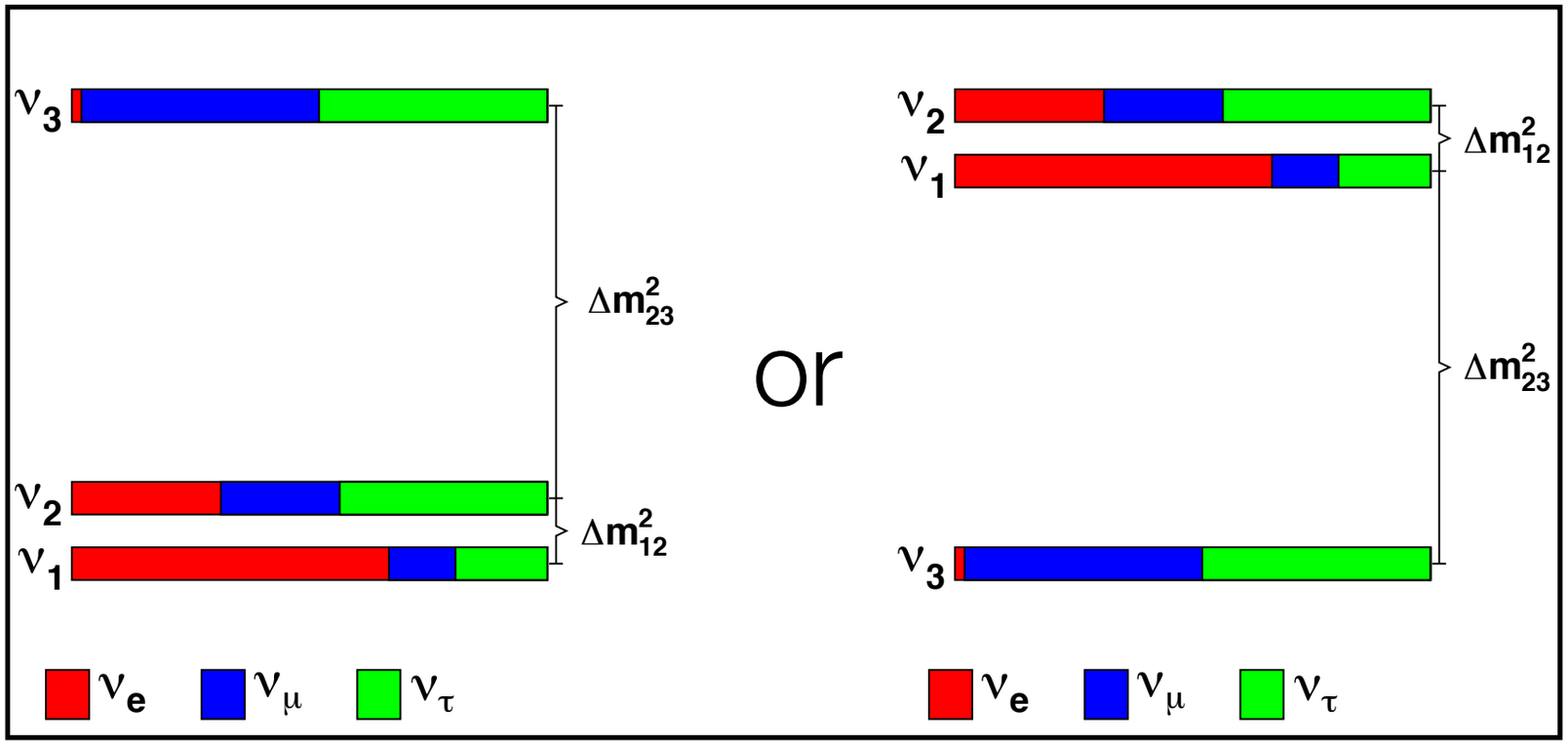


Detector + Hierarchy

- PINGU has sensitivity to lower energy neutrinos than DeepCore

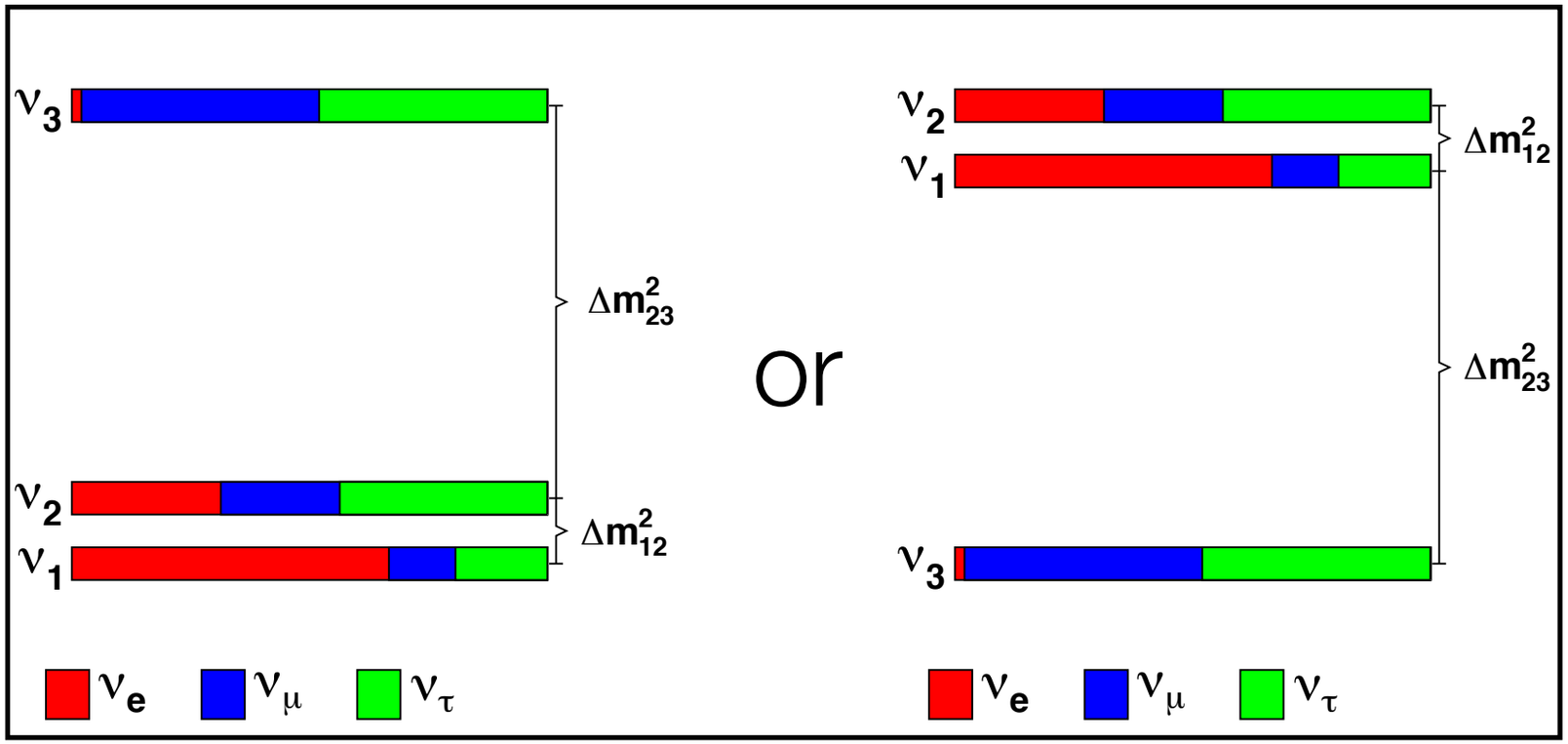


Neutrino Hierarchy



Neutrino Hierarchy

- A big detector with sensitivity at O(1) GeV energy is in the range of measuring the neutrino hierarchy order



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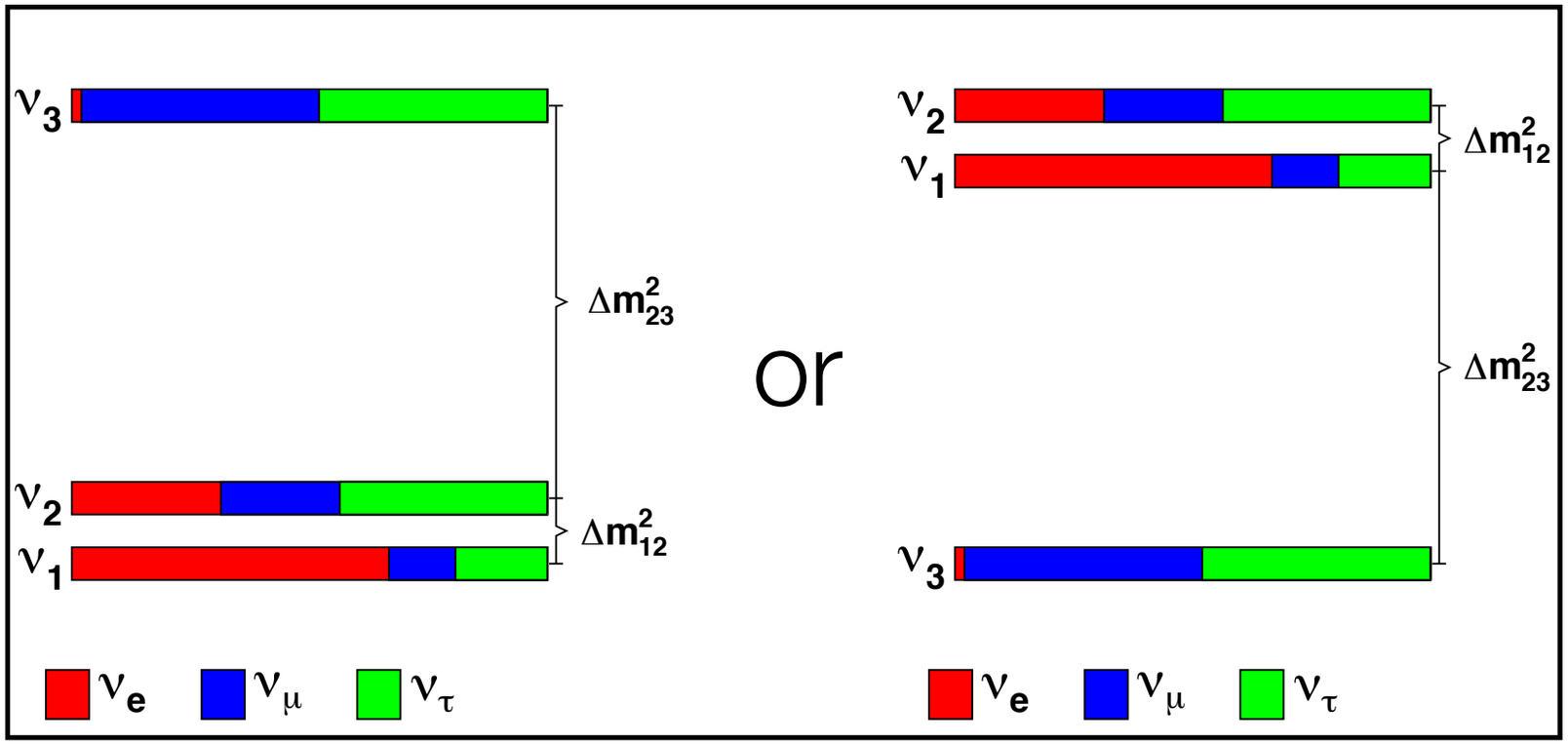

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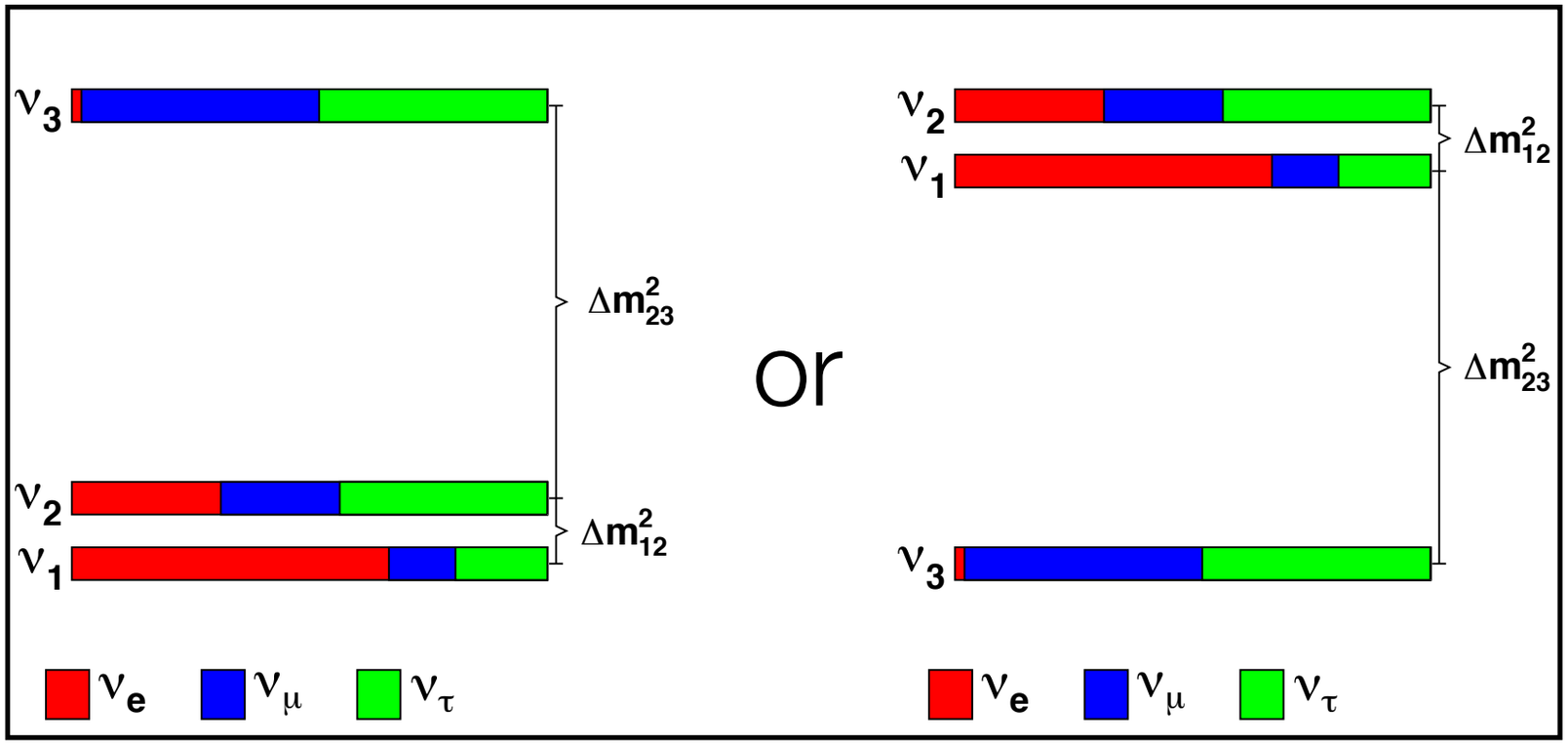

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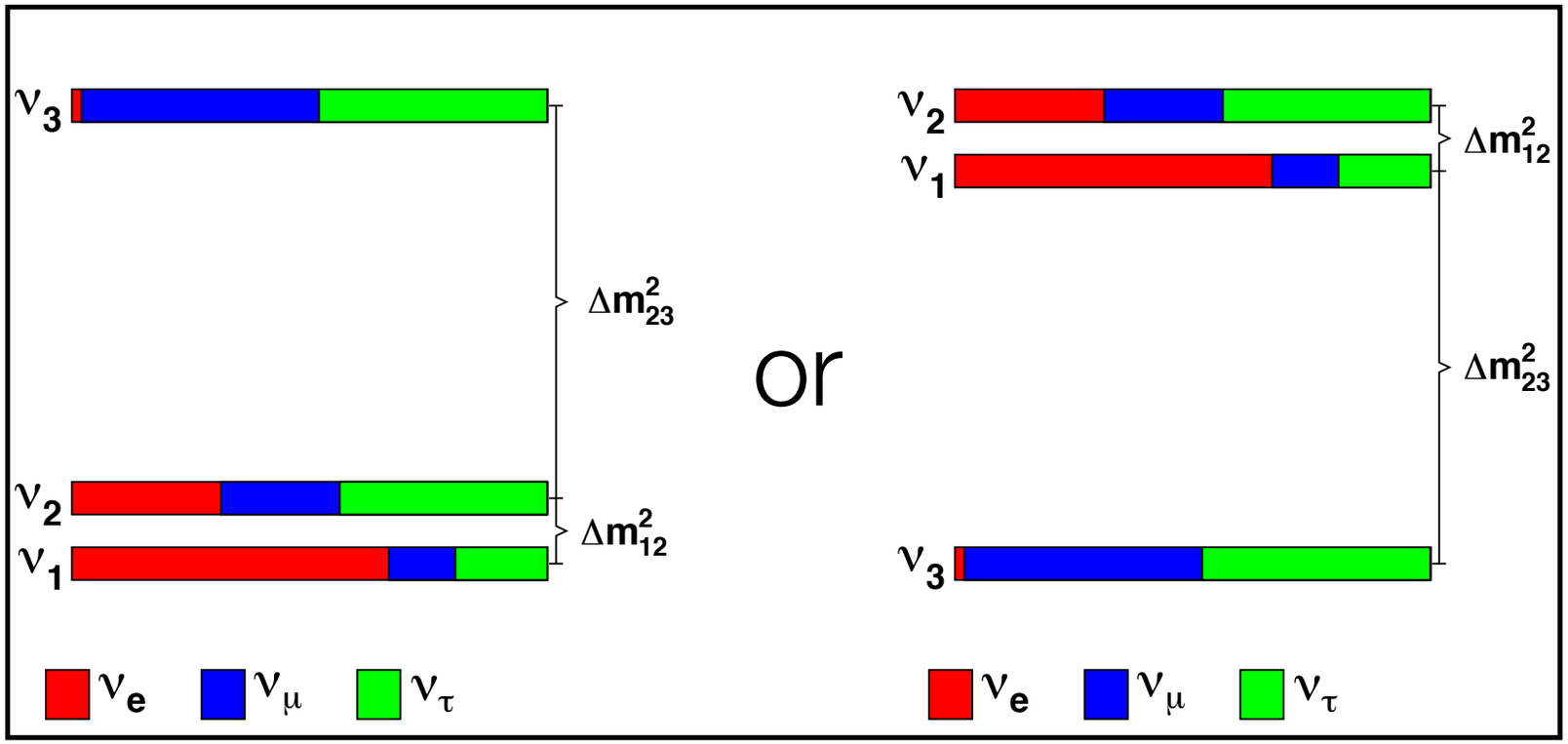
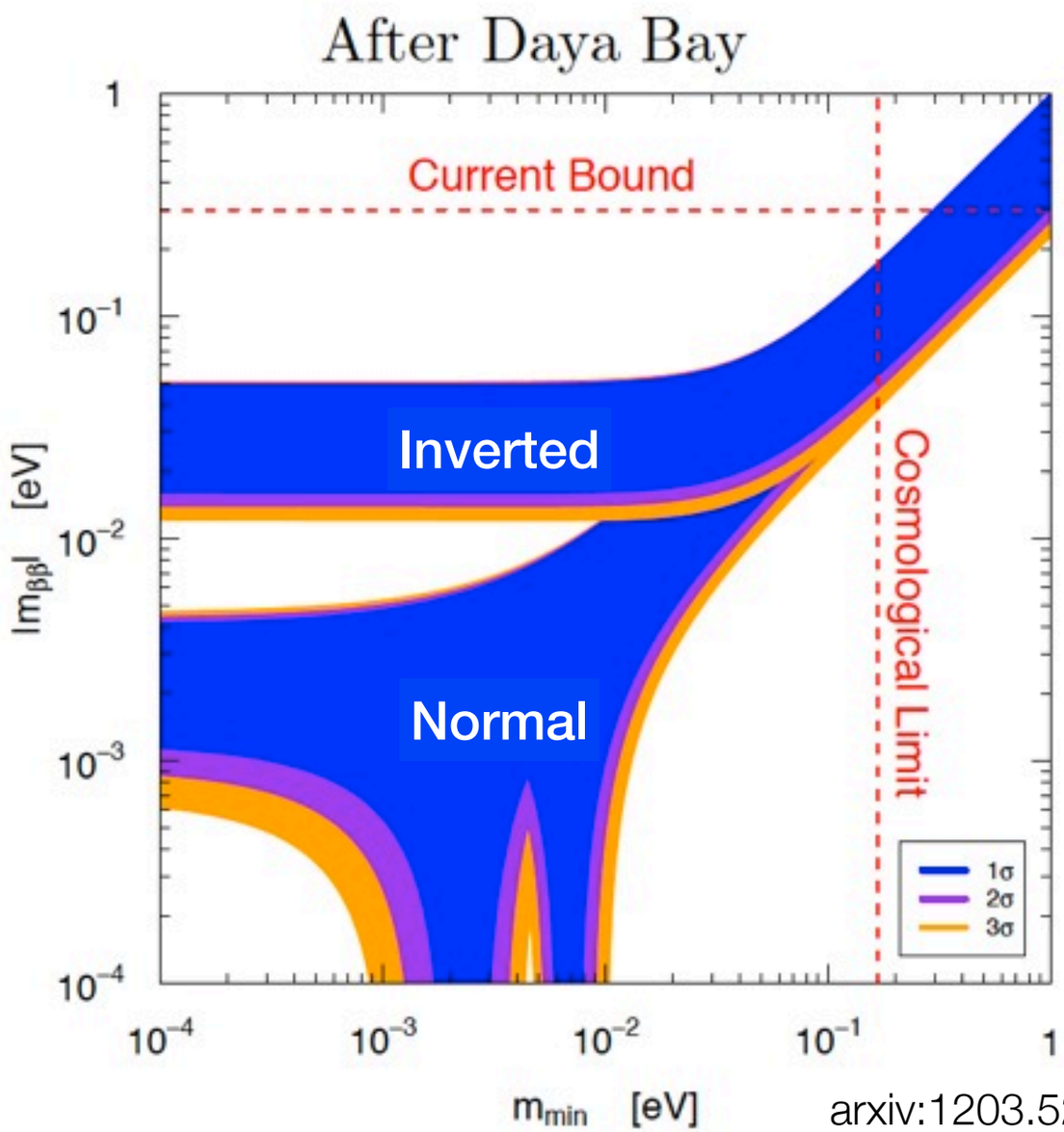
- Ok, fine. But, why would anyone?
  - Fundamental physics is fundamental
  - Cosmology - Normal hierarchy puts more mass into neutrinos

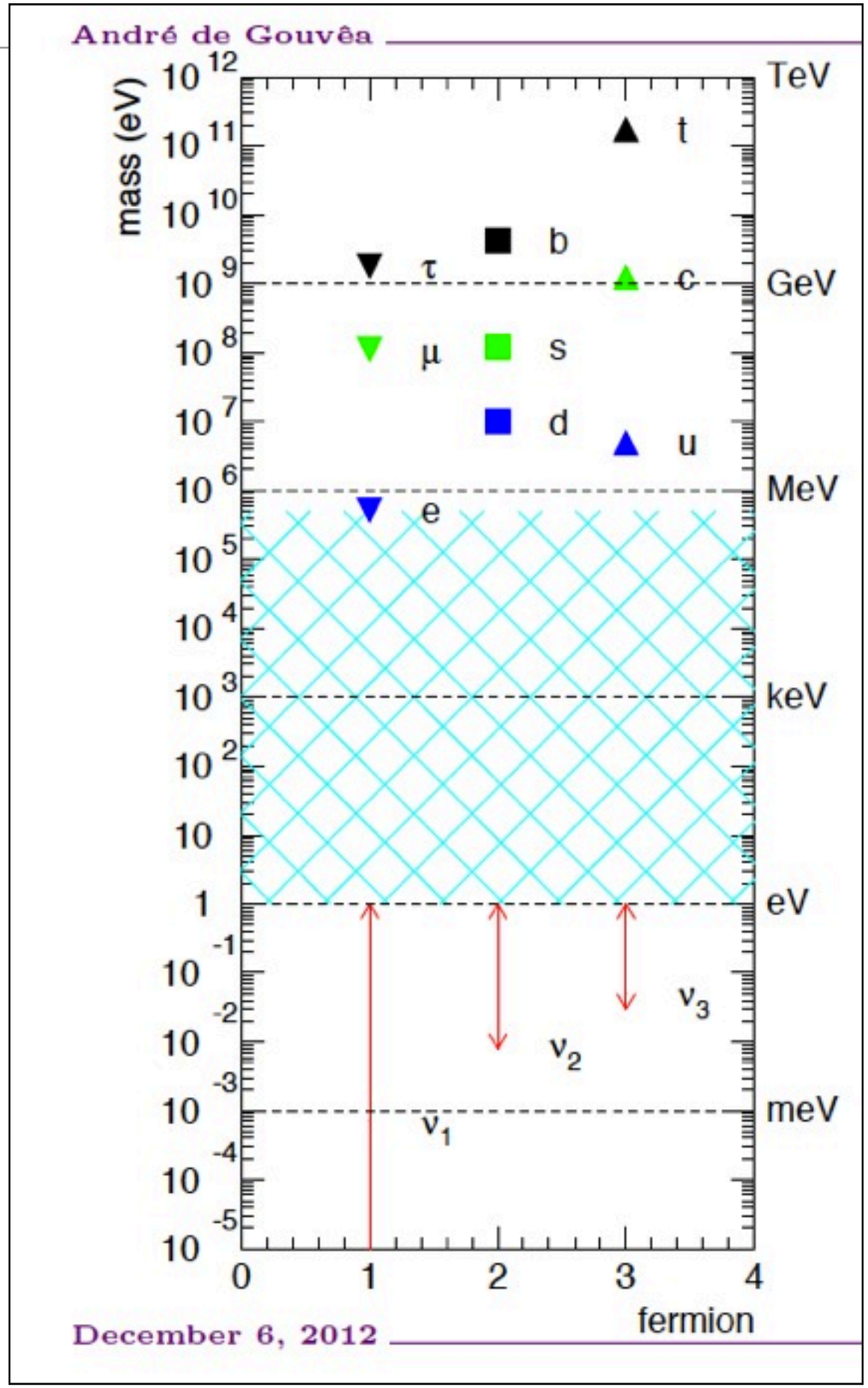


More Reasons

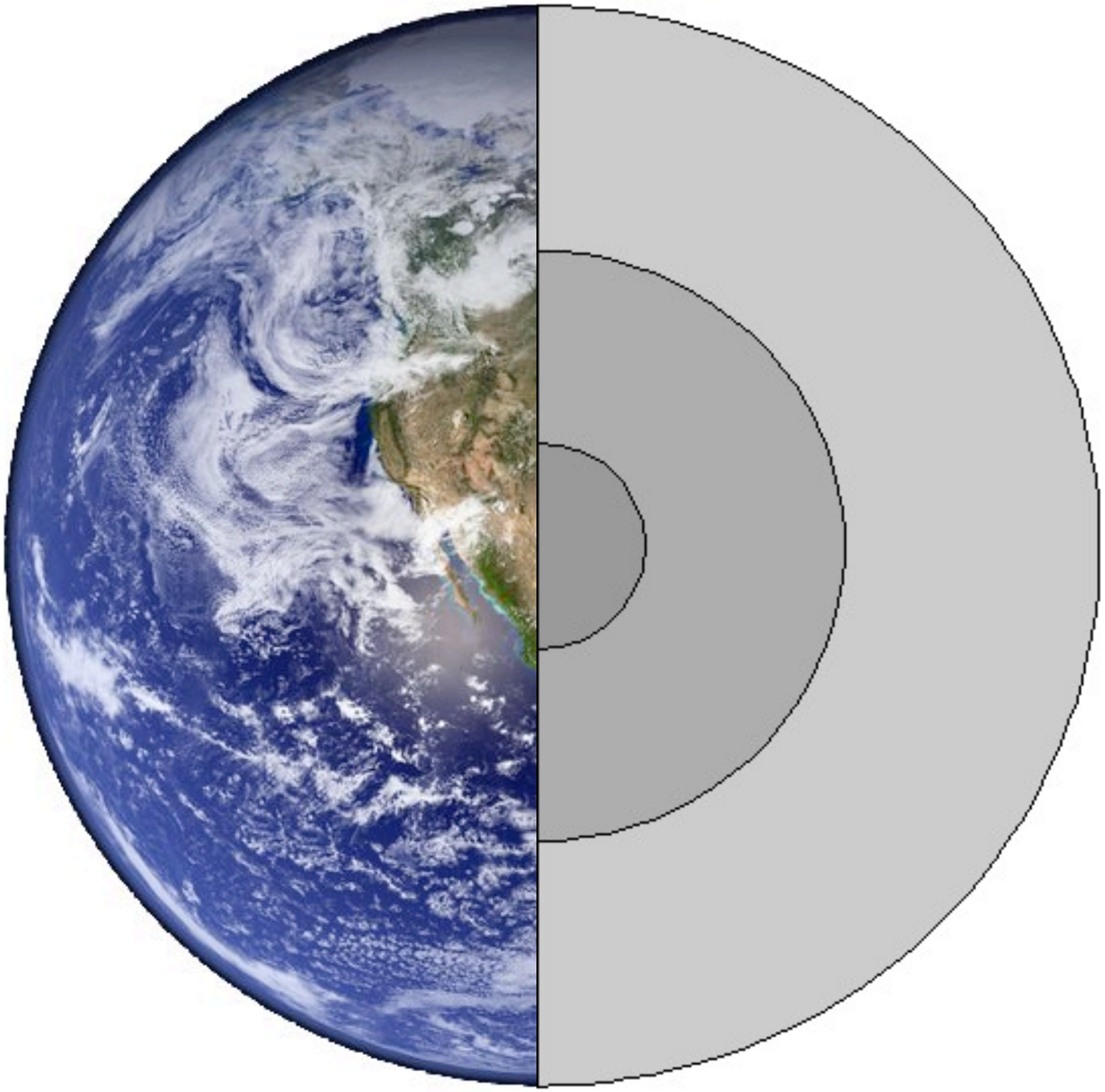
- Neutrinos having mass is outside Standard Model. Is it a Majorana mass, i.e. neutrino is its own anti-particle?
- GUT - Do neutrinos resemble quark and charged lepton mass hierarchy?



arxiv:1203.5250



Matter Effects & Neutrino Hierarchy



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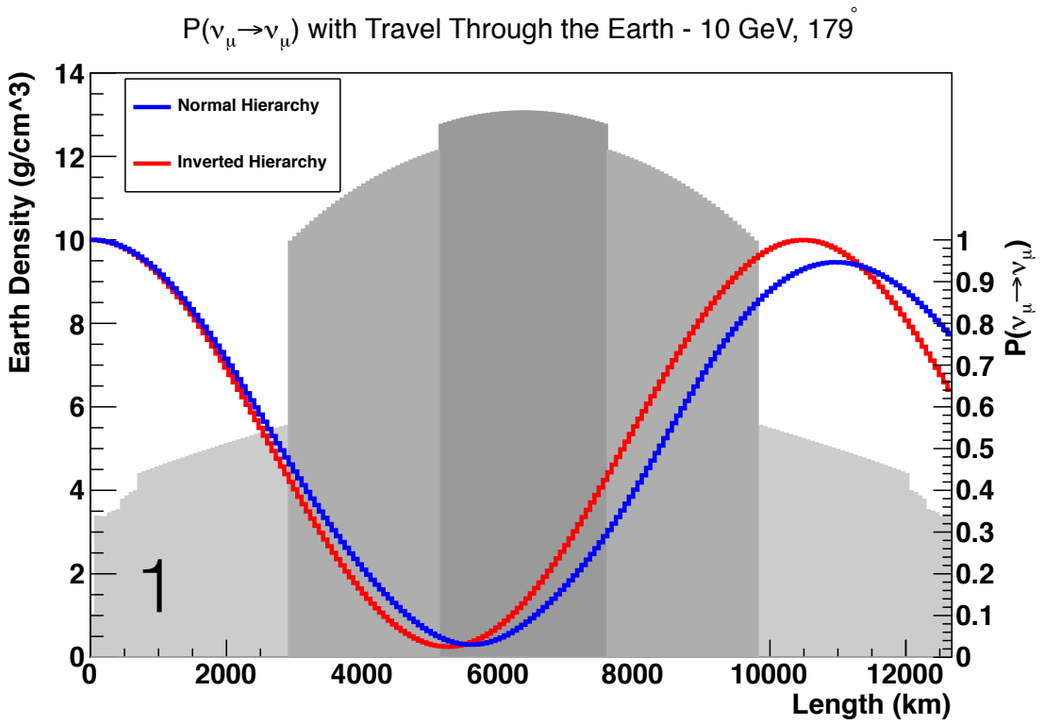

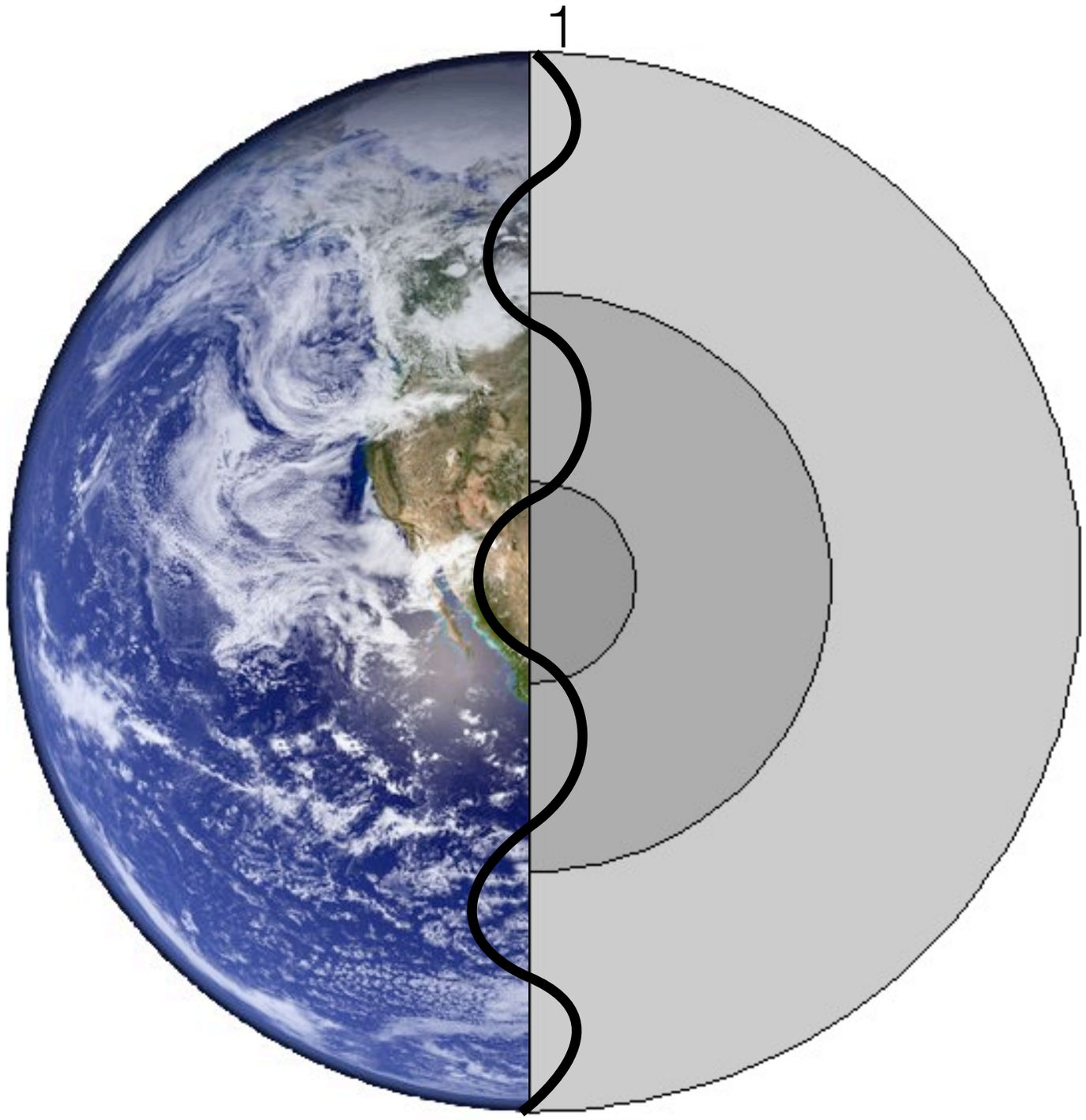

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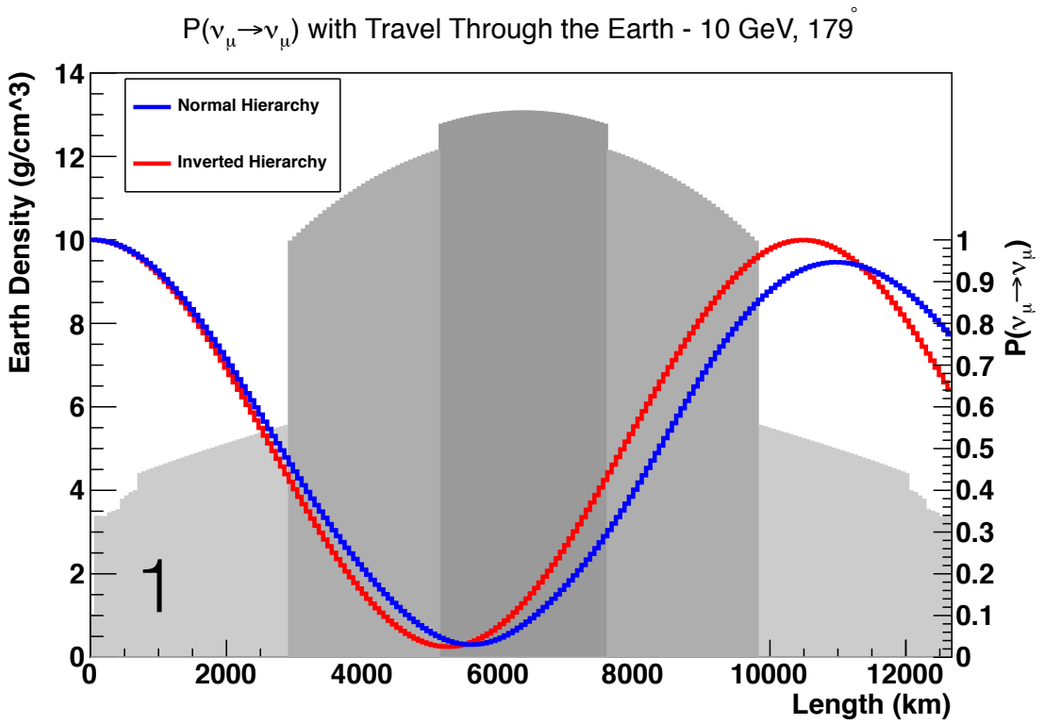
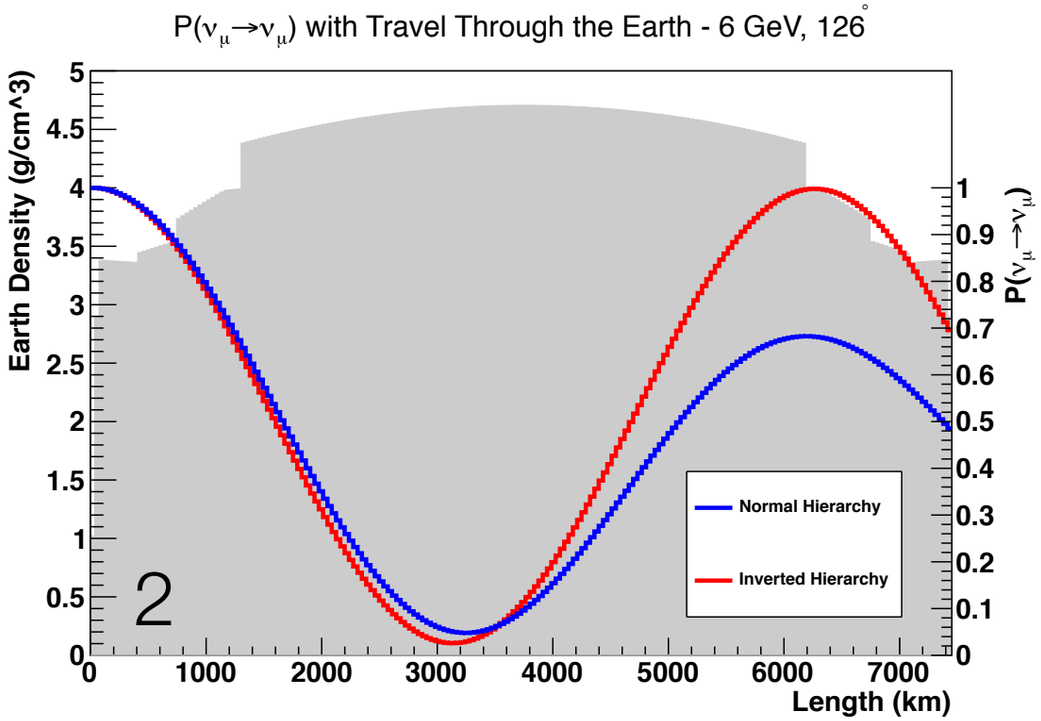
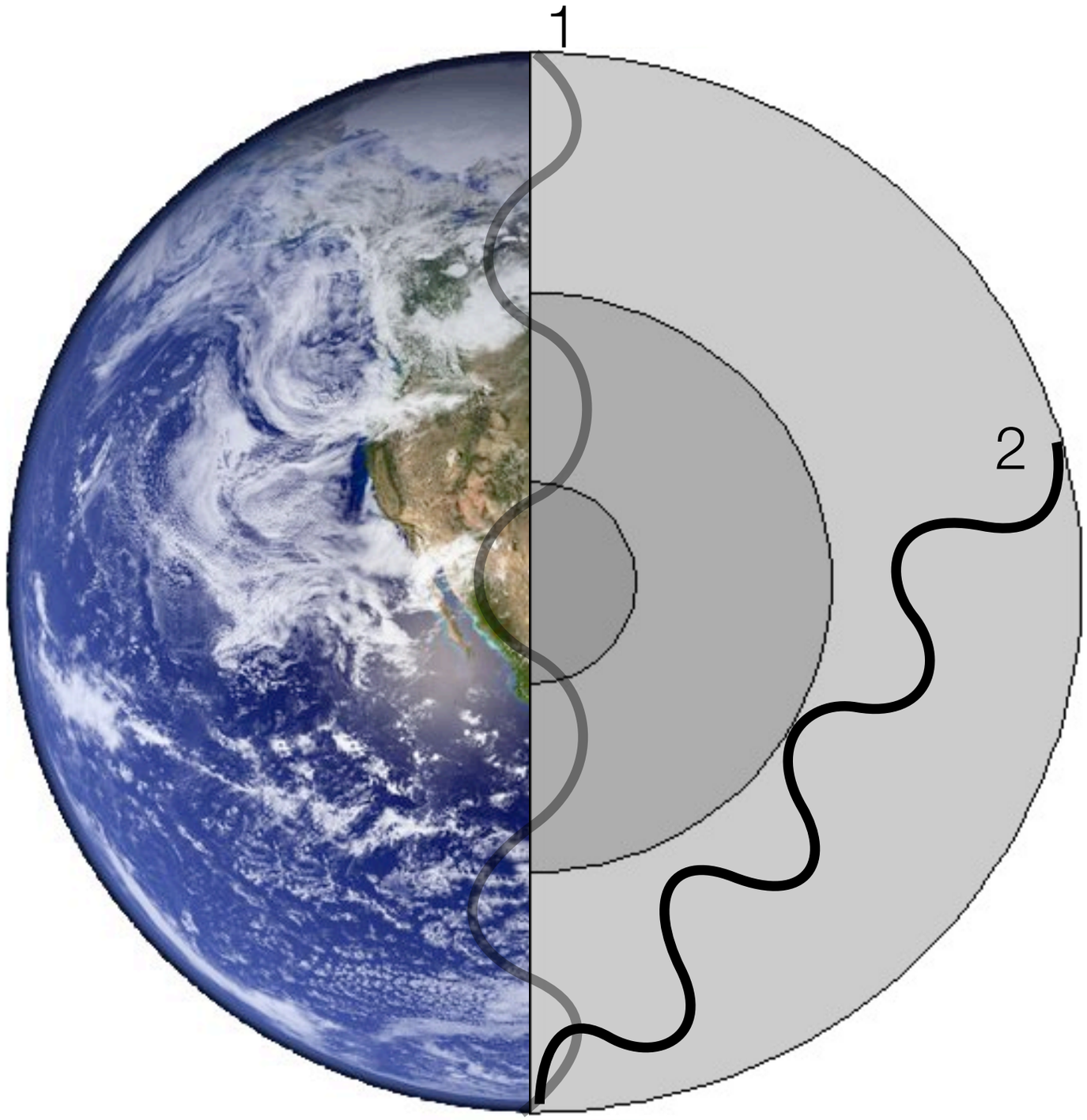
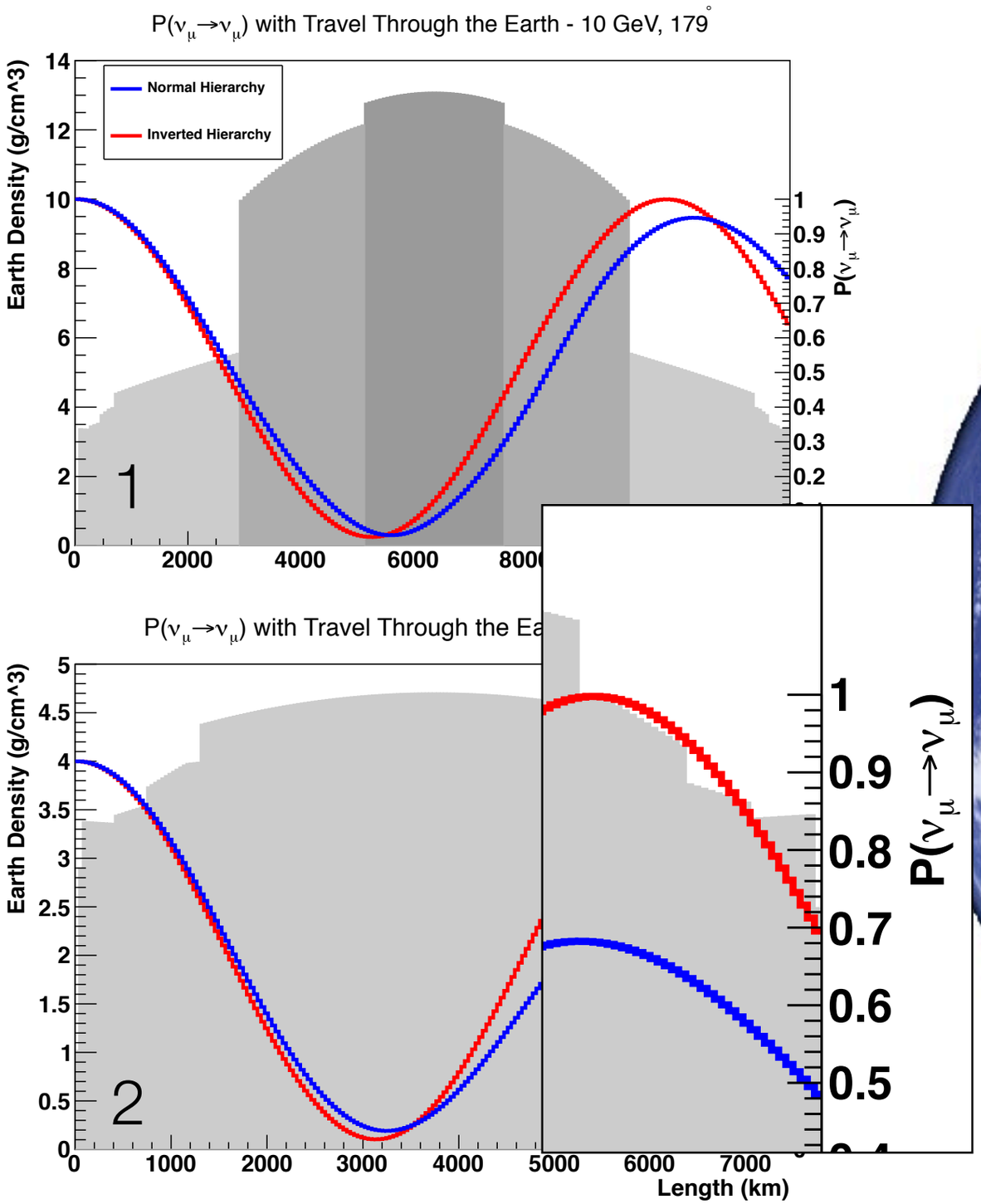


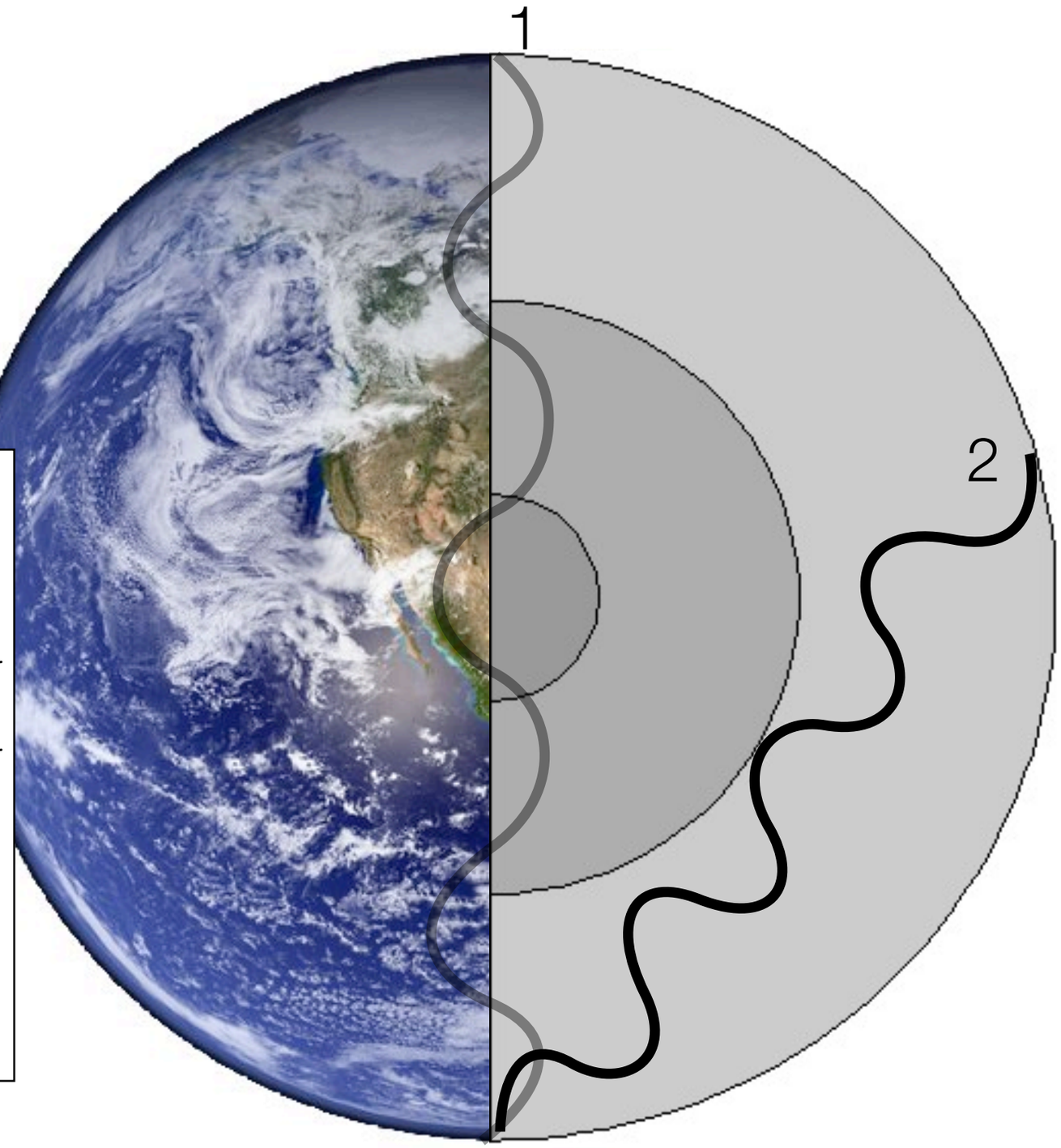




- Inverted/Normal hierarchy has up to a 20% difference in oscillation probability for specific energies and zenith angles (baselines)

Matter Effects & Neutrino Hierarchy





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Hierarchy Distinguishability Metric

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

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

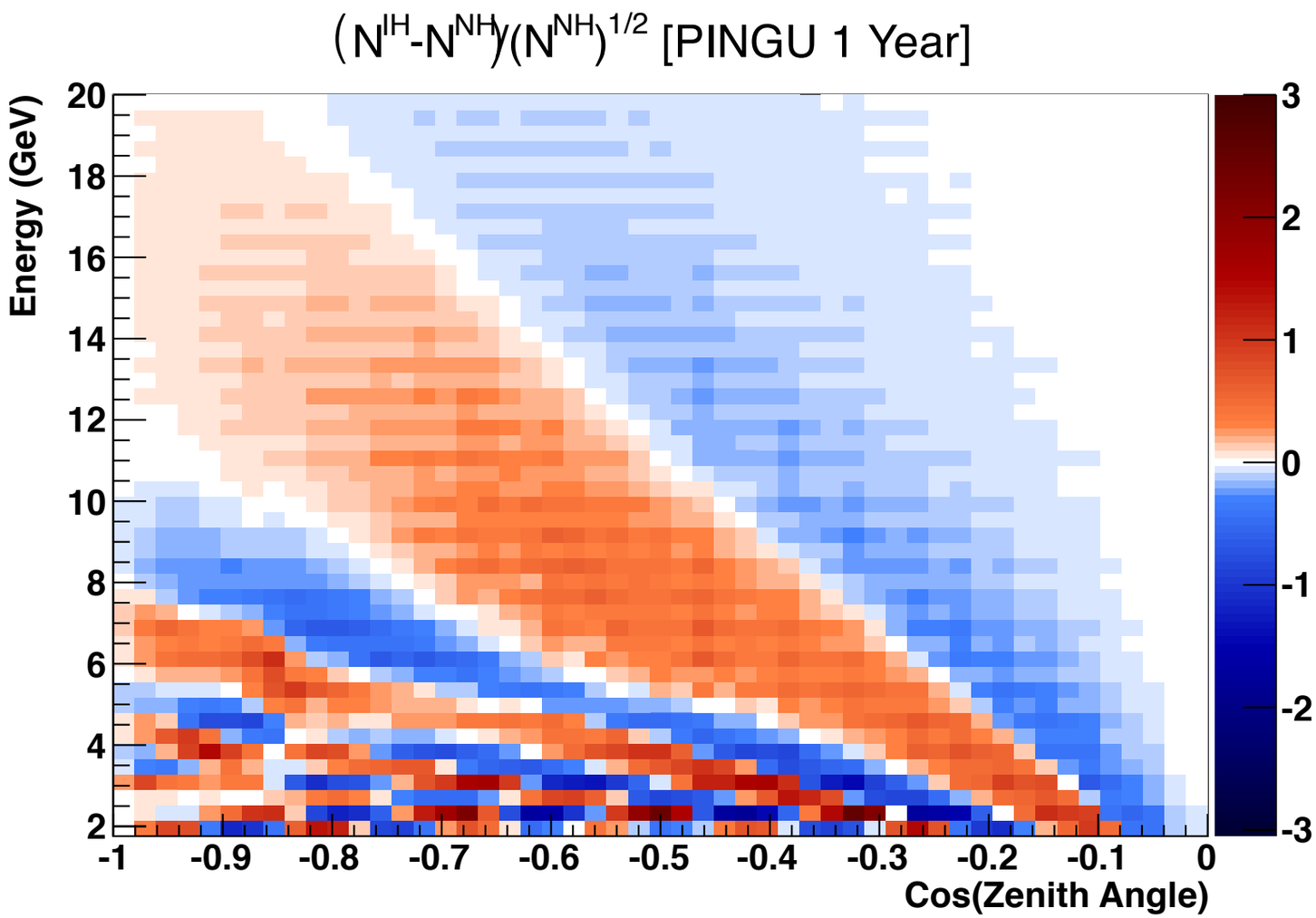
$$\begin{aligned} i &= \cos(zenith) \\ j &= energy \\ V^{eff} &= effective\ volume \end{aligned}$$

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

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

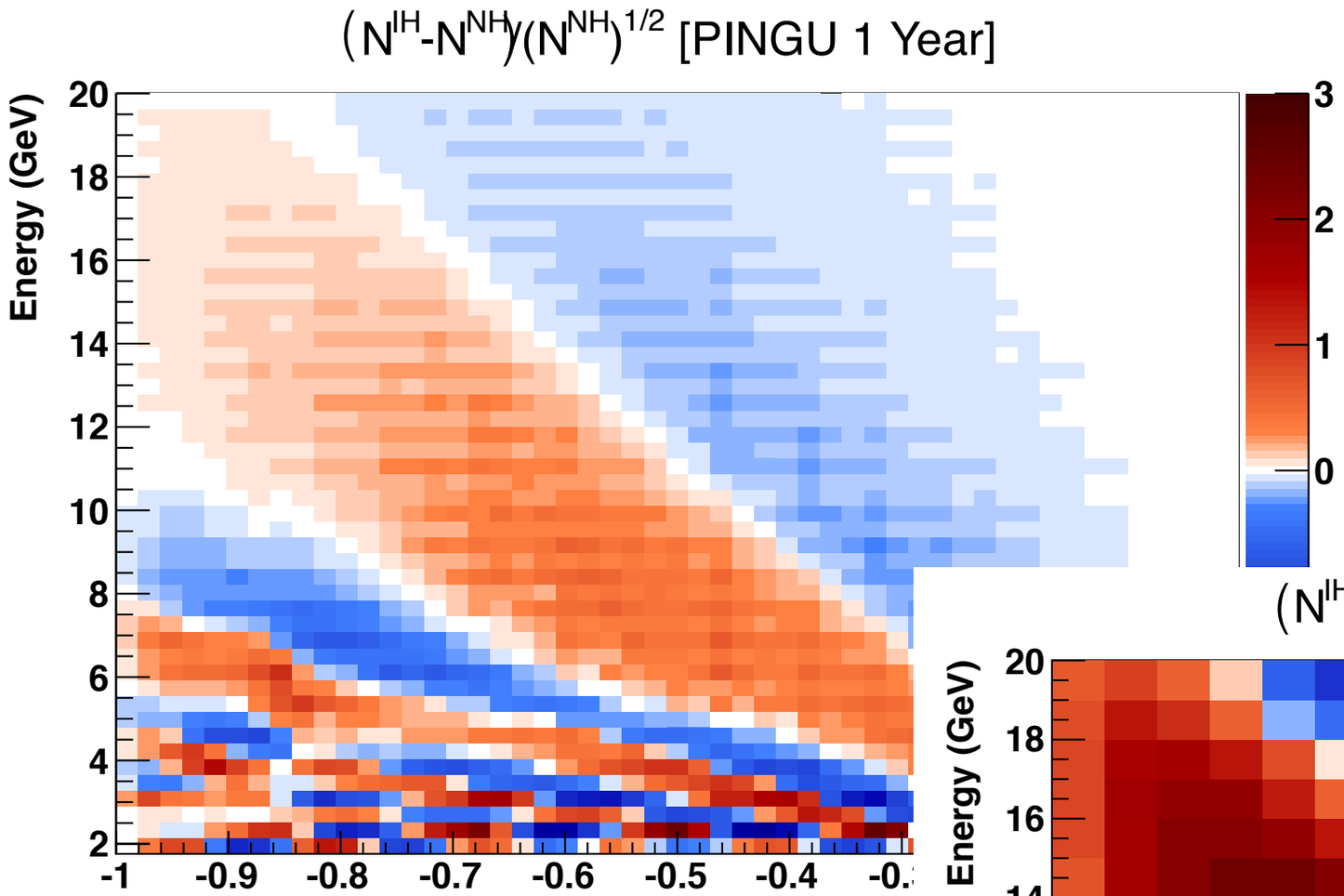
$$\begin{aligned} Probability &: P(\nu_\mu)^{IH} + P(\overline{\nu_\mu})^{IH} \neq P(\nu_\mu)^{NH} + P(\overline{\nu_\mu})^{NH} \\ Flux &: \Phi(\nu_\mu) > \Phi(\overline{\nu_\mu}) \\ Cross-Section &: \sigma(\nu_\mu) > \sigma(\overline{\nu_\mu}) \end{aligned}$$

Hierarchy

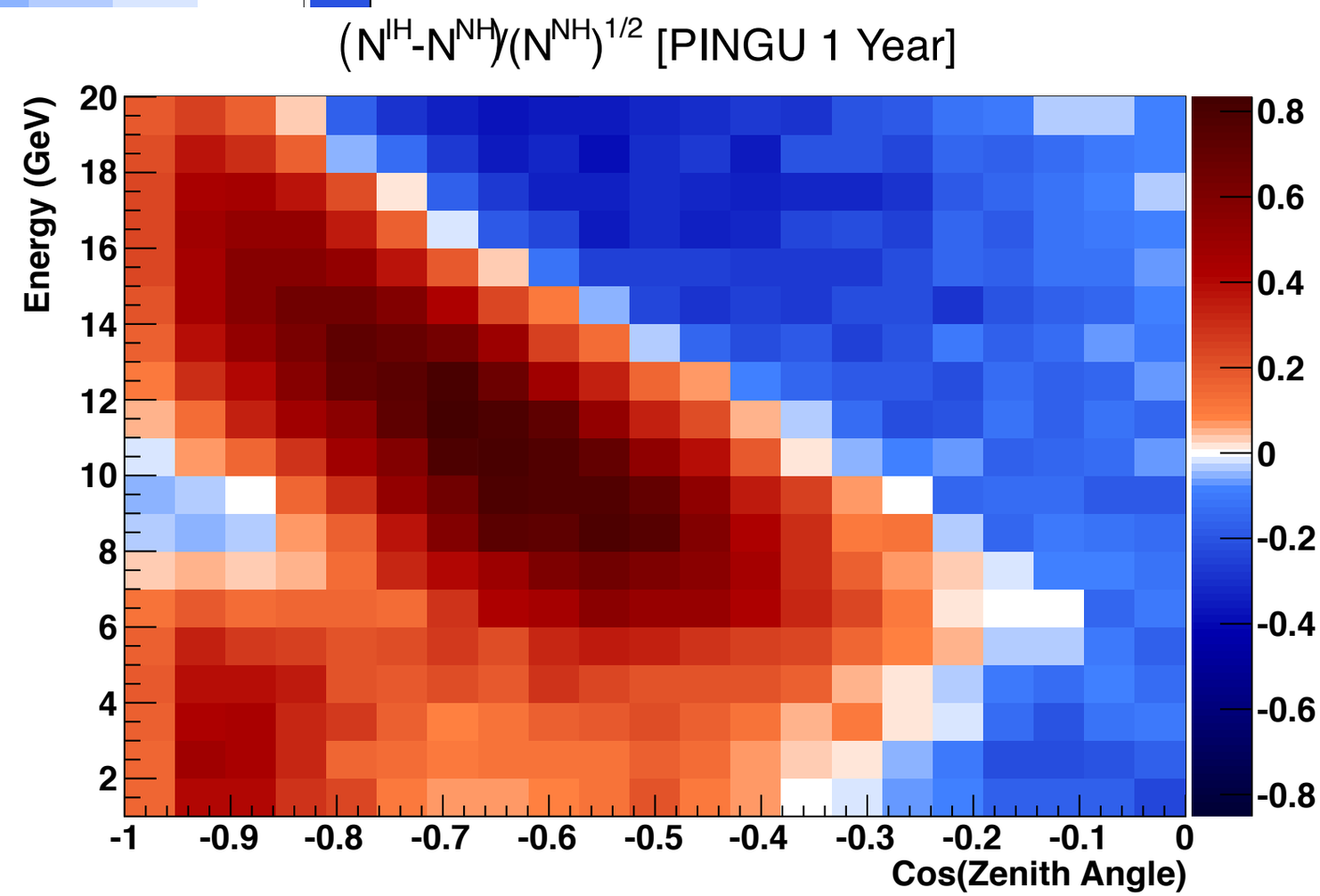


- Idealized case w/ perfect event ID, 100% event selection efficiency, no quality cuts and no background
- Evaluations of angular and energy resolution are ongoing
- Detector response (ice modeling, DOM efficiency) may play a major role in final sensitivity

Hierarchy



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



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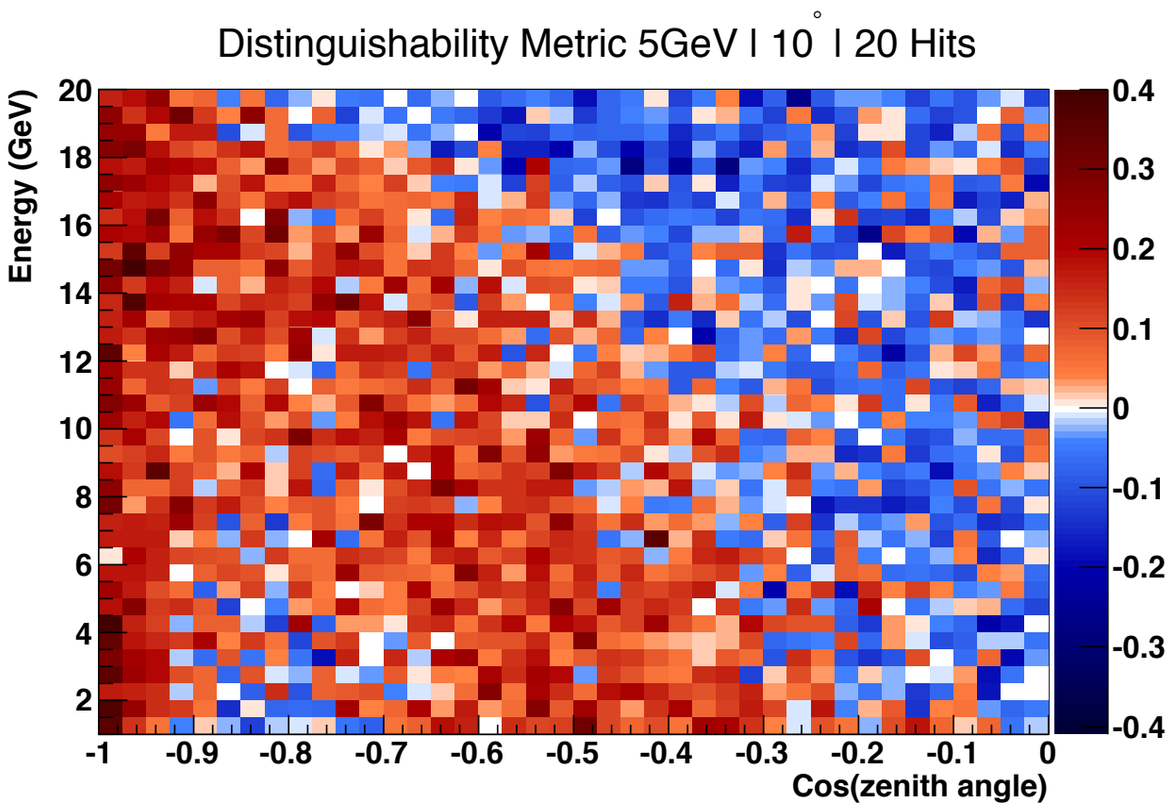
- There are benchmarks that relate hierarchy distinguishability to reconstruction uncertainties
  - A cut on 20 hits represents a reconstruction efficiency
  - Provide targets for ongoing reconstruction effort



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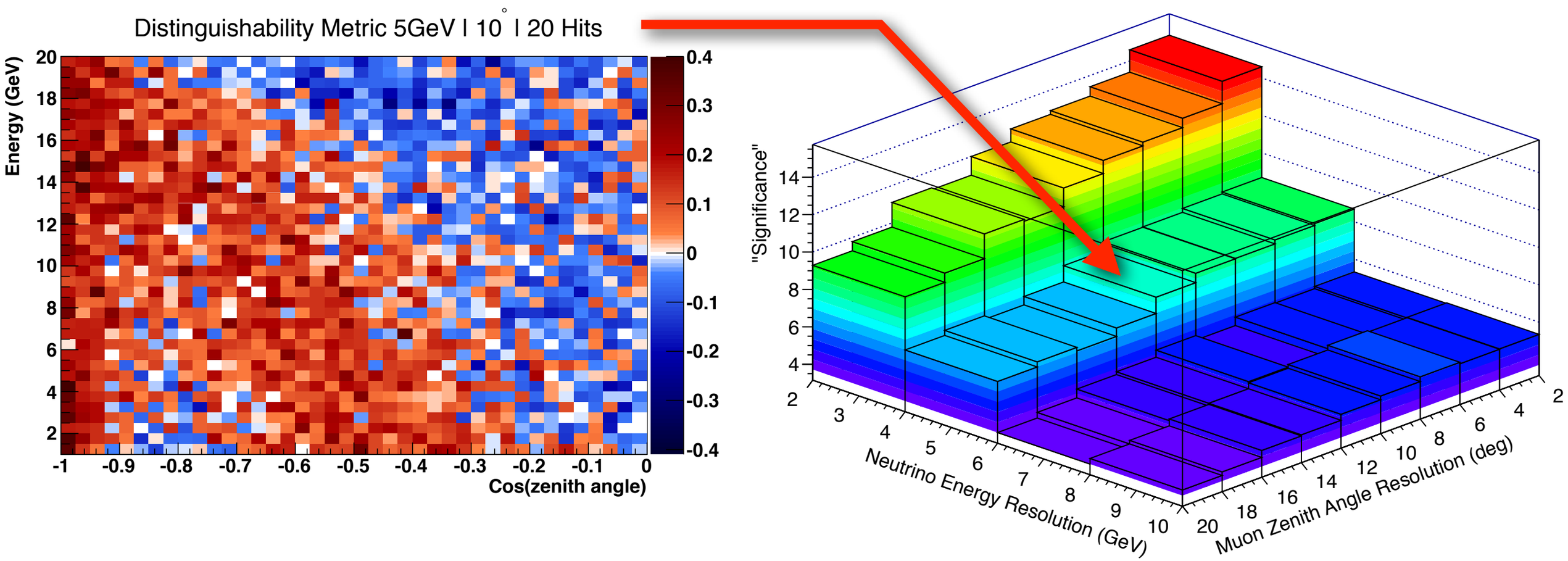
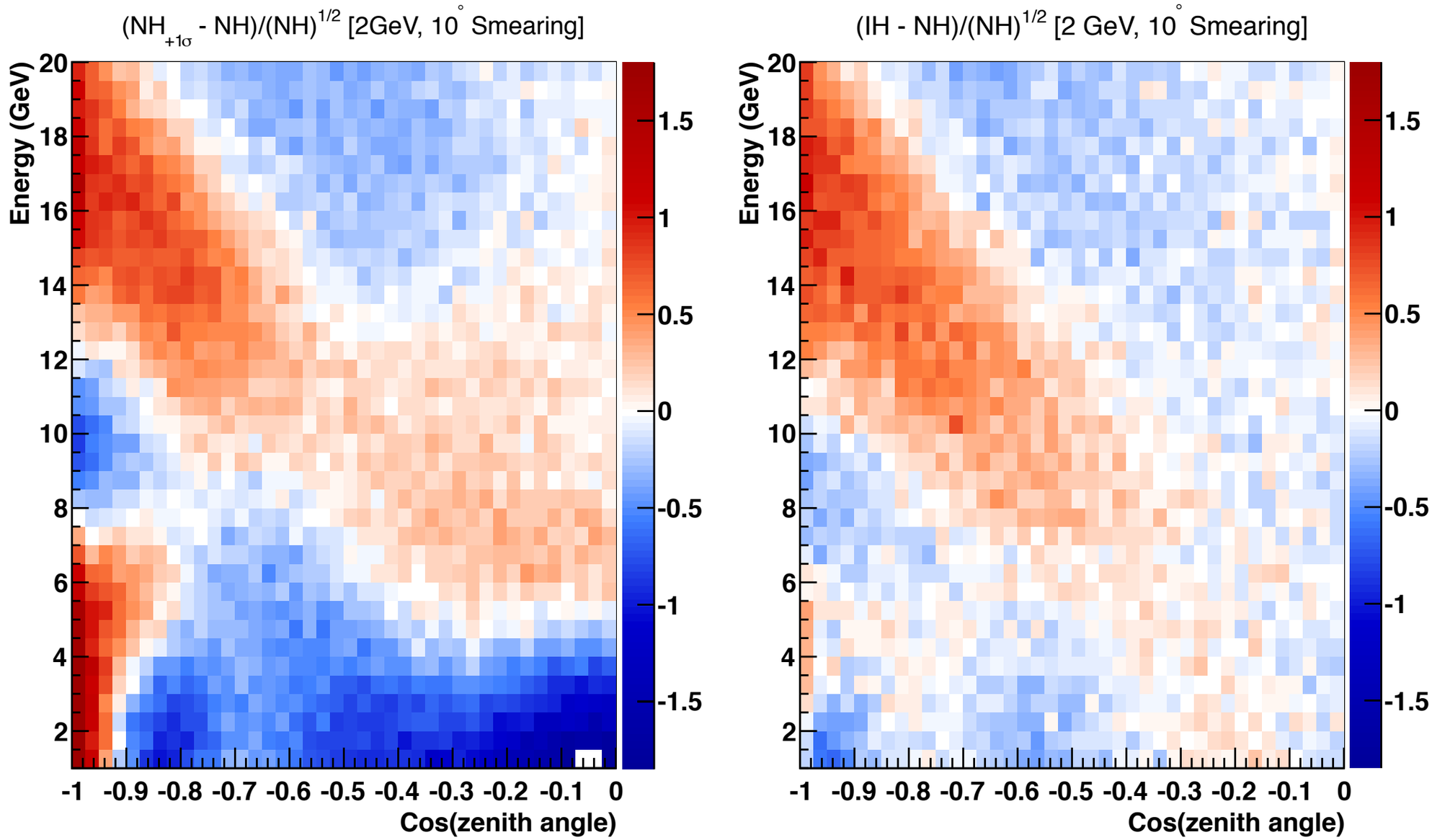


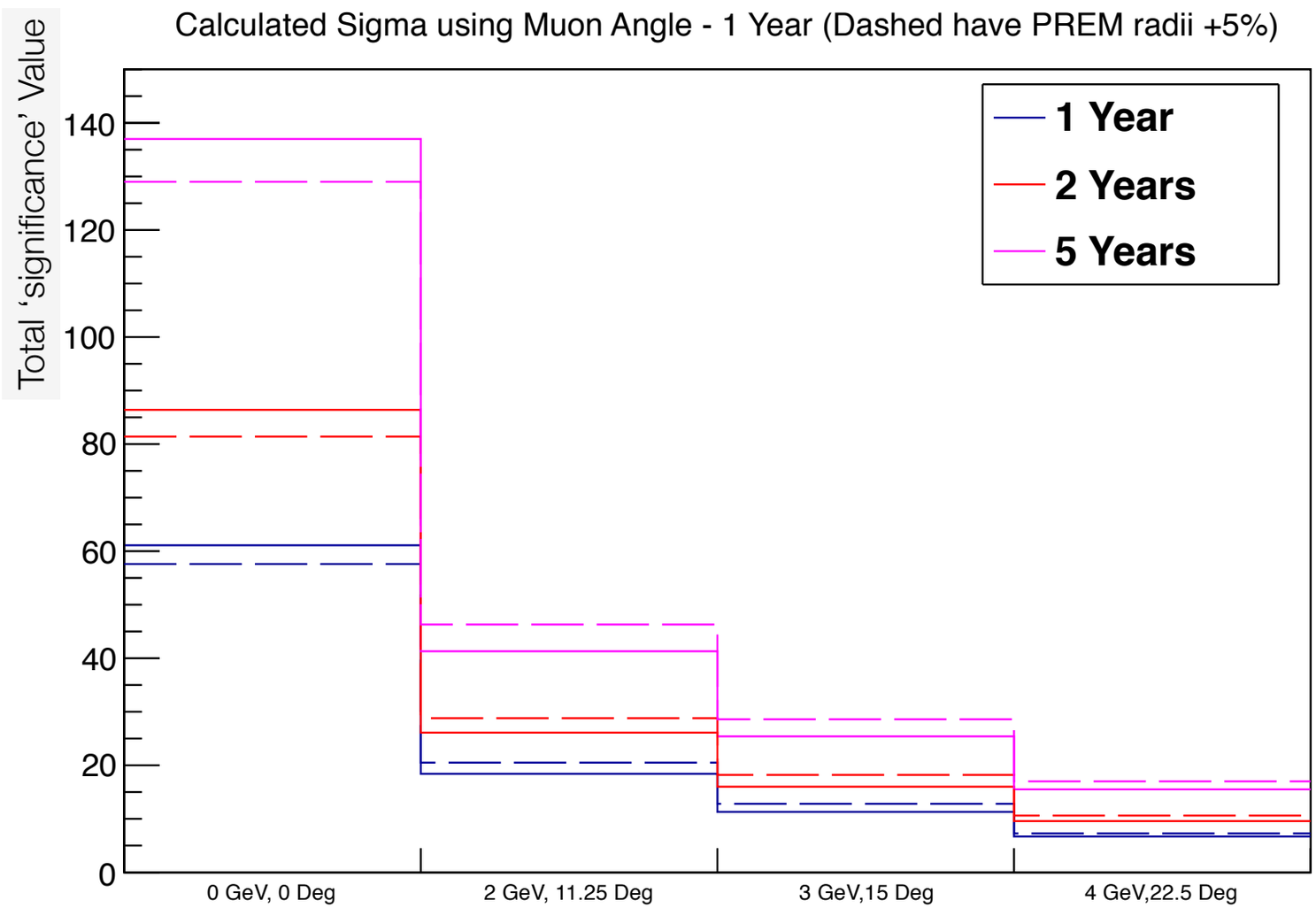
Physics Challenges

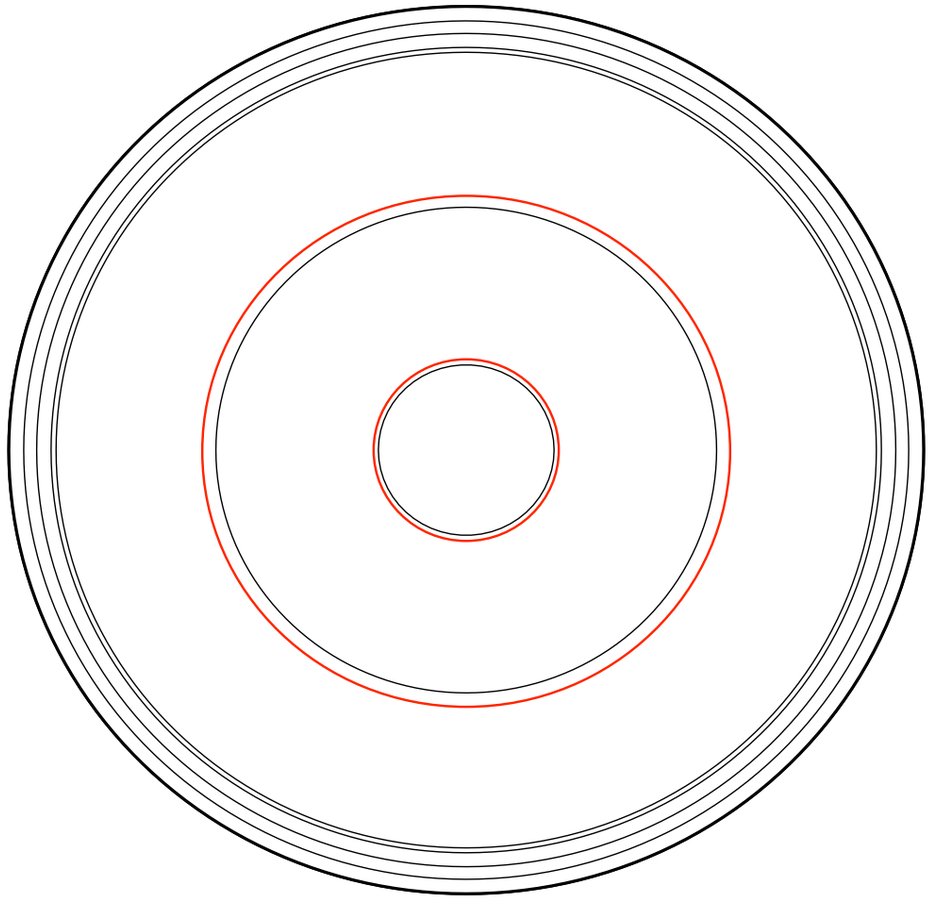
- Uncertainty in global Δm^2_{31} creates some degeneracy in the distinguishability metric
  - Plots have perfect event ID and 100% selection efficiency, but include energy and angle smearing



PREM Model

- Change the earth layers within the PREM model radii +5%, which is a 5x overestimate from geophysics measurments
- Distinguishability is largely unaffected by PREM model uncertainty

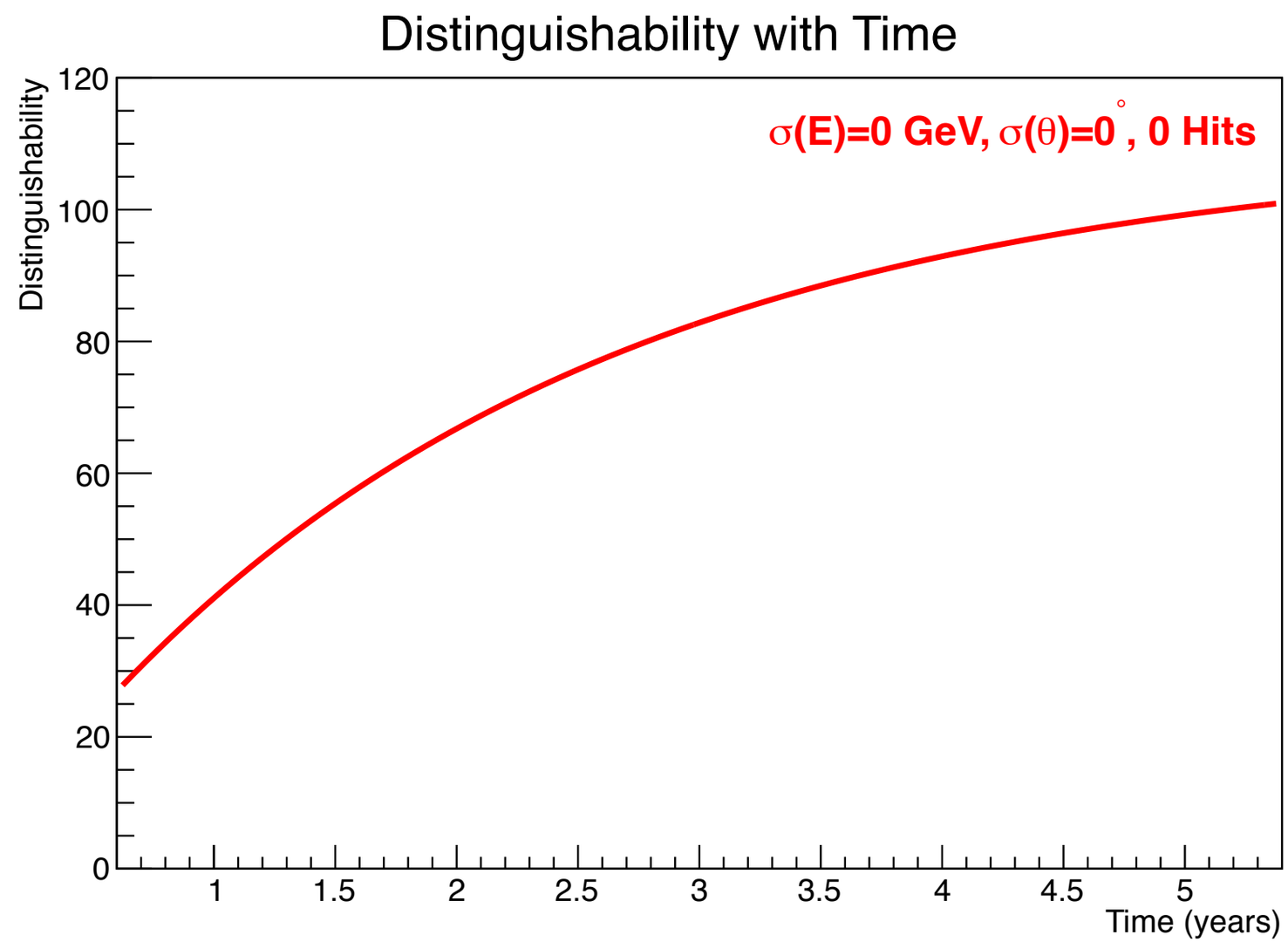




How Long?

- The effect of all of the caveats needs to be determined

- Apply no conditions



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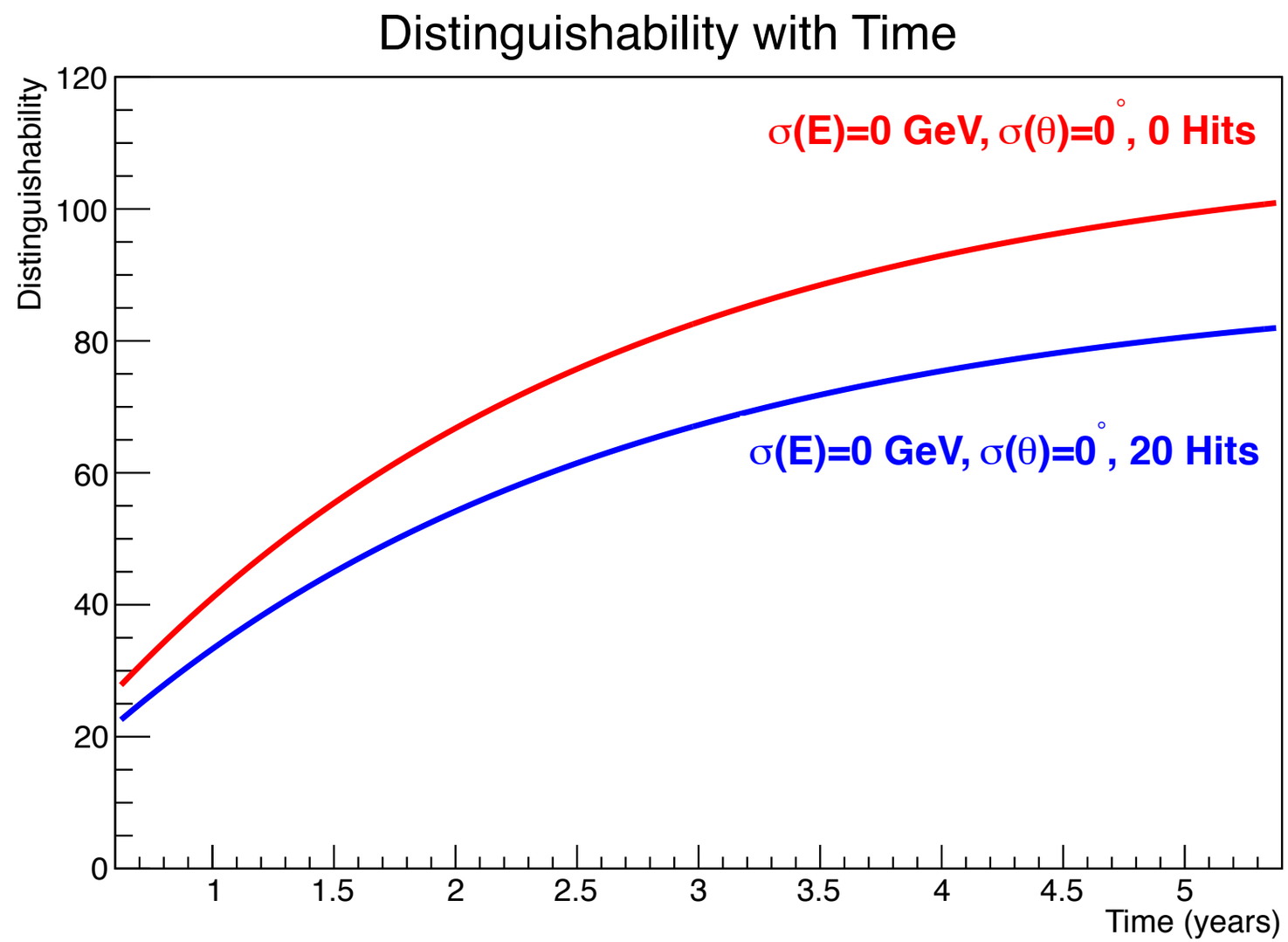

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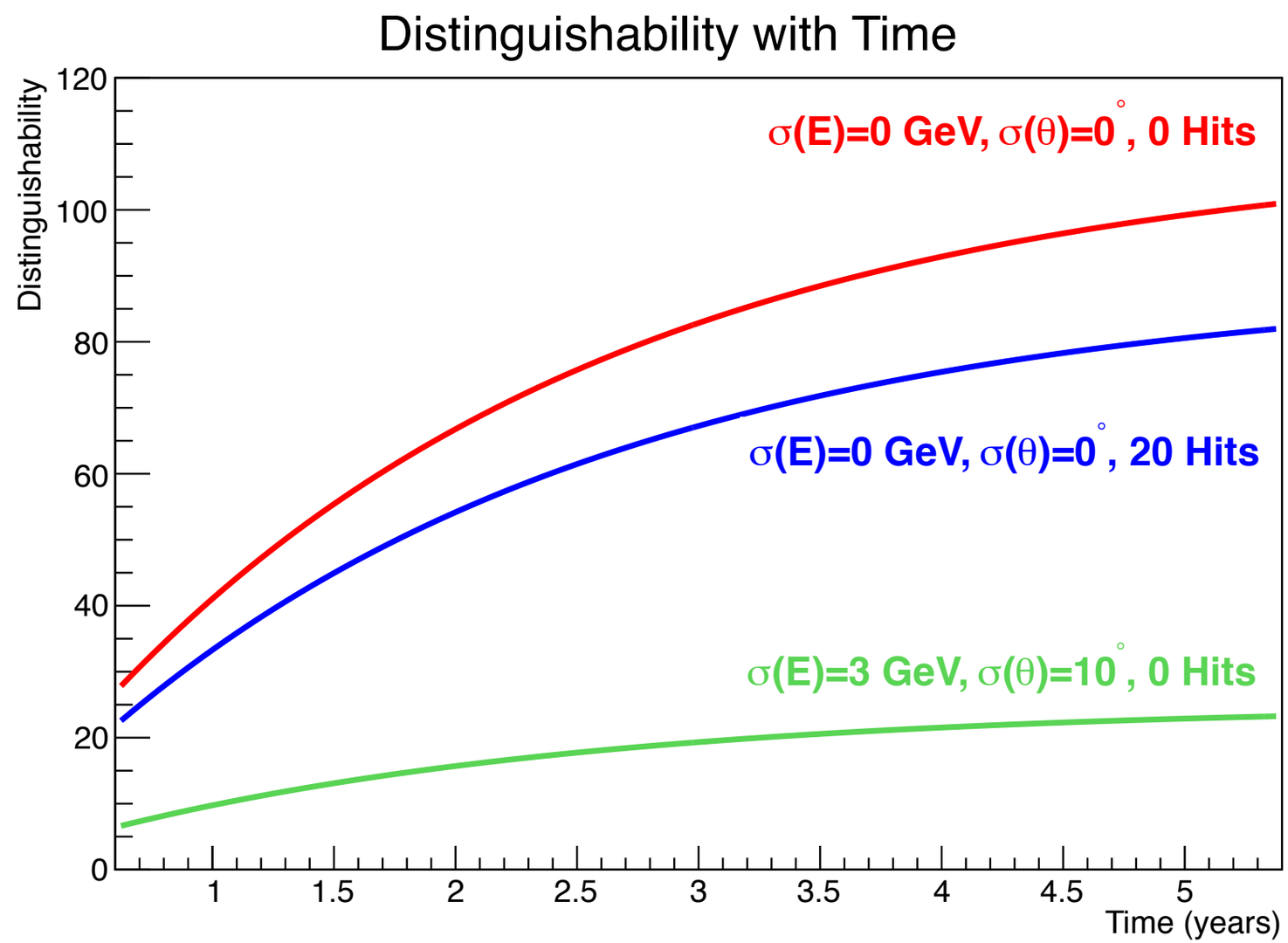

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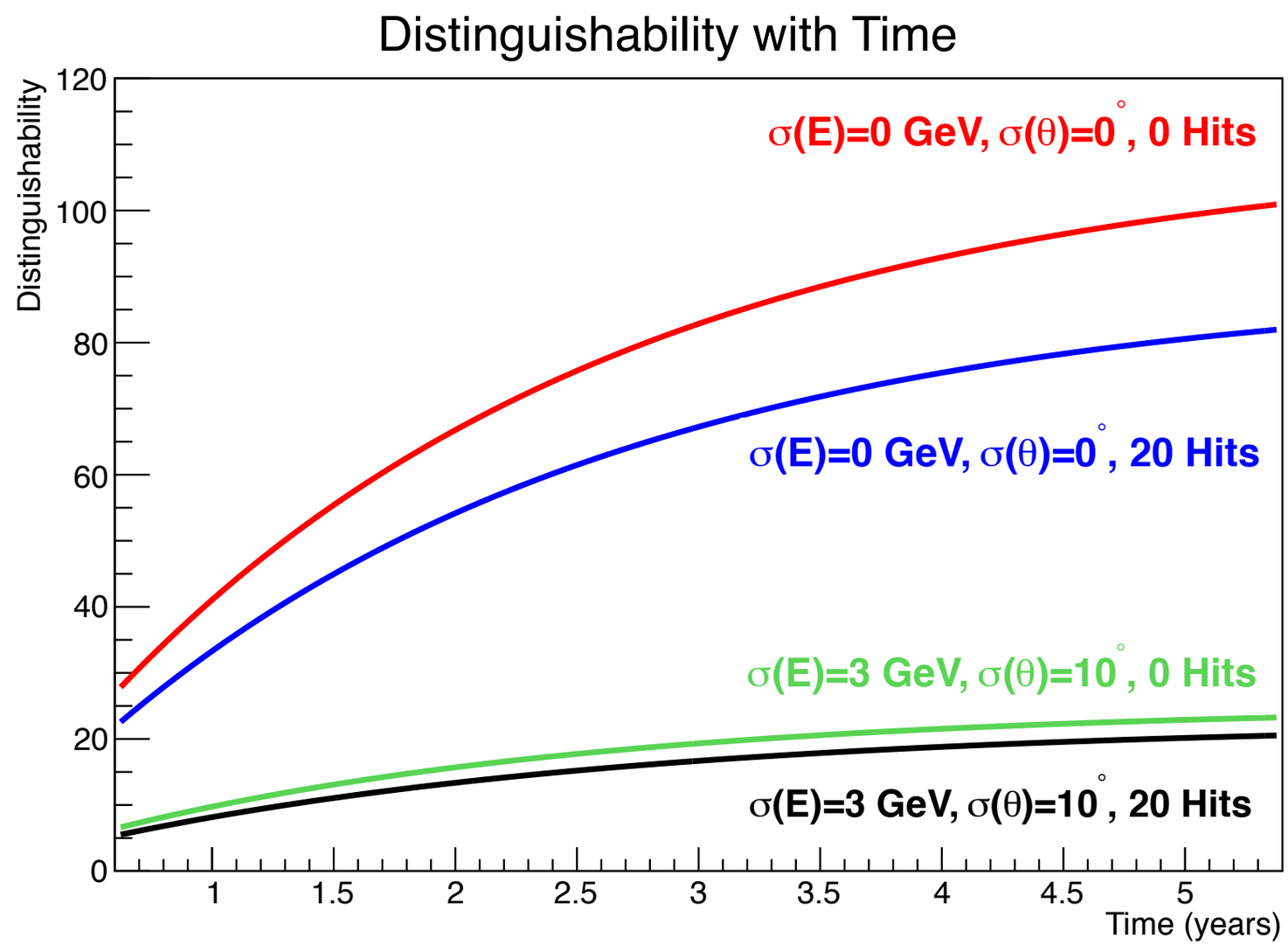
- Apply resolutions and 20 hit cut



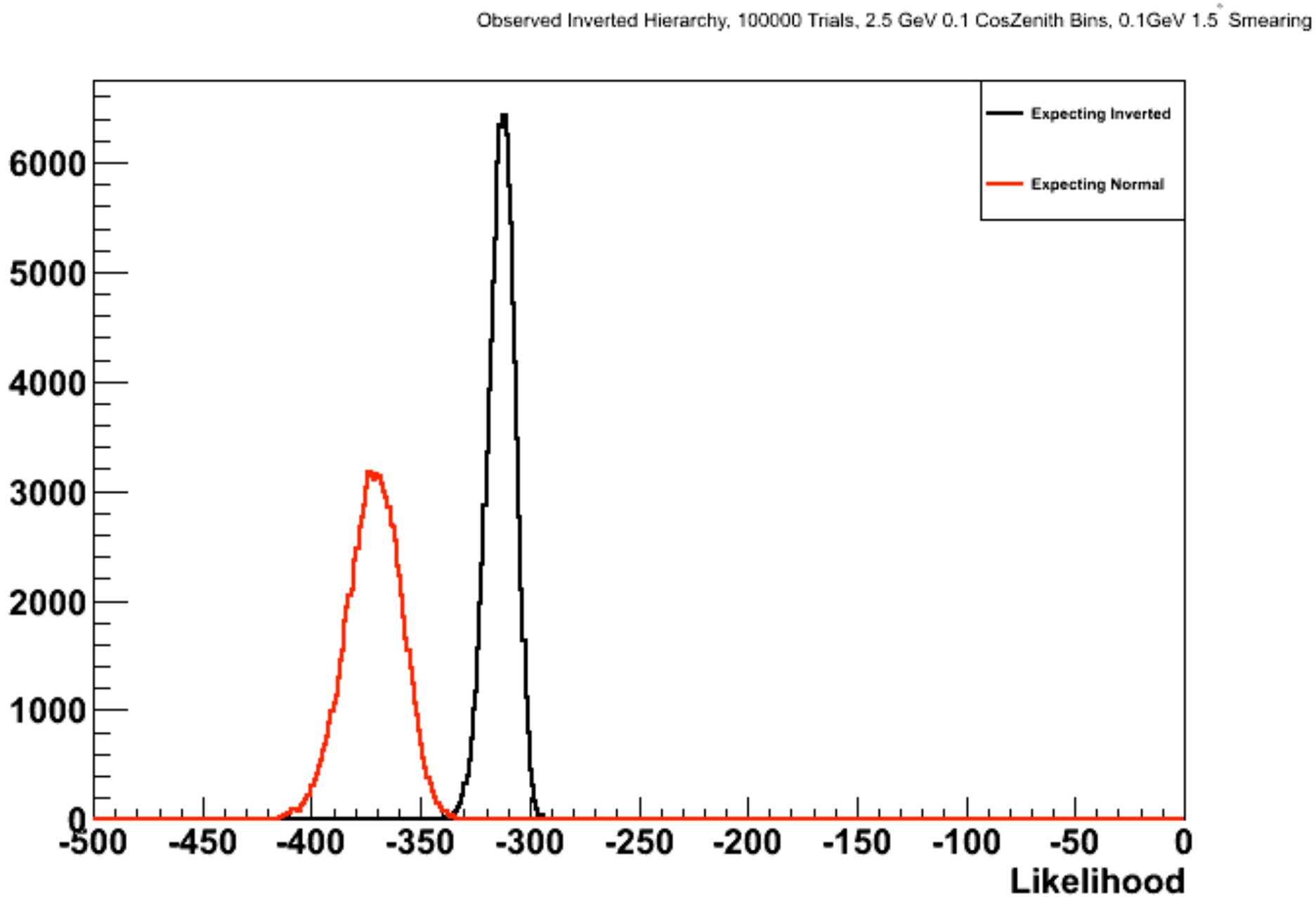
Statistics Issues from Literature

*arXiv:1210.3651

- Since this is a “discussion”...
- The Akhmedov et. al. method may be optimistic
  - Uses a chi-squared like statistic, but the discrete aspect of the neutrino hierarchy fails regularity condition of Wilks’ theorem
- Alternative possibility is a MC method*
  - Create many sets smearing the reconstructed angle and/or energy for a specific hierarchy
  - Compare likelihood of smeared set(s) to a normal hierarchy template and an inverted hierarchy template

Likelihood Tests

- True hierarchy is ‘inverted’, with a constant energy smearing of 2.5 GeV and increasing smearing in zenith angle (1.5-9.5 degrees)



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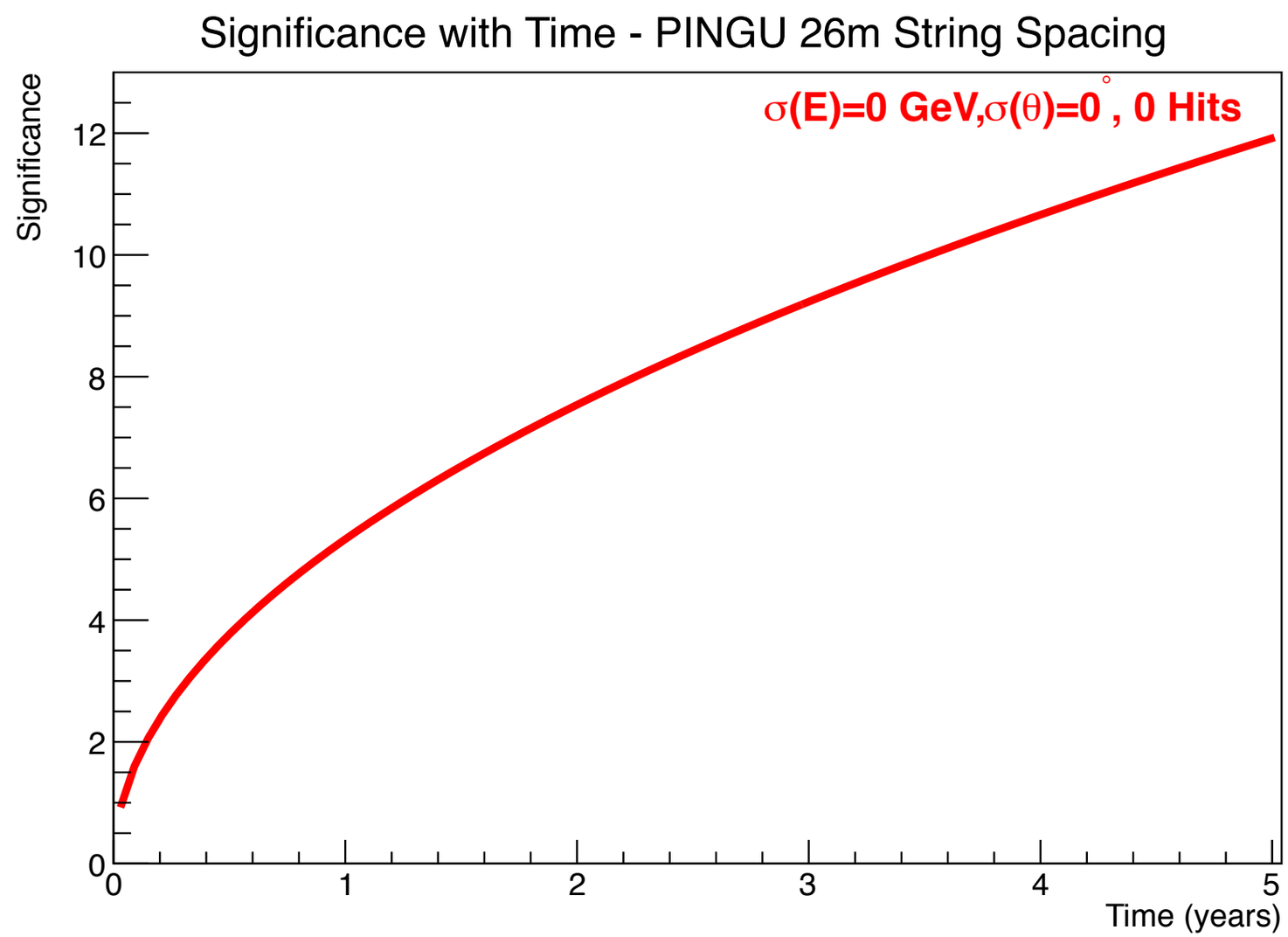

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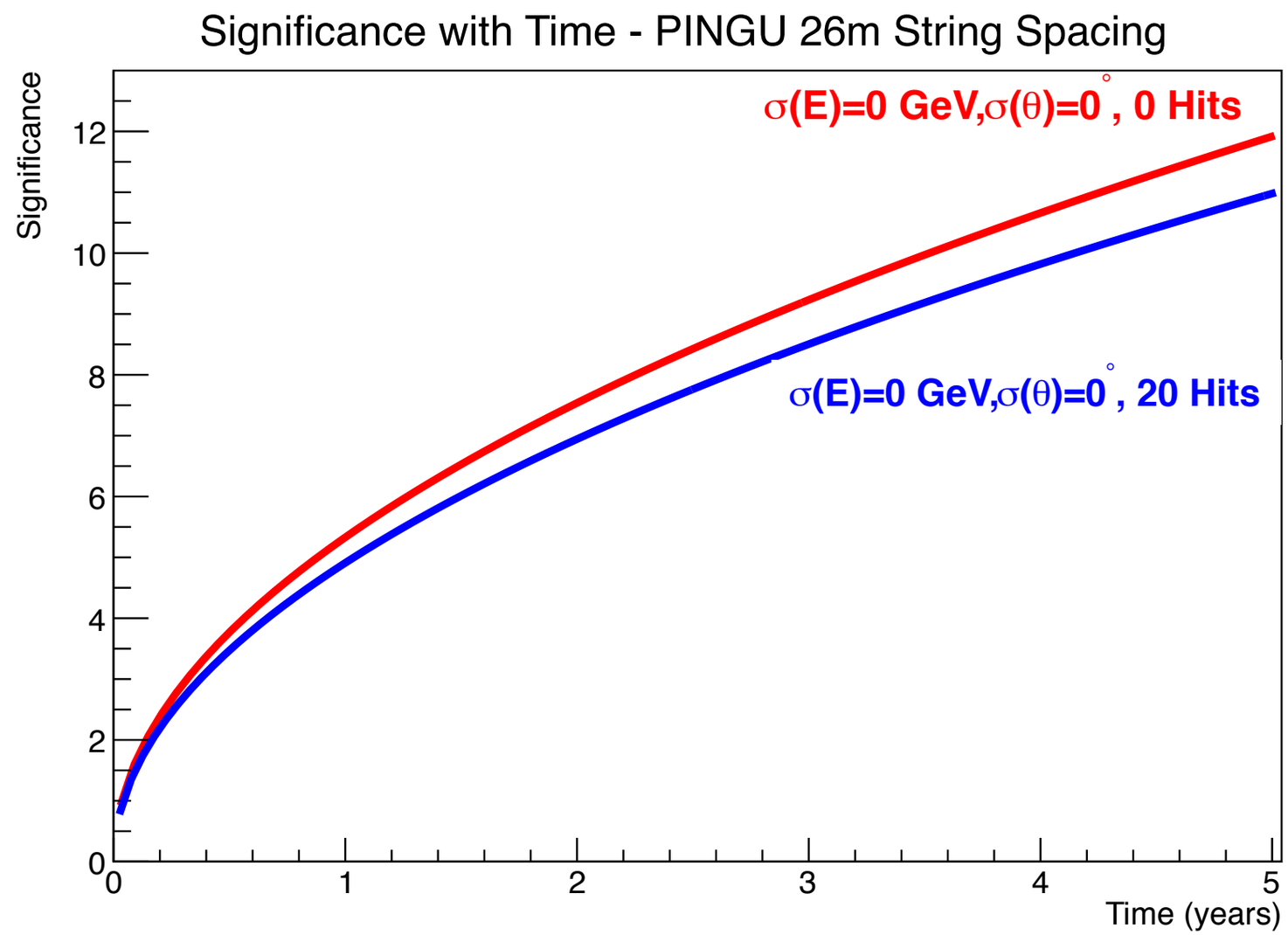

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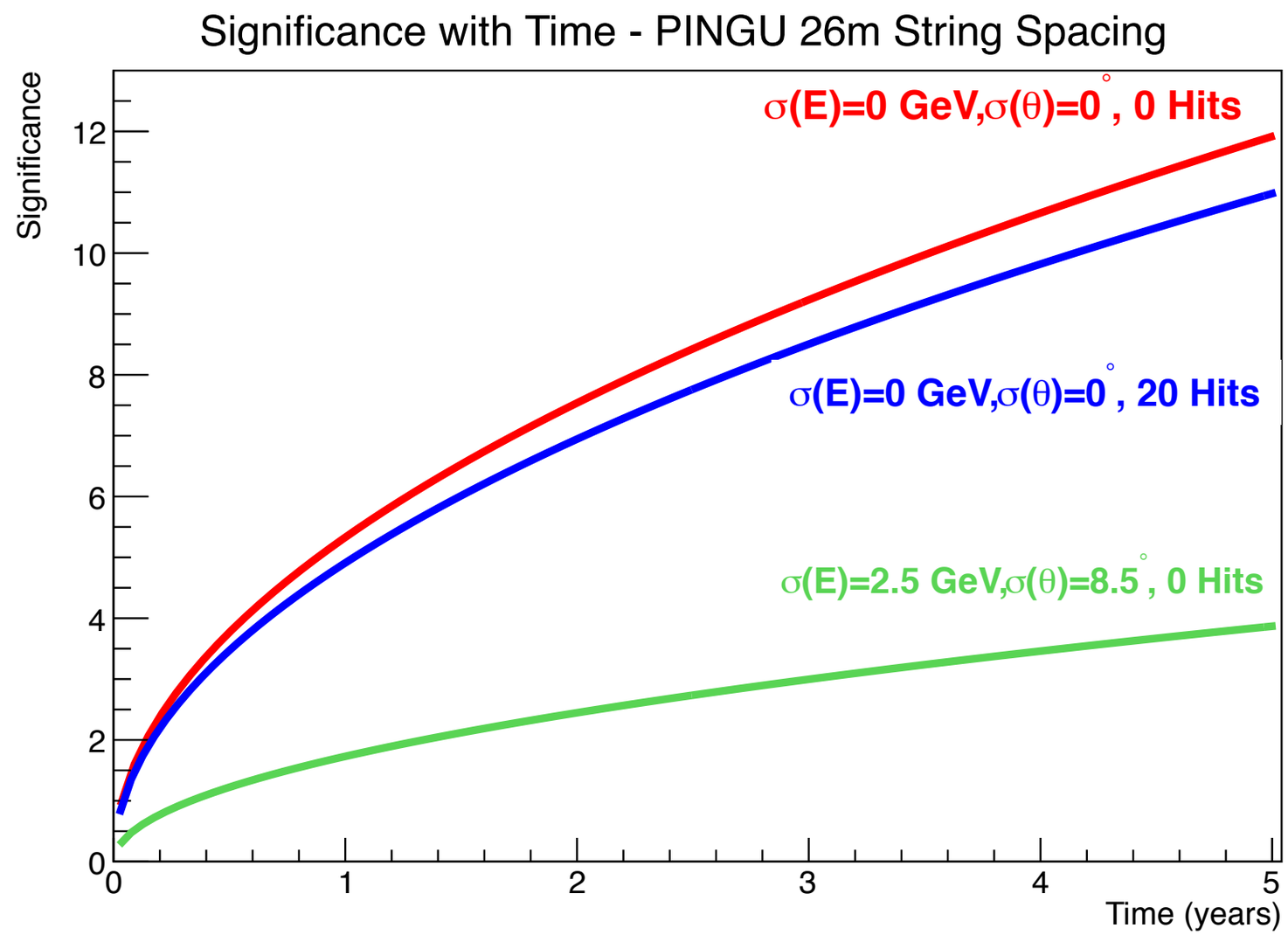

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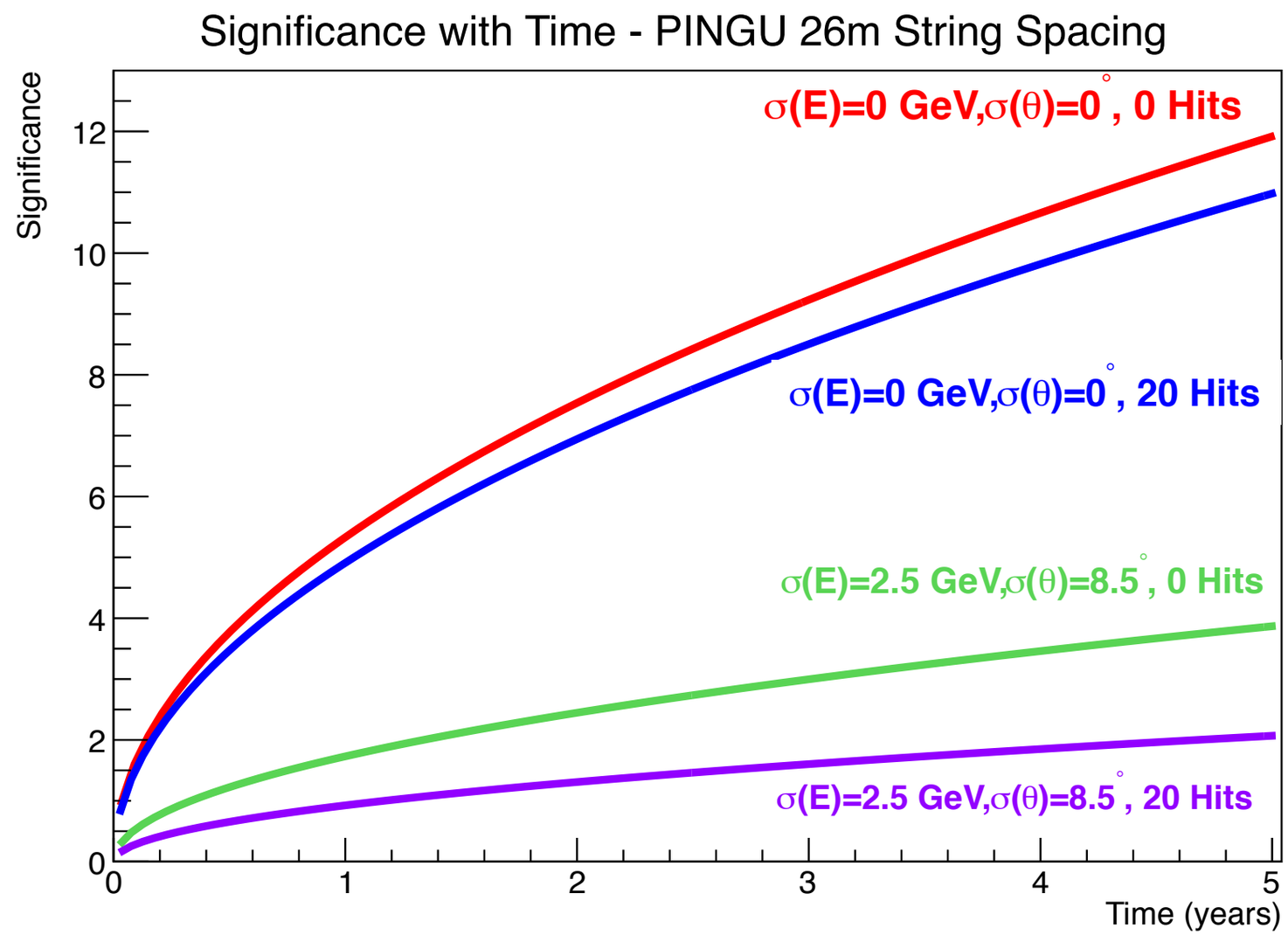


Moving Forward

- PINGU's sensitivity to the neutrino hierarchy order is still an on-going effort, requiring additional features that will both degrade and improve the final result

Degrade

- Detector Uncertainties
  - DOM quantum efficiency
  - Ice Model (scattering and absorption)
  - Absolute energy scale
- Physics
  - Atmospheric neutrino flux rate
  - Δm_{32}^2

Improve

- Add additional strings/ DOMs
- Remove 20 hit cut
- Use bjorken-Y to statistically separate ν from anti-ν

arXiv:1303.0758

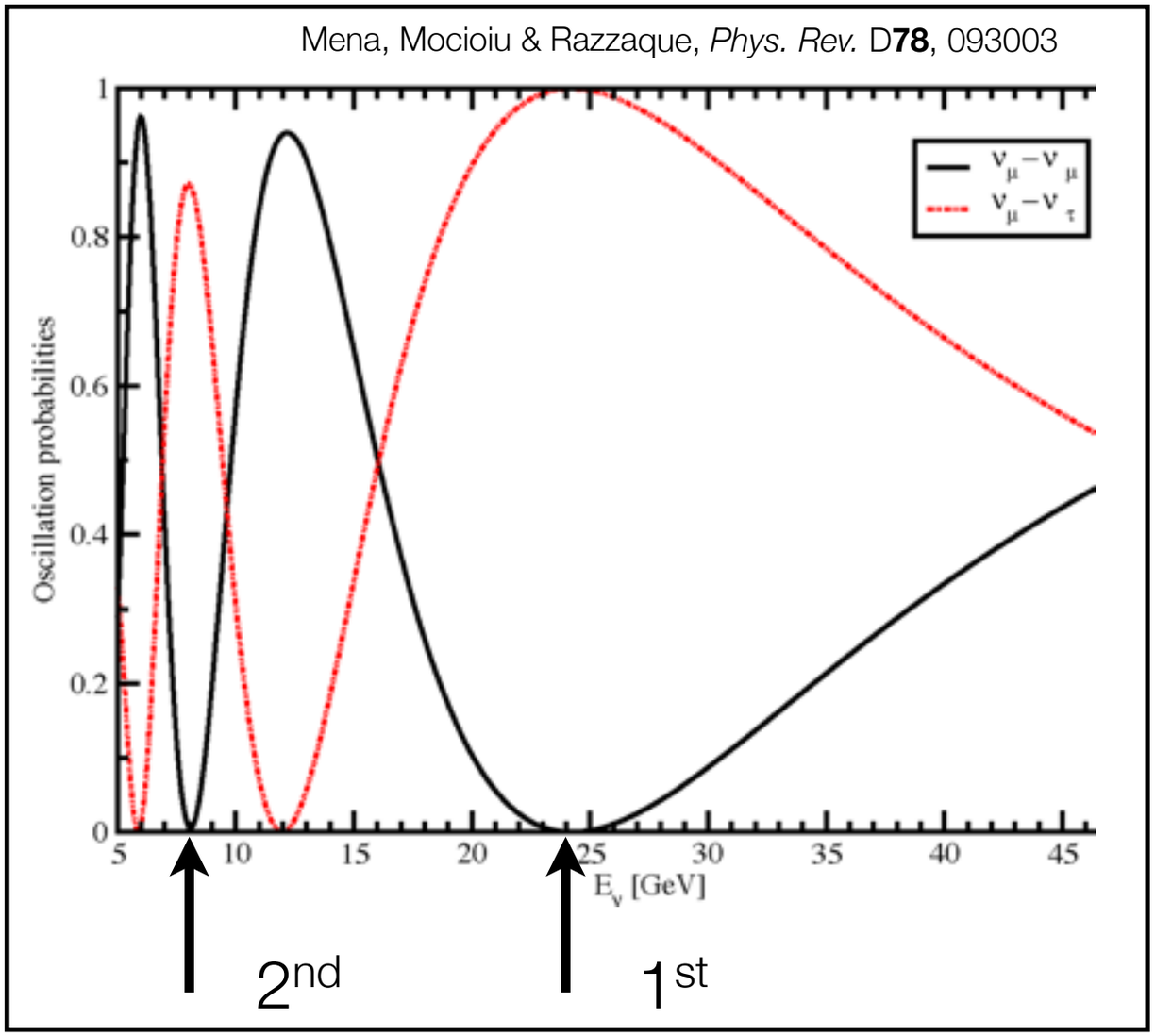
Where are we going?

Alberto Giacometti “L’homme qui marche”

Physics Beyond DeepCore

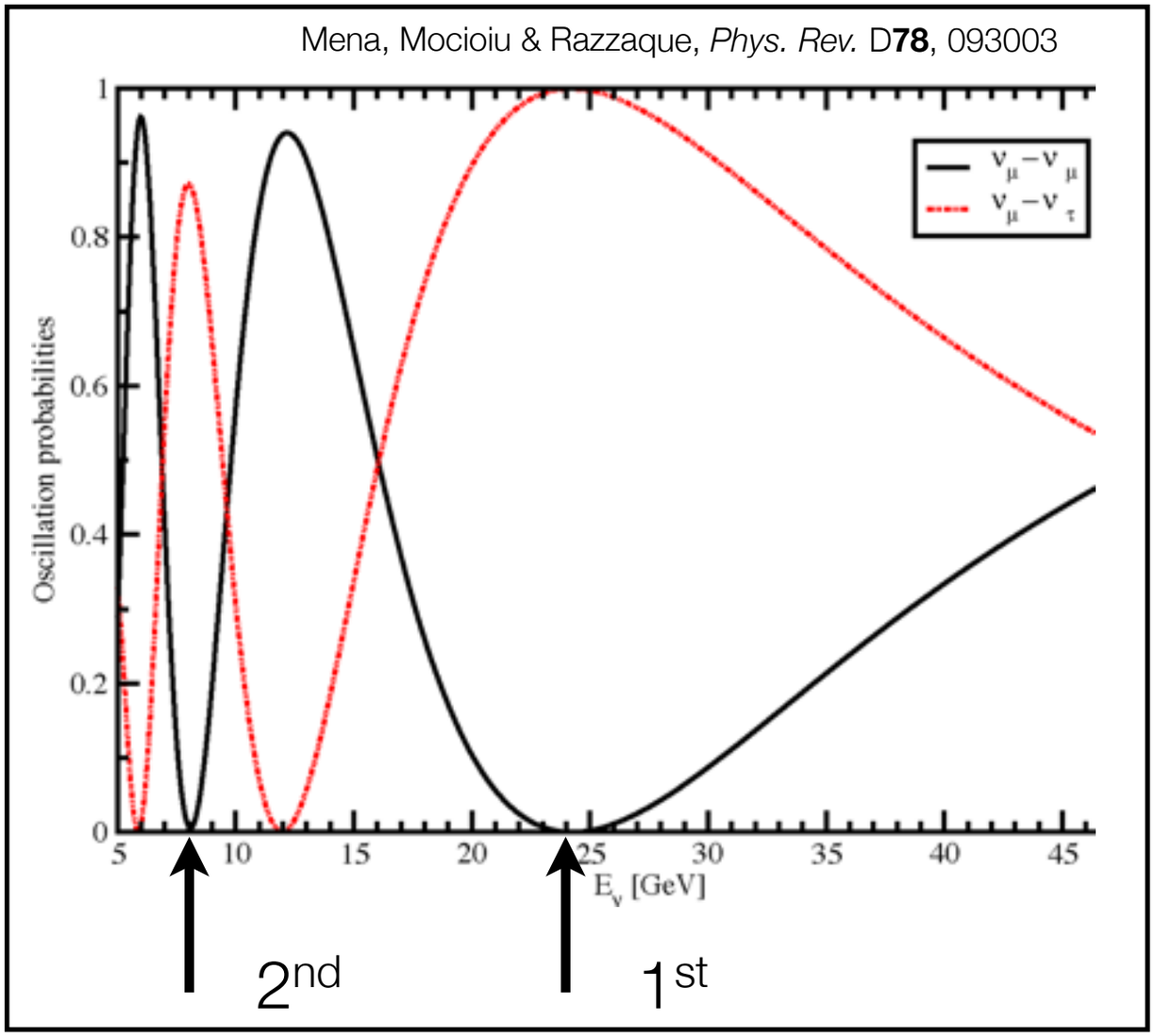
Physics Beyond DeepCore

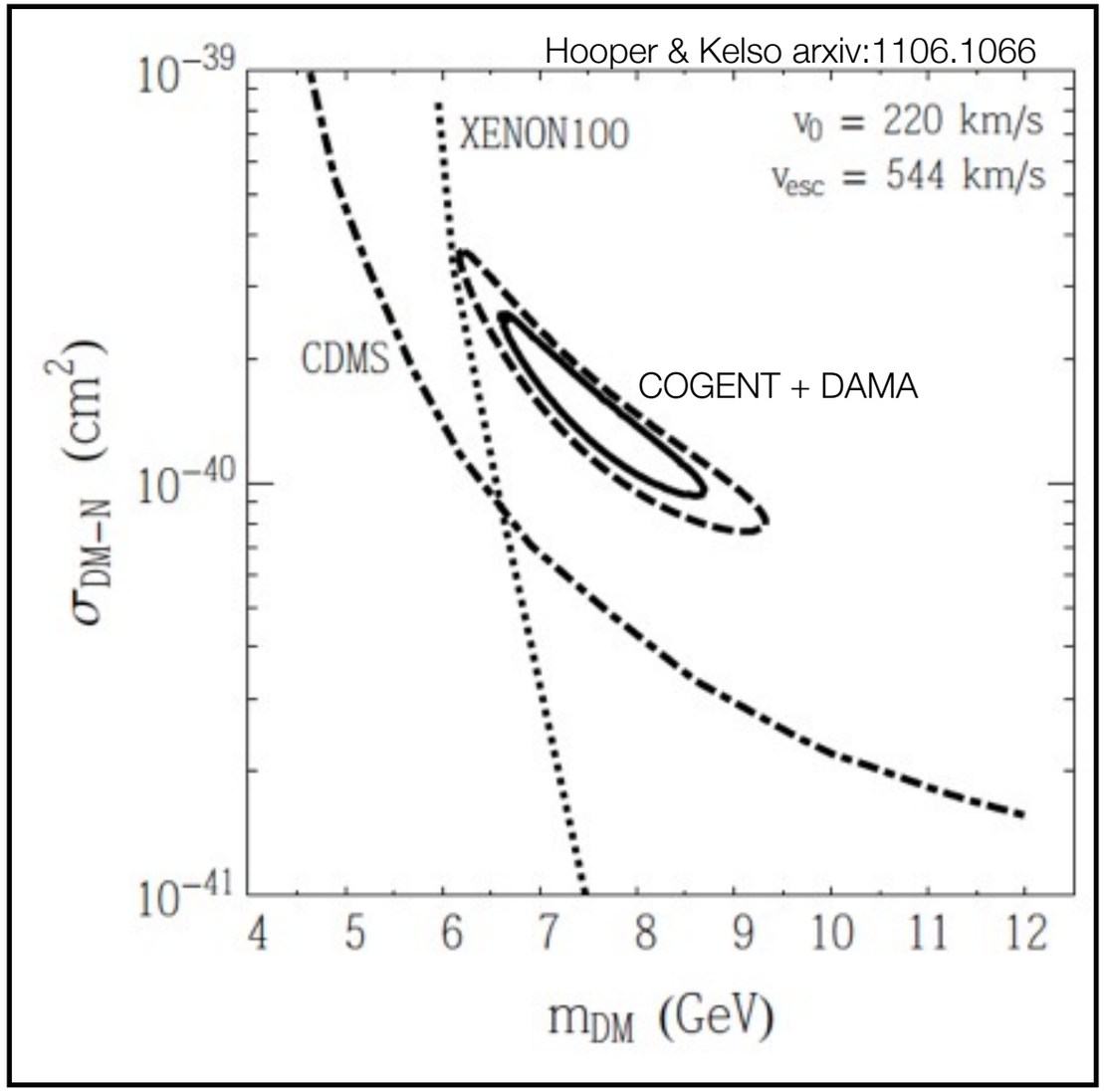
- DeepCore only has access to the first oscillation minima/maxima



Physics Beyond DeepCore

- DeepCore only has access to the first oscillation minima/maxima
- GeV Dark Matter

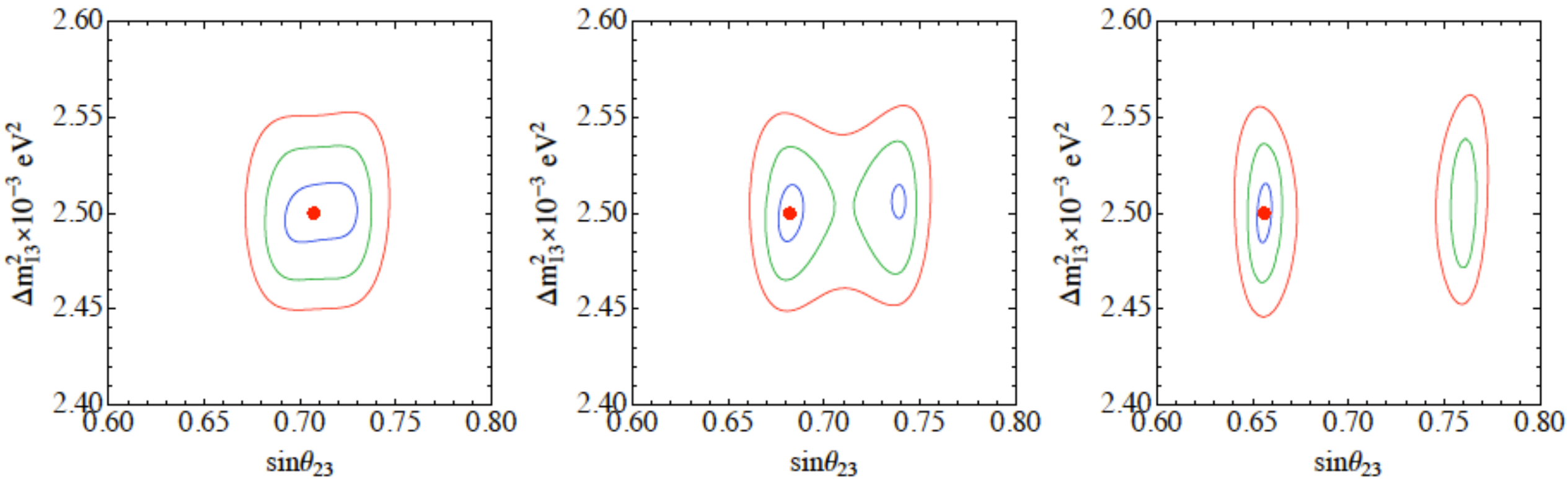




θ_{23} Maximal? Octant?

- 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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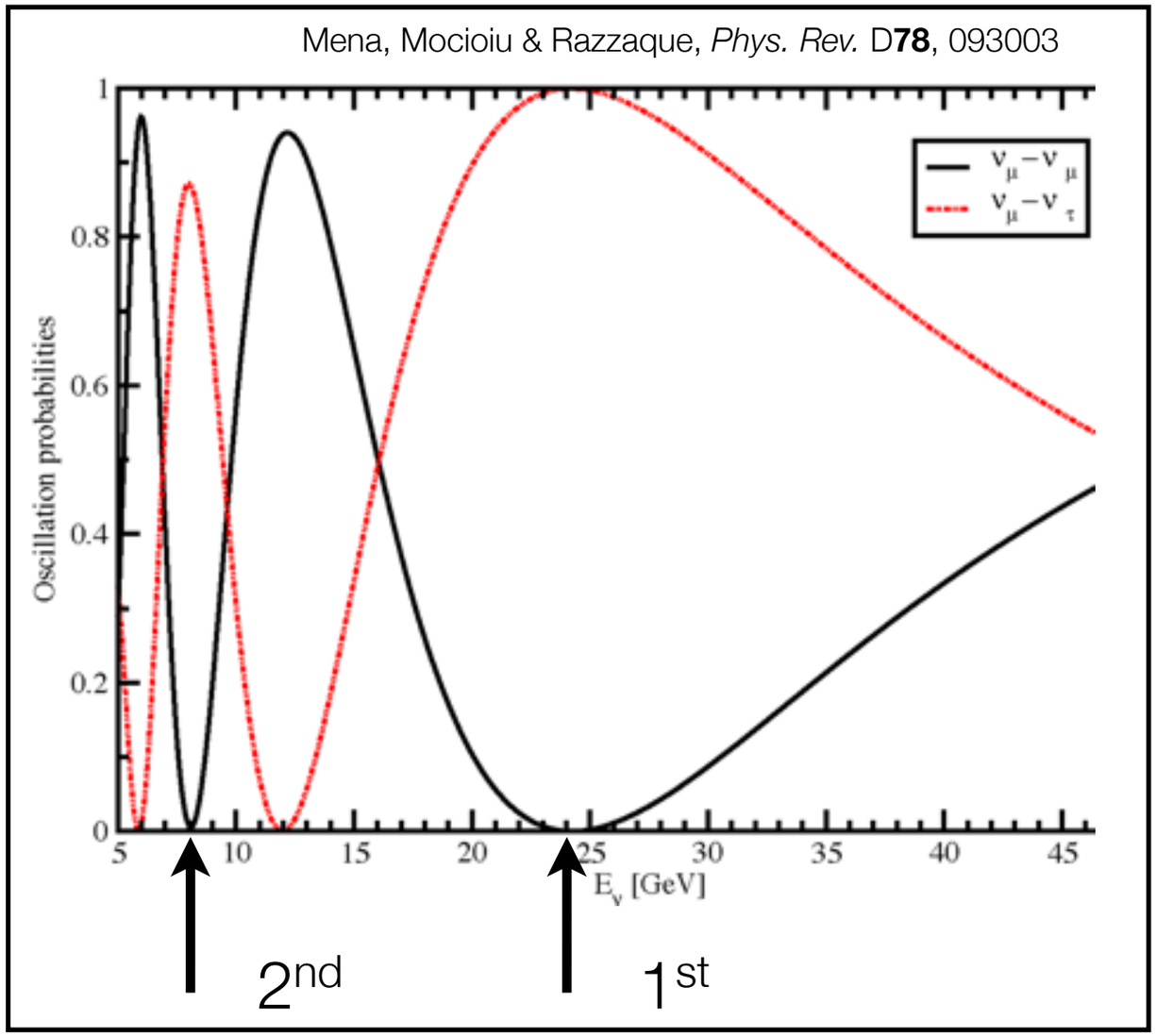

$\sin^2(2\theta_{13})=0.1$

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 neutrino disappearance
  - tau neutrino appearance
- Gains sensitivity to additional neutrino oscillation features
  - 2nd oscillation minima/maxima
  - Neutrino hierarchy over all possible values of δ_{cp}

Challenges

Cerberus

Noise Effect

- After online DeepCore filter there is bkg:signal of 1,000+:1
- Background rejection methods work at higher energies (> ~100 GeV), away from low NChannel region

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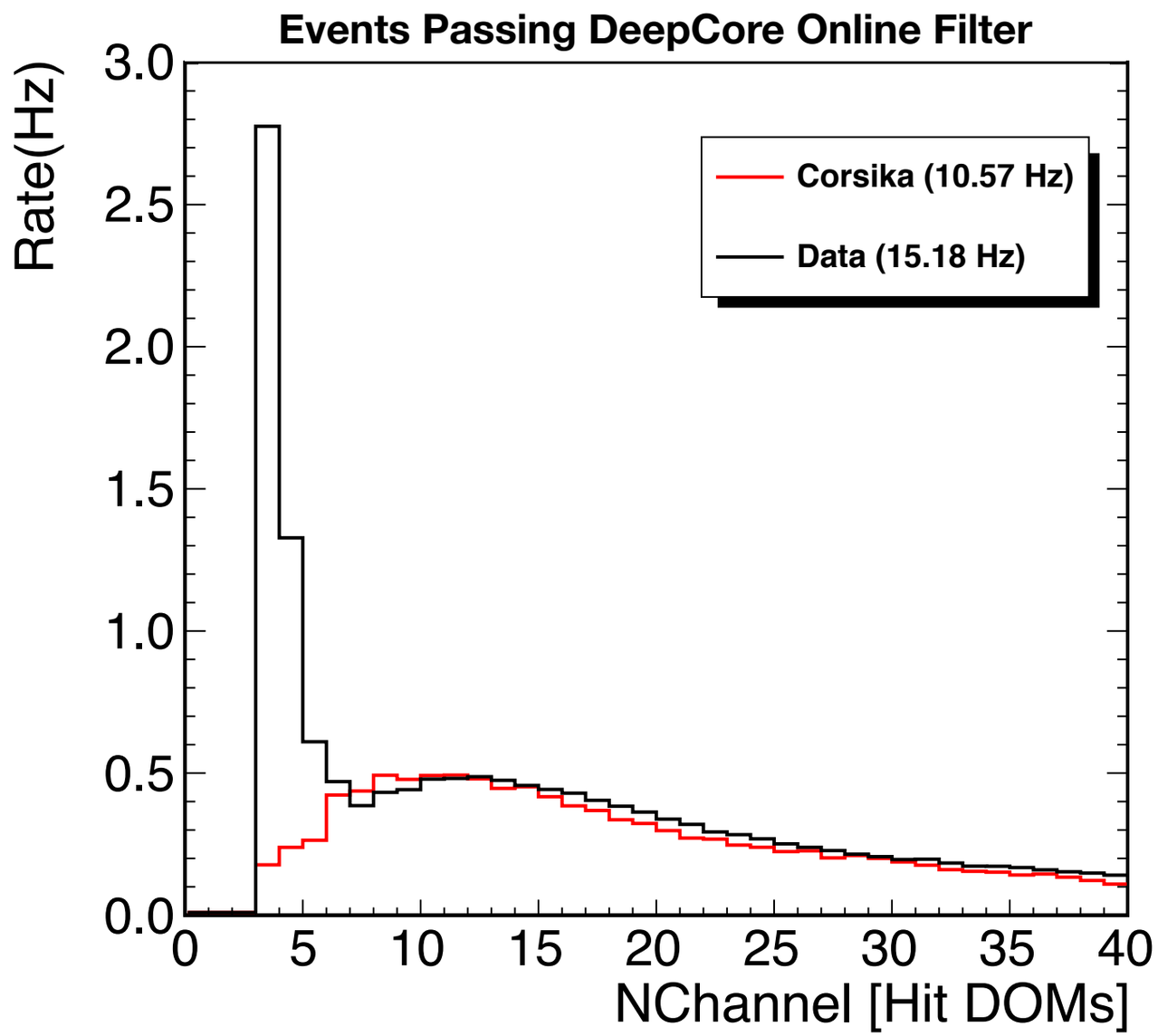

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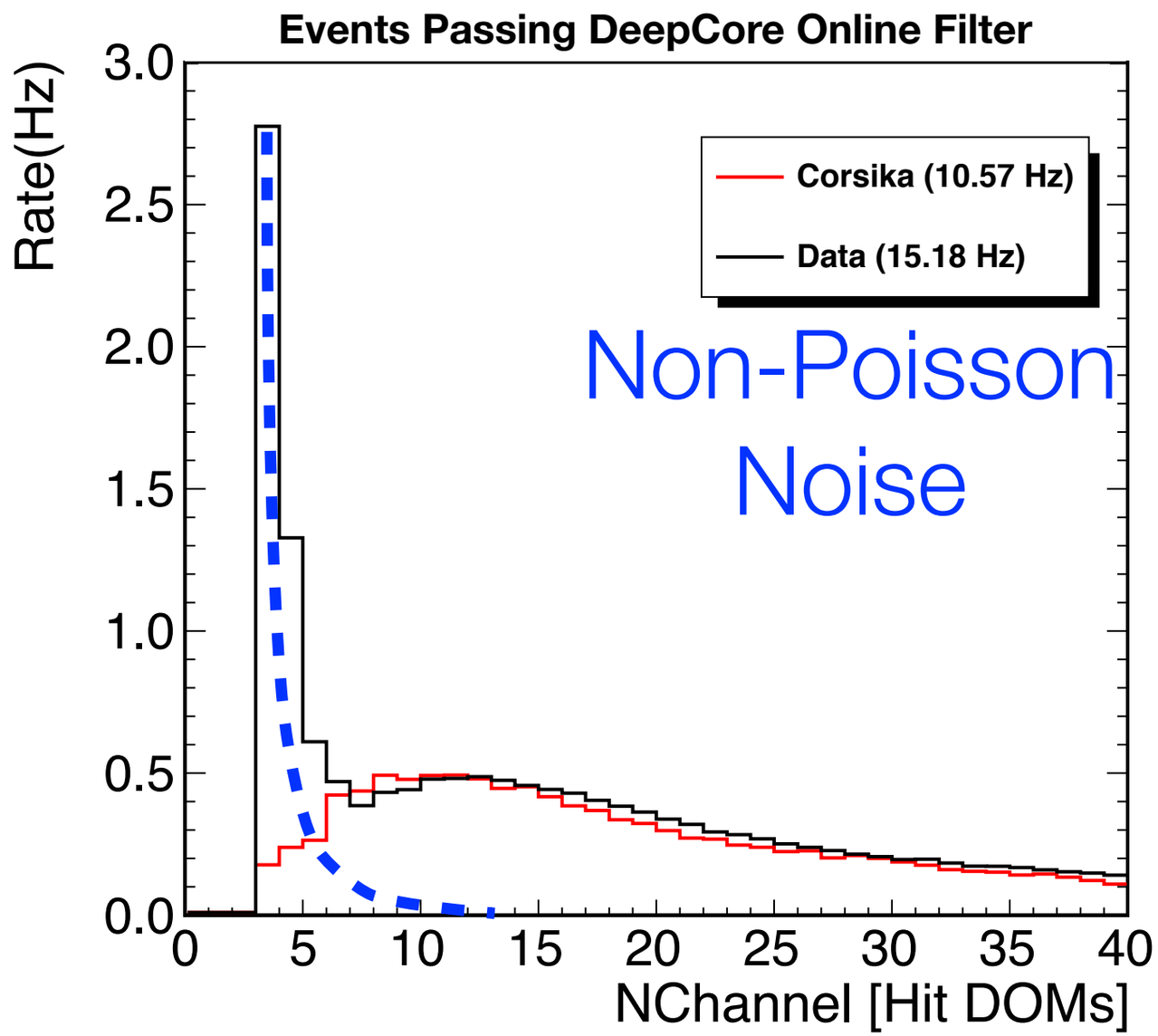

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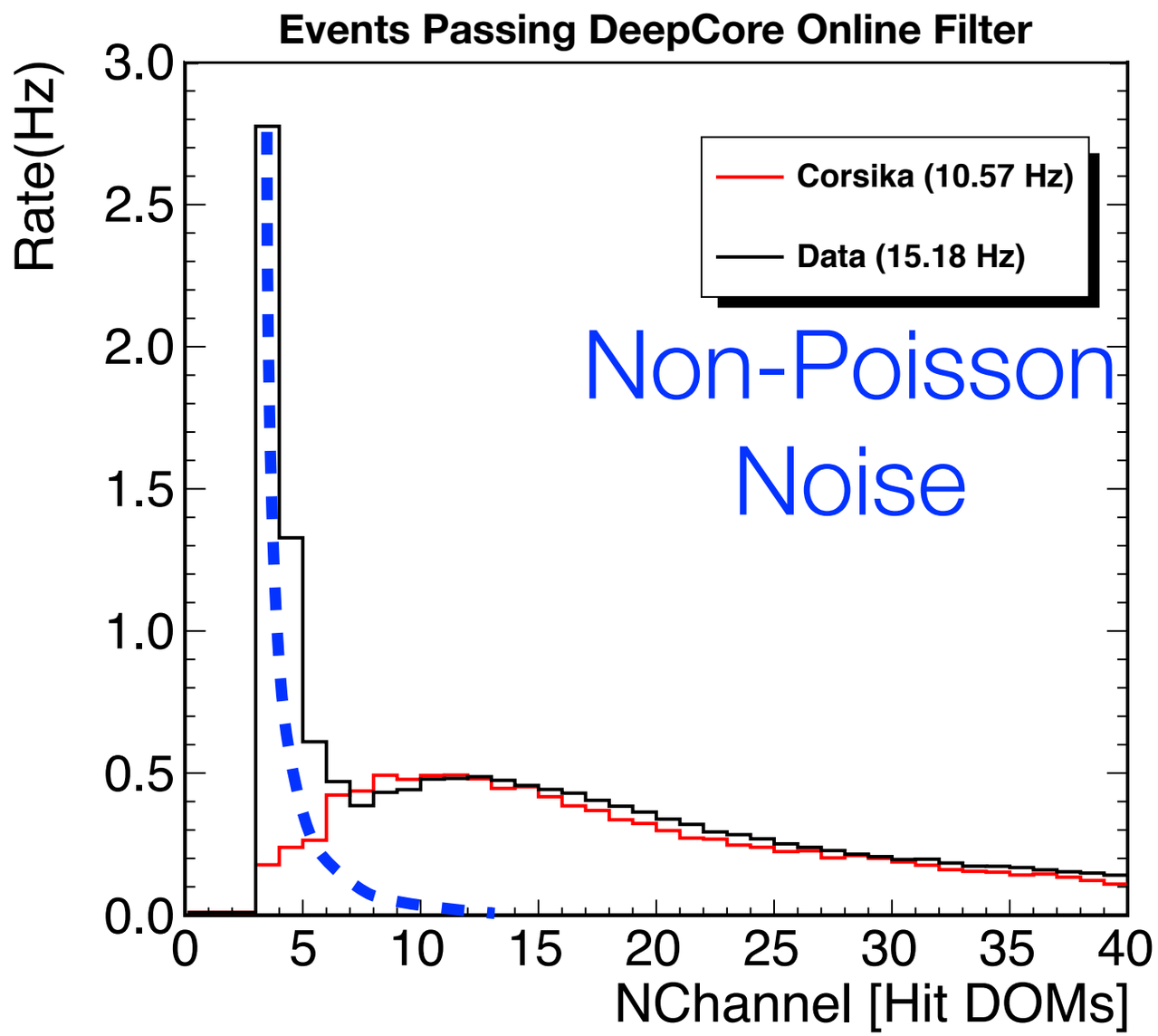

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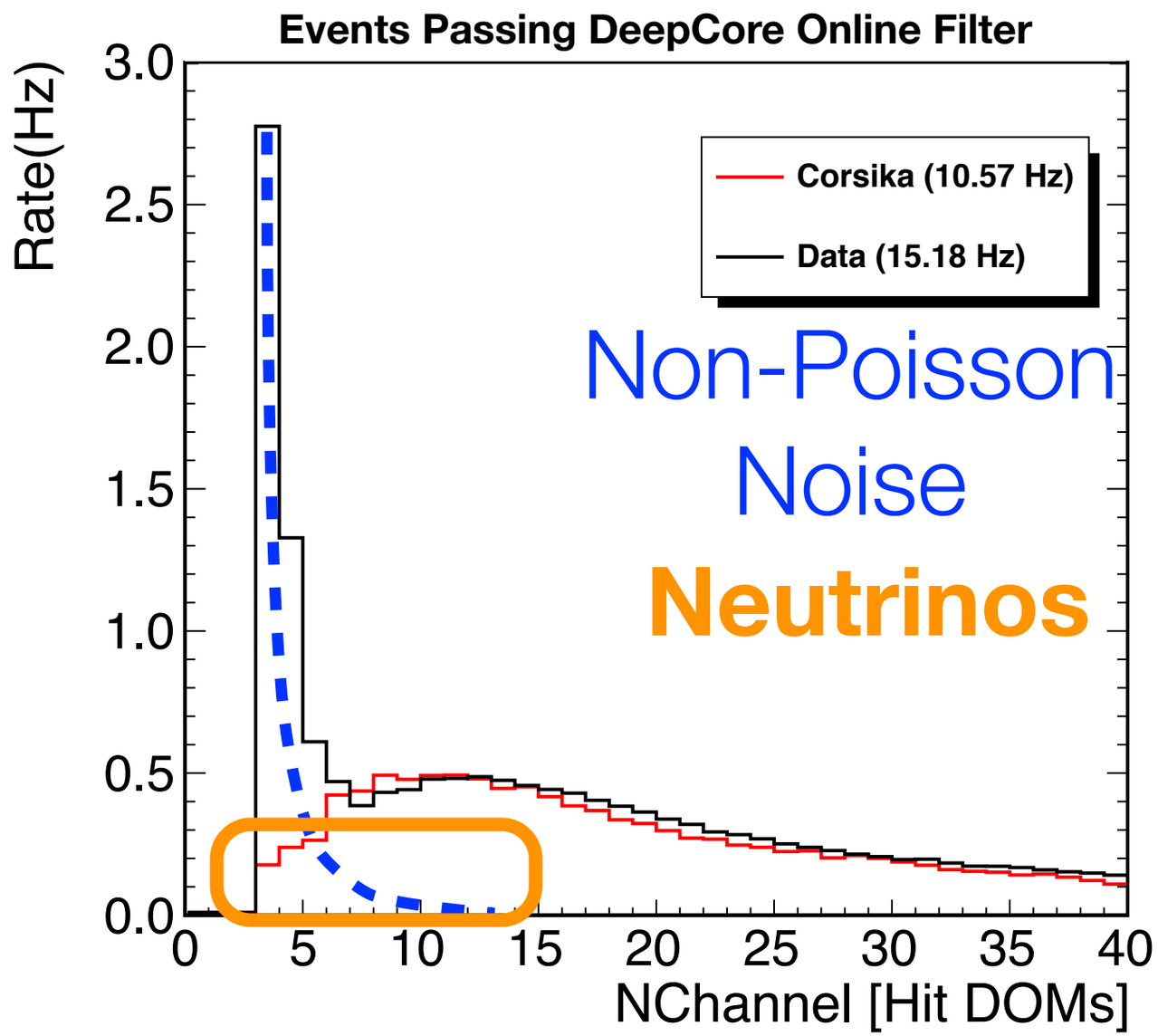
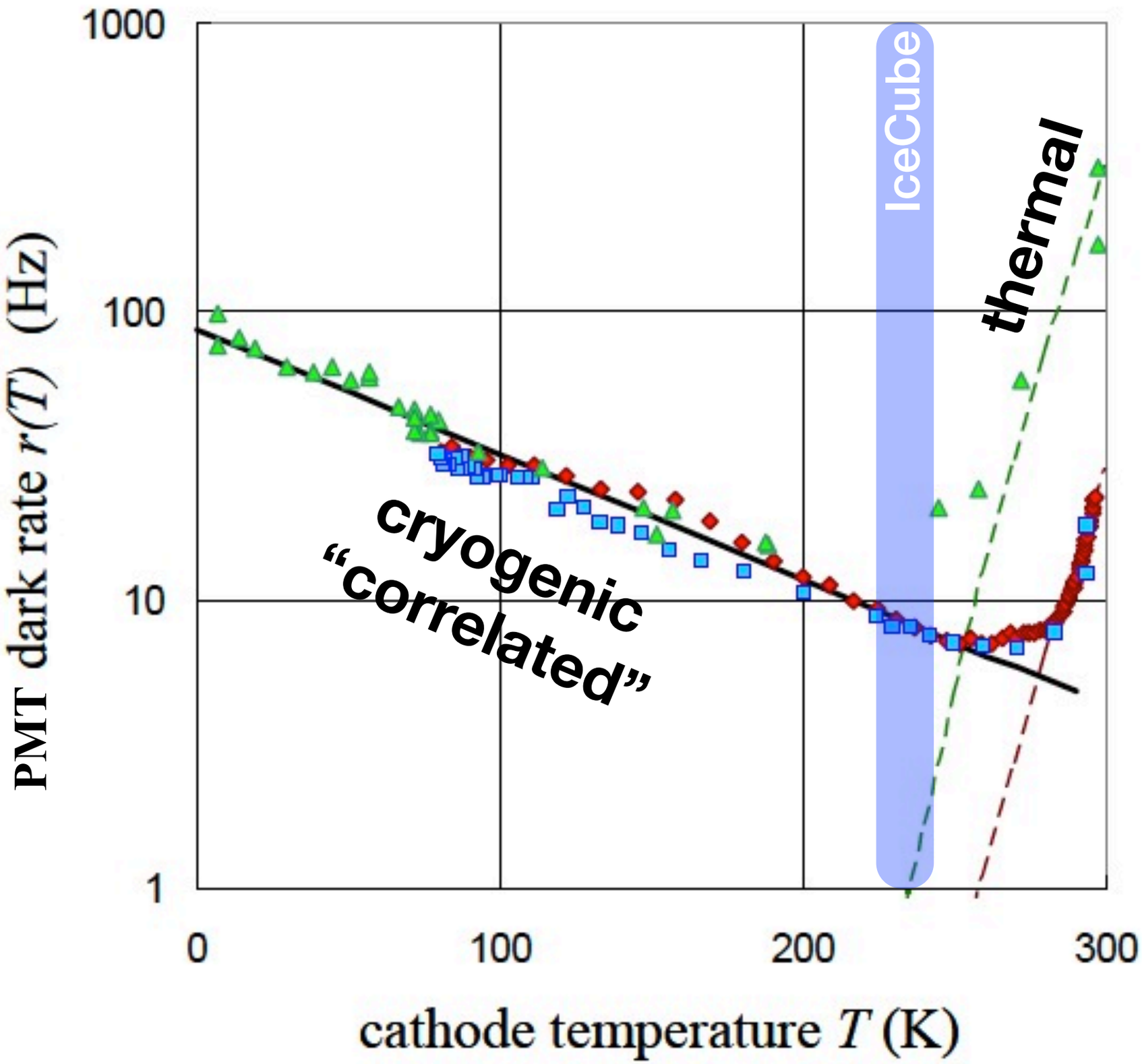
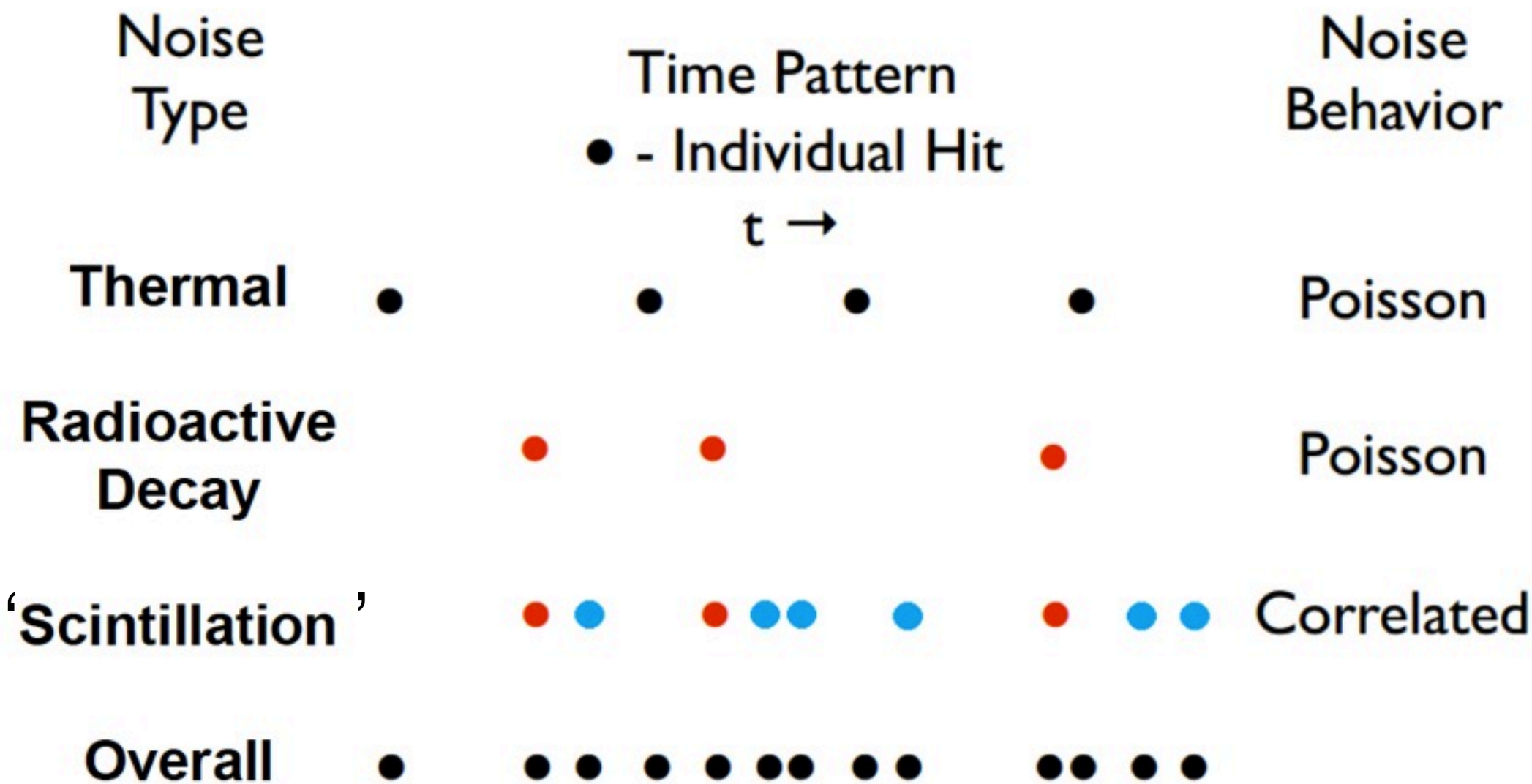


PMT/Glass Noise



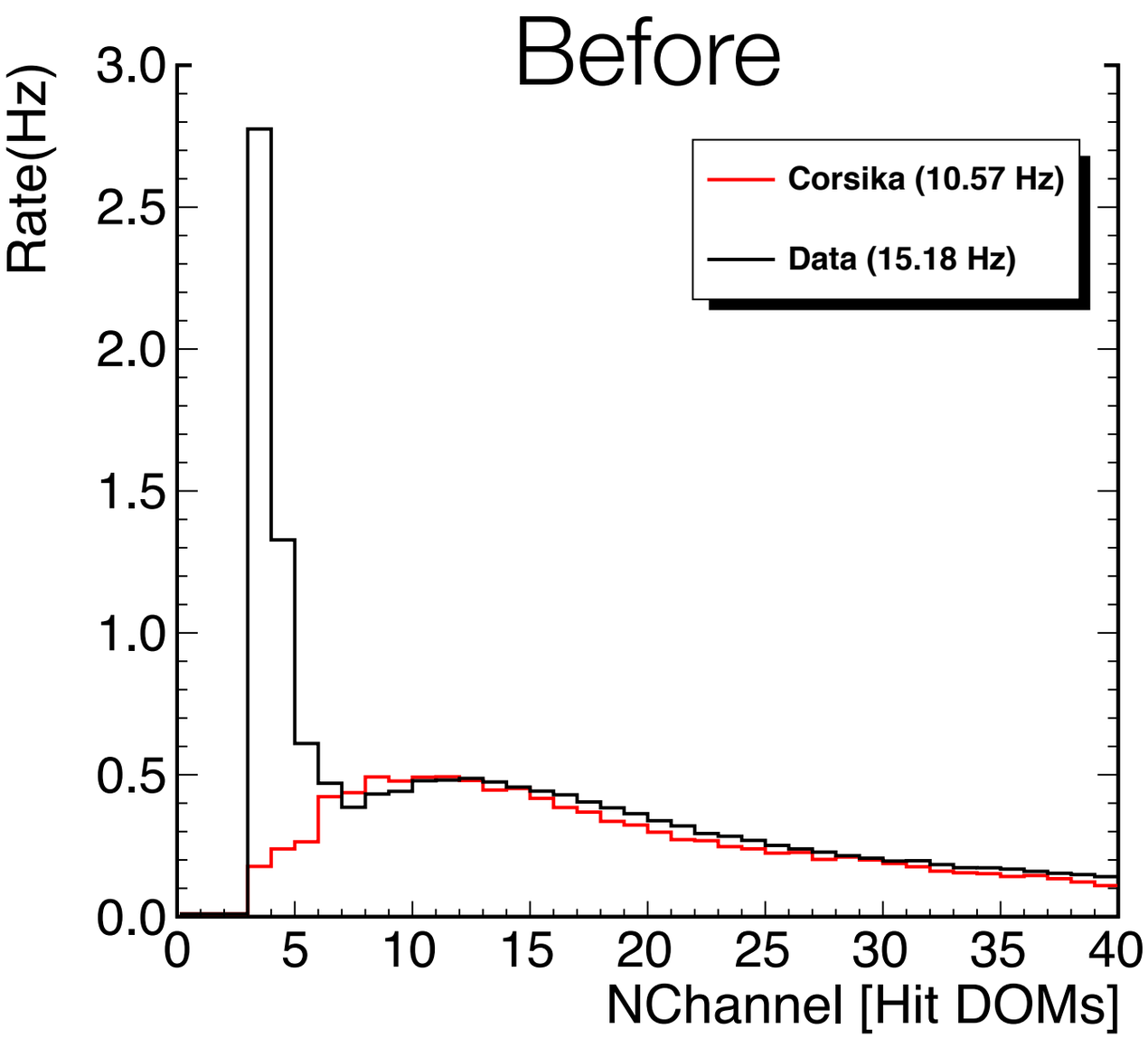
H.O. Meyer http://arxiv.org/abs/0805.0771

Correlated Noise: Model



B. Reidel - UW-Madison
M. Larson - Alabama

Noise Removal



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  - Noise should be relatively unclustered
  - Physics (neutrinos, muons, etc...) should create clustered hits
- Other systematics now rise to the top (PMT efficiency, ice modeling, atmospheric neutrino flux spectral index, etc...)

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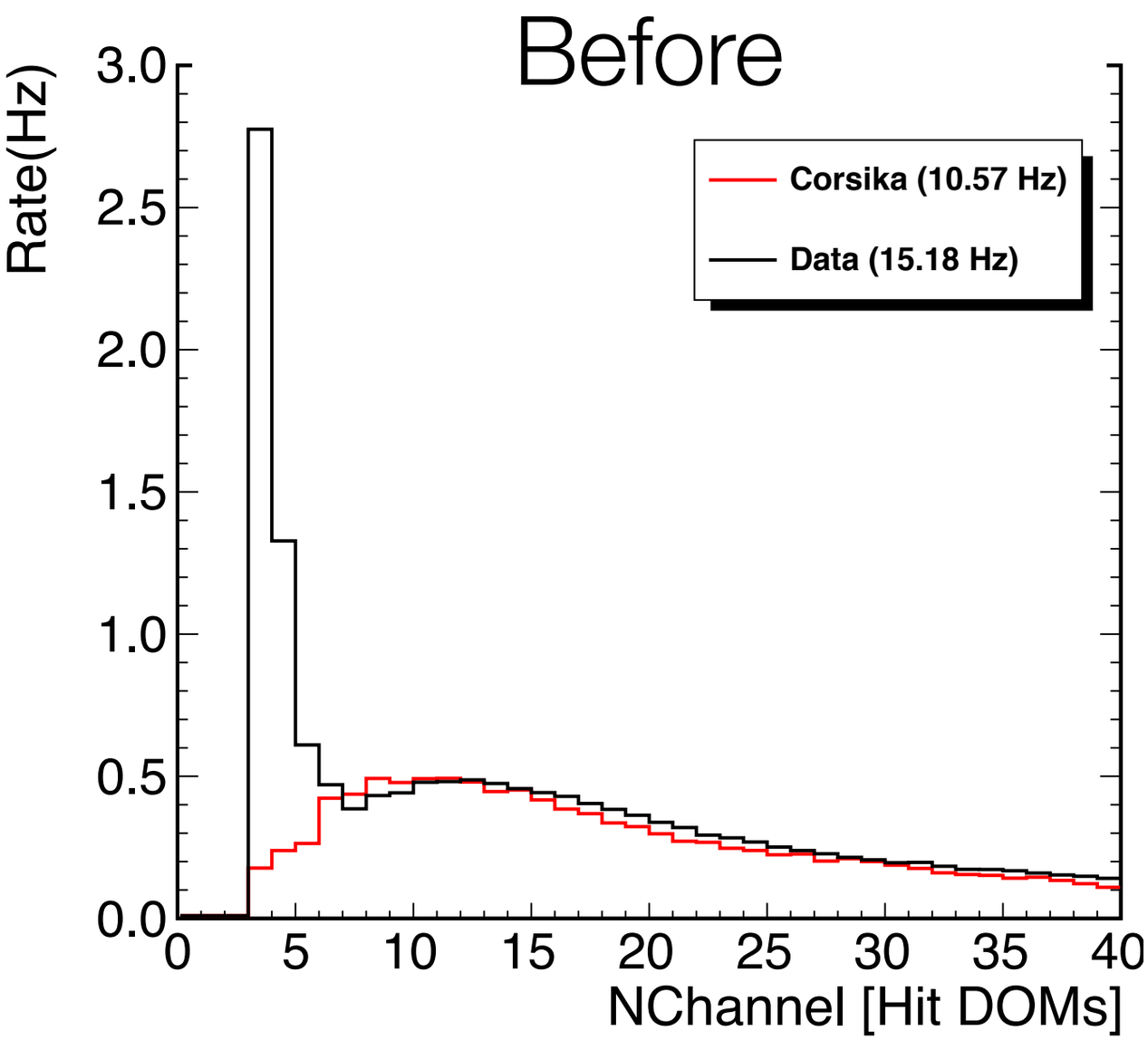

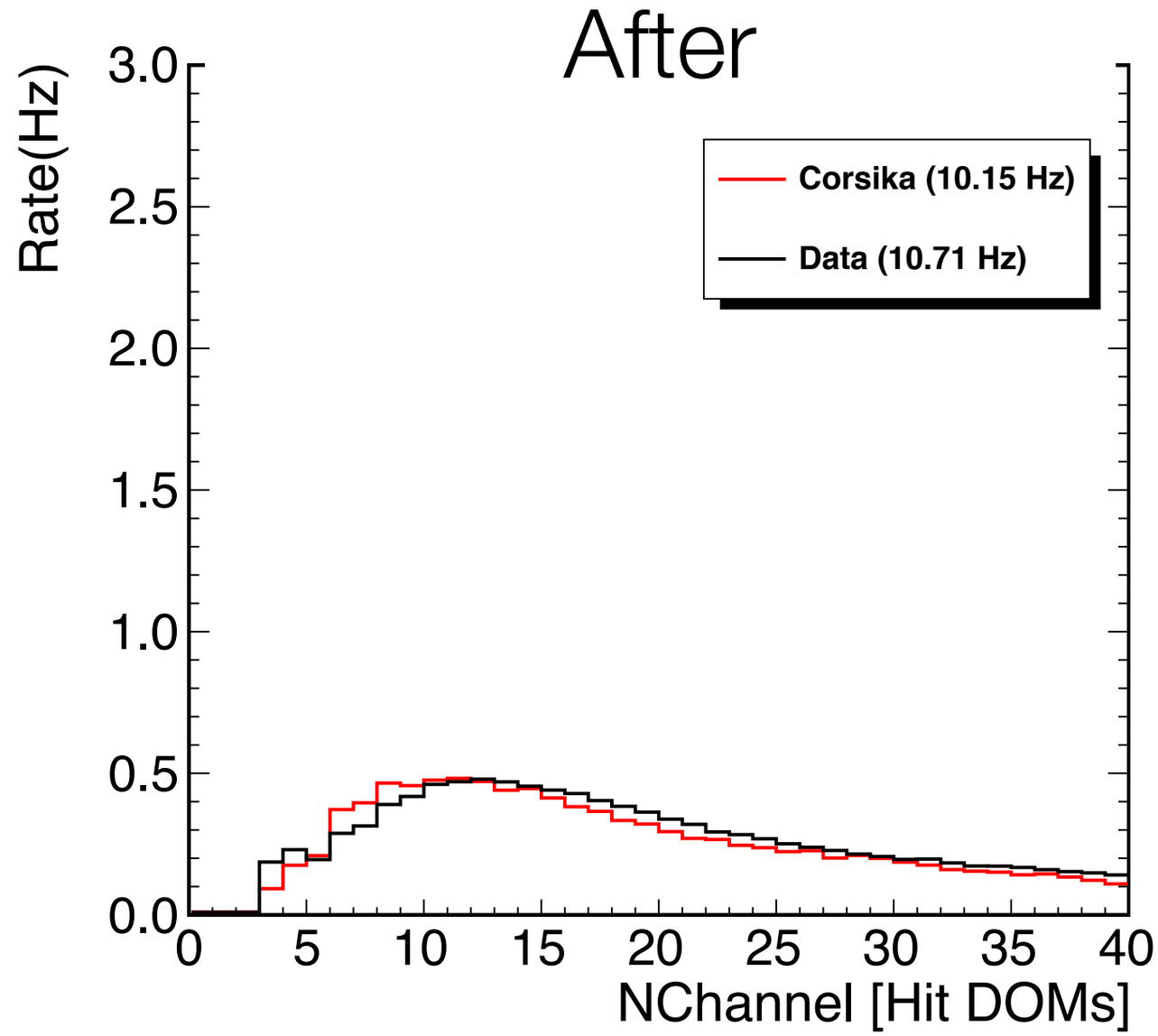

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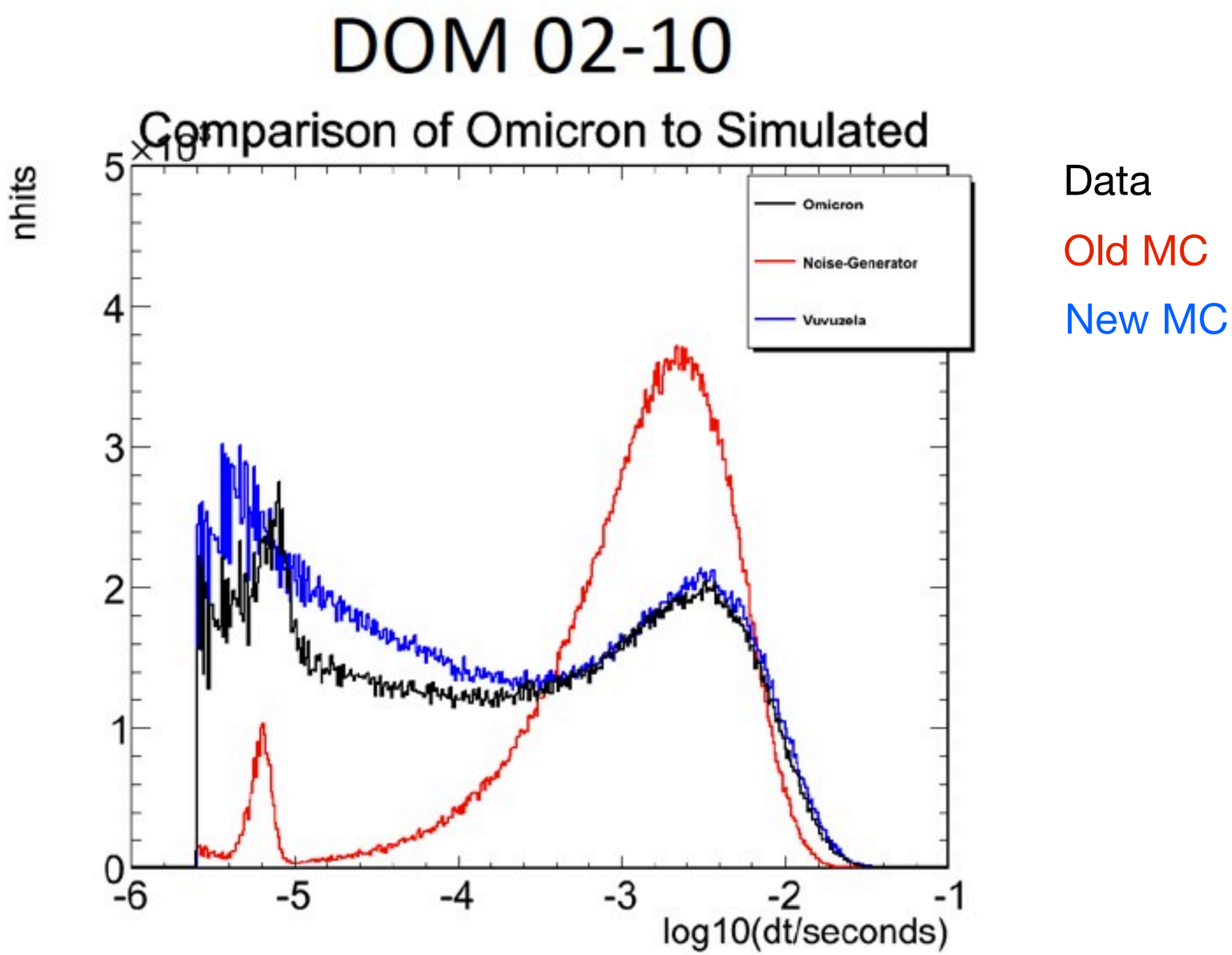
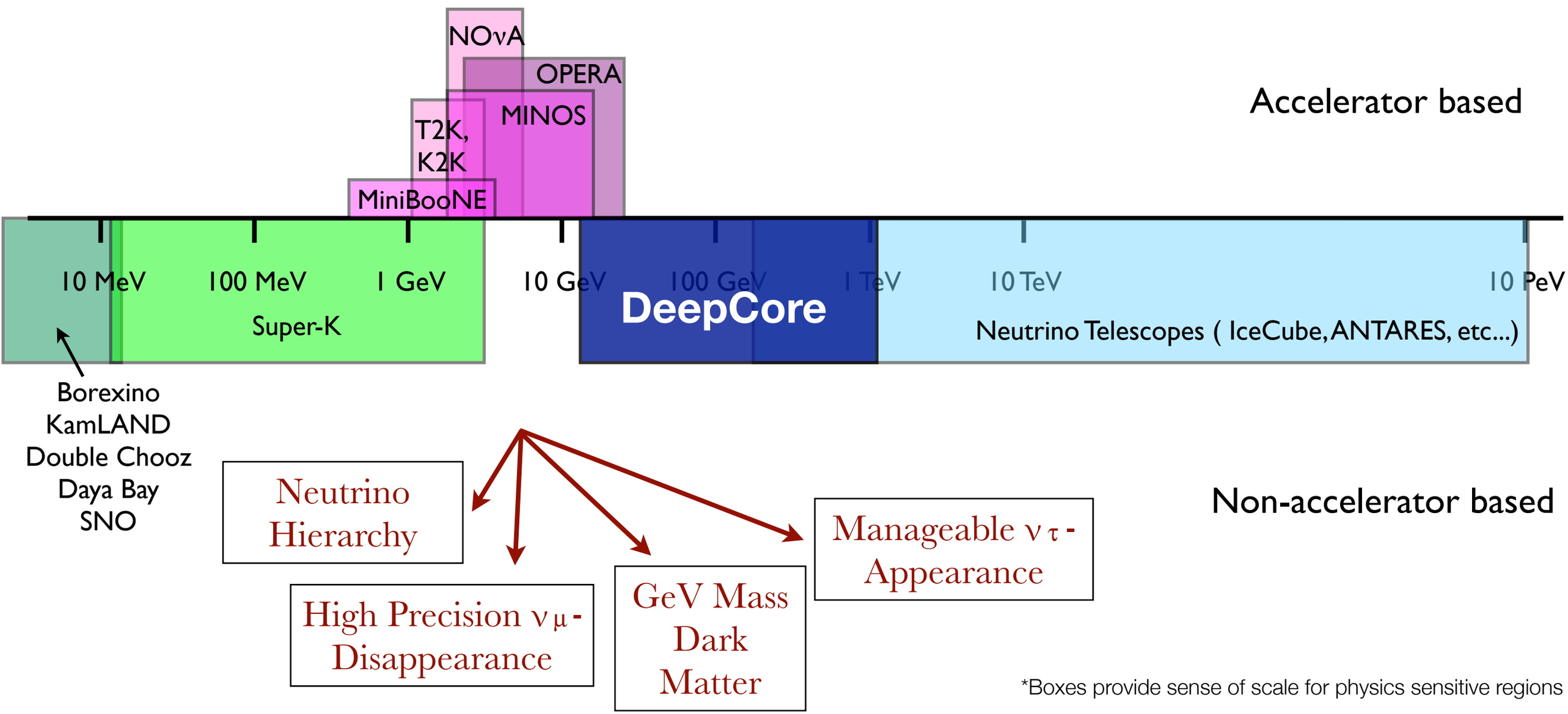
Simulated Noise

- Not only can we remove most of the coincident noise, but we can now simulate it as well



Experimental Landscape



*Boxes provide sense of scale for physics sensitive regions

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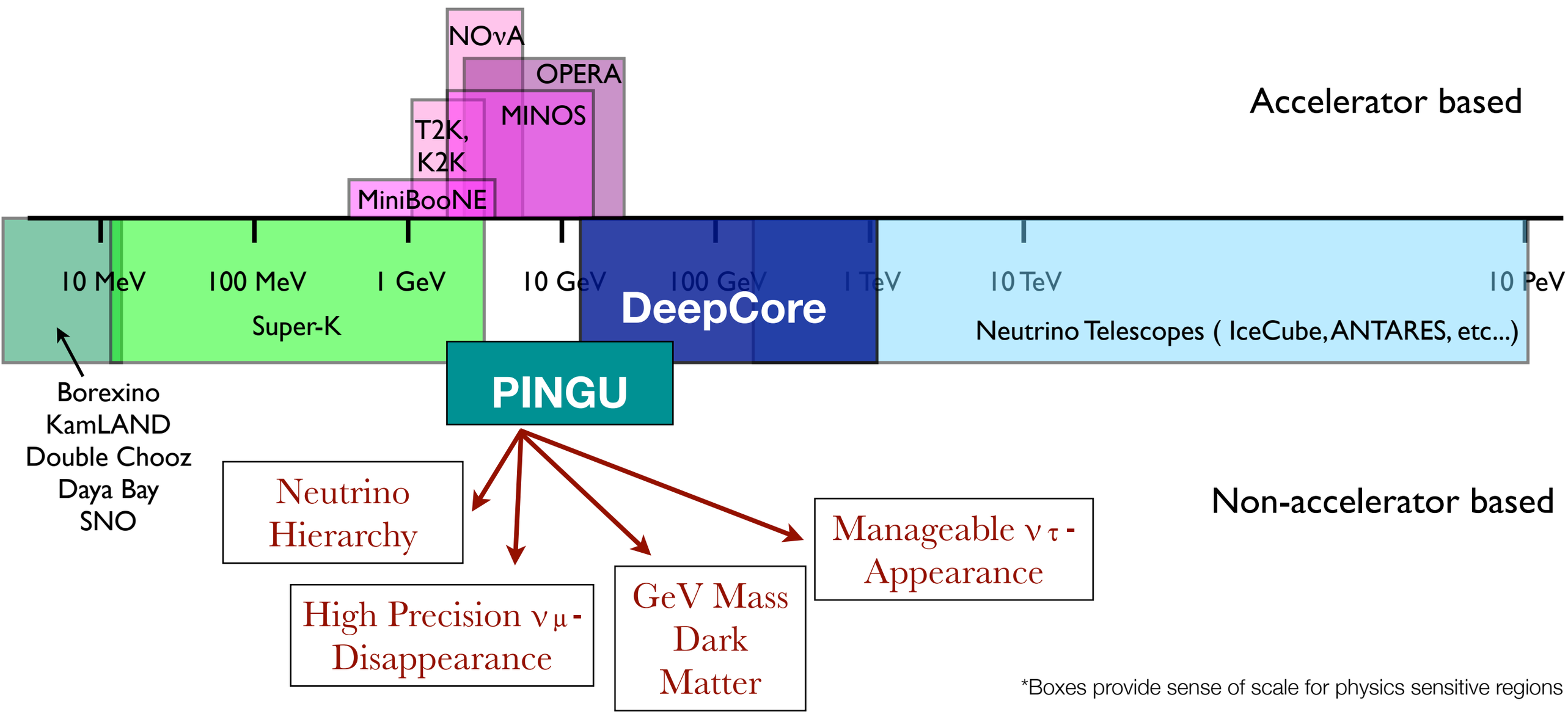


*Boxes provide sense of scale for physics sensitive regions

Really Beyond DeepCore

Really Beyond DeepCore

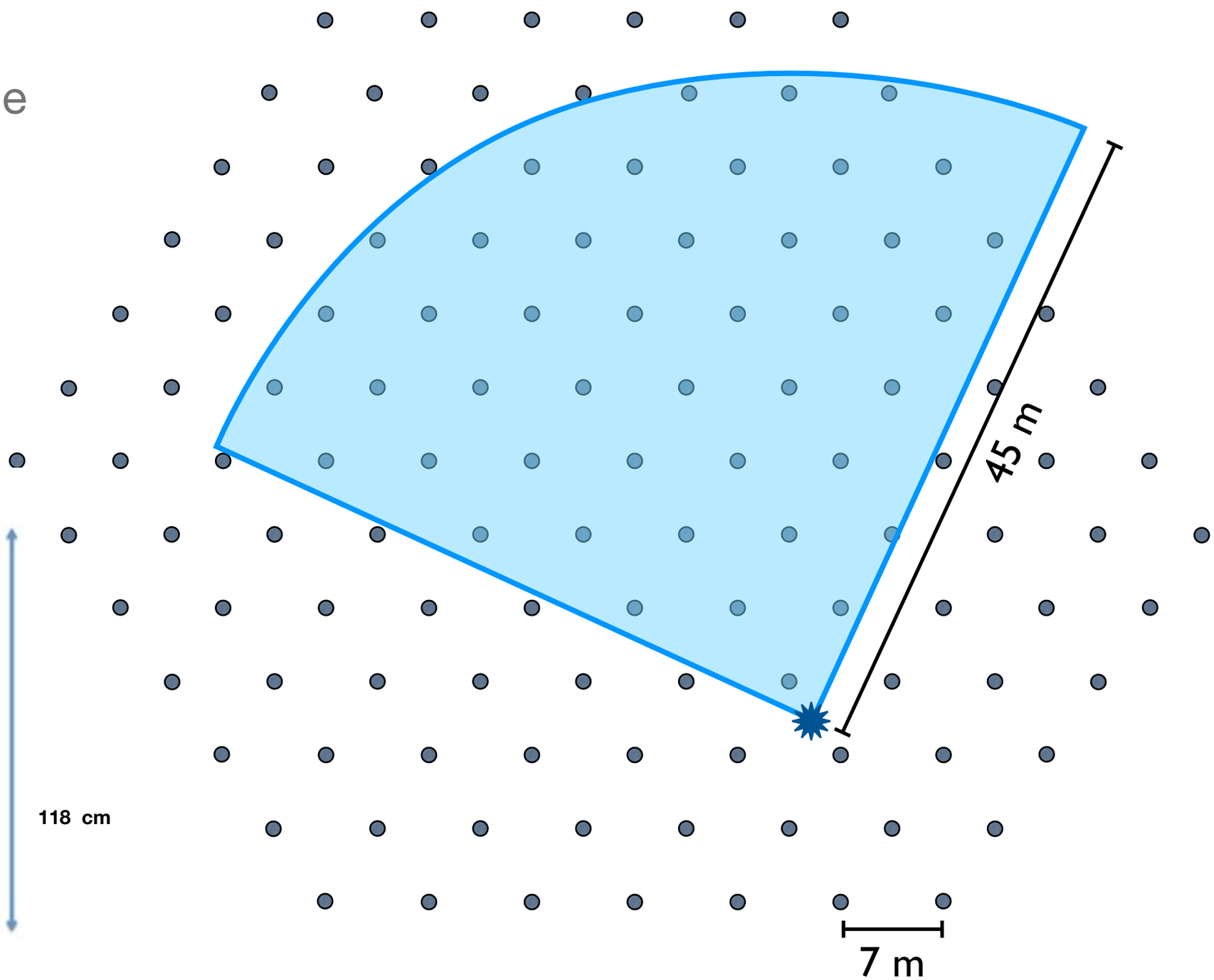
IceCube DeepCore PINGU

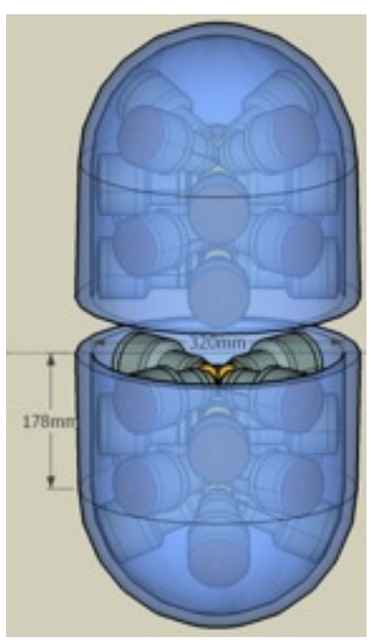
Low Energy Large Volume

- South Pole Infrastructure
  - No excavation
  - Deployment is a now a precision process
- Unchanging, low-background medium
- Move from GeV to tens of MeV
  - Cerenkov Ring Imaging
  - Single PMT Module is no longer feasible
- Multi-megaton Ice Cherenkov Array (MICA)

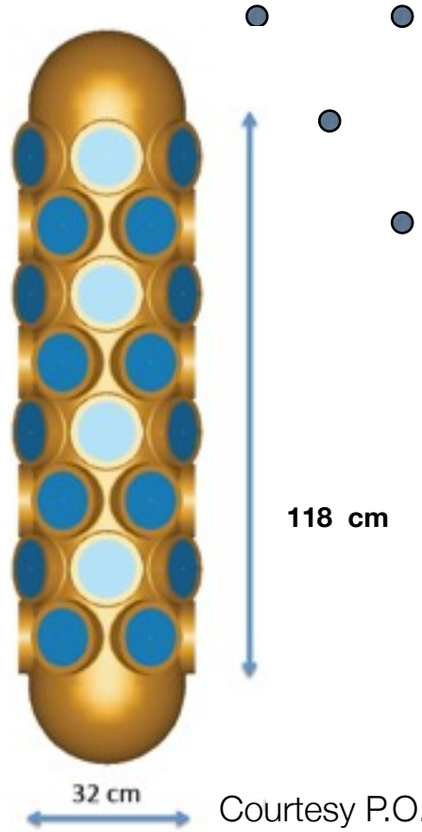
Cerenkov Ring Imager

- 120 strings of 125 composite DOMs each
  - Instrumented volume of 250 m height, ~40 m radius
- 1 MegaTon fiducial volume, at depths of 2200-2450 m





Courtesy P. Kooijman



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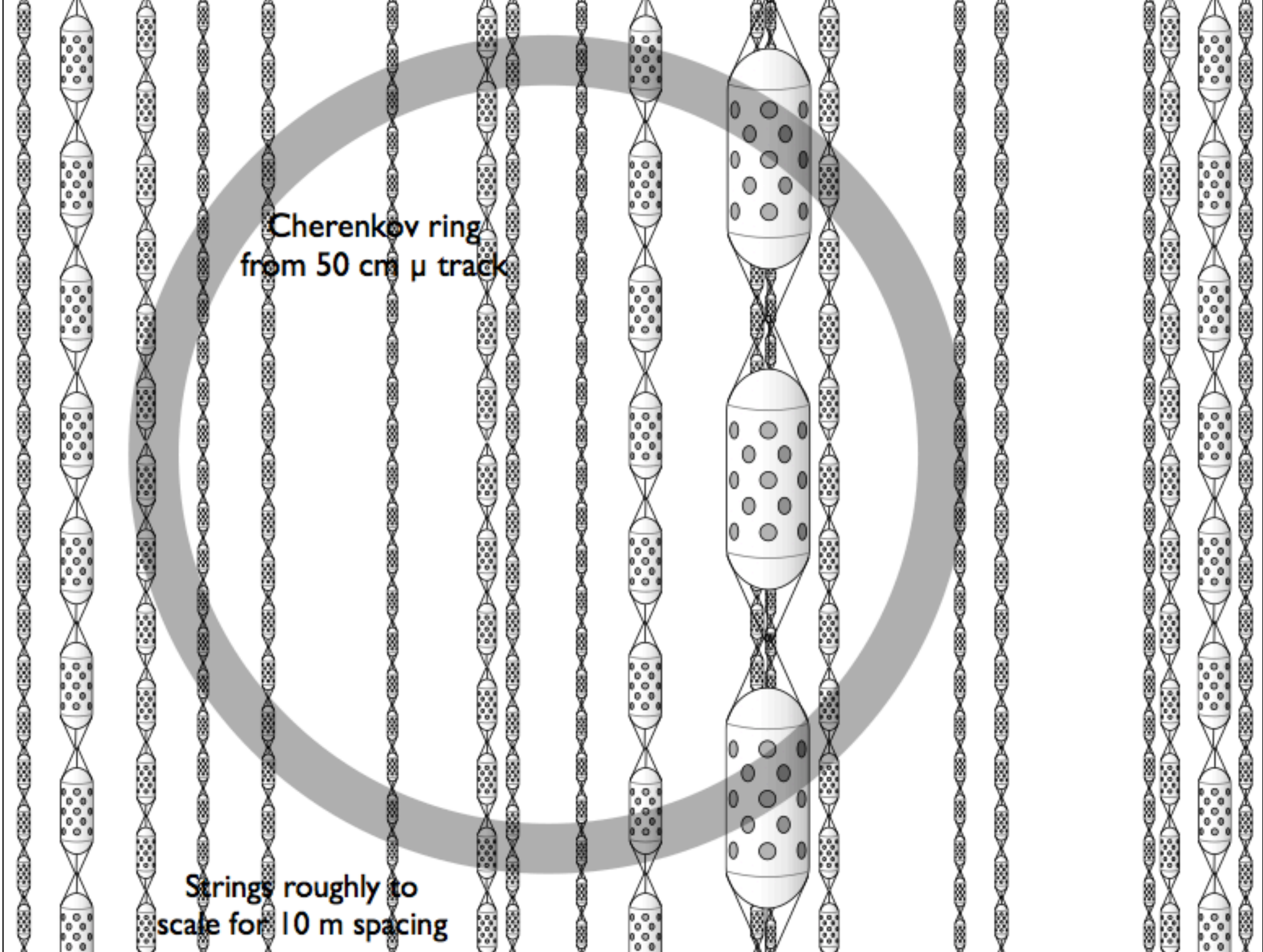
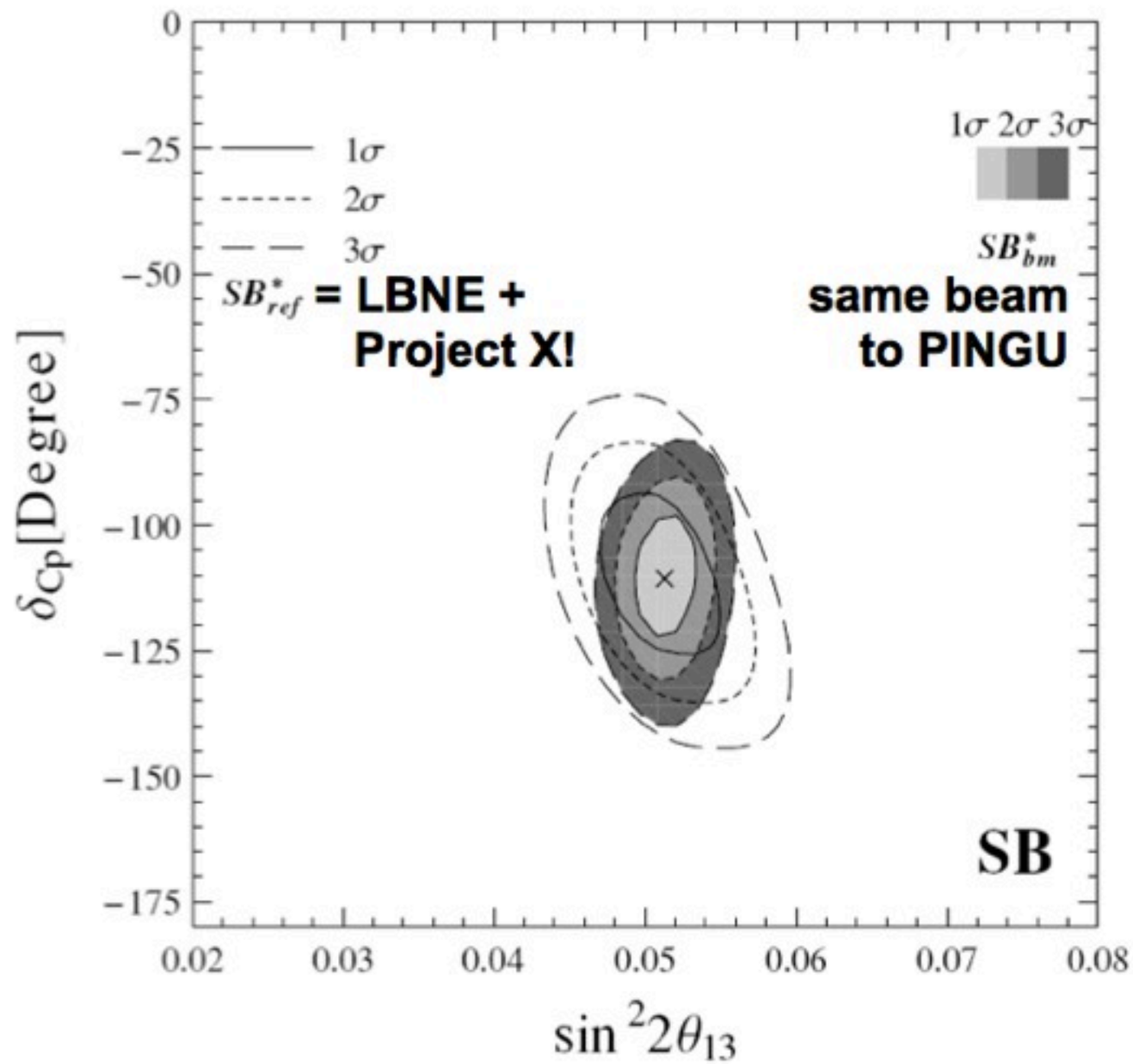

Cherenkov ring
from 50 cm μ track
Strings roughly to
scale for 10 m spacing

"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)

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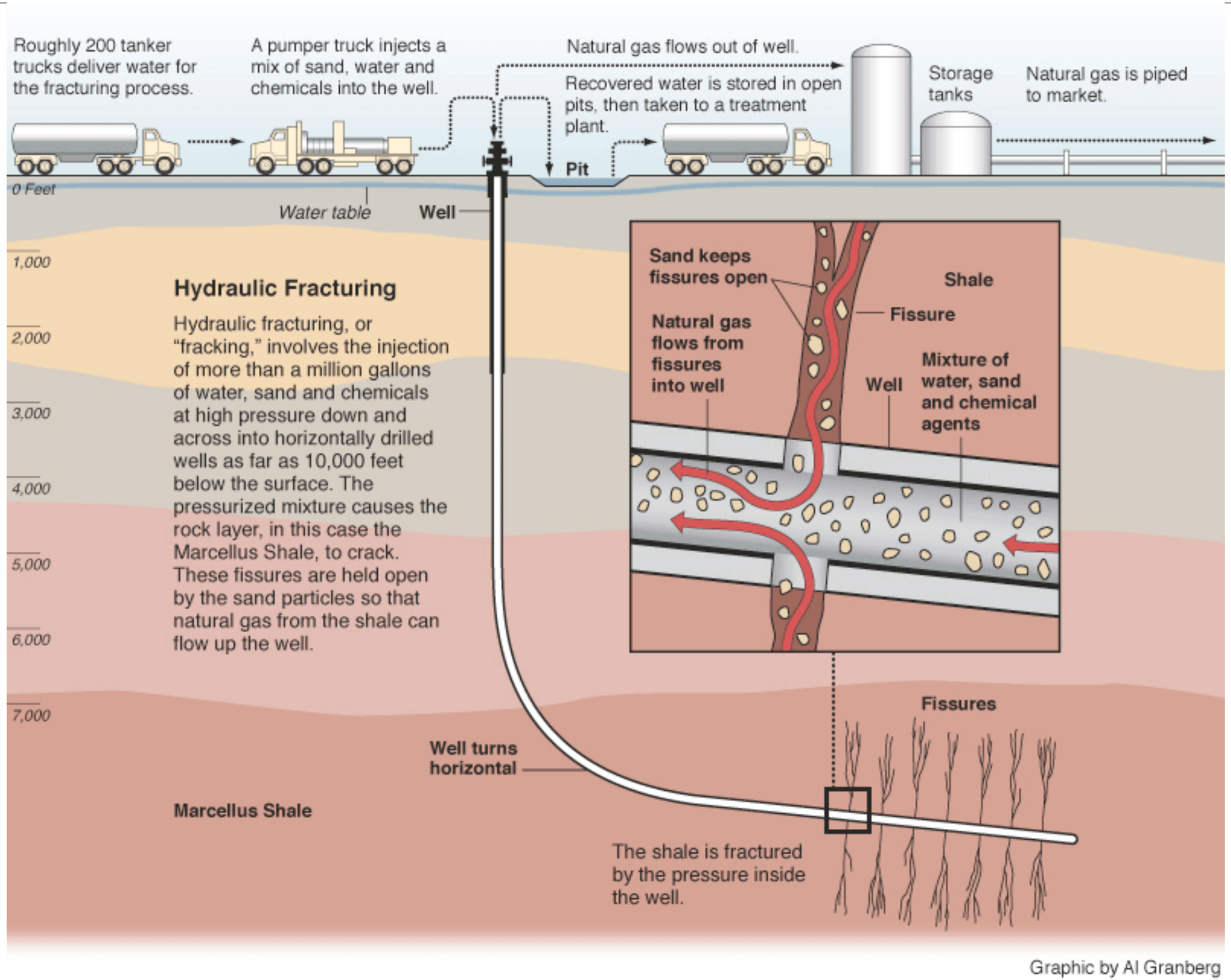
Future

- 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 65.8º from FNAL (similar for CERN)
  - Hydraulic fracturing drills *may* provide help

‘Frakking’

- Maximal Mixing
- **Beam?**



‘Frakking’

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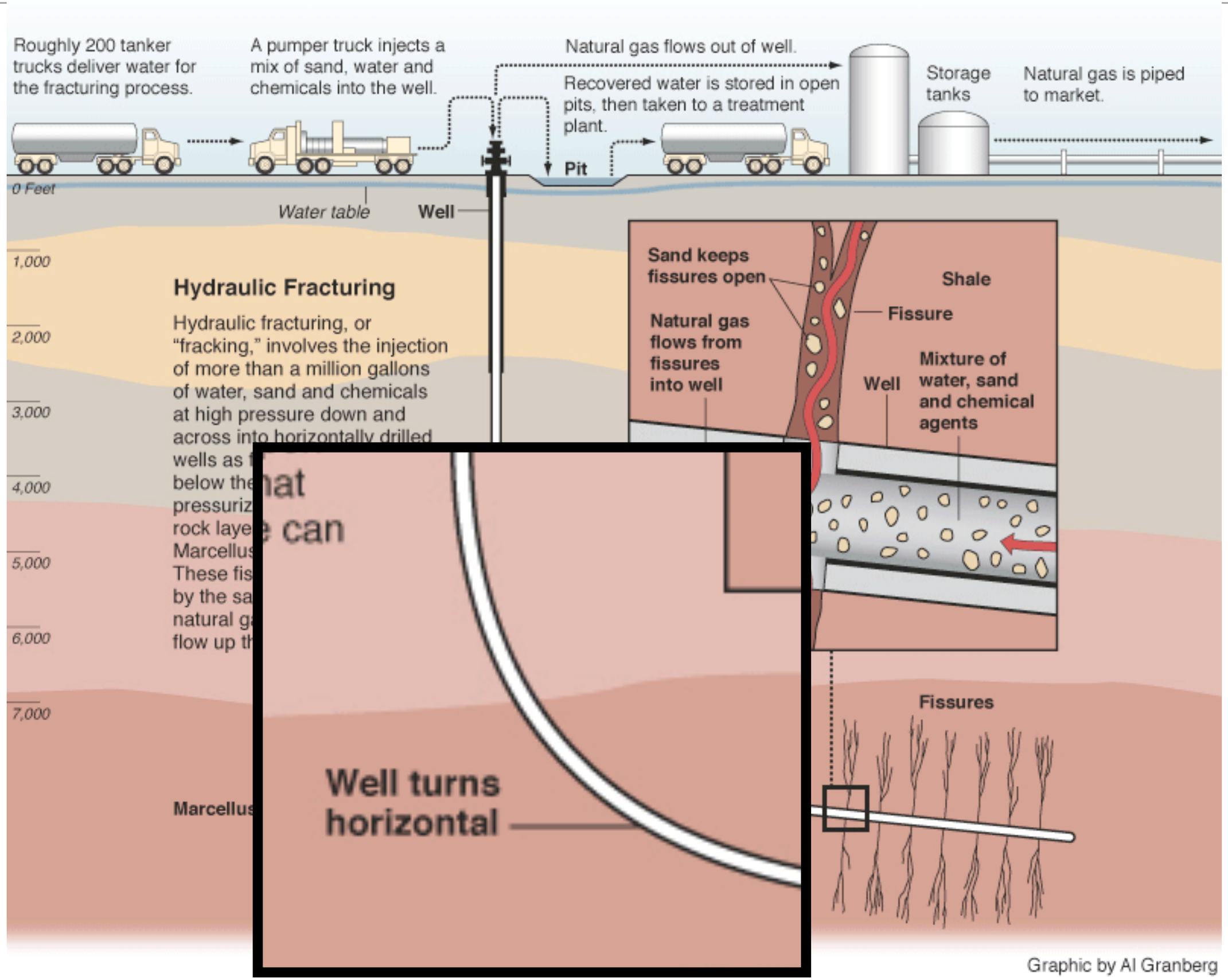
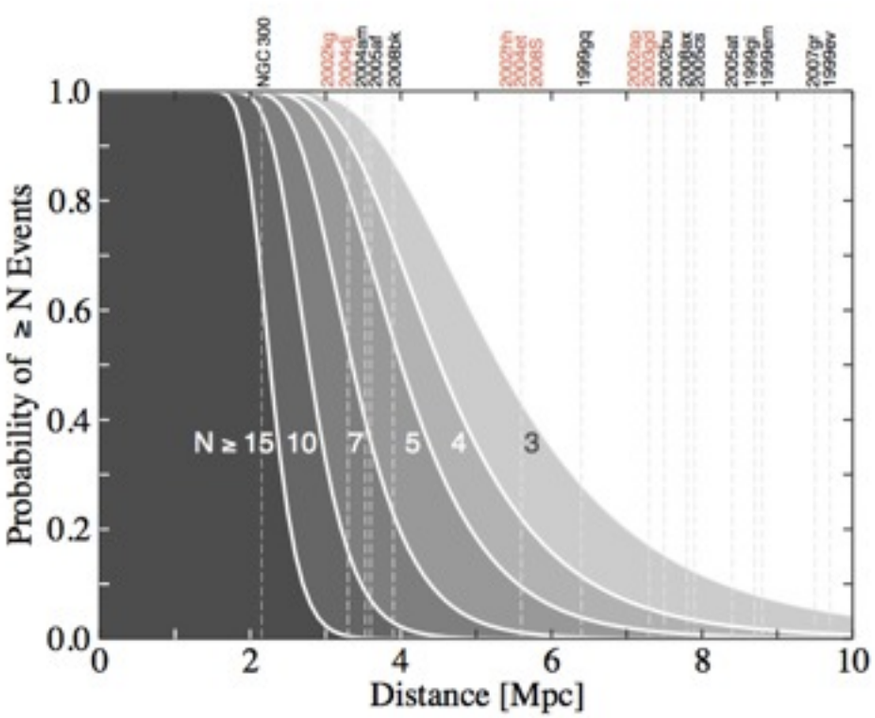
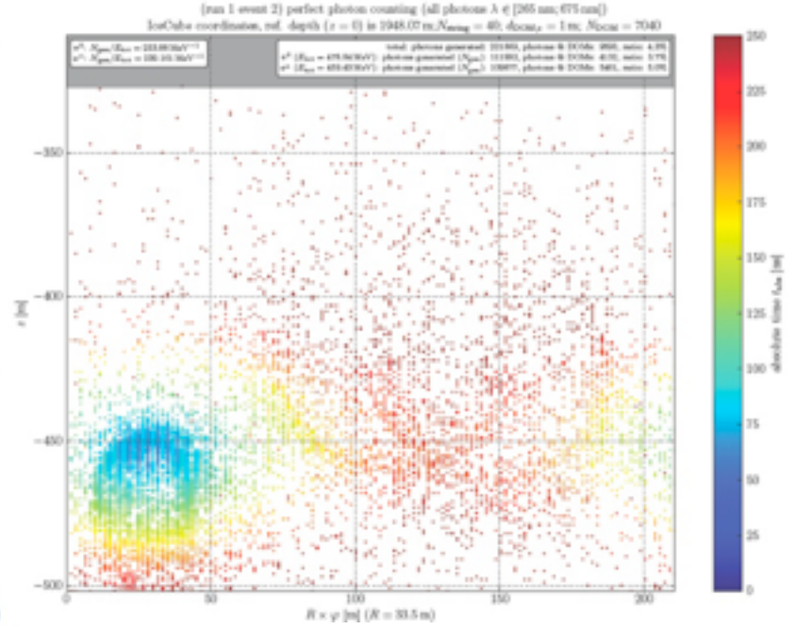


- Physics
  - Extra galactic supernova
  - Proton Decay
  - Option for Neutrino Factory, Beta beam or Super Beam
    - Lepton CP Violation
- Using PMTs, ~2/3 of the detector cost is electronics
  - APDs, MCPs, large (1/2 m^3) wavelength shifter, something else?





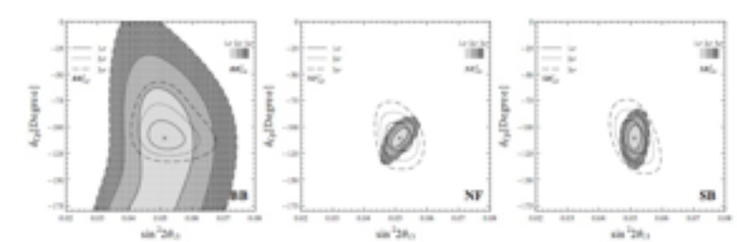


Figure 12: The precision measurements of CP phase δ_{CP} and $\sin^2 2\theta_{13}$ for three single-baseline neutrino experiments: Beta Beam (BB), Neutrino Factory (NF), and SuperBeam (SB). The contours represent the 1σ, 2σ and 3σ confidence levels (2 d.o.f.). Filled contours represent the PINGU benchmark setups, unfilled contours the reference setups. The crosses mark the best fit value of $\sin^2 2\theta_{13}$ and δ_{CP}. Here we assume the normal (true) hierarchy, the inverted (fit) hierarchy solution can be ruled out by the experiments.

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}

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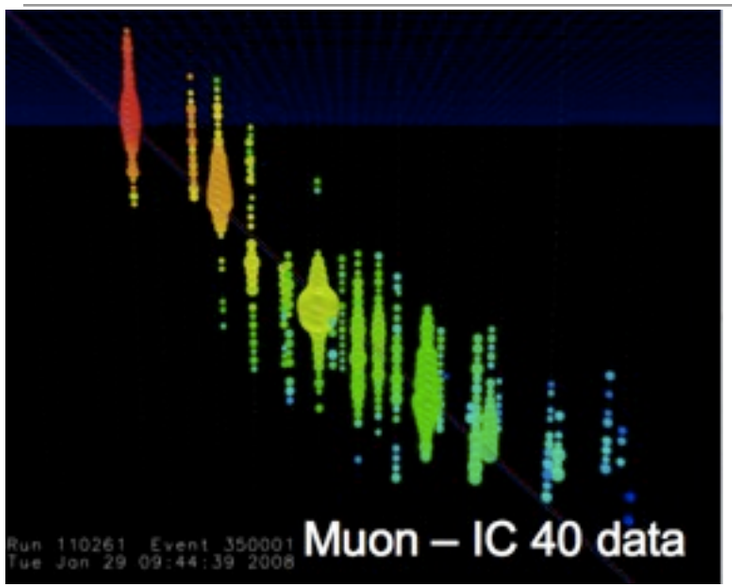
Backup

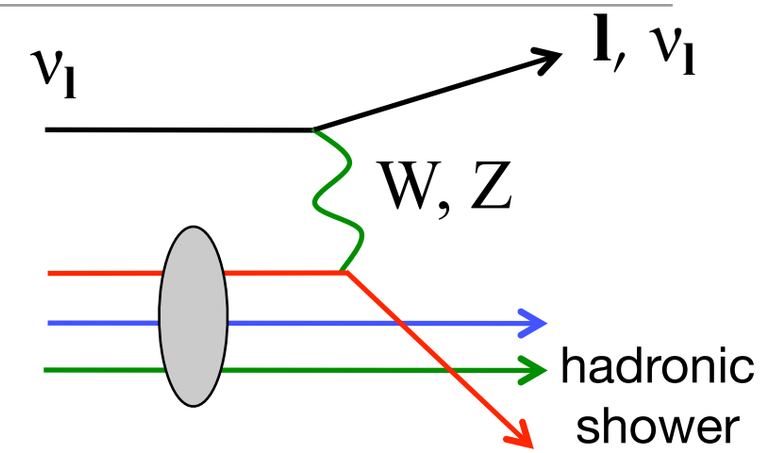
Detection Principles



ν_μ

Tracks:

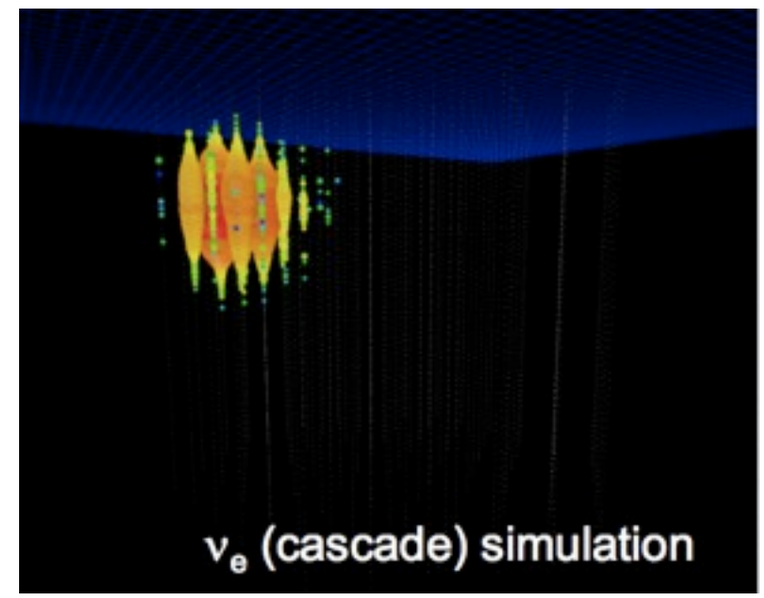
- through-going muons
- km long at > TeV energy

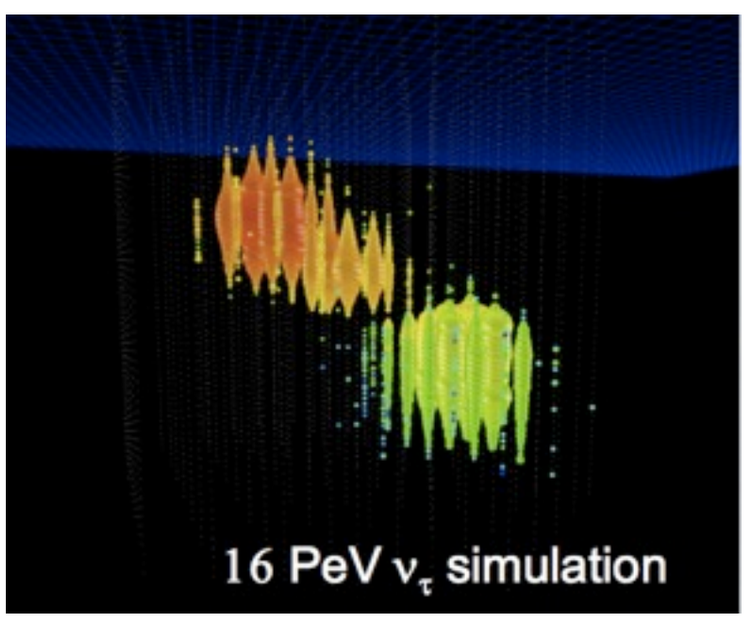


ν_τ, ν_e

Cascades:

- Neutral current for all flavors
- few m at low energy
- Charged current for ν_e and low-E ν_τ





ν_τ

Composites:

- Starting tracks
- high-E (PeV) ν_τ (Double Bangs)
- Good directional and energy resolution

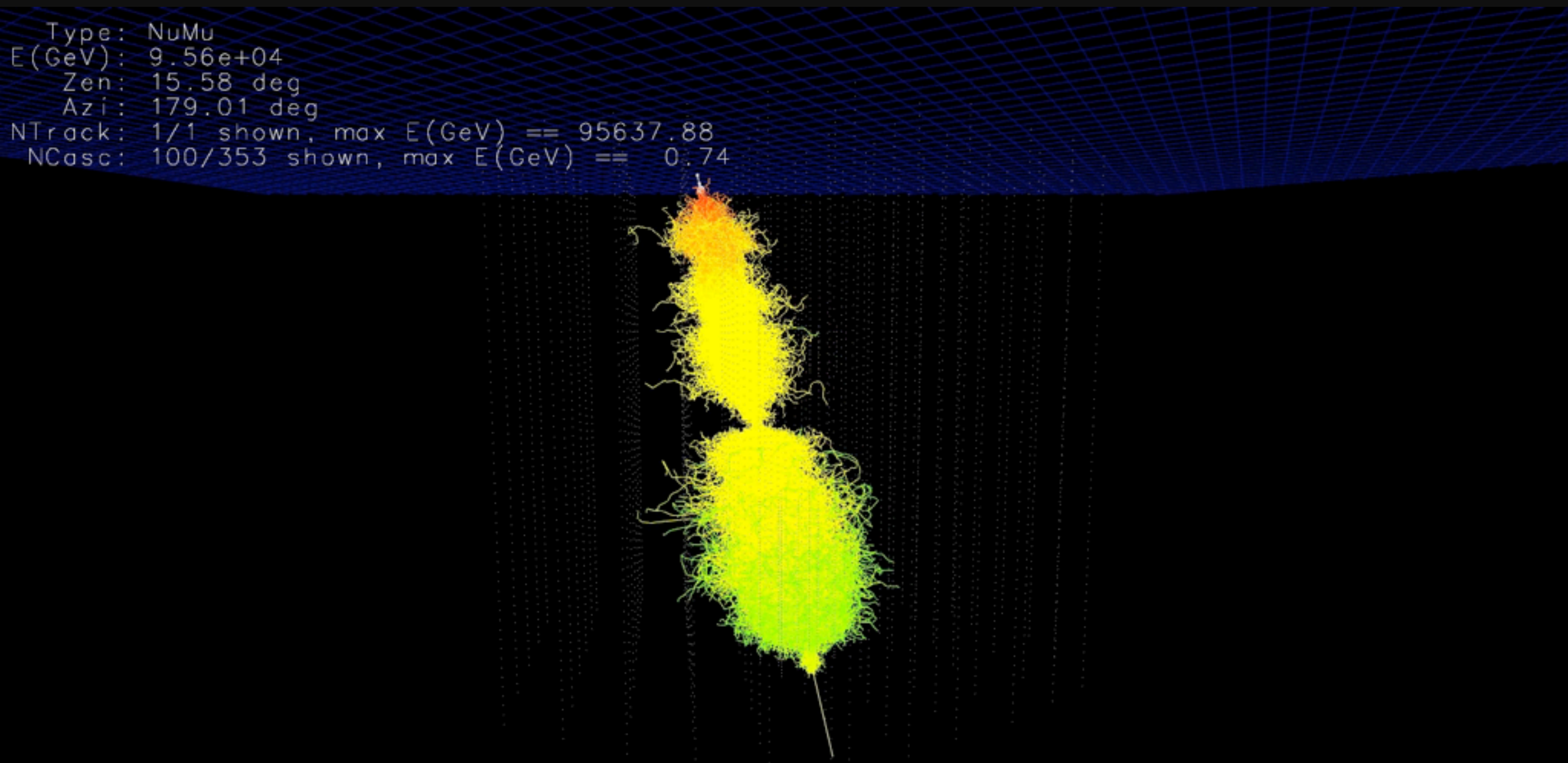
The IceCube Neutrino Observatory

Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)

Courtesy of C. Kopper - UW Madison

The IceCube Neutrino Observatory

Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)

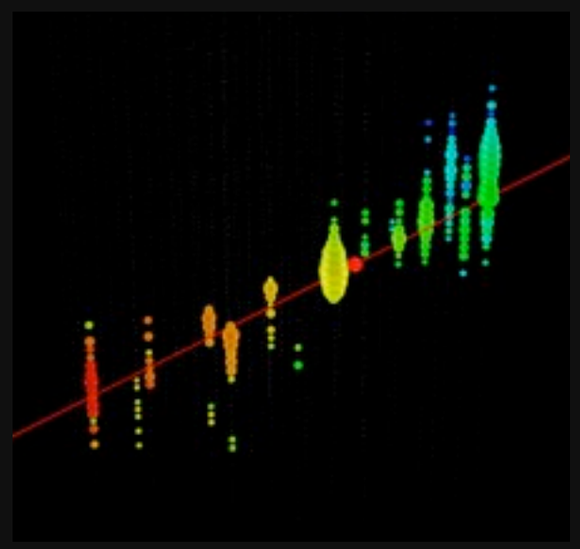


Courtesy of C. Kopper - UW Madison

TeV+ Neutrino Event Signatures

Signatures of TeV+ signal events

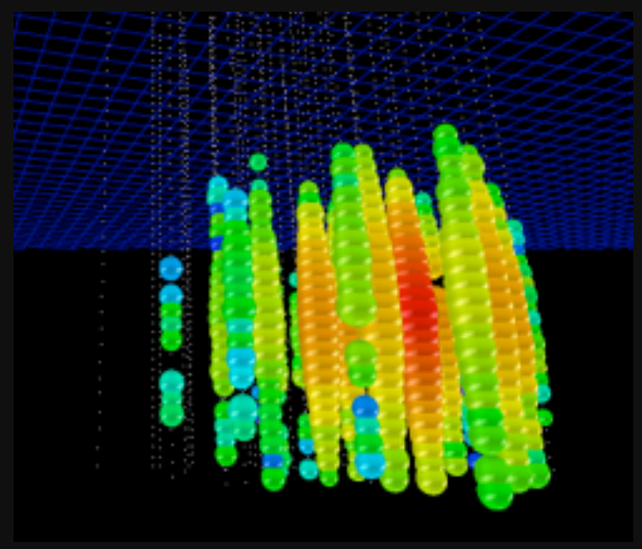
CC Muon Neutrino



$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

Neutral Current / Electron Neutrino

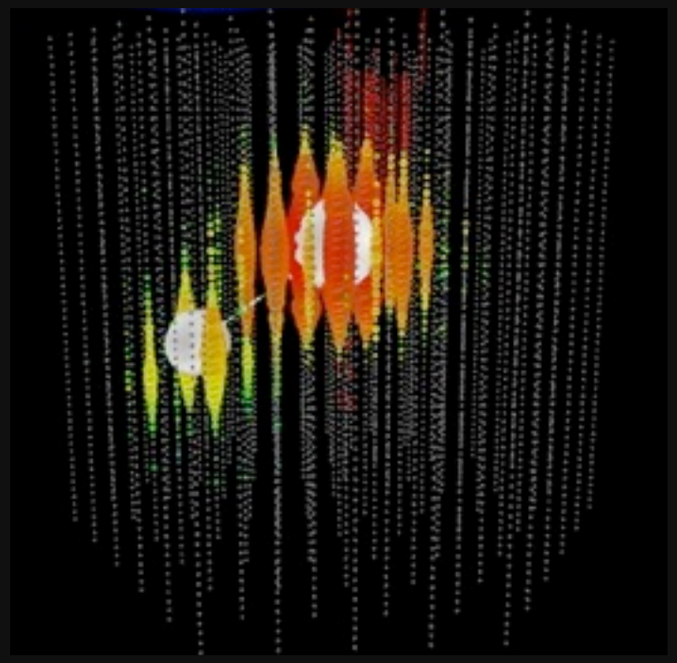


$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} \ + X$$

$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

cascade (data)

CC Tau Neutrino



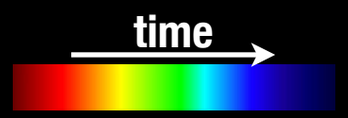
$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” and other signatures (simulation)

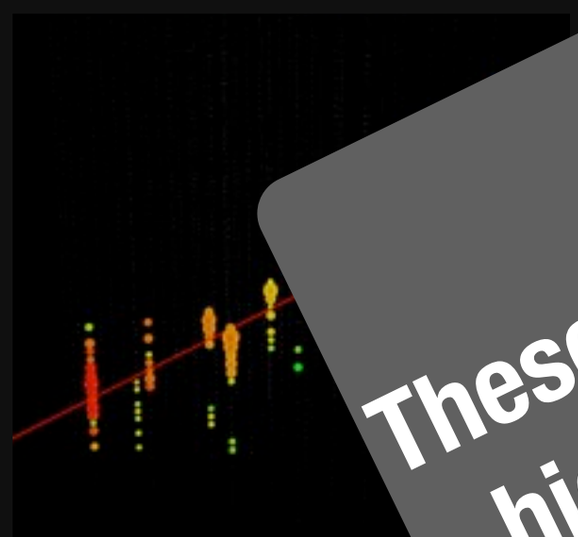
(not observed yet)

TeV+ Neutrino Event Signatures

Signatures of TeV+ signal events



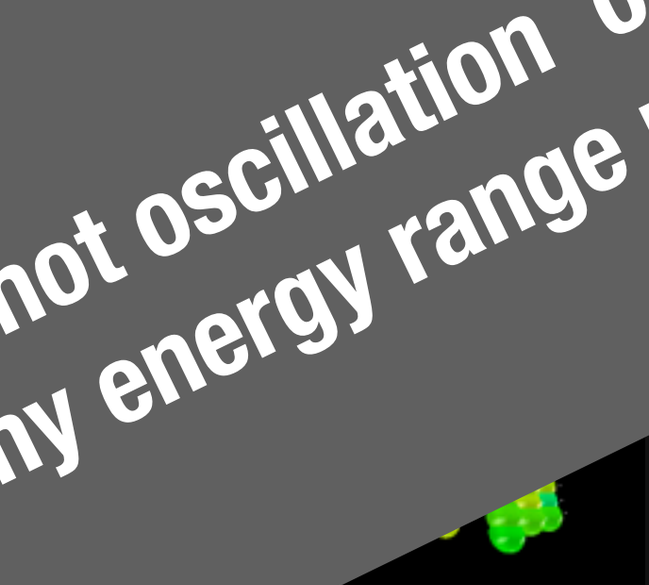
CC Muon Neutrino



$$\nu_\mu + N \rightarrow \mu$$

track (data)

Neutral C
El

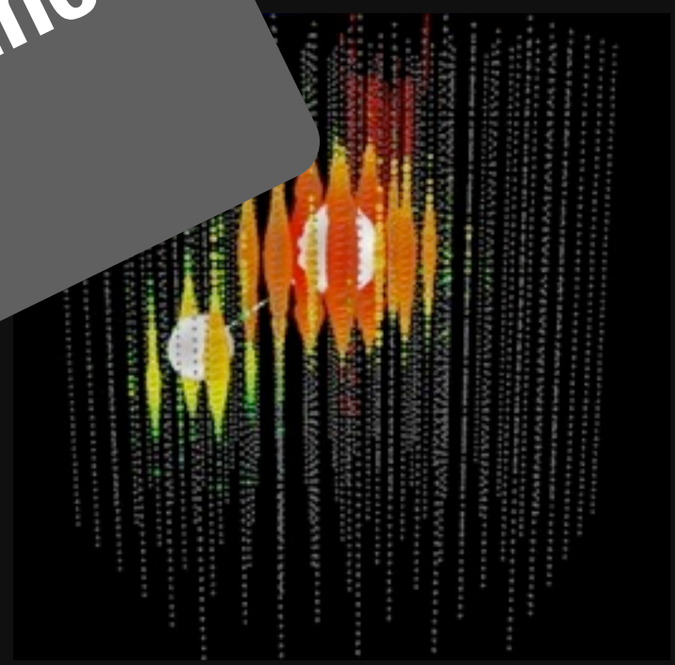


$$+ N \rightarrow \mathrm{e} \ + X$$

$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

cascade (data)

au Neutrino



$$\nu_\tau + N \rightarrow \tau + X$$

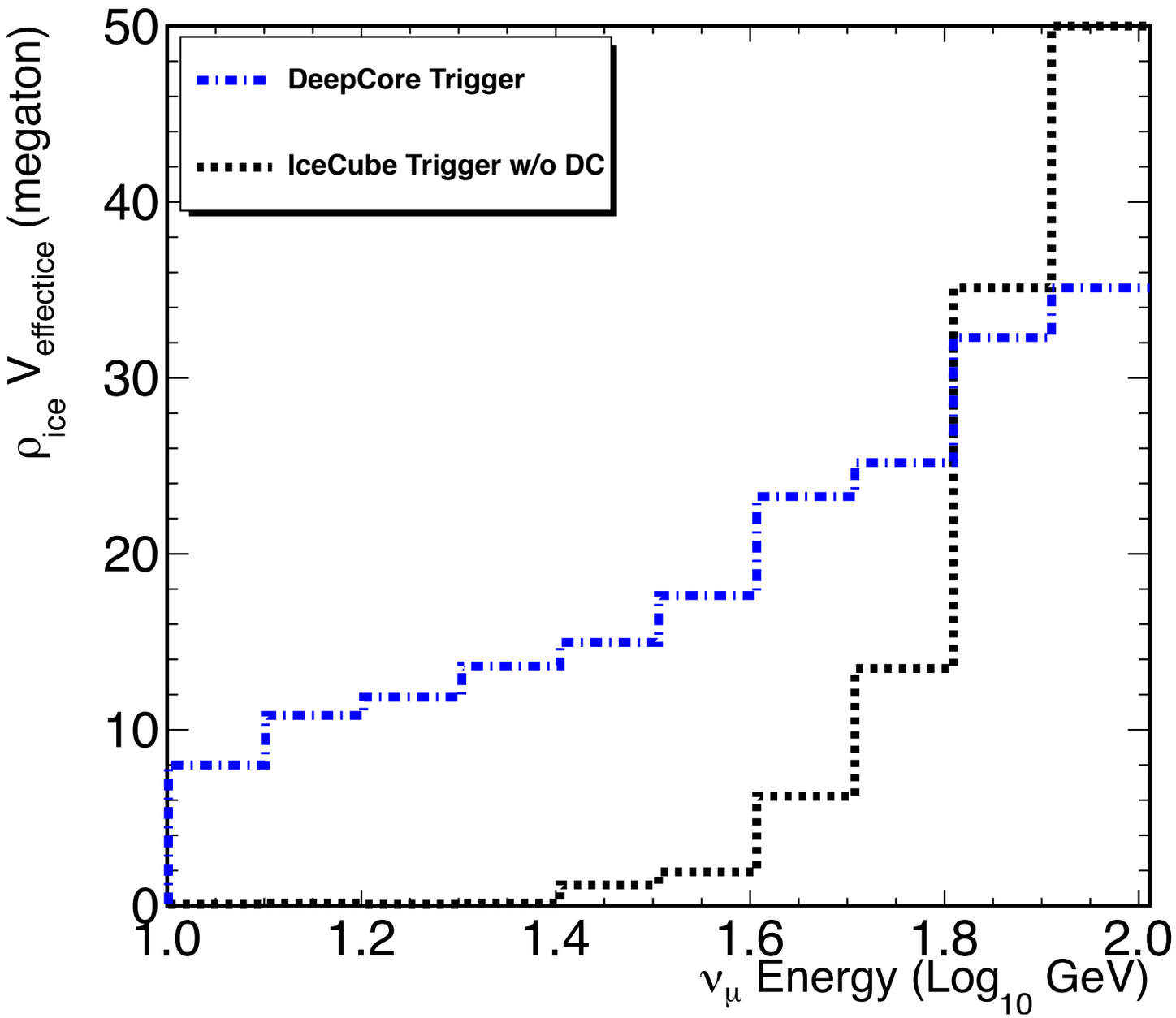
"double-bang" and other signatures (simulation)

(not observed yet)

These are not oscillation or neutrino hierarchy energy range neutrinos

Oscillation

- IceCube + DeepCore collects > 100k isotropic neutrinos *at trigger level*, tens of thousands have undergone oscillation. Even single percent final analysis efficiency contains 1,000s of atm. nu events/ year



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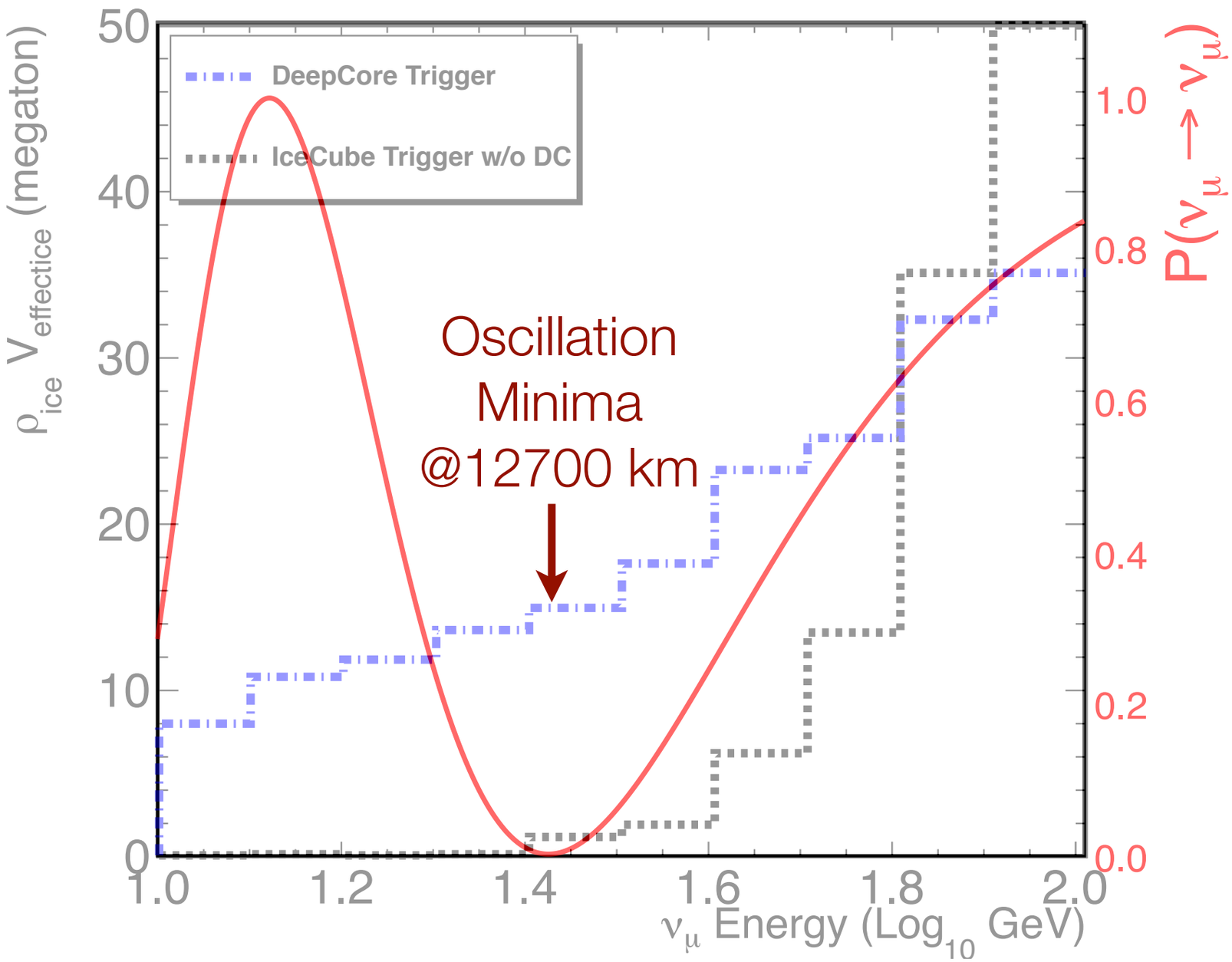
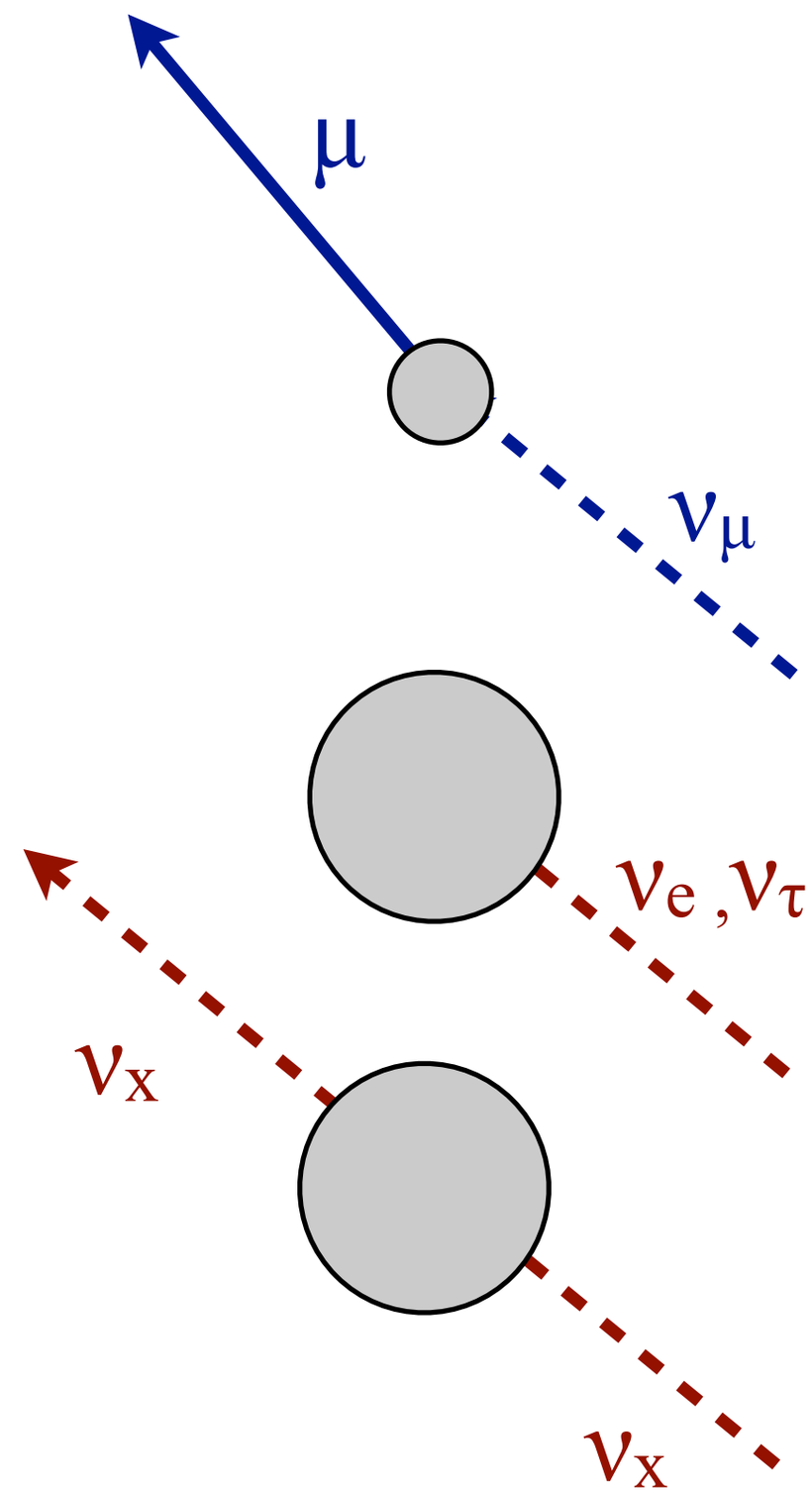


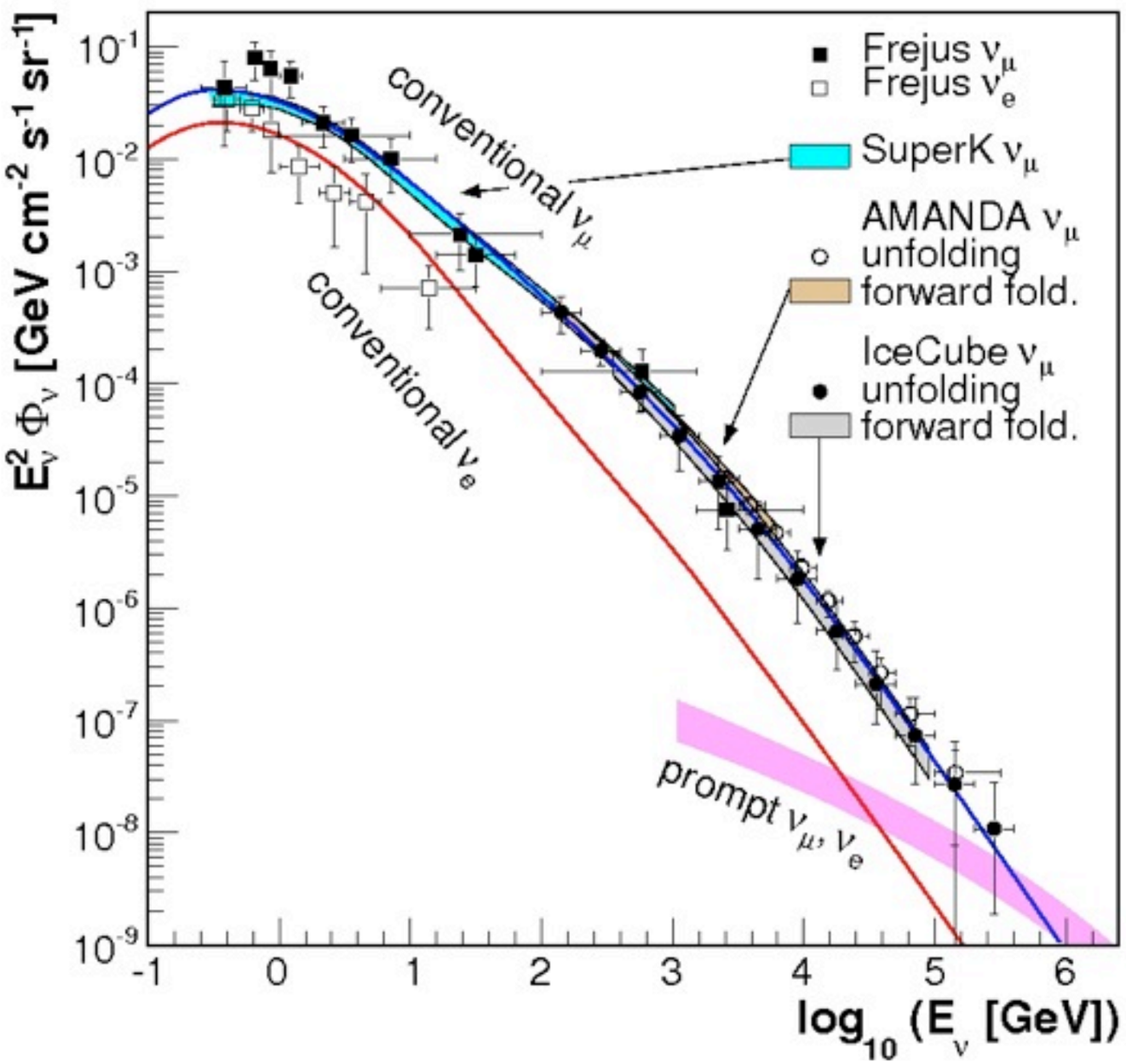
Tau Neutrino Appearance

- Measure $|U_{\tau 3}|^2$ in PMNS matrix
- Neutral Current ν_x, Charged Current ν_e, and Charge Current ν_τ events produce **cascade-like** signatures
- DeepCore has been infilled with 2 additional strings
  - Increases ν_τ event rate by > 15%
  - Increases DOM density, which improves reconstructions and particle identification
- Look for statistical excess in cascade events



Atmospheric flux

- Previous IceCube + AMANDA searches have been insensitive to ANY neutrino induced cascades



- DeepCore cascade candidate event

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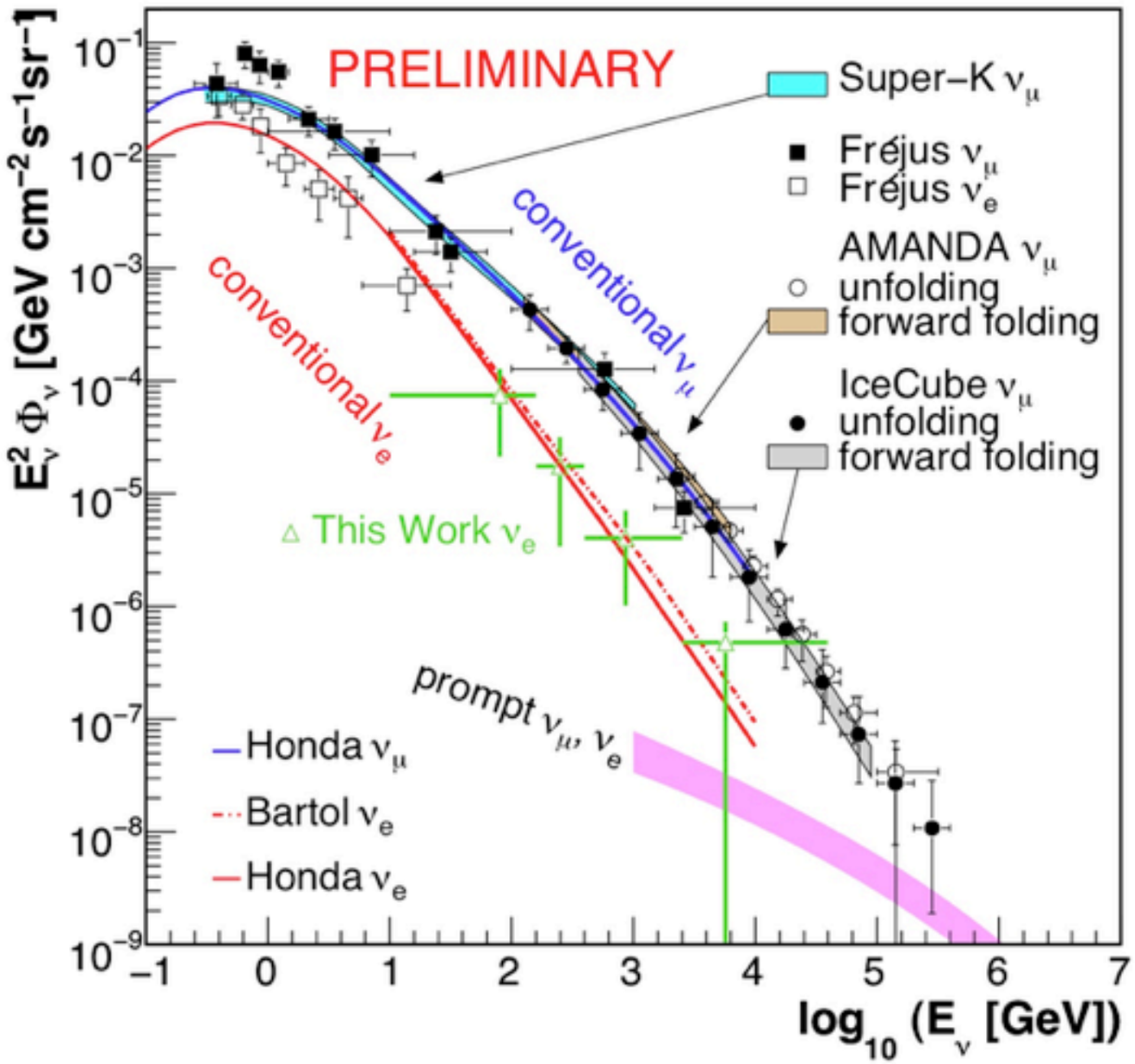
Neutrino Induced

- First observation of neutrino induced cascades in IceCube
- Higher average energy (~180 GeV) than oscillation region, but show that they can be identified



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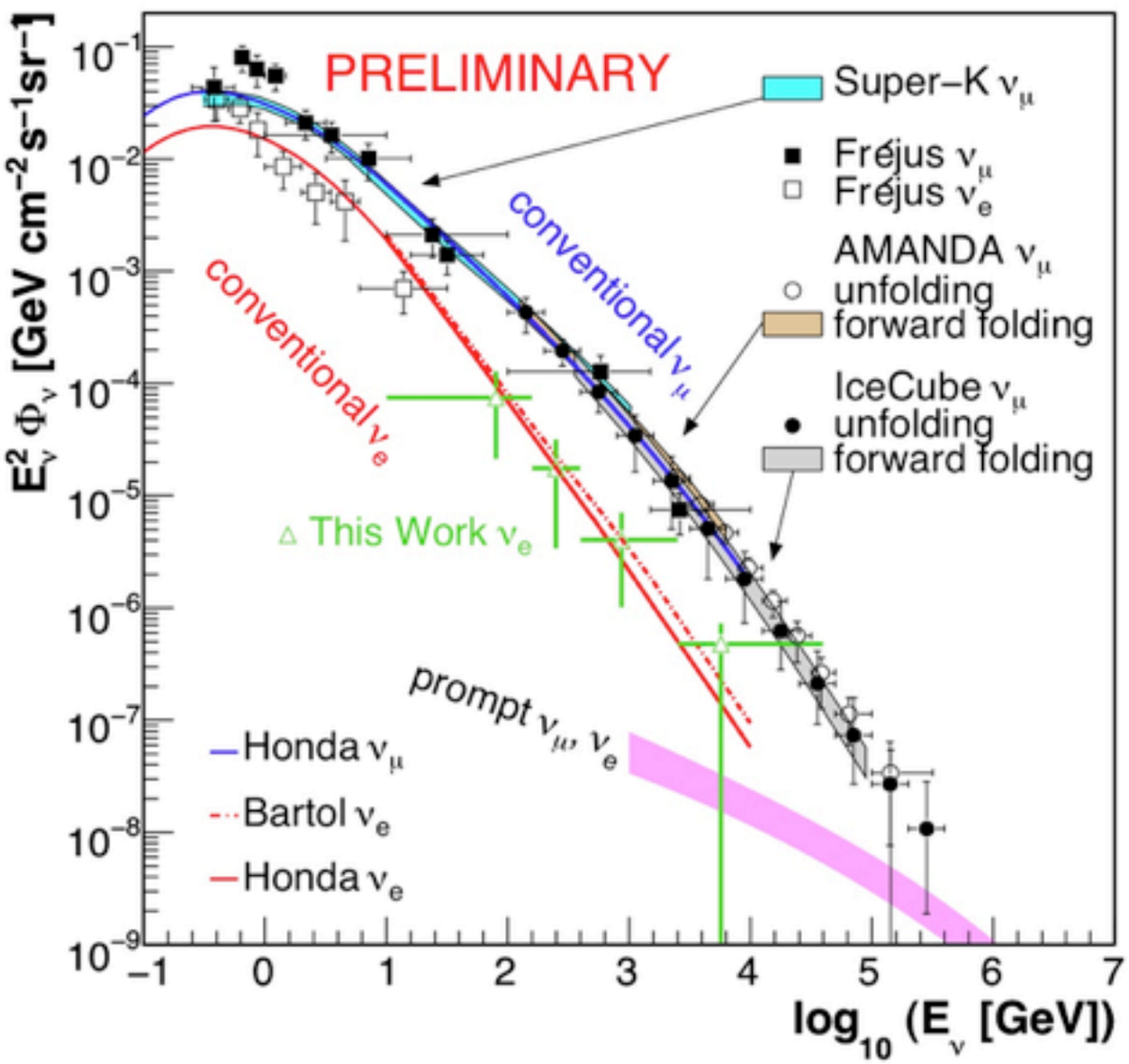
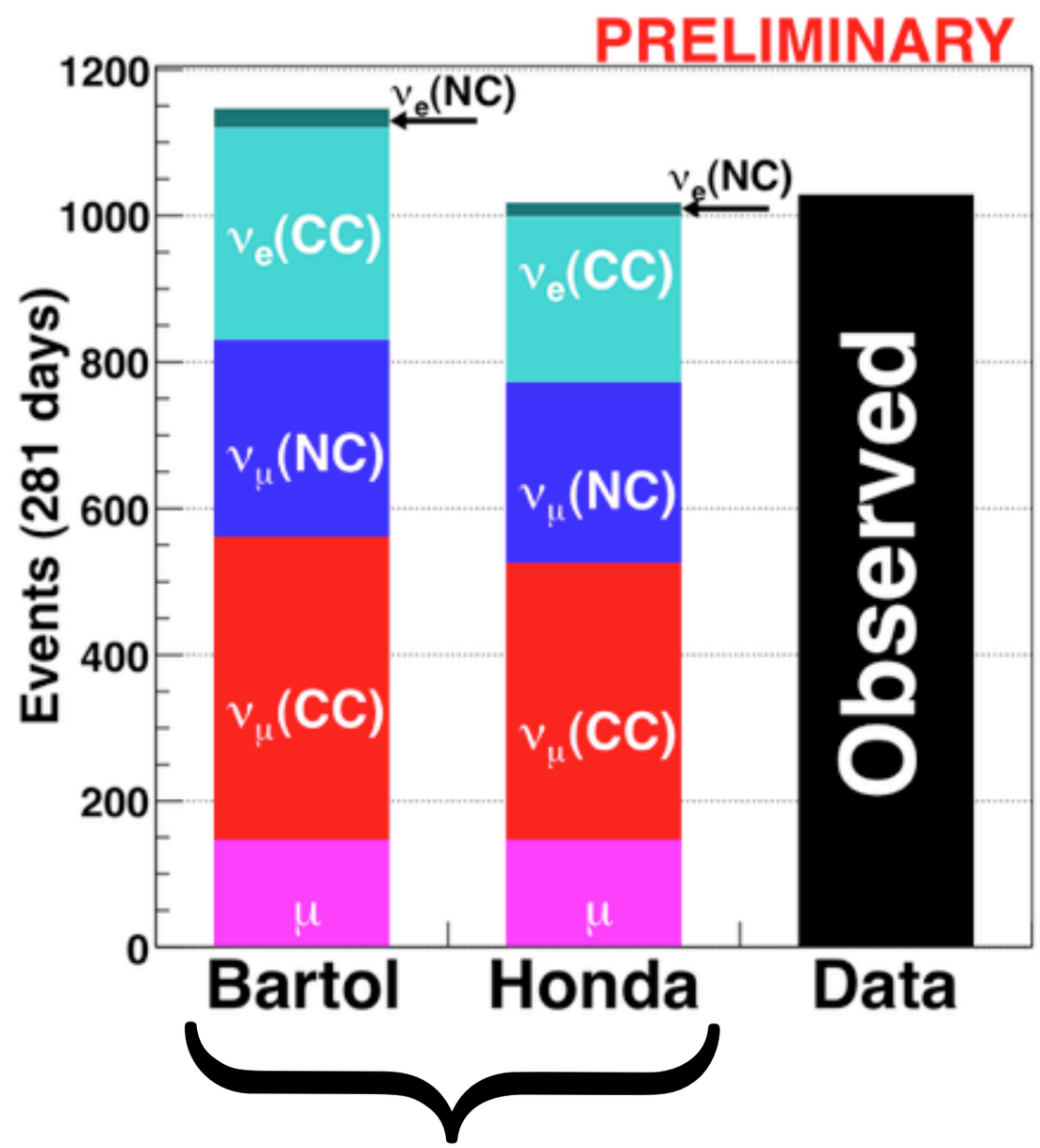
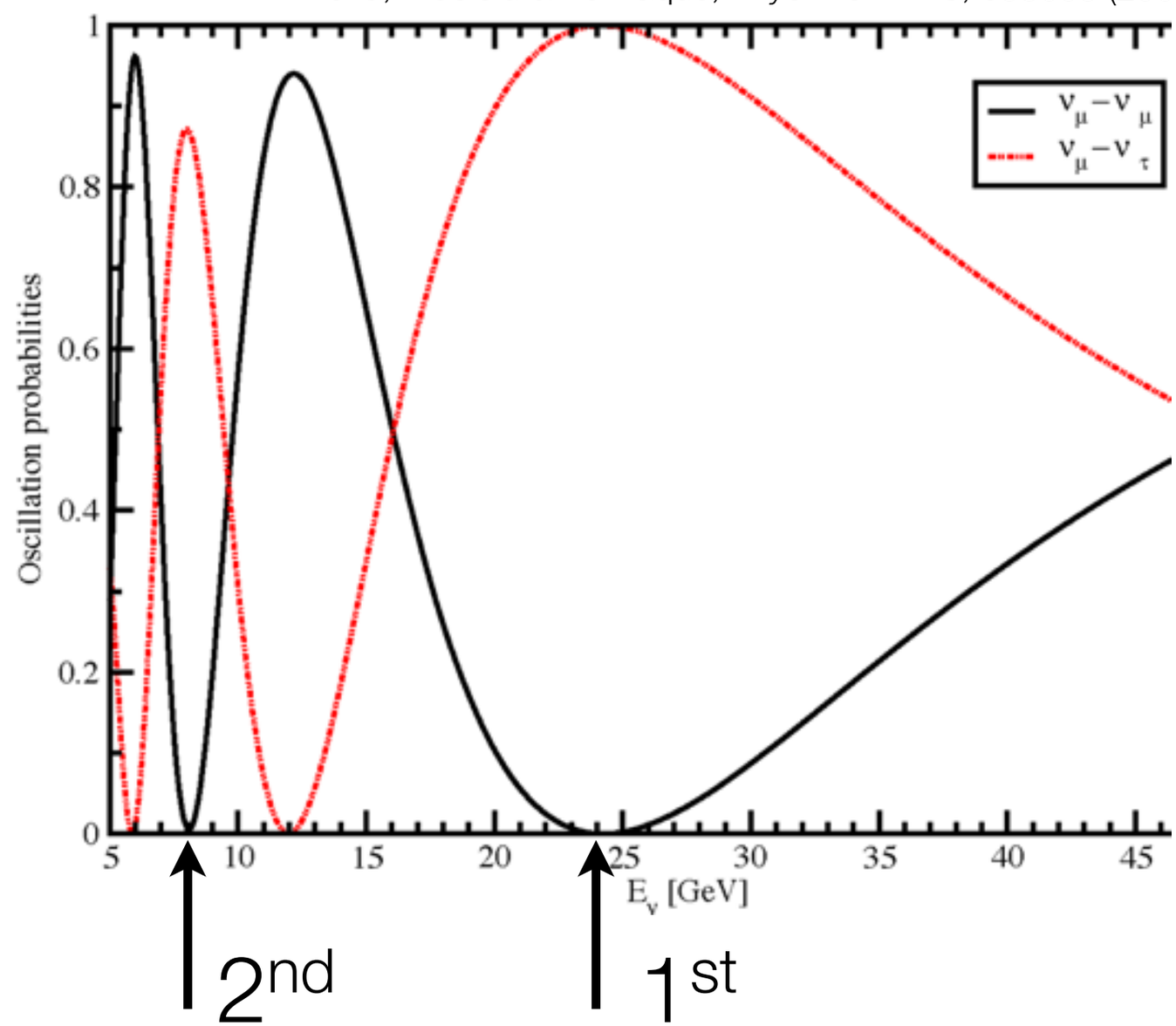




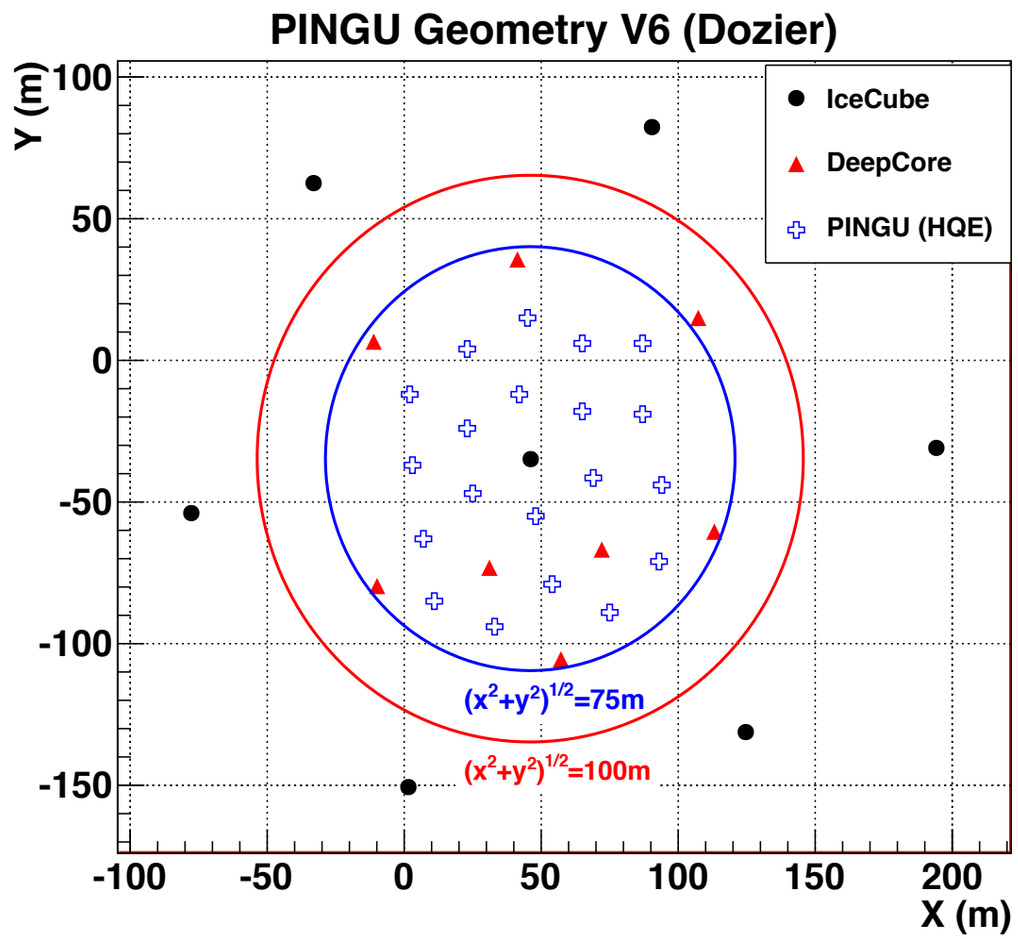
PINGU Oscillation Impact

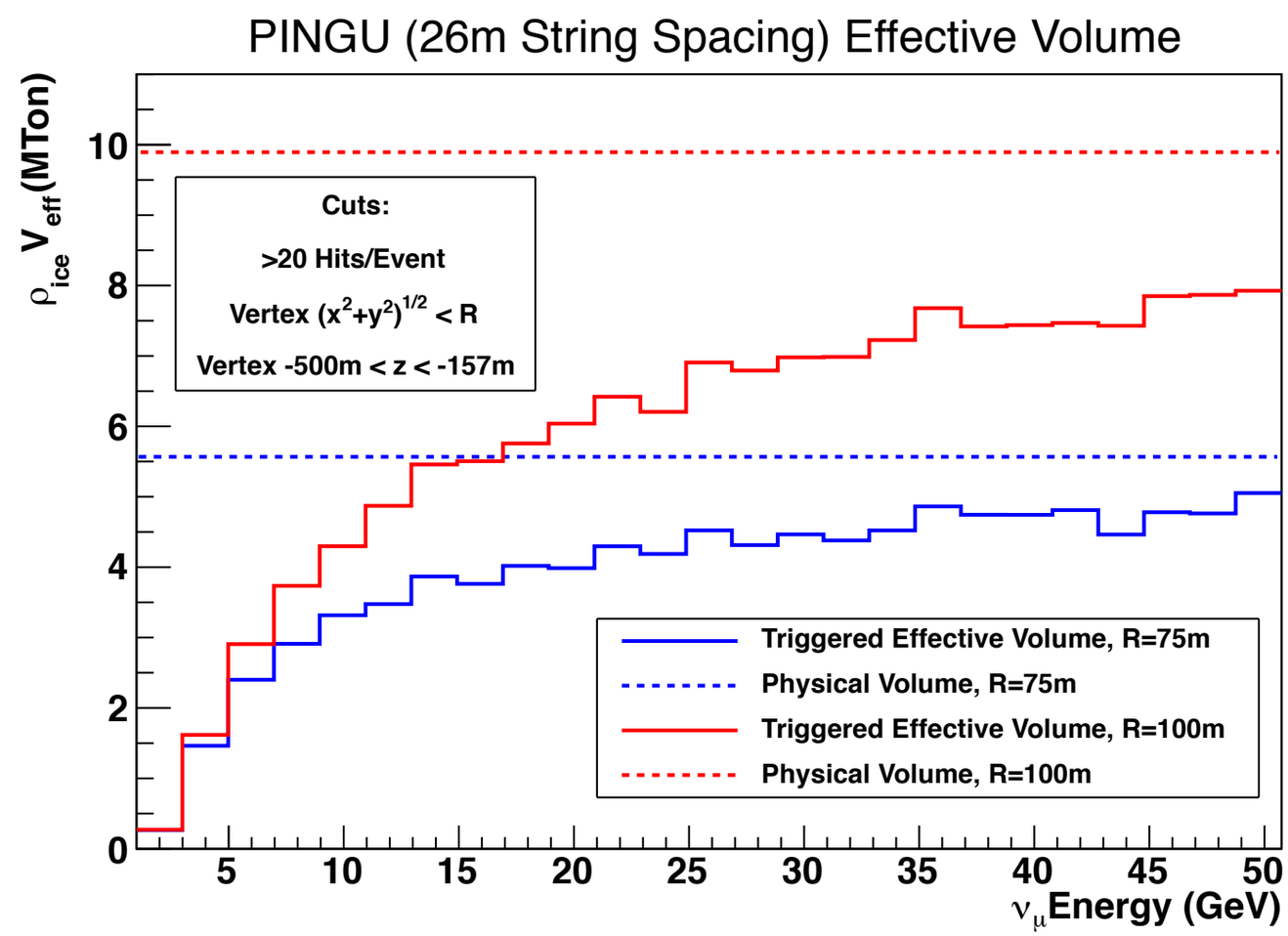
- With an infill that achieves ~GeV resolution, the 2nd oscillation minimum becomes accessible
- Improve Cascade reconstruction
  - Tau appearance

Mena, Mocioiu & Razzaque, *Phys. Rev.* D**78**, 093003 (2008)

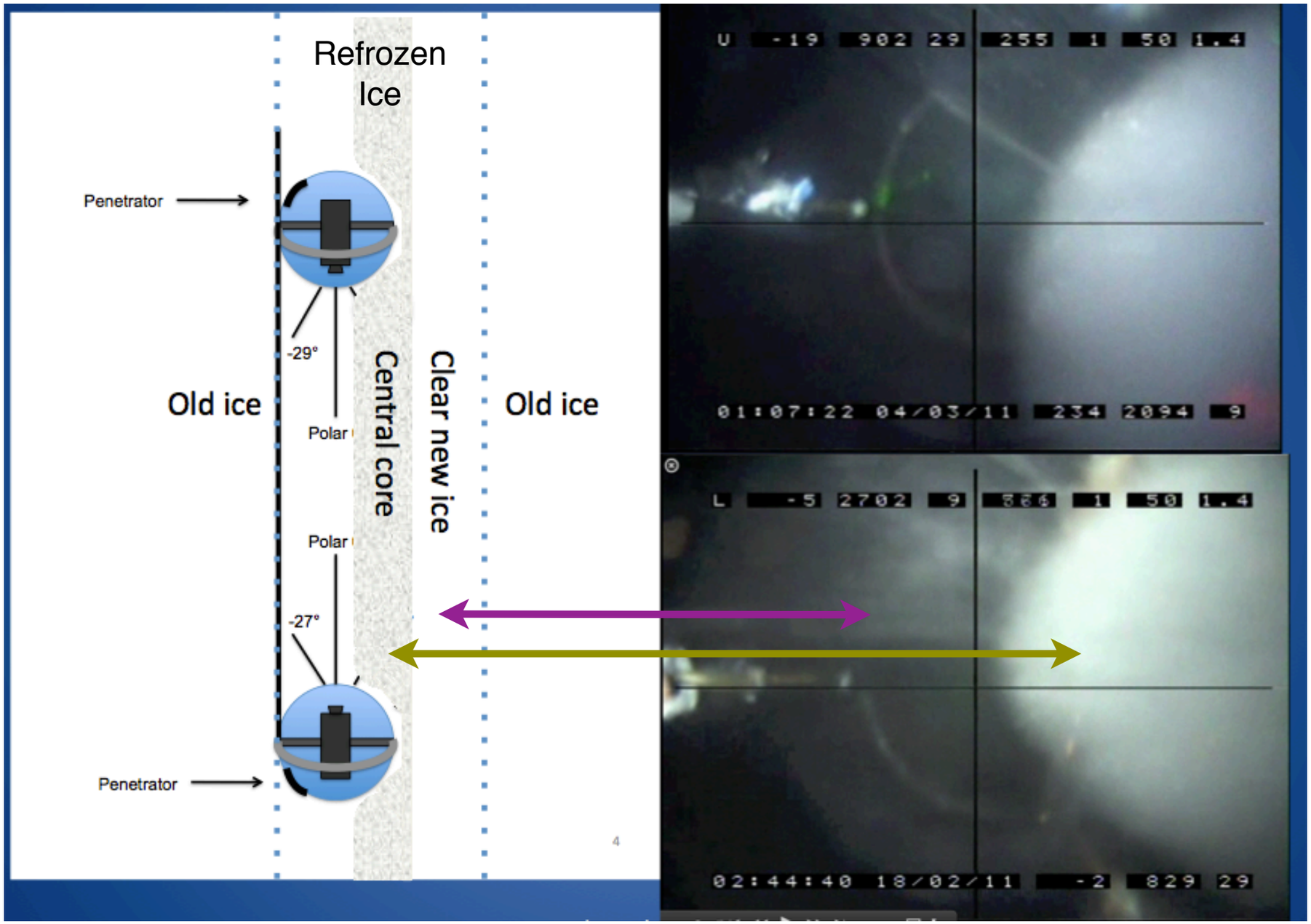


DeepCore/PINGU





- Several megatons effective volume at a few GeV
  - Interaction vertex containment is a proxy for event quality
  - Number of hits requirement is a proxy for event reconstructability

Calibration

- 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