Neutrino Oscillations w/ PINGU

D. Jason Koskinen
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Niels Bohr Institute

VILLUM FONDEN

*Felipe Pedreros, IceCube/NSF

NBIA PhD School: Neutrinos Underground
and in the Heavens II
August, 2016

Neutrino Oscillations w/ PINGU, IceCube/DeepCore and other stuff too

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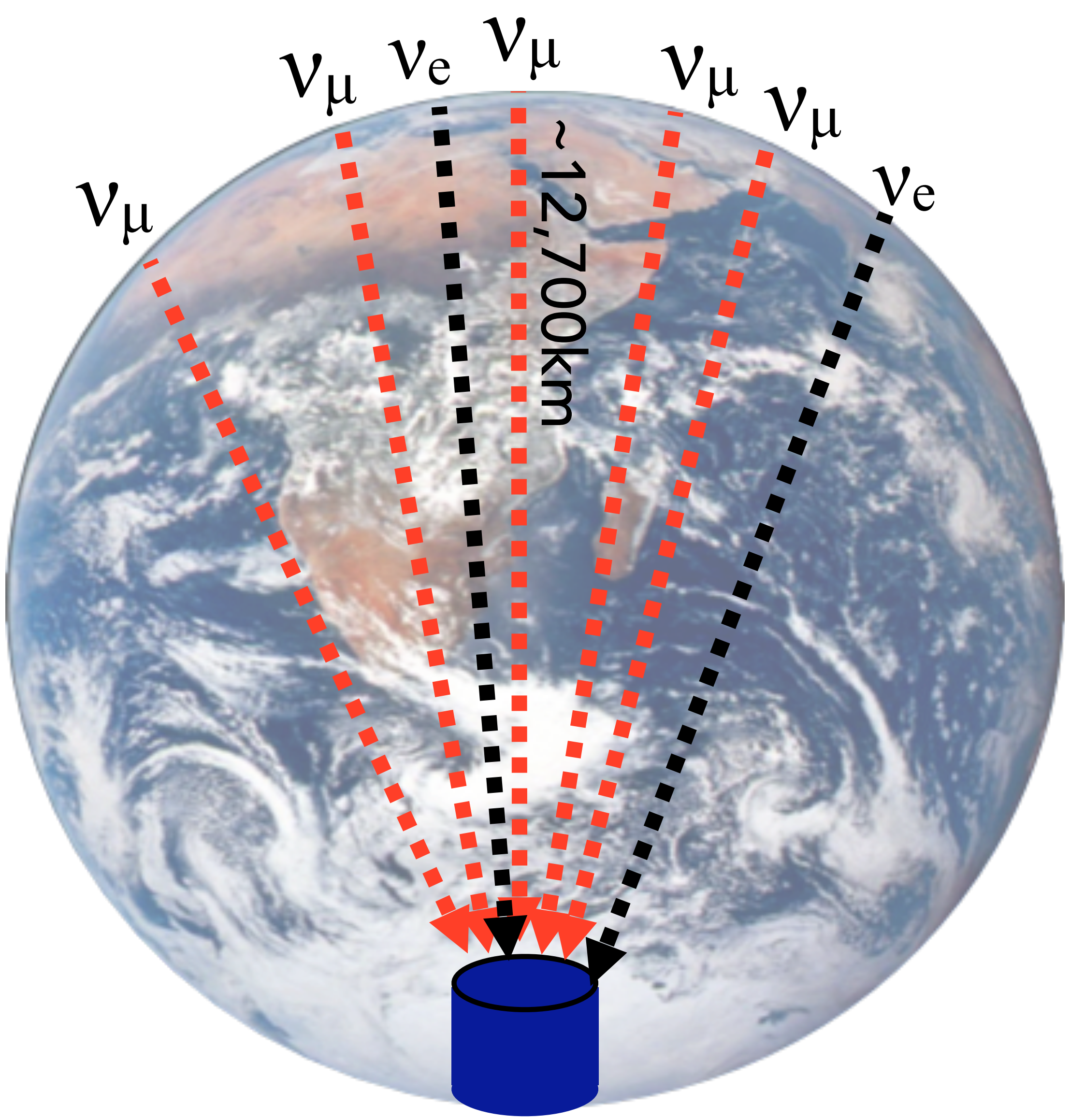
Atmospheric Neutrino Oscillation



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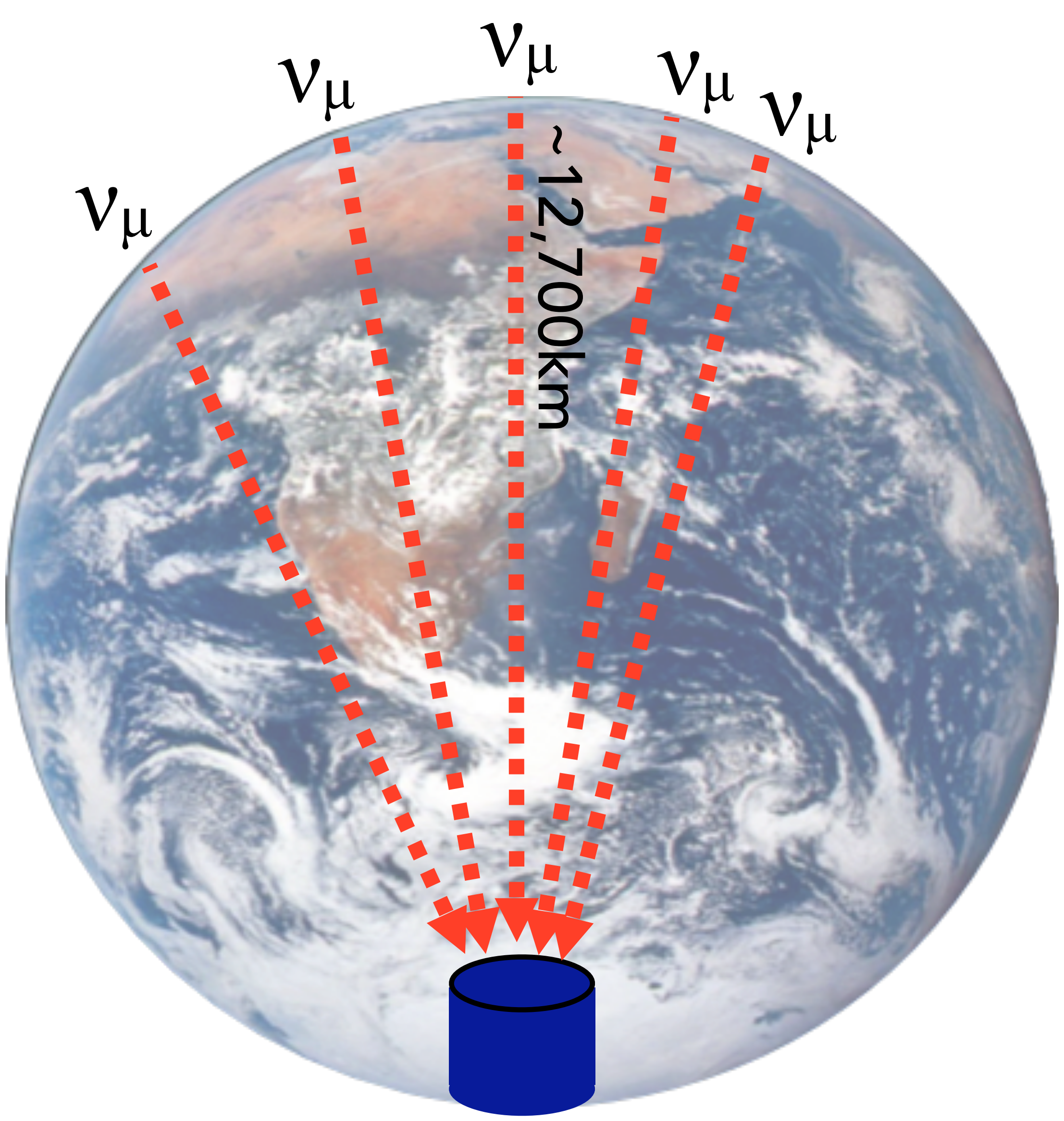

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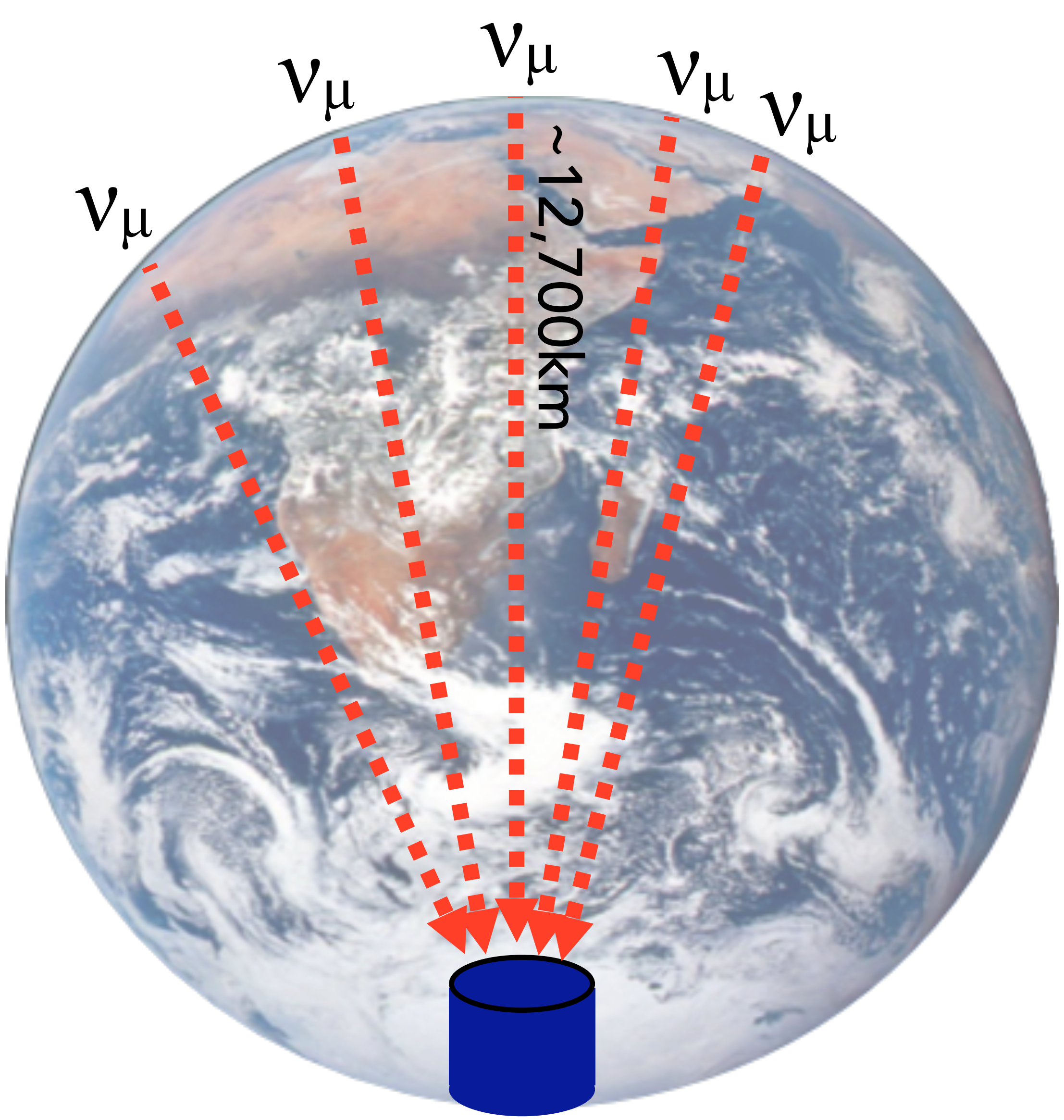
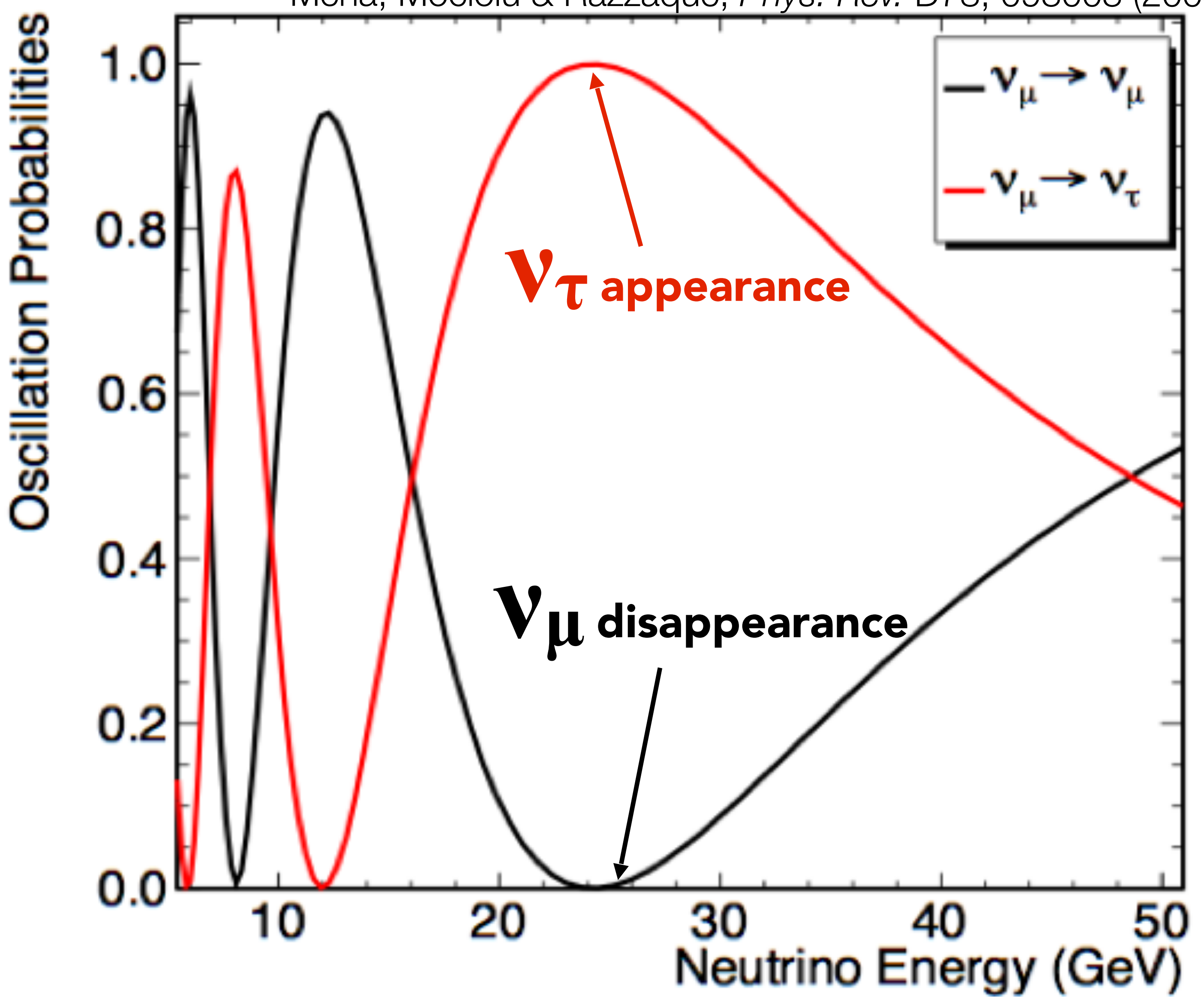
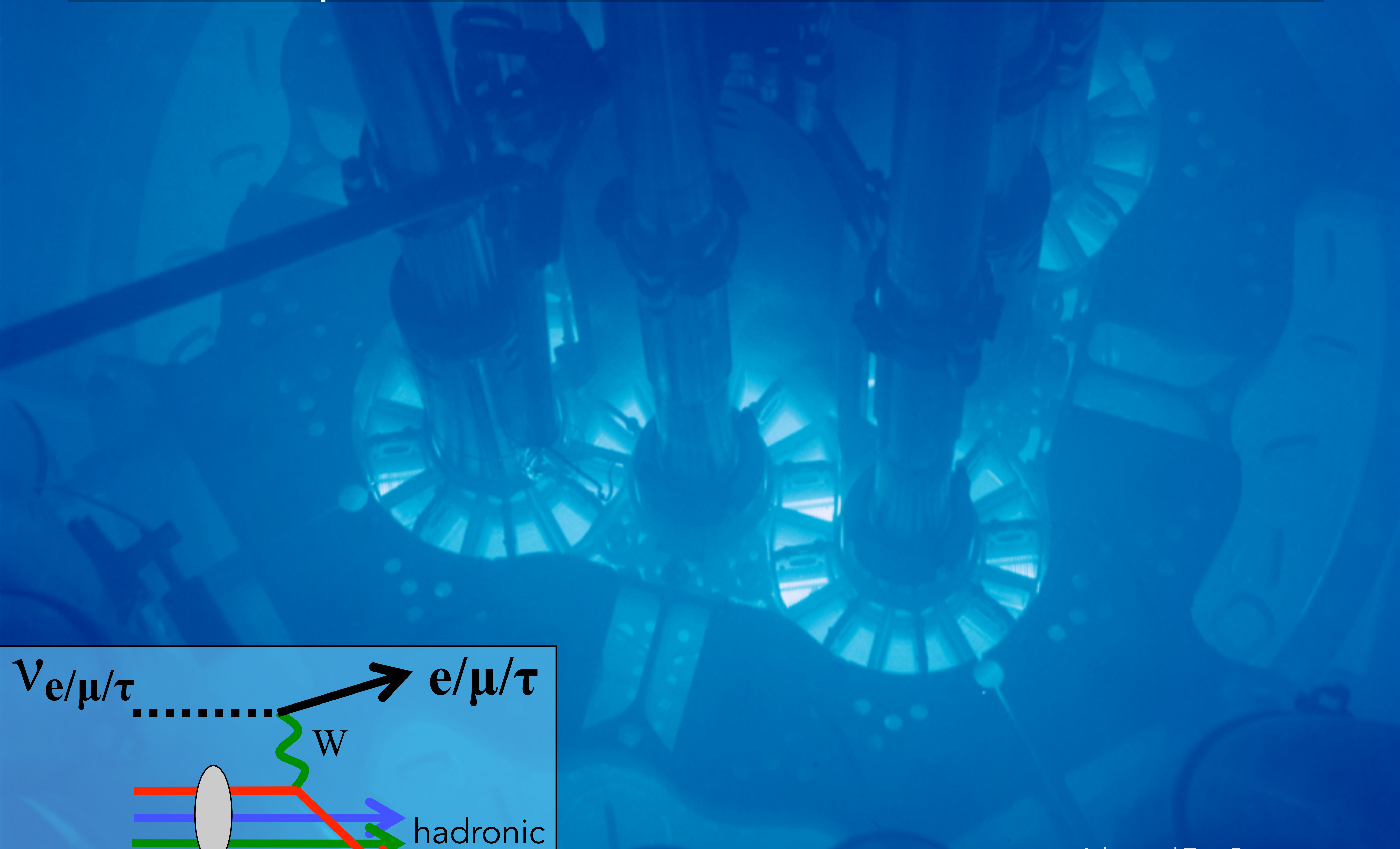


Mena, Mocioiu & Razzaque, *Phys. Rev.* D78, 093003 (2008)



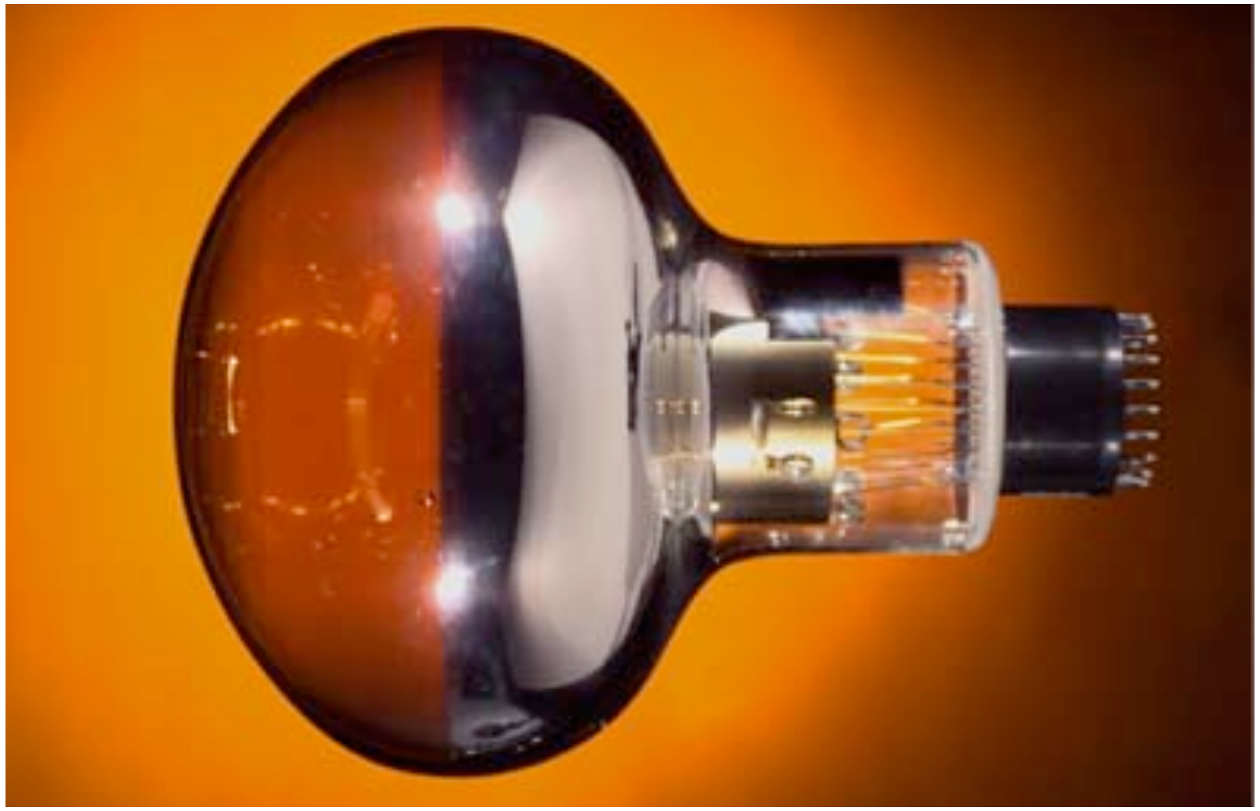
- Osc. probabilities $P(\nu_\mu \rightarrow \nu_\mu)$ at earth diameter baselines produce 1st oscillation maximum/minimum at ~25 GeV

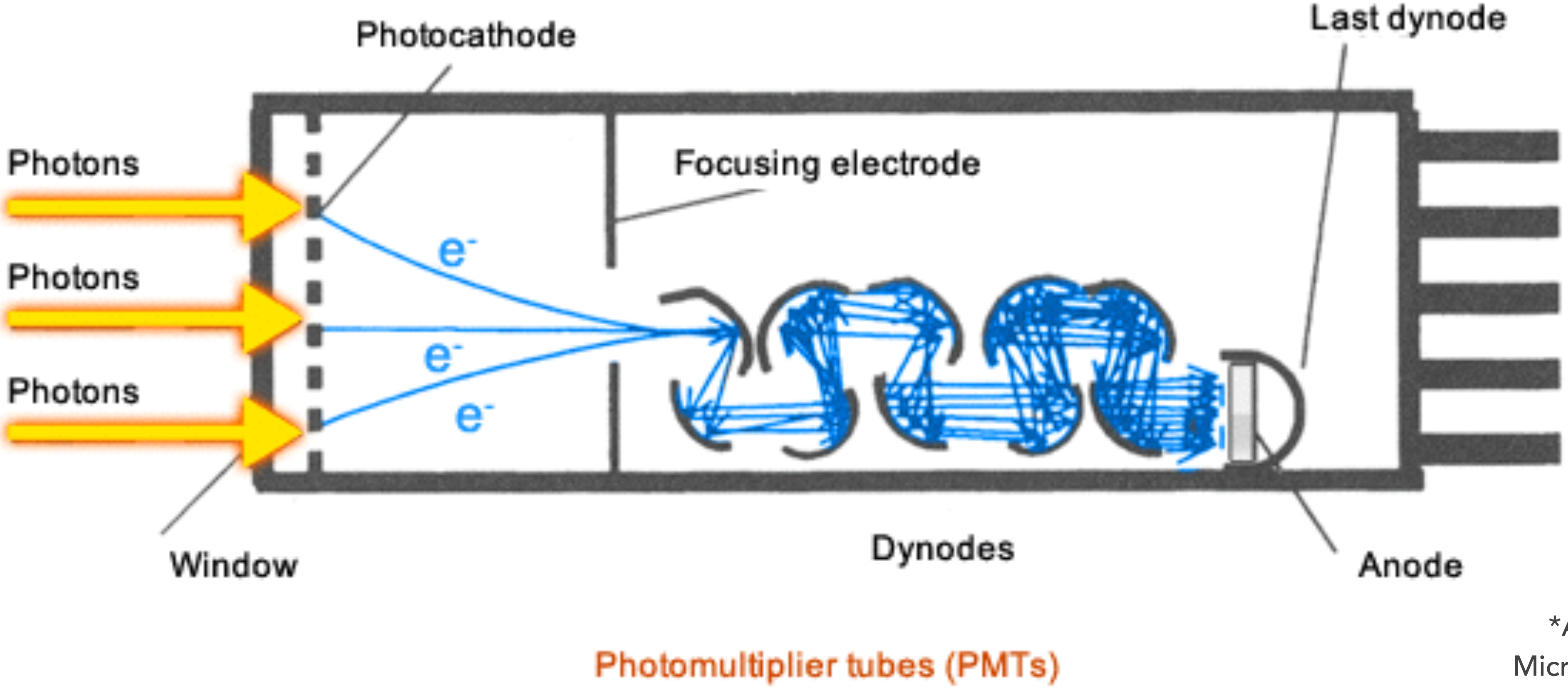
Charged particles traveling through water/ice produce Cherenkov radiation



Advanced Test Reactor
Idaho National Laboratory

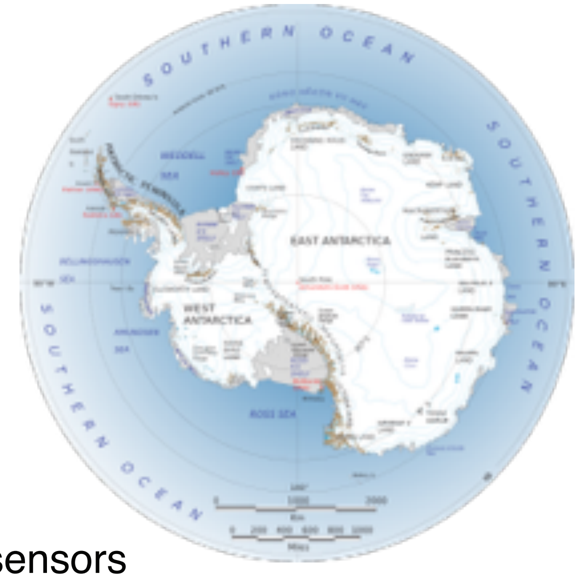
Photo-Multiplier Tubes

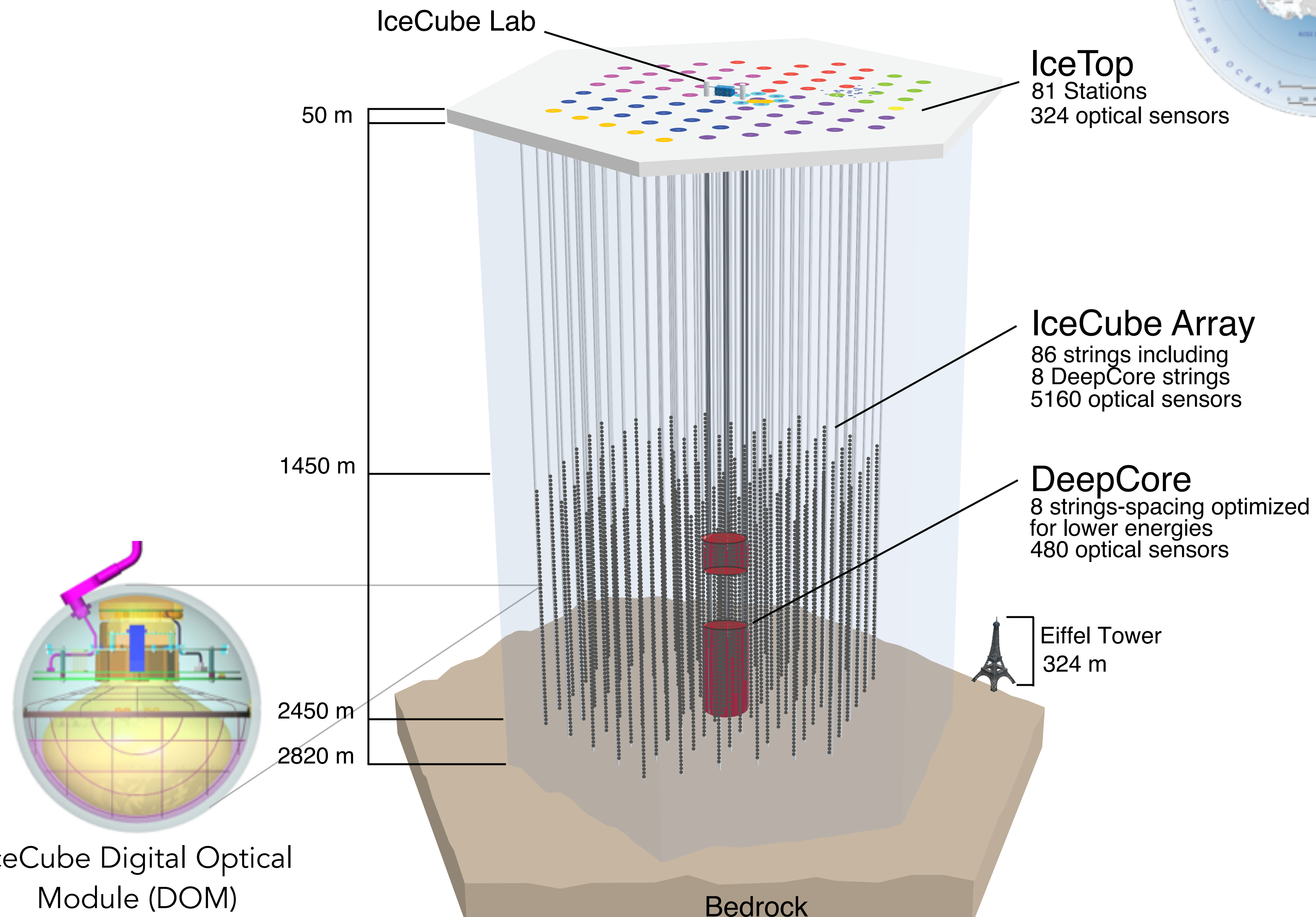




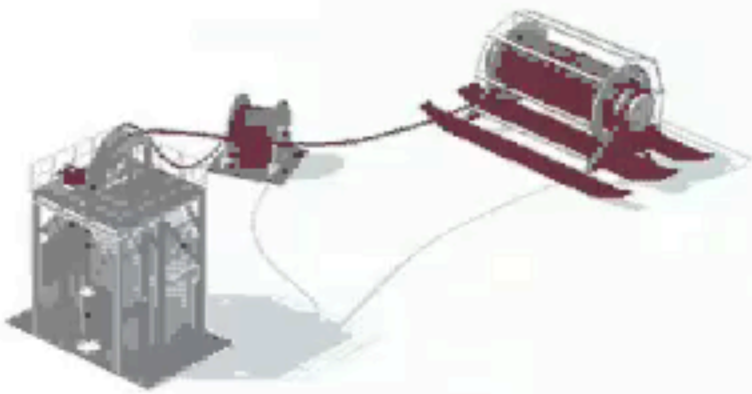
*Australian Microscopy & Microanalysis Research Facility

IceCube/DeepCore





IceCube Hot Water Drill Animation



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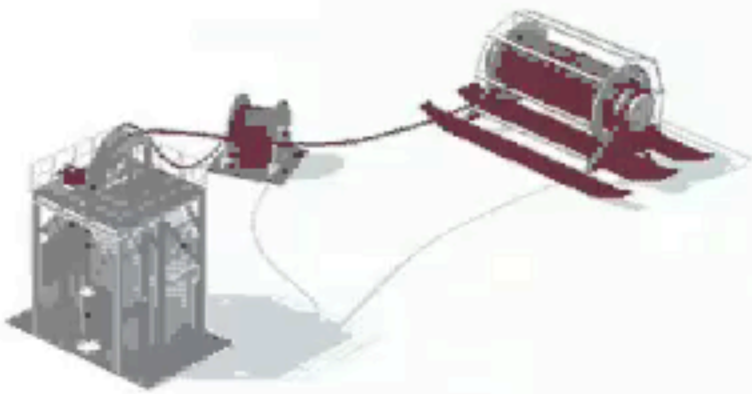
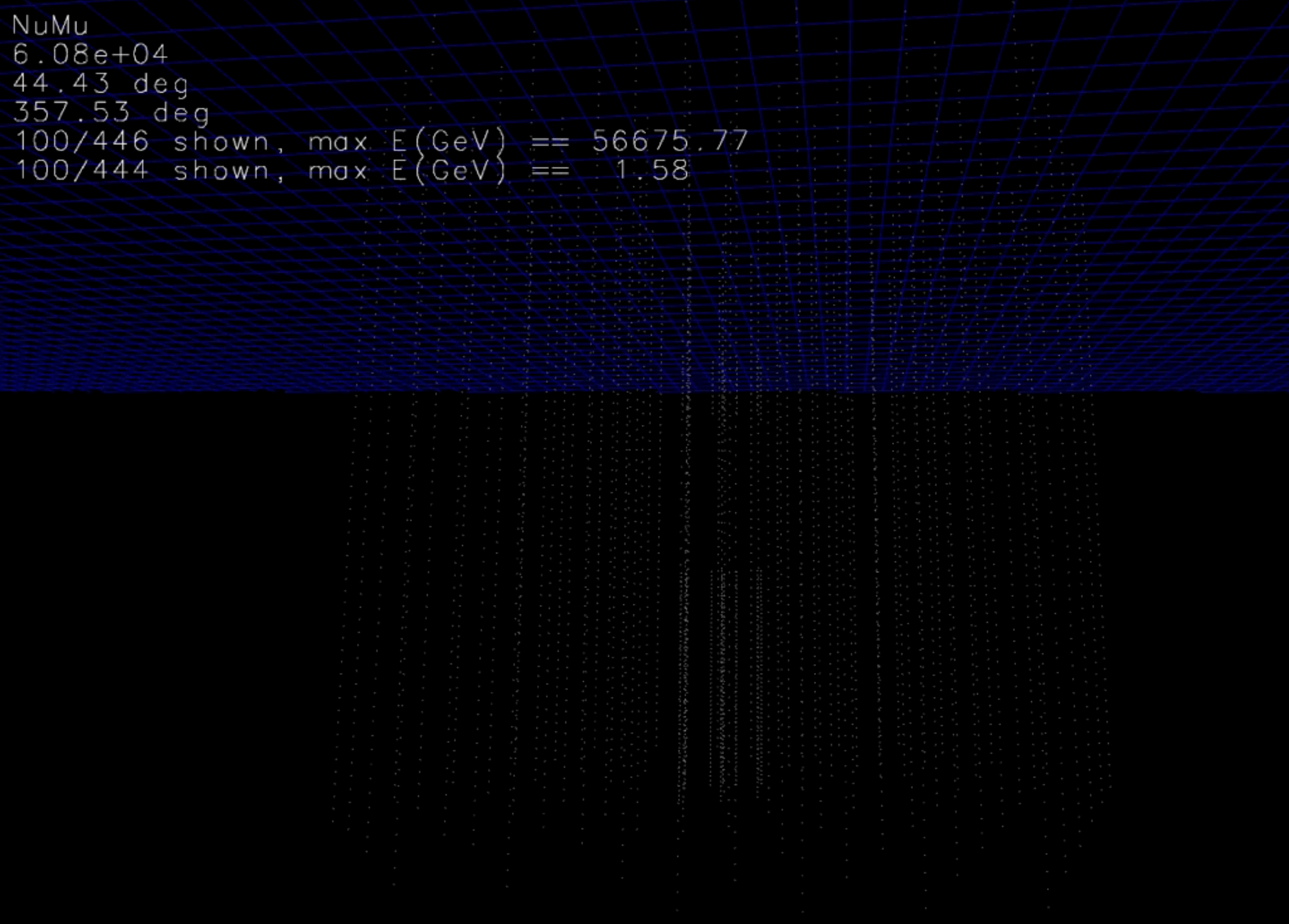
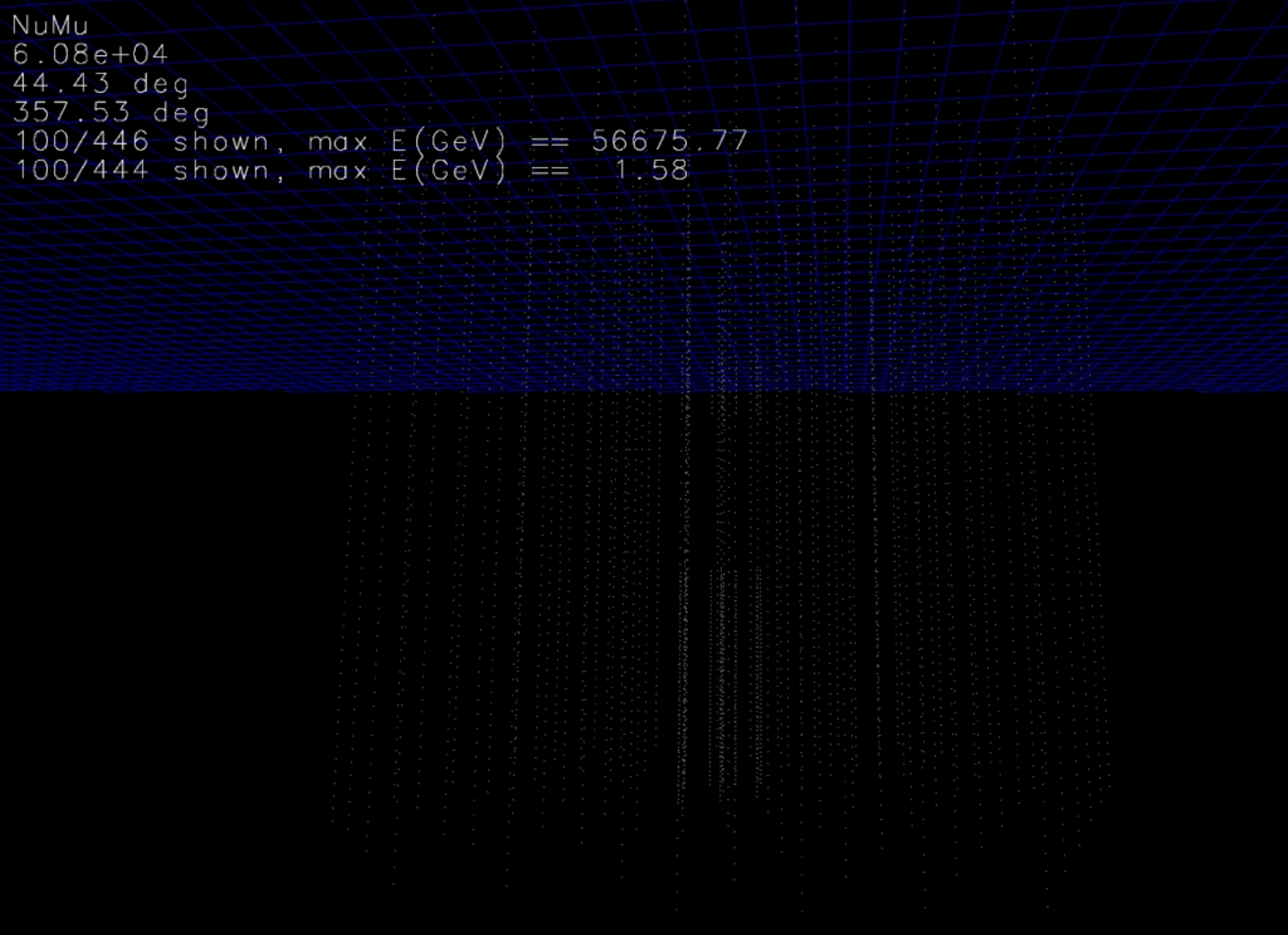



NuMu
6.08e+04
44.43 deg
357.53 deg
100/446 shown, max E(GeV) == 56675.77
100/444 shown, max E(GeV) == 1.58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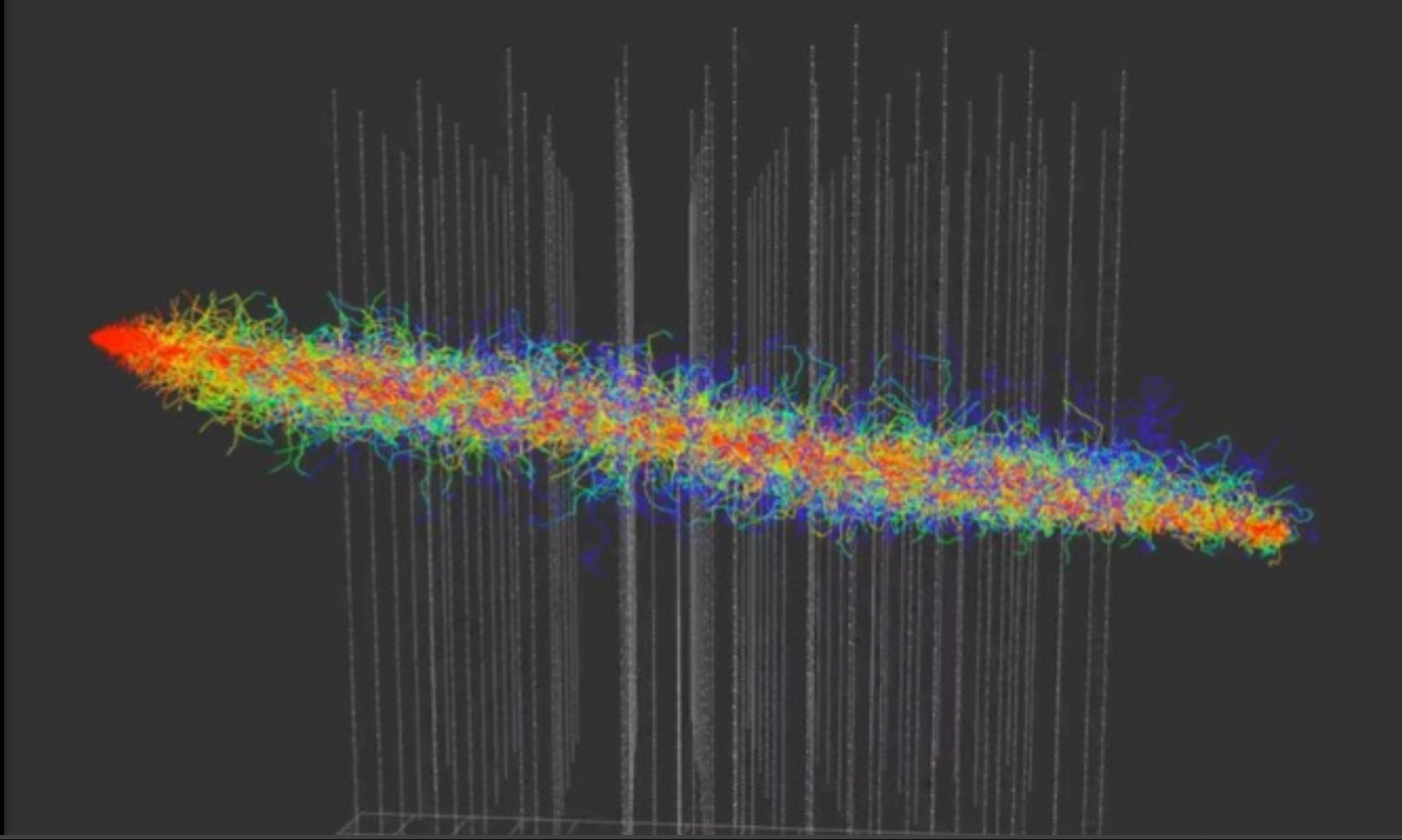
Track topology
(e.g. induced by muon neutrino)

Good pointing

IceCube: lower bound on energy for through-going events

DeepCore: well contained and provide good energy via muon track length



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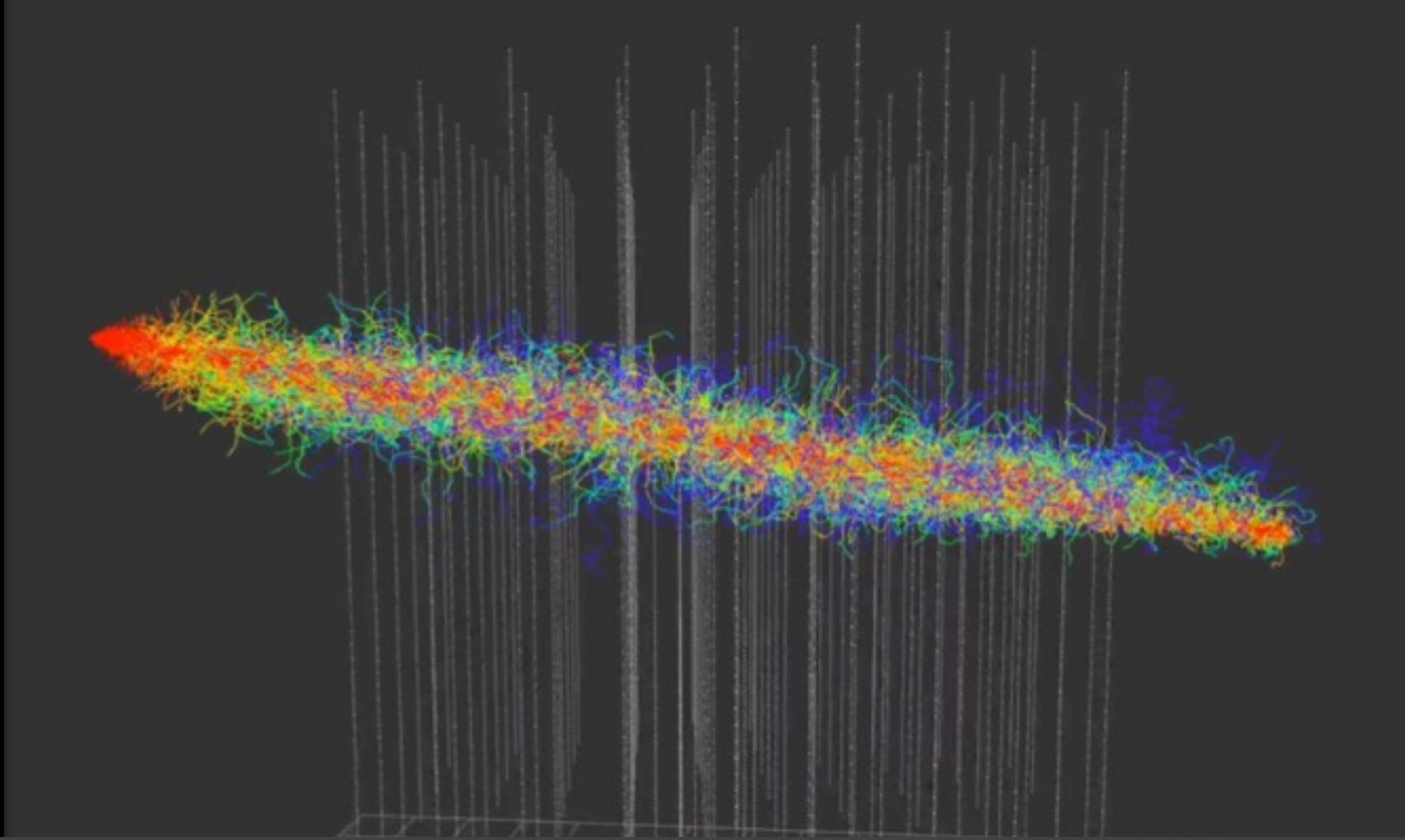


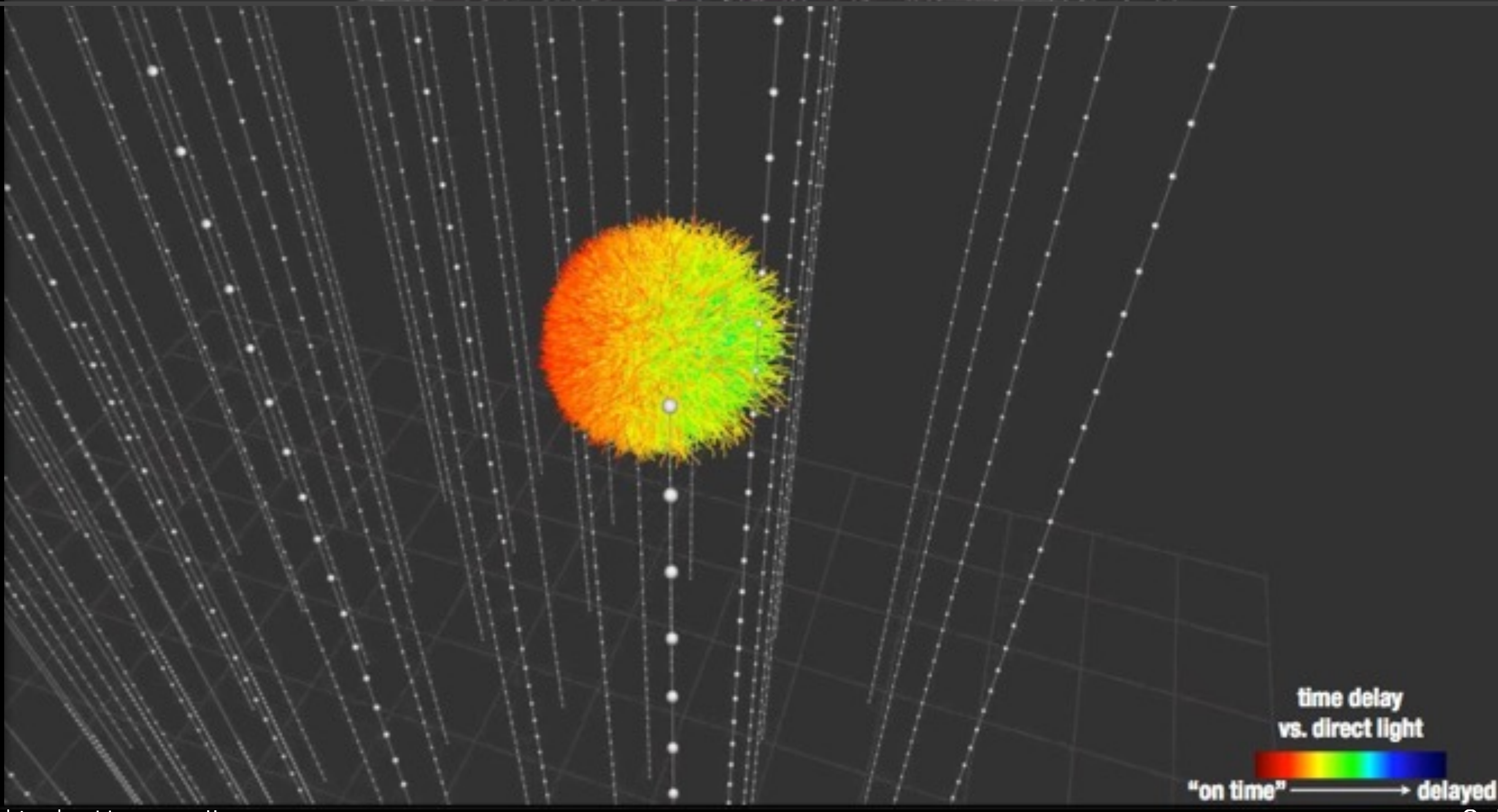
Cascade topology

(e.g. induced by electron neutrino)

Good energy resolution

IceCube: some pointing

DeepCore: poor pointing, more difficult to ID and reconstruct



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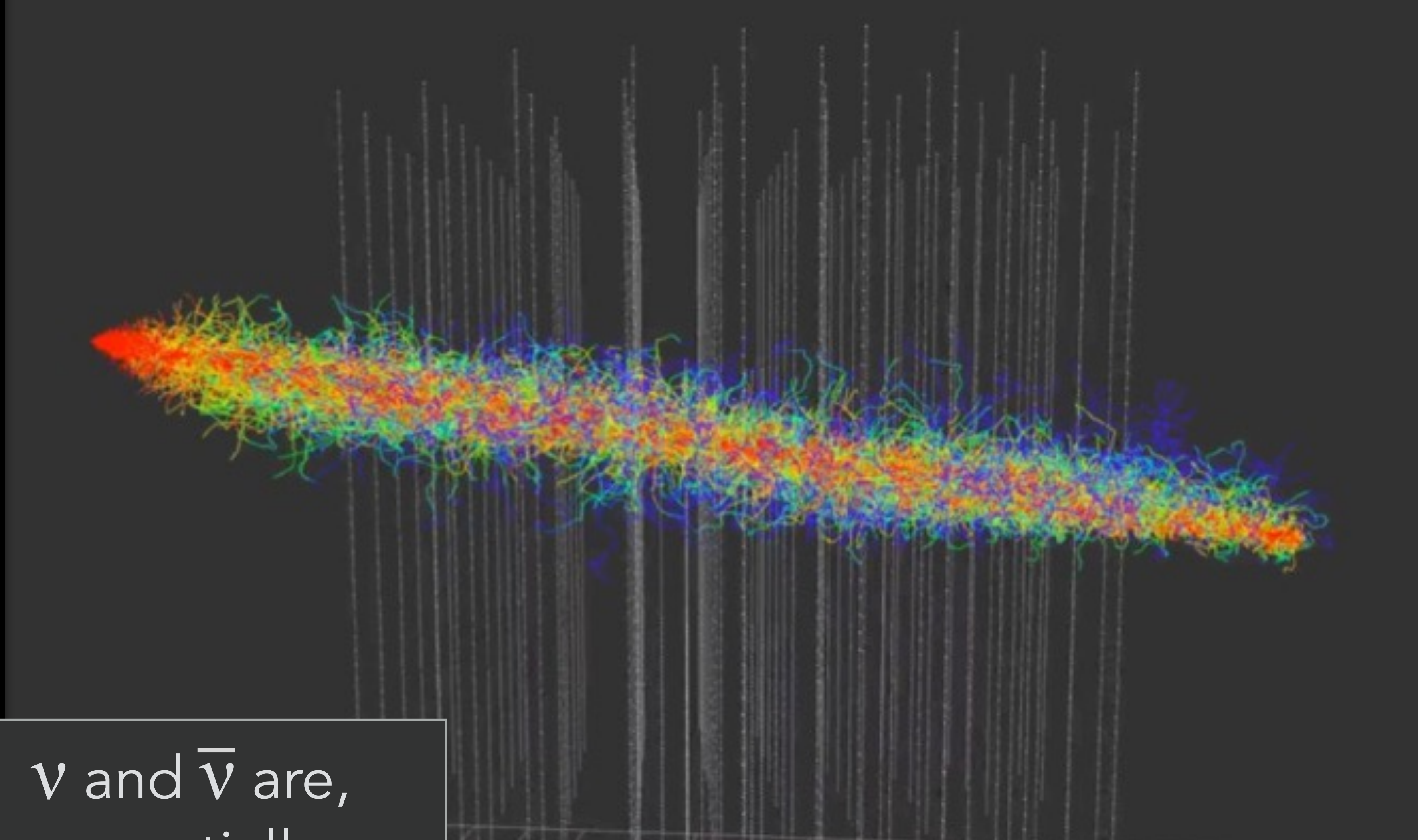

ν and $\overline{\nu}$ are, essentially, indistinguishable

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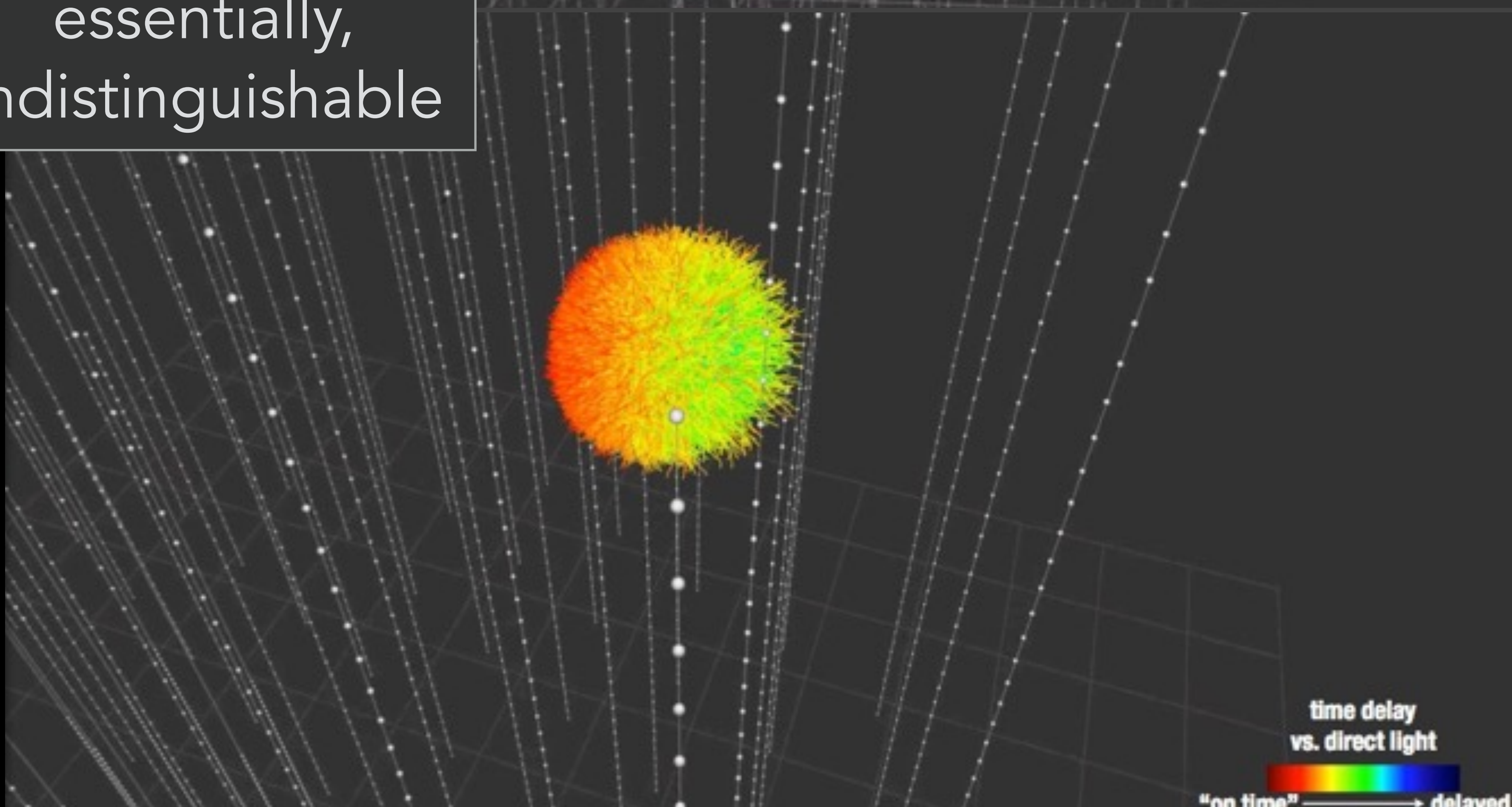
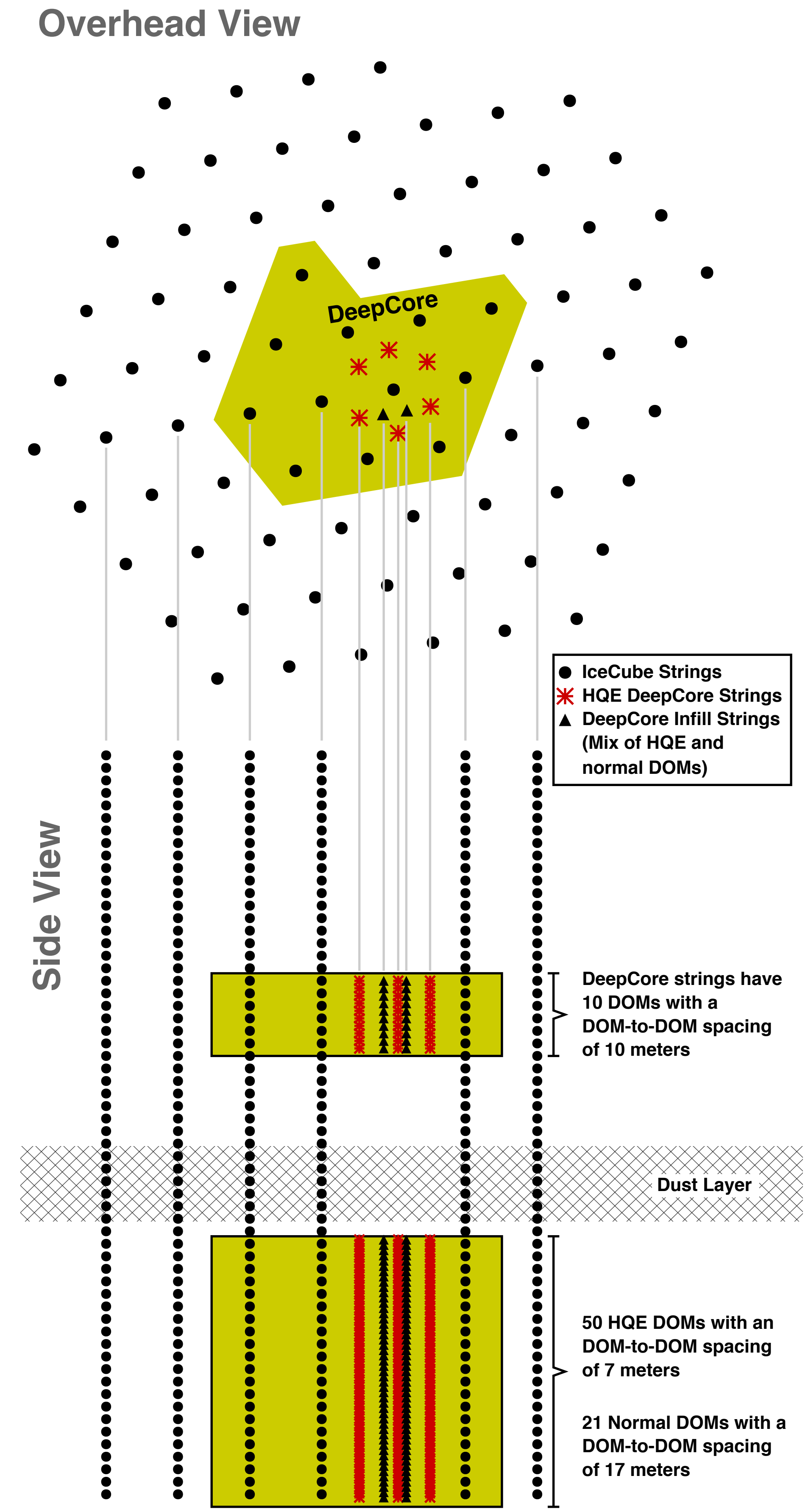


IceCube/DeepCore

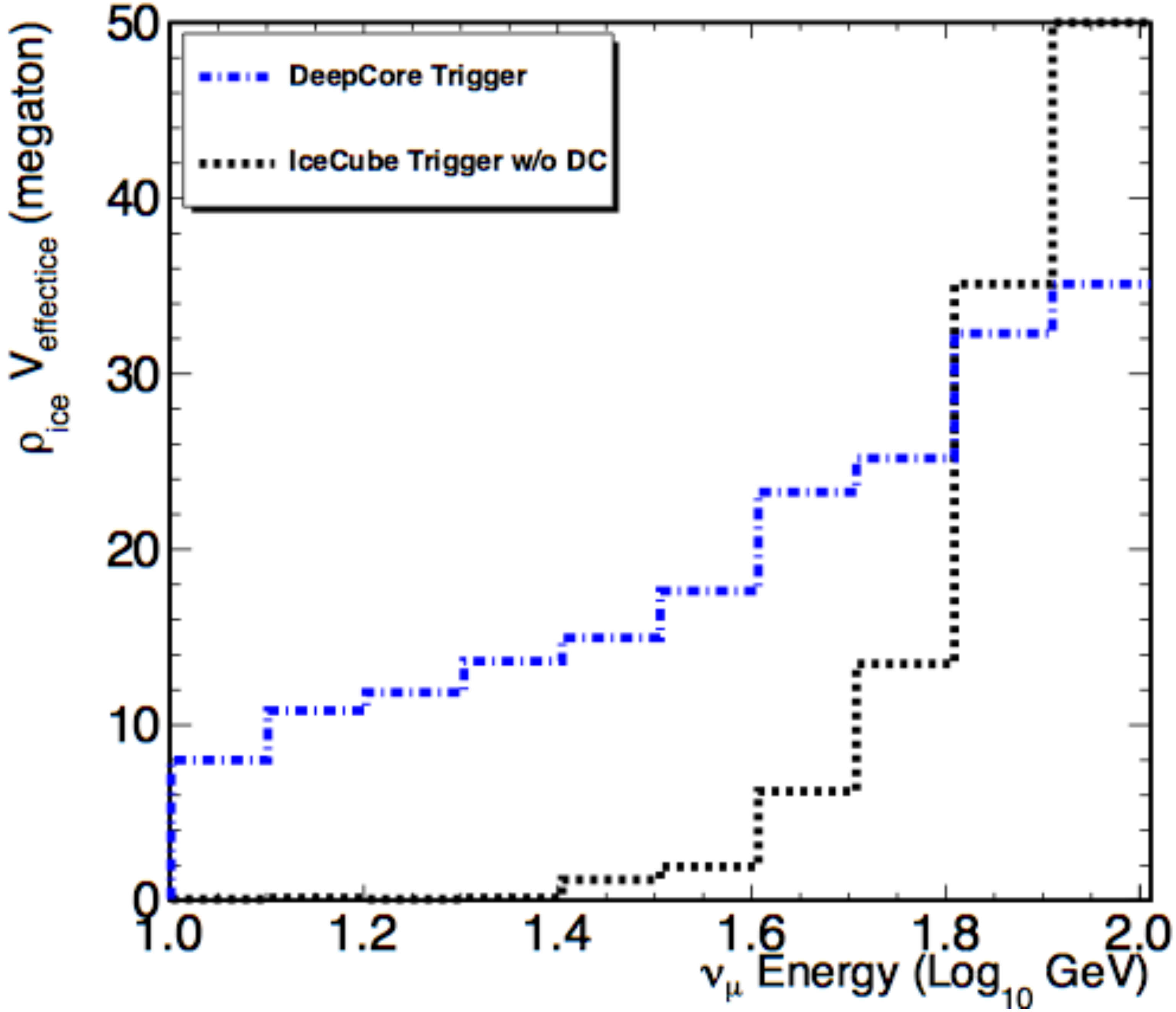
- DeepCore
  - Increased sensitivity at energies less than 100-200 GeV
  - 8 special strings plus 12 closest IceCube-standard strings
  - Denser DOM and string spacing
  - Deepest and clearest Ice
  - Higher efficiency photon sensors
  - Lower trigger threshold

- IceCube is not only a high energy neutrino detector, but also a cosmic ray muon veto for any inner detectors



Oscillation w/ DeepCore

- 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. ν events/year



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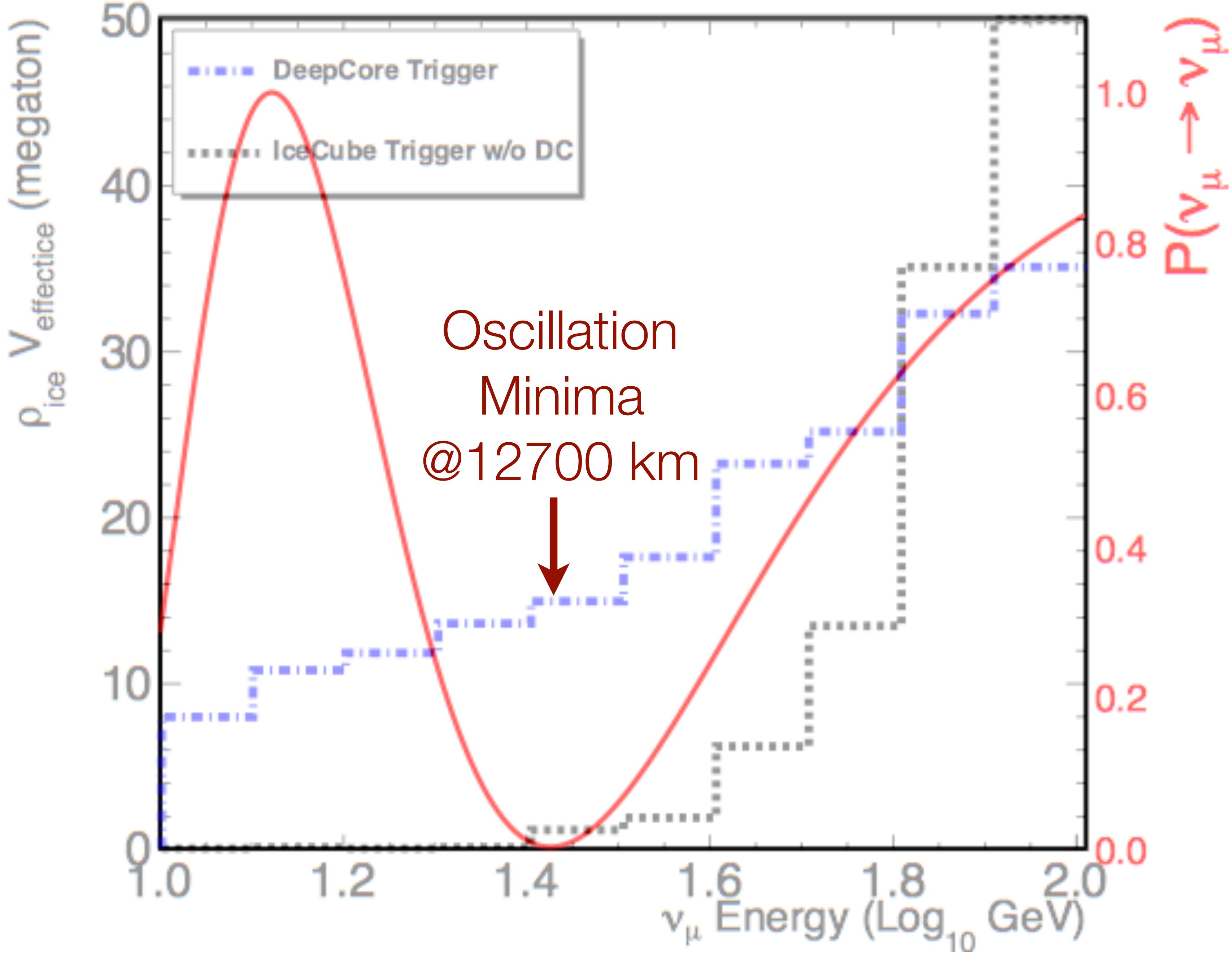
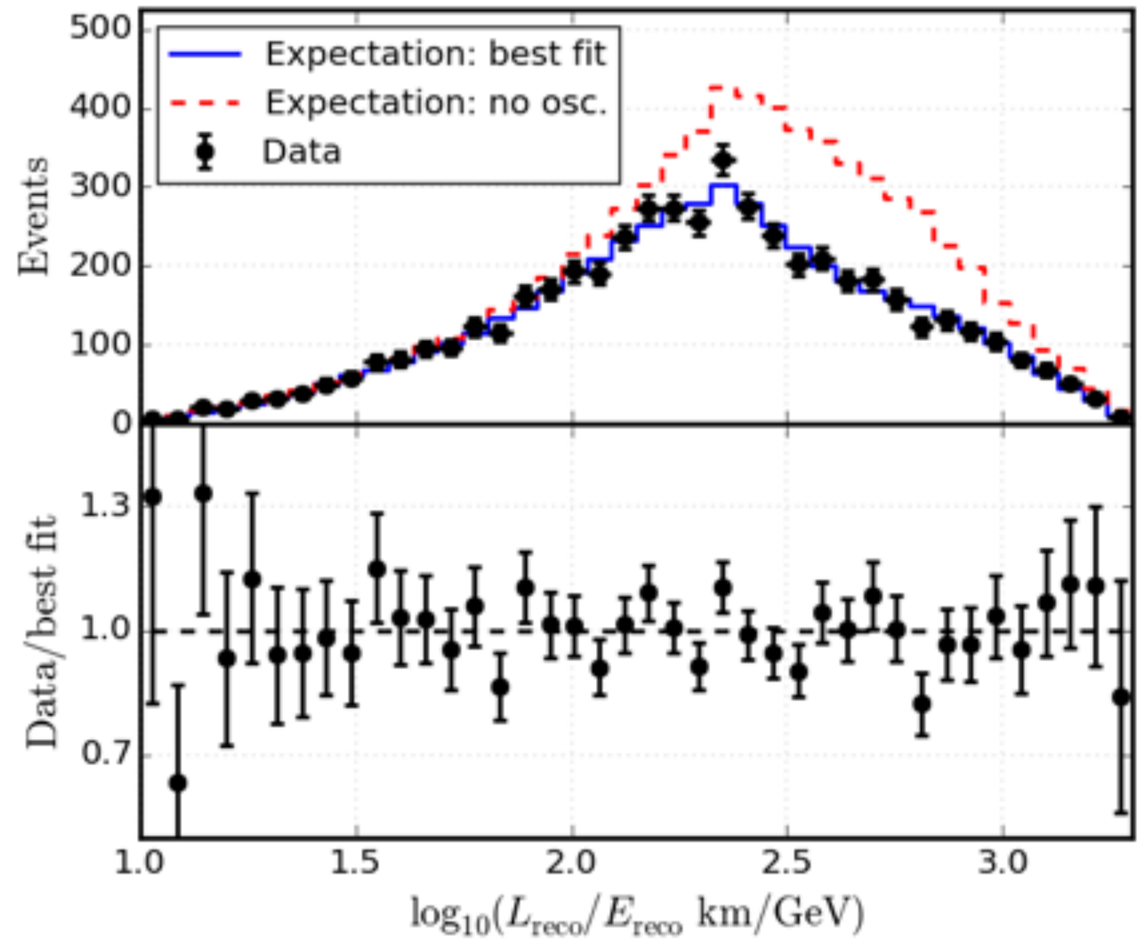
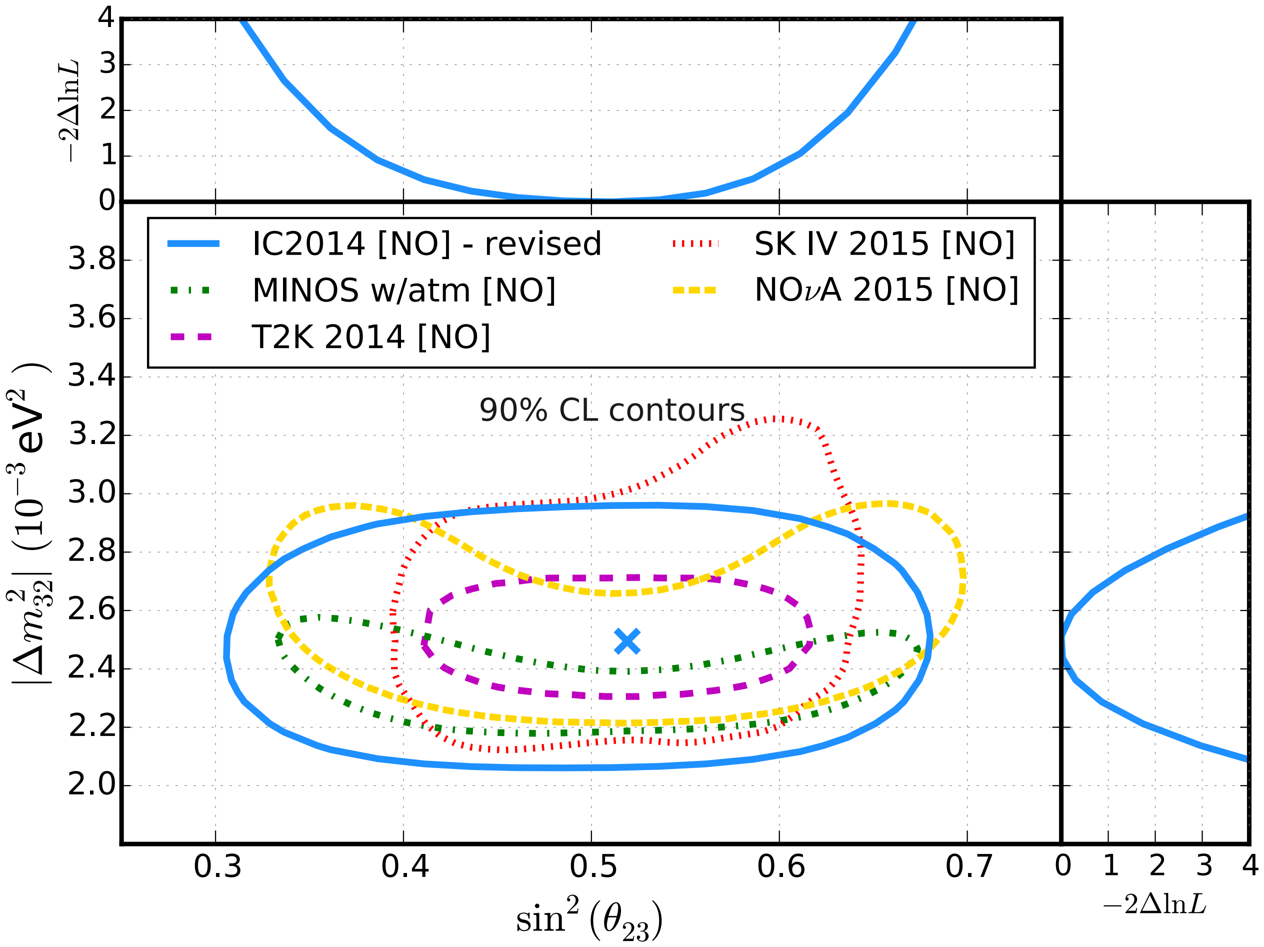


Current Results





*DJK, Neutrino 2016

Measuring Parameters

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

underlying nature of weak mixing

$C_{12} = \cos\theta_{12}$ $S_{12} = \sin\theta_{12}$

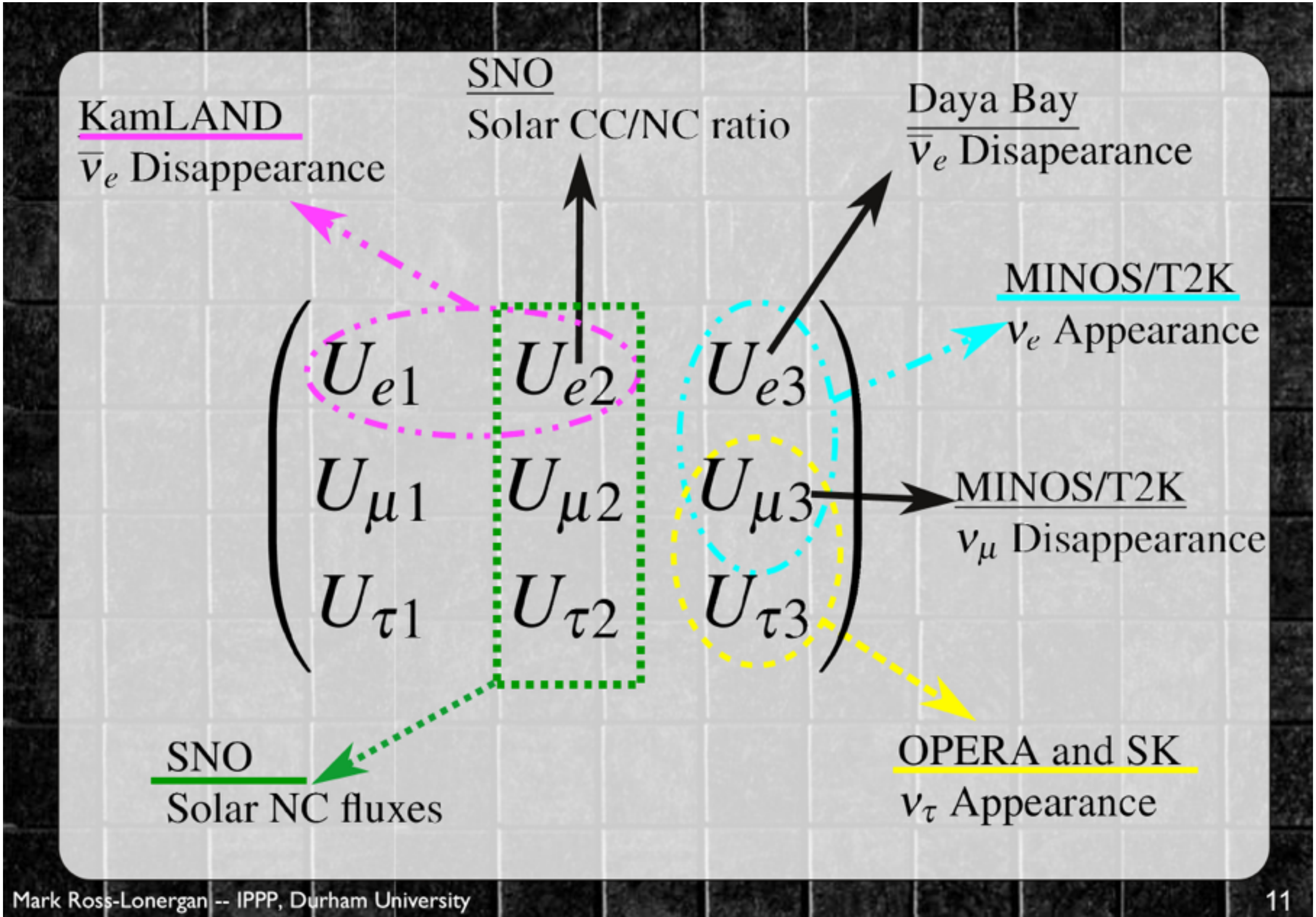
$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Experimentally measured values

Three angles and one Charge-Parity phase

What Is Being Measured?

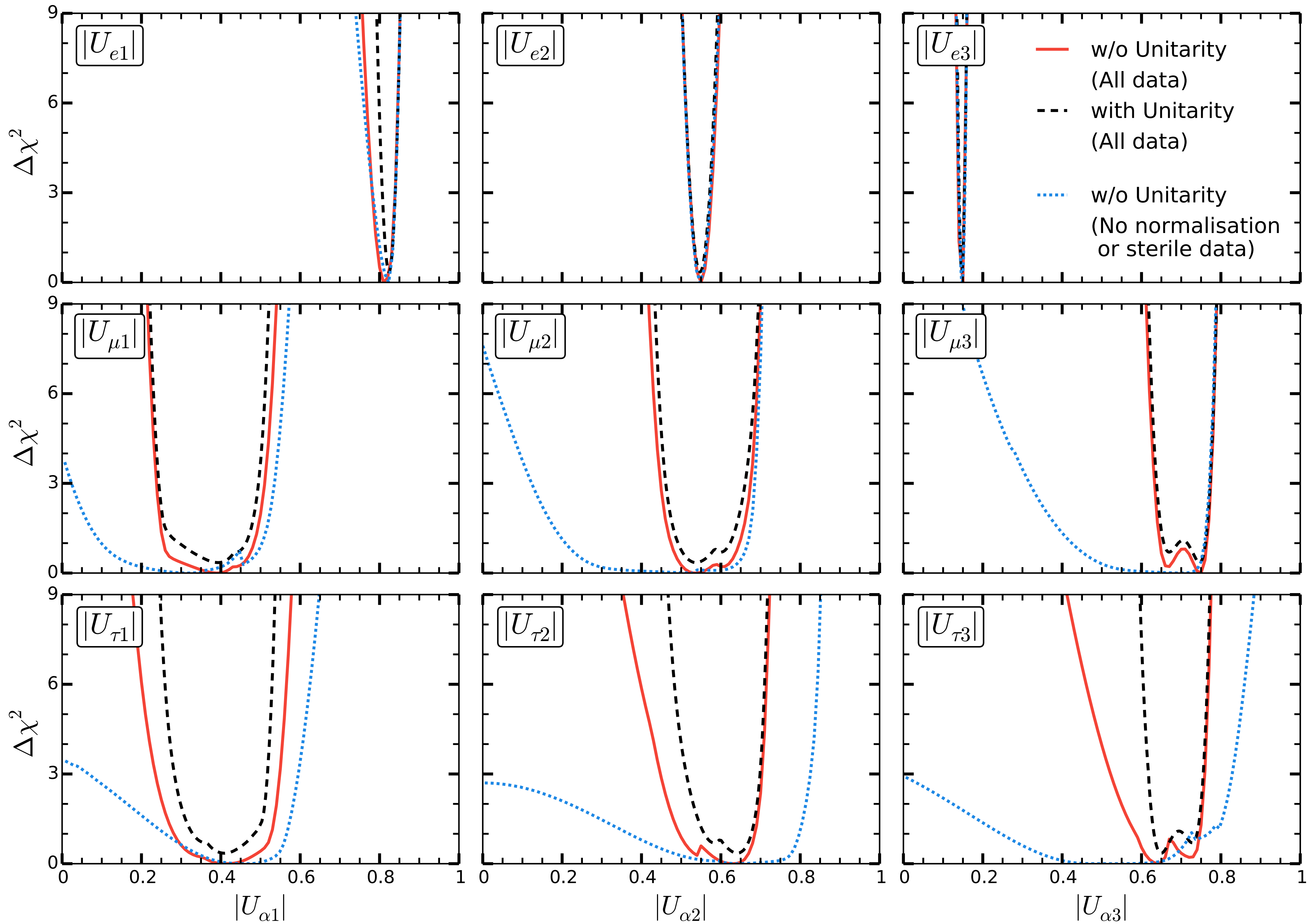
*NOW2014



Unitarity

- Minimal assumption direct experimental constraints for PMNS unitarity can be improved upon

*arXiv:1508.05095



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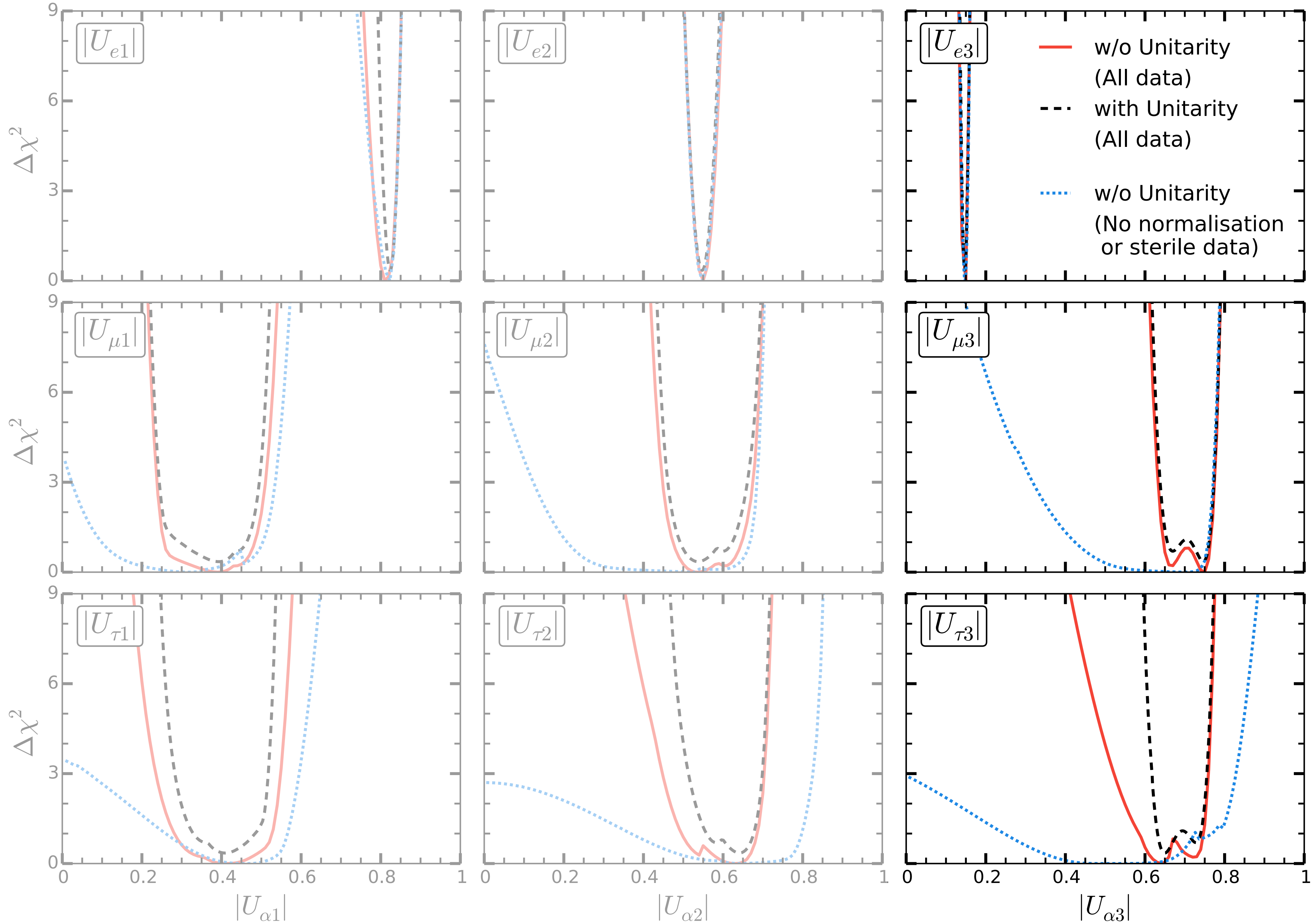

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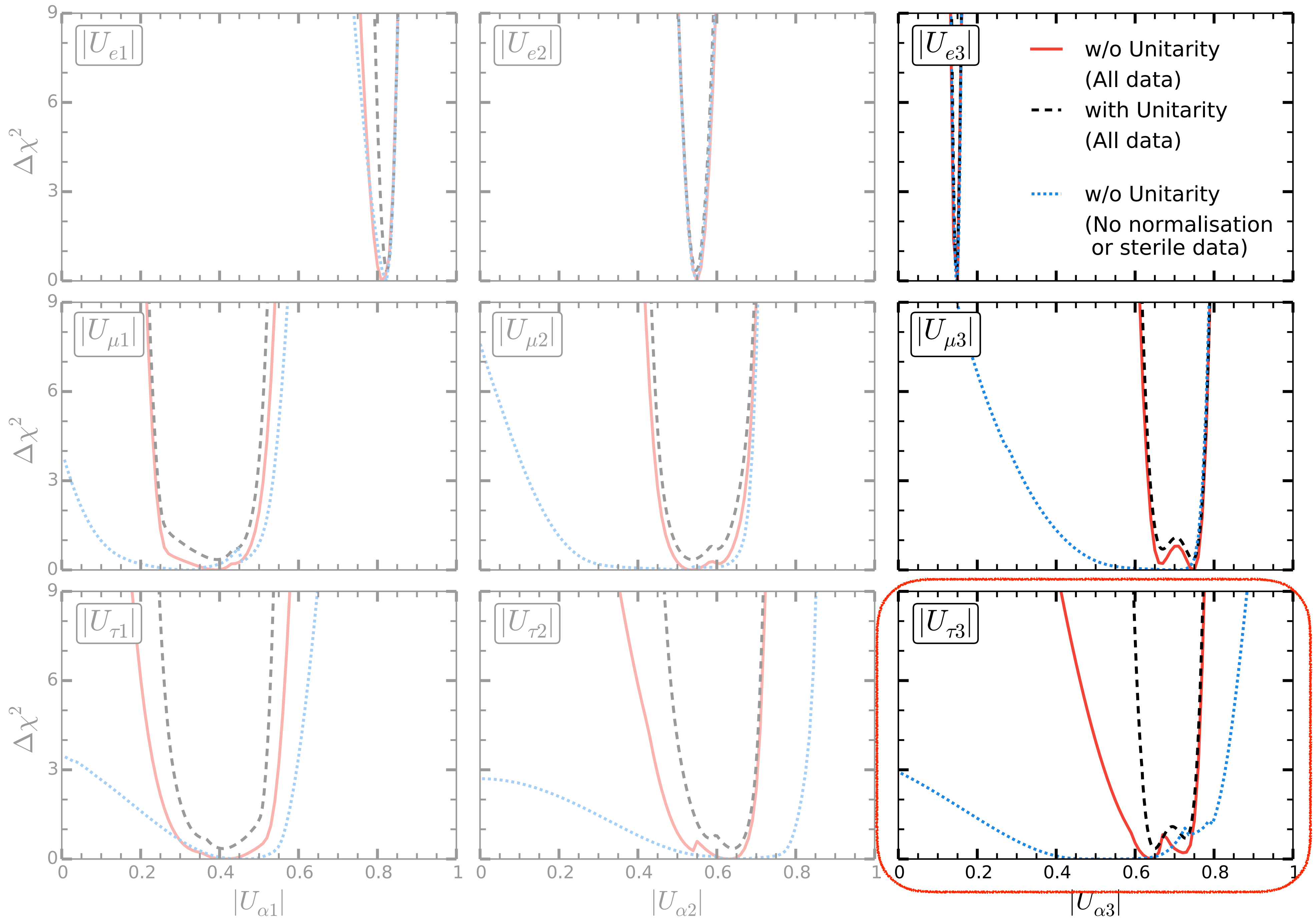
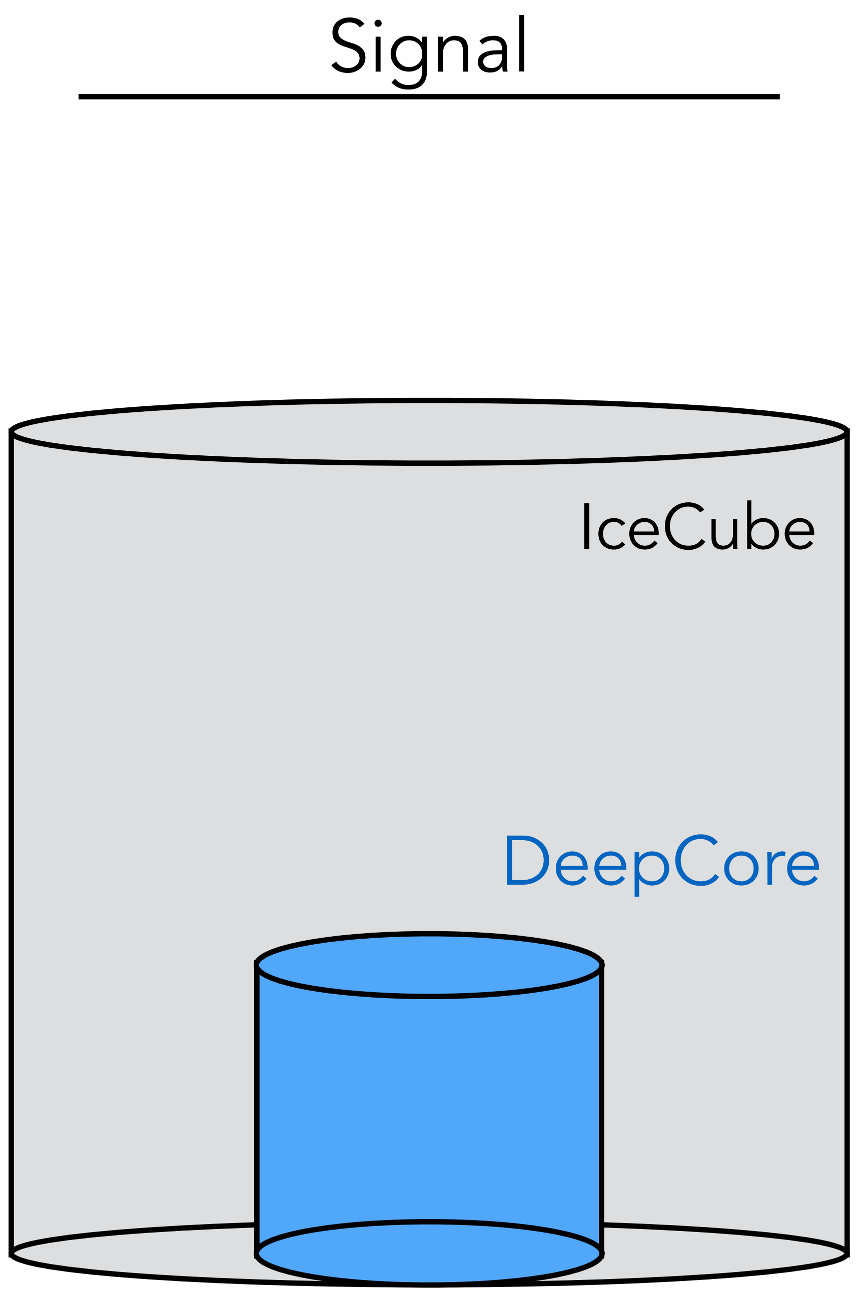


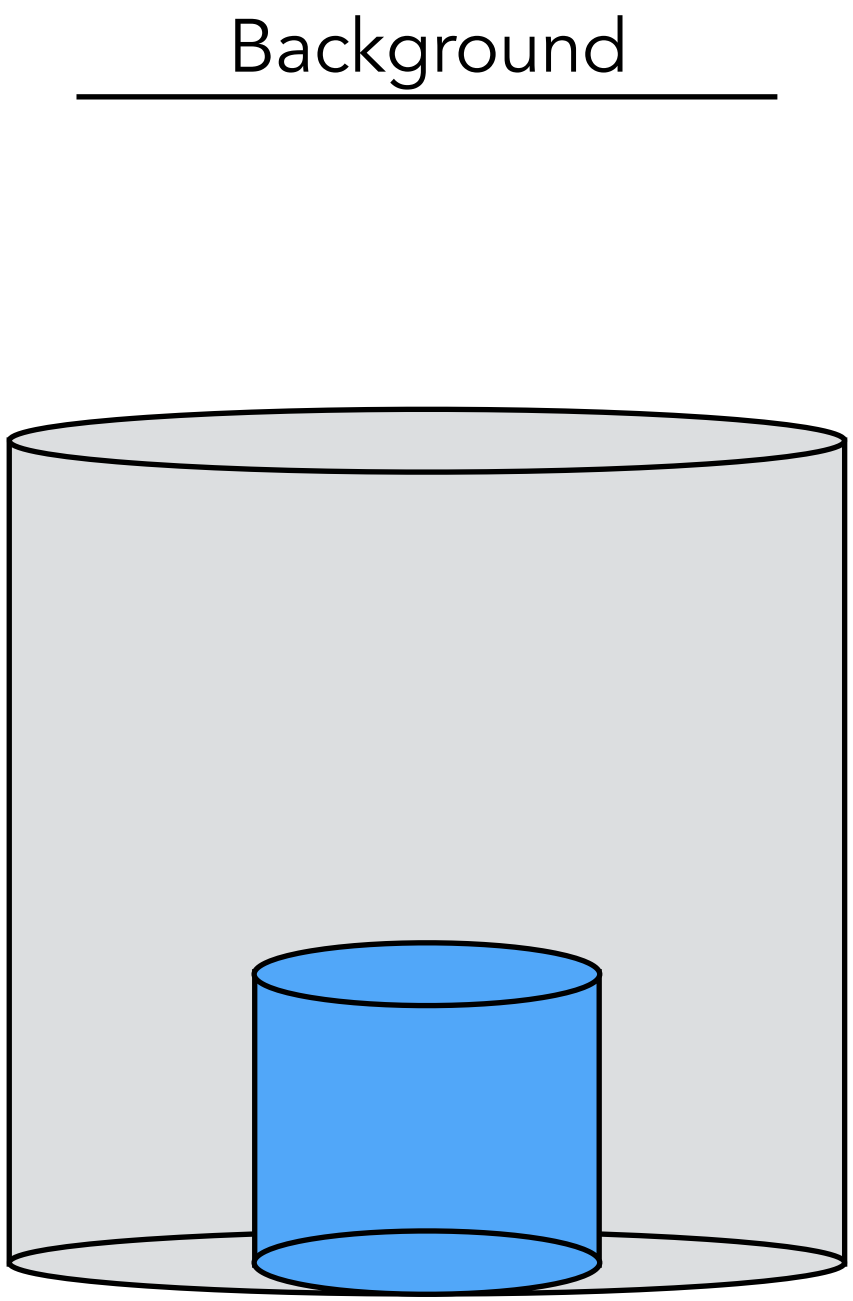
From OPERA $|U_{\tau 3}|^2 > 0$

*arXiv:1507:01417

Experimental Approach

- IceCube-DeepCore will collect the largest sample of oscillated ν_τ **ever**





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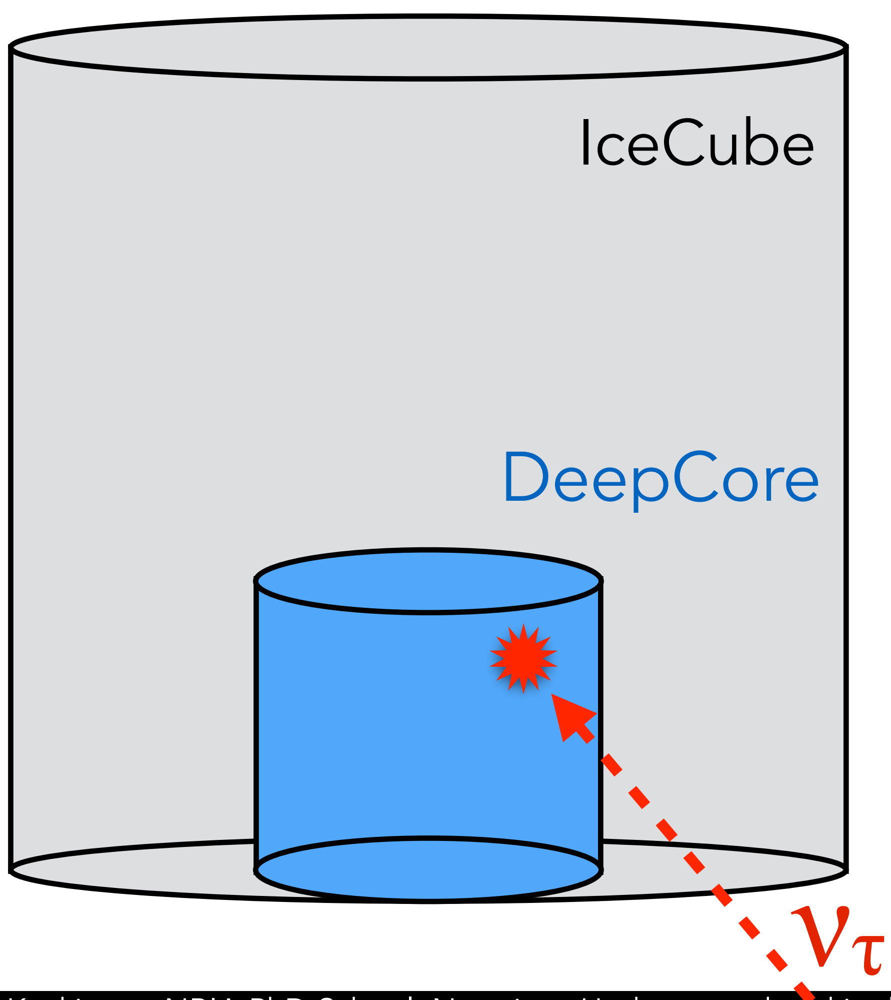
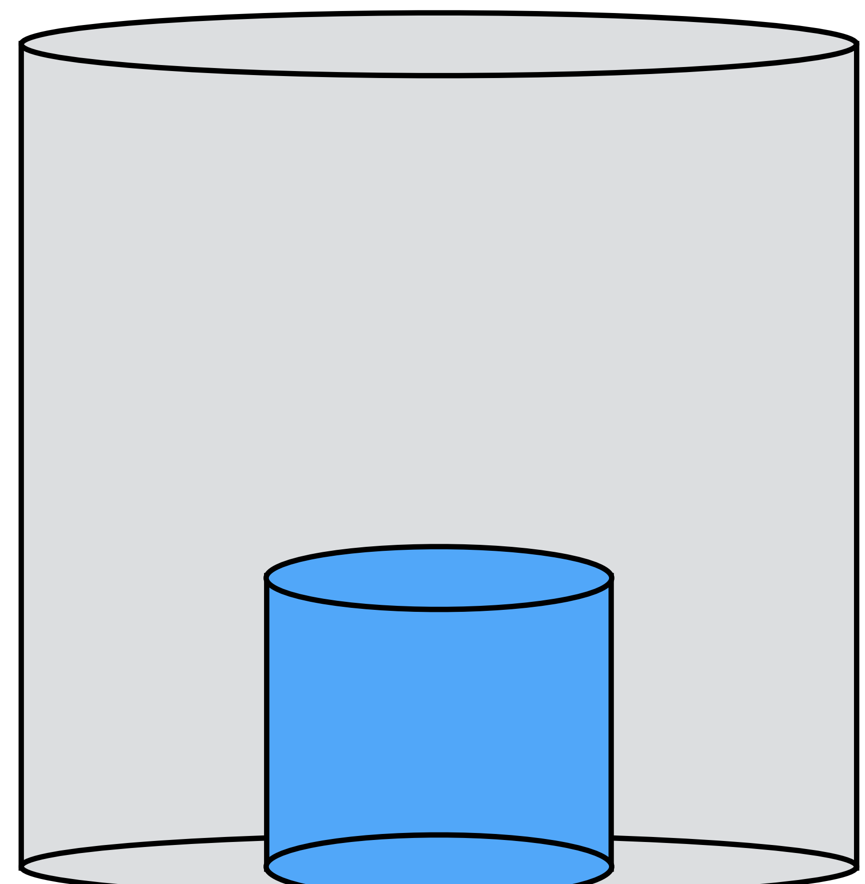
Signal

- ν-cascade at $\mathcal{O}(25)$ GeV



Background



Experimental Approach

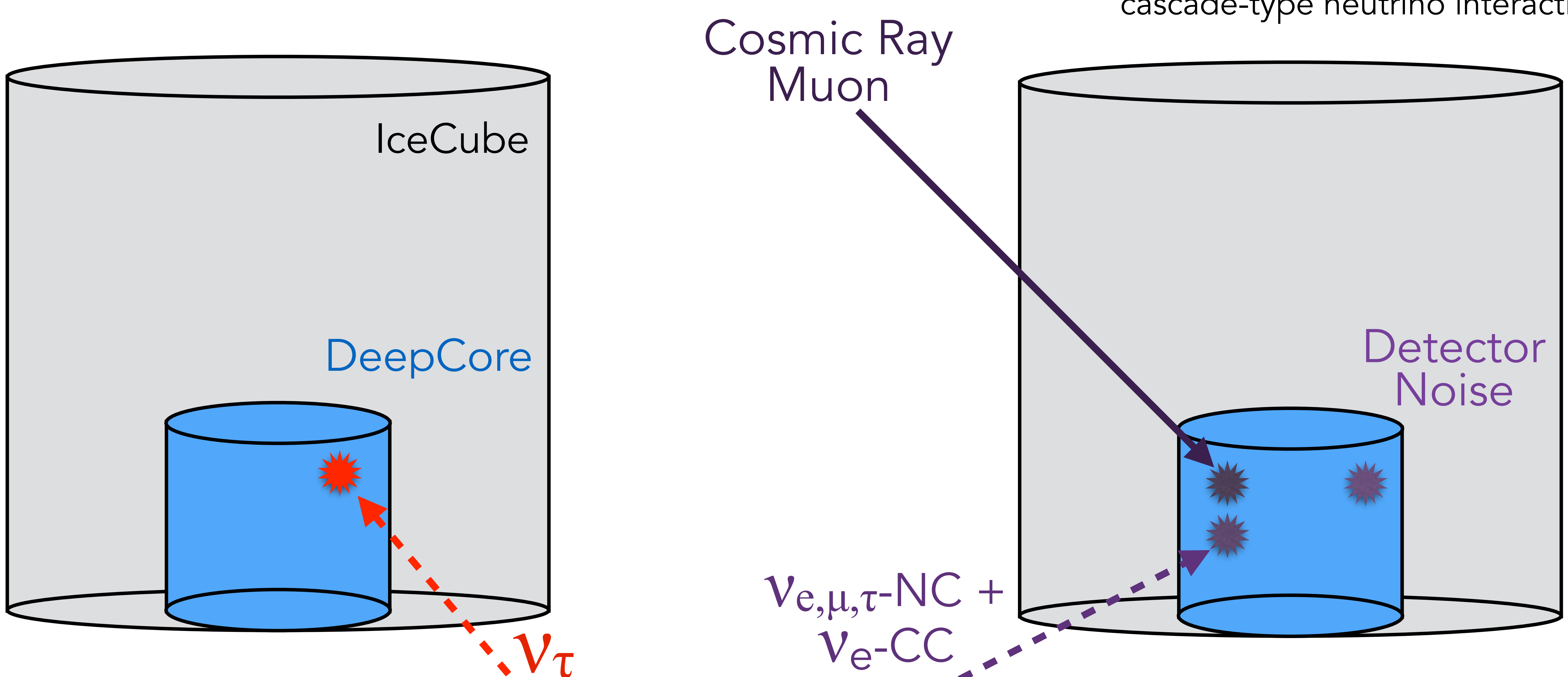
- IceCube-DeepCore will collect the largest sample of oscillated ν_τ **ever**

Signal

- ν-cascade at $\mathcal{O}(25)$ GeV

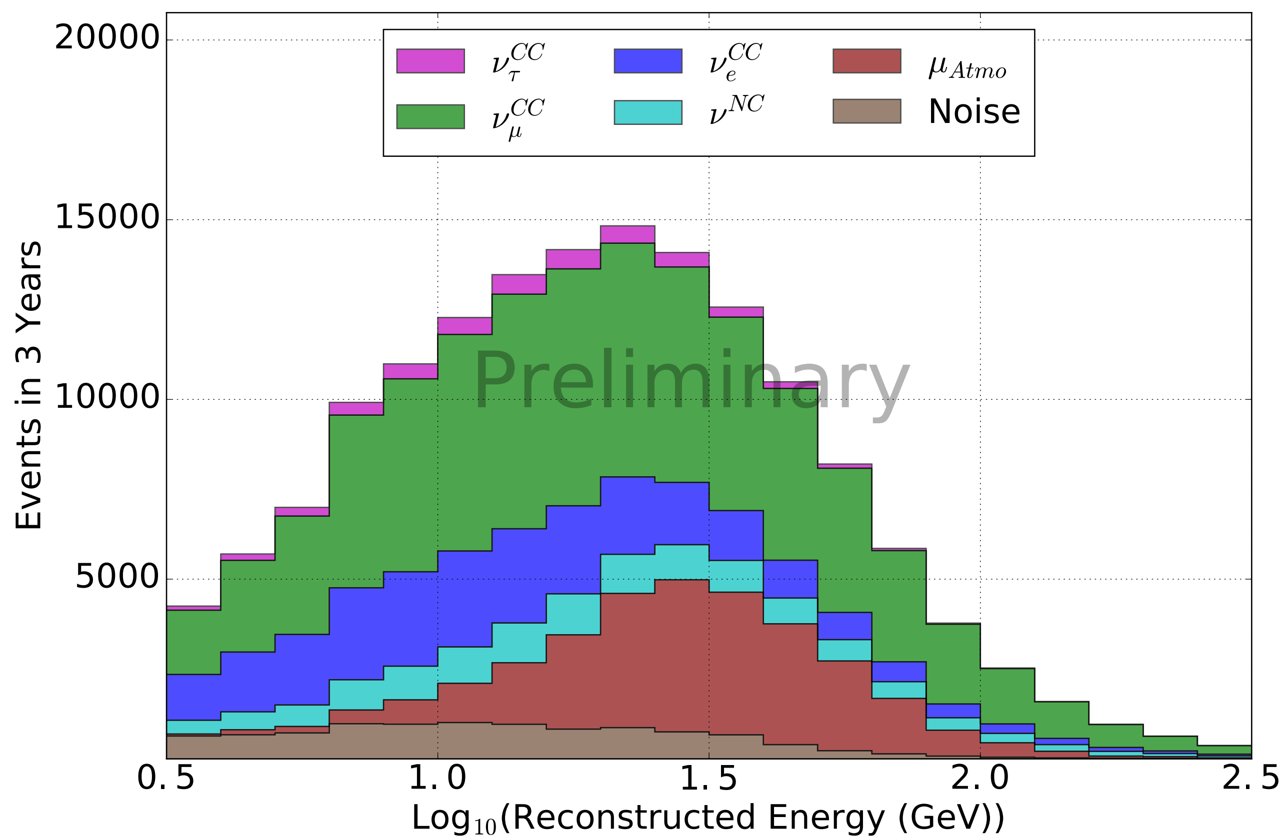
Background

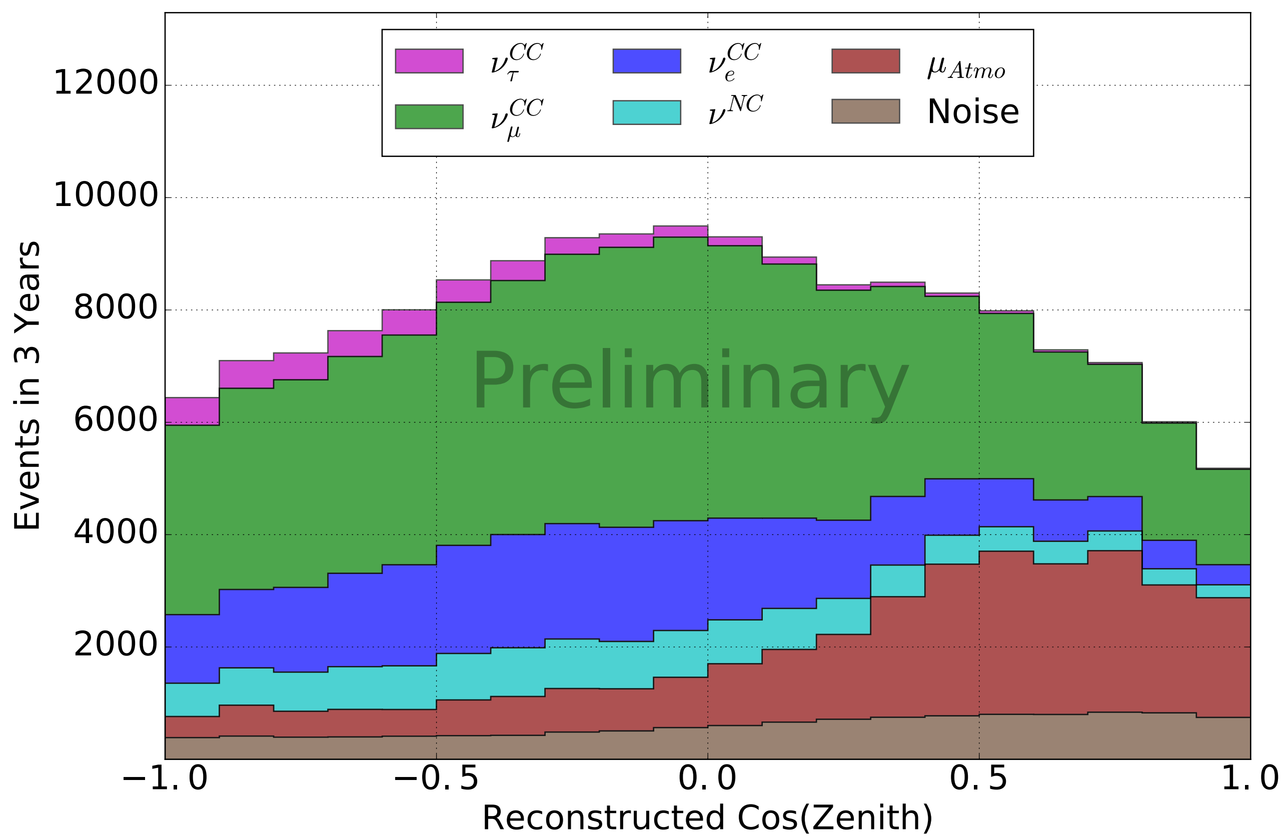
- Pure-noise events
- 'Ghost' cosmic ray muons
- Irreducible background from cascade-type neutrino interactions



Event Rate for ν_τ Appearance

- Expected rate is low compared to background
  - Kinematic suppression to the ν_τ cross-section versus $\nu_{e,\mu}$
  - τ-lepton decays quickly w/ final state neutrino resulting in missing energy

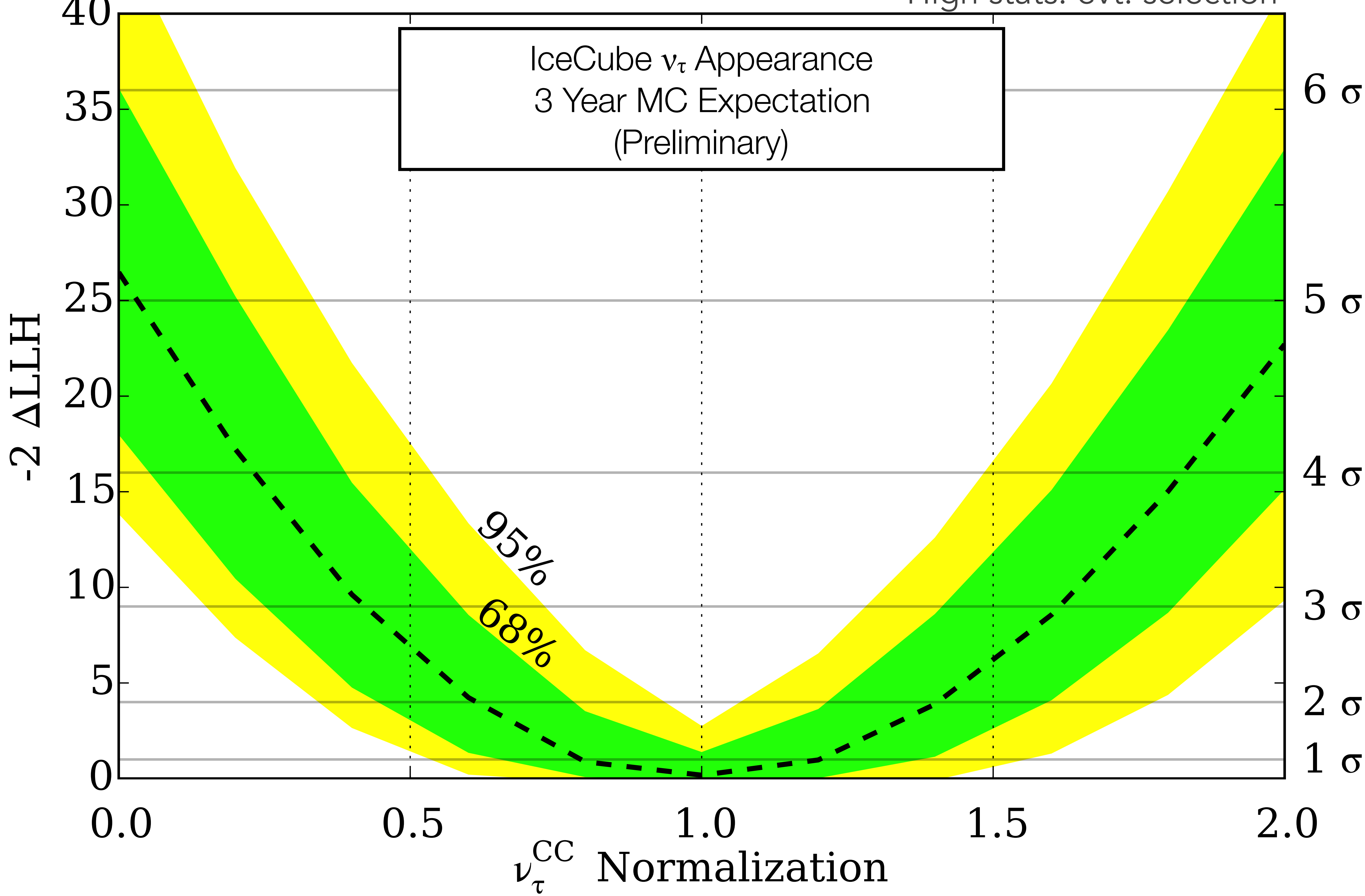




*M. Larson, Neutrino 2016 (poster)

IceCube/DeepCore ν_τ Appearance

High stats. evt. selection



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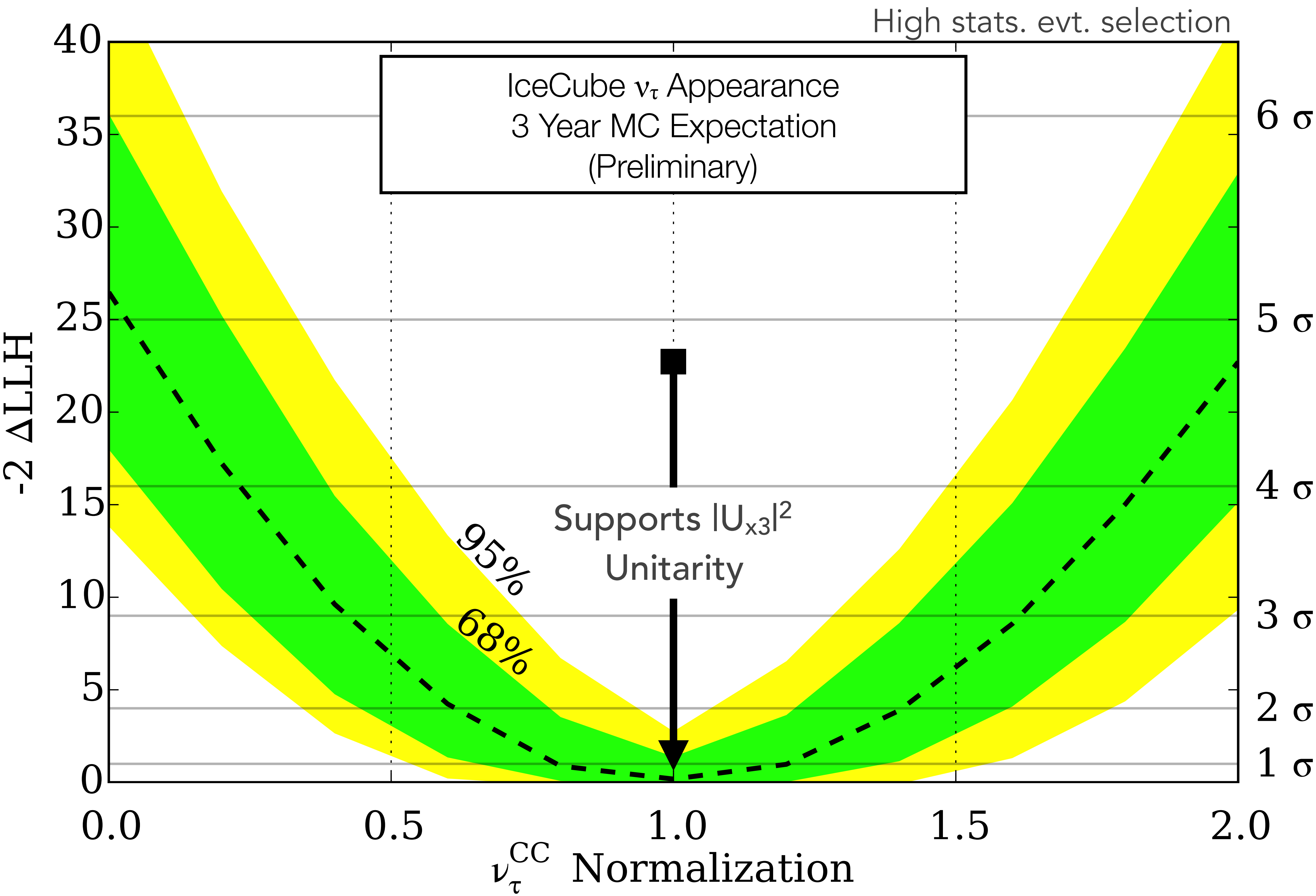

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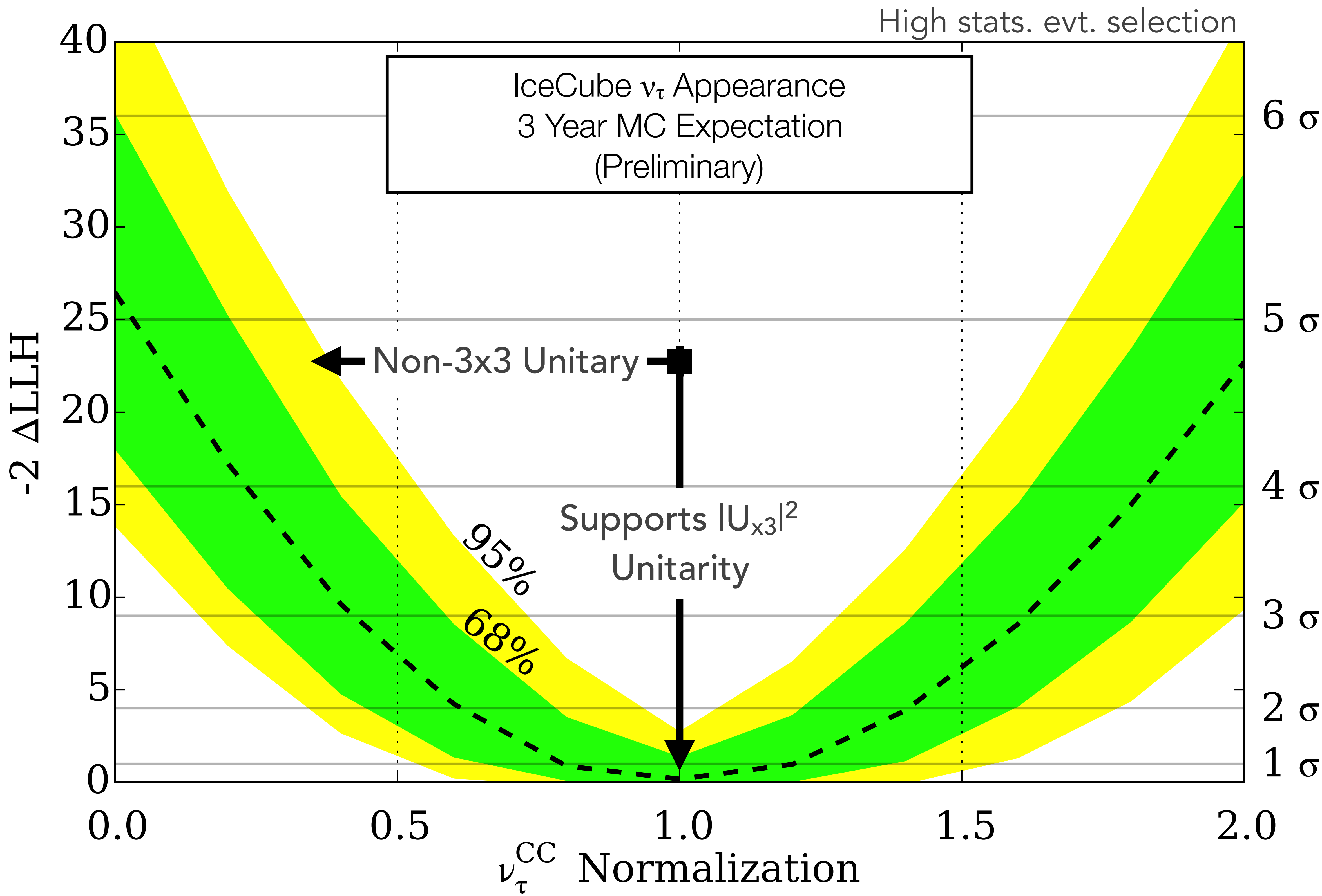

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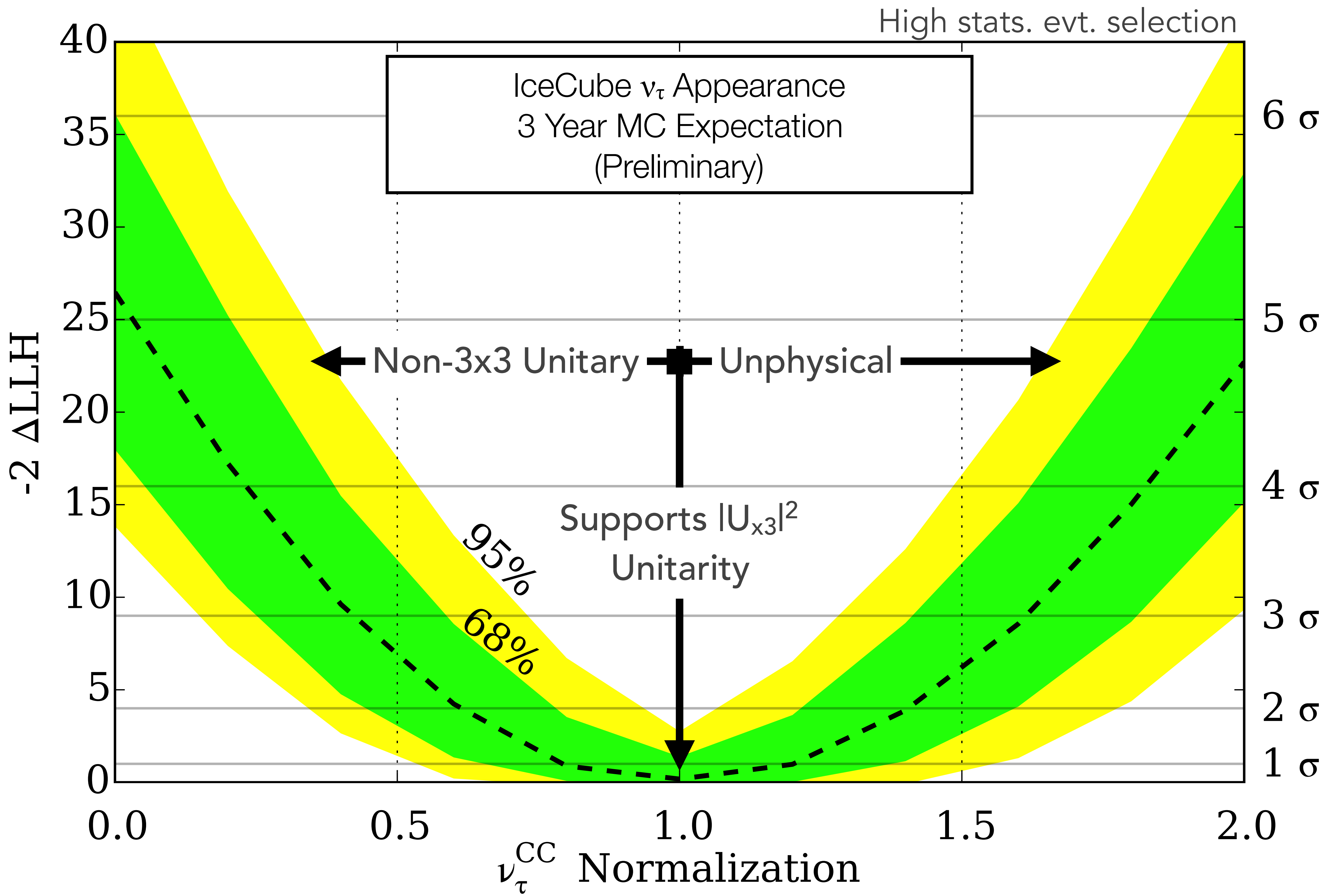

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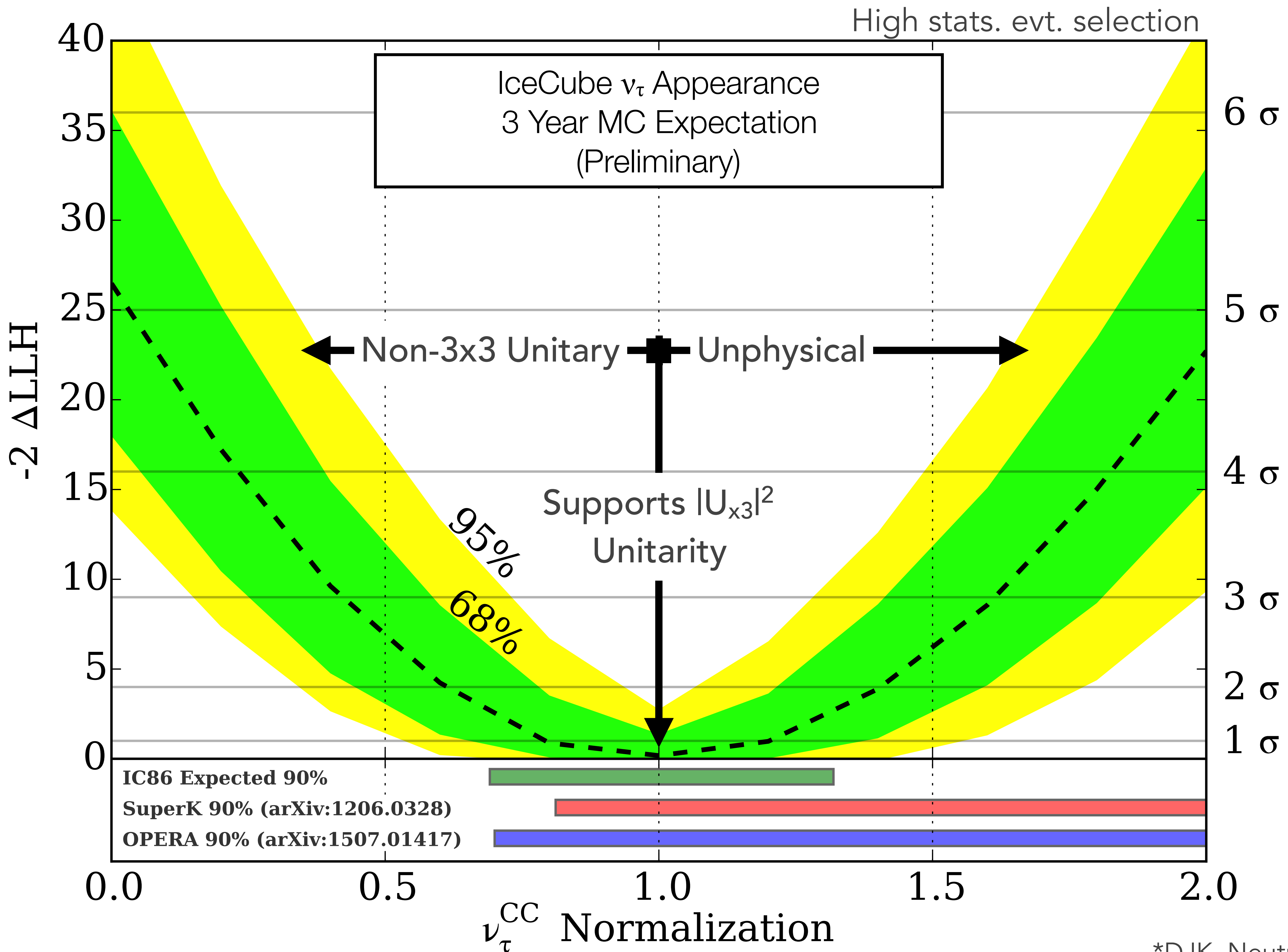

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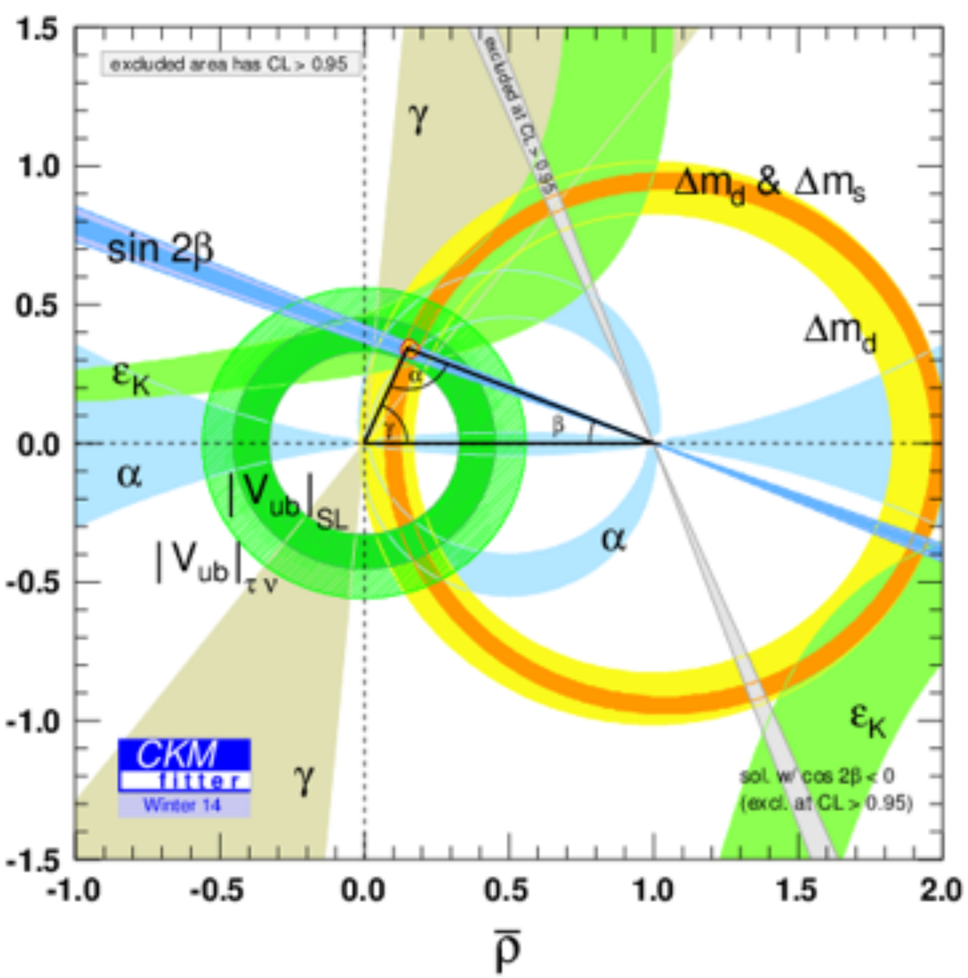
Fundamental Mixing Today

Quarks (CKM)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Confirms Unitarity

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Currently Assumes Unitarity

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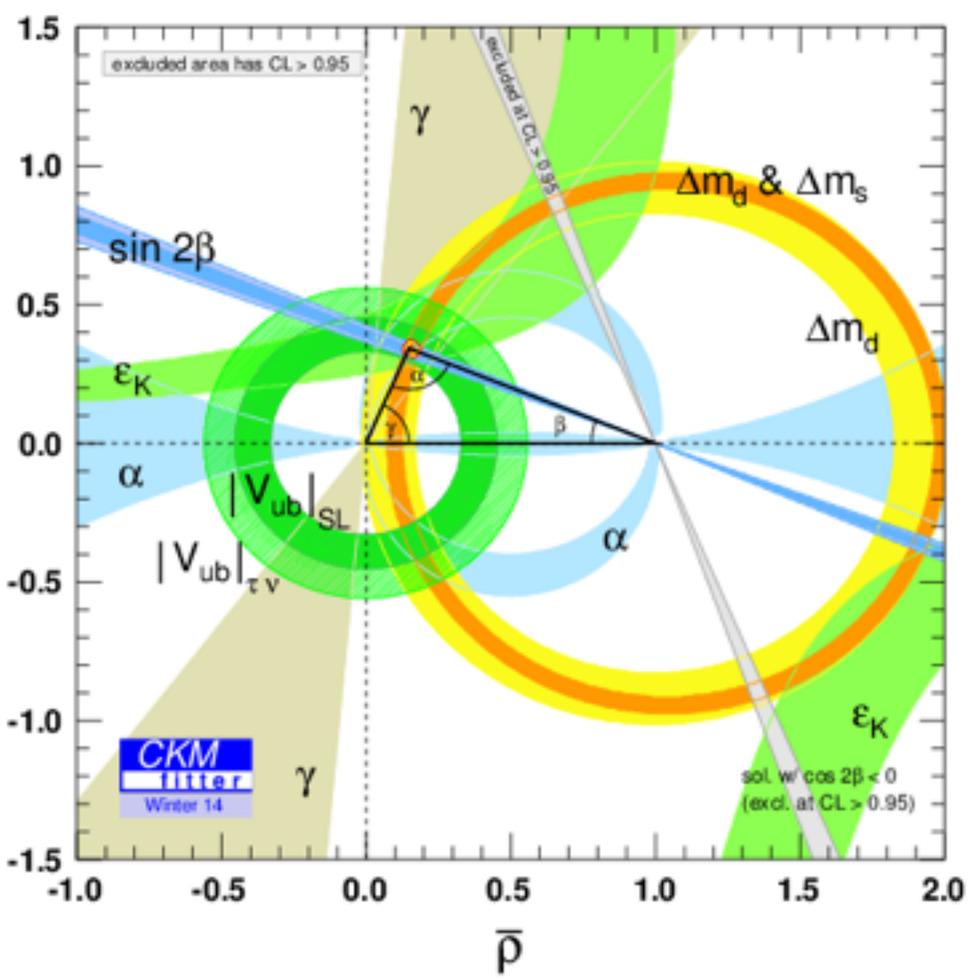

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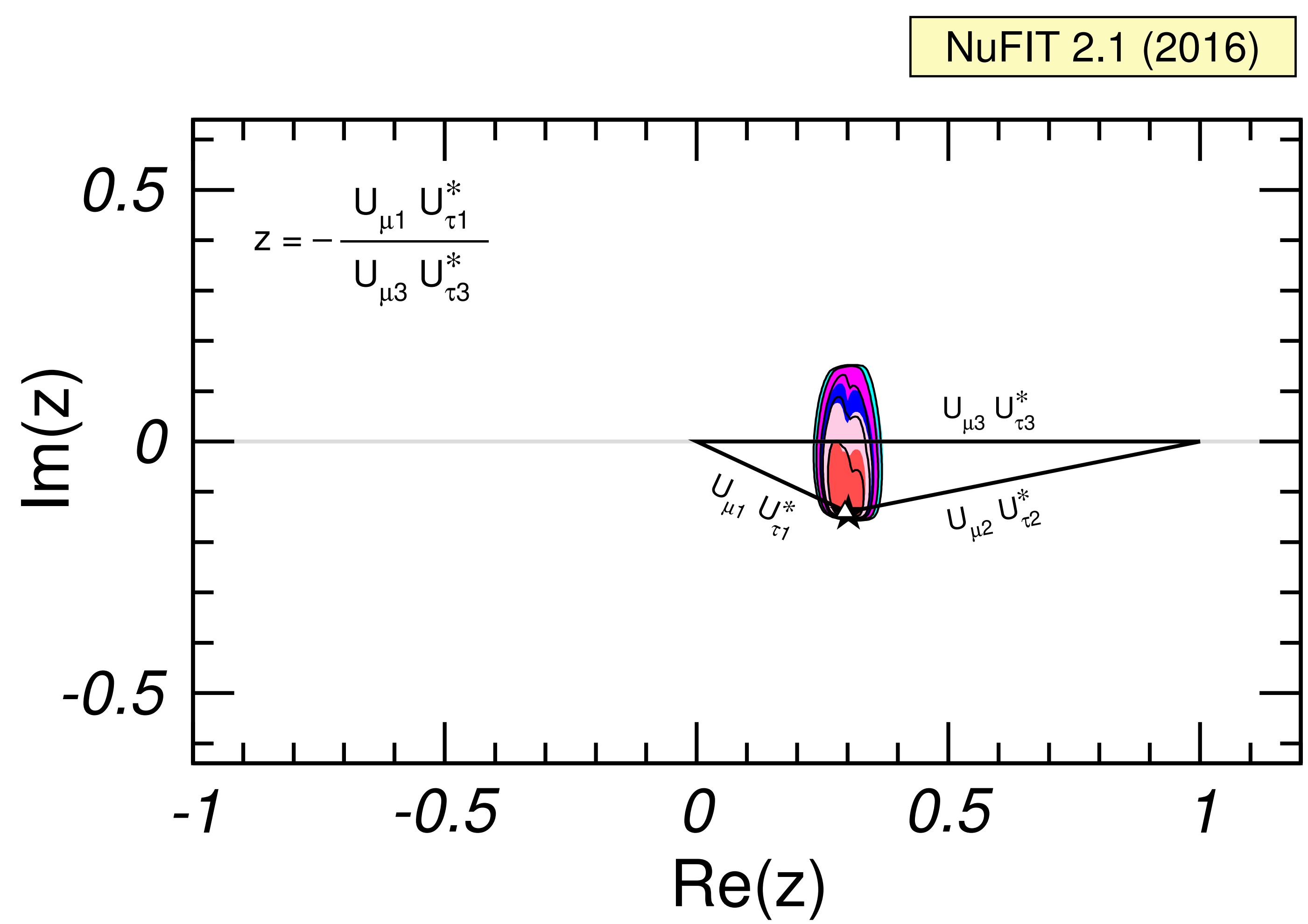
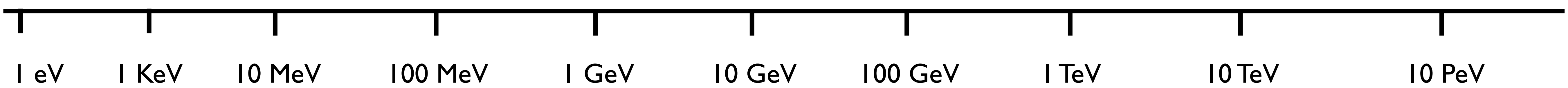


Currently Assumes Unitarity

`Current' Experimental Landscape

Accelerator Based



Non-Accelerator Based

*Boxes provide sense of scale for physics sensitive regions

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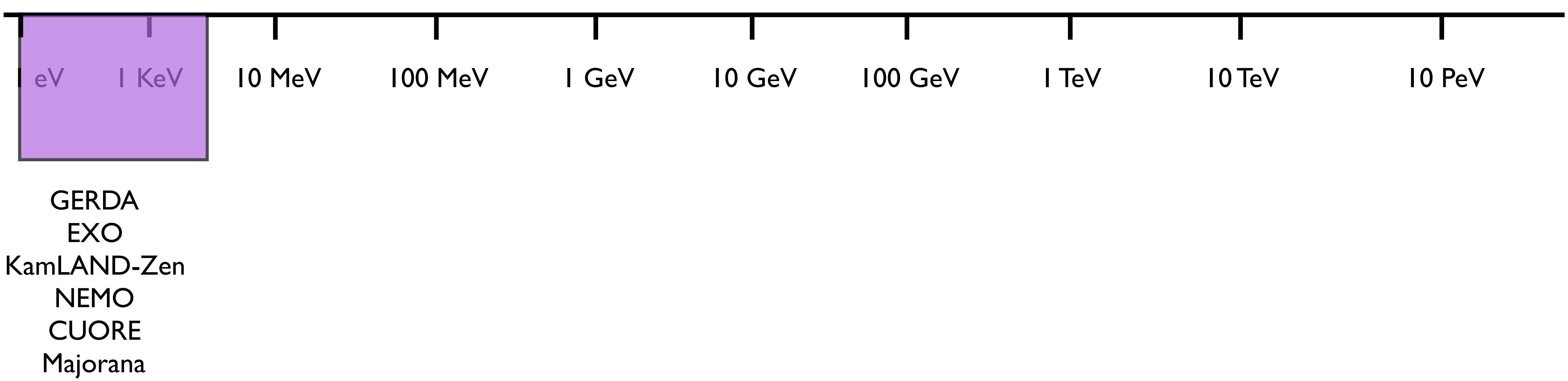

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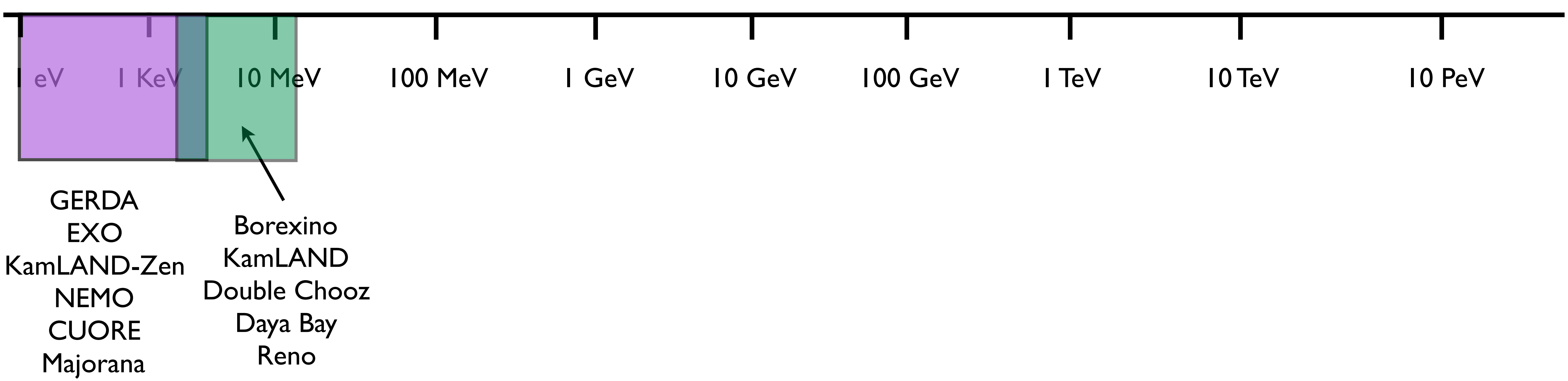

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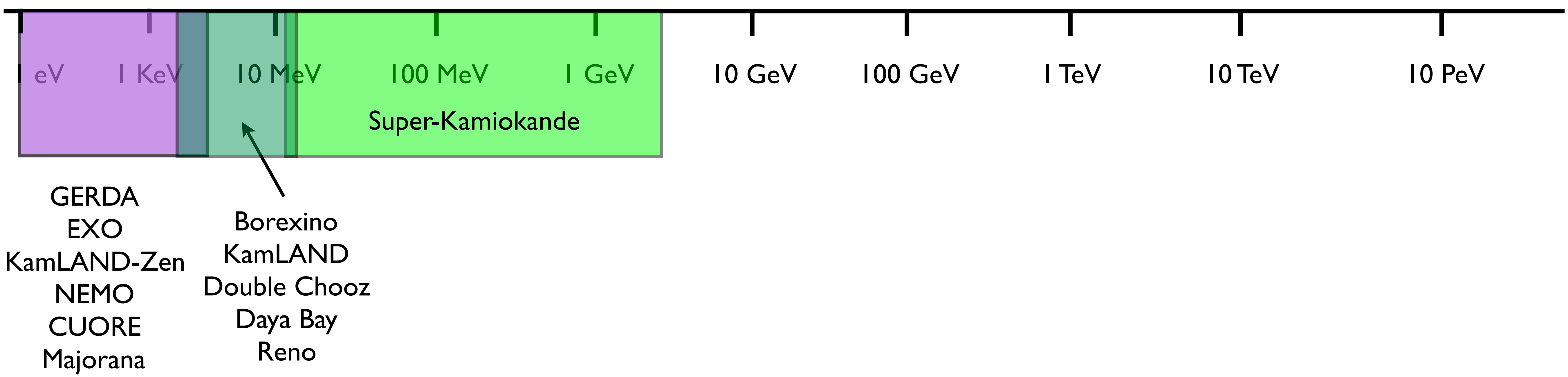

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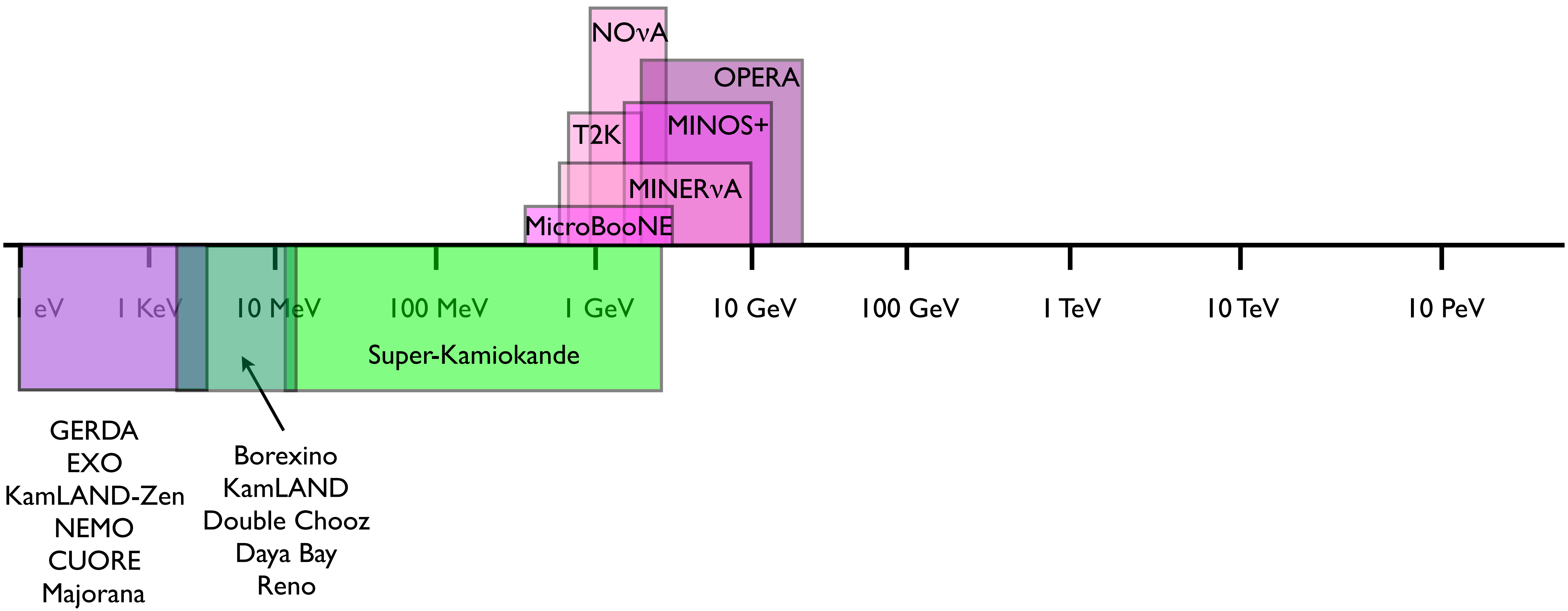

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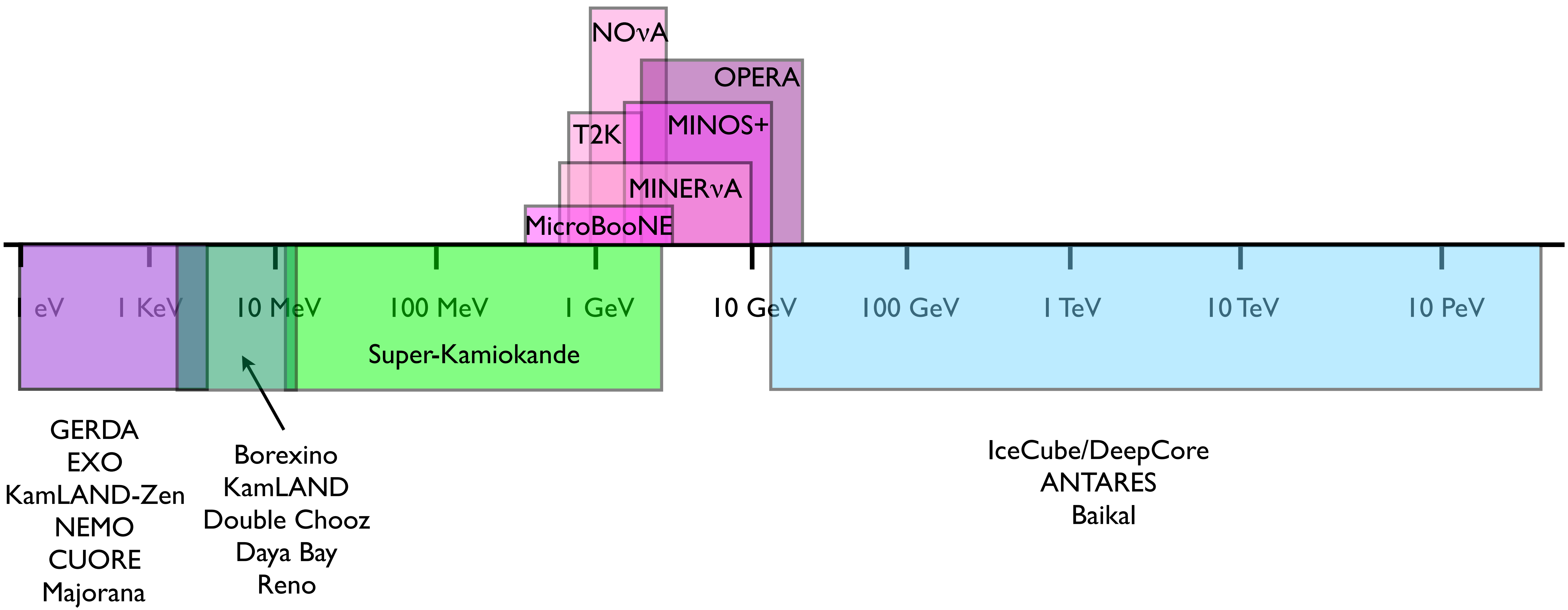

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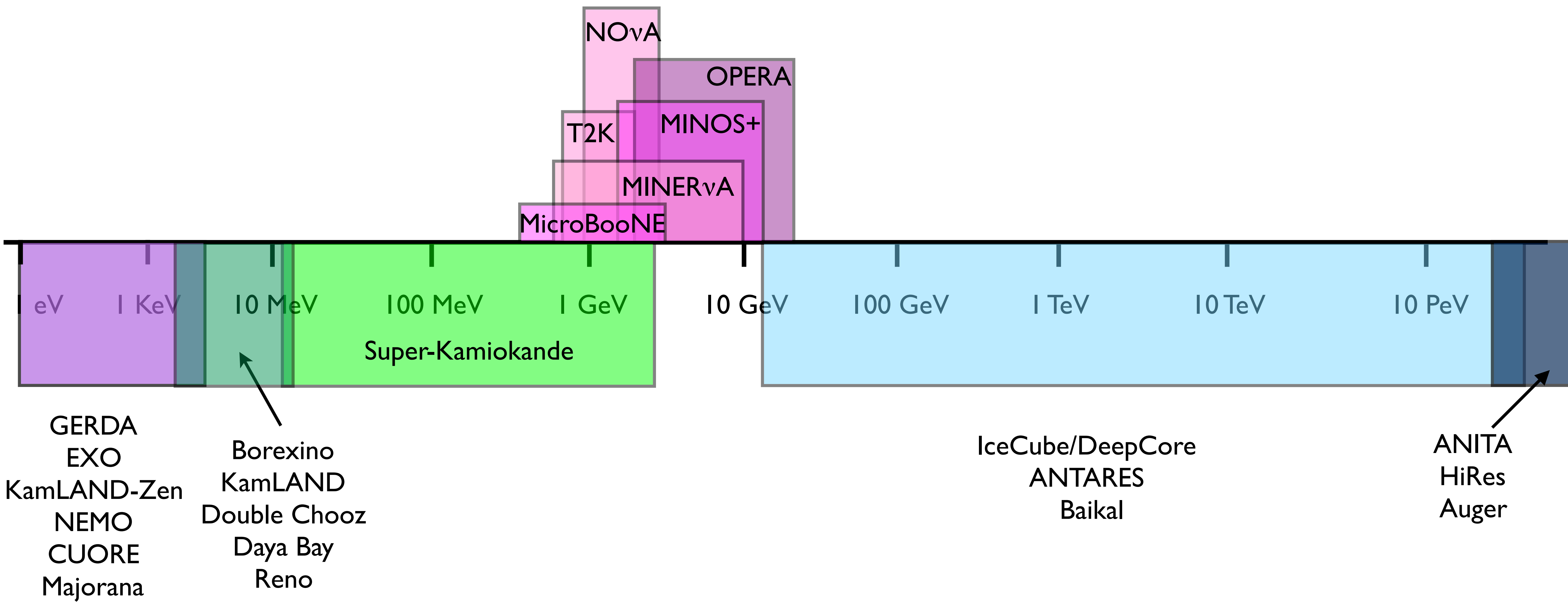

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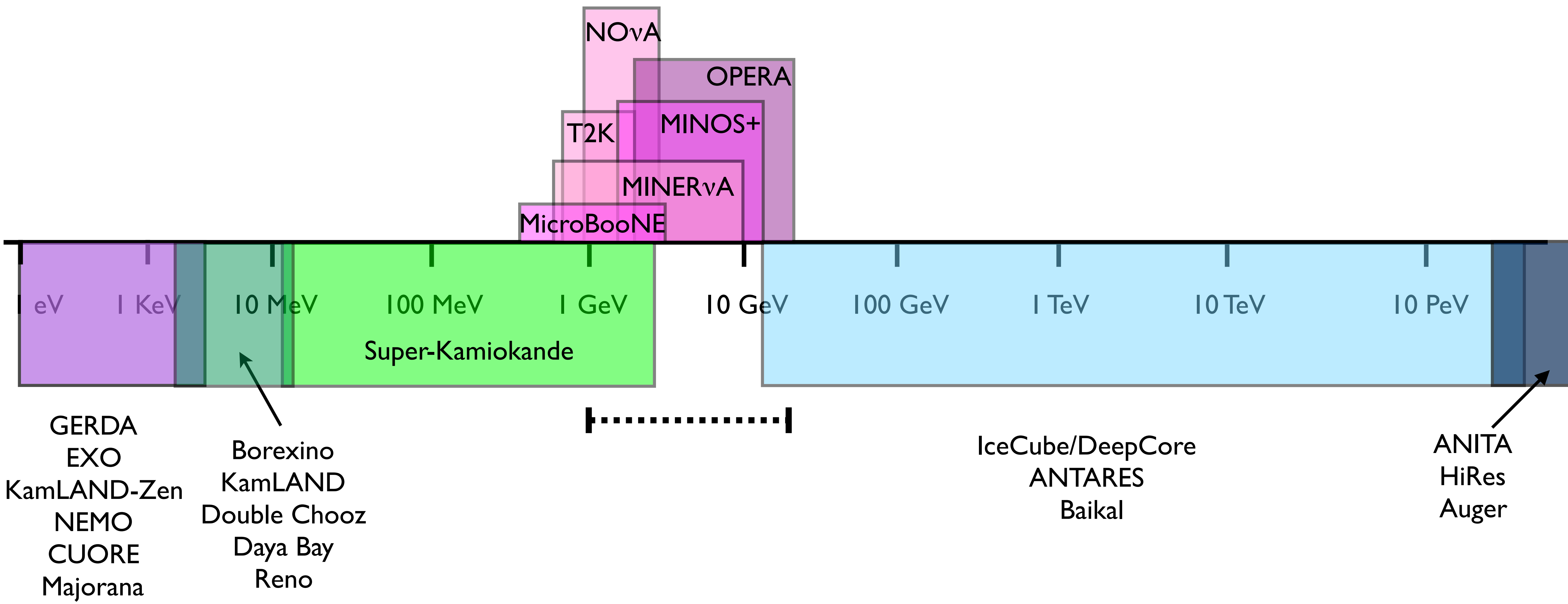

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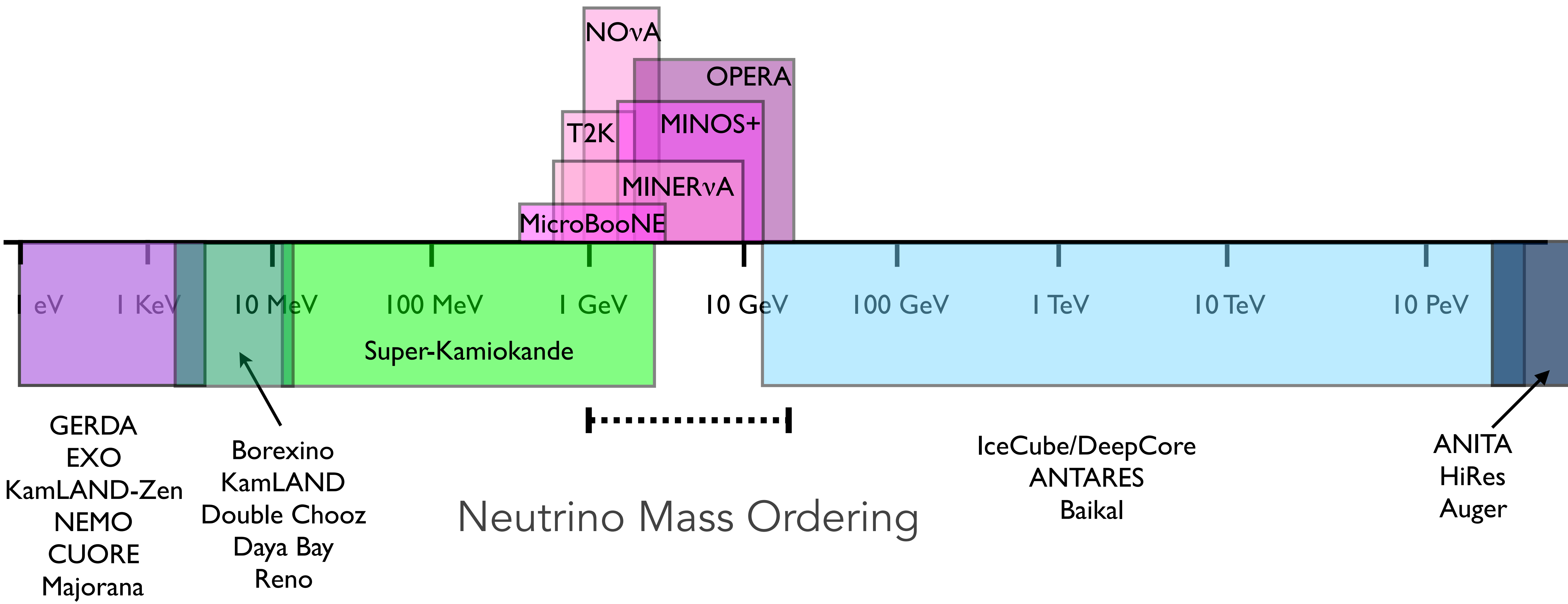

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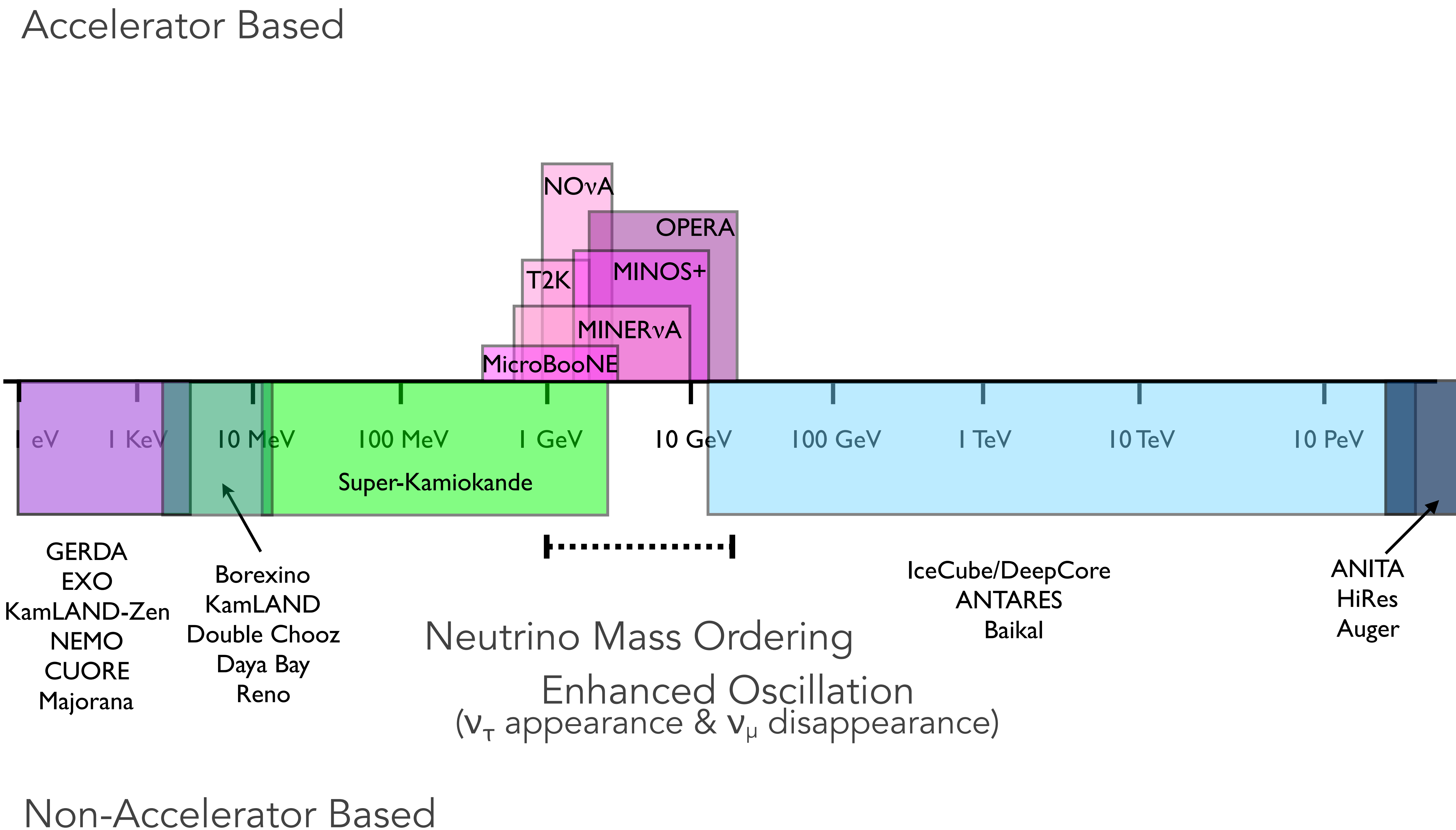
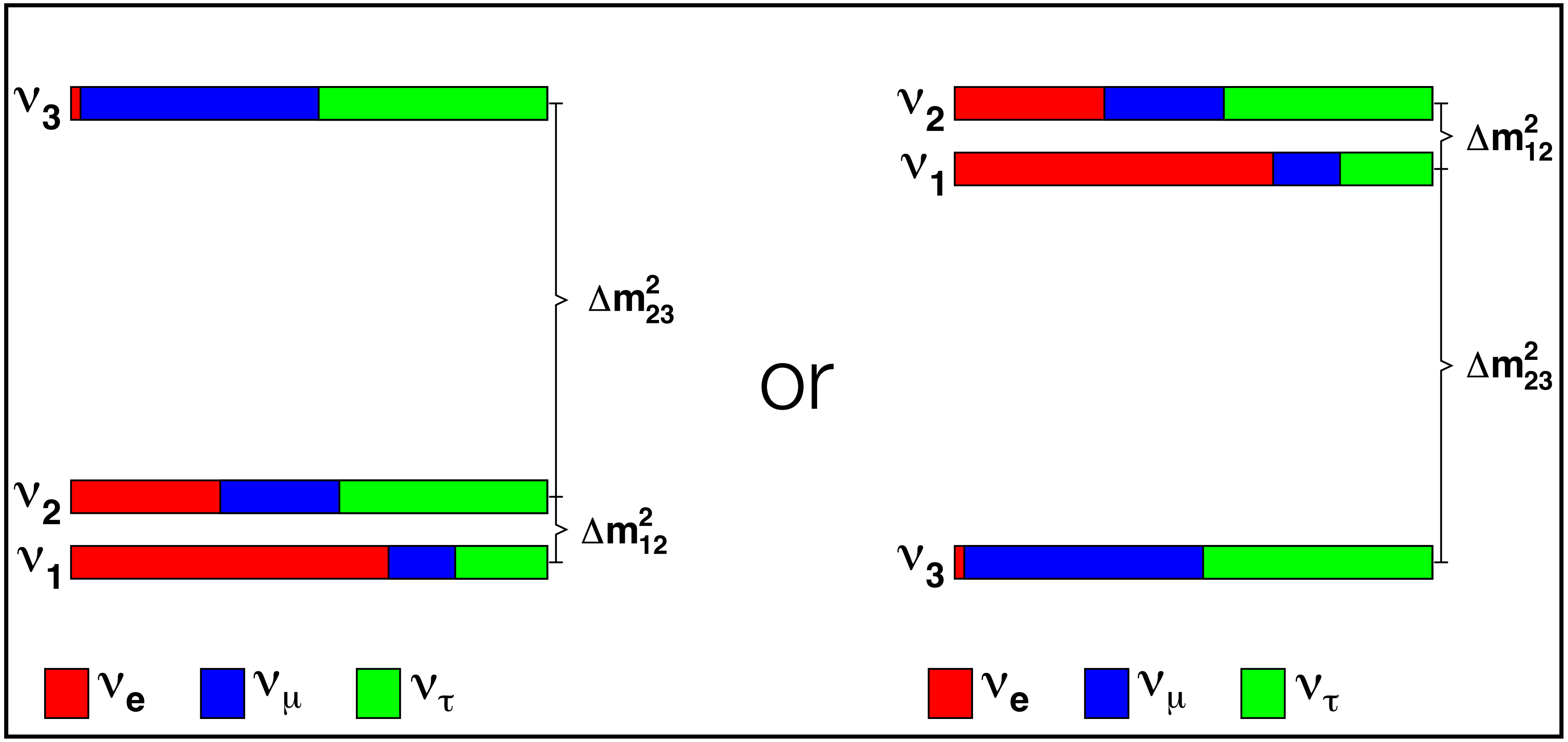


*Boxes provide sense of scale for physics sensitive regions

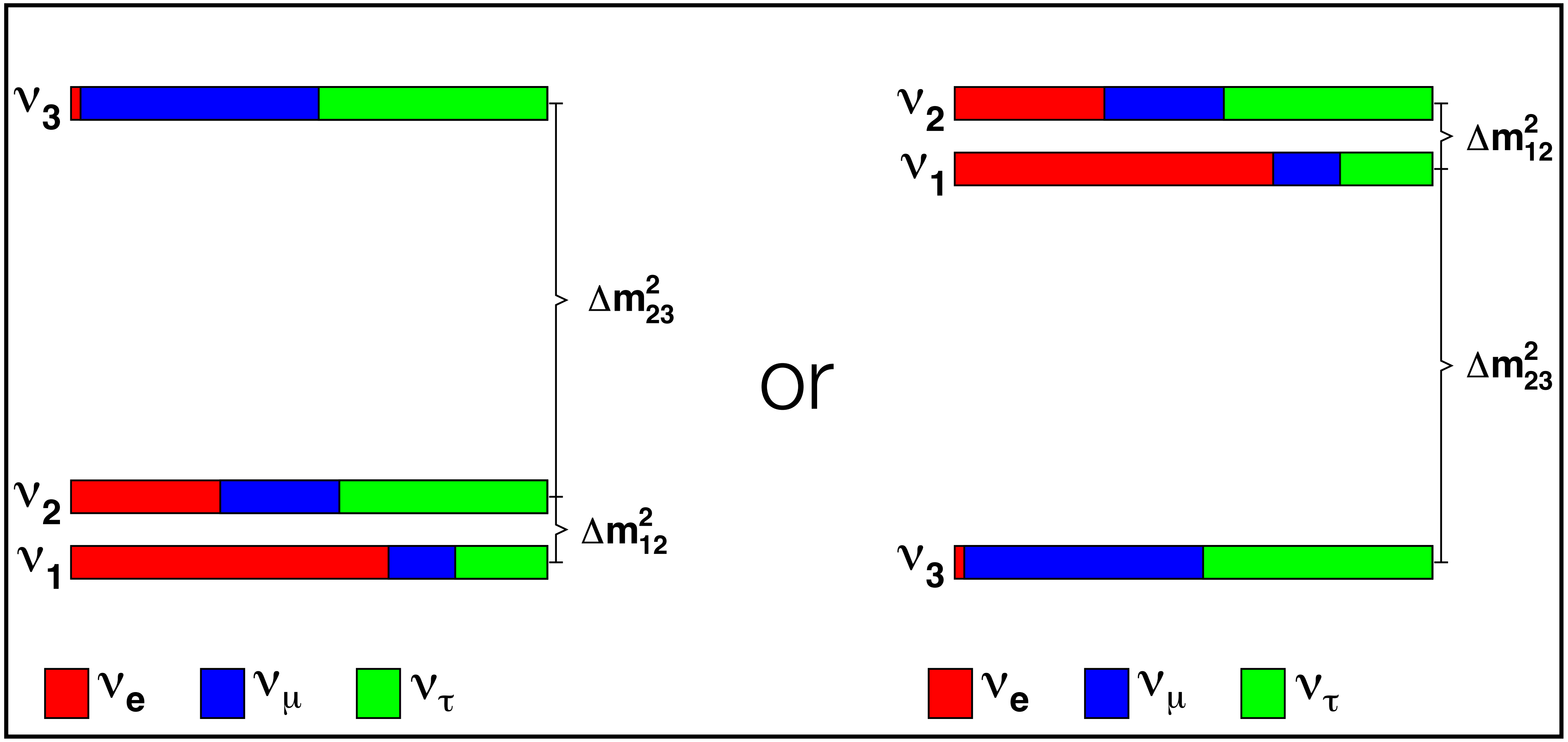
Neutrino Hierarchy/Ordering



n.b. "Neutrino Mass Ordering" and "Neutrino Mass Hierarchy" are used interchangeably

Neutrino Hierarchy/Ordering

- A big detector with sensitivity at $\mathcal{O}(1)$ GeV energy is in the range of measuring the neutrino hierarchy/ordering



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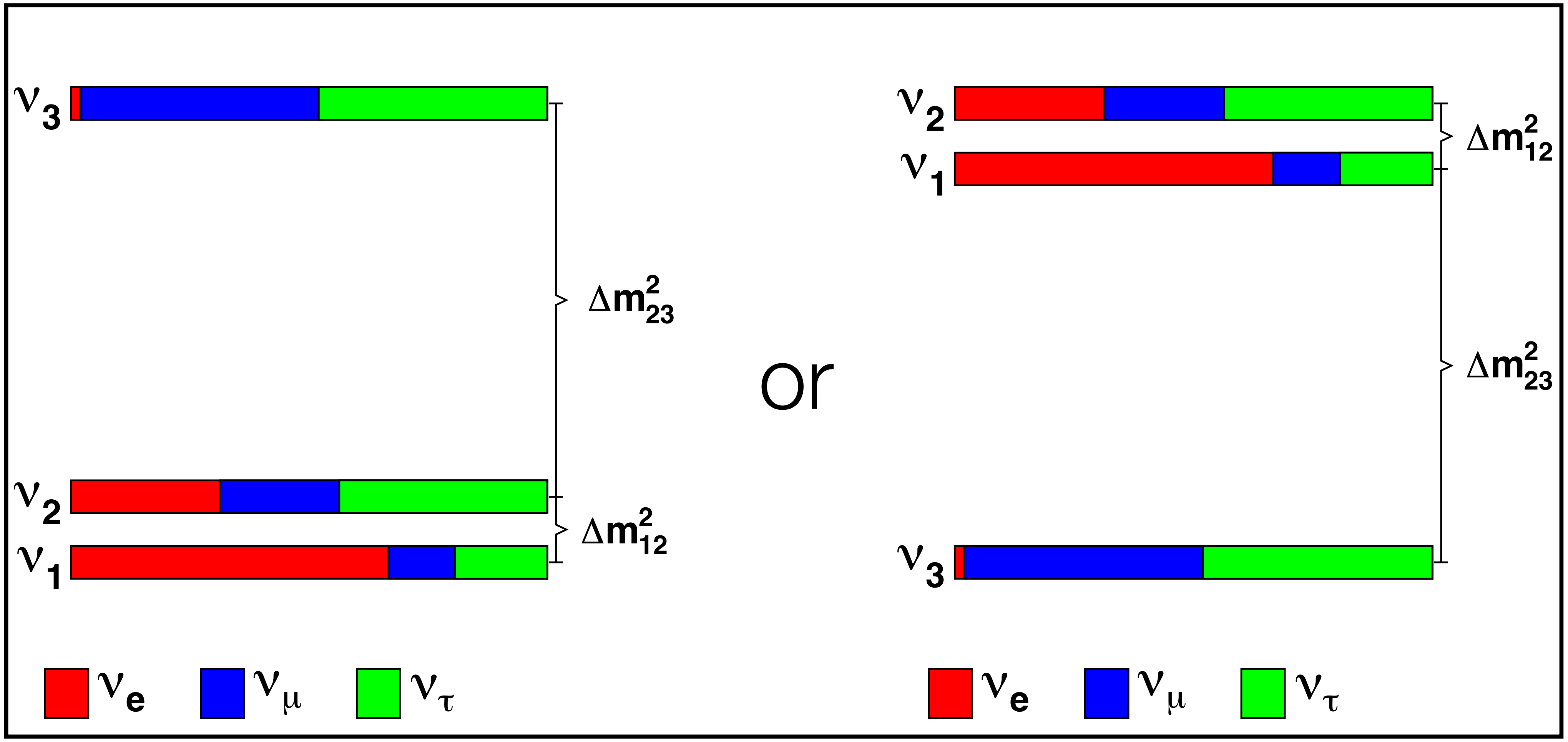

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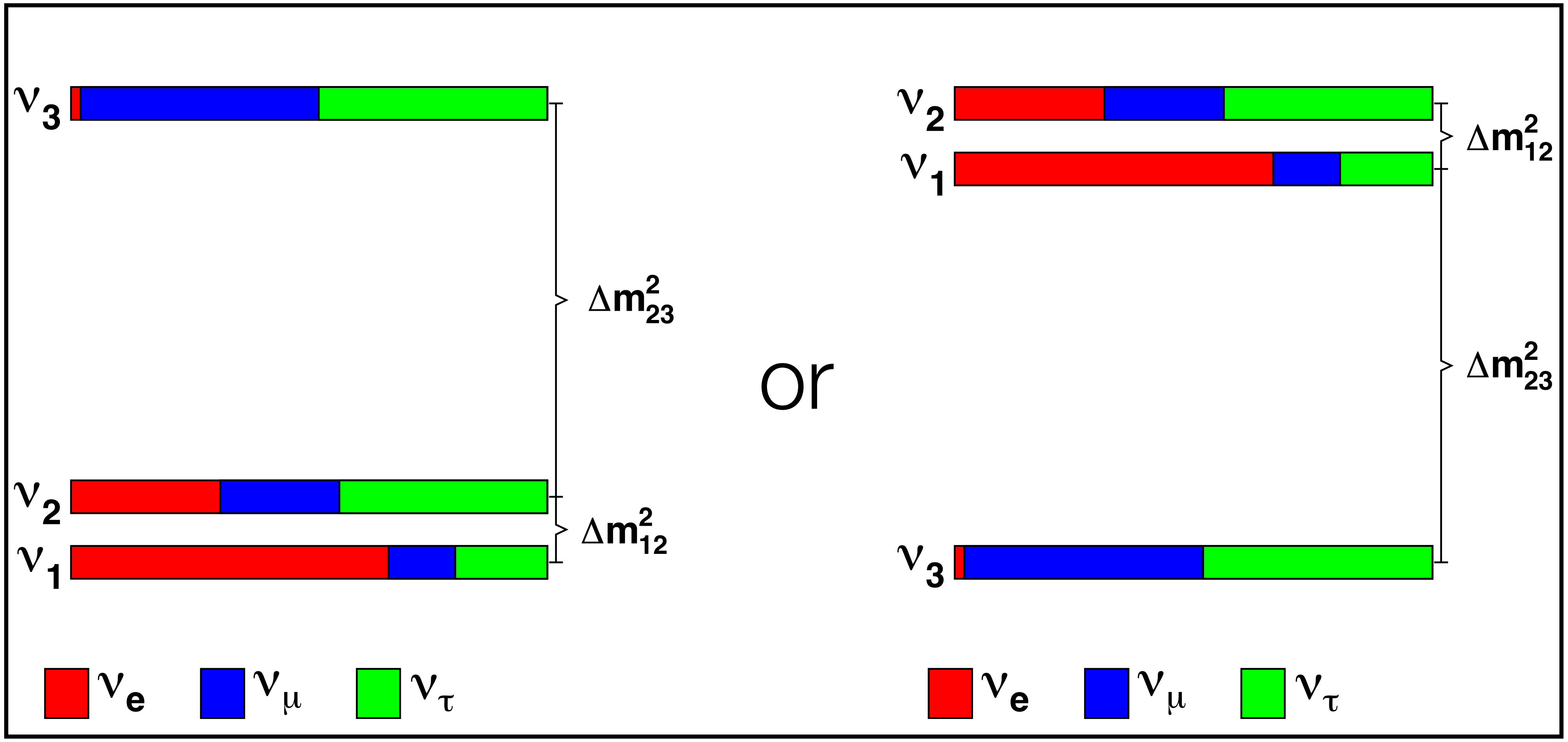
Neutrino Hierarchy/Ordering

- A big detector with sensitivity at $\mathcal{O}(1)$ GeV energy is in the range of measuring the neutrino hierarchy/ordering
- Ok, fine. But, why would anyone?
  - Besides, of course, fundamental physics is fundamental



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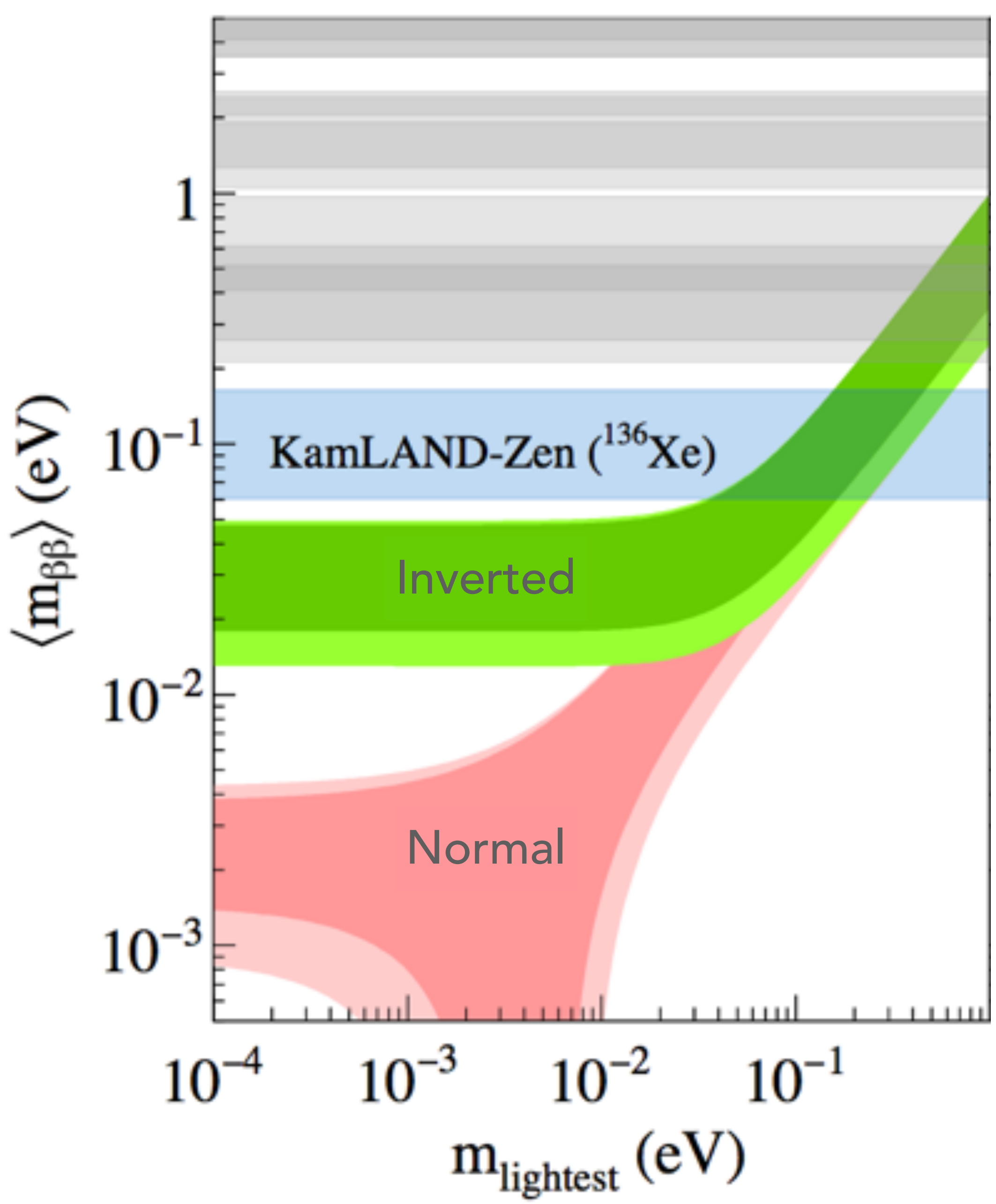
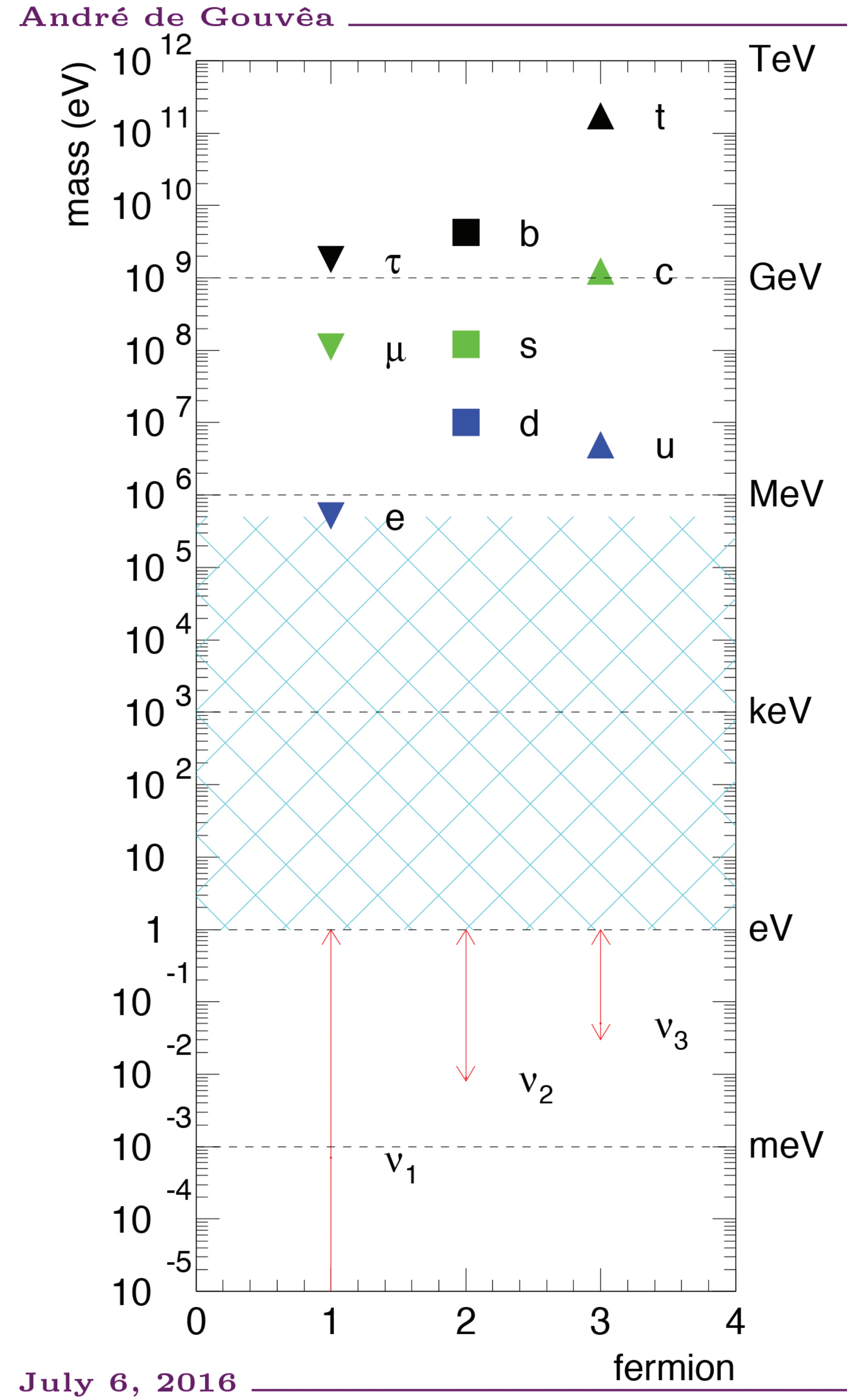
Neutrino Mass

*J. Shirai, Neutrino 2016





- Why is the neutrino mass ordering (hierarchy) relevant?

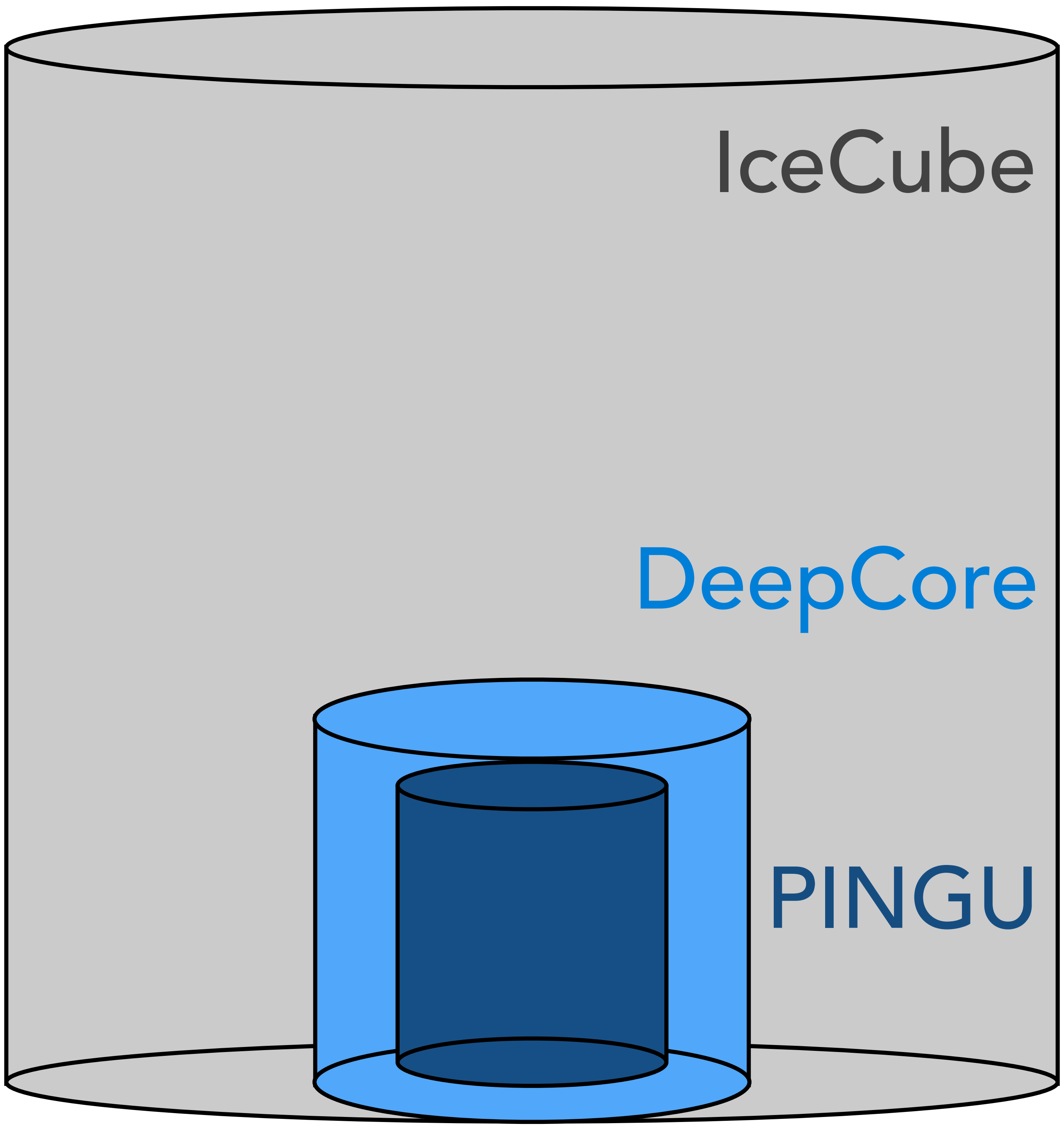
Precision

IceCube

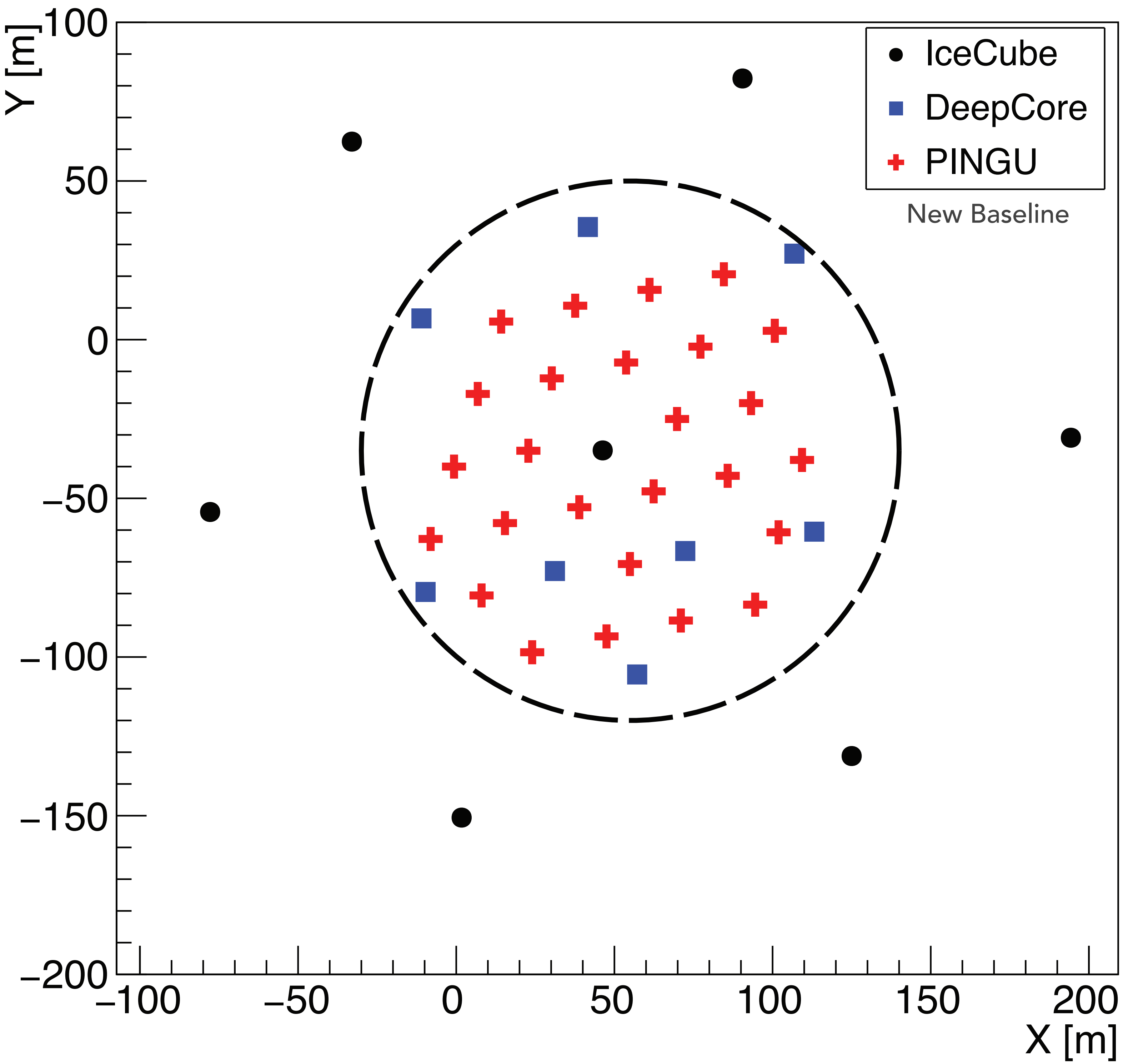
Next

Generation

Upgrade



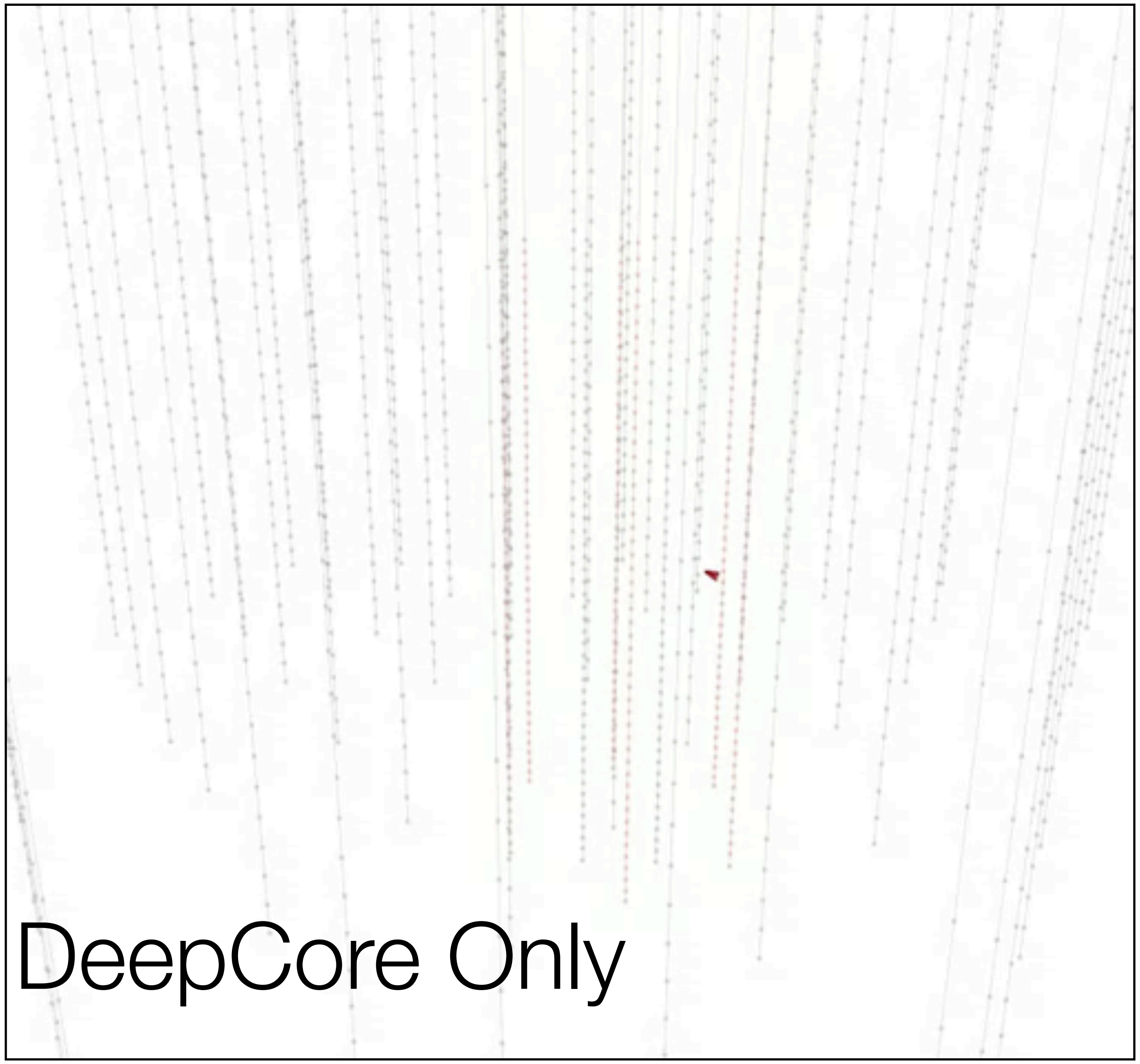
Geometry Optimization



Current

26 strings
192 DOMs/string
1.5 m DOM-DOM spacing

PINGU Simulated Event (Old)



- 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade
- Older PINGU geometry w/ ~1/3 the number of DOMs/string, but illustrative of the potential

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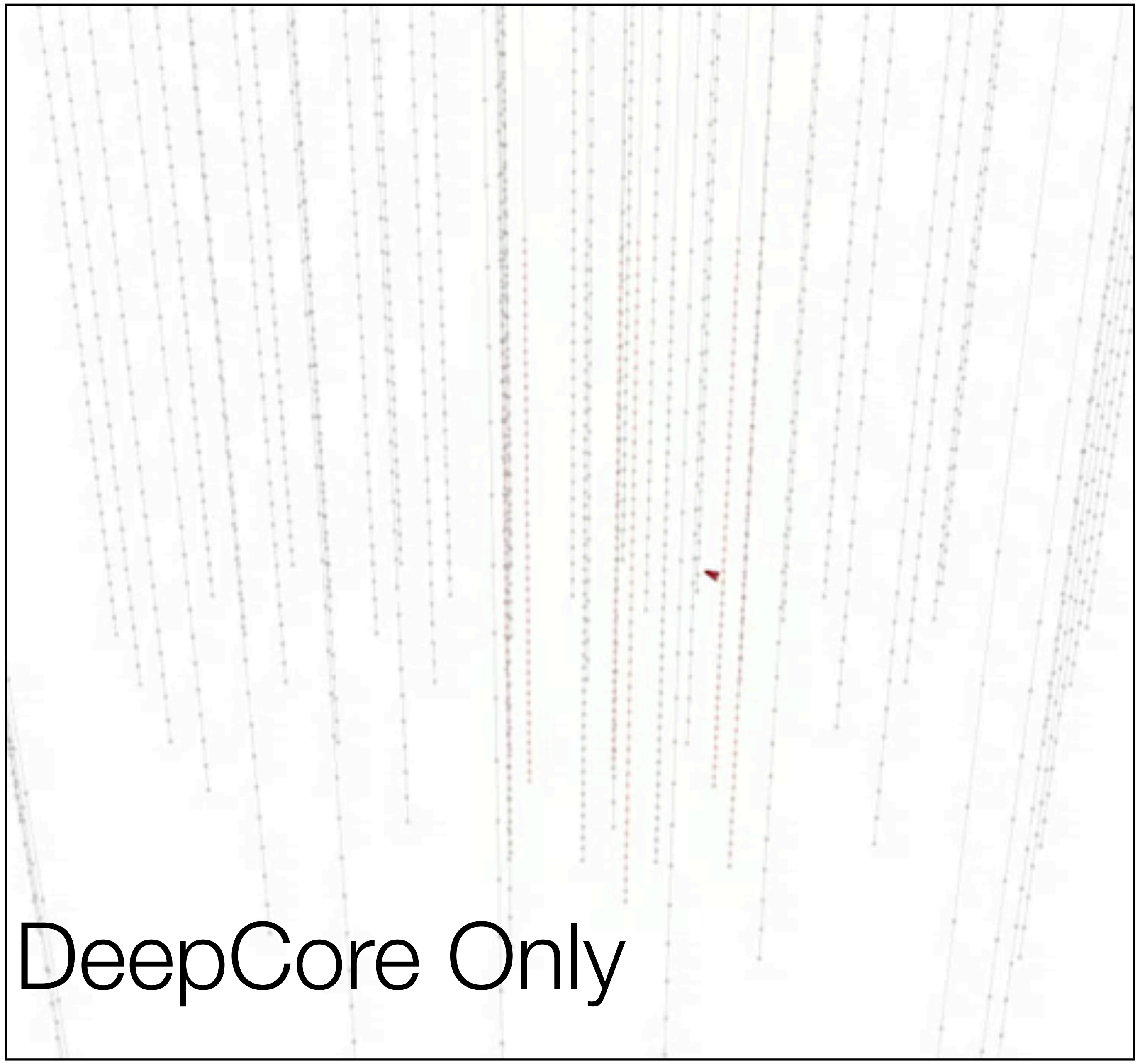

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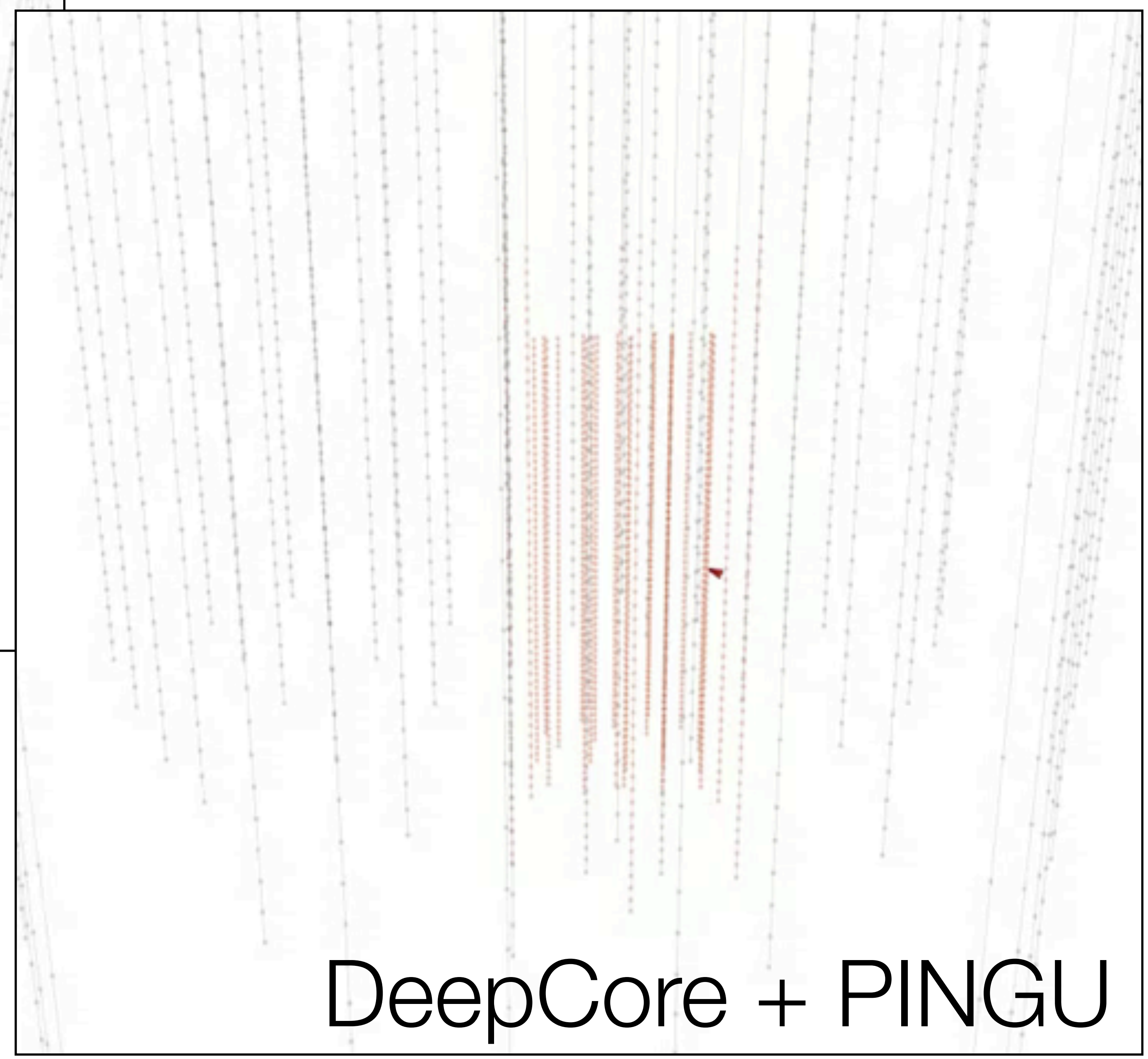
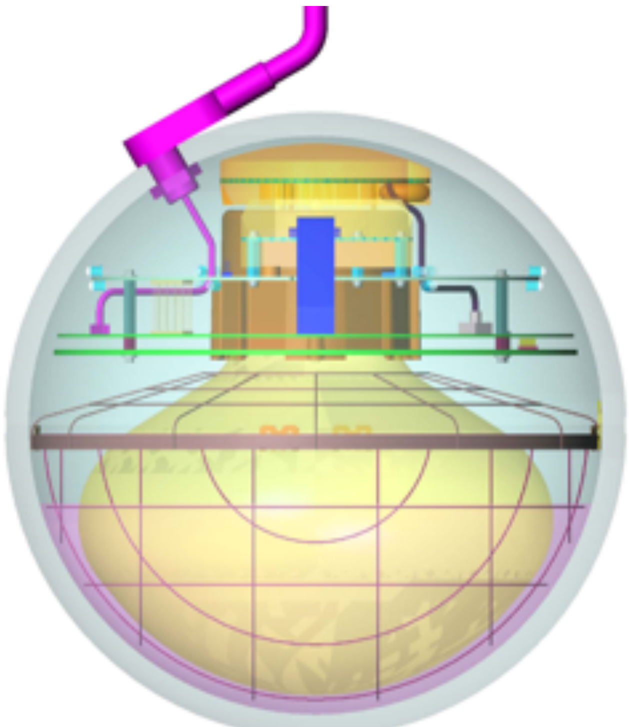


- 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade
- Older PINGU geometry w/ ~1/3 the number of DOMs/string, but illustrative of the potential

PINGU Technology Options

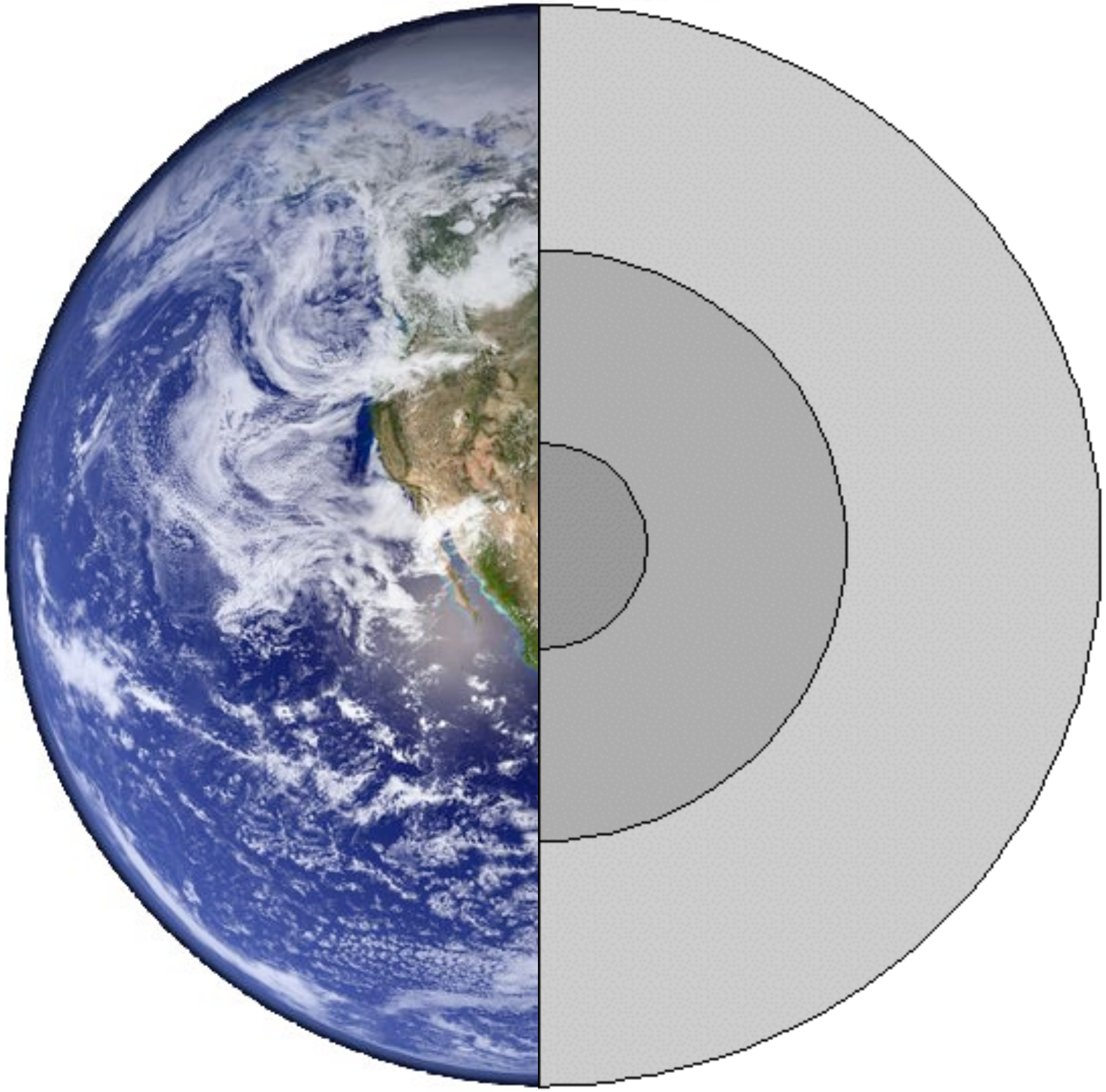
- Conventional 10″ single PMT DOM
- Possibility for using multi-PMT DOM (mDOM)
  - 3″ PMTs providing almost 4π angular coverage
  - Up to factor 2 increase in photon collection vs. 10″ PMT

*L. Classen, ICRC 2015 (proc.)

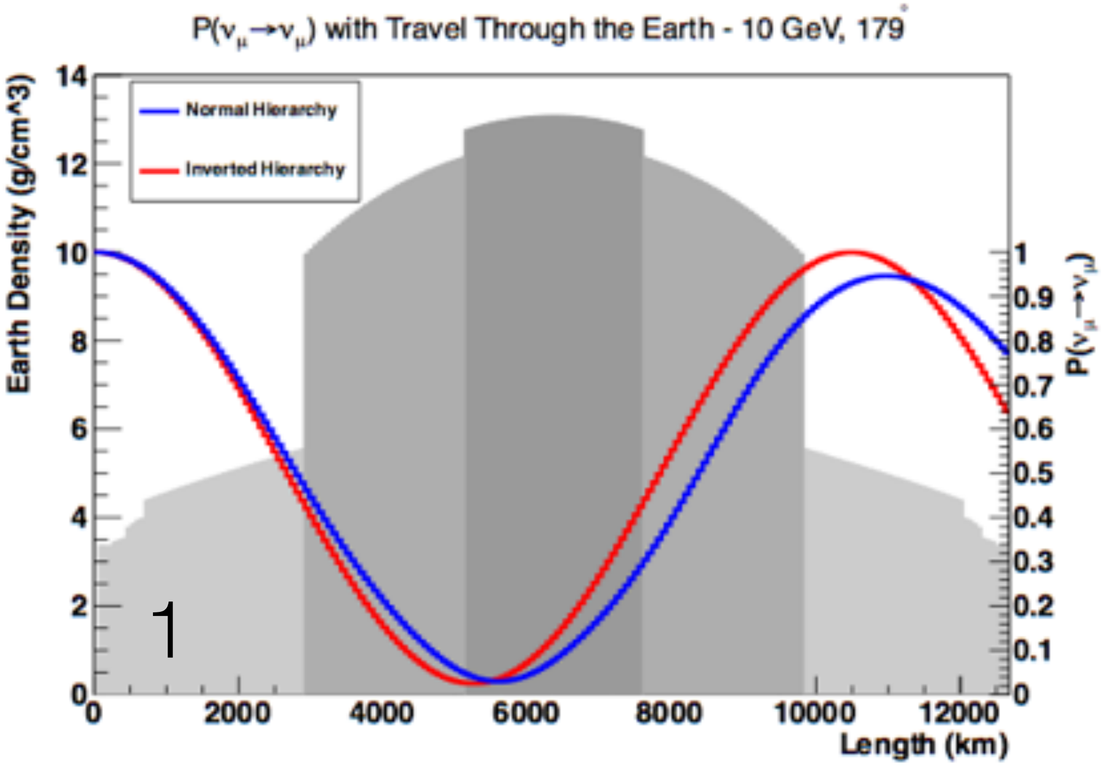


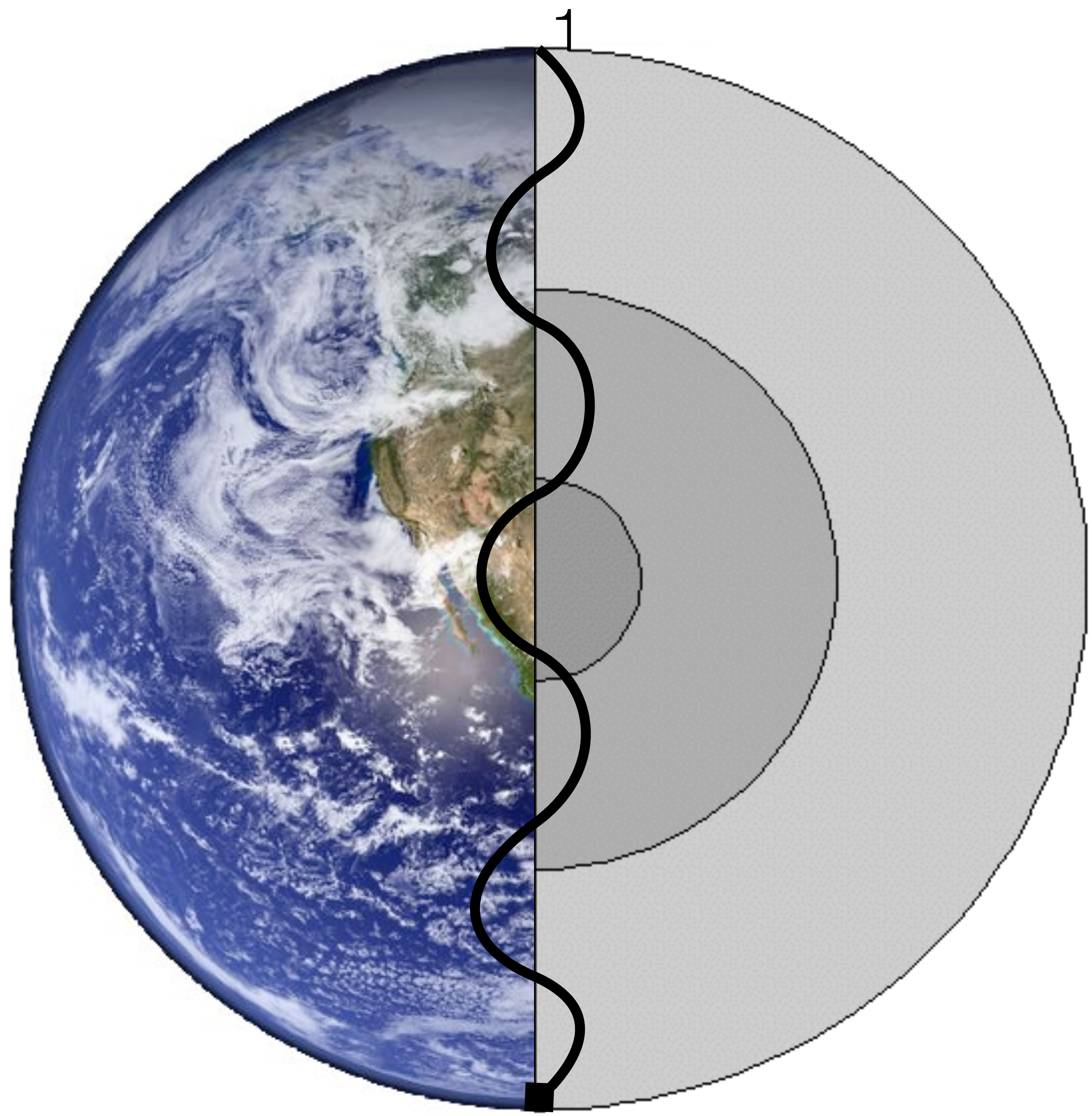
IceCube
Digital Optical Module (DOM)

PINGU Neutrino Mass Ordering

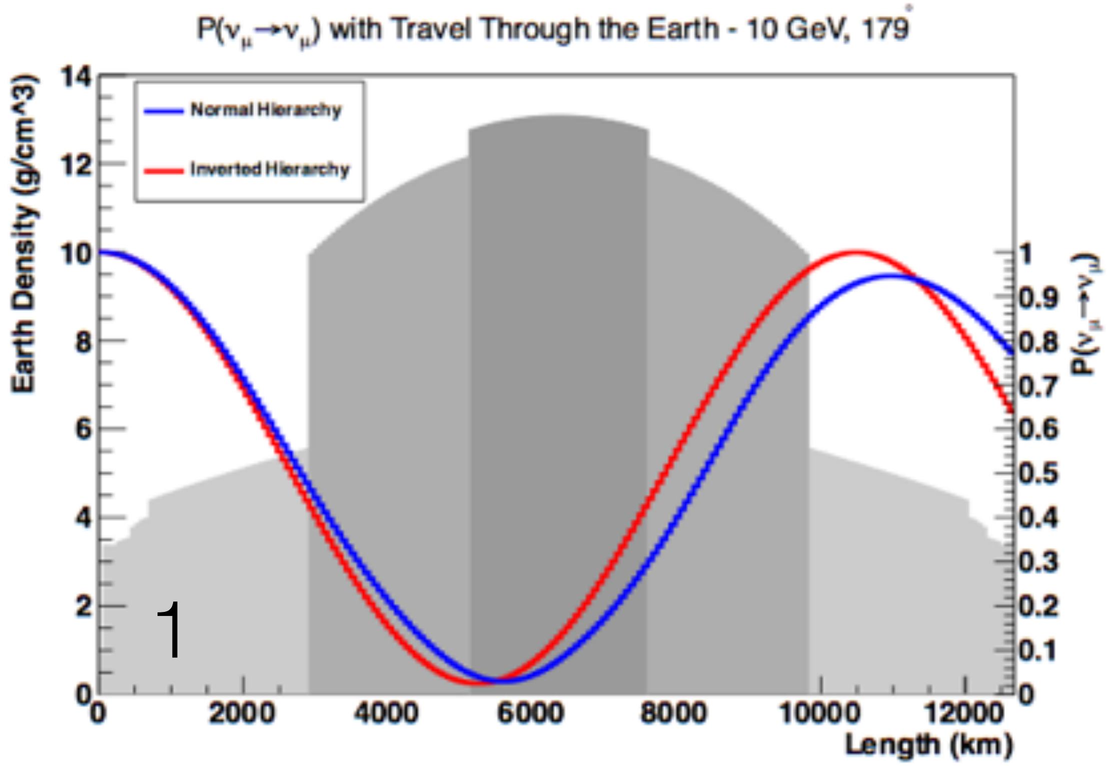


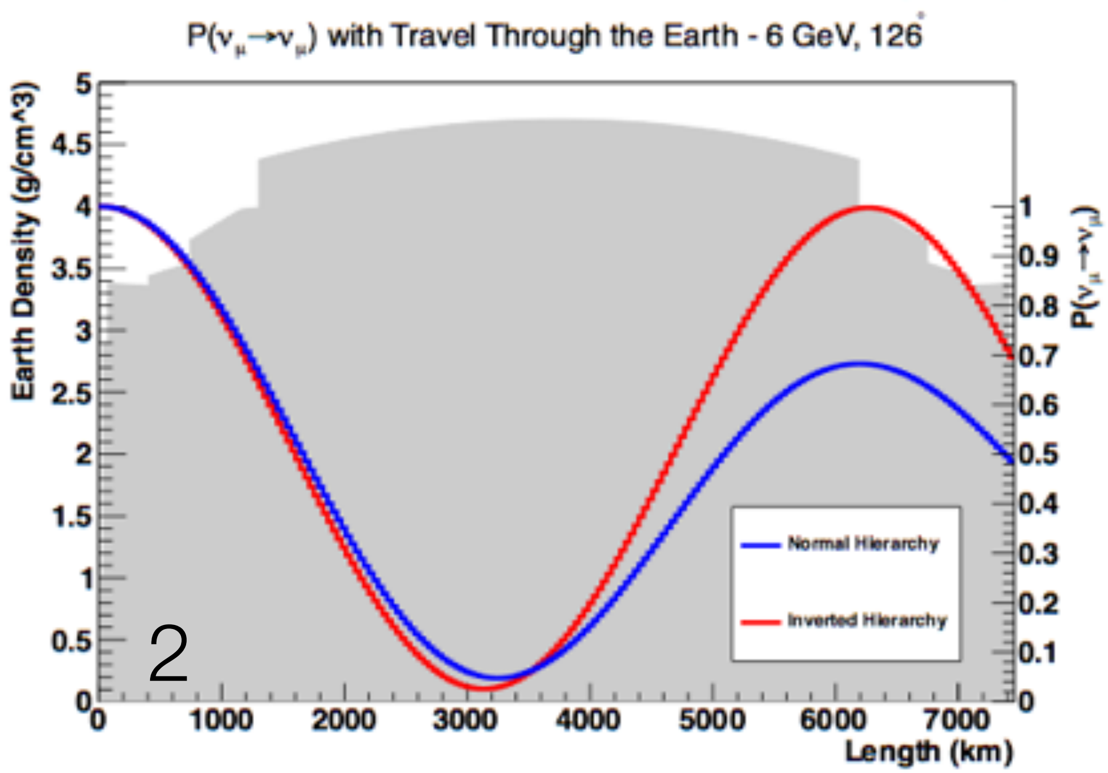
PINGU Neutrino Mass Ordering

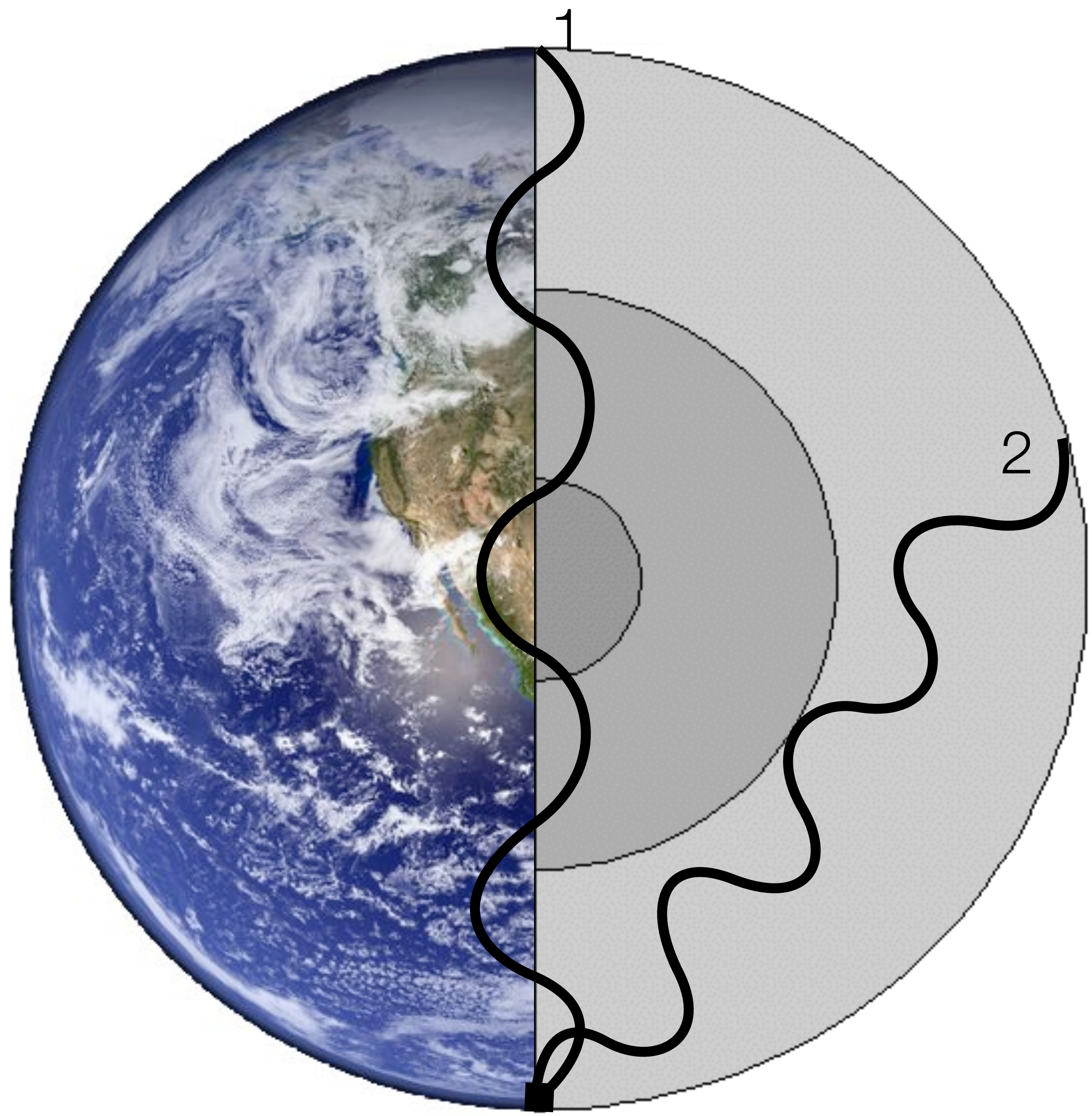




PINGU Neutrino Mass Ordering







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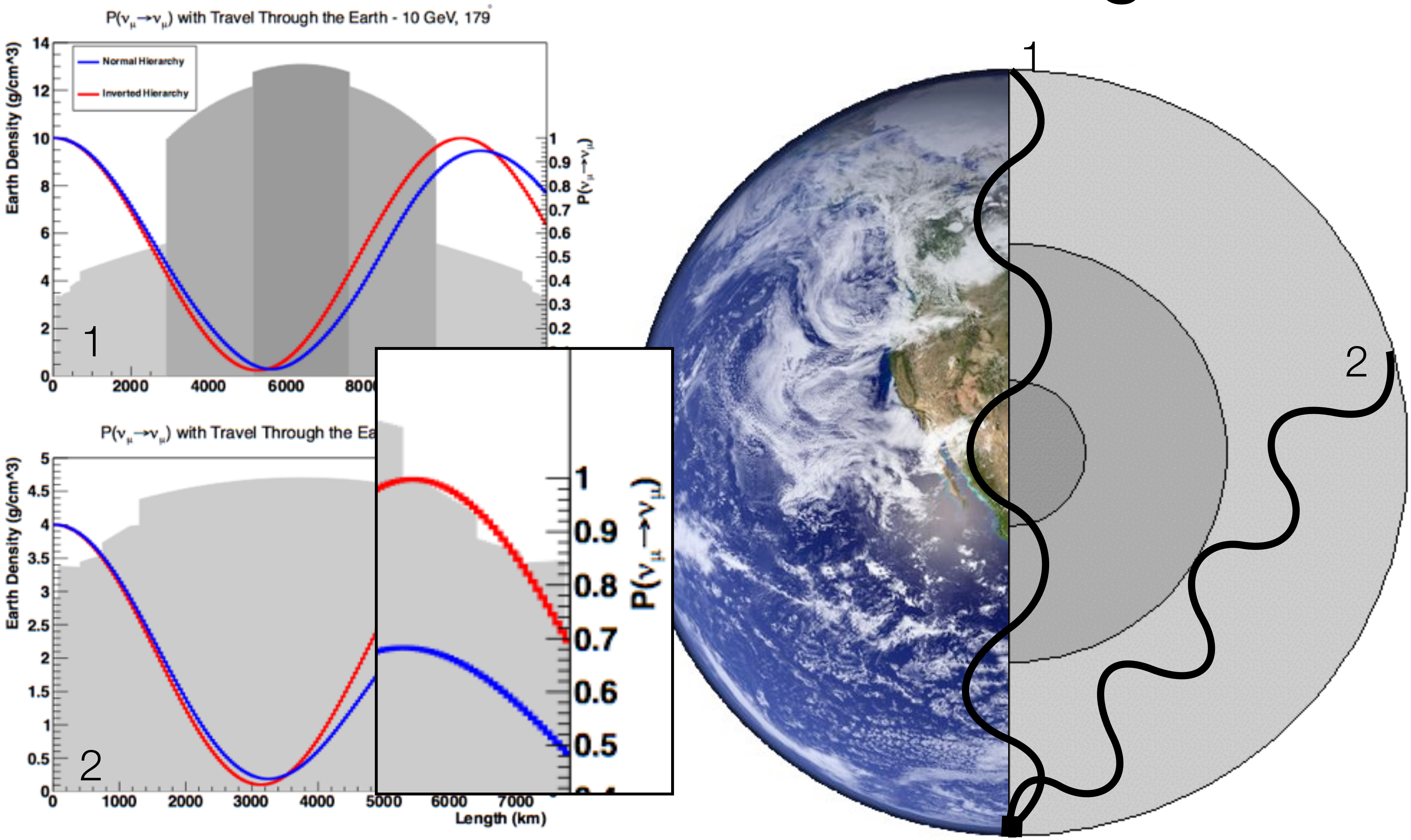
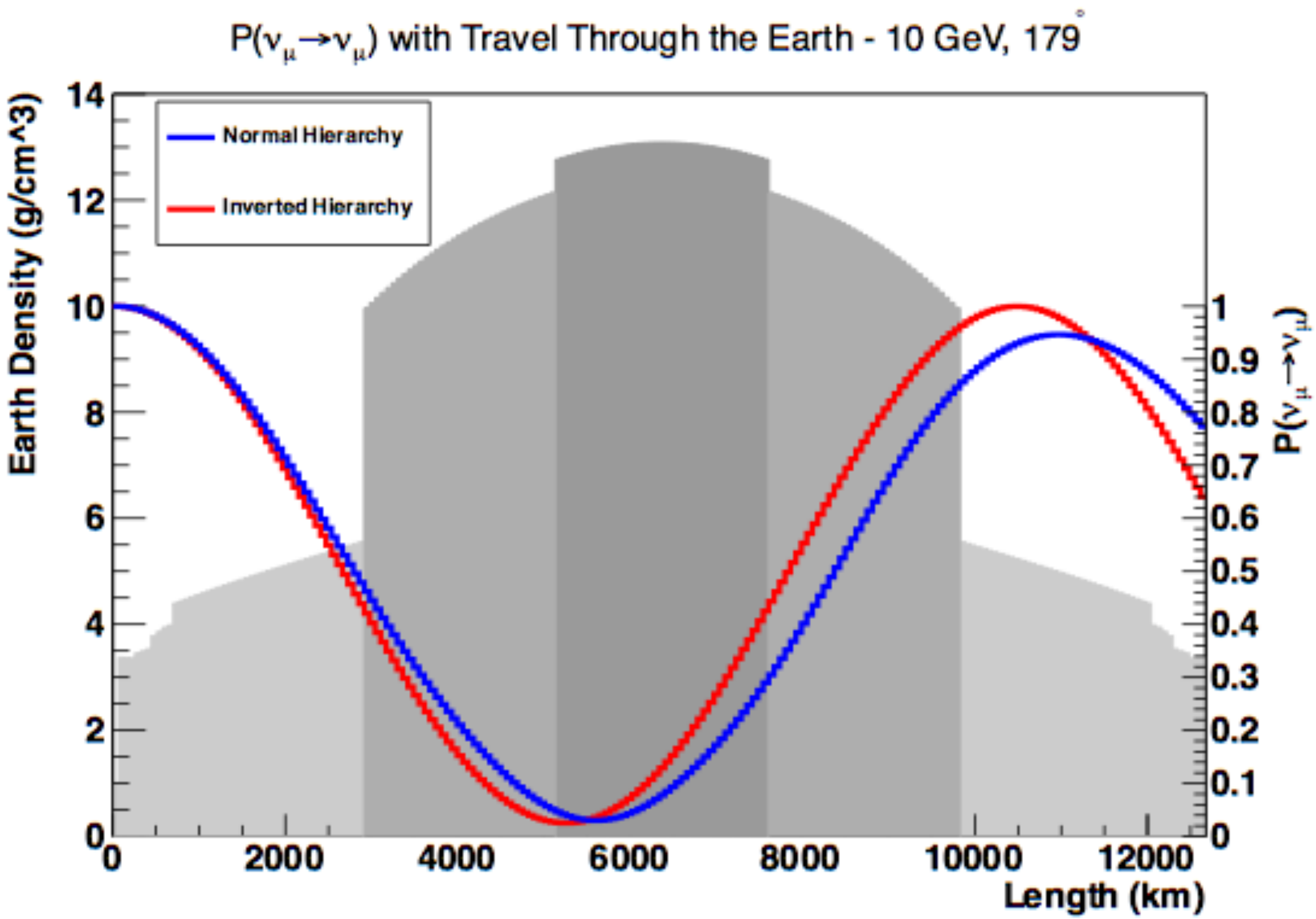


- Inverted/Normal ordering has up to 20% different in oscillation probability for specific energies and zenith angles (baselines)

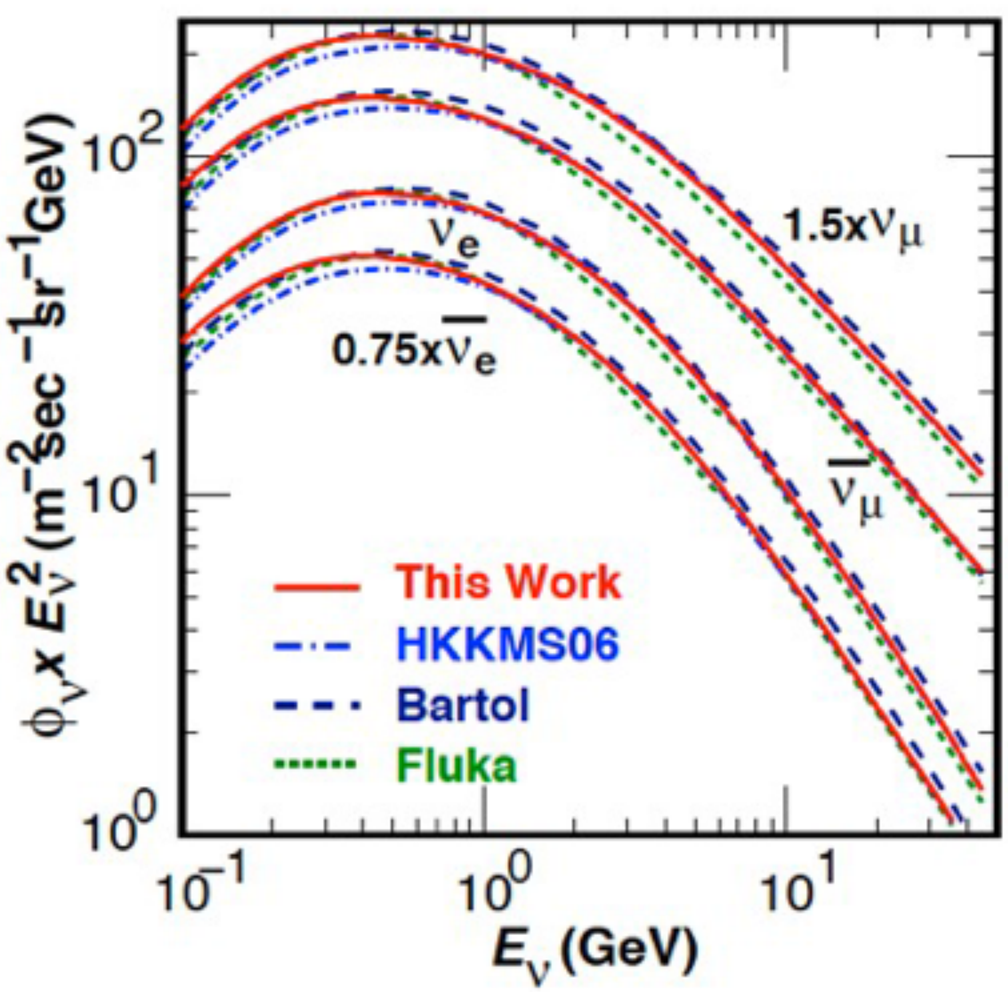
Neutrino Ordering w/ No Magnet



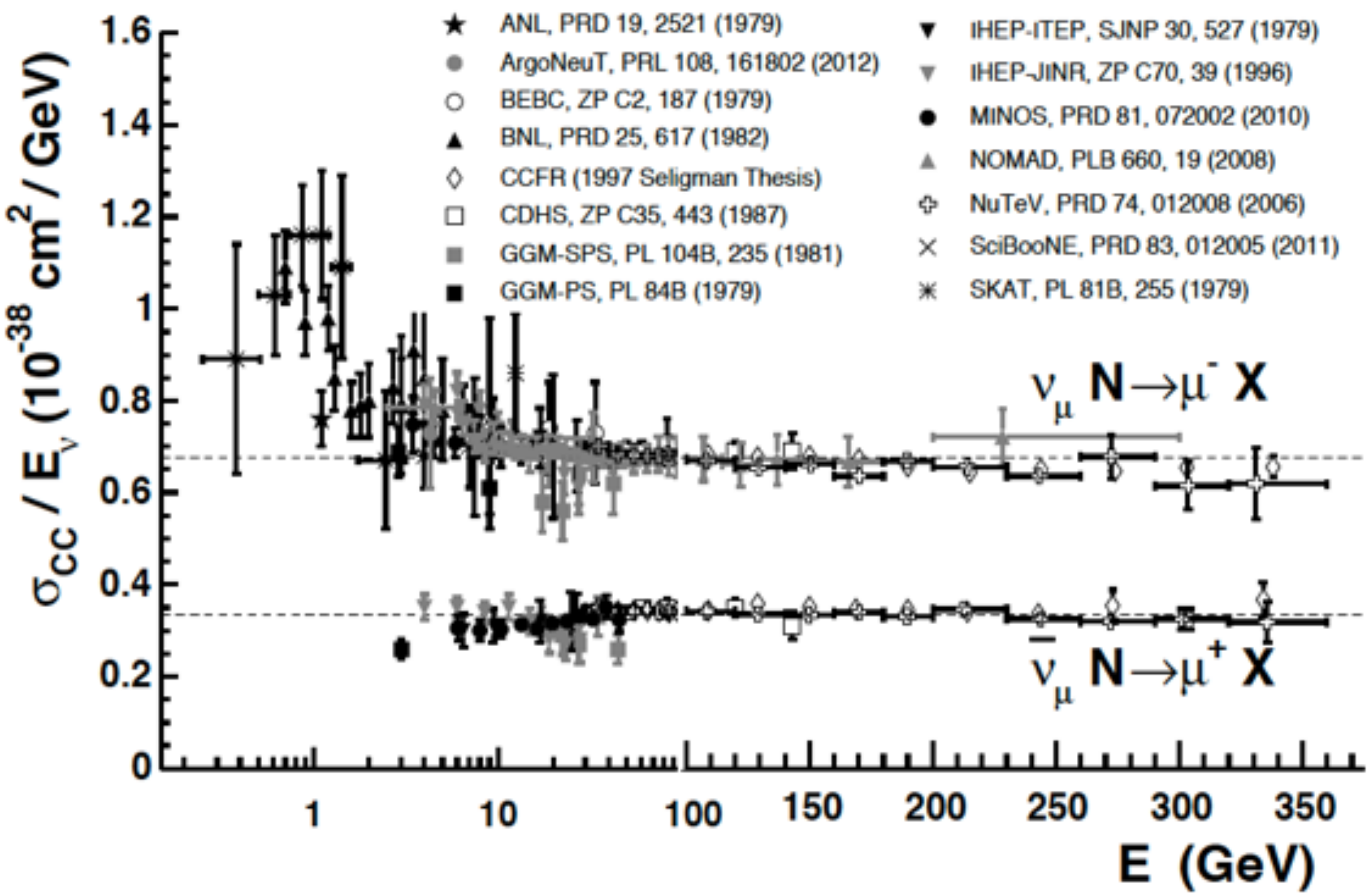
- Neutrinos will see either enhancement or suppression of oscillation probability, but anti-neutrinos will experience an opposite sign modulation of the exact same magnitude

Neutrino Ordering w/ No Magnet

arXiv:0203272

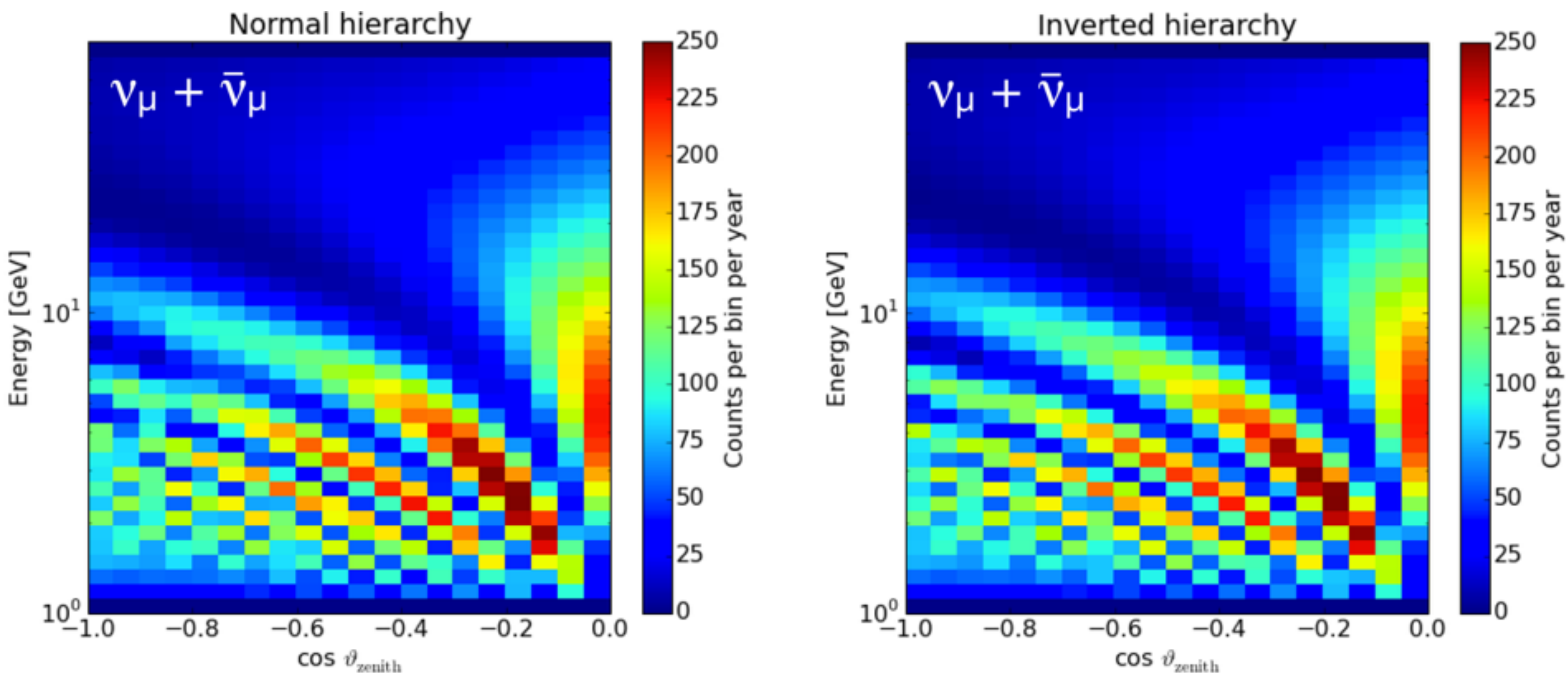


*G. Zeller, PDG 2012



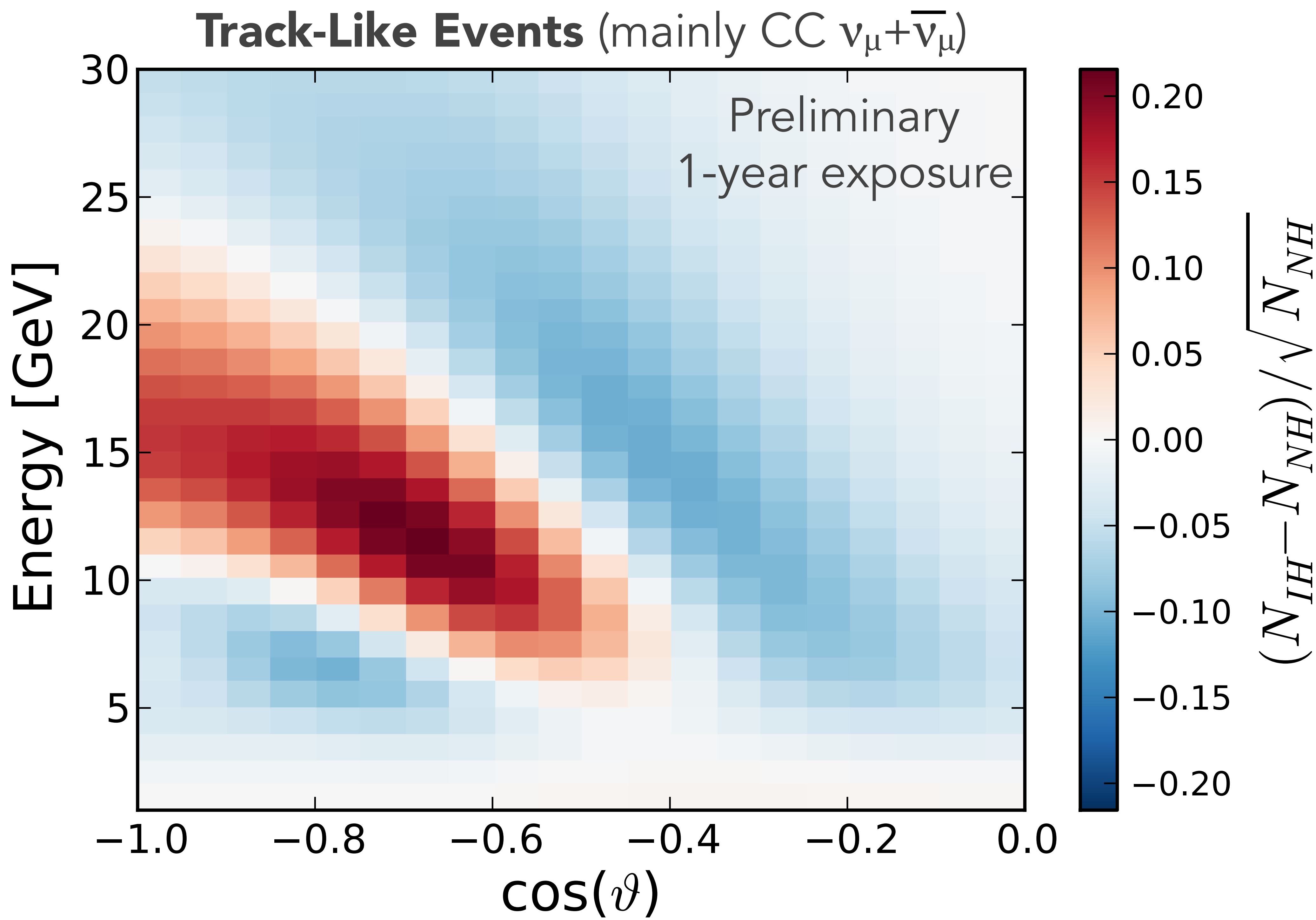
- PINGU has no magnet to separate neutrino from anti-neutrinos, but there is a cross-section and flux difference between neutrinos and anti-neutrinos

Oscillation Pattern



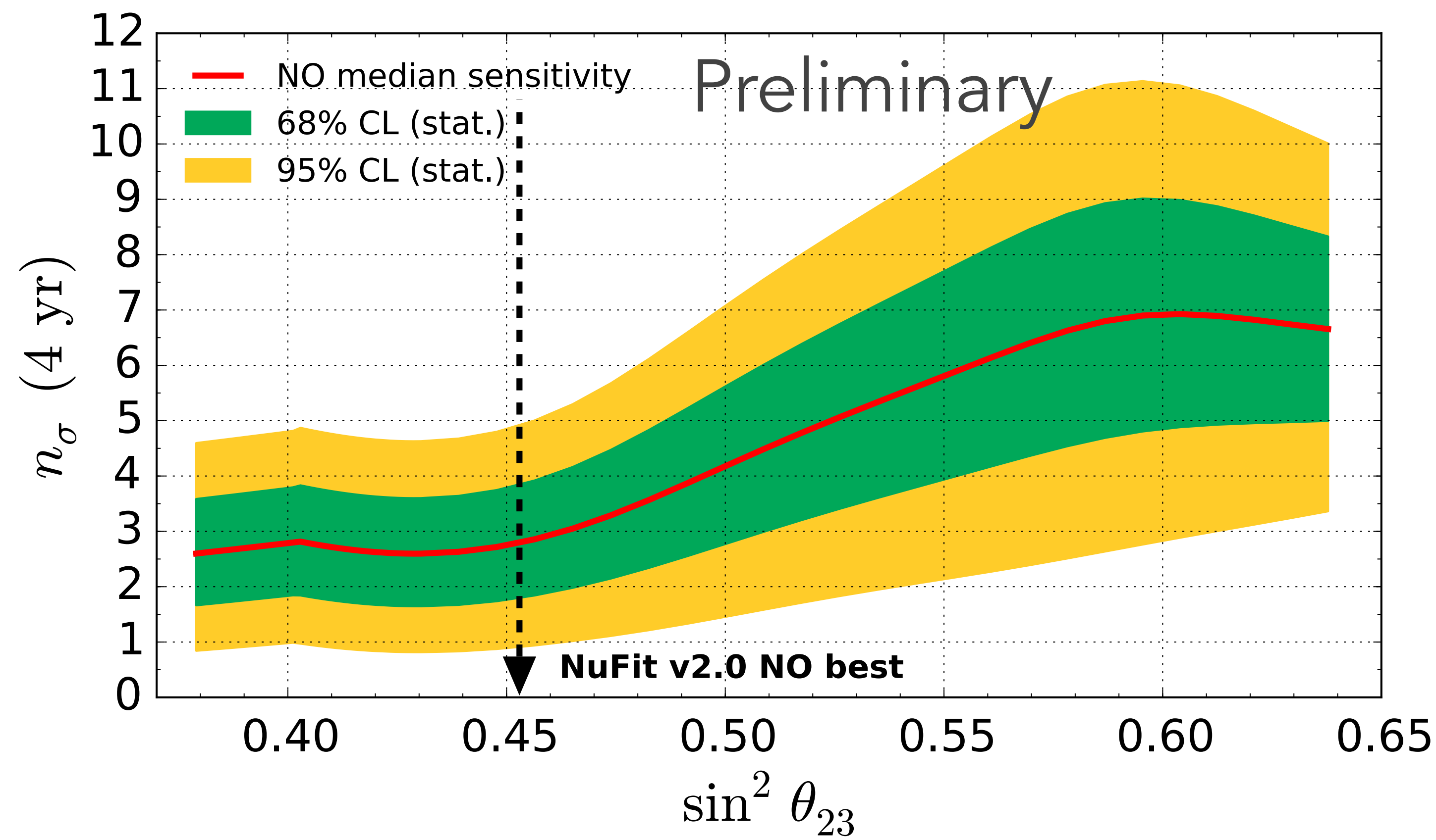
- Even before including detector effects and reconstruction smearing, the event rate histograms are quite similar

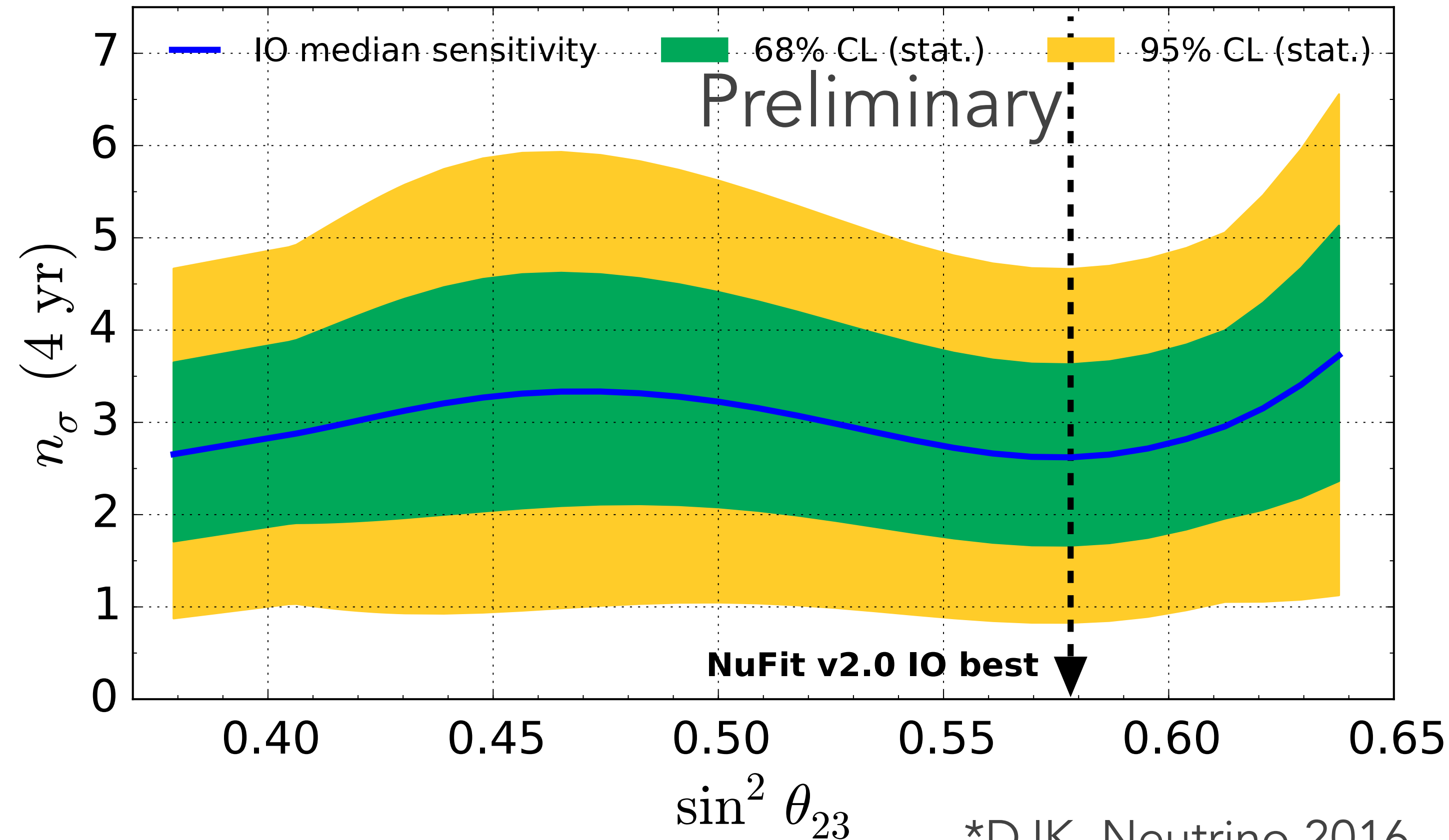
Neutrino Mass Hierarchy by Eye



PINGU NMO Sensitivities

- Brazilian flag sensitivities for the NMO analysis
- Sensitivity is mostly insensitive to the value of δ_{cp}, which is in contrast to other beam-based experiments





*DJK, Neutrino 2016

Statistics - A slight aside

Hierarchy Distinguishability Metric

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

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

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

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

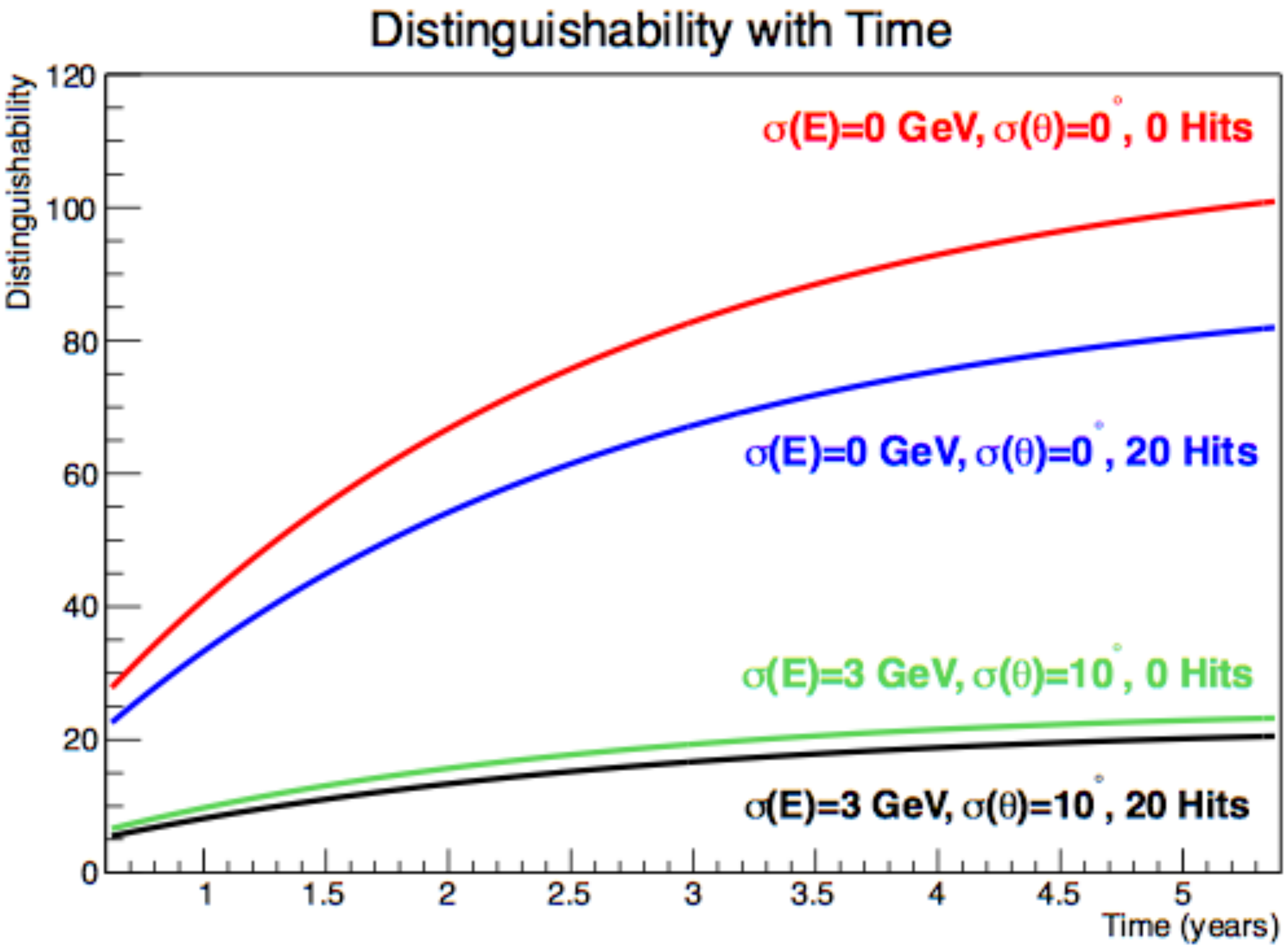
- Essentially bin, sum, and subtract one hierarchy from the other. It works because:

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

How Long?

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

- Apply no conditions
- Apply 20 hit "reconstructability" cut
- Apply detector resolution
- Apply resolutions and 20 hit cut



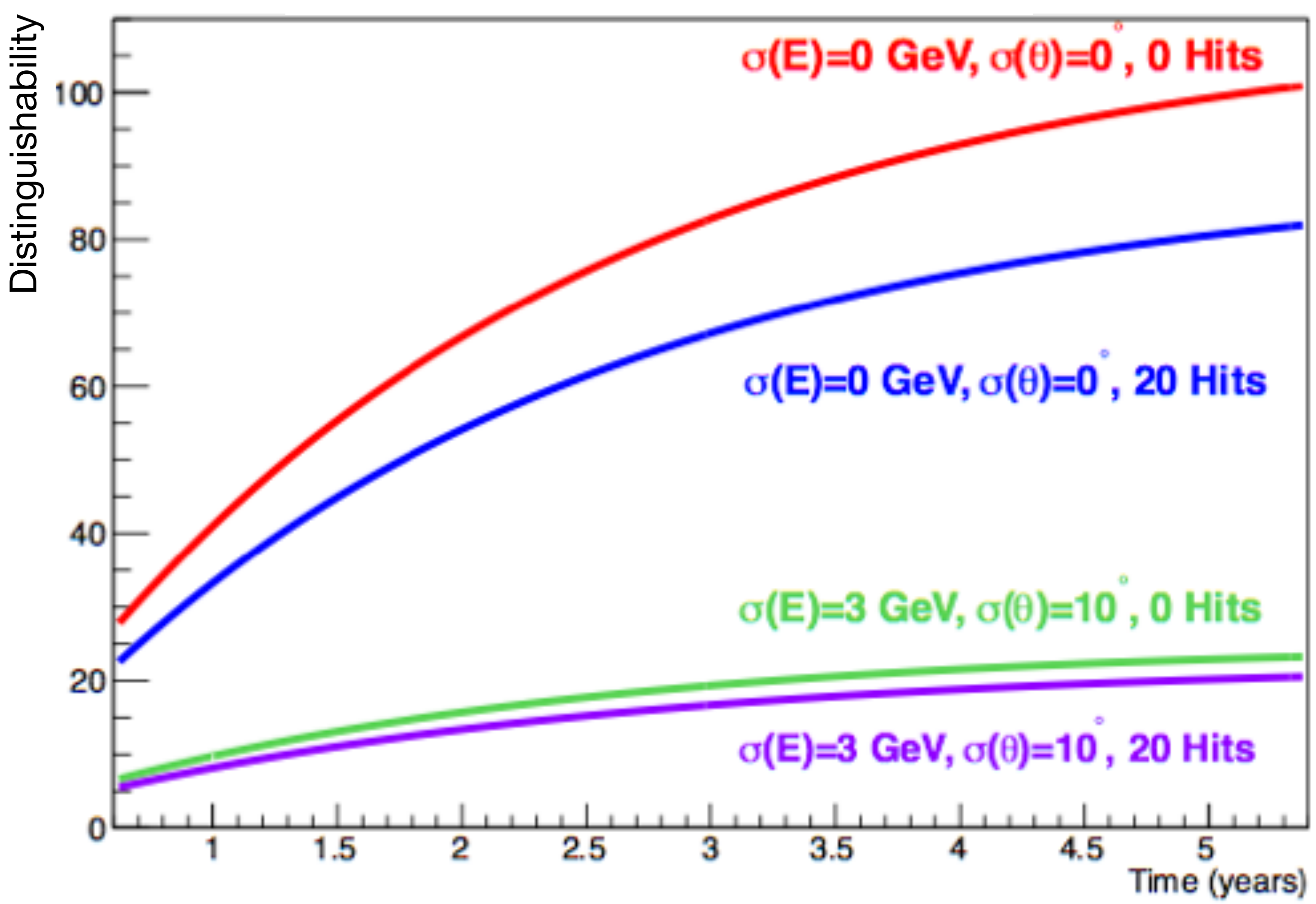
*arXiv:1210.3651

- 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's 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

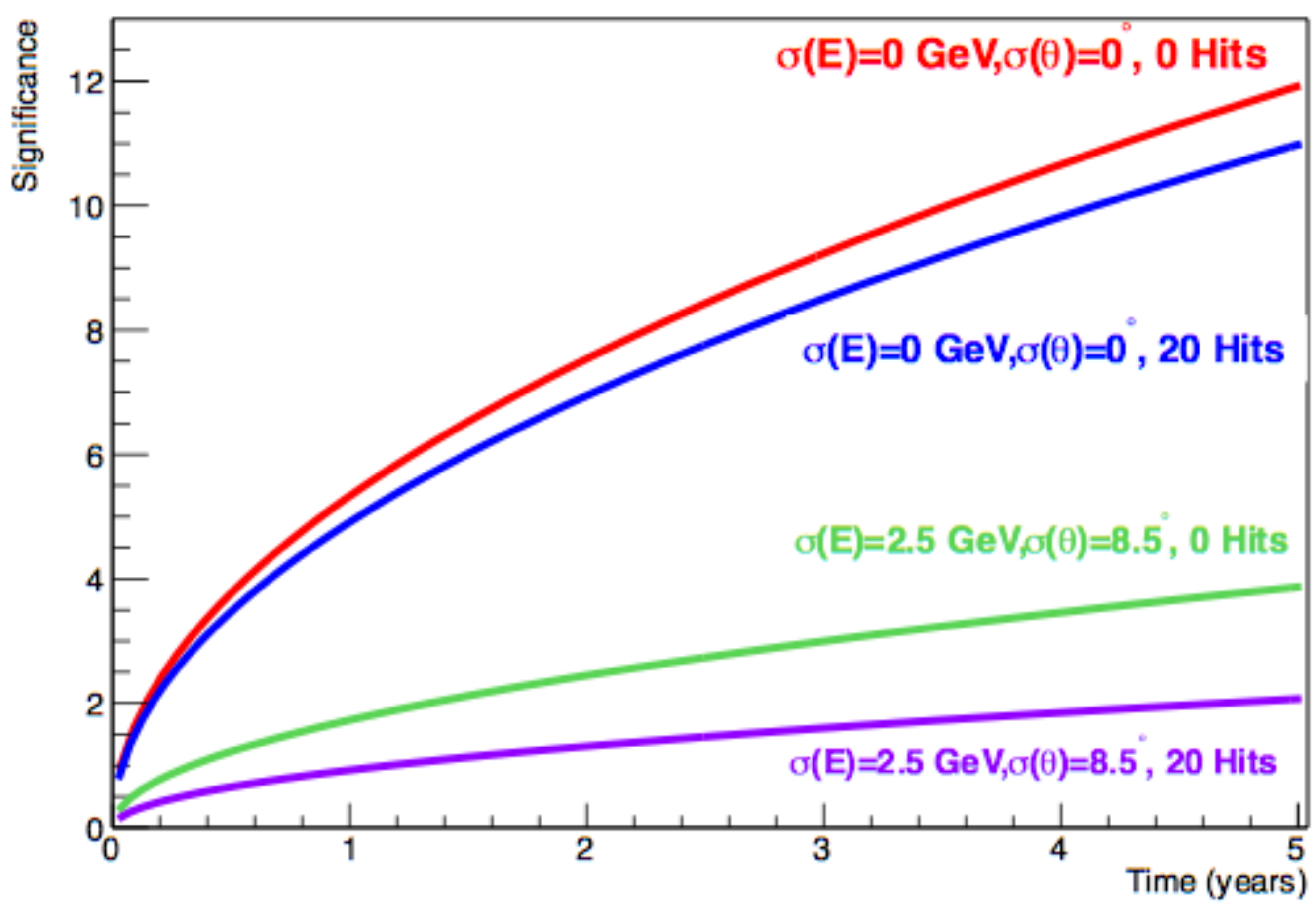
Time to Distinguishing

- 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 neutrino flux...

Akhmedov Method

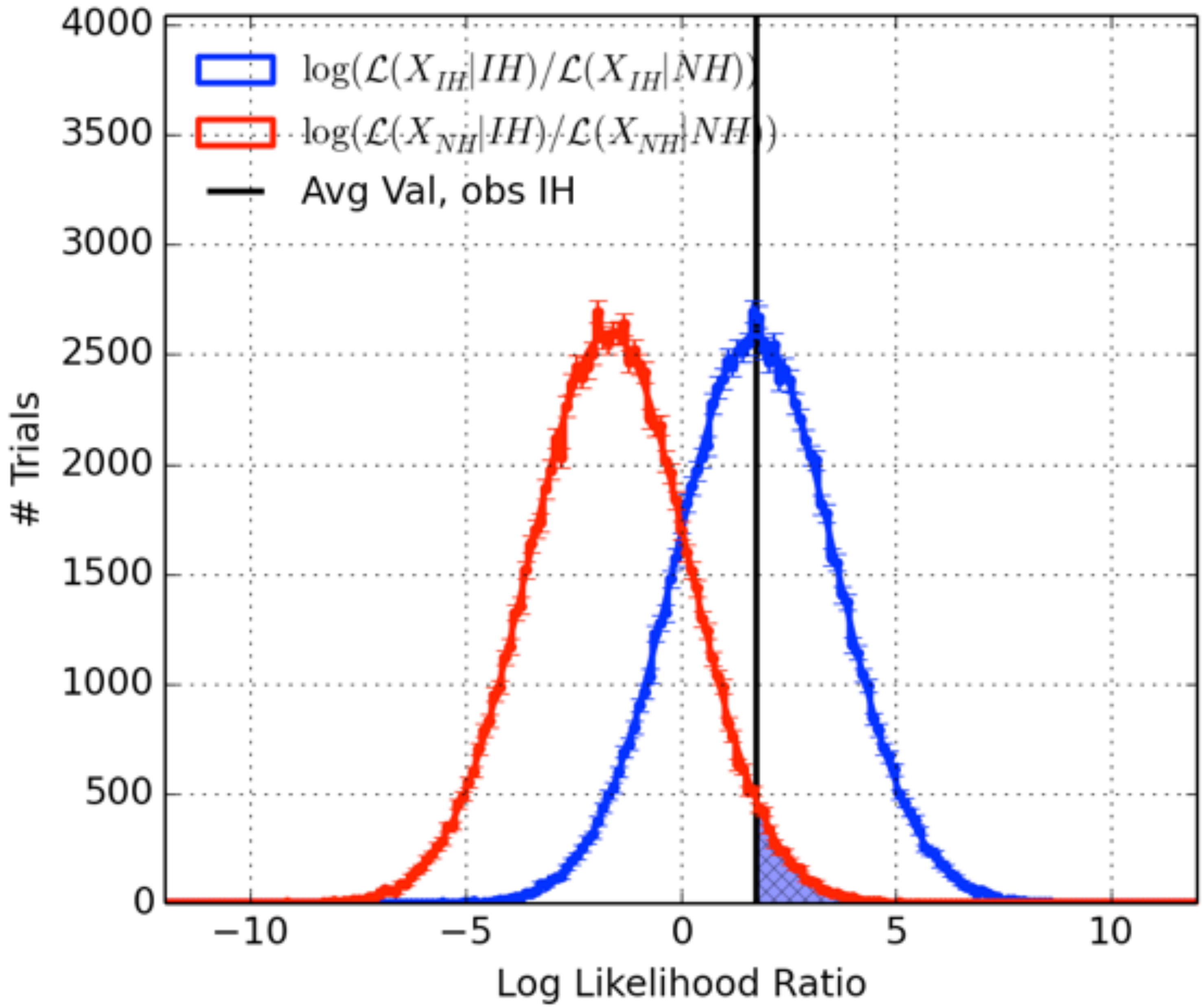


MC Method



Differentiation Between Inverted/ Normal

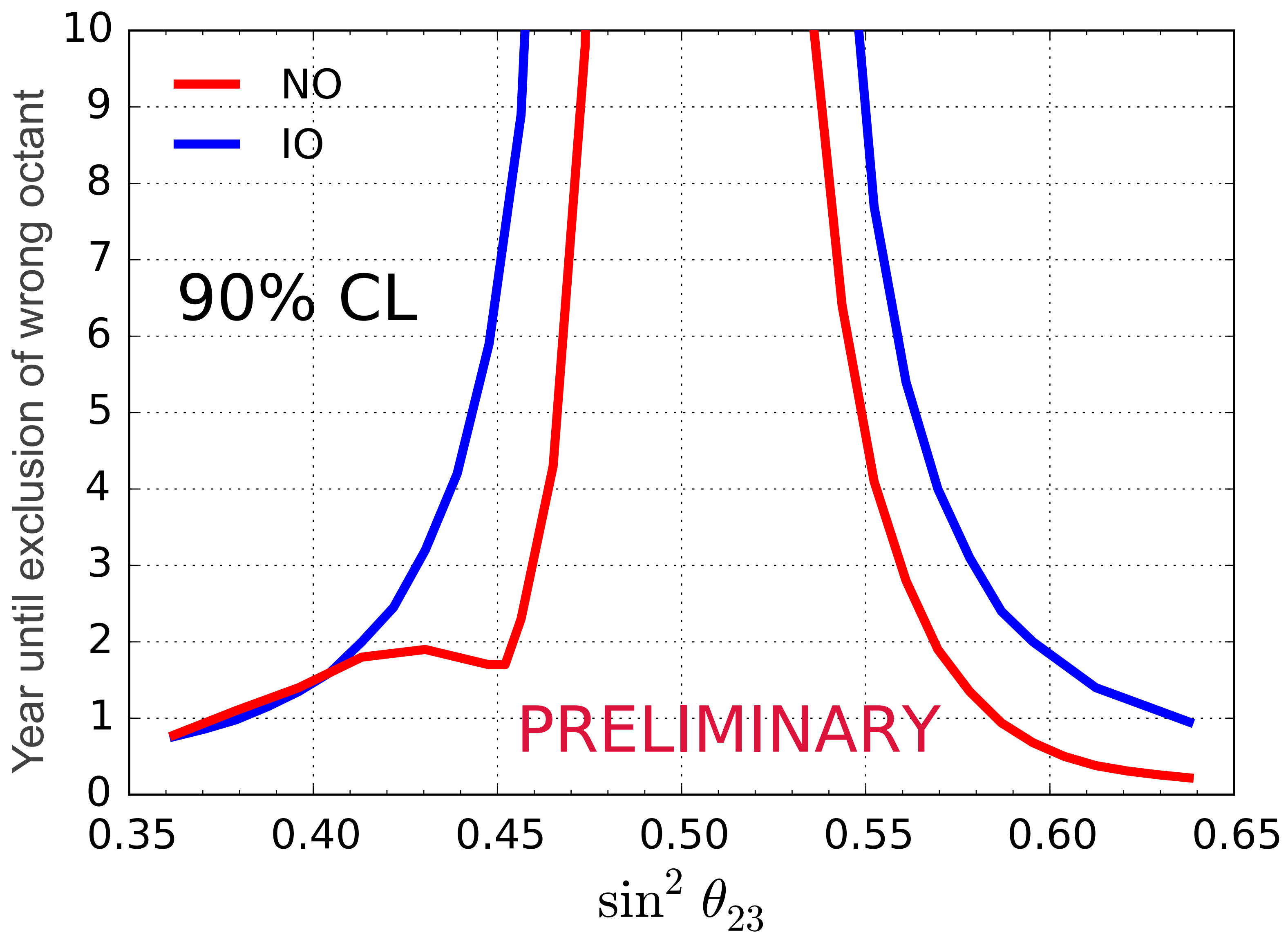
- Use a likelihood ratio with many simulated trials



Back to our regularly scheduled physics

PINGU Octant

- Number of years to exclude the wrong θ_{23} octant
  - Compare goodness-of-fit between best-fit over the entire range and best-fit where the search is restricted to opposite octant
  - IO less sensitive because MSW effect is in the anti-ν channel



*DJK, Neutrino 2016

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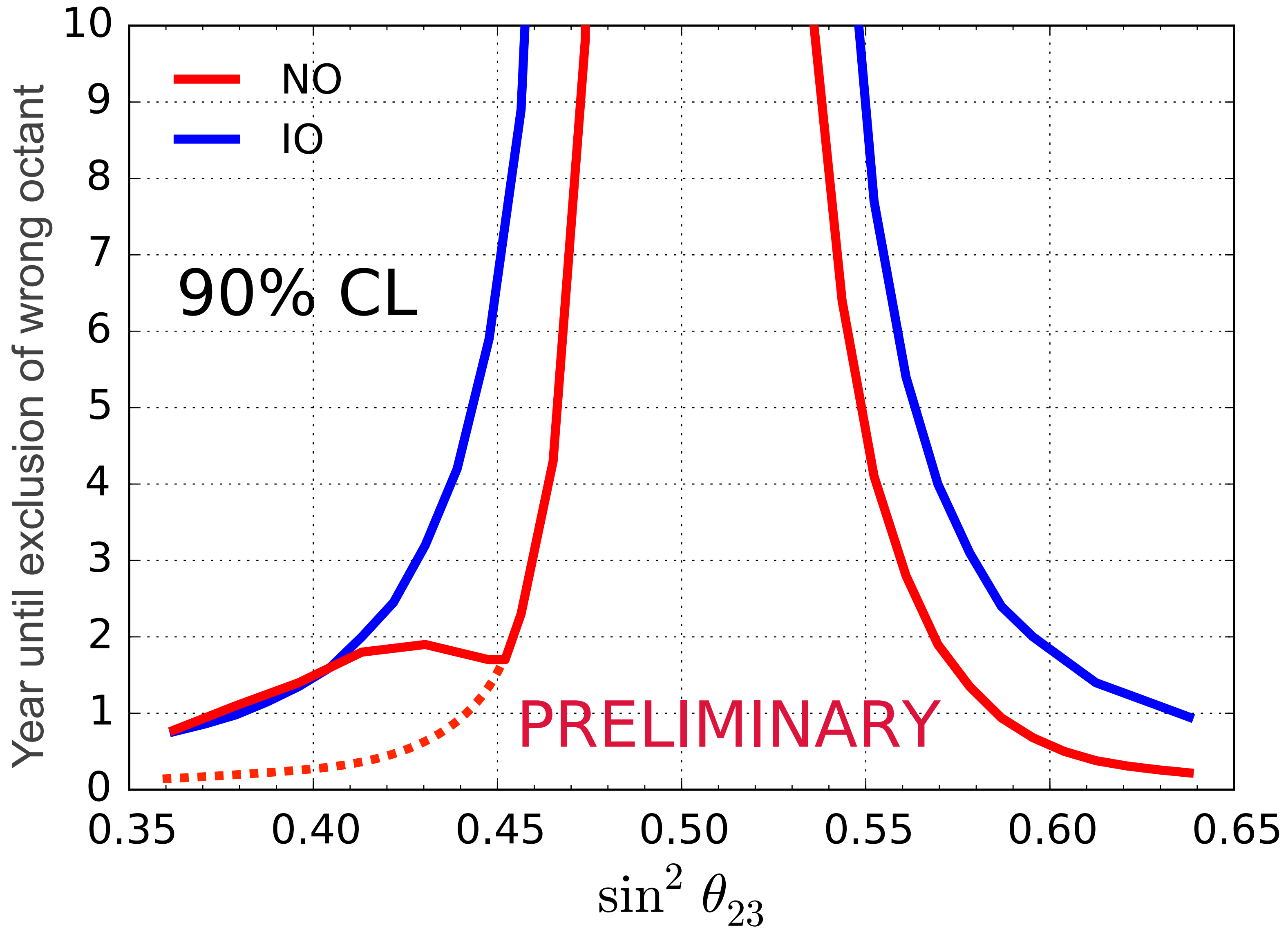

*DJK, Neutrino 2016

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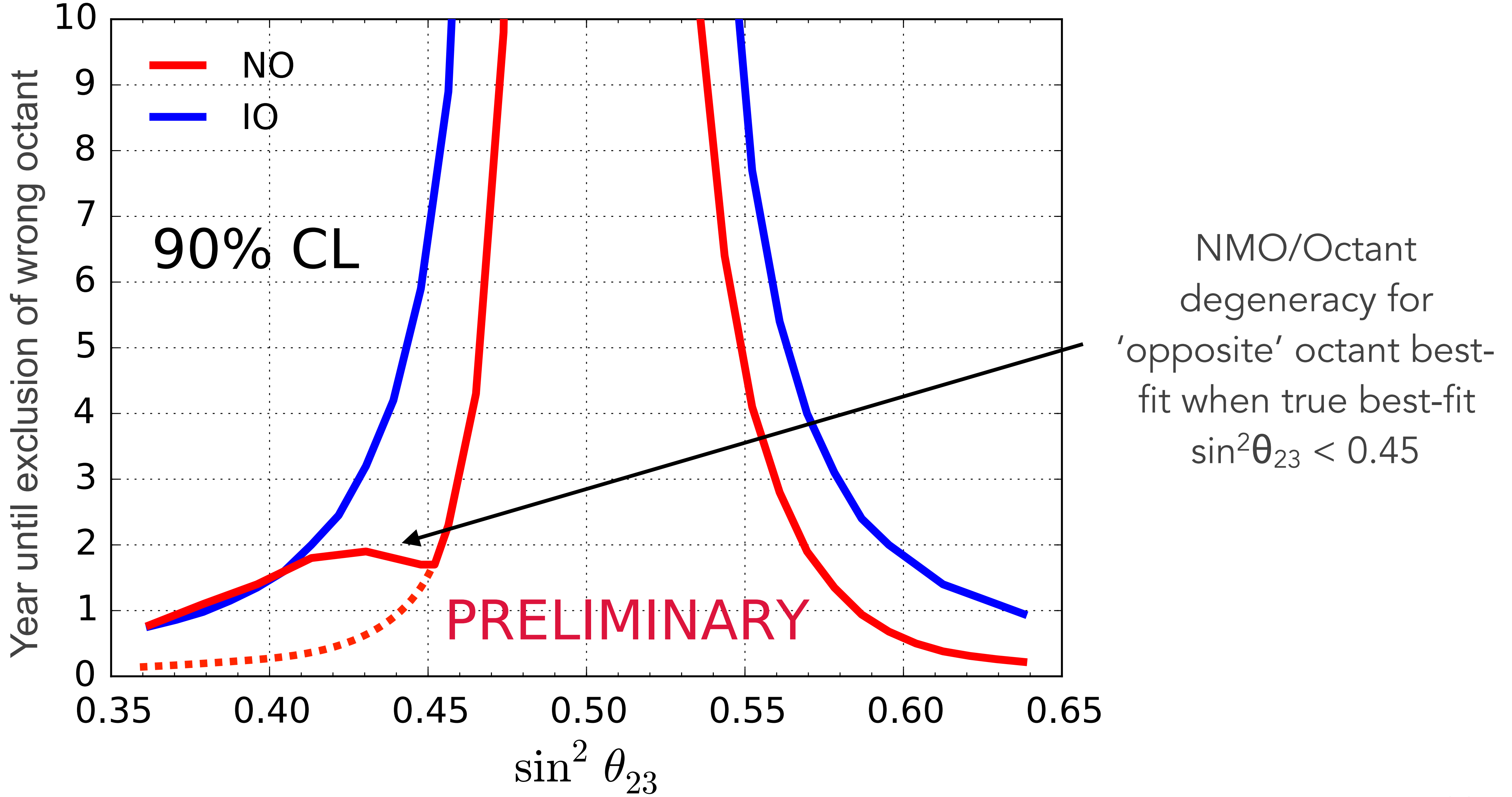
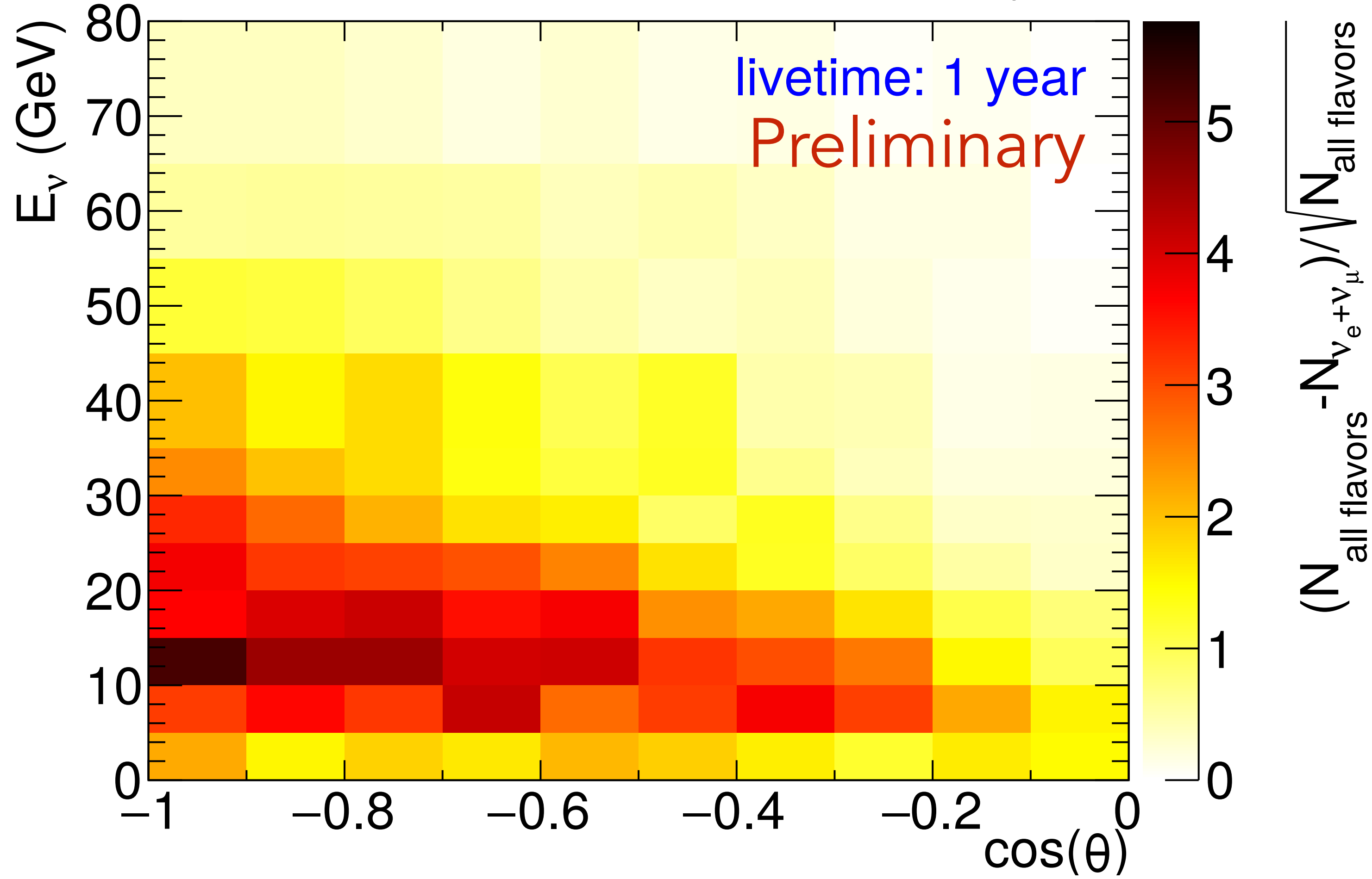


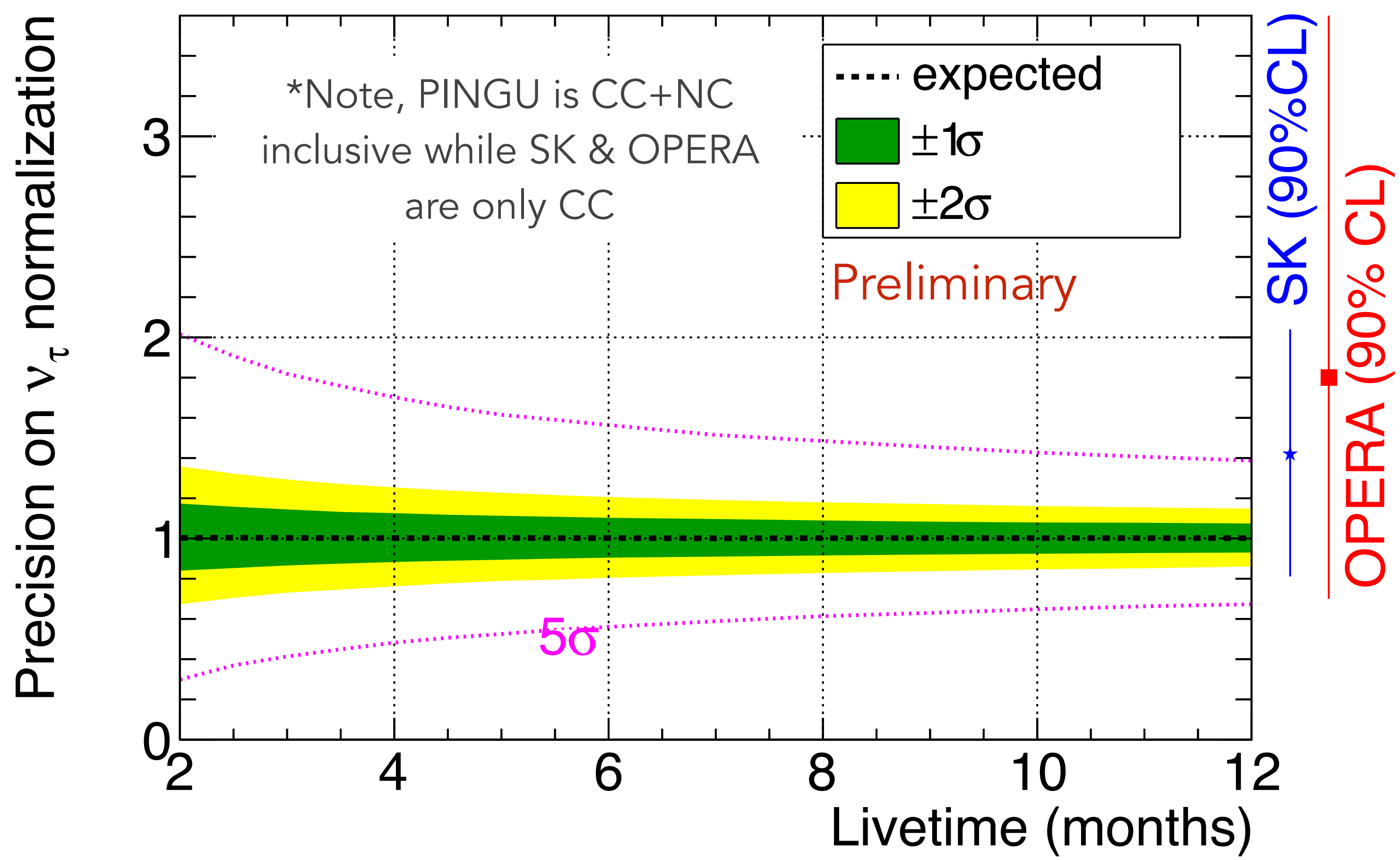
*DJK, Neutrino 2016

ν_τ Appearance in PINGU

*DJK, Neutrino 2016

- Similarity to a DeepCore measurement
  - Direct measure of $|U_{\tau 3}|^2$
  - Energy and zenith angle excess in cascade channel
- PINGU analysis currently uses same initial Boosted Decision Tree as NMO, but secondary selection for `cascades'





Conclusion

- IceCube/DeepCore is producing results using high-purity track-like events and working towards improved and new results with multiyear datasets which will allow for the most sensitive probes of ν_τ-appearance, which is a direct test of neutrino mixing unitarity

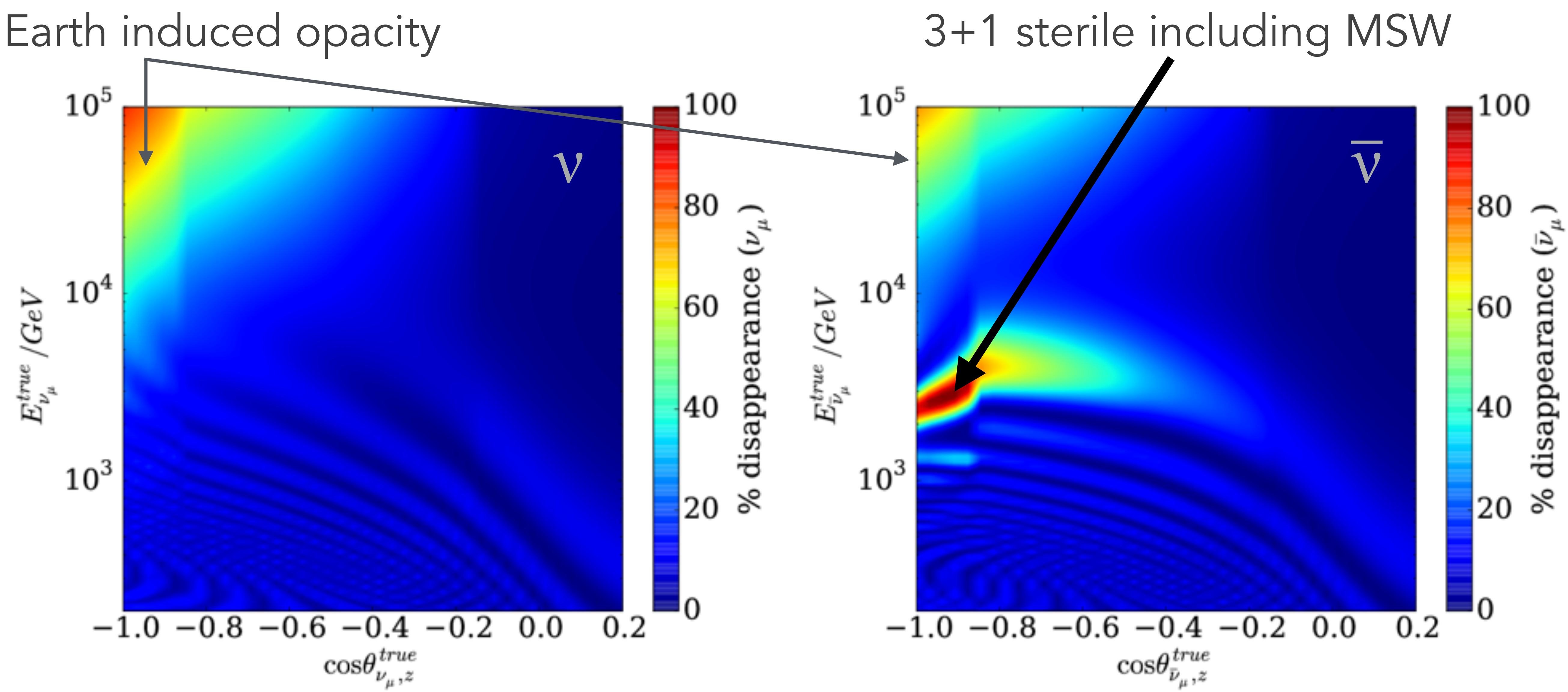
- Moving further into precision neutrino physics, e.g. δ_{cp}, requires extended precision measurements of PMNS unitarity

- PINGU can resolve the Neutrino Mass Ordering at 3σ in 3-4 years and greatly enhances the reach of IceCube/DeepCore physics portfolio (ν_τ appearance, octant, precision θ_{23}, …)

Backup

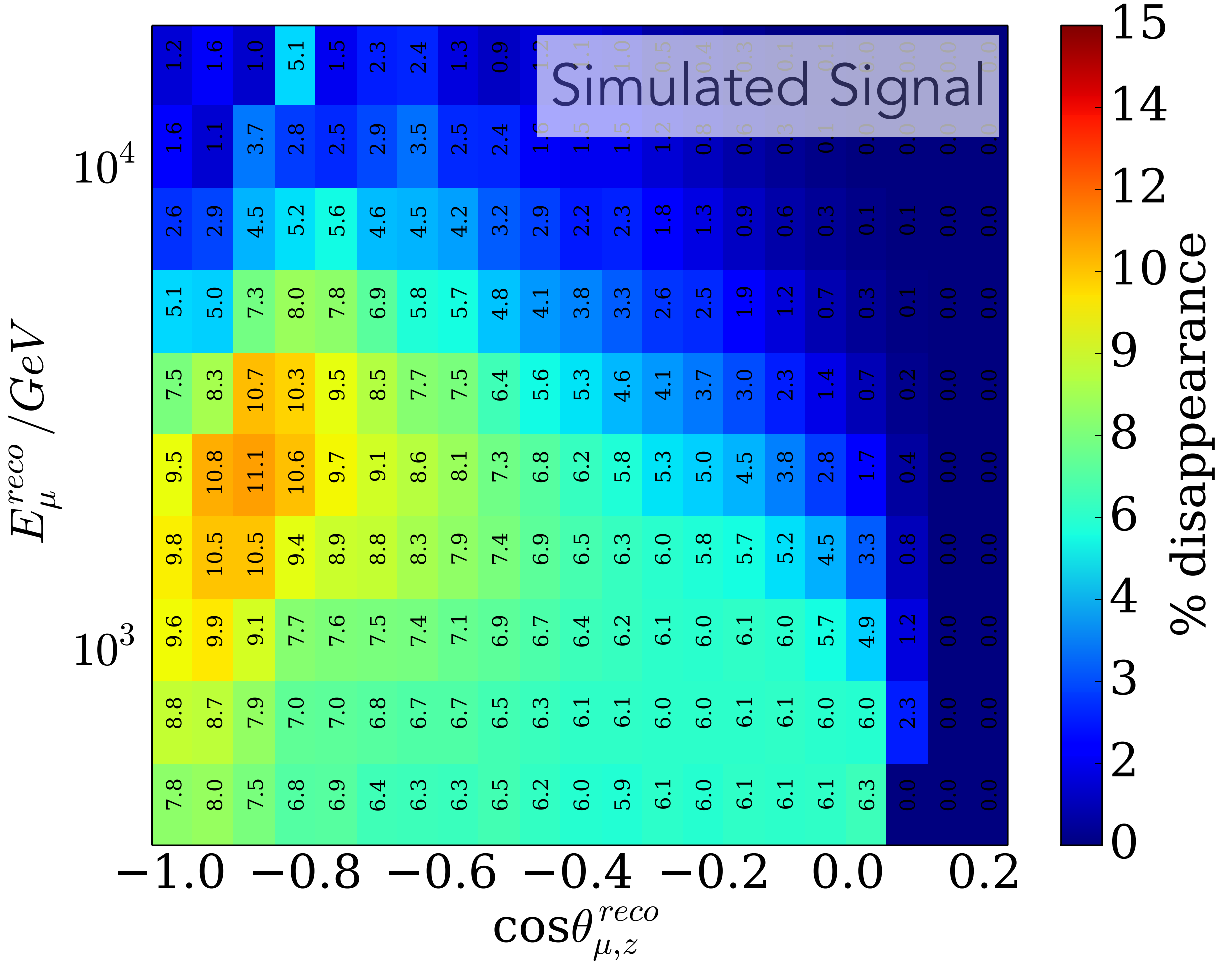
Sterile Neutrinos

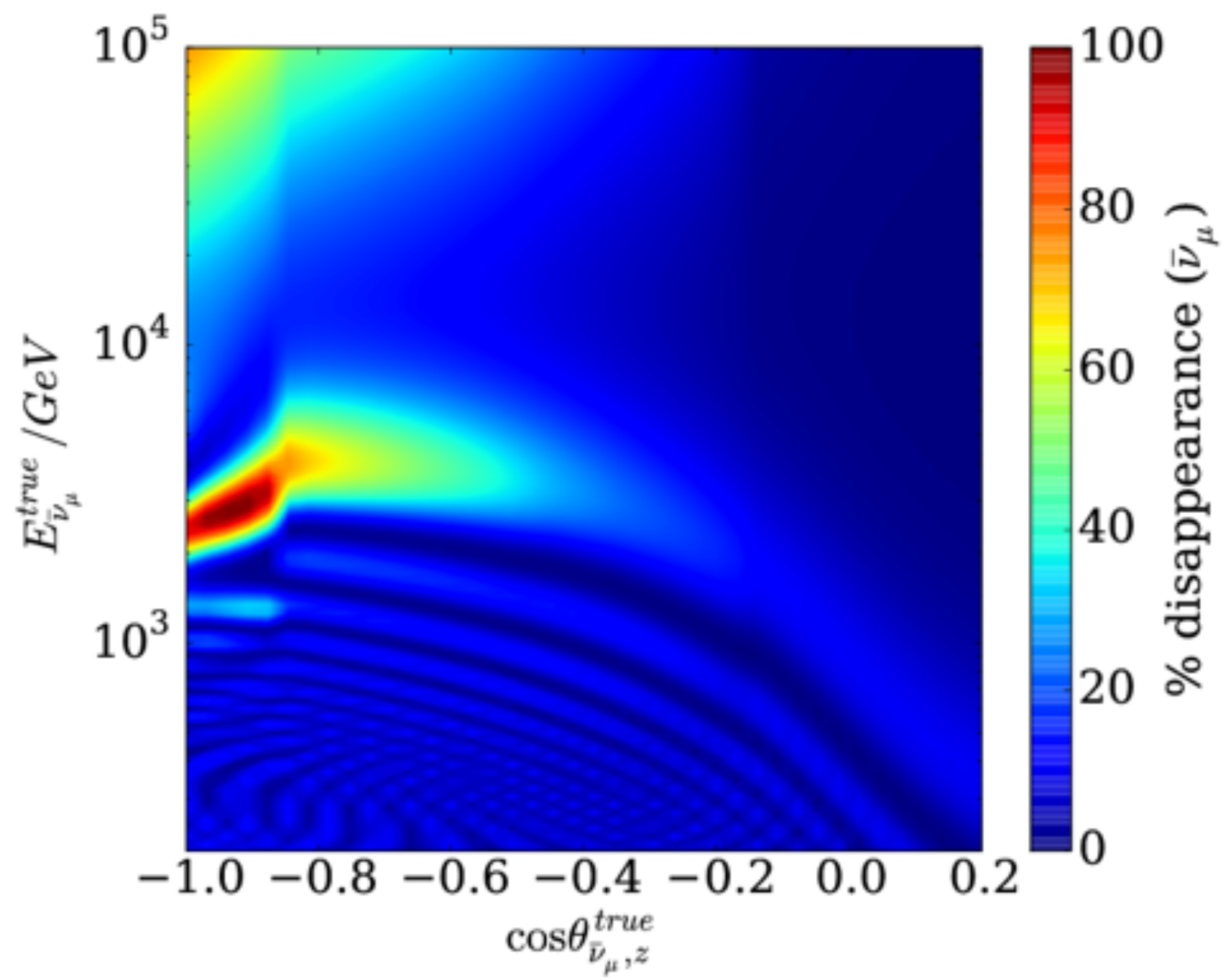
- Sterile neutrino signatures extend in energy beyond the conventional reactor and accelerator searches
- At $\Delta m^2 \simeq 1$ eV^2 there is a matter induced resonance at $\bar{\nu}$ energies of $\mathcal{O}(1)$ TeV for 3+N models, or ν for N+3



Sterile Search Approach

- Two separate diffuse ν_μ event selections of 1-year livetime (IC59 and IC86-1) were used to search for a sterile signal [deployment map in backup]
- The pronounced sterile feature for $\bar{\nu}$ is smeared out by:
  - Reconstruction uncertainty
  - The ν-induced muons are uncontained
  - Signal is combination of ν + $\bar{\nu}$

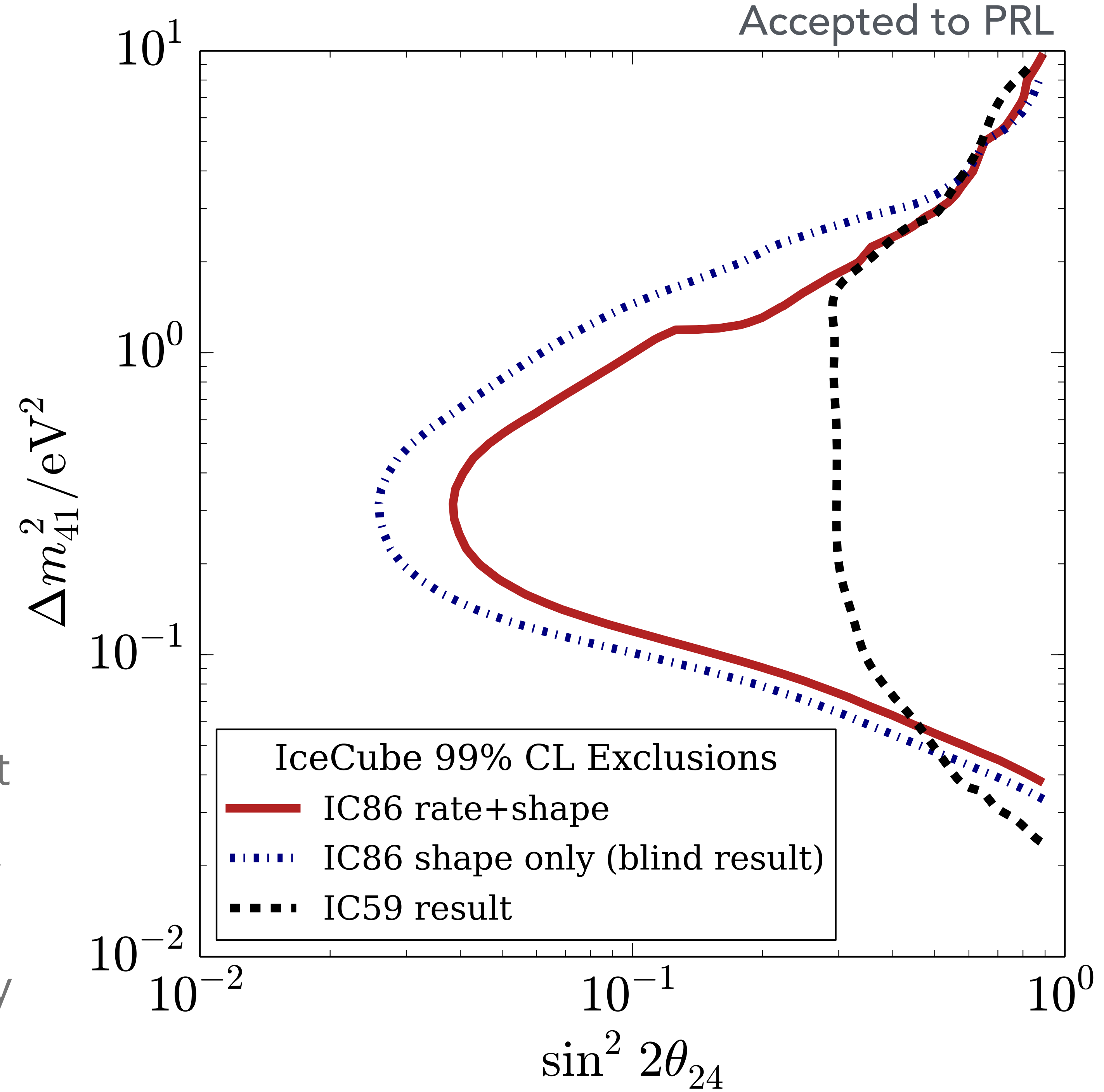




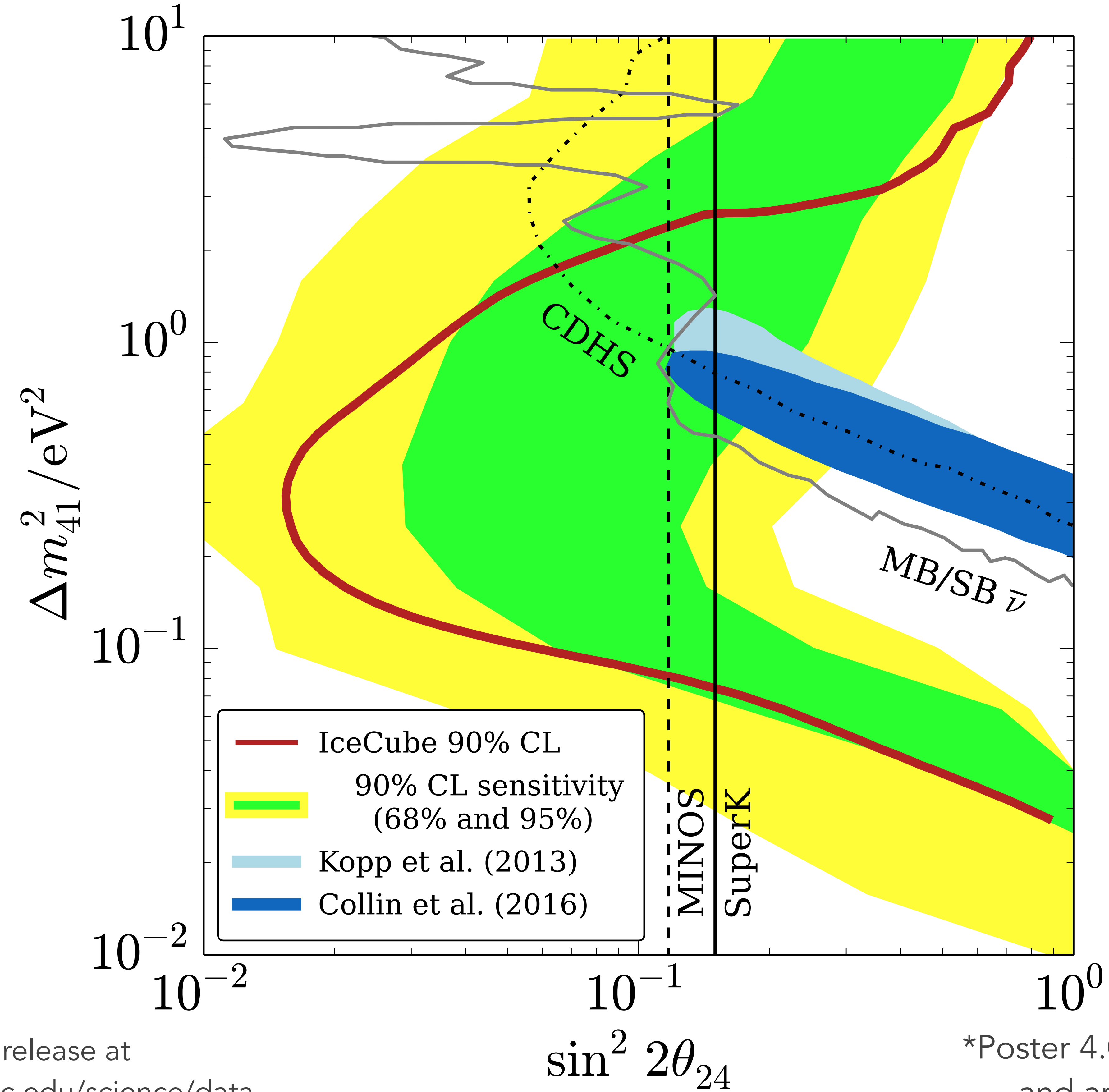
No Sterile Signature

- Primary result is IC86 “rate+shape”, complemented by IC59 and IC86 “shape only”
  - “rate+shape” is *a posteriori* inclusion of a 40% prior on the atm. ν flux normalization
    - From rapid oscillations, results at $\Delta m^2 \gtrsim 5$ eV^2 with an unphysical flux normalization are highly degenerate with a no-sterile result
    - The loose prior constrains the flux normalization to be physical and breaks degeneracy between many high Δm^2 results

Accepted to PRL



IceCube Sterile ν Result



Public IC86-1 data release at
https://icecube.wisc.edu/science/data

*Poster 4.088 by C. Argüelles and arXiv:1605.01990