PENNSTATE

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# IceCube-DeepCore-PINGU: Atmospheric Neutrino Physics at the South Pole

D. Jason Koskinen

High energy physics seminar
Brookhaven National Laboratory
September, 2012

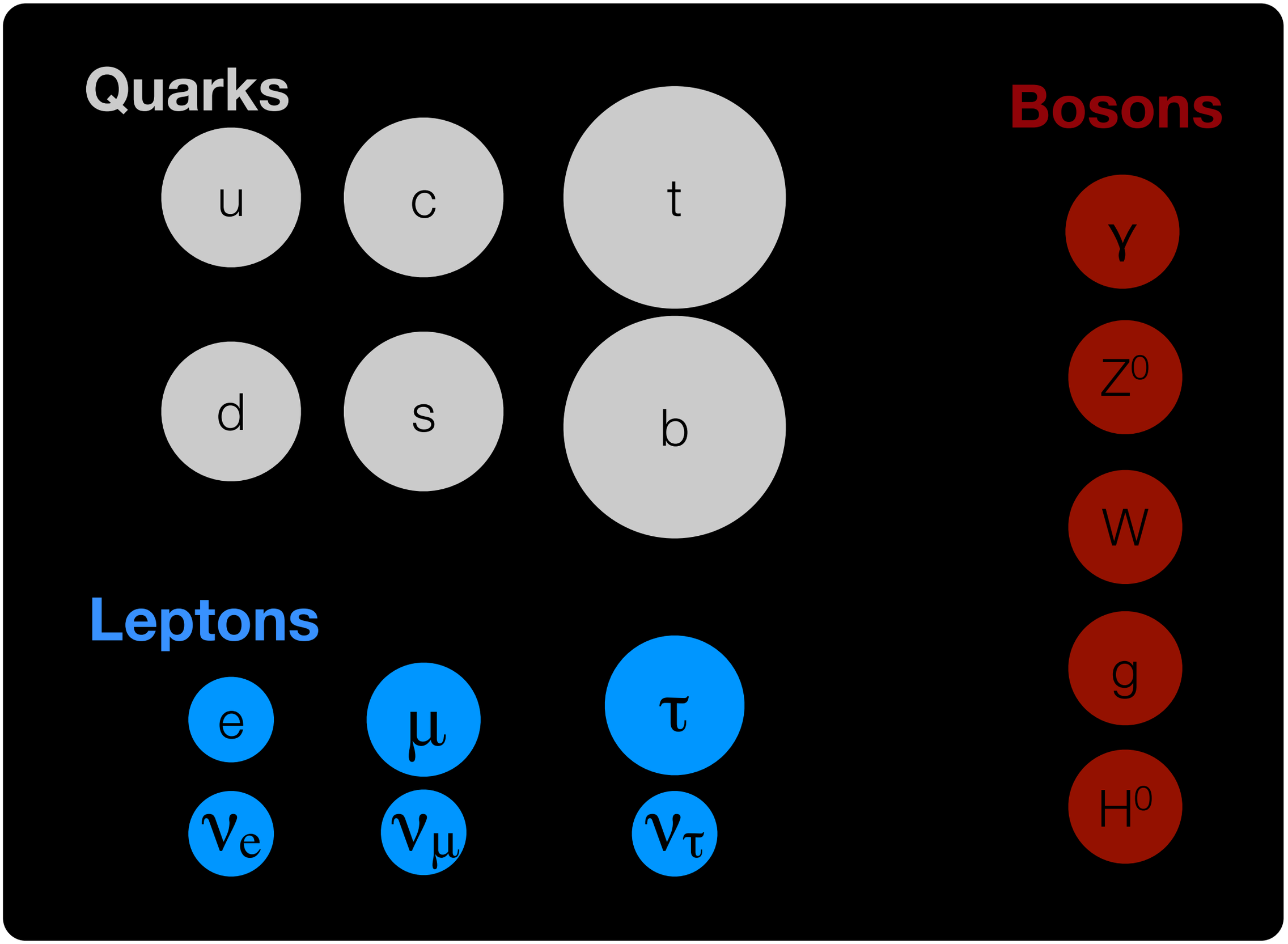
# Title

- Oscillation
- IceCube-DeepCore Physics
- PINGU
- Beyond

# Why Neutrinos?

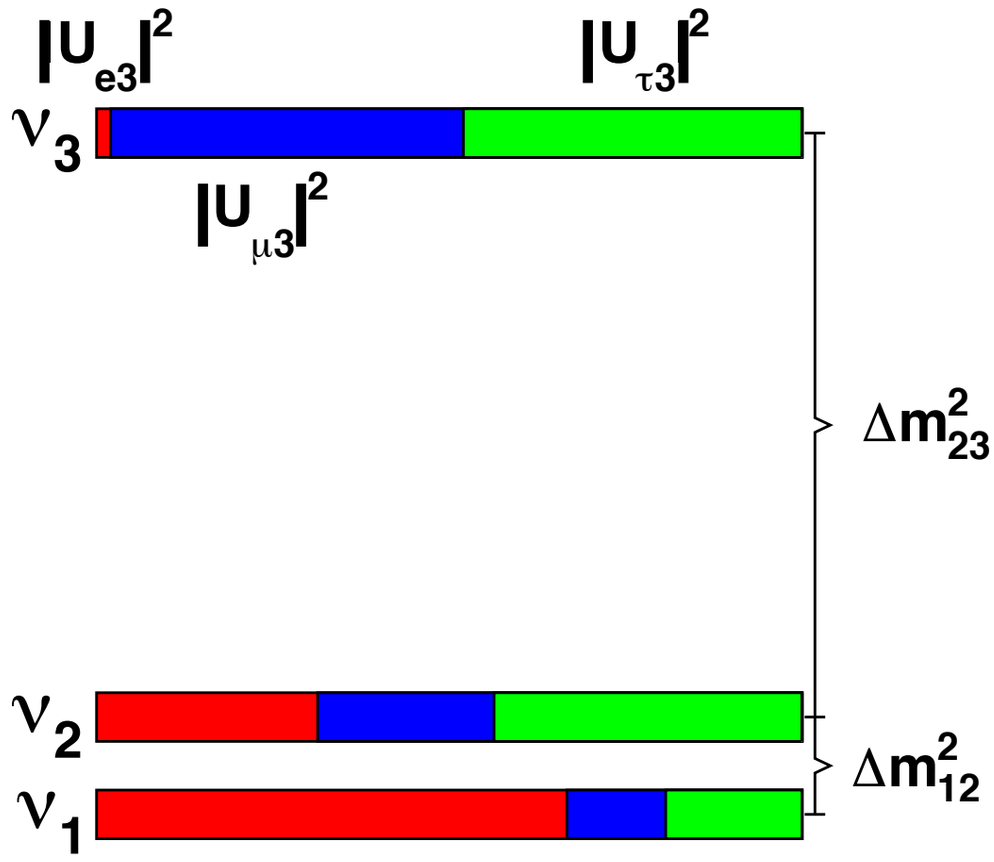
# Standard Model





# Neutrino Mixing Diagram



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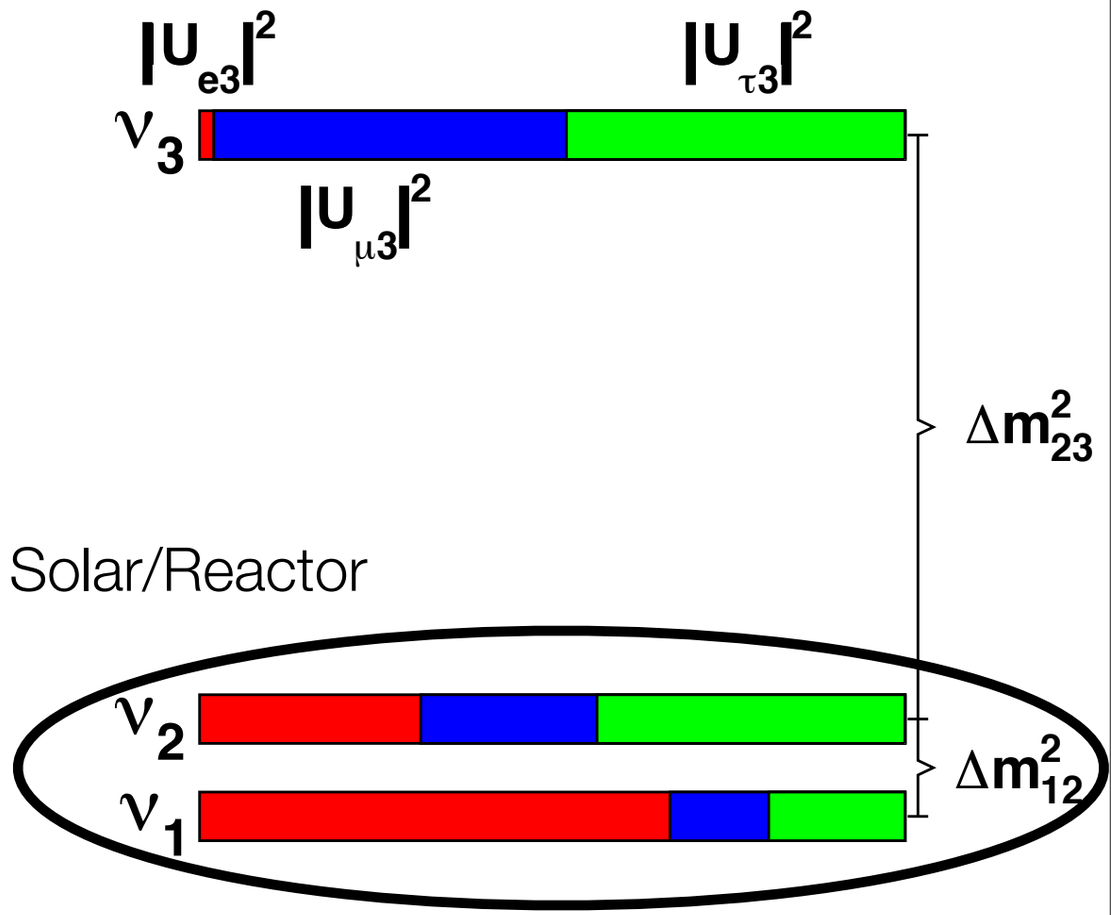


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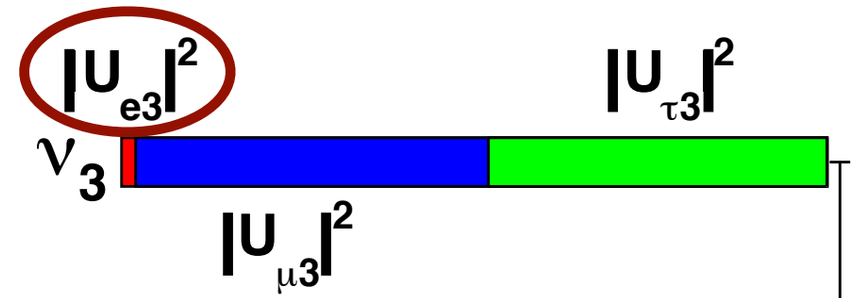
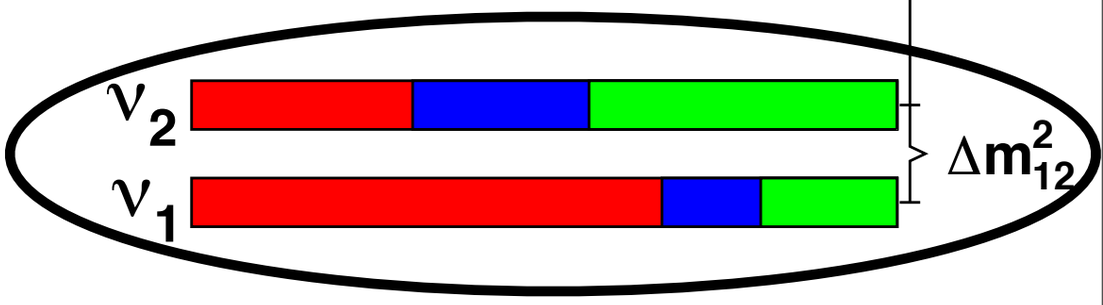
| Solar & Reactor | $\left(\nu_e \rightarrow \nu_\mu\right)$ |
| Short Baseline (SBL) & Off-Axis | $\left(\nu_e \rightarrow \nu_e\right)$ $\left(\nu_\mu \rightarrow \nu_e\right)$ |

Short Baseline & Off-Axis Accelerator




$\Delta m^2_{23}$

Solar/Reactor

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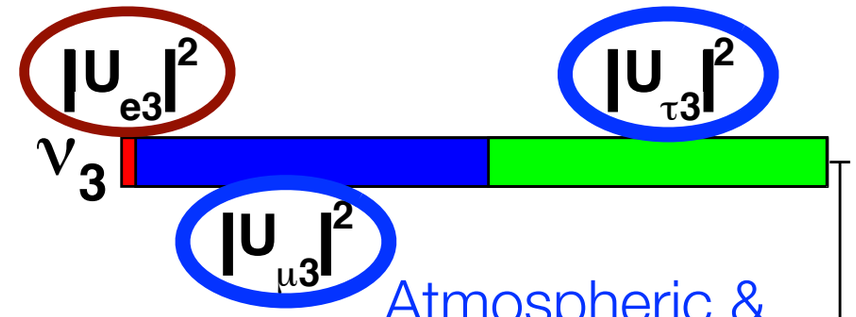
| | $(\nu_\mu \rightarrow \nu_e)$ |
| Atmospheric & Long Baseline | $(\nu_\mu \rightarrow \nu_\mu)$ |
| | $(\nu_\mu \rightarrow \nu_\tau)$ |

Short Baseline & Off-Axis Accelerator

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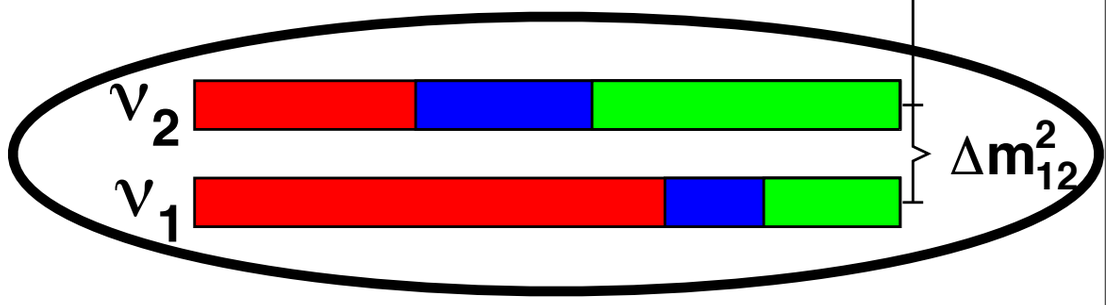


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## PMNS - $\nu$ Mixing

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# Large Weak Mixing



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Tri Bi

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**Tri** **Bi**

Is Tribimaximal a real Symmetry?

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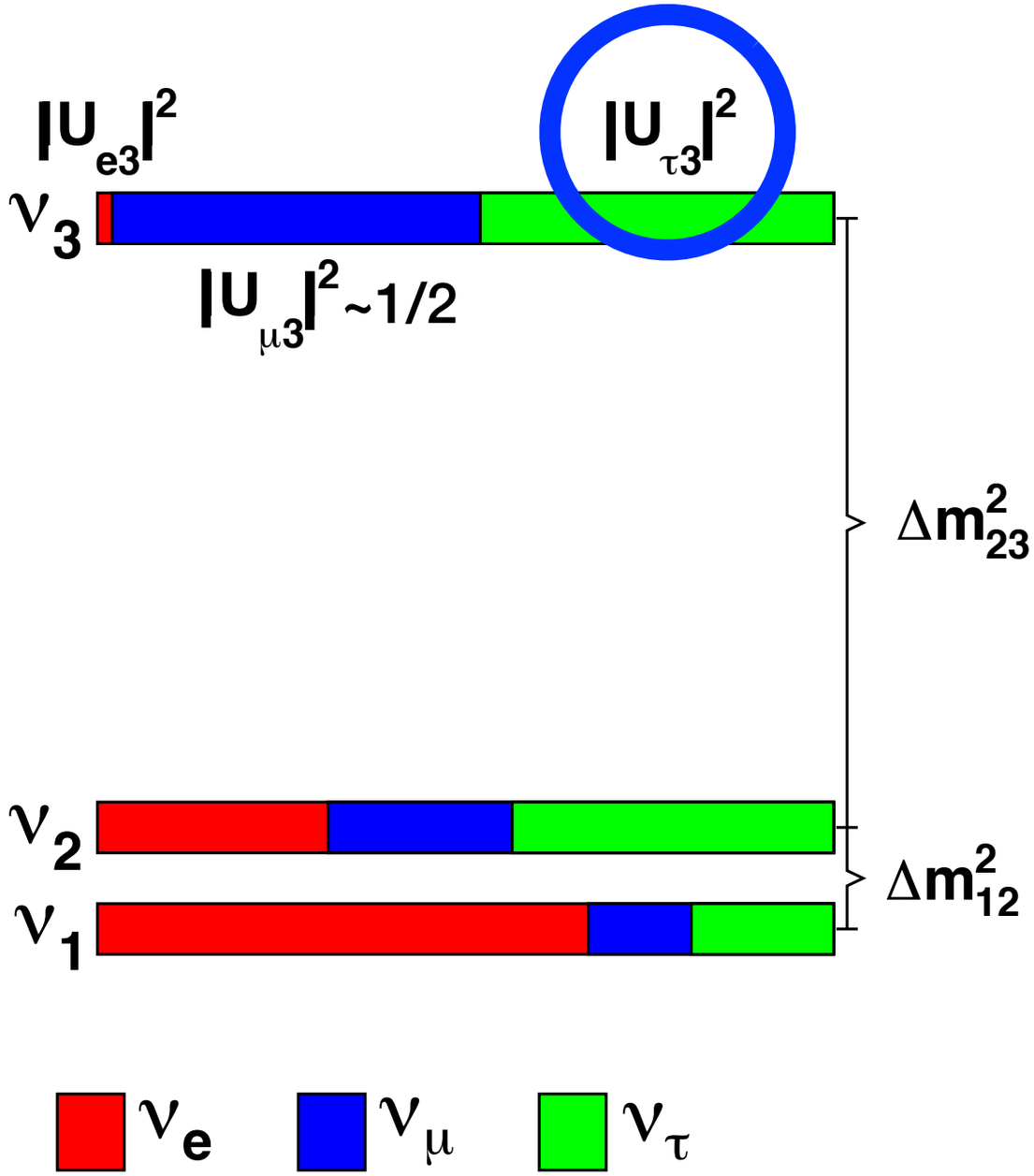
## CKM - Quark Mixing

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{bmatrix}.$$

Okay, but why so big versus CKM?

# Importance of $|U_{\tau 3}|^2$



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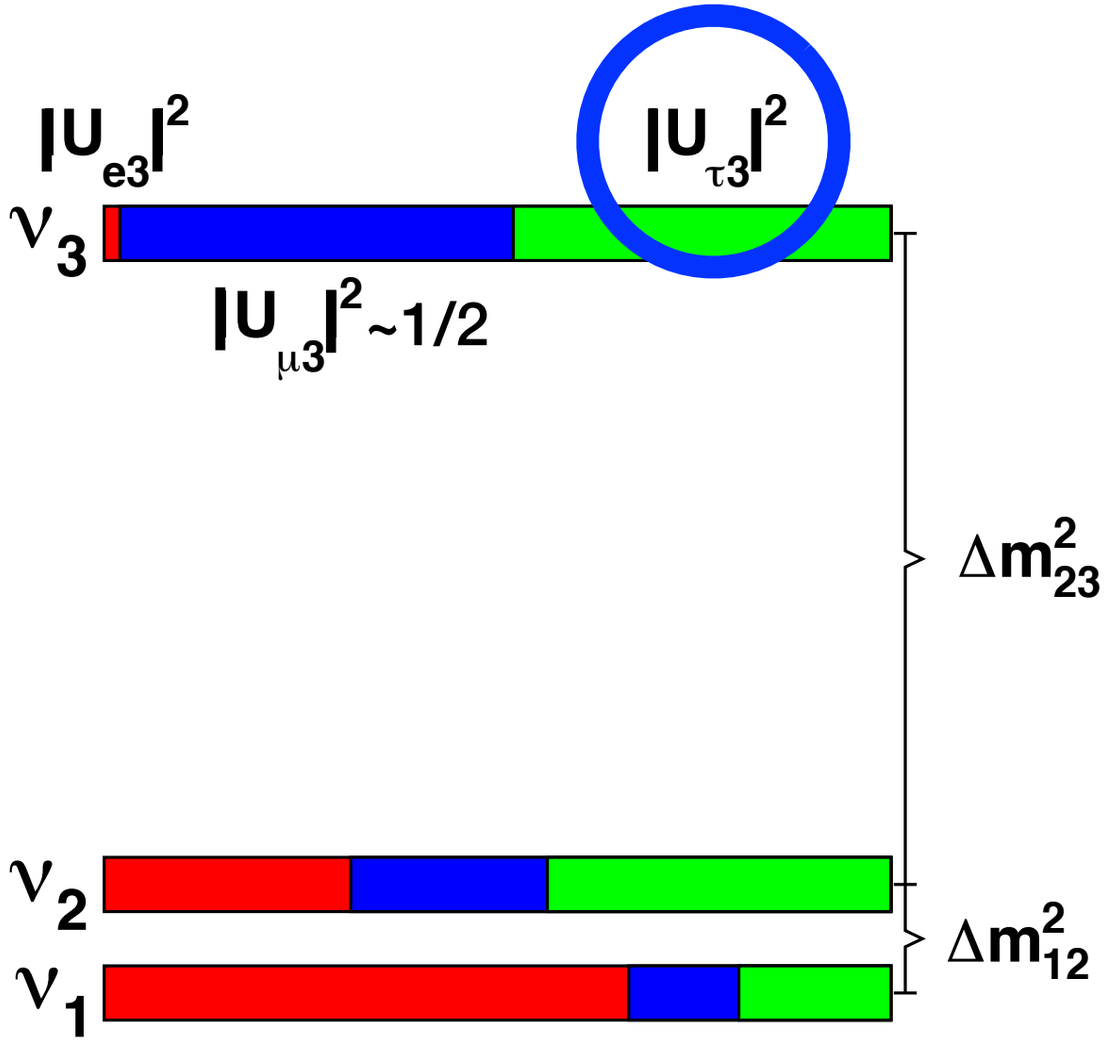


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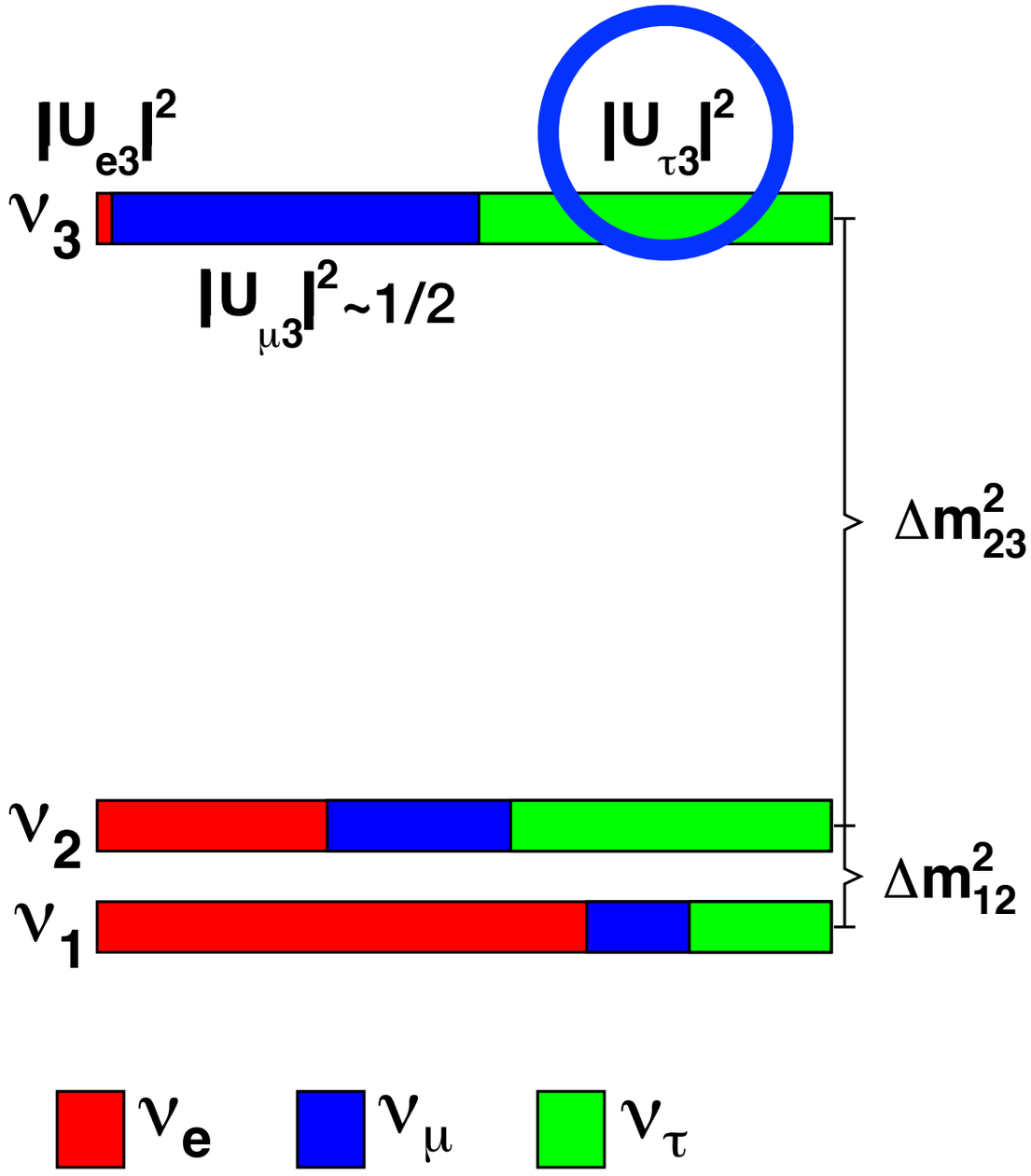


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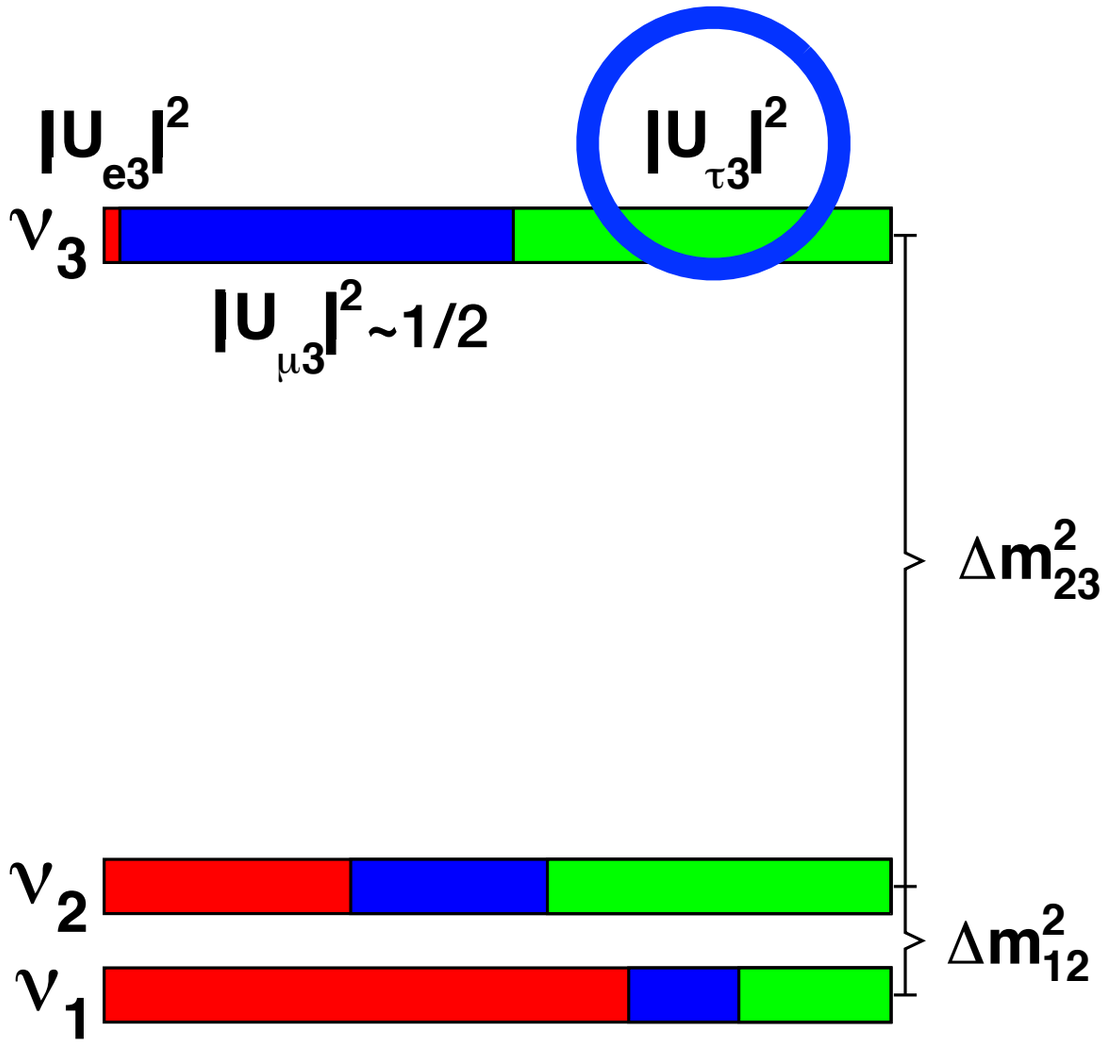


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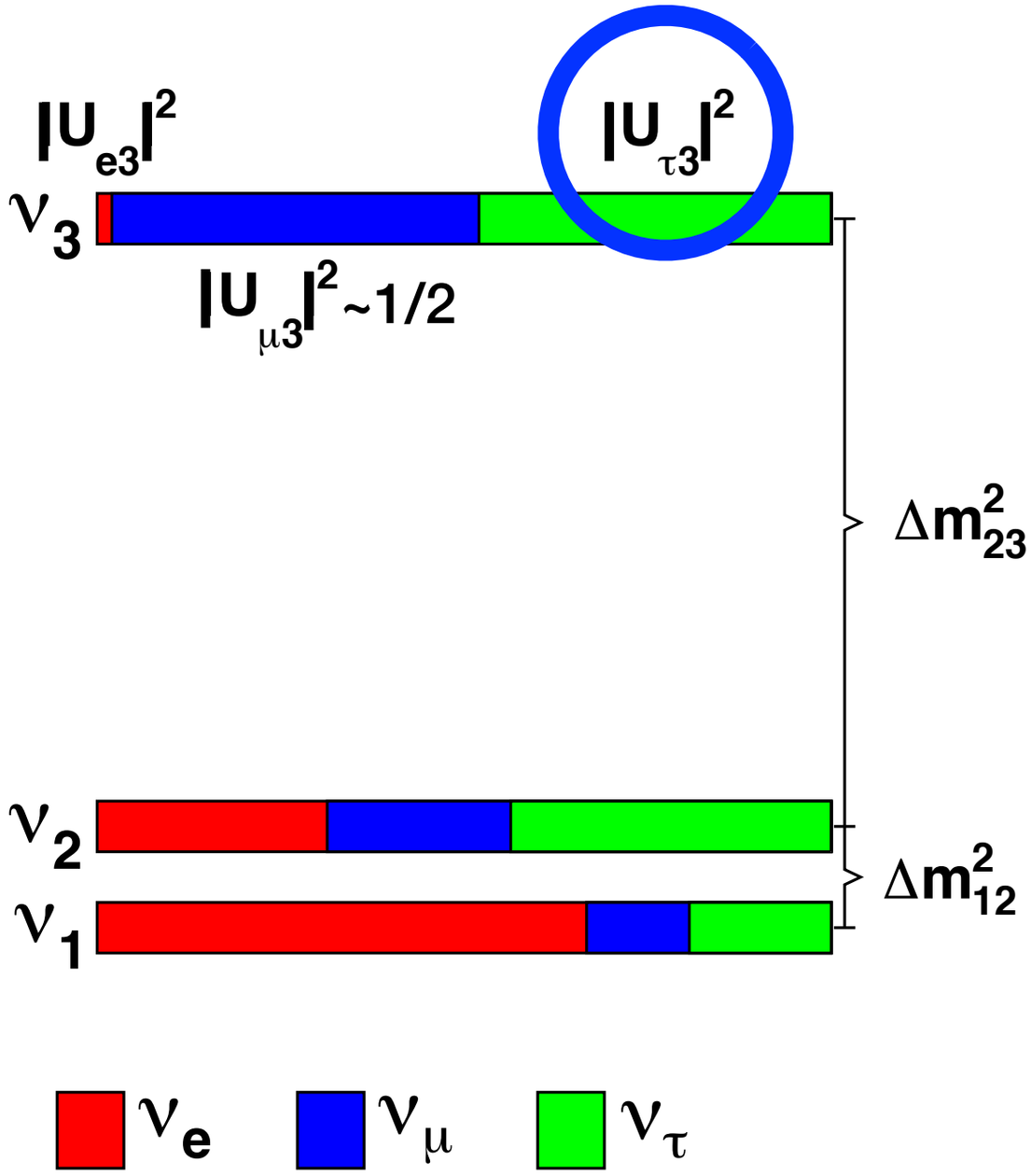


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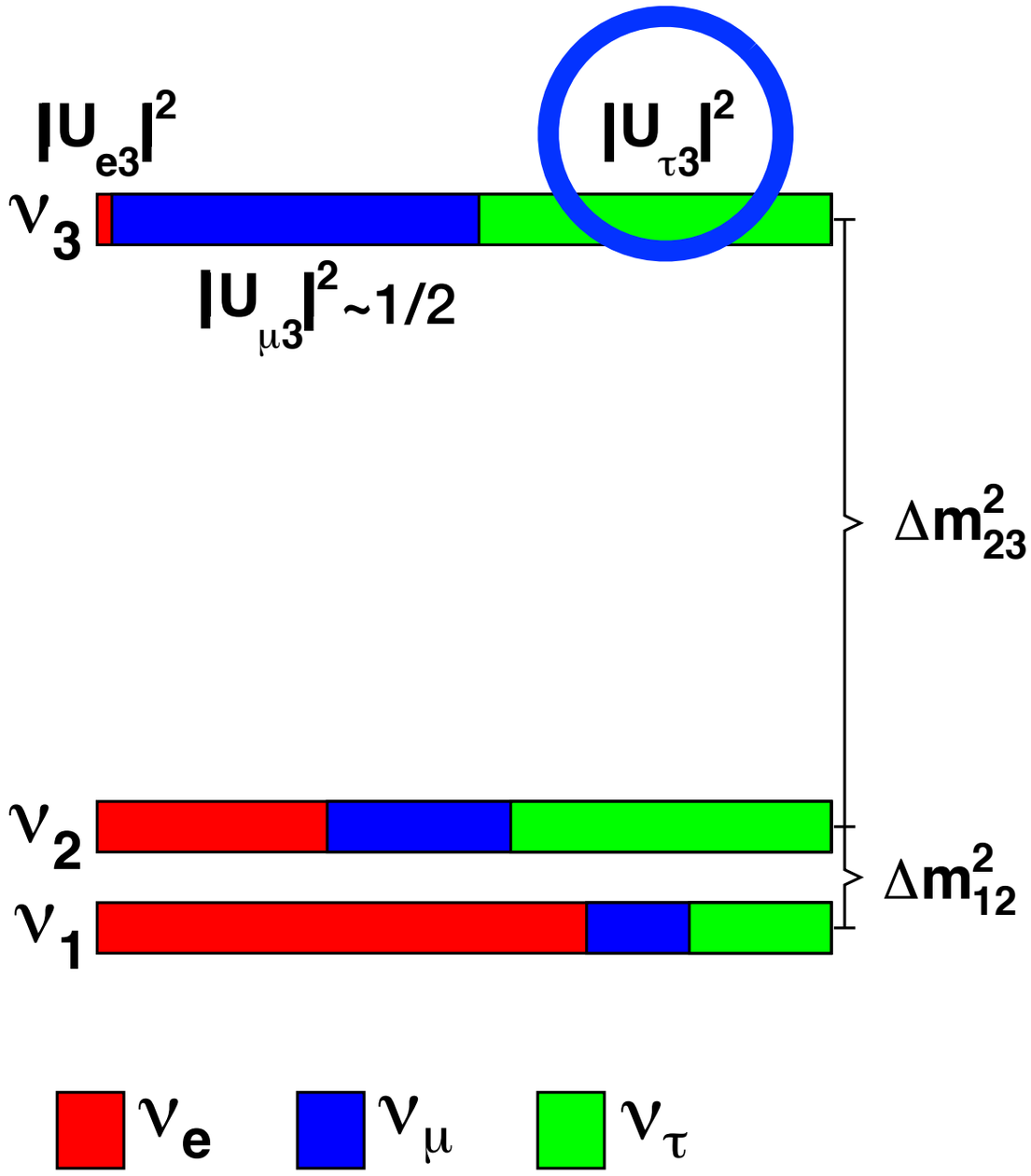


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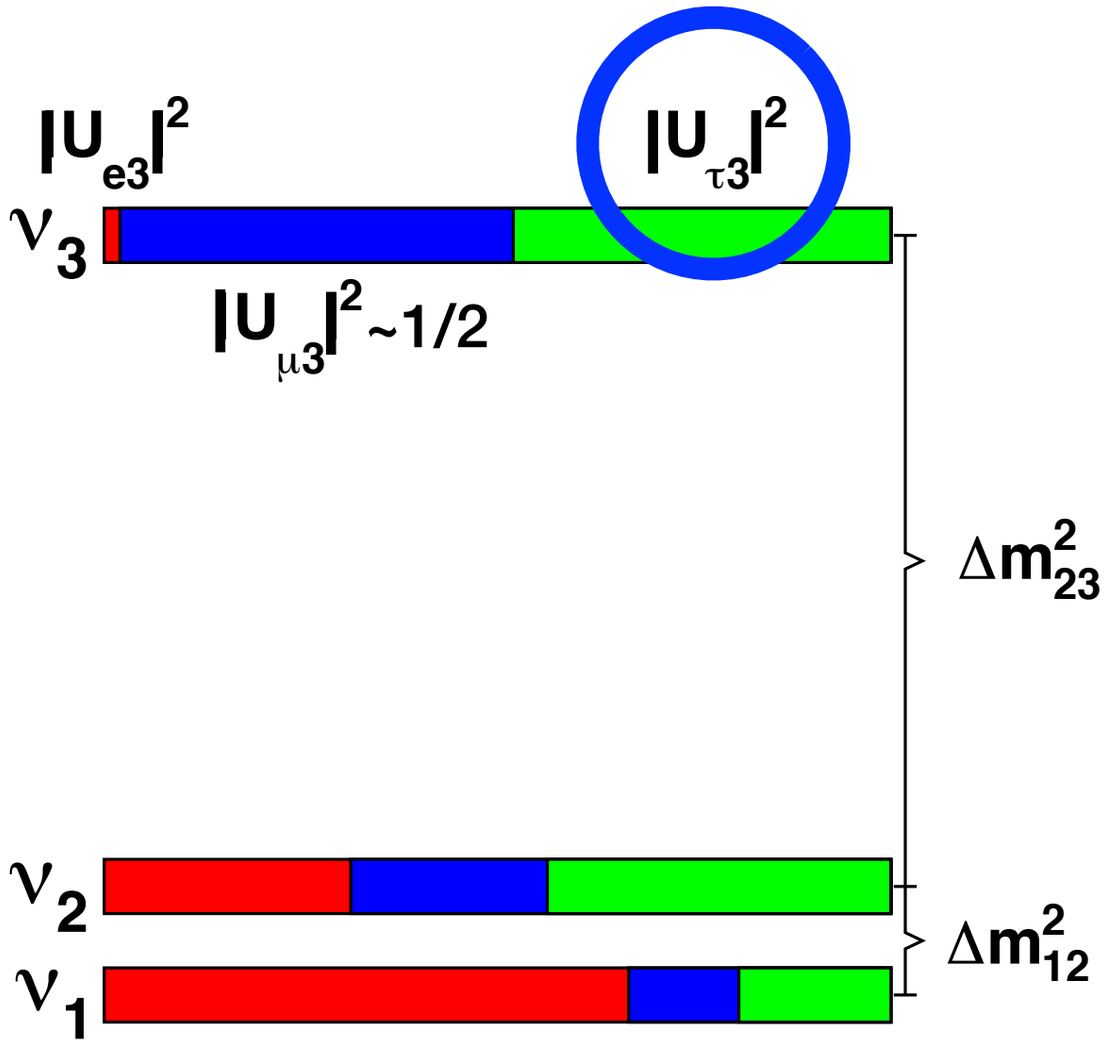
- Directly measured via observation of nutau appearance

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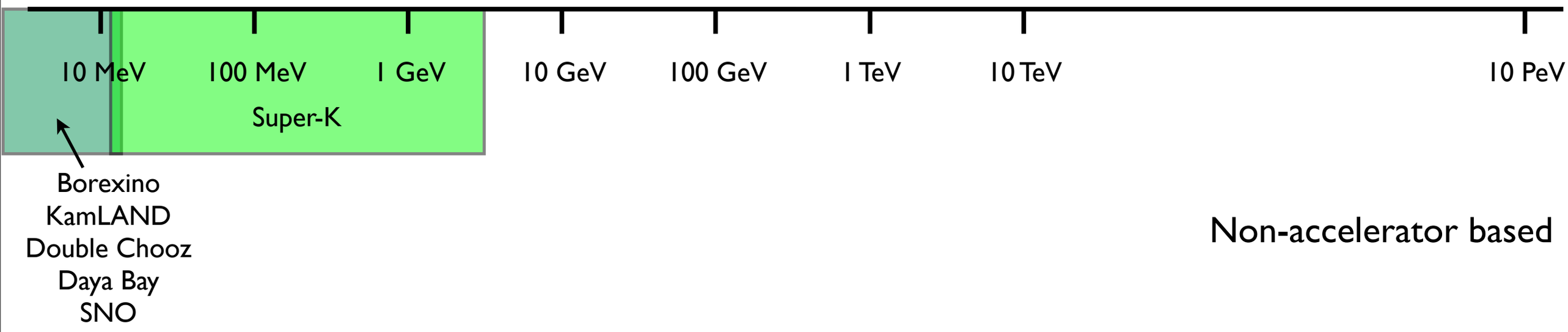
# Neutrino Experimental Landscape

# Experimental Landscape

- Reactor neutrino experiments dominate the < 1 GeV non-accelerator region

Accelerator based




Non-accelerator based

*Boxes provide sense of scale for physics sensitive regions
*concept from D. Grant

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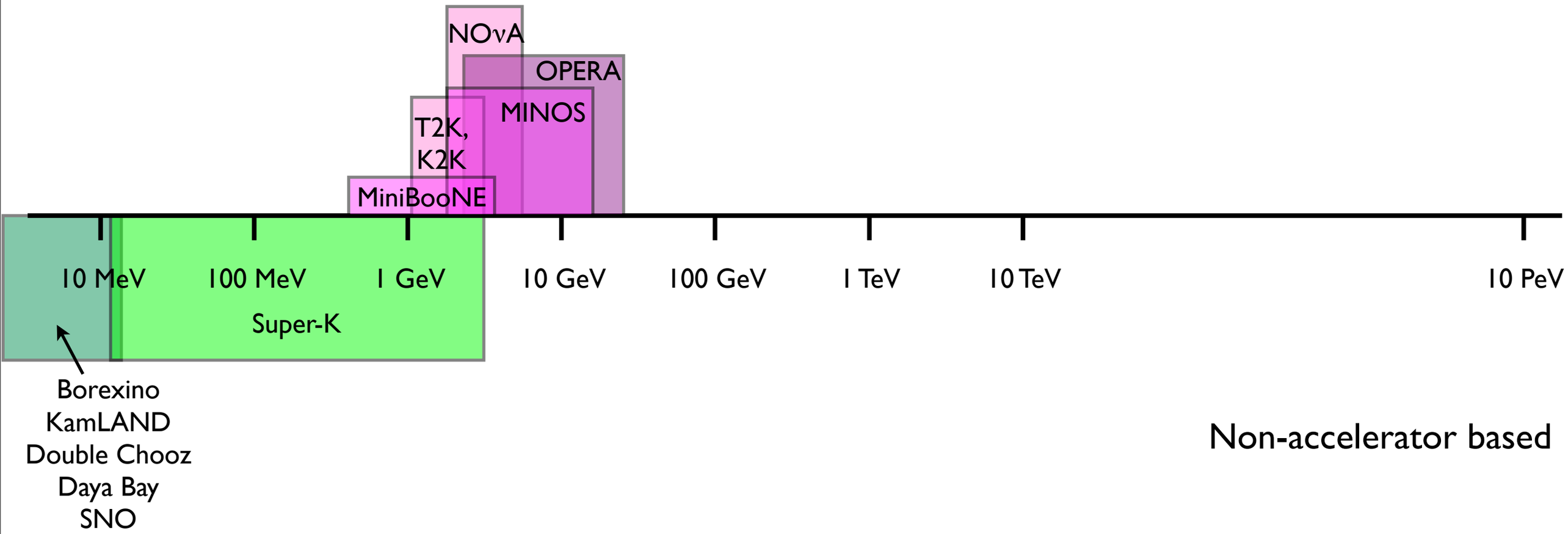


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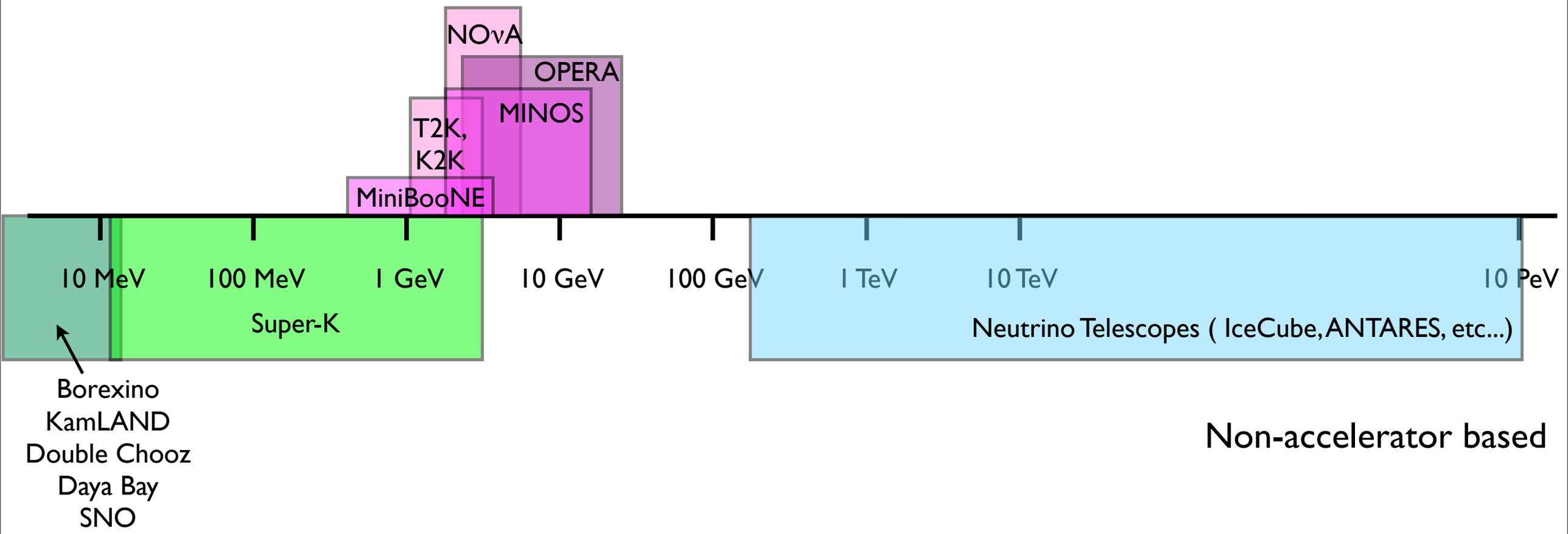


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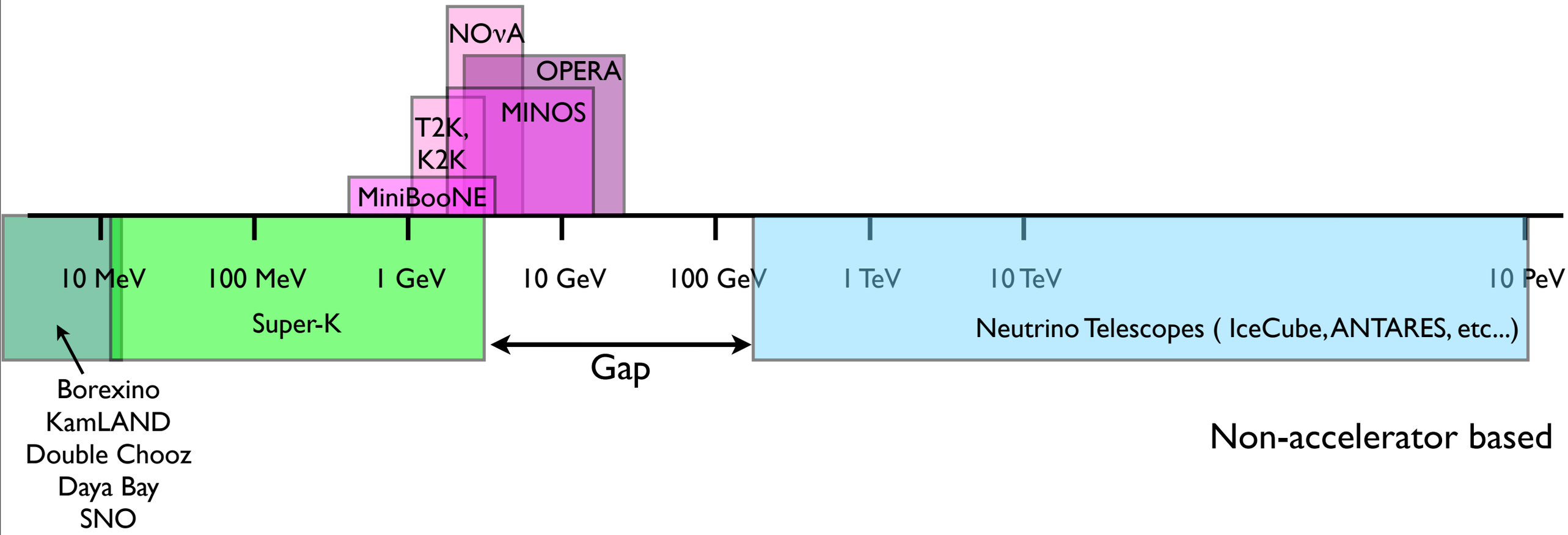


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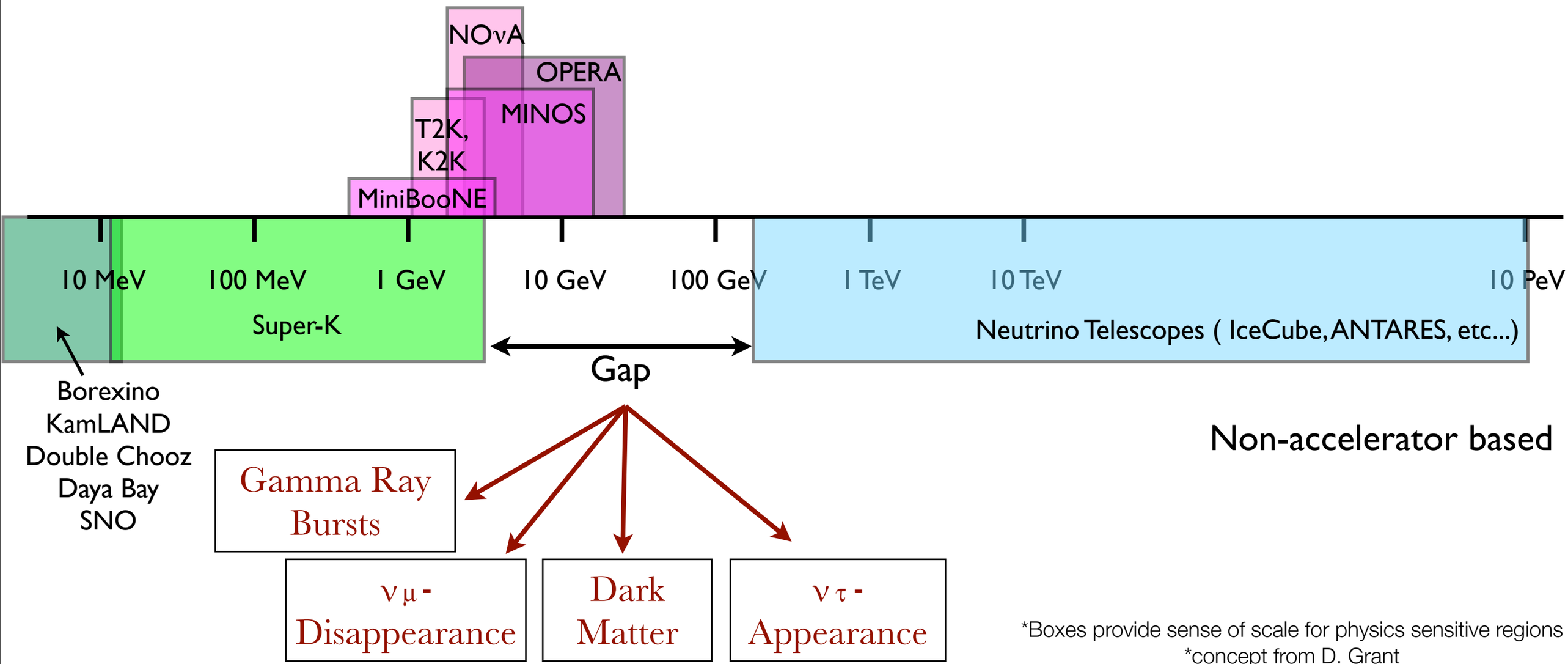


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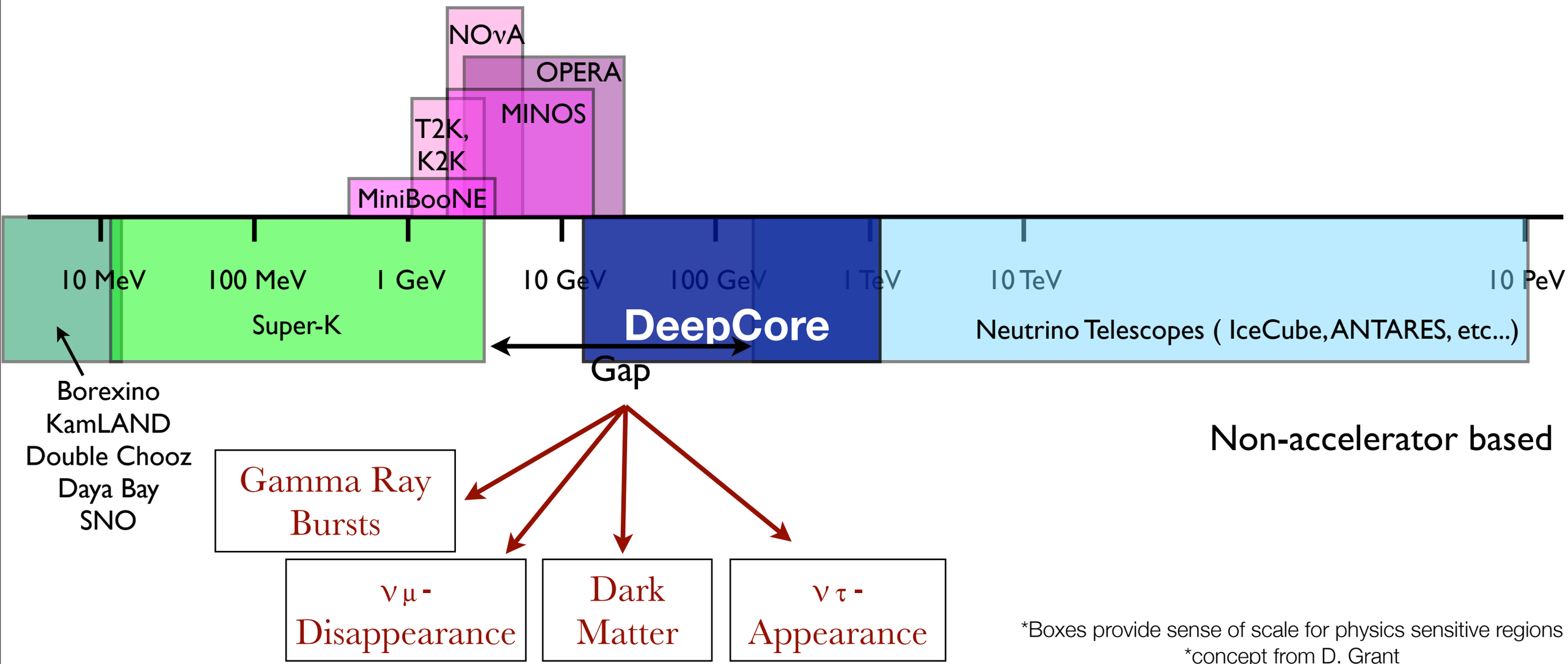


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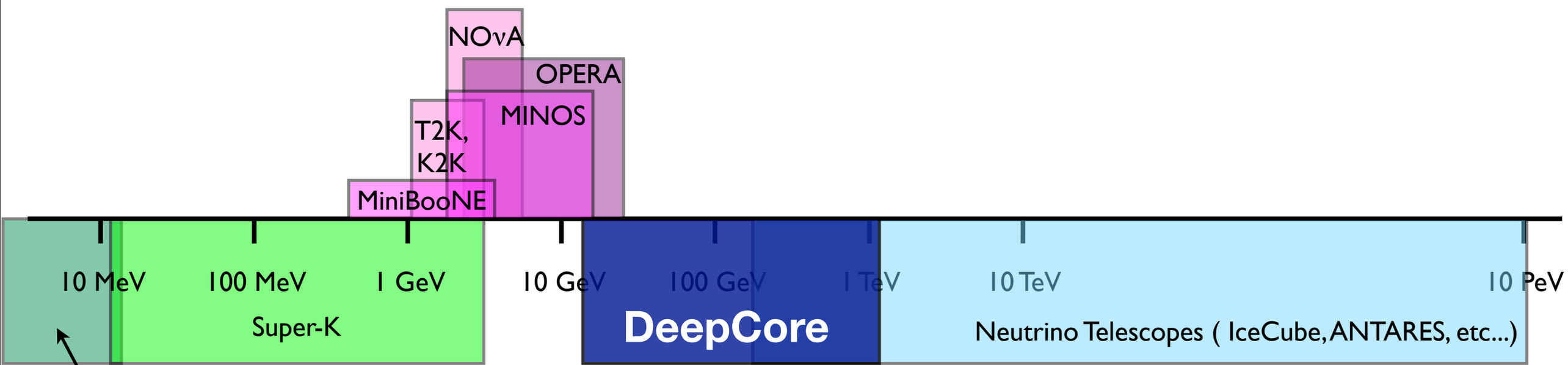


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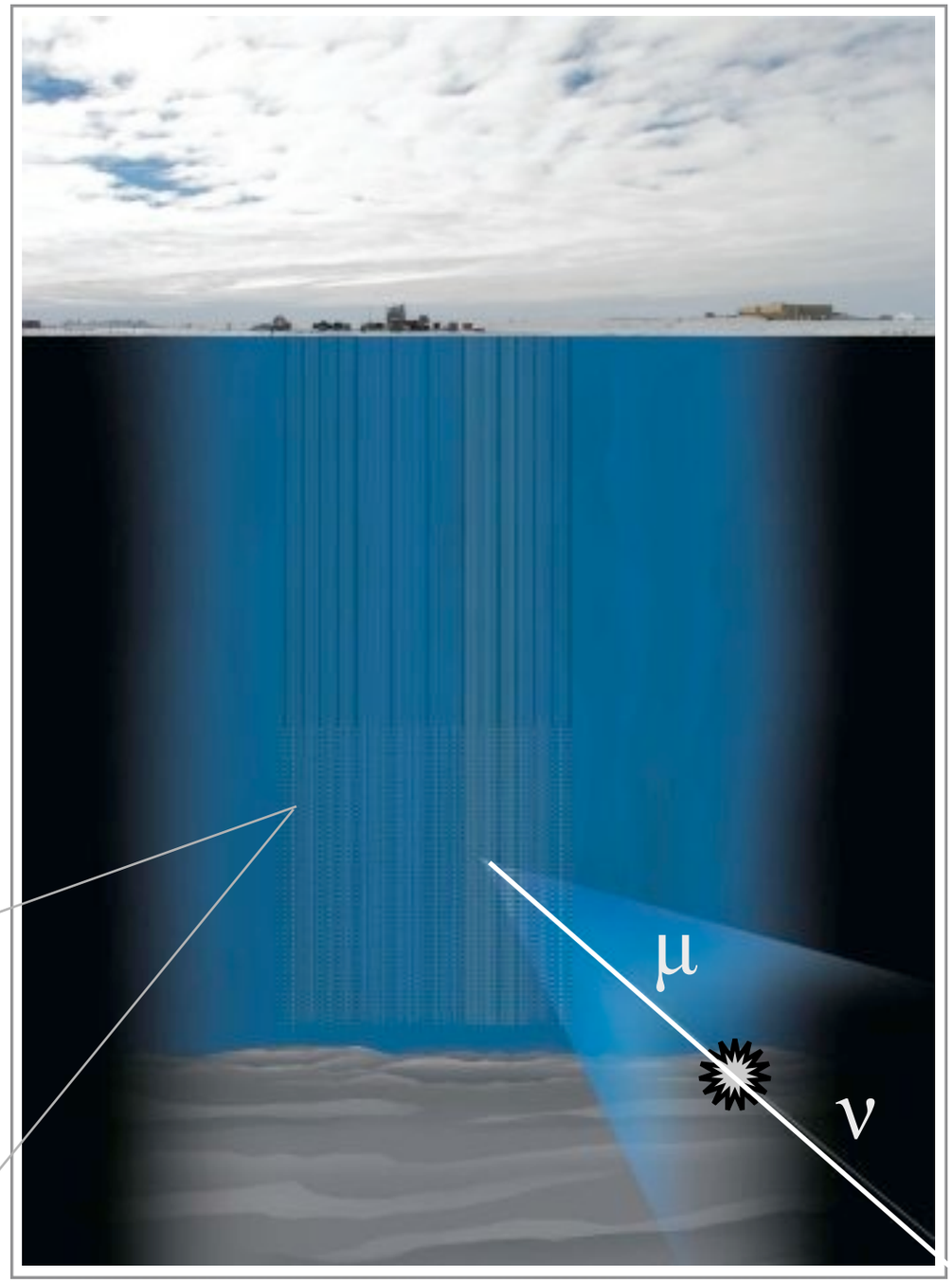
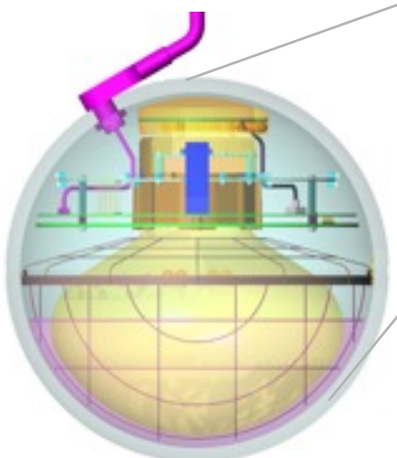
- ~1km$^3$ of instrumented ice
- Uses 5160 Digital Optical Modules (DOMs) across 86 strings within the ice to detect Cherenkov radiation
- 160 Cherenkov tank surface array (IceTop)
- Deployed 1.5-2.5km below the surface



IceCube DOM

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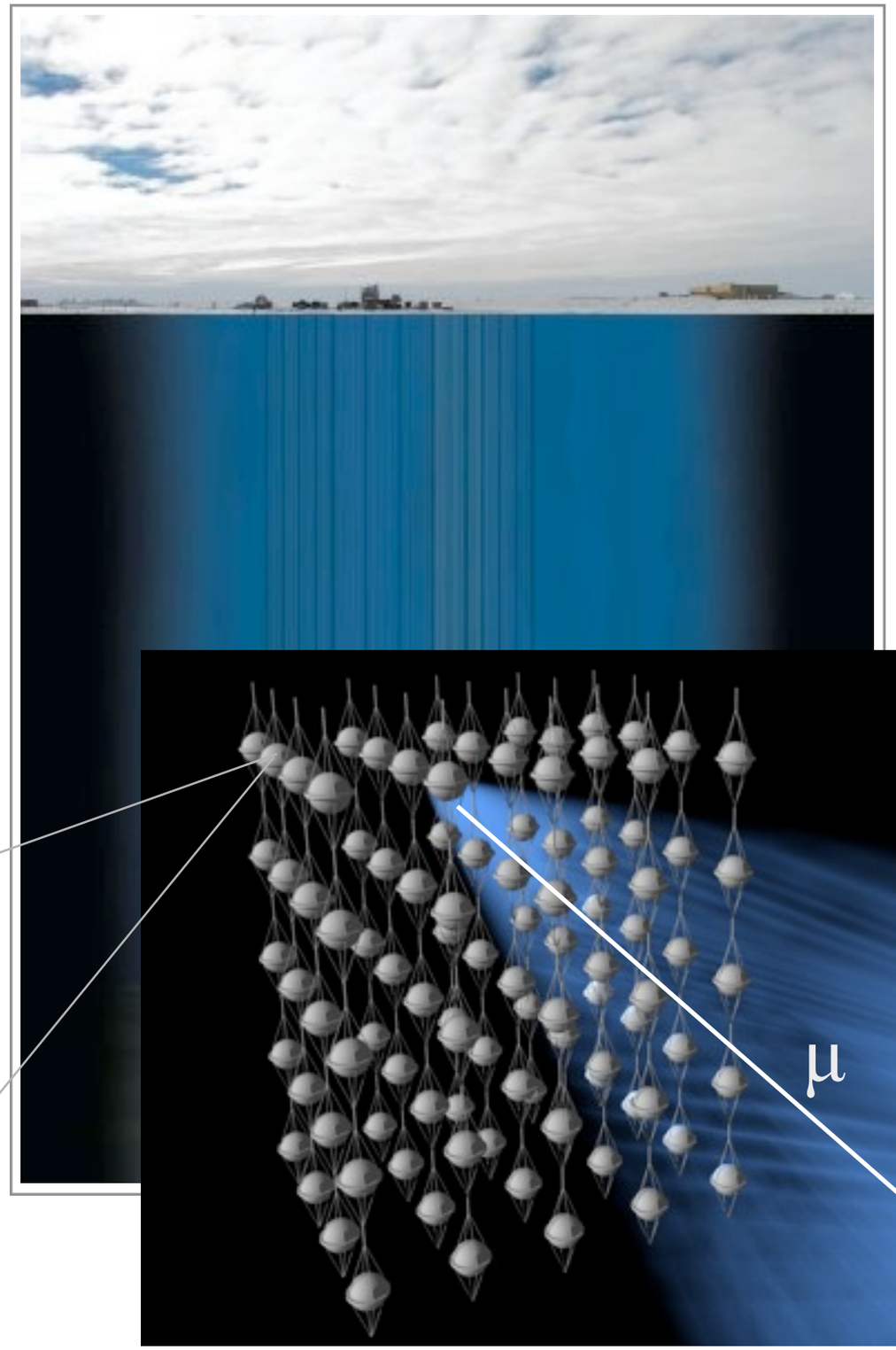
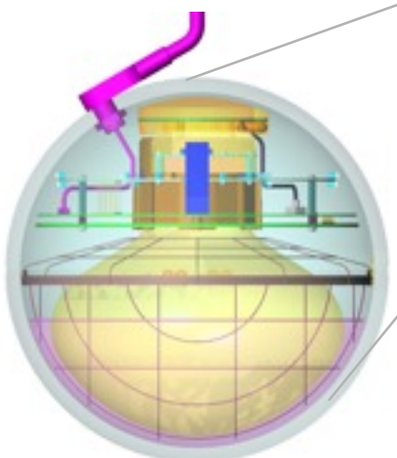
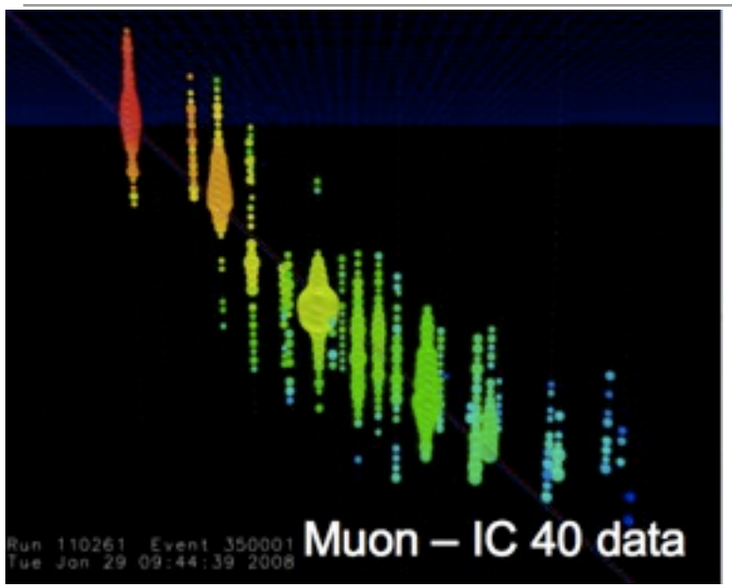


IceCube DOM

# Detection Principles

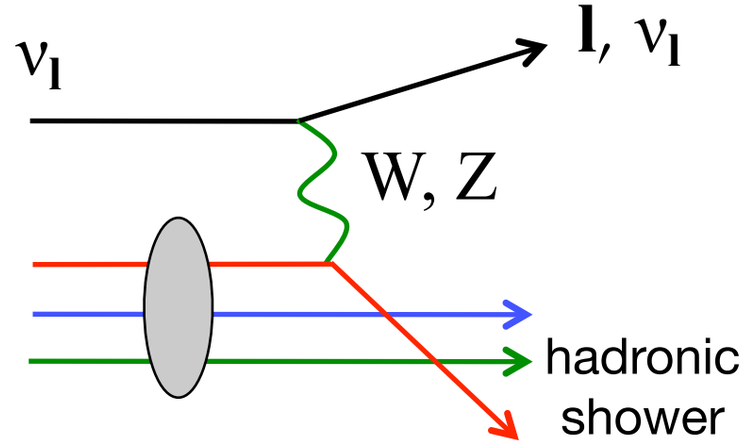





$\nu_\mu$

Tracks:

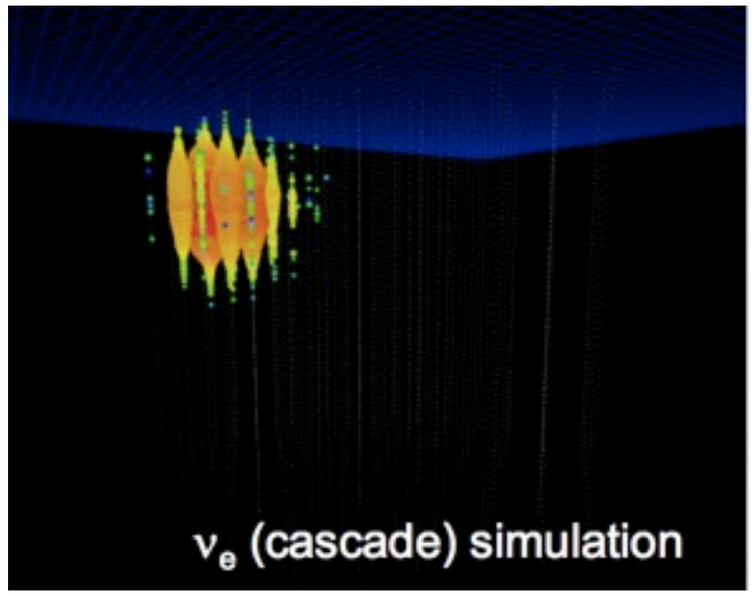
- through-going muons
- km long at high energy

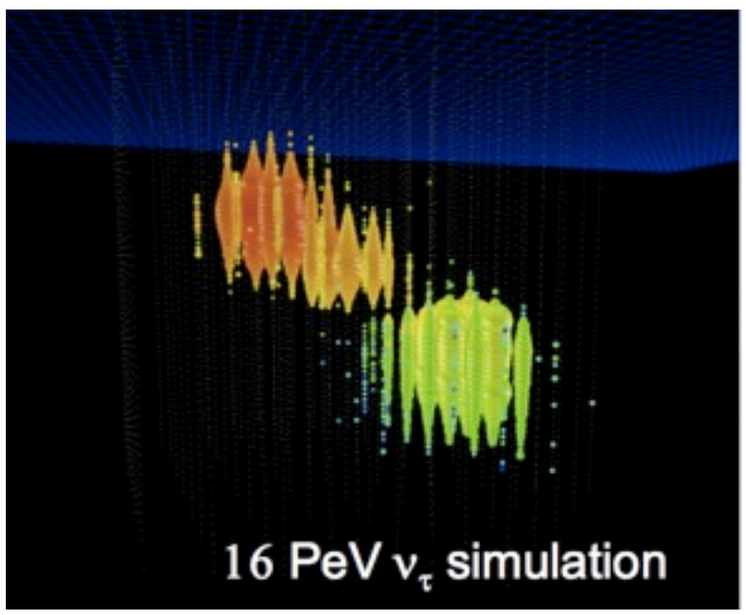



$\nu_\tau, \nu_e$

Cascades:

- Neutral current for all flavors
- few m at low energy
- Charged current for $\nu_e$ and low-E $\nu_\tau$




$\nu_\tau$

Composites:

- Starting tracks
- high-E (PeV) $\nu_\tau$ (Double Bangs)
- Good directional and energy resolution

# Collaboration

- Oscillation
- IceCube-DeepCore Physics
- PINGU
- Beyond

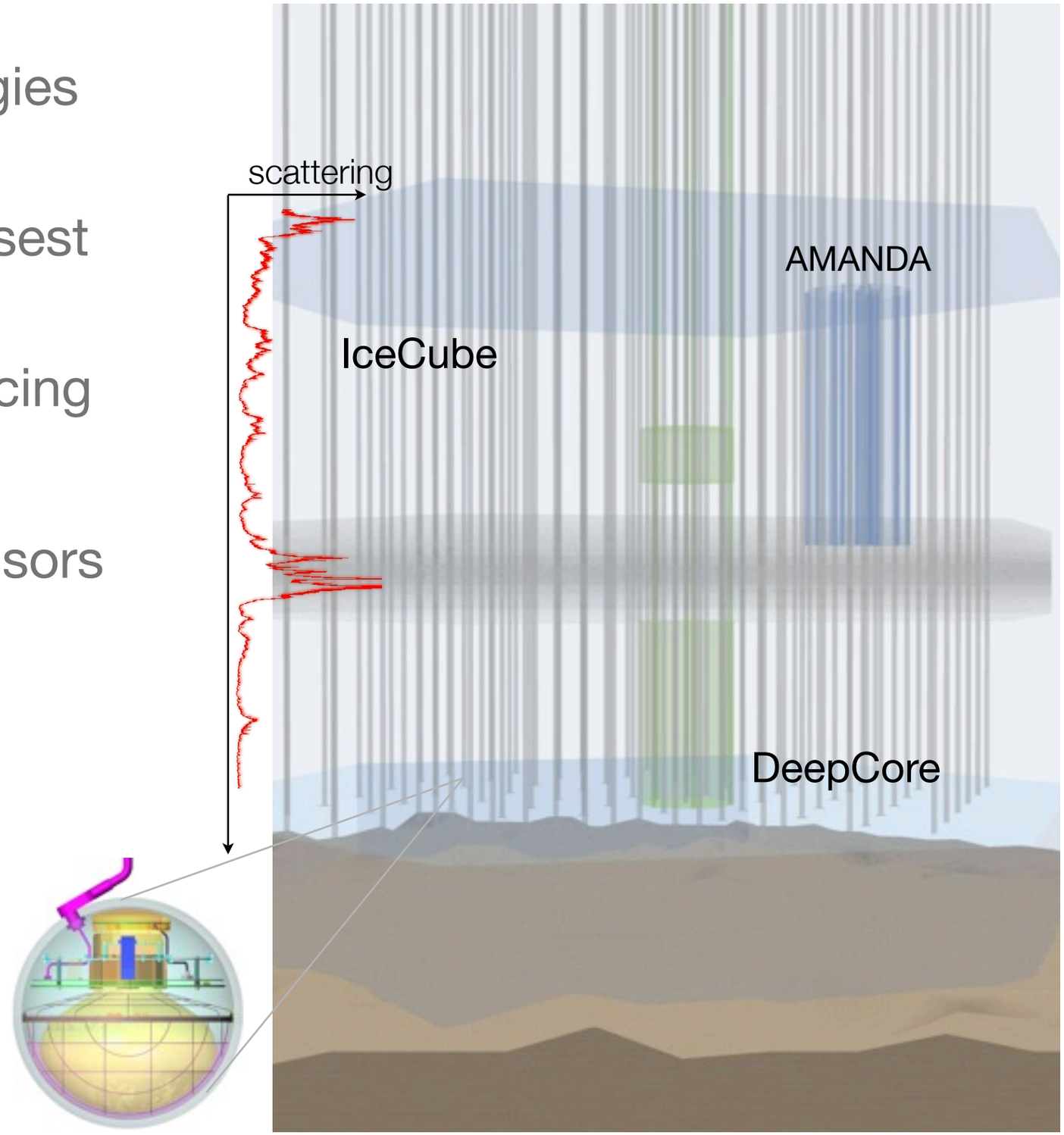


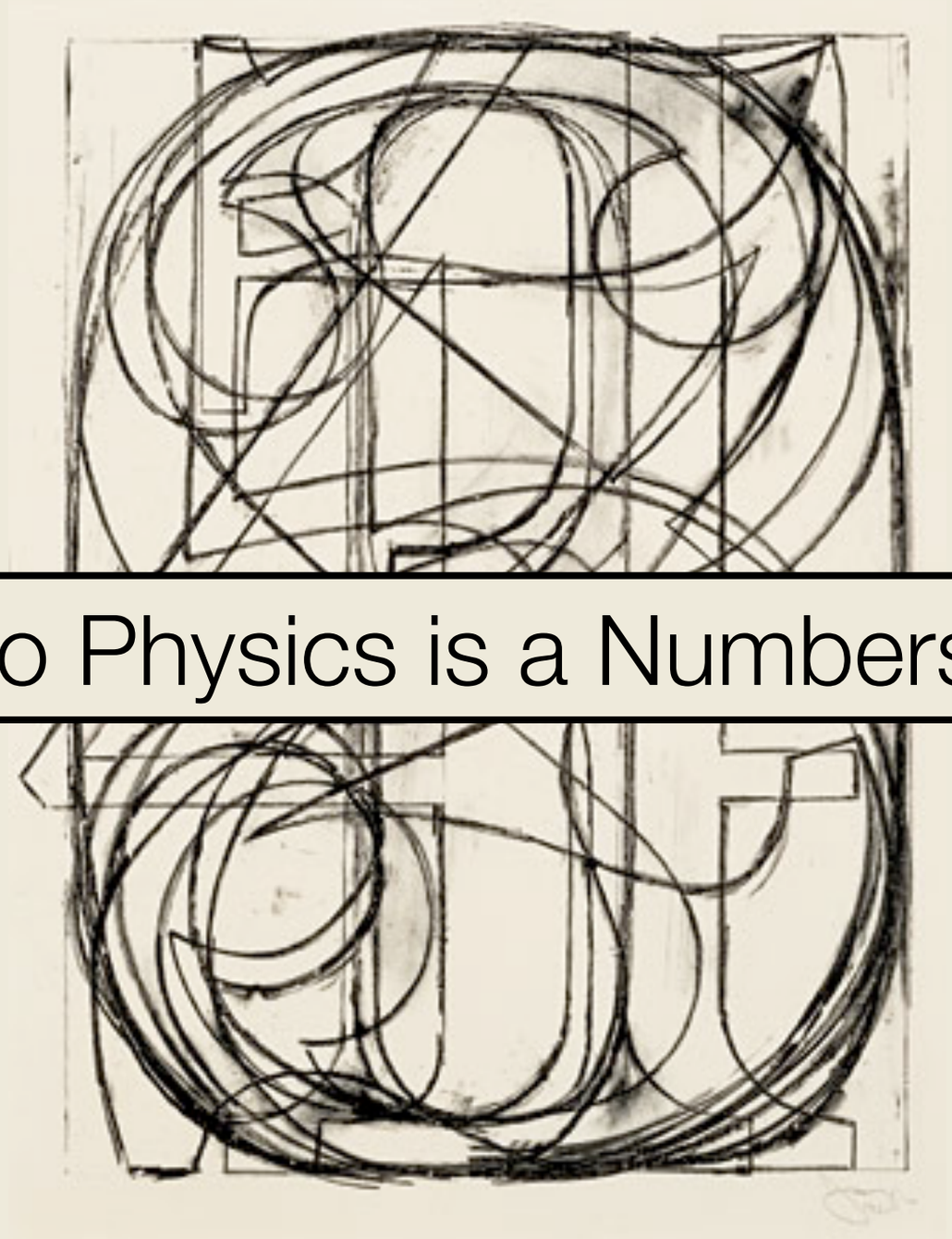

# The IceCube Collaboration

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



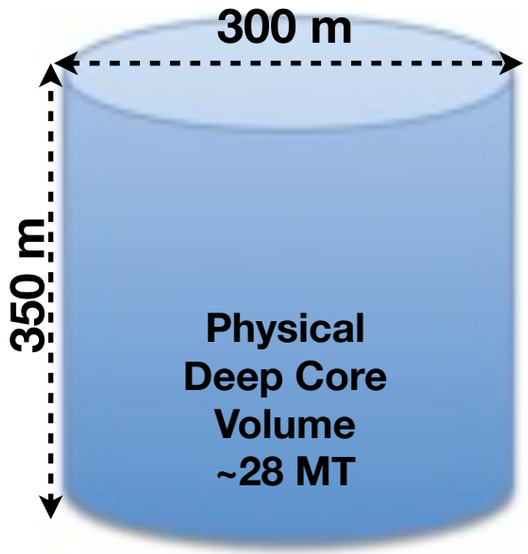


# Neutrino Physics is a Numbers Game

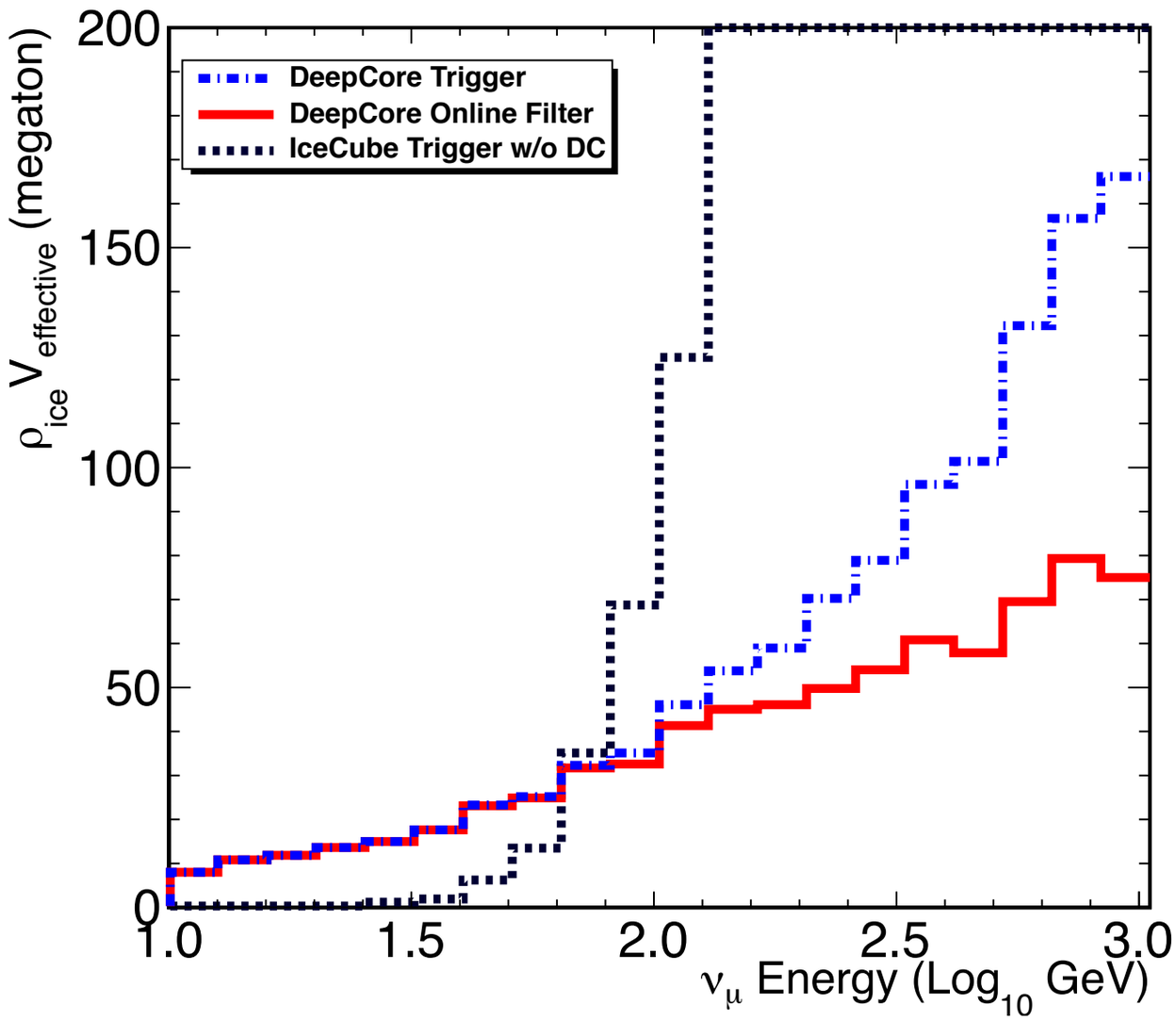
Jasper Johns “0 through 9”

# Size Matters

- IceCube gains a dramatic improvement in sensitivity to neutrinos < 100 GeV with DeepCore




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



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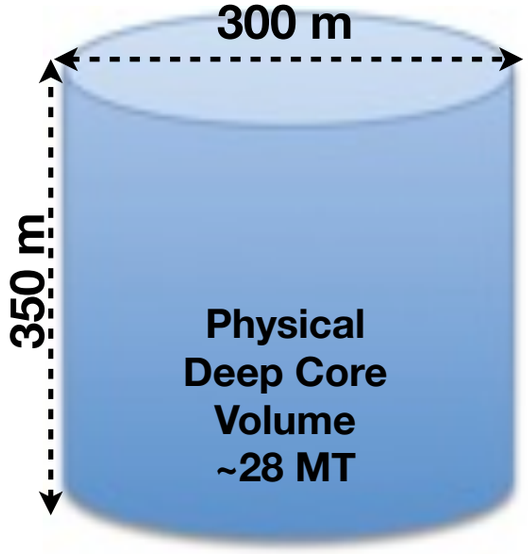


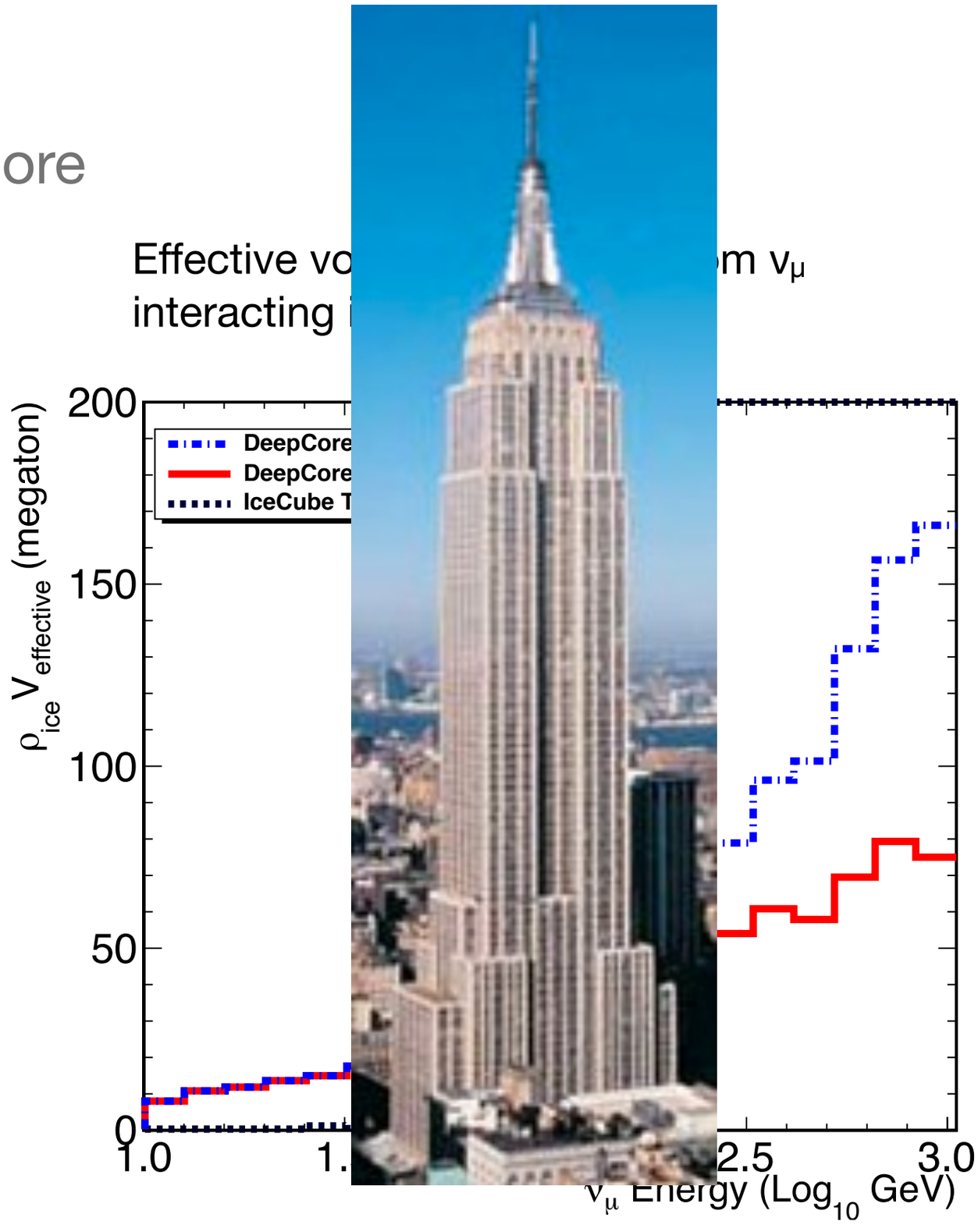

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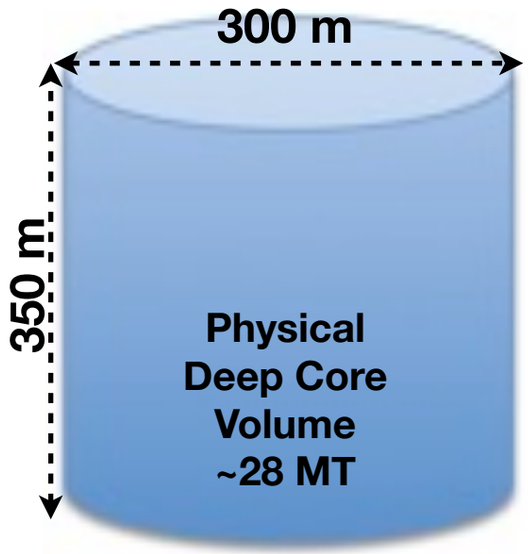




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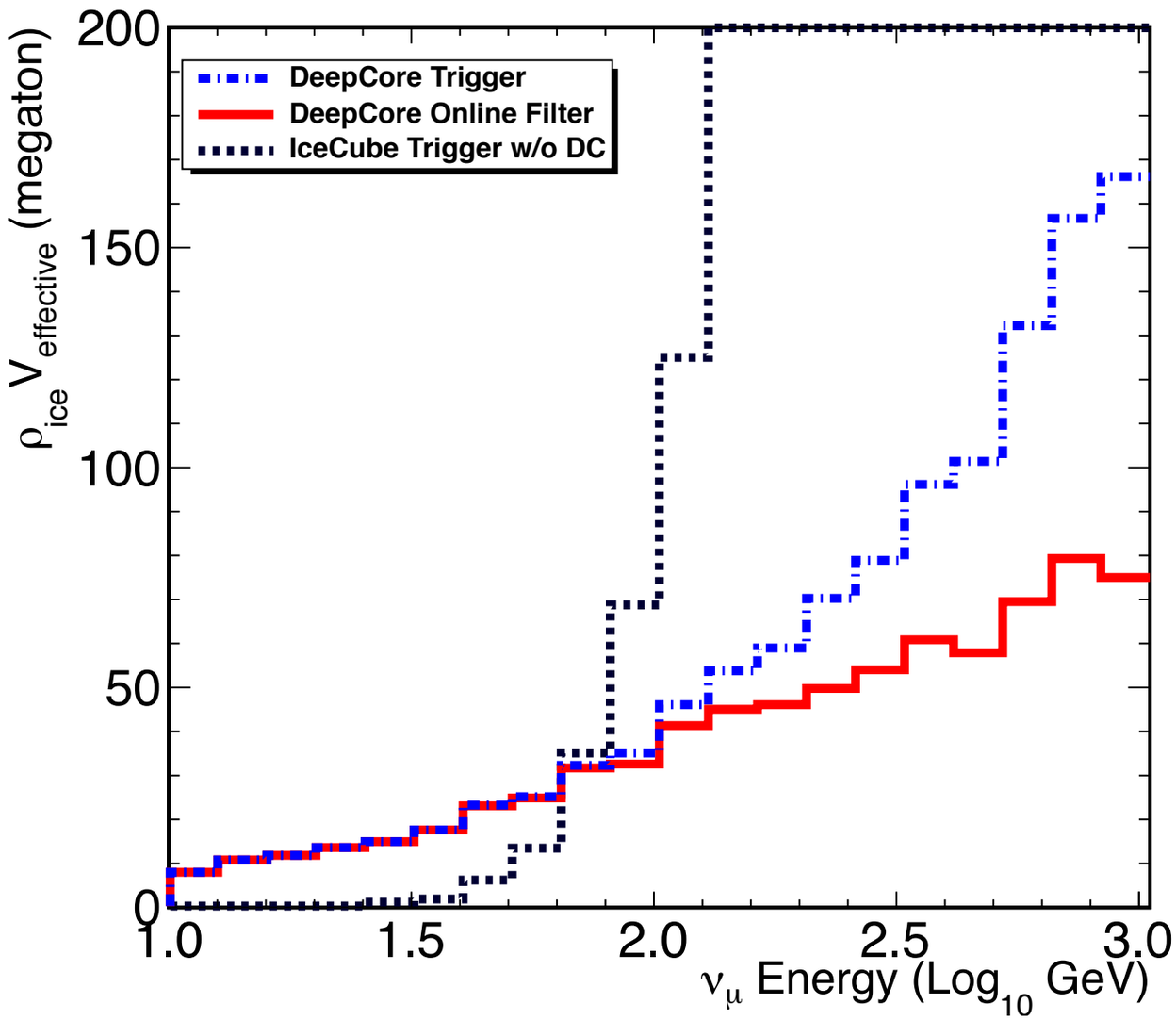
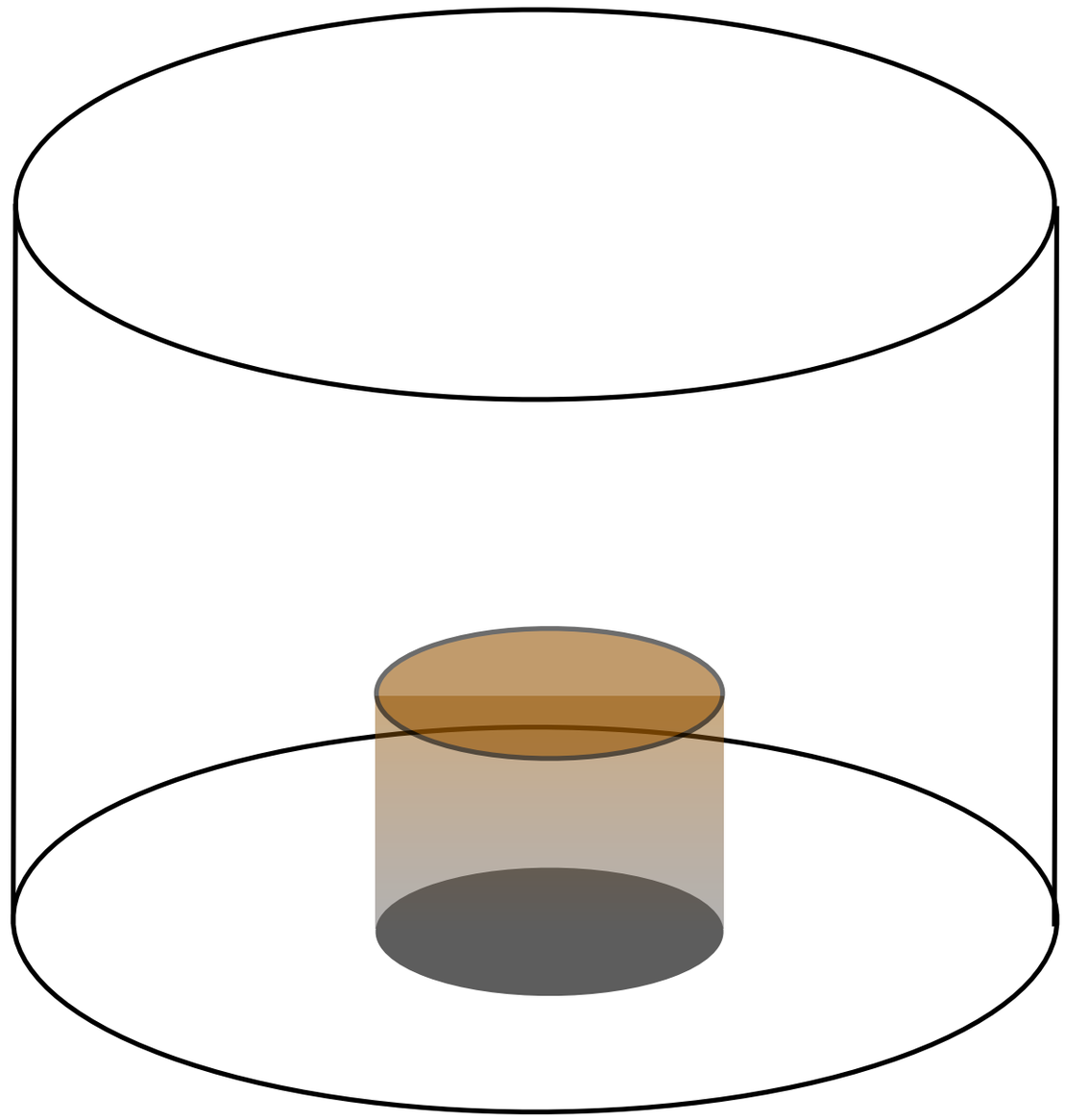
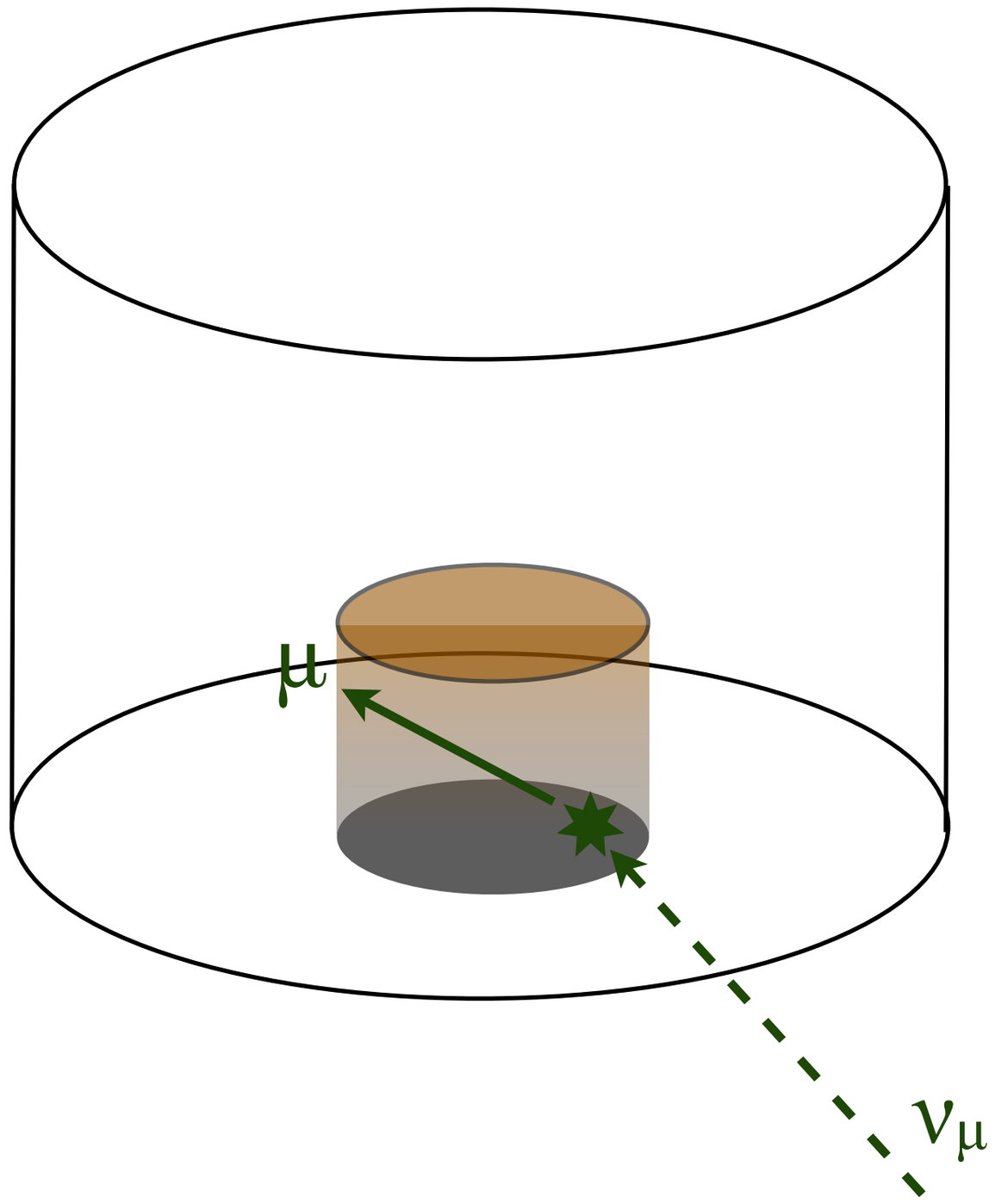
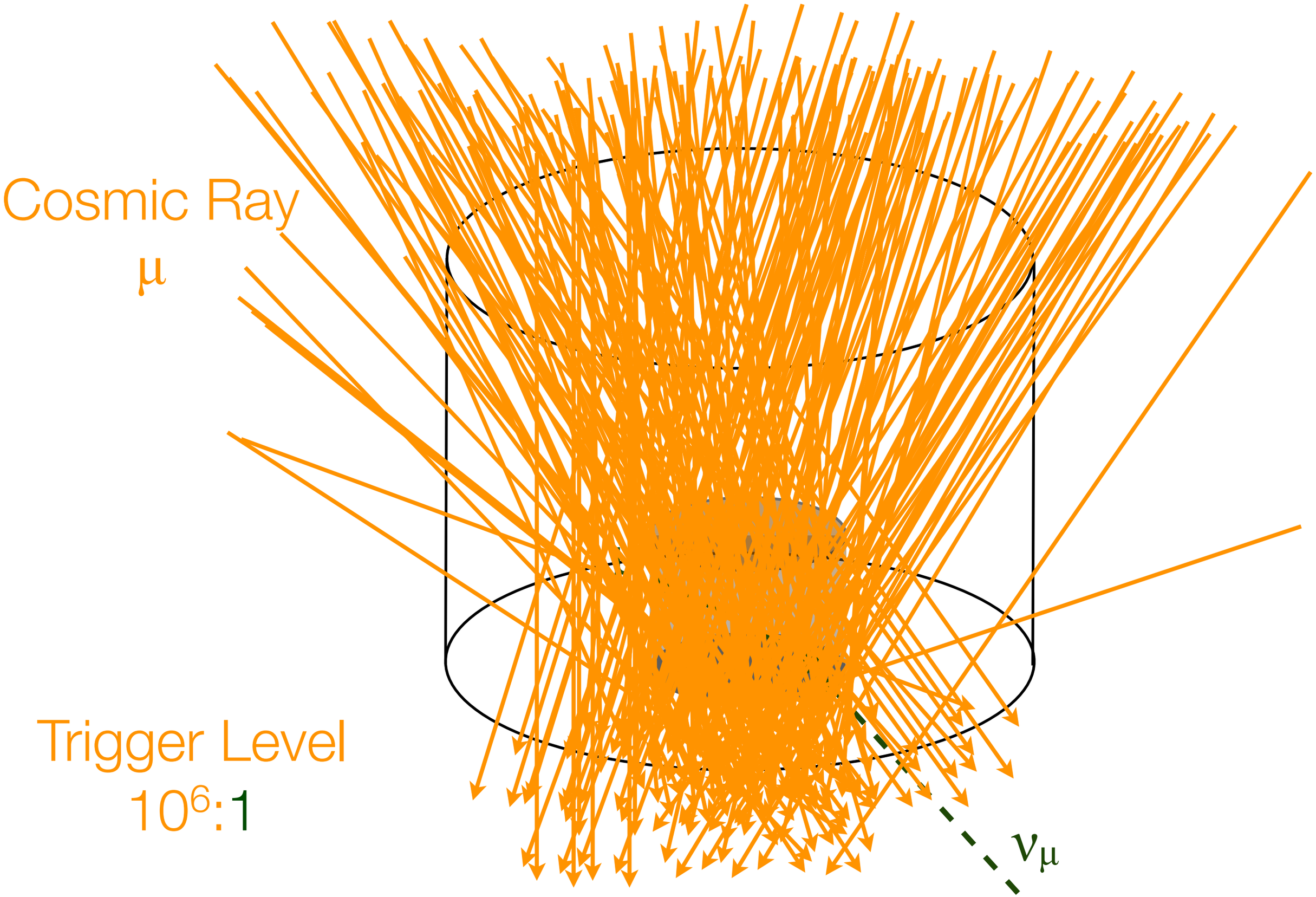




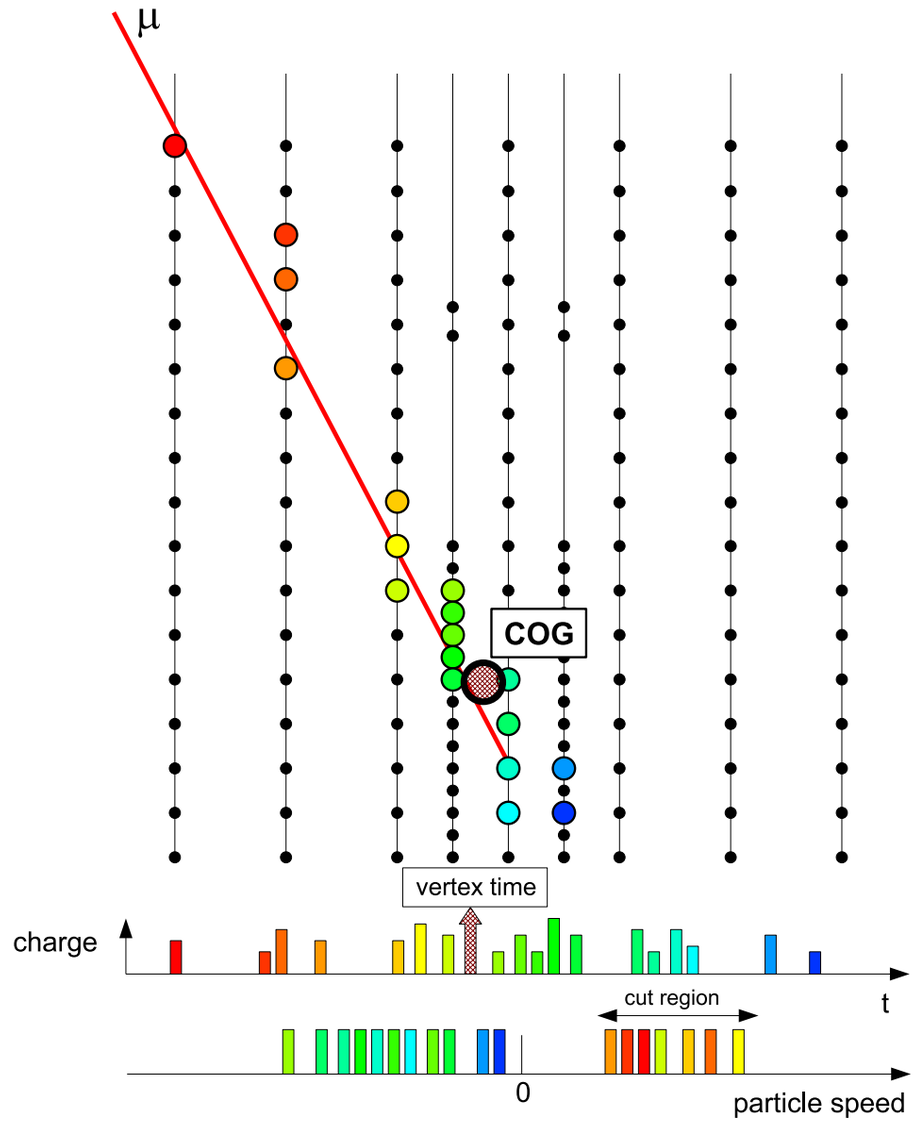

μ
$\nu_\mu$


Cosmic Ray
μ
Trigger Level
10⁶:1
$\nu_\mu$

# Background Rejection



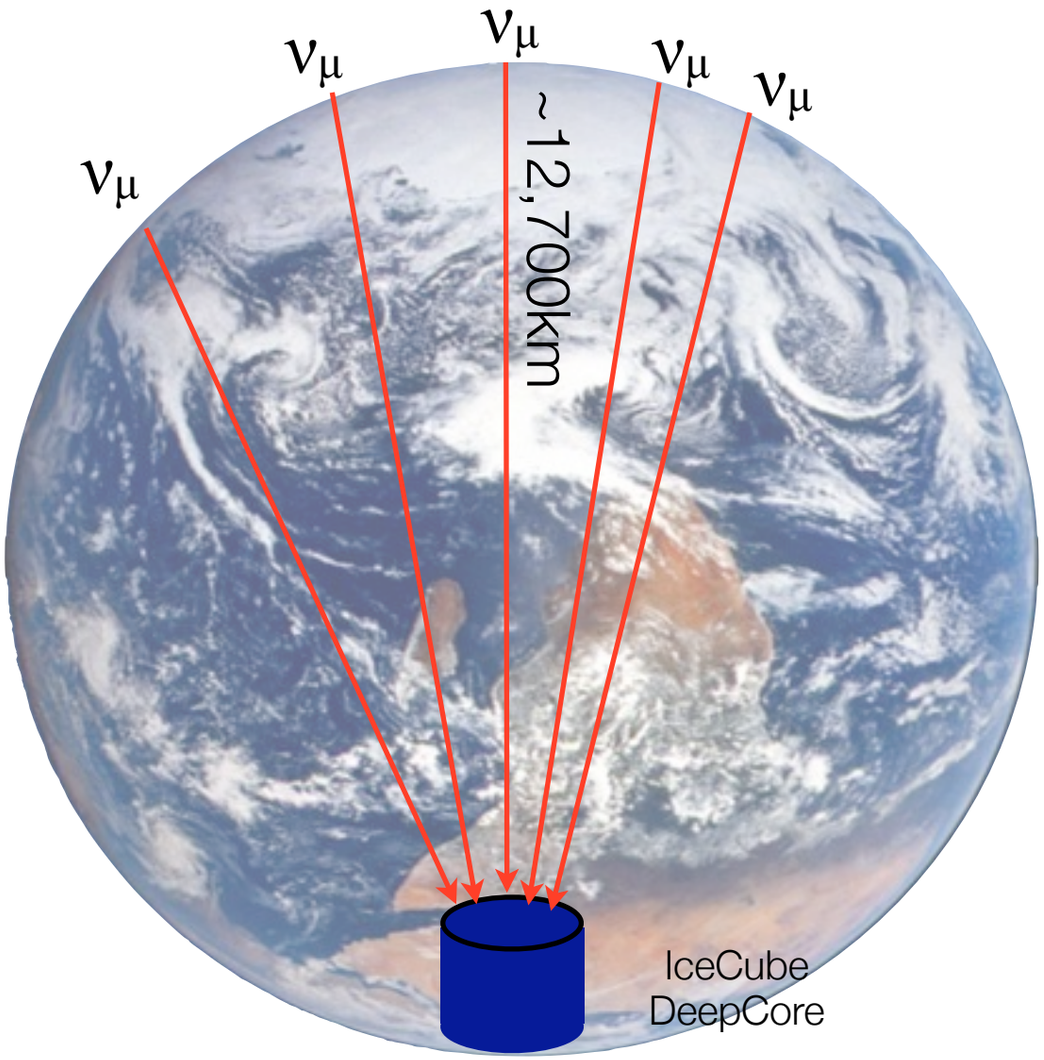
- Trigger level background to signal ratio is $10^6$:1
- DeepCore uses IceCube as an active veto to reject down-going atmospheric muons and neutrinos
  - Atmospheric muon rejection of ~$8x10^3$ with neutrino retention of ~99%
  - Further rejection employed offline



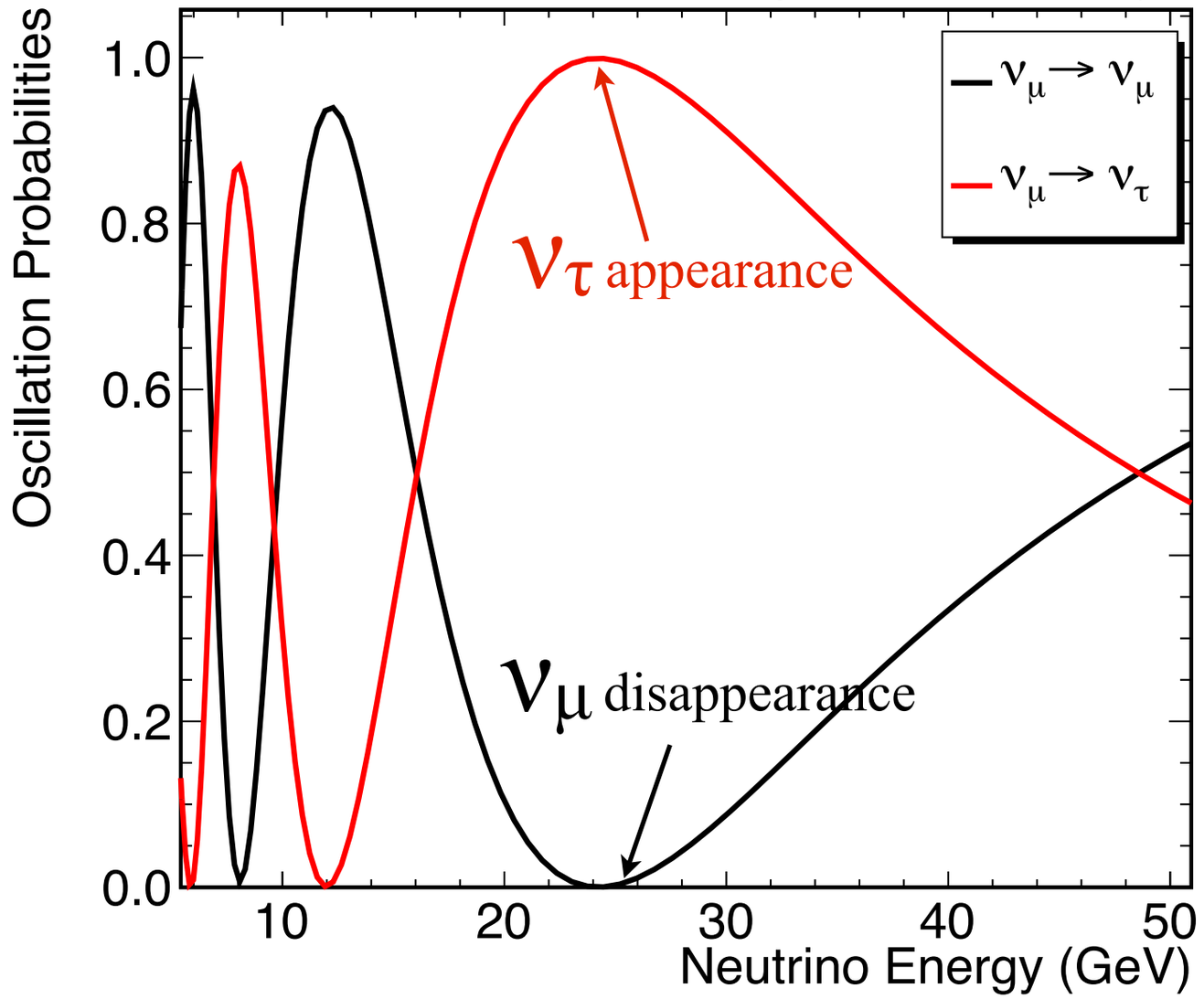
# Neutrino Oscillation Source



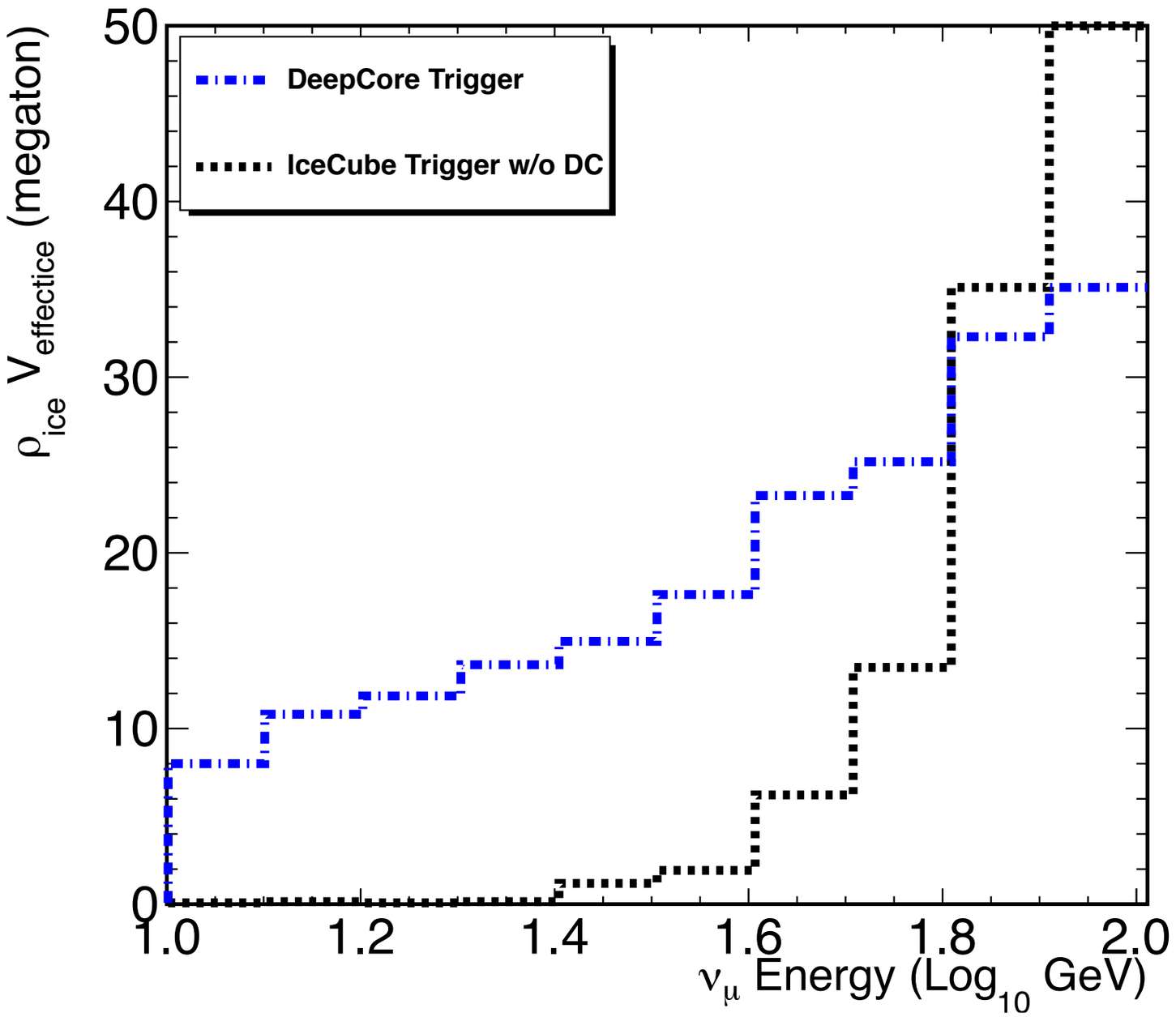
- Northern Hemisphere $\nu_\mu$ oscillating over one earth radii produces $\nu_\mu$ ($\nu_\tau$) oscillation minimum(maximum) at ~25 GeV
  - Covers all possible terrestrial baselines
  - "Beam" is free and never turns off




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



- IceCube + DeepCore will collect ~200k isotropic neutrinos at trigger level, tens of thousands have undergone oscillation



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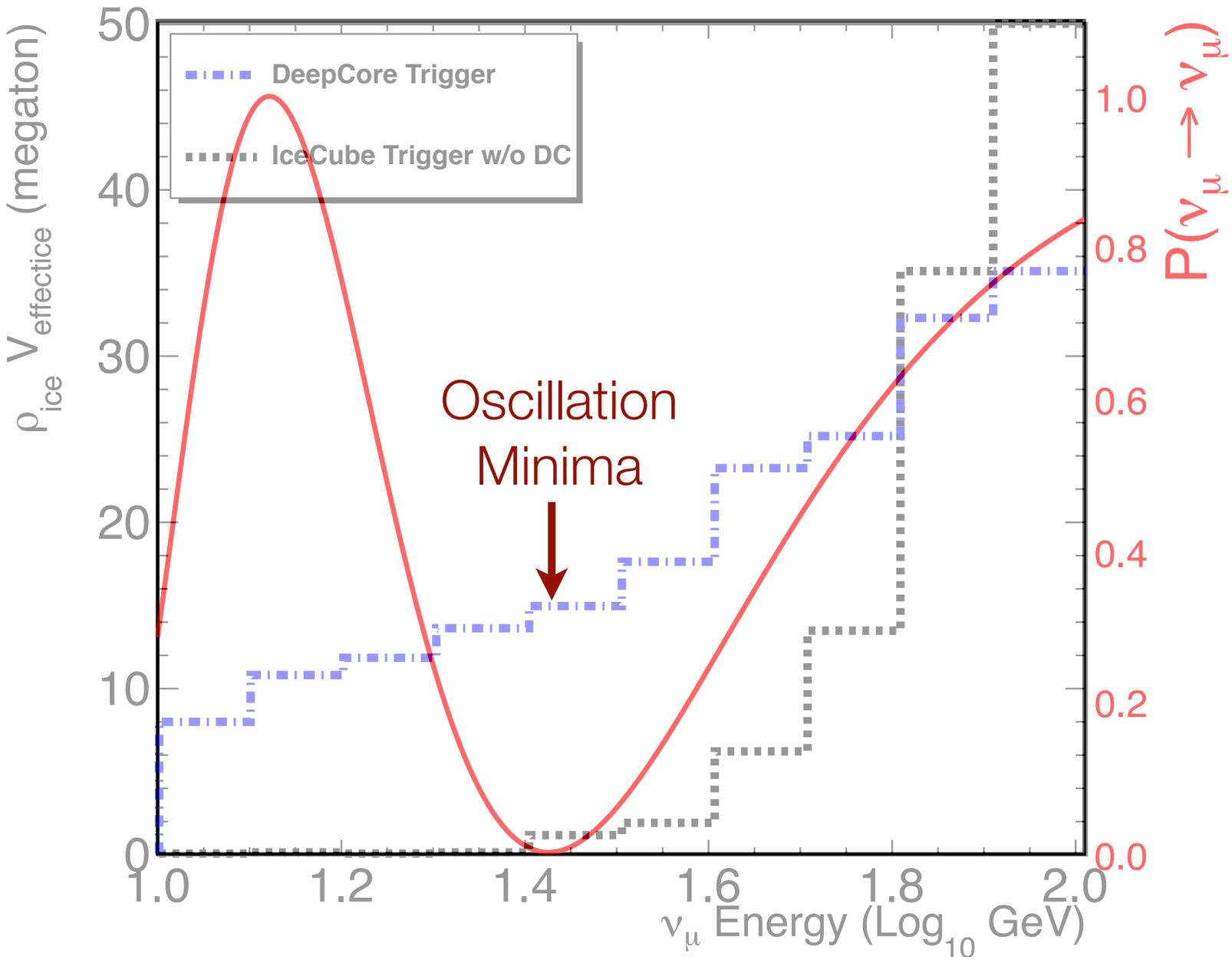

# Neutrino Candidate



- 8 hours of real data
- Preliminary event selection
- Up-Going muon neutrino "candidate"
  - ~15 GeV from track length

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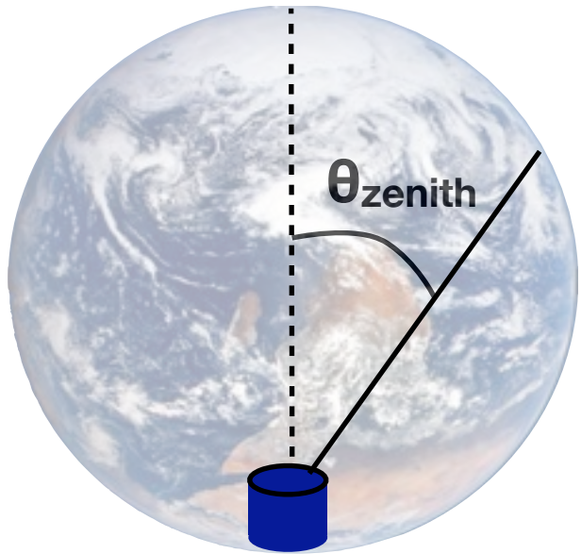
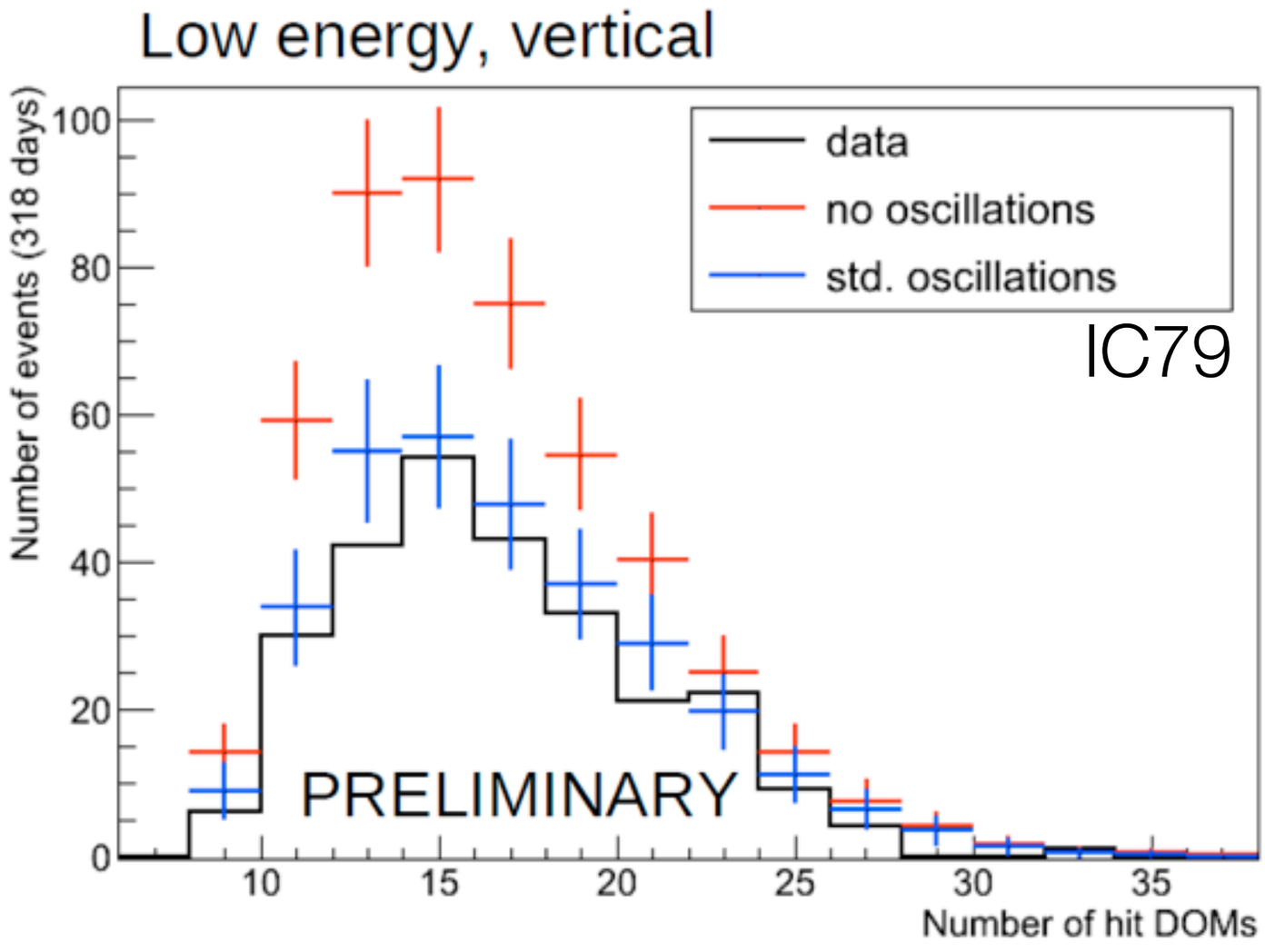
# Muon Neutrino Disappearance



- 1 year data with 79 total strings (Includes DeepCore)
- Tests oscillation hypothesis using high energy IceCube techniques
- Additional analyses using dedicated DeepCore methods are on-going
  - Higher event rate
  - Better reconstructions

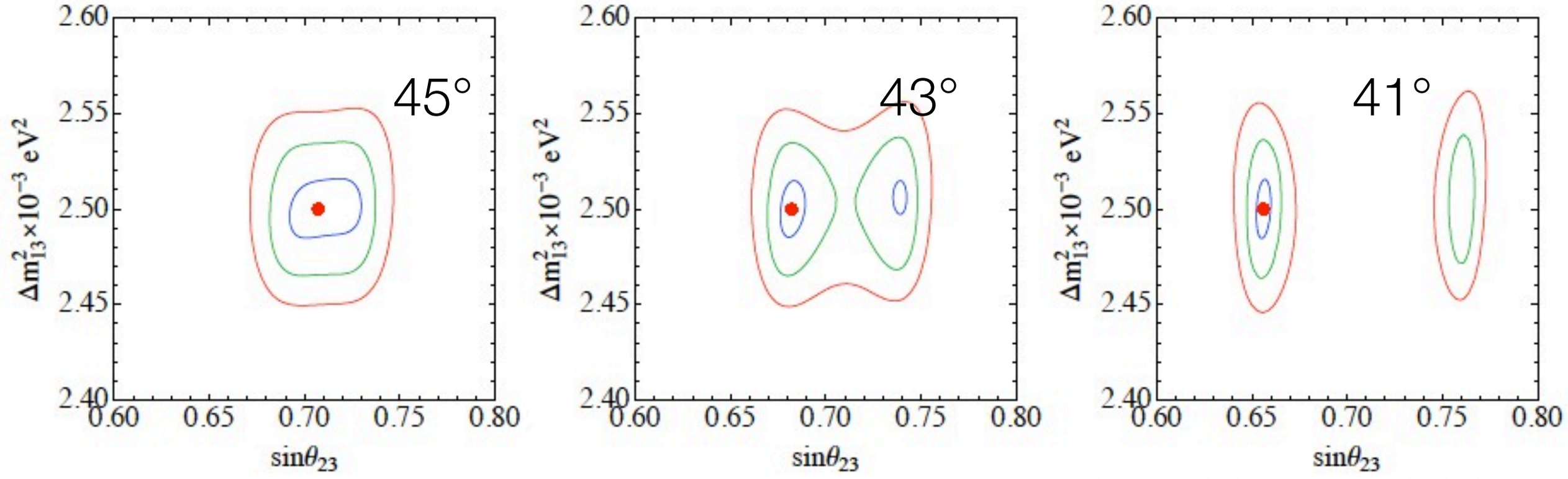


# $\theta_{23}$ Maximal? Octant?

- Instead of fitting $\sin^2 2\theta_{23}$ fit $\sin\theta_{23}$
- The large and already well measured value of $\theta_{13}$ increases the chance
- Requires lots of events
  - 10 years DeepCore exposure

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

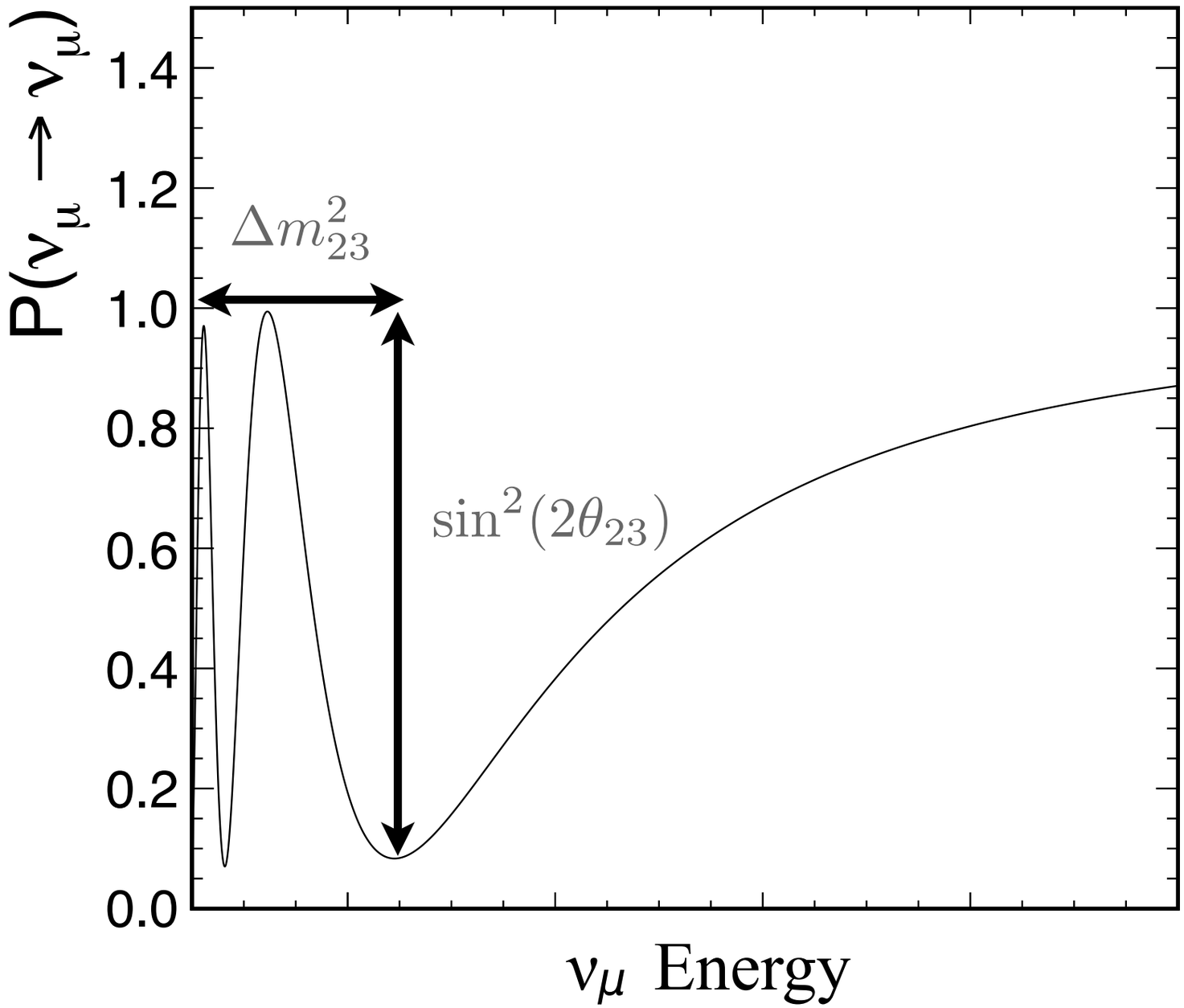



Fernandez-Martinez,Giordano, Mena, Mocioiu, PhysRevD.82.093011

# Generic Oscillation

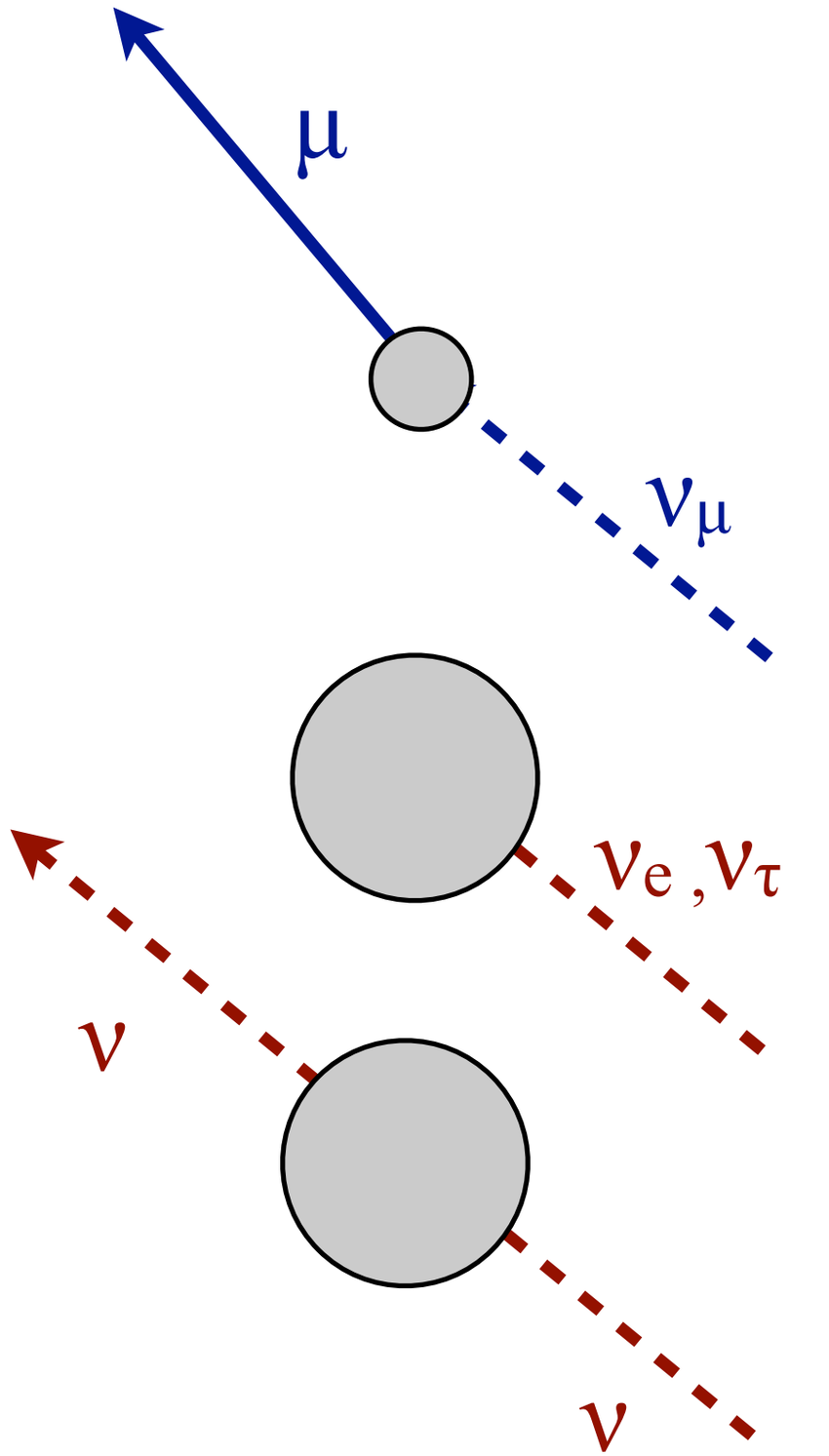


## Fixed Baseline L



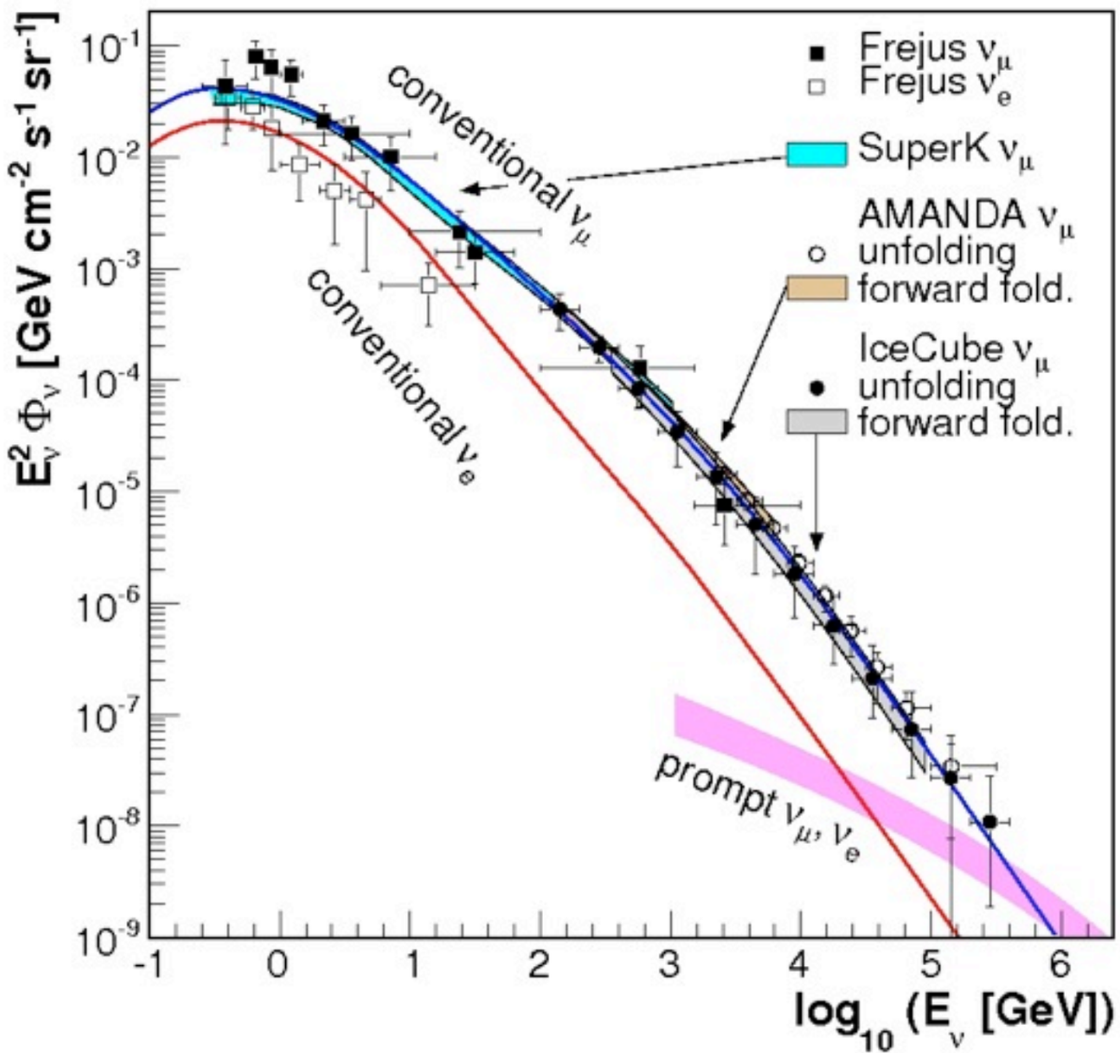
# Tau Neutrino Appearance

- Neutral Current, Charged Current $\nu_e$, and CC $\nu_\tau$ events produce cascade-like signatures
- Look for statistical excess in cascade events
- DeepCore has been infilled with 2 additional strings
  - Increases $\nu_\tau$ event rate by > 15%



# Atmospheric flux

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



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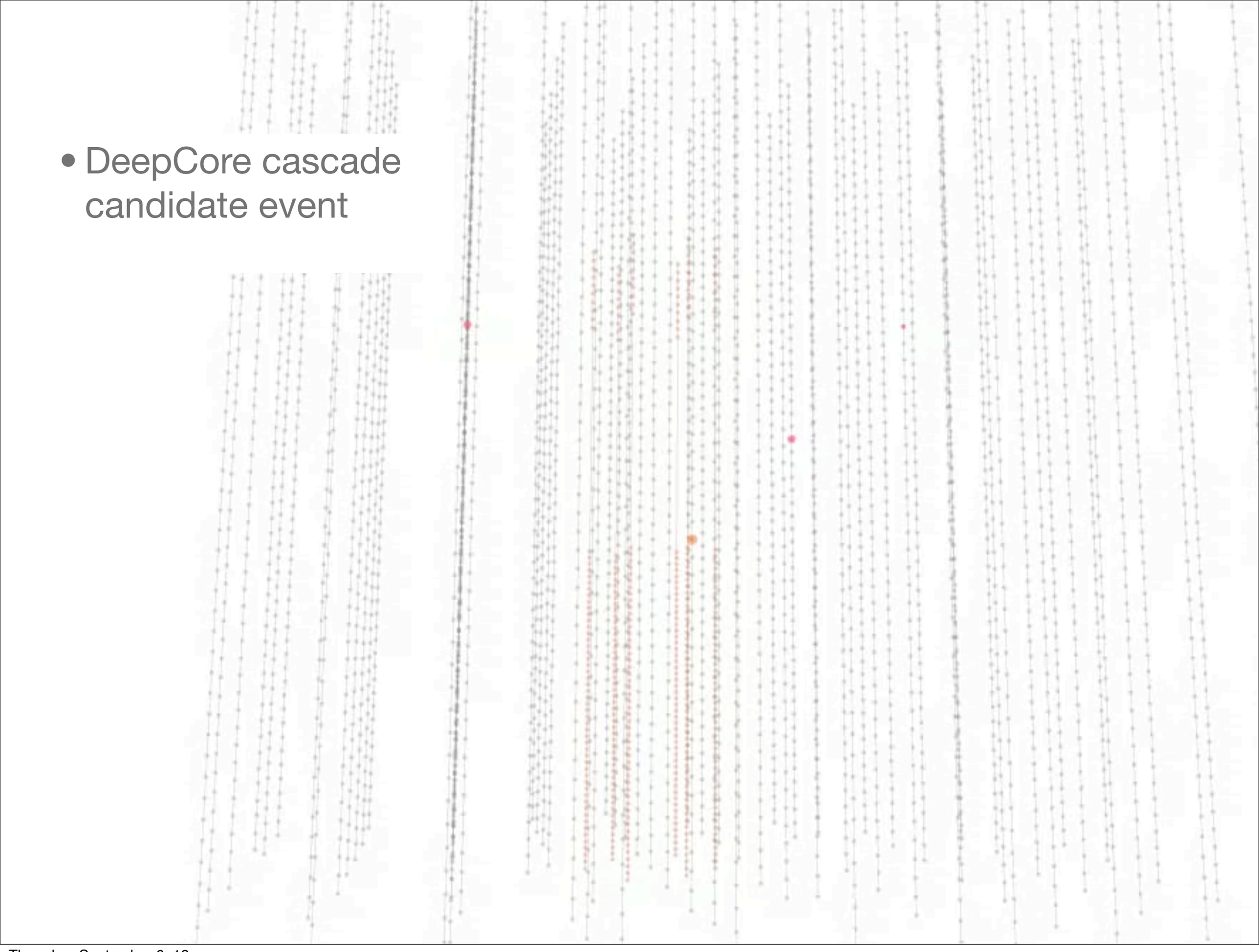
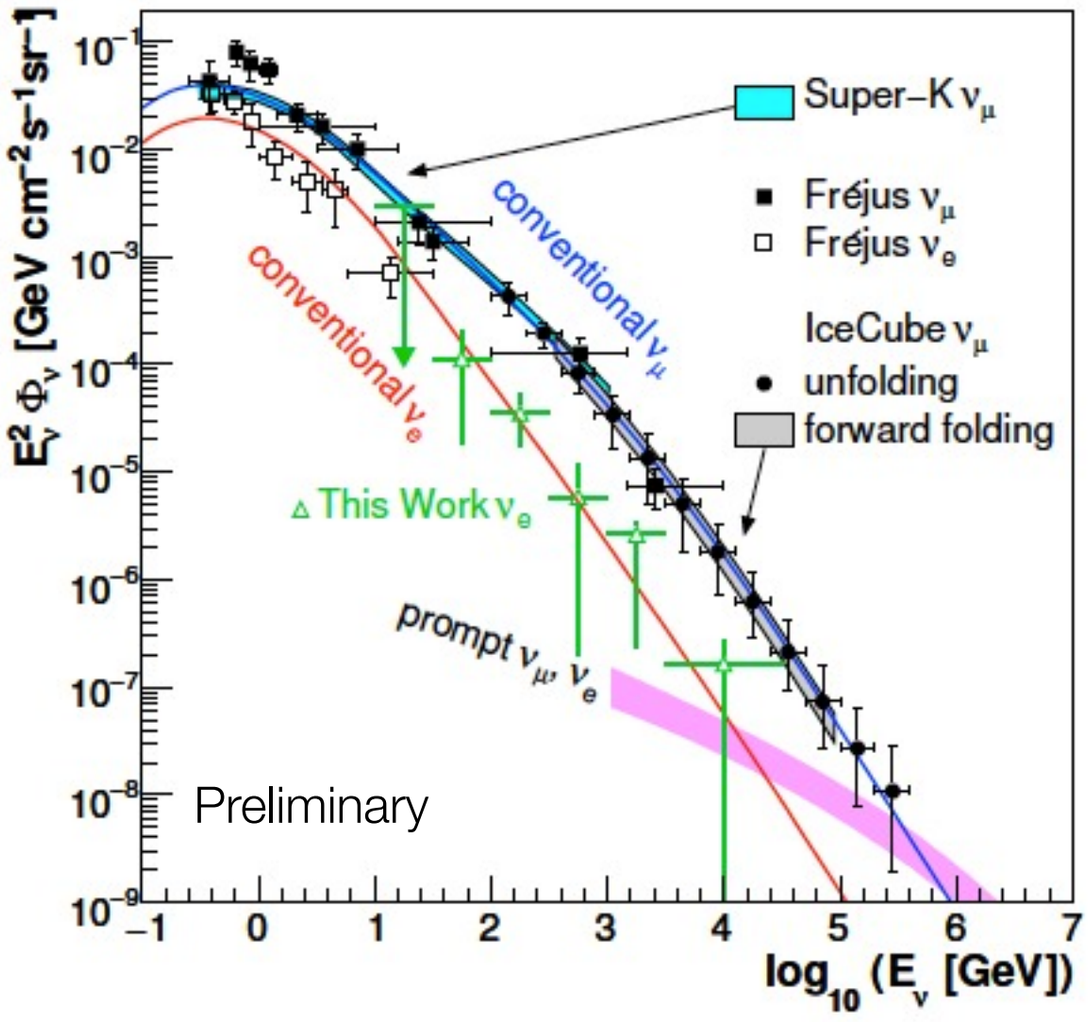
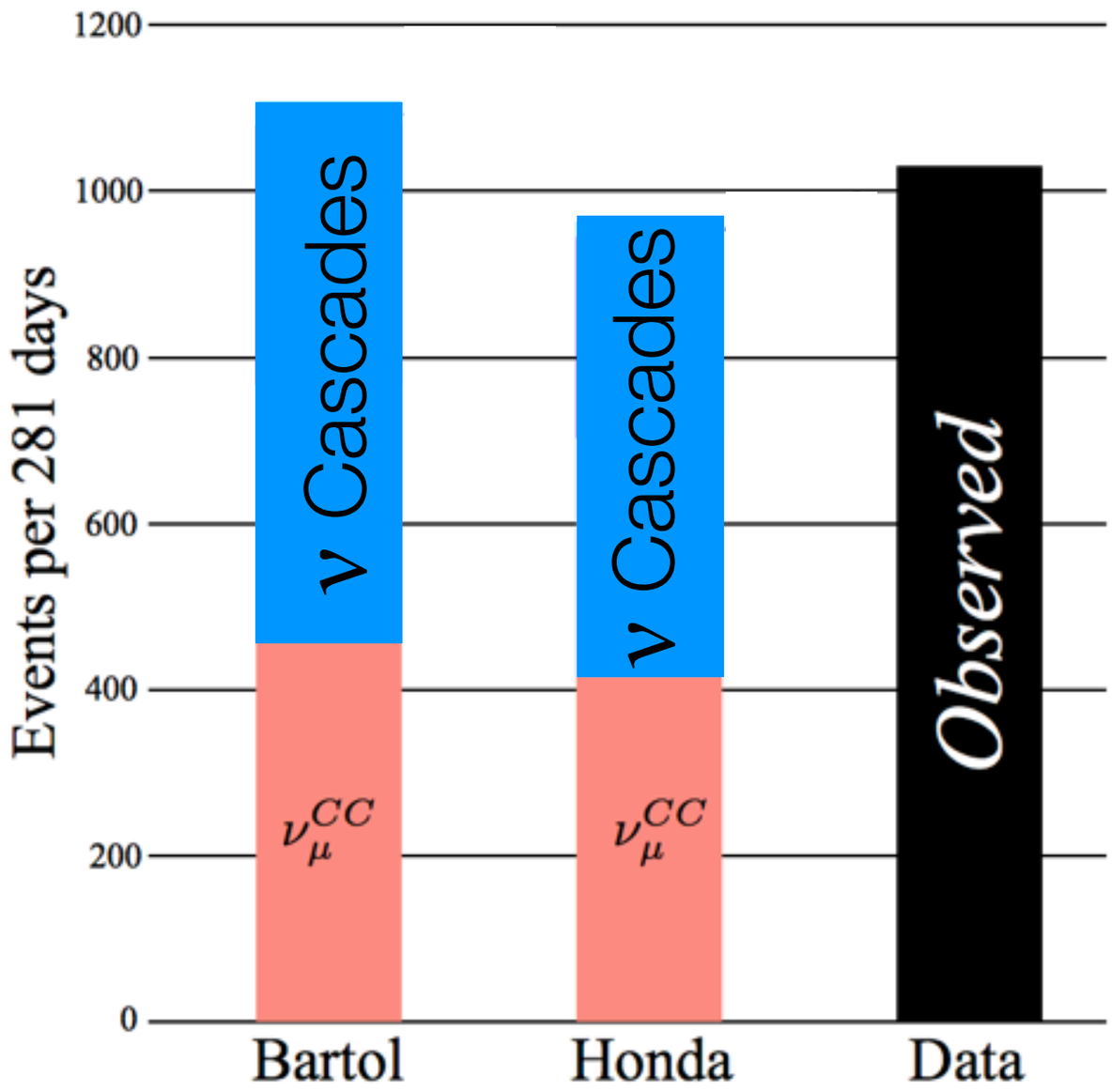


# Neutrino Induced Cascades

- First observation of neutrino induced cascades in IceCube
- Higher average energy (~180 GeV) than oscillation region





# 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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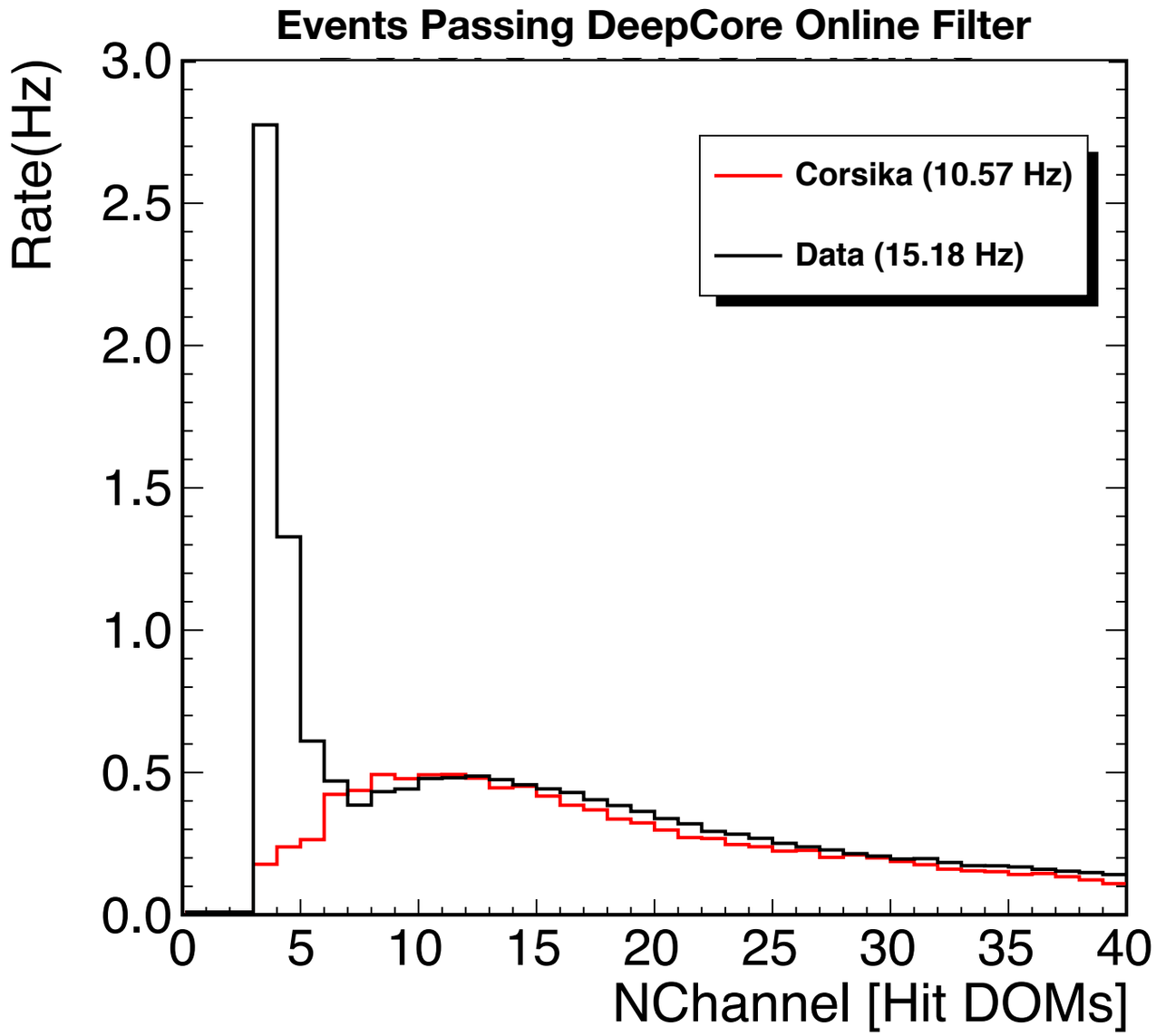

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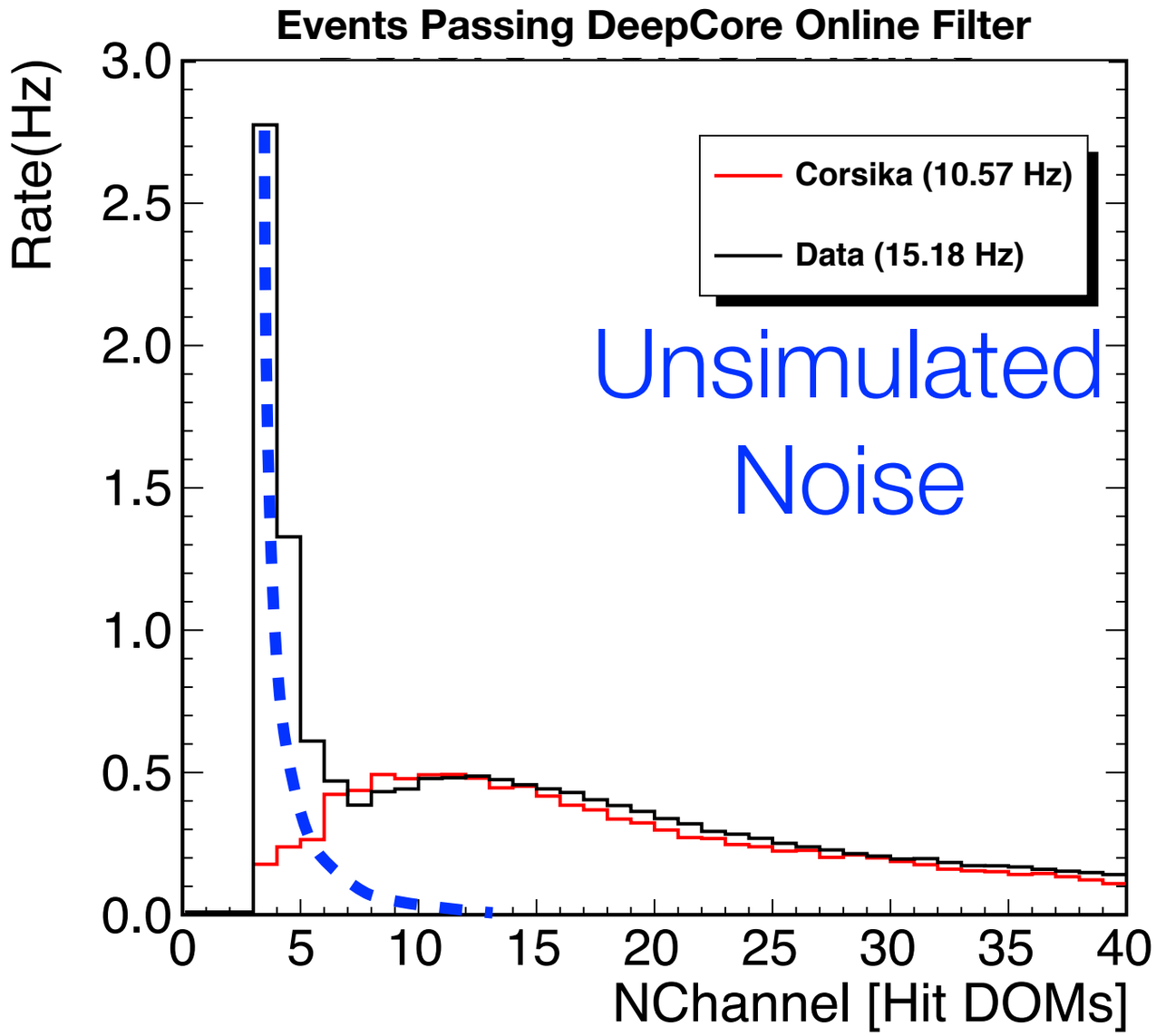

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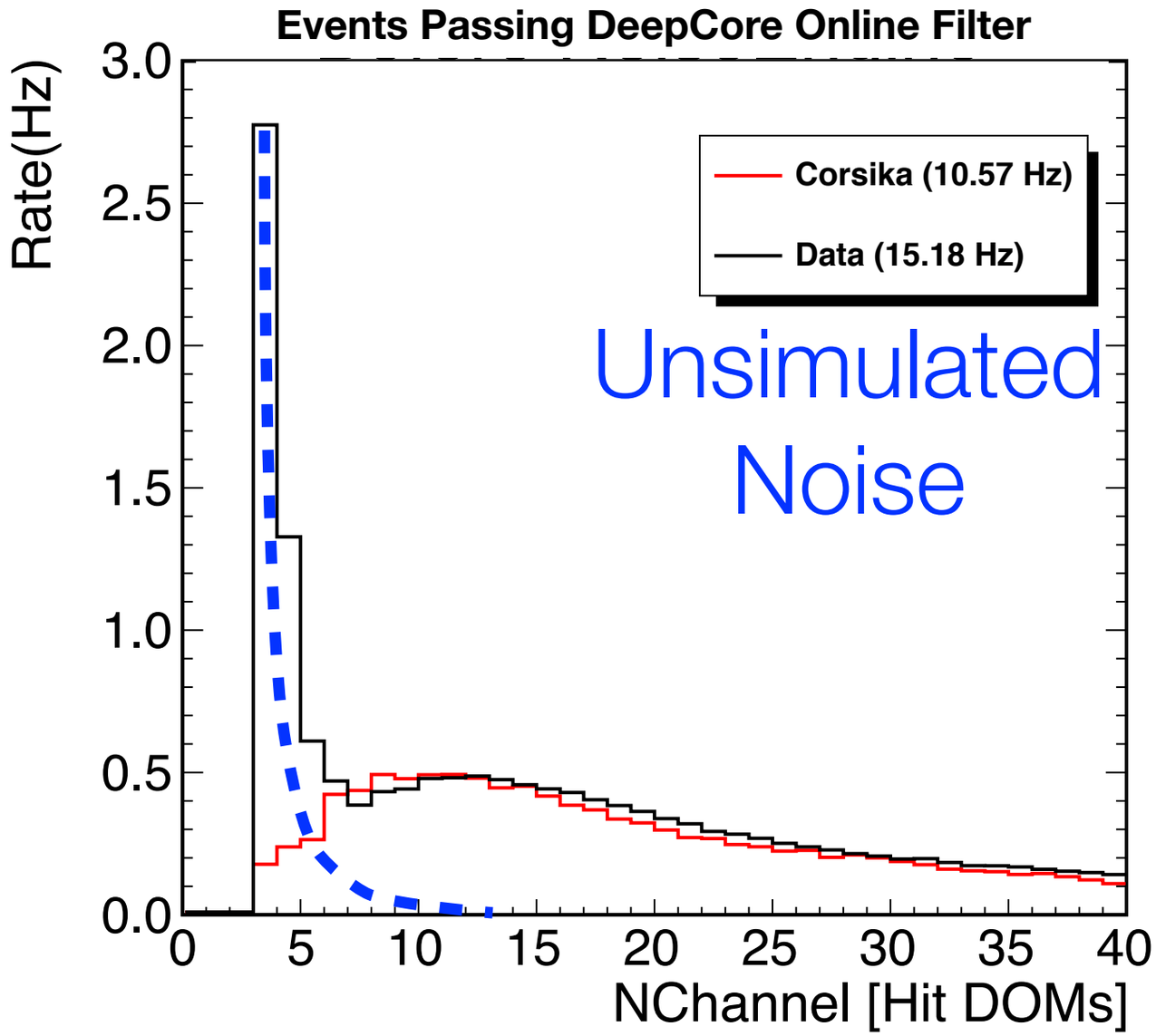
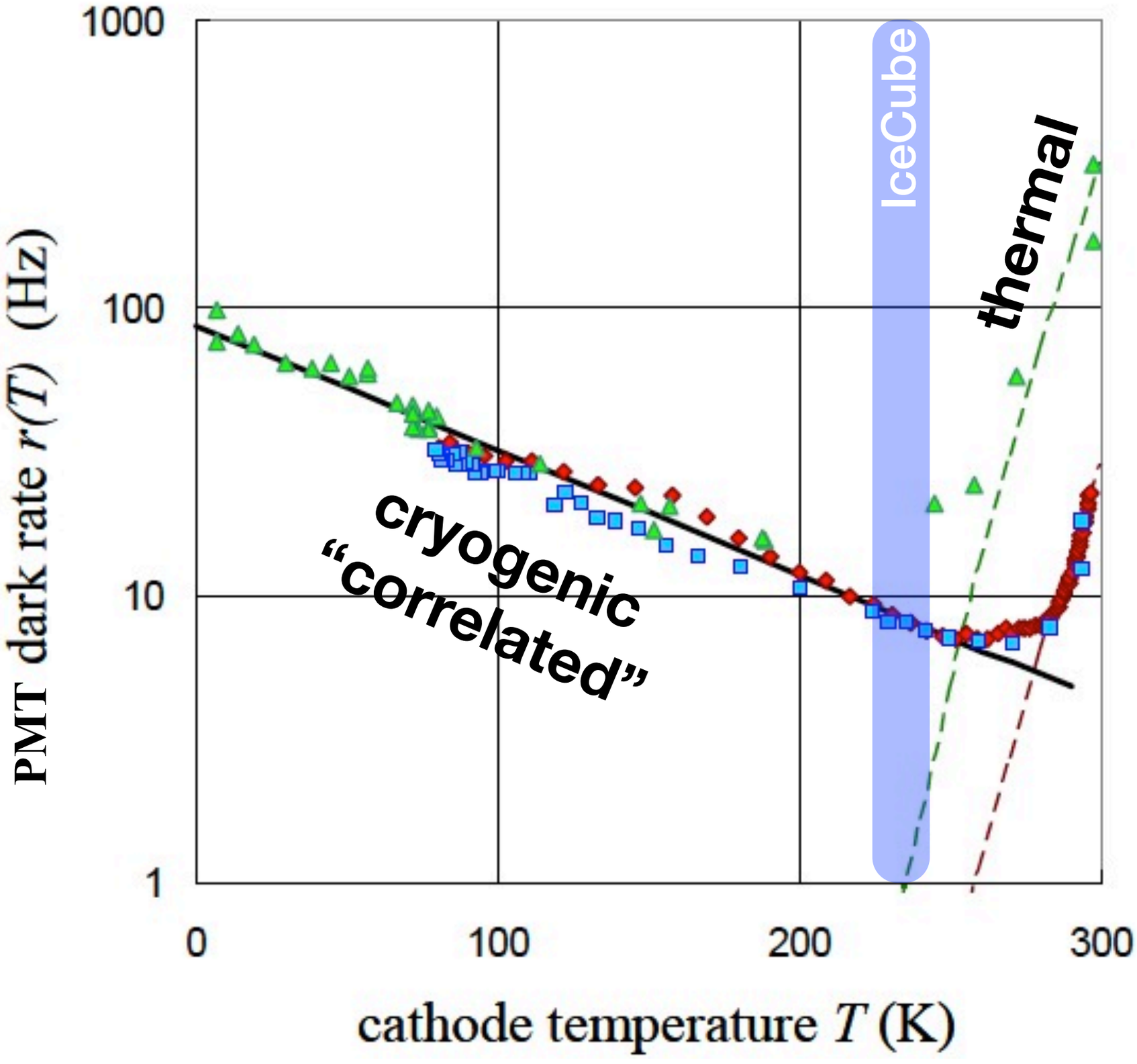


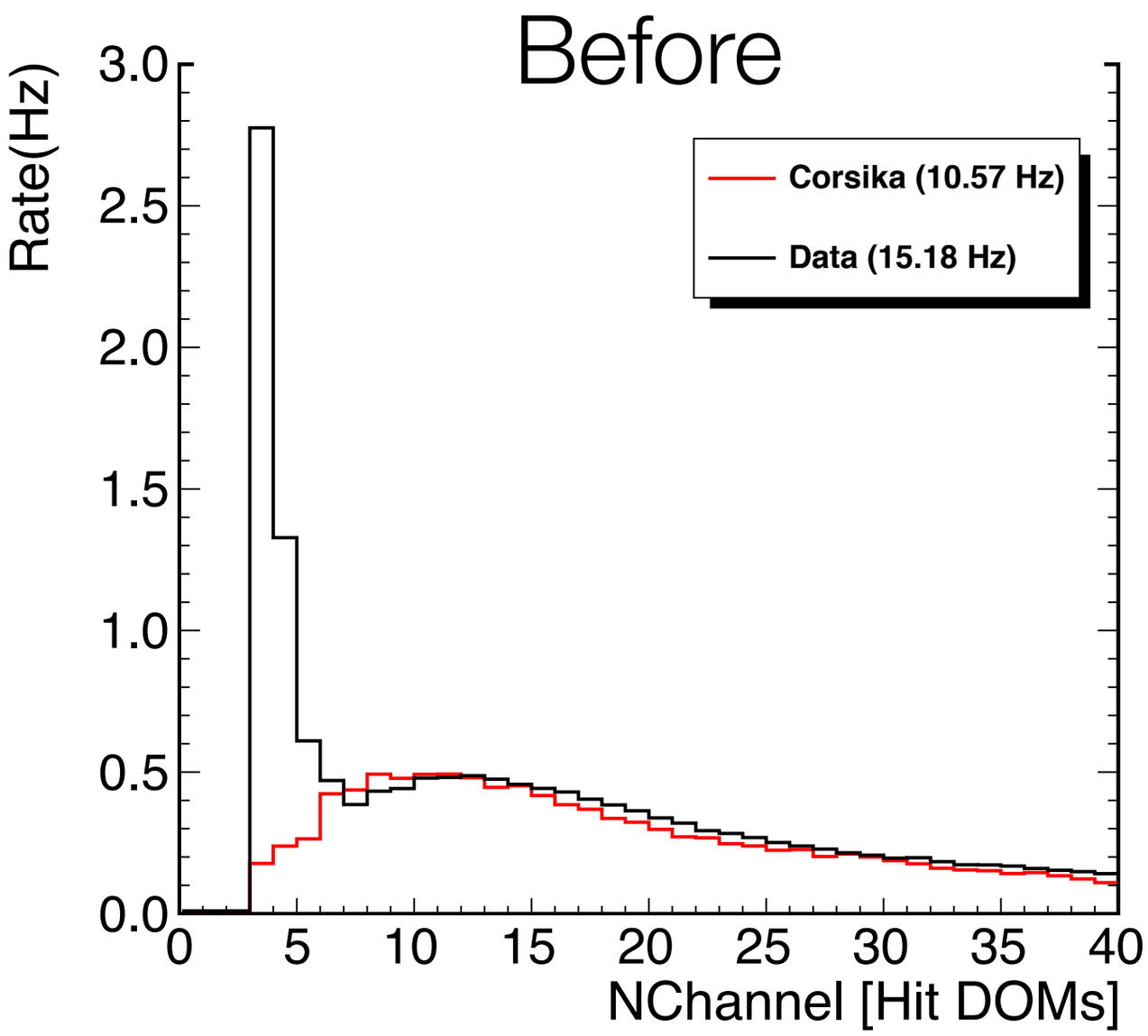
# PMT Noise

- Oscillation
- IceCube-DeepCore Physics
- PINGU
- Beyond




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

# Noise Removal




- Algorithm based on IceCube “TrackEngine” hit clustering trigger
- Hough Transform of angles ($\theta$,$\phi$) between hits
  - Noise should be relatively unclustered
  - Physics (neutrinos, muons, etc...) should create clustered hits

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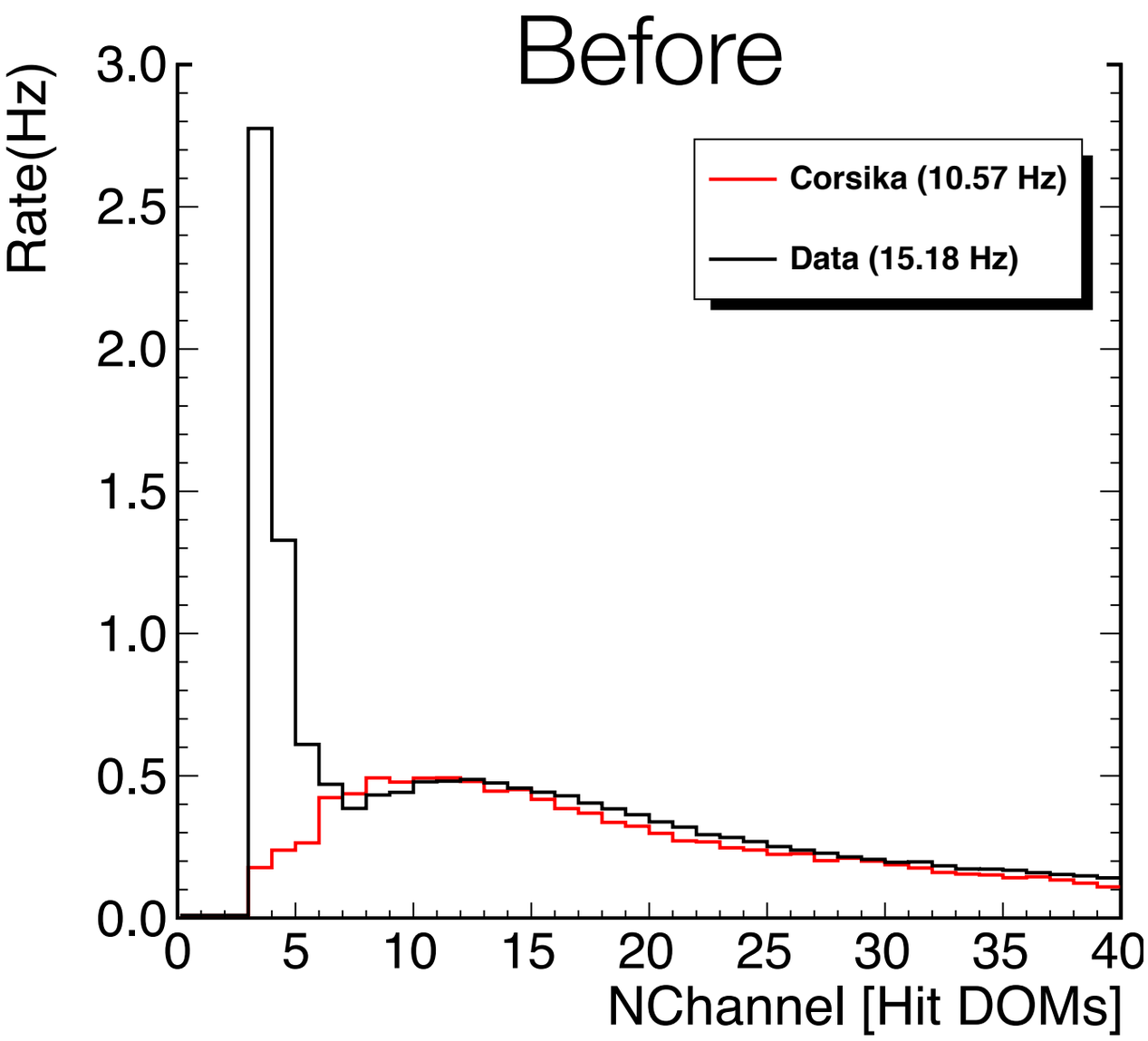


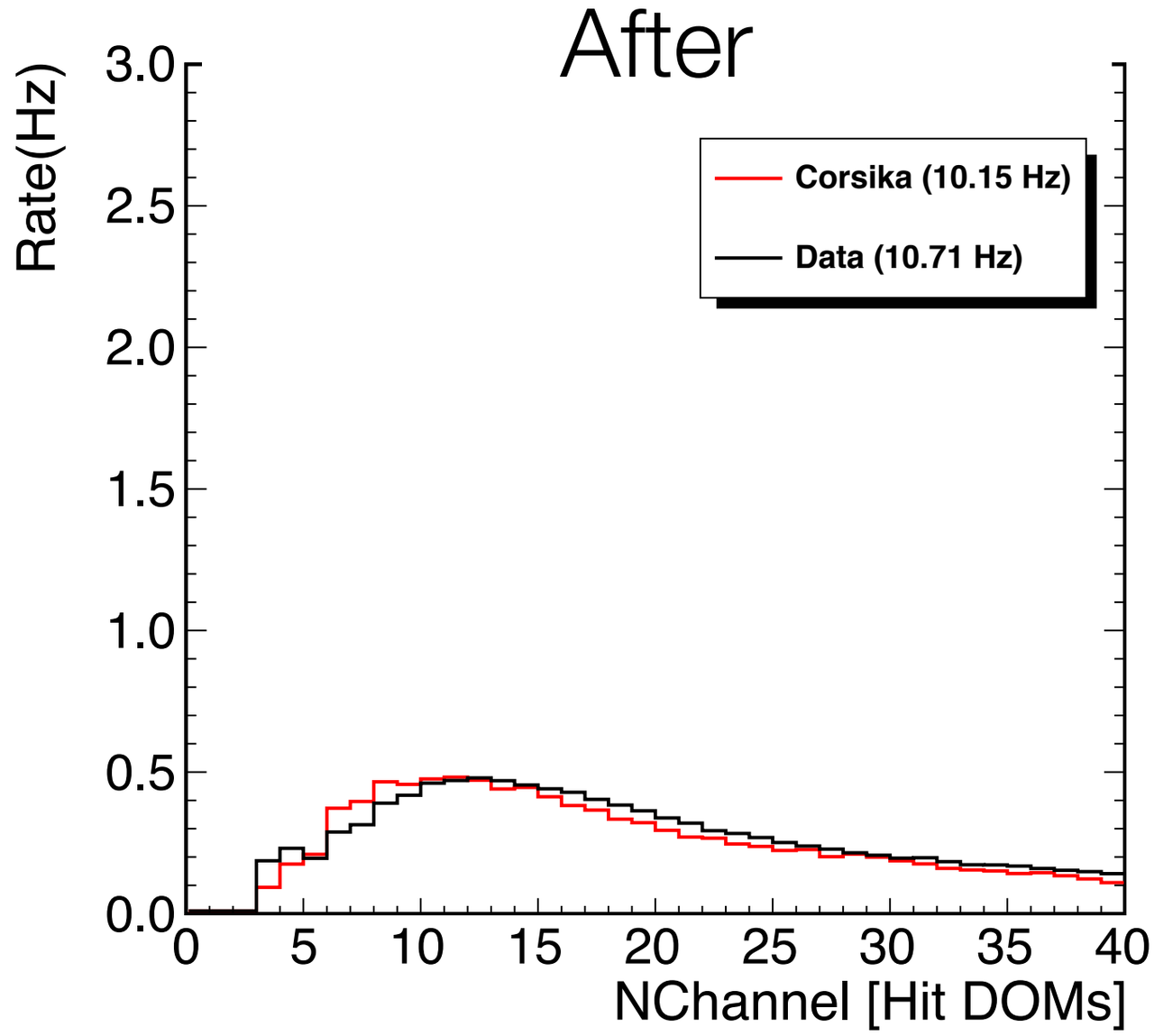


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# IceCube-DeepCore Wrapup

- Oscillation
- IceCube-DeepCore Physics
- PINGU
- Beyond

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- Tau appearance
  - Deployment of DeepCore has resulted first observation of neutrino induced cascades in IceCube
- Chance to do simultaneous fit to both numu disappearance and nutau appearance
- Moving down in energy from traditional IceCube physics presents new challenges

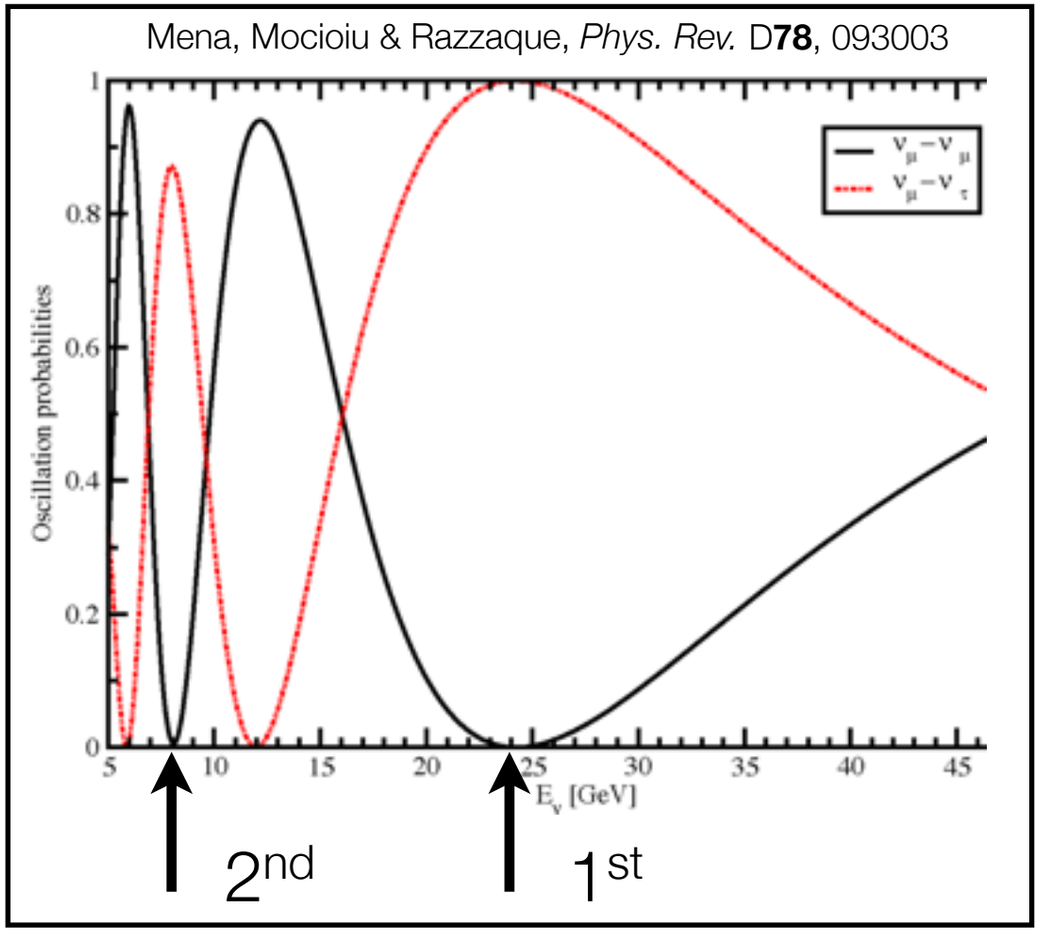



Alberto Giacometti “L’homme qui marche”

# Physics

- Oscillation
- IceCube-DeepCore Physics
- PINGU
- Beyond

- DeepCore has access to the first oscillation minima/maxima



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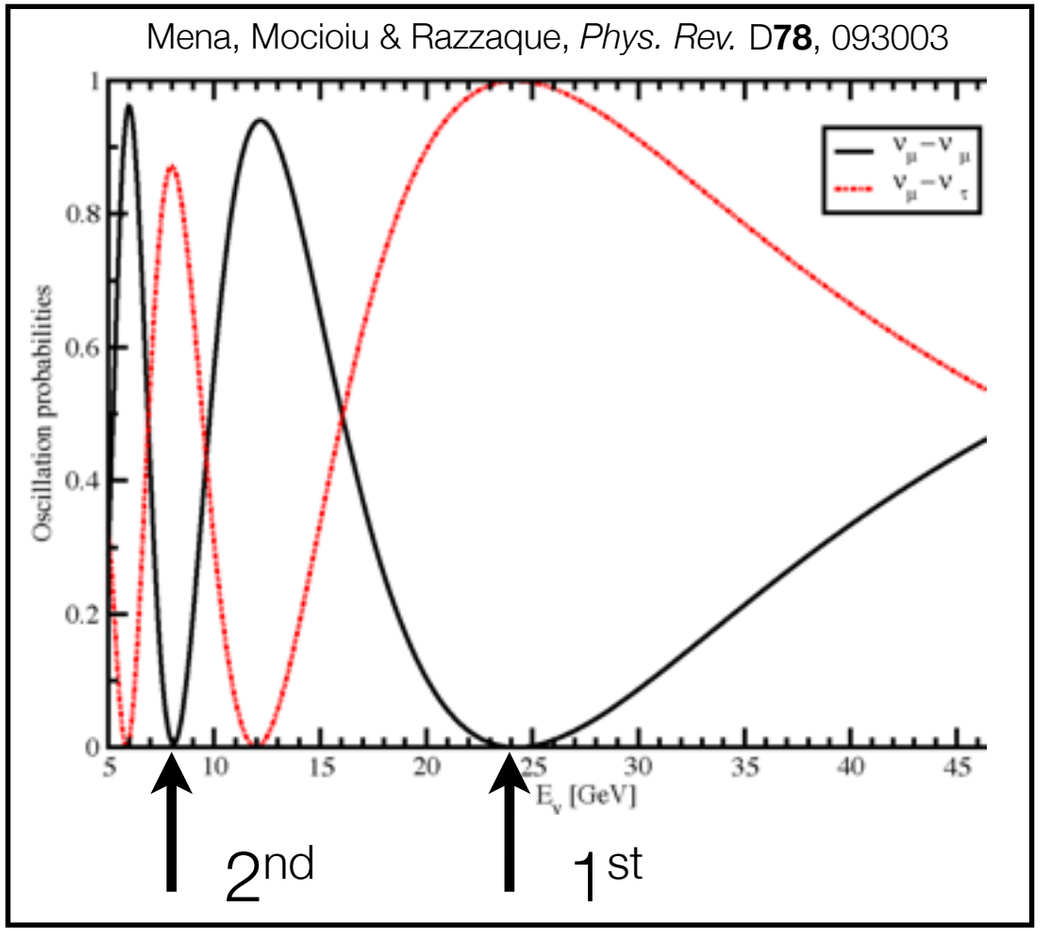
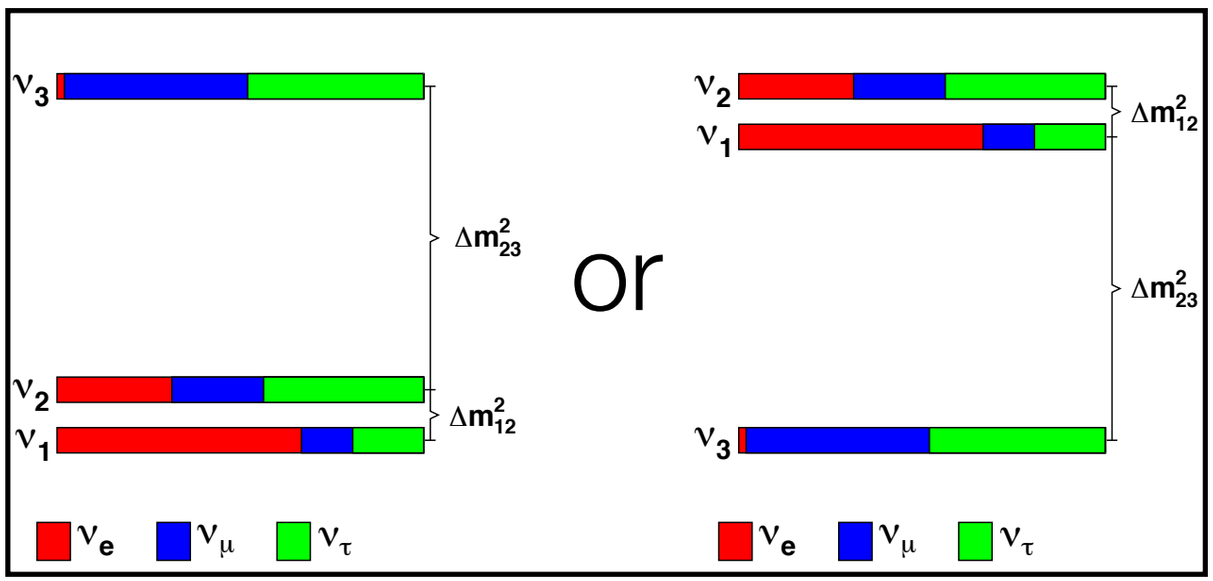
- Neutrino Hierarchy



# Physics



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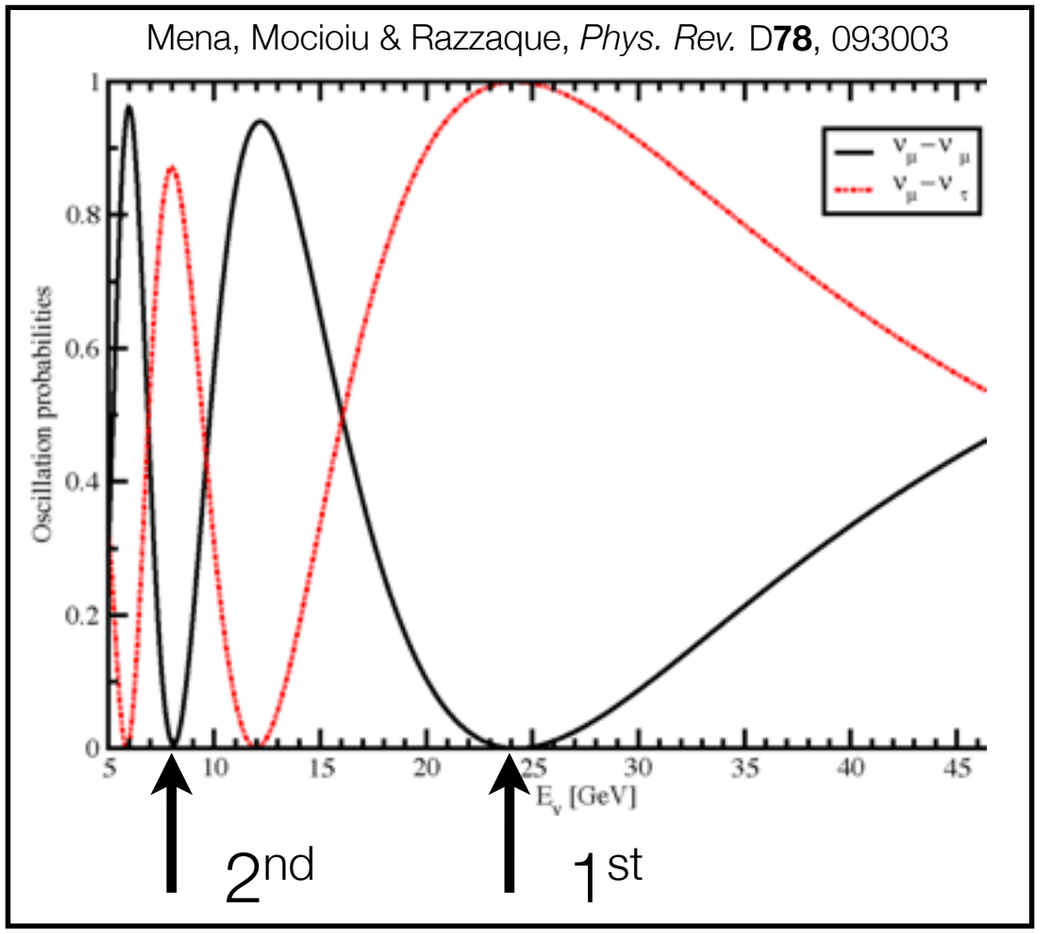
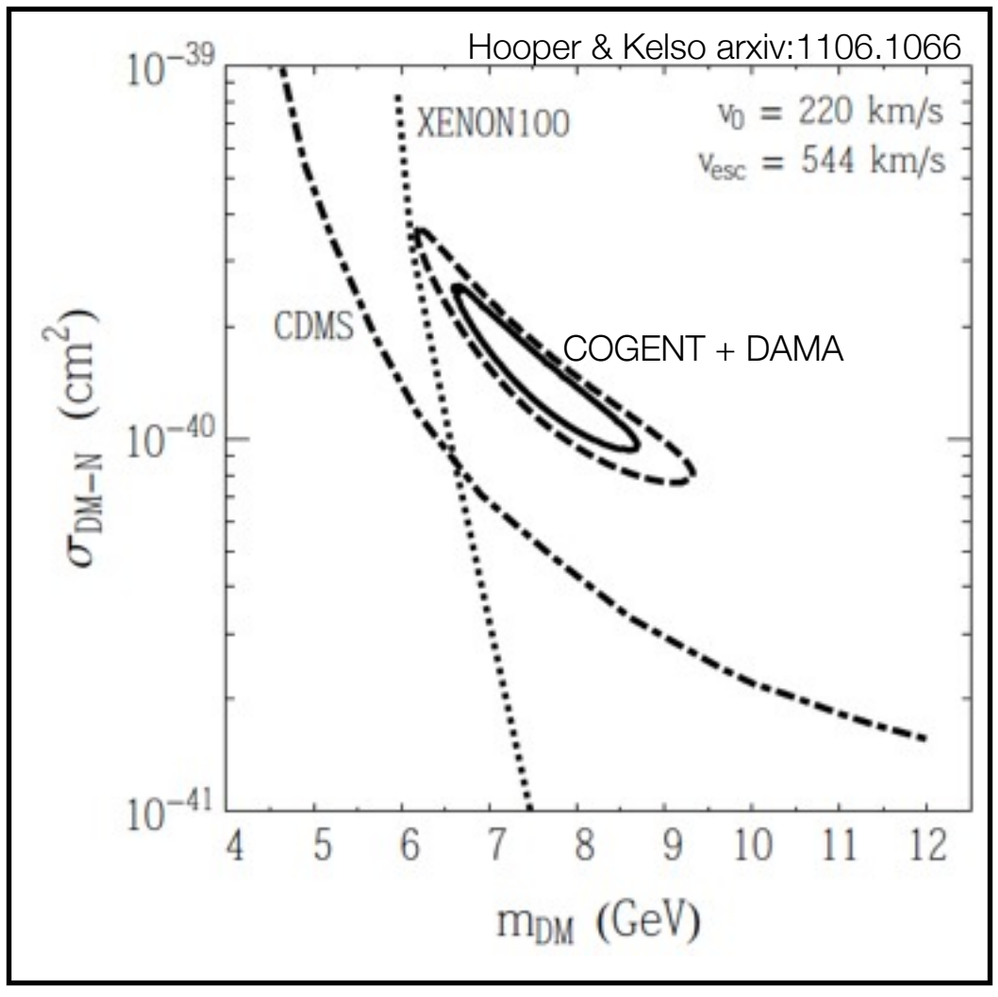
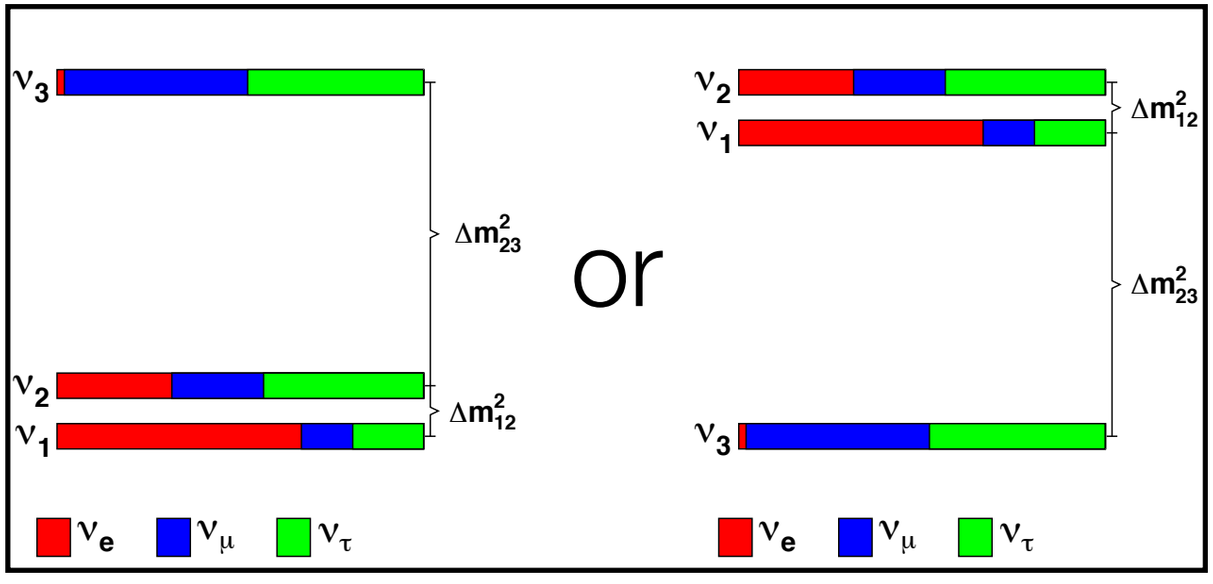
- Neutrino Hierarchy
- GeV Dark Matter



# Beyond DeepCore



IceCube

# Beyond DeepCore





IceCube

# Beyond DeepCore





IceCube



DeepCore

# Beyond DeepCore





IceCube



DeepCore

# Beyond DeepCore



IceCube



DeepCore

# Beyond DeepCore



IceCube



DeepCore



PINGU

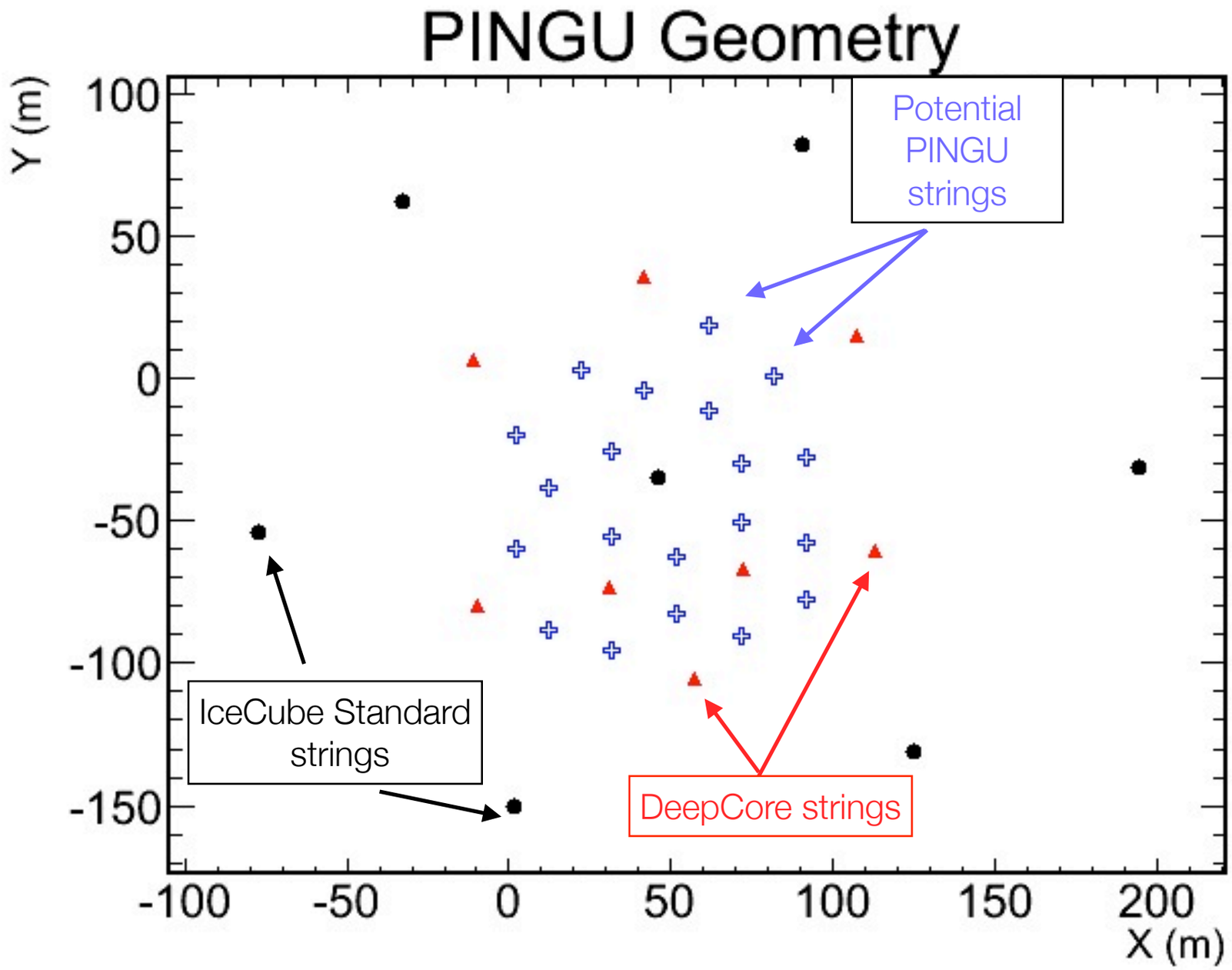
# Idea

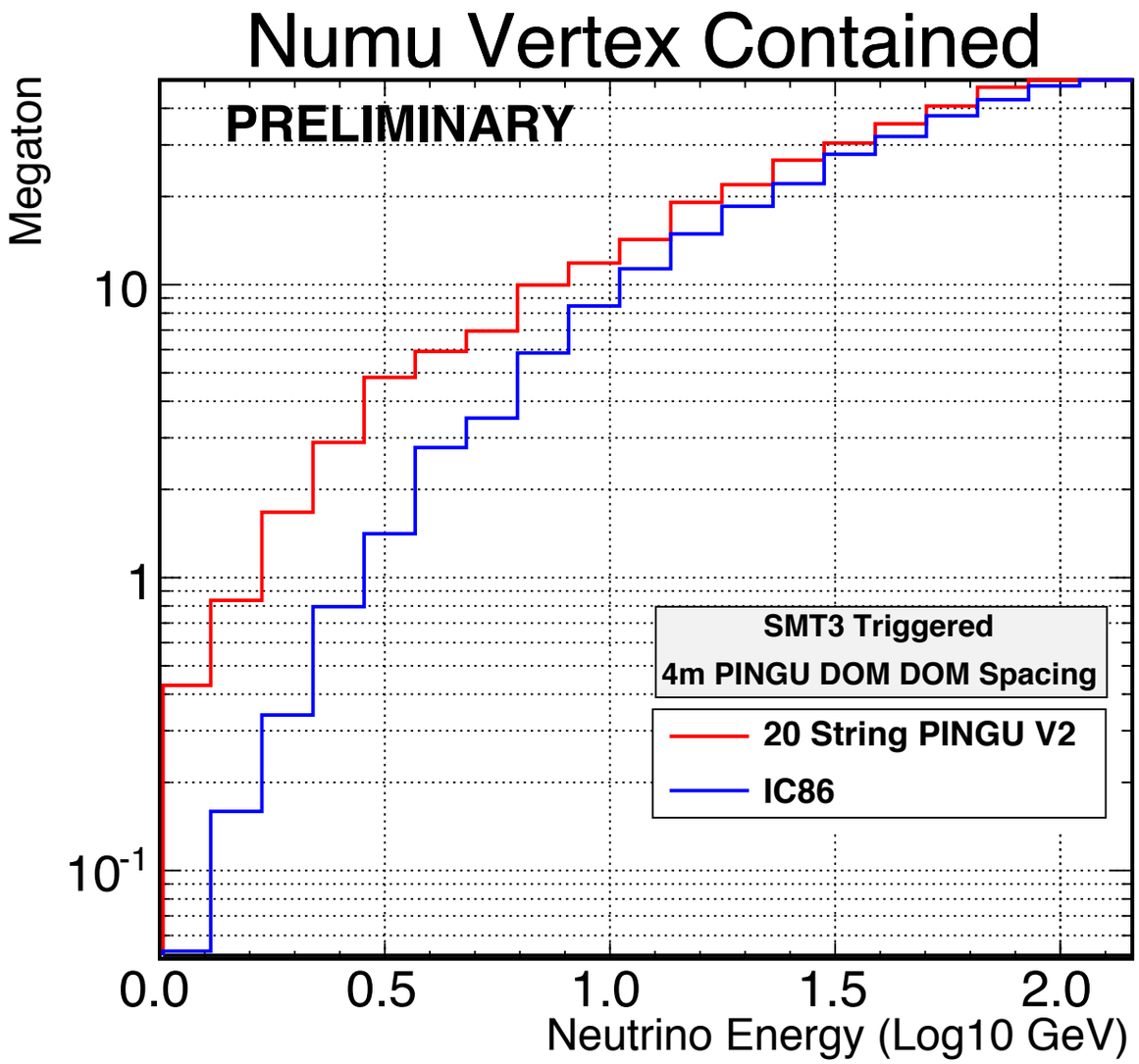
- Using existing and familiar technology ( hot water drill, HQE PMT DOMs) infill DeepCore with additional Strings
- Drive neutrino energy reach down to few GeV while maintaining multi-megaton scale size
- Precision IceCube Next Generation Upgrade (PINGU)

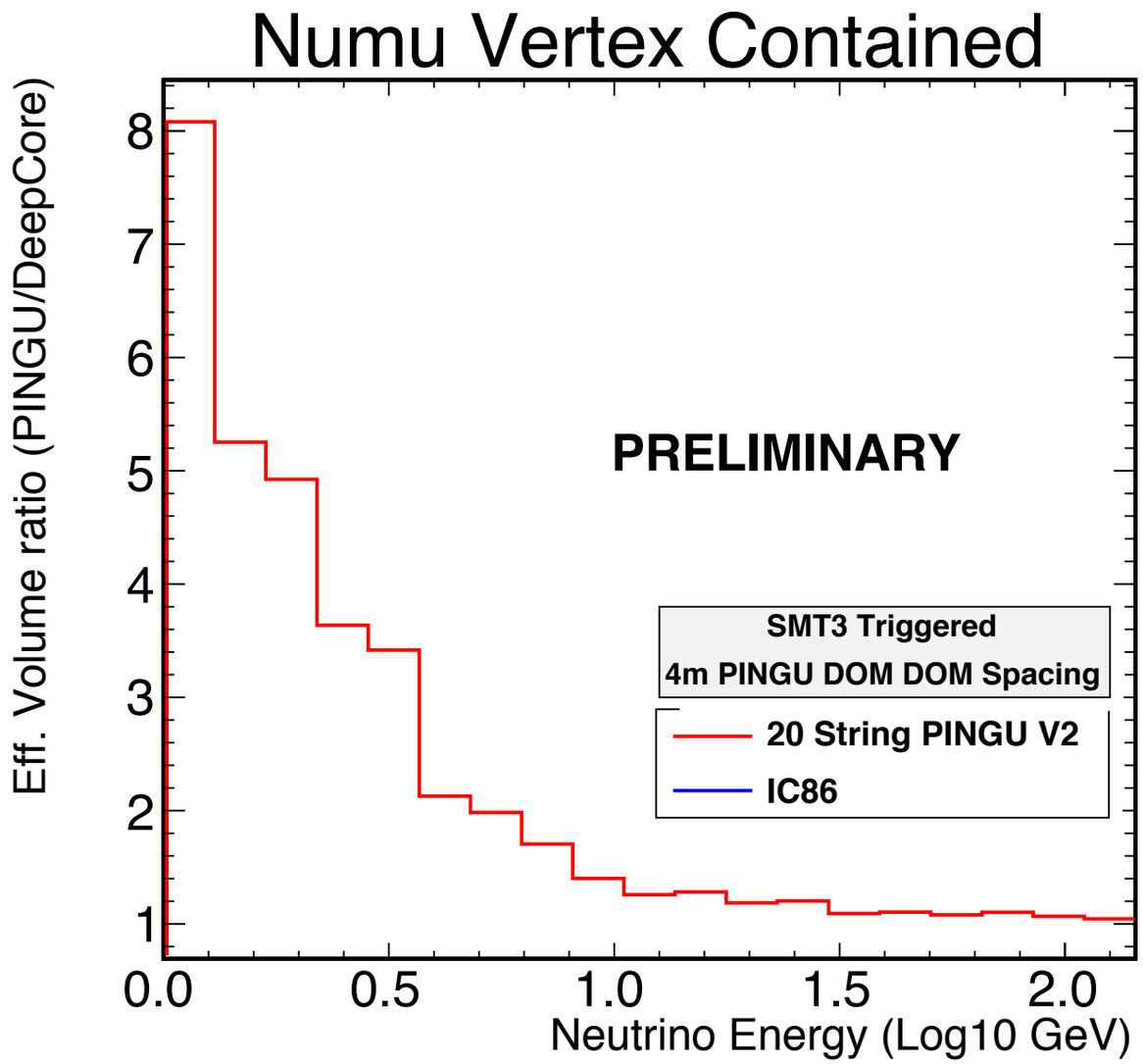
# PINGU: Possible Geometry



- ~20 strings within DeepCore volume w/ short string-string spacing
  - IC-IC: 125m
  - DC-DC: ~80m
  - PINGU-PINGU: <= 26m
- Shorter DOM-DOM spacing
  - IC-IC: 17m
  - DC-DC: 7m
  - PINGU-PINGU: <= 5m
- R & D for future water/ice cerenkov



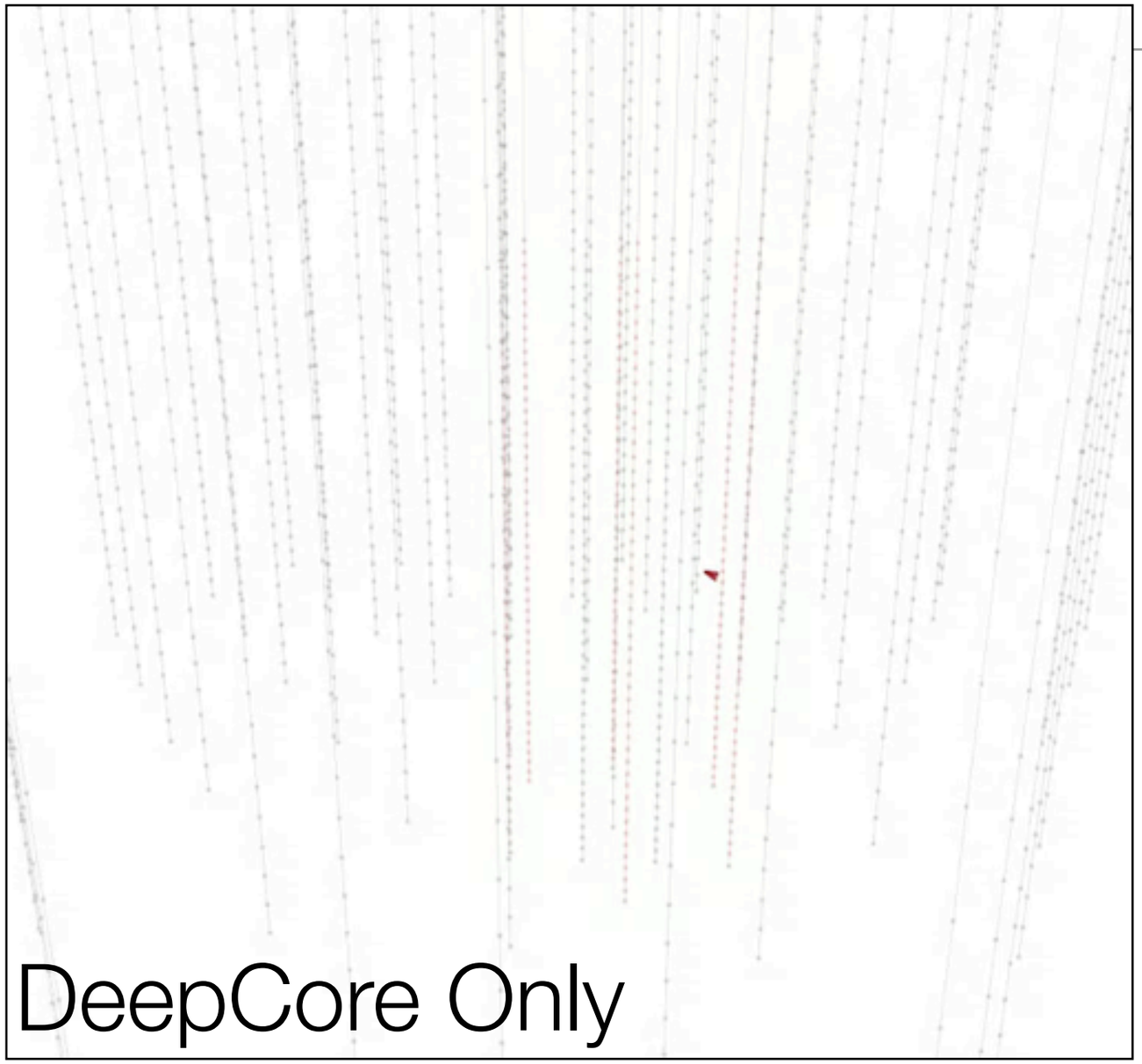



- Increased effective volume for energies below ~10 GeV
- Several megatons effective volume at a few GeV

# PINGU Events

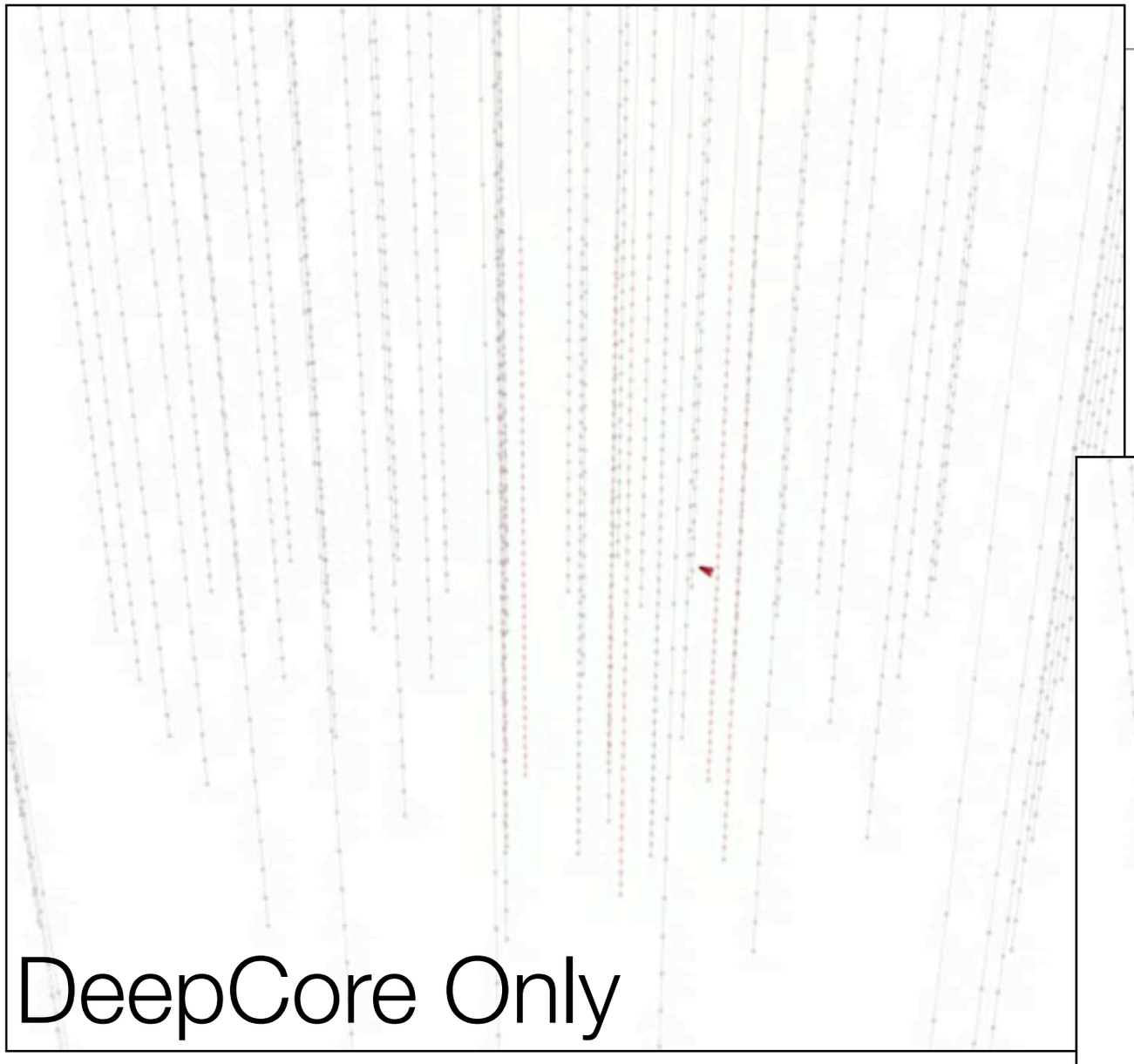





- 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade

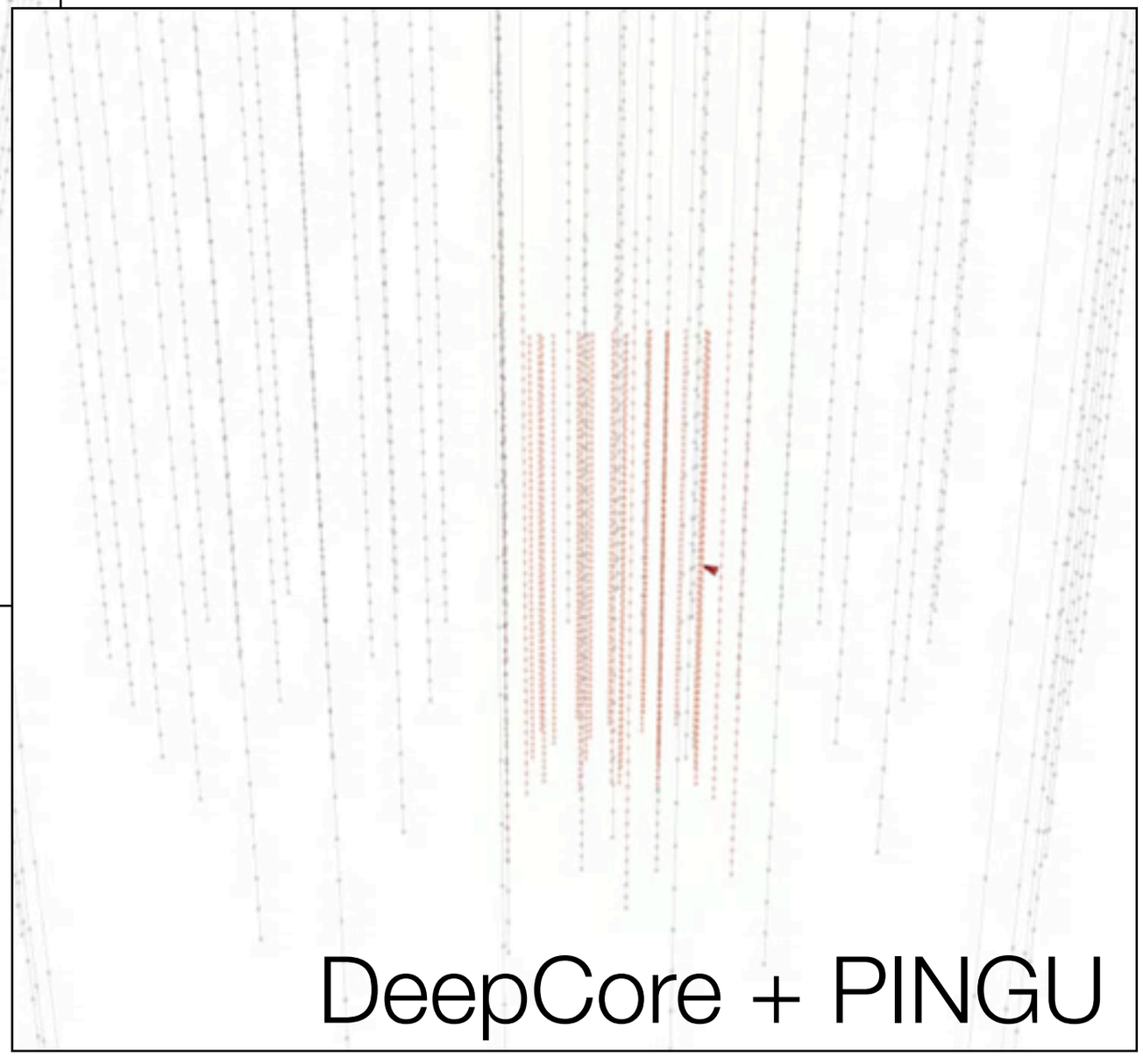
# PINGU Events





DeepCore Only

- 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade
- ~20 vs. ~50 Hit Modules

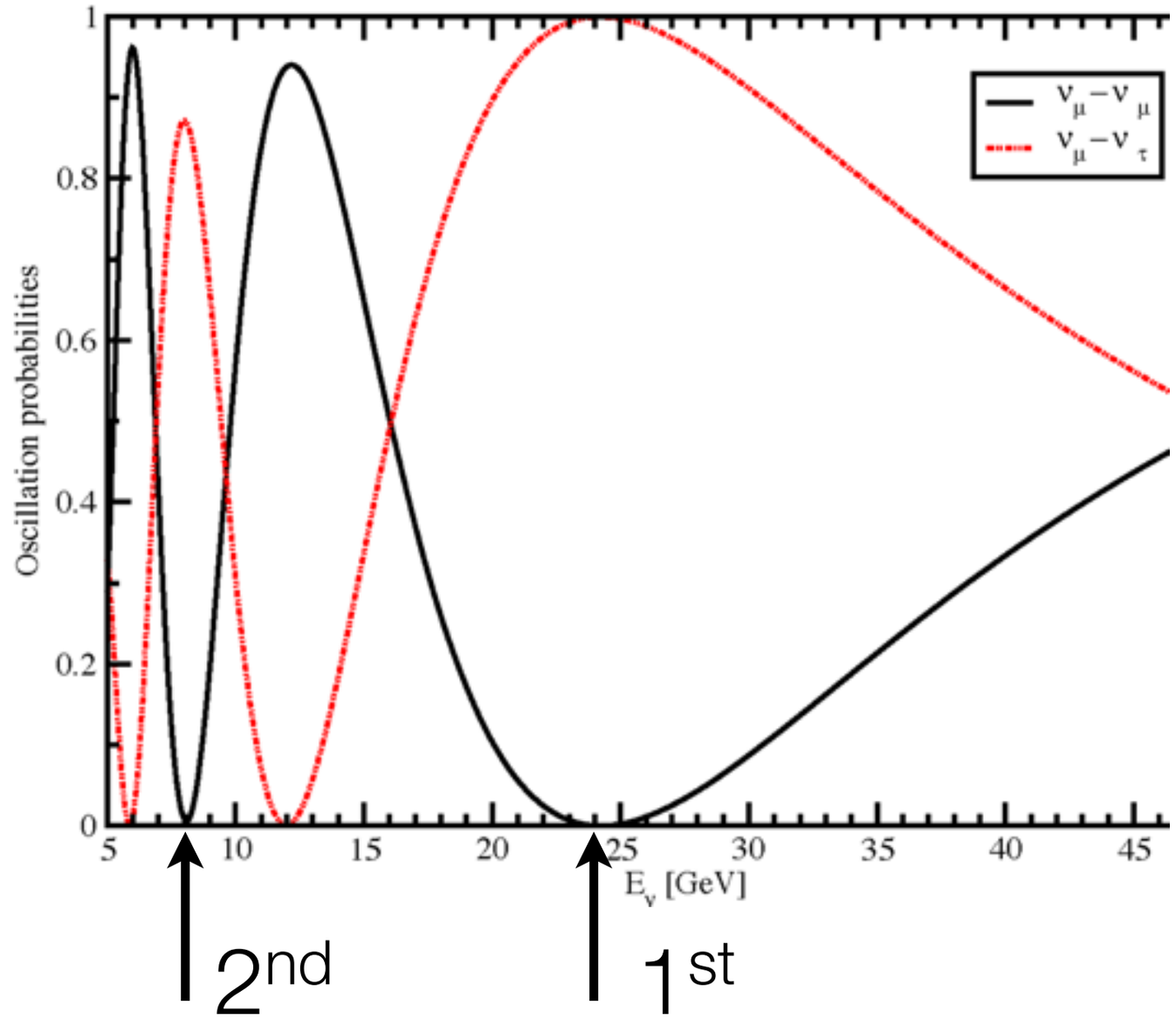


DeepCore + PINGU

# PINGU Oscillation Impact

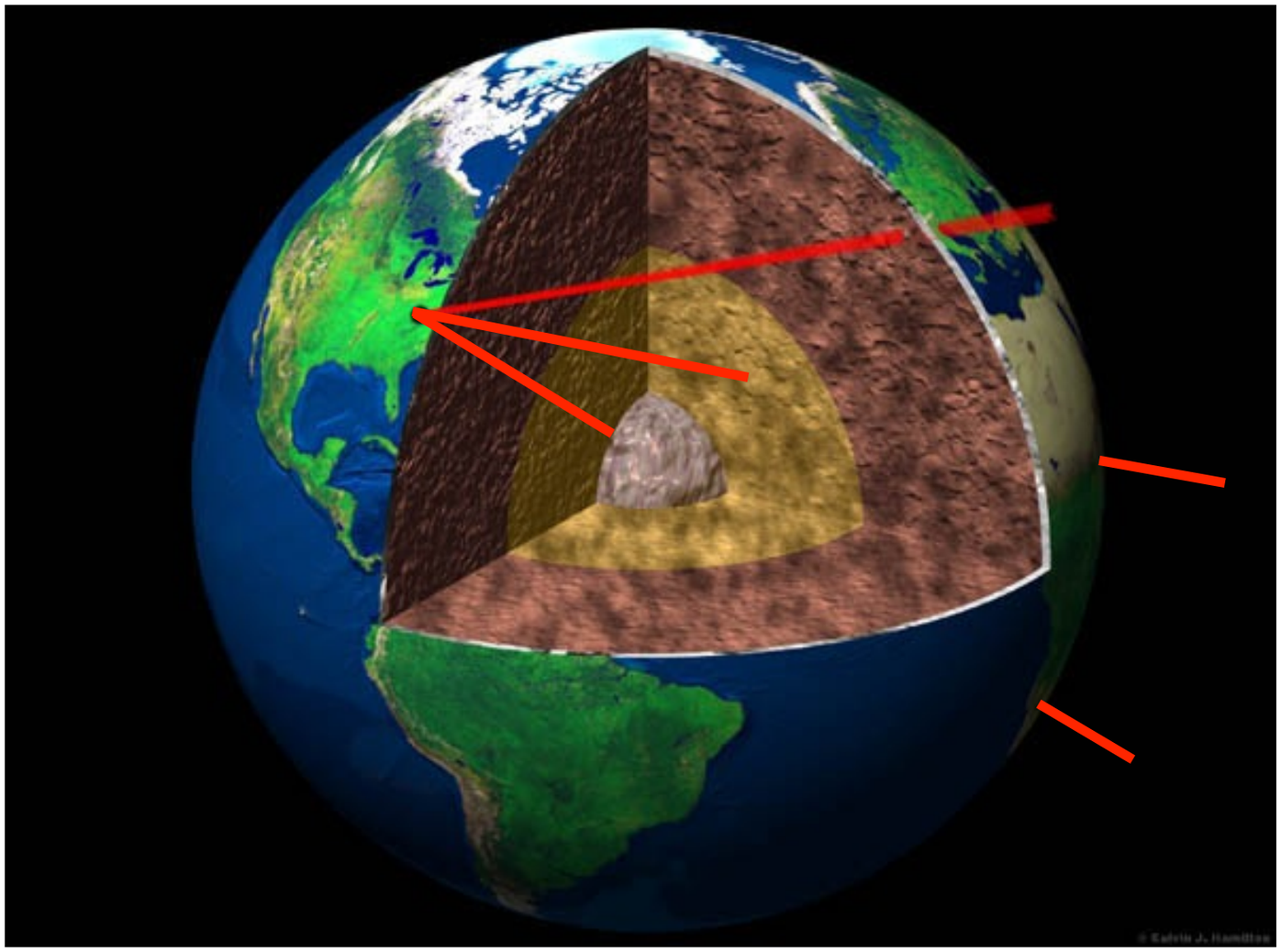
- With an infill that achieves ~GeV resolution, the 2nd oscillation minimum becomes accessible
- Improve both track and cascade reconstruction

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

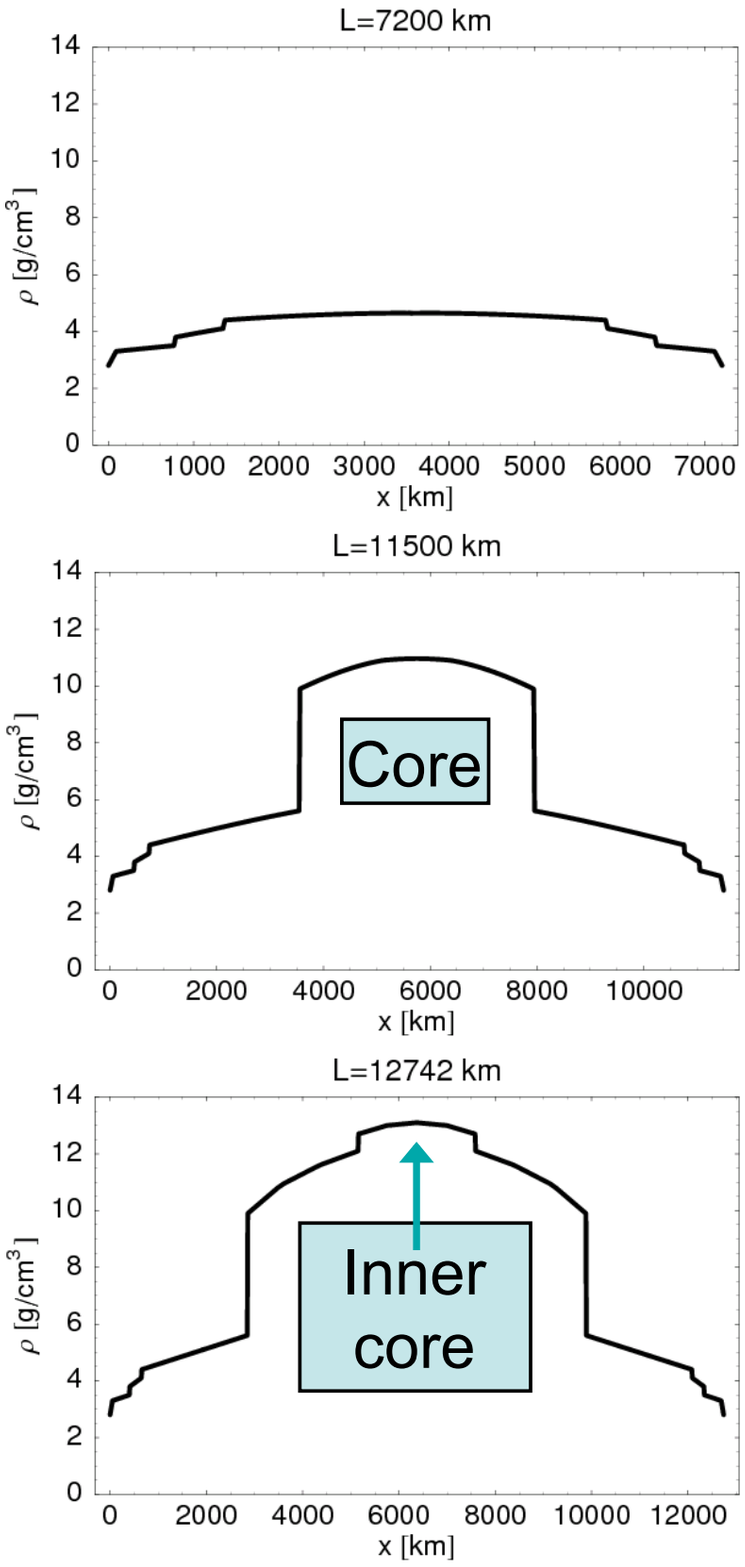


# Neutrino Baselines





*Walter Winter, Wurzburg

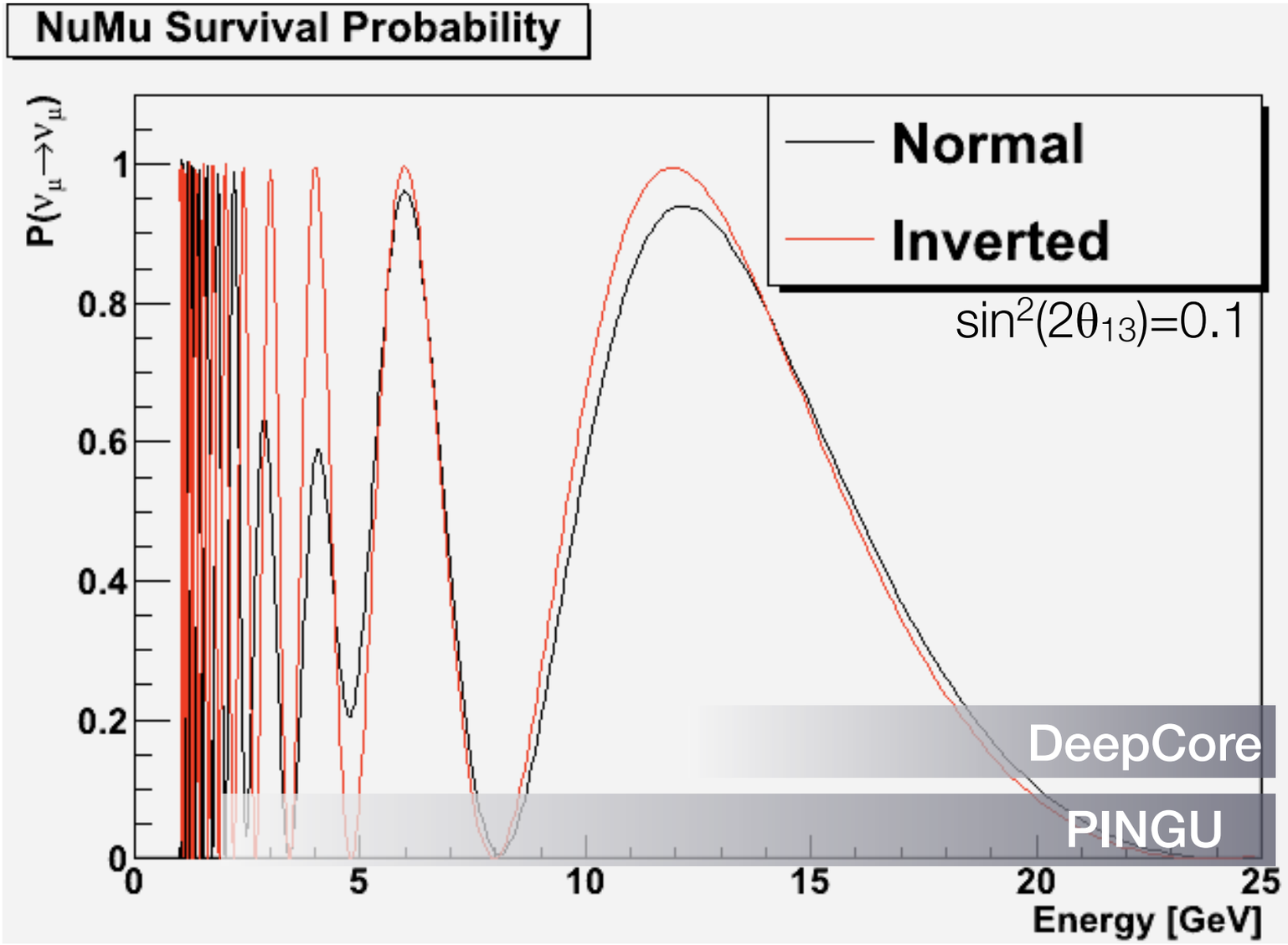



**(PREM: Preliminary Reference Earth Model)**

# Low energy oscillation features

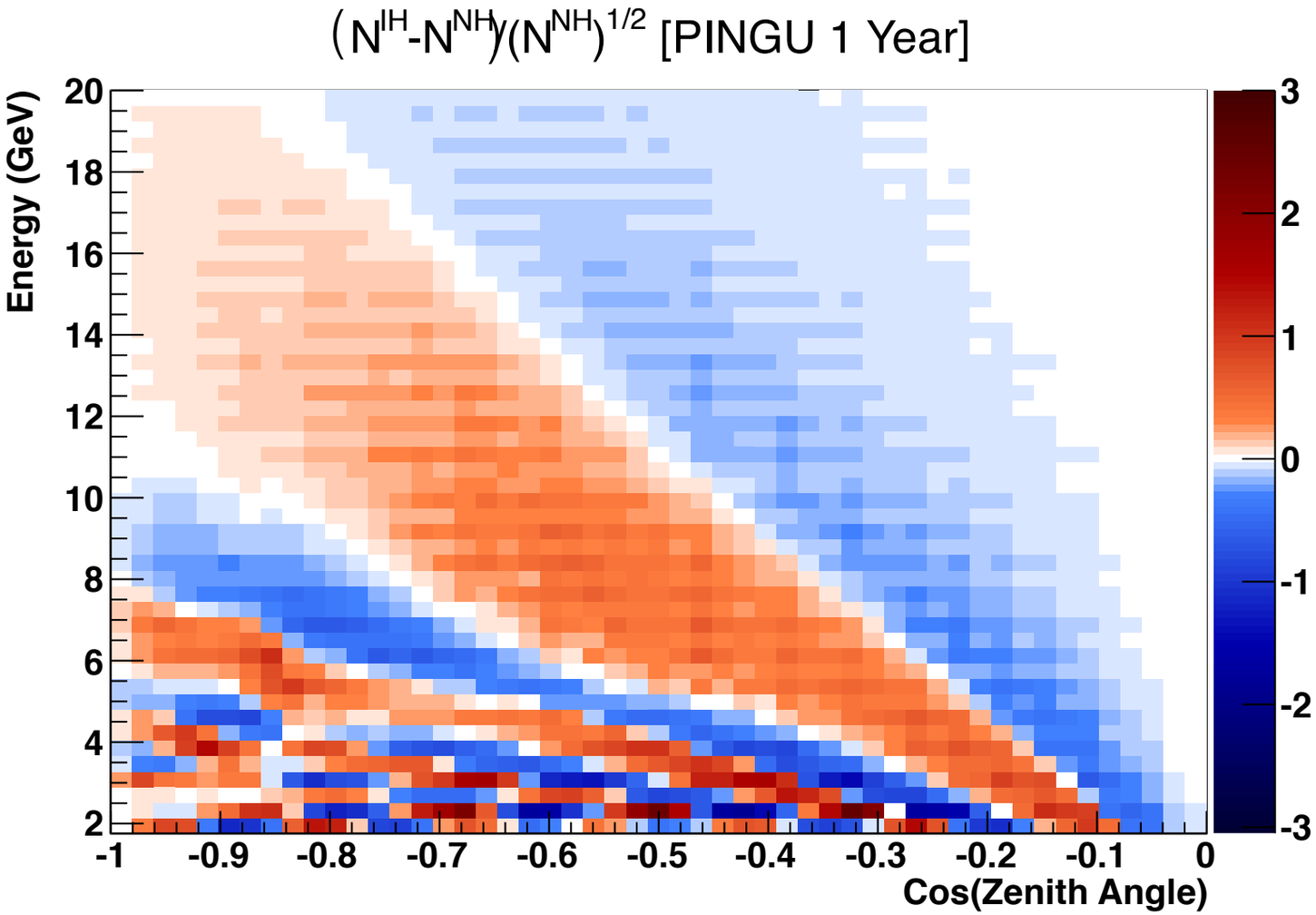


- Matter effects (MSW) change oscillations at lower energy
- Earth density changes also alter the oscillations
- Normal/Inverted Hierarchy



# Hierarchy



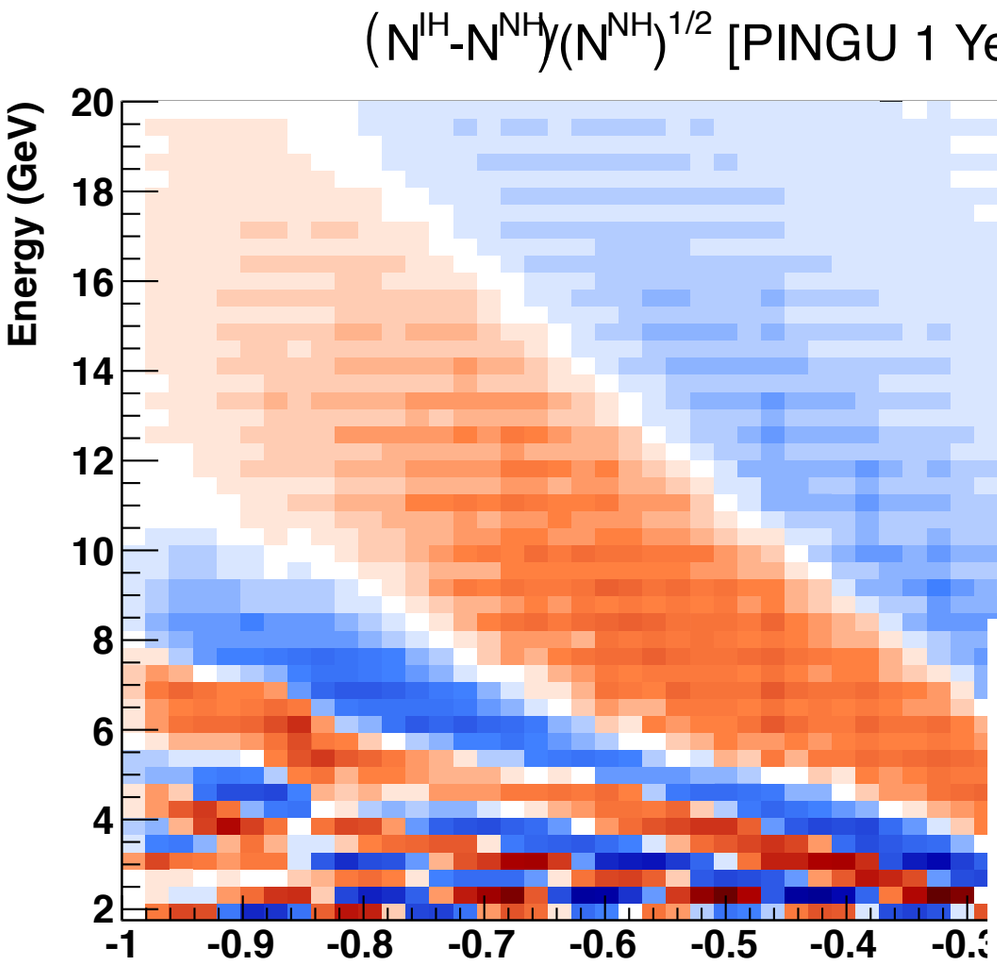



*reproduction using of technique described in Akhmedov, Razzaque, Smirnov arXiv:1205.7071v3

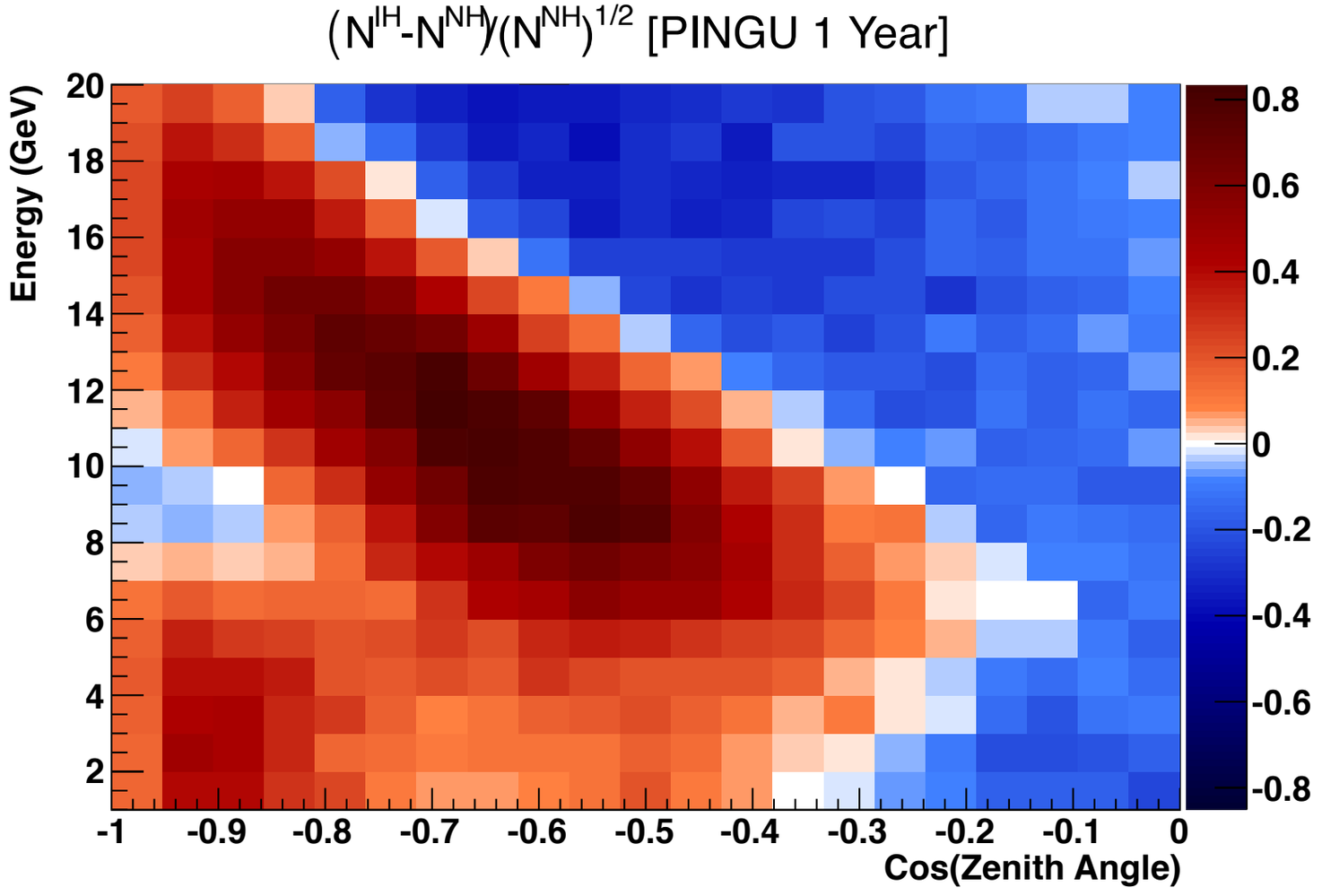
# Hierarchy



*reproduction using of technique described in Akhmedov, Razzaque, Smirnov arXiv:1205.7071v3



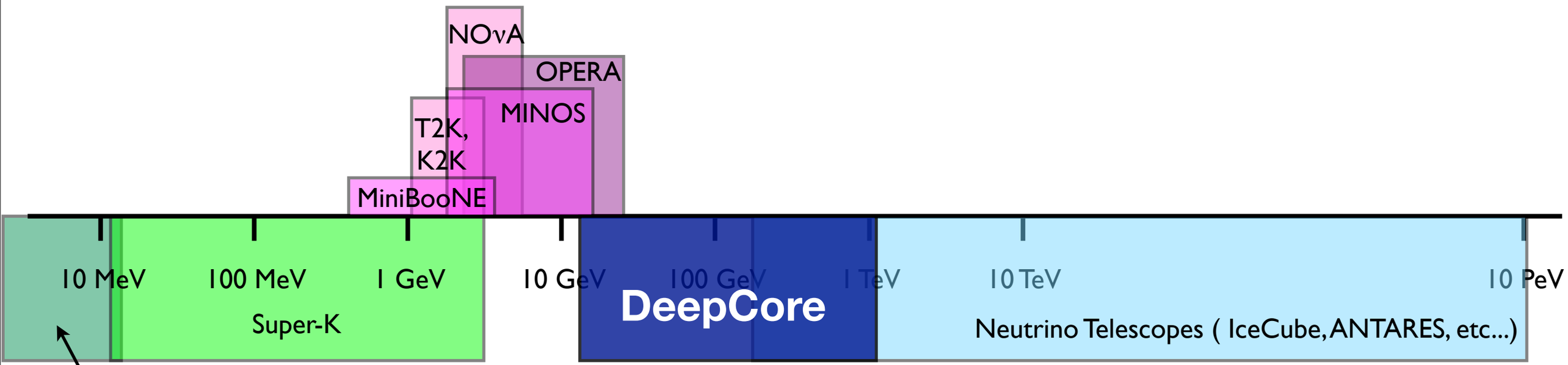

smeared: 3 GeV in energy and 11.25° in angular resolution



# Experimental Landscape

- Oscillation
- IceCube-DeepCore Physics
- PINGU
- Beyond

Accelerator based




Borexino
KamLAND
Double Chooz
Daya Bay
SNO

Non-accelerator based

- Neutrino Hierarchy
- High Precision νμ - Disappearance
- GeV Mass Dark Matter
- Manageable ντ - Appearance

# Experimental Landscape

- Oscillation
- IceCube-DeepCore Physics
- PINGU
- Beyond

Accelerator based

NOνA
OPERA
MINOS
T2K,
K2K
MiniBooNE

10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
10 PeV

Super-K
DeepCore
Neutrino Telescopes ( IceCube, ANTARES, etc...)

Borexino
KamLAND
Double Chooz
Daya Bay
SNO

**PINGU**

Non-accelerator based

Neutrino Hierarchy

High Precision $\nu_\mu$ - Disappearance

GeV Mass Dark Matter

Manageable $\nu_\tau$ - Appearance

# PINGU Advantages



- Relatively quick, cost effective, huge and unique
  - 2 season deployment w/ additional ~1.5 year procurement/shipping
  - *O*(25-30M)$
  - Megaton size at GeV energies
  - Samples many angle, many baselines and crosses the earth core
- Enhance on-going DeepCore physics
  - muon disappearance
    - $\theta_{23}$ maximal mixing
    - octant of $\theta_{23}$
  - tau appearance
- Gains sensitivity to the rich neutrino oscillation features
  - 2nd oscillation minima/maxima
  - Neutrino hierarchy

# PINGU Advantages



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  - 2 season deployment w/ additional ~1.5 year procurement/shipping
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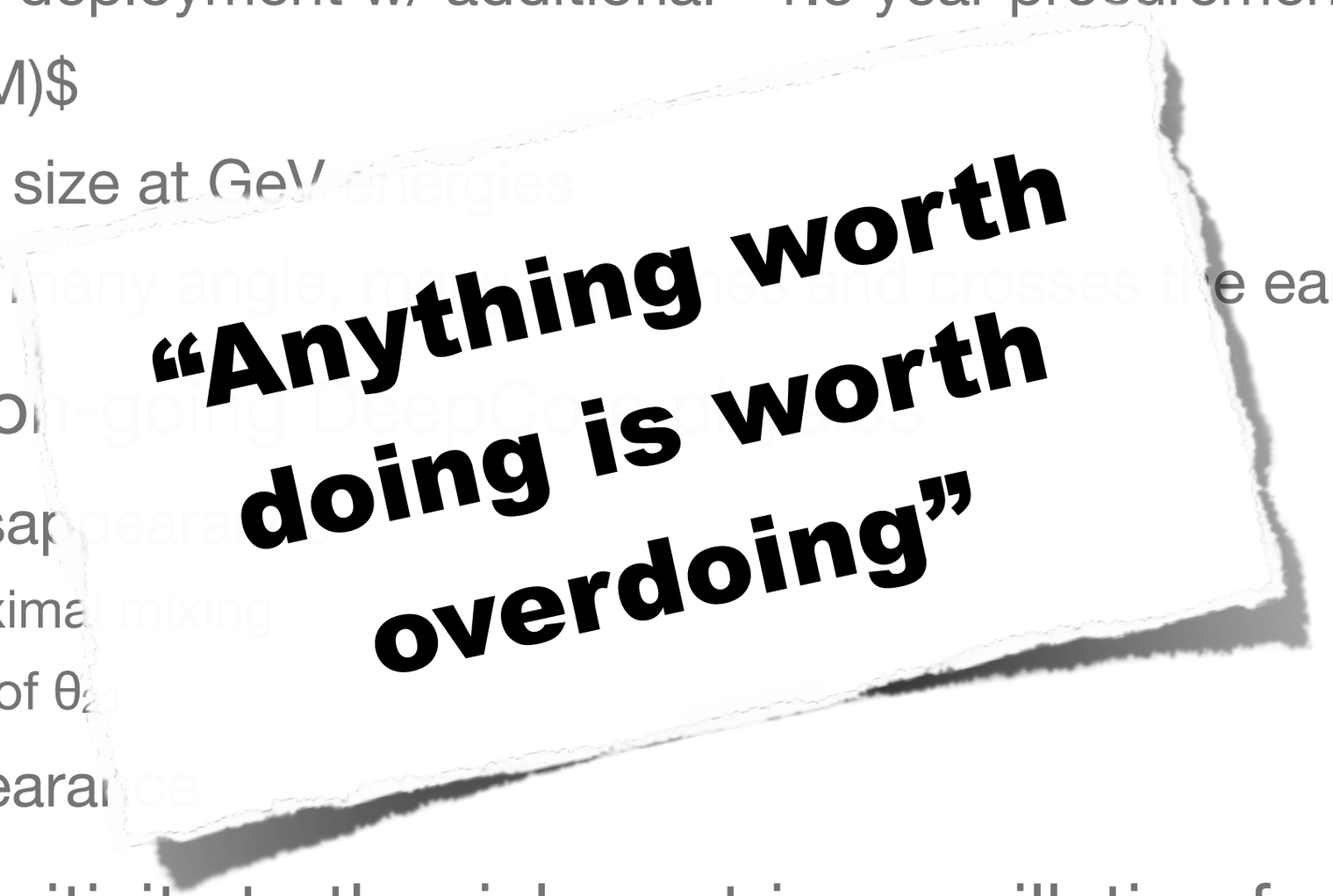
  - Megaton size at GeV
  - Samples … e earth core
- Enhance o…
  - muon disap…
    - $\theta_{23}$ maxima…
    - octant of $\theta_{2}$…
  - tau appearan…
- Gains sensitivity to the rich neutrino oscillation features
  - 2nd oscillation minima/maxima
  - Neutrino hierarchy

**"Anything worth doing is worth overdoing"**



# Really Beyond DeepCore



IceCube



DeepCore



PINGU

# Really Beyond DeepCore



IceCube



DeepCore



PINGU

# Really Beyond DeepCore









IceCube



DeepCore



PINGU



# Low Energy Large Volume

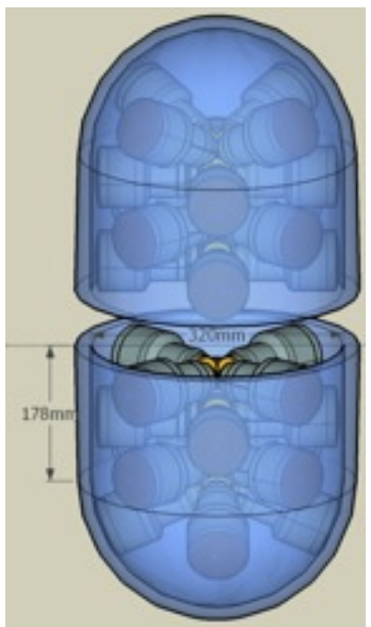


- South Pole Infrastructure
  - No excavation
  - Deployment is a now a refined process
- Unchanging, low-background ice
- Move from GeV to tens of MeV
  - Cherenkov ring imaging
  - IceCube/DeepCore style single-PMT module is no longer attractive
- Multi-megaton Ice Cherenkov Array (MICA)

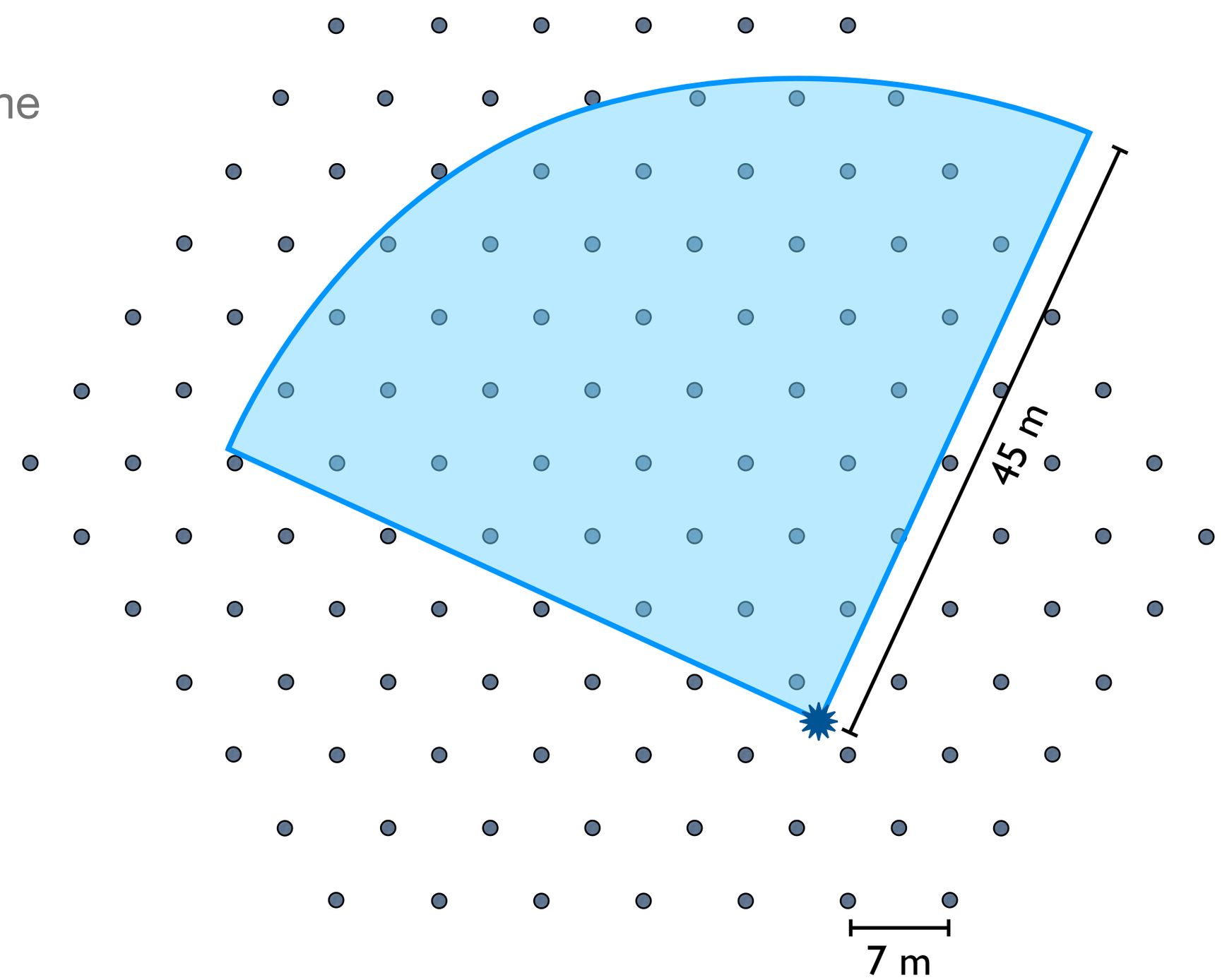
# Cerenkov Ring Imager



- 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

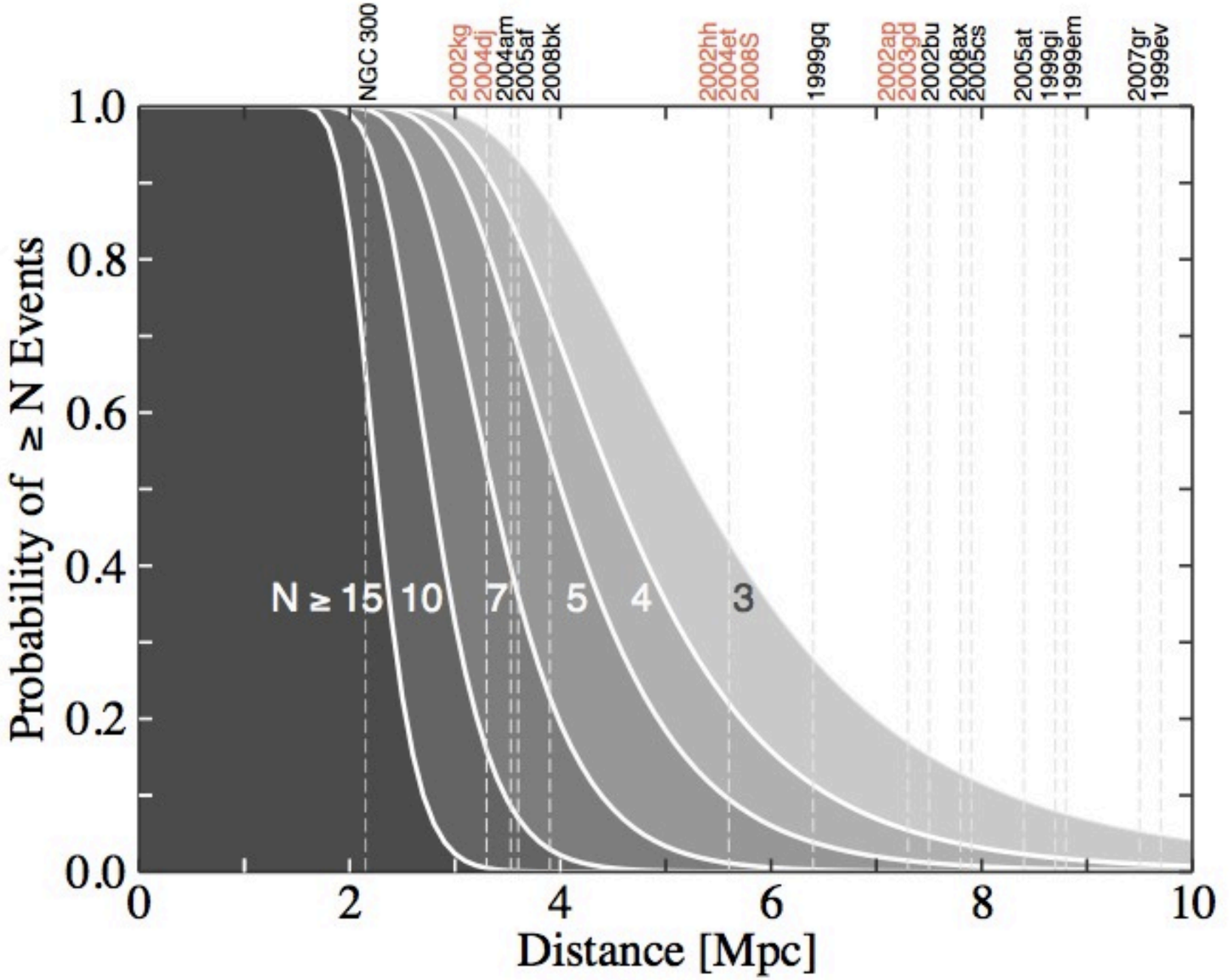



Courtesy P. Kooijman



- Extend core-collapse SN search beyond Milky Way
- 5 megaton detector with sensitivity down to 15 MeV

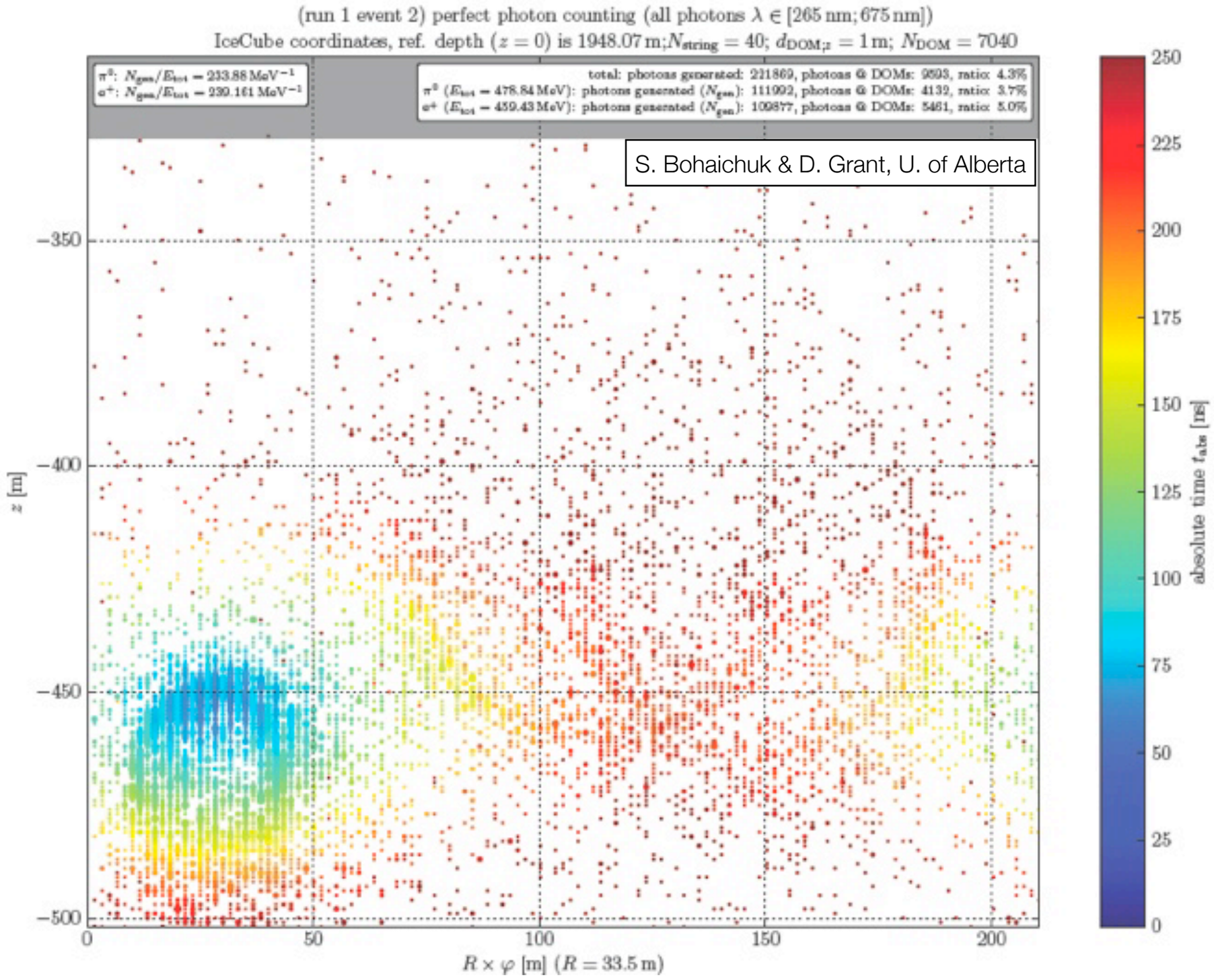
Kistler et. al.
arXiv:0810.1959



# Proton Decay Rings



$$p \rightarrow \pi^0 + e^+$$



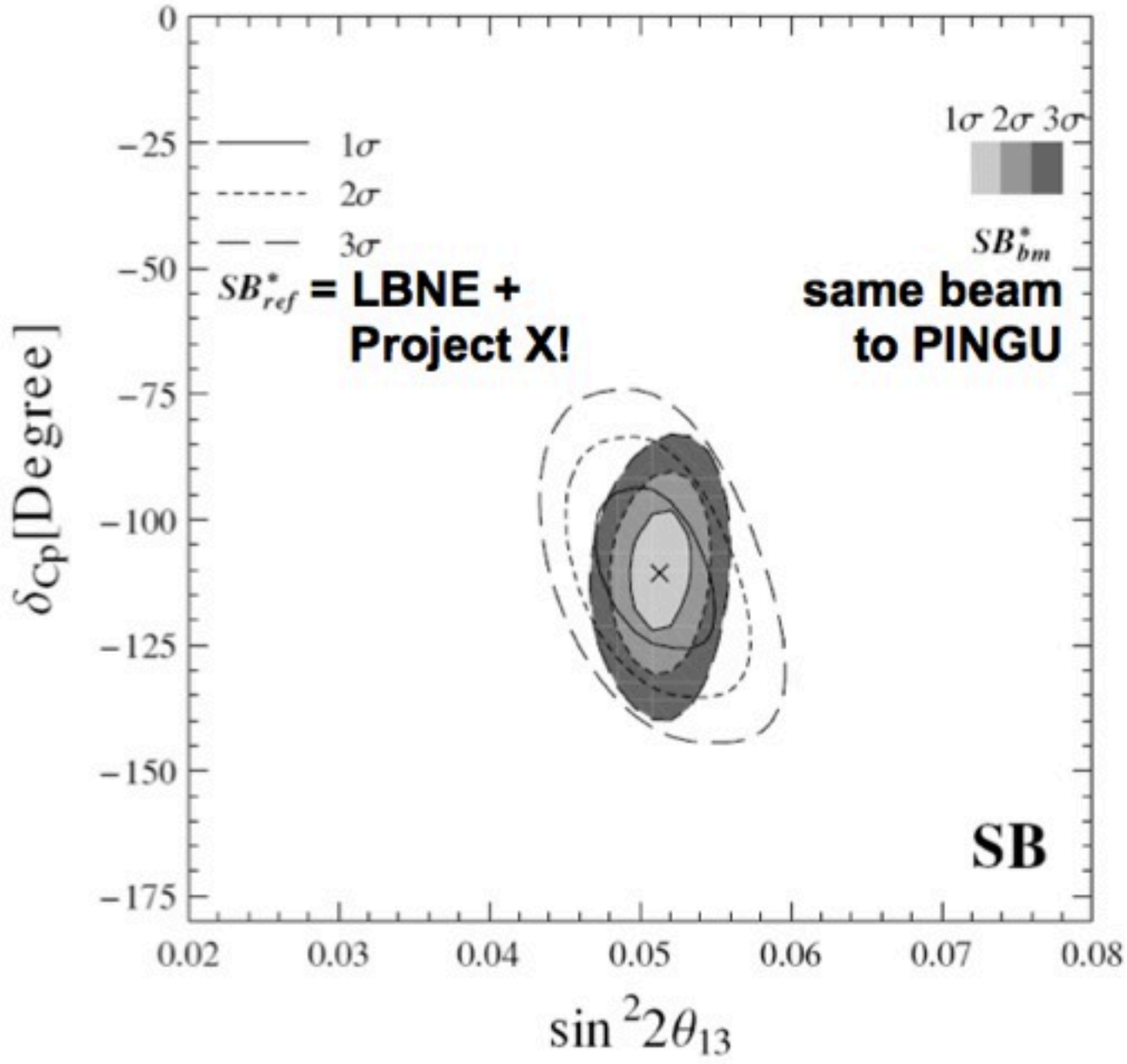
# Beam?

- Oscillation
- IceCube-DeepCore Physics
- PINGU
- Beyond

Julius-Maximilians-
UNIVERSITÄT
WÜRZBURG

## Upgrade path towards $\delta_{CP}$?

- Measurement of $\delta_{CP}$ 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



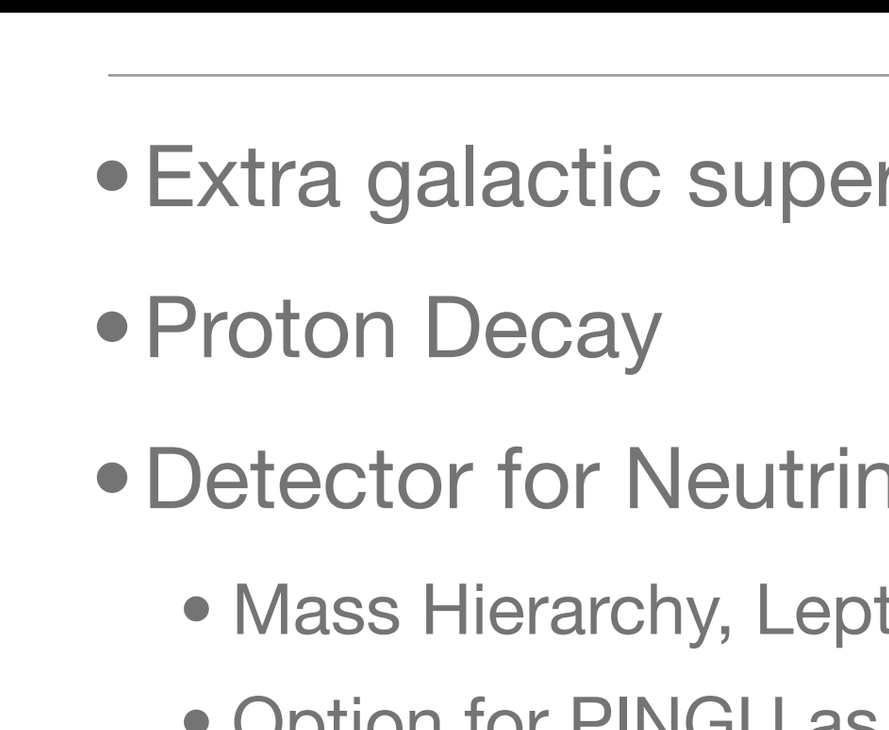

(Tang, Winter, JHEP 1202 (2012) 028)

15

"Superbeam FNAL-PINGU?", W. Winter

# MICA Physics

- Extra galactic supernova
- Proton Decay
- Detector for Neutrino Factory, Beta beam or Super Beam
  - Mass Hierarchy, Lepton CP Violation
  - Option for PINGU as well depending on beam characteristics
  - Using PMTs, ~90% of detector cost is electronics



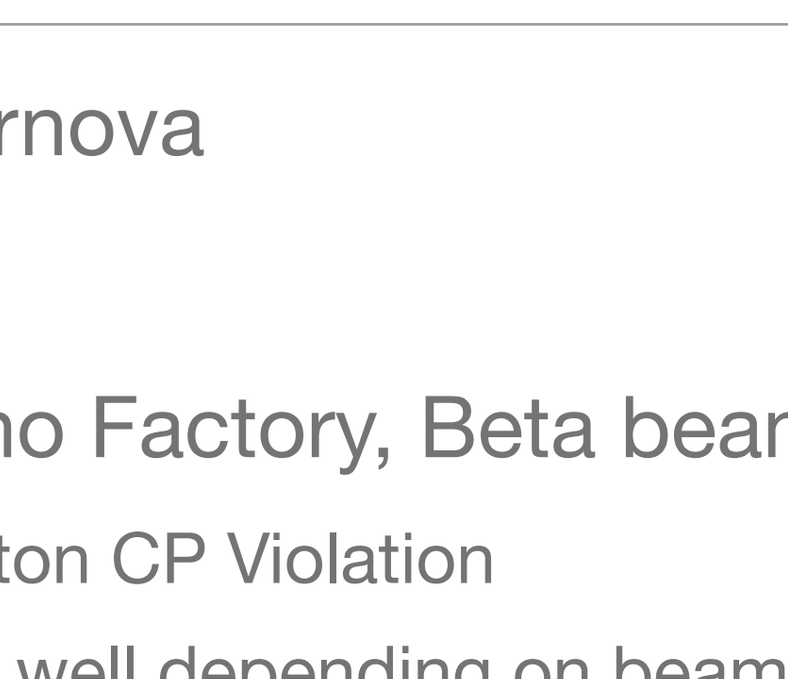





**Figure 12**: The precision measurements of CP phase $\delta_{CP}$ and $\sin^2 2\theta_{13}$ for three single-baseline neutrino experiments: Beta Beam (BB), Neutrino Factory (NF), and SuperBeam (SB). The contours represent the $1\sigma$, $2\sigma$ and $3\sigma$ confidence levels (2 d.o.f.). Filled contours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

# Message

- Atmospheric neutrinos (still) offer rich physics
  - IceCube + DeepCore is a statistical juggernaut, *O*(100,000) triggered events/year
  - DeepCore + IceCube has observed neutrino induced cascades and numu disappearance
- Proposed extensions
  - PINGU - Down to *O*(1) GeV improves oscillation searches, lower mass Dark Matter, and neutrino hierarchy resolution
  - MICA - Down to *O*(10) MeV opens up new physics

# Thanks

# Backup

# Neutrino Oscillation



Flavor Eigenstate

Mass Eigenstate

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

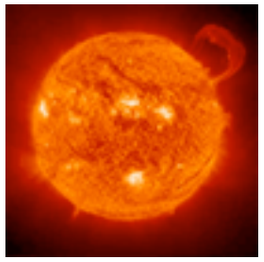
$$= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

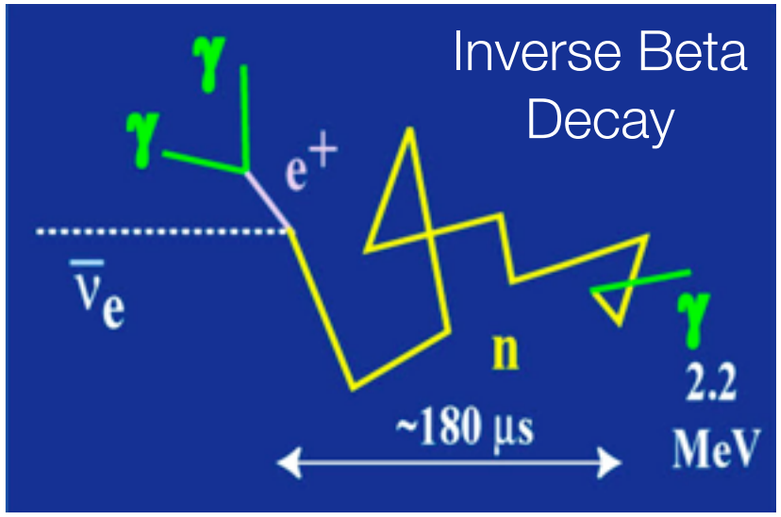
- Neutrino flavor eigenstates are related to mass eigenstates via the PMNS Unitary mixing matrix

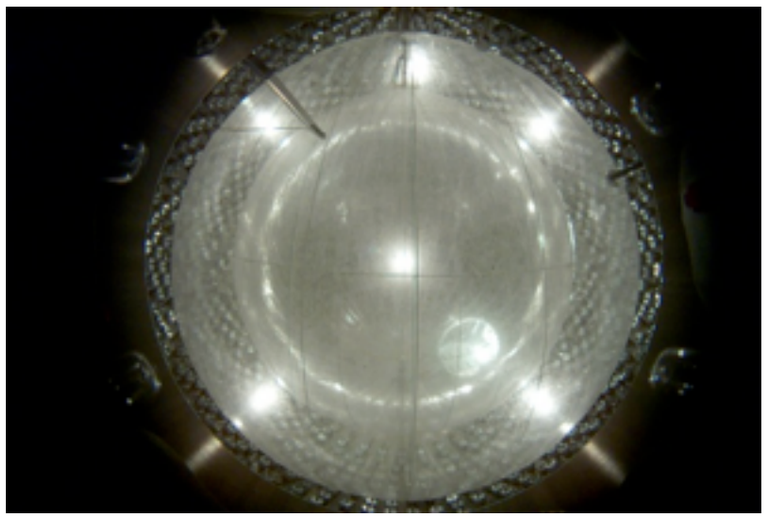
# Reactor/Solar

- Optimized for MeV anti-neutrinos undergoing inverse beta decay
- High precision
- Isotropic sources

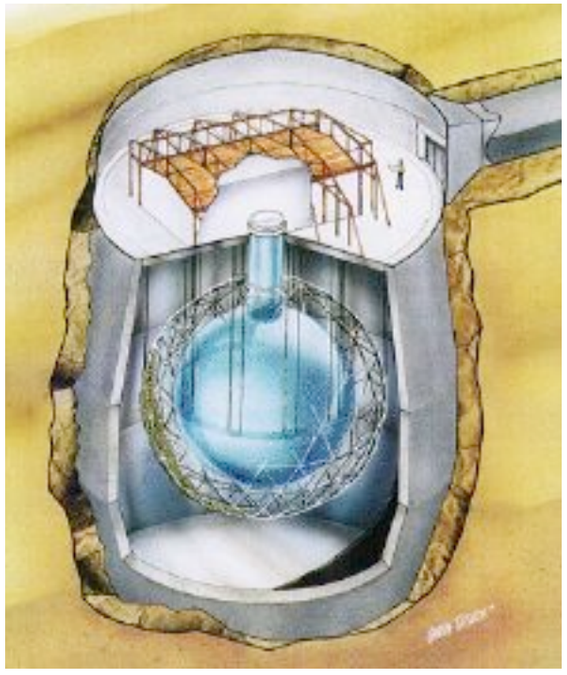




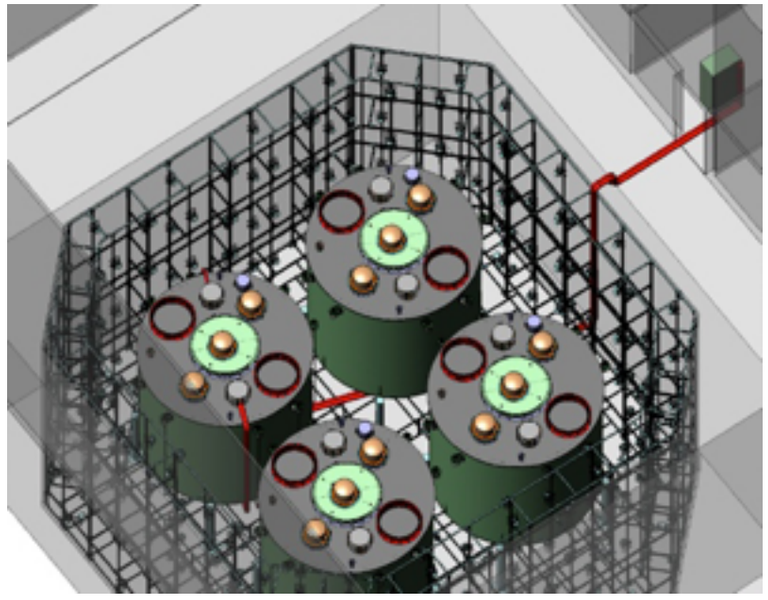


Borexino



SNO



Daya Bay

# Measuring Oscillation 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

# Measuring Oscillation Parameters



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

Experimentally measured values

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

Experimentally measured values

- Experimentally $|U_{\tau 3}|^2$ is measured via an energy dependent ***excess*** of tau neutrinos over a long baseline using the weak mixing angles
  - $P_{\nu_\mu \to \nu_\tau} = \sin^2(2\theta_{23}) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$

L = Length
E = Neutrino Energy

# Measuring Oscillation Parameters

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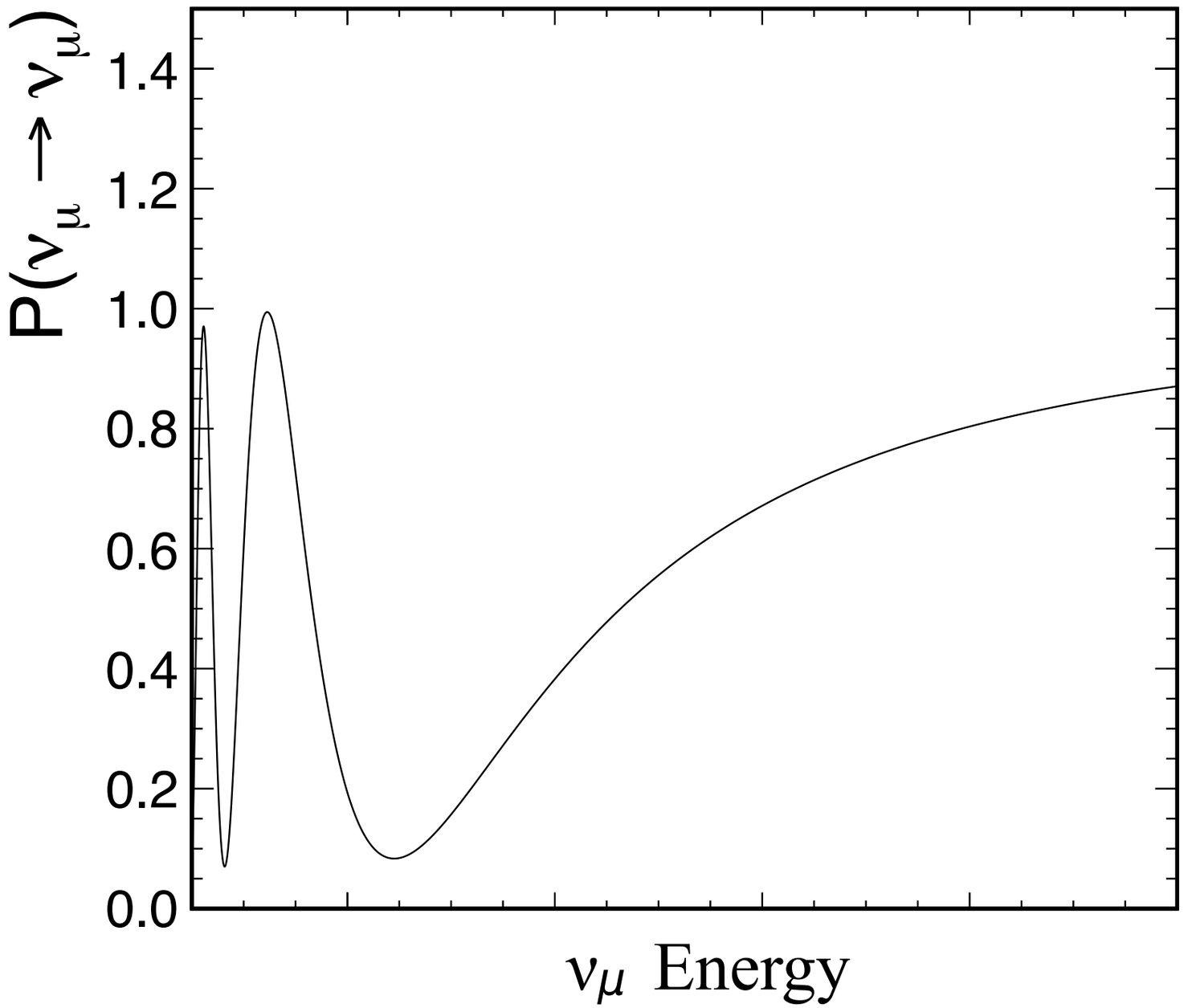
L = Length
E = Neutrino Energy

- $|U_{\mu 3}|^2$ is measured via an energy dependent ***deficit*** of muon neutrino events over a long baseline
  - $P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$

# Generic Oscillation



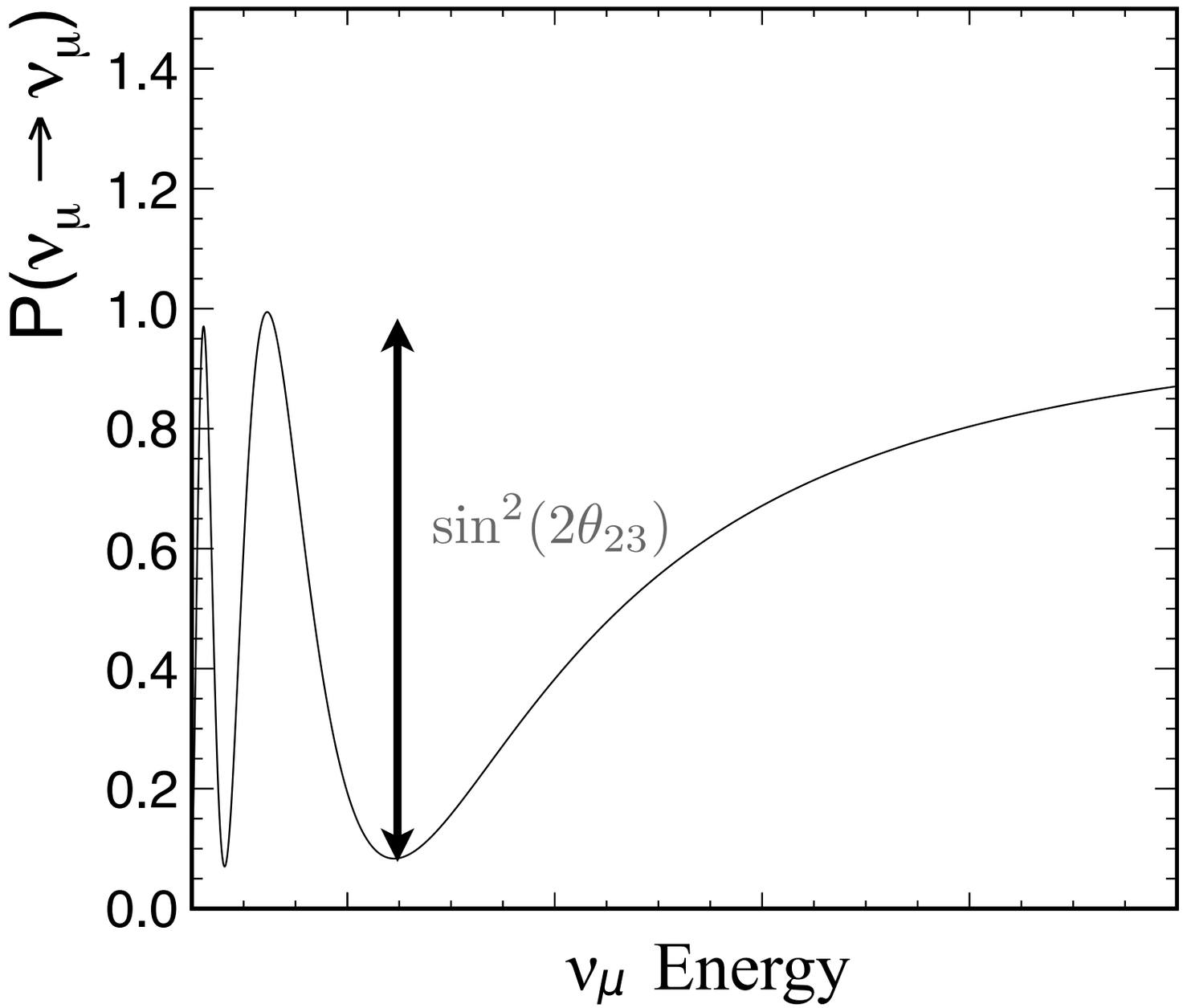
## Fixed Baseline L



# Generic Oscillation



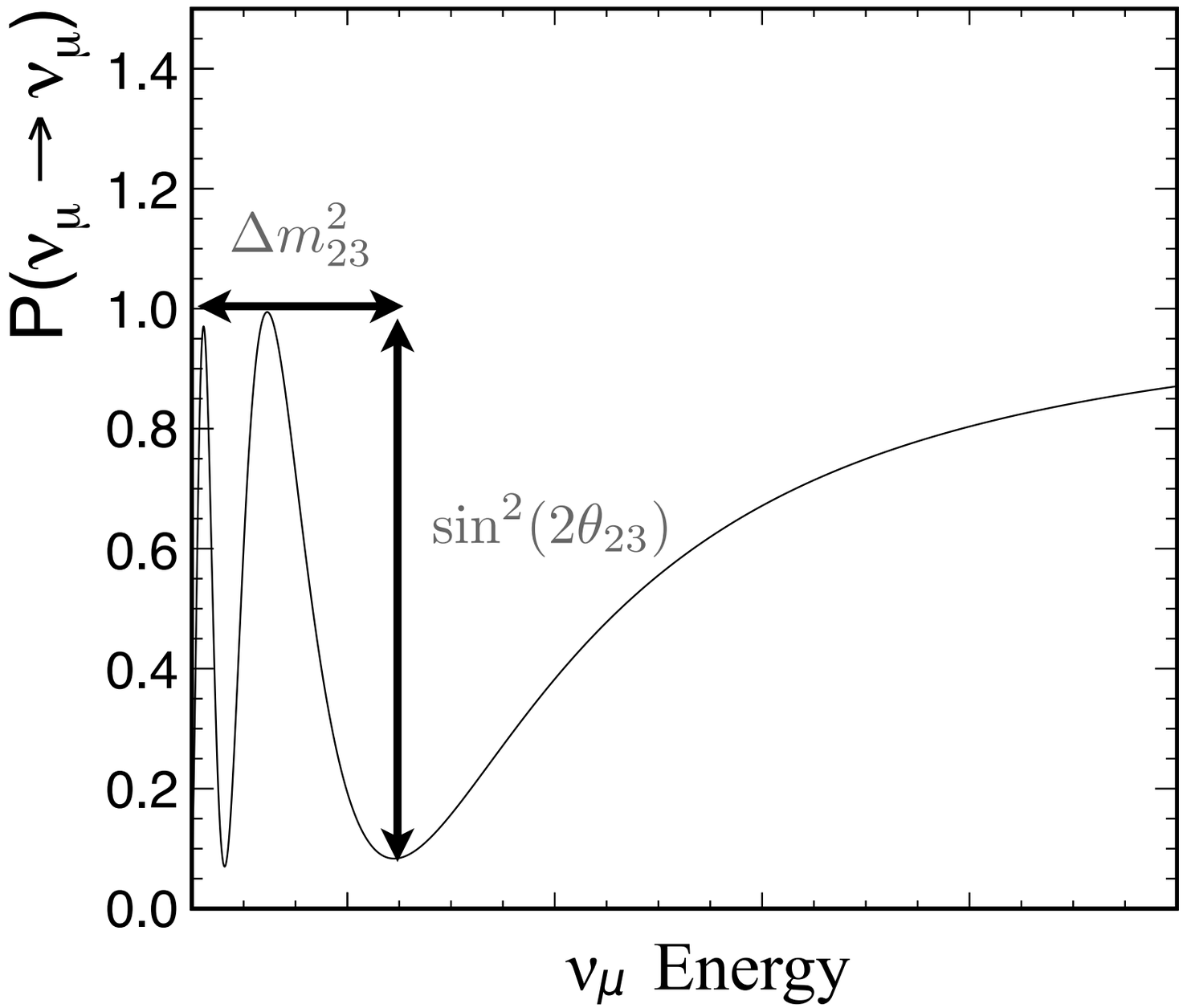
## Fixed Baseline L



# Generic Oscillation



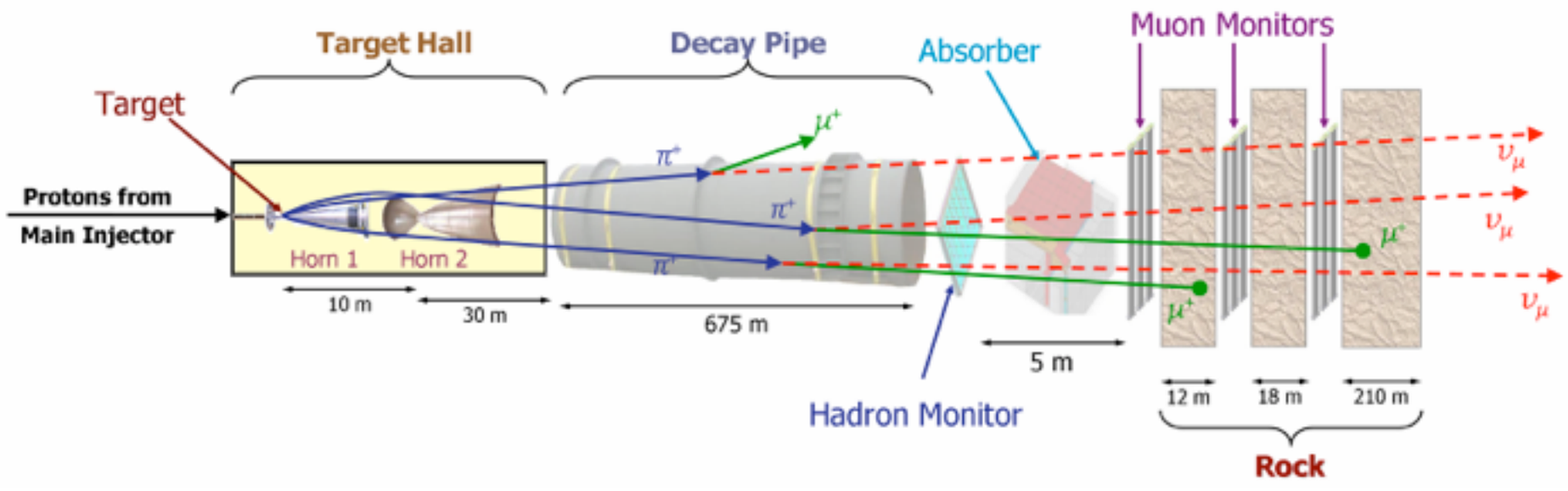
## Fixed Baseline L

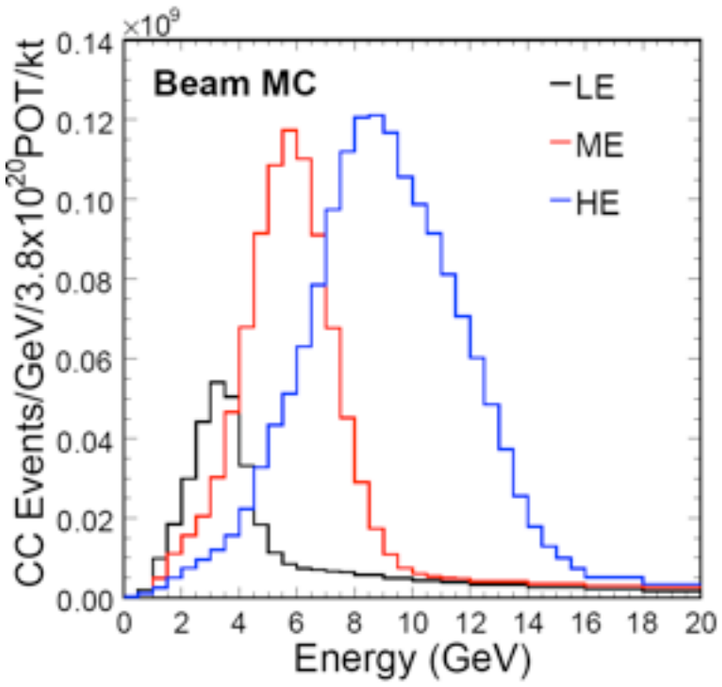


# Accelerator

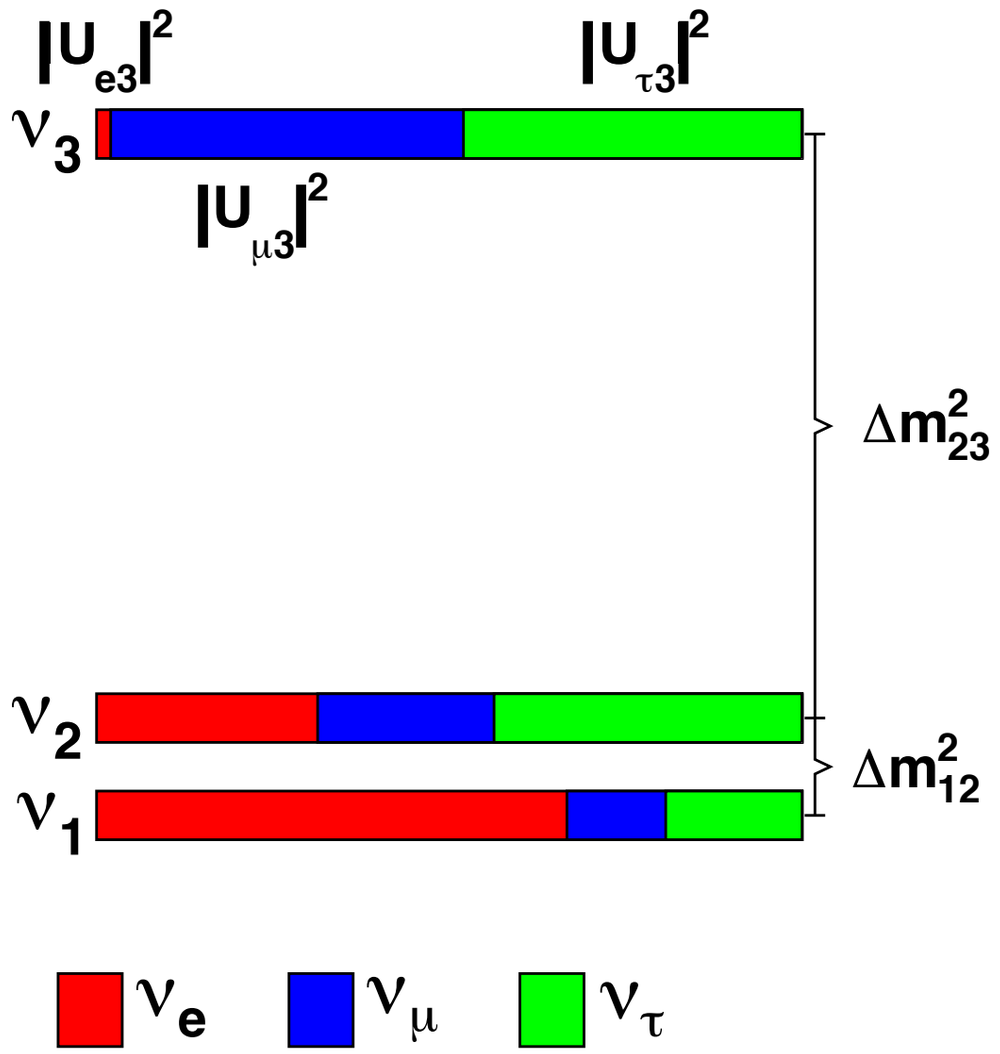
- Accelerators use variable energy neutrino beam to select region of interest
- Place Far Detector km away from beam
- Event timing and direction provide excellent background rejection

## NuMI Beamline at Fermilab



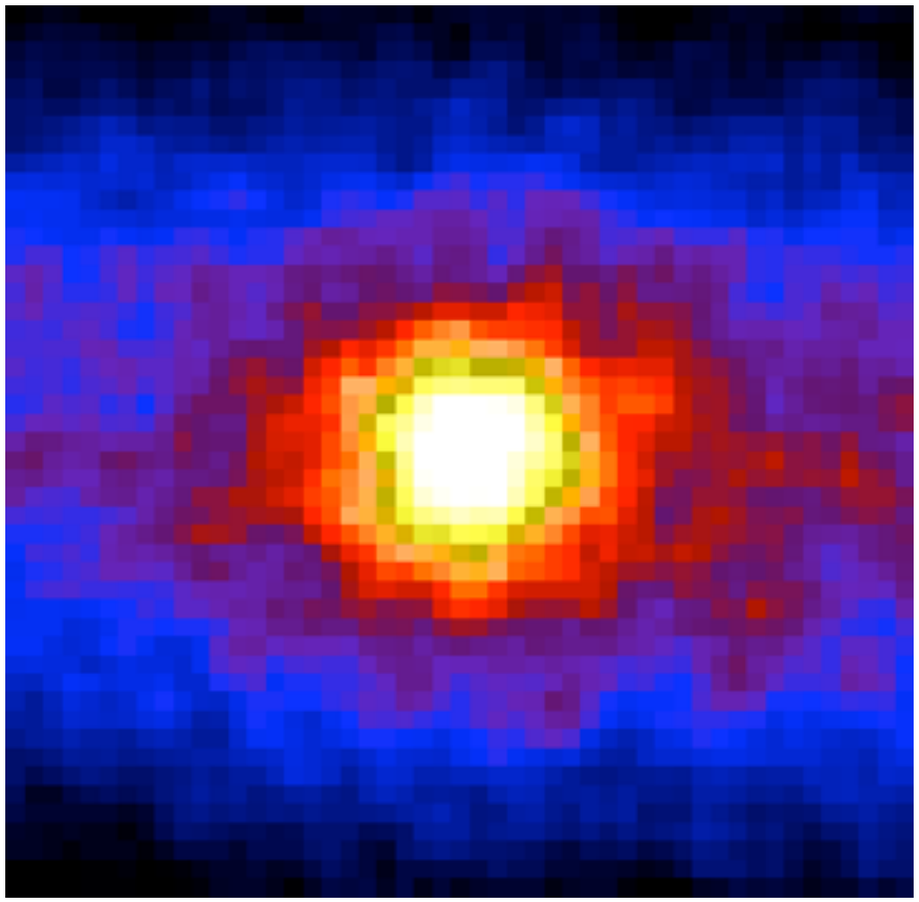
# Neutrino Mixing Diagram

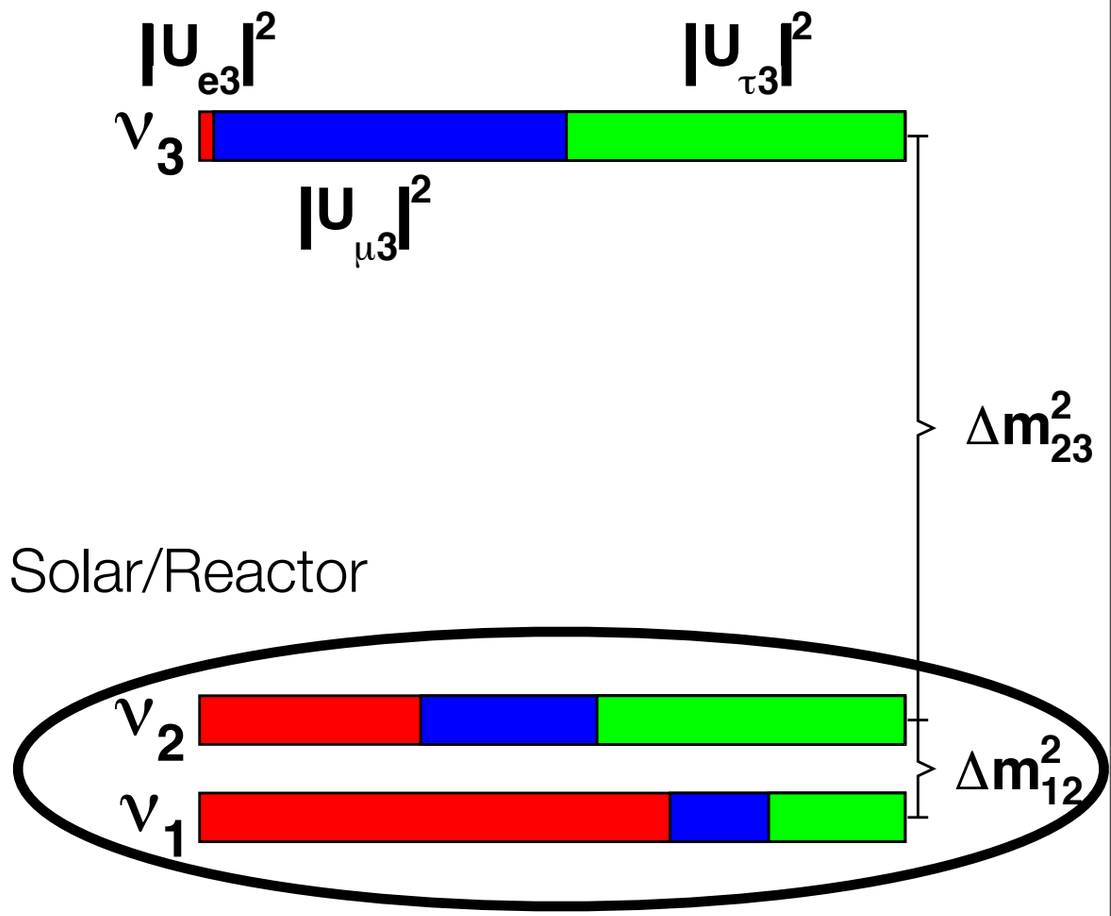



$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

# Neutrino Mixing Diagram








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

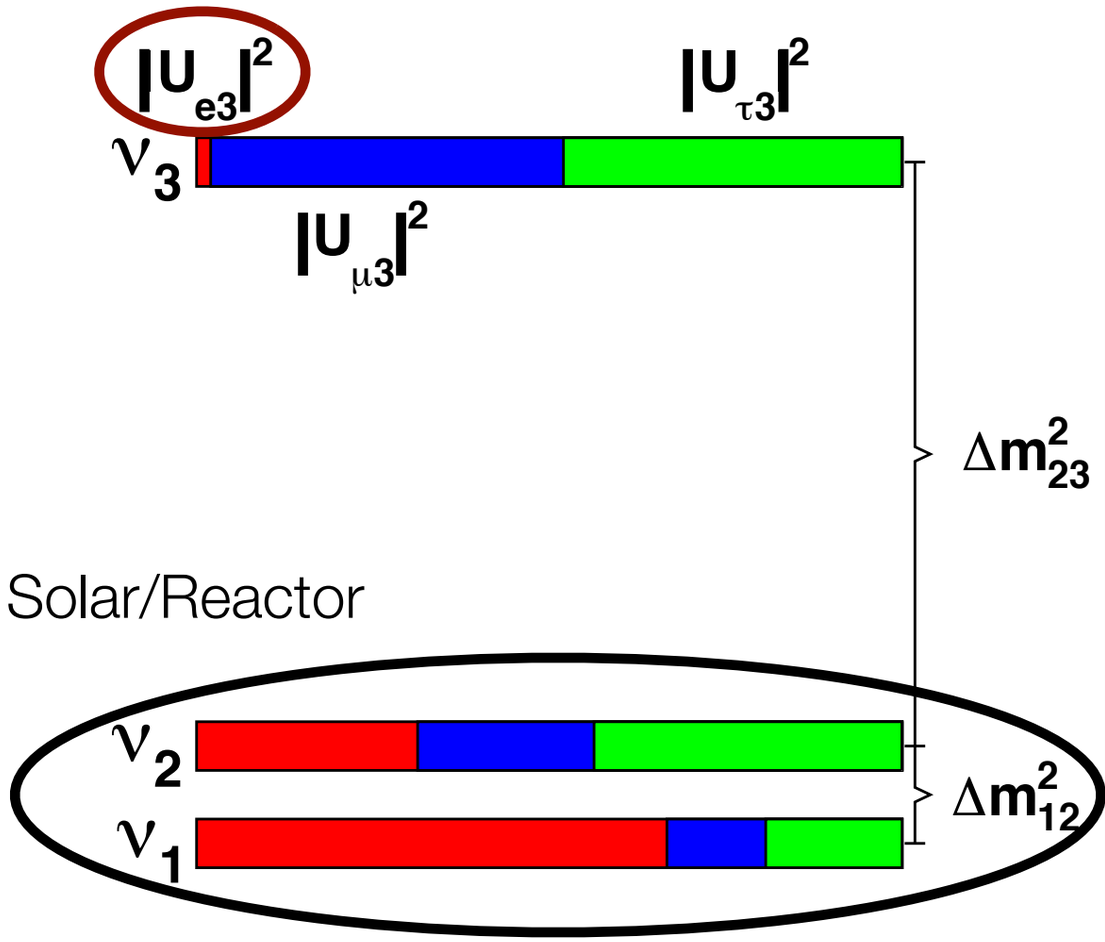
$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

# Neutrino Mixing Diagram






Off-Axis Accelerator &
Short Baseline



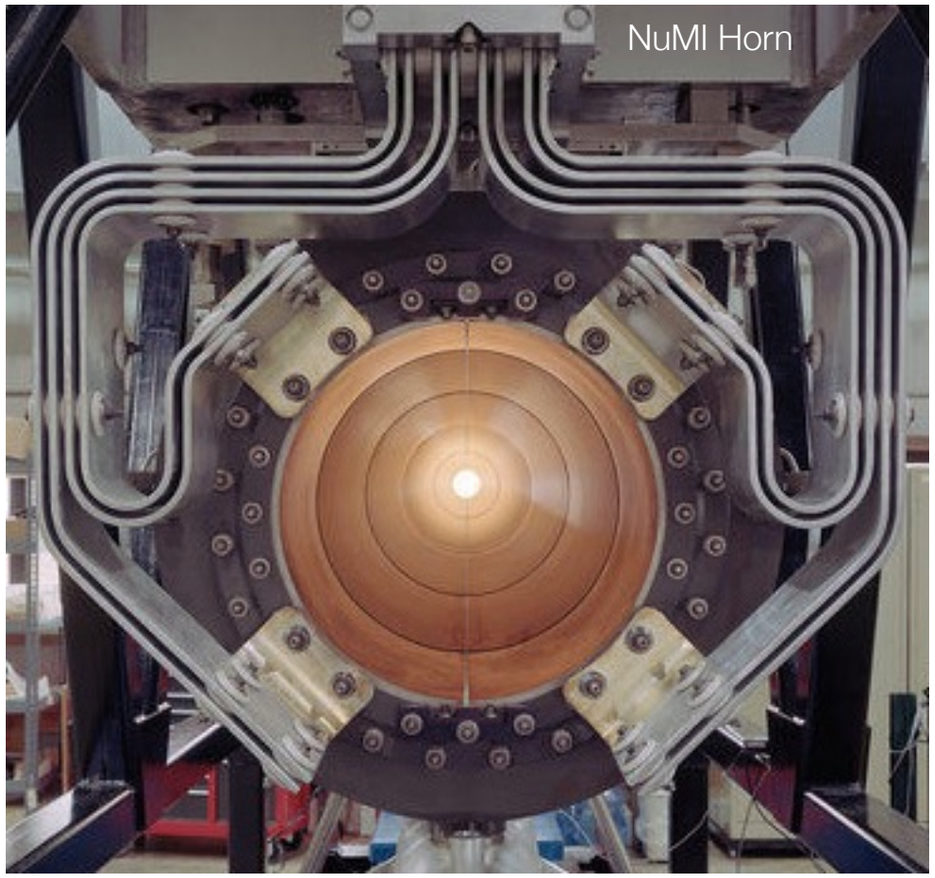

| Experiment type | Oscillation Channel |
|---|---|
| Solar & Reactor | $(\nu_e \to \nu_\mu)$ |
| Off-Axis & SBL | $(\nu_e \to \nu_e)$<br>$(\nu_\mu \to \nu_e)$ |

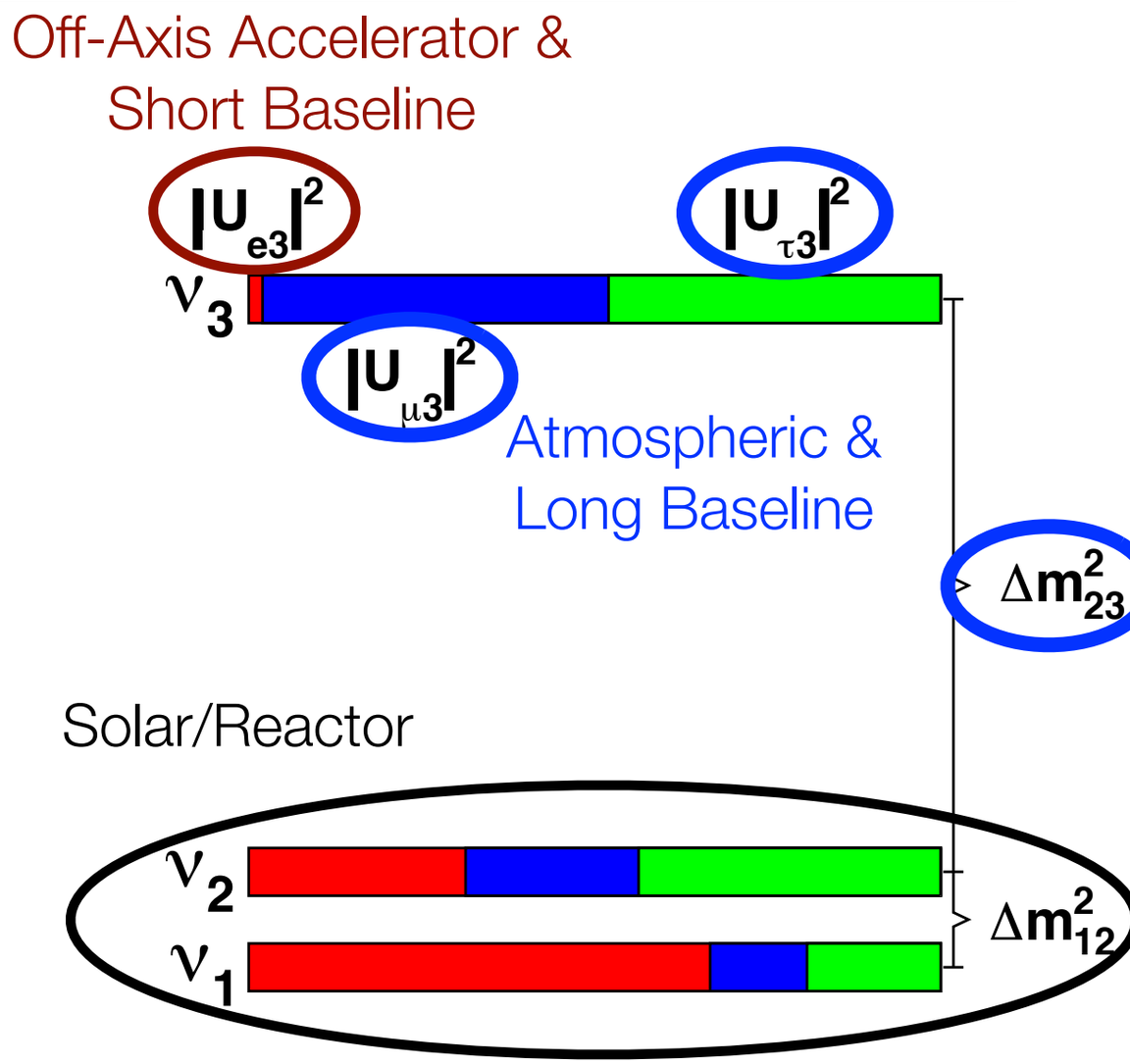
$\nu_e$ $\nu_\mu$ $\nu_\tau$

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

# Neutrino Mixing Diagram



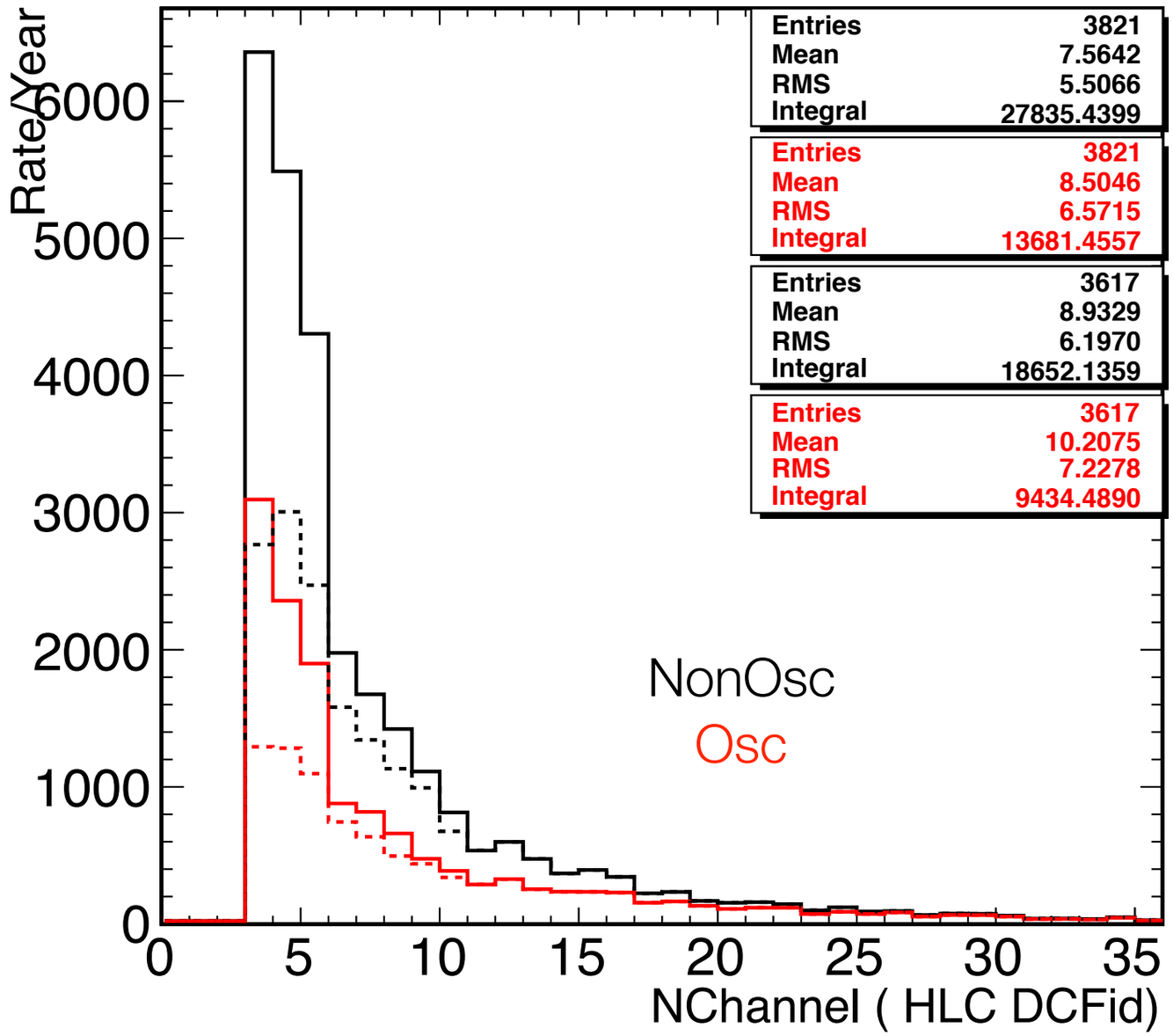



| Experiment type | Oscillation Channel |
|---|---|
| Solar & Reactor | $(\nu_e \to \nu_\mu)$ |
| Off-Axis & SBL | $(\nu_e \to \nu_e)$ $(\nu_\mu \to \nu_e)$ |
| Atmospheric & LBL | $(\nu_\mu \to \nu_\mu)$ $(\nu_\mu \to \nu_\tau)$ |

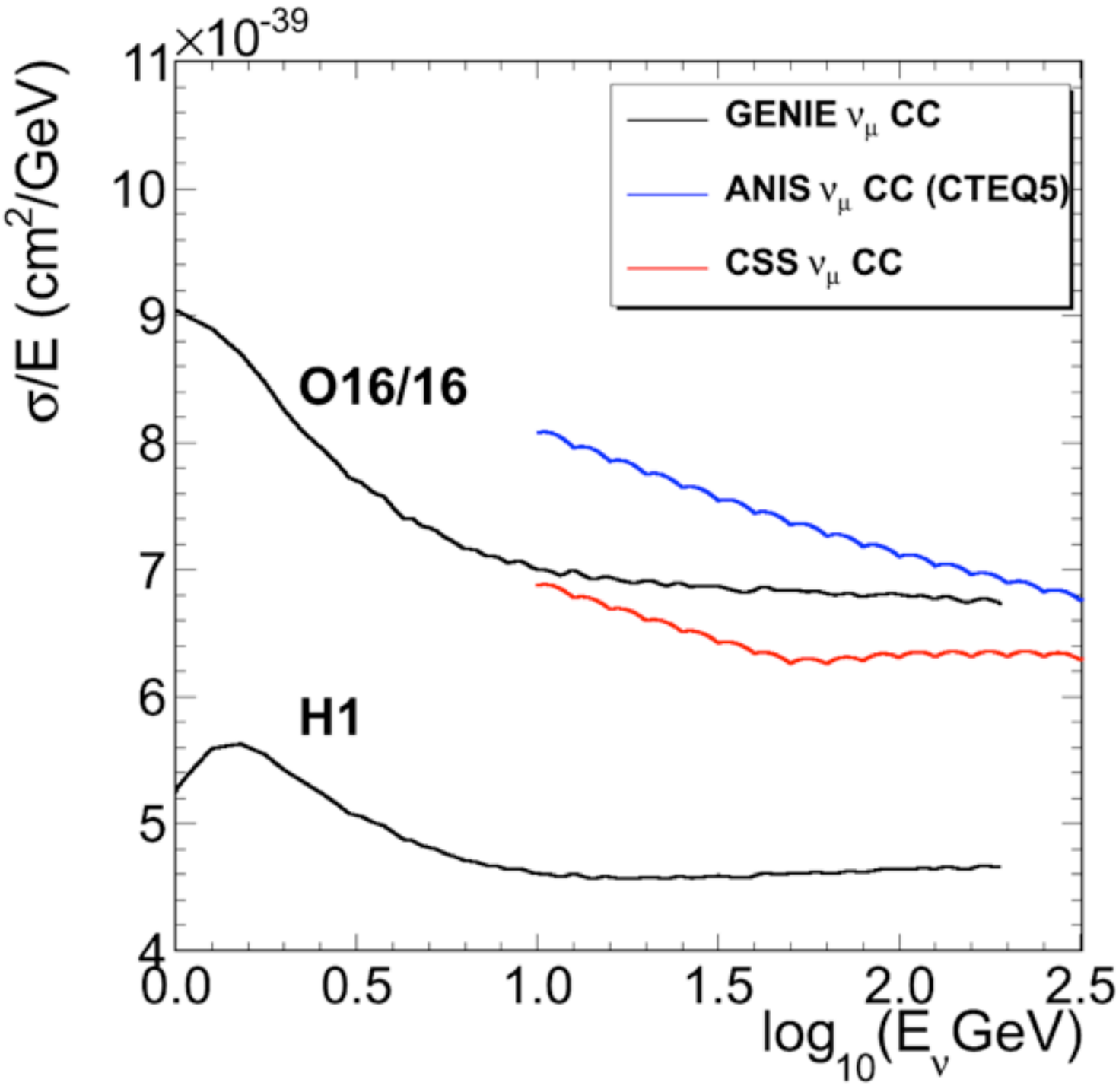
$\nu_e$ $\nu_\mu$ $\nu_\tau$

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


Rate/Year
6000
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
30
35
NChannel ( HLC DCFid)
NonOsc
Osc
Entries 3821
Mean 7.5642
RMS 5.5066
Integral 27835.4399
Entries 3821
Mean 8.5046
RMS 6.5715
Integral 13681.4557
Entries 3617
Mean 8.9329
RMS 6.1970
Integral 18652.1359
Entries 3617
Mean 10.2075
RMS 7.2278
Integral 9434.4890

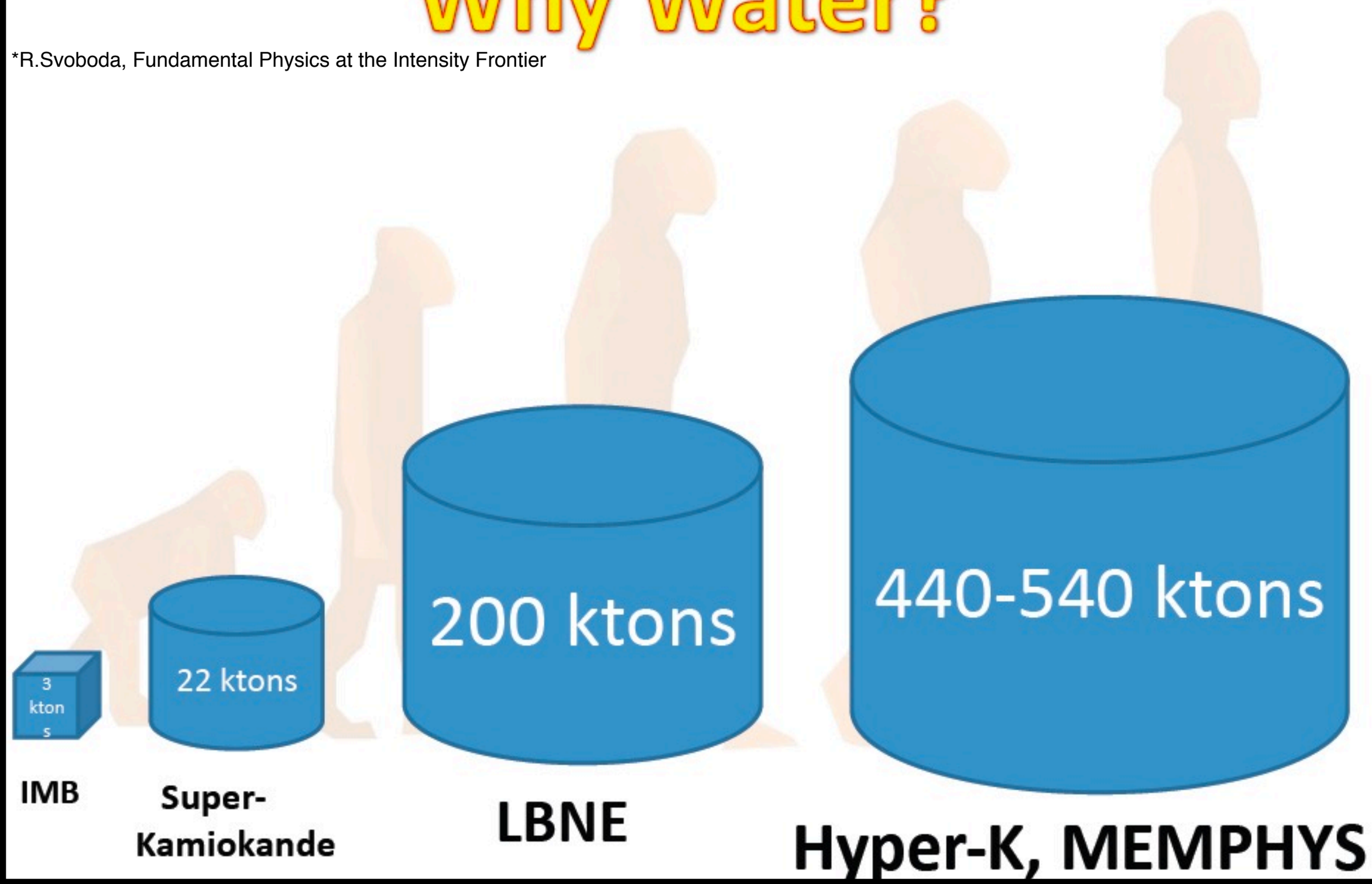
# New World - New Physics

- Oscillation
- IceCube-DeepCore Physics
- PINGU
- Beyond

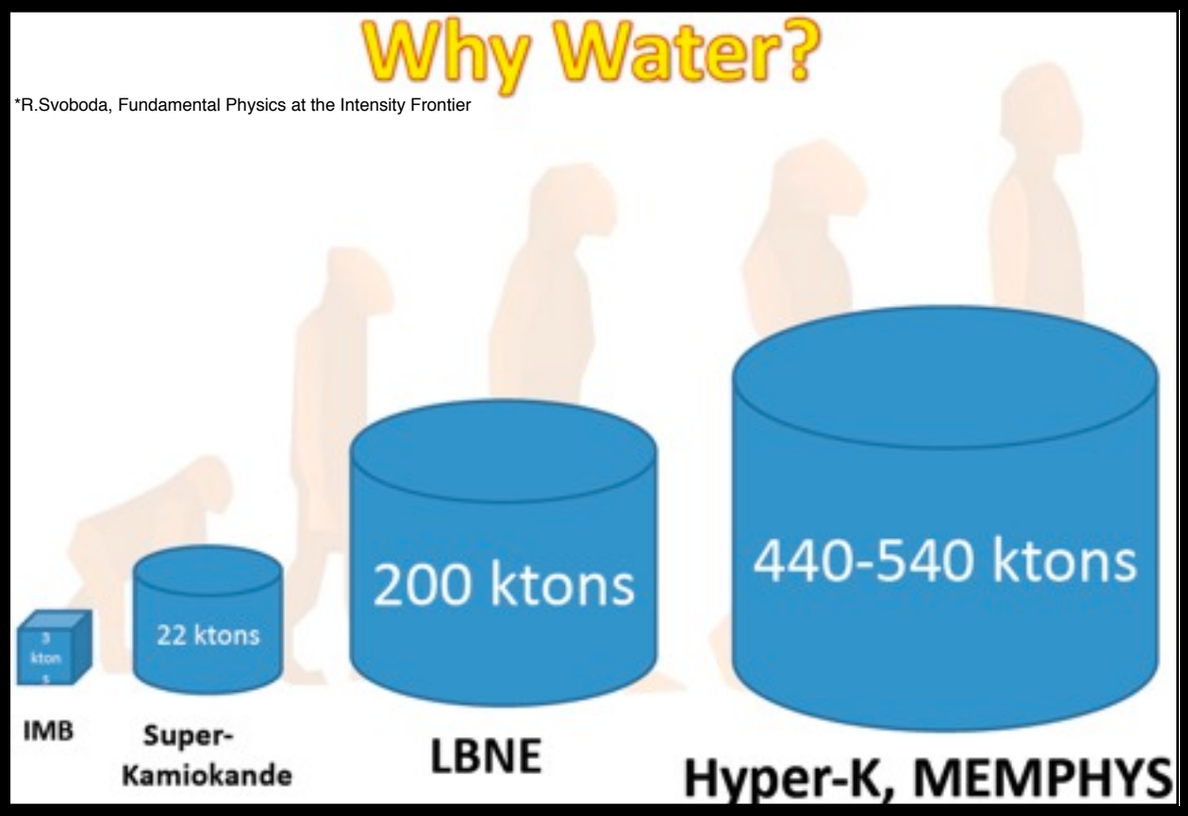


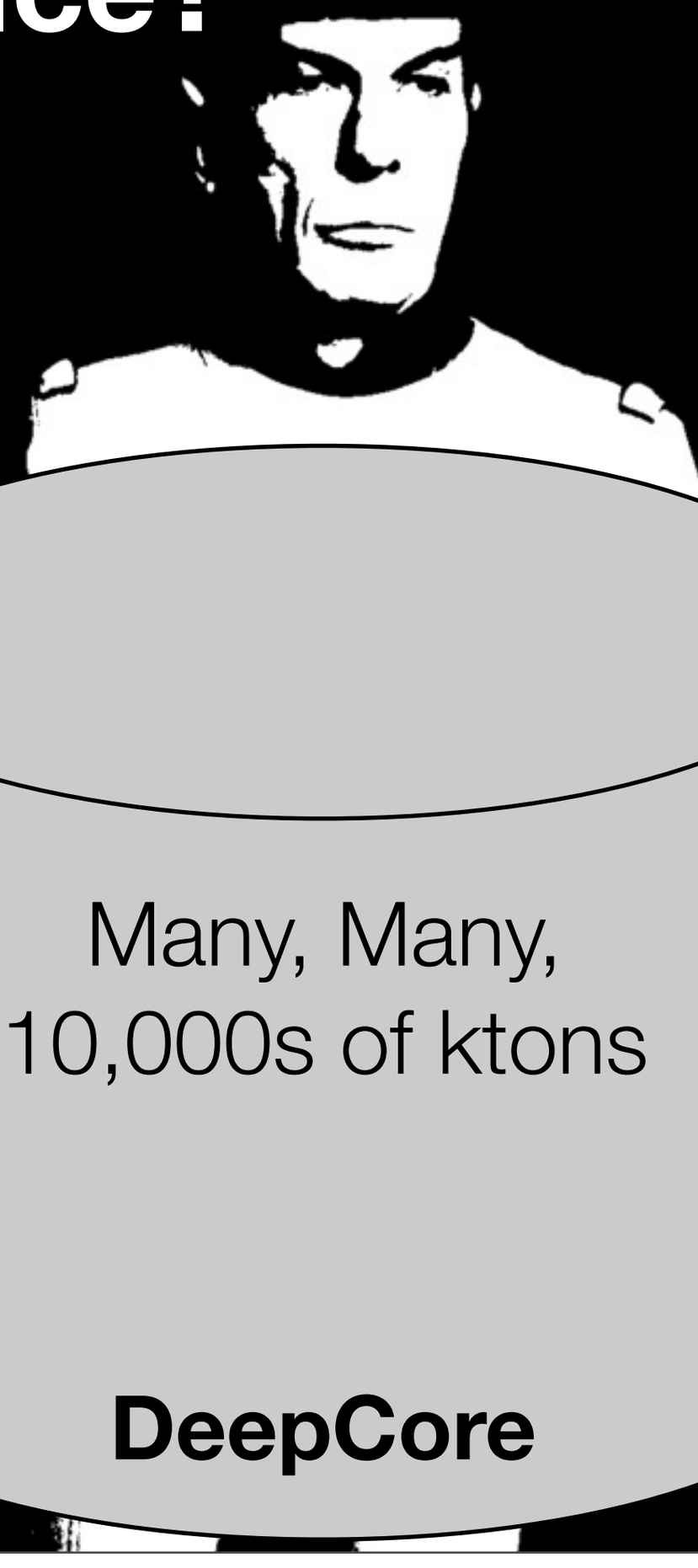
# Why Water?

*R.Svoboda, Fundamental Physics at the Intensity Frontier



# Why Not Ice?



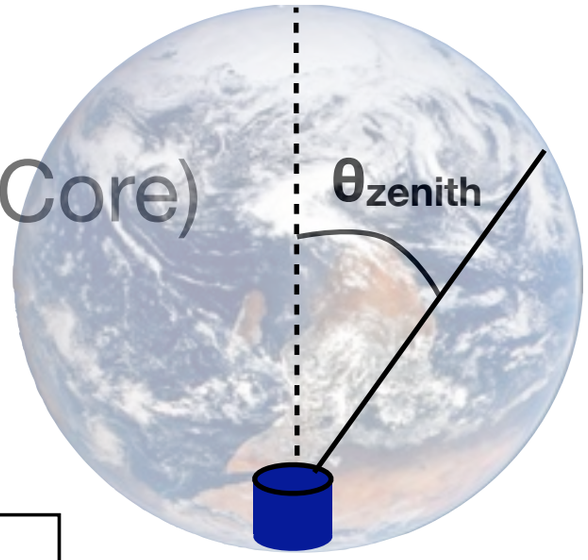
Many, Many,
10,000s of ktons

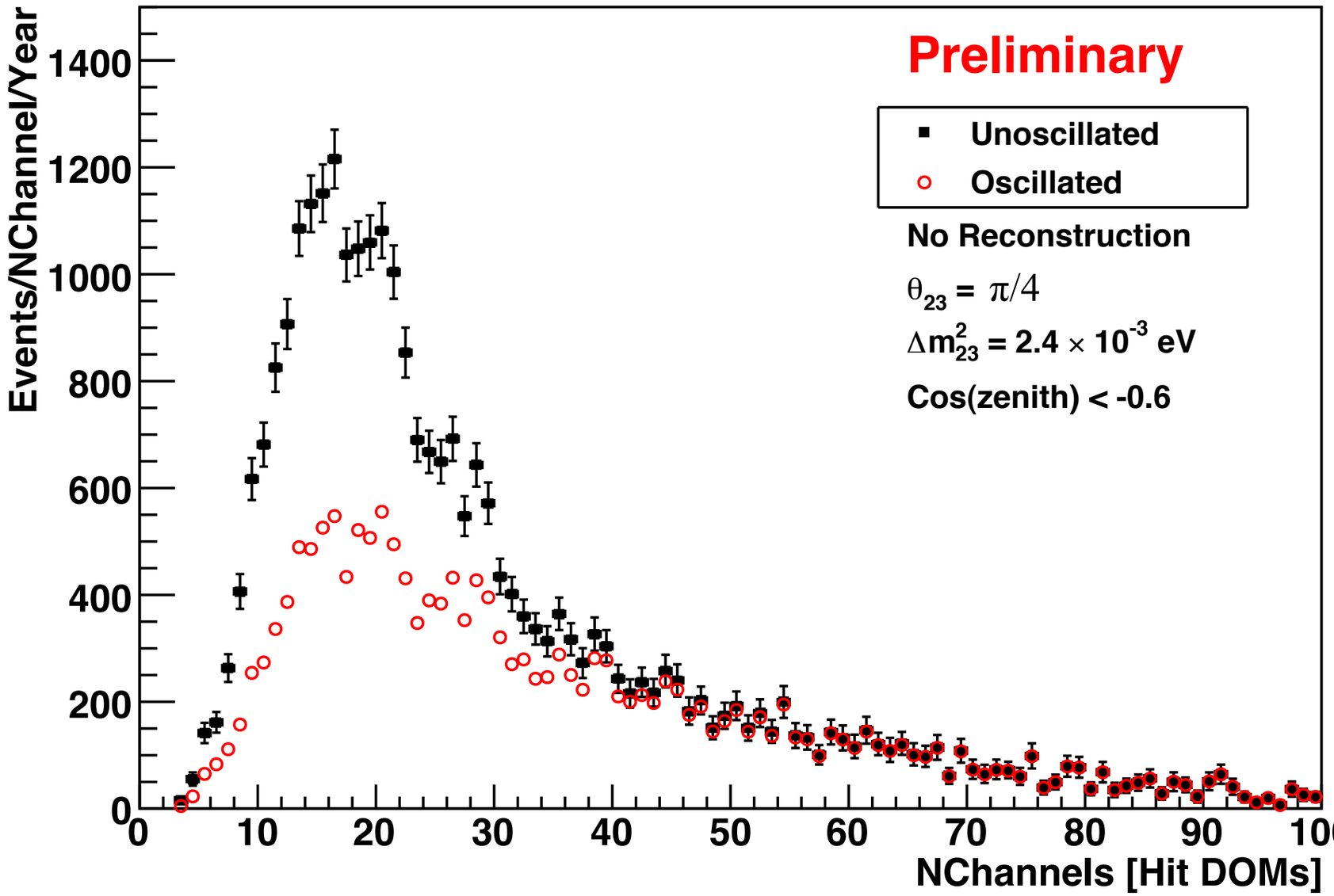
**DeepCore**

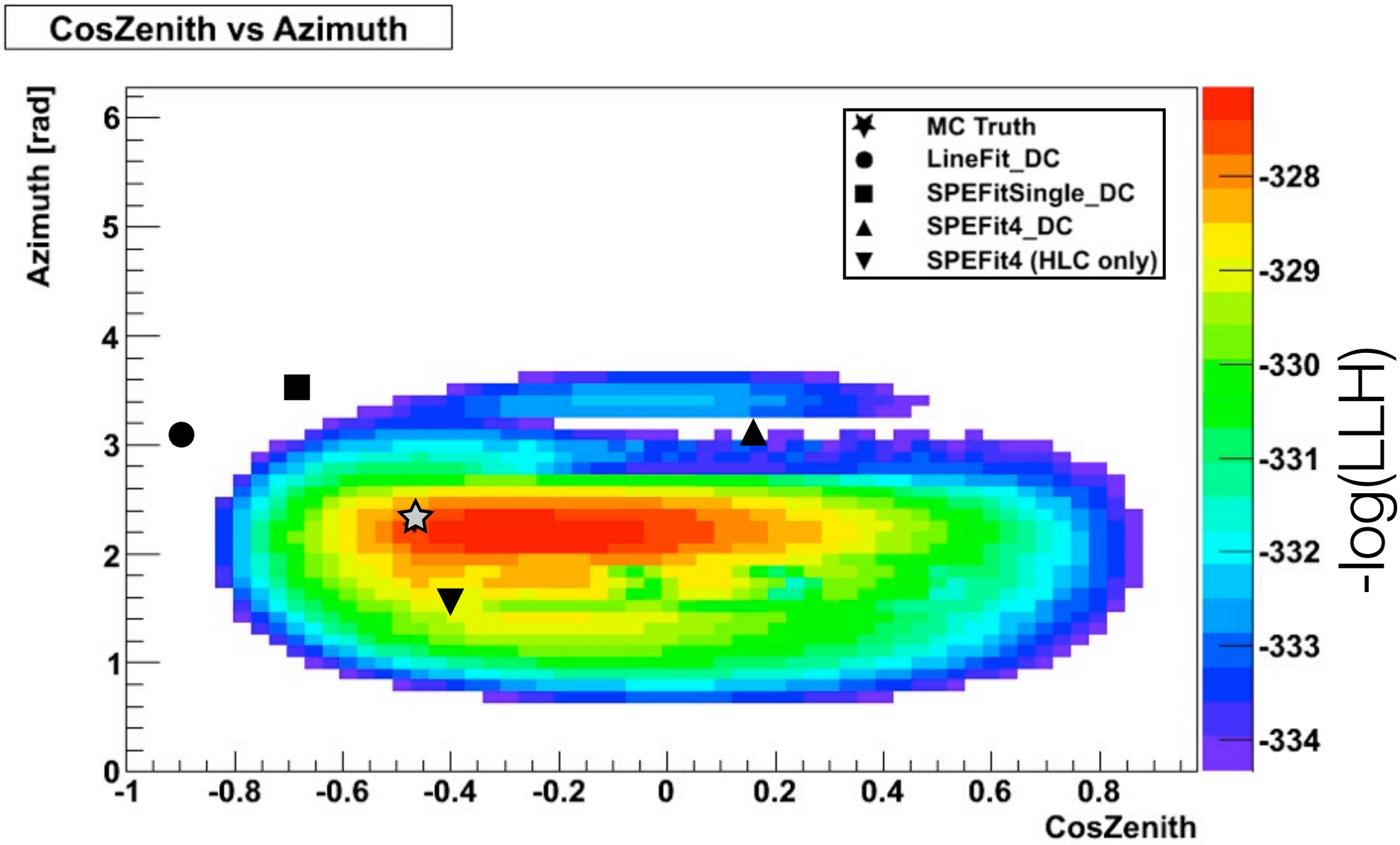
# Muon Neutrino Disappearance



- 1 year data with 79 total strings (Includes DeepCore)
- Monte Carlo signal only






Matt Dunkman, PSU

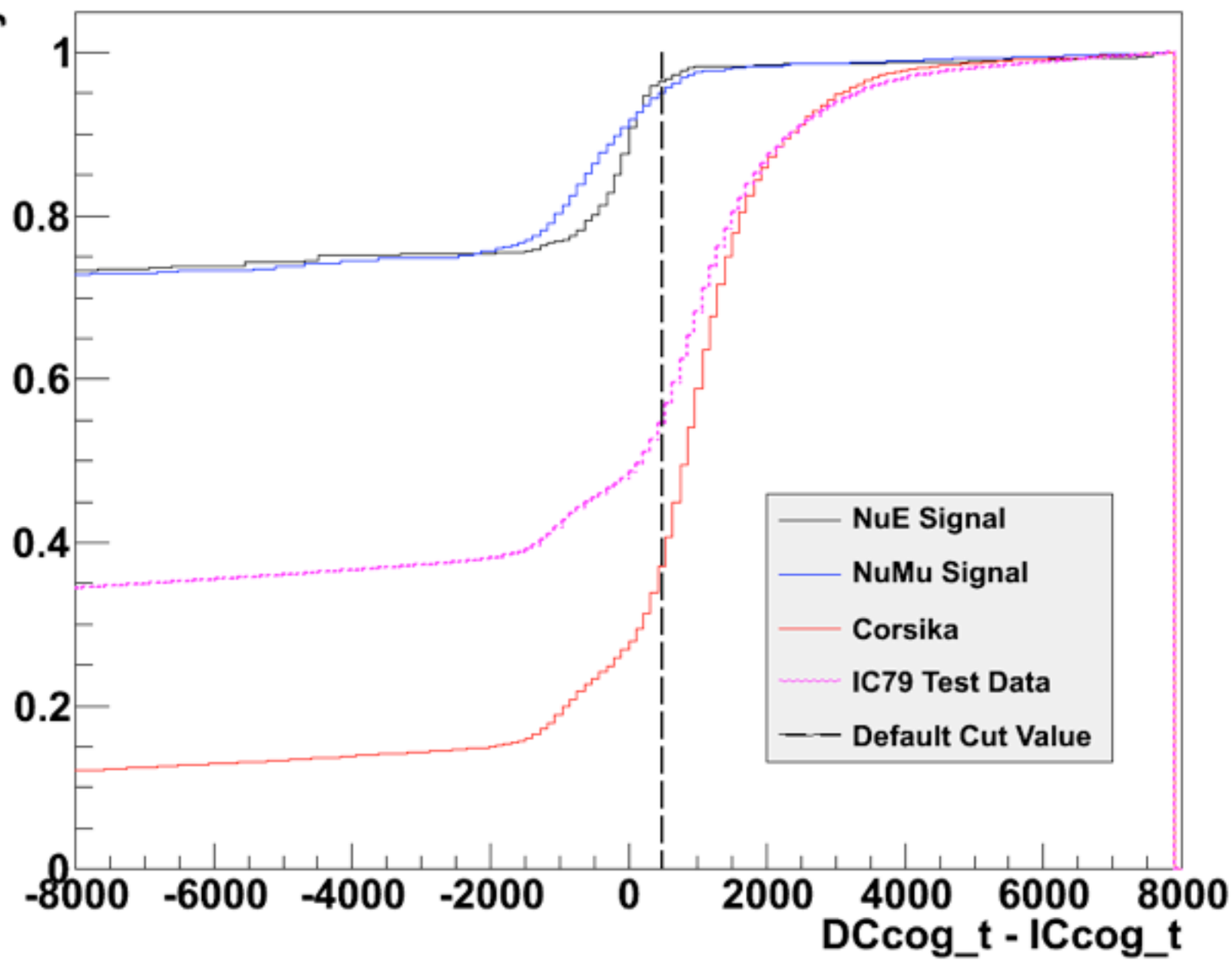
# Vetoes



- Online DeepCore veto gets rid of ~100x background CR muons. Still 1,000:1 - Bkg:Signal
- TimeVeto - 70% BKG rejection at ~5% signal loss
- ConeCut - 80% BKG rejection at ~5% signal loss

# Vetoes

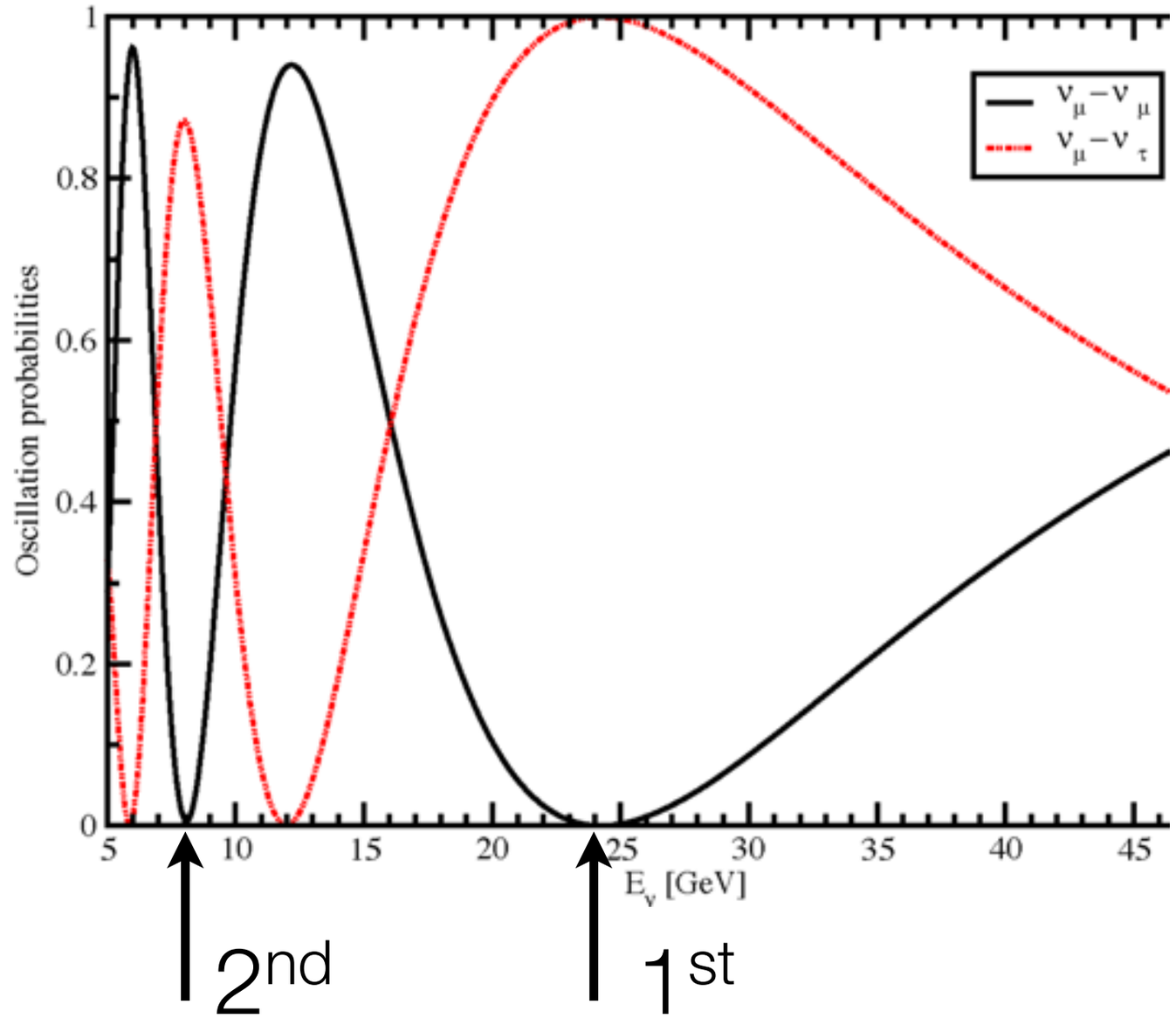
- Online DeepCore veto gets rid of ~100x background CR muons
- TimeVe
- ConeC



# 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)



# Because it's there



Tang & Winter http://arxiv.org/pdf/1110.5908v1

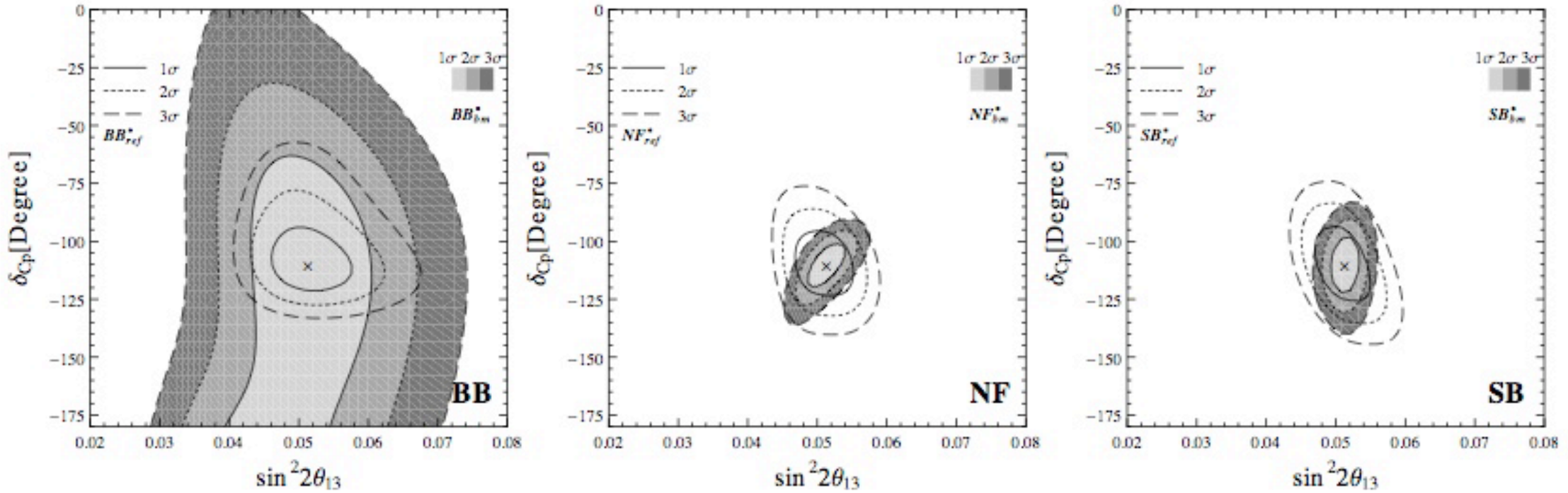
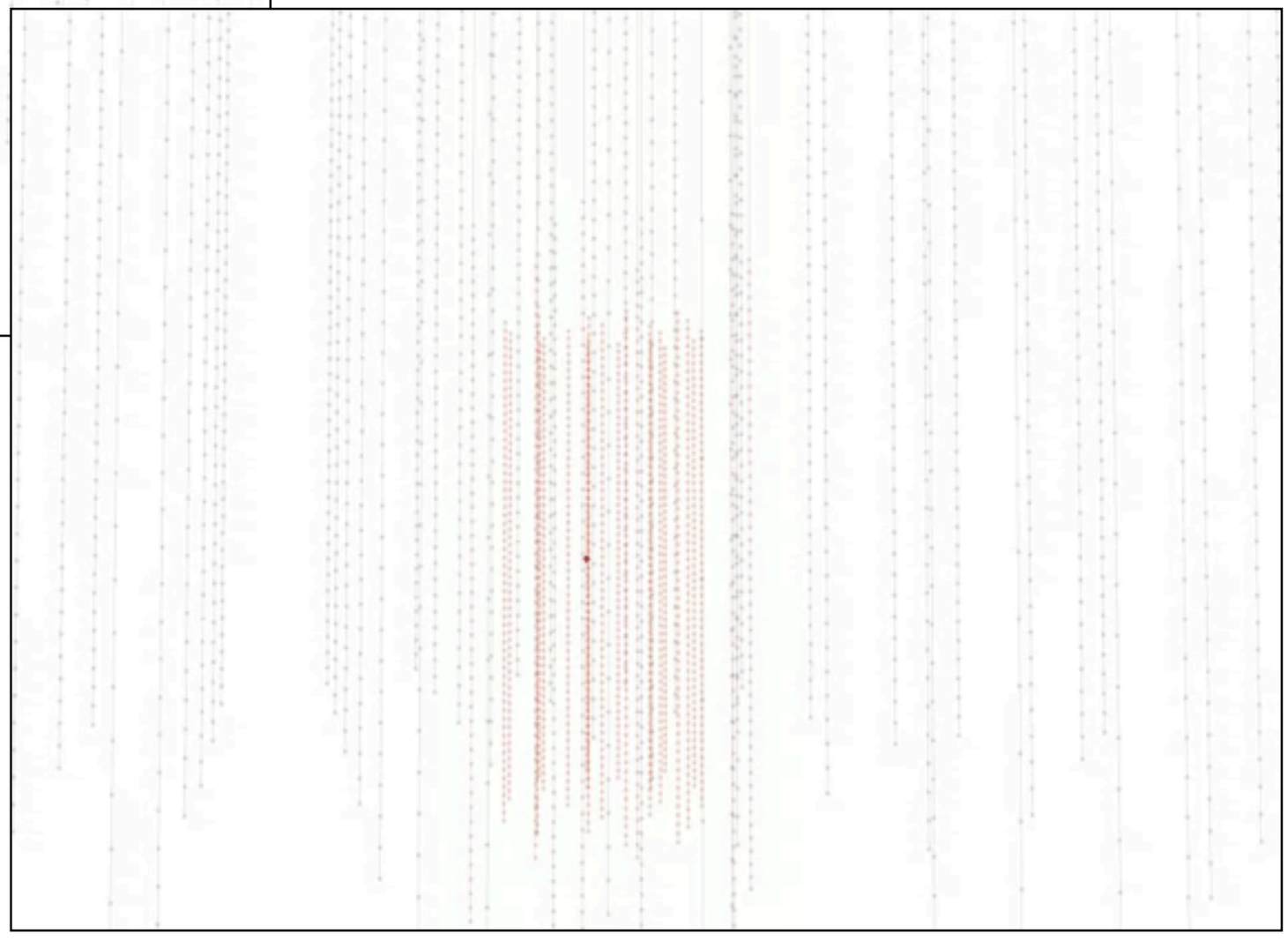



**Figure 12**: The precision measurements of CP phase $\delta_{\rm CP}$ and $\sin^2 2\theta_{13}$ for three single-baseline neutrino experiments: Beta Beam (BB), Neutrino Factory (NF), and SuperBeam (SB). The contours represent the $1\sigma$, $2\sigma$ and $3\sigma$ confidence levels (2 d.o.f.). Filled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

# Lower Energy







- 3.94 GeV Neutrino, 3.88 GeV muon, 0.29 GeV cascade

Zoom In more!

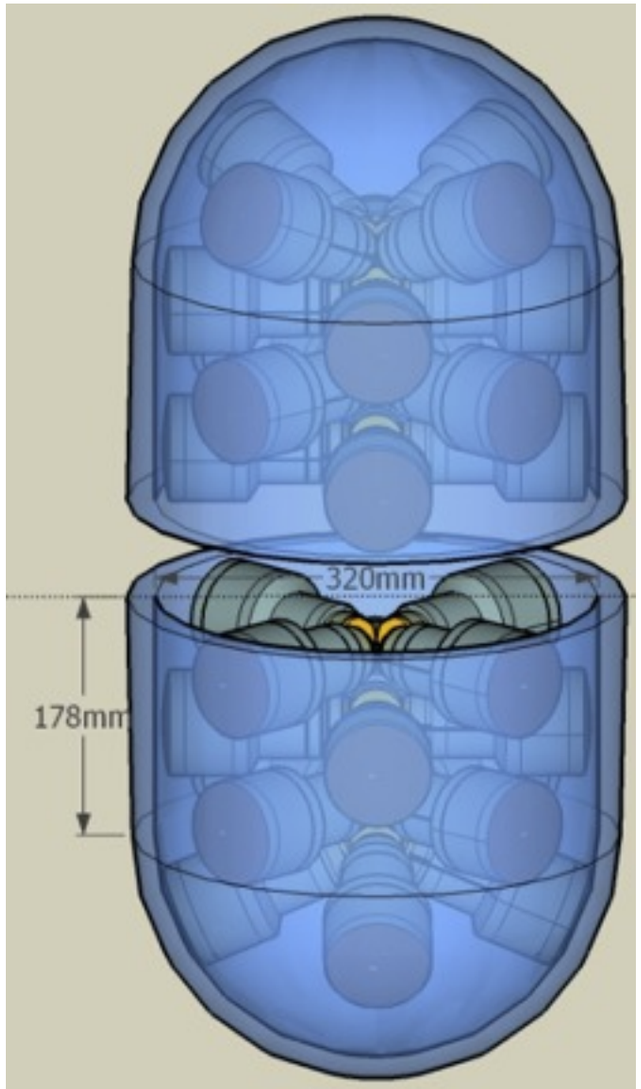
# Possible Module

- Based on a KM3NeT proposed design

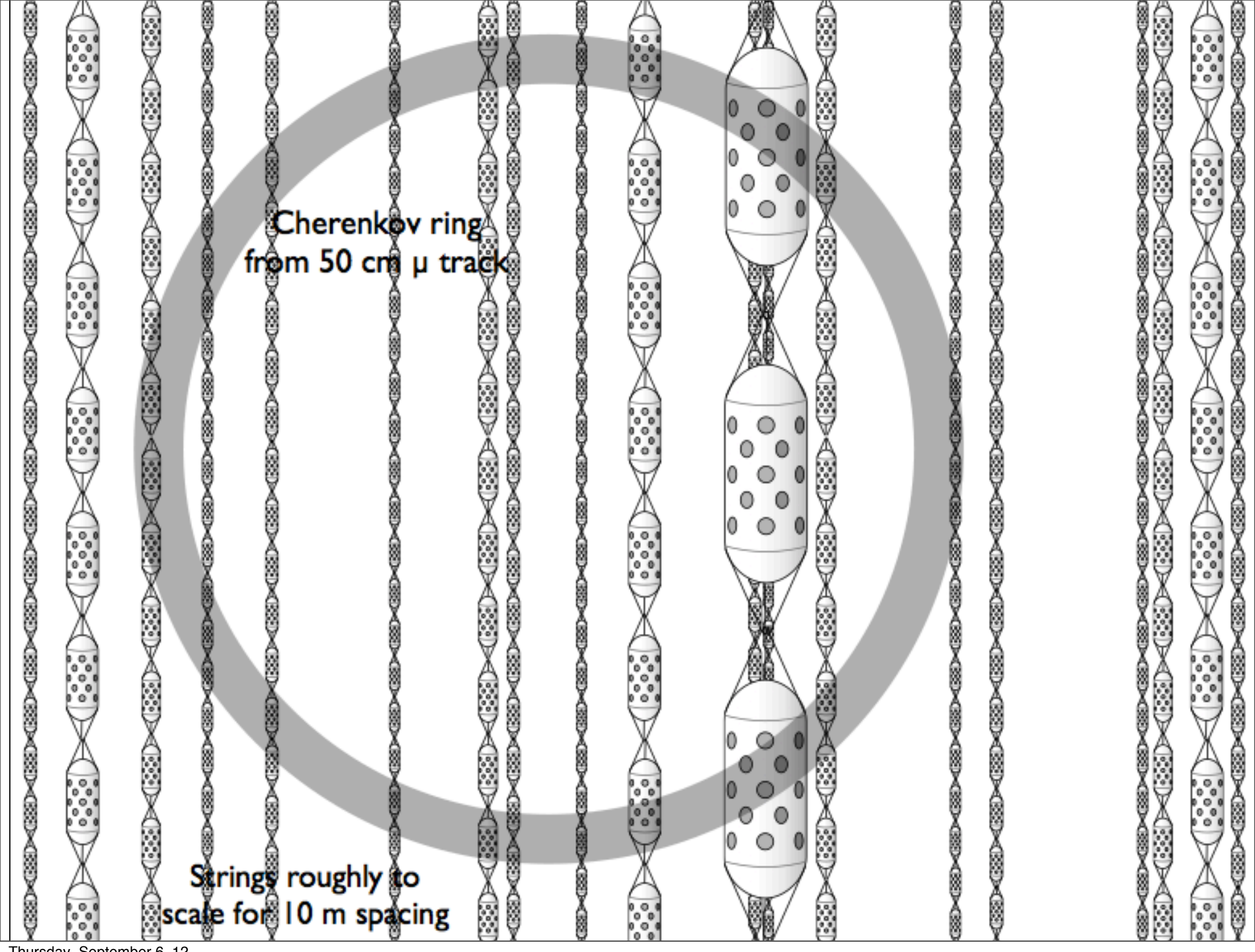
  P. Kooijman, *NIM* A**567** (2006), S. Kuch *NIM* A**567** (2006), KM3NeT TDR

- One meter glass cylinder containing 30 3” PMTs and associated electronics
  - Comparable width to IceCube DOM
  - Effective photocathode area of 265 sq. in. – 3.4x that of standard 10” IceCube PMT, but granular

- Could allow spatial imaging of Cherenkov ring




Courtesy P. Kooijman


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



# Challenges

Cerberus

# NoiseEngine

- Noise removal algorithm based on IceCube “TrackEngine” hit clustering trigger
- Hough Transform of angles ($\theta$,$\phi$) between hits
  - Noise should be relatively unclustered
  - Physics (neutrinos, muons, etc...) should create clustered hits

# Notes

- Solar Neutrinos - Look hard enough and you'll find something Bahcall
- Some of the best neutrino detectors in history did wonderful physics beyond their original design (MACRO, IMB, Super-K, Soudan-2, etc...) why not IceCube?
- OPERA can't measure tau oscillation parameters. How much wiggle room for unitarity in utau3?