ICECUBE

PINGU

IceCube/DeepCore and IceCube/PINGU: Prospects for Few-GeV Scale ν Physics in the Ice

Tenth International Conference on Hyperons, Charm and Beauty Hadrons
BEACH 2012
July 23-28, 2012
Wichita, KS, USA

Doug Cowen
IceCube and PINGU Collaborations
and
Department of Physics
Penn State University

PENNSTATE
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Outline

- Neutrino oscillations
- IceCube/DeepCore
  - Design, geometry
  - Performance
  - Physics goals, first results
- Future plans
  - PINGU*
    - Possible design, geometry
    - Physics goals

*Precision IceCube Next-Generation Upgrade

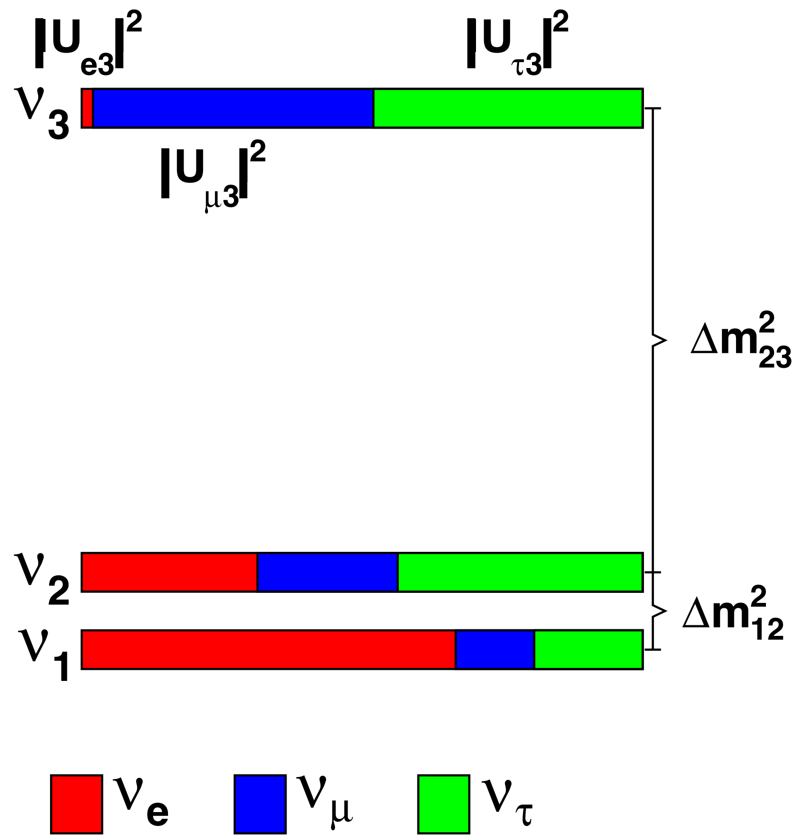
The IceCube Collaboration

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Neutrino Oscillations

- Measuring the PMNS matrix



$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

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Experiment type	Oscillation Channel
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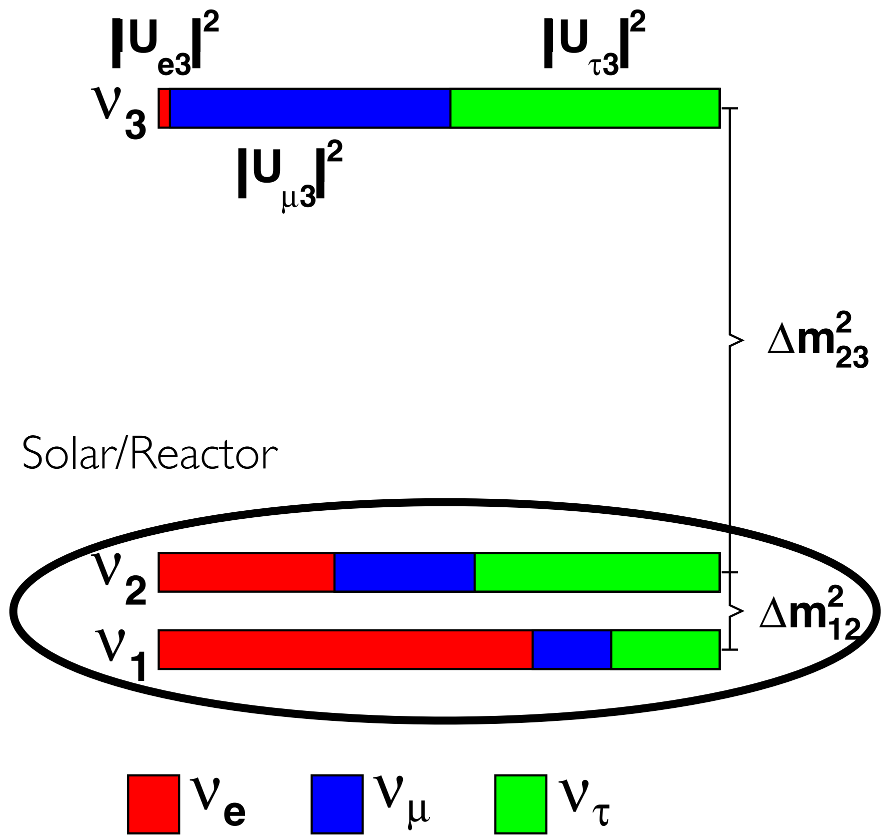

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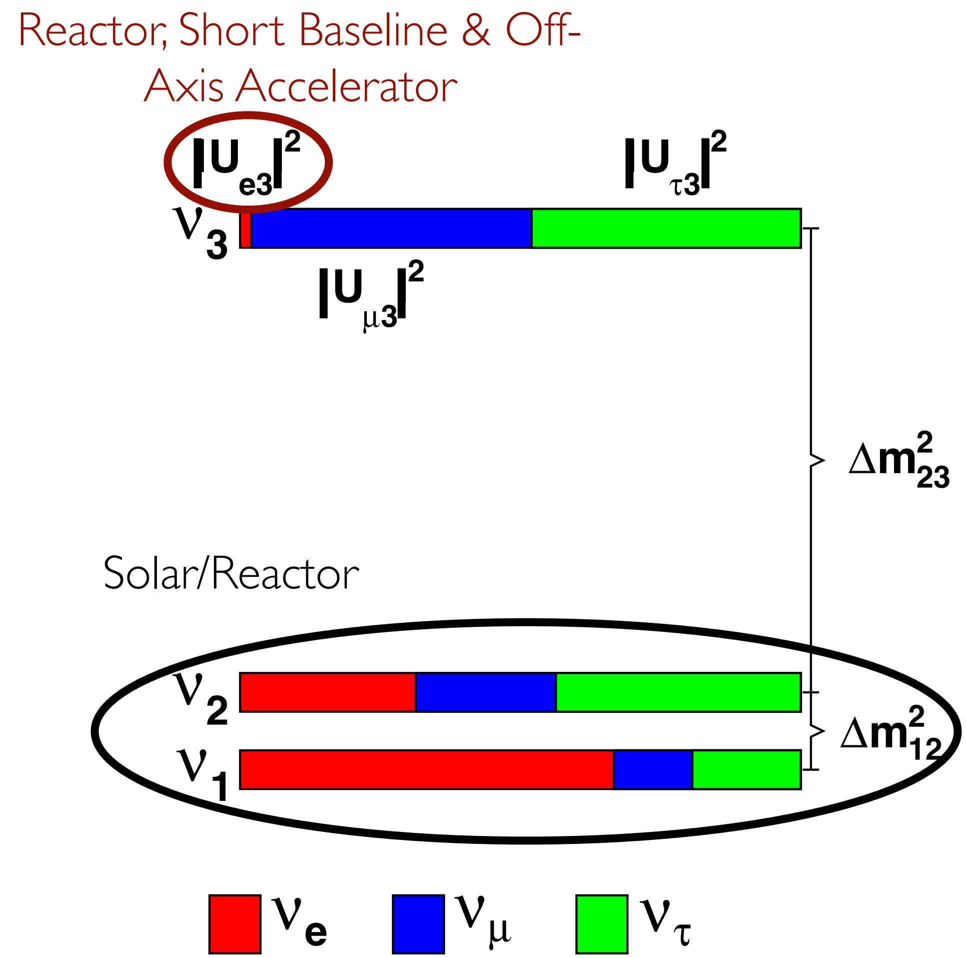

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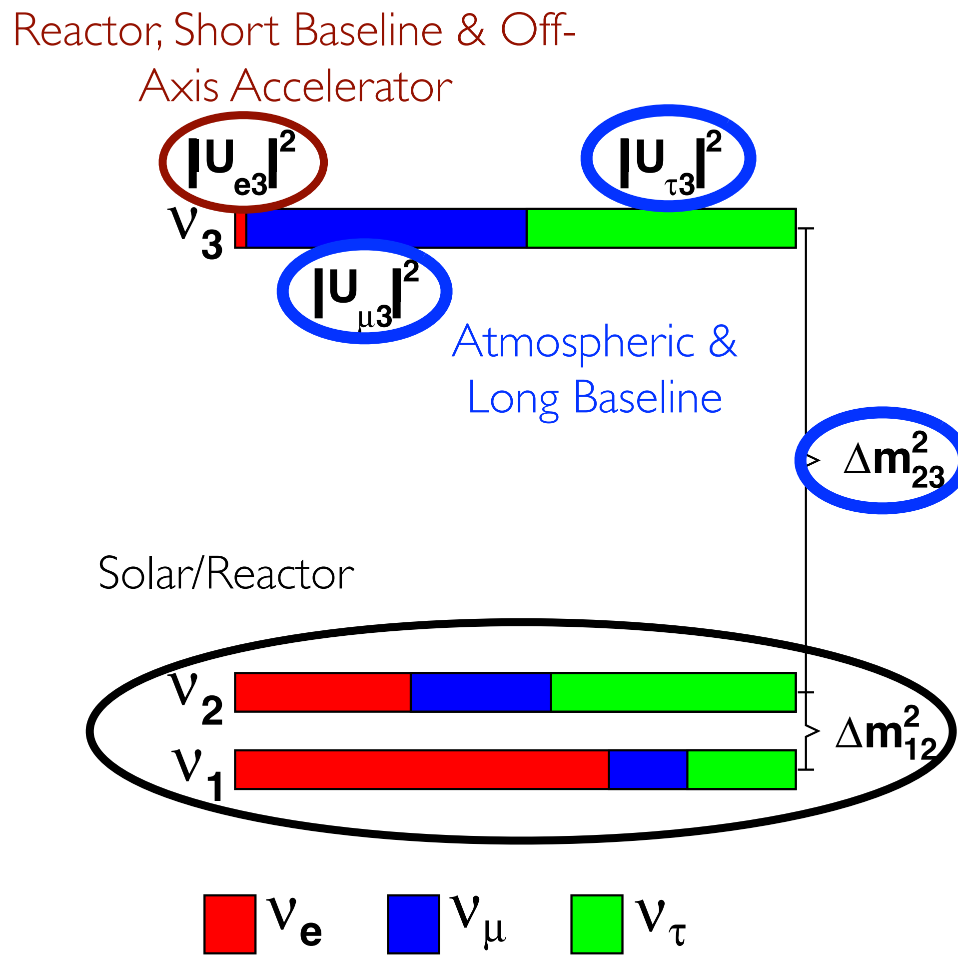
Atmospheric & Long Baseline	$(\nu_\mu \rightarrow \nu_\mu)$ $(\nu_\mu \rightarrow \nu_\tau)$



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Neutrino Oscillations

- Measuring the PMNS matrix

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Solar, Reactor	$(\nu_e \to \nu_\mu)$
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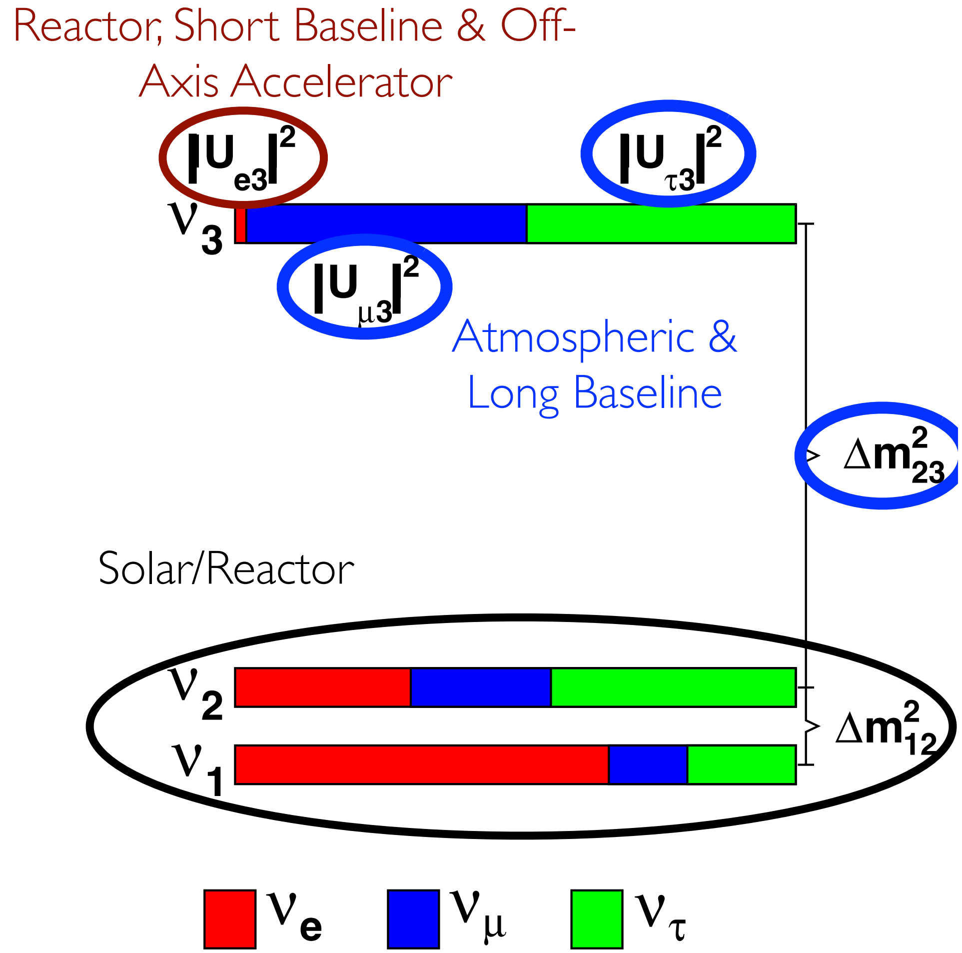

$$|U_{PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$|V_{CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

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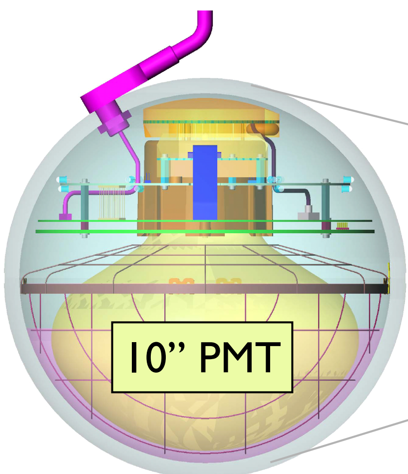
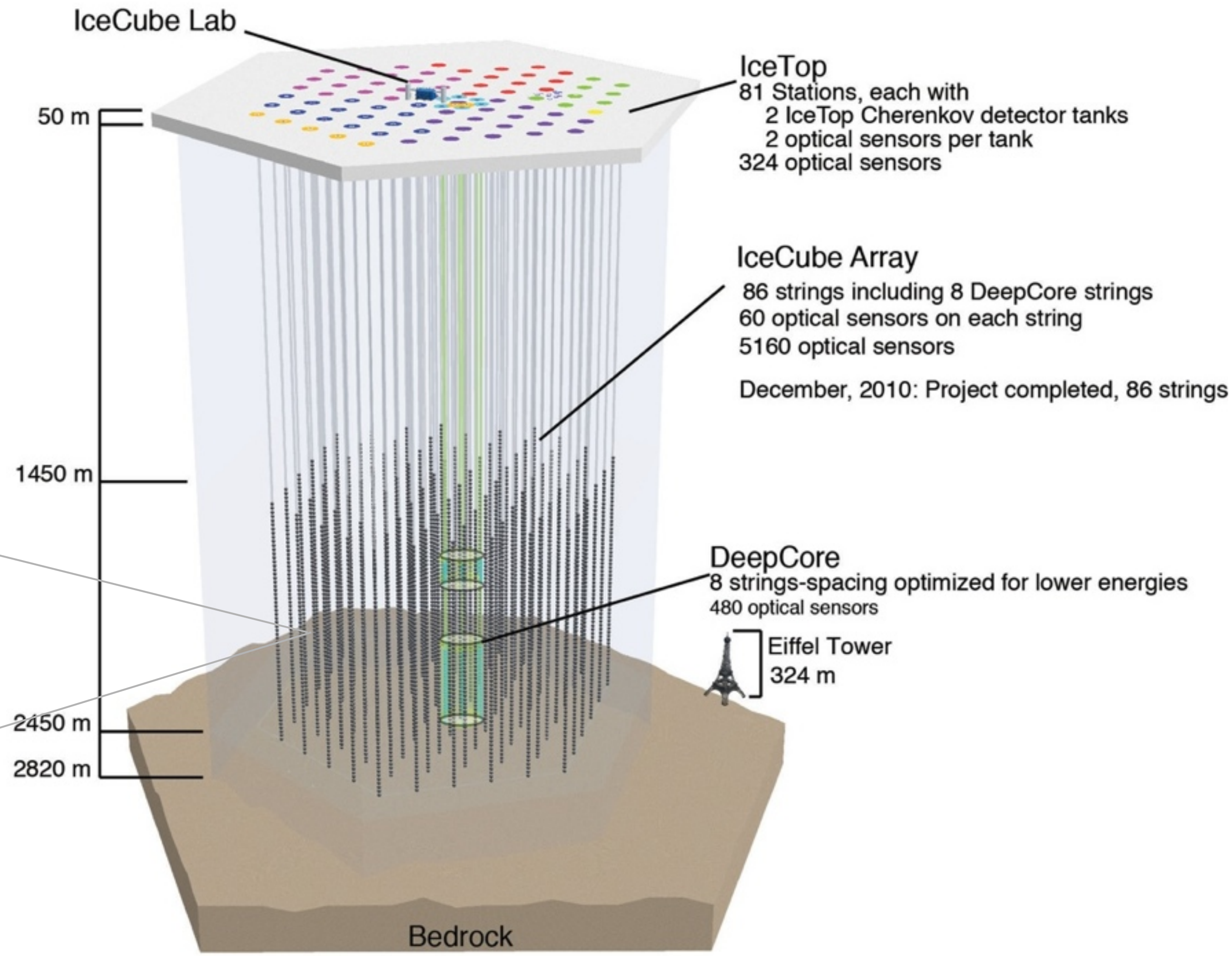
Neutrino Oscillations

- Some observations and some questions:
  - Neutrino mass is clear evidence that the Standard Model of particle physics is incomplete.
  - Thus-far-unmeasurable lightness of neutrinos may be indicative of new physics at E ~ 10^{15} GeV scale.
  - Are there more than 3 generations of fundamental particles?
  - Why are quark mixing parameters so different from those of neutrinos?
  - Very recently an important matrix element of neutrino mixing was measured.
    - Daya Bay and RENO found fairly large θ_{13} at ~5σ
      - Opens door to other fundamental measurements with neutrinos
  - What is the neutrino mass hierarchy? (Is ν_3 heaviest or lightest?)
  - CP violation in lepton sector could explain matter-antimatter asymmetry.
- Atmospheric neutrinos v. useful for studying neutrino oscillations.
  - Can't control them, but "You can observe a lot by just watching."–Y. Berra

IceCube and DeepCore

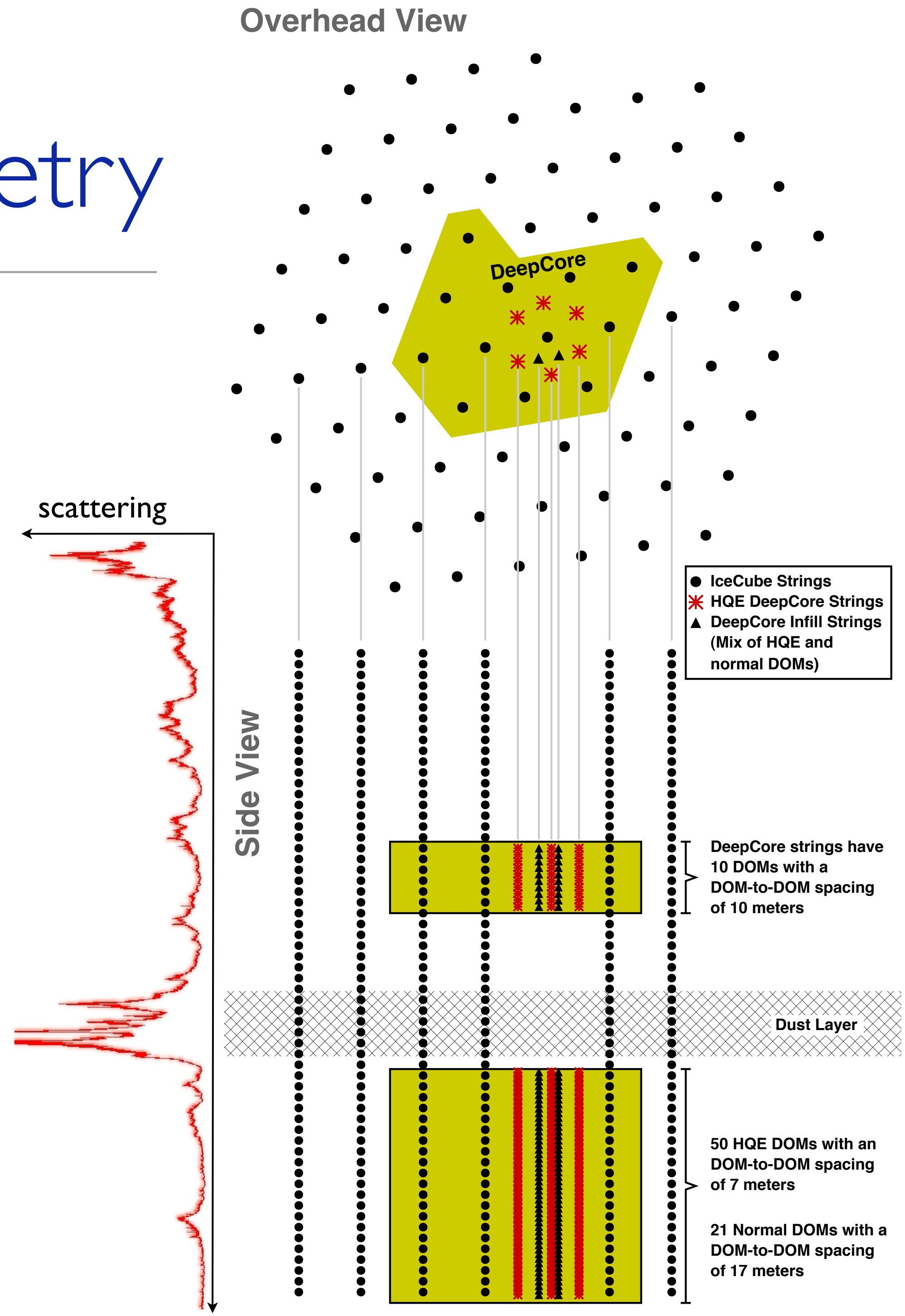


Digital Optical Module (DOM)



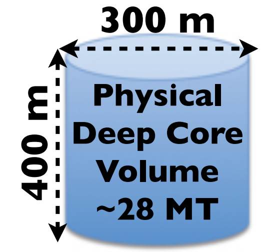
DeepCore Geometry

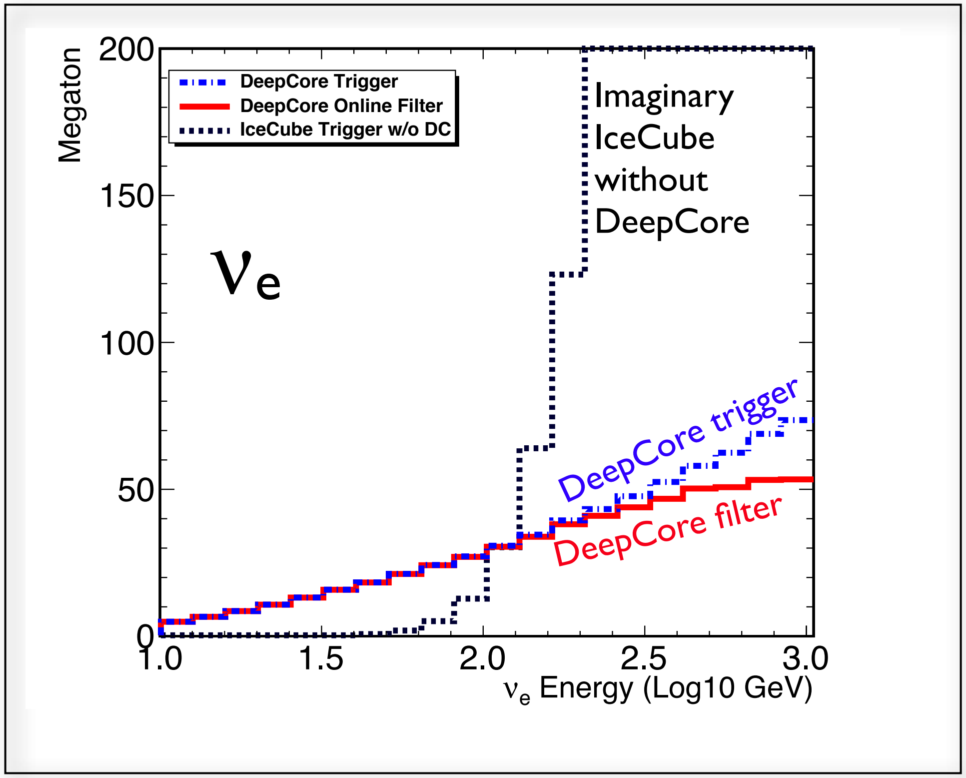
- Eight special strings plus 12 nearby standard IceCube strings
  - 72 m interstring horizontal spacing (six with 42 m spacing)
  - 7 m DOM vertical spacing
  - ~40% higher Q.E. PMTs
  - ~5x higher effective photocathode density (but still only ~0.1% coverage)
  - DOMs: ~few ns timing, 0.25 p.e. threshold
- Roughly 30 MTon physical volume
  - ~10 GeV threshold
  - $\mathcal{O}$(200k) atmospheric ν/yr

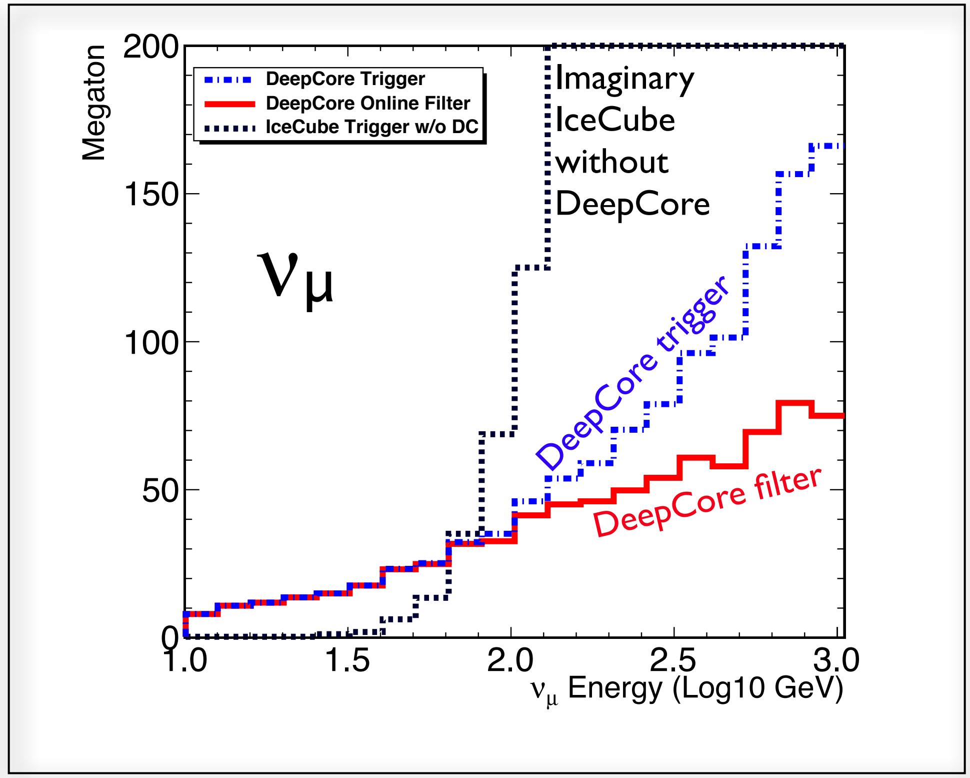


DeepCore: Effective Volume

$$V_{eff} = \frac{N_{acc}}{N_{gen}} V_{gen}$$





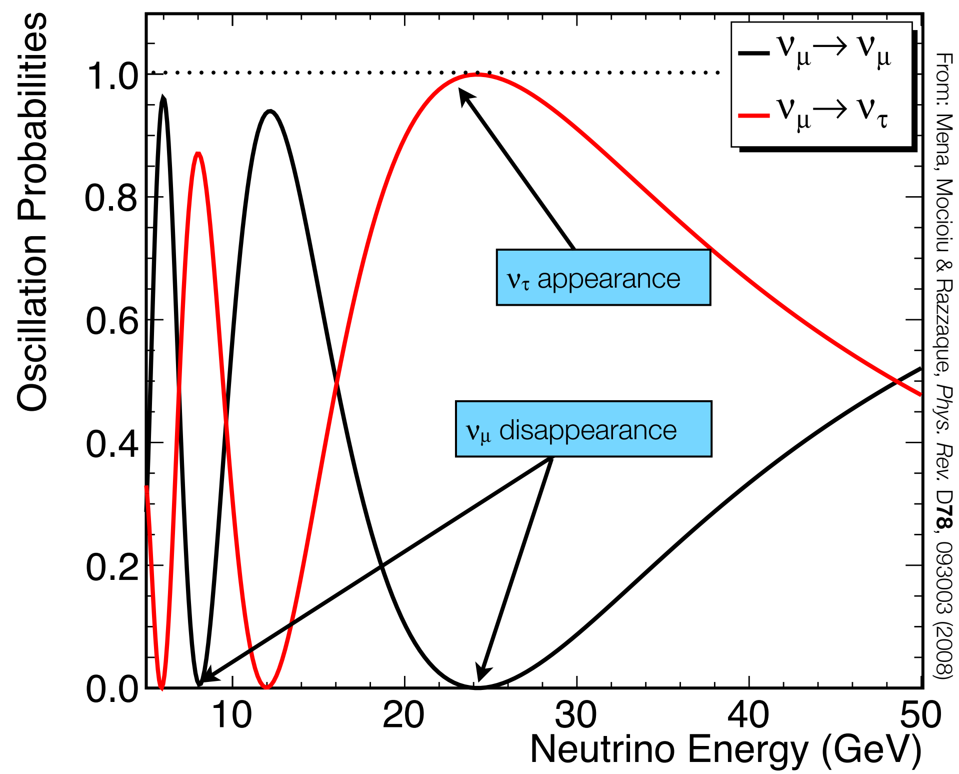


J. Koskinen/Penn State

- Many **ν** and **μ** events in IceCube will also trigger DeepCore
  - These events are rejected by the online veto algorithm
- Below ~100 GeV, DeepCore improves V_{eff} significantly
- Final V_{eff} will be lower than shown once we require good event reconstruction

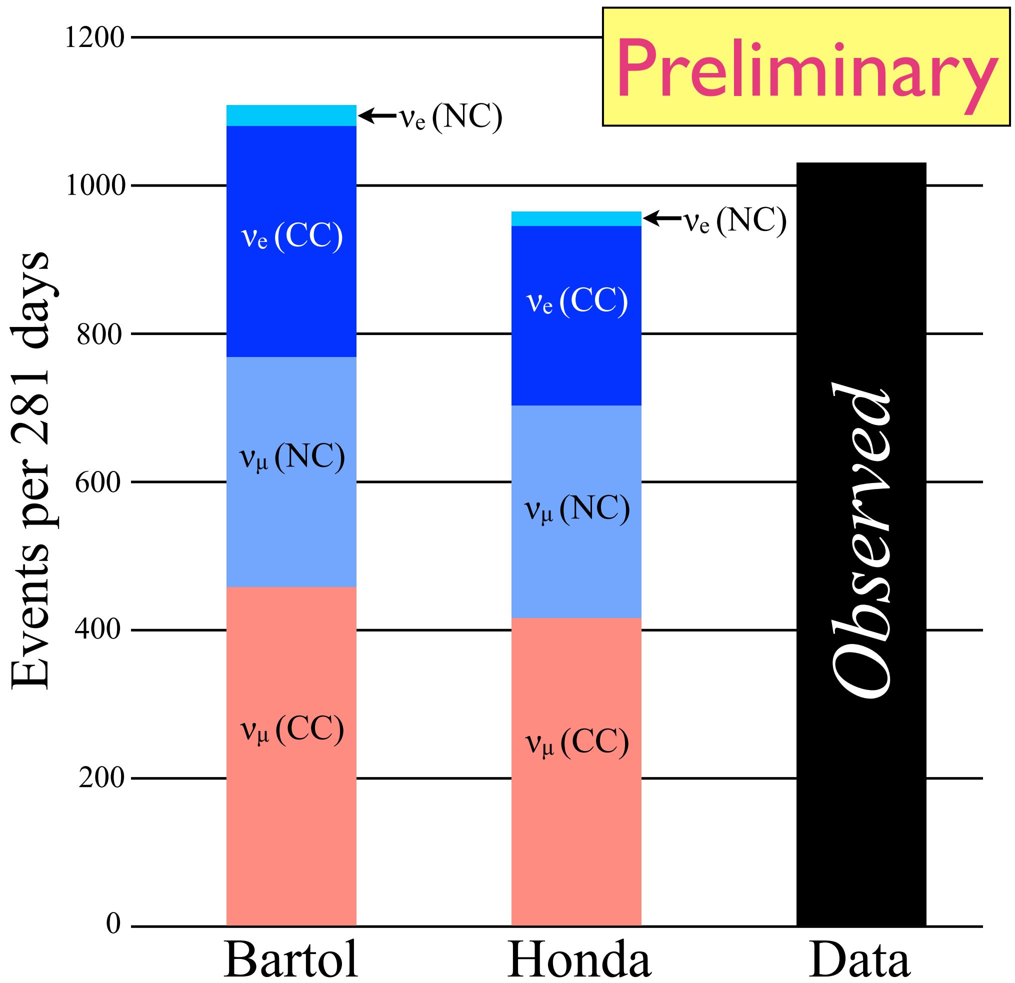
DeepCore Physics

- Atmospheric neutrinos
  - DeepCore gives access to a previously unexplored and physics-rich neutrino oscillation energy regime
    - muon neutrino disappearance at ~25 GeV (and ~8 GeV)
    - tau neutrino appearance at ~25 GeV
  - Enables high-statistics study of oscillations at higher energies than with accelerators



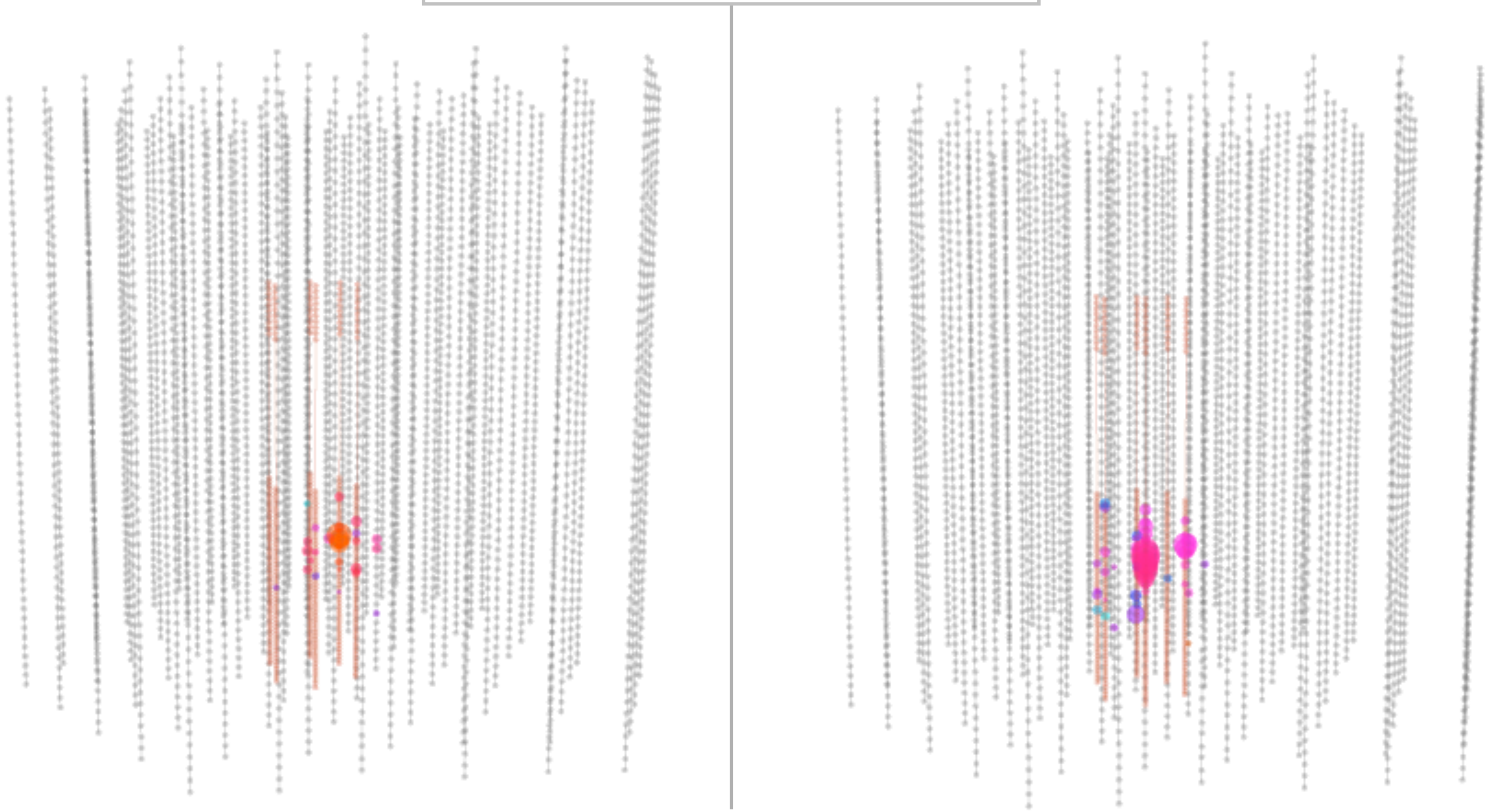
First Result from DeepCore

- Isolation of atmospheric ν-induced "cascade" sample (ν_e CC, ν_x NC)
- 1029 events:
  - 59% cascade
  - 41% ν_μ CC
- ~5x enrichment of cascade sig.: $[\text{casc/trk}]_{\text{veto}}$ / $[\text{casc/trk}]_{\text{final}}$ (without reconstructions)
- ~10^8 downward-going cosmic ray muon rejection factor
- Average energy: ~200 GeV
- Paper being written
- Loosening cuts: see $\nu_\mu \rightarrow \nu_\tau$ a la SK?



First Result from DeepCore

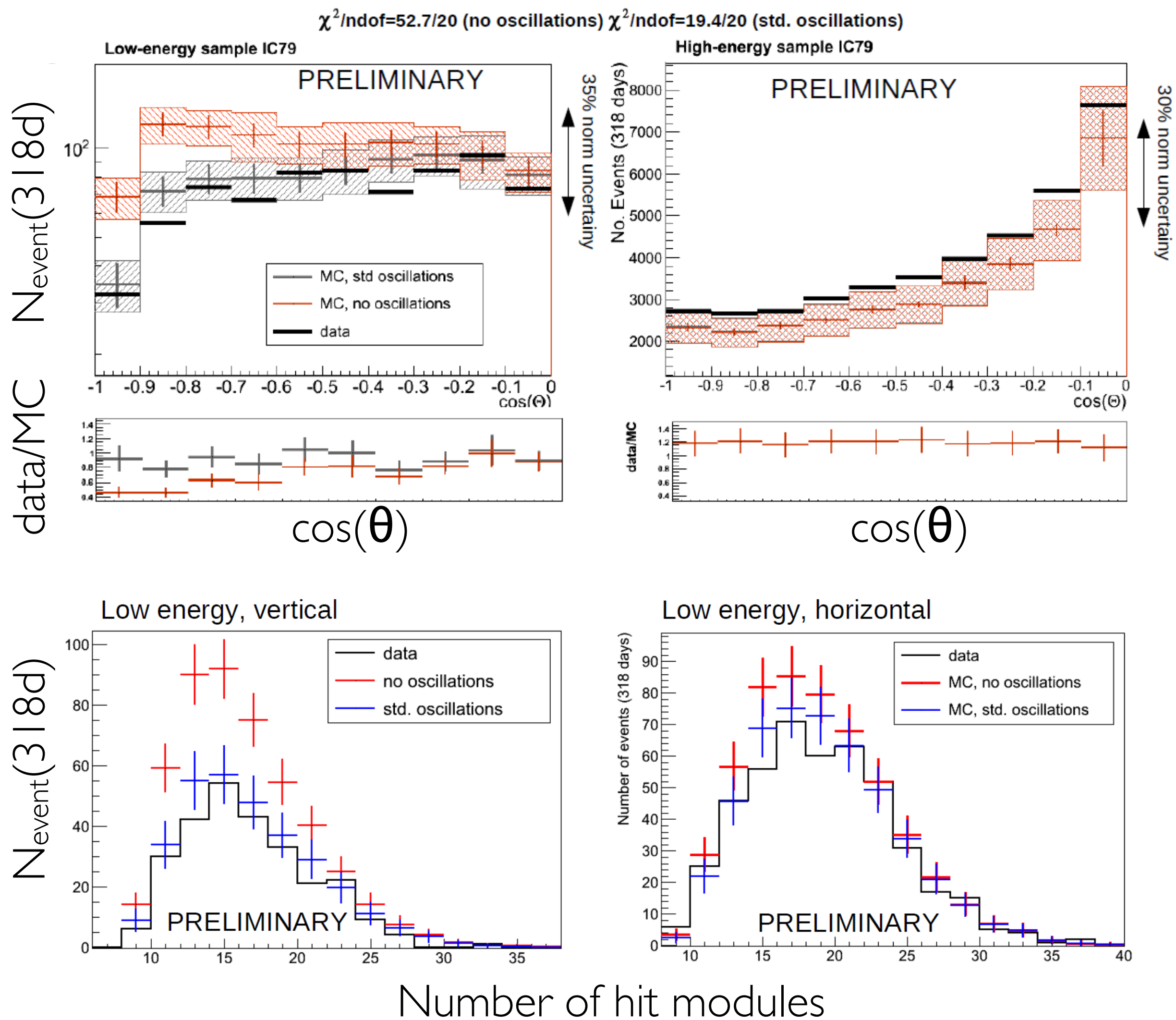
Two candidate events



(Standard hit cleaning algorithm removed all noise hits in rest of detector.)

Second Result from DeepCore

- Looked for (expected) atmospheric ν_μ oscillations at highest energies ever
- Oscillations seen
- Analysis was not designed to measure oscillation parameters
  - Ruled out no-disappearance hypothesis



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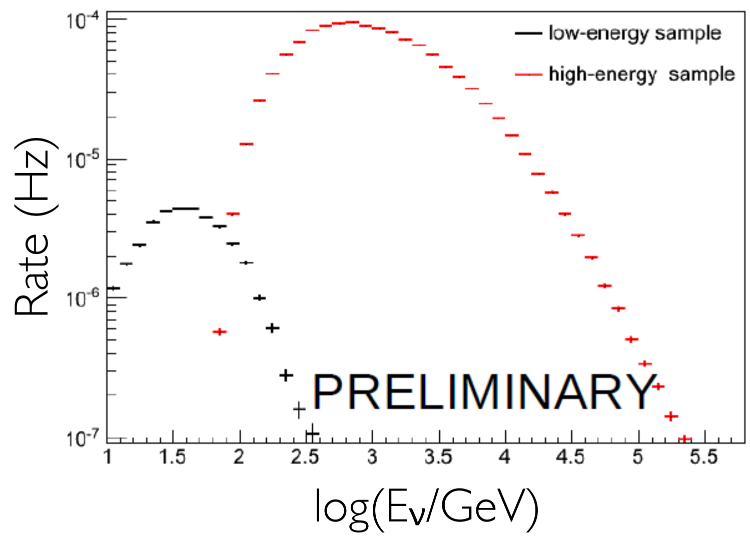
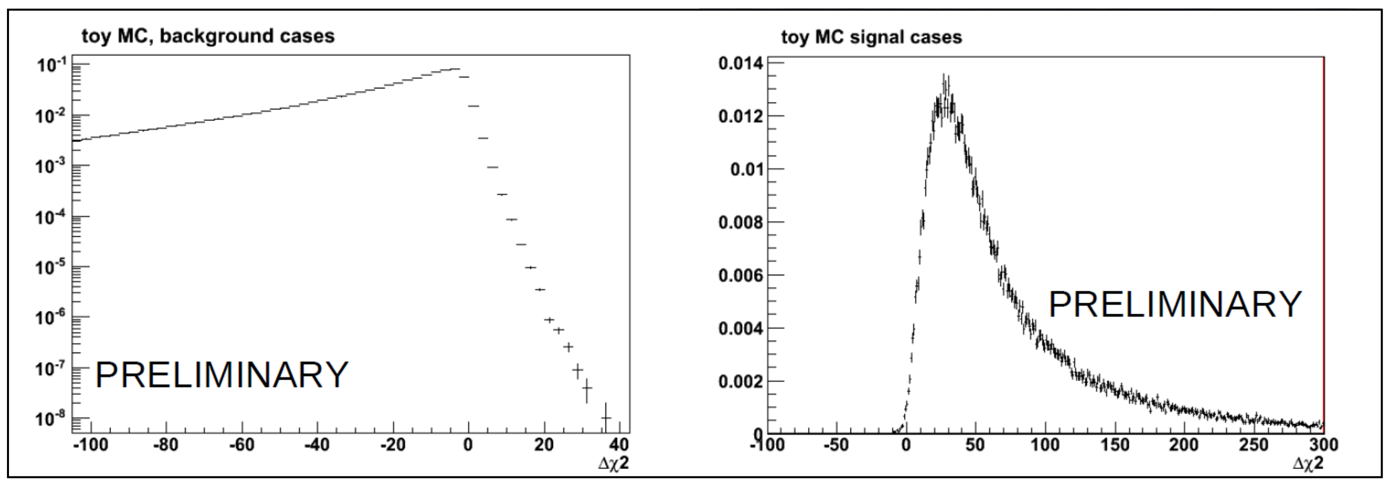


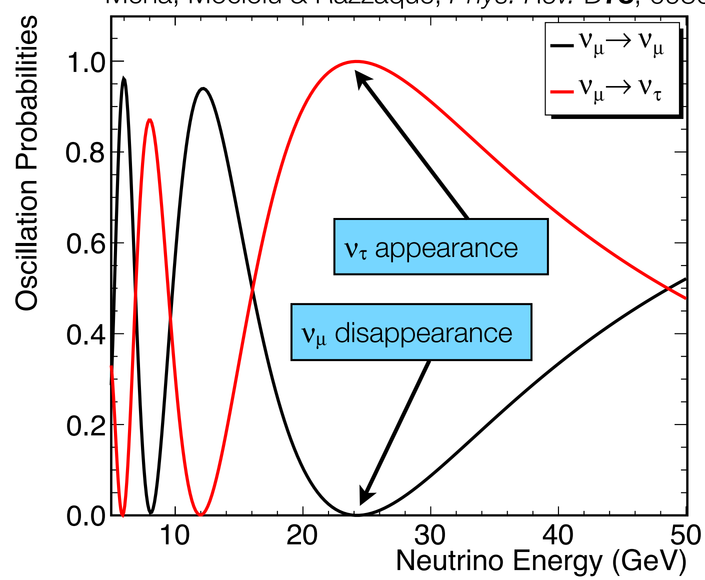


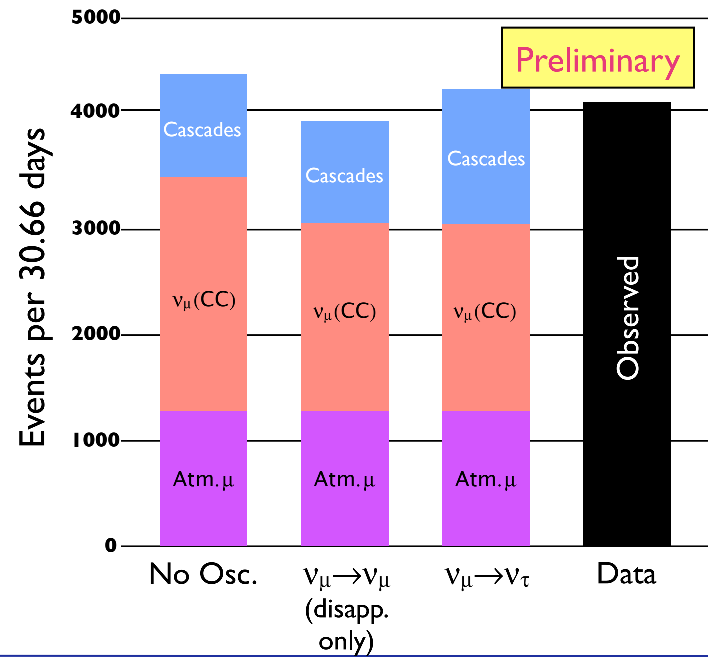
$$\Delta\chi^2 = \chi^2_{\text{no osc}} - \chi^2_{\text{osc}} (= 33 \text{ in this analysis})$$

Third Result from DeepCore?

- Loosen cascade analysis cuts for possible sensitivity to ν_τ appearance
  - $P(\nu_\mu \rightarrow \nu_\tau) \propto |U_{\tau 3}|^2$
  - test for unitarity
    - do the three fractions of $\nu_{e,\mu,\tau}$ making up ν_3 sum to 1.0?
- Lots of statistics
  - ~1 month shown; ~25x more data in hand
  - Key: control of systematics
- Similar to SuperK msmt.
  - PRL 97:171801 (2006)
  - "disfavors the no tau neutrino appearance hypothesis by 2.4 sigma"

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





Statistical power:

- 80k cascade-like events in 2 years.
- 10% decrease due to ν_μ disappearance.
- 2/3 of those reappear as ν_τ cascades.

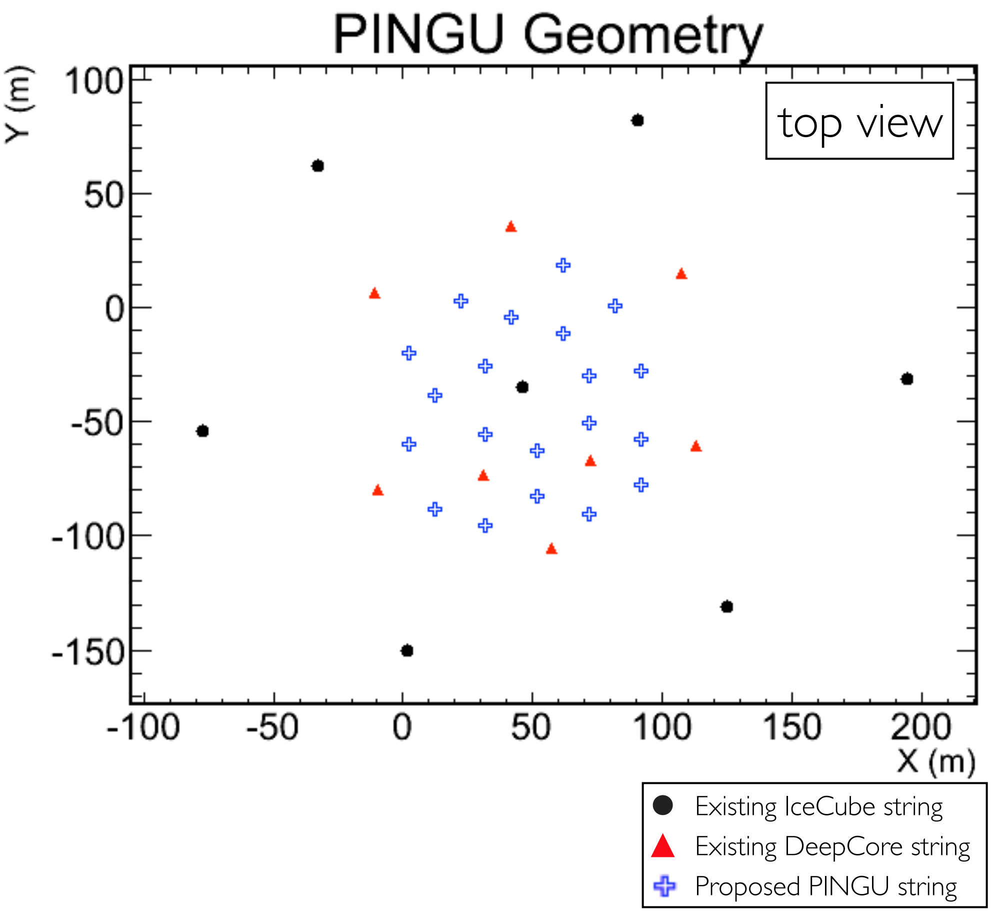
5333/sqrt(80000) = 18σ

Beyond DeepCore

- DeepCore's early results show the feasibility and promise of doing fundamental neutrino physics at the 10 GeV energy scale
- More interesting DeepCore results are in the works (ν_τ appearance, WIMP searches,...)
- What if we could go lower in energy?

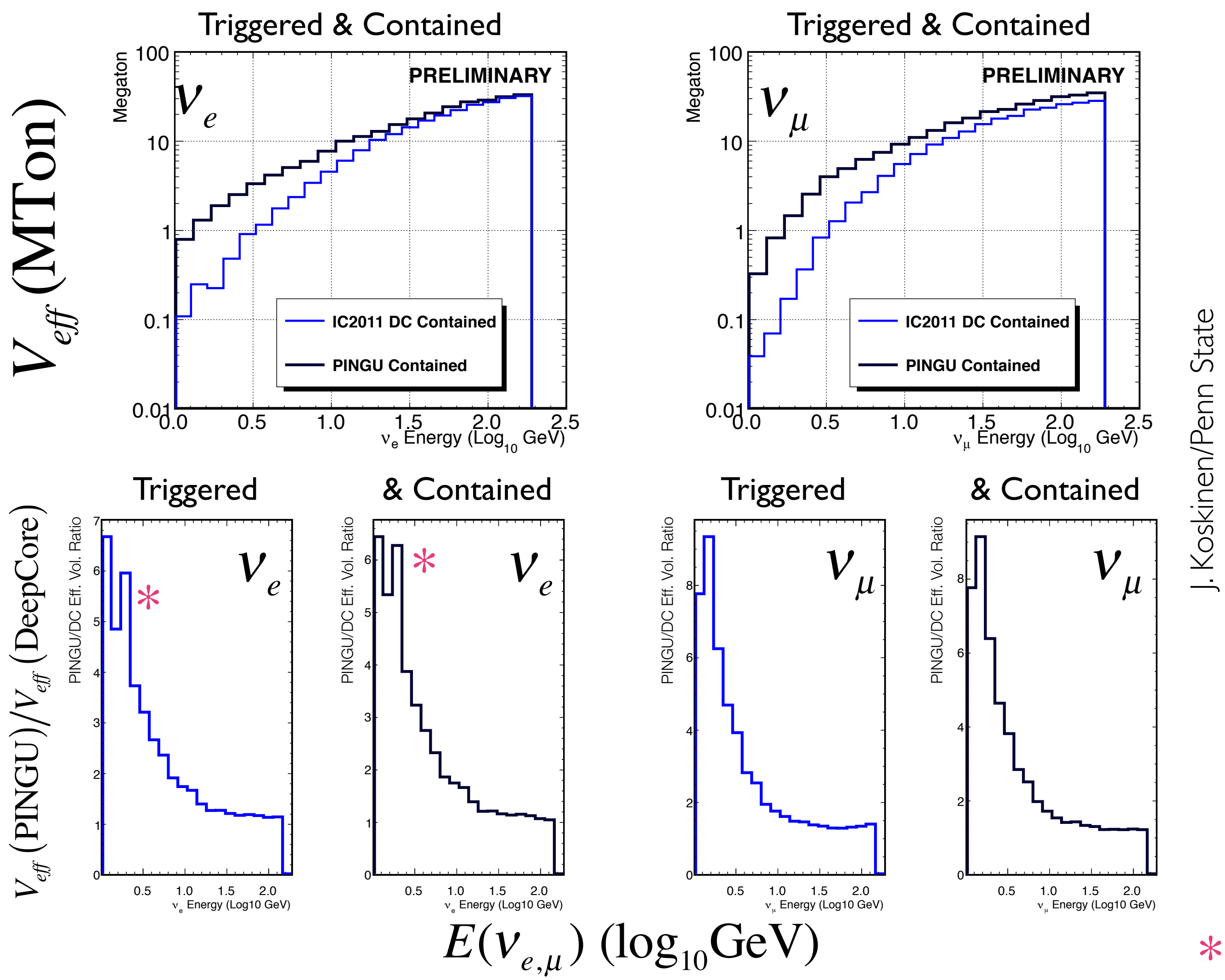
The Next Step: PINGU

- Further increase sensor density
  - ~20 additional strings
    - Mostly IceCube technology plus some R&D modules
    - Include new low-E calibration devices
  - Aims:
    - Physics program at E_{thr} ~ few GeV
      - Neutrino hierarchy
      - Low mass WIMPs
    - R&D: Cherenkov ring segment reconstruction
    - Calibrate for light levels at E ~ 1 GeV
- Collaboration
  - IceCube, U.M.-Duluth, U. Erlangen, T.U.-Muenchen, NIKHEF, U. Wuerzburg



PINGU Effective Volumes

- V_{eff} increased by ~8x at ~1 GeV relative to DeepCore



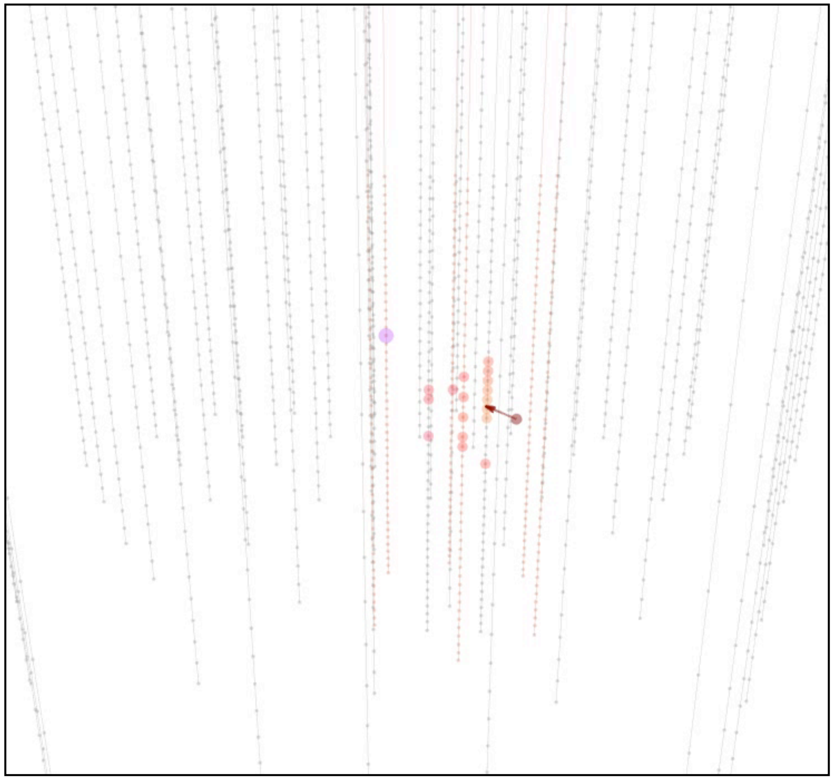
"Triggered": Event satisfies trigger condition of 3 neighboring hits within 1 μs.

"Contained": Event's true vertex is within fiducial volume.

* Wiggles due to low MC statistics

Simulated PINGU Events

- 9.3 GeV neutrino
  - 4.4 GeV initial cascade, 4.9 GeV muon
- Physics hits only (no noise)



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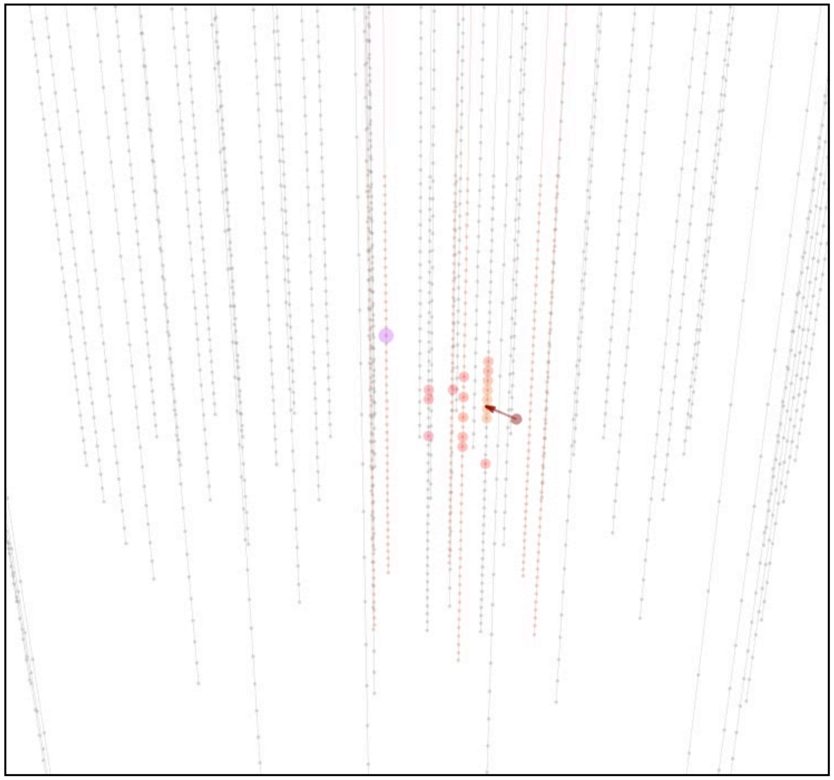

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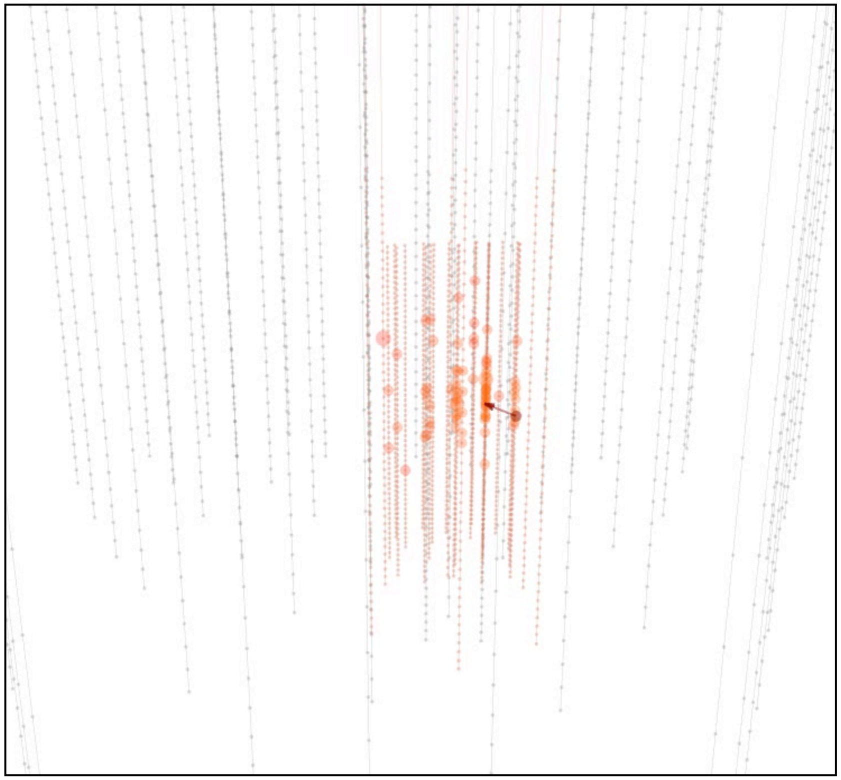
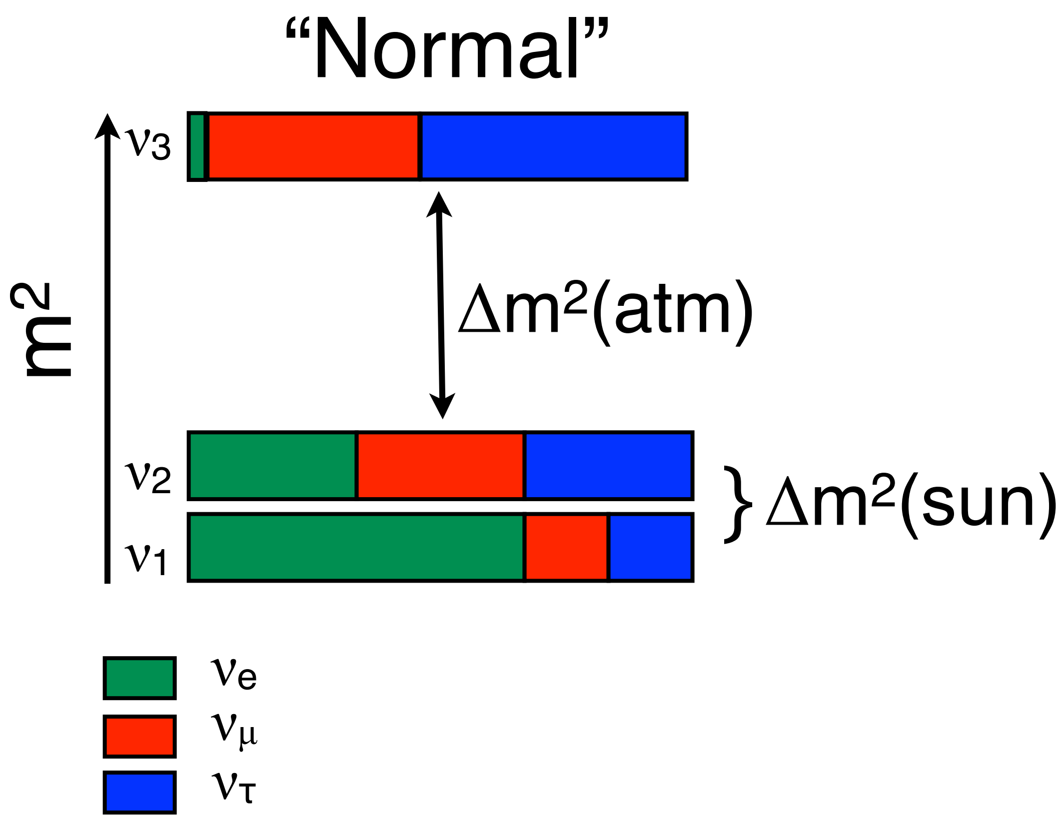


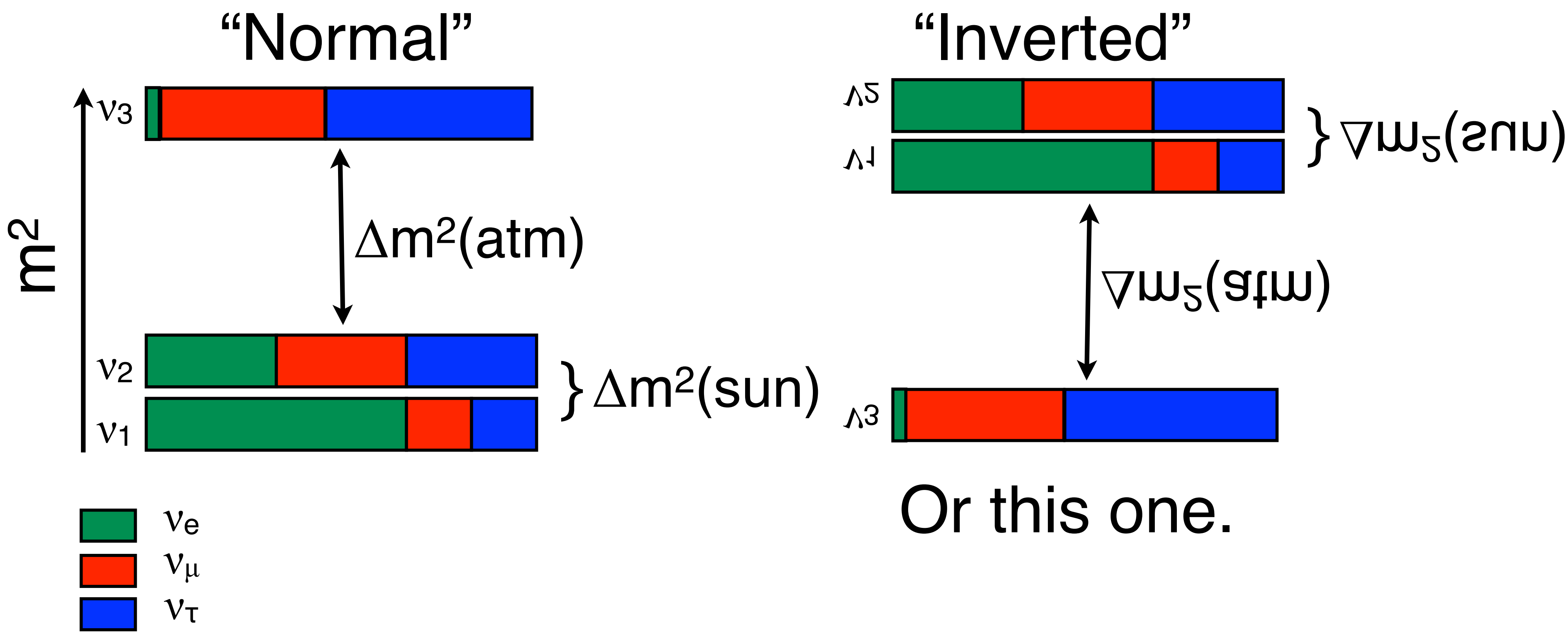
DeepCore + PINGU

Neutrino Hierarchy



- "Sign" of the hierarchy can discriminate among unification theories
- Hierarchy can be determined as neutrinos pass through matter
  - ν oscillation probability is enhanced if hierarchy is <u>normal</u>
  - $\bar{\nu}$ oscillation probability is enhanced if hierarchy is <u>inverted</u>
  - and: ν, $\bar{\nu}$ have different cross sections

Neutrino Hierarchy



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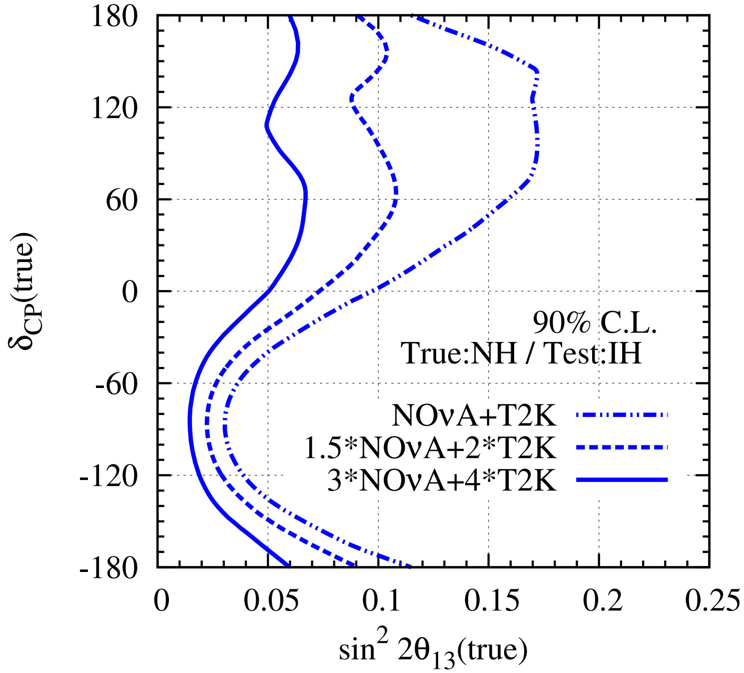
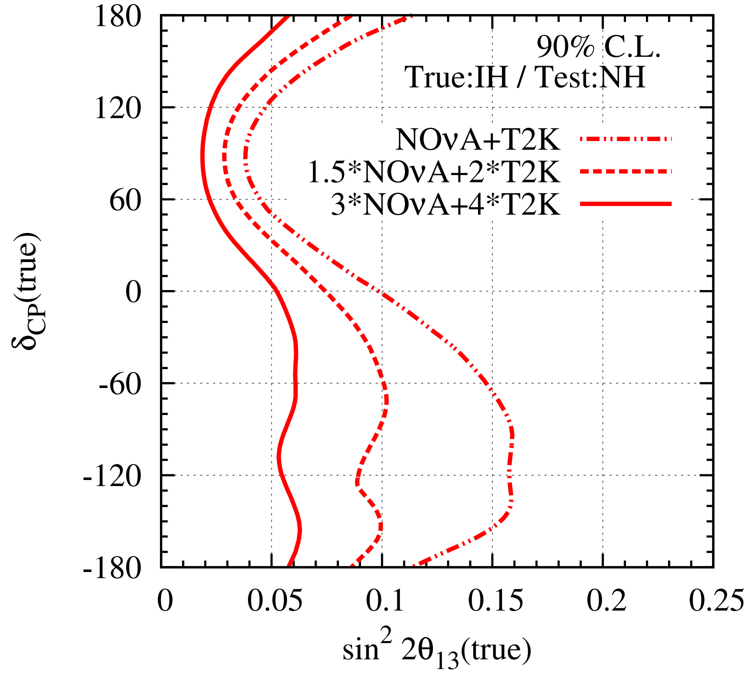
Neutrino Hierarchy

- Nova and T2K
  - Hierarchy–δ_{CP} degeneracy





For all points to the right of the contours, wrong hierarchy hypothesis can be ruled out.

Baseline statistics is 3+3 years.

Impact of enhanced statistics shown as well.

Prakash, Raut & Sankar, ArXiv:1201.6485v2

- Can avoid degeneracy with atmospheric neutrinos & parametric resonances

Neutrino Hierarchy and Parametric Resonances

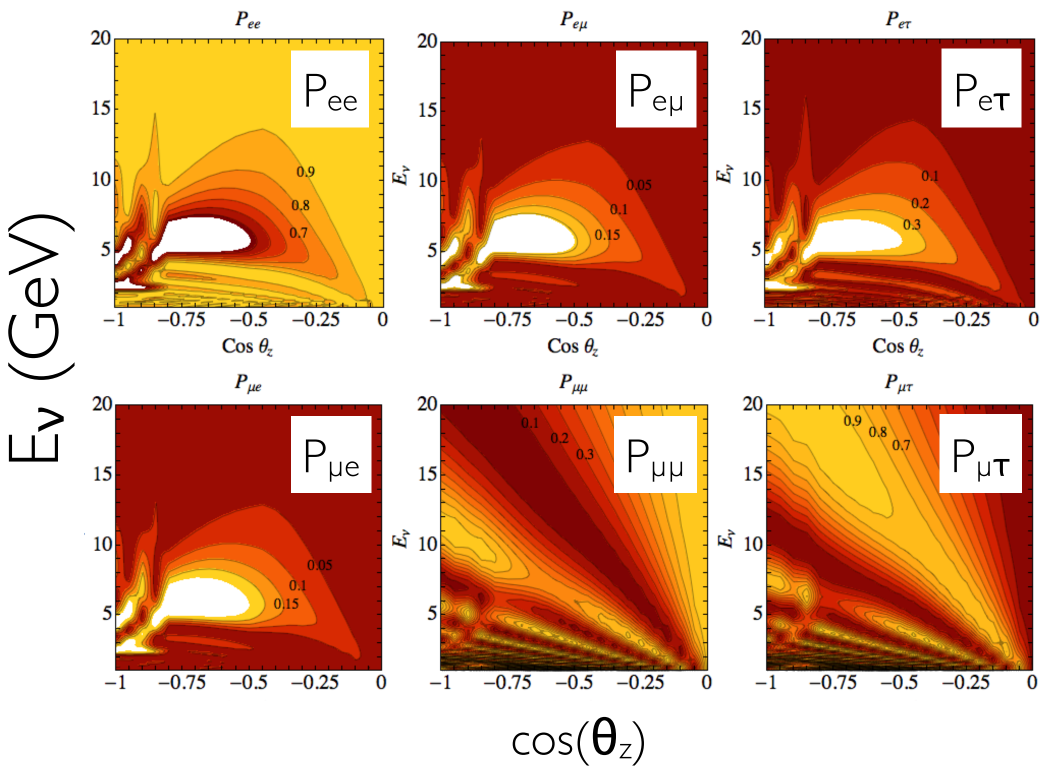
- Parametric resonances can occur as neutrinos cross regions of distinct density
  - Flavor transitions enhanced due to matter-induced modifications in oscillation phase
    - (MSW occurs through modifications in neutrino mixing angle)
  - If travel through periodically varying density, transition probabilities can add up and become large, but generally speaking need lots of periods
- Relevant Exception: For matter densities close to MSW resonance densities, can have parametric enhancement of oscillations with a very small number of periods
  - This is the case for Earth and neutrinos at ~5 GeV(!!) *and*
  - The character of the effect depends strongly on the hierarchy.

E. Kh. Akhmedov, *Pramana* 54:47-63,2000 or hep-ph/9907435

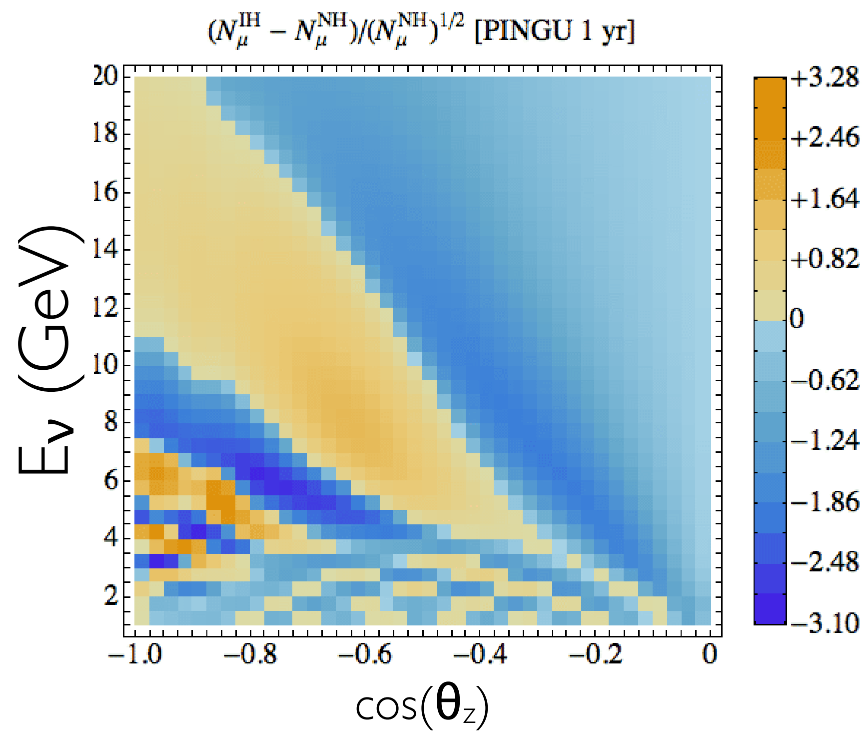
$\Delta m^2_{32} = 2.35 \times 10^{-3}$
$\Delta m^2_{21} = 7.6 \times 10^{-5}$
$\sin^2\theta_{23} = 0.42$
$\sin^2\theta_{12} = 0.312$
$\sin^2\theta_{13} = 0.025$

Neutrino Hierarchy and Parametric Resonances

Neutrino Oscillograms (Normal hierarchy)



Hierarchy Asymmetry (Perfect detector)



Summed significance: 45σ

Impact of δ_{CP} negligible.
Study by IceCube collaboration with full detector simulation and reconstructions underway.

Akhmedov, Razzaque, Smirnov. arXiv:1205.7071v2

Neutrino Hierarchy and Parametric Resonances

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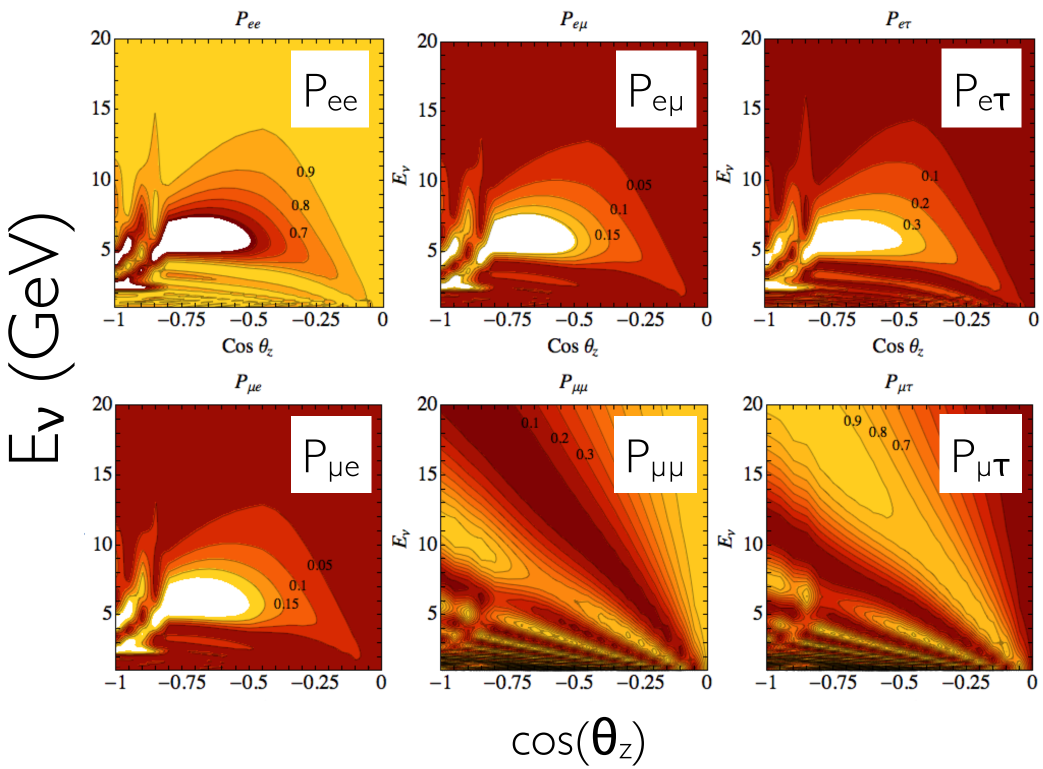
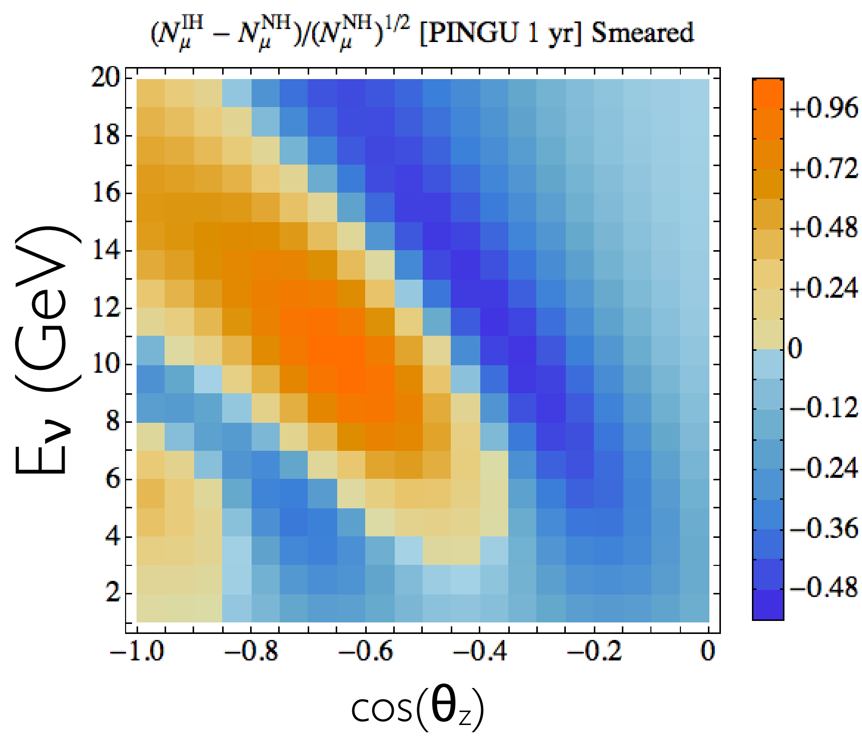


Hierarchy Asymmetry (σ_E=3GeV σ_φ=15°)



Impact of smearing: summed significance drops to 10σ (no systematics), 7σ (5% uncorr. syst.), 4.5σ (10% uncorr. syst.).

Impact of δ_{CP} negligible.
Study by IceCube collaboration with full detector simulation and reconstructions underway.

Akhmedov, Razzaque, Smirnov. arXiv:1205.7071v2

PINGU: Possible Timeline

- **Early 2012** — Begin simulation studies for 18-20 string detector with threshold ~1GeV. Targeted Physics: neutrino hierarchy, WIMPs, SN
- **Spring 2012** — Complete 1st DeepCore analyses.
- **Fall 2012** — Submit Letter of Interest to NSF
- **Summer 2013** — Finish Detailed PINGU studies
- **Fall 2013** — Submit PINGU Proposal
- **Winter 2016/17** — Begin deploying PINGU
- **Winter 2017/18** — Finish deploying PINGU including R&D strings. Start data-taking early 2018

- **March 2011** — 1st PINGU workshop - NIKHEF
- **Jan 2012** — 2nd PINGU workshop - Penn State
- **May 2012** — 3rd PINGU workshop - Erlangen

Conclusions

- DeepCore has much promise at the 10-100 GeV scale
  - atmospheric neutrino oscillations
  - WIMP dark matter
  - southern sky sources, exotica,...
- PINGU could reach to a few GeV
  - can be built quickly, reliably and relatively cheaply
  - will improve on many DeepCore measurements, and perhaps measure hierarchy with atmospheric neutrinos
  - with beam, PINGU could measure hierarchy (and possibly also CP)
  - perform R&D for future lower energy detector ("MICA") with possible sensitivity to
    - proton decay
    - SN neutrinos ~annually
  - New members welcome!

The End

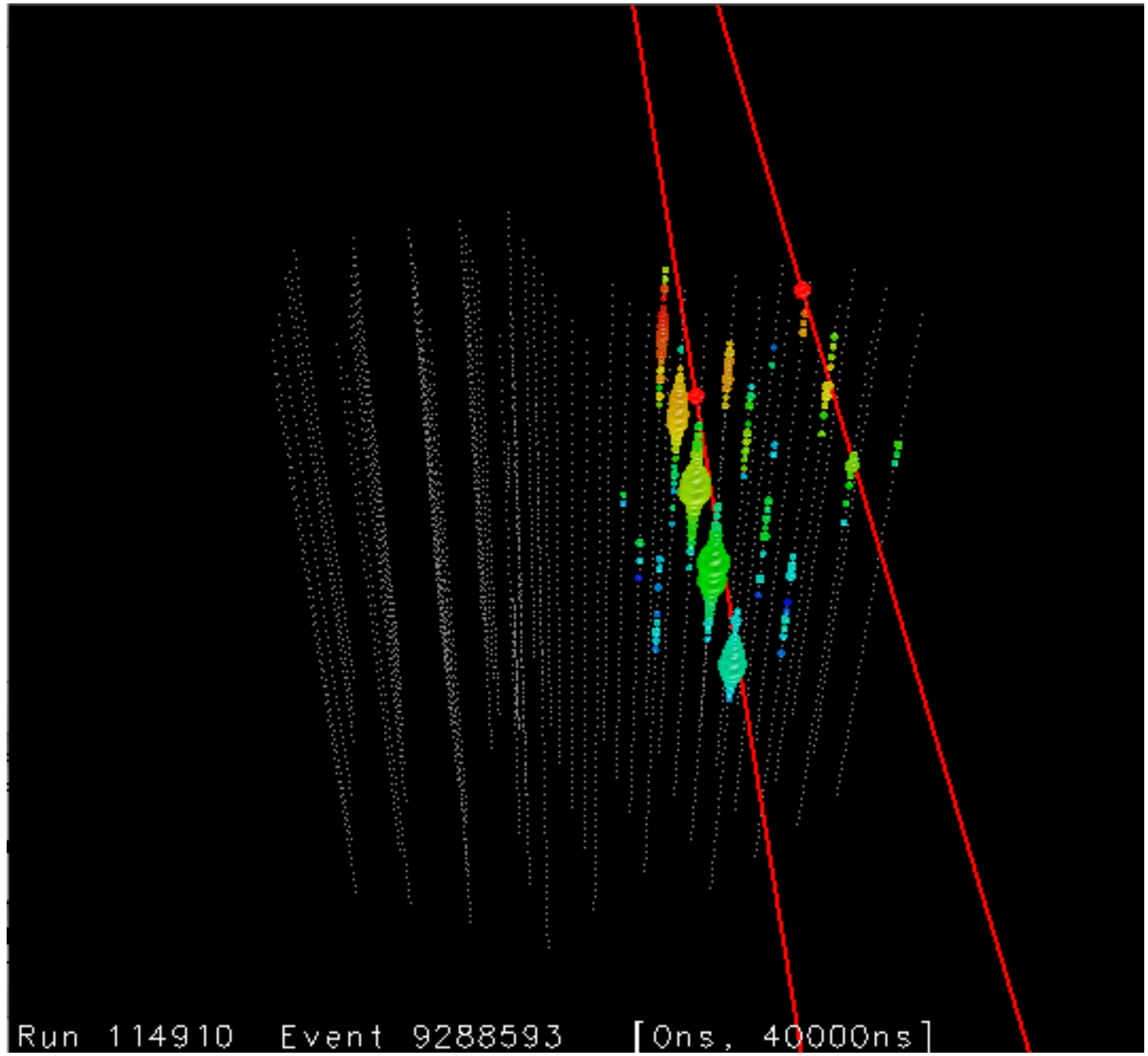
Backup slides follow

High P_T Muons

- Study transverse structure of hadronic interactions in cosmic ray interactions
  - Tracer: high-P_T muons
  - MACRO analysis (PRD 60 032001)
    - less than 70 m lateral separation of muons
    - parent mesons with $P_T < 1$–2 GeV/c
  - IceCube (with IceTop):
    - *greater* than ~200 m lateral separation
    - parent mesons with $P_T >$ ~8 GeV/c

High P_T Muons

- Sample data event
  - 233 m and 3.7° separation
- Geometry:
  - 125 m horizontal string separation
  - 17 m vertical module separation

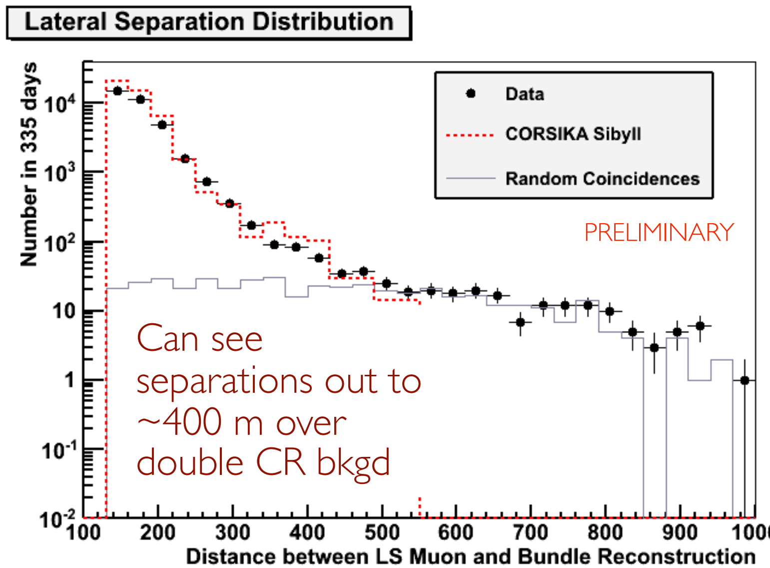


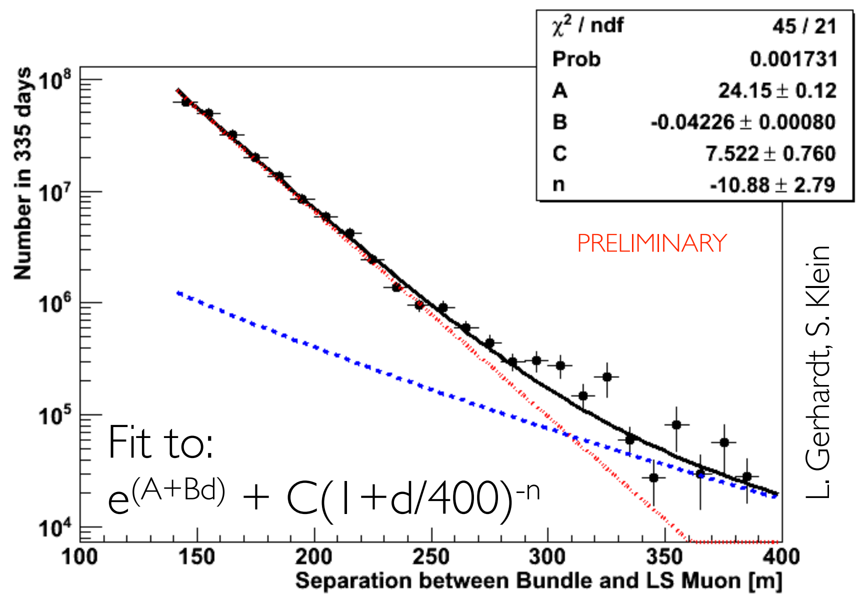
High P_T Muons

- At $P_T \sim 2$ GeV/c, expect to see a transition from soft to hard interactions
  - Soft: exponential spectrum, $\exp(-P_T/T)$
    - $T \sim 220$ MeV for pions
  - Hard: power law spectrum, $(1+P_T/P_o)^{-n}$
    - $P_o \sim 1.9$ GeV/c; $n \sim 13$
- Search for this transition to pQCD regime in high P_T muons in IceCube

Preliminary Results

- Lateral separation
  - $d_T = \dfrac{p_T H c}{E_\mu \cos\theta}$
  - Final sample has 35k events on a background of ~450; mean CR primary energy 10^6 GeV
- Best fit crossover point at 310 m separation
- See APS 2012 talk by L. Gerhardt for more details; paper in the works





L. Gerhardt, S. Klein

Neutrino Hierarchy & Models

The hierarchy is a good model discriminator:

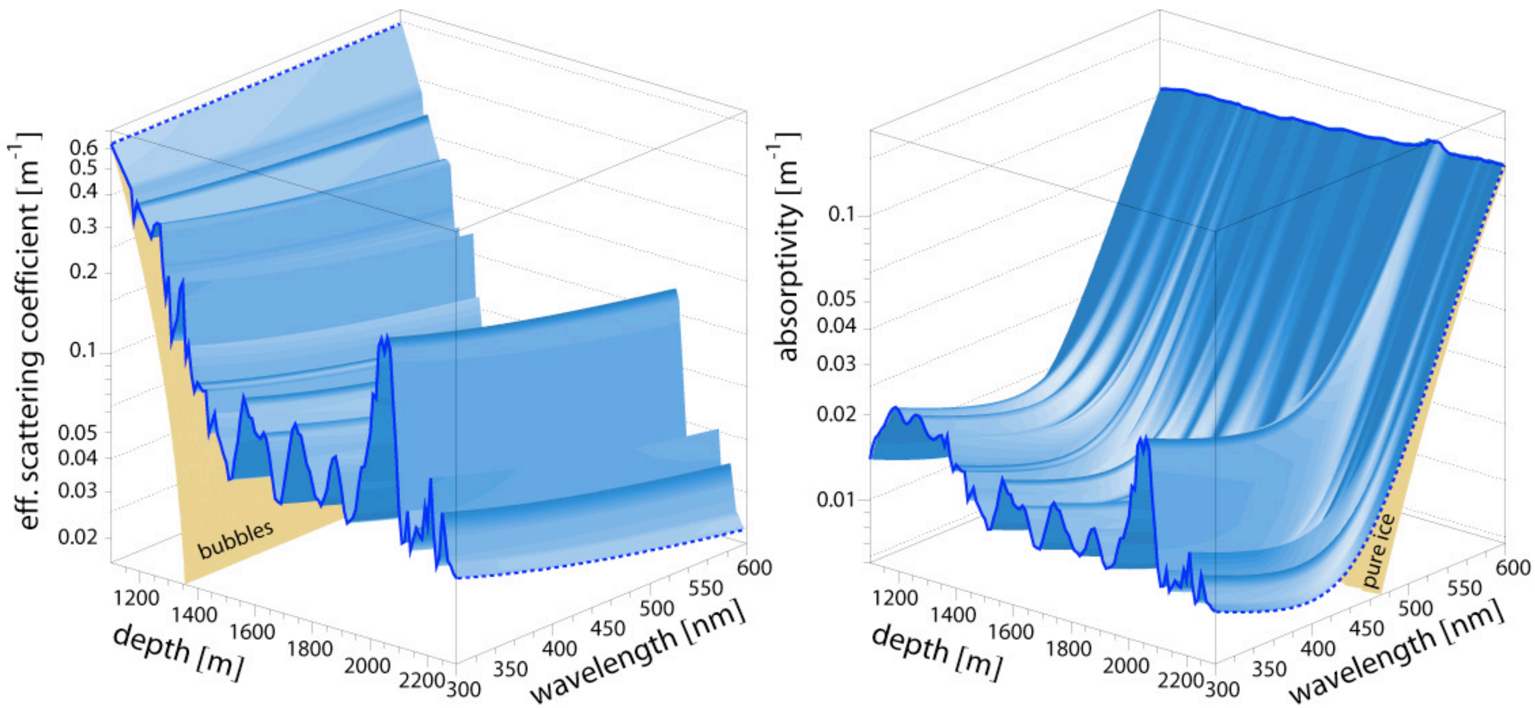
TABLE I: Mixing Angles for Models with Lepton Flavor Symmetry.

Reference		Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2 \theta_{12}$	$\sin^2 \theta_{13}$
Anarchy Model:					
dGM	[18]	Either			≥ 0.011 @ 2σ
$L_e - L_\mu - L_\tau$ Models:					
BM	[35]	Inverted			0.00029
BCM	[36]	Inverted			0.00063
GMN1	[37]	Inverted		≥ 0.52	≤ 0.01
GL	[38]	Inverted			0
PR	[39]	Inverted		≤ 0.58	≥ 0.007
S_3 and S_4 Models:					
CFM	[40]	Normal			0.00006 - 0.001
HLM	[41]	Normal	1.0	0.43	0.0044
		Normal	1.0	0.44	0.0034
KMM	[42]	Inverted	1.0		0.000012
MN	[43]	Normal			0.0024
MNY	[44]	Normal			0.000004 - 0.000036
MPR	[45]	Normal			0.006 - 0.01
RS	[46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
		Normal	$\theta_{23} \leq 45°$		0
TY	[47]	Inverted	0.93	0.43	0.0025
T	[48]	Normal			0.0016 - 0.0036
A_4 Tetrahedral Models:					
ABGMP	[49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL	[50]	Normal			0.006 - 0.04
Ma	[51]	Normal	1.0	0.45	0
SO(3) Models:					
M	[52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:					
CPP	[53]	Normal			0.007 - 0.008
		Inverted			≥ 0.00005
		Inverted			≥ 0.032
WY	[54]	Either			0.0006 - 0.003
		Either			0.002 - 0.02
		Either			0.02 - 0.15

Table courtesy W. Winter

Ice Properties

- Depth dependence of λ_{eff} and λ_{abs} from *in situ* LEDs
- Ice below 2100 m in DeepCore fiducial region <u>very</u> clear
  - $<\lambda_{eff}>$ ~ 47 m, $<\lambda_{abs}>$ ~ 155 m



- Constant temperature ~ -35C

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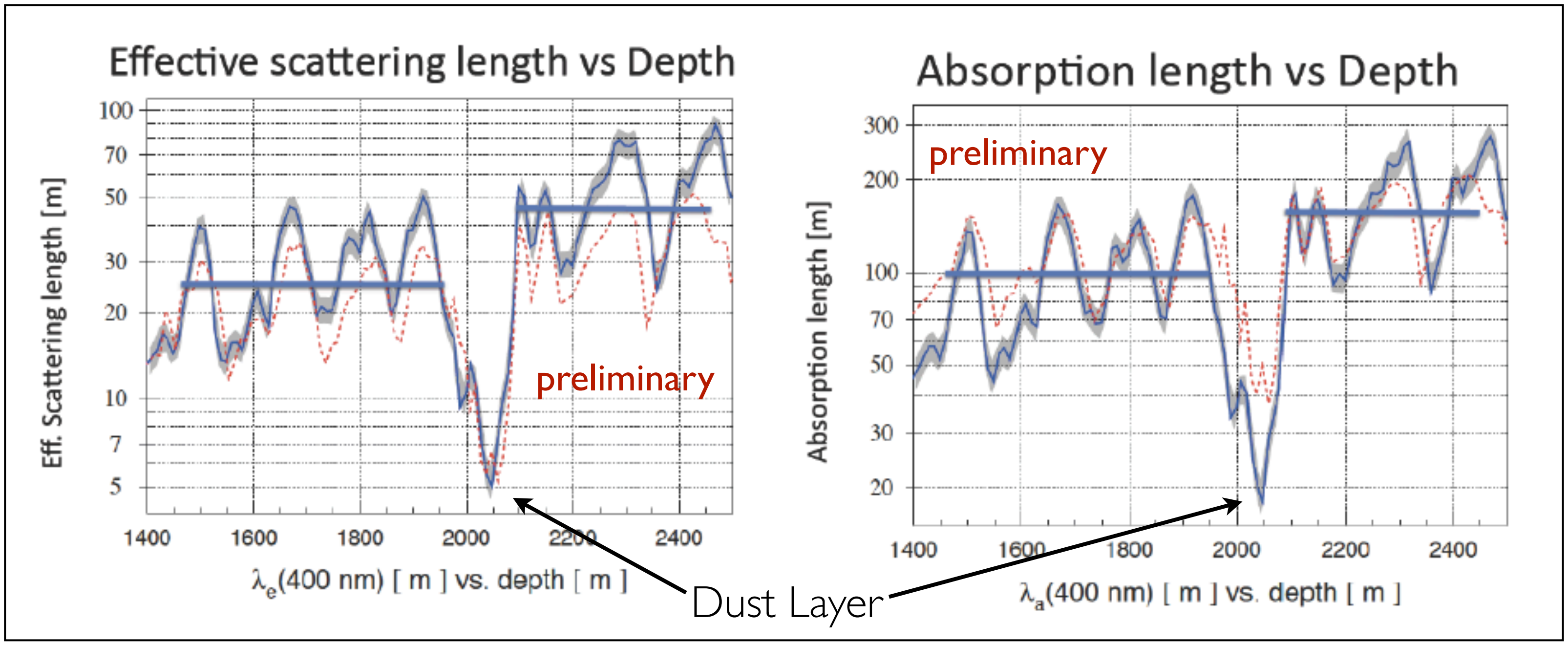
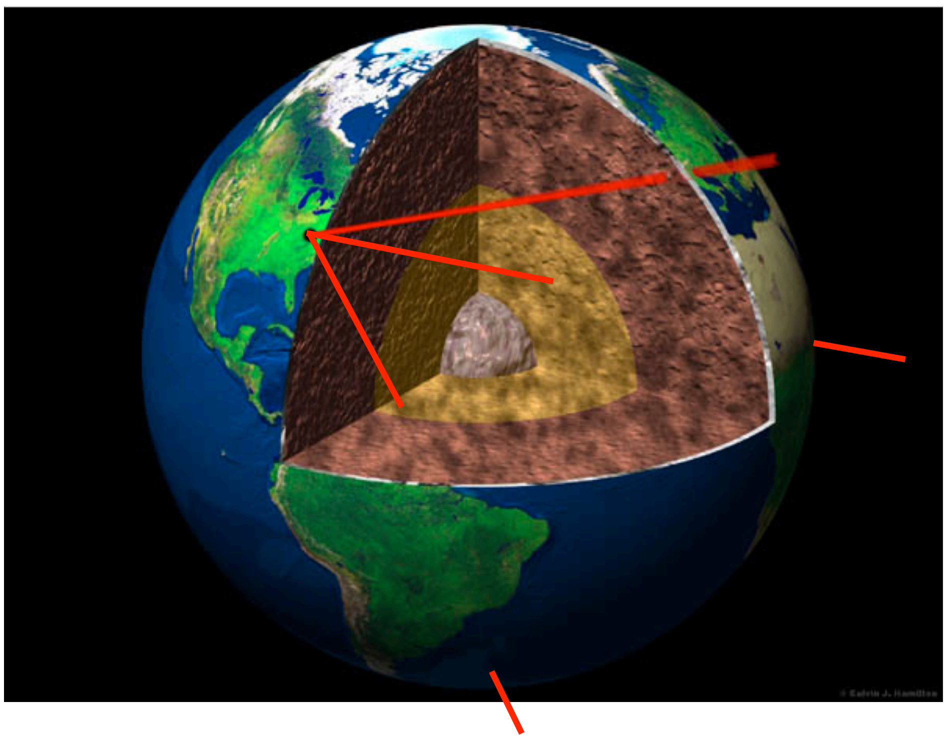
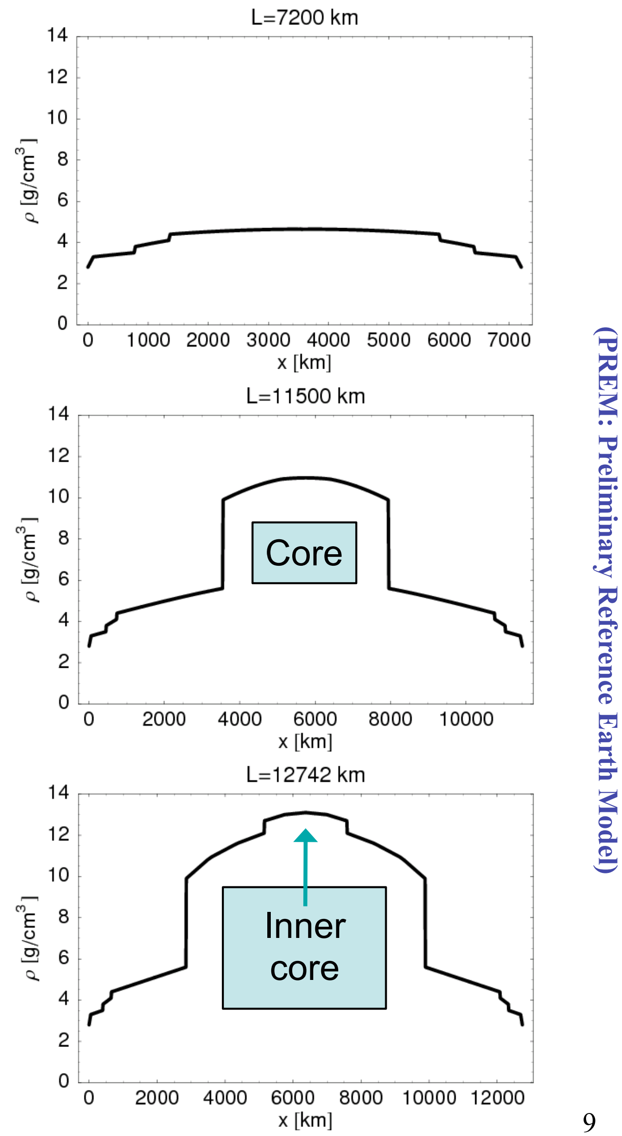


- Constant temperature ~ -35C

Even Better: PINGU + ν–Beam

- A neutrino beam can also exploit parametric resonances and
  - Can enable hierarchy determination with much less dependence on detector performance

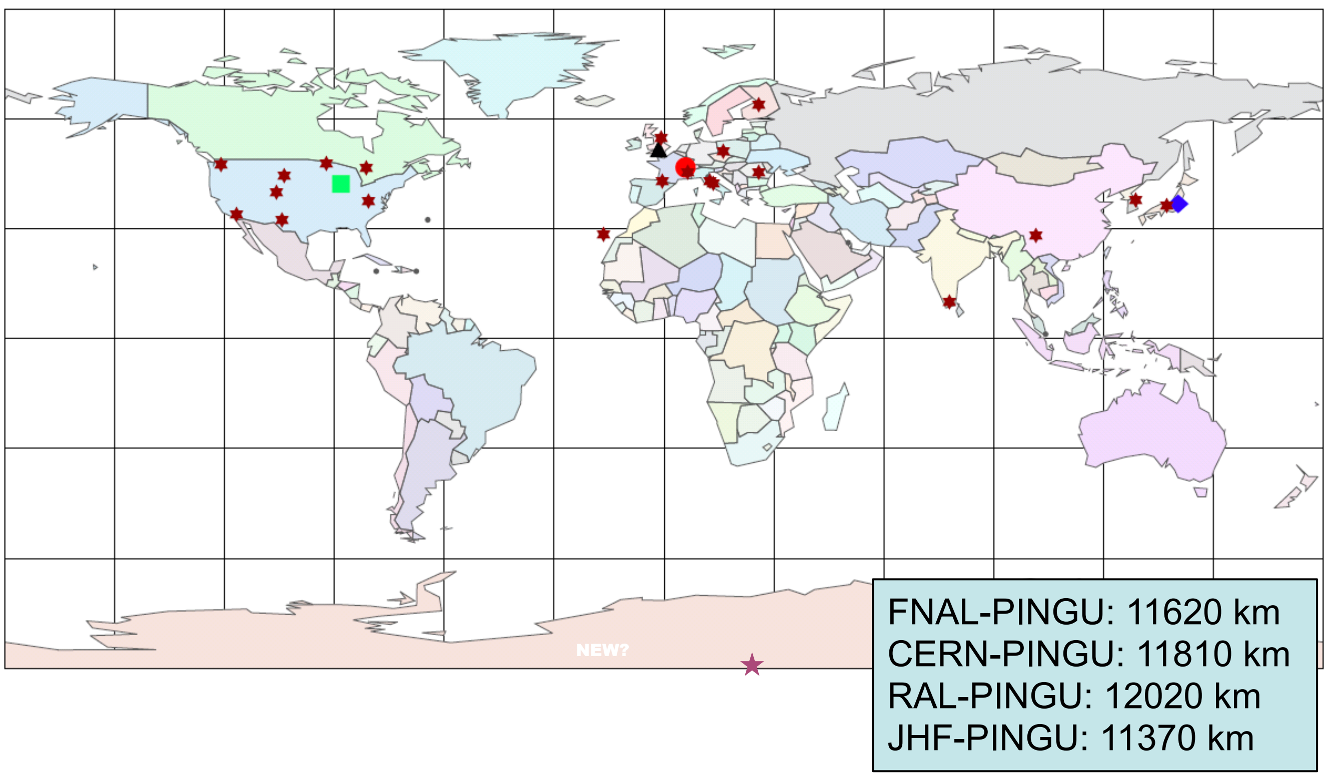




Figures courtesy W. Winter

PINGU + ν–Beam

- Distances from labs to PINGU (and other experiments)
  - All baselines to PINGU cross Earth's outer core



(Agarwalla, Huber, Tang, Winter, 2010)

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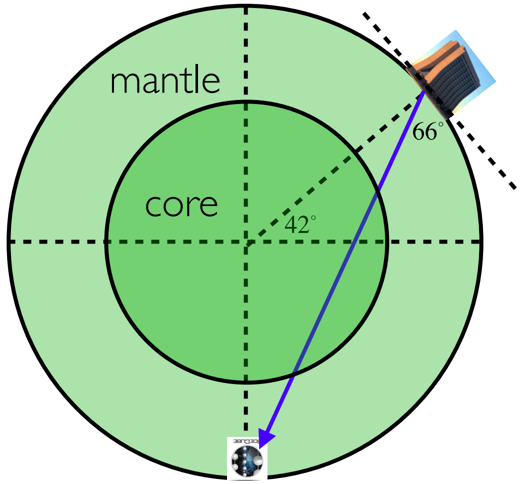
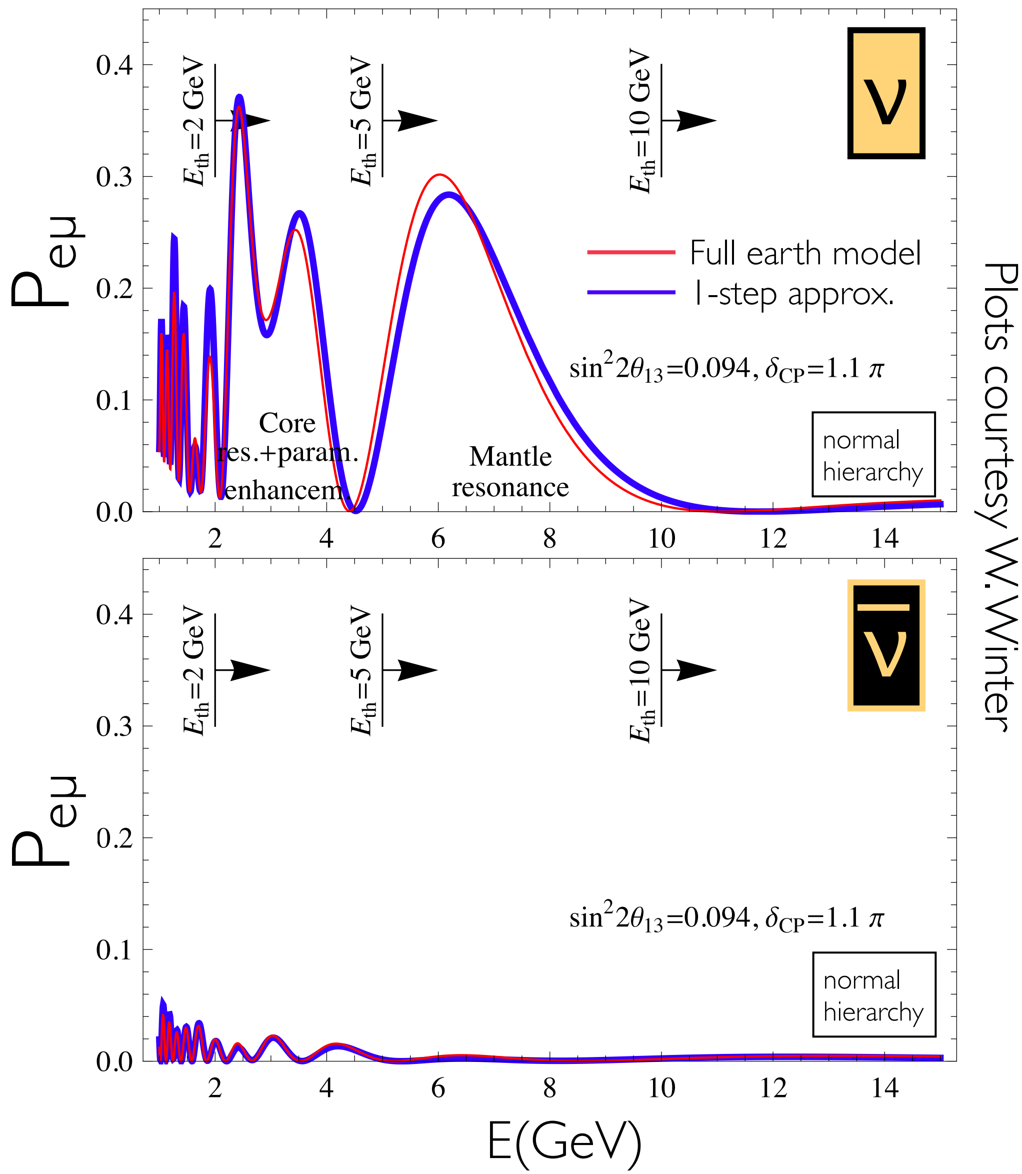
Figure courtesy W. Winter

Specific Example: FNAL to PINGU



- Parametric enhancement due to mantle-core-mantle profile can be exploited at convenient neutrino energies
  - (The beam angle is somewhat less convenient)
- Strong dependence on hierarchy
  - Since $\sigma(\nu)\sim2\sigma(\bar{\nu})$:
    - N_{ev}(NH)~2N_{ev}(IH) at 2-10 GeV
  - δ_{CP} = 0 looks similar



PINGU Effective Volume

- A few MTon fiducial mass for superbeam made by FNAL main injector protons at 120 GeV
    - makes lots of 2-5 GeV neutrinos
    - can use low intensity beam (shorter decay pipe)
- N.B.: At trigger level, without selection criteria or reconstruction inefficiencies
    - Ultimate effective (a.k.a. fiducial) volume will be smaller

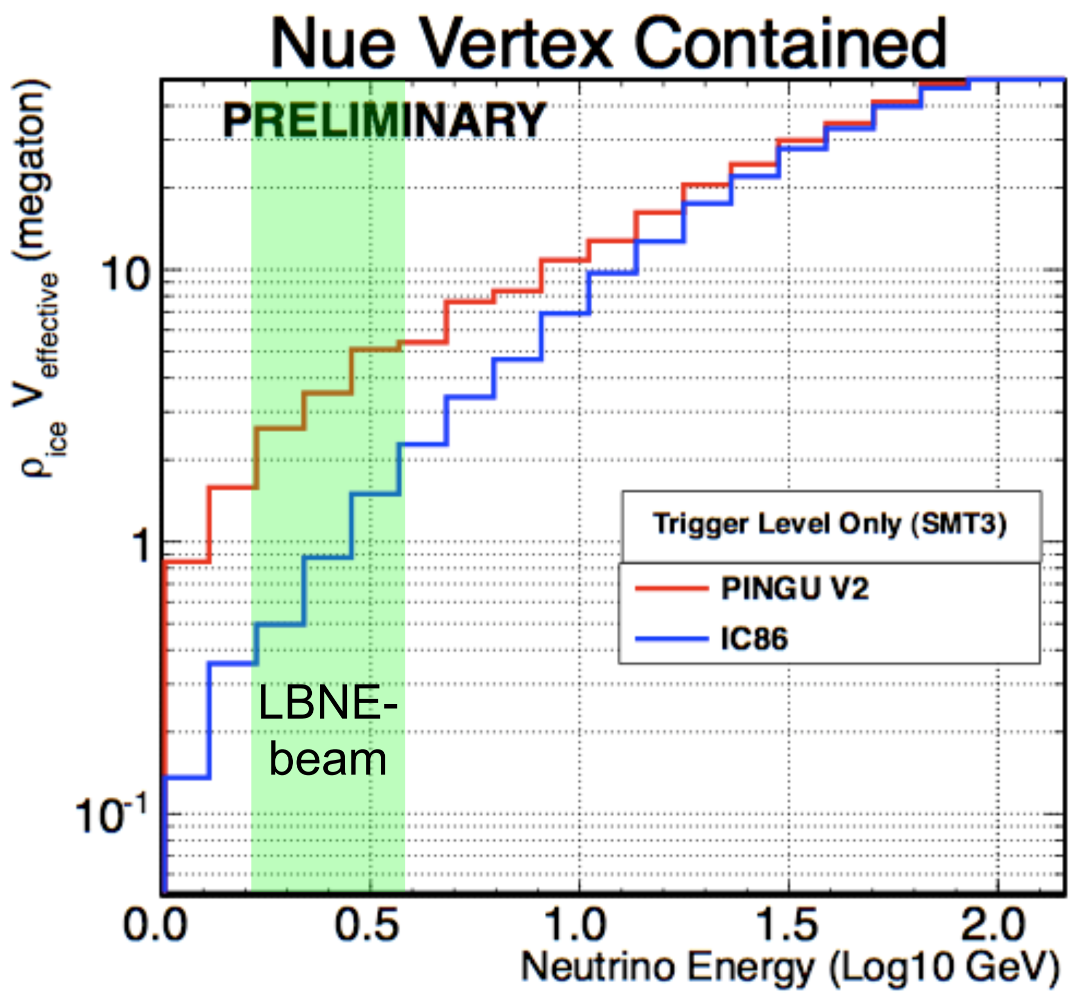


Figure courtesy J. D. Koskinen and W. Winter. For more details, see Tang and Winter, JHEP 1202 (2012) 028.

The Hierarchy with PINGU + ν–Beam

- Assumptions:
  - 20% ν_μ CC misID
  - No energy resolution
    - A counting experiment!
  - Include irreducible backgrounds
    - intrinsic beam, NC events, ν_τ
  - signal & bkgd. systematics uncorrelated
- Conclusions:
  - 18σ effect (stat. only)
  - With particle ID, might be also sensitive to CP

NUMI beam at 10^{21} PoT

	Normal hier.	Inv. hierarchy
Signal	**1560**	**54**
Backgrounds:		
ν_e beam	39	59
Disapp./track mis-ID	511	750
ν_τ appearance	3	4
Neutral currents	2479	2479
Total backgrounds	3032	3292
Total signal+backg.	4592	3346

Table courtesy W. Winter. See also Tang and Winter, JHEP 1202 (2012) 028.