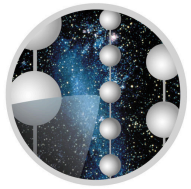


IceCube/DeepCore and IceCube/PINGU: Prospects for Few-GeV Scale ν Physics in the Ice

International Workshop on Neutrino Factories, Super Beams and Beta Beams
NuFact 2012
July 23-28, 2012
Williamsburg, VA, USA

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

PENNSTATE
1855

Outline

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

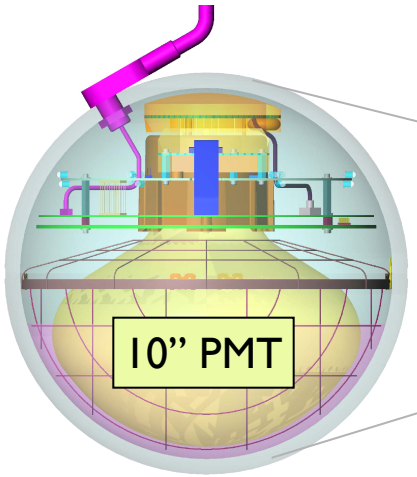
*Precision IceCube Next-Generation Upgrade

The IceCube Collaboration

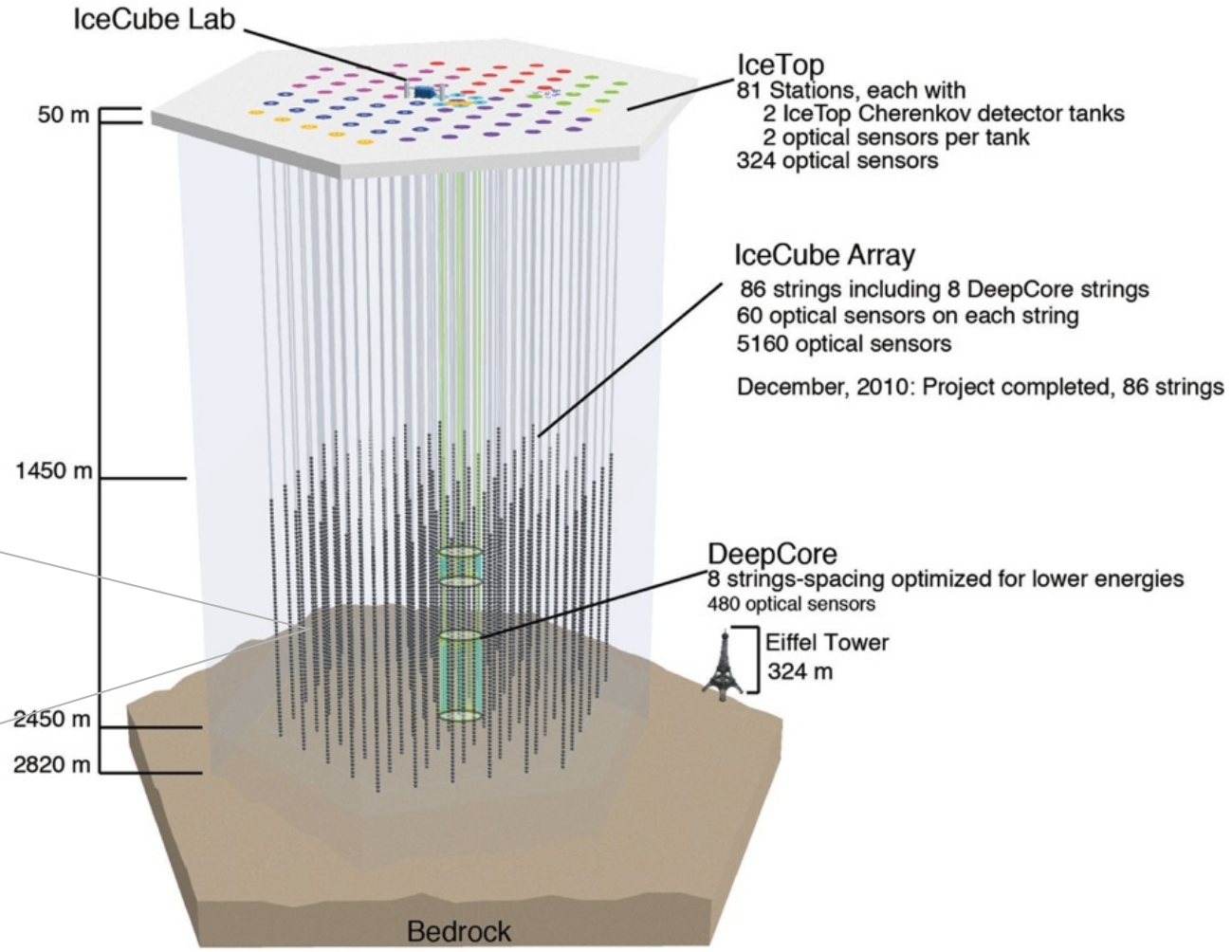
International Funding Agencies

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)

IceCube and DeepCore

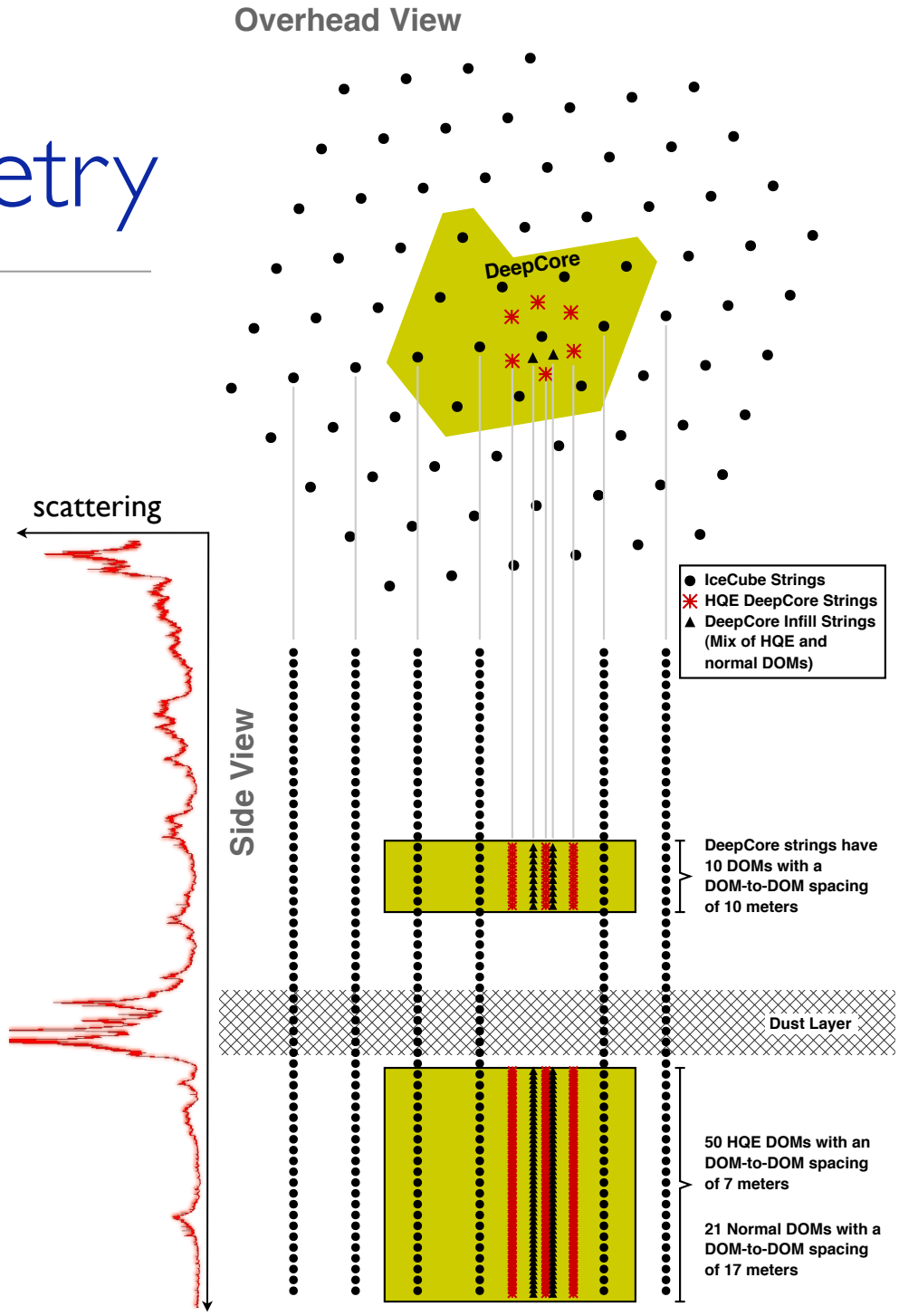


Digital Optical Module (DOM)



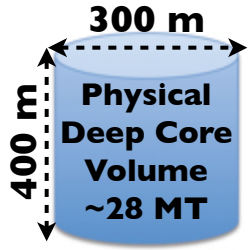
DeepCore Geometry

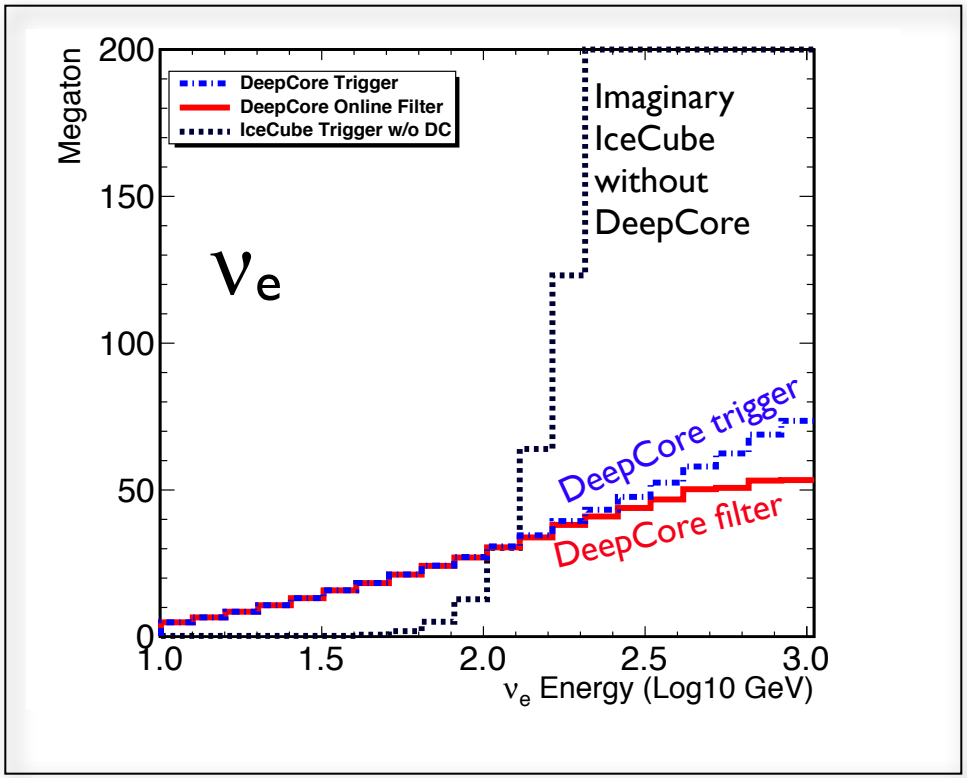
- Eight special strings plus 12 nearby standard IceCube strings
  - 72 m interstring horizontal spacing (six with 42 m spacing)
  - 7 m DOM vertical spacing
  - ~40% higher Q.E. PMTs
  - ~5x higher effective photocathode density (but still only ~0.1% coverage)
  - DOMs: ~few ns timing, 0.25 p.e. threshold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

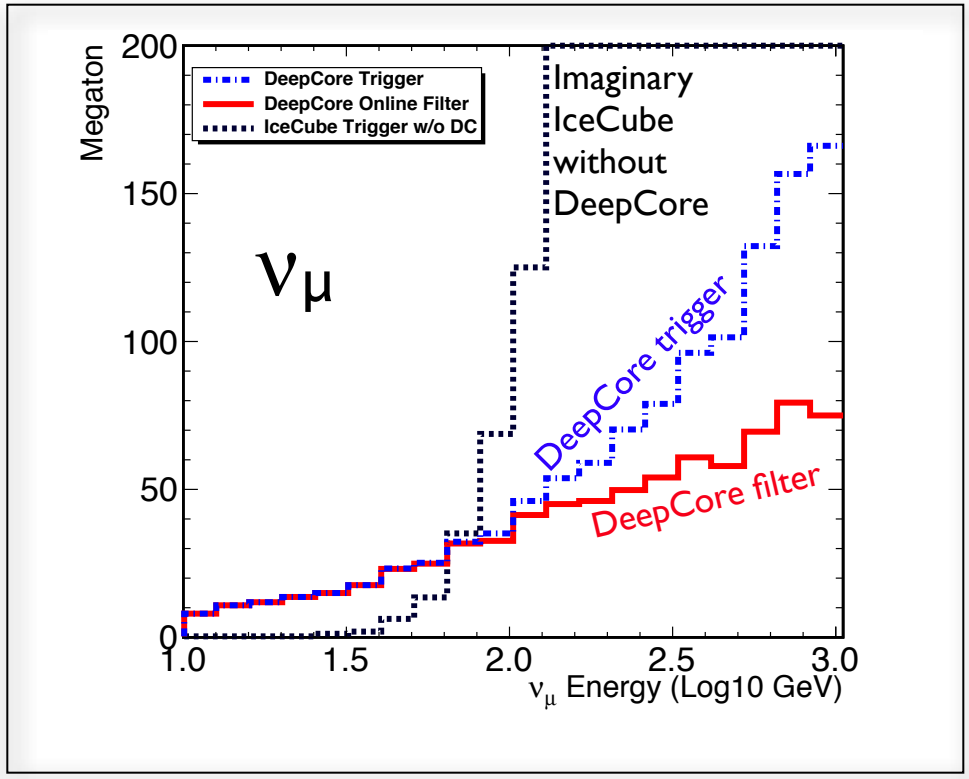


DeepCore: Effective Volume

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





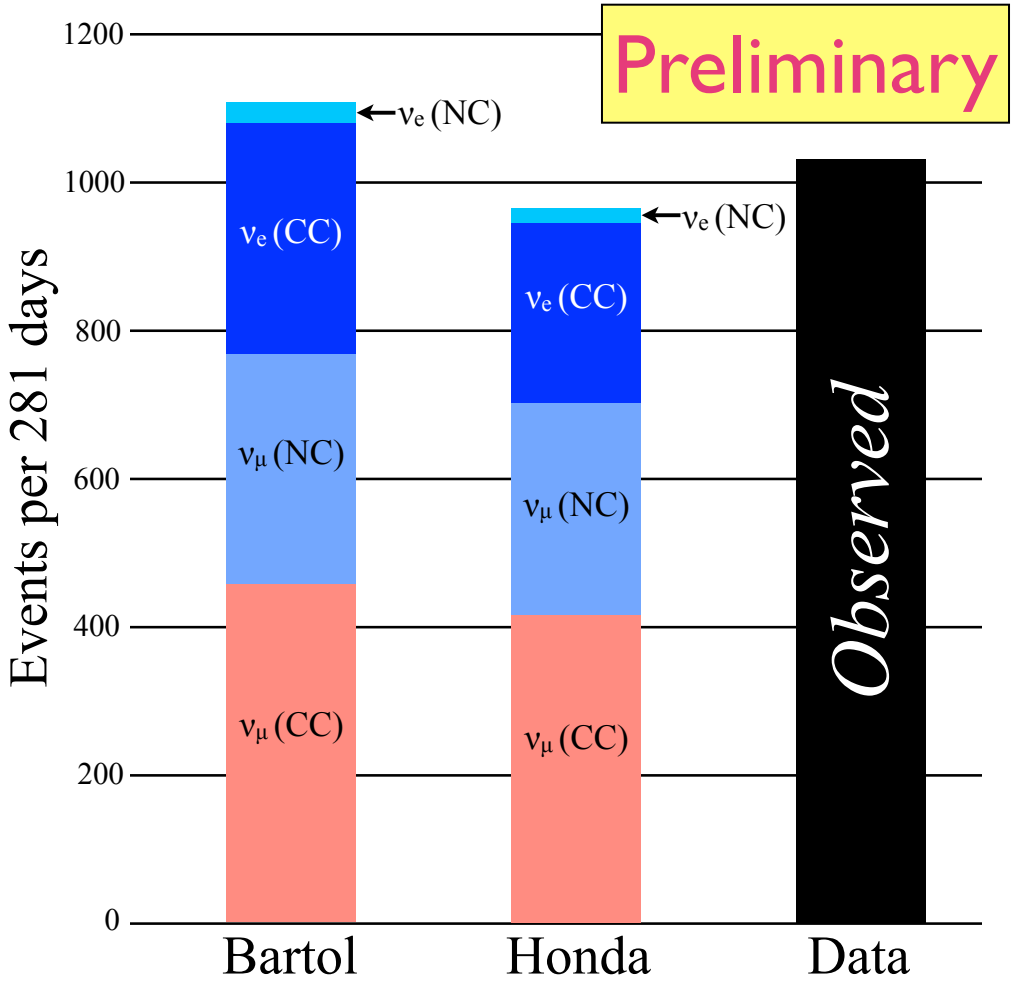


J. Koskinen/Penn State

- 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

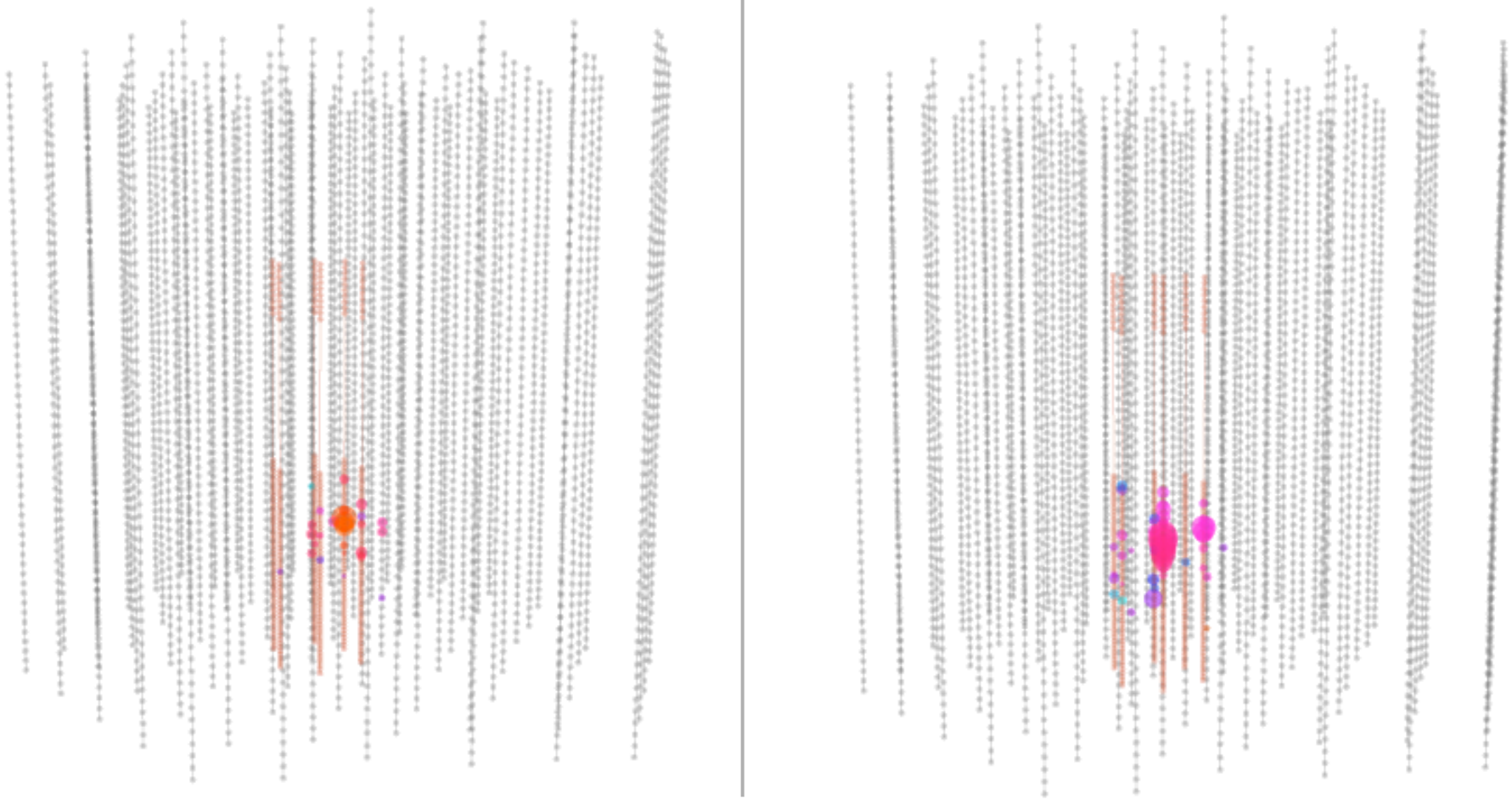
First Result from DeepCore

- 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.: $[casc/trk]_{veto}$ / $[casc/trk]_{final}$ (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

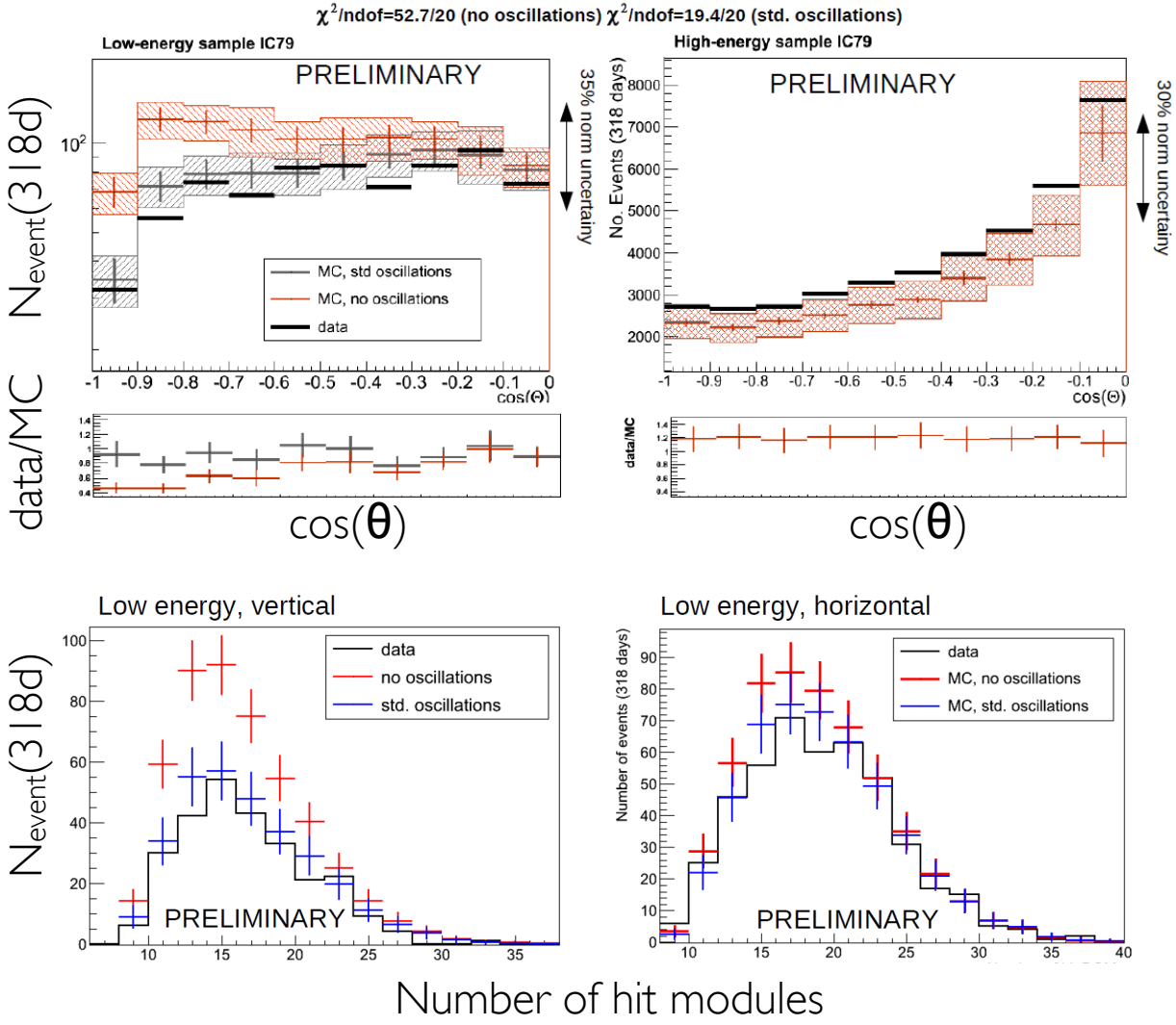
Two candidate events



(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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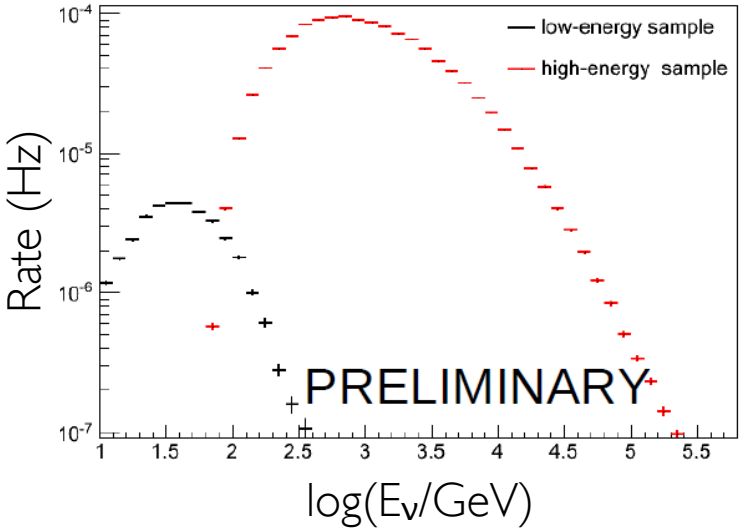
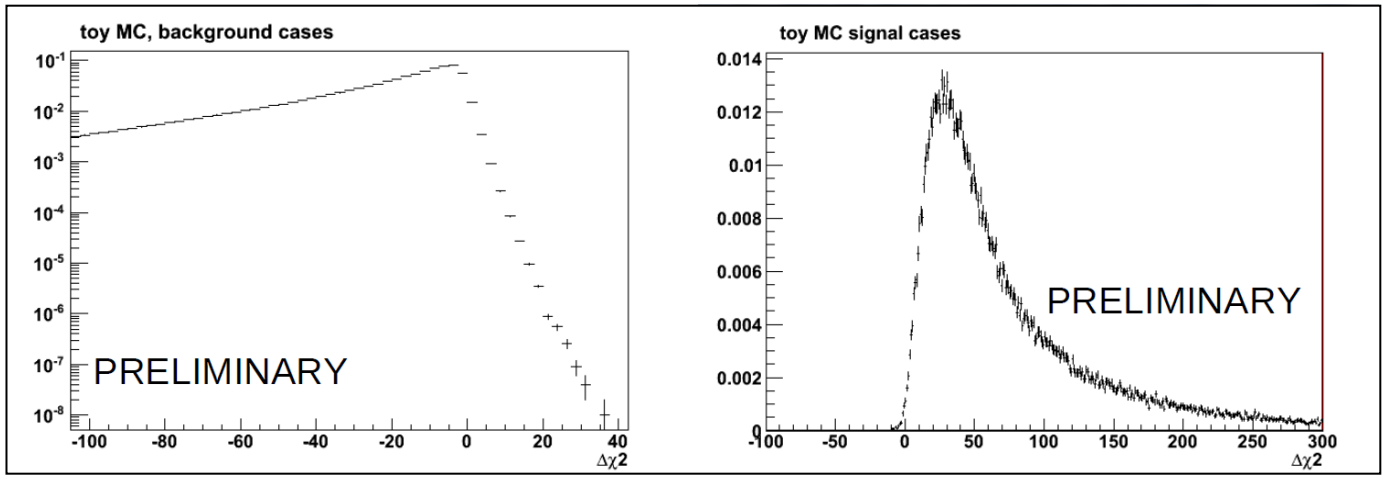




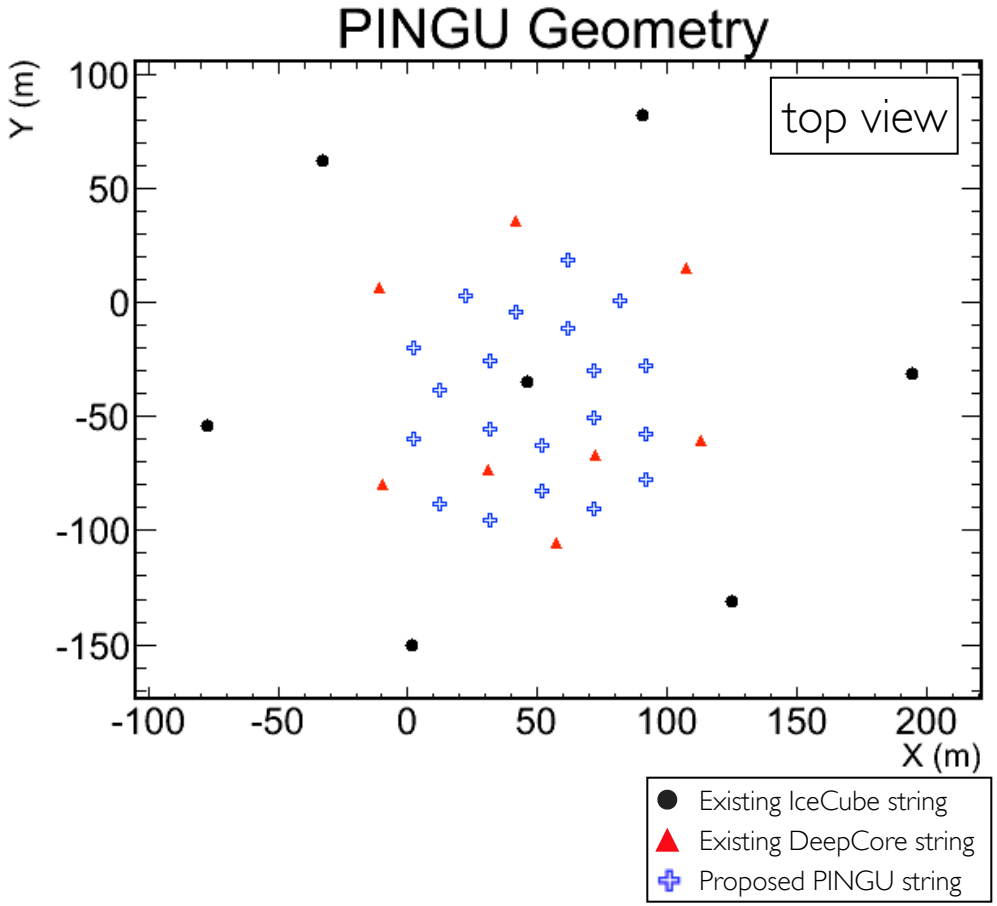
$$\Delta\chi^2 = \chi^2_{\text{no osc}} - \chi^2_{\text{osc}} \; (= 33 \text{ in this analysis})$$

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?

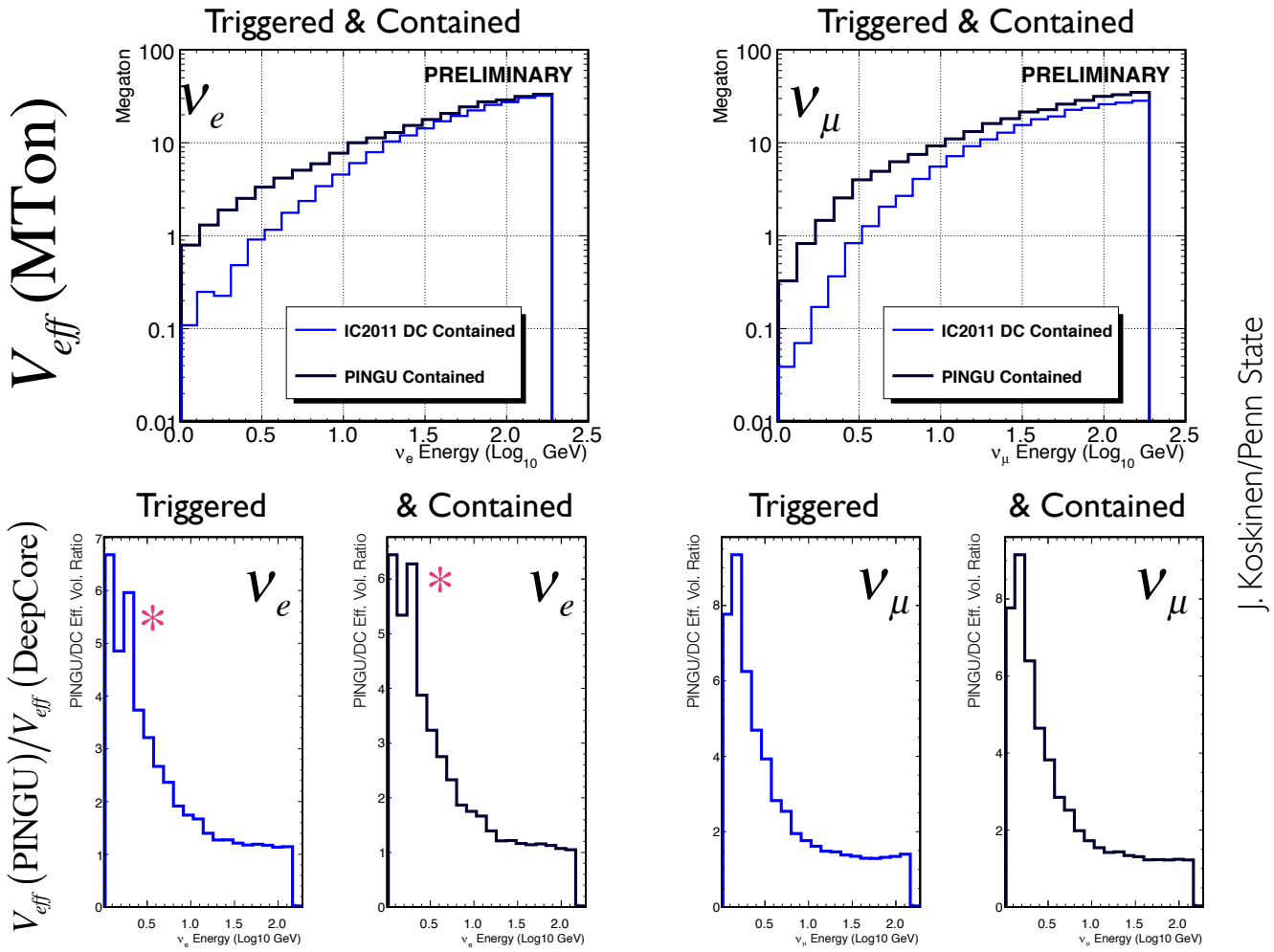
The Next Step: PINGU

- 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



J. Koskinen/Penn State

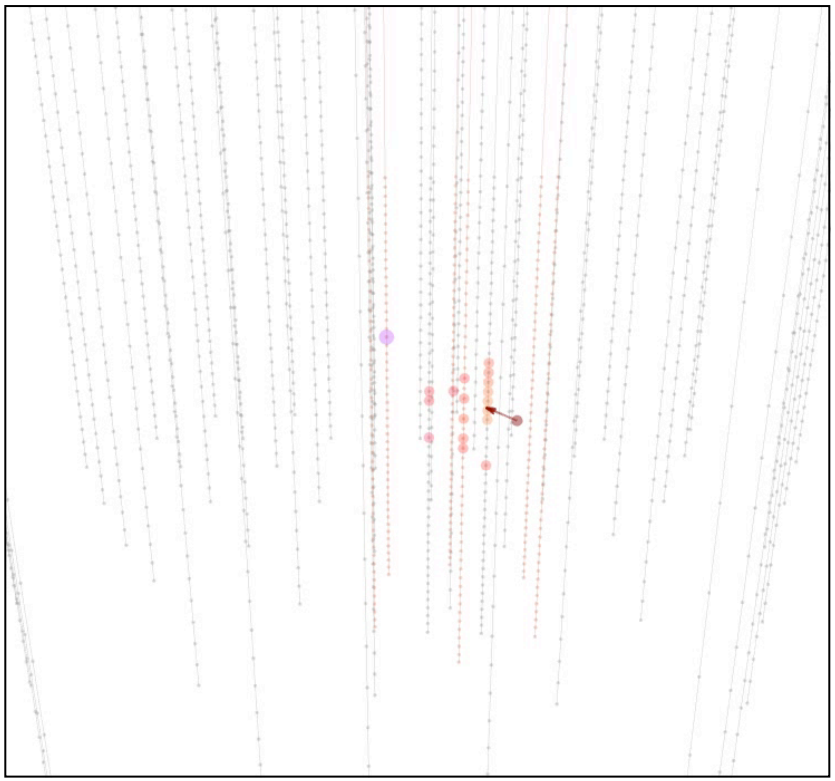
"Triggered": Event satisfies trigger condition of 3 neighboring hits within 1 μs.

"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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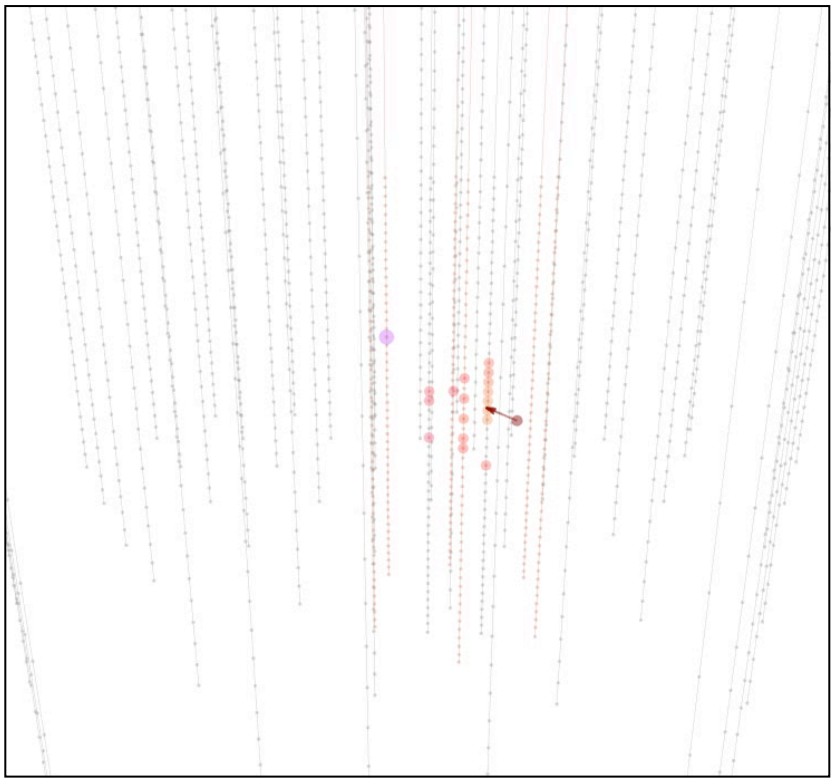
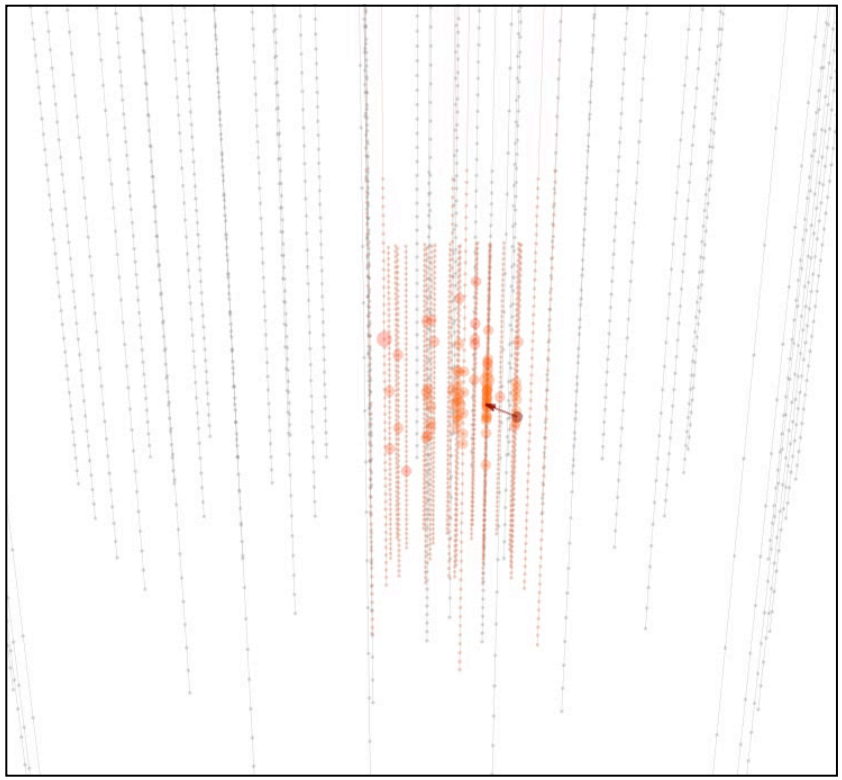
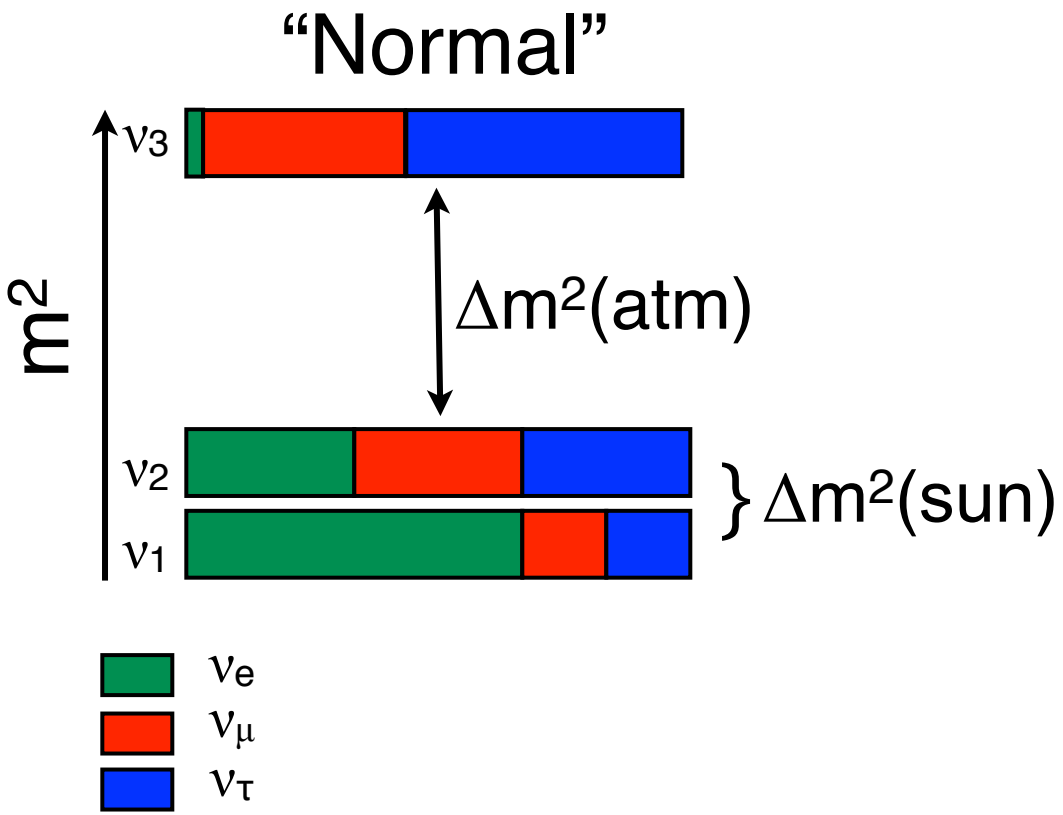


DeepCore Only



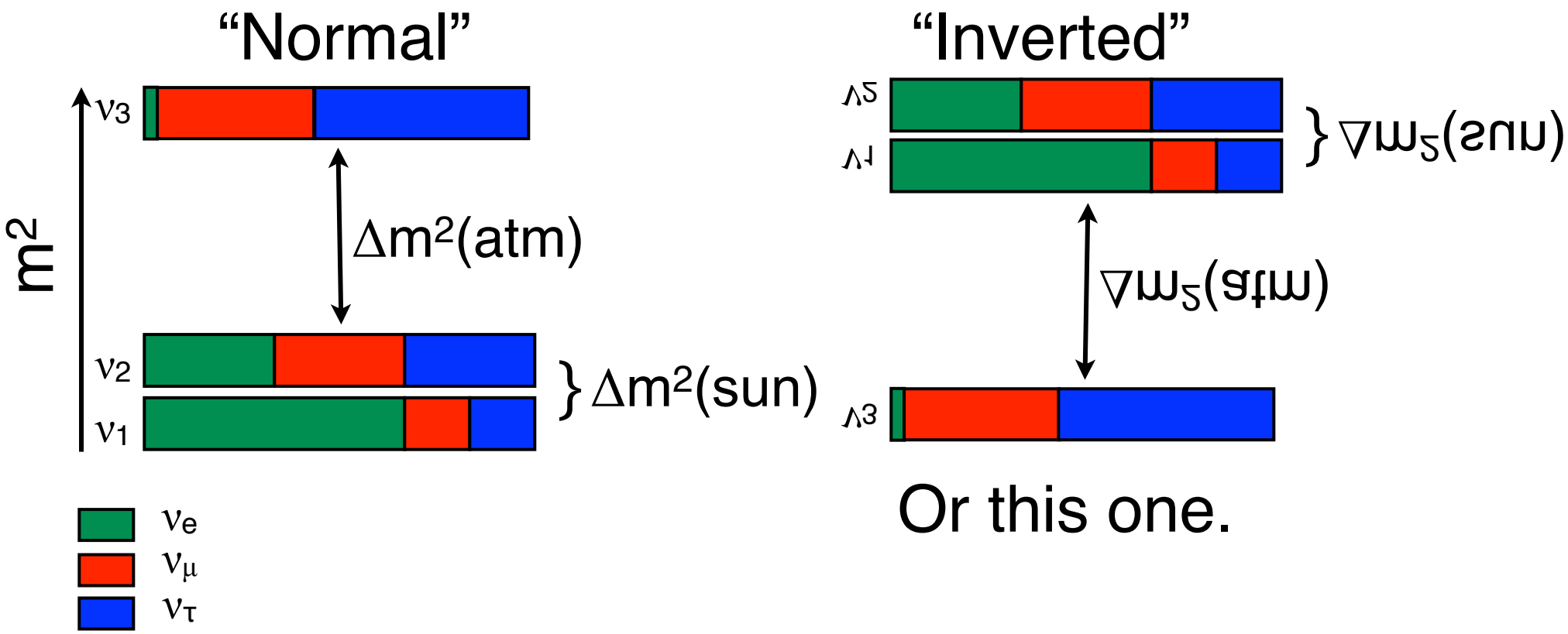
DeepCore + PINGU

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 normal
  - $\bar{\nu}$ oscillation probability is enhanced if hierarchy is inverted
  - and: $\nu, \bar{\nu}$ have different cross sections

Neutrino Hierarchy



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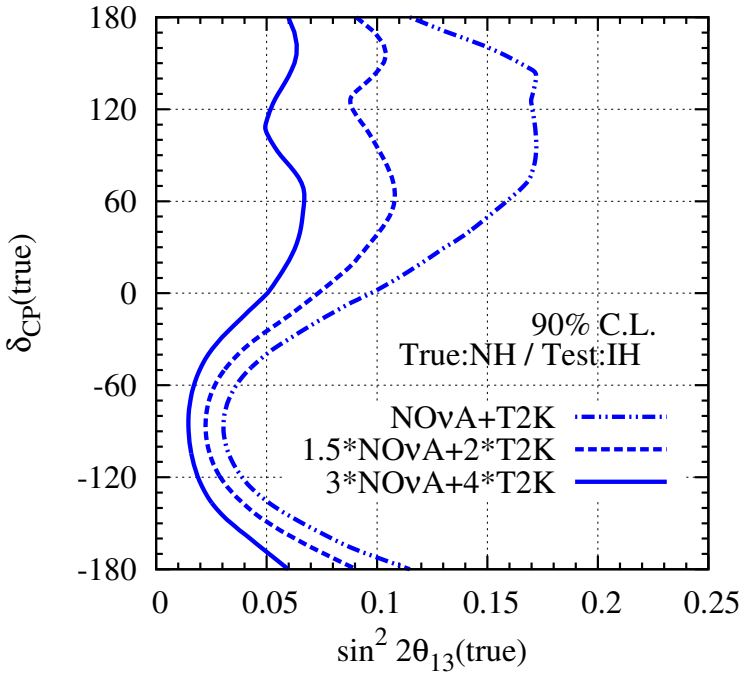
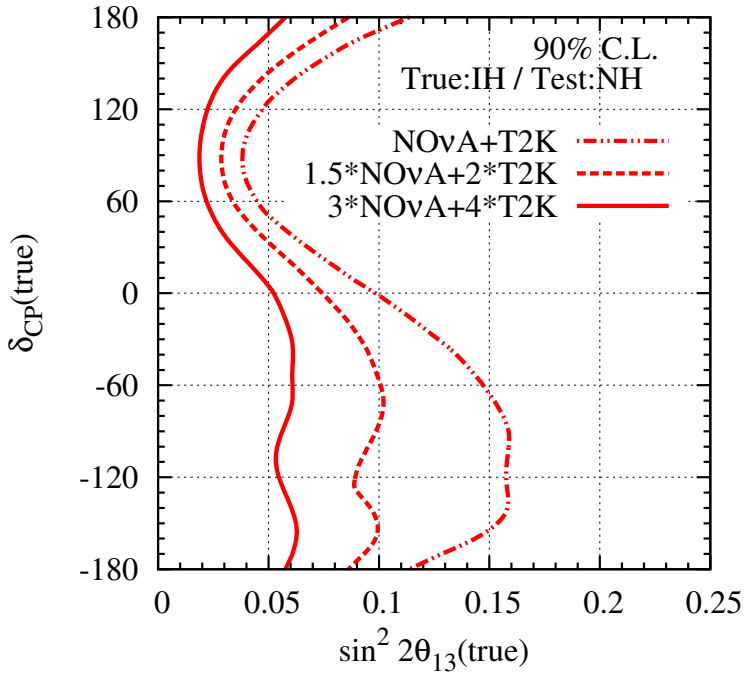
  - and: $\nu, \bar{\nu}$ have different cross sections

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

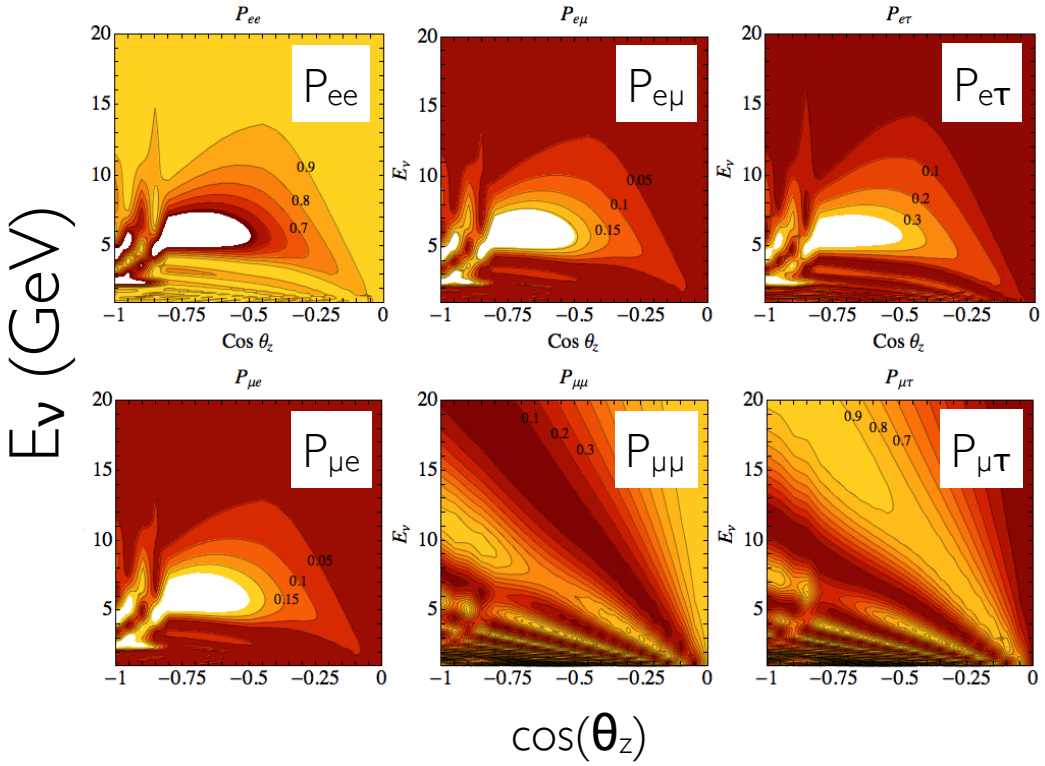
- Parametric resonances can occur as neutrinos cross regions of distinct density
  - Flavor transitions enhanced due to matter-induced modifications in oscillation phase
    - (MSW occurs through modifications in neutrino mixing angle)
  - If travel through periodically varying density, transition probabilities 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

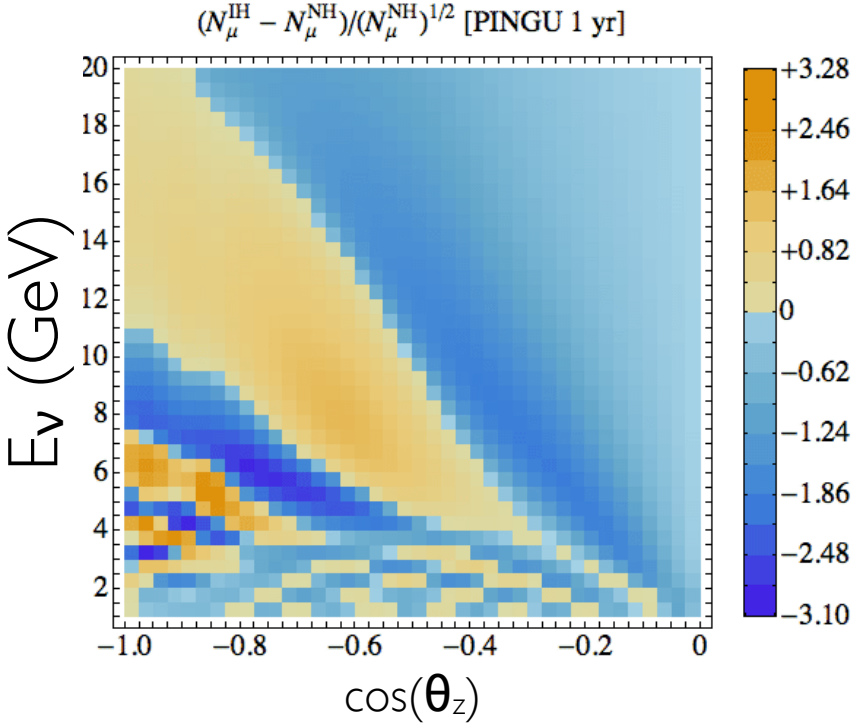
Neutrino Hierarchy and Parametric Resonances

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

Neutrino 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

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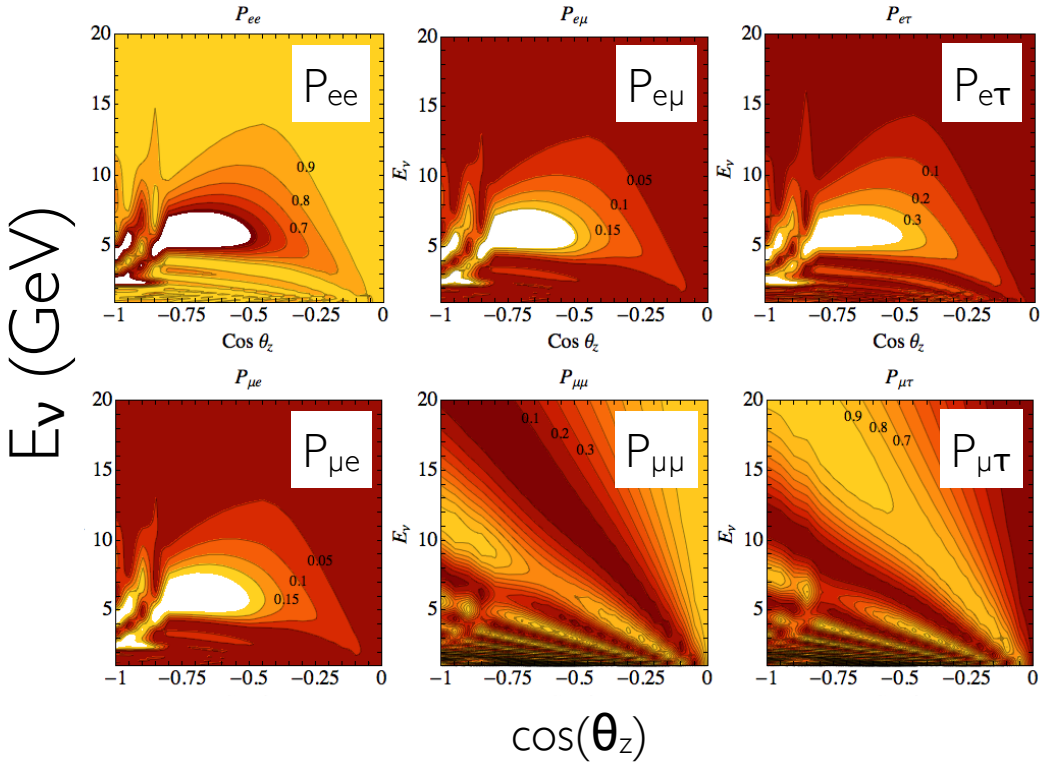
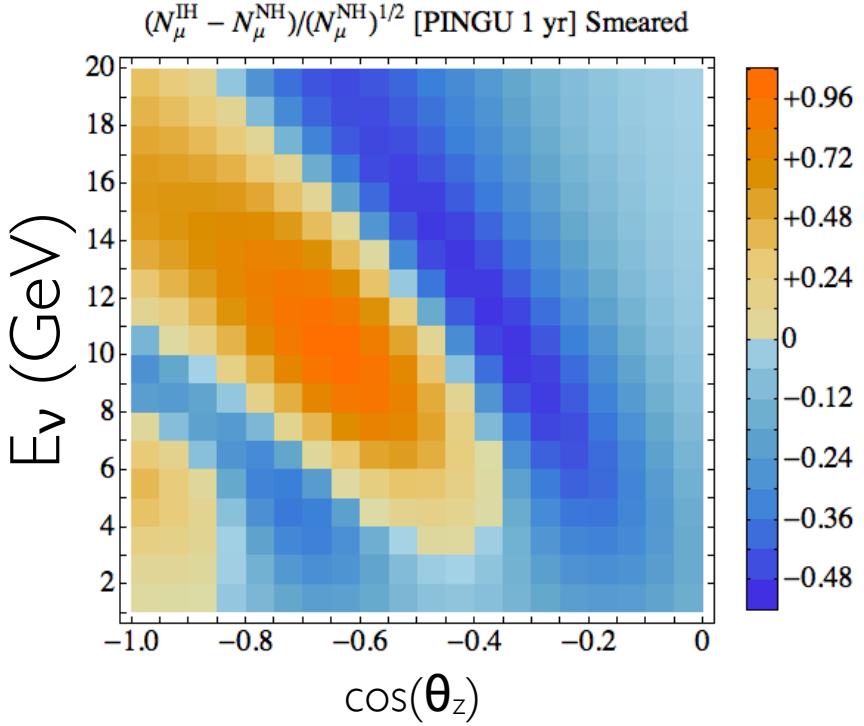


Hierarchy Asymmetry (σ_E=3GeV σ_φ=15°)



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

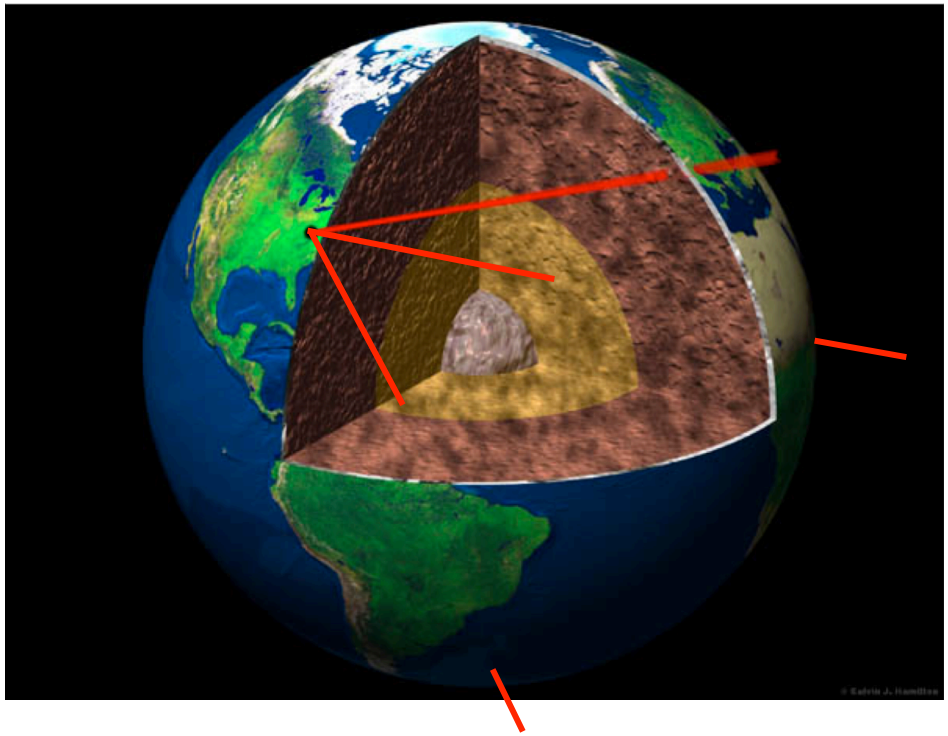
Impact of δ_{CP} negligible.

Study by IceCube collaboration with full detector simulation and reconstructions underway.

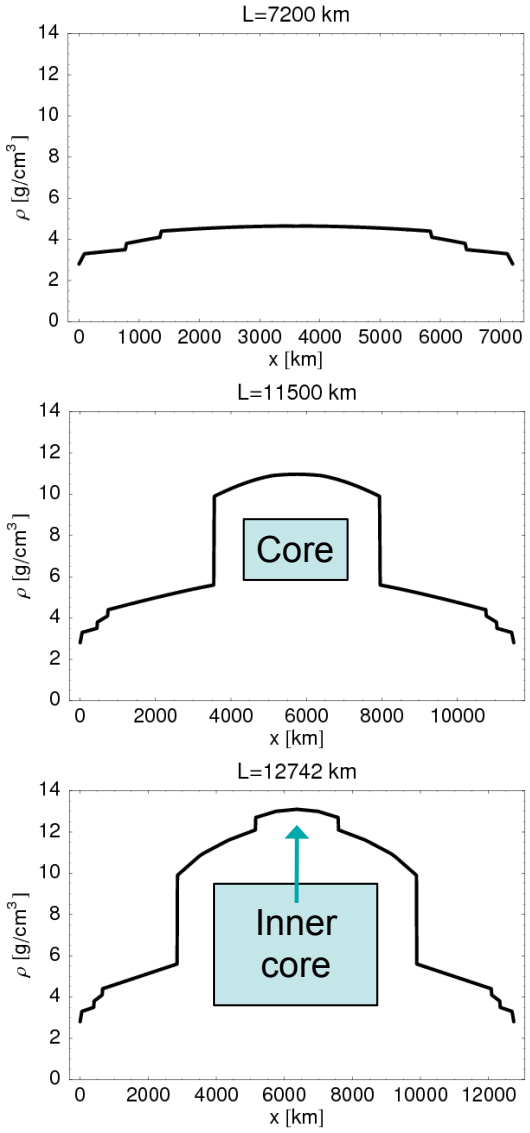
Akhmedov, Razzaque, Smirnov. arXiv:1205.7071v2

Even Better: PINGU + ν–Beam

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

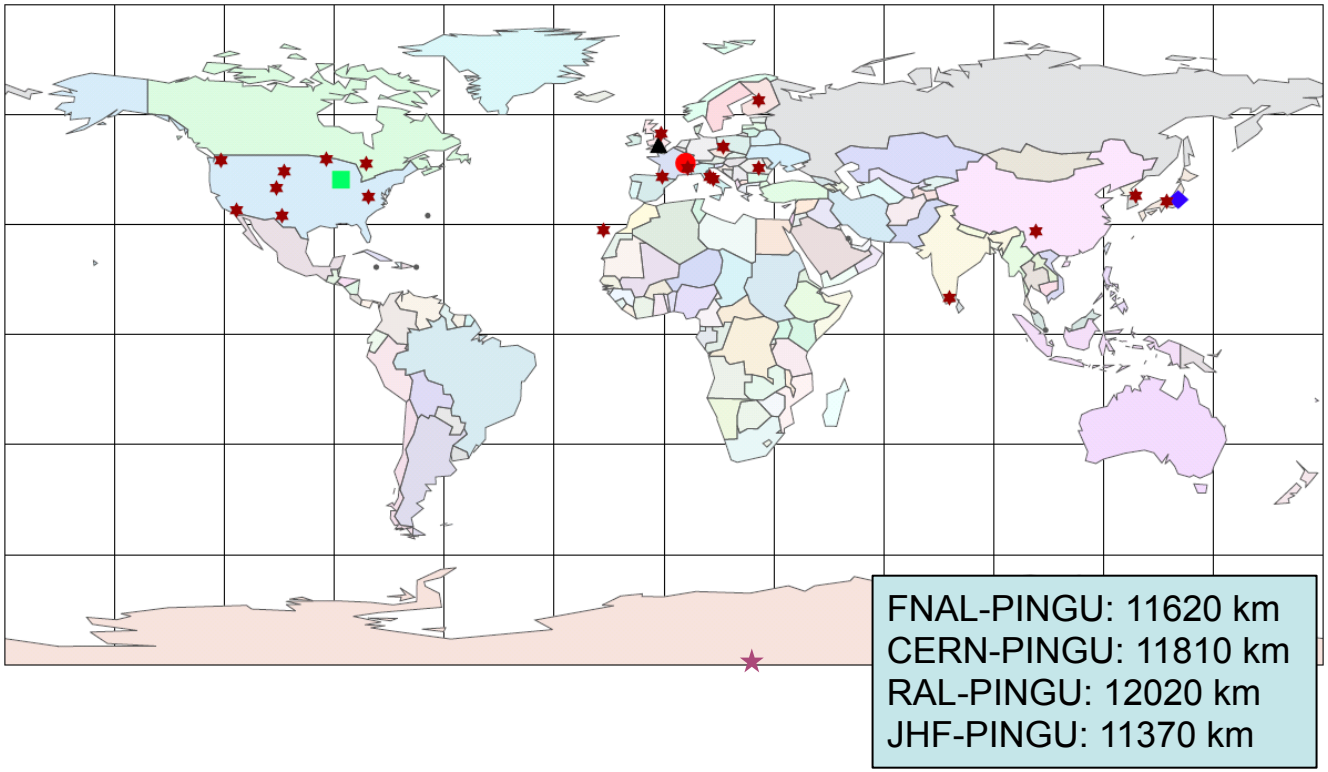


Figures courtesy W. Winter



PINGU + ν–Beam

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

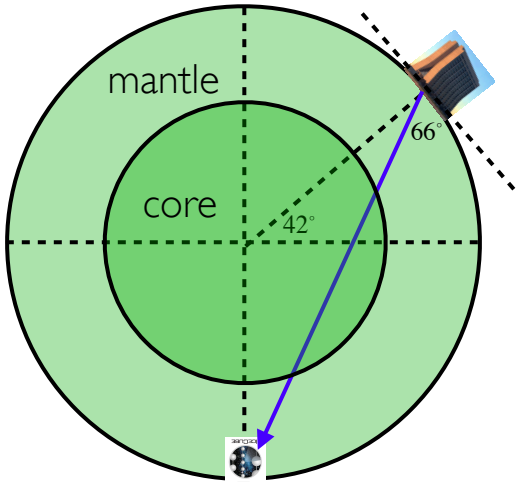


(Agarwalla, Huber, Tang, Winter, 2010)

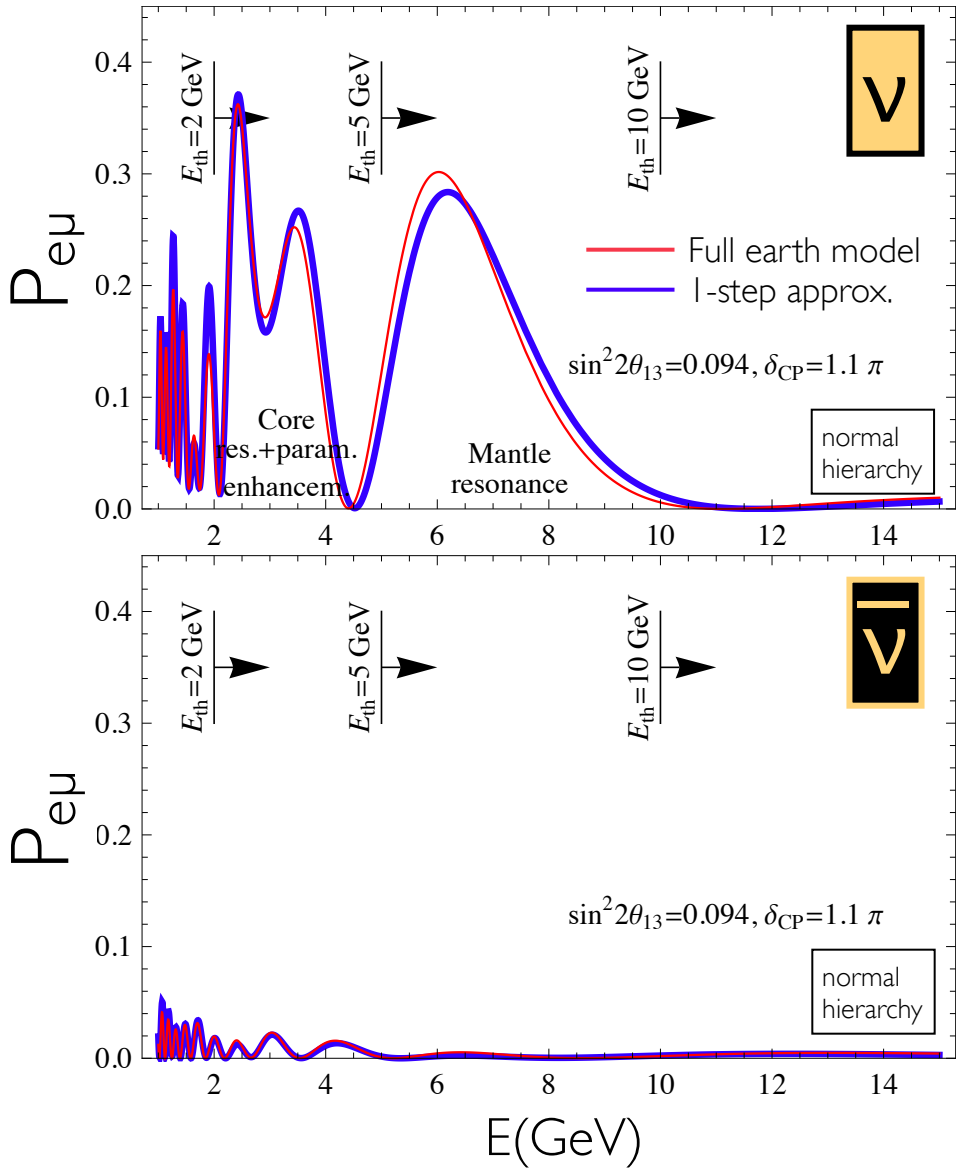
10

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 $\sigma(\nu) \sim 2\sigma(\bar{\nu})$:
    - $N_{ev}(NH) \sim 2N_{ev}(IH)$ at 2-10 GeV
    - $\delta_{CP} = 0$ looks similar (but not identical)



Plots courtesy W. Winter

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

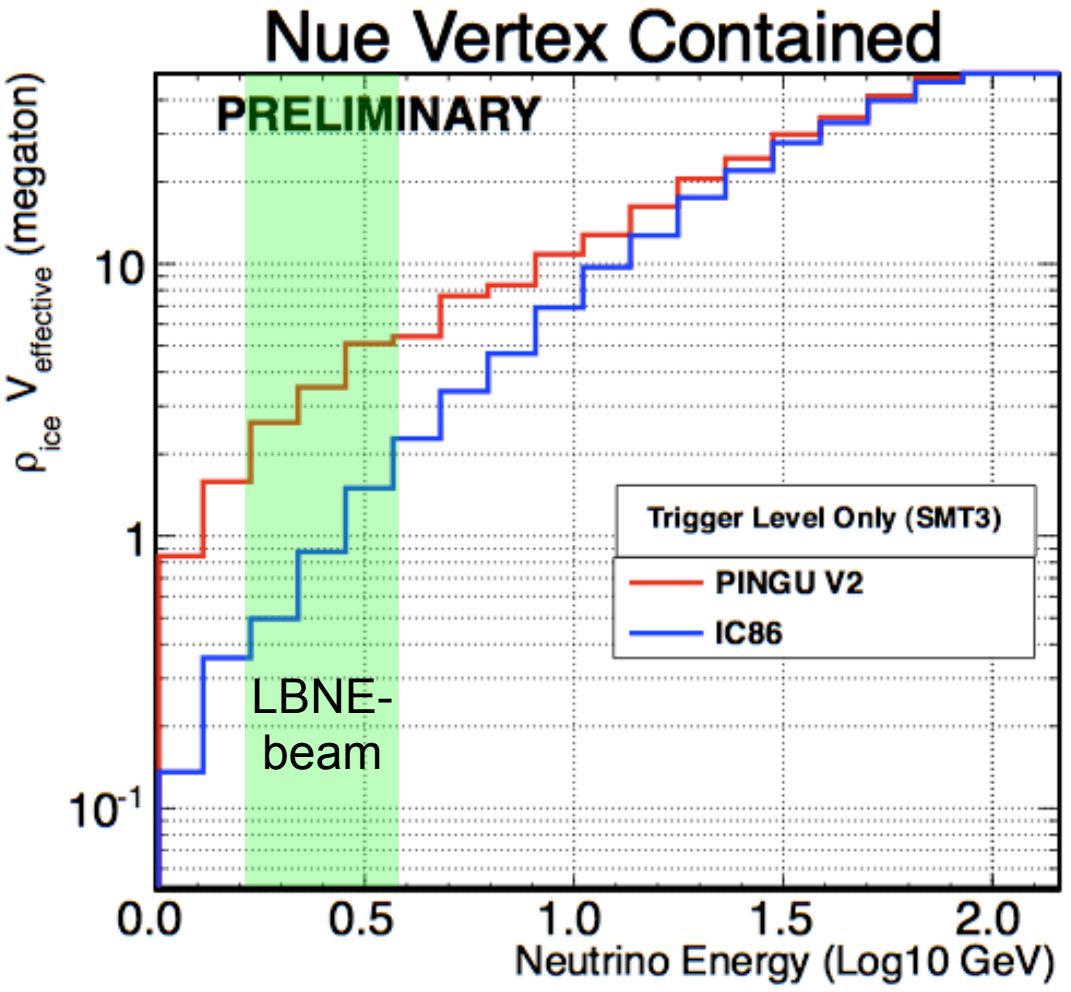


Figure courtesy J. D. Koskinen and W. Winter. For more details, see Tang and Winter, JHEP 1202 (2012) 028.

The Hierarchy with PINGU + ν–Beam

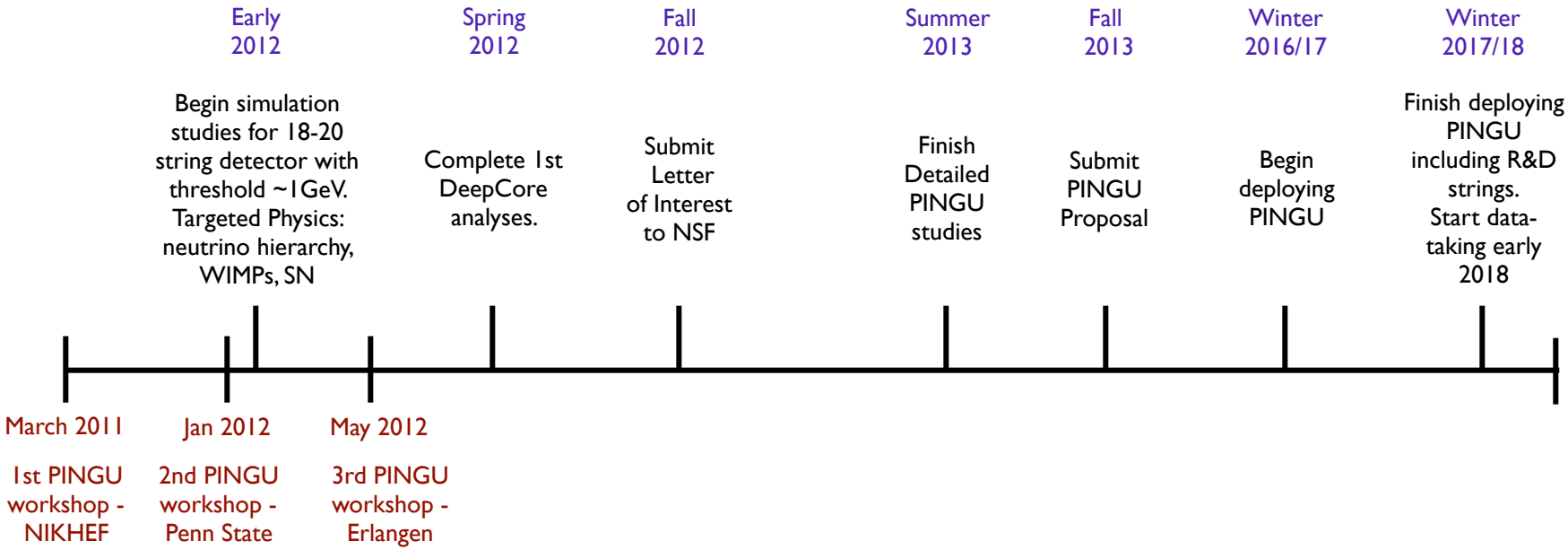
- Assumptions:
  - 20% ν_μ CC misID
  - No energy resolution
    - A counting experiment!
  - Include irreducible backgrounds
    - intrinsic beam, NC events, ν_τ
  - signal & bkgd. systematics uncorrelated
- Conclusions:
  - 18σ effect (stat. only)
  - With particle ID, might be also sensitive to CP

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.

PINGU: Possible Timeline



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

Choice of Beam

Want to study ν_e-ν_μ oscillations

- Beta beams:

$$n \rightarrow p + e^- + \bar{\nu}_e \rightarrow \bar{\nu}_\mu$$

  - In principle best choice for PINGU (need muon flavor ID only)

- Superbeams:

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

  - Need (clean) electron flavor sample. Difficult?

- Neutrino factory:

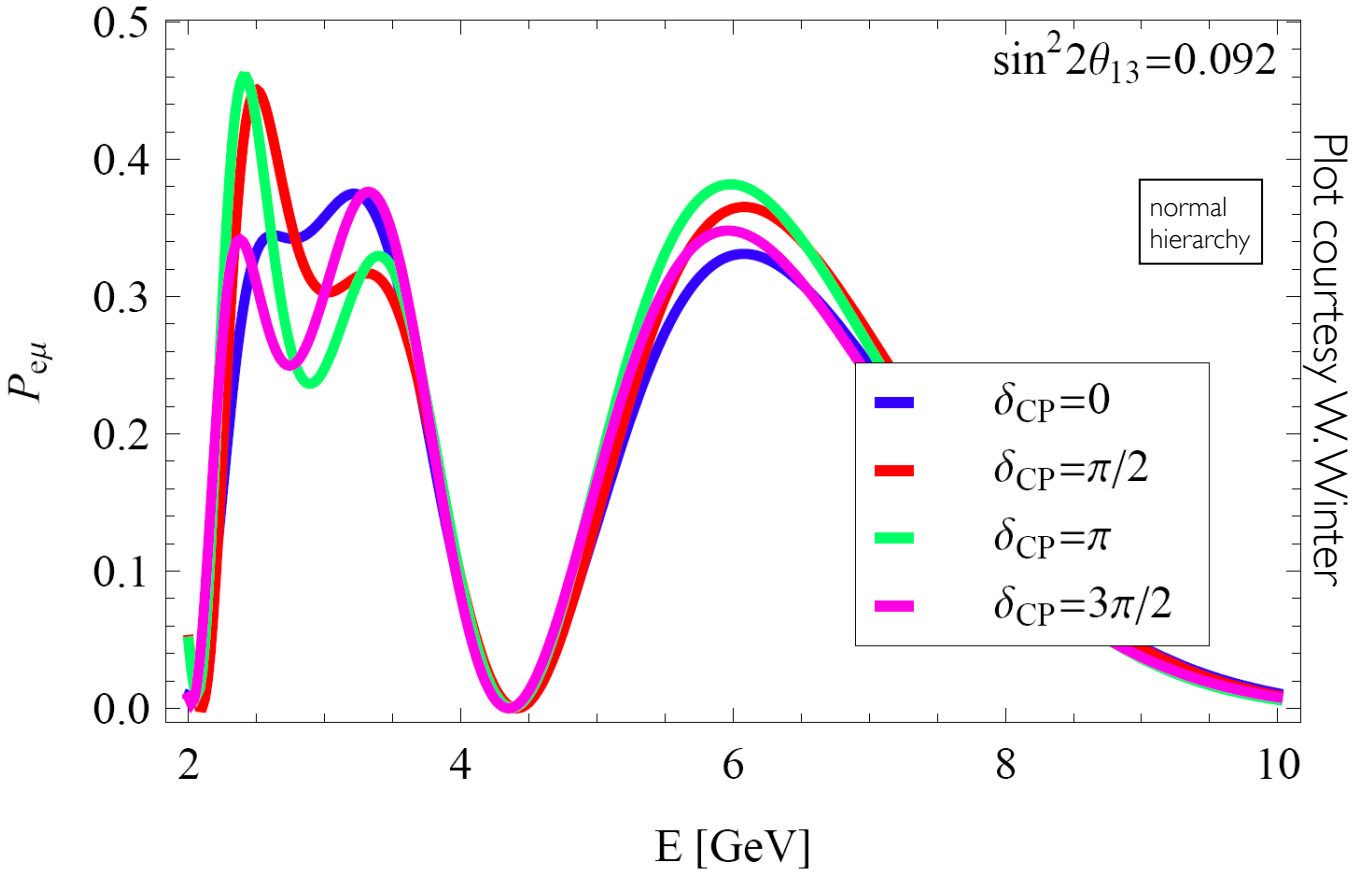
$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e \rightarrow \bar{\nu}_\mu$$
$$\hookrightarrow \nu_\mu$$

  - Need charge identification of μ^+ and μ^- (normally)

Slide courtesy W. Winter

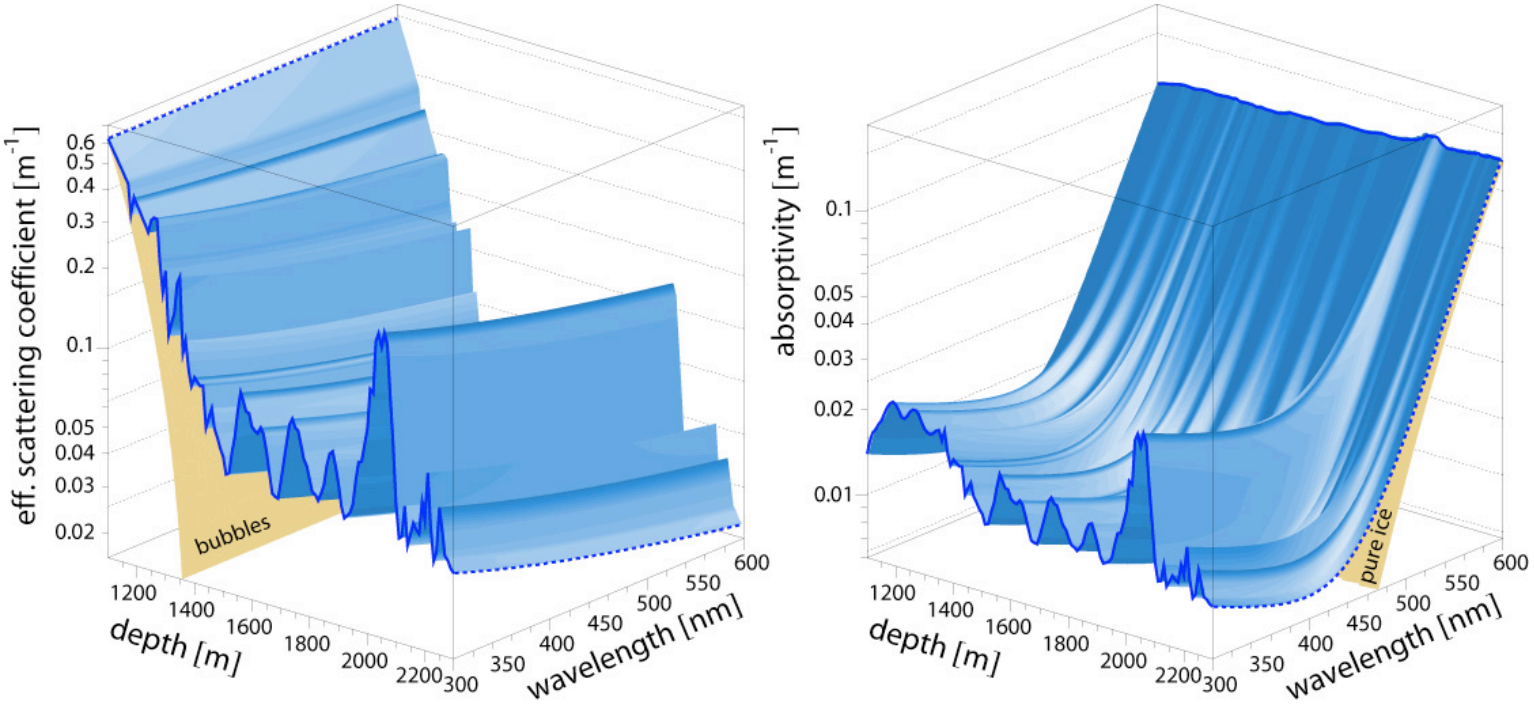
CP Violation

- Dependence on δ_{CP}
- Requires good E resolution and particle ID
- Probably works only for NH
- Needs further study



Ice Properties

- Depth dependence of λ_{eff} and λ_{abs} from *in situ* LEDs
- Ice below 2100 m in DeepCore fiducial region very clear
  - $\langle\lambda_{eff}\rangle \sim 47$ m, $\langle\lambda_{abs}\rangle \sim 155$ m



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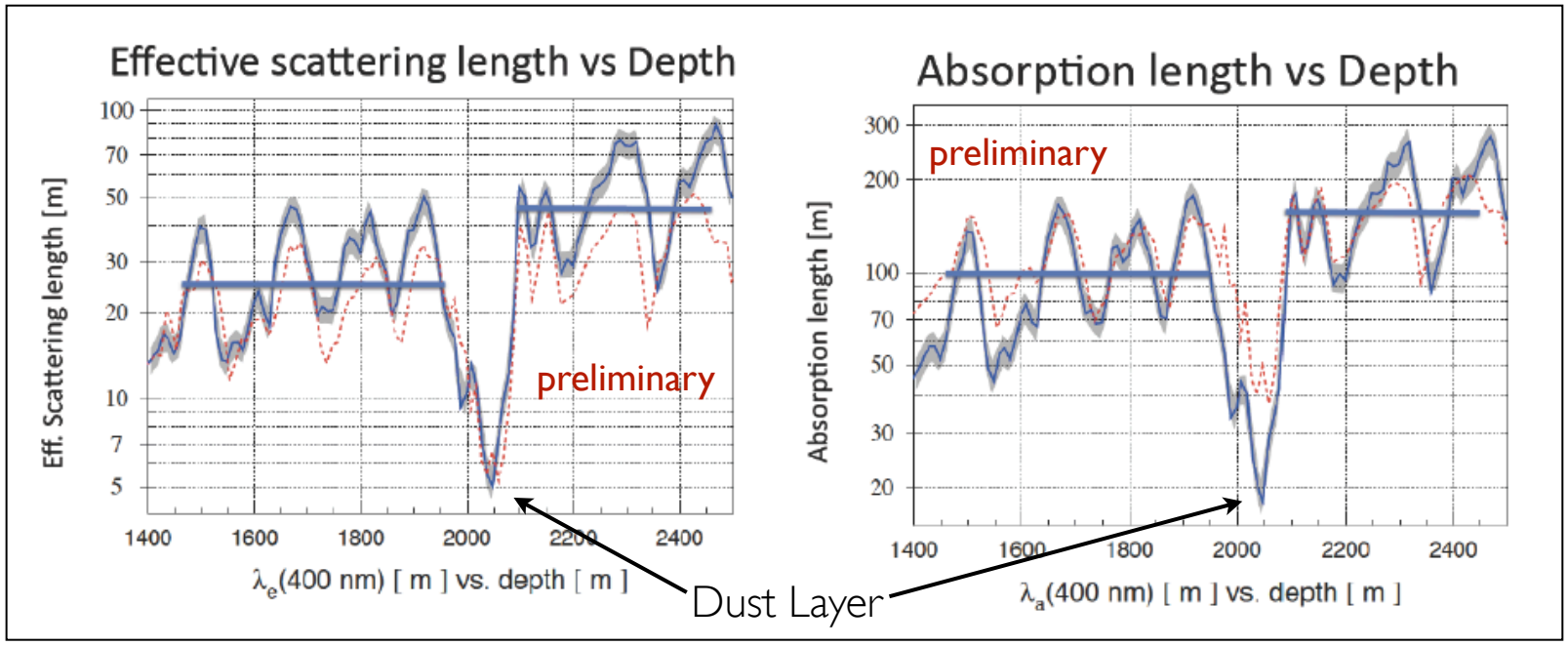

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