Neutrino Oscillation Tomography

(and Neutrino Absorption Tomography)

(and Neutrino Parametric-Refraction Tomography)

Sanshiro Enomoto
University of Washington

CIDER Geoneutrino Working Group Meeting, UCSB, 1 July 2014

Everything Shown Here was Taken from:

Letter of Intent:
The Precision IceCube Next Generation Upgrade (PINGU)

arXiv:1401.2046v1 [physics.ins-det] 9 Jan 2014

Letter of Intent:

The Hyper-Kamiokande Experiment

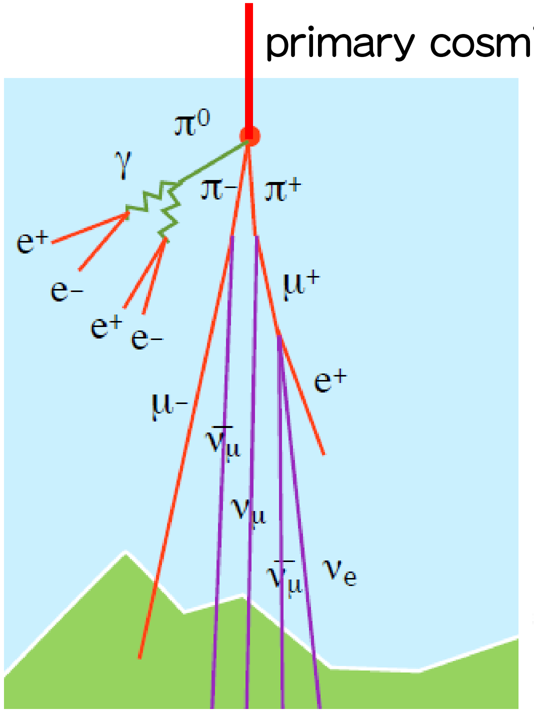
— Detector Design and Physics Potential —

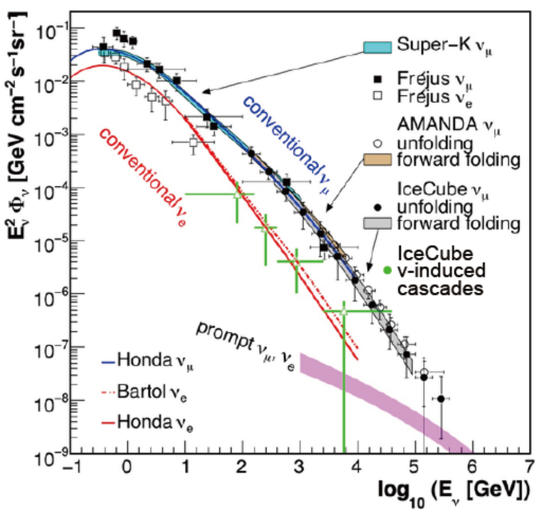
arXiv:1109.3262v1 [hep-ex] 15 Sep 2011

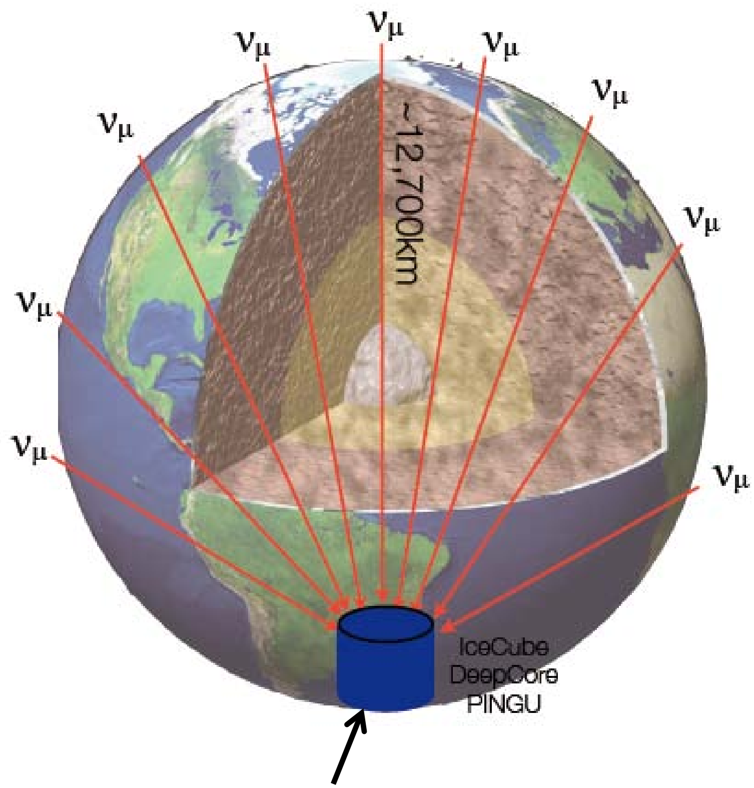
and references in there

Atmospheric Neutrinos

primary cosmic ray (proton)



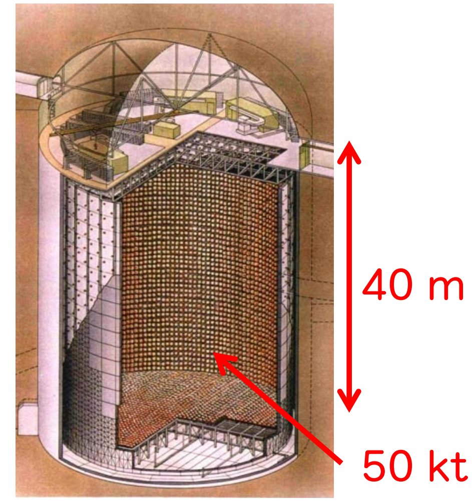




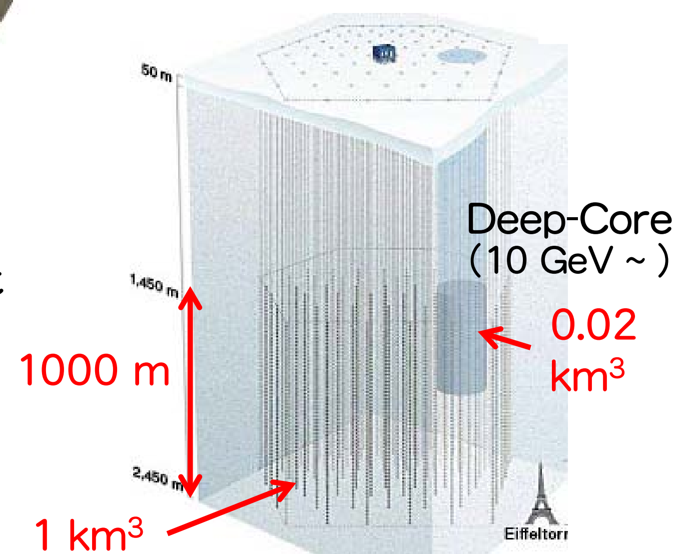
Detection by Charged-Current

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

Super-Kamiokande in Japan
(10 MeV ~ 100 GeV)



Ice Cube at South Pole
(100 GeV ~)

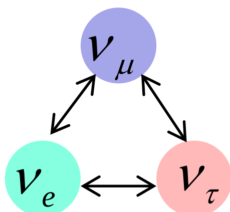


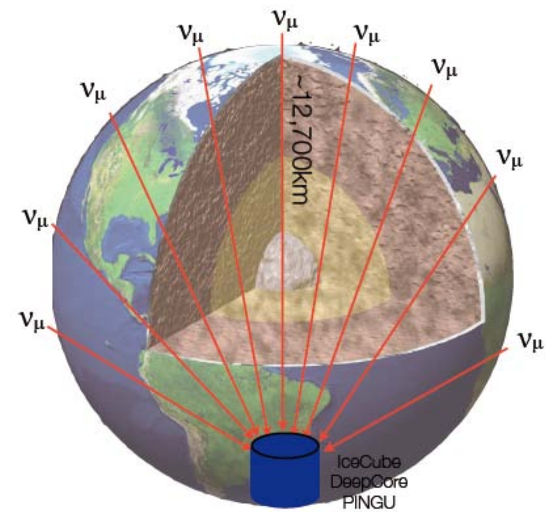
Atmospheric Neutrinos and Neutrino Oscillation

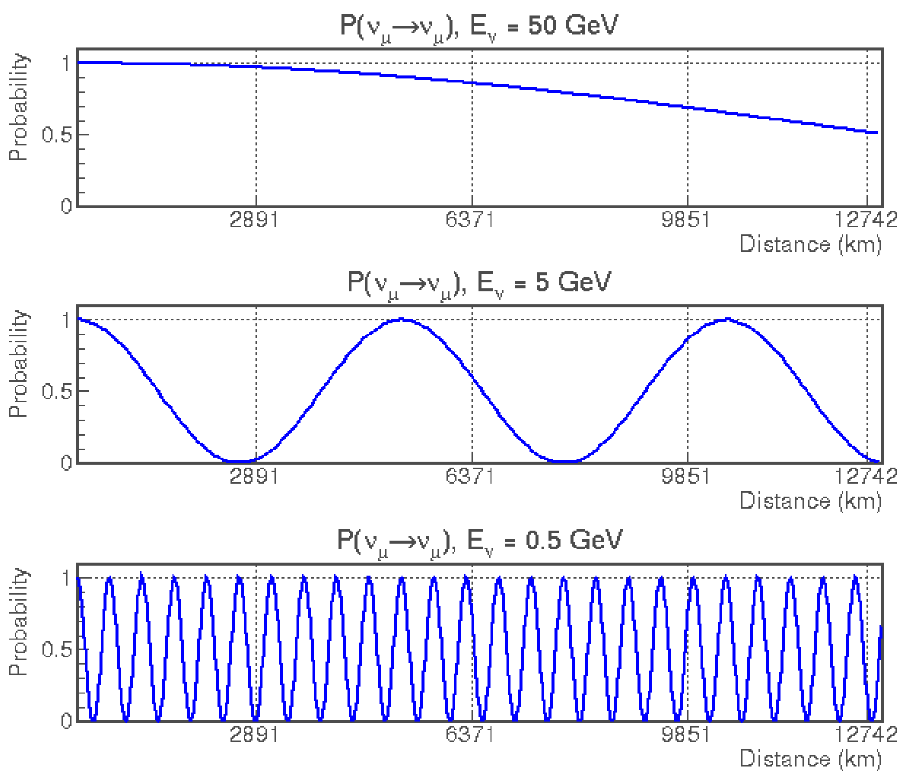
Probability of detecting ν_μ after distance L

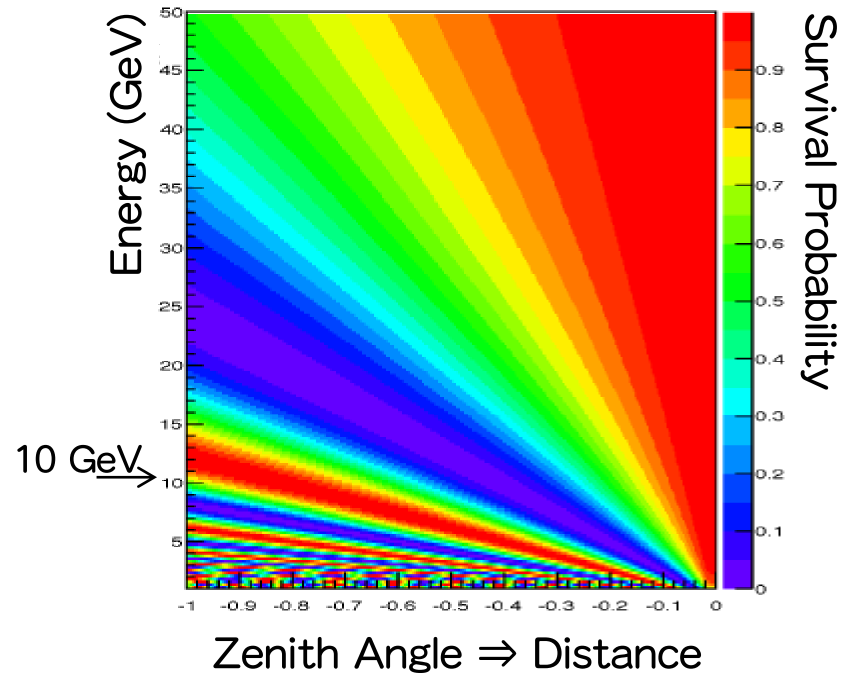
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2\left(3\times10^{-3}\cdot\frac{L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$

(w/o matter effects)



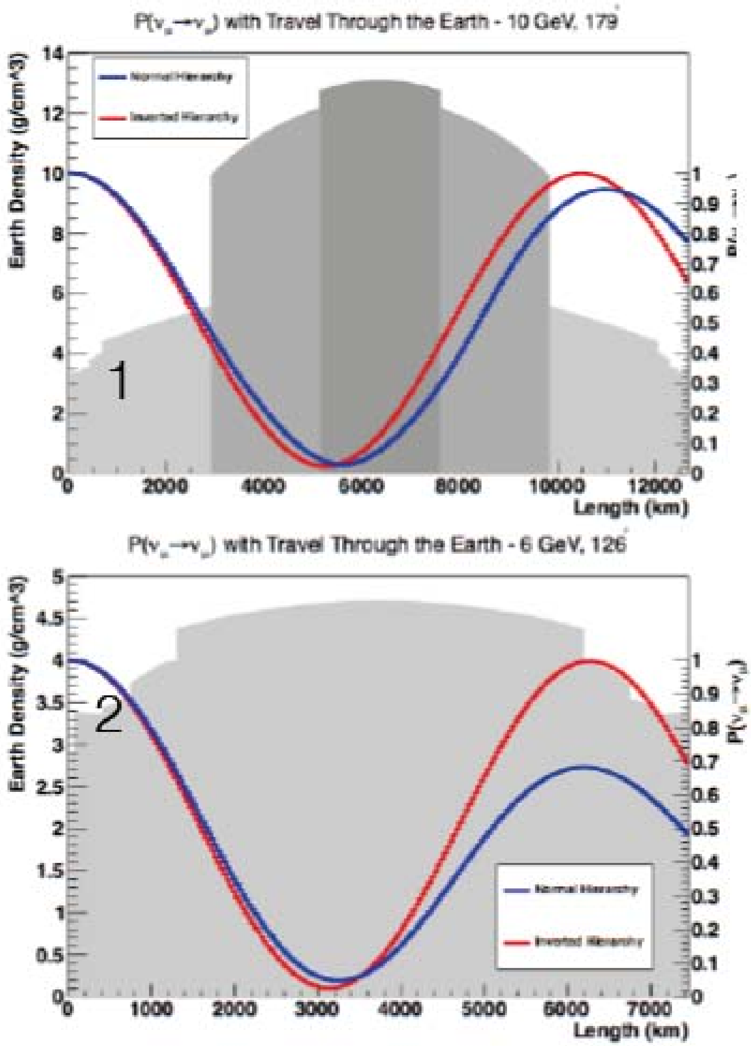


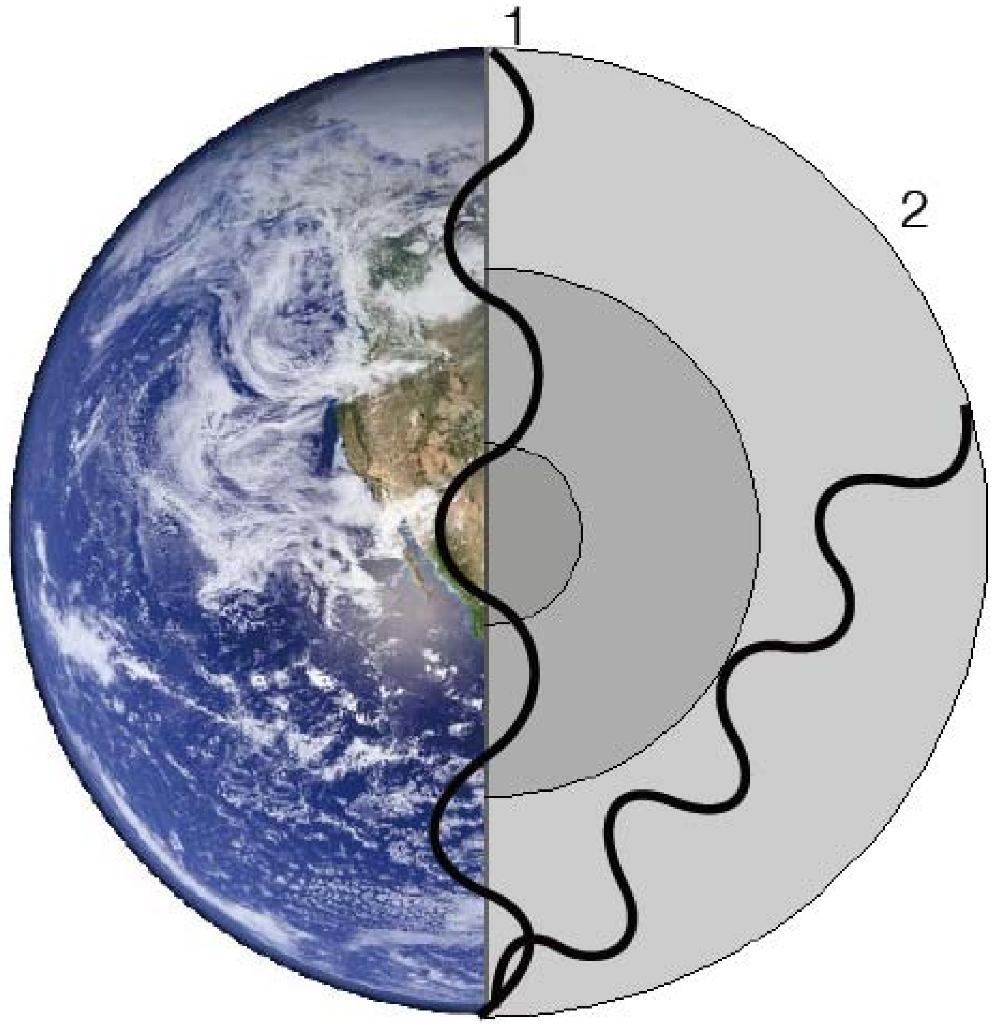




Oscillation Tomography using Matter Effect

Neutrino oscillation is affected by Electron Density

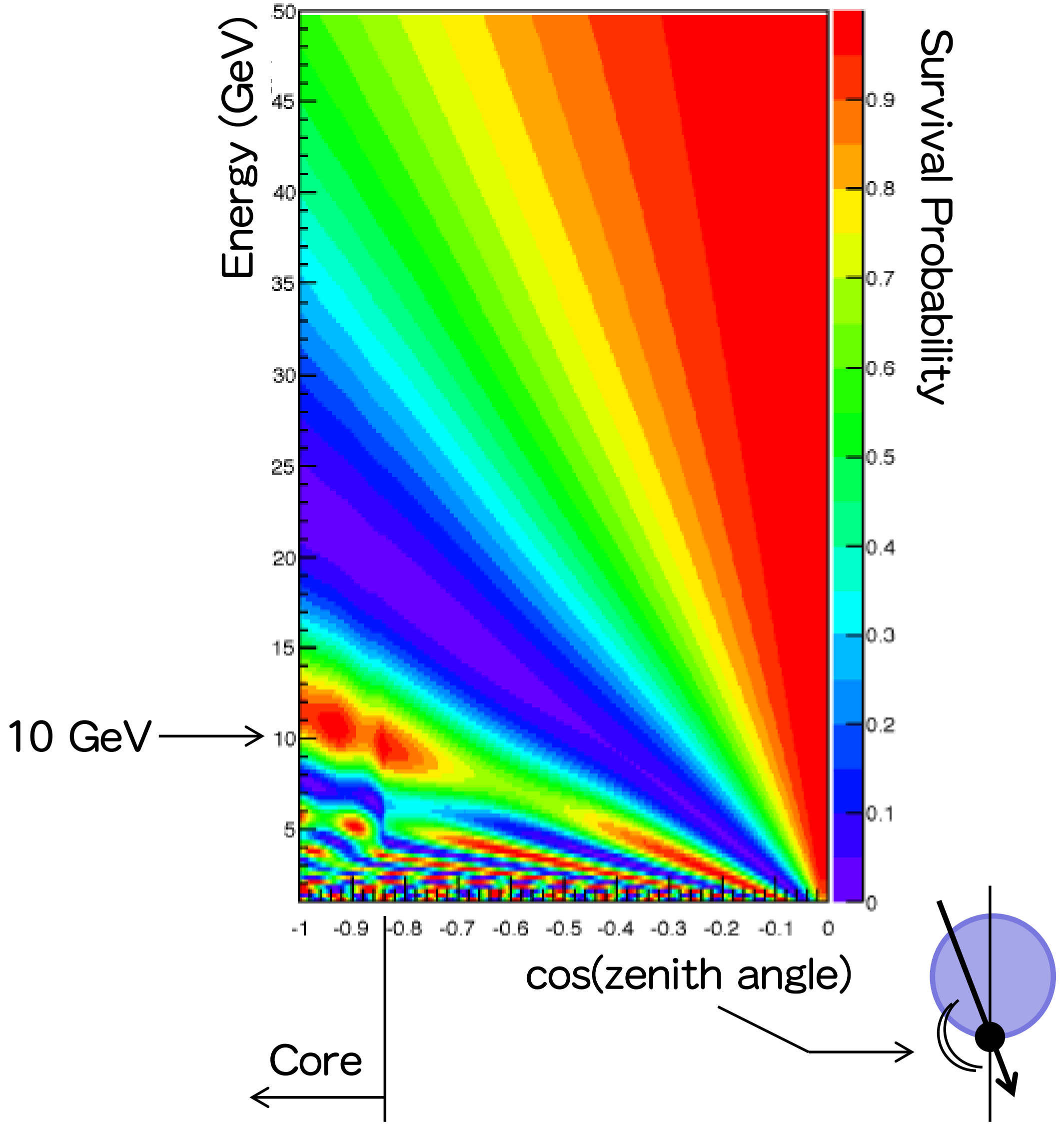




D. R. Grant, Neutrino 2014

Neutrino Oscillation though Earth

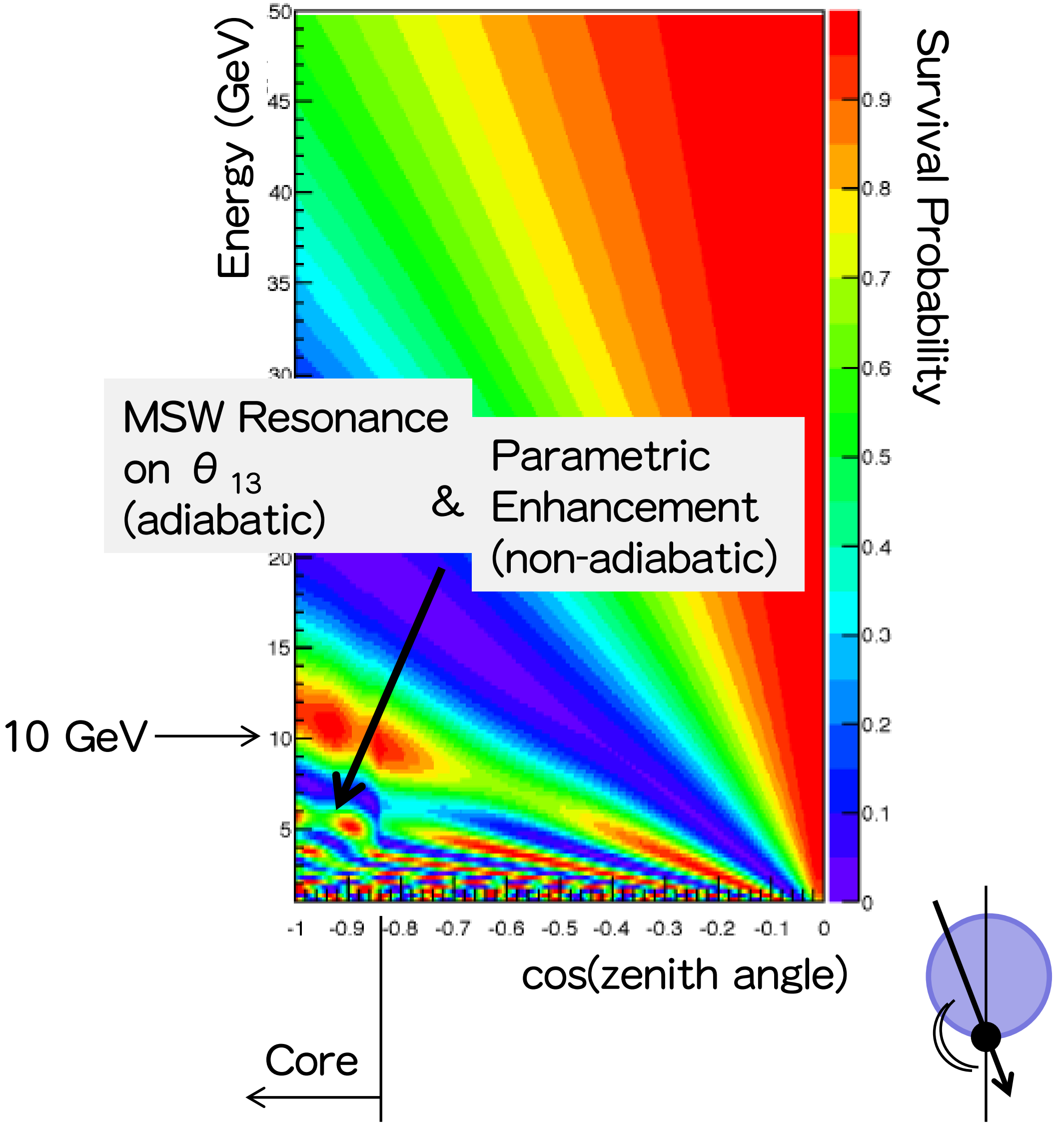
$P(\nu_\mu \to \nu_\mu)$ – Normal Hierarchy
$\sim P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ – IH



$P(\nu_\mu \to \nu_\mu)$ – Inverted Hierarchy
$\sim P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ – NH

Neutrino Oscillation though Earth

$P(\nu_\mu \to \nu_\mu)$ – Normal Hierarchy
$\sim P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ – IH



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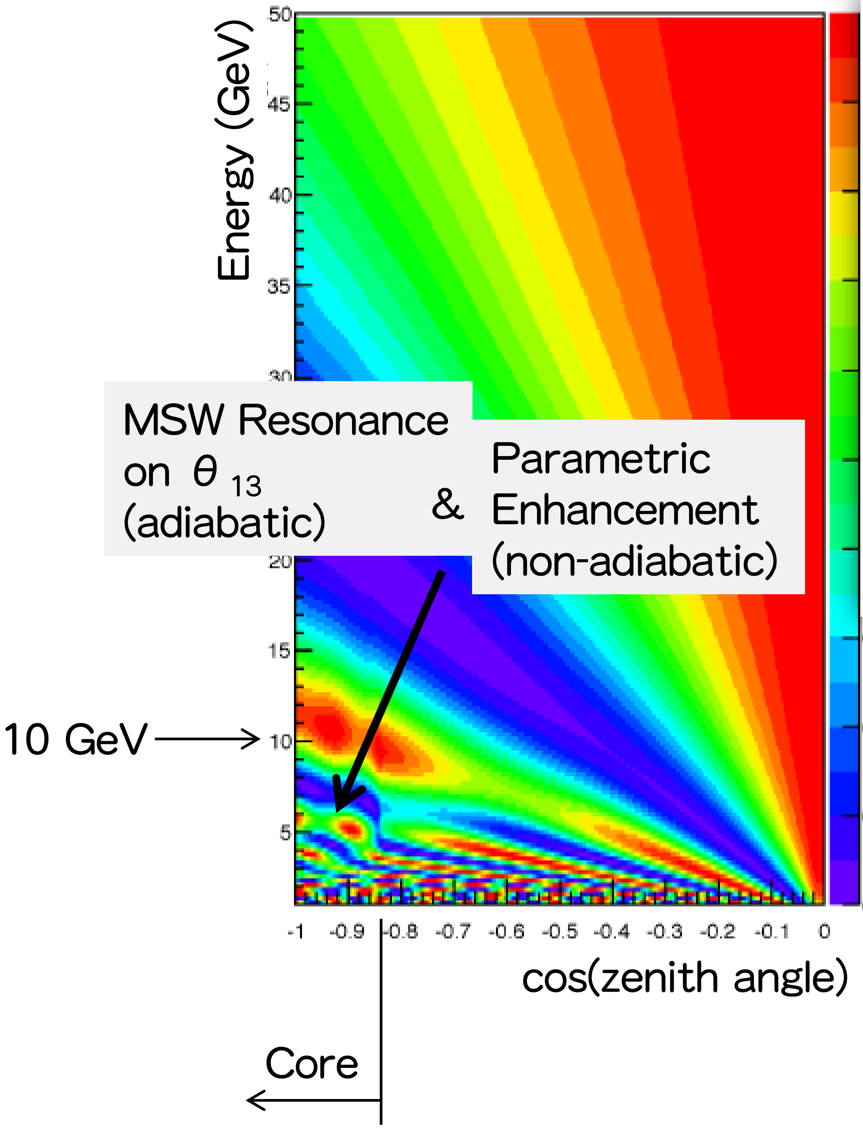
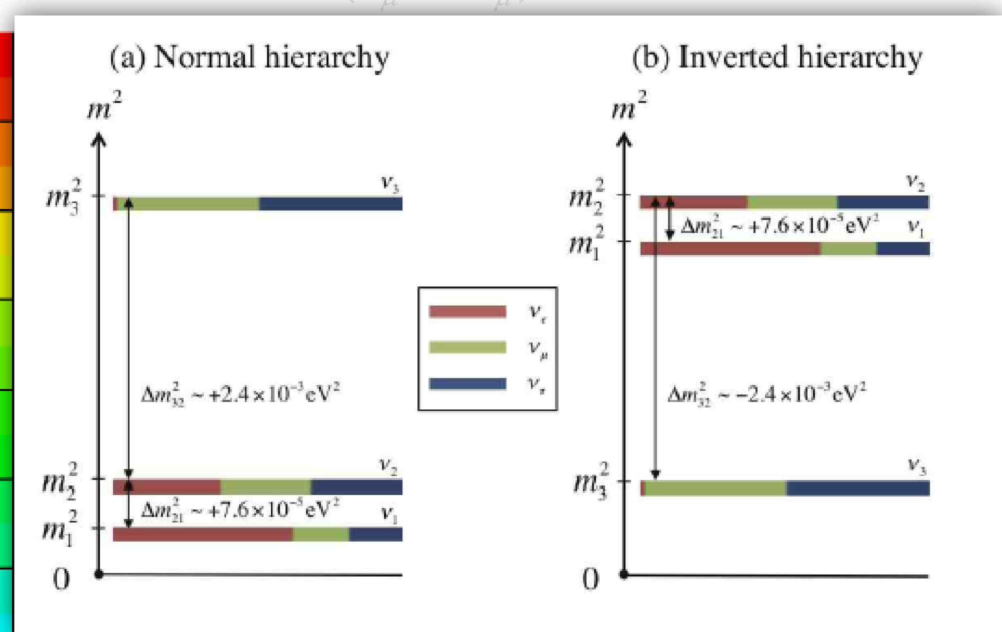
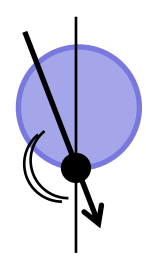
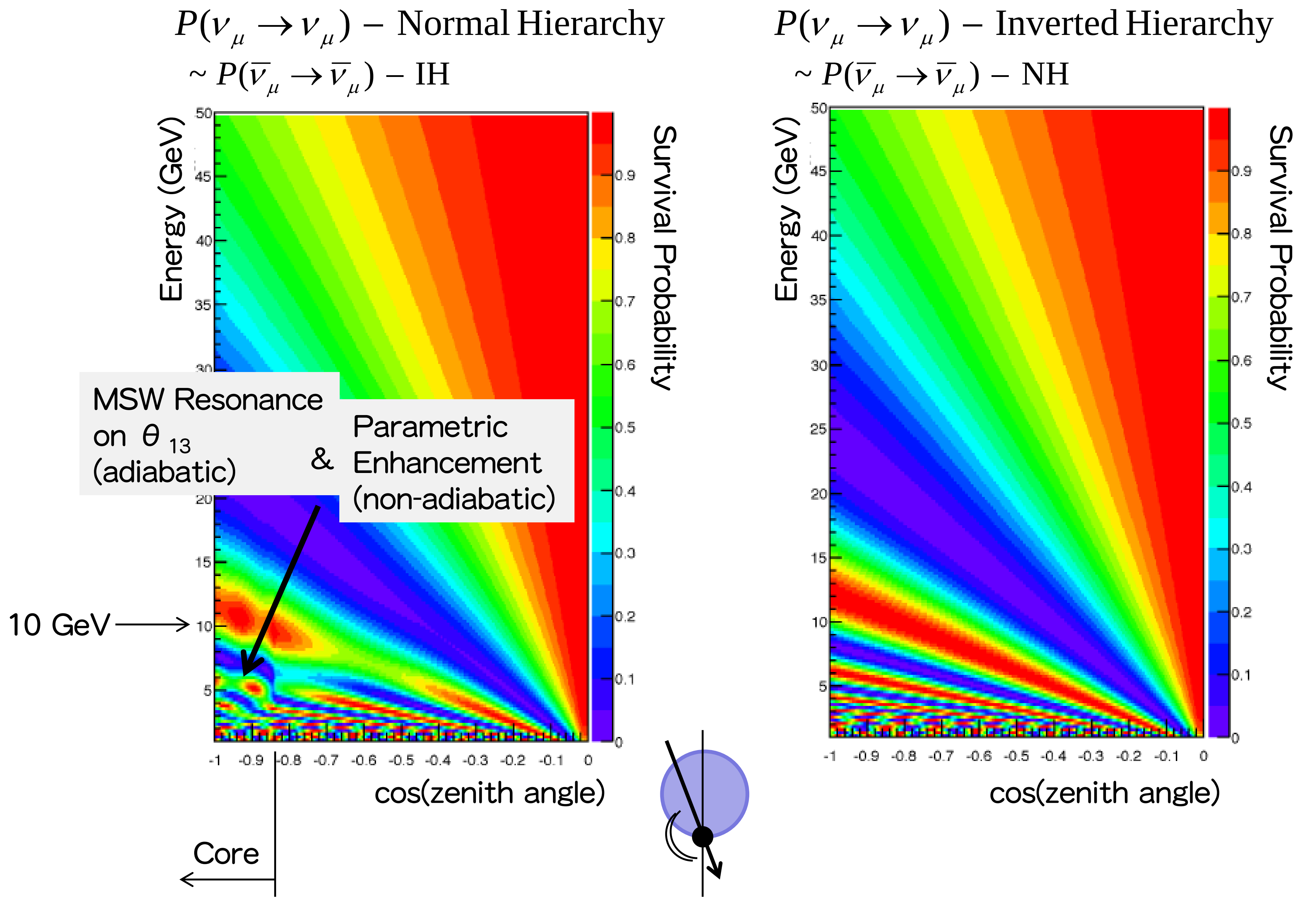






Neutrino Oscillation though Earth



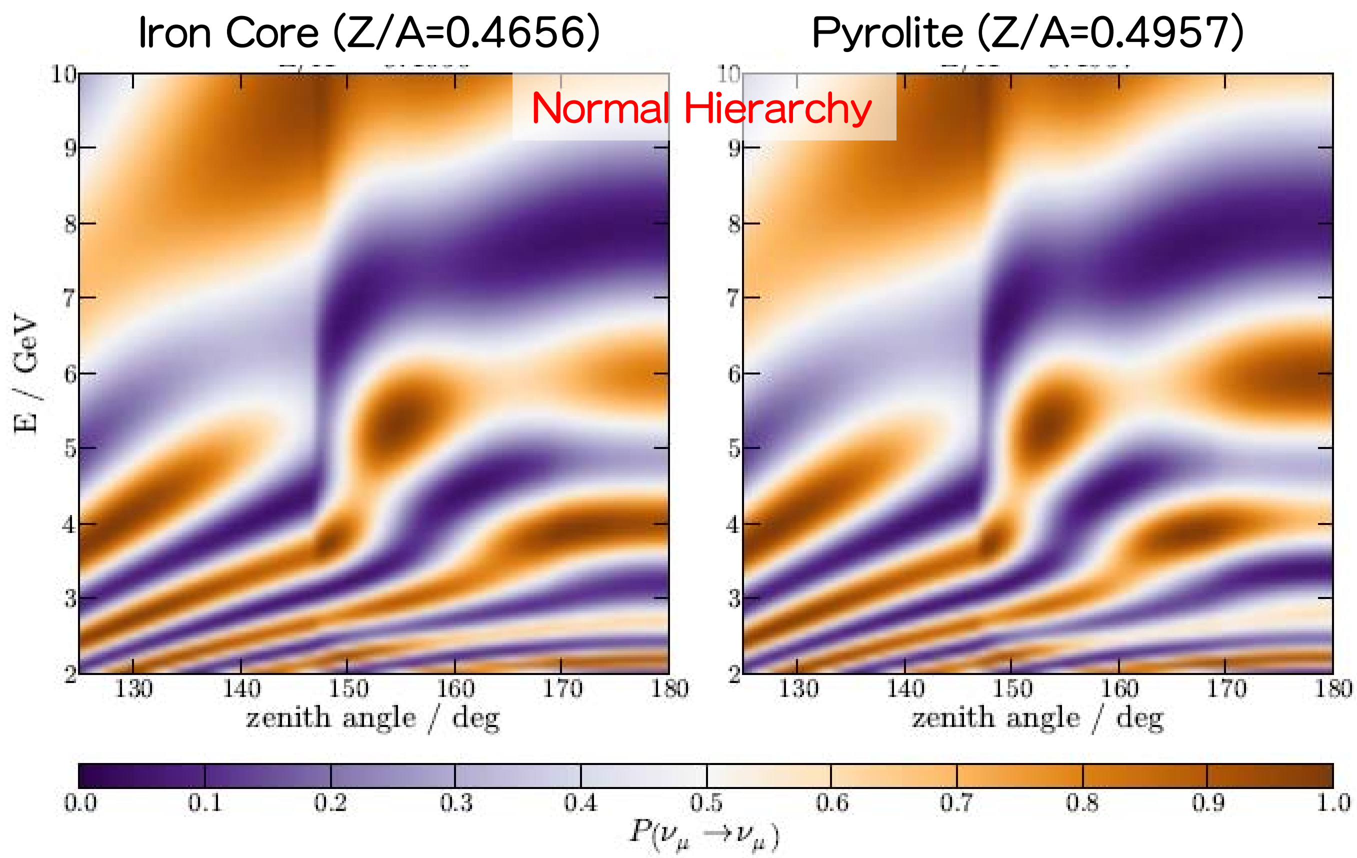
Sensitivity to Core Z/A

If Density is known, electron density gives Z/A ratio

Z/A Ratio:

Hydrogen:	1
Light Elements:	0.5
Mantle (Pyrolite):	0.4957
Iron:	0.4656

6.5% difference

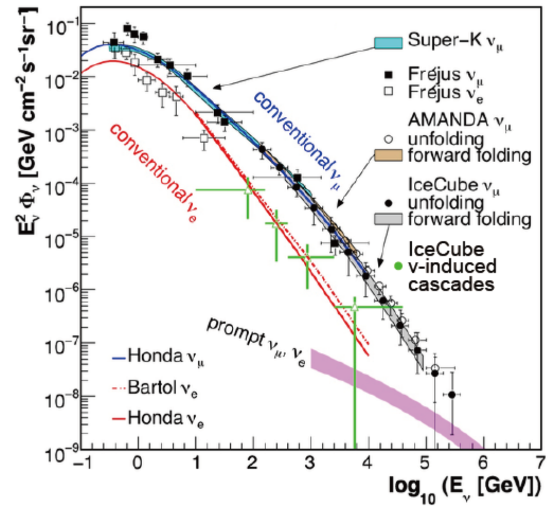


Wish List

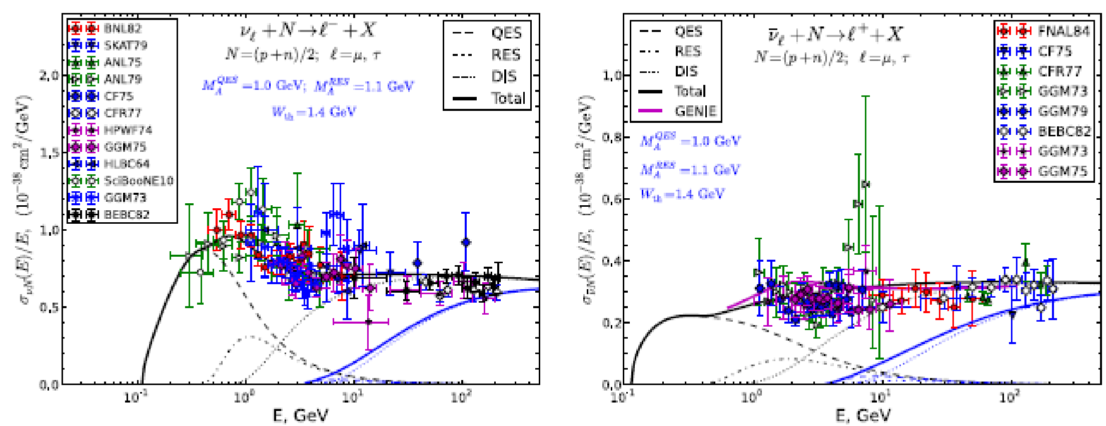
- ✓ Gigantic Detector (~ Mega ton)
- ✓ Dense Detector (~1 GeV threshold)

- ✓ Good Energy and Angular Sensitivity
- ✓ Normal Hierarchy Preferred ☺
  (antineutrino cross-section is smaller)

Atmospheric Neutrino Flux



Neutrino Charged-Current Cross-section



(a) Neutrino cross-sections (b) Anti-neutrino cross-sections

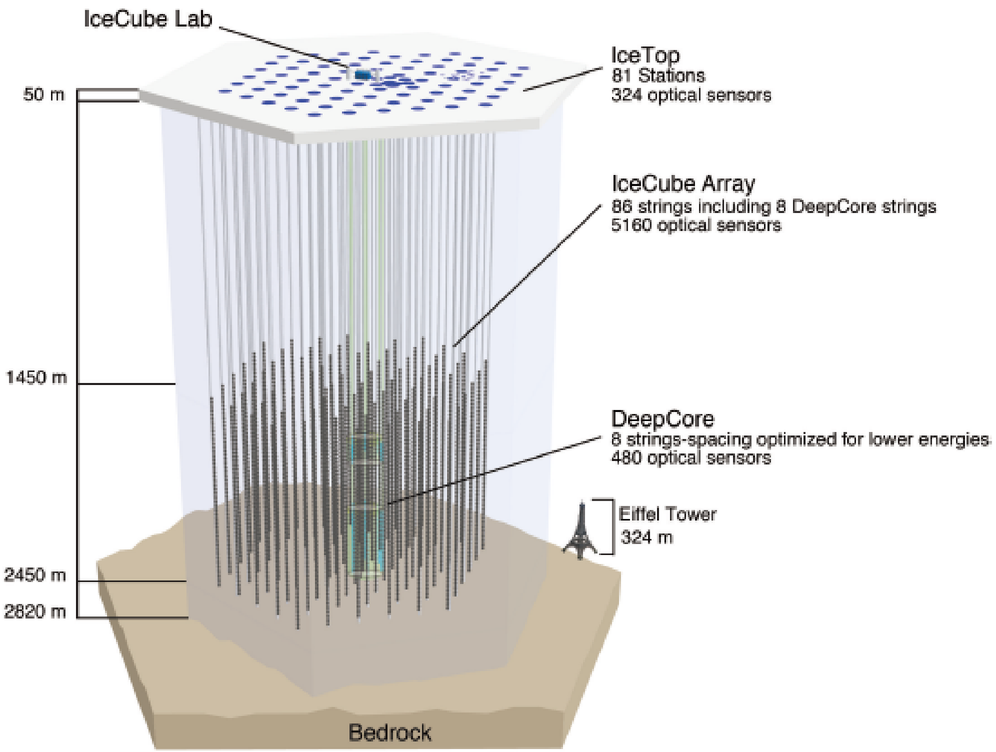
- Ice-Cube is too sparse (Deep-Core detects E >10GeV)
- Super-Kamiokande is too small (total 50 k-ton)

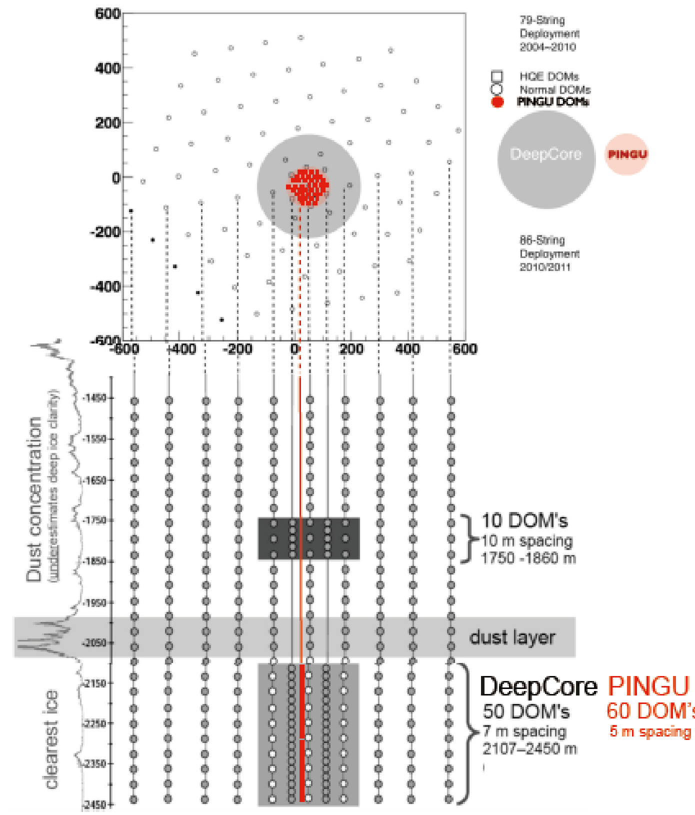
PINGU: Ice-Cube Upgrade for Lower Energy

Letter of Intent:

The Precision IceCube Next Generation Upgrade (PINGU)

arXiv:1401.2046 (9 Jan 2014)





- ✓ ~3 M-ton effective volume
- ✓ x20 photo cathode density
- ✓ sensitivity downto few GeV

$100M, ready in ~5 years

Hyper-Kamiokande (Super-K successor)

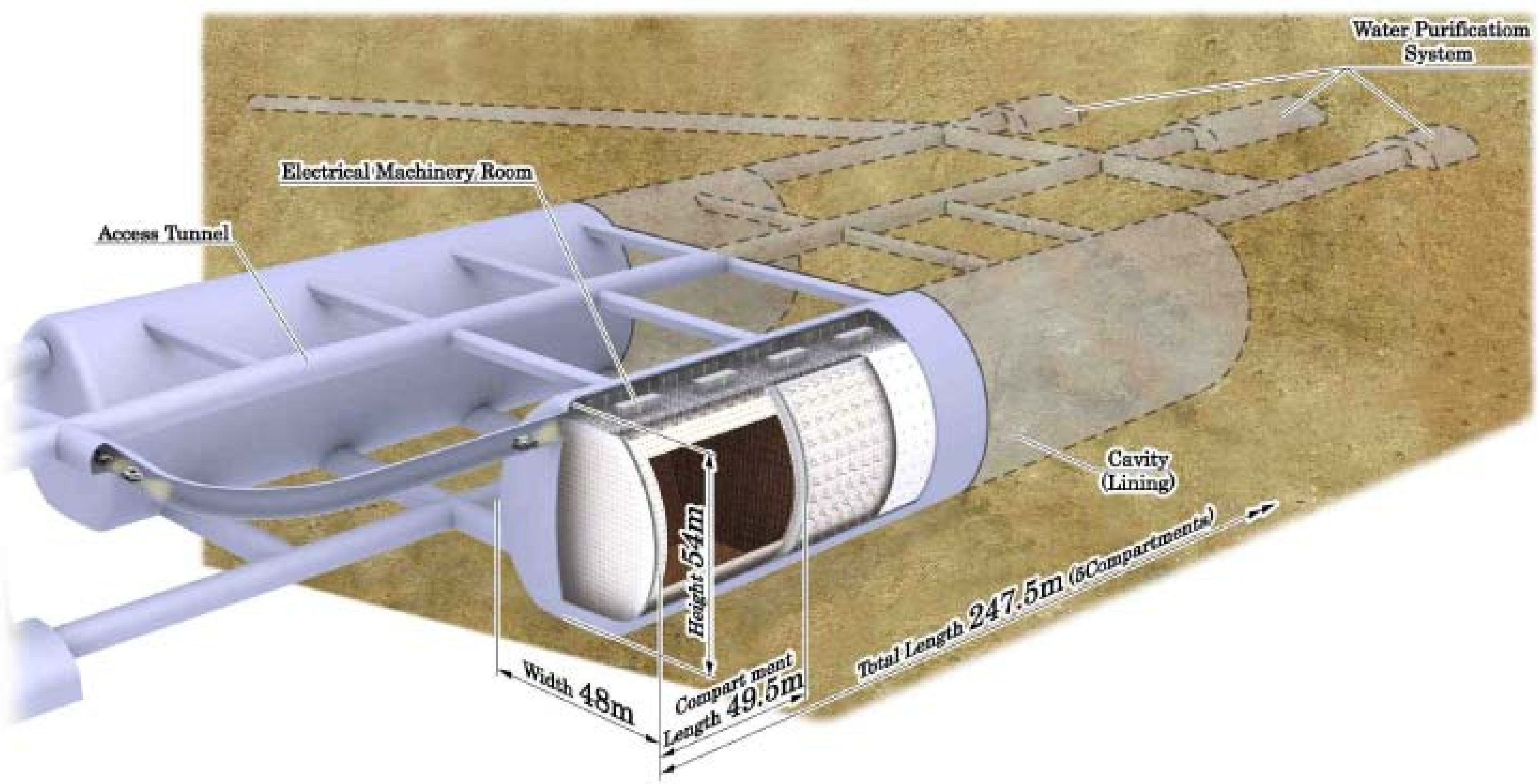
Letter of Intent:

The Hyper-Kamiokande Experiment

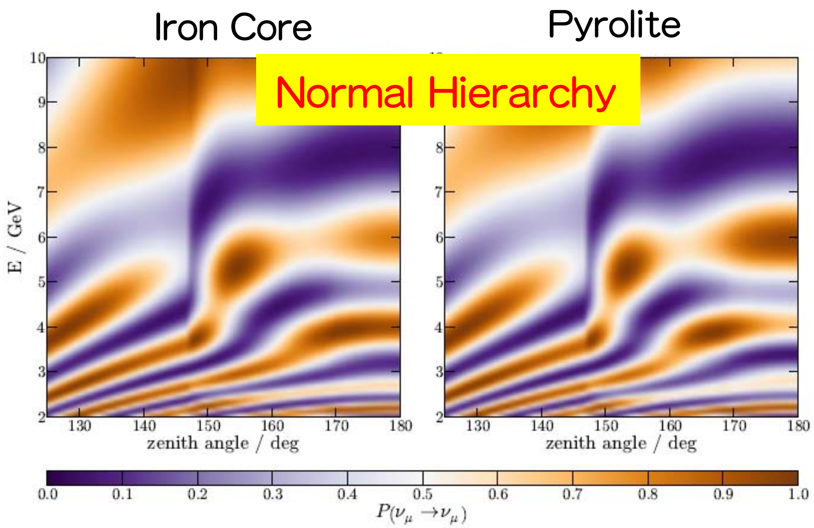
— Detector Design and Physics Potential —

arXiv:1109.3262 (15 Sep 2011)

- ✓ 0.99 M-ton
- ✓ 20% photo coverage
- ✓ few MeV threshold



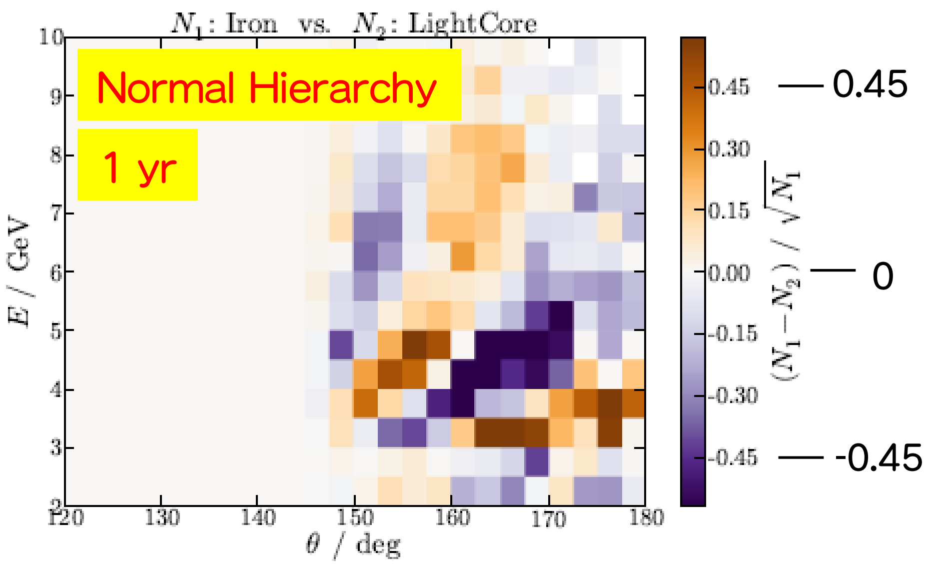
PINGU: Sensitivity to Core Z/A

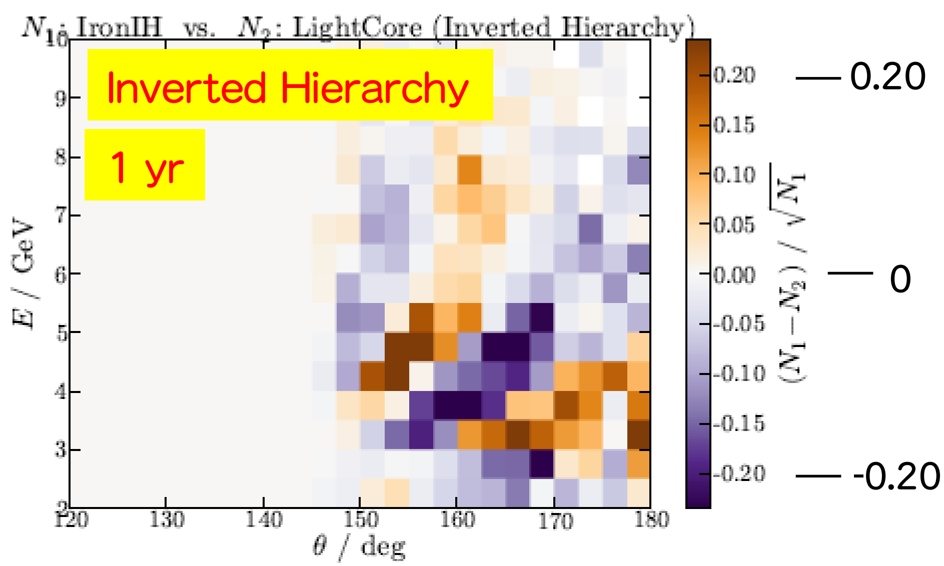


← Difference in ν_μ Survival Probability

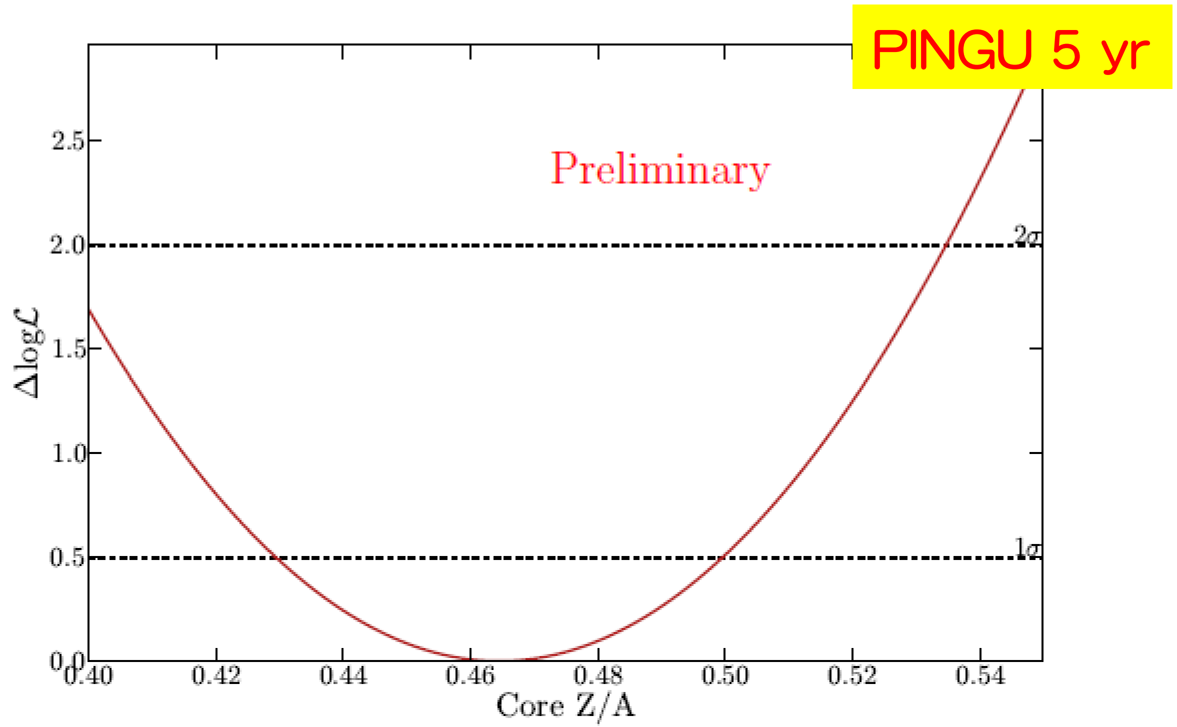
- PINGU volume (40 string)
- PINGU energy resolution ($\Delta E/E = 0.33$)
- PINGU angular resolution ($\Delta\theta = 15°$)
- PINGU systematic errors

Difference in Number of Events





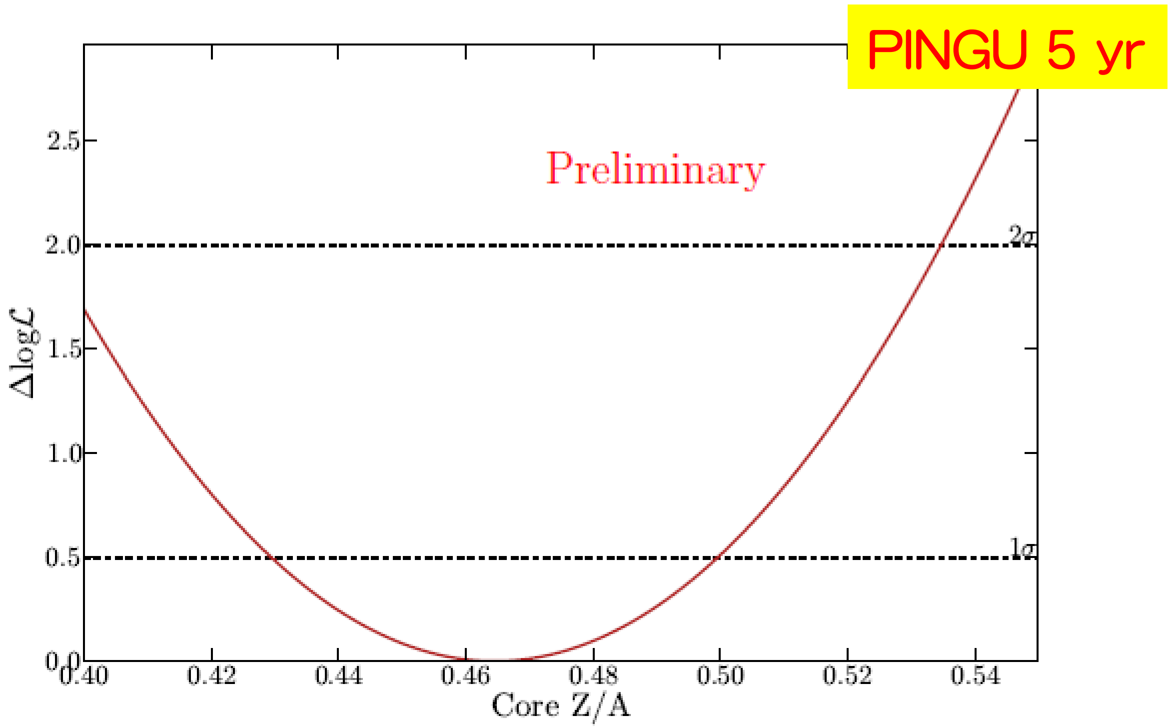
PINGU: Sensitivity to Core Z/A



Fe: 0.4656

Pyrolite: 0.4957 (+6.5% to all-Fe)

PINGU: Sensitivity to Core Z/A

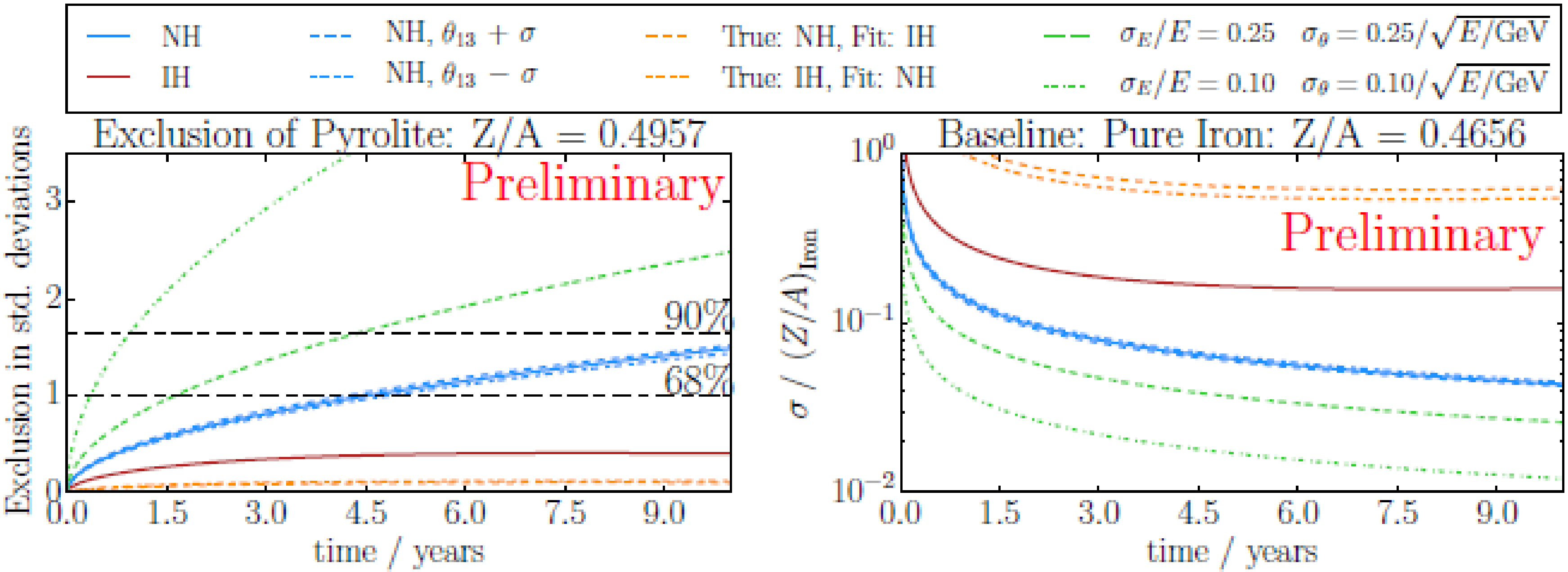


Fe: 0.4656

Pyrolite: 0.4957 (+6.5% to all-Fe)

Fe + H (1 wt%): 0.4709 (+1.0% to all-Fe)

PINGU: Sensitivity to Core Z/A



✓ Pyrolite model can be tested at 1 σ after 5 years (Normal Hierarchy)

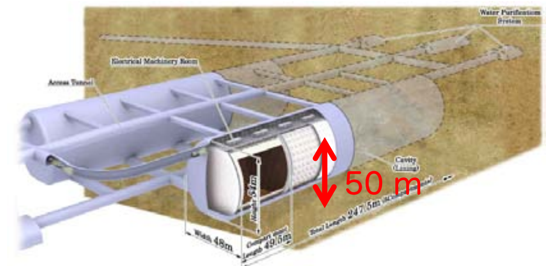
✓ Inverted Hierarchy will limit the sensitivity to ~20%,
"because antineutrino cross-section is half of neutrinos" ...

✓ Dependence on θ_{13} value is small
✓ Better energy resolution will largely improve the sensitivity

Hyper-Kamiokande might do it better

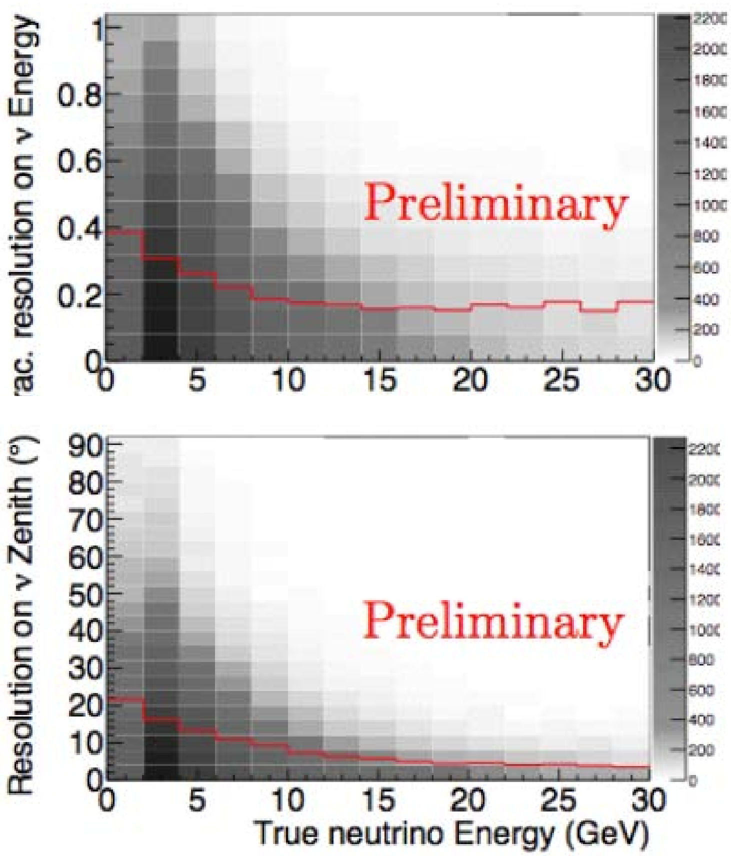
✓ Better energy and angular resolutions
✓ ν_e channel usable

- Smaller active volume??

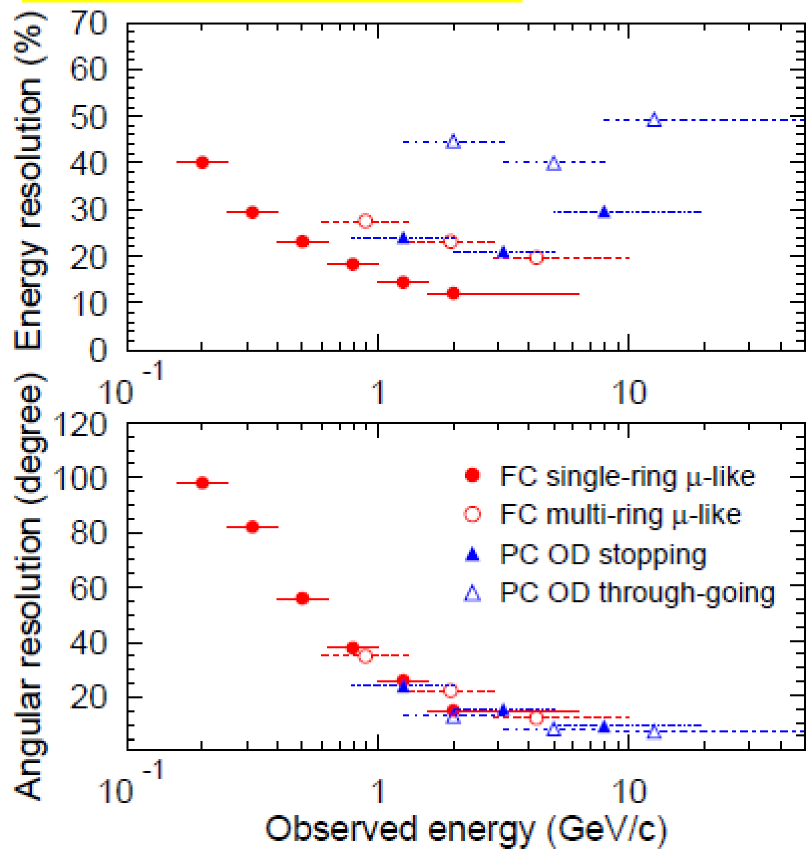


HK: 1 M-ton water cherenkov

PINGU

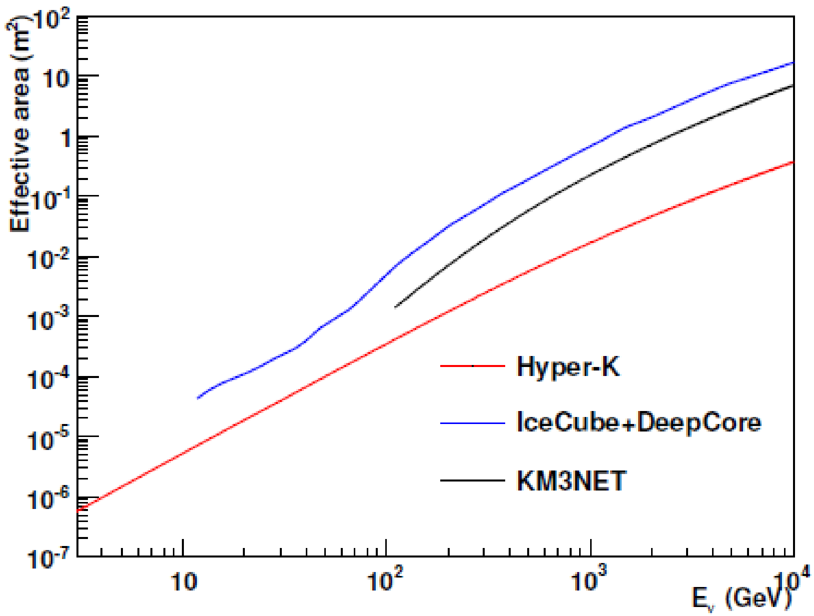


Hyper-Kamiokande

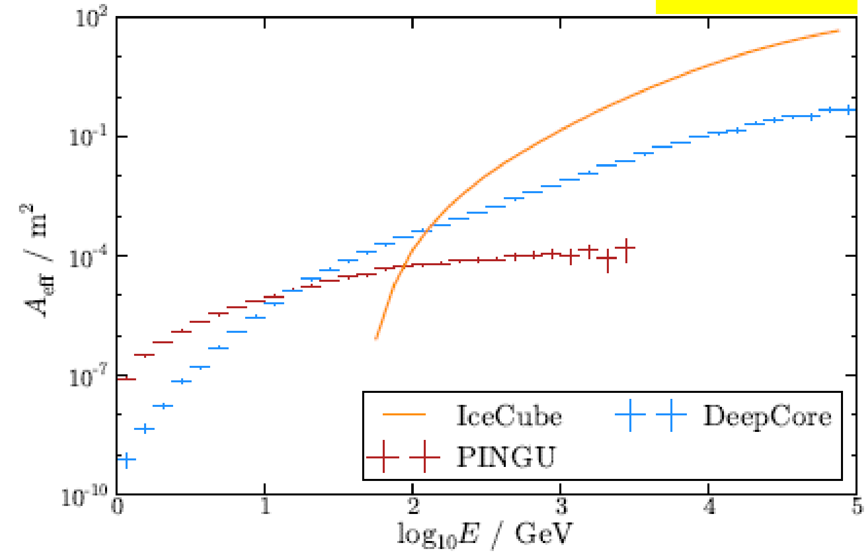


Low-energy sensitivity increases effective volume

Hyper-Kamiokande Letter of Intent
arXiv:1109.3262 (15 Sep 2011)

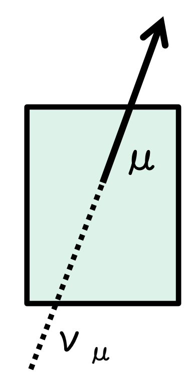


PINGU



Thanks to its good low energy performance for upward-going muons, Hyper-K has a larger effective area for upward-going muons below 30 GeV than do cubic kilometer-scale neutrino telescopes (see Fig. 65 in Sec. III E). Additionally, fully contained events in Hyper-K have energy, direction, and flavor reconstruction and resolutions as good as those in Super-K. This high performance will

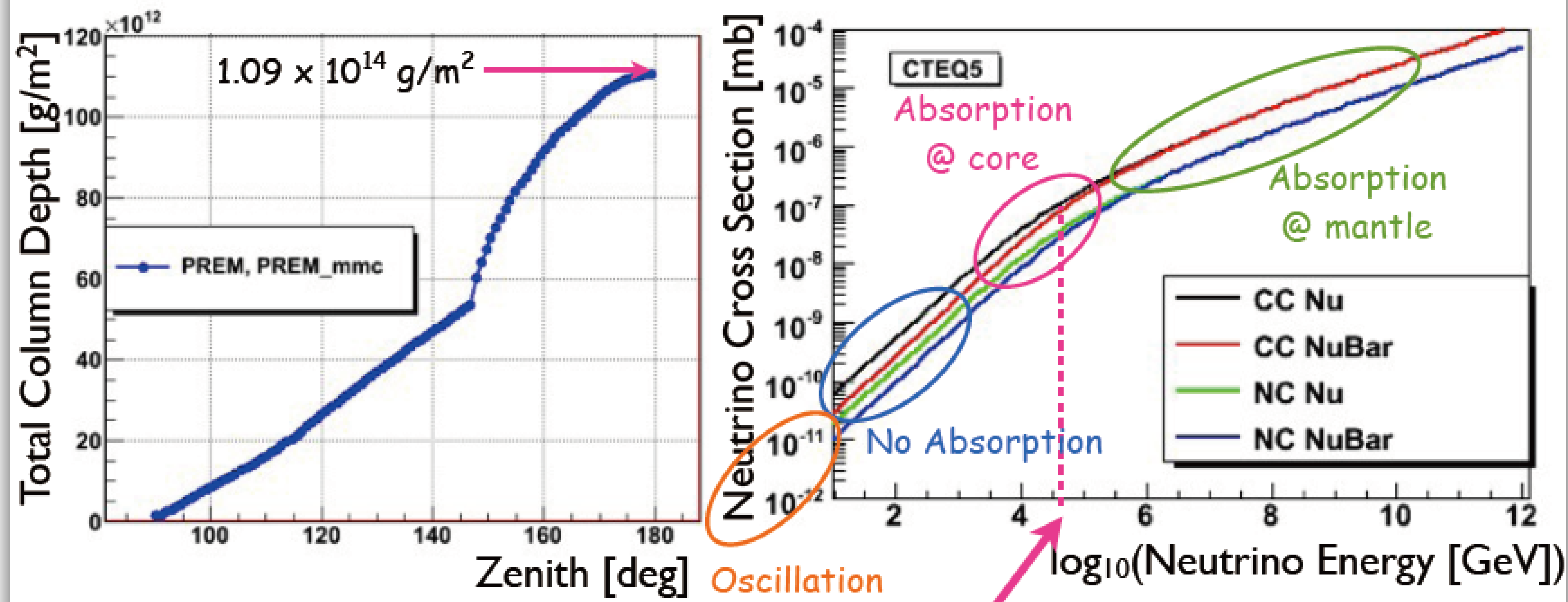
Partially-Contaned Event



Neutrino Absorption Tomography

Kotoyo Hoshina, AGU Fall 2012

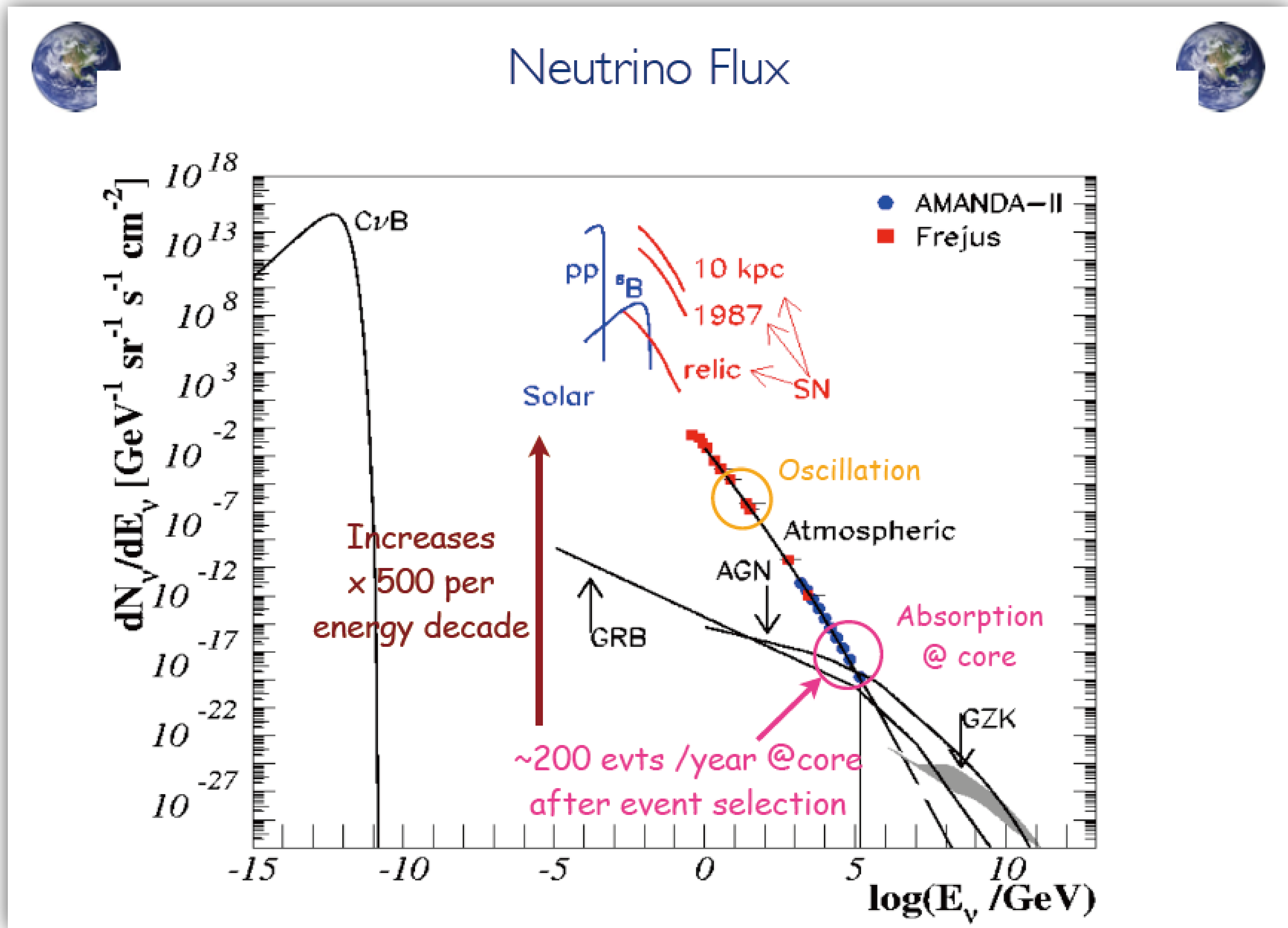
Absorption of Neutrino depends on energy



Mean free path of ~40TeV neutrino is equivalent to the Earth's total column depth at 180 deg

Neutrino Absorption Tomography

Kotoyo Hoshina, AGU Fall 2012



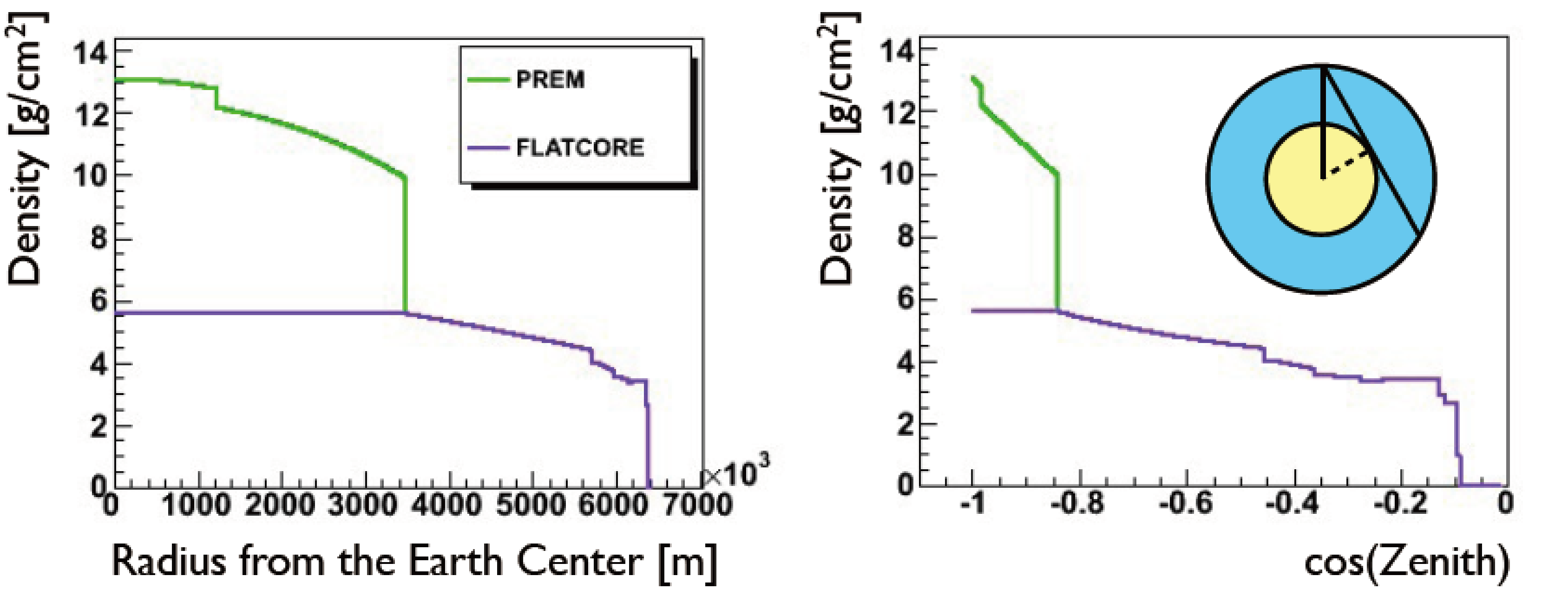
Neutrino Absorption Tomography

Kotoyo Hoshina, AGU Fall 2012

PREM vs FLATCORE model

PREM (Preliminary Reference Earth Model)

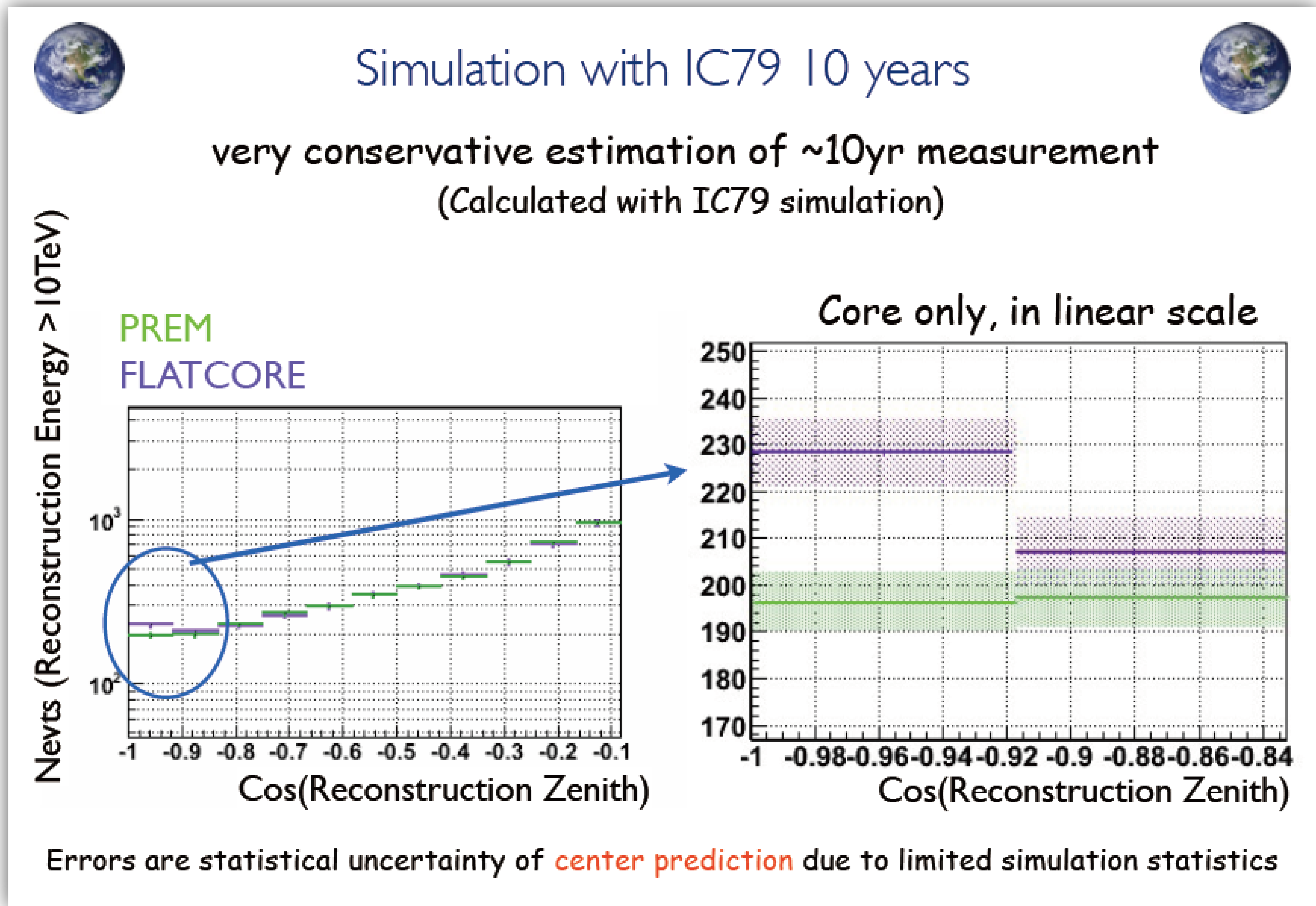
FLATCORE (Density of Core is constant)



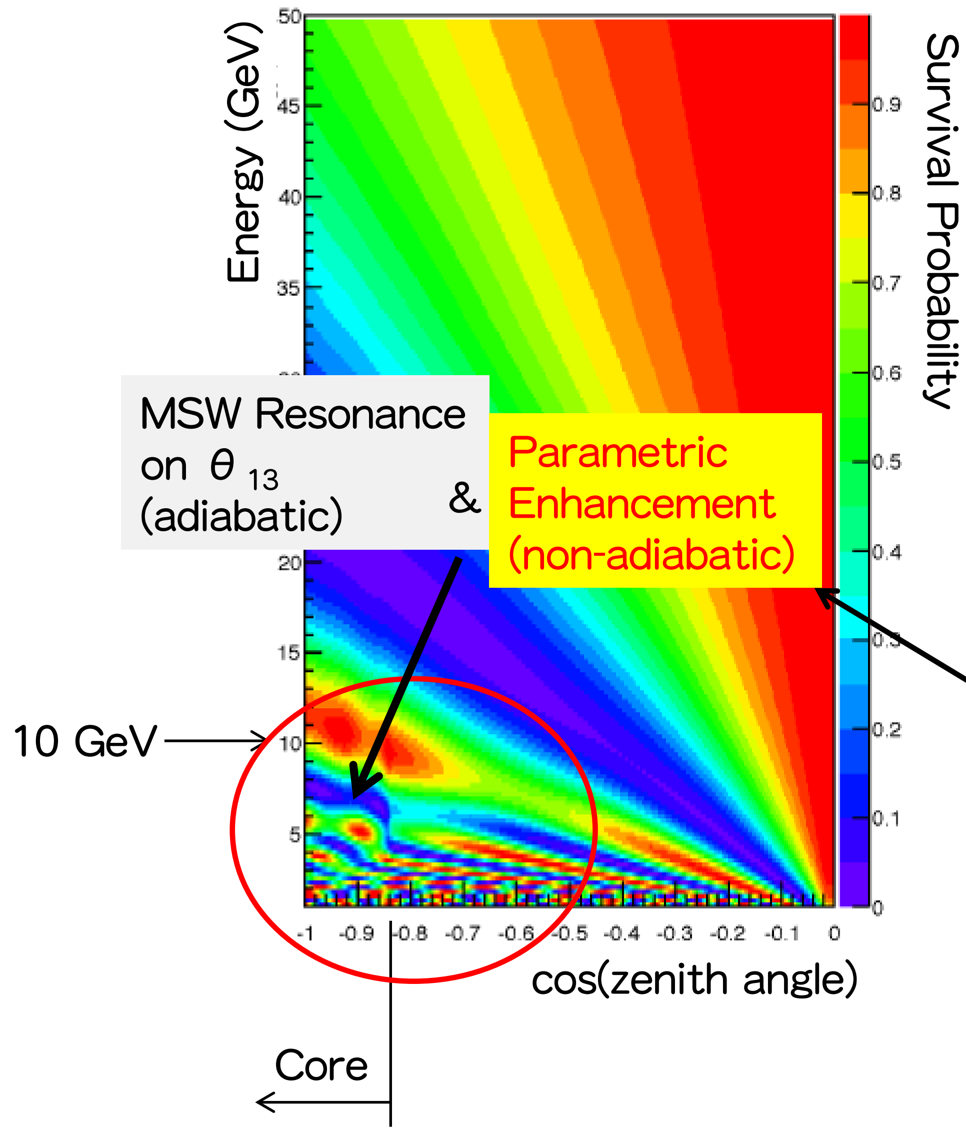
FLATCORE model doesn't conserve Earth's mass, but still useful to estimate the resolution of Earth's density at core angle with the IceCube

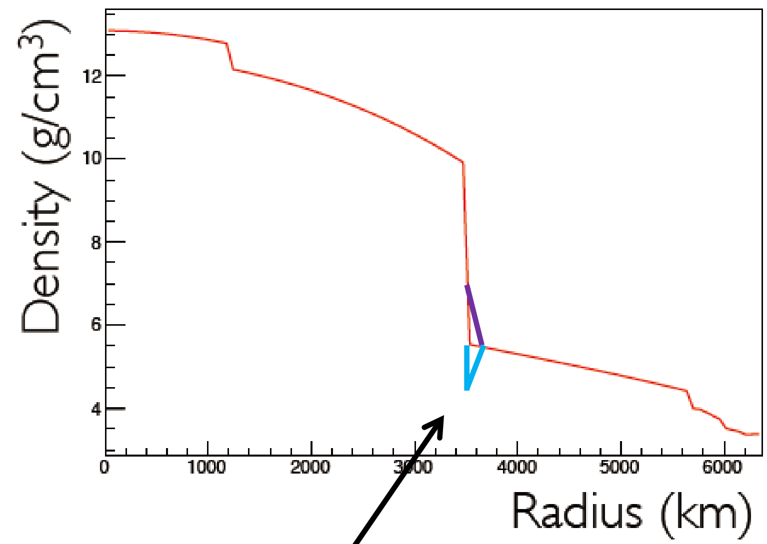
Neutrino Absorption Tomography

Kotoyo Hoshina, AGU Fall 2012



Appendix: Parametric Enhancement is Sensitive to CMB?





Transition probability depends on structures of density step

Summary

- Neutrino Oscillation Tomography
  - Direct measurement of core composition
  - Uses oscillation matter effect (MSW) at 1~10 GeV

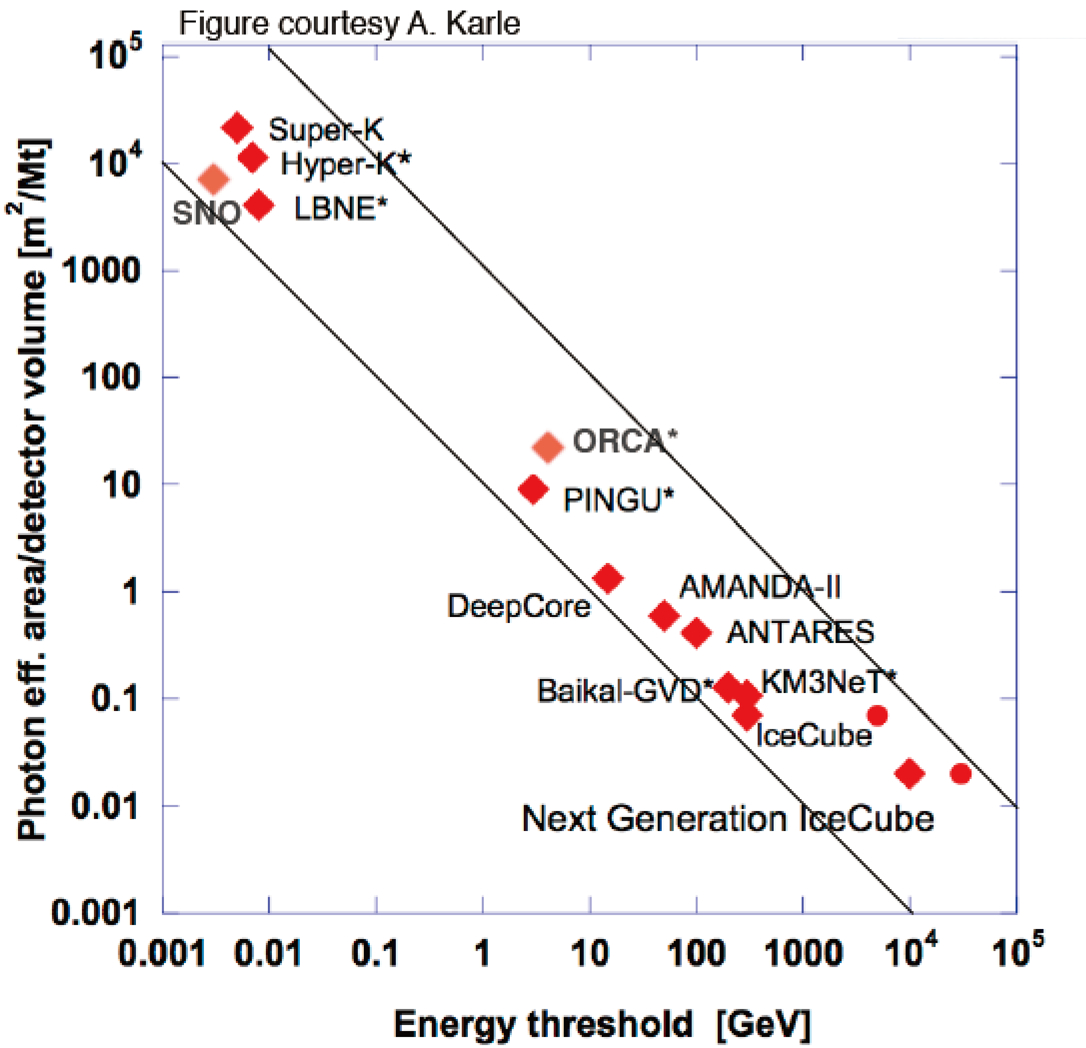
  - PINGU will measure Z/A at ~8% accuracy (NH case), possibly better
  - Inverted hierarchy will limit the sensitivity to ~20%
  - Hyper-Kamiokande might be able to do it better
  - ORCA (KM3NeT, 1.8 M-ton in sea water) can do the same?

- Neutrino Absorption Tomography
  - Direct measurement of core density
  - Uses neutrino absorption at ~10 TeV

  - 10 yr Ice-Cube will discriminate core from mantle

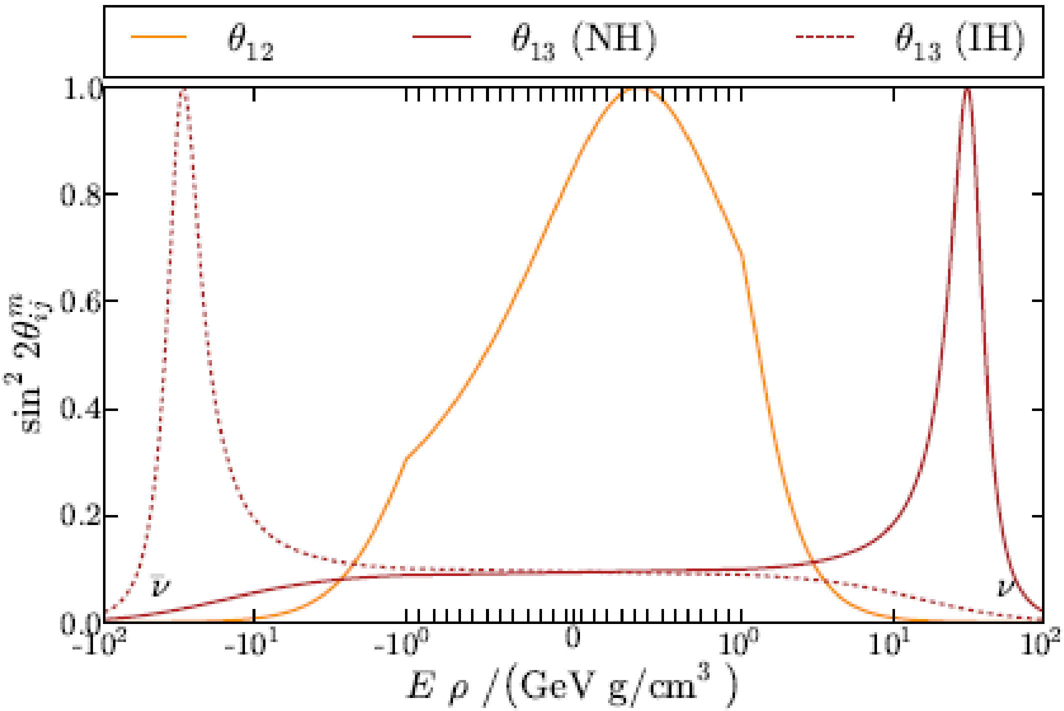
Back Up

Photo Coverage vs Energy Threshold

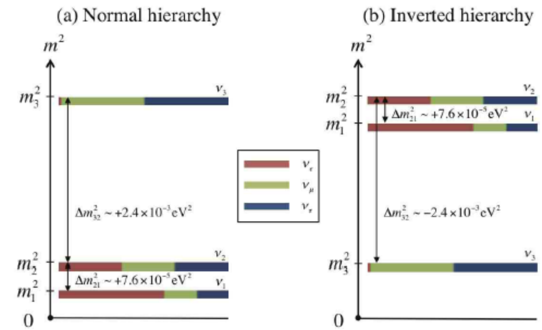


D. R. Grant, Neutrino 2014

MSW Resonance

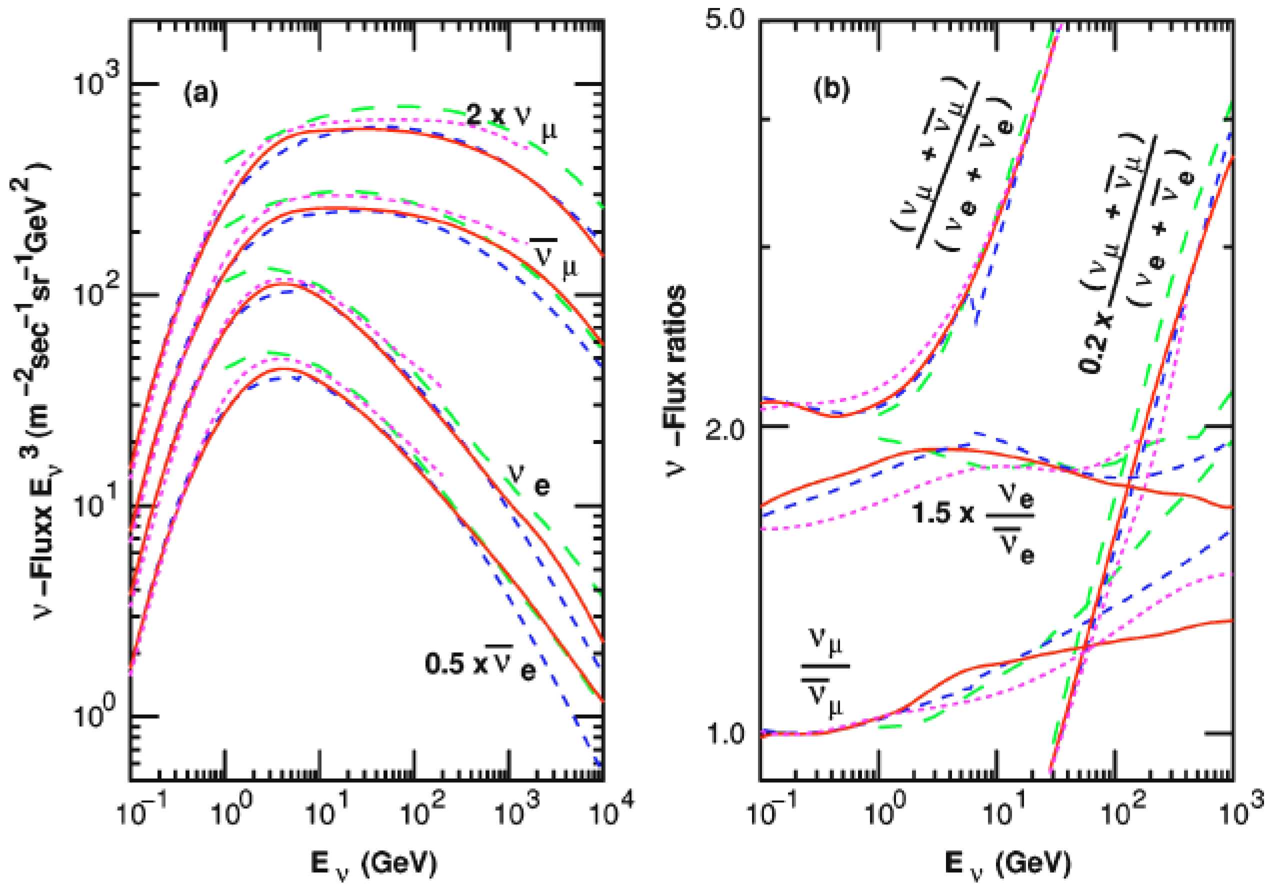


antineutrinos | neutrinos



$$\sin^2 2\theta^m = \frac{\sin^2 2\theta}{\left(\cos 2\theta \mp \frac{2\sqrt{2} E G_F N_e}{\Delta m^2}\right)^2 + \sin^2 2\theta}$$

Atmospheric Neutrino Composition



M. Honda et al, Phys Rev D 70, 043008 (2004)