Prospects for Neutrino Oscillation Tomography

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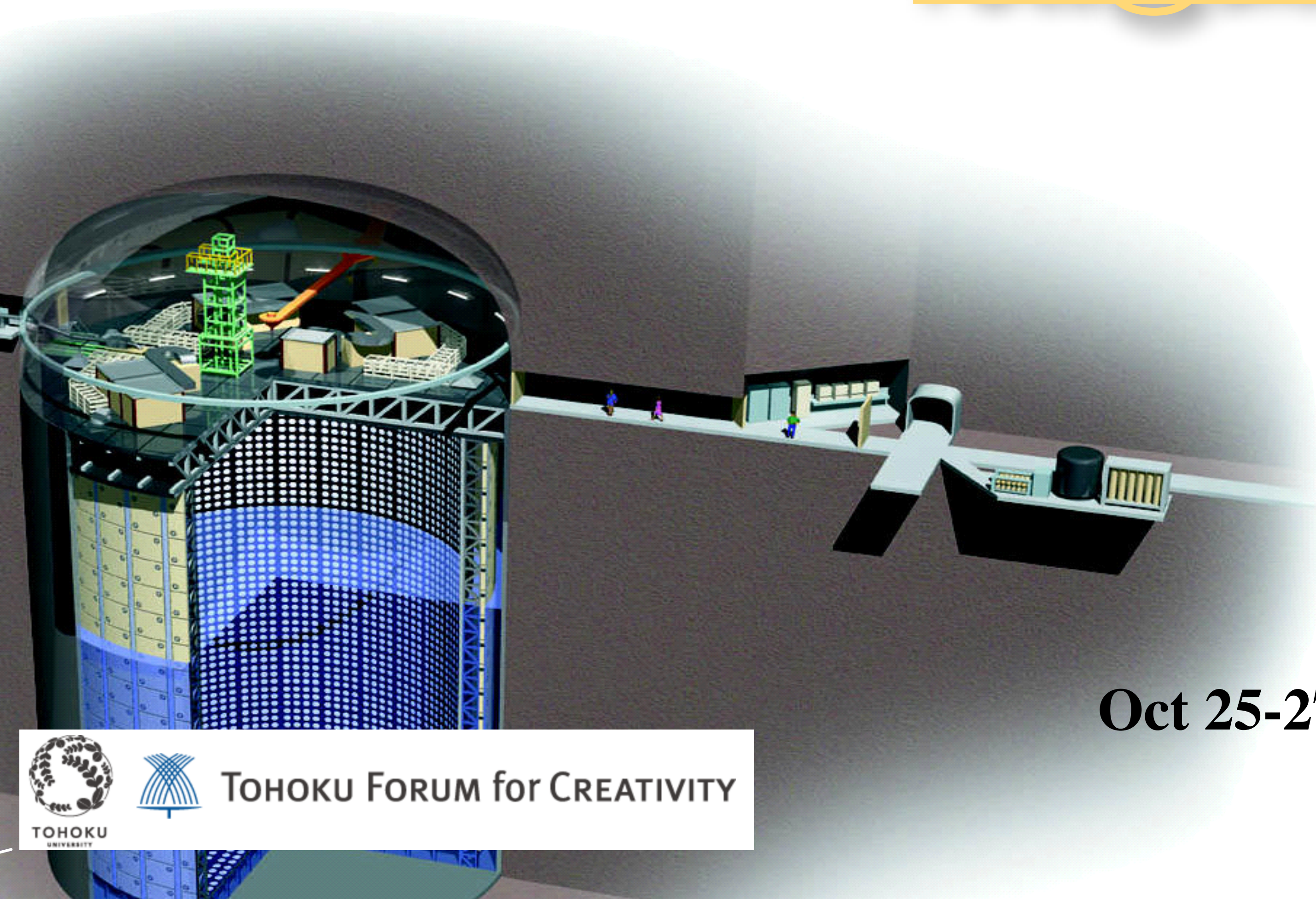
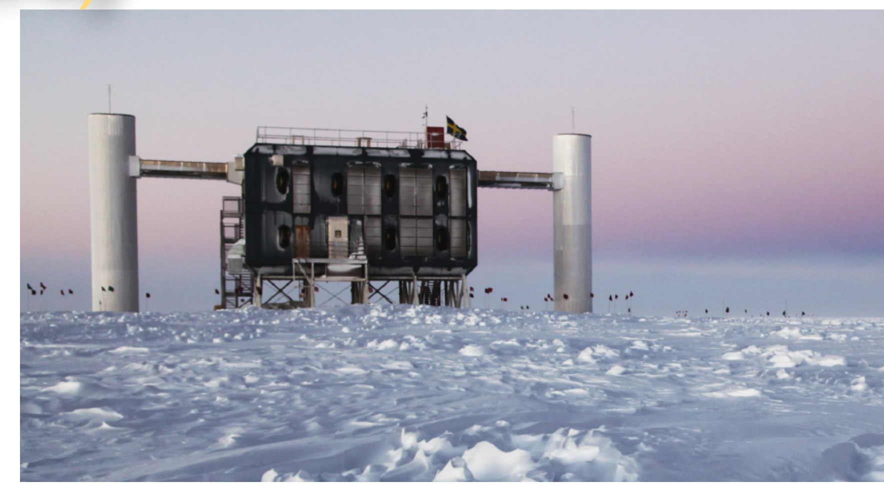
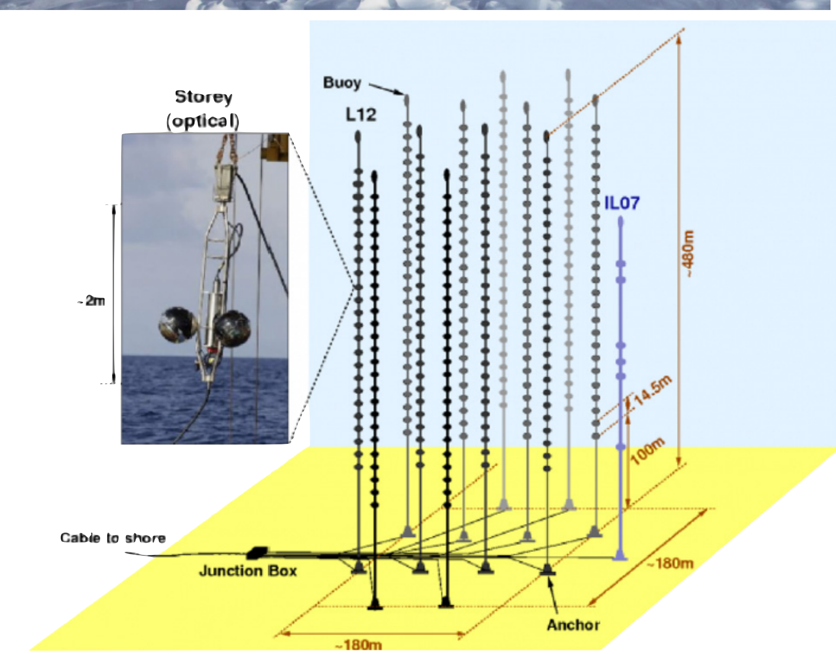




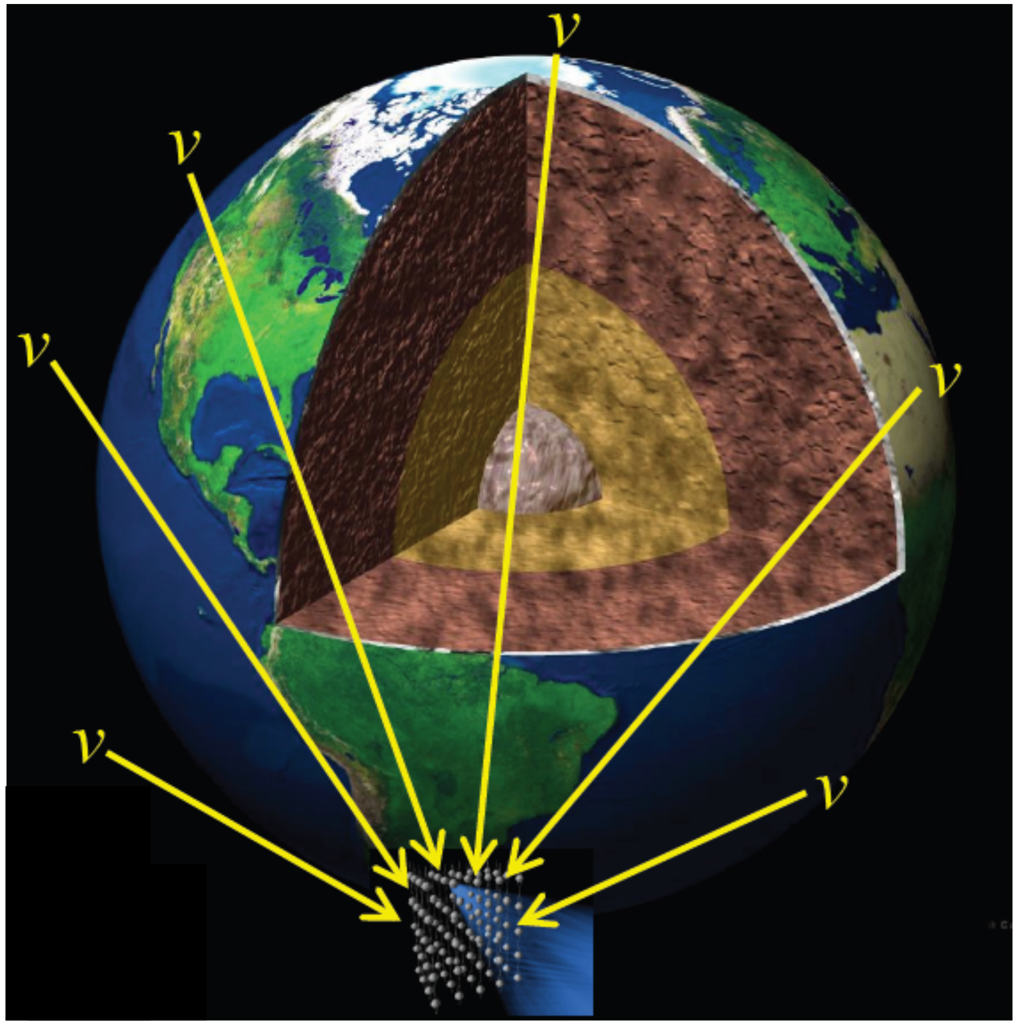


Oct 25-27, 2016

TOHOKU FORUM for CREATIVITY

Outline

- Motivation
- Methodology of Neutrino Oscillation Tomography
- Neutrino Detectors and IceCube
- Prospects for Neutrino Oscillation Tomography with PINGU
- Conclusions



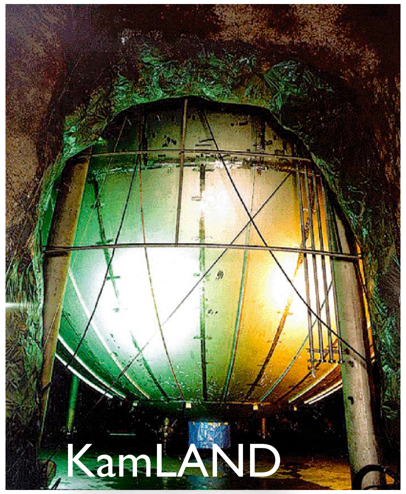
Motivation

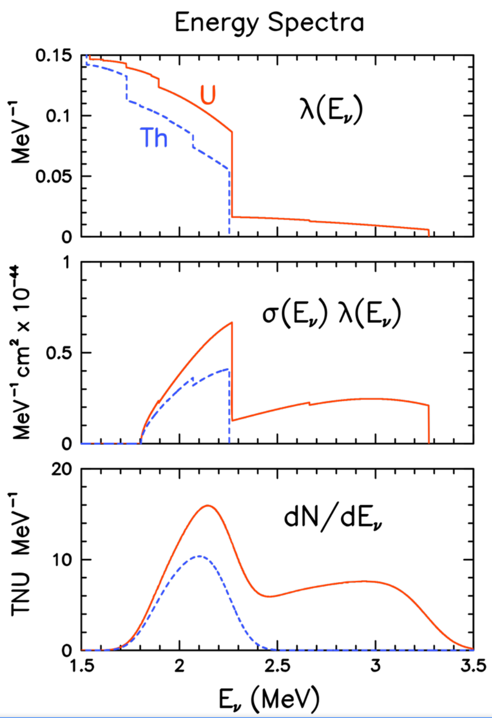
Motivation (Particle Physics ⇒ Geo-science)

- What can neutrino detectors do for Solid Earth Science ?
  - **Muon Radiography**
    - Atm. airshower muon absorption
  - **Geo-neutrinos**
    - Low-energy neutrino detection from nuclear decays
  - **Neutrino absorption tomography**
    - Atm. air shower high-energy neutrino absorption
  - **Neutrino oscillation tomography**
    - Atm. air shower neutrino oscillations

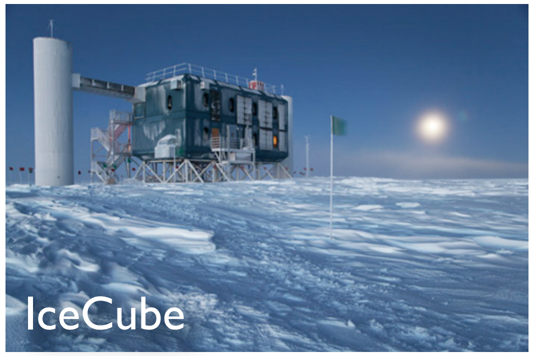
Geo-neutrinos

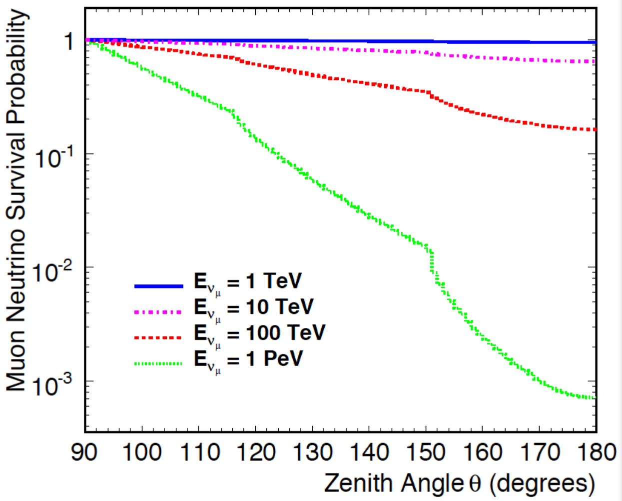
U and Th geo-ν





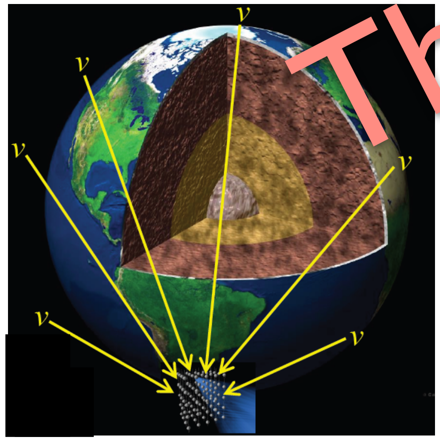
Neutrino absorption tomography

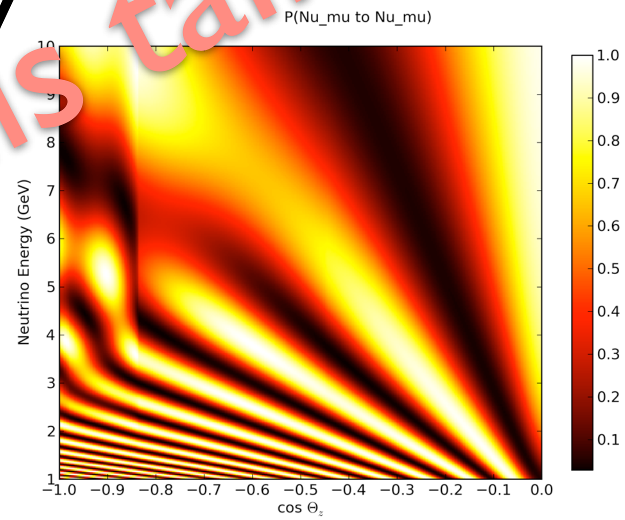




Neutrino oscillation tomography

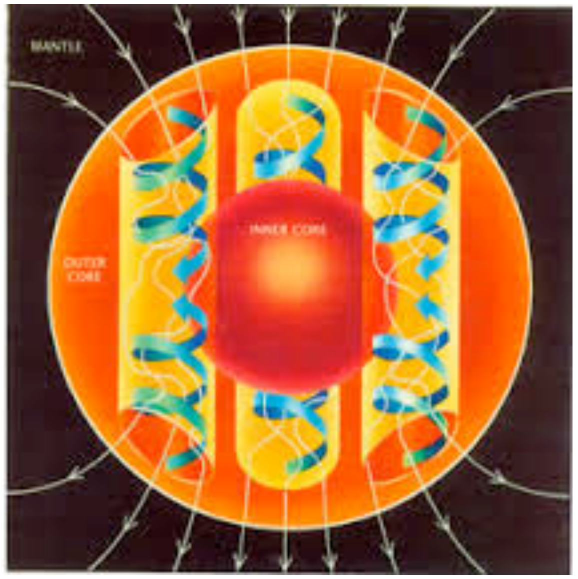
This talk



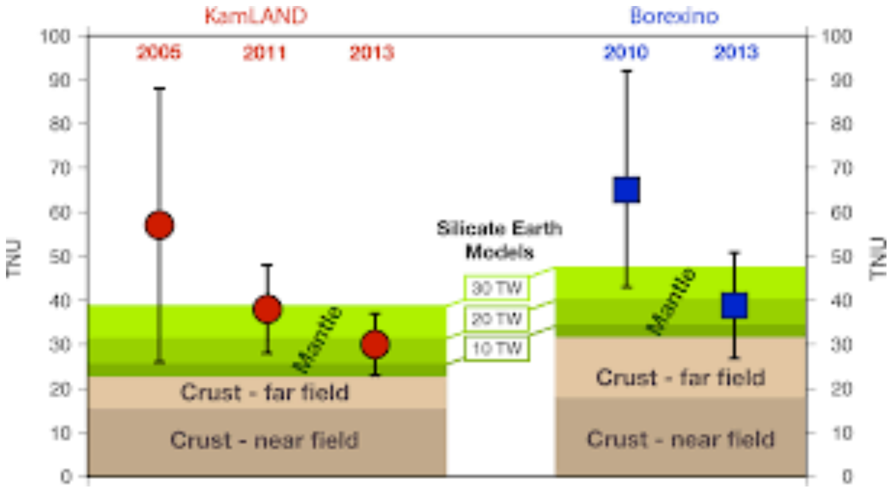


Motivation - Neutrino Oscillation Tomography

- New Method to understand inner Earth
  - Inner Earth Composition
    - Light elements in the outer core ?
  - Understand the Geodynamo
- Apply neutrino physics to Earth Science



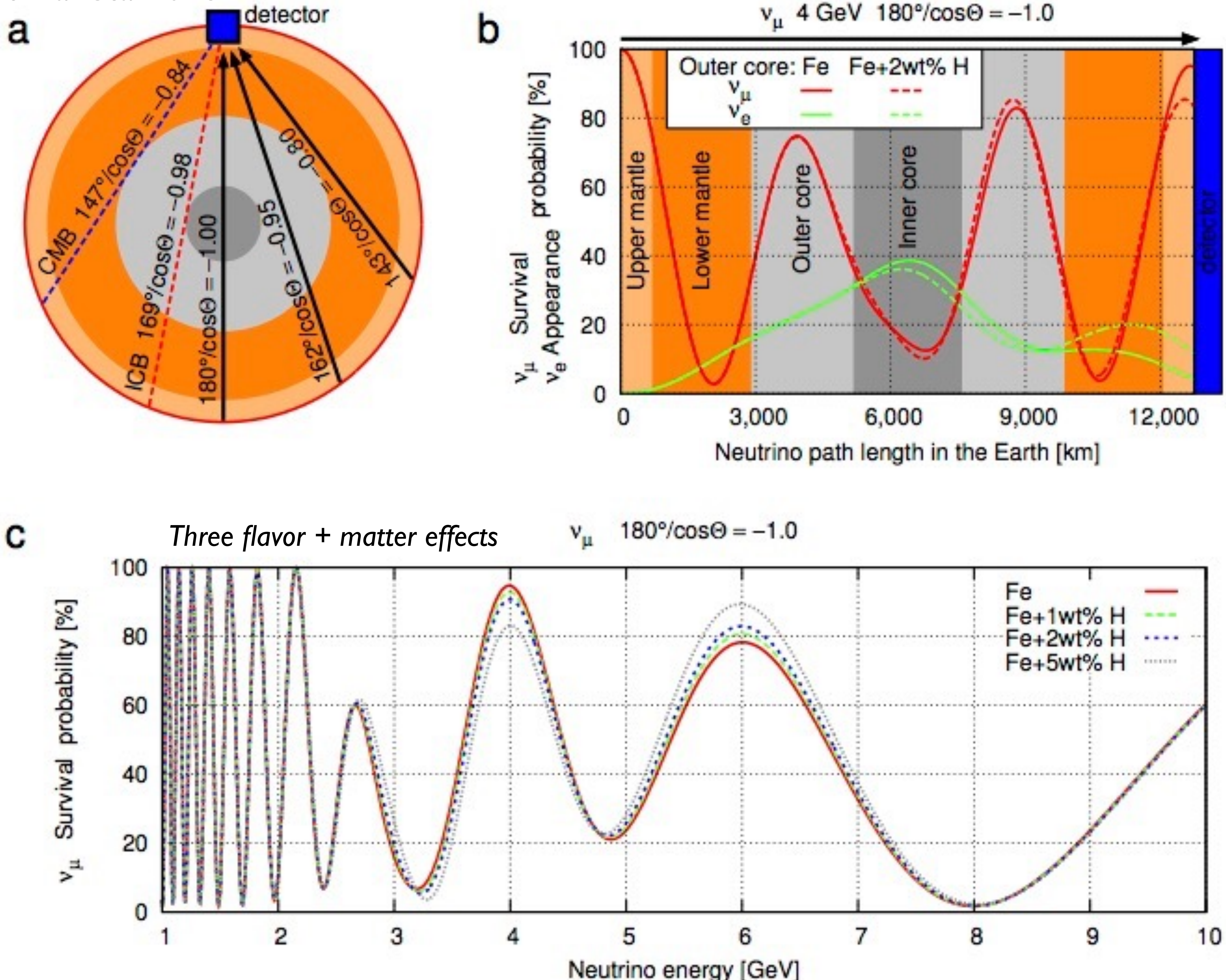
Nature Geoscience; Volume: 4, 647–651 (2011)



1st Tomography Workshop @ ERI Jan 2016

Neutrino Oscillation Tomography

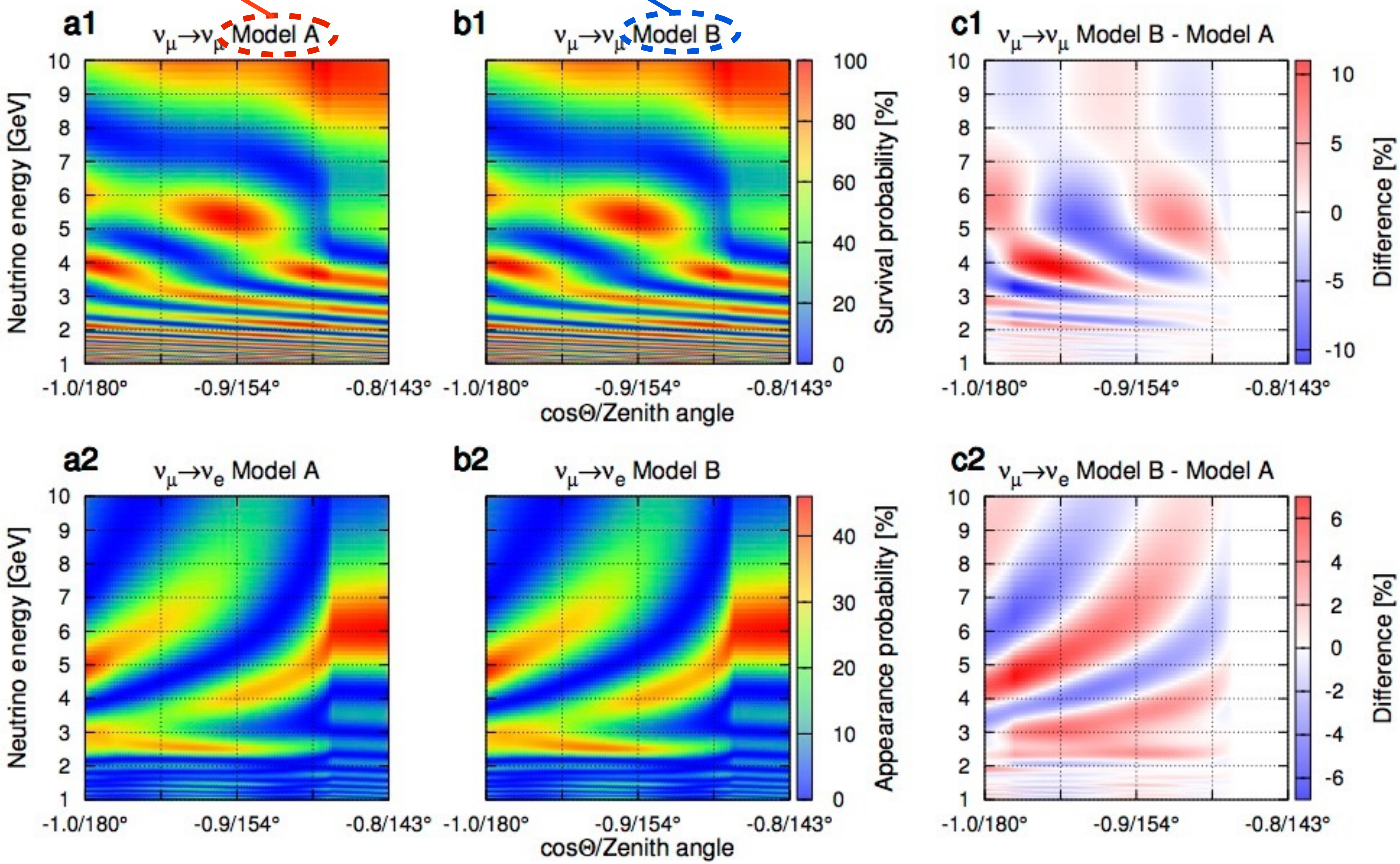
Rott & Taketa 2015



Oscillograms

Pure Fe

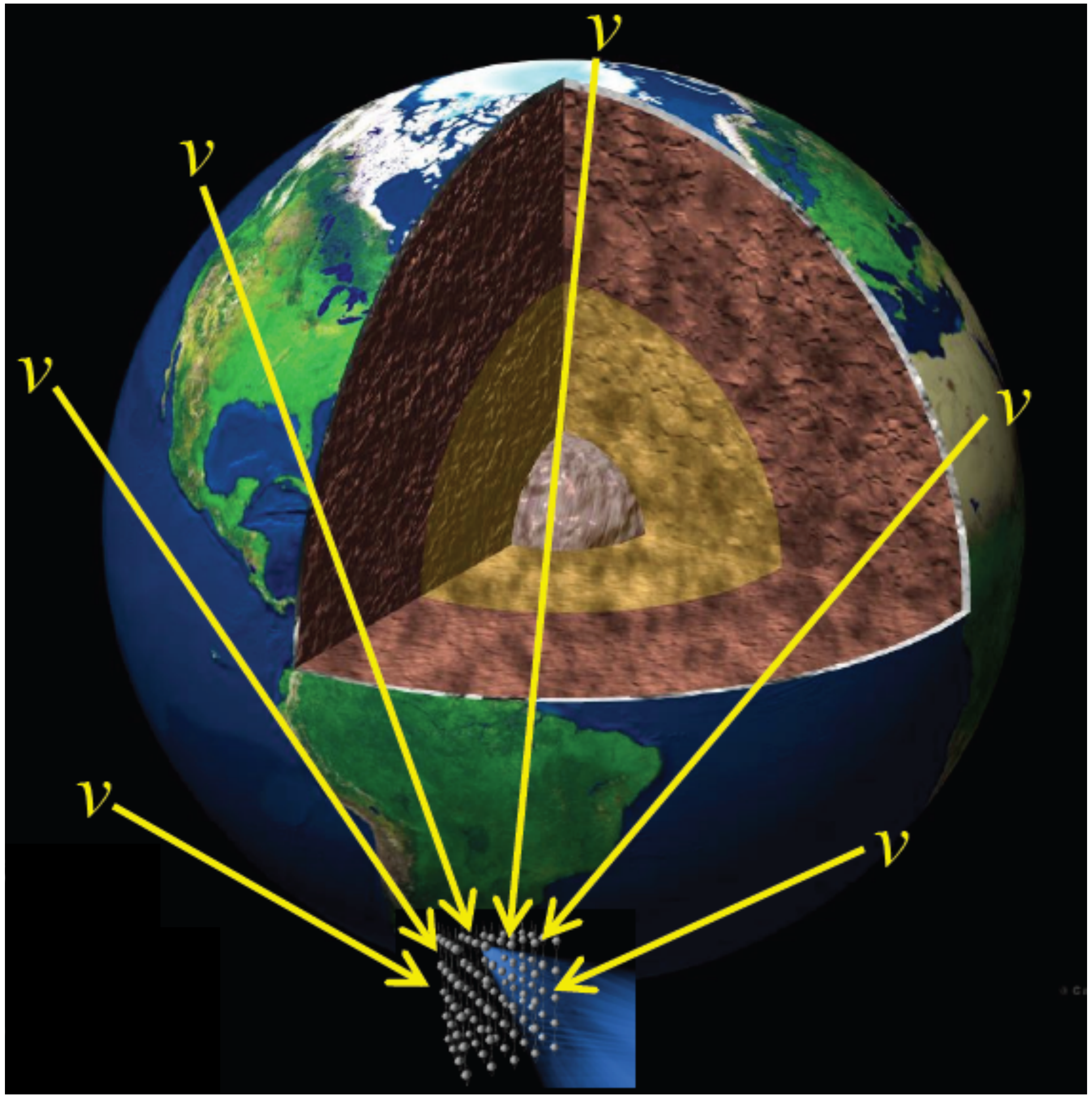
Fe + 2wt% H



Motivation - Methodology

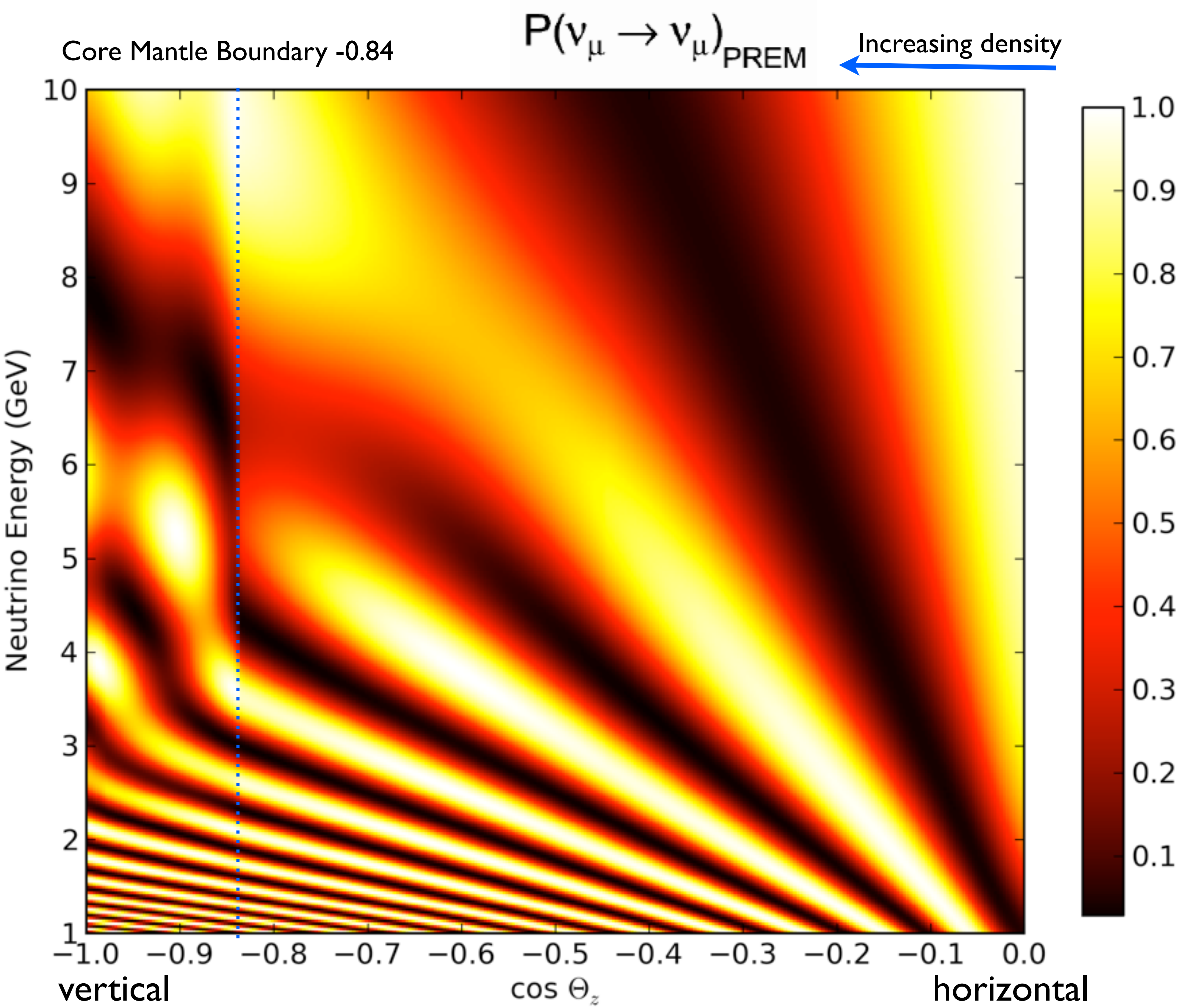
- The Earth matter density profile can be determined from seismic measurements
- Matter induced neutrino oscillation effects however dependent on the electron density
- Given a matter density profile the “average” composition (or Z/A) along the neutrino path can be determined using neutrino signals (Oscillation tomography)

Electron density in core
Y_c=electron/nucleons

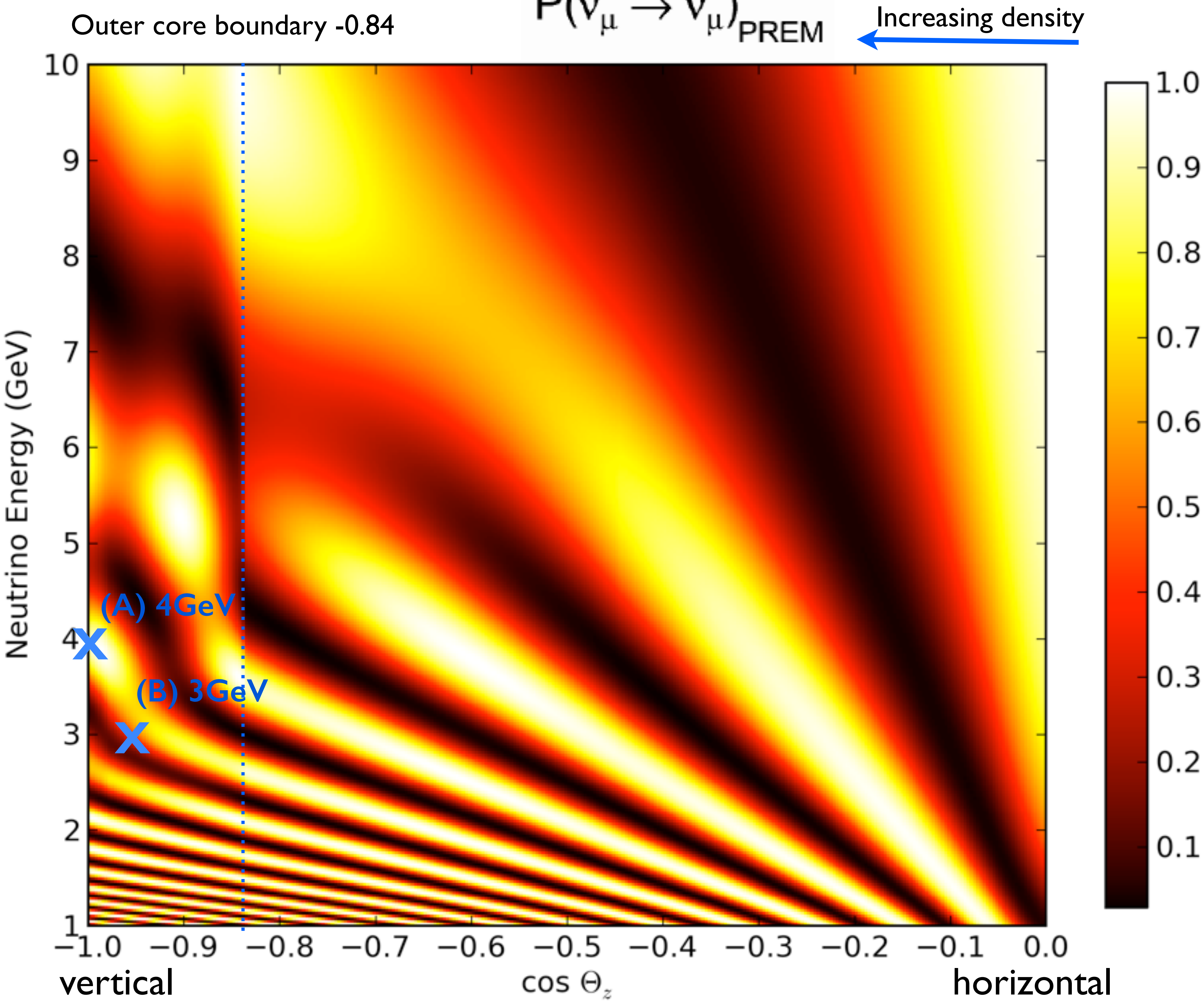


corresponding zenith angles for boundaries
inner core $\theta_\nu < 169°$ ($\cos\theta_\nu < -0.98$)
outer core $\theta_\nu < 147°$ ($\cos\theta_\nu < -0.84$)

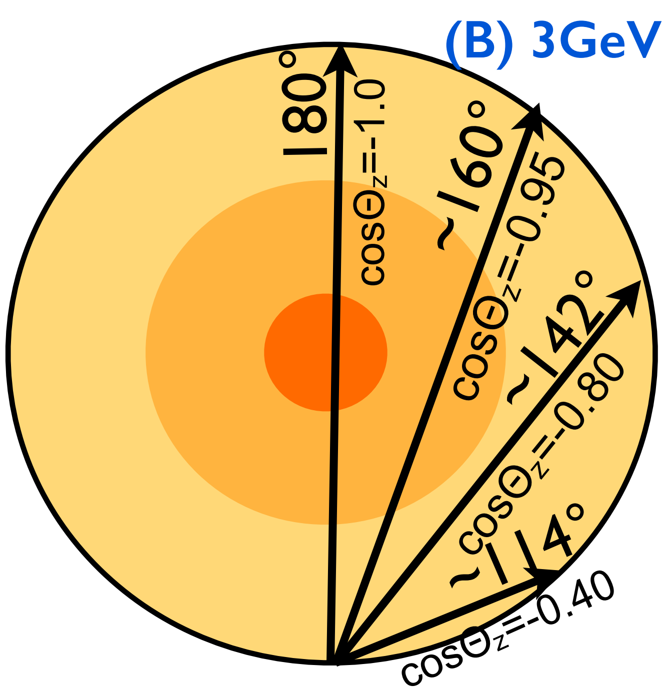
Oscillograms



How to read an oscillograms



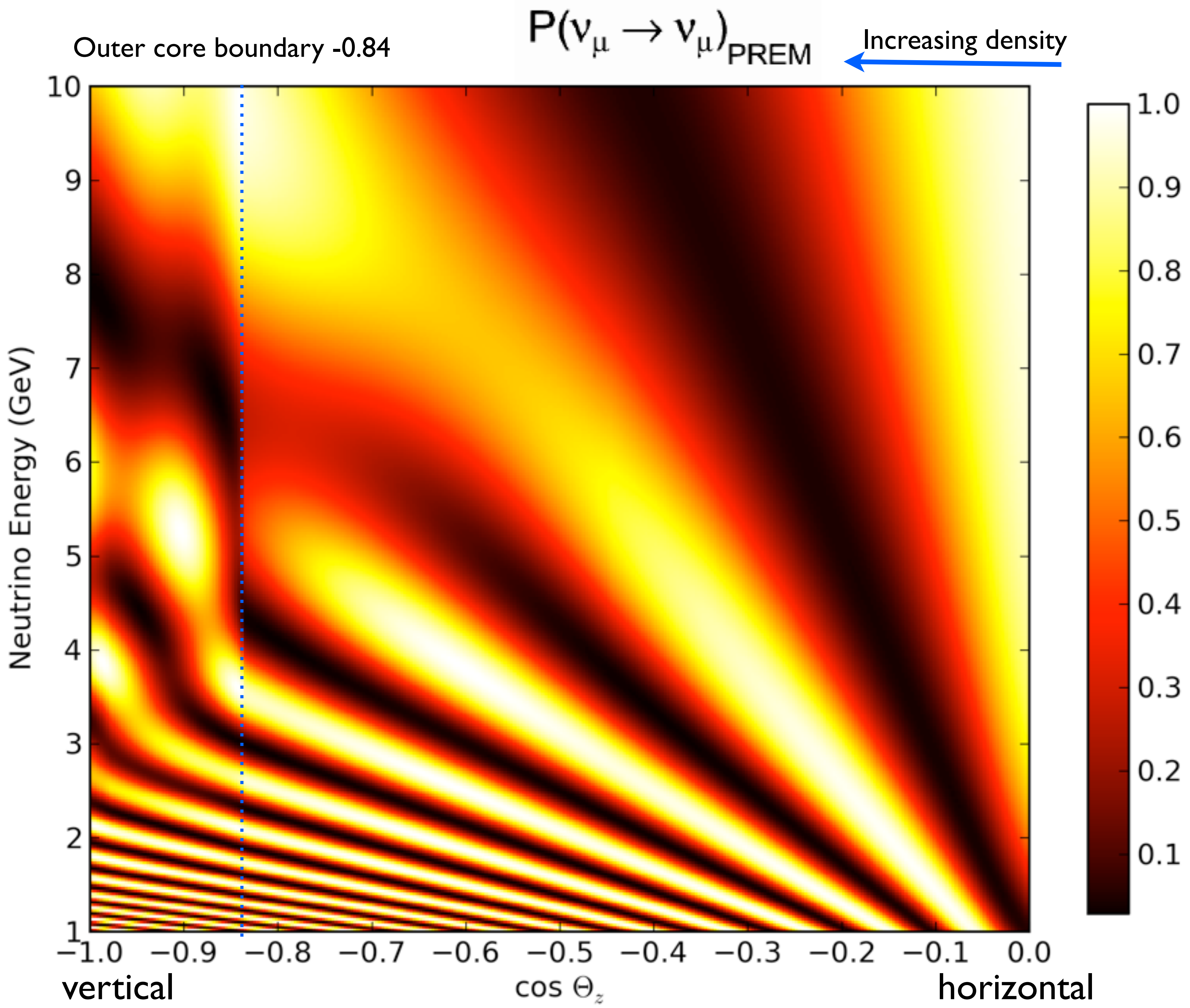
An example ...



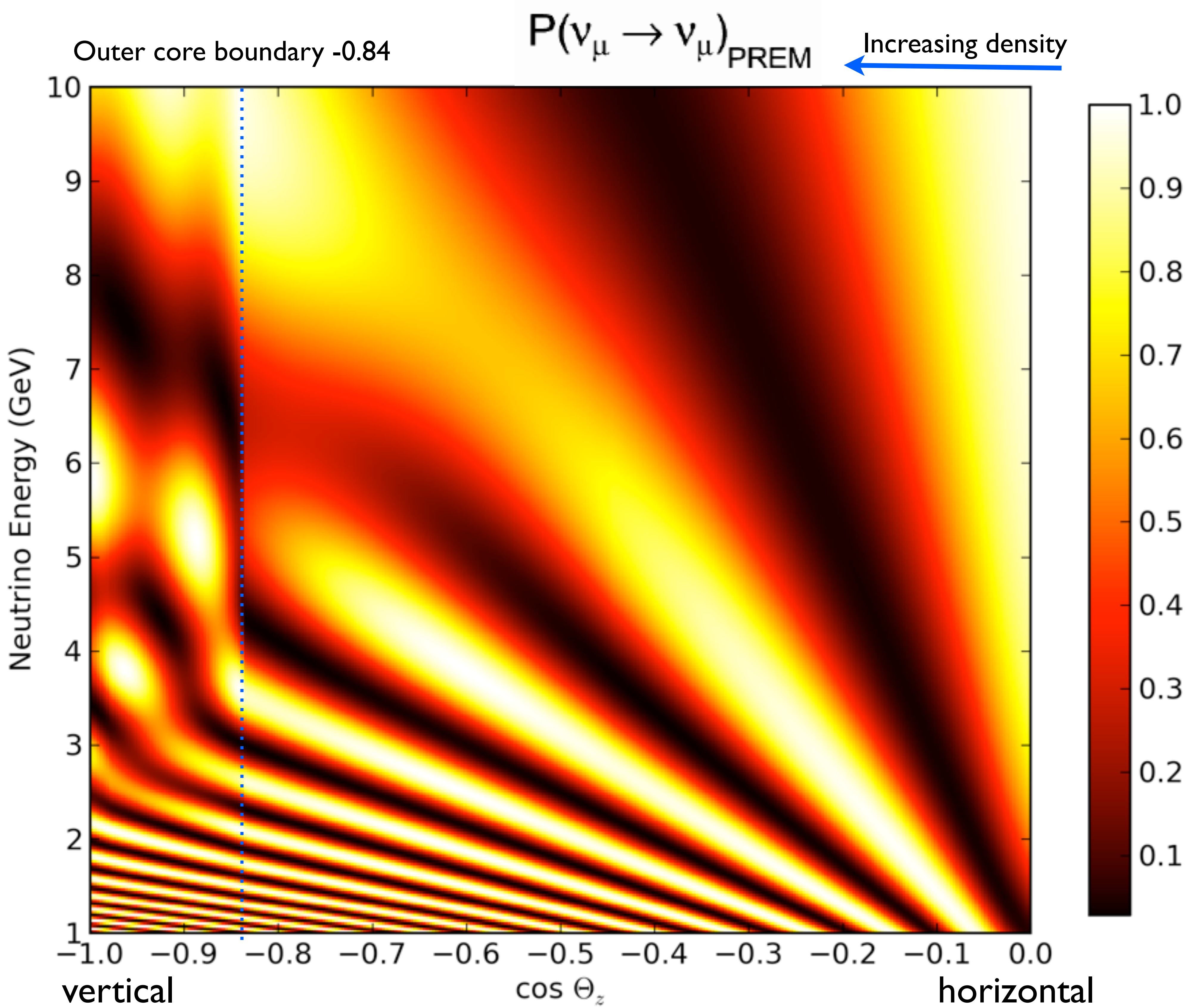
A muon neutrino created at **(A)** with energy 4GeV has a ~**90%** chance to be detected as such after traversing the Earth

A muon neutrino created at **(B)** with energy 3GeV has a ~**40%** chance to be detected as such after traversing the Earth

Oscillogram (“normal” electron density)



Oscillogram (enhance electron density)

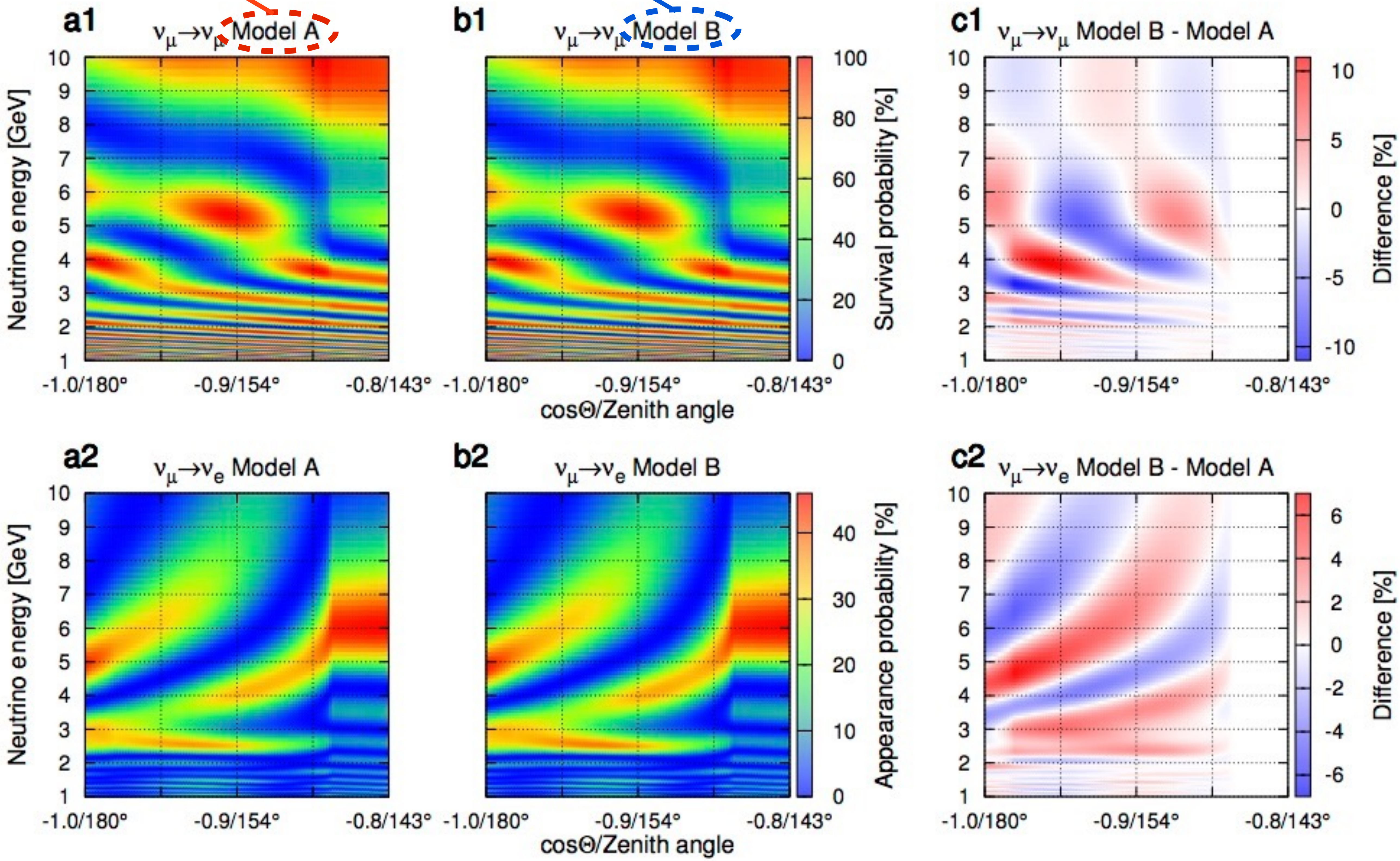


Change Earth core electron density by 10% to visualize change in survival probability

Most significant changes are seen in an energy range of **2-10GeV** and for neutrinos passing through the core region(**cosθ < -0.84**)

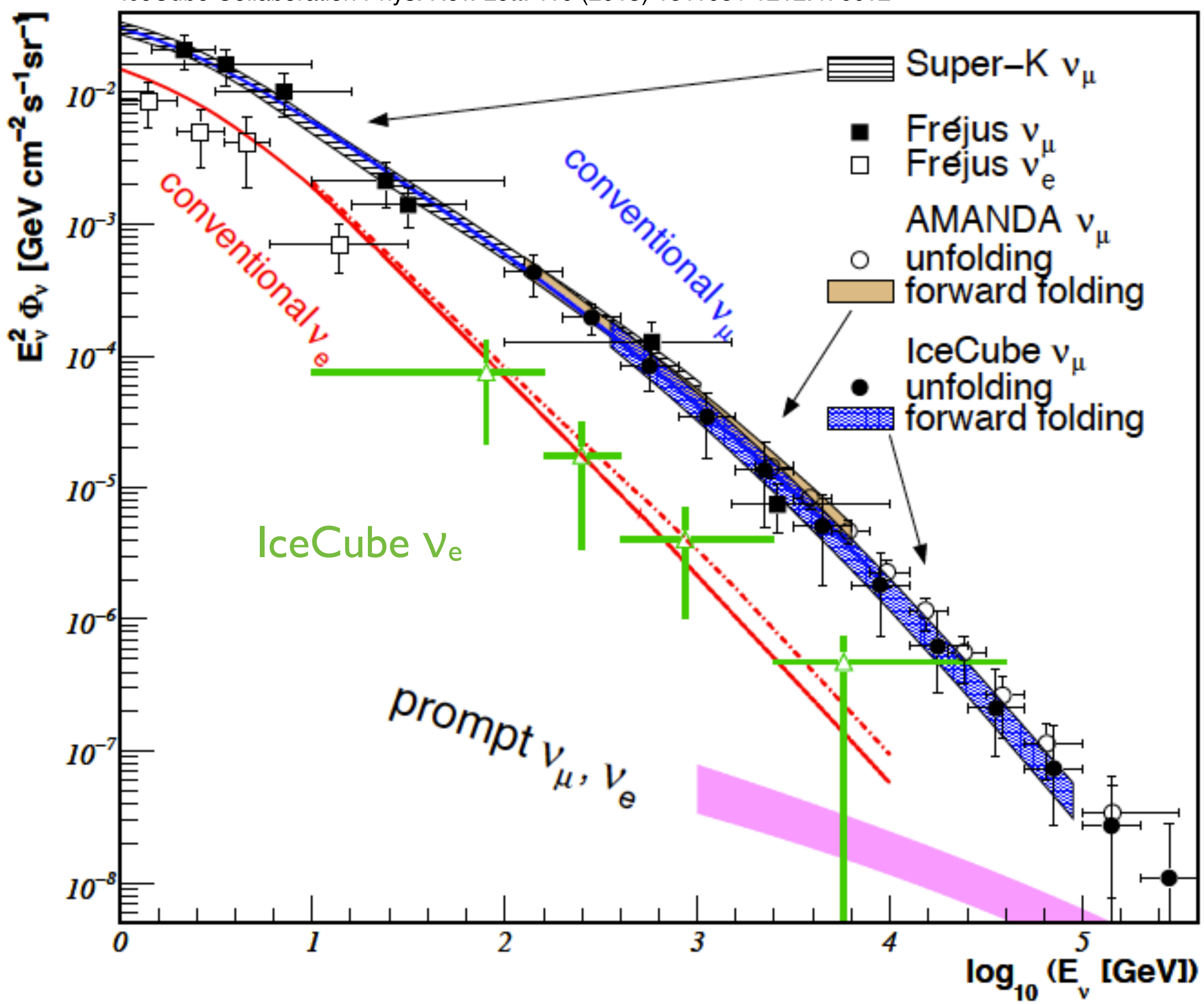
Pure Fe

Fe + 2wt% H



Neutrino Source and Detectors

Atmospheric neutrinos are a **natural** steady **source of muon and electron neutrinos** at the energy range relevant for neutrino oscillation tomography

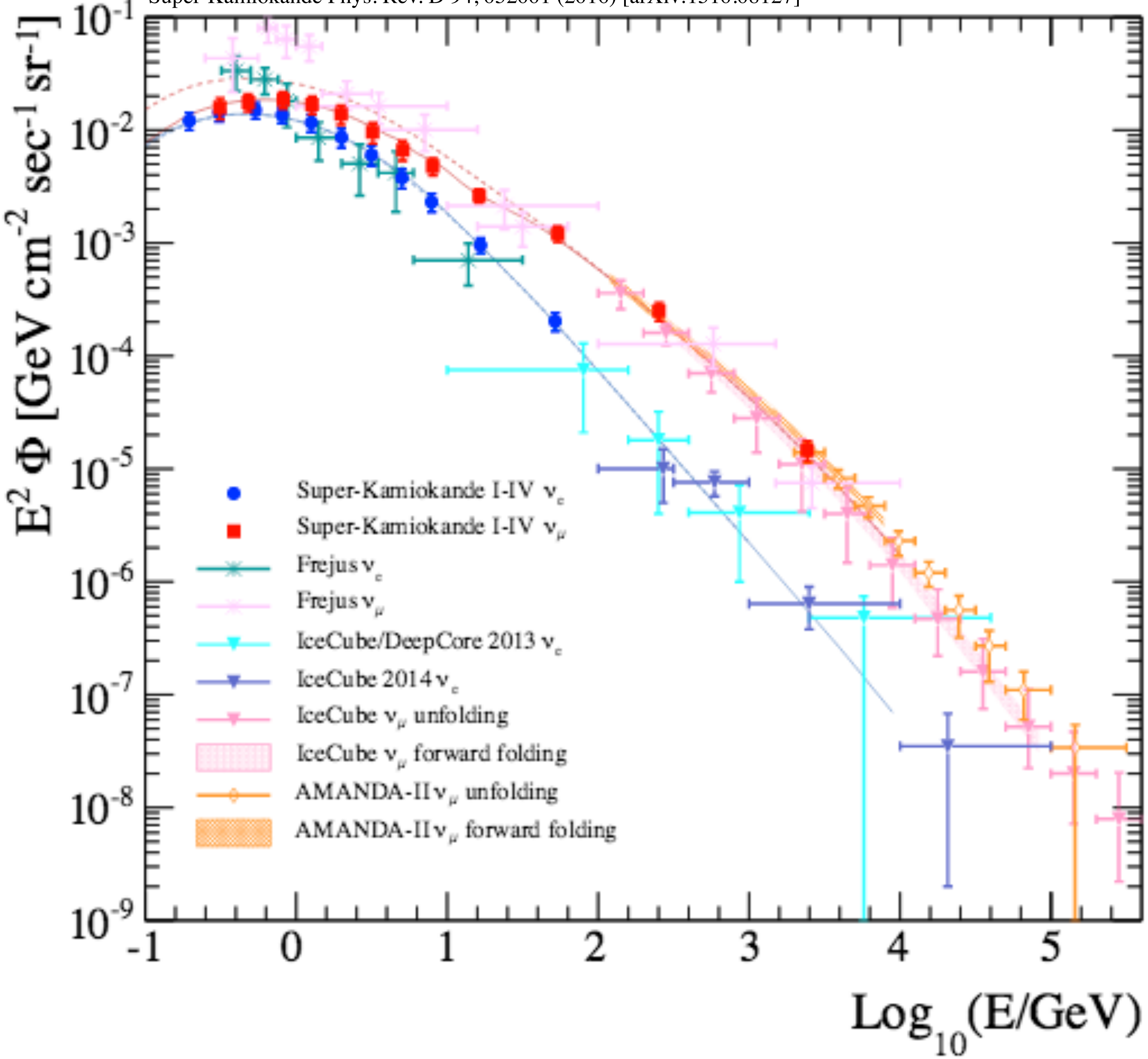


- $p + A \rightarrow \pi^\pm\ (K^\pm)$ + other hadrons
  - $\pi^\pm \rightarrow \mu^\pm\ \nu_\mu \rightarrow e^\pm\ \nu_e \nu_\mu \nu_\mu$

Atmospheric Neutrinos

Atmospheric neutrinos are a **natural** steady **source of muon and electron neutrinos** at the energy range relevant for neutrino oscillation tomography

Super-Kamiokande Phys. Rev. D 94, 052001 (2016) [arXiv:1510.08127]



- p + A → $\pi^\pm$ ($K^\pm$) + other hadrons
  - $\pi^\pm \rightarrow \mu^\pm \nu_\mu \rightarrow e^\pm \nu_e \nu_\mu \nu_\mu$

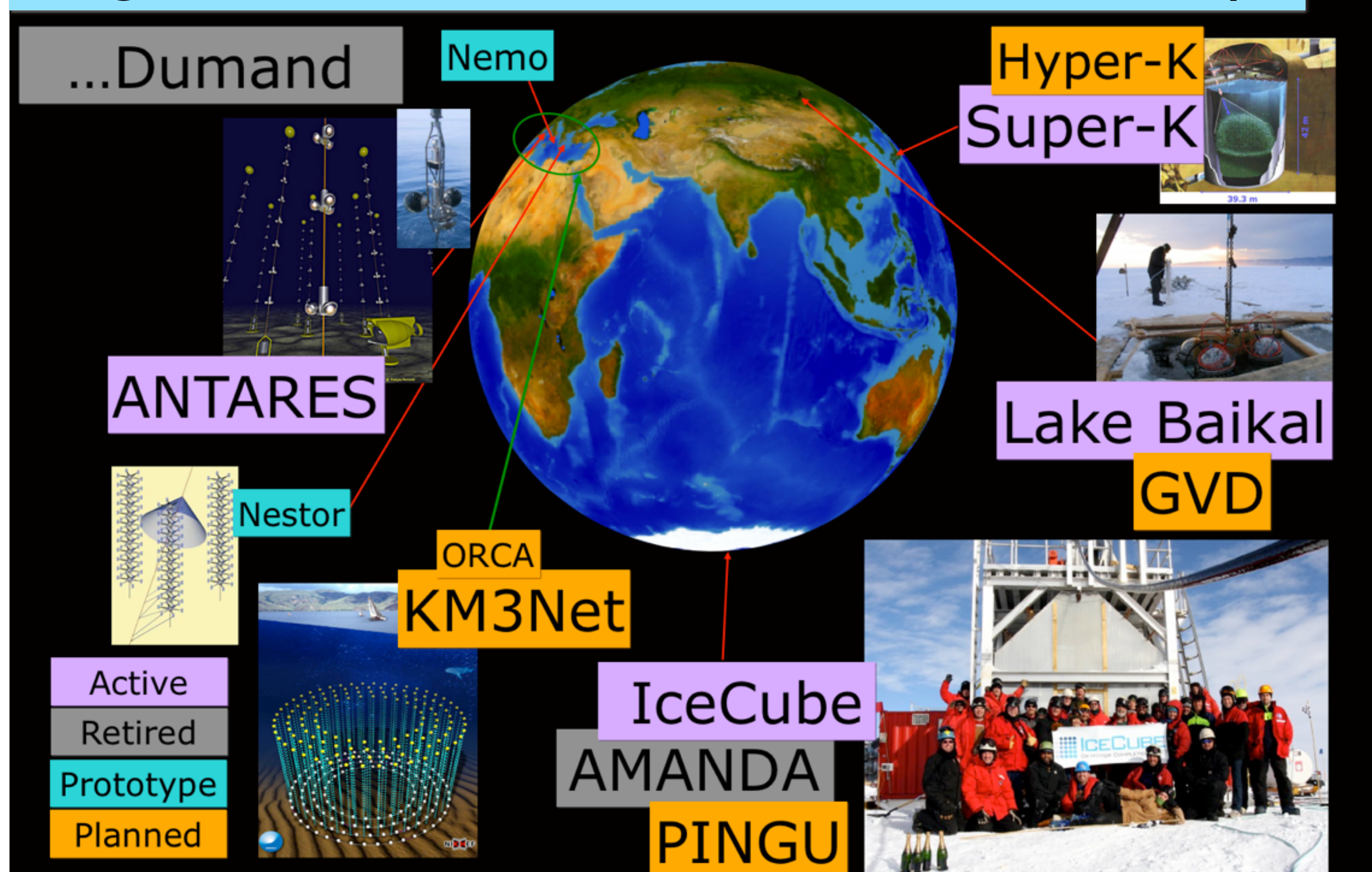
Neutrino Source and Detectors

Atmospheric neutrinos are a **natural** steady **source of muon and electron neutrinos** at the energy range relevant for neutrino oscillation tomography

- $p + A \rightarrow \pi^\pm (K^\pm) +$ other hadrons
    - $\pi^\pm \rightarrow \mu^\pm \nu_\mu \rightarrow e^\pm \nu_e \nu_\mu \nu_\mu$

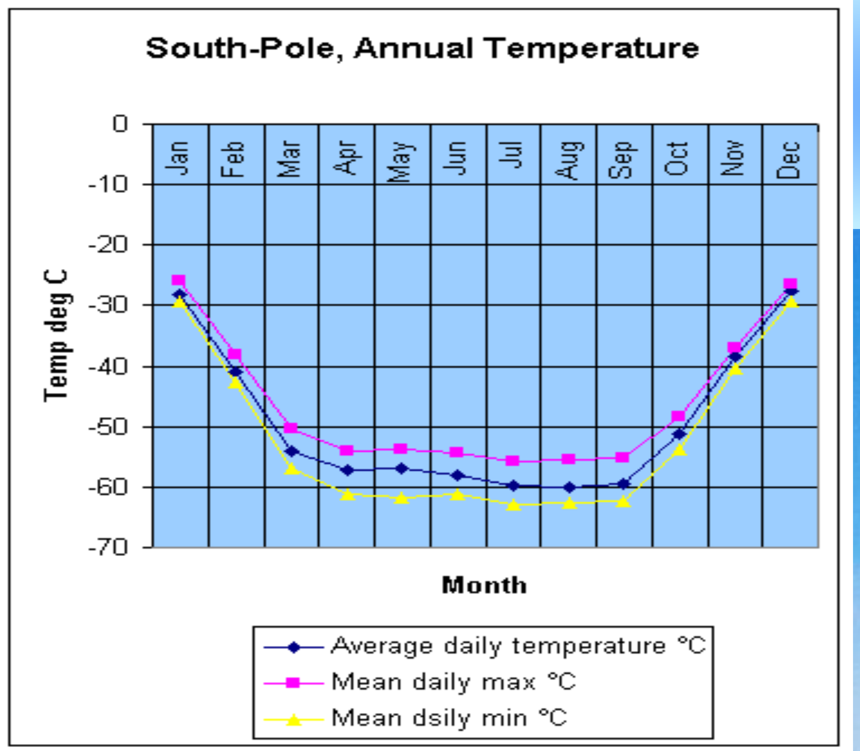
- Detector requirements for neutrino oscillation tomography
    - **good energy resolution** ⇒ fully contained events, good optical coverage
    - **good angular resolution** ⇒ precise timing, good optical coverage
    - **large volume** ⇒ acquire high statistics neutrino sample

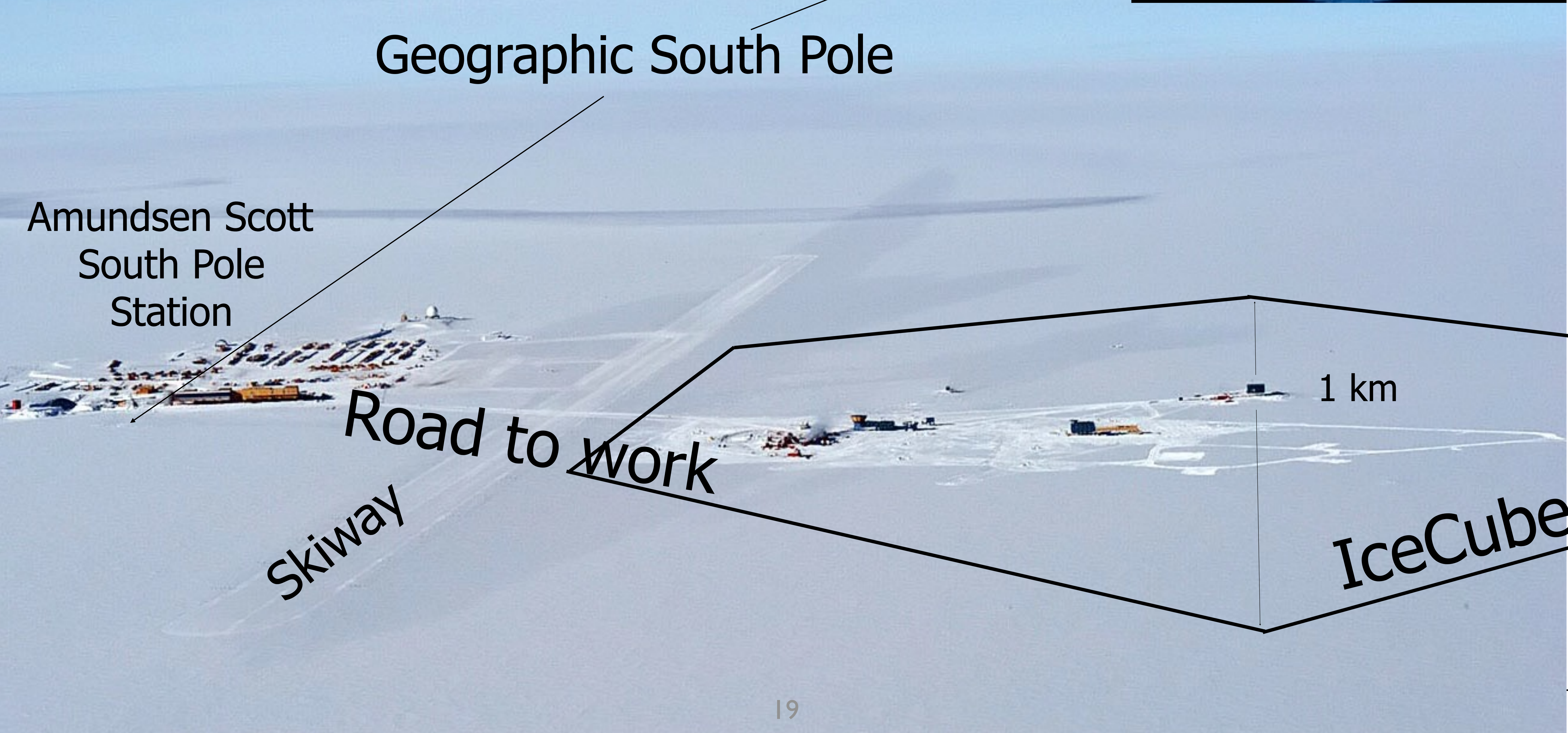
Large Volume Water/Ice Cherenkov Telescope



The IceCube Neutrino Telescope

Laboratory at the South Pole

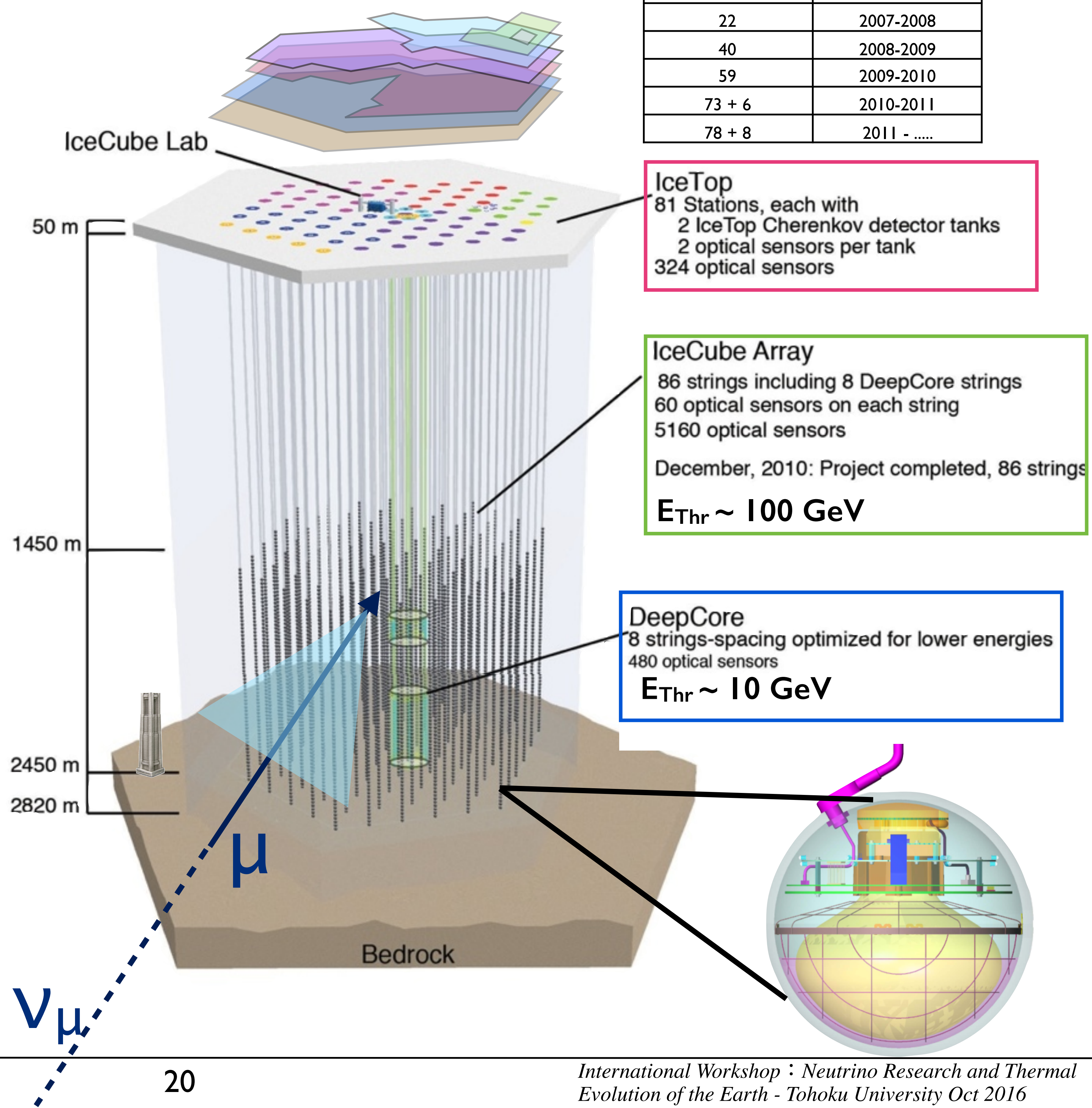




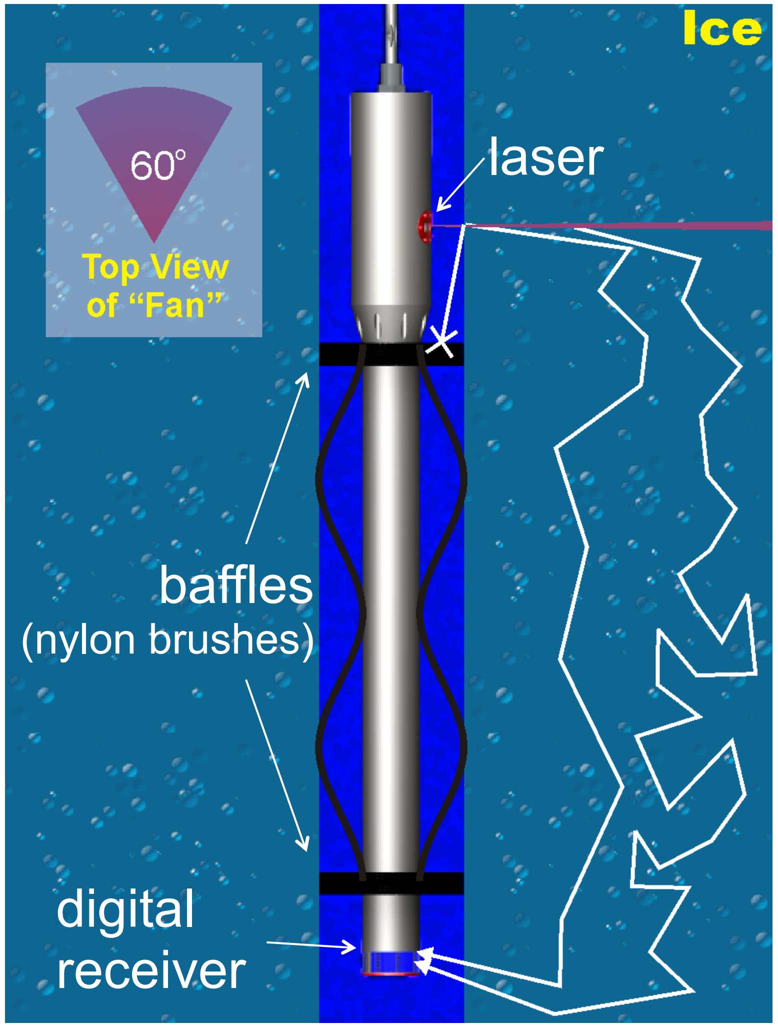
The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010, start of data taking with full detector May 2011
- Data acquired during the construction phase has been analyzed
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

Strings	Dataset
1	2005-2006
9	2006-2007
22	2007-2008
40	2008-2009
59	2009-2010
73 + 6	2010-2011
78 + 8	2011 - .....



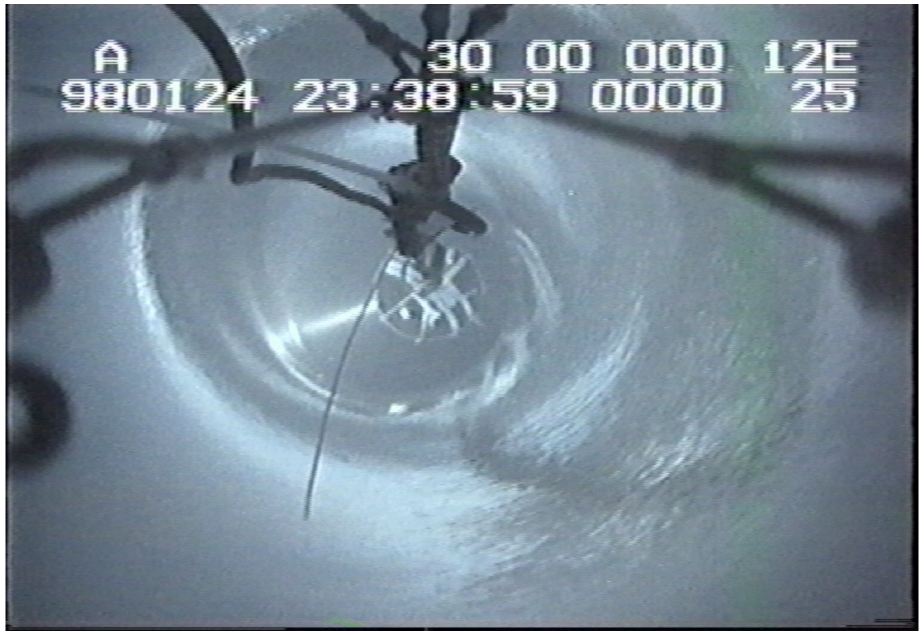
The Ice

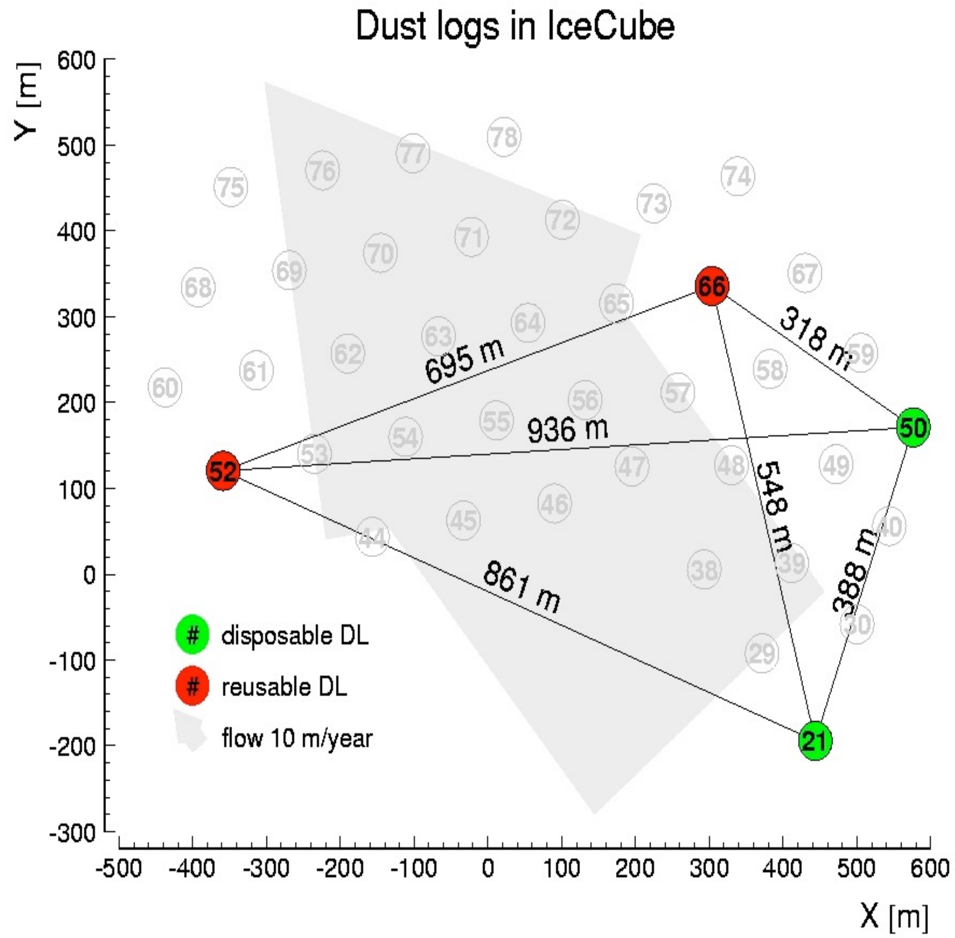


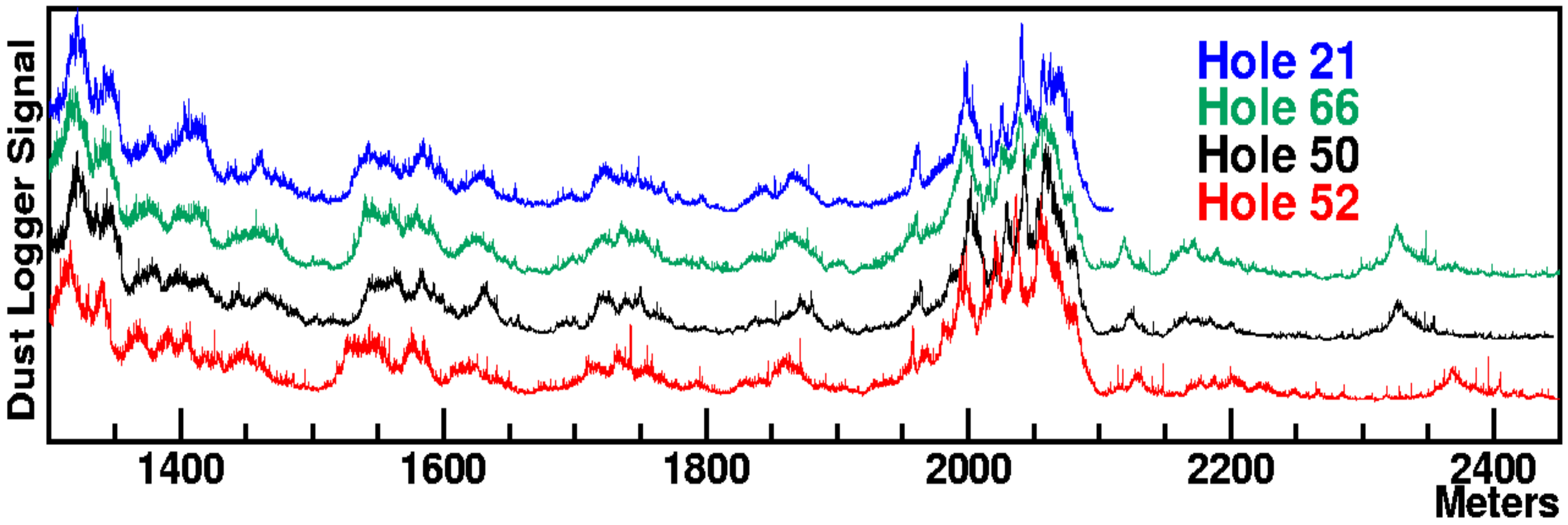
Major calibration efforts resulted in a very precise understanding of the ice surrounding the IceCube detector

- Calibration Sources:
  - 12 LED flashers on each DOM
  - In-Ice Calibration Laser
  - Cosmic Rays
  - One pair of Camera DOMs

absorption length ~ 210m
scattering length ~20-40m



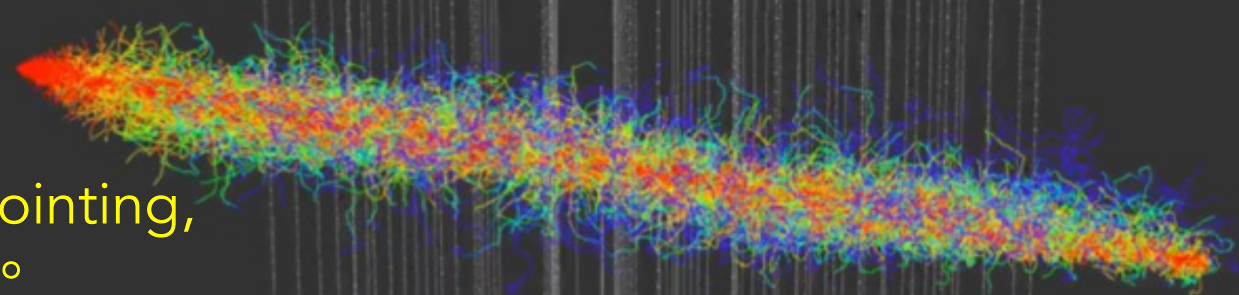




Event Topologies in IceCube

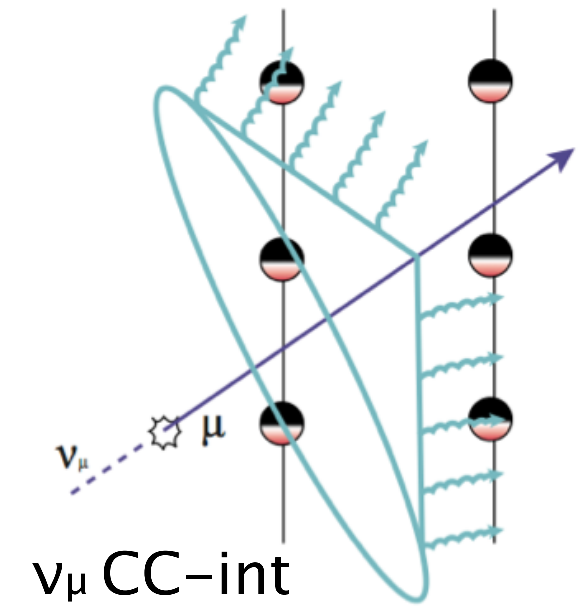
Track topology

(e.g. induced by muon neutrino)



Good pointing,
0.2° - 1°

Lower bound on energy for through-going events



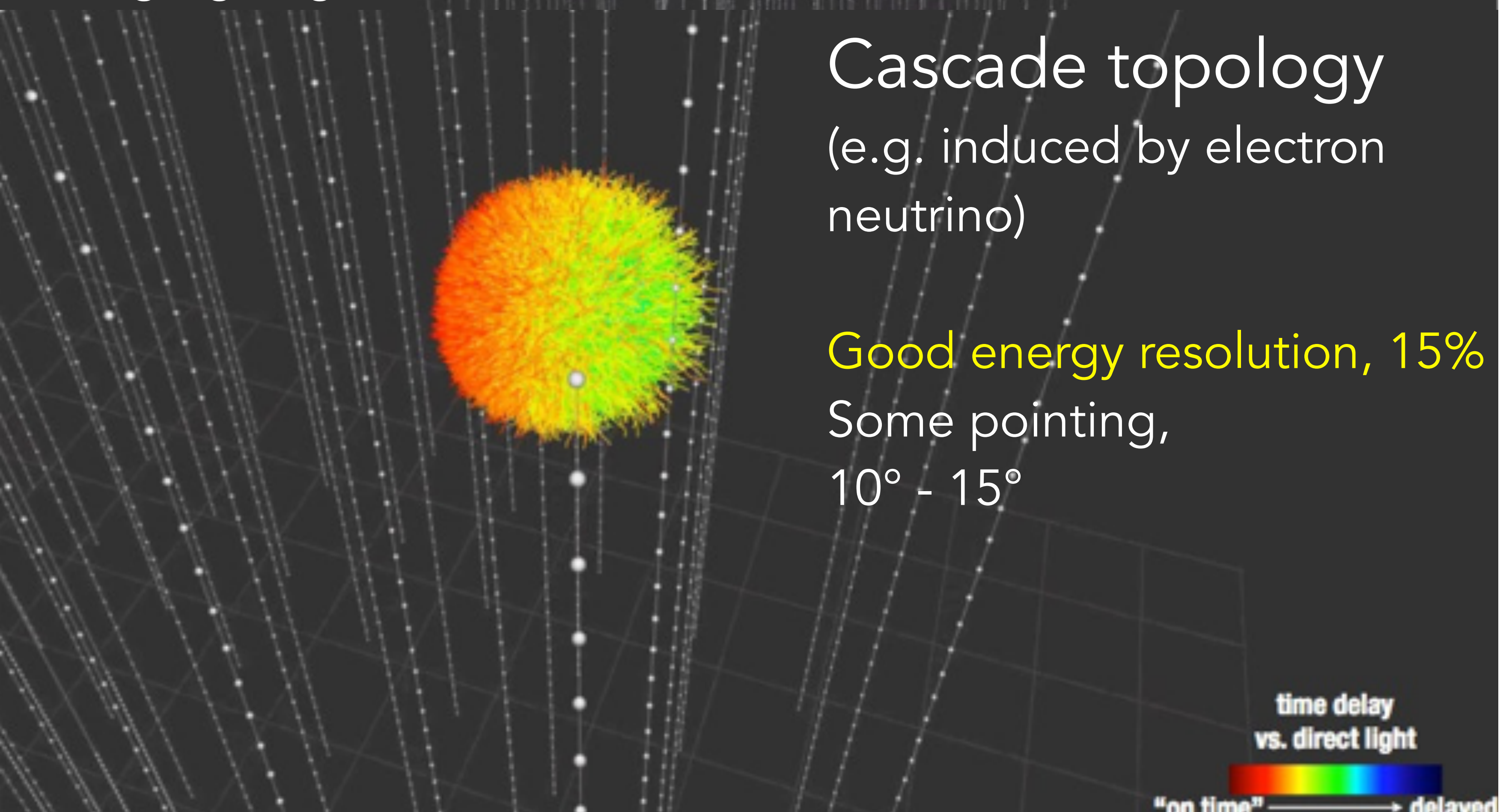
ν_μ CC–int

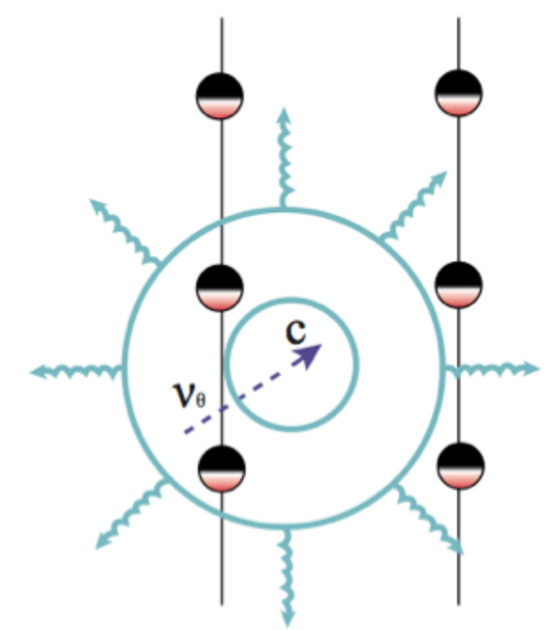
Cascade topology

(e.g. induced by electron neutrino)

Good energy resolution, 15%

Some pointing,
10° - 15°



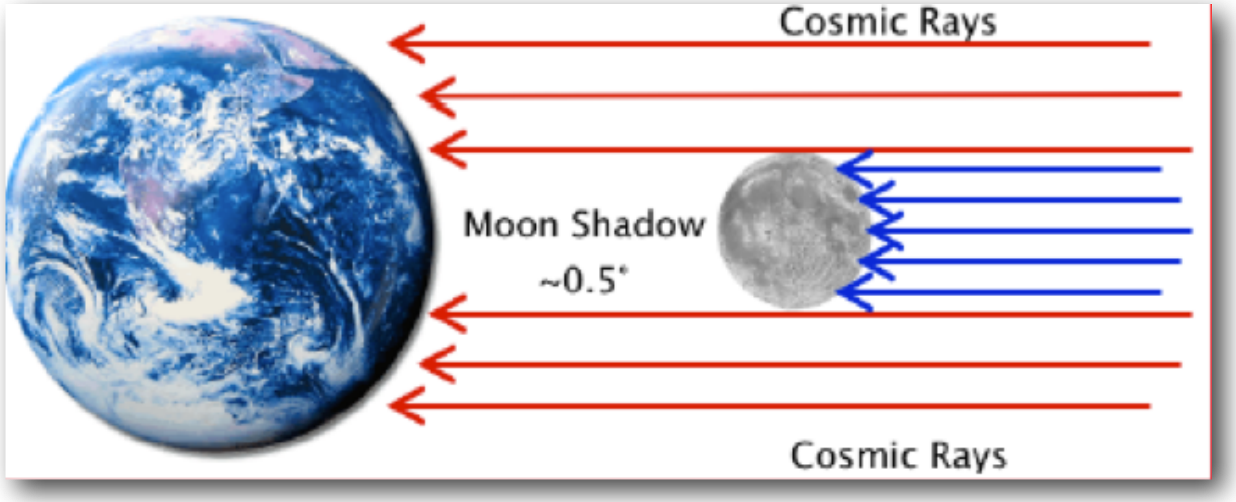


ν_e ν_τ CC–int & ν_i NC–int

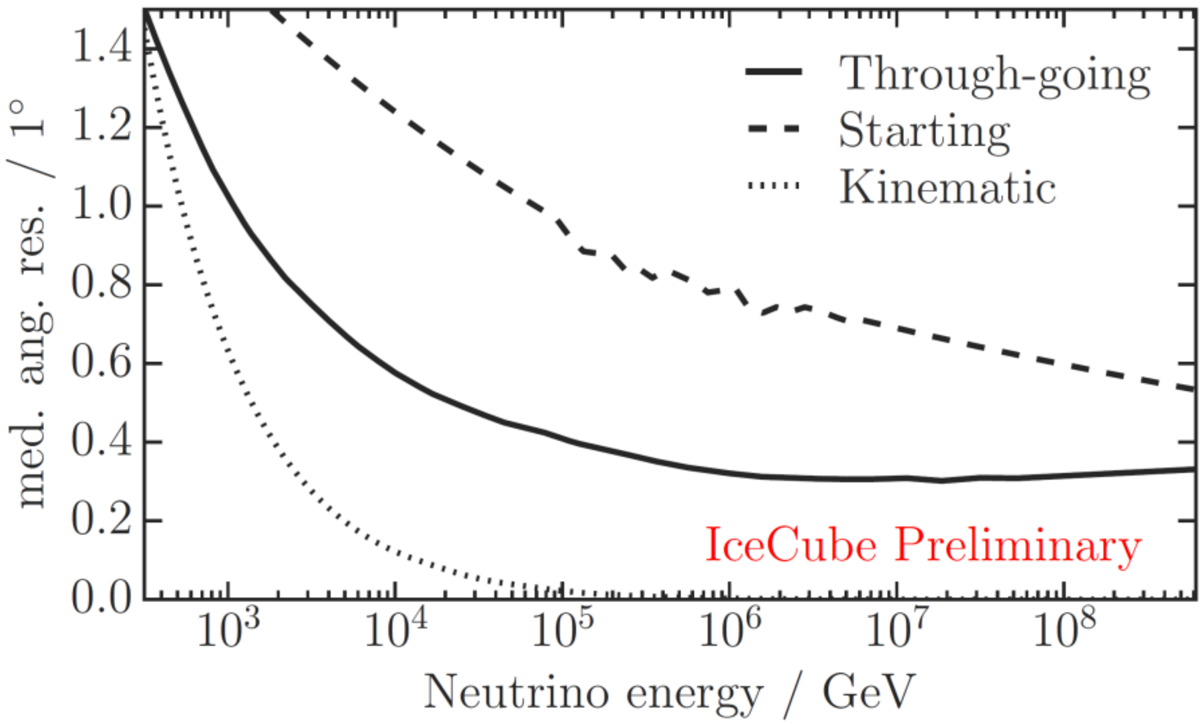
Calibration and Performance

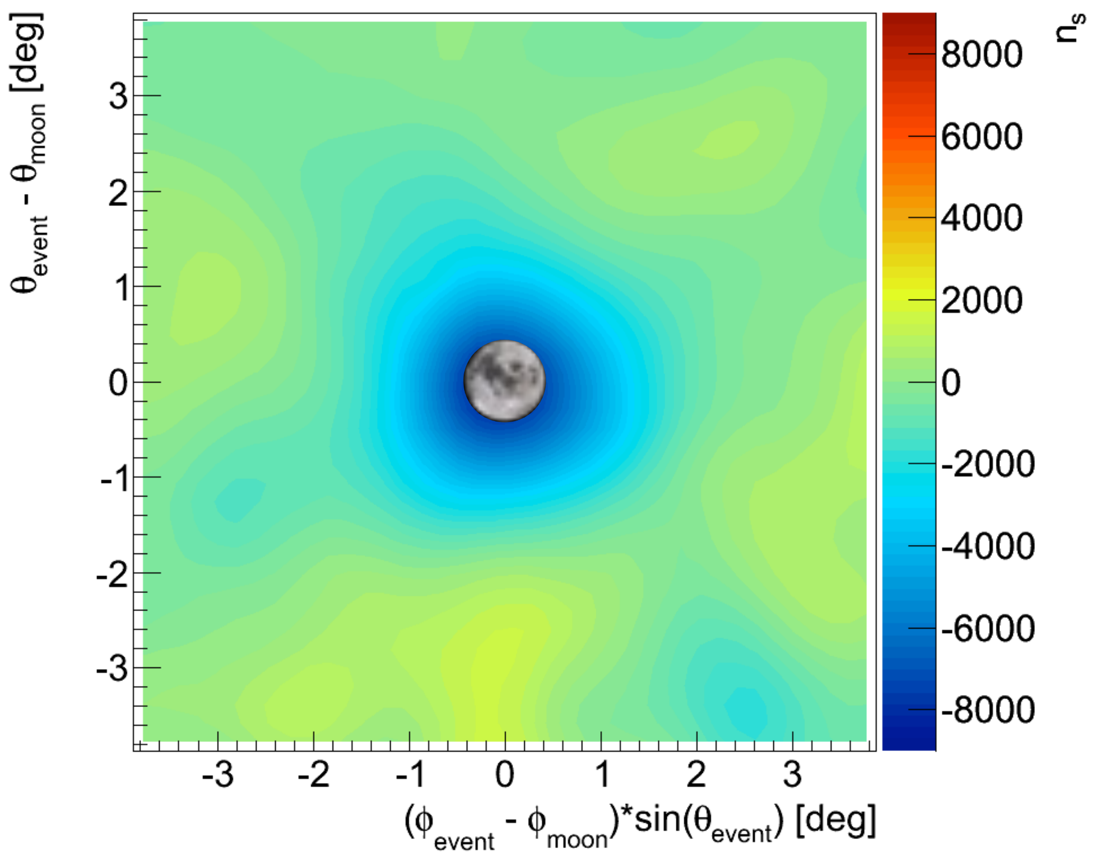
Physical Review D89 (2014) 102004

- Calibration Sources:
  - 12 LED flashers on each DOM
  - In-Ice Calibration Laser
  - Cosmic Rays
  - Moon Shadow
  - Atmospheric Neutrinos
  - Minimum-ionizing Muons



- Moon blocks cosmic rays - Observed muon deficit 14σ significance
  - systematic pointing error <0.1°

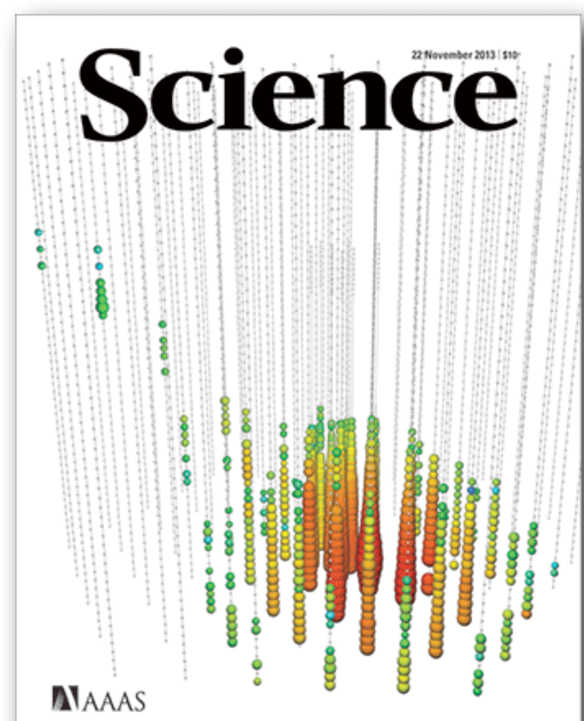


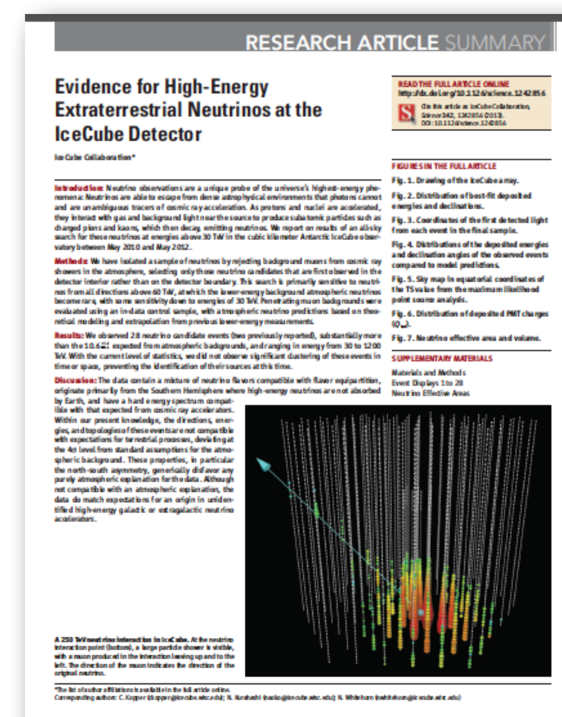


IceCube Observations

Scientific Scope

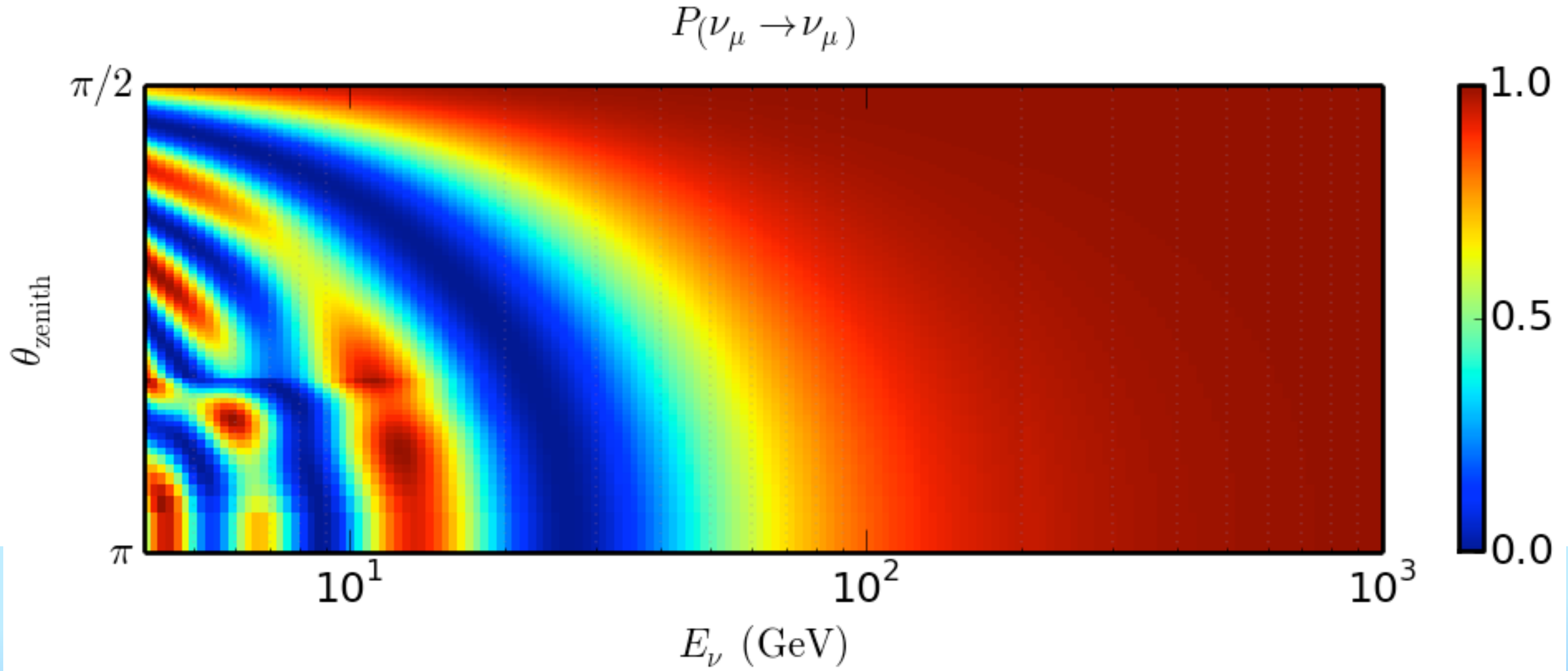
- ASTROPHYSICS
  - point sources of ν's (SNR, AGN …), extended sources
  - transients (GRBs, AGN flares …)
  - diffuse fluxes of ν's (all sky, cosmogenic, galactic plane …)
- COSMIC RAY PHYSICS
  - energy spectrum around "knee", composition, anisotropy
- DARK MATTER
  - indirect searches (Earth, Sun, galactic center/ halo)
- EXOTIC SOURCES OF ν'S
  - magnetic monopoles
- PARTICLE PHYSICS
  - ν oscillations, sterile ν's
  - charm in CR interactions
  - violation of Lorentz invariance
- SUPERNOVAE (galactic/LMC)
- GLACIOLOGY & EARTH SCIENCE




RESEARCH ARTICLE SUMMARY

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

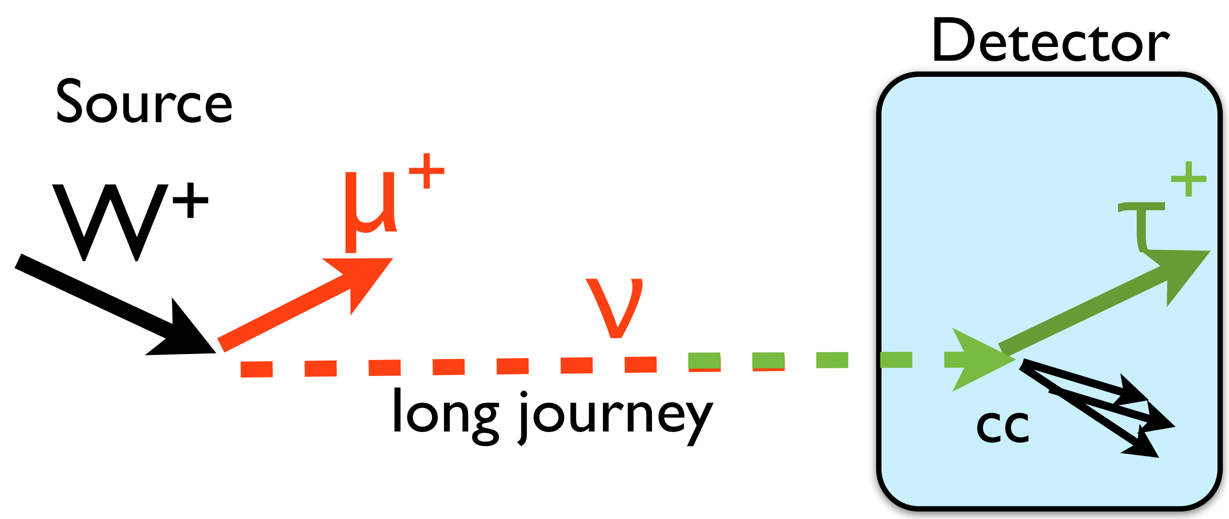
IceCube Collaboration*

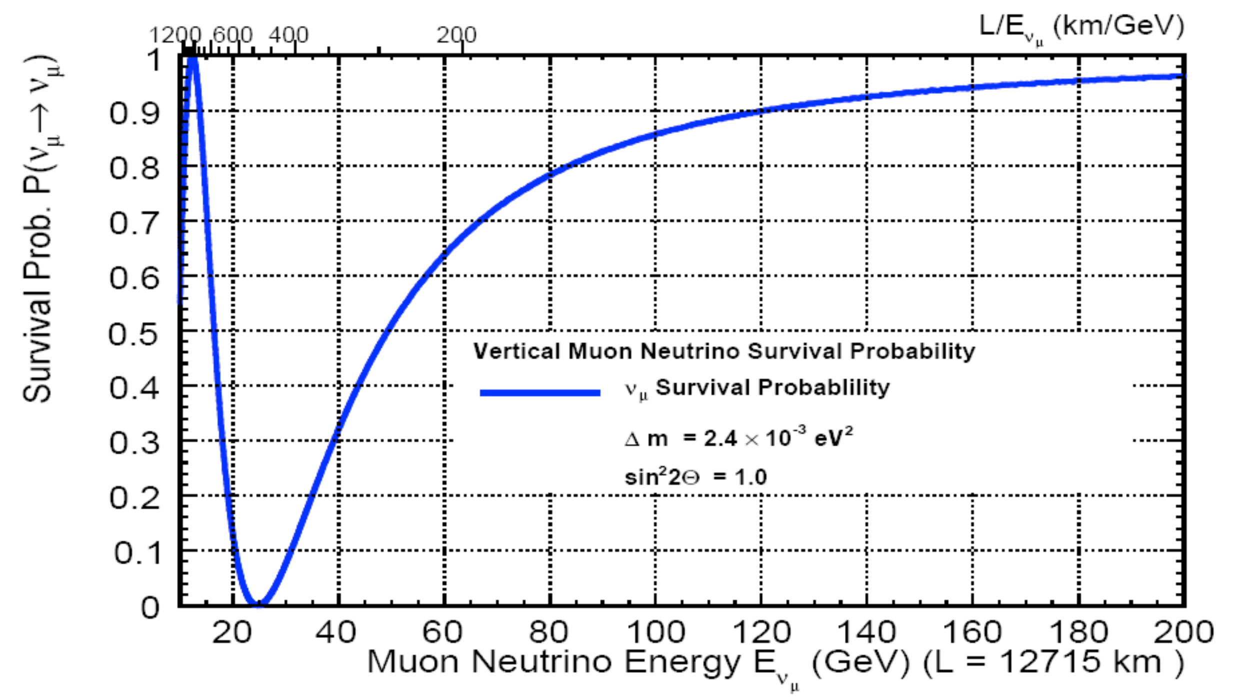


Neutrino Oscillations in IceCube

Neutrino Oscillations

- Neutrinos come in three different flavors: ν_e, ν_μ, ν_τ
- A neutrino created as one flavor can change into a different flavor
- This phenomenon (neutrino oscillations) depends on the energy of the neutrino and the distance traveled
- It further depends on the “potential” the neutrino travels through





$$P(\nu_\alpha \to \nu_\beta) = 4\sin^2\theta\cos^2\theta\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

oscillation probability

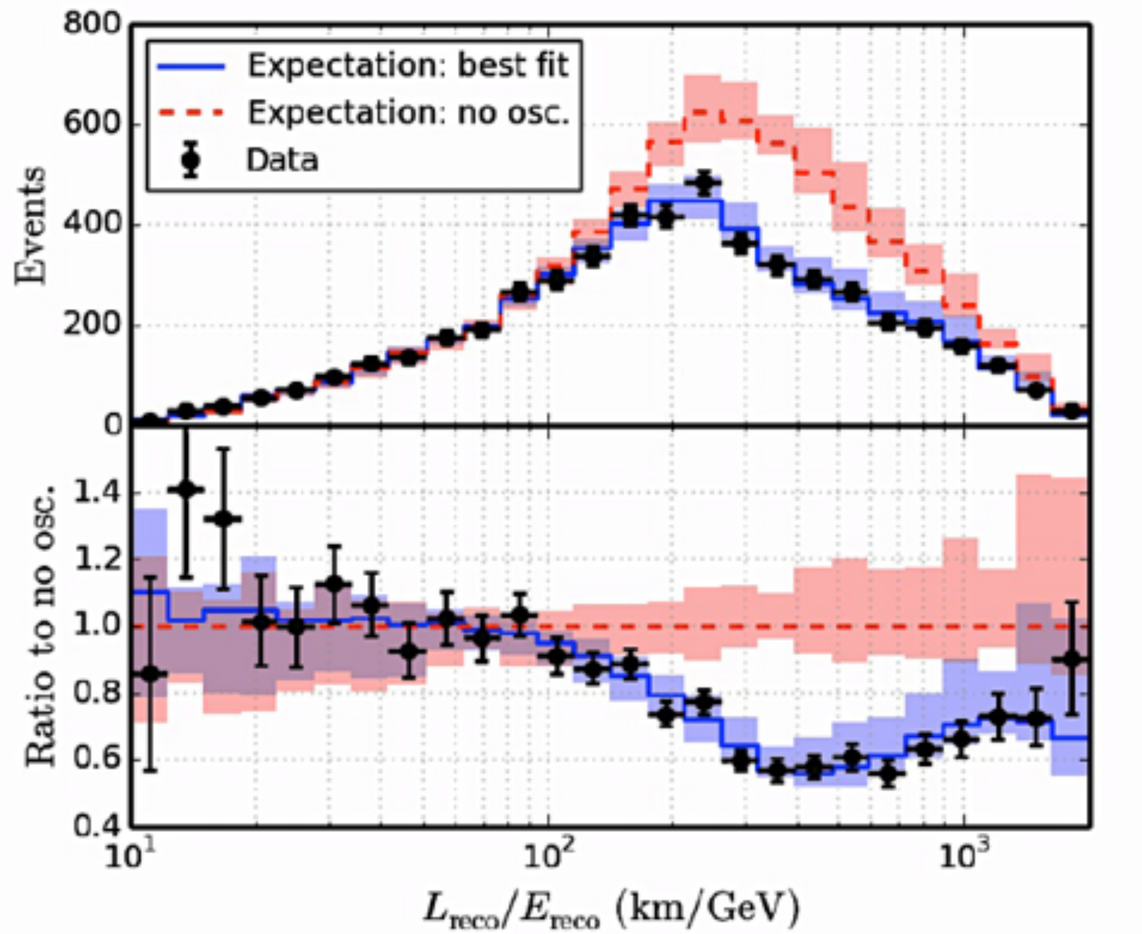
oscillation parameters

energy

distance

IceCube Neutrino Oscillations

IceCube Phys. Rev.D91:072004 (2015)



- select
  starting events
  clear μ tracks
  rely on direct photons

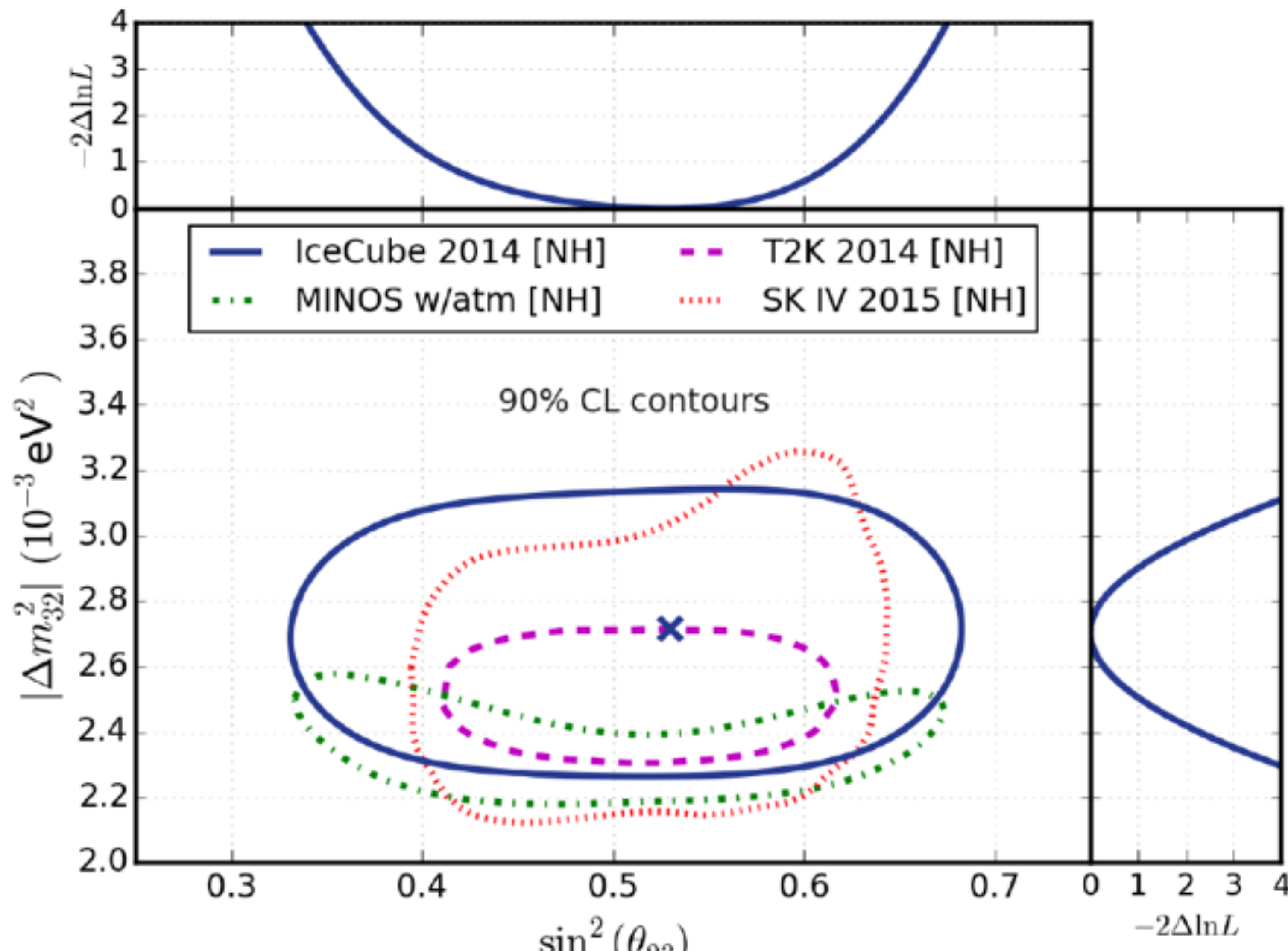
- 5174 events observed cf. 6830 expected if no oscillation

- perform 2D fit in *E* and *cos(θ)*

[IceCube, Phys.Rev.D91:072004 (2015)]

- competitive result (3 years)
- will improve further

$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$



PINGU

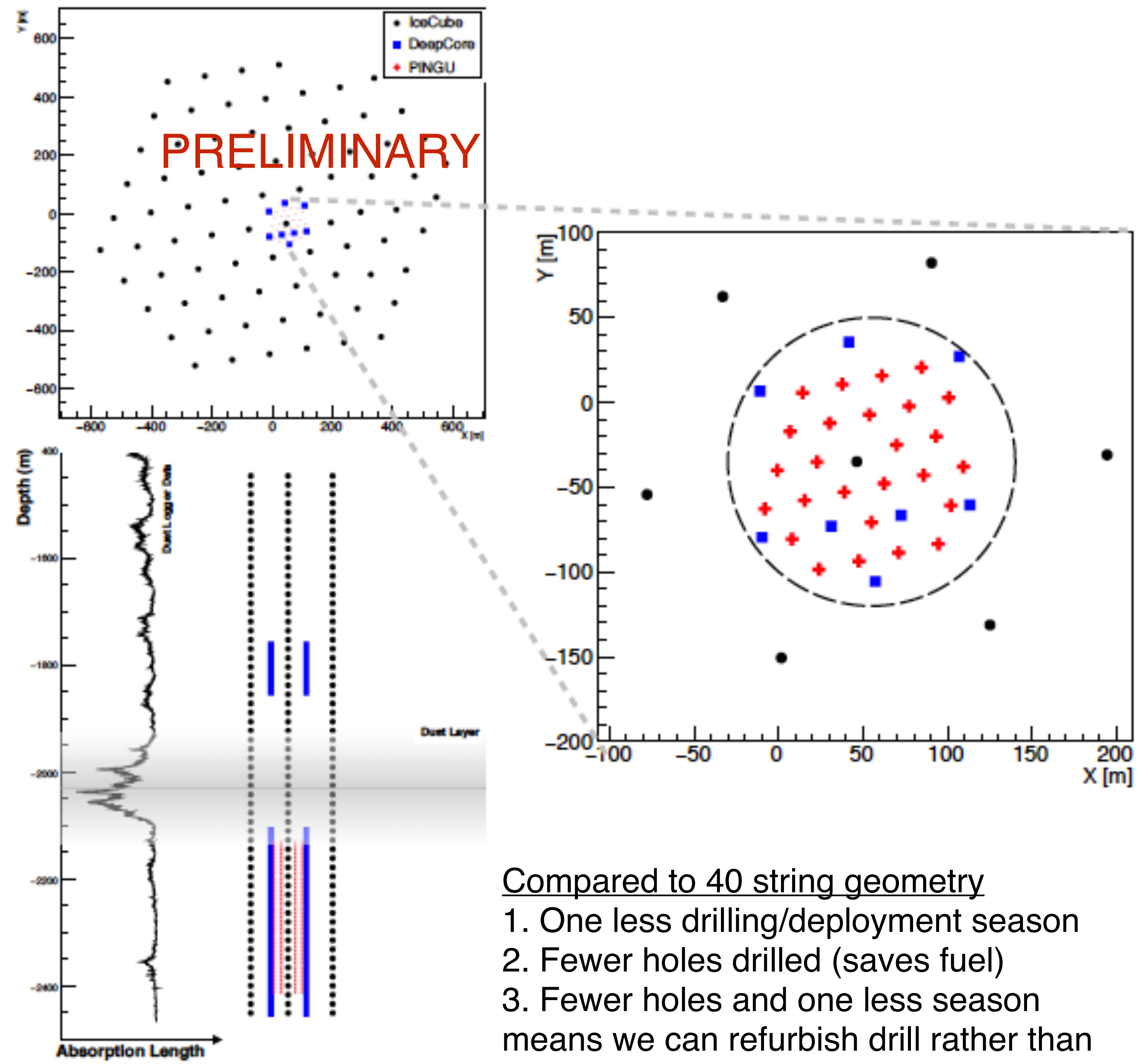
PINGU - Precision IceCube Next Generation Upgrade

IceCube PINGU Collaboration arXiv:1401.2046

- PINGU upgrade plan
  - Instrument a volume of about 5MT with 20-26 strings
  - Rely on well established drilling technology and photo sensors
  - Create platform for calibration program and test technologies for future detectors
- Physics Goals:
  - Precision measurements of neutrino oscillations (mass hierarchy, ...)
  - Test low mass dark matter models

Updated LOI later this year
Proposal in preparation

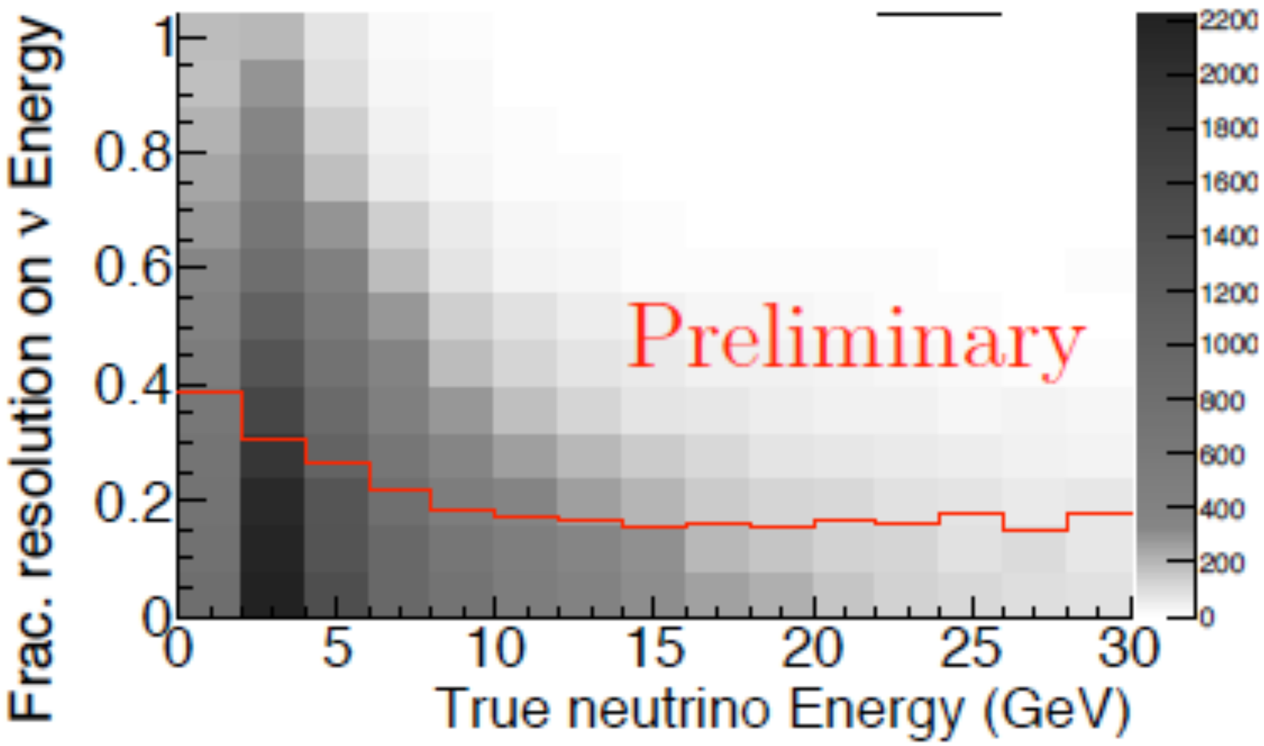
New PINGU Geometry



Compared to 40 string geometry
1. One less drilling/deployment season
2. Fewer holes drilled (saves fuel)
3. Fewer holes and one less season means we can refurbish drill rather than build a new one.

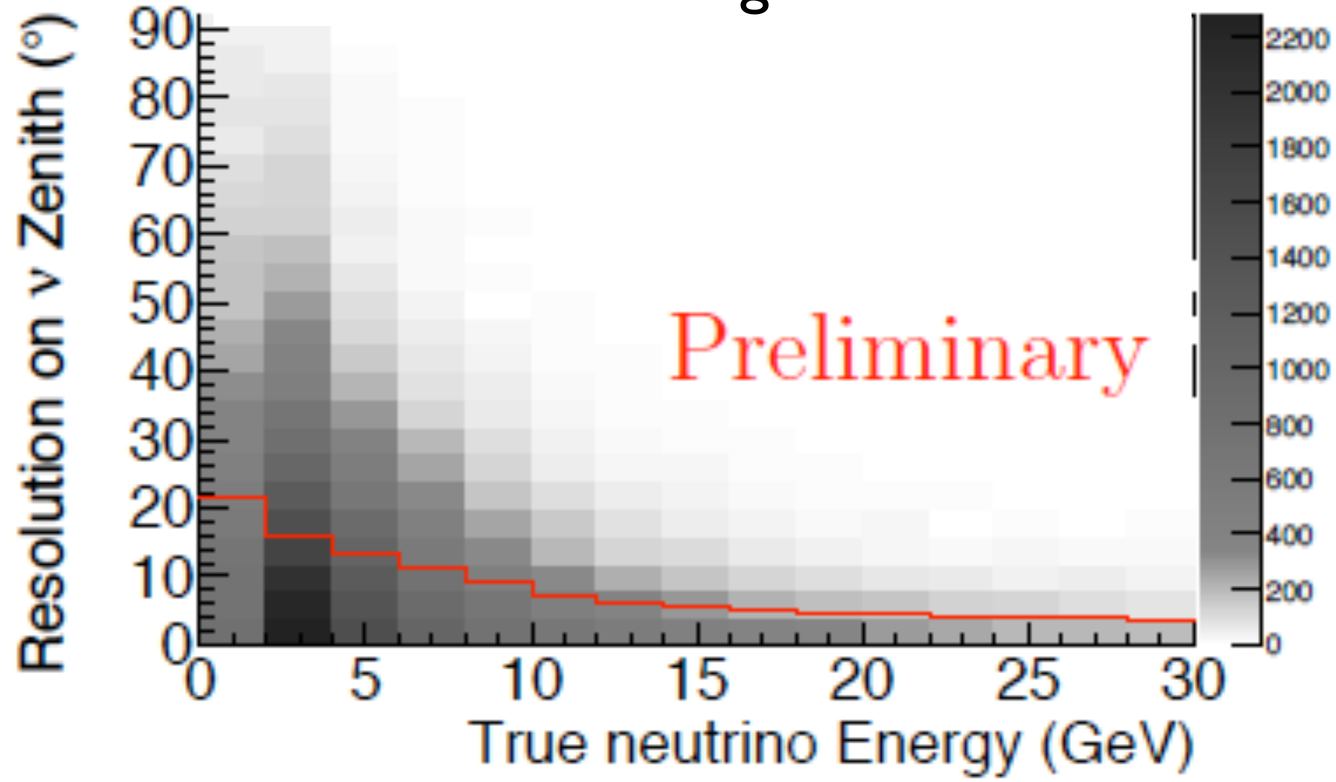
PINGU Detector Performance

Muon Neutrino Energy Resolution



$|E_{\nu,\mathrm{reco}} - E_{\nu,\mathrm{true}}|/E_{\nu,\mathrm{true}}$ vs. $E_{\nu,\mathrm{true}}$.

Muon Neutrino Angular Resolution

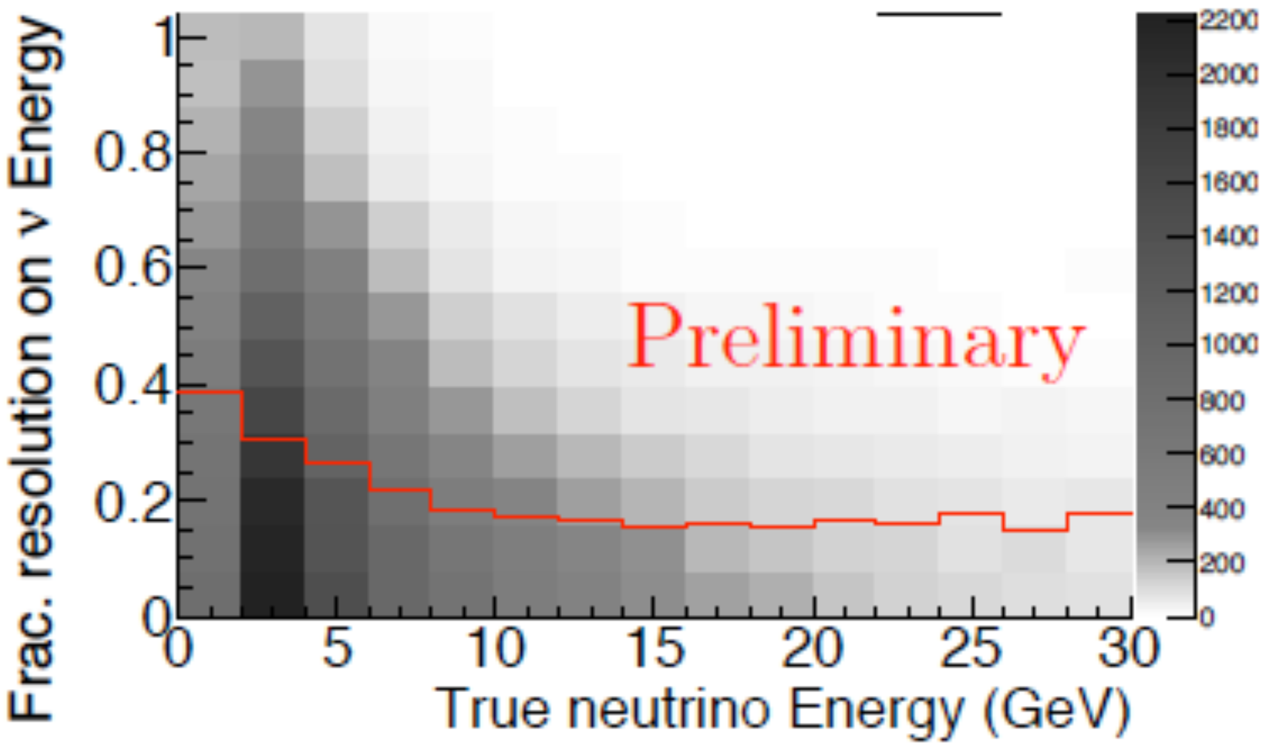


$|\theta_{\nu,\mathrm{true}} - \theta_{\nu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.

- PINGU performance using existing algorithms for IceCube
  - More computationally intensive algorithms are expected to further improve performance

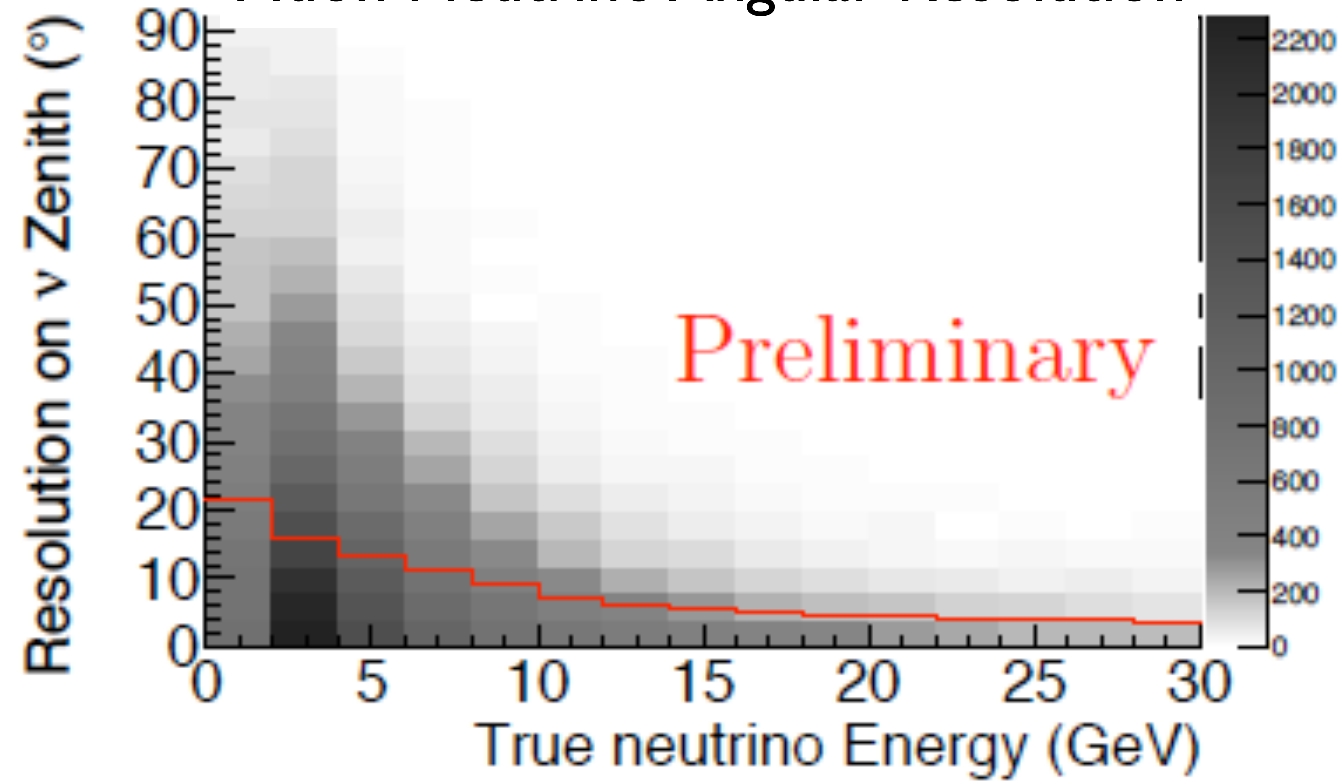
Parameterize Detector Performance

Muon Neutrino Energy Resolution



$|E_{\nu,\mathrm{reco}} - E_{\nu,\mathrm{true}}|/E_{\nu,\mathrm{true}}$ vs. $E_{\nu,\mathrm{true}}$.

Muon Neutrino Angular Resolution



$|\theta_{\nu,\mathrm{true}} - \theta_{\nu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.

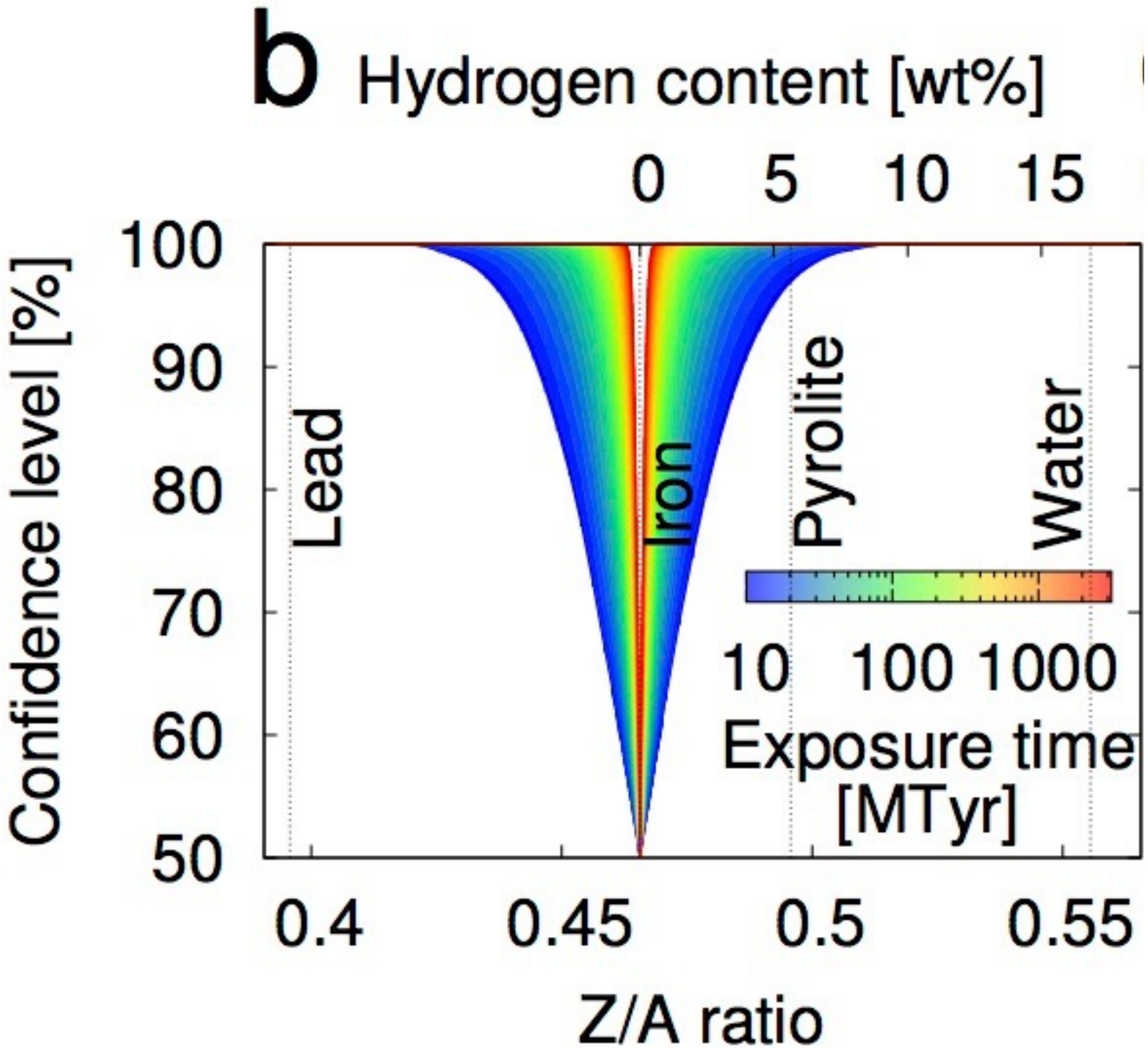
Energy resolution
$\alpha = \Delta E/E$

Zenith angle resolution
$\beta = \Delta\Theta \times (E[\mathrm{GeV}])^{0.5}$

We adopt a value of α=0.2 as benchmark

We adopt $\Delta\Theta$=0.25 as benchmark

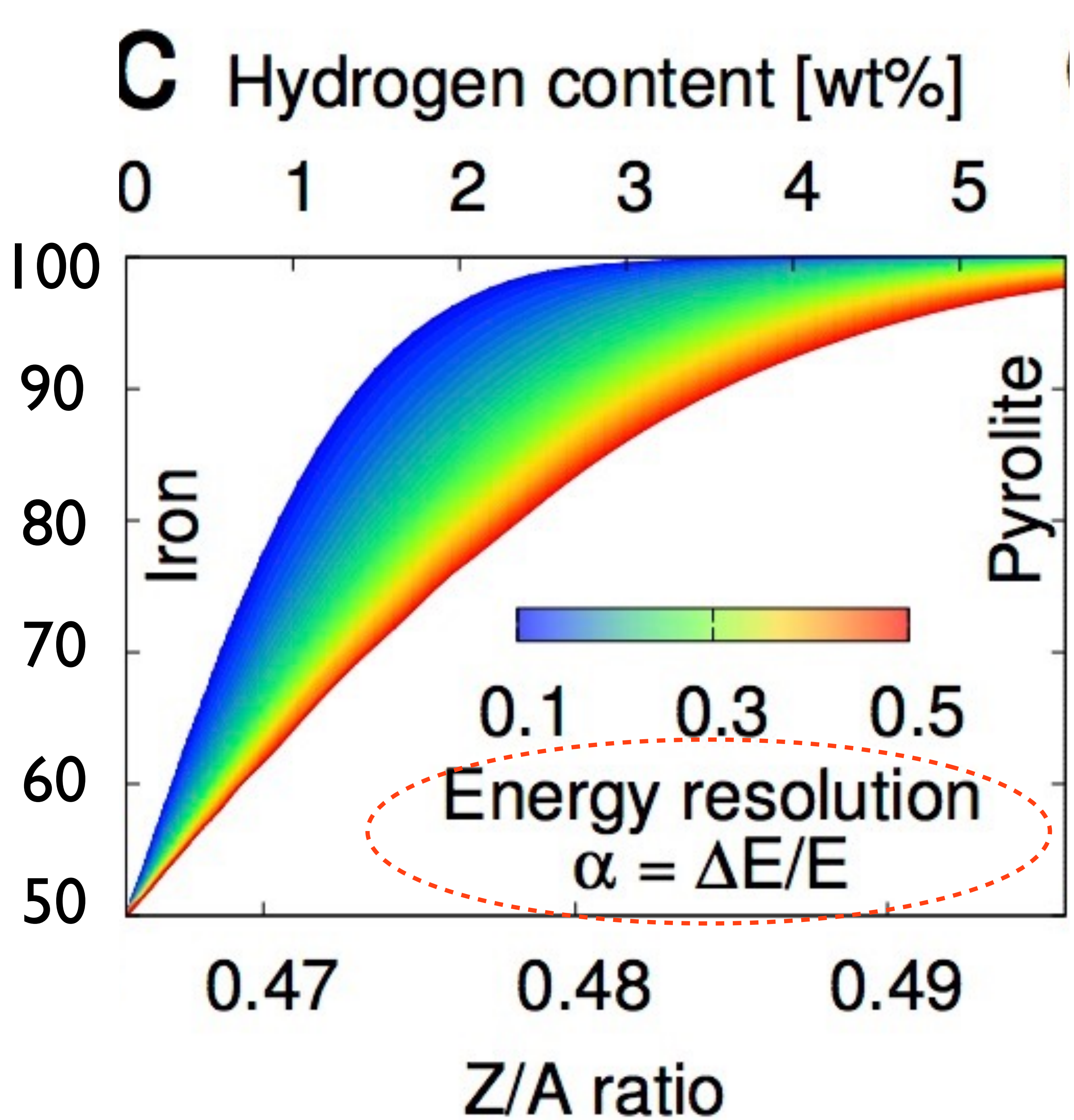
Sensitivity

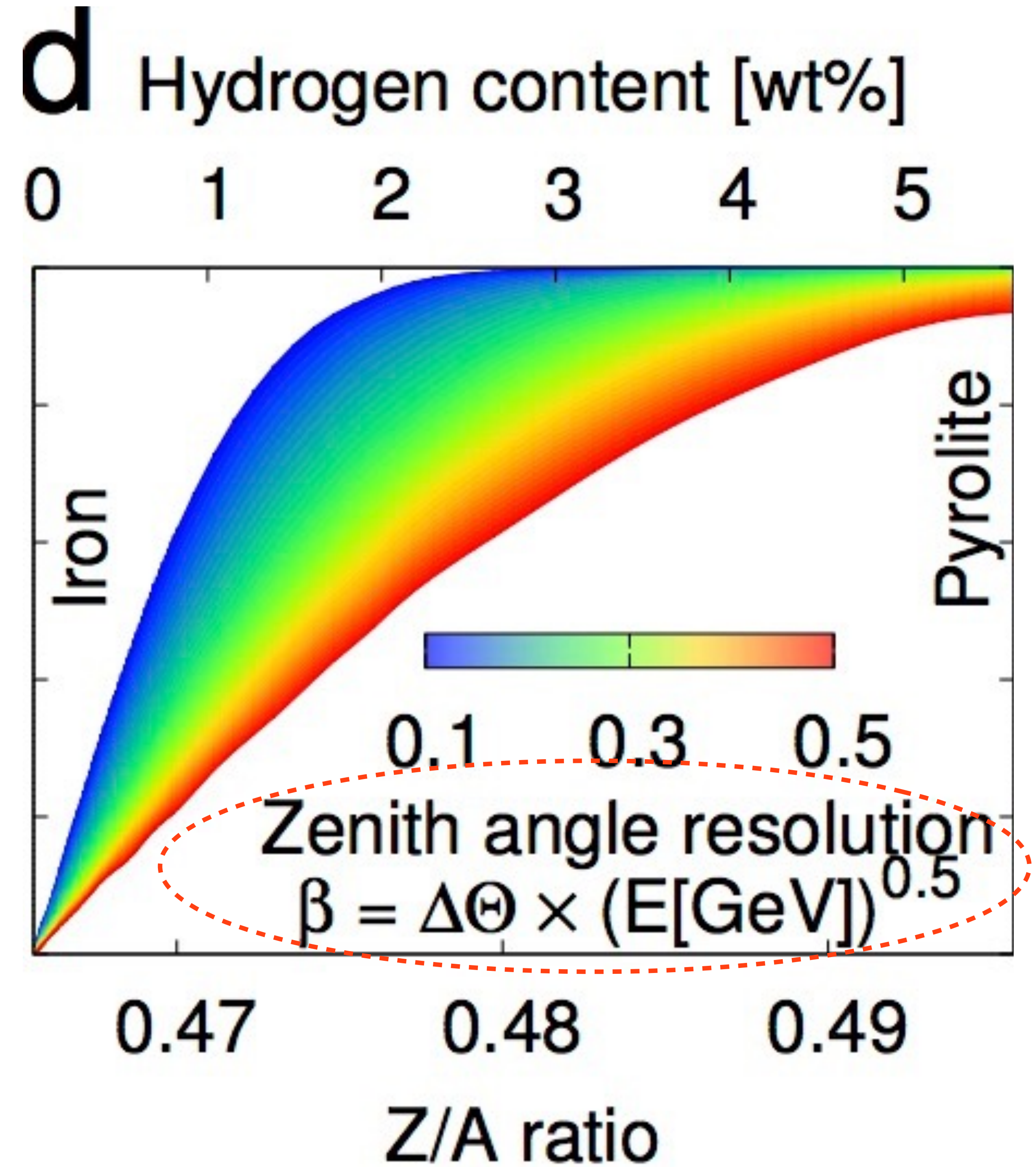


- A few years of PINGU data would yield a few 10MTyrs
- Probe ~2-4wt% hydrogen
- Reject extreme core composition models

How can we increase sensitivity ?

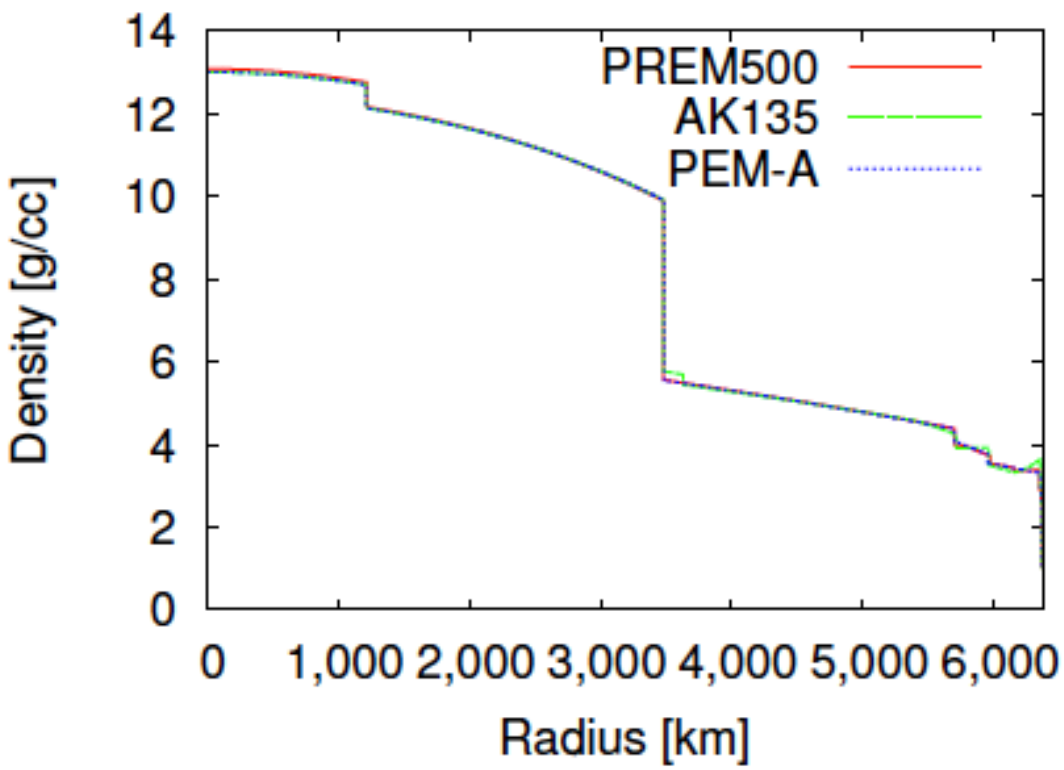
- Dependence on the angular resolution and energy resolution:

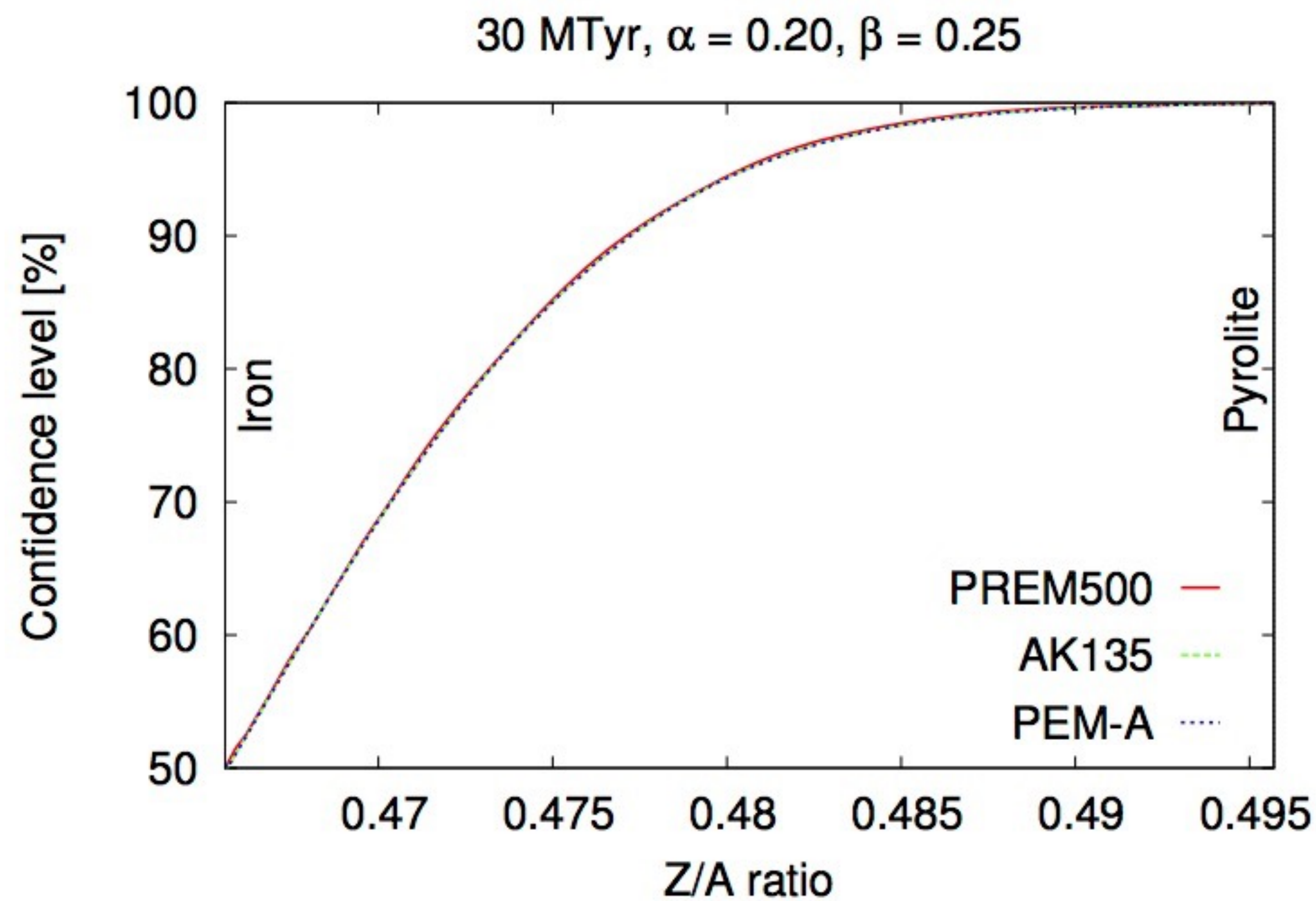


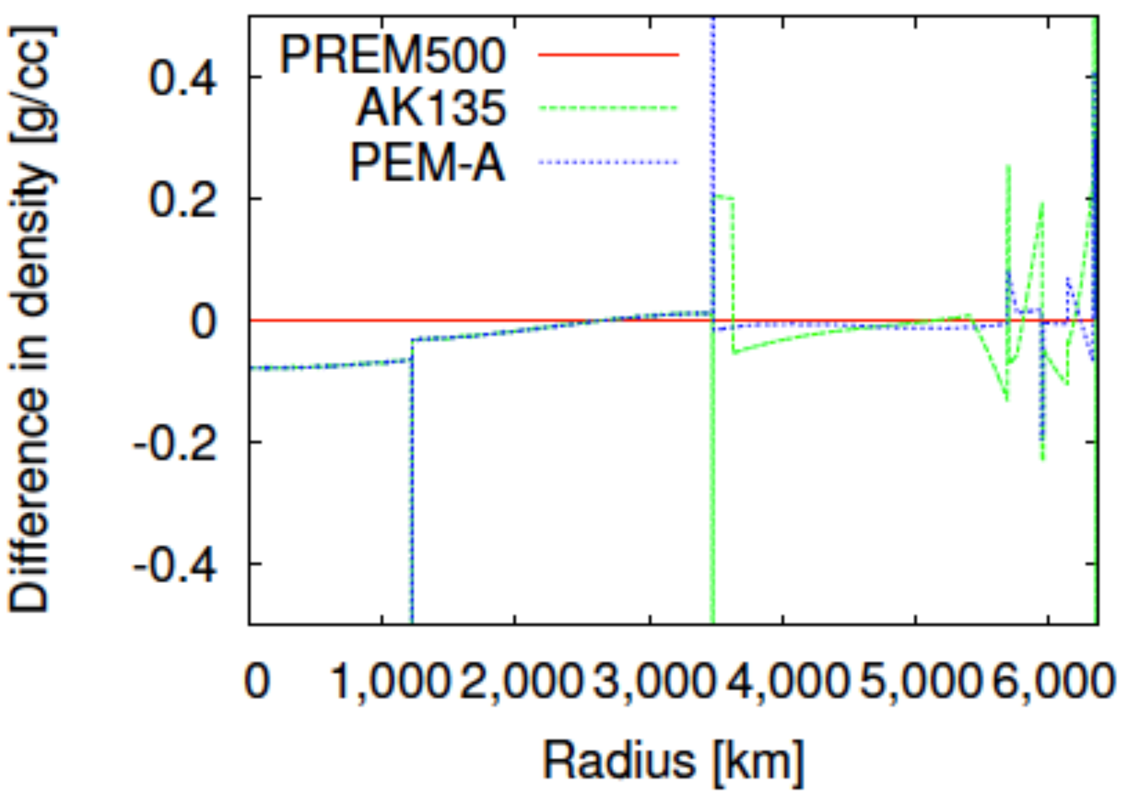


Rott & Taketa 2015

Uncertainty due to Earth model







Uncertainty due to the Earth mass density profile is negligible

PREM500 - Dziewonski, A. & Anderson, D. Preliminary reference Earth model. Physics of the Earth and Planetary Interiors 25, 297–356 (1981).

AK135 - Kennett, B., Engdahl, E. & Buland, R. Constraints on seismic velocities in the earth from travel times. Geophysical Journal International 122, 108–124 (1995).

PREM-A - Dziewonski, A., Hales, A. & Lapwood, E. Parametrically simple earth models consistent with geophysical data. Physics of the Earth and Planetary Interiors 10, 12–48 (1975).

PINGU LOI *arxiv:1401.2046*

In PINGU we expect approximately **30000** upward-going neutrinos per year, with many coming from the energy region between **5–10 GeV**.

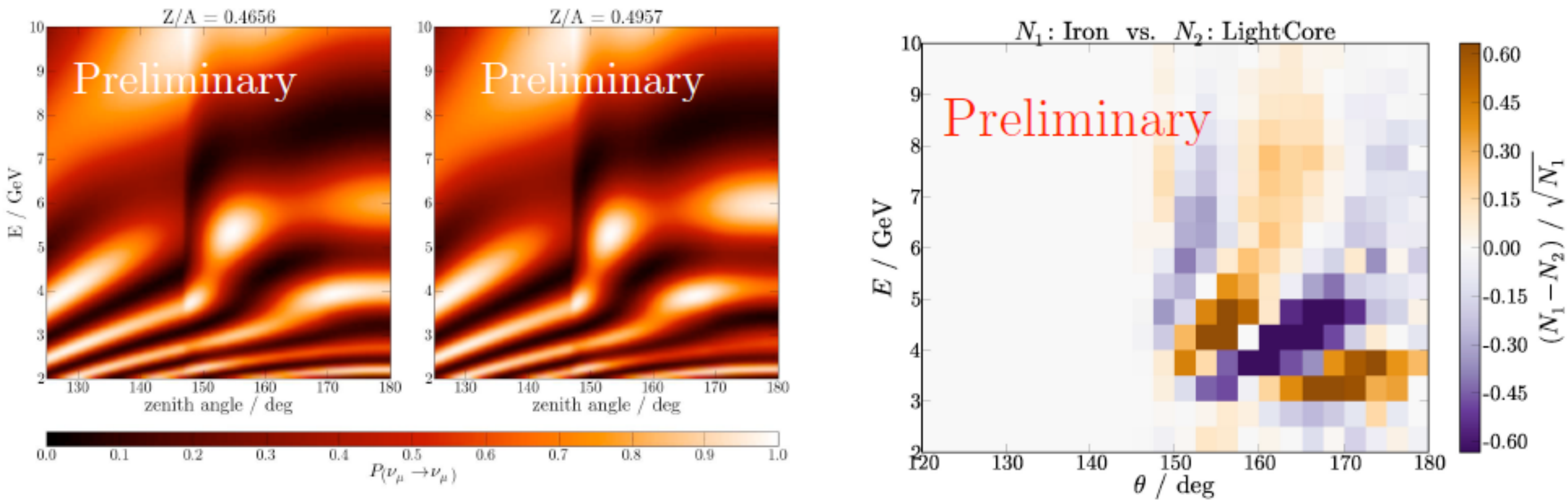
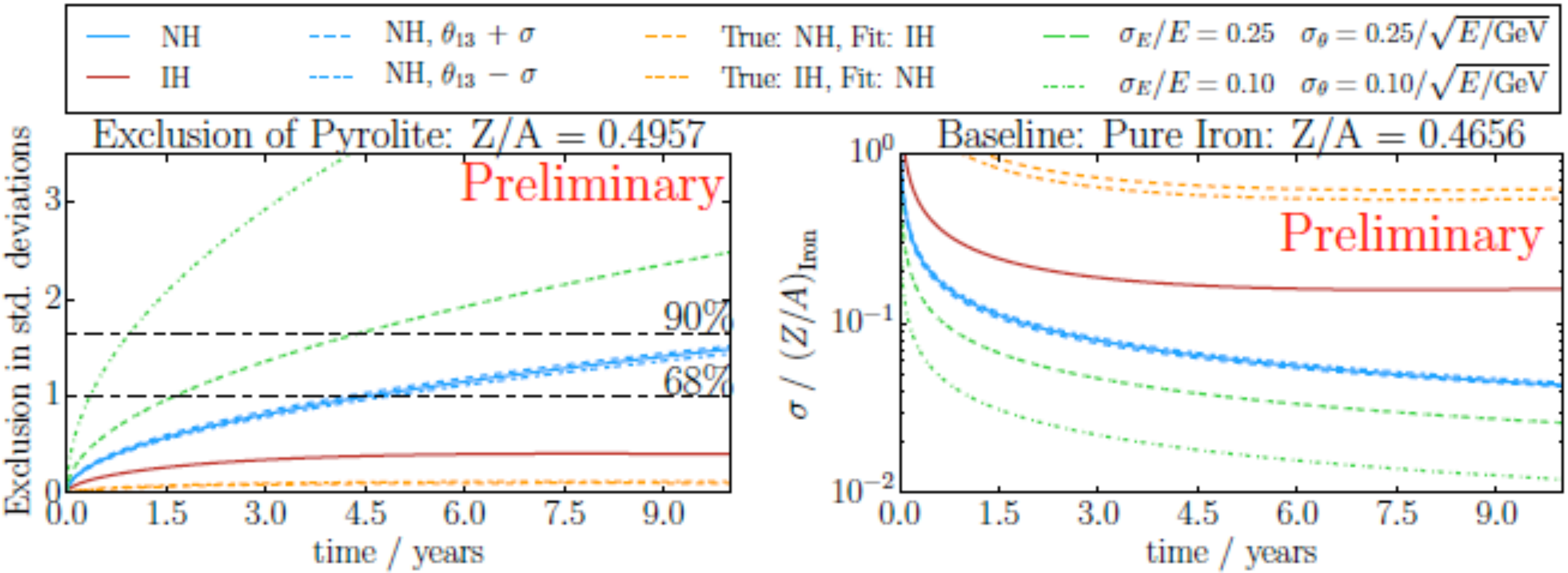


Figure 25: The impact of a changed core composition on the muon-neutrino survival probabilities is demonstrated by comparing the left most figure (pure iron core) and the middle figure (iron mixed with lighter elements). Signature of a pure iron Earth core with respect to a model assuming the same composition for mantle and core are shown on the right. The true neutrino energy and direction are shown for one year of data with 35% electron neutrino contamination.

PINGU Sensitivity



$$\sigma_E = A_E\, E \text{ and } \sigma_\theta = A_\theta \,/\, \sqrt{E/\mathrm{GeV}}$$

Baseline: $\sigma_{E_\nu} \approx 0.33\, E_\nu$

Parametric: A_i= 0.25 and A_i= 0.10

to be updated with full PINGU detector simulation

Neutrino Oscillation Tomography

Goals

(1) Demonstrate feasibility of neutrino oscillation tomography →

(2) Perform first neutrino oscillation tomography measurement →

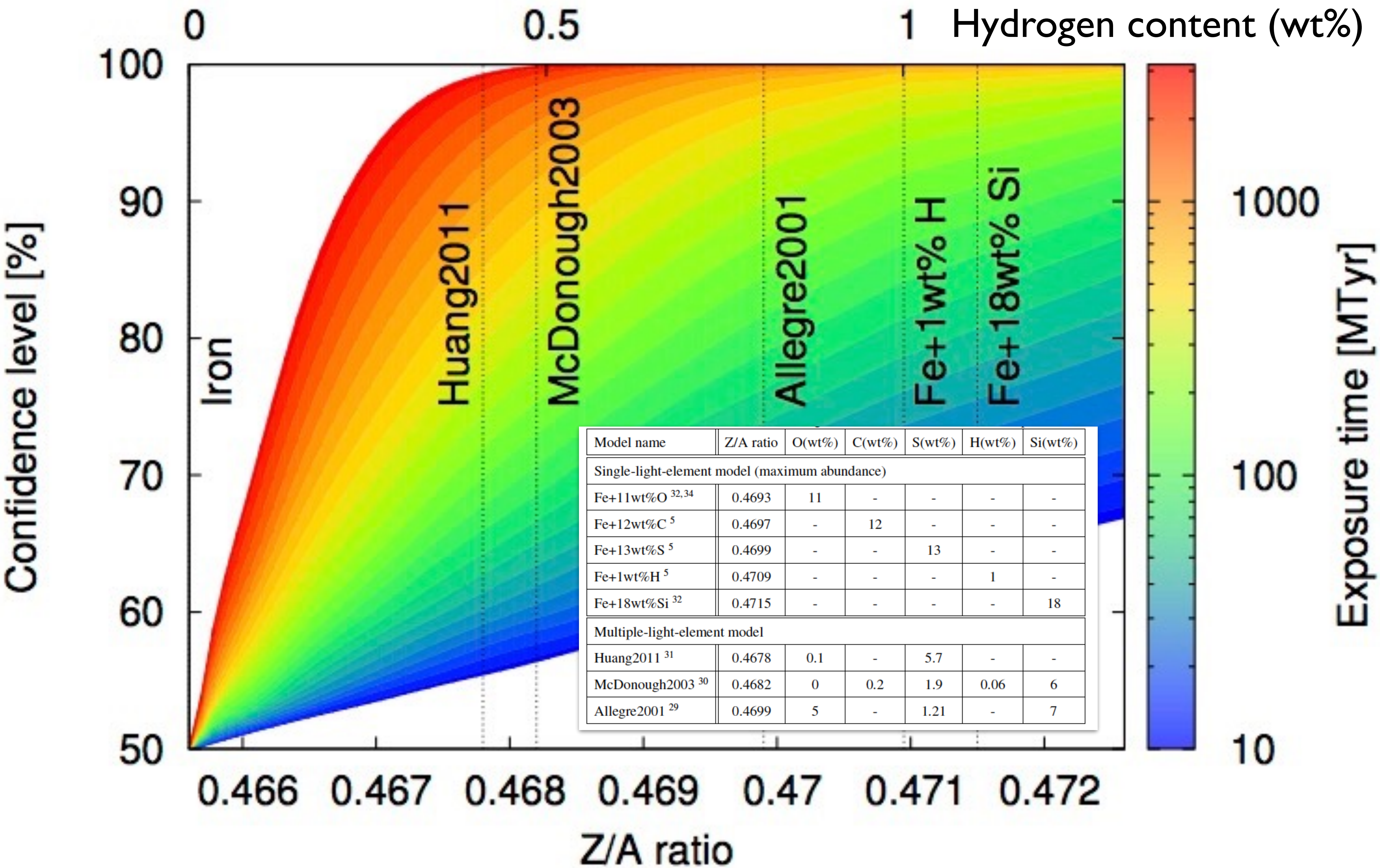
(3) Distinguish specific Earth composition models via oscillation tomography →

Detectors

- Now
  - Feasibility of very large volume neutrino detectors has been demonstrated (IceCube, ...)
  - High-precision neutrino detectors demonstrated (Super-K, ...)
- Near future
  - ~1MT detectors with 2-10GeV neutrino sensitivity (PINGU, ORCA, Hyper-K, Baikal (?) ...)
- More distant future
  - >>10MT detector with 2-10GeV neutrino sensitivity (new detector, augmented PINGU or ORCA)

Rott & Taketa 2015

Distinguishing Outer core models

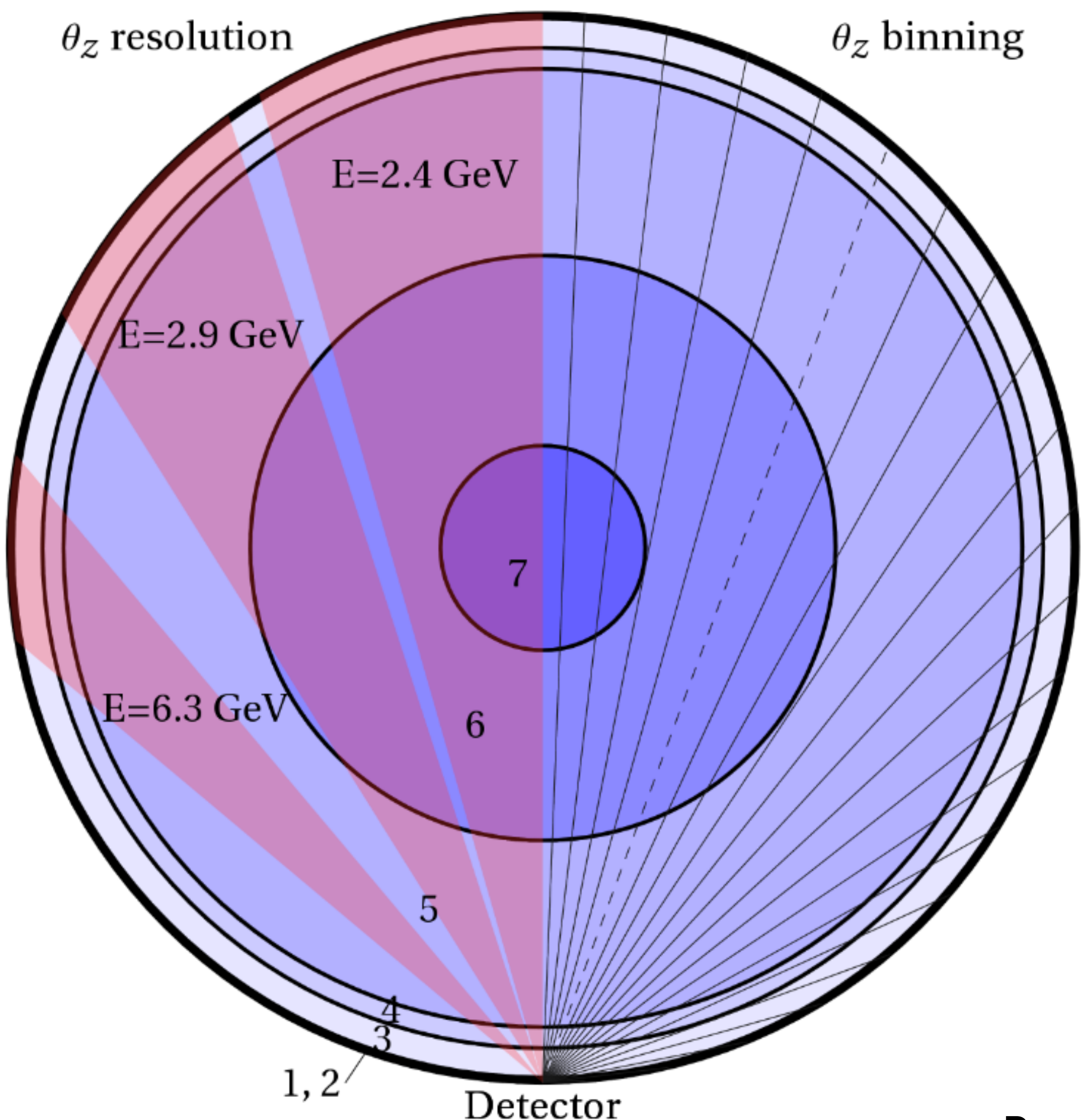


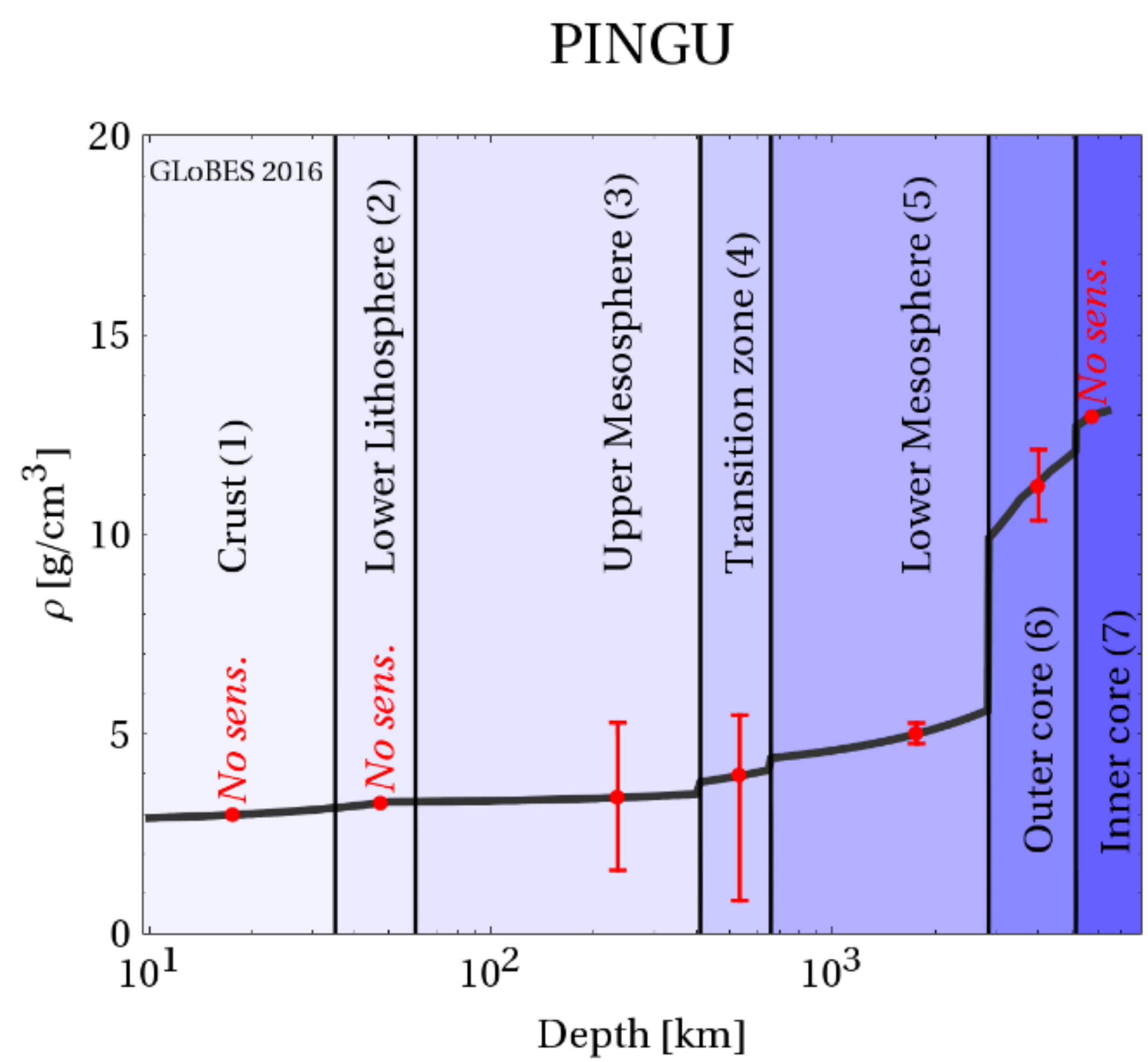
Model name	Z/A ratio	O(wt%)	C(wt%)	S(wt%)	H(wt%)	Si(wt%)
Single-light-element model (maximum abundance)						
Fe+11wt%O [32,34]	0.4693	11	-	-	-	-
Fe+12wt%C [5]	0.4697	-	12	-	-	-
Fe+13wt%S [5]	0.4699	-	-	13	-	-
Fe+1wt%H [5]	0.4709	-	-	-	1	-
Fe+18wt%Si [32]	0.4715	-	-	-	-	18
Multiple-light-element model						
Huang2011 [31]	0.4678	0.1	-	5.7	-	-
McDonough2003 [30]	0.4682	0	0.2	1.9	0.06	6
Allegre2001 [29]	0.4699	5	-	1.21	-	7

Other prospects

W. Winter Nucl.Phys. B908 (2016) 250-267

Density measurements





Excellent sensitivities to the lower mantle density and give a robust lower bound on the outer core density

PINGU and ORCA can provide complementary information due to different locations. Seismic measurements show irregular wave propagation zones in the lower mantle

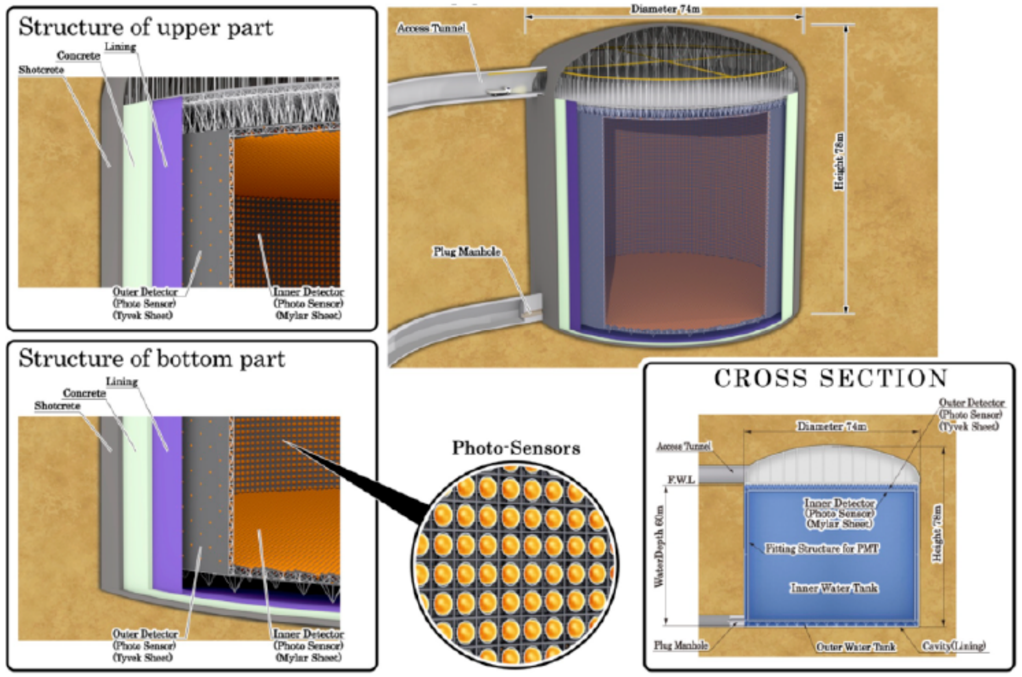
Percentage errors achievable with 10 years of data

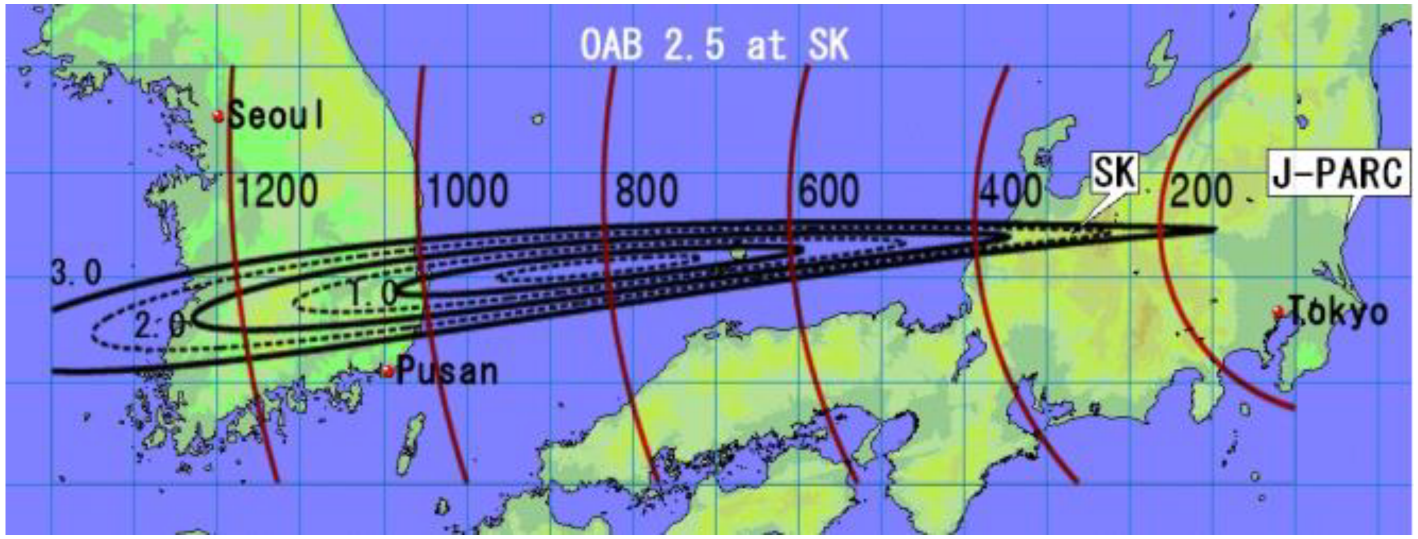
	PINGU		ORCA	
Layer	NO	IO	NO	IO
Crust (1)	No sens.	No sens.	No sens.	No sens.
Lower Lithosphere (2)	No sens.	No sens.	No sens.	No sens.
Upper Mesosphere (3)	-53.4/+55.0	No sens.	-51.2/+53.4	-69.1/+52.2
Transition zone (4)	-79.2/+38.3	No sens./+72.2	-61.2/+35.6	-52.7/+45.8
Lower Mesosphere (5)	-5.0/+5.2	-10.5/+11.6	-4.0/+4.0	-4.7/+4.8
Outer core (6)	-7.6/+8.2	-40.2/No sens.	-5.4/+6.0	-6.5/+7.1
Inner core (7)	No sens.	No sens.	-60.8/+32.9	No sens.

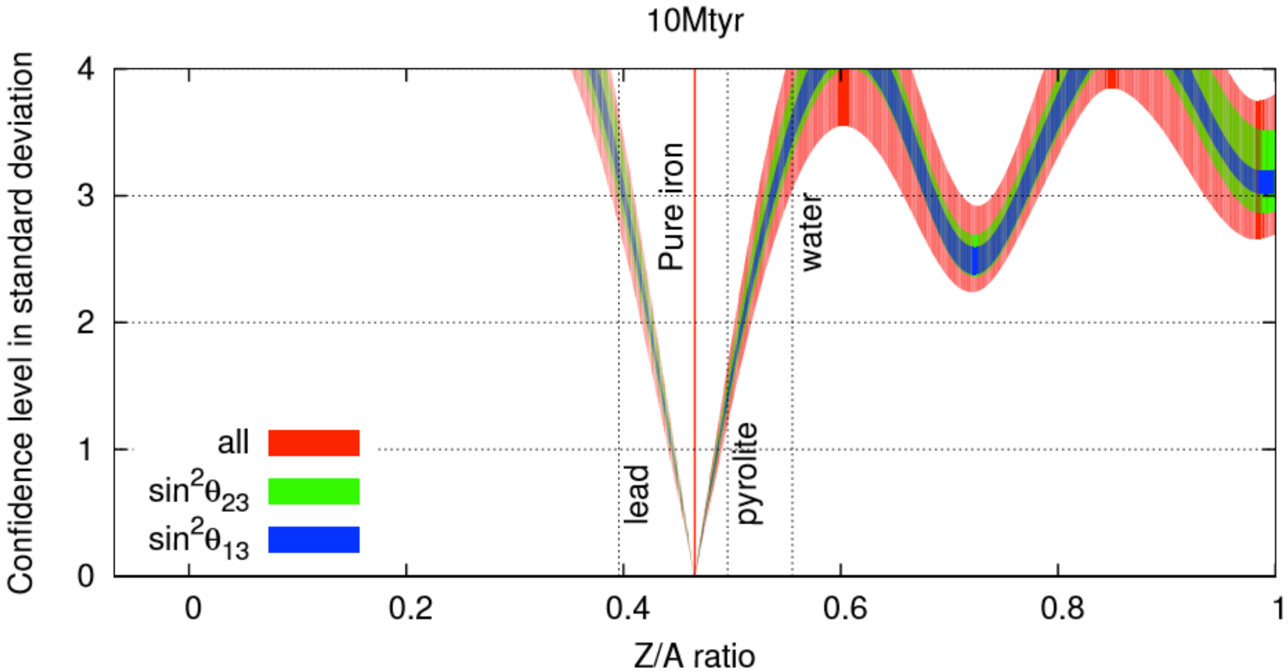
KEK Preprint 2016-21
ICRR-Report-701-2016-1

https://lib-extopc.kek.jp/preprints/PDF/2016/1627/1627021.pdf

Hyper-K Sensitivity







Sensitivity of the electron density of the Earth's core at Hyper-K with 10 Megaton-years

- Prospects for second detector in Korea ?

Conclusions

- Great prospects for PINGU to measure neutrino mass hierarchy
  - Build on expertise from IceCube / DeepCore
- Neutrino oscillation tomography offers the potential to measure the Earth interior composition
  - Extremely sensitivity to hydrogen
- PINGU (ORCA/Hyper-K) could put first constrain on the Earth Core water content within first few years of operations (given normal mass hierarchy)
- Next-generation, large volume detectors are needed to distinguish specific core models
  - very large - high statistics sample
  - good energy resolution and angular resolutions

Thank you !

Z/A ratios

Element		Z	A	Z/A
Hydrogen	H	1	1.008	0.9921
Carbon	C	6	12.011	0.4995
Oxygen	O	8	15.999	0.5
Magnesium	Mg	12	24.305	0.4937
Silicon	Si	14	28.085	0.4985
Sulfur	S	16	32.06	0.4991
Iron	Fe	26	55.845	0.4656
Nickel	Ni	28	58.693	0.4771

Z - Atomic Number

A - Atomic Mass

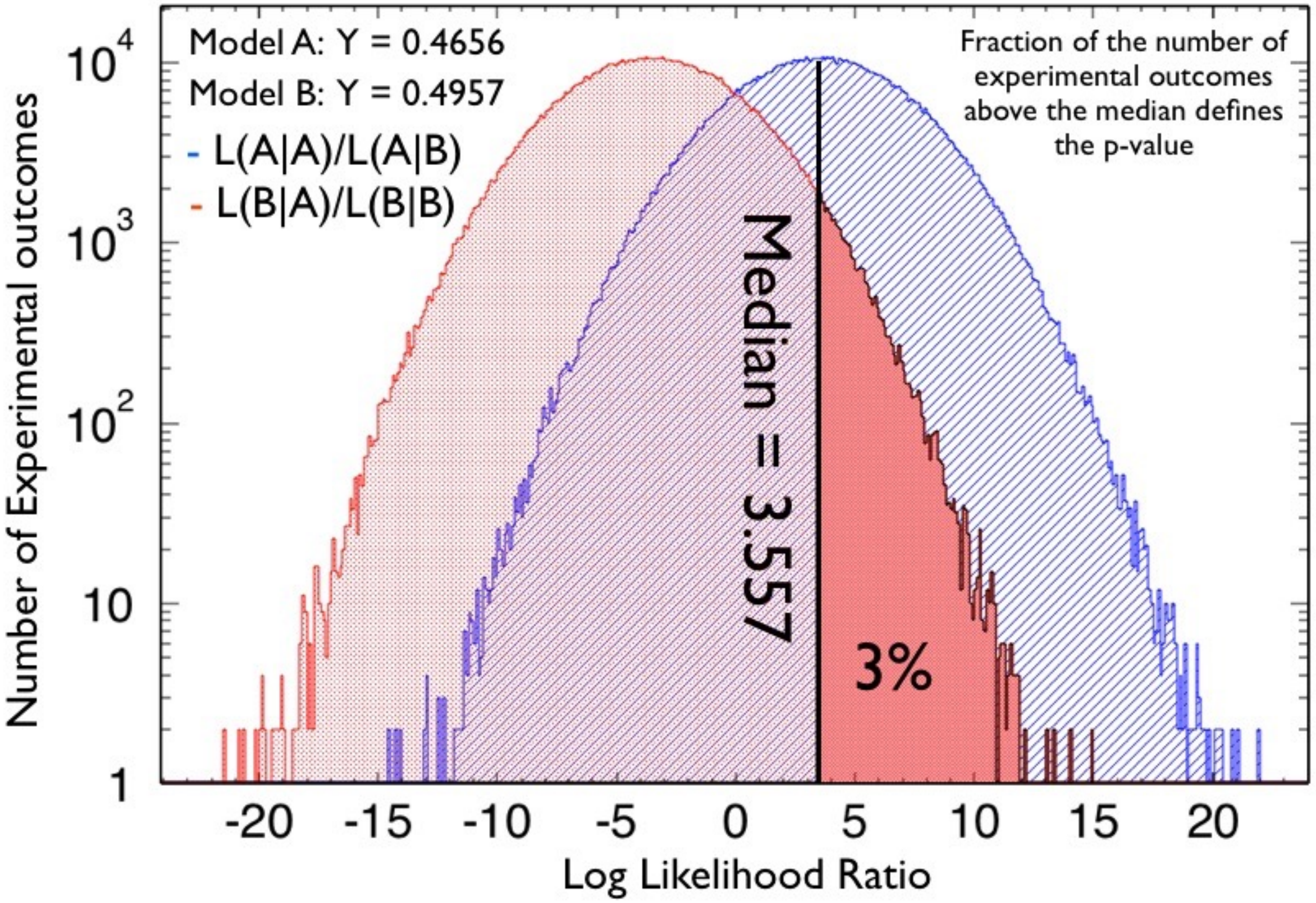
- Z/A ratios

Predicted Detector Performance

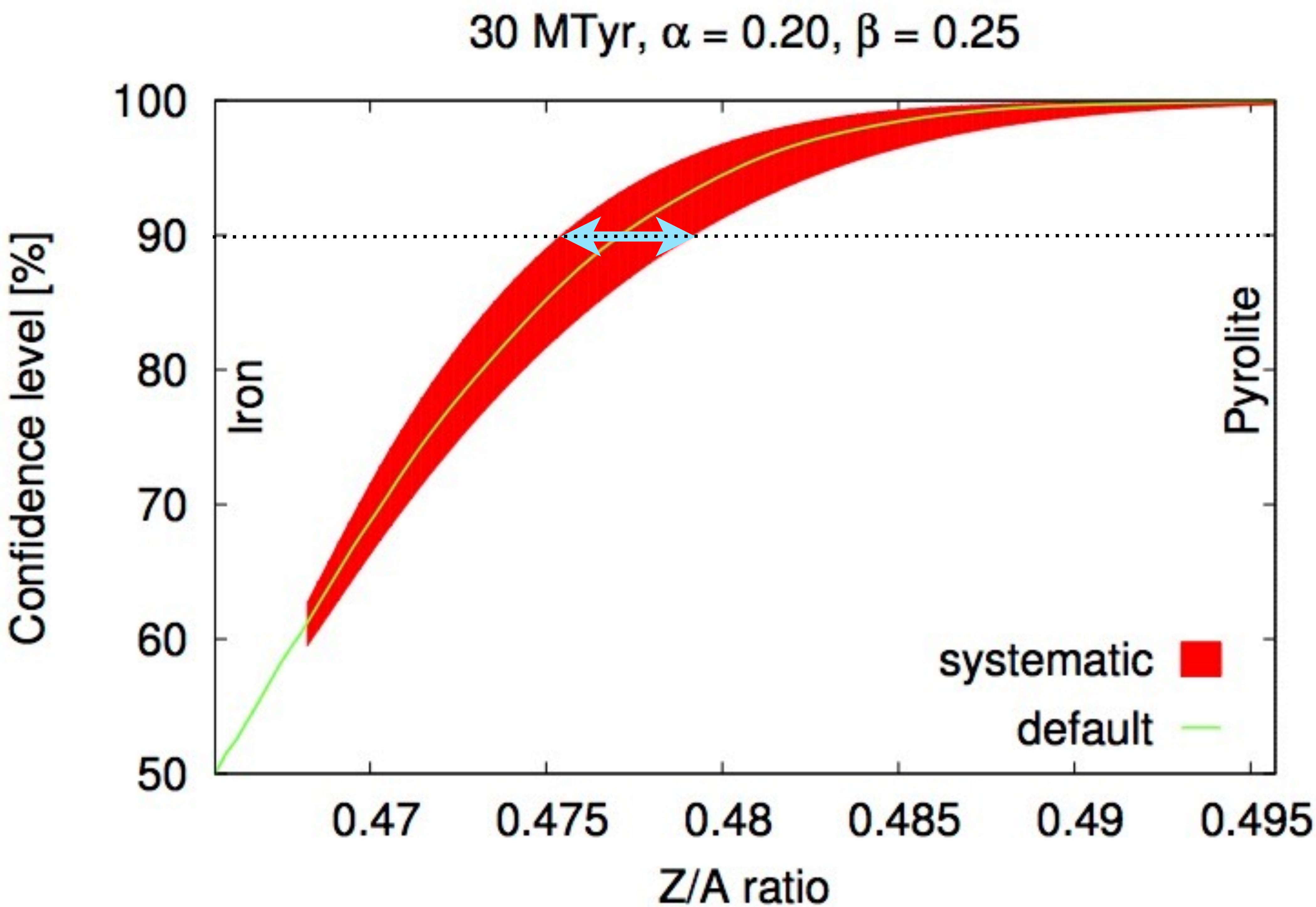
	INO India-based Neutrino Observatory	**ORCA** Oscillation Research with Cosmics in the Abyss	**PINGU** Precision IceCube Next-Generation Upgrade
Energy $(\sigma(E_{reco}-E_{true})/E_{true}$ @10GeV)	Tracks: ~11%	Tracks: ~20% Showers: ~25%	Tracks: ~25% Showers: ~25%
Direction	Tracks: σ_{cos} = ~0.005	Tracks: σ_θ = ~5° Showers: σ_θ = ~10°	Tracks: σ_{cos} = ~0.14 Showers: σ_{cos} = ~0.14
Particle ID (charge ID or % of ν_μ CC ID'd as tracks)	~99%	ν_μ: ~60% $\bar{\nu}_\mu$: ~80%	~80%
Inelasticity	Significant NMH improvement, based on $\sigma(E_\nu-E_\mu)/E_\nu \sim 45\%$	NMH improvement expected, not yet used	Small NMH improvement; not used

Statistical Method

- Generate template for expected number of events and their distribution in energy and zenith angle for two different outer core composition models (Model A and Model B)
- Assume one composition and calculate likelihood with respect to A and B and take ratio
- Perform pseudo experiments
- Distribution tells us the probability to distinguish the two models if the measurement were to be done



Uncertainty due to mixing parameters



Use the best fit oscillation parameters and their uncertainties of:
Capozzi, F. et al. Status of three-neutrino oscillation parameters, circa 2013. Physical Review D 89, 093018 (2014).