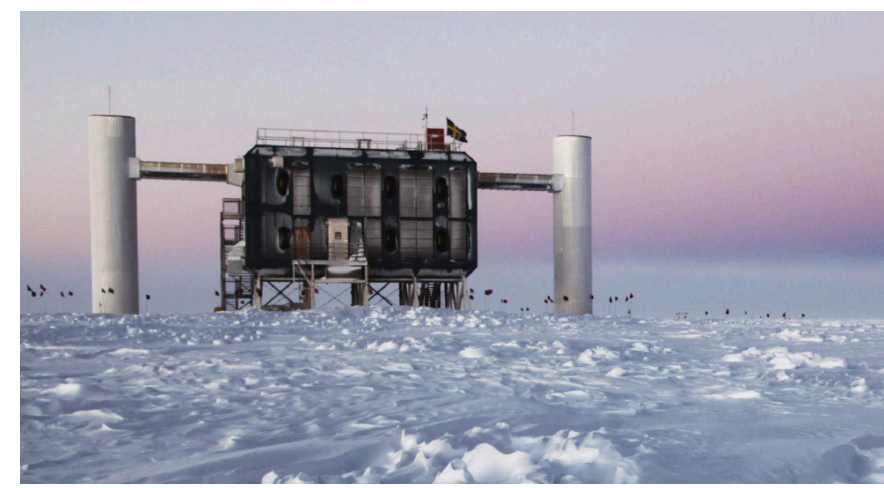
Neutrino Oscillation Tomography

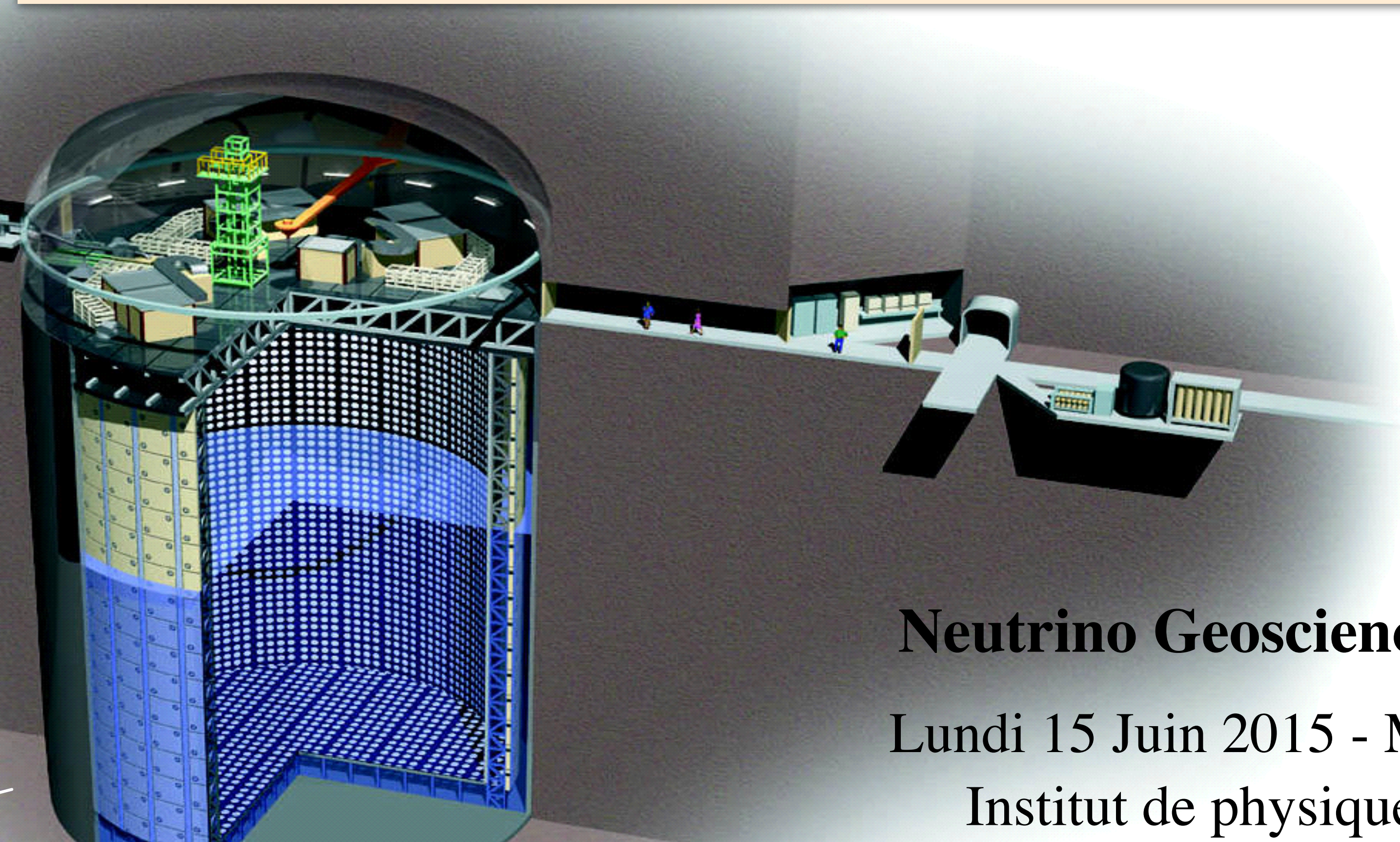
Carsten Rott

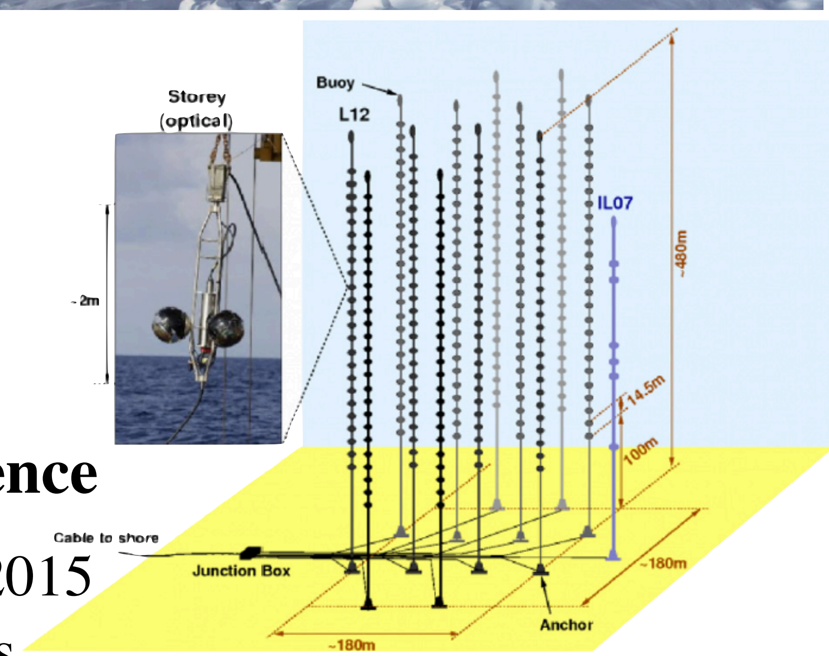
rott@skku.edu

Sungkyunkwan University, Korea

Spectrometry of the Earth using Neutrino Oscillations
Carsten Rott (Sungkyunkwan U.), **Akimichi Taketa** (ERI, Tokyo), Debanjan Bose (Sungkyunkwan U.). Feb 17, 2015
e-Print: **arXiv:1502.04930** **[physics.geo-ph] (submitted Scientific Reports)**







Neutrino Geoscience 2015 Conference

Lundi 15 Juin 2015 - Mercredi 17 Juin 2015

Institut de physique du globe de Paris

Outline

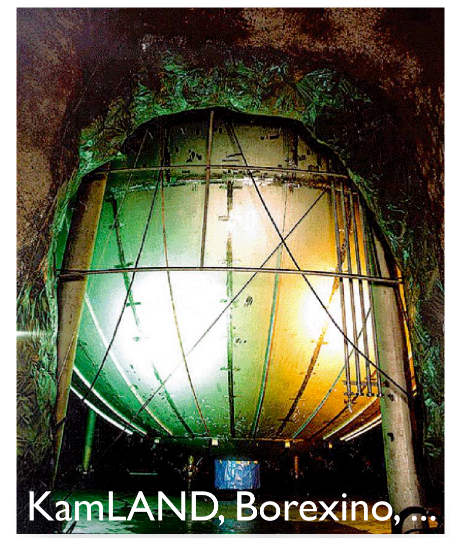
- Motivation
- Methodology of Neutrino Oscillation Tomography
- Optical Neutrino Detectors
- Prospects for Neutrino Oscillation Tomography
- Outlook

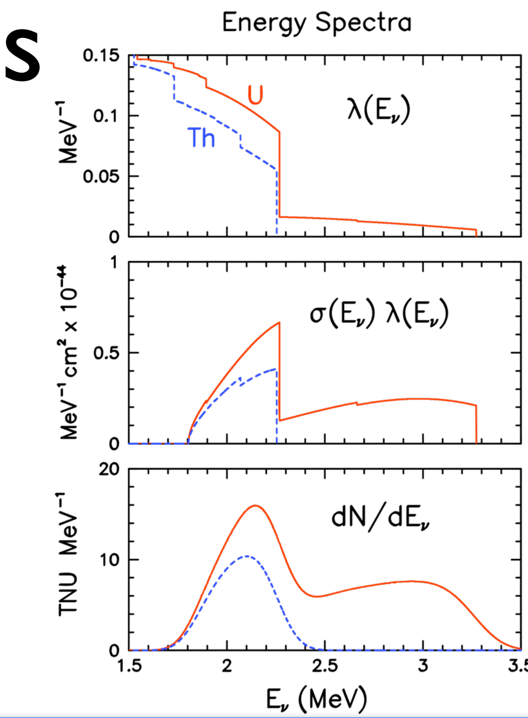
Motivation (Particle Physics ⇒ Geo-science)

- 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

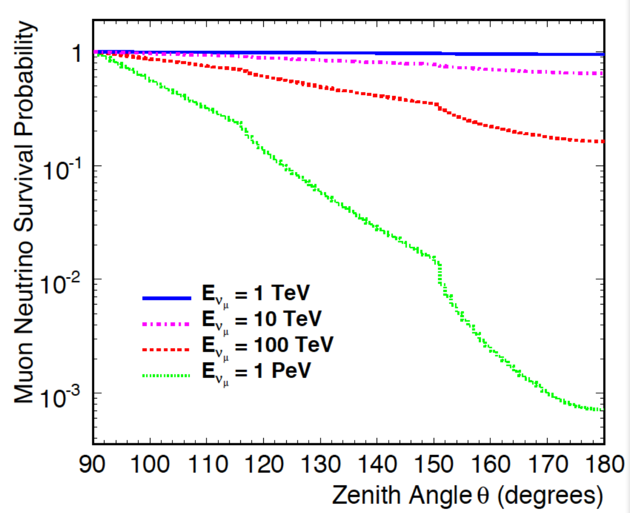
Geo-neutrinos

U and Th geo-ν



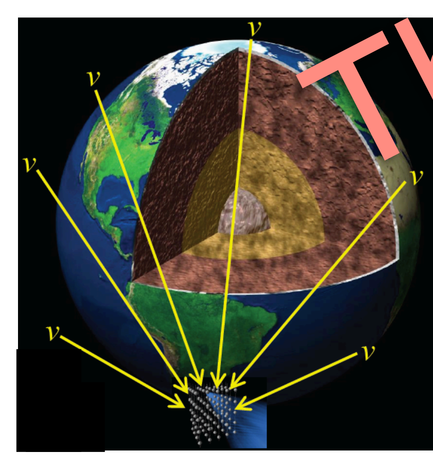


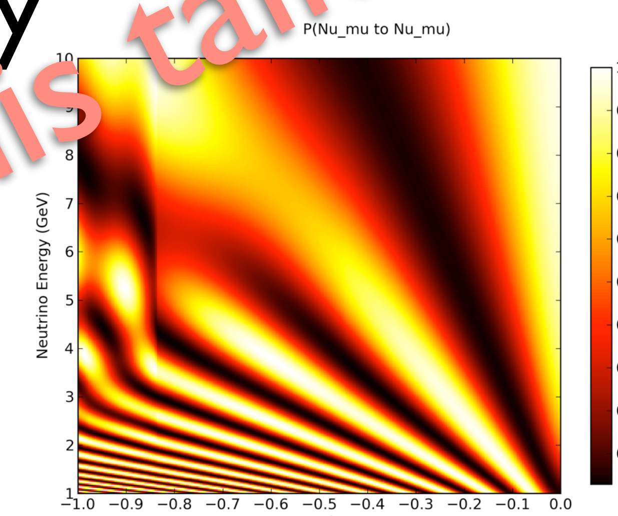
Neutrino absorption tomography



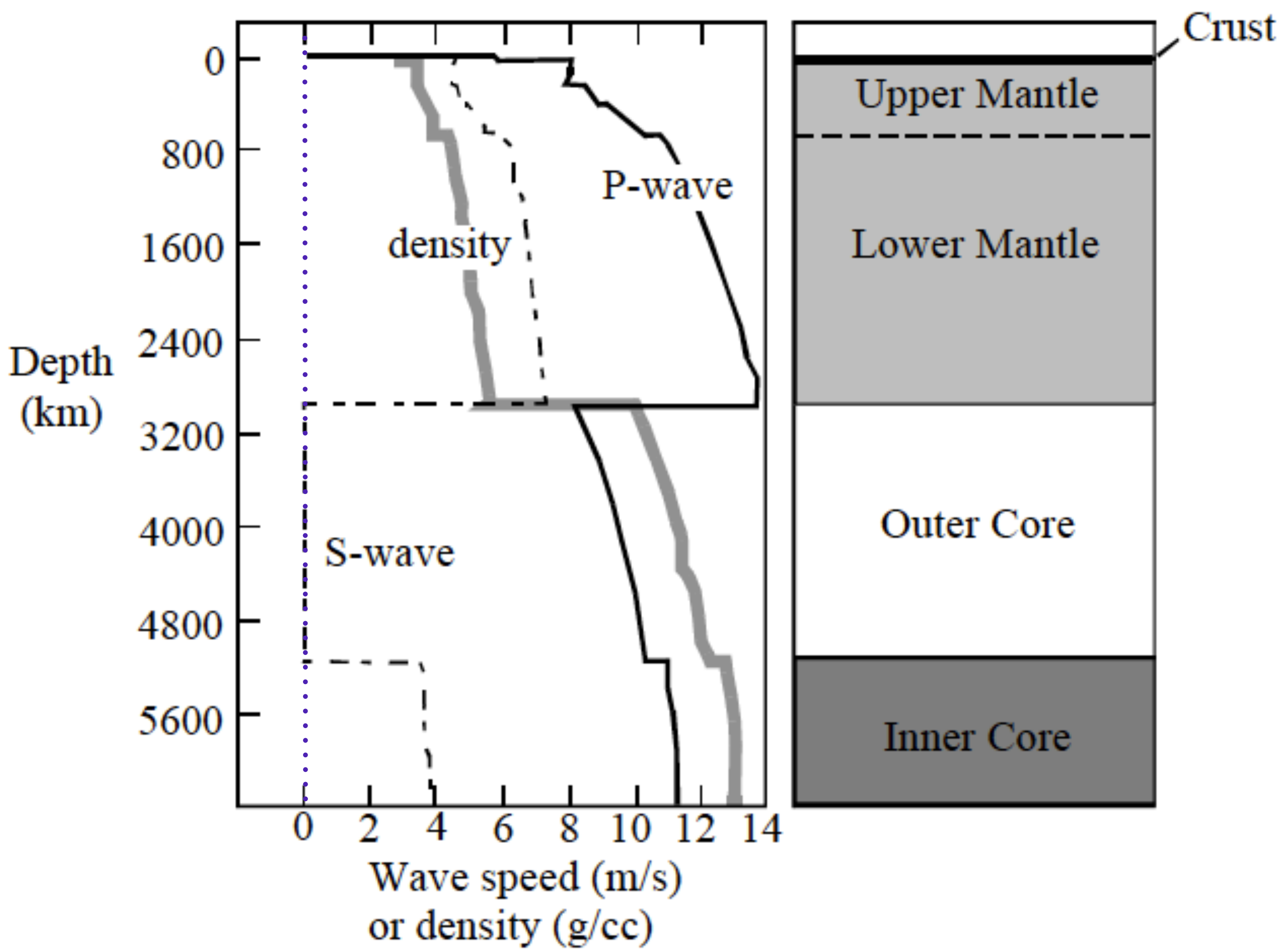
Neutrino oscillation tomography

This talk

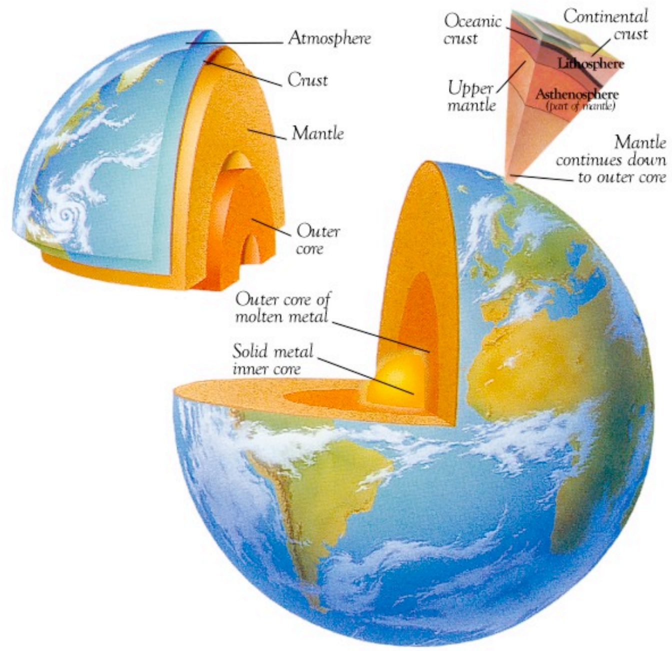




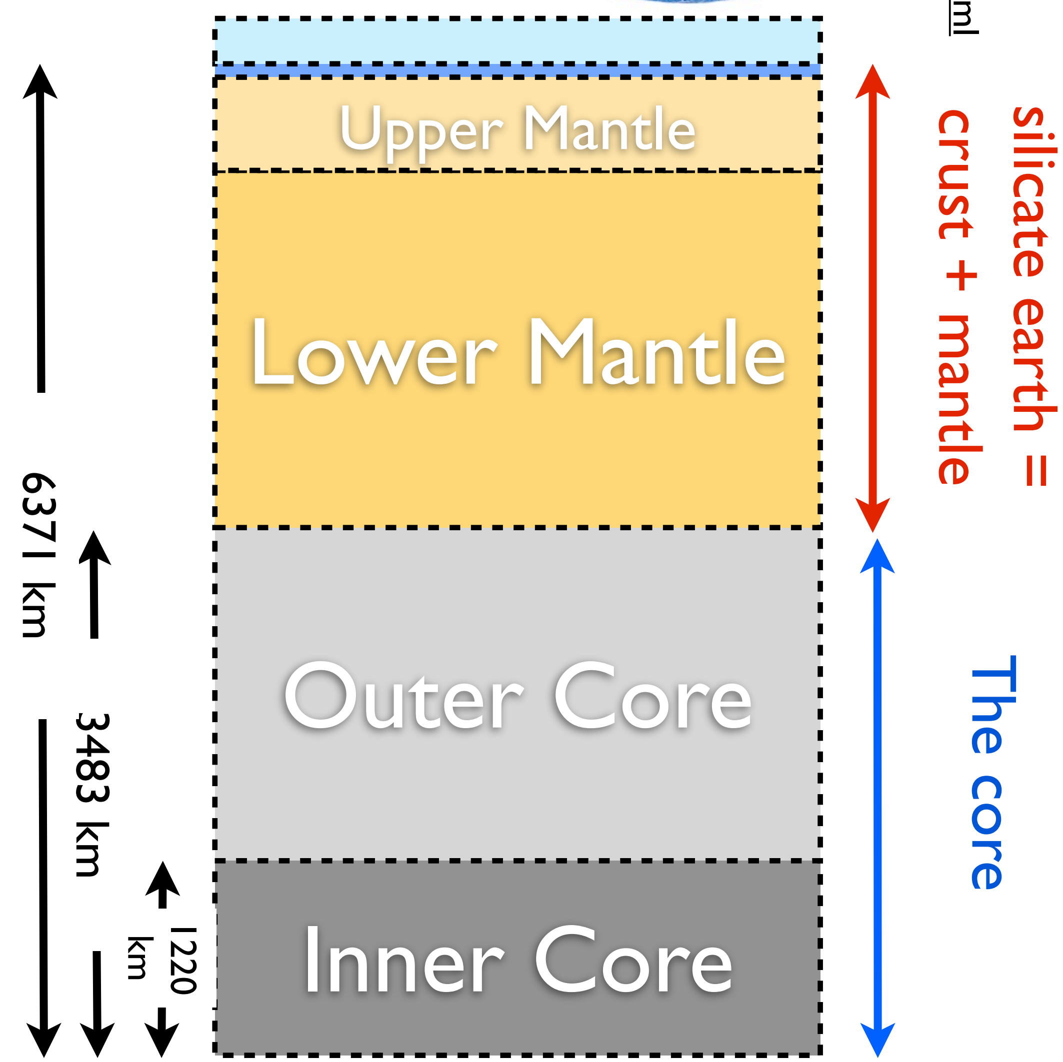
Seismological profile of the Earth



William F. McDonough "The Composition of the Earth"



http://www.phys.hawaii.edu/~sdye/hnsc.html

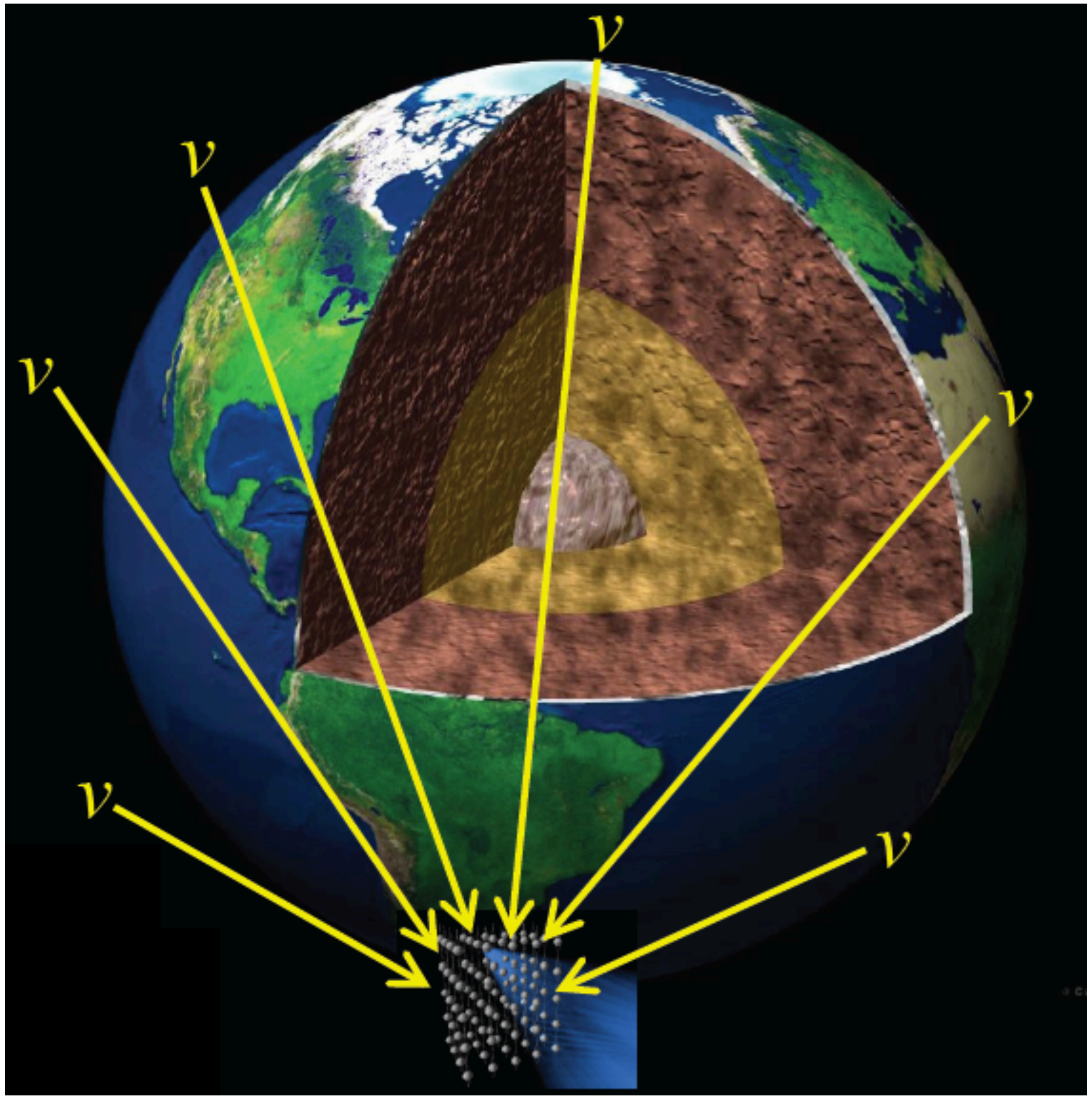


- Density relatively well described through seismic measurements (⇒PREM)
- ... but **whats the composition ?**

Neutrino Oscillation Tomography

Motivation - Methodology

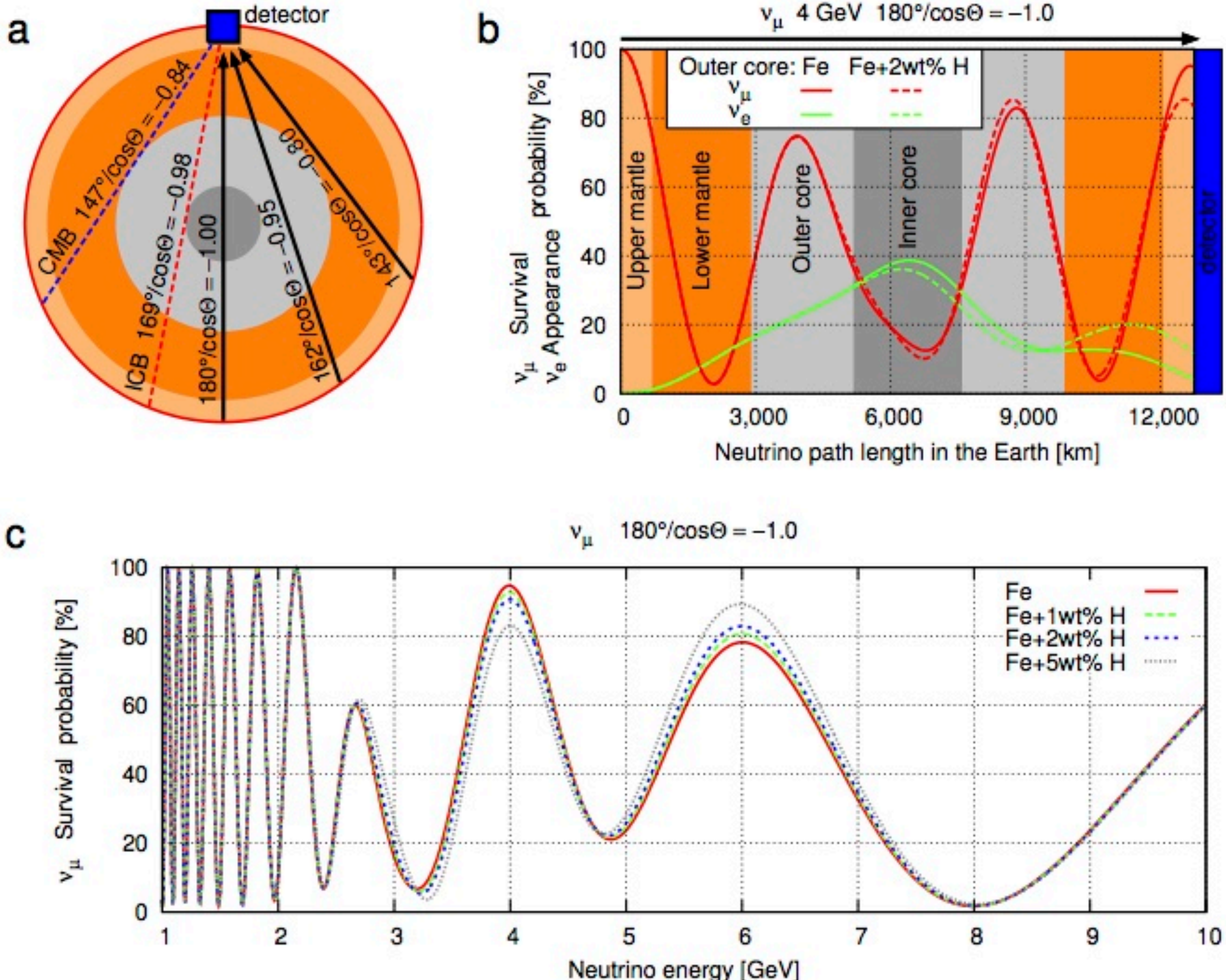
- The Earth matter density profile can be determined from seismic measurements
- Matter induced neutrino oscillation effects however dependent on the electron density
- Given a matter density profile the composition (or Z/A) along the neutrino path can be determined using neutrino signals (Oscillation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



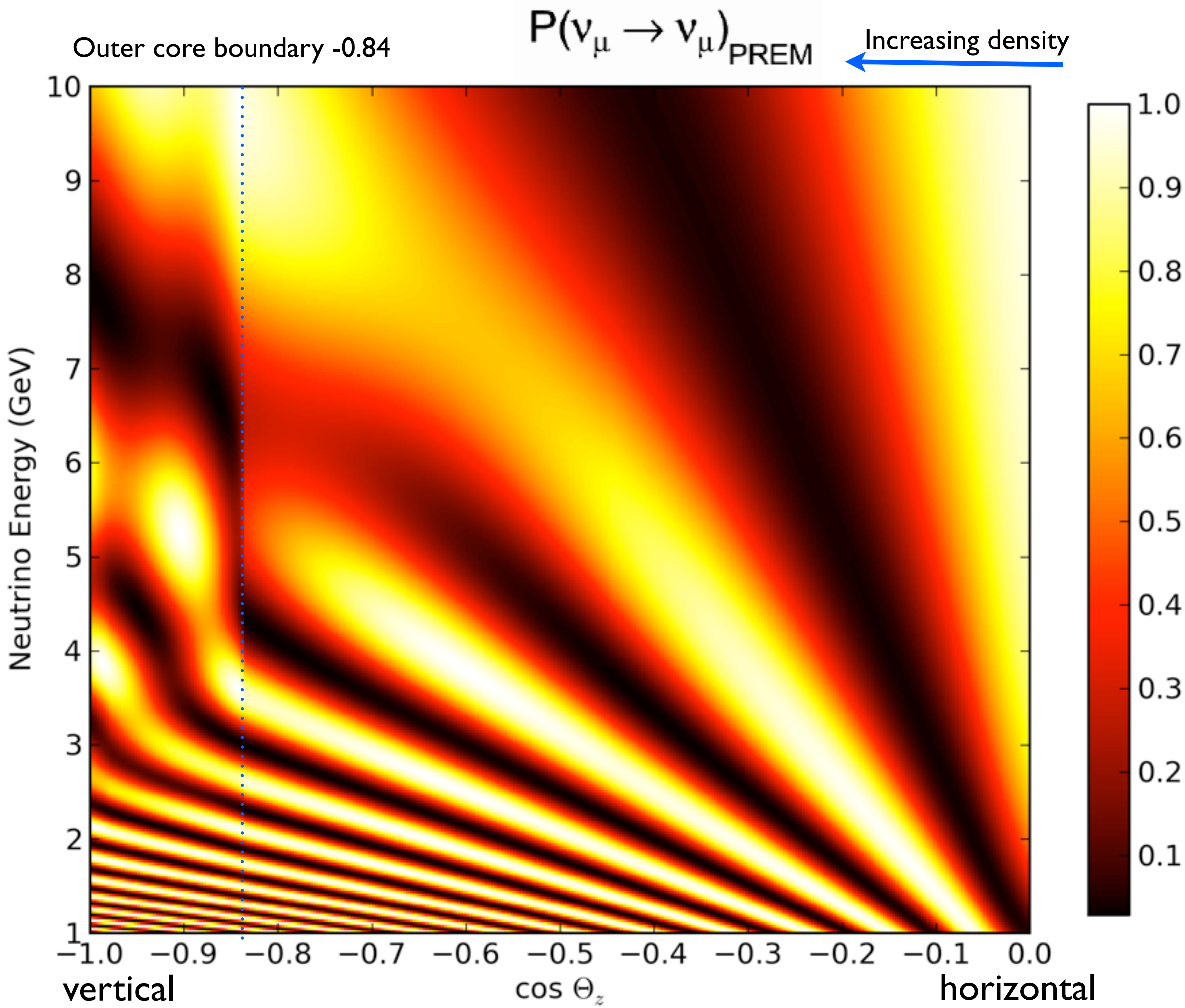
Electron density in core
Y_c=electron/nucleons

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

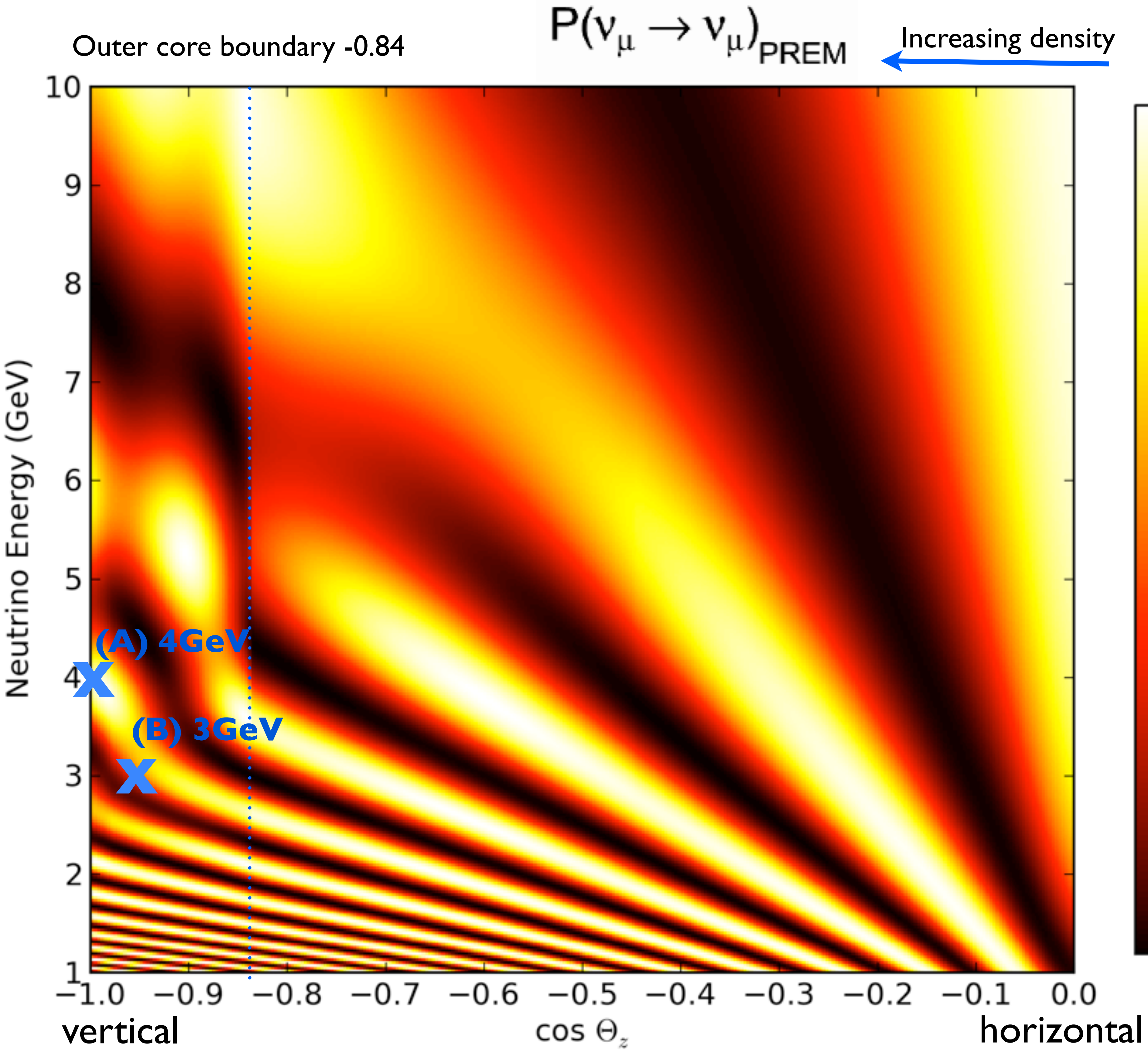
Rott & Taketa 2015



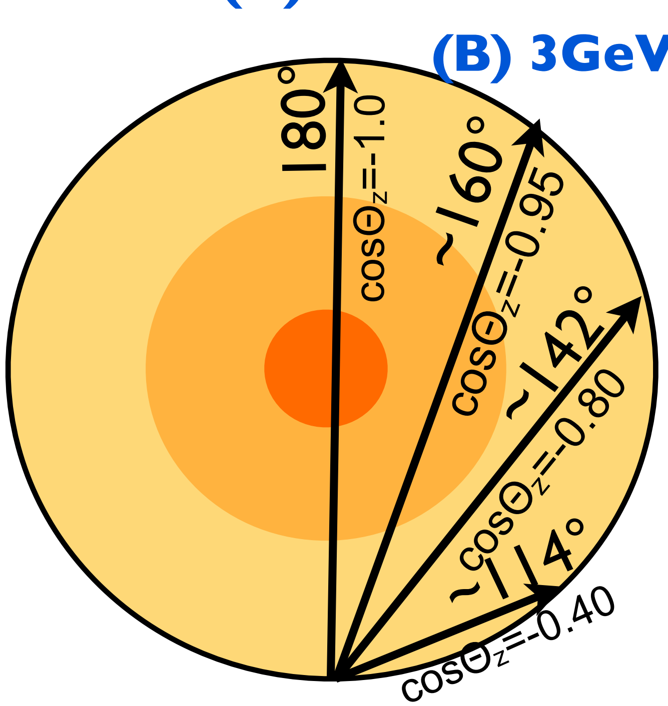
Oscillograms



How to read an oscillograms



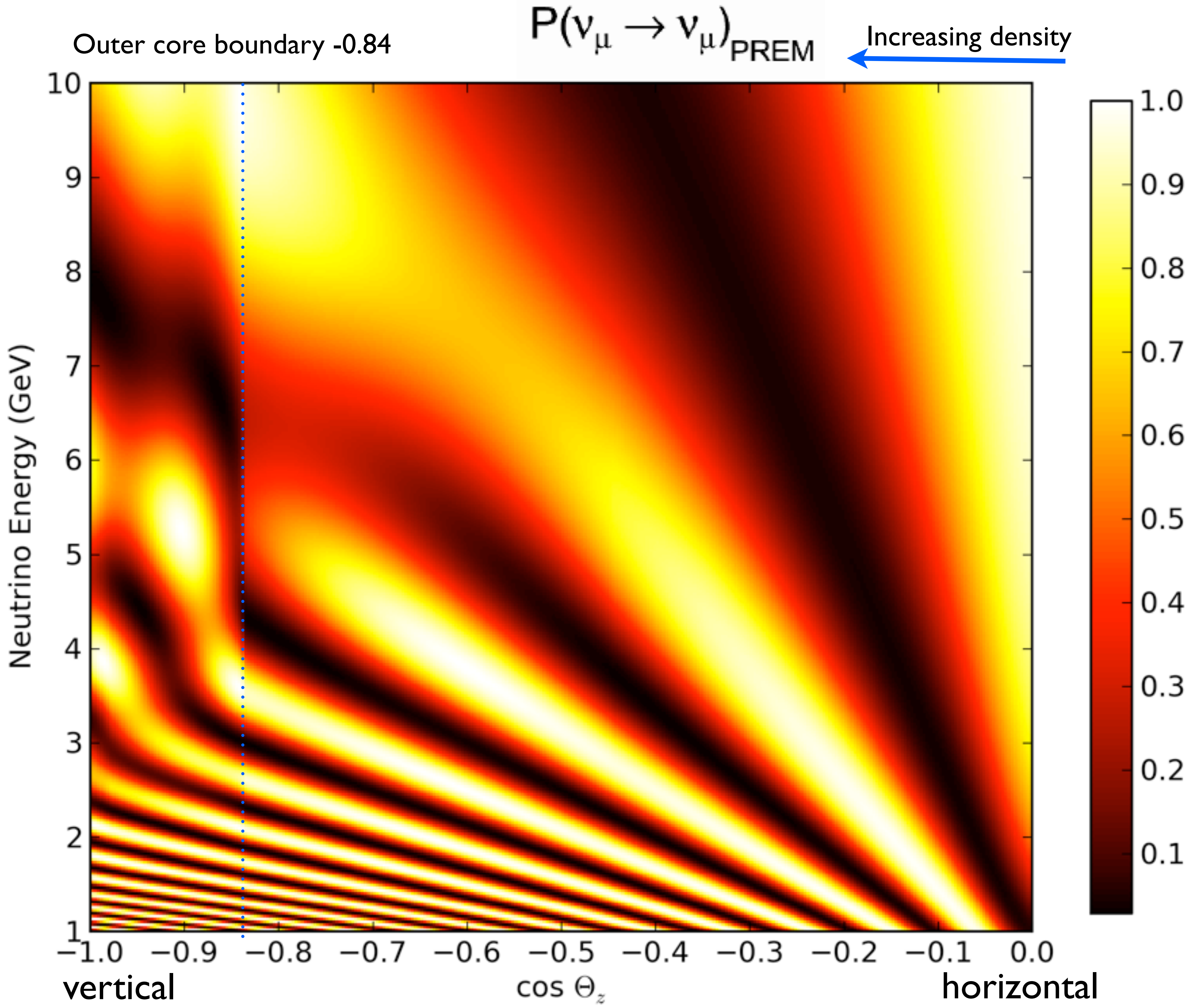
An example ...



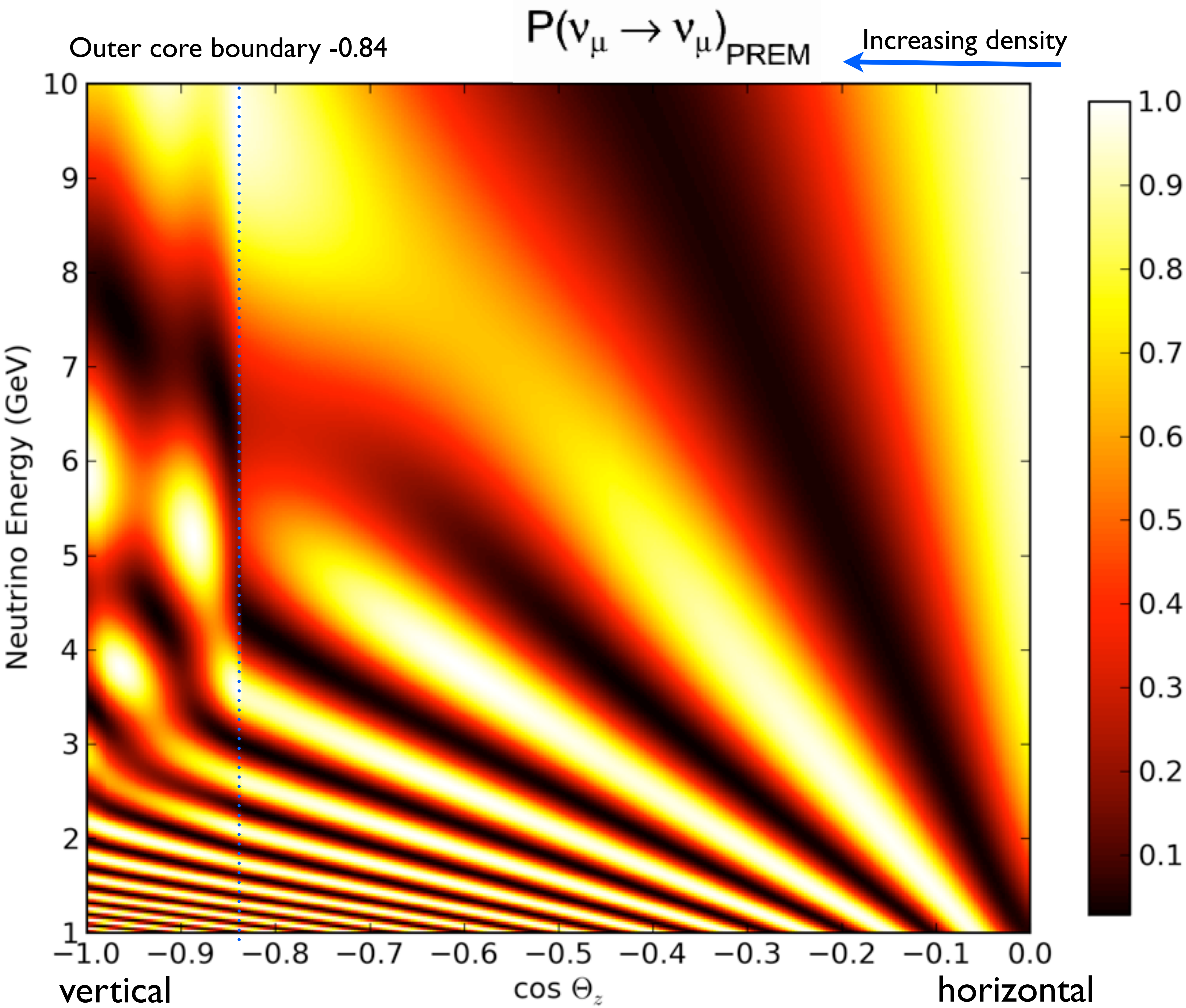
A muon neutrino created at **(A)** with energy 4GeV has a **~90%** chance to be detected as such after traversing the Earth

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

Oscillogram



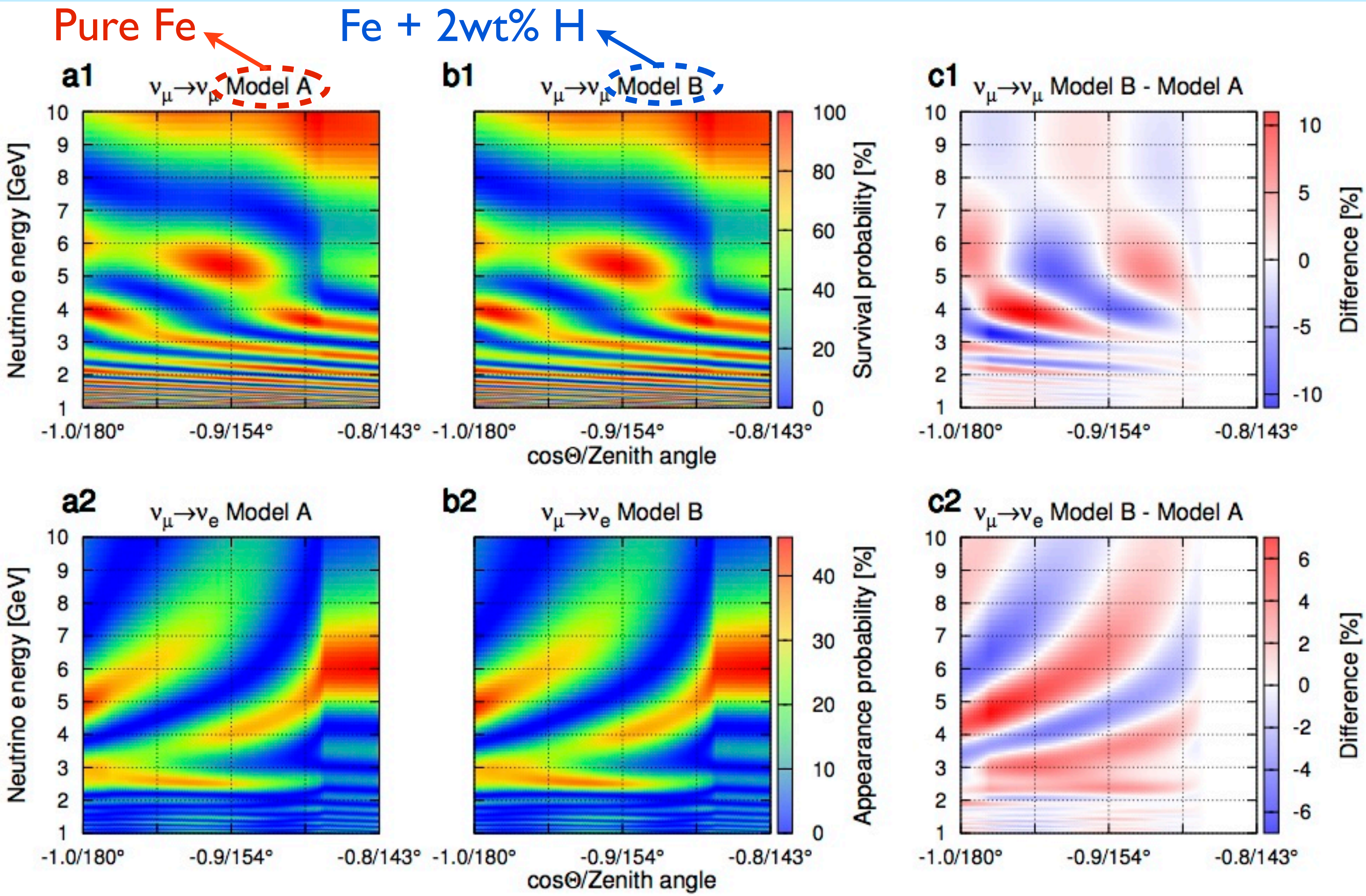
Oscillogram (enhance electron density)



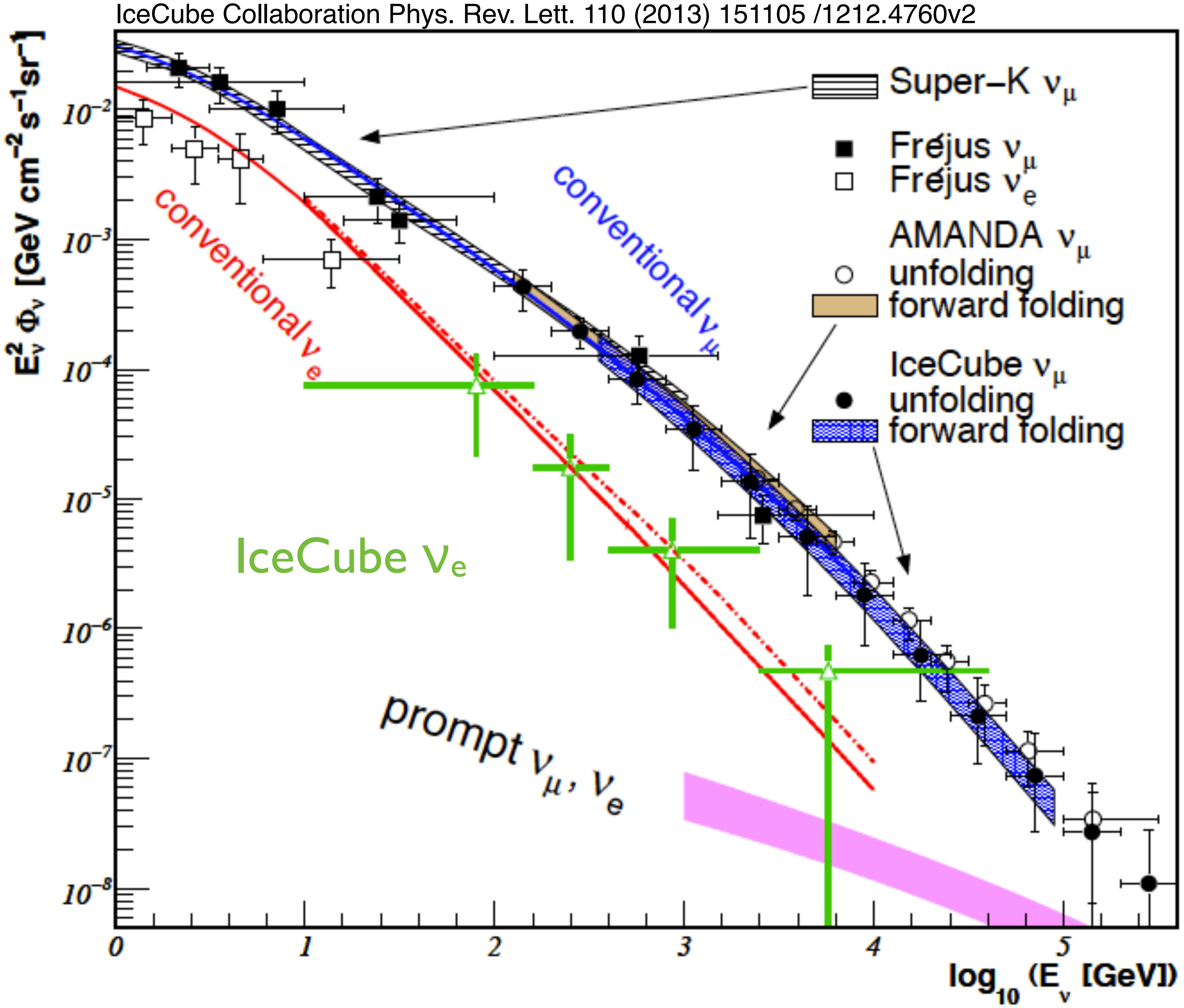
Change Earth core electron density by 10% to visualize change in survival probability

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

Rott & Taketa 2015



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
  - $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$

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
  - $\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\nu_\mu\nu_\mu$

- 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

The IceCube Neutrino Telescope

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

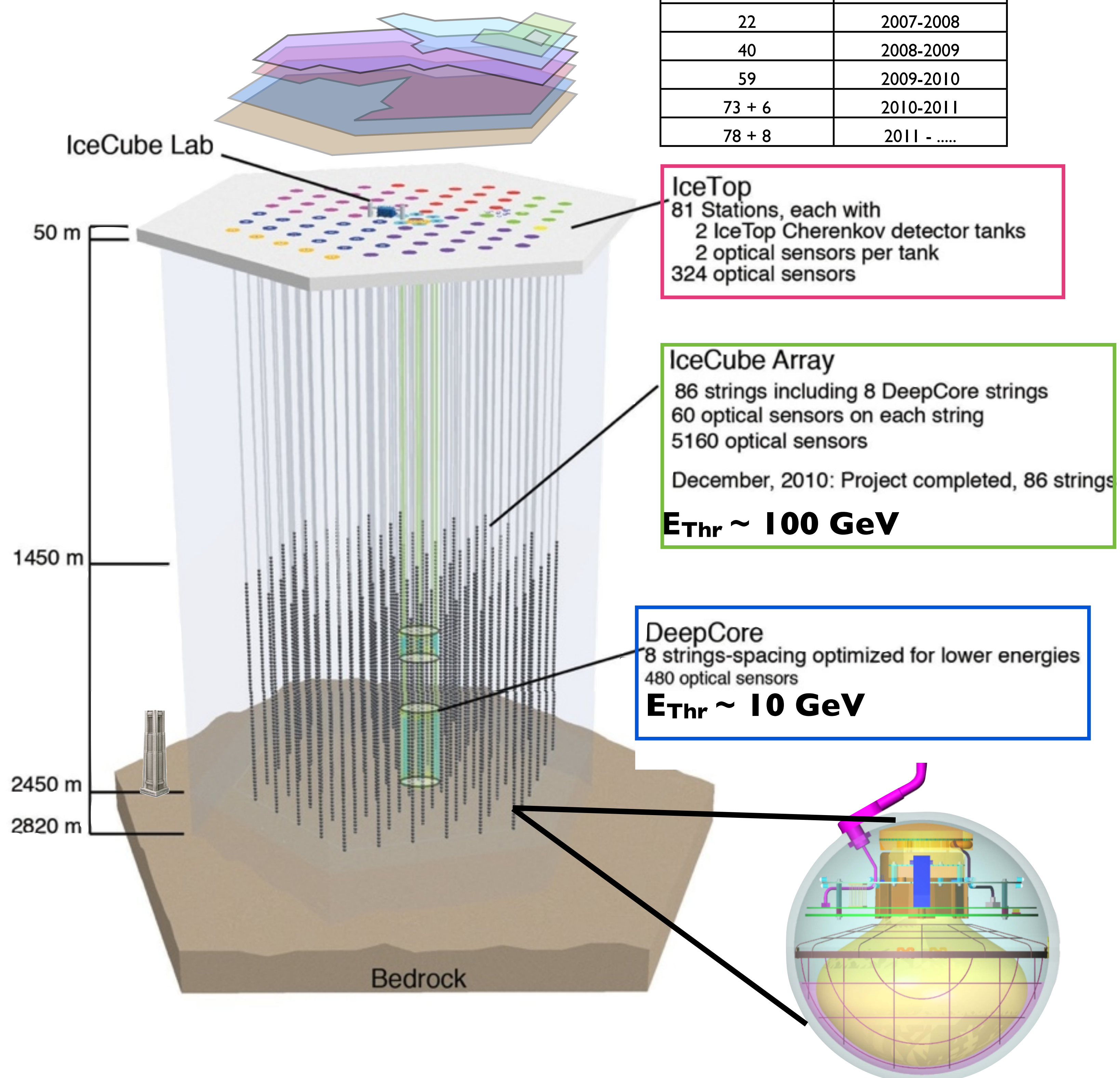
Gigaton Neutrino Detector at the Geographic South Pole

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



The IceCube Neutrino Telescope

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

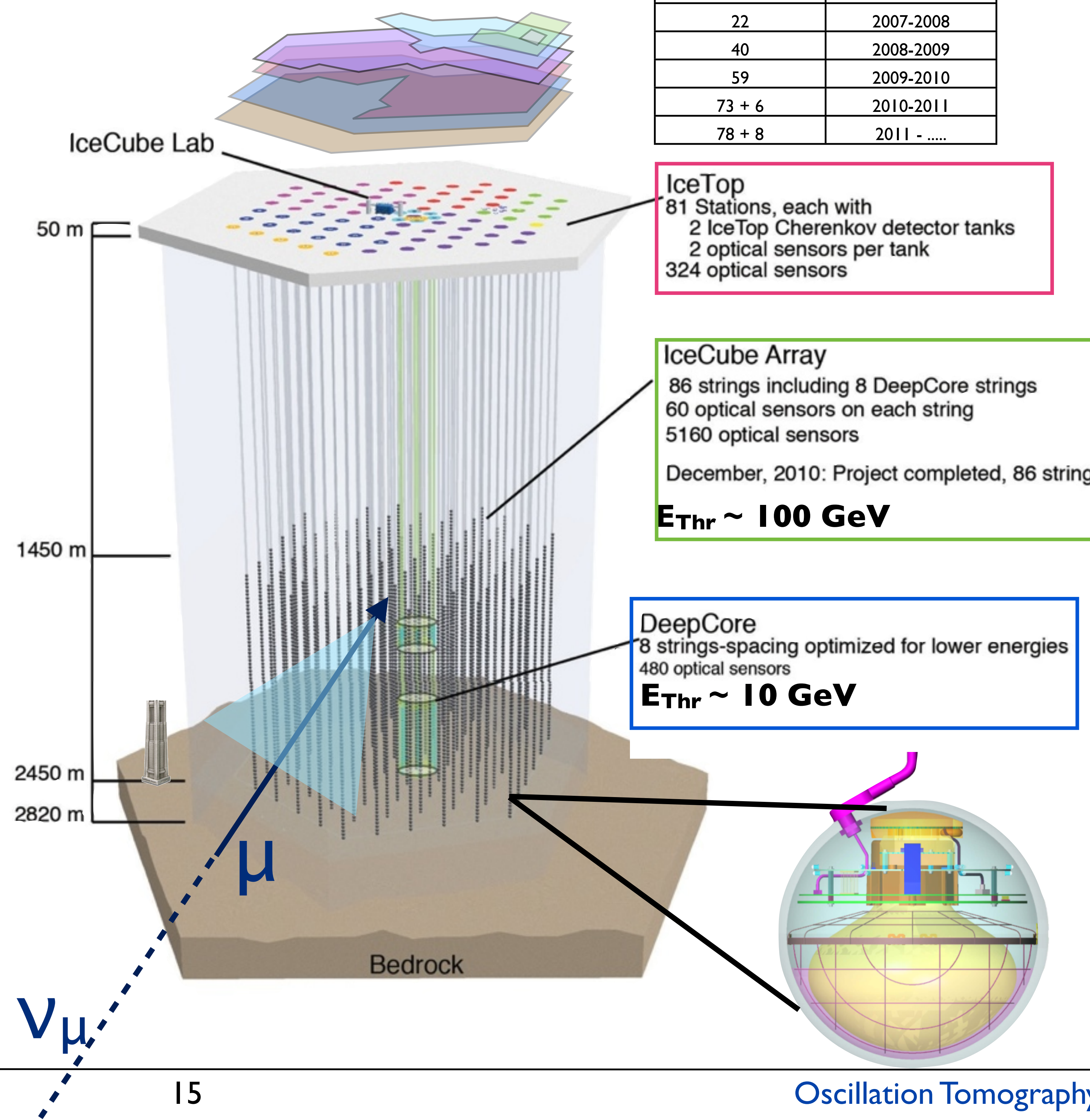
Gigaton Neutrino Detector at the Geographic South Pole

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

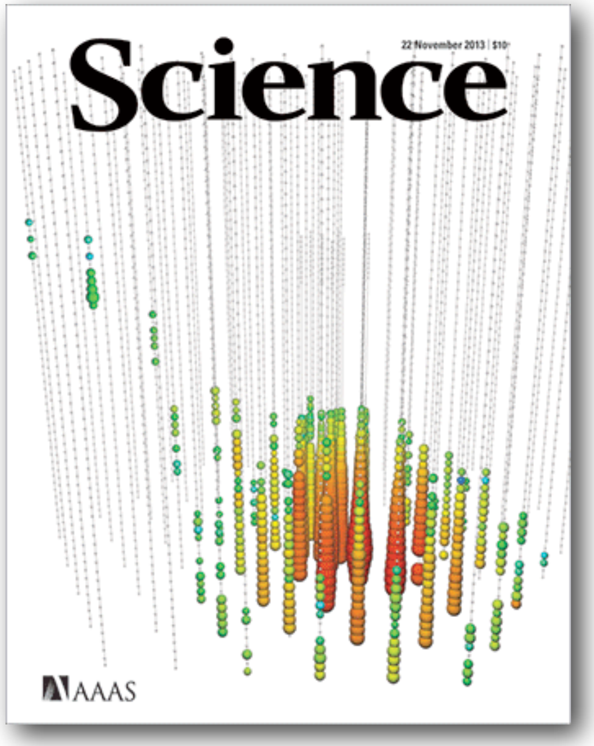
Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

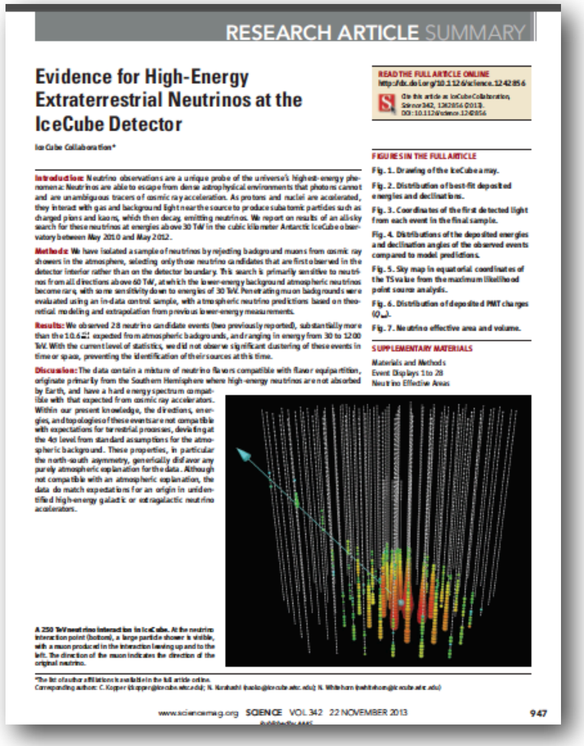


IceCube Observations

Scientific Scope

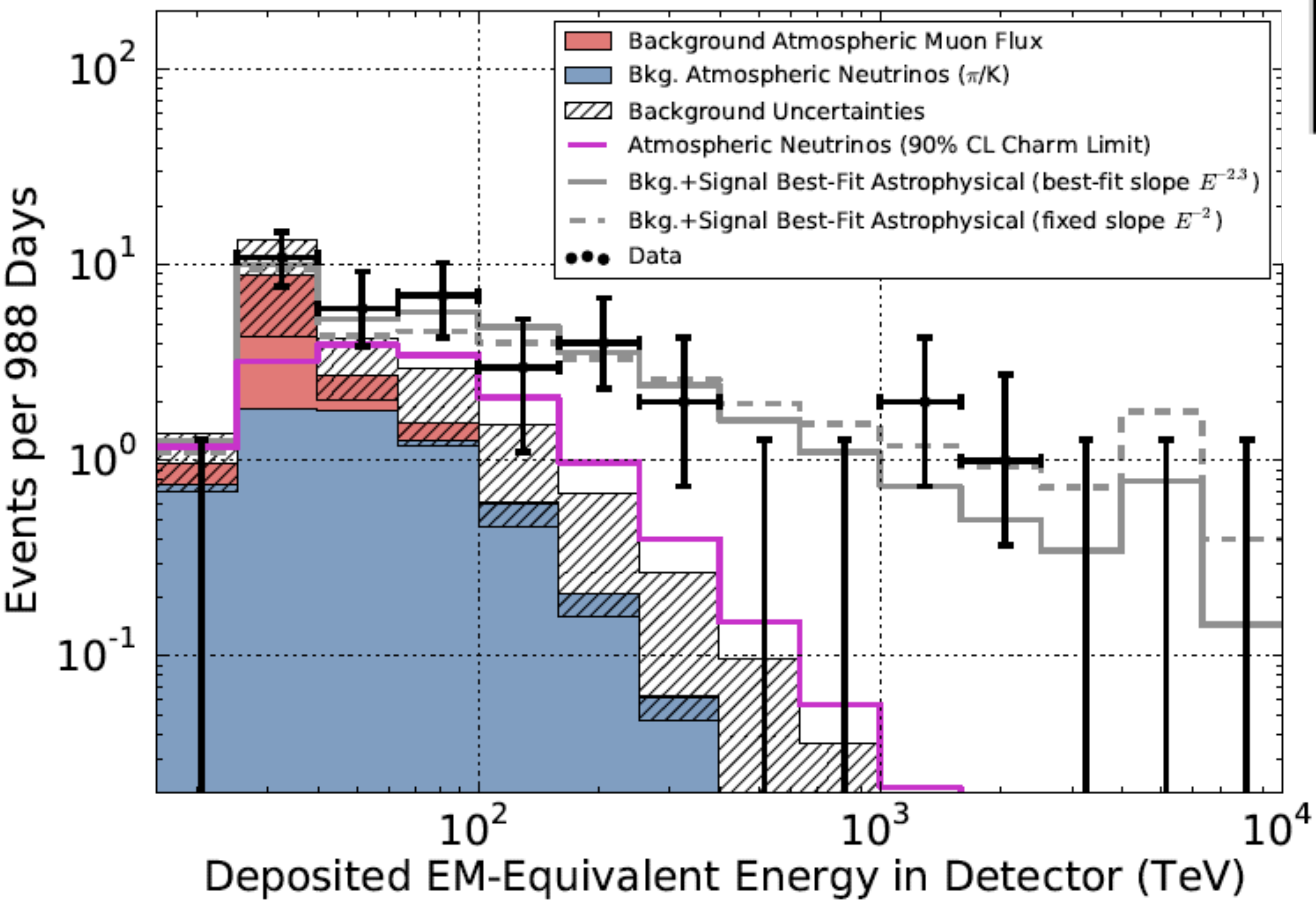
- ASTROPHYSICS
  - point sources of ν's (SNR, AGN …), extended sources
  - transients (GRBs, AGN flares …)
  - diffuse fluxes of ν's (all sky, cosmogenic, galactic plane …)
- COSMIC RAY PHYSICS
  - energy spectrum around "knee", composition, anisotropy
- DARK MATTER
  - indirect searches (Earth, Sun, 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

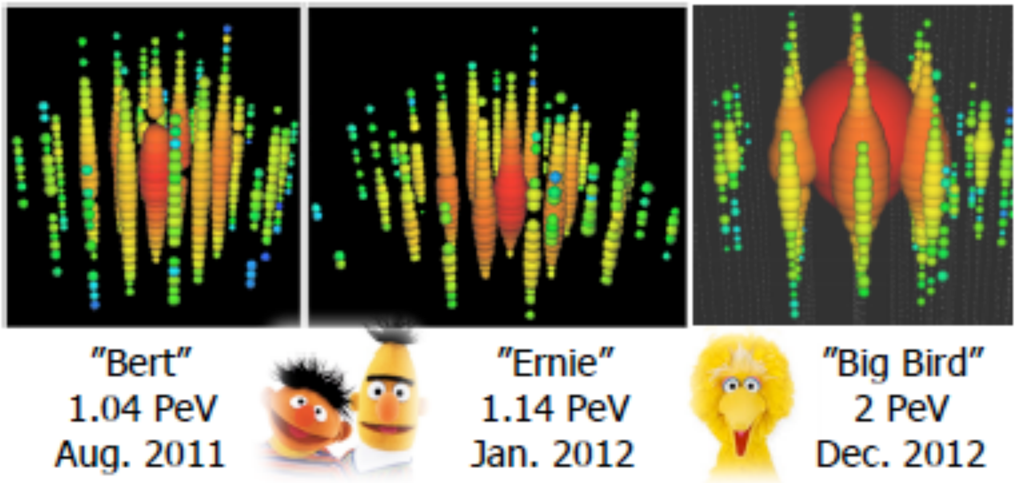




High-energy neutrino search

IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*



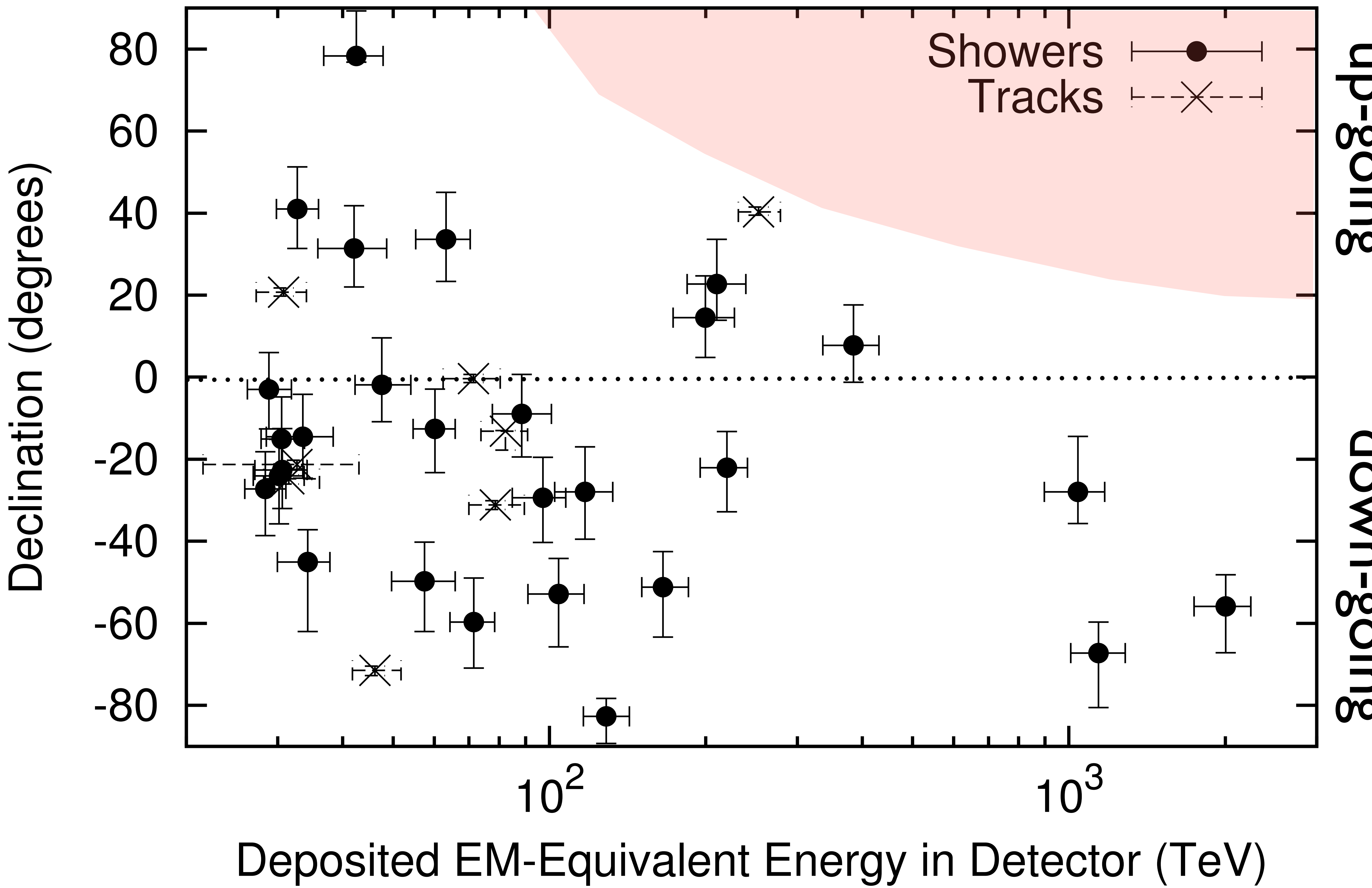


- In 988days observed 37 events (9 track-like, 28 showers) observed
- Atmospheric Bkg :
  - Atm. Muon (8.4±4.2),
  - Atm. Neutrino (conventional) ($6.6^{+5.9}_{-1.6}$),

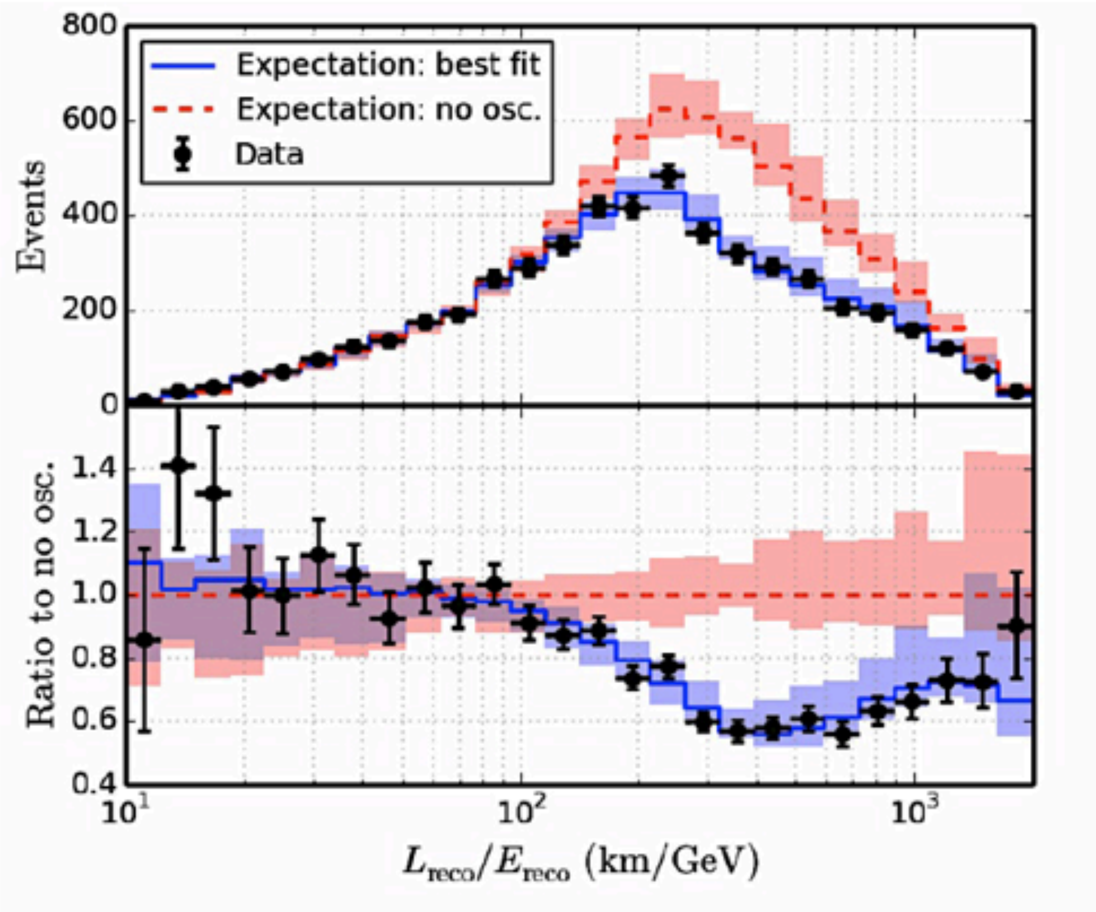
5.7 sigma rejection of atmospheric-only hypothesis

best fit flux: $E^2\Phi = 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

A hints of Neutrino Absorption ?



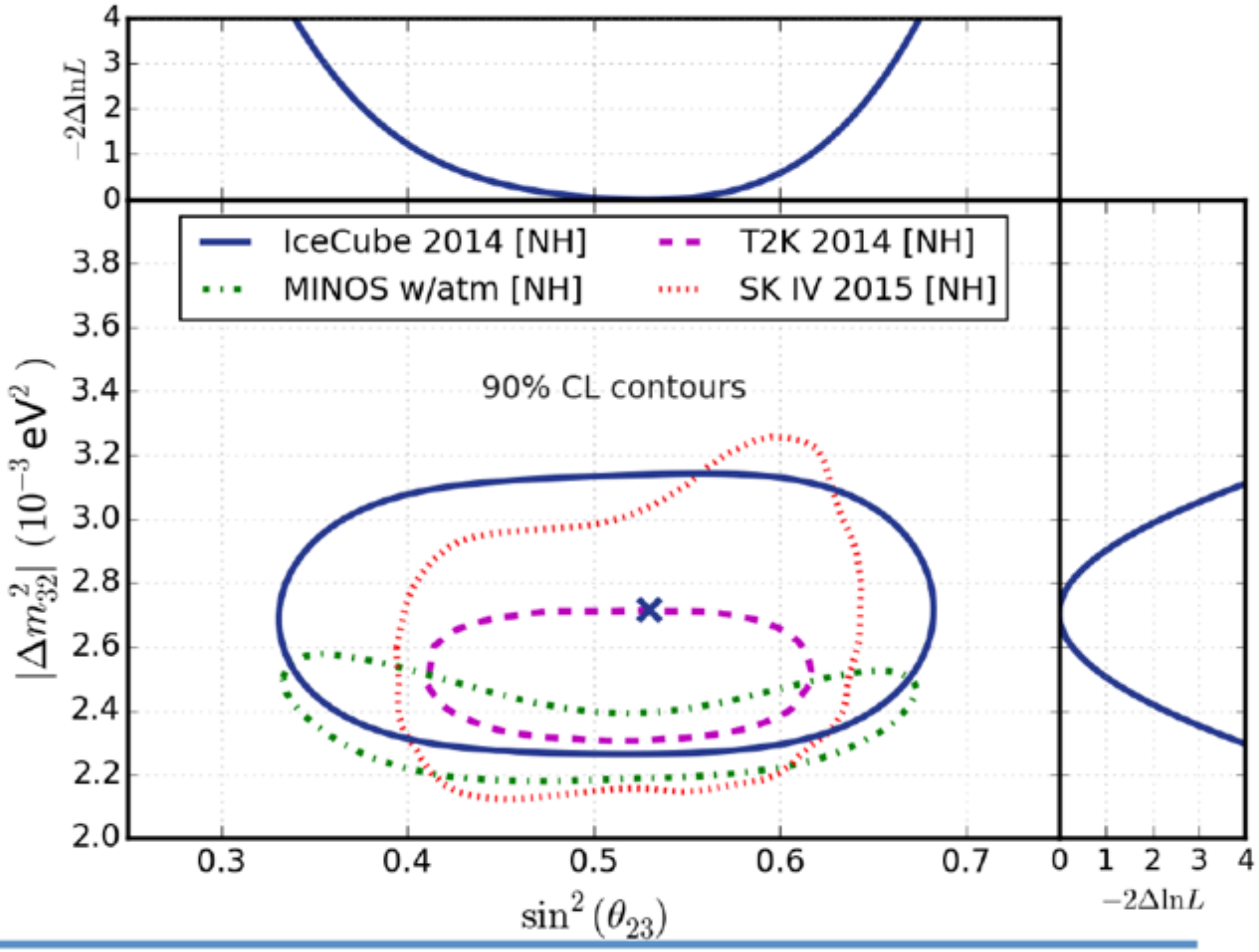
IceCube Neutrino Oscillations



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

- competitive result (3 years)
- will improve further

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

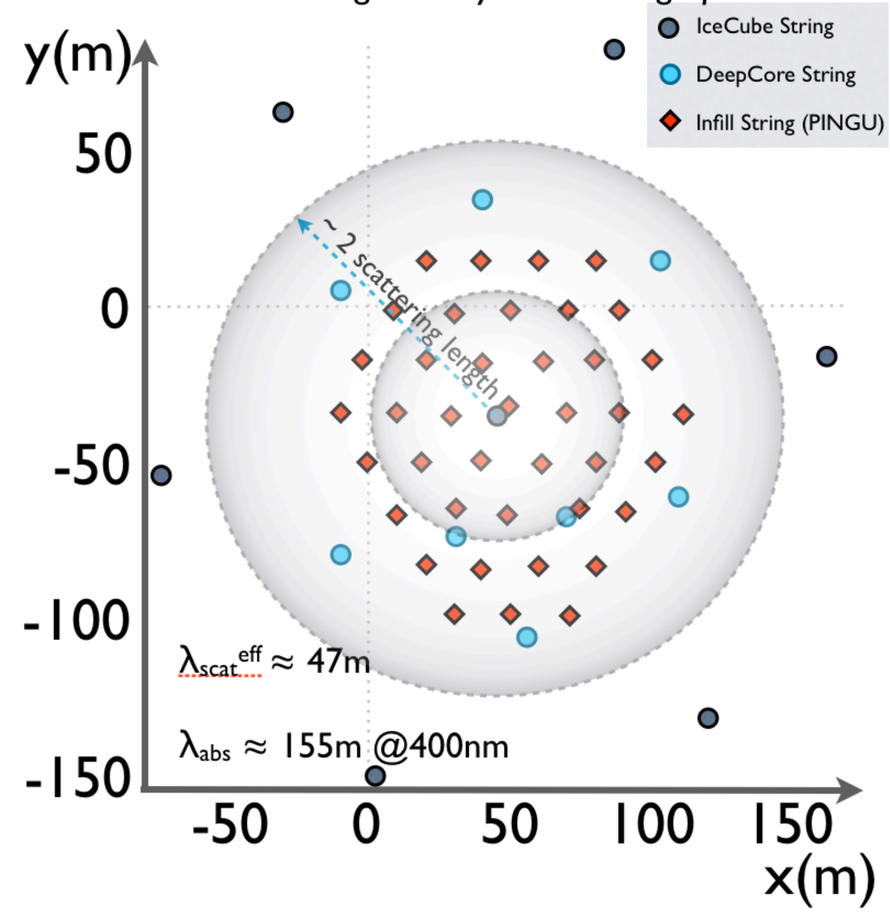


- select
  - starting events
  - clear μ tracks
  - rely on direct photons
- 5174 events observed cf. 6830 expected if no oscillation
- perform 2D fit in *E* and *cos(θ)*

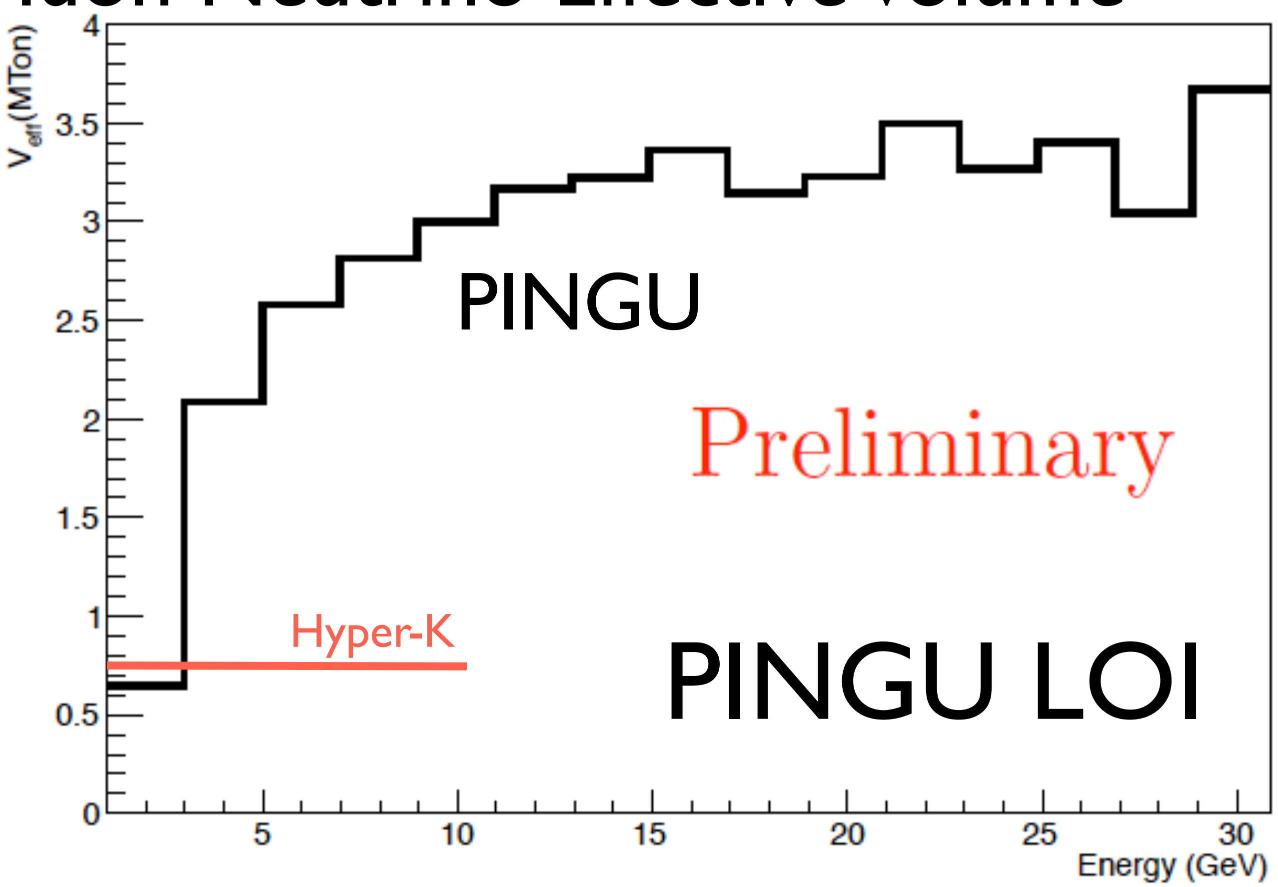
Potential Detectors for Tomography

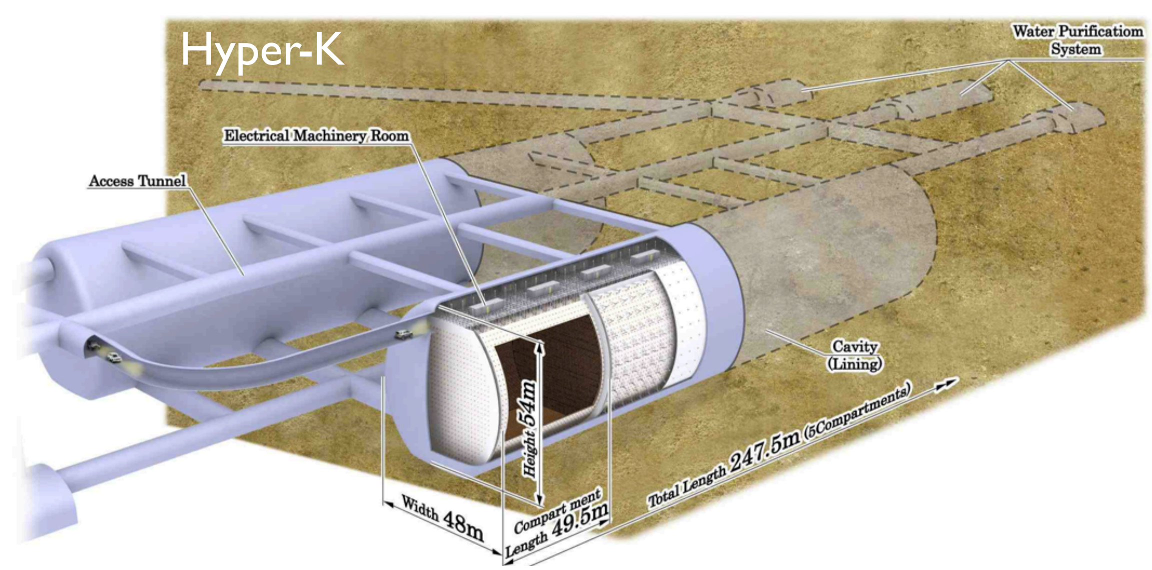
- PINGU (**P**recision **I**ceCube **N**ext **G**eneration **U**pgrade) (LOI *arxiv:1401.2046*)
  - 40 additional strings to IceCube
  - 26m string spacing
  - 96 High Quantum efficiency optical sensors per string (~3m spacing)
  - achieve GeV threshold

An example PINGU geometry (40 strings)
Note: PINGU geometry is still being optimized



Muon Neutrino Effective Volume

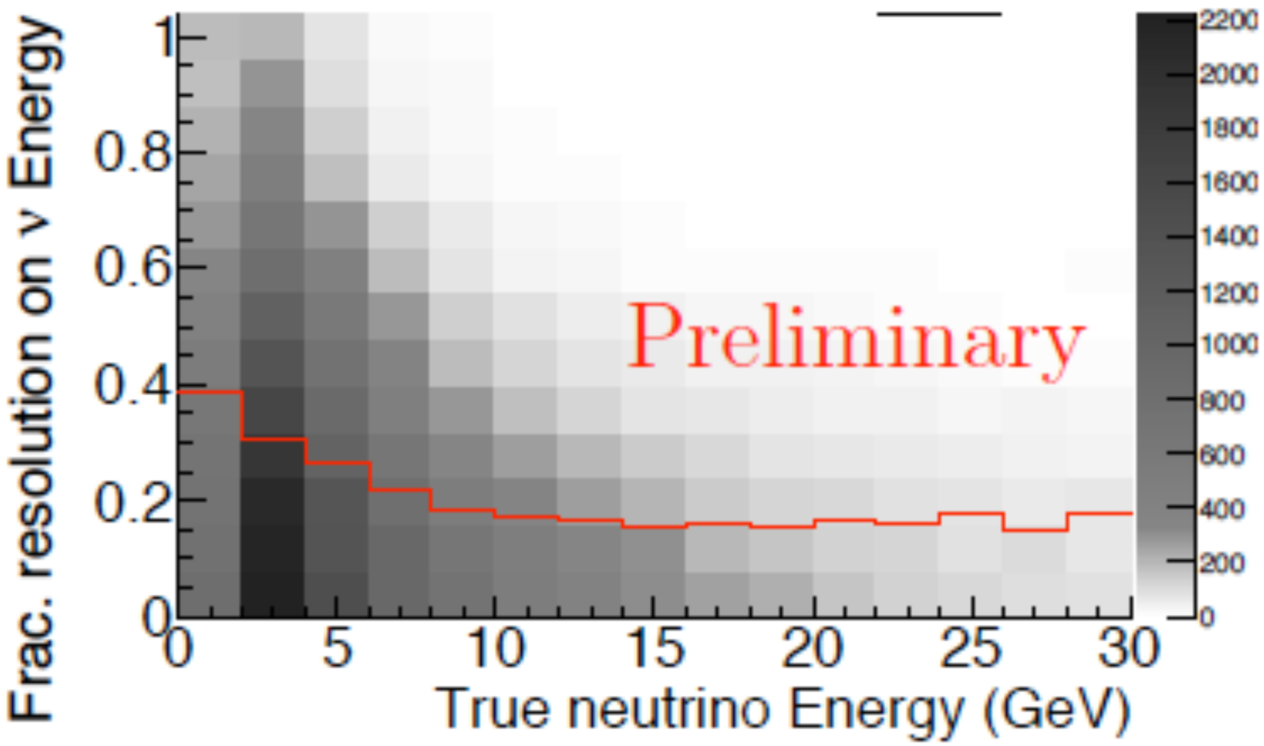




- Hyper-K (LOI *arxiv:1109.3262*)

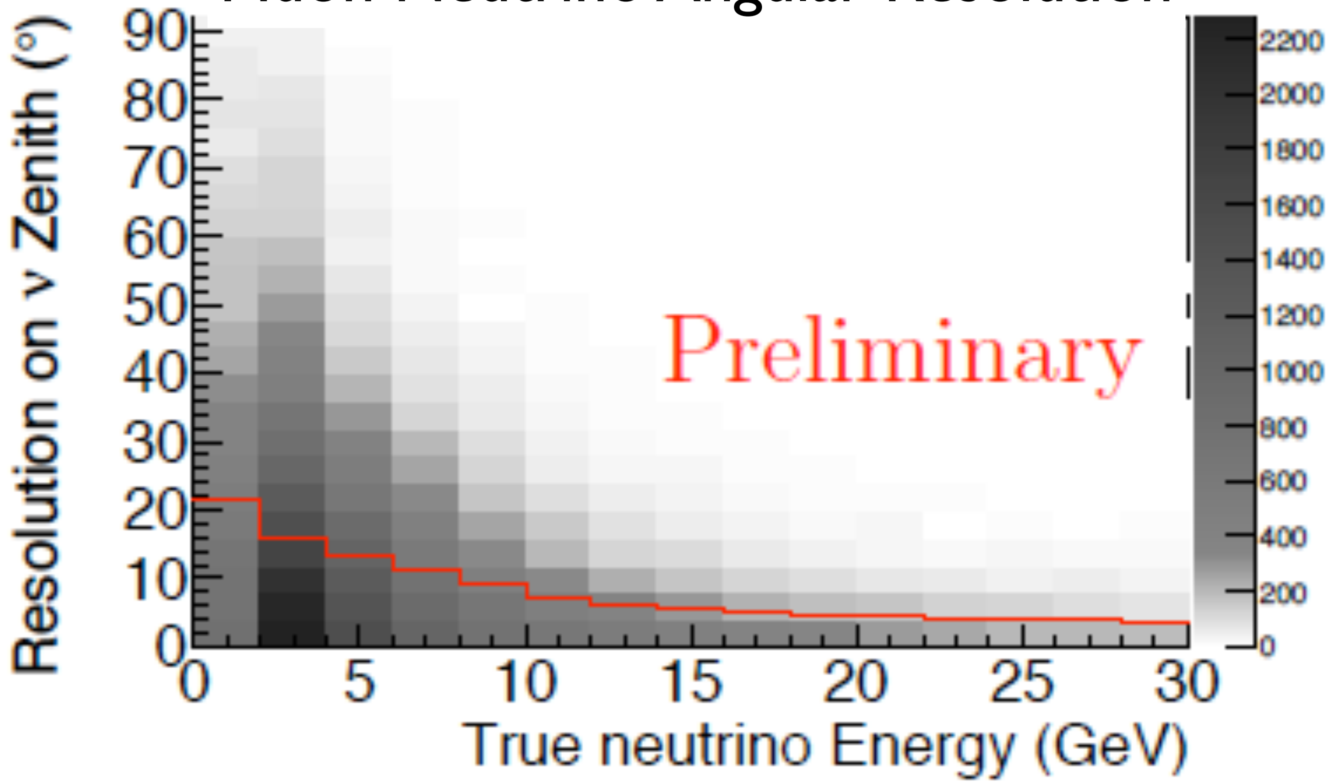
PINGU Detector Performance

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. $E_{\nu,\mathrm{true}}$.

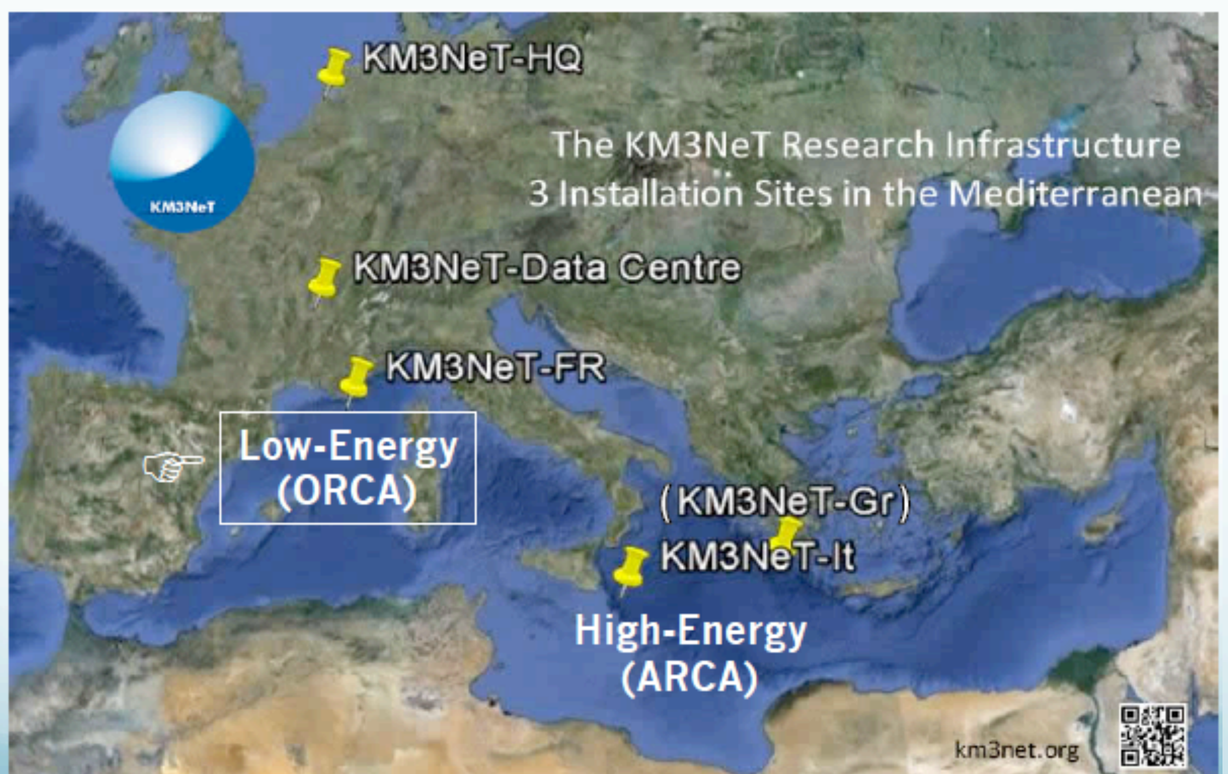
- PINGU performance using existing algorithms for IceCube
  - More computationally intensive algorithms are expected to further improve performance

A phased implementation

PHASE 1:
Shore and deep-sea infrastructure at KM3NeT-Fr & KM3NeT-It
31 lines deployed by end 2016 (**3-4 x ANTARES sensitivity**)
Proof of feasibility of network of distributed neutrino telescopes and more?
ORCA demonstrator

31 M€ FUNDED ONGOING

2016 PHASE 2: ARCA (+80-90 M€) and ORCA (+40 M€)
230 lines (2 building blocks in Italy) + 115 lines (1 building block) in France
Investigation of IceCube signal — *Neutrino Mass Hierarchy*

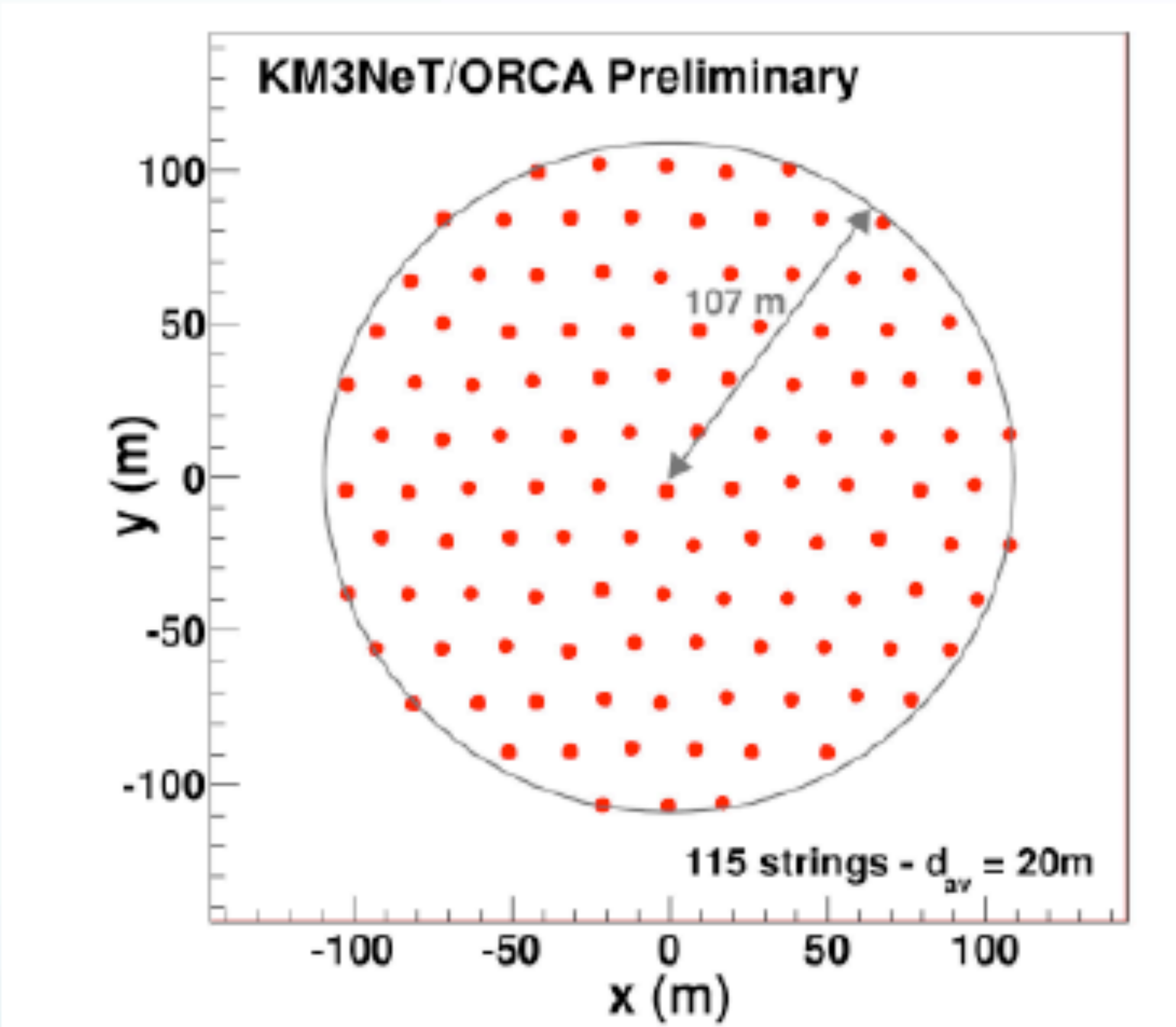


ARCA and ORCA Letters of Intent in preparation → Summer 2015

2020 KM3NeT NEXT: *Neutrino astronomy*
6 building blocks

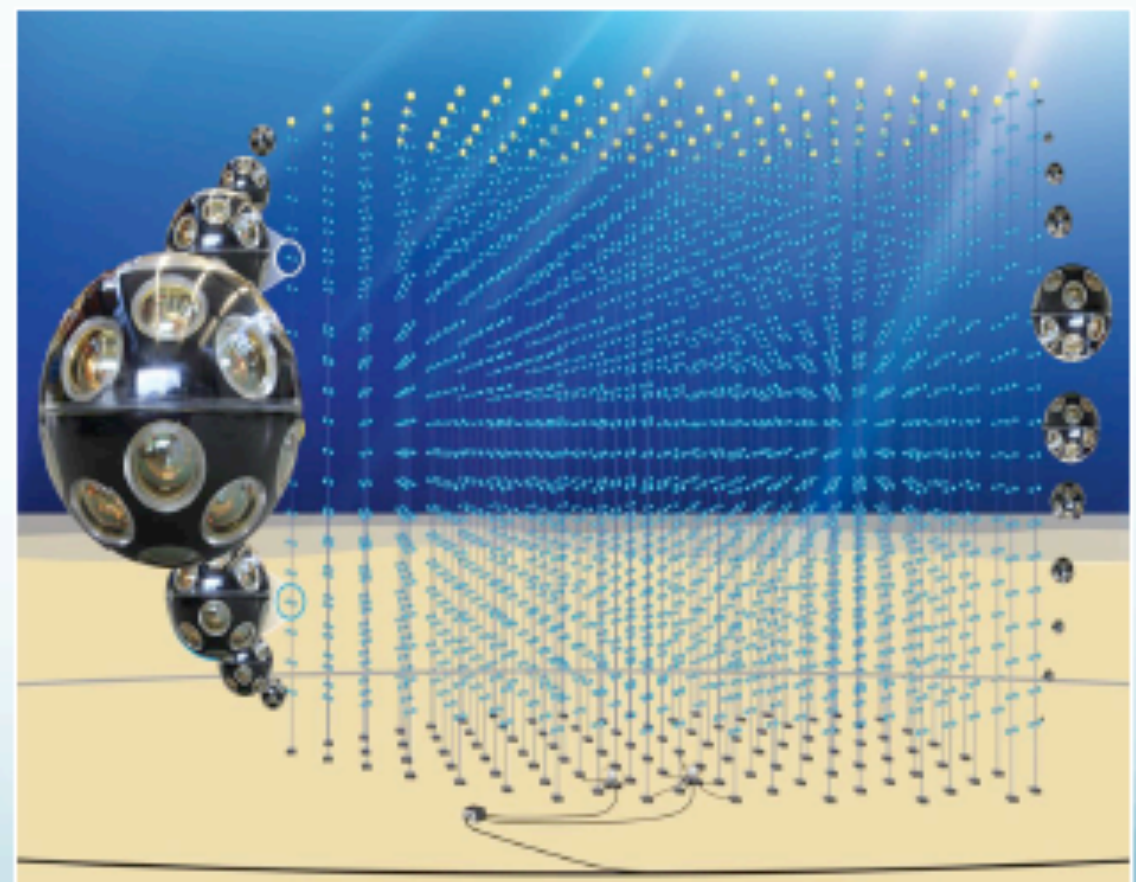
220-250 M€ ESFRI Roadmap

The ORCA (benchmark) design



115 lines, 20m spaced,
18 OM/line 6m spaced
Instrumented volume ~3.8 Mt, 2070 OM

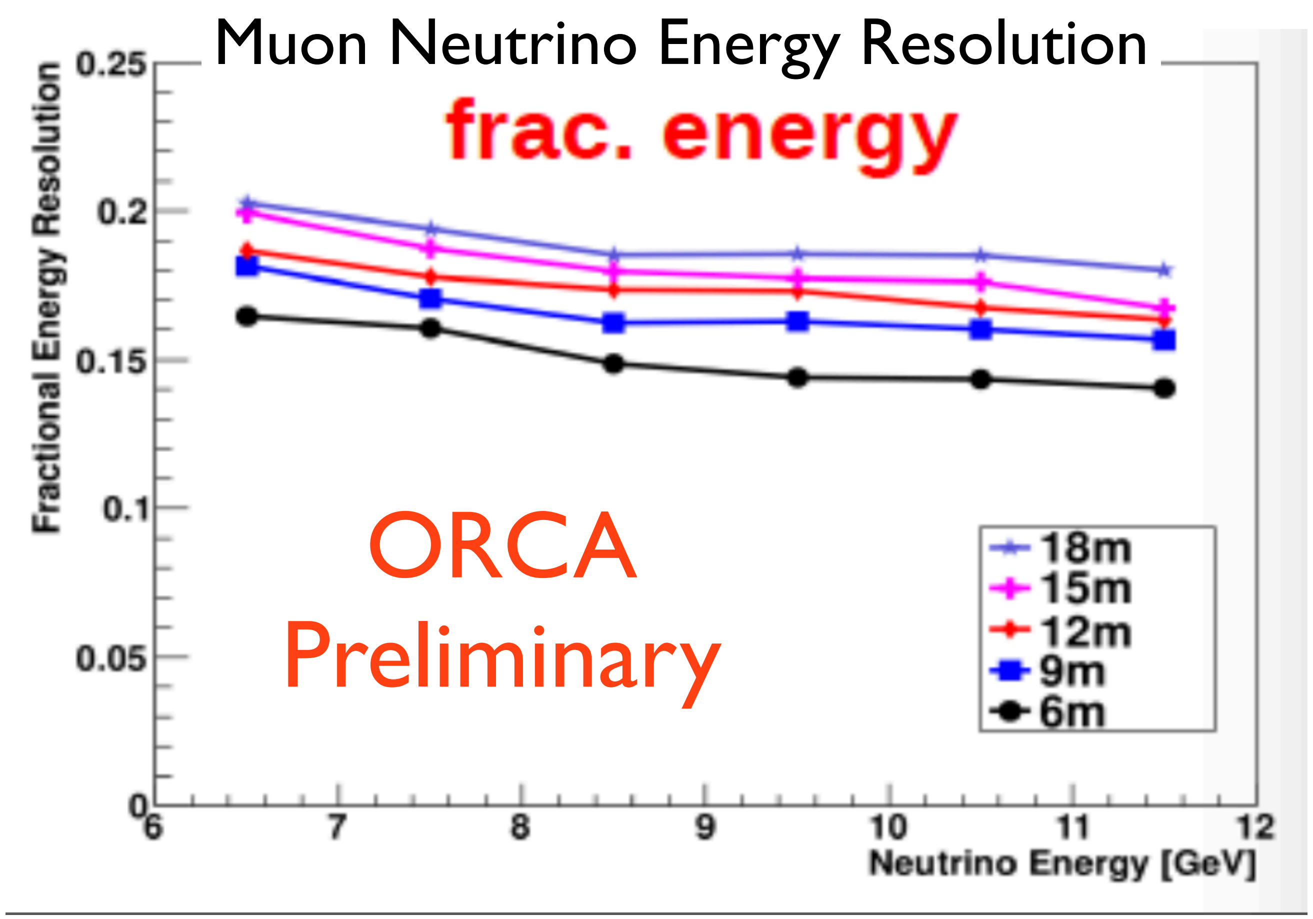
Optimized layouts still under study

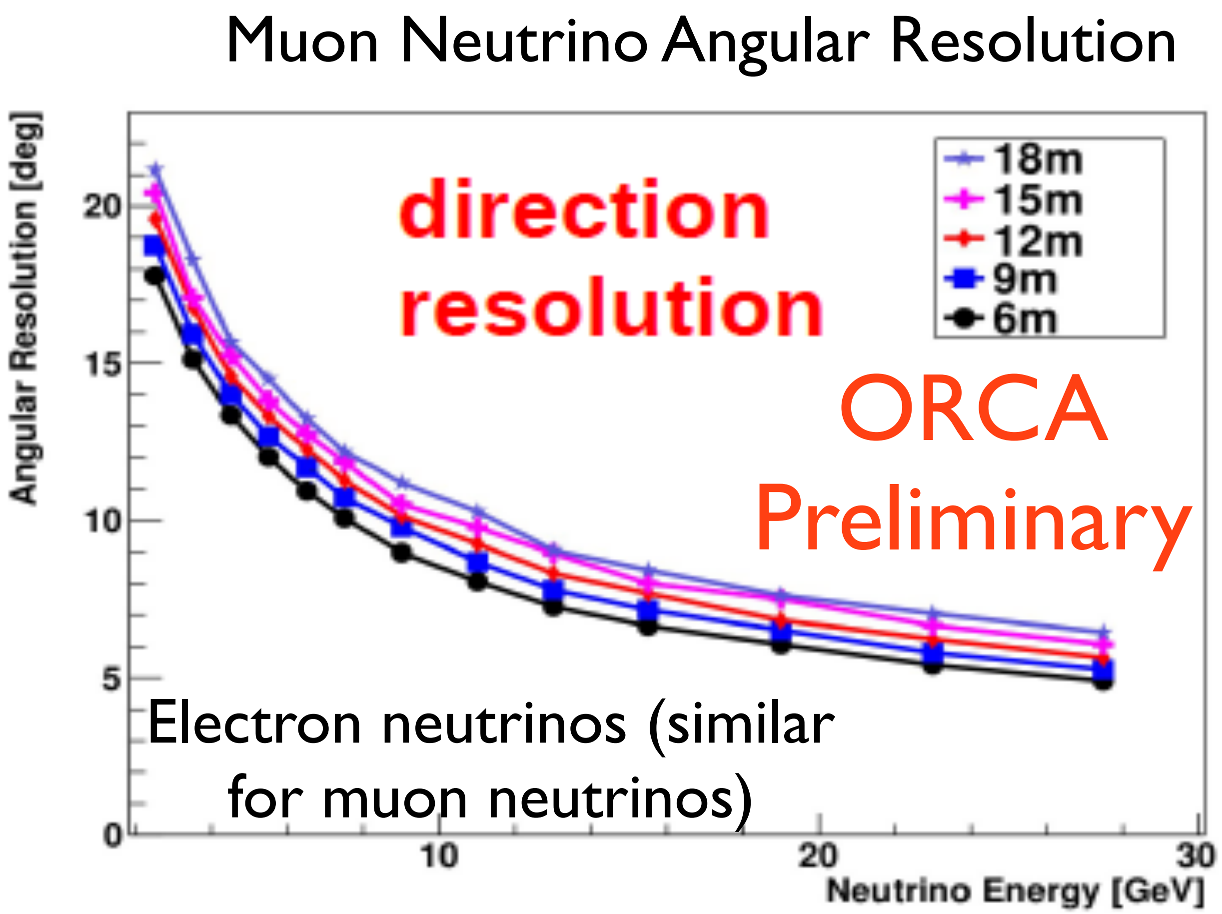


- 31 3" PMTs
- Digital photon counting
- Directional information

- Wide angle of view
- More photocathode than 1 ANTARES storey
- Cost reduction wrt ANTARES

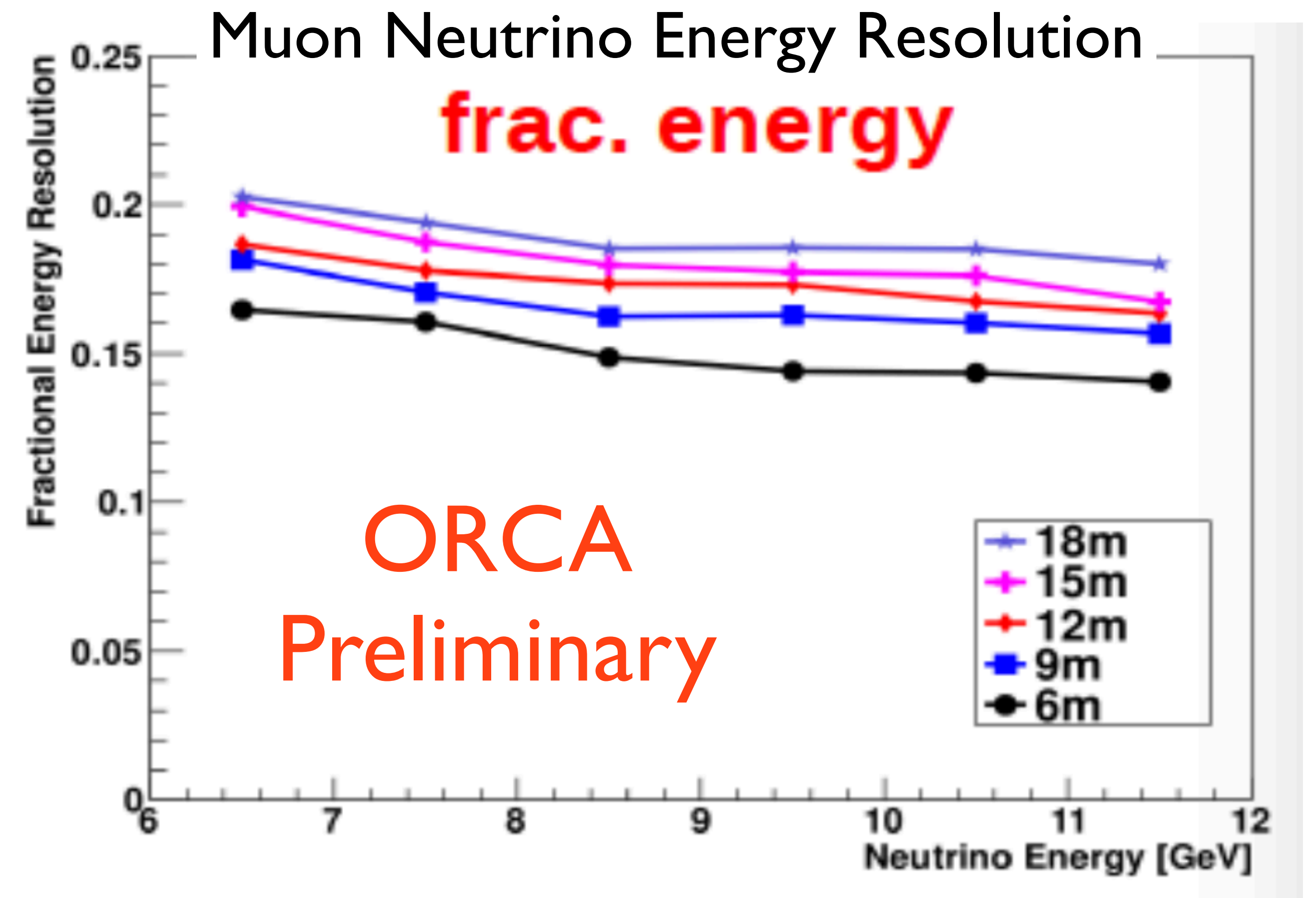
ORCA Detector Performance

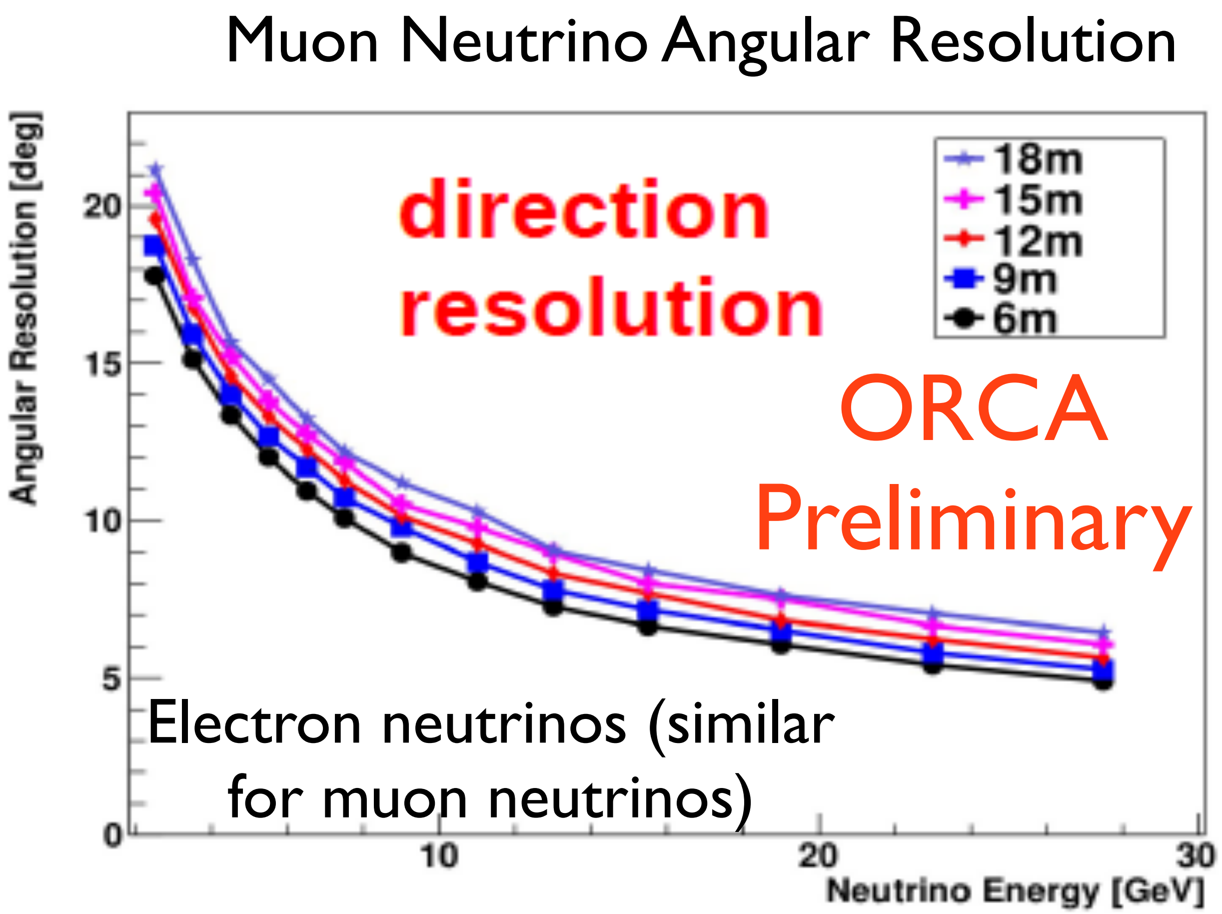




- Expected ORCA performance similar to PINGU

Parameterize Detector Performance





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

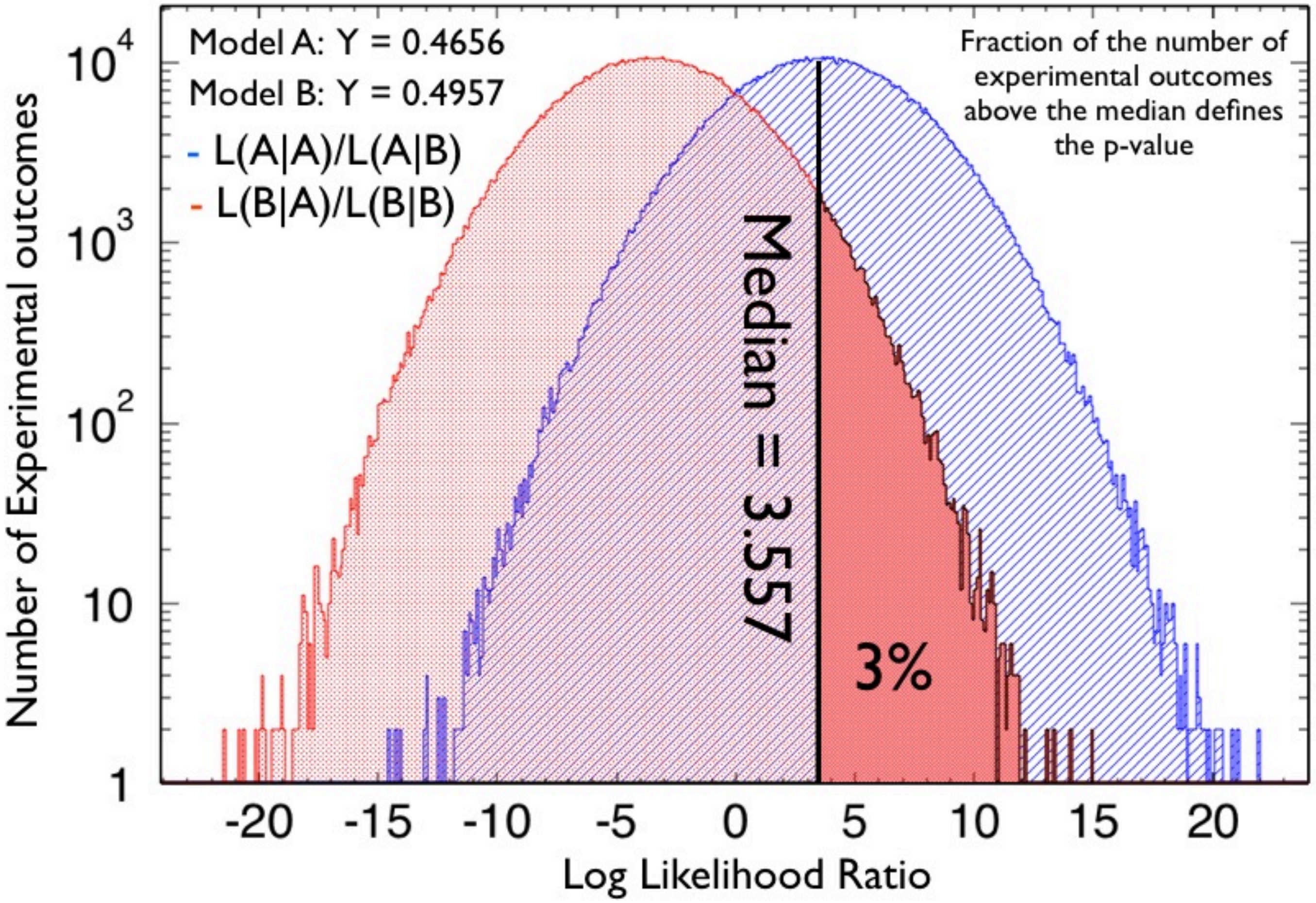
Zenith angle resolution
$\beta = \Delta\Theta \times (E[GeV])^{0.5}$

We adopt a value of α=0.2 as benchmark

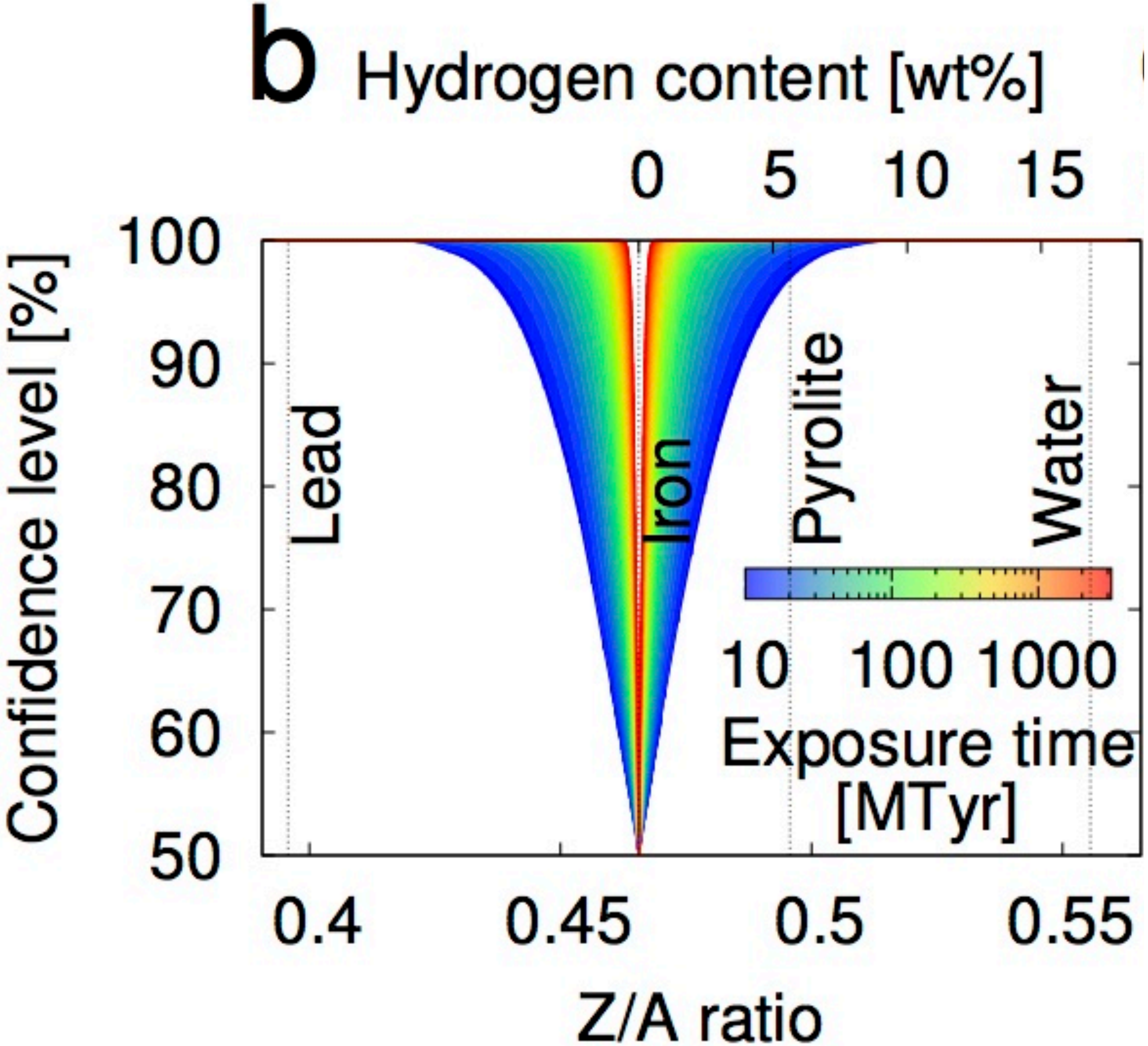
We adopt $\Delta\Theta$=0.25 as benchmark

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



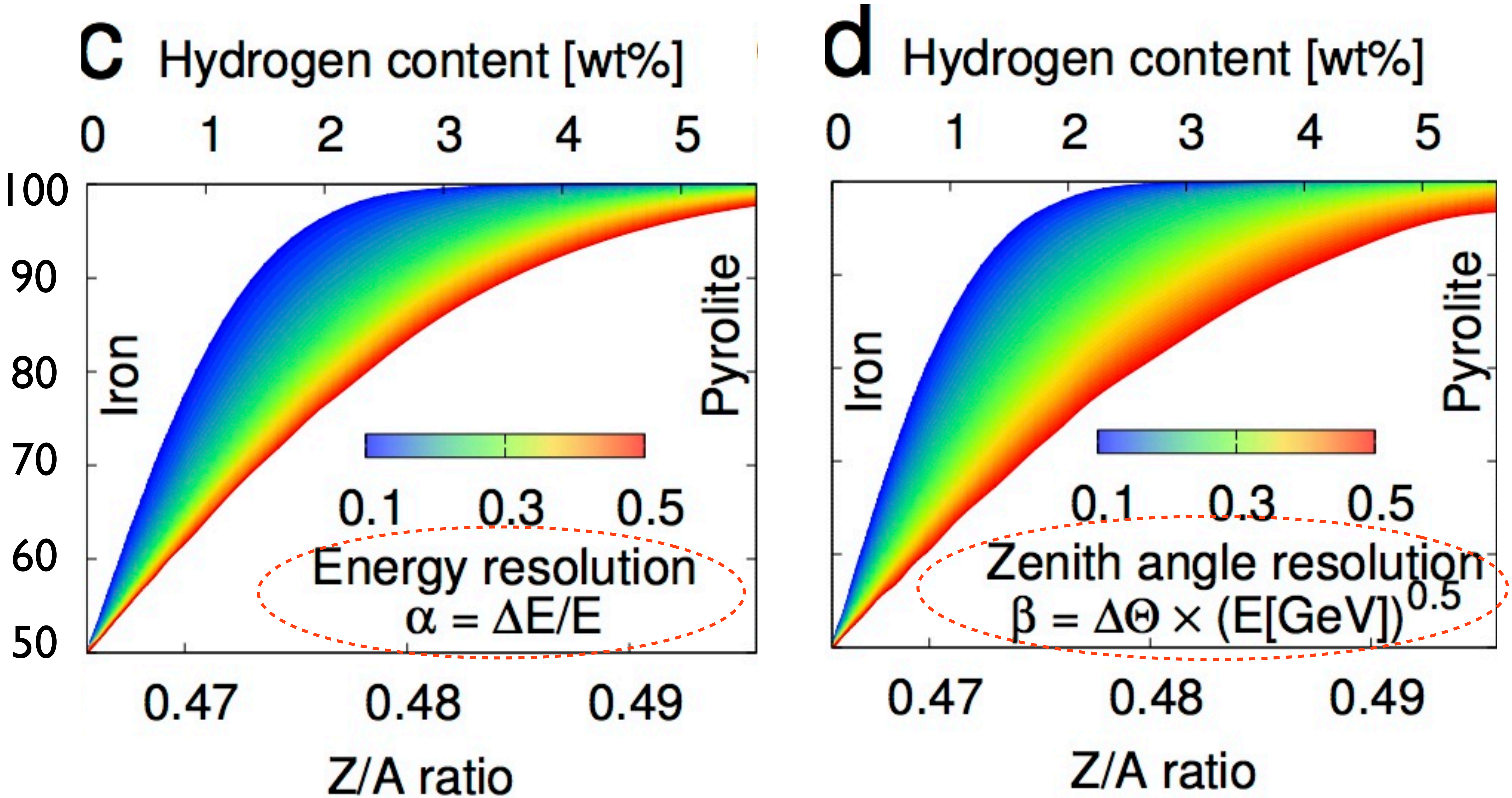
Sensitivity



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

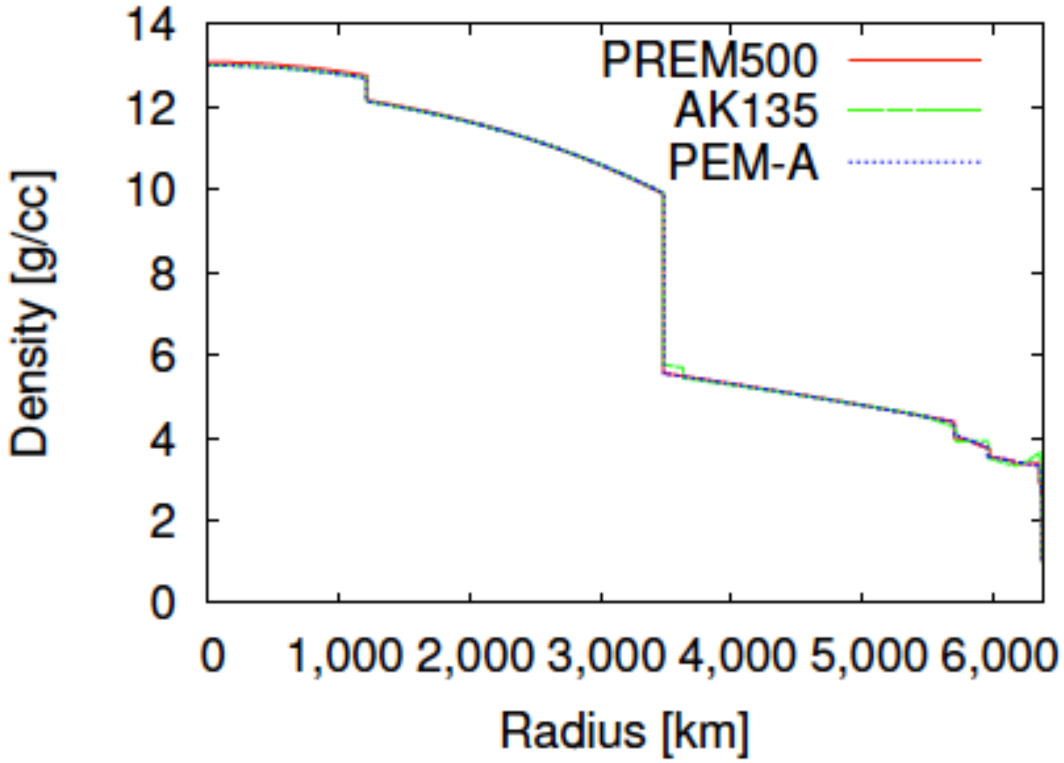
How can we increase sensitivity ?

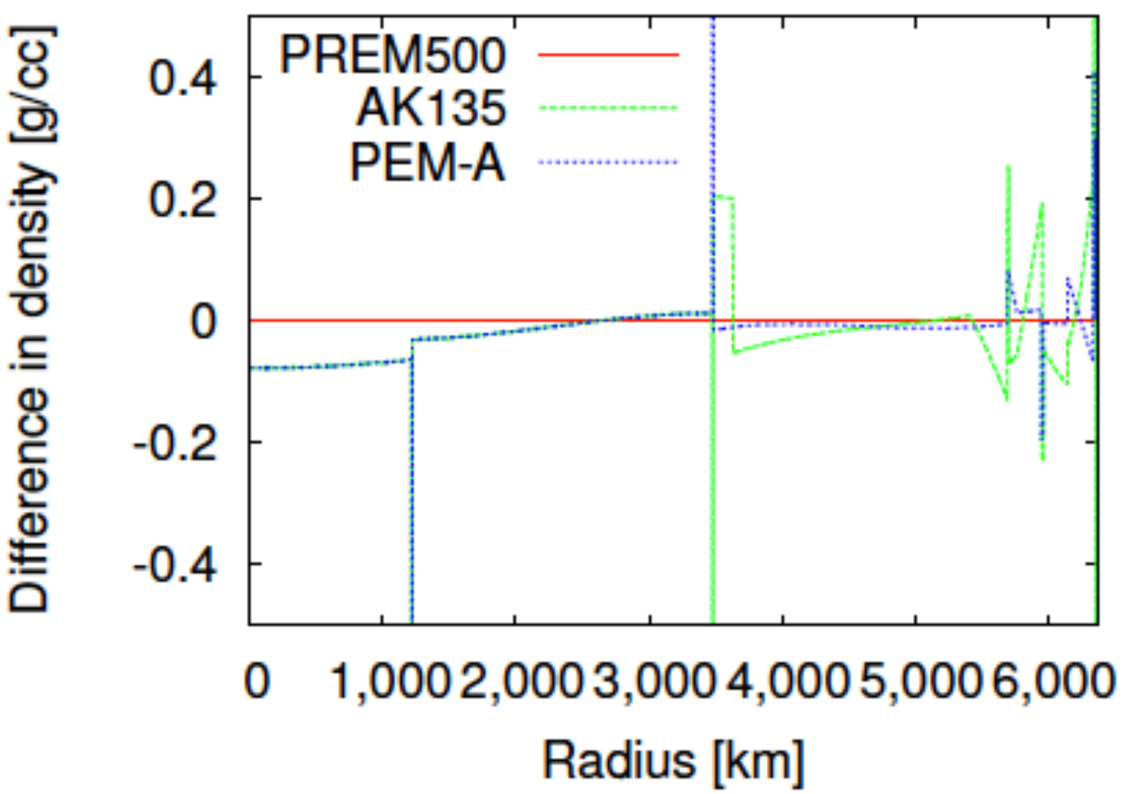
- Dependence on the angular resolution and energy resolution:

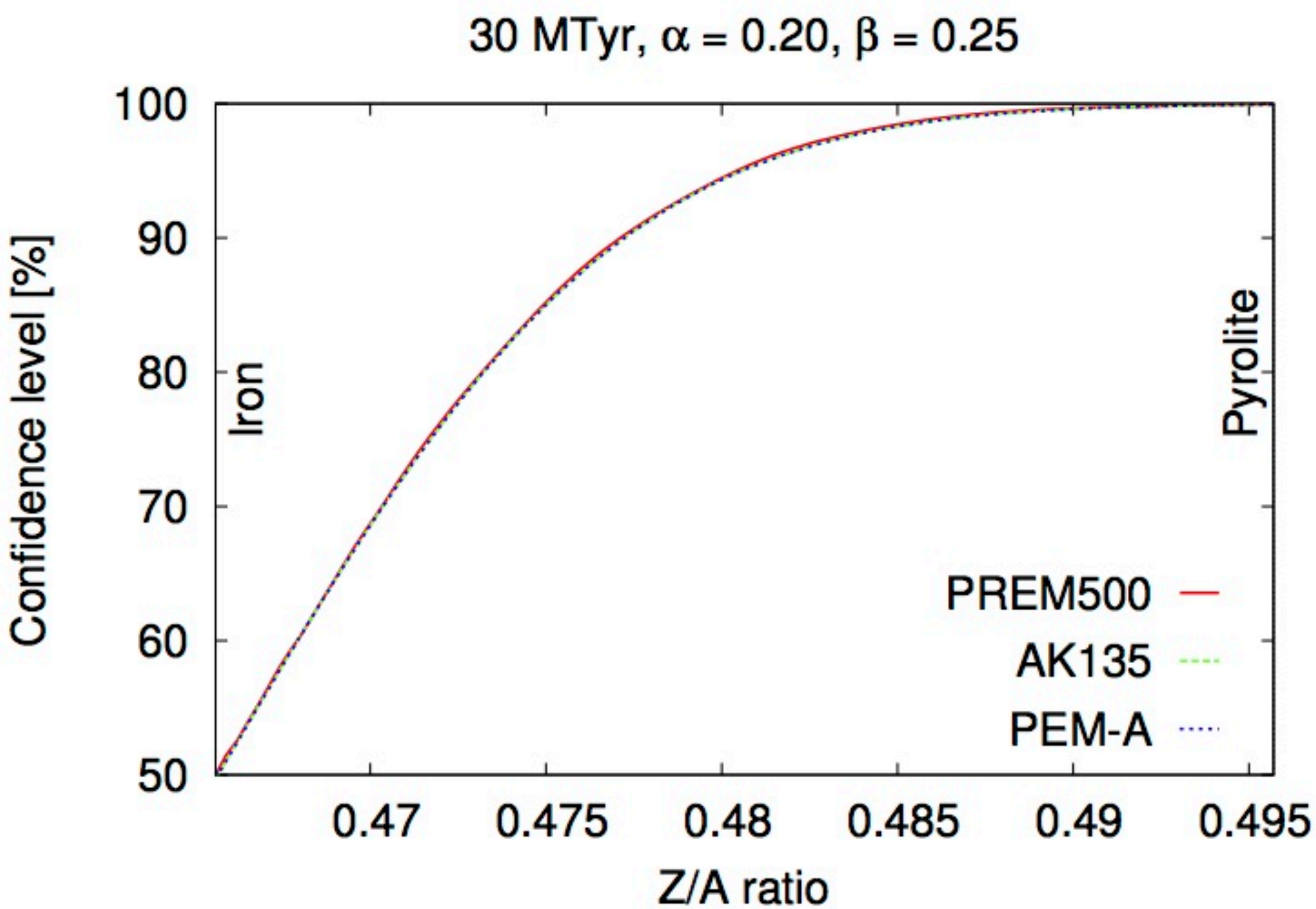


Rott & Taketa 2015

Uncertainty due to Earth model







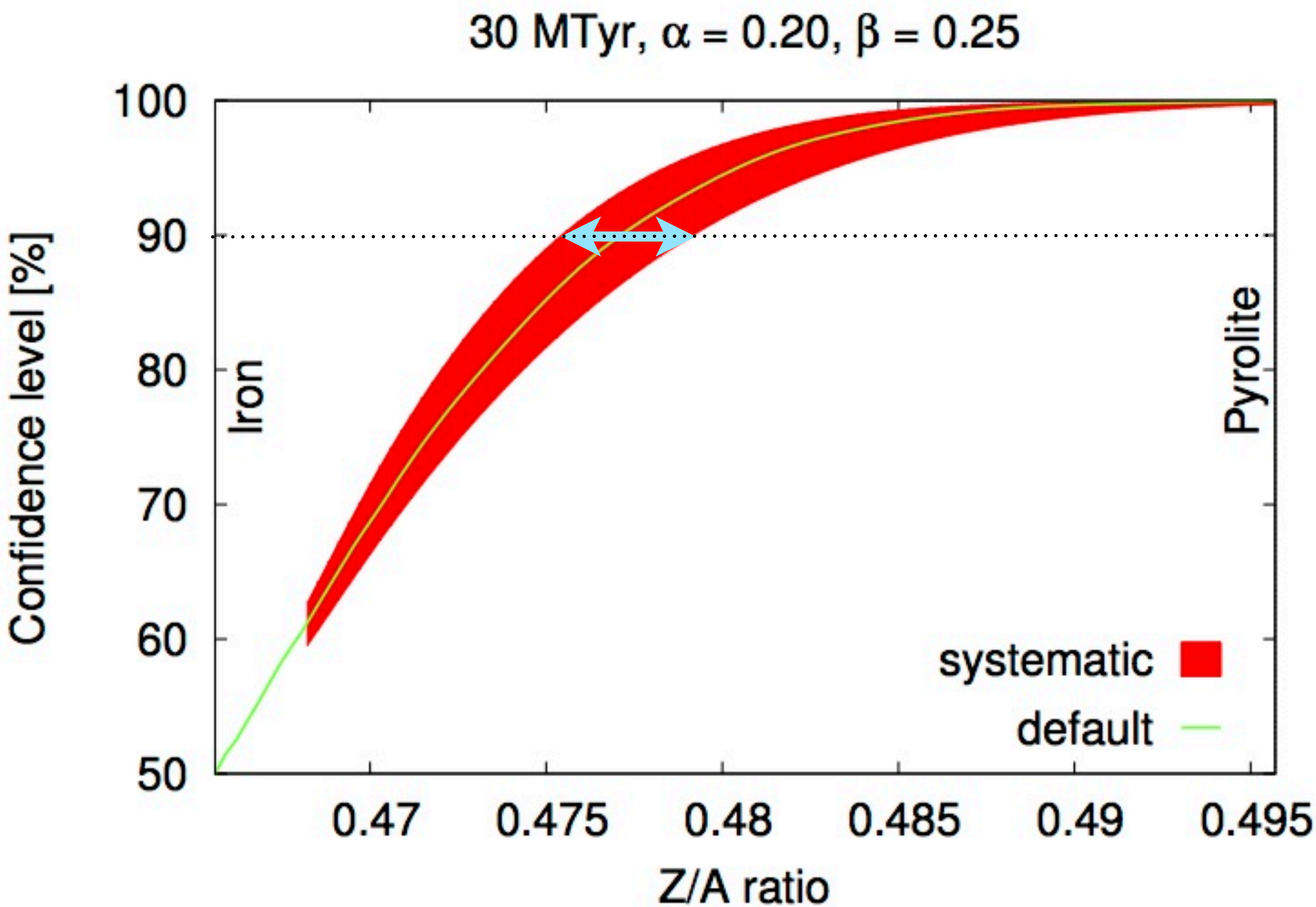
Uncertainty due to the Earth mass density profile is negligible

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).

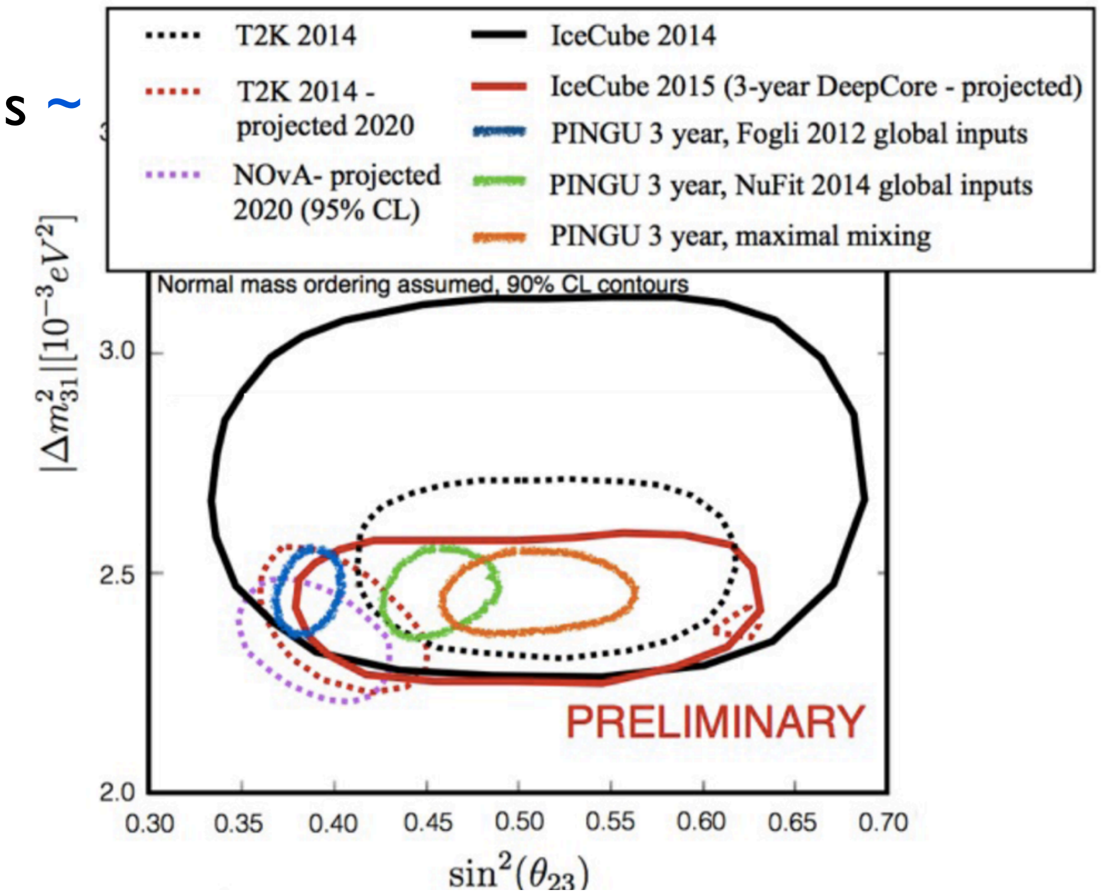
Uncertainty due to mixing parameters

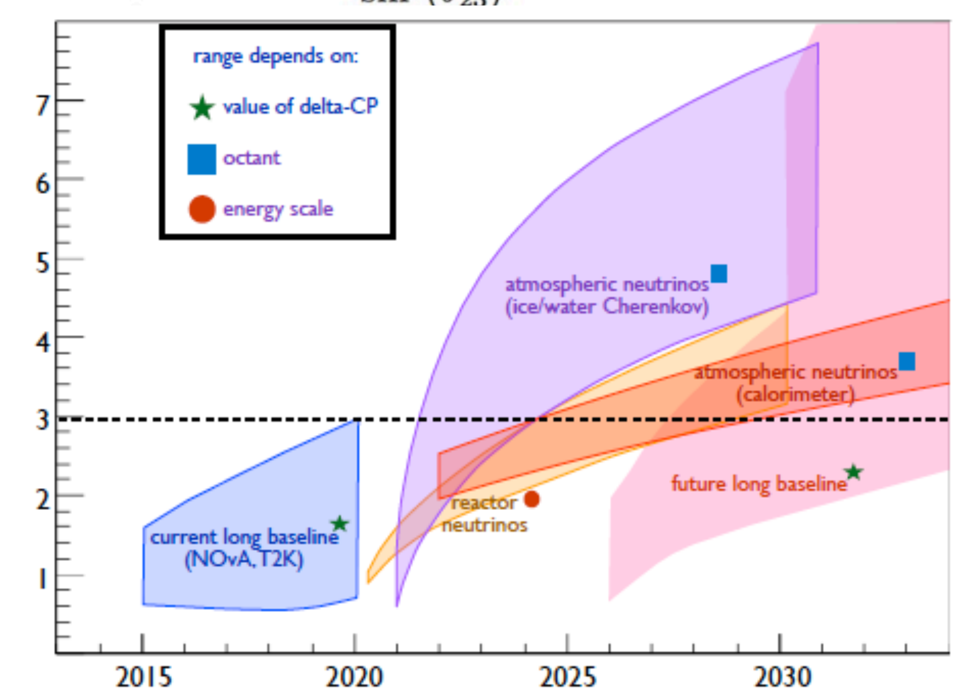


Use the best fit oscillation parameters and their uncertainties of:
Capozzi, F. et al. Status of three-neutrino oscillation parameters, circa 2013. Physical Review D 89, 093018 (2014).

PINGU Merits and potential schedule

- Well-established detector and construction technology
- Relatively low cost: Main costs: ~$20M design/startup plus ~ $1.25M per string
- Rapid schedule
  - 2014 -- 2017: R&D and Verification activities
  - 2016 -- 2019: Instrumentation Production
  - 2017 -- 2020: Drilling and Installation
- Proposal preparation - 2017 PINGU + Gen2
- Quick accumulation of statistics once complete
- Provides a platform for more detailed calibration systems to reduce detector systematics
- Multipurpose detector: Neutrino Properties (Mass hierarchy !), Dark Matter, Supernovae, Galactic Neutrino Sources, Neutrino Tomography, ...
- Opportunity for R&D toward other future ice/water Cherenkov detectors





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**.

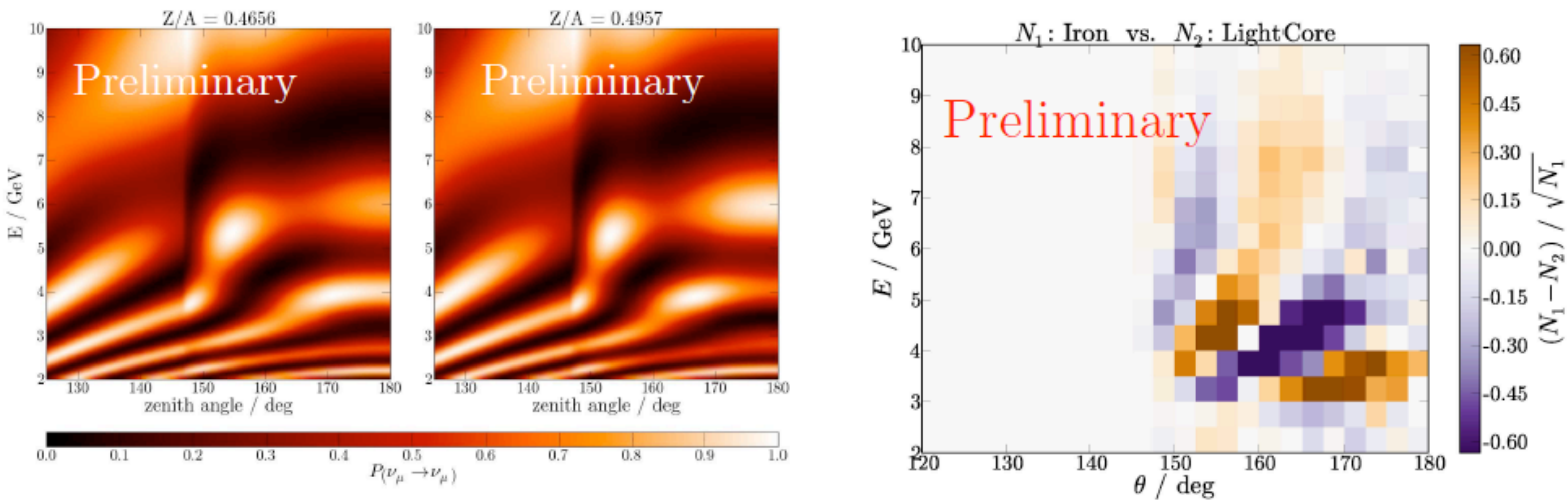
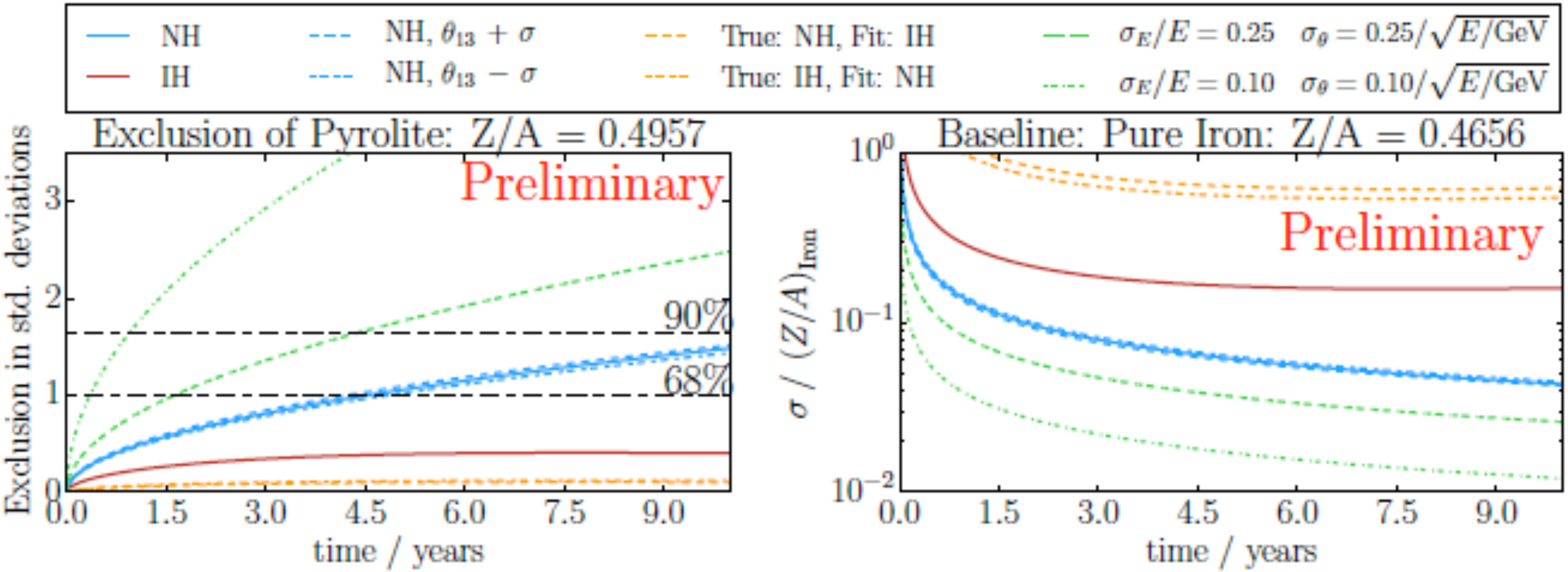


Figure 25: The impact of a changed core composition on the muon-neutrino survival probabilities is demonstrated by comparing the left most figure (pure iron core) and the middle figure (iron mixed with lighter elements). Signature of a pure iron Earth core with respect to a model assuming the same composition 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 LOI *arxiv:1401.2046*

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 →

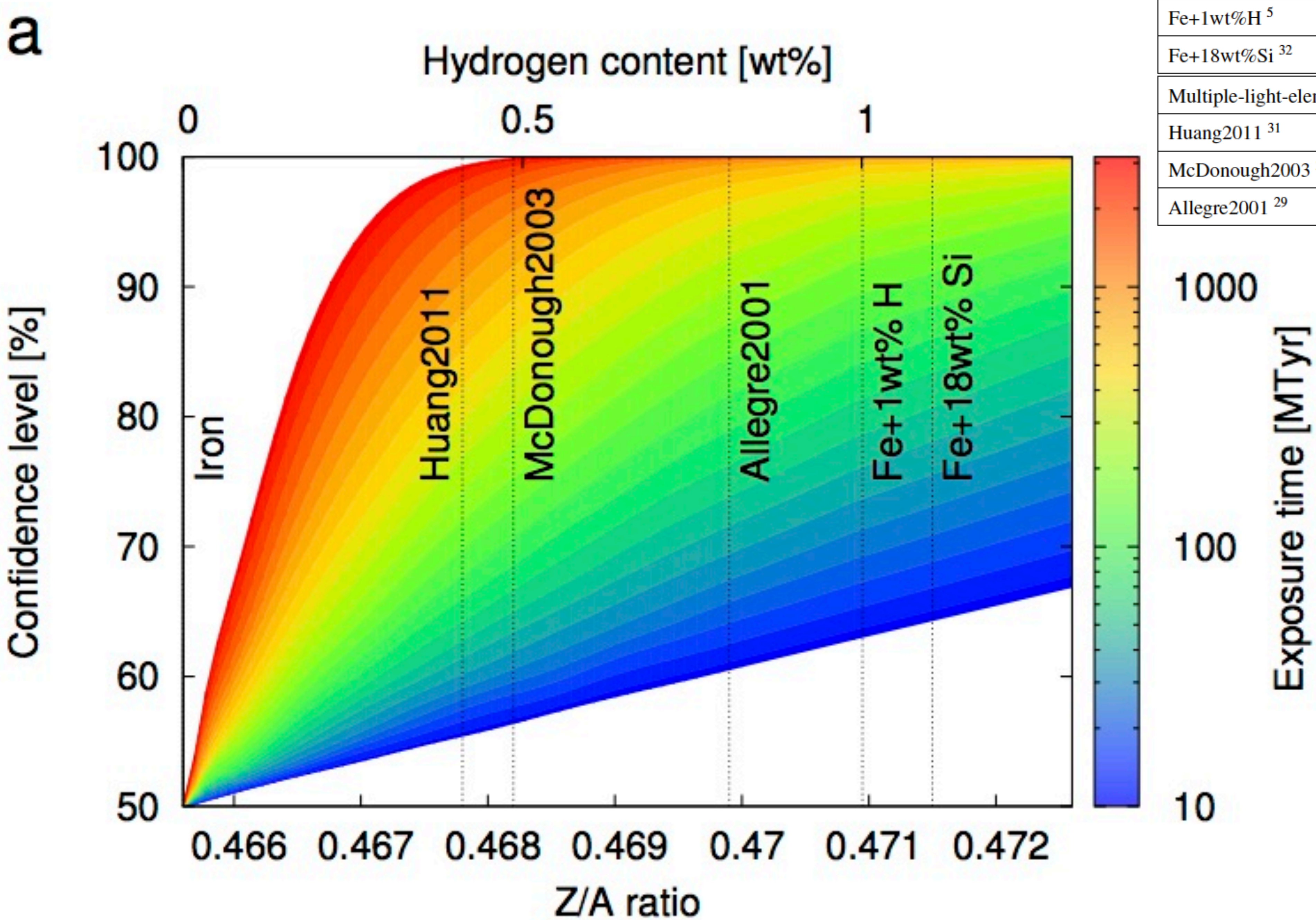
(3) Distinguish specific Earth composition models via oscillation tomography →

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, ...)
- More distant future
  - >>10MT detector with 2-10GeV neutrino sensitivity (new detector, augmented PINGU or ORCA)

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



Conclusions

- Neutrino oscillation tomography offers the potential to measure the Earth interior composition
  - Extremely sensitivity to hydrogen
- PINGU/ORCA/Hyper-K could test extreme Earth Core composition models 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
- More detailed studies are needed
  - Systematic uncertainties
  - Detailed study for PINGU / ORCA / Hyper-K
  - Complementarity: Oscillation Tomography with high-pressure experiments, ...
- Prospects of neutrino beams to be evaluated

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	0.5000
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

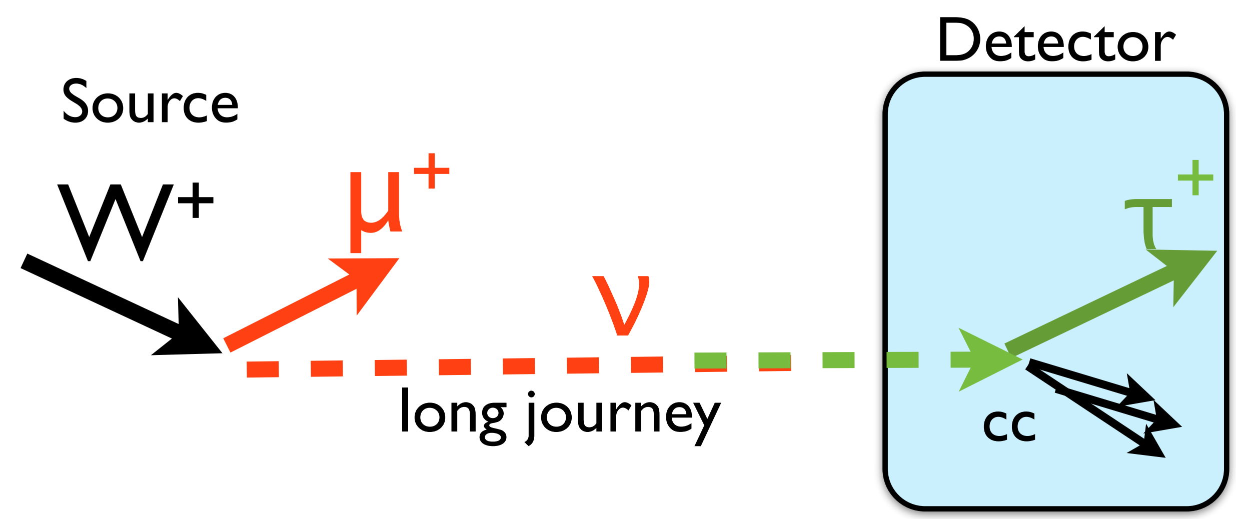
Z - Atomic Number

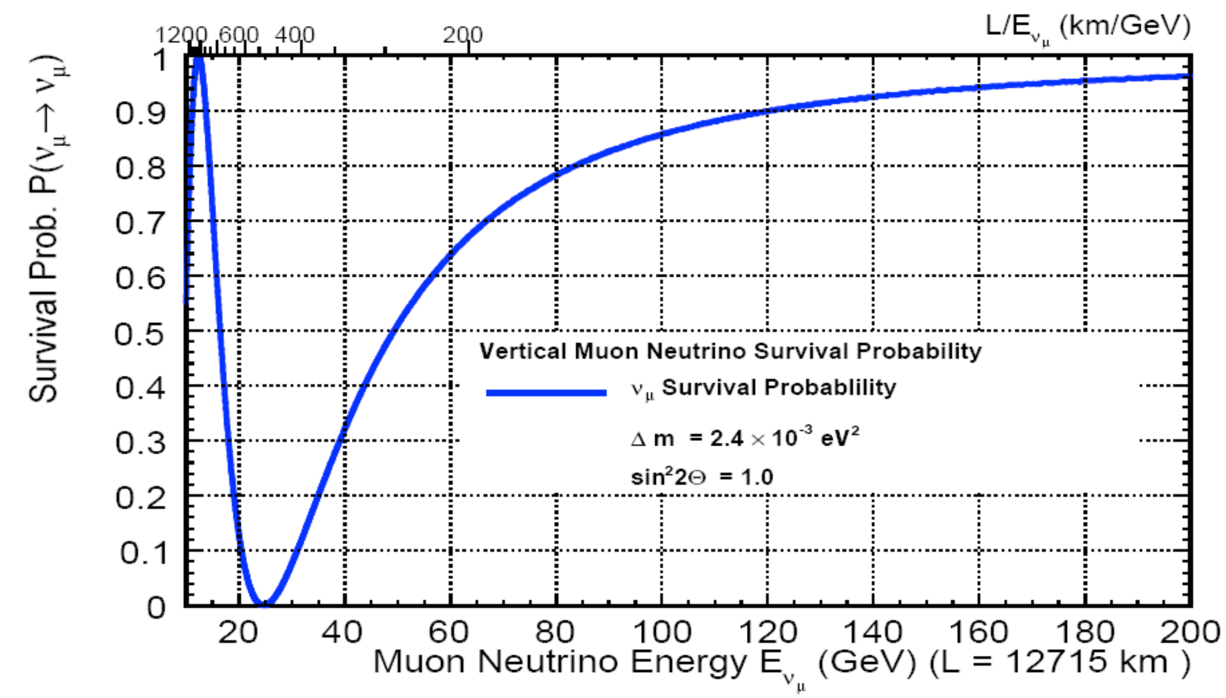
A - Atomic Mass

- Z/A ratios

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





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

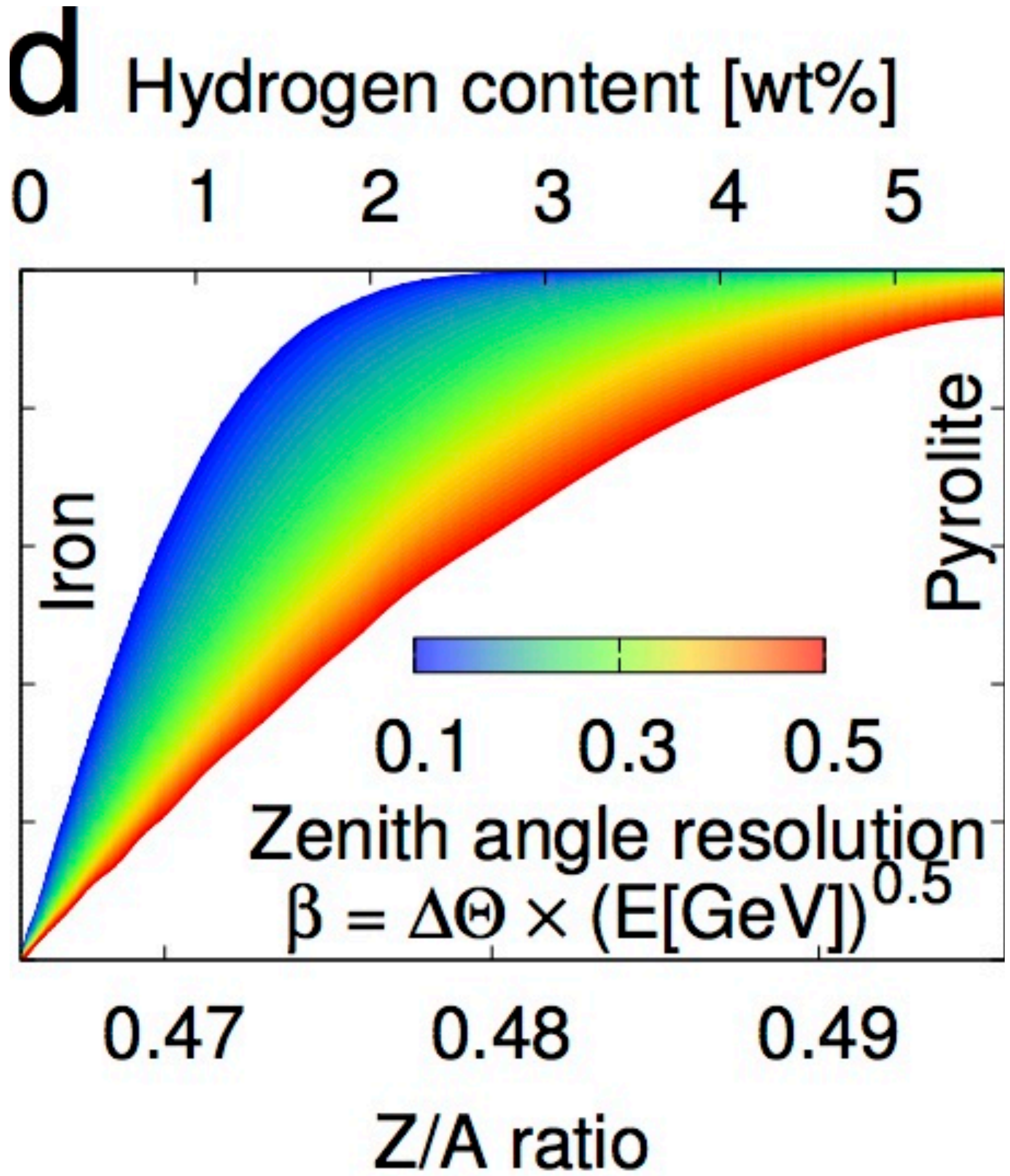
oscillation probability

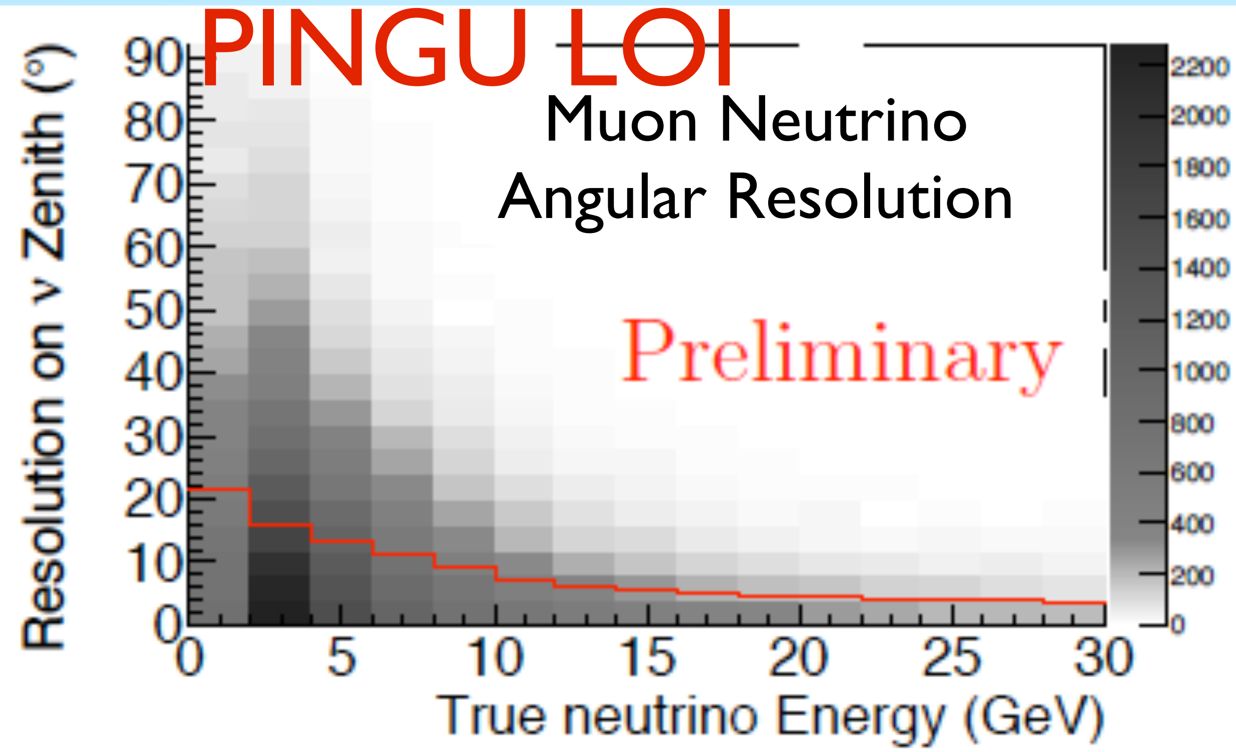
oscillation parameters

energy

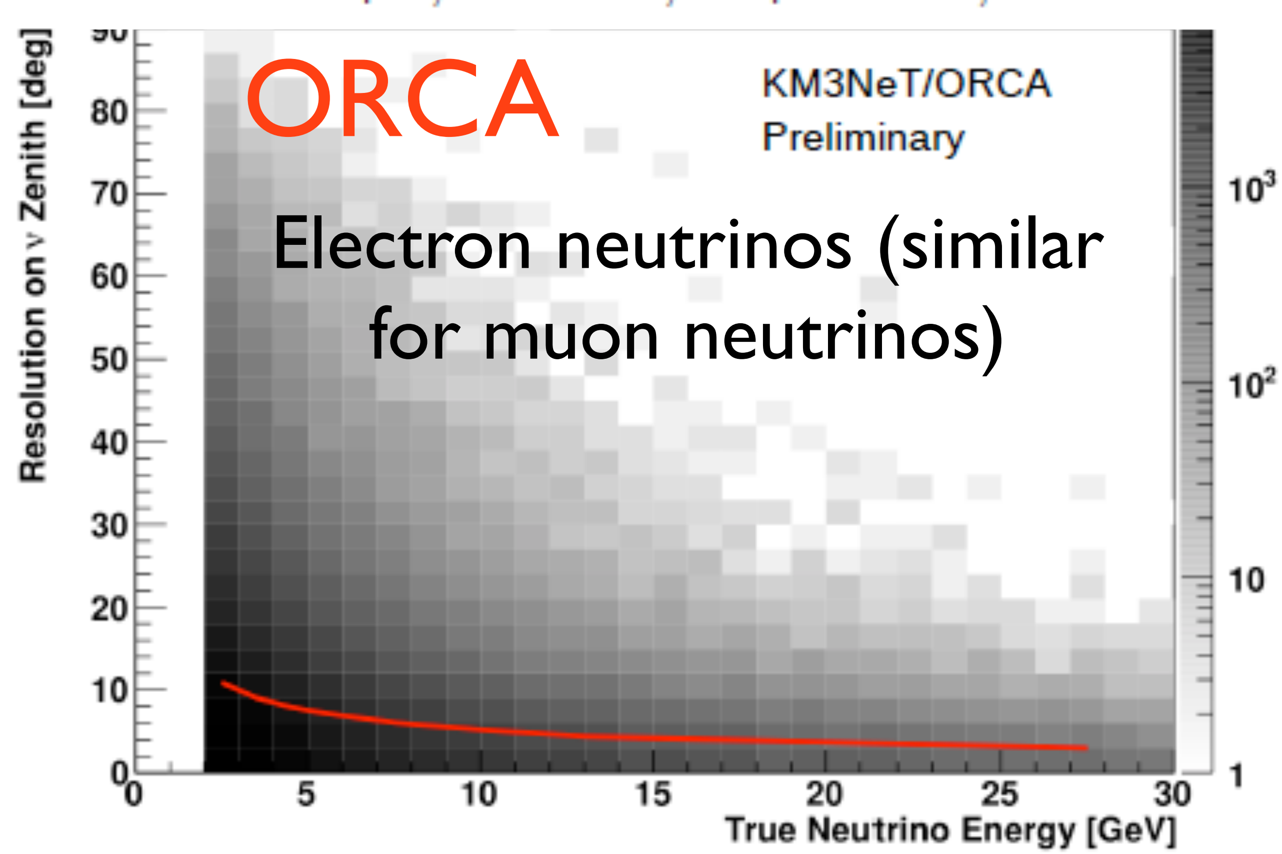
distance

Zenith Angle Resolution Dependence





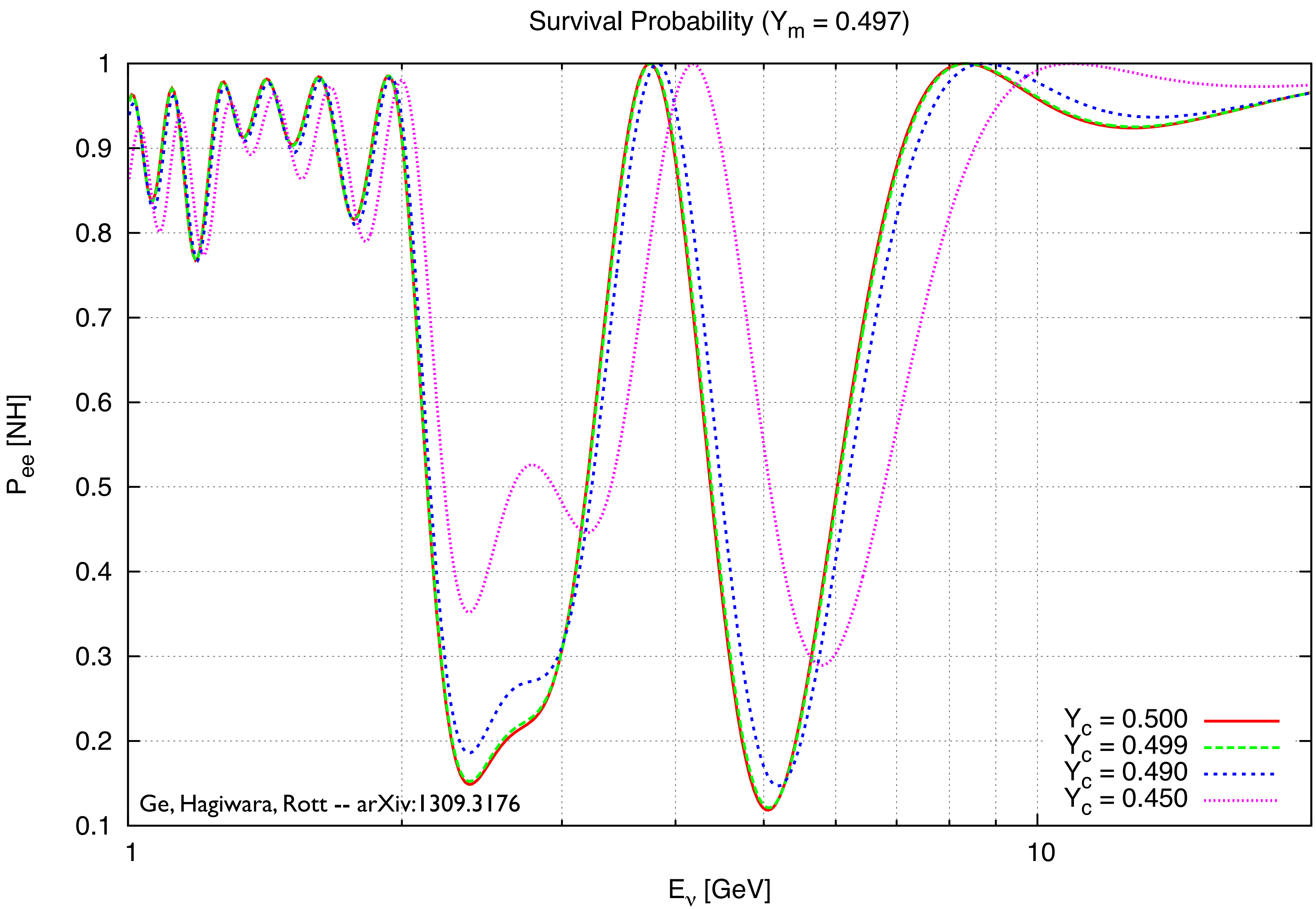
$|\theta_{\nu,\mathrm{true}} - \theta_{\nu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.



- We adopt ΔΘ=0.25 as benchmark, which is close to the current estimates for ORCA or PINGU

Impact of core electron density

Change in electron neutrino survival probability if the electron density in the core is change. Mantle density is assumed constant.



Z/A determines the electron density Y_C

Despite large uncertainty in composition, electron density relatively minor impacted (Z/A~0.5)

Y_C uncertainty based on Earth composition a few %

PINGU cost example

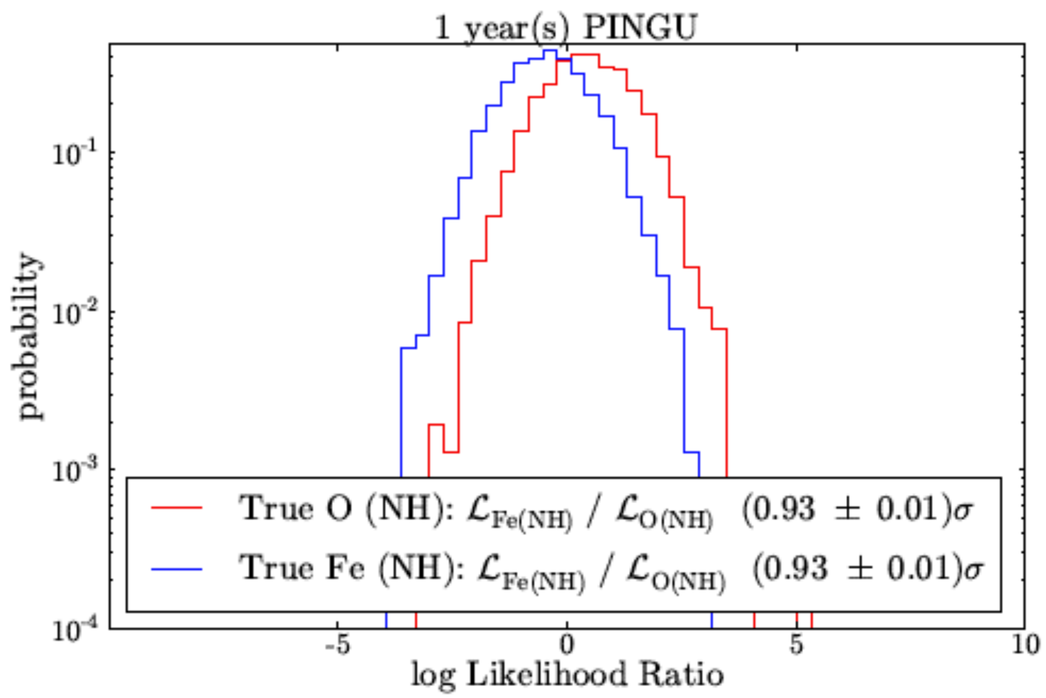
WBS Number	WBS Name	Total w/o Contin. ($M)	Estimated Contingency	Total with Contin. ($M)
1.1	Project Office	6.3	16%	7.4
1.2	Drilling	11.7	28%	15.0
1.3	PDOM	19.7	25%	24.6
1.4	Cable System	12.8	25%	16.0
1.5	Surface Instrumentation	3.4	25%	4.2
1.6	Calibration System	3.9	22%	4.8
1.7	IceCube Integration	5.9	16%	6.8
1.8	Polar Operations (except drilling)	3.6	16%	4.2
1.1-8	Subtotal	67.5		83.1
1.9	Antarctic Support Contractor (ASC)	17.4	22%	21.2
1.1-9	Grand Total	84.8	23%	104.3

Table 9: Estimated costs for the construction of the baseline 40-string PINGU detector alone, broken down by WBS element. No foreign funding agency contributions are included. Contingency is based on estimated risk factors at WBS Level 2.

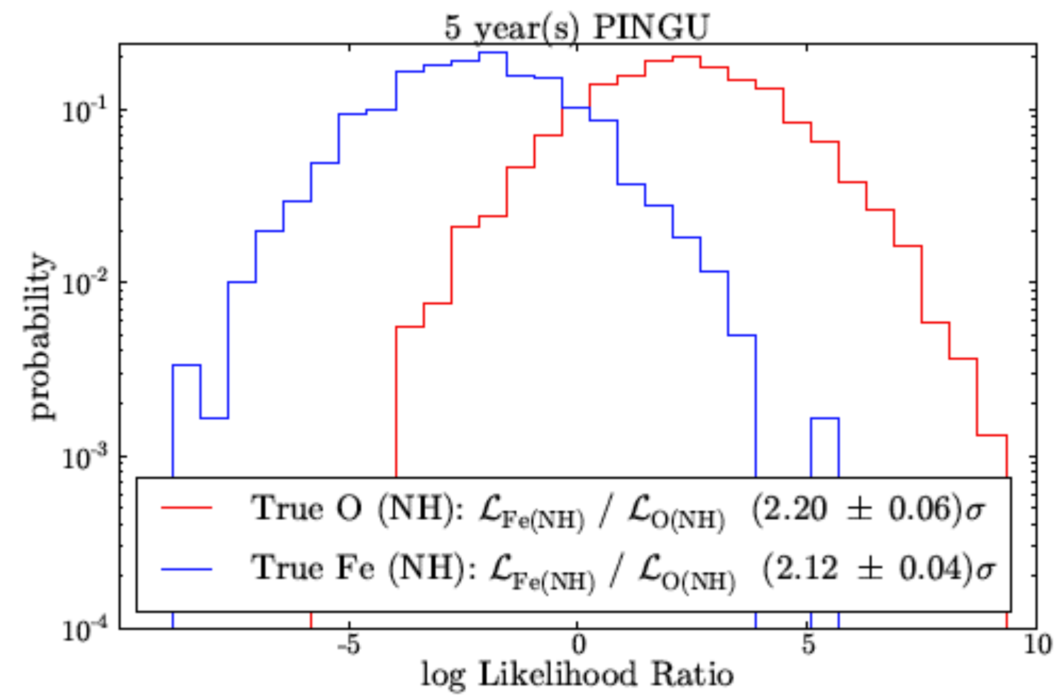
Example study for PINGU

- Two different Earth models (extreme case) are compared:
  - a pure iron core (Yc=0.4656)
  - a core with a composition similar to the mantle (Yc= 0.497)

Exclusion limits are calculated using a likelihood ratio analysis:
- 5 years of PINGU data, including reconstruction



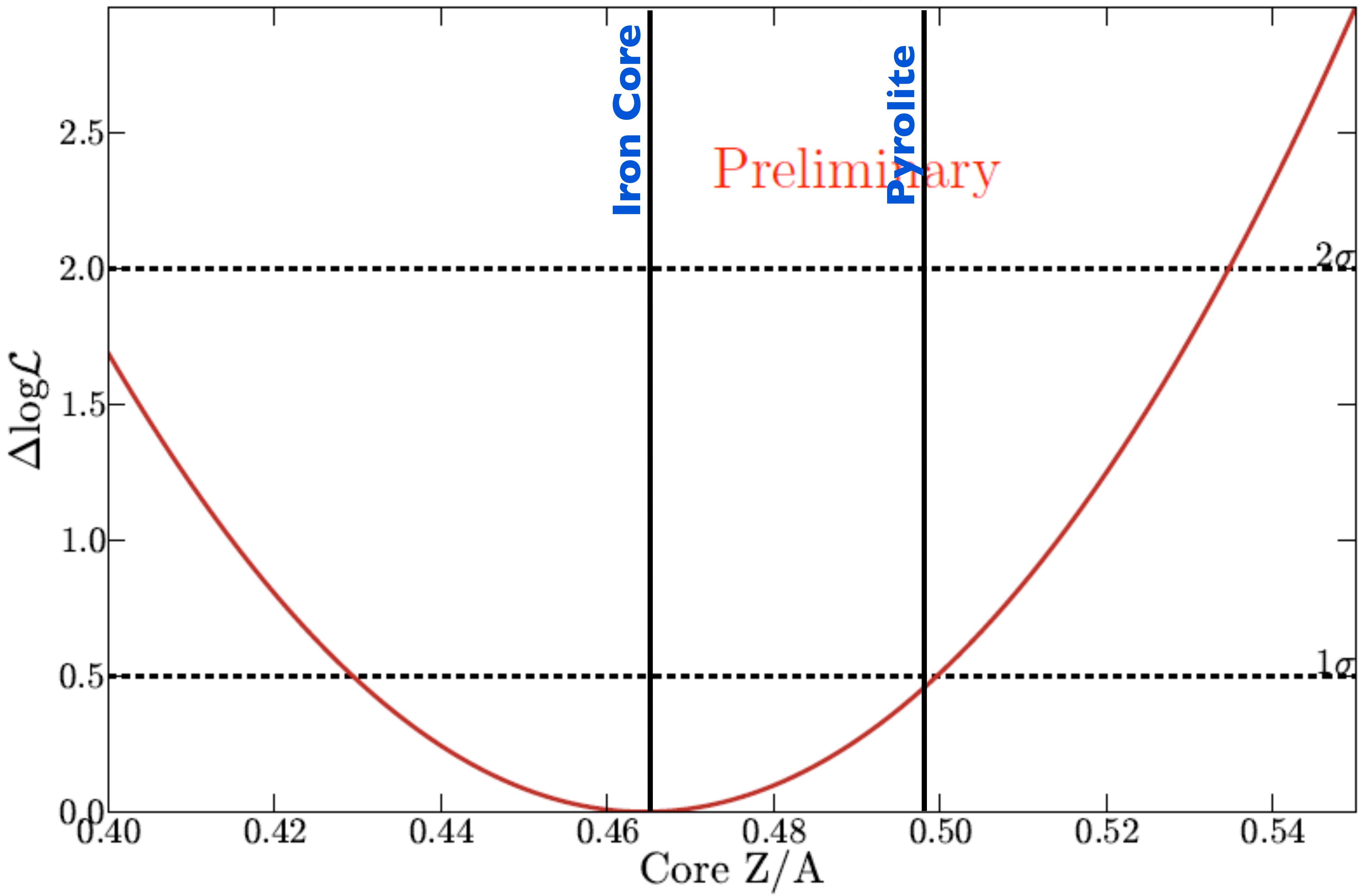
(a) 1 year of data.



(b) 5 years of data.

Sensitivity of Core Z/A

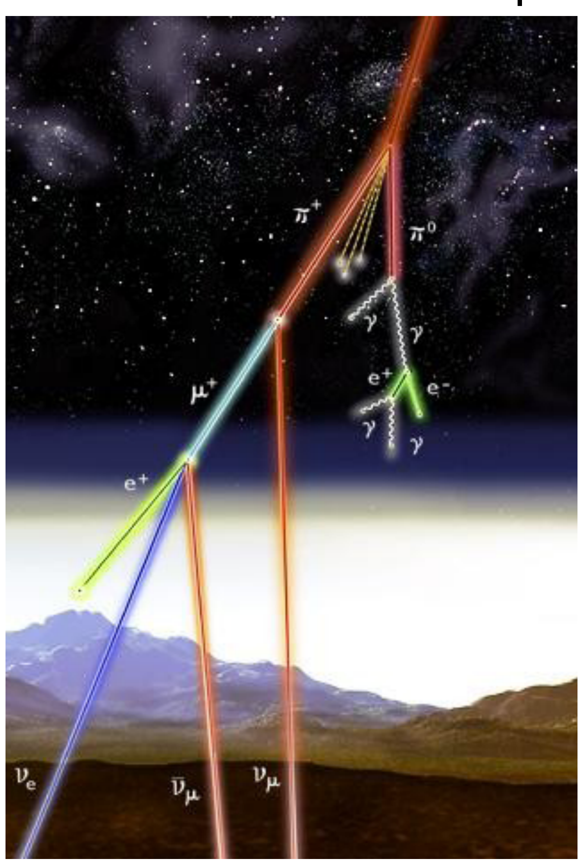
5 years of PINGU data

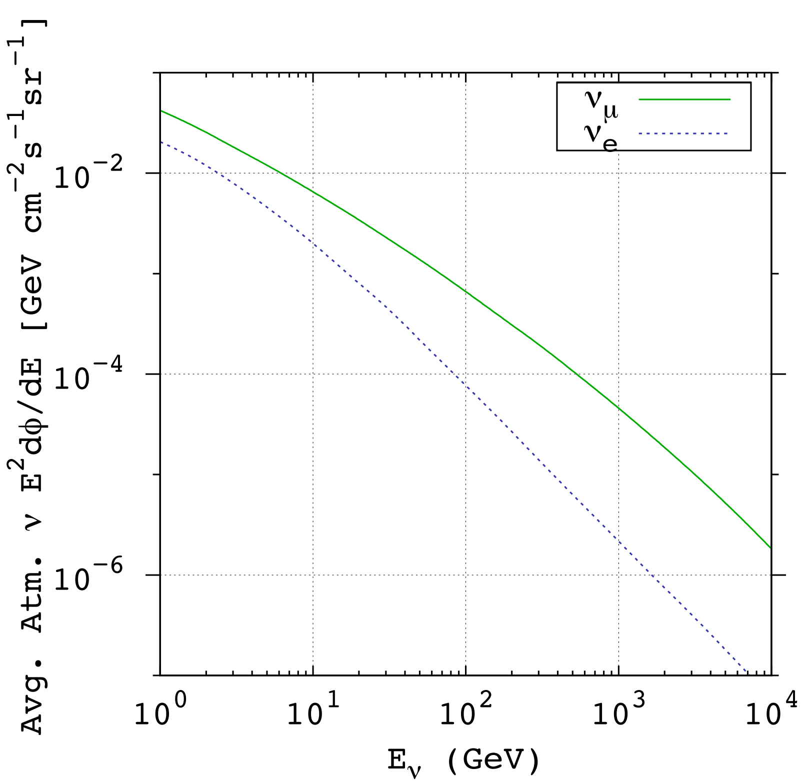


Considerations

- Y=Z/A≈0.5 is very similar for all elements
  - Even relatively large change in composition could result in small change in Y ~ 1%
  - Exception Hydrogen Y=1
- To measure an effect due to the core composition we need:
  - good energy resolution -> fully contained events, good optical coverage
  - good angular resolution -> precise timing, good optical coverage
  - high statistics sample -> large effective detector volume

Neutrino Source - Atmospheric neutrinos



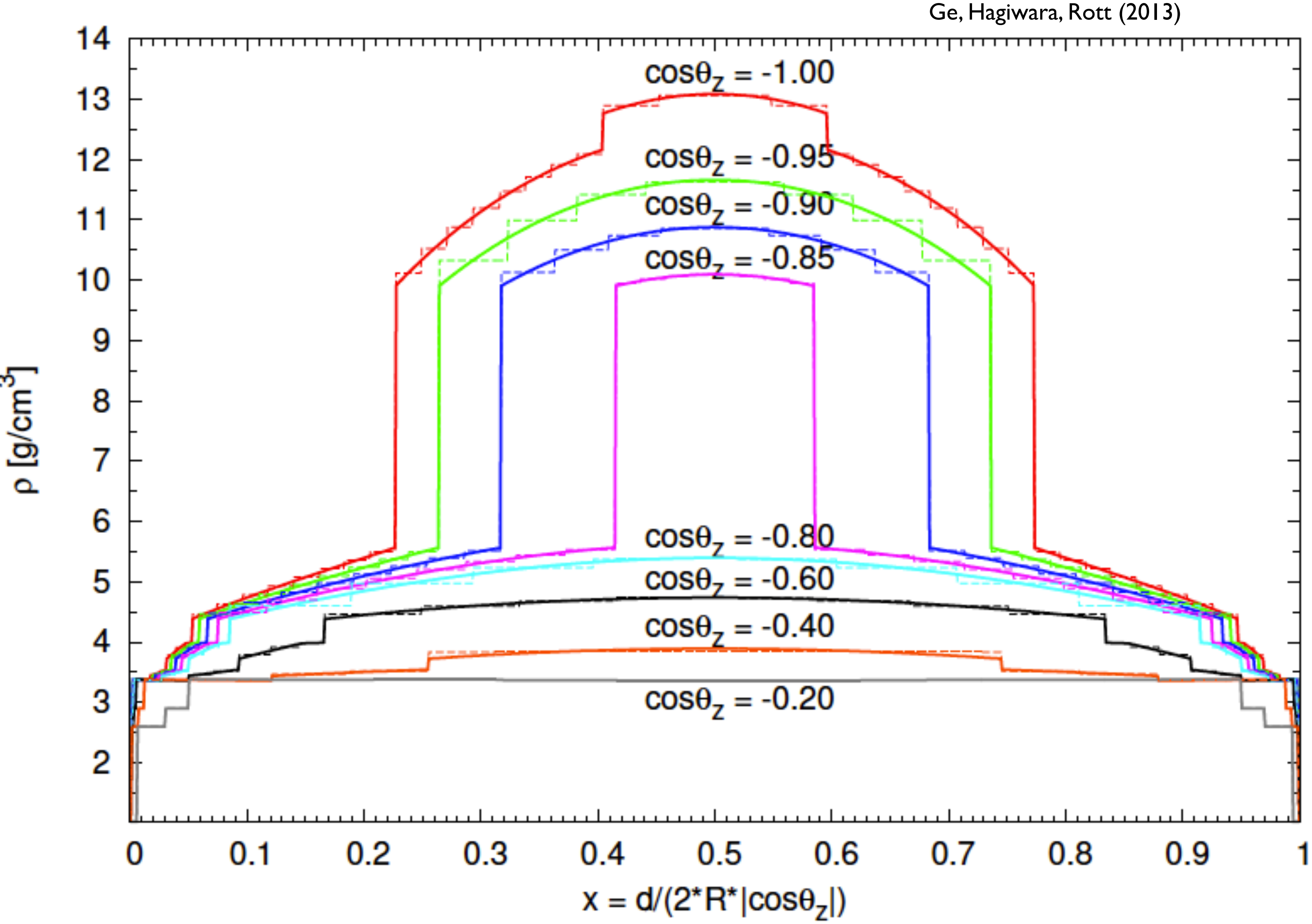


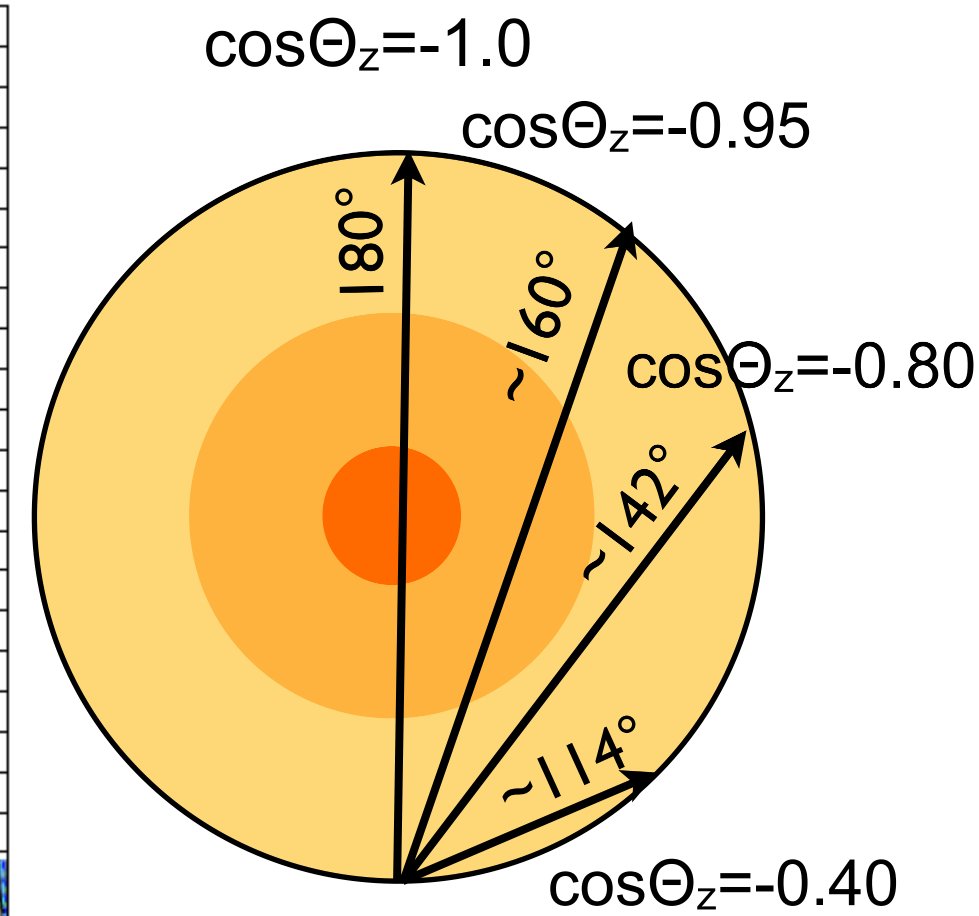
- $p + A \rightarrow \pi^\pm (K^\pm)$ + other hadrons
  - $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$

Atmospheric neutrino spectrum follows power law with spectral index of γ~3.7

Preliminary Reference Earth Model

Ge, Hagiwara, Rott (2013)





- The PREM - Preliminary Reference Earth Model is based on a paper by Dziewonski and Anderson in 1981. It still still represents the standard framework for interpretation of seismological data