# ISAPP Summer School
# Part 4
# (Neutrino Oscillation Tomography)


## Carsten Rott (SKKU)

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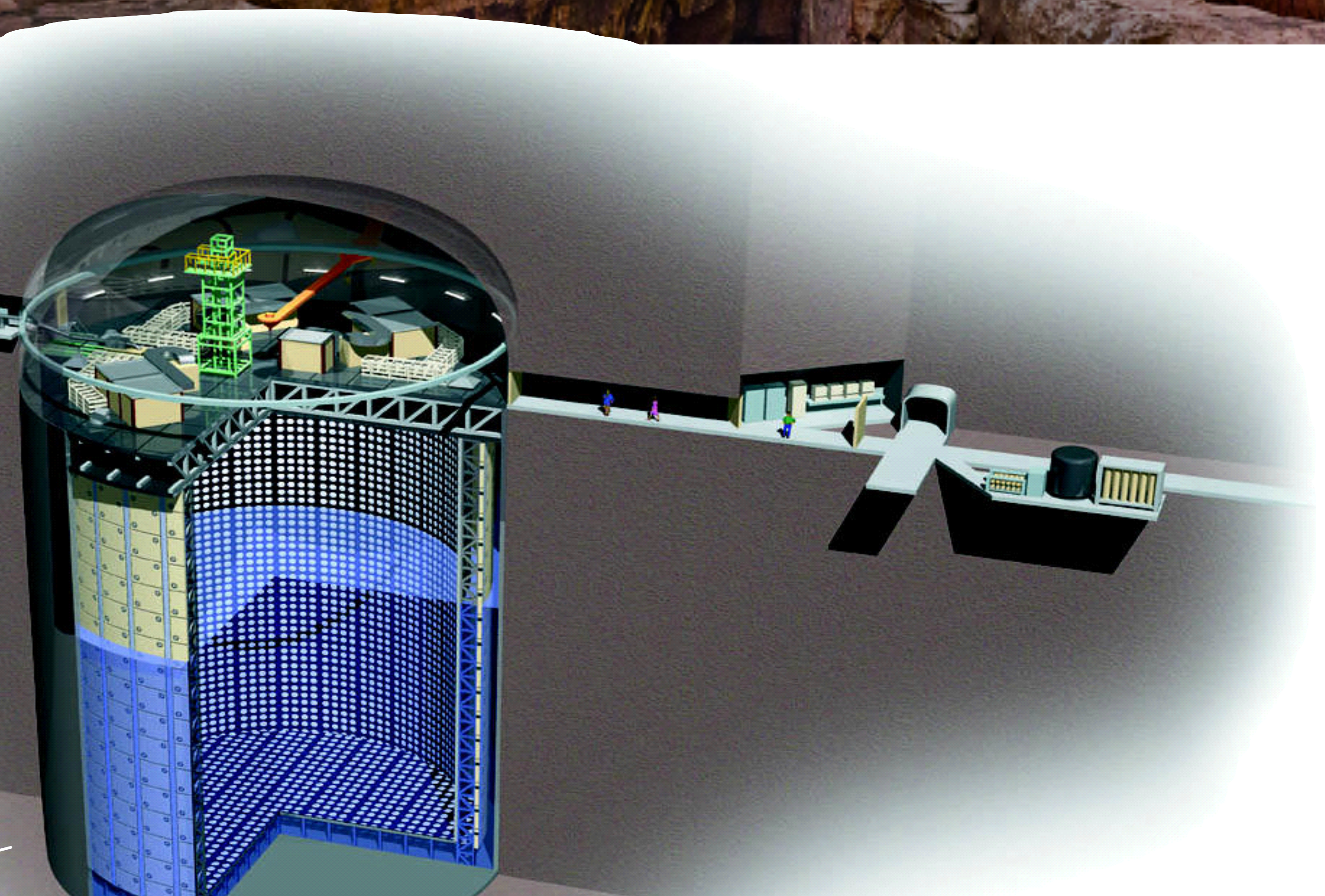
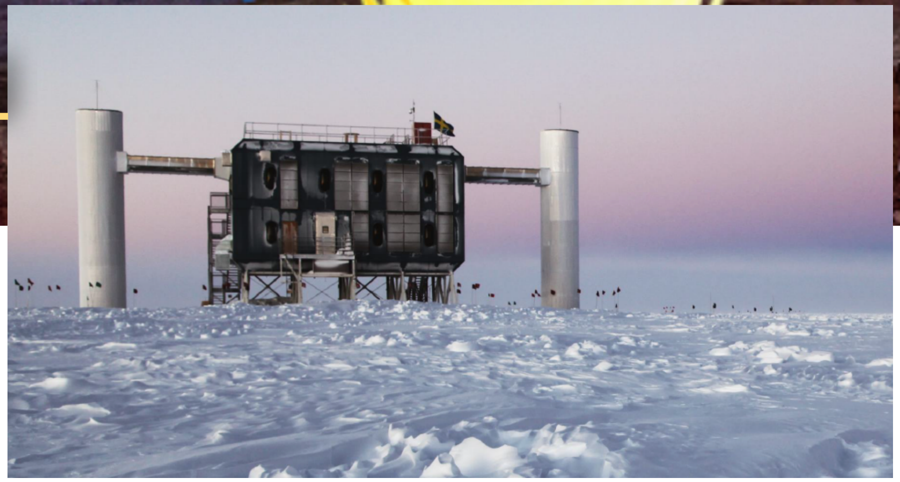
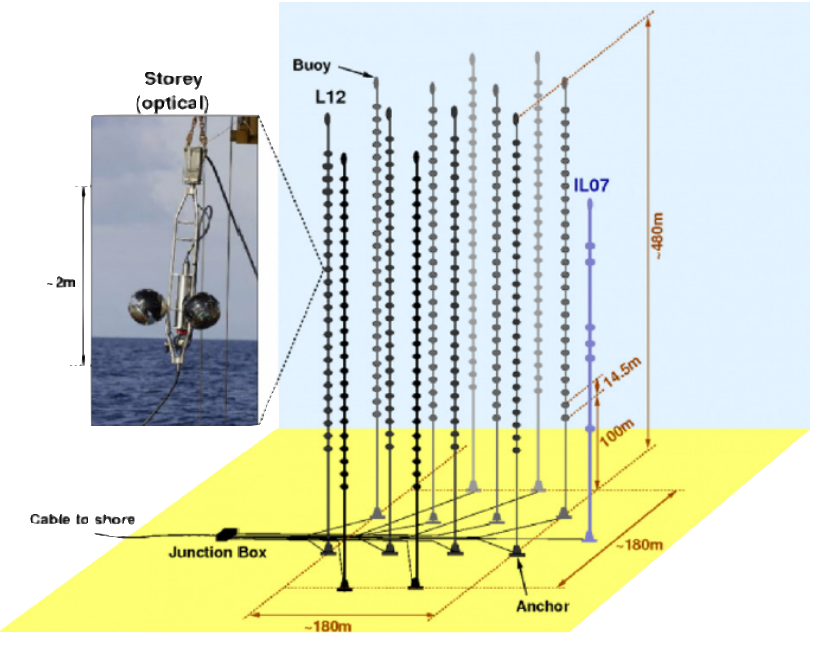




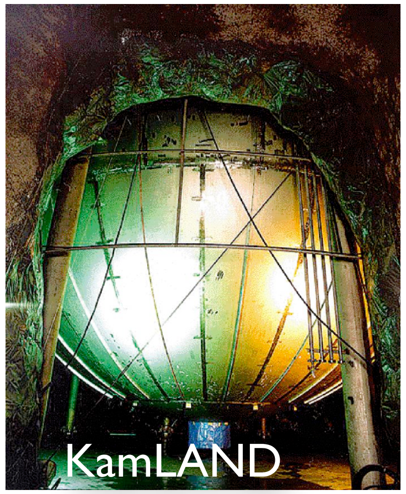


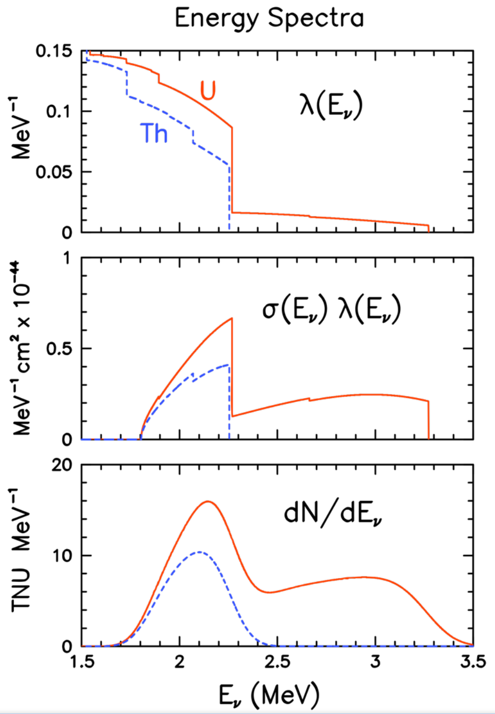
# Motivation (Particle Physics ⇒ Earth Science)

- 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

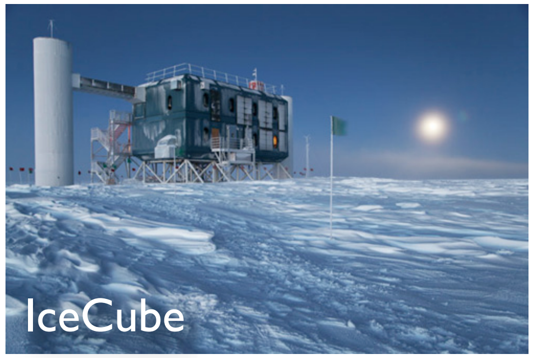
## Geo-neutrinos

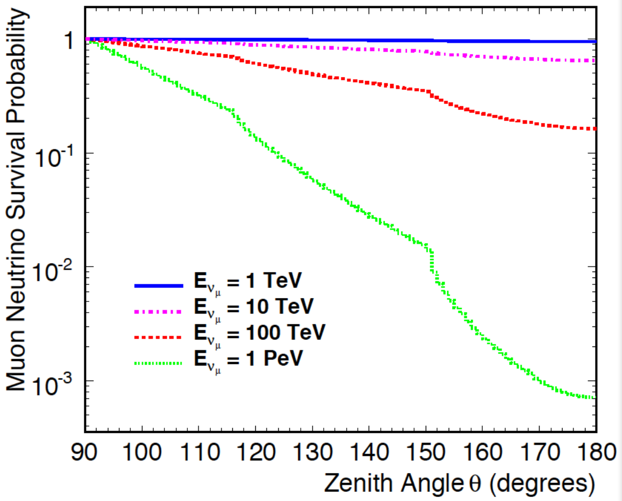
U and Th geo-ν



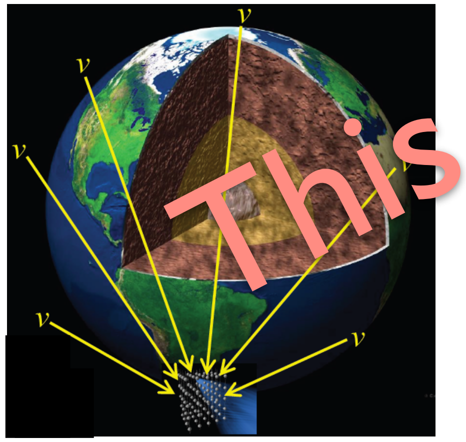

## Neutrino absorption tomography

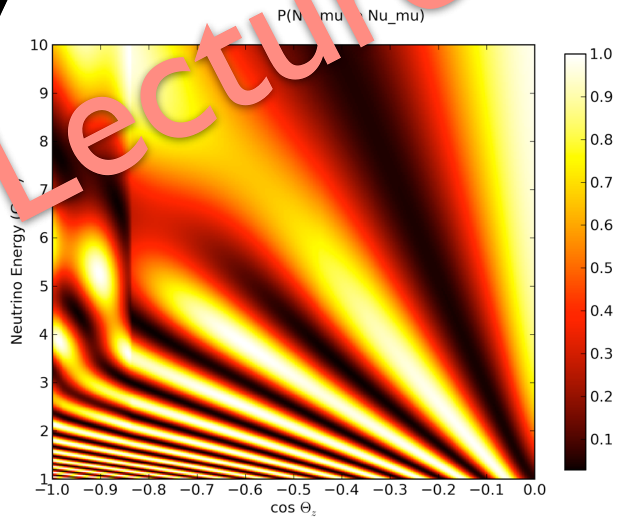


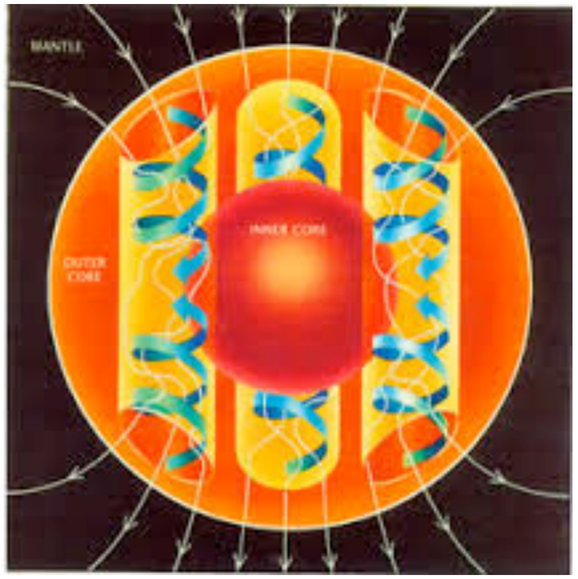

## Neutrino oscillation tomography

This Lecture



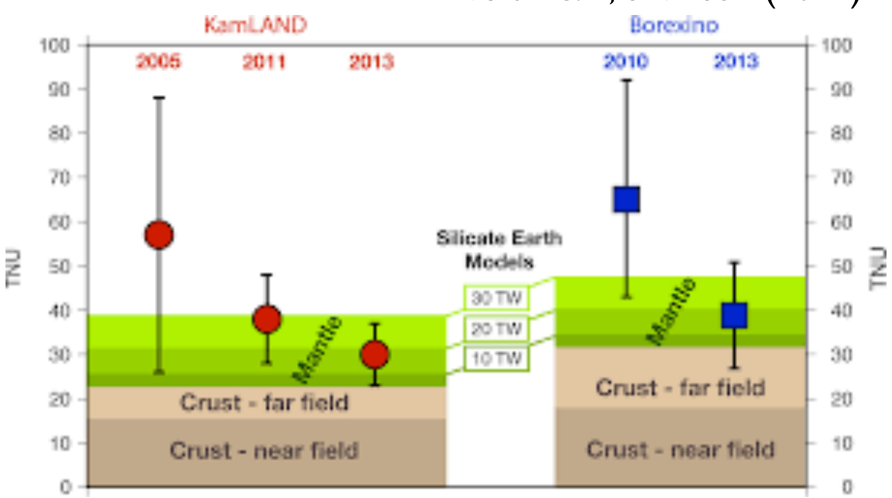



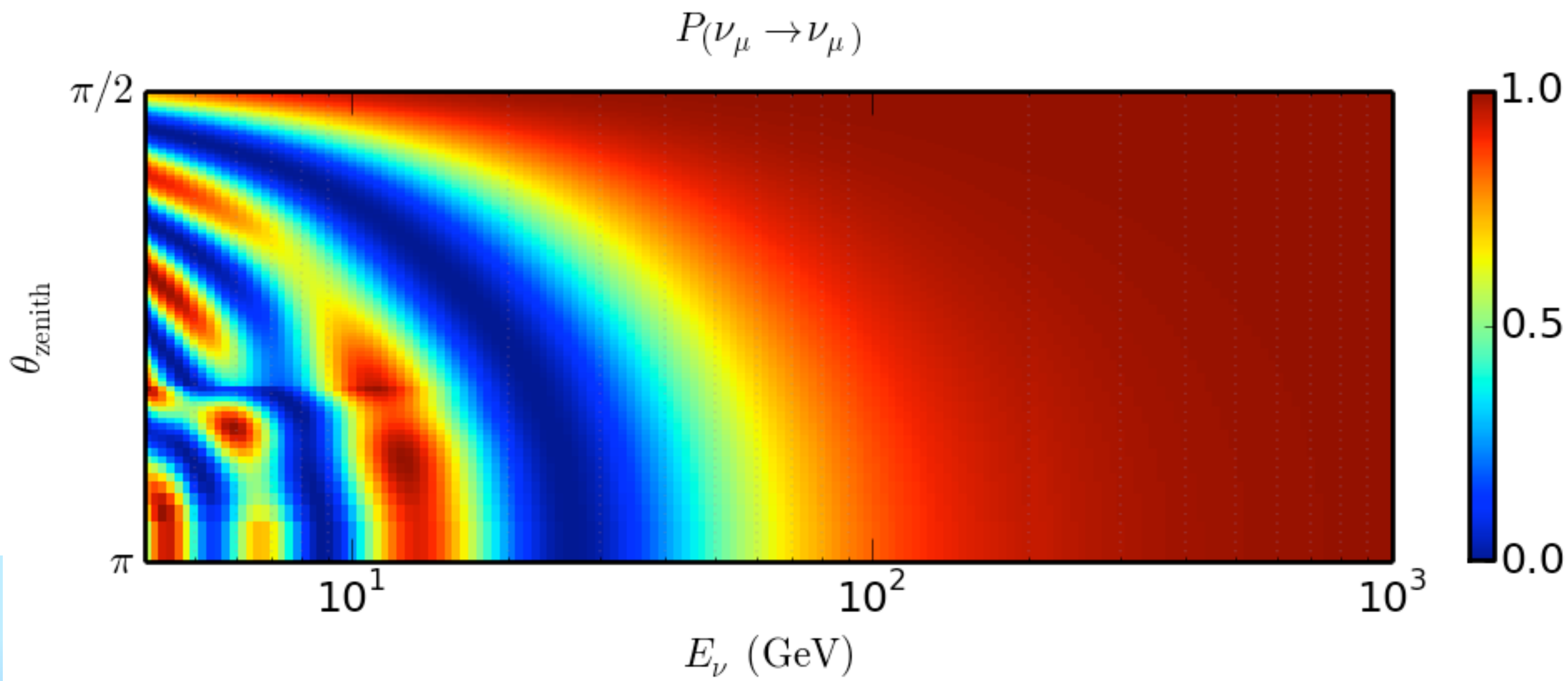
- New Method to understand inner Earth
  - Inner Earth Composition
    - Light elements in the outer core ?
    - Understand the Geodynamo
  - Lower mantle density and anisotropy
- Apply neutrino physics to Earth Science





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

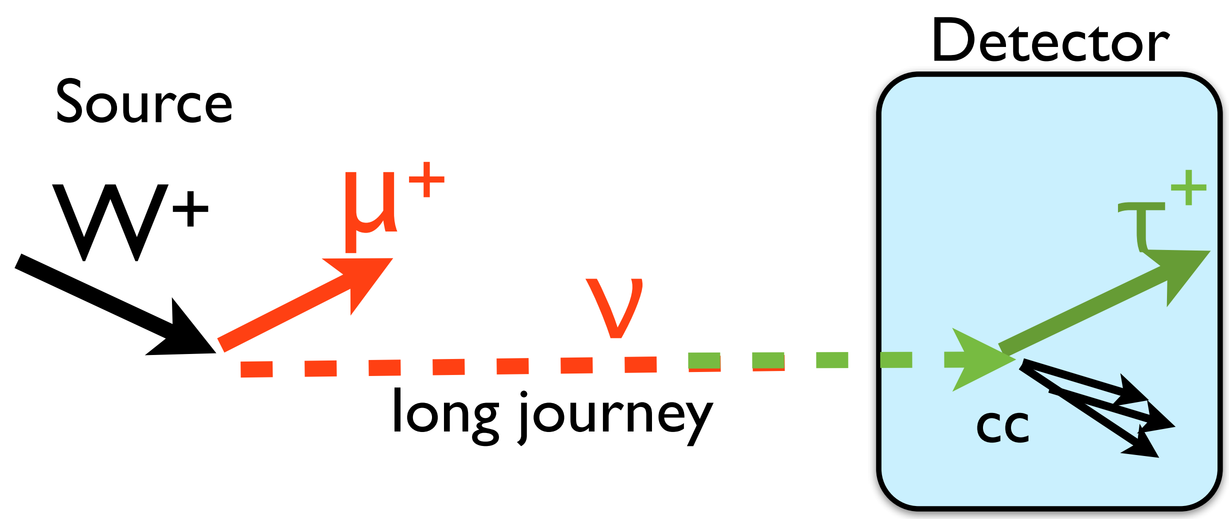


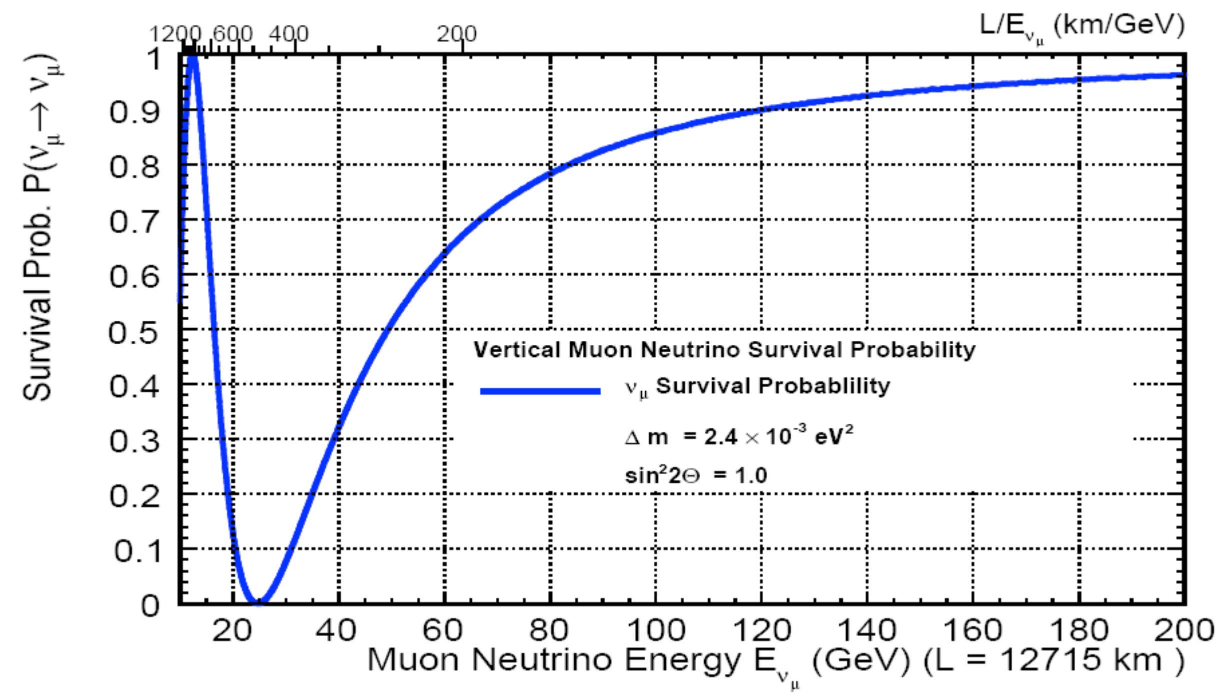




# Neutrino Oscillations

# Neutrino Oscillations Basics

- Neutrinos come in three different flavors: $\nu_e, \nu_\mu, \nu_\tau$
- 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




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

oscillation probability

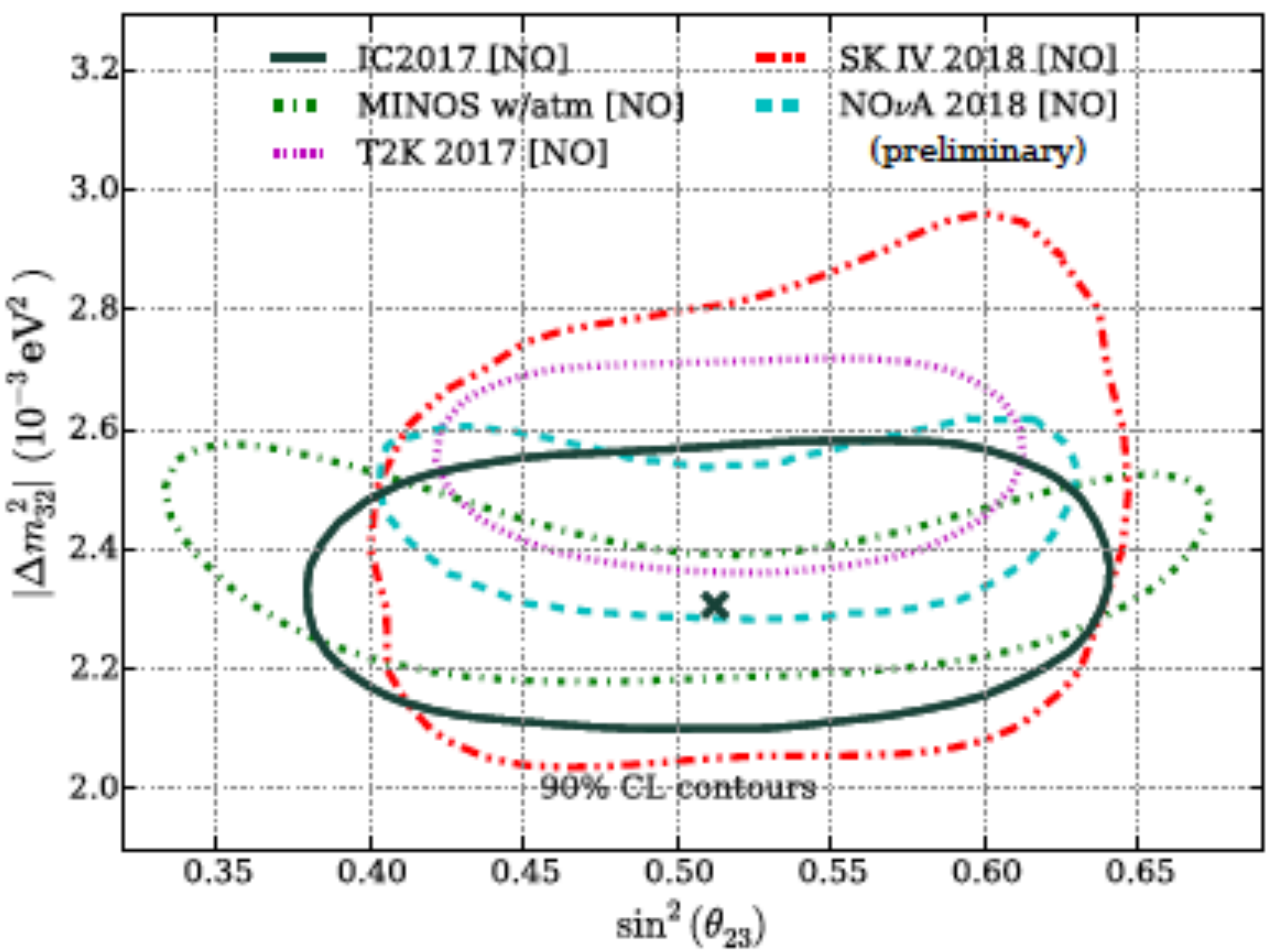
oscillation parameters

energy

distance

# Recent IceCube Results

M. Aartsen et al. (IceCube), *Phys. Rev. Lett.* 120, 071801 (2018)




- 1,022 days live time 2012-14
- 41,599 events (full-sky)
  - 15,138 track, 26,461 cascade events
  - $E_\nu$ reconstructed from muon range plus cascade energy
  - Est. 5.2% atm. $\mu$ BG
- Best fit $\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$, $\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}$ eV$^2$
  - Most precise atmospheric measurement, highest energy range (constraints primarily from 15-50 GeV neutrinos)

IceCube results competitive with measurements from neutrino detectors focused on neutrino property measurements

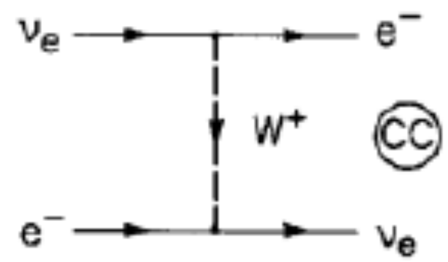
# Neutrino Oscillations in Matter

slide from Walter Winter

- Oscillation probabilities in

vacuum: $$P_{\alpha\alpha} = 1 - \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E}$$

matter: $$P_{\alpha\alpha} = 1 - \sin^2 2\tilde{\theta} \, \sin^2 \frac{\Delta \tilde{m}^2 L}{4E}$$




(Wolfenstein, 1978; Mikheyev, Smirnov, 1985)

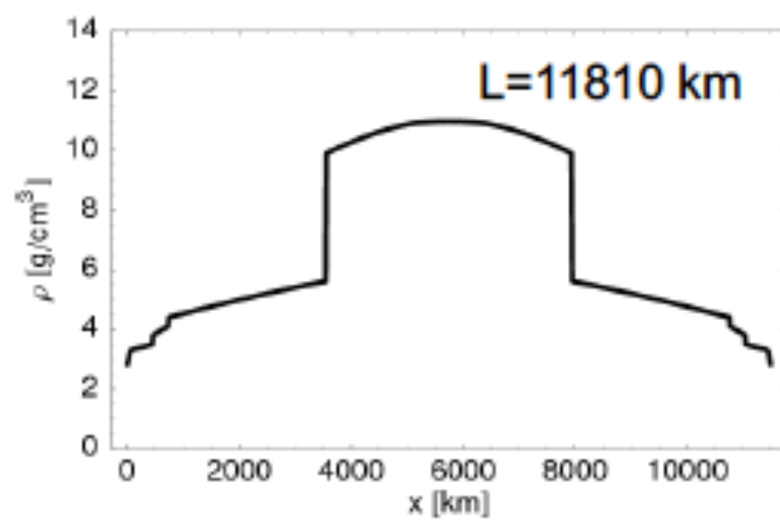
$$\boxed{\Delta \tilde{m}^2 = \xi \cdot \Delta m^2, \quad \sin 2\tilde{\theta} = \frac{\sin 2\theta}{\xi},}$$

$$\xi \equiv \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \hat{A}\right)^2},$$

$$\hat{A} = \frac{2EV}{\Delta m^2} = \frac{\pm 2\sqrt{2} E\, G_F\, n_e}{\Delta m^2} \Rightarrow \textbf{MO}$$

Resonance energy (from $\hat{A} \rightarrow \cos 2\theta$):

$$E_{\mathrm{res}}\,[\mathrm{GeV}] \sim 13\,200 \, \cos 2\theta \, \frac{\Delta m^2\,[\mathrm{eV}^2]}{\rho\,[\mathrm{g/cm}^3]}$$



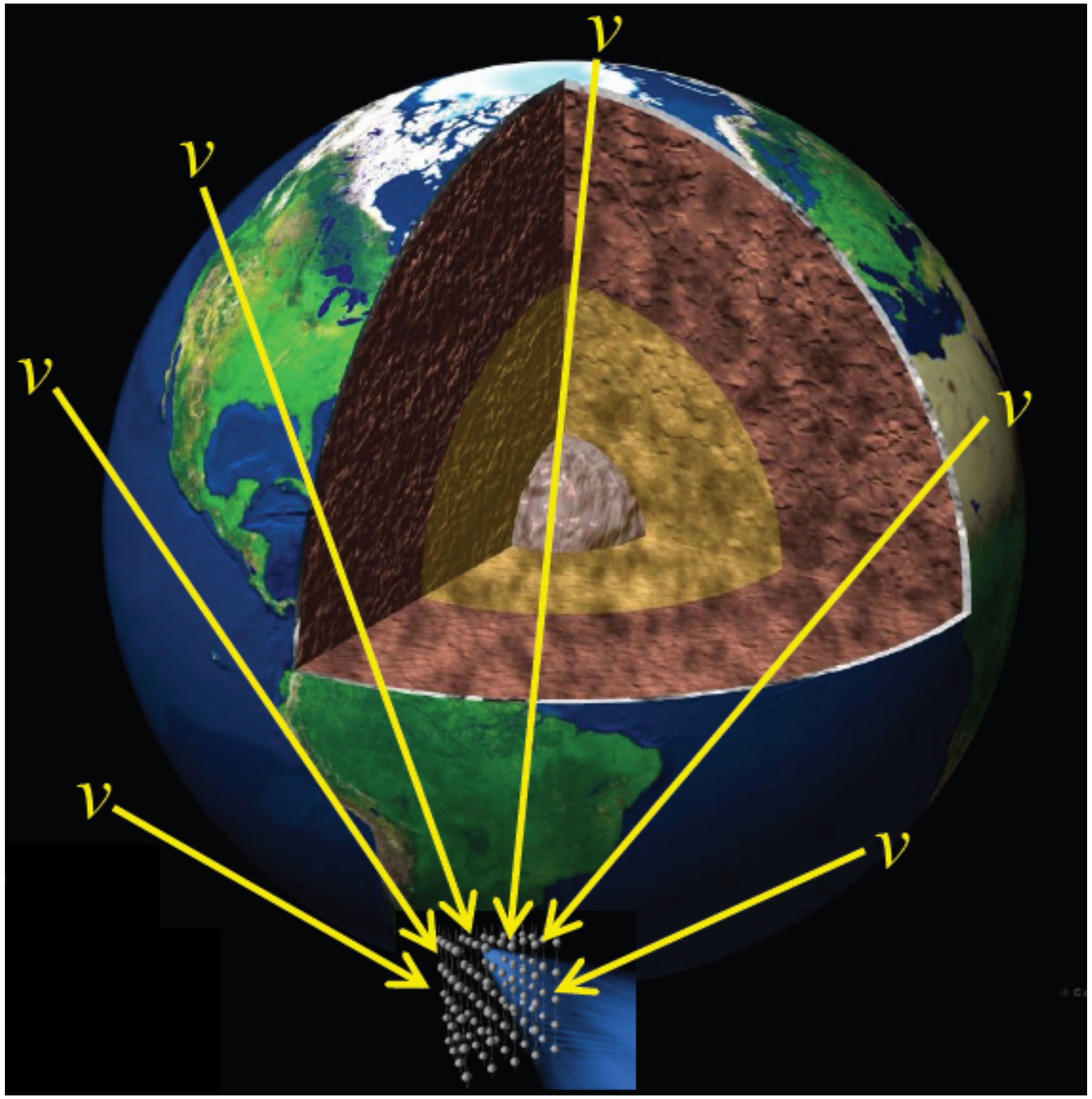

For $\nu_\mu$ appearance, $\Delta m_{31}^2$:
- $\rho \sim 4.7$ g/cm³ (Earth's mantle): **$E_{res} \sim 6.4$ GeV**
- $\rho \sim 10.8$ g/cm³ (Earth's outer core): **$E_{res} \sim 2.8$ GeV**

Walter Winter | PANE 2018 | 31.05.2018 | Page 10

# 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 "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)

# Z/A ratios

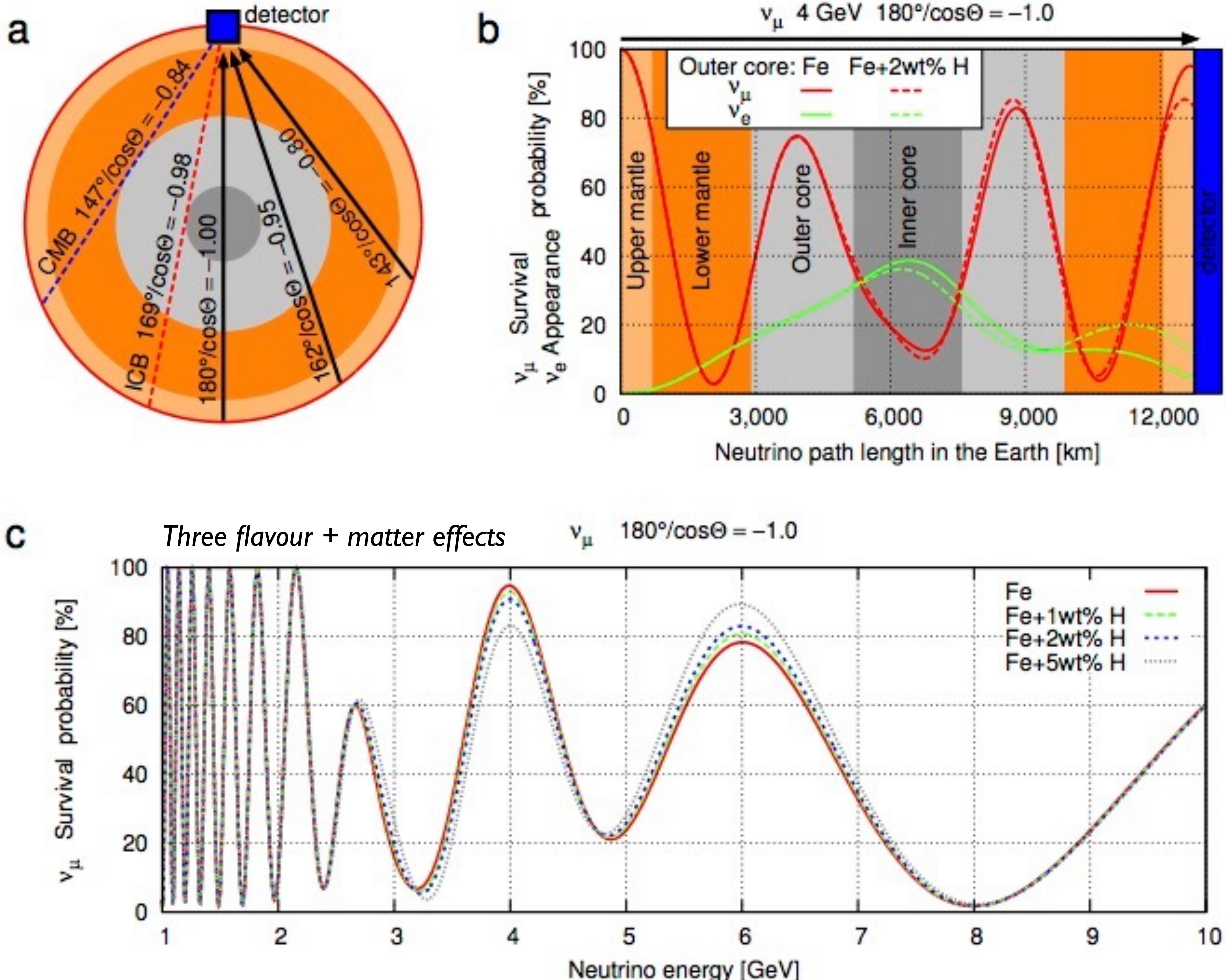
| Element | | Z | A | Z/A |
|---|---|---|---|---|
| Hydrogen | H | 1 | 1.008 | 0.9921 |
| Carbon | C | 6 | 12.011 | 0.4995 |
| Oxygen | O | 8 | 15.999 | 0.5 |
| Magnesium | Mg | 12 | 24.305 | 0.4937 |
| Silicon | Si | 14 | 28.085 | 0.4985 |
| Sulfur | S | 16 | 32.06 | 0.4991 |
| Iron | Fe | 26 | 55.845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

**Z** - Atomic Number

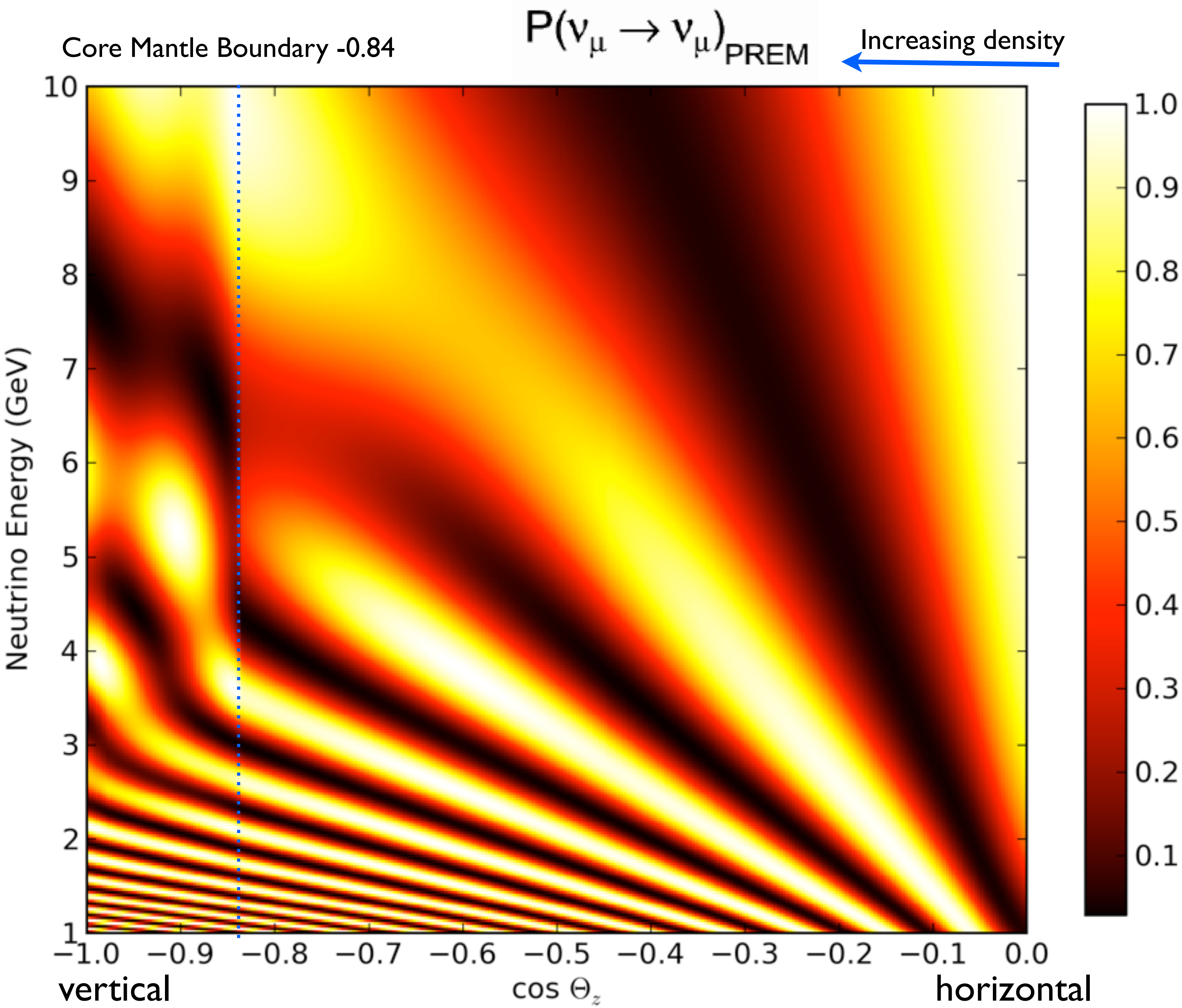
**A** - Atomic Mass

- Z/A ratios

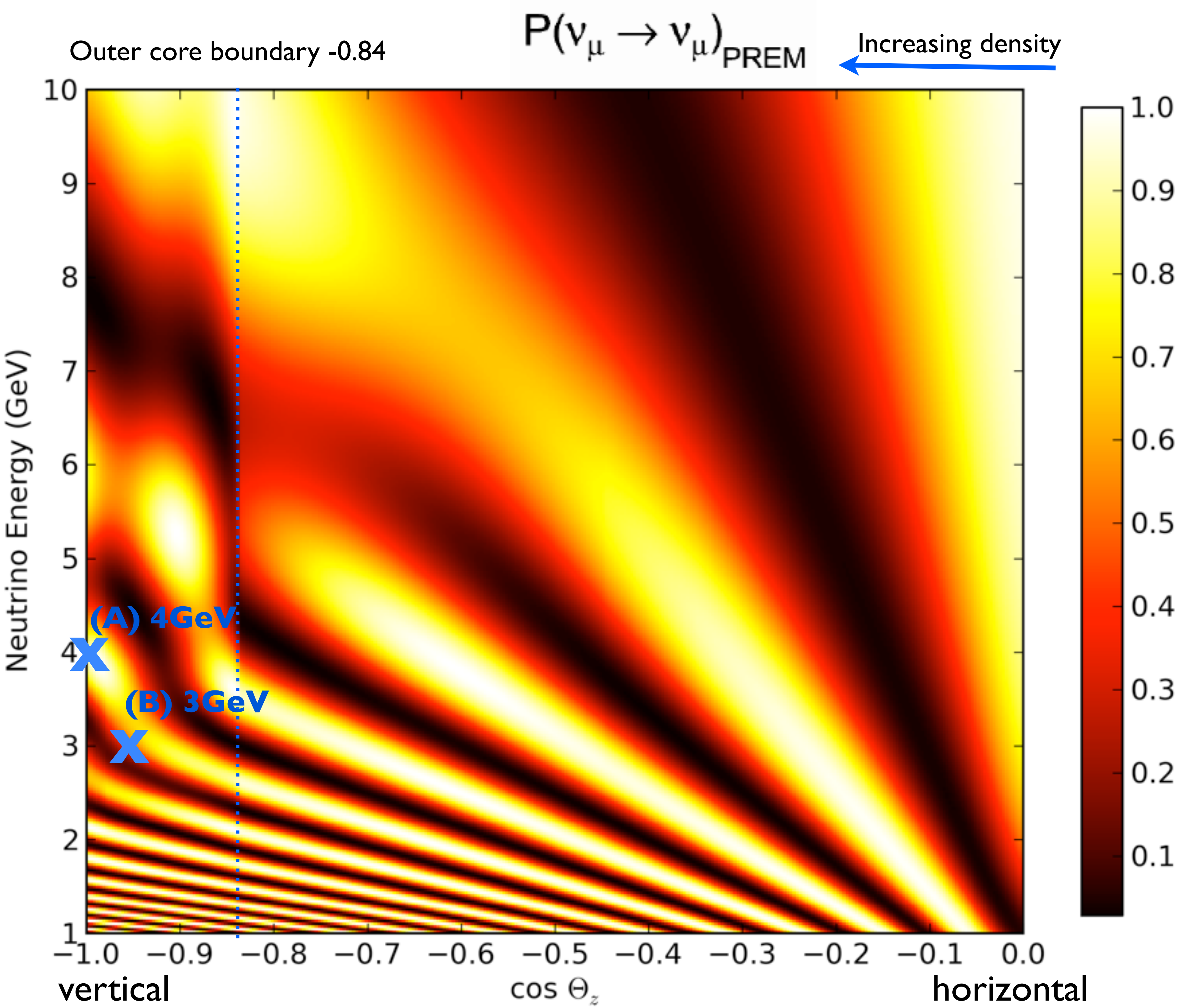
Rott & Taketa 2015



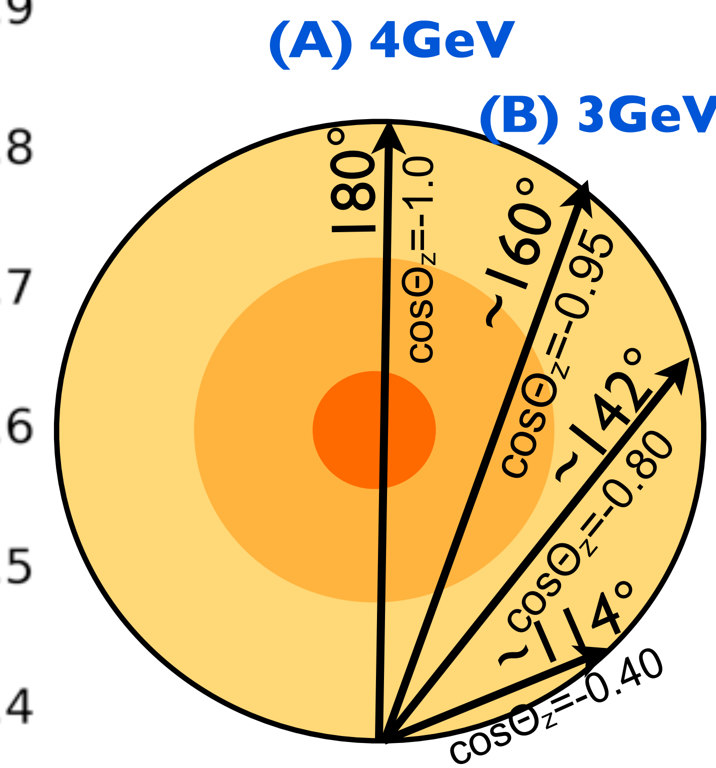
# Oscillograms



# How to read an oscillograms



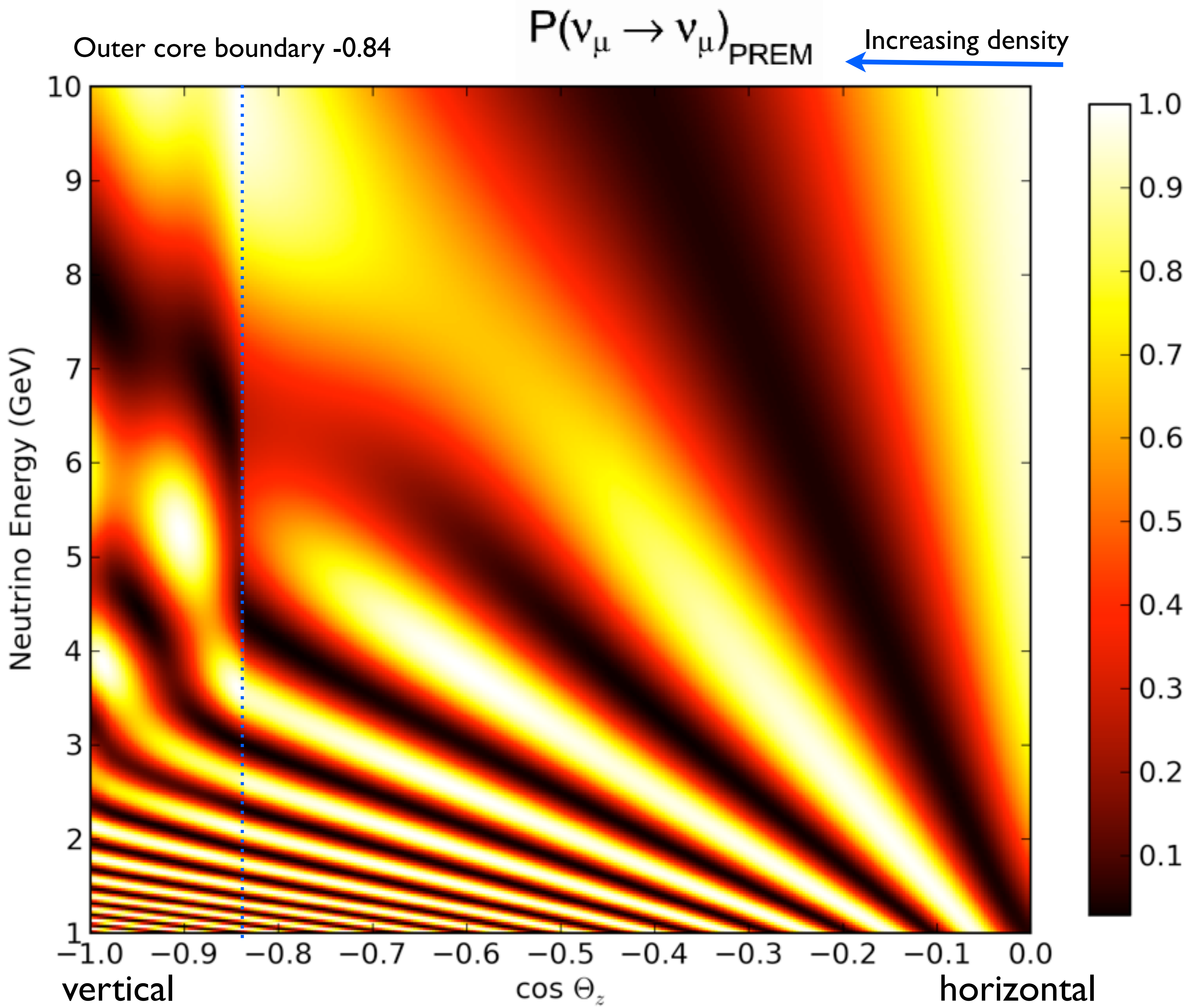

An example ...



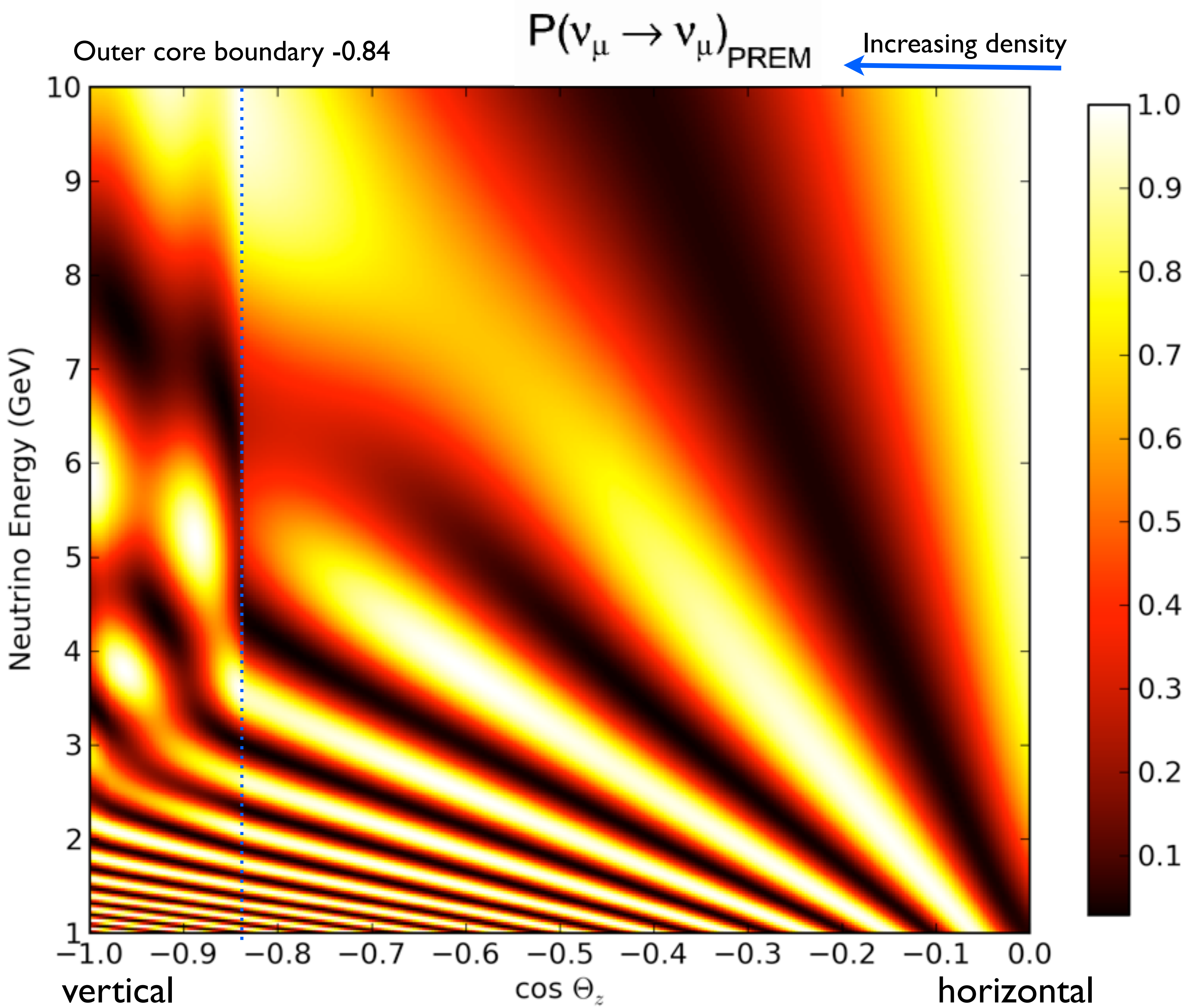

A muon neutrino created at **(A)** with energy 4GeV has a ~**90%** chance to be detected as such after traversing the Earth

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

# Oscillogram ("normal" electron density)



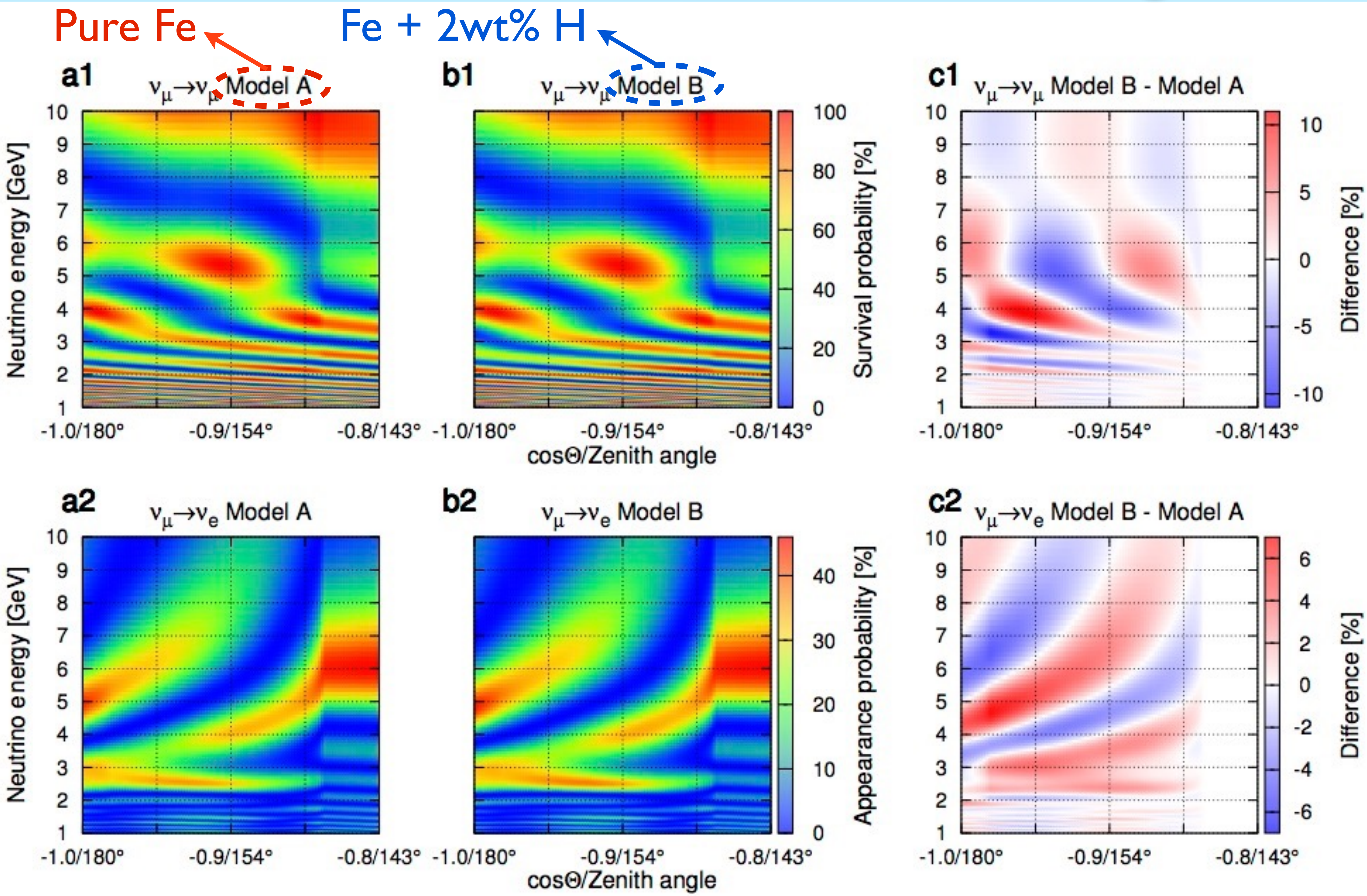
# Oscillogram (enhance electron density)




**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**)

# Oscillograms

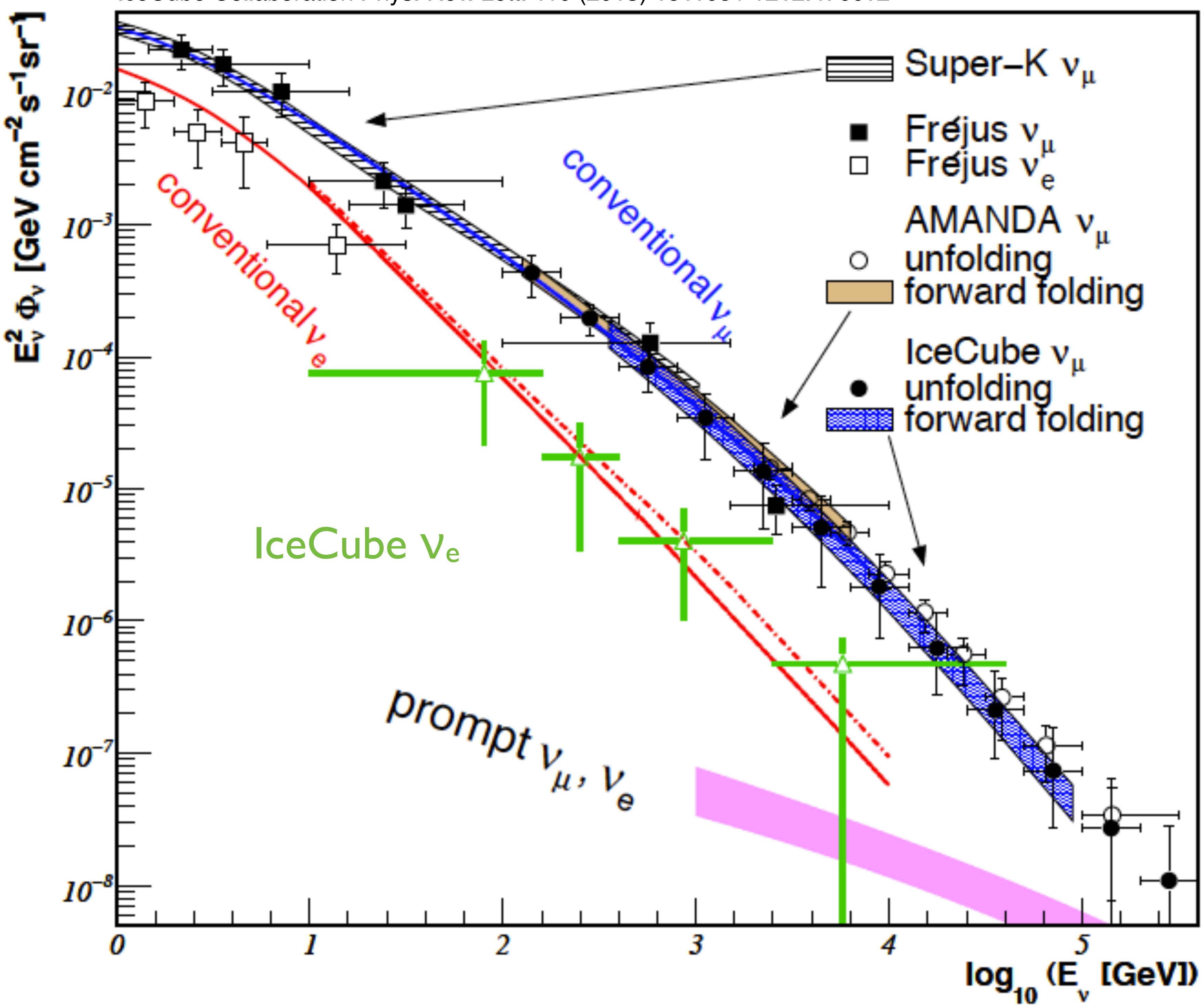


# Neutrino Source and Detectors

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


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

IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 / 1212.4760v2



# Atmospheric Neutrinos

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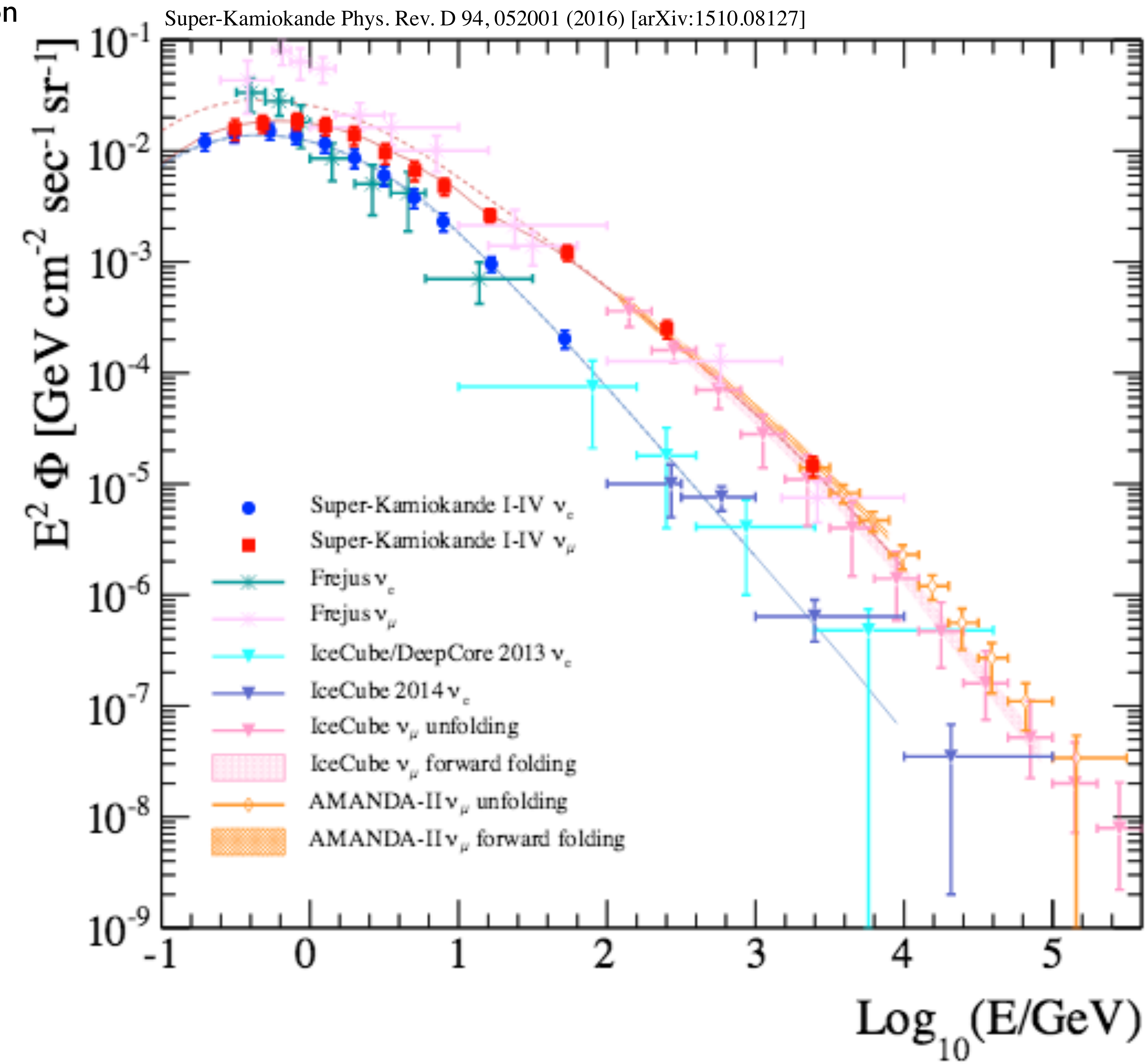
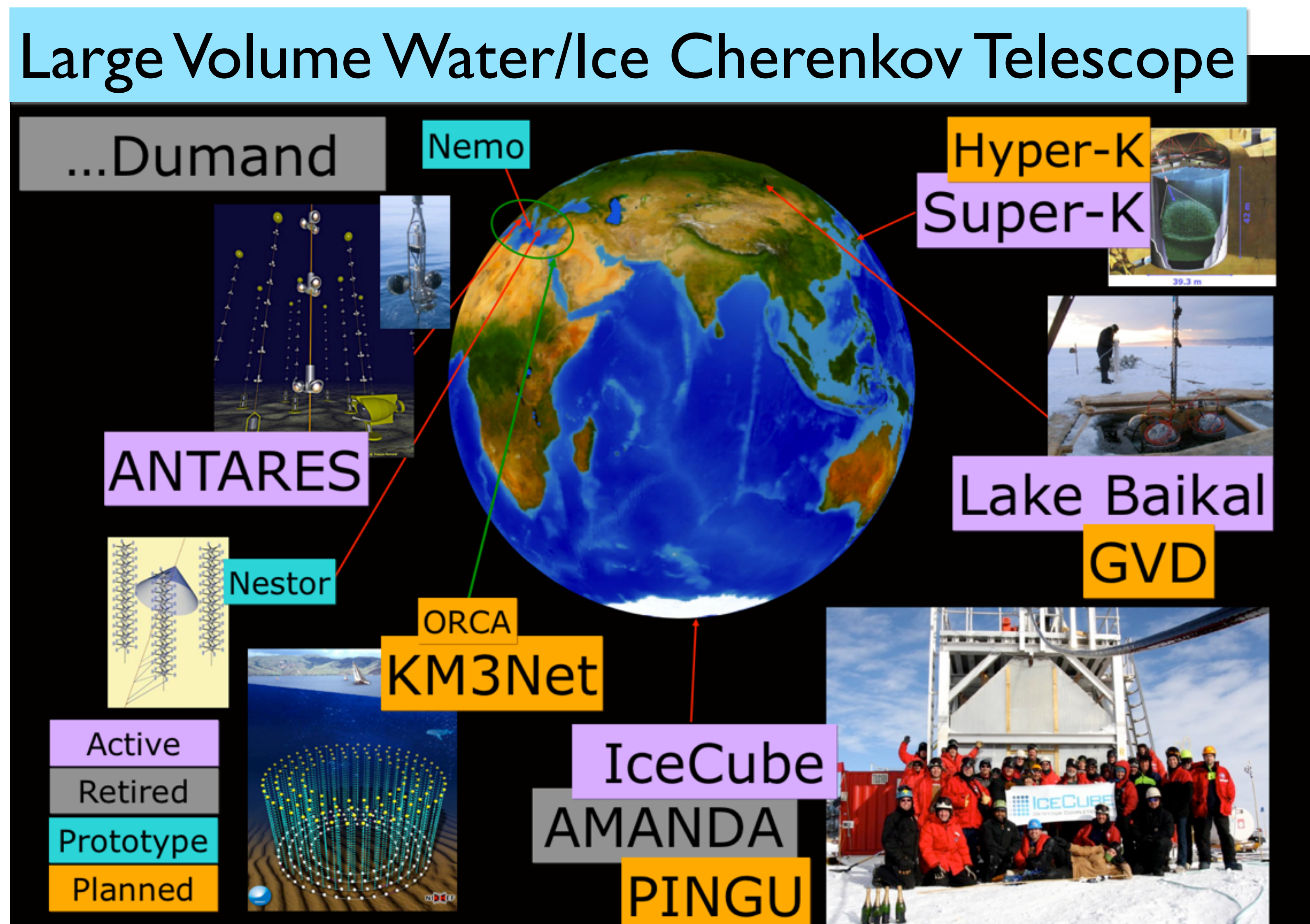


# Neutrino Source and Detectors

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


- p + A → $\pi^\pm$ ($K^\pm$) + 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



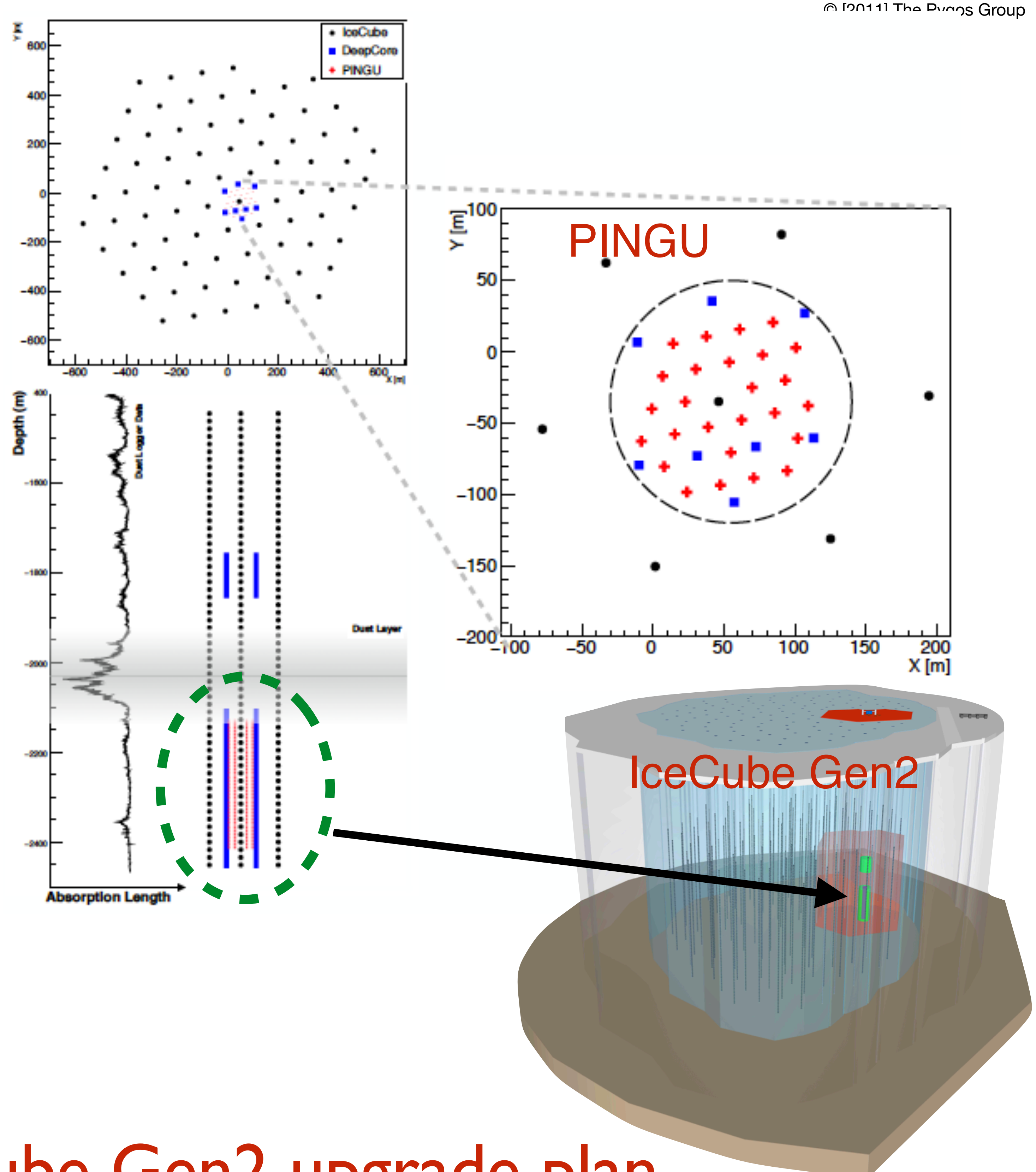
# PINGU

# PINGU - Precision IceCube Next Generation Upgrade

IceCube PINGU Collaboration arXiv:1401.2046

© [2011] The Pygos Group

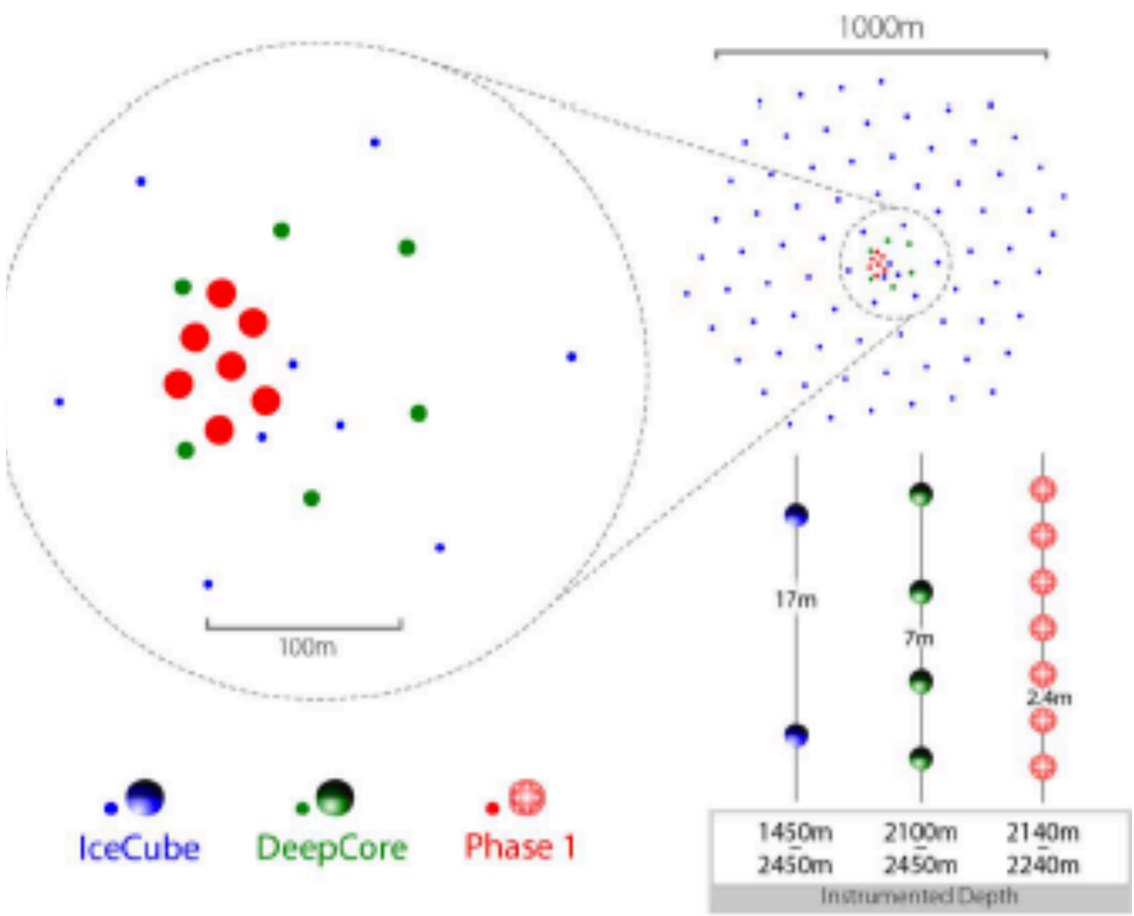
- PINGU upgrade plan
  - Instrument a volume of about 5MT with 20-26 strings
  - Rely on well established drilling technology and photo sensors
  - Create platform for calibration program and test technologies for future detectors
- Physics Goals:
  - Precision measurements of neutrino oscillations (mass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




PINGU now part of the IceCube Gen2 upgrade plan ….

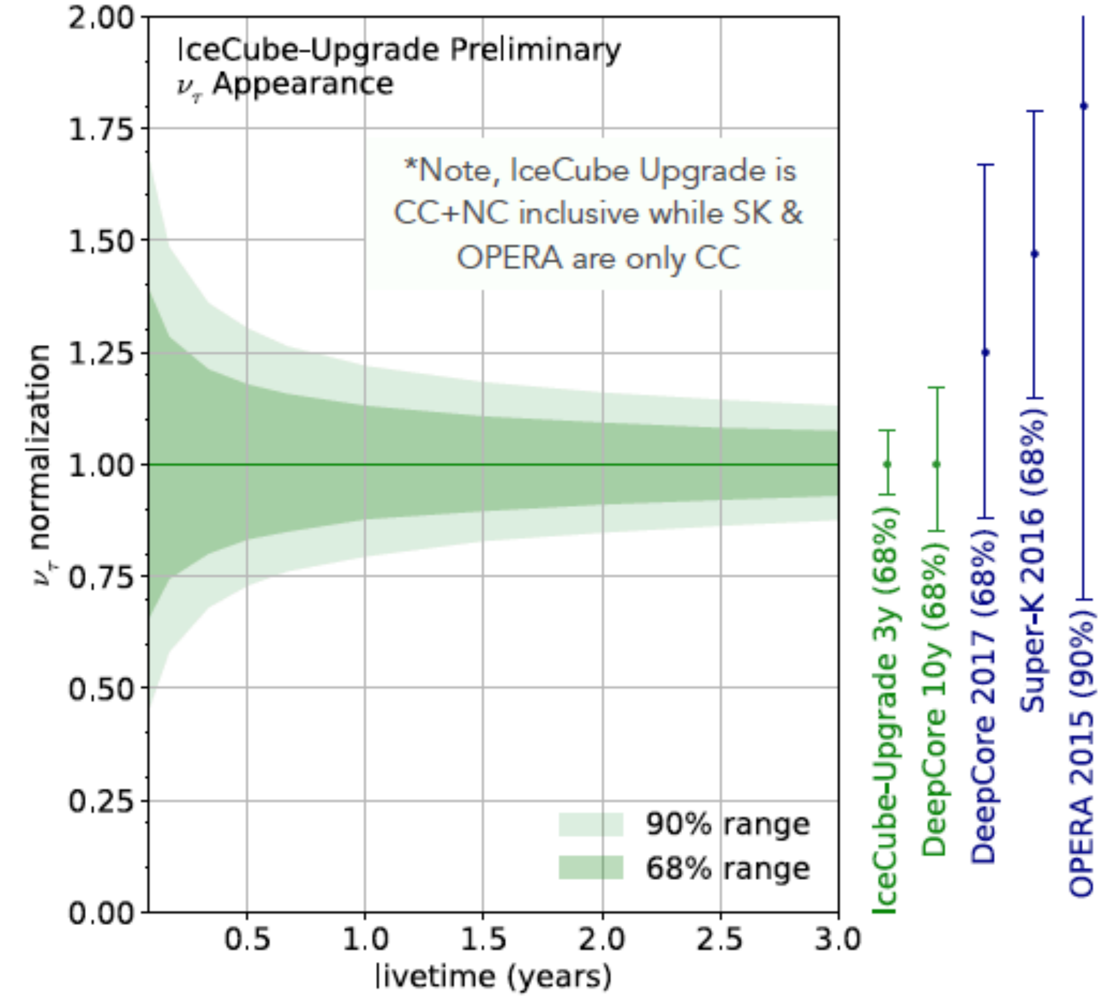
see also:
- PINGU LOI arXiv:1412.5106

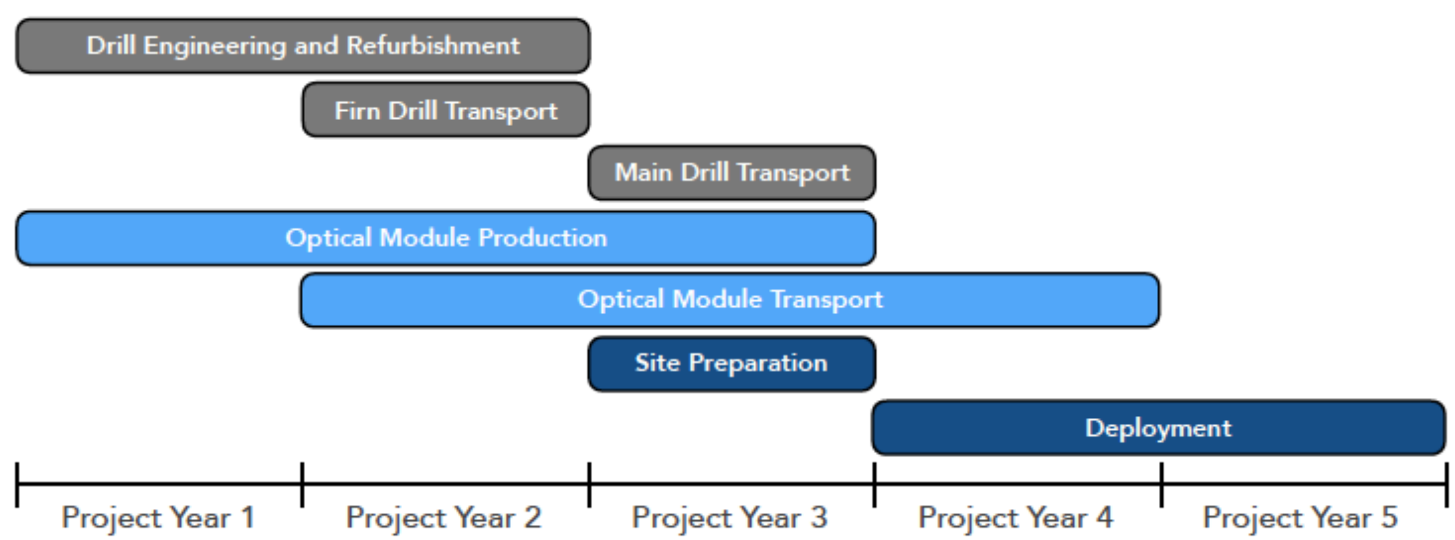
# Next Step Now - The IceCube Upgrade




| Array | String Spacing | Module Spacing | Modules / String |
|---|---|---|---|
| IceCube | 125 m | 17 m | 60 |
| DeepCore | 75 m | 7 m | 60 |
| Upgrade | 20 m | 2 m | 125 |

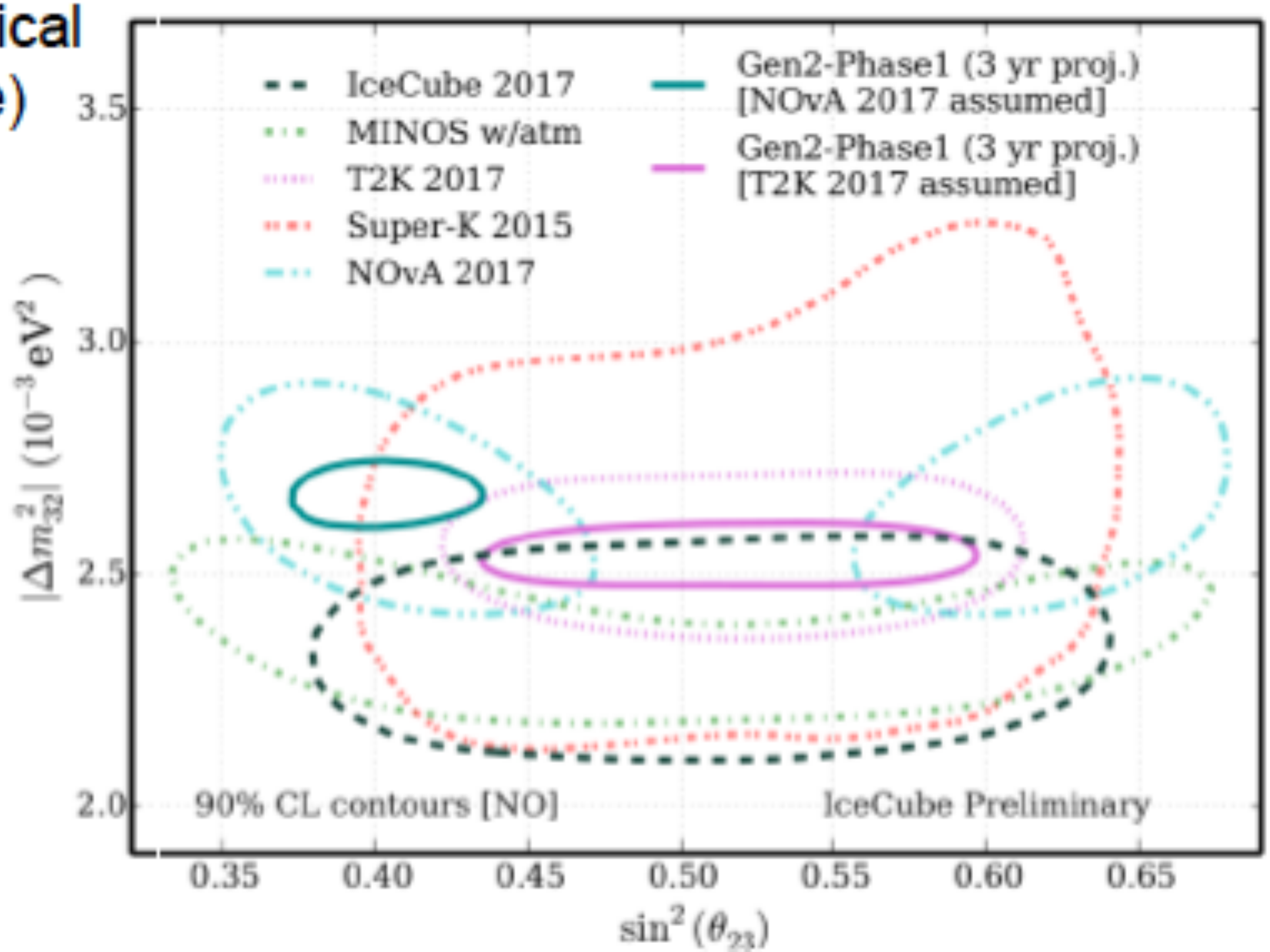
First step to restart South Pole activities
- Tau neutrino appearance - Test unitarity of the PMNS matrix
- Calibration devices
- Platform to test new technologies



# The IceCube Upgrade

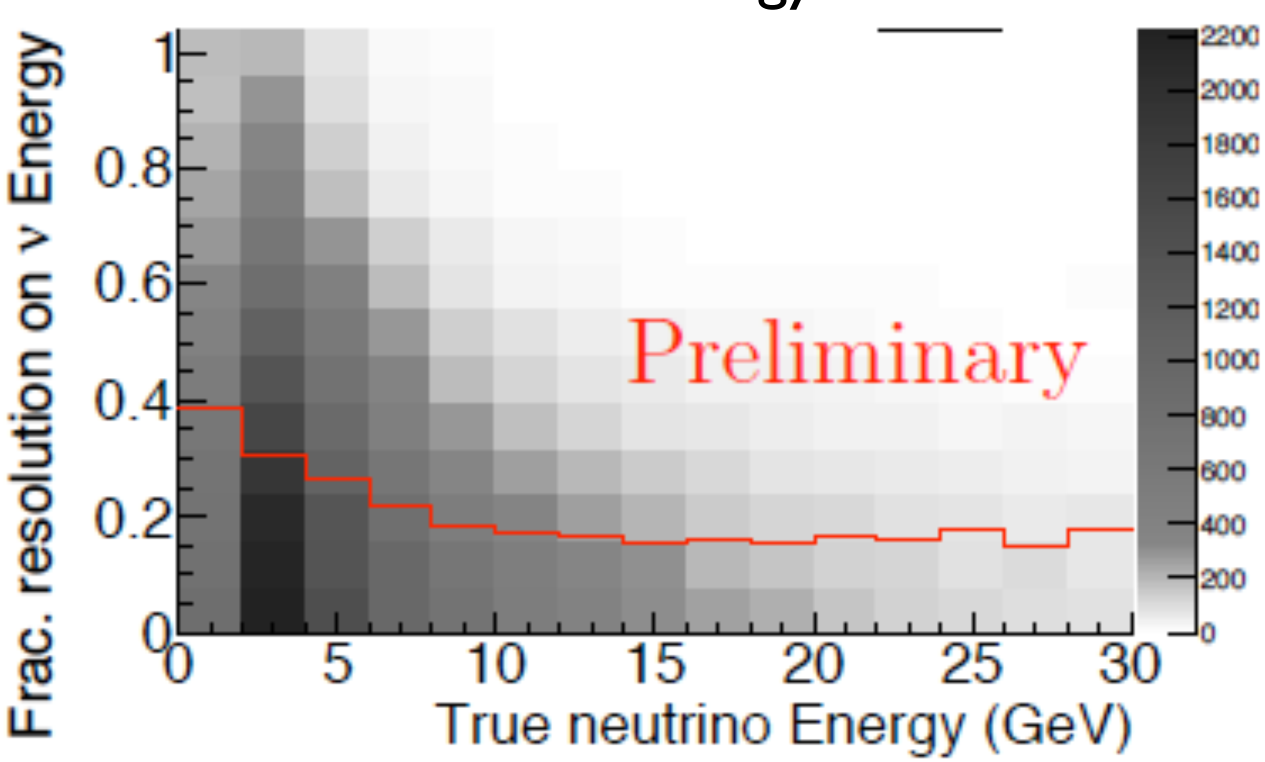
- Target $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Detect $\nu_\tau$ events on a statistical basis (up-going, shower-like)
- Case study for IceCube Upgrade:
  - ~2500 $\nu_\tau$ events / year
  - Drastically improve measurement of atmospheric mixing parameters
  - Chance to determine octant of $\theta_{23}$
- Also possible with ORCA



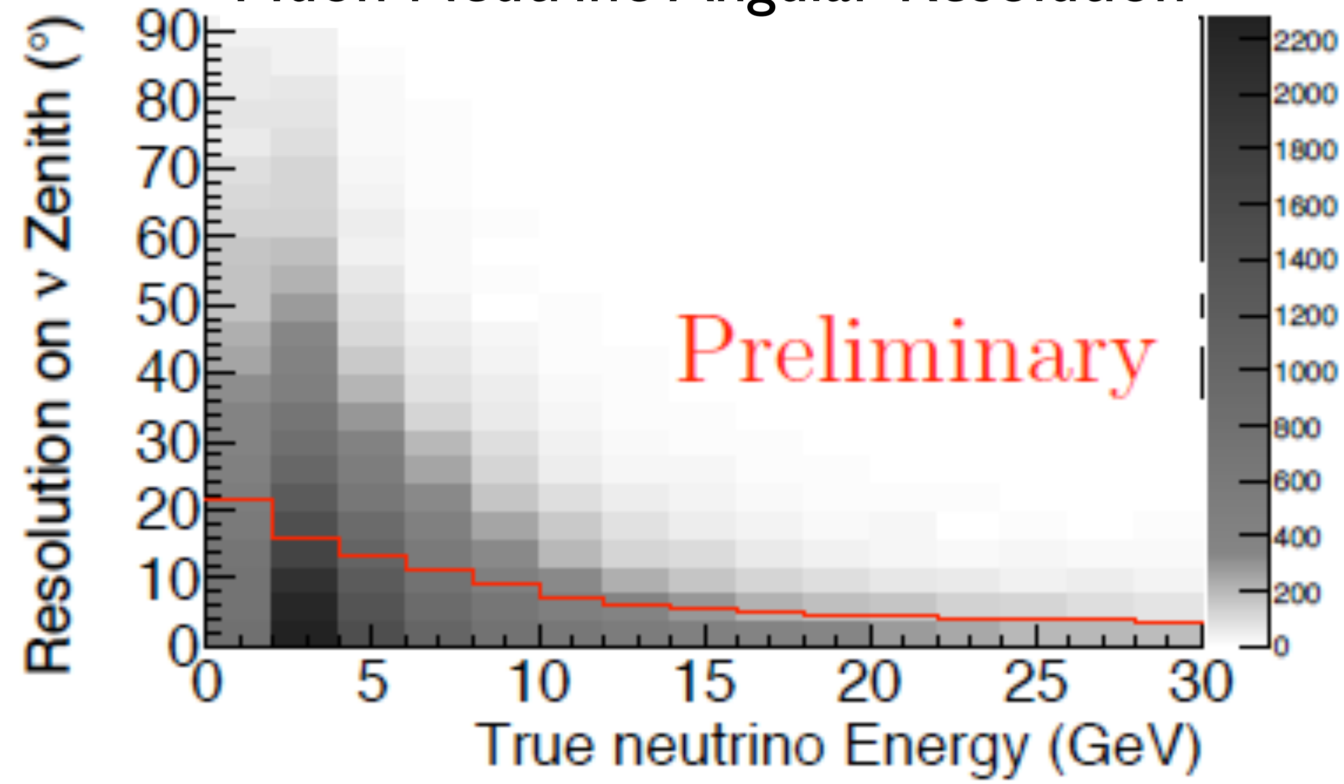

IceCube extremely competitive for neutrino oscillation parameter measurements using atmospheric neutrinos

# PINGU Detector Performance

IceCube PINGU Collaboration arXiv:1401.2046




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

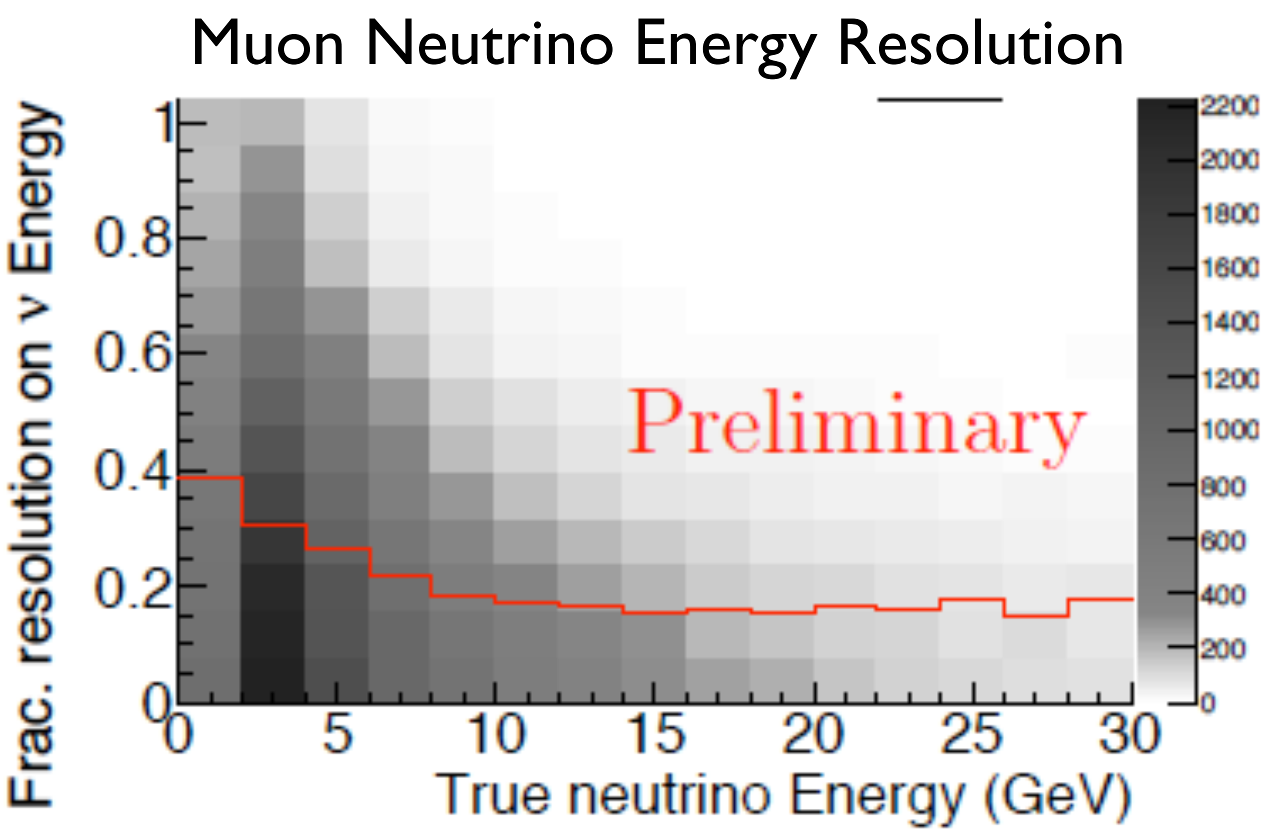



$|\theta_{\nu,\mathrm{true}} - \theta_{\nu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.

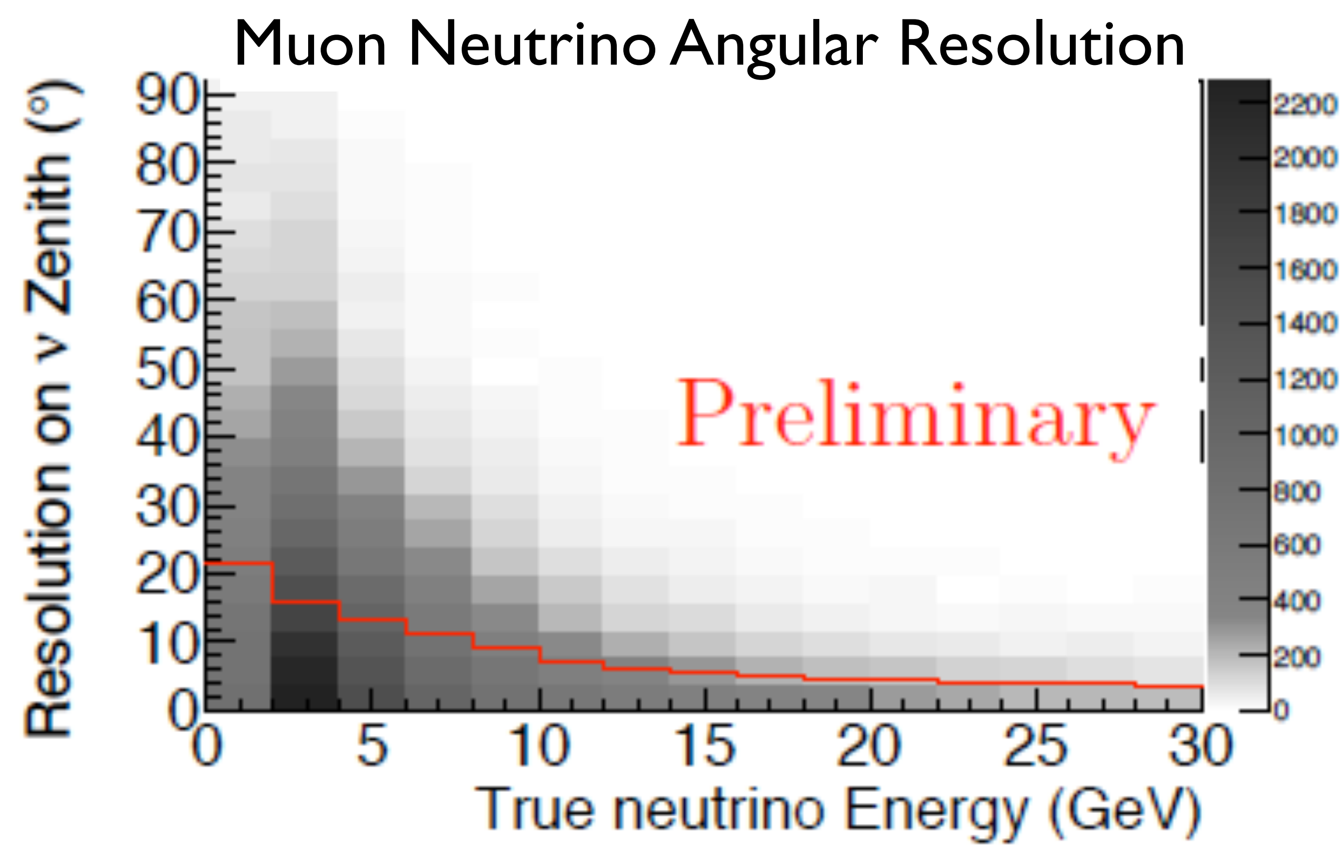
- PINGU performance using existing algorithms for IceCube
  - More computationally intensive algorithms are expected to further improve performance

# Parameterize Detector Performance

IceCube PINGU Collaboration arXiv:1401.2046




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




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

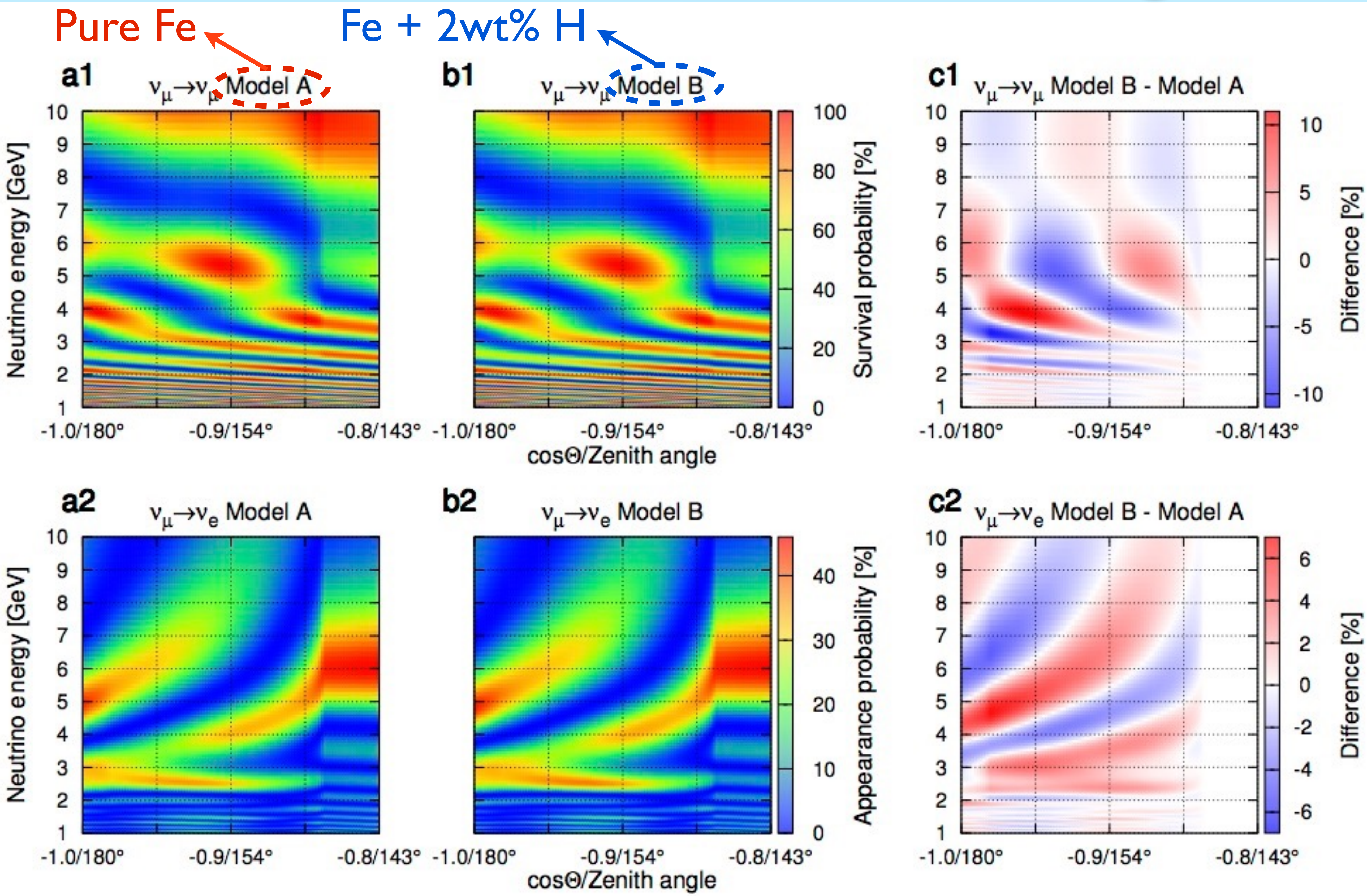
**Energy resolution**
$\alpha = \Delta E/E$

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

We adopt a value of $\alpha$=0.2 as benchmark

We adopt $\beta$=0.25 as benchmark

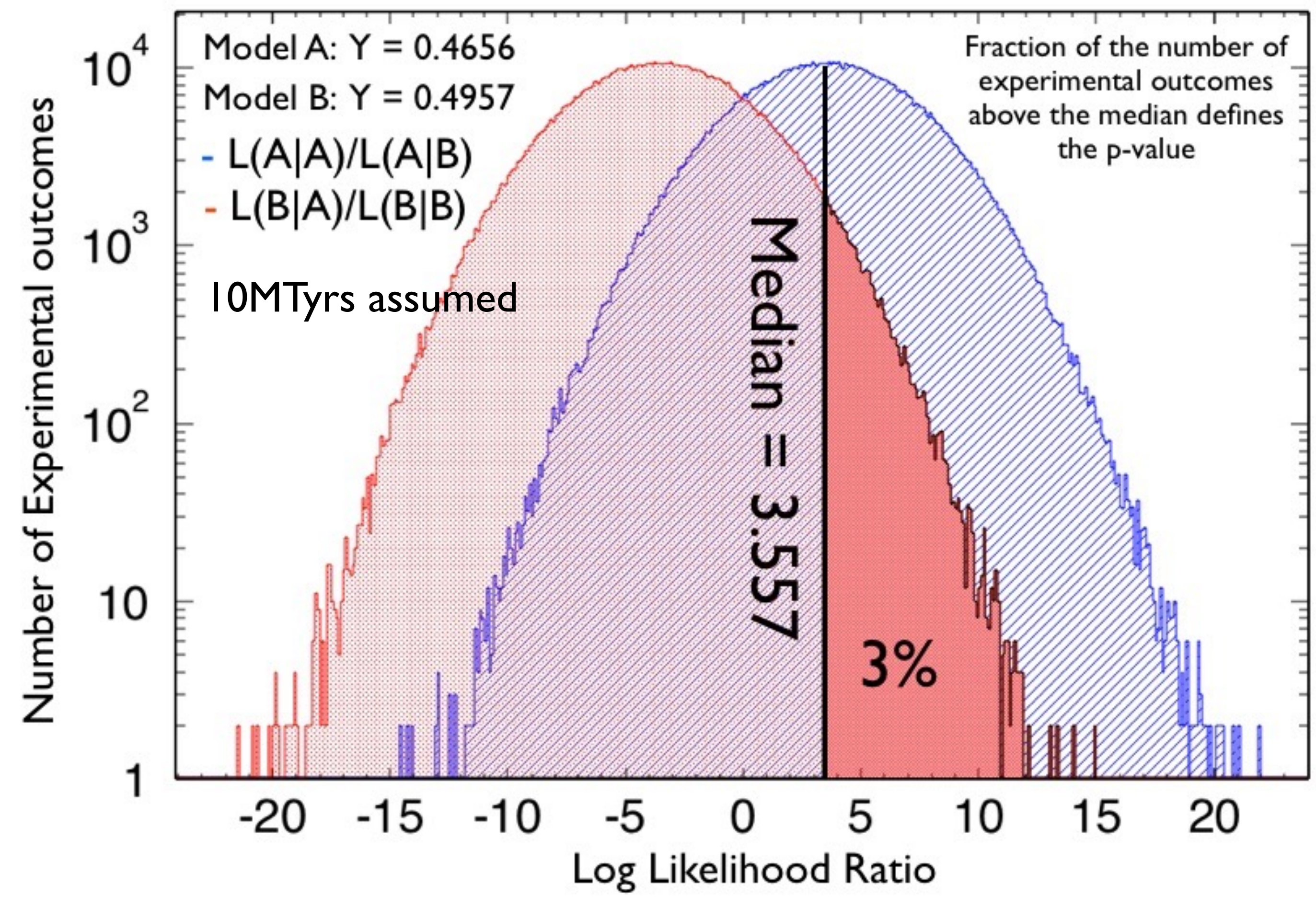
# Oscillograms



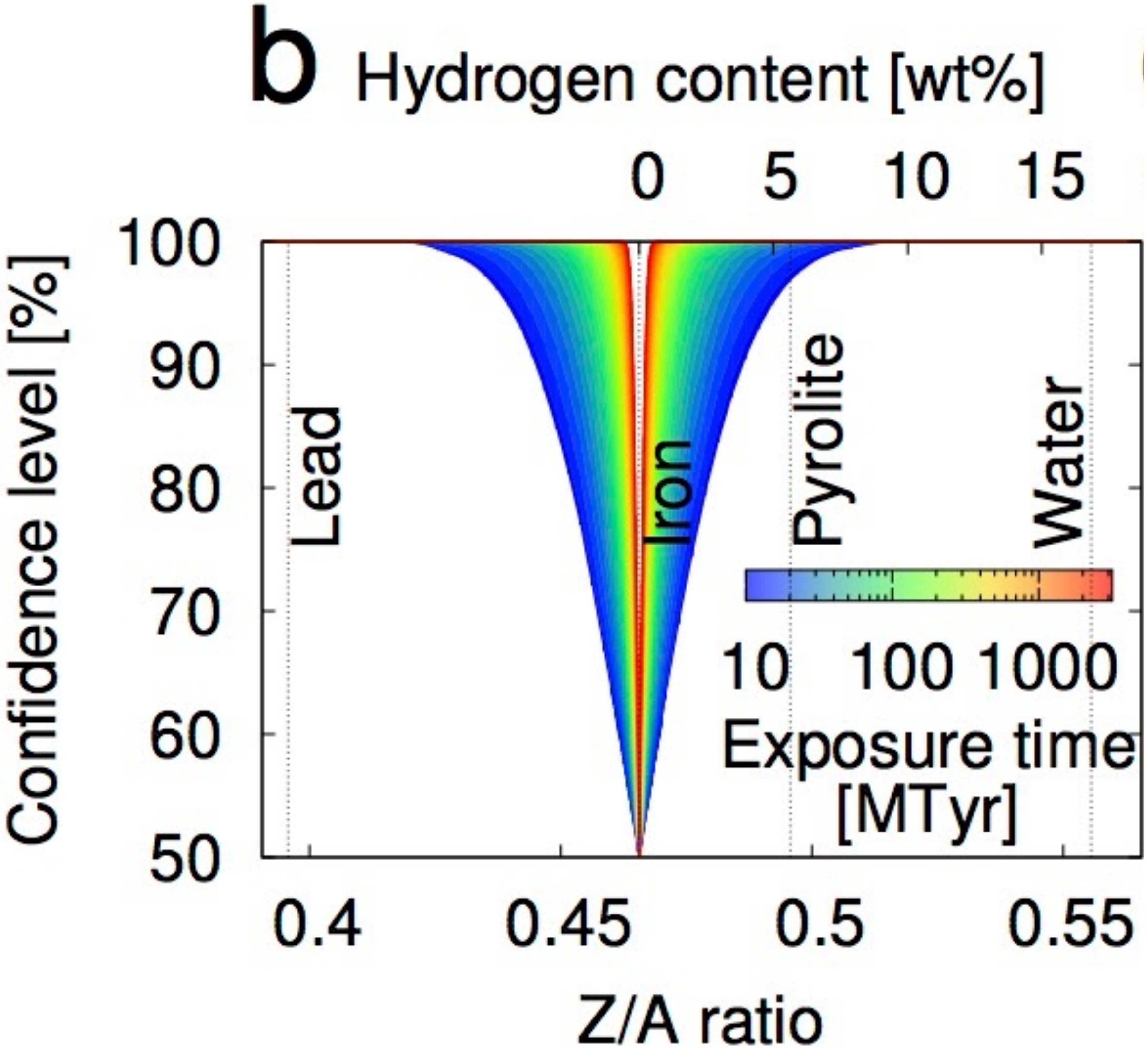
Rott & Taketa 2015

# 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



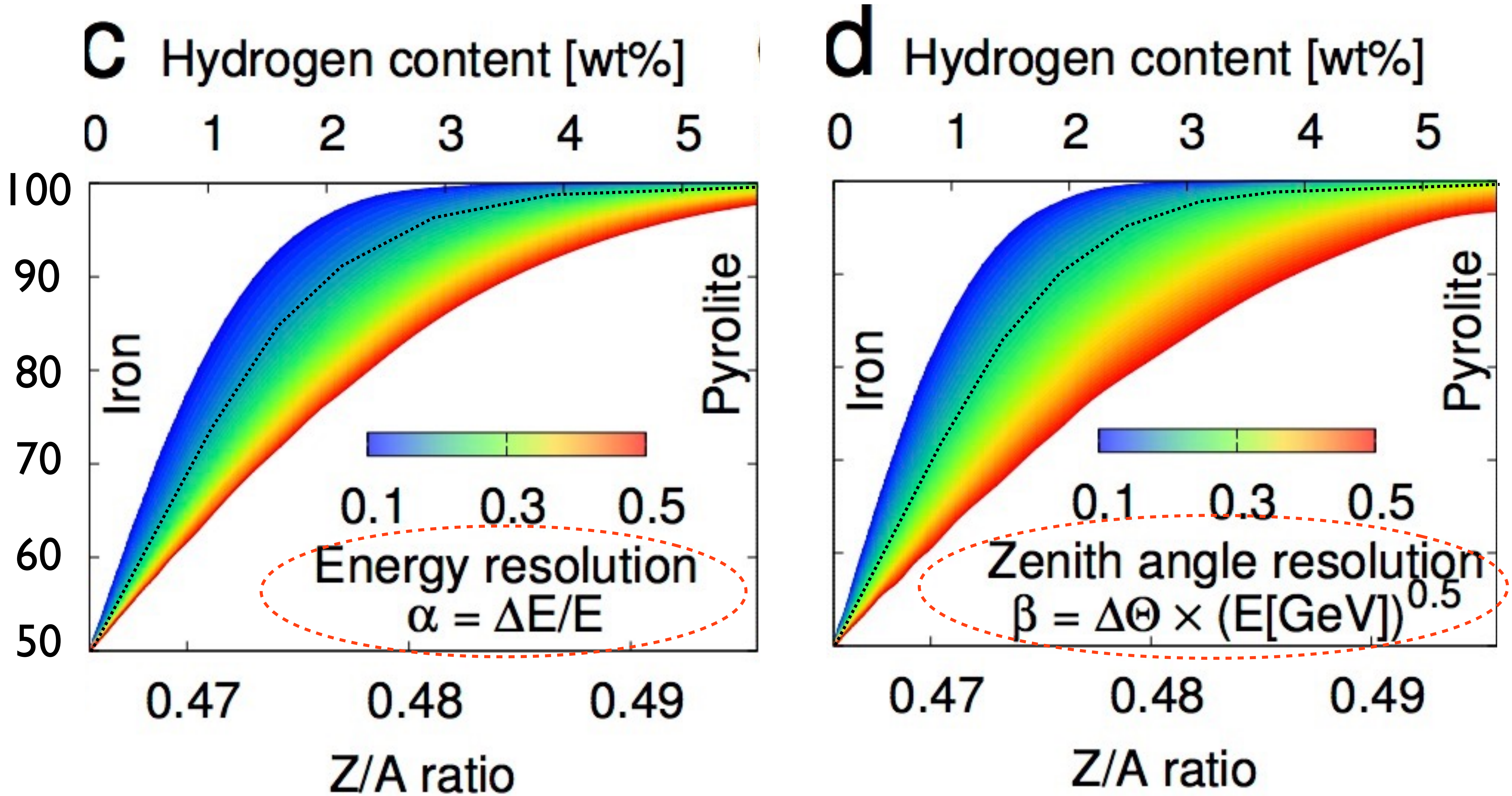
# Sensitivity



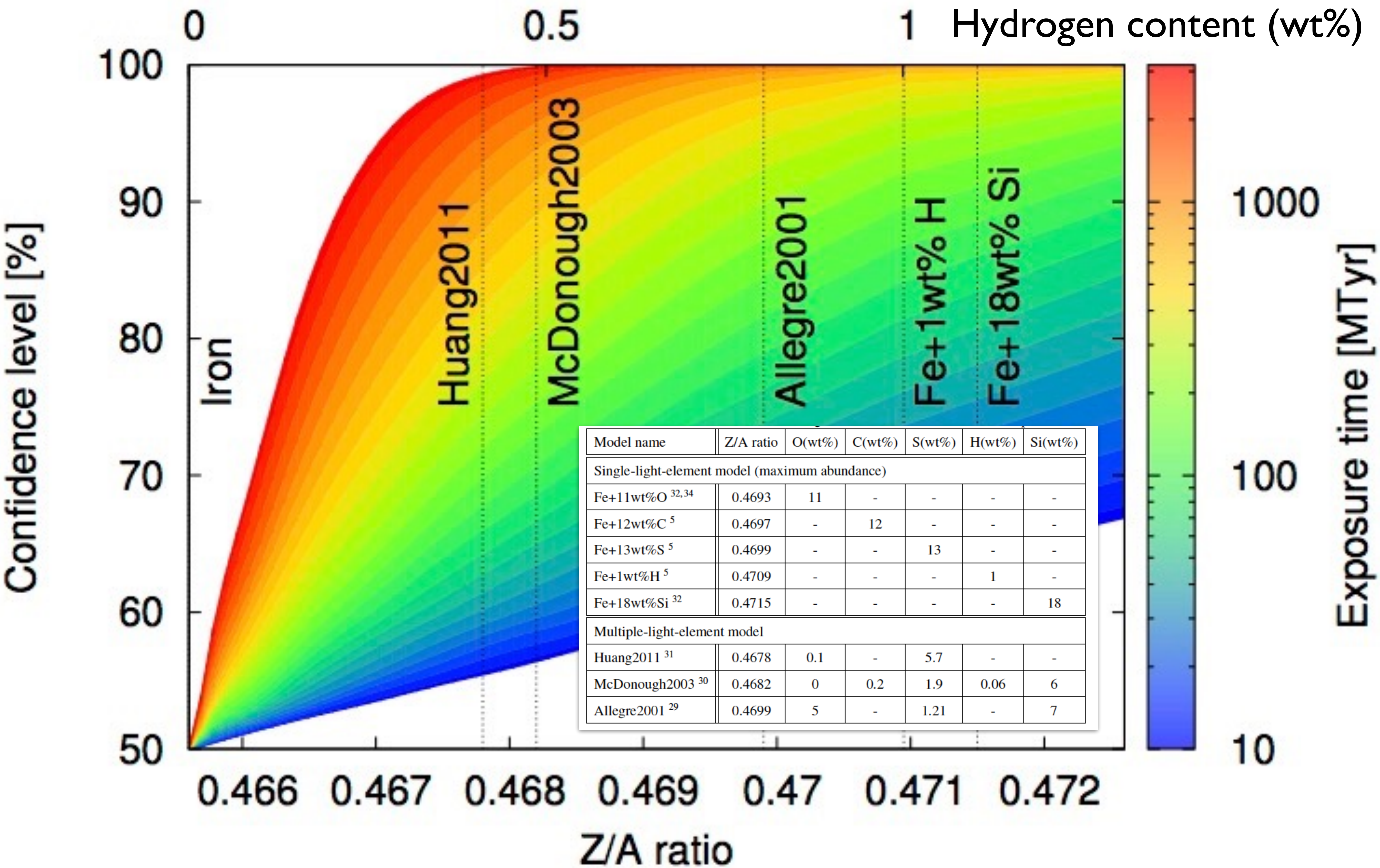

- A few years of PINGU data would yield a few 10MTyrs
- Probe ~2-4wt% hydrogen
- Reject extreme core composition models

# How can we increase sensitivity ?

- Dependence on the angular resolution and energy resolution
  - Assuming 30MTyrs



# Distinguishing Outer core models

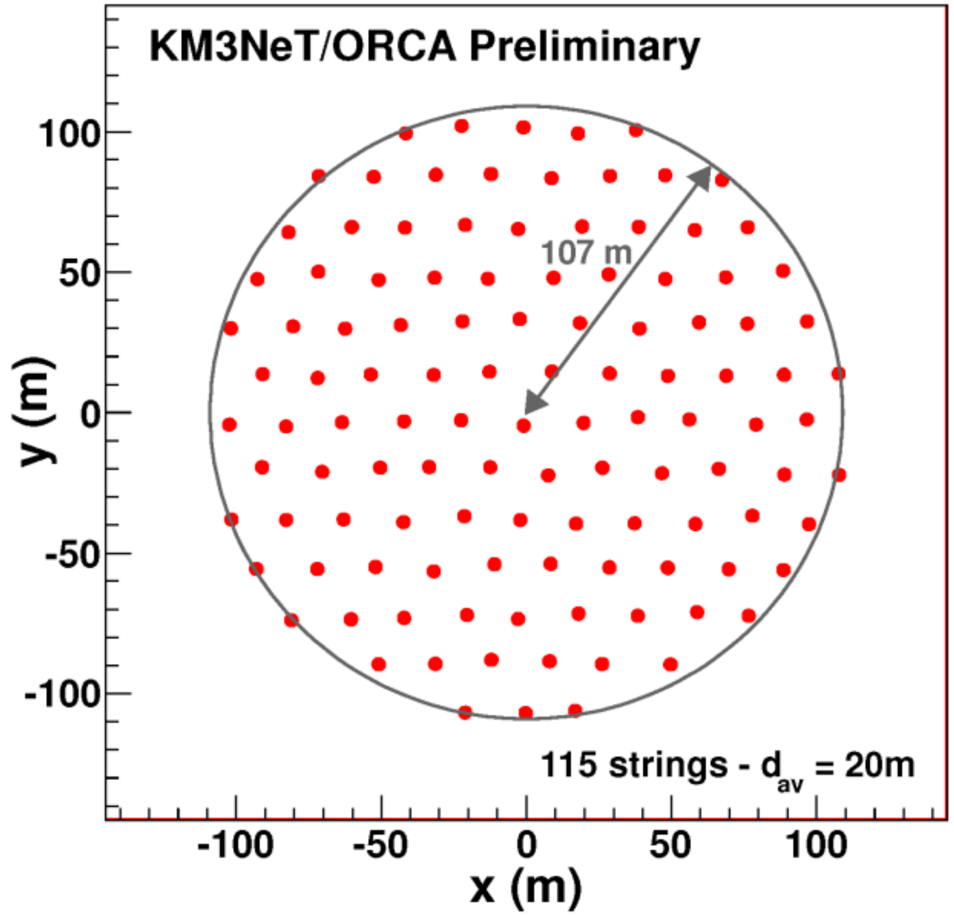



| Model name | Z/A ratio | O(wt%) | C(wt%) | S(wt%) | H(wt%) | Si(wt%) |
|---|---|---|---|---|---|---|
| Single-light-element model (maximum abundance) | | | | | | |
| Fe+11wt%O [32,34] | 0.4693 | 11 | - | - | - | - |
| Fe+12wt%C [5] | 0.4697 | - | 12 | - | - | - |
| Fe+13wt%S [5] | 0.4699 | - | - | 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 |

# ORCA Sensitivity

# ORCA

- ORCA (Oscillation Research with Cosmics in the Abyss)
  - anchored on the seabed off the shore of Toulon (France)
  - Volume of 5.7 Mton of seawater
  - 115 vertical strings (20m horizontal spacing)
  - 18 modules per string with 9m vertical separation

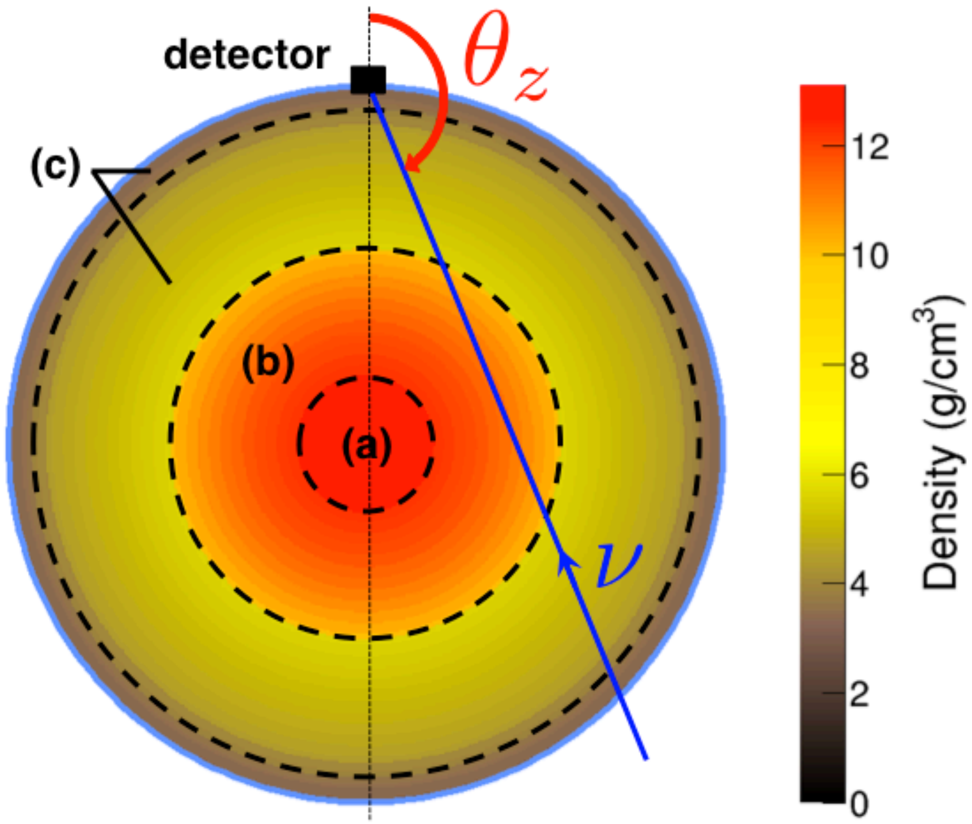



- **ORCA Status:**
  - Phase I fully funded
    - Deployments 2018-2019
  - Phase II partially funded
  - Successful deployment & operation of first string (Sept 2017)
  - Cable problem, replacement in summer 2018, resume operations thereafter

# KM3NeT / ORCA Sensor modules

- 31 3-inch PMTs in 17-inch glass sphere (cathode area ~3x10-inch PMTs)
- Front-end electronics,
  digitisation,
  optical signal → glass fibre
- Single penetrator
- Advantages:
  - Increased photocathode area
  - 1-vs-2 photo-electron separation
    → better detection of coincidences
  - Directionality
  - Cost / photocathode area
  - Minimal number of penetrations
    → reduced risk

# ORCA Sensitivity




Assume 3 layers with uniform Z/A ratio

- (a) solid iron inner core: R = 0 - 1221km
- (b) liquid iron outer core: R = 1221 - 3480km
- (c) silicate mantle (and crust): R = 3480 - 6368km

$$(E_{\text{true}}, \cos\theta_{\text{true}}) \rightarrow (E_{\text{reco}}, \cos\theta_{\text{reco}})$$

## 16 distinct channels considered

$$\{\text{CC } \nu_e/\overline{\nu_e},\ \text{CC } \nu_\mu/\overline{\nu_\mu},\ \text{CC } \nu_\tau/\overline{\nu_\tau},\ \text{NC } \nu/\overline{\nu}\} \times \{\text{track-like, cascade-like}\}$$

**Binned 4-dimensional response matrices built from Monte Carlo simulation including:**

- detection and reconstruction efficiencies
- event classification performance
- error on reconstruction

$$\Delta\chi^2 = \sum_{\substack{\text{Tracks,}\\ \text{Cascades}}} \sum_{\substack{\text{bins } \log E\\ \text{bins } \cos\theta_z}} 2\left[n_{\text{exp}} - n_{\text{obs}} + n_{\text{obs}} \cdot \ln\left(\frac{n_{\text{obs}}}{n_{\text{exp}}}\right)\right]$$

- Statistical uncertainty only
- Systematics under study

Simon Bourret, Joao Coelho and Veronique Van Elewyck
(for KM3NeT)arXiv:1702.03723v1

# ORCA Sensitivity

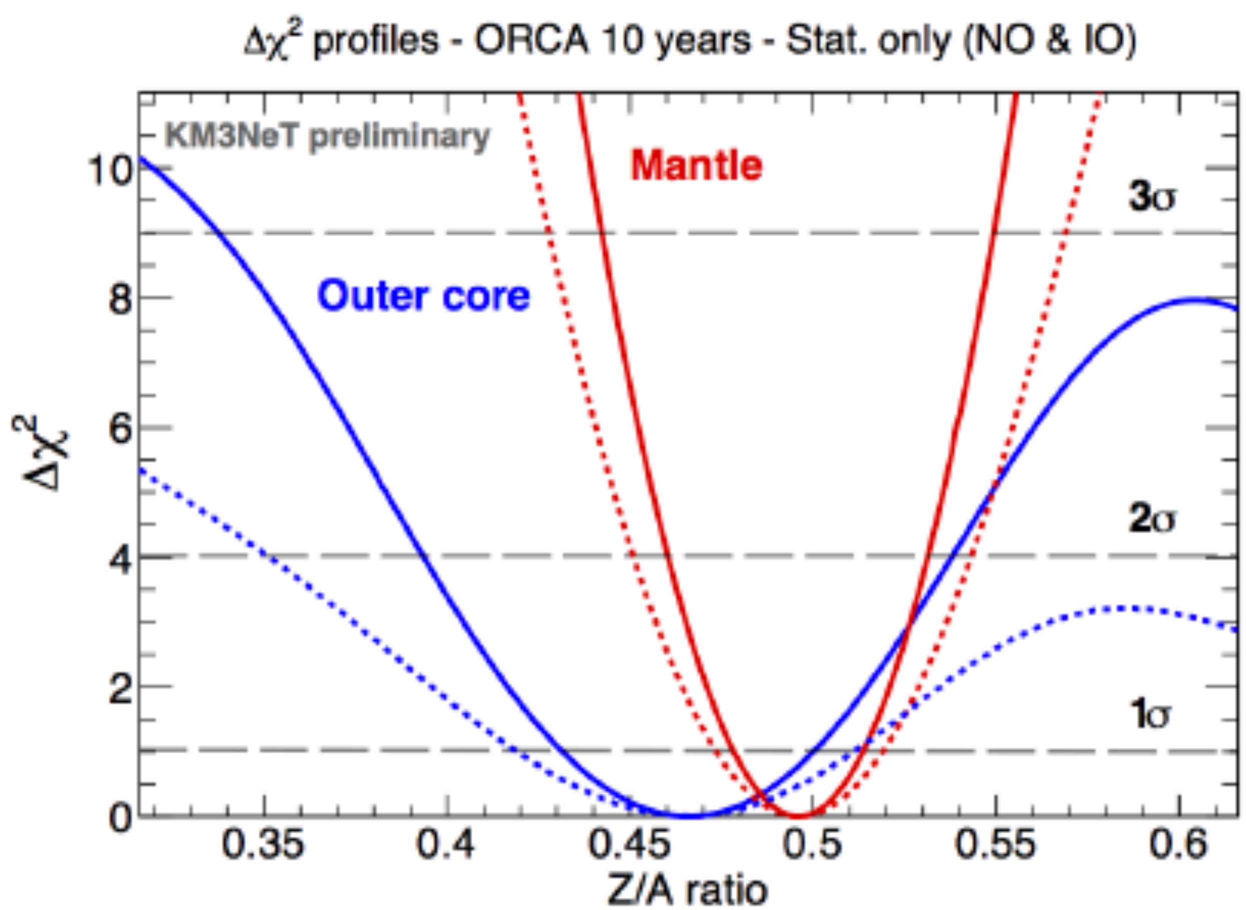



**Figure 2.** $\Delta\chi^2$ profiles for mantle and outer core. Solid lines: normal ordering assumed. Dotted lines: inverted ordering assumed.

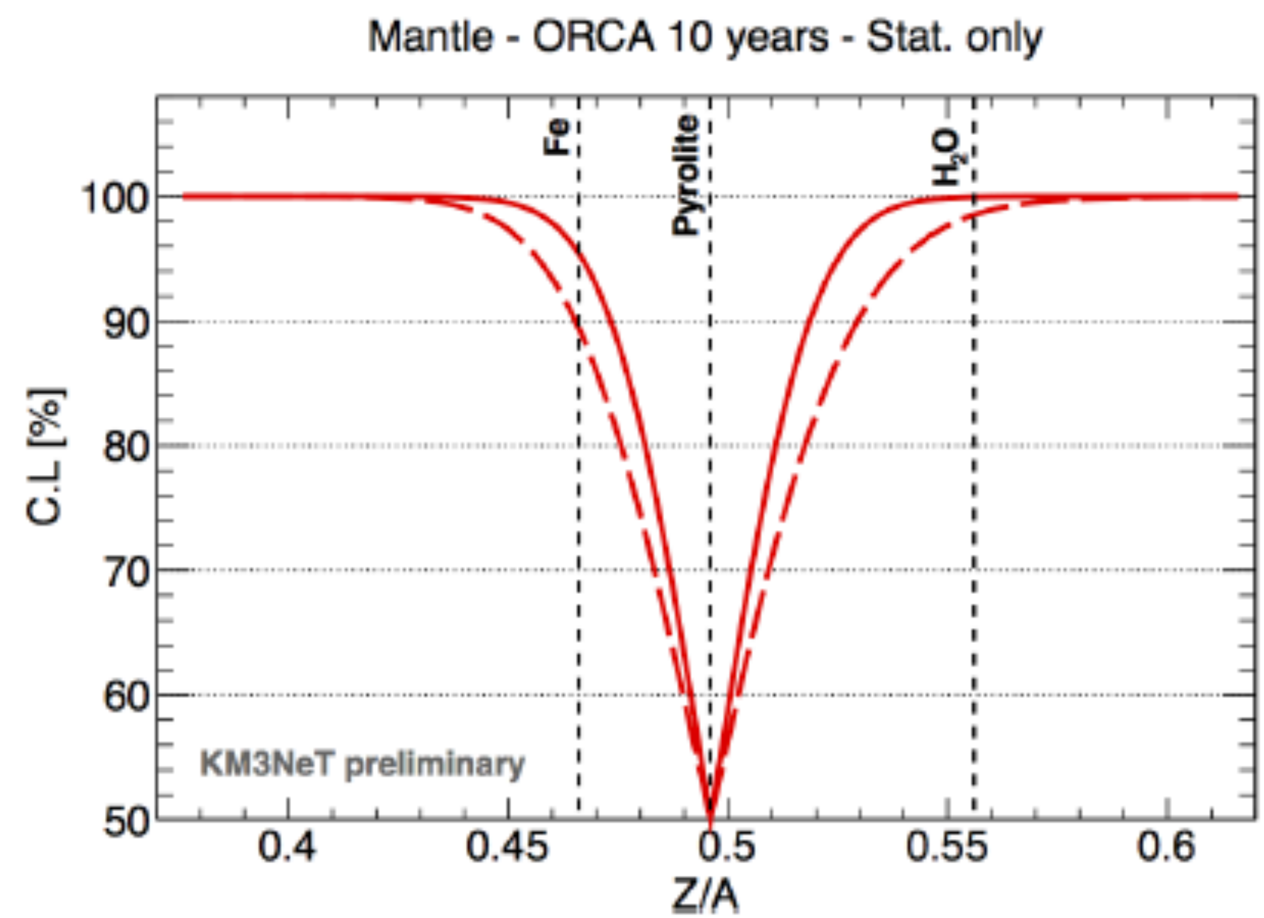


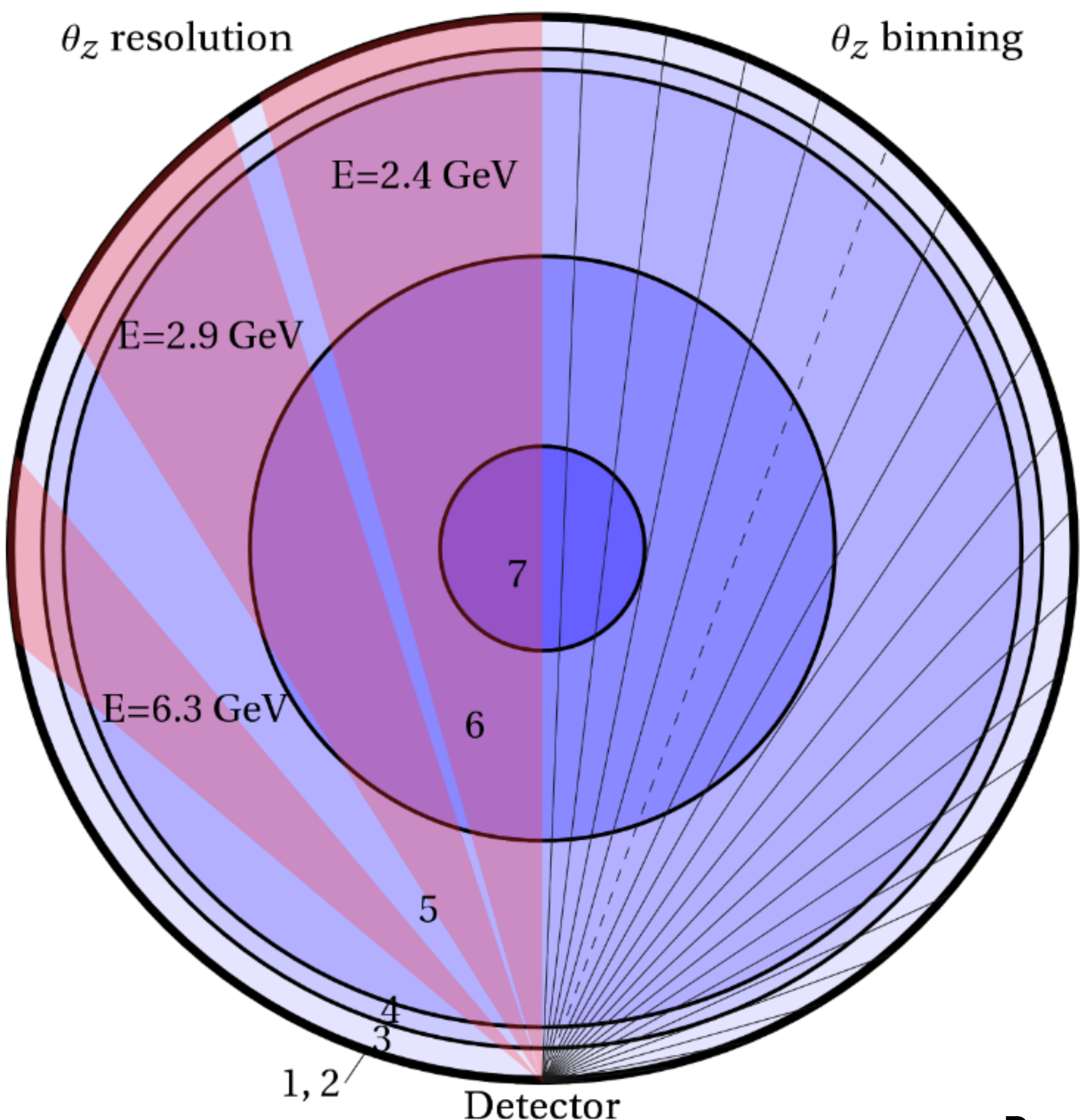

**Figure 3.** Confidence level for rejecting the pyrolitic mantle hypothesis (normal ordering). Solid line: combined channels. Dashed line: track-like only.

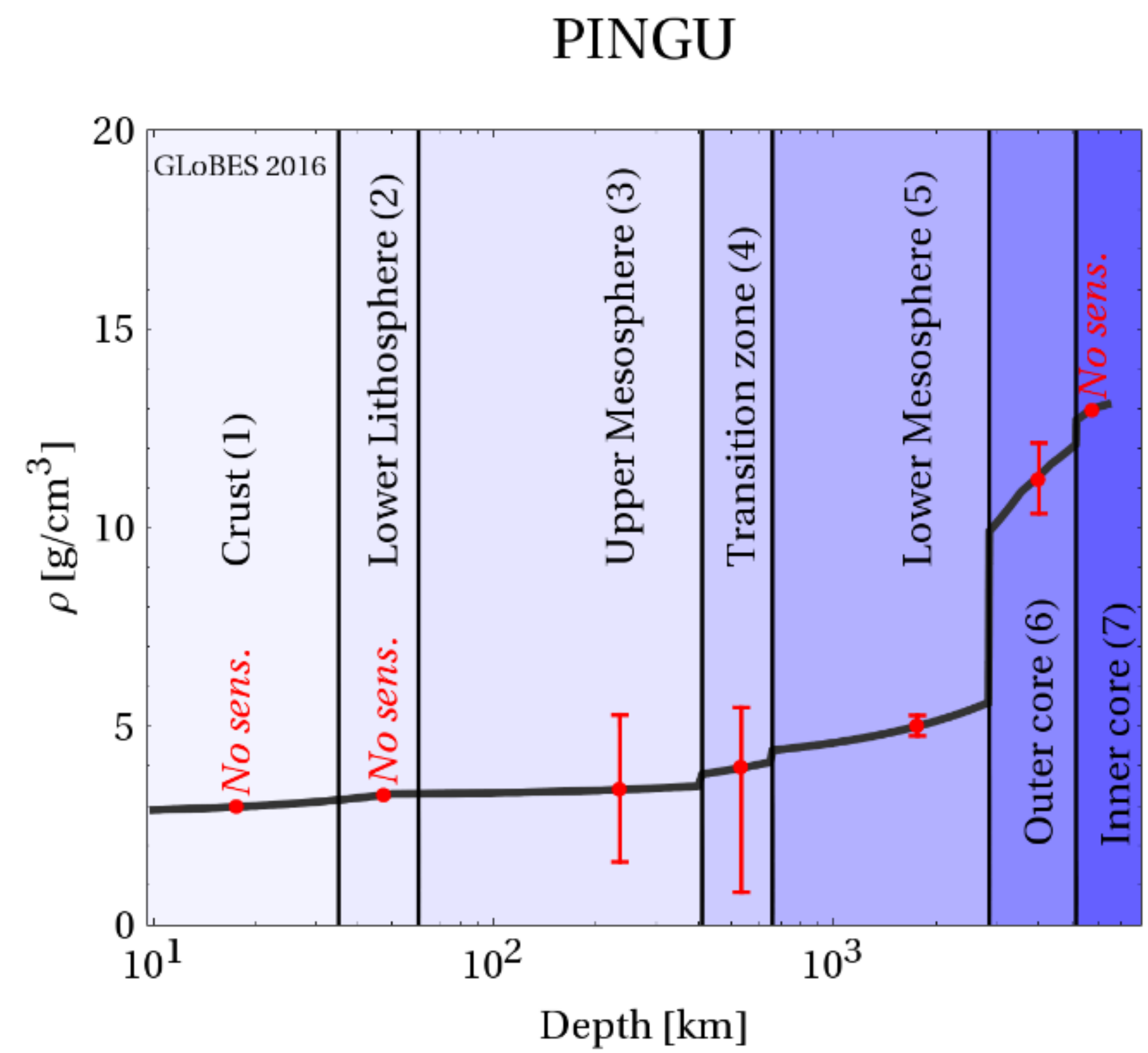
Expect that with 10 years of ORCA data we can measure the electron density in the mantle to 3.6% (4.6%) accuracy [at 1σ] for normal (inverted) mass ordering

# Density measurement

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

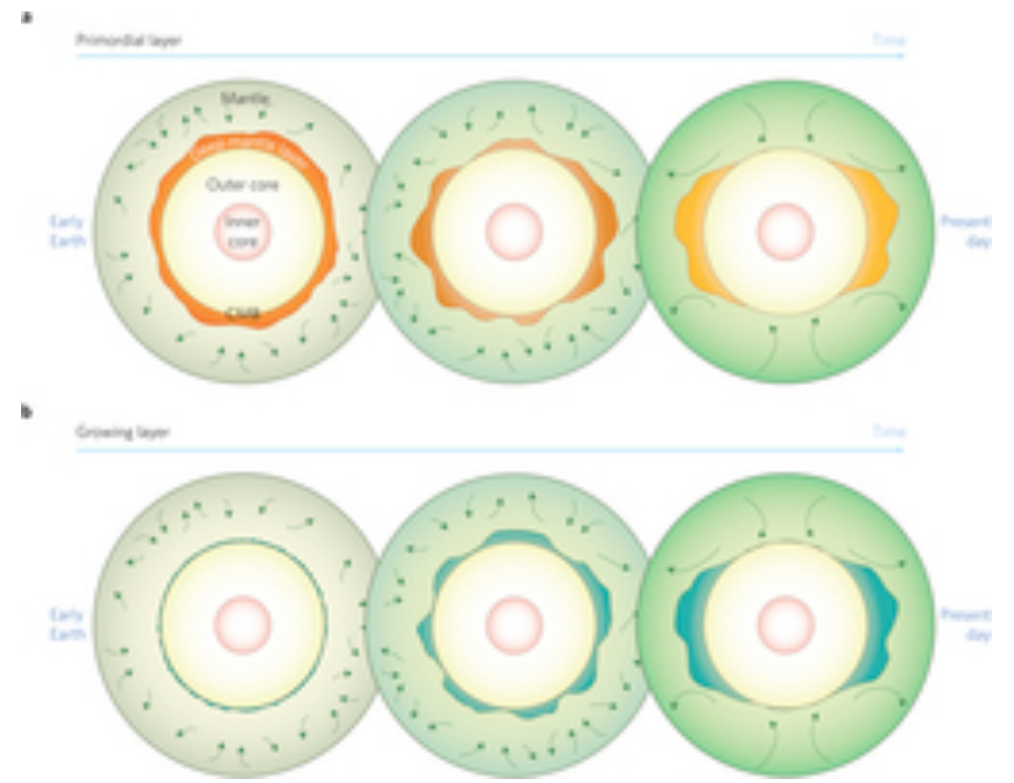
| | PINGU | | ORCA | |
|---|---|---|---|---|
| Layer | NO | IO | NO | IO |
| Crust (1) | No sens. | No sens. | No sens. | No sens. |
| Lower Lithosphere (2) | No sens. | No sens. | No sens. | No sens. |
| Upper Mesosphere (3) | -53.4/+55.0 | No sens. | -51.2/+53.4 | -69.1/+52.2 |
| Transition zone (4) | -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. |

Garnero, McNamara, Shim Nature Geoscience 9, 481–489 (2016)

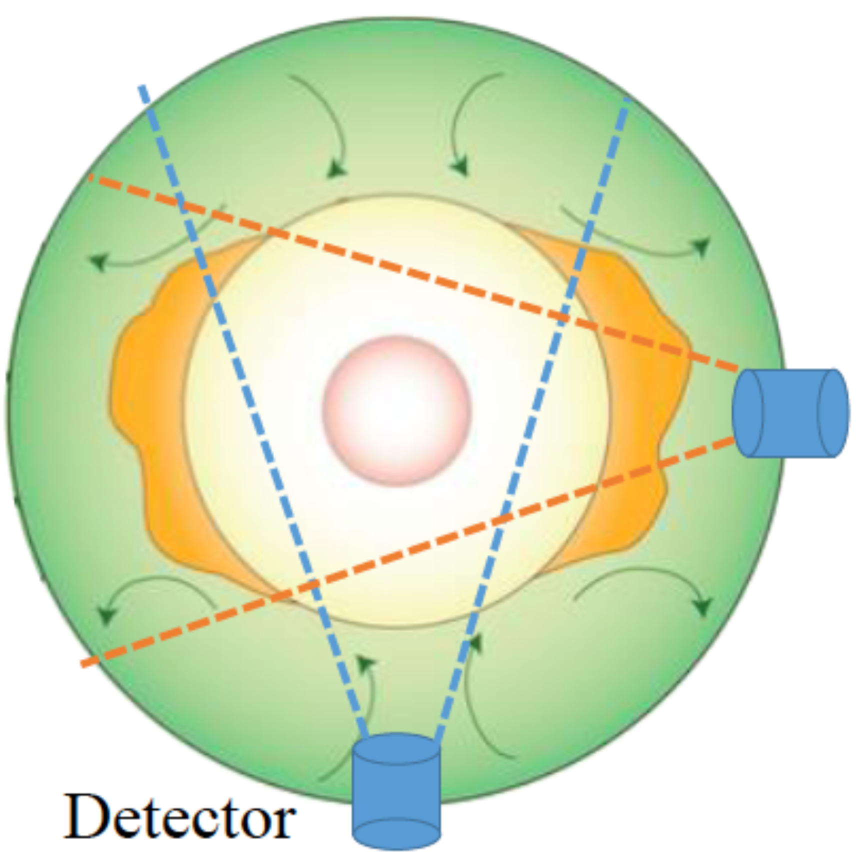
http://www.nature.com/ngeo/journal/v9/n7/pdf/ngeo2733.pdf

# Lower mantle

- Continent-sized anomalous zones with low seismic velocity at the base of Earth's mantle
- Large low shear velocity provinces (LLSVP) up to 1,200km above CMB

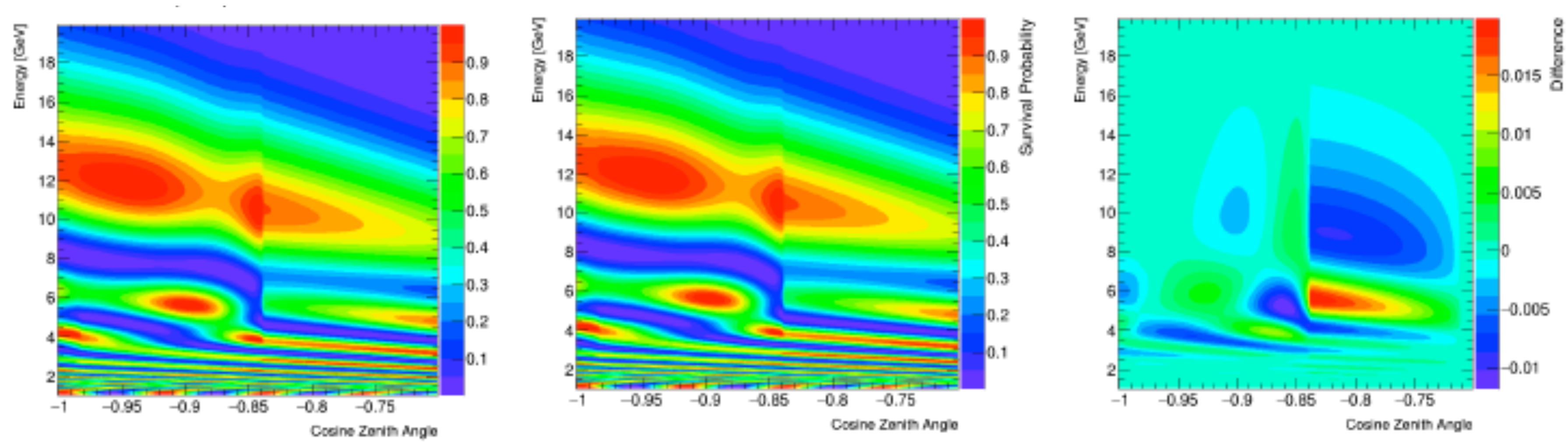


Anisotropic lower mantle




Muon neutrino survival probability

Z/A=0.4957 Z/A=0.5007 Difference




- Tomography with multiple detectors

# Neutrino Oscillation Tomography Road Ahead

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

# Conclusions

- Neutrino oscillation tomography is a novel method to better understand the Earth interior
    - Measure the Earth interior composition
        - Extremely sensitivity to hydrogen
    - Sensitivity to lower mantle density / LLSVP
- 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

# PINGU LOI Study

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**.

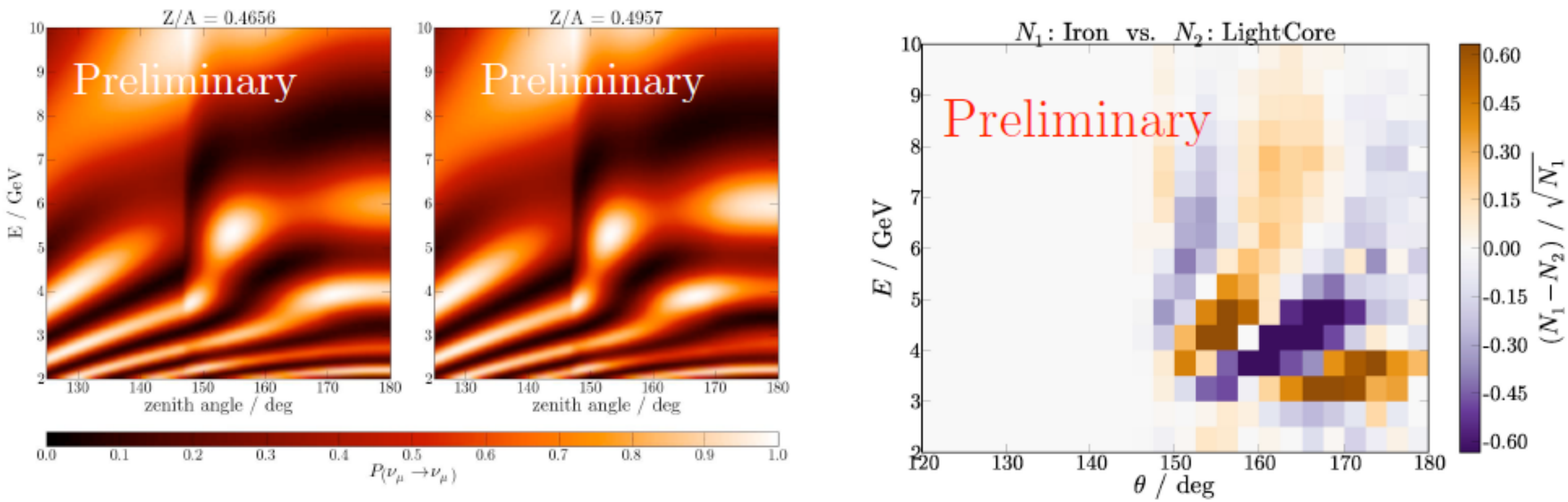
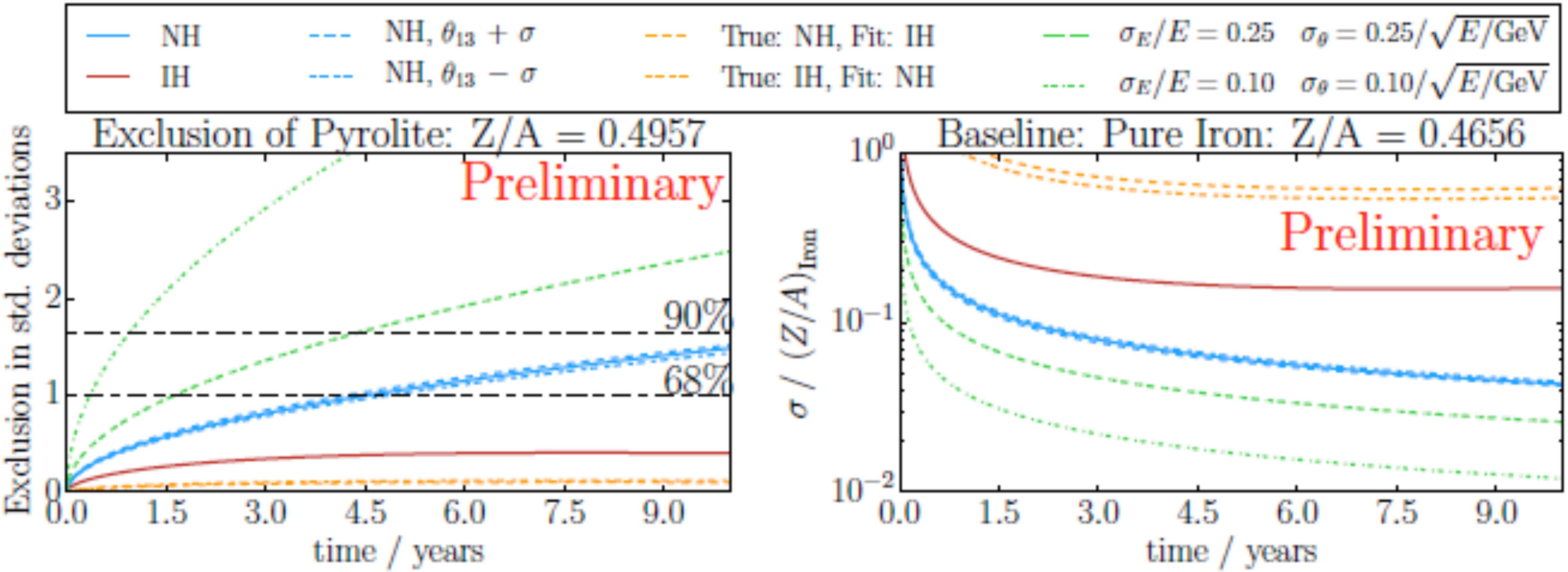



Figure 25: The impact of a changed core composition on the muon-neutrino survival probabilities is demonstrated by comparing the left most figure (pure iron core) and the middle figure (iron mixed with lighter elements). Signature of a pure iron Earth core with respect to a model assuming the same composition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



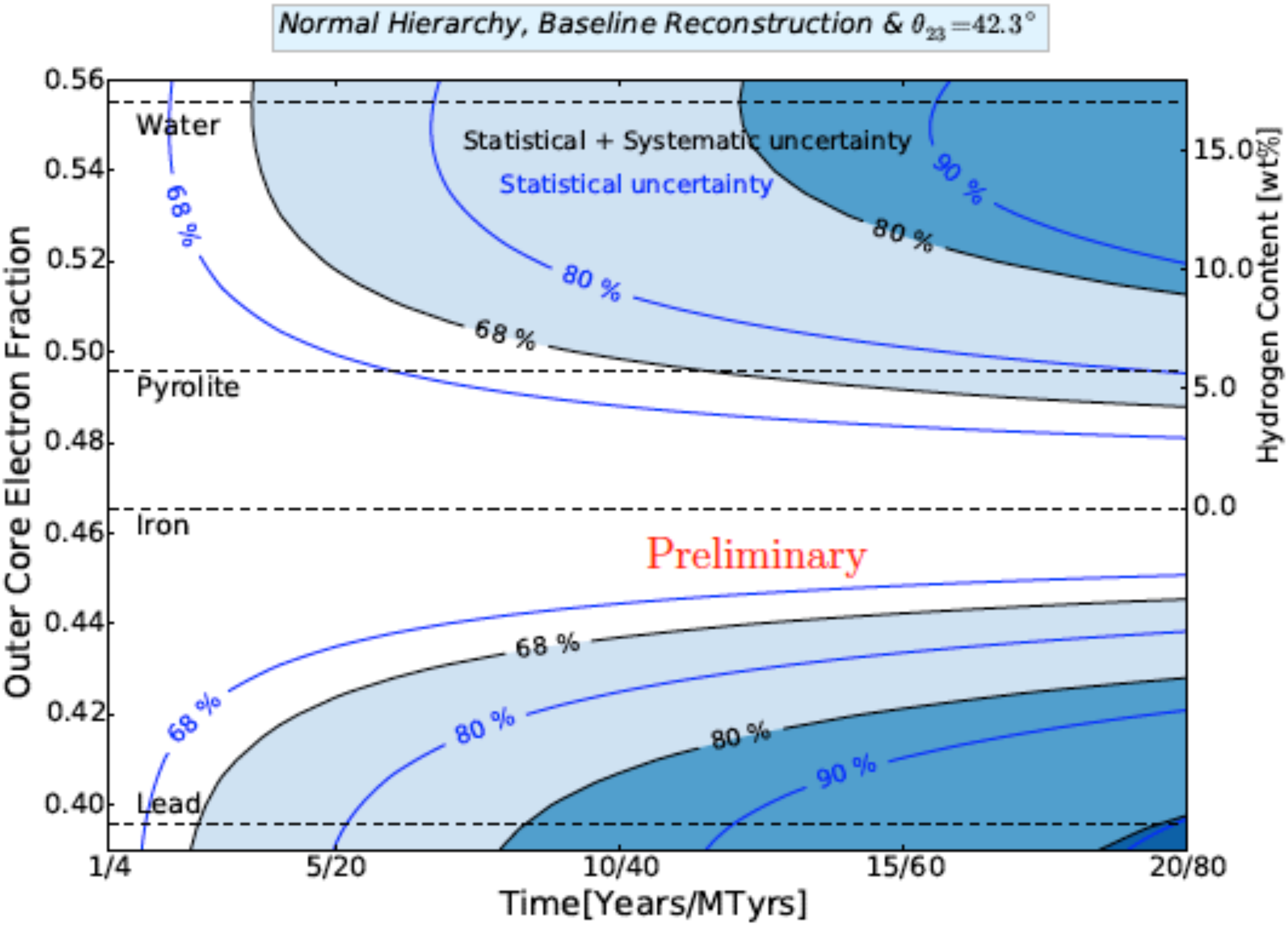

$$\sigma_E = A_E\, E \text{ and } \sigma_\theta = A_\theta \,/\, \sqrt{E/\mathrm{GeV}}$$

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

Parametric: $A_i$= 0.25 and $A_i$= 0.10

to be updated with full PINGU detector simulation

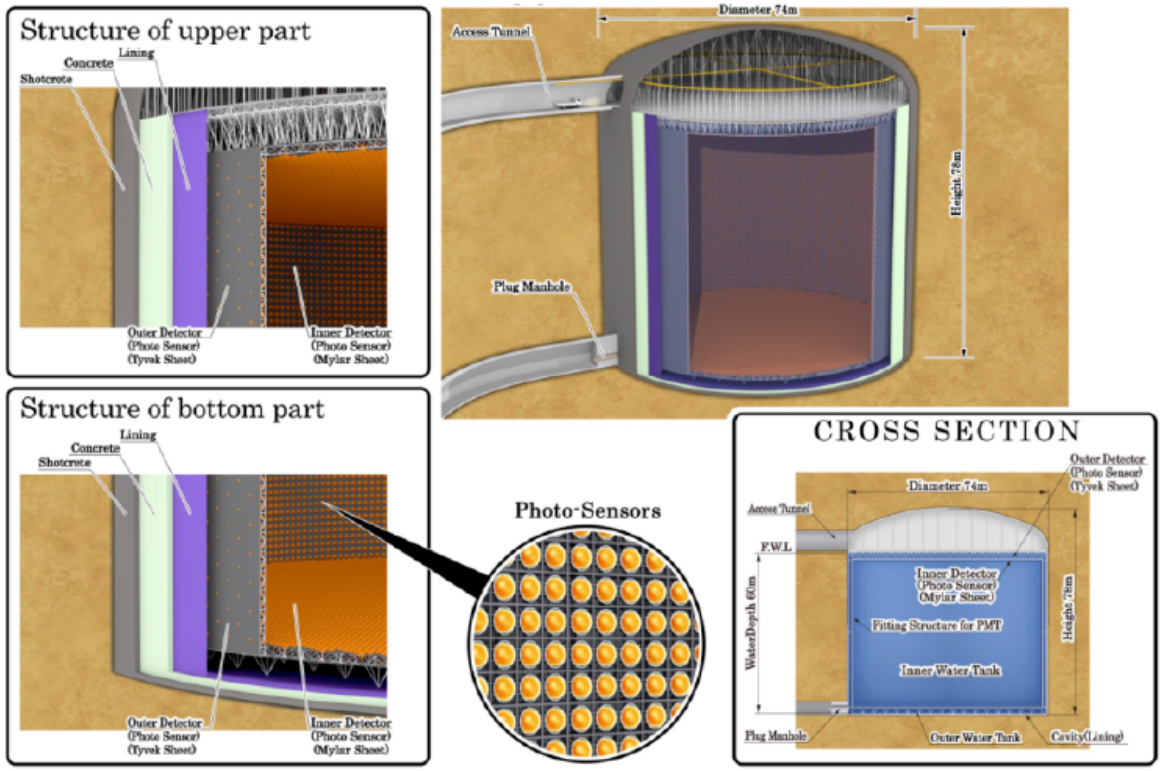
# PINGU Sensitivity

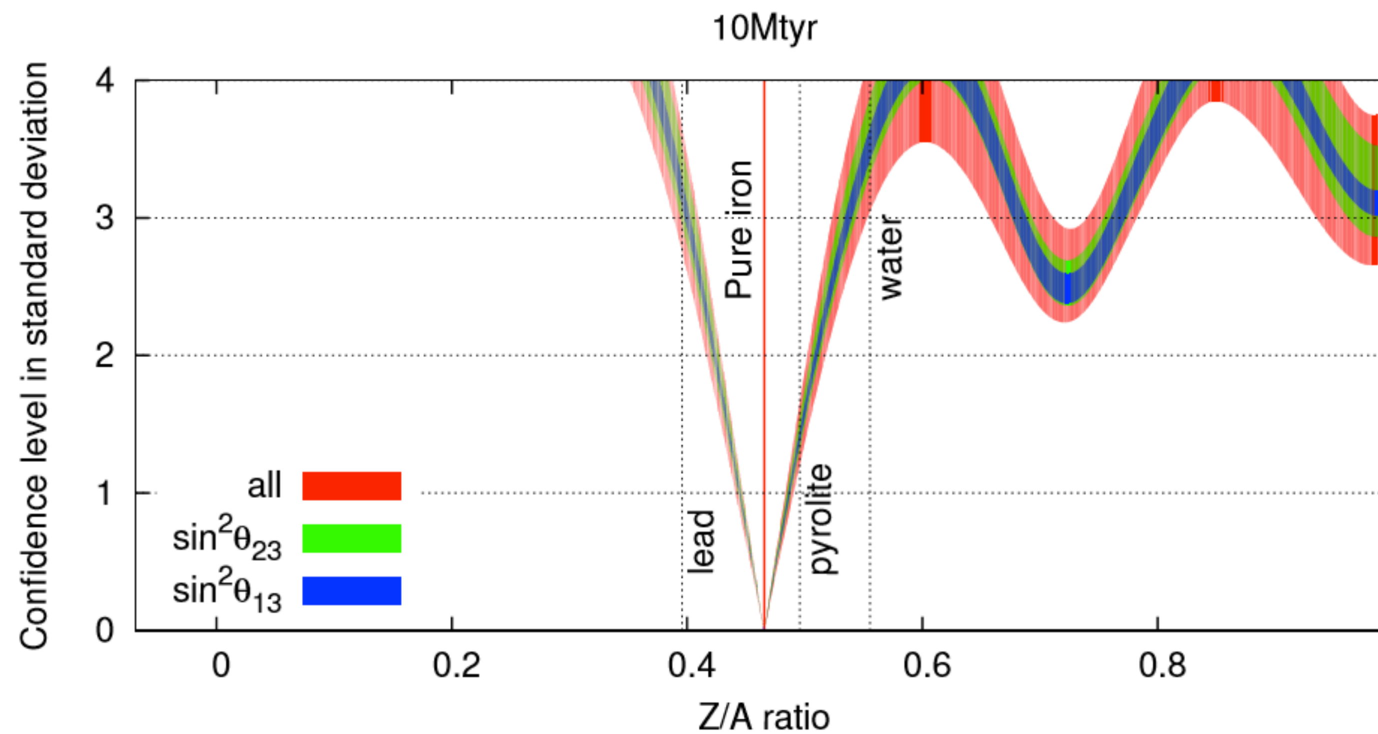


KEK Preprint 2016-21
ICRR-Report-701-2016-1

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

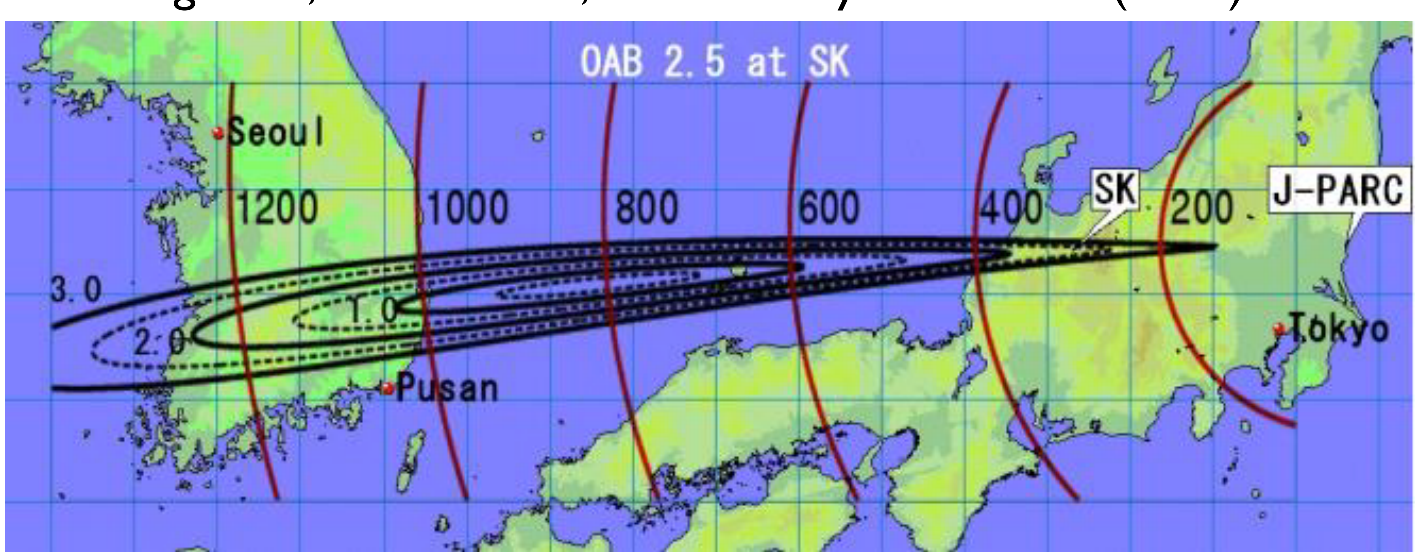
# Hyper-K Sensitivity




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

K. Hagiwara, N. Okamura, K. Senda Phys.Lett. B637 (2006) 266-273




Next: Nov. 21–22 2016: 1st International T2HKK workshop at SNU

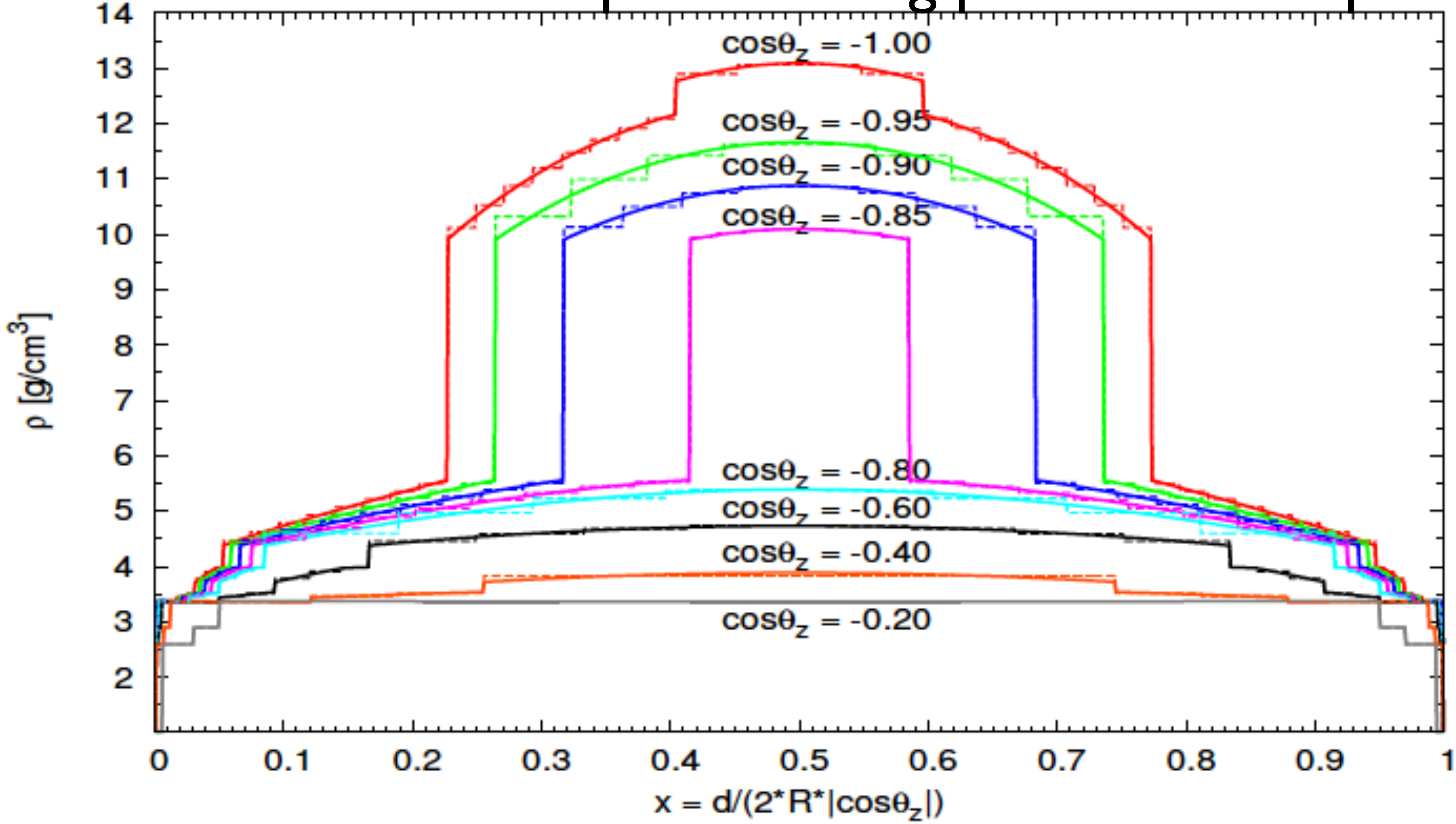
- Prospects for hosting second Hyper-K tank in Korea … stay tuned

KPS 2016 Fall Meeting
Kimdaejung Convention Center, Gwangju
Oct 19 (Wed) -Oct 21 (Fri)

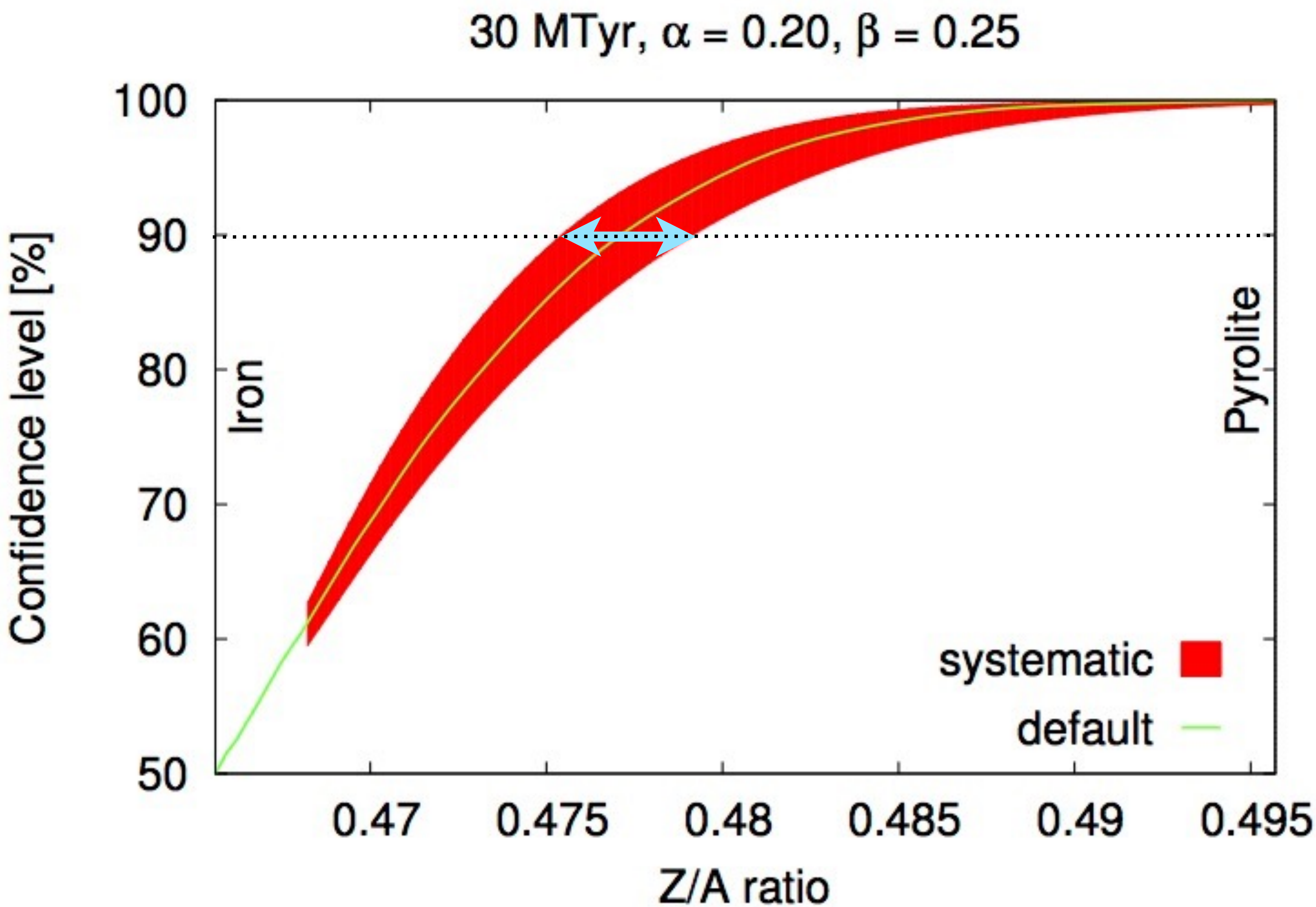
**T2HKK: 한국에 설치될 두 번째 하이퍼카미오칸데 검출기** - 서선희 (서울대), Carsten Rott (성균관대학교)
중성미자들간의 세 번째 섞임각을 최근에 측정함으로써 세 중성미자의 진동변환은 확고히 정립되었다. 예상보다 큰 값으로 측정된 theta 13 섞임각 덕분에 중성미자 물리학의 남아있는 근원적 문제인 CP 비대칭성 위상과 중성미자 질량 순서를 결정할 수 있다는 가능성을 제시했다. 25만톤 하이퍼카미오칸데 검출기는 J-PARC에서 만든 중성미자 빔을 이용하여 CP 위상과 질량순서를 결정할 수 있다. 이 검출기는 양성자 붕괴 탐색과 초신성 폭발 중성미자, 대기 중성미자, 태양 중성미자와 관련된 연구를 하는 다목적 용도이다. 최근에 CP 위상과 질량순서 결정의 효율을 향상시키고자 한국에 제2의 하이퍼카미오칸데 검출기 설치가 제안되었다. 본 세션에서는 한국의 하이퍼카미오칸데 검출기 설치 계획과 물리학적 연구목표와 기대효과에 대해 논의를 하게 된다.

# Thank you !

https://arxiv.org/pdf/1309.3176.pdf

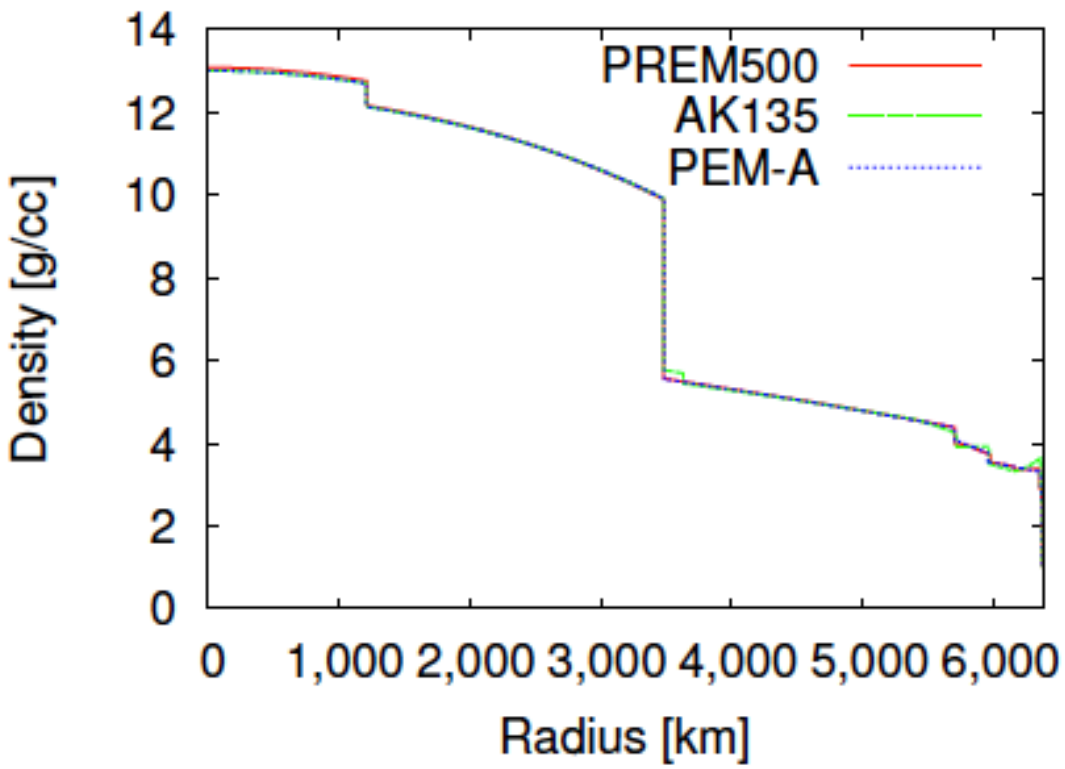


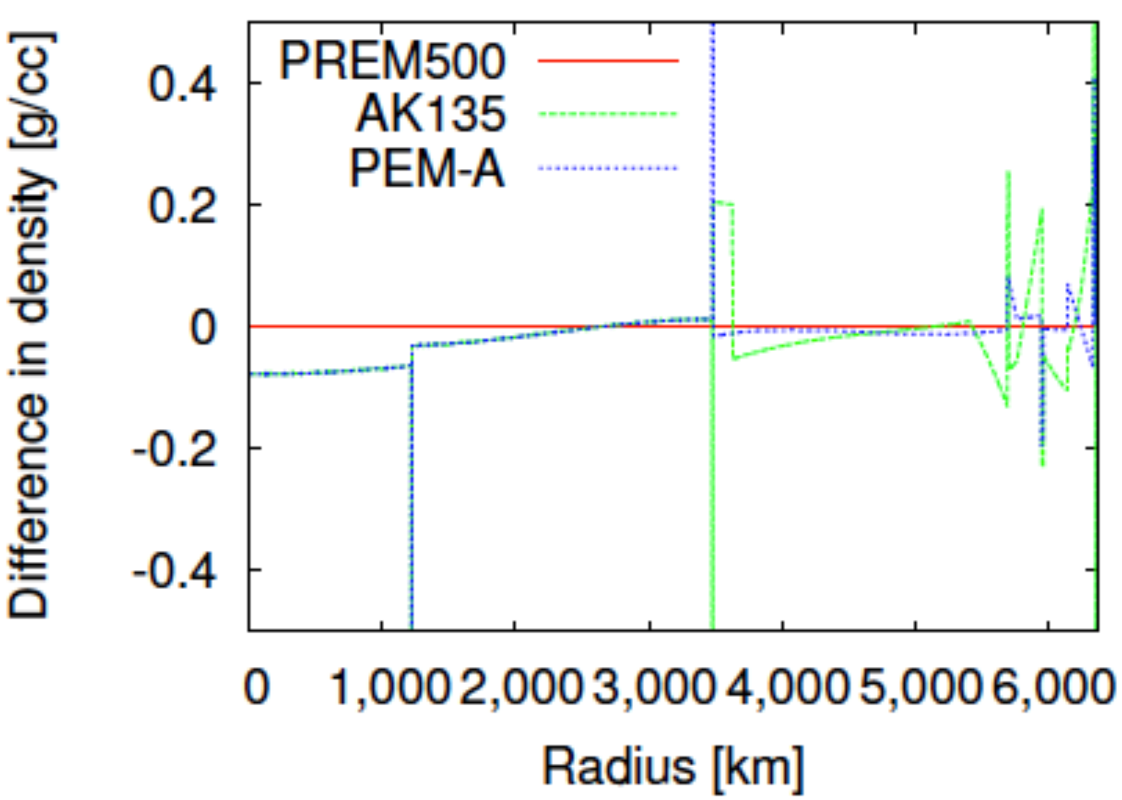
# Uncertainty due to mixing parameters

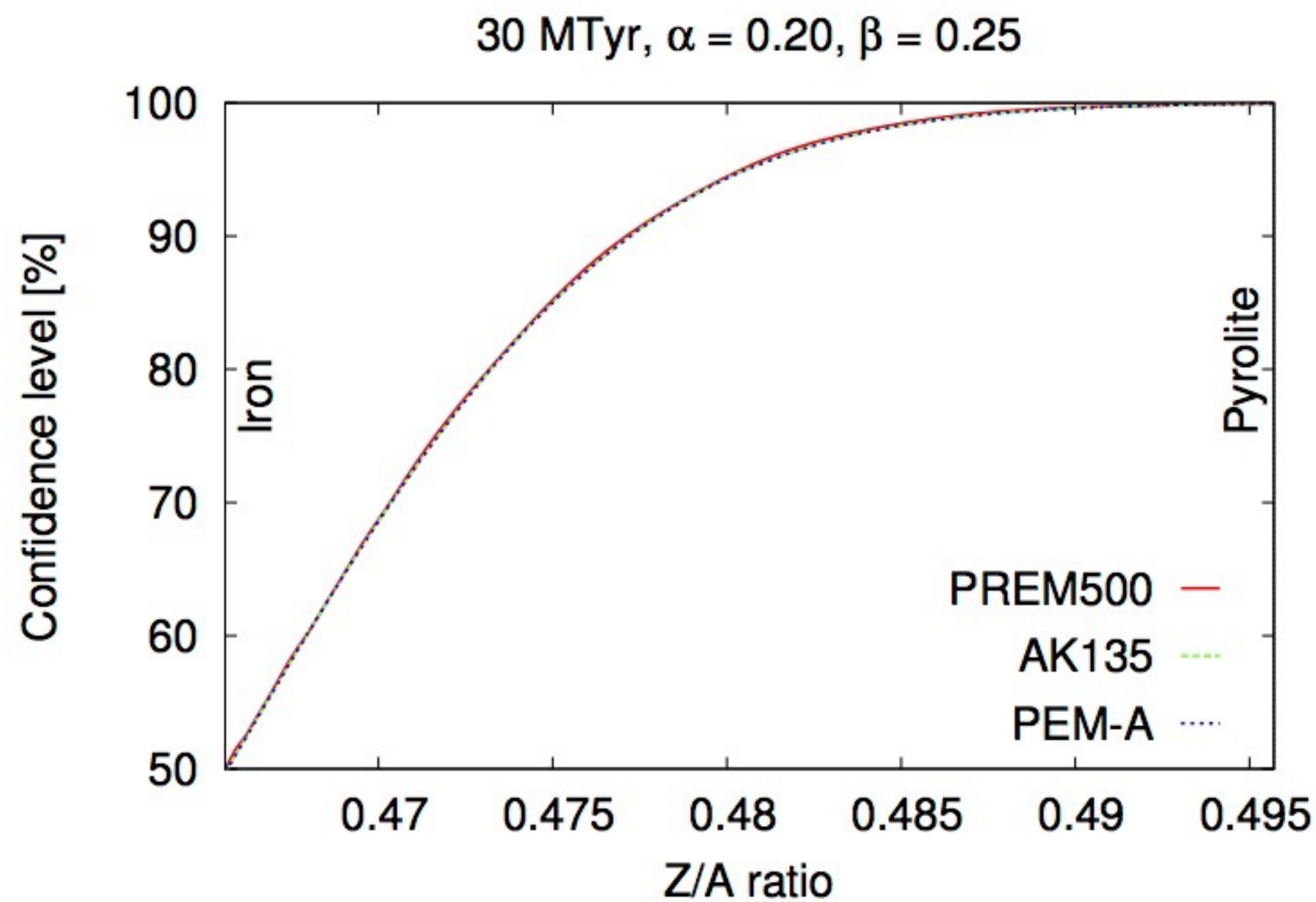



**Use the best fit oscillation parameters and their uncertainties of:**
*Capozzi, F. et al. Status of three-neutrino oscillation parameters, circa 2013. Physical Review D 89, 093018 (2014).*

# 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).