Earth tomography with neutrinos

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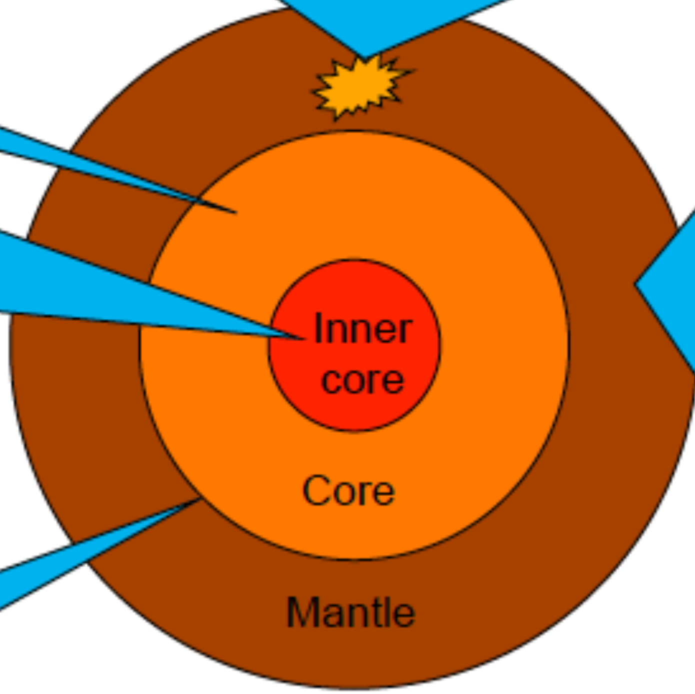
on behalf of the KM3NeT Collaboration

Looking at the Earth's interior

Outer core: Liquid (as no seismic shear waves)

Zones with local anomalies in seismic wave velocities

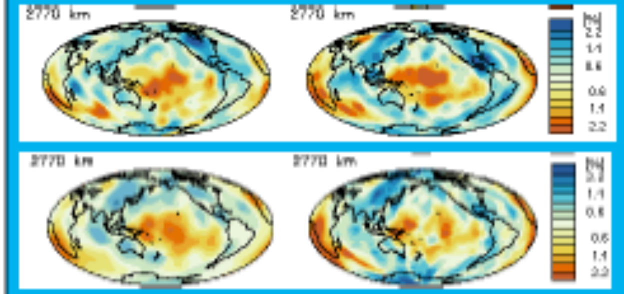
Inner core: Solid. Anisotropies? Dynamics? State? [Probably least known part …]



Mantle: Probed by seismic waves; parameterization relative to REM

(Reference Earth Model, Dziewonski, Anderson, 1981)

Velocities among 3D models consistent within percentage errors:



(http://igppweb.ucsd.edu/~gabi/rem.html)

Seismic wave reflection/refraction

Density constrained by collective constraints from mass and moment of inertia

$M = 2\pi \int r^2 \rho(r) dr, \qquad I = 2\pi \int (x^2 + y^2) r^2 \rho(r) dr$

… and free oscillation modes at percent level

(taken from W. Winter, ISAPP School 2016 « Understanding and imaging the Earth»)

Looking at the Earth's interior: composition

Outer core: Liquid (as no seismic shear waves)

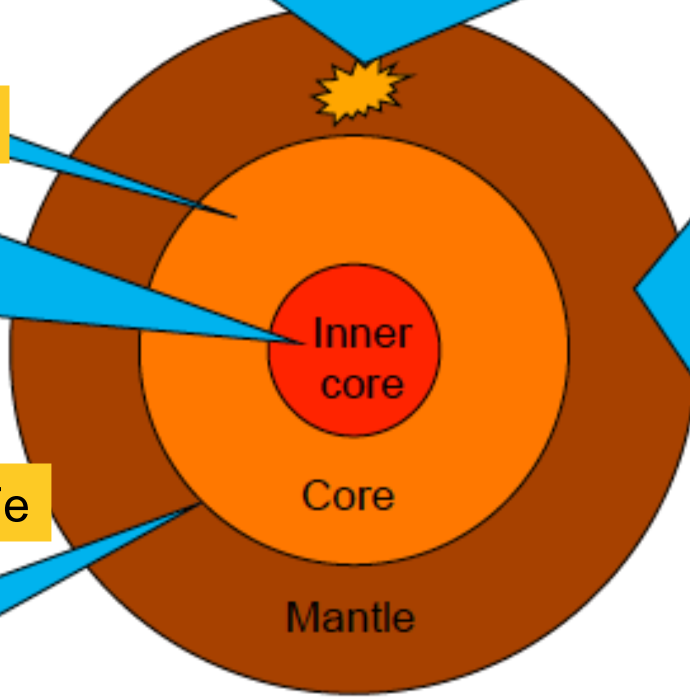
Fe + Ni, light elements ?

Inner core: Solid. Anisotropies? Dynamics? State? [Probably least known part …]

Pure Fe

Seismic wave reflection/refraction

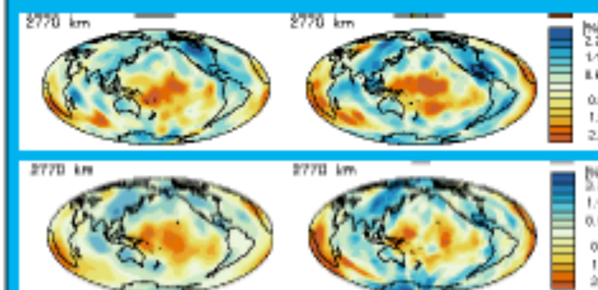
Zones with local anomalies in seismic wave velocities



Mantle: Probed by seismic waves; parameterization relative to REM

Pyrolite (silicate Earth)

Velocities among 3D models consistent within percentage errors:



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… and free oscillation modes at percent level

(taken from W. Winter, ISAPP School 2016 « Understanding and imaging the Earth»)

Looking at the Earth's interior: matter density

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Inner cor...
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Density ...
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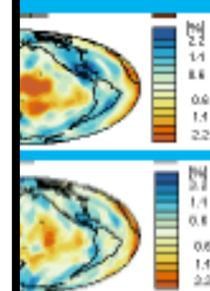
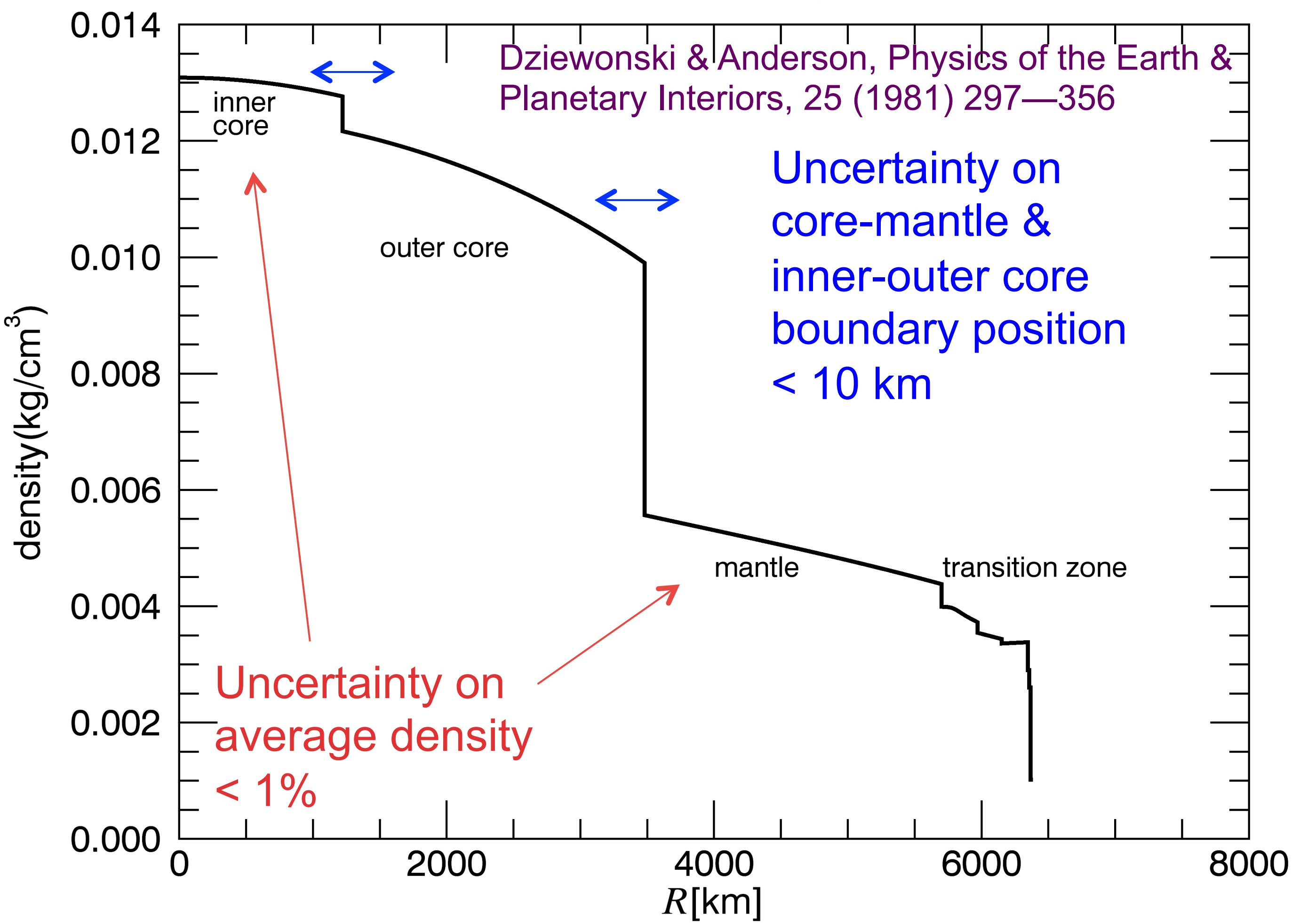
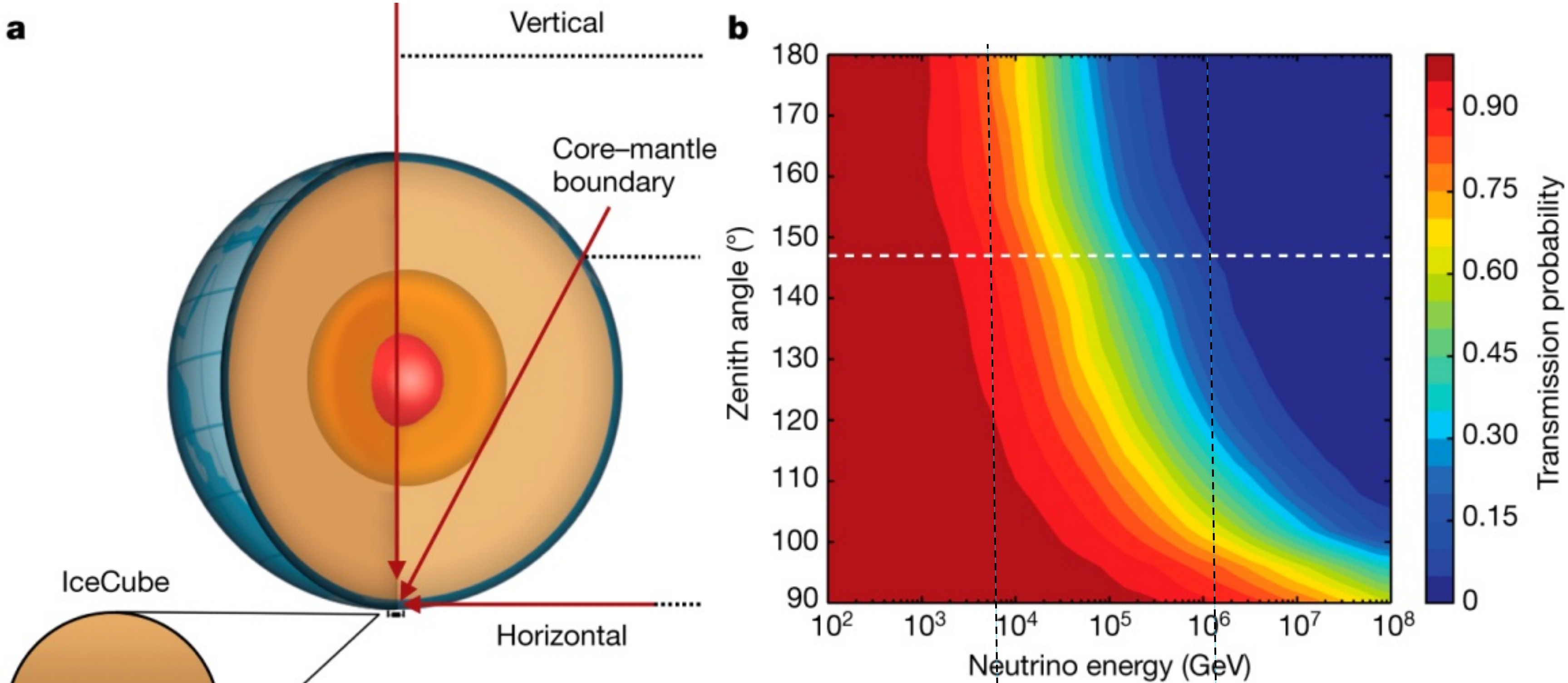


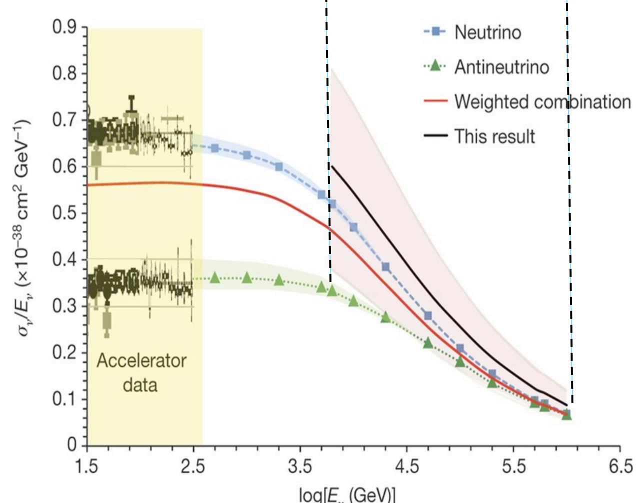
...csd.edu/

The Preliminary Reference Earth Model (PREM)



At high energies: Earth absorption tomography

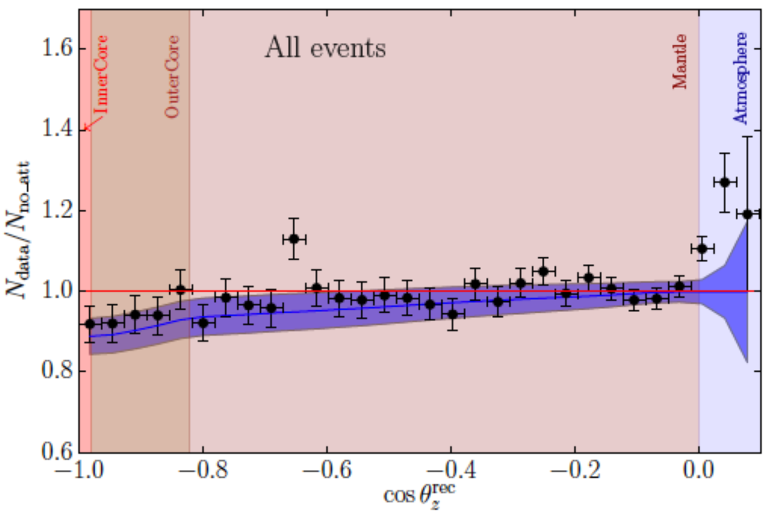


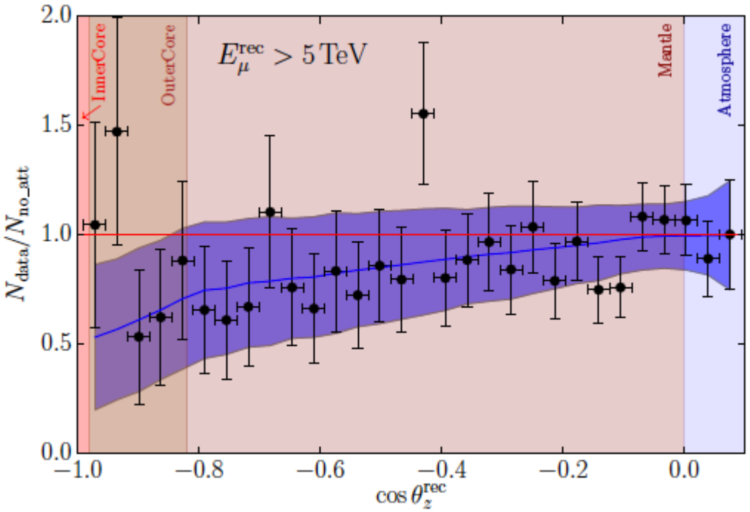


…driven by the increase of neutrino-nucleon cross-section at high energies (~10 TeV → PeV)

IceCube Coll., Nature 551 (2017) 596-600

At high energies: Earth absorption tomography

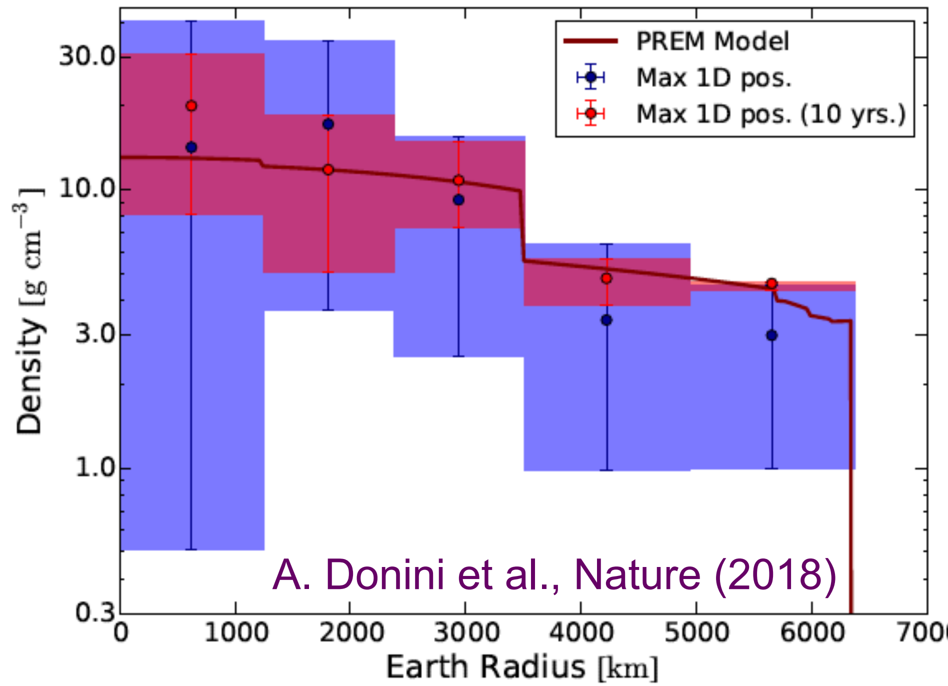




No attenuation (transparent Earth)

PREM expectation

Absorption tomography is sensitive to Earth matter density



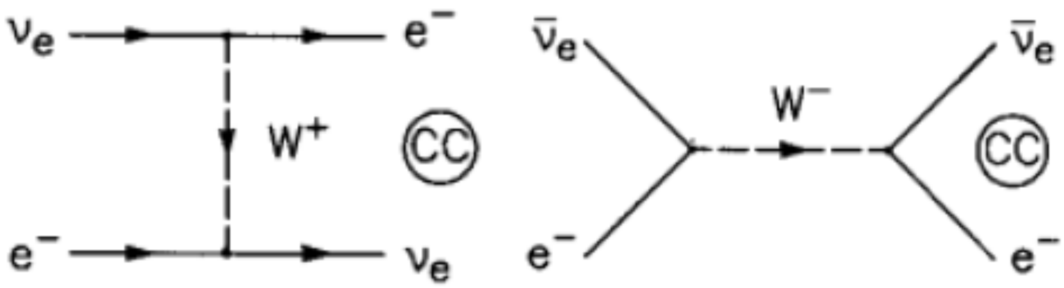
1st study with real data:
IceCube 1 yr sample (2011-2012)
20145 up-going ν_μ with 400 GeV < E < 20 TeV

- (much) more statistics needed
- Systematics must be controlled: neutrino flux, cross-section & detection effects (ice model)

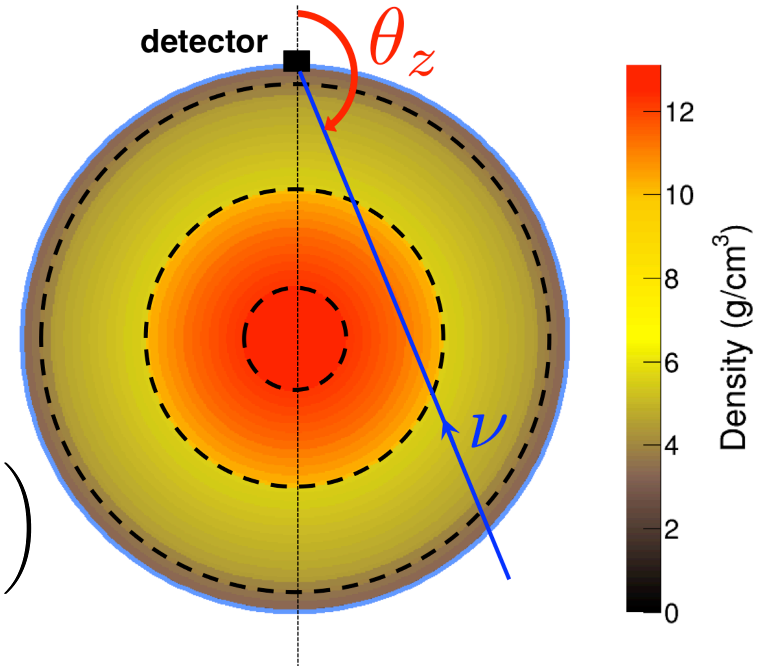
At low energies: oscillation tomography

Ordinary matter contains e's but no μ's or τ's
→ extra potential in propagation Hamiltonian,
proportional to electron density in medium

$$A \equiv \pm\sqrt{2} G_F N_e$$



$$L = 2R_{\mathrm{Earth}} \cos\theta_z$$



$$P^m_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta^m_{13} \sin^2\left(\frac{\Delta^m m^2 L}{4E_\nu}\right)$$

$$\sin^2 2\theta^m_{13} \equiv \sin^2 2\theta_{13}\left(\frac{\Delta m^2_{31}}{\Delta^m m^2}\right)^2$$

$$\Delta^m m^2 \equiv \sqrt{(\Delta m^2_{31}\ \cos 2\theta_{13} - 2\boxed{E_\nu} A)^2 + (\Delta m^2_{31} \sin 2\theta_{13})^2}$$

→ Resonance energy (for neutrinos in NH/antineutrinos in IH)

$$E_{\mathrm{res}} \equiv \frac{\Delta m^2_{31}\ \cos 2\theta_{13}}{2\sqrt{2}\, G_F\, N_e} \simeq 7\,\mathrm{GeV}\left(\frac{4.5\,\mathrm{g/cm^3}}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times 10^{-3}\,\mathrm{eV}^2}\right)\cos 2\theta_{13}$$

≅ 3 GeV (core)
≅ 7 GeV (mantle)

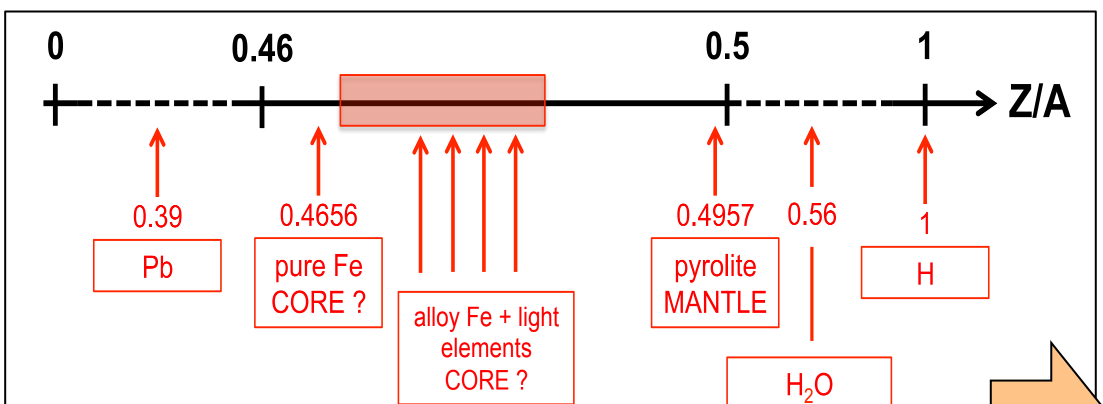
At low energies: oscillation tomography

Measured in neutrino oscillation patterns

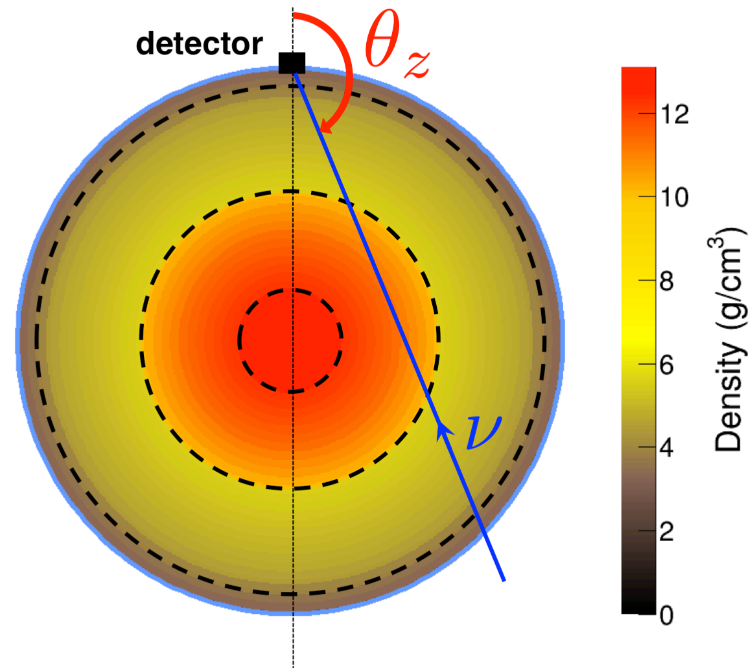
assume known matter density profile from PREM model

$$N_e = \frac{N_A}{m_n} \times \frac{Z}{A} \times \rho_{matter}$$

Constrain Z/A in core/mantle



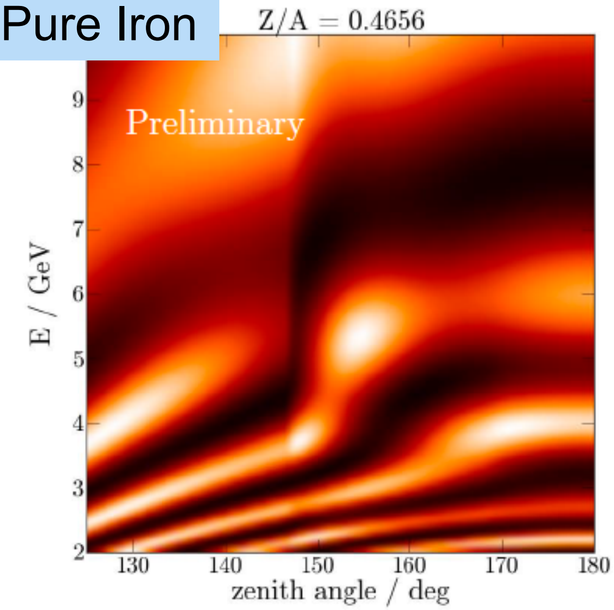
Typical values of Z/A for chemical elements or alloys present in the Earth



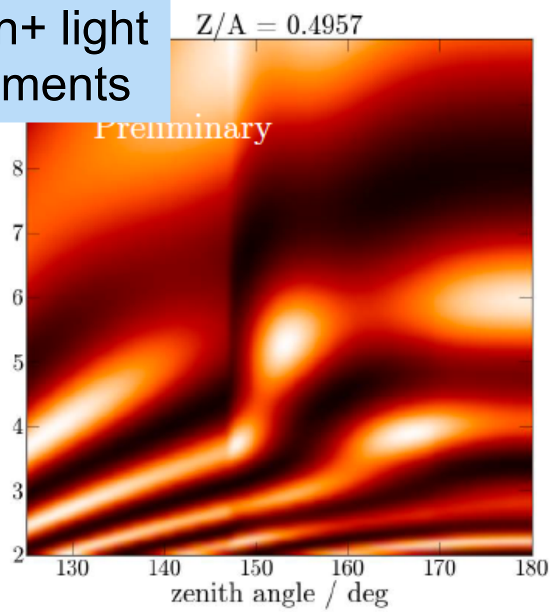
Oscillation tomography is sensitive to Earth composition

Example: outer core tomography (PINGU LoI 2014)

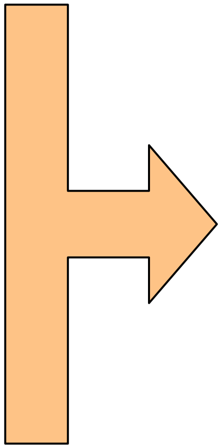
Pure Iron

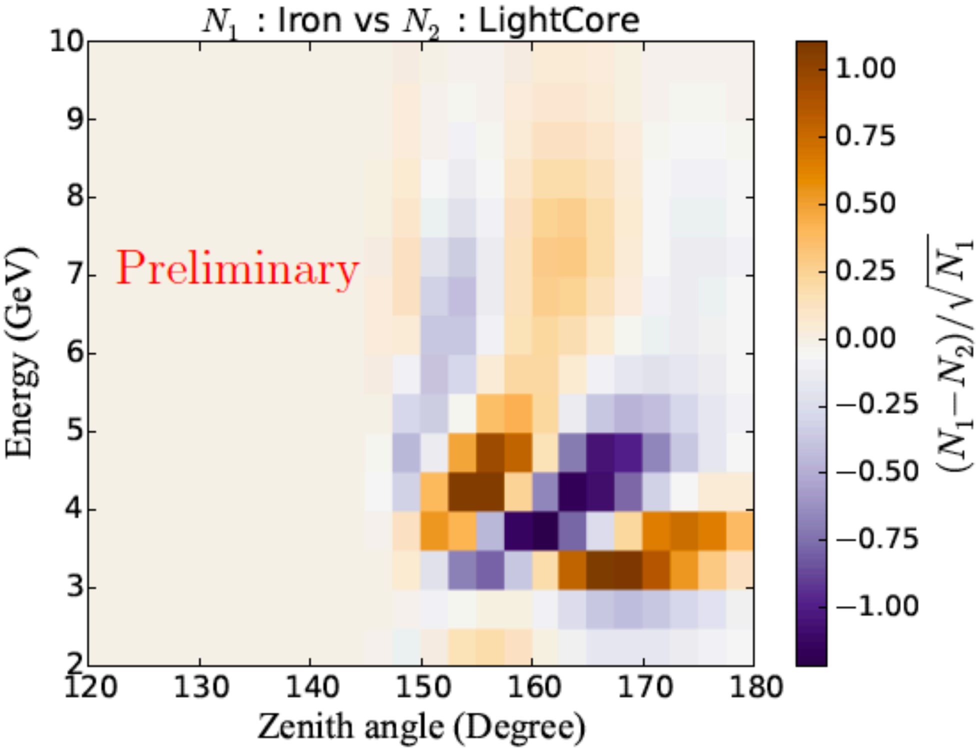


Iron+ light elements



- PINGU LoI detector (26 strings x 192 DOMs)
- ~4 Mton effective mass @ 2 – 6 GeV
- only up-going ν_μ CC events
- systematics included: oscillation param., atmospheric flux, detector energy scale
- fixed (pyrolitic) composition in mantle

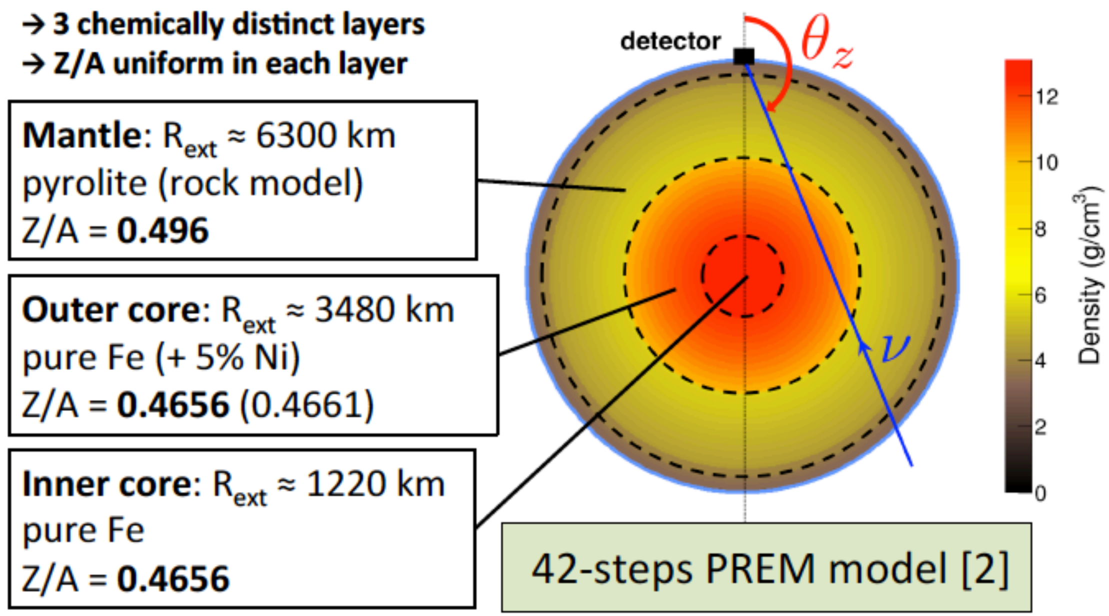


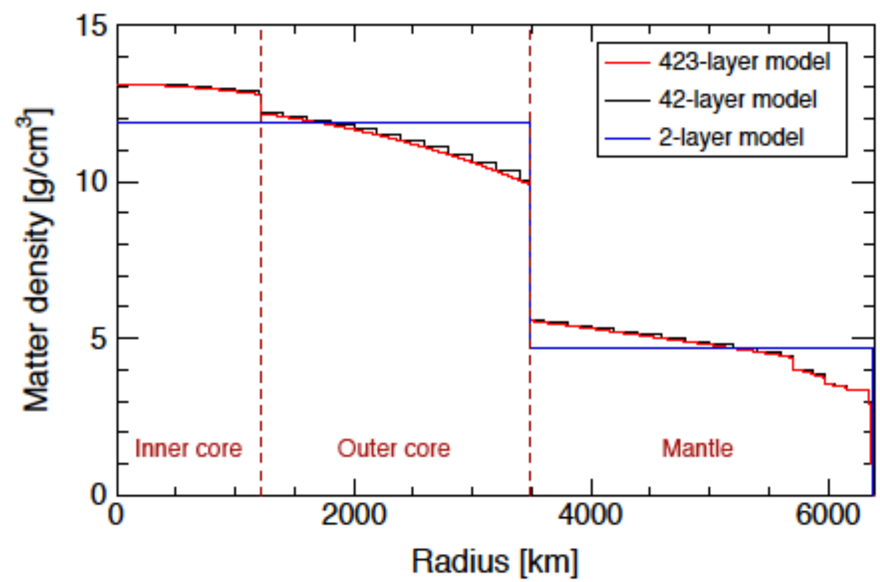


PINGU LoI, arXiv:1401.2046
See also C. Rott, A. Taketa and D. Bose, Sci.Rep. 5 (2015) 15225

ORCA: core & mantle tomography

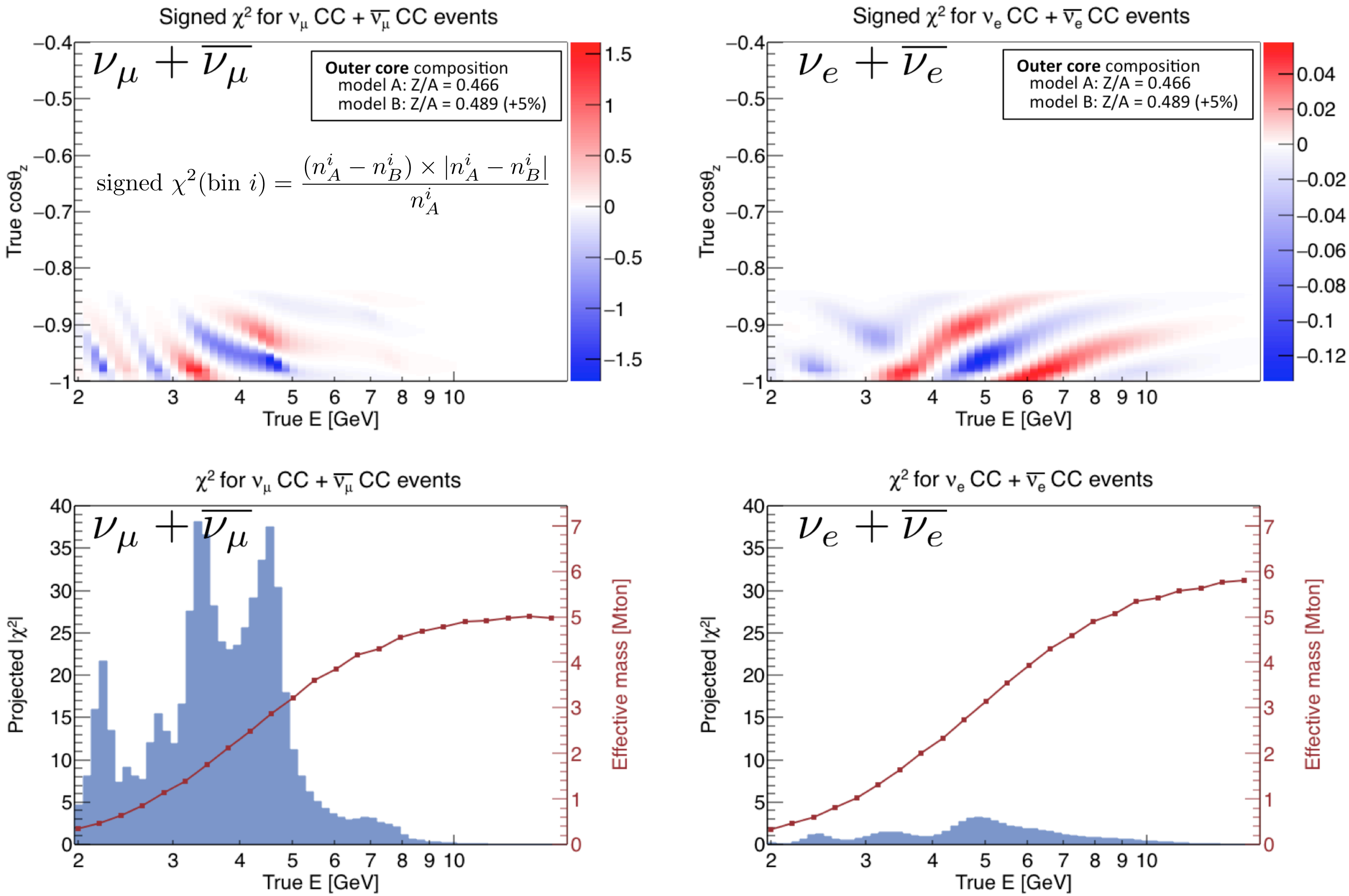
- ORCA layout:
115 lines x 18 DOMs
- 5,7 Mton effective volume
- Tracks & cascades; reconstruction/PID performances as in neutrino mass hierarchy studies
- Oscillation probabilities computed with OscProb (J. Coelho)
- Earth density profile: 42-steps PREM model
- 3 chemical layers
- Log-likelihood ratio analysis for outer core and mantle





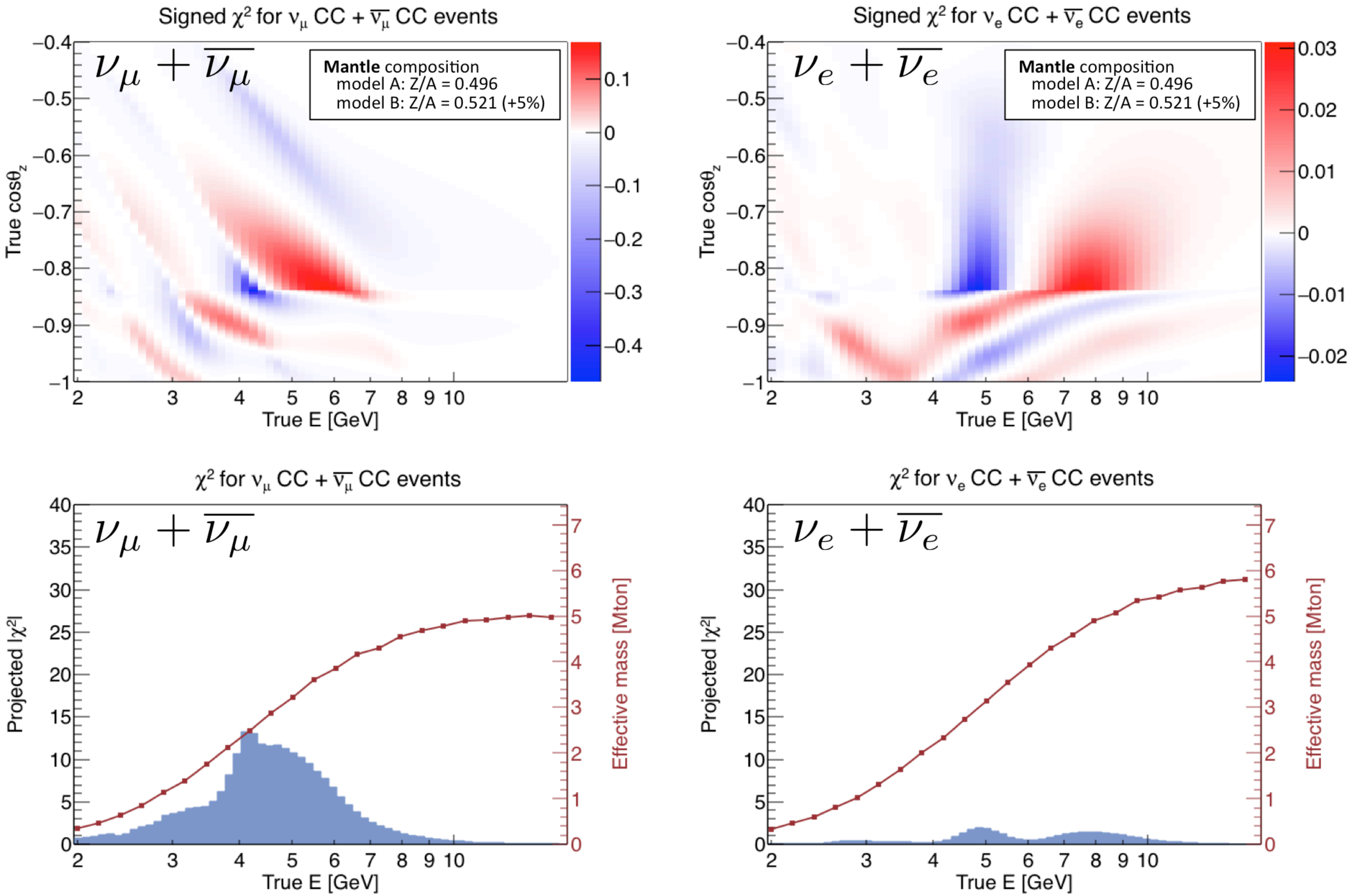
ORCA: outer core (interacting events)

Z/A varied by 5% in outer core only: ORCA 10 years, perfect detector



ORCA: mantle (interacting events)

Z/A varied by 5% in mantle only: ORCA 10 years, perfect detector



ORCA: detector response

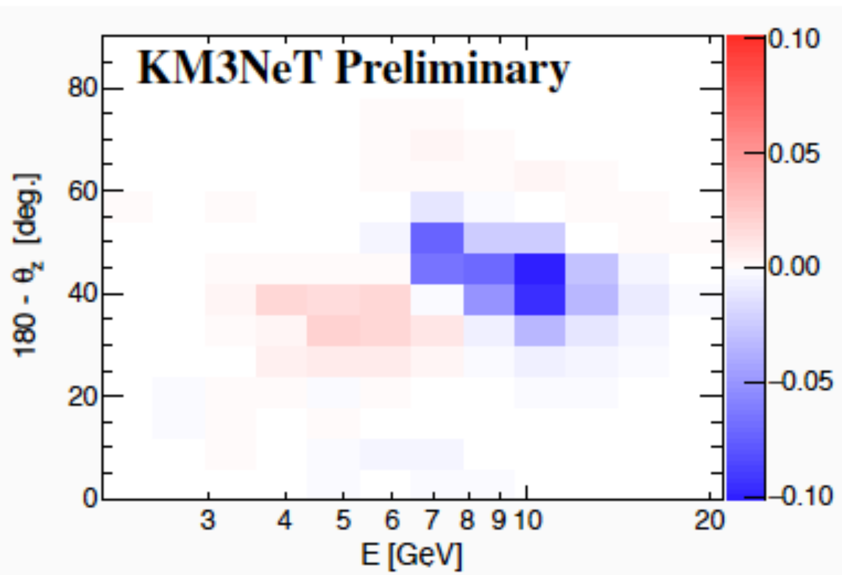
- Theoretical signal more visible in muon (track) channel
- Theoretical signal is higher for outer core, but concentrated in fast-oscillating patterns at low energy
- Detector effects described by response matrix from full MC simulations:

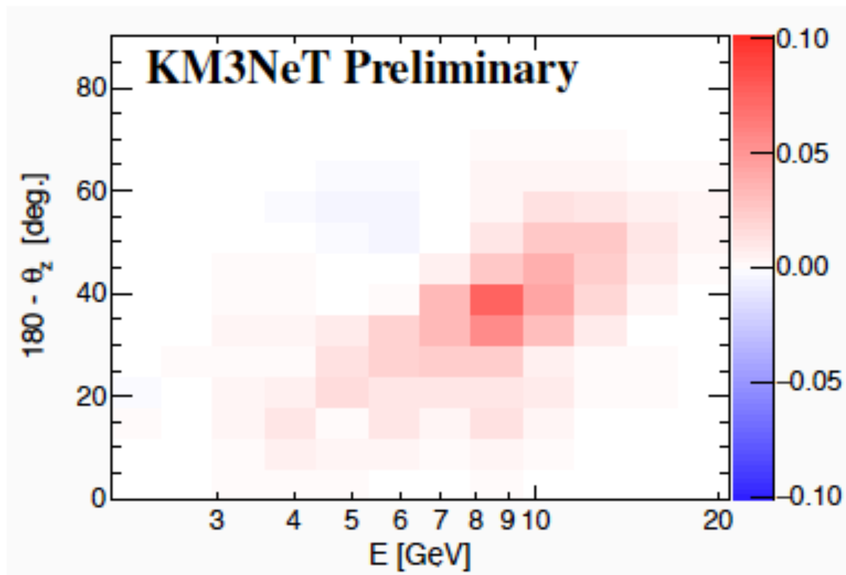
- True $(E, \cos\theta_z, Y_{\rm Bj})$
- True channel:
  $\rightarrow$ CC $\nu_e/\overline{\nu_e}$, $\nu_\mu/\overline{\nu_\mu}$, $\nu_\tau/\overline{\nu_\tau}$
  $\rightarrow$ NC $\nu/\overline{\nu}$

Reconstruction & Classification →

- Reco $(E, \cos\theta_z, Y_{\rm Bj})$
- Event classification ("flavour ID"):
  $\rightarrow$ Track / Cascade / $\mu_{\rm atm}$

- Both channels end up with comparable contributions to asymmetry:

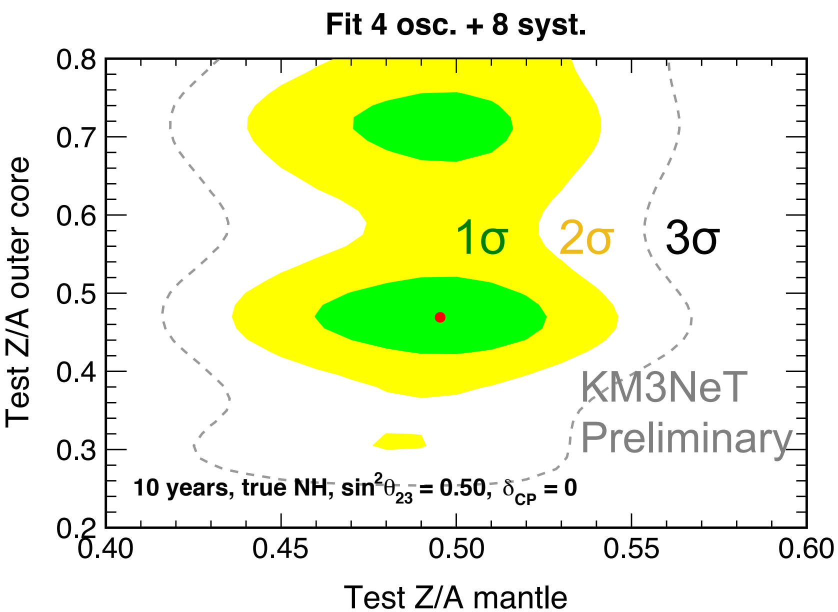


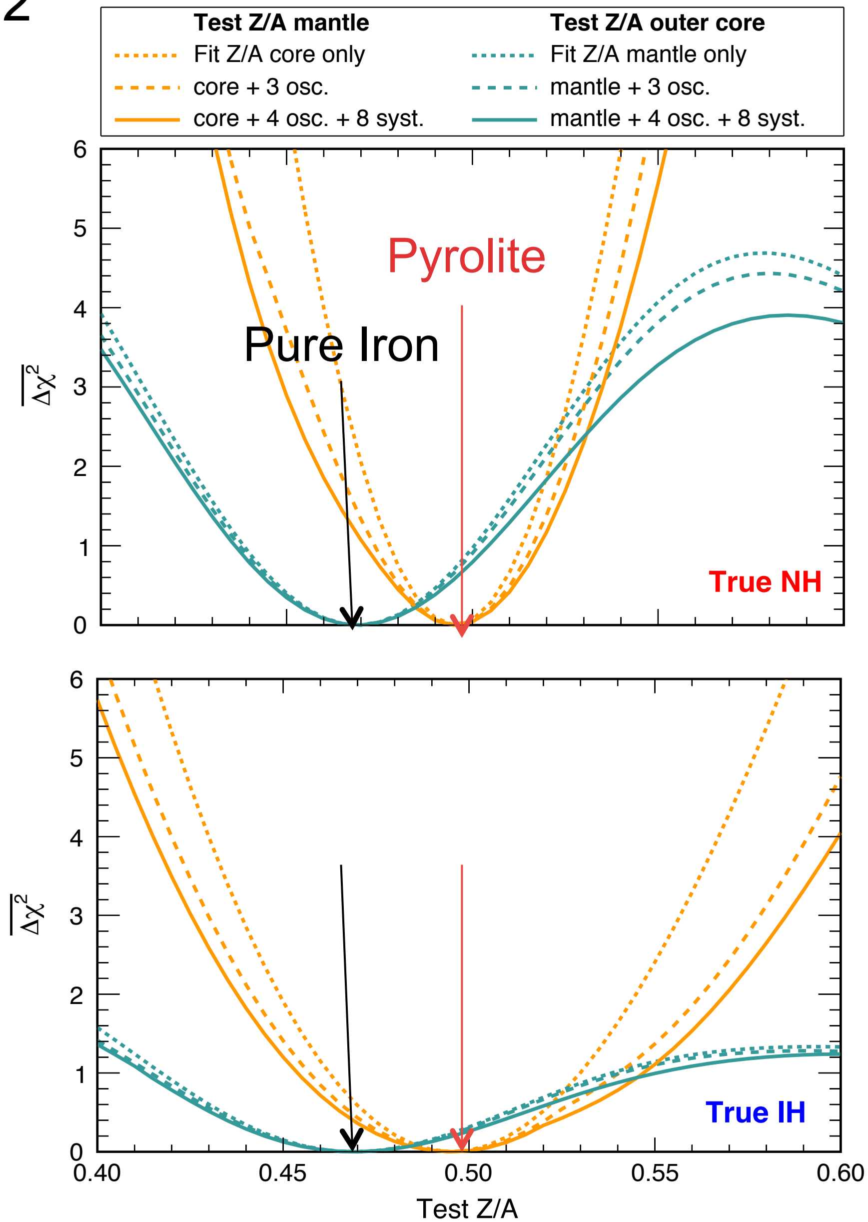


ORCA: latest results

- Oscillation parameters from NUFIT 3.2
  $\sin^2\theta_{23} = 0.5$; $\delta_{CP} = 0$
- Systematics treatment improved:
  - includes MC sparseness effect
  - flavour and polarity skews
  - channel-by-channel normalization
- Simultaneous fit of other layer

Combined measurement:





Perspectives for neutrino tomography

Novel methods to probe the Earth's with neutrinos:

❖ absorption tomography

→ inform on Earth matter density

→ needs large statistics of events at >10 TeV energies

→ main systematics: atmospheric neutrino flux, detector performance, crosssections

❖ oscillation tomography

→ inform on Earth composition (actually on ρ x Z/A)

→ needs large statistics of events at ~GeV energies:

… a case for Super-ORCA/Super-PINGU ?

→ main systematics: atmospheric neutrino flux, detector response

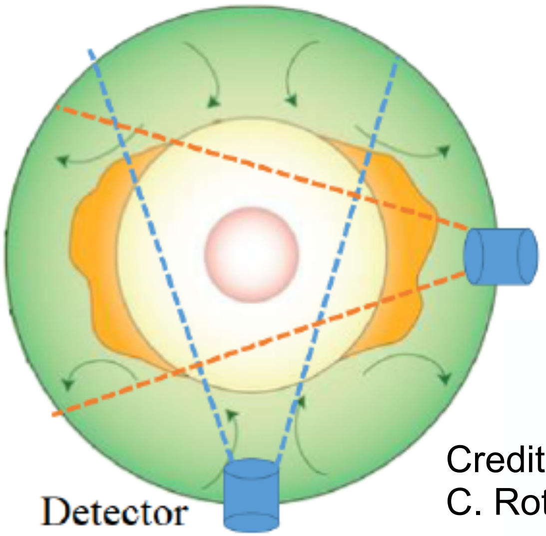
→ need to resolve first the neutrino mass hierarchy

+ better knowledge of oscillation parameters

+ Opportunity for combined measurements:
reconstruction of 3D density profiles

→Possibility to resolve large-scale inhomogeneities in the lower mantle:

IceCube + ARCA ?
Super-ORCA + Super-PINGU ?



Credits:
C. Rott

Backup slides

PINGU: outer core tomography (LoI 2014)

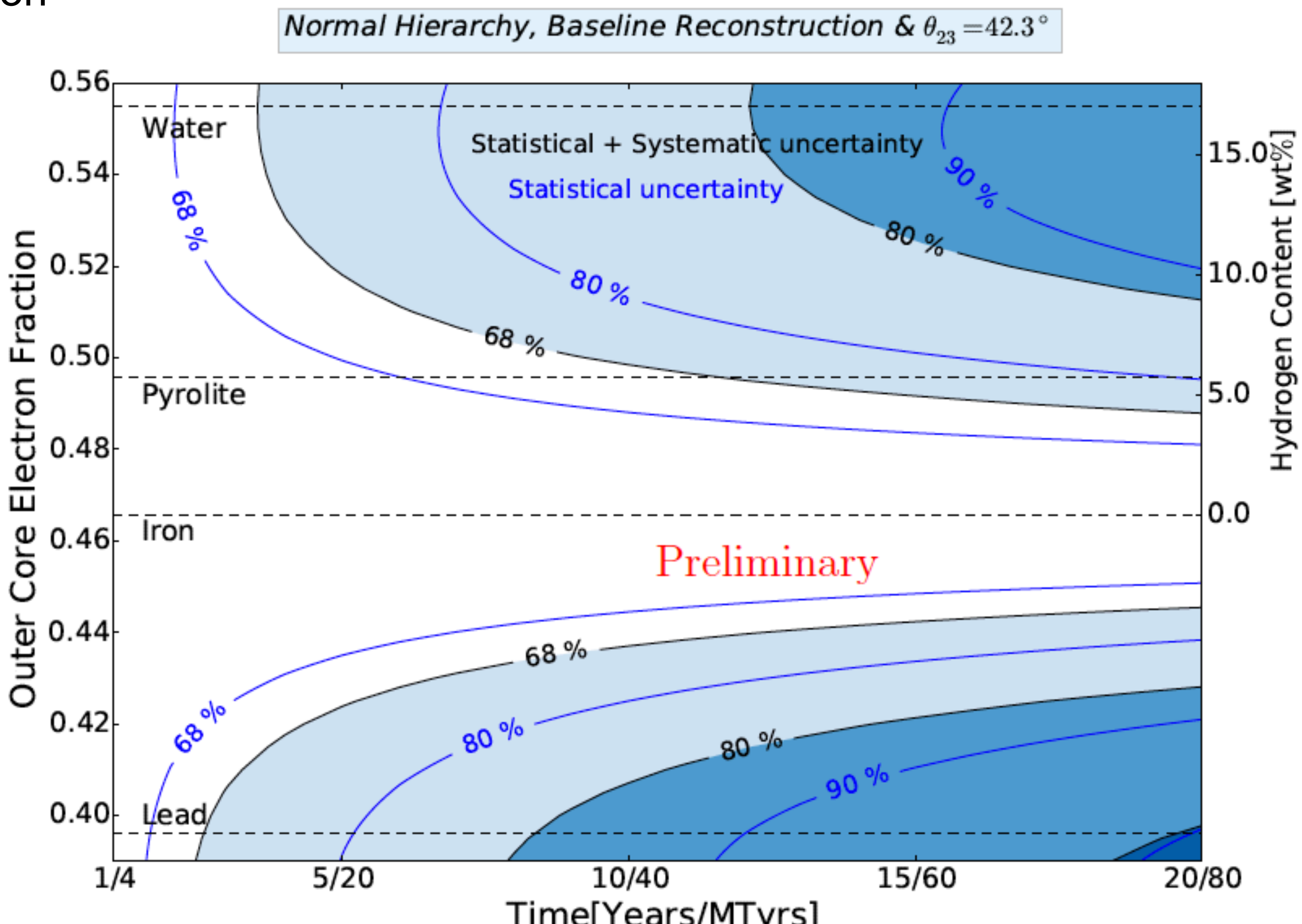
Log-likelihood ratio

$$\Delta\chi^2 = -2\ln\left[\frac{L(x|B)}{L(x|A)}\right]$$

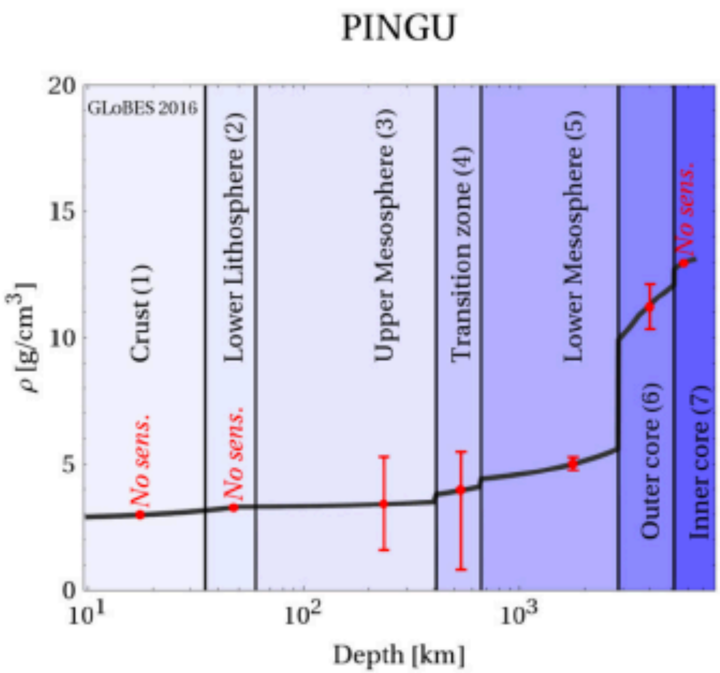
x = observed data

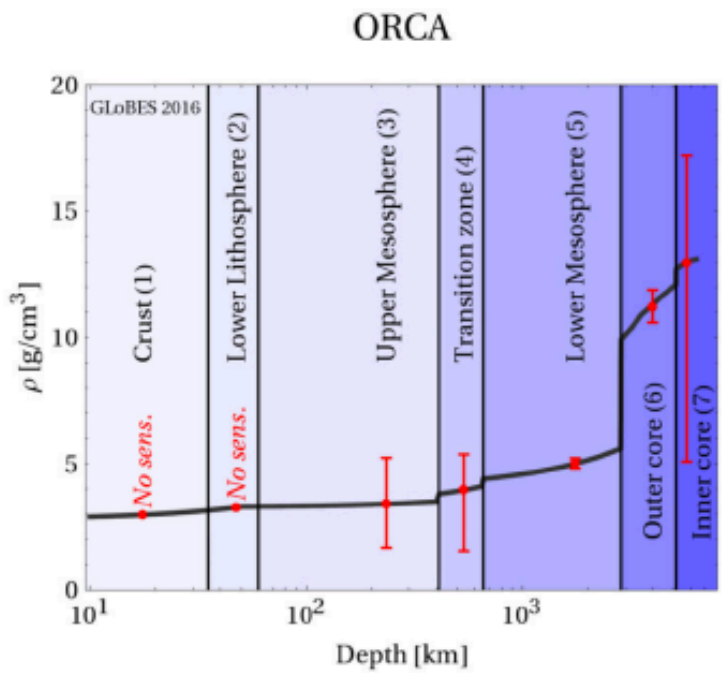
A,B = model hypotheses

Model A: pure Iron



Expected matter profile precision





(NO, 10 yr)

Layer	PINGU		ORCA	
	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.

Precision on ρ x Z/A in %

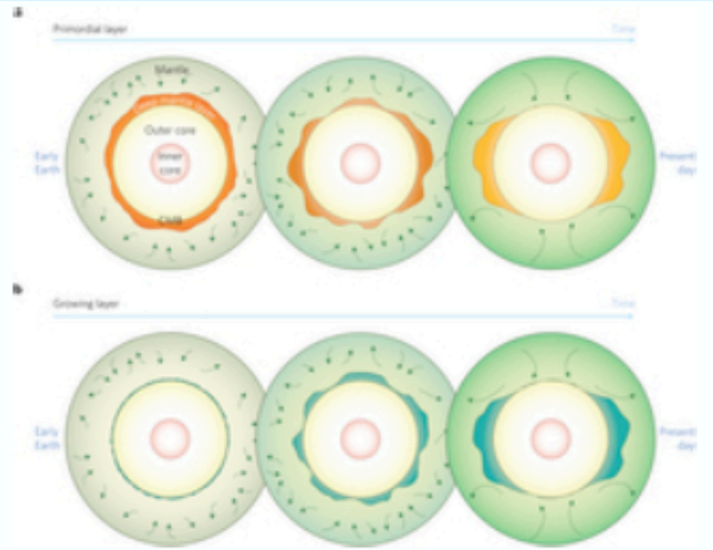
WW, special issue "Neutrino Oscillations: Celebrating the Nobel Prize in Physics 2015", Nucl. Phys. B908, 2016, 250

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

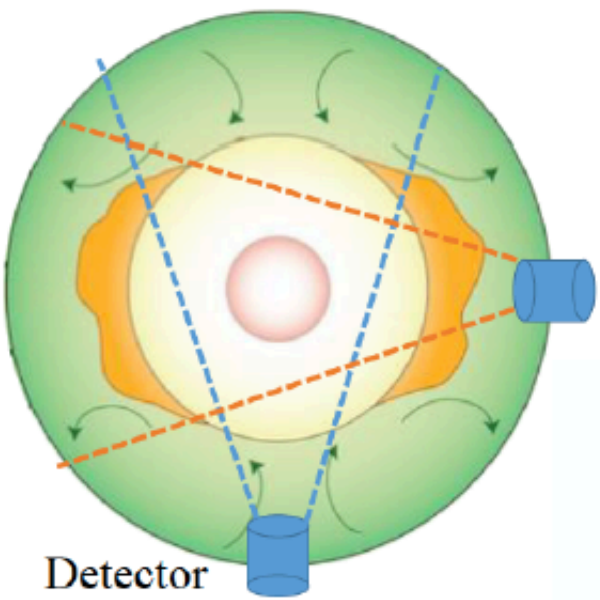
http://www.nature.com/ngeo/journal/v9/n7/pdf/ngeo2733.pdf

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

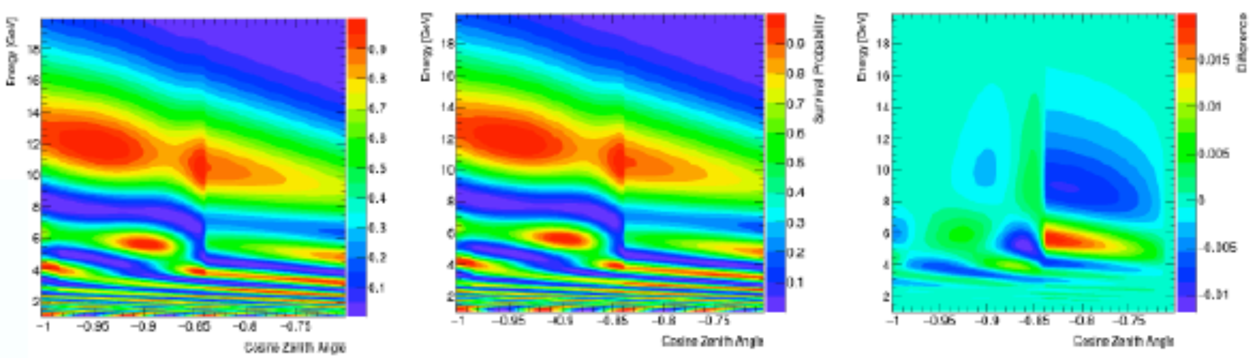


Anisotropic lower mantle



Muon neutrino survival probability

Z/A=0.4957 | Z/A=0.5007 | Difference



- Tomography with multiple detectors

parameter	*treatment*	*true value*	*prior*	1σ *width*
$\mathrm{sign}(\Delta m^2_{31})$	fix	NH or IH	–	–
$\lvert\Delta m^2_{31}\rvert_{NH}$ (eV^2)	fitted	$2.494\,10^{-3}$	no	–
$\lvert\Delta m^2_{31}\rvert_{IH}$ (eV^2)	fitted	$2.391\,10^{-3}$	no	–
Δm^2_{21} (eV^2)	fix	$7.40\,10^{-5}$	–	–
θ_{13} ($^\circ$)	fitted	8.54	yes	0.15
θ_{12} ($^\circ$)	fix	33.62	–	–
θ_{23} ($^\circ$)	fitted	45	no	–
δ_{CP} ($^\circ$)	fitted	0	no	–
Inner core Z/A	fix	0.466	–	–
Tracks normalization	fitted	1	no	–
Showers normalization	fitted	1	no	–
NC events normalization	fitted	1	yes	0.10
$\nu_e/\overline{\nu_e}$ flux ratio	fitted	0	yes	0.10
$\nu_\mu/\overline{\nu_\mu}$ flux ratio	fitted	0	yes	0.10
e/μ flavour flux ratio	fitted	0	yes	0.10
Energy slope	fitted	0	no	–
Zenith angle slope	fitted	0	no	–