Neutrino Oscillation Tomography of the Earth

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Contents

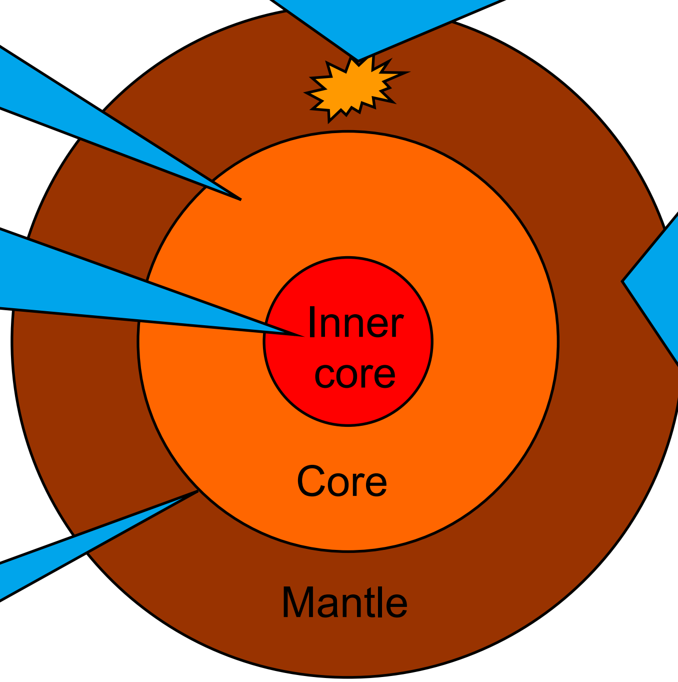
Earth's interior: What we know

Outer core: Liquid (as no seismic shear waves). Composition?

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

Seismic wave reflection/refraction

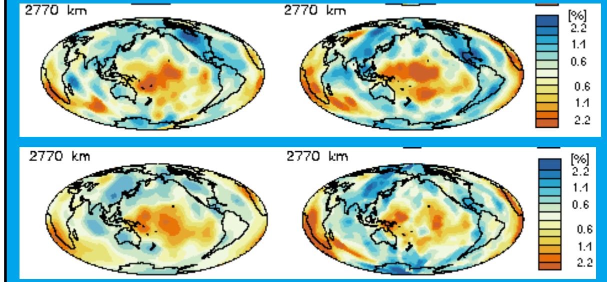
Zones with local anomalies in seismic wave velocities



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)

Density constrained by collective constraints from mass and moment of inertia

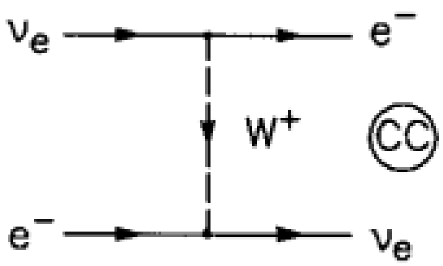
$$M = 2\pi \int r^2 \rho(r) dr, \qquad I = 2\pi \int (x^2 + y^2) r^2 \rho(r) dr$$

… and free oscillation modes at percent level

Neutrino tomography: Basic approches

Matter effects in neutrino oscillations

- Coherent forward scattering in matter leads to phase shift
- Net effect on electron flavor:

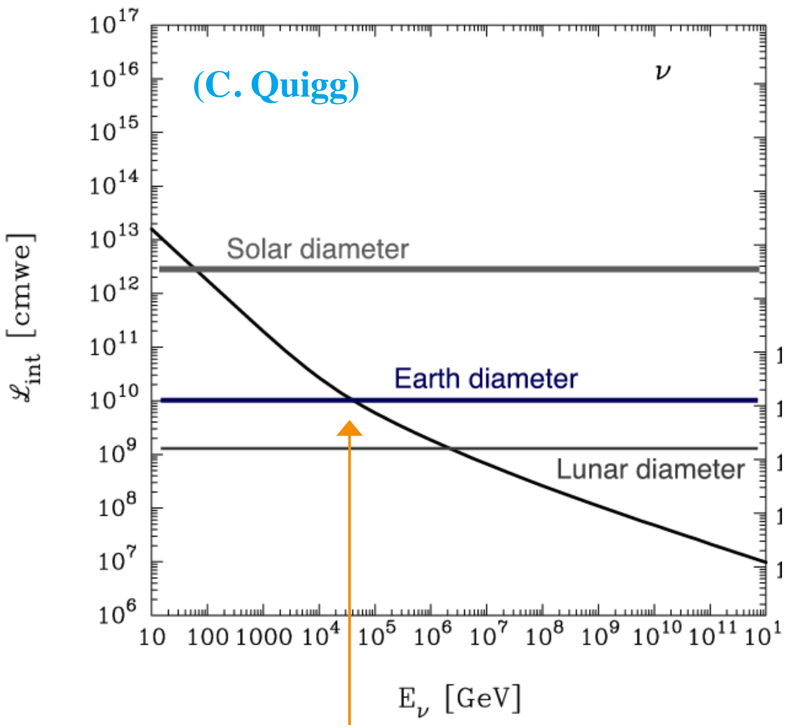


(Wolfenstein, 1978; Mikheyev, Smirnov, 1985)

(Earth matter does not contain muons and taus!)

- Evidence: Neutrino conversion in the Sun, solar day-night-effect,...
- Relevant energy in Earth matter ~ 2 - 10 GeV (later)

Neutrino absorption of energetic neutrinos

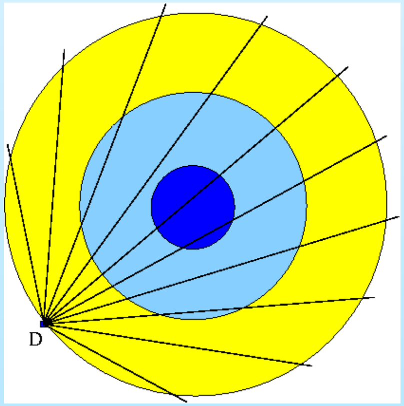
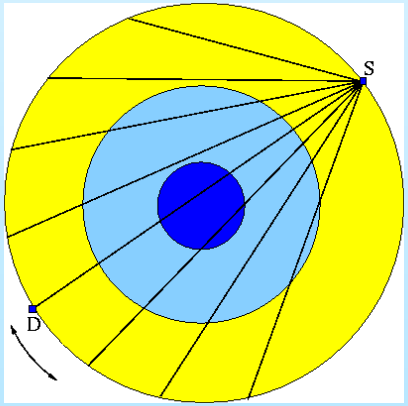
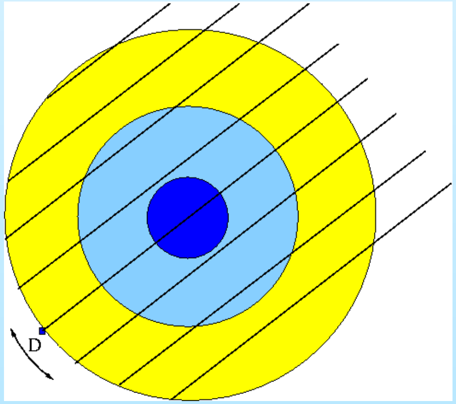


Relevant for E >> 10 TeV

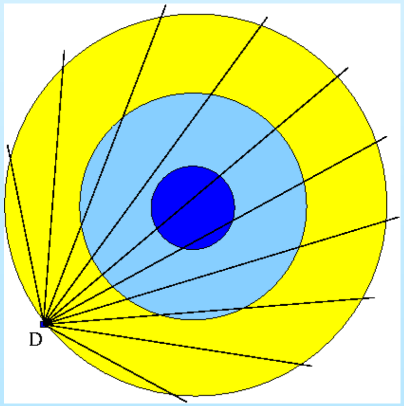
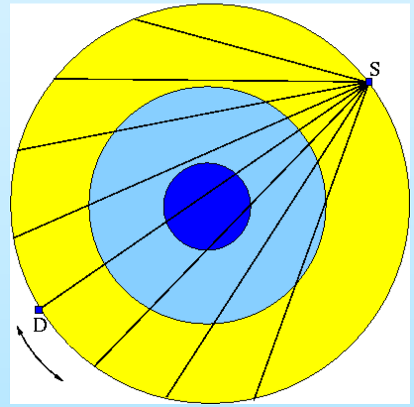
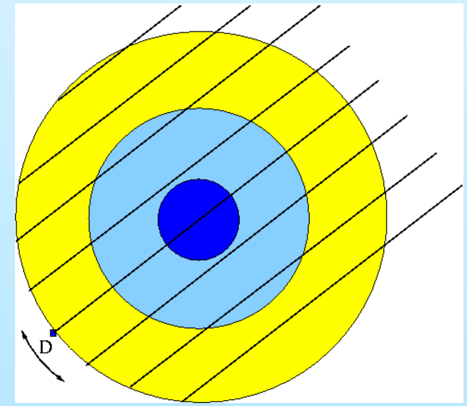
Example: Neutrino telescopes!

More in Donini's talk

Ideas using *absorption* tomography

	Isotropic flux (atmospheric, cosmic diffuse) 	TeV beam 	Astro point source 
+	Sources available, good directional resolution (ν_μ)	Potentially high precision	Earth rotation ➔ different baselines
-	**<u>Atmospheric neutrinos</u>:** low statistics at E>10 TeV <u>Diffuse cosmic flux:</u> unknown flux norm.	Build and safely operate a **moving** TeV neutrino beam (need FCC-scale accelerator)	Very low statistics
Refs.	**Jain, Ralston, Frichter, 1999; Reynoso, Sampayo, 2004; Gonazales-Garcia, Halzen, Maltoni, Tanaka, 2005+2008; Donini et al, 2018**	**De Rujula, Glashow, Wilson, Charpak, 1983; Askar`yan, 1984; Borisov, Dolgoshein, Kalinovskii, 1986; …**	**Wilson, 1984; Kuo, Crawford, Jeanloz, Romanowicz, Shapiro, Stevenson, 1994; …**

Ideas using *oscillation* tomography

	Isotropic flux (atmospheric, diffuse cosmic?)	Neutrino beam	Astro point source (supernova, Sun)
			
+	Sources available, atmospheric ν just right	Potentially high precision	Earth rotation ➔different baselines
-	Directional resolution at GeV energies (atm. ν)	Moving decay tunnel+ detector? Also discussed for existing experiments.	Supernovae rare Solar neutrinos have somewhat too low E
Refs.	**Rott, Taketa, Bose, 2015; Winter, 2016; Bourret, Coelho, van Elewyck, 2017; …**	**Ohlsson, Winter, 2002; Winter, 2005; Gandhi, Winter, 2007; Arguelles, Bustamante, Gago, 2015; Asaka et al, 2018; Kelly, Parke, 2018; ...**	**Lindner, Ohlsson, Tomas, Winter, 2003; Akhmedov, Tortola, Valle, 2005; …**

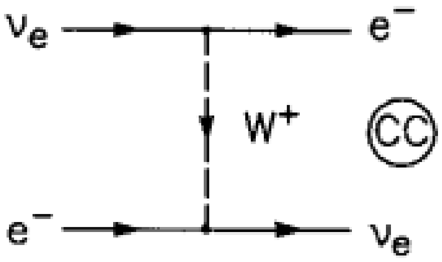
How does it work?
Recap: Neutrino oscillations in matter

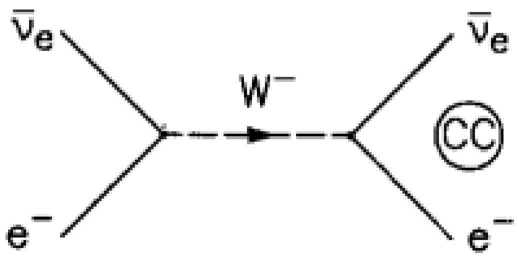
(Neutrino oscillation tomography)

Matter effect (MSW effect)

- Ordinary matter:
  electrons, but no μ, τ
- Coherent forward scattering in matter:
  Net effect on electron flavor
- Hamiltonian in matter
  (matrix form, flavor space):

(Wolfenstein, 1978; Mikheyev, Smirnov, 1985)





$$\mathcal{H}(n_e) = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} V(n_e) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$V_\nu = +\sqrt{2} G_F n_e, \; V_{\bar{\nu}} = -\sqrt{2} G_F n_e, \; n_e = Y \rho_j / m_N$$

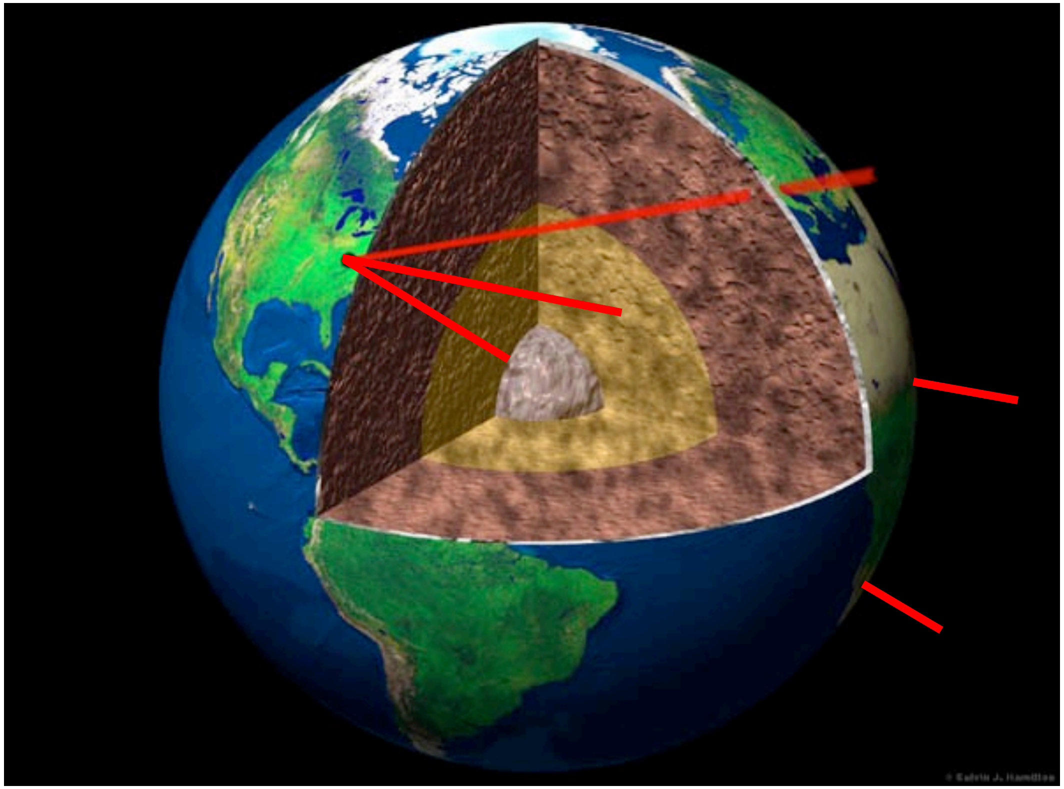
Y: electron fraction Z/A ~ 0.5

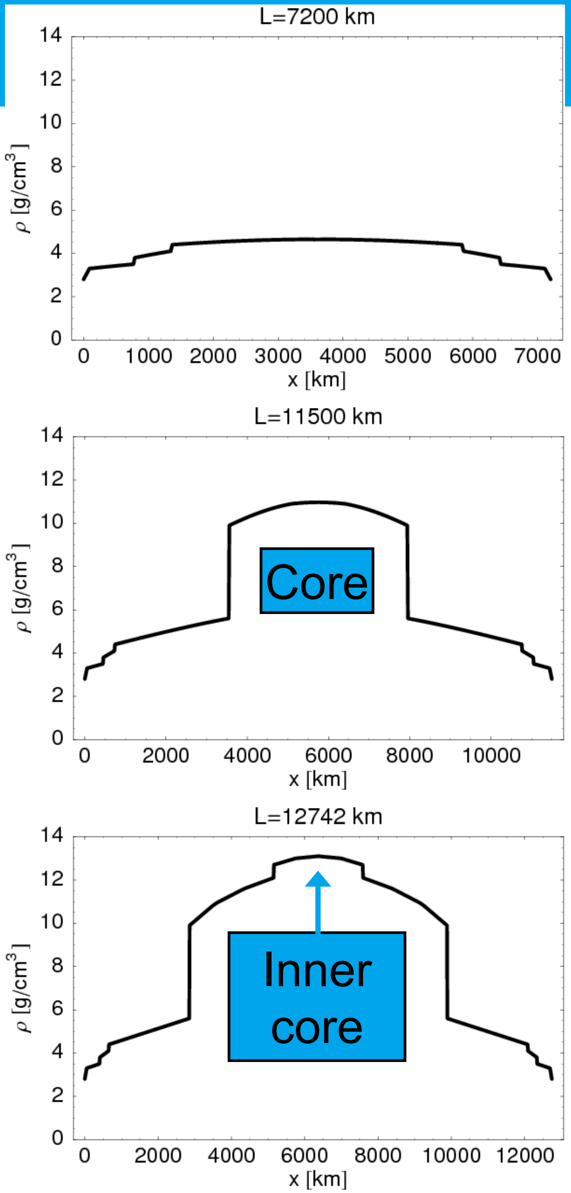
(electrons per nucleon)

Matter density and composition are degenerate!

Matter profile of the Earth

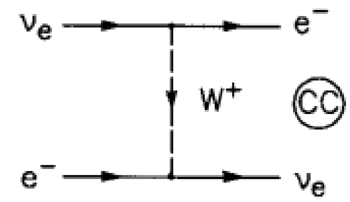
… as seen by a neutrino





(PREM: Preliminary Reference Earth Model)

Parameter mapping ... for two flavors, constant matter density



(Wolfenstein, 1978; Mikheyev, Smirnov, 1985)

- Oscillation probabilities in

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

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

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

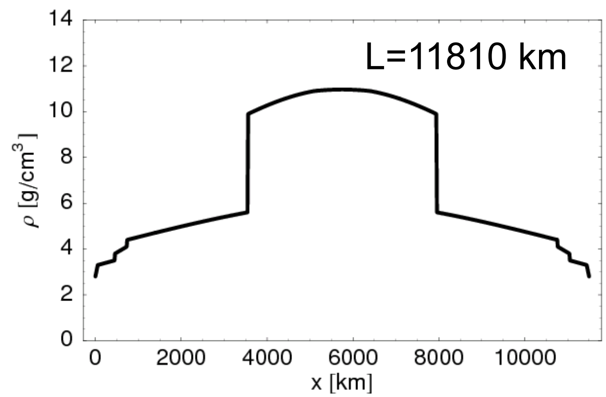
$$\xi \equiv \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \hat{A}\right)^2},$$

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

⇨ **MO**

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

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

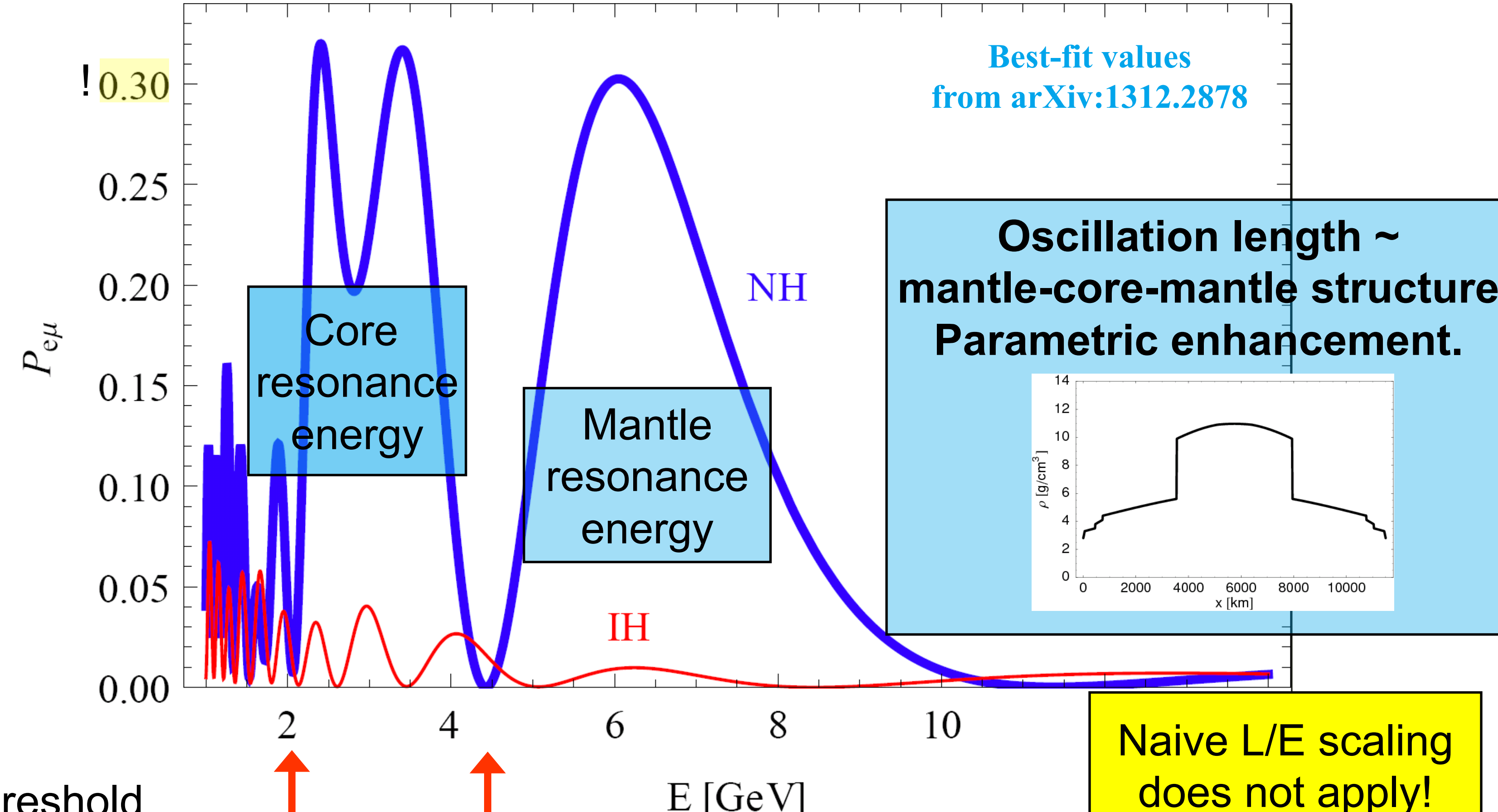


For ν_μ appearance, Δm_{31}^2:
- ρ ~ 4.7 g/cm^3 (Earth's mantle): **E_{res} ~ 6.4 GeV**
- ρ ~ 10.8 g/cm^3 (Earth's outer core): **E_{res} ~ 2.8 GeV**

Mantle-core-mantle profile

(Parametric enhancement: Akhmedov, 1998; Akhmedov, Lipari, Smirnov, 1998; Petcov, 1998)

- Probability for L=11810 km



Naive L/E scaling does not apply!

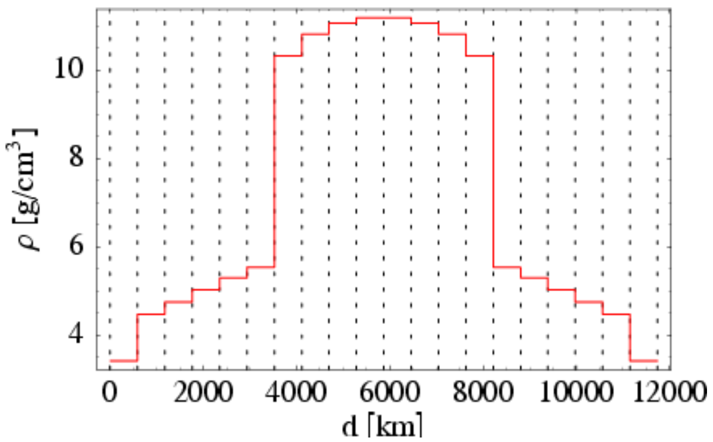
Threshold effects expected at: 2 GeV 4-5 GeV

Neutrino oscillations with varying profiles, numerically

- Evolution operator method:

$$\mathcal{V}(x_j, n_j) = e^{-i\mathcal{H}(n_j)x_j}$$

H(n_j): Hamilton operator in constant electron density n_j



- Matter density from $n_j = Y\, \rho_j/m_N$, Y: electrons per nucleon (~0.5)
- Probability:

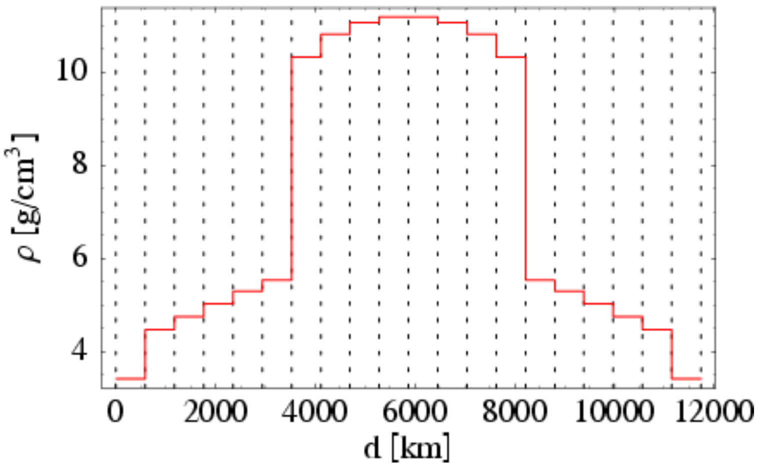
$$P_{\alpha\beta} = \left| \langle \nu_\beta | \mathcal{V}(x_m, n_m) \ldots \mathcal{V}(x_1, n_1) | \nu_\alpha \rangle \right|^2$$

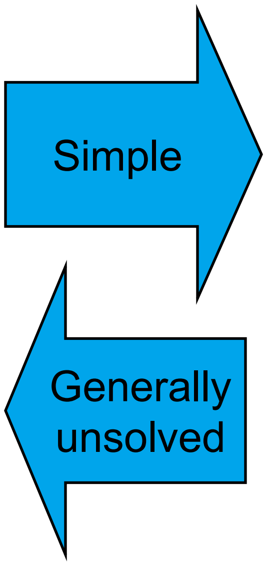
- NB: There is additional information through *interference* compared to absorption tomography because

$$[\mathcal{V}(x_i, n_i), \mathcal{V}(x_j, n_j)] \neq 0 \quad \text{for} \quad n_i \neq n_j$$

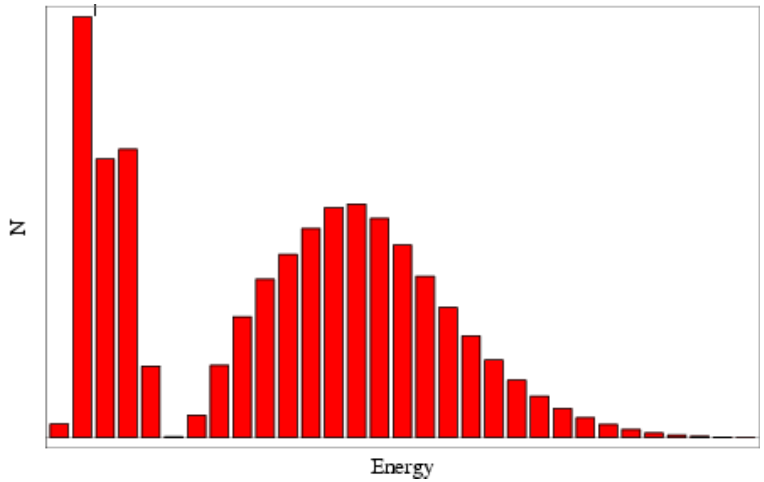
Matter profile inversion problem

Matter profile





Observation

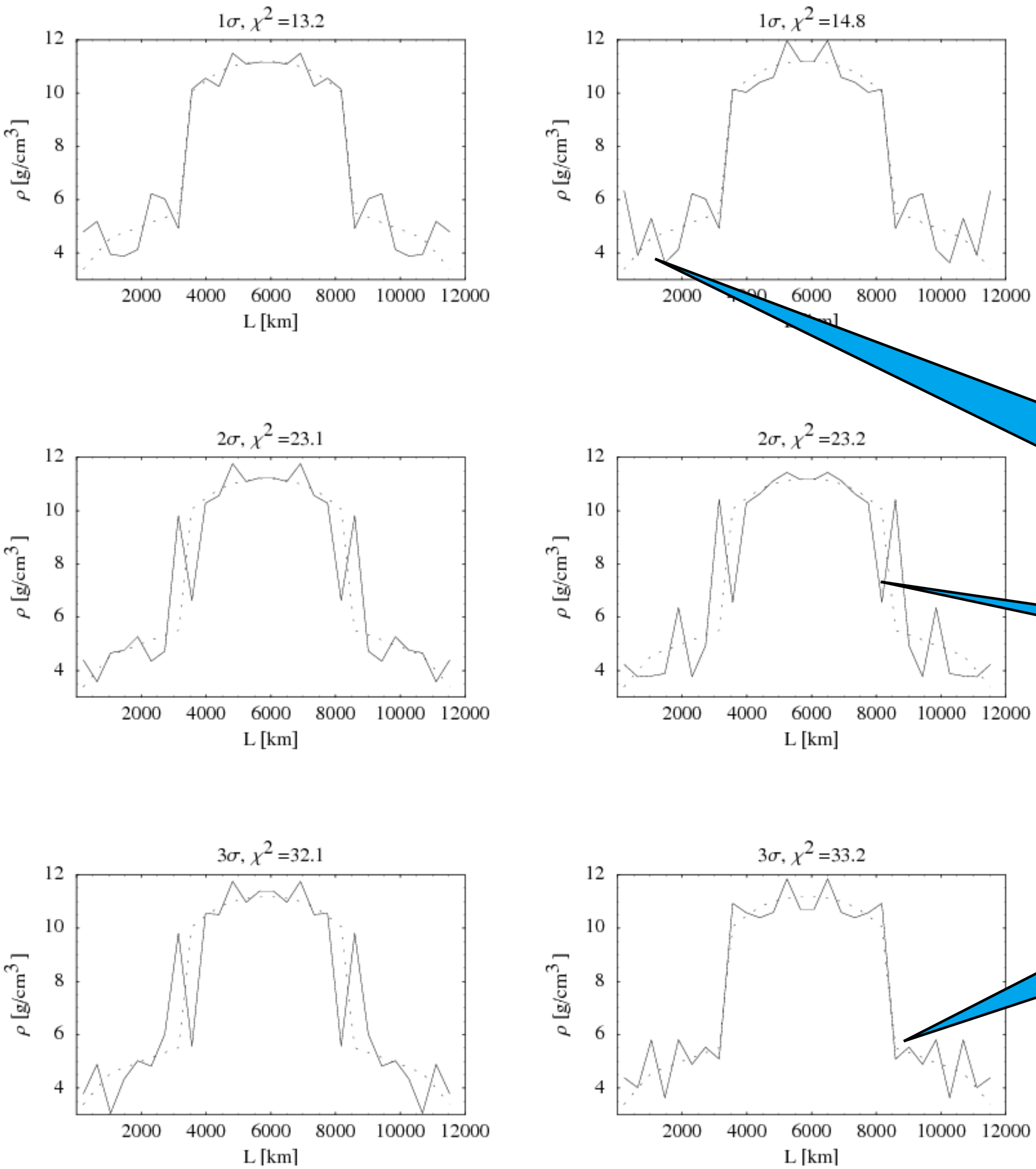


(Ermilova, Tsarev, Chechin, 1988)

<u>Some approaches/directions for direct inversion:</u>

- Simple models, such as one zone (cavity) with density contrast
  Nicolaidis, 1988; Ohlsson, Winter, 2002; Arguelles, Bustamante, Gago, 2015
- Linearization for low densities Akhmedov, Tortola, Valle, 2005
- Use non-deterministic methods to reconstruct profile, e.g. genetic algorithm Ohlsson, Winter, 2001
- Expansion in terms of Fourier modes/perturbation theory
  Ota, Sato, 2001; Akhmedov, Tortola, Valle, 2005; Asaka et al, 2018; ...

Example: structural resolution with a single baseline (11750 km)



Some characteristic examples close to 1σ, 2σ, 3σ (14 d.o.f.)

Can reconstruct mantle-core-mantle profile

Fluctuations on short scales (<< L^{osc}) cannot be resolved

Cannot localize mantle-core-boundary

Cannot resolve very small density contrasts

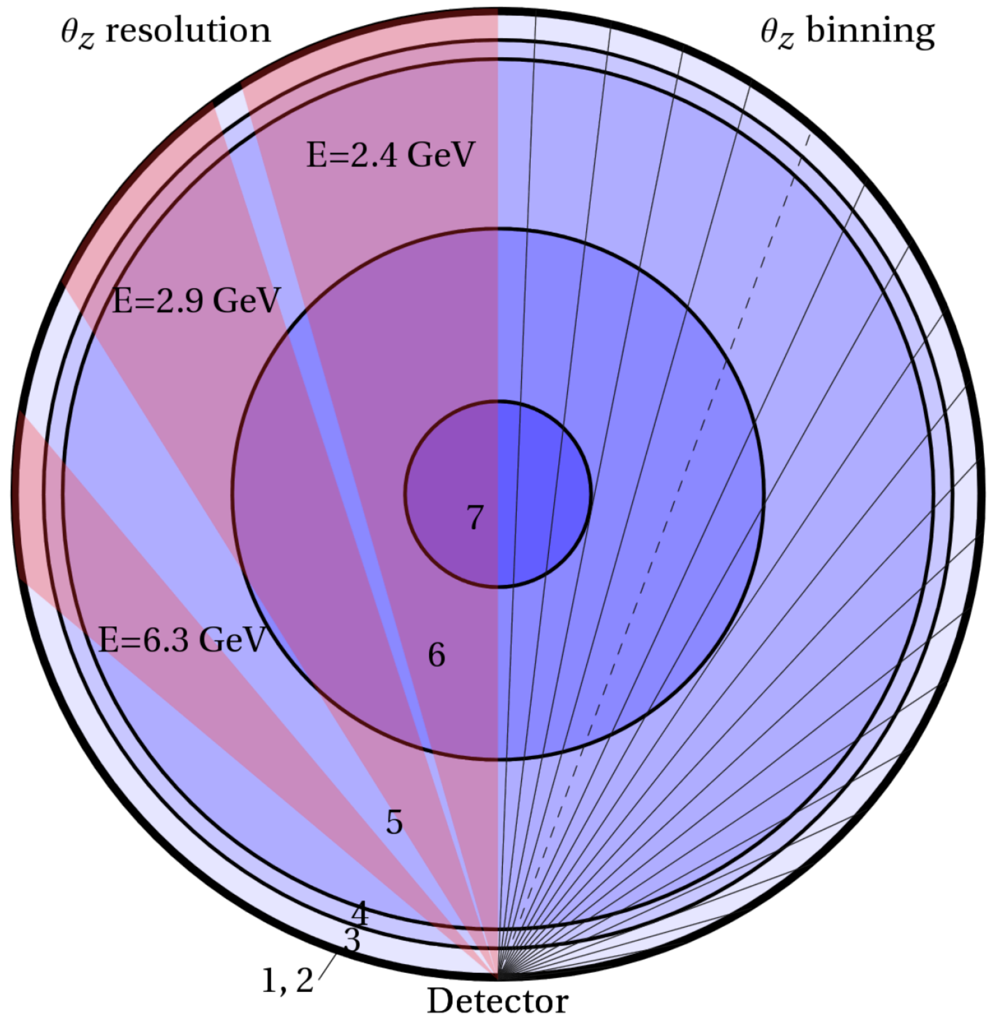
Ohlsson, Winter, Phys. Lett. B512 (2001) 357

Neutrino oscillation tomography of Earth: Towards realistic applications

Neutrino oscillation tomography using atmospheric νs

- Need very large number of neutrinos in relevant energy range
- **Point towards Mt-sized detector using atmospheric neutrinos**
- For atmospheric *oscillation* tomography, the big plus is statistics, the critical issue the directional resolution →
- Use binning in θ_z (instead of cos θ_z) to be sensitive to inner core

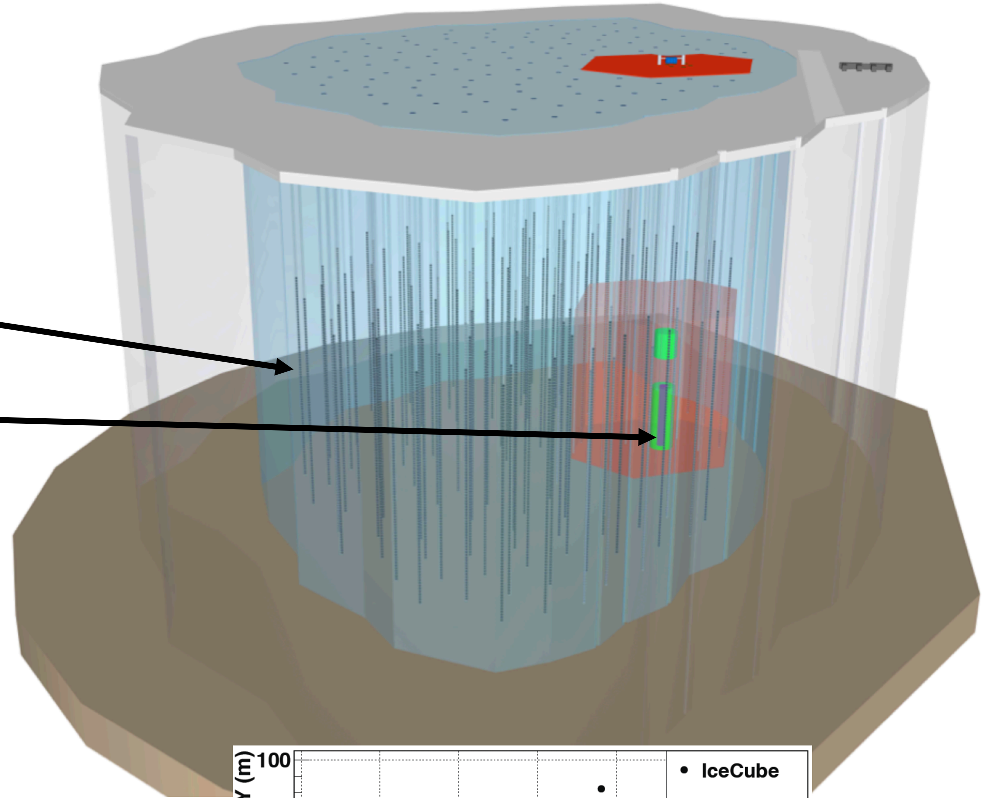
(ORCA)

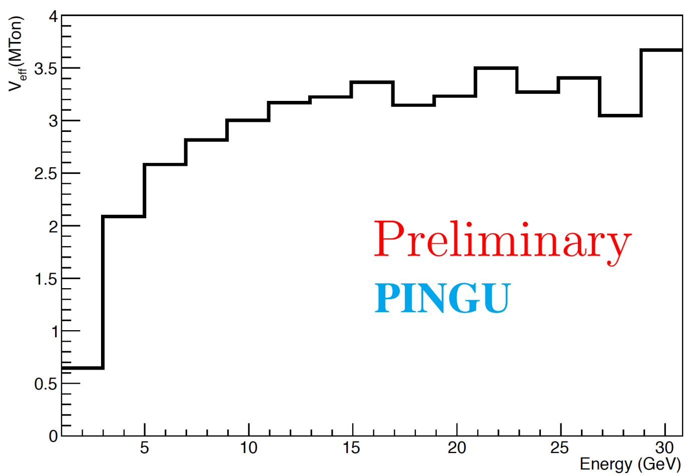


WW, Nucl. Phys. B908, 2016, 250

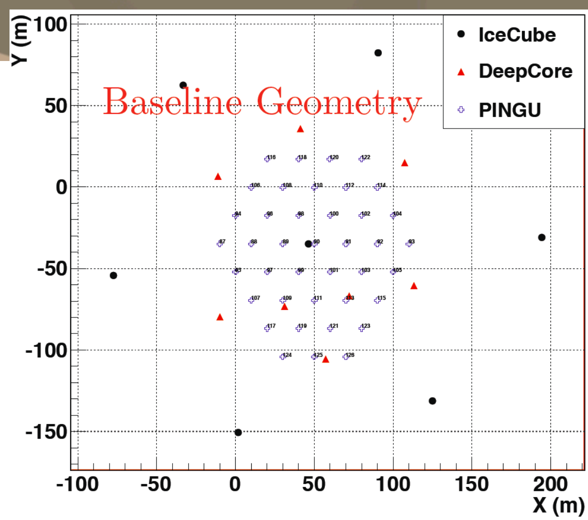
Emerging technologies: mass ordering with atm. neutrinos

- Plans for upgrade of IceCube experiment (South Pole)
- Volume upgrade (cosmic neutrinos) and density upgrade (mass ordering): PINGU



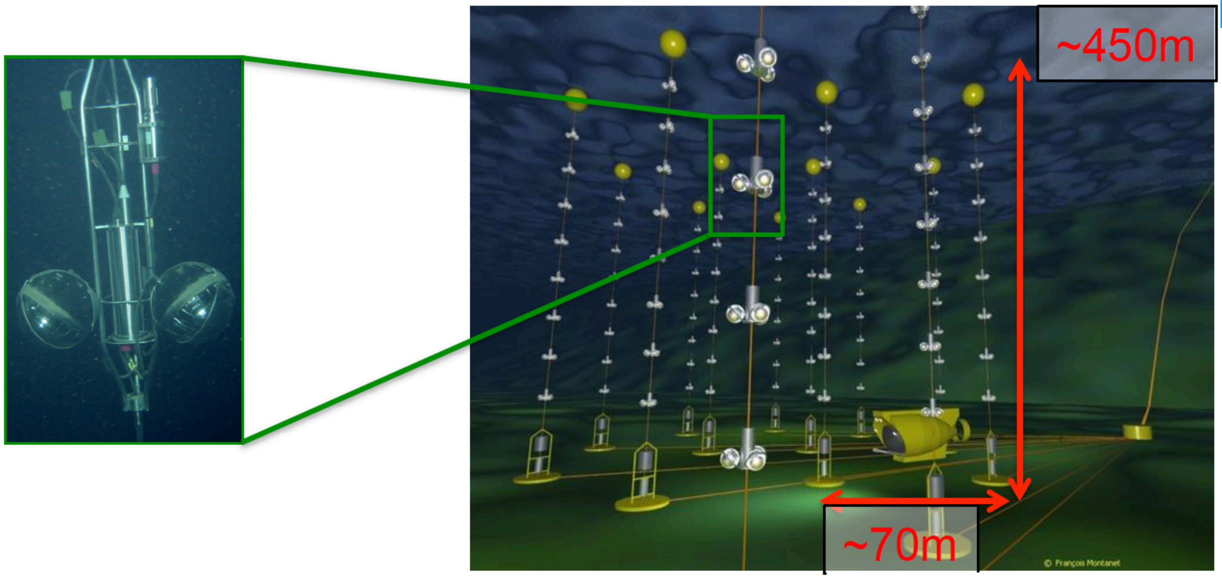


(a) $V_{eff}(\nu_\mu)$

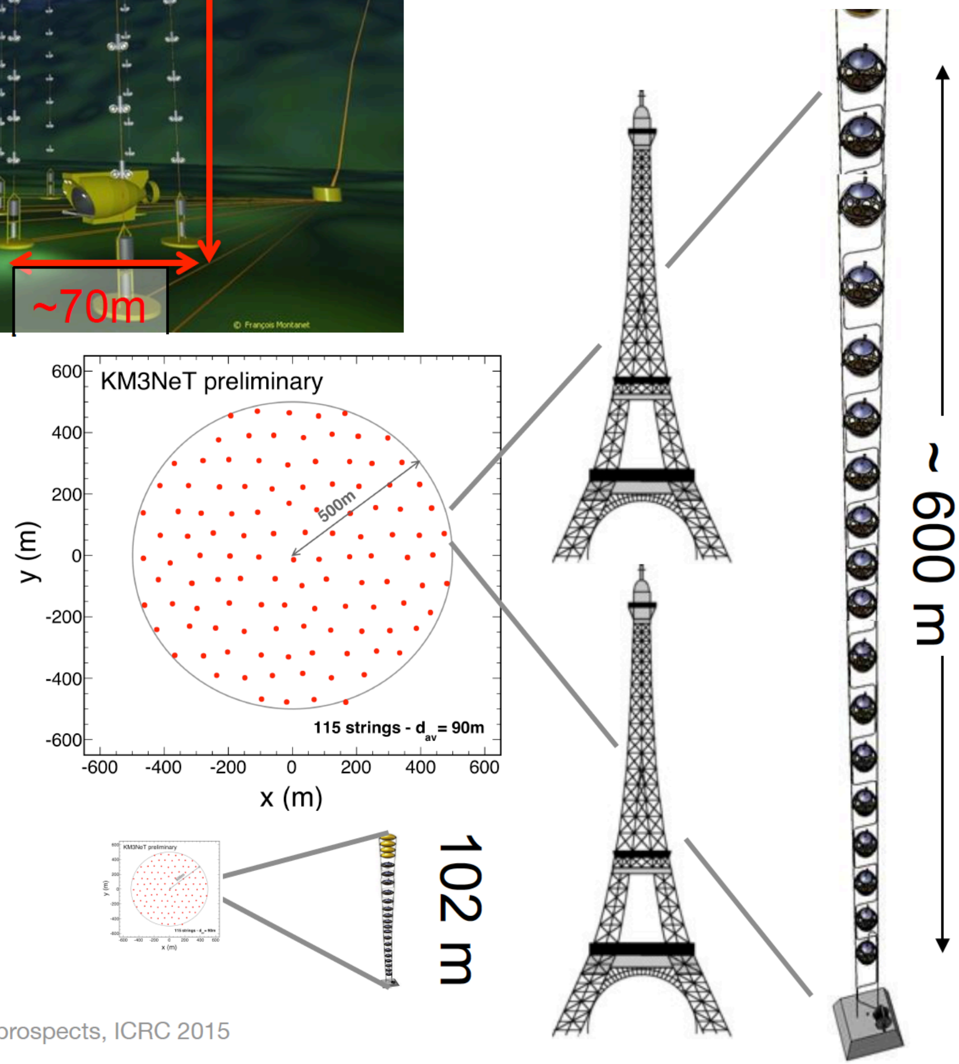


(arXiv:1401.2046, arXiv:1412.5106; arXiv:1601.07459)

ARCA/ORCA: volume/density upgrades of ANTARES



- KM3NeT ARCA/ORCA: similar ideas in sea water
- Different properties of detection medium; potentially better directional/energy resolutions?

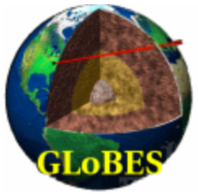


prospects, ICRC 2015

(C. W. James, ICRC 2015)

A self-consistent approach to Earth tomography

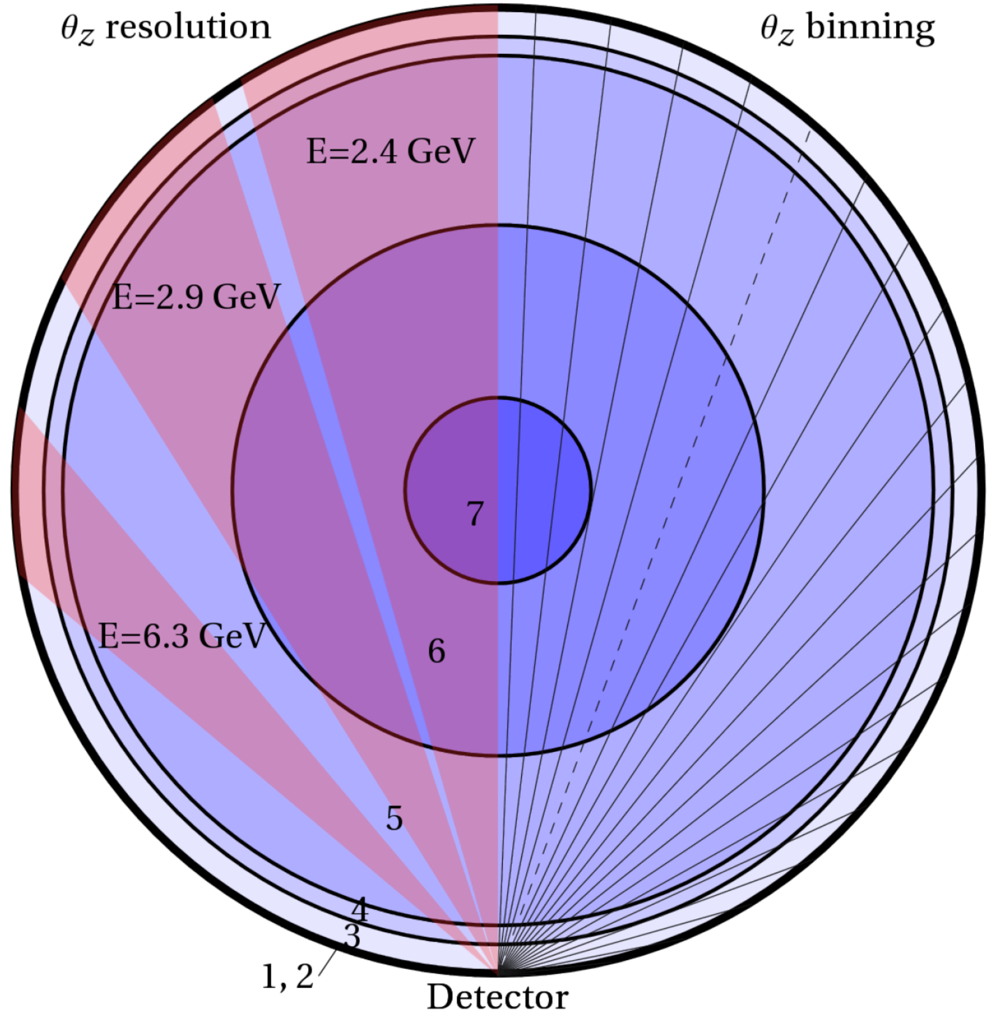
- Layers inspired by REM model: where highest sensitivity?
- Self-consistent simulation of mass ordering sensitivity and matter profile sensitivity with GLoBES



- Projection on parameter of relevance (marginalization)

Crust (1)
Lower Lithosphere (2)
Upper Mesosphere (3)
Transition zone (4)
Lower Mesosphere (5)
Outer core (6)
Inner core (7)

(allows for inner core res.)



WW, Nucl. Phys. B908, 2016, 250

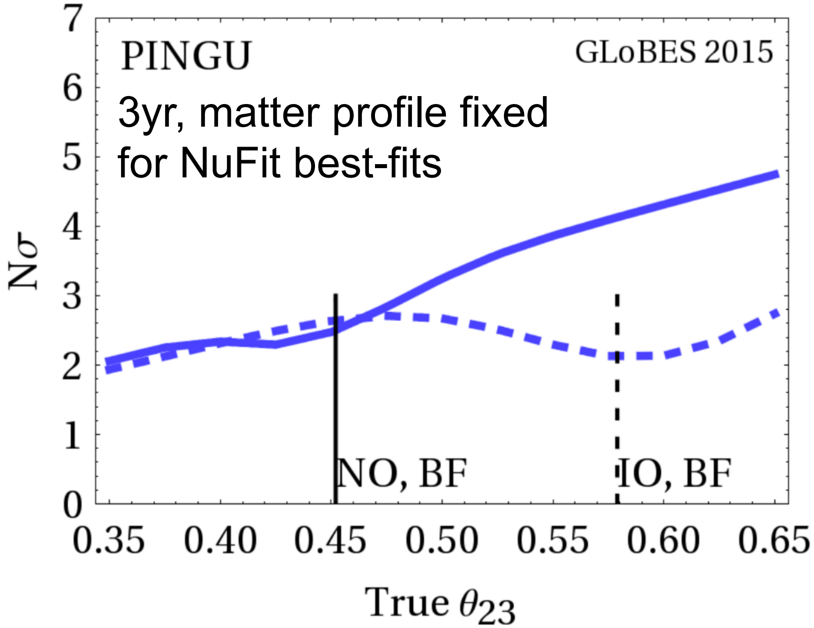
Implementation and systematics treatment

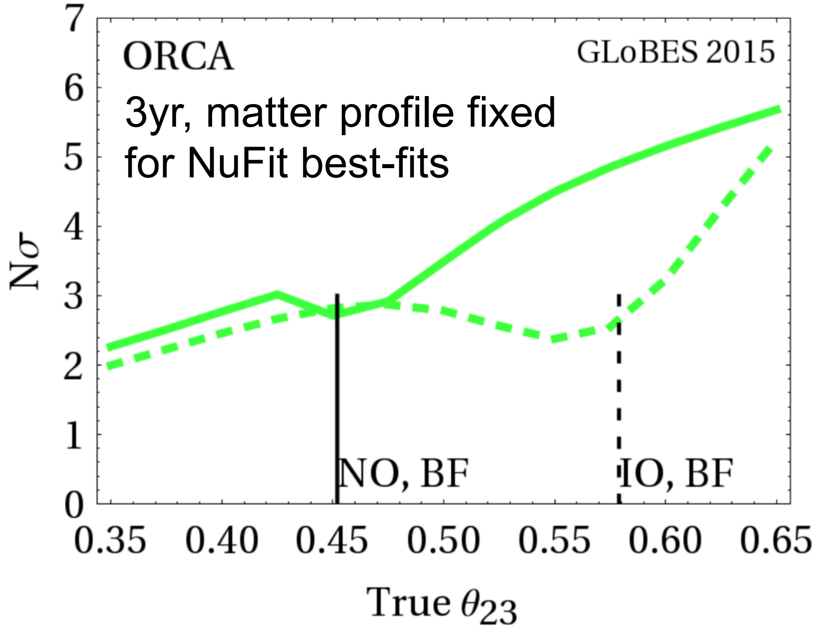
- Include syst. (12), correlations among matter layers (7) and oscillation parameters (6)
- Systematics fully correlated in oscillation analysis, but uncorrelated among atmospheric priors
- Energies up to 100 GeV and down-going events (PINGU only, atm. muon veto assumed) included to control systematics with non-oscillation regions

Systematics	PINGU	ORCA	Comments
Experiment-related systematics:			
Normalization	0.25	0.25	Includes atmospheric flux normalization
Cross sections ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ (CC)	0.05	0.05	Includes uncertainty in M_{eff}. Uncorrelated among different cross sections.
NC normalization	0.11	0.11	Value comparable to pull obtained in recent ORCA studies
Uncertainties of atmospheric neutrino flux:			
Normalization	Included in "Normalization" above.		
Slope error (zenith bias)	0.04	0.04	Tilt of spectrum in $\cos\theta_z$
Flavor ν_e/ν_μ	0.01	0.01	Error in flavor ratio
Polarity $\bar{\nu}_\mu/\nu_\mu$	0.02	0.02	Error in neutrino-antineutrino ratio
Polarity $\bar{\nu}_e/\nu_e$	0.025	0.025	Error in neutrino-antineutrino ratio
Normalization down-going events	0.04	0.04	Value similar to zenith bias

WW, Nucl. Phys. B908, 2016, 250; updated from Phys.Rev. D88, 2013, 013013

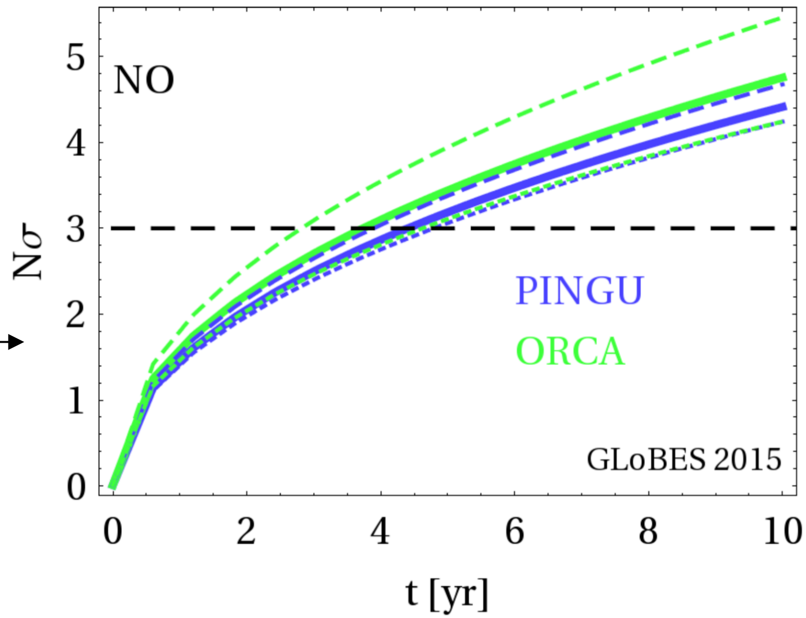
Simulation of standard oscillation sensitivities





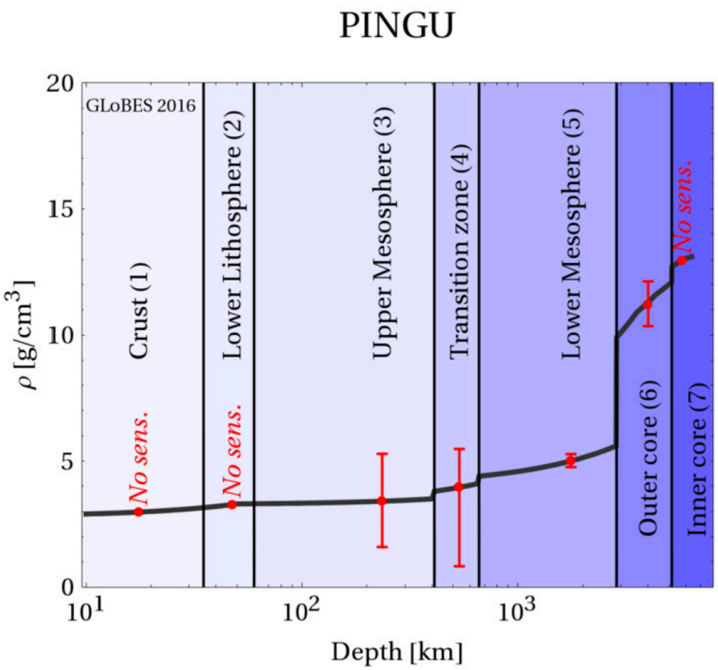
- Self-consistent reproduction of standard oscillation analyses
- Sensitivity and PINGU and ORCA comparable

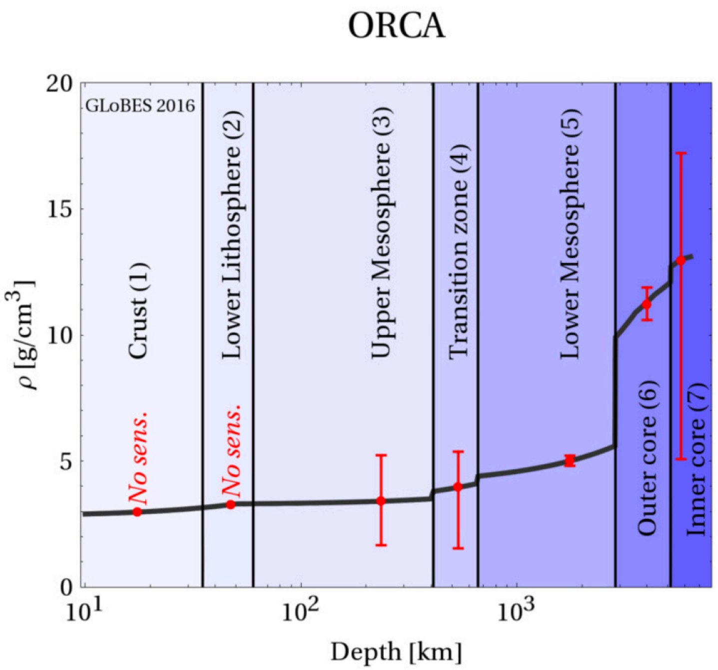
Dashed: δ_{CP} fixed, dotted: matter profile marginalized →



WW, Nucl. Phys. B908, 2016, 250

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.

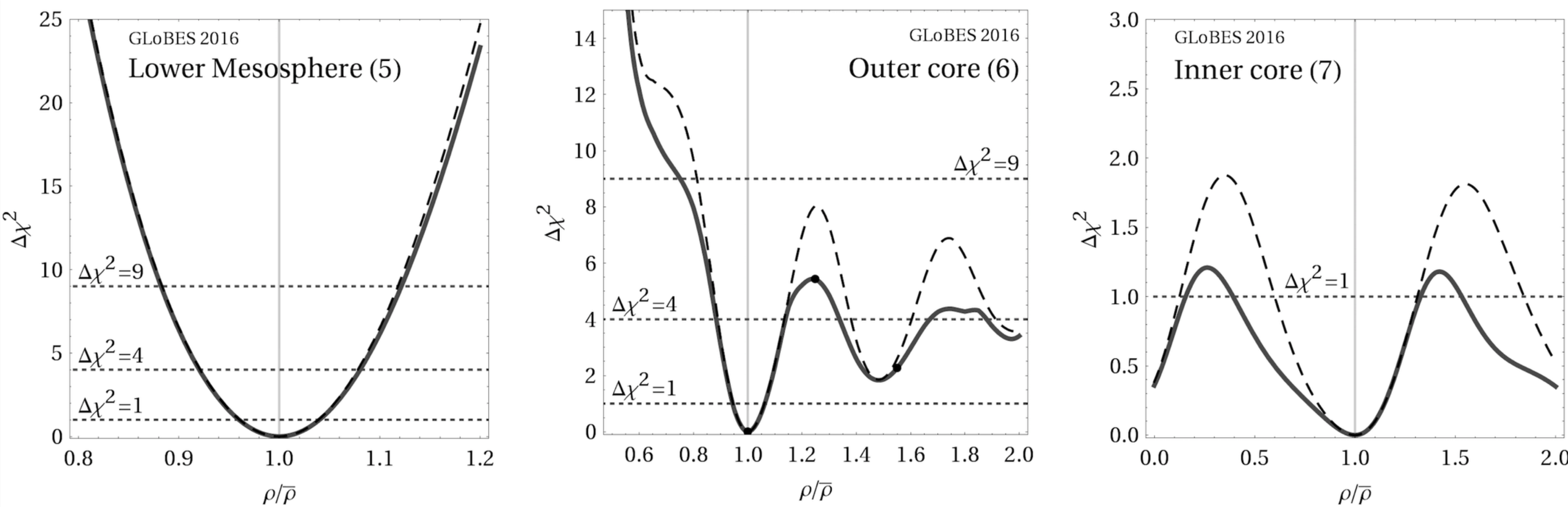
Precision on ρ x Z/A in %

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

Matter profile sensitivity. Example: ORCA

- Highest precision in lower mantle (5)
- Outer core sensitivity suffers from detection threshold
- Inner core requires better resolutions

10 yr; dashed: no correlations among matter layers

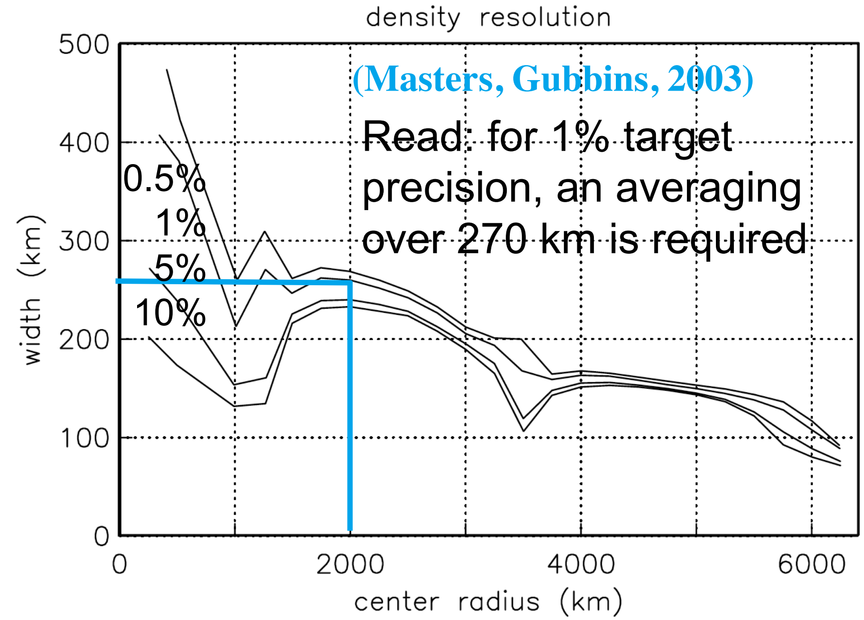


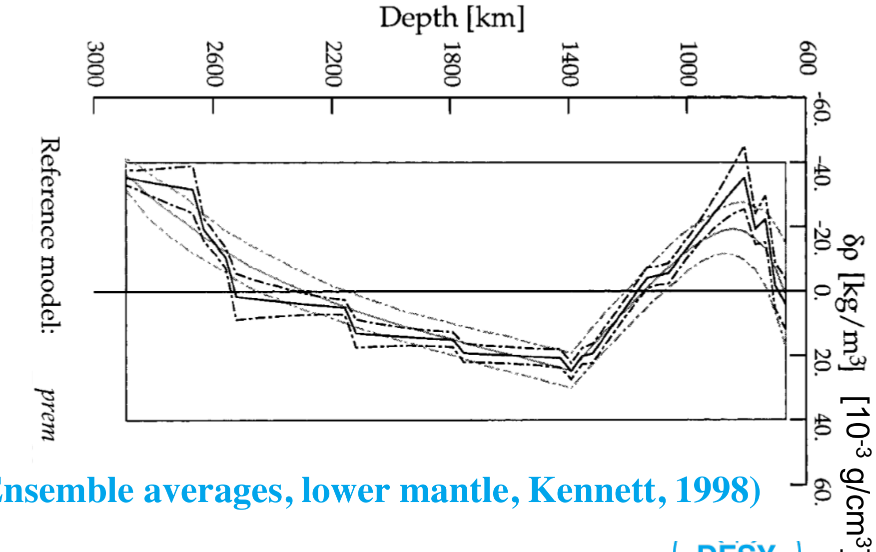
(Z/A sensitivity equivalent)

(WW, arXiv:1511.05154; special issue "Neutrino Oscillations: Celebrating the Nobel Prize in Physics 2015", Nucl. Phys. B908, 2016, 250)

Comparison to geophysical methods

- Especially free oscillations of Earth effective for “direct” access to density profile
- Similar issues: degeneracy between target precision and length of layers averaged over (i.e., one needs some “external” knowledge/smoothing …)
- Precision claimed at the percent level from deviation of reconstructed profiles; but: rigid statistical interpretation?
- Yet unclear how data can be combined, and what effect mass and rotational inertia constraints would have





(Ensemble averages, lower mantle, Kennett, 1998)

DESY

Outlook: Core composition measurement

- Very difficult measurement, as core composition models deviate in Y=Z/A (electron fraction) by at most one percent

Table 1: Z/A ratios for alloys of iron and light elements and some selected composition models.

Model name	Z/A ratio	Si(wt%)	O(wt%)	S(wt%)	C(wt%)	H(wt%)	reference
Single-light-element model (maximum abundance)							
Fe+18wt%Si	0.4715	18	-	-	-	-	Poirier [29]
Fe+11wt%O	0.4693	-	11	-	-	-	Poirier [29]
Fe+13wt%S	0.4699	-	-	13	-	-	Li and Fei [5]
Fe+12wt%C	0.4697	-	-	-	12	-	Li and Fei [5]
Fe+1wt%H	0.4709	-	-	-	-	1	Li and Fei [5]
Multiple-light-element model							
Allegre2001	0.4699	7	5	1.21	-	-	Allègre et al. [26]
McDonough2003	0.4682	6	0	1.9	0.2	0.06	McDonough [27]
Huang2011	0.4678	-	0.1	5.7	-	-	Huang et al. [28]

Rott, Taketa, Bose, Scientific Reports 15225, 2015

- Reason: for heavier stable isotopes proton number ~ neutron number
- Beyond precisions of PINGU and ORCA; requires a detector with a lower threshold (around 1 GeV); Super-PINGU/Super-ORCA?

Summary and conclusions

- Neutrino tomography is a wide subject with many ideas: neutrino absorption, neutrino oscillations
- The observation of atmospheric neutrino oscillations has opened a new window; the relevant neutrino oscillation parameters are known to relatively high precisions
- Emerging technologies include Mt-sized detectors in ice or sea water for neutrino mass ordering measurements; tomography as a spin-off? Clearly one should do that analyses if the data are there ...
- The obtainable precision is limited and has to rely on some “external“ knowledge. However, the approach is totally different from any geophysical method (e.g. neutrinos travel on straight paths)
- The evolution operator properties (do, in general, not commute) lead to interesting structural information even from a single baseline only

Review on neutrino tomography: WW, Earth Moon Planets 99 (2006) 285

Open issues/discussion

- Geophysical "smoking gun" contribution from neutrinos?
  Can one really learn something qualitatively or quantitatively new?
- Is it worth to develop new dedicated technology?
  Or should one rely on spin-offs only?
- Required improvements (especially lower threshold) to achieve sensitivity to the inner core?
- Synergies between two experiments (PINGU/ORCA)? Oscillations or absorption? Combination? 3D models?
- How does one best combine geophysical and neutrino data?
  Statistical interpretation of geophysical methods?
- Impact of total mass and rotational inertia constraints?
- New neutrino analyses in geophysicist's language?
  Example: Simulate profiles satisfying all constraints?