Atmospheric neutrino oscillations for Earth Tomography

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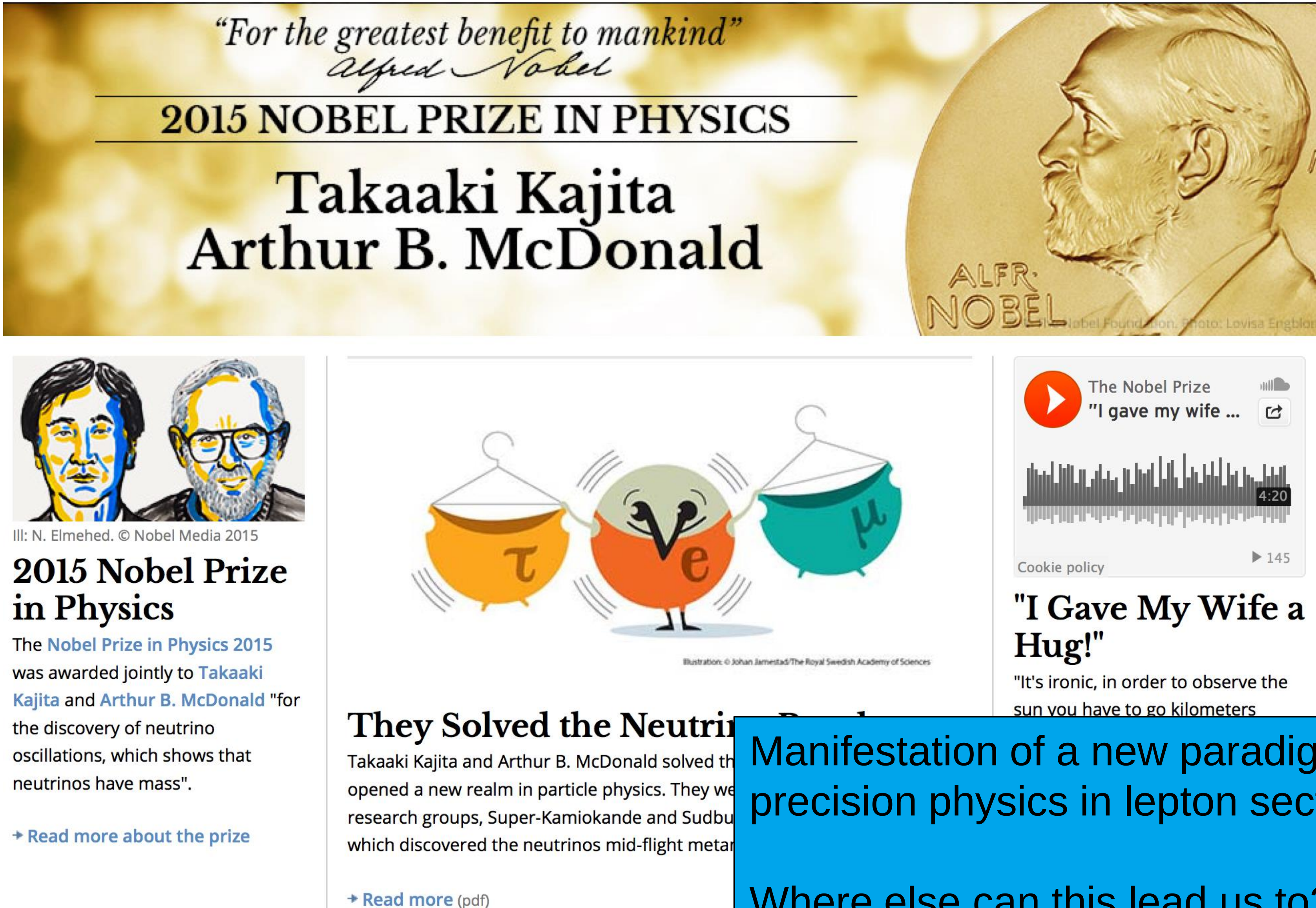
DESY, Zeuthen

TeVPA 2016

CERN
Sept. 12-16, 2016

Nobel prize 2015: Neutrino oscillations


"For the greatest benefit to mankind"

Alfred Nobel

2015 NOBEL PRIZE IN PHYSICS

Takaaki Kajita
Arthur B. McDonald

Ill: N. Elmehed. © Nobel Media 2015

2015 Nobel Prize in Physics

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

→ Read more about the prize

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

They Solved the Neutri

Takaaki Kajita and Arthur B. McDonald solved th opened a new realm in particle physics. They we research groups, Super-Kamiokande and Sudbu which discovered the neutrinos mid-flight metar

→ Read more (pdf)

The Nobel Prize
"I gave my wife ...
4:20
Cookie policy
145

"I Gave My Wife a Hug!"

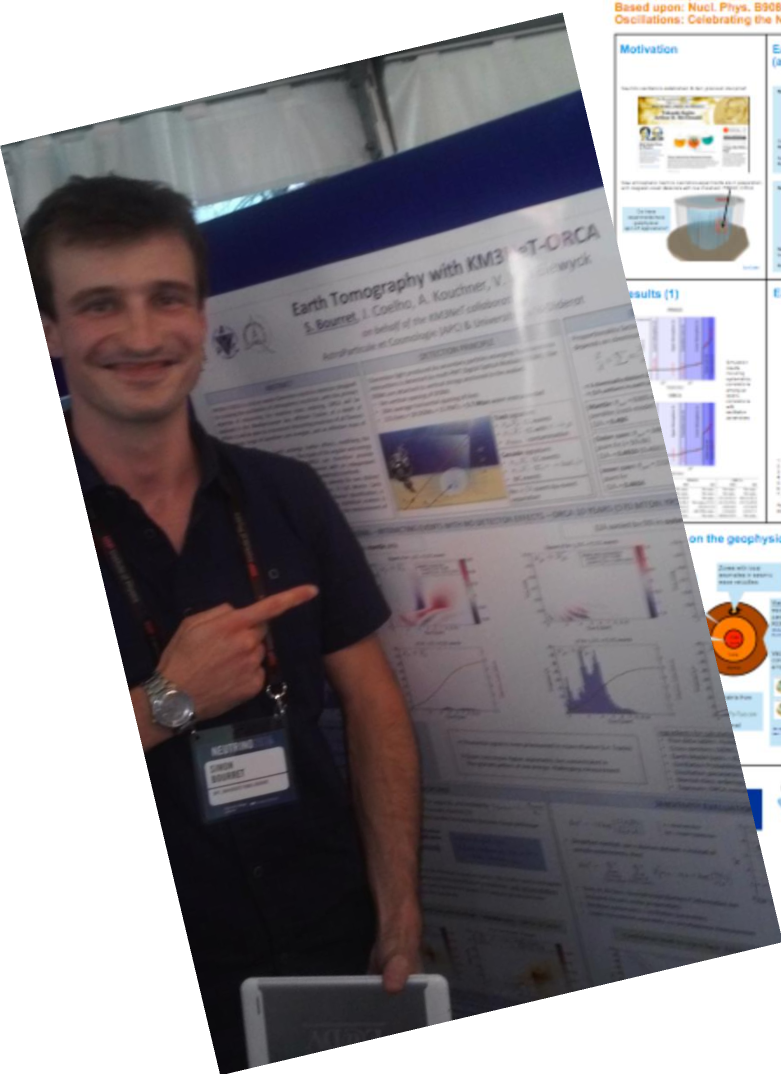
"It's ironic, in order to observe the sun you have to go kilometers

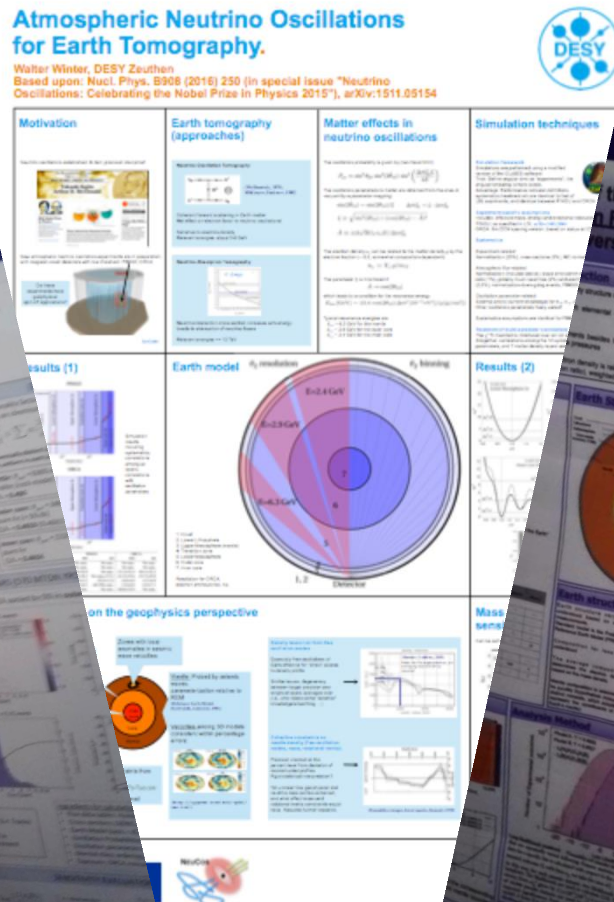
Manifestation of a new paradigm: precision physics in lepton sector

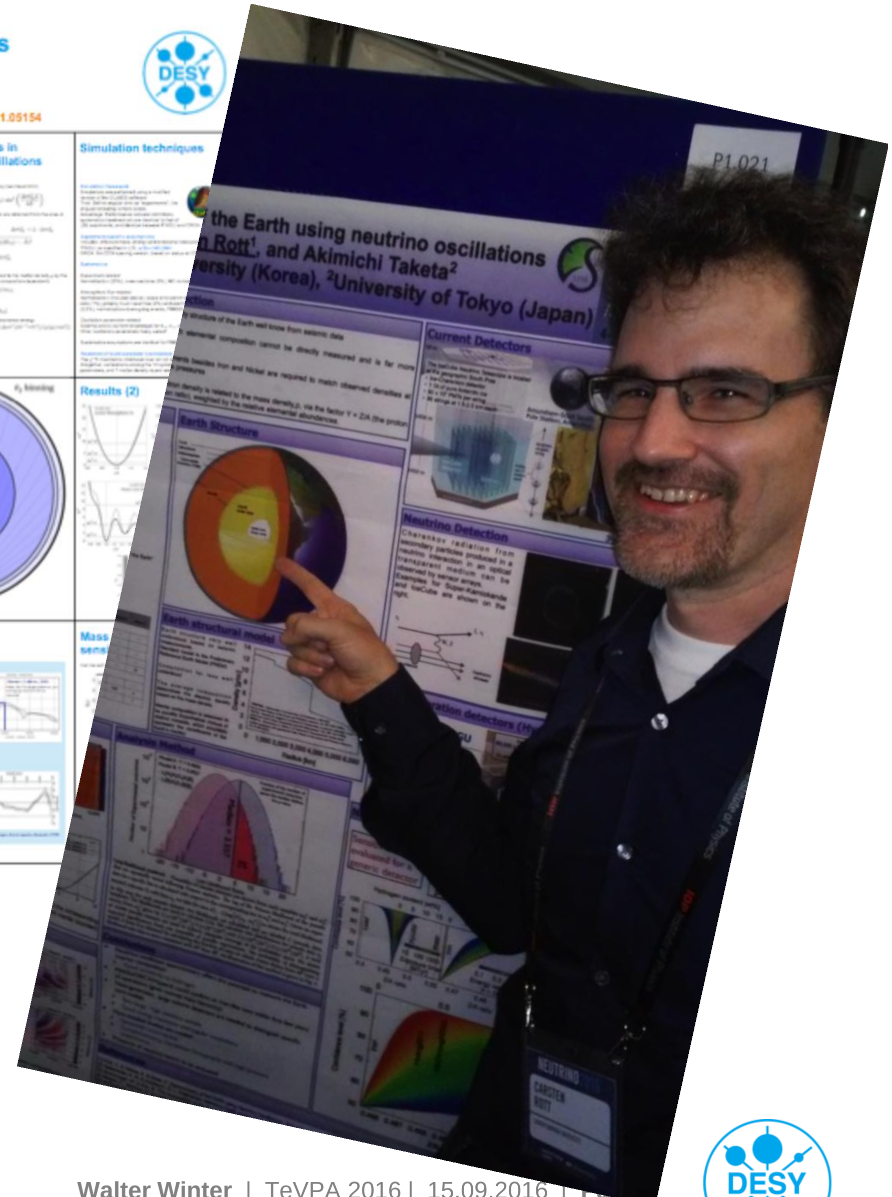
Where else can this lead us to?
Neutrino tomography of Earth?

(http://www.nobelprize.org, Oct. 6th, 2015)

Impressions from Neutrino 2016



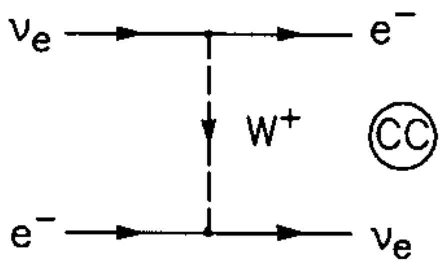




Neutrino tomography: Principle approches

Matter effects in neutrino oscillations

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

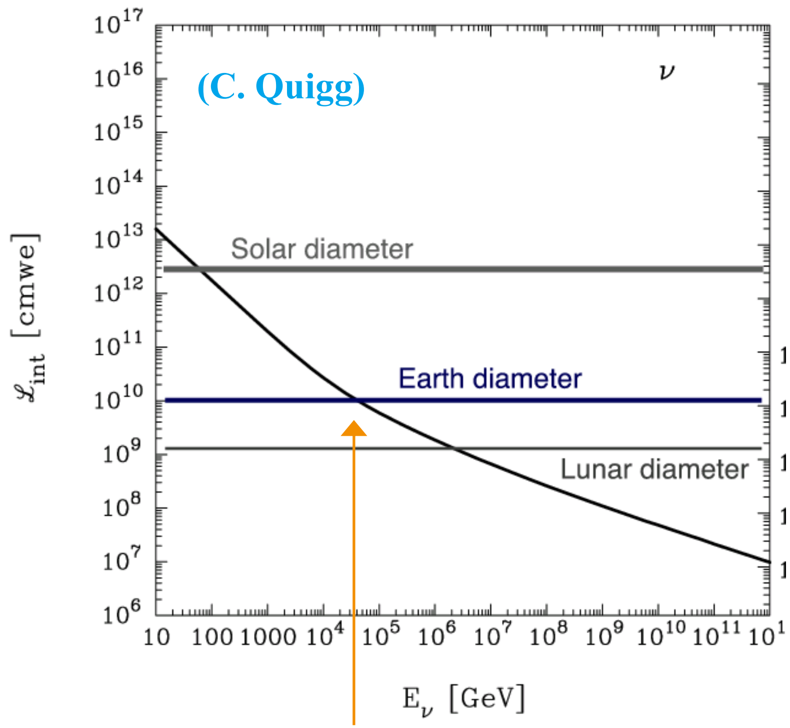


(Wolfenstein, 1978; Mikheyev, Smirnov, 1985)

(Earth matter does not contain muons and taus!)

- Depends on $n_e \sim Y \rho/m_N$, $Y=Z/A \sim 0.5$ (electrons per nucleon) Somewhat composition-dependent!
- Relevant energy ~3-6 GeV (later)

Neutrino absorption of energetic neutrinos



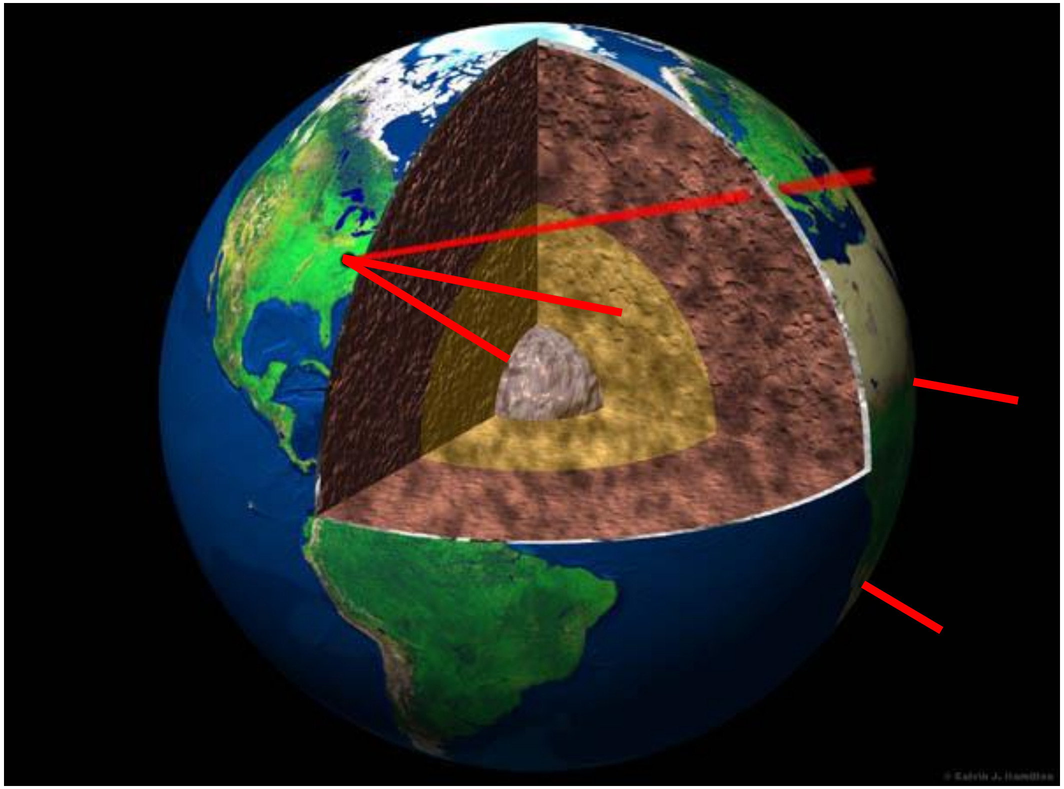
Relevant for E >> 10 TeV
Competitive scenarios?
See e. g. Gonzalez-Garcia et al, PRL 100 (2008) 061802

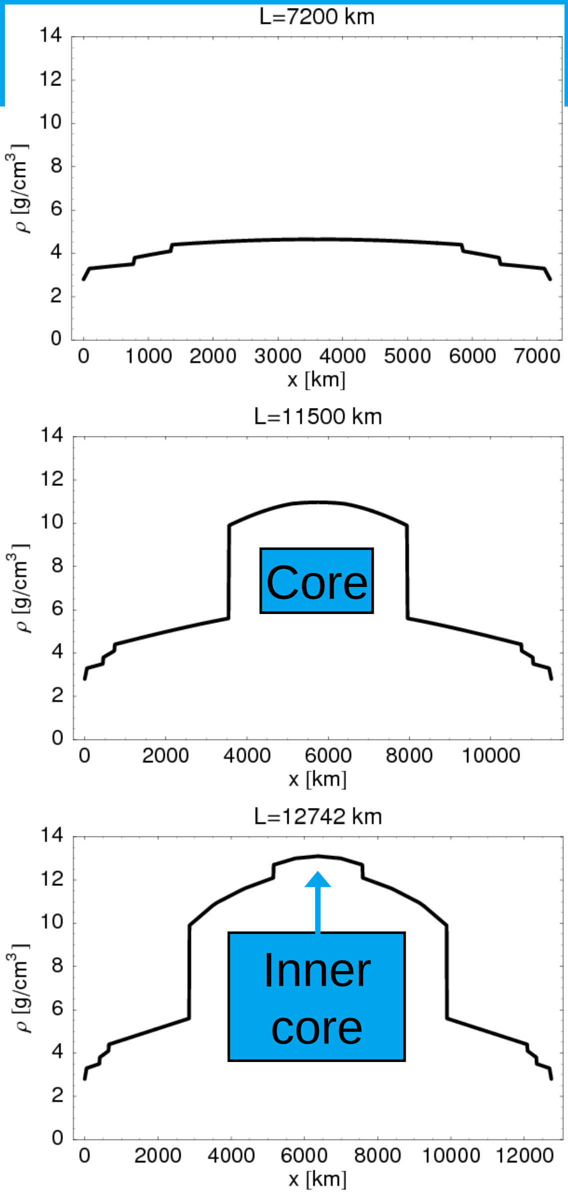
Review on neutrino tomography: WW, Earth Moon Planets 99 (2006) 285

DESY

Matter profile of the Earth

… as seen by a neutrino





(PREM: Preliminary Reference Earth Model)

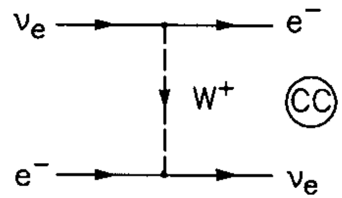
Neutrino oscillations in matter [for two flavors, constant matter density]

- 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)

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

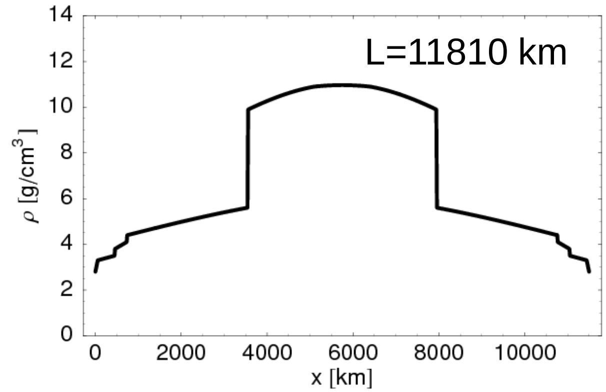
$$\xi \equiv \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \hat{A}\right)^2},$$

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

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

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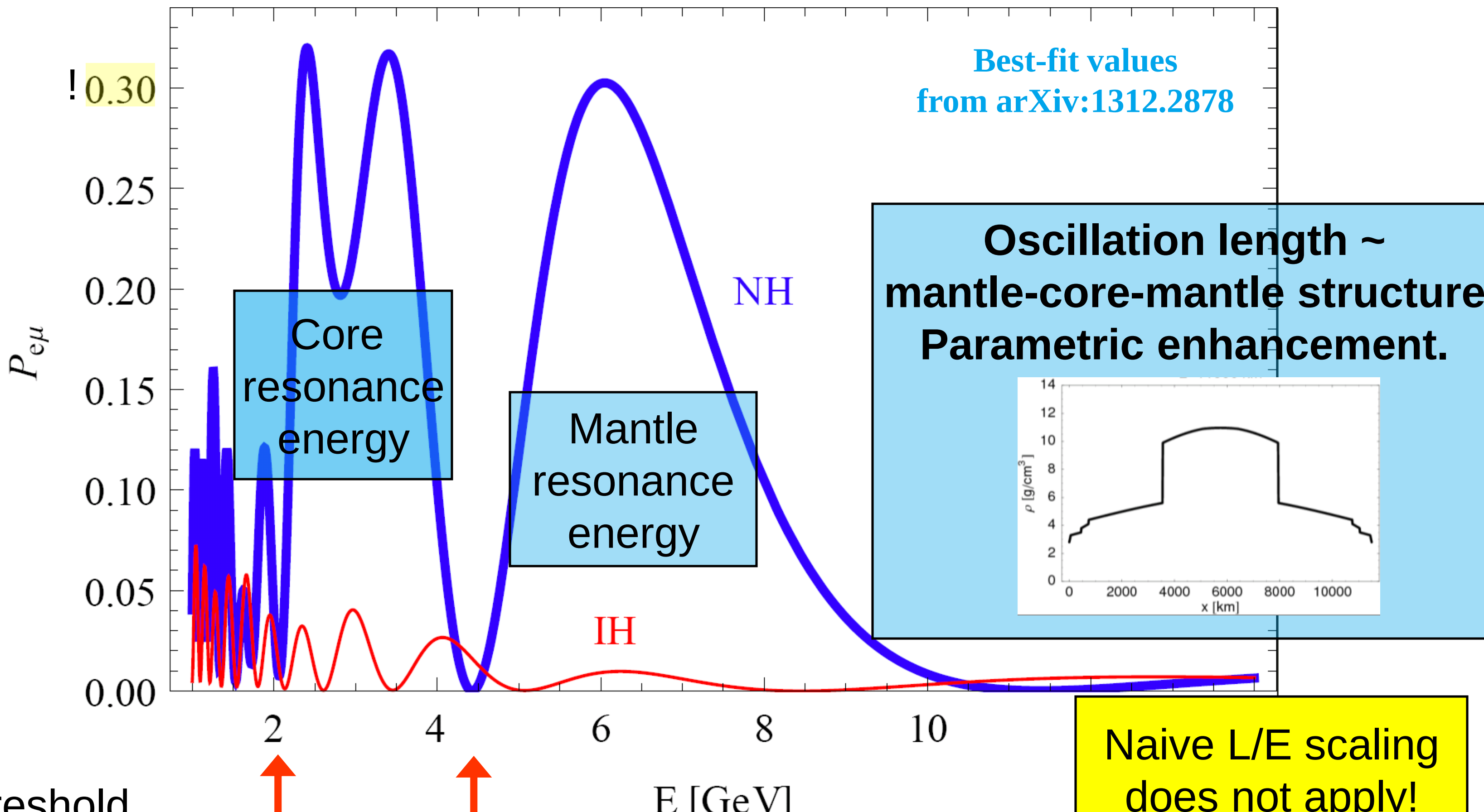
Mantle-core-mantle profile

(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

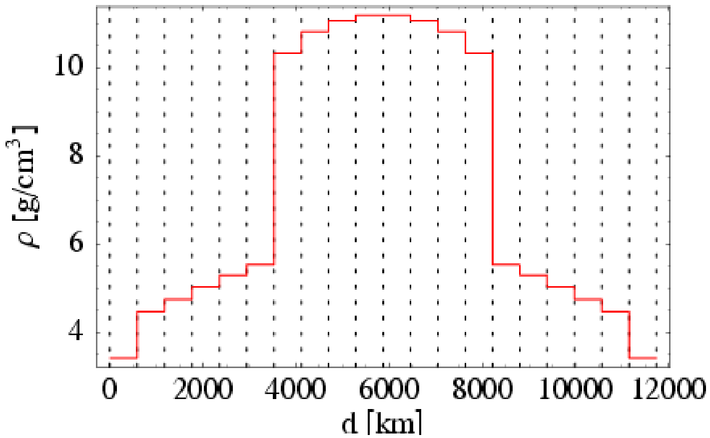
4-5 GeV

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 ρ_j/m_N , Y: electrons per nucleon (~0.5)
- Probability:

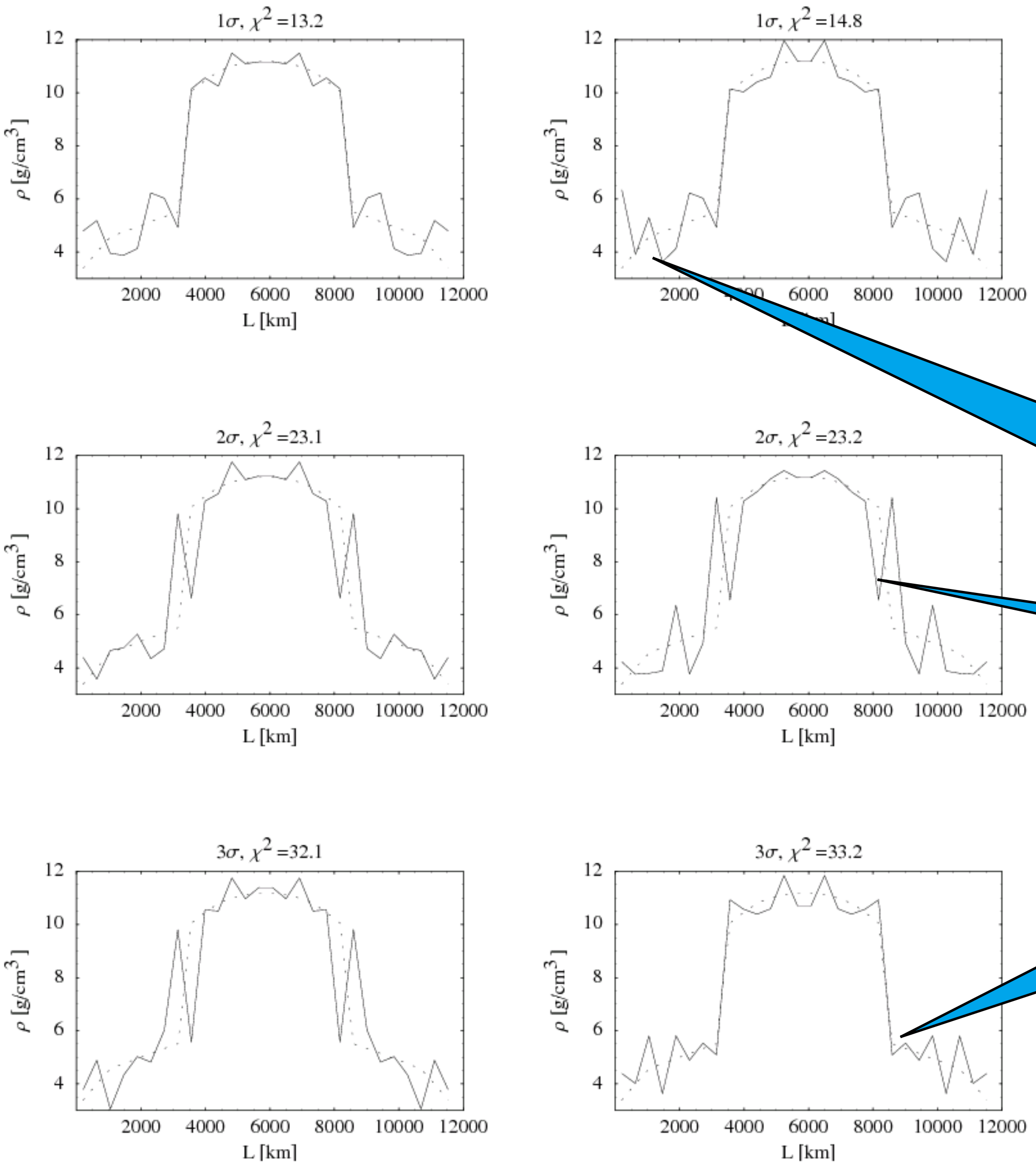
$$P_{\alpha\beta} = \left| \langle \nu_\beta | \mathcal{V}(x_m, n_m) \ldots \mathcal{V}(x_1, n_1) | \nu_\alpha \rangle \right|^2$$

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

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

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

[genetic algorithm reconstruction method used]



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)

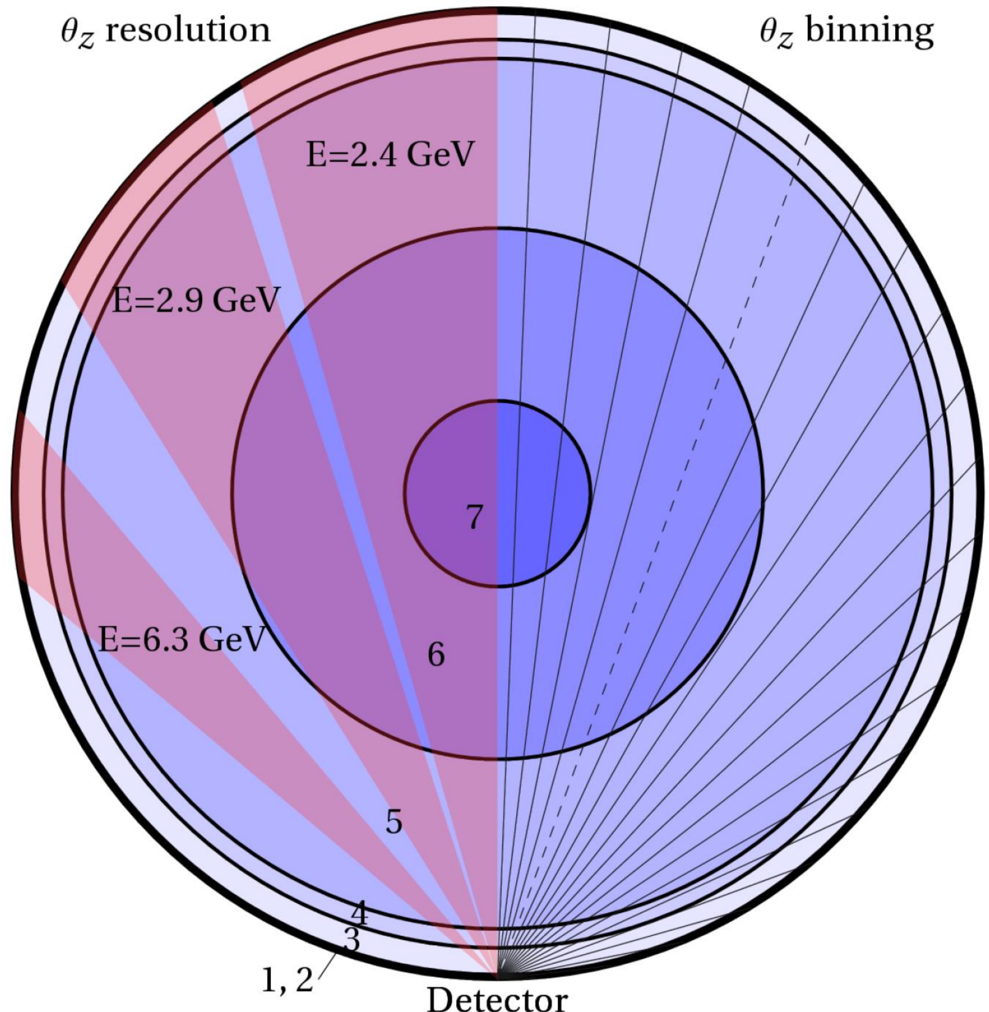
Towards realistic applications

- Need very large number of neutrinos in relevant energy range.
  Point towards oscillations of atmospheric neutrinos

- Assumption: Cannot afford any additional equipment; spin-off from other measurement.
  Use Mt-sized density upgrades of neutrino telescopes (PINGU, ORCA)

  See talks by J. Koskinen and J. Barrios-Marti on Monday

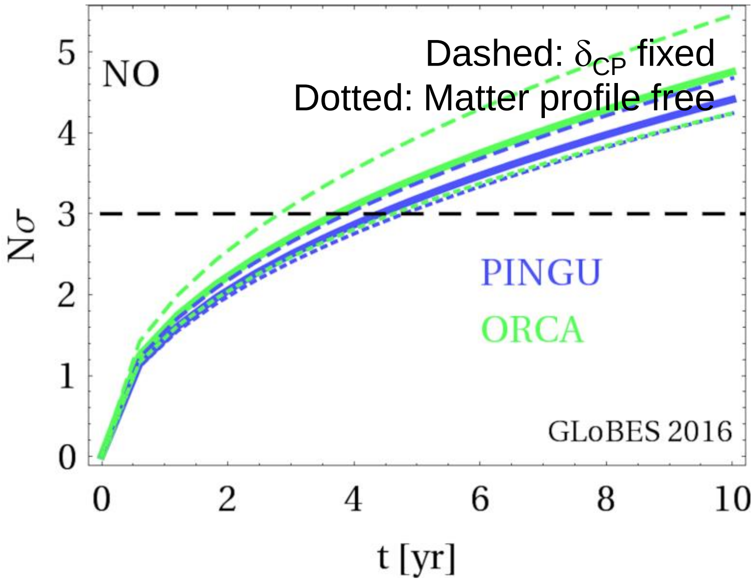
- Key issue: complicated analysis; need to deal with multi-parameter correlations for “proof of principle”

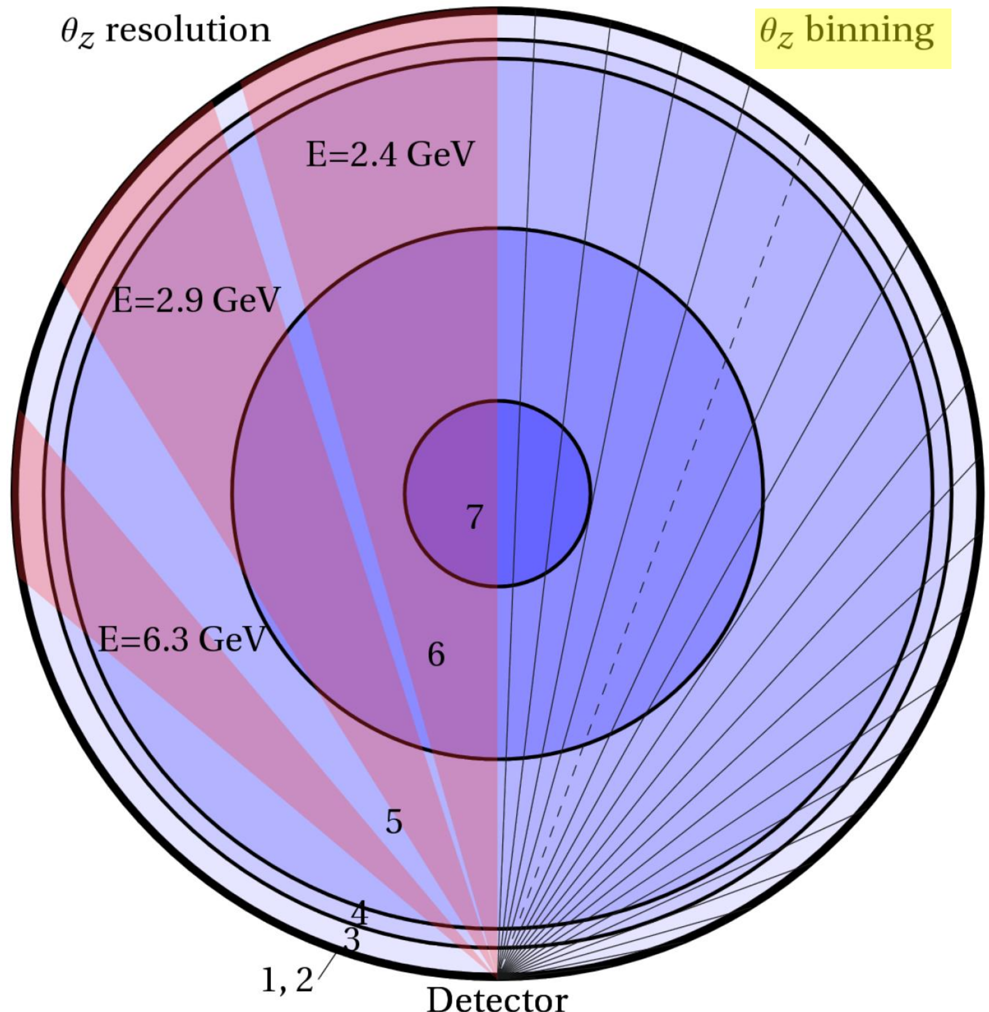


(WW, arXiv:1511.05154)

Towards realistic applications

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

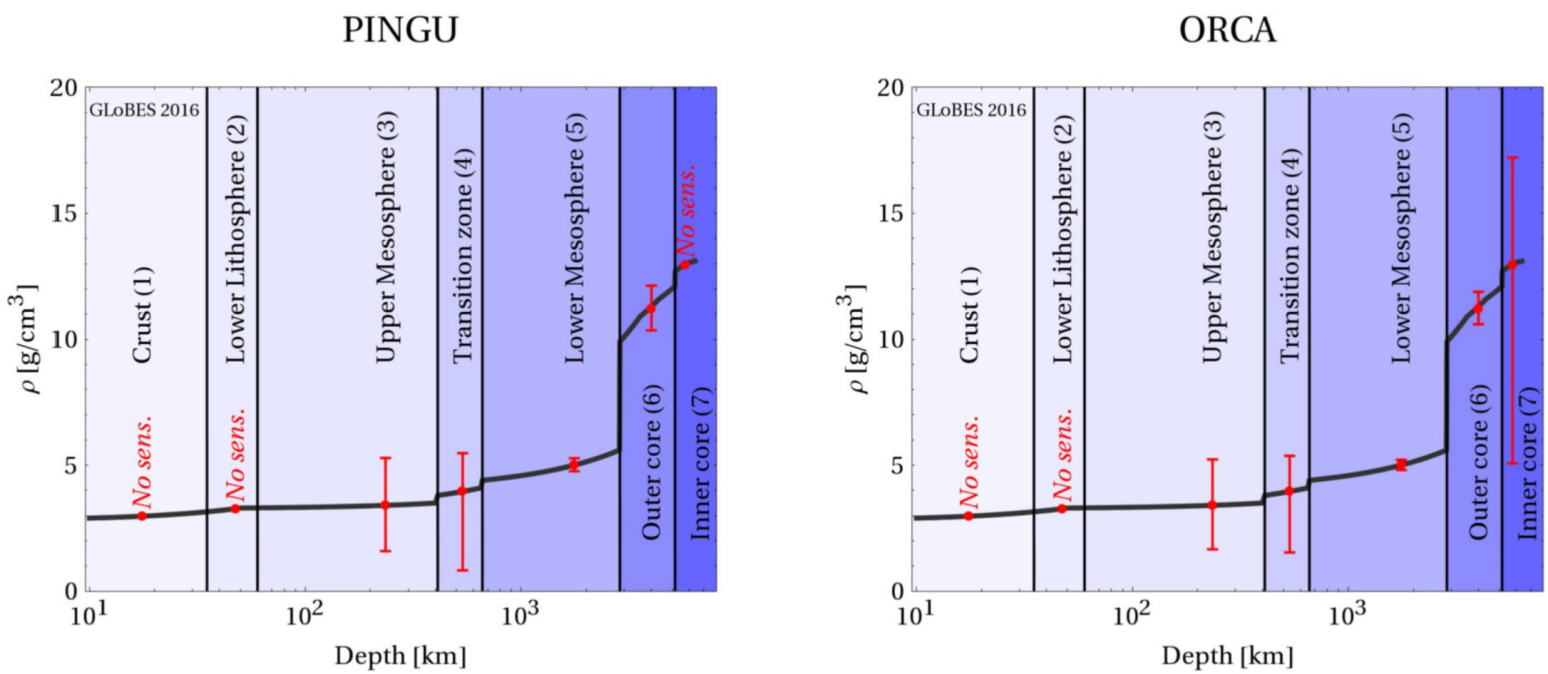




(WW, arXiv:1511.05154)

- Include systematics (12), correlations among matter layers (7) and with oscillation parameters (6)

Expected matter profile precision – proof of principle



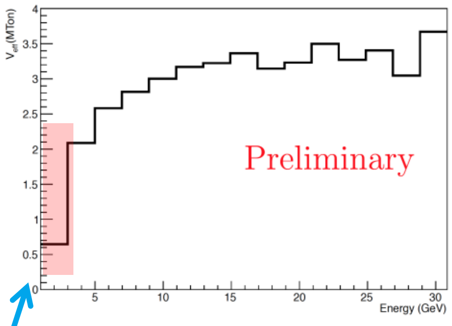
(NO, 10 yr)

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.

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

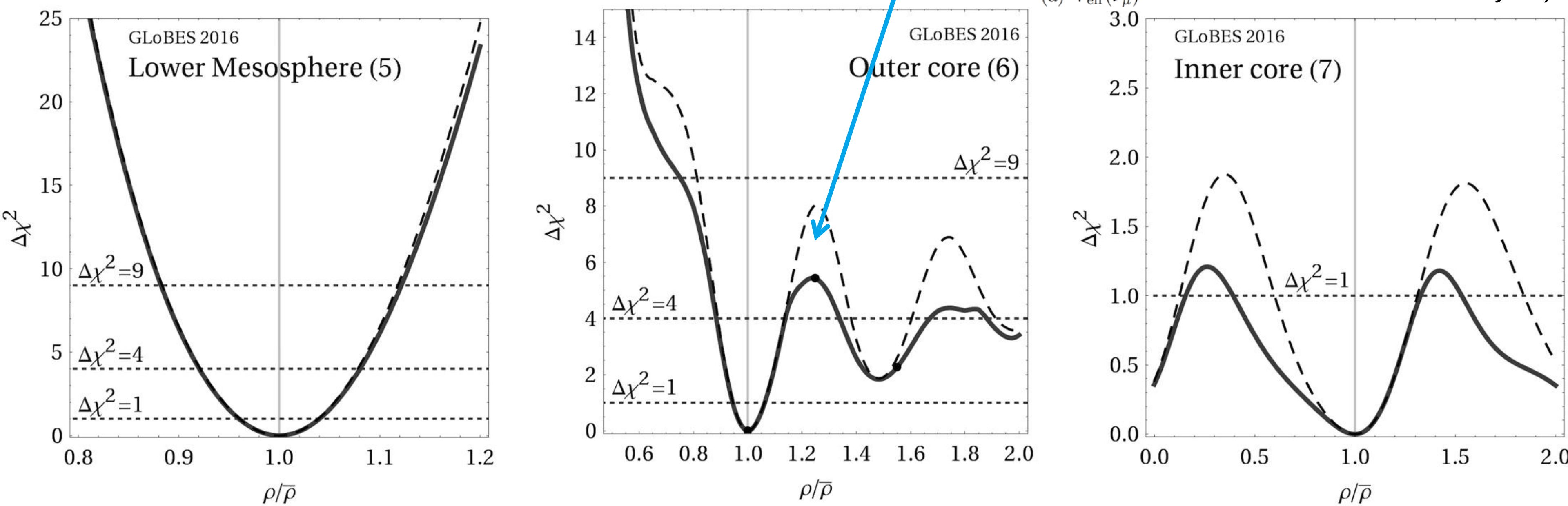
Matter profile sensitivity. Example: ORCA

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



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

(10 yr; dashed: no correlations among matter layers)



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

Outlook: Core composition measurement

- Same relative precisions apply to composition (degeneracy: $n_e \sim Y\,\rho$)
- Very difficult measurements, as core composition models deviate in Y (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]

(from: Rott, Taketa, Bose, Nature 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), new technology

Open issues (instead of conclusions …)

- 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)? 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 geophysict’s language?

BACKUP

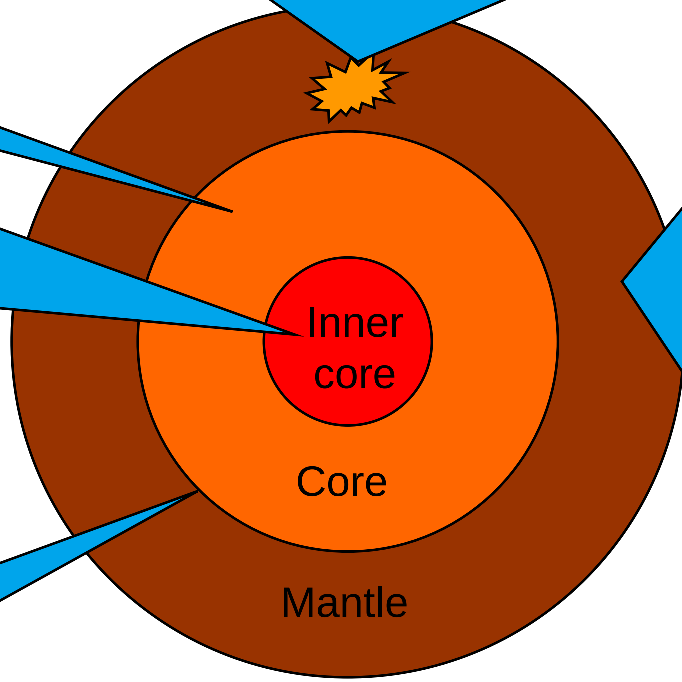
Earth's interior: What we know (served with apologies to geophysicists …)

Outer core: Liquid (as no seismic shear waves)

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

Seismic wave reflection/refraction

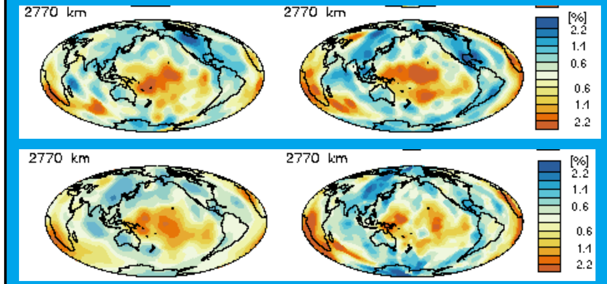
Zones with local anomalies in seismic wave velocities



Mantle: Probed by seismic waves; parameterization relative to REM

(Reference Earth Model, Dziewonski, Anderson, 1981)

Velocities among 3D models consistent within percentage errors:



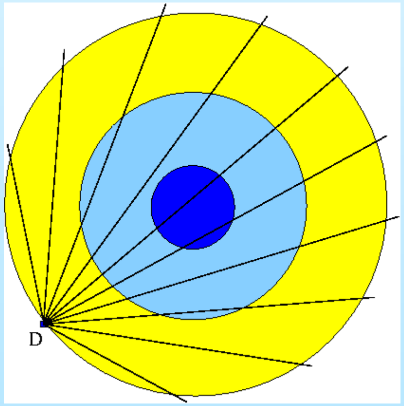
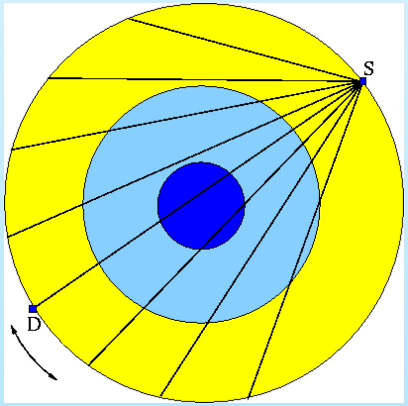
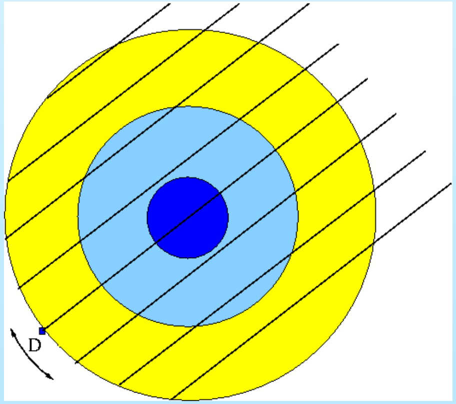
(http://igppweb.ucsd.edu/~gabi/rem.html)

Density constrained by collective constraints from mass and moment of inertia

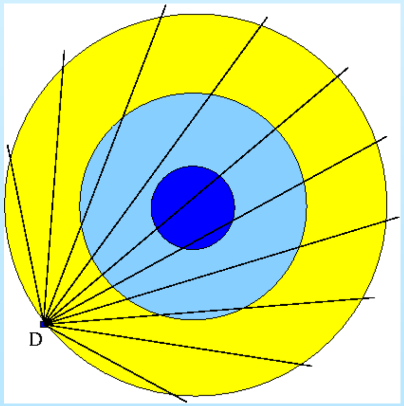
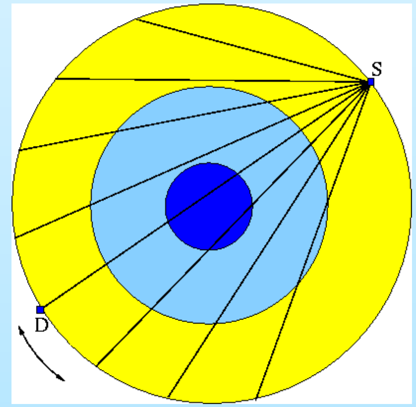
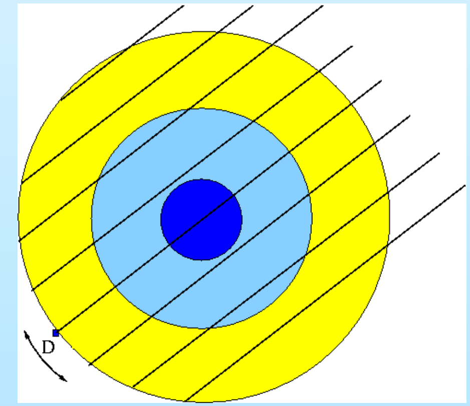
$$M = 2\pi \int r^2 \rho(r) dr, \qquad I = 2\pi \int (x^2 + y^2) r^2 \rho(r) dr$$

… and free oscillation modes at percent level

Ideas using *absorption* tomography

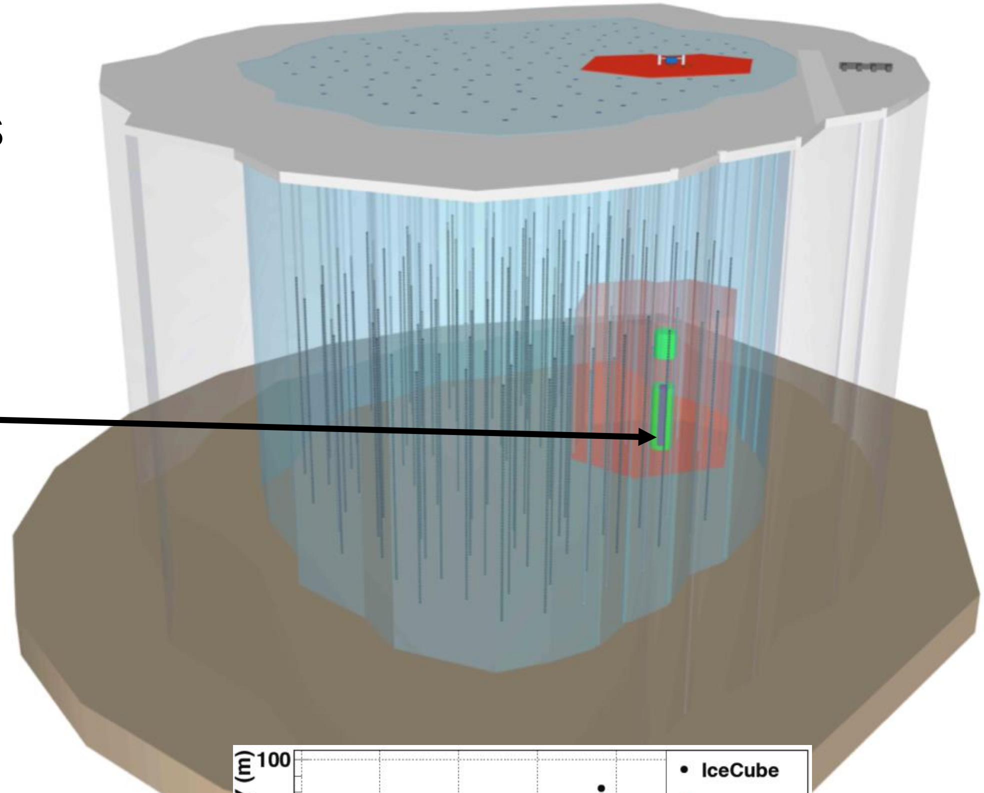
	Isotropic flux (cosmic diffuse, atmospheric)	TeV beam	Astro point source
			
+	Sources available	Potentially high precision	Earth rotation ➔different baselines
-	<u>Atmospheric neutrinos:</u> low statistics at E>10 TeV <u>Diffuse cosmic flux:</u> low statistics, unknown flux normalization	Build and safely operate a TeV neutrino beam (need FCC-scale accelerator); moving decay tunnel+ detector?	No sources resolved yet; most probably low statistics
	Jain, Ralston, Frichter, 1999; Reynoso, Sampayo, 2004; Gonazales-Garcia, Halzen, Maltoni, 2005; …	**De Rujula, Glashow, Wilson, Charpak, 1983; Askar`yan, 1984; Borisov, Dolgoshein, Kalinovskii, 1986; …**	**Wilson, 1984; Kuo, Crawford, Jeanloz, Romanowicz, Shapiro, Stevenson, 1994; …**

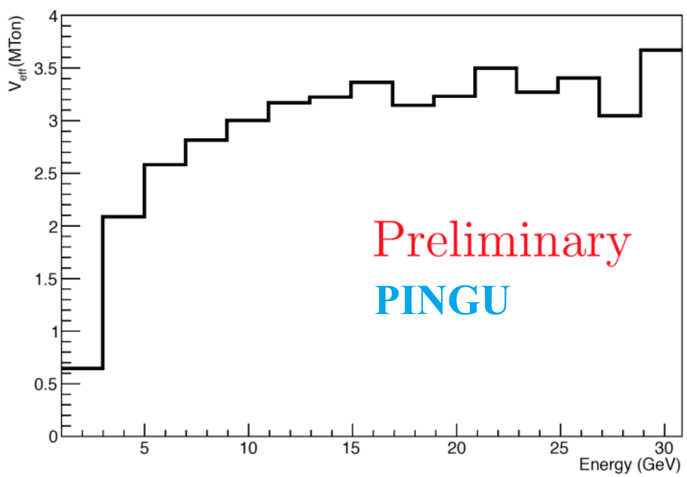
Ideas using *oscillation* tomography

	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
-	Diffuse cosmic flux: too high neutrino energies	Moving decay tunnel+ detector? Or: new dedicated experiment?	Supernovae in neutrinos are rare events Solar neutrinos have somewhat too low E
	Rott, Taketa, Bose, 2015; Winter, 2016 + some earlier ideas; …	**Ohlsson, Winter, 2002; Winter, 2005; Gandhi, Winter, 2007; Arguelles, Bustamante, Gago, 2015; …**	**Lindner, Ohlsson, Tomas, Winter, 2003; Akhmedov, Tortola, Valle, 2005; …**

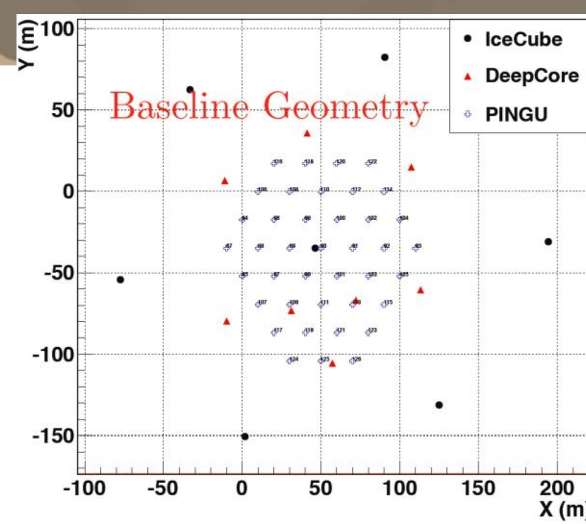
Emerging technologies: mass ordering with atm. neutrinos

- Plans for high-density atmospheric neutrino detectors in ice (PINGU) and sea water (ORCA)
- Mton-size volume in relevant energy range:



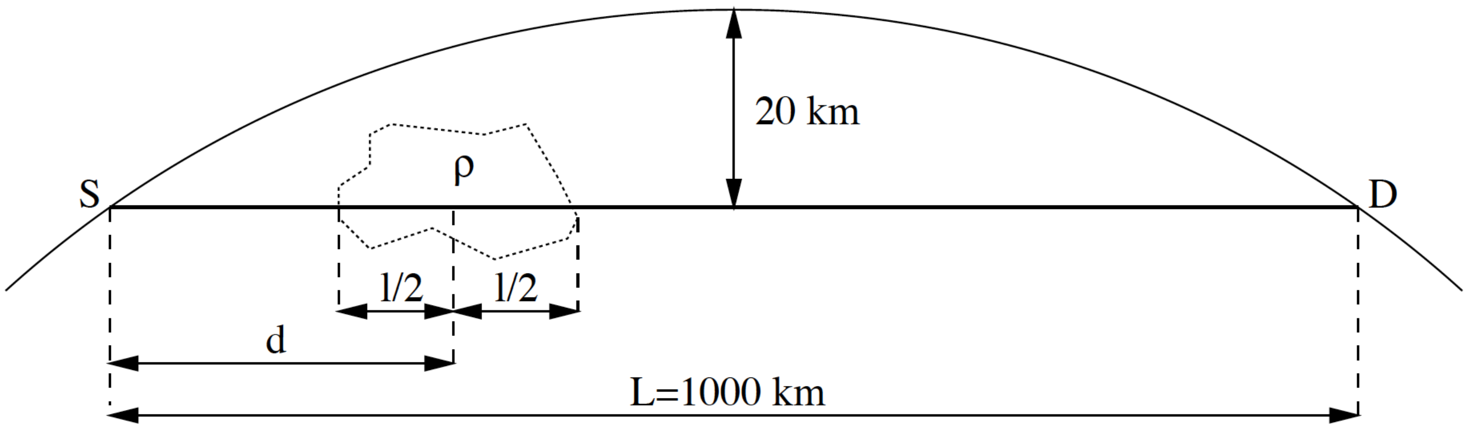


(a) $V_{\rm eff}(\nu_\mu)$

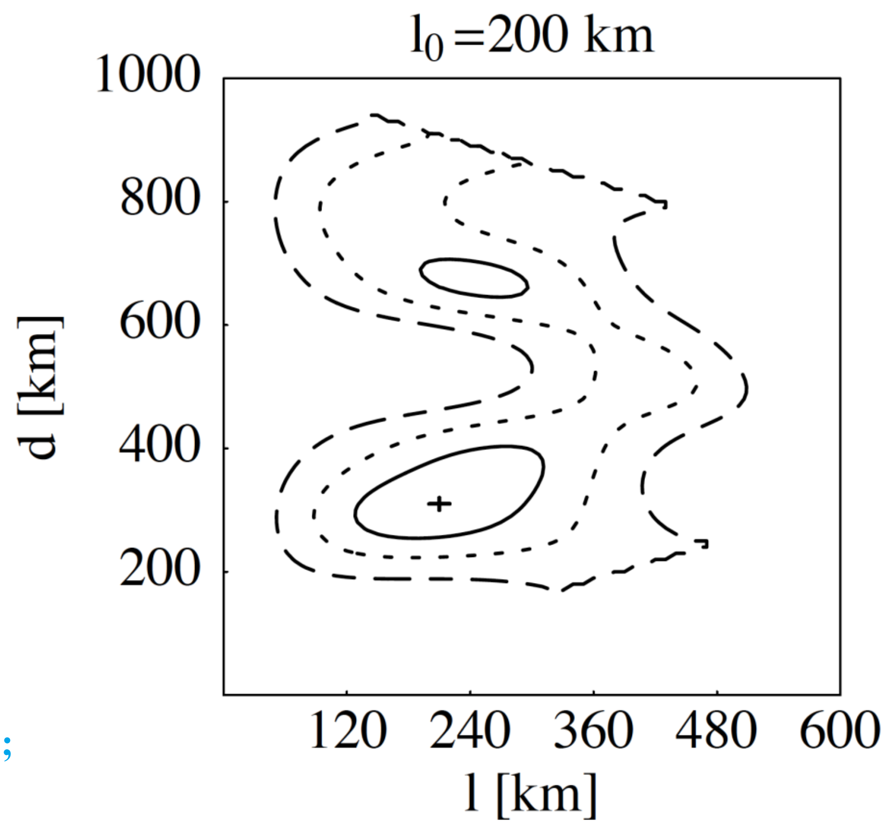


(arXiv:1401.2046, arXiv:1412.5106; arXiv:1601.07459)

Resolution of cavities = zones with a density contrast



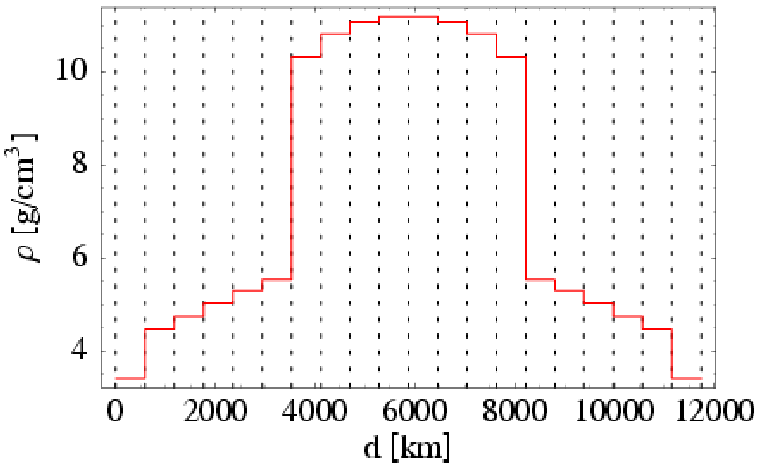
- Low-energy (300-500 MeV) superbeam
- The cavity can be located if long enough and density contrast strong enough (here: water)
- **There is some positional information (one baseline!)**

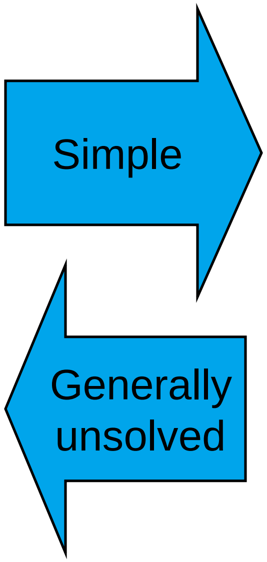


(from Ohlsson, Winter, Europhys. Lett. 60 (2002) 34; see also Arguelles, Bustamante, Gago, 2015)

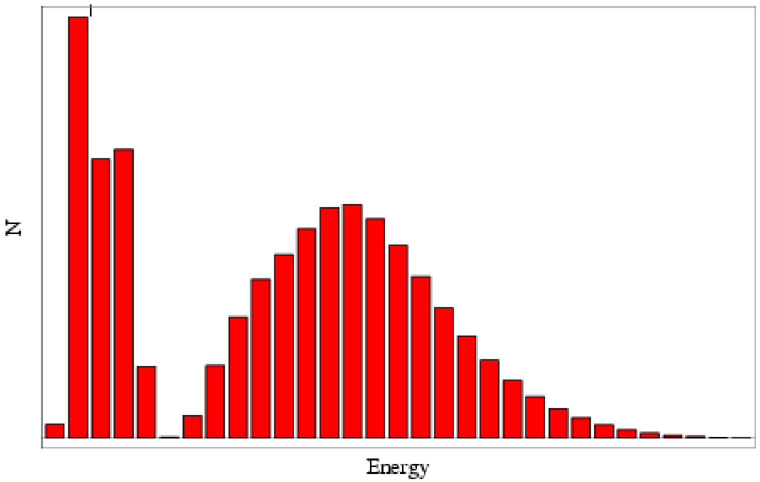
Matter profile inversion problem

Matter profile





Observation



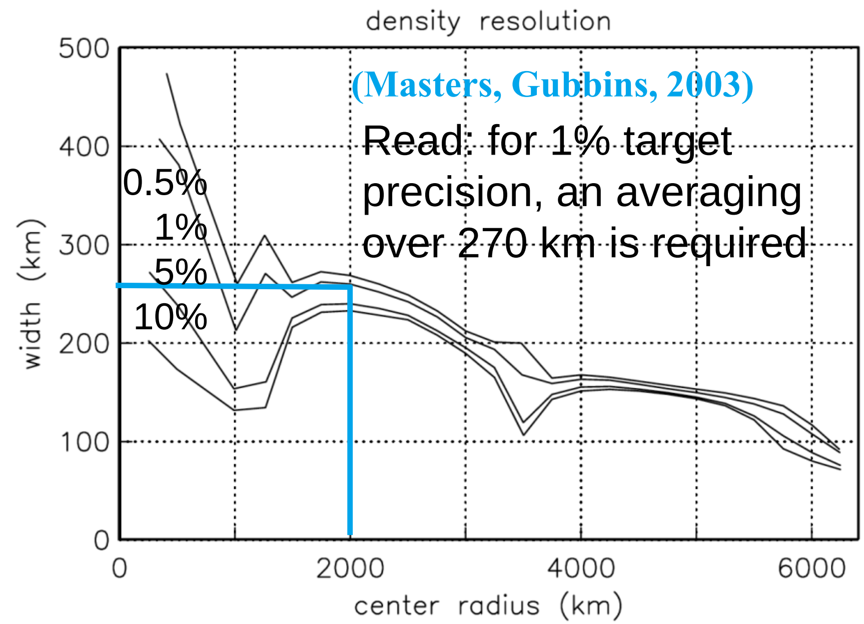
(Ermilova, Tsarev, Chechin, 1988)

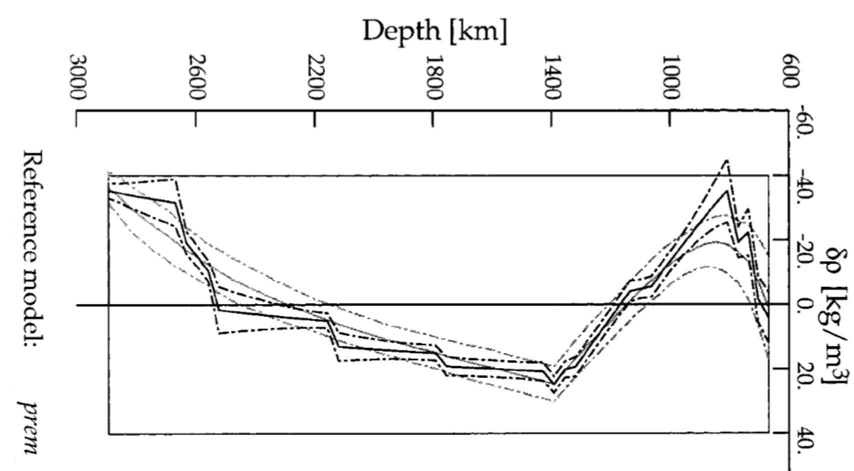
<u>Some approaches for direct inversion:</u>

- 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)
- Discretization with many (N) parameters:
  Use non-deterministic methods to reconstruct these parameters
  (e. g. genetic algorithm in Ohlsson, Winter, 2001)

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)