Neutrino oscillation tomography

or

What could be learned about the Earth's interior from neutrino oscillations in matter?

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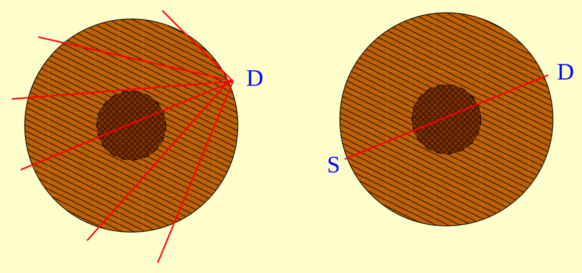
In collaboration with **T. Ohlsson**: Phys. Lett. B512 (2001) 357 (hep-ph/0105293) and hep-ph/0111247; In collaboration with **M. Lindner**, **T. Ohlsson**, and **R. Tomàs**: in preparation

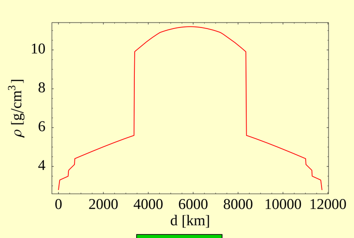
Neutrino tomography



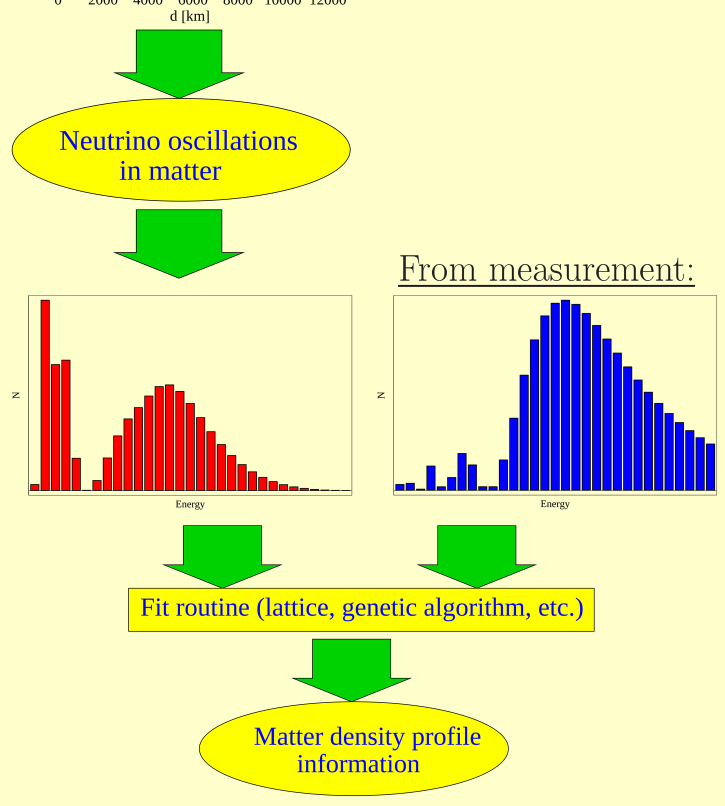
	Neutrino *absorption* tomography	Neutrino *oscillation* tomography
Principle	Neutrino absorption in matter	MSW effect
Baselines	Many	At least one
Energies	$\geq$ TeV	$\sim 0.005 - 50\,\text{GeV}$
Sources	Cosmic	LB experiments, Supernovae, etc.
Analogy	X-ray tomography	Interference experiments
	De Rújula et al. (1983) and others	Ermilova et al. (1988) and others

Principles

- Short or long baseline experimental setup
- Oscillation parameters assumed to be measured with high precision: Δm^2_{31}, Δm^2_{21}, θ_{13}, θ_{12}, θ_{23}, δ_{CP}



Matter density profile (in some model)



The evolution operator method

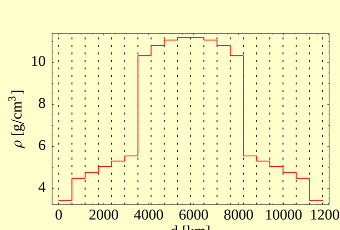
Propagation in a layer of length x_j and constant density ρ_j described by *evolution operator*

$$\mathcal{U}(x_j, \rho_j) = e^{-i\mathcal{H}(\rho_j)x_j},$$

where $\mathcal{H}(\rho_j)$ is the Hamiltonian in constant matter density

$$\mathcal{H}(\rho_j) = U \begin{pmatrix} 0 & 0 & \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} A(\rho_j) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$

For an arbitrary matter density (step) profile

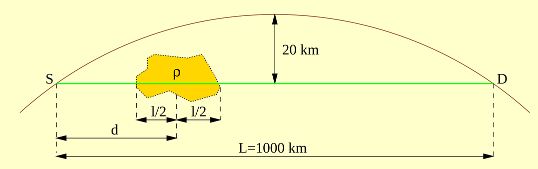


$$P_{\alpha\beta} = \left| \langle \nu_\beta | \mathcal{U}(x_n, \rho_n) \ldots \mathcal{U}(x_1, \rho_1) | \nu_\alpha \rangle \right|^2.$$

Note that in general $[\mathcal{U}(x_i, \rho_i), \mathcal{U}(x_j, \rho_j)] \neq 0$ for $i \neq j$
→ Additional information by interference effects compared to neutrino absorption tomography

The search for large cavities in the Earth's mantle

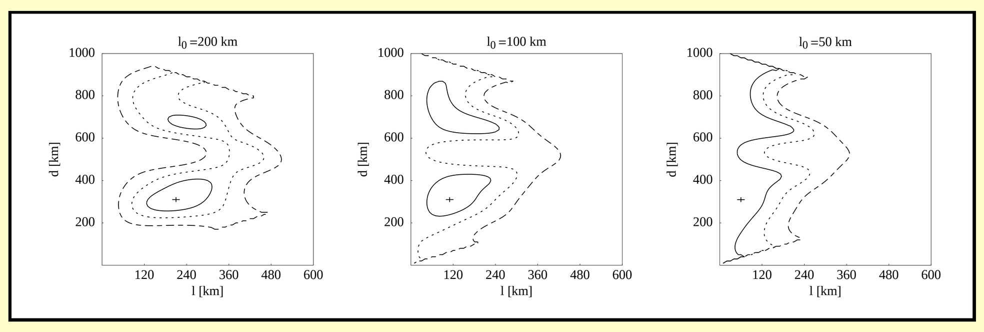
Experimental setup: Low energy superbeam 500 MeV, $\nu_\mu \to \nu_e$



In this scenario:

- Cavity centered at d_0 with length l_0
- Maximum depth 20 km
- Average depth 13 km
- Average matter density: $2.9\,\text{g/cm}^3$
- Matter density in the cavity: $\rho = 1.0\,\text{g/cm}^3$

For a cavity centered at $d_0 = 300\,\text{km}$:

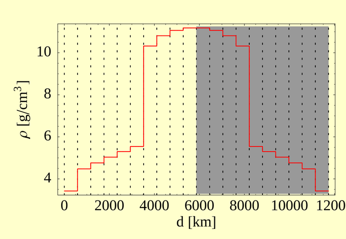


The cavity can be seen on the 3σ-level for $l_0 = 200\,\text{km}$, 1σ-level for $l_0 = 100\,\text{km}$, and not at all for $l_0 = 50\,\text{km}$.

Reconstruction of the Earth's matter density profile

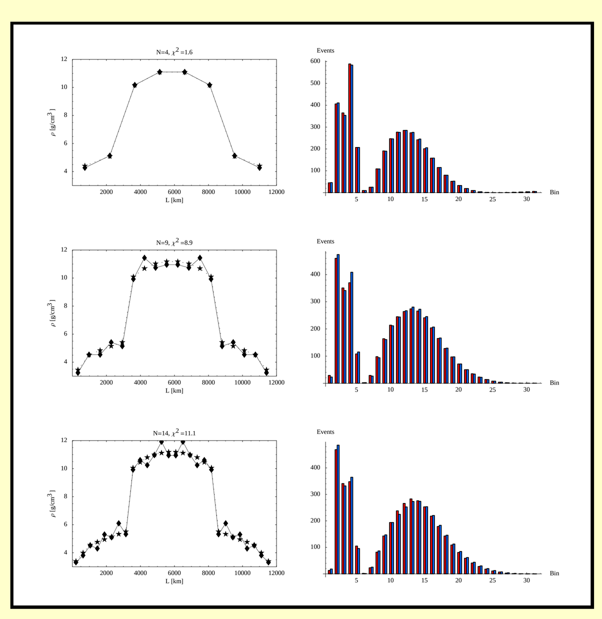
Experimental setup: 20 GeV neutrino factory, baseline $L = 11700\,\text{km}$, $\nu_\mu \to \nu_e$

Symmetric Earth matter density profile with $2N$ layers assumed, which means that the dimension of the parameter space is N.



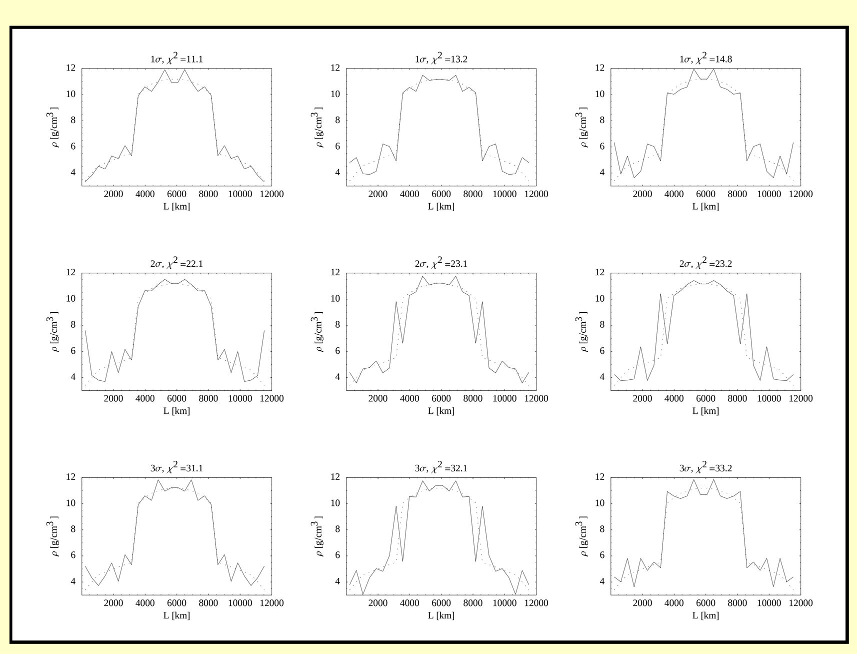
Use genetic algorithm with many trial runs to find matter density profiles fitting the measured energy spectrum.

Best results of genetic algorithm fits ($N = 4, 9, 14$):



All results are within the 1σ level. Therefore a preciser measurement is not possible and small fluctuations in mantle and core are not resolvable.

Examples for matter density profiles close to the 1σ (first row), 2σ (second row), and 3σ (third row) contours:

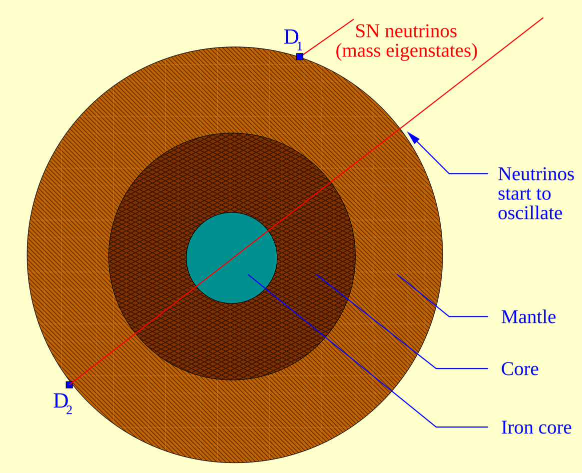


Tomography of the Earth's core using supernova neutrinos

Experimental setup: Galactic Supernova at $d = 10\,\text{kpc}$

Additional assumptions:

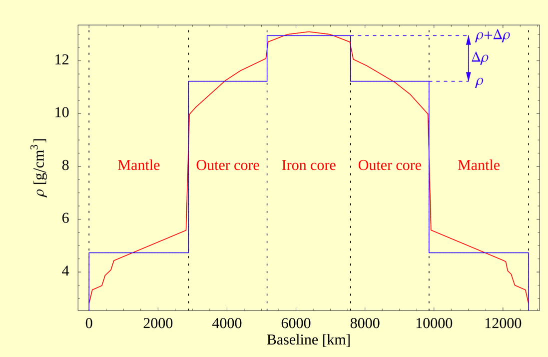
- LMA solution
- Adiabatic neutrino conversion in the supernova
- Mass eigenstates arrive at the Earth
- Energy spectrum measured by at least one detector D_1 on the Earth's surface
- At least one detector D_2 observes supernova with a baseline going through the Earth's core
- Knowledge on the Earth's mantle well–established from seismic wave geophysics, but less knowledge on the Earth's core provided (seismic s–waves cannot traverse the Earth's core)



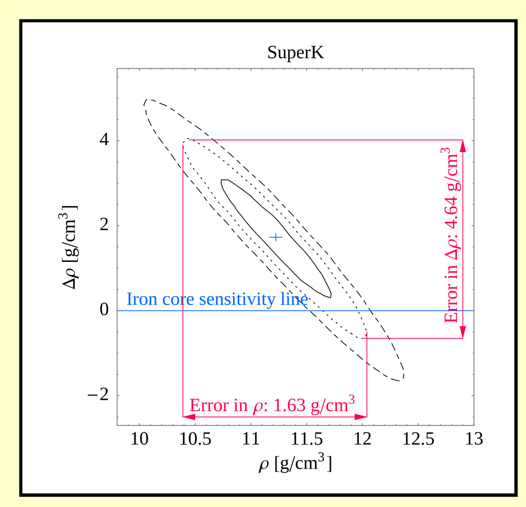
Mechanism: Mass eigenstates from Supernova start to oscillate when entering the Earth matter

The probability for a single detector to observe the supernova through the Earth's core is about 7.5% and through the Earth's iron core about 1%
→ A large number of detectors improves the chance to have a baseline through the Earth's core

The matter density profile an the step function approximation for a baseline of $L = 12,742\,\text{km}$:

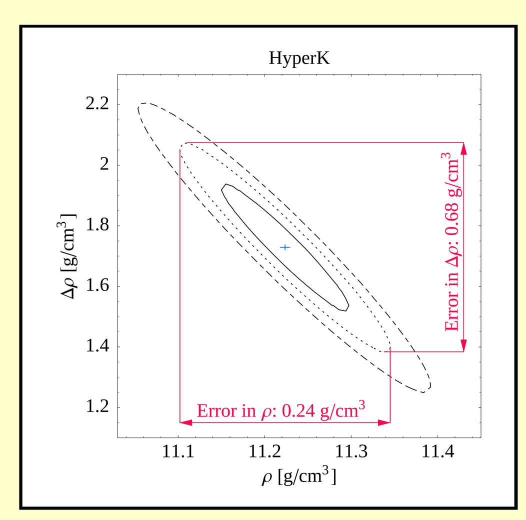


Results for SuperKamkionade–like detectors:



→ No sensitivity to the iron core (2σ, 3σ)
→ Mean core density measurable up to about 3% (for a one–parameter measurement at the 2σ level)

Results for HyperKamkionade–like detectors:



→ Iron core can be identified (or rejected) at the 99% confidence level
→ Mean core density measurable up to about 0.5% (for a one–parameter measurement at the 2σ level)
→ Outer core density measurable up to about 2% and $\Delta\rho$ up to about 40% (for a two–parameter measurement at the 2σ level)