Neutrino tomography of the Earth's lower mantle: first study with a full 3D model

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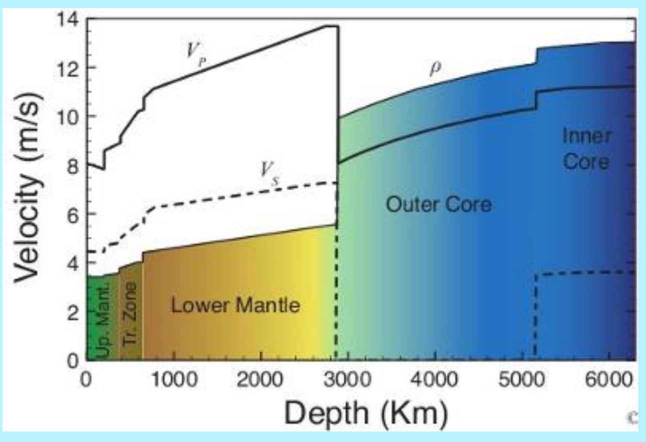
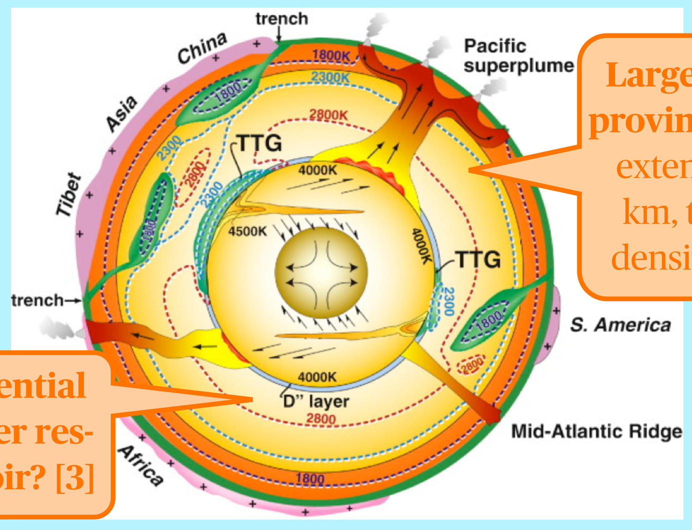
1 3D structures in the Earth's mantle

Preliminary Reference Earth Model (PREM) [1]: average **1D** matter density profile, known at -few % level



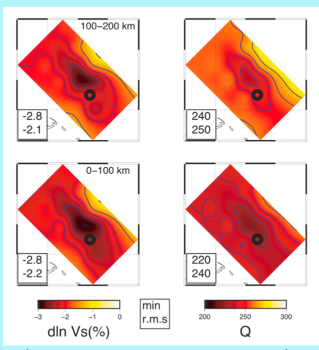
... but the inner Earth is not radially symmetric!

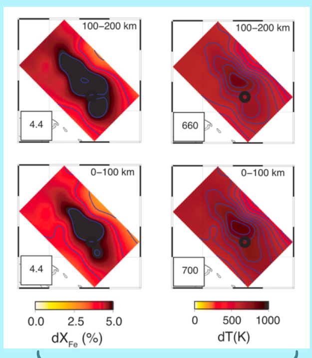


Large low velocity provinces (LLVP) [2]: extend over ~1000 km, temperature/ density anomalies?

Potential water reservoir? [3]

Possible approach to study the inner Earth: Imaging of the edge of the Hawaiian LLVP [4]





seismic data* → interpretation in terms of Fe content and temperature

***1D/3D imaging techniques in seismology:**
- P-wave and S-wave **velocities** from seismic travel times
- **Density** from long-period normal mode analysis
- **Attenuation** (Q) and **anisotropy** study using waveform amplitudes

Disentangling thermal from compositional origin of inhomogeneities requires a multi-parameter analysis
→ can the electron density be a new observable ?

2 Neutrino oscillation tomography

Atmospheric neutrinos:

→ isotropic beam of known composition of ν_e and ν_μ that cross the Earth [6]
- Wide range of **energies**: GeV-TeV
- Wide range of **oscillation path lengths** through the Earth: 50 km - 12.800 km

ν_e (not ν_μ, ν_τ) interact with electrons in matter:
- Extra potential proportional to the electron density N_e
- Matter effects modify flavour oscillations along the neutrino path

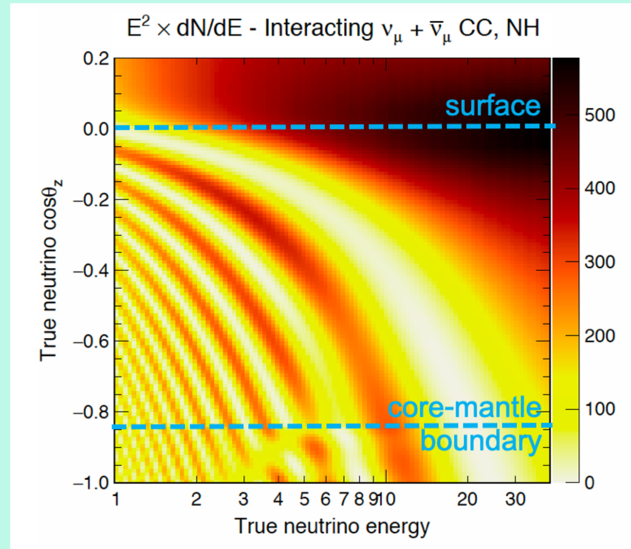


Figure taken from [5]

Maximal effect at resonance energy:

$$E_{\mathrm{res}} = \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}G_f N_e} \simeq 7\,\mathrm{GeV}\left(\frac{4.5\,\mathrm{g/cm^3}}{\rho_{\mathrm{matter}}}\right)\left(\frac{\Delta m^2_{31}}{2.4\;10^{-3}\,\mathrm{eV^2}}\right)\cos 2\theta_{13} \approx 7\,\mathrm{GeV}$$

For mantle density

Differential rate of interacting (anti)neutrinos of flavour β:

$$\frac{dN^{\mathrm{int}}_\beta(E,\theta)}{dE\,d\theta} = \sigma_{\nu_\beta}(E)\cdot\sum_{\nu_\alpha} P_{\nu_\alpha\to\nu_\beta}(E,\theta)\cdot\frac{d\Phi_{\nu_\alpha}}{dEd\theta}(E,\theta)$$

Cross section — Oscillation probabilities — Differential flux of atmospheric neutrinos

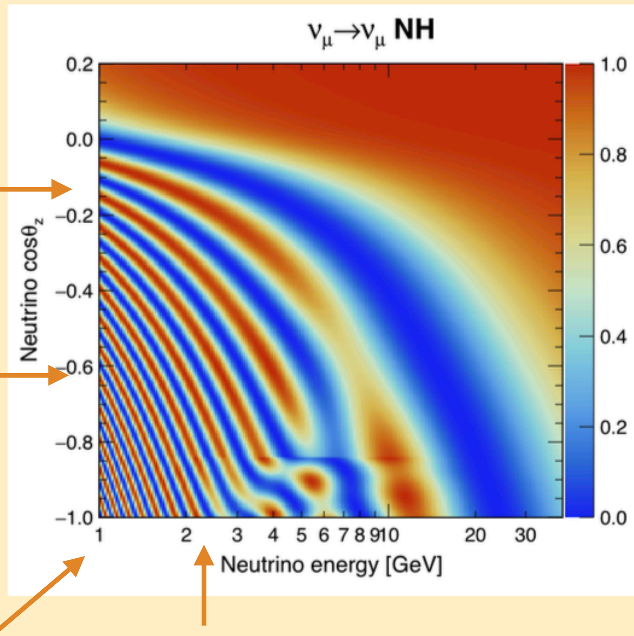
3 Simulations with EarthProbe

OscProb module

Neutrino **energy** and **zenith angle** sampling points

Neutrino oscillation parameters
→ Standard 3-flavours

Following the neutrino baselines - with layer information, followed in 3D:

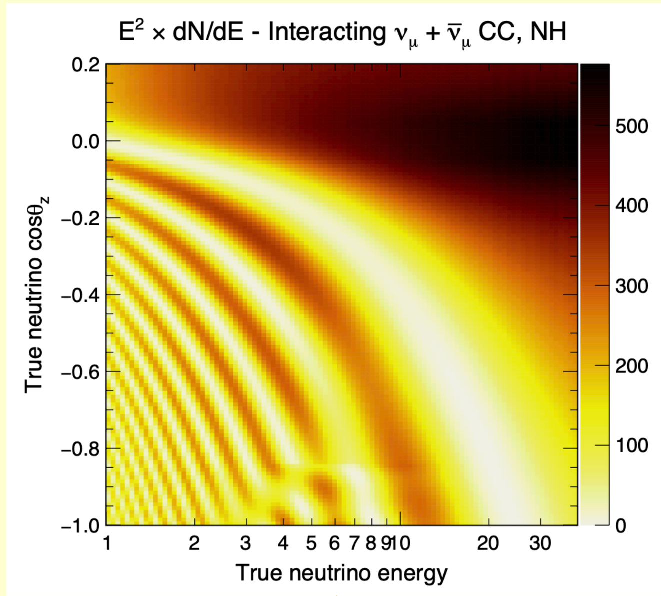


- Neutrino fluxes
- Neutrino cross sections

Earth model
1D PREM → 3D PREM with LLVPs
Detector position → latitude, longitude, depth

NEW

Interacting events



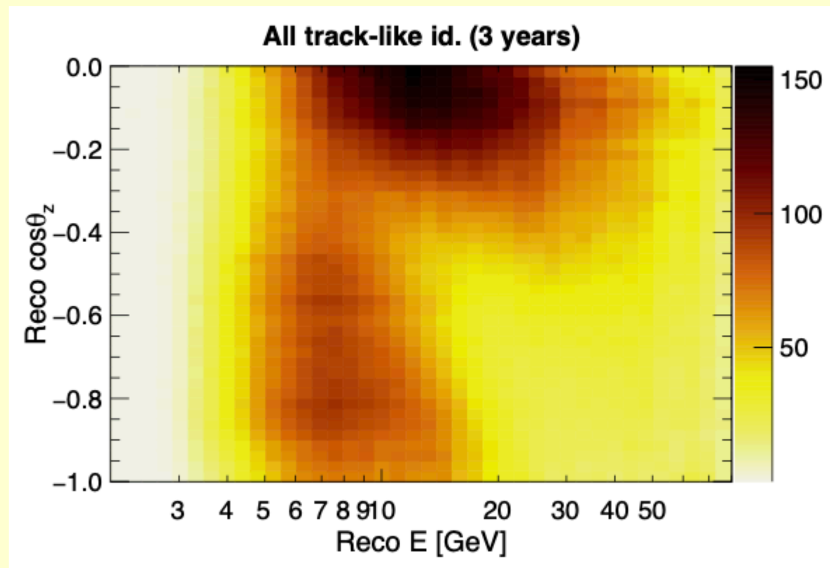
Exposure of 1 Mt · yr for a detector in sea-water

Parameterised detector response:
E, θ, ϕ resolutions

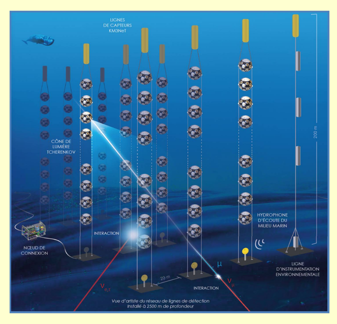
- Effective mass
- Particle identification → track vs. Shower

Binning for reconstructed neutrino energy and angle of incidence

Reconstructed events



Exposure of ~18 Mt · yr at KM3NeT/ORCA



4 3D implementation

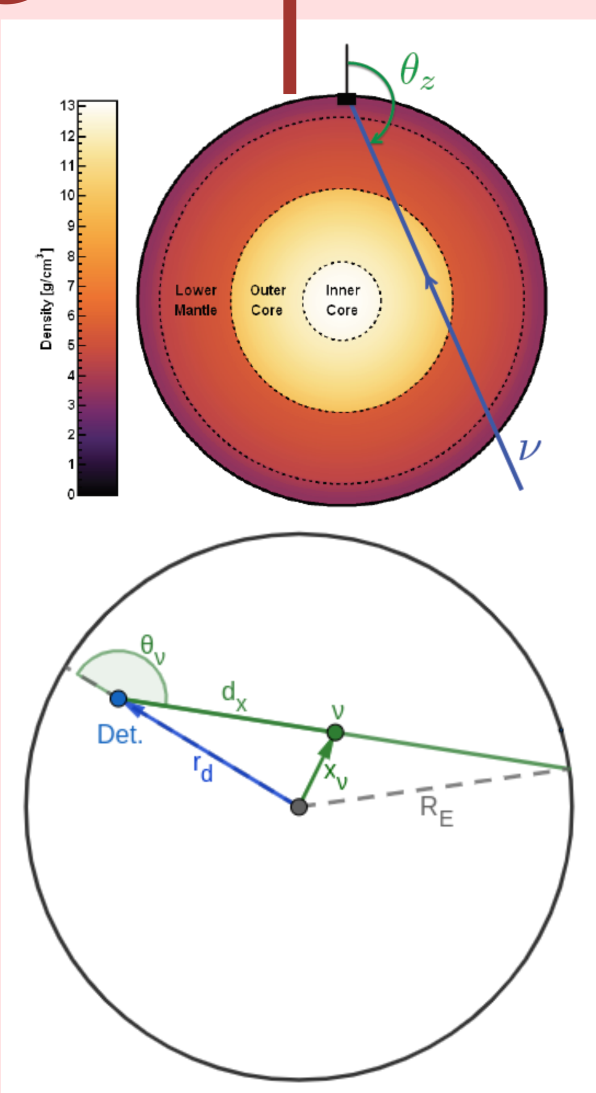
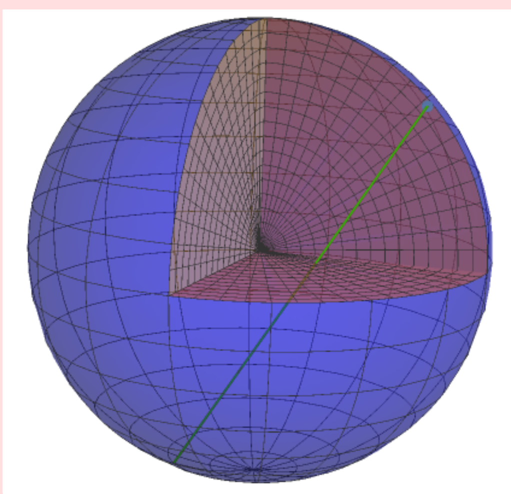


Figure taken from [7]

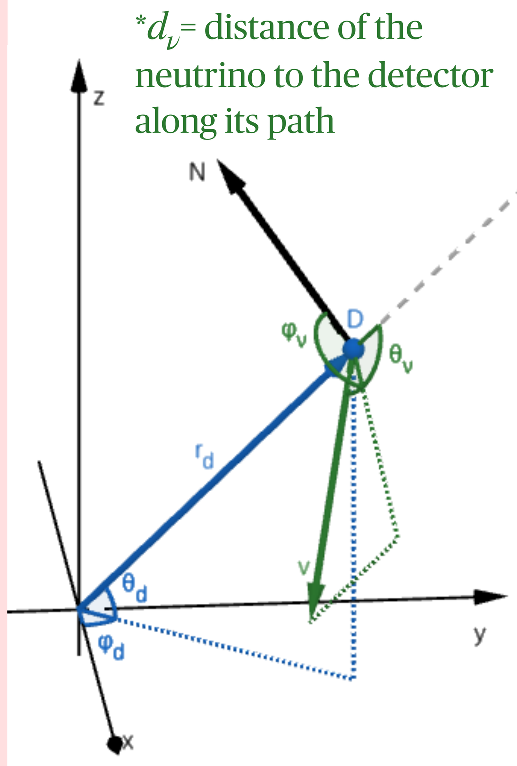
- Coordinates of the **detector** in the Earth's frame: d_d (depth), θ_d (latitude), ϕ_d (longitude)
- Coordinates of the **neutrino trajectory** as measured at the detector: d_ν*, θ_ν, ϕ_ν

All these coordinates need to be combined to obtain: the neutrino trajectory in the Earth's coordinate frame

Trajectory is distributed among **radial, θ and ϕ bins.**



*d_ν = distance of the neutrino to the detector along its path



5 Framework validation

Work in progress

PREM with modifiable region
Example : Binned "pancake" in the location and with the size of the **African and Pacific LLVPs**

```
African LLVP:
radius   = 3572 km
height   = 274 km
diameter = 5400 km

Pacific LLVP:
radius   = 3572 km
height   = 200 km
diameter = 5000 km
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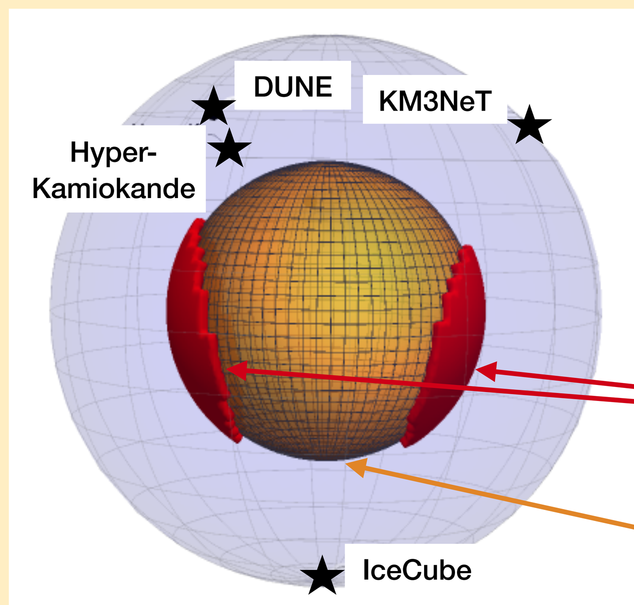
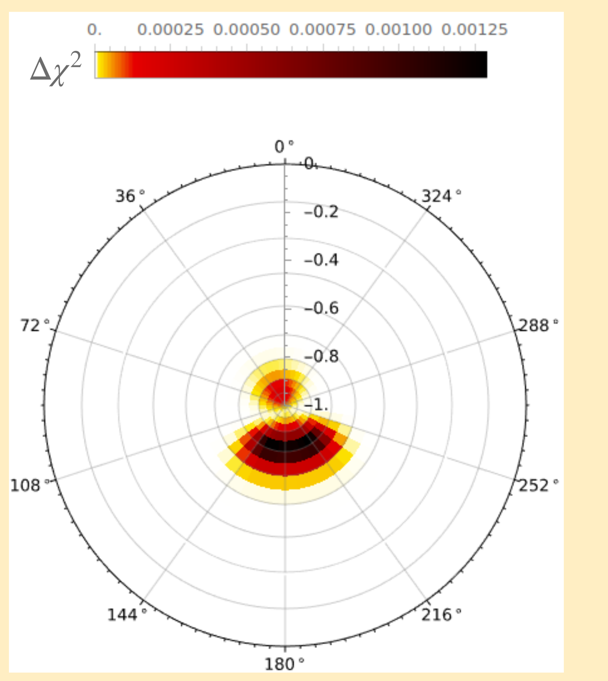


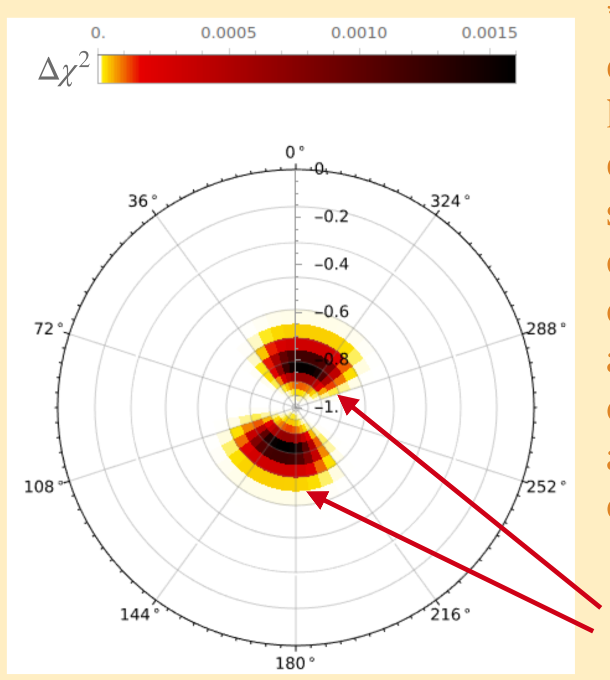
Outlook:
- Proof of concept for the detection of large inhomogeneities in the deep Earth by neutrino detectors
- Ongoing study exploring the requirements for next-generation neutrino detectors to achieve desired sensitivity

Sensitivity to discern between PREM and a +3% LLVP density anomaly:

*Next-generation detector in the **Mediterranean Sea**: Total $\Delta\chi^2$ = 0.045



Next-generation detector in the **South Pole**: Total $\Delta\chi^2$ = 0.059



*Next-generation detector = hypothetical detector with a size of 10 Mt, an energy resolution of < 10%, an angular resolution of ~7 degrees and an exposure time of 20 years.

[1] A. Dziewonski et al., Phys. Earth Planet. Int. 25, 4 (1981).
[2] A. McNamara et al., Tectonophysics 760 (2019).
[3] S. Karato, EPSL 301, 3-4 (2011).
[4] K. Konishi et al., J. Geophys. Res. Solid Earth 125, 2 (2020).
[5] S. Bourret, Ph. D. Thesis, USPC (2018).
[6] Honda M. et al., Phys. Rev. D 92, 2 (2015).
[7] Maderer L. et al., Front. Earth Sci. 11 (2023).