Neutrino tomography III: (high-energy) neutrinos to probe the Earth's core and mantle

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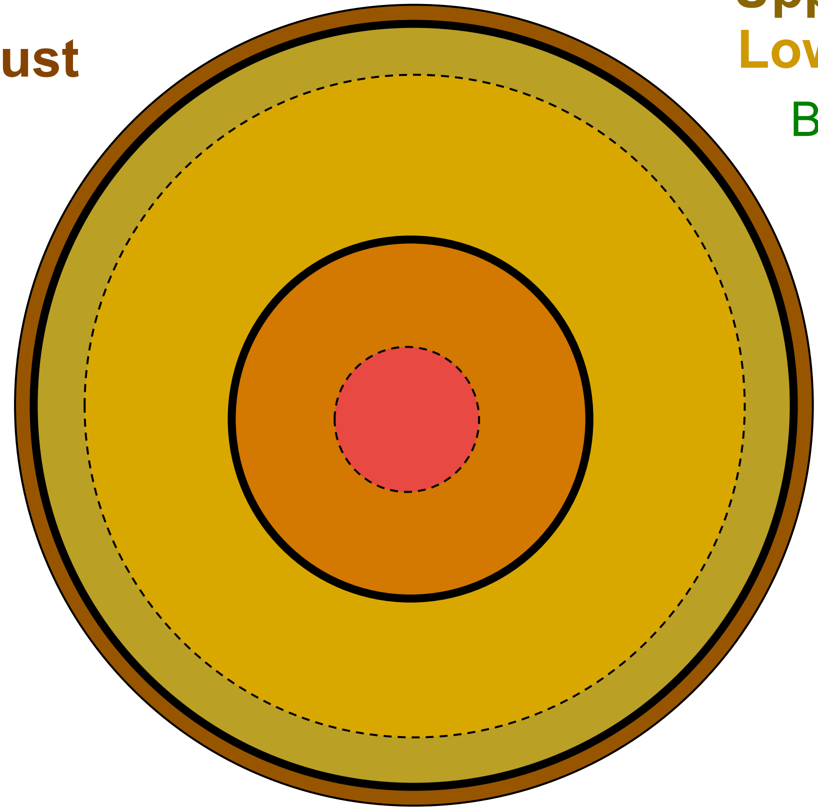
Looking at the Earth's interior…



Crust

Upper mantle Silicate minerals (Si,O,…)
Lower mantle Probed by seismic waves

Benchmark composition: pyrolite (Z/A=0.496)

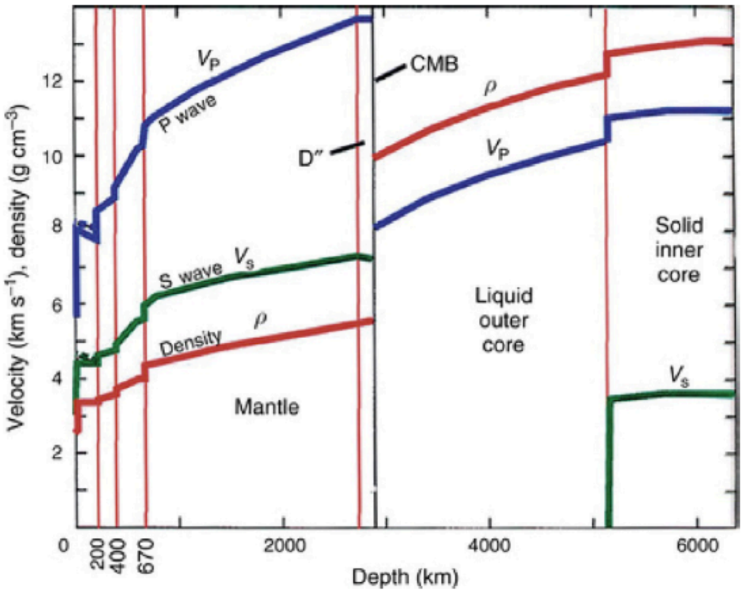
Outer core Liquid (no S-waves)
Inner core Solid

Benchmark composition:
Fe-Ni alloy (Z/A=0.466) + light elements ?
(Si, O, S, C, H)

inversion of seismic data
+ gravimetric constraints on
total mass, momentum of inertia

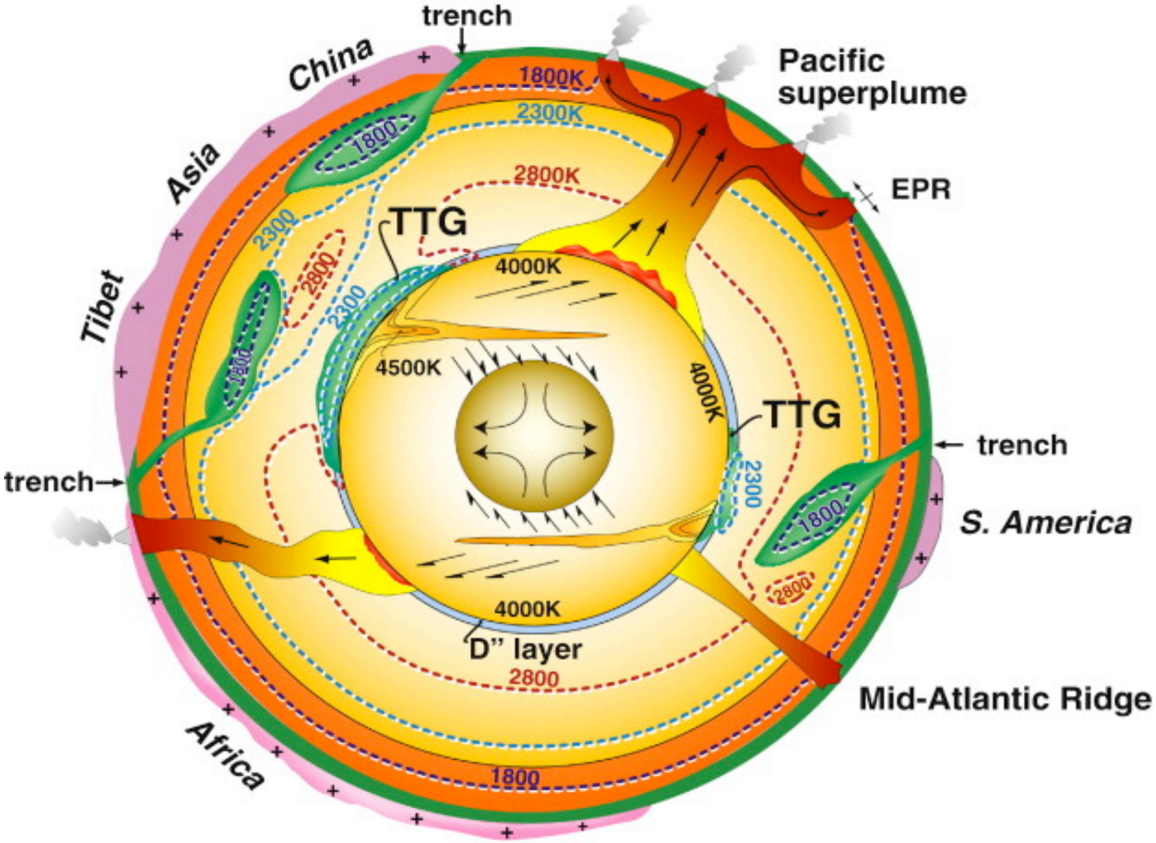
→ radial profile of Earth matter density
precision ~1% (?)

Preliminary Reference Earth Model



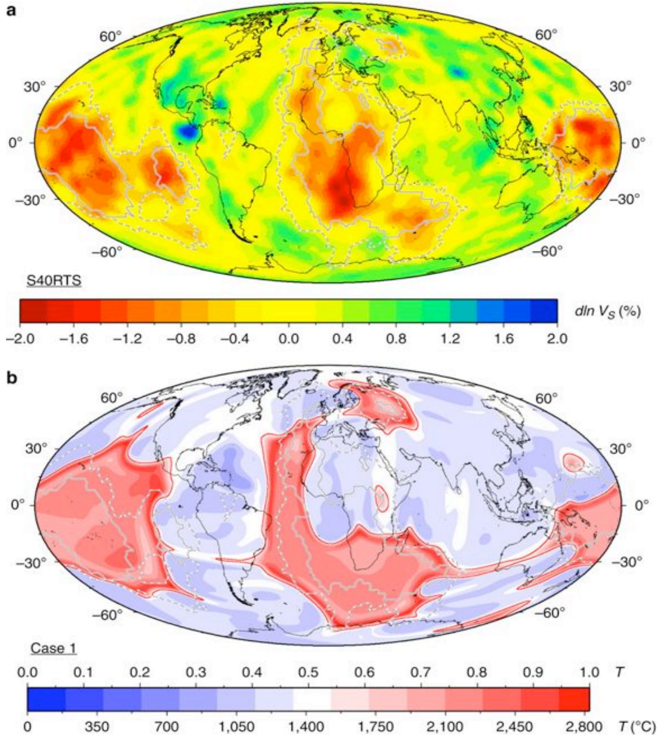
Dziewonski and Anderson, 1981

Looking at the Earth's interior…



Presence of large-scale anisotropies in the mantle:

Large Low-Shear-Velocity Provinces (LLSVP) extending over ~1000km



Mantle transition zone
D'' layer (at core-mantle boundary)
→ potential water reservoirs ?

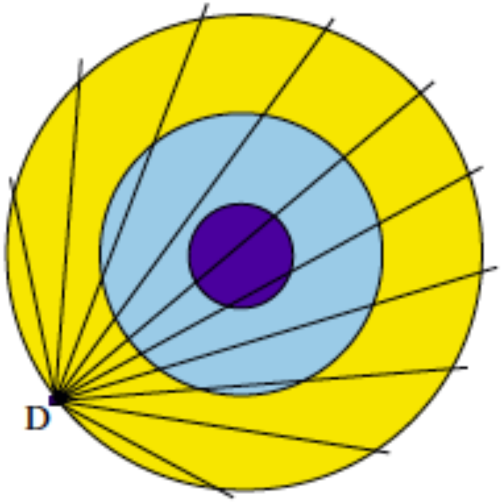
Nature ? Composition ?

→ Need for a reference 3D seismological model
… and complementary methods to investigate the deep Earth

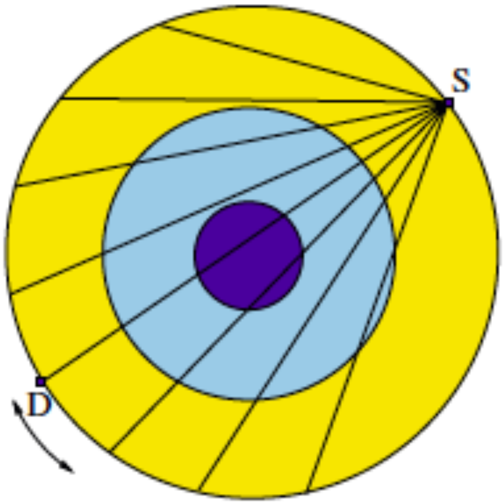
…with neutrinos

Early (conceptual) attempts:

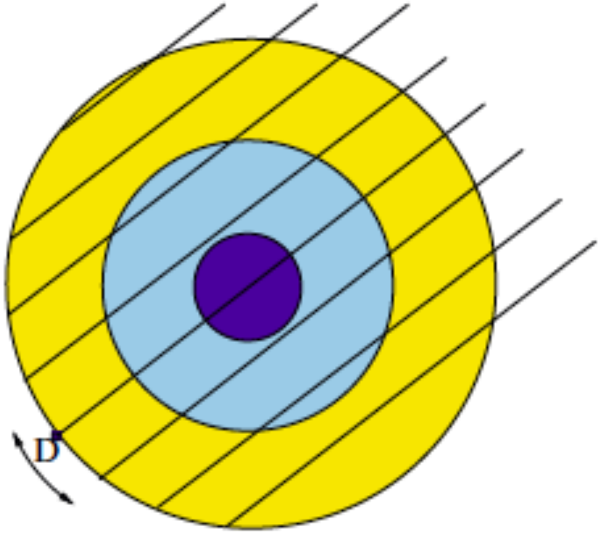
See review by W. Winter,
Earth Moon Planets 99 285 (2006)



a) Isotropic flux



b) High-energy neutrino beam



c) Cosmic point source

Need distributed sources…

✓ Atmospheric neutrinos !

Controlled source

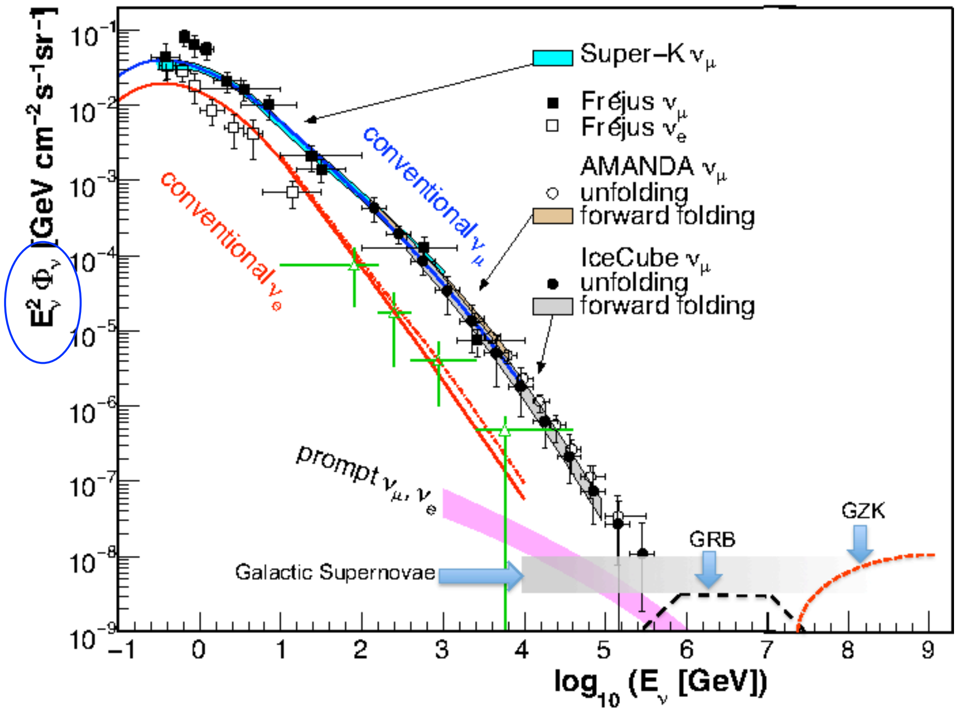
Needs steerable beam & moving detector…

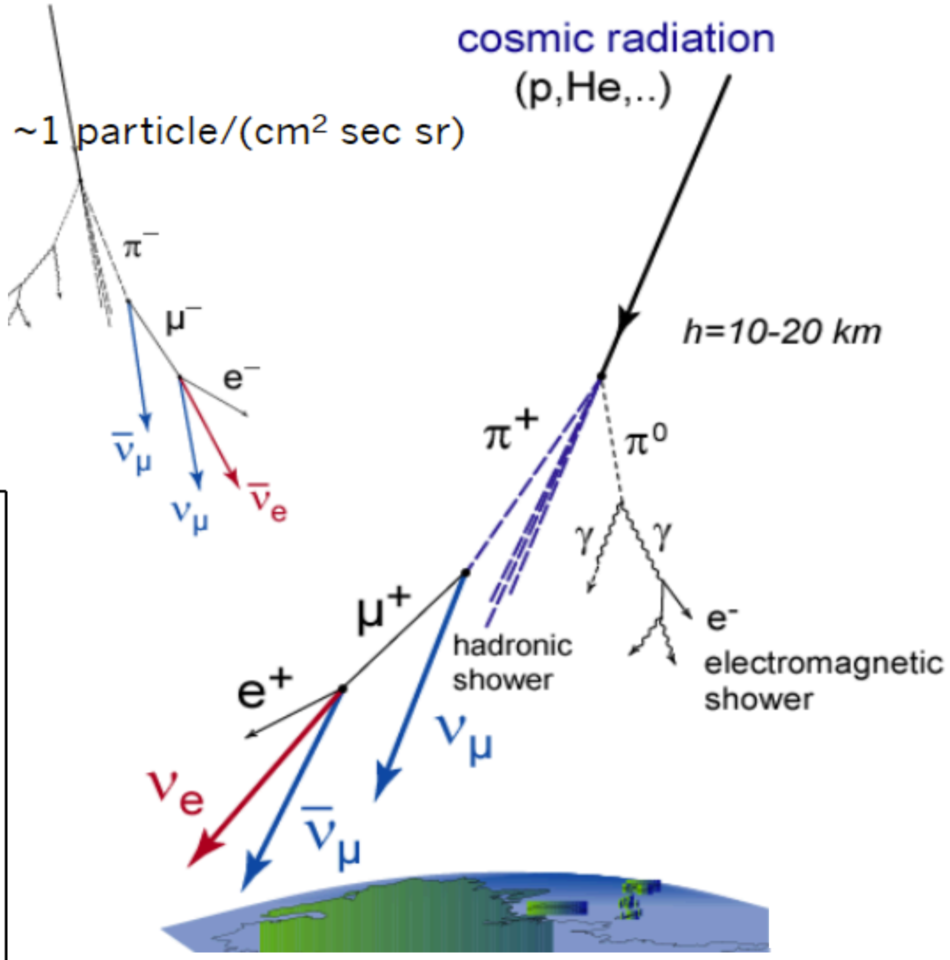
Uncontrolled source

Needs moveable detector

Atmospheric neutrinos

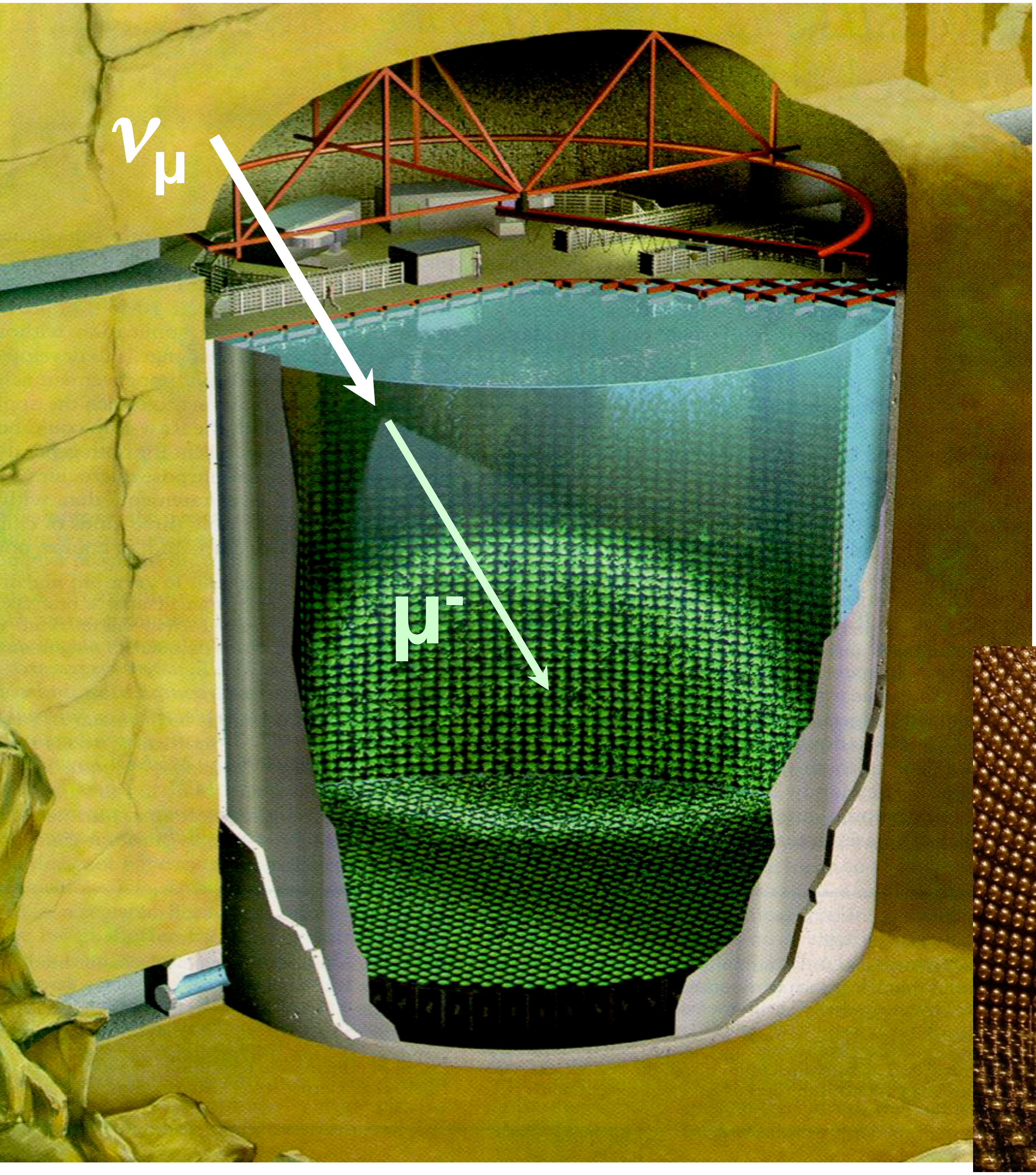
- (almost) isotropic flux
- known flavour composition
  (ν_e, ν_μ + antiparticles)
- Wide range of energies (GeV → PeV)
- steeply falling power-law spectrum:

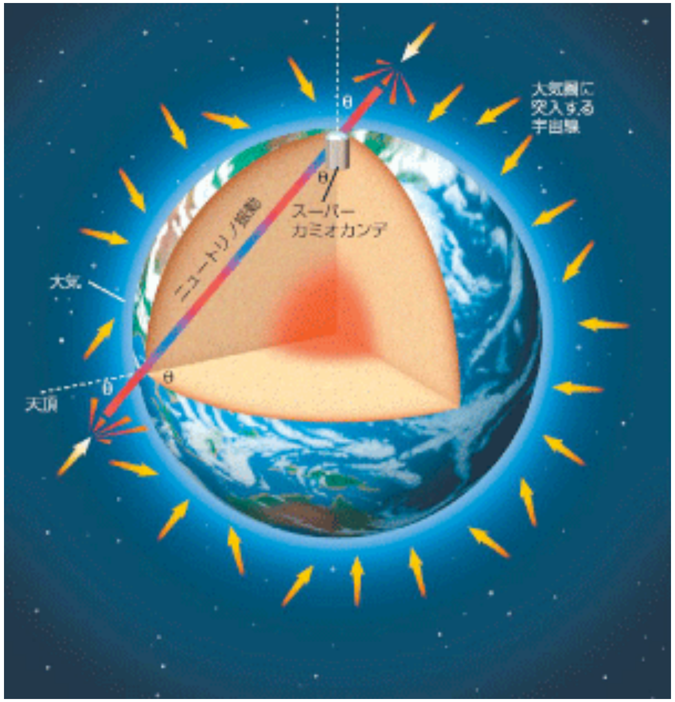


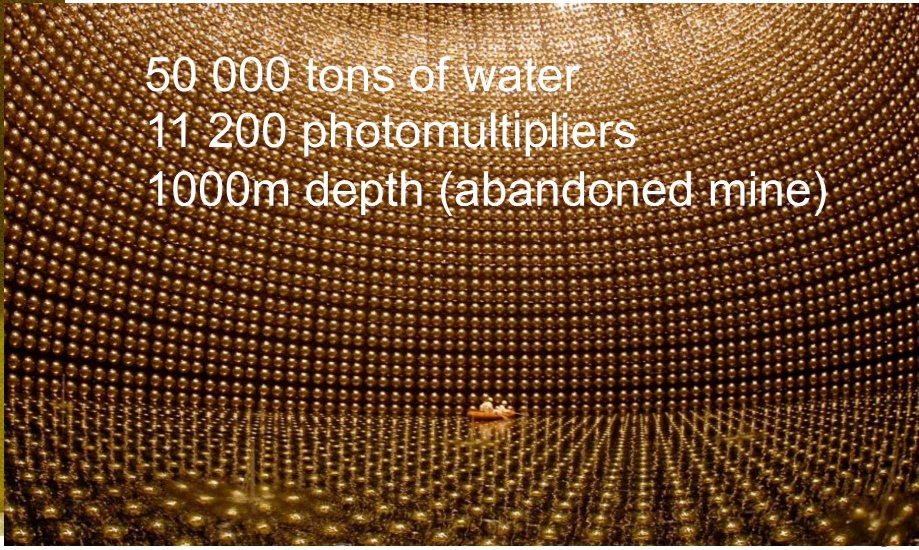


Atmospheric neutrinos

The Superkamiokande Cherenkov detector

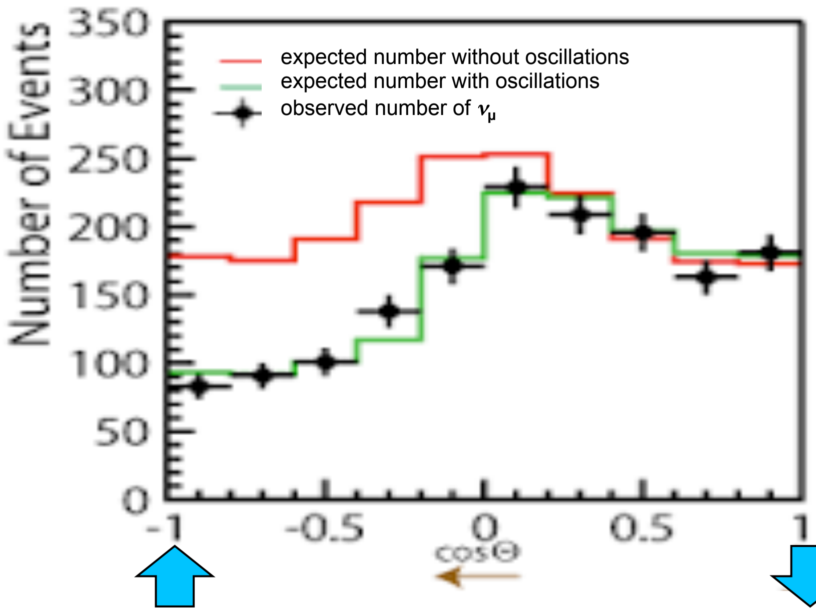






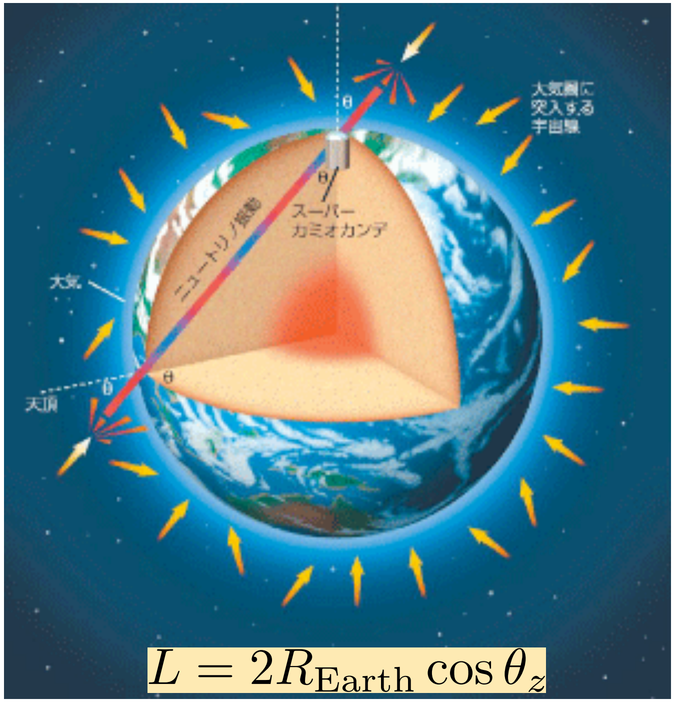
50 000 tons of water
11 200 photomultipliers
1000m depth (abandoned mine)

Atmospheric neutrinos



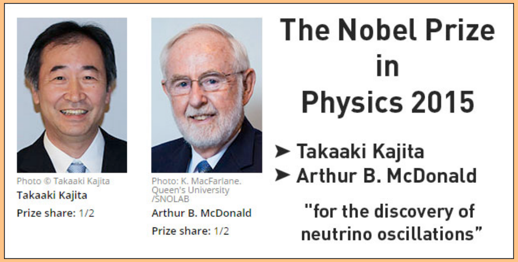
Upward going
Baseline ~13 000 km

Downward going
Baseline ~20 km



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

1998: discovery of neutrino oscillations



The Nobel Prize in Physics 2015

- Takaaki Kajita
- Arthur B. McDonald

"for the discovery of neutrino oscillations"

Photo © Takaaki Kajita
Takaaki Kajita
Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB
Arthur B. McDonald
Prize share: 1/2

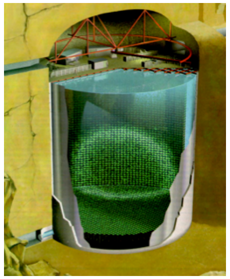
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} U_{PMNS} \end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \begin{matrix} \updownarrow \Delta m^2_{12} \\ \updownarrow \Delta m^2_{23} \end{matrix}$$

mixing matrix
3 angles (θ_{12}, θ_{23}, θ_{13})
+ 1 phase (δ)

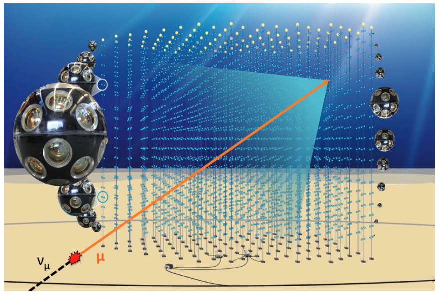
Flavour eigenstates

Mass eigenstates

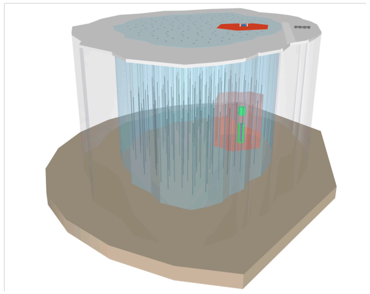
Earth tomography with atmospheric neutrinos



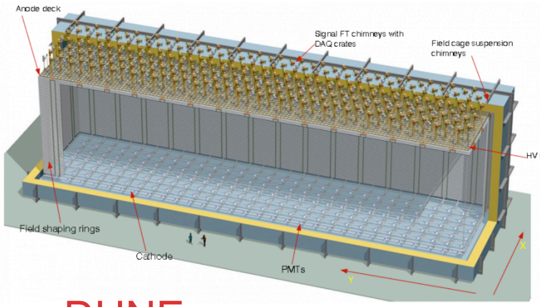
SuperKamiokande
HyperKamiokande



KM3NeT/ORCA



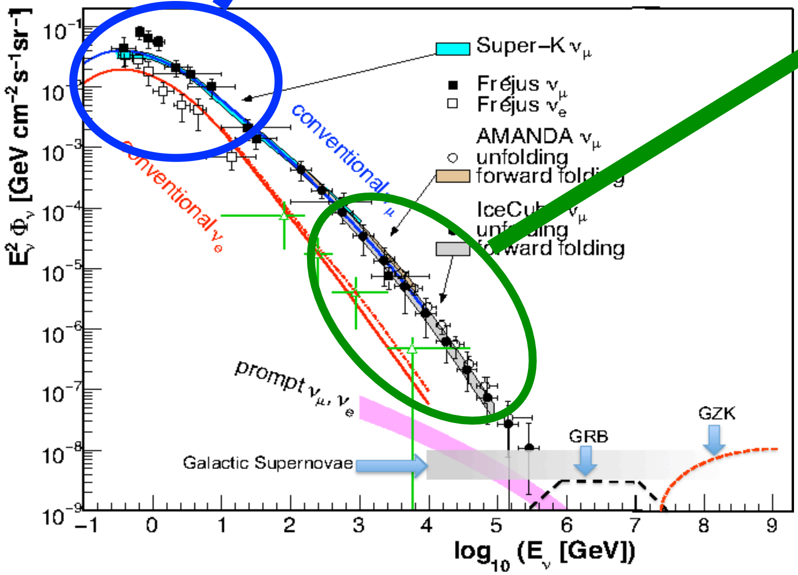
PINGU (IceCube)



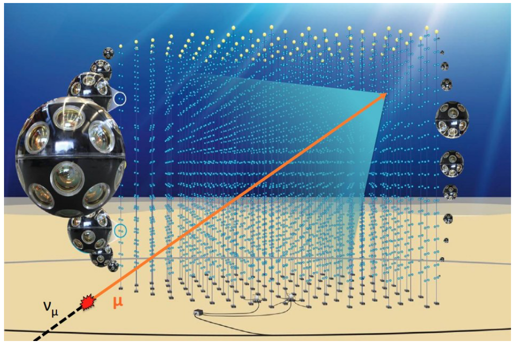
DUNE

At low (GeV) energies:
Neutrino oscillation tomography
(sub- or multi-)Megaton-scale detectors

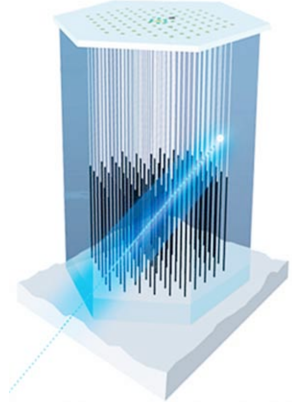
active
in construction
proposed/prototyping



At high (TeV-PeV) energies:
Neutrino absorption tomography
~ Gigaton-scale detectors

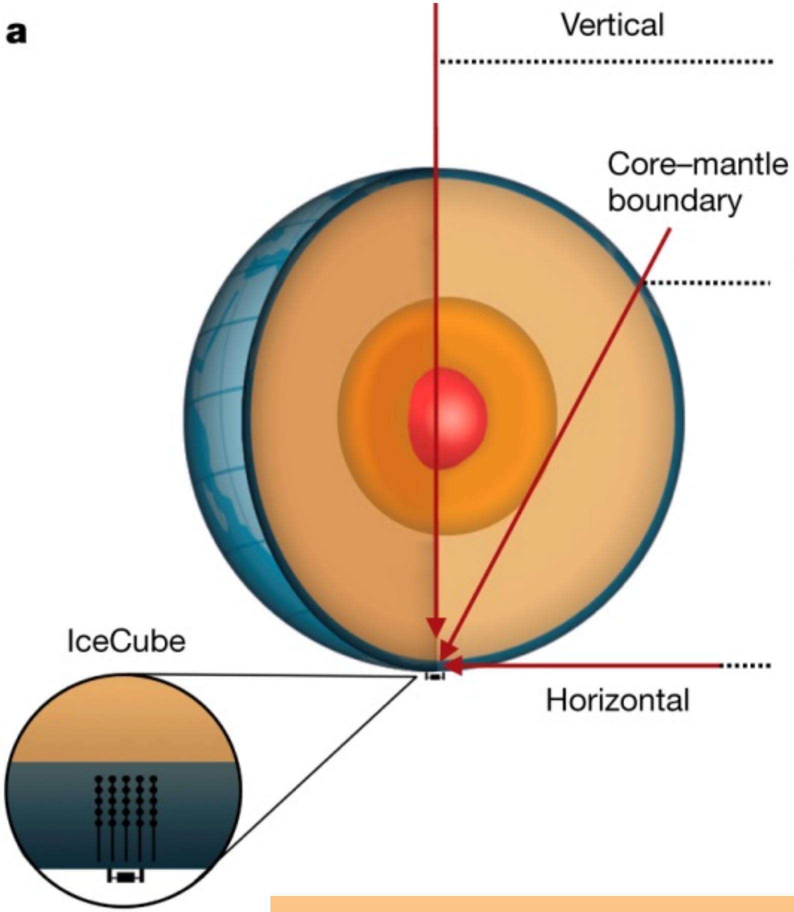


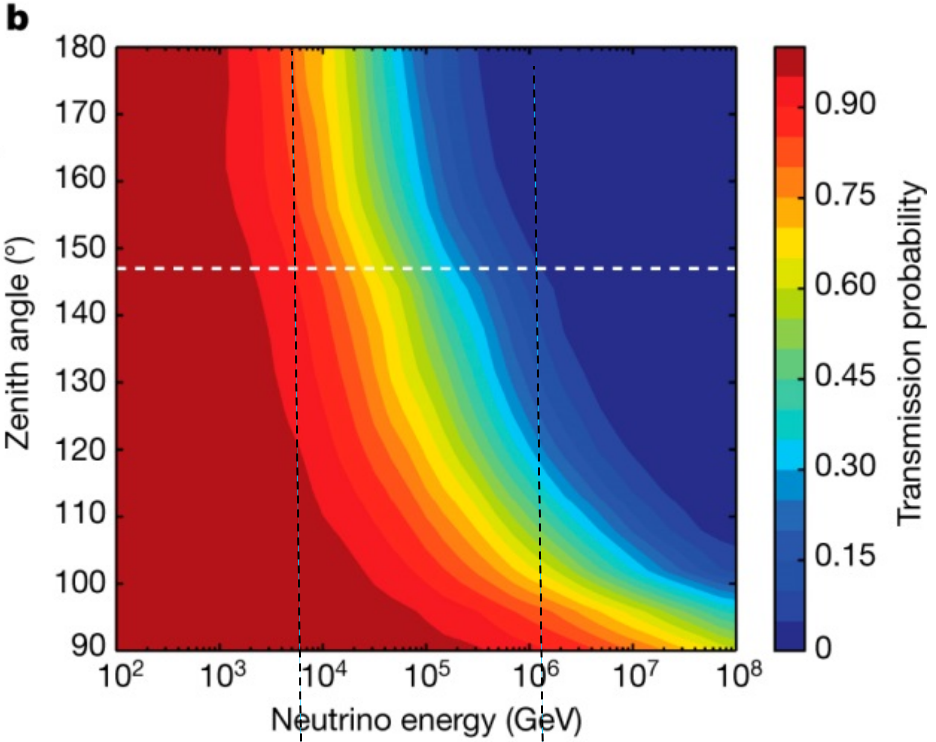
KM3NeT/ARCA



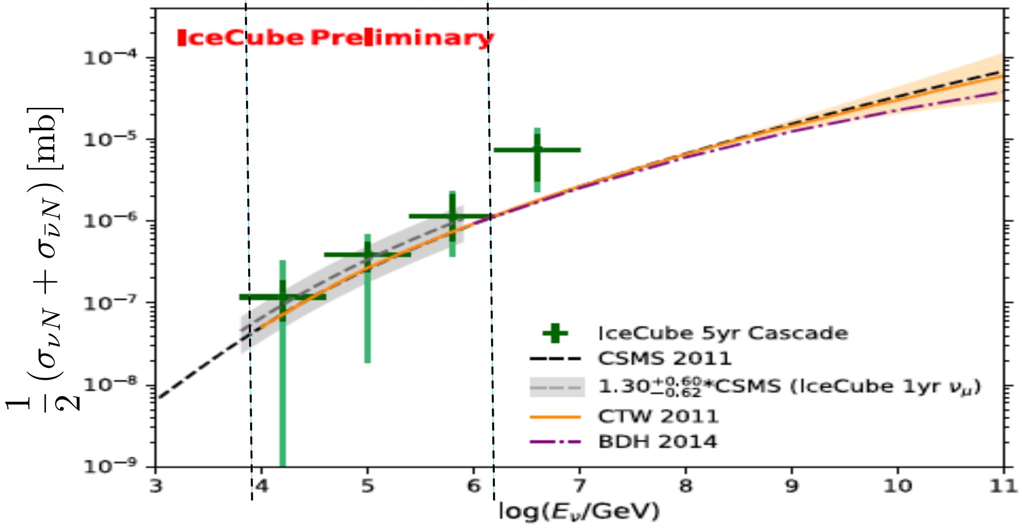
IceCube/Gen2

At high energies: absorption tomography





$$P(L) = 1 - \int_0^L \frac{dx}{L} \exp\left(-\frac{x m_N}{\sigma_{\nu N}\,\rho_m}\right)$$

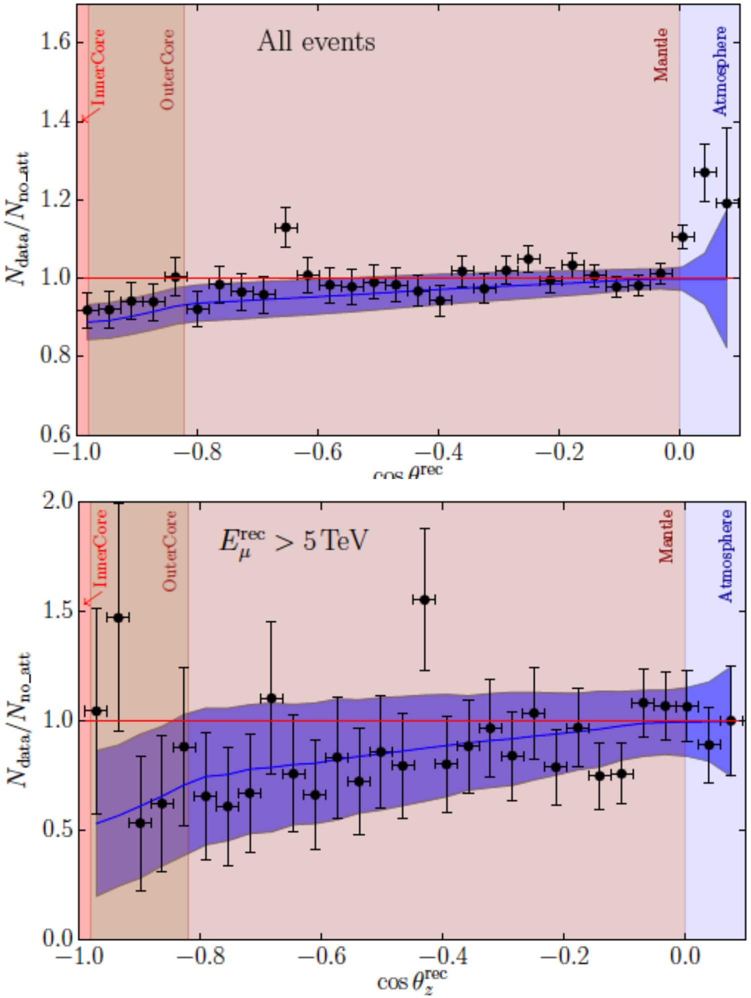


driven by the increase
of neutrino-nucleon
cross-section
at high energies

IceCube Coll., Nature 551 (2017)
& arXiv:1809.06782v1

At high energies: absorption tomography

Absorption tomography is sensitive to Earth matter density ρ_m



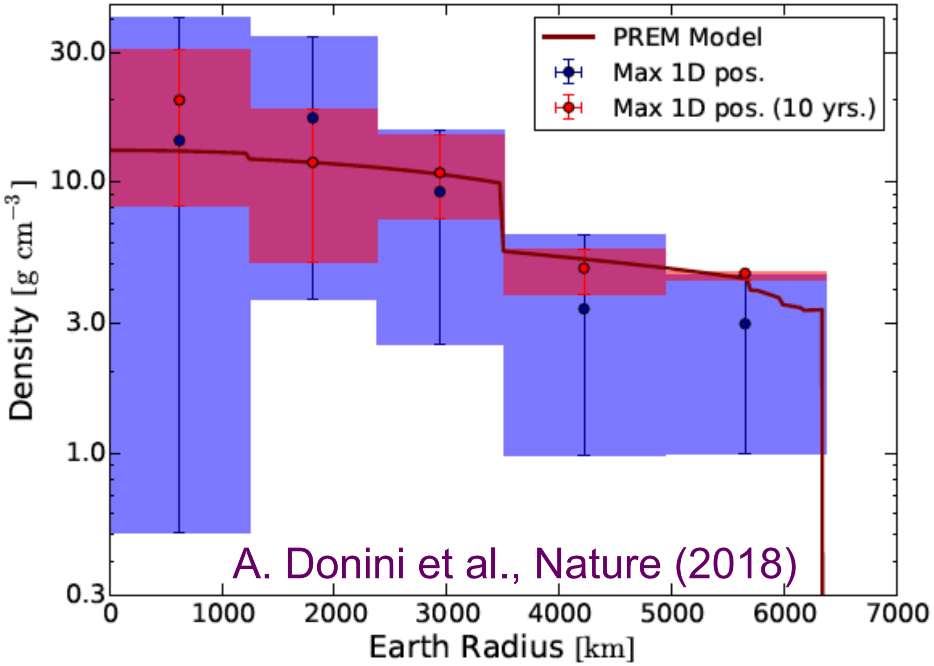
No attenuation (transparent Earth)

PREM expectation

2018: first study with real data

IceCube 1 yr sample (2011-2012) – upgoing ν_μ

Radial model with 5 layers of constant density



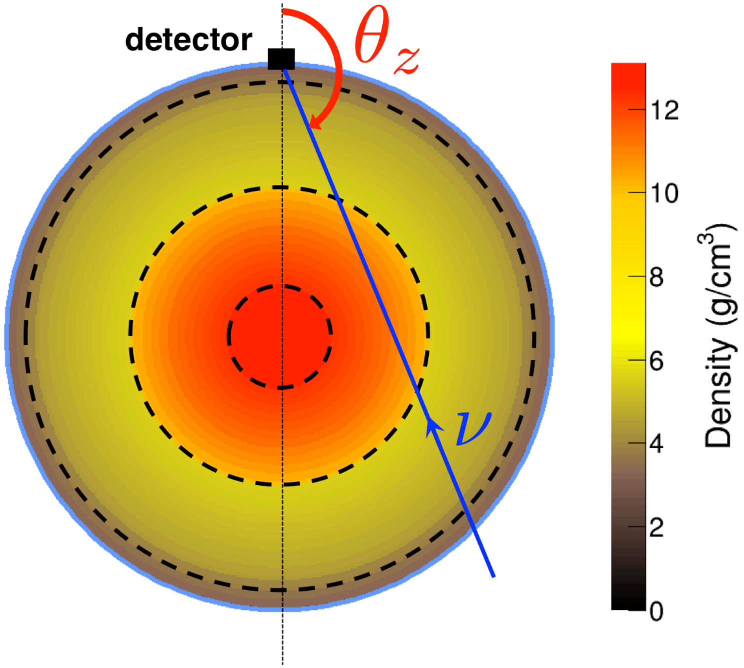
A. Donini et al., Nature (2018)

→ (much) more statistics needed to reach < few % uncertainty level

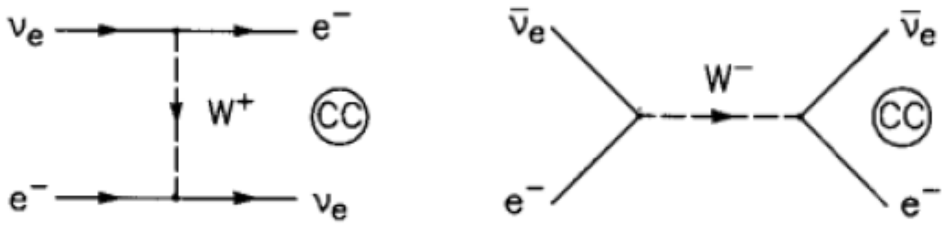
→ Will need good control of systematics

At low energies: oscillation tomography

Neutrino oscillations are affected by the presence of matter:



ordinary matter contains e's but no μ's or τ's
→ extra interaction channels for ν_e / $\bar{\nu}_e$



→ extra potential in propagation Hamiltonian, proportional to electron density in medium

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

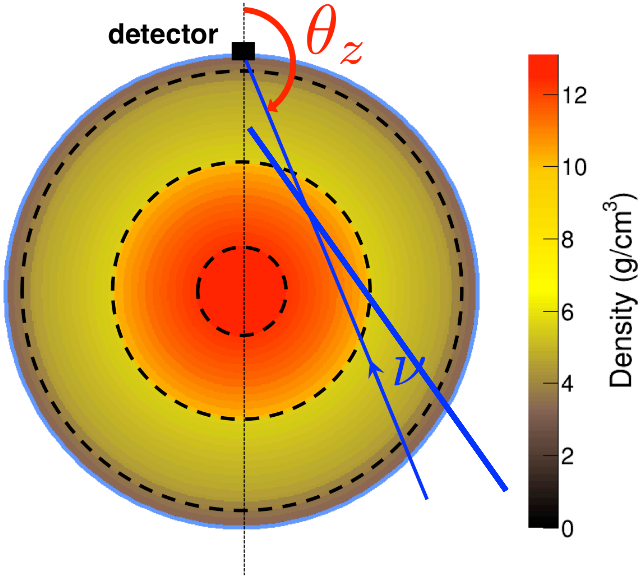
→ Resonance energy for neutrino oscillations:

$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}\,G_F\,N_e} \simeq 7\,{\rm GeV}\left(\frac{4.5\,{\rm g/cm^3}}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times10^{-3}\,{\rm eV^2}}\right)\cos 2\theta_{13}$$

≅ 3 GeV (core)
≅ 7 GeV (mantle)

for neutrinos if $\Delta m^2_{13} > 0$ / antineutrinos if $\Delta m^2_{13} < 0$
→ depends on the neutrino mass hierarchy – not yet measured…

Constraining the deep Earth composition ?



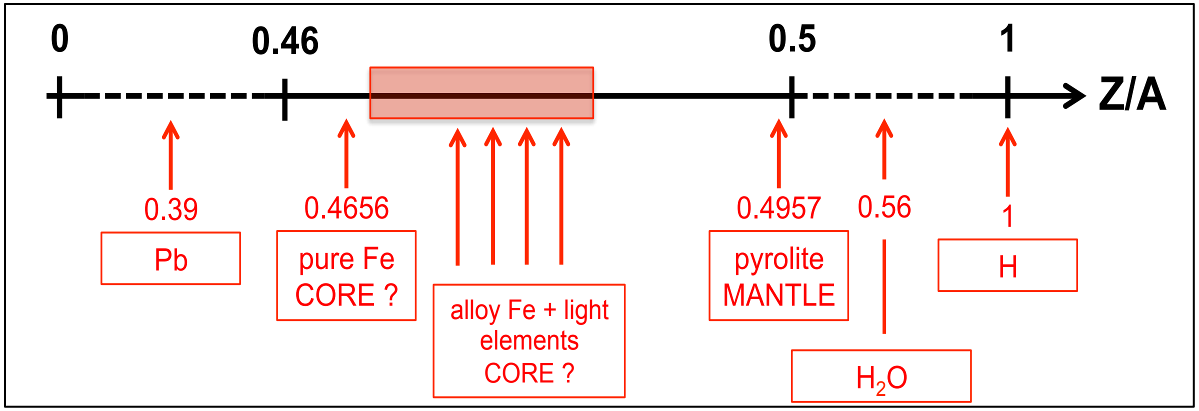
Measured in neutrino oscillation patterns

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

assume known matter density profile (PREM)

Constrain Z/A in core/mantle

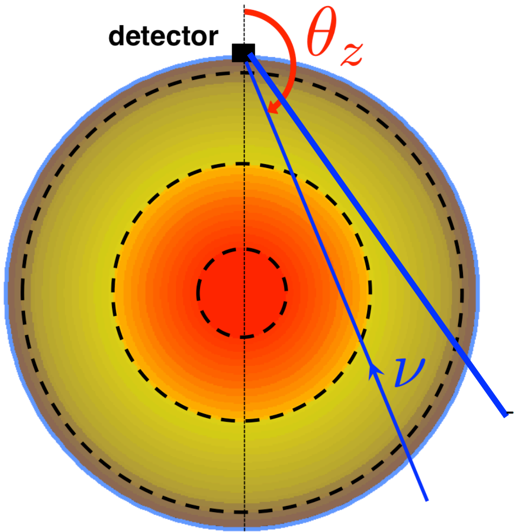
Assuming known density profile, oscillation tomography
is sensitive to Earth composition !



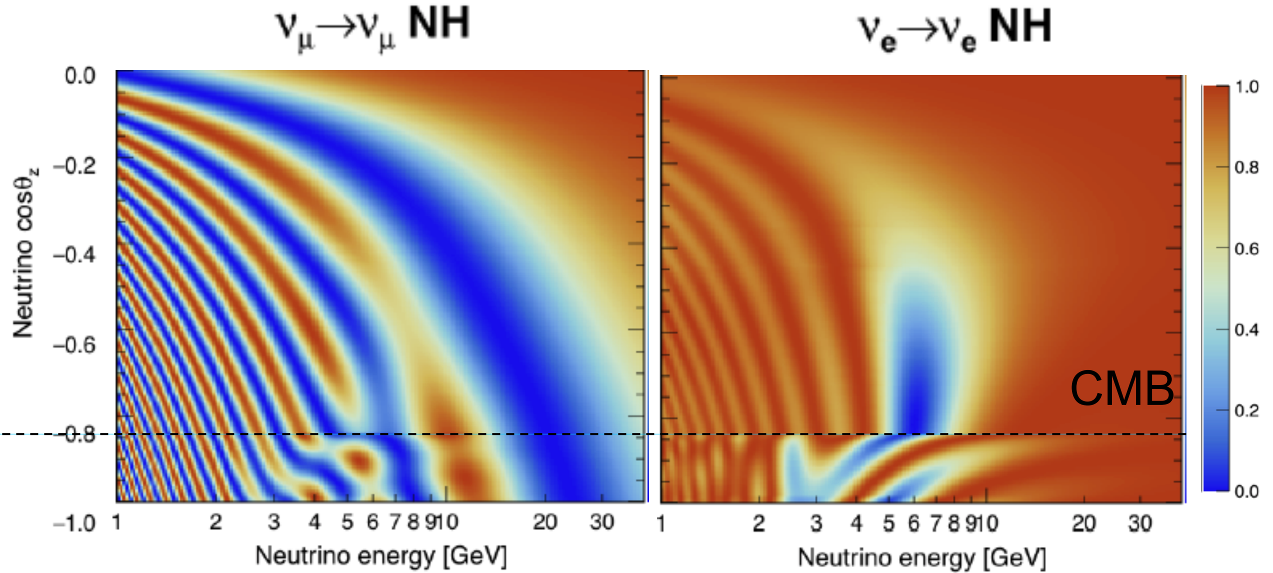
Typical values of Z/A for chemical elements or alloys present in the Earth

At low energies: oscillation tomography

Oscillation (survival) probabilities for ν_e and ν_μ crossing the Earth



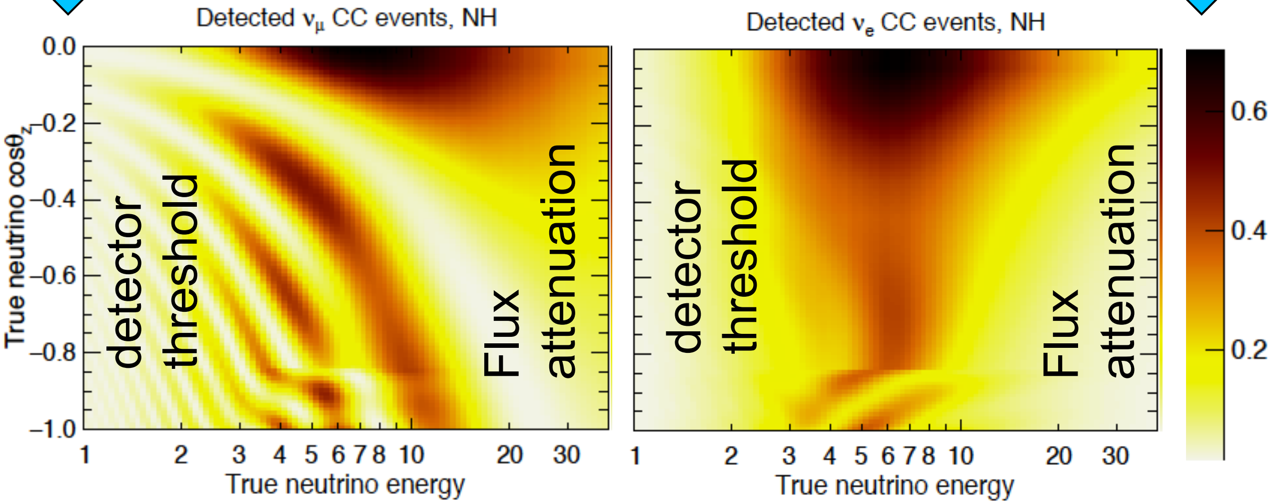
PREM + benchmark composition



$$\times \Phi_{\nu_X}(E,\theta) \times \sigma_{\nu N}(E) \times M^{eff}_{\nu_X}(E,\theta) \times t$$

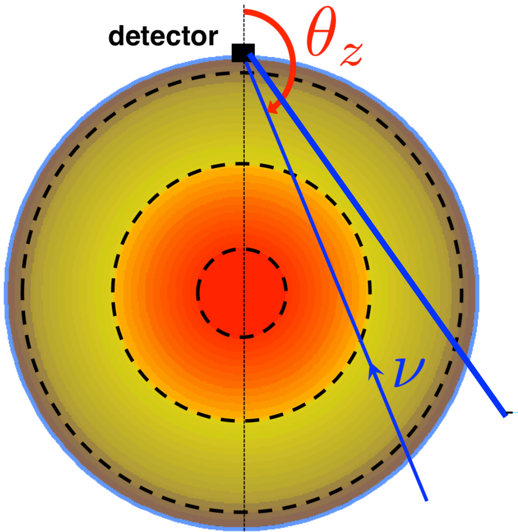
→infer the electron density by measuring the ν_e / ν_μ event rates at the detector

(here:
1 Mton yr exposure)

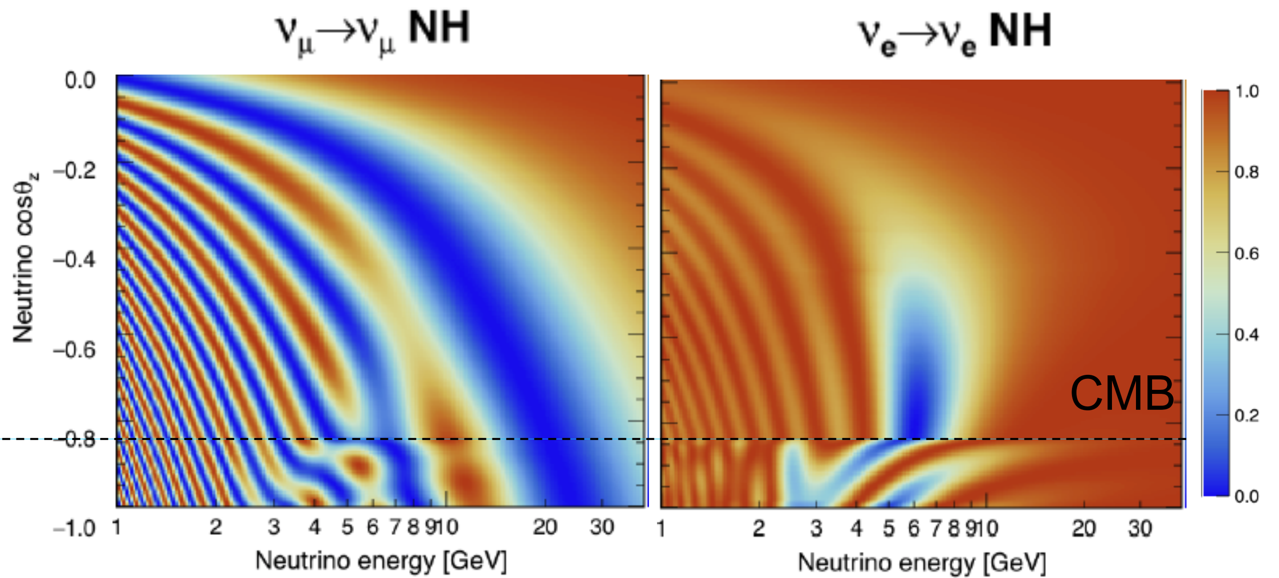


At low energies: oscillation tomography

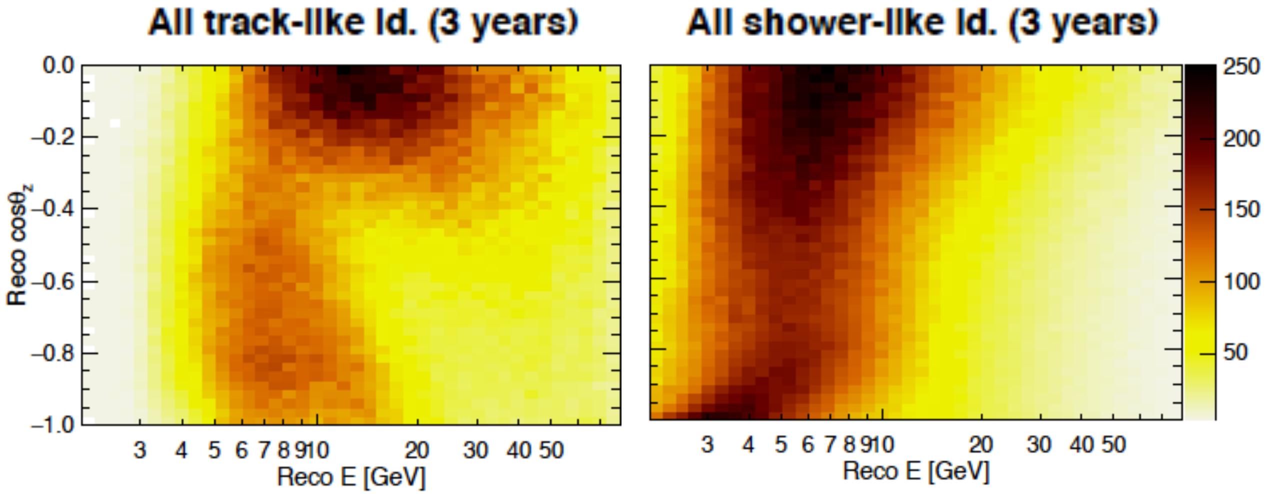
Oscillation (survival) probabilities for ν_e and ν_μ crossing the Earth



PREM + benchmark composition



All detector effects included



CHALLENGE:
Achieve sufficient Reconstruction/ID performances in the detector !!

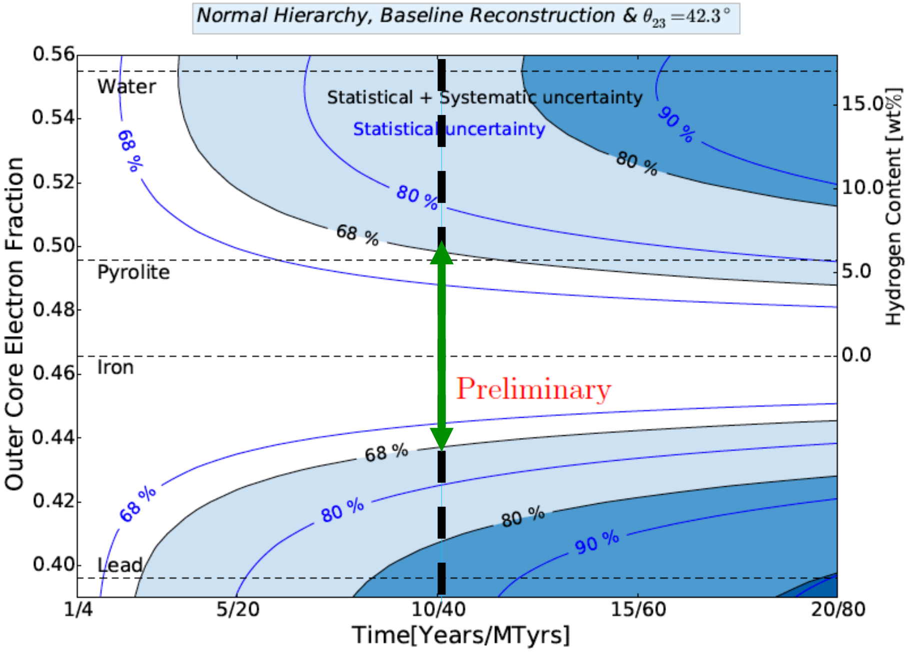
(here: ORCA 3 years)

Constraining the deep Earth composition ?

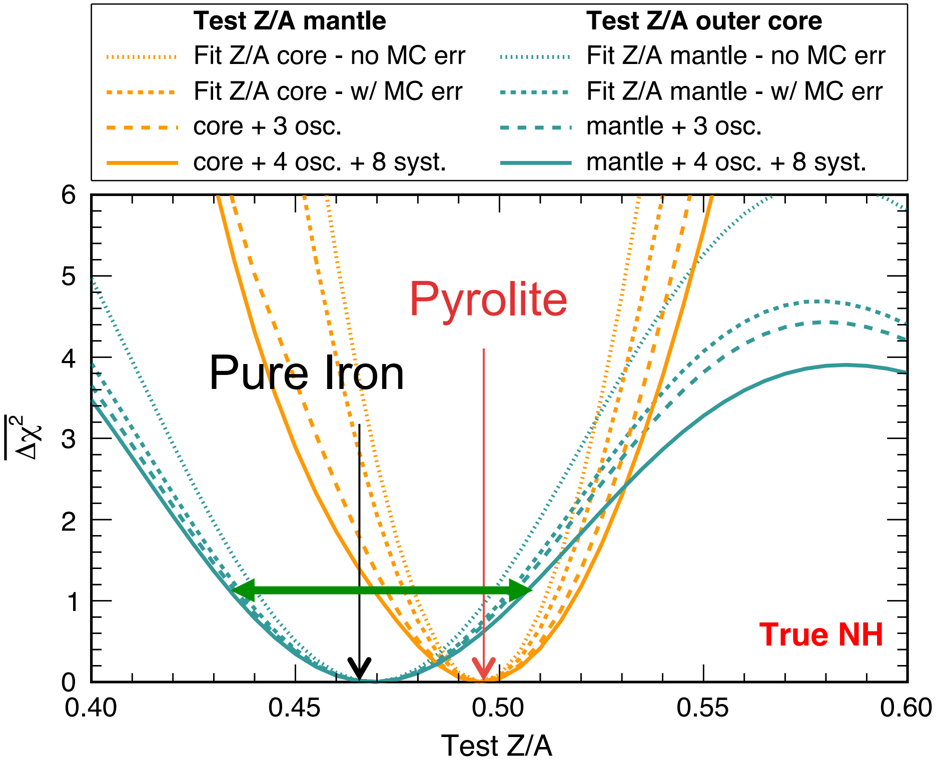
PINGU LoI, arXiv:1401.2046
See also C. Rott et al., Sci.Rep. 5 (2015) 15225

Bourret at al., proc. VLVnT 2018 (in press)

PINGU outer core, normal neutrino hierarchy



ORCA 10 years, normal neutrino hierarchy



→ A few % sensitivity on Z/A in outer core and lower mantle within reach of the upcoming generation of Cherenkov detectors (10 years timescale)

BUT needs measurement of neutrino mass hierarchy first! (aka sign of Δm^2_{13})

Perspectives

Neutrinos offer novel methods to probe the Earth's interior:

◆ Absorption tomography (TeV-PeV neutrinos)

can inform on **Earth matter density in D" and LLSVP**

→ needs large statistics of events at >10 TeV energies (IceCube/ARCA)

◆ Oscillation tomography (~GeV neutrinos)

can inform on **core/lower mantle composition**

→ needs large statistics of events at ~GeV energies (ORCA/PINGU)

→ needs improved detector performances (lower threshold/better reco: DUNE ?)

→ needs to resolve first the neutrino mass hierarchy

Upcoming detectors → benchmark sensitivity ~ few % after 10 years
…then: systematics might become an issue

→ The case for next-generation detectors optimised for neutrino tomography ?

… reach 1% sensitivity level

(H in outer core, H_2O in mantle…)

… **detector network** for combined measurements

(3D profiles and large-scale inhomogeneities)

…see poster by Simon Bourret