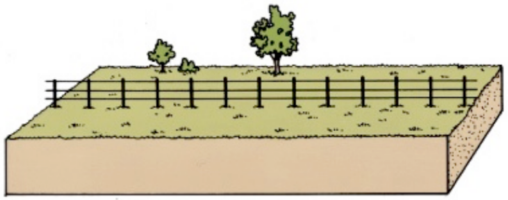
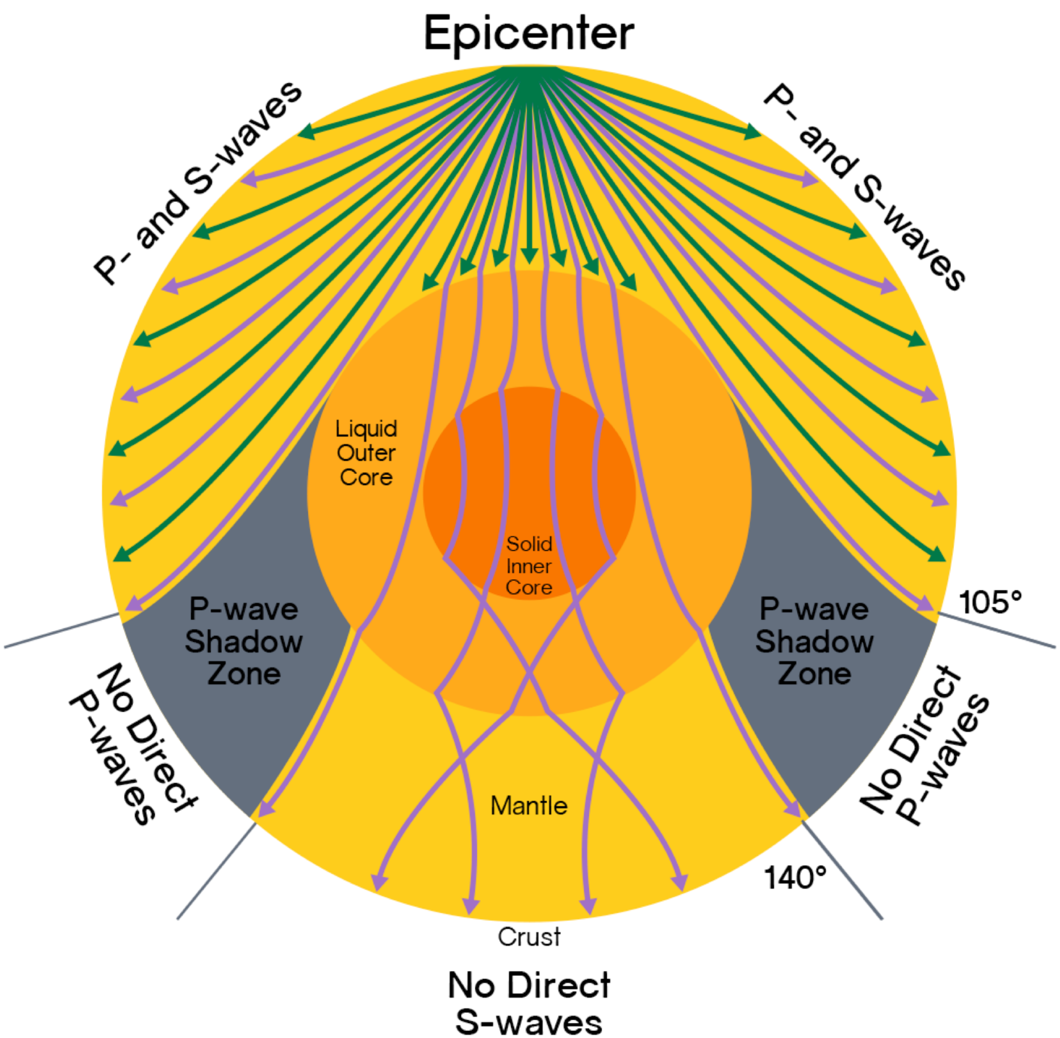
Probing the interior of the Earth with *high-energy* neutrinos

Véronique Van Elewyck
Laboratoire AstroParticule et Cosmologie
Université Paris Cité & Institut Universitaire de France

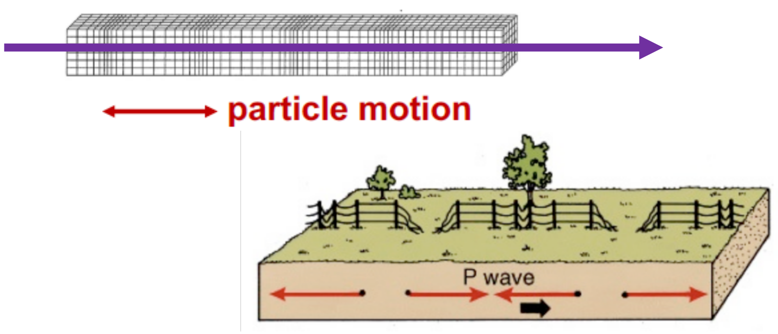
Looking at the Earth's interior…

The geophysicists' way: studying seismic waves

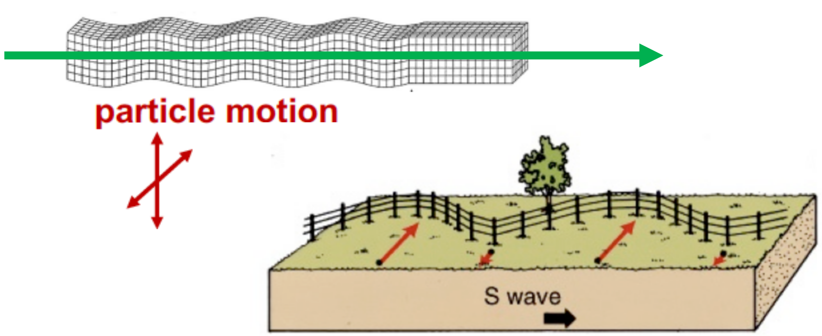




P waves (fastest) : pressure waves



S waves (slower): shear waves

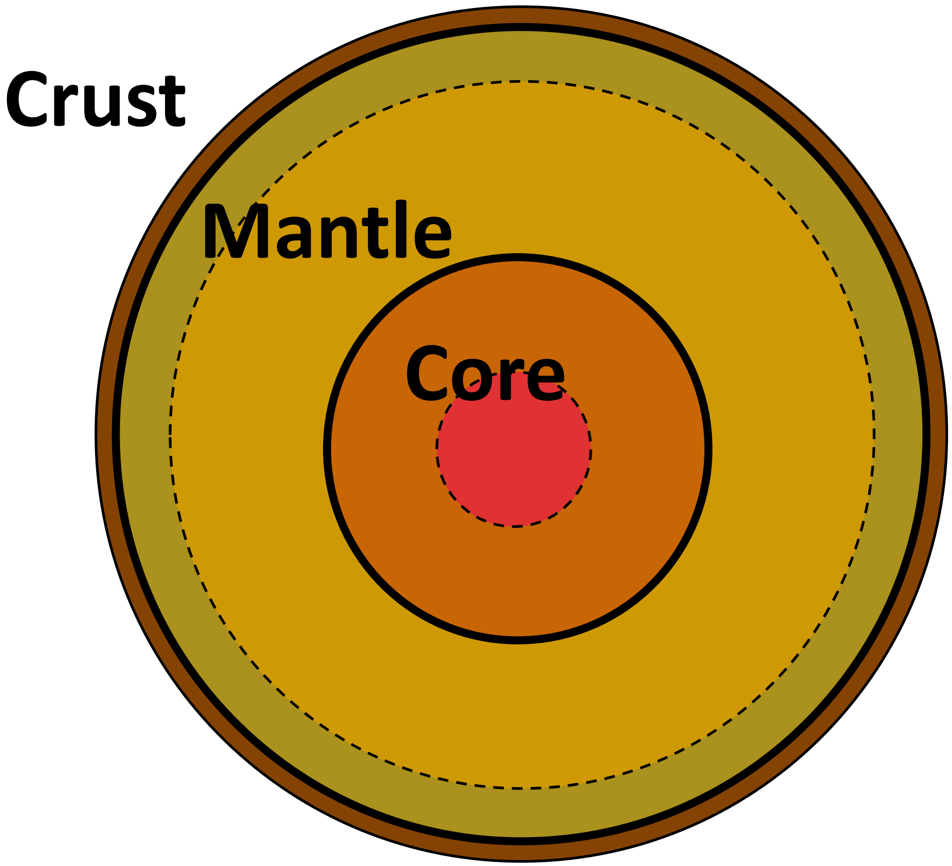


Looking at the Earth's interior…

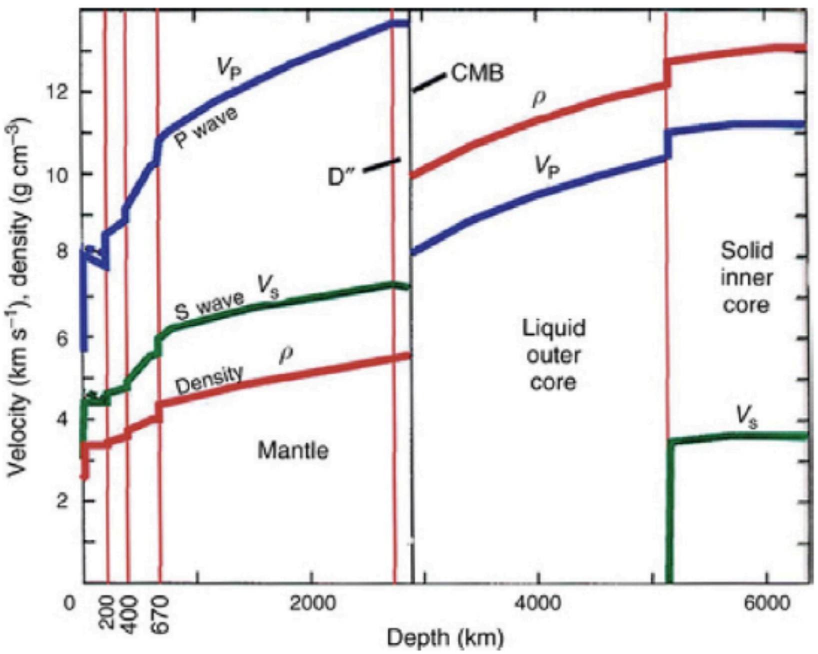
Inversion of seismic wave data

+ gravimetric constraints on Earth's total mass & moment of inertia:

→ radial profile of Earth matter density inferred at ~1% precision



Preliminary Reference Earth Model



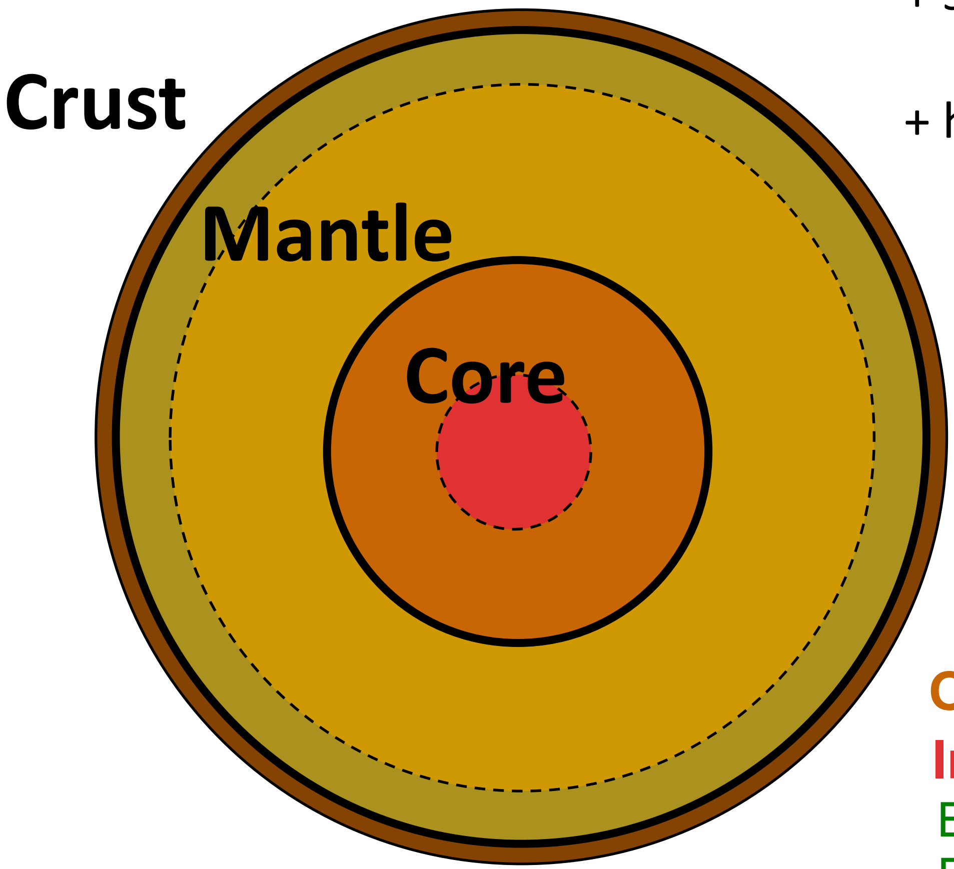
Dziewonski and Anderson, 1981

In a given layer: velocity of seismic waves increases with depth due to higher pressure/density

Looking at the Earth's interior…

Inversion of seismic wave data
+ gravimetric constraints on Earth's total mass & moment of inertia:

→ radial profile of Earth matter density inferred at ~1% precision



+ study of rock samples from crust & mantle, meteorites
+ high-pressure experiments

→ chemical composition of mantle/core:

Upper mantle / Lower mantle:

Silicate minerals (Si, O + Fe, Mg, Mn…)

Benchmark composition: pyrolite (Z/A=0.496)

Outer core Liquid (no S-waves)

Inner core Solid

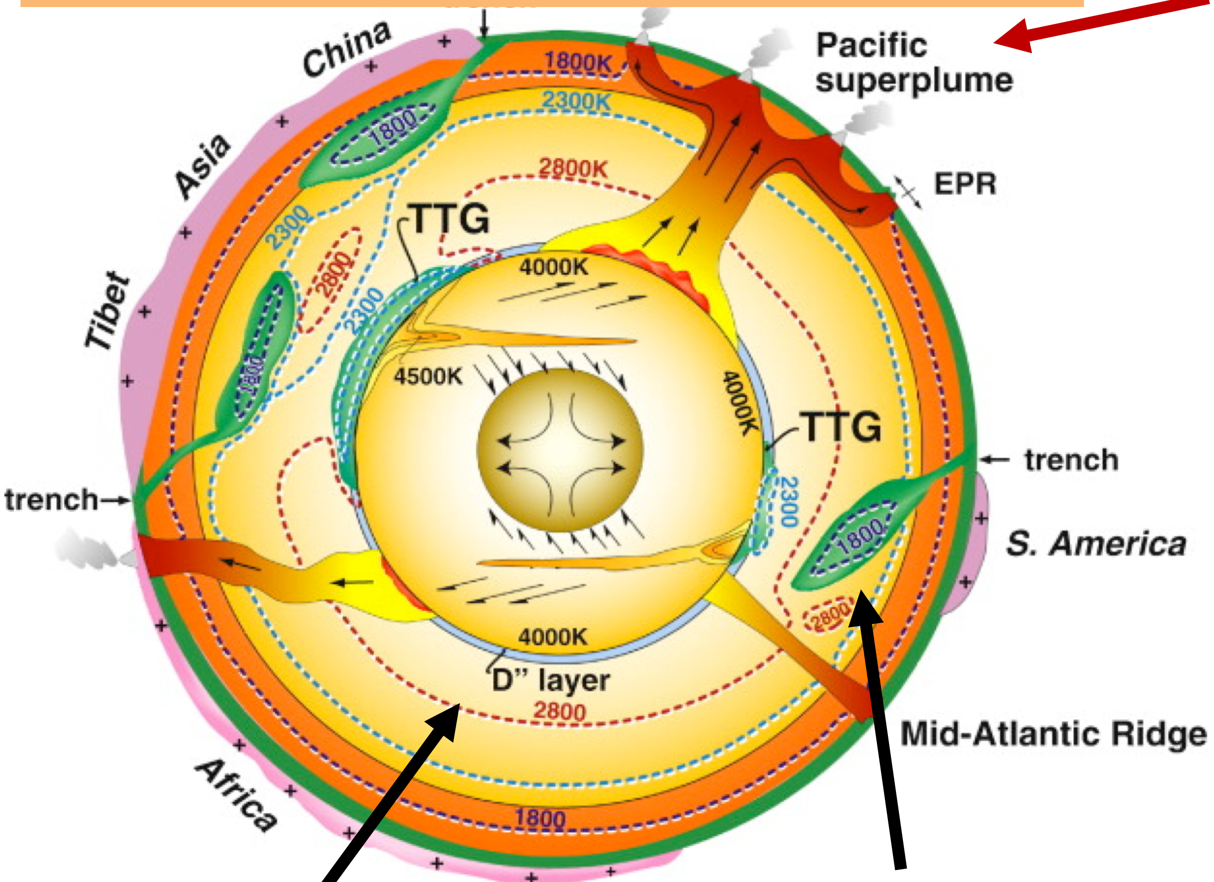
Benchmark composition: Fe-Ni alloy (Z/A=0.466)

+ light elements in outer core ? (Si, O, S, C, H)

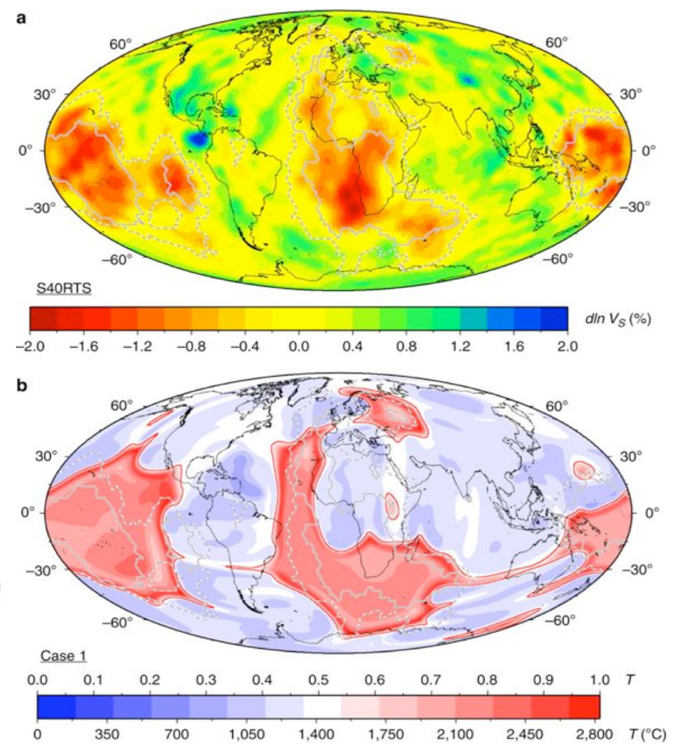
Looking at the Earth's interior…

CAVEAT: the radial model is only an approximation!

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



Large Low-Shear-Velocity Provinces (LLSVP)
extending over ~1000km
related to temperature/ density anomalies ?



potential water reservoir ?

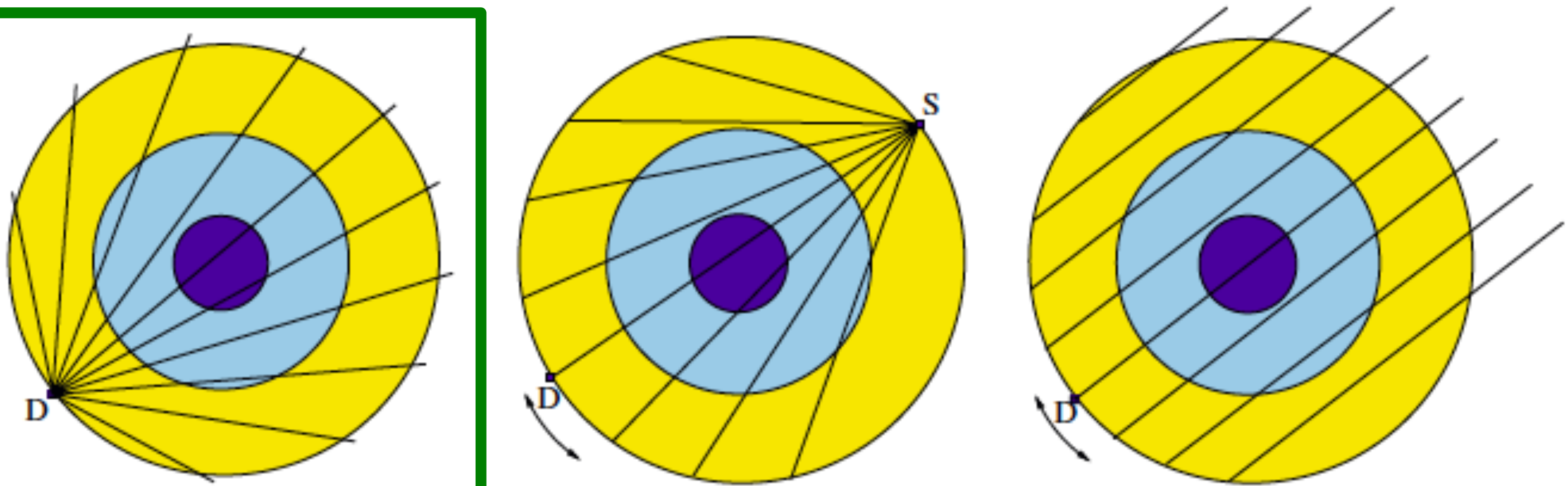
Subduction of cooler material

Nature ? Composition ?

…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

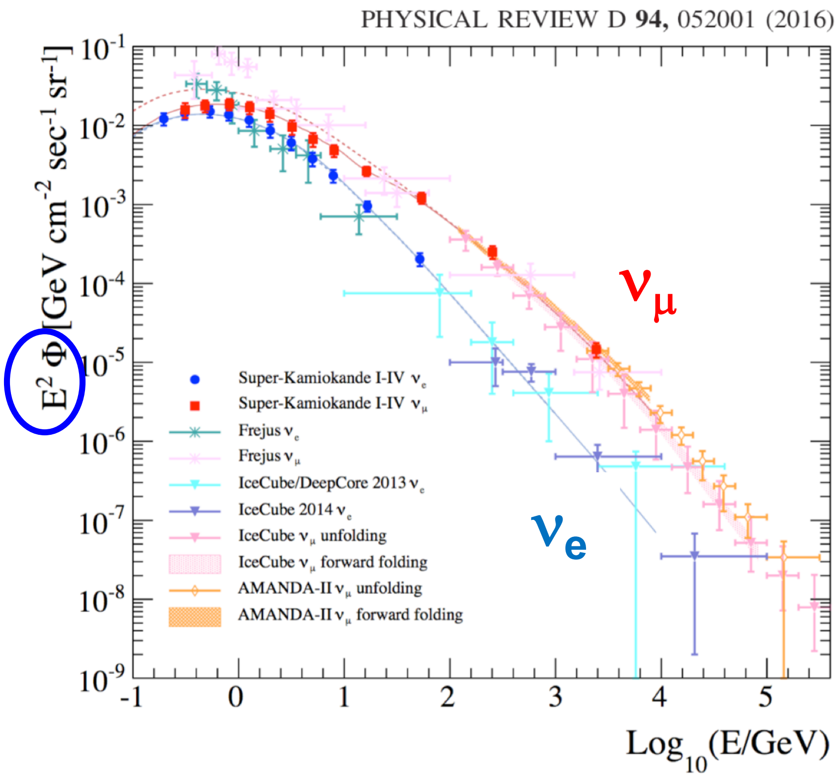
Needs steerable beam & moving detector…

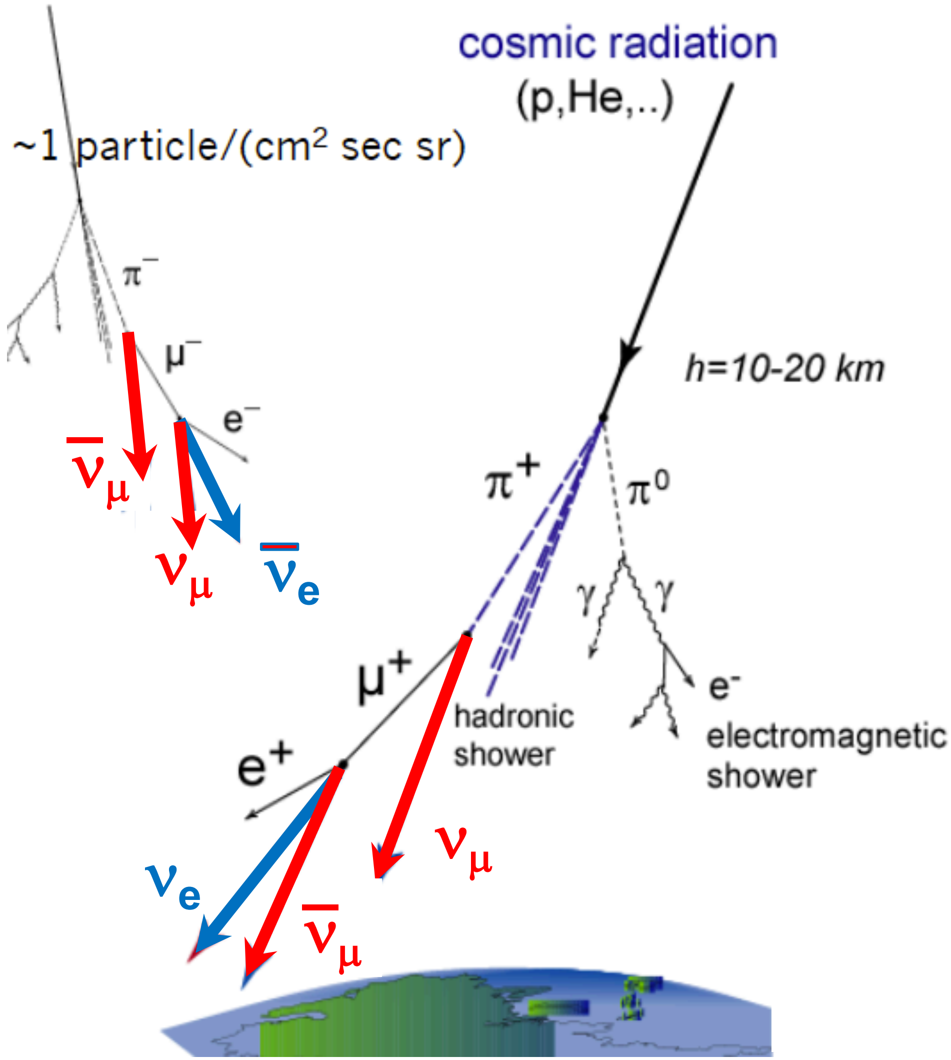
Uncontrolled source

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:

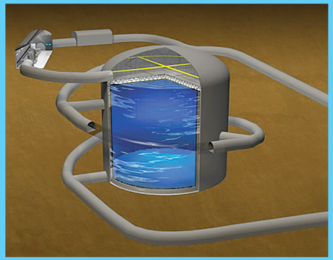




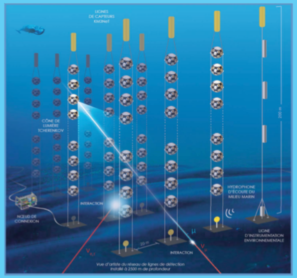
A new generation of detectors for tomography ?

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

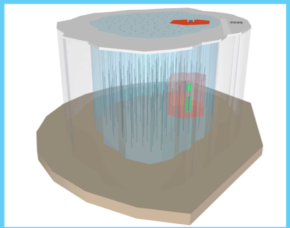
active
in construction
proposed/prototyping



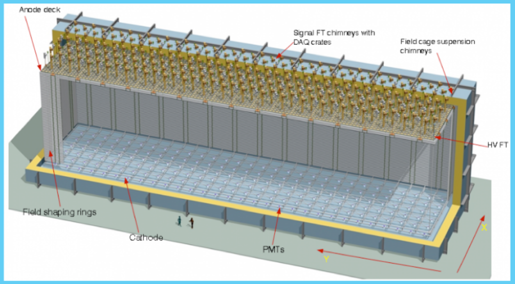
SuperK (50 kton)
HyperK (260 ktons)



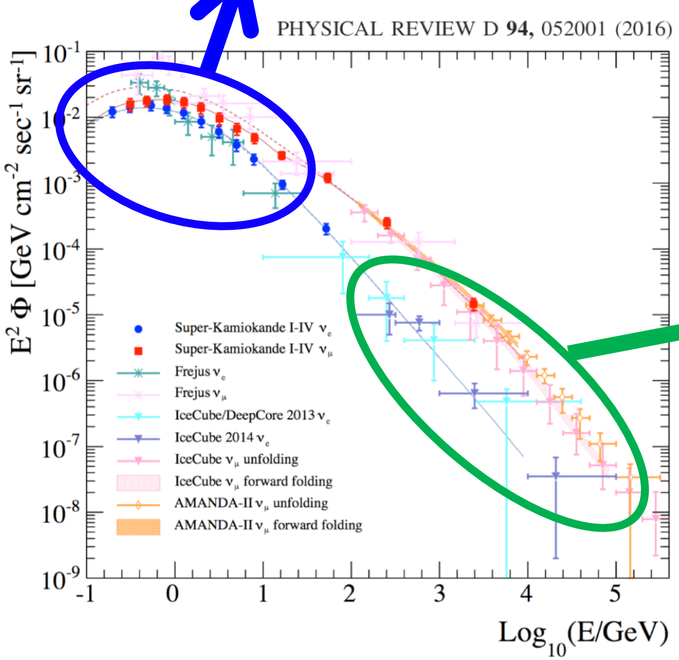
KM3NeT/ORCA
(6 Mton)



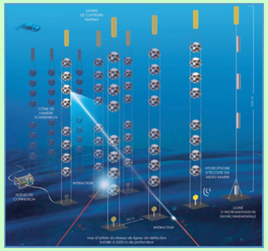
IceCube Upgrade
(1-5 Mton)



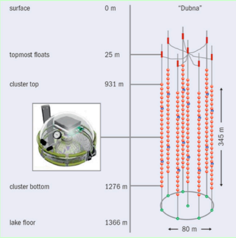
DUNE (40 kton)



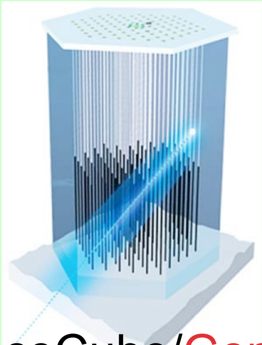
At high (TeV-PeV) energies: Neutrino absorption tomography
~ Gigaton-scale detectors



KM3NeT/ARCA
(1 Gton)

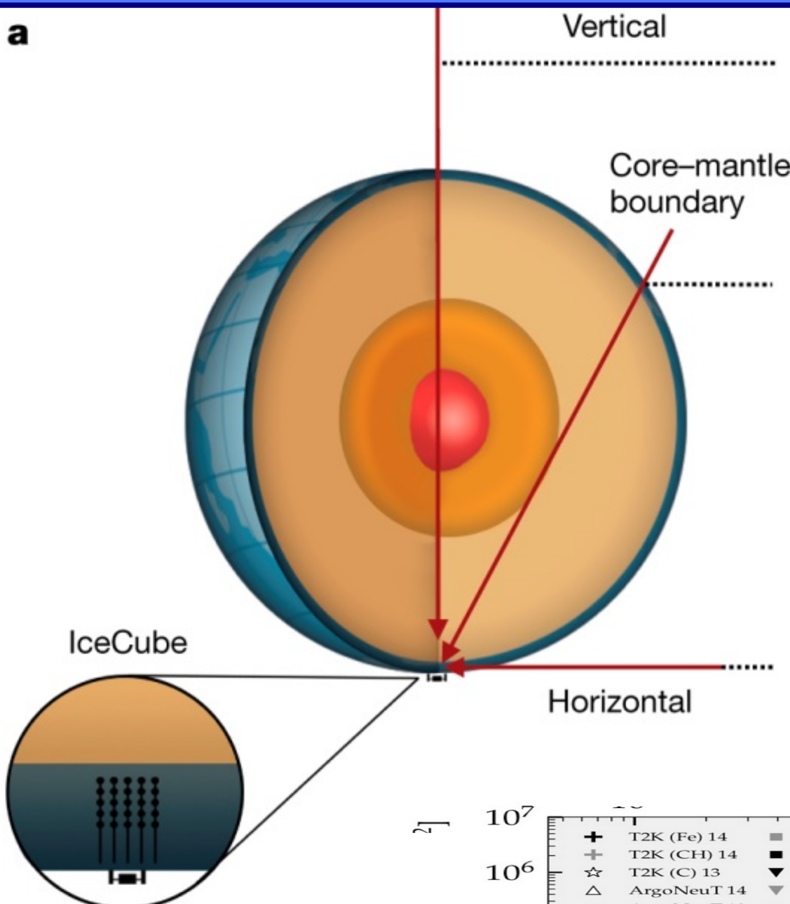


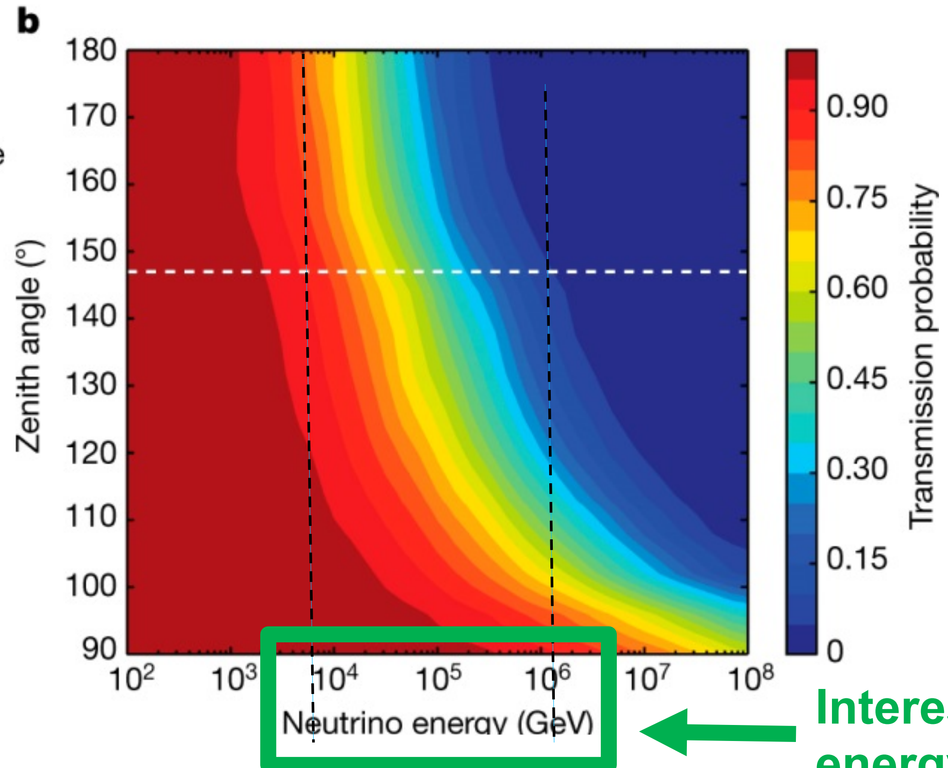
Baikal
(1 Gton)



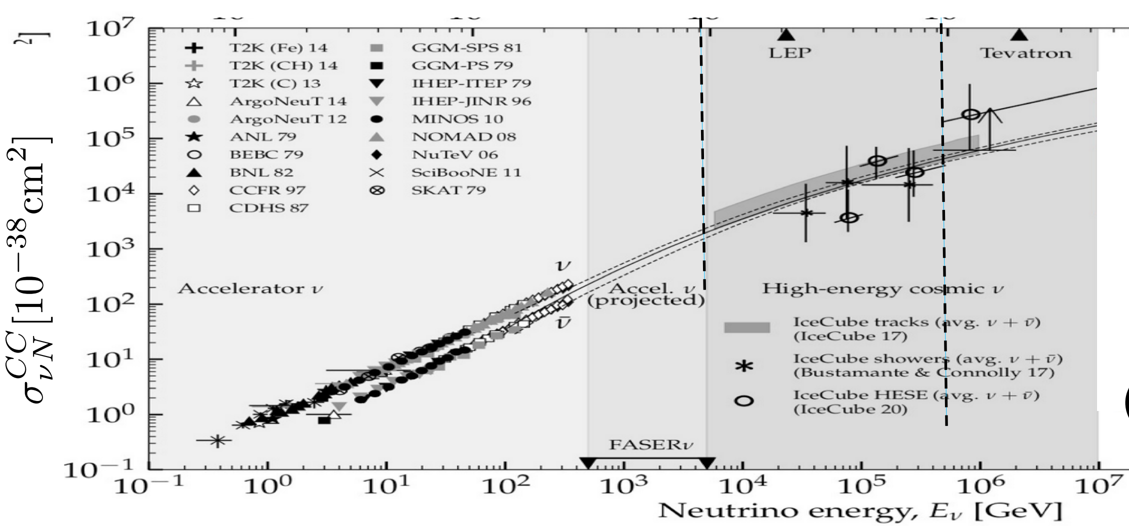
IceCube/Gen2
(1+ Gton)

At high energies: Earth absorption tomography





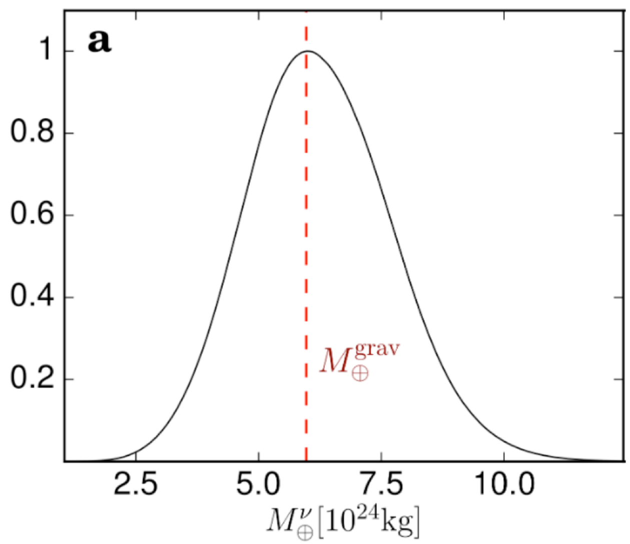
Interesting energy band

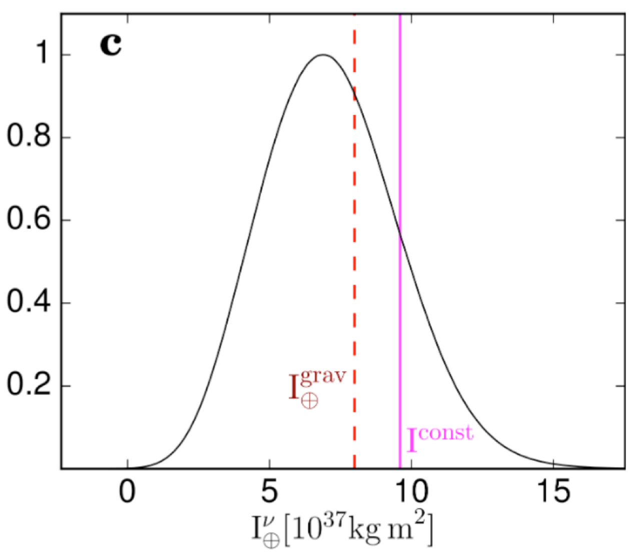


…driven by the increase of neutrino-nucleon cross-section at high energies (~10 TeV → PeV)

adapted from Branco Valera et al. (2022)

At high energies: absorption tomography



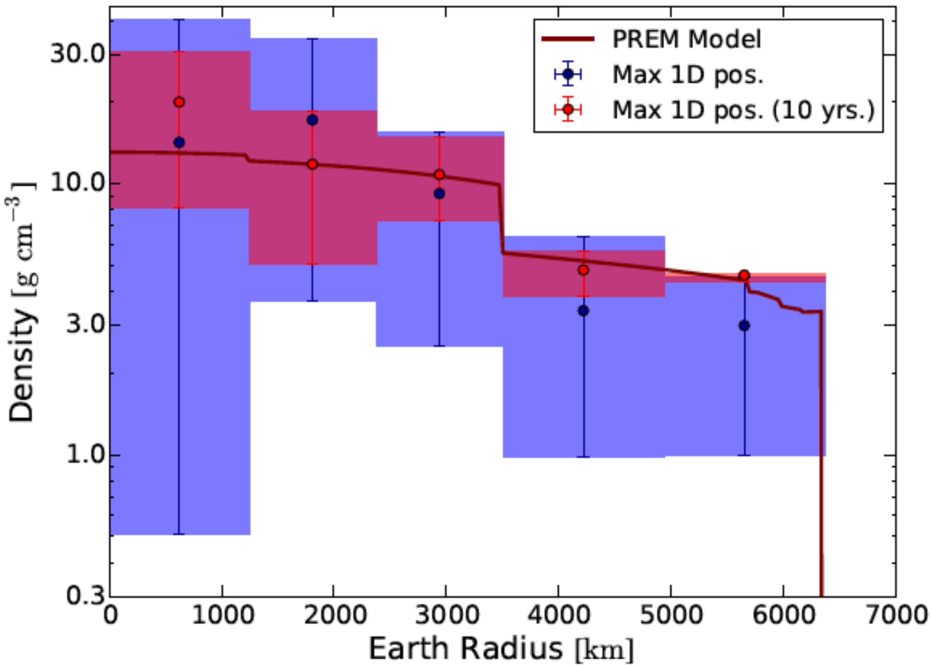


2018: first study with real IceCube data

1 yr sample (2011-2012) – upgoing ν_μ

Radial model with 5 layers of constant density

A. Donini et al., *Nature Phys.* 15 (2019) 1, 37-40

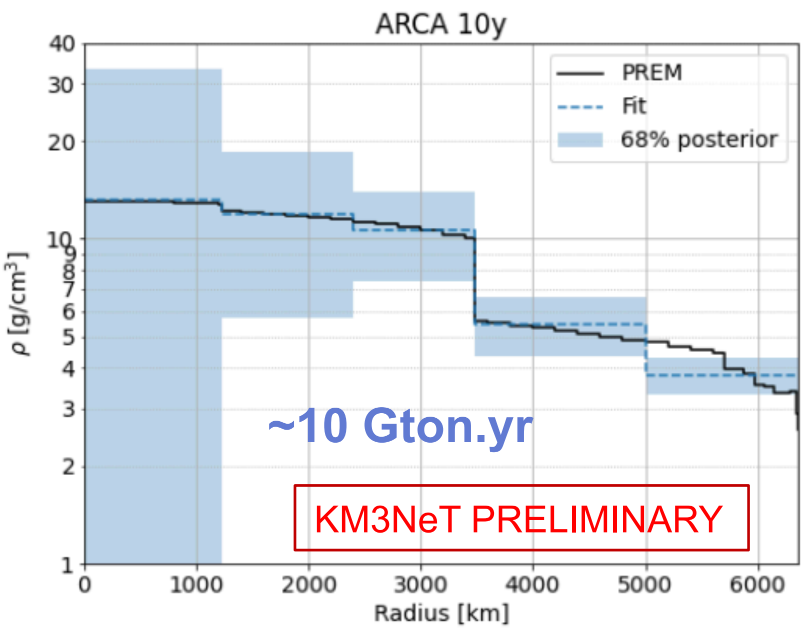


Global quantities inferred from neutrino data are in agreement with gravimetric measurements (but large uncertainties!)

At high energies: absorption tomography

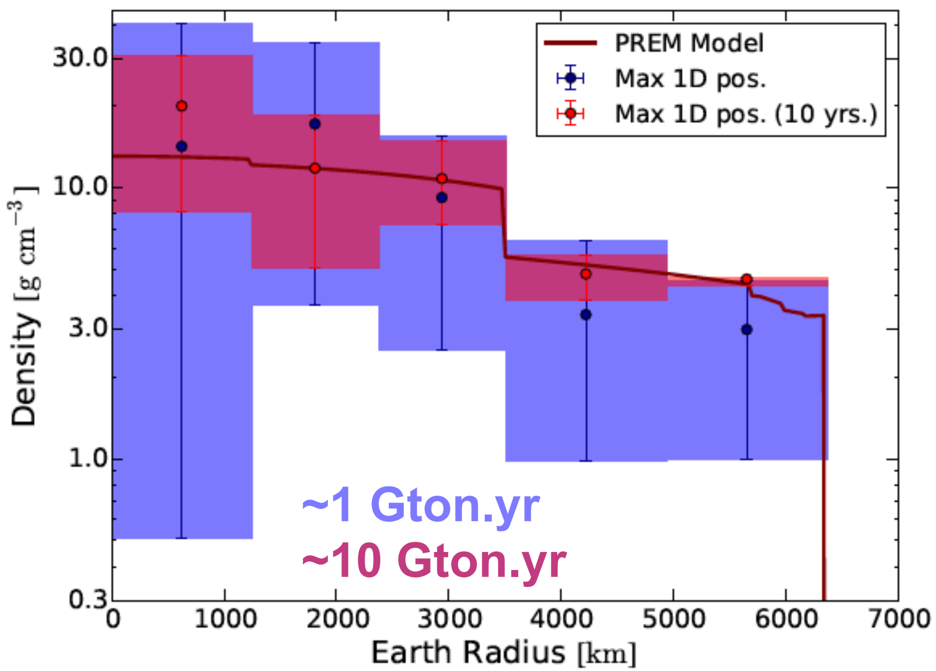
Similar projections for ARCA
(preliminary study, no systematics)

PoS(ICRC 2021) 1172



2018: first study with real IceCube data
1 yr sample (2011-2012) – upgoing ν_μ
Radial model with 5 layers of constant density

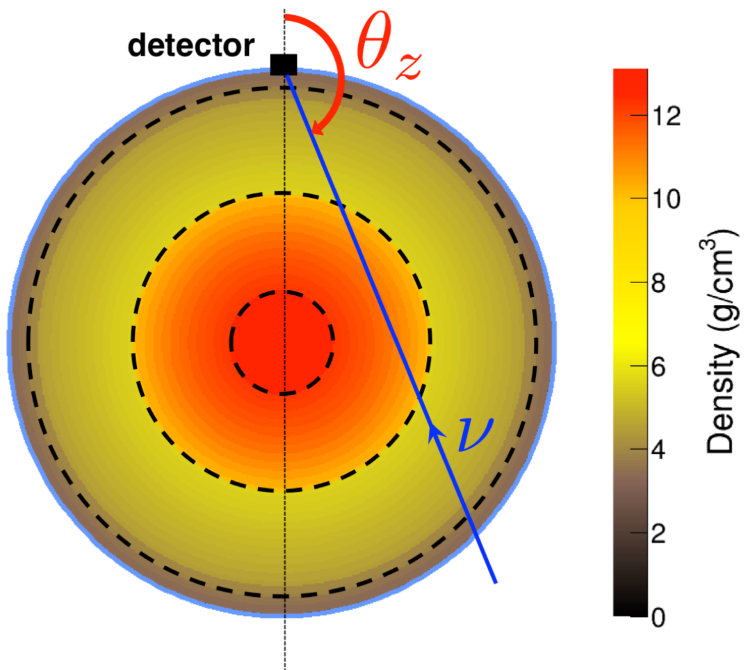
A. Donini et al., *Nature Phys.* 15 (2019) 1, 37-40



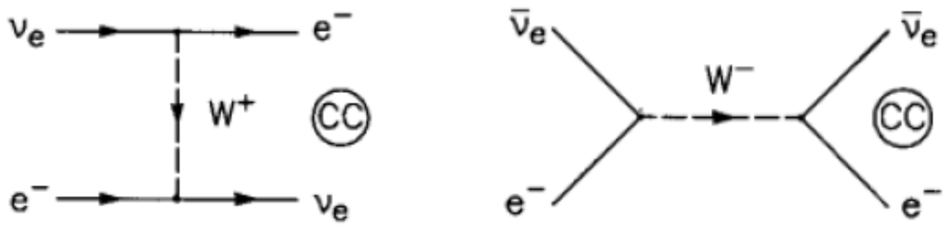
→ Provides a complementary measurement of the matter content/profile of Earth
→ (much) more statistics needed to reach < few % uncertainty level
→ main systematics: neutrino flux & cross-section, detector effects

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
→ additional interaction channels for ν_e / $\bar{\nu}_e$



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

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

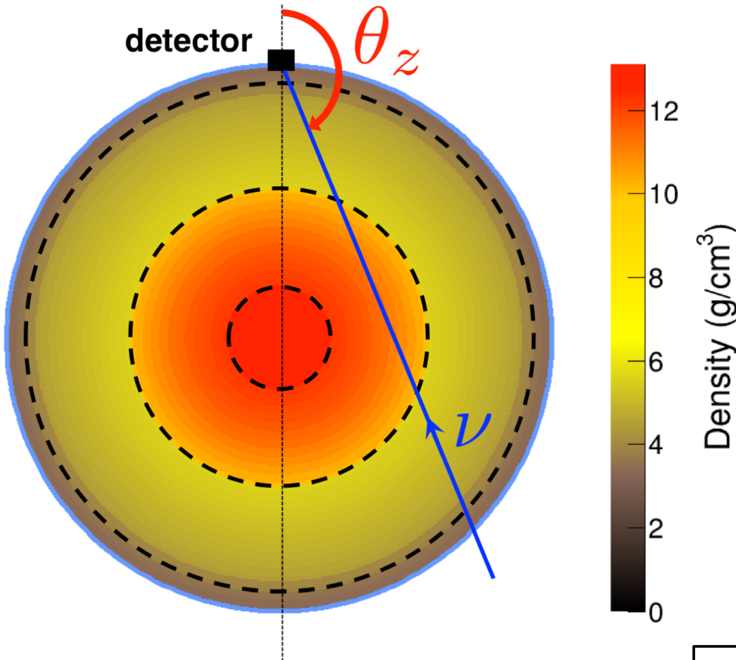
→ Resonance energy for enhanced neutrino oscillations in matter :

$$E_{\mathrm{res}} \equiv \frac{\Delta m^2_{31} \cos 2\theta_{13}}{2\sqrt{2} G_F N_e} \simeq 7\,\mathrm{GeV} \left(\frac{4.5\,\mathrm{g/cm^3}}{\rho}\right) \left(\frac{\Delta m^2_{31}}{2.4 \times 10^{-3}\,\mathrm{eV}^2}\right) \cos 2\theta_{13}$$

≅ 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…

At low energies: oscillation tomography

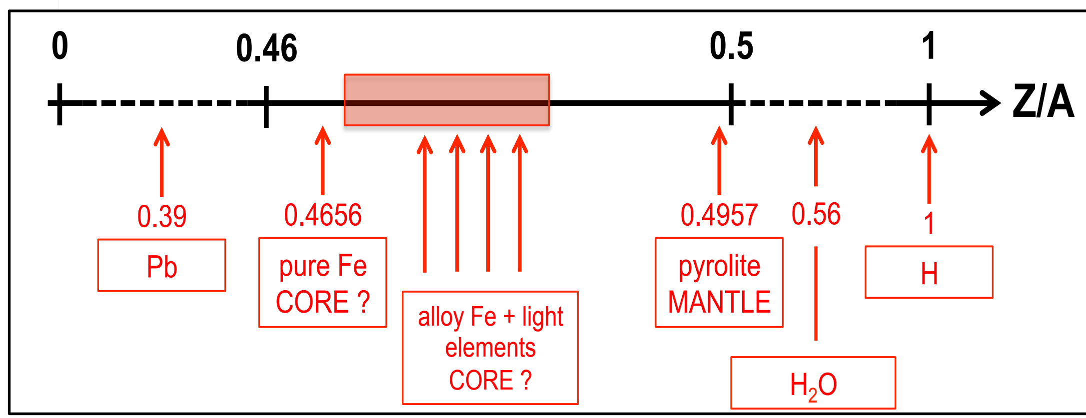


Measured in neutrino oscillation patterns

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

Probes matter density

Probes composition in core/mantle:

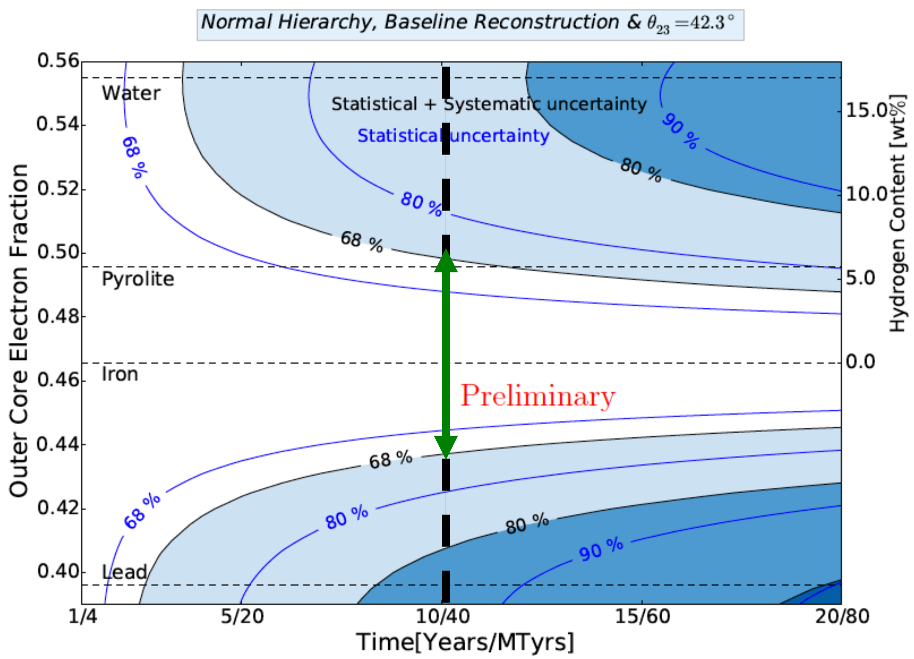


Typical values of Z/A for chemical elements or alloys present in the Earth

Oscillation tomography is also sensitive to Earth composition

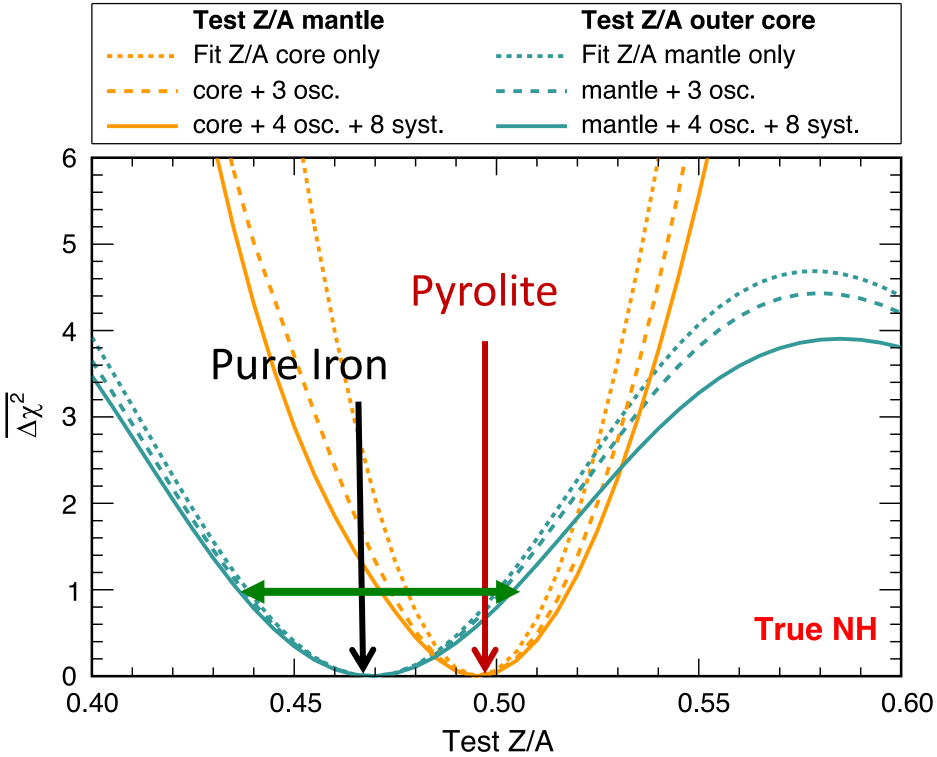
Constraining the deep Earth composition ?

PINGU (now IceCube Upgrade)
outer core, normal neutrino hierarchy



PINGU LoI, arXiv:1401.2046

ORCA 10 years, normal neutrino hierarchy



Bourret et al.[KM3NeT Coll.], *EPJ Web Conf.* 207 (2019) 04008

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

(…assuming normal hierarchy; should be measured before)

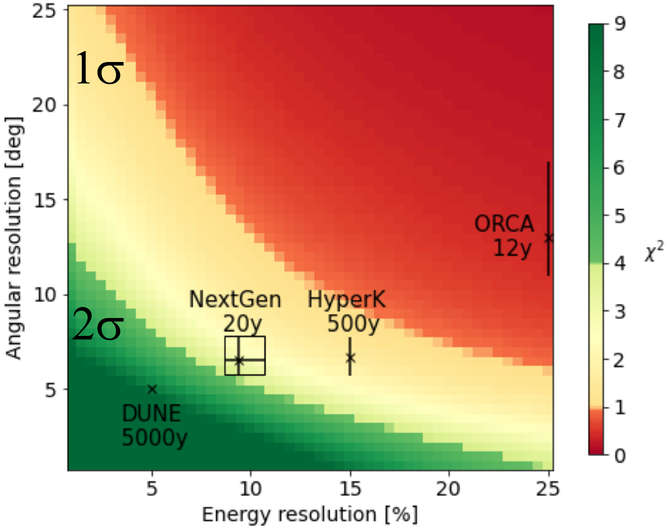
→ Can we go beyond and constrain geophysically motivated models ?

Core composition: which neutrino detector ?

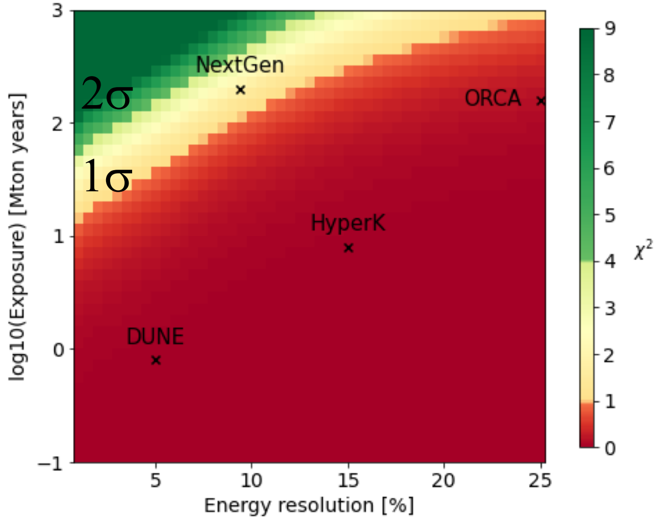
Model Label	FeNi	$FeNiSi_2O_4$	$FeNiSi_7O_2$	FeNiSiH	FeNiH
	-	Kaminski & Javoy[6]	Badro[5]	Tagawa[19]	Sakamaki[8]
Composition	95 wt% Fe	94 wt% Fe	91 wt% Fe	93.2 wt% Fe	94 wt% Fe
	5 wt% Ni	5 wt% Ni	5 wt% Ni	5 wt% Ni	5 wt% Ni
	-	2 wt% Si	7 wt% Si	6.5 wt% Si	1 wt% H
	-	4 wt% O	2 wt% O	0.3 wt% H	
Z/A	0.4661	0.4682	0.4691	0.4699	0.4714

Scan the detector parameter space for realistic composition models (up to 1wt% H)
→ statistical significance (signed chi2) maps:

- Angular/energy resolution at fixed exposure: 200 Mton yr



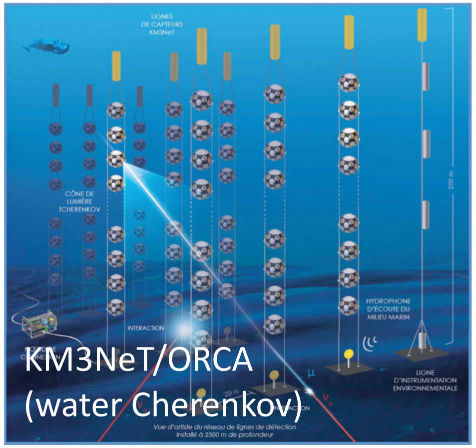
- Exposure/energy resolution at fixed lifetime: 20 yr

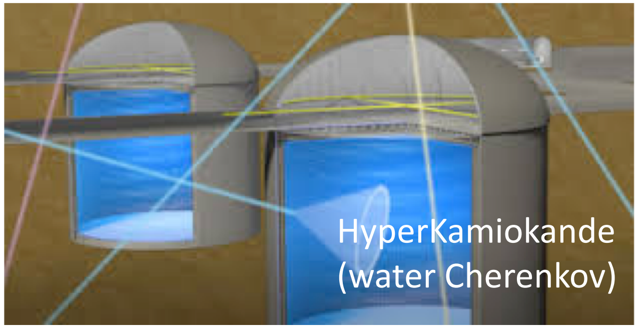


here:
FeNi vs FeNiH

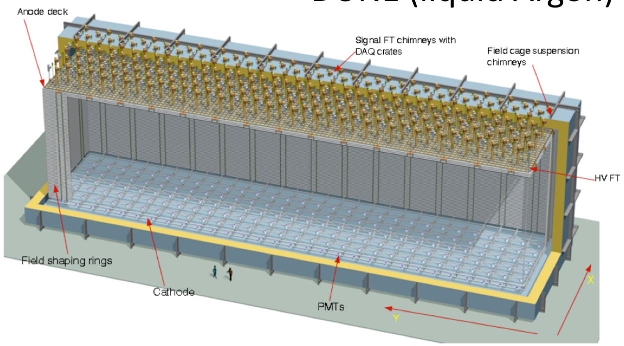
→ Needs a combination of large target mass and very good angular/energy resolution

Core composition: which neutrino detector ?



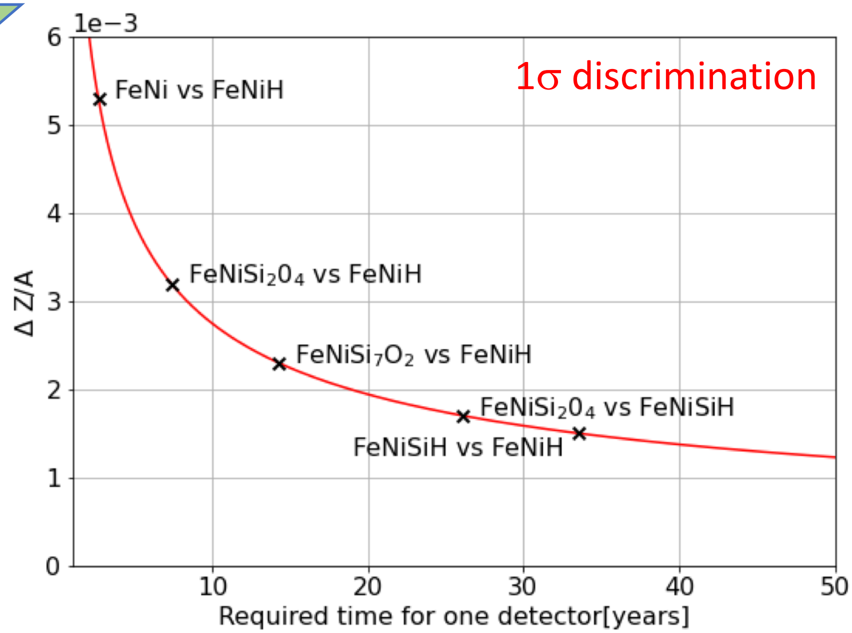


DUNE (liquid Argon)



A NEXT-GENERATION NEUTRINO DETECTOR OPTIMISED FOR TOMOGRAPHY ?

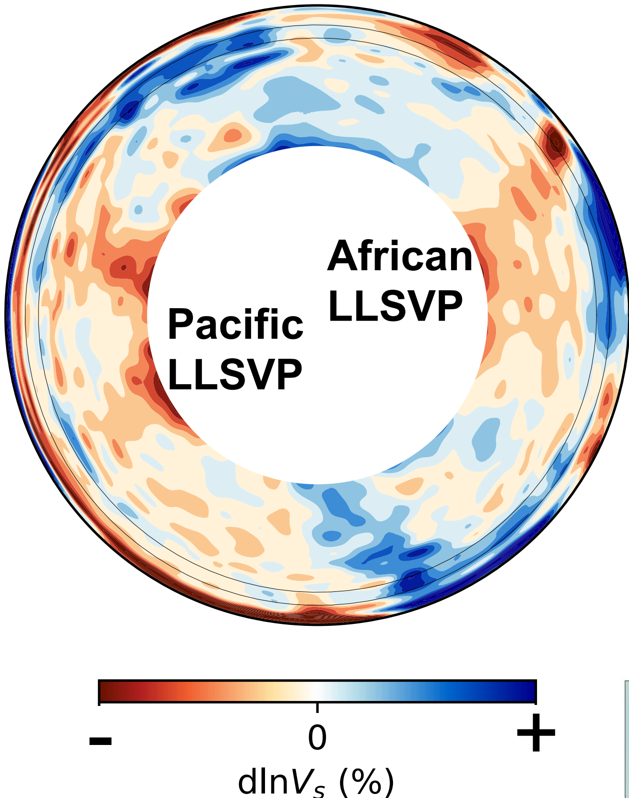
Effective mass	→ need > 10 Mton
Energy threshold	→ need < 1 GeV
Track/shower (PID)	→ need > 95%
Energy resolution	→ need < 15%
Angular resolution	→ need < 10°



→ > 1σ discrimination for $FeNiSi_2O_4$ vs FeNiH in less than 10 years (> 2σ in 30 yrs)
→ Possible discrimination between models with/without hydrogen in less than 30 years!

Outlook: composition anisotropies in the mantle ?

S40RTS (Ritsema et al. 2011)



LLSVP =
'Large Low Shear Velocity Province'

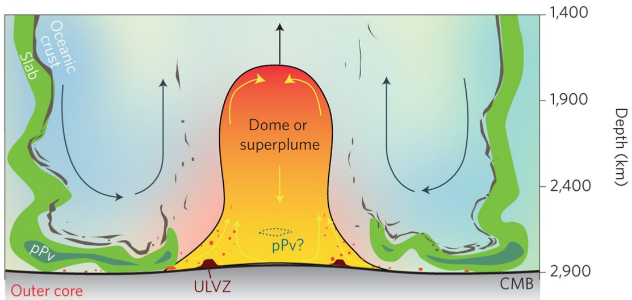
Low seismic velocity $\stackrel{?}{=}$ hot $\stackrel{?}{=}$ upgoing

High seismic velocity $\stackrel{?}{=}$ cold $\stackrel{?}{=}$ downgoing

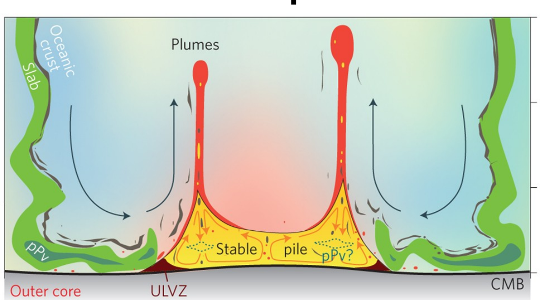
→ This interpretation does not hold for changes in chemical composition

→ Need to know the density!

Rising superplumes?

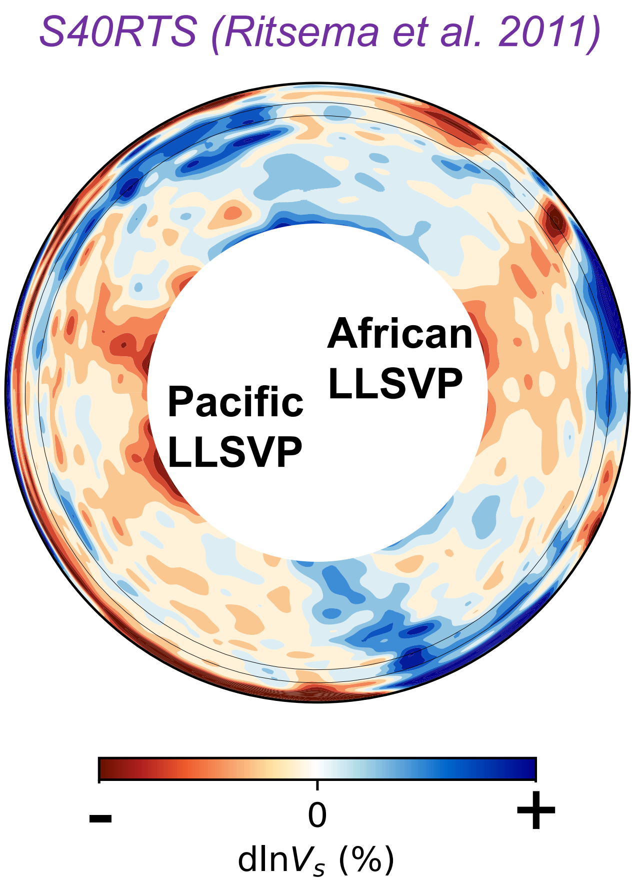


Stable piles?



From Garnero et al. (2016)

Outlook: composition anisotropies in the mantle ?



LLSVP =
'Large Low Shear Velocity Province'

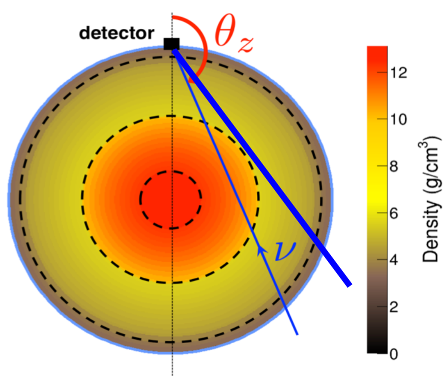
Low seismic velocity $\stackrel{?}{=}$ hot $\stackrel{?}{=}$ upgoing

High seismic velocity $\stackrel{?}{=}$ cold $\stackrel{?}{=}$ downgoing

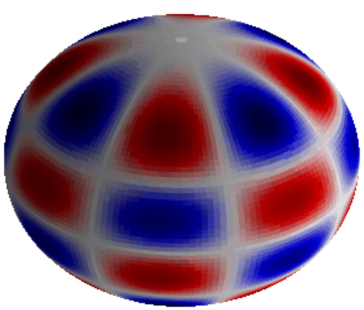
→ This interpretation does not hold for changes in chemical composition

→ Need to know the density!

→ **Combine neutrino data with seismic normal modes measurements: whole-Earth oscillations, directly sensitive to matter density**



+



Conclusions and 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/HyperK)

→ improved detector performances (lower threshold/better reco)

→ to resolve first the neutrino mass hierarchy (ORCA/JUNO/DUNE)

Upcoming detectors → benchmark sensitivity ~ few % after 10 years: not enough to constrain realistic models

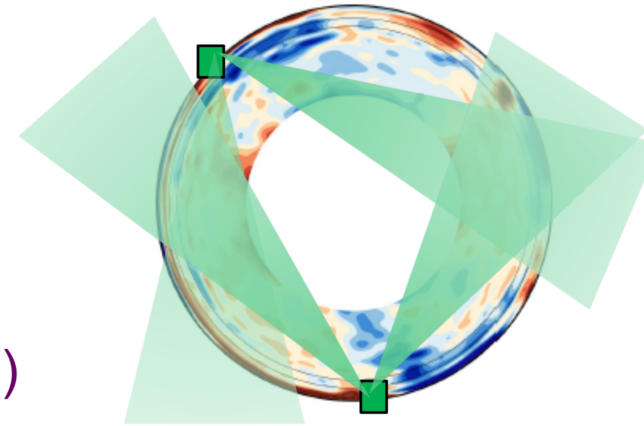
→ Case for next-generation detectors optimised for neutrino tomography

… reach 1% sensitivity level on composition

(H in outer core, H_2O in mantle…)

… **detector network** for combined measurements

(3D profiles and large-scale inhomogeneities)



... also to my collaborators:

J. Coelho,
L. Maderer,
R. Pestes

IPGP
N. Fuji
E. Kaminski

Universiteit Utrecht
A. Deuss
R. van Tent

LGL TPE
Laboratoire de Géologie de Lyon
Terre - Planètes - Environnement
S. Durand

University of Idaho
Y. Deniz Hernandez
E. Mittelstaedt

Backup slides

Core composition: which neutrino detector ?

Detector	M (Mton)	E_{th} (GeV)	E_{pl} (GeV)	$\sigma(E)/E$	σ_θ (deg)	E_{th}^{class} (GeV)	E_{pl}^{class} (GeV)	P_{max}^{class}
ORCA-like	8	2	10	25%	$30/\sqrt{E}$	2	10	85%
HyperKamiokande-like	0.40	0.1	0.2	15%	$15/\sqrt{E}$	0.1	0.2	99%
DUNE-like	0.04	0.1	0.2	5%	5	0.1	0.2	99%
Next-Generation	10	0.5	1.0	$5\% + 10\%/\sqrt{E}$	$2 + 10/\sqrt{E}$	0.5	1	99%

large target mass (~ORCA)

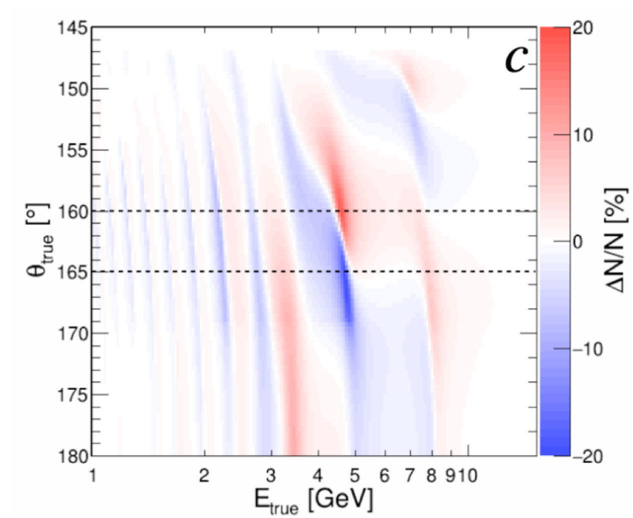
low energy threshold (~DUNE/HyperK)

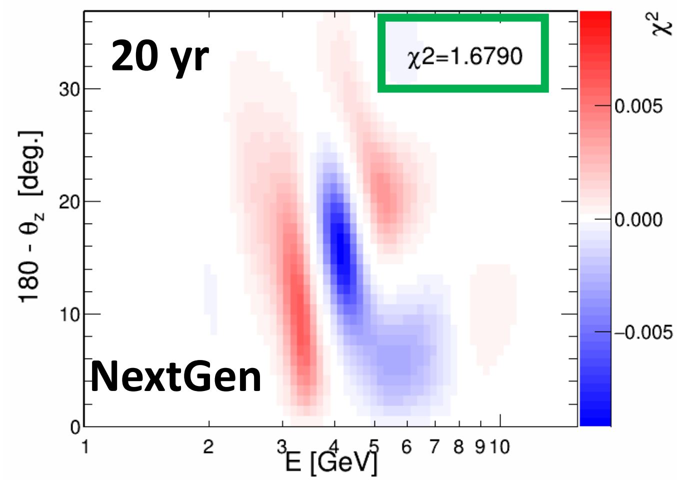
moderate E/θ resolutions (~HyperK)

excellent event ID (~DUNE/HyperK)

Relative difference in ν_μ interacting events

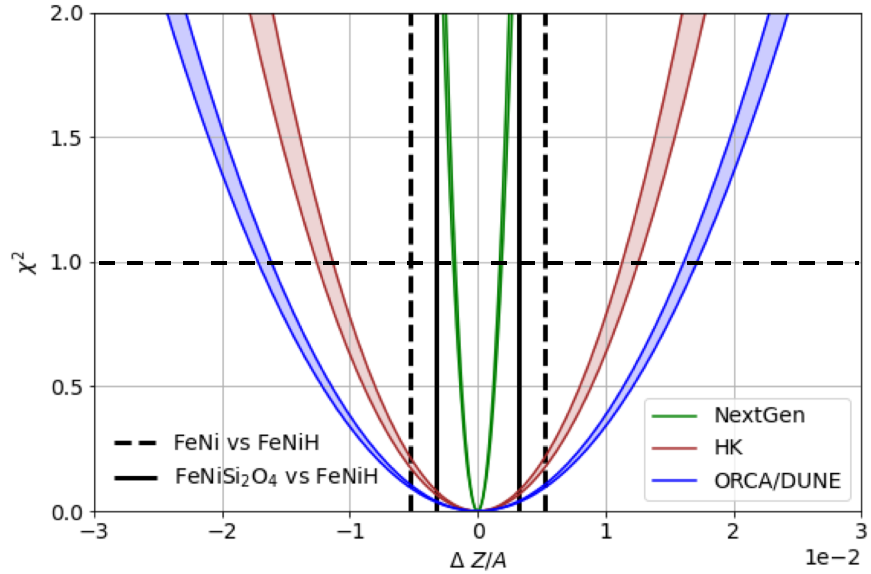
FeNi vs FeNiH



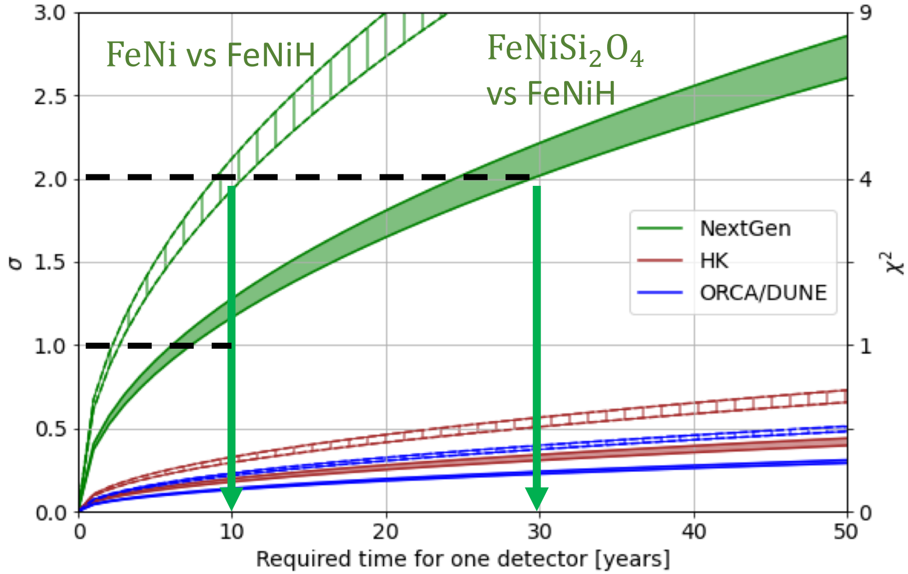


Core composition: which neutrino detector ?

chi2 for model discrimination
20 yr detector lifetime



chi2 for model discrimination
as a function of time



The bands indicate potential of CC/NC separation (→ background reduction)

→ Similar performance of ORCA & DUNE, despite different detection techniques
→ HyperKamiokande : best upcoming detector, but resolution/size still not sufficient to test realistic core composition models

→ **NextGen detector achieves > 1σ discrimination for $FeNiSi_2O_4$ vs FeNiH in less than 10 years (> 2σ in 30 yrs)**

ORCA: detector response

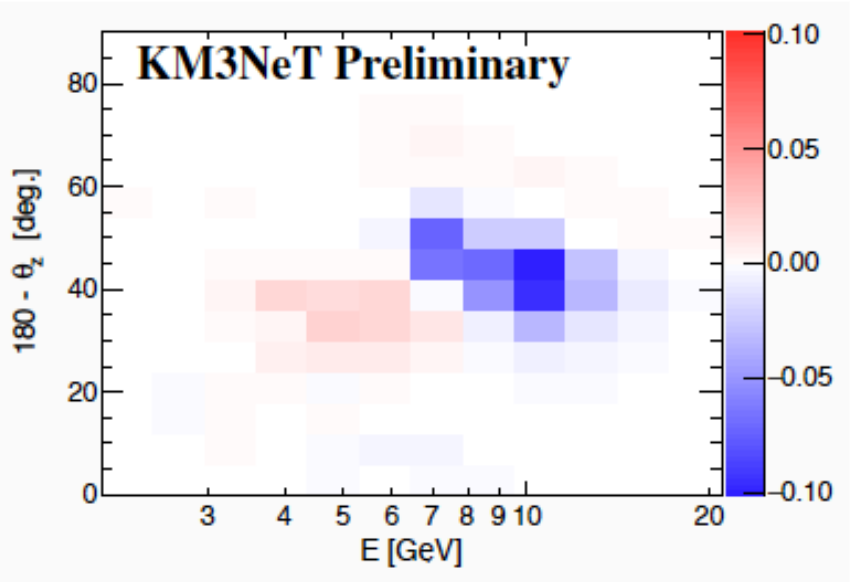
- Theoretical signal more visible in muon (track) channel
- Theoretical signal is higher for outer core, but concentrated in fast-oscillating patterns at low energy
- Detector effects described by response matrix from full MC simulations:

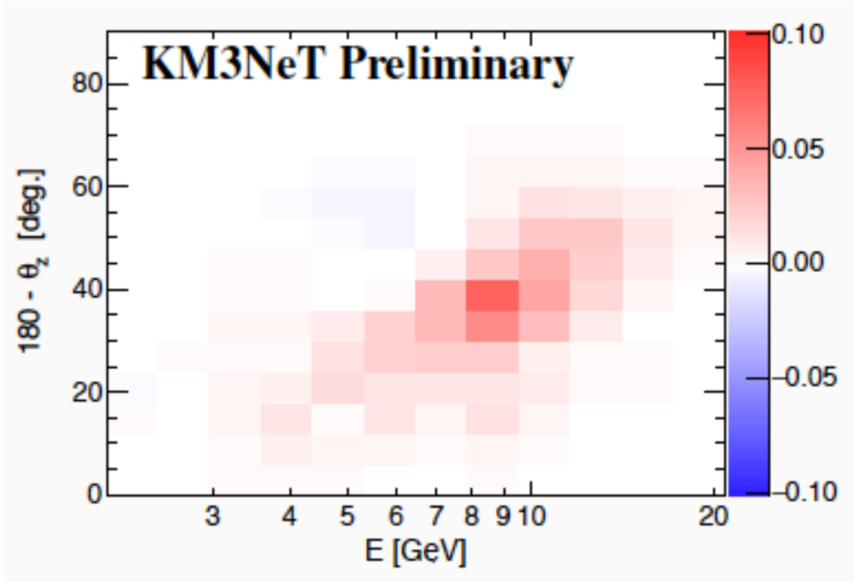
- True $(E, \cos\theta_z, Y_{\mathrm{Bj}})$
- True channel:
  - $\rightarrow$ CC $\nu_e/\overline{\nu_e}$, $\nu_\mu/\overline{\nu_\mu}$, $\nu_\tau/\overline{\nu_\tau}$
  - $\rightarrow$ NC $\nu/\overline{\nu}$

Reconstruction & Classification $\Rightarrow$

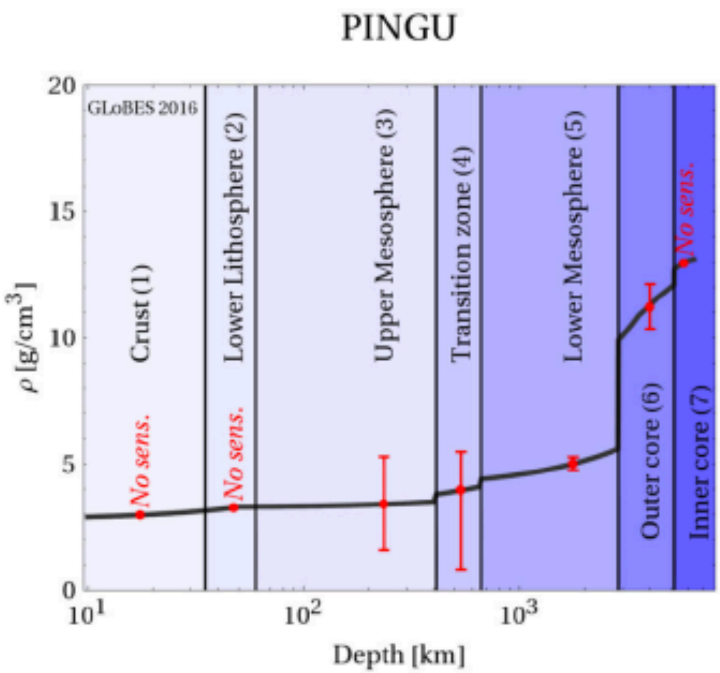
- Reco $(E, \cos\theta_z, Y_{\mathrm{Bj}})$
- Event classification ("flavour ID"):
  - $\rightarrow$ Track / Cascade / μ_{atm}

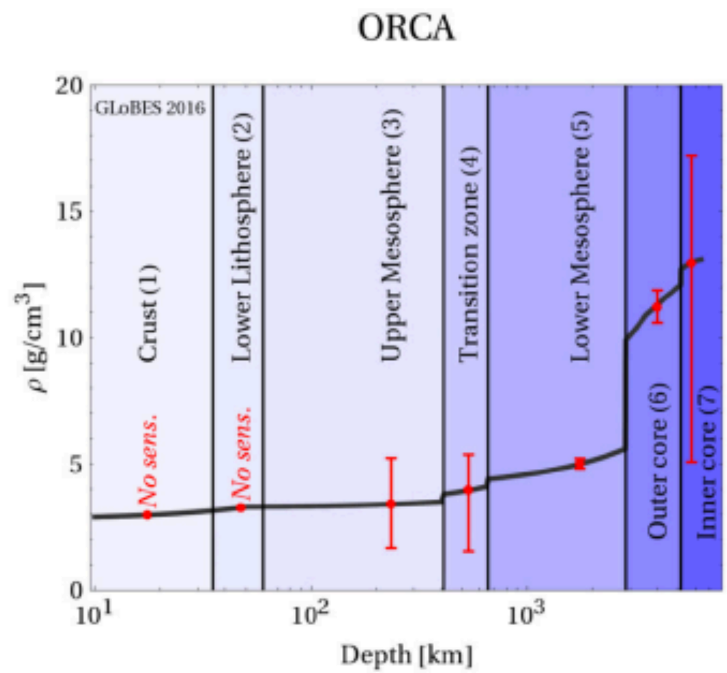
- Both channels end up with comparable contributions to asymmetry:





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