Neutrino tomography of the Earth

Andrea Donini (IFIC, Valencia)

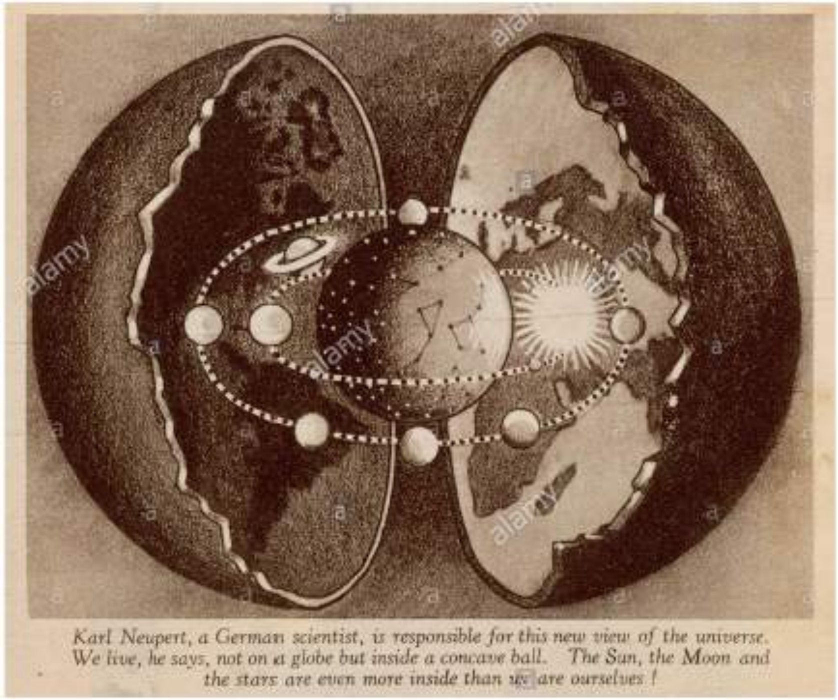
(under revision in Nature Physics)

in collaboration with:
S. Palomarez-Ruiz
J. Salvadó

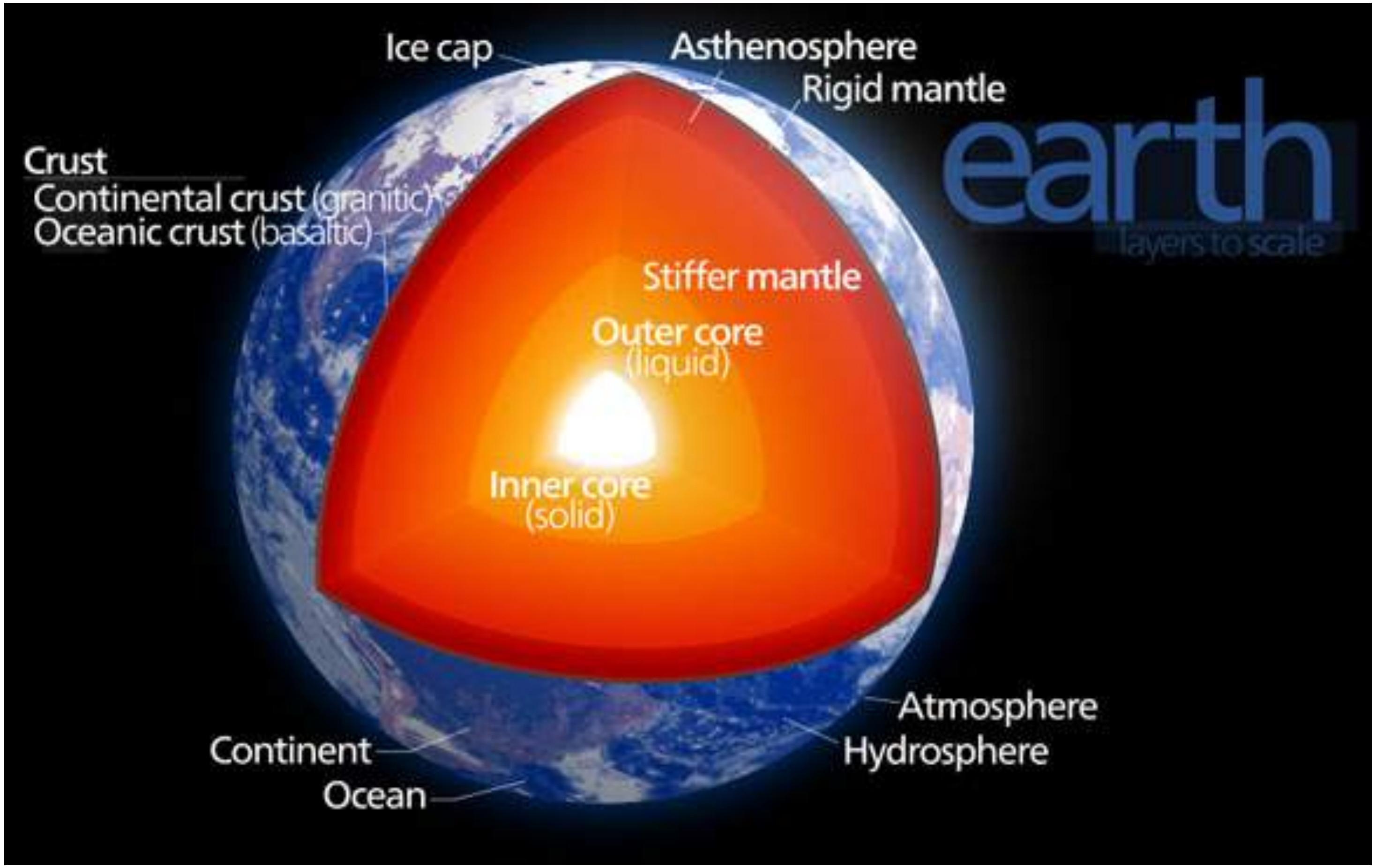
What do we know about the Earth?

The surface, you know it pretty well.....

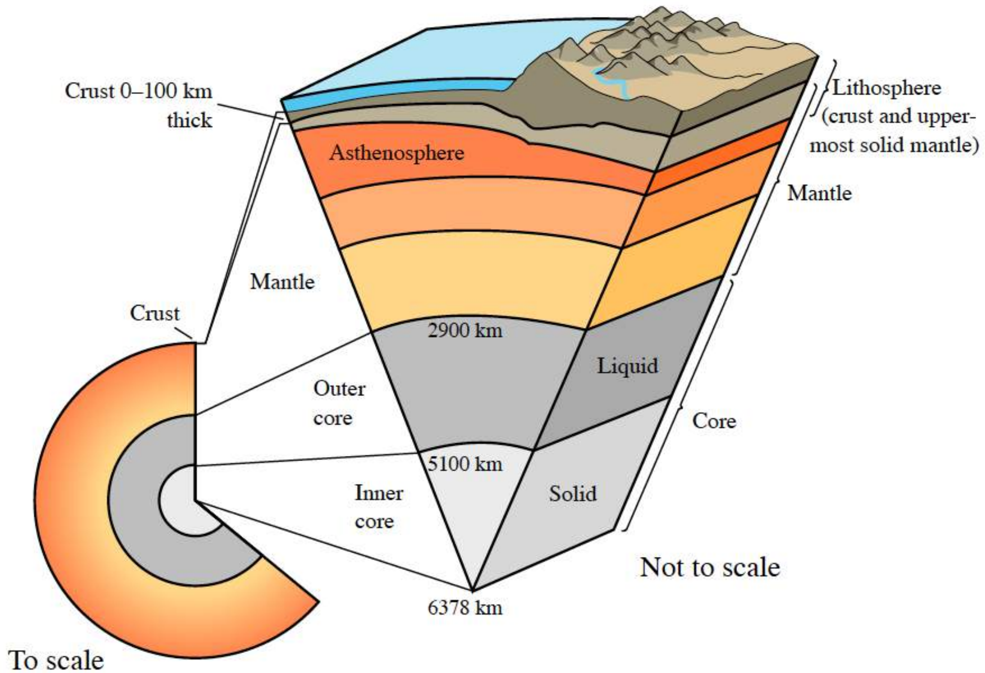
What do we know about the Earth?



The interior of the Earth



Density at different depths



Depth[103] km	Component layer	Density g/cm³
0–60	Lithosphere[n 14]	–
0–35	Crust[n 15]	2.2–2.9
35–60	Upper mantle	3.4–4.4
35–2890	Mantle	3.4–5.6
100–700	Asthenosphere	–
2890–5100	Outer core	9.9–12.2
5100–6378	Inner core	12.8–13.1

Earth's average density: $\rho = 5.5148$ g/cm^3

(granite density is 2.7 g/cm^3)

Constraints and derived quantities

- Gravitational measurement of the Earth's mass

$$M_\oplus = \frac{4\pi}{3}\int_0^{R_\oplus} dr r^2 \rho(r) = 5.972 \times 10^{24}\mathrm{kg}$$

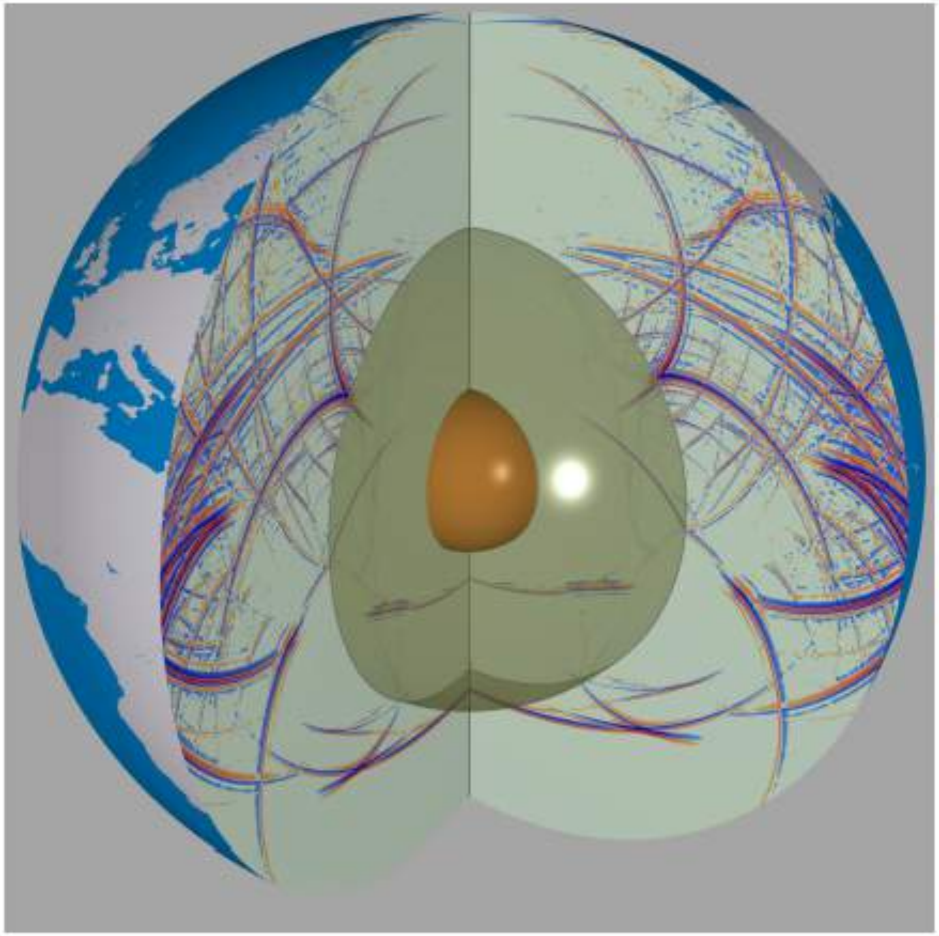
- A derived quantity: Earth's mean moment of inertia

$$I_\oplus = \frac{8\pi}{3}\int_0^{R_\oplus} dr r^4 \rho(r) = 0.3307144 M_\oplus R_\oplus^2$$

A constant density would give $I_\oplus(\rho(r) = \rho_0) = 0.4\, M_\oplus R^2$

How densities are measured?

seismology



How densities are measured?

seismology

propagation of earthquake waves
through the Earth: p-waves and s-waves
(v_p and v_s)
composition dependence!

How densities are measured?

seismology

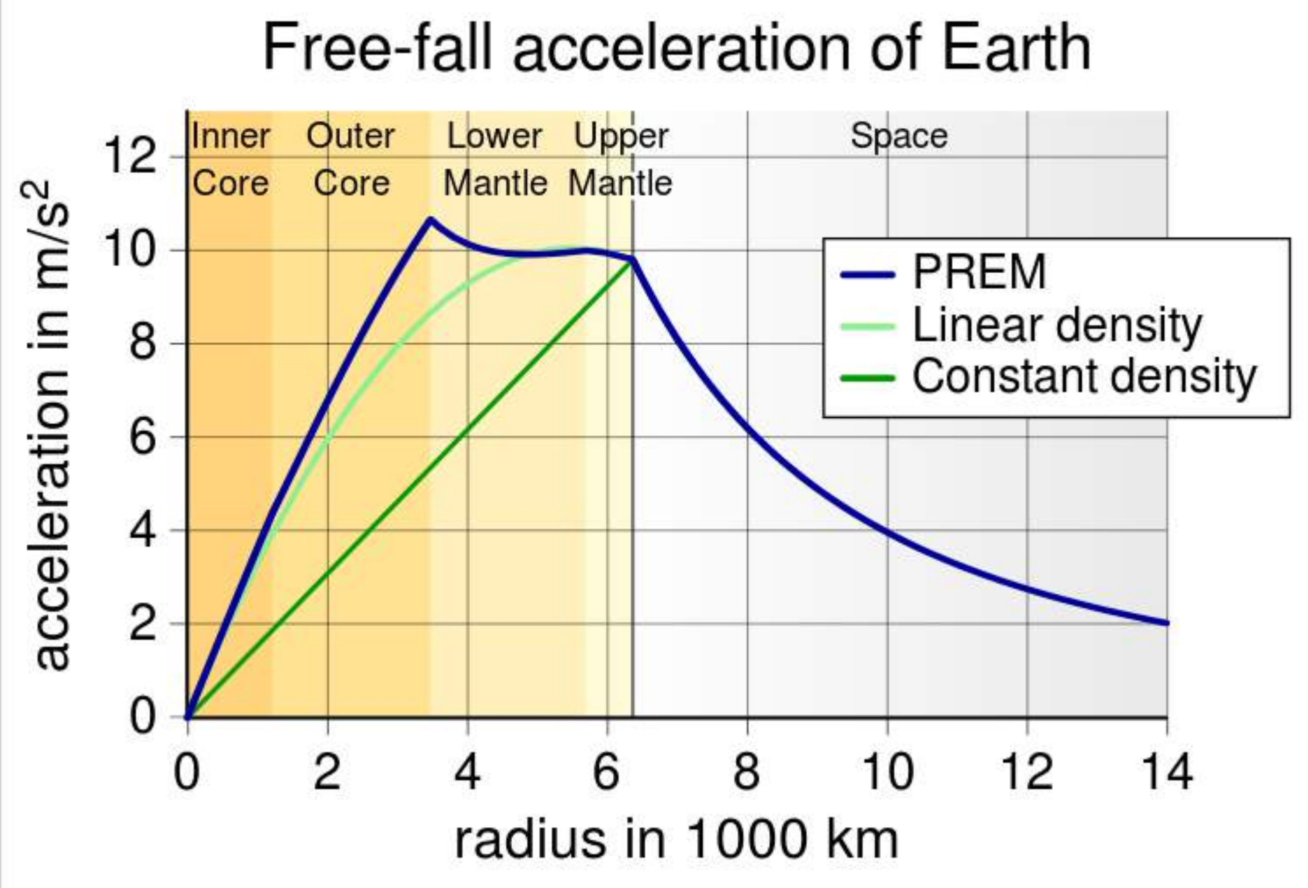
propagation of earthquake waves through the Earth: p-waves and s-waves (v_p and v_s)
composition dependence!

Adams-Williamson equation (1924)

$$\frac{d\rho}{dr} = -\rho(r)\frac{g(r)}{\Phi(r)}$$

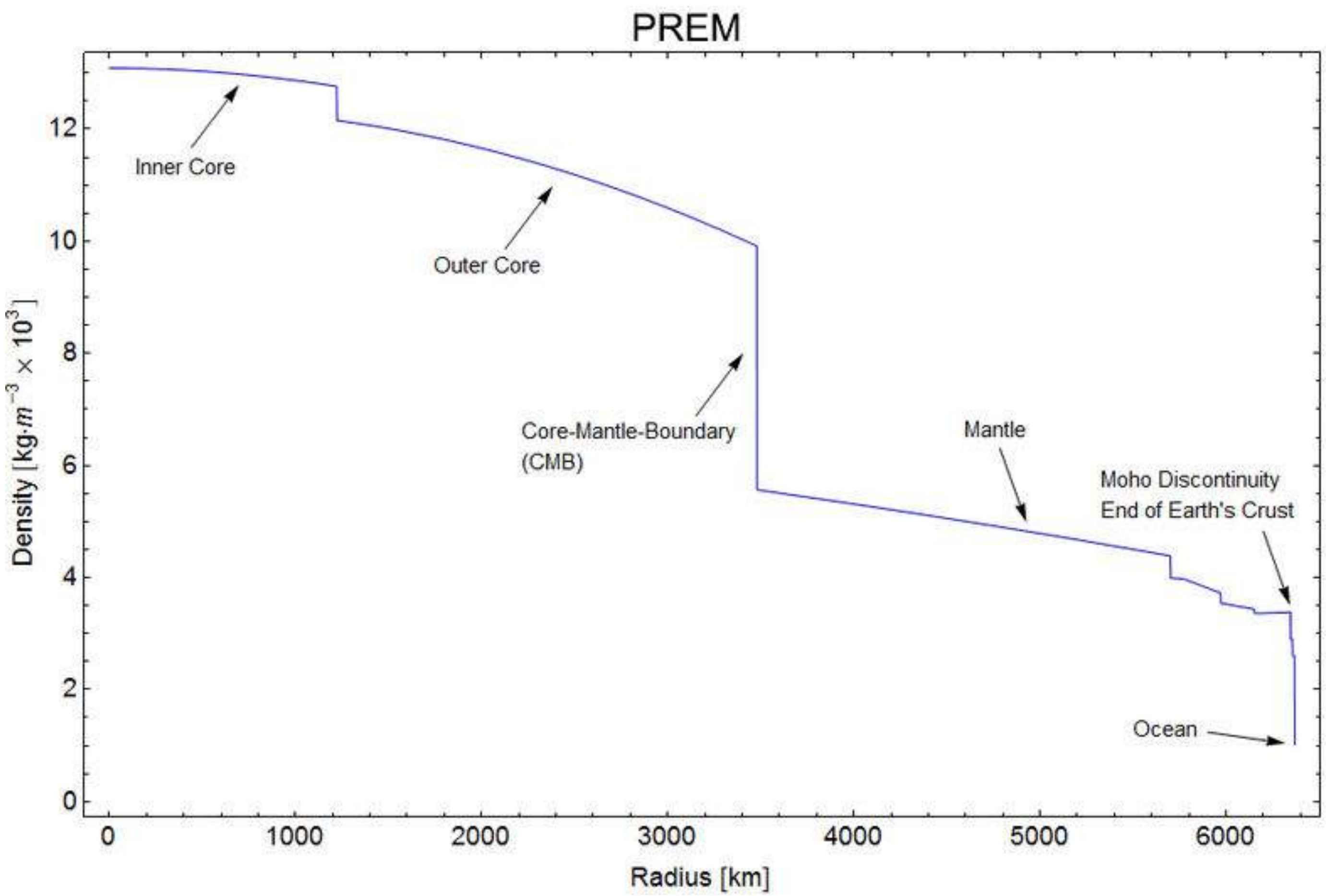
$$\Phi(r) = v_p^2 - \frac{4}{3}v_s^2$$

An important constraint



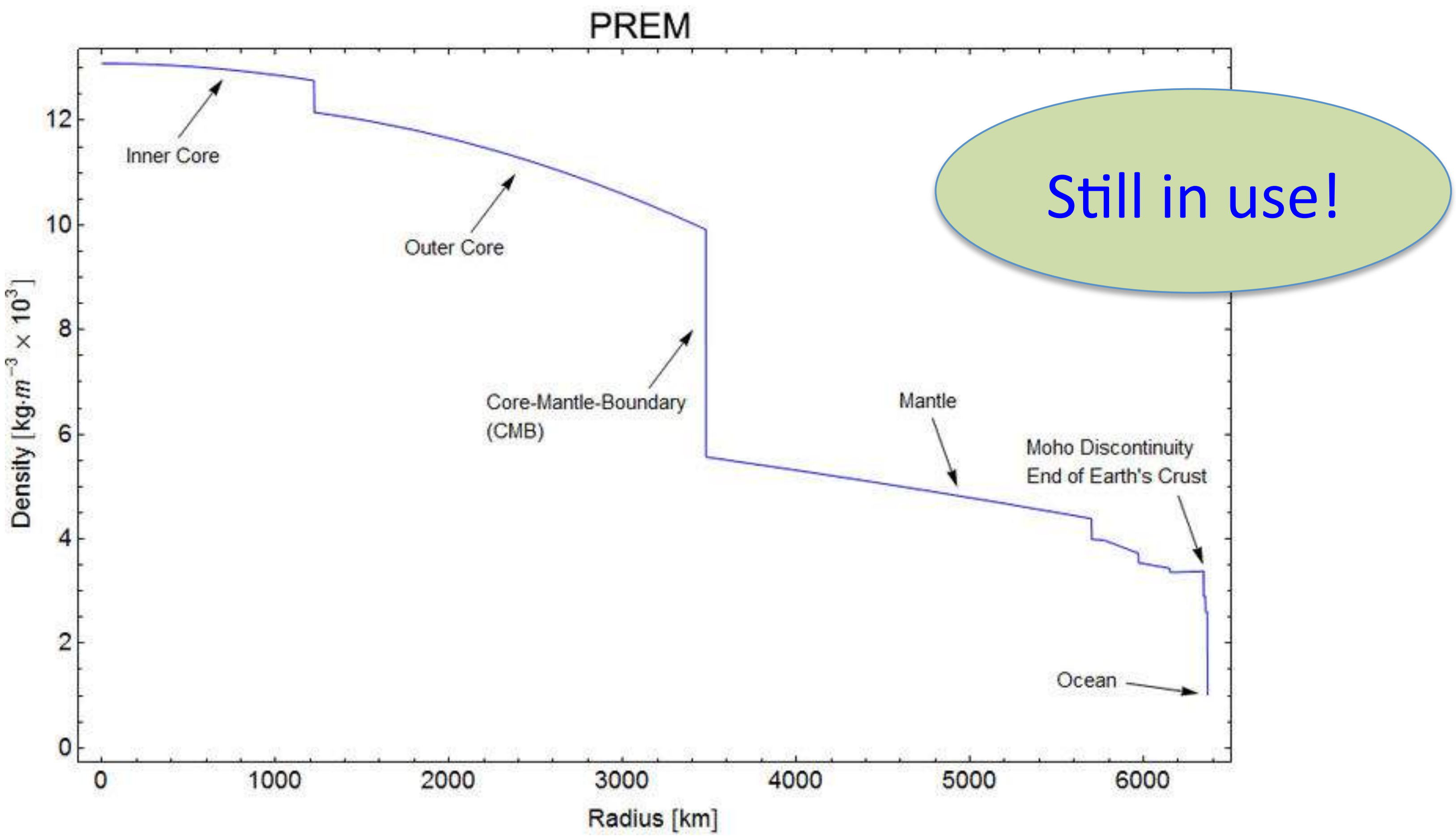
The Earth's gravitational profile is needed to integrate the Adams-Williamson equation!

1-dimensional density profile



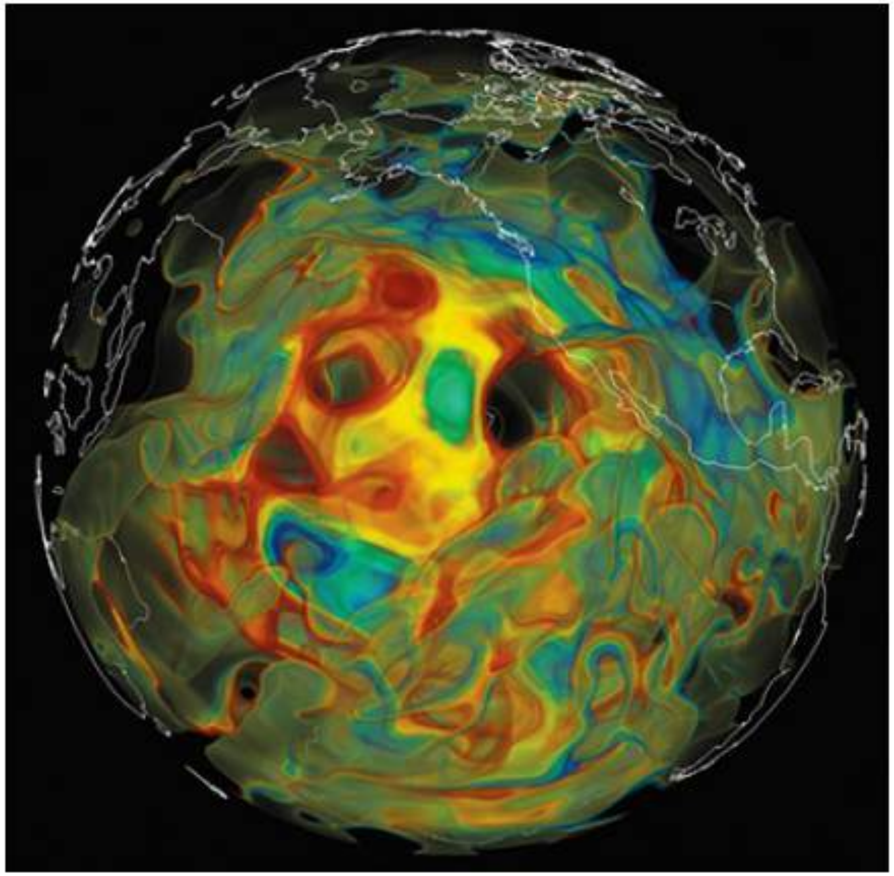
[Dziewonski and Anderson, Physics of the Earth and Planetary Interiors, 25 (1981)]

1-dimensional density profile

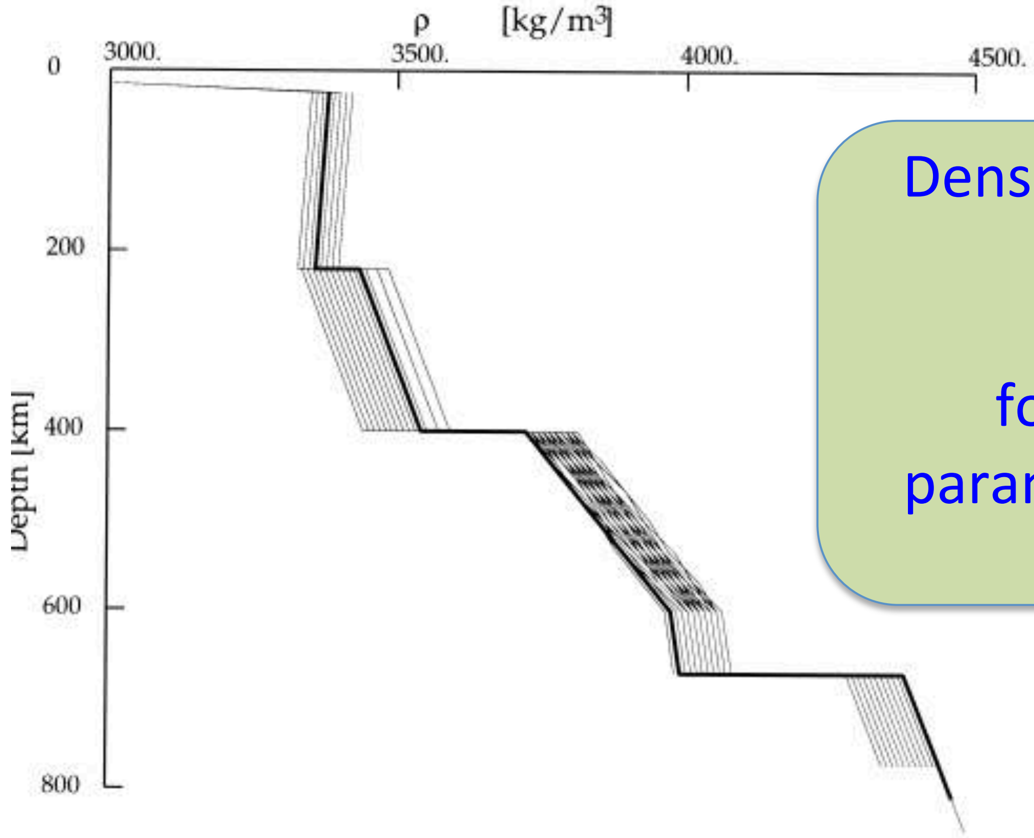


[Dziewonski and Anderson, Physics of the Earth and Planetary Interiors, 25 (1981)]

State-of-art three-dimensional picture



Model dependence of the profile…

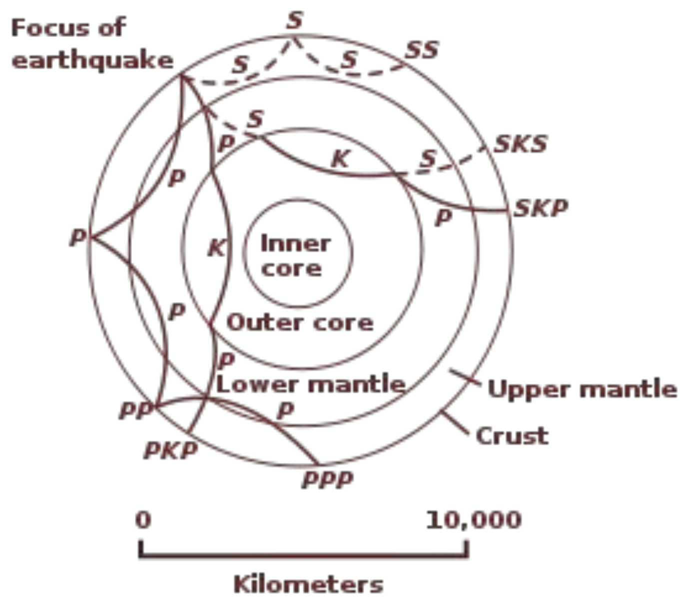


Density variation in the CRUST for different parameter choices: 3-5%

[Kennett, Geophysical Journal International, 132 (1998)]

The Earth's core

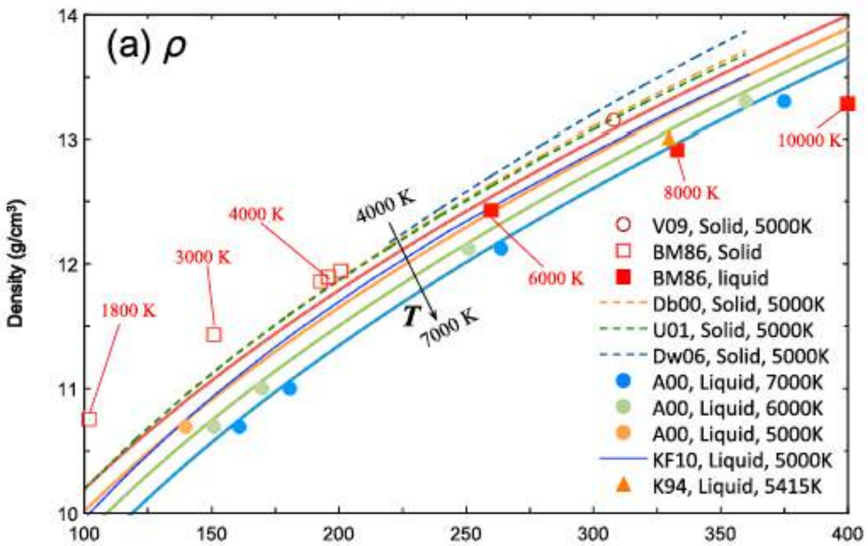
A problem:
The OUTER CORE IS LIQUID:
EARTHQUAKE WAVES CANNOT CROSS THE INNER CORE



We only have information about the INNER CORE through global constraints and extrapolations

Inner core uncertainties

Strong dependence of the IC density on temperature, pressure and composition



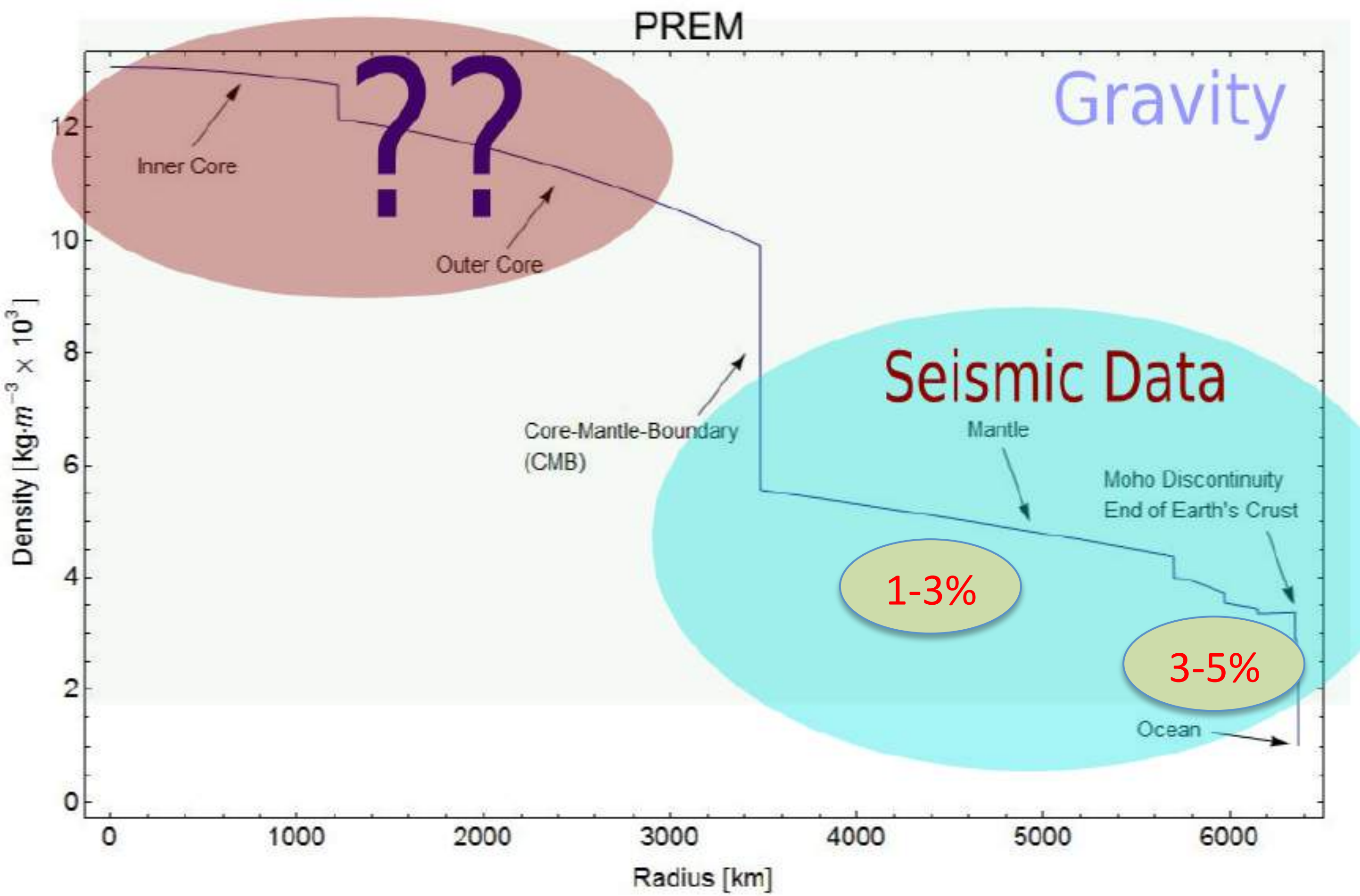
Ishikawa, Tsuchiya, Tange, J. GeoPhys. Res. (Solid Earth) 119 (2014)

Estimated temperature range still very large: 4000-10000 K

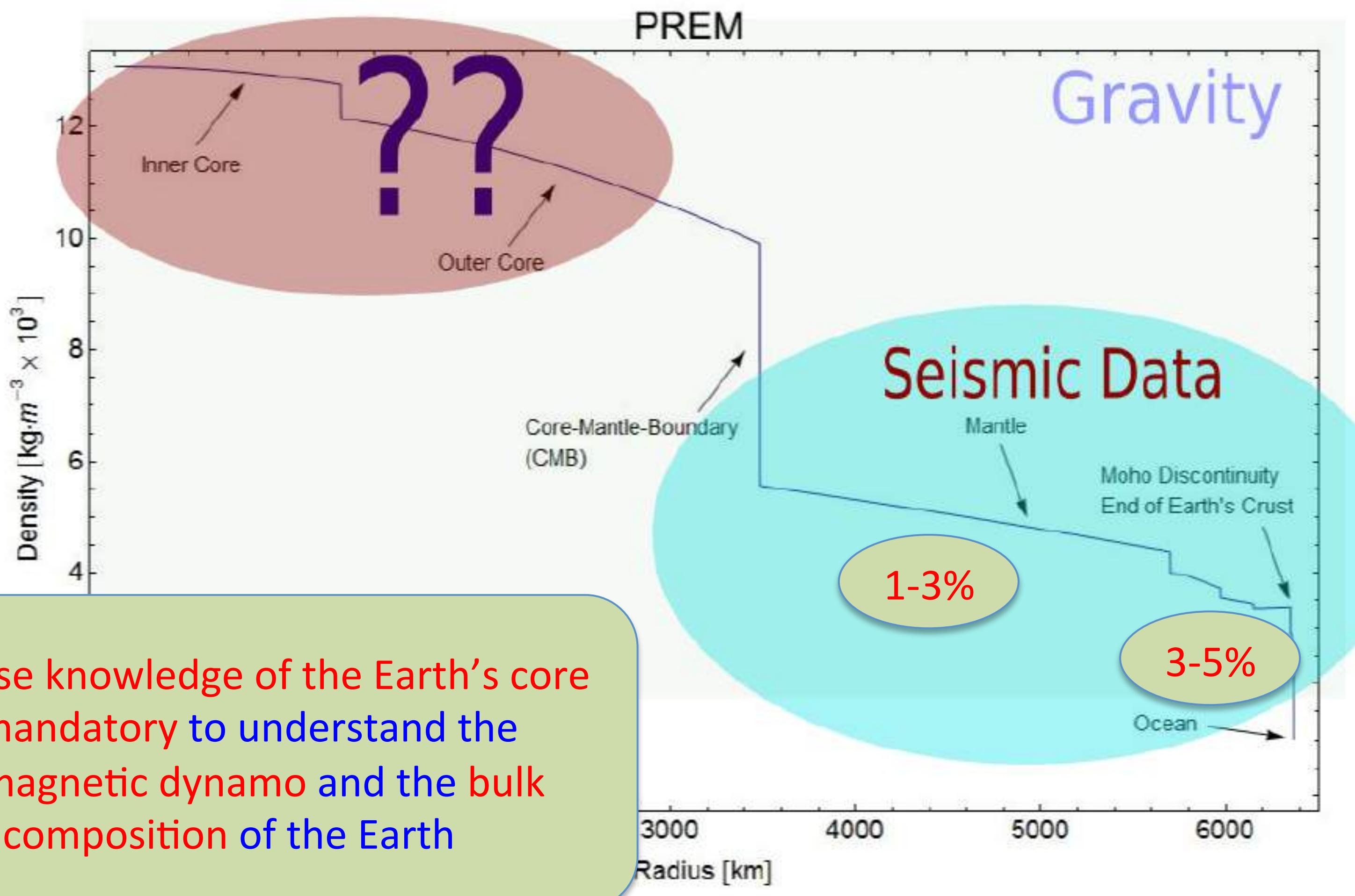
Composition guessed (iron-nickel?)

Missing Xenon problem

Uncertaintes from seismology



Uncertaintes from seismology



A precise knowledge of the Earth's core is mandatory to understand the geomagnetic dynamo and the bulk composition of the Earth

Neutrinos to study the Earth's interior

An old idea: first mentioned in an unpublished CERN preprint,

A.Placci and E. Zavattini, submitted in Oct 1973 to Nuovo Cimento; rejected?... never received?....

and in a talk

L. V. Volkova and G. T. Zatsepin, Izv. Akad. Nauk. Ser. Fiz. 38N5 (1974)

In modern language, a long-baseline experiment

The idea was premature!

Tomography

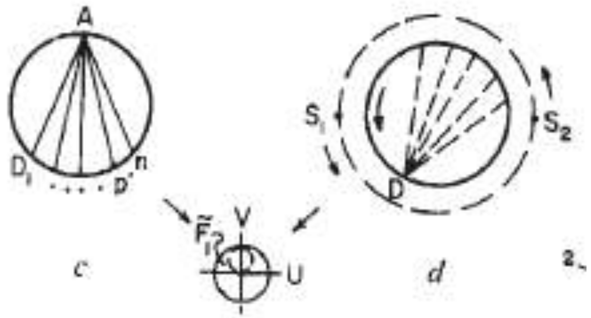
noun to·mog·ra·phy \ tō-ˈmä-grə-fē \

imaging by sections or sectioning, through the use of any kind of penetrating wave (Wikipedia)

a method of producing a three-dimensional image of the internal structures of a solid object (such as the human body or the earth) by the observation and recording of the differences in the effects on the passage of waves of energy impinging on those structures (Merriam-Webster)

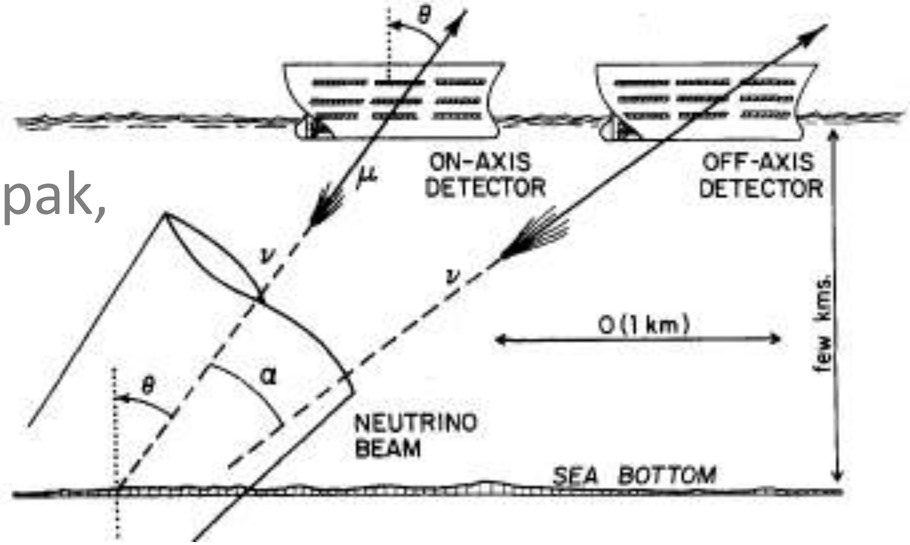
Neutrino tomography

Even more premature…

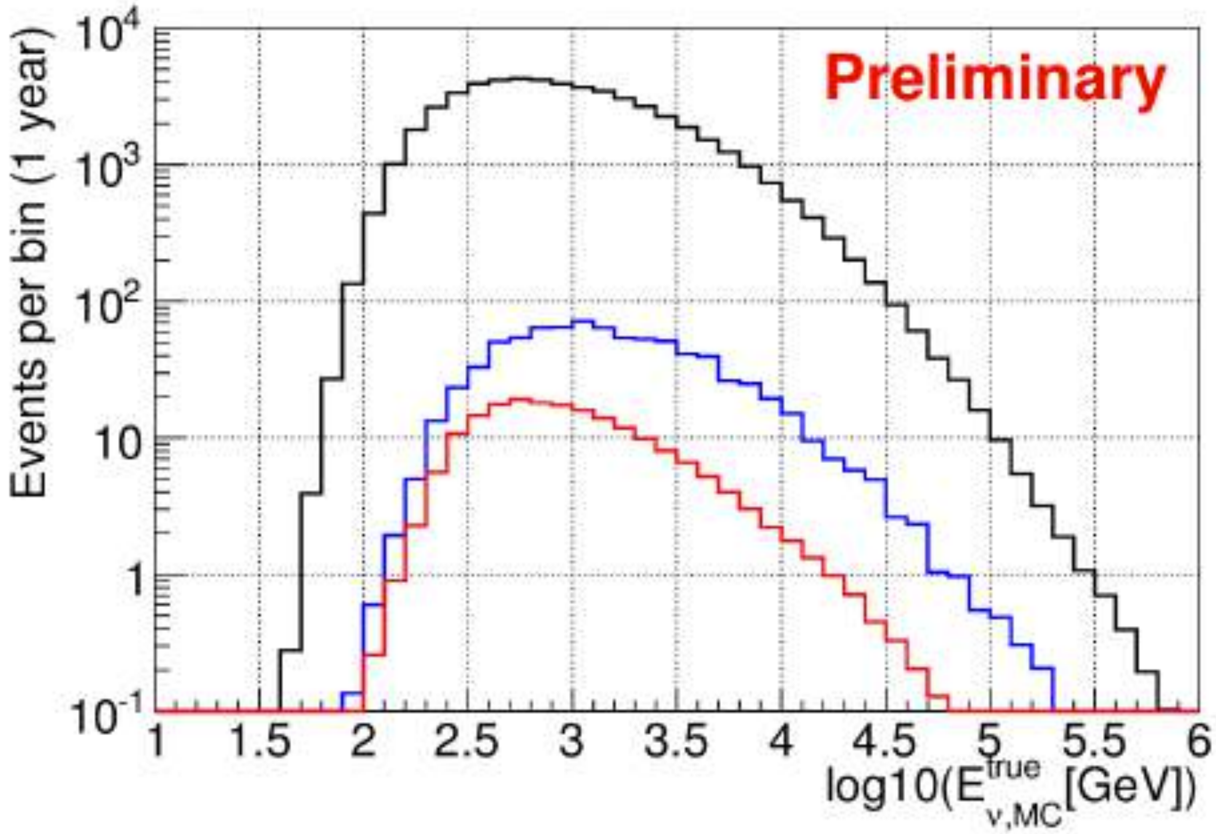


De Rújula, Glashow, Wilson, Charpak, Phys. Rept. 99 (1983)

T. Wilson, Nature 309 (1984)



Use atmospheric neutrinos!



IceCube contribution to ICRC 2015, arXiv:1510.05223

Two ways to scan the Earth

- Atmospheric neutrino oscillations (< 1 TeV)

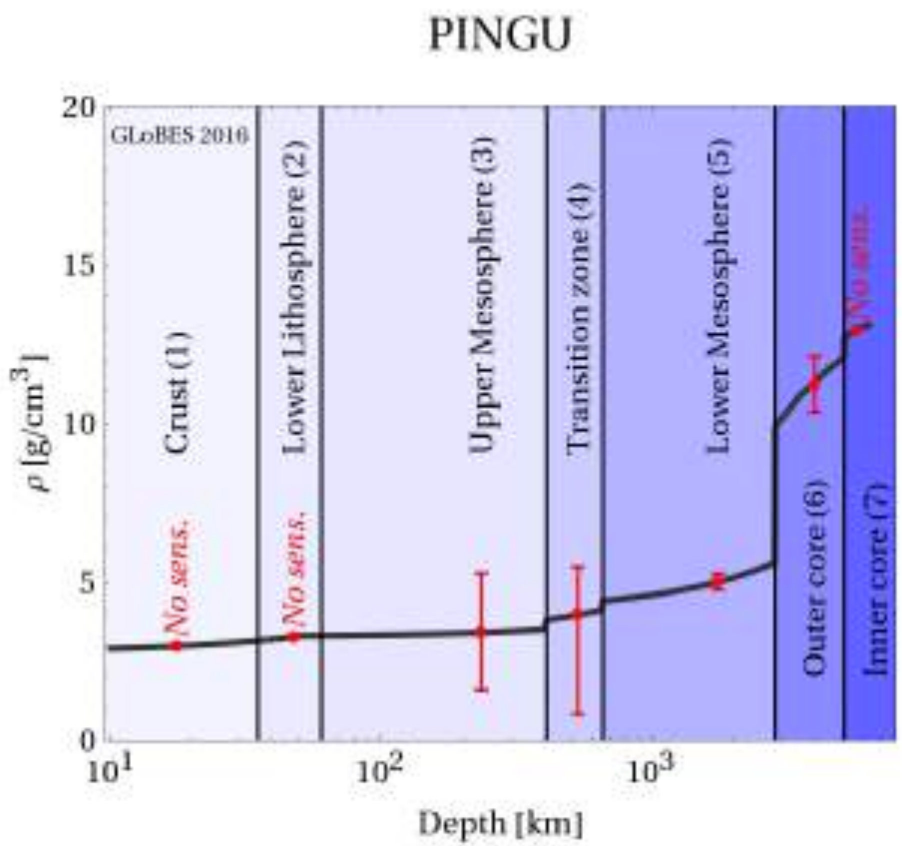
$$P_{ee}^{\pm} = 1 - \left(\frac{\Delta_{23}}{B_{\mp}}\right)^2 \sin^2(2\theta_{13})\,\sin^2\left(\frac{B_{\mp}\,L}{2}\right) - \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2(2\theta_{12})\,\sin^2\left(\frac{A\,L}{2}\right)$$

Two ways to scan the Earth

- Atmospheric neutrino oscillations (< 1 TeV)

$$P_{ee}^{\pm} = 1 - \left(\frac{\Delta_{23}}{B_{\mp}}\right)^2 \sin^2(2\theta_{13}) \sin^2\left(\frac{B_{\mp} L}{2}\right) - \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2(2\theta_{12}) \sin^2\left(\frac{A L}{2}\right)$$

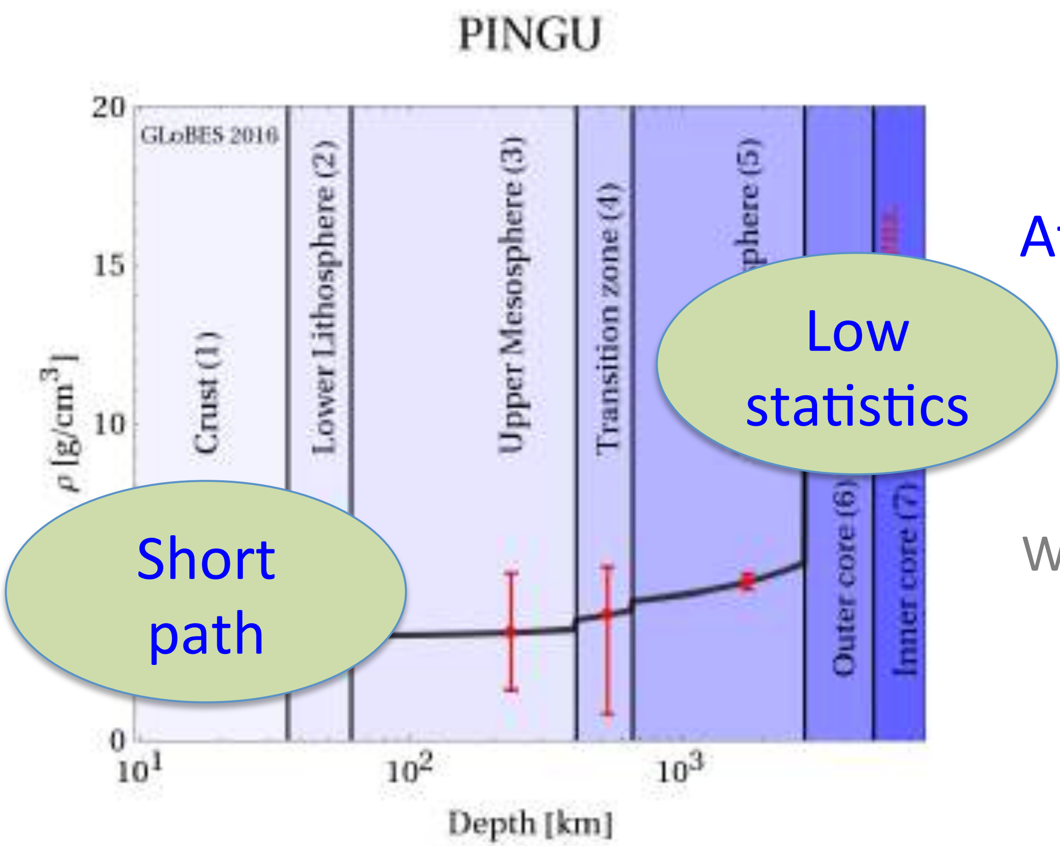
“Recent” forecasts, 1



After 10 years of data taking at PINGU or ORCA using neutrino oscillations

Winter, Nucl. Phys B908 (2016)

“Recent” forecasts, 1



After 10 years of data taking at PINGU or ORCA using neutrino oscillations

Winter, Nucl. Phys B908 (2016)

Two ways to scan the Earth

- Atmospheric neutrino oscillations (< 1 TeV)

$$P_{ee}^{\pm} = 1 - \left(\frac{\Delta_{23}}{B_{\mp}}\right)^2 \sin^2(2\theta_{13}) \sin^2\left(\frac{B_{\mp} L}{2}\right) - \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2(2\theta_{12}) \sin^2\left(\frac{A L}{2}\right)$$

- Atmospheric neutrino flux attenuation (> 1 TeV)

$$\frac{d\phi_\nu(E,\tau)}{d\tau} = -\sigma_{tot}(E)\phi_\nu(E,\tau)$$

Two ways to scan the Earth

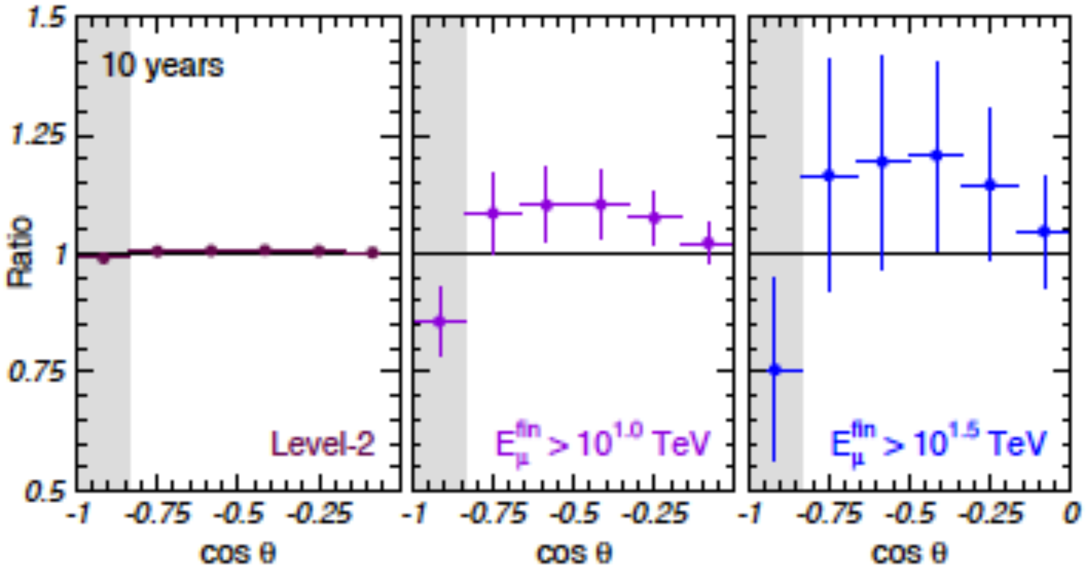
- Atmospheric neutrino oscillations (< 1 TeV)

$$P_{ee}^{\pm} = 1 - \left(\frac{\Delta_{23}}{B_{\mp}}\right)^2 \sin^2(2\theta_{13}) \sin^2\left(\frac{B_{\mp} L}{2}\right) - \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2(2\theta_{12}) \sin^2\left(\frac{A L}{2}\right)$$

- Atmospheric neutrino flux attenuation (> 1 TeV)

$$\frac{d\phi_\nu(E,\tau)}{d\tau} = -\sigma_{tot}(E)\phi_\nu(E,\tau)$$

"Recent" forecasts, 2

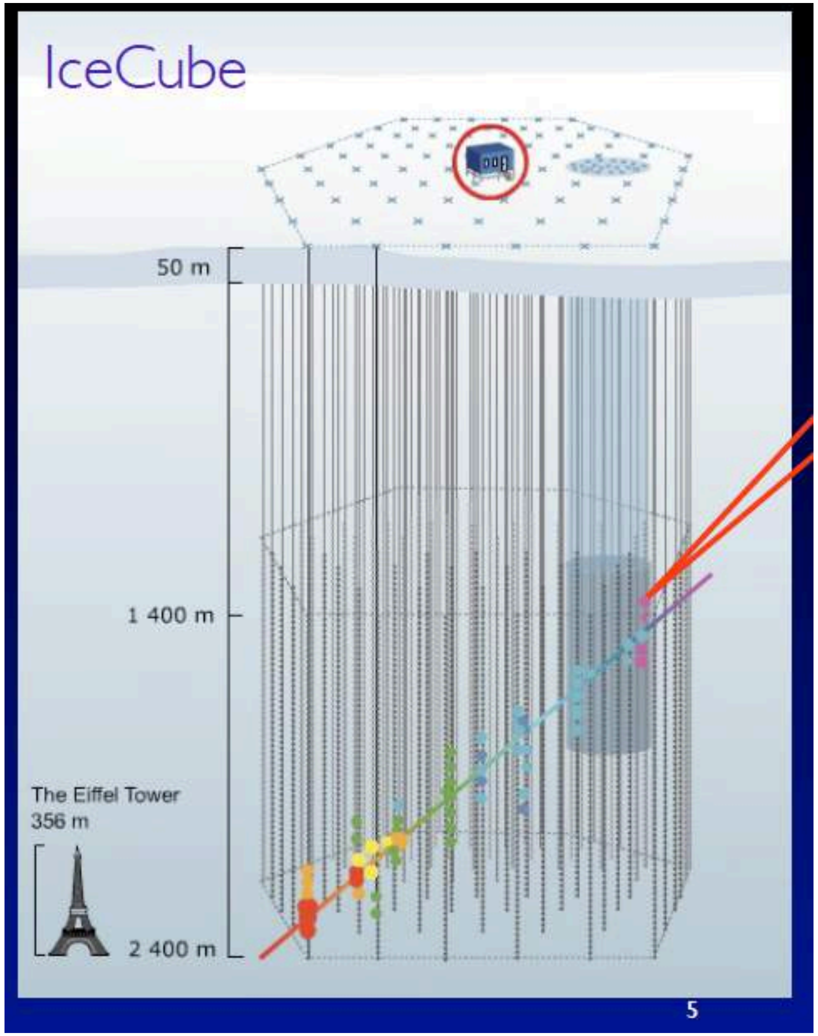


After 10 years of data taking at IceCube using neutrino attenuation

Claim: IceCube could reject a homogeneous Earth at 5σ in ten years

Gonzalez-García, Halzen, Maltoni, Tanaka, Phys. Rev. Lett. 100 (2008)

The IceCube Experiment



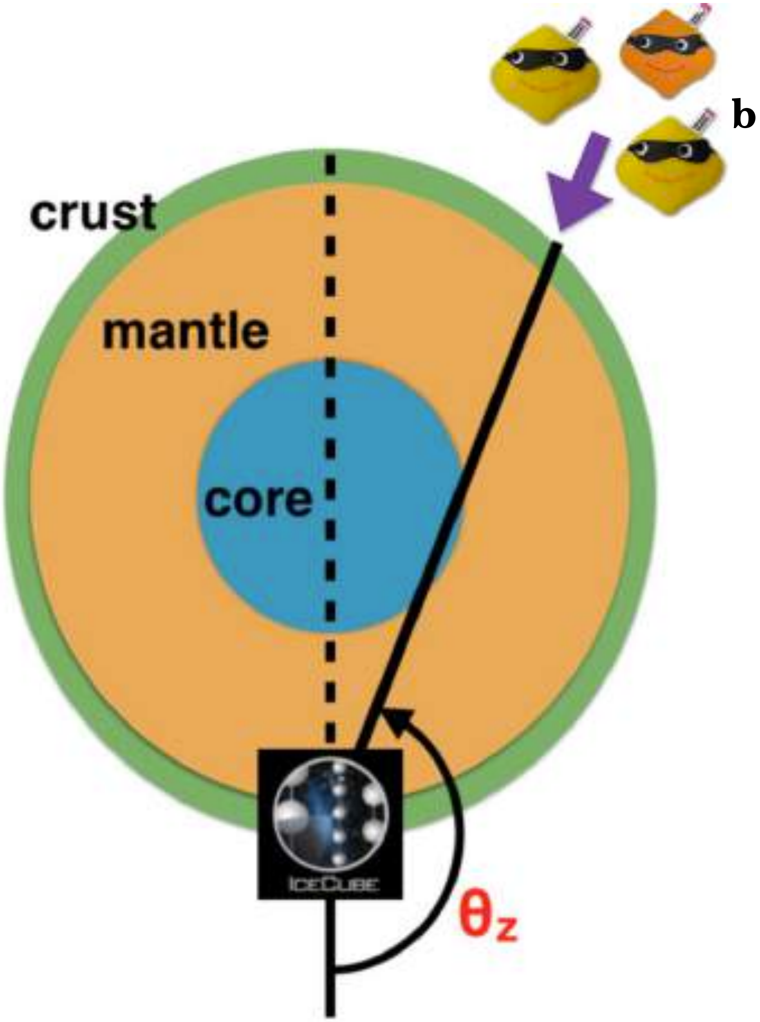
- Deployed in glacial ice at the South Pole
- Array size $1 km^3$, 86 strings, 60 optical sensors (DOMs) per string

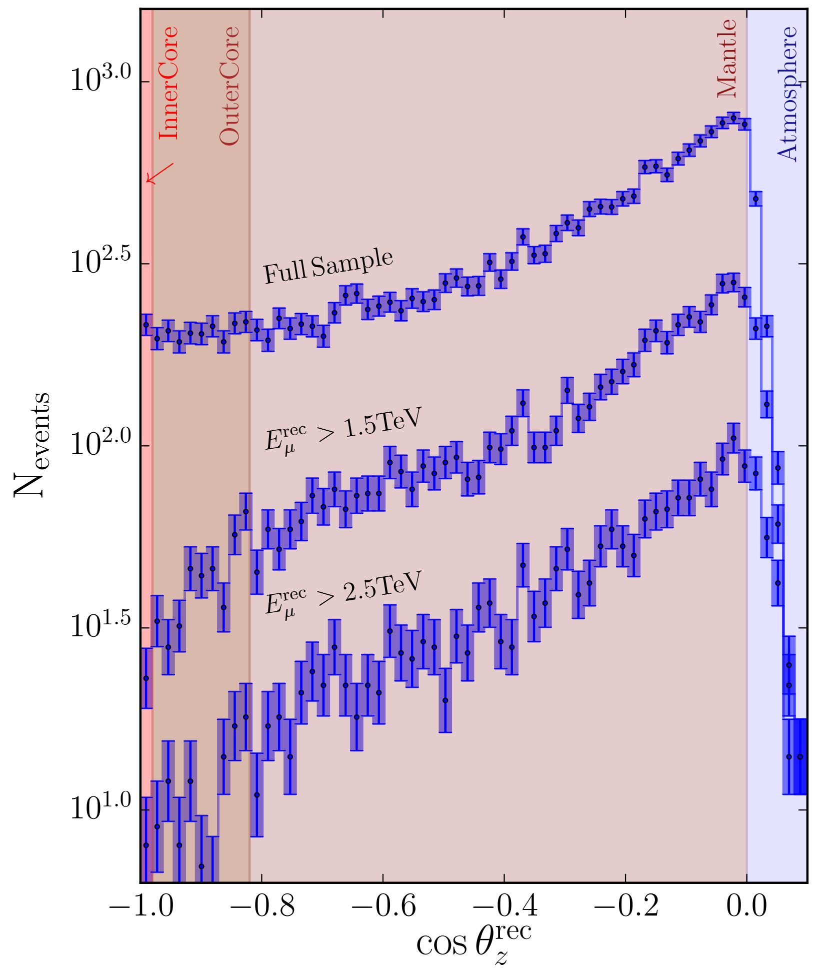
The IceCube IC86 data sample

- 1 year of data taking (2011-2012)
- 20145 muon events over 343.7 days
- E_μ = [400 GeV ÷ 20 TeV]
- The muon direction is a very good proxy of the neutrino direction, with $\Delta\cos\theta < 0.01$
- PUBLICLY AVAILABLE!

7 more years of data are not yet available to mortals.....

Raw data as a function of E_μ and θ





Comparison with expectations

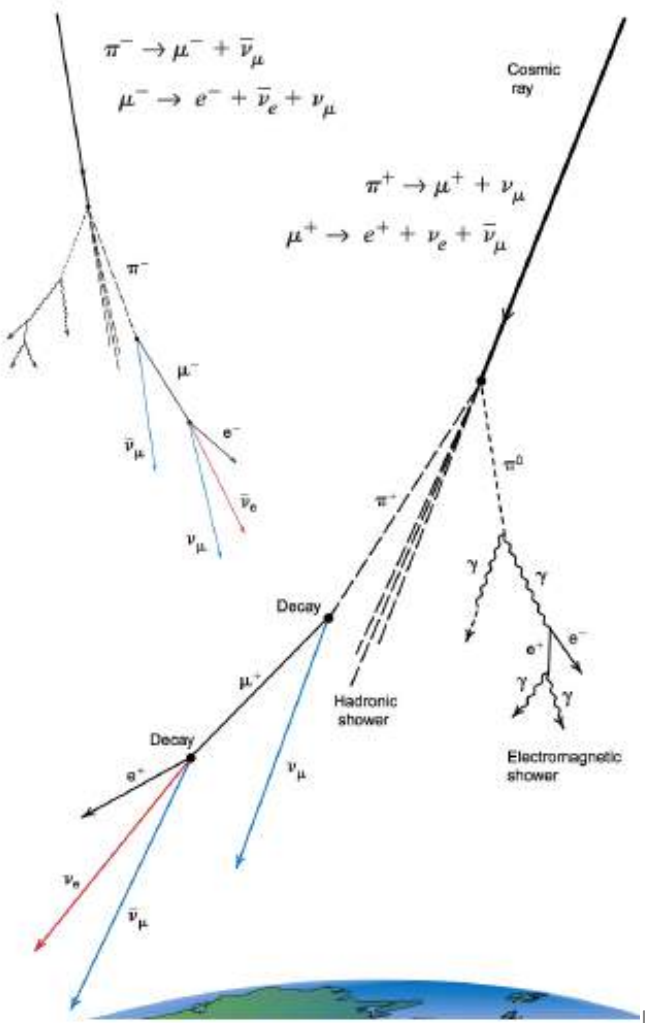
Flux model

Propagation

Interaction with nucleons

Detector simulation

Flux model dependence



Primary cosmic ray flux: Honda-Gaisser model + Gaisser-Hillas corrections (HG-GH-H3a)

Hadronic model: QGSJET-II-4

We have considered other options → discrete systematics

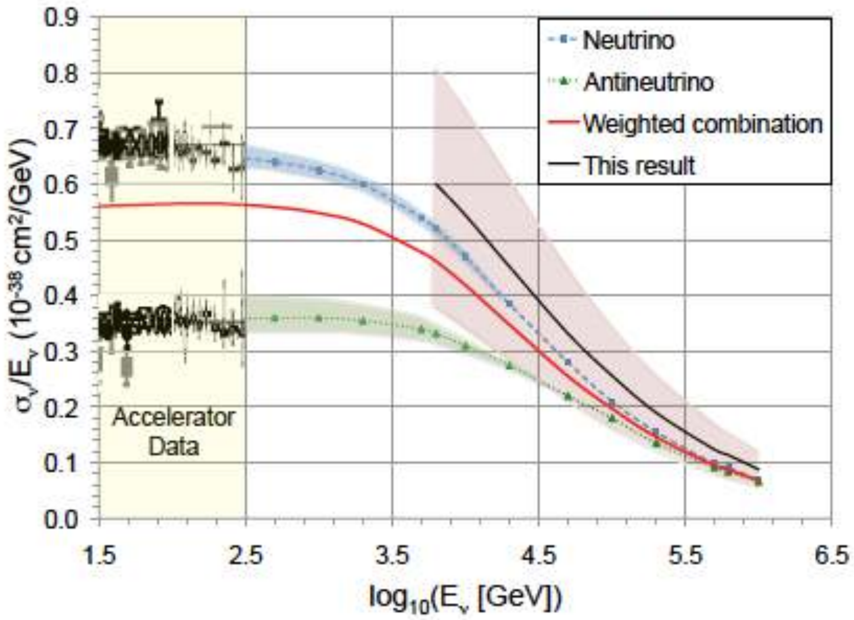
Neutrino propagation

$$\frac{dF_\nu(E)}{dx} \;=\; -i[\mathrm{H_o} + \mathrm{Vm}, F_\nu(E)] - \sum_\alpha \frac{1}{2\lambda^\alpha(E)} \{\Pi_\alpha, F_\nu(E)\}$$

Propagation through the Earth with ν-SQuIDs
(includes oscillations)

Neutrino-nucleon interaction

Parton distribution functions: HERAPDF



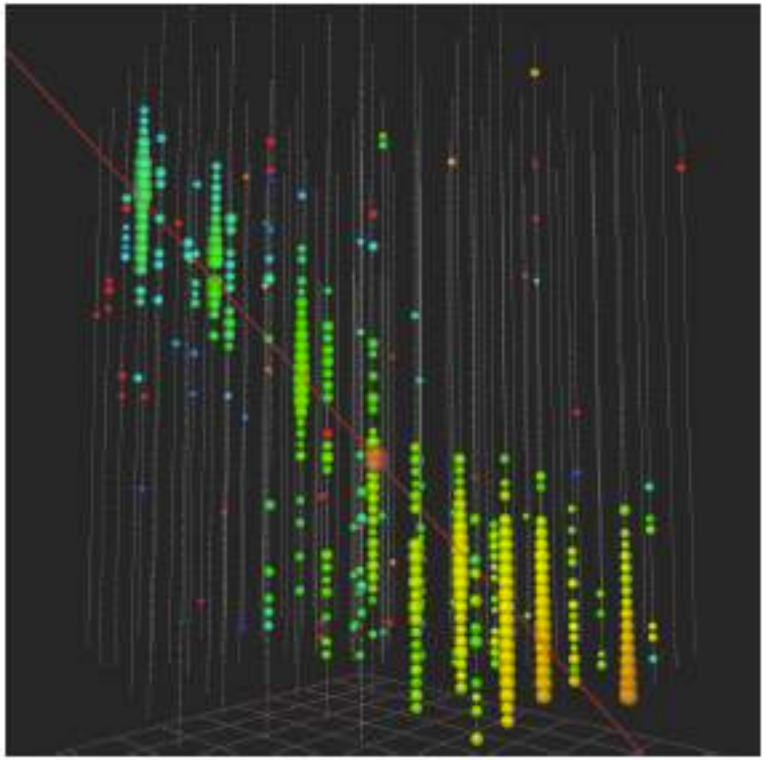
Aarsten et al, Nature 2017

νN (νN) cross-sections at 2-3% (4-10%) errors

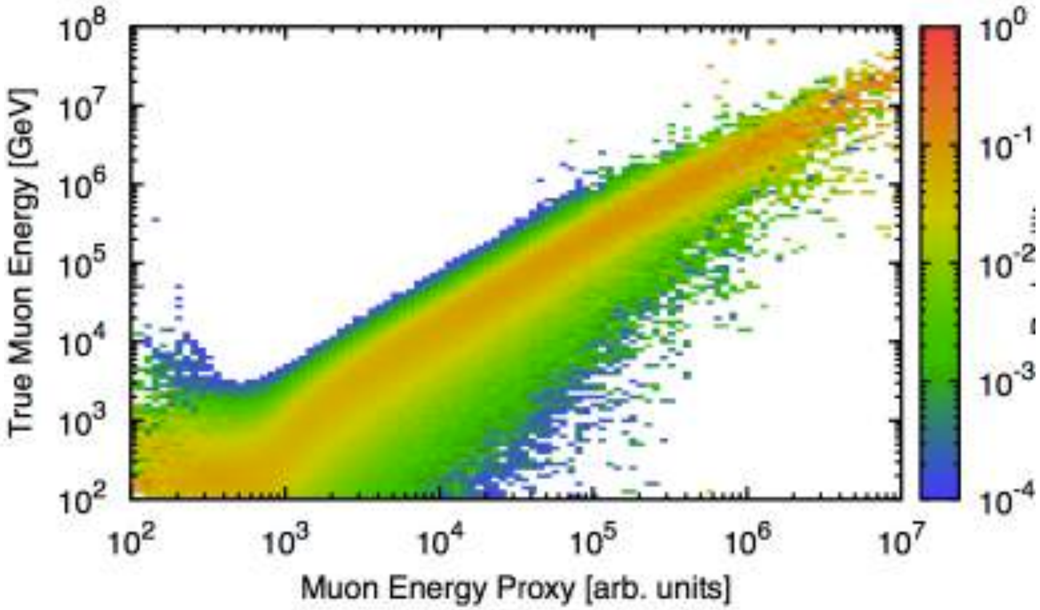
CAUTION: NEW ICECUBE MEASUREMENT!

$1.30^{+0.21}_{-0.19}$ (stat.) $^{+0.39}_{-0.43}$ (syst.) x σ_{SM}

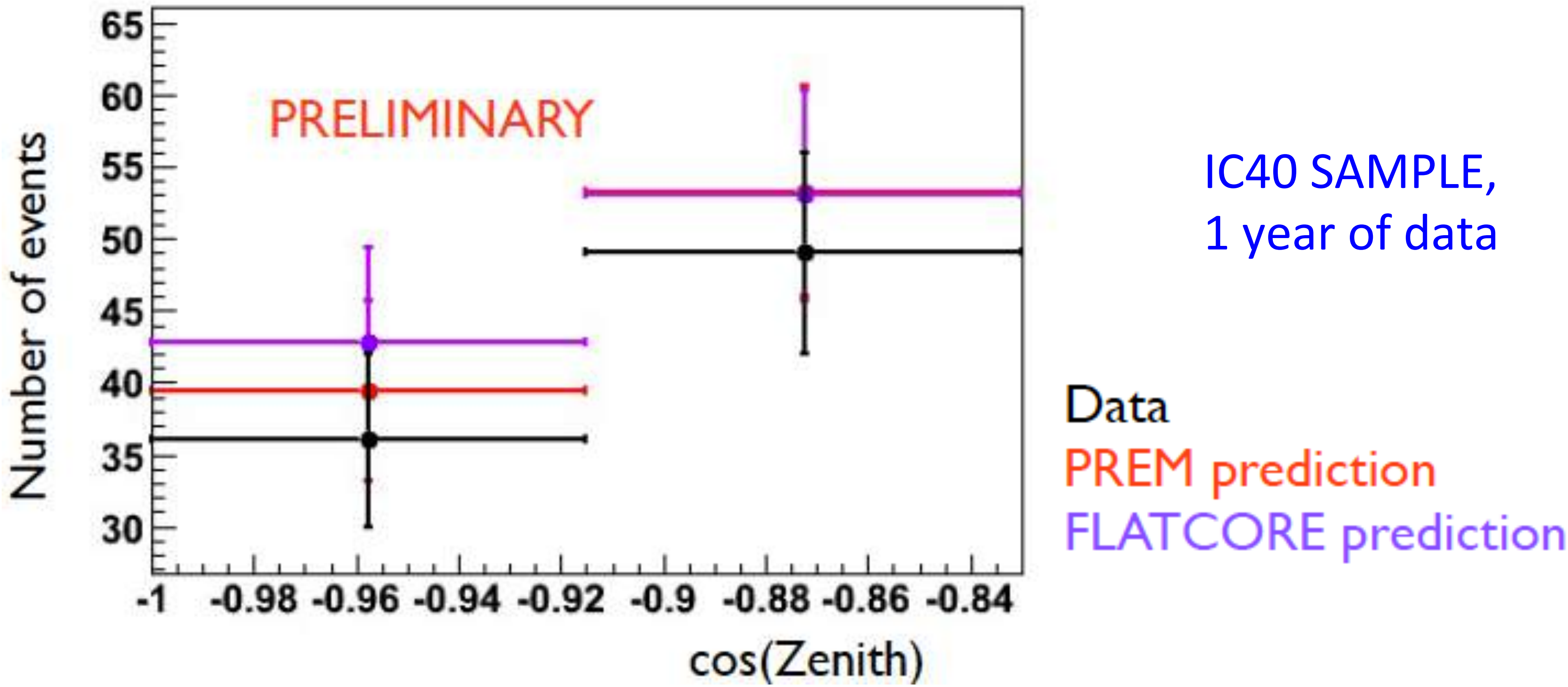
Detector simulation



We use the official IceCube MC to map E^{μ}_{real}, θ^{μ}_{real} into E^{ν}_{rec}, θ^{ν}_{rec}



An early attempt by IceCube collaboration



IC40 SAMPLE,
1 year of data

Hoshina, Tanaka, 2011, International Workshop on High-Energy Geophysics, Tokyo

Yesterday Prof. Halzen said...

"We will see the core effect within 5 years"

But after the talk, he said secretly to me...

"We won't need 5 sigma or 3 sigma separation to say 'we see the core effect' :) "

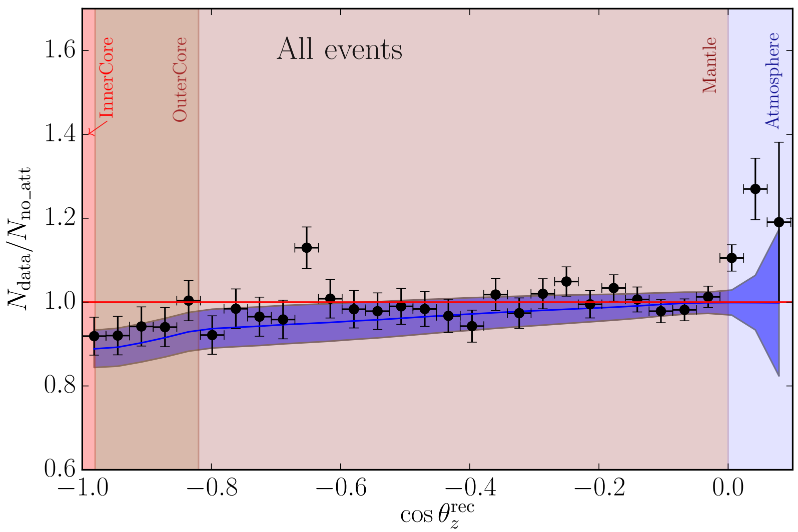
We expect to see the effect of core in 5 years :

- After improving energy resolution and understanding systematics of detector and neutrino flux
- with one sigma (or "Francis level") separation :)

Including energy cuts: N_{data}/N_{noatt}

a

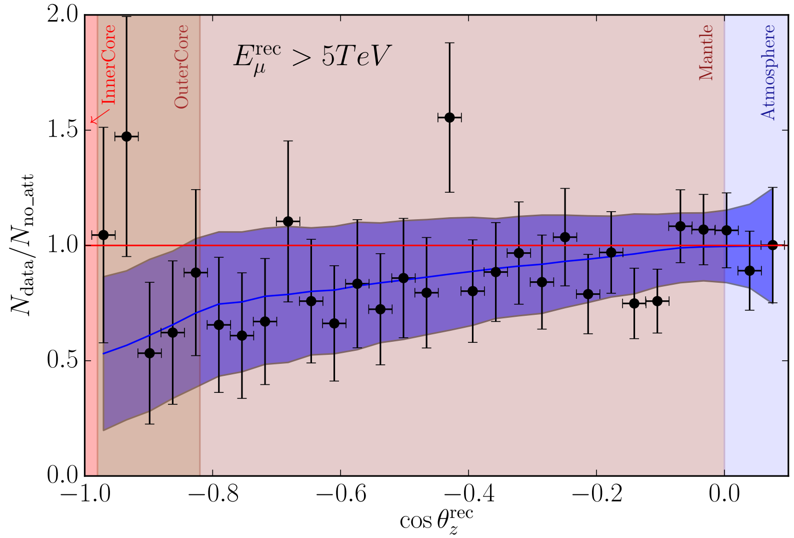
Full sample



Full sample useful for normalization

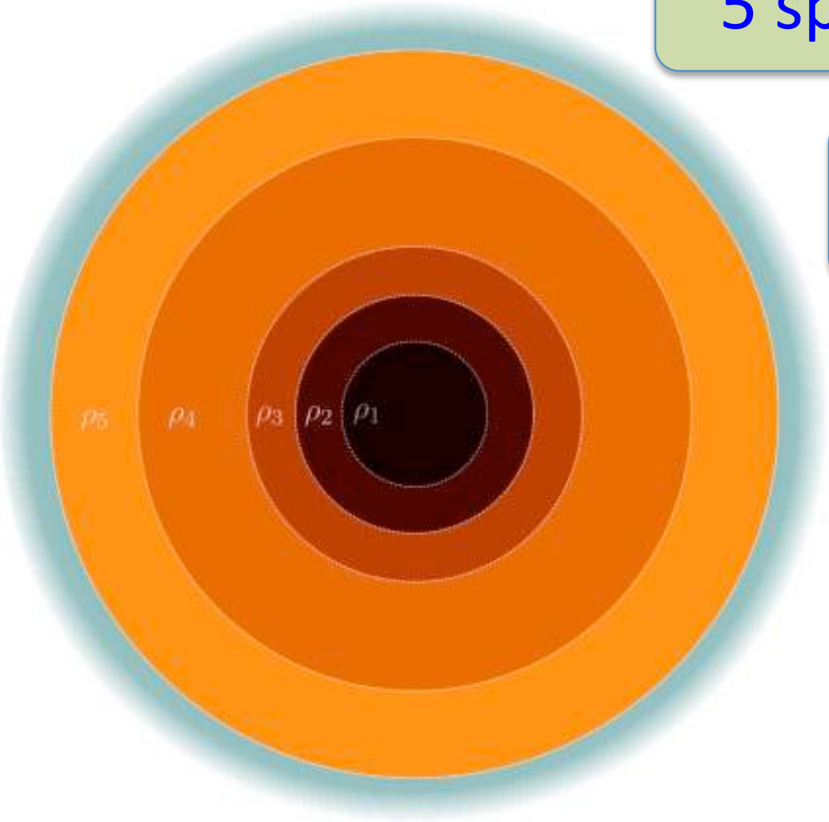
b

Above 5 TeV



For cosθ > -0.6, attenuation can be as large as 50%

Our Earth's model



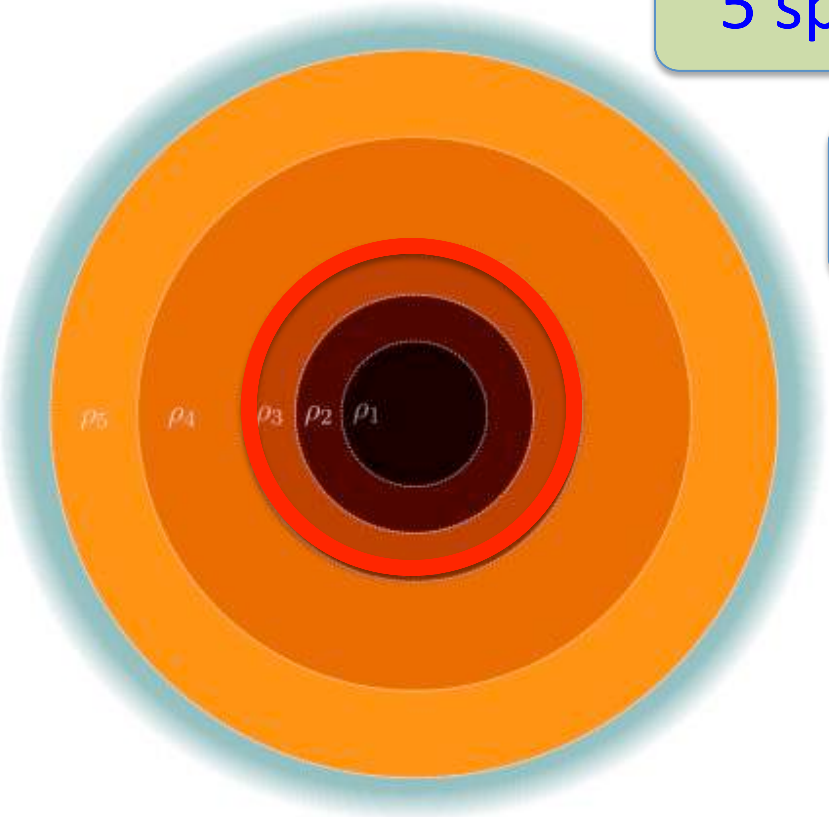
5 spherical layers

Inner Core, one layer
L_1 = 1242 km

Outer Core, two layers
L_2 = 2373 km,
L_3 = 3504 km

Mantle, two layers
L_4 = 2373 km,
L_5 = 3504 km

Our Earth's model



5 spherical layers

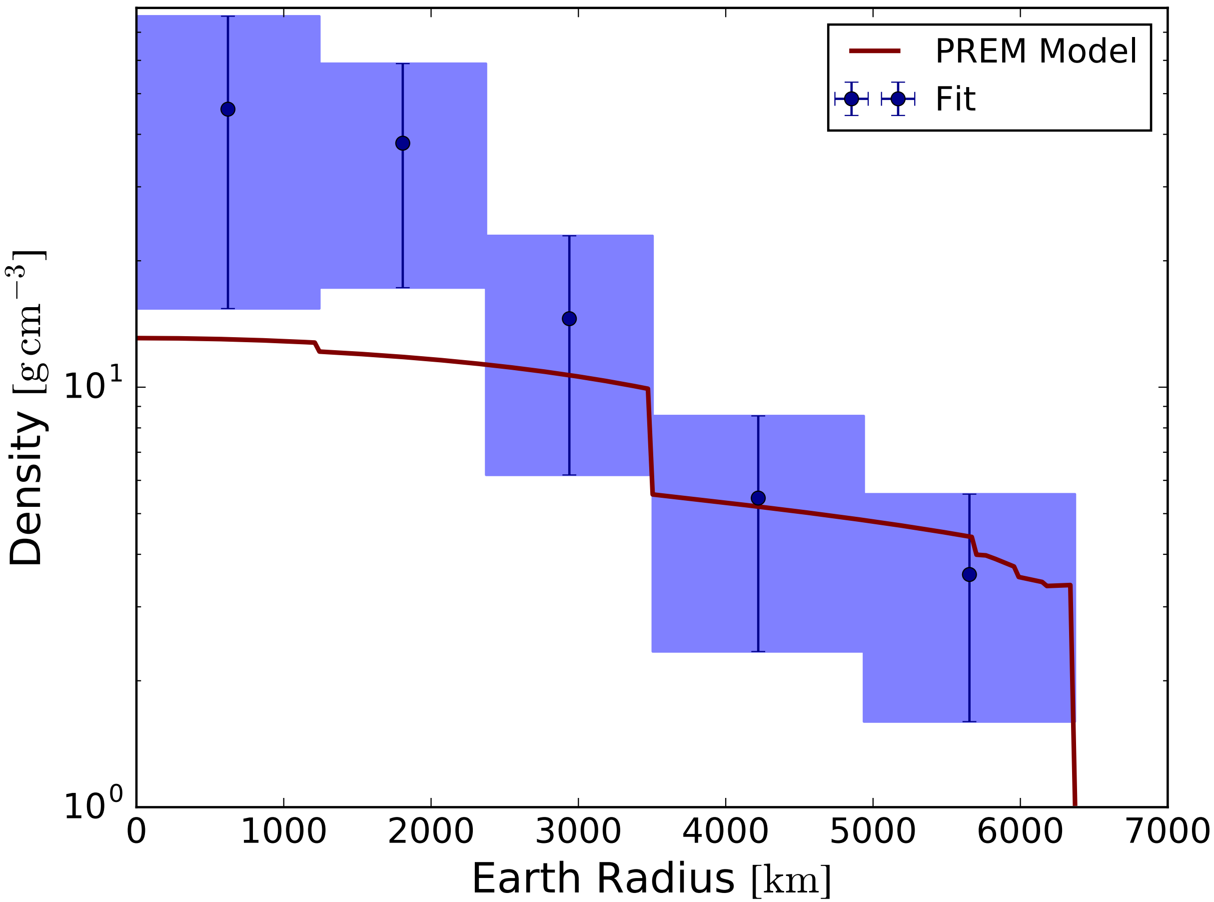
Inner Core, one layer
L_1 = 1242 km

Outer Core, two layers
L_2 = 2373 km,
L_3 = 3504 km

Mantle, two layers
L_4 = 2373 km,
L_5 = 3504 km

Core-Mantle Boundary fixed!

First 1-d density profile with neutrinos



Analysis performed with MultiNest

5 Earth layers densities

and

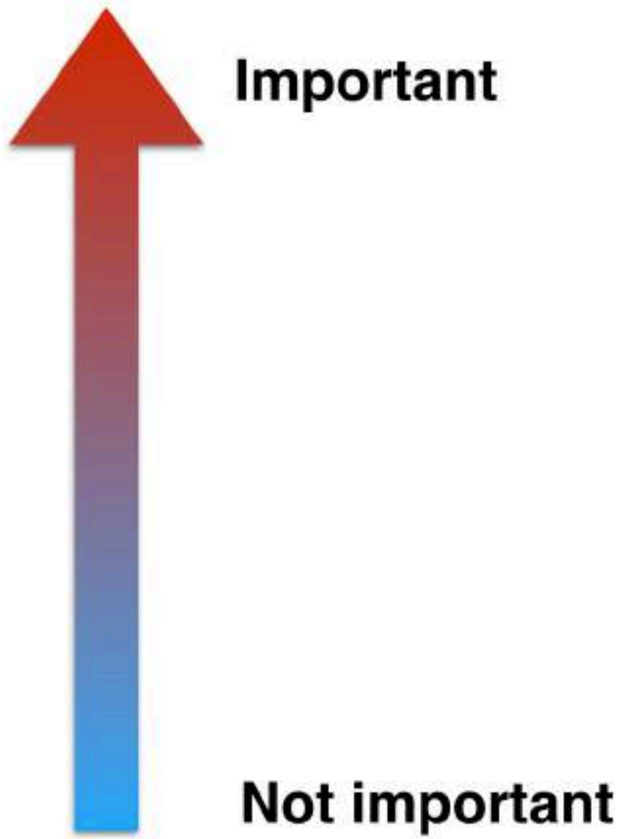
4 systematic errors:

- Flux normalization
- Pion-to-kaon ratio
- Spectral shape
- DOM Efficiency

Systematics importance

- *DOM efficiency*
- *Flux continuous parameters*
  - *spectral index*
  - *π/K ratio*
  - *$\nu/\bar{\nu}$ ratio* Full Implementation
- Air shower hadronic models Marginally irrelevant precise check
- Primary cosmic ray fluxes Marginally irrelevant precise check
- Hole Ice Irrelevant
- Neutrino cross sections Irrelevant
- Bulk ice scattering/absorption Irrelevant

continuous systematics
discrete systematic

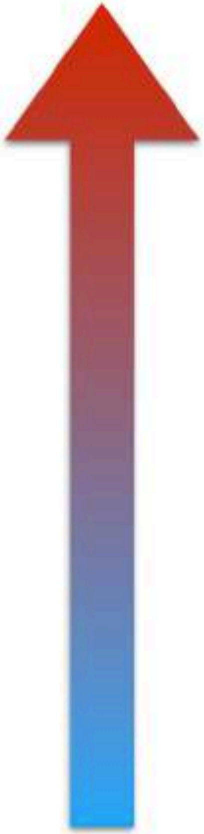


Systematics importance

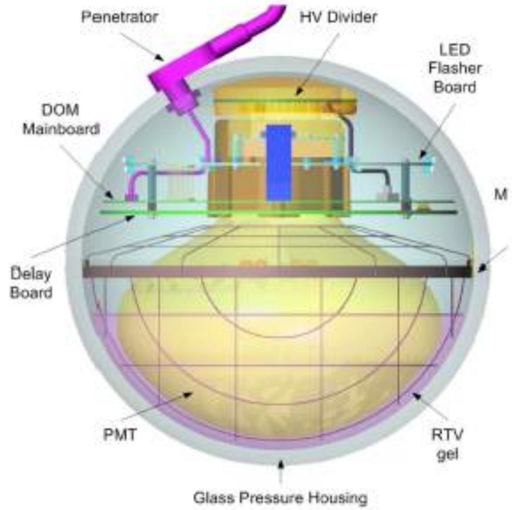
- *DOM efficiency*
- *Flux continuous parameters*
  - *spectral index*
  - π/K *ratio*
  - $\nu/\bar{\nu}$ *ratio* Full Implementation
- Air shower hadronic models Marginally irrelevant precise check
- Primary cosmic ray fluxes Marginally irrelevant precise check
- Hole Ice Irrelevant
- Neutrino cross sections Irrelevant
- Bulk ice scattering/absorption Irrelevant

continuous systematics

discrete systematic



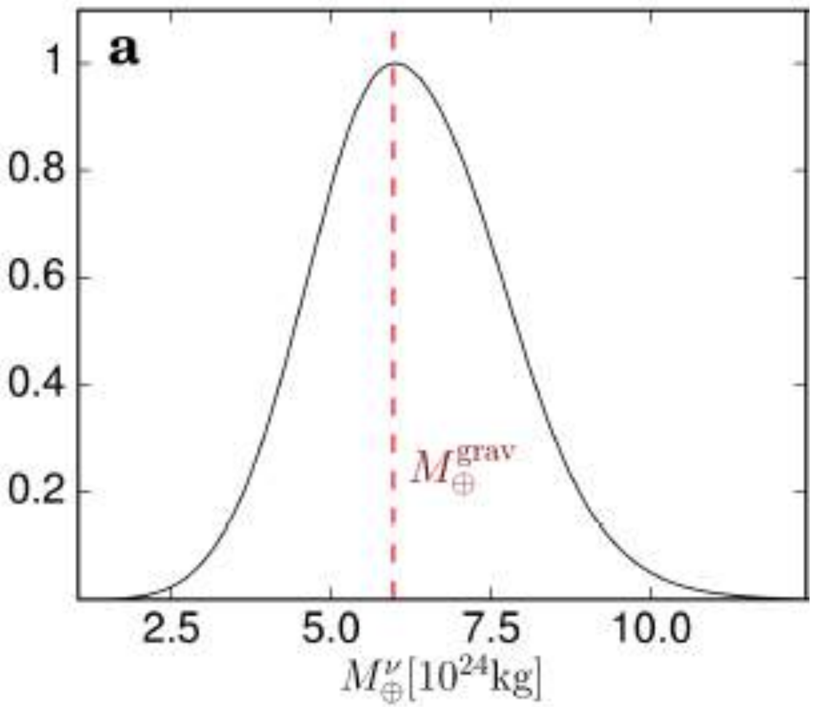
Important



D.O.M.

Not important

The Earth's mass



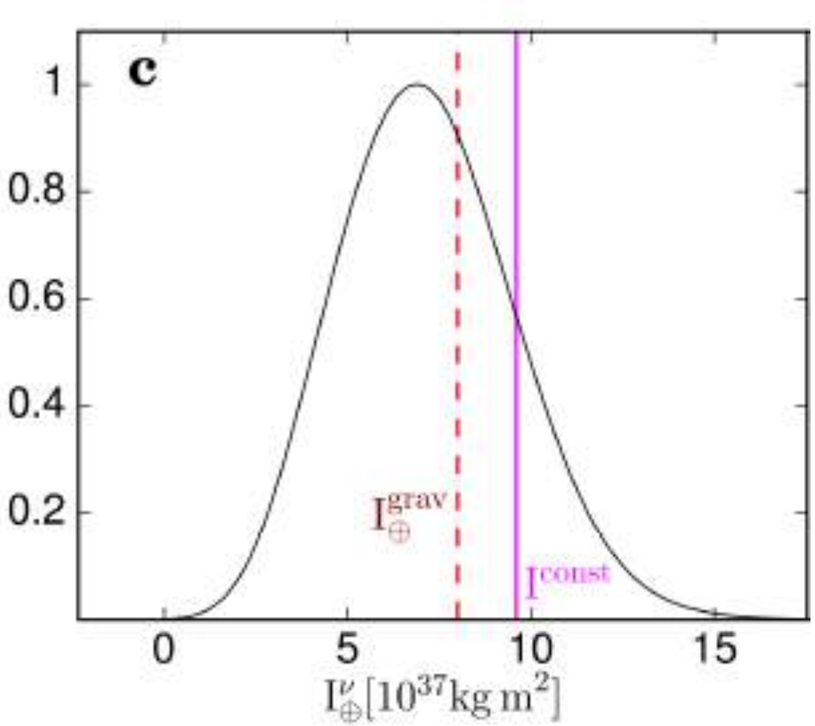
First Electro-weak measurement of the Earth's mass

$M_{earth\text{-}\nu} = (6.2 \pm 1.4) \times 10^{24}$ kg

Gravitational measurement of the Earth's mass

$M_{earth\text{-}grav} = (5.9722 \pm 0.0006) \times 10^{24}$ kg

The Earth's moment of inertia



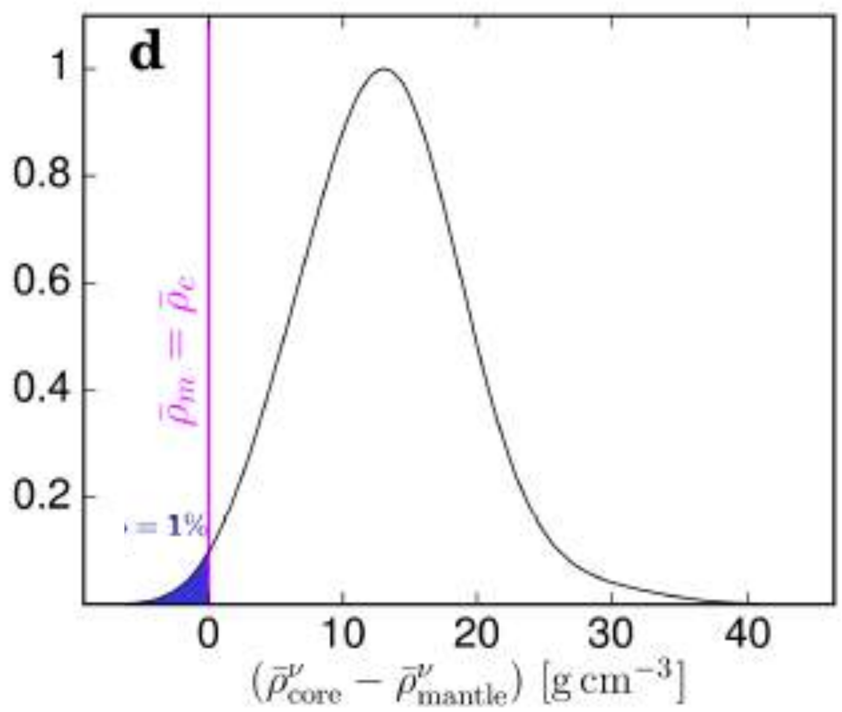
Electro-weak measurement of the Earth's moment of inertia

$I_{earth\text{-}\nu} = (7.1 \pm 2.5) \times 10^{37}$ kg m^2

Gravitational measurement of the Earth's moment of inertia

$I_{earth\text{-}grav} = (8.01736 \pm 0.00097) \times 10^{37}$ kg m^2

Earth's non-homogeneity

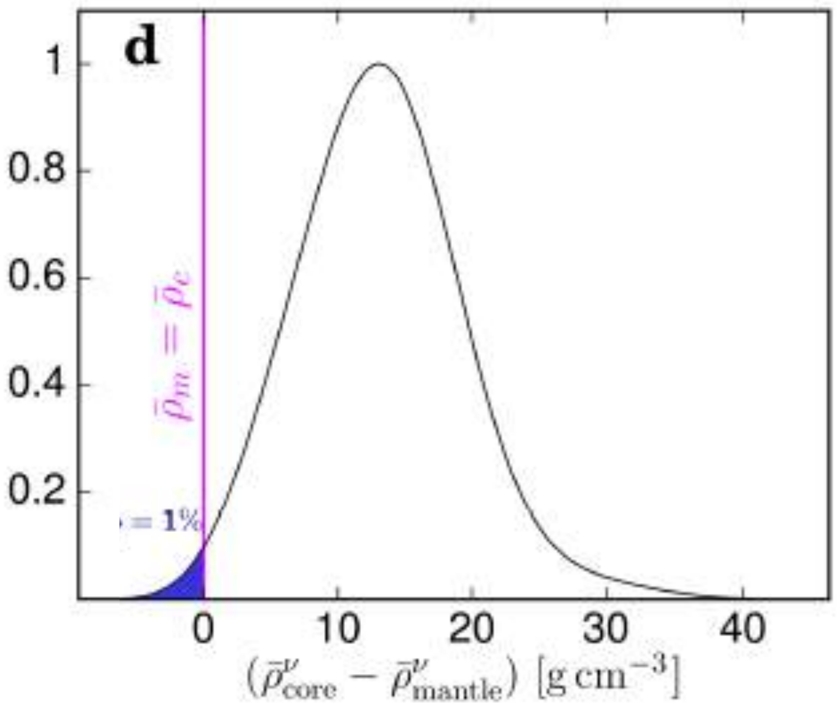


Electro-weak measurement of the Core-Mantle discontinuity

$\Delta\rho_{CMB-\nu}$ = (13 ± 6) g/cm3

A homogenous Earth has a p-value p = 0.01 !!!

Earth's non-homogeneity



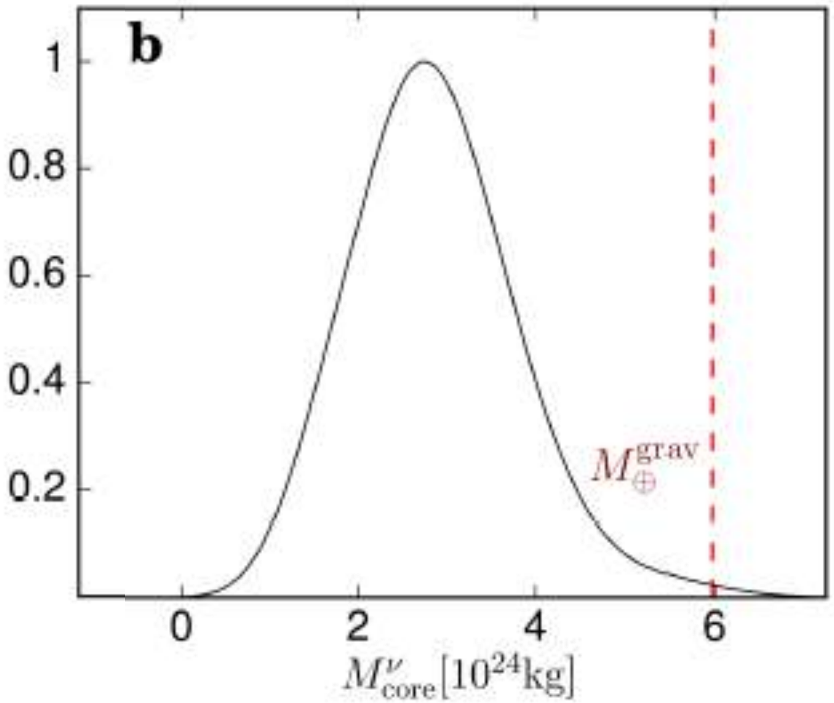
Electro-weak measurement of the Core-Mantle discontinuity

$\Delta\rho_{CMB-\nu}$ = (13 ± 6) g/cm3

A homogenous Earth has a p-value p = 0.01 !!!

2008: IceCube could reject a homogeneous Earth at 5σ in ten years

The Earth's core mass



Electro-weak measurement of the Earth's core mass

$M_{core-\nu} = (2.8 \pm 1.0) \times 10^{24}$ kg

This quantity may be used as a new constraint in seismological analyses

Comment on Inner Core over-density

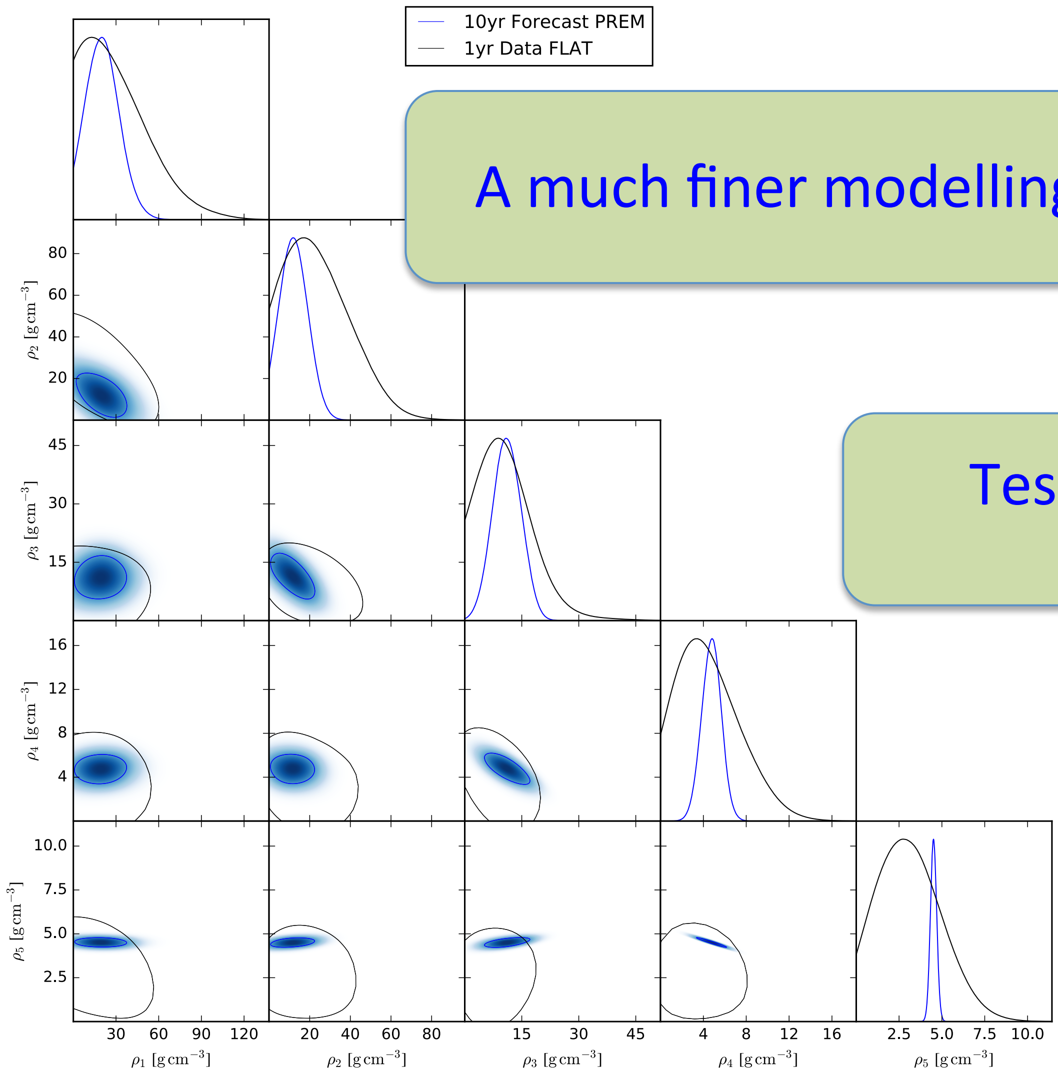
We measure ρ_1 = [15-40] g/cm^3, whereas for the PREM ρ_1 = [11.9 ± 0.2] g/cm^3
The over-density with respect to PREM is statistically irrelevant! YET…..

Comment on Inner Core over-density

We measure ρ_1 = [15-40] g/cm^3, whereas for the PREM ρ_1 = [11.9 ± 0.2] g/cm^3
The over-density with respect to PREM is statistically irrelevant! YET.....

Statistics will increase non-homogeneously for the different layers
We are trying to do a fit with 1-2-4 layers using the forecast for ten years of IceCube data

Forecast with 10 years of data



A much finer modelling of the Earth could be done

Test of the Inner-Outer Core discontinuity

Independent localization of the Core-Mantle Boundary

Conclusions and outlook

It is eventually possible to make a neutrino tomography of the Earth: first 1-dimensional density profile (with just one year of IceCube data)! M_{earth}, I_{earth}, $\Delta\rho_{CMB}$, M_{core}

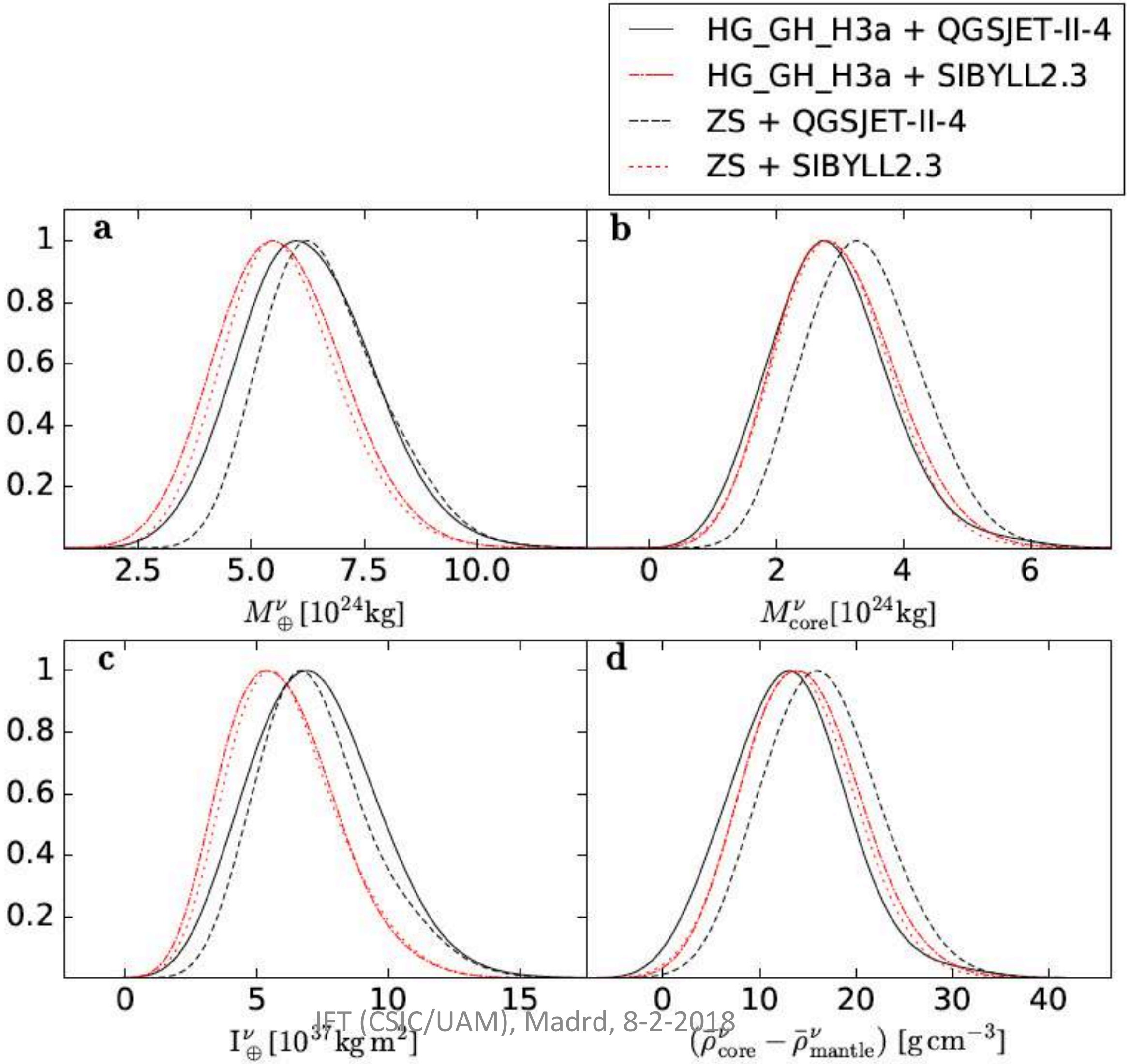
Precision will hugely increase as soon as 7 other years of IceCube data will be released (percent level in the mantle)

Waiting for Km3Net, we started discussions with the Antares Collaboration to include their data into our analysis (at some point, test of anisotropies)

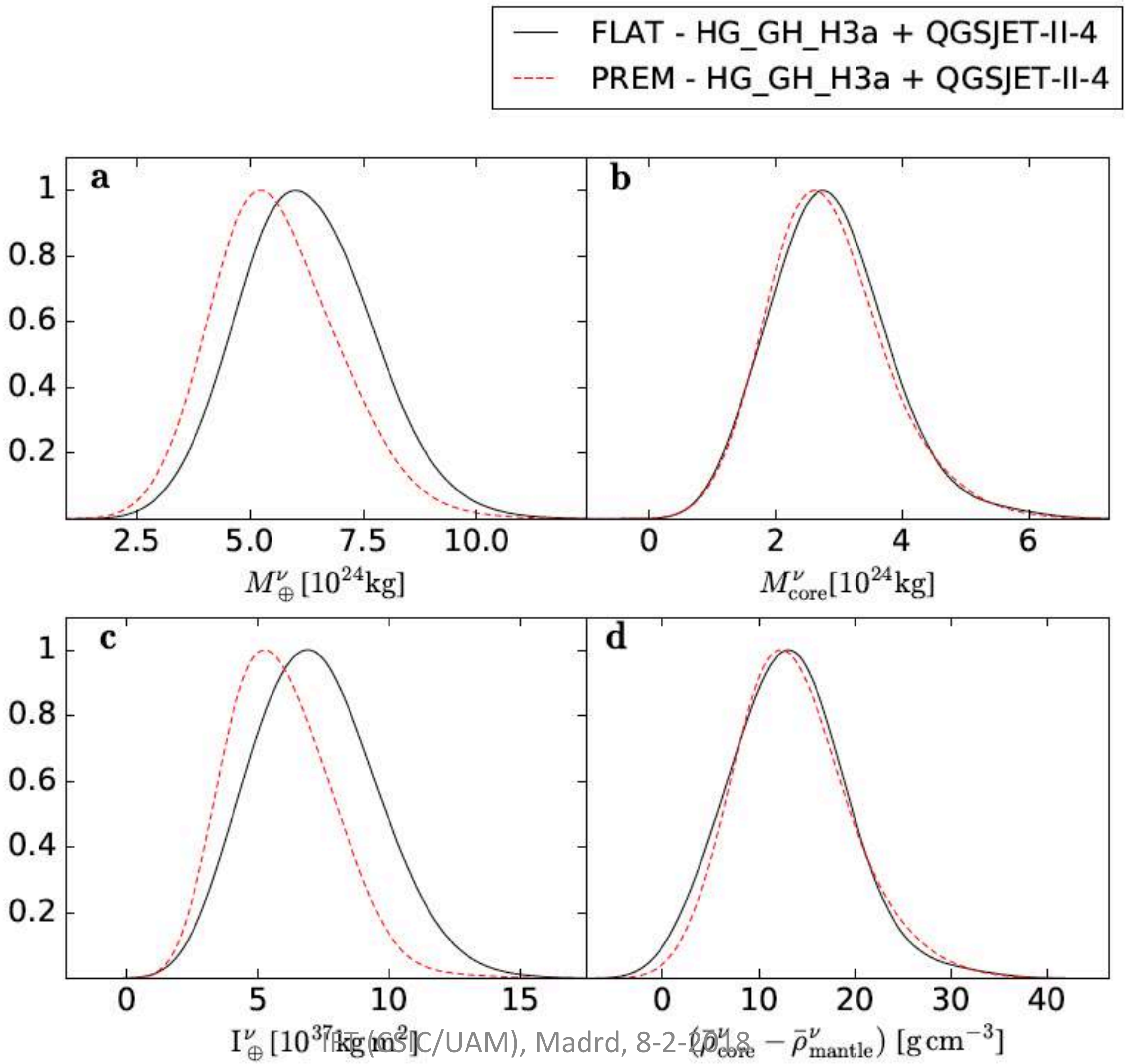
Conclusions and outlook

- It is eventually possible to make a neutrino tomography of the Earth: first 1-dimensional density profile (with just one year of IceCube data)! M_{earth}, I_{earth}, $\Delta\rho_{CMB}$, M_{core}
- Precision will hugely increase as soon as 7 other years of IceCube data will be released (waiting for Km3Net)
- Electro-weak testing of the Earth's interior has officially started

Flux and hadronic model dependence



Earth modelling dependence



Results for different models

	Piecewise flat Earth's profile				PREM Earth's profile
	HG-GH-H3a + QGSJET-II-4	HG-GH-H3a + SIBYLL2.3	ZS + QGSJET-II-4	ZS + SIBYLL2.3	HG-GH-H3a + QGSJET-II-4
$M_\oplus^\nu$ $[10^{24}$ kg]	6.2 ± 1.4	5.6 ± 1.4	$6.6^{+1.4}_{-1.3}$	$5.7^{+1.3}_{-1.2}$	5.6 ± 1.4
M_{core}^ν $[10^{24}$ kg]	$2.8^{+0.9}_{-1.0}$	2.9 ± 0.9	3.4 ± 0.9	2.9 ± 0.9	2.8 ± 0.9
$I_\oplus^\nu$ $[10^{37}$ kg cm^2]	$7.1^{+2.4}_{-2.5}$	5.9 ± 2.1	7.2 ± 2.1	6.0 ± 2.1	$5.8^{+2.1}_{-2.0}$
$\bar{\rho}_{core}^\nu - \bar{\rho}_{mantle}^\nu$ [g/cm^3]	13 ± 6	14 ± 6	16 ± 6	14 ± 6	14 ± 6
p – value mantle denser than core	1.1×10^{-2}	2.4×10^{-3}	9.4×10^{-4}	4.6×10^{-3}	3.8×10^{-3}

Impact of systematics on the error