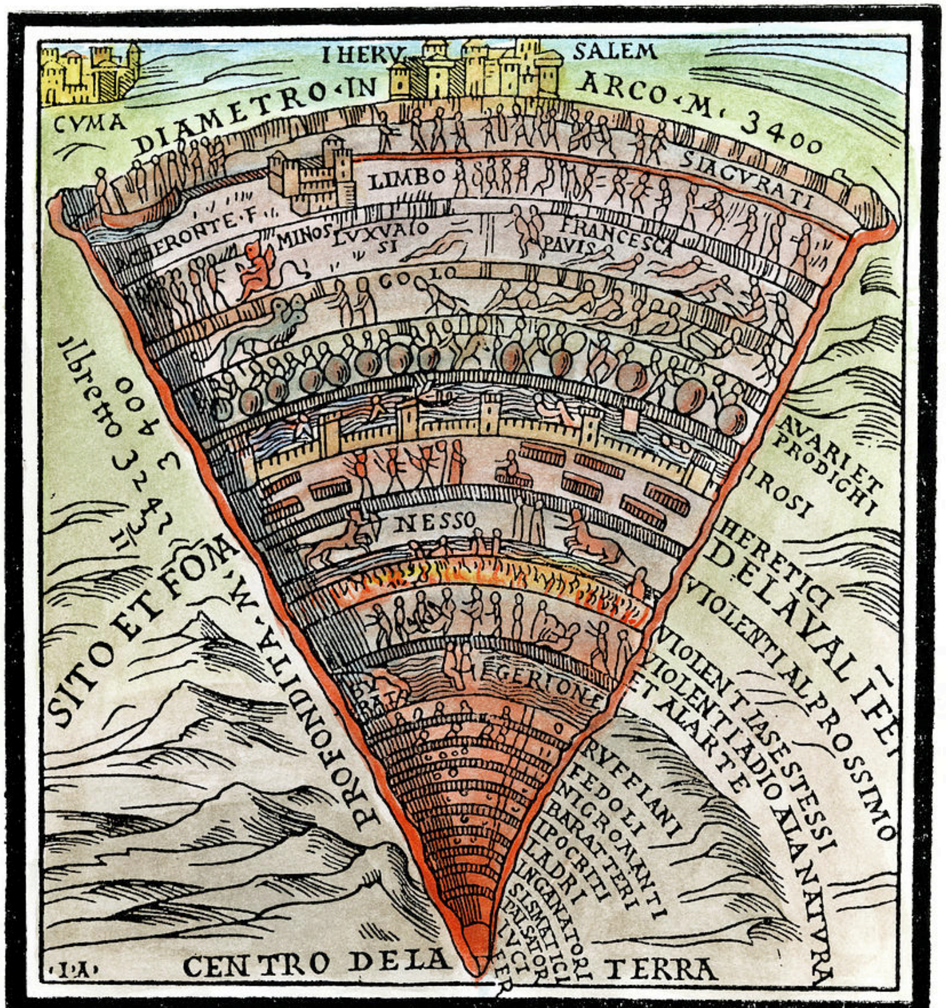
Earth tomography with neutrinos

Andrea Donini (IFIC, Valencia)

Nature Physics 15 (2019) 37

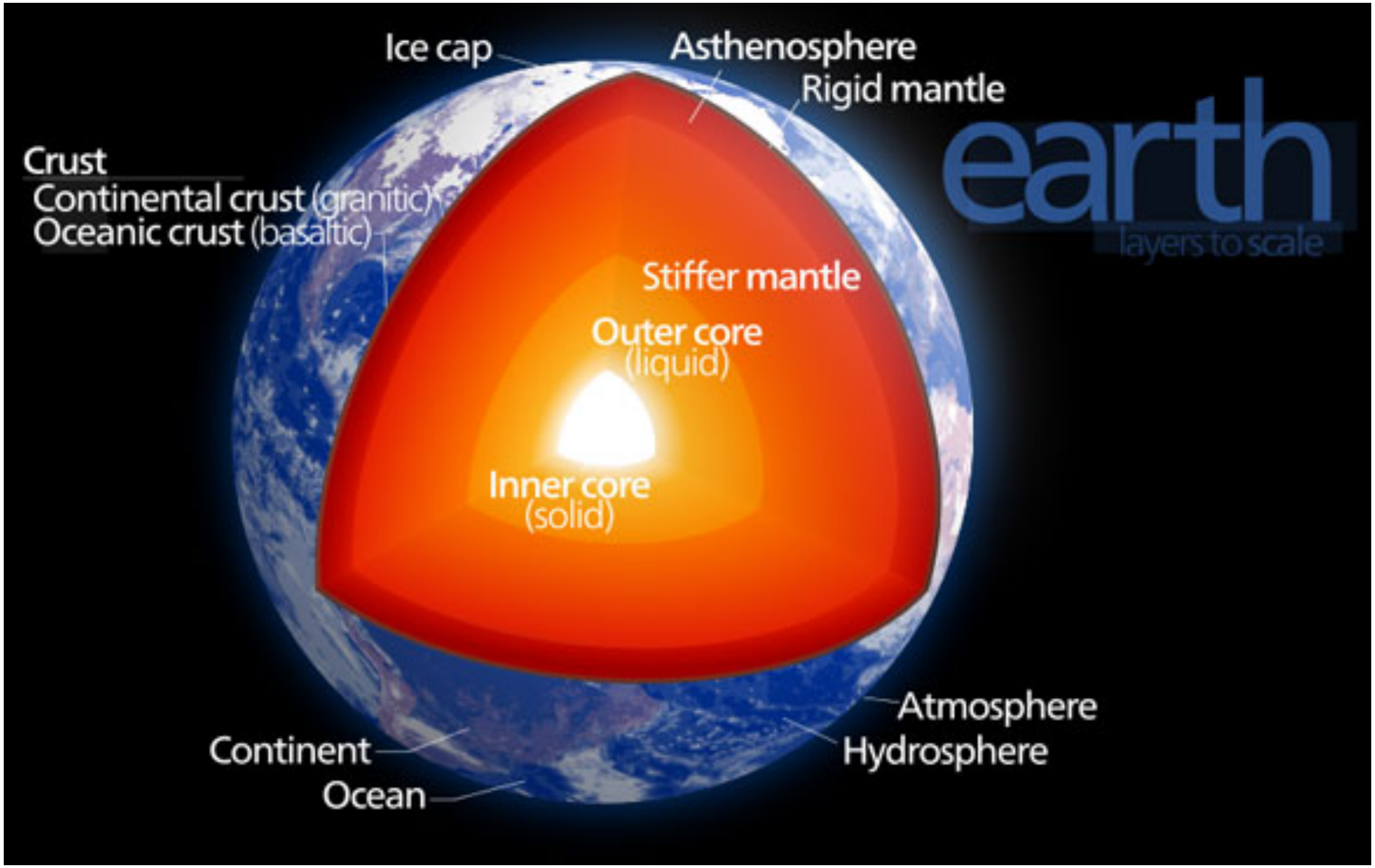
in collaboration with:
S. Palomares-Ruiz
J. Salvadó

An outdated view of Earth's interior



DANTE'S INFERNO, c1520.
Woodcut from a Venetian edition of the Divine Comedy.

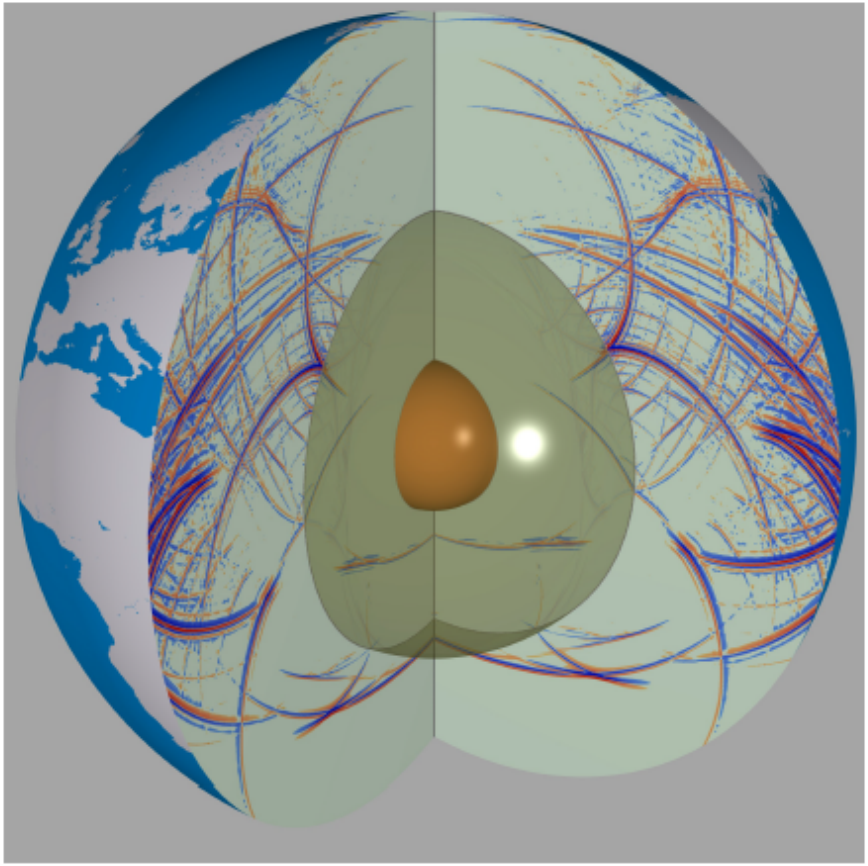
A more recent view



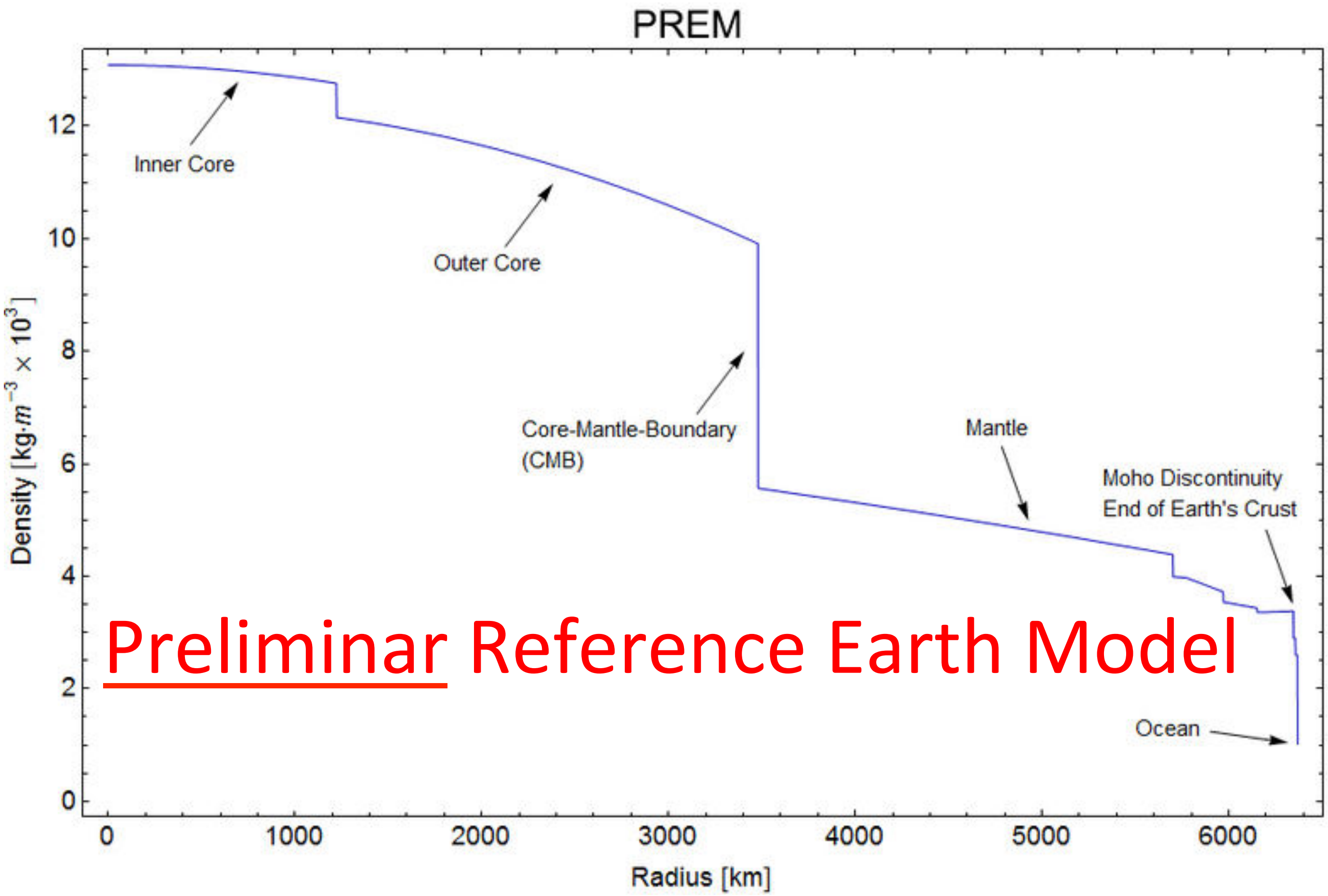
How densities are measured?

seismology

O(100)/year earthquakes with magnitudo larger than 6



1-dimensional density profile



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

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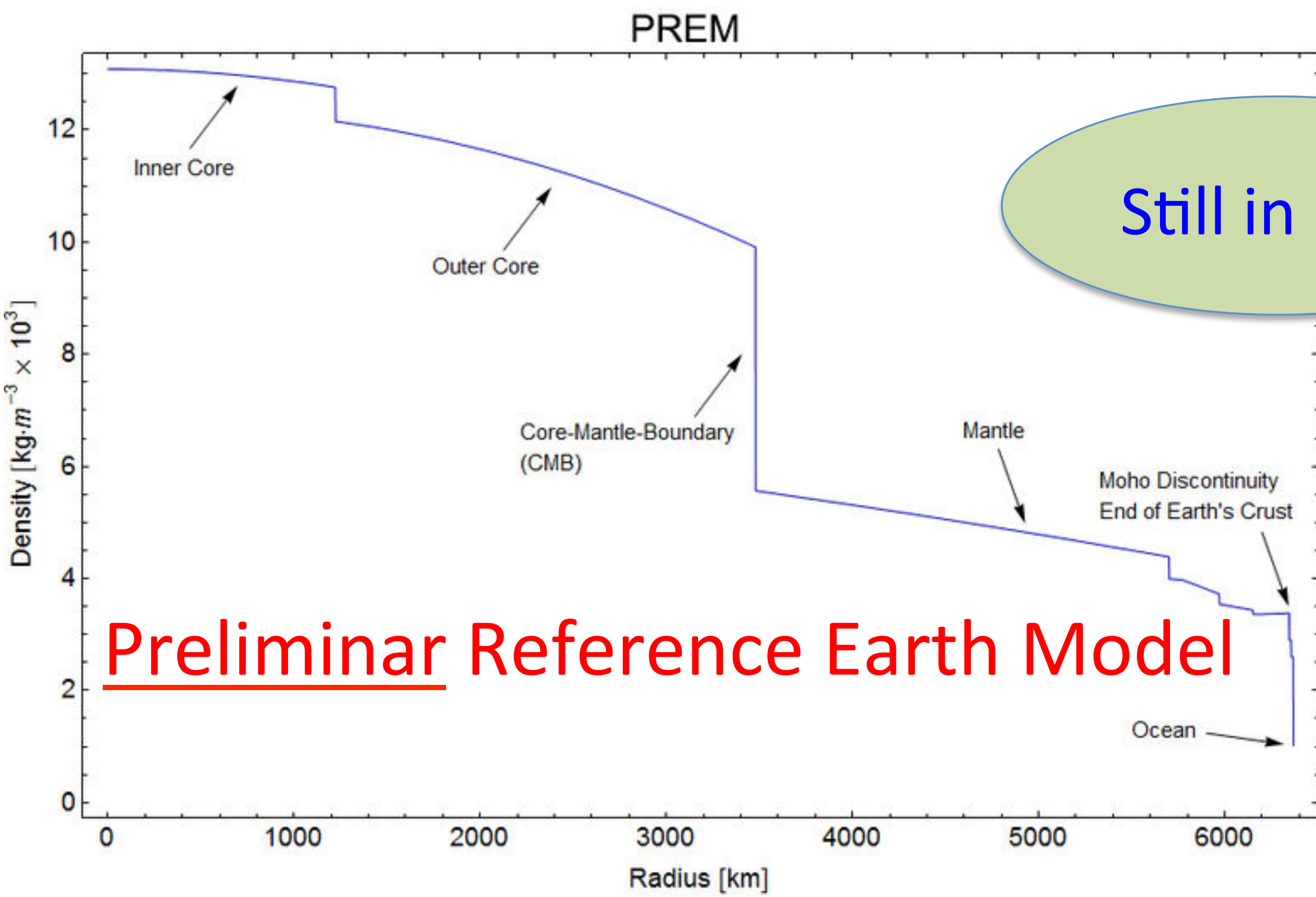


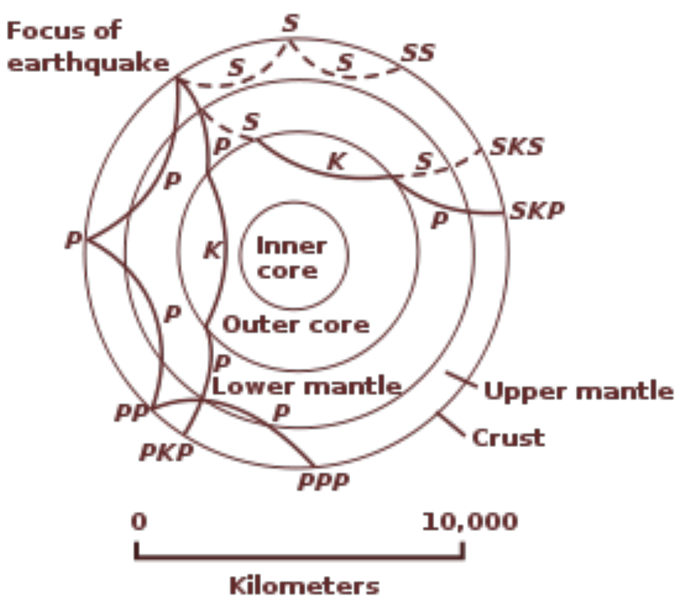
Still in use!

Preliminar Reference Earth Model

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

The Earth's core

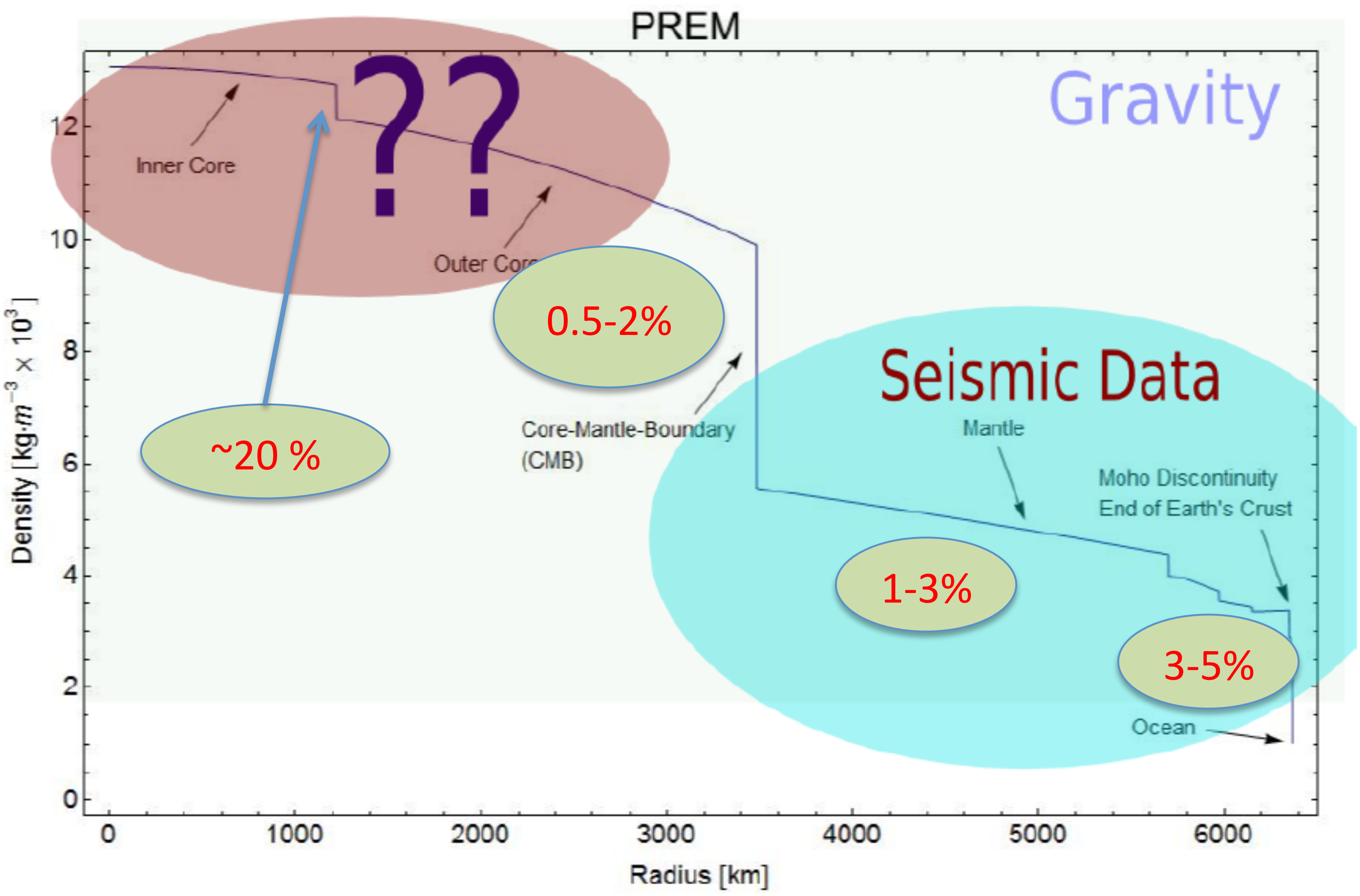
The OUTER CORE IS LIQUID,
whereas
the INNER CORE IS SOLID
(source of the geodynamo)



IT IS VERY DIFFICULT TO HAVE DIRECT INFORMATIONS from the INNER CORE

Mostly through global constraints and extrapolations

Uncertaintes from seismology



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An old idea: first mentioned in an unpublished CERN preprint,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

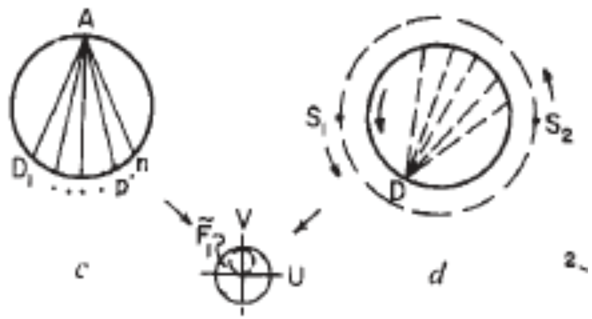
L. V. Volkova and G. T. Zatsepin, Izv. Akad. Nauk. Ser. Fiz. 38N5 (1974)

In modern language, a long-baseline experiment

The idea was premature!

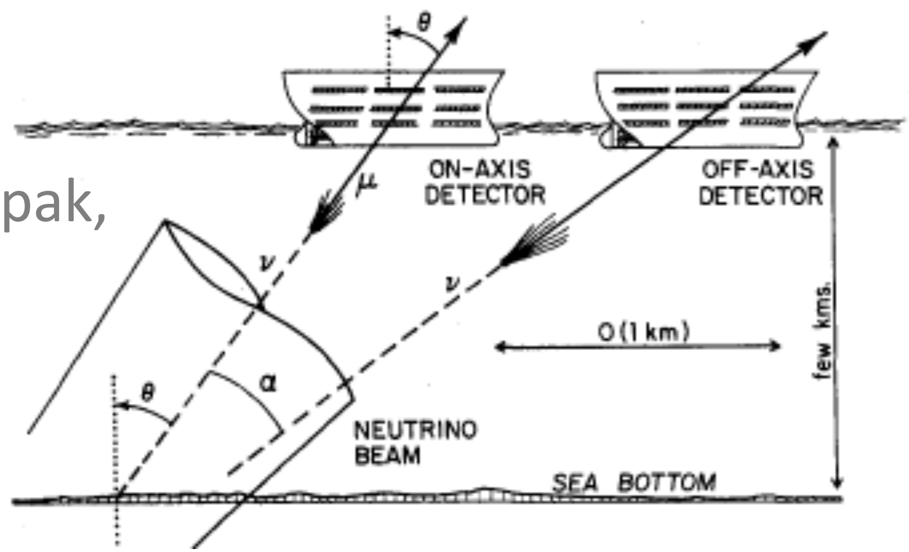
Neutrino tomography

Even more premature…

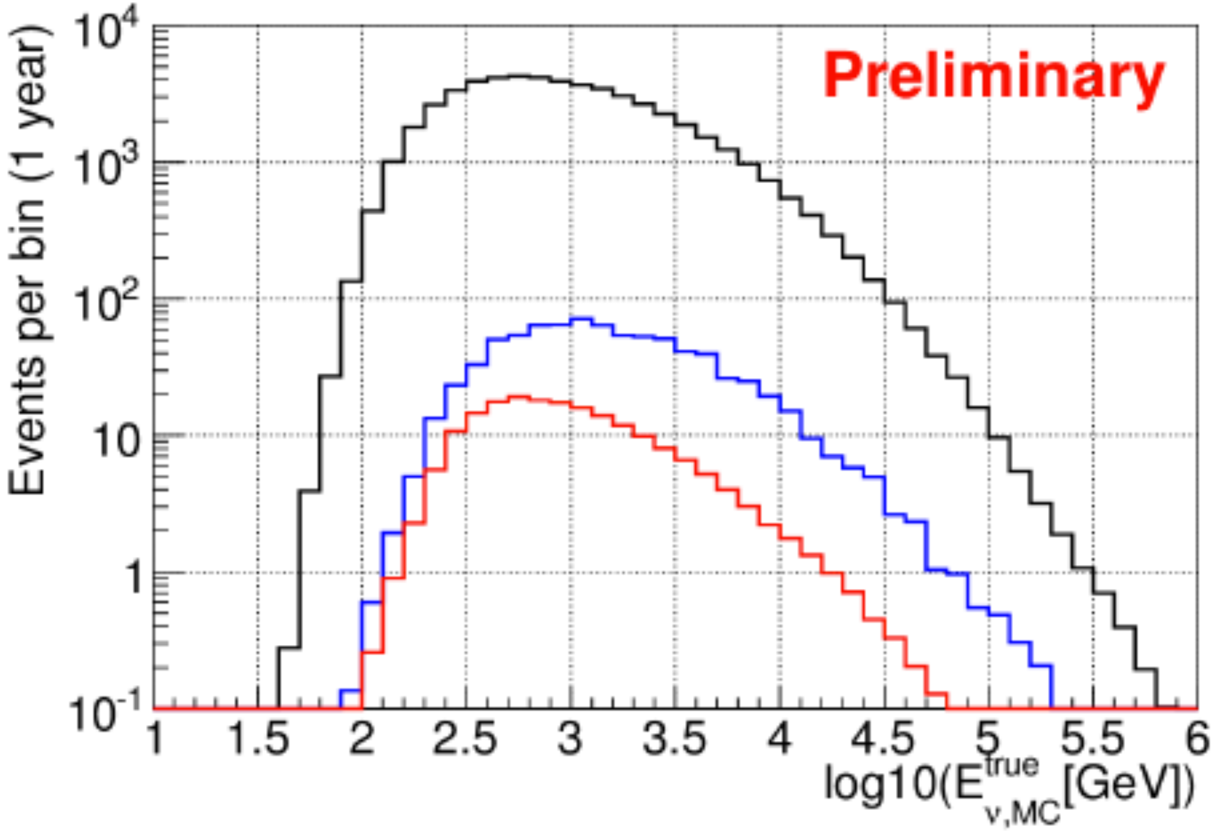


T. Wilson, Nature 309 (1984)

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



An optimal source: atmospheric neutrinos



IceCube contribution to ICRC 2015, arXiv:1510.05223

Two ways to scan the Earth

- Neutrino oscillations (< 1 TeV)

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

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W. Winter, Nucl. Phys. B 908 (2016) 250; Km3Net, PoS ICRC2017 (2018) 1020

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

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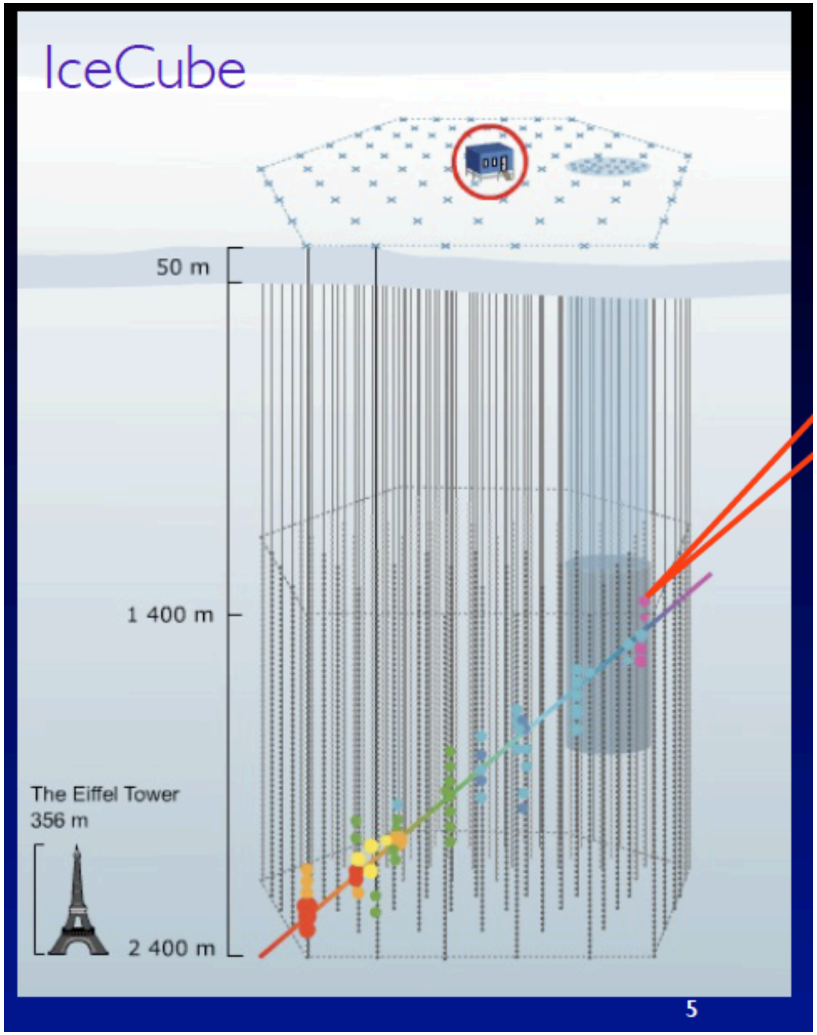
$$\frac{d\phi_\nu(E,\tau)}{d\tau} = -\sigma_{tot}(E)\phi_\nu(E,\tau)$$

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

The IceCube Experiment



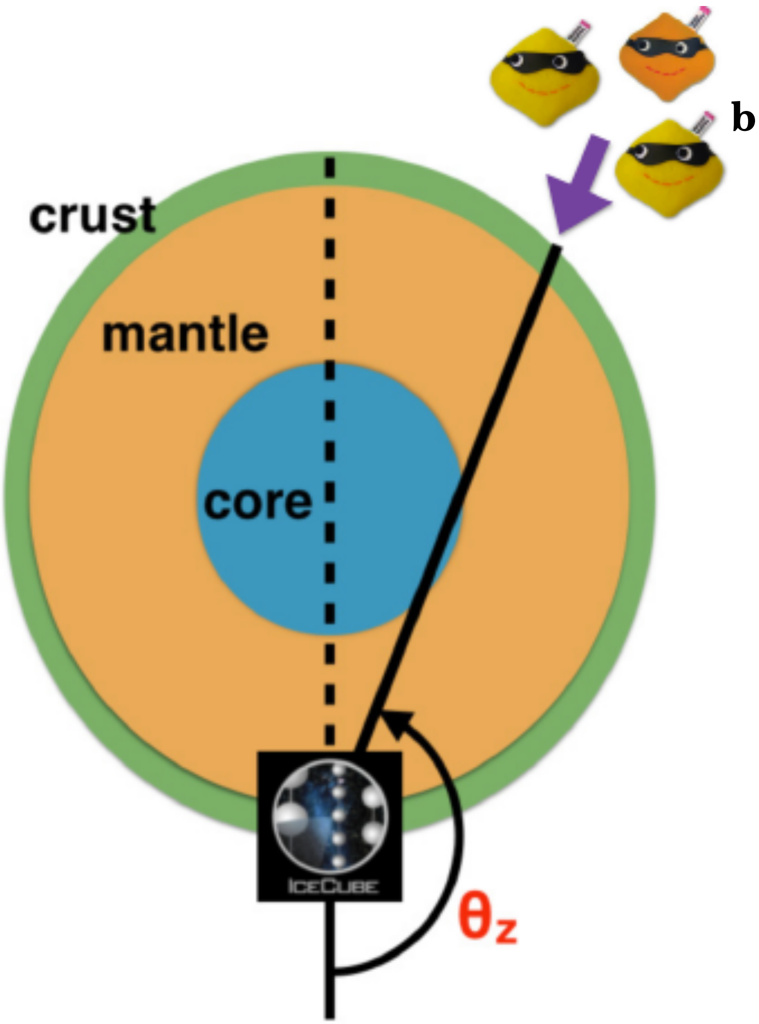
- Deployed in glacial ice at the South Pole
- Array size 1km^3, 86 strings, 60 optical sensors (DOMs) per string

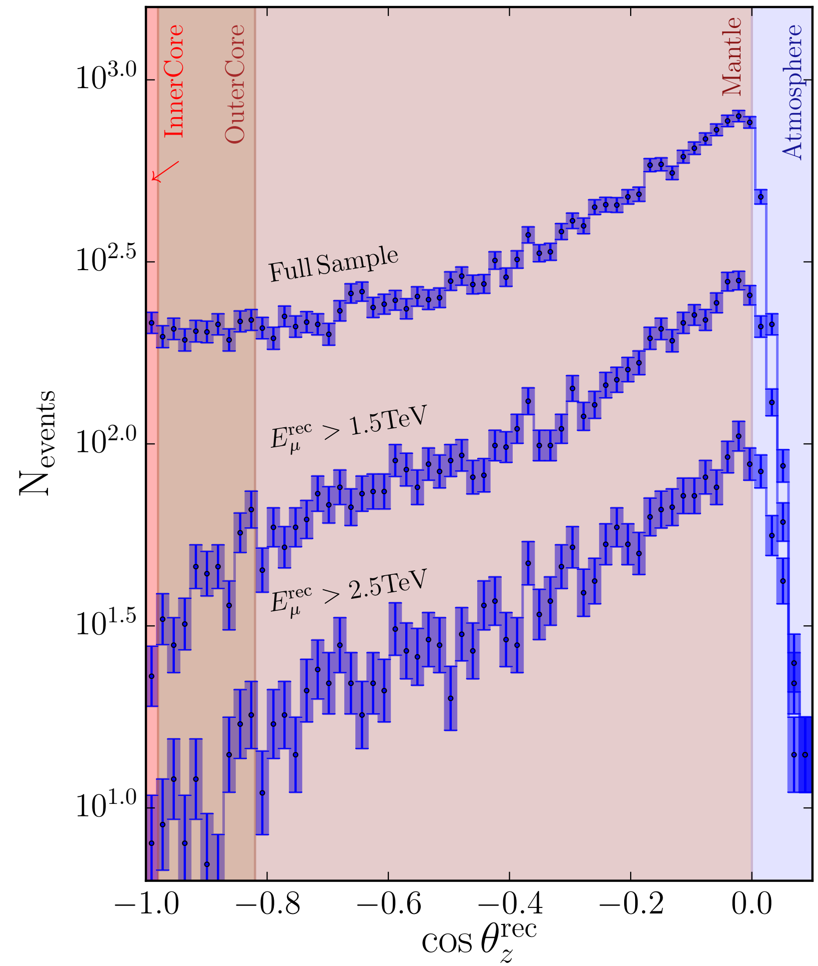
The IceCube IC86 data sample

- 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.....

Raw data as a function of E_μ and θ





Comparison with expectations

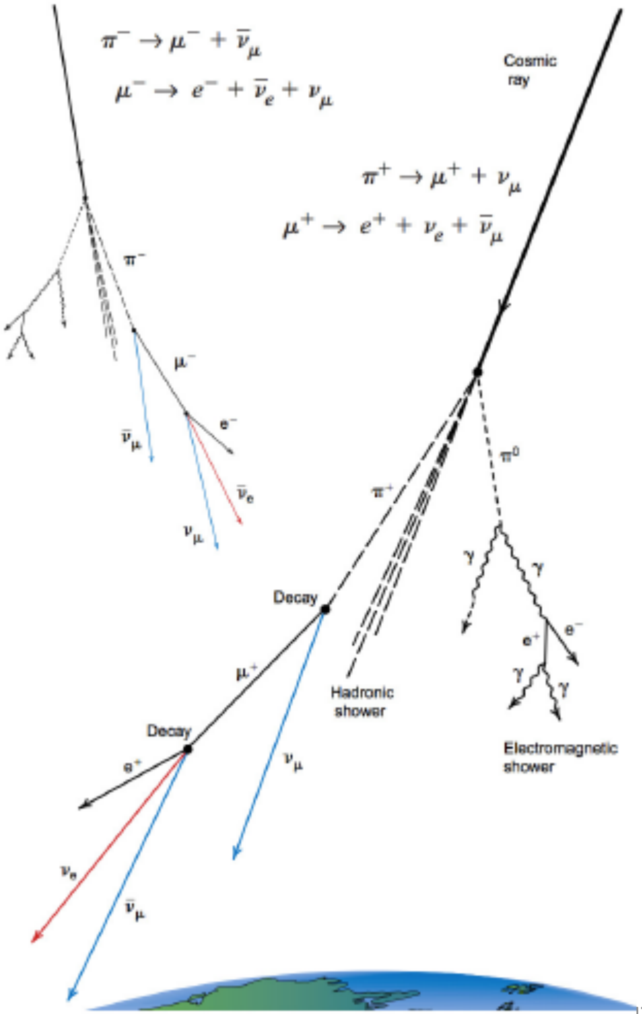
Flux model

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-04

Other options → "discrete" systematics
(improvements expected, PANE18 talks)

Neutrino propagation

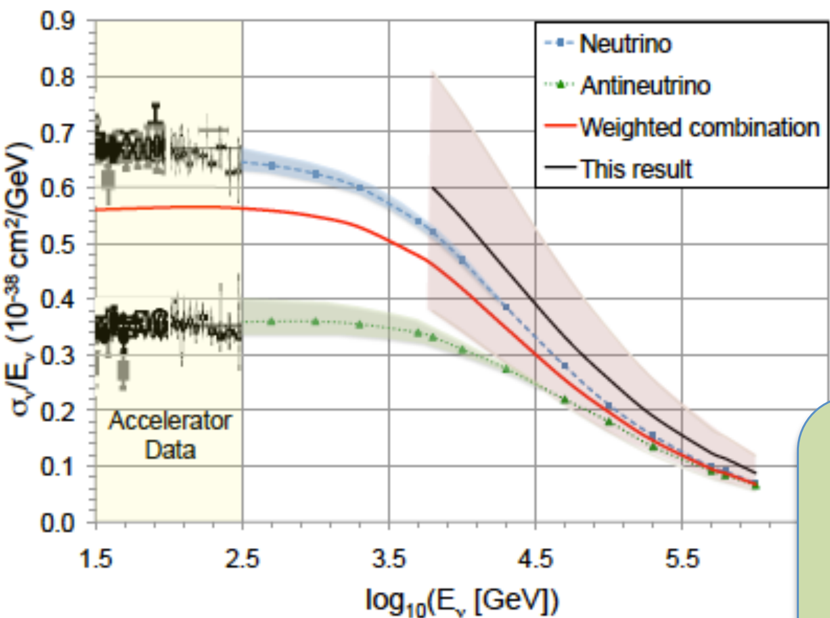
Propagation through the Earth with ν-SQuIDs

Argüelles Delgado, Salvado & Weaver, Comput. Phys. Commun. 196 (2015)

- Neutrino Oscillations: evolution Hamiltonian in matter (dominant below 1 TeV)
- Neutrino Attenuation: inelastic CC and NC interactions with matter (dominant above 1 TeV)
- Neutrino regeneration due to tau decays
- Migration to lower energy bins due to NC interactions

Neutrino-nucleon interaction

Parton distribution functions: HERAPDF



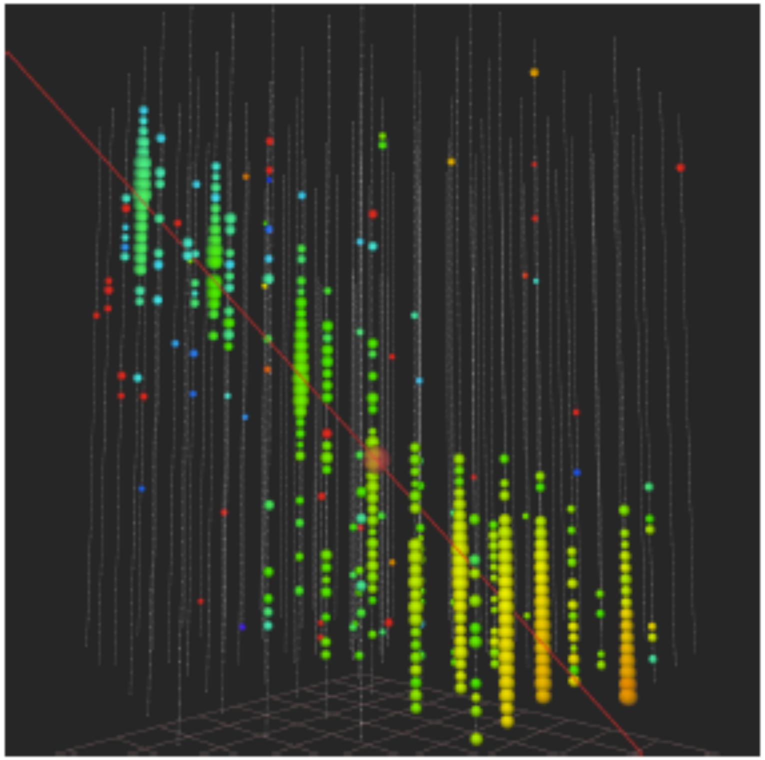
Aarsten et al, Nature 551 (2017)

νN ($\bar{\nu}$N) cross-sections at 2-3% (4-10%) errors

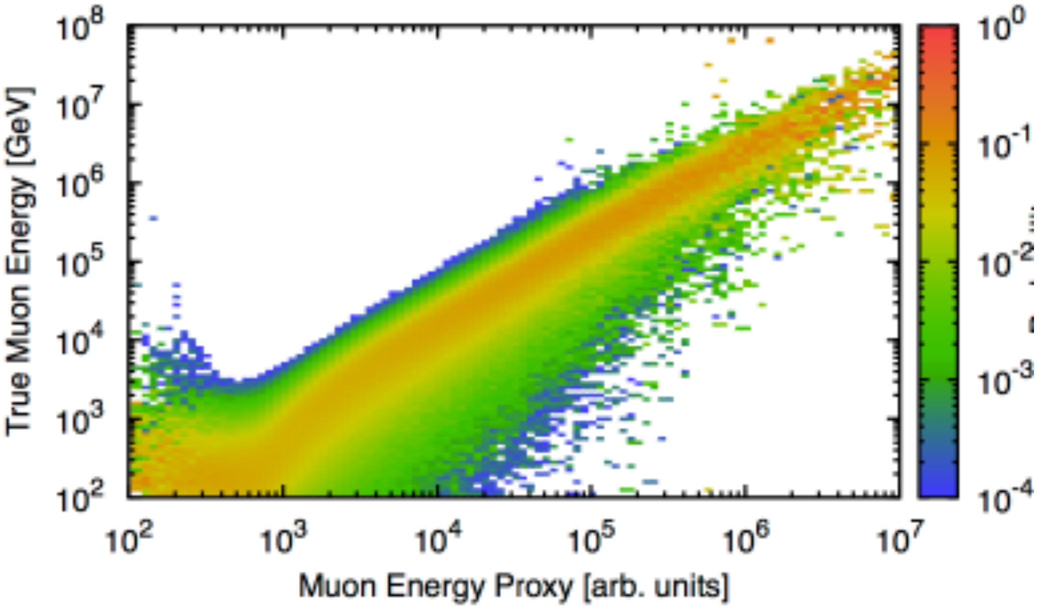
ICECUBE MEASUREMENT

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

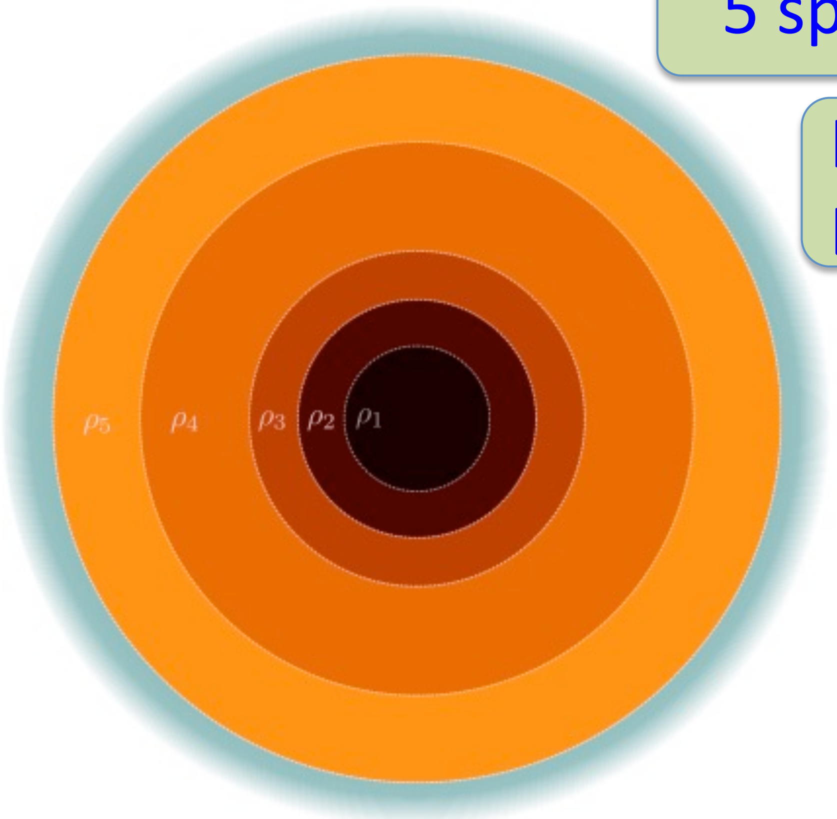
Detector simulation



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



Our Earth's model



5 spherical layers

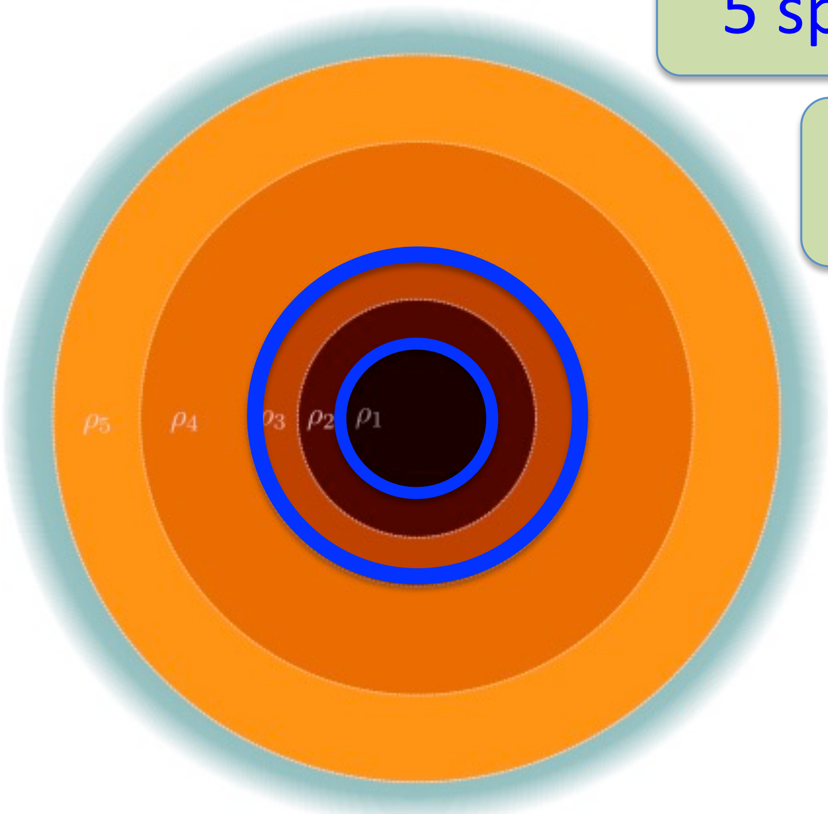
Inner Core, one layer
L_1 = 1242 km

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

Mantle, two layers
L_4 = 4938 km,
L_5 = 6371 km

No crust!

Our Earth's model



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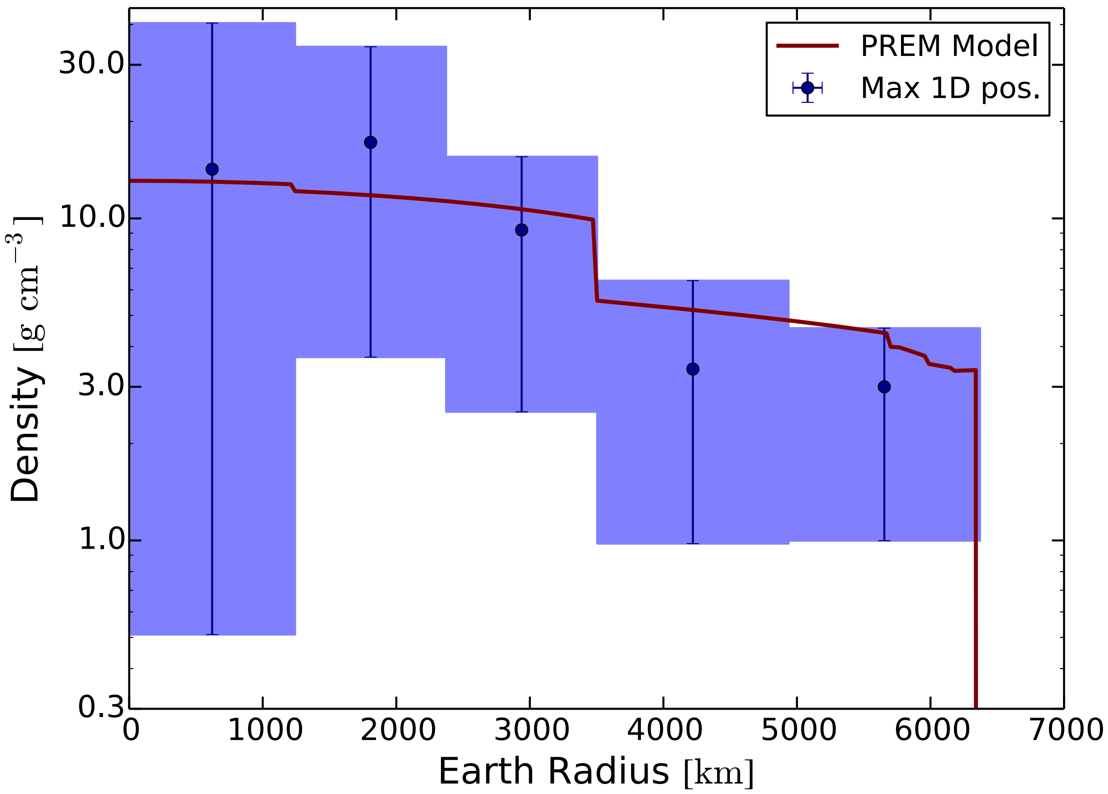
No crust!

ICB and CMB fixed!

First 1-d density profile with neutrinos



Analysis performed with MultiNest

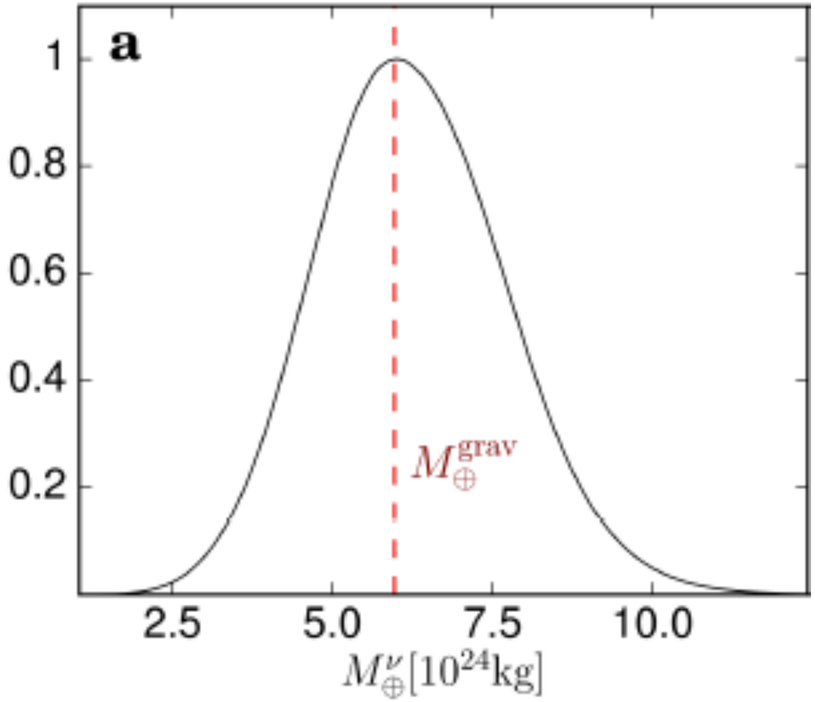
5 Earth layers densities

and

4 systematic errors:

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

The Earth's mass



First Electro-weak measurement of the Earth's mass

$$M_{earth\text{-}\nu} = (6.0\,^{+1.6}_{-1.3}) \times 10^{24}\ \mathrm{kg}$$

Gravitational measurement of the Earth's mass

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

The Earth's mass

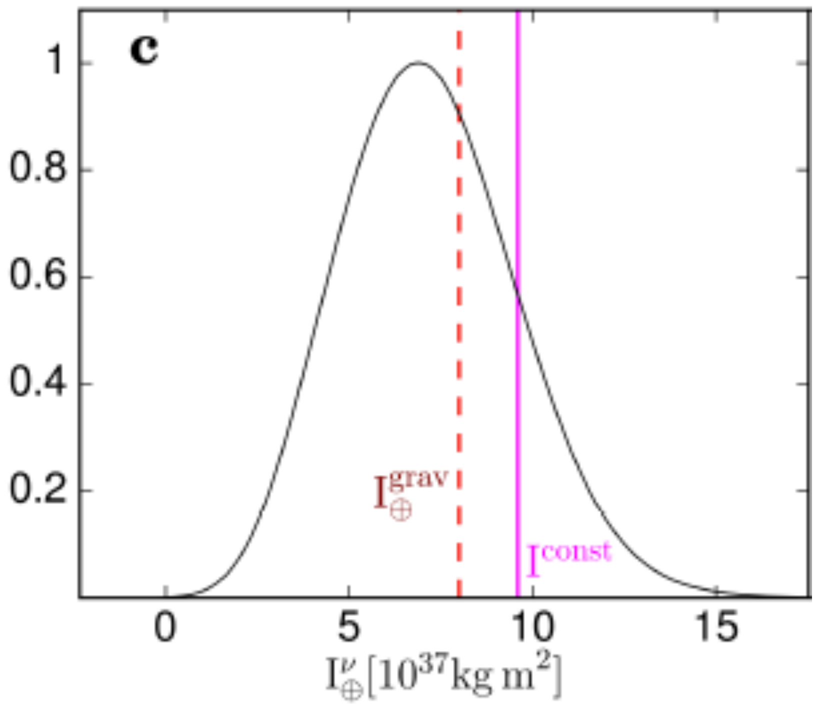
nt

NO (SIGNIFICANT AMOUNT OF)
DARK MATTER INSIDE THE EARTH!

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



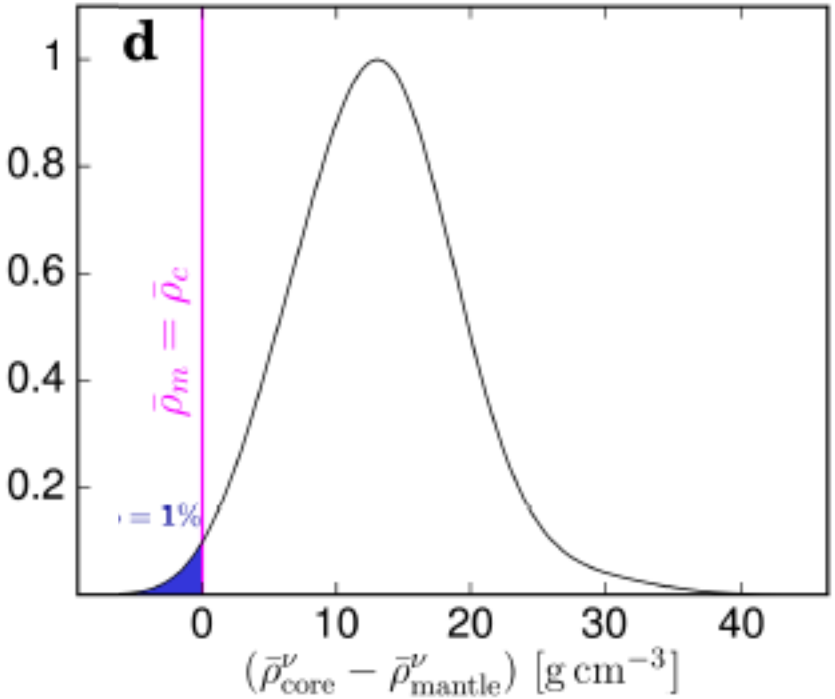
Electro-weak measurement of the Earth's moment of inertia

$I_{earth\text{-}\nu} = (6.9 \pm 2.4) \times 10^{37}$ 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



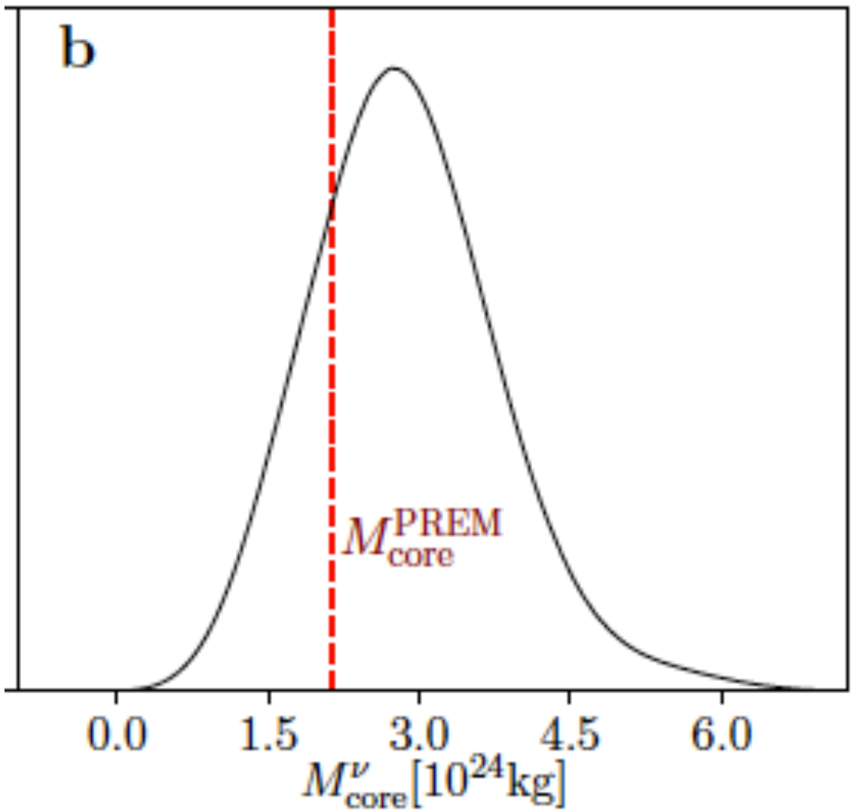
Electro-weak measurement of the Core-Mantle discontinuity

$$\Delta\rho_{CMB-\nu} = (13\,^{+5.8}_{-6.3})\ \ g/cm^3$$

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

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

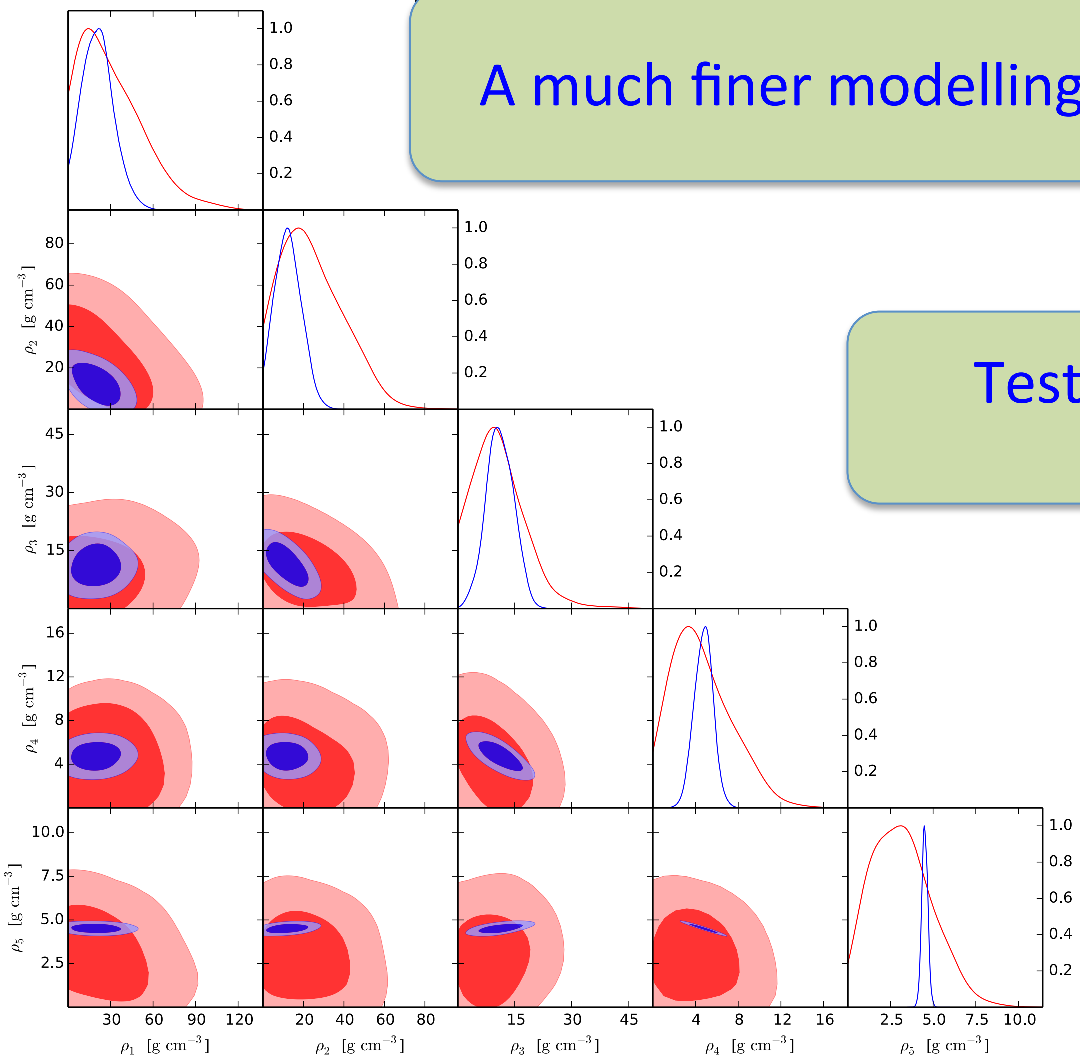
The Earth's core mass



Electro-weak measurement of the Earth's core mass

$$M_{core\text{-}\nu} = (2.7\ ^{+1.0}_{-0.9}) \times 10^{24}\ \text{kg}$$

Forecast with 10 years of data

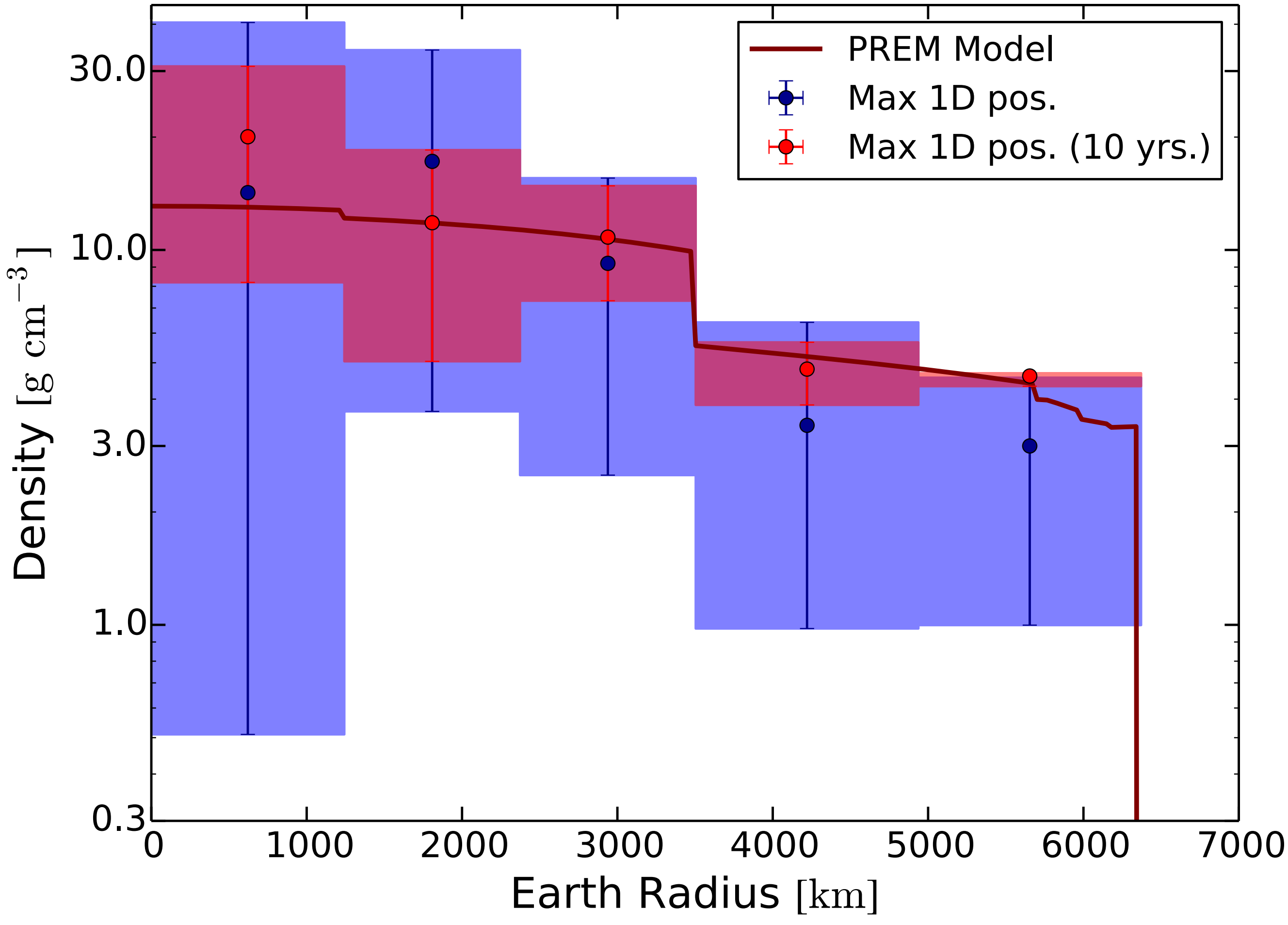


A much finer modelling of the Earth could be done

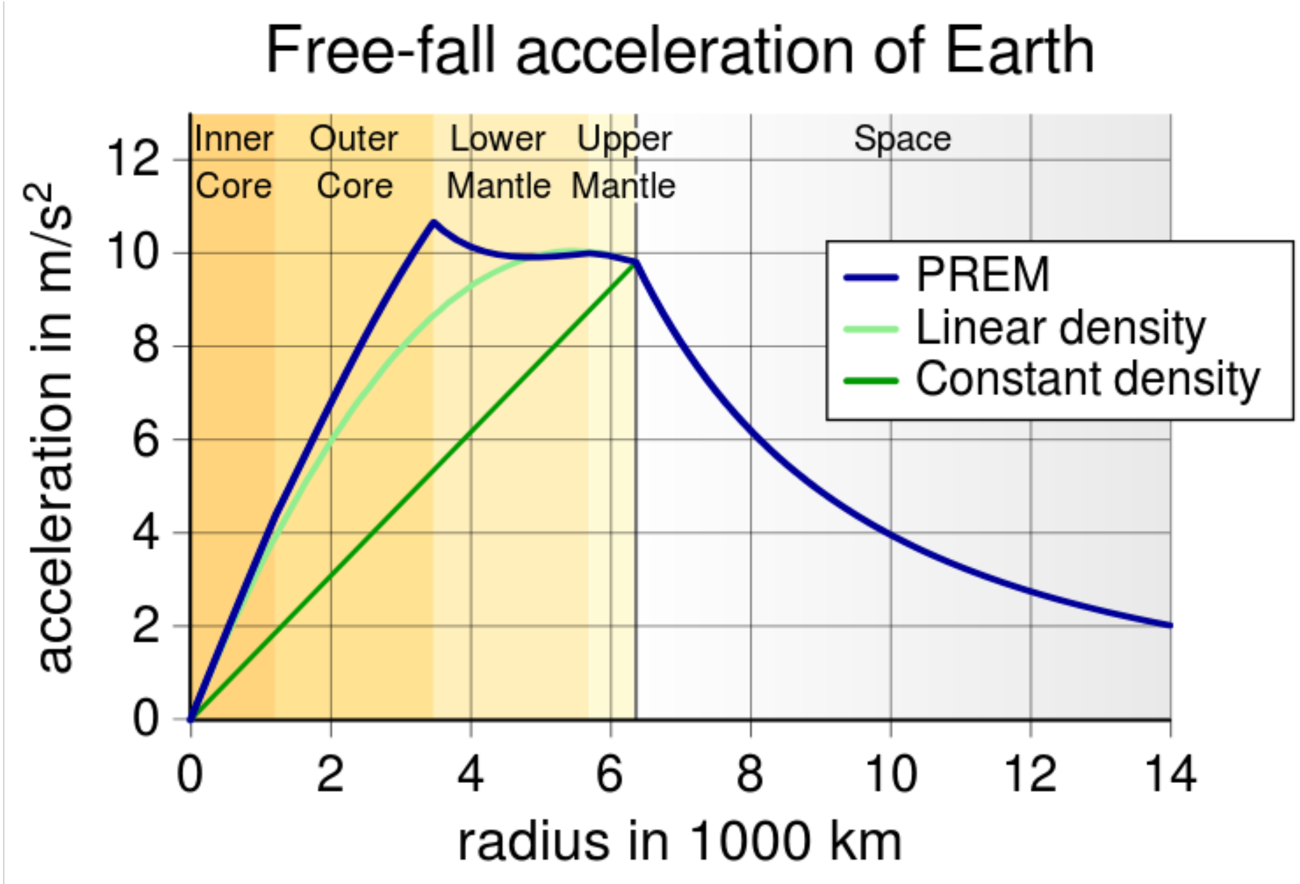
Test of the Inner-Outer Core discontinuity

Independent localization of the Core-Mantle Boundary

1-d density profile with 10 years



An input to geophysics: g(r)



The Earth's gravitational profile is needed to compute ρ(r) from earthquake waves velocities

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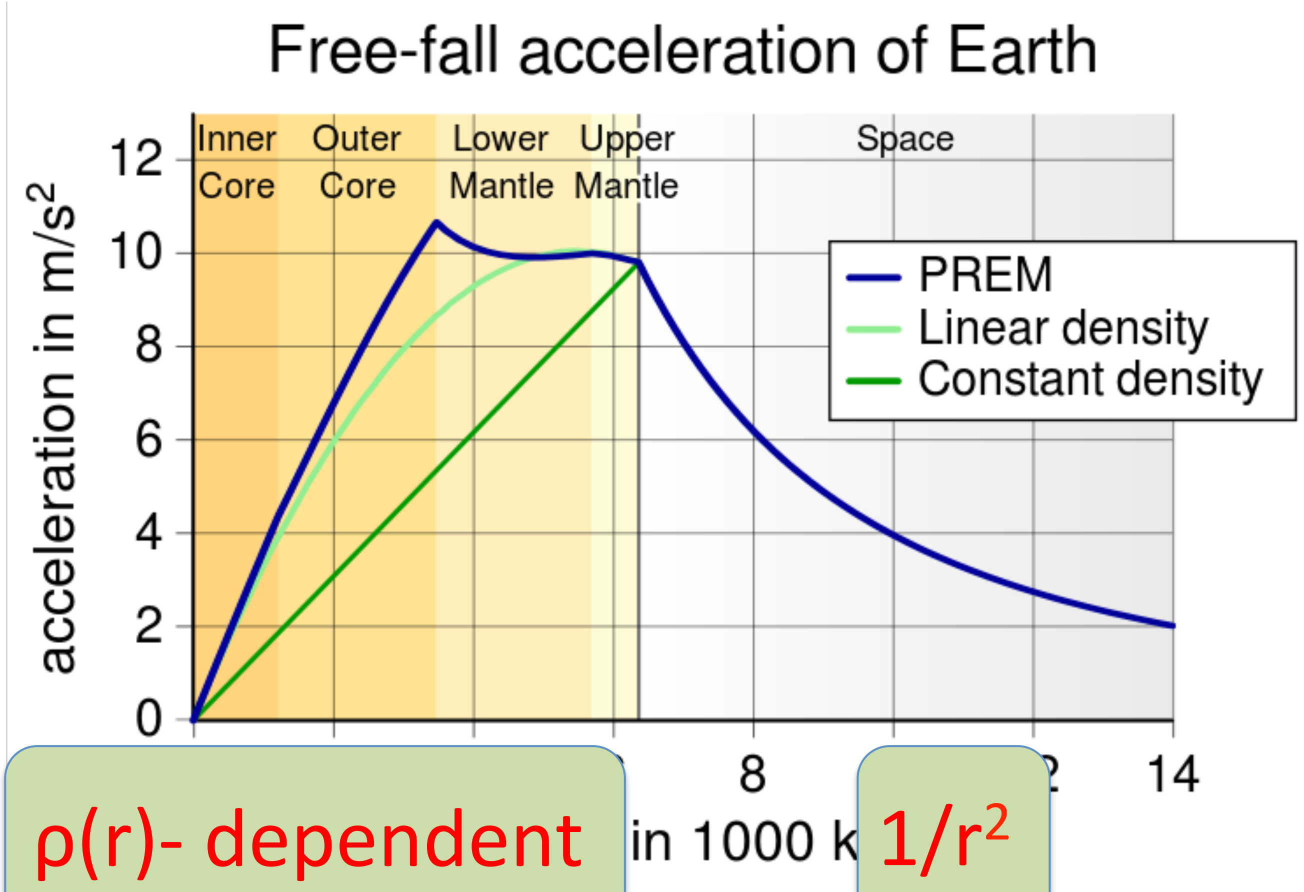

ρ(r)- dependent

$1/r^2$

The Earth's gravitational profile is needed to compute ρ(r) from earthquake waves velocities

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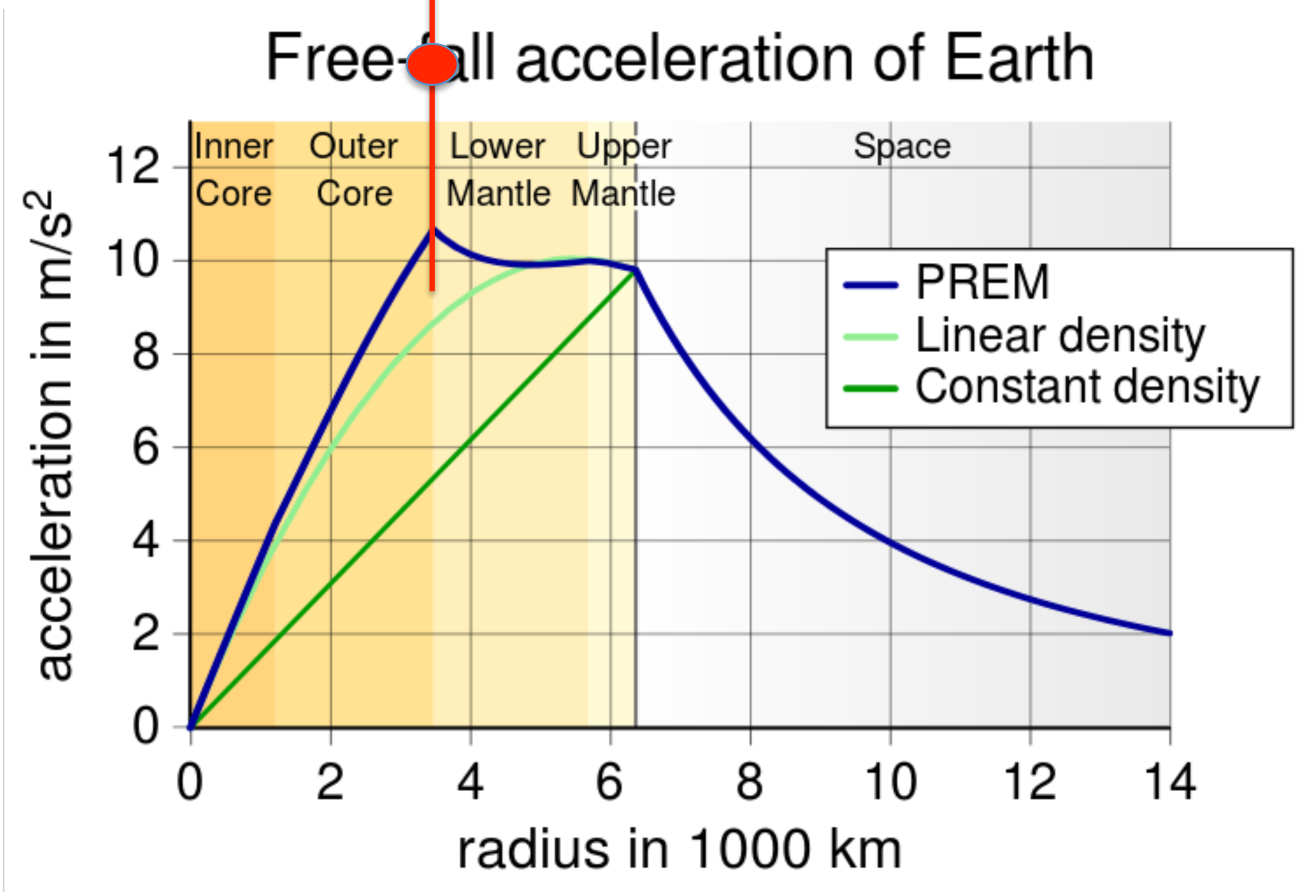

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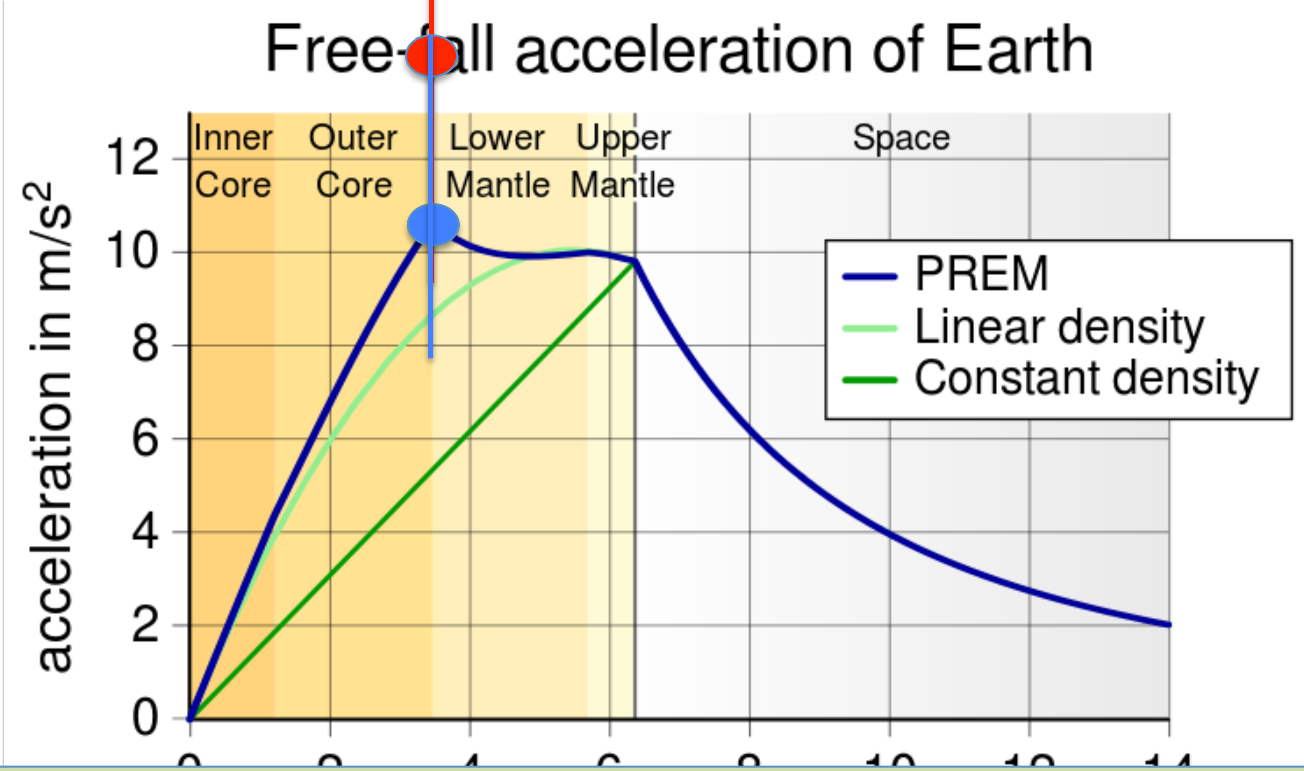


A GOOD NEUTRINO MEASUREMENT OF g(r) COULD BE ADDED TO SEISMOLOGY AS A PRIOR TO REDUCE ERRORS (STILL TO TEST THE IMPACT)

The Earth's gravitational profile is needed to compute ρ(r) from earthquake waves velocities

Conclusions

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 become accessible (percent level in the mantle)!

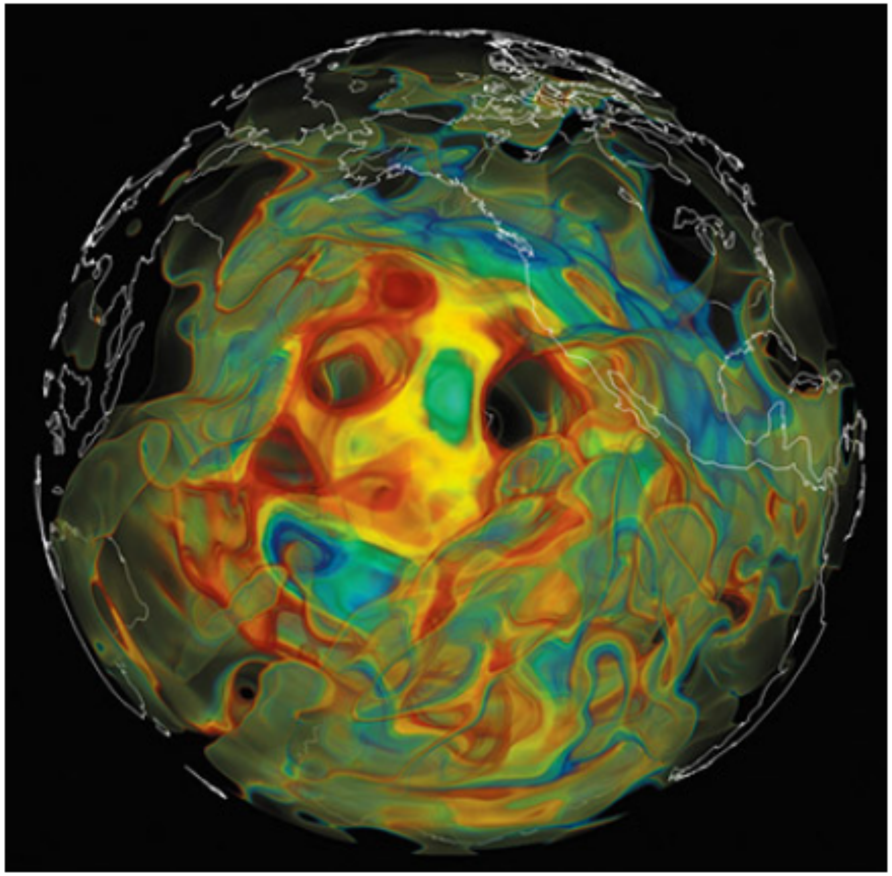
Outlook

Waiting for Km3Net, we made contact with the Antares Collaboration to include their data into our analysis (still to be done)

After ARCA is completed, we will look at the Earth's interior from both emispheres (test of anisotropies)

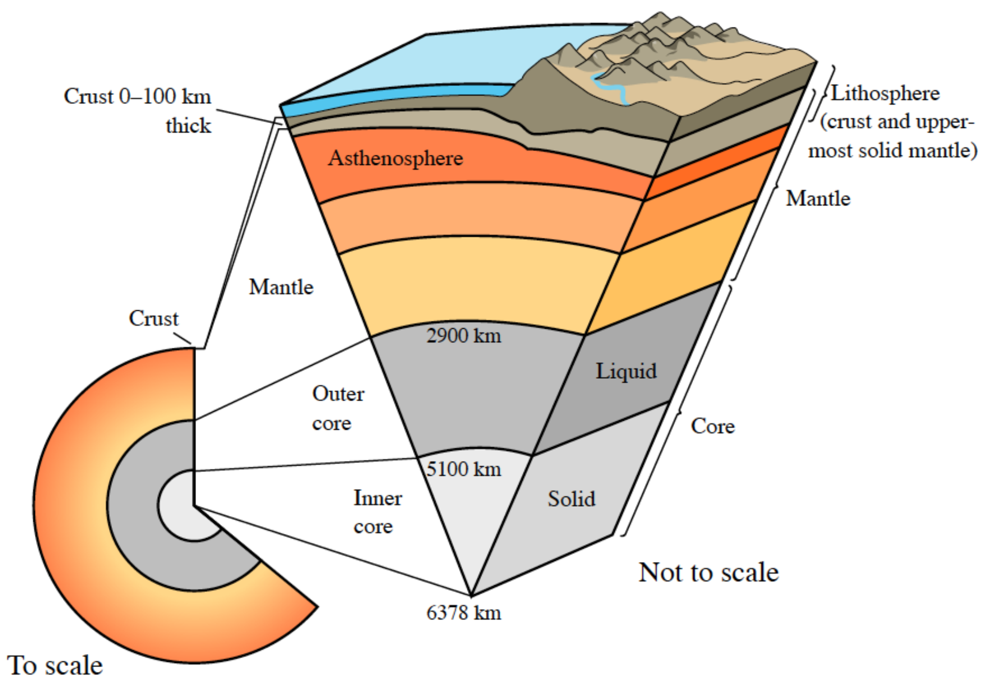
Together with medical imaging techniques (started discussions with experts in the field) we could perform EARTH'S THREE-DIMENSIONAL ν-TOMOGRAPHY

State-of-art three-dimensional picture from seismography



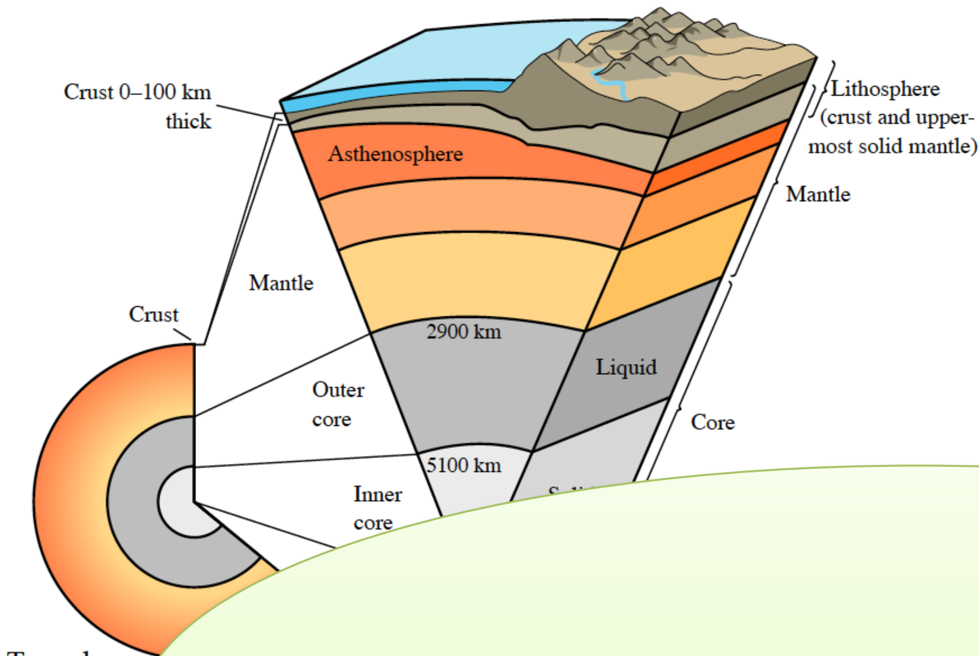
Backup slides

Density at different depths



Depth[103] km	Component layer	Density g/cm^3
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

Density at different depths



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[illegible]	…thenosphere	–
[illegible]	[illegible]	9.9–12.2
[illegible]	[illegible]	…8–13.1

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

(granite density is $2.7\ g/cm^3$)

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)

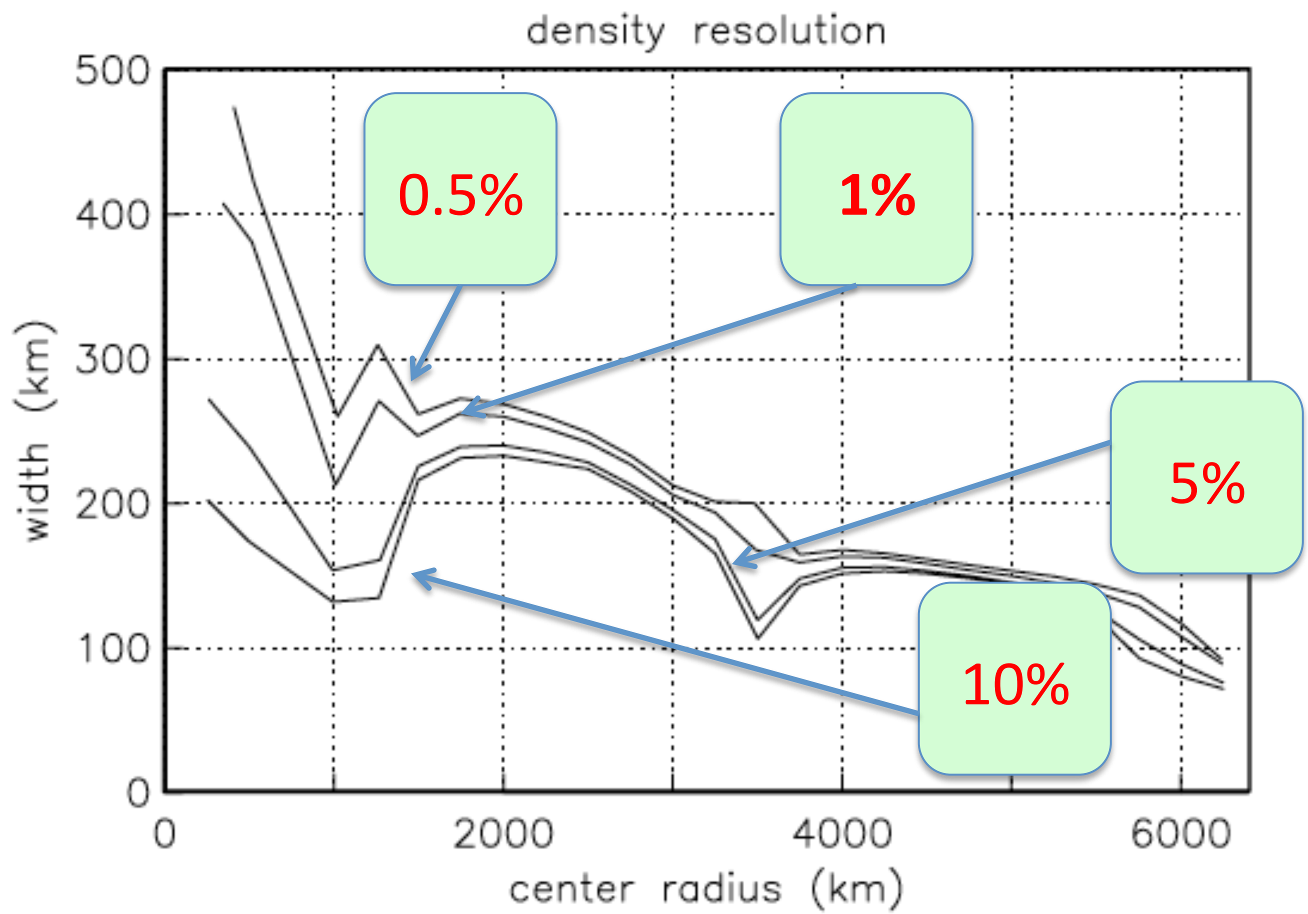
Adams-Williamson equation (1924)

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

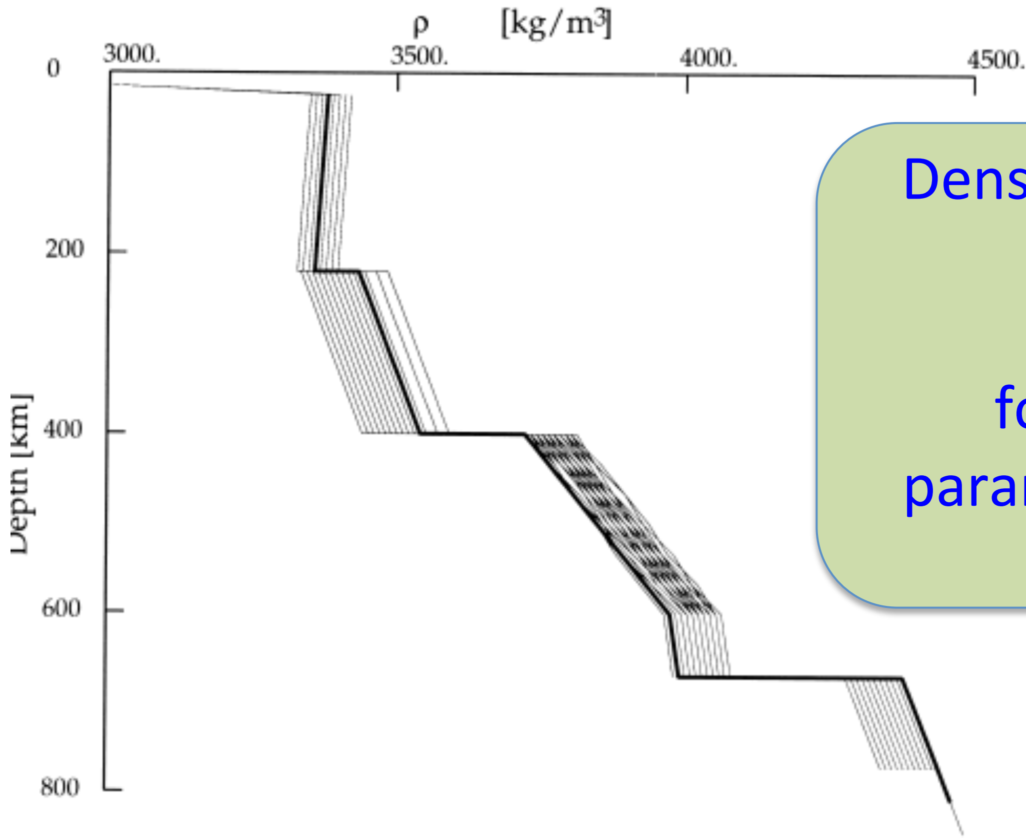
$$\Phi(r) = v_p^2 - \frac{4}{3}v_s^2$$

Composition dependence! Gravitational profile dependence!

Uncertainties in the core density



Model dependence of the profile…

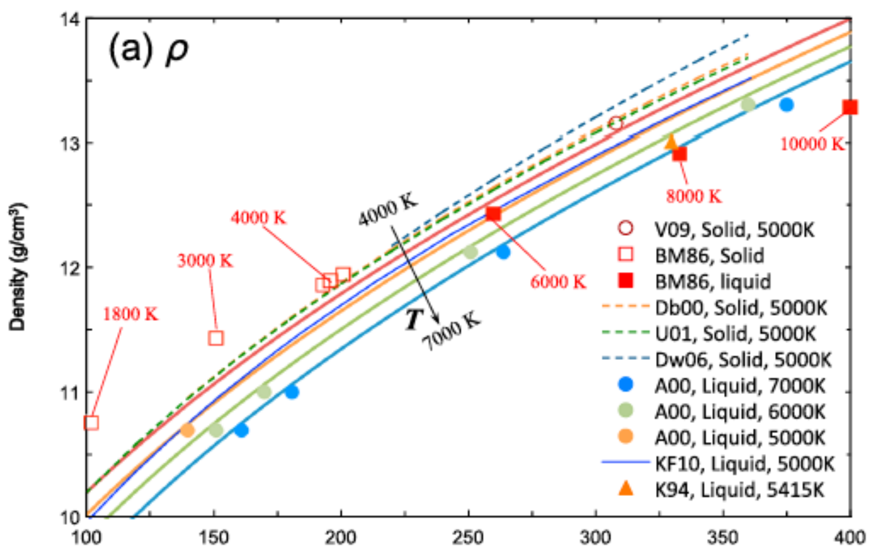


Density variation in the CRUST for different parameter choices: 3-5%

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

Inner core uncertainties

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



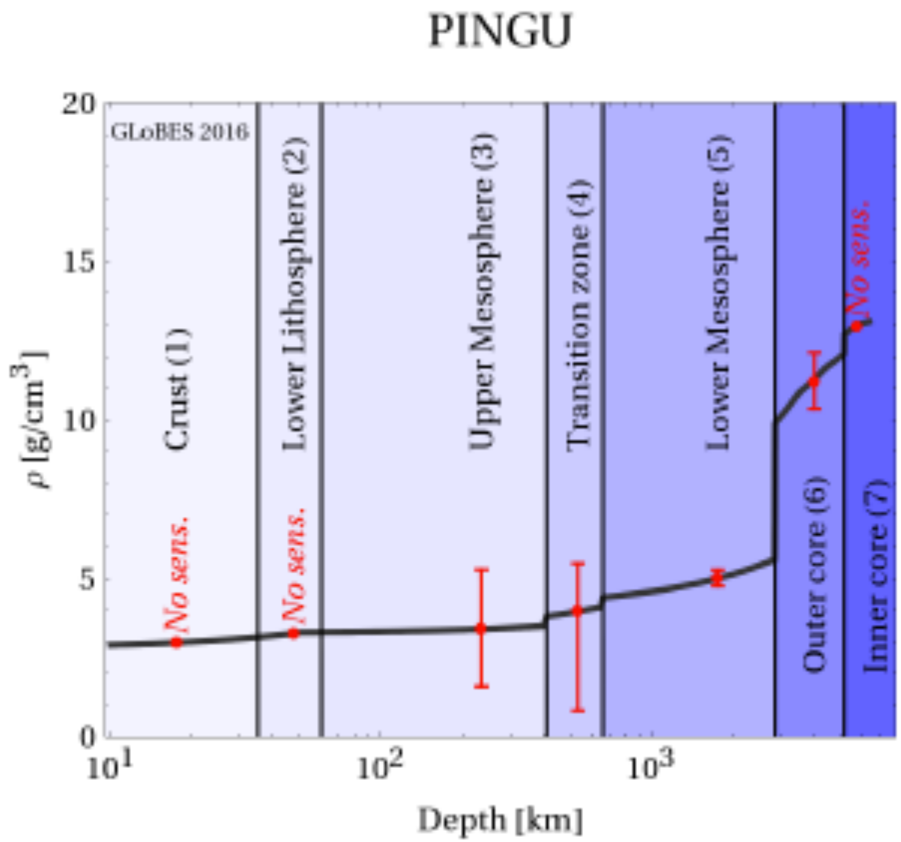
Ishikawa, Tsuchiya, Tange, J. GeoPhys. Res. (Solid Earth) 119 (2014)

Estimated temperature range still very large: 4000-10000 K

Composition guessed (iron-nickel?)

Missing Xenon problem

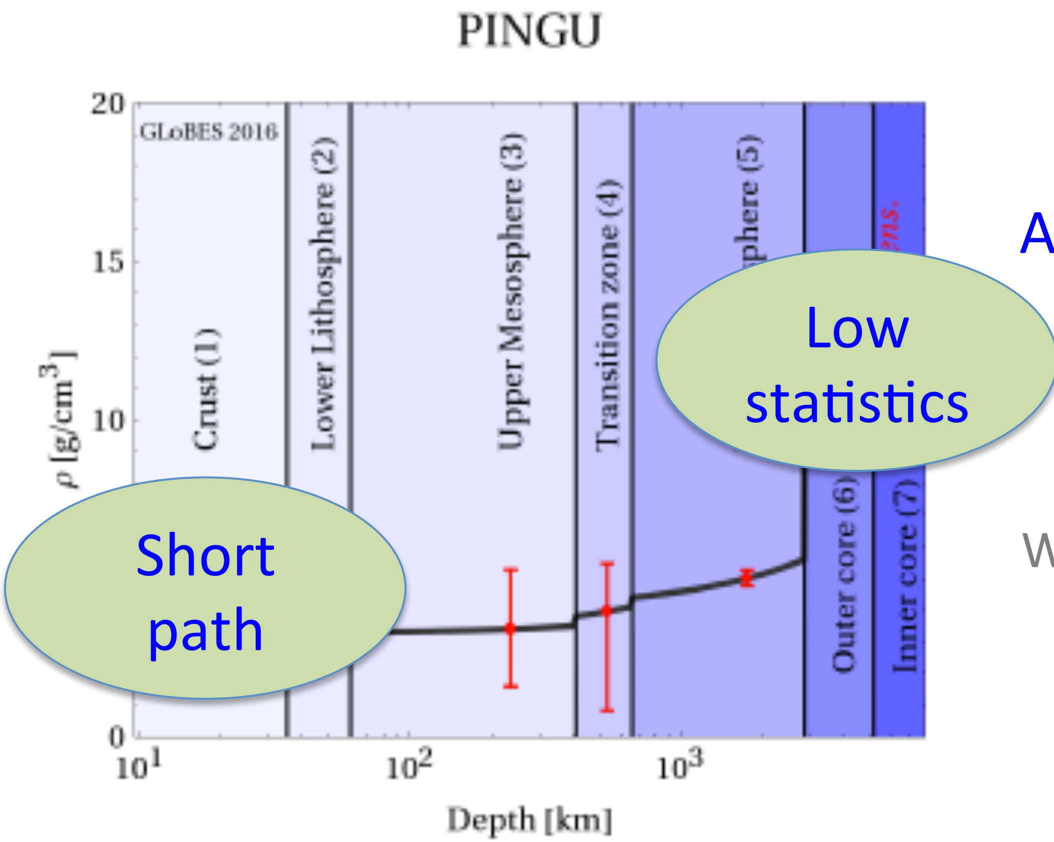
“Recent” forecasts, 1



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

Winter, Nucl. Phys B908 (2016)

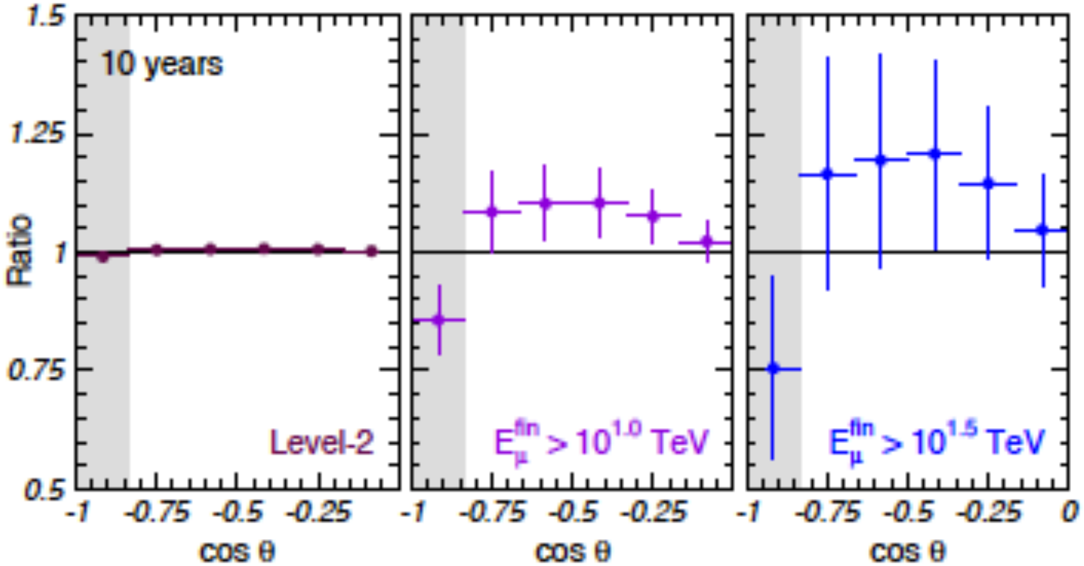
“Recent” forecasts, 1



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

Winter, Nucl. Phys B908 (2016)

“Recent” forecasts, 2



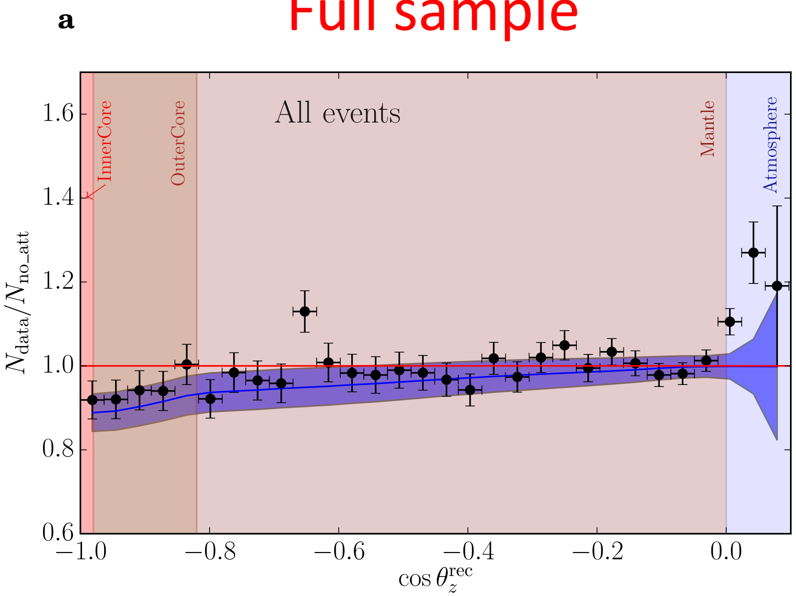
After 10 years of data taking at IceCube using neutrino attenuation

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

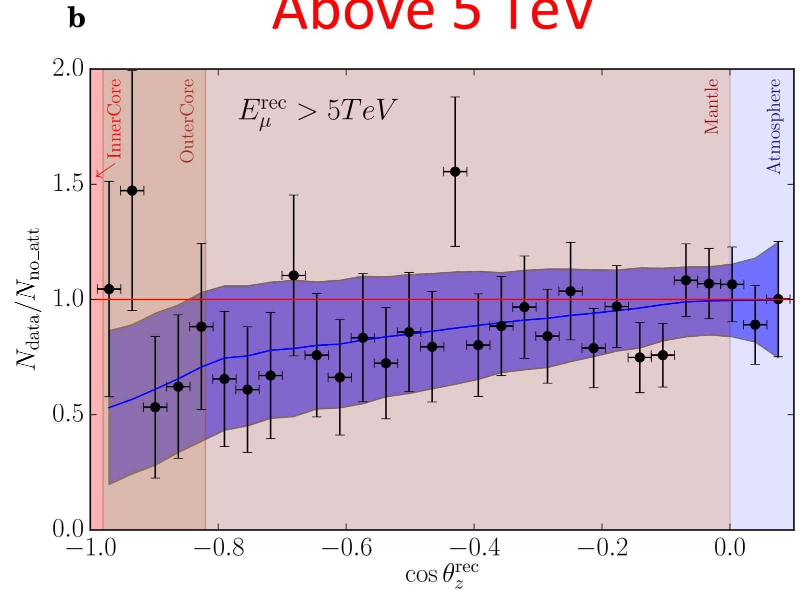
Gonzalez-García, Halzen, Maltoni, Tanaka, Phys. Rev. Lett. 100 (2008)

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

Full sample



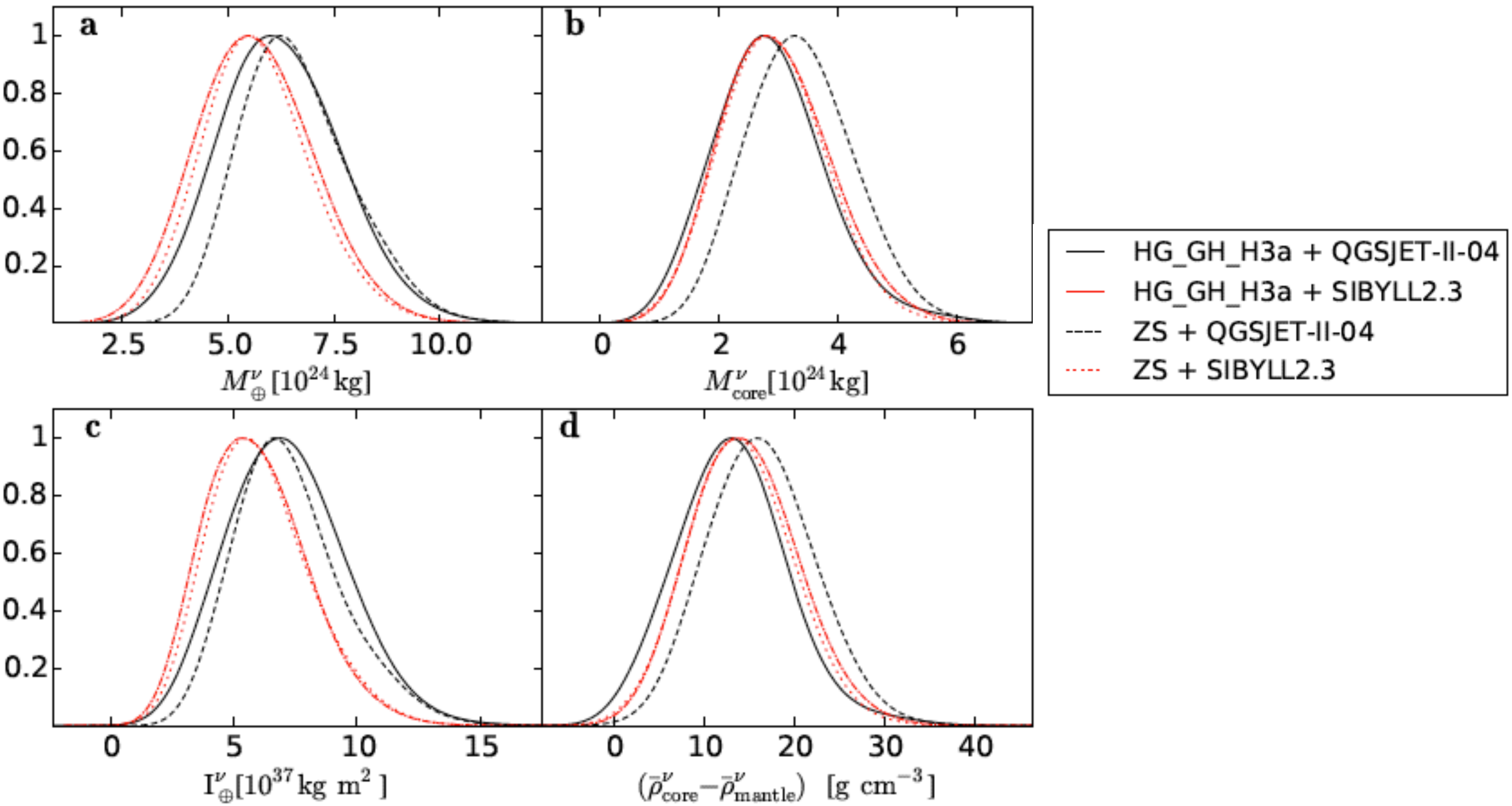
Above 5 TeV



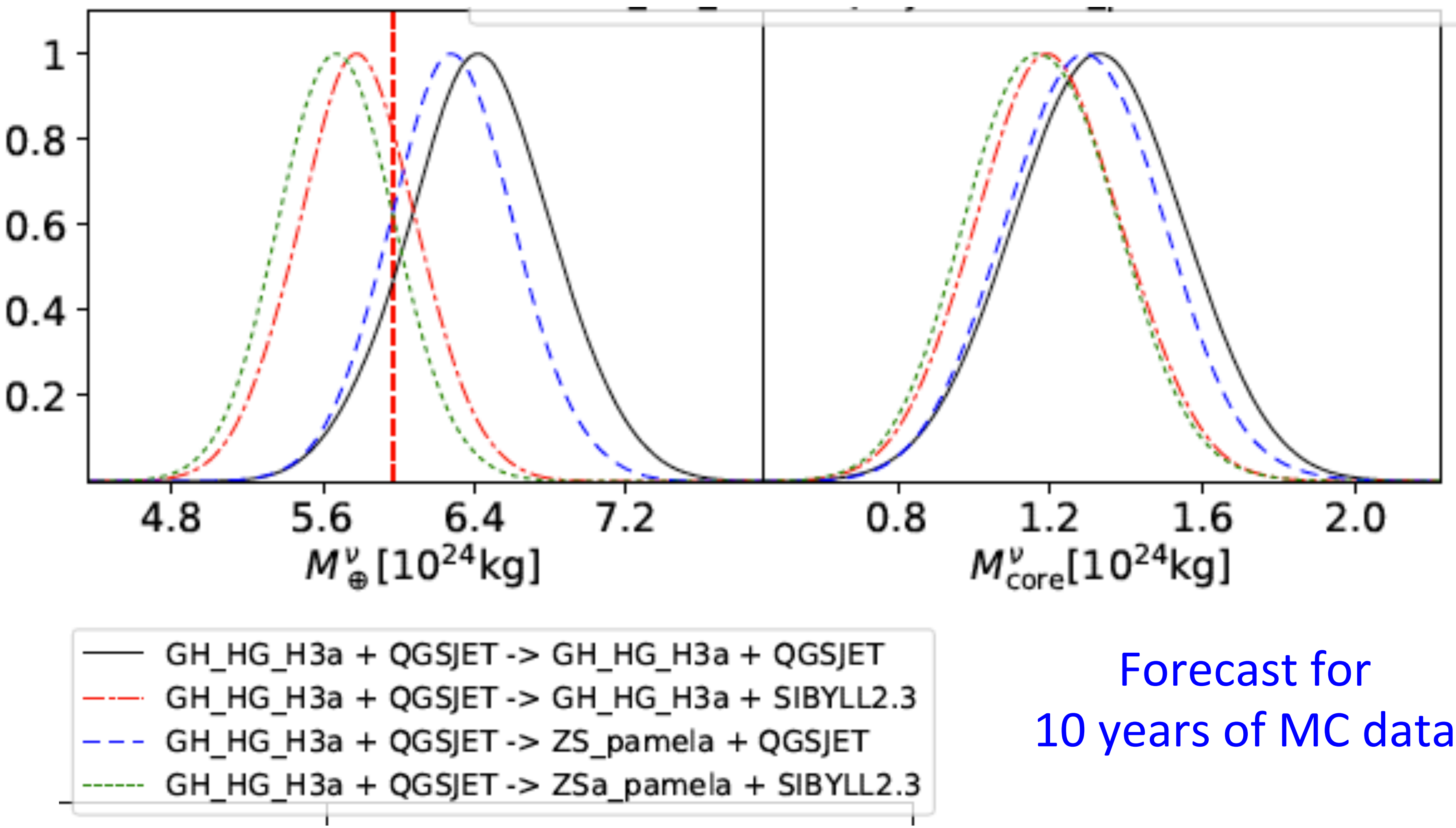
Full sample useful for normalization

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

Flux and hadronic model dependence

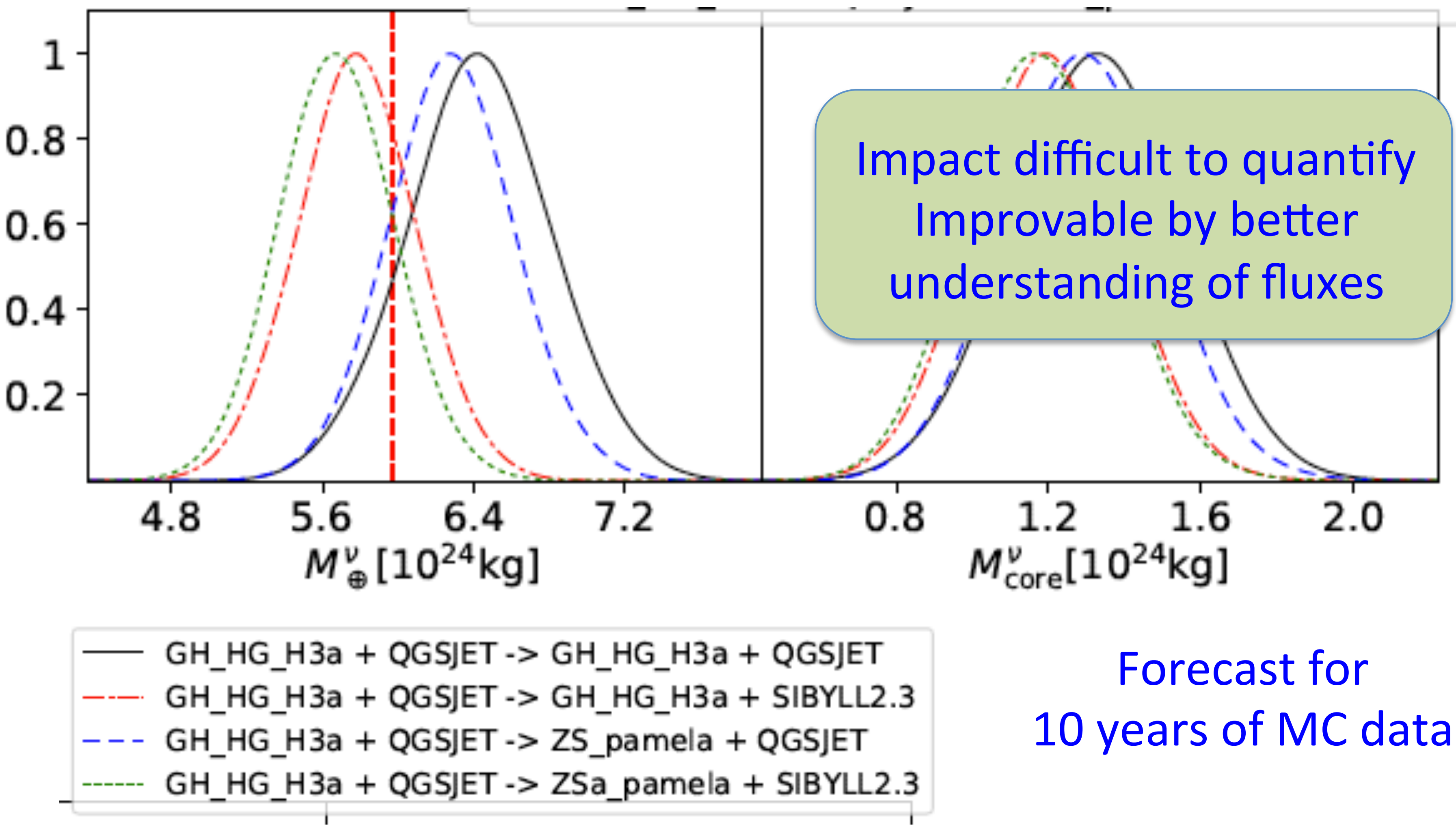


Flux and hadronic model dependence, 2



Forecast for
10 years of MC data

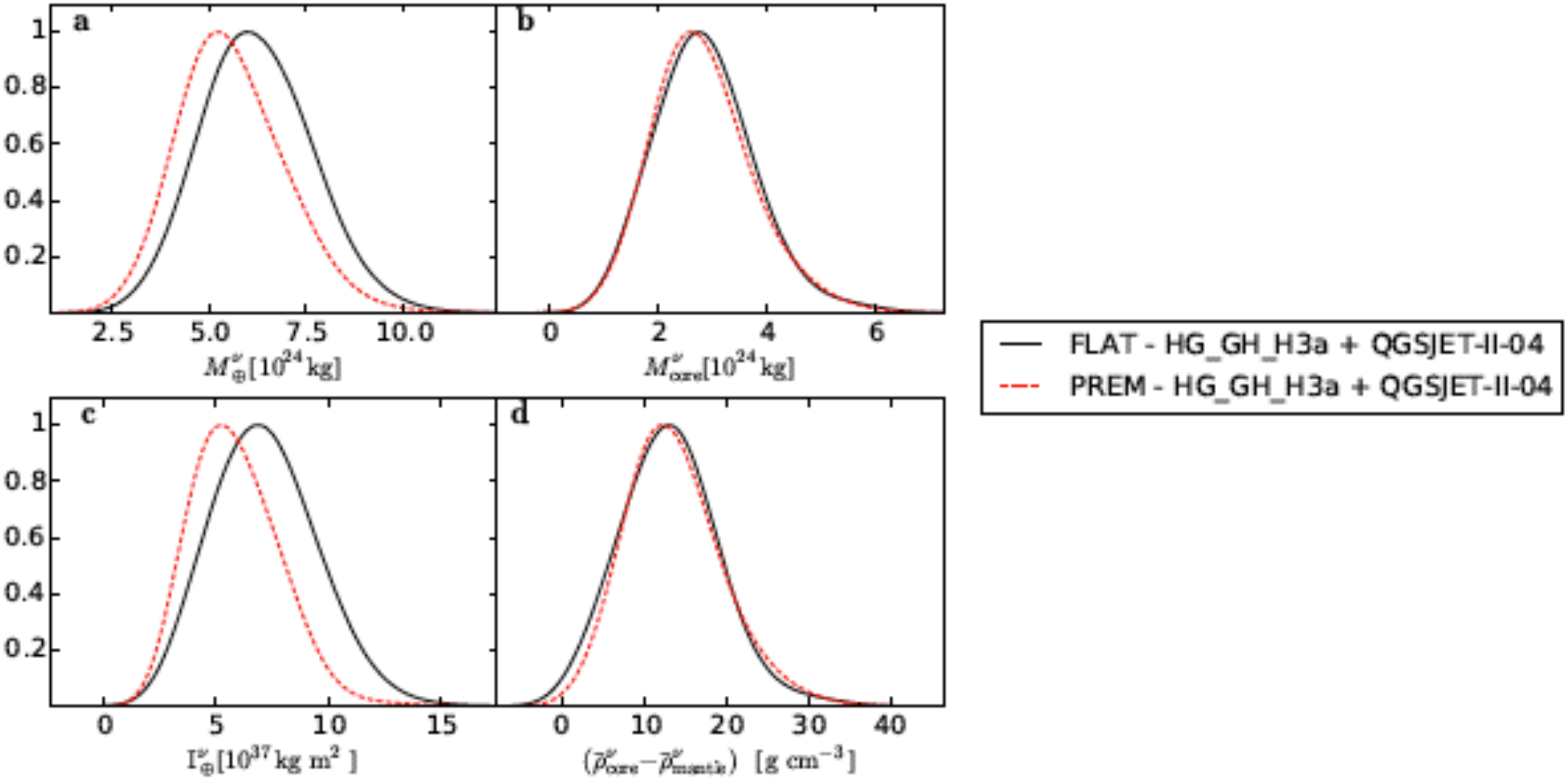
Flux and hadronic model dependence, 2



Impact difficult to quantify
Improvable by better understanding of fluxes

Forecast for
10 years of MC data

Earth's profile dependence

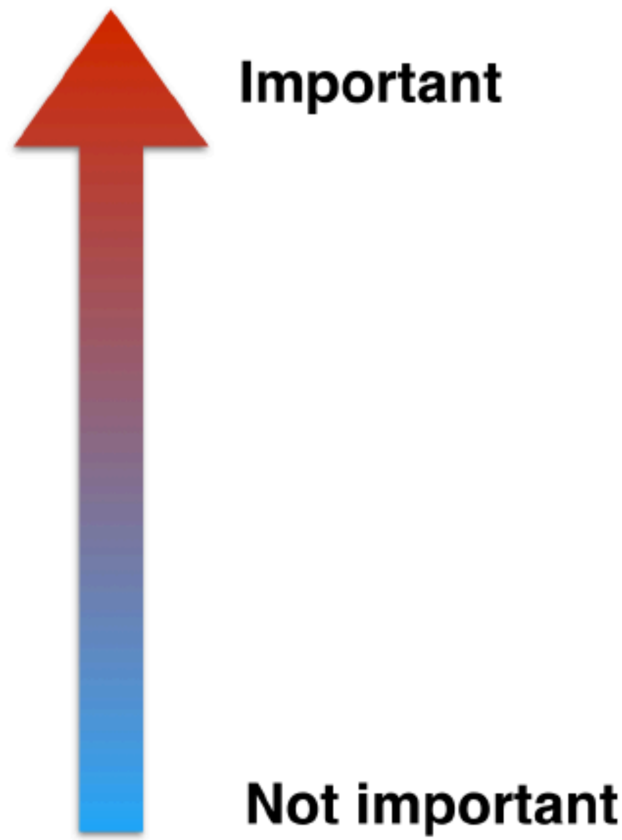


Systematics importance

- *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



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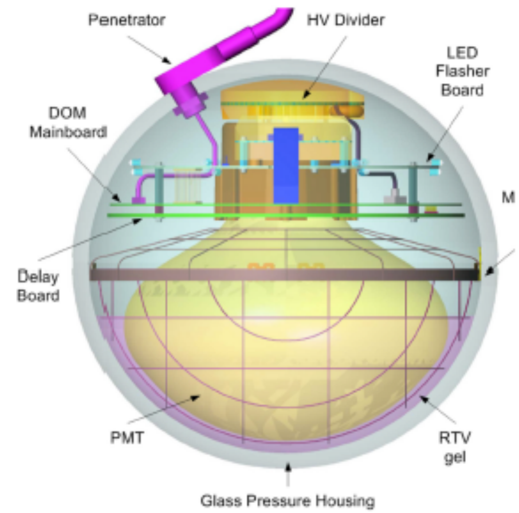
Important



D.O.M.

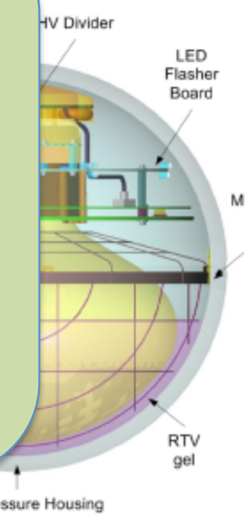
Not important

Systematics importance
(as in Salvado talk on sterile neutrinos)

- *DOM efficiency*
- *Flux continuous parameters*
  - *S*
  -
  -
- Air sh
  irrele
- Prima
  irrele
- Hole
- Neutr
- Bulk ic
  Irrelevant

Important

Not taken into account:
OPTICAL PROPERTIES OF THE ICE

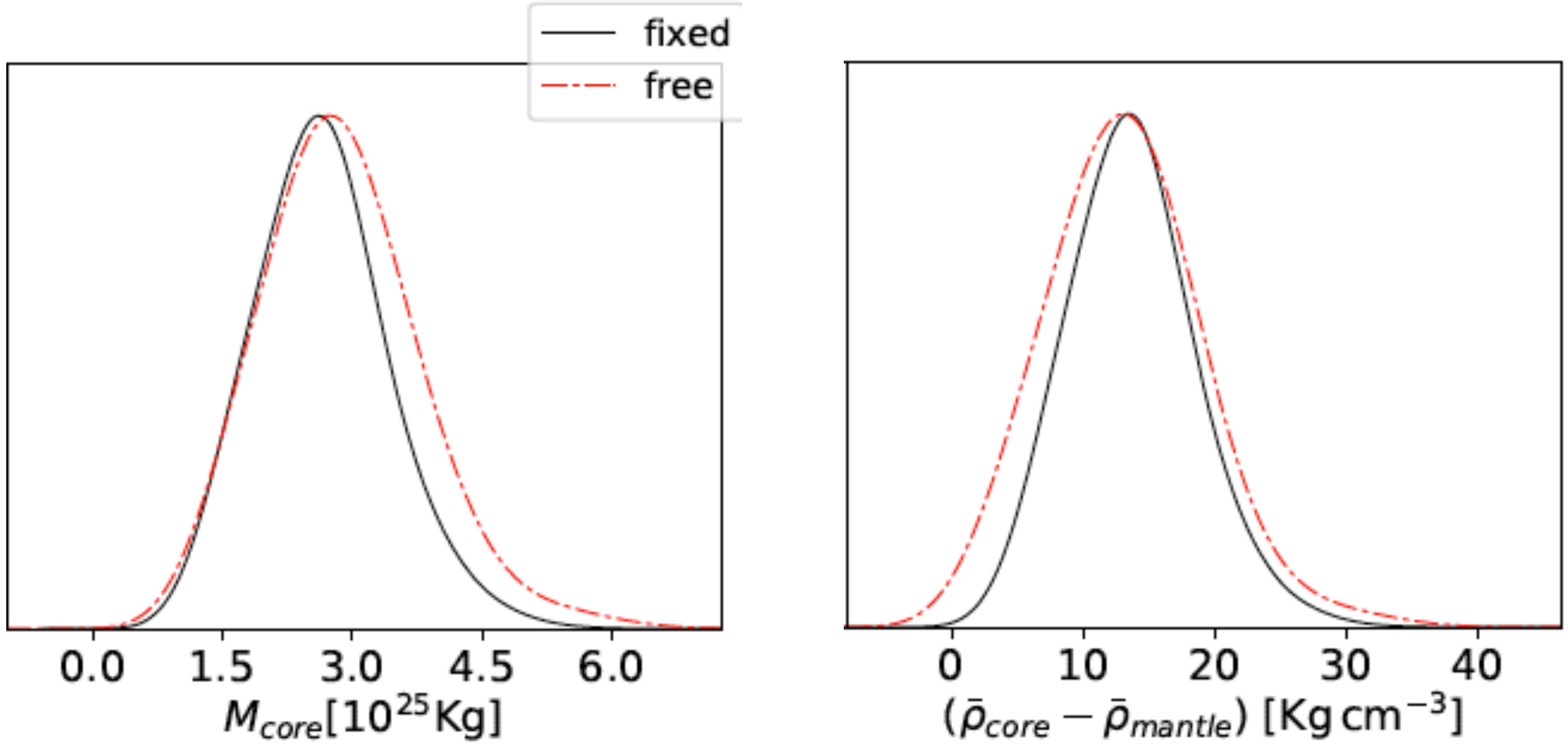


D.O.M.

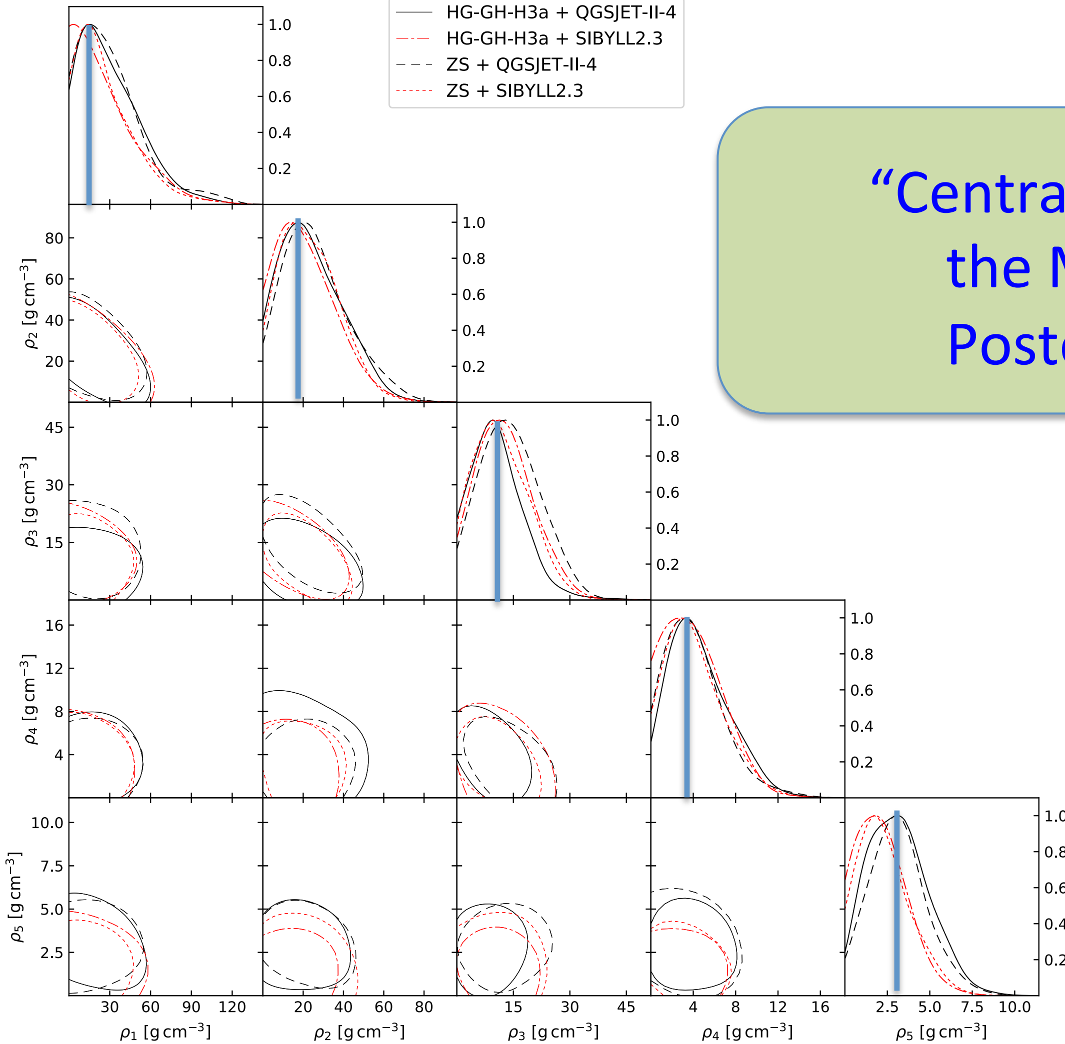
Not important

continuous systematics
discrete systematic

Impact of systematics on the error

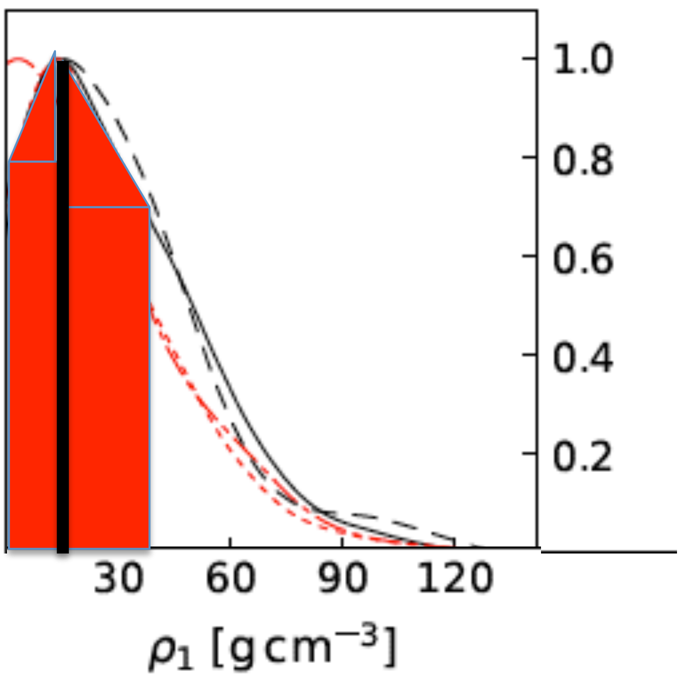


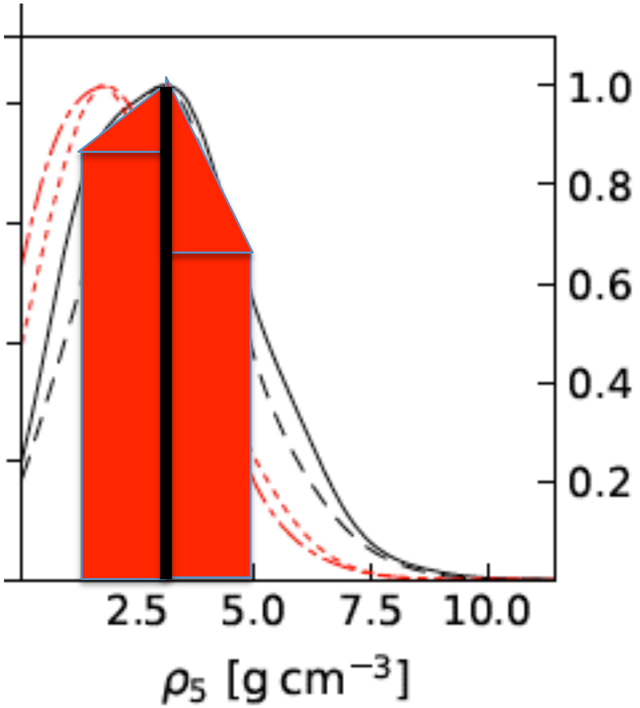
What are the dots?



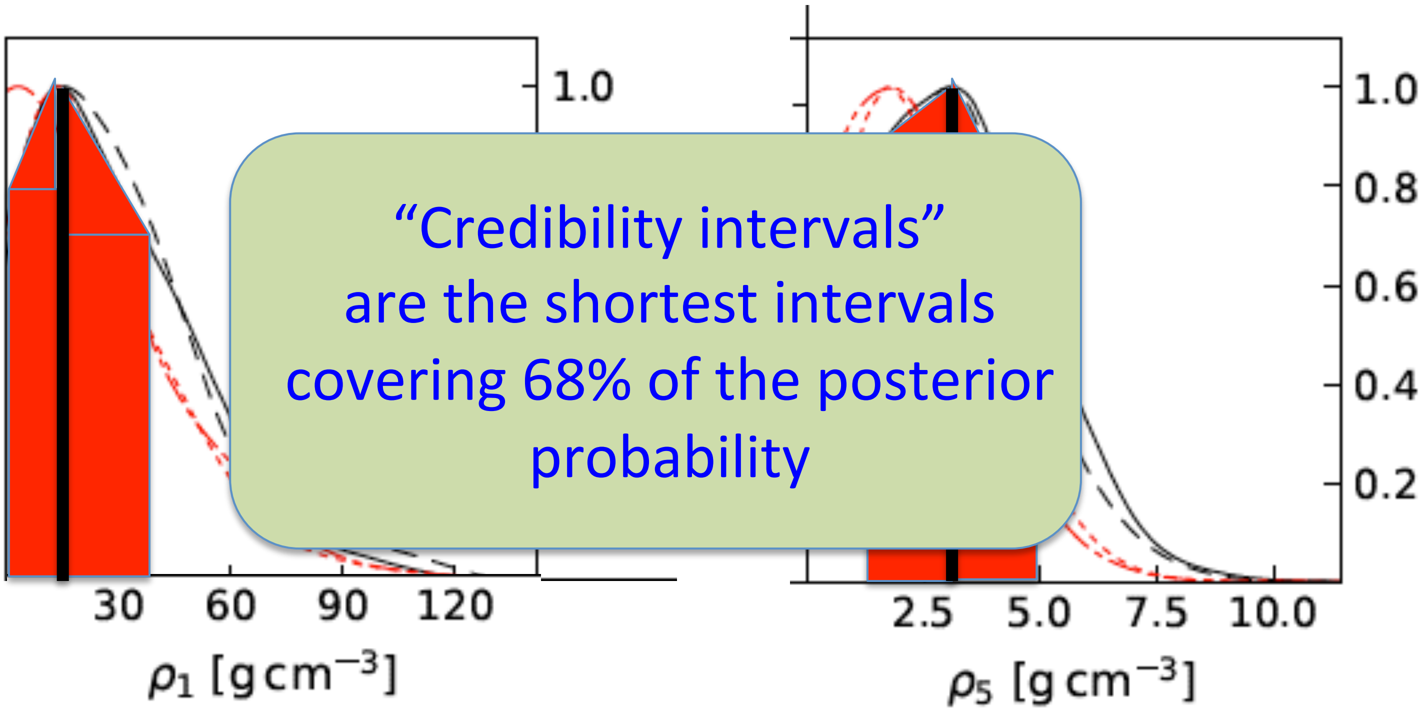
"Central values" represent the Maximum of the Posterior Probability

How to get asymmetric (bayesian) credibility intervals?





How to get asymmetric (bayesian) intervals?



"Credibility intervals"
are the shortest intervals
covering 68% of the posterior
probability

Results for different models

	Piecewise flat Earth's profile				PREM Earth's profile
	HG-GH-H3a + QGSJET-II-04	HG-GH-H3a + SIBYLL2.3	ZS + QGSJET-II-04	ZS + SIBYLL2.3	HG-GH-H3a + QGSJET-II-04
$M^{\nu}_{\oplus}$ [10^{24} kg]	$6.0^{+1.6}_{-1.3}$	$5.5^{+1.5}_{-1.3}$	$6.2^{+1.4}_{-1.2}$	$5.5^{+1.3}_{-1.2}$	$5.3^{+1.5}_{-1.3}$
$M^{\nu}_{\rm core}$ [10^{24} kg]	$2.72^{+0.97}_{-0.89}$	$2.79^{+0.98}_{-0.85}$	$3.27^{+0.92}_{-0.89}$	$2.84^{+0.89}_{-0.88}$	$2.62^{+0.97}_{-0.84}$
$I^{\nu}_{\oplus}$ [10^{37} kg cm^2]	6.9 ± 2.4	$5.4^{+2.3}_{-1.9}$	$6.7^{+2.3}_{-2.0}$	$5.5^{+2.2}_{-1.9}$	$5.3^{+2.3}_{-1.7}$
$\bar{\rho}^{\nu}_{\rm core} - \bar{\rho}^{\nu}_{\rm mantle}$ [g/cm^3]	$13.1^{+5.8}_{-6.3}$	$14.0^{+6.0}_{-5.9}$	$15.9^{+6.0}_{-5.9}$	$13.5^{+6.1}_{-5.5}$	$12.3^{+6.3}_{-5.4}$
$p-$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}

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 $I_\oplus(\rho(r) = \rho_0) = 0.4 M_\oplus R^2$.

Impact of constraints

Adding the gravitational Earth's mass as an external constraint, results in fixing the mantle density:

ρ_5 = [1.22-4.78] g/cm^3 → [4.43-4.79] g/cm^3

Rather small impact on the core density, instead:

ρ_{core} = [10.2-20.8] g/cm^3 → [9.7-18.6] g/cm^3

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)