



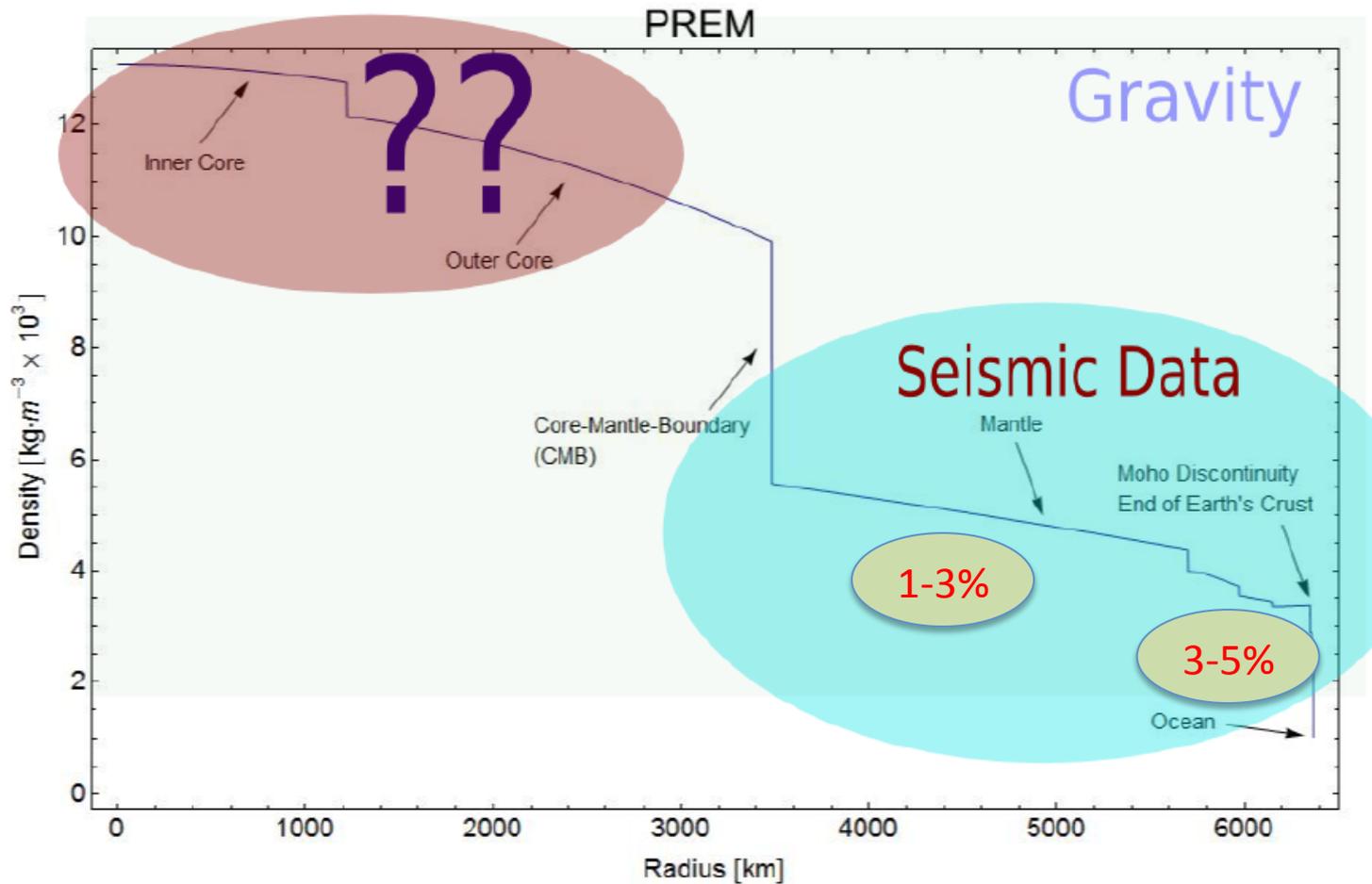
Neutrino Tomography of the Earth with Icecube

Andrea Donini (IFIC, Valencia)

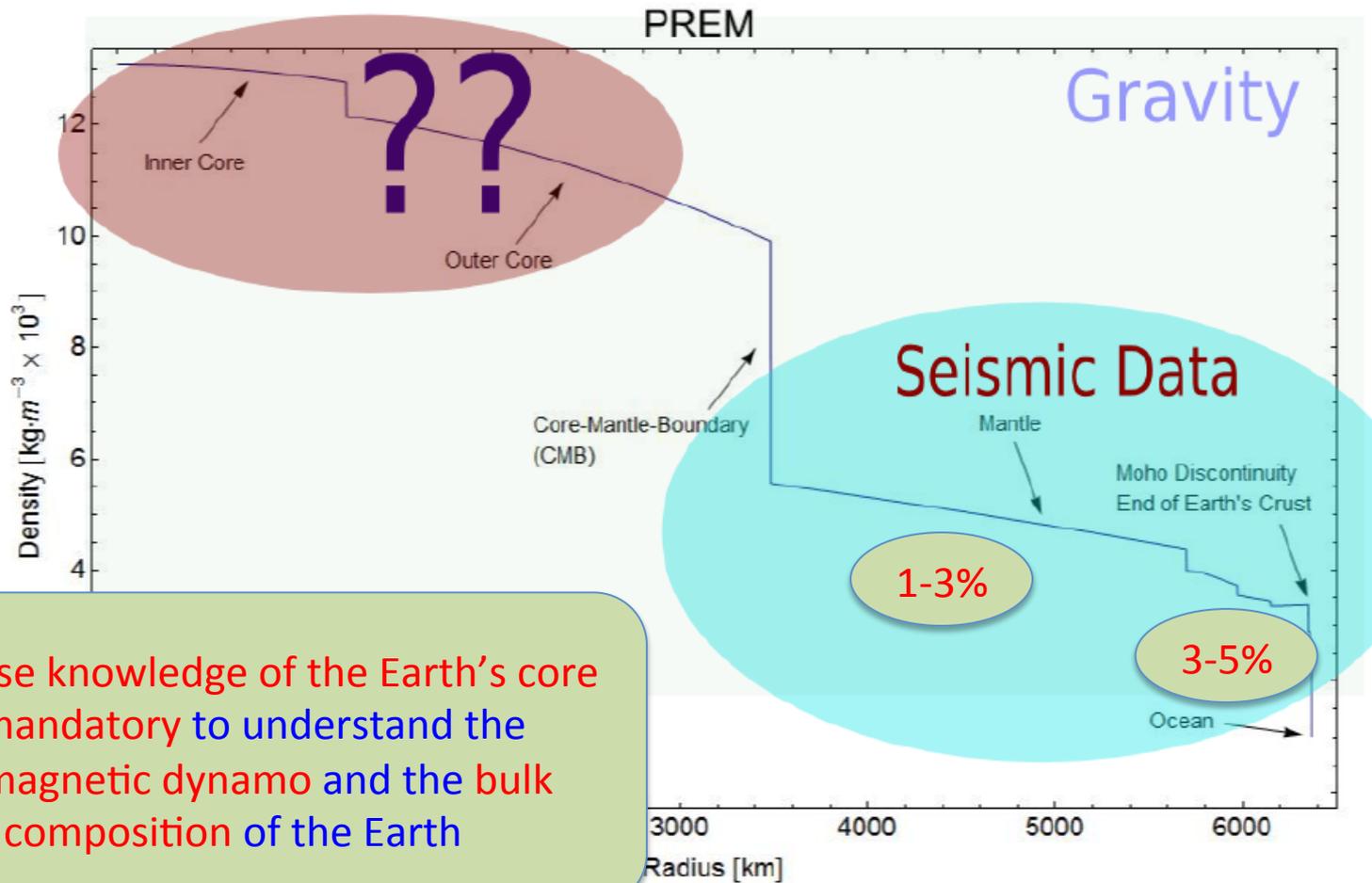
arXiv:1803.05901

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

Uncertainties from seismology



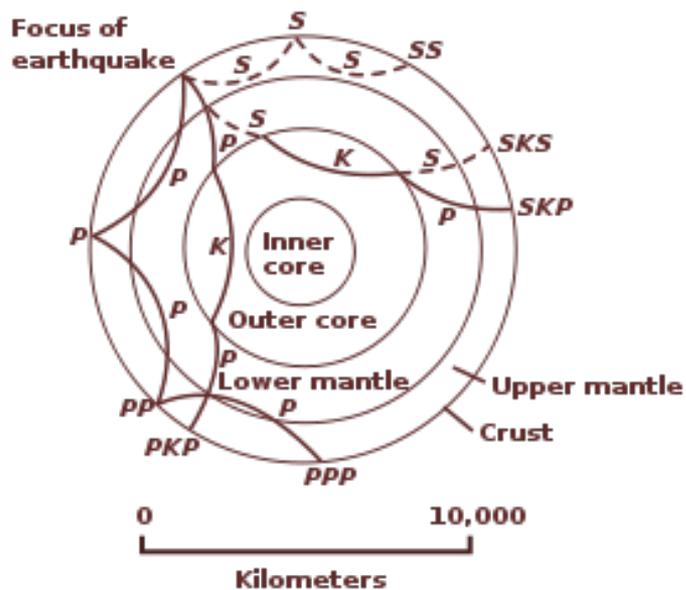
Uncertainties from seismology



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

The Earth's core

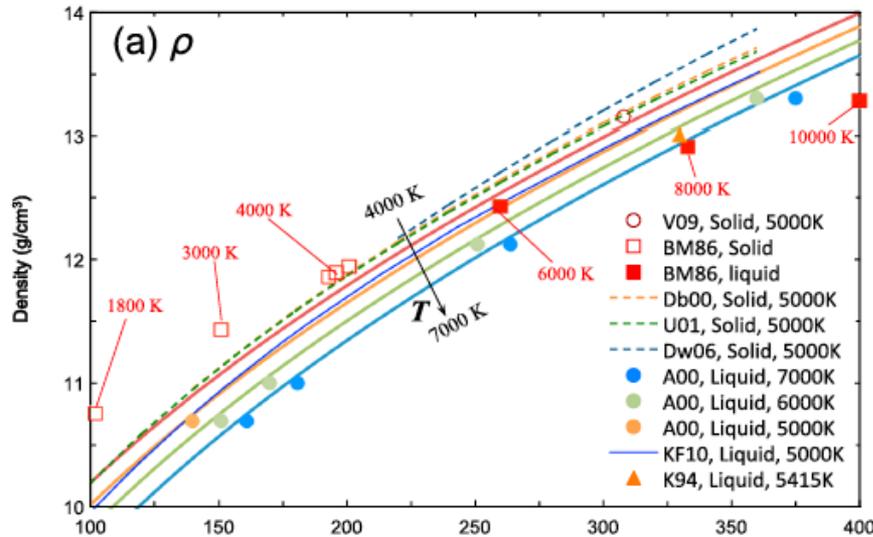
A problem:
The **OUTER CORE IS LIQUID**:
EARTHQUAKE WAVES CANNOT CROSS
THE INNER CORE



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



Estimated temperature range still very large: 4000-10000 K

Composition guessed (iron-nickel?)

Missing Xenon problem

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

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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PREVIOUS TALK!

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- 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

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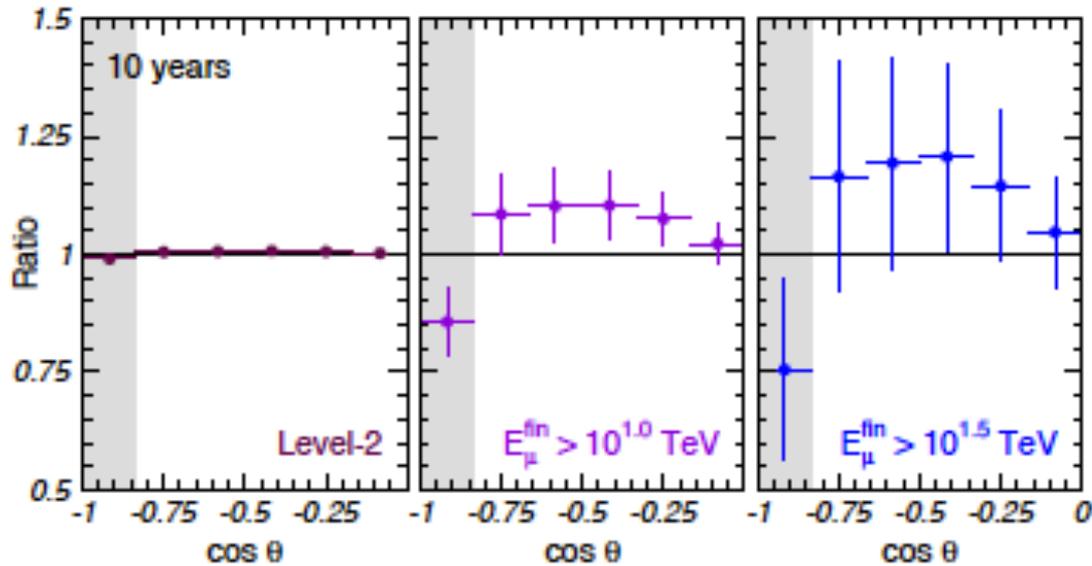
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A forecast...

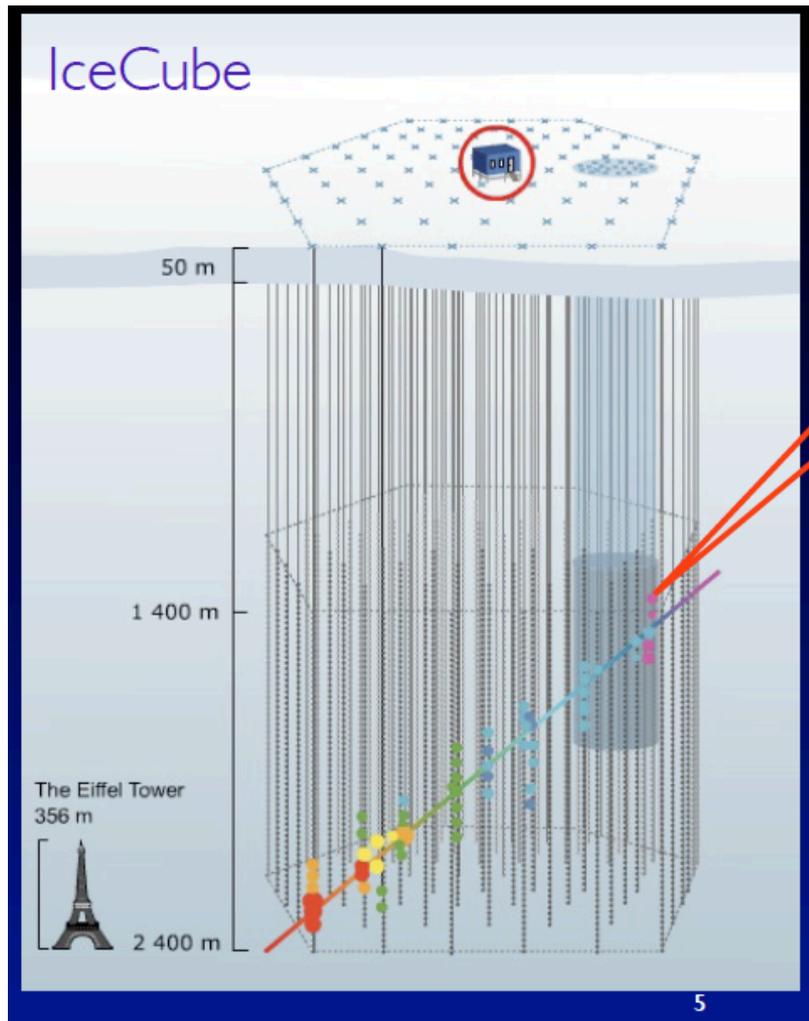


After 10 years of
data taking
at IceCube using
neutrino attenuation

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

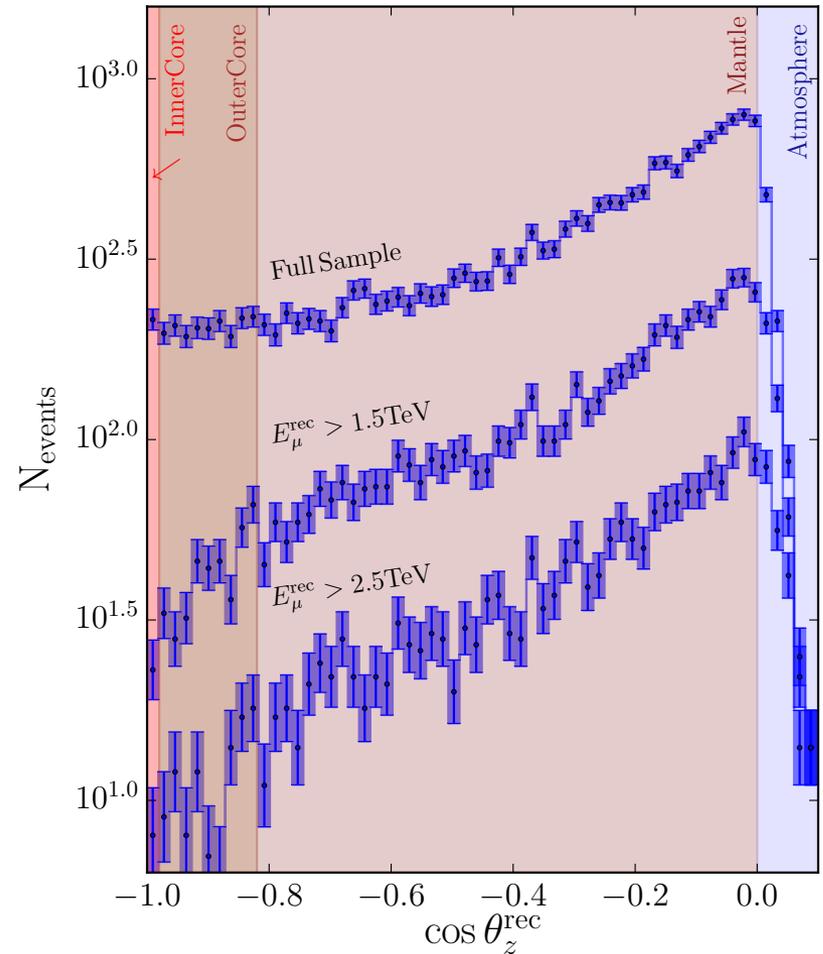
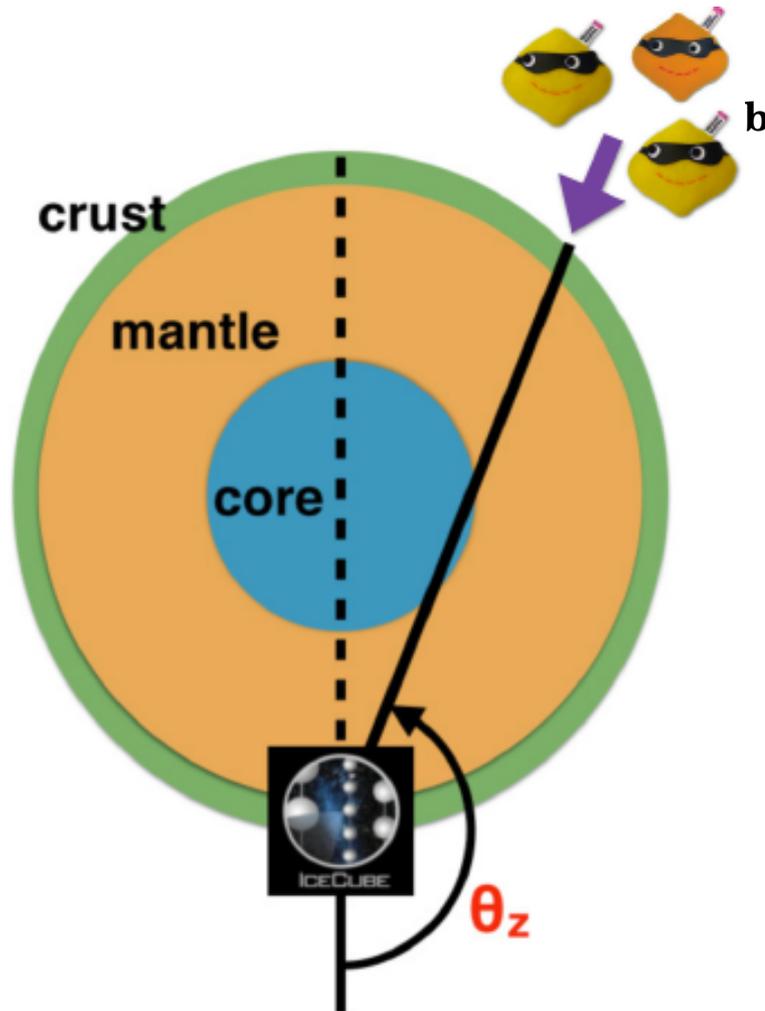


- Deployed in glacial ice at the South Pole
- Array size 1 km^3 , 86 strings, 60 optical sensors (DOMs) per string

The IceCube IC86 data sample

- 1 year of data taking (2011-2012)
 - 20145 muon events over 343.7 days
 - $E_{\mu} = [400 \text{ GeV} \div 20 \text{ TeV}]$
 - The muon direction is a very good proxy of the neutrino direction, with $\Delta\cos\theta_z < 0.01$
 - **PUBLICLY AVAILABLE!**
- 7 more years of data are not yet available to mortals.....

Raw data as a function of E_μ and θ_z



Comparison with expectations

Flux model

Propagation

Interaction with
nucleons

Detector
simulation

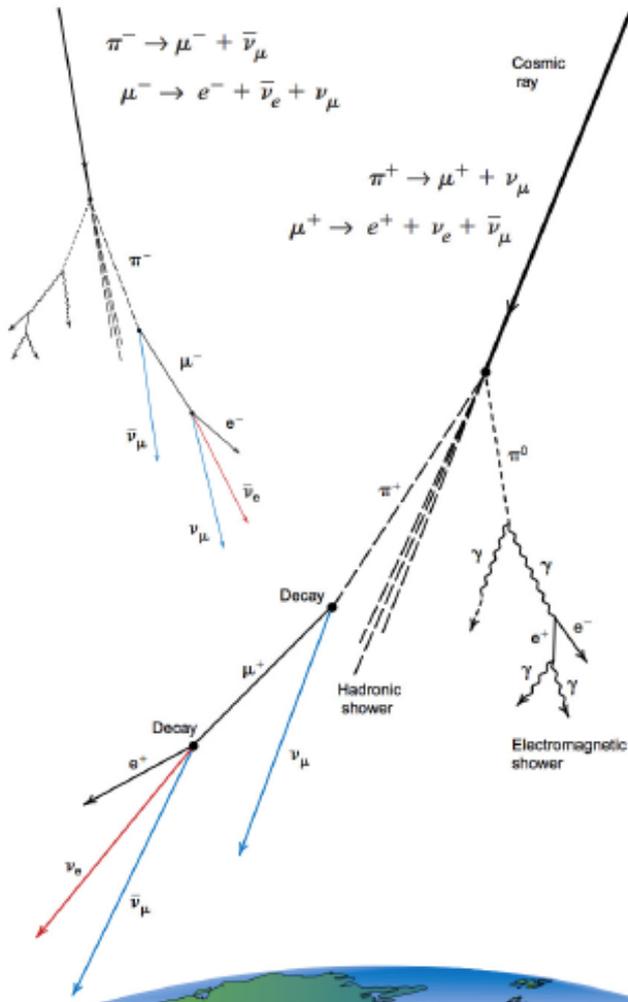
Flux model dependence

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

Hadronic model: QGSJET-II-04

Other options → “discrete”
systematics

(see talks by Fedynitch, Gaisser, Honda)



Neutrino propagation

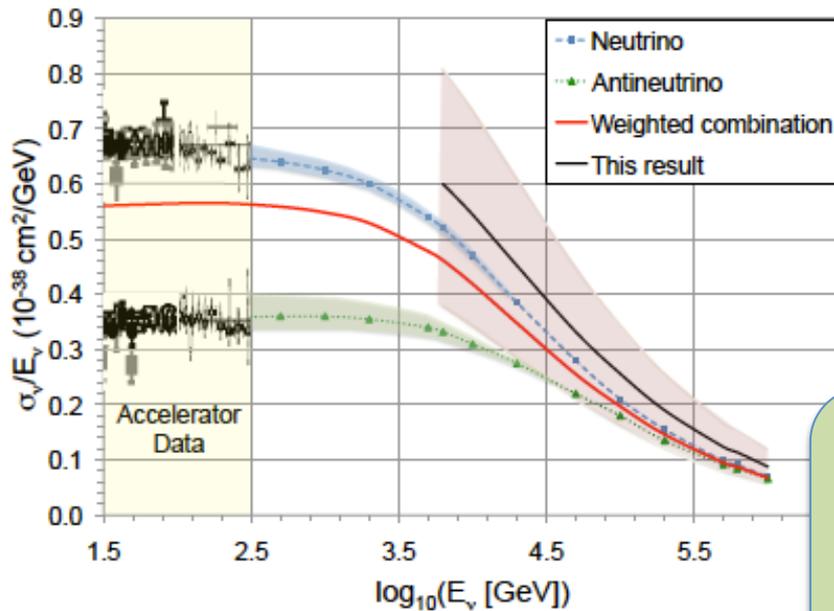
$$\frac{dF_\nu(E)}{dx} = -i[H_o + V_m, F_\nu(E)] - \sum_\alpha \frac{1}{2\lambda^\alpha(E)} \{\Pi_\alpha, F_\nu(E)\}$$

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

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

Neutrino-nucleon interaction

Parton distribution functions: HERAPDF

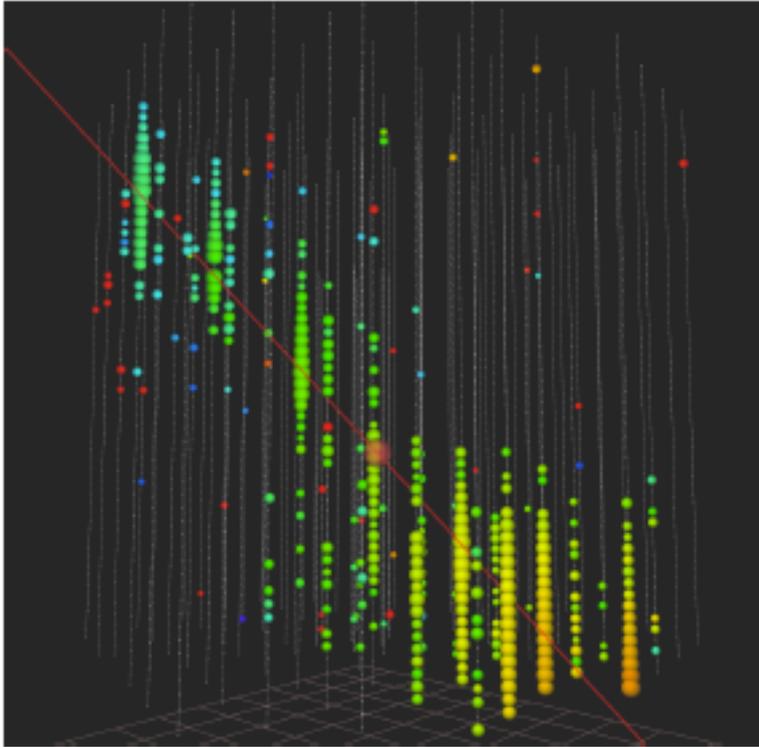


Aarsten et al, Nature 551 (2017)

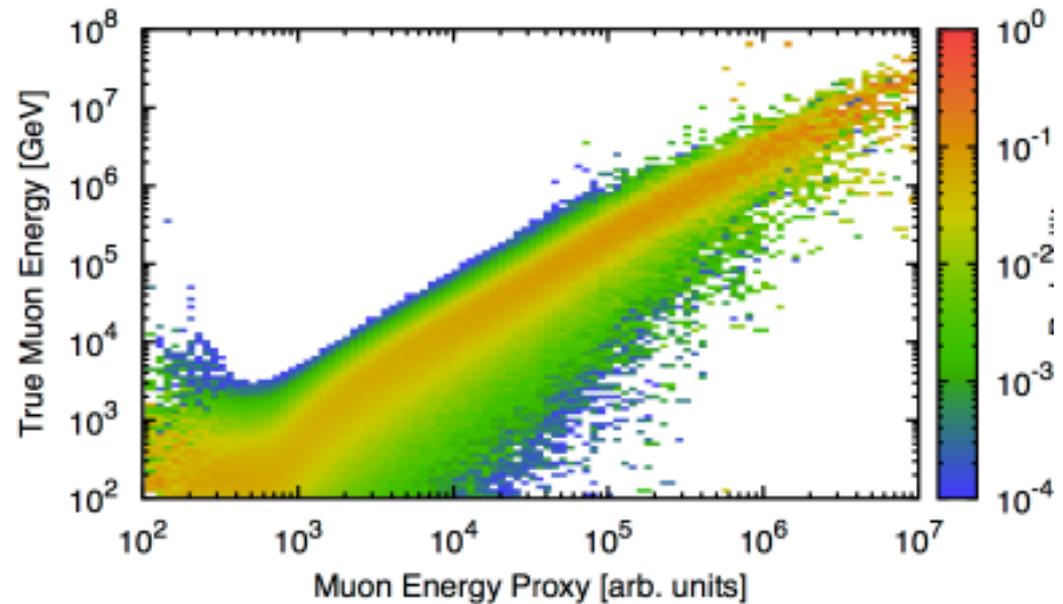
νN ($\bar{\nu} N$) cross-sections
at 2-3% (4-10%) errors

ICECUBE MEASUREMENT
 $1.30^{+0.21}_{-0.19}$ (stat) $^{+0.39}_{-0.43}$ (syst) $\times \sigma_{SM}$

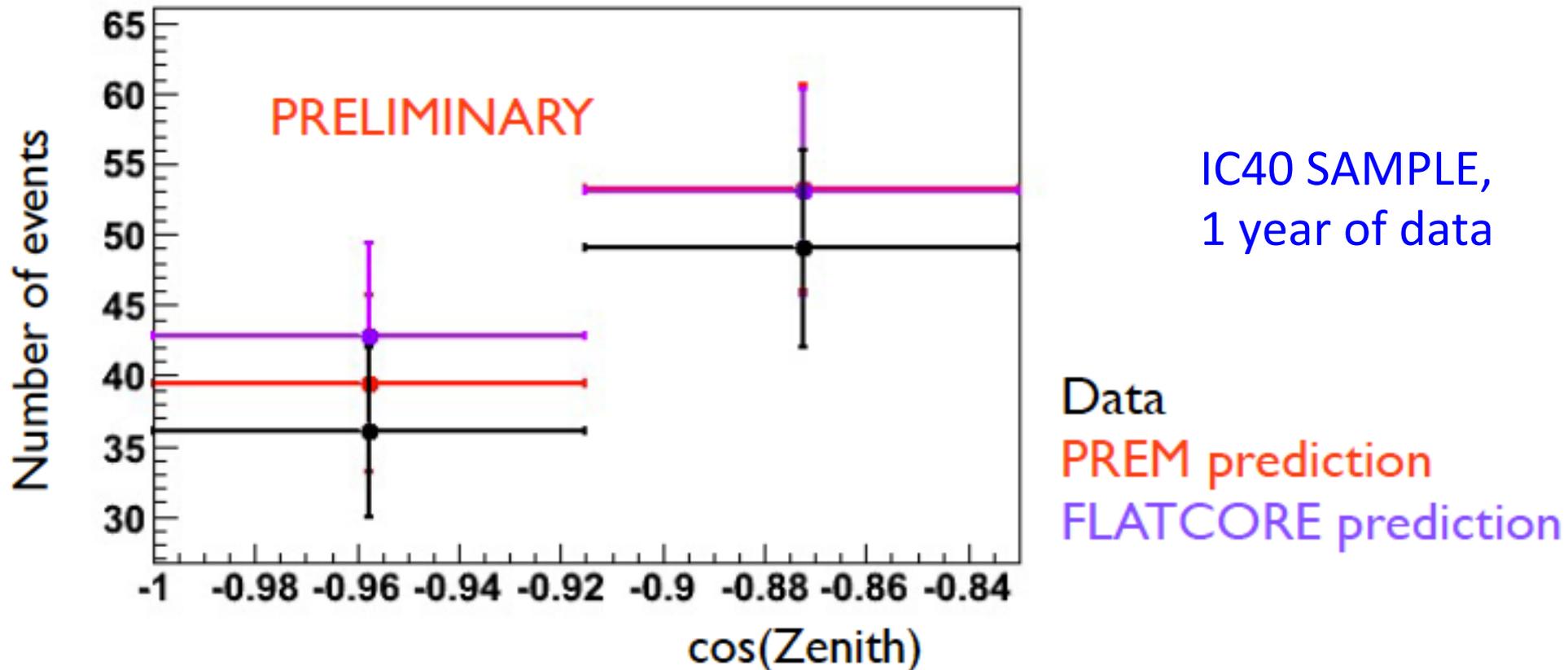
Detector simulation



We use the official
IceCube MC to map
 E_{true}^{μ} , $\theta_{\text{true}}^{\mu}$ into E_{rec}^{ν} , $\theta_{\text{rec}}^{\nu}$

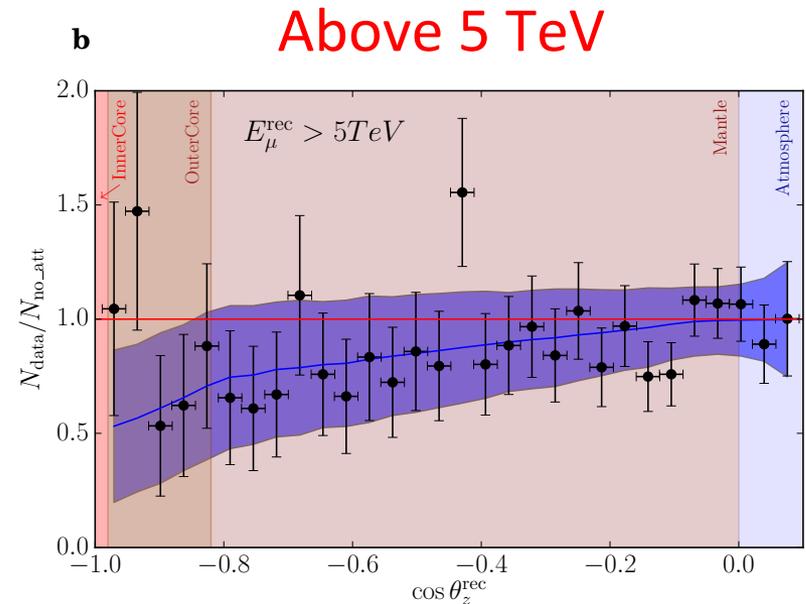
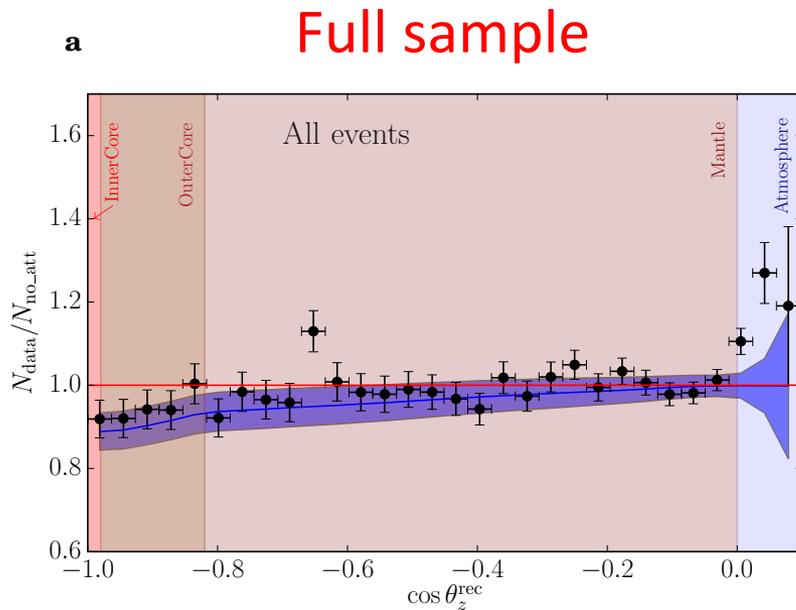


An early attempt by IceCube collaboration



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

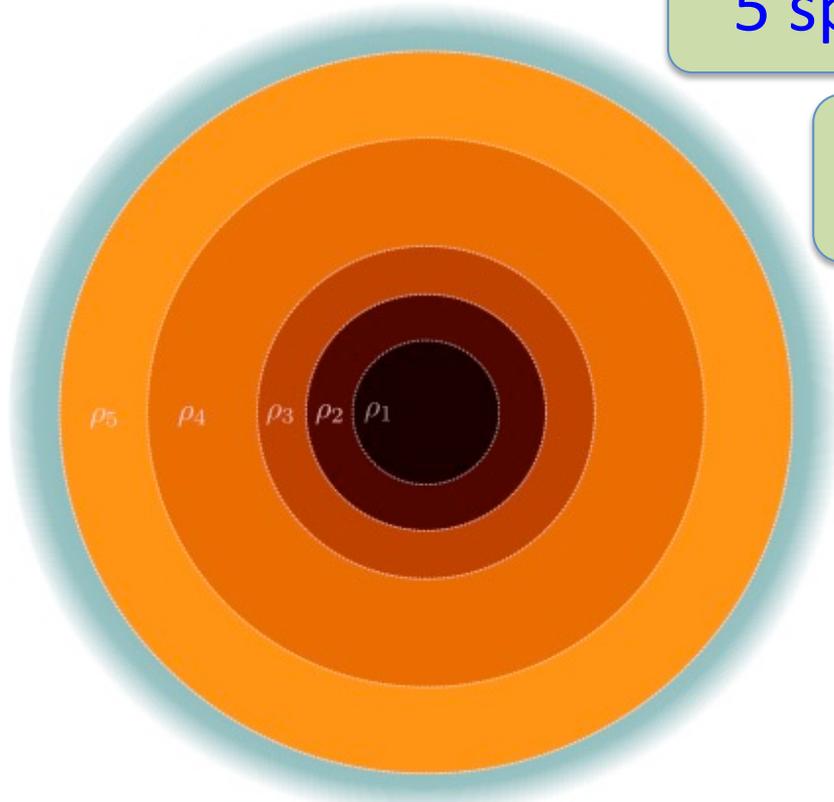
Including energy cuts: $N_{\text{data}}/N_{\text{noatt}}$



Full sample
useful for
normalization

For $\cos \theta_z > -0.6$,
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

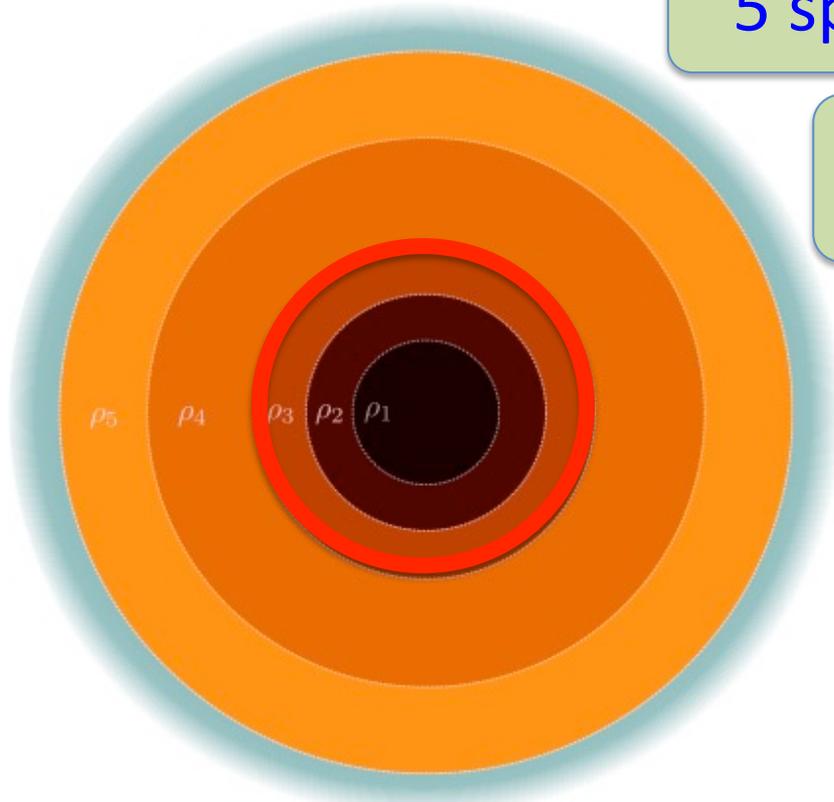
Mantle, two layers

$L_4 = 4938$ km,

$L_5 = 6371$ km

No crust!

Our Earth's model



5 spherical layers

Inner Core, one layer

$L_1 = 1242$ km

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Mantle, two layers

$L_4 = 4938$ km,

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Core-Mantle Boundary fixed!

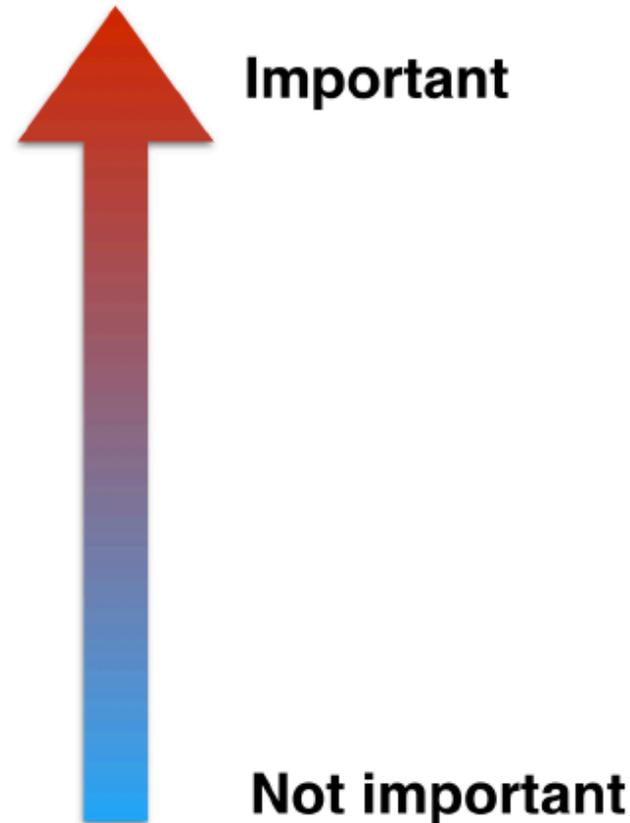
No crust!

Systematics importance

(as in Salvado talk on sterile neutrinos)

- ▶ 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

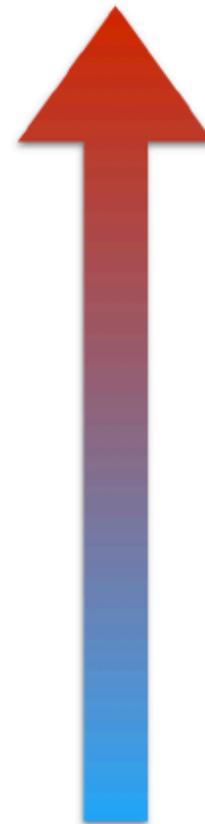


Systematics importance

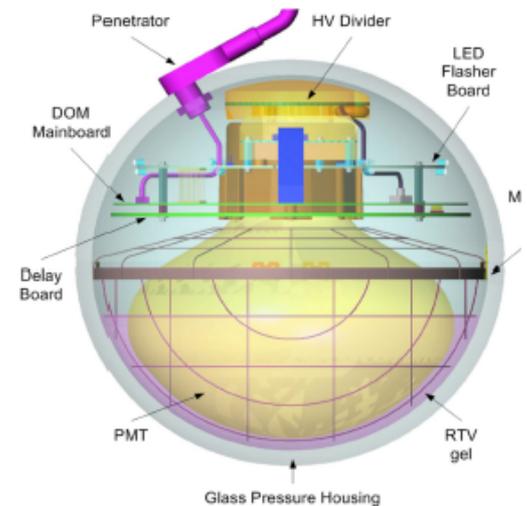
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continuous systematics
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Important



D.O.M.

Not important

Systematics importance

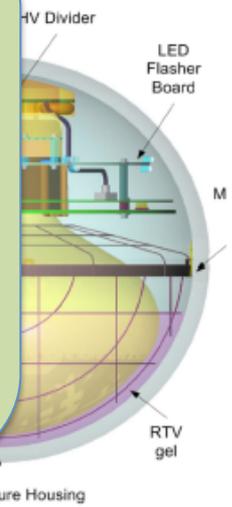
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- ▶ DOM efficiency
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- ▶ S
- ▶
- ▶

- ▶ Air sh
irrelev
- ▶ Prima
irrelev
- ▶ Hole
- ▶ Neutr
- ▶ Bulk ic
Irrelevant

Not taken into account:
OPTICAL PROPERTIES OF THE ICE

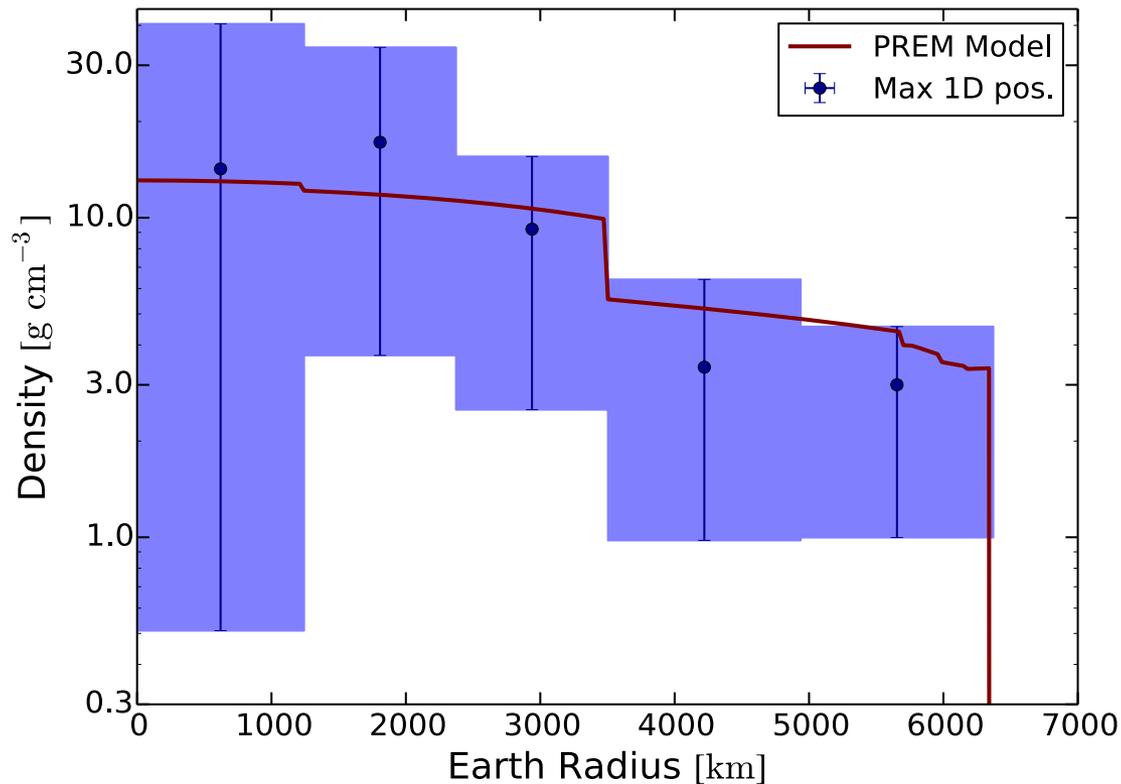


D.O.M.

Not important

continuous systematics
discrete systematic

First 1-d density profile with neutrinos



Analysis performed
with MultiNest

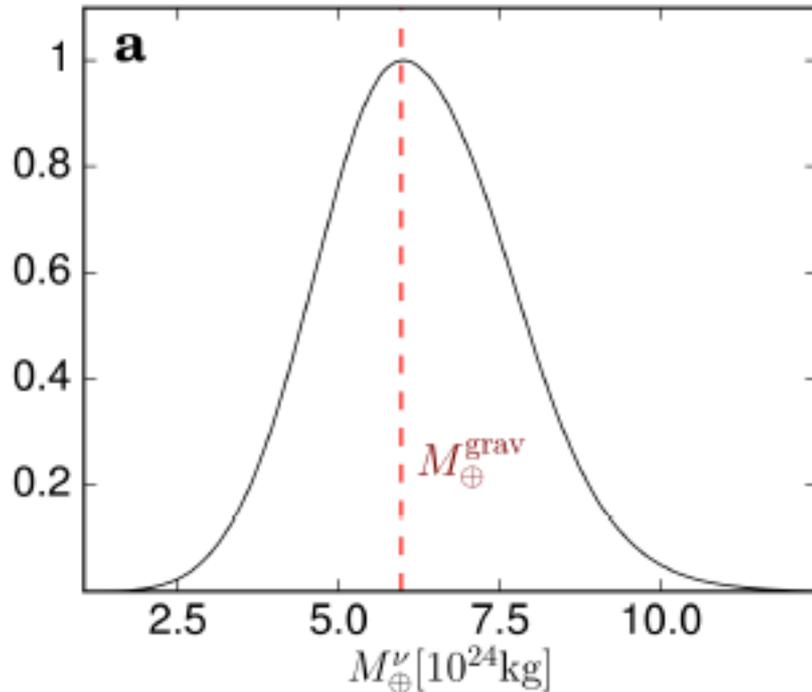
5 Earth layers densities

and

4 systematic errors:

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

The Earth's mass



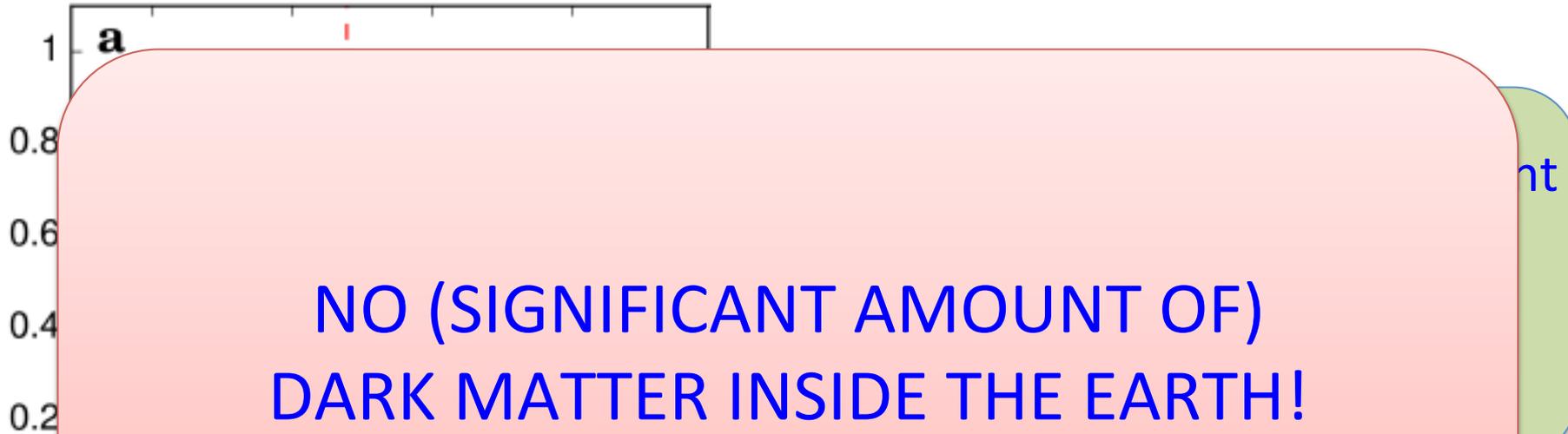
First Electro-weak measurement
of the Earth's mass

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

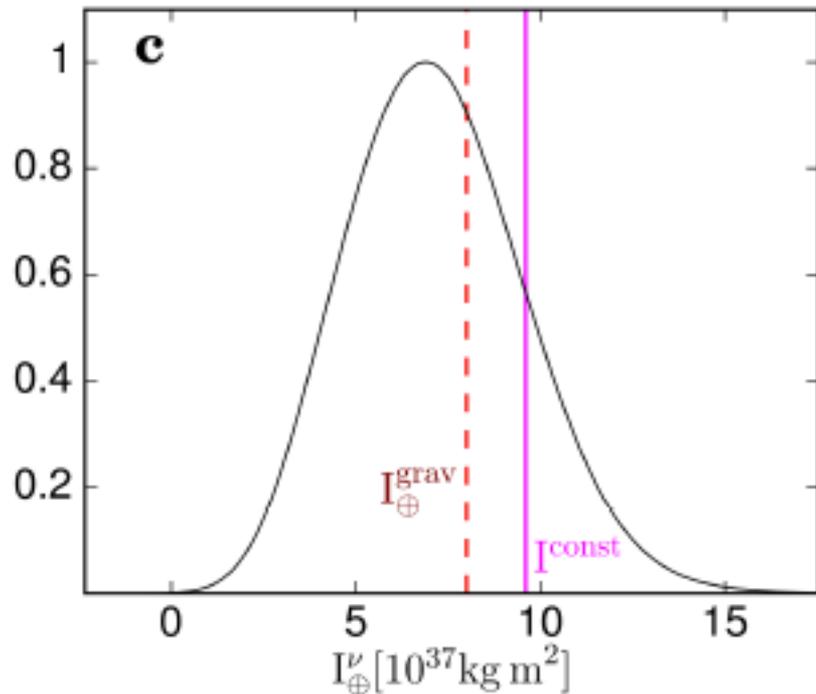
Gravitational measurement of the Earth's mass

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

The Earth's mass



The Earth's moment of inertia



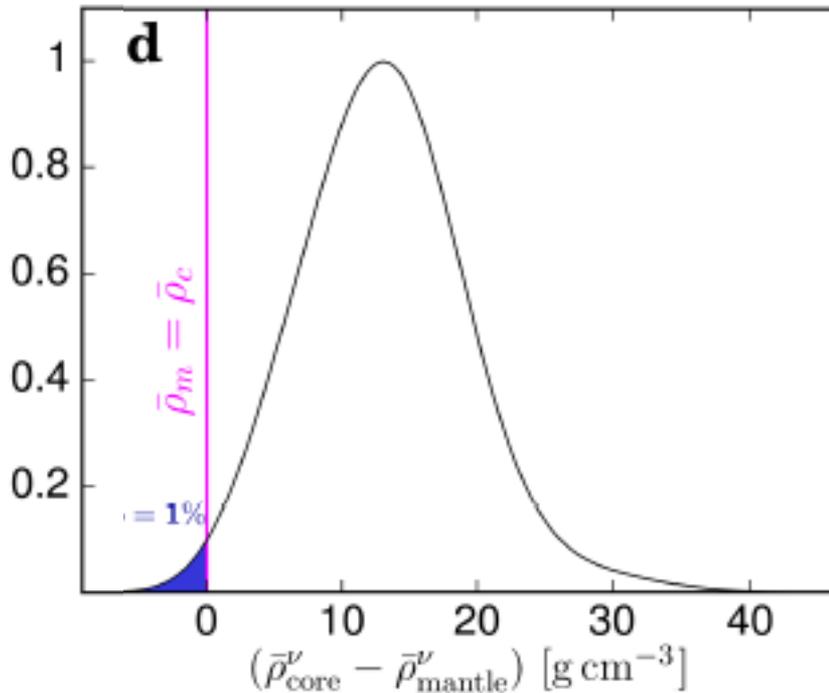
Electro-weak measurement of the Earth's moment of inertia

$$I_{\text{earth-}\nu} = (6.9 \pm 2.4) \times 10^{37} \text{ kg m}^2$$

Gravitational measurement of the Earth's moment of inertia

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

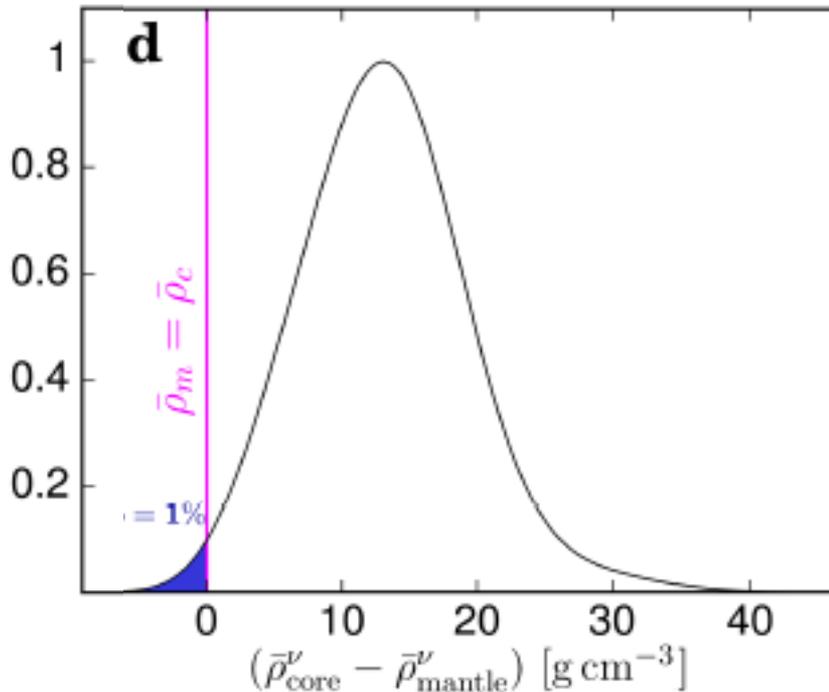
Earth's non-homogeneity



Electro-weak measurement of
the Core-Mantle discontinuity

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

Earth's non-homogeneity



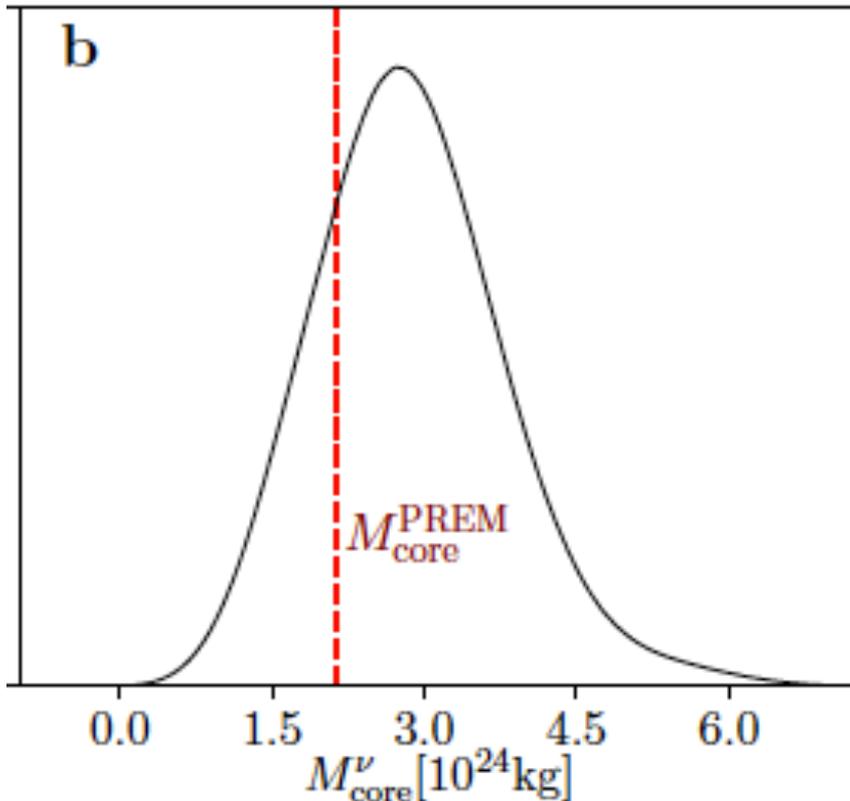
Electro-weak measurement of the Core-Mantle discontinuity

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

However: 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

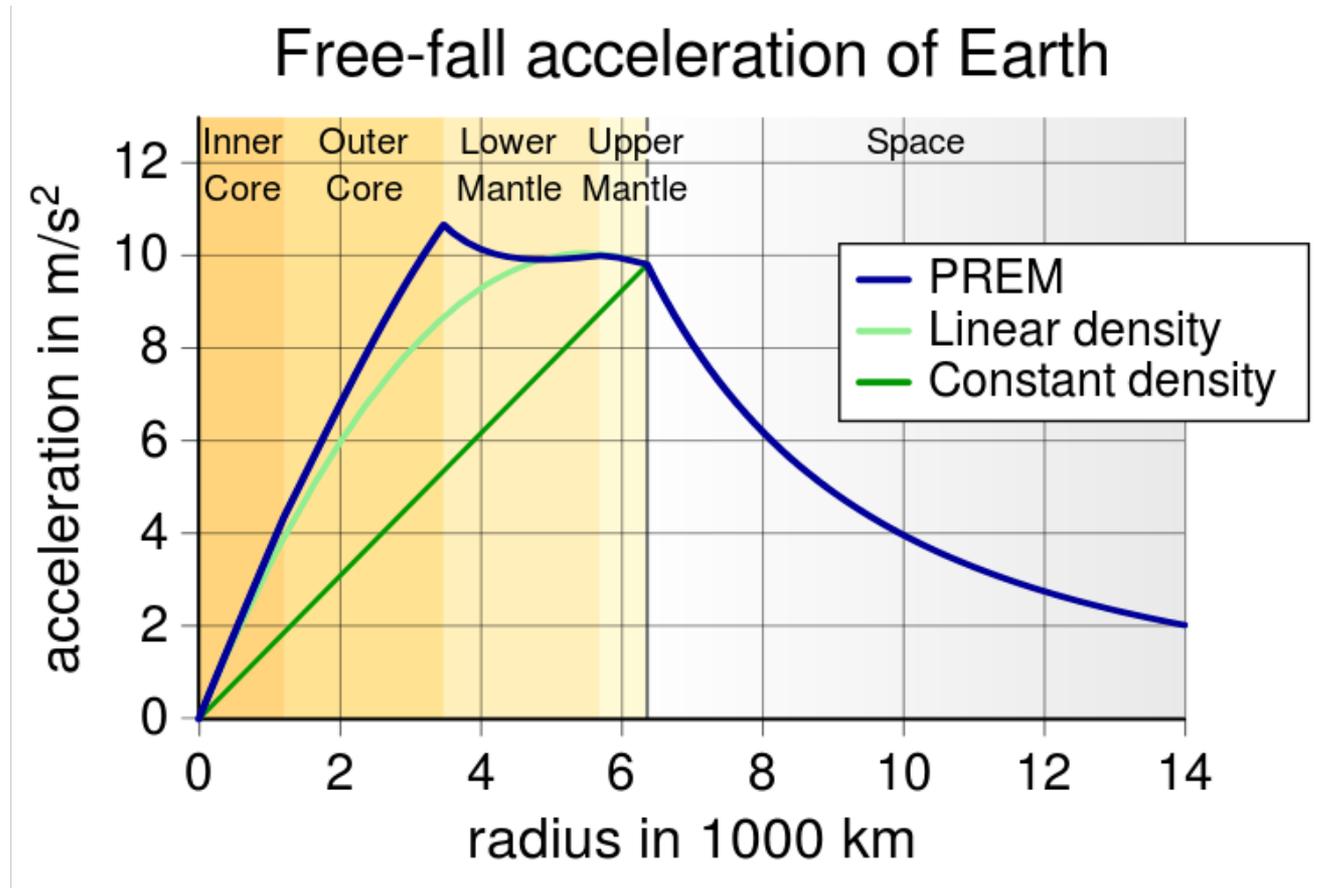


Electro-weak measurement of
the Earth's core mass

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

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

An important constraint



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

Comment on Inner Core over-density

We measure $\rho_{\text{core}} = [10.2-20.8] \text{ g/cm}^3$,
whereas for the PREM $\rho_1 = 11.9 \pm 0.2 \text{ g/cm}^3$
Slightly larger central value with respect to
PREM. Statistically irrelevant! YET.....

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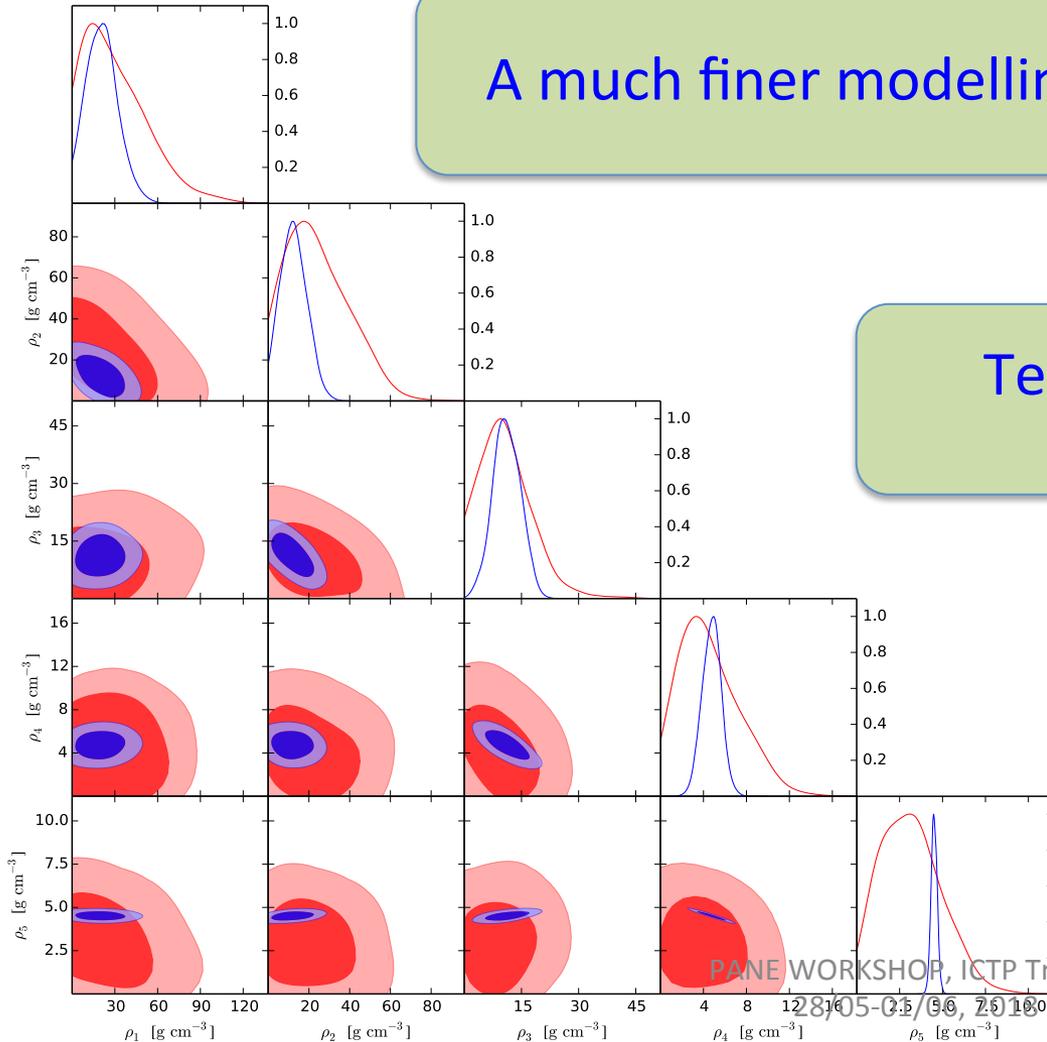
Statistics will increase non-homogeneously for the
different layers, as 70% of the nucleons are
in the mantle. Wait and see.....

Forecast with 10 years of data

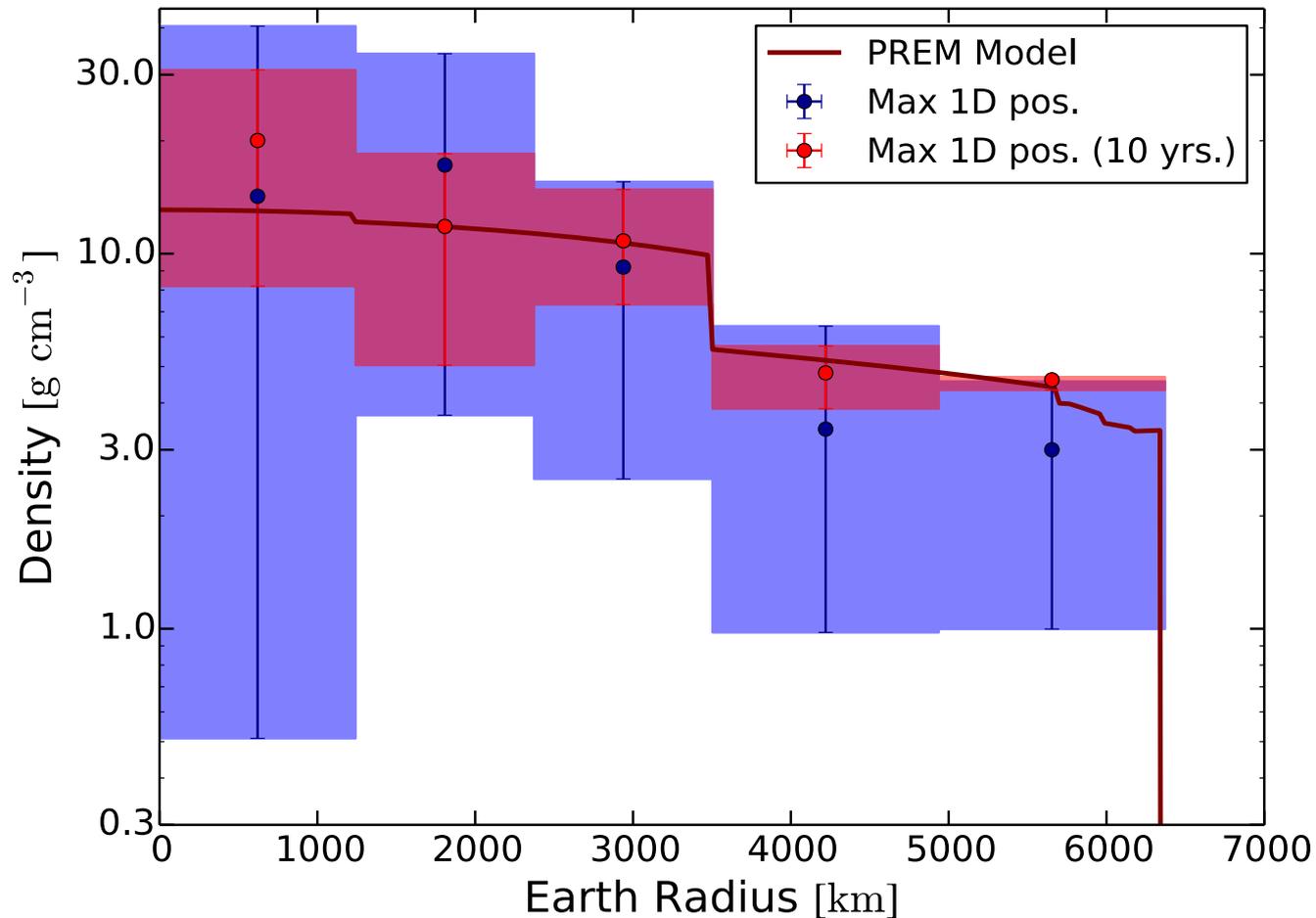
A much finer modelling of the Earth could be done

Test of the Inner-Outer Core discontinuity

Independent localization of the Core-Mantle Boundary



1-d density profile with 10 years



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} , $\Delta\rho_{\text{CMB}}$, M_{core}

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

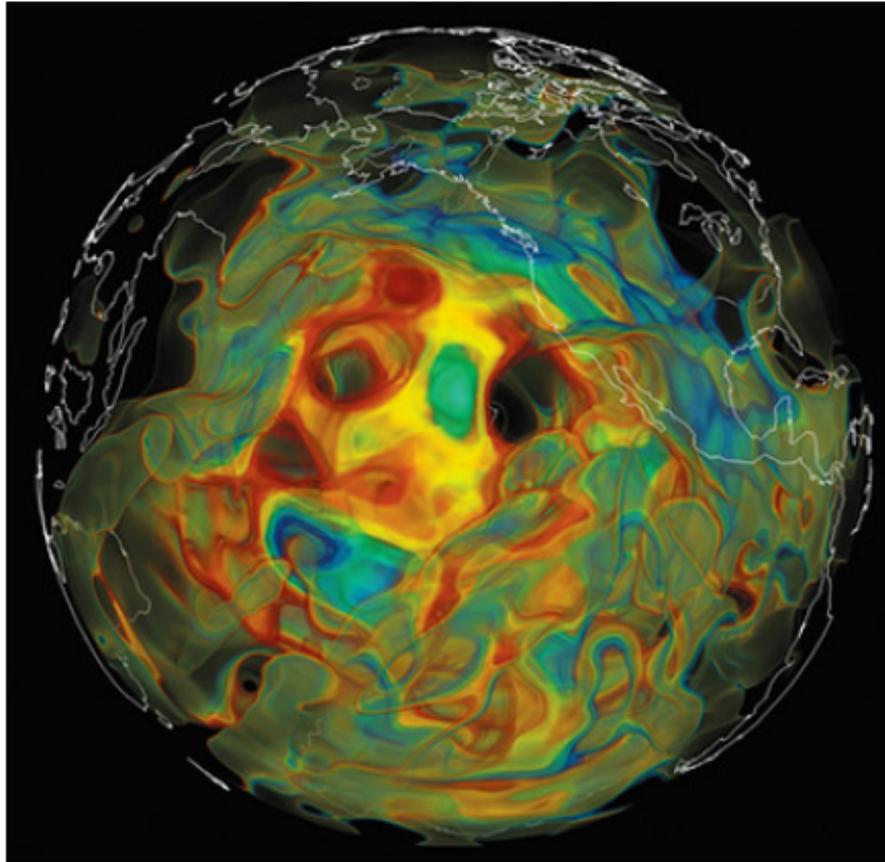
Outlook

Waiting for Km3Net, we make contact with the Antares Collaboration to include their data into our analysis

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

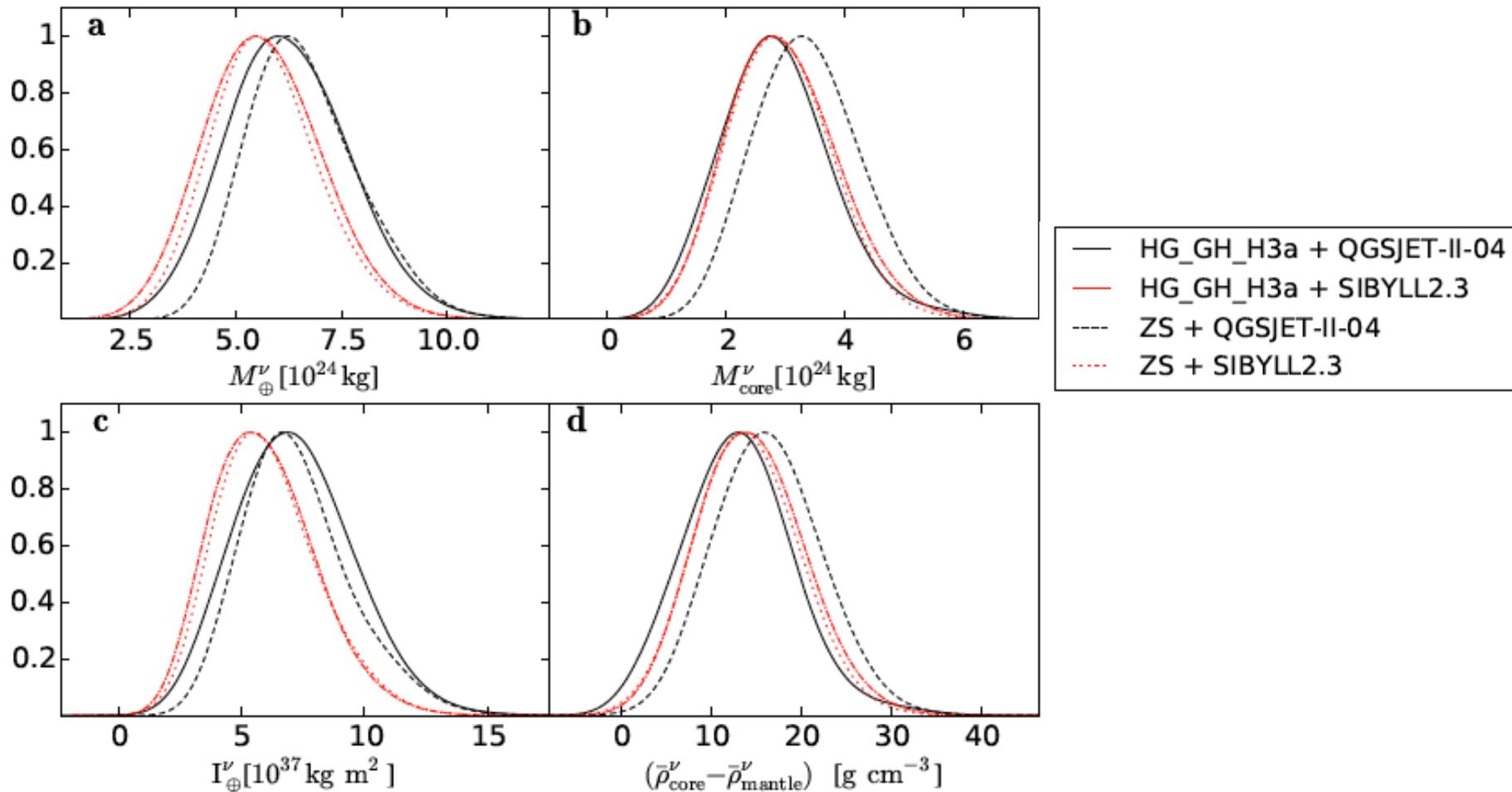
With a third detector (around the equator?) we could do
EARTH'S THREE-DIMENSIONAL ν -TOMOGRAPHY

State-of-art three-dimensional picture from seismology

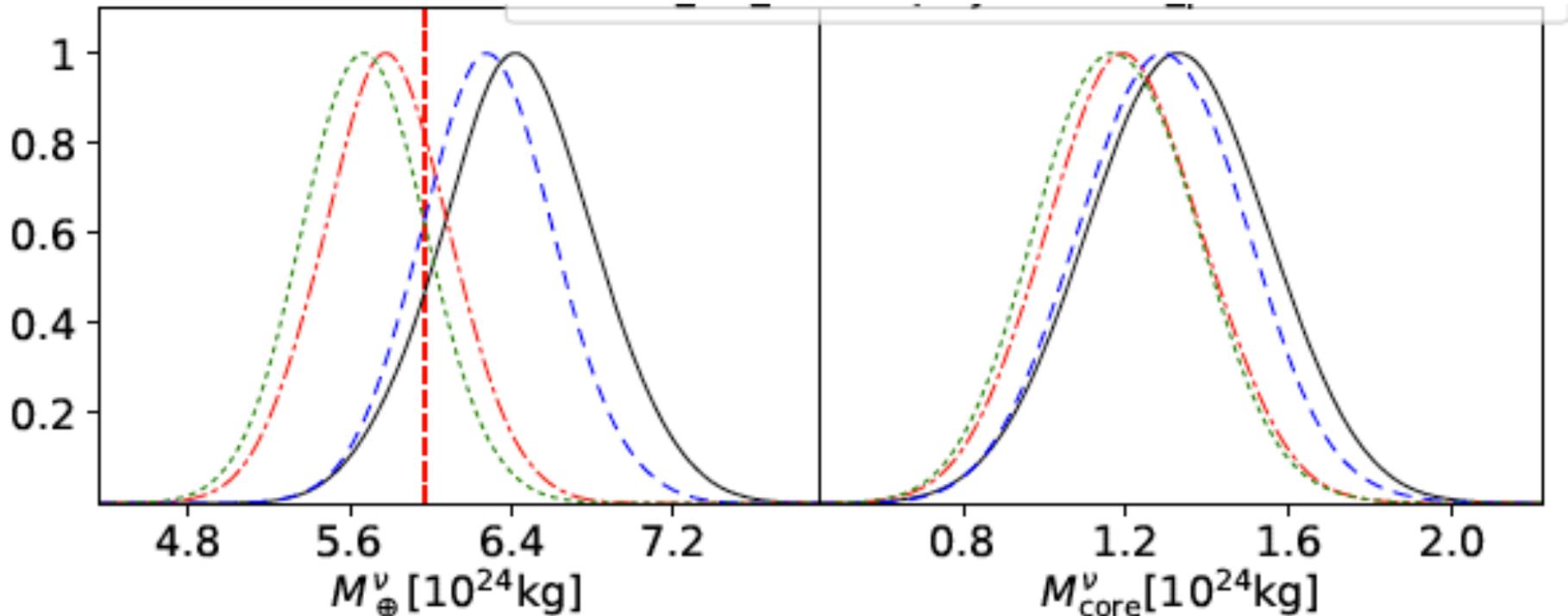


Backup slides

Flux and hadronic model dependence



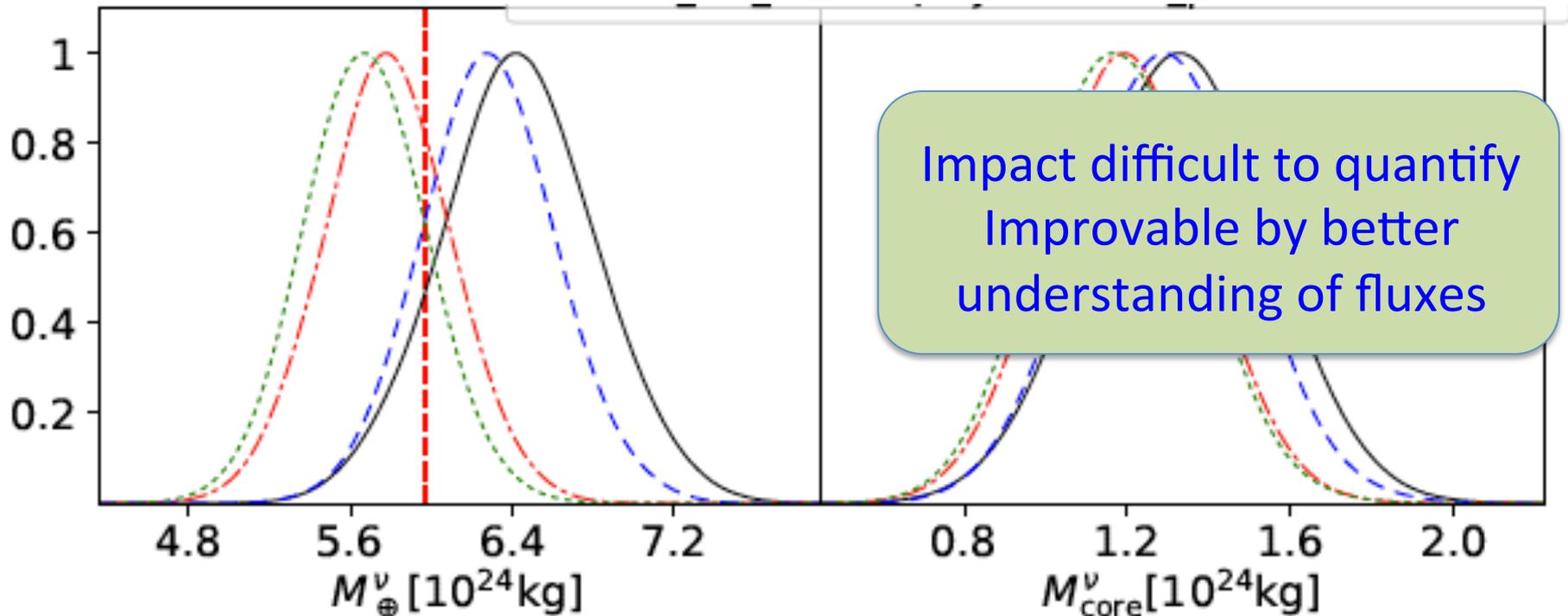
Flux and hadronic model dependence, 2



- GH_HG_H3a + QGSJET -> GH_HG_H3a + QGSJET
- - - GH_HG_H3a + QGSJET -> GH_HG_H3a + SIBYLL2.3
- - - GH_HG_H3a + QGSJET -> ZS_pamela + QGSJET
- - - GH_HG_H3a + QGSJET -> ZSa_pamela + SIBYLL2.3

Forecast for
10 years of MC data

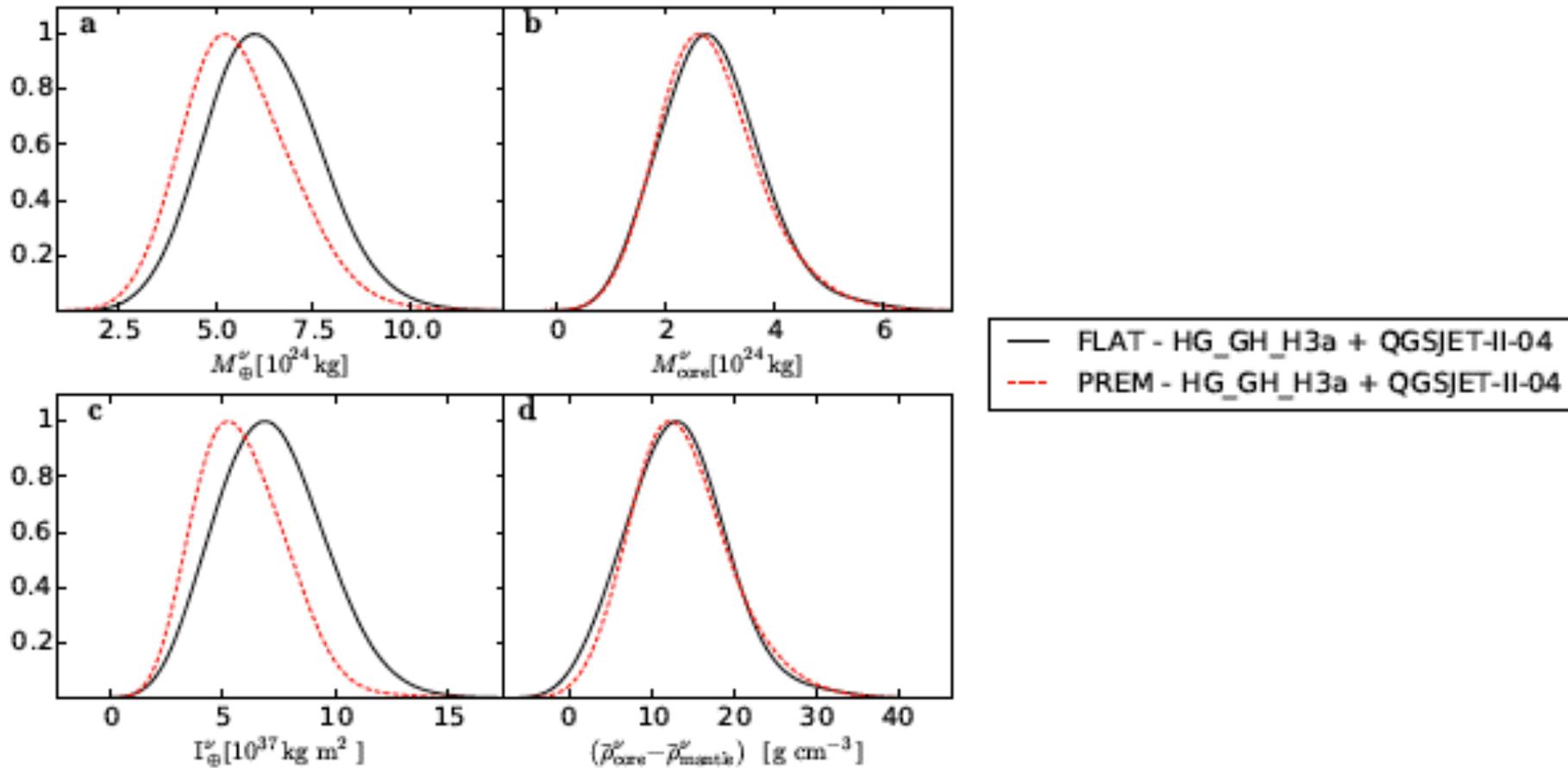
Flux and hadronic model dependence, 2



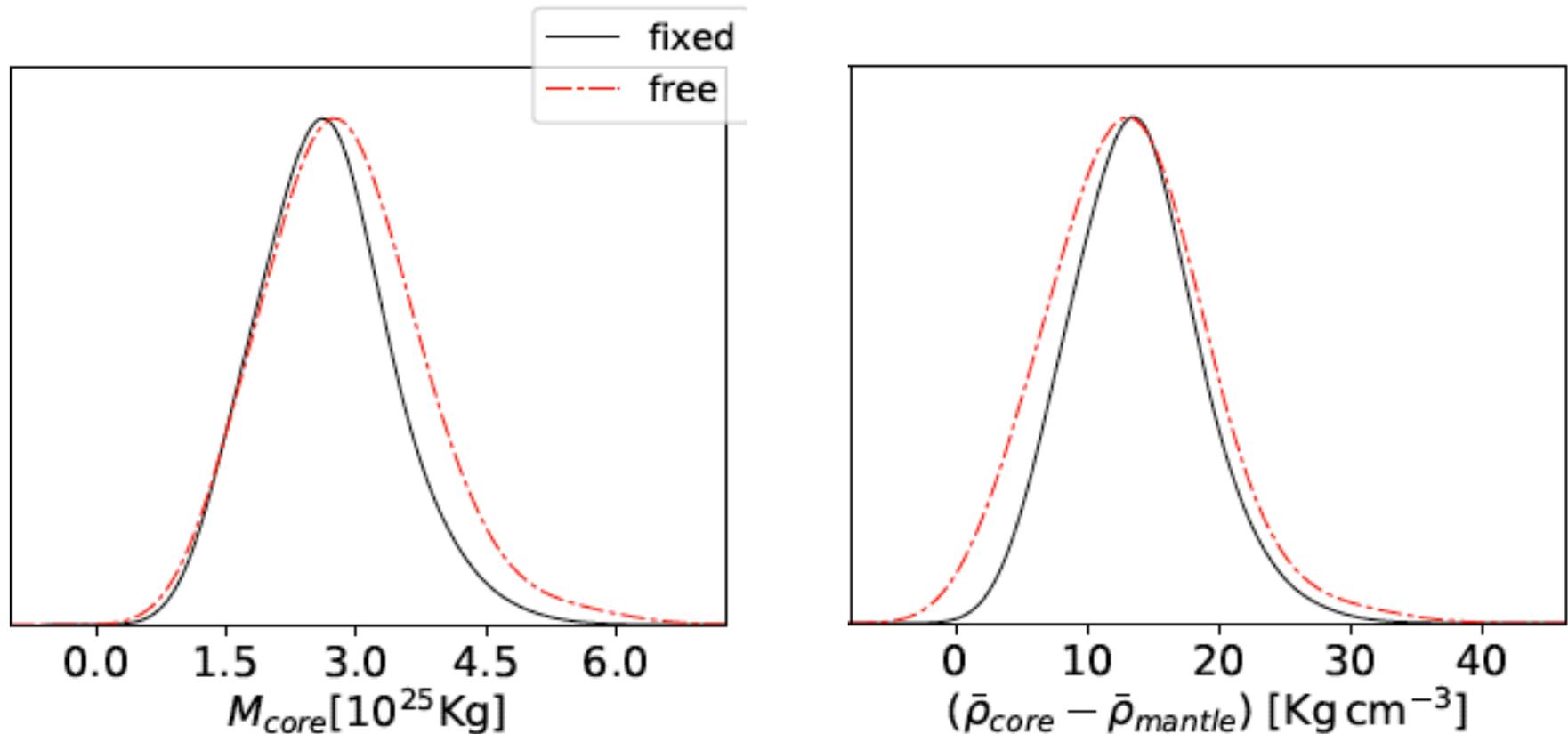
- GH_HG_H3a + QGSJET -> GH_HG_H3a + QGSJET
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- - - GH_HG_H3a + QGSJET -> ZSa_pamela + SIBYLL2.3

Forecast for
10 years of MC data

Earth's profile dependence



Impact of systematics on the error



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_{\oplus}^{ν} [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_{core}^{ν} [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_{\oplus}^{ν} [10^{37} kg cm ²]	6.9 ± 2.4	$5.4^{+2.3}_{-1.9}$	$6.7^{+2.3}_{-2.0}$	$5.5^{+2.2}_{-1.9}$	$5.3^{+2.3}_{-1.7}$
$\bar{\rho}_{\text{core}}^{\nu} - \bar{\rho}_{\text{mantle}}^{\nu}$ [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

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

- 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 $I_{\oplus}(\rho(r) = \rho_0) = 0.4 M_{\oplus} R_{\oplus}^2$.

Impact of constraints

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

$$\rho_5 = [1.22-4.78] \text{ g/cm}^3 \rightarrow [4.43-4.79] \text{ g/cm}^3$$

Rather small impact on the core density, instead:

$$\rho_{\text{core}} = [10.2-20.8] \text{ g/cm}^3 \rightarrow [9.7-18.6] \text{ g/cm}^3$$