Earth tomography with neutrinos

Sergio Palomares Ruiz

IFIC, CSIC-U. Valencia

Based on A. Donini, **SPR** and J. Salvado, *Nature Physics 15:37, 2019*

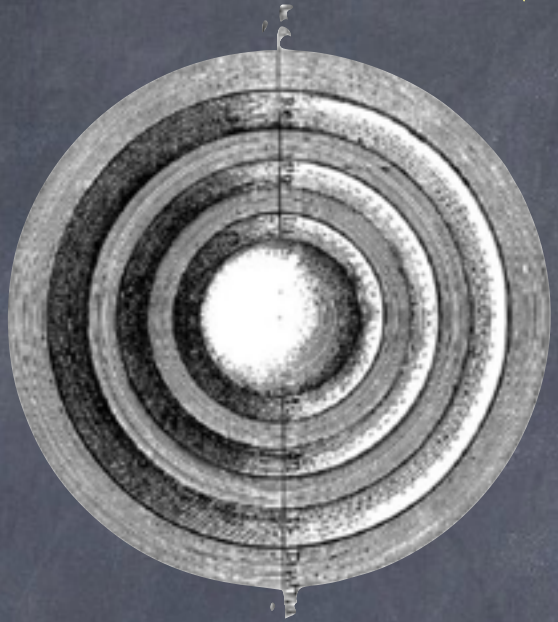
4th Uppsala workshop on
Particle Physics with Neutrino Telescopes

October 9, 2019

The Earth's interior: Early (crazy) ideas

First hypothesis based on observations: Hollow Earth

E. Halley, 1692



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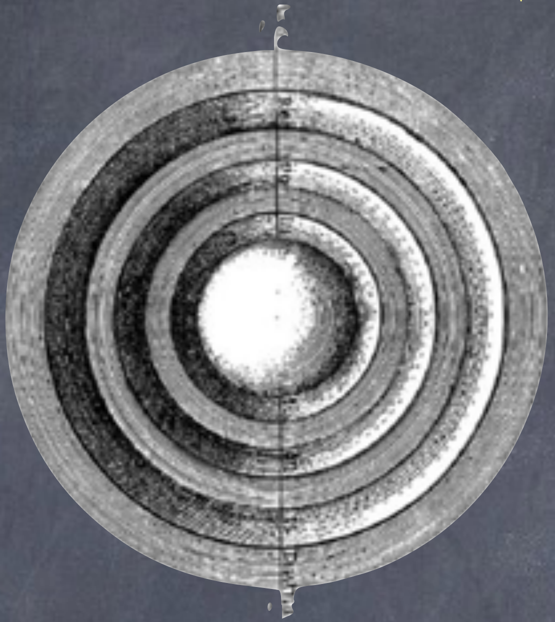

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… and then even crazier ideas…

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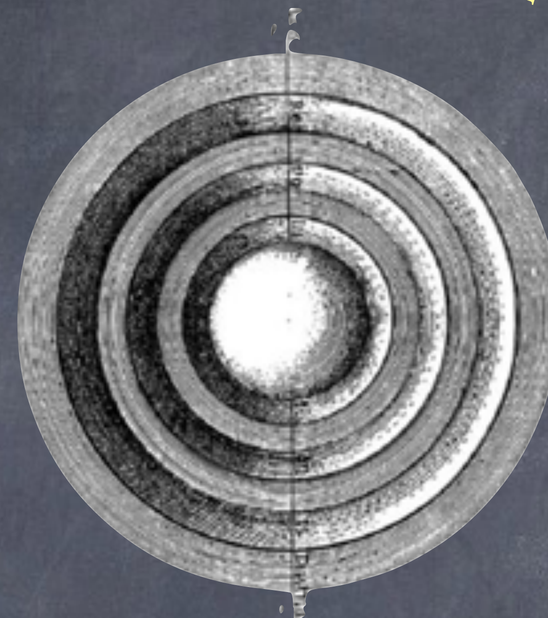

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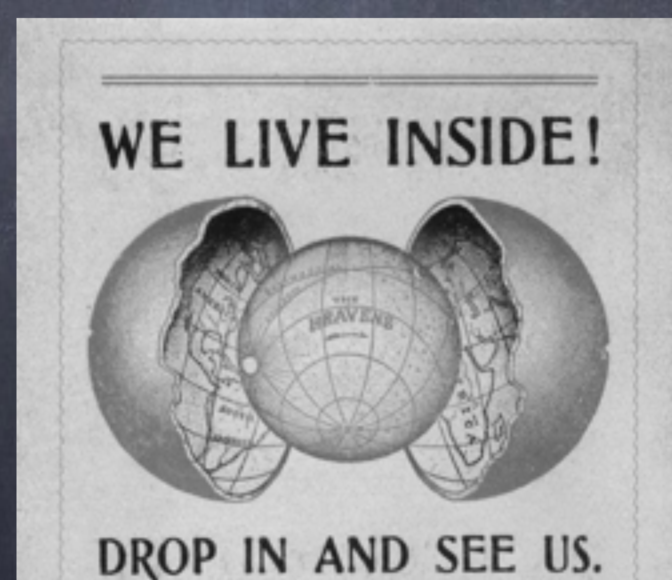

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W. Reed, The phantom of the poles, 1906

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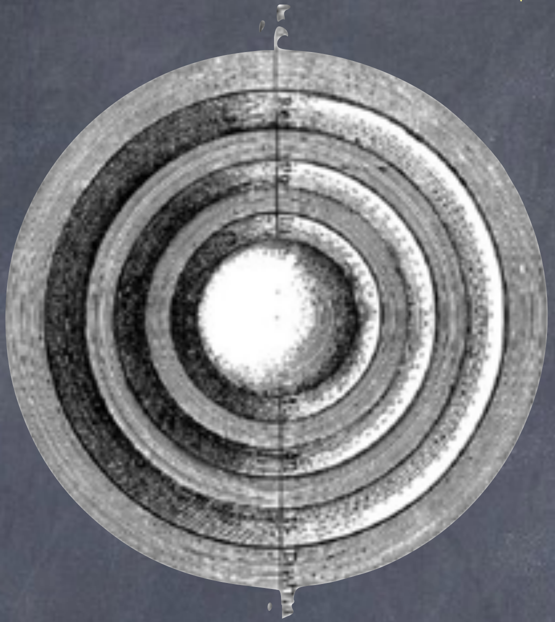

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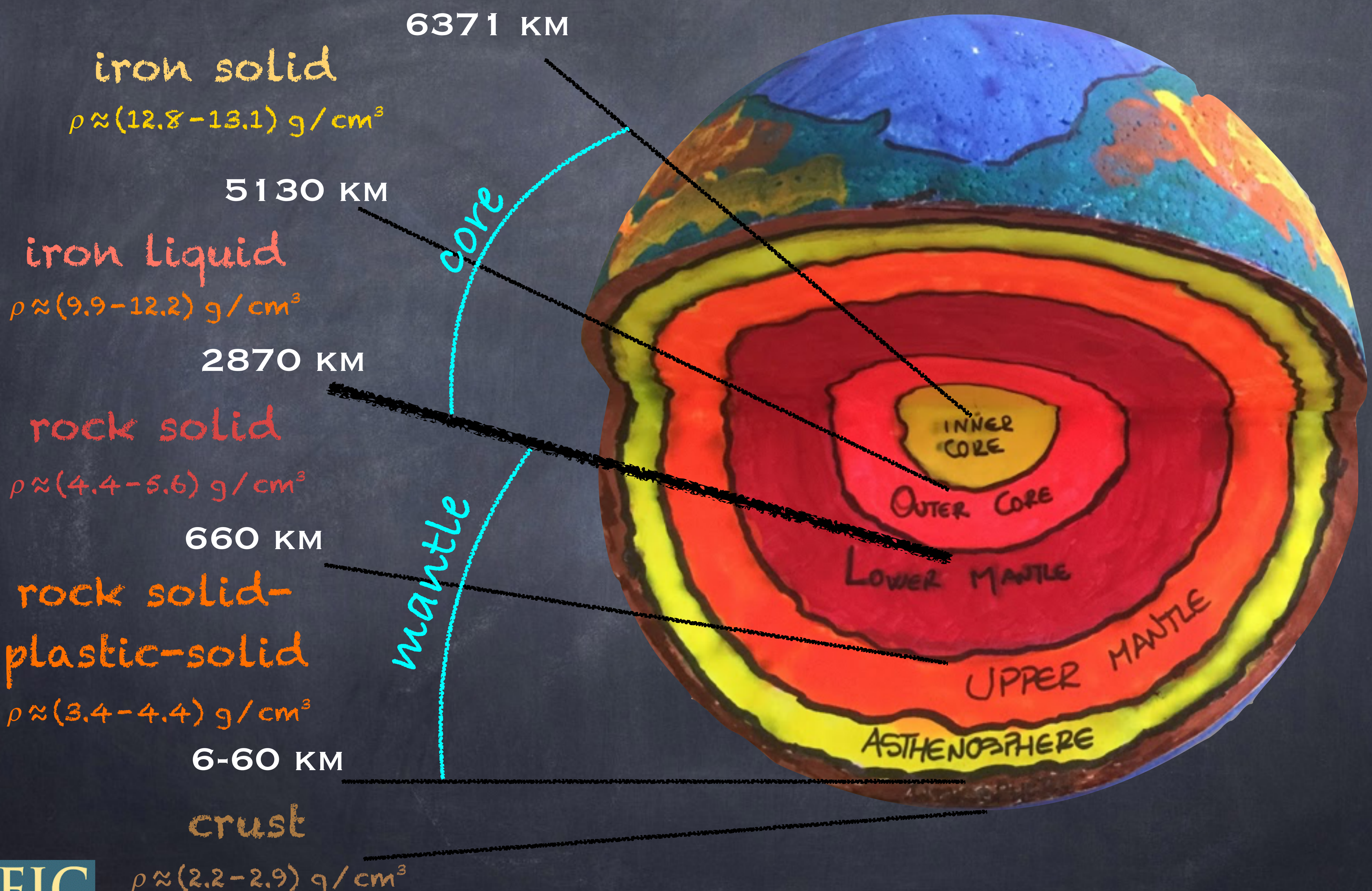
GLOBE SHOWING SECTION OF THE EARTH'S INTERIOR

The earth is hollow. The poles so long sought are but phantoms. There are openings at the northern and southern extremities. In the interior are vast continents, oceans, mountains and rivers. Vegetable and animal life are evident in this new world, and it is probably peopled by races yet unknown to the dwellers upon the earth's exterior.

THE AUTHOR.

W. Reed, The phantom of the poles, 1906

The Earth's interior: The modern view

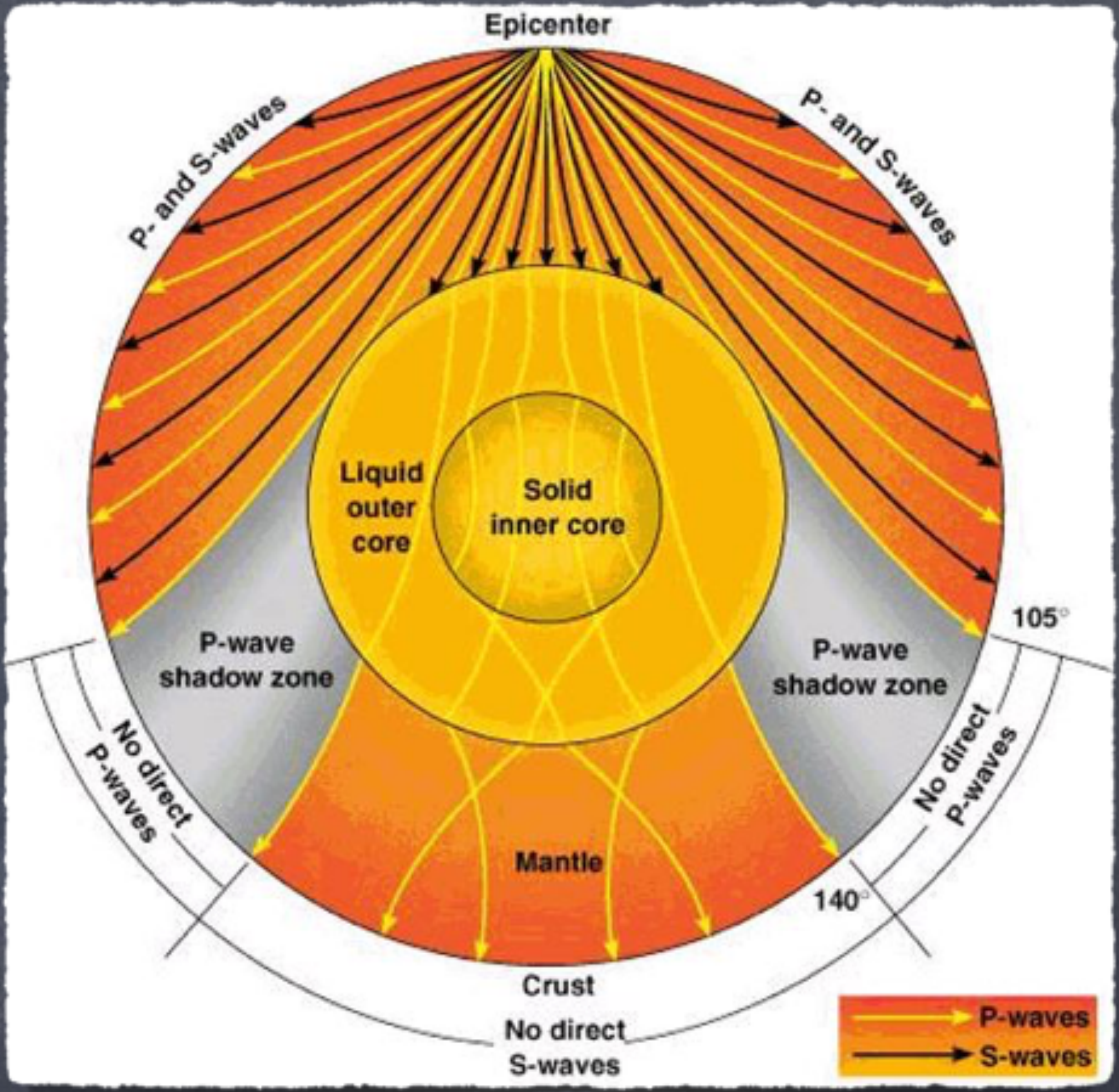


The Earth's interior: how is it inferred?

Earthquakes:

O(100/yr) with magnitude > 6

Shaking and trembling of Earth's surface caused by sudden release of stress within the crust



Seismic waves:

P-waves -> compressional: travel through liquids and solids

S-waves -> shear: travel through solids only

propagation depends on composition, temperature and pressure

The Earth's mass and moment of inertia: gravitational measurements

GM: satellite laser ranging (SLR)

Measures the gravity field

$$GM = 3.986004418(4) \times 10^{14}\ \mathrm{m^3 s^{-2}}$$

J. C. Ries, Geophys. Res. Abs. 9:10809, 2007

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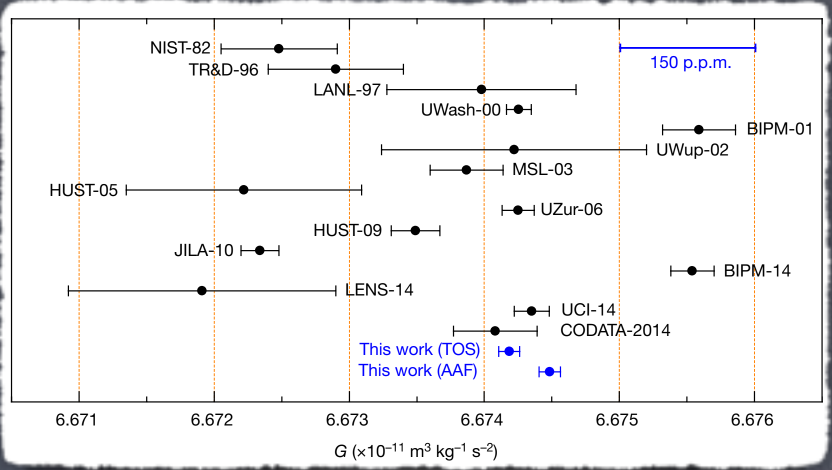

G: variations of the Cavendish experiment

$$G = 6.67408(31)\times10^{-11}\ kg^{-1} m^3 s^{-2}$$

P. J. Mohr, D. B. Newell and B. N. Taylor, CODATA-2014, Rev. Mod. Phys. 88:035009, 2016

Q. Li et al., Nature 560:582, 2018

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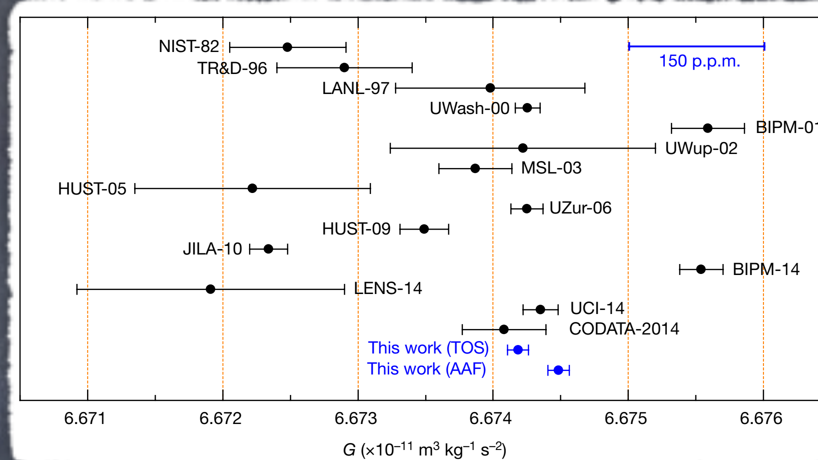

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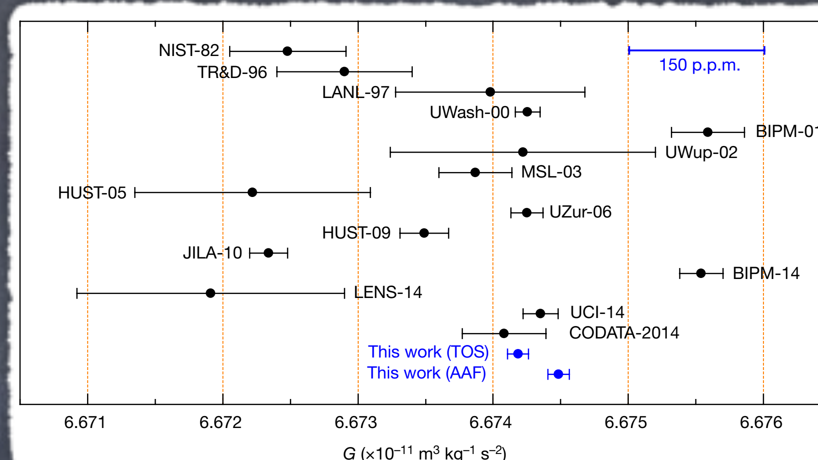

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Earth gravity model: terrestrial, altimetry-derived and airborne gravity data

$$I = 8.01736(96) \times 10^{37}\ \mathrm{kg\, m^2}$$

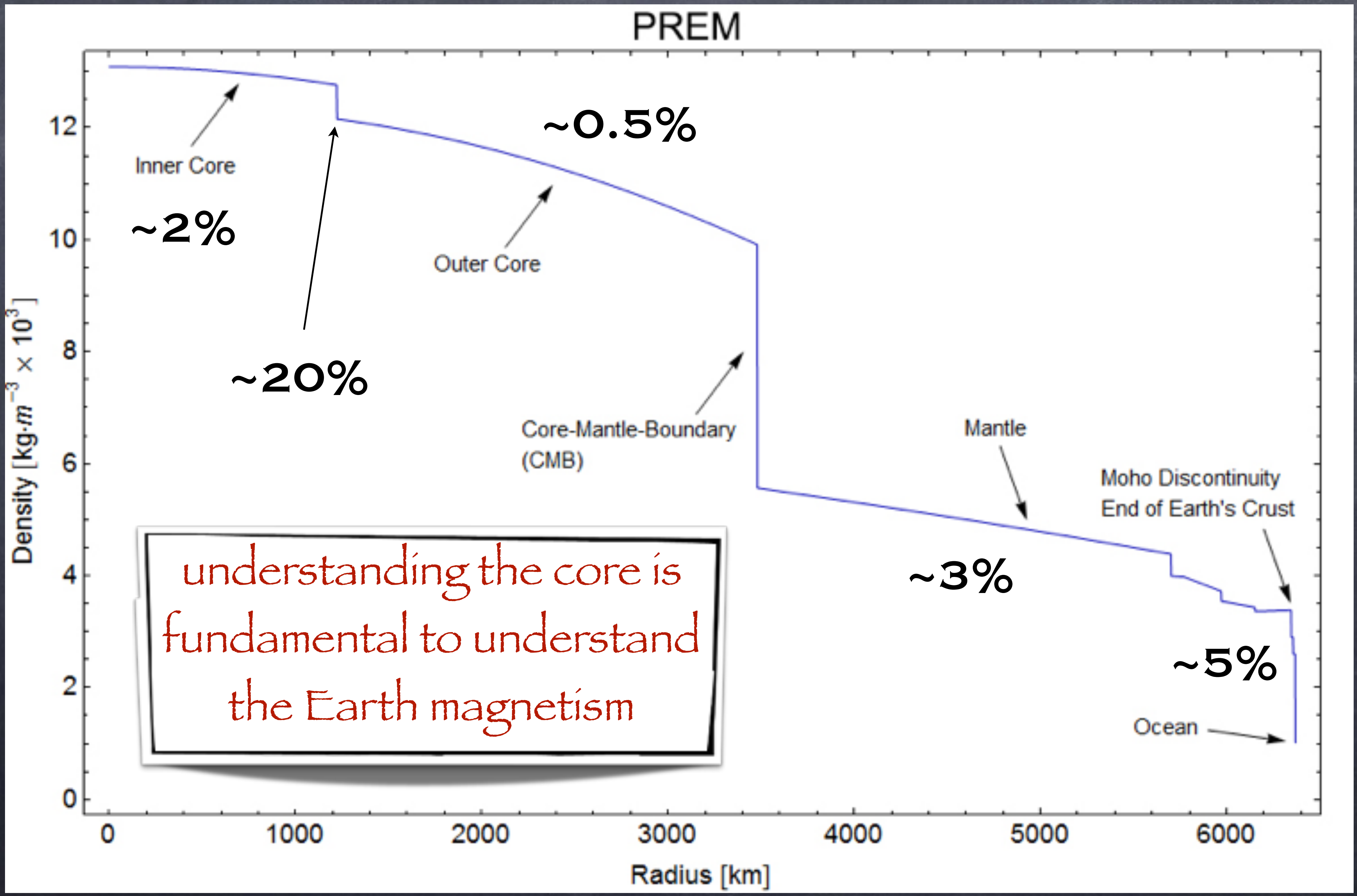
W. Chen et al., J. Geod. 89:179, 2015

Preliminary reference Earth Model (PREM)

A. M. Dziewonski and D. L. Anderson, Phys, Earth Planet. Inter. 25:297, 1981

1-D density profile

From seismic wave data and imposing the Earth's radius, mass and moment of inertia as additional constraints



understanding the core is fundamental to understand the Earth magnetism

Is there any other way to study the Earth's internal structure beyond seismic waves and gravitational measurements?

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Yes!

Weak interactions: Neutrinos!

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Old idea: First mentioned in...

a 1973 CERN report

A. Placci and E. Zavattini, submitted in October 1973 to Nuovo Cimento... but never published

and a 1974 talk

L. V. Volkova and G. T. Zatsepin, Izv. Akad. Nauk. Ser. Fiz. 38N5:1060, 1974

Using man-made neutrino beams

Review: W. Winter, Earth Moon Planets 99:285, 2006

oscillation tomography

Man-made beams

V. K. Ermilova, V. A. Tsarev and V. A. Chechin, JETP Lett. 43:453, 1986

Solar neutrinos

A. N. Ioanissian and A. Smirnov, hep-ph/0201012

Supernova neutrinos

E. K. Akhmedov, M. A. Tórtola and J. W. F. Valle, JHEP 0506:053, 2005

Atmospheric neutrinos

S. K. Agarwalla, T. Li, O. Mena and SPR, arXiv:1212.2238

Coherent effect in neutrino propagation

$$\frac{d\phi_\nu(E_\nu,x)}{dx} = -i\left(U\, H_{vac}\, U^\dagger + V_m\right)\phi_\nu(E_\nu,x)$$

$$P_{2\nu}\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta^m \sin^2\left(\frac{\Delta^m L}{4E}\right)$$

$$\Delta^m = \sqrt{\left(\Delta m^2 \cos 2\theta \mp 2EV\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

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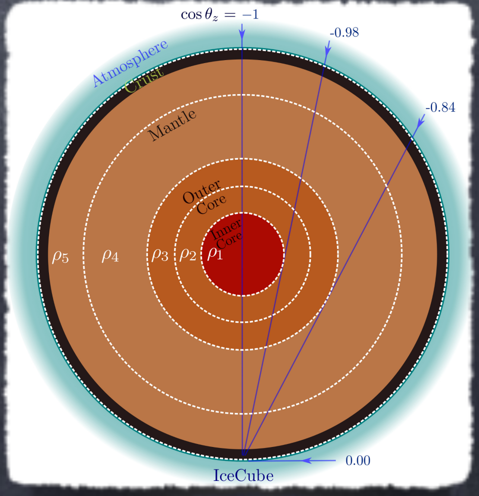

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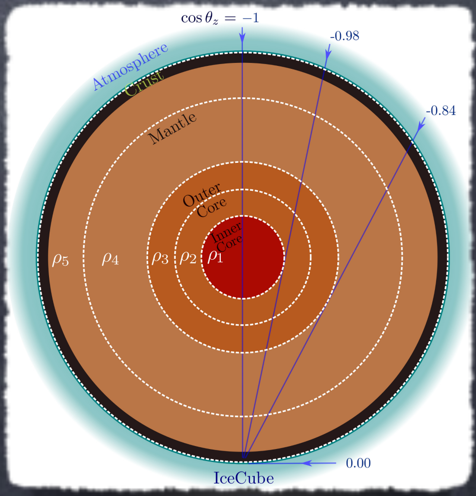

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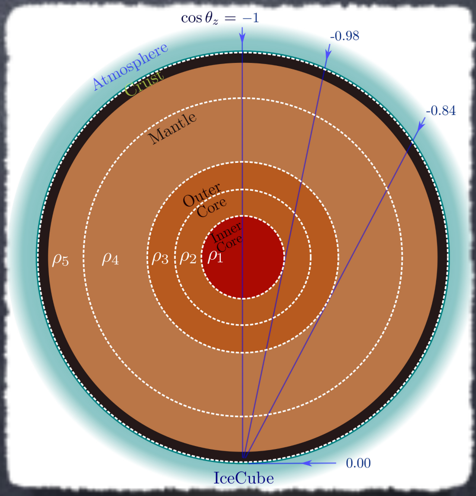


diffraction

Coherent effect: Unfeasible

A. D. Fortes, I. G. Wood and L. Oberauer, Astron. Geophys, 47:5.31, 2006

Atmospheric neutrinos

$$p + X \to \pi^\pm / K^\pm + Y$$

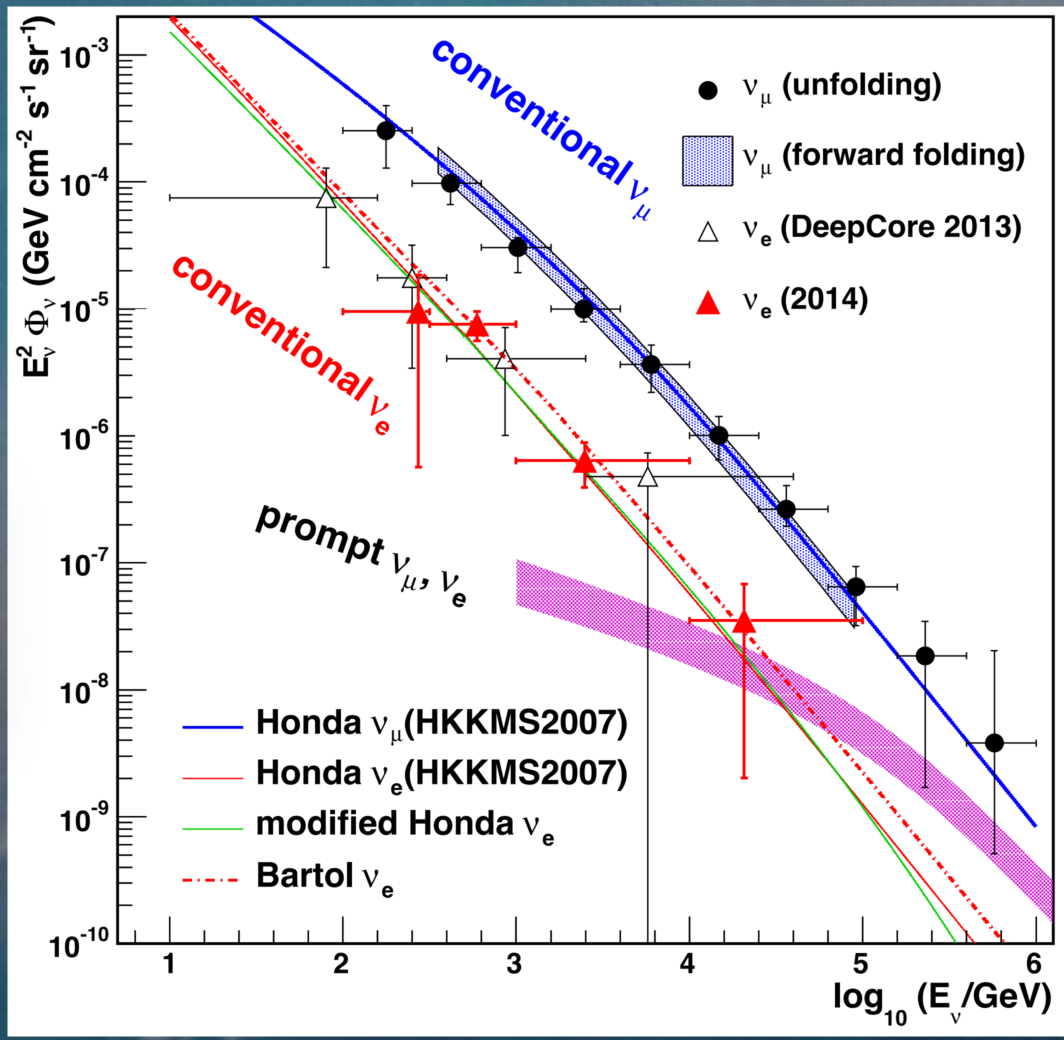
$$\mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

$$e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

Huge range of energies and baselines

E < 100 TeV

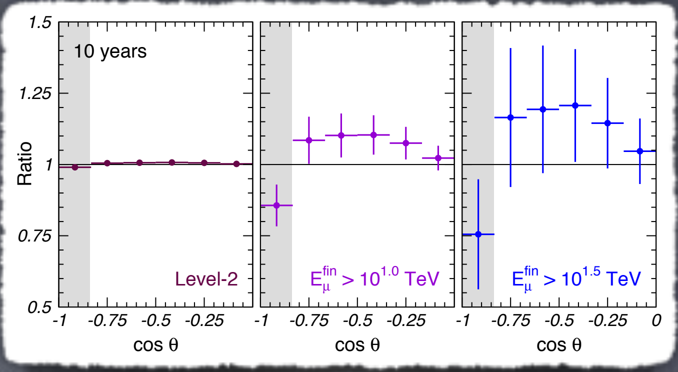
$$n\sigma \sim \left(\frac{E}{40\,\text{TeV}}\right) R_\oplus^{-1}$$



M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. D91:122004, 2015

Previous studies

First forecast of absorption neutrino tomography using atmospheric neutrinos (for IceCube)



M. C. González-García, F. Halzen, M. Maltoni and H. K. M. Tanaka, Phys. Rev. Lett. 100:061802, 2008

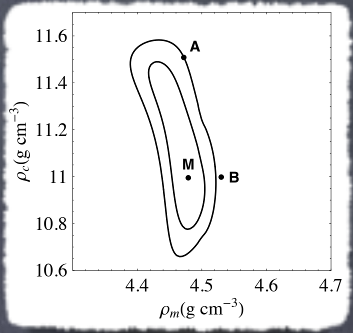
Non-homogeneity at (3.4-4.7)σ after 10 years

First forecast for KM3NeT

E. Borriello et al., JCAP 0906:030, 2009

E. Borriello et al., Earth Planets Space 62:211, 2010

few percent error after 10 years



Study of lateral heterogeneities (with IceCube)

Needs ~300 years

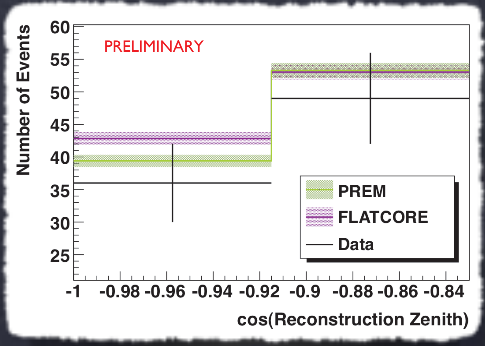
N. Takeuchi, Earth Planets Space 62:215, 2010

Another study of Earth non-homogeneity (with IceCube)

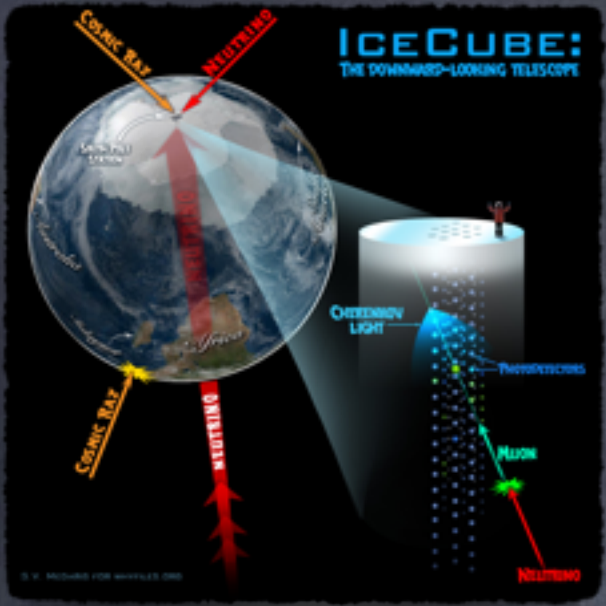
I. Romero and O. A. Sampayo, Eur. Phys. J. C71:1696, 2011

First attempt using 1 year of IC-40 data

K. Hoshina and H. K. M. Tanaka, Poster at Neutrino 2012



IceCube data set



1 year of up-going high-energy muon neutrino events (IC86)

used and prepared for the IC sterile neutrino analysis

M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 117:071801, 2016

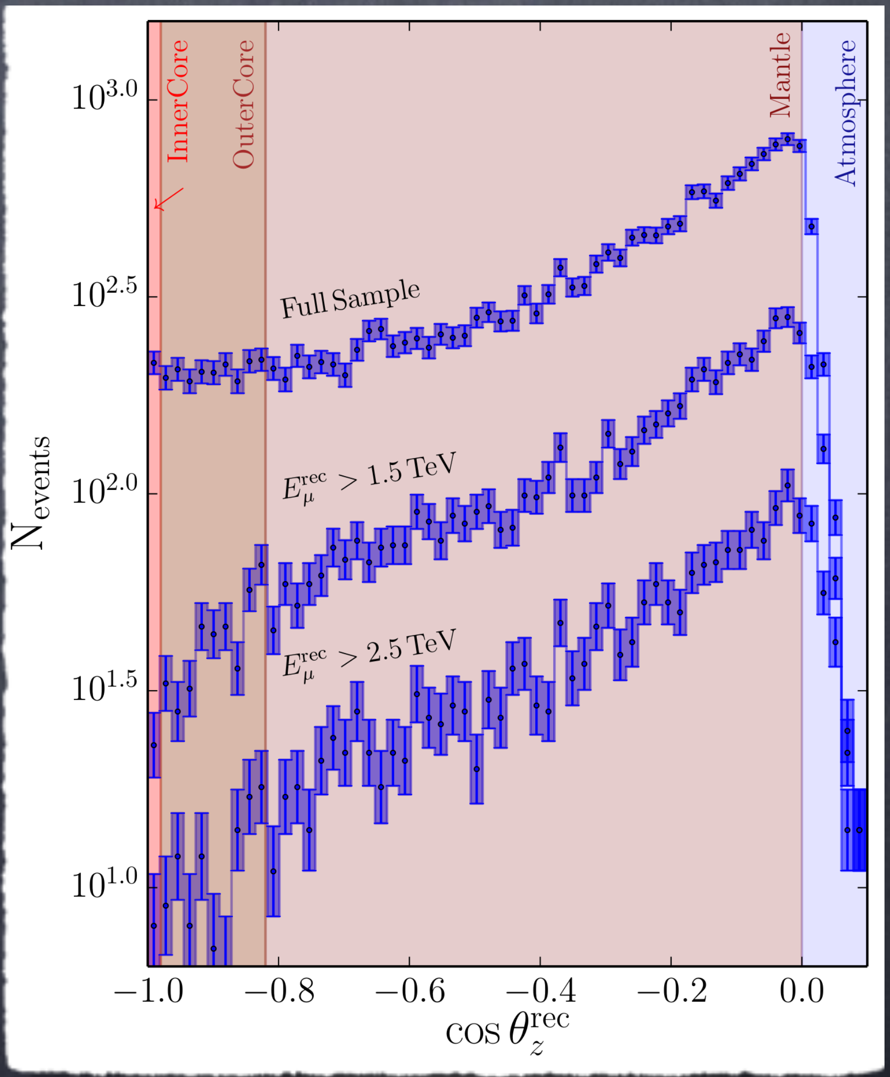
Energy range: ~ 400 GeV - 20 TeV

Zenith angle range: cos θ = [-1, 0.2]

Number of events: 20145 (343.7 days)

>99.9% muon neutrino purity

Publicly available!



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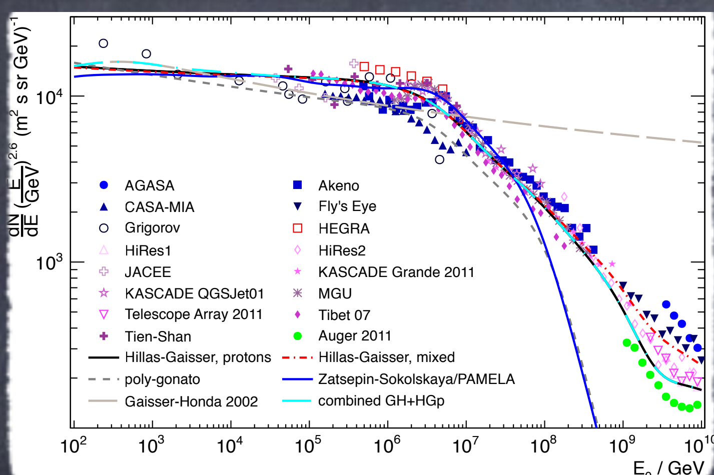
Analysis ingredients

Primary cosmic-ray spectrum

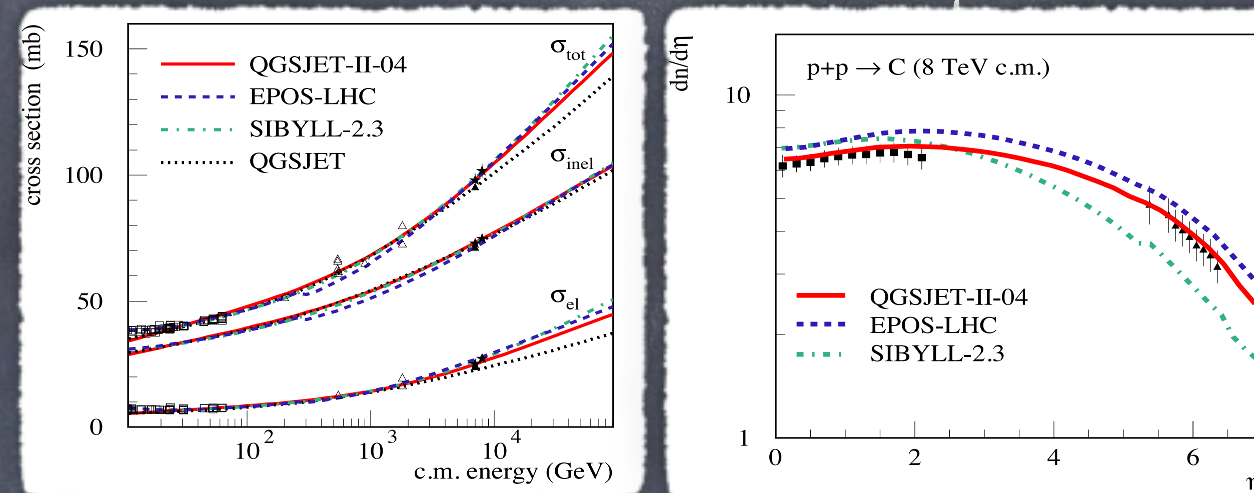
3-population models to fit cosmic-ray data



A. Fedynitch, J. B. Tjus and P. Desiati, Phys. Rev. D86:114024, 2012

Hadronic-interaction model

Models for cascade development



S. Ostapchenko, ECRS 2016, arXiv:1612.09461

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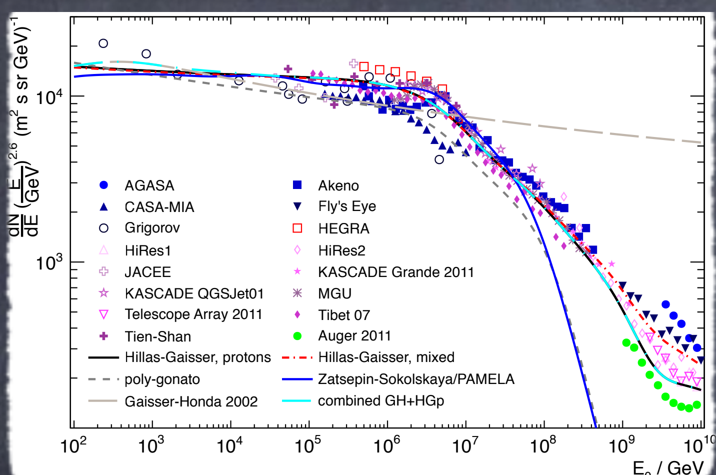

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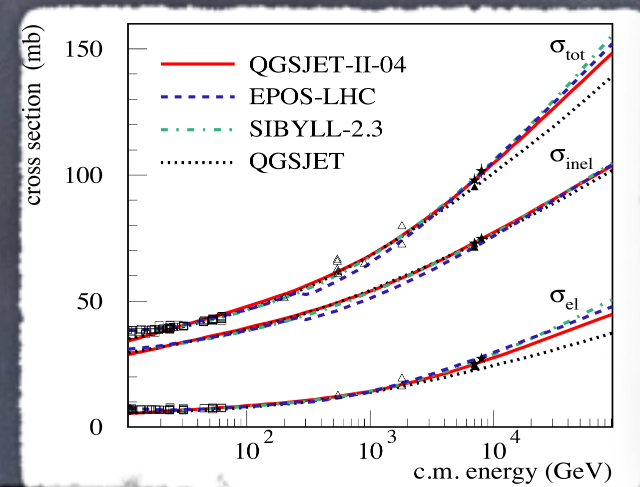
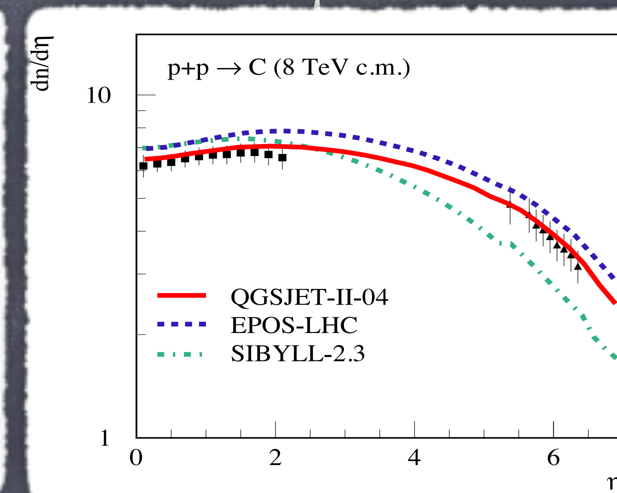
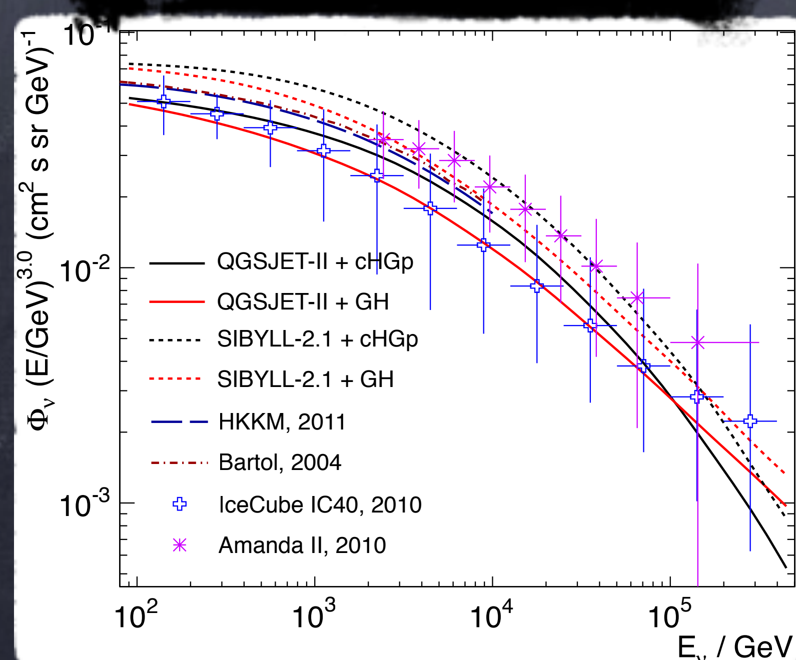




S. Ostapchenko, ECRS 2016, arXiv:1612.09461

Neutrino flux



A. Fedynitch, J. B. Tjus and P. Desiati, Phys. Rev. D86:114024, 2012

Analysis ingredients

Neutrino propagation through the Earth

we propagate neutrinos with ν-SQuIDS

C. Argüelles, J. Salvado and C. Weaver, https://github.com/arguelles/nuSQuIDS

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Neutrino propagation through the Earth

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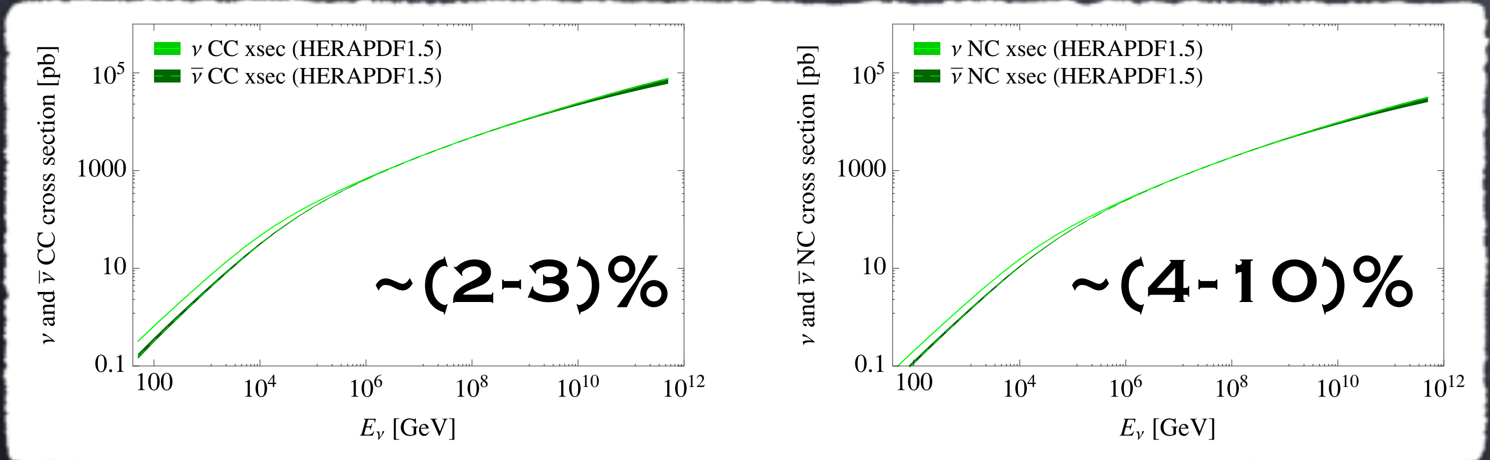
Neutrino interactions with nucleons



A. Cooper-Sarkar, P. Mertsch and S. Sarkar, JHEP 1108:042, 2011

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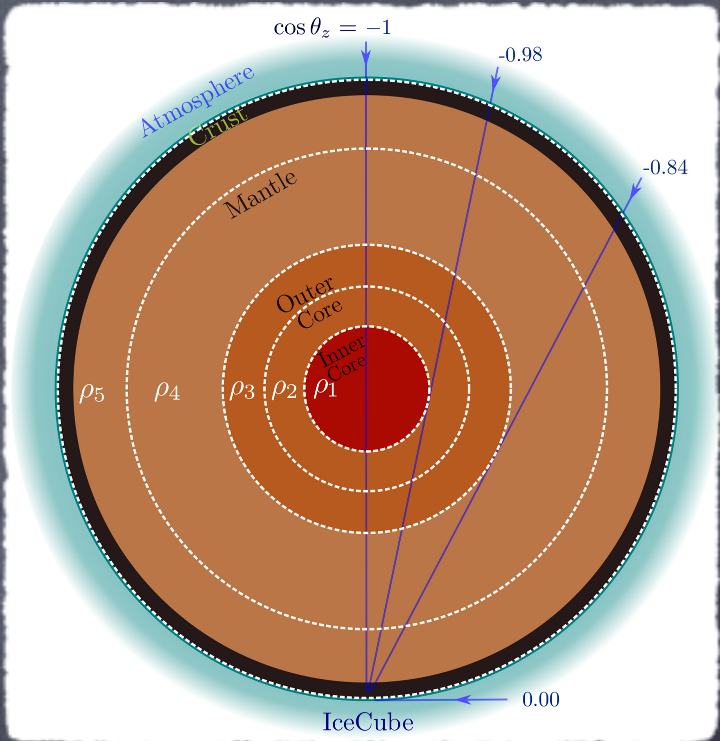
Earth model



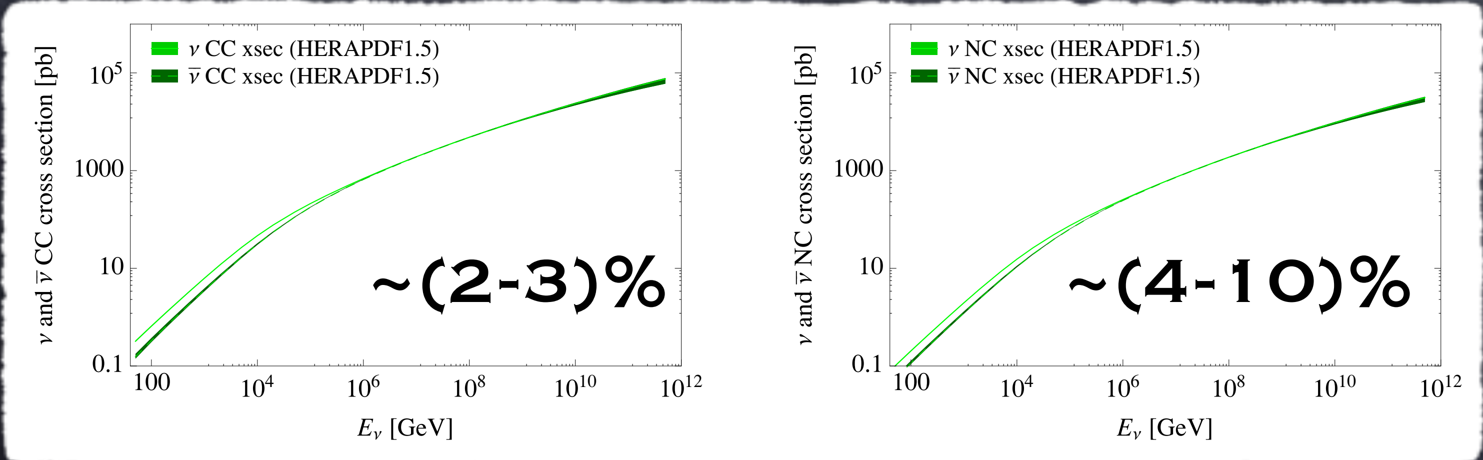
5 spherical layers:

1 for the inner core

2 for the outer core

2 for the mantle

Neutrino interactions with nucleons



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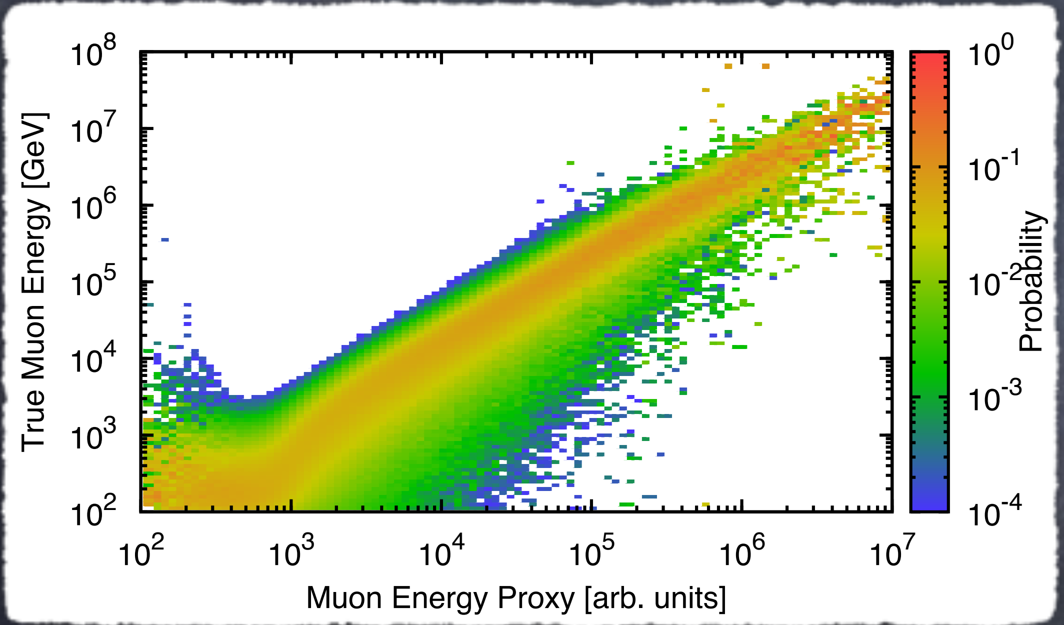
Analysis ingredients

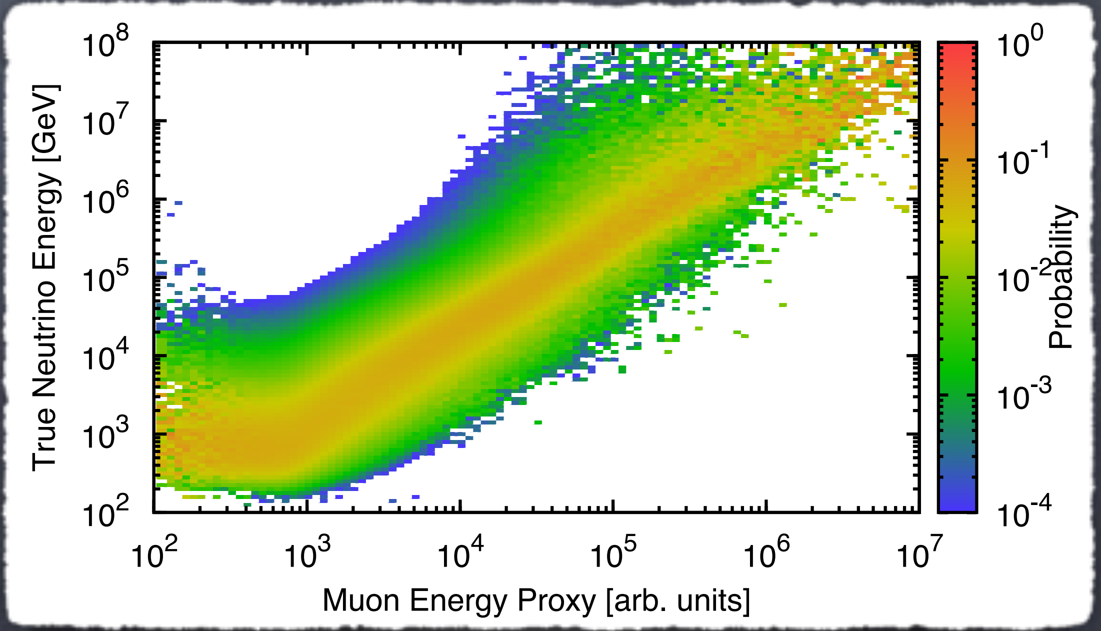
Detector simulation

Publicly available!

We map E_ν and θ_ν to E_{rec} and θ_{rec} using the official IceCube Monte Carlo

https://icecube.wisc.edu/science/data/IC86-sterile-neutrino





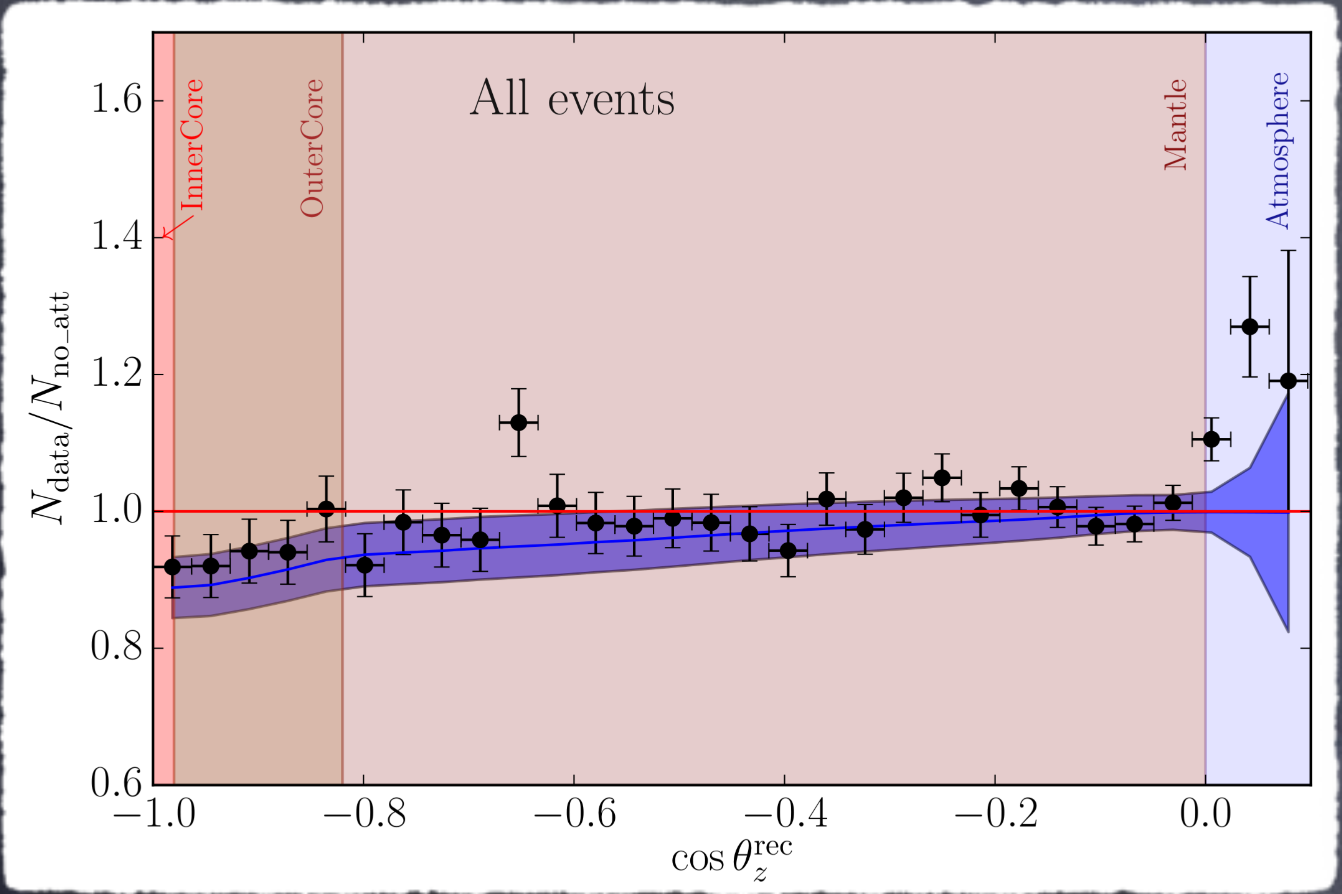
M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 115:081102, 2015

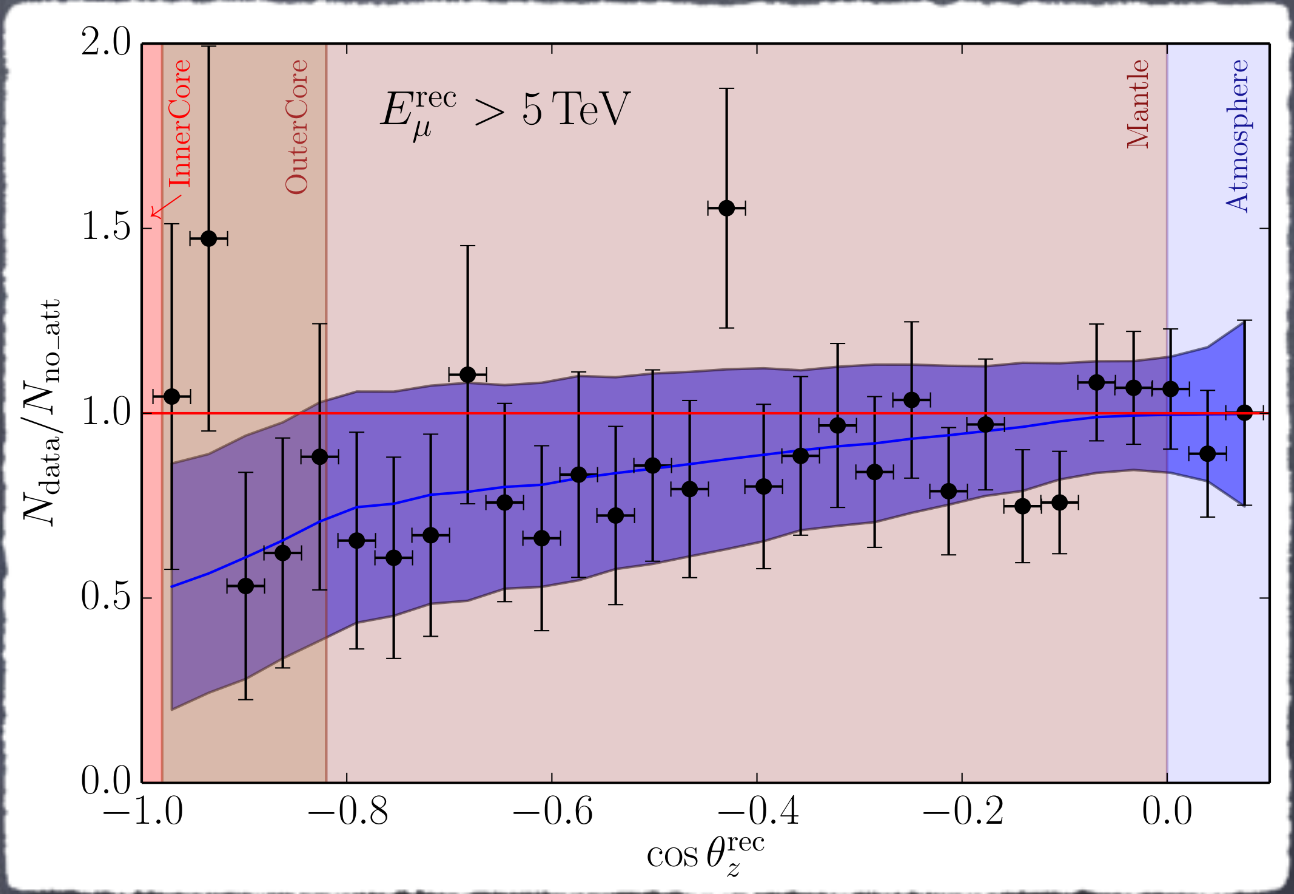
$\sigma_{\log(E_\mu/\mathrm{GeV})} \sim 0.5$ $\quad$ $\sigma_{\cos(\theta)} \sim 0.005 - 0.015$

Is the Earth there?

All events

E > 5 TeV





A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

Full sample:
useful to fix normalization

core-crossing neutrinos:
attenuation can be 50% (>5 TeV)

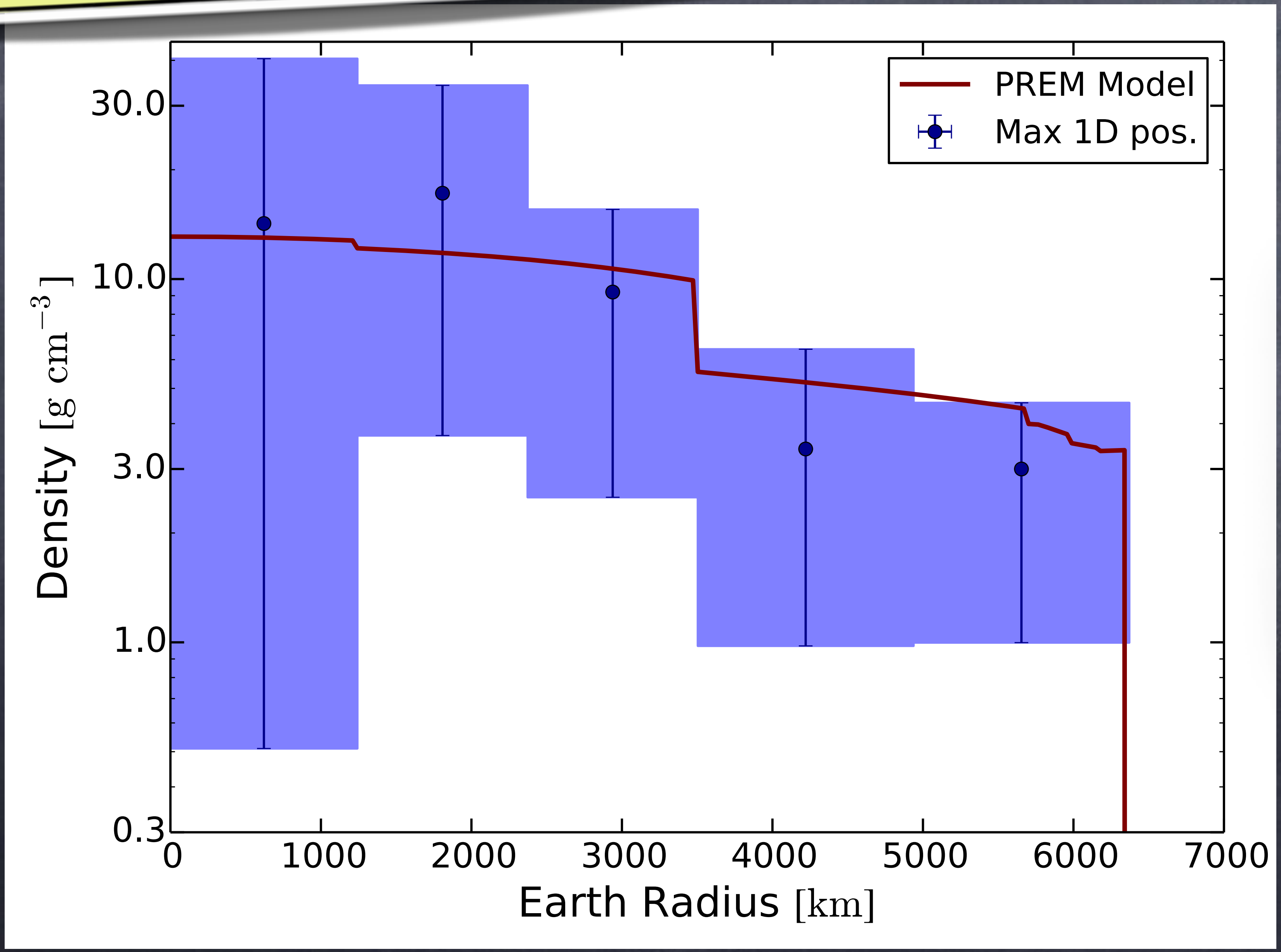
Main result: 1-D density profile

First Earth tomography with neutrinos!

nature physics

Neutrino tomography of Earth

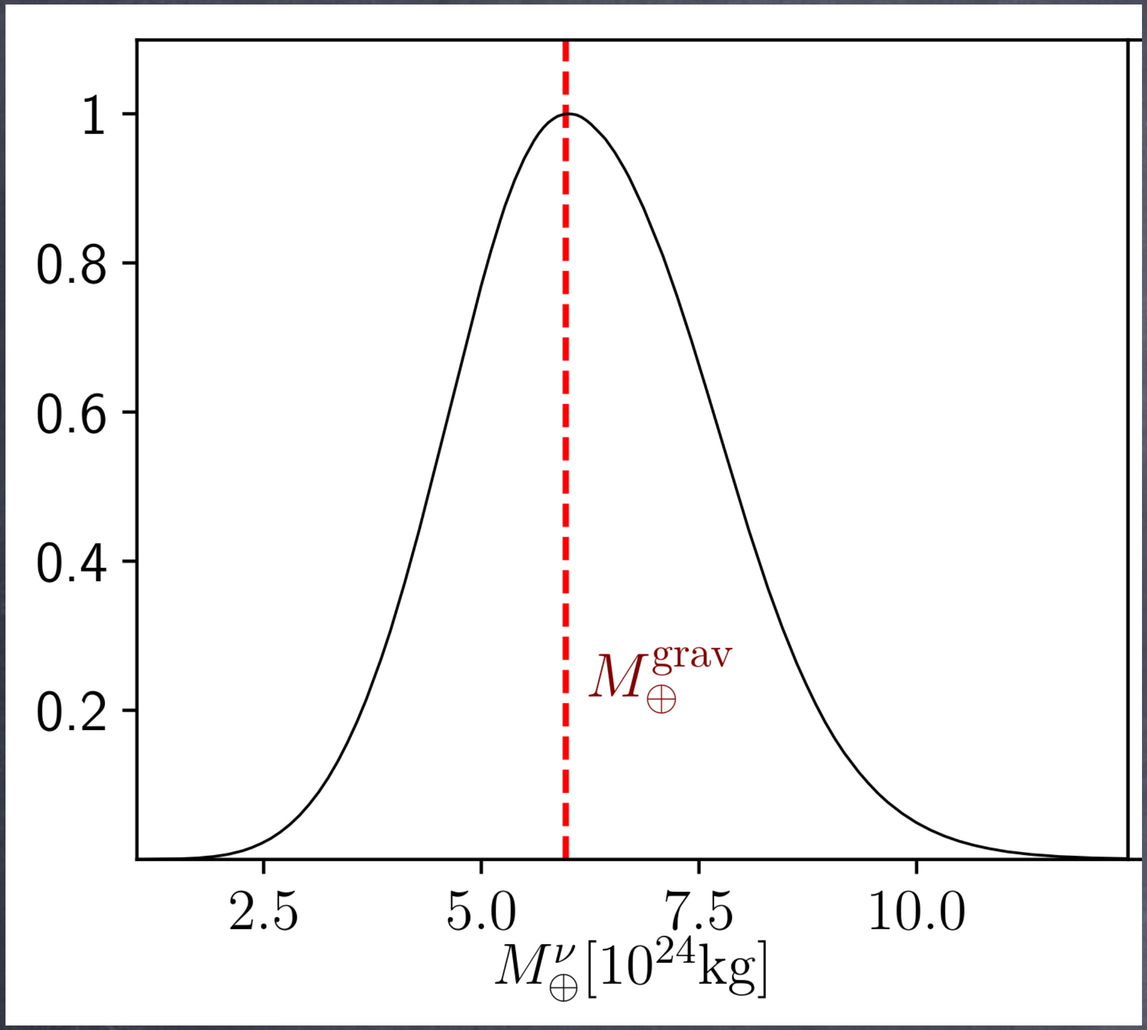
Andrea Donini [1], Sergio Palomares-Ruiz [1*] and Jordi Salvado [1,2]



unlike reconstructions with seismic data, NO constraint on the Earth mass or moment of inertia

A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

Earth's mass



A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

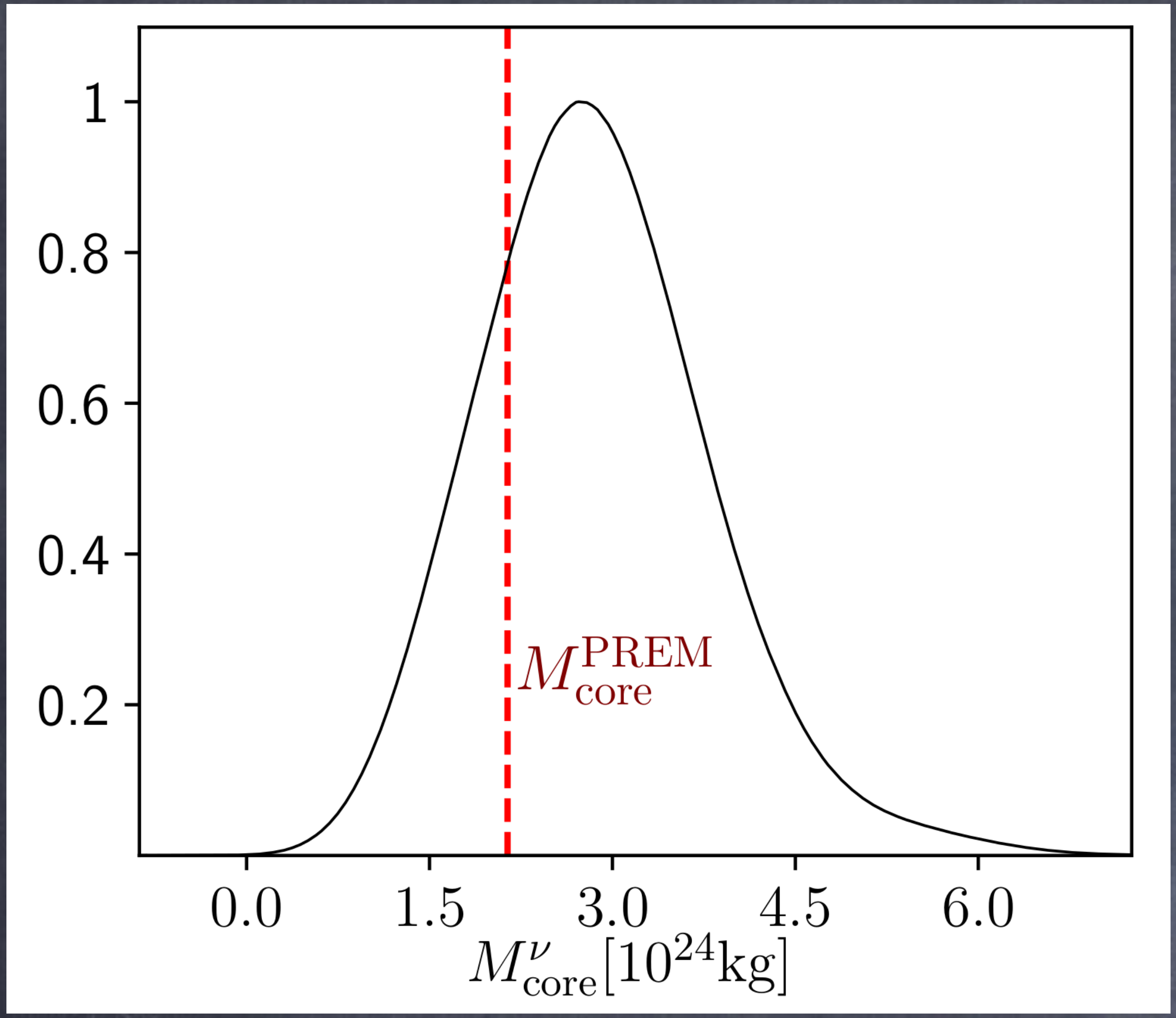
First measurement of the Earth's mass using the weak force!

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

Gravitational measurement

$$M_{grav} = 5.9724(3) \times 10^{24}\ \mathrm{kg}$$

Earth's core mass



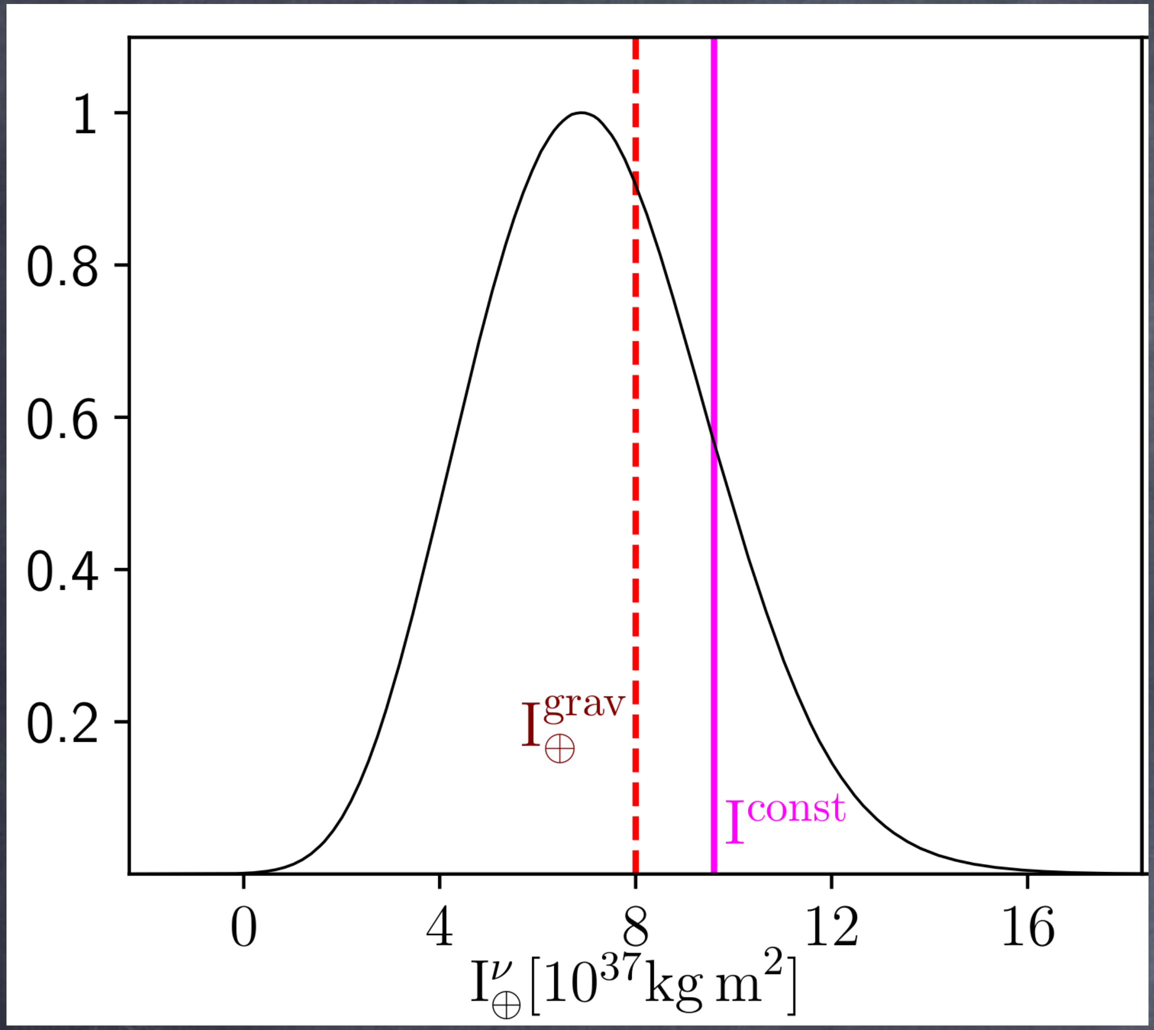
A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

First measurement of the Earth's core mass using the weak force!

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

$$\frac{M_{\text{core-}\nu}}{M_\nu} = 0.45^{+0.21}_{-0.18}$$

Earth's moment of inertia



A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

First measurement of the Earth's moment of inertia using the weak force!

$$I_\nu = (6.9 \pm 2.4) \times 10^{37}\ \mathrm{kg\,m^2}$$

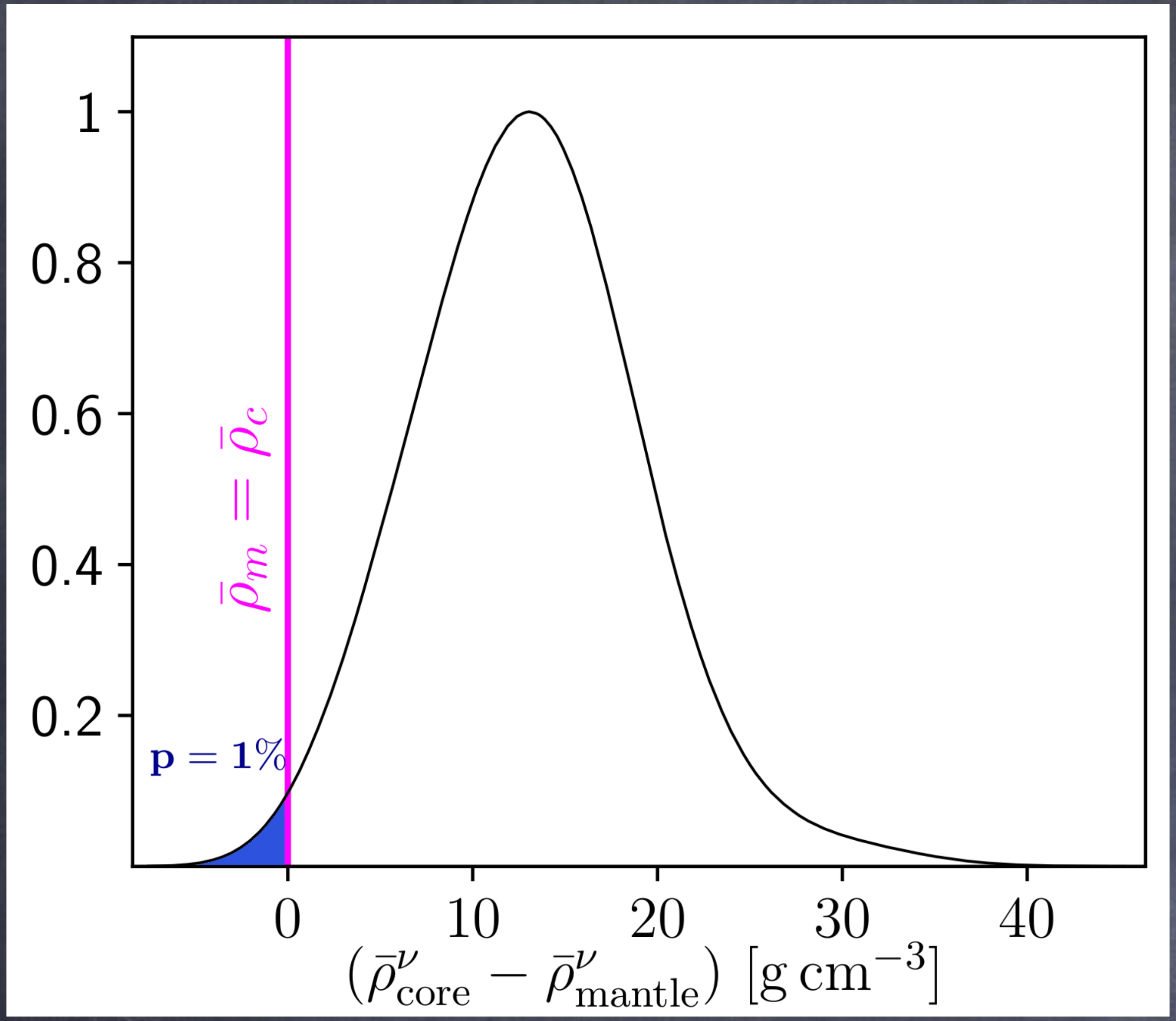
$$\frac{I_\nu}{I_{sphere-\nu}} = 0.7 \pm 0.3$$

Gravitational measurement

$$\frac{I_{grav}}{I_{sphere}} = 0.82681(11)$$

$$I_{grav} = 8.01736(96) \times 10^{37}\ \mathrm{kg\,m^2}$$

CORE DENSER THAN MANTLE



First measurement of the Earth's core-mantle discontinuity using the weak force!

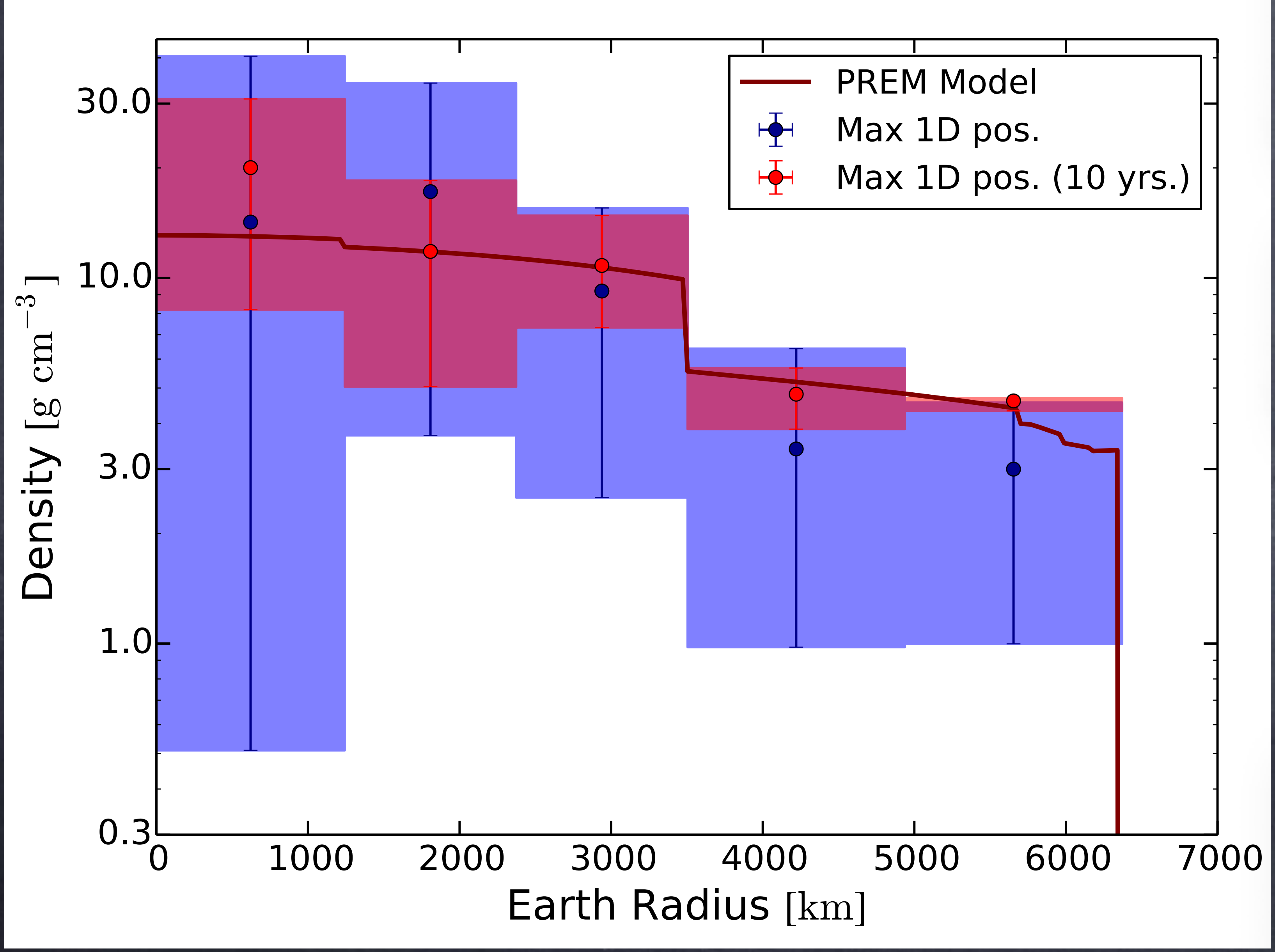
$$\left(\overline{\rho}^{\nu}_{core} - \overline{\rho}^{\nu}_{mantle}\right) = \left(13.1^{+5.8}_{-6.3}\right)\ g/cm^3$$

A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

A denser mantle has a p-value of p=0.011

What about the future? ... Actually present

Forecast for 10 years of data



A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

Few per cent error in the mantle

A finer modeling can be considered

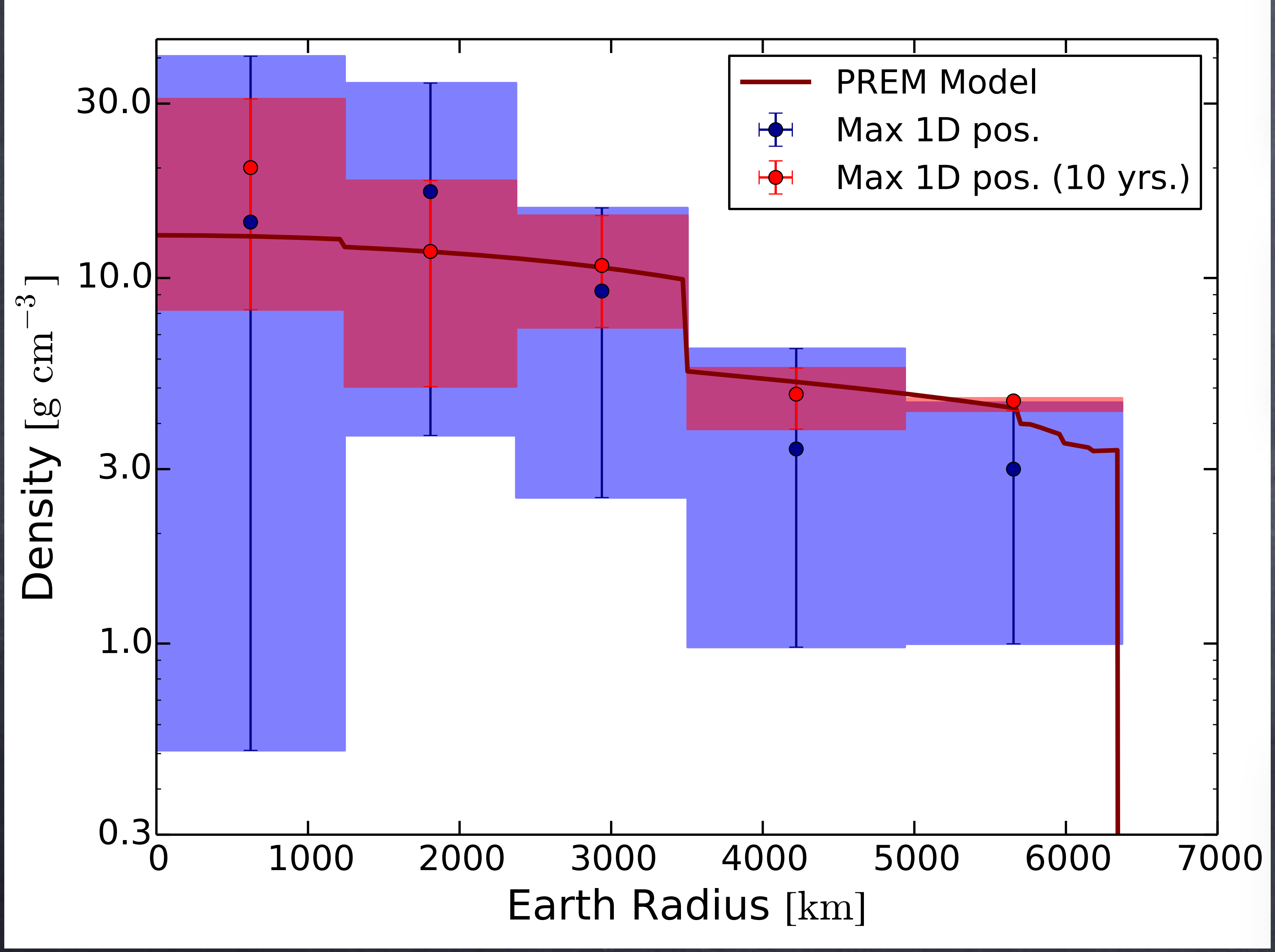
Test of discontinuities

Knowledge of hadronic-interaction model impacts systematics

What about the future? ... Actually present

Forecast for 10 years of data

... but at least already 8 years of actual data!



A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

Few per cent error in the mantle

A finer modeling can be considered

Test of discontinuities

Knowledge of hadronic-interaction model impacts systematics

Conclusions

After 44 years of being proposed, we have performed the first Earth (absorption) tomography with neutrinos

First measurement of the Earth's mass and moment of inertia using only the weak force!

Although still not precise, it might become a technique complementary to seismic wave studies

Highlight talk at
EGU General Assembly 2019
Vienna | Austria | 7–12 April 2019

Analysis with 1 year of data

8 years of data already collected by IceCube

… and other future experiments: KM3NeT, Baikal-GVD

Edmund Halley,

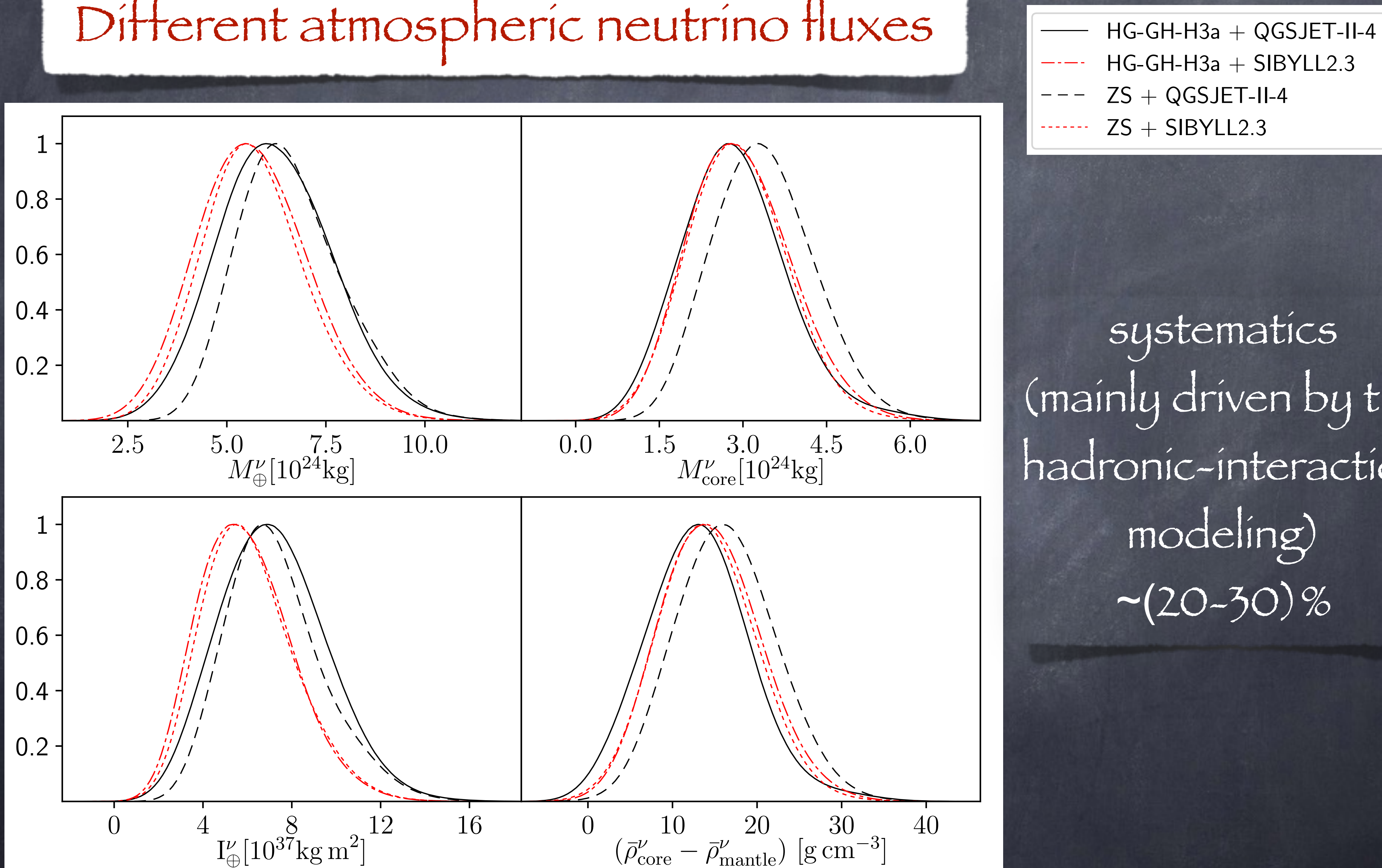
Philosophical Transactions of the Royal Society of London XVII:195, 563 (1692):

"what curiosity in the structure, what accuracy in the mixture and composition of the parts, ought not we to expect in the fabrick of this globe"

Thanks!

Impact of discrete systematics

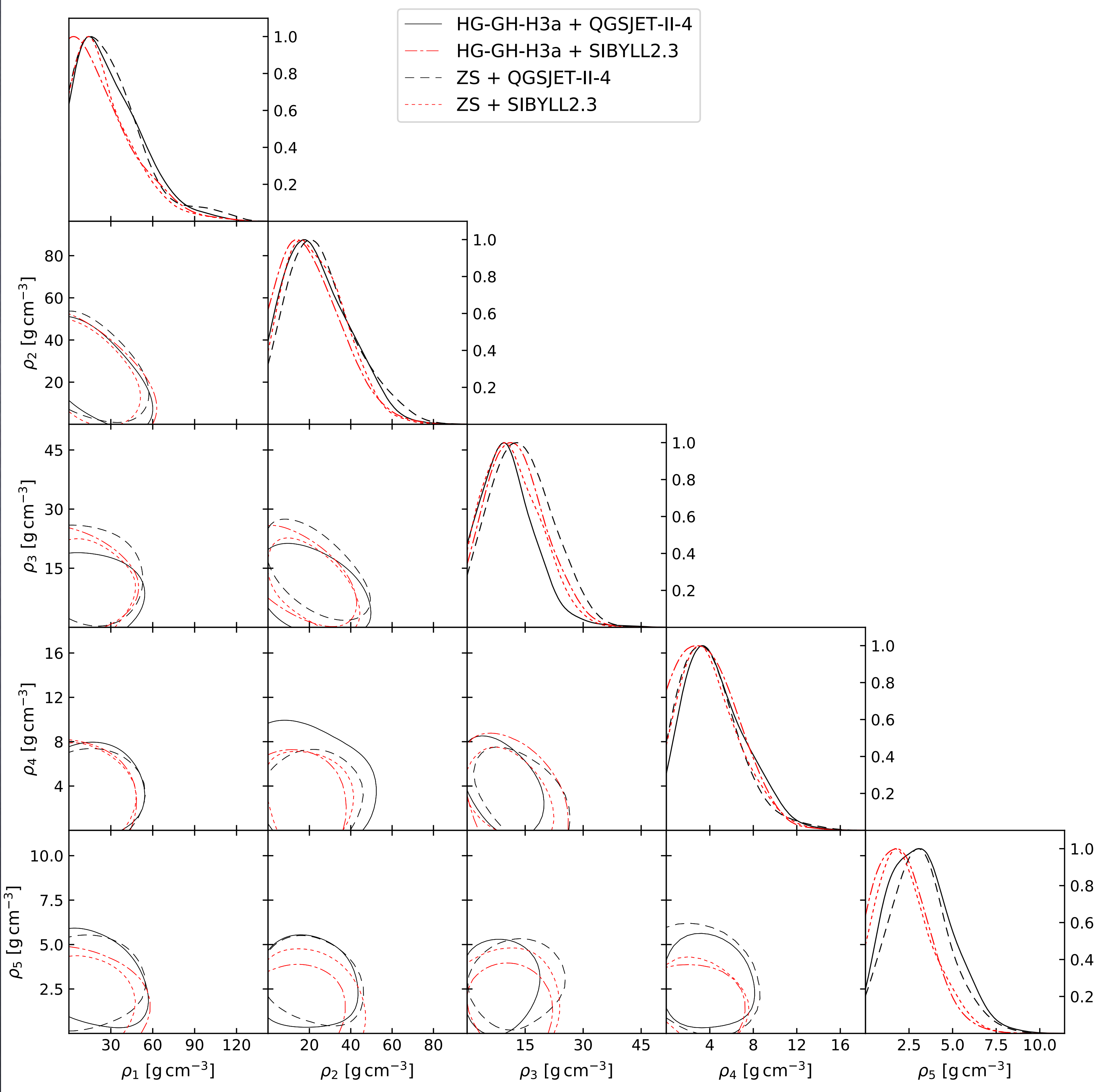
Different atmospheric neutrino fluxes



systematics
(mainly driven by the
hadronic-interaction
modeling)
~(20-30)%

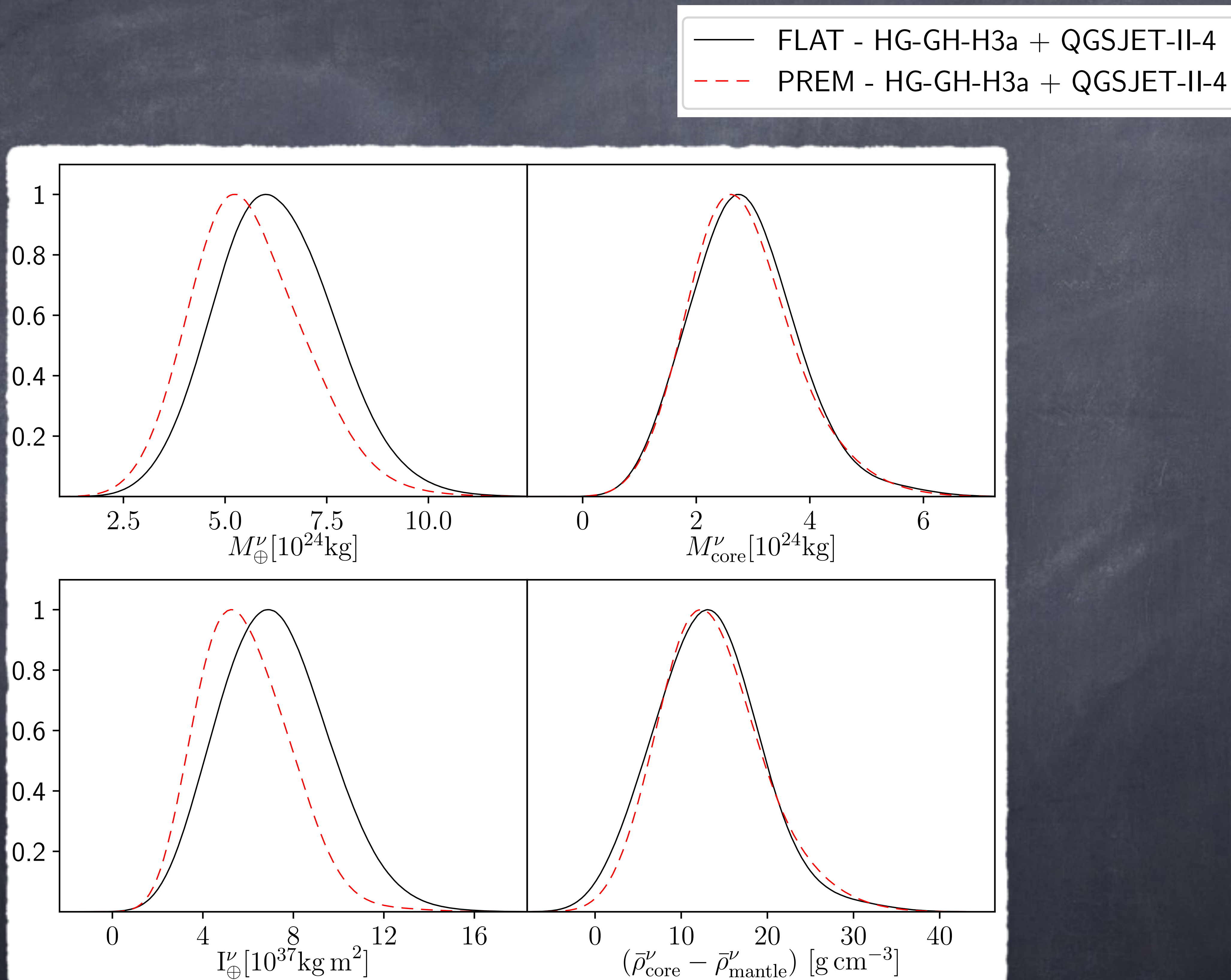
A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

NEUTRINO FLUXES: CORRELATIONS



A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

Impact of density profile



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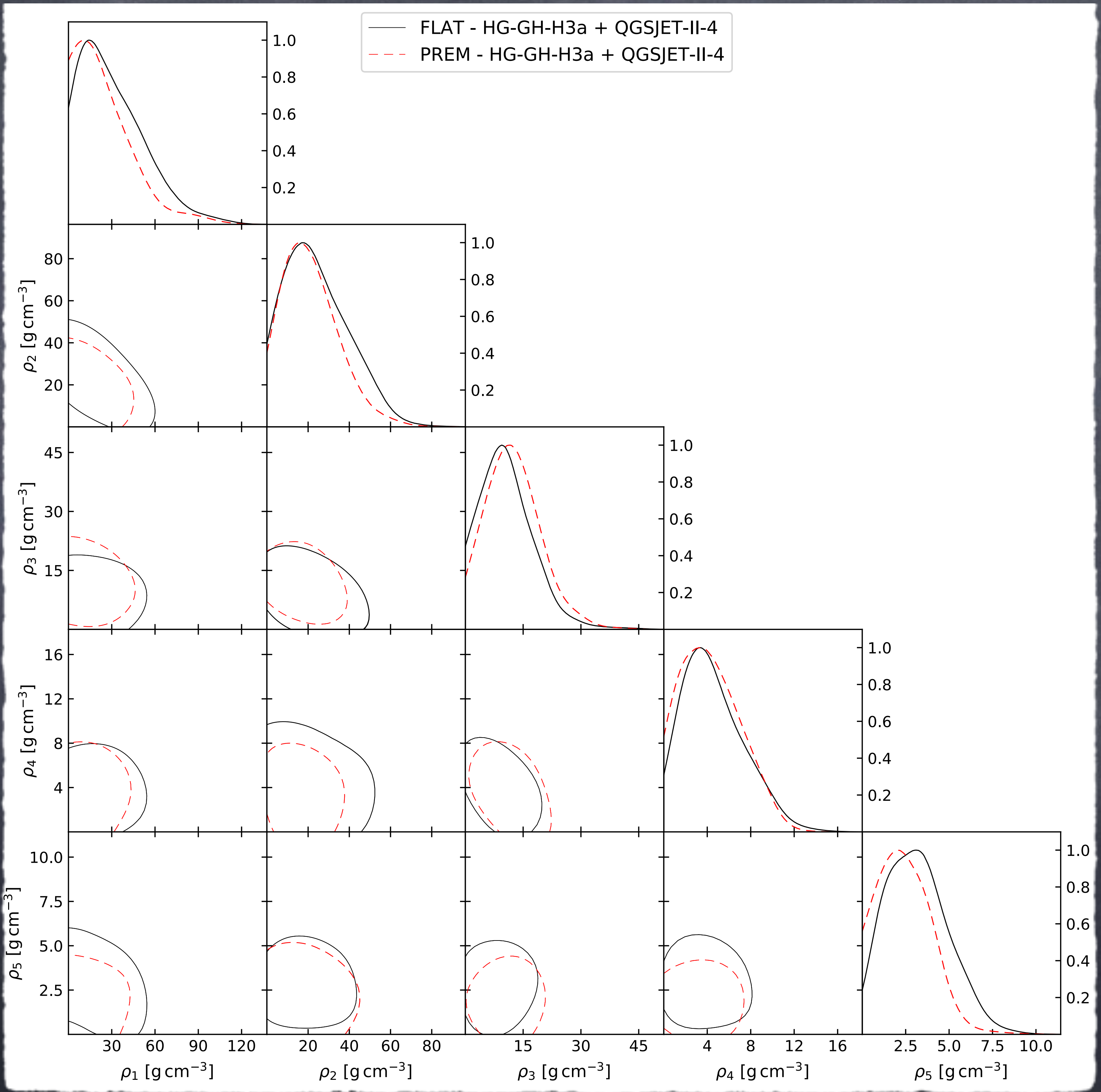
Impact of density profile:Correlations



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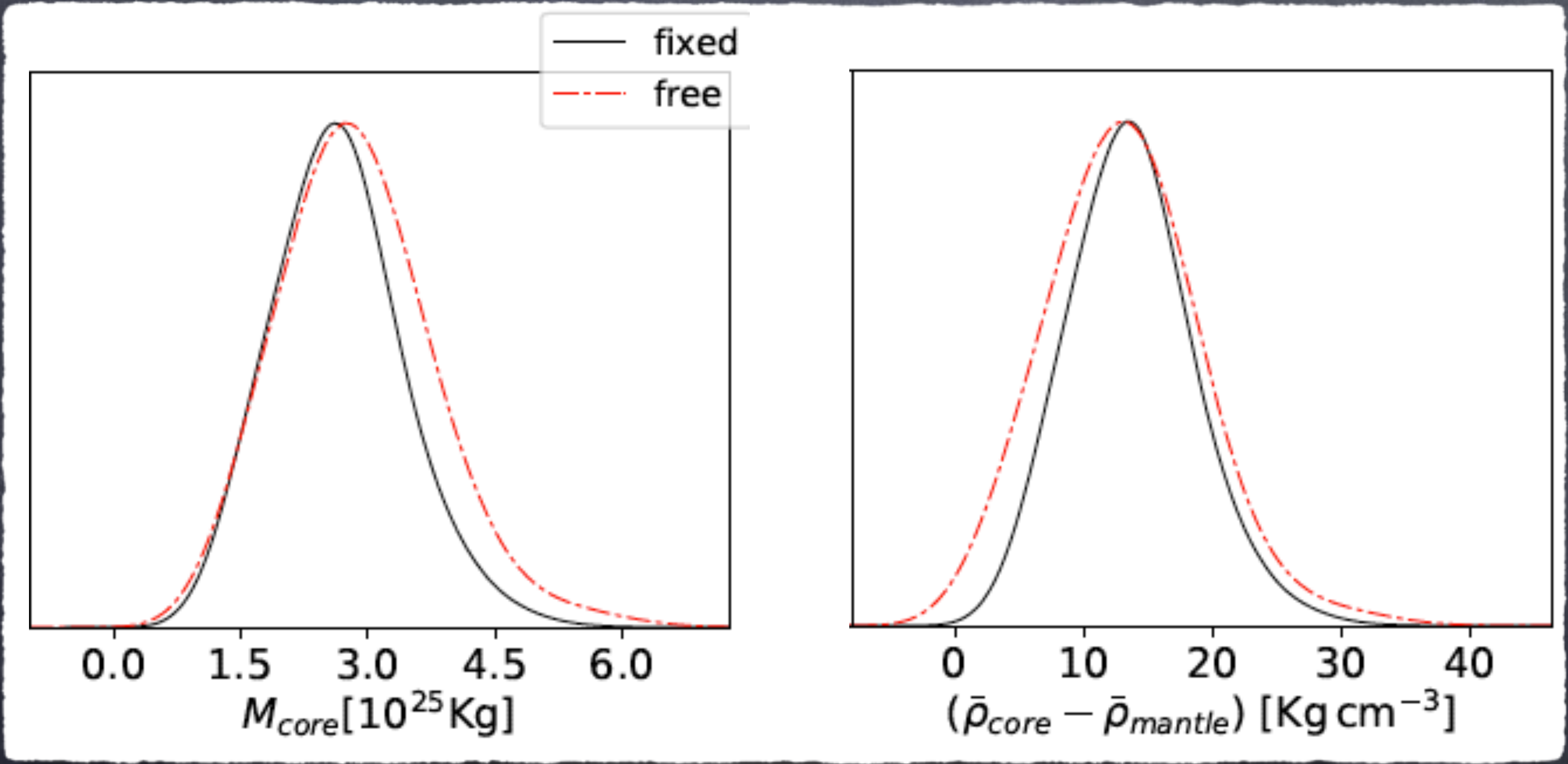
Impact of systematics

	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
$M_\oplus^\nu$ [10^{24} kg]	$6.0^{+1.6}_{-1.3}$	$5.5^{+1.5}_{-1.3}$	$6.2^{+1.4}_{-1.2}$	$5.5^{+1.3}_{-1.2}$	$5.3^{+1.5}_{-1.3}$
$M_{\rm core}^\nu$ [10^{24} kg]	$2.72^{+0.97}_{-0.89}$	$2.79^{+0.98}_{-0.85}$	$3.27^{+0.92}_{-0.89}$	$2.84^{+0.89}_{-0.88}$	$2.62^{+0.97}_{-0.84}$
$I_\oplus^\nu$ [10^{37} kg cm^2]	6.9 ± 2.4	$5.4^{+2.3}_{-1.9}$	$6.7^{+2.3}_{-2.0}$	$5.5^{+2.2}_{-1.9}$	$5.3^{+2.3}_{-1.7}$
$\bar\rho_{\rm core}^\nu - \bar\rho_{\rm mantle}^\nu$ [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}

A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

ADDING GRAVITY CONSTRAINTS



Density of the mantle determined at ~4%