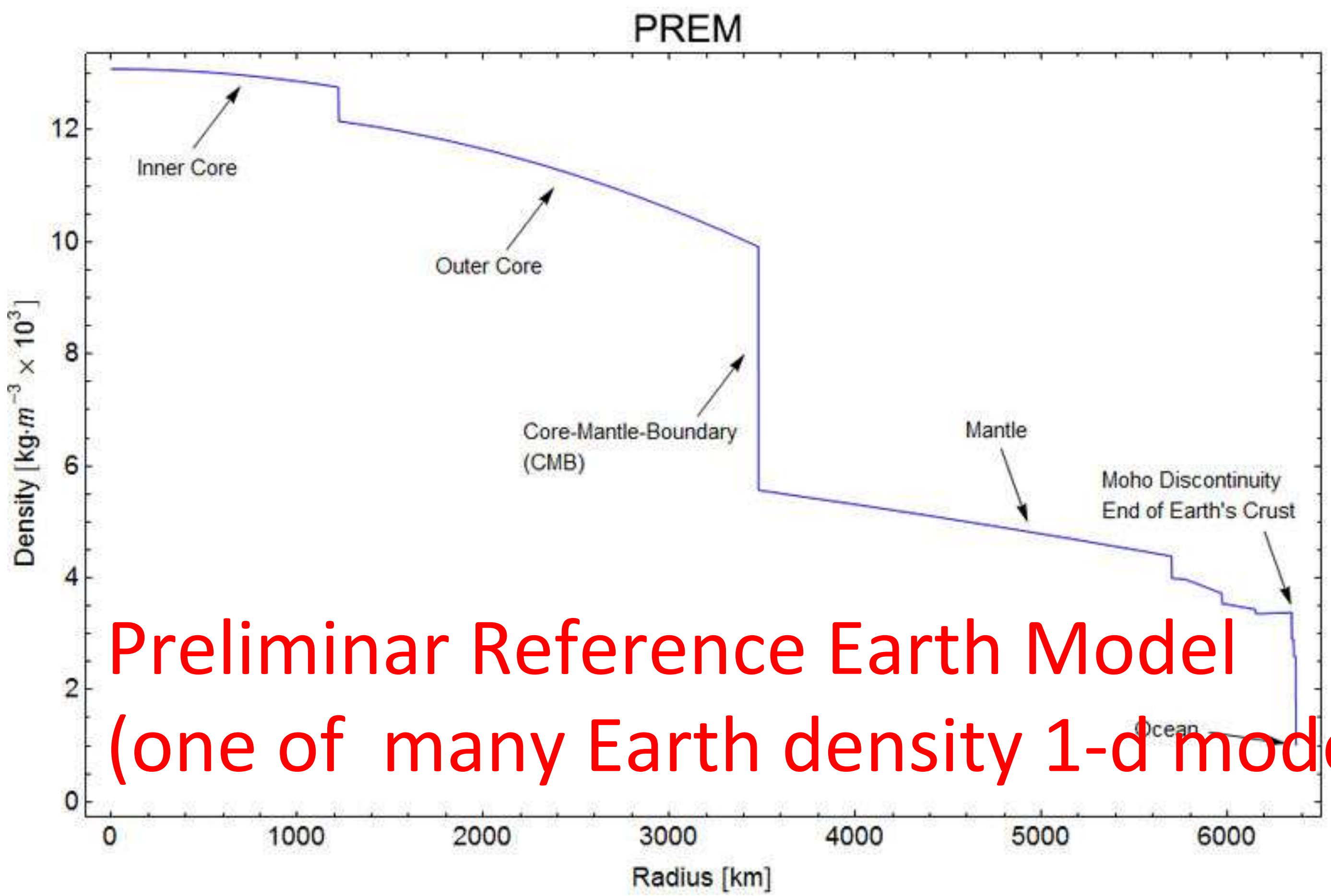
The first Neutrino Absorption Earth Tomography

Andrea Donini (IFIC, Valencia)

in collaboration with S. Palomares Ruiz and J. Salvado

Nature Physics 15 (2019) 37

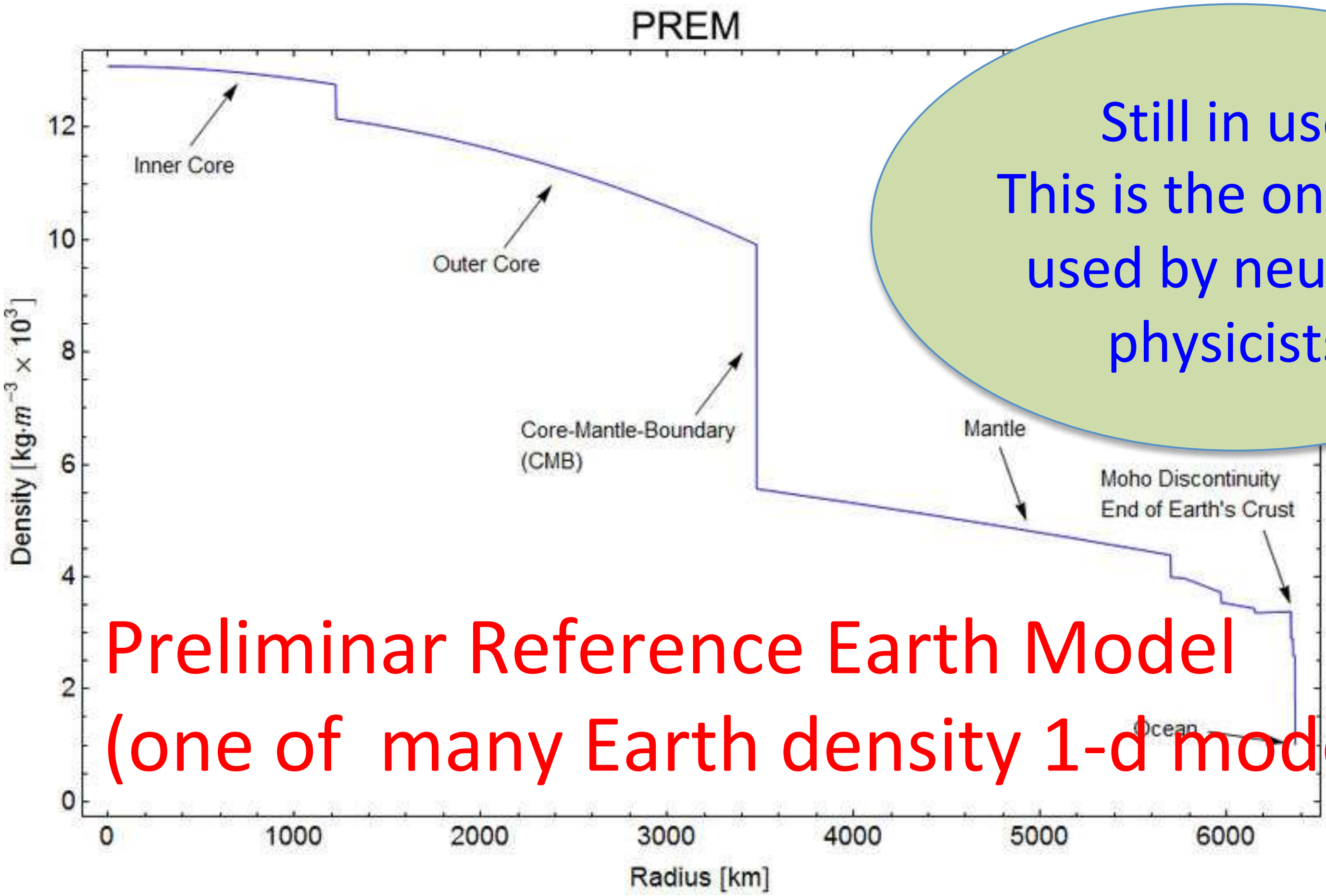
A seismological Earth tomography



Preliminar Reference Earth Model
(one of many Earth density 1-d models)

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

A seismological Earth tomography

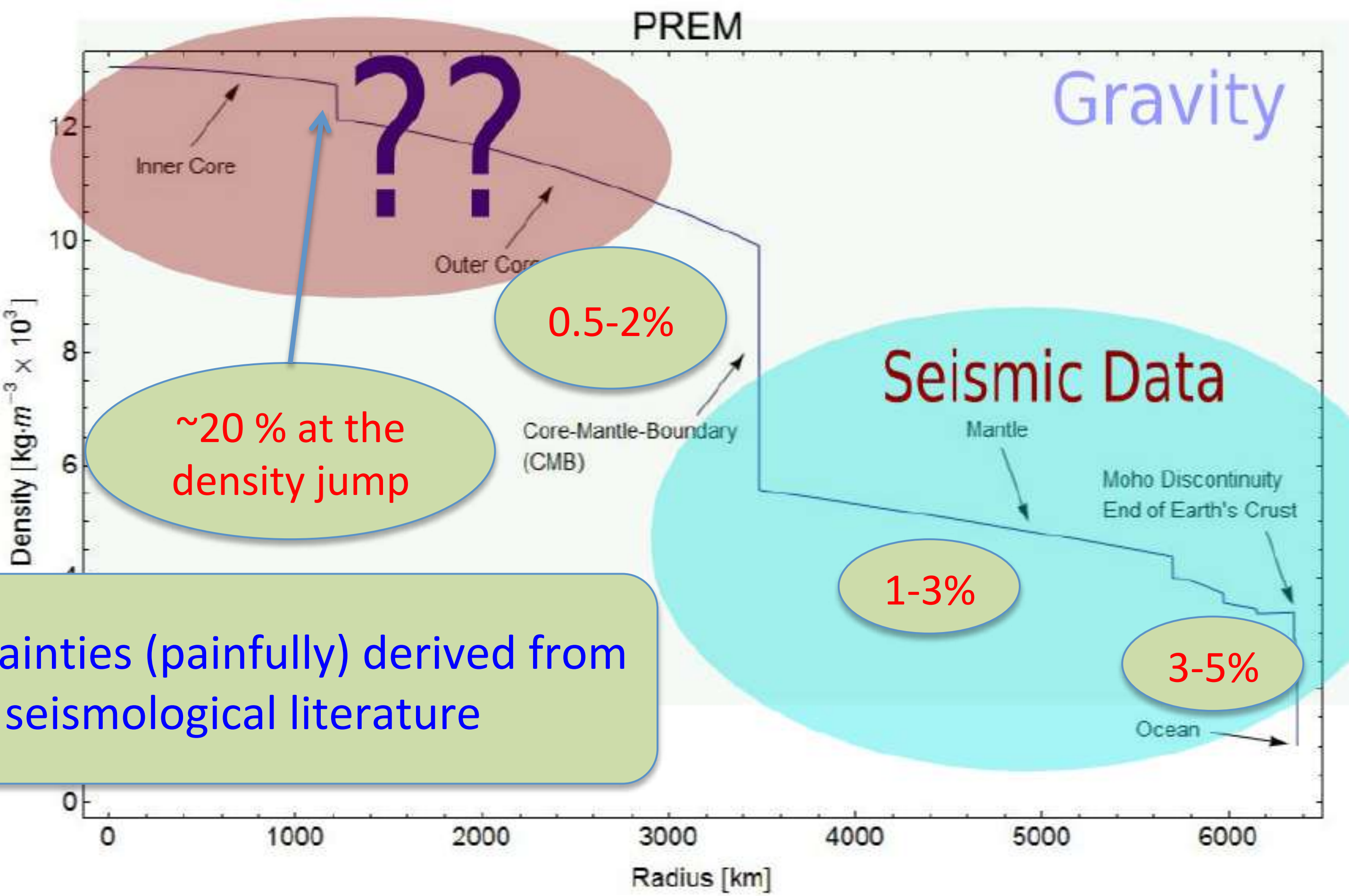


Still in use!
This is the only one used by neutrino physicists!

Preliminar Reference Earth Model
(one of many Earth density 1-d models)

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

Uncertaintes from seismology



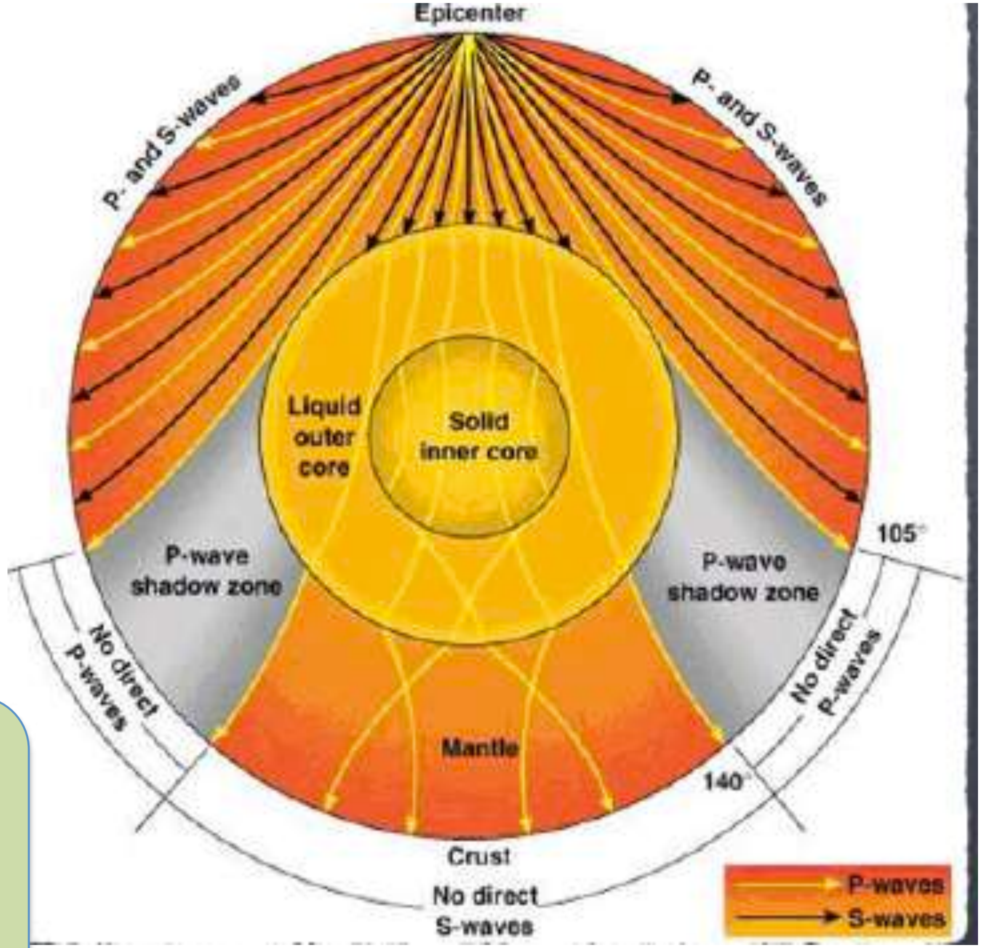
Uncertainties (painfully) derived from seismological literature

A bit on seismic waves propagation

P-waves:
Compressional waves, travel through solid and liquid media

S-waves:
Shear waves, travel only through solid medium

Difficult to extract informations about the Earth's core
(source of geomagnetism)



Using neutrinos to scan the Earth

Studying the Earth's interior with neutrinos is an old idea, first mentioned in an unpublished CERN preprint:

A.Placci and E. Zavattini, submitted in Oct 1973 to Nuovo Cimento, but not published. Rejected?... never received?....

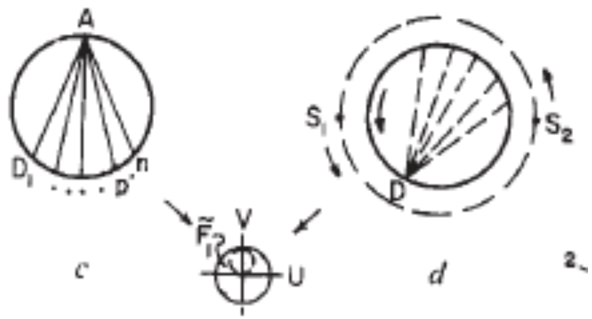
and in a talk:

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

MAKE A NEUTRINO BEAM! SHOOT IT THROUGH THE EARTH!

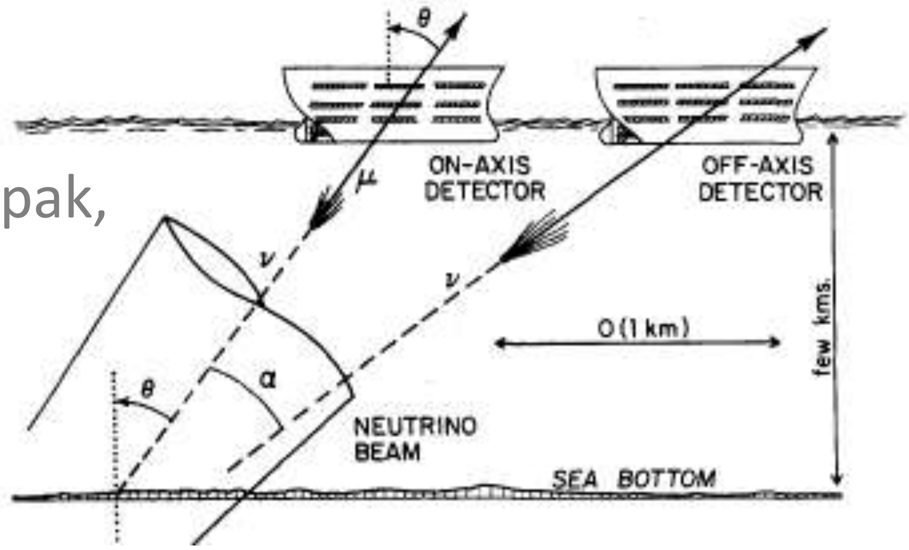
The idea was premature for the '70s!... and for the '80, the '90s, the '00s, the '10s and, probably, the '20s...

More ideas during the '80s

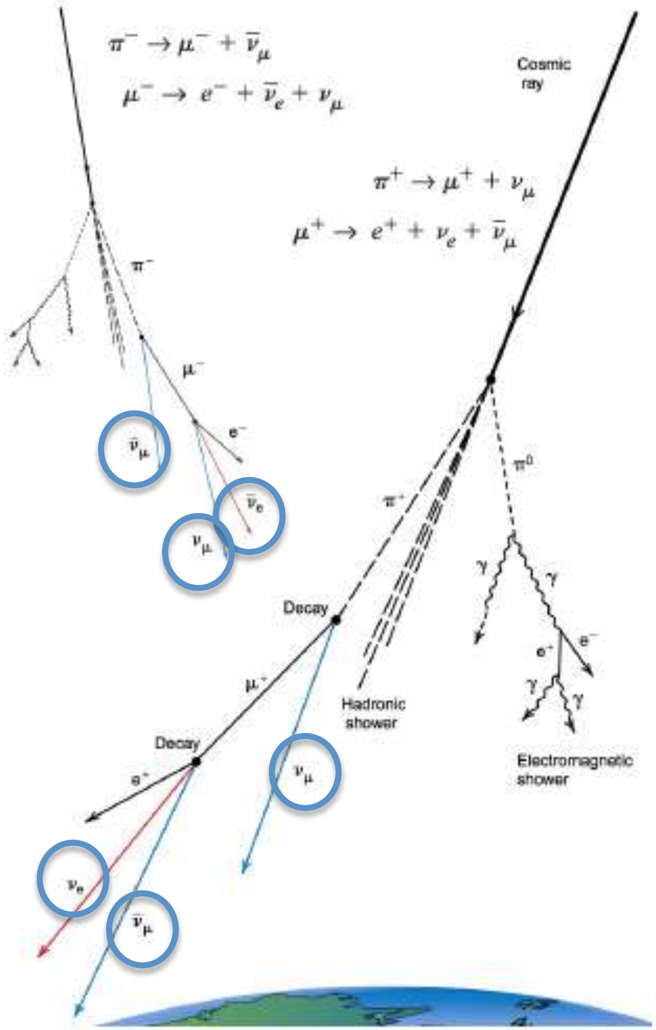


T. Wilson, Nature 309 (1984)

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



Using atmospheric neutrinos



Model of Primary Cosmic Ray Flux

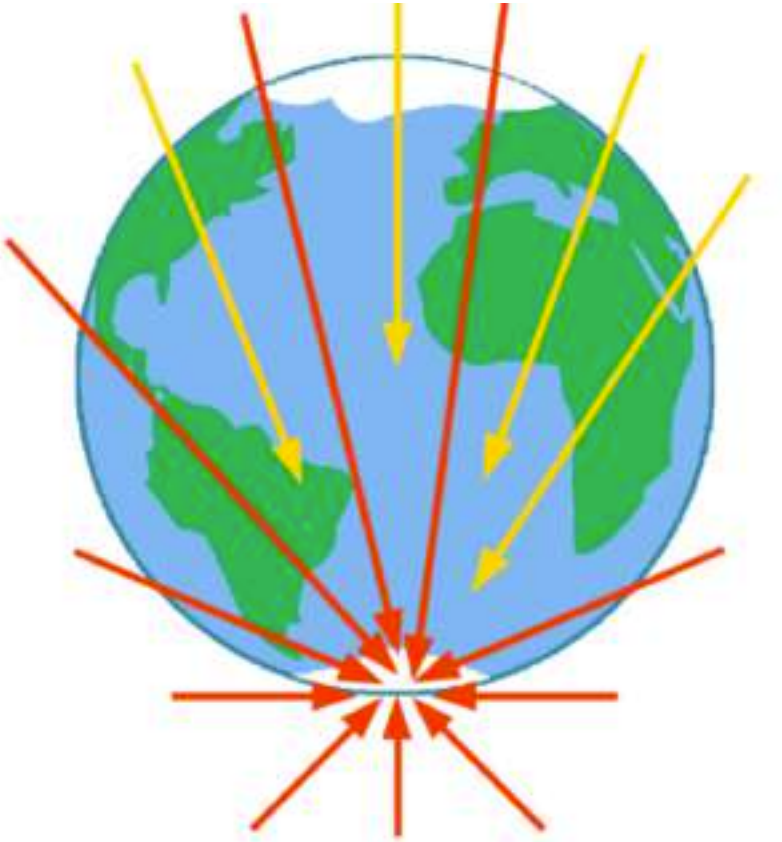
+

Model of the interactions of Cosmic Rays with outer layers of the atmosphere

↓

Atmospheric Neutrino Flux

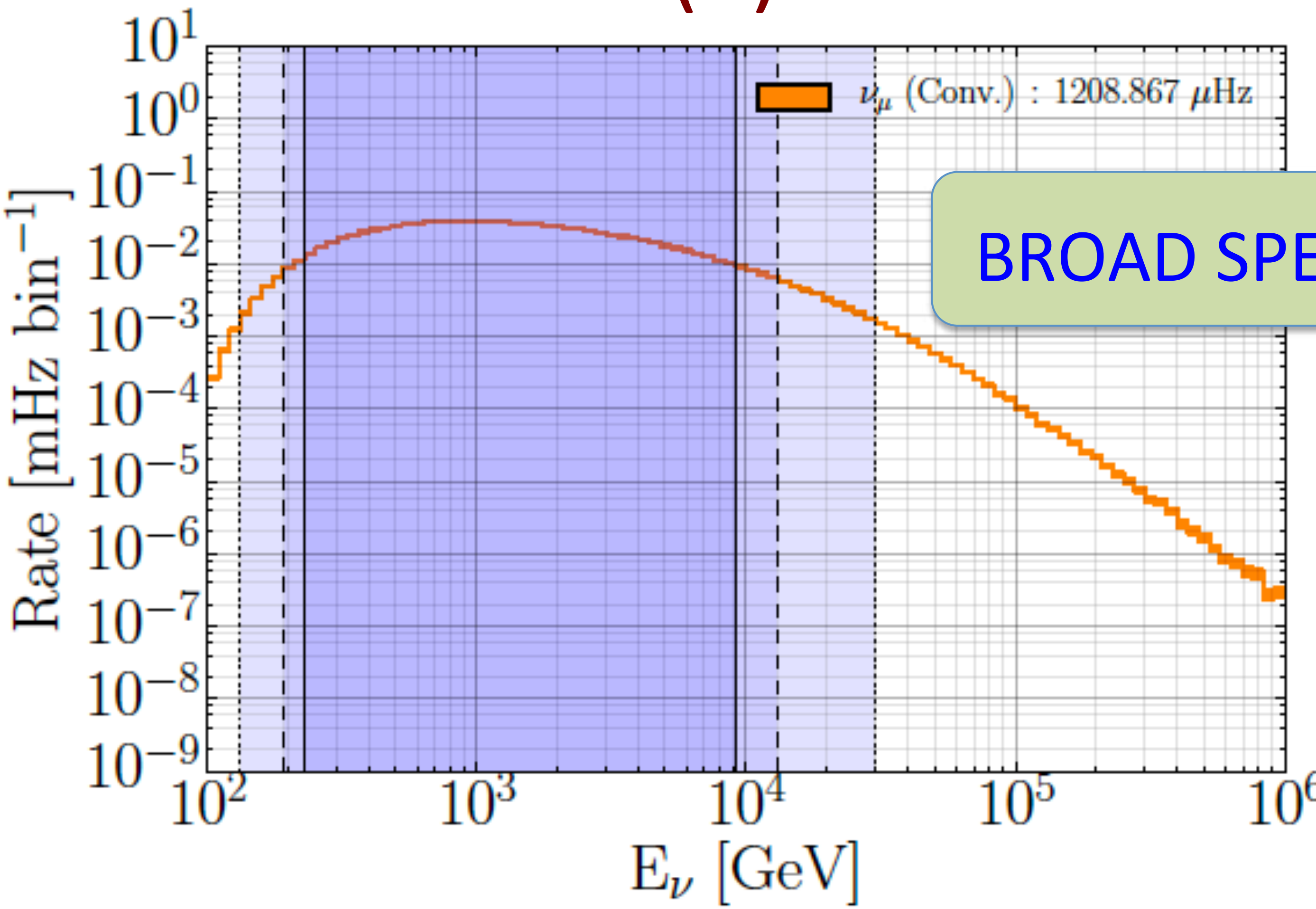
Atmo-neutrinos are an optimal source (1)



They reach a detector from all directions

Lipari, NeuTel 2019, Venice

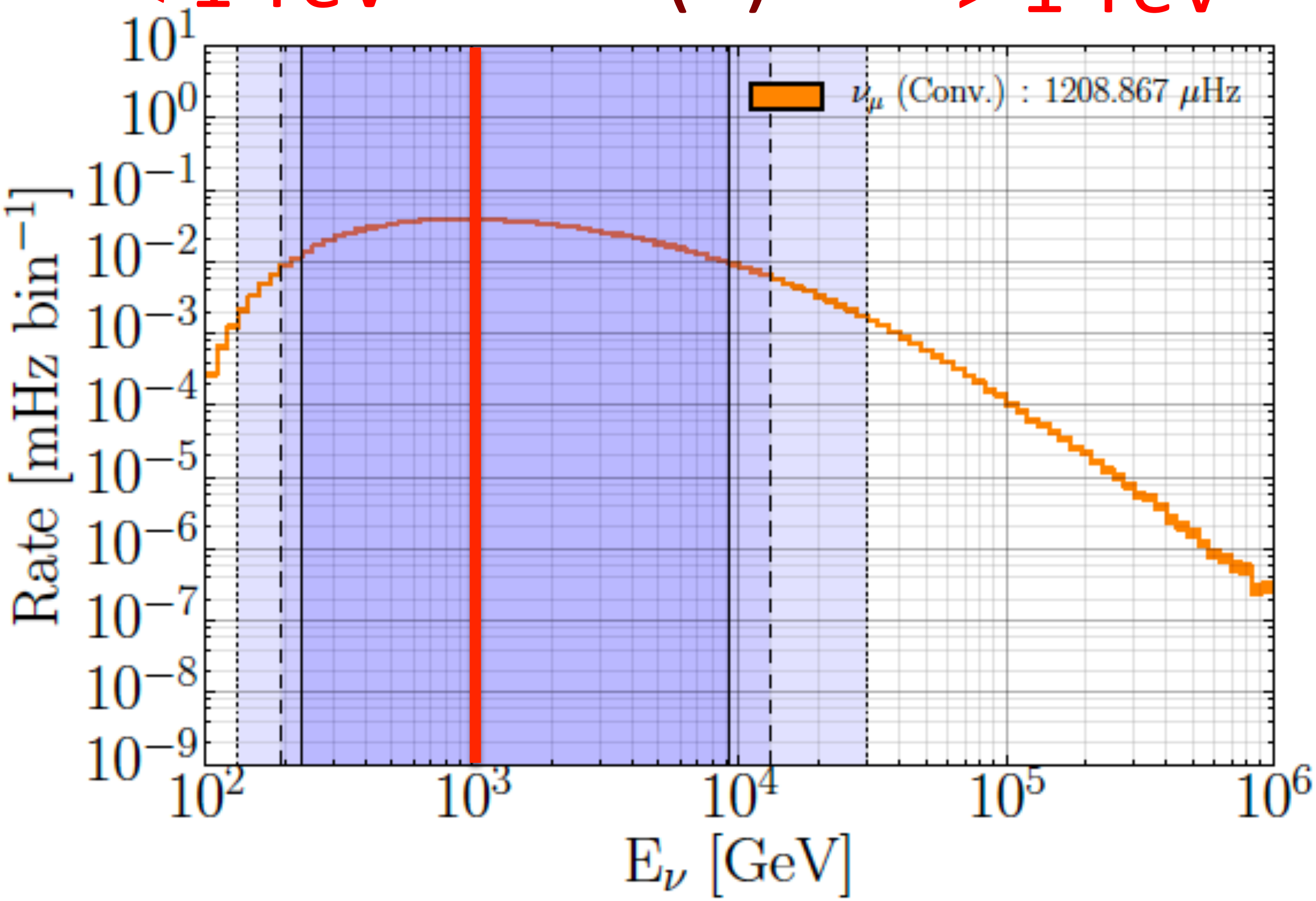
Atmo-neutrinos are an optimal source (2)



BROAD SPECTRUM!

IceCube Collaboration, Aartsen et al , Phys. Rev. D102 (2020)

Atmo-neutrinos are an optimal source (2)



IceCube Collaboration, Aartsen et al , Phys. Rev. D102 (2020)

Two ways to scan the Earth

- Neutrino oscillations (< 1 TeV)

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

Two ways to scan the Earth

- Neutrino oscillations (< 1 TeV)

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

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

Two ways to scan the Earth

- Neutrino oscillations (< 1 TeV)

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

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

SEE TALKS BY BAKHTI, PETCOV, COELHO, TAKETA
KUMAR, PESTES AND MARTÍNEZ-SOLER
AT THIS WORKSHOP

Two ways to scan the Earth

- Neutrino oscillations (< 1 TeV)

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

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

- 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

- Neutrino oscillations (< 1 TeV)

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

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

- Neutrino flux attenuation (> 1 TeV)

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

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

Two ways to scan the Earth

- Neutrino oscillations (< 1 TeV)

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

See, e.g., W. Winter, Nucl. Phys. B 908 (2016) 250;

This is what we are interested in!

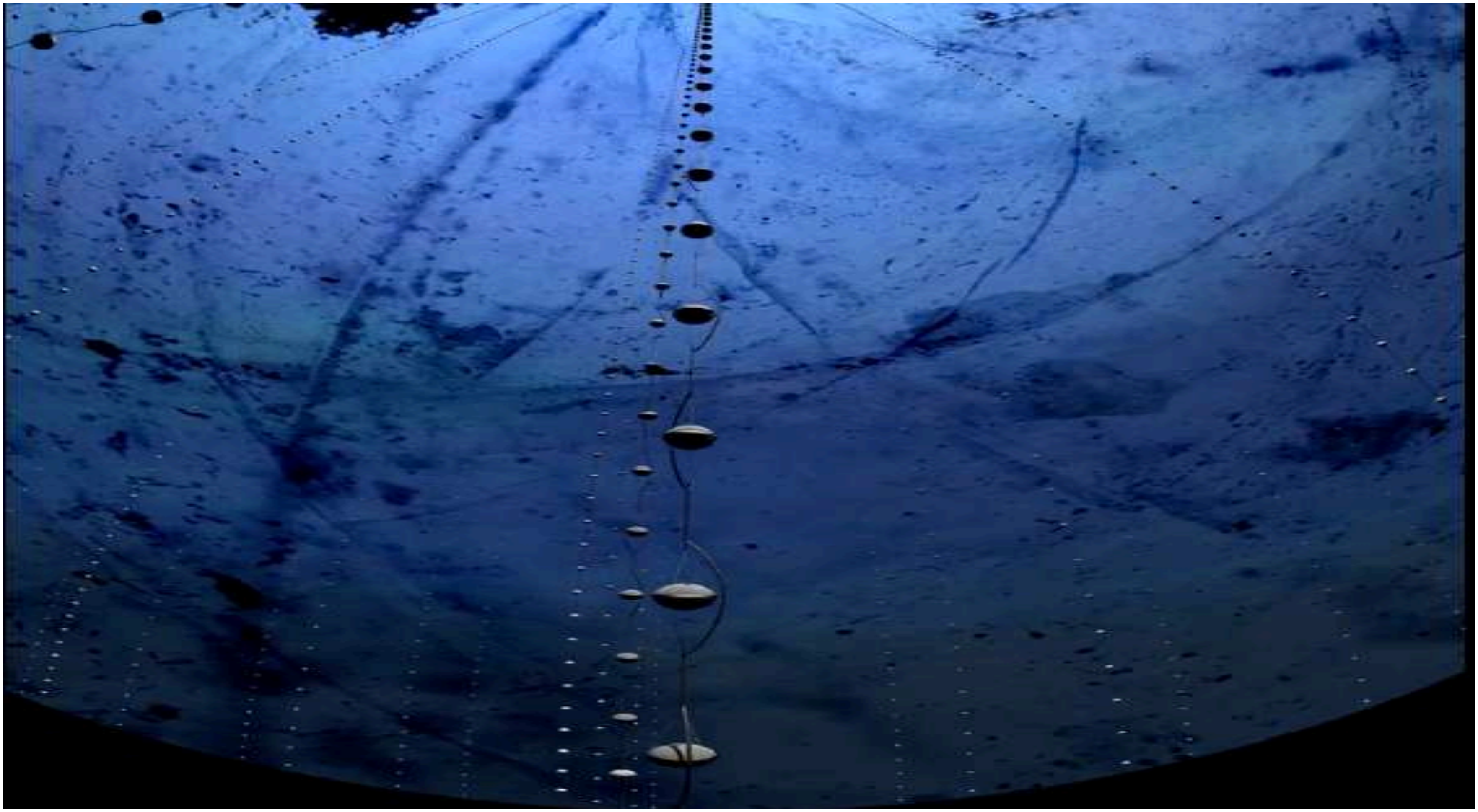
- Neutrino flux attenuation (>

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

$\sigma_{tot} = \sigma_{\nu N} \times \rho_E$

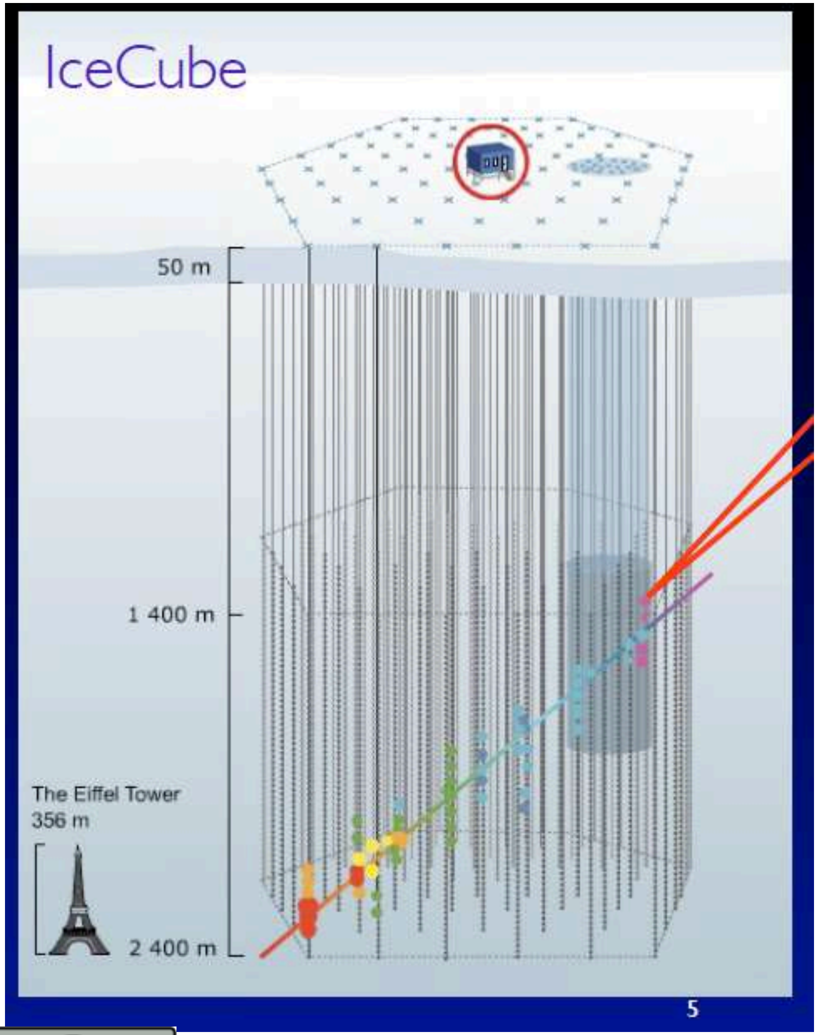
Gonzalez-García, Halzen, Maltoni, Tanaka, Phys. Rev. Lett. 100 (2008)

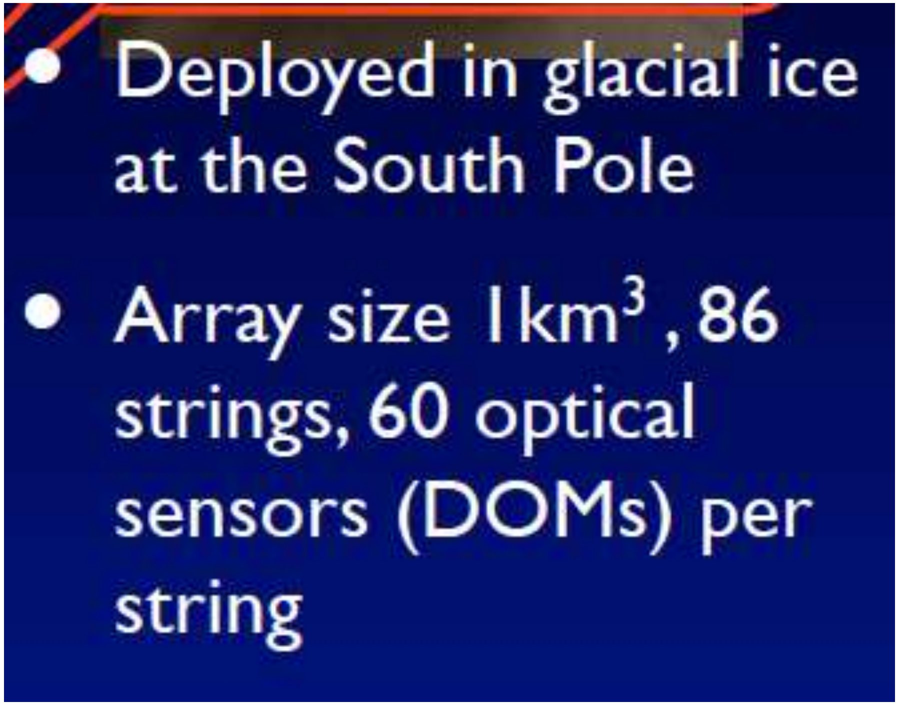
The IceCube Experiment



Halzen, NeuTel 2019, Venice

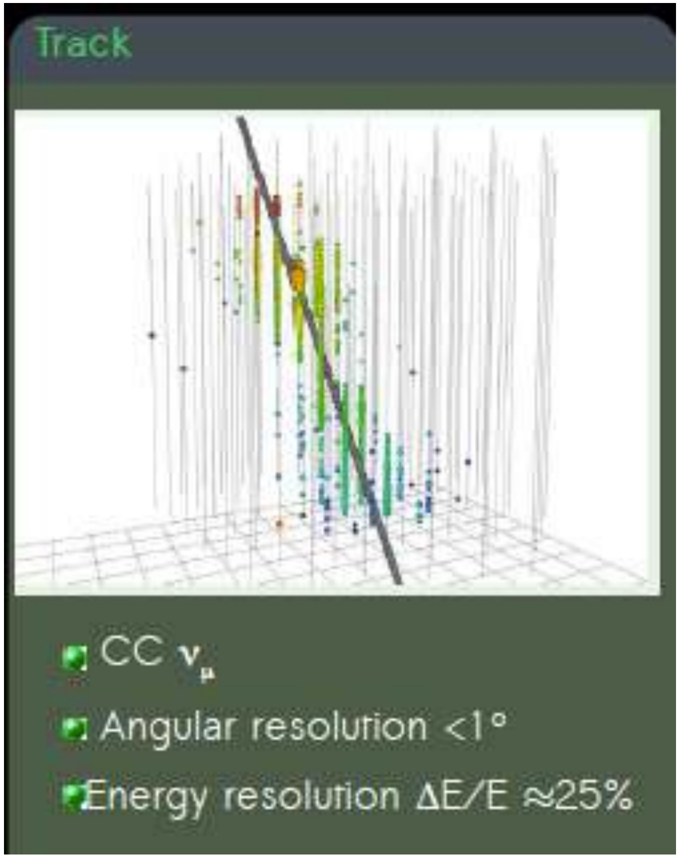
The IceCube Experiment





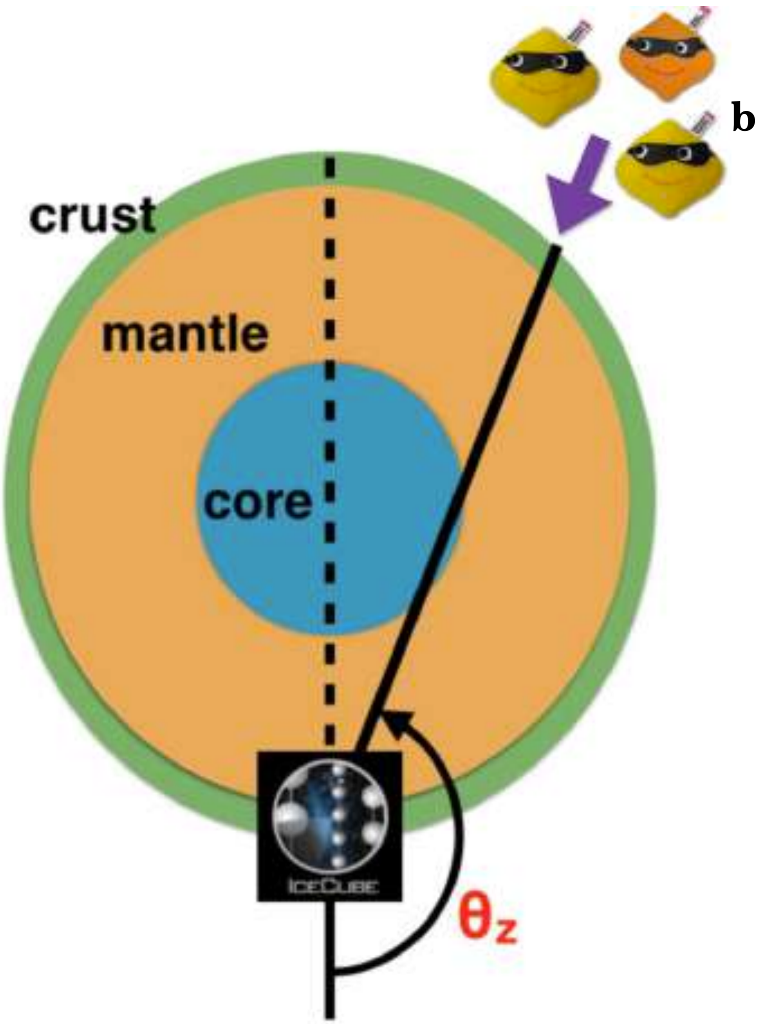
The IceCube IC86 data sample

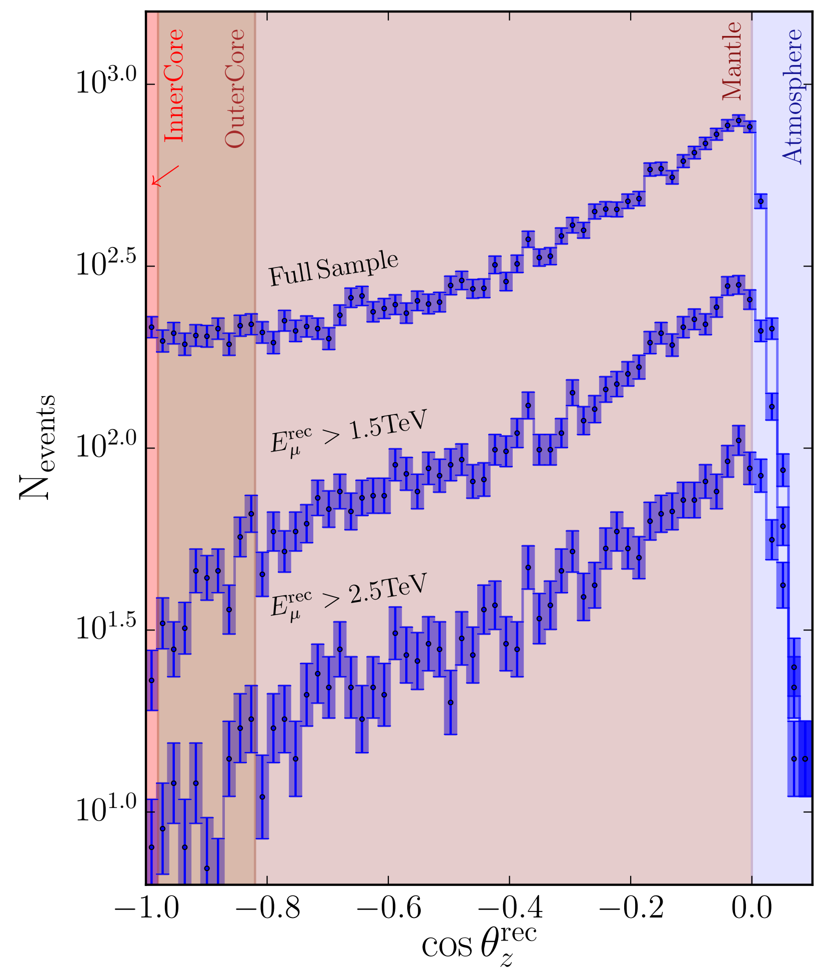
- Data taking: 2011-2012
- 20145 muons
- E_μ = [400 GeV ÷ 20 TeV]
- Good reconstruction of ν energy and direction
- PUBLICLY AVAILABLE!
- 10 more years of data are not (yet) available…..



C. de los Heros, NeuTel 2019, Venice

Raw data as a function of E_μ and θ





From raw data to measurements

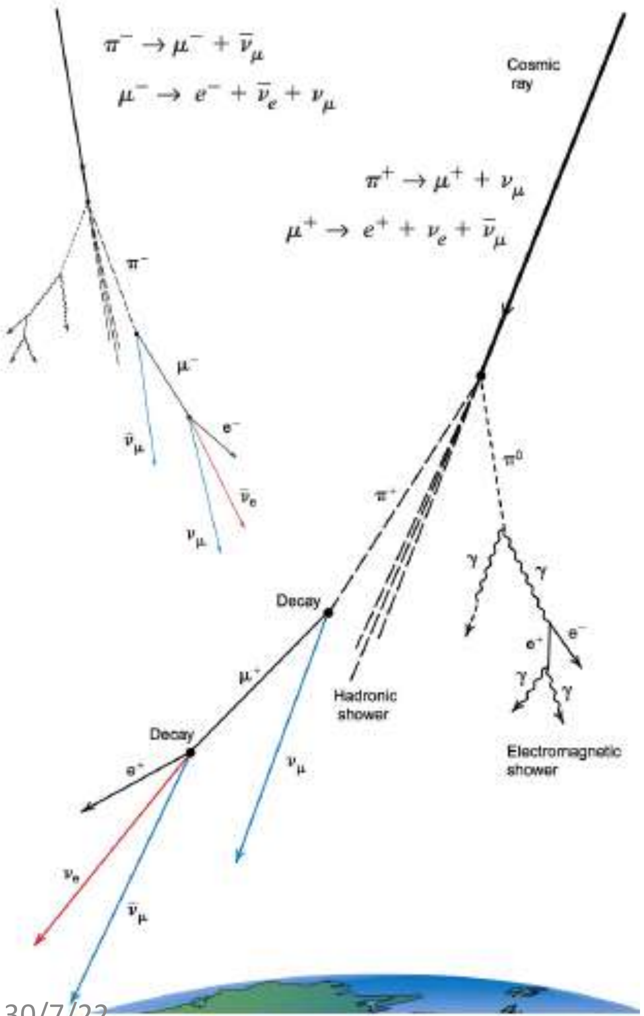
(1) Atmospheric Neutrino Flux →

(2) Propagation through Earth ↙

(3) N interaction with nucleons ↘

(4) Detector response simulation

N_{exp}: (1) atmo-ν flux model



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

Hadronic model: QGSJET-II-04

We tried other options → "discrete" systematics

N_{exp}: (2) neutrino propagation

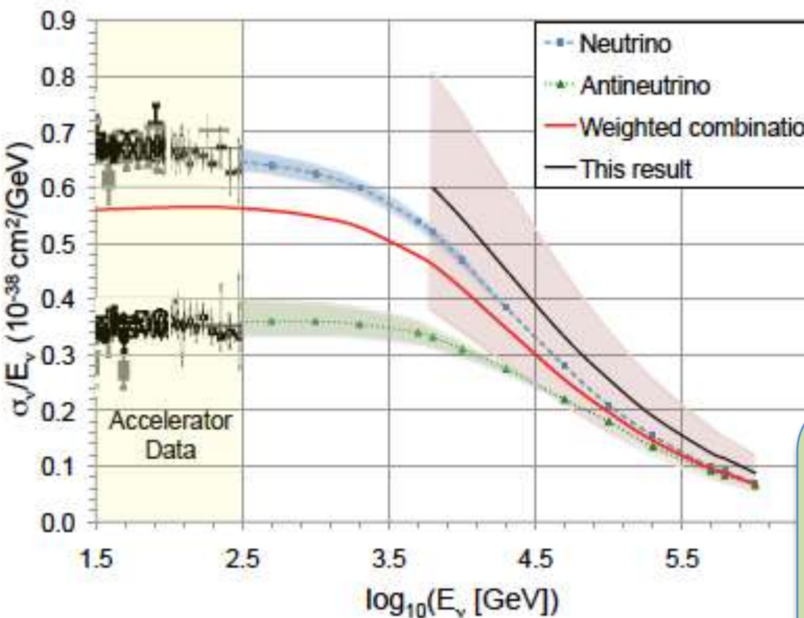
Propagation through the Earth with ν-SQuIDs

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: $\nu_e, \nu_\mu \rightarrow \nu_\tau \rightarrow$ CC $\tau \rightarrow \nu_e, \nu_\mu$ through leptonic decays
- Migration to lower energy bins: due to NC interactions

N_{exp}: (3) neutrino-nucleon interaction

Remember: $\sigma_{tot} = \sigma_{\nu N} \times \rho_E$



Aarsten et al, Nature 551 (2017)

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

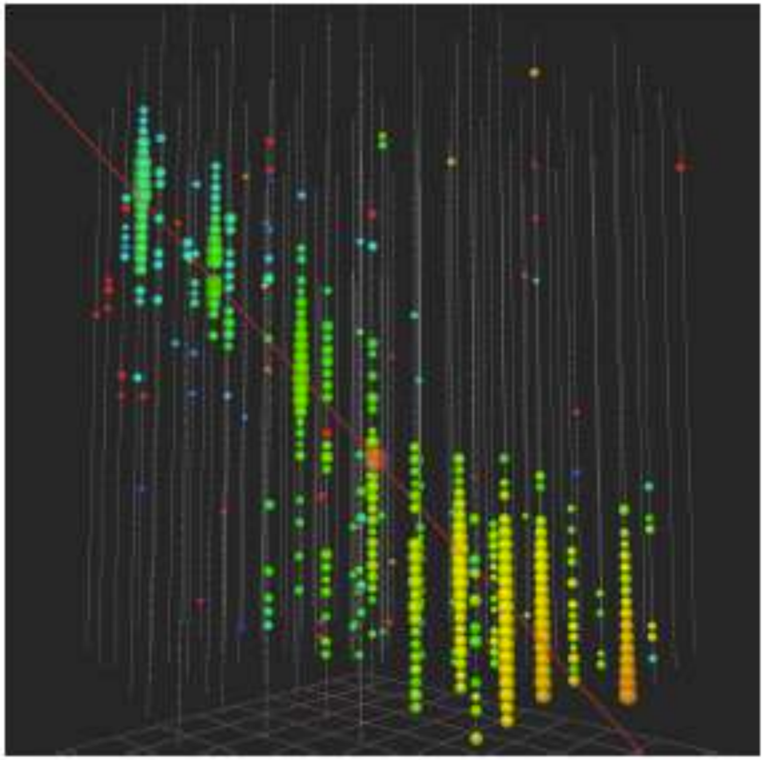
ICECUBE MEASUREMENT

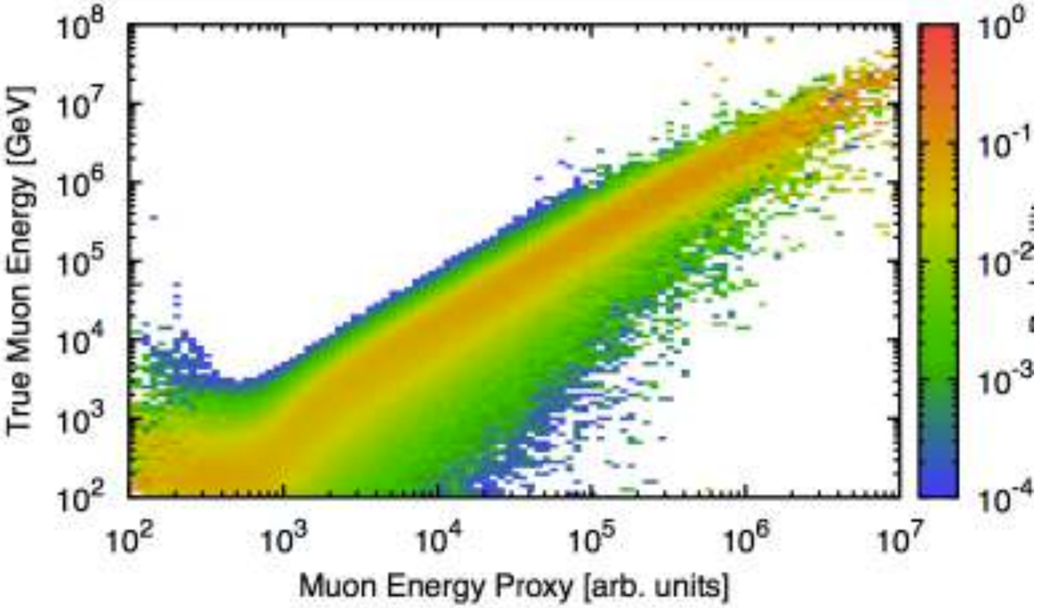
$1.30^{+0.21}_{-0.19}$ (stat) $^{+0.39}_{-0.43}$ (syst) x σ_{SM}

N_{exp}: (4) detector simulation

We use the official IceCube MC to map

E^{μ}_{obs}, θ^{μ}_{obs} into E^{ν}_{rec}, θ^{ν}_{rec}

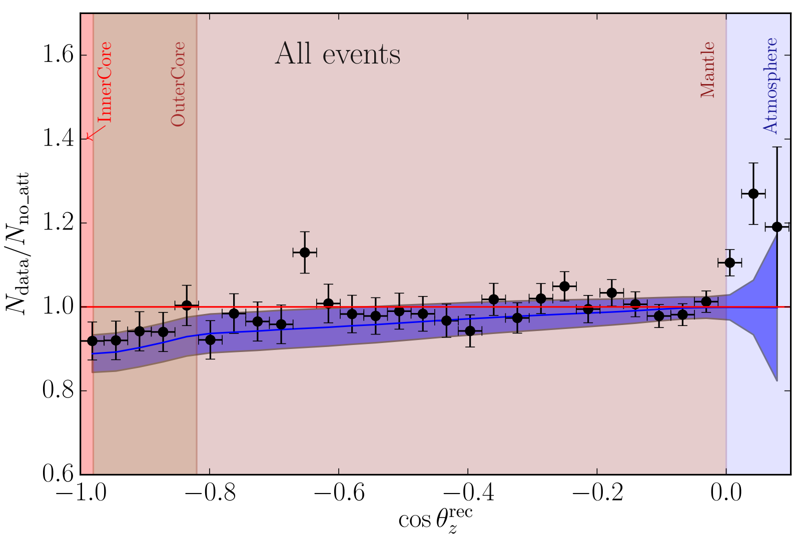




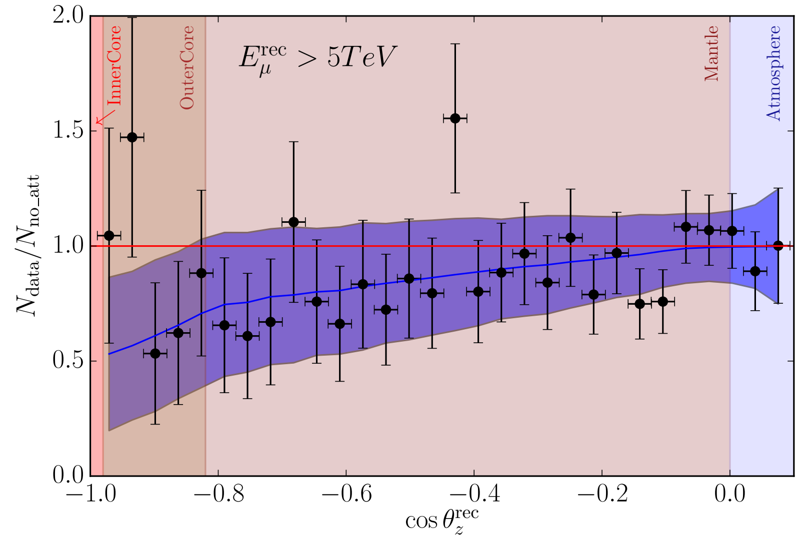
https://icecube.wisc.edu/science/data/IC86-sterile-neutrino

“Observed” vs “Expected with NO EARTH”

a Full sample



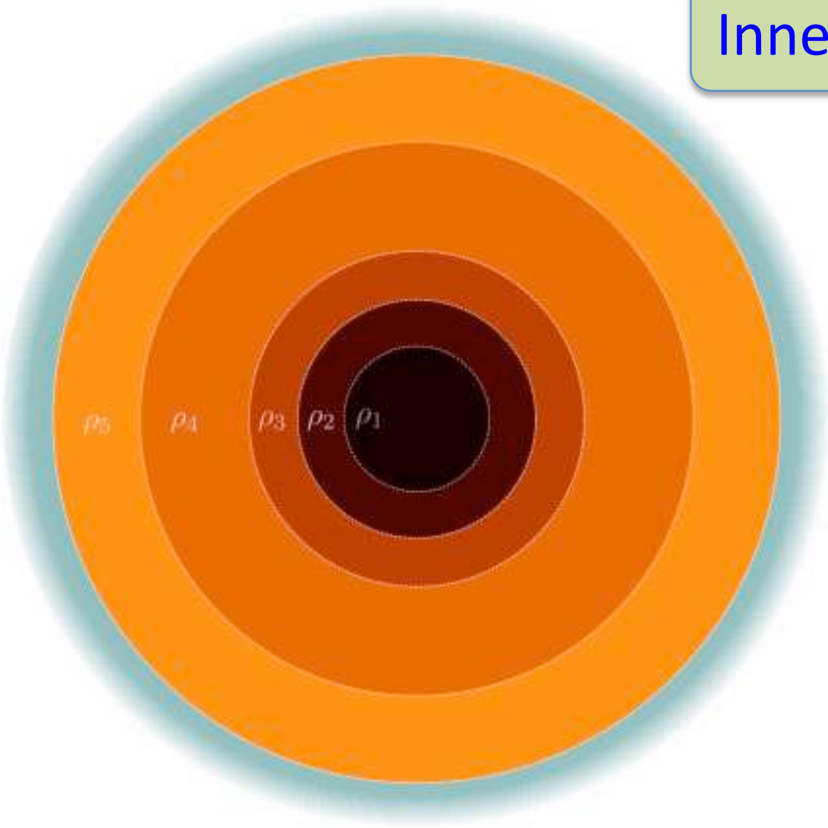
b Above 5 TeV



Full sample useful for normalization

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

A five-shells Earth's model



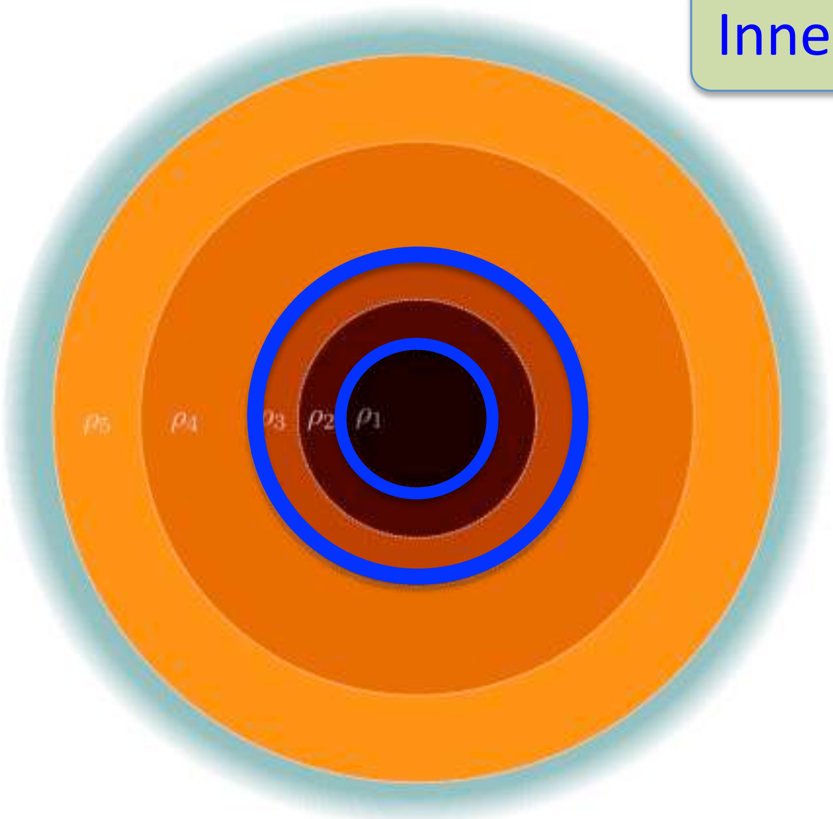
Inner Core, one shell L_1 = 1242 km

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

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

No crust!

A five-shells Earth's model



Inner Core, one shell L_1 = 1242 km

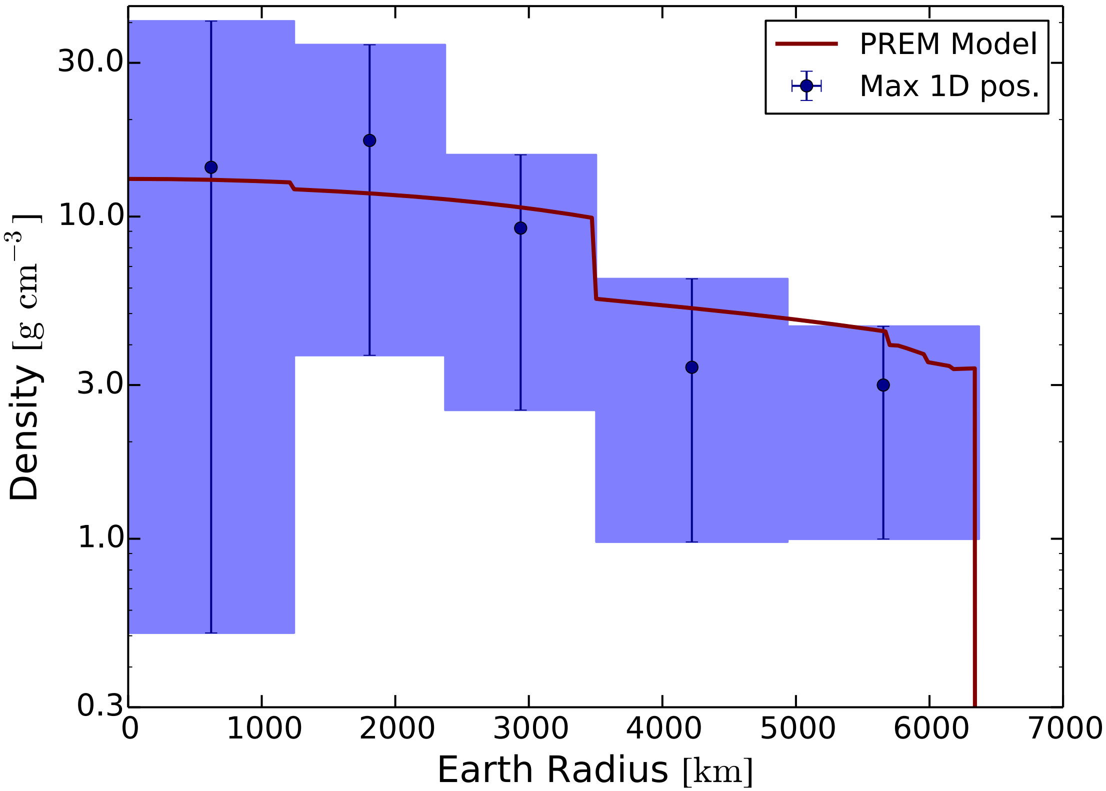
Outer Core, two shells
L_2 = 2373 km, L_3 = 3504 km

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

No crust!

Depths of ICB and CMB fixed!

First Earth Tomography with neutrinos



Analysis performed with MultiNest:

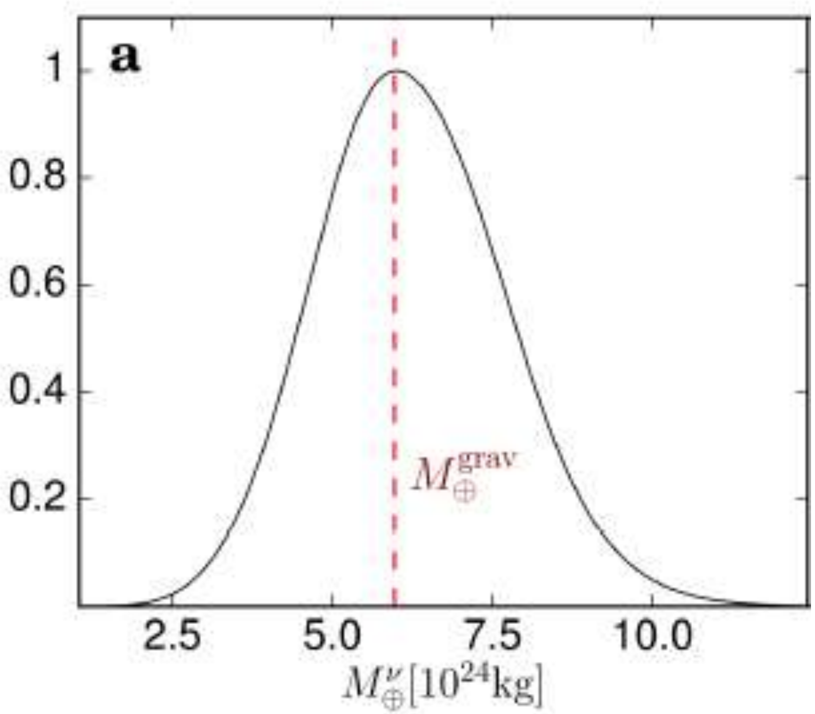
5 Earth layers densities

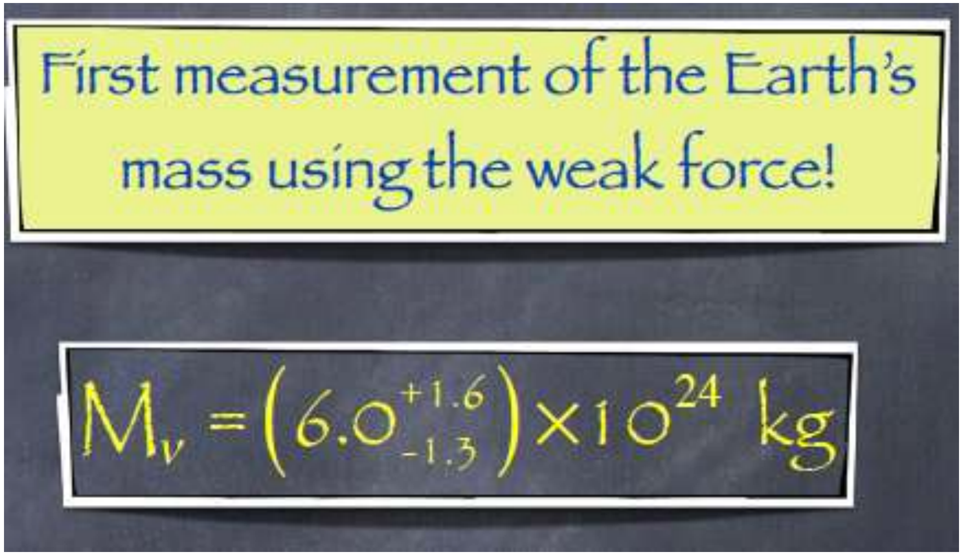
+

4 systematic errors:

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

However: (1) The Earth's mass

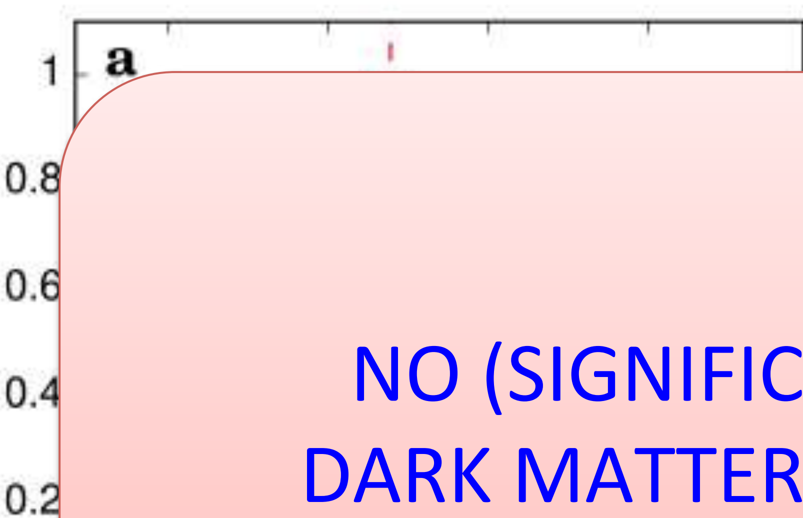


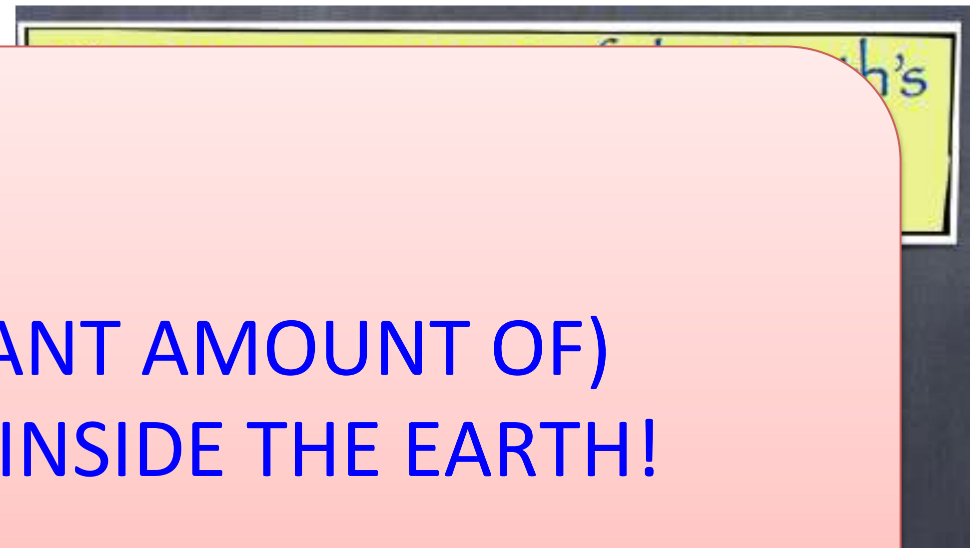


Gravitational measurement of the Earth's mass

$M_{earth\text{-}grav} = (5.9724 \pm 0.0003) \times 10^{24}$ kg

However: (1) The Earth's mass



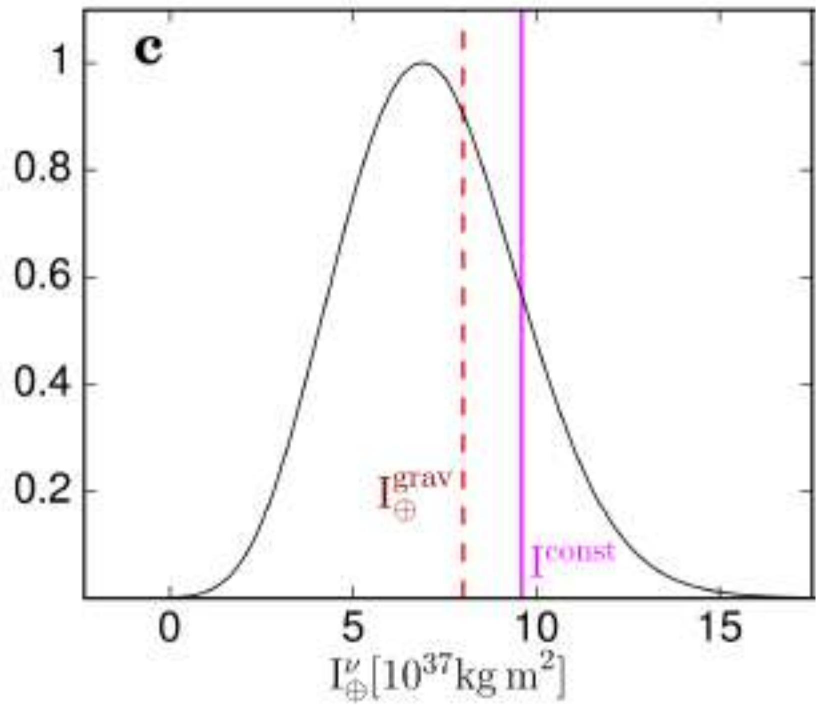


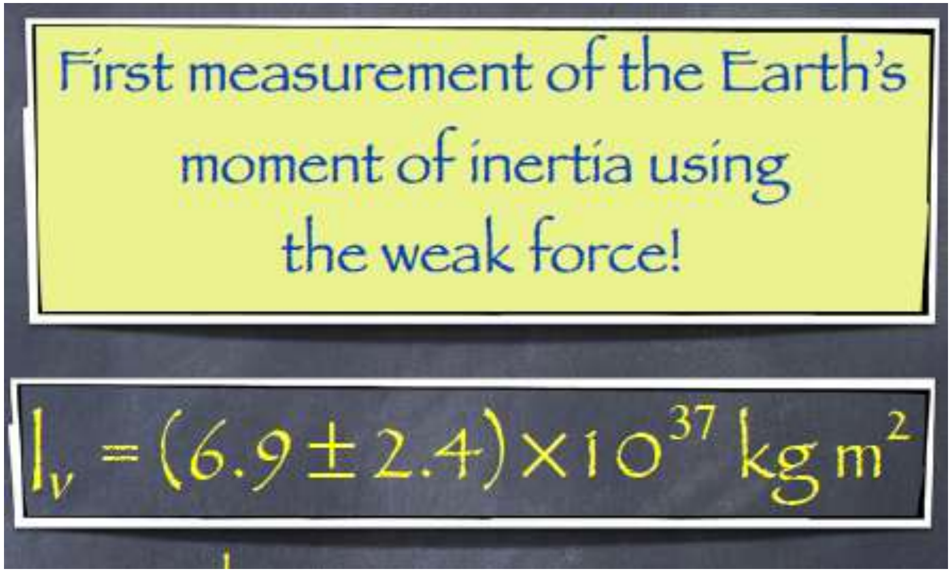
NO (SIGNIFICANT AMOUNT OF)
DARK MATTER INSIDE THE EARTH!

Gravitational measurement of the Earth's mass

$M_{earth\text{-}grav} = (5.9724 \pm 0.0003) \times 10^{24}$ kg

(2) The Earth's moment of inertia

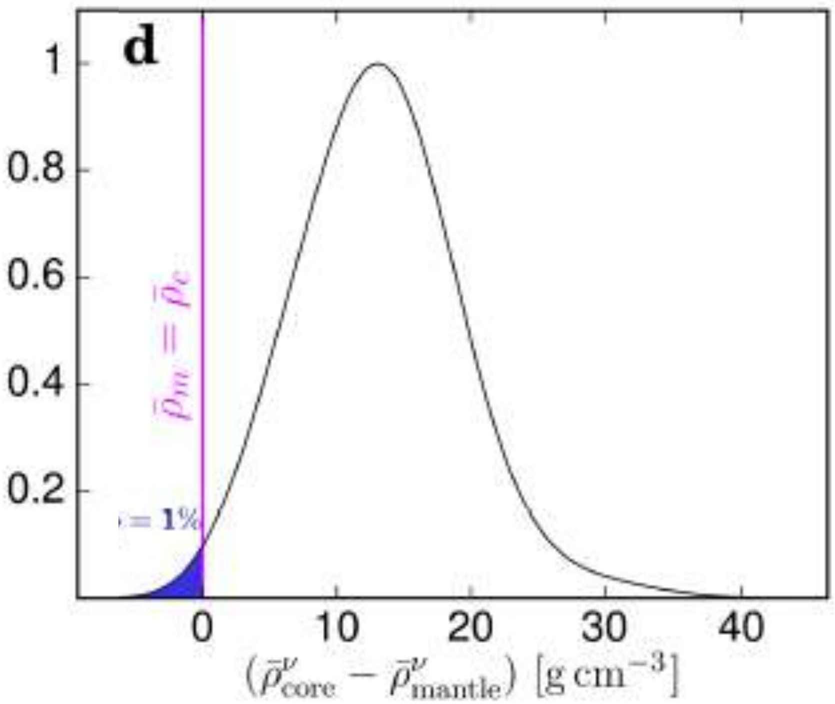


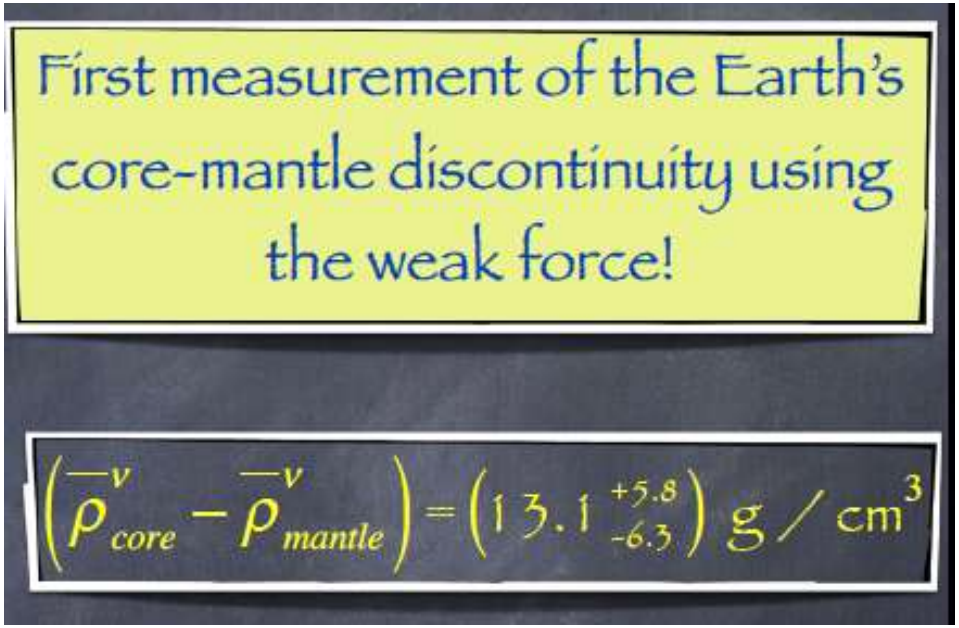


Gravitational measurement of the Earth's moment of inertia

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

(3) Core denser than the Mantle

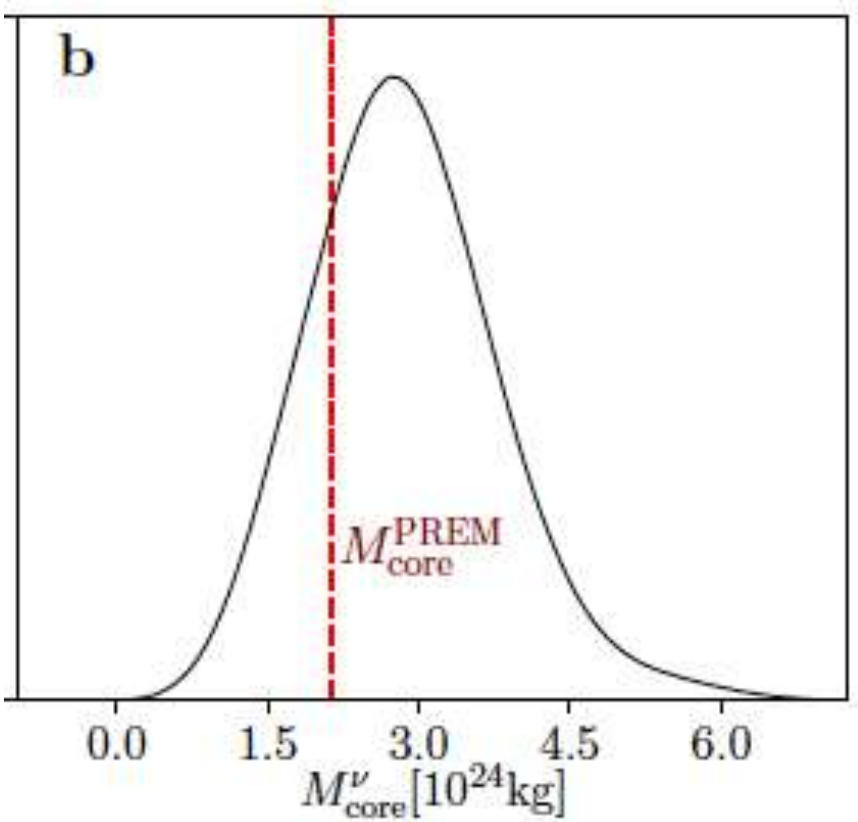


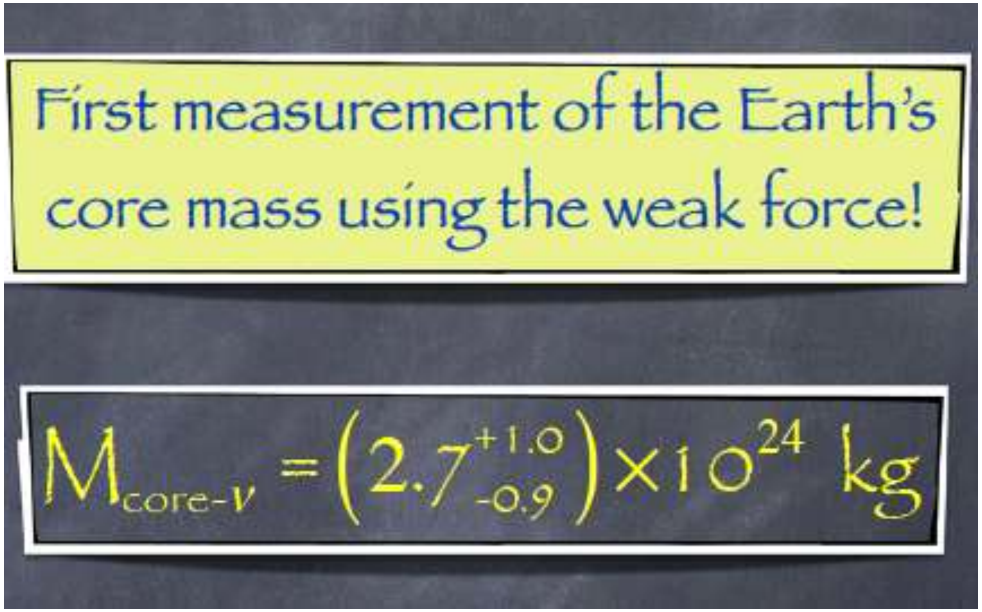


A Mantle denser than the Core has a p-value p = 0.011 !!!

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

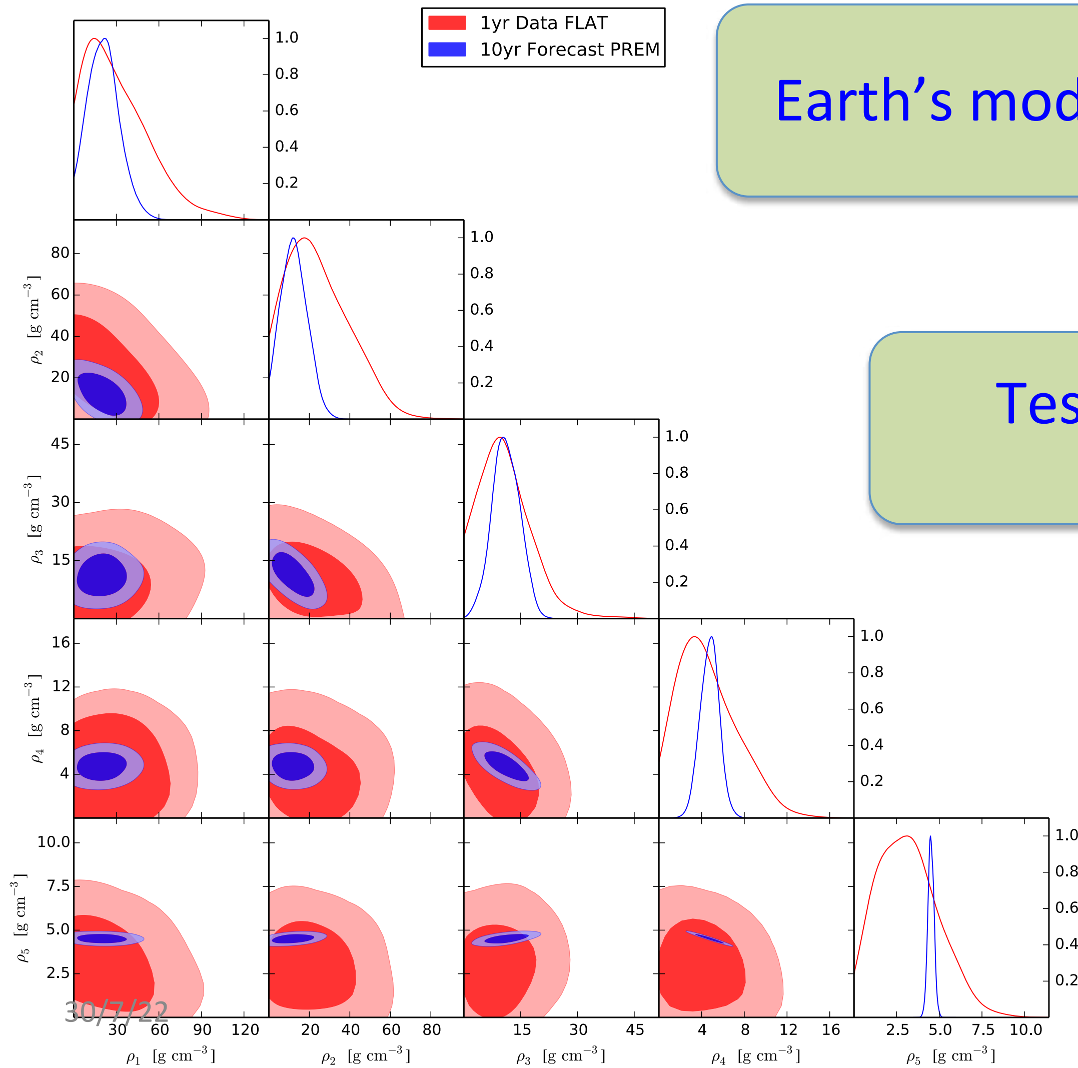
(4) The Earth's core mass





Important constraint for seismology!

Forecast with 10 years of data

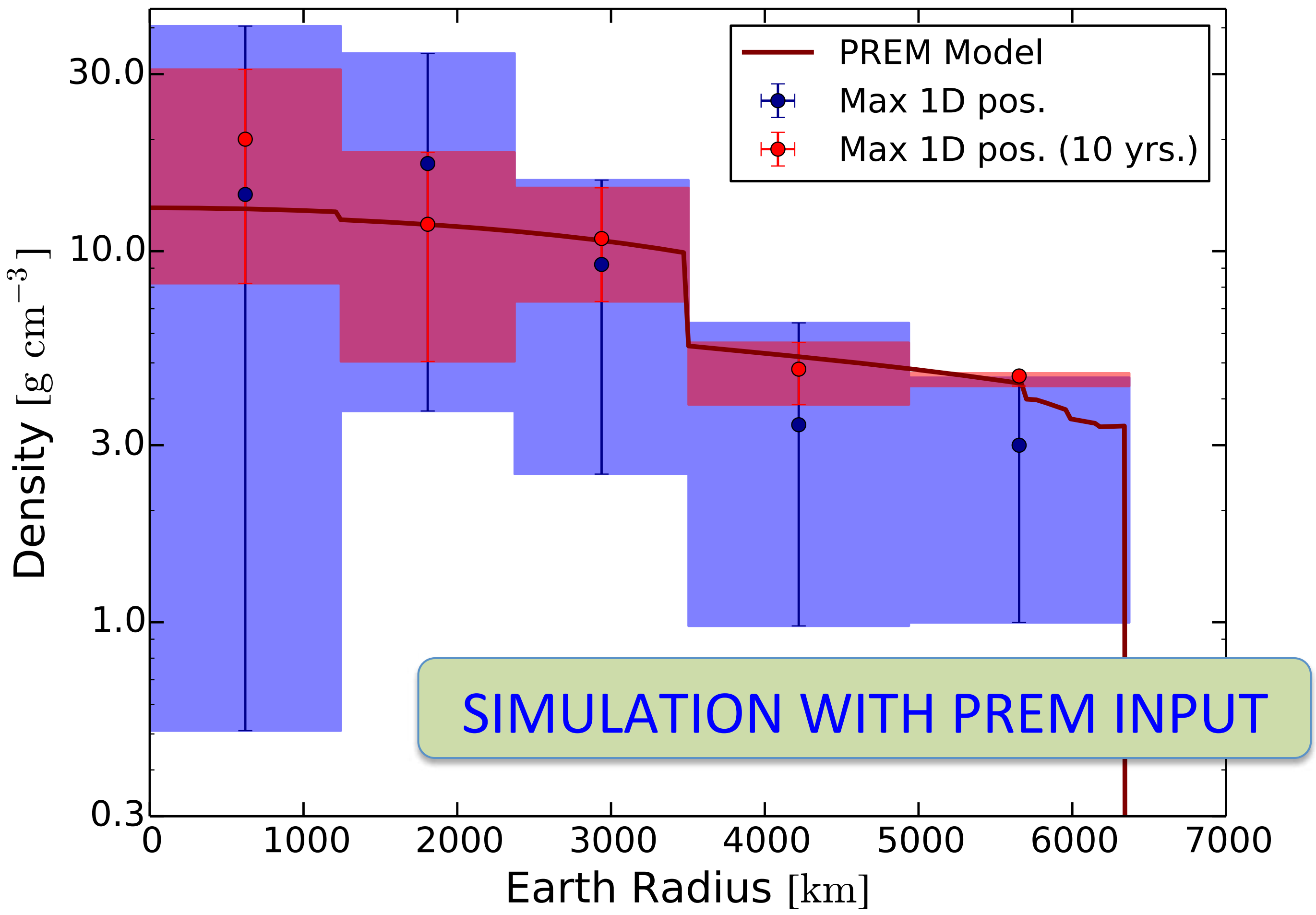


Earth's modelling: more shells

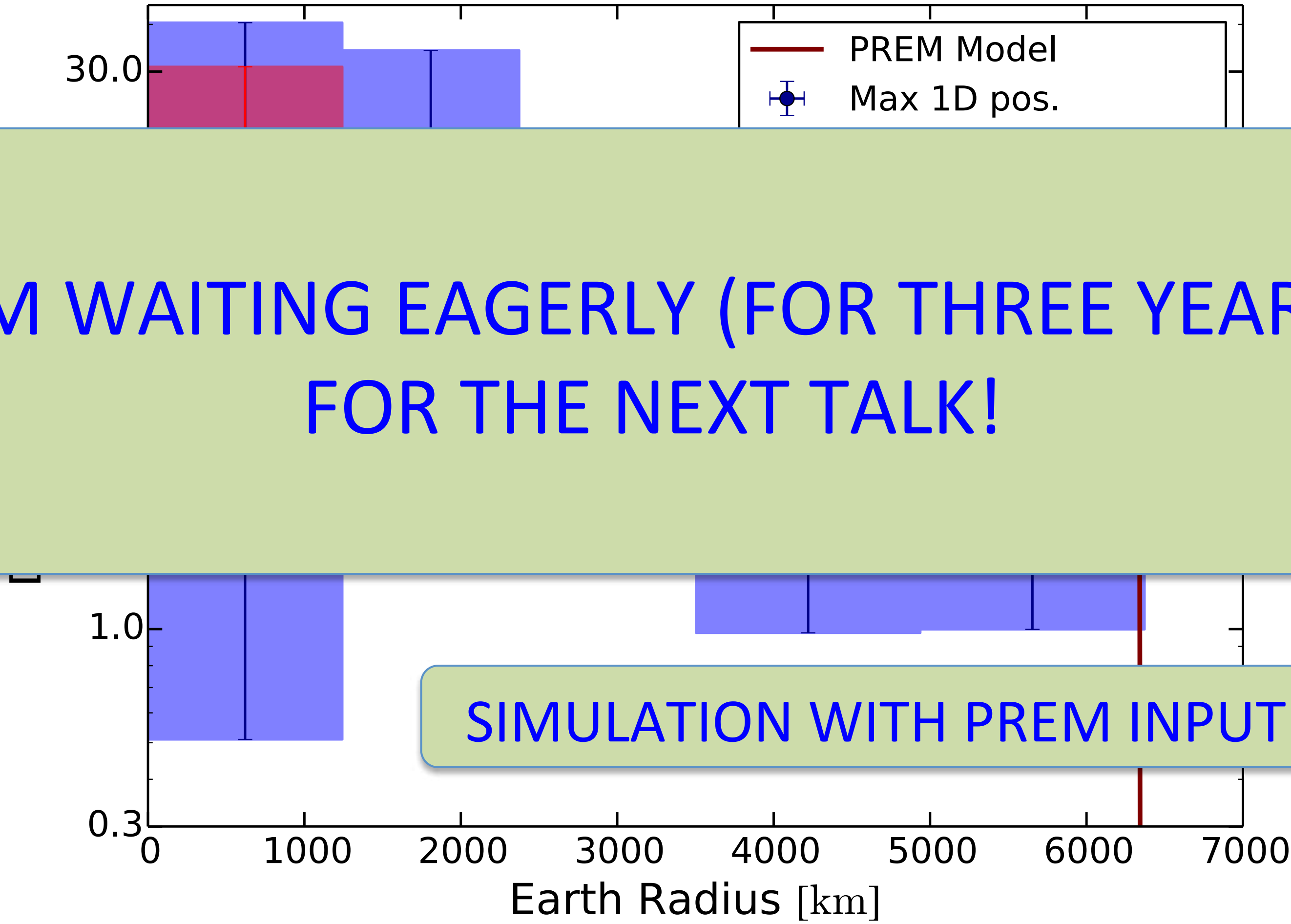
Test of the Inner-Outer Core discontinuity

Independent localization of the Core-Mantle Boundary

1-d density profile with 10 years



1-d density profile with 10 years



I'M WAITING EAGERLY (FOR THREE YEARS) FOR THE NEXT TALK!

SIMULATION WITH PREM INPUT

MY OWN CONCLUSIONS AT THE 2019 EGU GENERAL ASSEMBLY

AN EPIPHANY:

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!

We hope to present the new results here NEXT YEAR!

MY CONCLUSIONS, NOW

OLD STUFF: the first 1-dimensional density profile
(with one year of IceCube data) gave us:
M_{earth}, I_{earth}, $\Delta\rho_{CMB}$, M_{core}

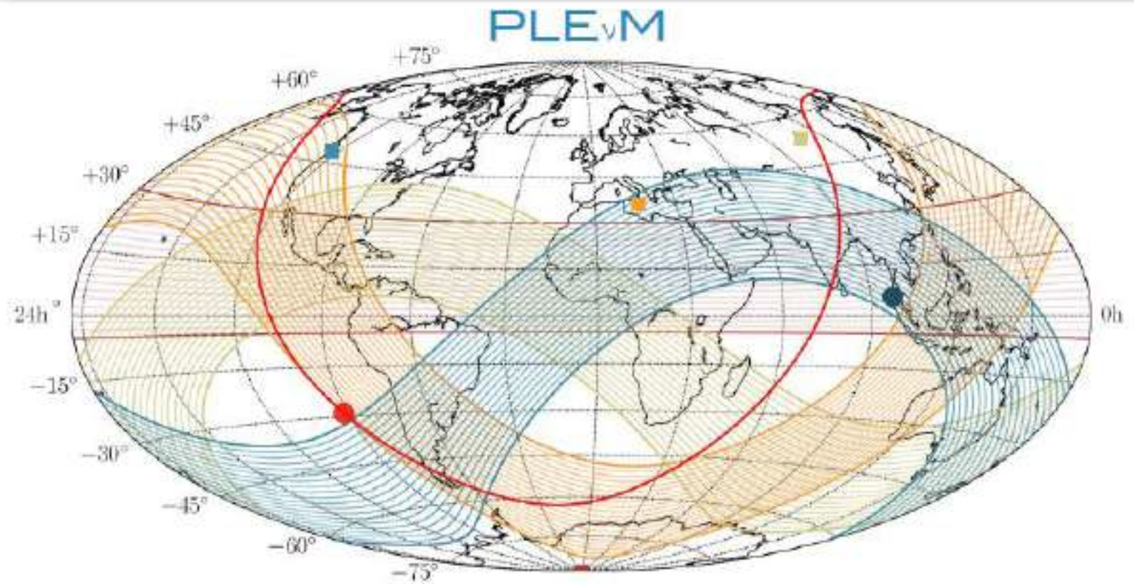
Donini, Palomares-Ruiz, Salvado, Nature Physics 15 (2019) 37

Hopefully, we will see a 10 times increase in statistics in next talk. Better measurements of the above observables, possibly a finer Earth's model (more shells)

WHAT NEXT?

MY CONCLUSIONS, NOW

New ν-Telescopes under construction or planned:
ARCA, Baikal-GVD, IceCube-Gen2….
1) increase in statistics will be approx. 10 times faster;
2) Looking from both emispheres: test of anisotropies!



By approx. 2030:
6-8 km^3 optical detectors in the Southern and Northern emispheres

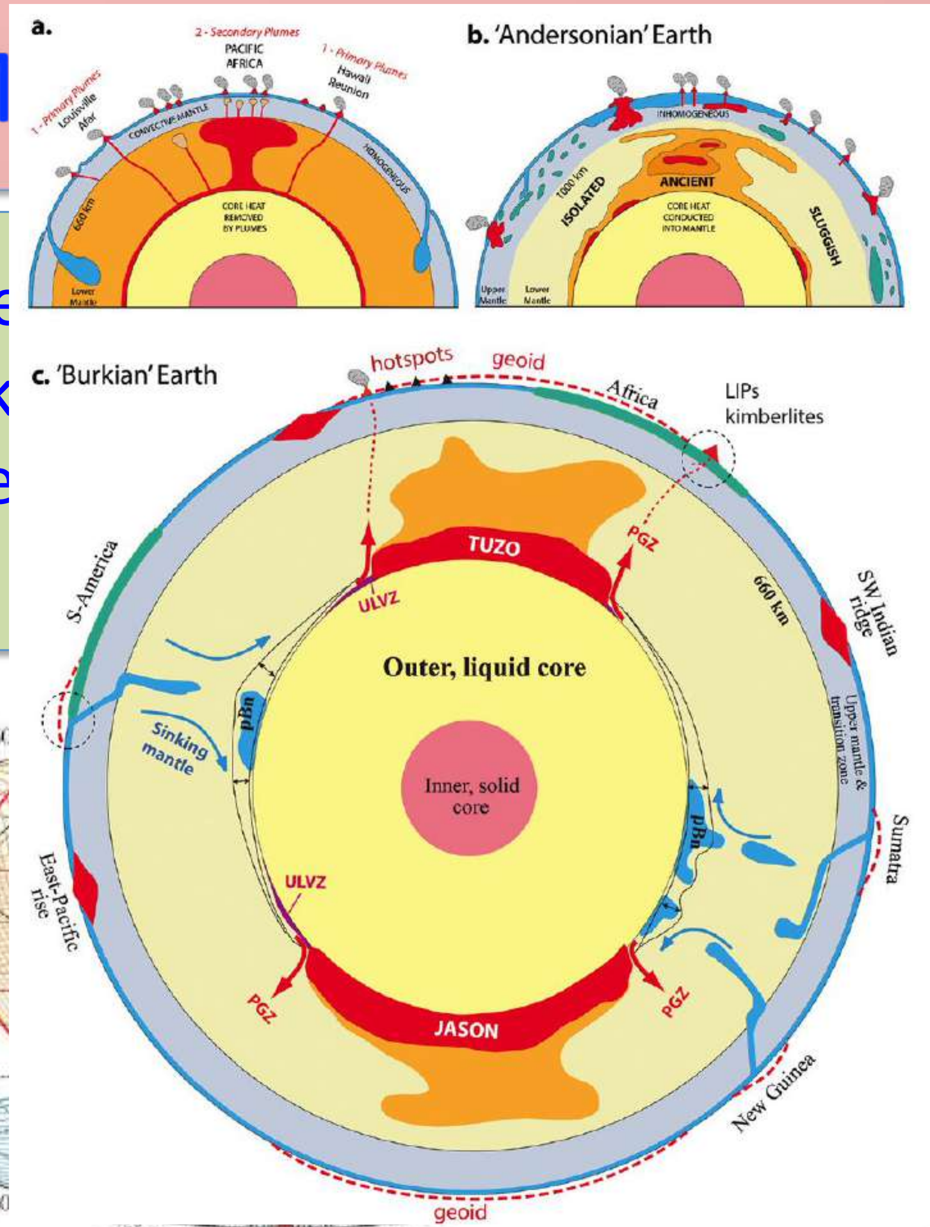
M W

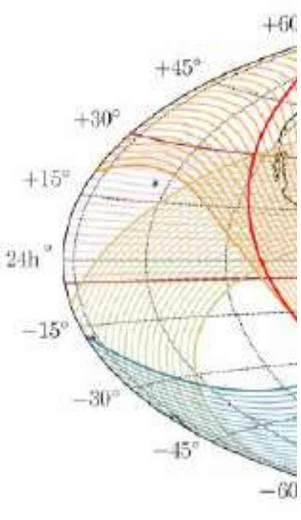
New ν-Tele planned:

ARCA, Baik

1) increase times faster;

2) Looking anisotropies!





By approx. 2030:
6-8 km^3 optical detectors in the Southern and Northern emispheres

Backup slides

Backup on Geophysics

How densities are measured?

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

1) Adams-Williamson equation ('20s)

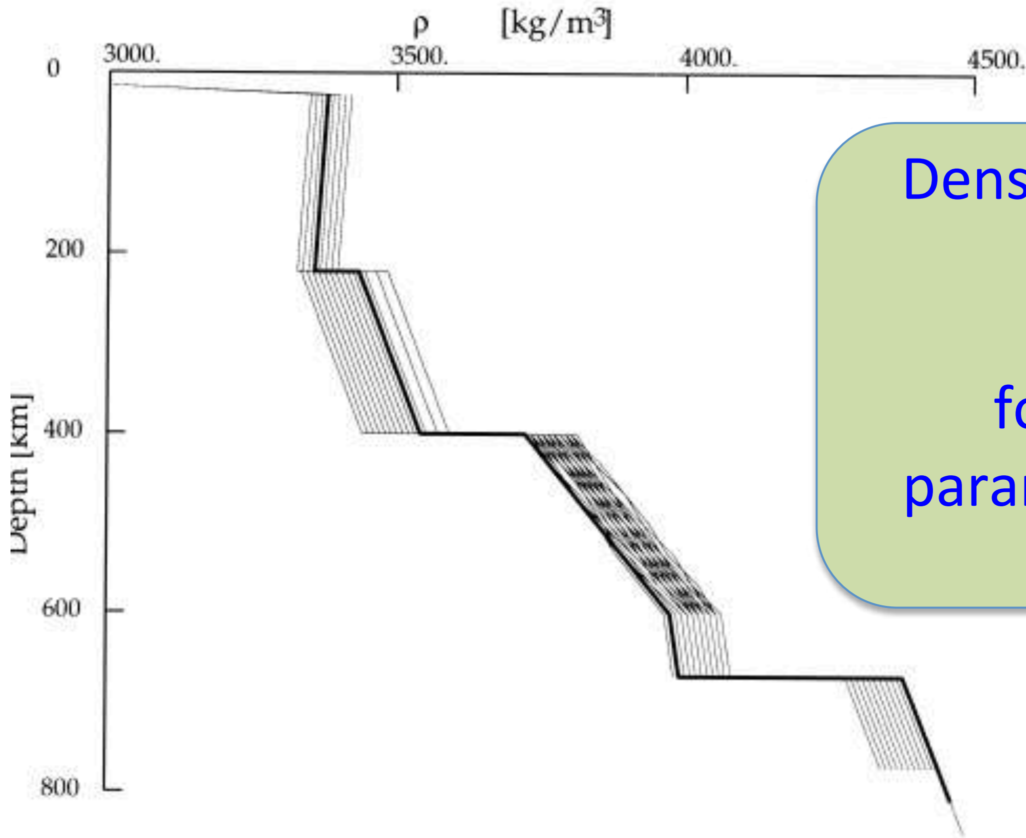
$$\frac{d\rho}{dr} = -\rho(r)\frac{g(r)}{\Phi(r)}$$

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

2) Free-oscillation modes ('90s on)

Composition dependence! Gravitational profile dependence!

Model dependence of the profile…

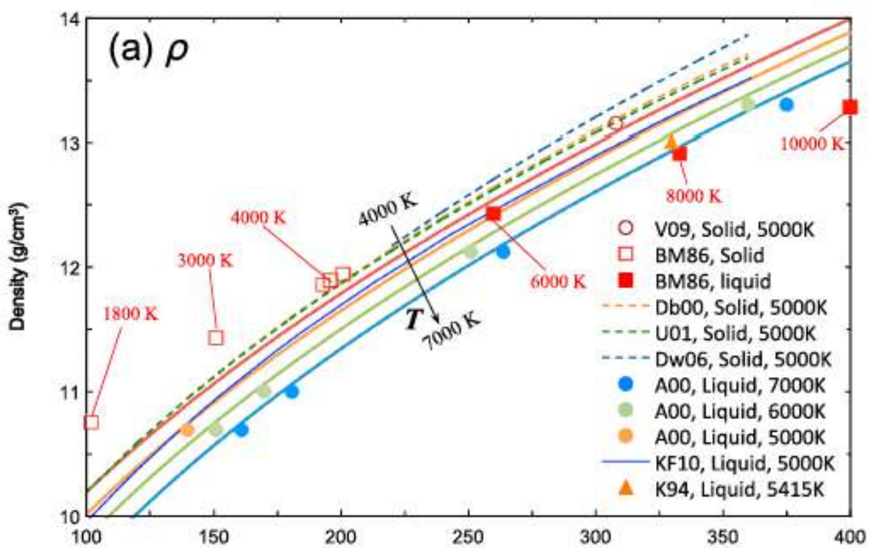


Density variation in the
CRUST
for different
parameter choices:
3-5%

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

Inner core uncertainties

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



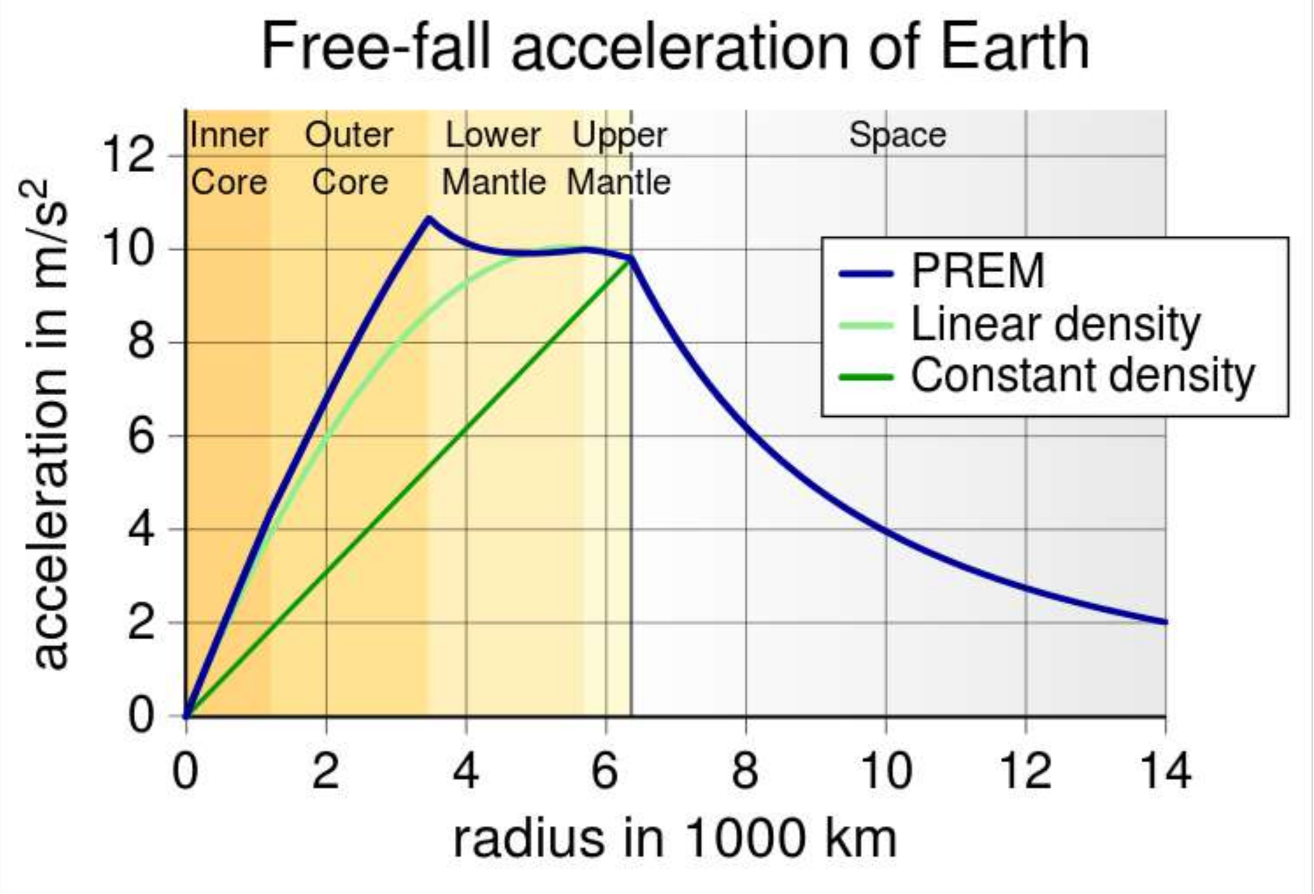
Estimated temperature range still very large: 4000-10000 K

Composition guessed (iron-nickel?)

Missing Xenon problem

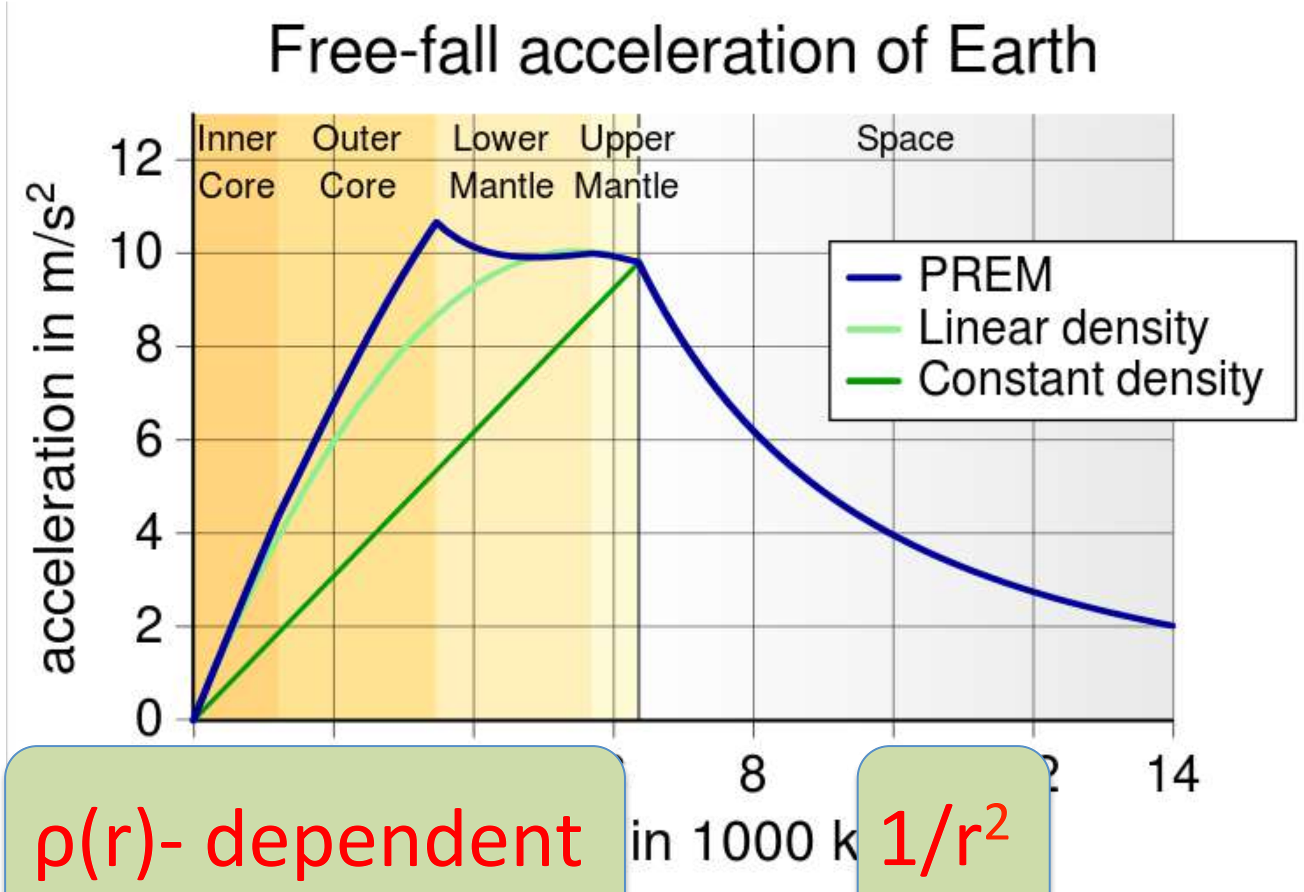
Ishikawa, Tsuchiya, Tange, J. GeoPhys. Res. (Solid Earth) 119 (2014)

An input to geophysics: g(r)



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

An input to geophysics: g(r)

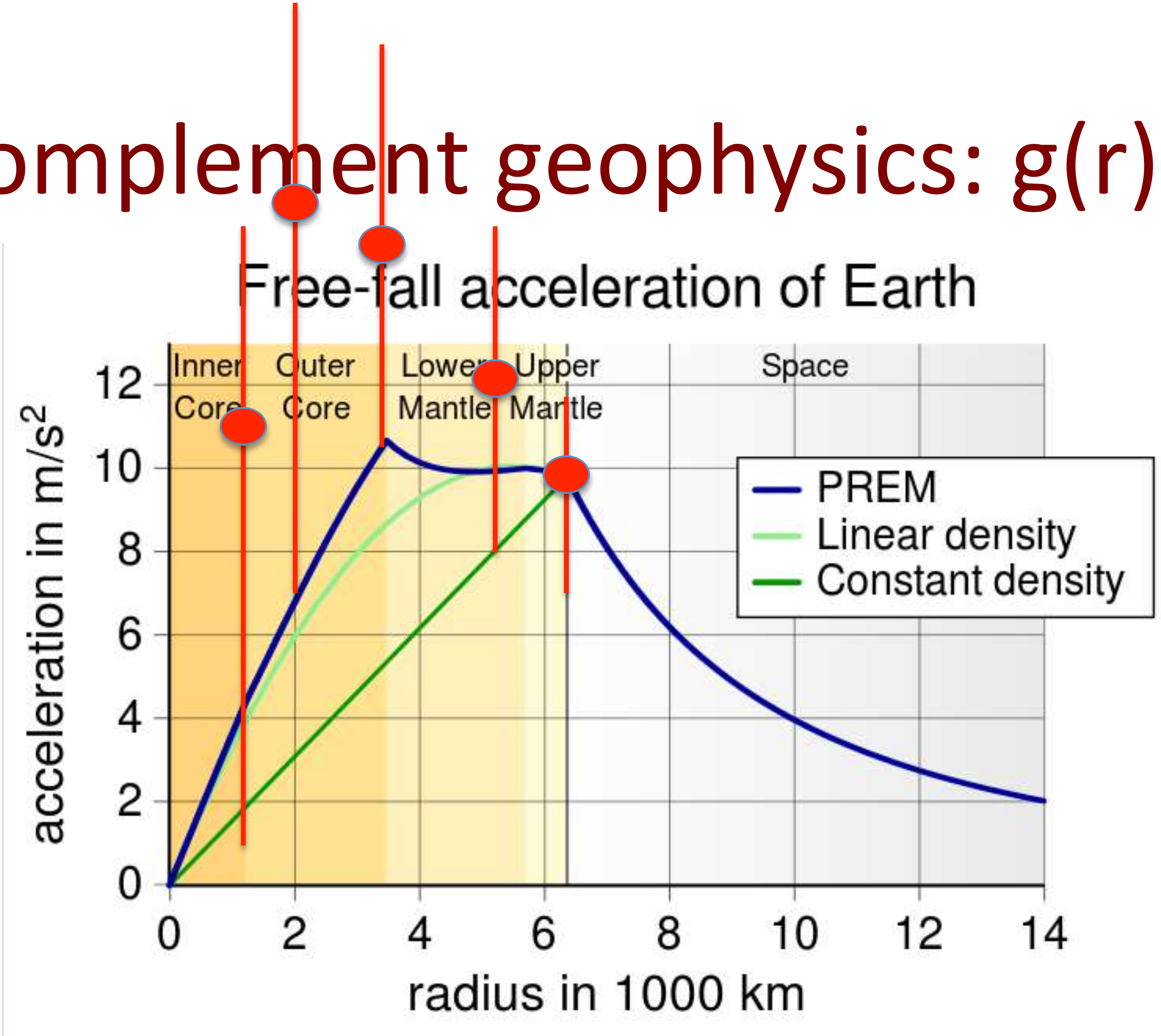


ρ(r)- dependent

$1/r^2$

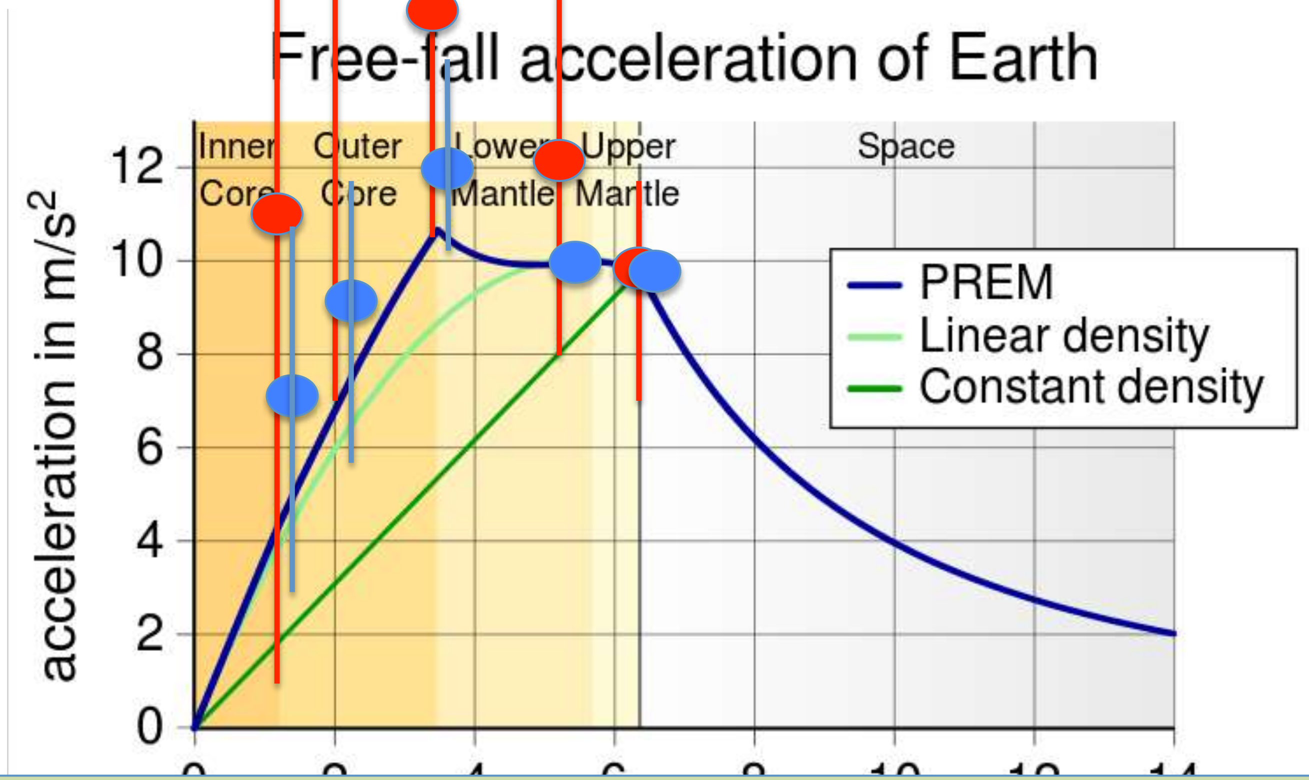
The Earth's gravitational profile is needed to compute ρ(r) from earthquake waves velocities

Complement geophysics: g(r)



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

Complement geophysics: g(r)

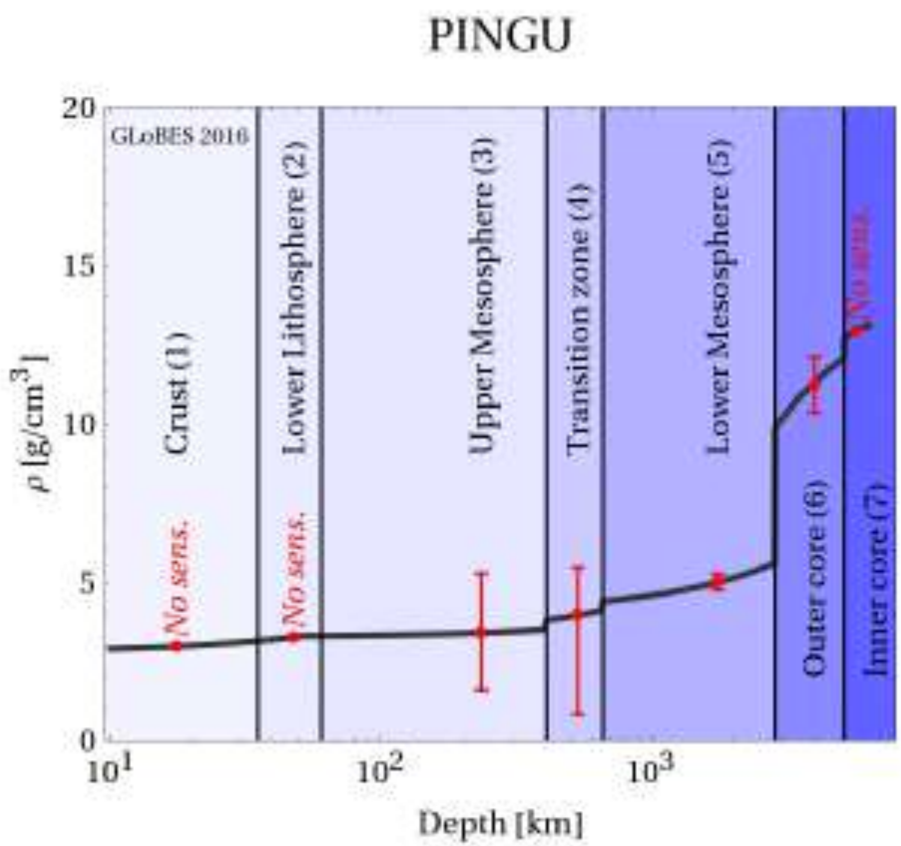


A GOOD NEUTRINO MEASUREMENT OF g(r) COULD BE ADDED TO SEISMOLOGY AS A CONSTRAINT TO REDUCE ERRORS

ties

Backup on Forecasts and new data

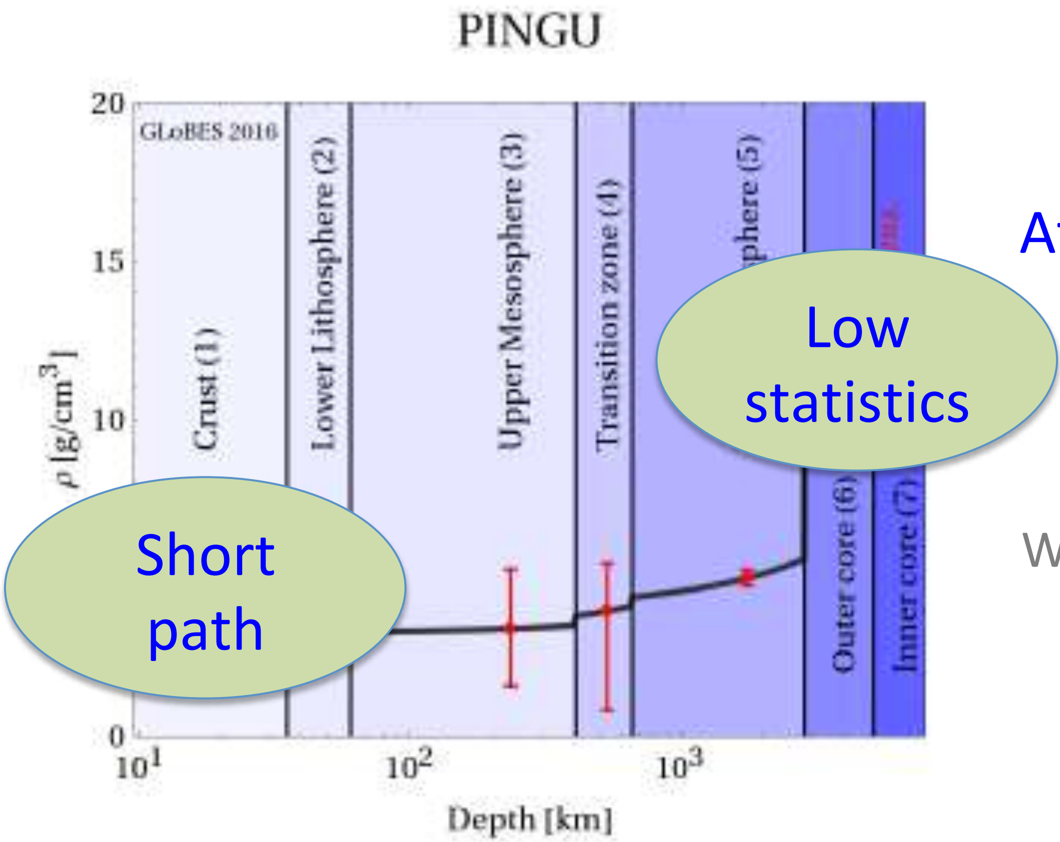
Oscillation forecast



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

Winter, Nucl. Phys B908 (2016)

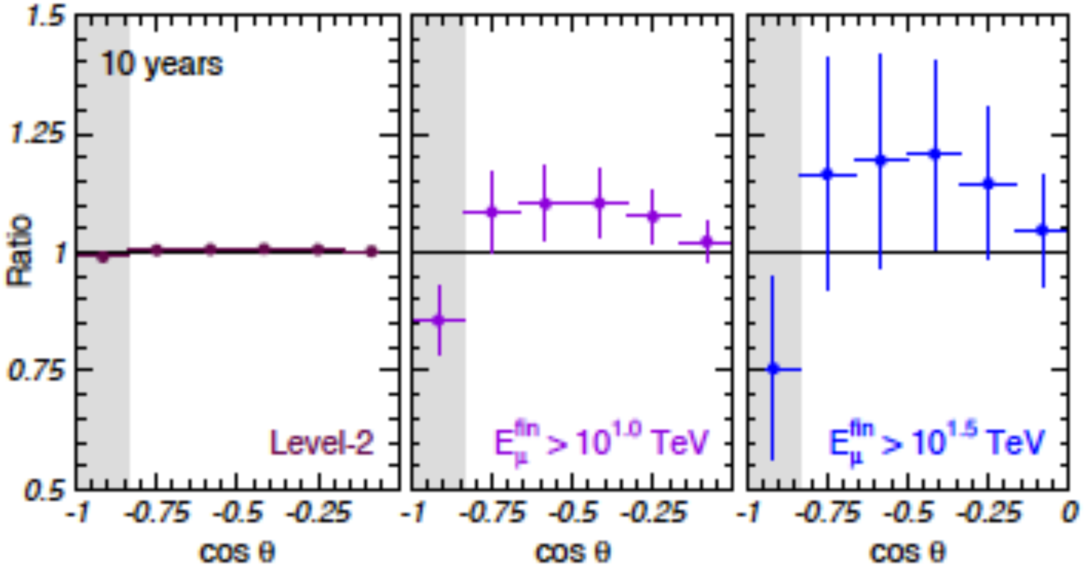
Oscillation forecast



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

Winter, Nucl. Phys B908 (2016)

Absorpion forecast

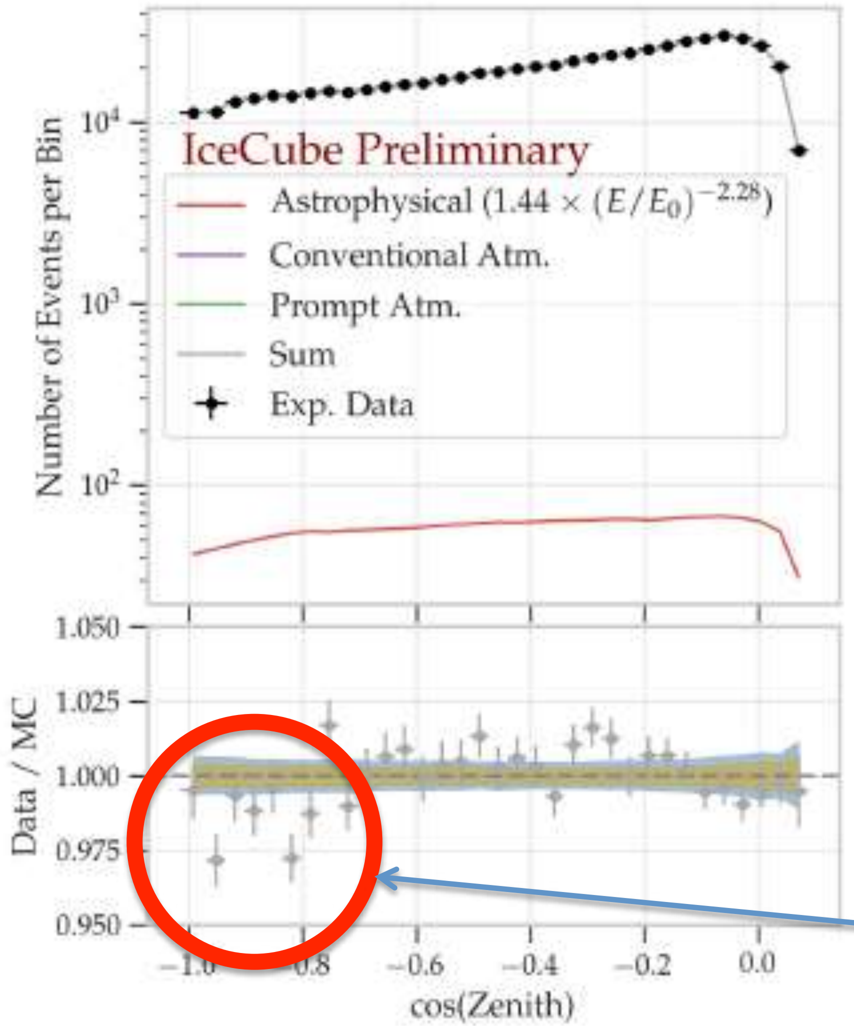


After 10 years of data taking at IceCube using neutrino attenuation

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

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

New IceCube samples



Same happens with the 9.5 years IceCube sample

J. Stettner, this workshop

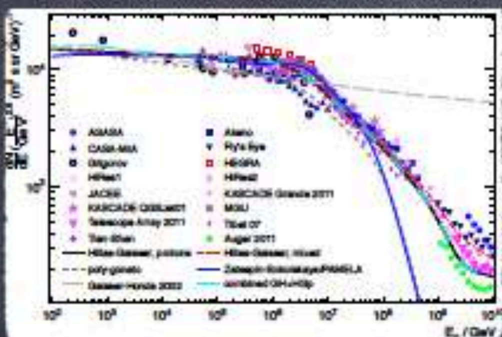
Possibly an up-going events suppression

Backup on Systematics and Statistical Errors

ANALYSIS INGREDIENTS

Primary cosmic-ray spectrum

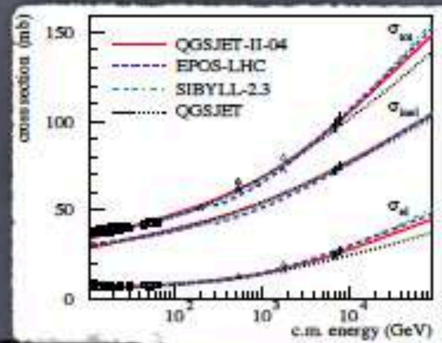
3-population models to fit cosmic-ray data

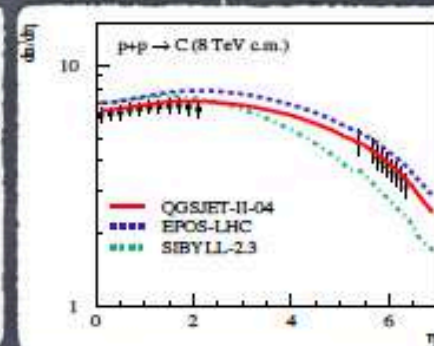


A. Fedynitch, J. B. Tjus and P. Desiati, Phys. Rev. D86:114024, 2012

Hadronic-interaction model

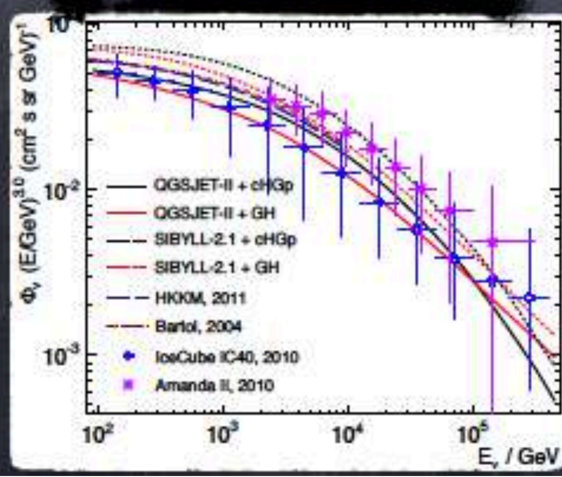
Models for cascade development





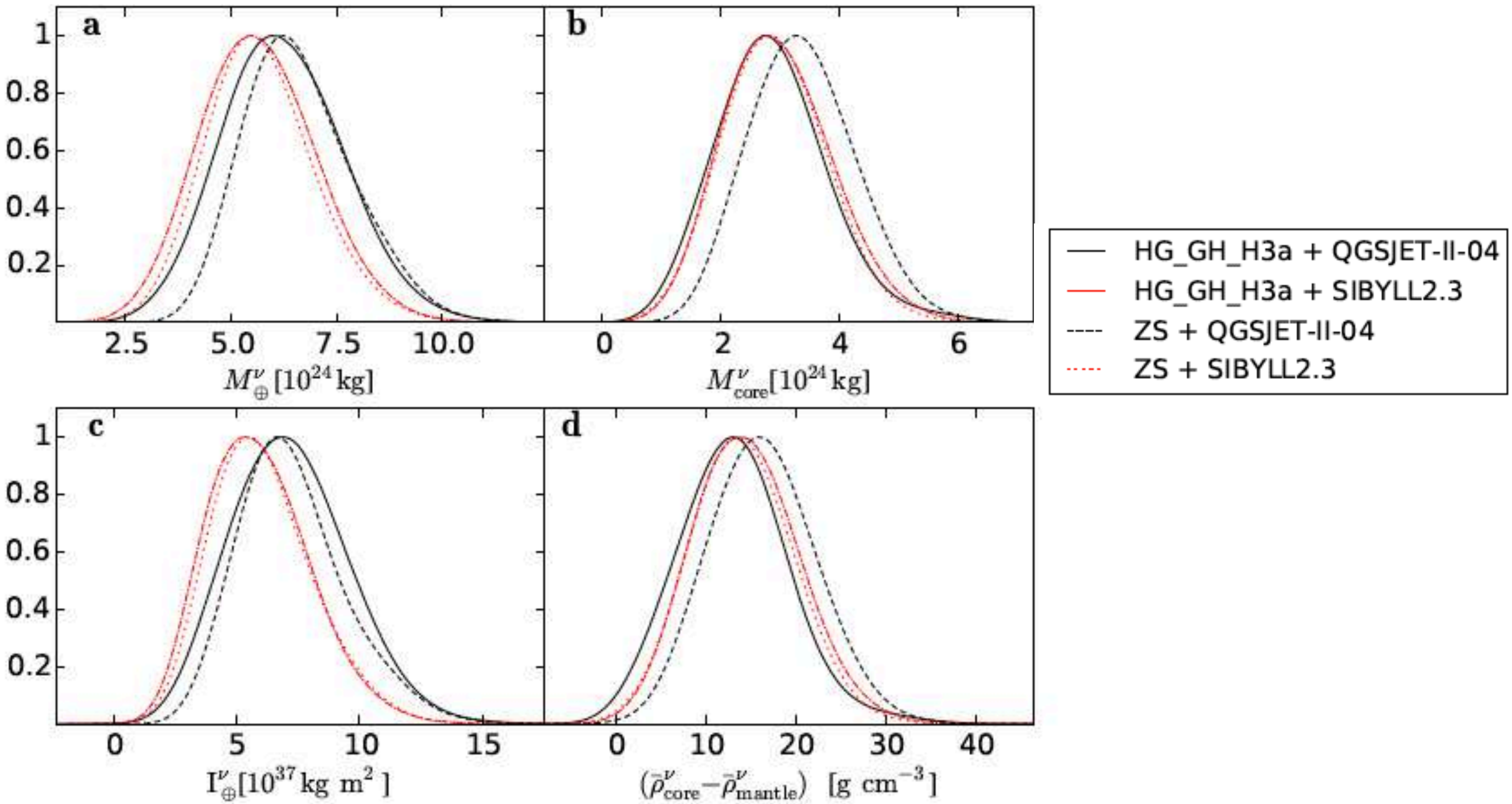
S. Ostapchenko, ECRS 2016, arXiv:1612.09461

Neutrino flux

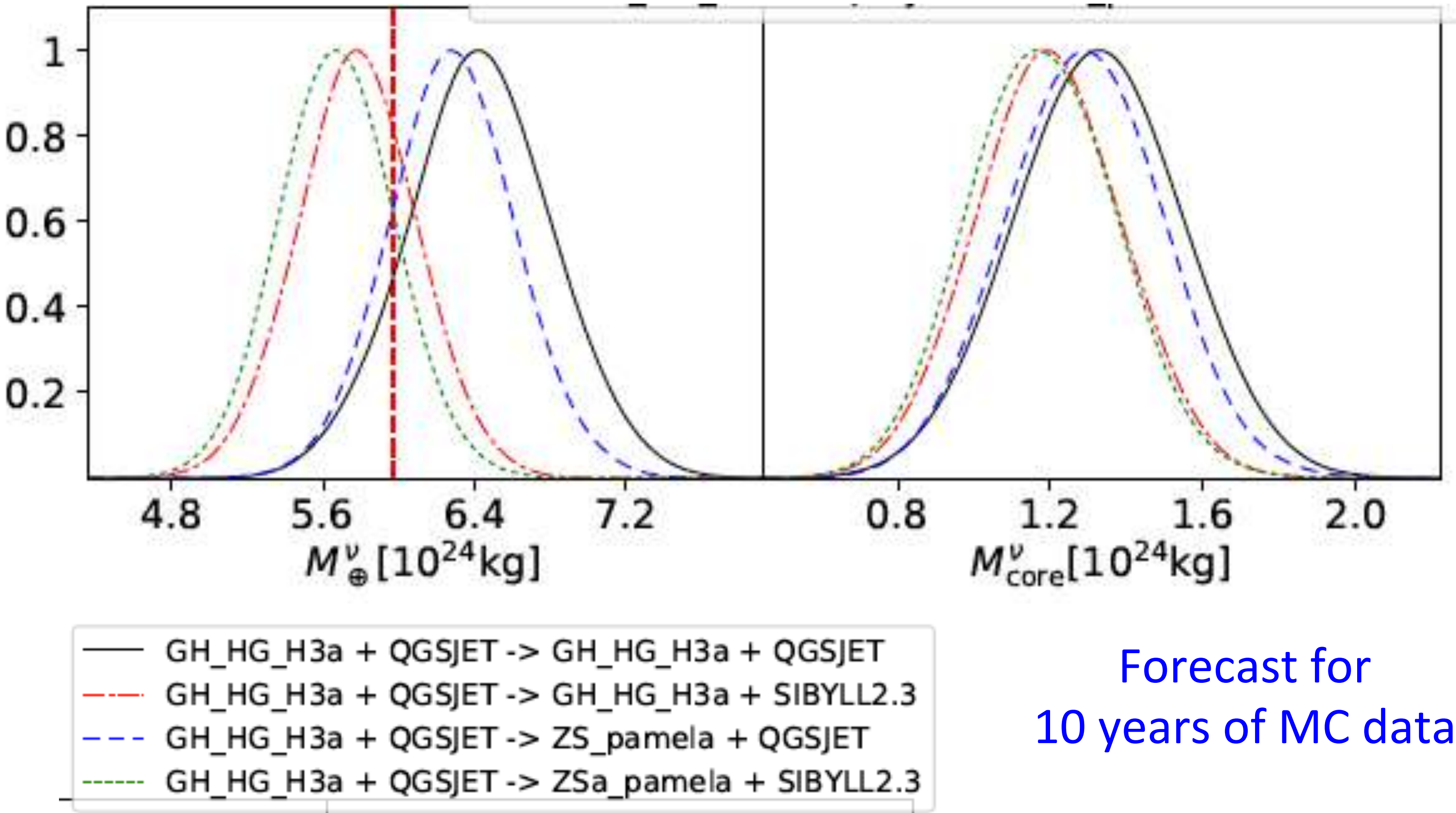


A. Fedynitch, J. B. Tjus and P. Desiati, Phys. Rev. D86:114024, 2012

Flux and hadronic model dependence

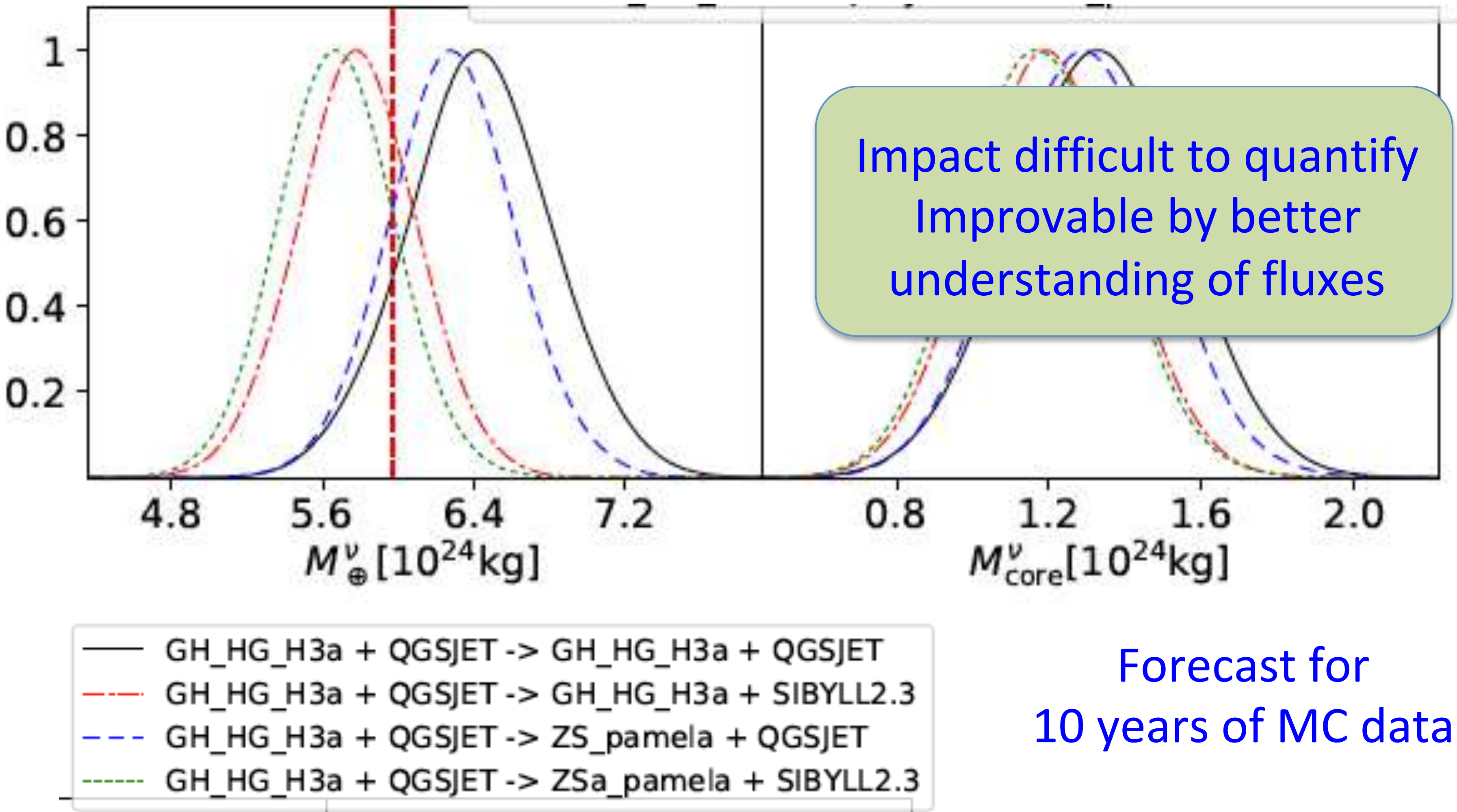


Flux and hadronic model dependence, 2



Forecast for
10 years of MC data

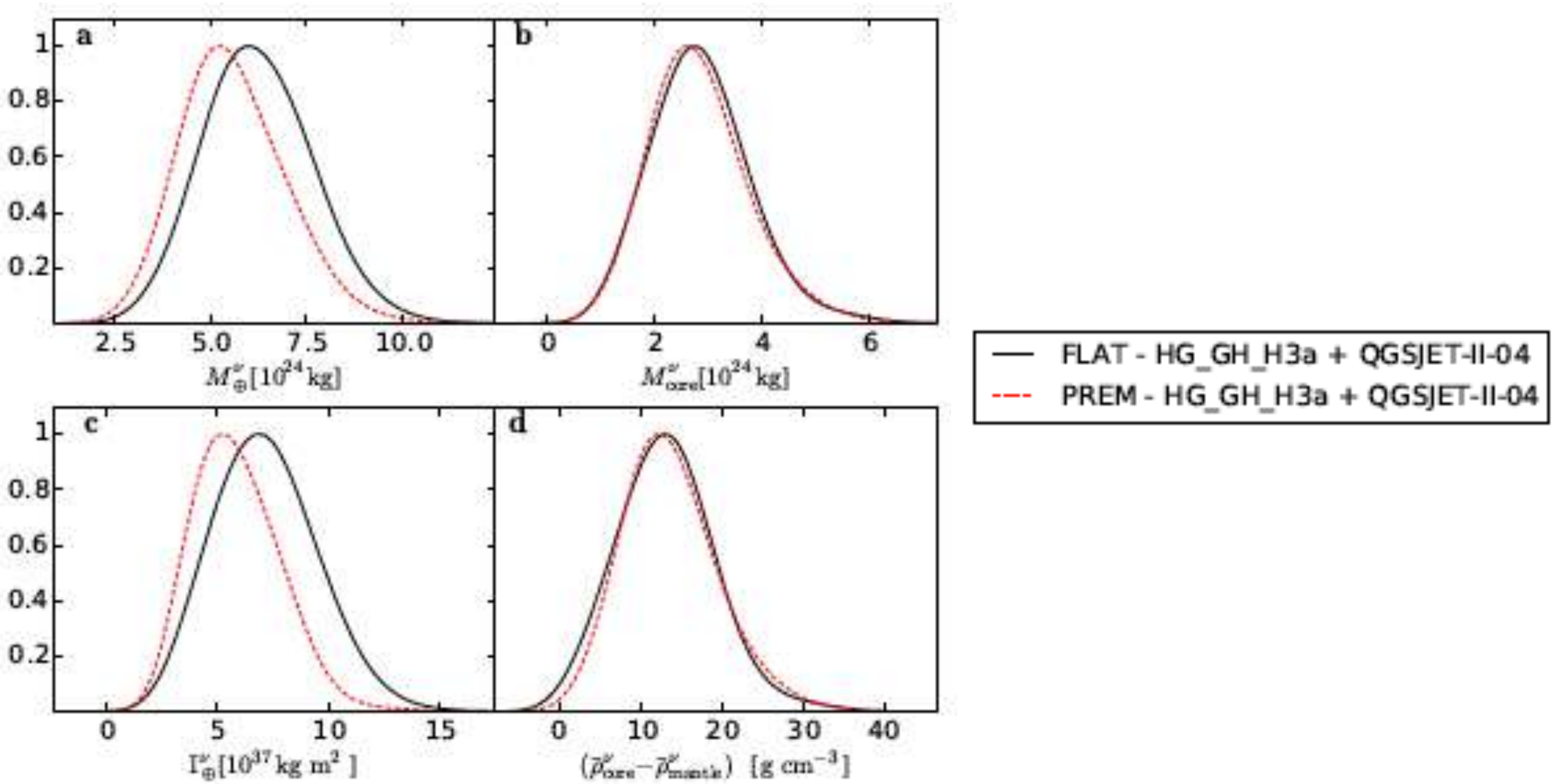
Flux and hadronic model dependence, 2



Impact difficult to quantify
Improvable by better understanding of fluxes

Forecast for
10 years of MC data

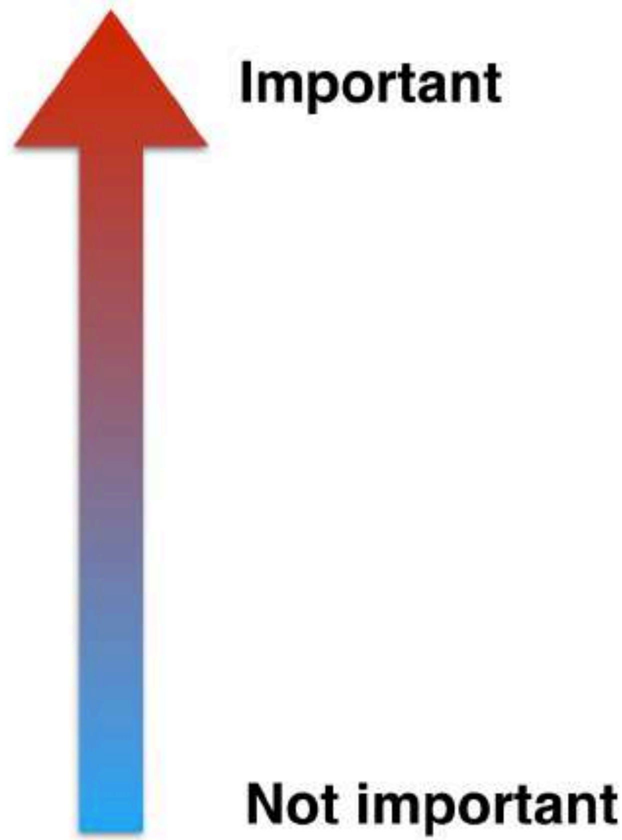
Earth’s profile dependence



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

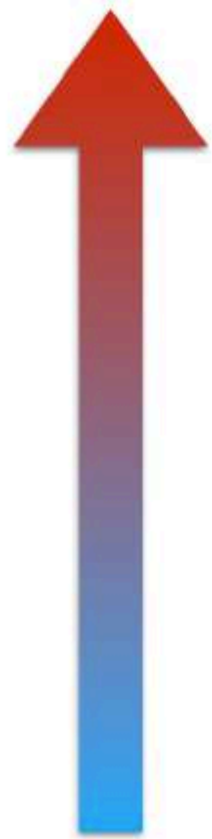


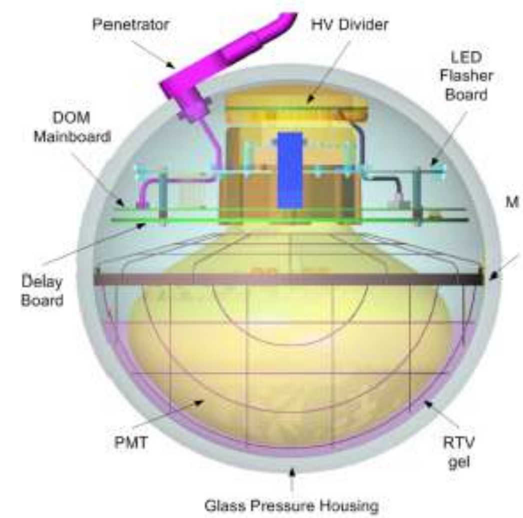
Systematics importance

- *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

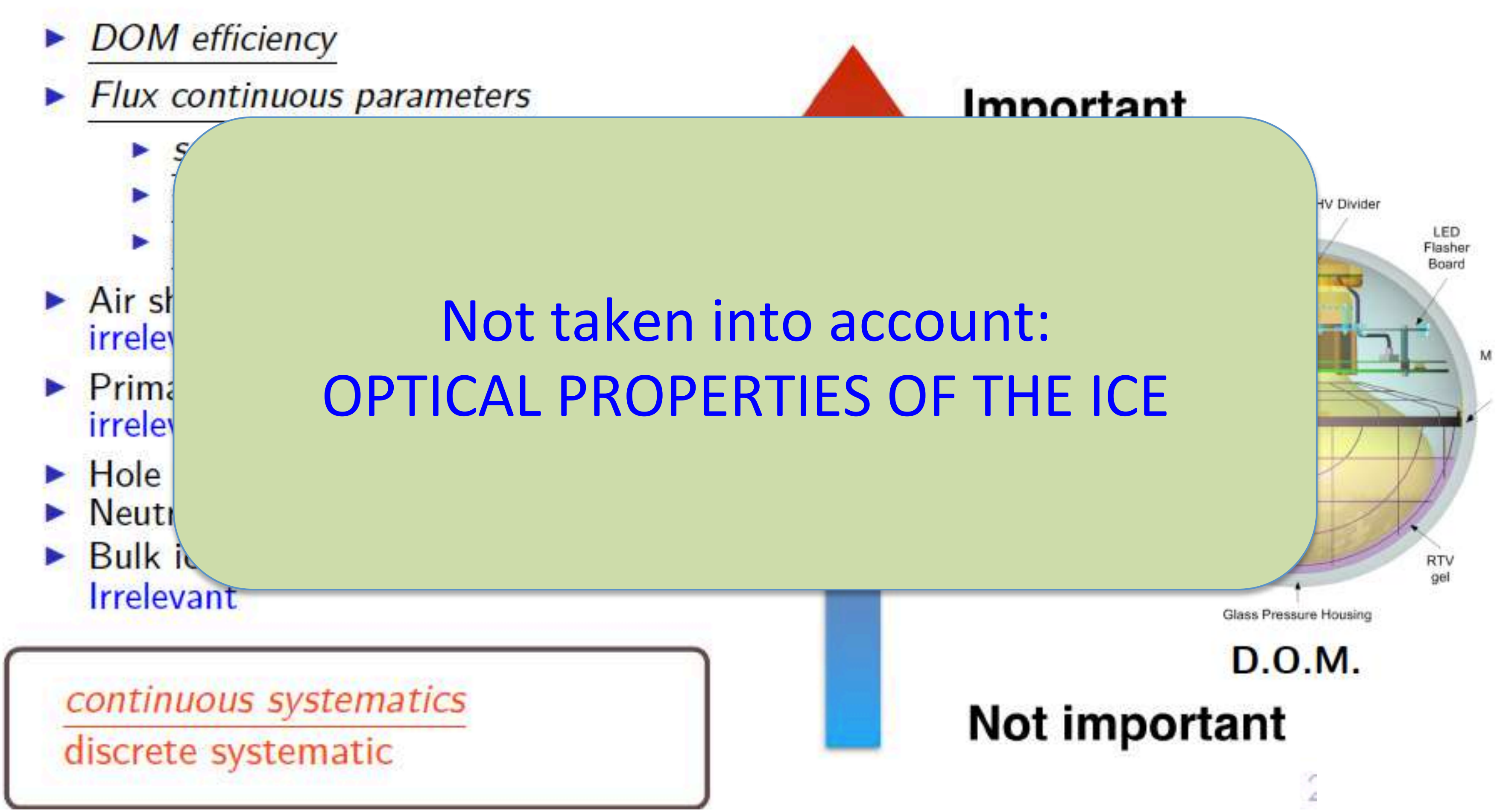




D.O.M.

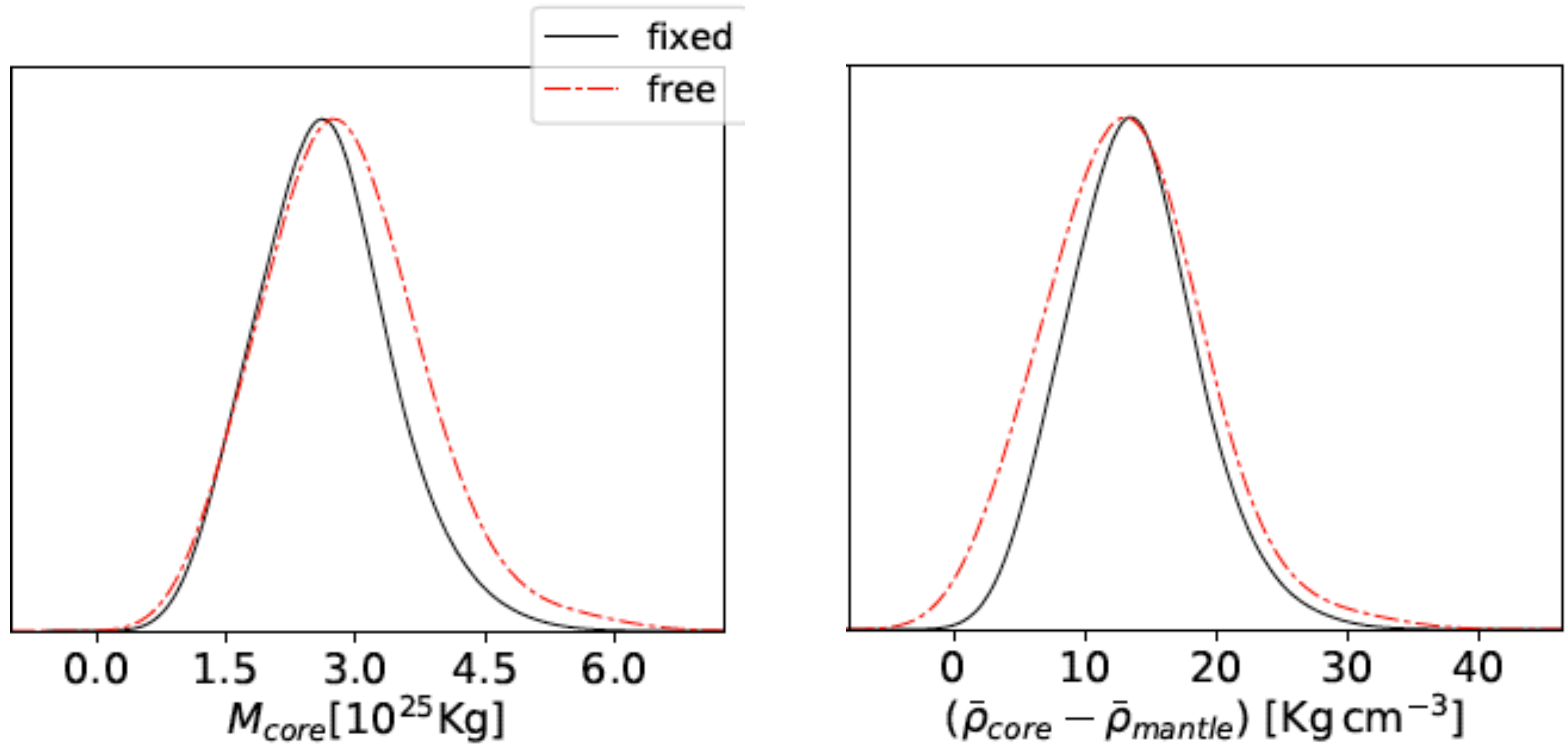
Not important

Systematics importance

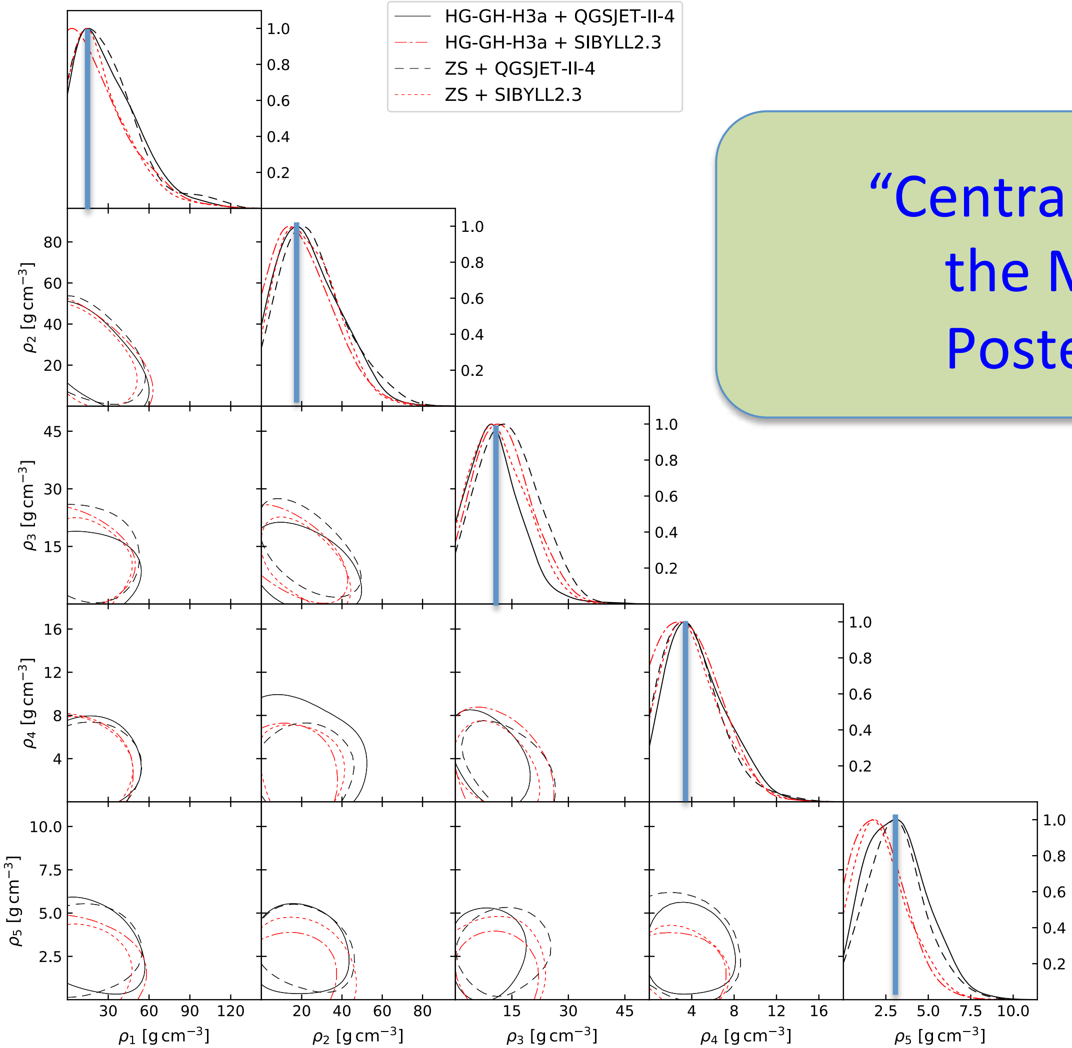


Not taken into account:
OPTICAL PROPERTIES OF THE ICE

Impact of systematics on the error

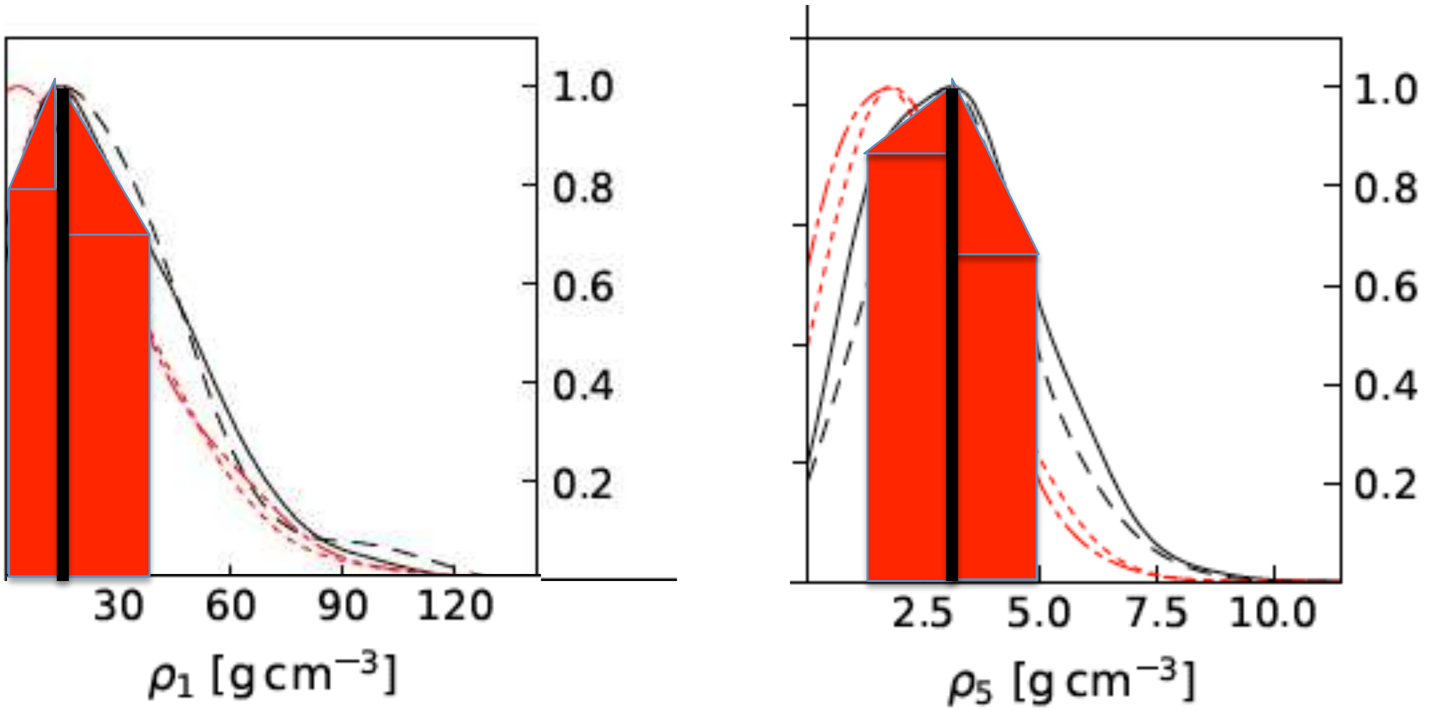


What are the dots?

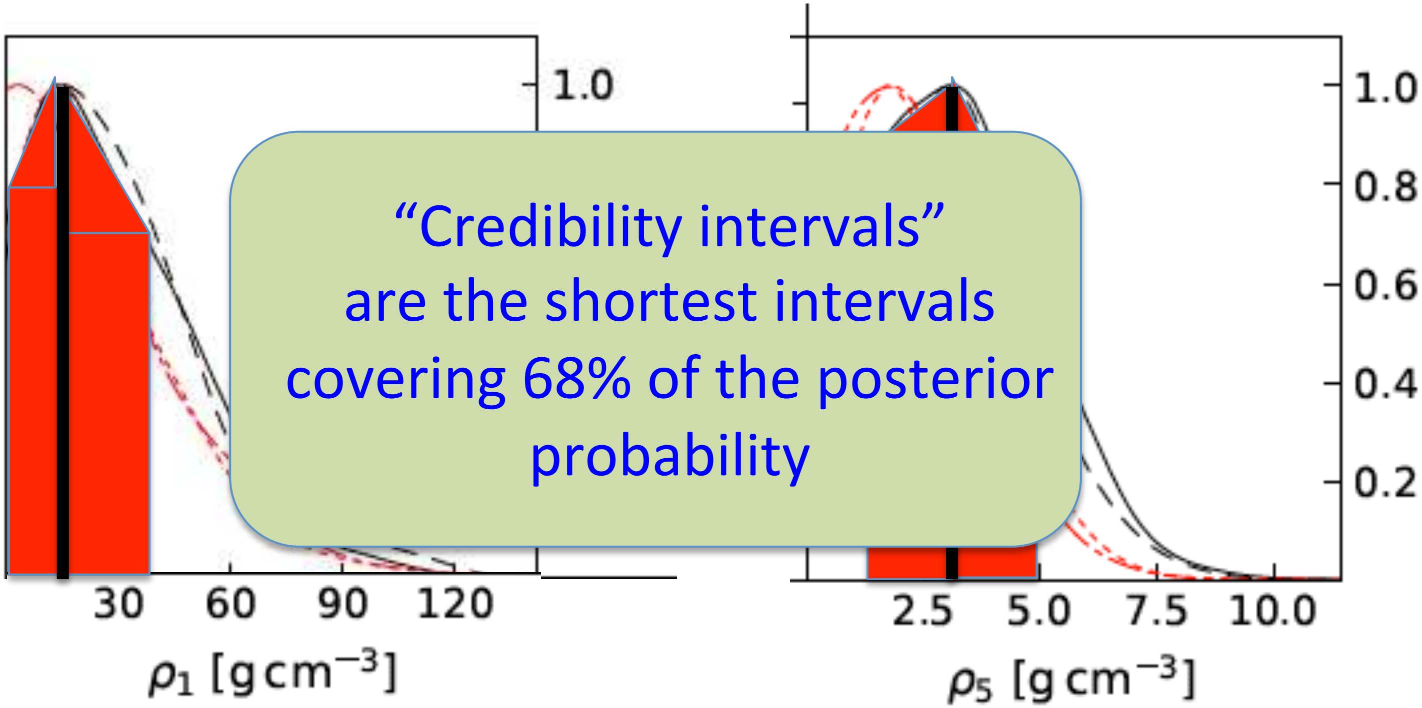


"Central values" represent the Maximum of the Posterior Probability

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

Variability 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
$M_{\oplus}^{\nu}$ [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}

Impact of constraints

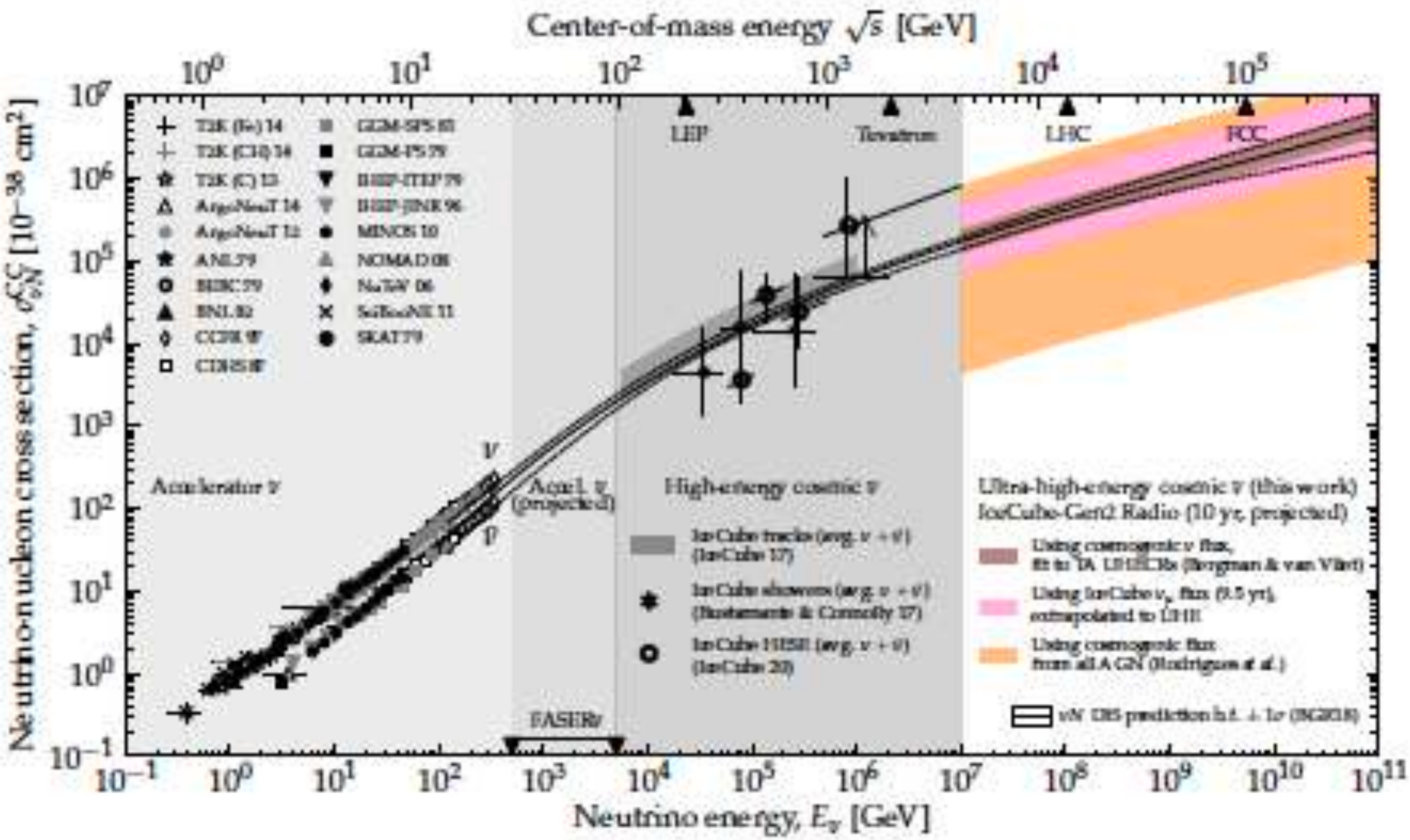
Adding the gravitational Earth's mass as an external constraint, results in fixing the mantle density:

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

More on HE cross-section



Valera, Bustamante, Glaser, JHEP 06 (2022)