Neutrino tomography of Earth

Andrea Donini (IFIC, Valencia)

Nature Physics 15 (2019) 37

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

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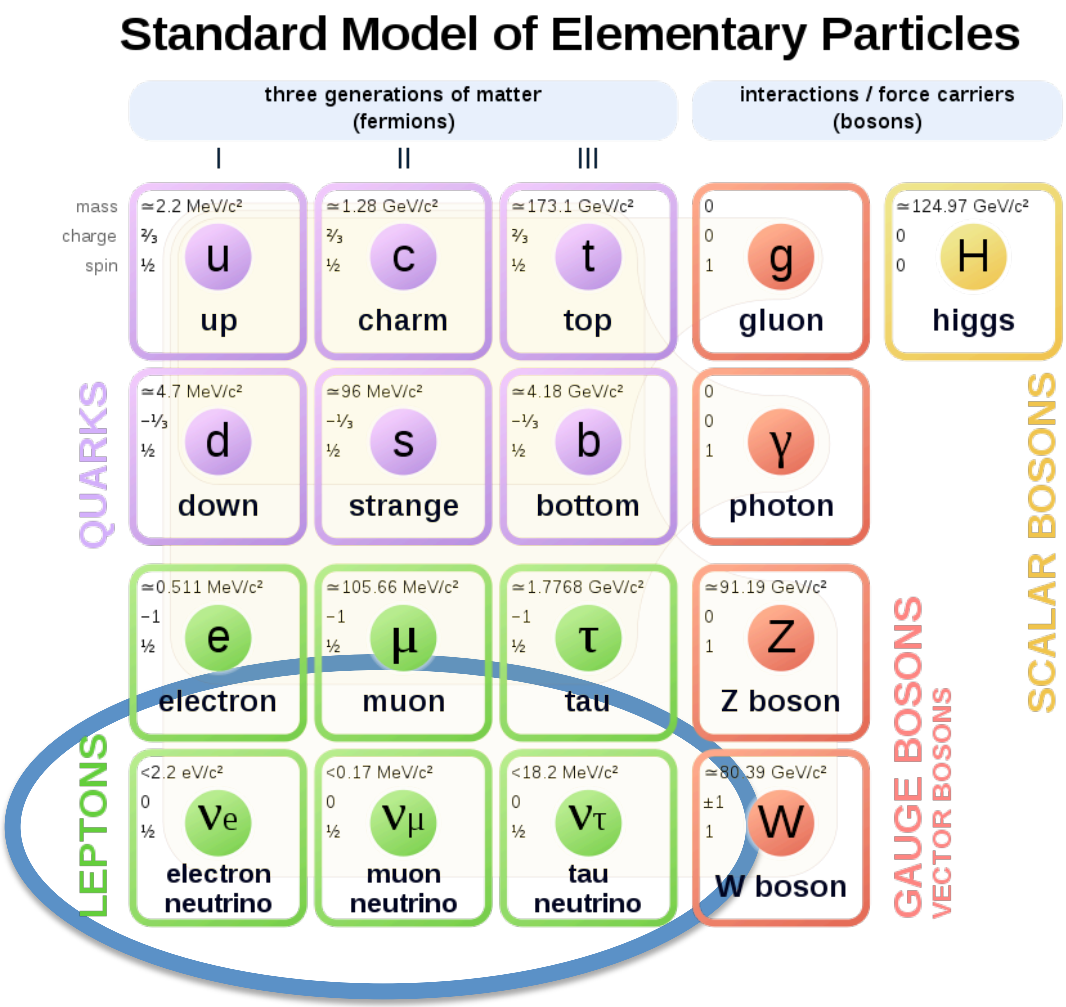
What neutrinos are…

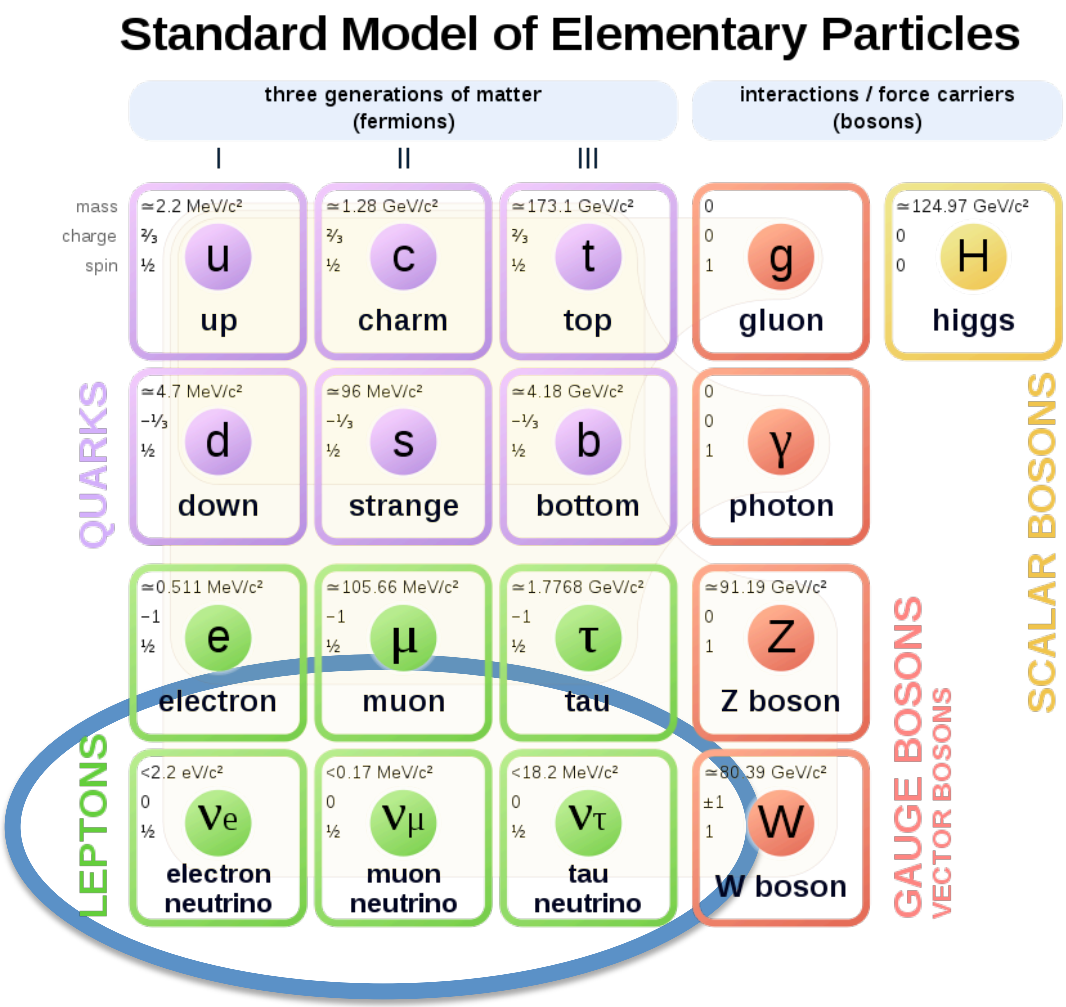


β-decay

$n \longrightarrow p\ e\ \nu_e$

(radioactivity…)

What neutrinos are…



β-decay

$n \longrightarrow p\ e\ \nu_e$

(radioactivity…)

Other decays

$\pi \longrightarrow \mu\ \nu_\mu$

$K \longrightarrow \mu\ \nu_\mu\ ,\ e\ \nu_e$

$\mu \longrightarrow \nu_\mu\ e\ \nu_e$

$\tau \longrightarrow \nu_\tau\ \mu\ \nu_\mu\ ,\ \nu_\tau\ e\ \nu_e$

What you need to know about neutrinos....

Neutrinos only interact WEAKLY
(no electromagnetic interactions, no strong interactions)

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What you need to know about neutrinos....

Neutrinos only interact WEAKLY
(no electromagnetic interactions, no strong interactions)

(1) Detectors must be gigantic (1 km^3) !

(2) The absorption length of a 40 TeV neutrino is the Earth's diameter

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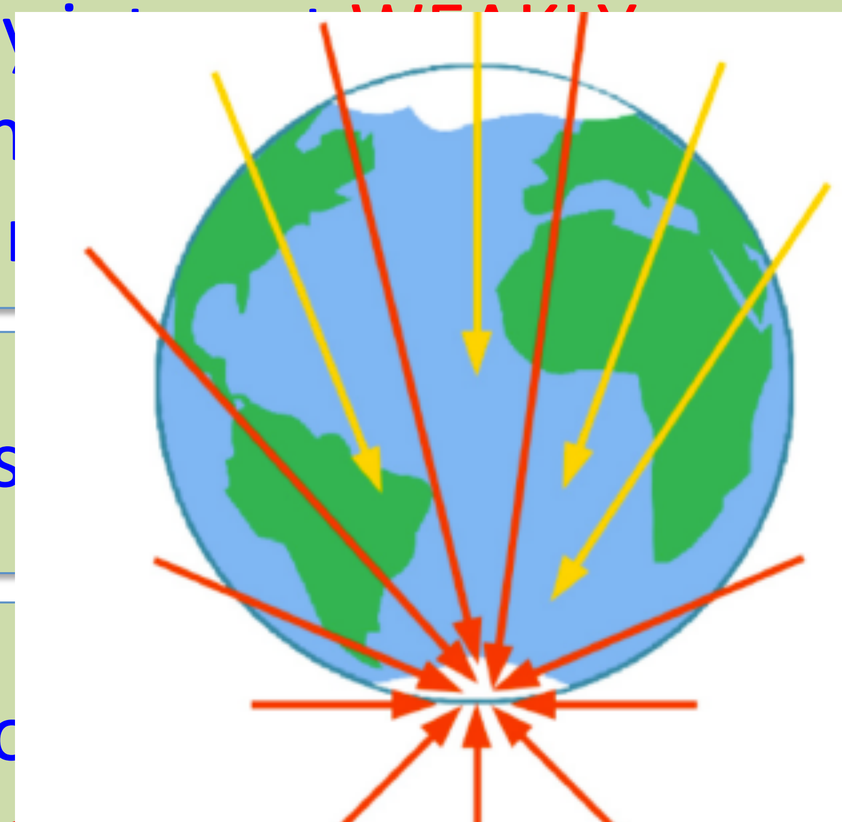
What you need to know about neutrinos….

Neutrinos only
(no electromagn
strong i

(1) Detectors mus

(2) The absorptio
neutrino is the


Lipari, NeuTel 2019, Venice

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Neutrinos and geophysics

GEO-NEUTRINOS…
(radiogenic heat)

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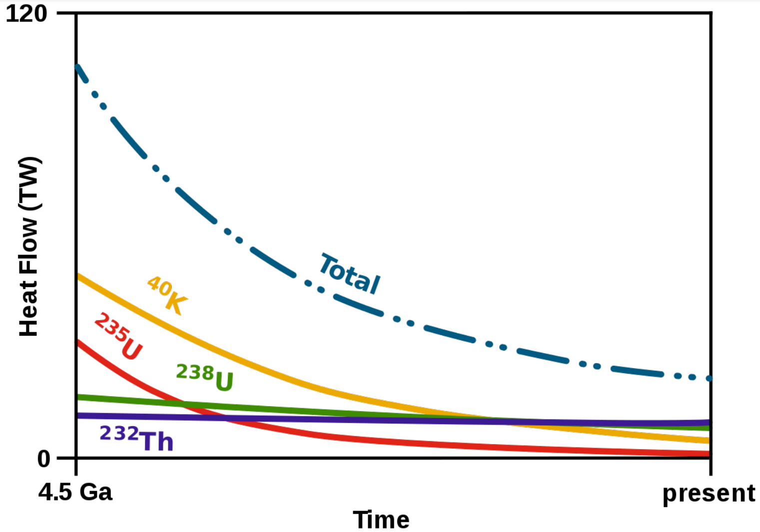
(radiogenic heat)



See, for example,
Dye, Rev. Geophysics 50 (2012)

https://en.wikipedia.org/wiki/Geoneutrino

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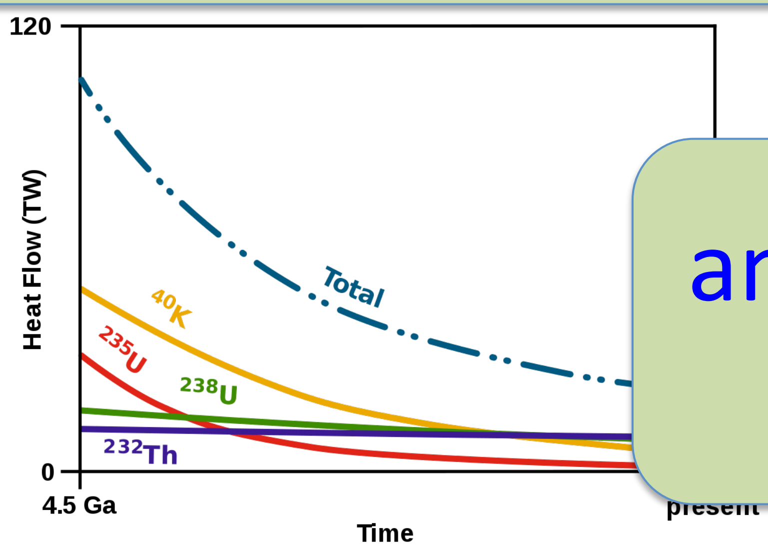
Neutrinos and geophysics

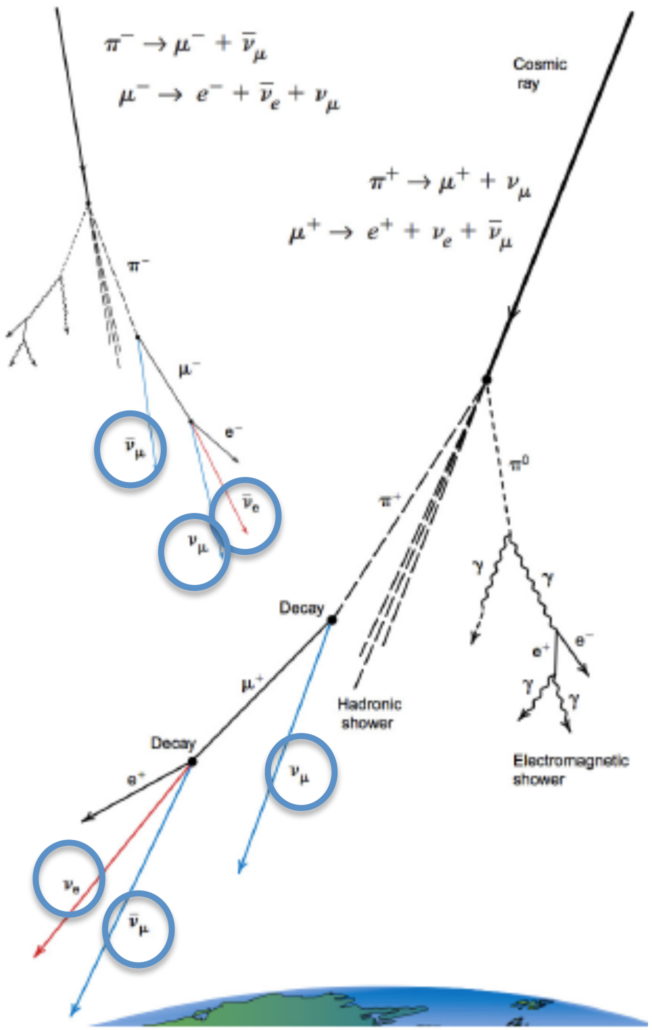
GEO-NEUTRINOS…
(radiogenic heat)



and ATMOSPHERIC NEUTRINOS…

https://en.wikipedia.org/wiki/Geoneutrino

Atmospheric neutrinos



Model of Primary Cosmic Ray Flux

+

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

↓

Atmospheric Neutrino Flux

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Why atmospheric neutrinos?

Using neutrinos to study the Earth's interior is 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 short: make a neutrino beam, and shoot far far away!

The idea was premature for the '70s!

... and for the '80, the '90s and the '00s...

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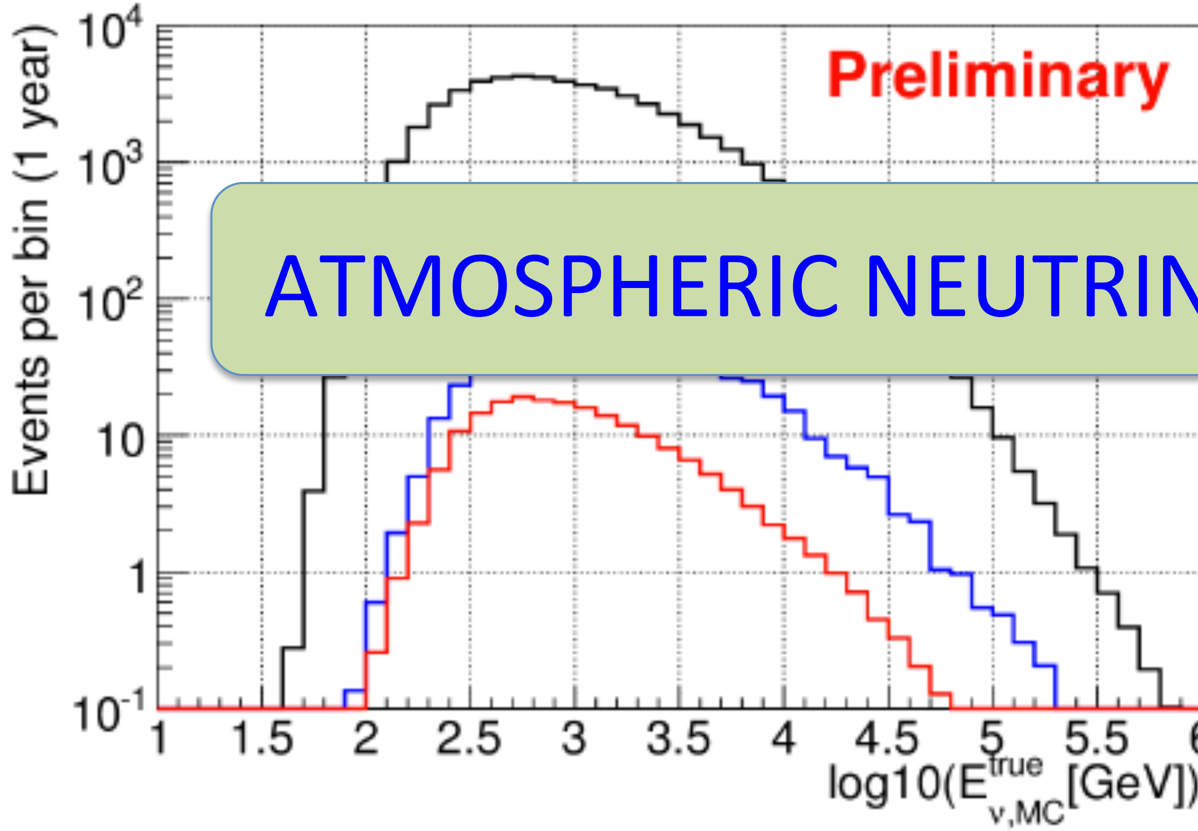
However: an optimal source exists!



IceCube contribution to ICRC 2015, arXiv:1510.05223

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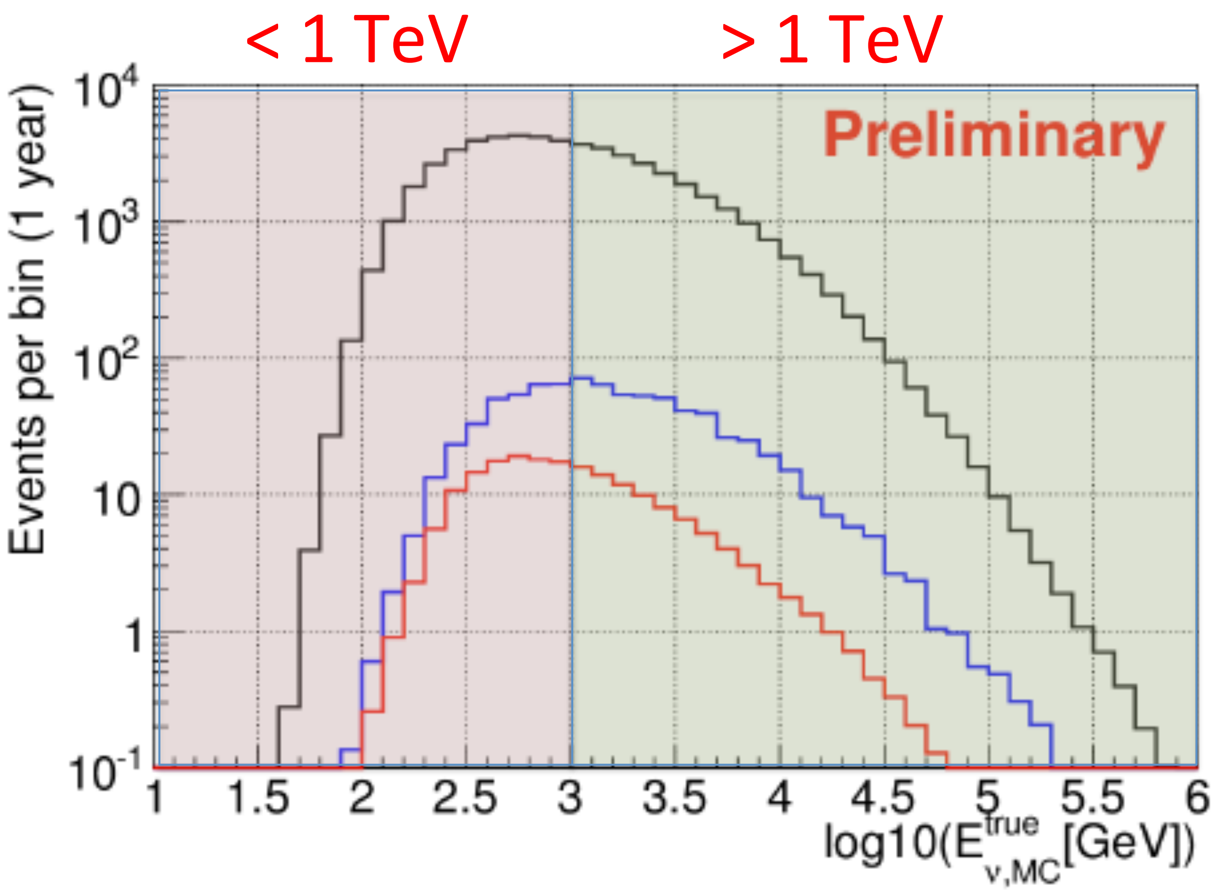
Why atmo-ν are an optimal source?



IceCube contribution to ICRC 2015, arXiv:1510.05223

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Two ways to scan the Earth with ν's

- 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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- Neutrino flux attenuation (> 1 TeV)

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

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Two ways to scan the Earth with ν's

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

- Neutrino flux attenuation (> 1 TeV)

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

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

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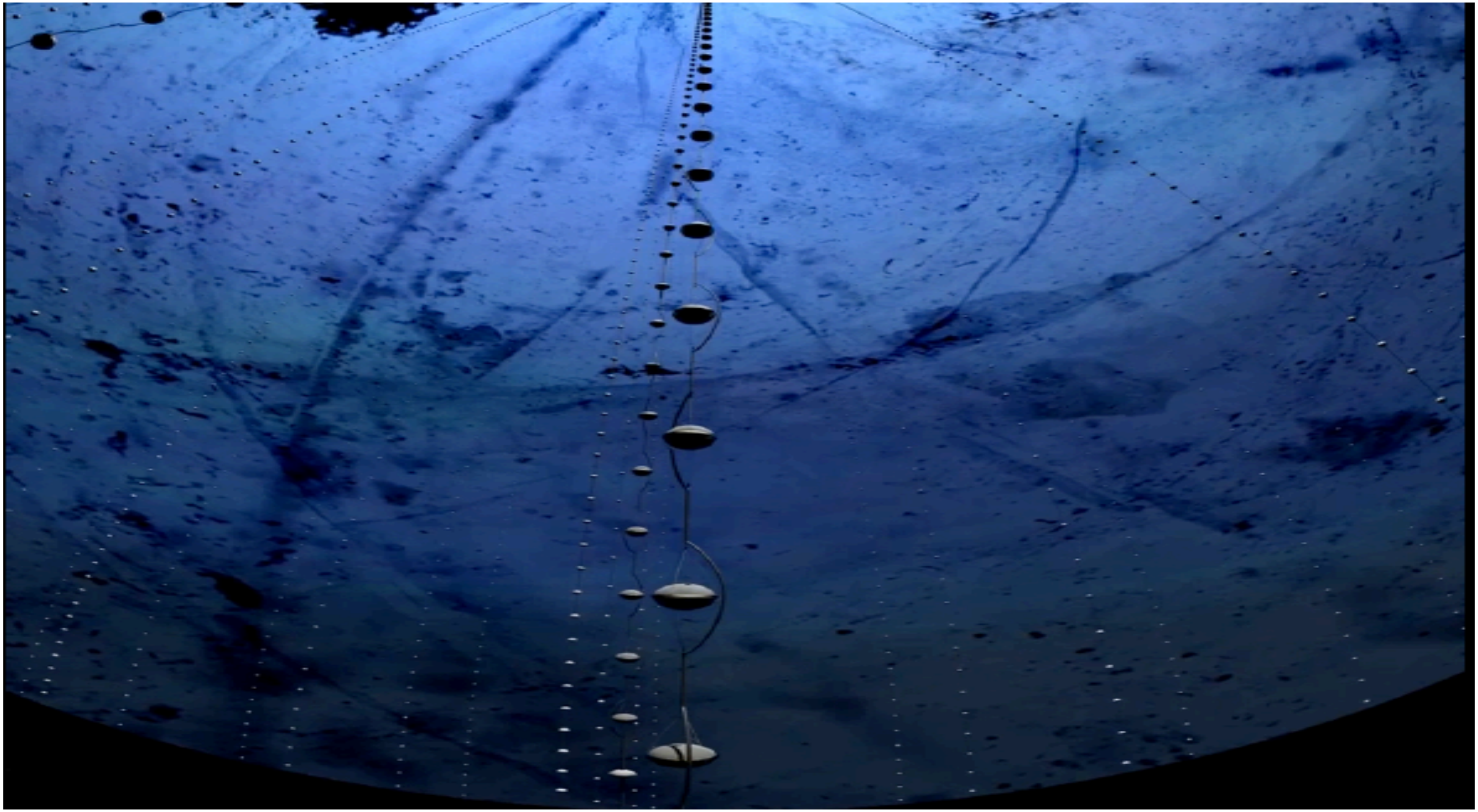
The IceCube Experiment



Halzen, NeuTel 2019, Venice

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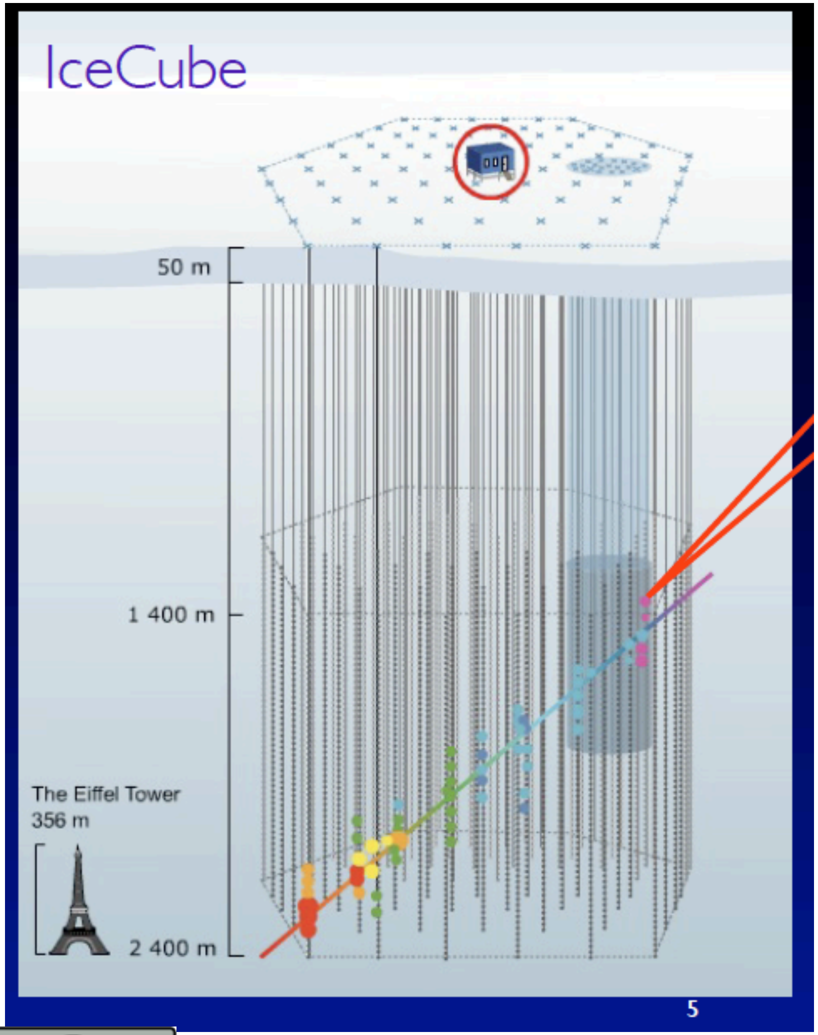

- Deployed in glacial ice at the South Pole
- Array size 1km^3, 86 strings, 60 optical sensors (DOMs) per string

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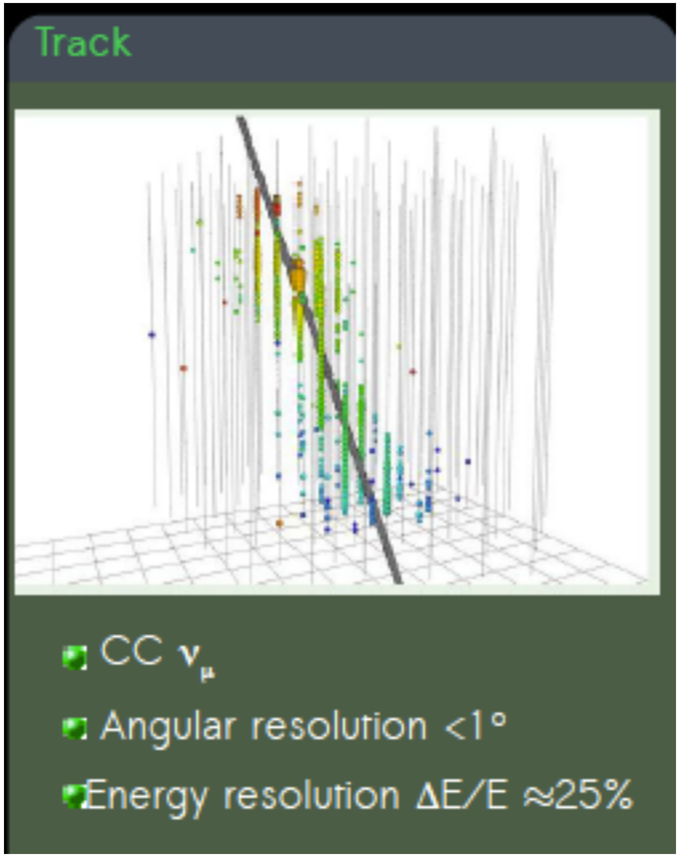
The IceCube IC86 data sample

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



C. de los Heros, NeuTel 2019, Venice

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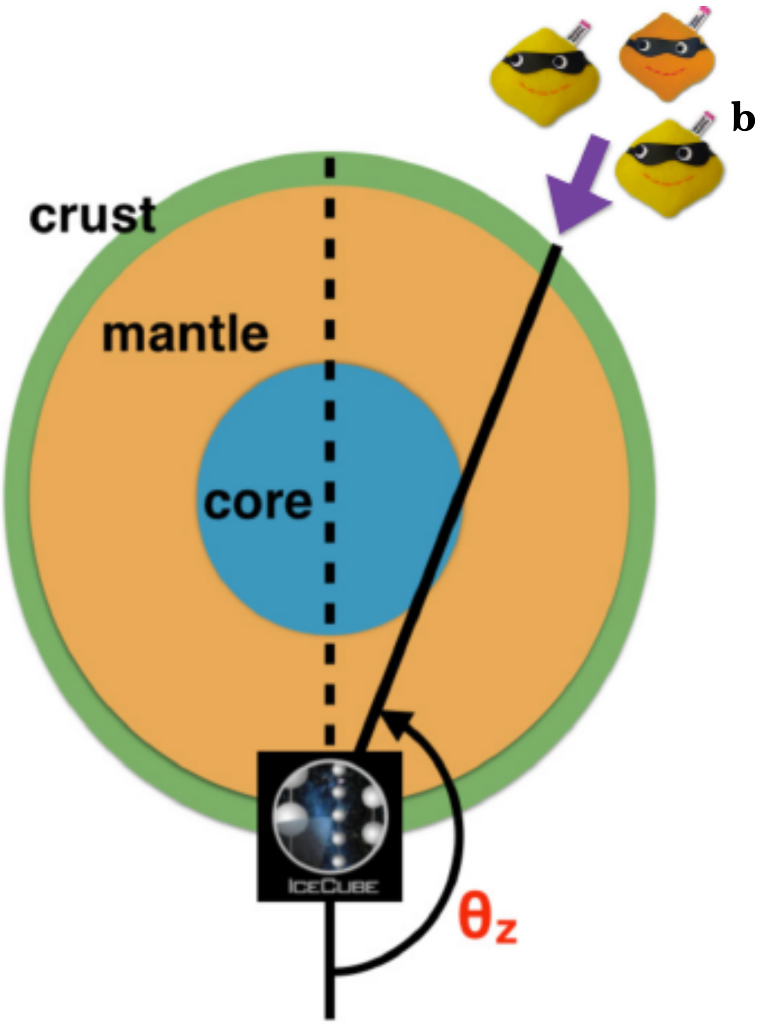
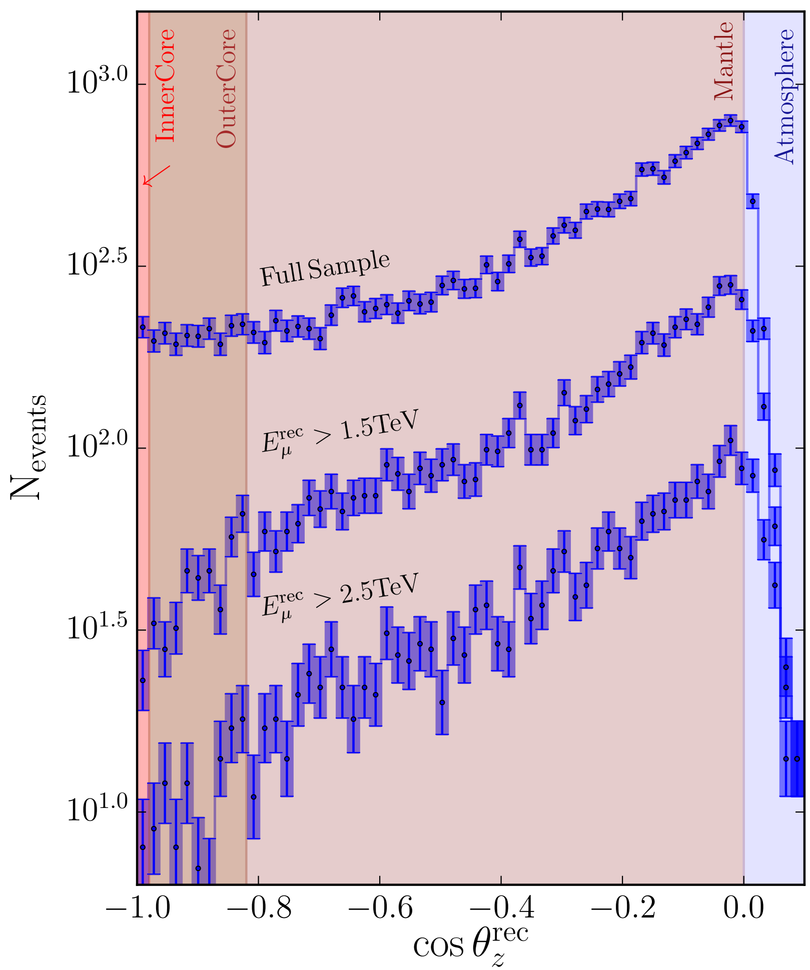
Raw data as a function of E_μ and θ





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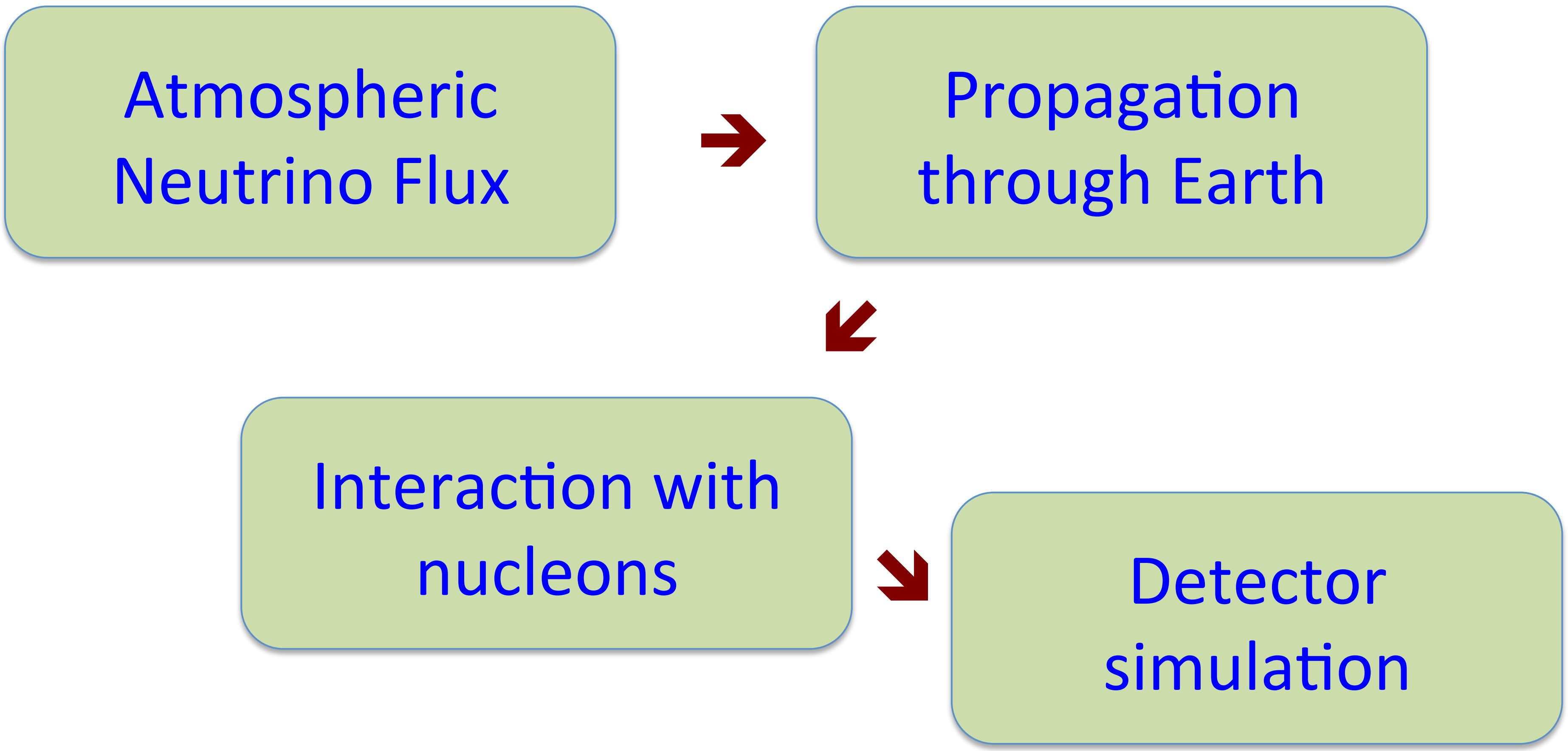
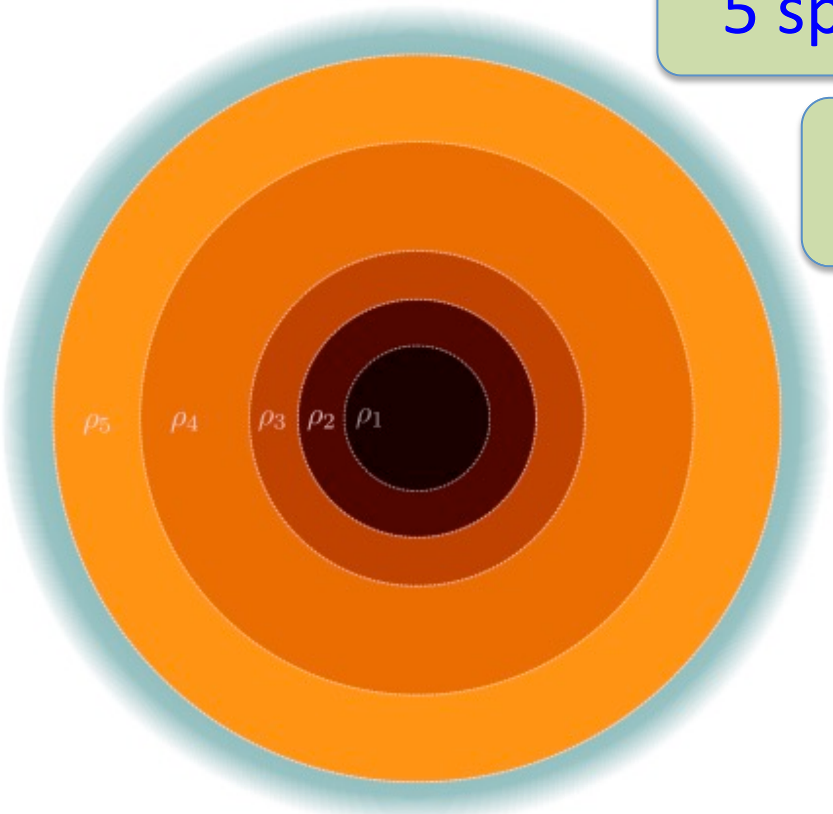
Comparison with expectations



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!

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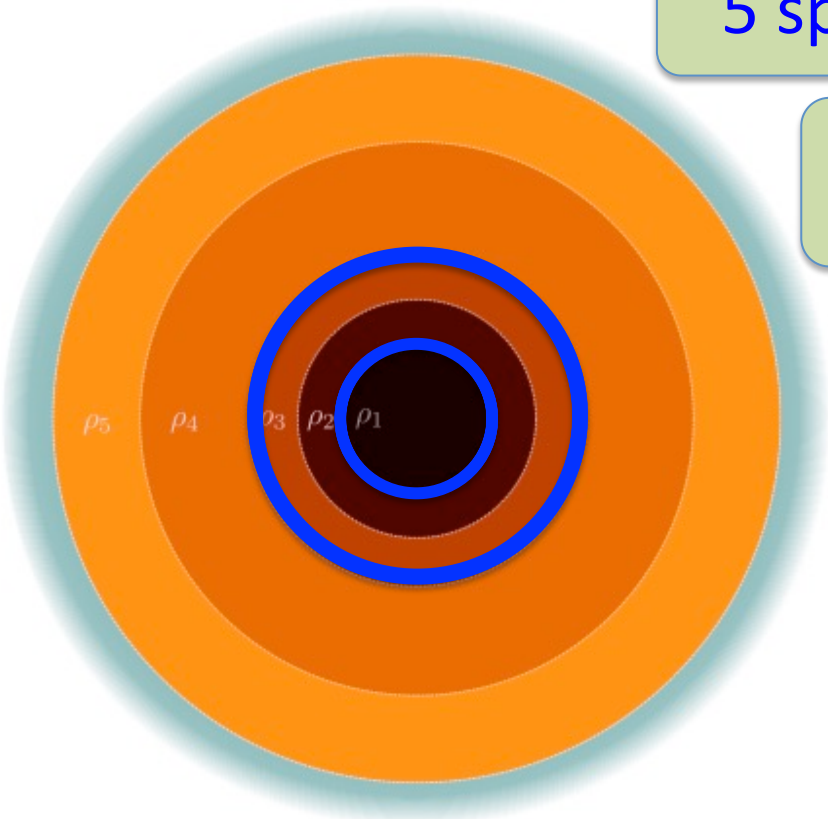
Our Earth's model



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ICB and CMB fixed!

No crust!

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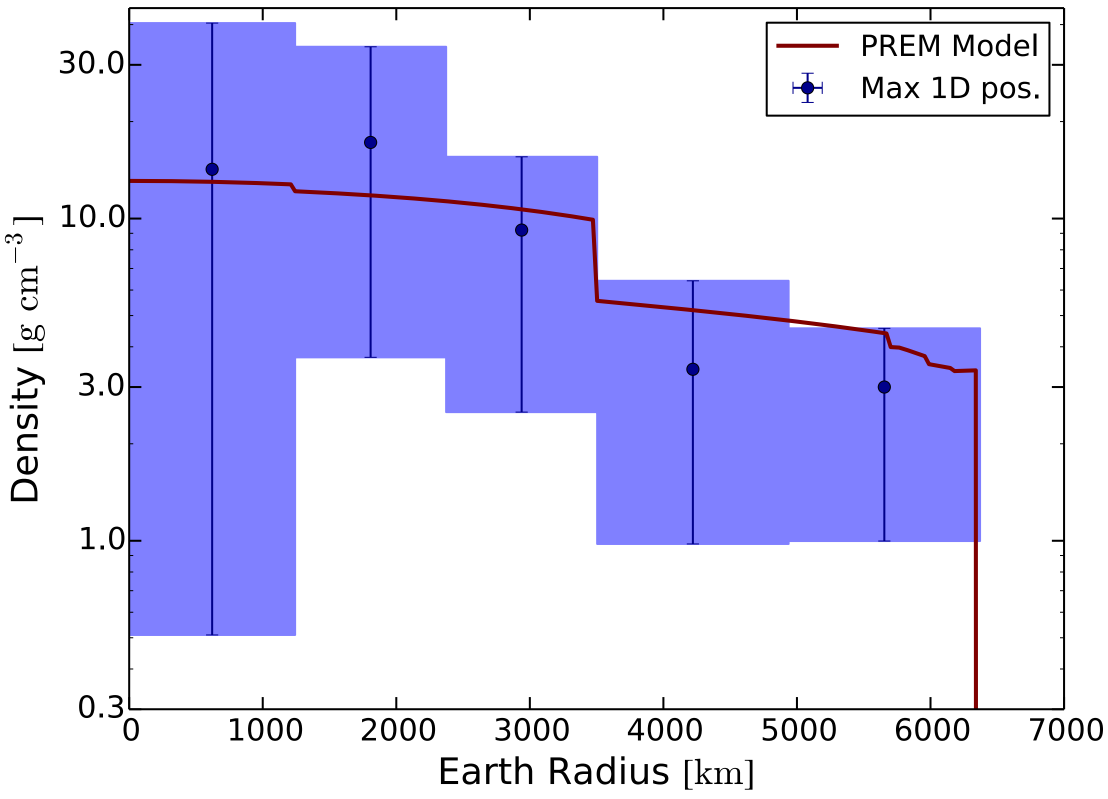
First 1-d density profile with neutrinos



Nature Physics 15 (2019) 37

Analysis performed with MultiNest

5 Earth layers densities

and

4 systematic errors:

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

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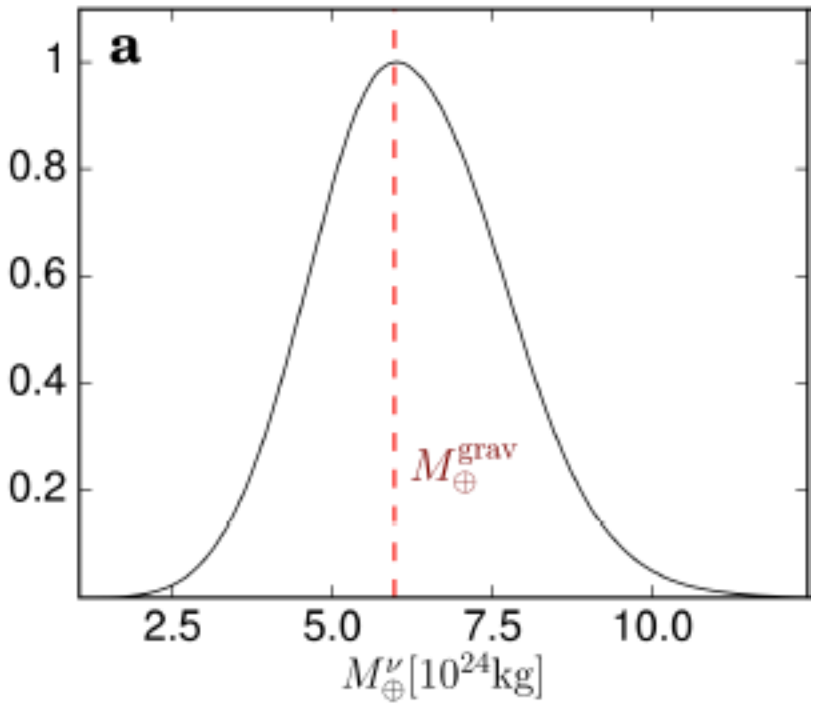
The Earth's mass by ν's



FIRST ELECTROWEAK MEASUREMENT OF THE EARTH'S MASS

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

Gravitational measurement of the Earth's mass

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

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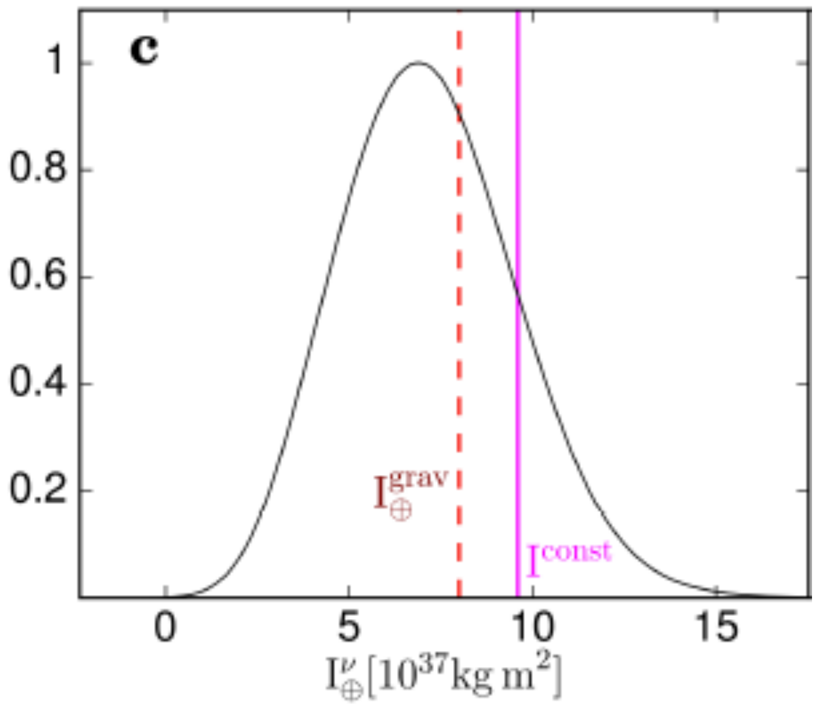
The Earth’s mass by ν’s

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

Gravitational measurement of the Earth’s mass

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

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

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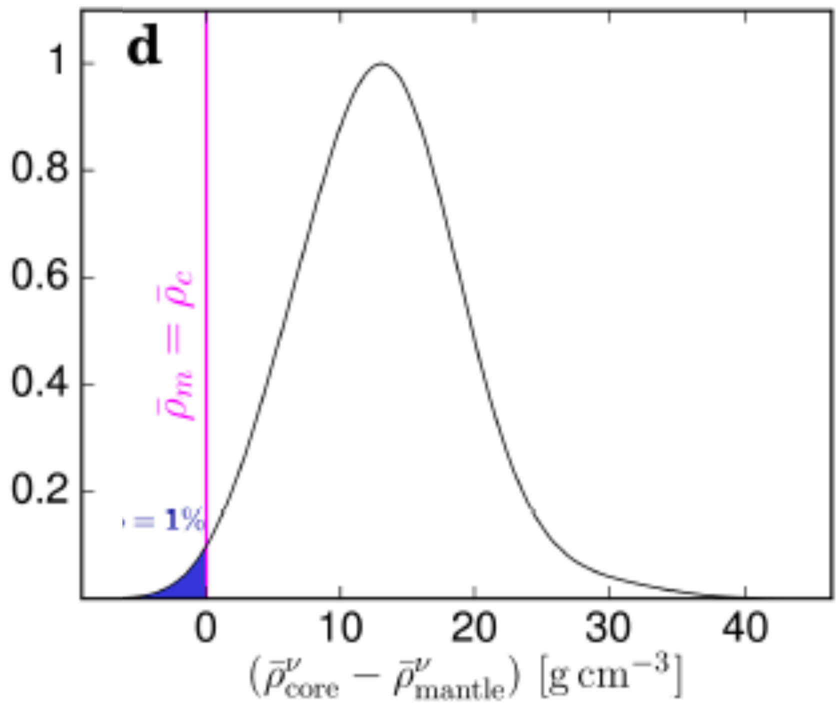
Earth's non-homogeneity



Electro-weak measurement of the Core-Mantle discontinuity

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

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

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

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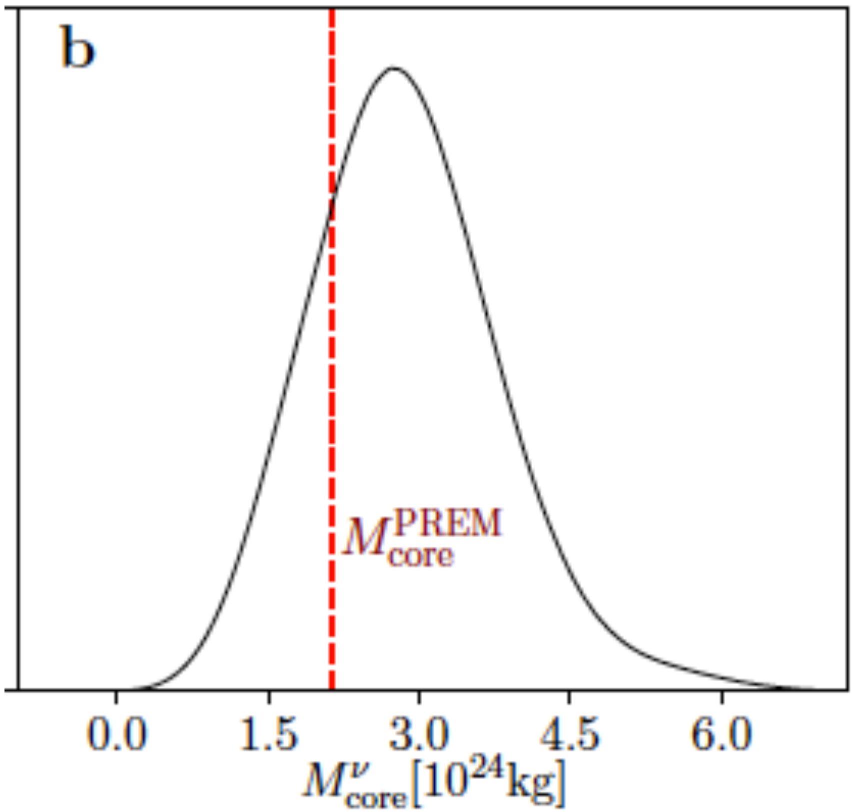
The Earth's core mass



Electro-weak measurement of the Earth's core mass

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

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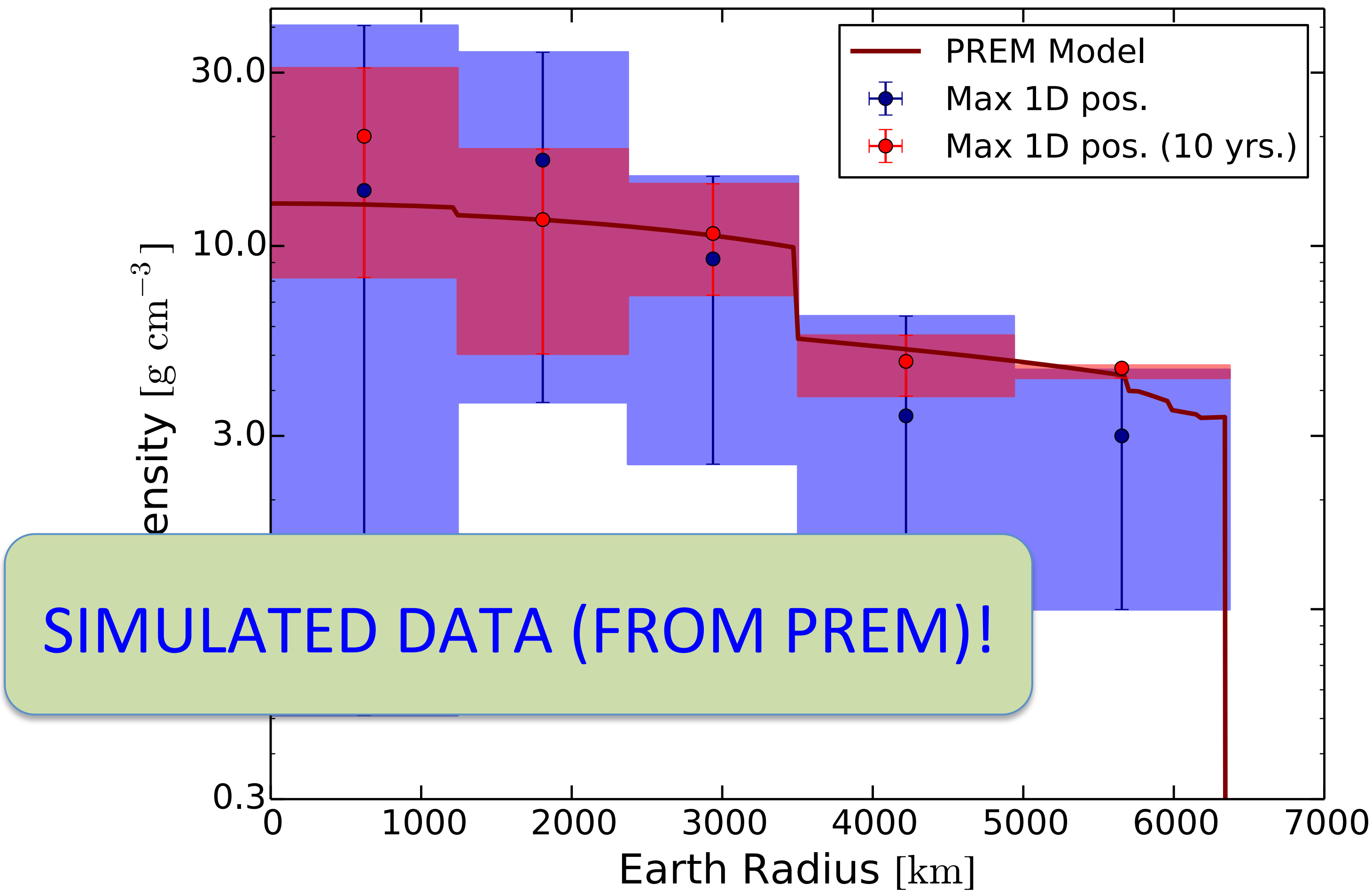
1-d density profile with 10 years



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Conclusions

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!

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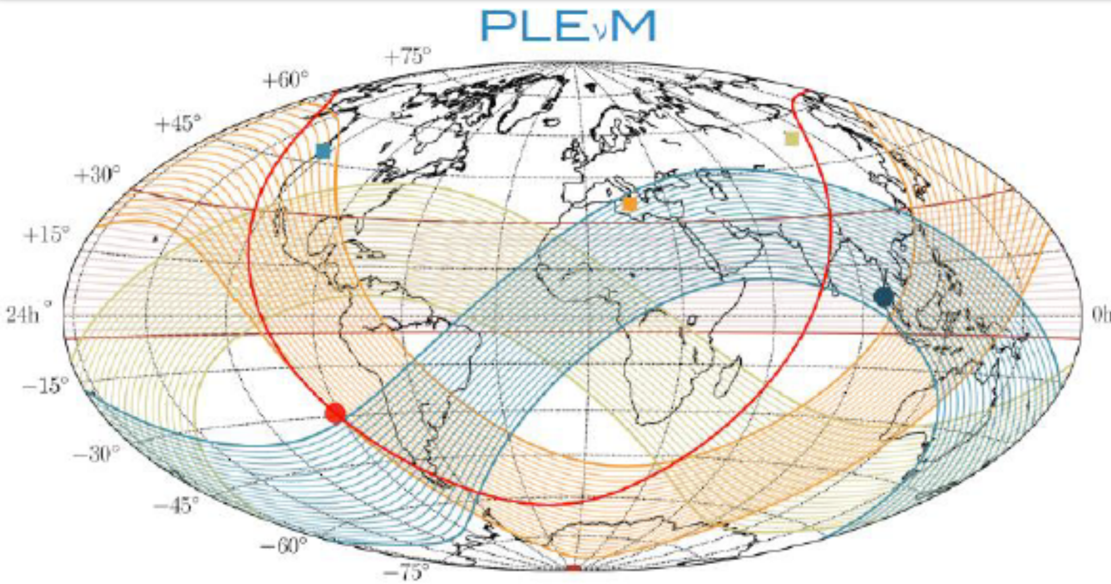
Outlook

New Neutrino Telescopes are under construction:

1) Increase in statistics will be ~ 10 x faster;
2) We will look at the Earth's interior from both emispheres (test of anisotropies)



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

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Complementarity with Geophysics

Neutrino Physics may provide independent constraints on the mass distribution inside the Earth that may be used by seismological modeling

Direct testing of the Inner Core: equation of state, composition, density jump….

Neutrino Data useful for Earth's Tomography will pour out FOR FREE, as neutrino telescopes are being built for other purposes

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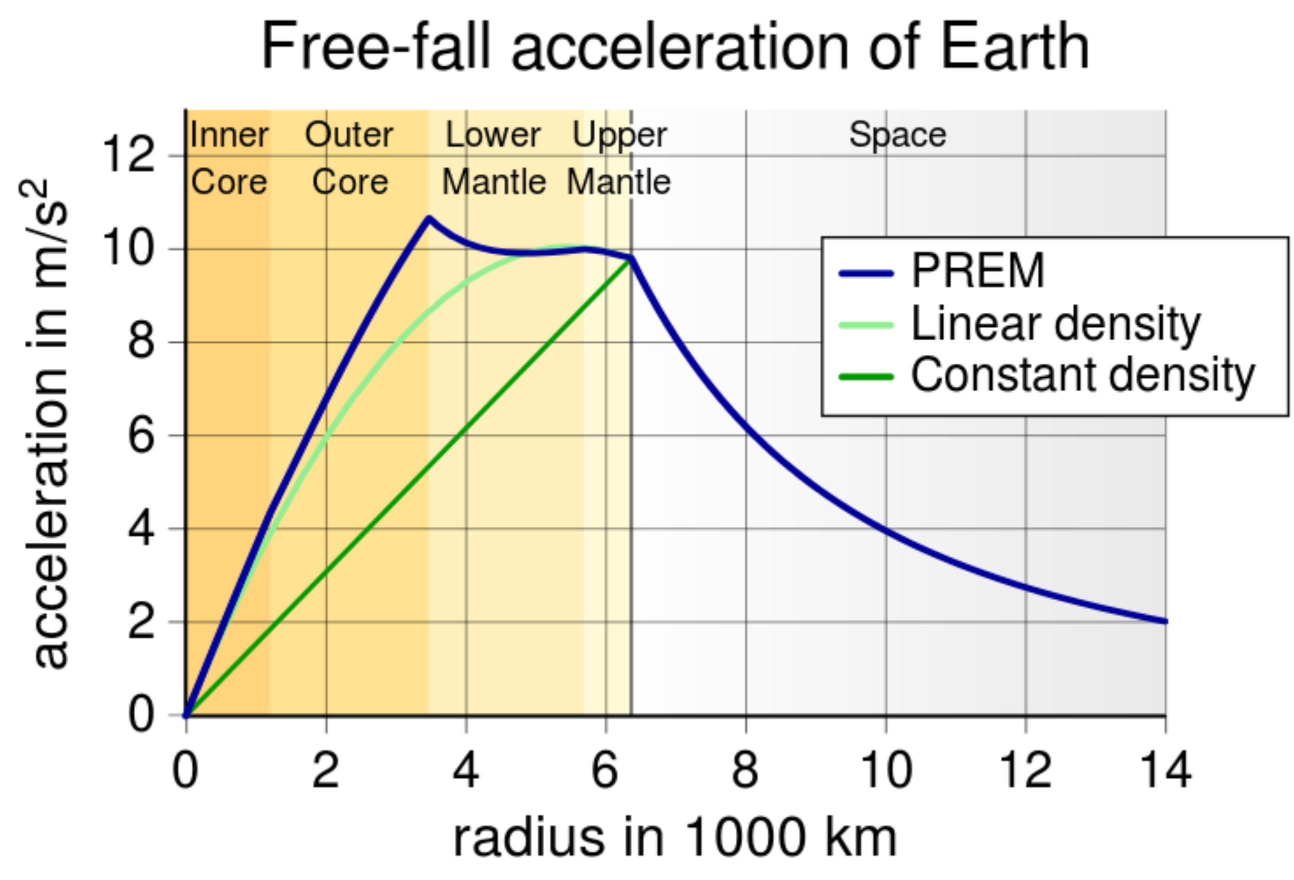
Backup slides

The Earth's gravitational acceleration profile

Complement geophysics: g(r)



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

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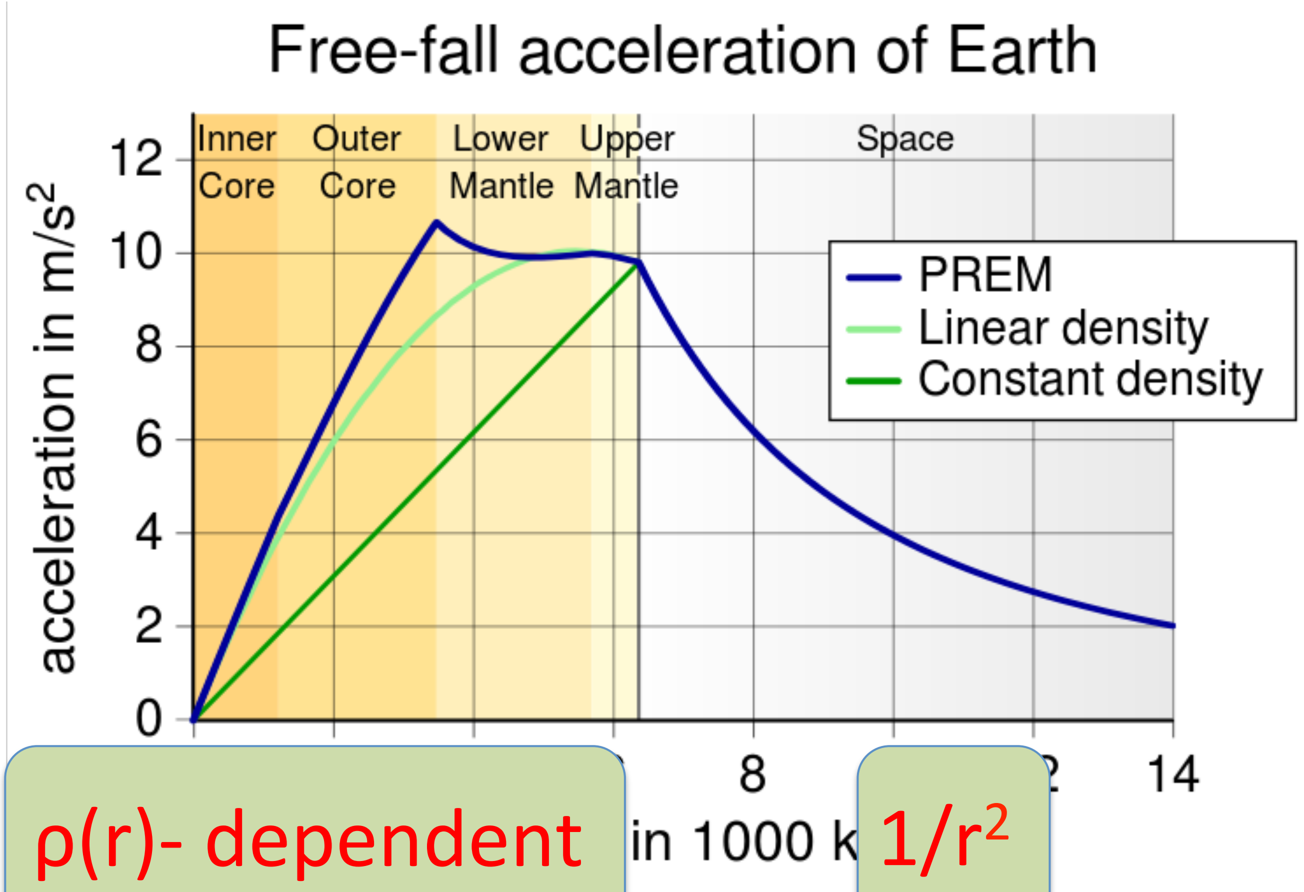
Complement geophysics: g(r)



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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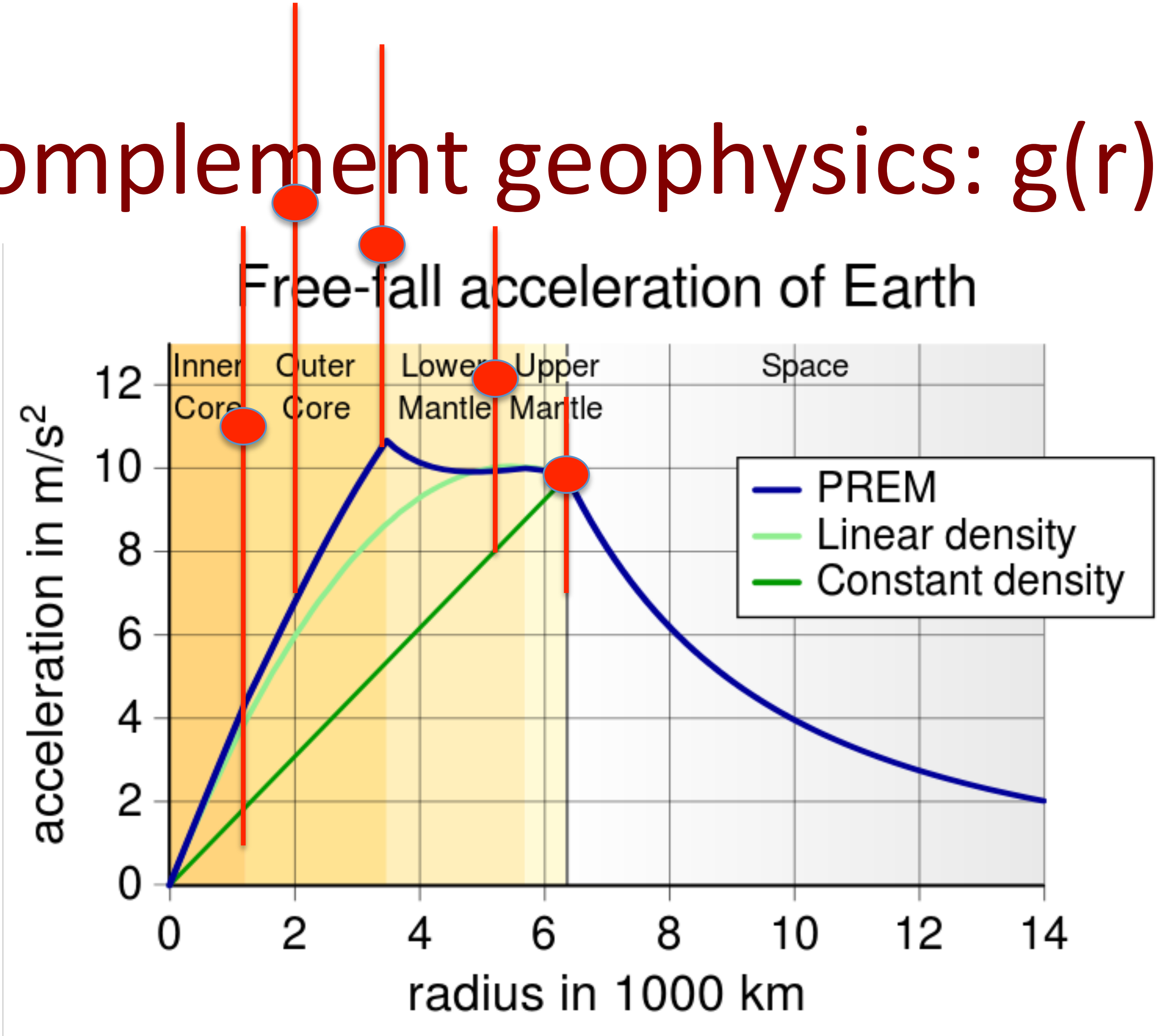
Complement geophysics: g(r)



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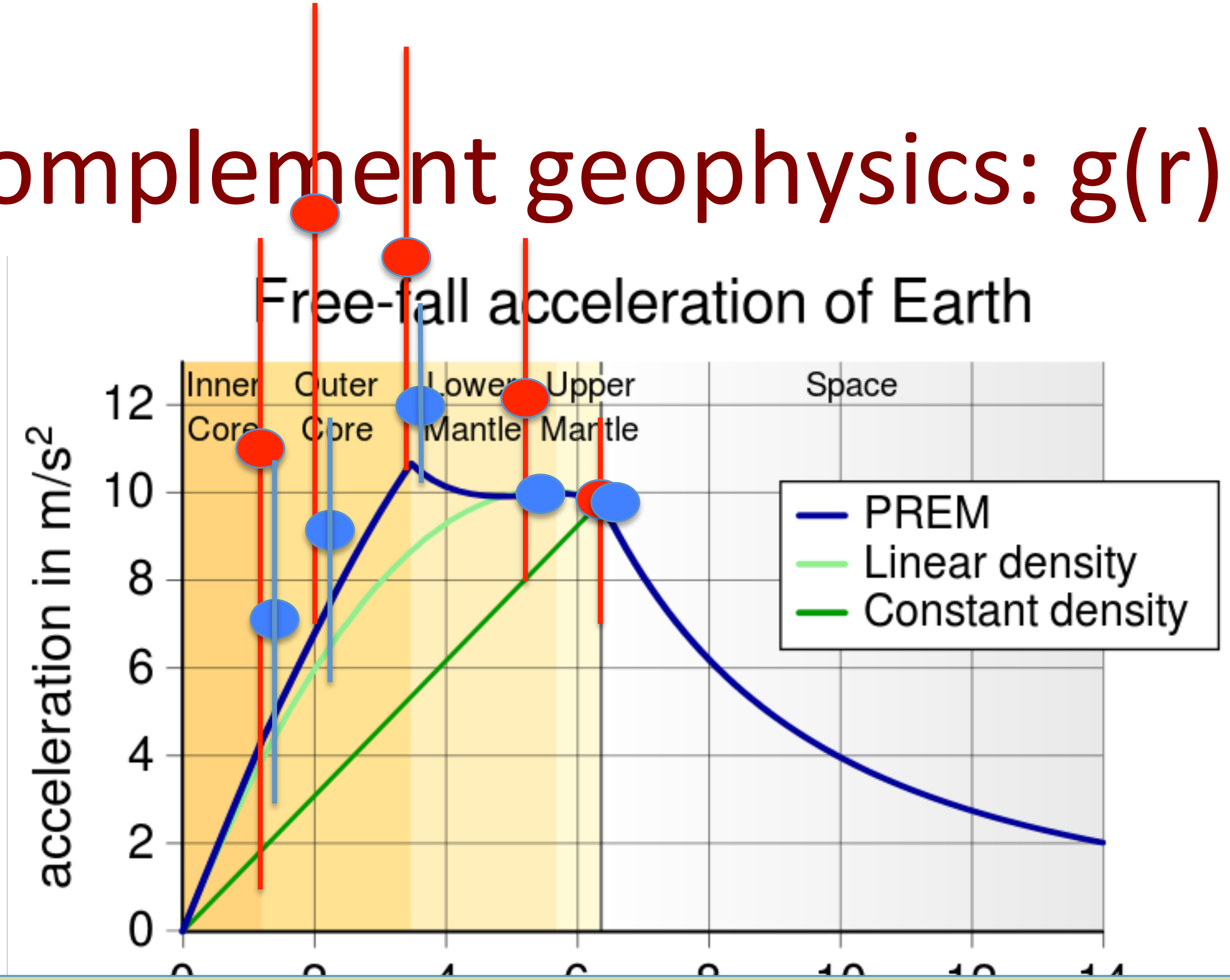
Complement geophysics: g(r)



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

ties

Older Forecasts

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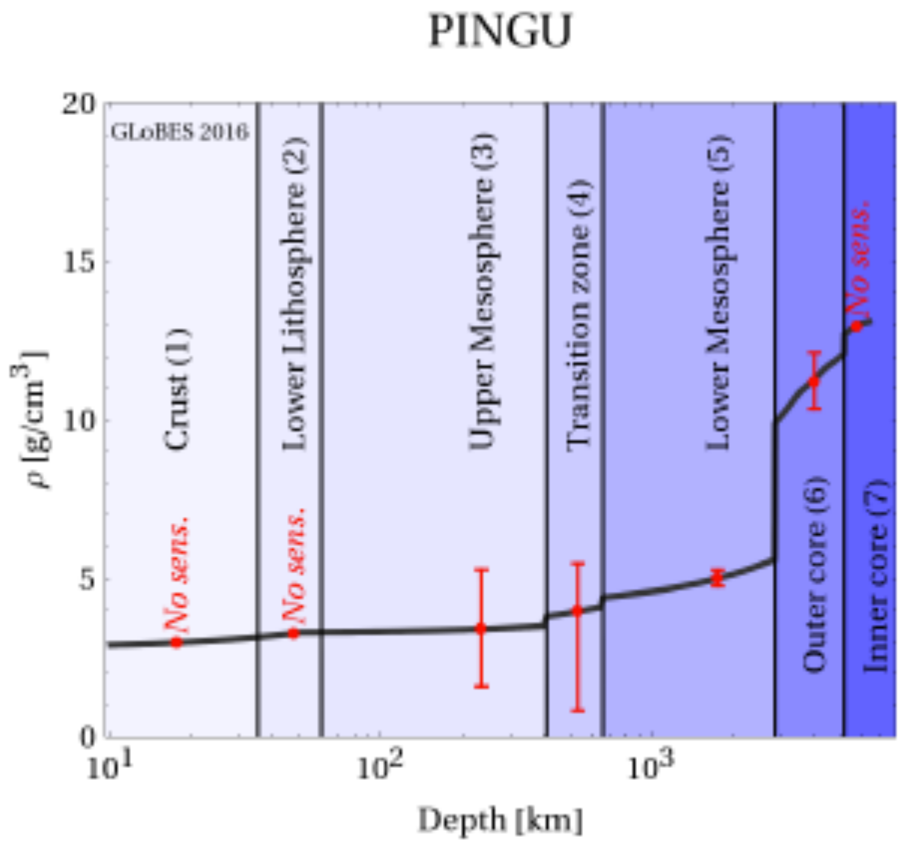
"Recent" forecasts, 1



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

Winter, Nucl. Phys B908 (2016)

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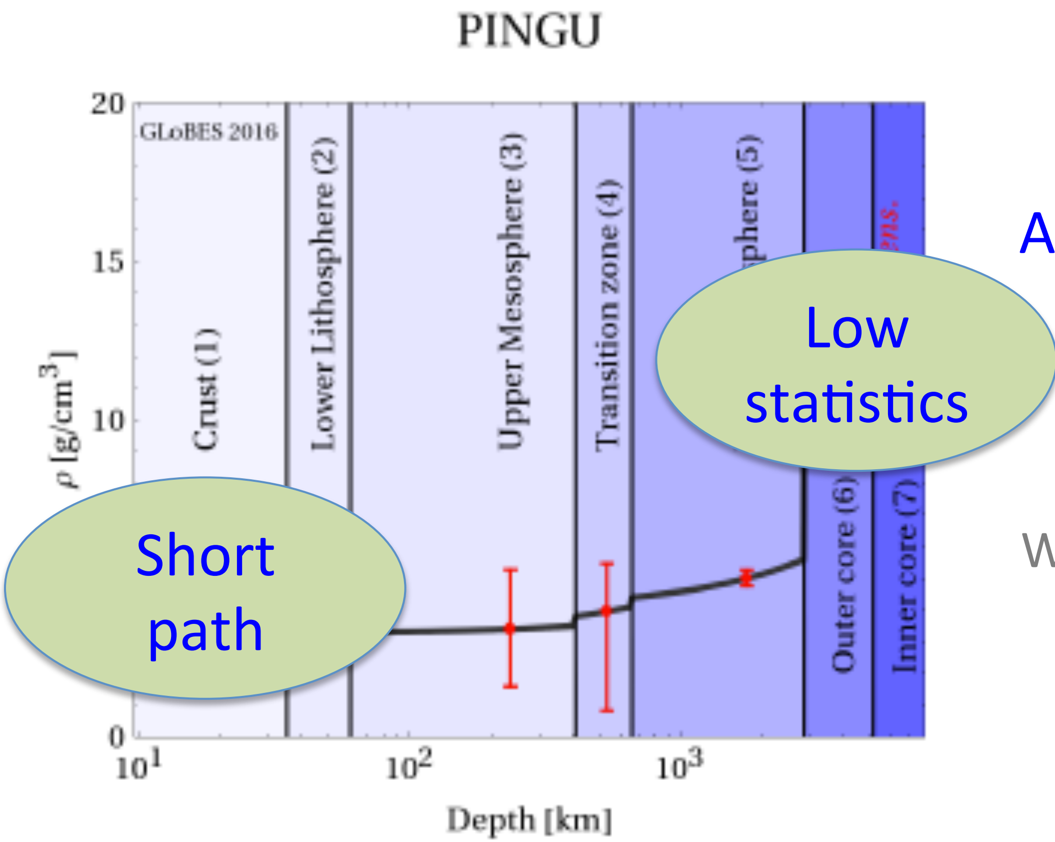
“Recent” forecasts, 1



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

Winter, Nucl. Phys B908 (2016)

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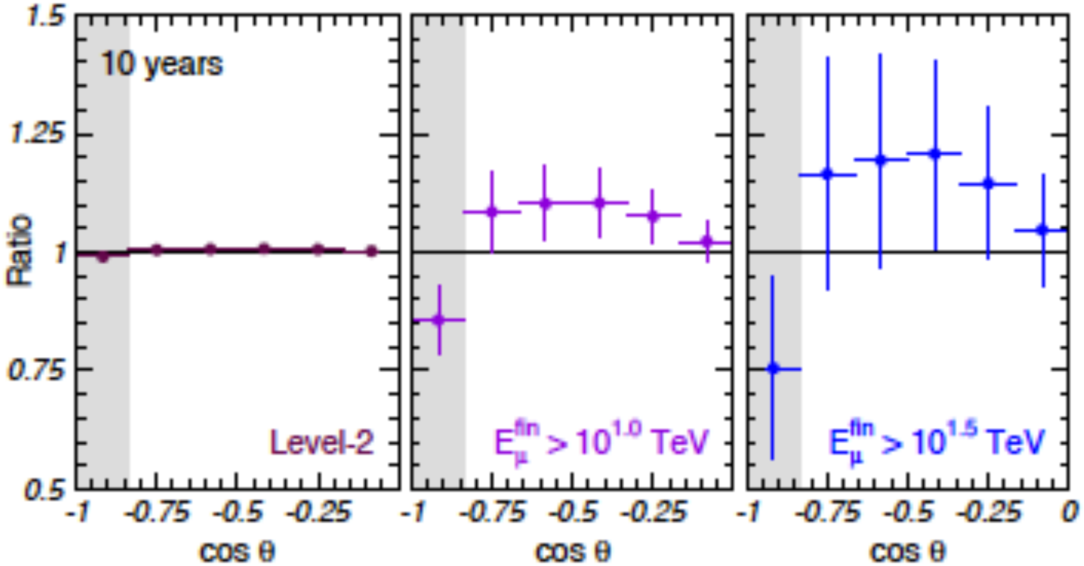
“Recent” forecasts, 2



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)

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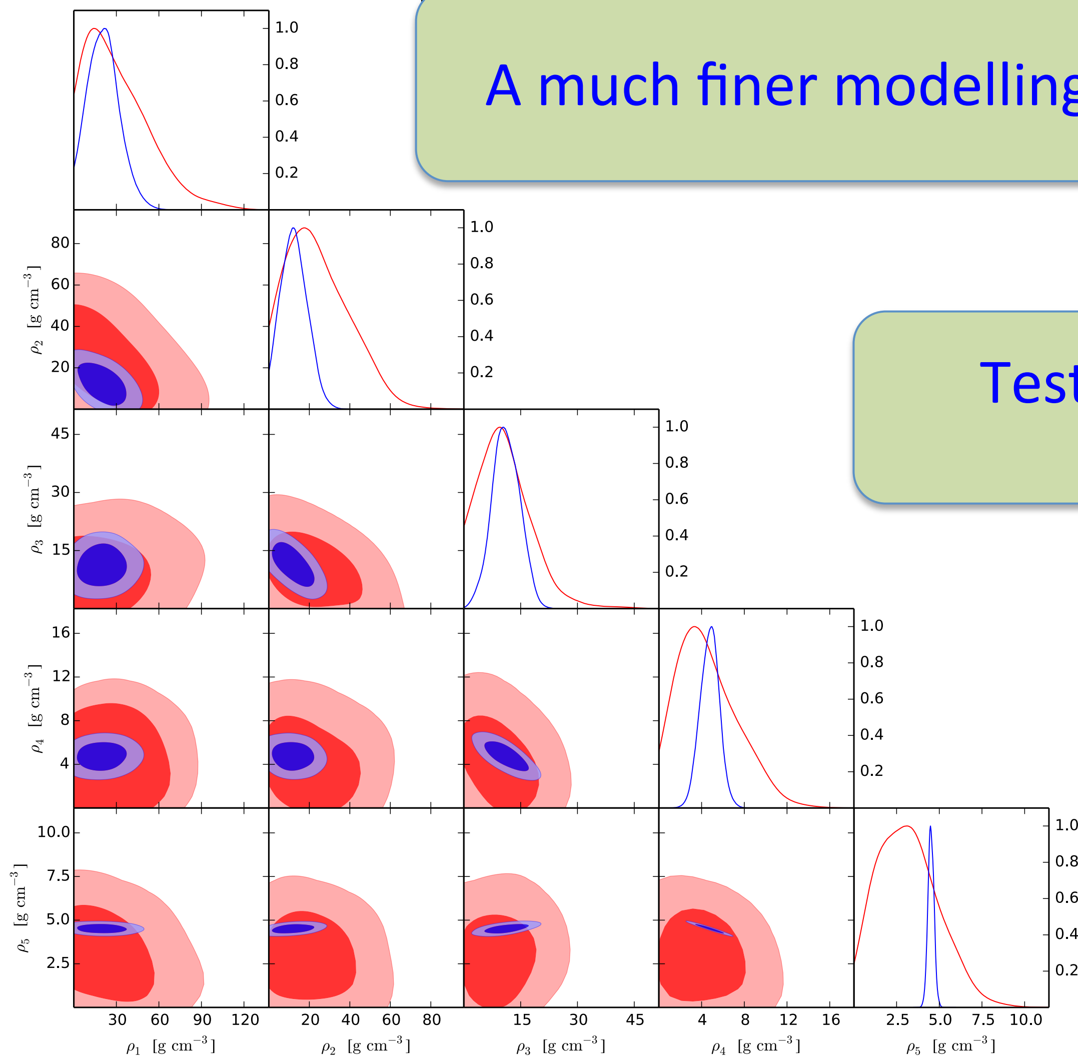
Our Forecast with 10 years of data



A much finer modelling of the Earth could be done

Test of the Inner-Outer Core discontinuity

Independent localization of the Core-Mantle Boundary

Data analysis

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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

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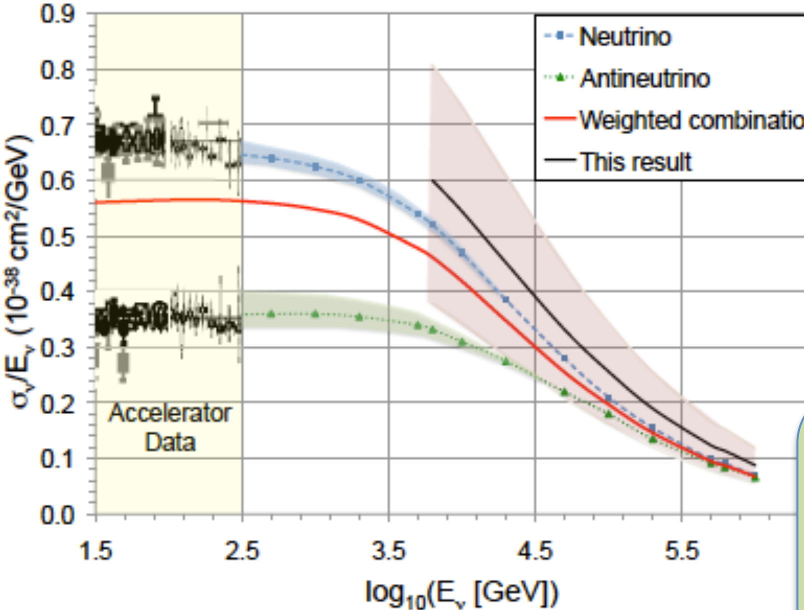
Neutrino-nucleon interaction

Parton distribution functions: HERAPDF



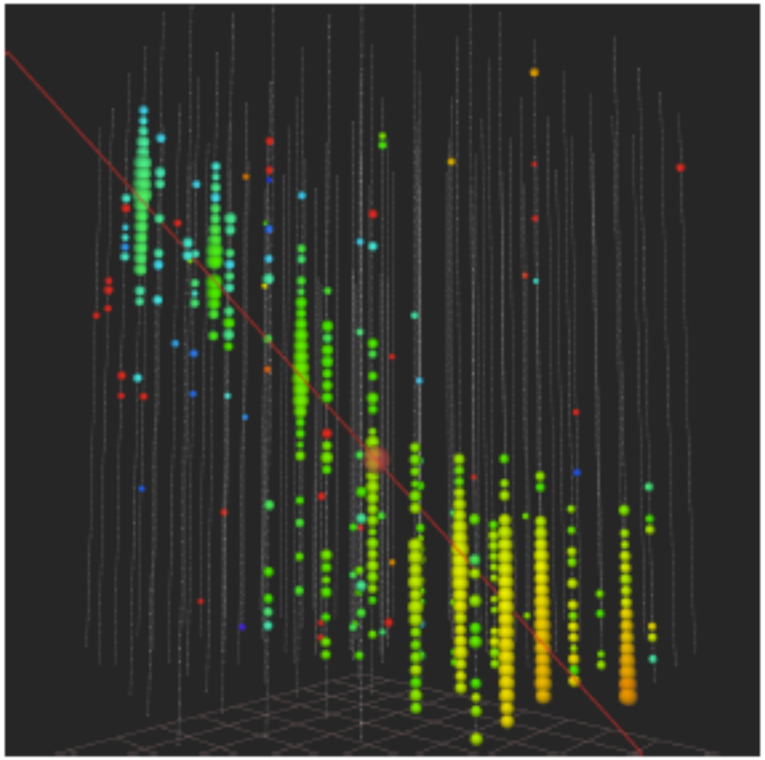
Aarsten et al, Nature 551 (2017)

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

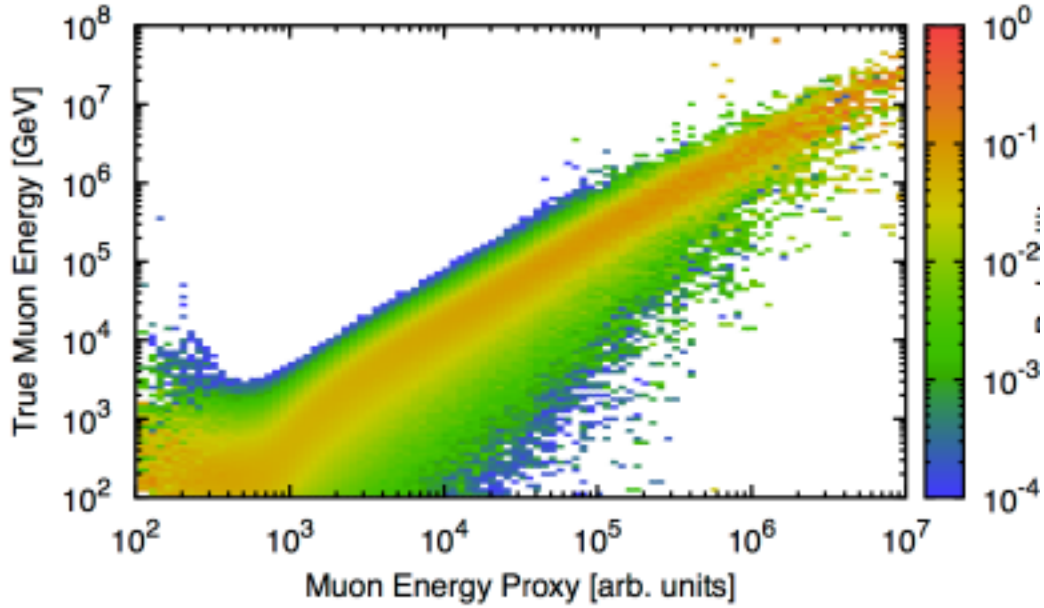
ICECUBE MEASUREMENT

$1.30^{+0.21}_{-0.19}$ (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}



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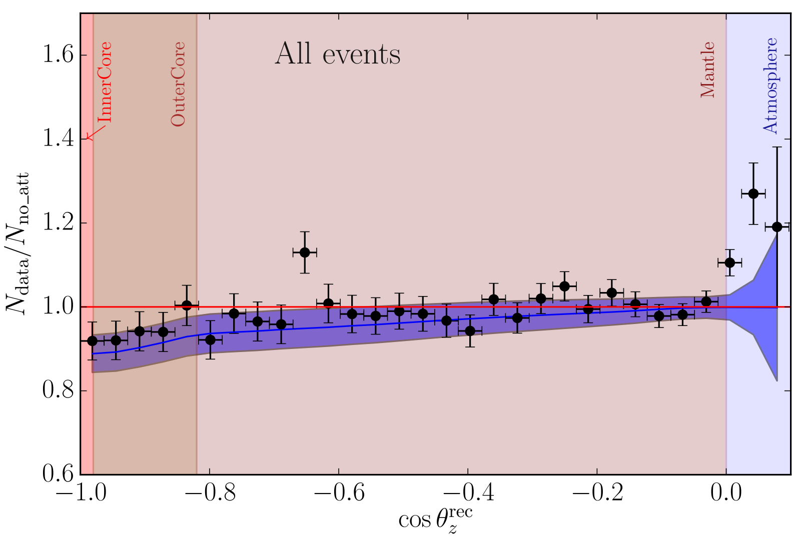
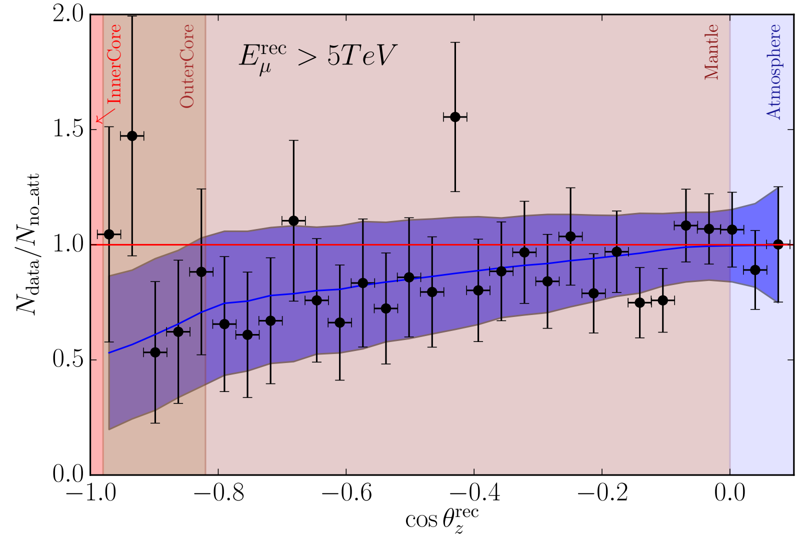
The IC86 Data Sample: N_{data}/N_{noatt}

a Full sample



b Above 5 TeV



Full sample useful for normalization

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

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Systematics

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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

Not important

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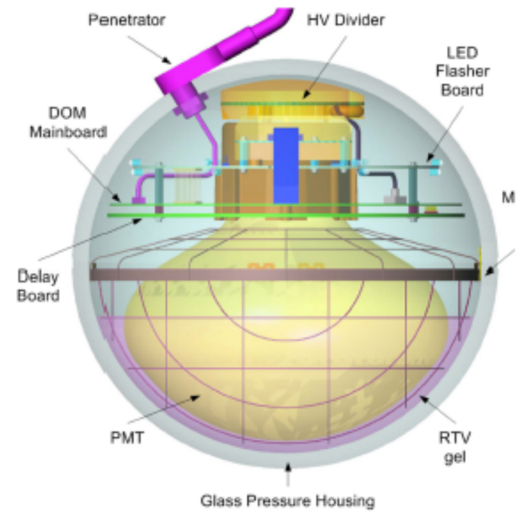
continuous systematics
discrete systematic

Important



D.O.M.

Not important

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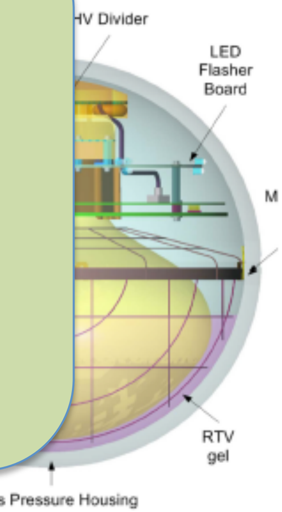
Systematics importance

- *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

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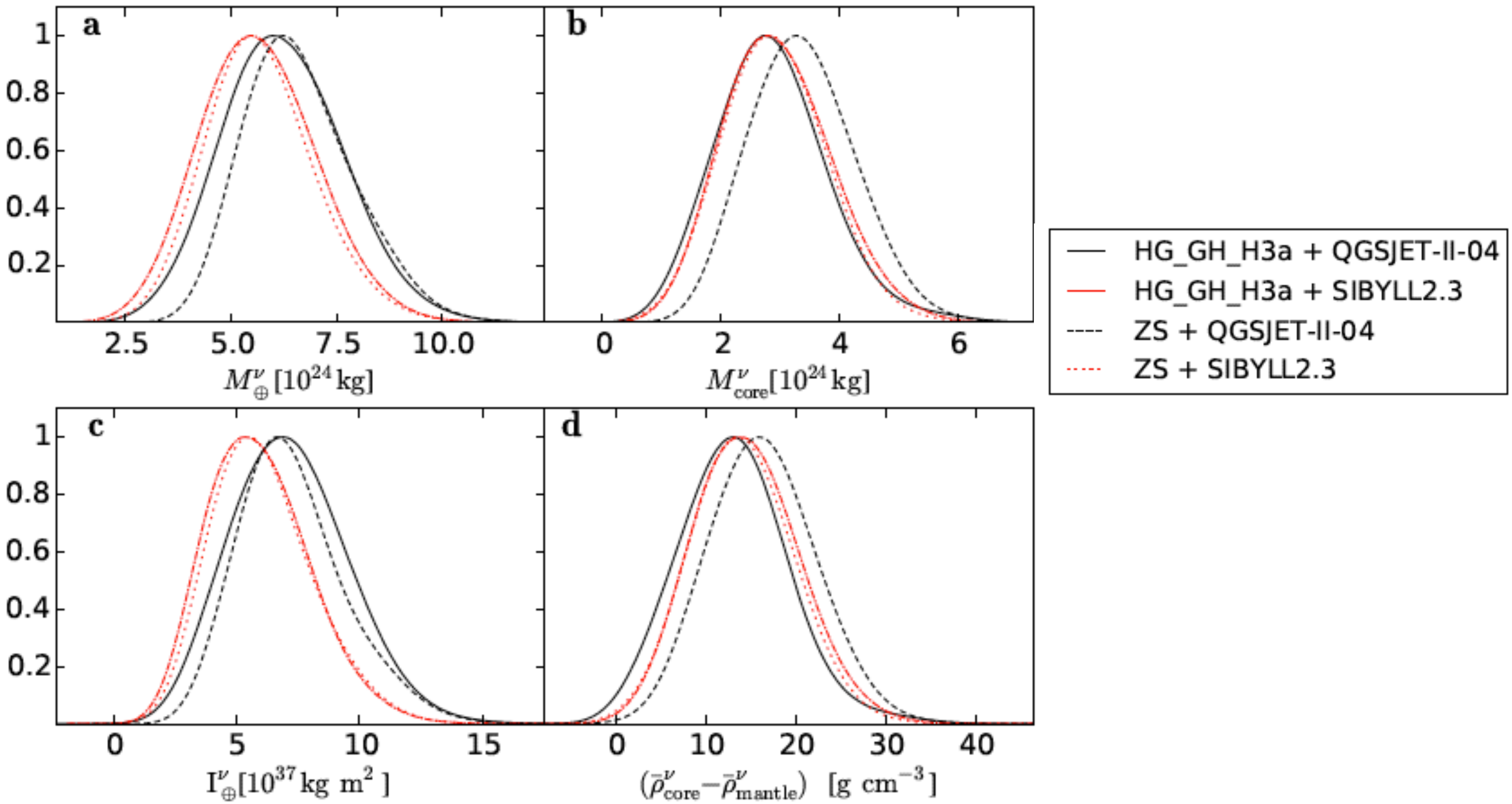
Flux dependence, IC86



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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
$M_\oplus^\nu$ [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}

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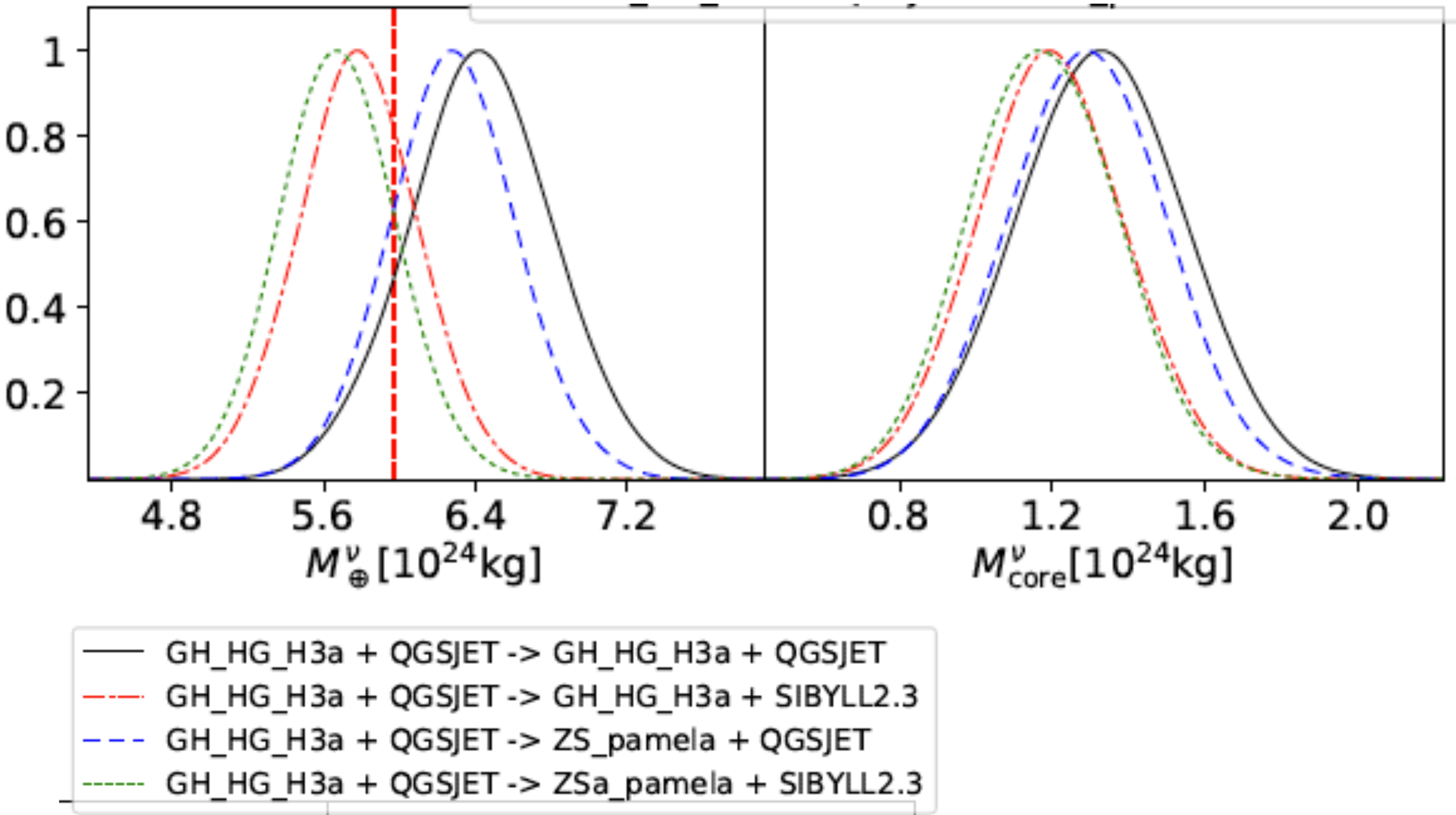
Flux dependence, 10 years forecast



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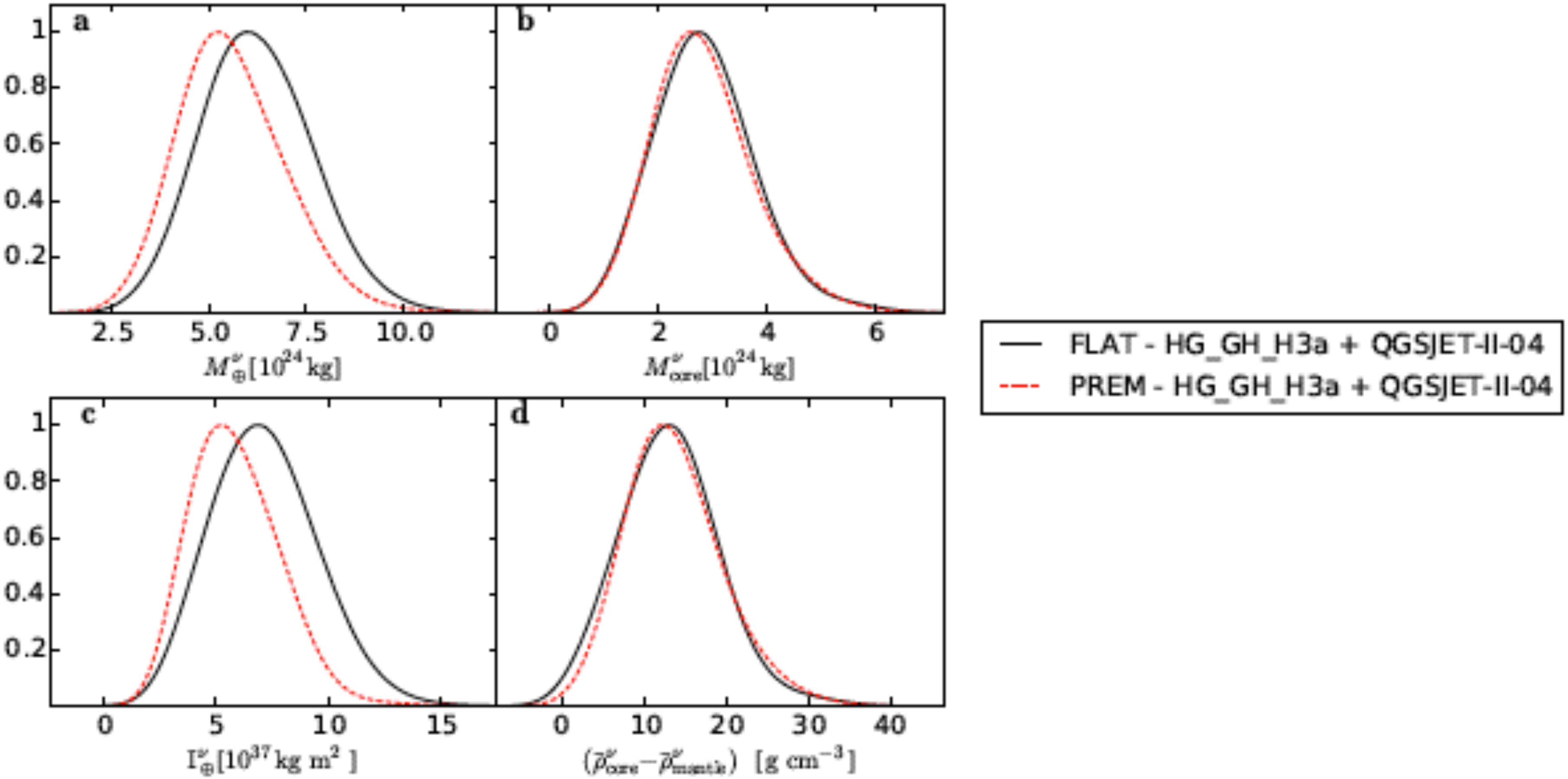
Earth’s profile dependence, IC86



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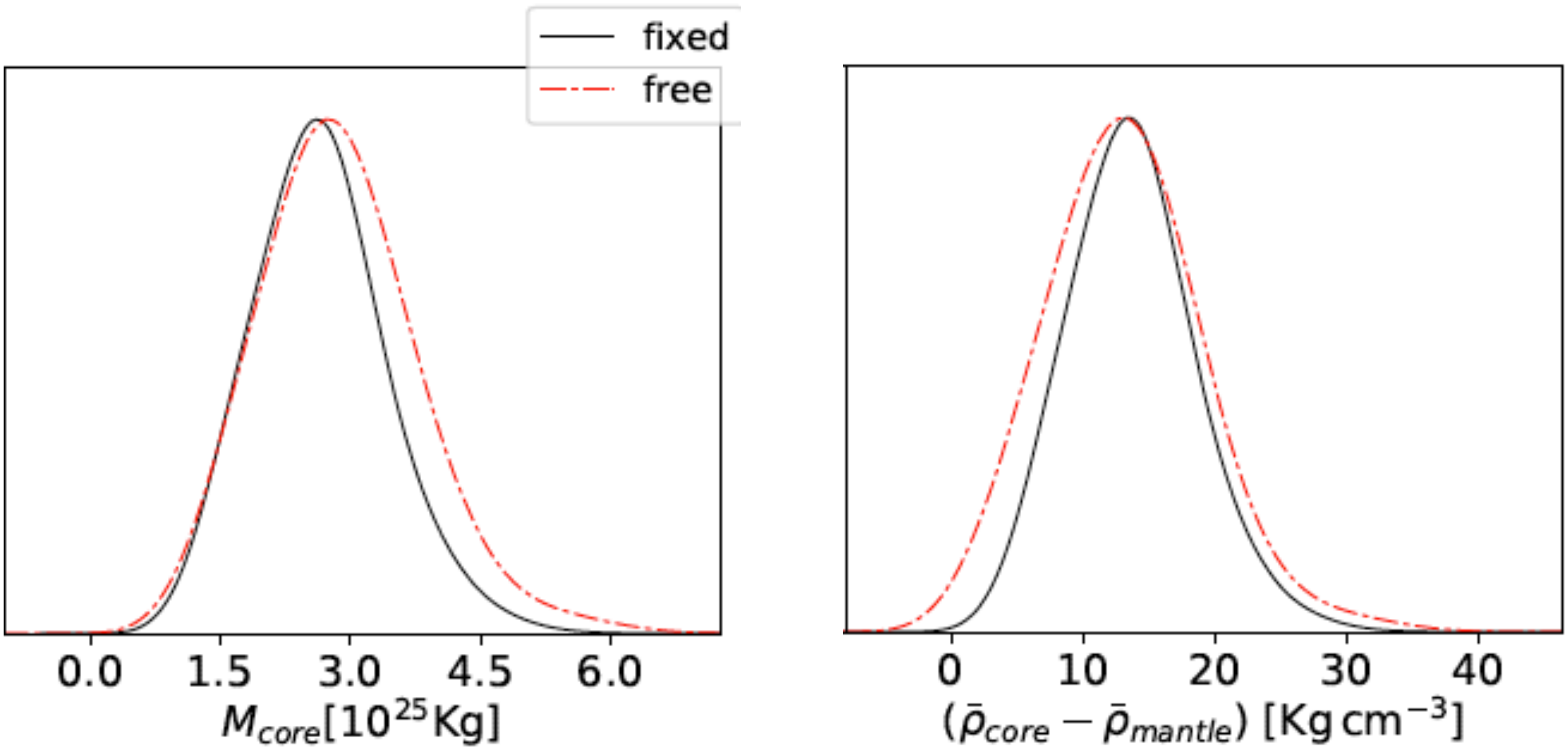
Impact of systematics on the error



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Errors

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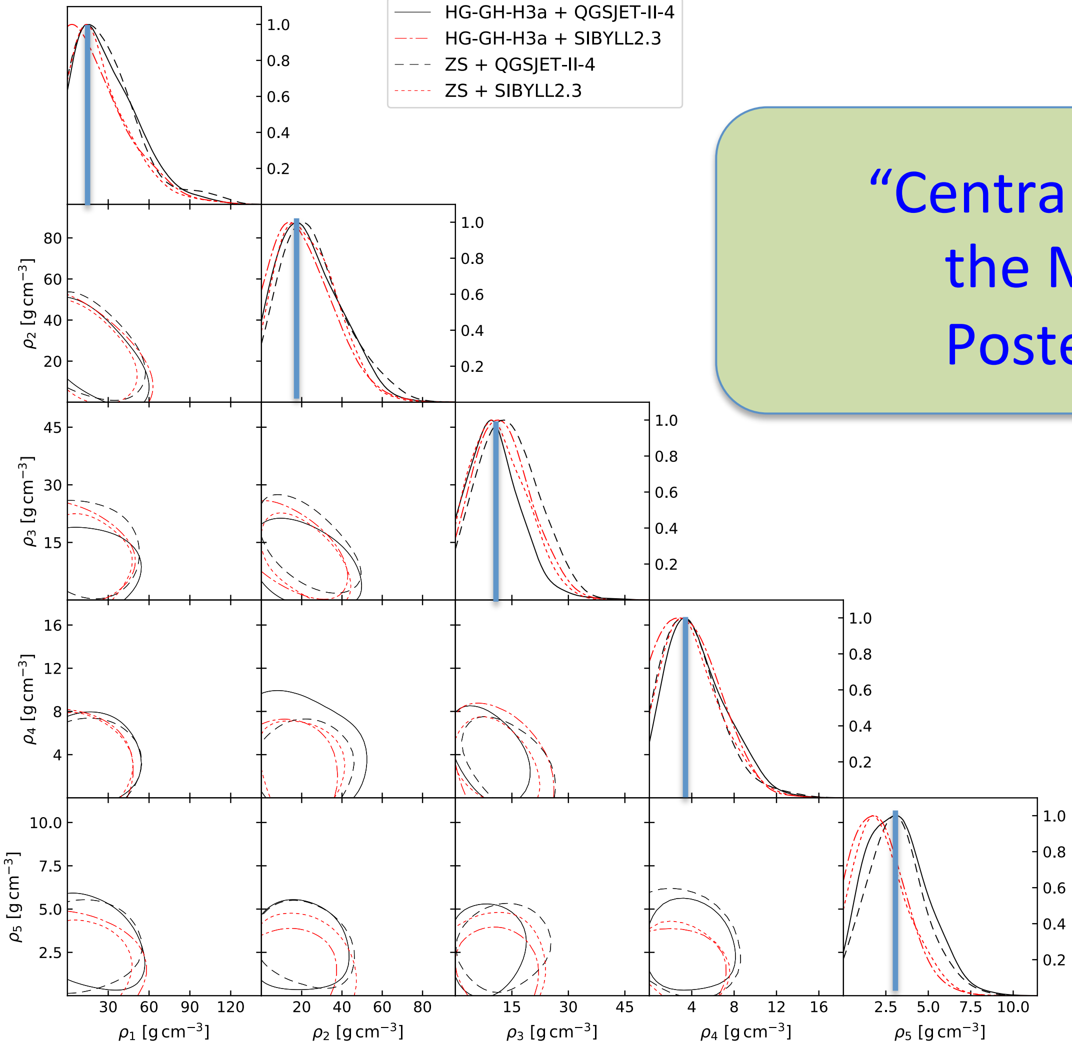
What are the dots in the 1d profile?



"Central values" represent the Maximum of the Posterior Probability

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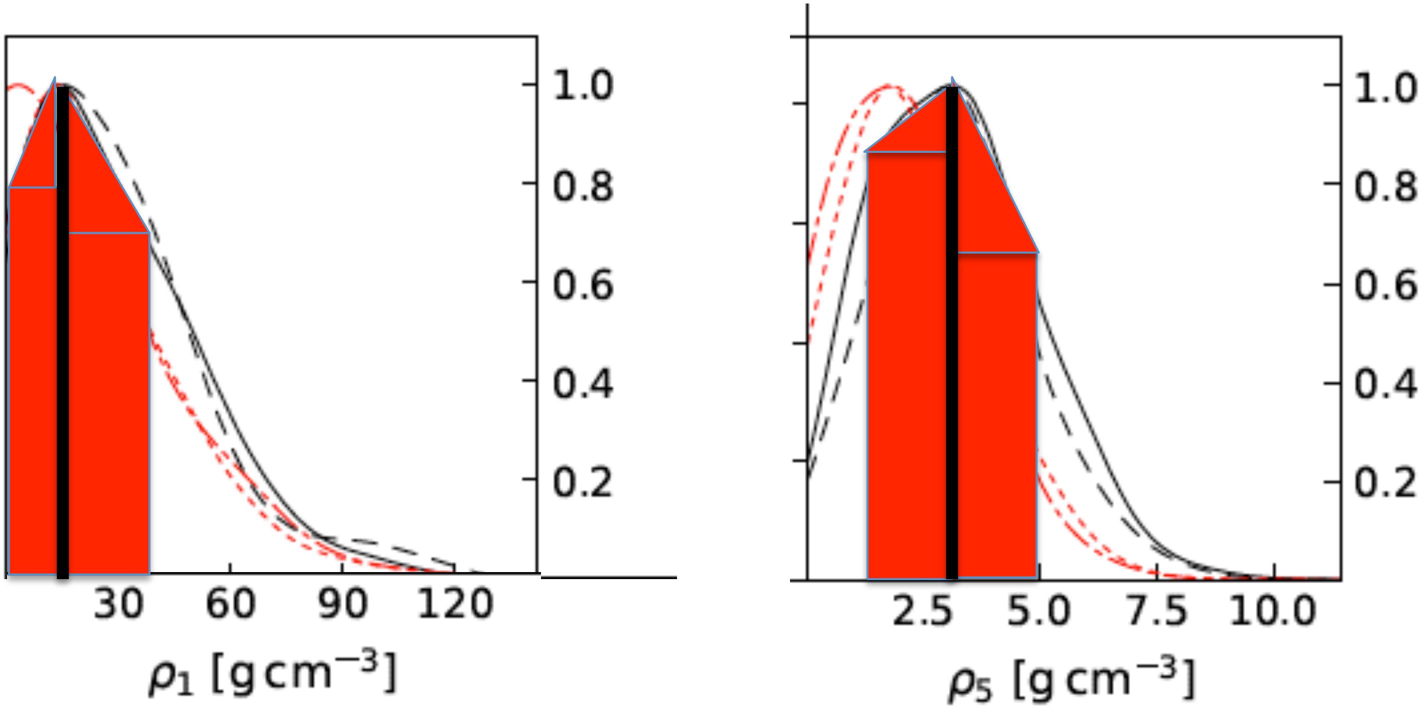
Asymmetric credibility intervals



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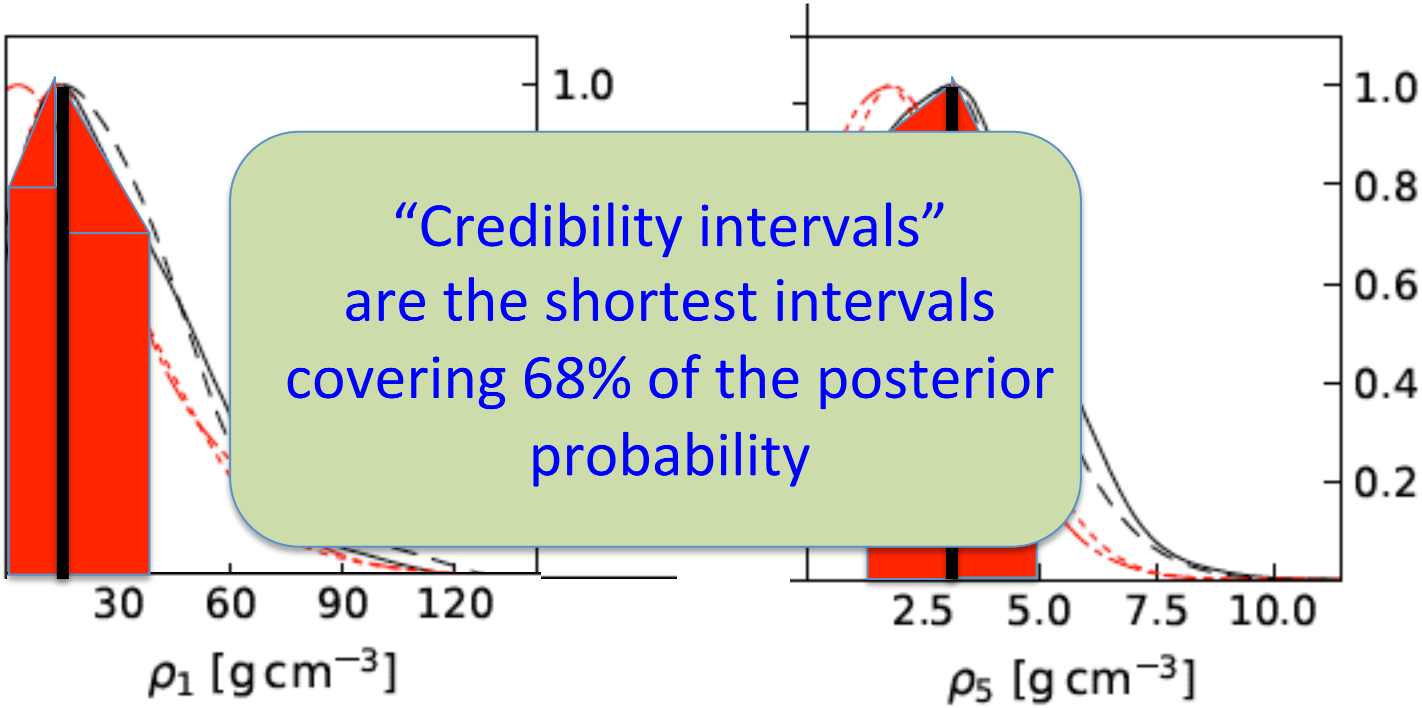
Asymmetric credibility intervals



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

Constrained fits

BY

Impact of external constraints

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

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Impact of external 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

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What I know about seismology

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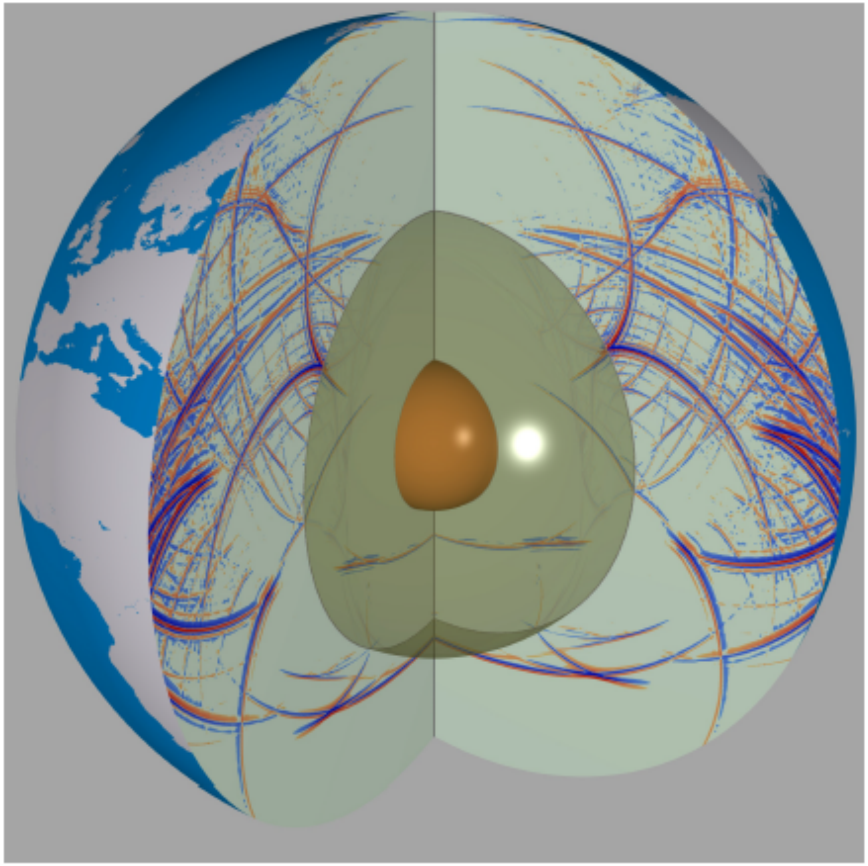
How densities are measured?

seismology

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



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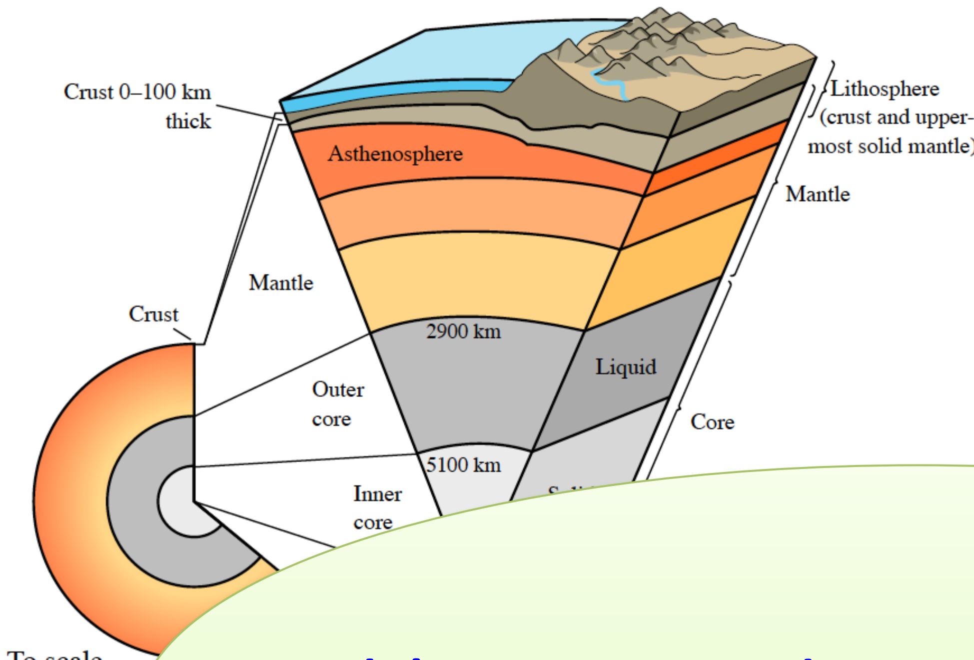
Density at different depths



Depth[103] km	Component layer	Density g/cm³
0–60	Lithosphere[n 14]	–
0–35	Crust[n 15]	2.2–2.9
35–60	Upper mantle	3.4–4.4
35–2890	Mantle	3.4–5.6
[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 $2.7\ g/cm^3$)

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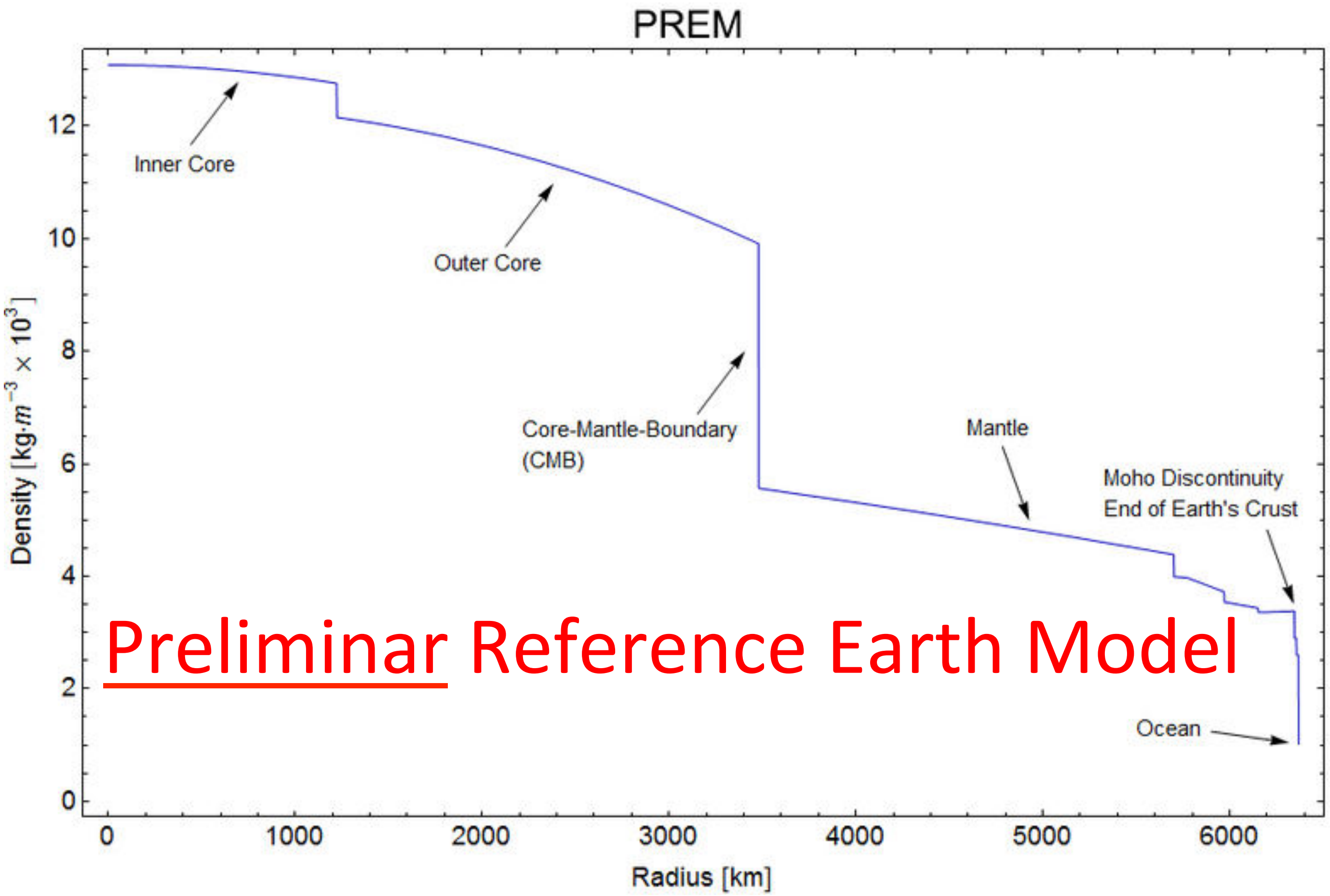
1-dimensional density profile



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

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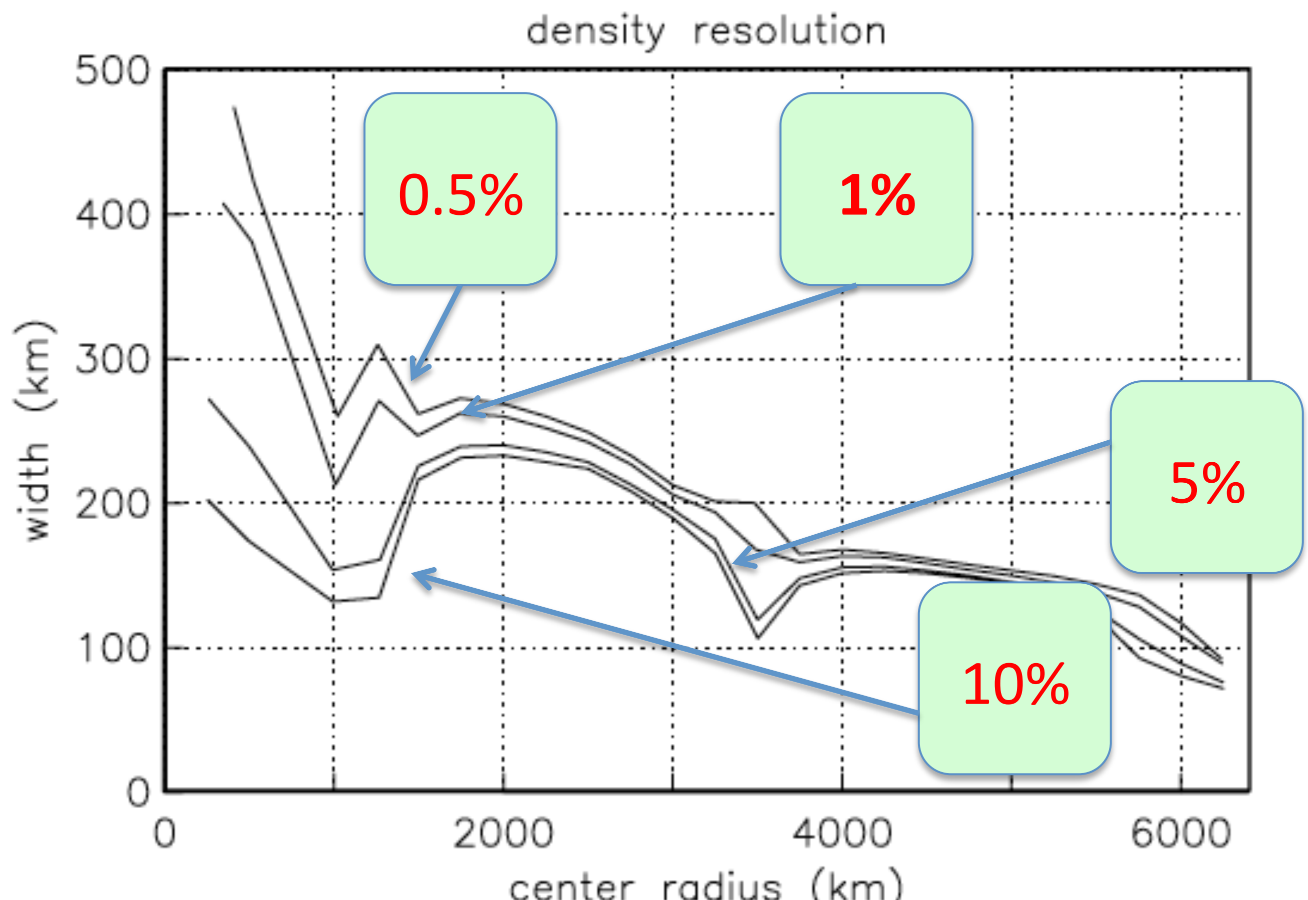
Uncertainties on the core density…



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

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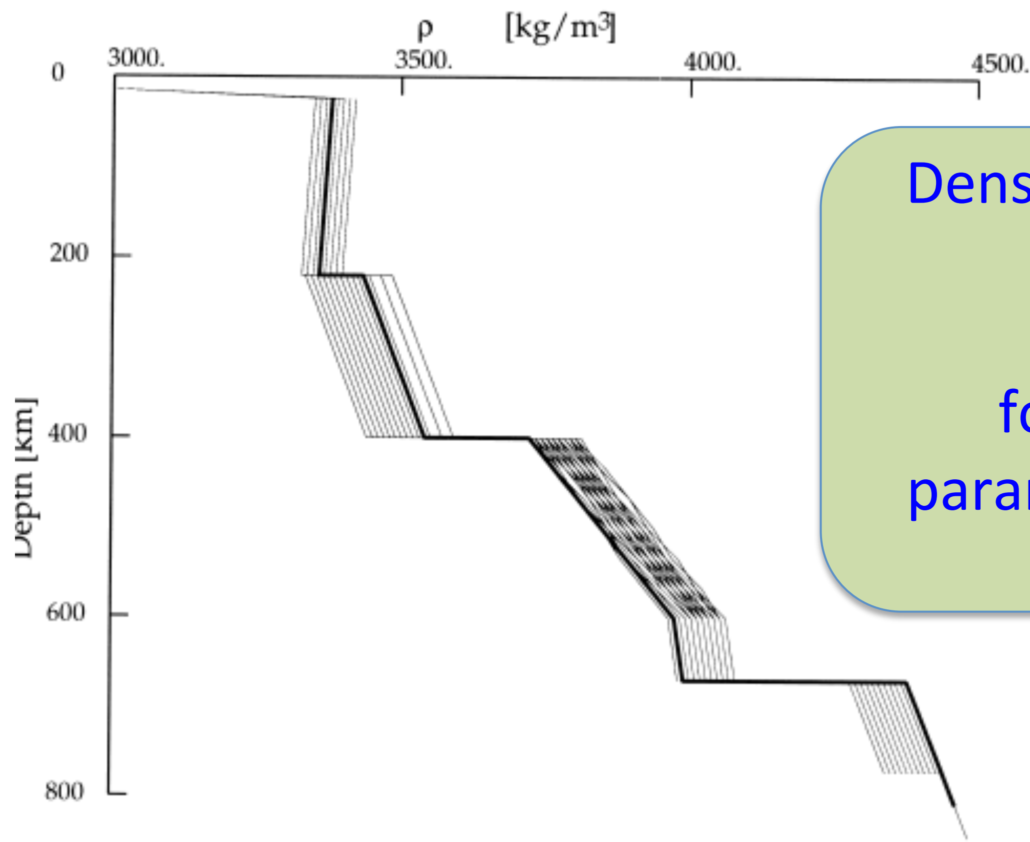
Uncertainties on the crust density…



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

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

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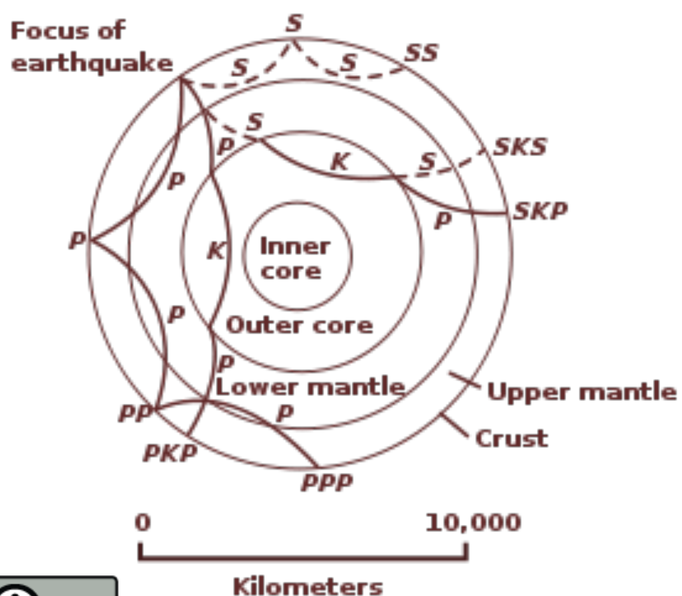
The Earth's core

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

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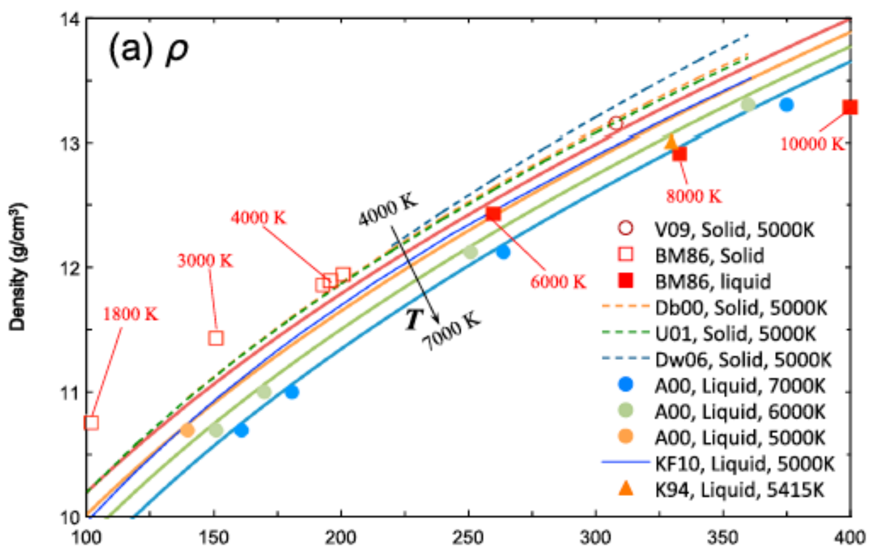
Inner Core equation of state dependence

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)

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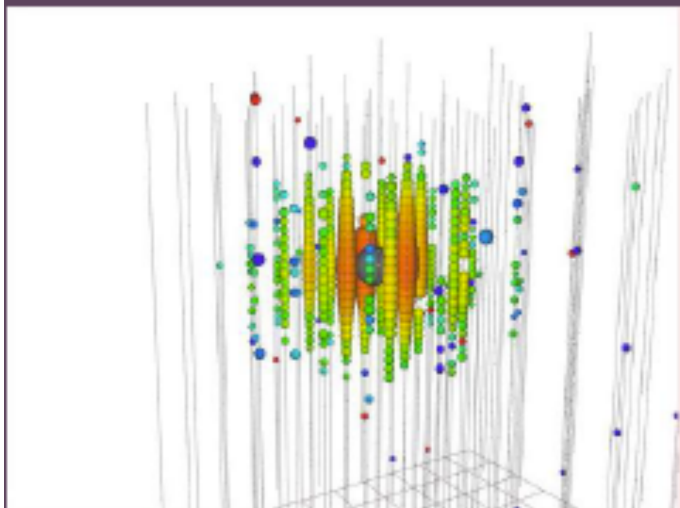
Nice pictures

BY

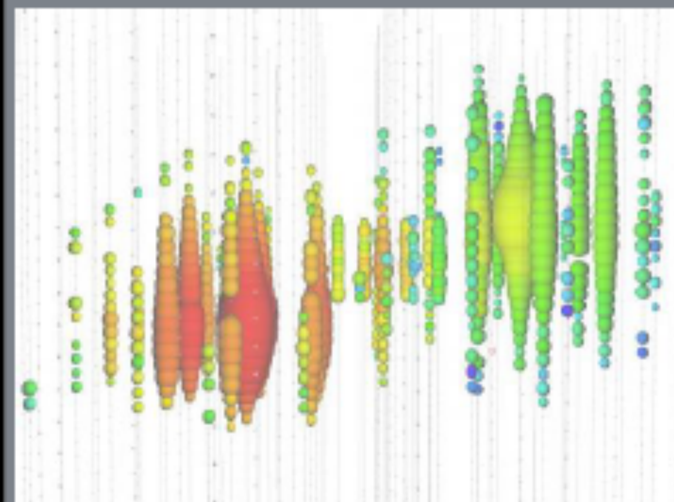
Events at IceCube

Cascade



- NC or CC ν_e/ν_τ
- Angular resolution $\approx 10°$
- Energy resolution $\Delta E/E \approx 10\%$

Double-bang



- High energy ν_τ ($\gtrsim$ 100 TeV)

de los Heros, NeuTel 2019, Venice

Kopper, NeuTel 2019, Venice

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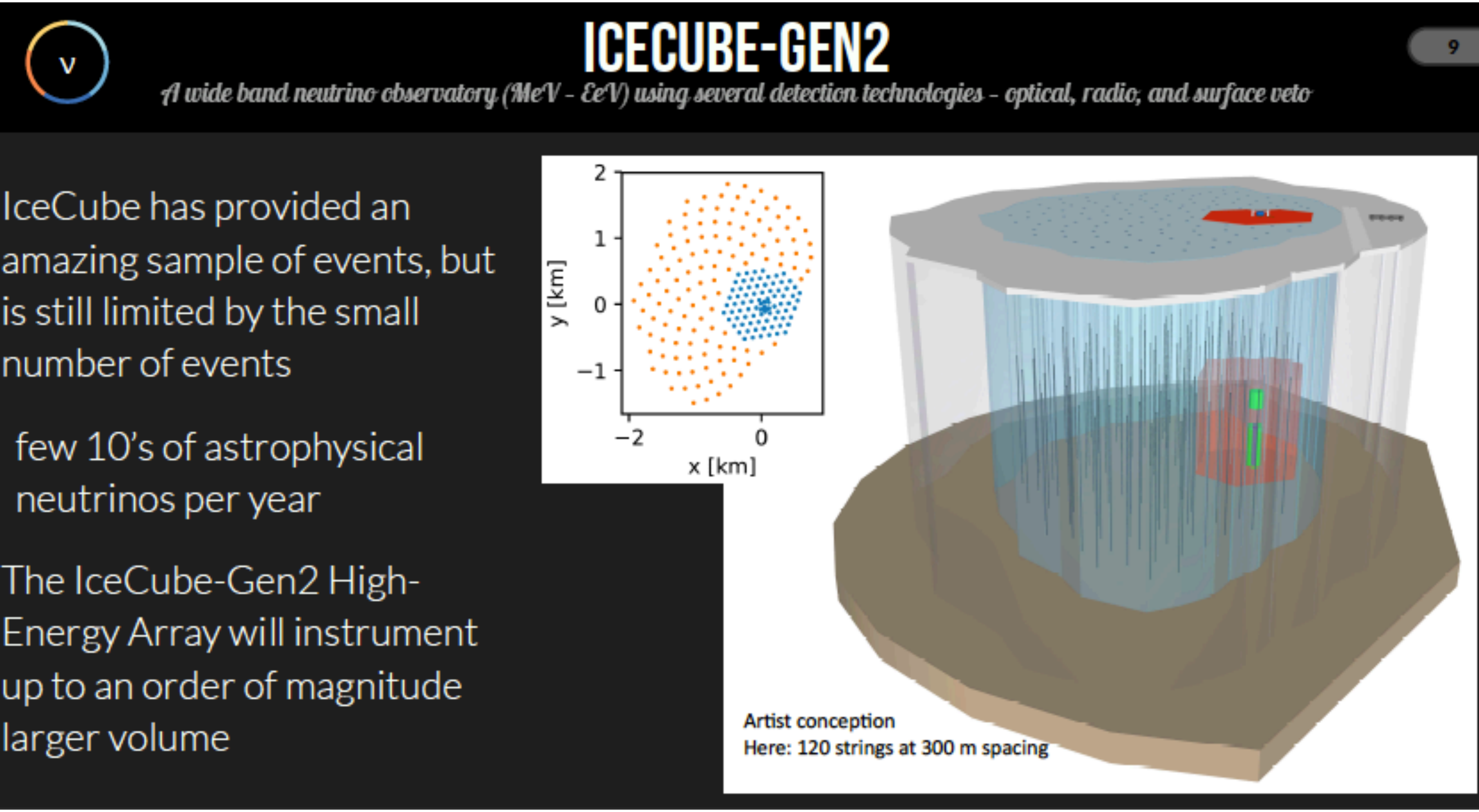

Kopper, NeuTel 2019, Venice

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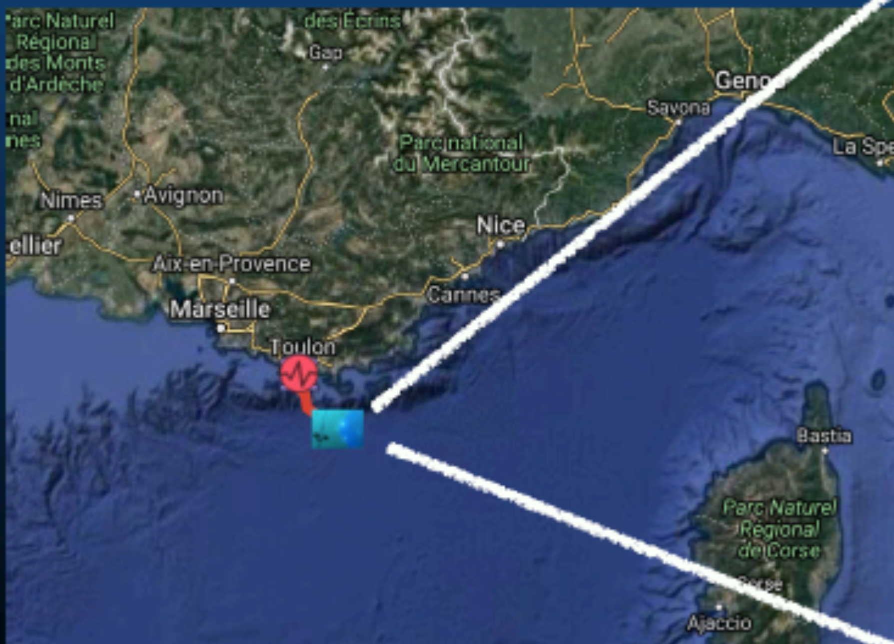
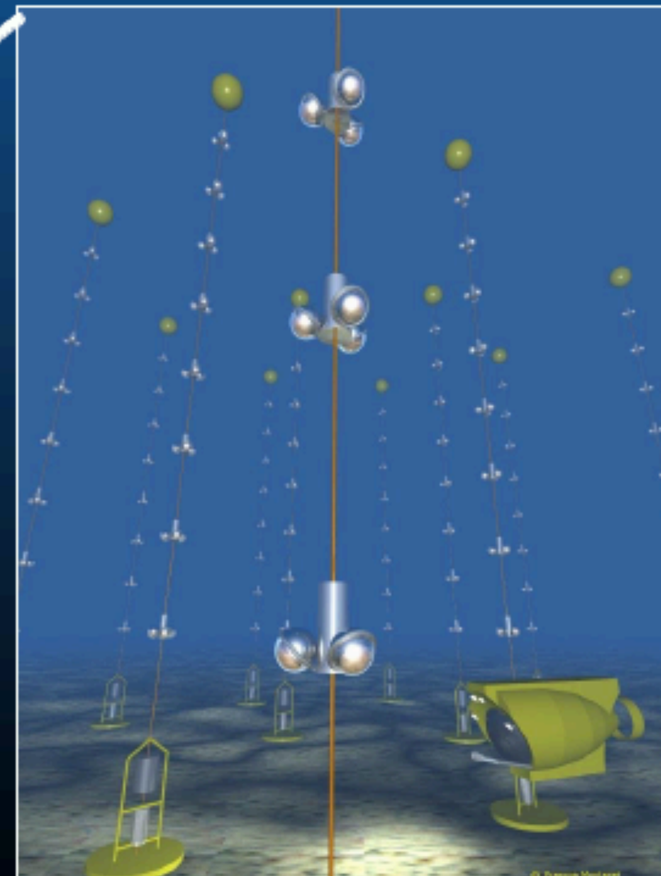
ANTARES

12 lines -> 350 m height
surface area 0.1 km^2

Largest underwater neutrino telescope running since 2007 (complete 2008) in the Mediterranean Sea.



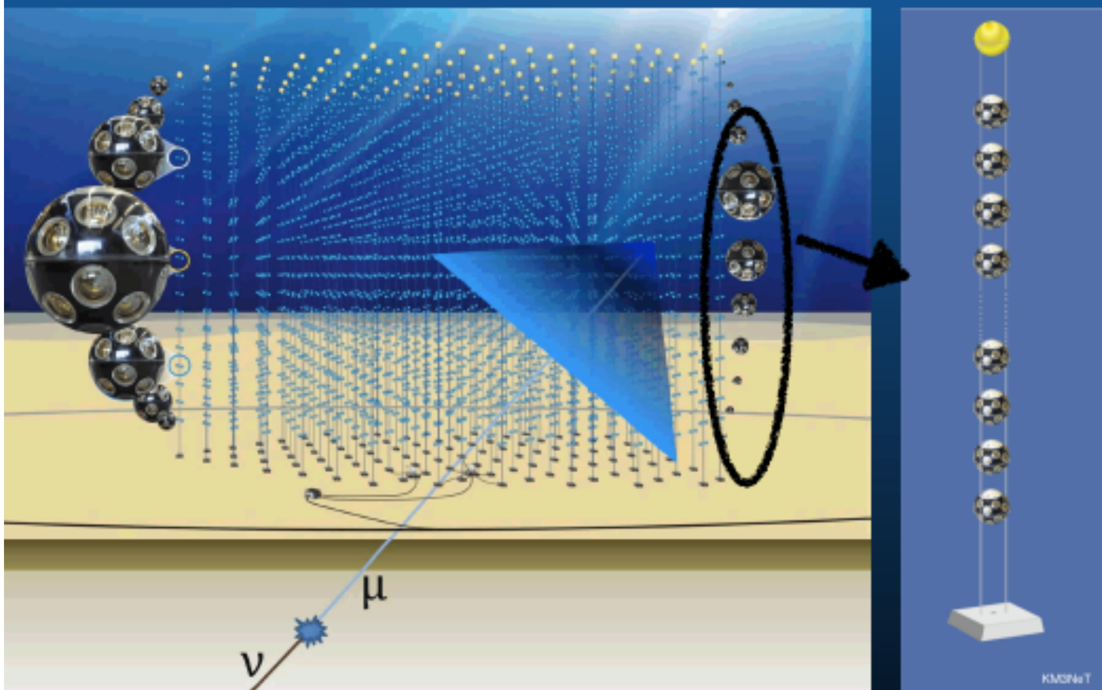


Domi, NeuTel 2019, Venice

BY

KM3NeT: ORCA & ARCA

Ref: KM3NeT LoI - J.Phys. G43 (2016) no.8, 084001



ORCA:
1 DENSE BUILDING BLOCK OPTIMISED FOR INTERMEDIATE ENERGIES (1-100 GEV)

ARCA:
2 SPARSE BUILDING BLOCKS OPTIMISED FOR HIGH ENERGIES (>1 TEV)

Domi, NeuTel 2019, Venice

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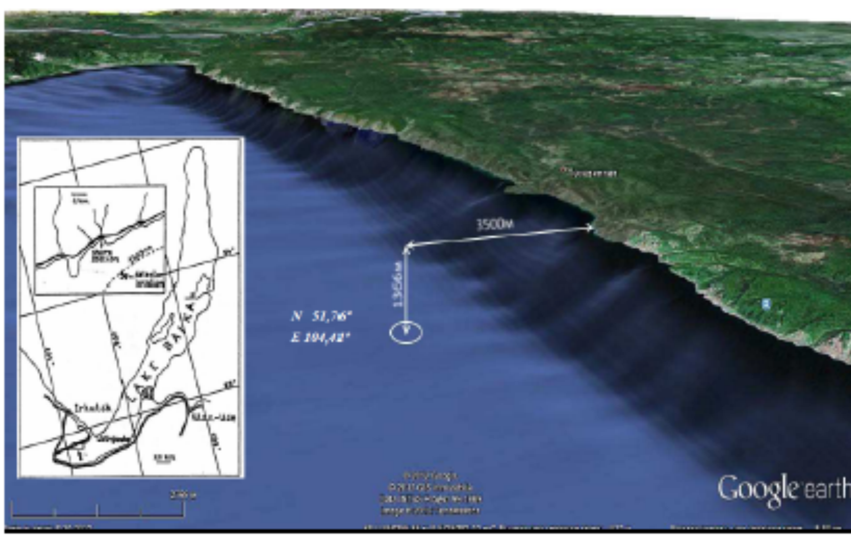

BAIKAL-GVD

Suvorova, NeuTel 2019, Venice

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