Neutrino Earth Tomography

Sort of…

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General view

1. Neutrinos in particle physics

2. Neutrino Earth Tomography

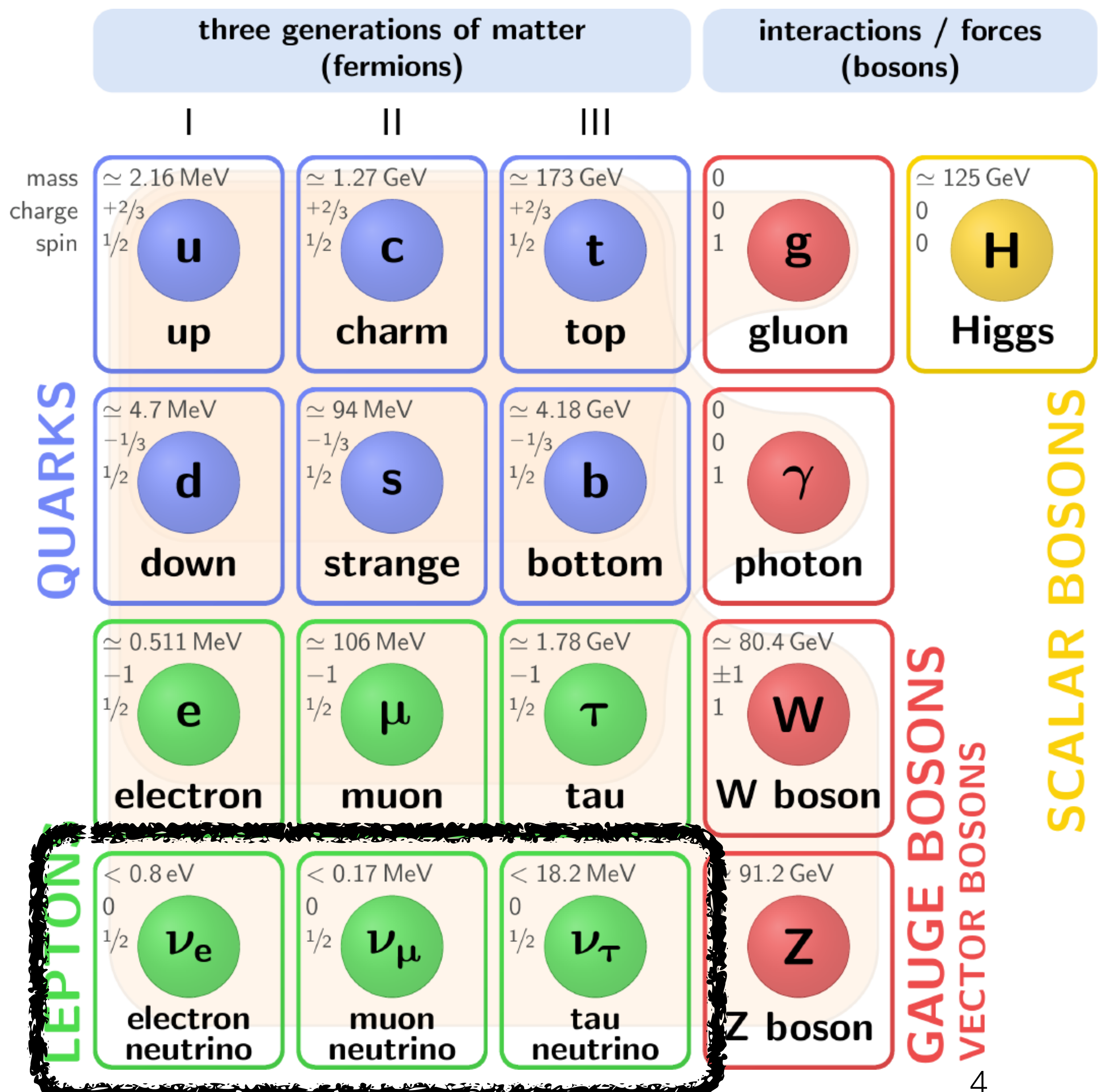
3. Hands-on: two simple exercises

Class 1: outline

1. Neutrinos in the Standard Model
2. Neutrino Masses
3. Neutrino Oscillations
4. Neutrino Sources

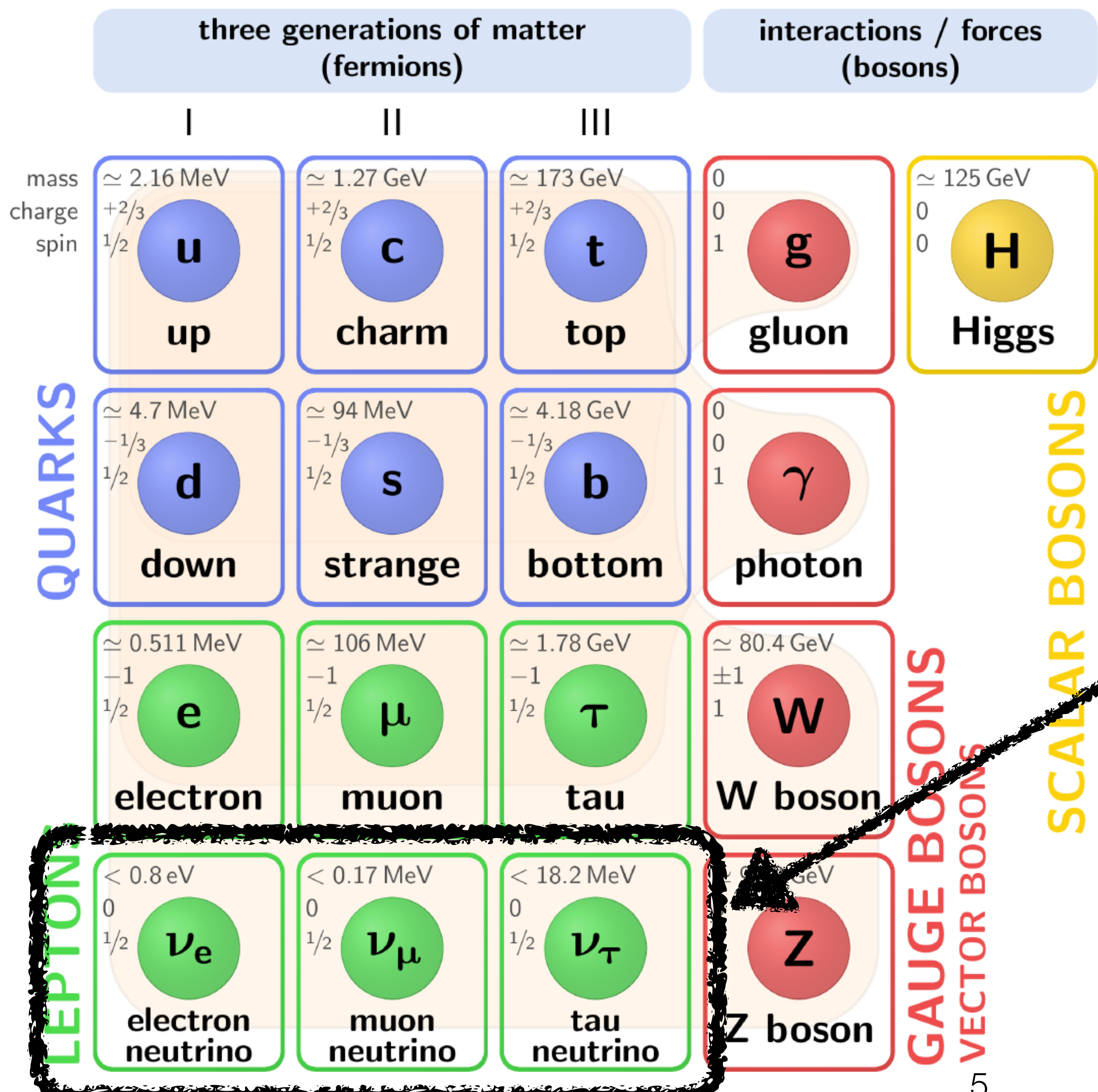
Neutrinos in the Standard Model

(of fundamental interactions)



Neutrinos in the Standard Model

(of fundamental interactions)

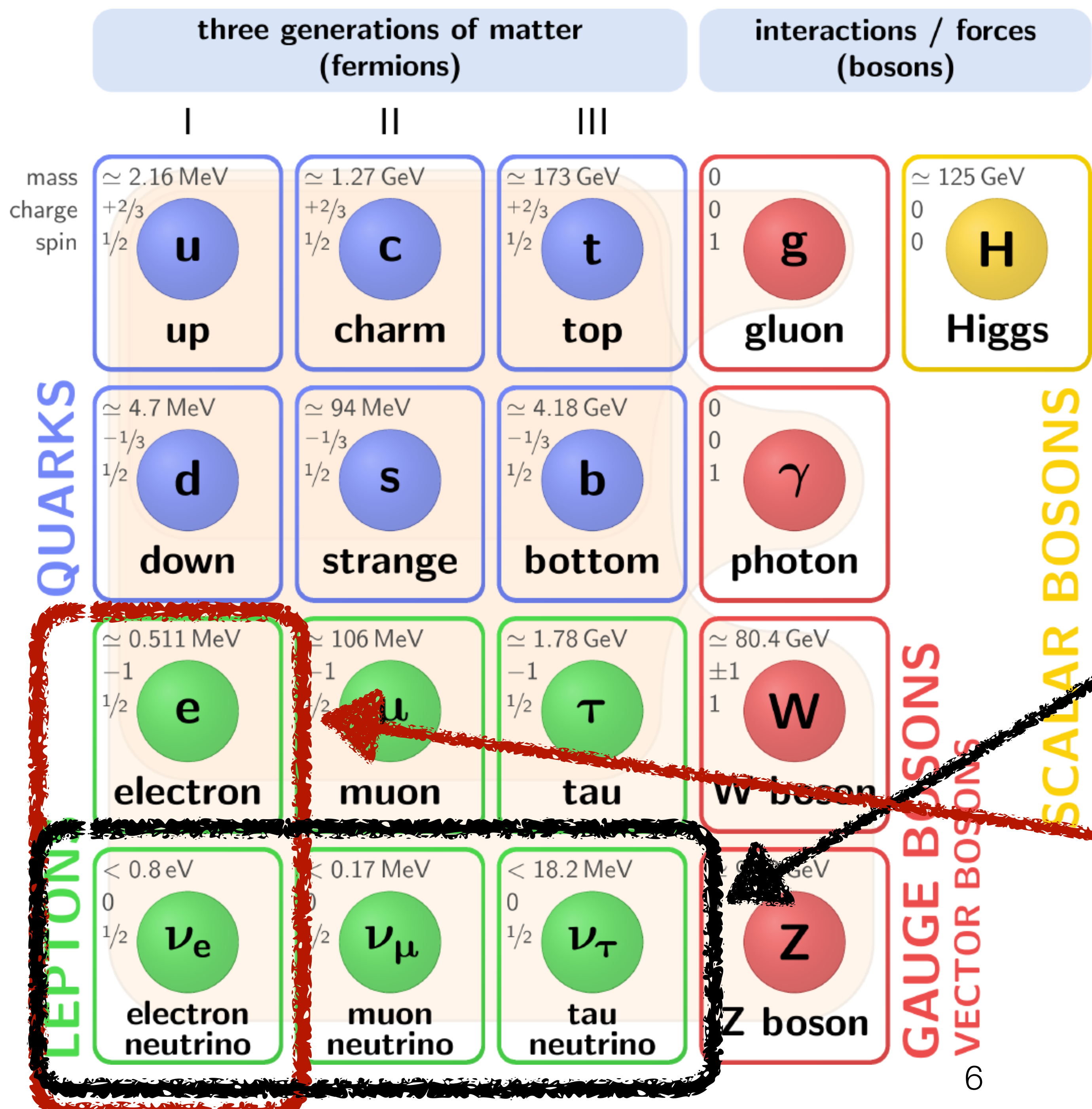


Three fermions

Chargeless
Colourless

Neutrinos in the Standard Model

(of fundamental interactions)

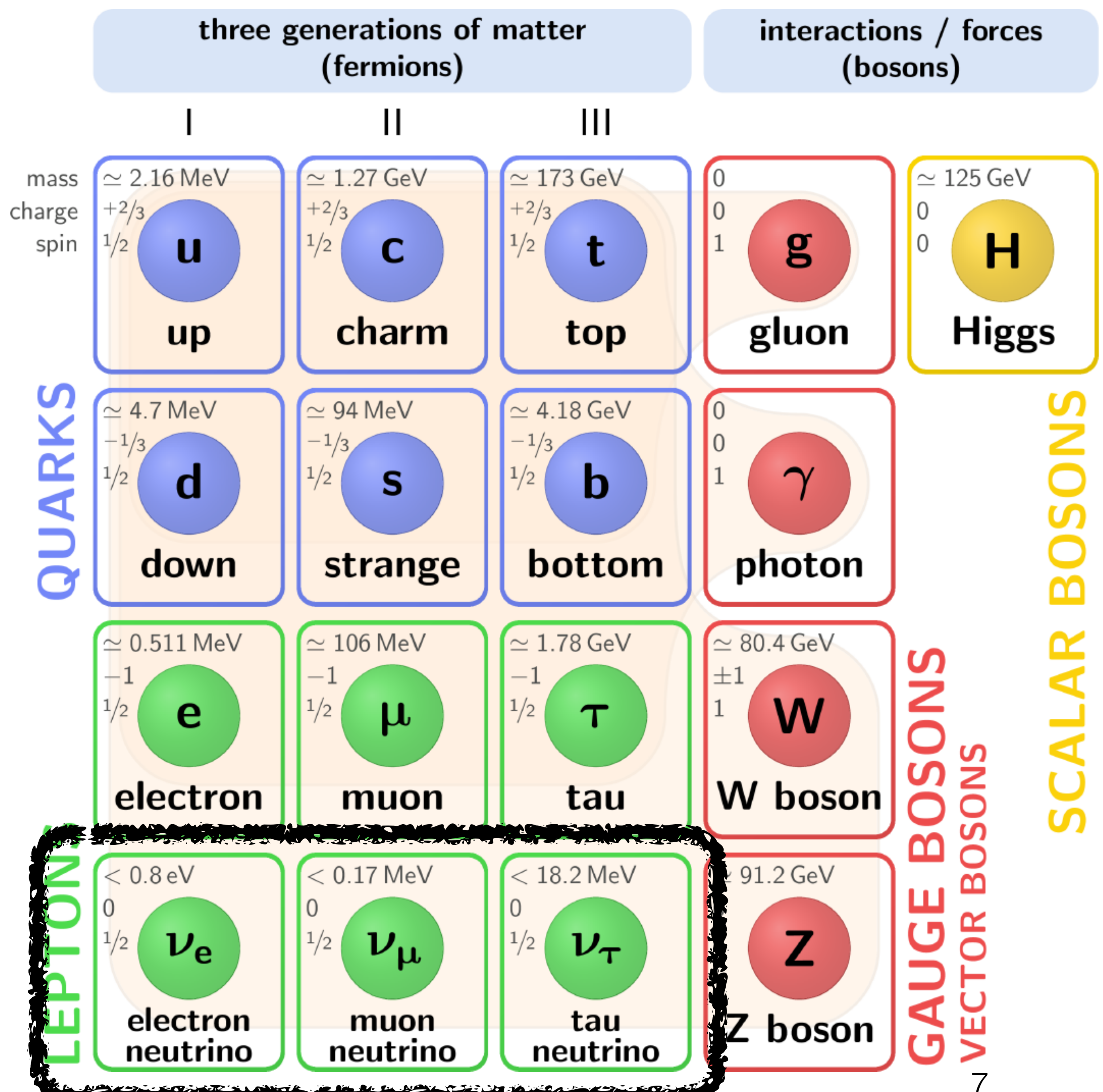


Three fermions

Chargeless
Colourless

SU(2) doublets
(weakly interacting)

Are neutrinos massive?



Not in the Standard Model

They are massive, though…

Neutrino oscillations, 1
(two families)

1. Flavour basis (interaction eigenstates)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \equiv (\nu_\alpha)_{\text{flavour}}$$

$$\mathcal{L}_{\text{CC}} \sim \bar{\ell}_\alpha \gamma^\mu P_L \nu_\alpha W_\mu + \text{h.c.}$$

2. Mass basis (propagation eigenstates)

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \equiv (\nu_i)_{\text{mass}} \qquad \mathcal{L}_{\text{mass}} = -\sum_{i=1}^{2} m_i \bar{\nu}_i \nu_i$$

Neutrino oscillations, 1
(two families)

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(…just as for quarks, 1)

1. Charged–current interactions (gauge basis)

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}}\, \bar{u}_\alpha \gamma^\mu P_L d_\alpha\, W^+_\mu + \frac{g}{\sqrt{2}}\, \bar{\ell}_\alpha \gamma^\mu P_L \nu_\alpha\, W^+_\mu + \text{h.c.}$$

Here α is a *flavour* index: (u, d) for quarks, (ℓ, ν) for leptons.

2. Mass diagonalization

$$u_L = U_u\, u_L^{\text{mass}}, \qquad d_L = U_d\, d_L^{\text{mass}},$$

$$\ell_L = U_\ell\, \ell_L^{\text{mass}}, \qquad \nu_L = U_\nu\, \nu_L^{\text{mass}}.$$

(...just as for quarks, 2)

3. Mixing matrices appear in the CC term After rotating to the mass basis:

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}}\,\bar{u}^{\text{mass}} U_u^\dagger U_d\,\gamma^\mu P_L d^{\text{mass}} W_\mu^+ + \frac{g}{\sqrt{2}}\,\bar{\ell}^{\text{mass}} U_\ell^\dagger U_\nu\,\gamma^\mu P_L \nu^{\text{mass}} W_\mu^+$$

Quark sector: CKM matrix $\quad V_{\text{CKM}} = U_u^\dagger U_d$

$$V_{\text{CKM}} \simeq \begin{pmatrix} 0.974 & 0.226 & 0.0036 \\ -0.226 & 0.973 & 0.042 \\ 0.0087 & -0.041 & 0.999 \end{pmatrix}$$

Mixing angles

$$\theta_{12}^q \simeq 13^\circ, \quad \theta_{23}^q \simeq 2.4^\circ, \quad \theta_{13}^q \simeq 0.2^\circ.$$

Hierarchical, close to identity.

Neutrino oscillations, 2a

(Three families)

Lepton sector: PMNS matrix

$$U_{\text{PMNS}} = U_\ell^\dagger U_\nu .$$

$$U_{\text{PMNS}} \simeq \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ -0.36 & 0.70 & 0.62 \\ 0.44 & -0.45 & 0.78 \end{pmatrix}$$

Mixing angles

$$\theta_{12}^\ell \simeq 33^\circ, \quad \theta_{23}^\ell \simeq 49^\circ, \quad \theta_{13}^\ell \simeq 8.6^\circ .$$

For massless neutrinos…

…there would be no misalignment

Neutrino oscillations, 2b

(Three families)

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\, \nu_i \qquad\qquad P_{\alpha\to\beta}(L) = \left| \sum_{i=1}^{3} U_{\beta i}\, U^*_{\alpha i}\, e^{-i\frac{m_i^2 L}{2E}} \right|^2$$

$$P_{\alpha\to\beta} = -4\sum_{i>j} \Re\left(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{i>j} \Im\left(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

Neutrino oscillations, 2b

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CP-even
(disappearance and appearance)

Neutrino oscillations, 2b

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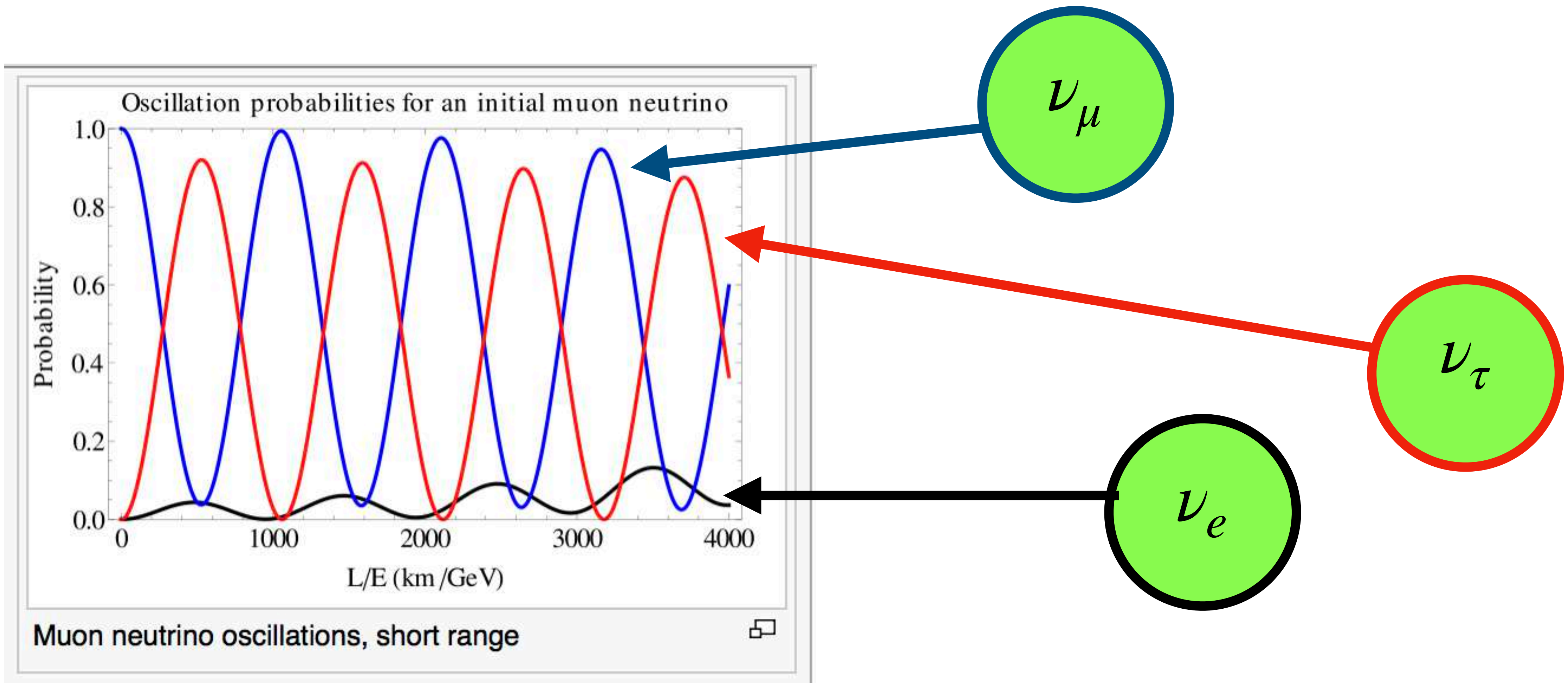
CP-even
(disappearance and appearance)

CP-odd
(appearance only)

Neutrino oscillations, 3a

(Probabilities in vacuum)

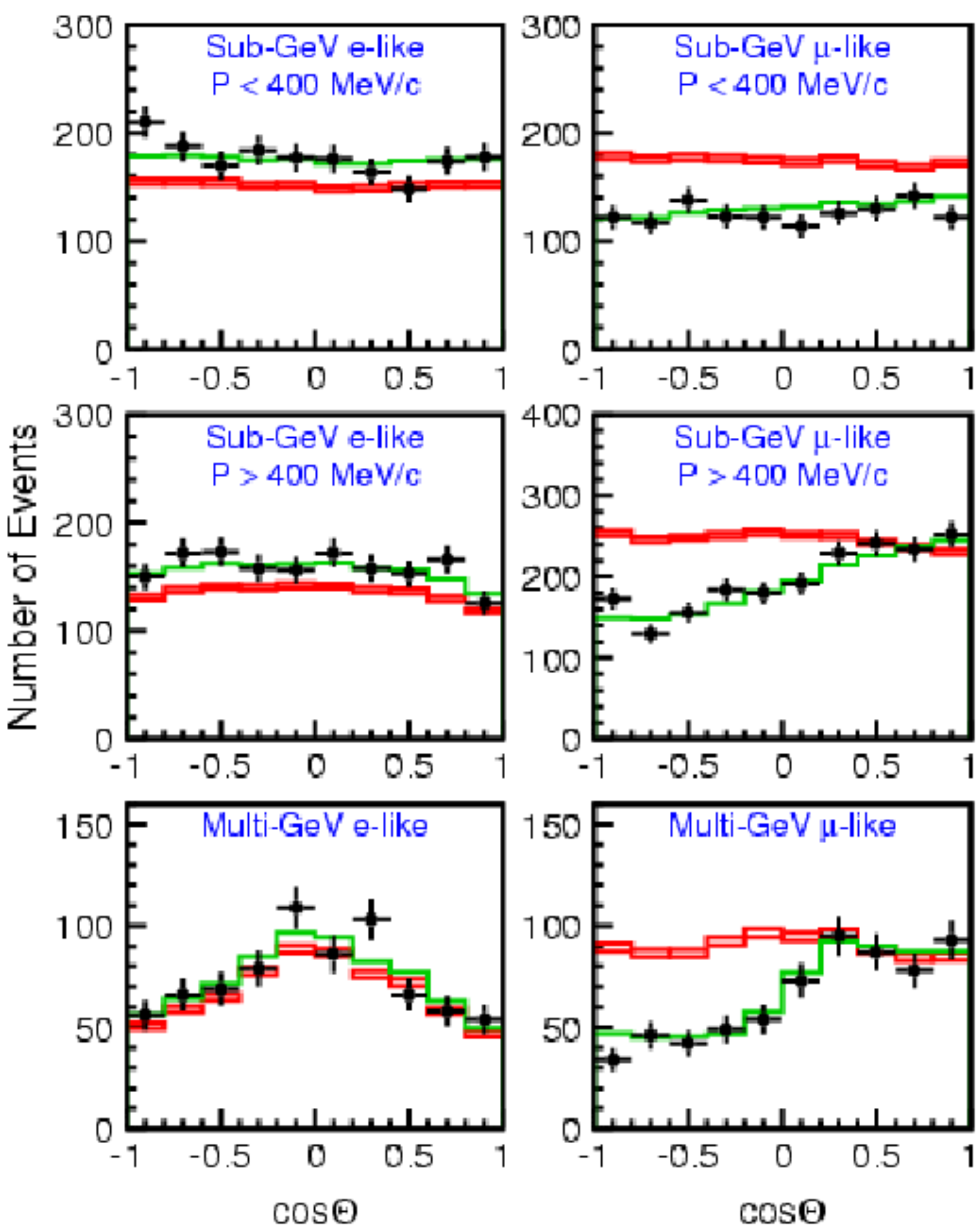


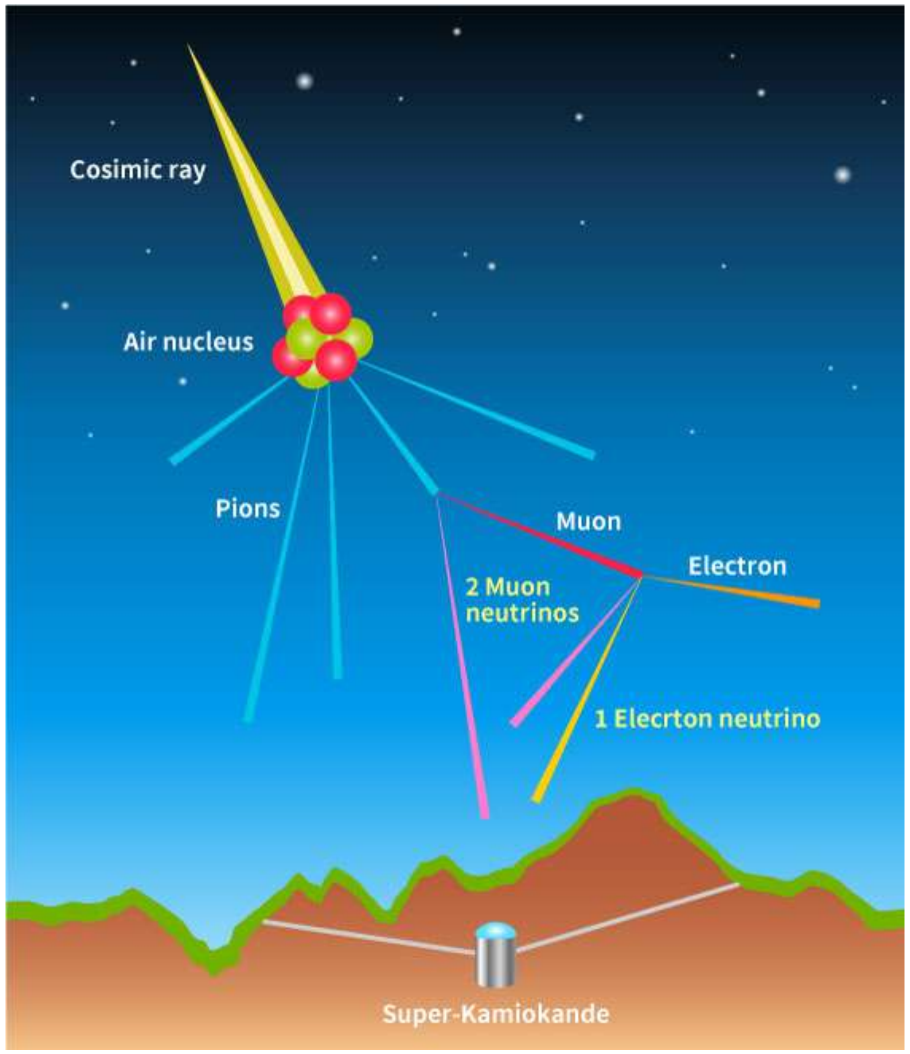
Muon neutrino oscillations, short range

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{\Delta m^2}{4E}\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}.$$

Neutrino oscillations, 3b

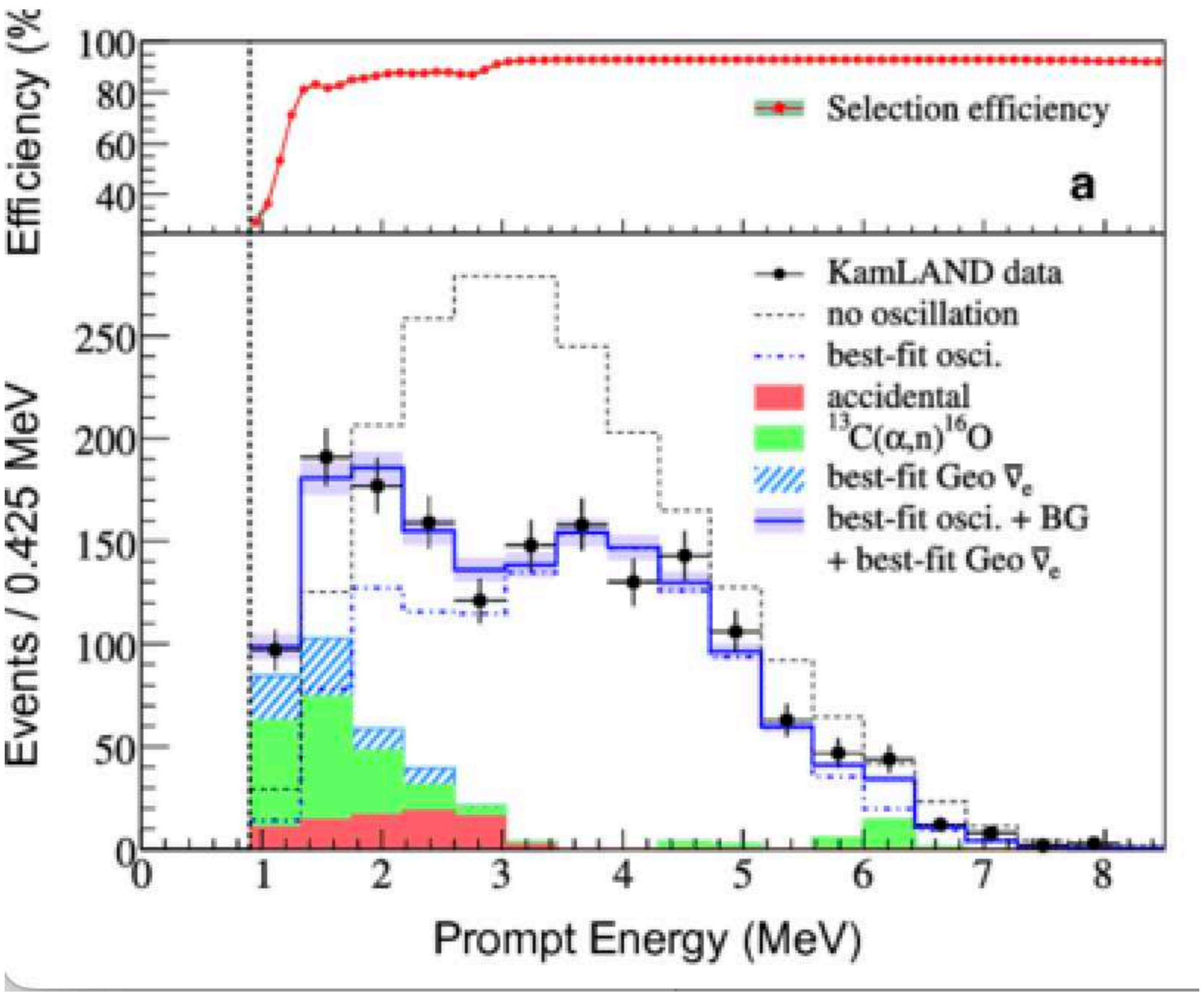
(SuperKamiokaNDE data: atmospheric neutrinos)





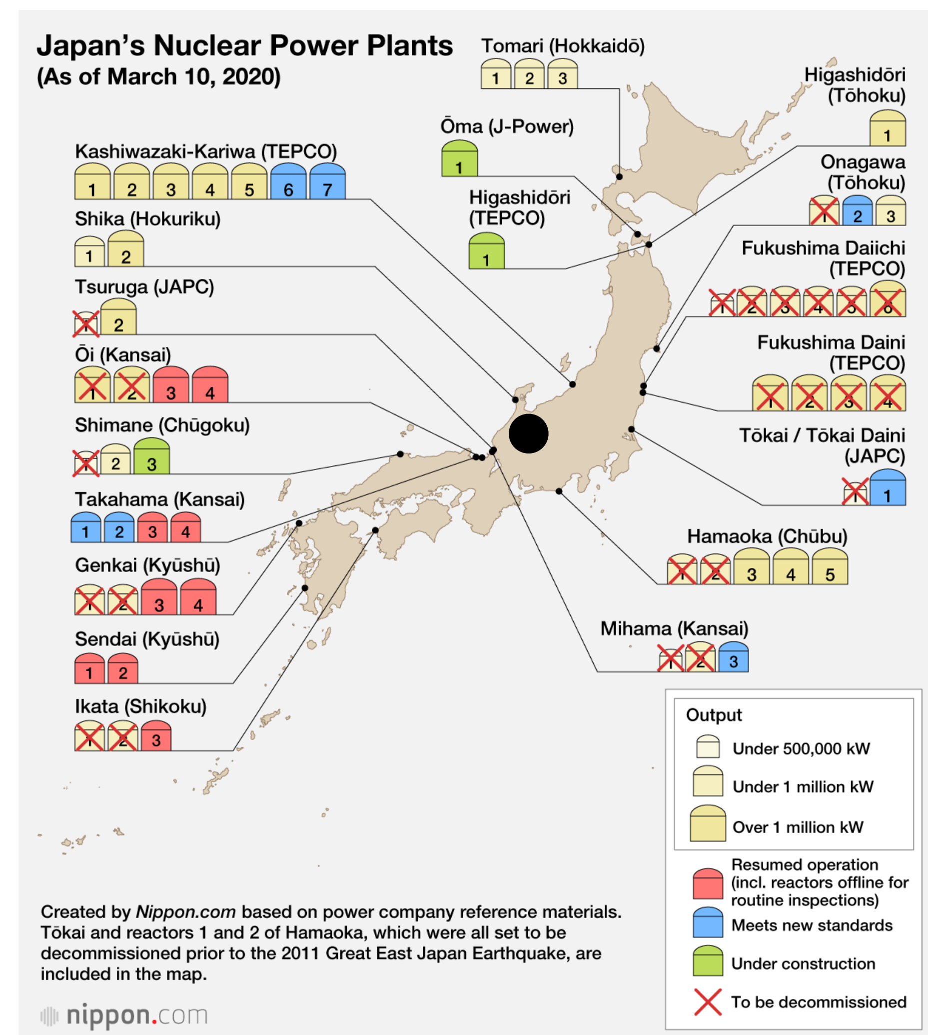
Neutrino oscillations, 3c

(KamLAND data: reactor neutrinos)



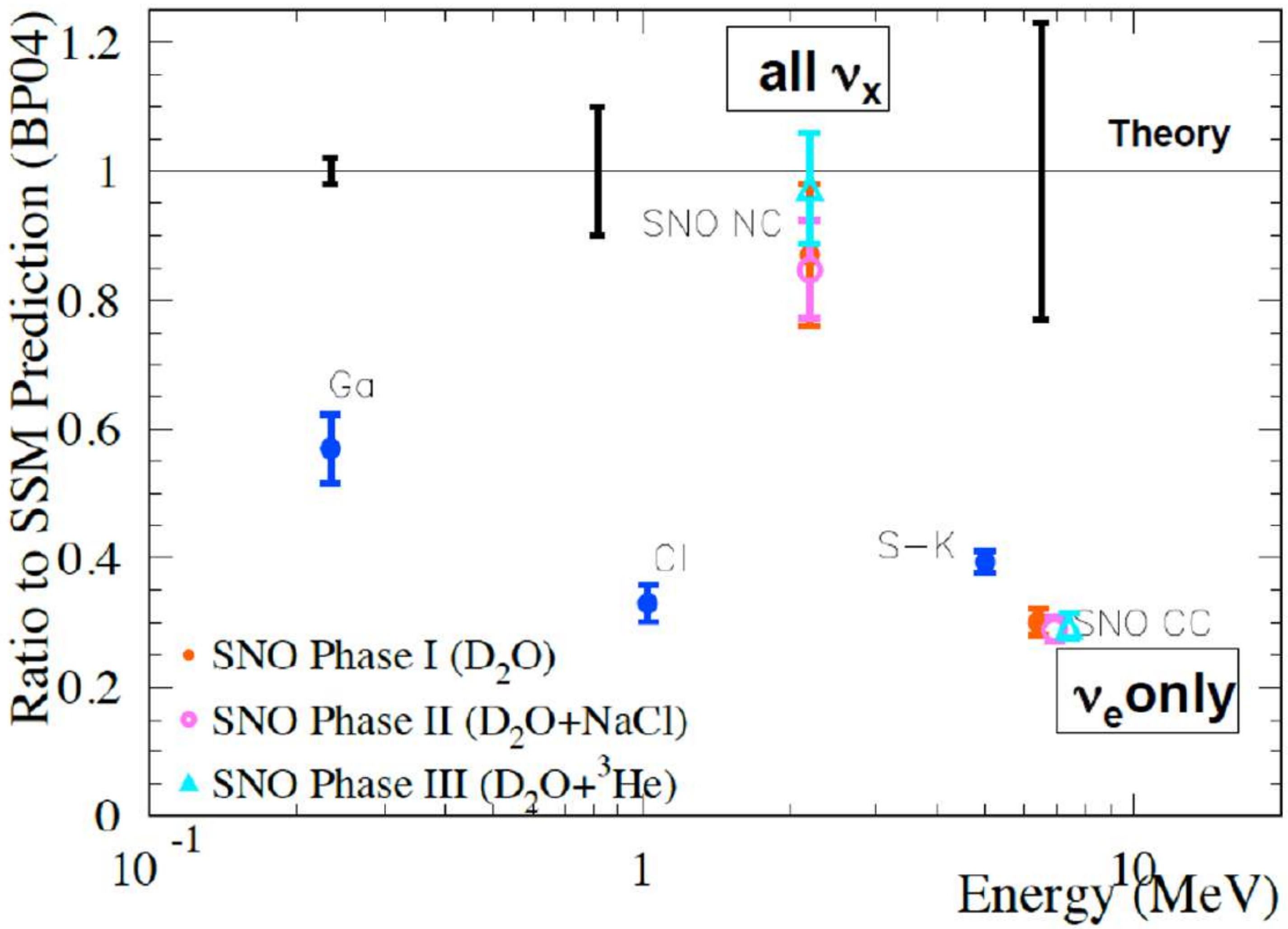
Expected

Observed



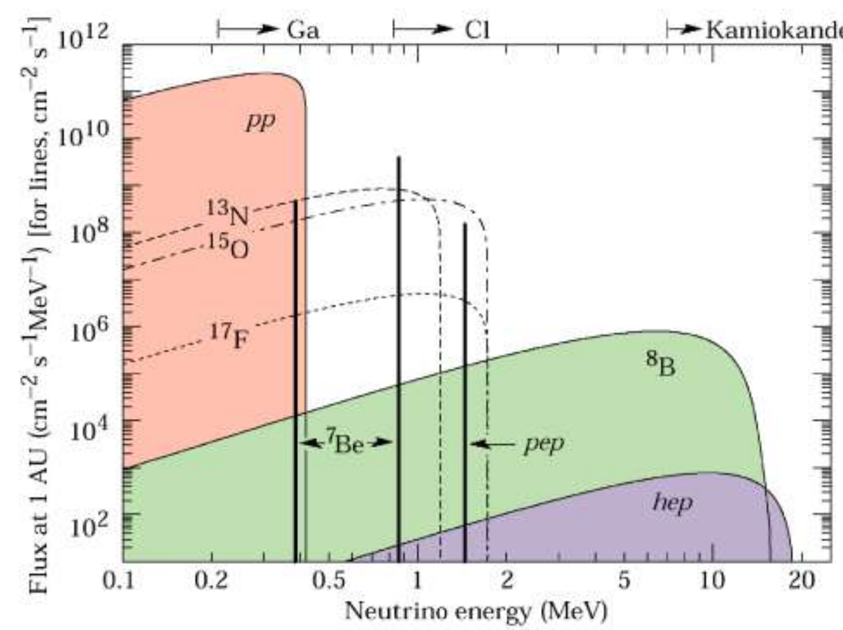
Neutrino oscillations, 3d

(SNO data: solar neutrinos NC vs CC)

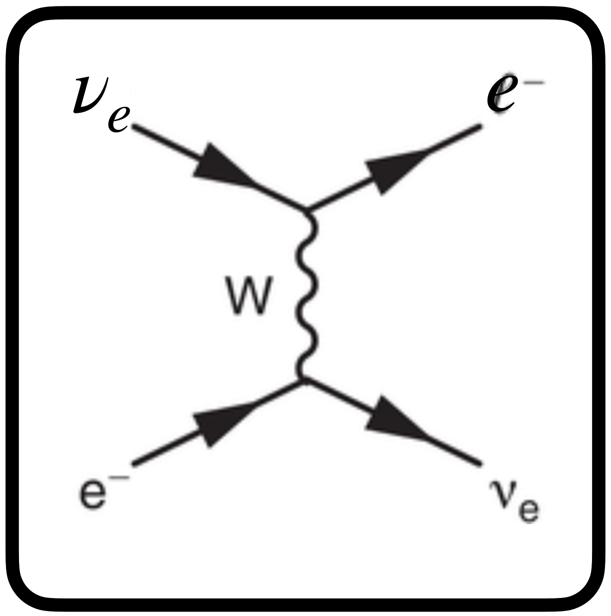


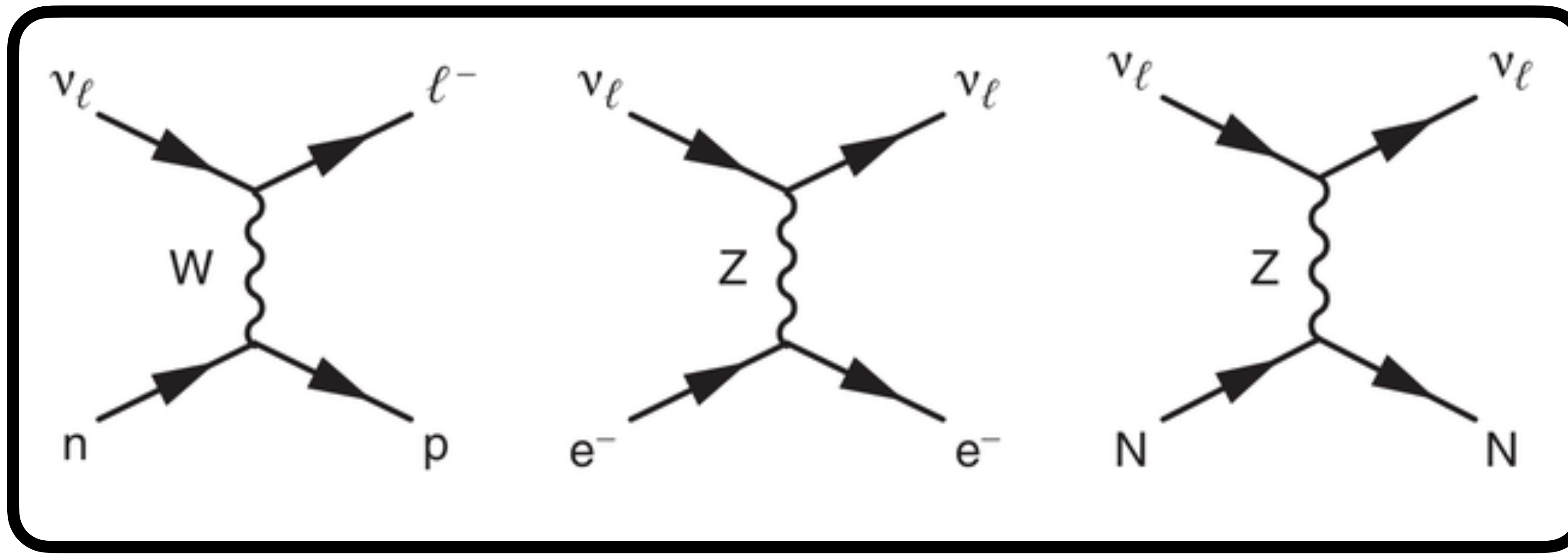
Observed all neutrinos

Observed ν_e



Neutrino oscillations, 4
(Probabilities in matter)





Only ν_e

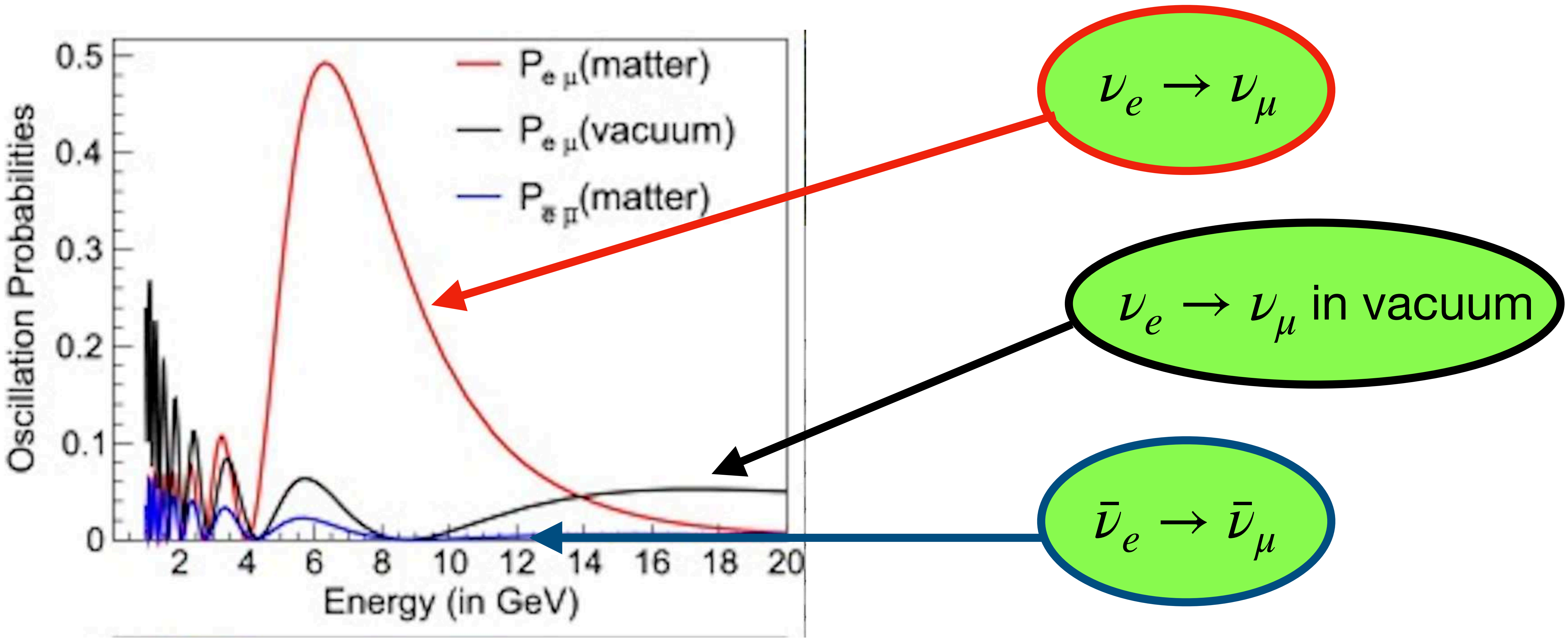
All neutrino species

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \left[\frac{\Delta m^2}{4E}\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix} + \begin{pmatrix}\sqrt{2}G_F n_e(x) & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e(x)\\ \nu_\mu(x)\end{pmatrix}$$

Hands-on session, exercise 1: diagonalize and find the value of the angle in vacuum for which there is resonant oscillation

Neutrino oscillations, 5a

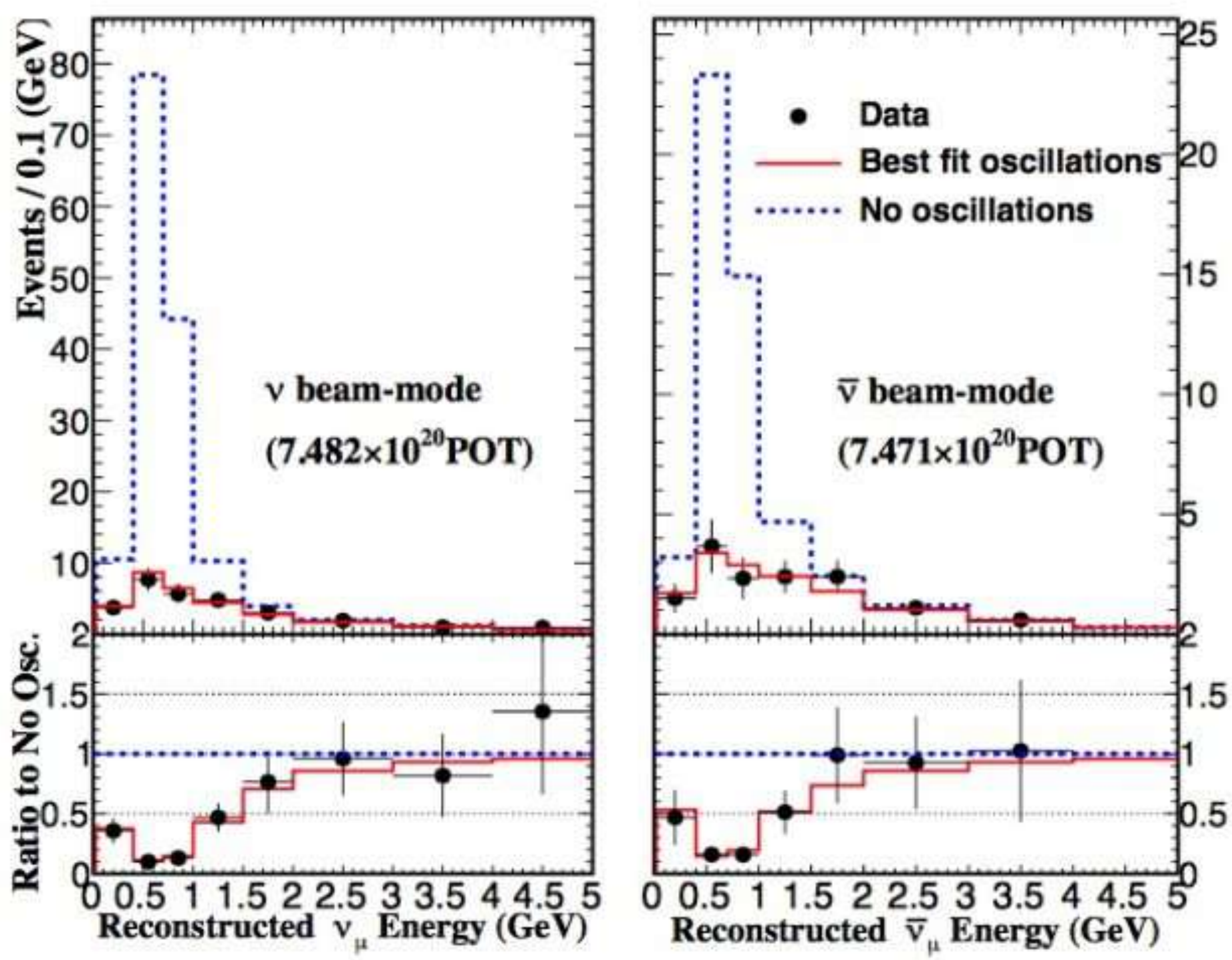
(Probabilities in matter)



Matter matters!

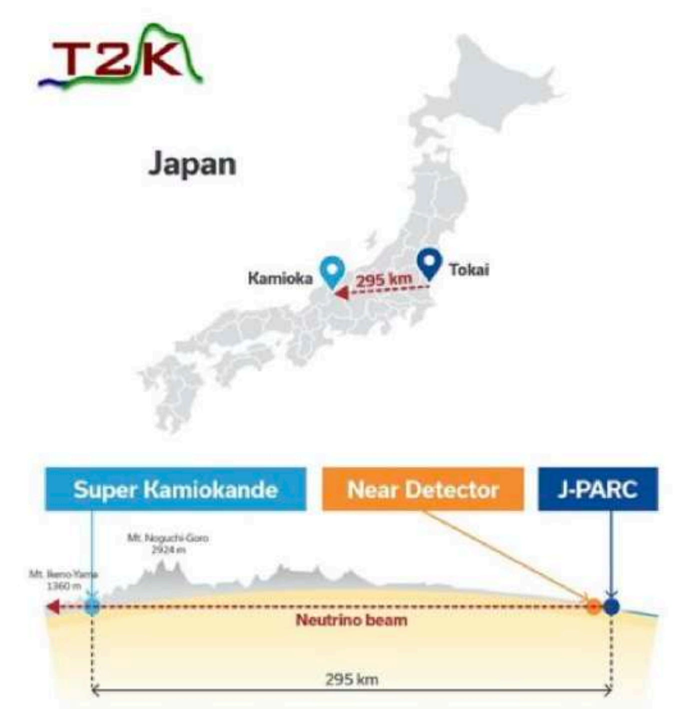
Neutrino oscillations, 5b

(Probabilities in matter)



Matter is CP-odd!

(if you are looking for leptonic CP-violation, better you know this…)



Neutrino sources

1. Solar neutrinos: ν_e

2. Atmospheric neutrinos: $\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$

3. Reactor neutrinos: $\bar{\nu}_e$

4. Accelerator-produced: $\nu_\mu, \bar{\nu}_\mu$ with some $\nu_e, \bar{\nu}_e$ component

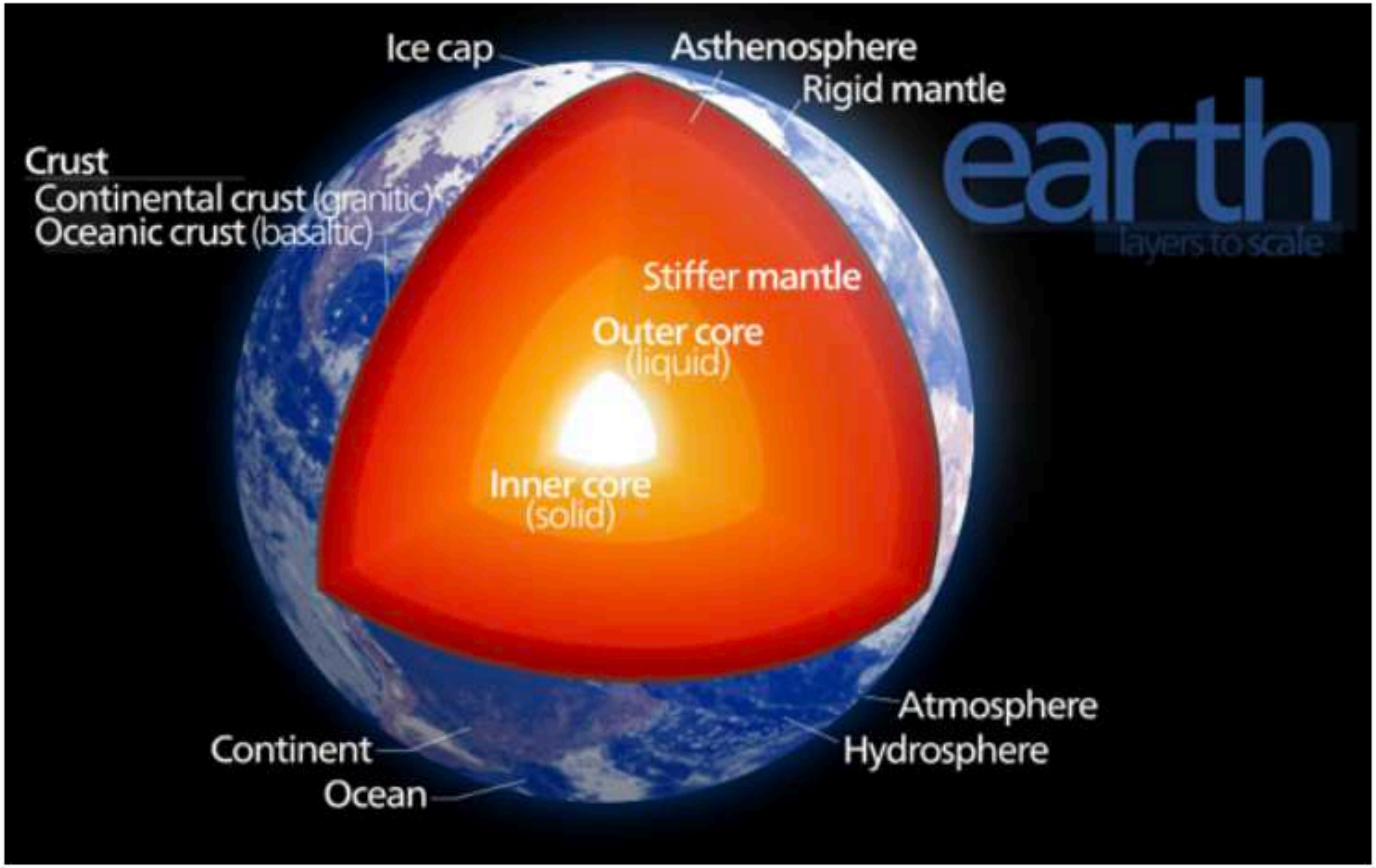
5. Geo-neutrinos: see L. Ludhova course

6. Astrophysical neutrinos (neutrino telescopes)

Class 2: outline

1. Why a neutrino Earth tomography
2. Neutrino telescopes
3. From the source to the detector
4. 1st Neutrino Earth Tomography (2019)
5. 2nd Neutrino Earth Tomography (2026)

The Earth interior



Tomography

noun to·mog·ra·phy \ tō-ˈmä-grə-fē \

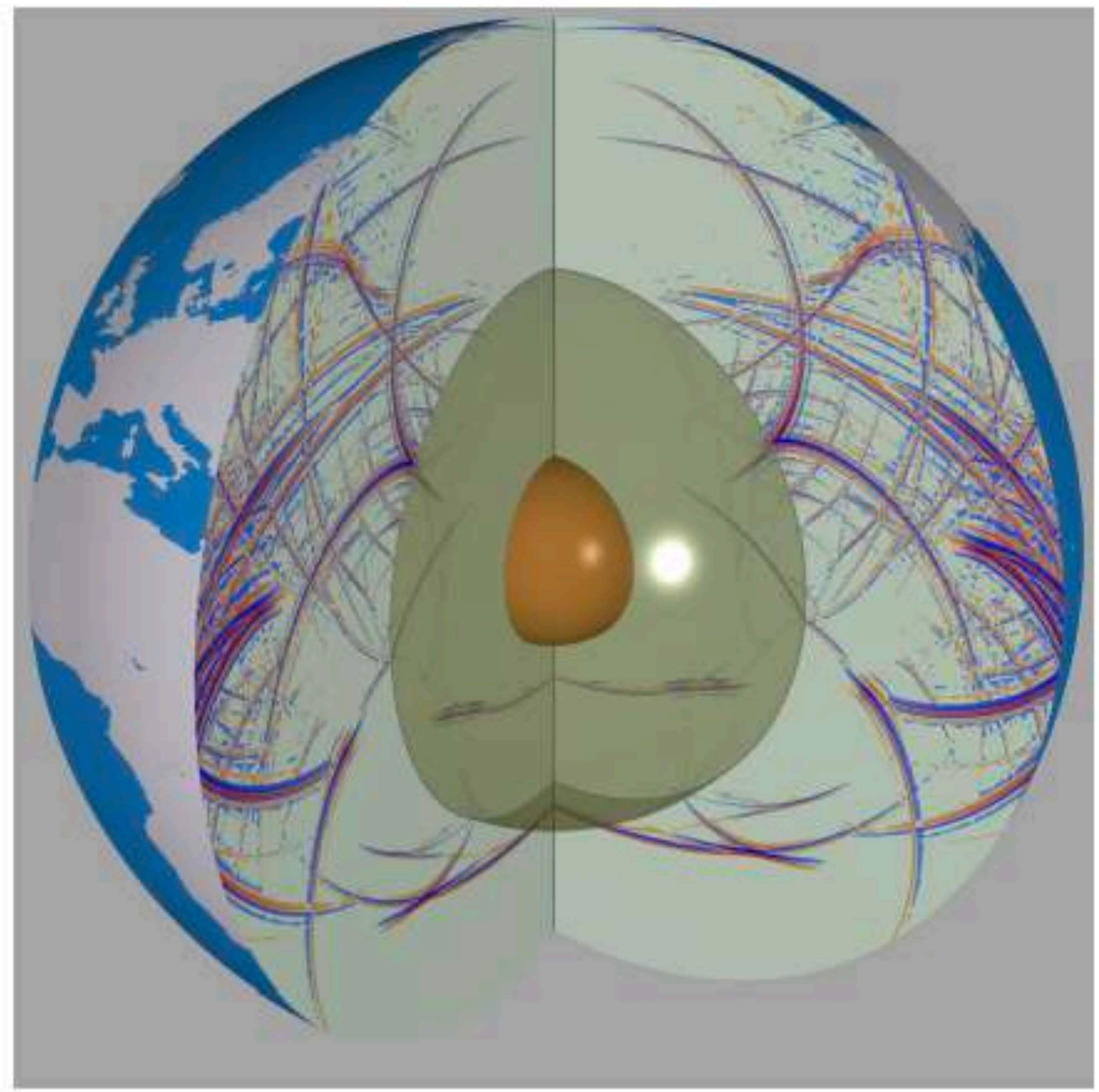
imaging by sections or sectioning, through the use of any kind of penetrating wave (Wikipedia)

a method of producing a three-dimensional image of the internal structures of a solid object (such as the human body or the earth) by the observation and recording of the differences in the effects on the passage of waves of energy impinging on those structures (Merriam-Webster)

How densities are measured?

seismology

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



How densities are measured?

seismology

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

Adams-Williamson equation (1924)

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

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

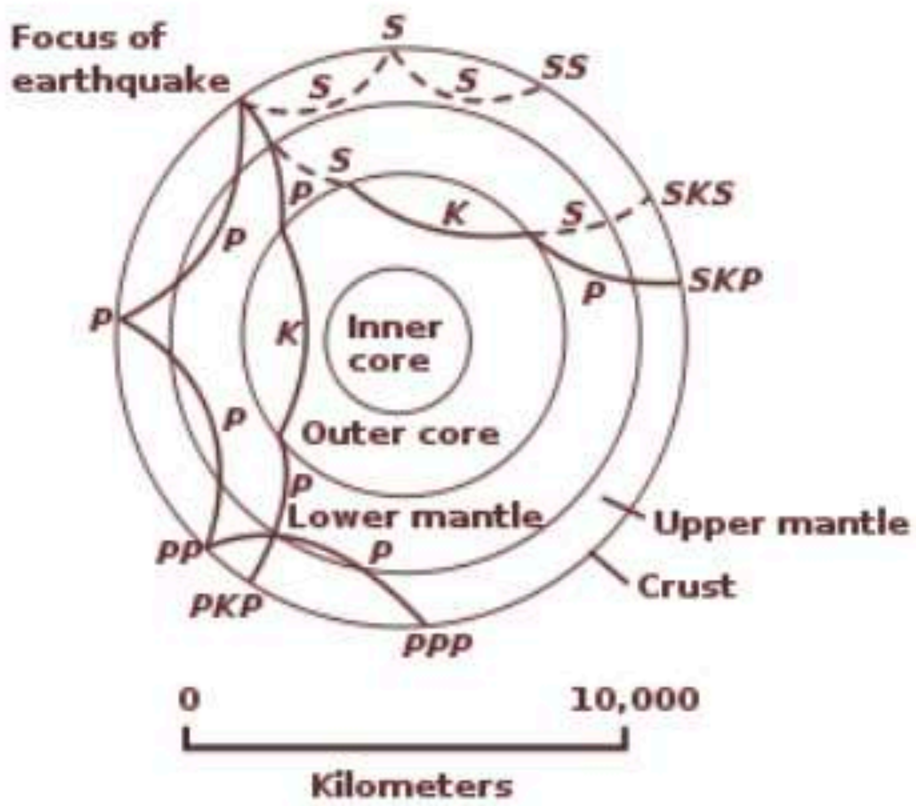
Composition dependence! Gravitational profile dependence!

The Earth's core

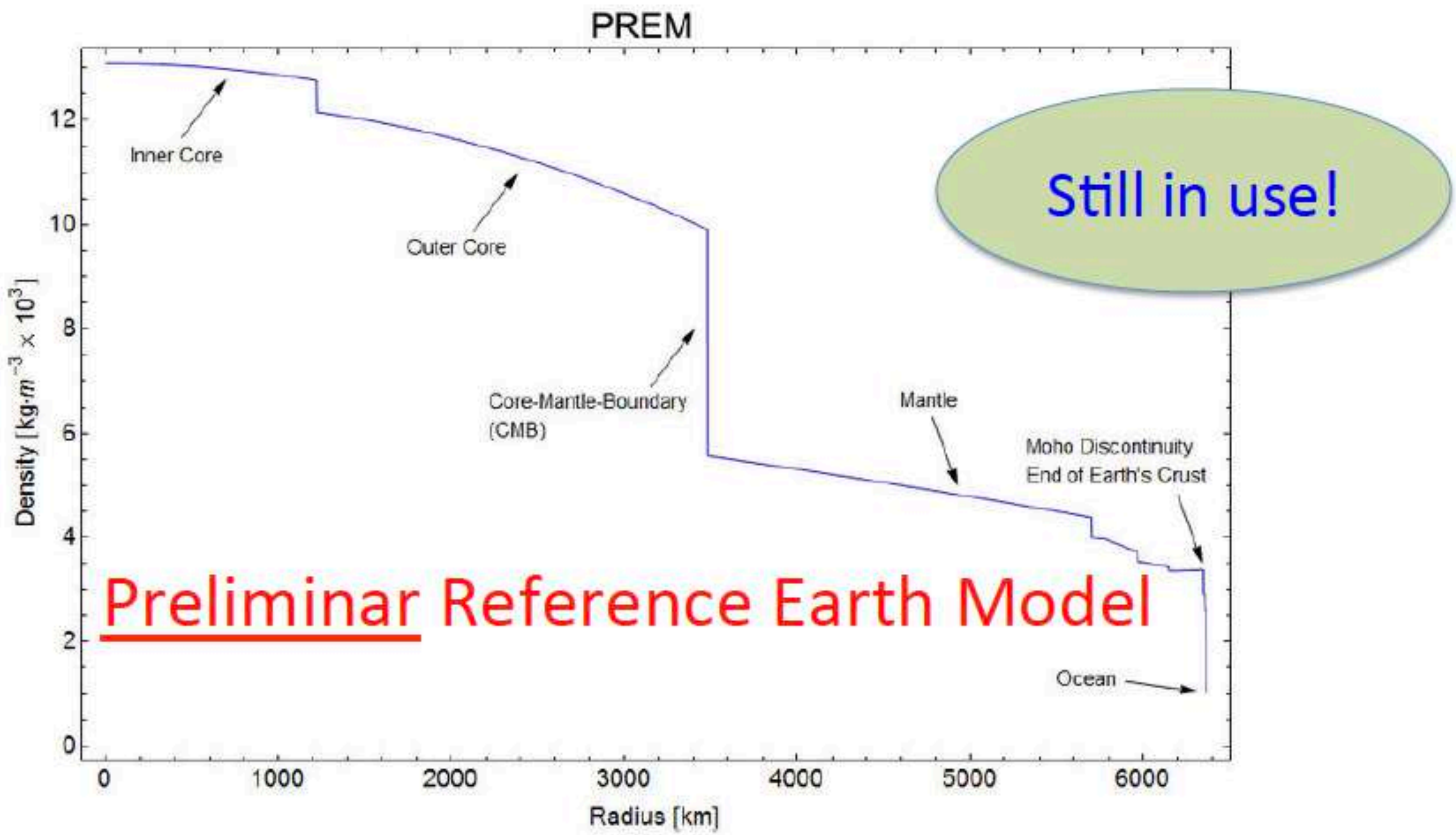
The OUTER CORE IS LIQUID,
whereas
the INNER CORE IS SOLID
(source of the geodynamo)

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

Mostly through global constraints and extrapolations

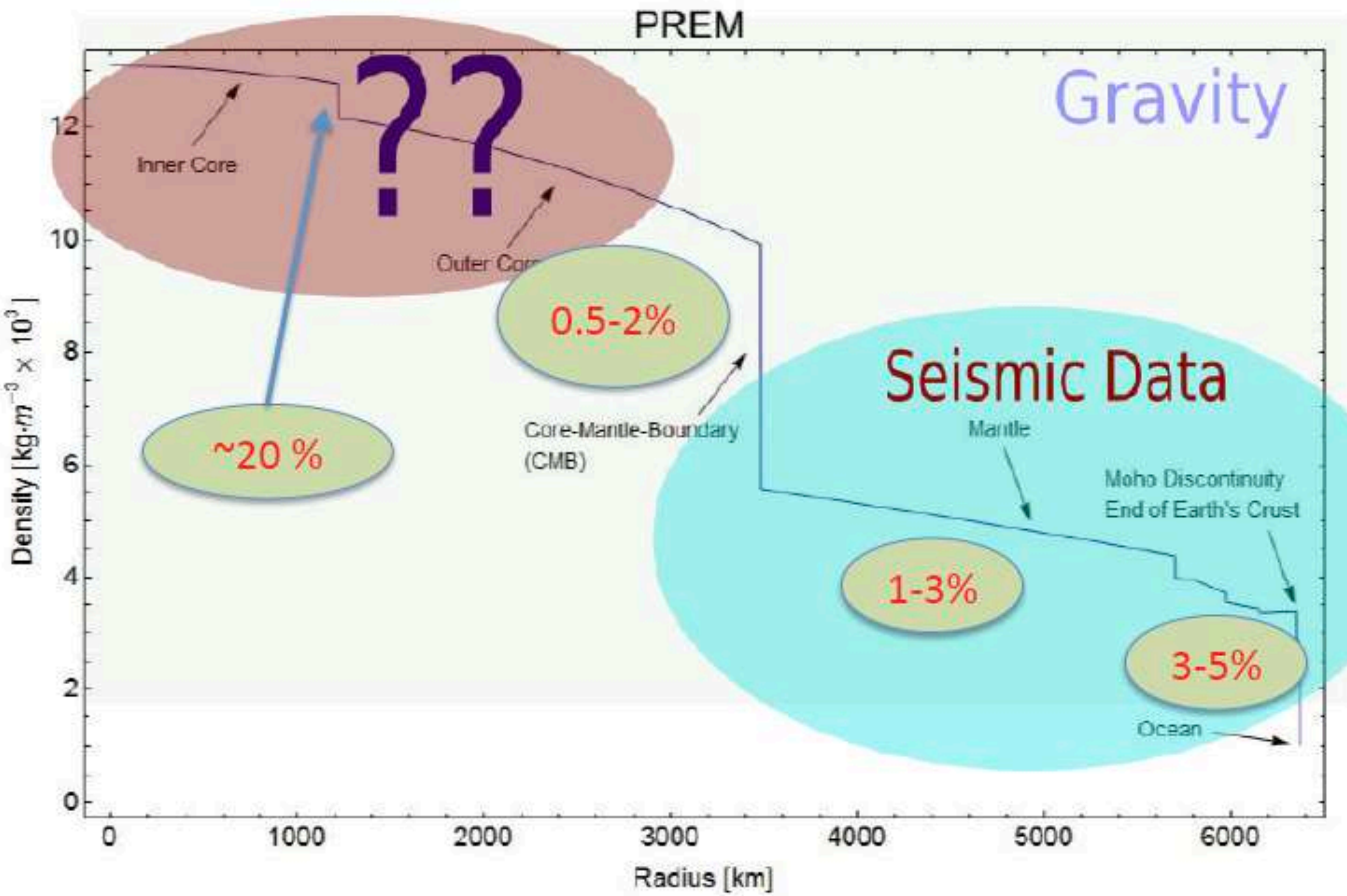


1-dimensional density profile



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

Uncertaintes from seismology



Neutrinos to study the Earth's interior

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

A.Placci and E. Zavattini, submitted in Oct 1973 to Nuovo Cimento; rejected?... never received?....

and in a talk

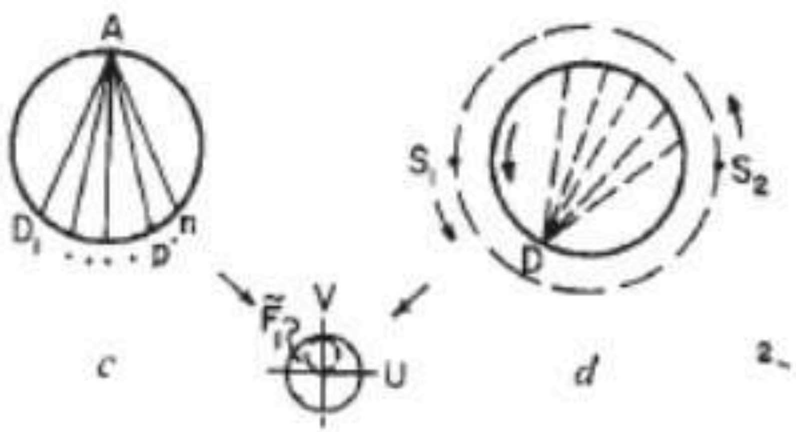
L. V. Volkova and G. T. Zatsepin, Izv. Akad. Nauk. Ser. Fiz. 38N5 (1974)

In modern language, a long-baseline experiment

The idea was premature!

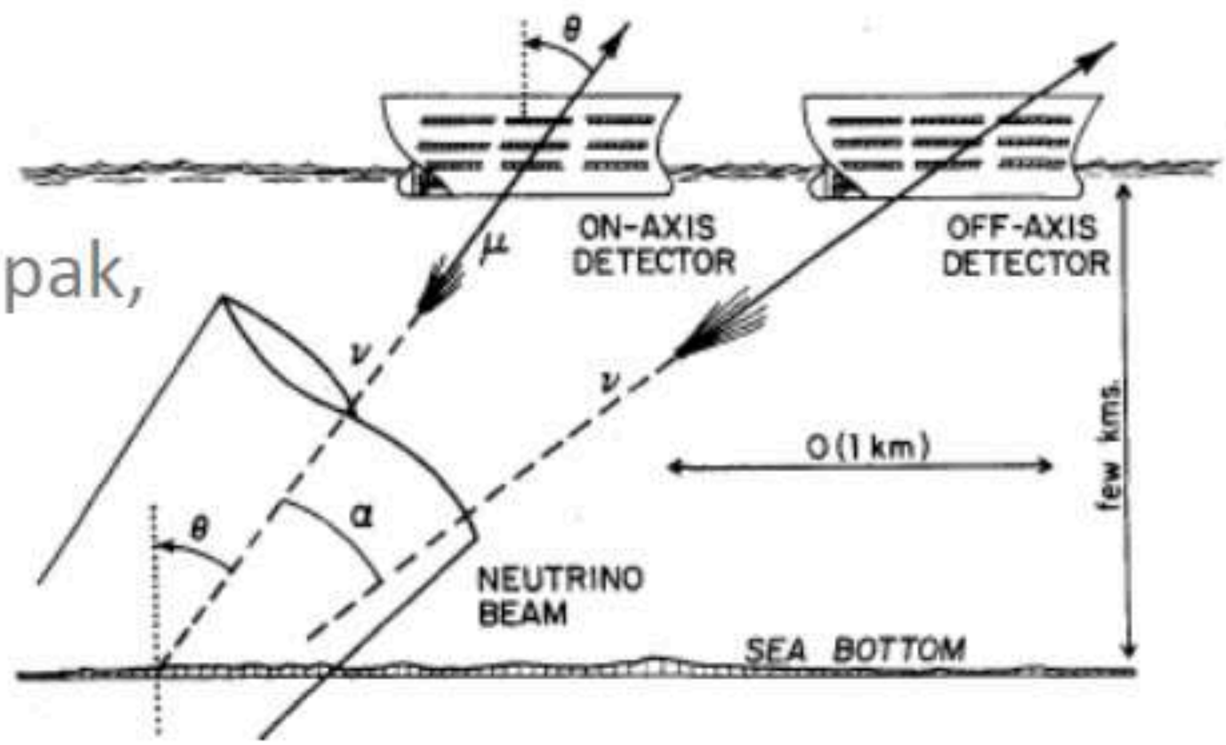
Neutrino tomography

Even more premature…



T. Wilson, Nature 309 (1984)

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



Two ways to scan the Earth

- Neutrino oscillations (< 1 TeV)

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

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

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- Neutrino flux attenuation (> 1 TeV)

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

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

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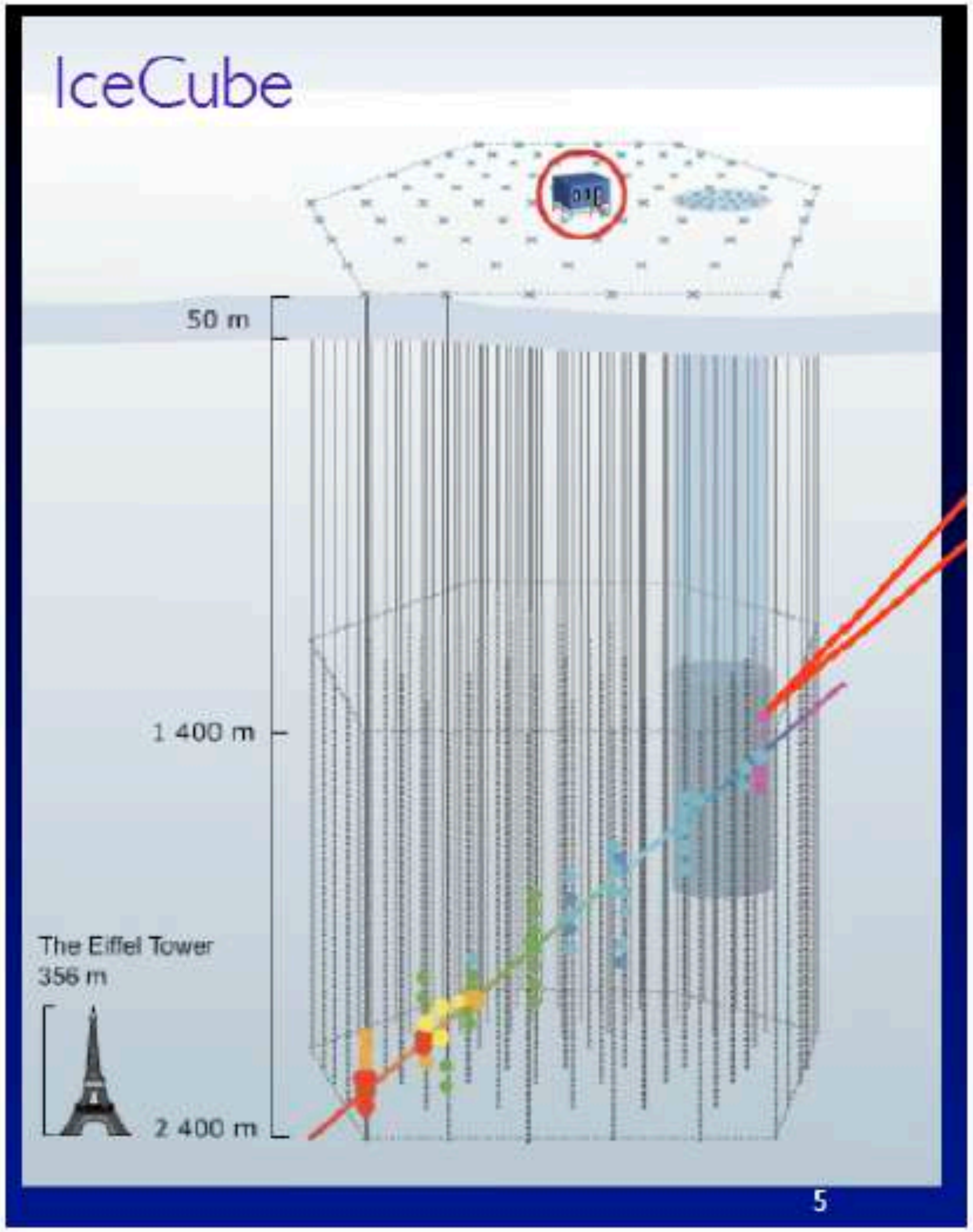
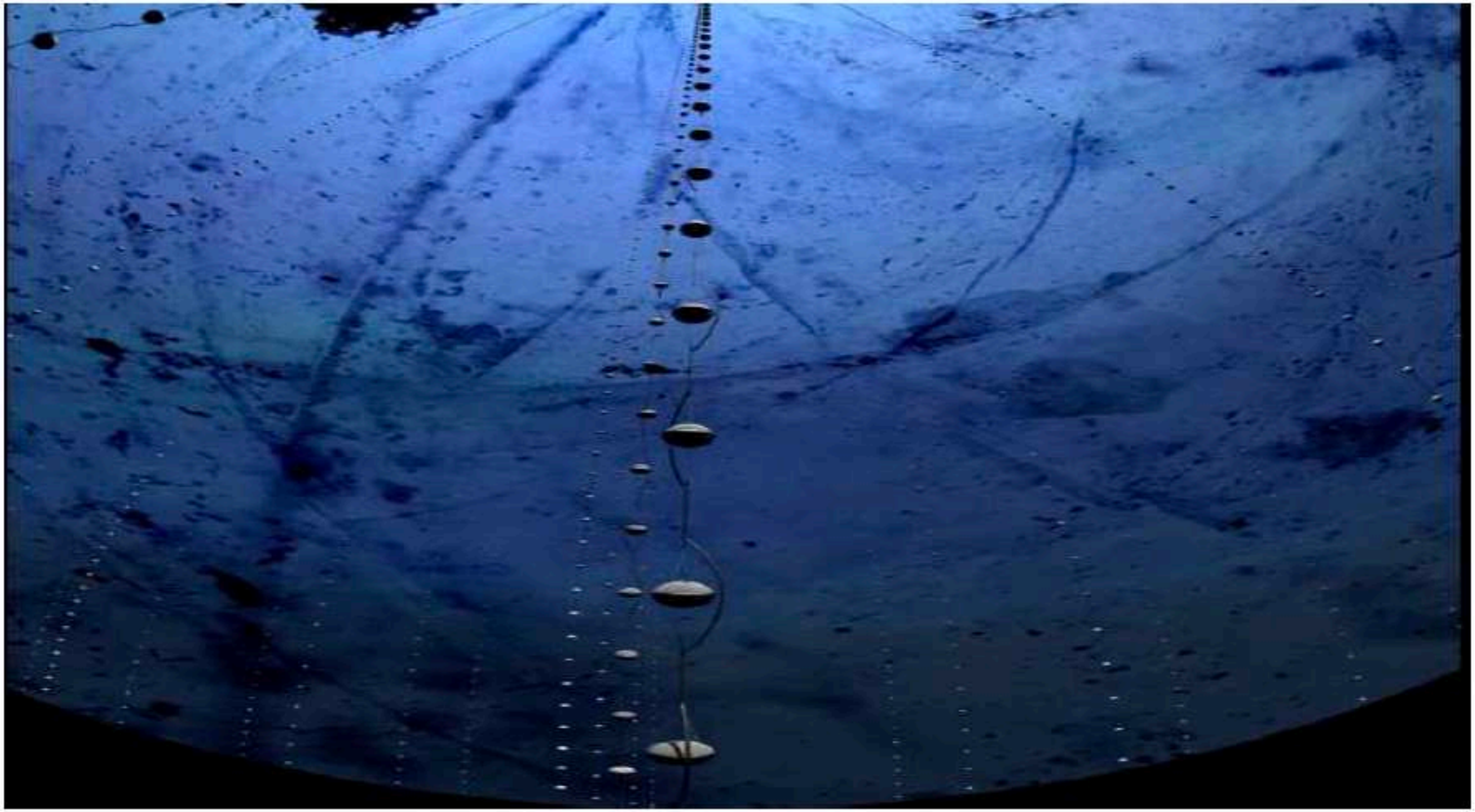
IceCube: a 1 km^3 neutrino telescope

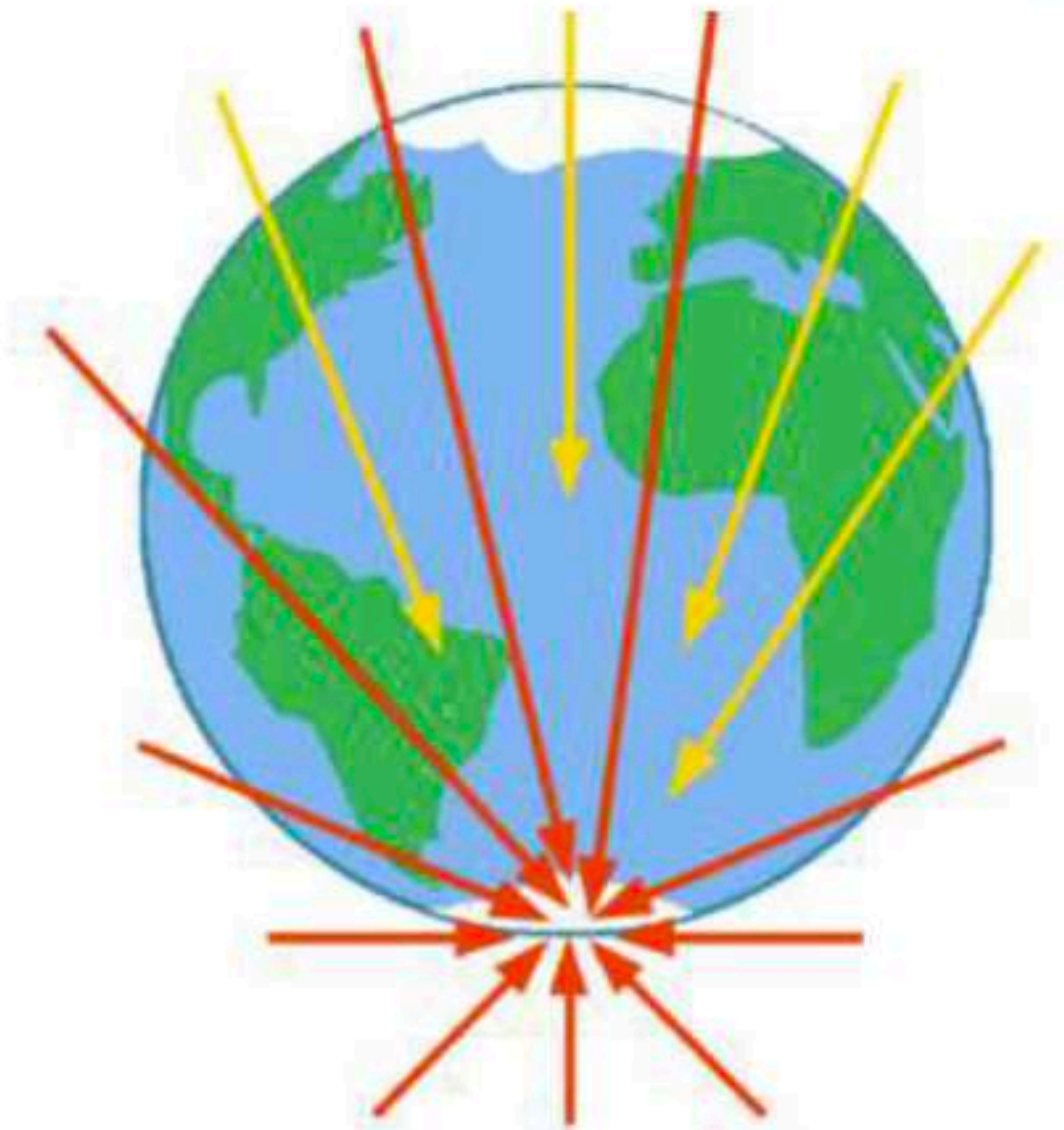
The IceCube Experiment



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

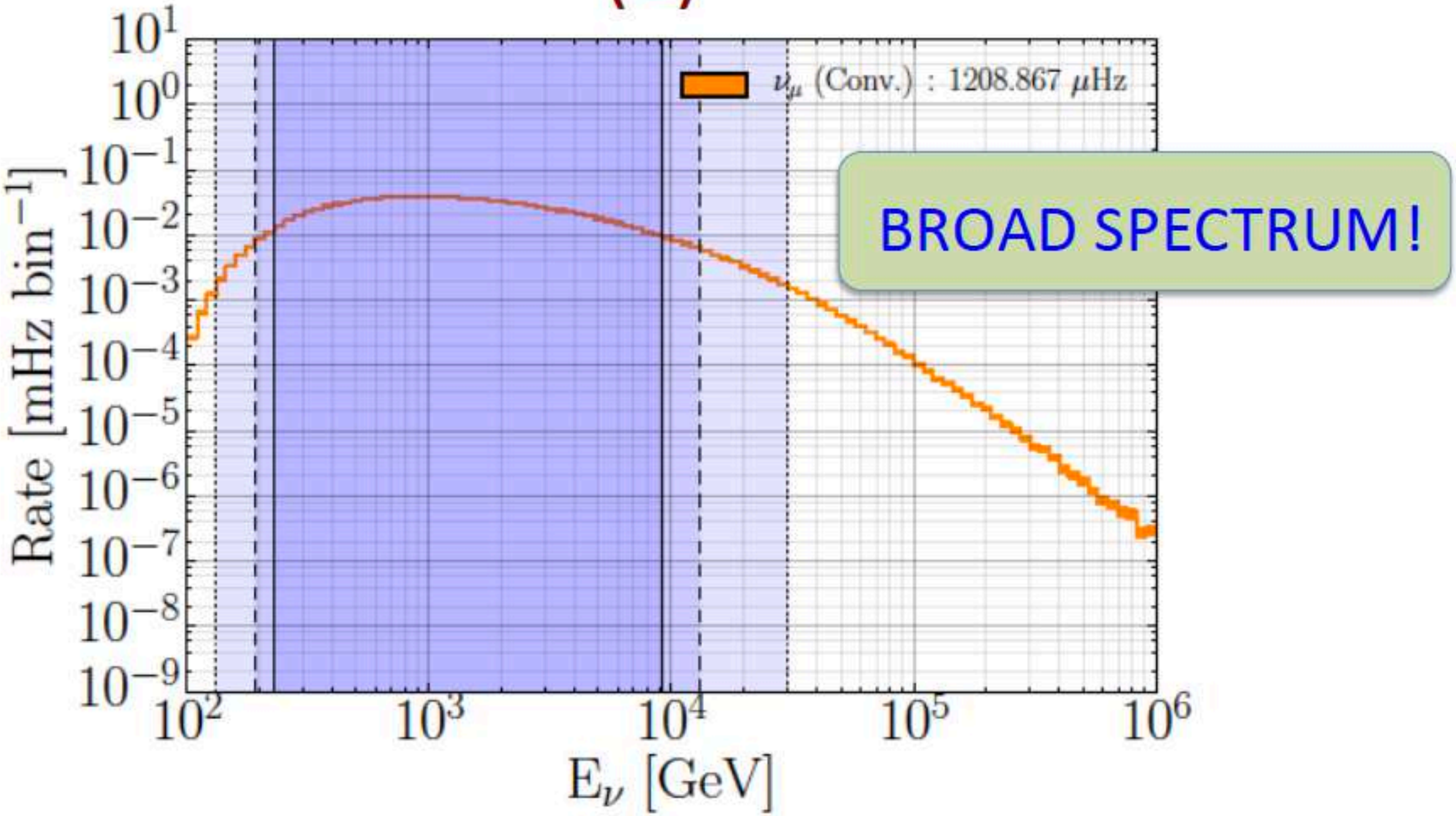


Atmo-neutrinos are an optimal source (1)



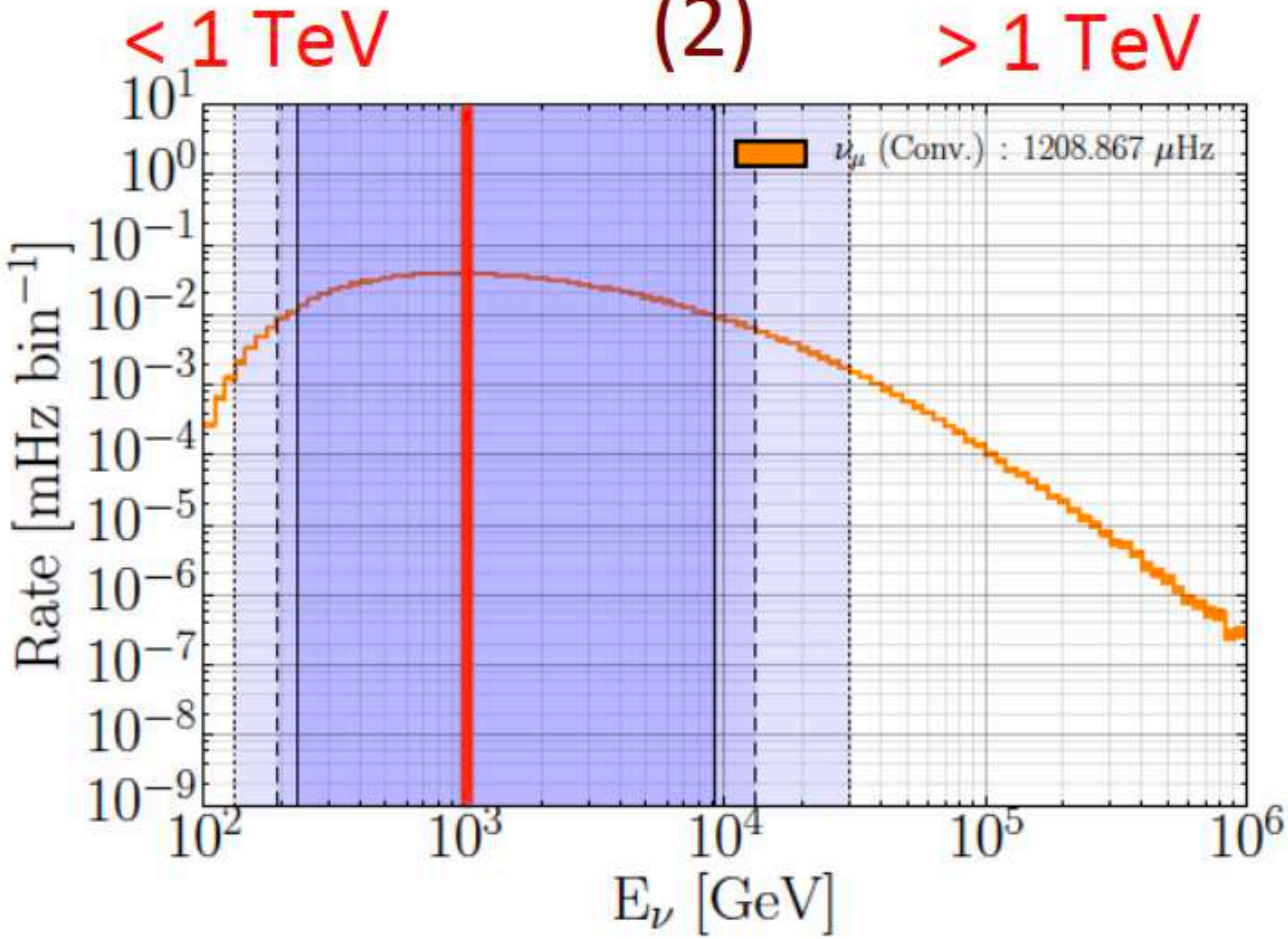
They reach a detector from all directions

Atmo-neutrinos are an optimal source (2)



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)

The IceCube IC86 data sample

- 1 year of data taking (2011-2012)
- 20145 muon events over 343.7 days
- E_μ = [400 GeV ÷ 20 TeV]
- The muon direction is a very good proxy of the neutrino direction, with $\Delta\cos\theta < 0.01$
- PUBLICLY AVAILABLE!

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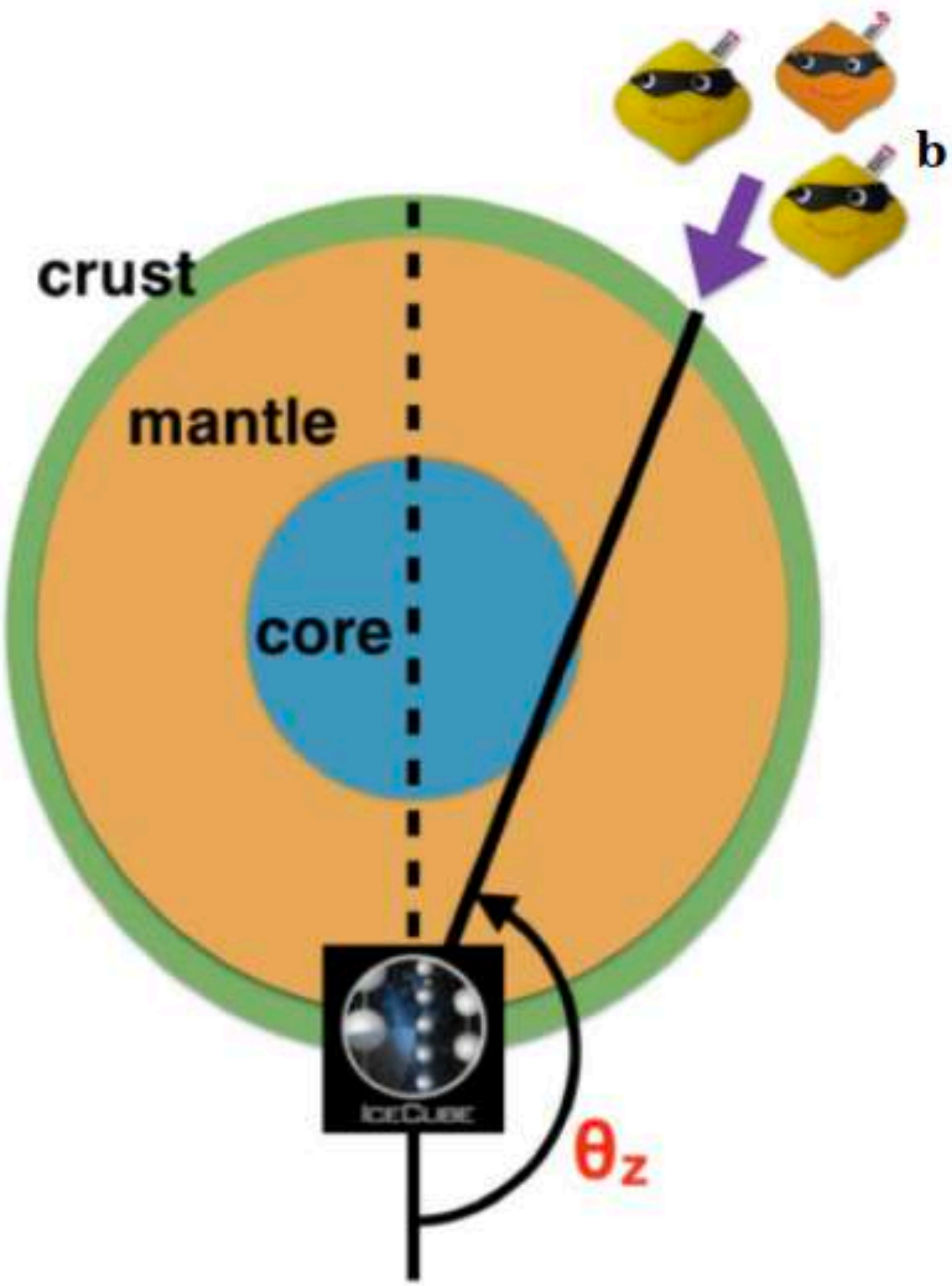
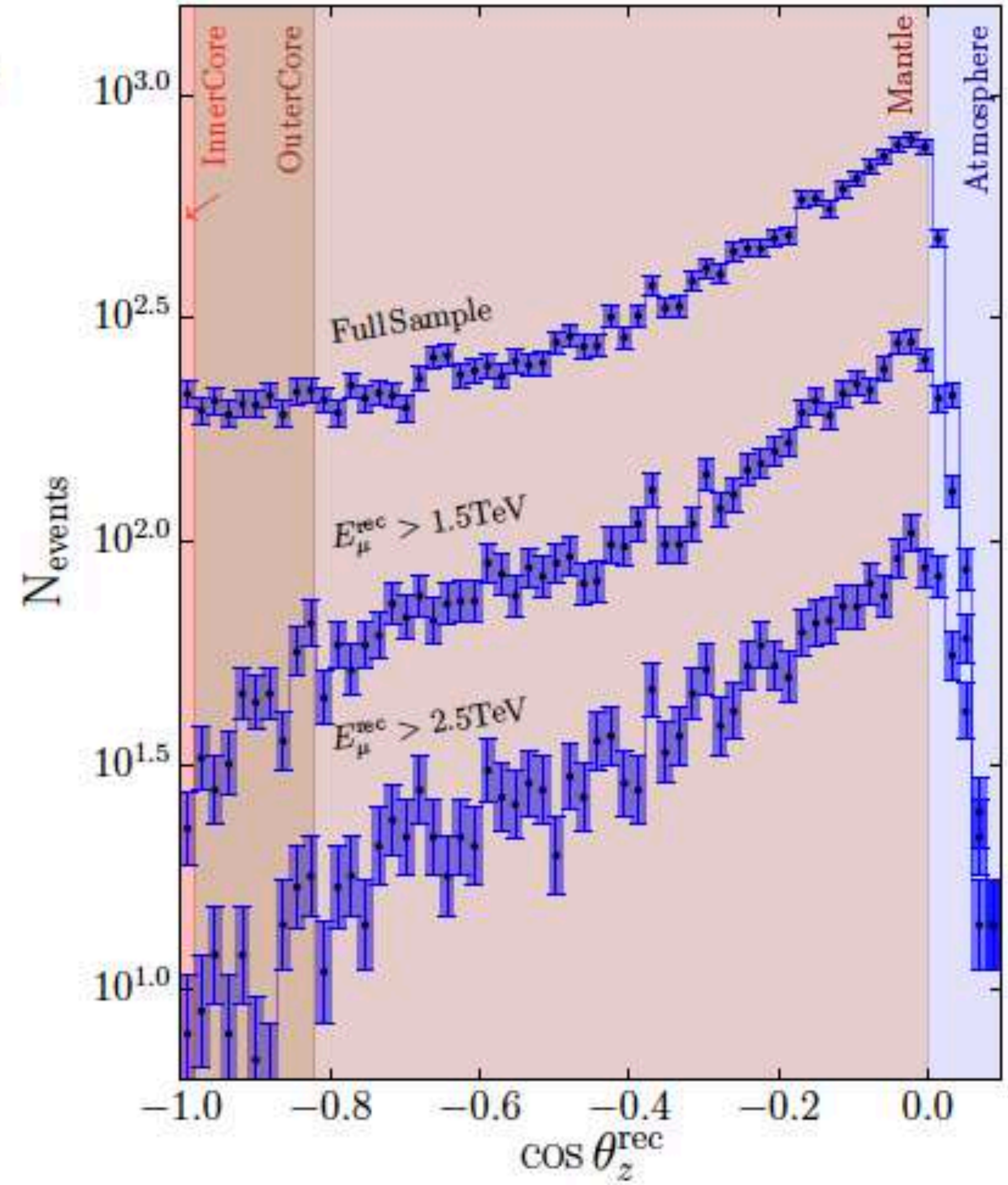
WE USED THIS SAMPLE IN 2018 TO PERFORM THE FIRST NEUTRINO EARTH TOMOGRAPHY. SEVEN MORE YEARS OF DATA WERE NOT AVAILABLE AT THAT TIME

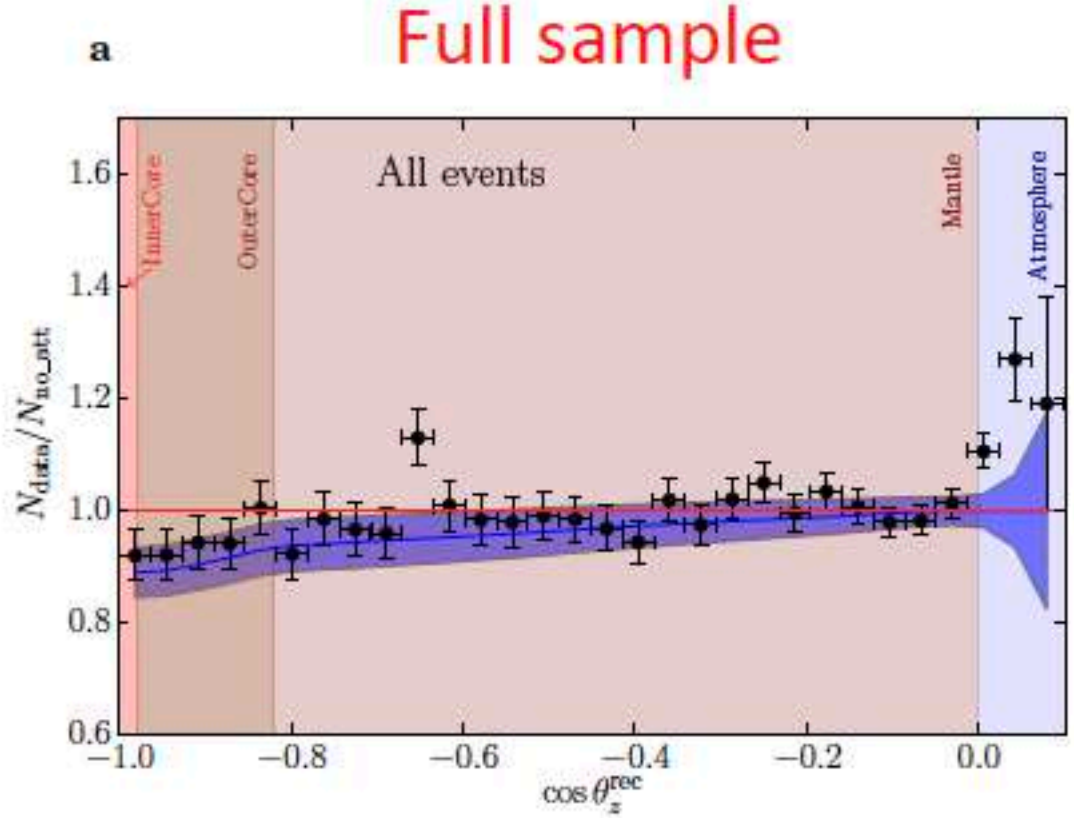
Raw data as a function of E_μ and θ



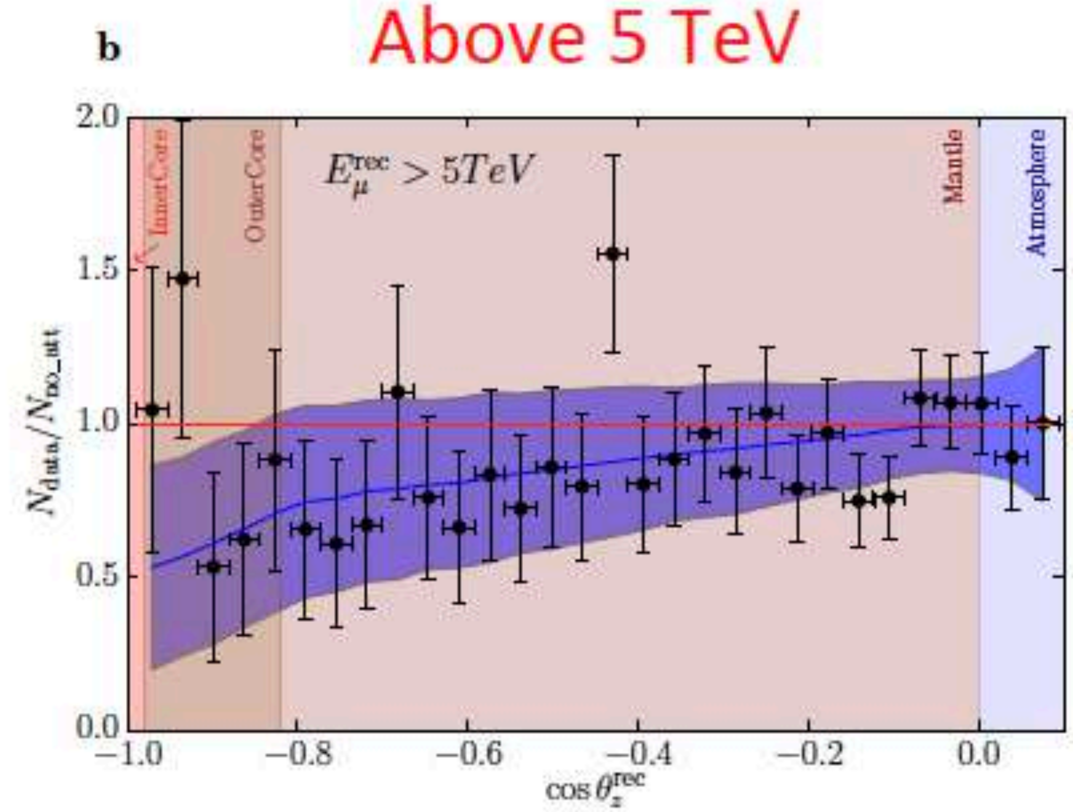


Including energy cuts: N_{data}/N_{noatt}

Full sample



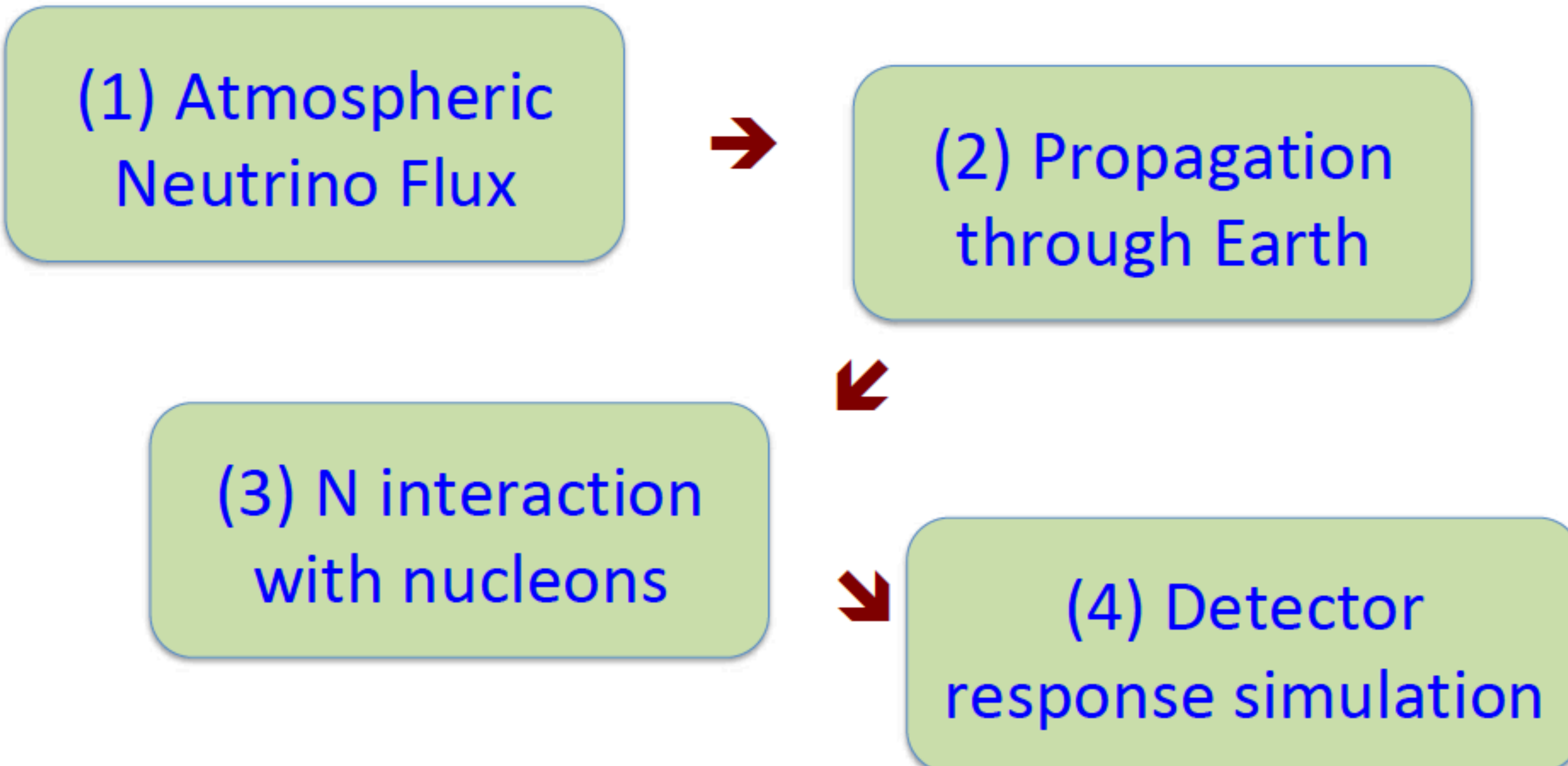
Above 5 TeV



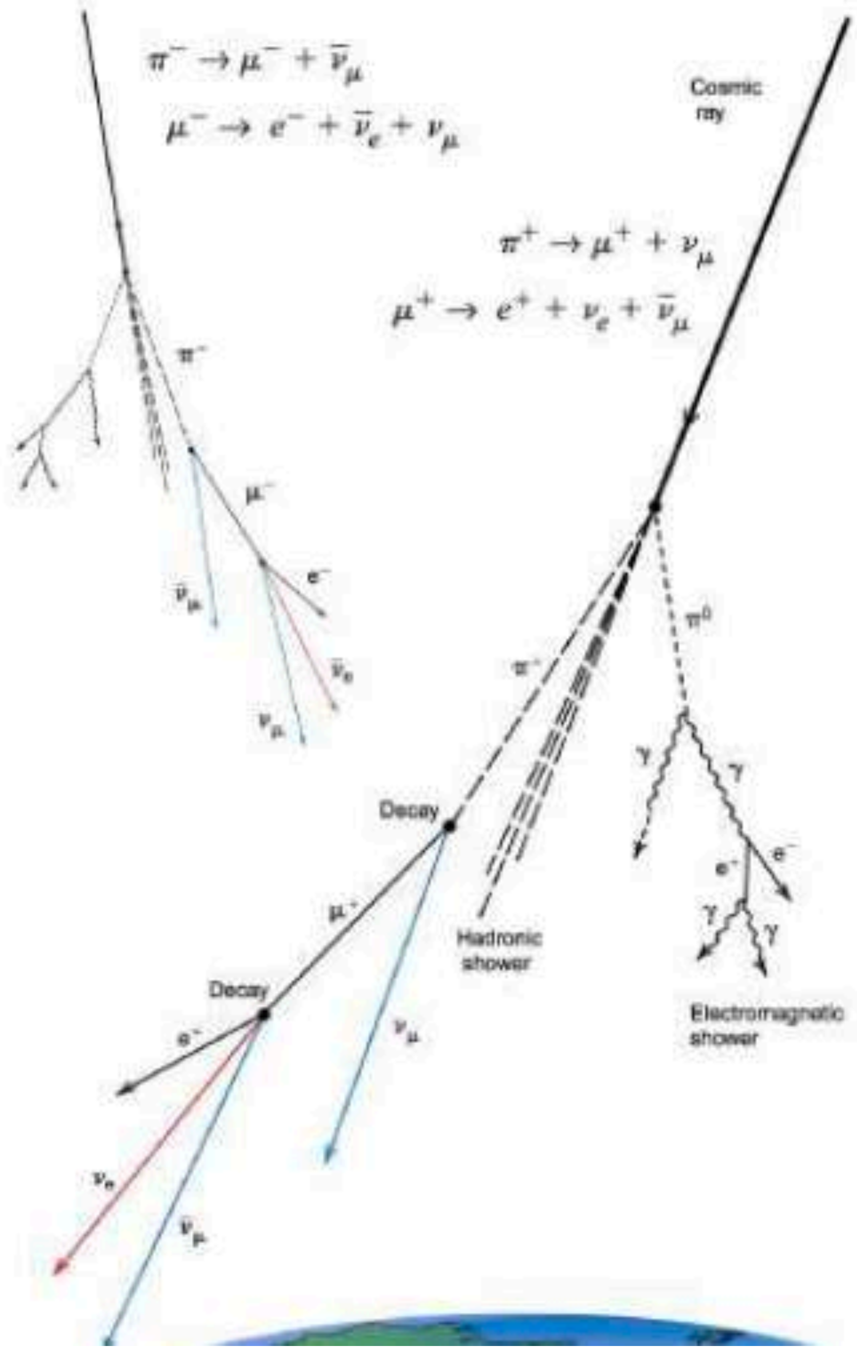
Full sample useful for normalization

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

From raw data to measurements



N_{exp}: (1) atmo-ν flux model



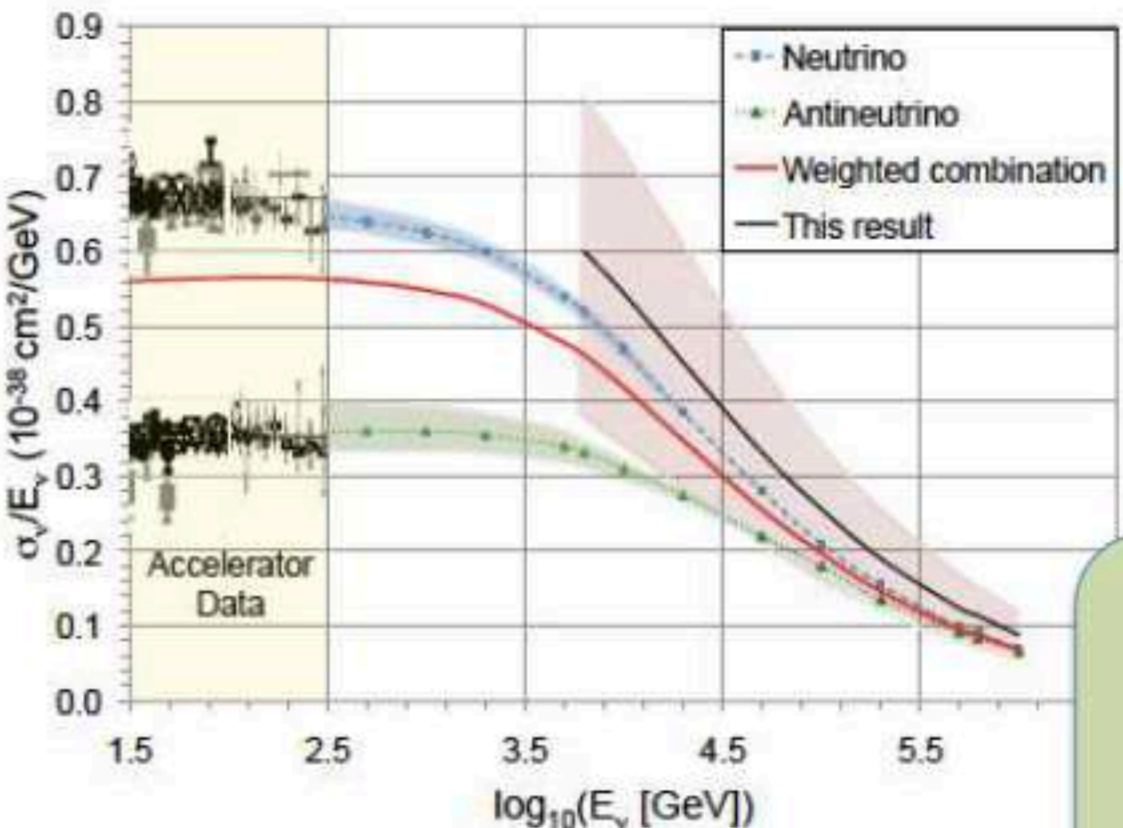
Primary cosmic ray flux:
Honda-Gaisser model +
Gaisser-Hillas corrections
(HG-GH-H3a)

Hadronic model: QGSJET-II-04

We tried other options →
"discrete" systematics

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

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



Aarsten et al, Nature 551 (2017)

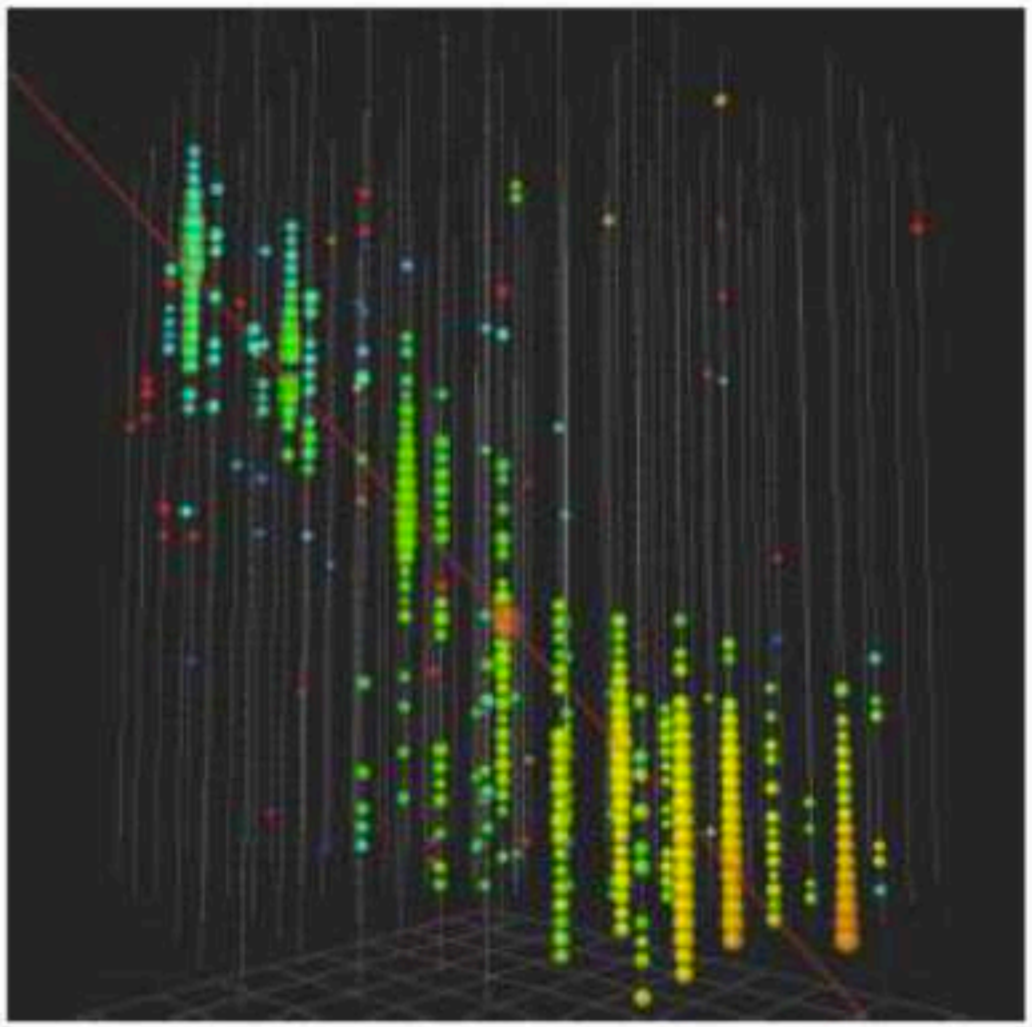
νN ($\bar{\nu} N$) cross-sections at 2-3% (4-10%) errors

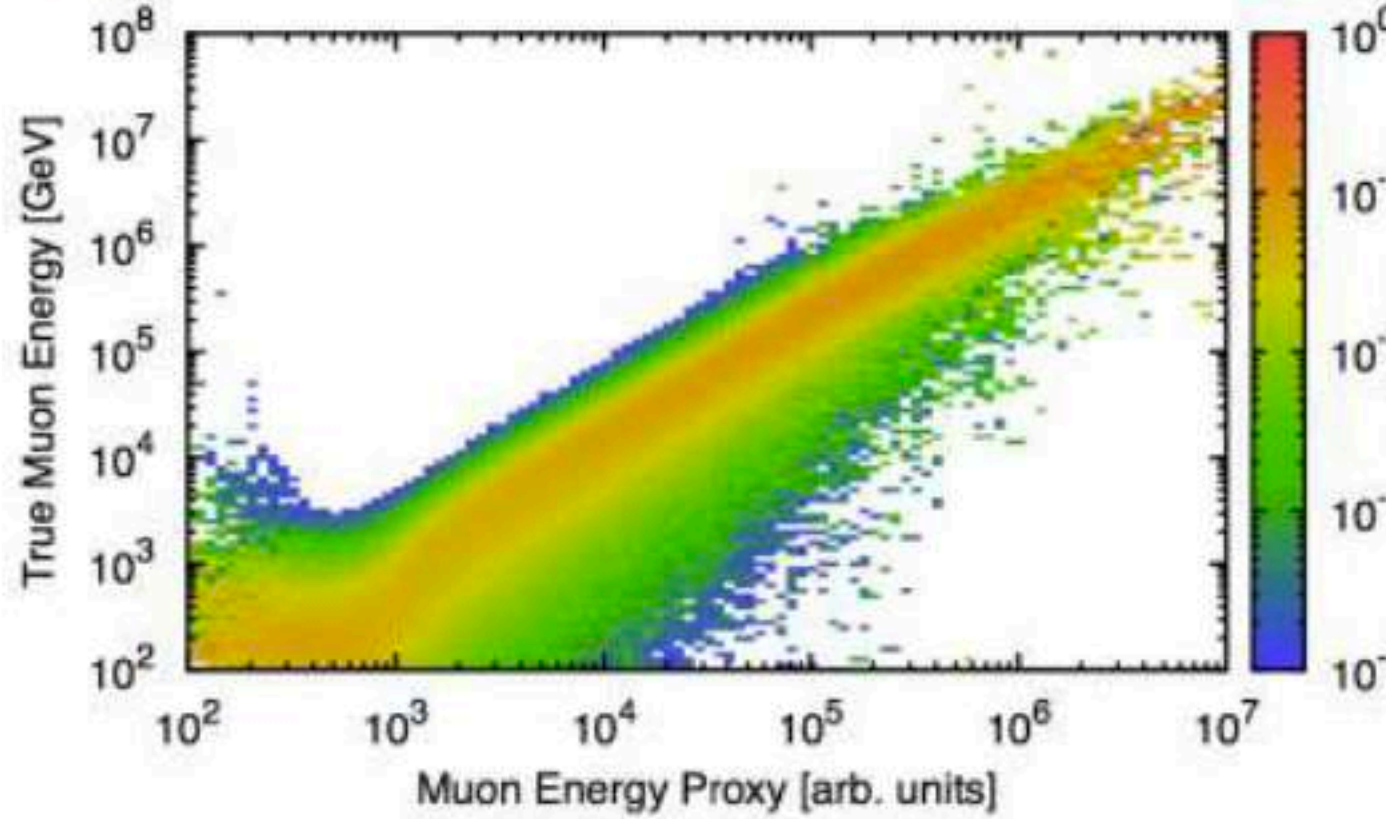
ICECUBE MEASUREMENT

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

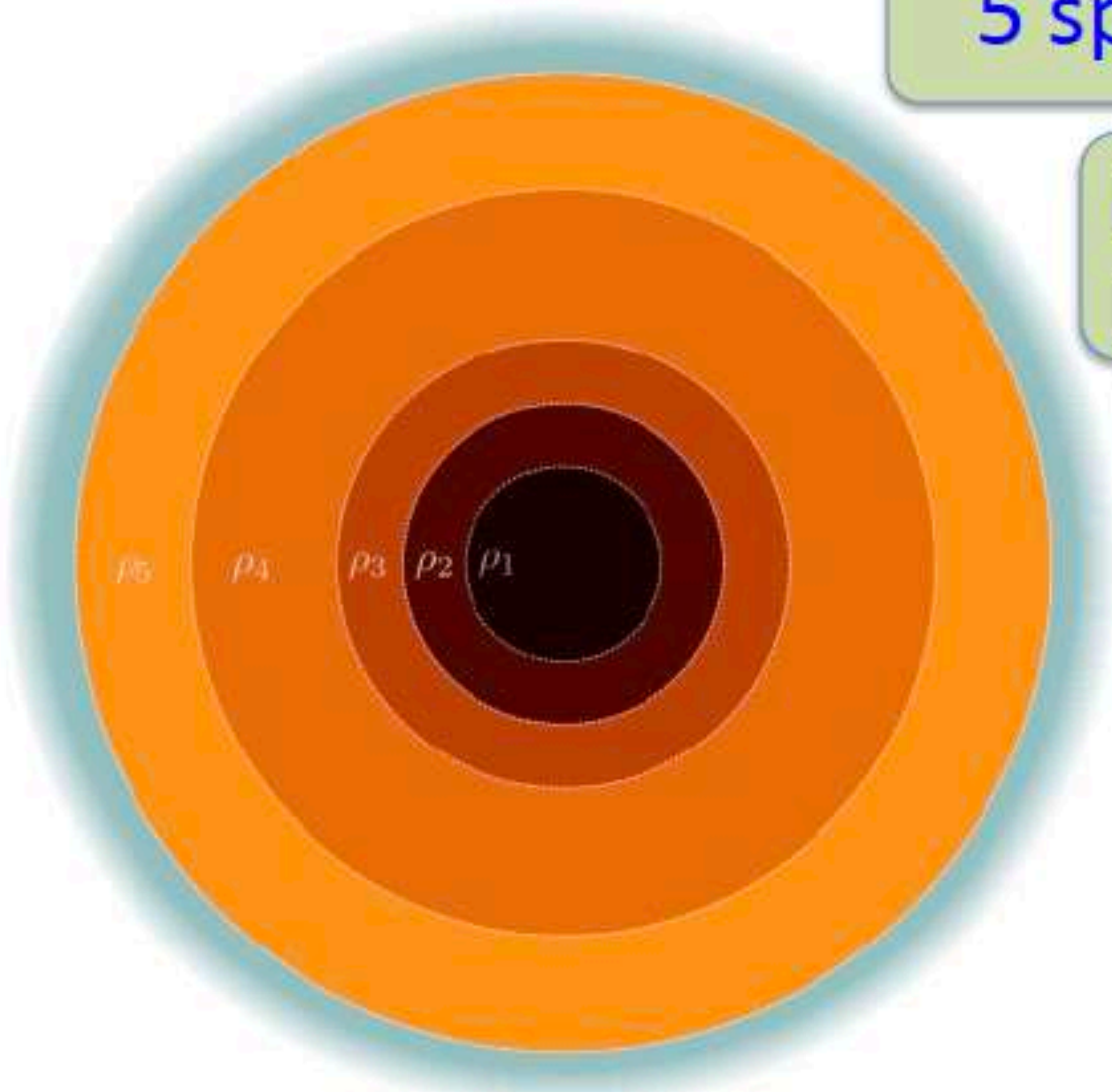
N_{exp}: (2) neutrino propagation

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: ν_e, ν_μ → ν_τ → CC τ → ν_e, ν_μ through leptonic decays
- Migration to lower energy bins: due to NC interactions

Our Earth's model



5 spherical layers

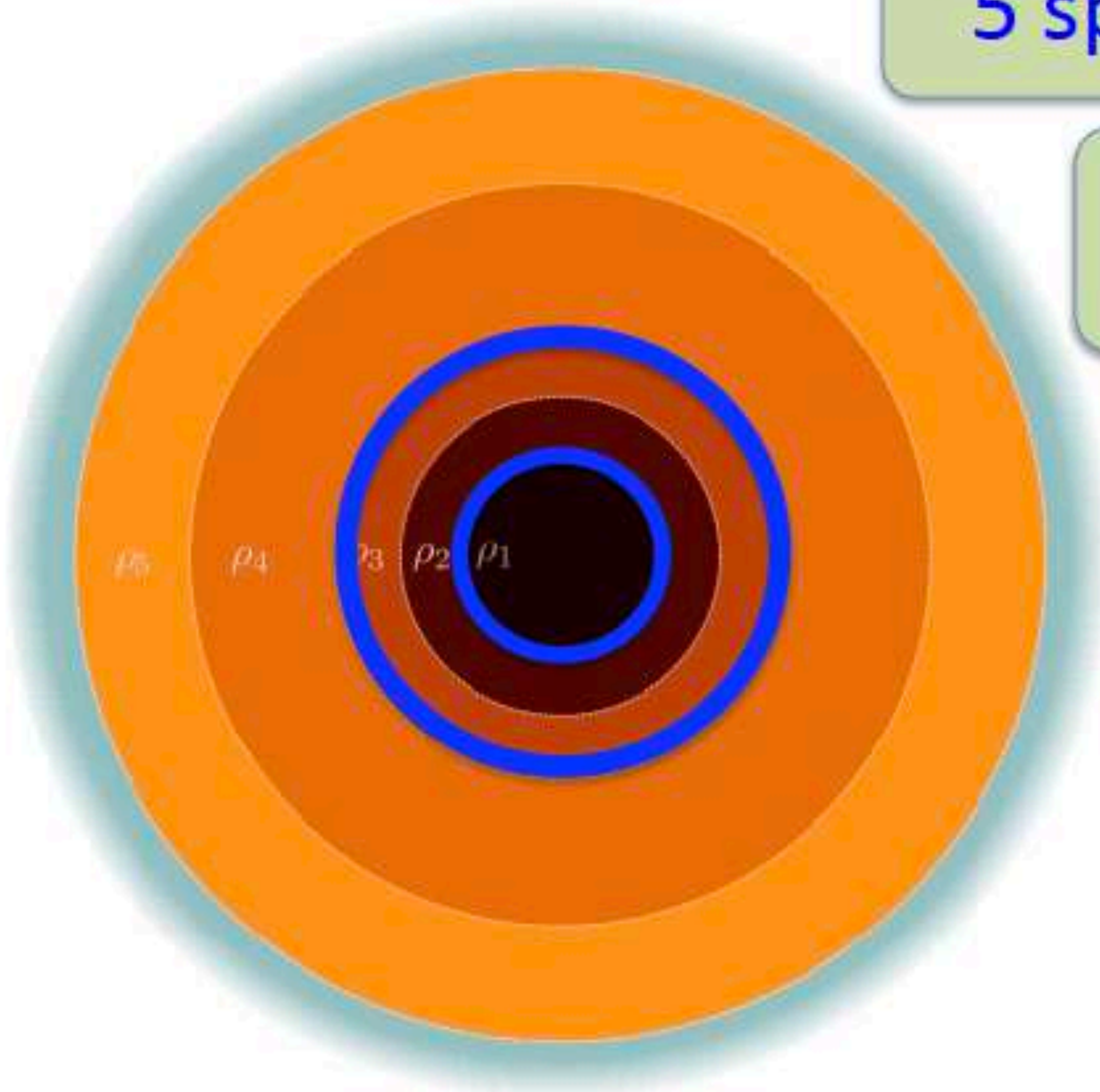
Inner Core, one layer
L_1 = 1242 km

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



ICB and CMB fixed!

5 spherical layers

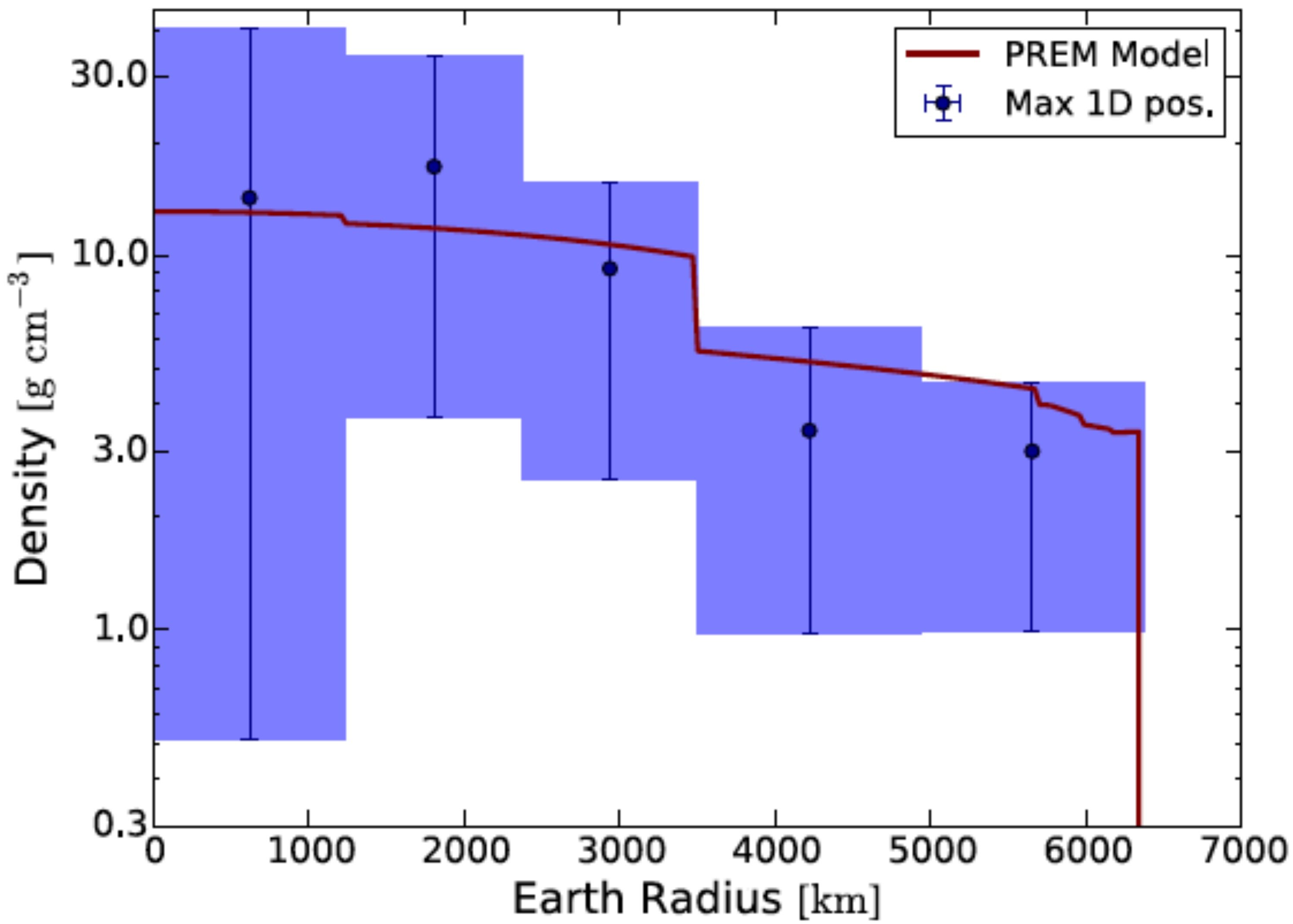
Inner Core, one layer
L_1 = 1242 km

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!

First 1-d density profile with neutrinos



Analysis performed with MultiNest

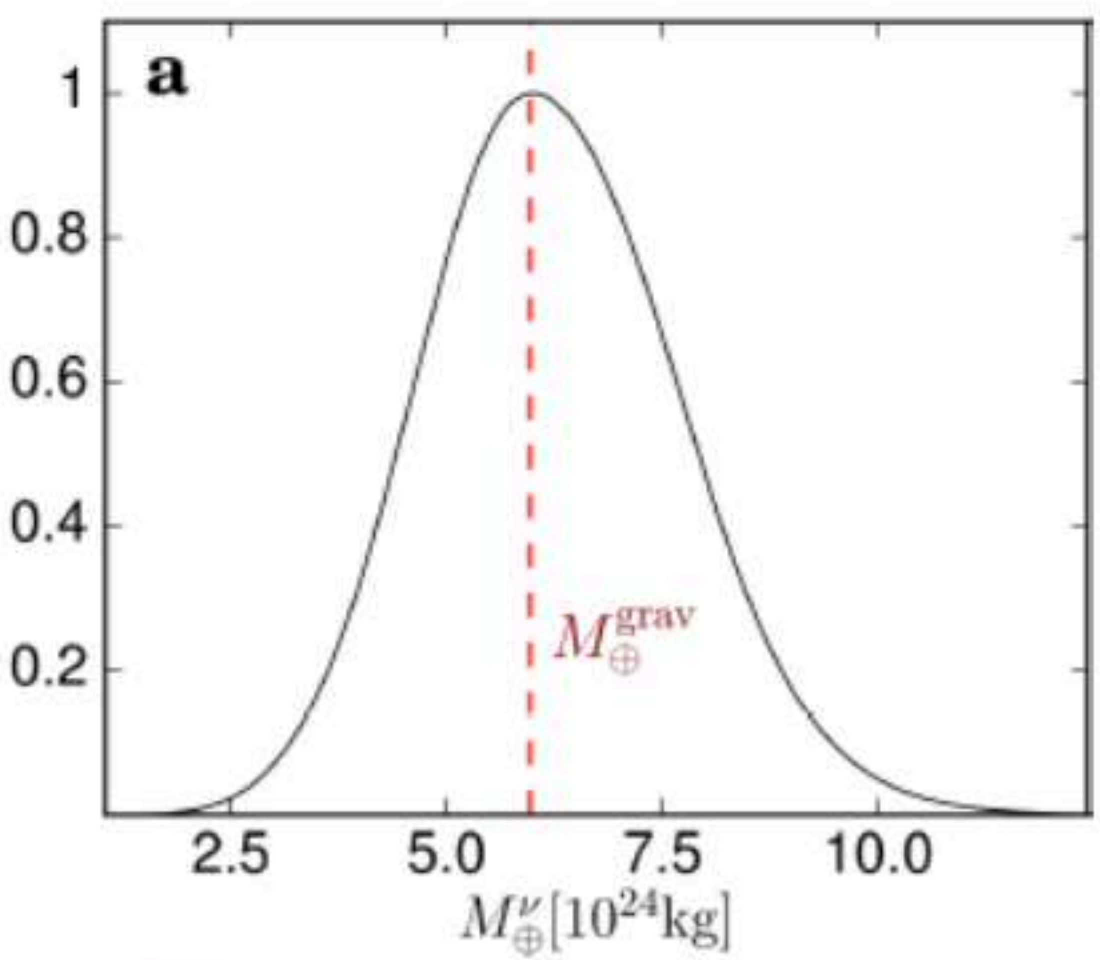
5 Earth layers densities

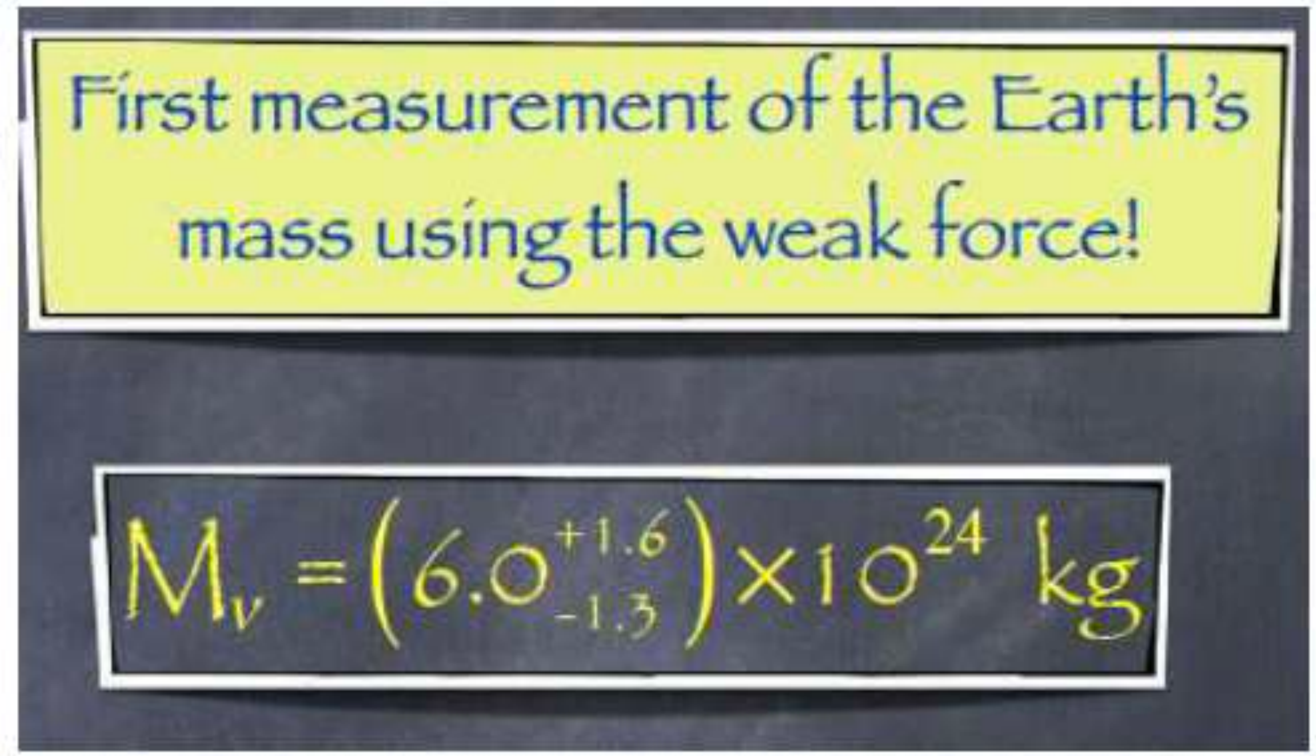
and

4 systematic errors:

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

The Earth's mass

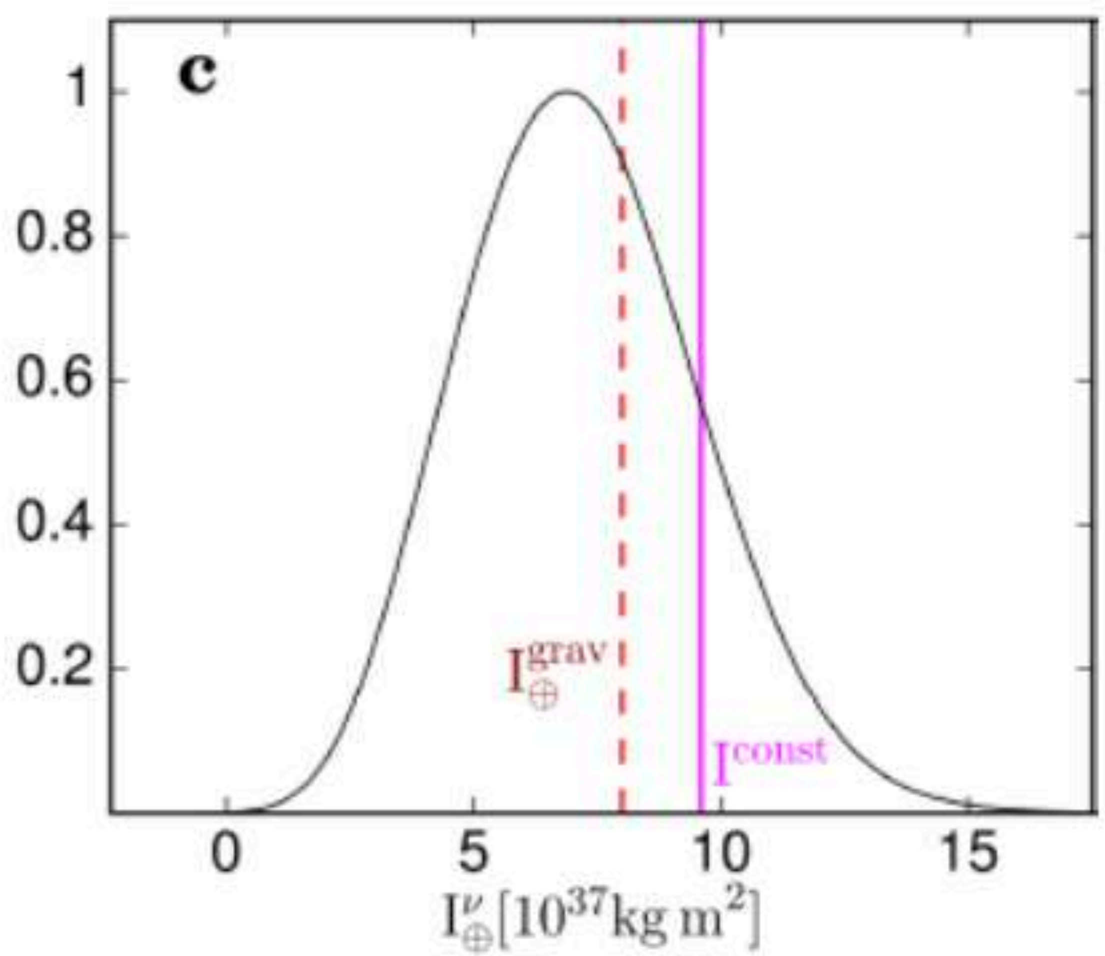


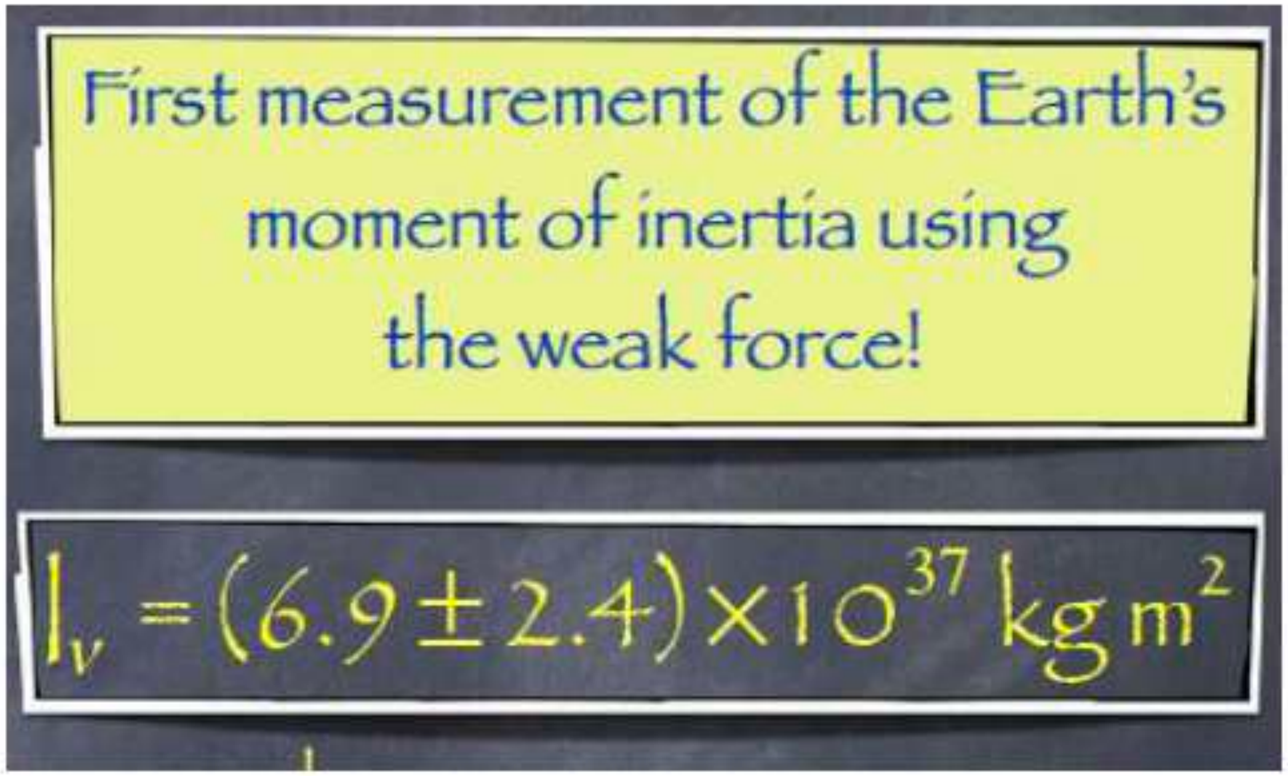


Gravitational measurement of the Earth's mass

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

The Earth's moment of inertia

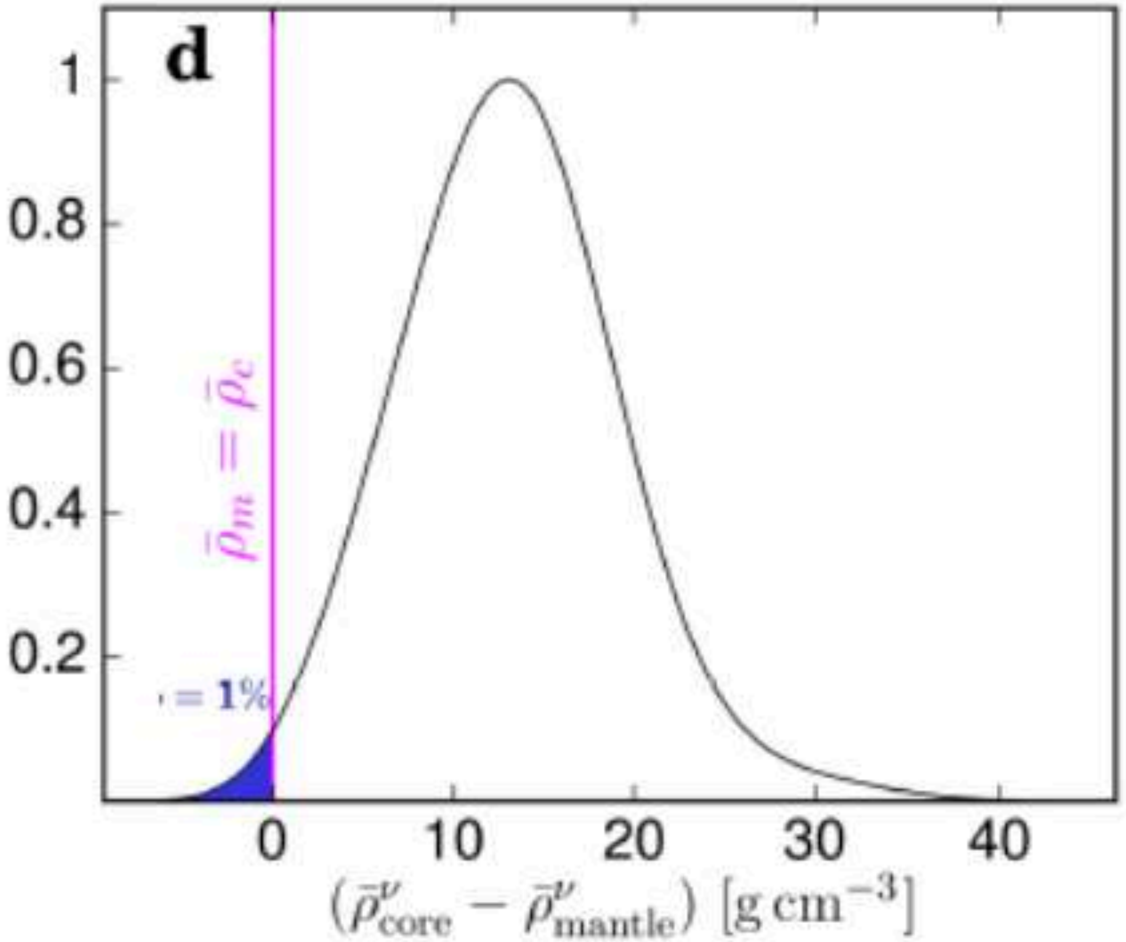


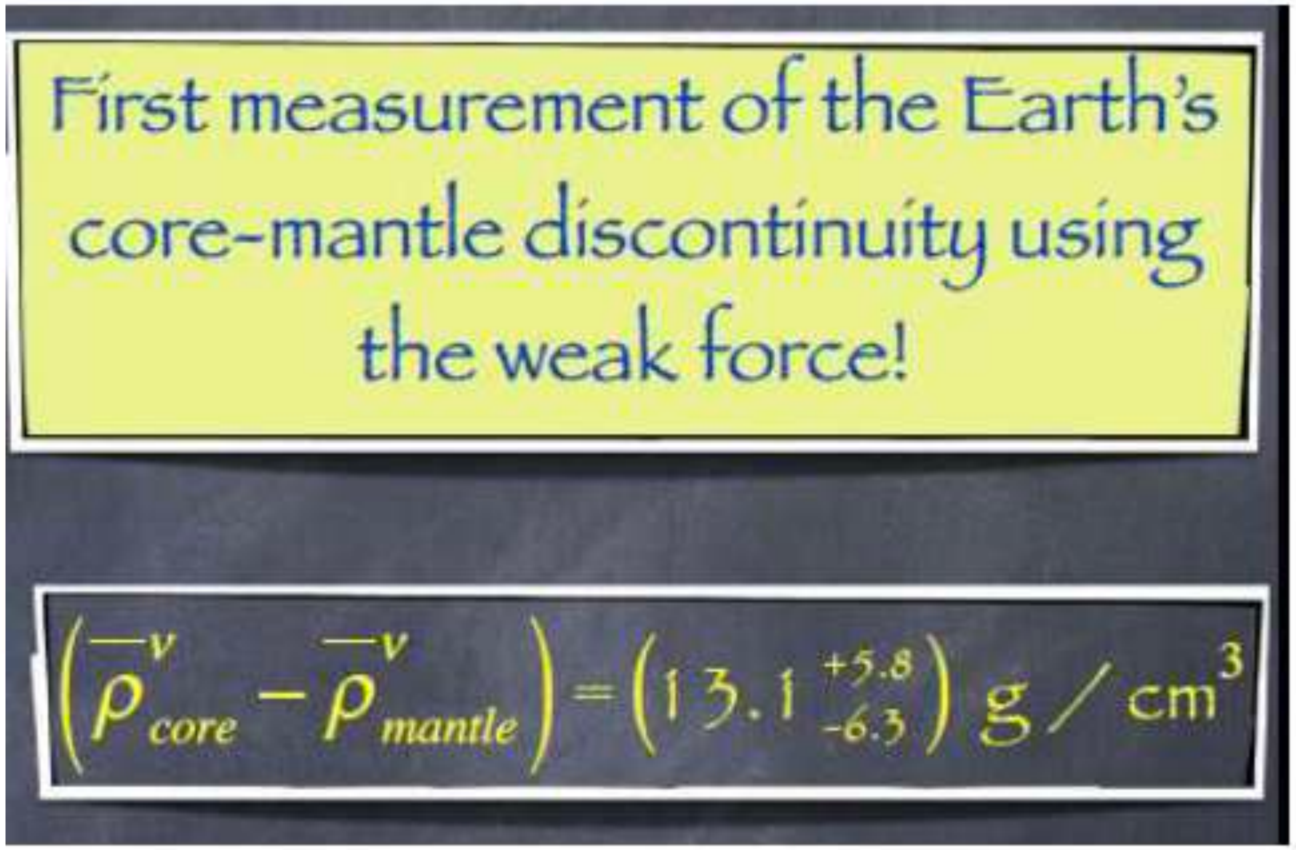


Gravitational measurement of the Earth's moment of inertia

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

Earth's non-homogeneity

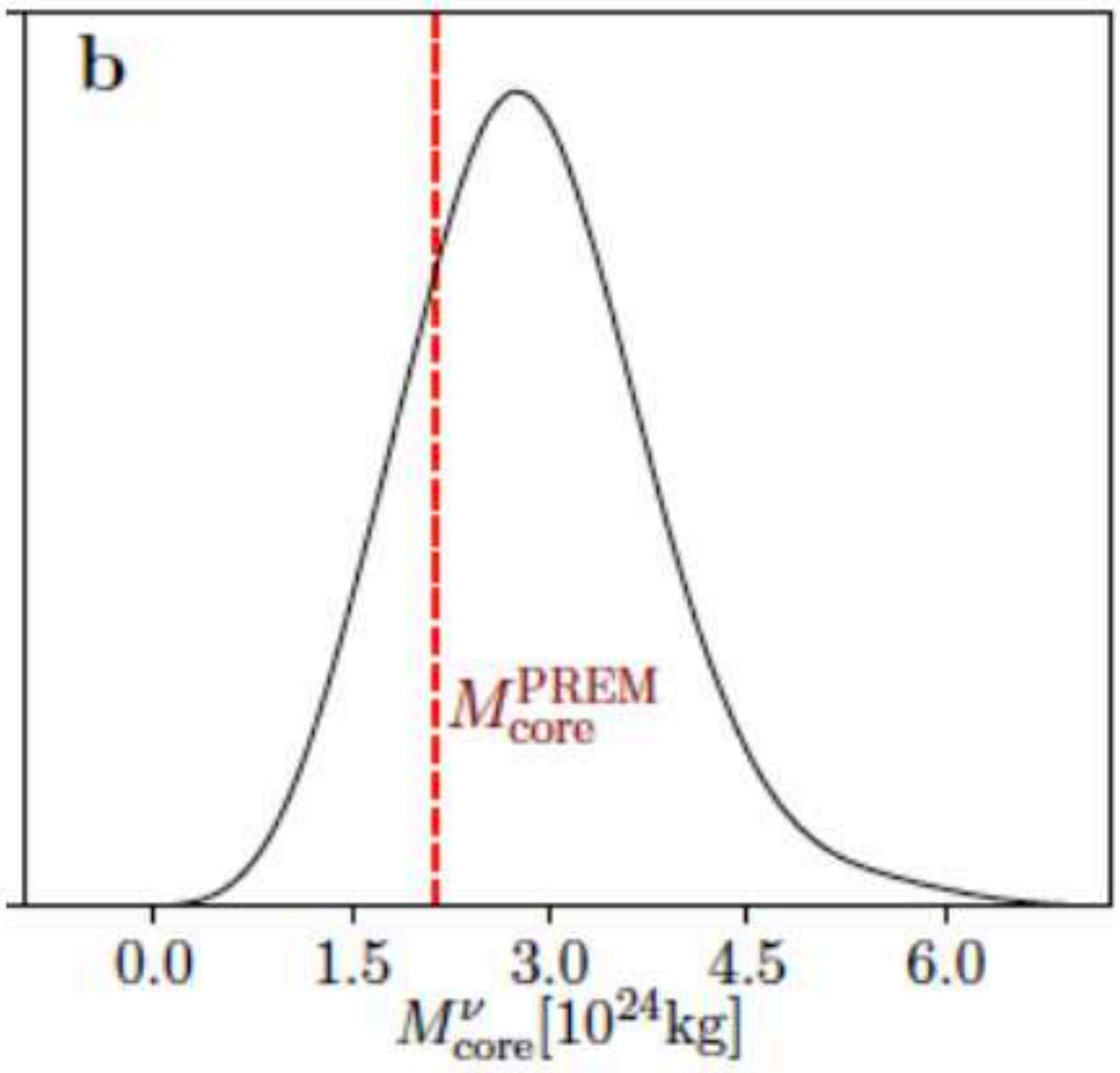


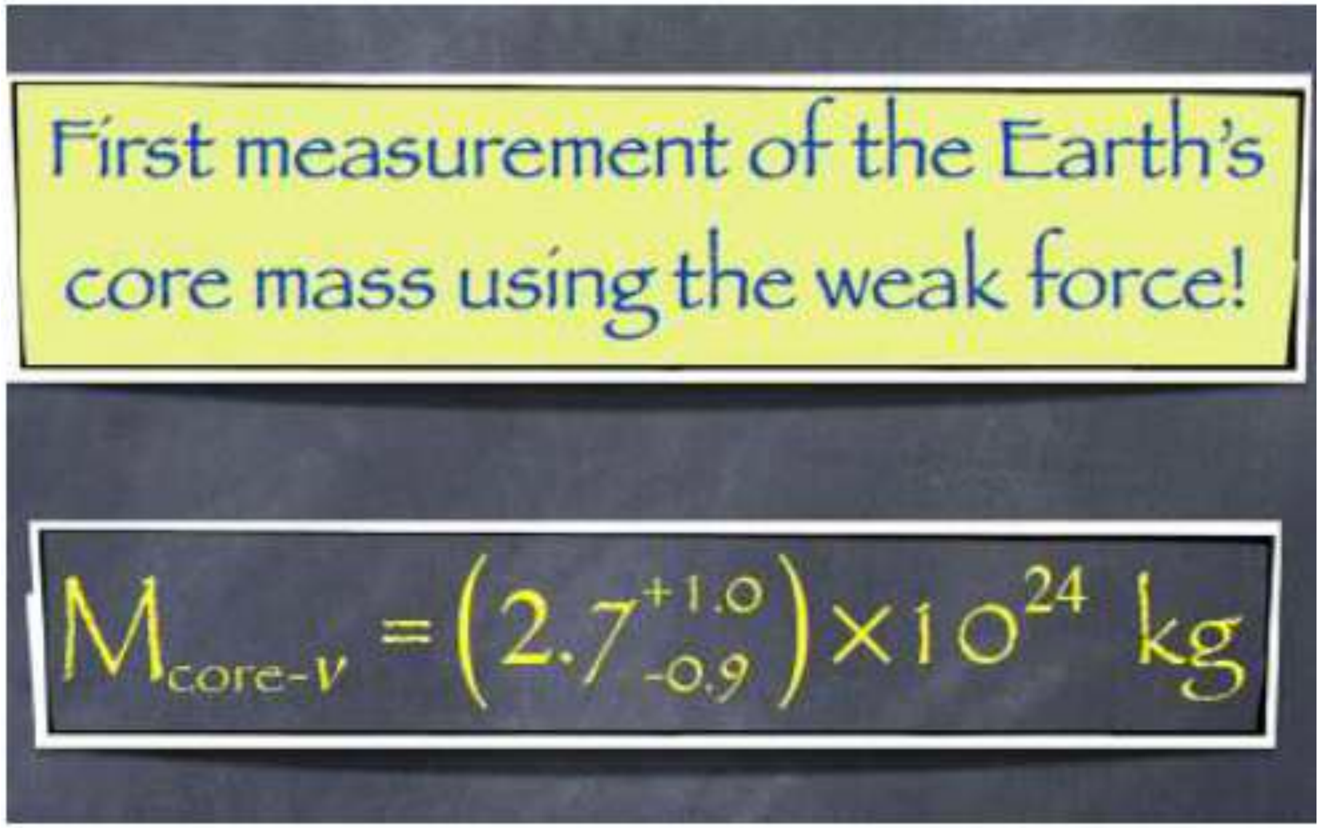


A homogenous Earth has a p-value p = 0.01 !!!

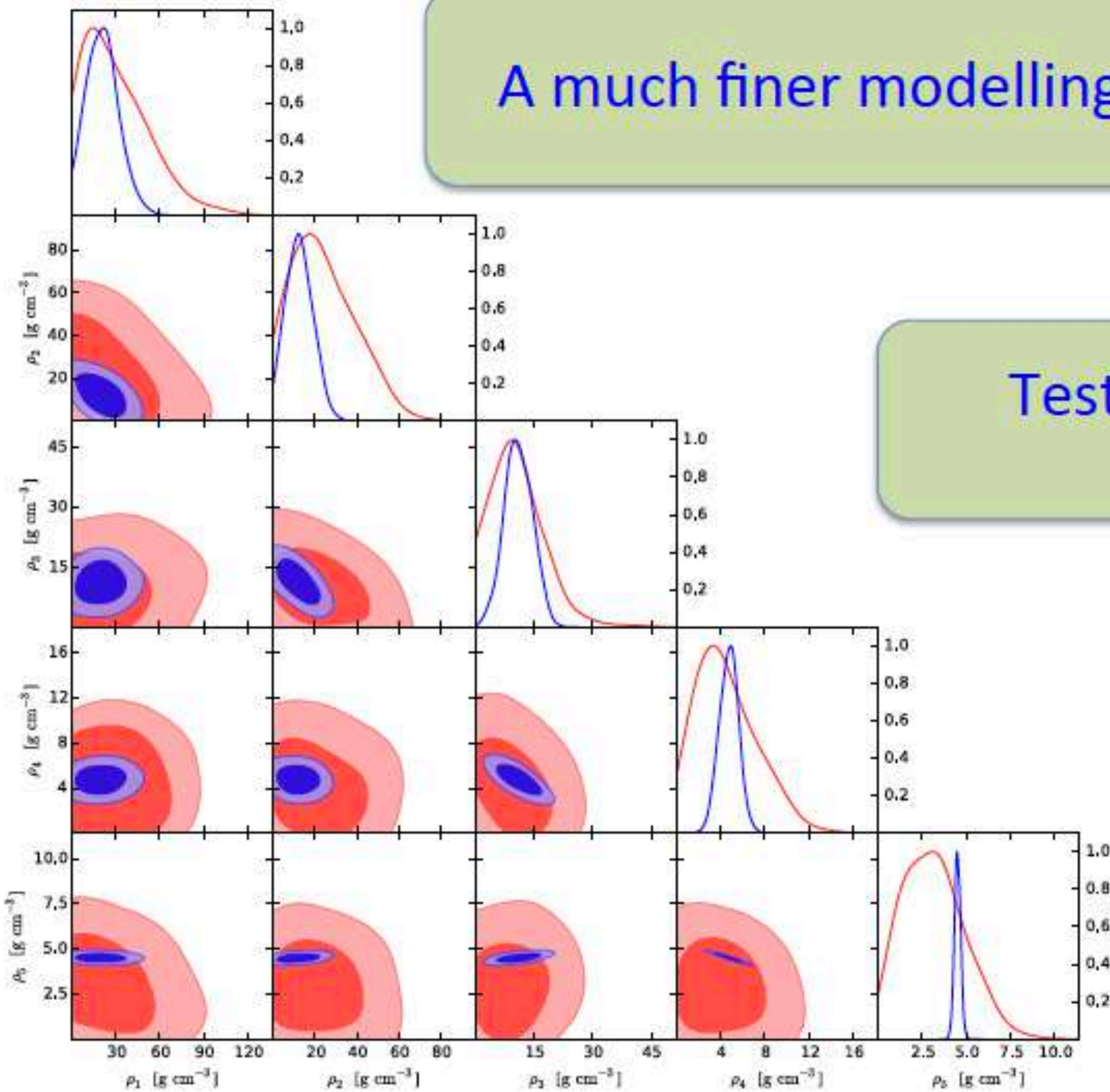
2008 Claim: IceCube could reject a homogeneous Earth at 5σ in ten years

The Earth's core mass





Forecast with 10 years of data

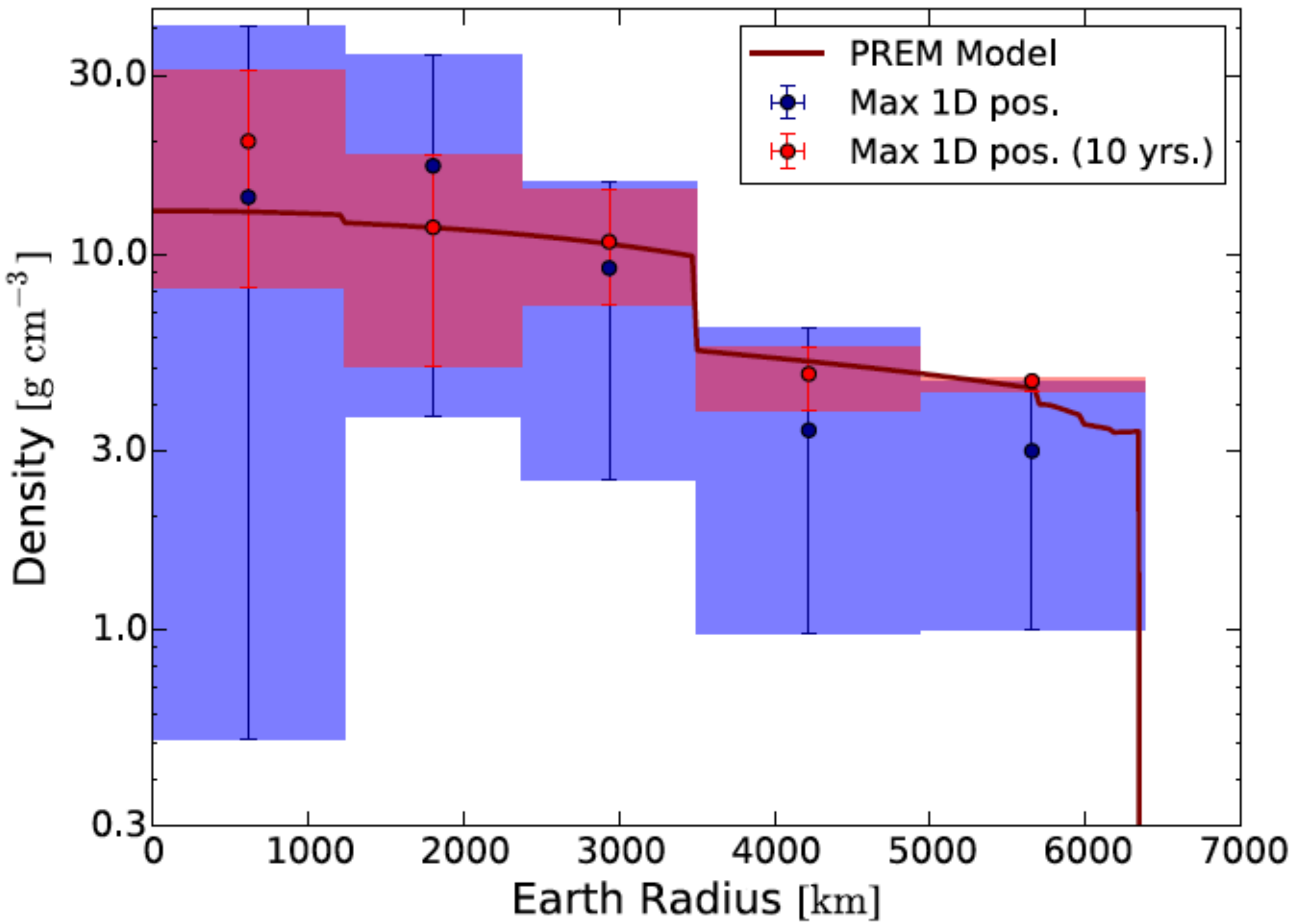


A much finer modelling of the Earth could be done

Test of the Inner-Outer Core discontinuity

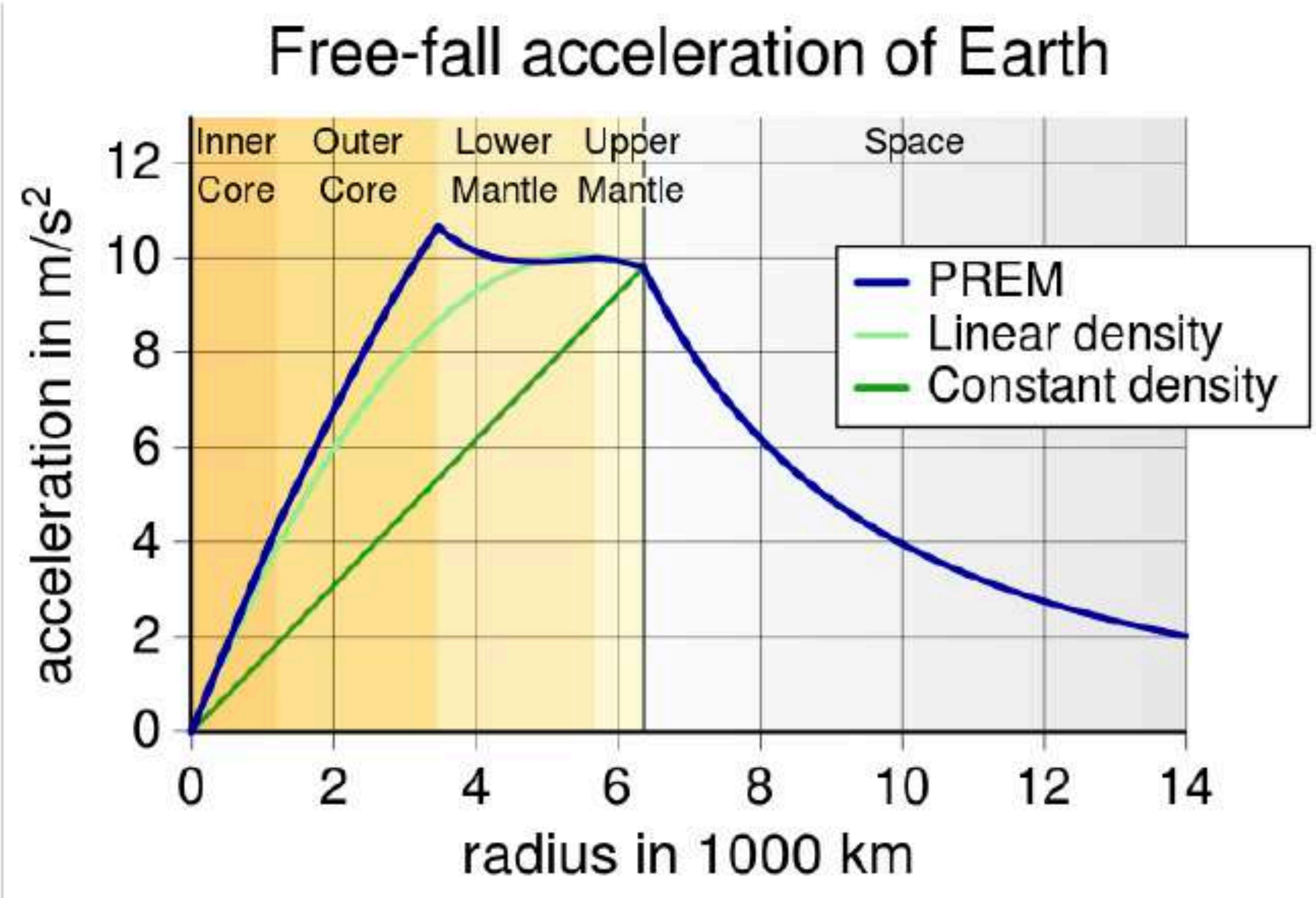
Independent localization of the Core-Mantle Boundary

1-d density profile with 10 years



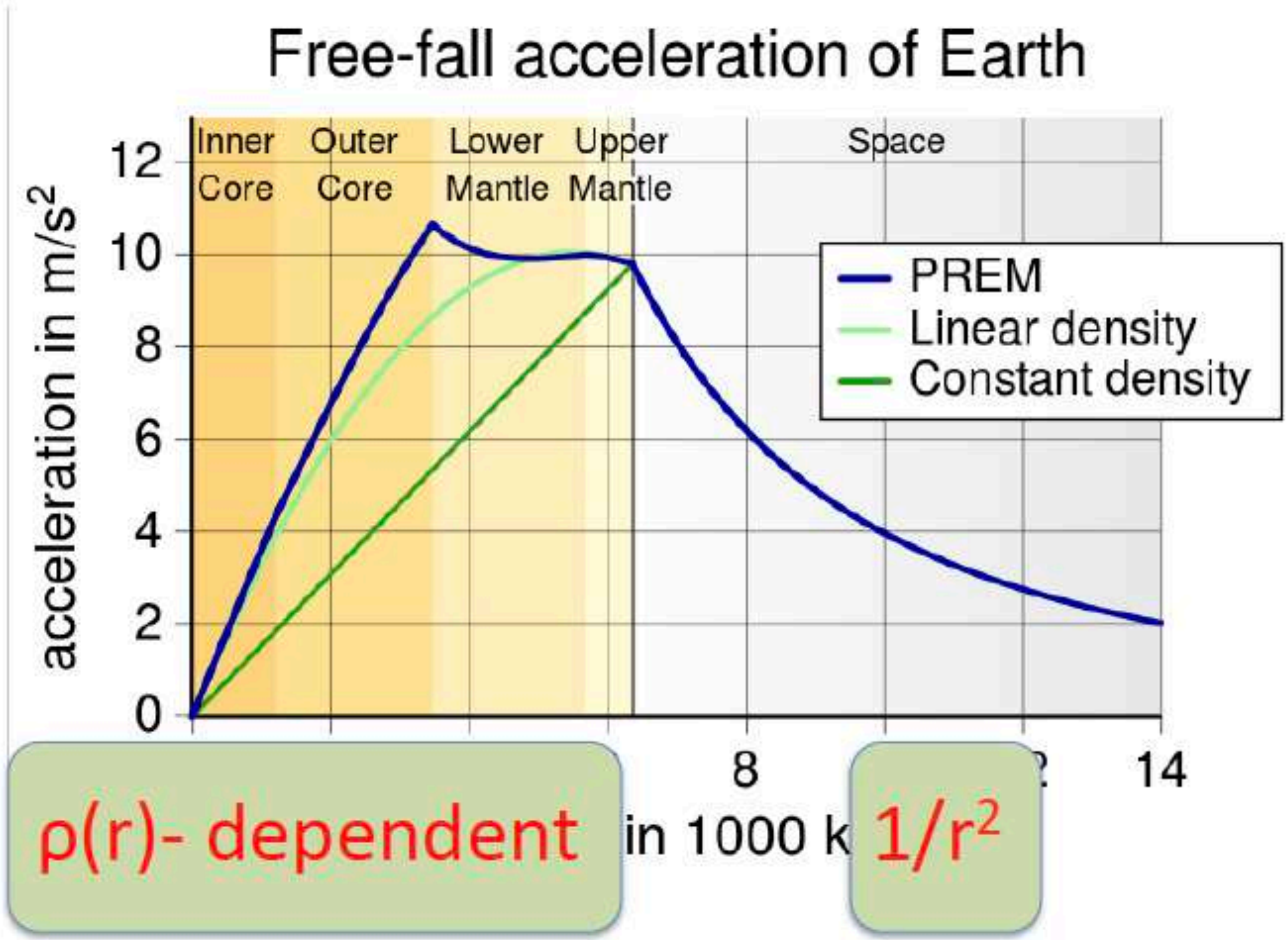
A. Donini, S. Palomares-Ruiz, J. Salvado, Nature Phys. (2019)

An input to geophysics: g(r)



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

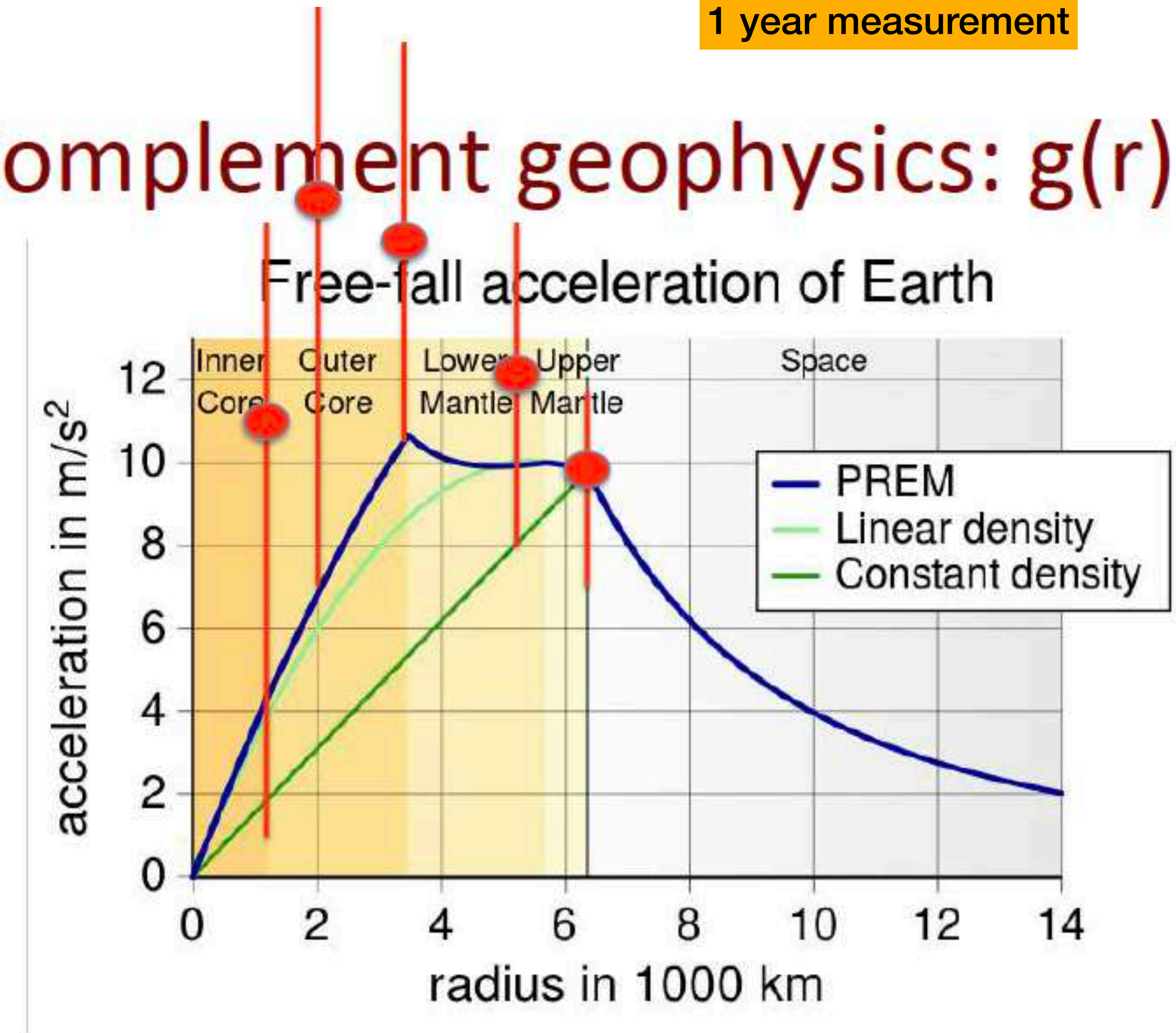
An input to geophysics: g(r)



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

1 year measurement

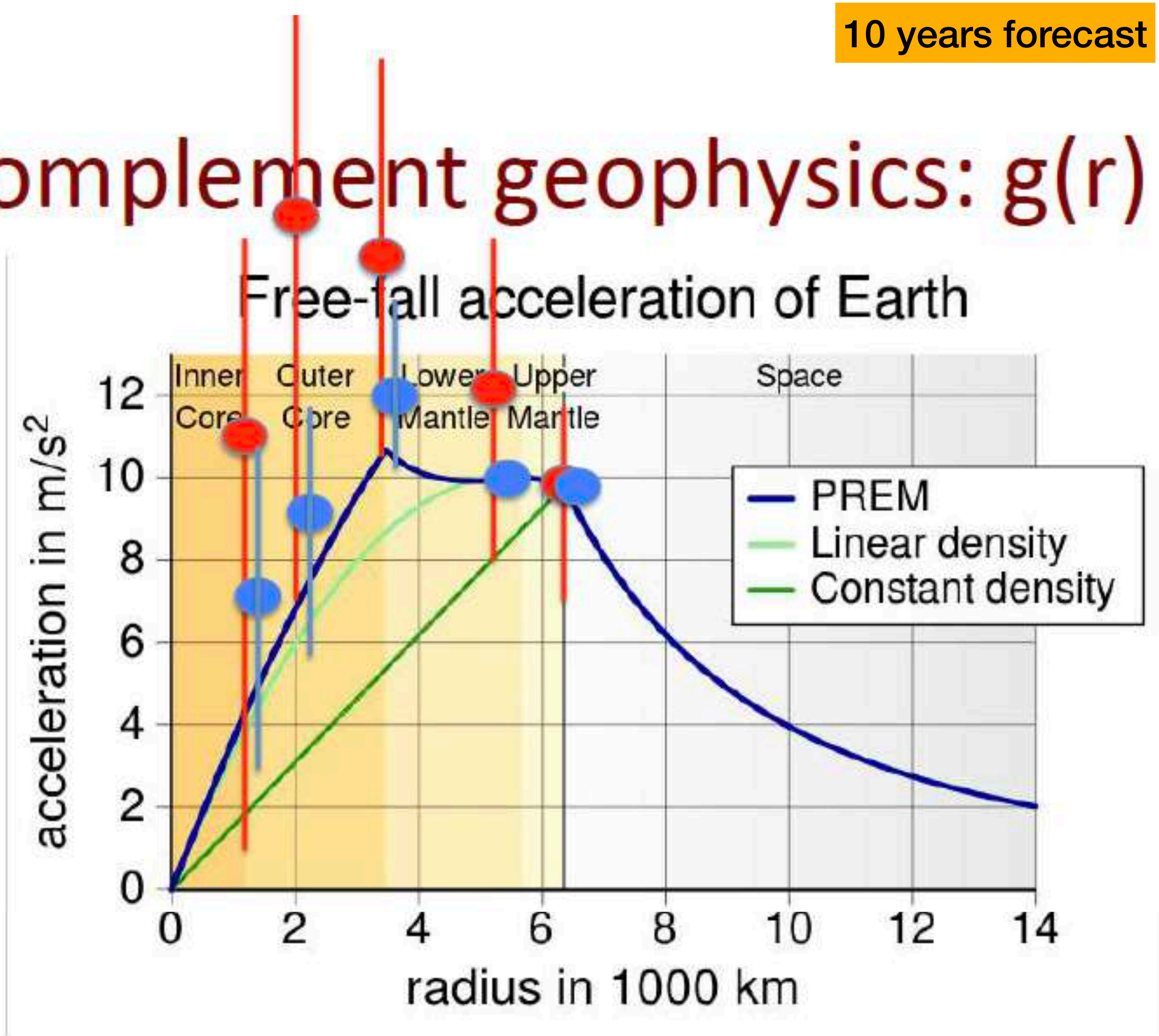
Complement geophysics: g(r)



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

10 years forecast

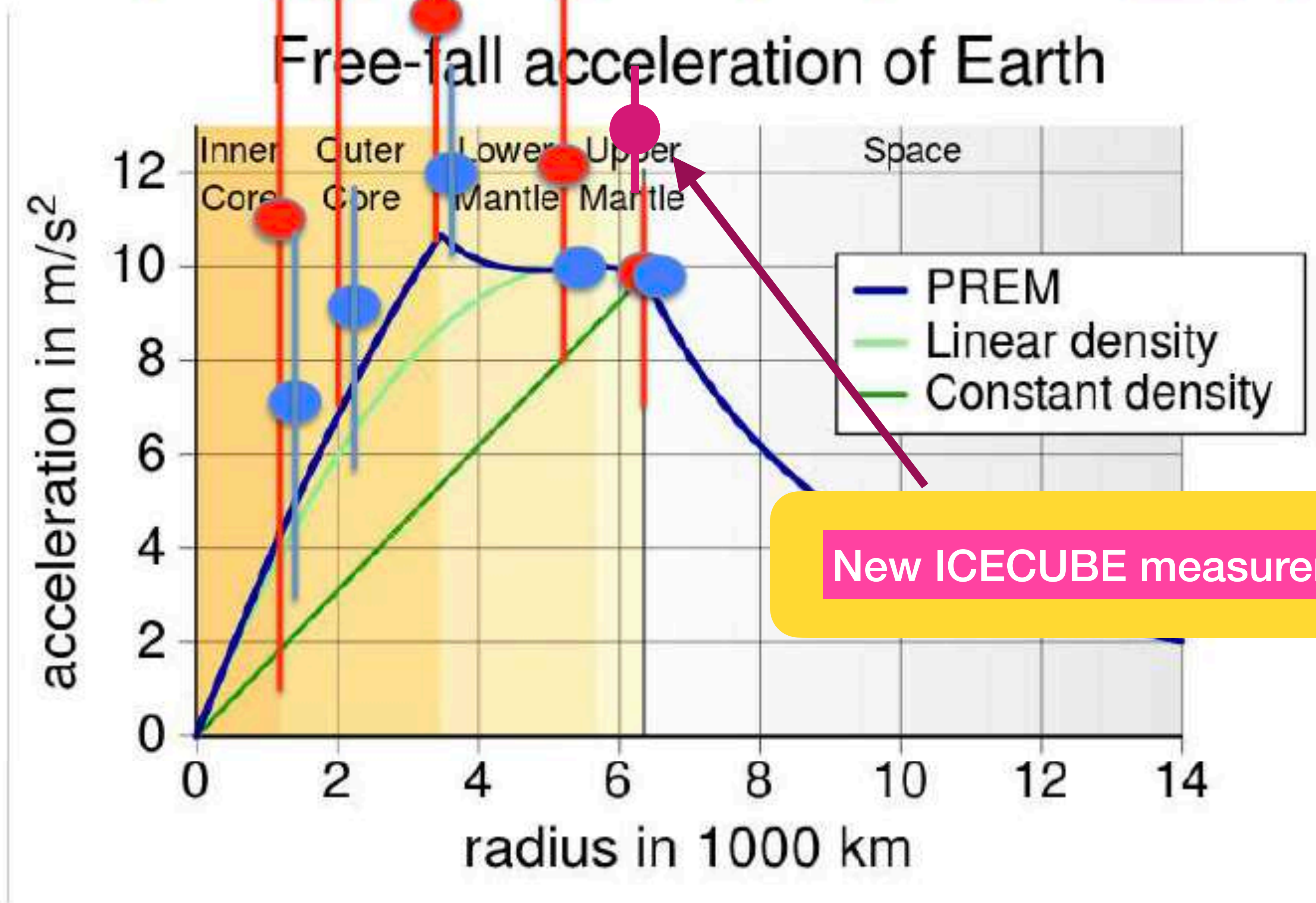
Complement geophysics: g(r)



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

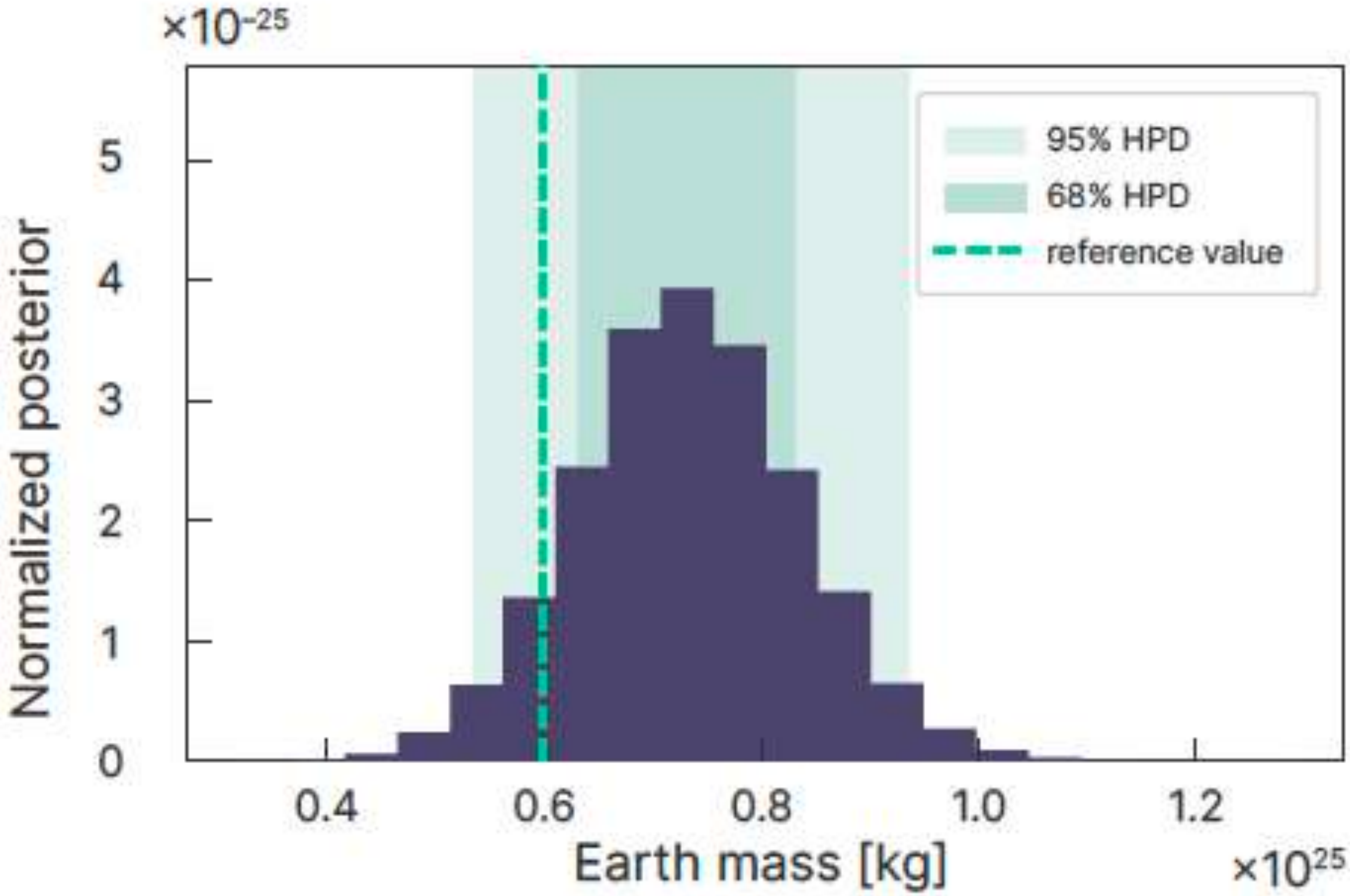
15 years measurement !!!!!!!

Complement geophysics: g(r)

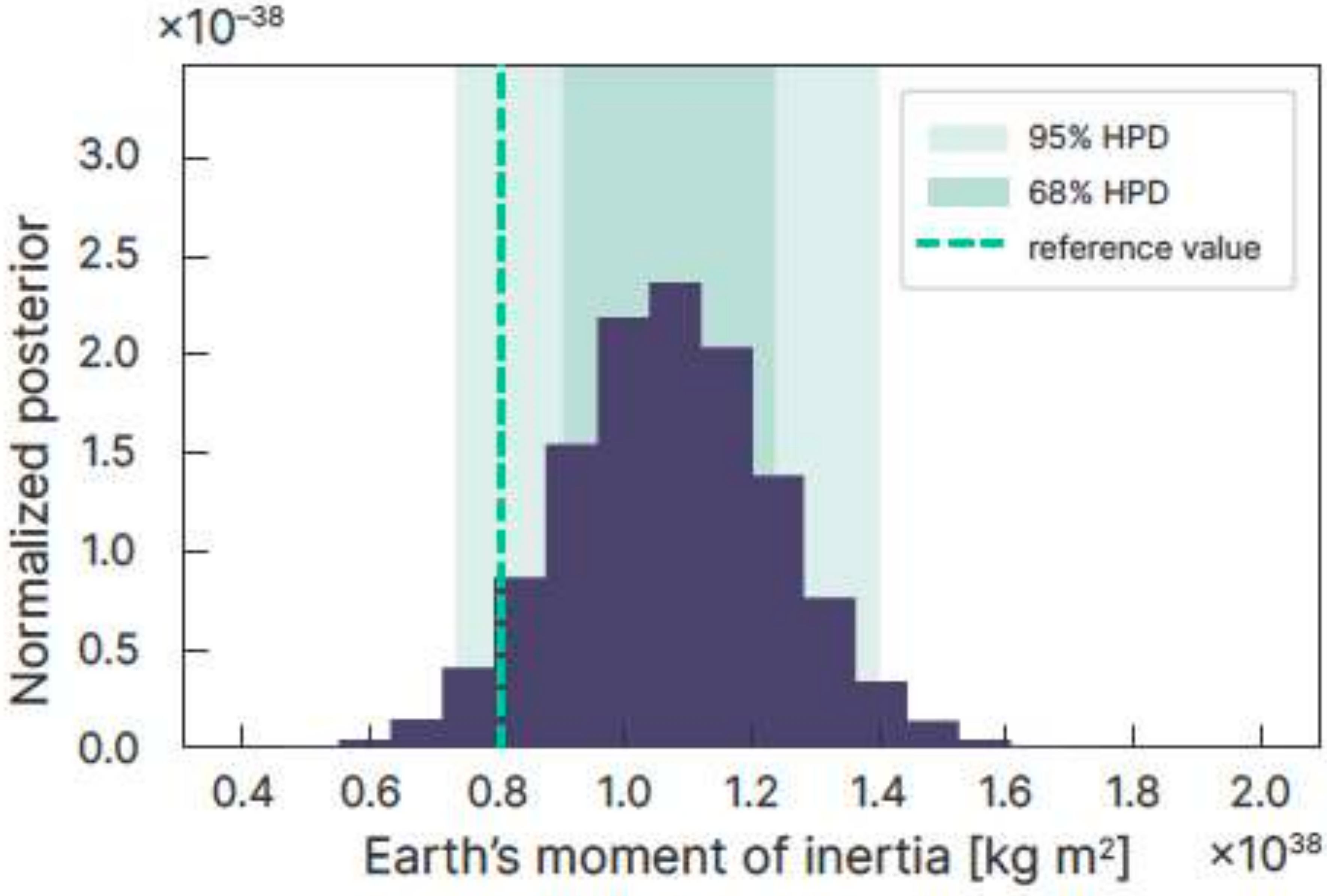


The Earth's gravitational profile is needed to compute ρ(r) from earthquake waves velocities

NEW measurement of Earth's mass: two sigma off



NEW measurement of Earth's moment of inertia: two sigma off



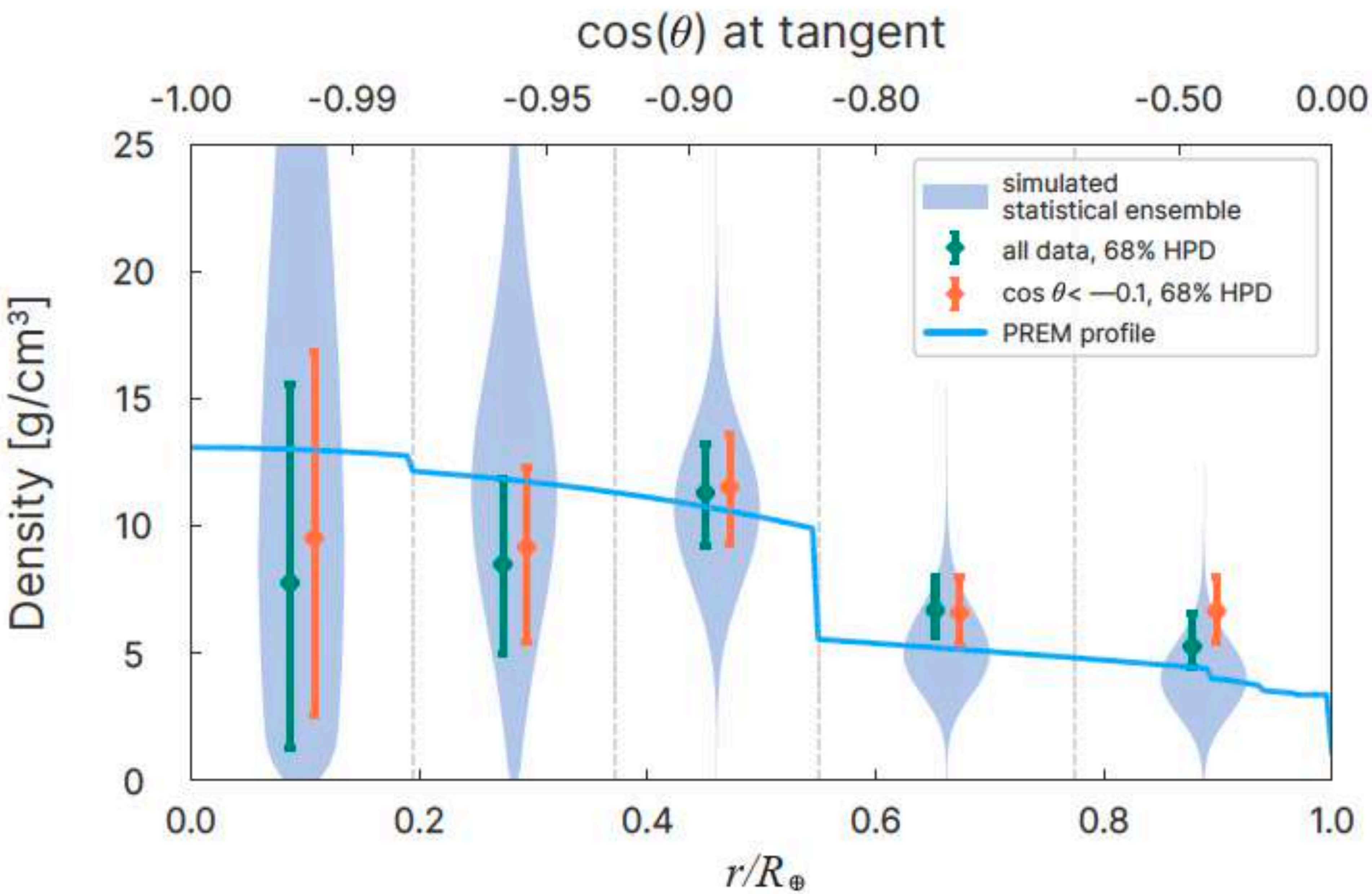
Understanding the new measurement

1. Which data push the Earth’s mass to large values?

2. What if we fix the Earth’s mass?

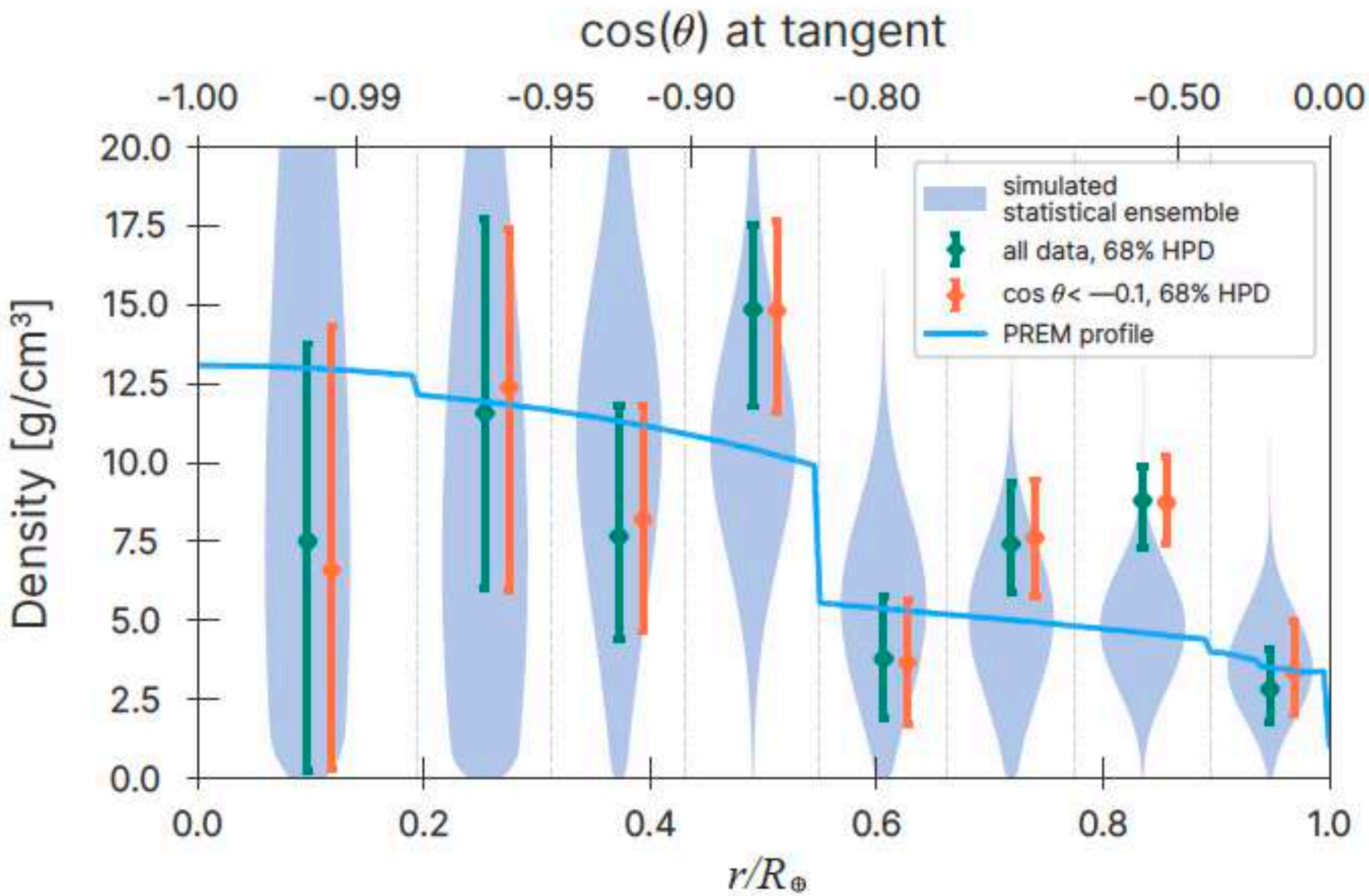
3. New vs Old analyses

FIVE LAYERS



cos(θ) at tangent
-1.00
-0.99
-0.95
-0.90
-0.80
-0.50
0.00
Density [g/cm³]
0
5
10
15
20
25
0.0
0.2
0.4
0.6
0.8
1.0
r/R⊕
simulated statistical ensemble
all data, 68% HPD
cos θ< —0.1, 68% HPD
PREM profile

EIGHT LAYERS



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

Impact of constraints

OLD DATA

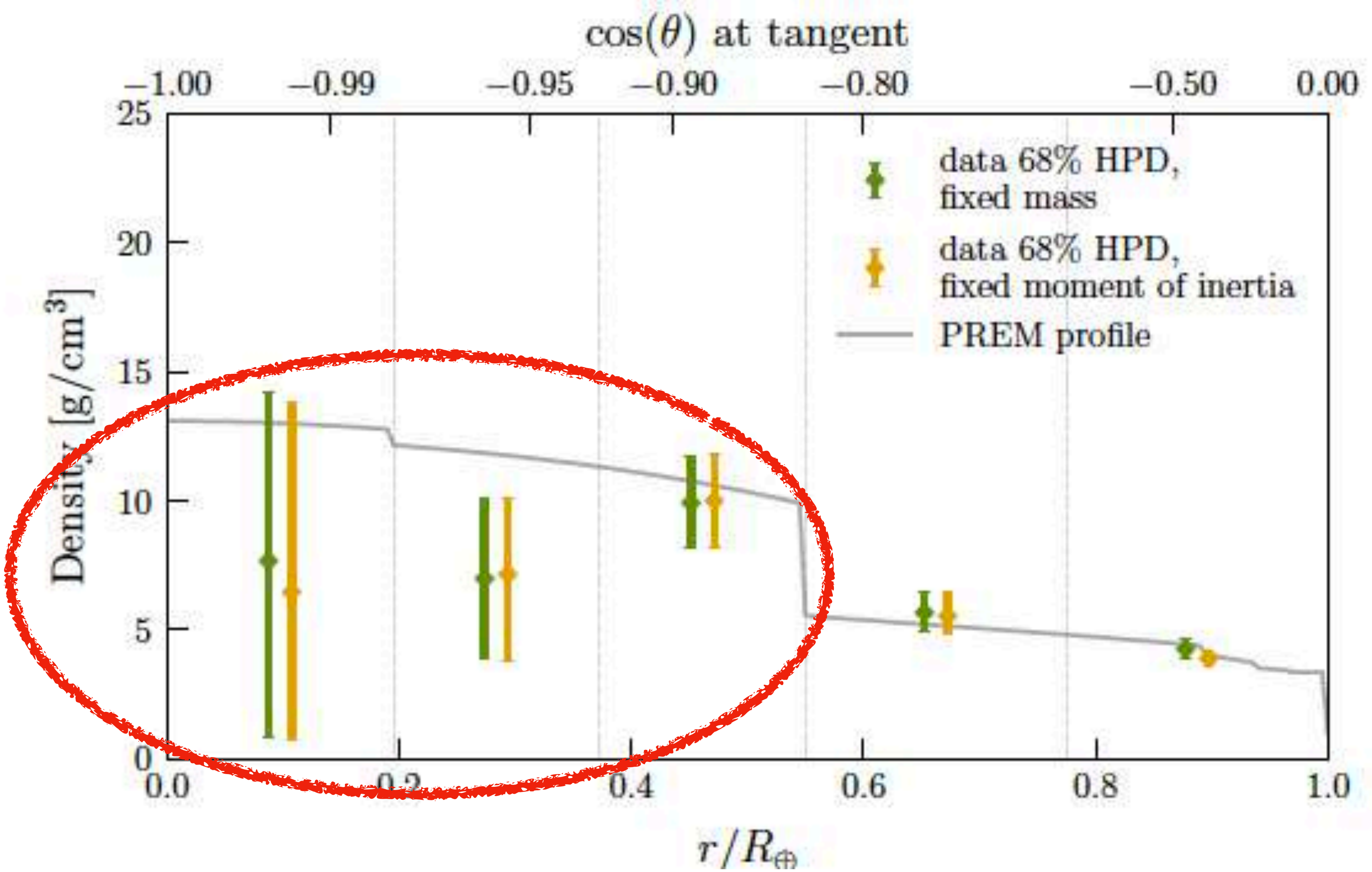
Adding the gravitational Earth's mass as an external constraint, results in fixing the mantle density:

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

Rather small impact on the core density, instead:

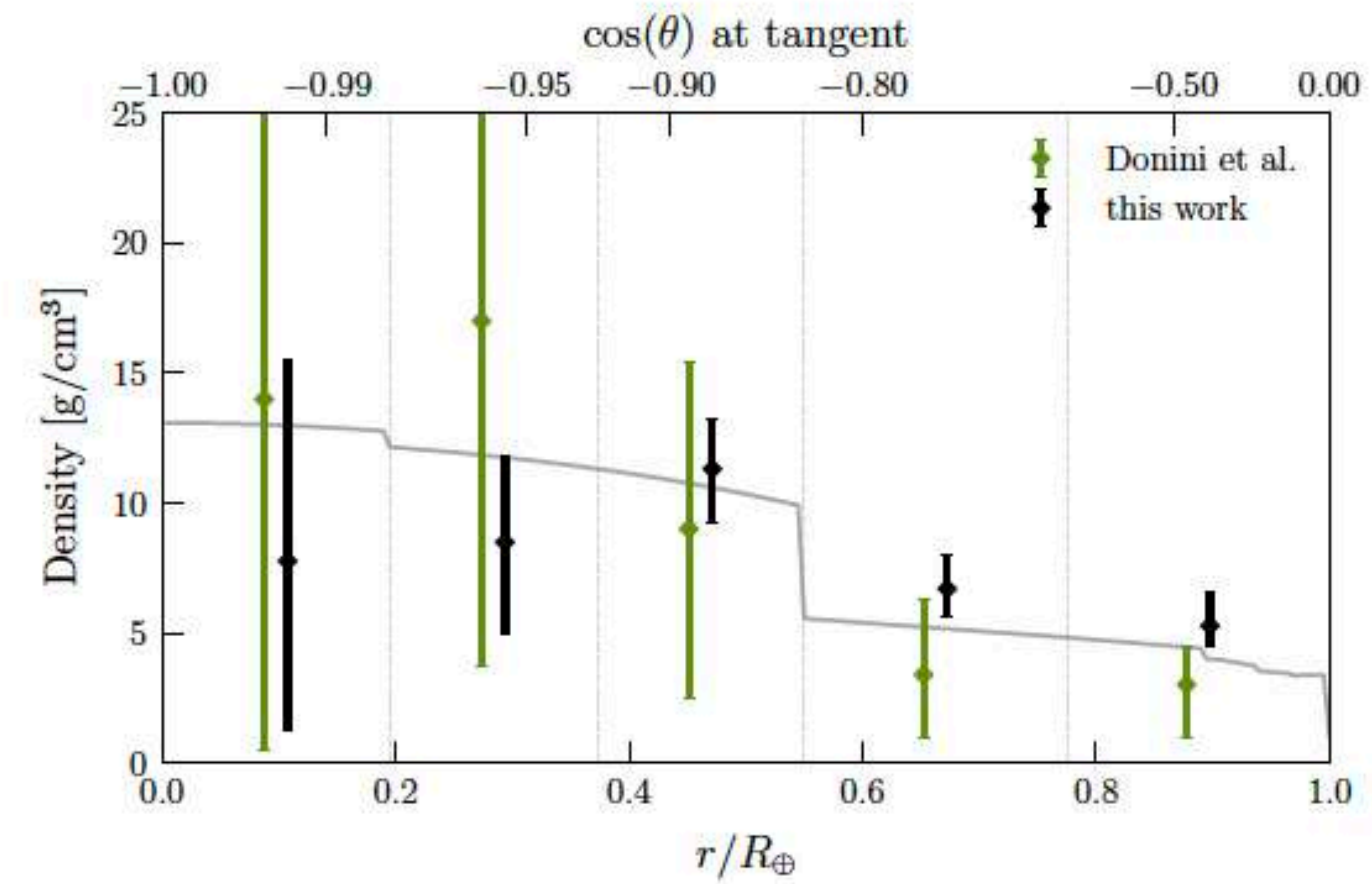
ρ_{core} = [10.2-20.8] g/cm^3 → [9.7-18.6] g/cm^3

NEW DATA



YOU NEED LESS MATTER IN THE CORE

OLD vs NEW DATA



My personal guess

1. Missing systematics: best choice could be related to ice opacity

   Dust accumulates on mostly horizontal planes,

   a wrong reconstruction may affect neutrino detection with low angle

My personal guess

1. Missing systematics: best choice could be related to ice opacity

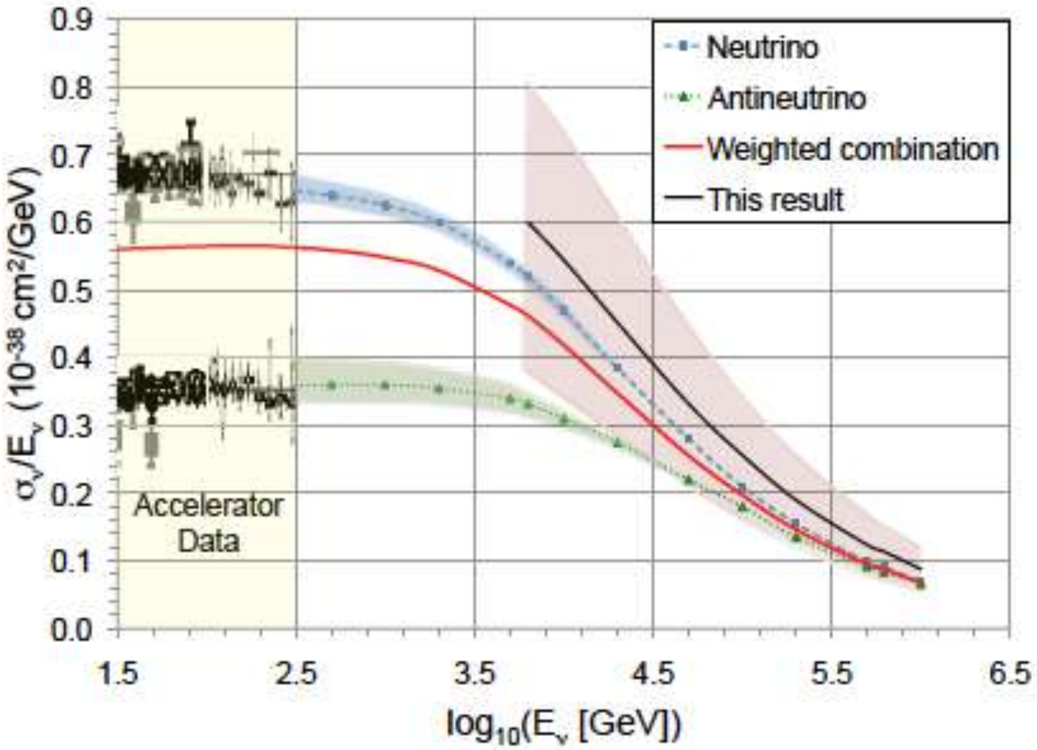
   Dust accumulates on mostly horizontal planes,

   a wrong reconstruction may affect neutrino detection with low angle

2. Do you remember this?

   1 year sample, 2017

Could you please check again?



How to use neutrinos?

What if we had a gravitational model different from Newtonian gravity?

1) Adams-Williamson equation ('20s)

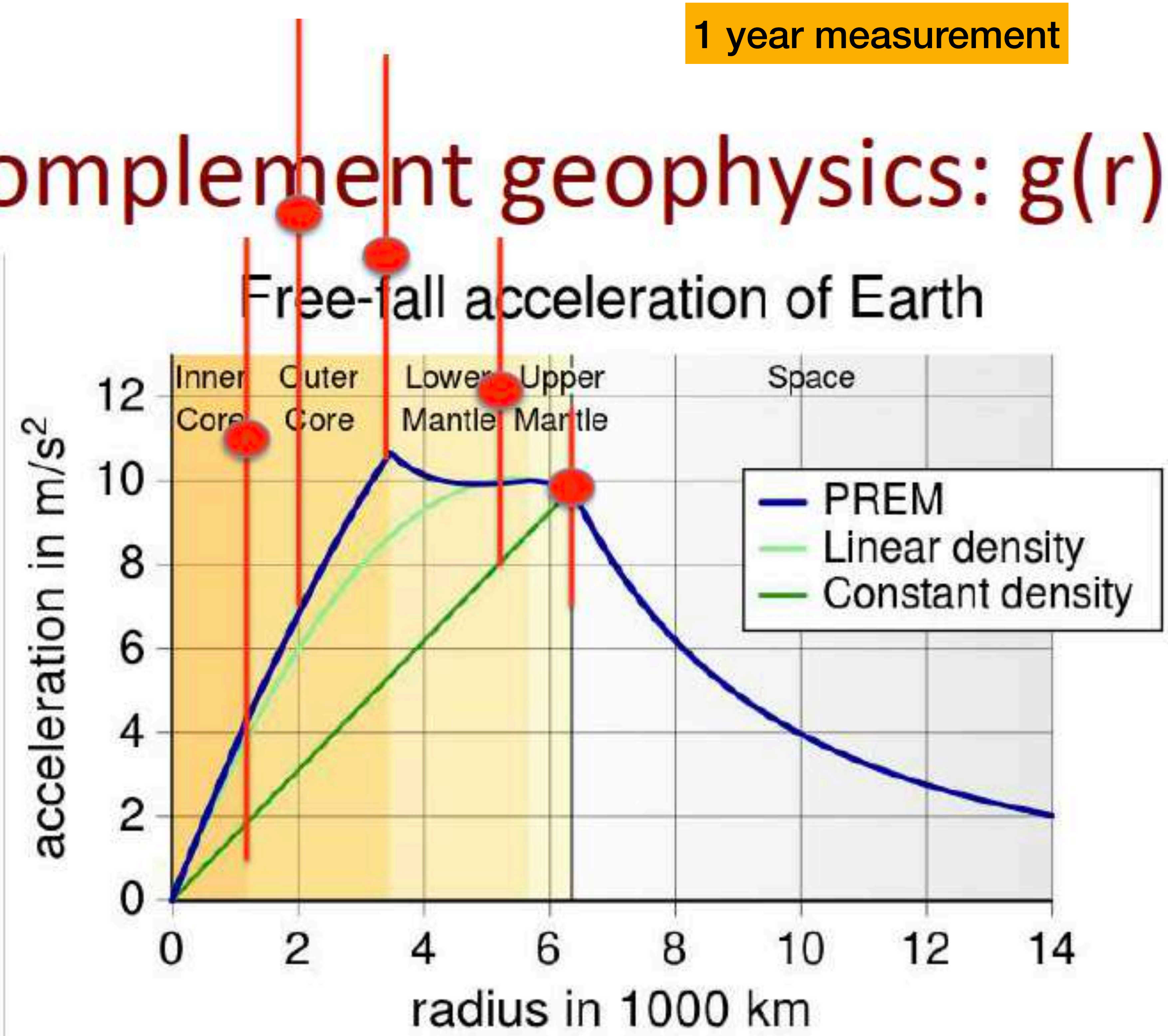
$$\frac{d\rho}{dr} = -\rho(r)\frac{g(r)}{\Phi(r)}$$

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

The density profile depends on the gravitational model!

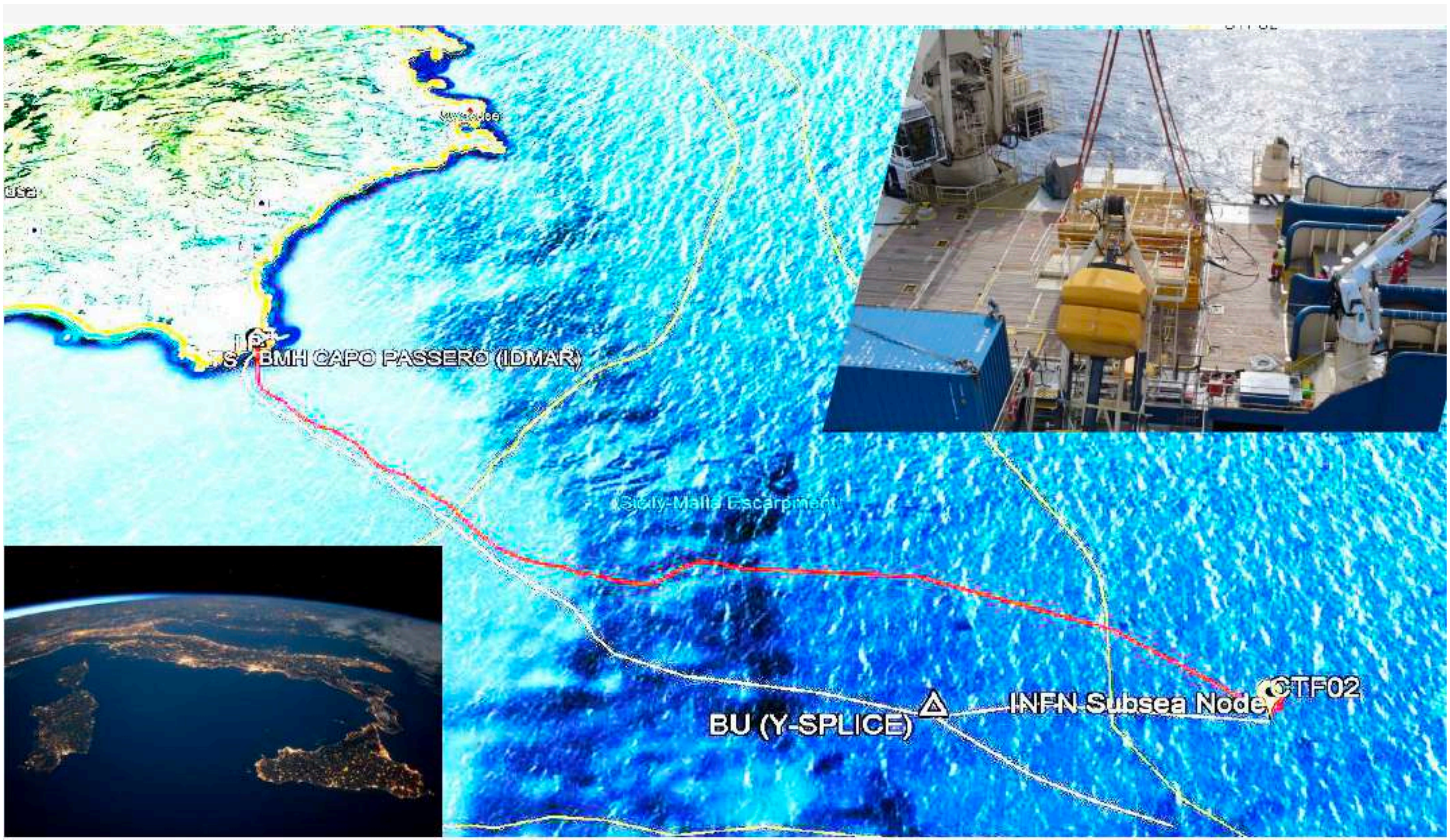
1 year measurement

Complement geophysics: g(r)

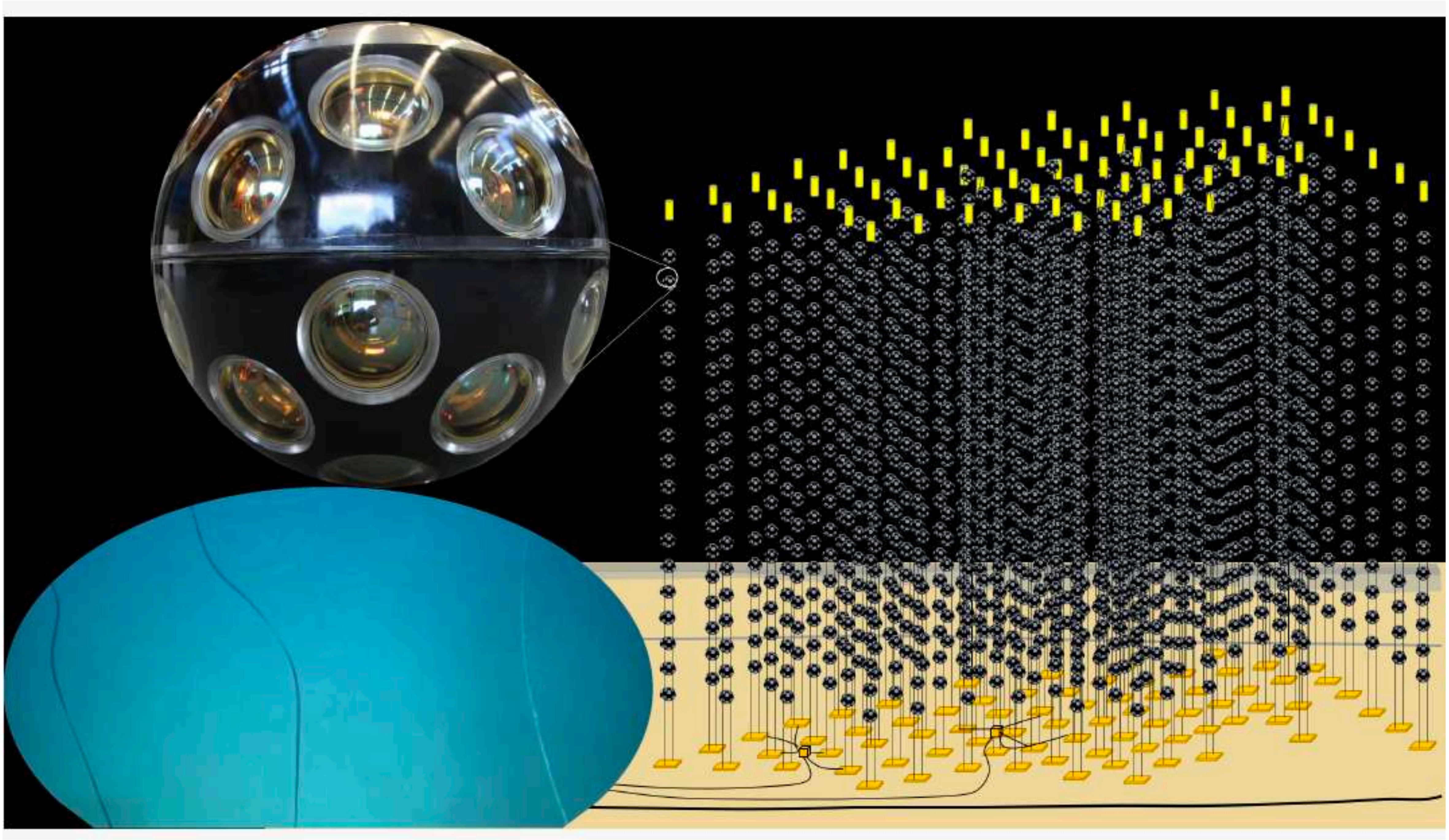


SO WE ARE BACK TO THIS!

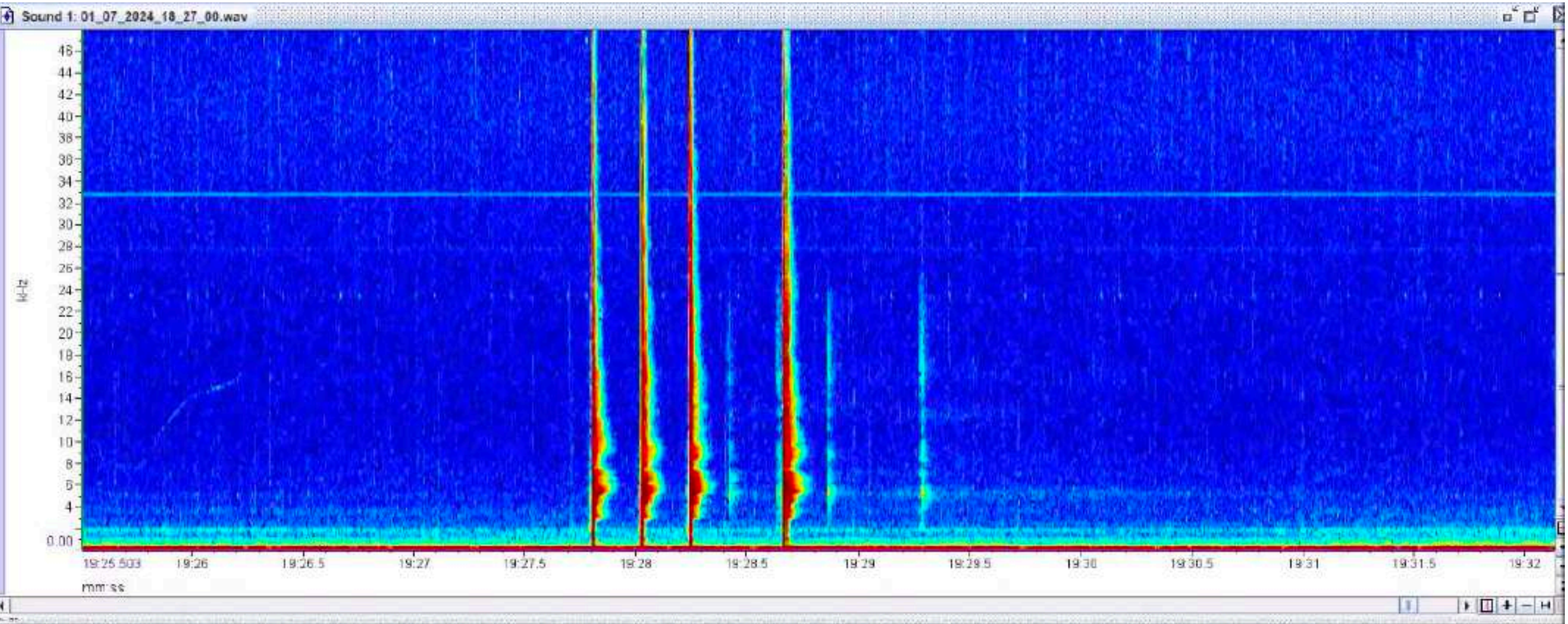
New telescopes: Km3Net



New telescopes: Km3Net

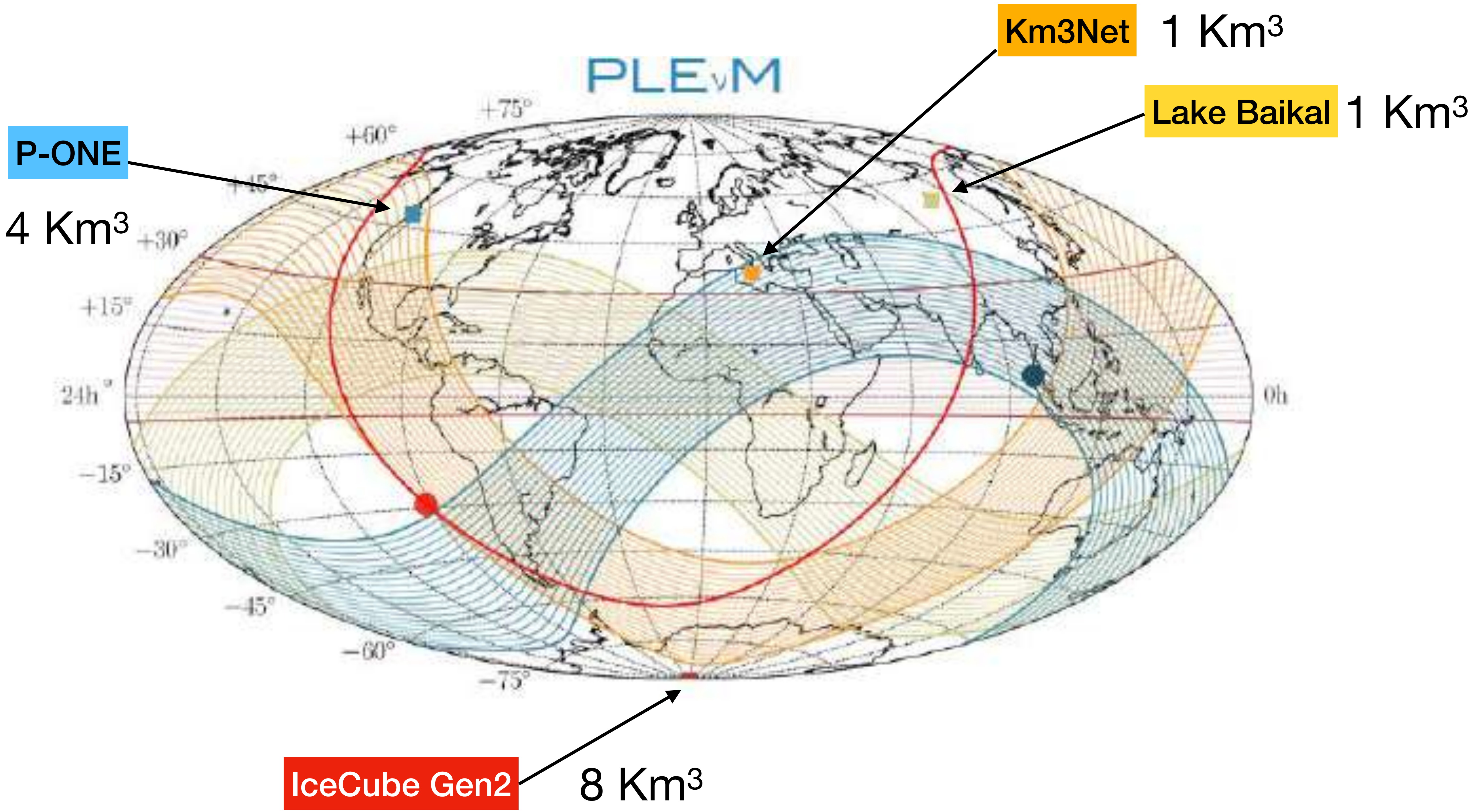


New telescopes: Km3Net



Mediterranean Sperm Whale-singing recorded by Km3Net

More telescopes



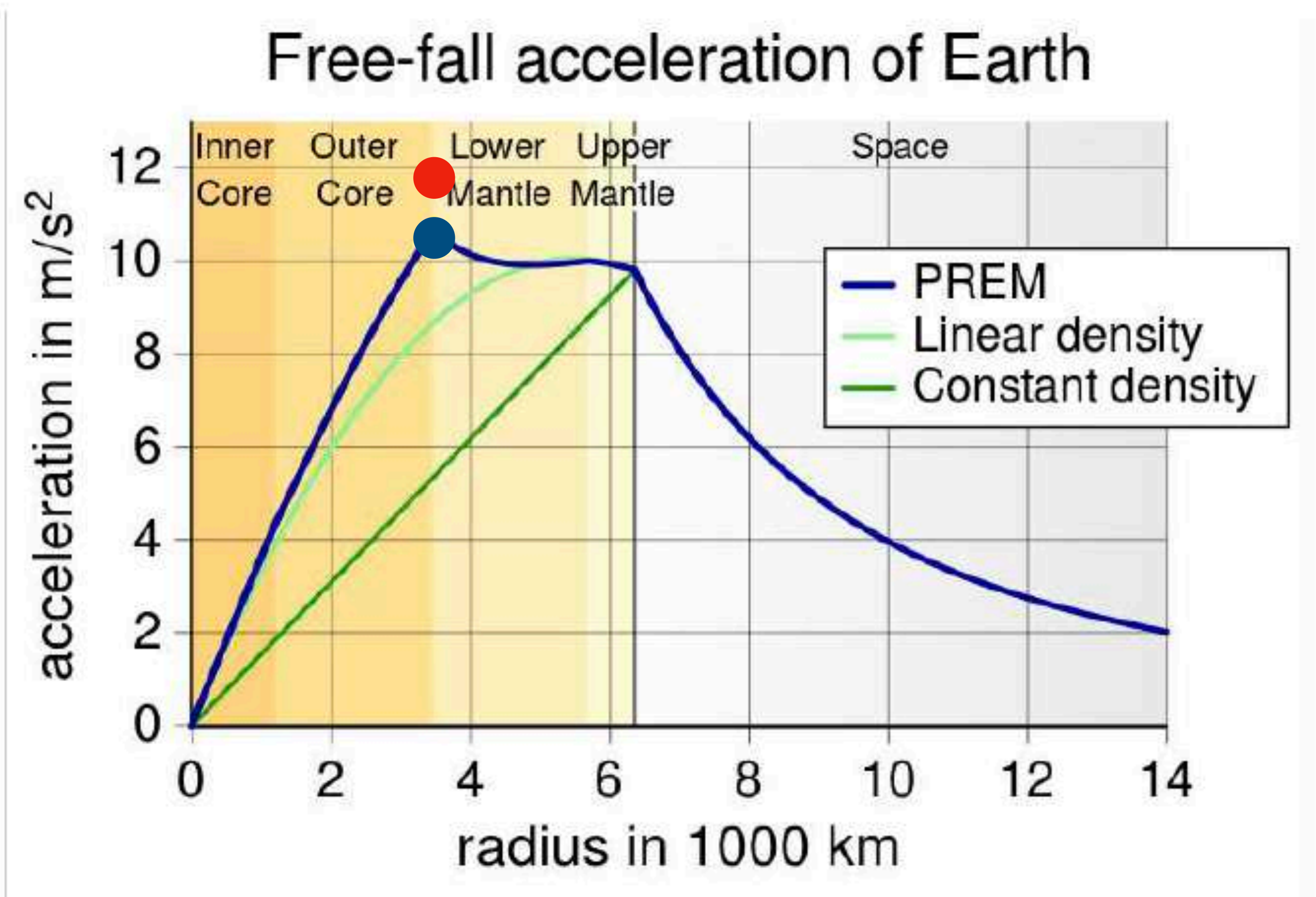
HANDS-ON

MSW resonance

Hands-on session, exercise 1: diagonalize and find the value of the angle in vacuum for which there is resonant oscillation

Neutrino usefulness

Hands-on session, exercise 2: estimate the exposure you need to test a 10% difference between the PREM (Newton-driven) and a mod-gravity model   Earth's core mass?



Assume that errors from seismology are negligible

SOLUTIONS

MSW resonance

Hands-on session, exercise 1: diagonalize and find the value of the angle in vacuum for which there is resonant oscillation

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\left[\frac{\Delta m^2}{4E}\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix}+\begin{pmatrix}\sqrt{2}G_F n_e(x) & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e(x)\\ \nu_\mu(x)\end{pmatrix}$$

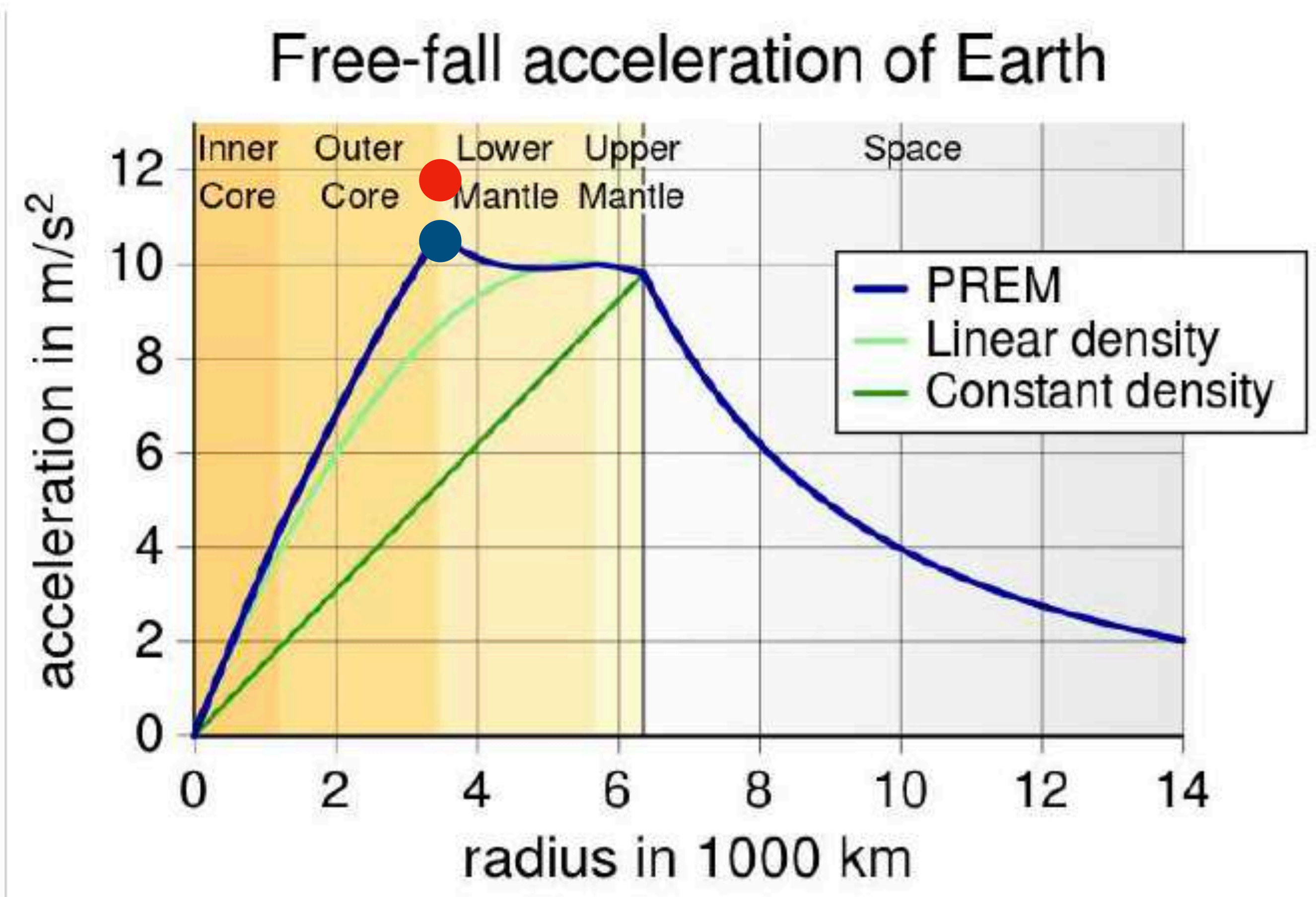
$$\sin 2\theta_m=\frac{\sin 2\theta}{\sqrt{(\cos 2\theta - A)^2+\sin^2 2\theta}},\qquad A=\frac{2\sqrt{2}G_F n_e E}{\Delta m^2}.$$

$$A_{\mathrm{res}}=\cos 2\theta \quad\Rightarrow\quad n_e^{\mathrm{res}}=\frac{\Delta m^2\cos 2\theta}{2\sqrt{2}G_F E}.$$

MSW condition

Neutrino usefulness

Hands-on session, exercise 2: estimate the exposure you need to test a 10% difference between the PREM (Newton-driven) and a mod-gravity model Earth's core mass?



Assume that errors from seismology are negligible

Neutrino usefulness

1-year IceCube analysis

$$m_{\text{core}}^{(1\text{ yr})} = (2.7 \pm 1.0) \times 10^{24}\text{ kg} \quad \Rightarrow \quad \frac{\sigma_1}{m_{\text{core}}} \approx \frac{1.0}{2.7} \approx 37\%.$$

15-year IceCube analysis (present)

$$m_{\text{core}}^{(15\text{ yr})} \simeq (2.7 \pm 0.27) \times 10^{24}\text{ kg} \quad \Rightarrow \quad \frac{\sigma_{15}}{m_{\text{core}}} \approx 10\%.$$

Empirical scaling of the error Pure statistics would give:

$$\sigma(T) \propto \frac{1}{\sqrt{T}} \quad \Rightarrow \quad \frac{\sigma_{15}}{\sigma_1} \approx \frac{1}{\sqrt{15}} \approx 0.26.$$

Neutrino usefulness

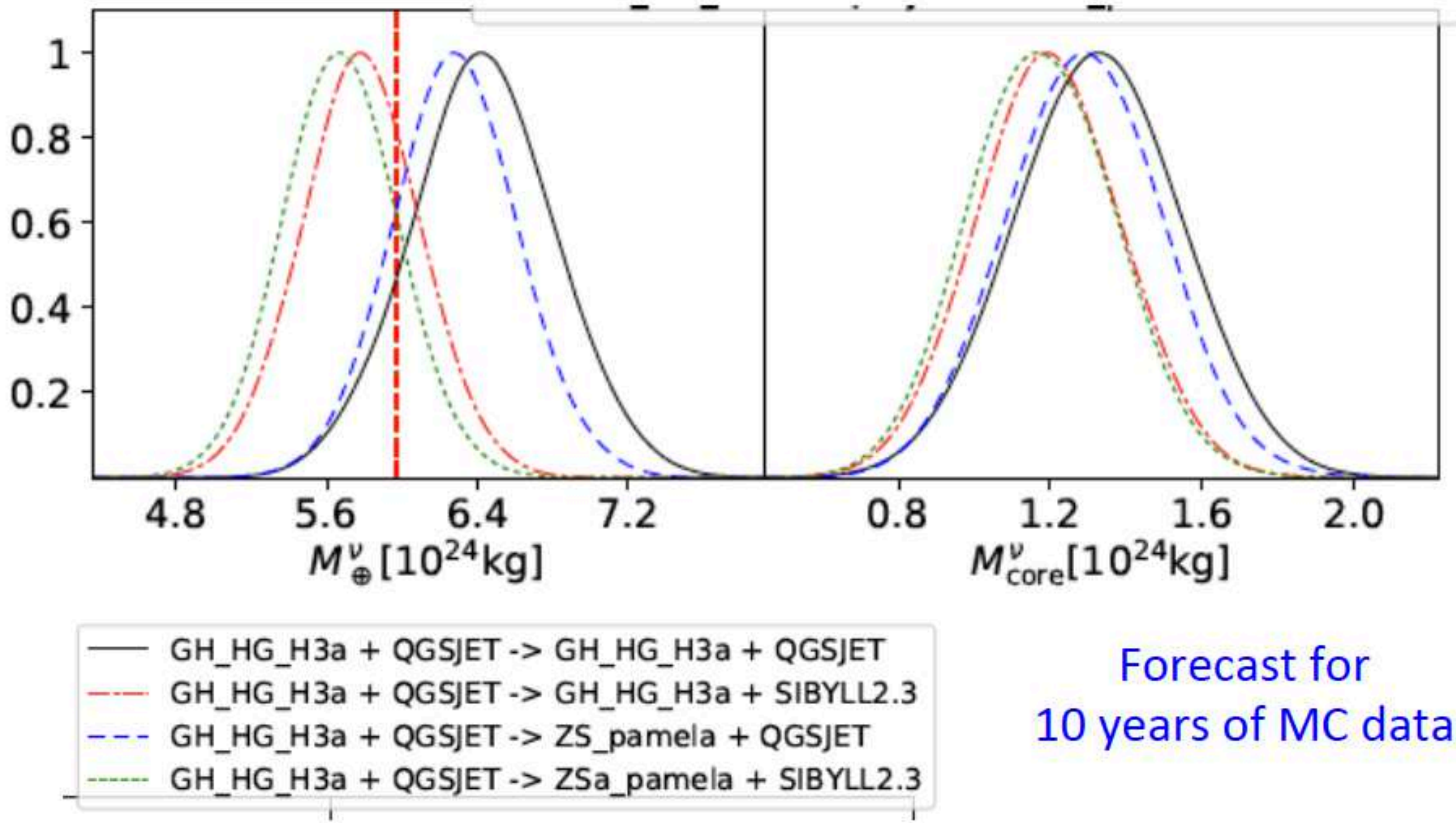
You need the error to go down to 2-3% in order to distinguish between two models 10% apart…

Extra factor 10: $$\frac{\sigma_{150}}{\sigma_{15}} \quad \frac{\sigma_{15}}{\sigma_1} \approx \frac{1}{\sqrt{15}} \quad \frac{1}{\sqrt{10}} \quad \sim 0.1$$

If you do not want to wait 150 years, we need at least 10 Km^3

BACKUPS

Flux and hadronic model dependence, 2



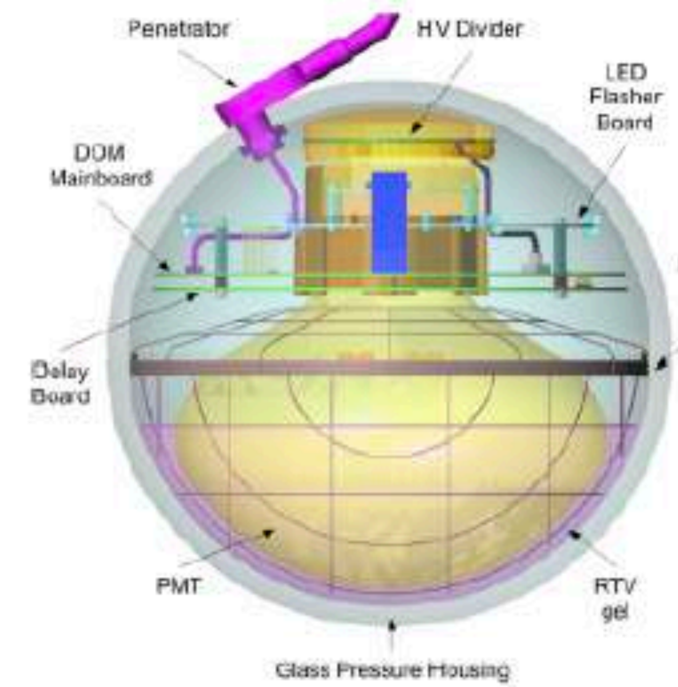
Forecast for
10 years of MC data

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.

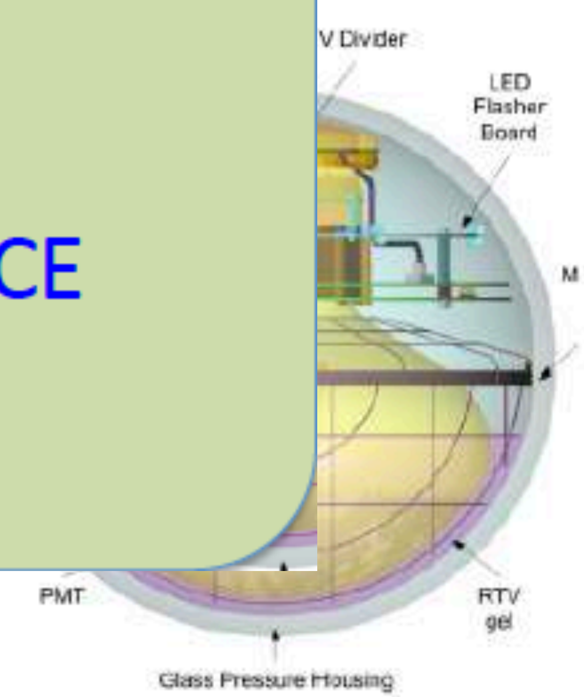
Not important

Systematics importance

- *DOM efficiency*
- *Flux c*
    - *s*
    - *π*
    - *ν*
- Air sh
  irrelev
- Prima
  irrelev
- Hole l
- Neutri
- Bulk ice scattering/absorption
  Irrelevant

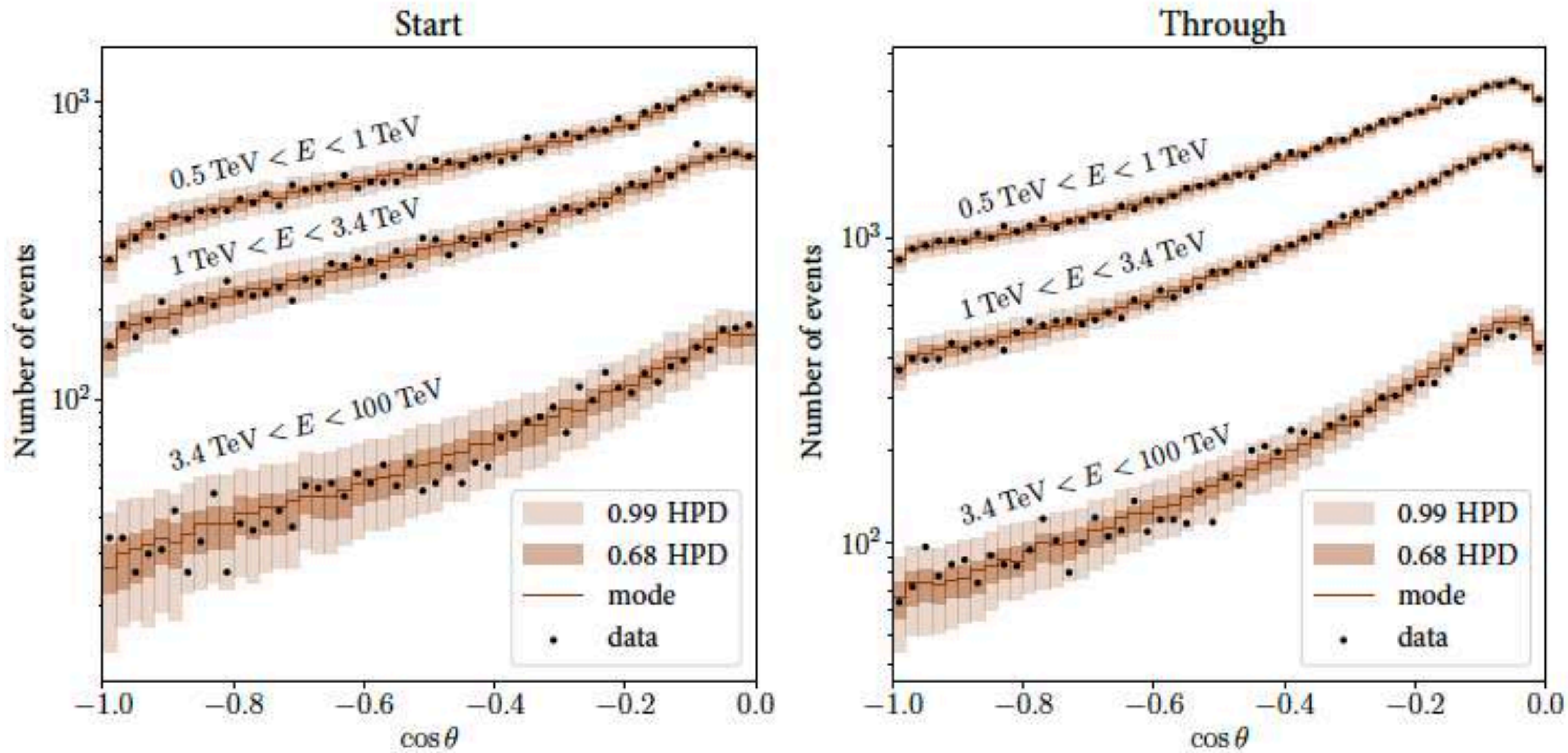
continuous systematics
discrete systematic

Not taken into account:
OPTICAL PROPERTIES OF THE ICE



D.O.M.

Not important


Start
Through
Number of events
10^3
10^2
0.5 TeV < E < 1 TeV
1 TeV < E < 3.4 TeV
3.4 TeV < E < 100 TeV
0.99 HPD
0.68 HPD
mode
data
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
cos θ