Earth from atmospheric neutrinos

Jordi Salvado
in collaboration with:
Andrea Donini
Sergio Palomares-Ruiz

Moriond EW 2018.

Today in Arxiv: "Neutrino tomography of the Earth" 1803.05901

Using a long range force

- The total (Gravitational) Mass

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

$$I_\oplus = \frac{8\pi}{3}\int_0^{R_\oplus} drr^4\rho(r) = 0.3307144 M_\oplus R_\oplus^2$$

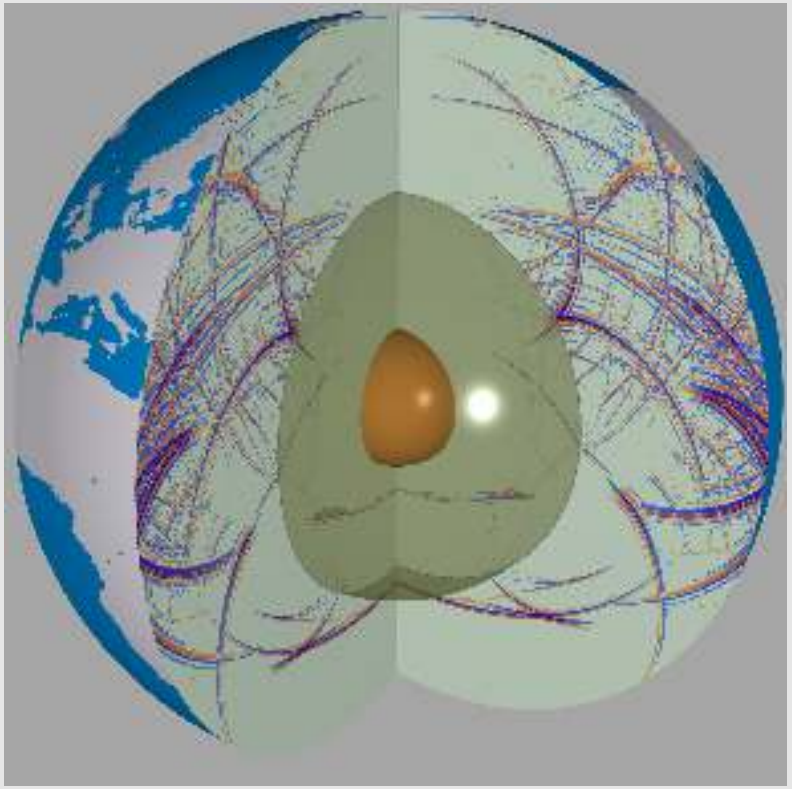
$$I_\oplus^{cnt} = 0.4 M_\oplus R_\oplus^2$$

The state of the art "sound" waves

- Seismic wave propagation S and P waves.
- Adams-Williamson equation.

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

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



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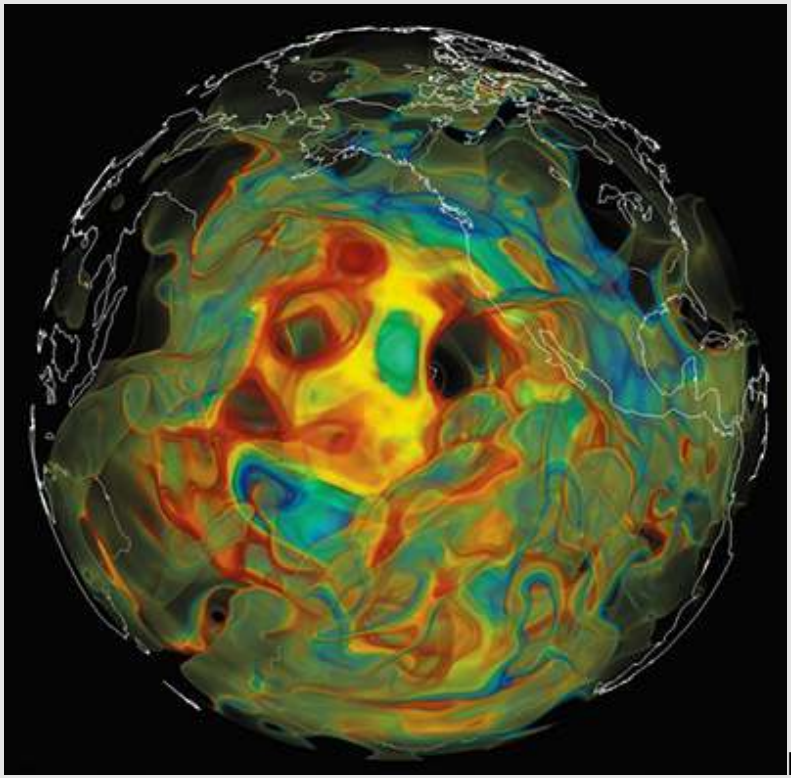
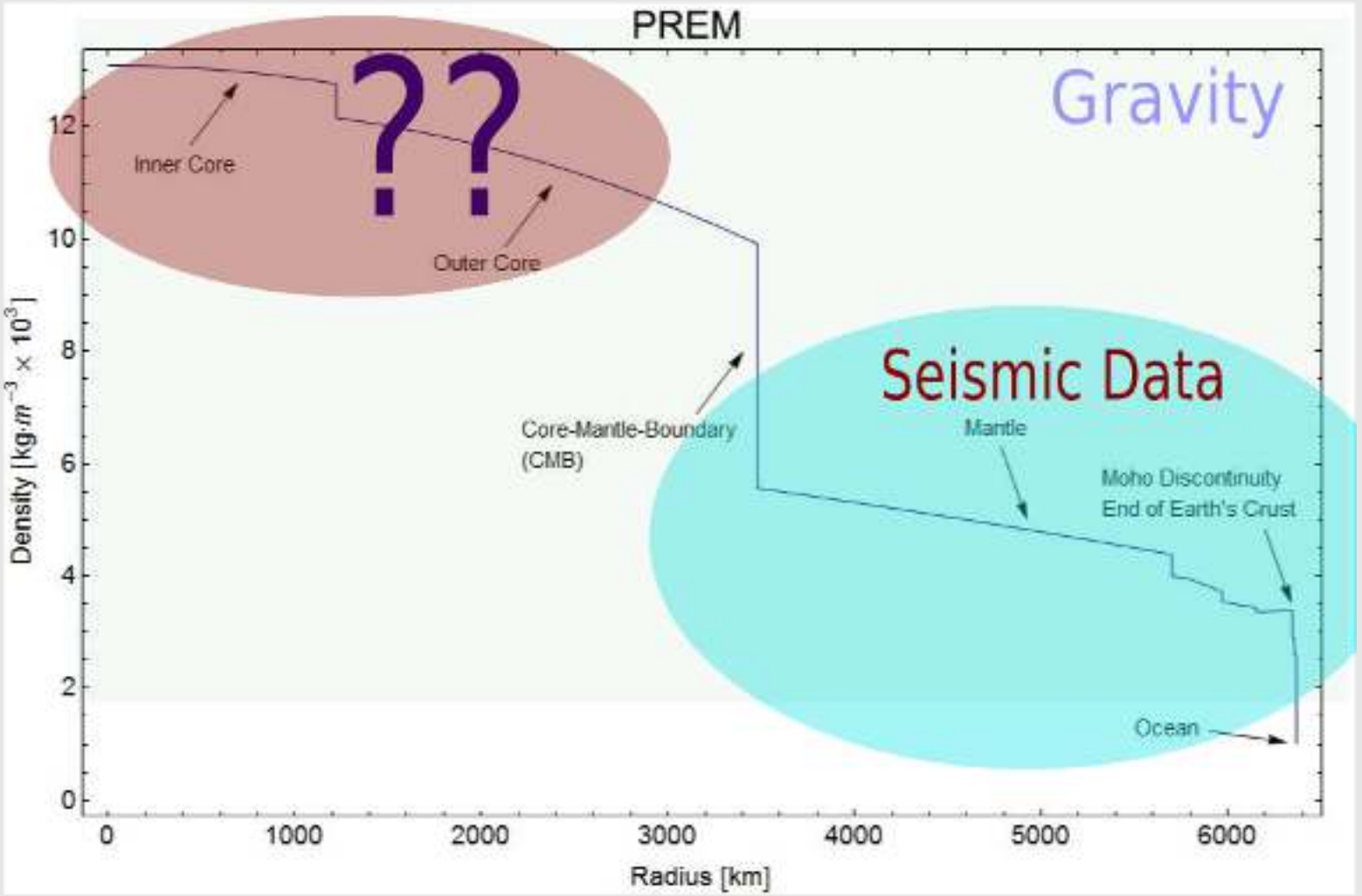


Ebru Bozdağ, University of Nice Sophia Antipolis, and David Pugmire, Oak Ridge National Laboratory. from phys.org

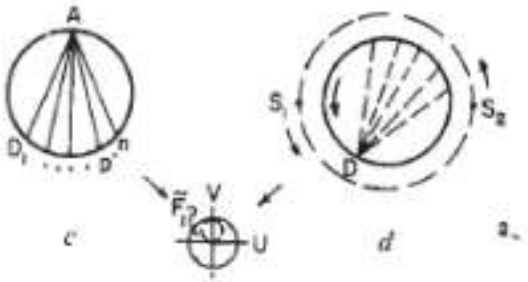
Earth picture



- Core still unknown but very relevant geomagnetic dynamo

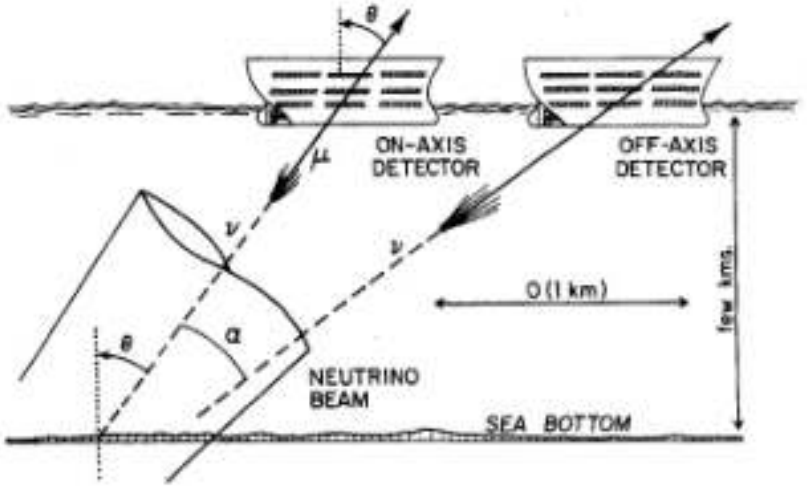
What if we use Neutrinos

- Proposed long time ago!
  A.Piacci and E. Zavalni, submited in Oct 1973 to Nuovo Cimento; never published
- Talk:
  L. V. Volkova and G. T. Zatsepin, Izv. Akad. Nauk. Ser. Fiz. 38N5 (1974)



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

T. Wilson, Nature 309 (1984)



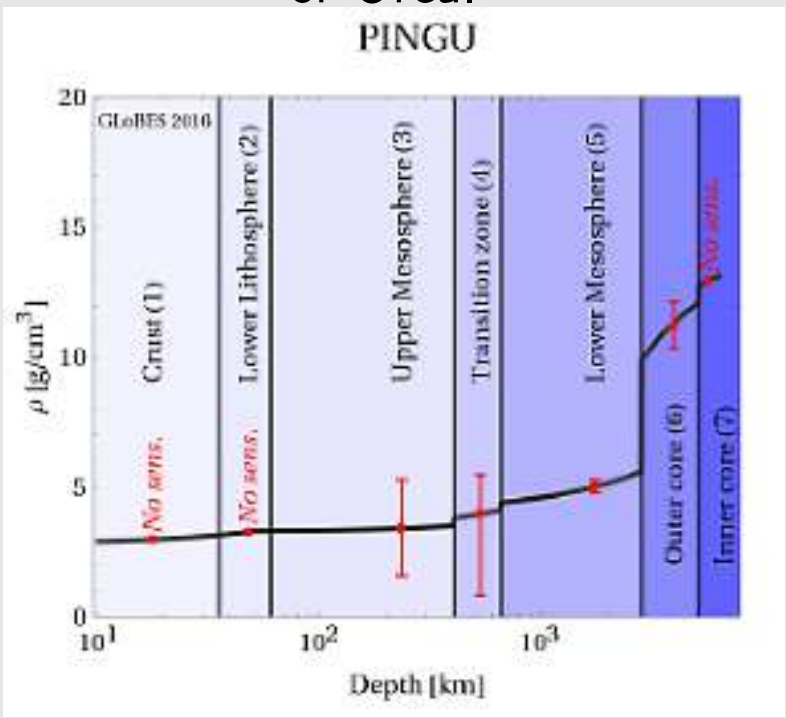
What if we use Neutrinos

- A lot of neutrinos cross the Earth comming from atmospheric cosmic ray showers.
- The propagation is affected by the amount of matter along the path.

Coherent approach

$$\frac{dF_\nu(E)}{dx} = -i[\mathrm{H_o} + \mathrm{Vm}, F_\nu(E)]$$

Matter interactions appear in ν propagations After 10 yrs, Pingu or Orca.

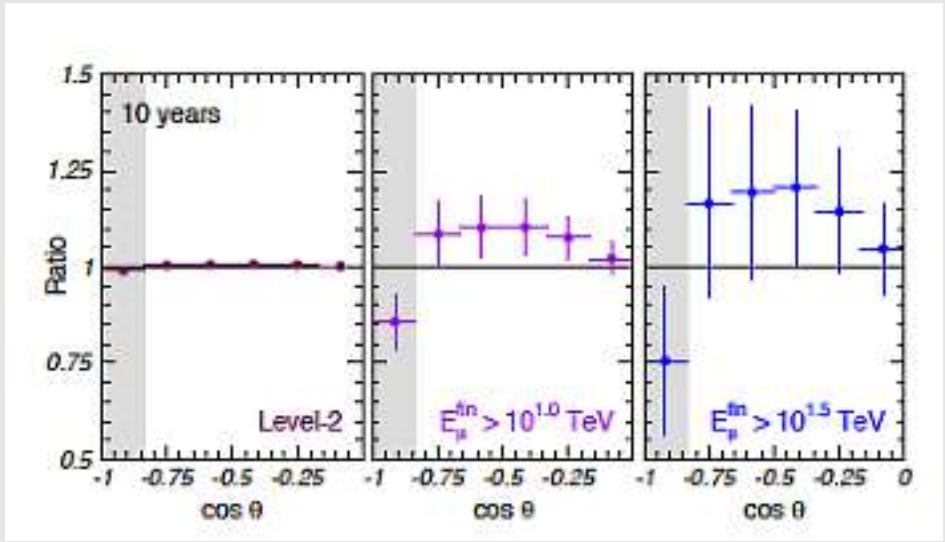


Winter, Nucl. Phys B908 (2016)

Incoherent (high E)

$$\frac{dF_\nu(E)}{dx} = -\sum_\alpha \frac{1}{2\lambda^\alpha(E)} \{\Pi_\alpha, F_\nu(E)$$

(Forecast) after 10 yrs, IceCube atmospheric ν.

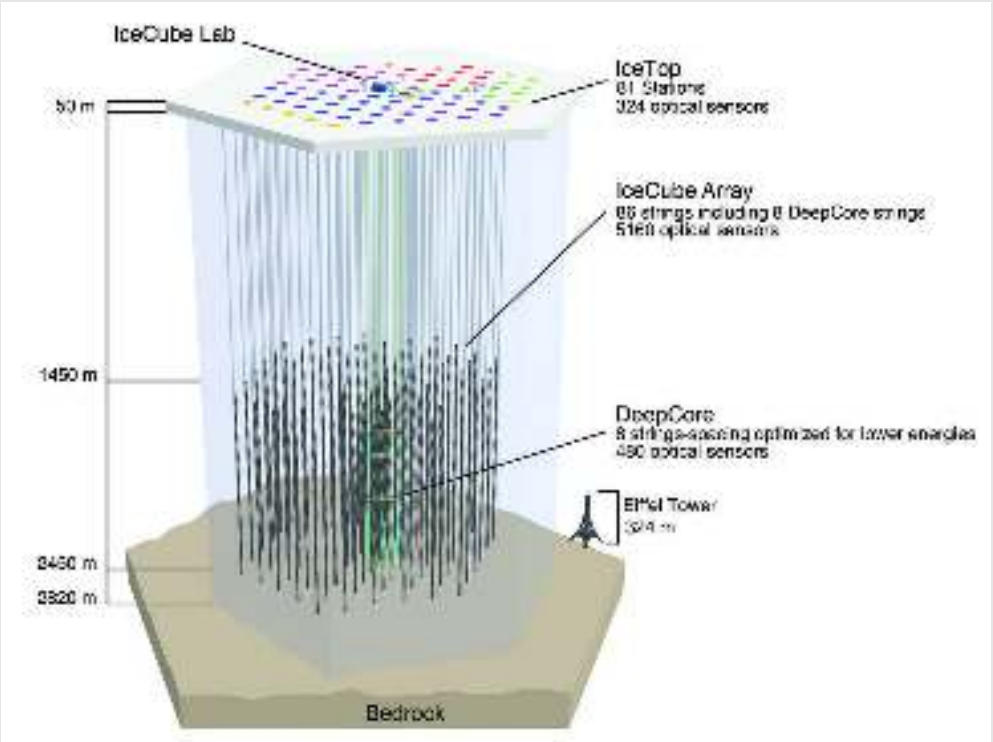


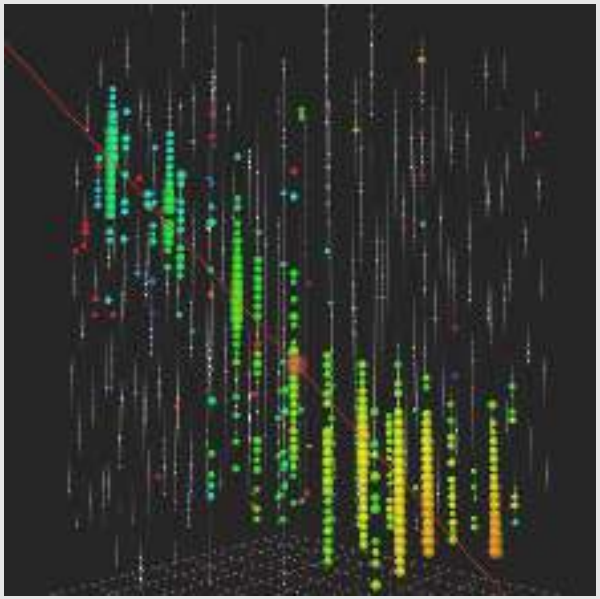
Gonzalez-García, Halzen, Maltoni, Tanaka, Phys. Rev. LeT. 100 (2008)

IceCube data set

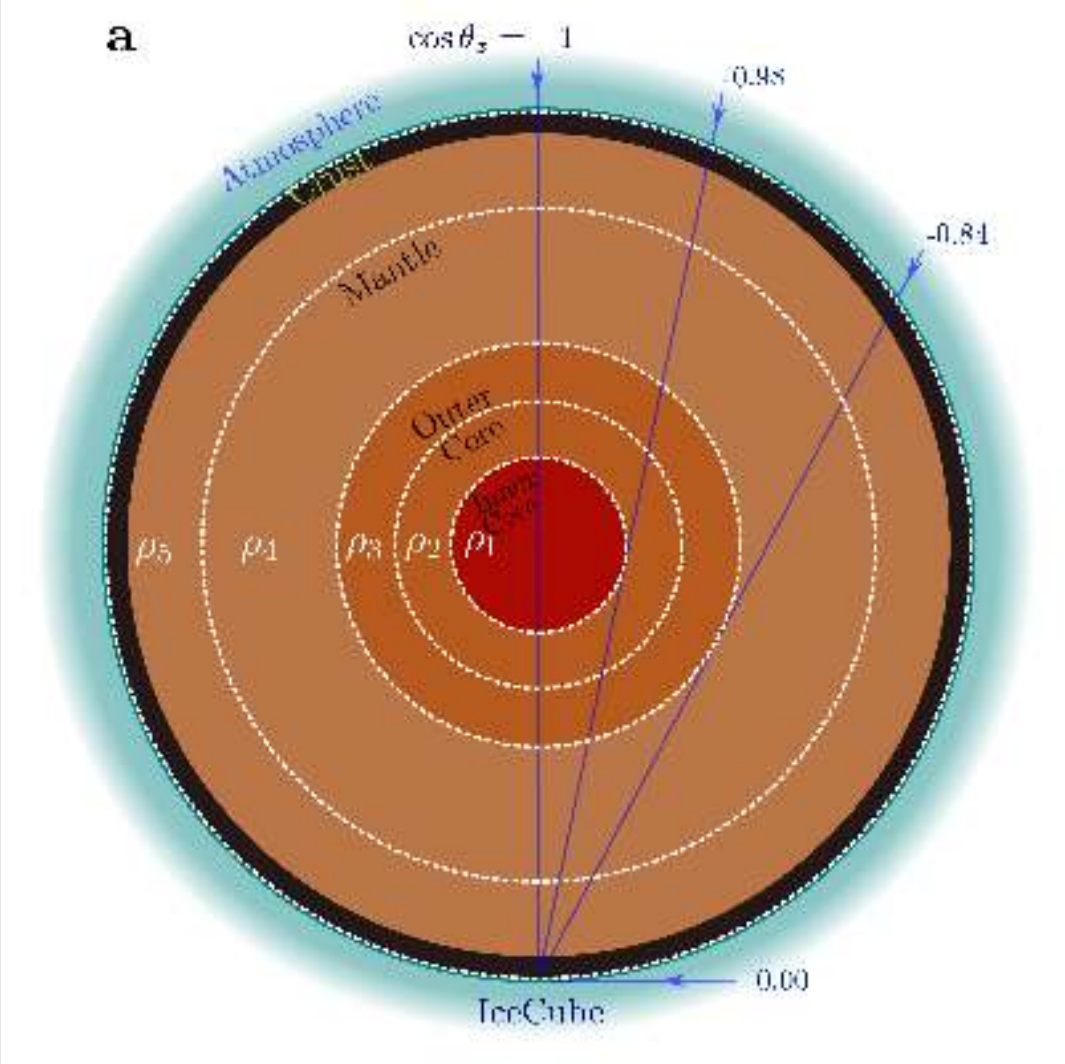
Analysis for one year of **up-going** IceCube-86 high energy ν_μ data (Energy Range : 400 GeV to 30 TeV) data and MC from IC sterile search Phys.Rev.Lett. 117 (2016) no.7, 071801.

- Number of events ~ 20000.
- Spans a zenith range from -1 to 0.2 in $\cos\theta_z$.
- 99% ν_μ purity.

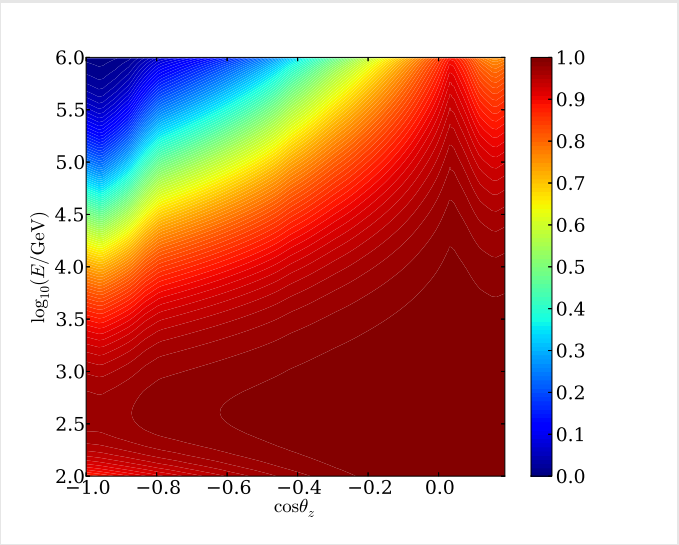




Parametrization of the Earth



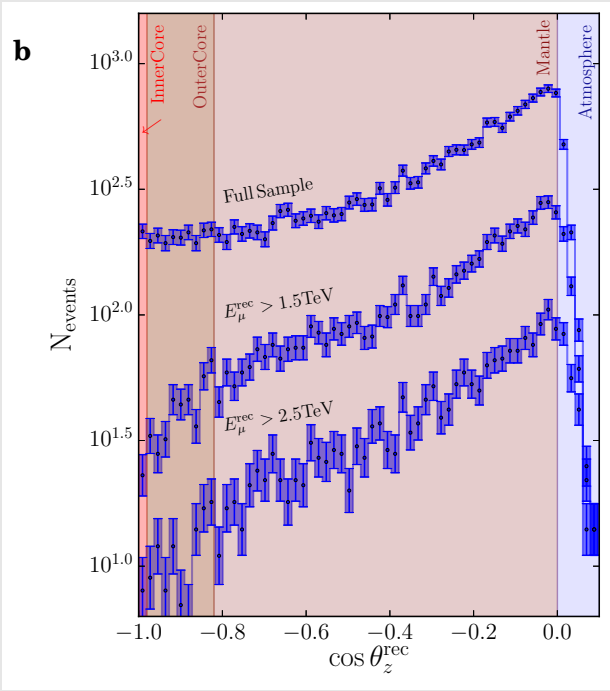
- We let the density free in 5 layers, 1-inner core, 2-outer core and 2-mantle.
- We propagate neutrinos with nuSQuIDS for every ρ_i
- We map the E_{real}, θ_{real} to E_{rec}, θ_{rec} using the official IceCube MC.



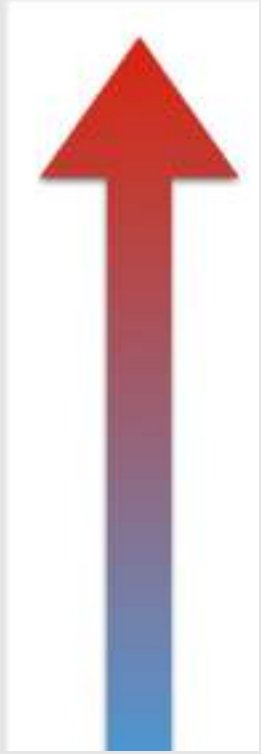
Statistics!

We did a standard binned maximum likelihood fit.

$$\log \mathcal{L}(\rho_1, \rho_2, \rho_3, \rho_4, \rho_5) = \min_{\vec{\theta},\{d\}} \left(\sum_{i=1}^{N_{bins}} \left[x_i \log \lambda_i(\vec{\theta}, d) - \lambda_i(\vec{\theta}, d) \right] + \sum_{\eta} \frac{(\theta_\eta - \Theta_\eta)^2}{\sigma_\eta^2} \right),$$

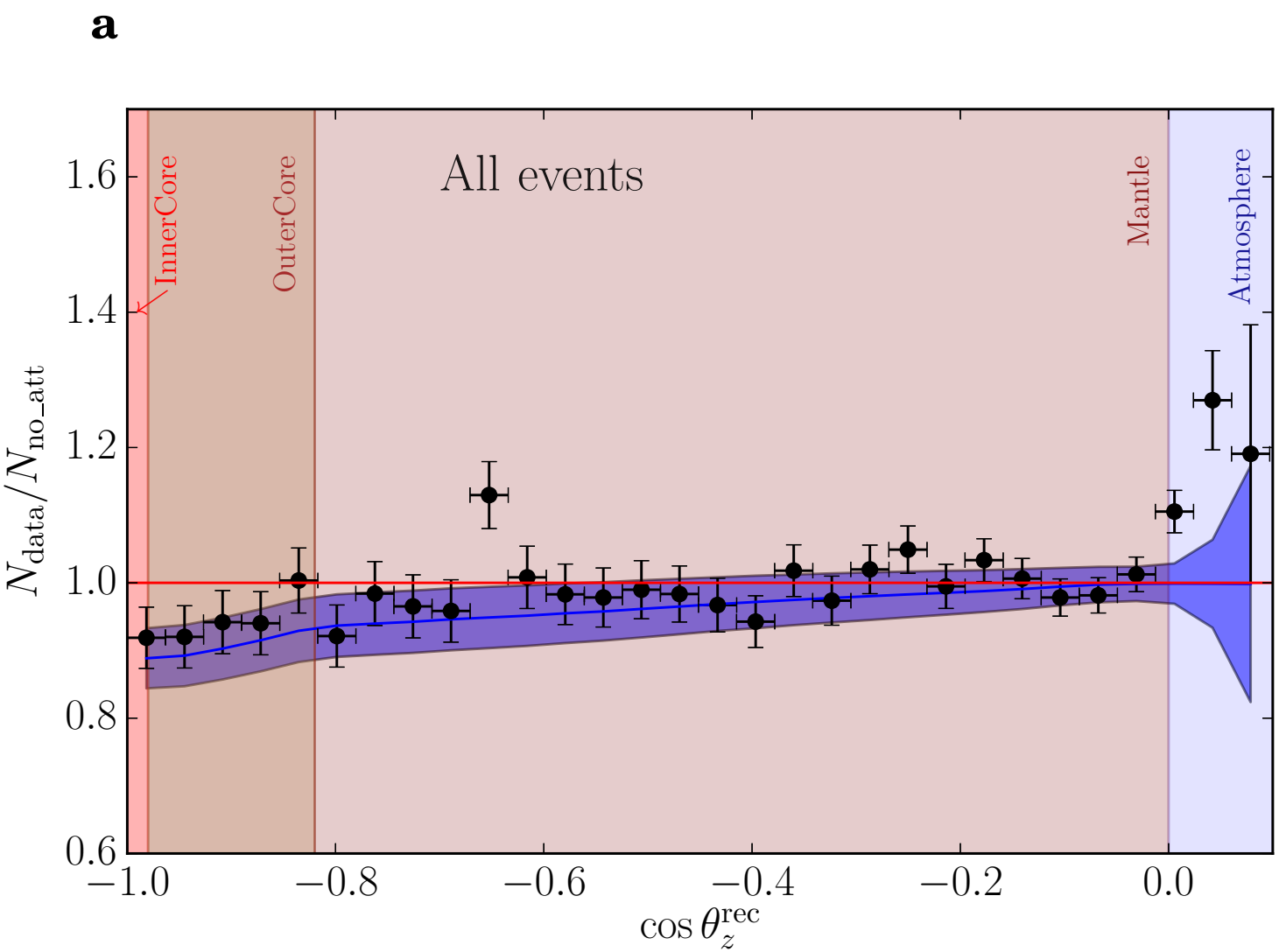


- *DOM efficiency*
- *Flux continuous parameters*
  - *spectral index*
  - *π/K ratio*
  - *$\nu/\bar{\nu}$ ratio* Full Implementation
- Air shower hadronic models Marginally irrelevant check
- Primary cosmic ray fluxes Marginally irrelevant check
- Neutrino cross sections Marginally irrelevant check
- Hole Ice Not included
- Bulk ice scattering/absorption Not Included

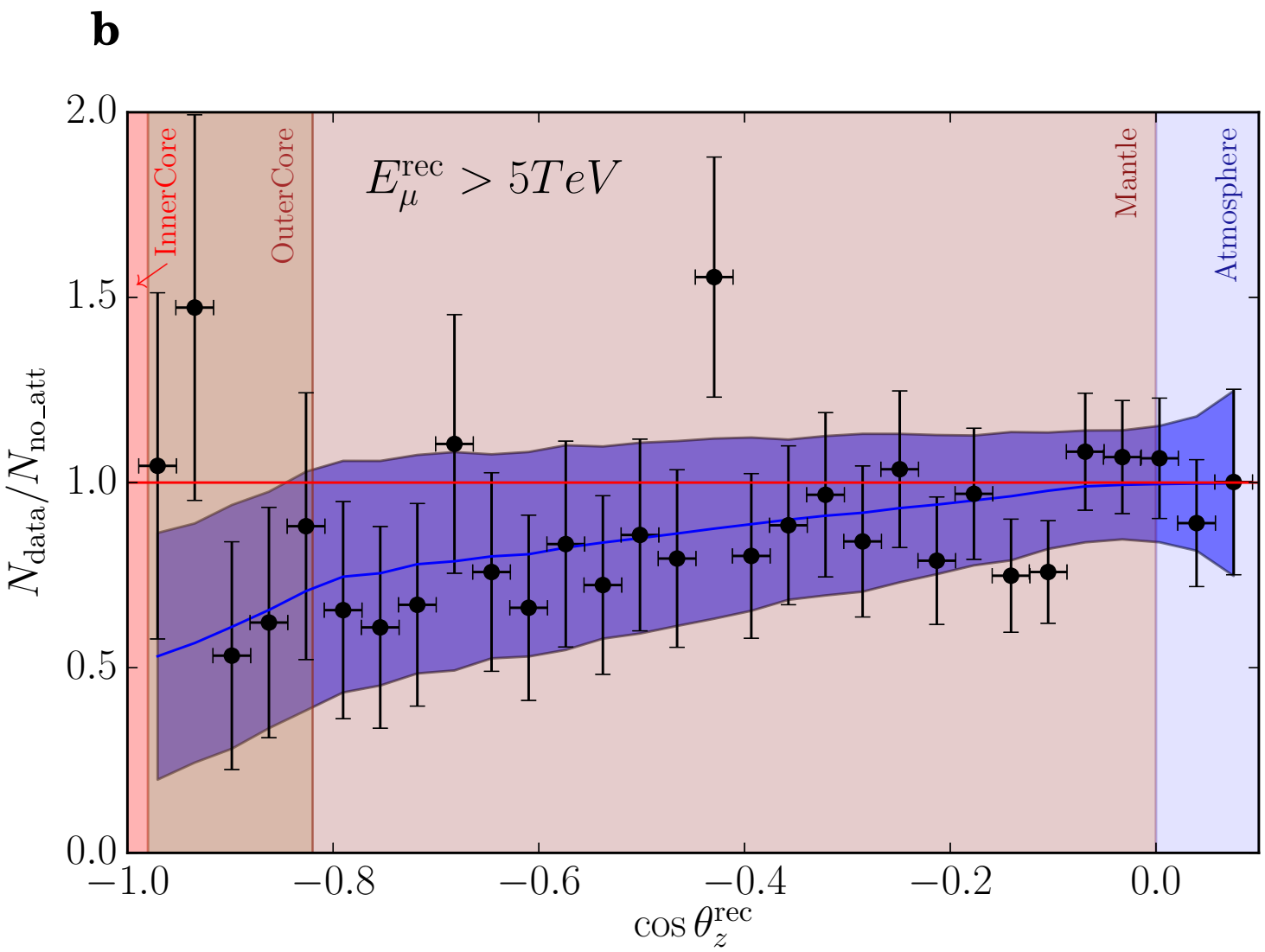


We use Multinest to perform a Bayesian inference for the systematic errors and $\{\rho_1, \rho_2, \rho_3, \rho_4, \rho_5\}$

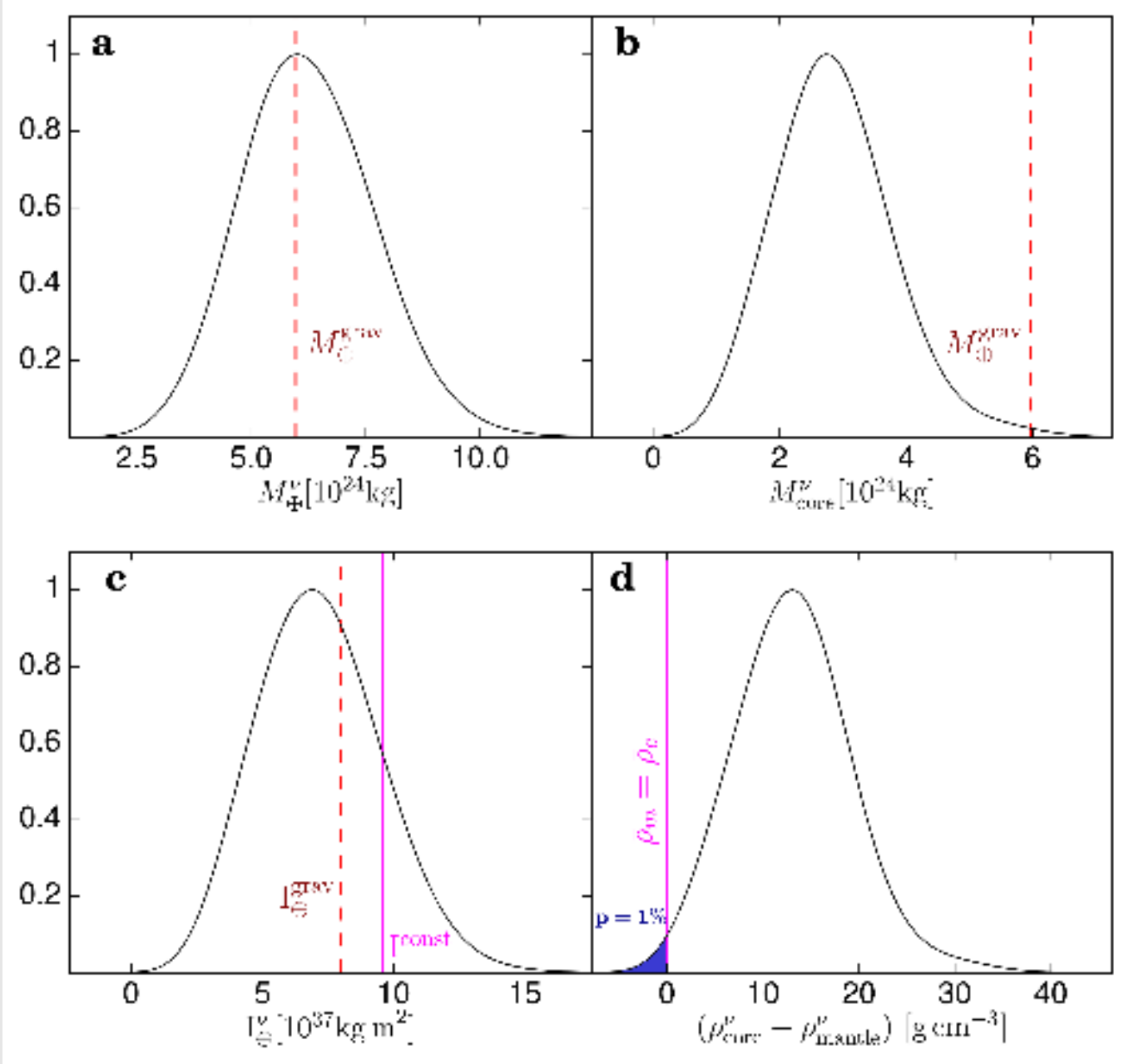
Is the earth there?



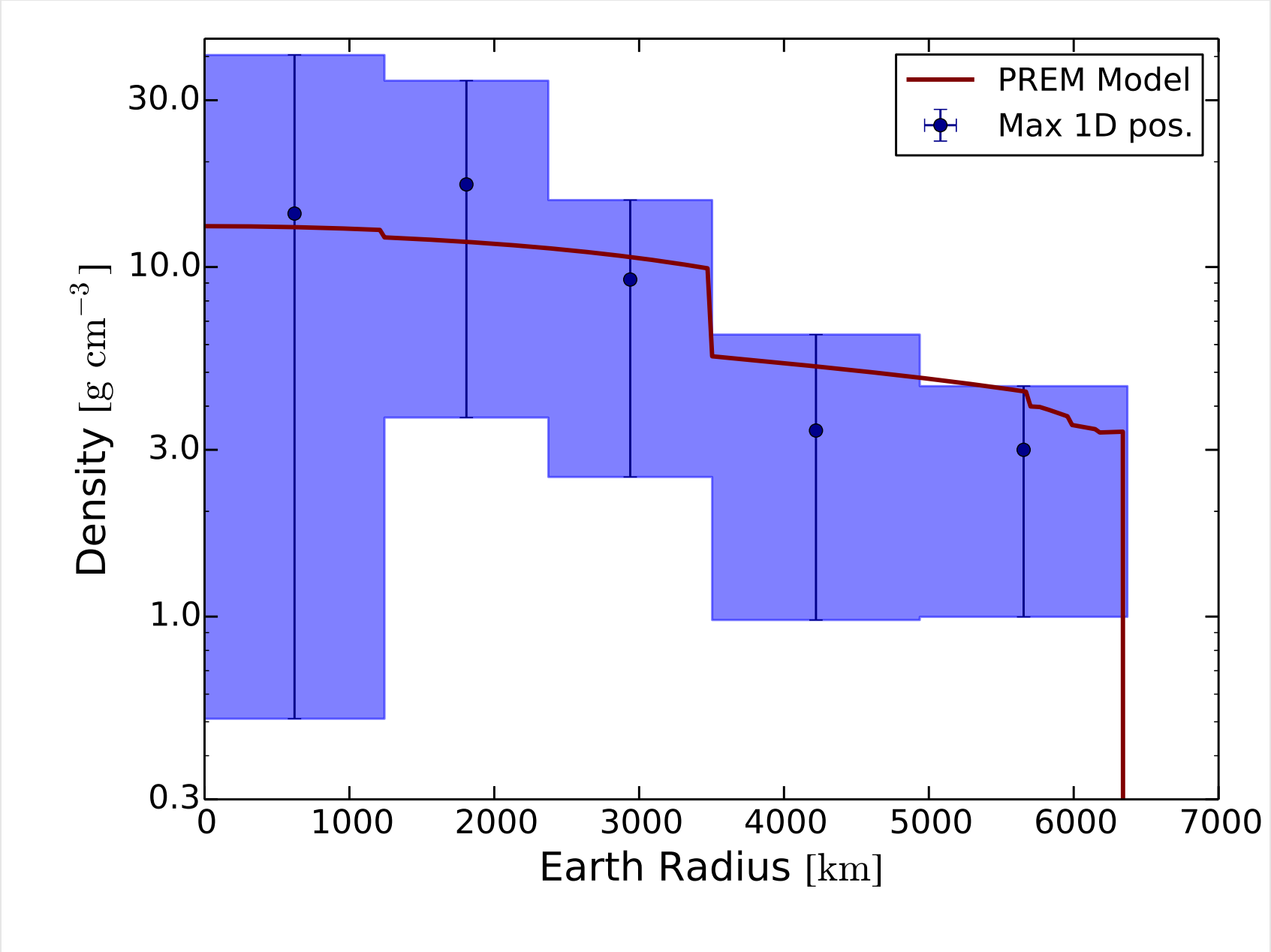
Is the earth there?



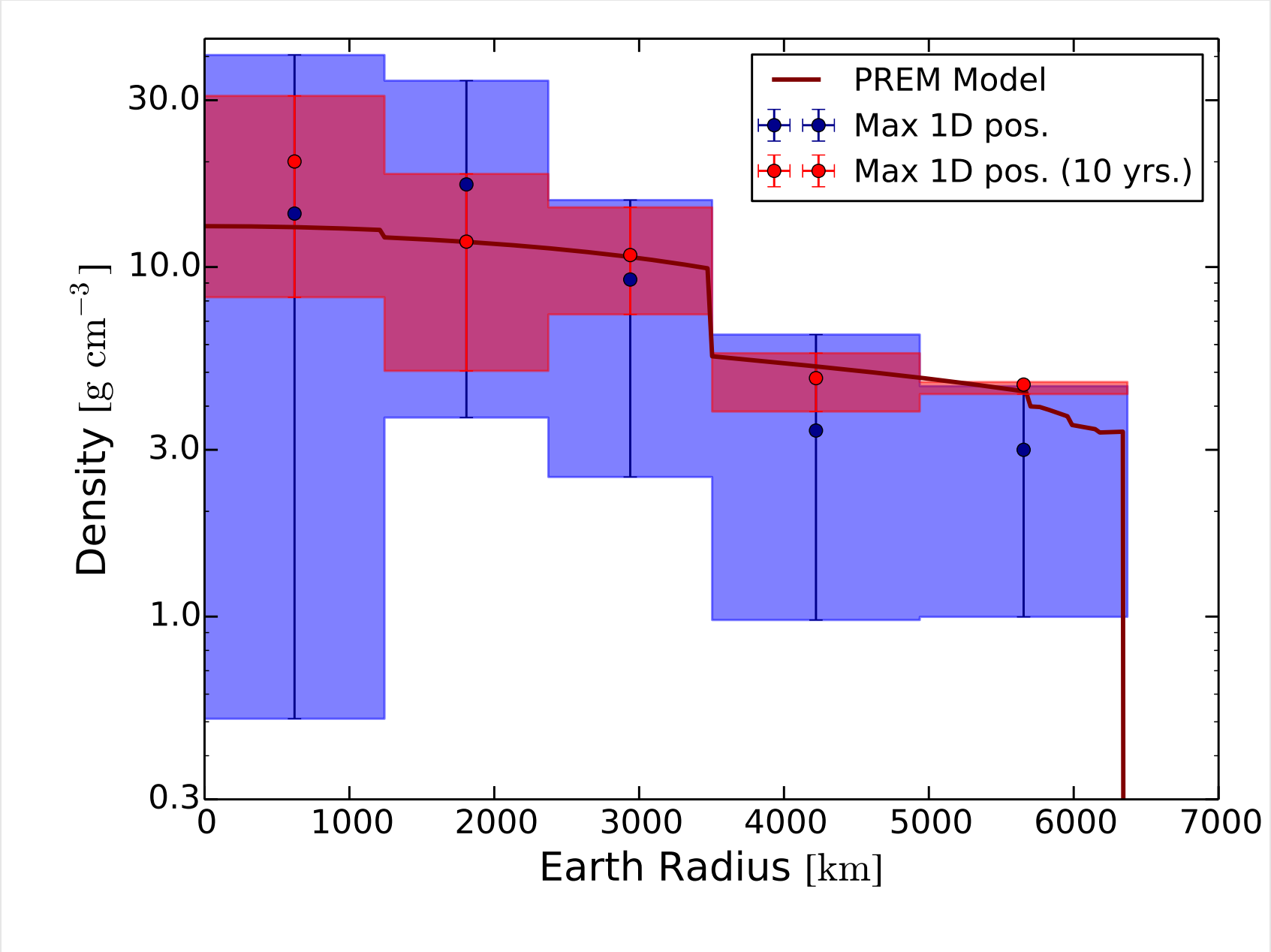
Posterior Probabilities for relevant parameters



Main result


PREM Model
Max 1D pos.
30.0
10.0
3.0
1.0
0.3
Density [g cm^{-3}]
0
1000
2000
3000
4000
5000
6000
7000
Earth Radius [km]

Main result


PREM Model
Max 1D pos.
Max 1D pos. (10 yrs.)
Density [g cm^{-3}]
30.0
10.0
3.0
1.0
0.3
0
1000
2000
3000
4000
5000
6000
7000
Earth Radius [km]

Conclusions

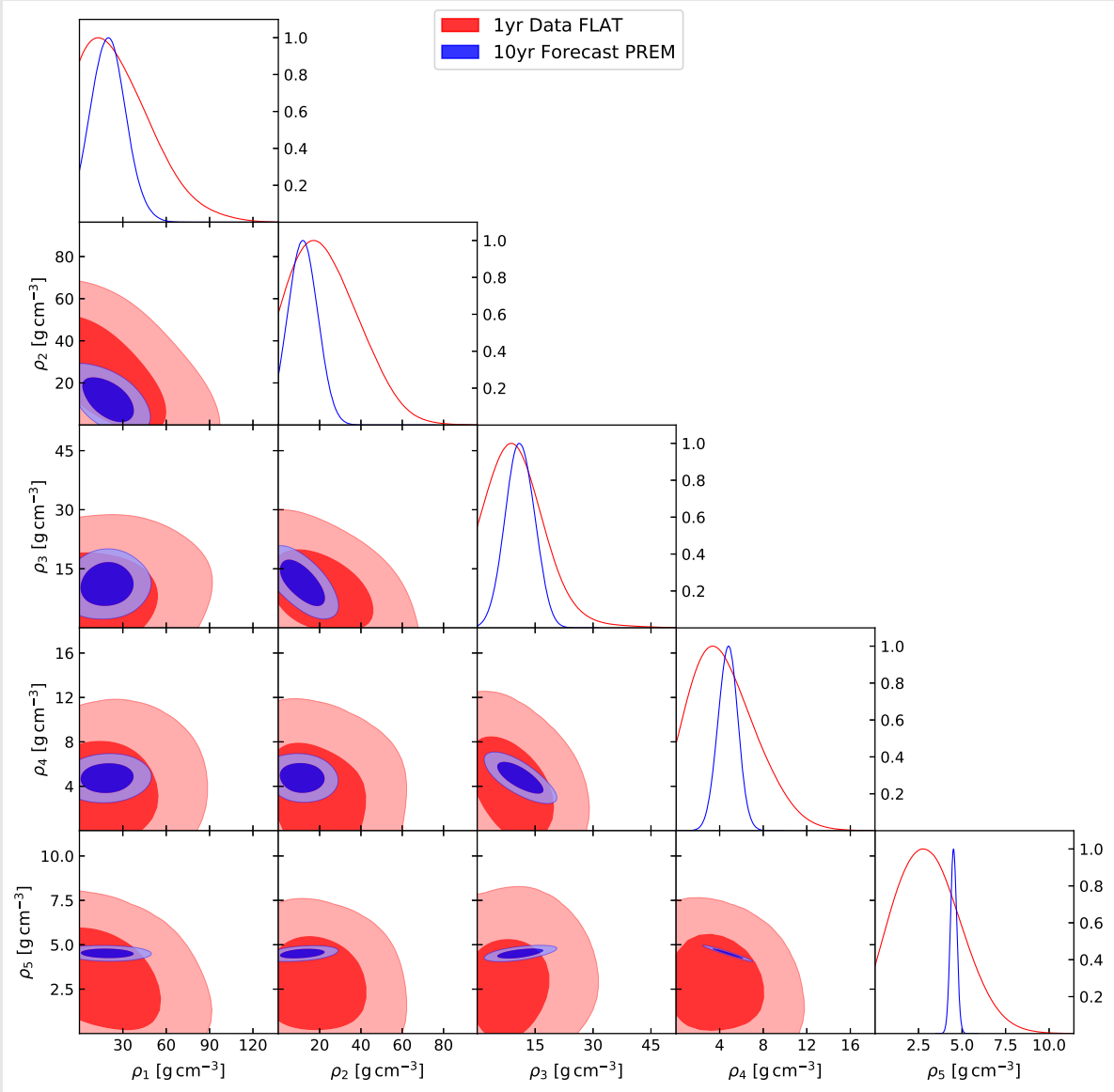
- We used one year of IceCube-86 data to do a tomography of the planet Earth.
- For the first time neutrinos give sensitive result measuring the earth and the density slope.
- As a tool to study the earth interior is complementary to seismology, allowing to explore the inner parts.
- The result is dominated by statistical errors and IceCube already collect more years of data.
- Other experiments such Antares, KM^3 may give an interesting complementary result from another point in the earth. Spherical core?, inner core?!?

Thanks!

BKP:

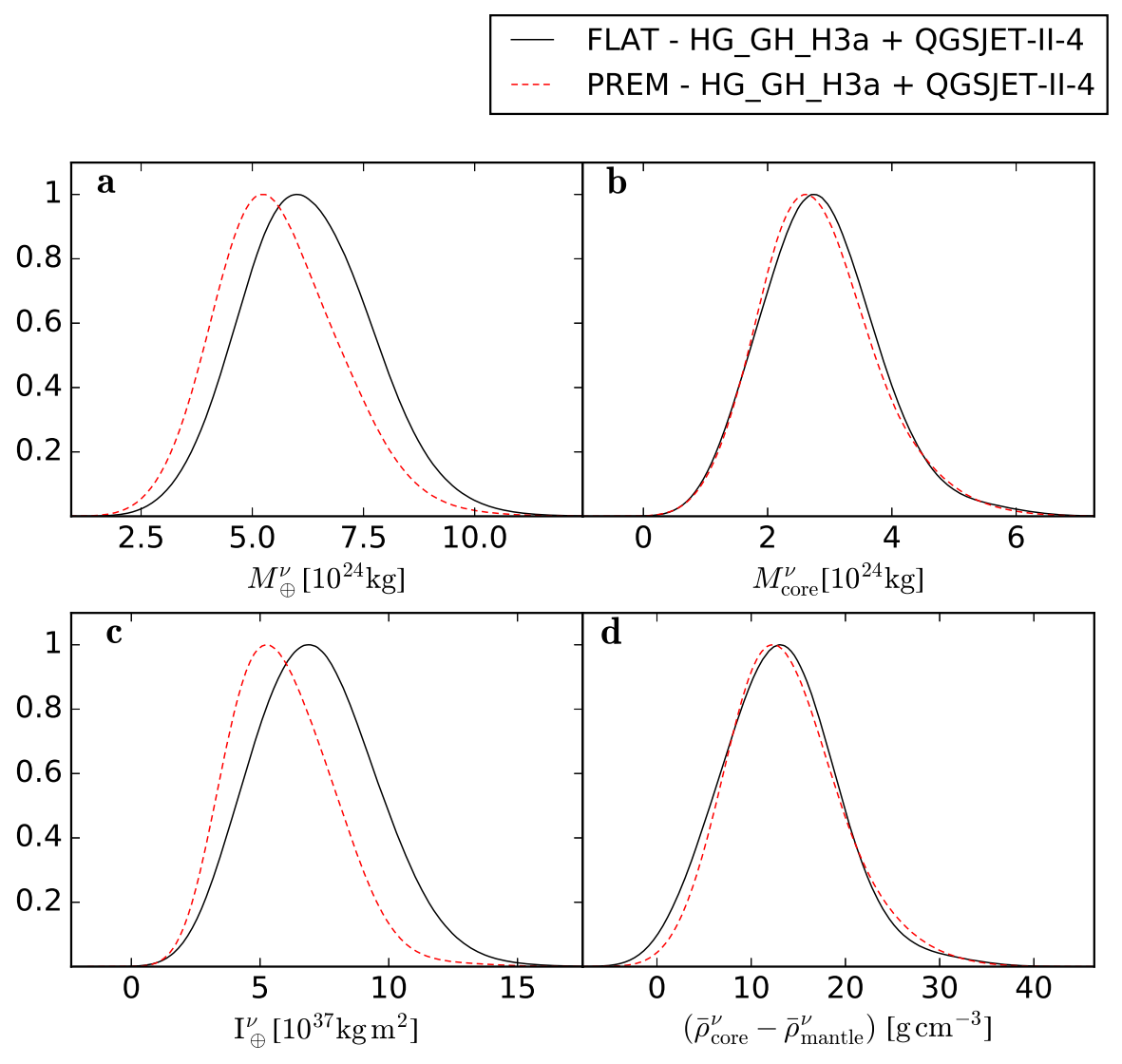
Forecast

- Soon IceCube will have 10yrs of data! what can we do?



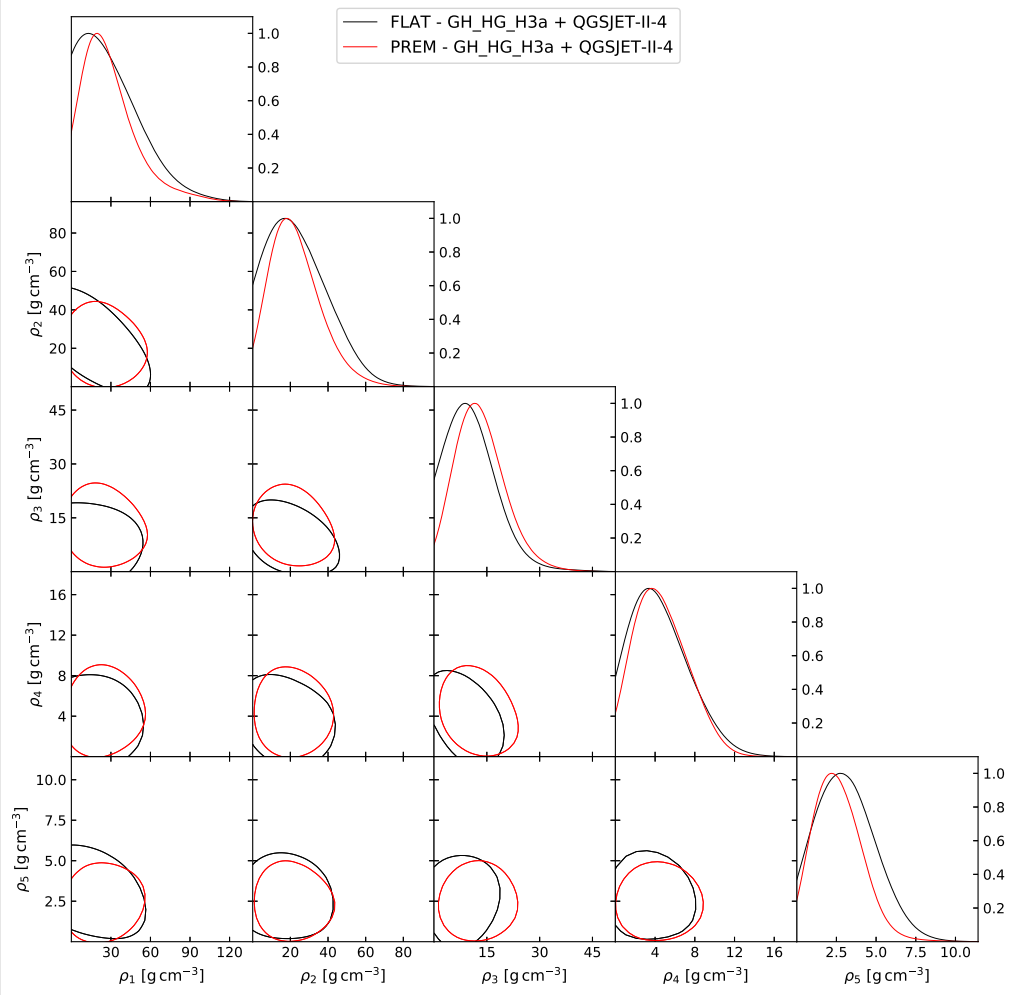
Checks!

- Is the assumption of constant density in the bins affecting the result?



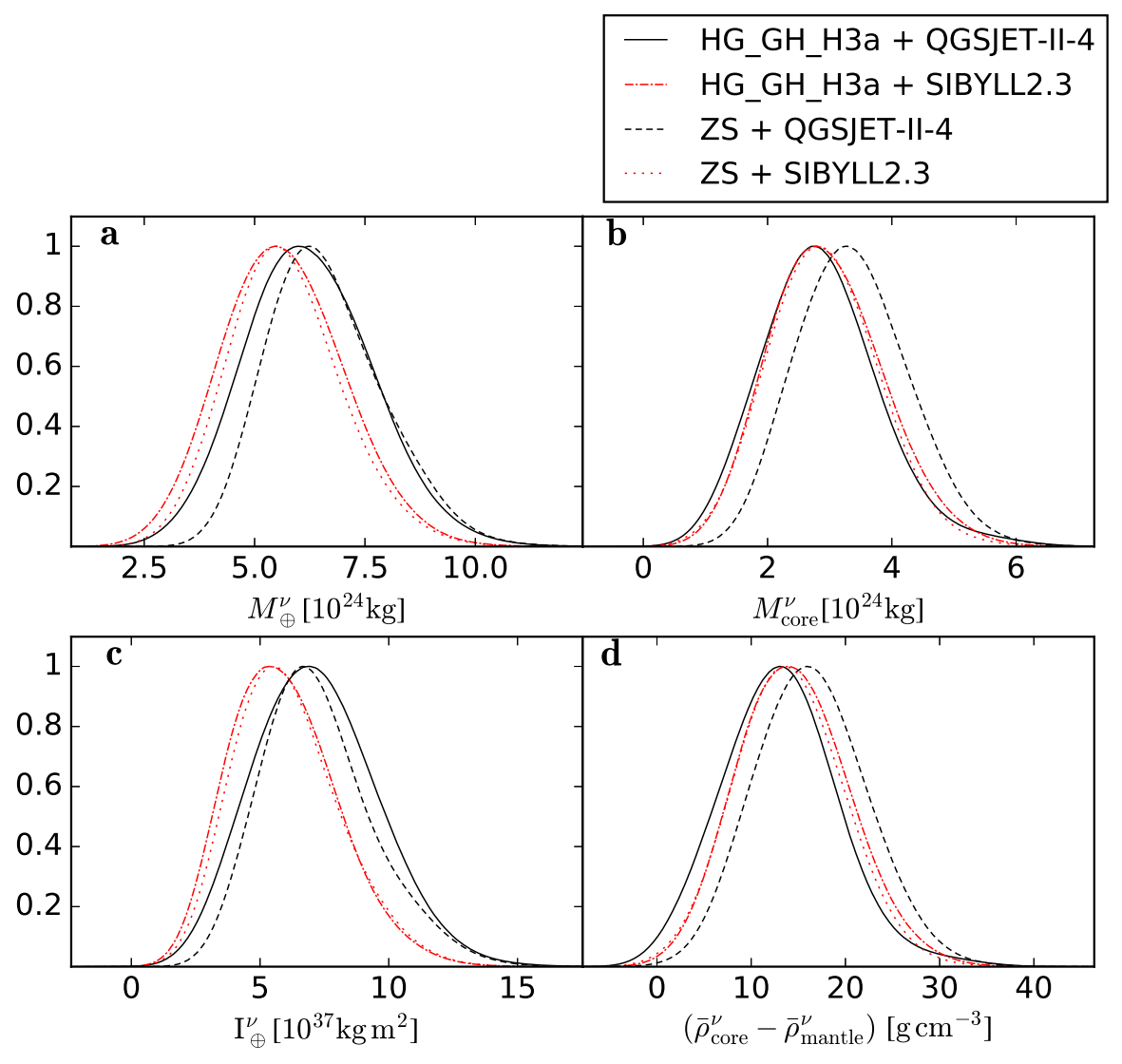
Checks!

- Is the assumption of constant density in the bins affecting the result? Not really



Checks!

- How it affects the initial flux, CR fluxes and Hadronic models?



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  also OK