Looking inside the Earth with neutrinos

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Particle & Astroparticle Physics

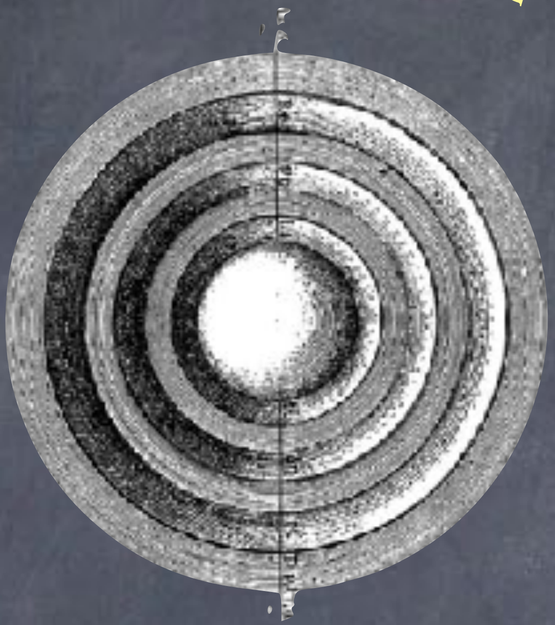
July 3, 2023

MINISTERIO DE CIENCIA E INNOVACIÓN

The Earth's interior: Early (crazy) ideas

First hypothesis based on observations: Hollow Earth

E. Halley, 1692



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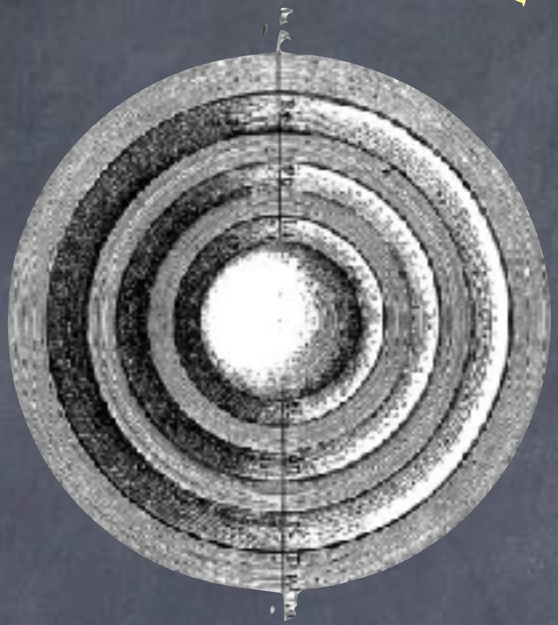

disproven by N. Maskelyne in 1774...

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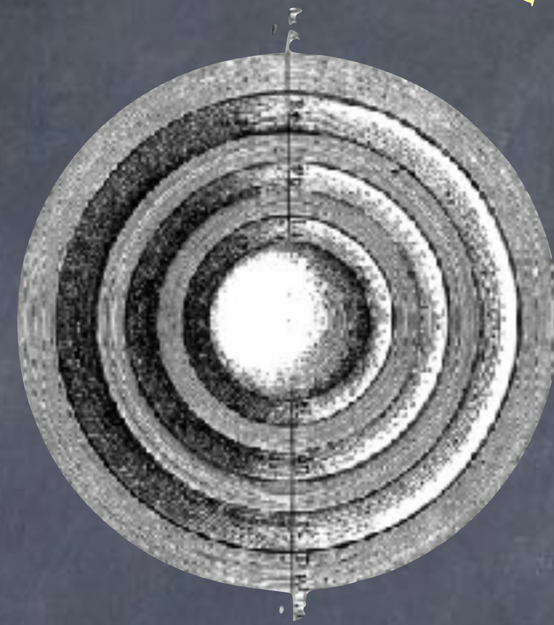

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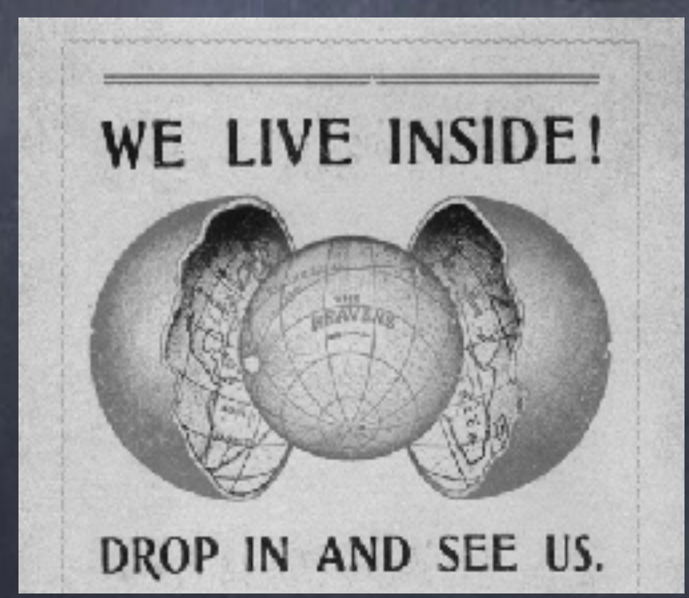

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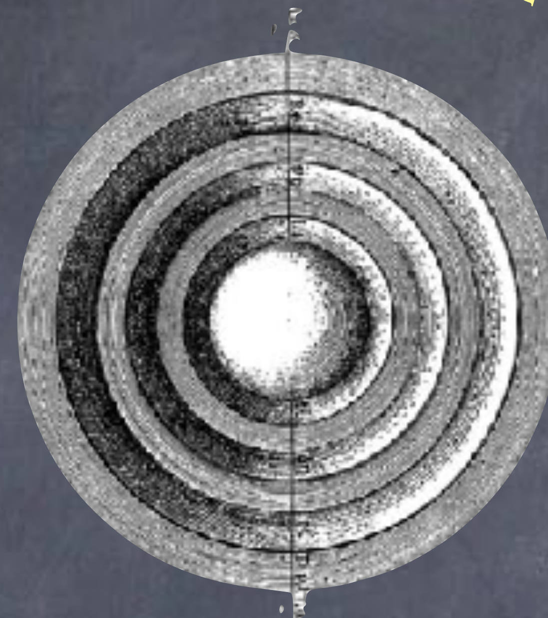

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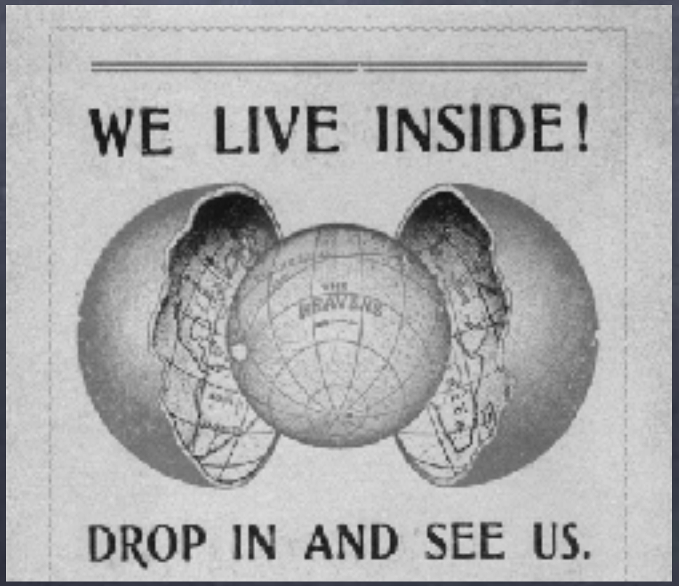

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GLOBE SHOWING SECTION OF THE EARTH'S INTERIOR

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

THE AUTHOR.

W. Reed, The phantom of the poles, 1906

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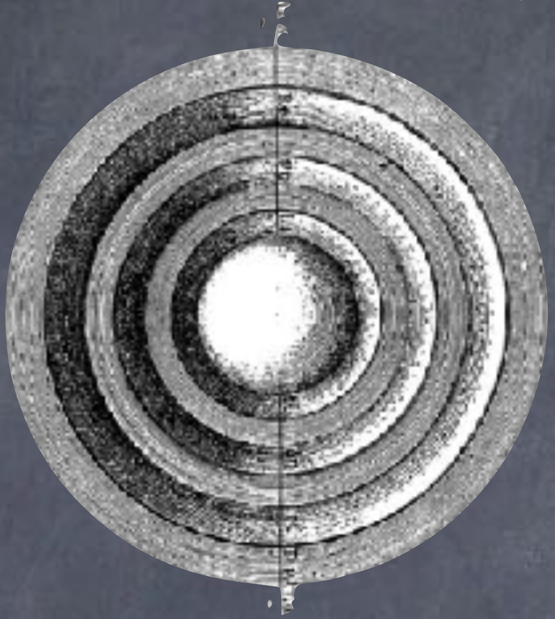

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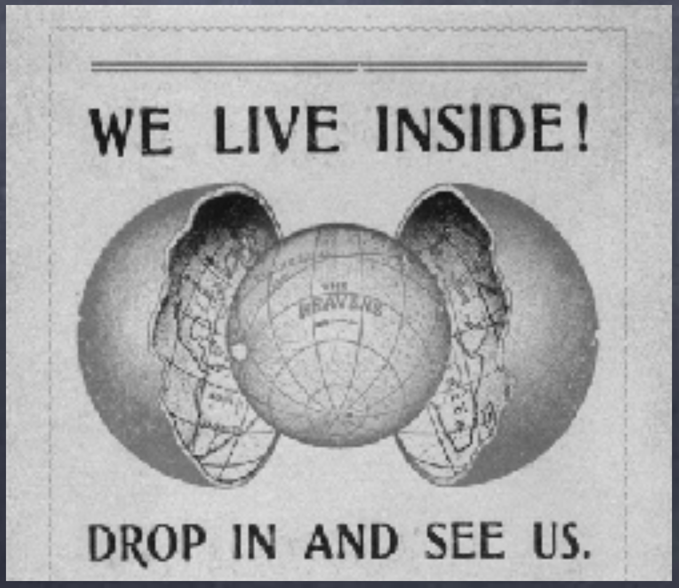


C. R. Teed, 1869

W. Reed, The phantom of the poles, 1906

The Earth's interior: The modern view

6371 km

iron solid

$\rho \approx (12.8-13.1)\ g/cm^3$

5130 km

iron liquid

$\rho \approx (9.9-12.2)\ g/cm^3$

2870 km

rock solid

$\rho \approx (4.4-5.6)\ g/cm^3$

660 km

rock solid-plastic-solid

$\rho \approx (3.4-4.4)\ g/cm^3$

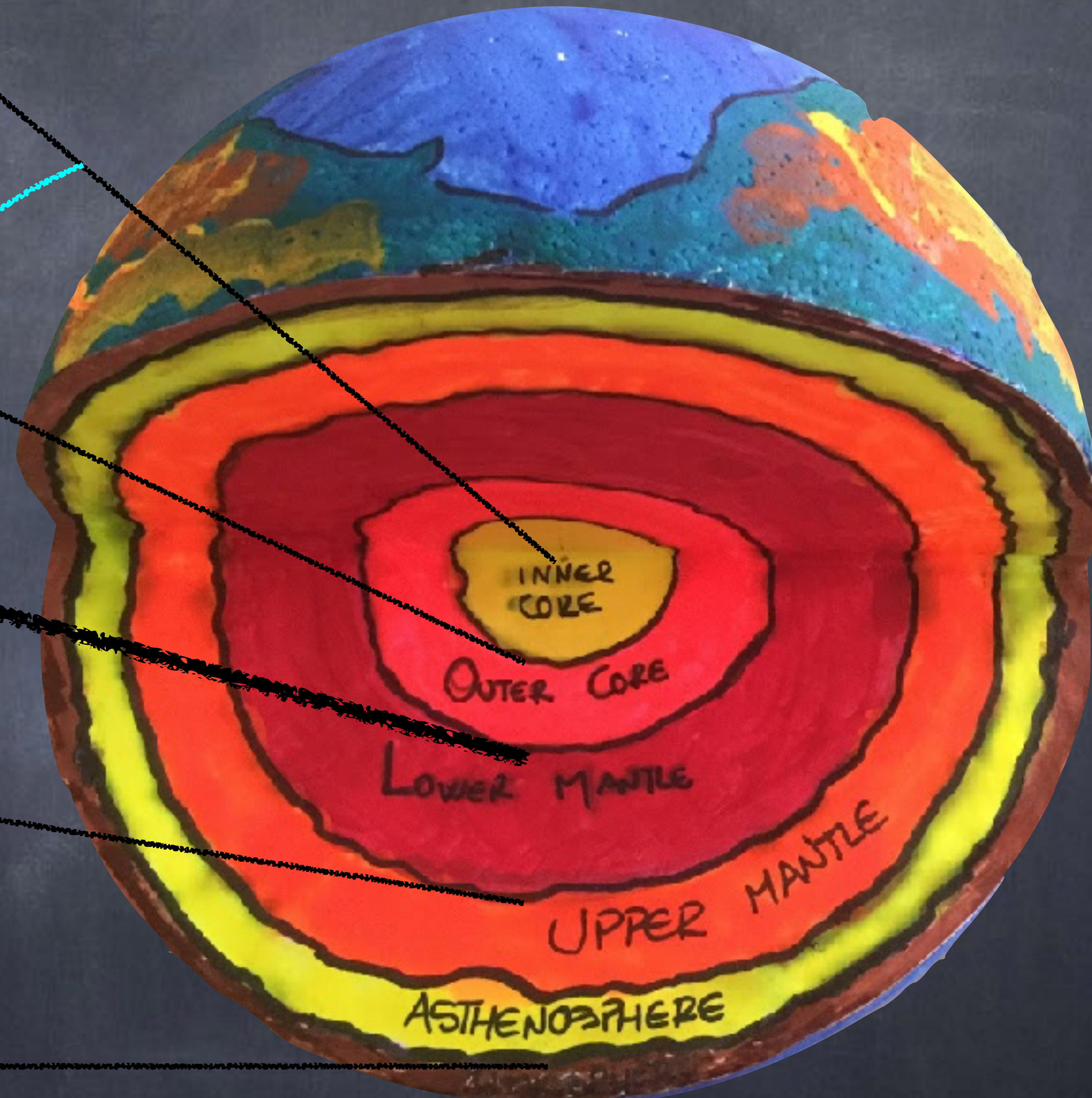
6-60 km

crust

$\rho \approx (2.2-2.9)\ g/cm^3$

core

mantle

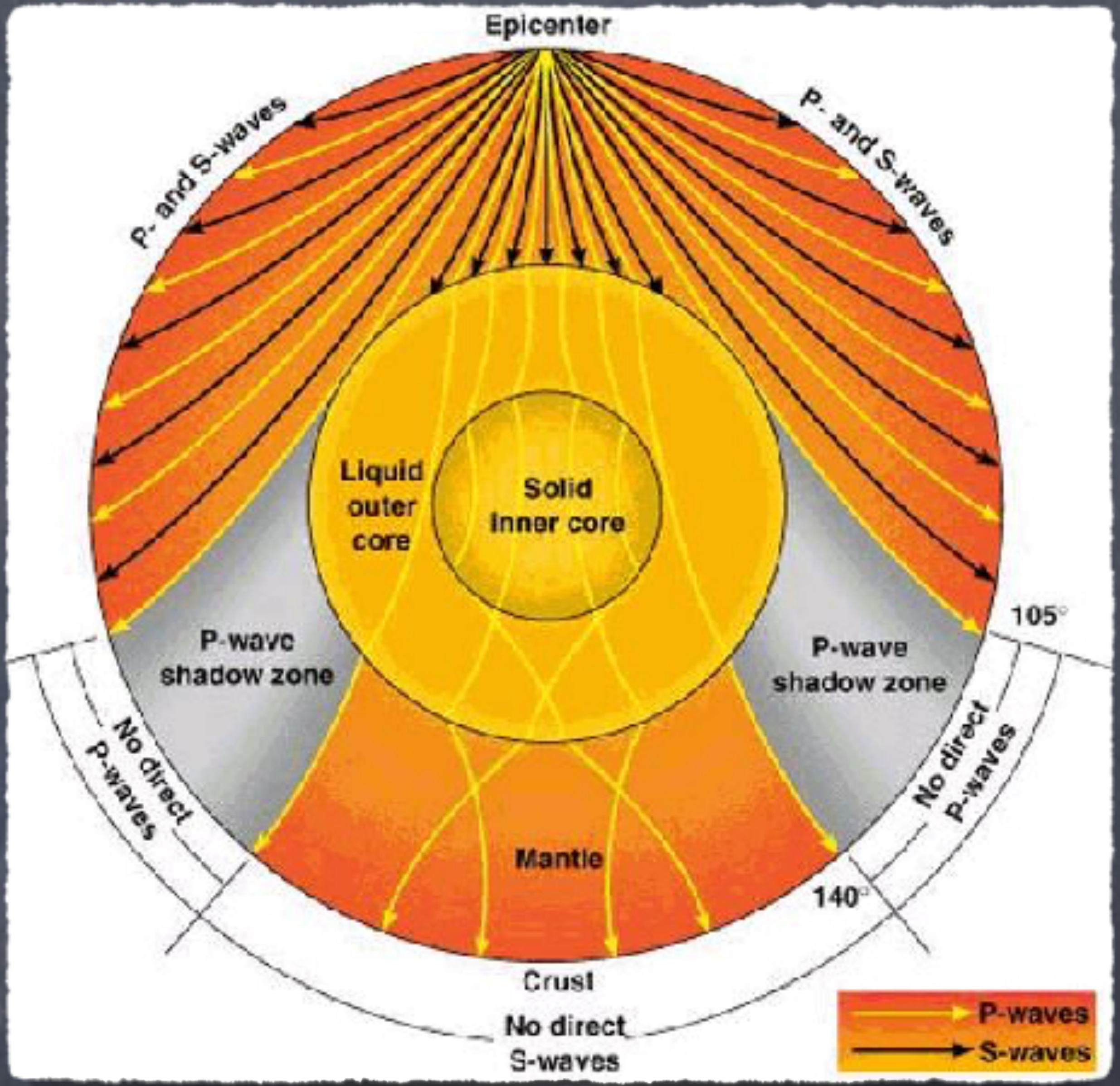


The Earth's interior: how is it inferred?

Earthquakes:

O(100/yr) with magnitude > 6

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



Seismic waves:

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

S-waves -> shear: travel through solids only

propagation depends on composition, temperature and pressure

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

GM: satellite laser ranging (SLR)

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

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

Measures the gravity field

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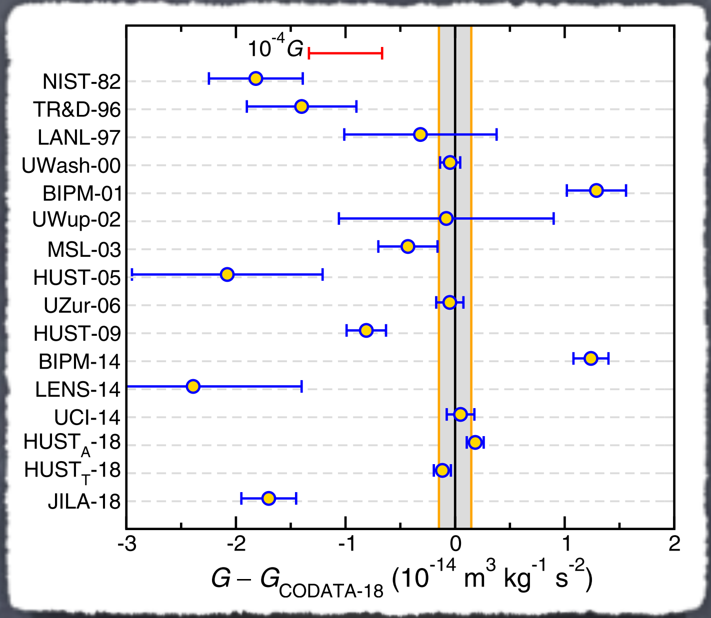
G: variations of the Cavendish experiment



$$G = 6.67430(15) \times 10^{-11}\ \mathrm{kg^{-1}\,m^3\,s^{-2}}$$

E. Tiesinga, P. J. Mohr, D. B. Newell and B. N. Taylor, CODATA-2018, Rev. Mod. Phys. 93:025010, 2021

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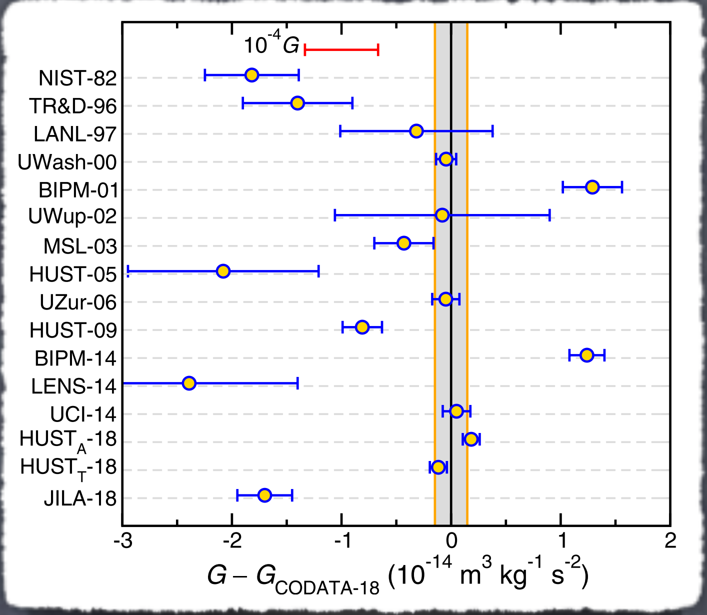

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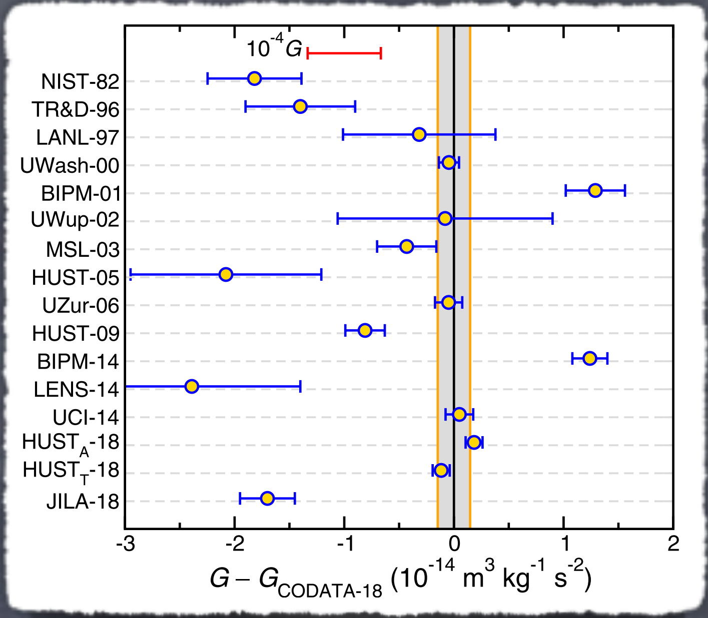

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Earth gravity model: terrestrial, altimetry-derived and airborne gravity data

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

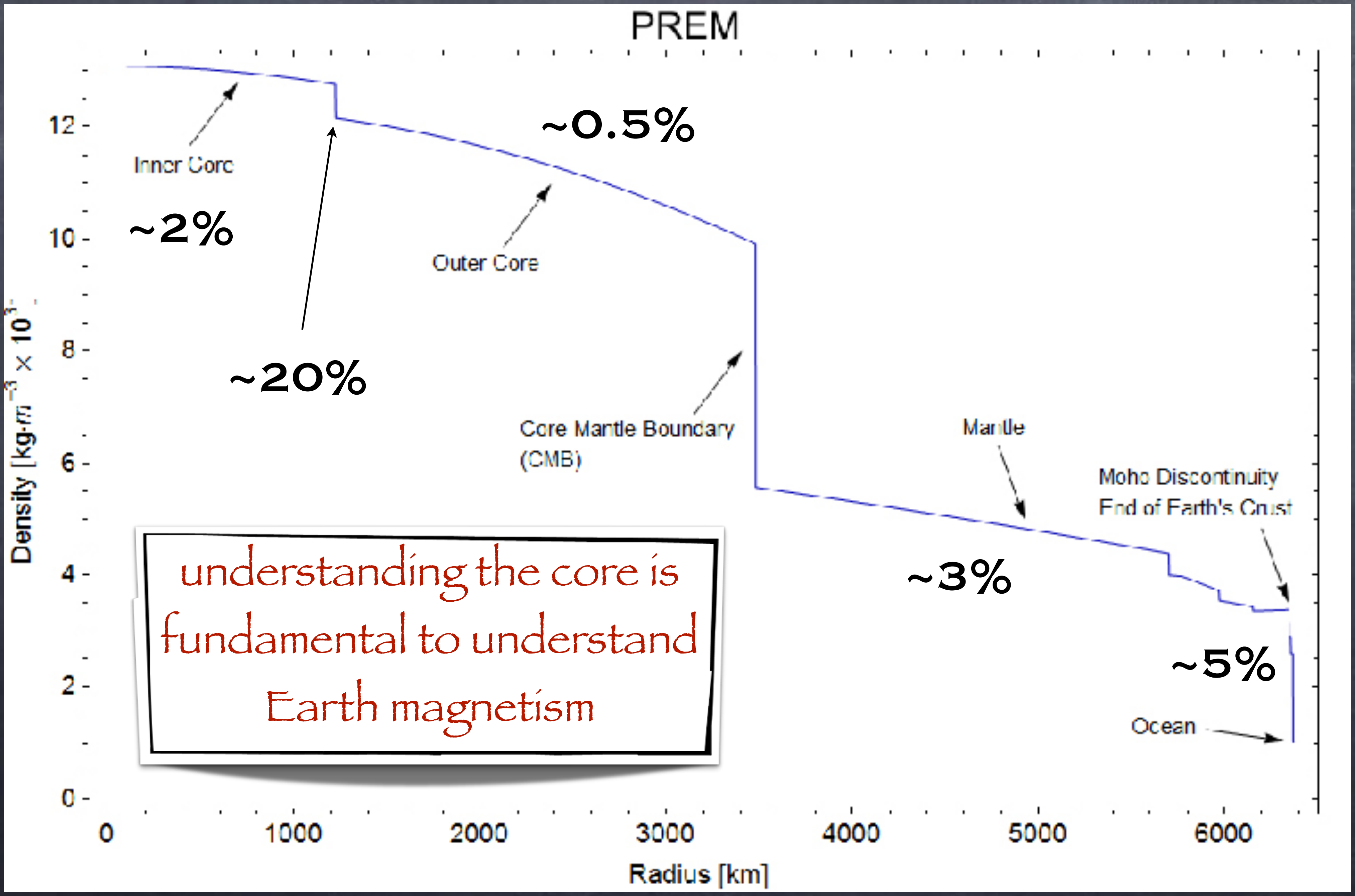
W. Chen et al., J. Geod. 89:179, 2015

Preliminary reference Earth Model (PREM)

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

1-D density profile

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



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

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Yes!

Weak interactions: Neutrinos!

Different ways to study the Earth's interior with neutrinos

Detecting neutrinos produced inside the Earth

Geoneutrinos:

produced by the decay of radioactive isotopes inside the Earth, sensitive to the heat power of the Earth

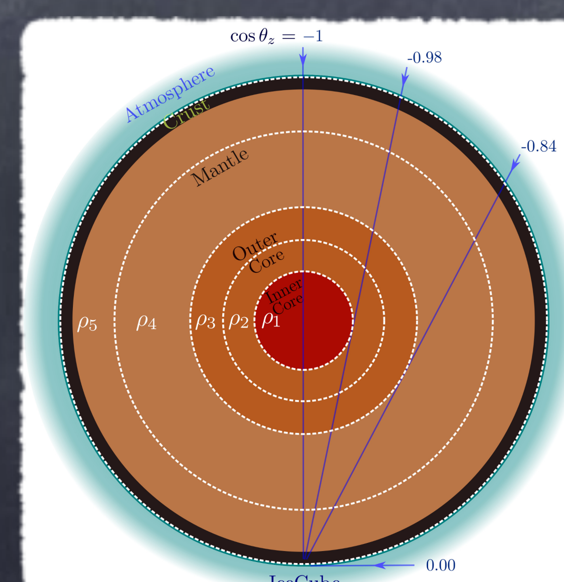
© Sandbox Studio, Chicago

first proposed by G. Eder in 1965
first detected by KamLAND in 2005

Searching for distortions on the spectra of (external) neutrino fluxes

Neutrino tomography:

inelastic scattering (absorption) or elastic forward scattering (refraction), sensitive to the Earth's density profile
(and, although technologically unfeasible, neutrino diffraction)

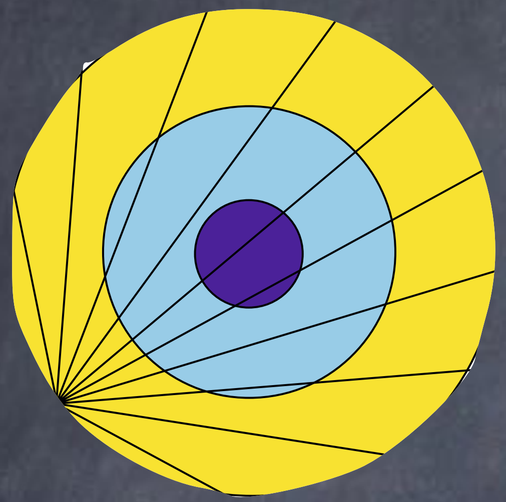


first proposed in a CERN report in October 1973 and also in a talk in 1974

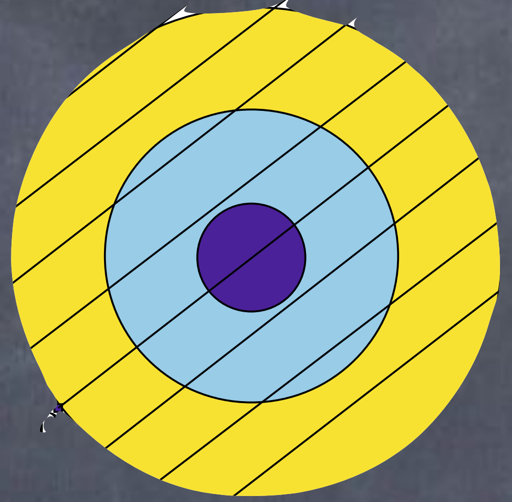
first performed in 2018 (with IceCube data)

Neutrino Earth tomography: approaches

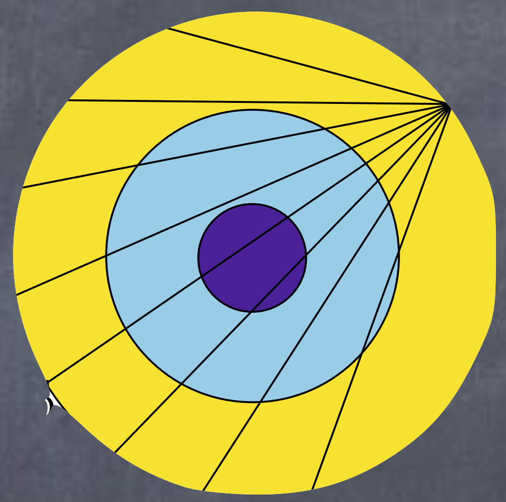
(quasi) isotropic flux



neutrino beam



astrophysical point source



oscillation tomography

Coherent effect in neutrino propagation

$E_\nu < 100$ GeV

sensitive to electron density

Neutrino oscillations in matter:
extra effective potential in the hamiltonian

distortion of the energy and angular spectrum per flavor, but the total neutrino flux remains unaffected

absorption tomography

Incoherent effect in neutrino propagation

$E_\nu >$ TeV

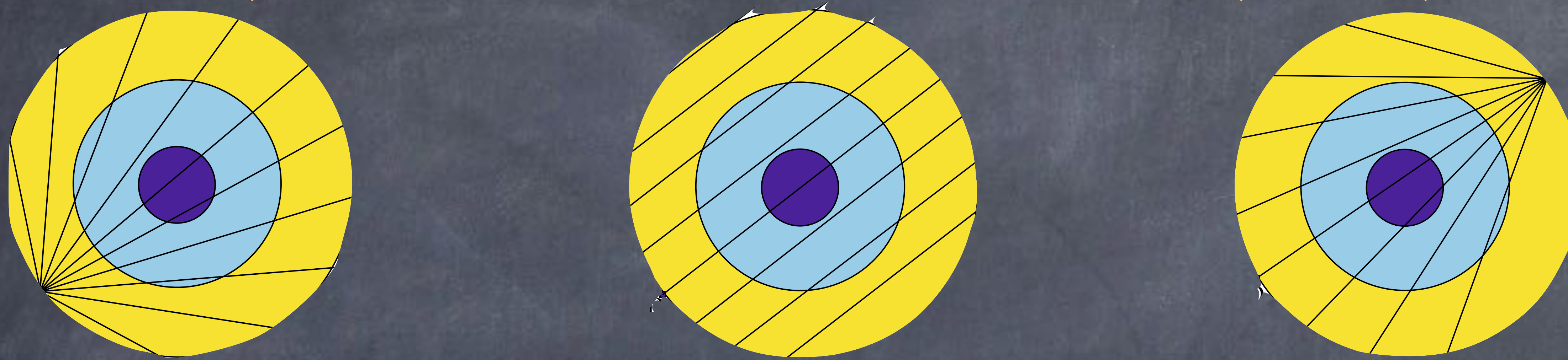
sensitive to nucleon density

$$\frac{d\phi_\nu(E_\nu,x)}{dx} \approx -n(x)\,\sigma(E_\nu)\,\phi_\nu(E_\nu,x)$$

absorption of the flux depending on direction (traversed column density) and energy

Neutrino Earth tomography: approaches

(quasi) isotropic flux | neutrino beam | astrophysical point source



oscillation tomography | **absorption tomography**

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

Man-made beams
V. K. Ermilova, V. A. Tsarev and V. A. Chechin, JETP Lett. 43:453, 1986

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

Supernova neutrinos
M. Lindner, T. Ohlsson, R. Tomàs and W. Winter, Astropart. Phys. 19:755, 2003

Cosmic neutrinos (diffuse flux)
P. Jain, J. P. Ralston and G. M. Frichter, Astropart. Phys. 12:193, 1999

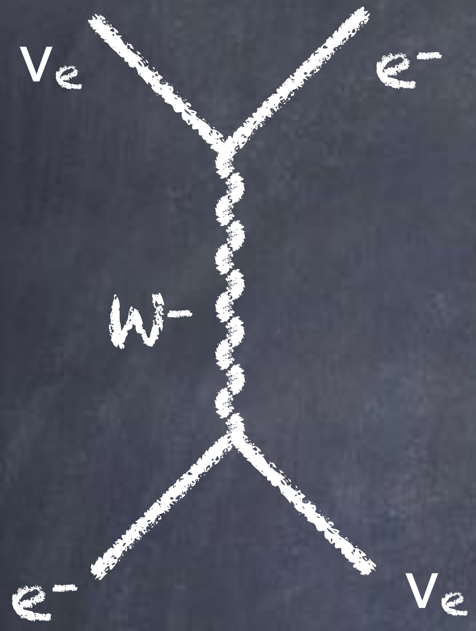
Atmospheric neutrinos
M. C. González-García, F. Halzen, M. Maltoni and H. K. M. Tanaka, Phys. Rev. Lett. 100:061802, 2008

Man-made beams
A. Placci and E. Zavattini, CERN report 1973… but never published
L. V. Volkova and G. T. Zatsepin, Izv. Nauk Ser. Fiz. 38N5:1060, 1974

Cosmic neutrinos (point sources)
T. L. Wilson, Nature 309:38, 1984

Neutrino Earth tomography: Matter effects

Propagation through matter induces a phase in the neutrino wave function



index of refraction

$$\text{Amplitude} \simeq e^{iEnL}$$

$$n \simeq 1 + 2\pi N f(0)/E^2 \simeq 1 + V/E$$

coherent forward scattering

$$E\, \mathrm{Re}(\Delta n) \propto N\, \mathrm{Re}\, f(0) / E$$

$$\mathrm{Re}\, f(0) \propto G_F$$

incoherent process

optical theorem $[4\pi\, \mathrm{Im}\, f(0) / E = \sigma]$

Absorption: $E\, \mathrm{Im}(\Delta n) \propto N \sigma$

$$\sigma \propto G_F^2$$

Neutrino matter effects

tiny Δn: a matter of scales

coherent forward scattering

$$\frac{\Delta m^2_{21}}{4\,\pi\,E_\nu\,(100\text{ MeV})} \sim \frac{\Delta m^2_{31}}{4\,\pi\,E_\nu\,(\text{GeV})} \sim V_\oplus \sim R_\oplus^{-1}$$

absorption

$$\sigma \sim \frac{G_F^2\, s}{\pi} \sim 10^{-38}\left(\frac{E_\nu}{\text{GeV}}\right)\text{cm}^2 \qquad n\,\sigma \sim \left(\frac{E_\nu}{40\text{ TeV}}\right) R_\oplus^{-1}$$

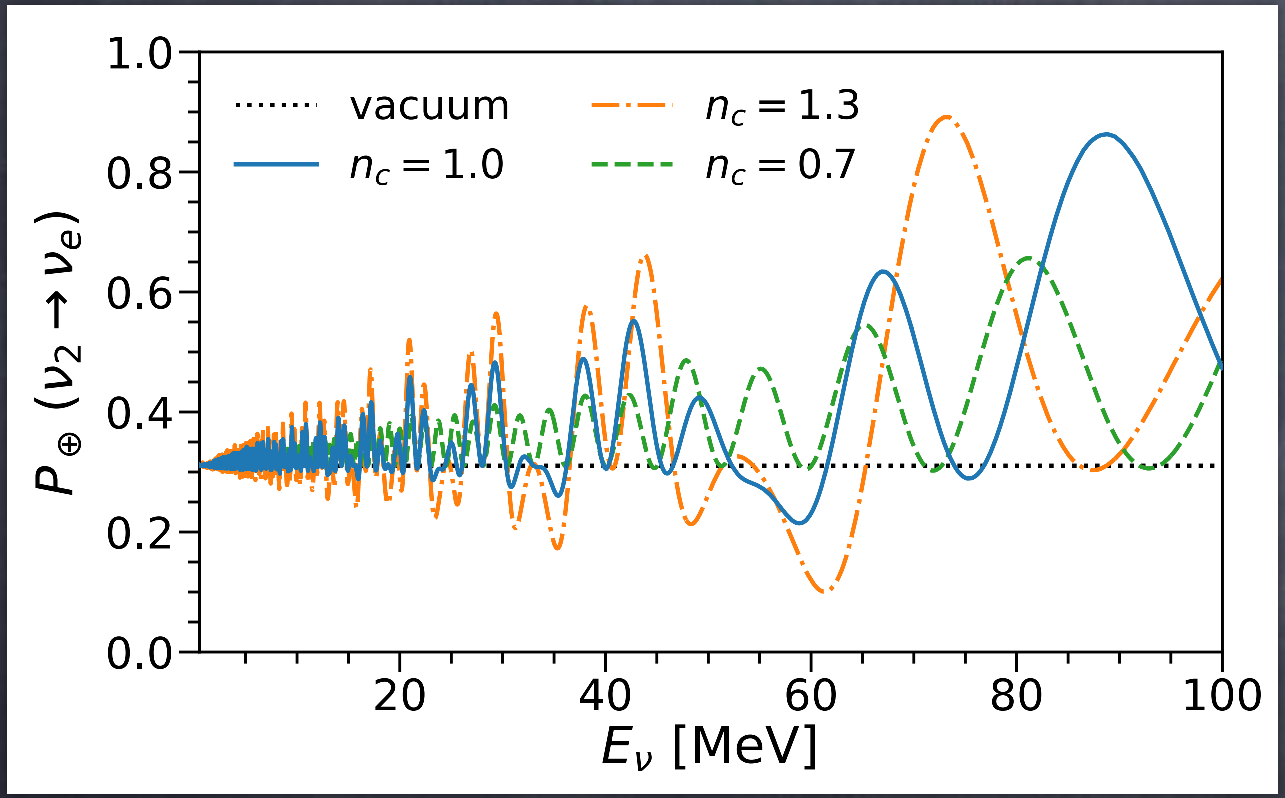
Neutrino oscillation tomography

3-neutrino problem simplifies to 2-neutrino problem as the two mass-square differences are separated

T. K. Kuo and J. Pantaleone, Phys. Rev. Lett. 57:1805, 1986

Δm^2_{21} – driven matter effect

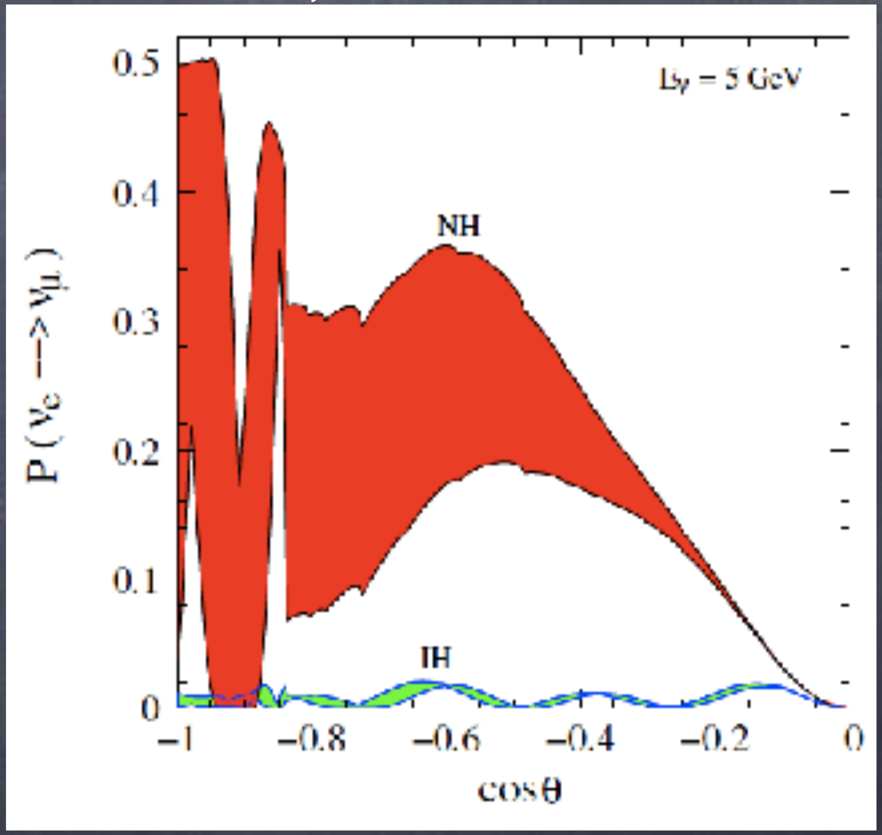
(solar and supernova neutrinos)



R. Hajjar, O. Mena and SPR, arXiv:2303.09369

Δm^2_{31} – driven matter effect

(atmospheric neutrinos)

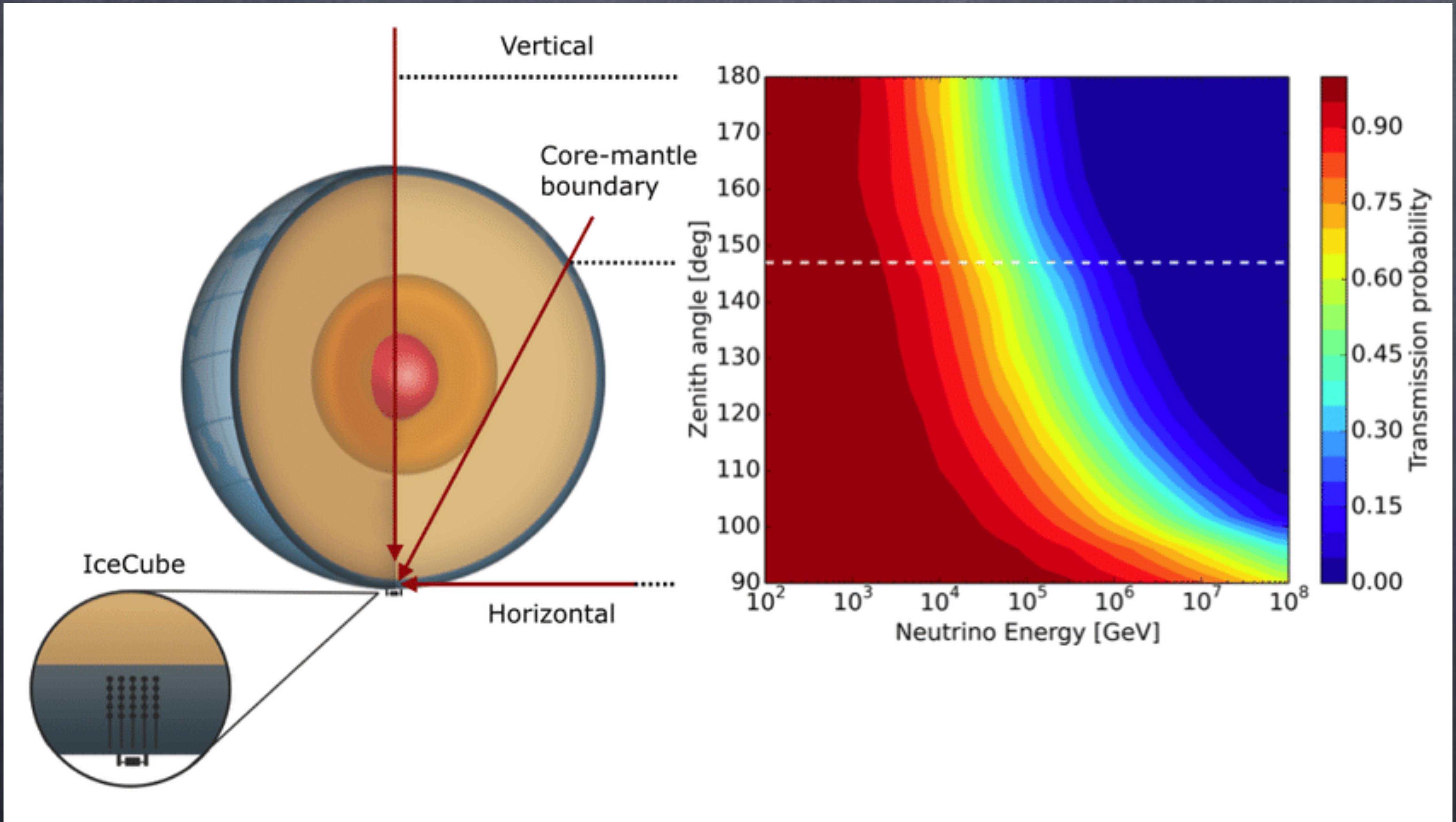


S. K. Agarwalla, T. Li, O. Mena and SPR, arXiv:1212.2238

Matter effect can be resonant for different directions and energies

Neutrino absorption tomography

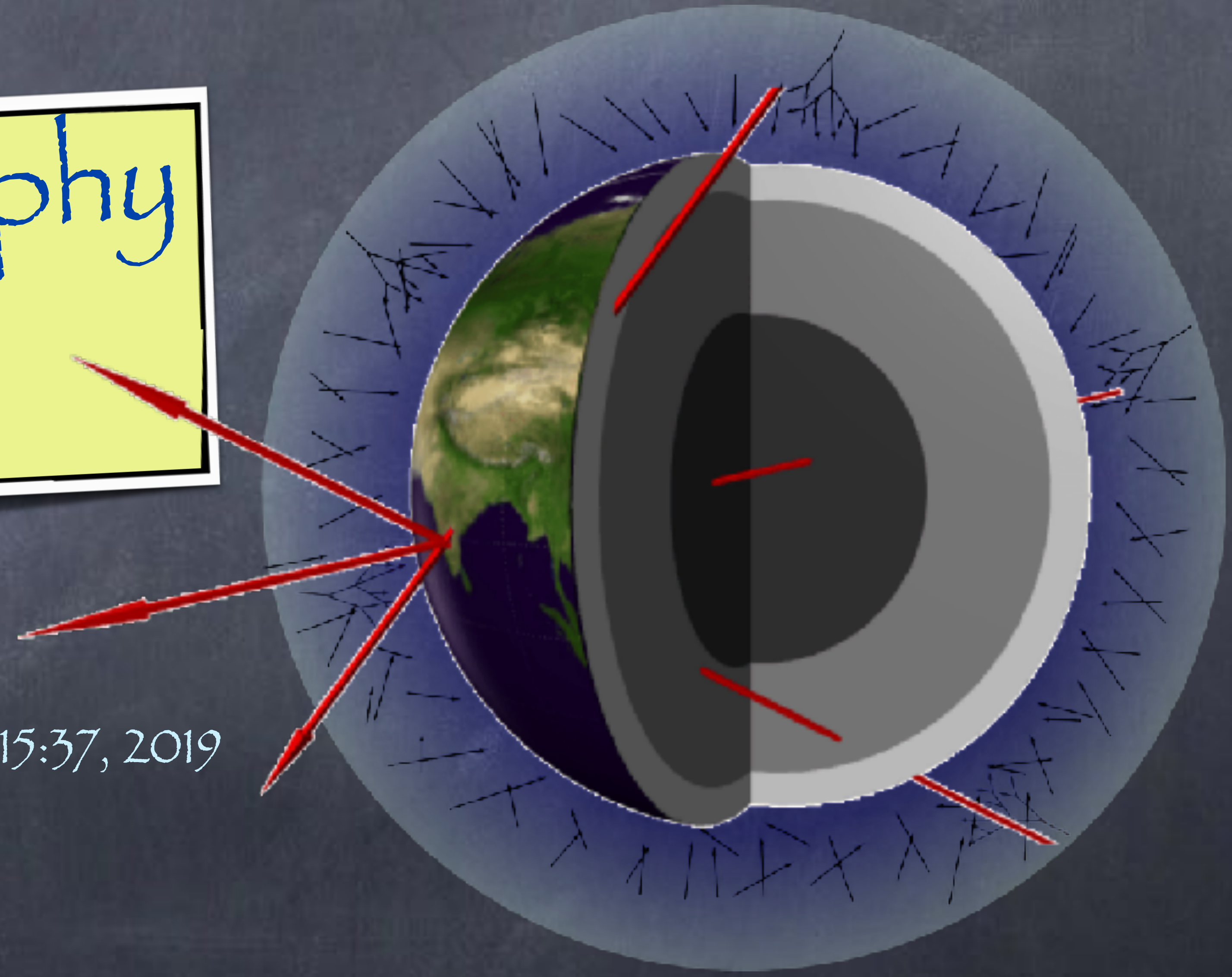
Different flux absorption for different directions and energies
(atmospheric and cosmic neutrinos)



M. G. Aartsen et al. [IceCube Collaboration], Nature 551:596, 2017

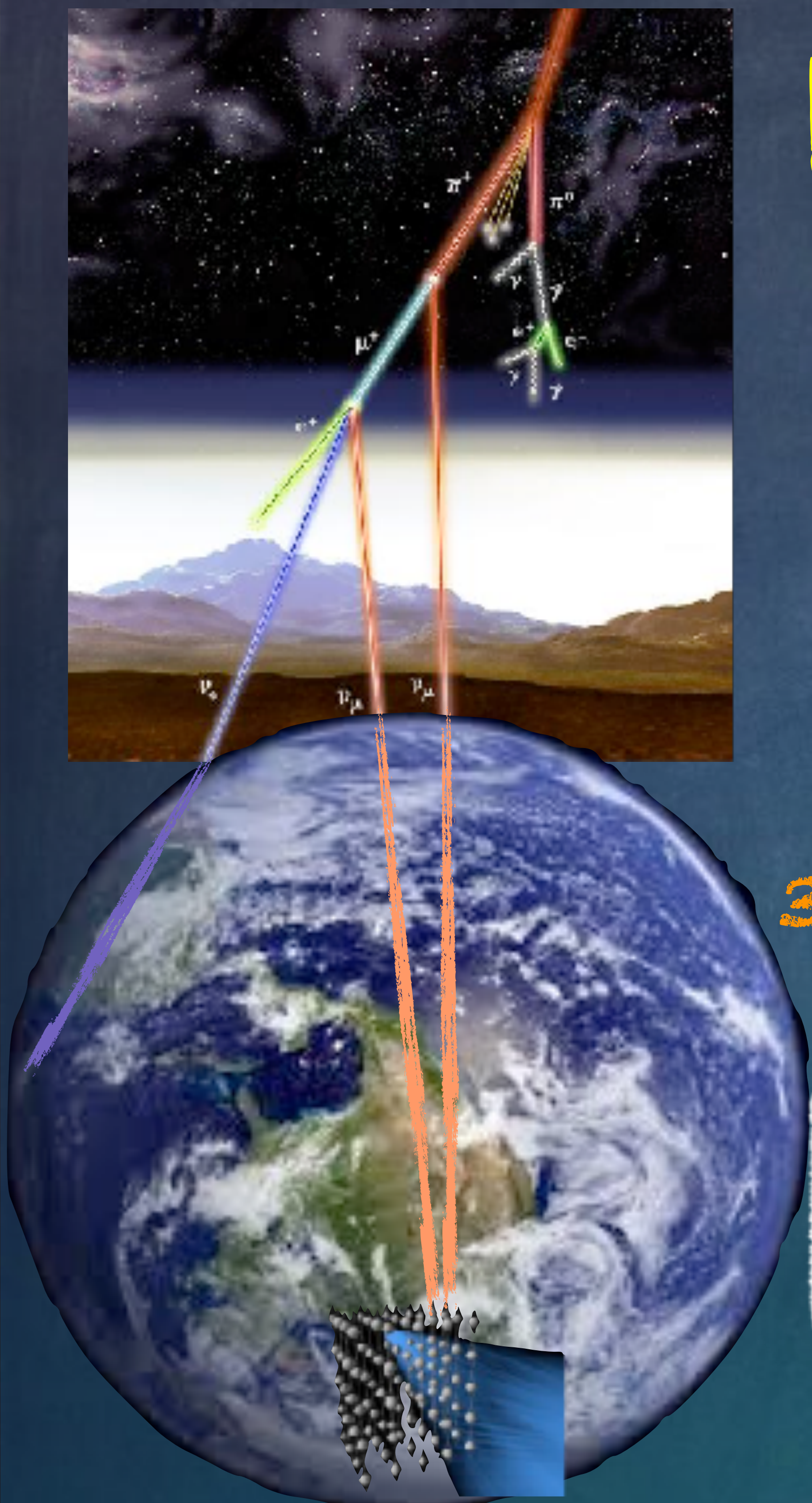
Neutrino absorption tomography

First Earth tomography with neutrinos!



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

Atmospheric neutrinos



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

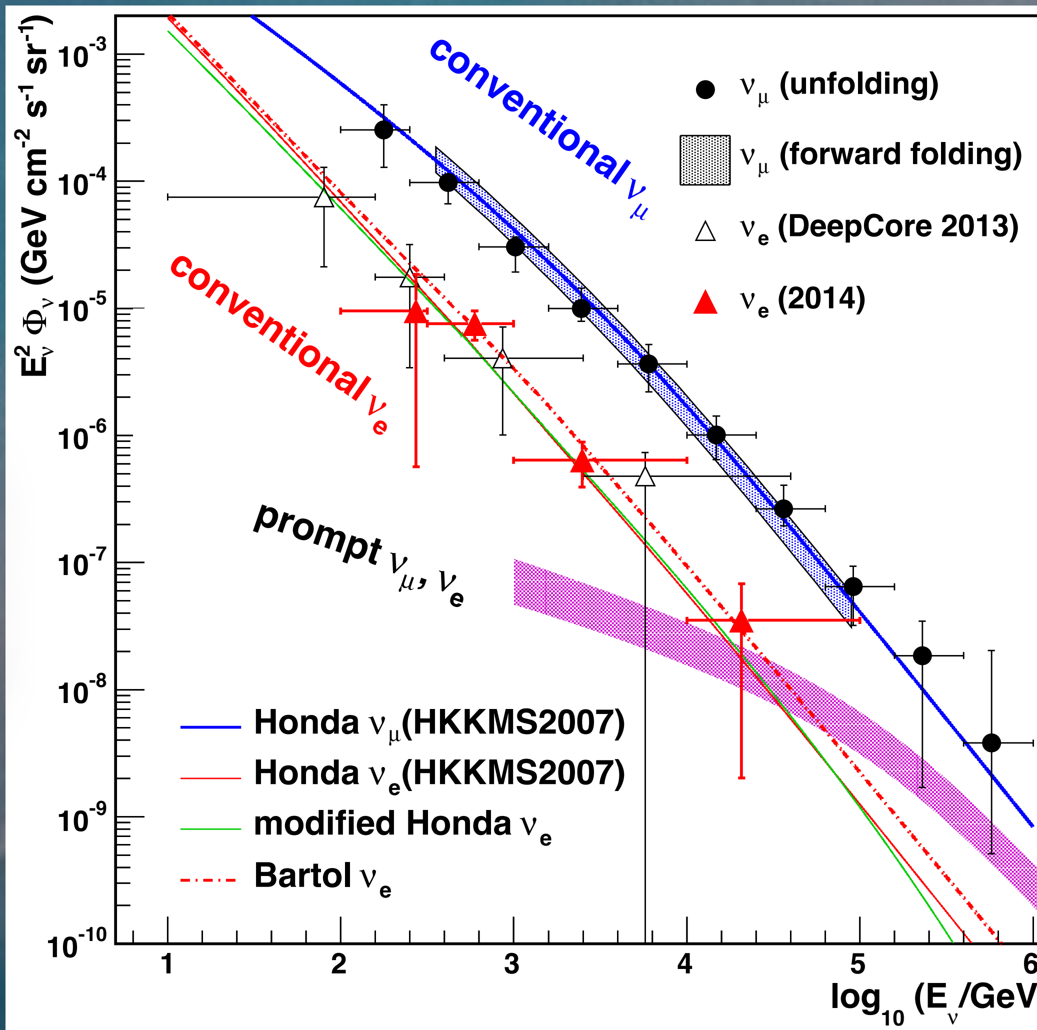
$$\mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

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

Interactions of cosmic rays in the atmosphere

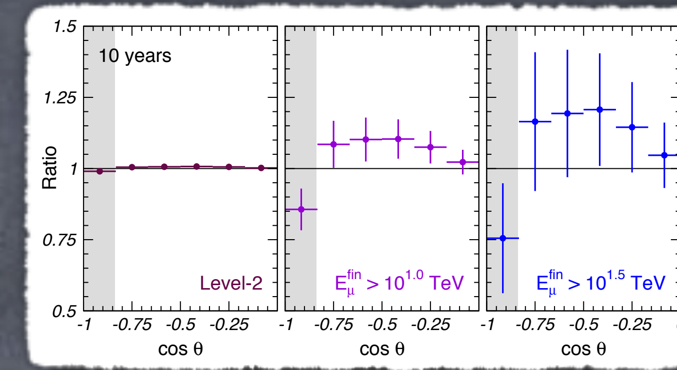
30 MeV < E < 100 TeV

Huge range of energies and baselines



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

Previous studies



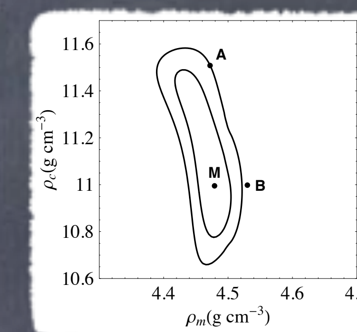
First forecast of absorption neutrino tomography using atmospheric neutrinos (for IceCube)

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

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

First forecast for KM3NeT

few percent error after 10 years



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

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

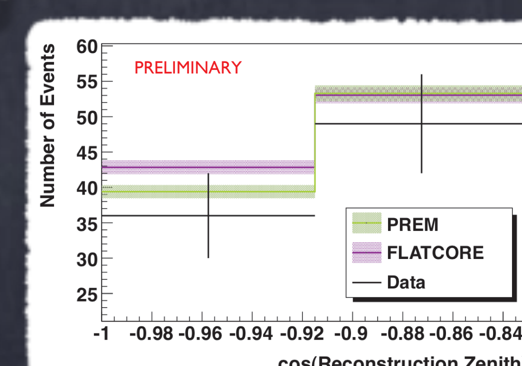
Study of lateral heterogeneities (with IceCube)

Needs ~300 years

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

Another study of Earth non-homogeneity (with IceCube)

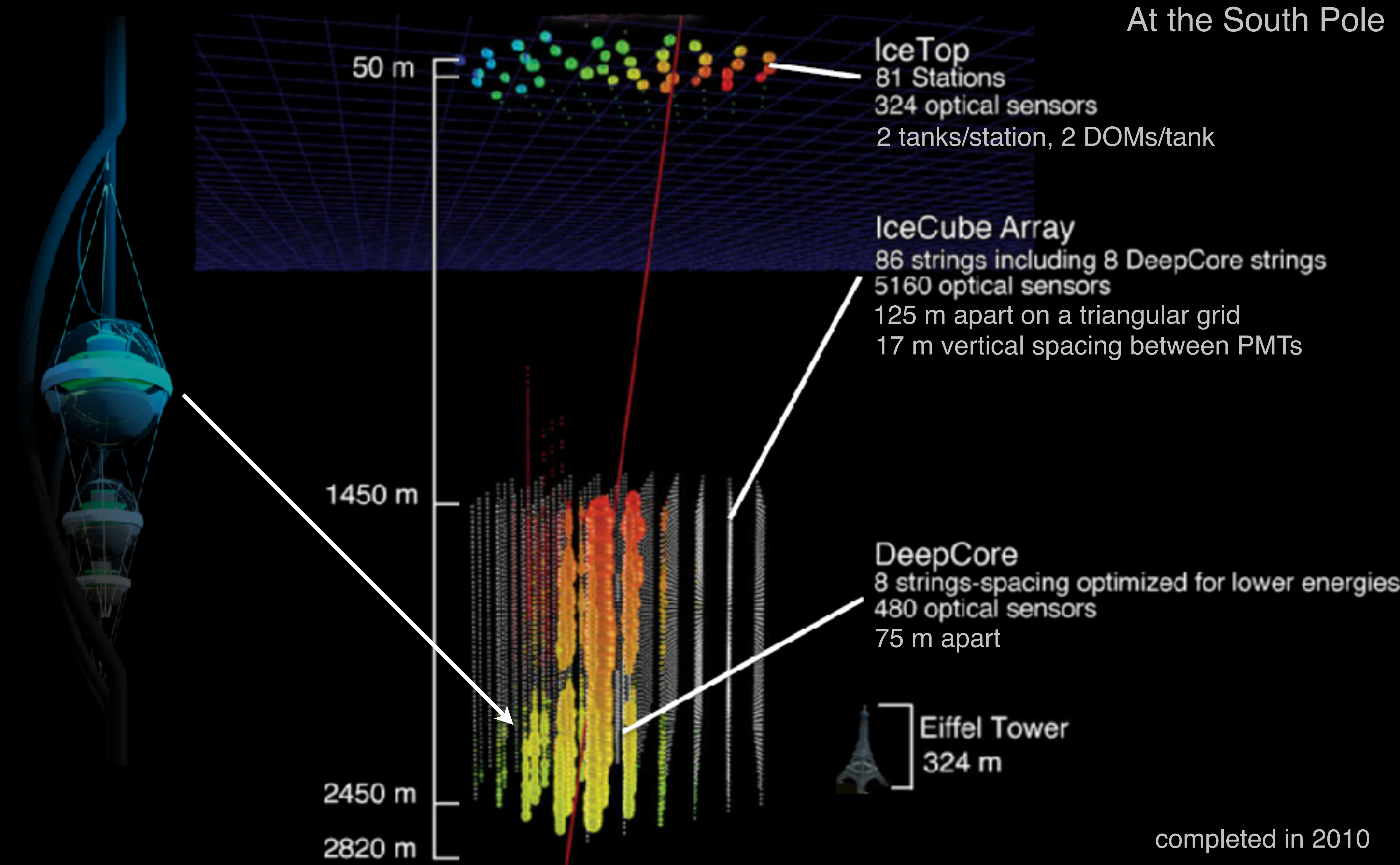
I. Romero and O. A. Sampayo, Eur. Phys. J. C71:1696, 2011



First attempt using 1 year of IC-40 data

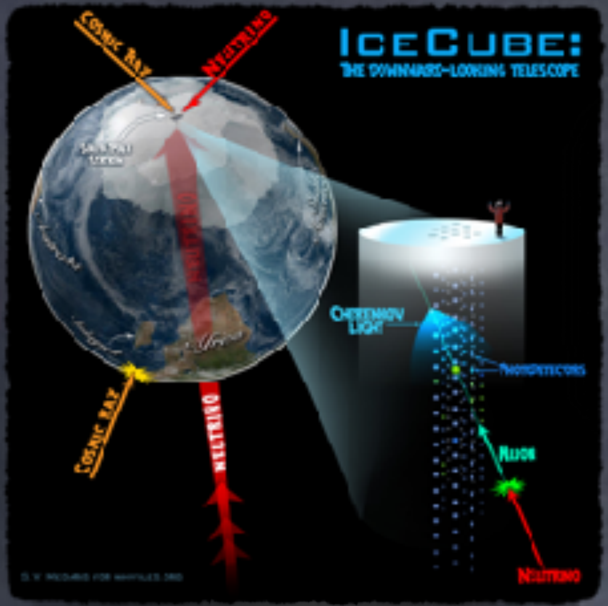
K. Hoshina and H. K. M. Tanaka, Poster at Neutrino 2012

The IceCube neutrino telescope



Secondary particles detected via Cherencov radiation

IceCube data set



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

used and prepared for the IC sterile neutrino analysis

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

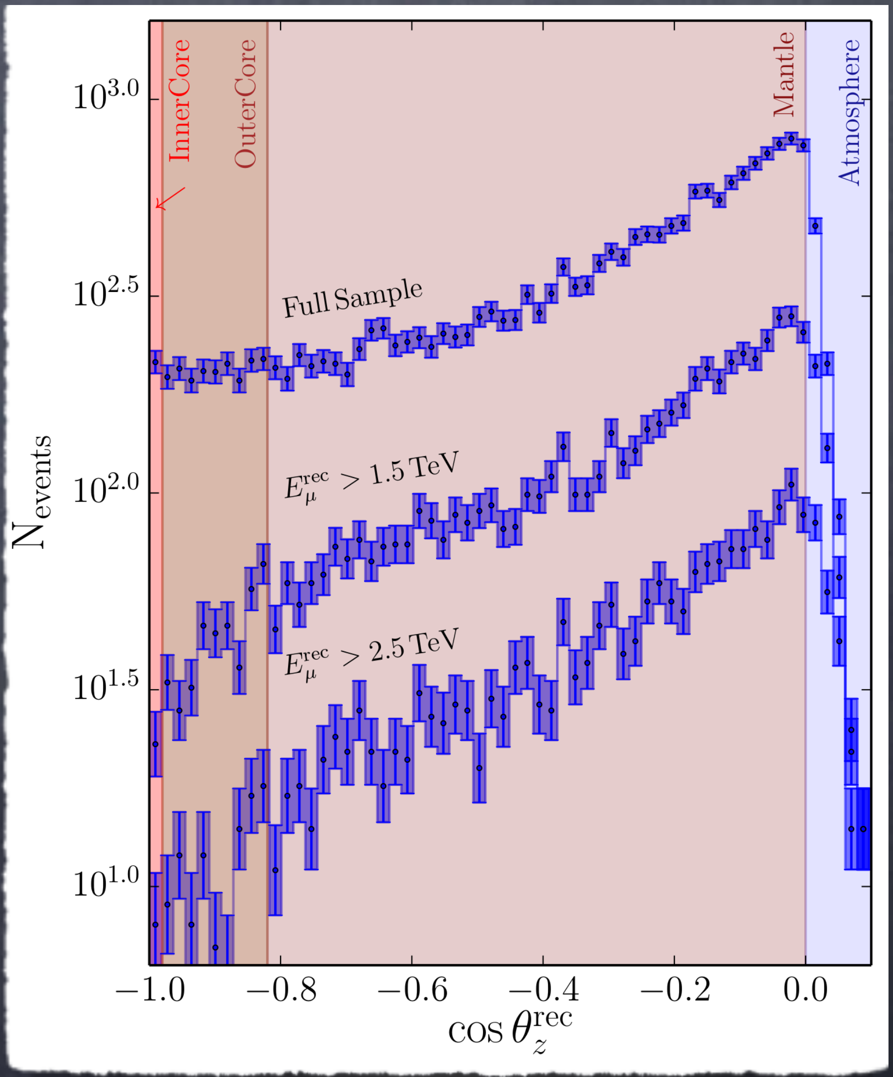
Energy range: ~ 400 GeV - 20 TeV

Zenith angle range: cos θ = [-1, 0.2]

Number of events: 20145 (343.7 days)

>99.9% muon neutrino purity

Publicly available!

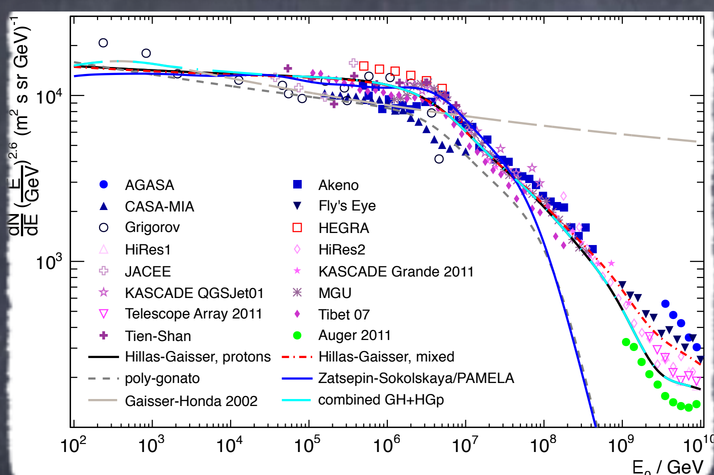


A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

Analysis ingredients

Primary cosmic-ray spectrum

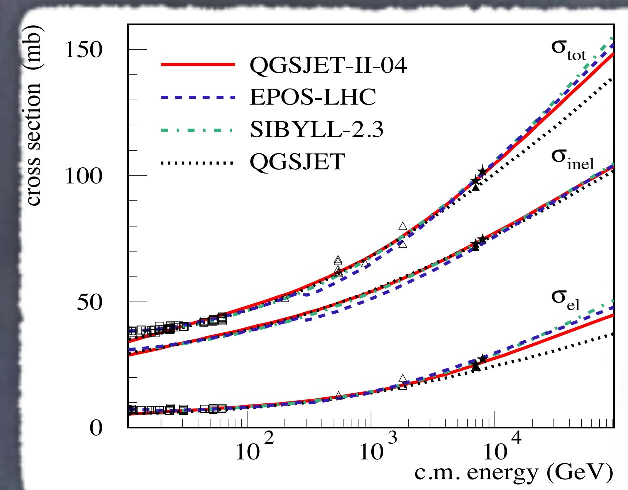
3-population models to fit cosmic-ray data

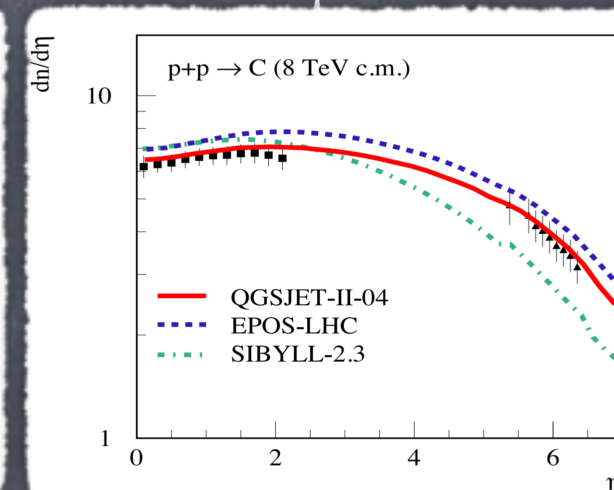


A. Fedynitch, J. B. Tjus and P. Desiati, Phys. Rev. D86:114024, 2012

Hadronic-interaction model

Models for cascade development





S. Ostapchenko, ECRS 2016, arXiv:1612.09461

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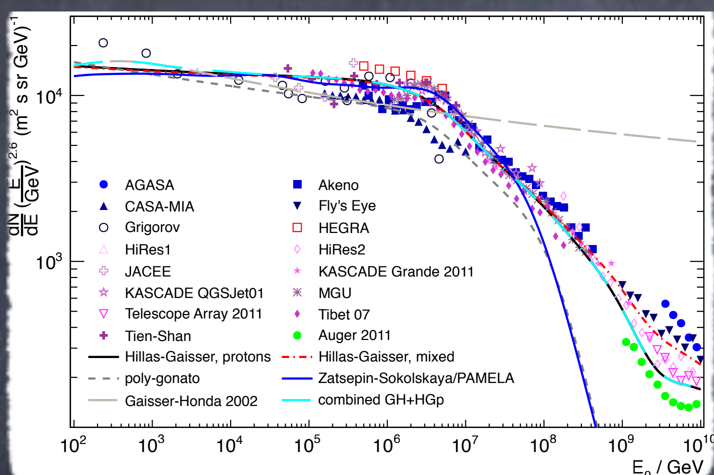

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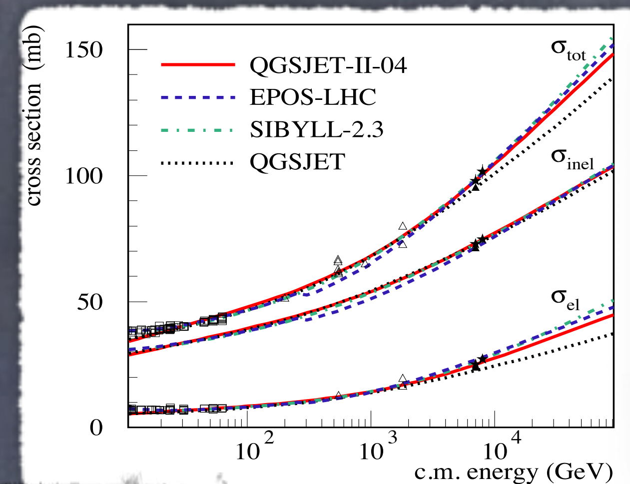
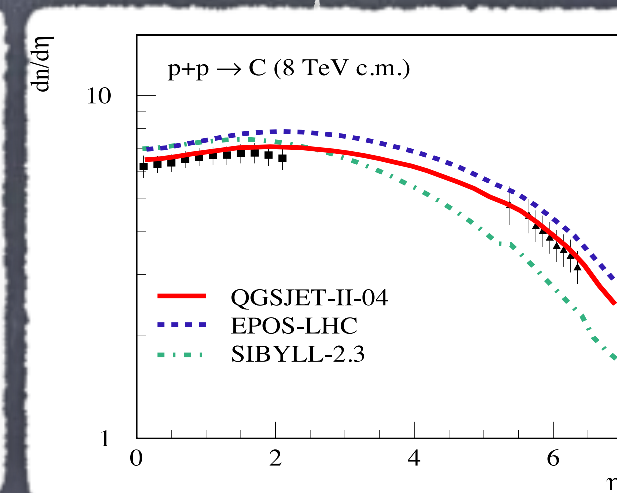
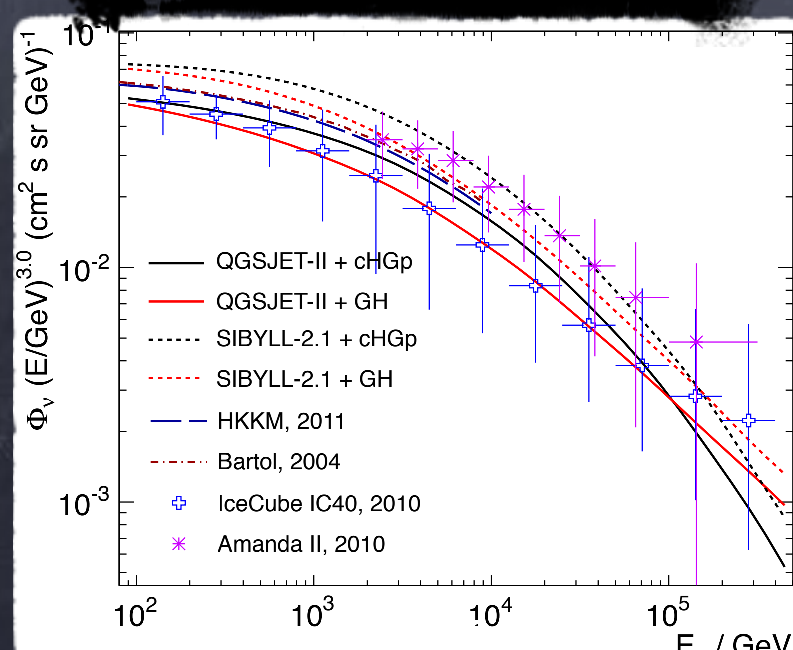




S. Ostapchenko, ECRS 2016, arXiv:1612.09461

Neutrino flux



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

Analysis ingredients

Neutrino propagation through the Earth

we propagate neutrinos with ν-SQuIDS

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

In addition to absorption, we also include neutrino oscillations

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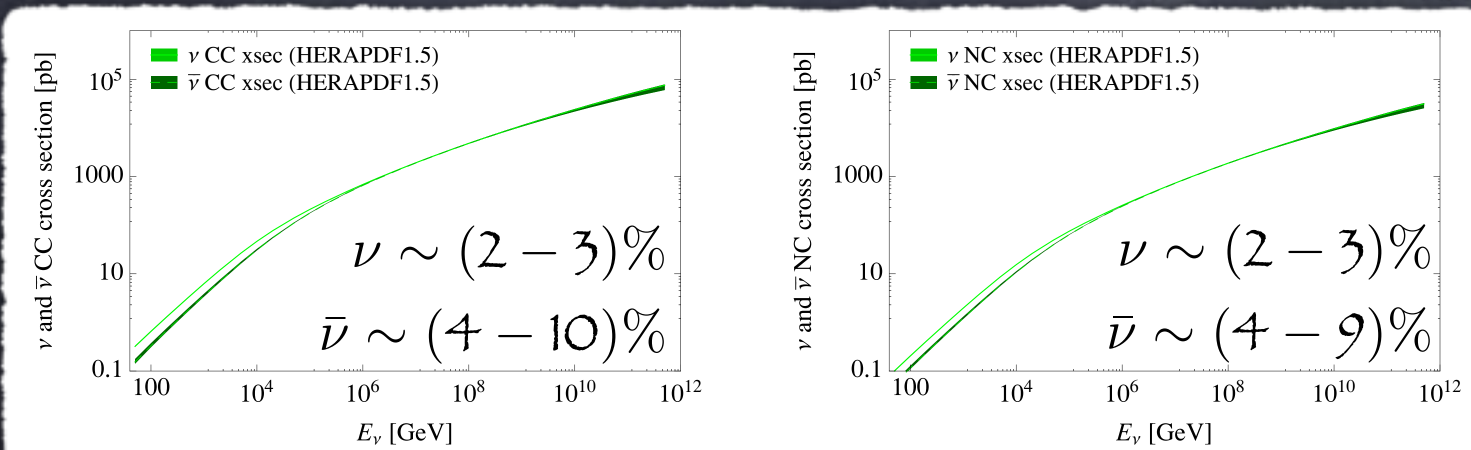
Neutrino interactions with nucleons



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

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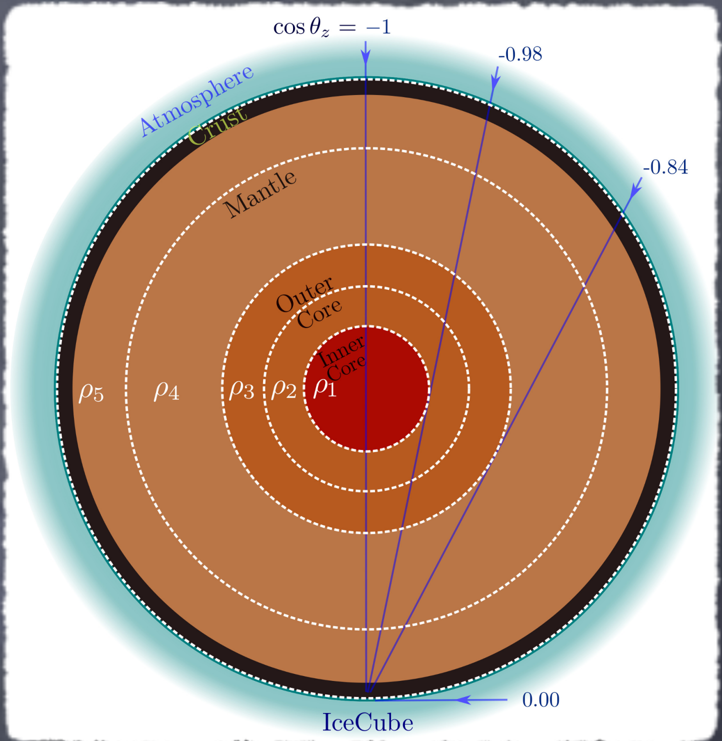
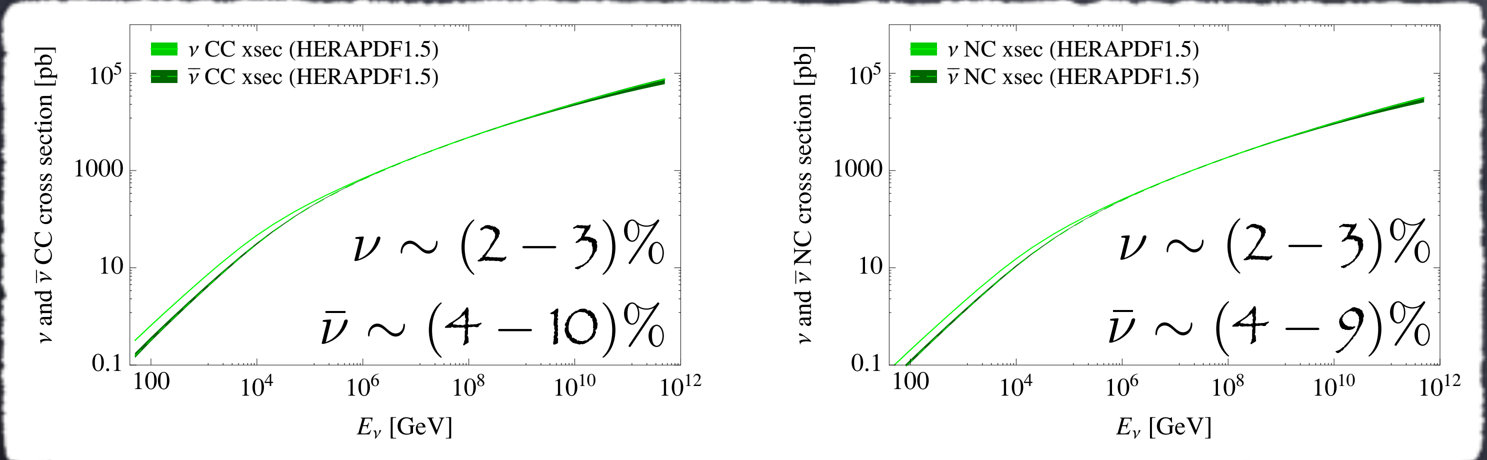
In addition to absorption, we also include neutrino oscillations

Earth model



Neutrino interactions with nucleons



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

5 spherical layers:

1 for the inner core

2 for the outer core

2 for the mantle

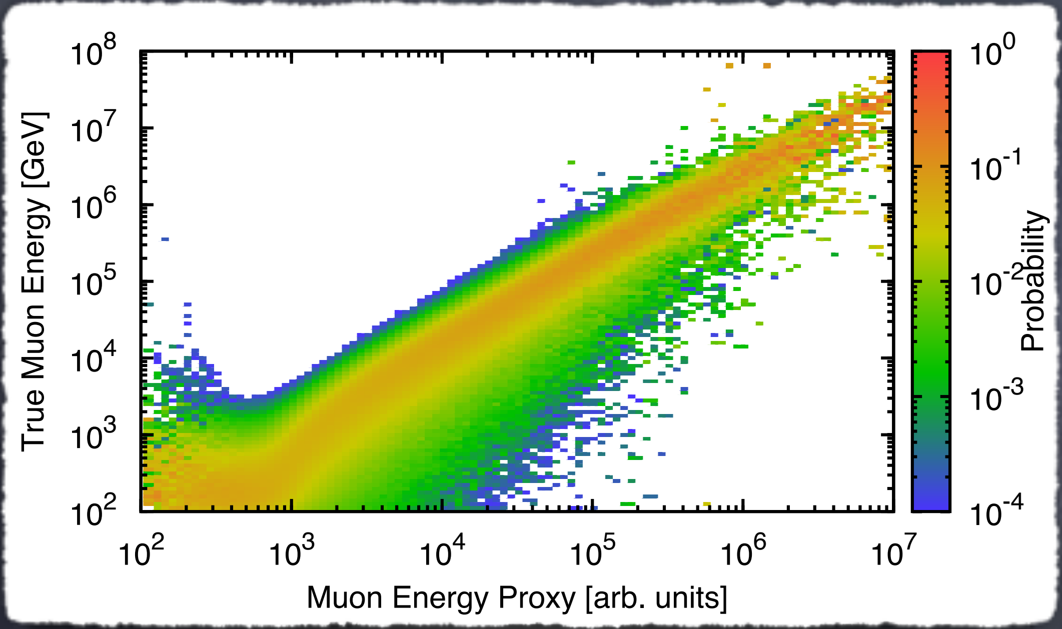
Analysis ingredients

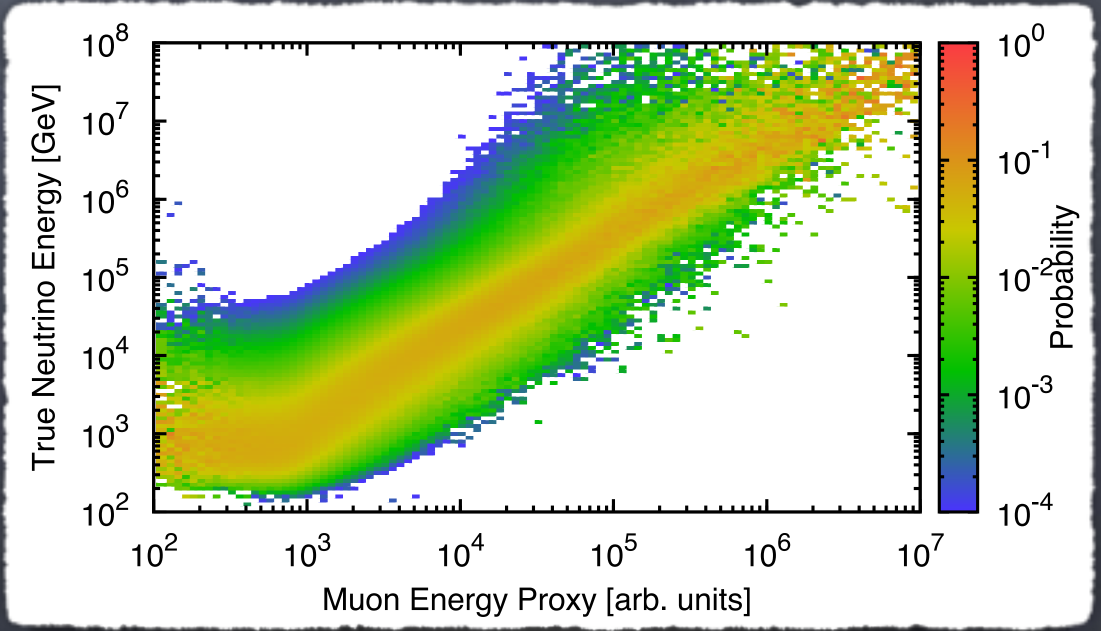
Detector simulation

Publicly available!

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

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





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

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

Statistical analysis

densities of the 5 Earth layers

Binned maximum likelihood analysis

$$\ln \mathcal{L}(\vec{\rho};\vec{\eta}) = \sum_{i\in \text{bins}} \left(N_i^{\text{data}} \ln N_i^{\text{th}}(\vec{\rho};\vec{\eta}) - N_i^{\text{th}}(\vec{\rho};\vec{\eta}) \right) - \sum_j \frac{\left(\eta_j - \eta_j^{\circ}\right)^2}{2\sigma_j^2}$$

4 nuisance parameters

DOM efficiency

Flux continuous parameters:

- overall normalization
- pion/kaon ratio
- spectral index

other systematics

Primary CR spectra

Hadronic-interaction models

Neutrino cross sections

We use MultiNest for parameter inference

F. Feroz and M. Robson, https://github.com/farhanferoz/MultiNest

Statistical analysis

densities of the 5 Earth layers

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$$\ln \mathcal{L}(\vec{\rho};\vec{\eta}) = \sum_{i \in \text{bins}} \left(N_i^{\text{data}} \ln N_i^{\text{th}}(\vec{\rho};\vec{\eta}) - N_i^{\text{th}}(\vec{\rho};\vec{\eta}) \right) - \sum_j \frac{\left(\eta_j - \eta_j^{\circ}\right)^2}{2\sigma_j^2}$$

4 nuisance parameters

DOM efficiency

Flux continuous parameters:

- overall normalization
- pion/kaon ratio
- spectral index

other systematics

Primary CR spectra

Hadronic-interaction models

Neutrino cross sections

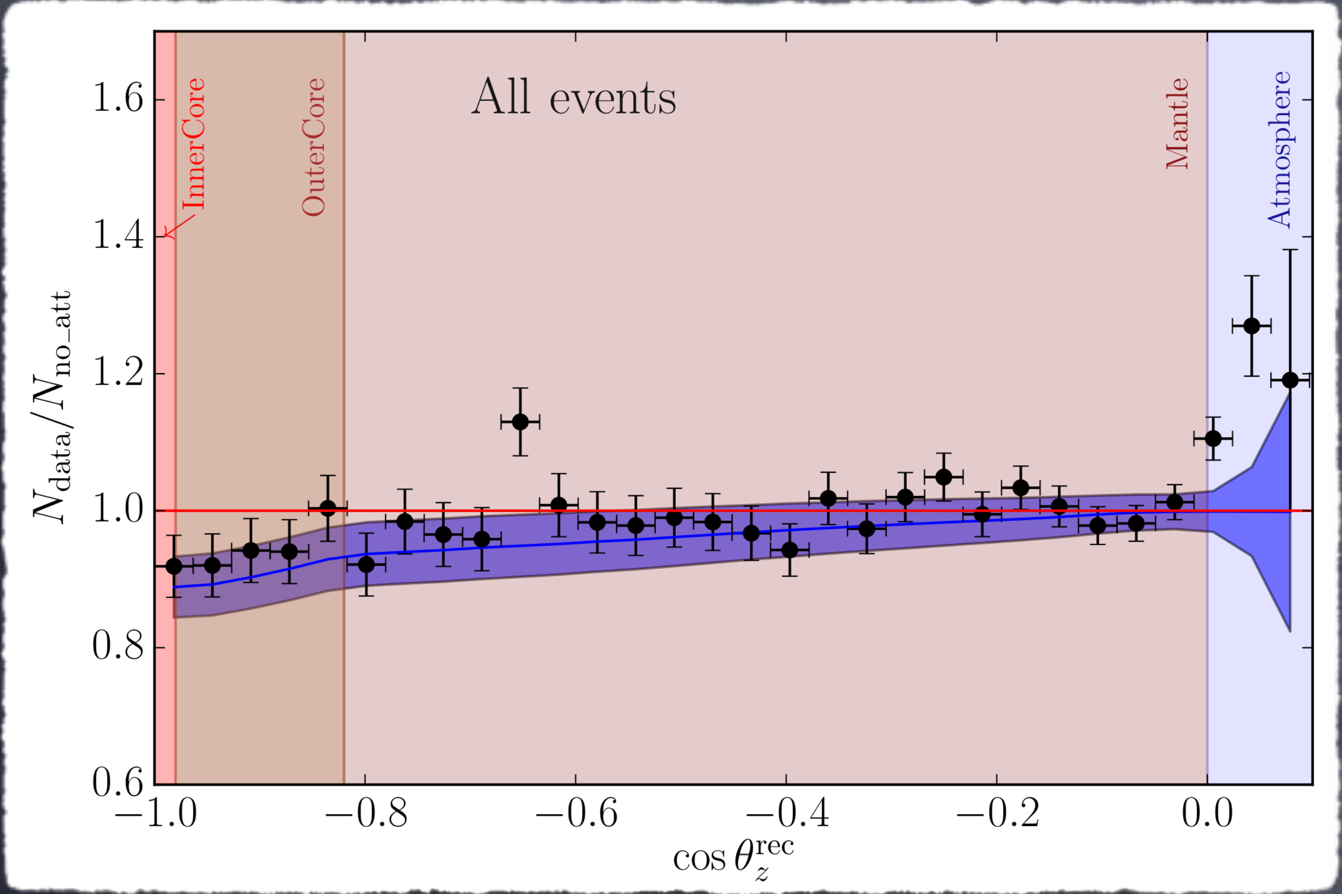
Optical properties of ice not included!

We use MultiNest for parameter inference

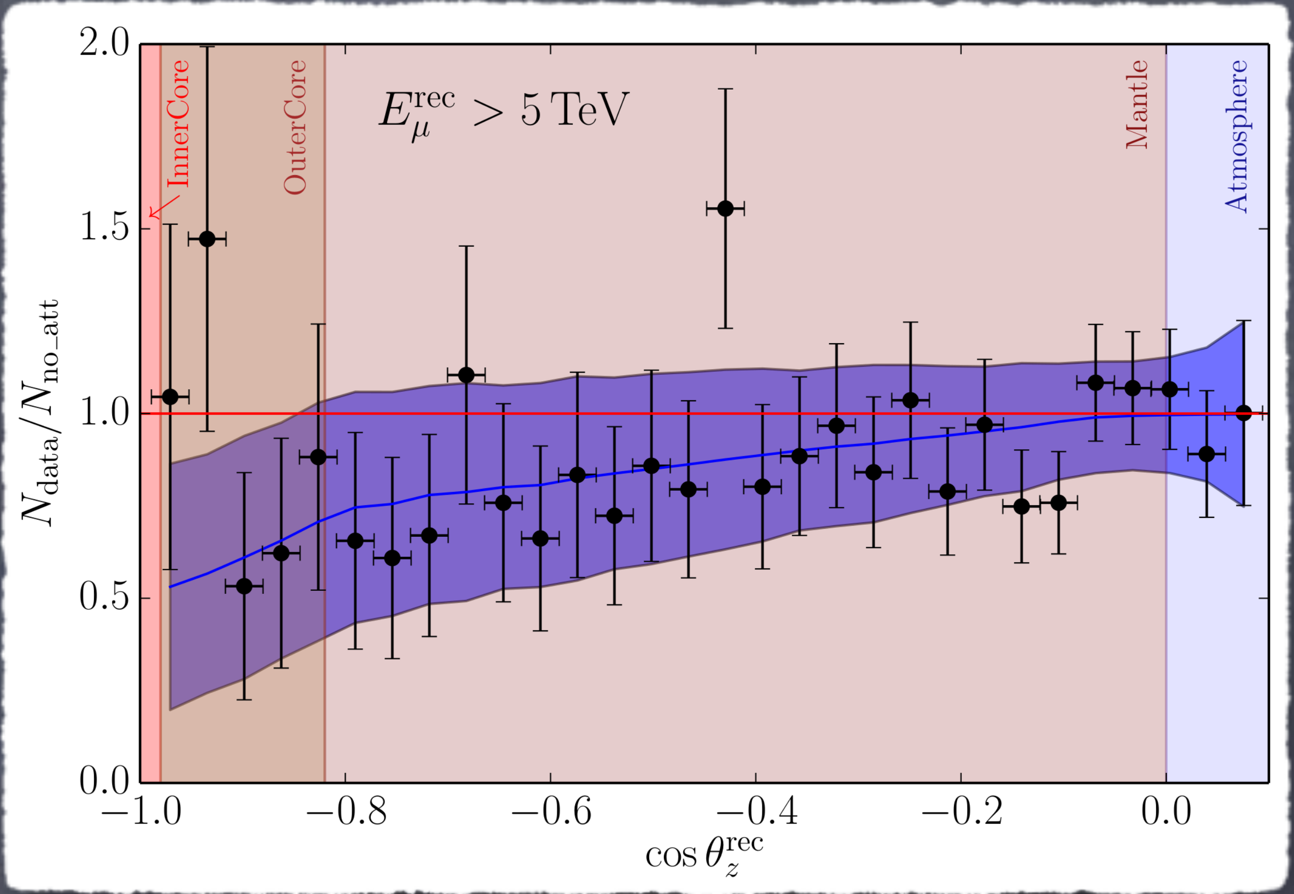
F. Feroz and M. Robson, https://github.com/farhanferoz/MultiNest

Is the Earth there?

All events



E > 5 TeV



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

Full sample:
useful to fix normalization

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

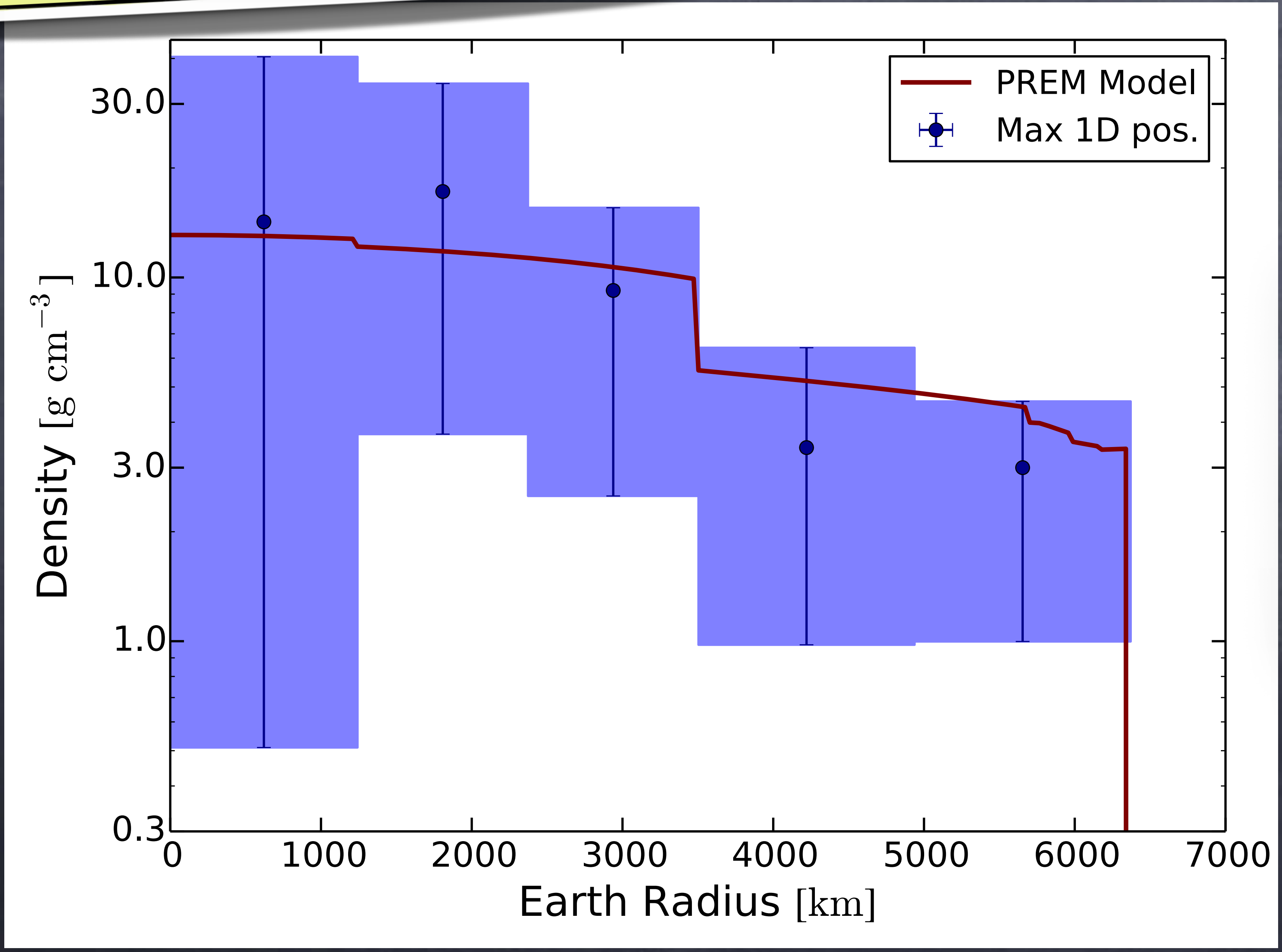
Main result: 1-D density profile

First Earth tomography with neutrinos!

nature physics

Neutrino tomography of Earth

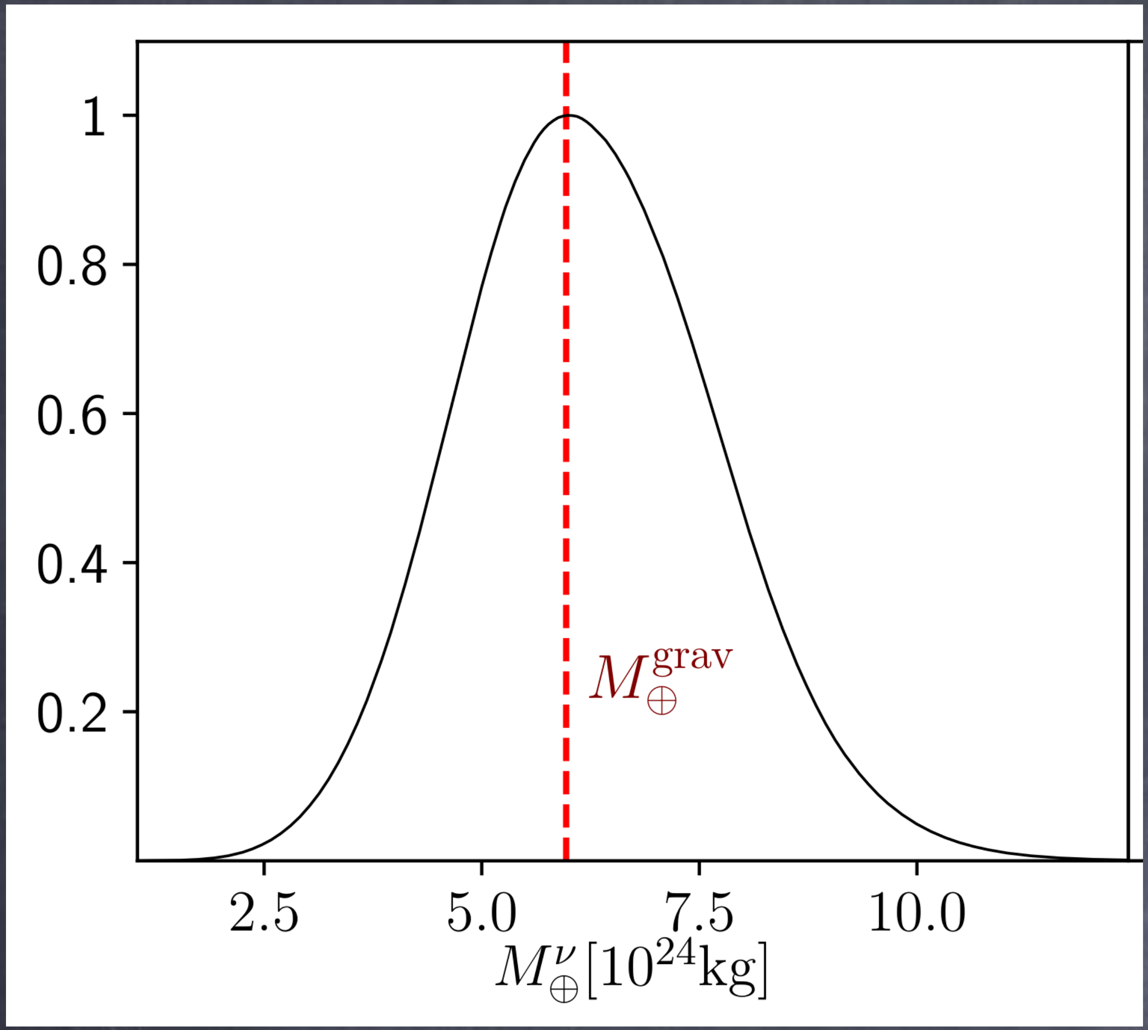
Andrea Donini[1], Sergio Palomares-Ruiz[1*] and Jordi Salvado[1,2]



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

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

Earth's mass



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

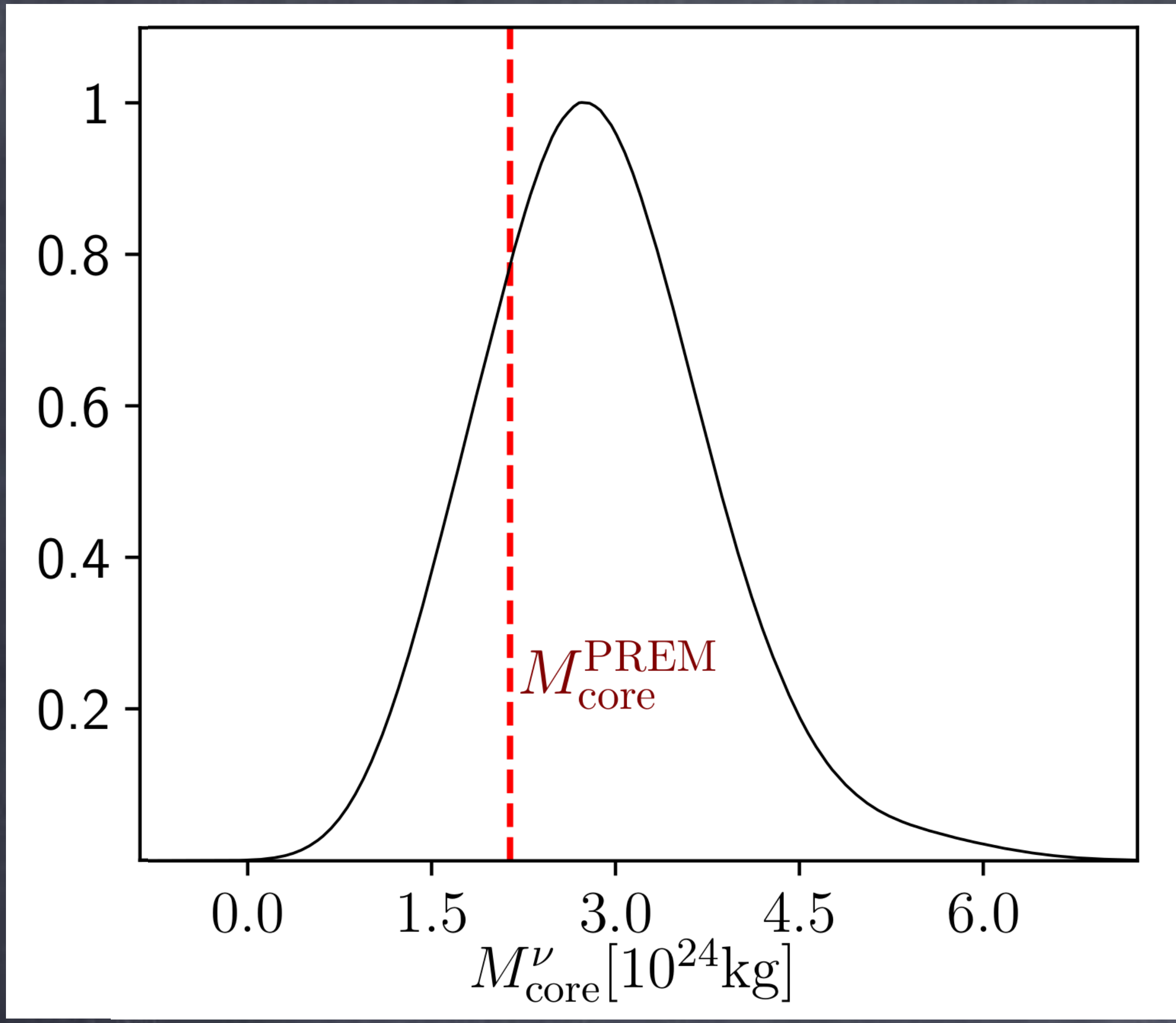
First measurement of the Earth's mass using the weak force!

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

Gravitational measurement

$$M_{grav} = 5.97217(13) \times 10^{24}\ \mathrm{kg}$$

Earth's core mass



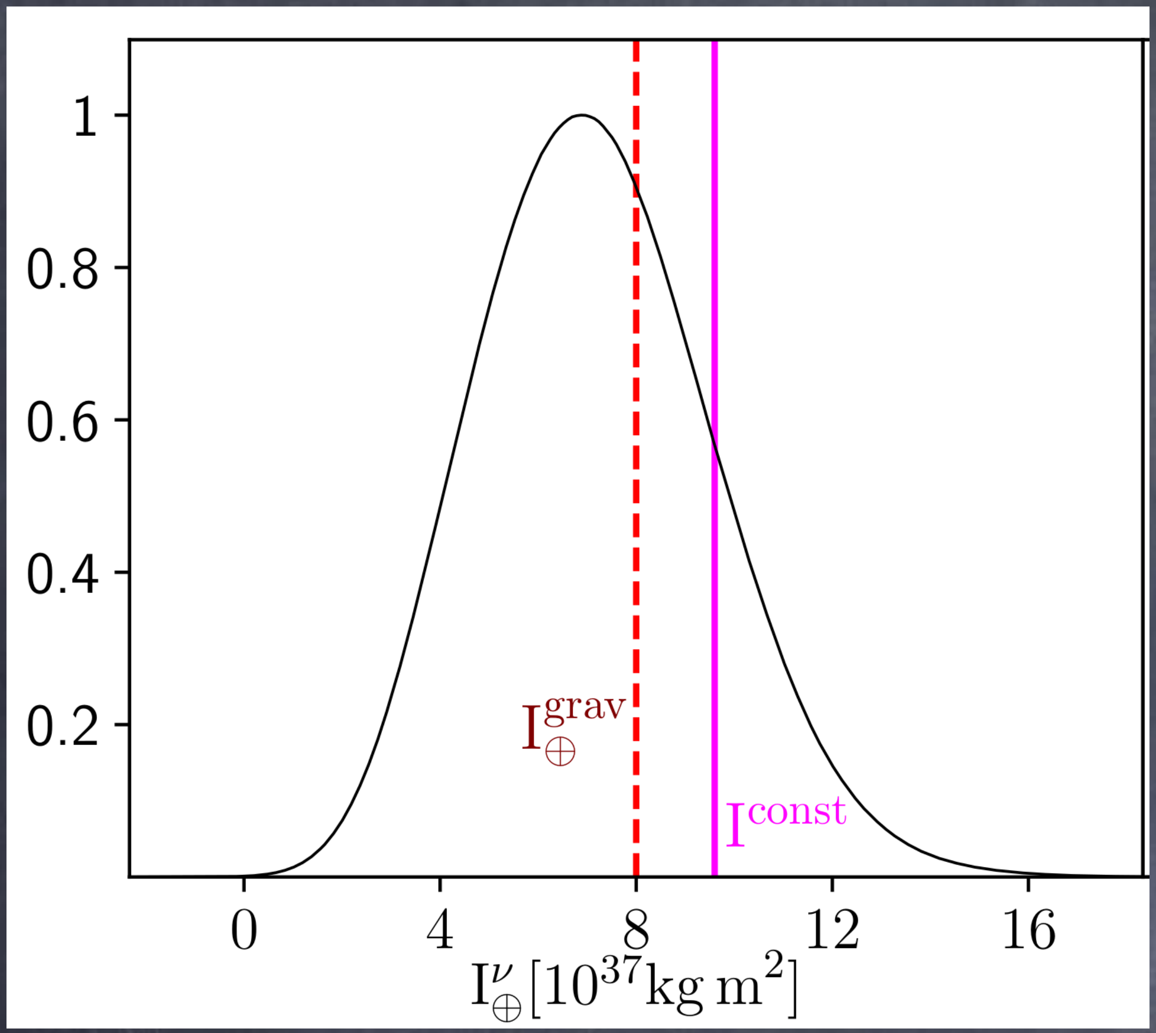
A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

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

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

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

Earth's moment of inertia



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

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

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

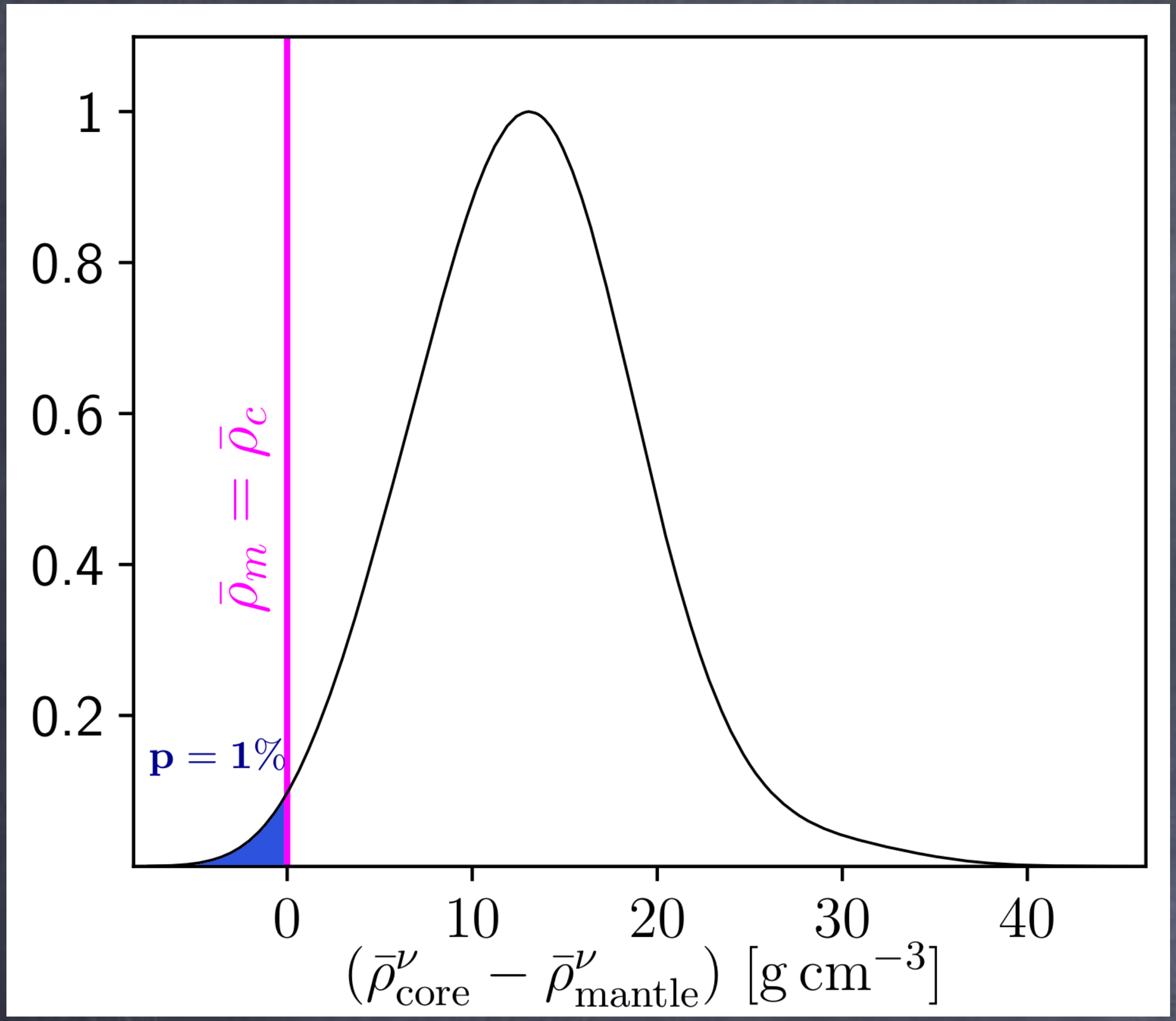
$$\frac{I_\nu}{I_{sphere\text{-}\nu}} = 0.7 \pm 0.3$$

Gravitational measurement

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

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

Mantle denser than core



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

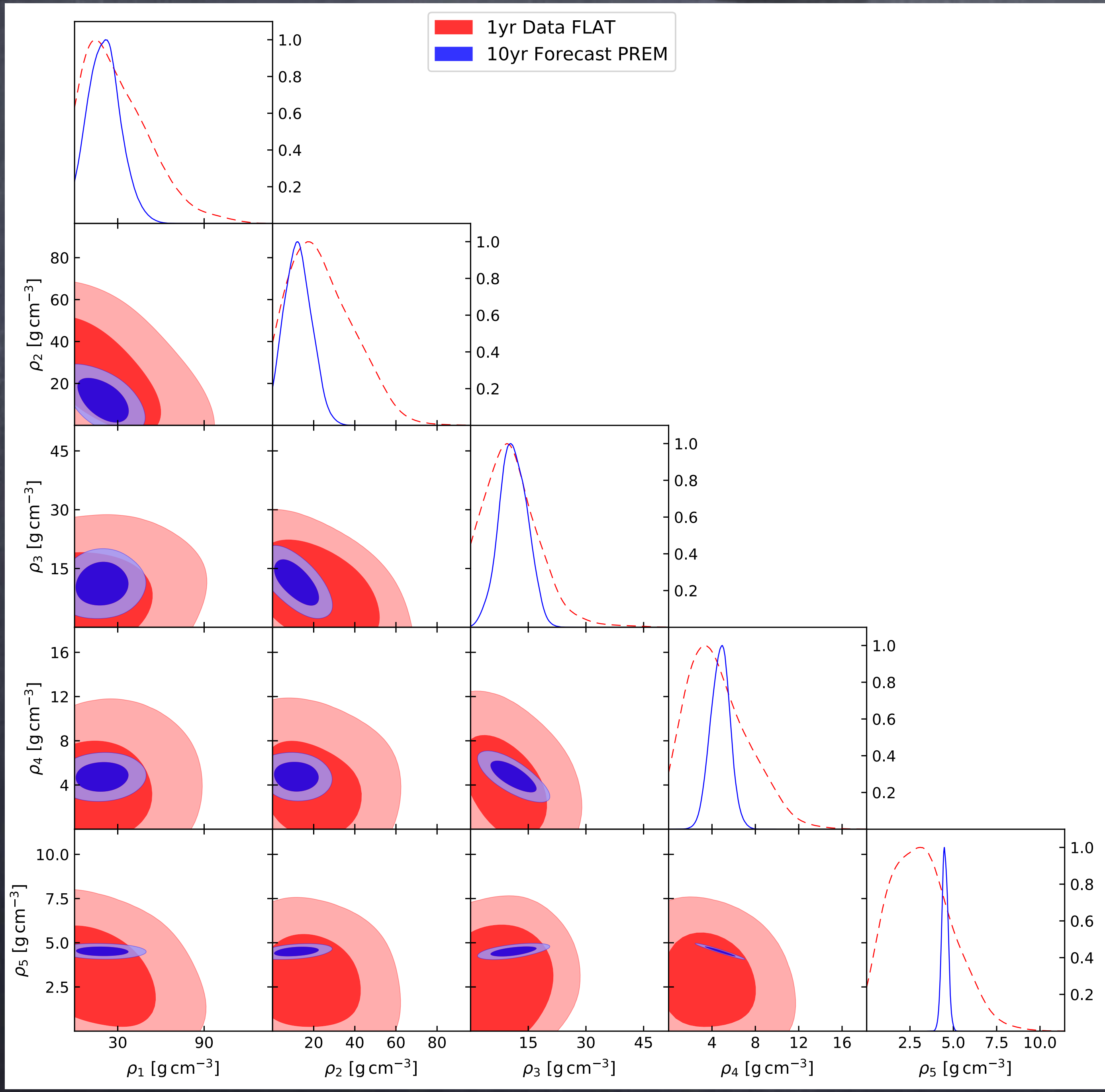
$$\left(\bar{\rho}^{\nu}_{core} - \bar{\rho}^{\nu}_{mantle}\right) = \left(13.1^{+5.8}_{-6.3}\right)\ g/cm^3$$

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

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

What about the future?
... Actually the present

Forecast for 10 years of data



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

Few per cent error in the mantle

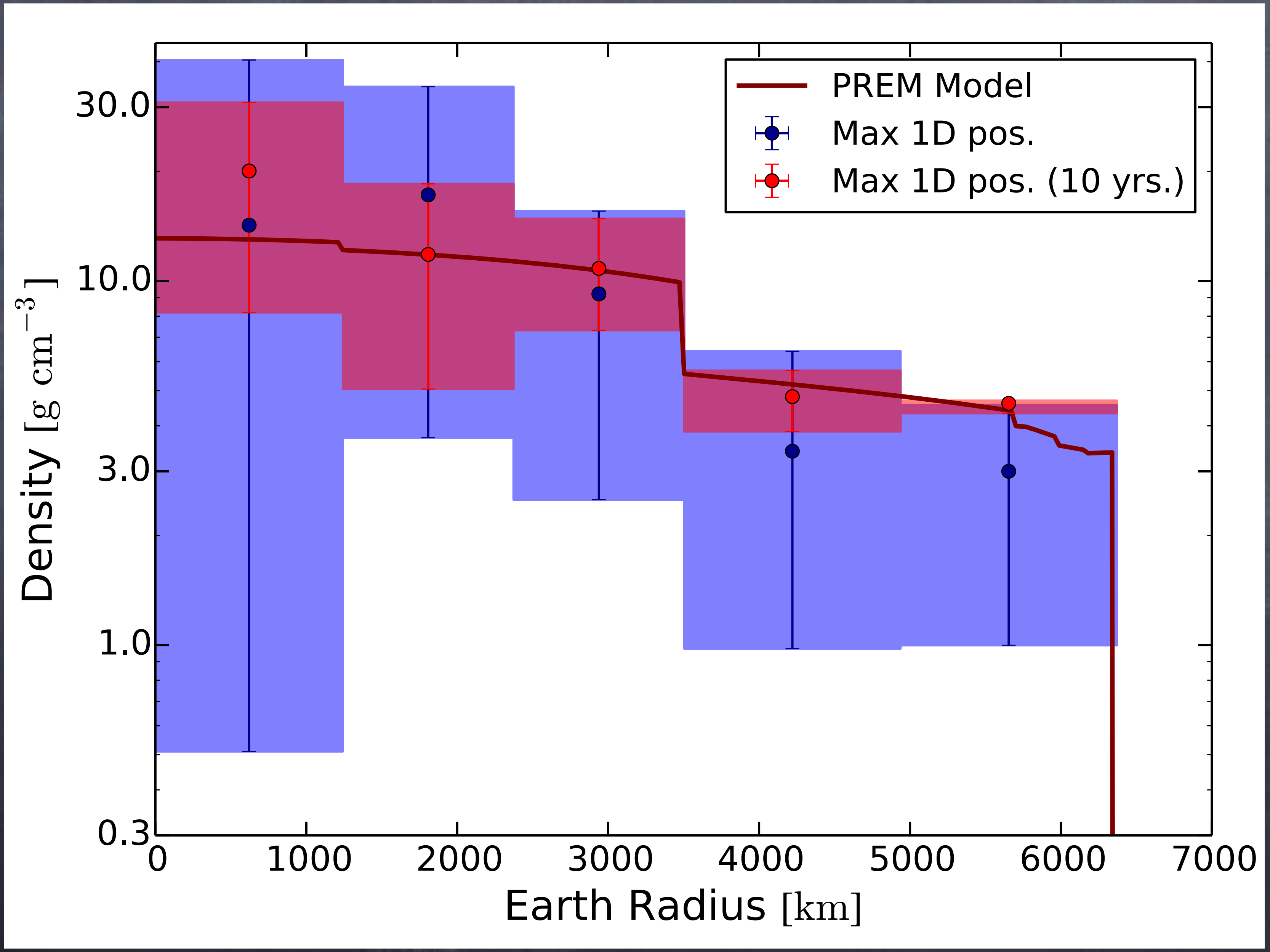
A finer modeling can be considered

Test of discontinuities

Knowledge of hadronic-interaction model impacts systematics

What about the future?
... Actually the present

Forecast for 10 years of data

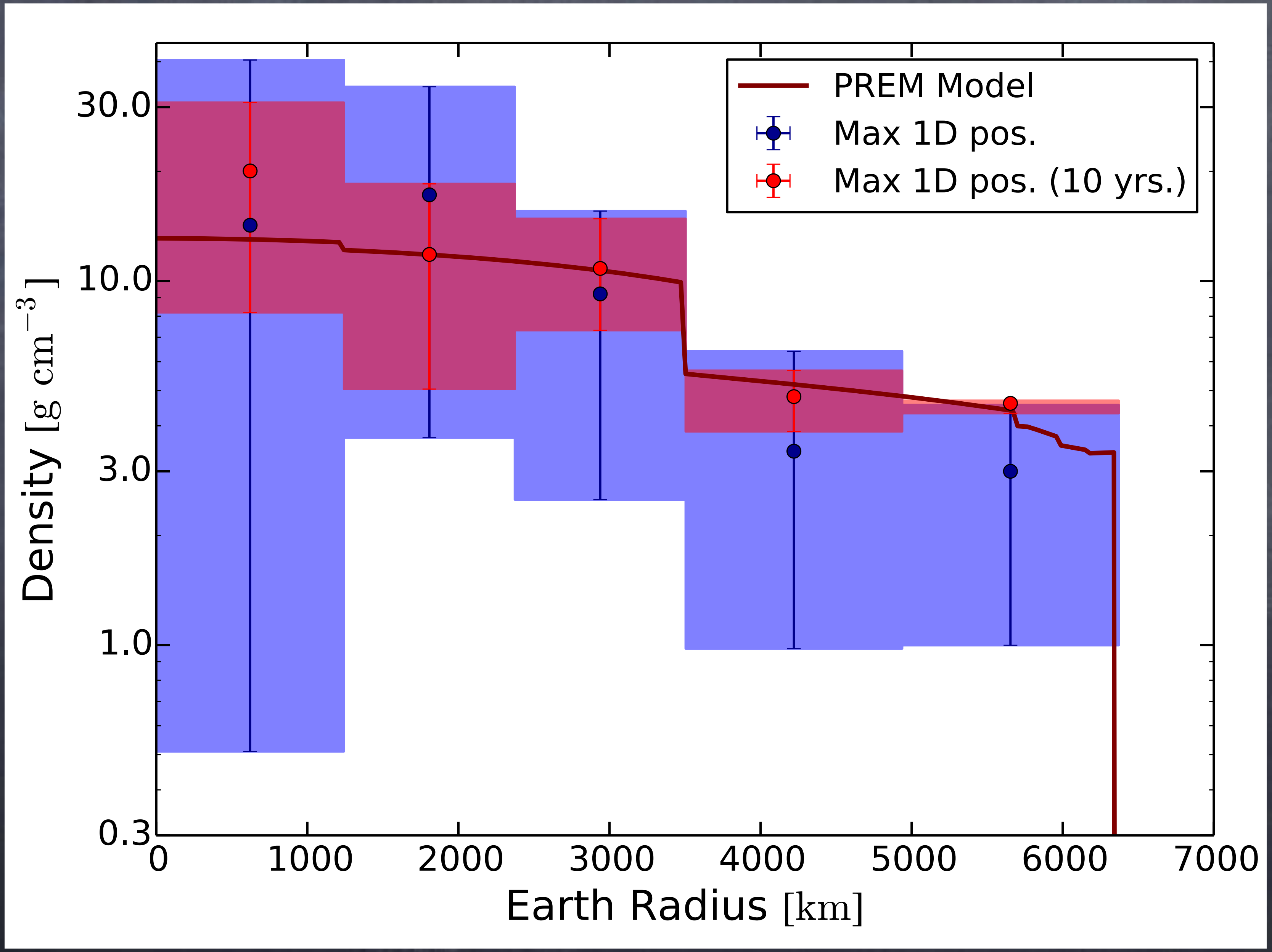


A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

What about the future? ... Actually the present

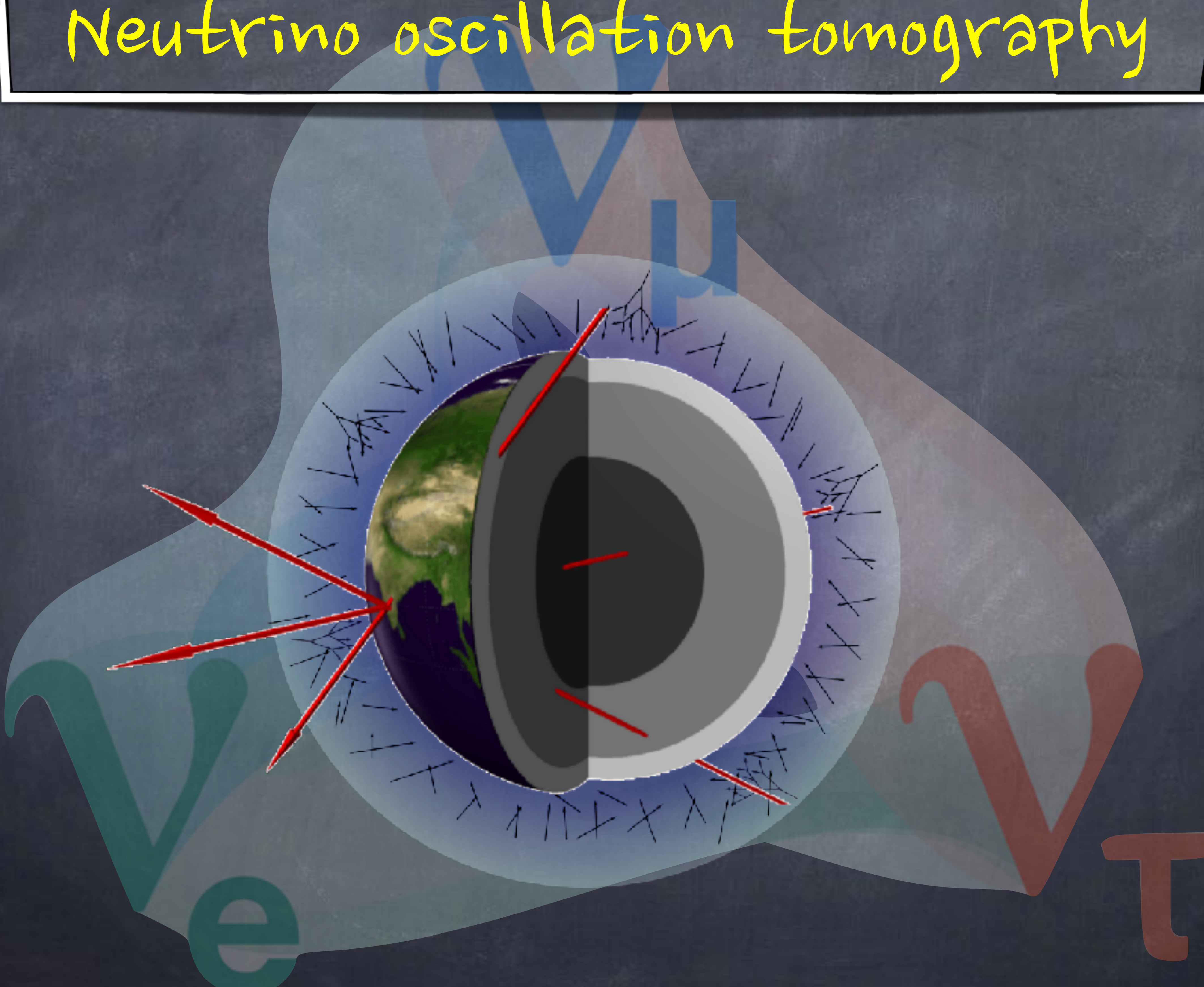
Forecast for 10 years of data

... but already 10 years of actual data!



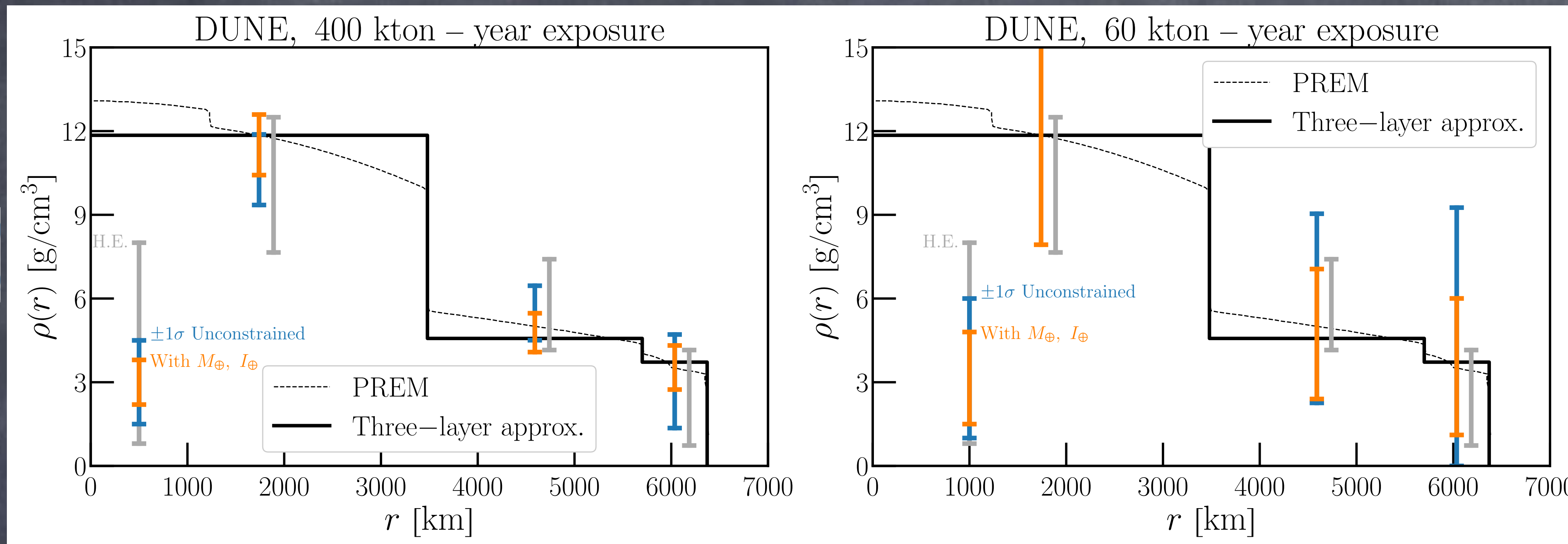
A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

Neutrino oscillation tomography

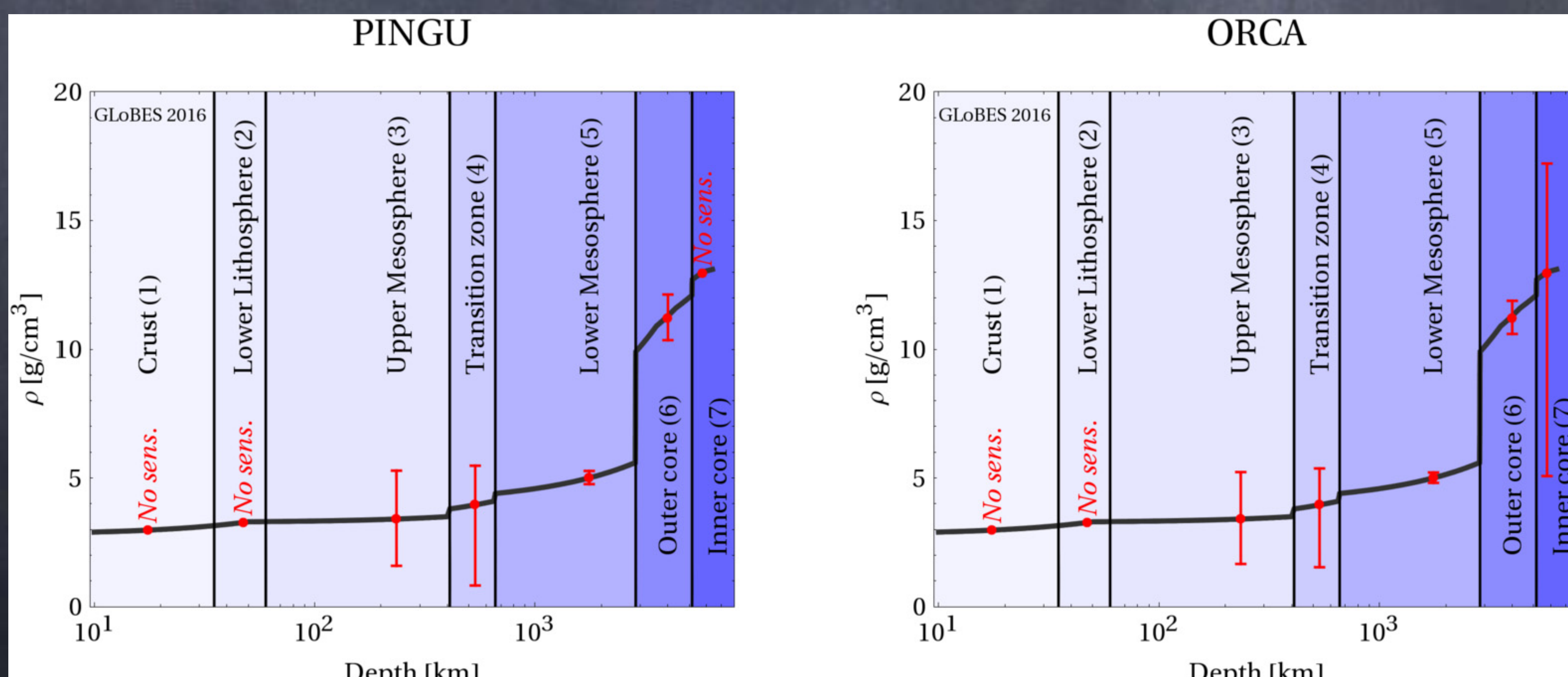


Atmospheric neutrinos (GeV)

Tomography first considered in S. K. Agarwalla, T. Li, O. Mena and SPR, arXiv:1212.2238



K. J. Kelly, P. A. N. Machado, I. Martínez-Soler and Y. F. Pérez-González, JHEP 05:187, 2022



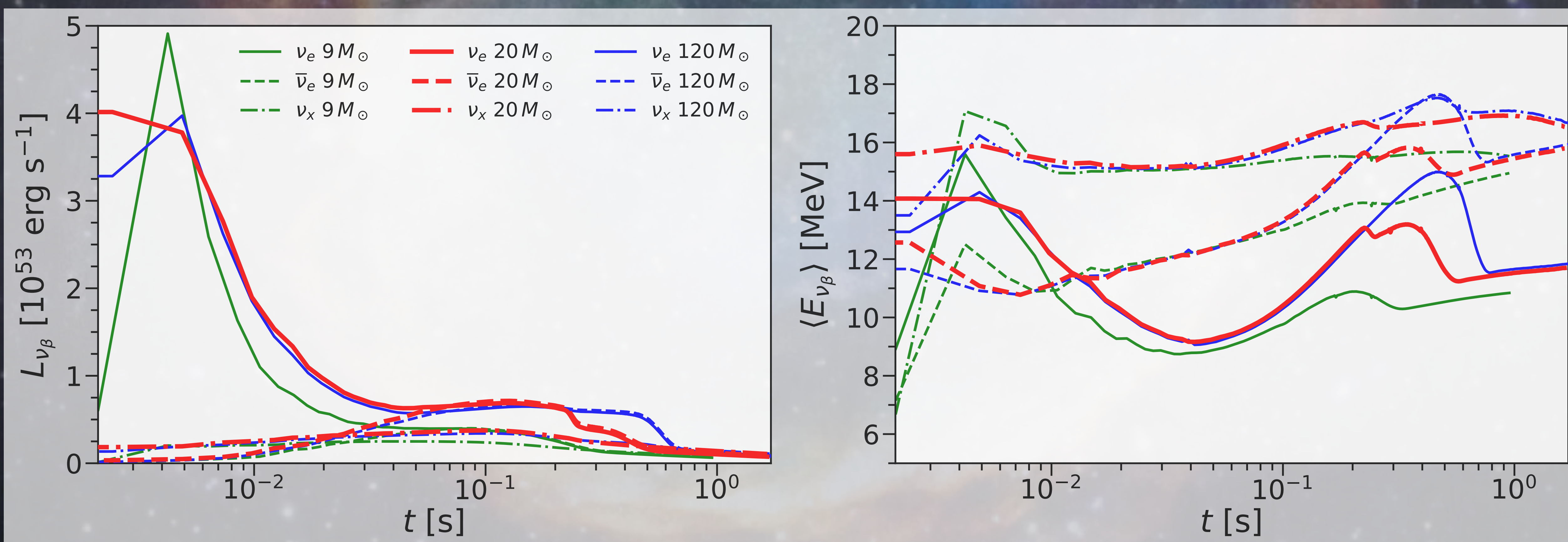
W. Winter, Nucl. Phys. B908:250, 2016

Supernova neutrinos (MeV)

Tomography first considered in M. Lindner, T. Ohlsson, R. Tomàs and W. Winter, Astropart. Phys. 19:755, 2003
and later also in E. K. Akhmedov, M. A. Tórtola and J. W. F. Valle, JHEP 06:053, 2005

$$\phi^0_{\nu_\beta}(t, E_\nu) = \frac{L_{\nu_\beta}(t)}{\langle E_{\nu_\beta}\rangle(t)} \frac{(\alpha_{\nu_\beta}(t)+1)^{\alpha_{\nu_\beta}(t)+1}}{\langle E_{\nu_\beta}\rangle(t)\,\Gamma(\alpha_{\nu_\beta}(t)+1)} \left(\frac{E_\nu}{\langle E_{\nu_\beta}\rangle(t)}\right)^{\alpha_{\nu_\beta}(t)} \exp\left(-\frac{(\alpha_{\nu_\beta}(t)+1)\,E_\nu}{\langle E_{\nu_\beta}\rangle(t)}\right)$$

M. T. Keil, G. G. Raffelt and H.-T. Janka, Astrophys. J. 590:971, 2003



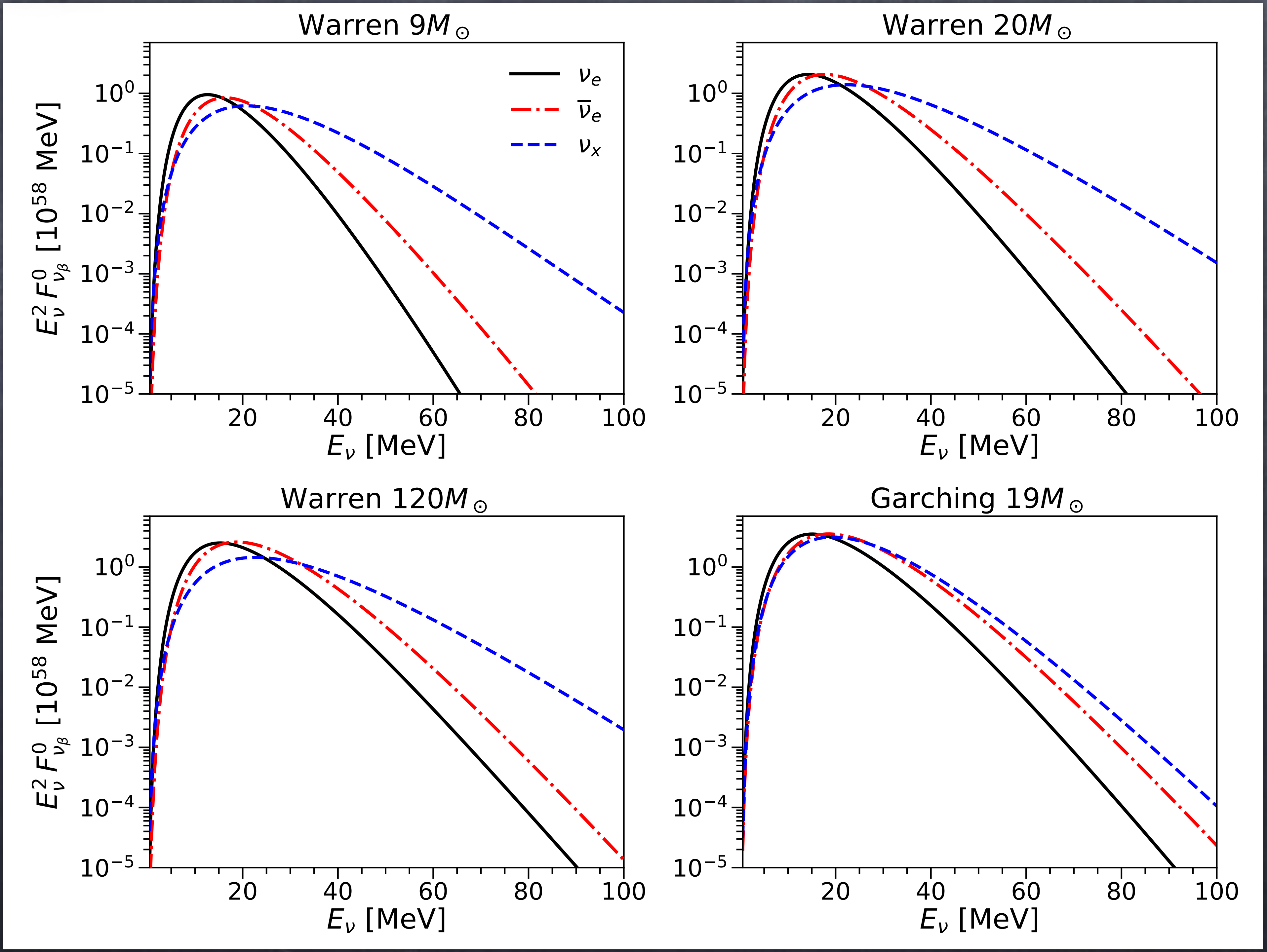
From the simulations of M. L. Warren, S. M. Couch, E. P. O'Connor and V. Morozova, Astrophys. J. 898:139, 2020

Supernova neutrino spectra at production

3 progenitor masses and 2 simulations

M. L. Warren, S. M. Couch, E. P. O'Connor and V. Morozova, Astrophys. J. 898:139, 2020
R. Bollig et al., Astrophys. J. 915:28, 2021

time-integrated spectra

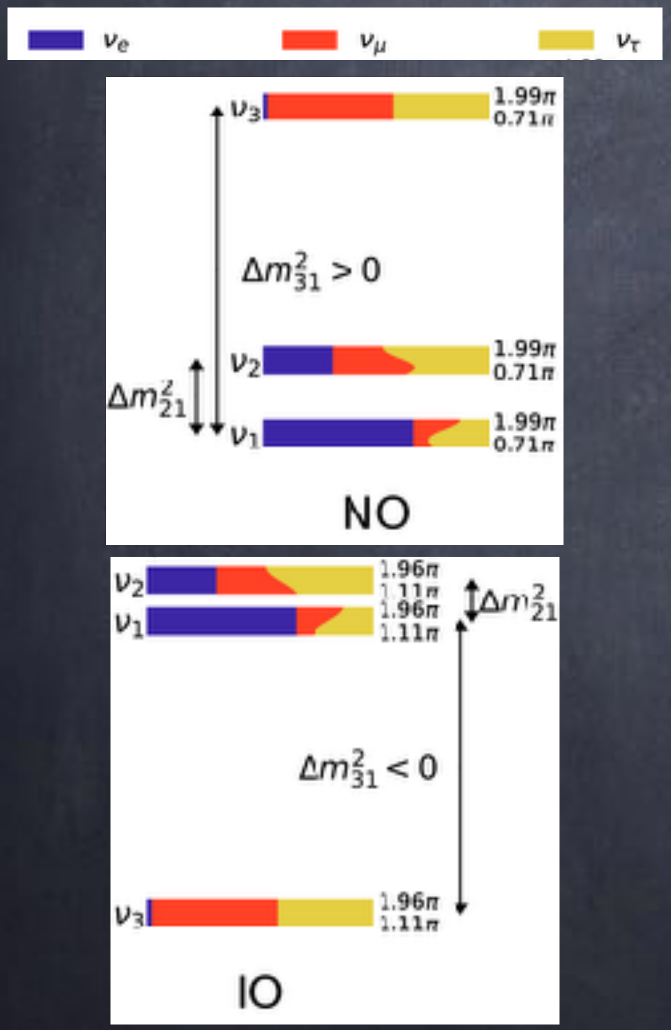


R. Hajjar, O. Mena and SPR, arXiv:2303.09369

Supernova neutrino spectra at Earth

Neutrinos are produced in a high-density medium, so the effective neutrino mixings are strongly suppressed and neutrinos are produced as mass eigenstates

Flavor conversions are fully adiabatic inside the SN, so mass eigenstates can be identified with flavor spectra at production



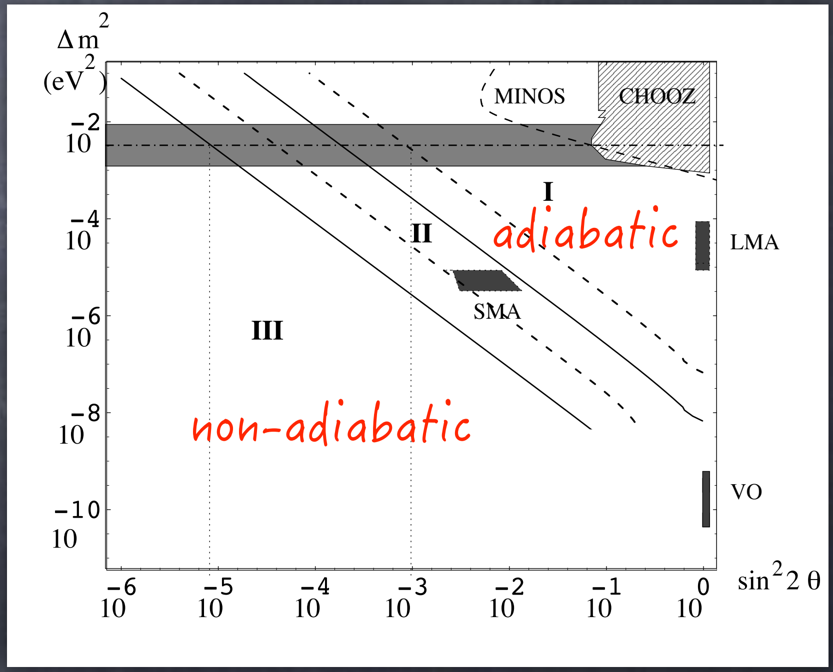
P. F. Salas et al., JHEP 02:071, 2021

$$F^0_{\nu_3} = F^0_{\nu_e} \qquad F^0_{\nu_1} = F^0_{\nu_2} = F^0_{\nu_x}$$

$$F^0_{\bar{\nu}_1} = F^0_{\bar{\nu}_e} \qquad F^0_{\bar{\nu}_2} = F^0_{\bar{\nu}_3} = F^0_{\nu_x}$$

$$F^0_{\nu_2} = F^0_{\nu_e} \qquad F^0_{\nu_1} = F^0_{\nu_3} = F^0_{\nu_x}$$

$$F^0_{\bar{\nu}_3} = F^0_{\bar{\nu}_e} \qquad F^0_{\bar{\nu}_1} = F^0_{\bar{\nu}_2} = F^0_{\nu_x}$$



A. S. Dighe and A. Yu. Smirnov, Phys. Rev. D62:033007, 2000

Neutrinos arrive at Earth as mass eigenstates

Supernova neutrino FLAVOR spectra at Earth

$$F^D_{\nu_e} = p\, F^0_{\nu_e} + (1-p)\, F^0_{\nu_x}$$

$$F^D_{\bar\nu_e} = \bar p\, F^0_{\bar\nu_e} + (1-\bar p)\, F^0_{\nu_x}$$

$$p^{NO}_\oplus \equiv P_\oplus(\nu_3 \to \nu_e) \simeq \sin^2\theta_{13}$$

$$\bar p^{NO}_\oplus \equiv P_\oplus(\bar\nu_1 \to \bar\nu_e) \simeq \cos^2\theta_{13}\ (1 - \bar P^{2\nu}_\oplus)$$

$$p^{IO}_\oplus \equiv P_\oplus(\nu_2 \to \nu_e) \simeq \cos^2\theta_{13}\, P^{2\nu}_\oplus$$

$$\bar p^{IO}_\oplus \equiv P_\oplus(\bar\nu_3 \to \bar\nu_e) \simeq \sin^2\theta_{13}$$

2-neutrino probability for constant density:

$$P^{2\nu}_\oplus = \sin^2\theta_{12} + \sin 2\theta^\oplus_{12}\ \sin\left(2\theta^\oplus_{12} - 2\theta_{12}\right)\sin^2\left(\pi\frac{L}{\ell_\oplus}\right)$$

$$\ell_\oplus = \frac{\frac{4\pi E_\nu}{\Delta m^2_{21}}}{\sqrt{(\cos 2\theta_{12} \mp \epsilon\, \cos^2\theta_{13})^2 + \sin^2 2\theta_{12}}}$$

$$\sin 2\theta^\oplus_{12} = \frac{\sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} \mp \epsilon\, \cos^2\theta_{13})^2 + \sin^2 2\theta_{12}}}$$

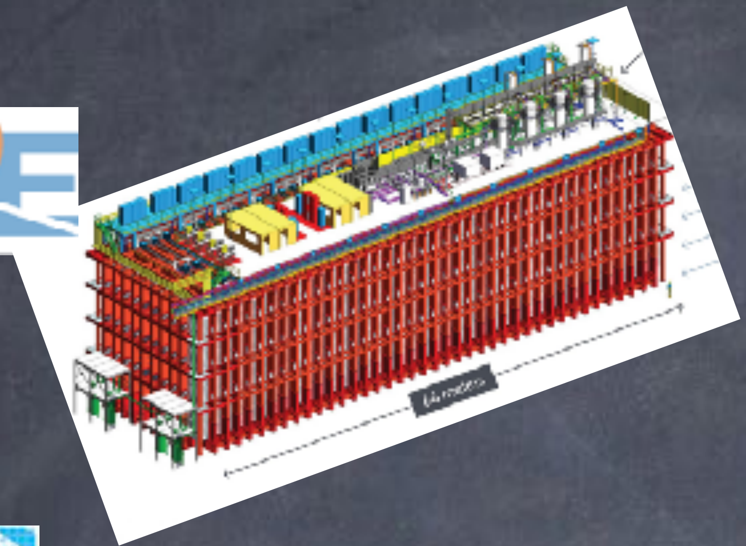
$$\epsilon \equiv \frac{2 E_\nu V}{\Delta m^2_{21}} \simeq 0.12 \left(\frac{E_\nu}{20\ \mathrm{MeV}}\right)\left(\frac{Y_e\,\rho}{3\ \mathrm{g/cm^3}}\right)\left(\frac{7.5\times 10^{-5}\ \mathrm{eV}^2}{\Delta m^2_{21}}\right)$$

Regeneration factor:

$$f_{reg} \equiv p_\oplus - p_{vac} = \epsilon\, \cos^4\theta_{13}\ \sin^2 2\theta^\oplus_{12}\ \sin^2\left(\pi\frac{L}{\ell_\oplus}\right)$$

$$F^D_{\nu_e} - F^{vac}_{\nu_e} = f_{reg}\left(F^0_{\nu_e} - F^0_{\nu_x}\right)$$

Future neutrino detectors



40 kton liquid Argon

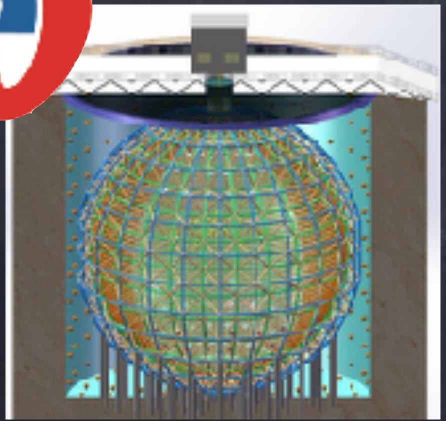
$\sigma_{\mathrm{DUNE-Ar}}/E_\nu = 0.2$

$$\nu_e \mathrm{Ar-CC}: \quad \nu_e + {}^{40}\mathrm{Ar} \to e^- + X$$
$$\bar{\nu}_e \mathrm{Ar-CC}: \quad \bar{\nu}_e + {}^{40}\mathrm{Ar} \to e^+ + X$$
$$\nu - e^- \ \mathrm{ES}: \quad \nu + e^- \to \nu + e^-$$

2x187 kton water Cherenkov
with Gadolinium

$\sigma_{\mathrm{HK}}/E_e \sim 0.08$

$$\mathrm{IBD}: \quad \bar{\nu}_e + p \to e^+ + n$$
$$\nu_e \mathrm{O-CC}: \quad \nu_e + {}^{16}\mathrm{O} \to e^- + X$$
$$\bar{\nu}_e \mathrm{O-CC}: \quad \bar{\nu}_e + {}^{16}\mathrm{O} \to e^+ + X$$
$$\nu - e^- \ \mathrm{ES}: \quad \nu + e^- \to \nu + e^-$$

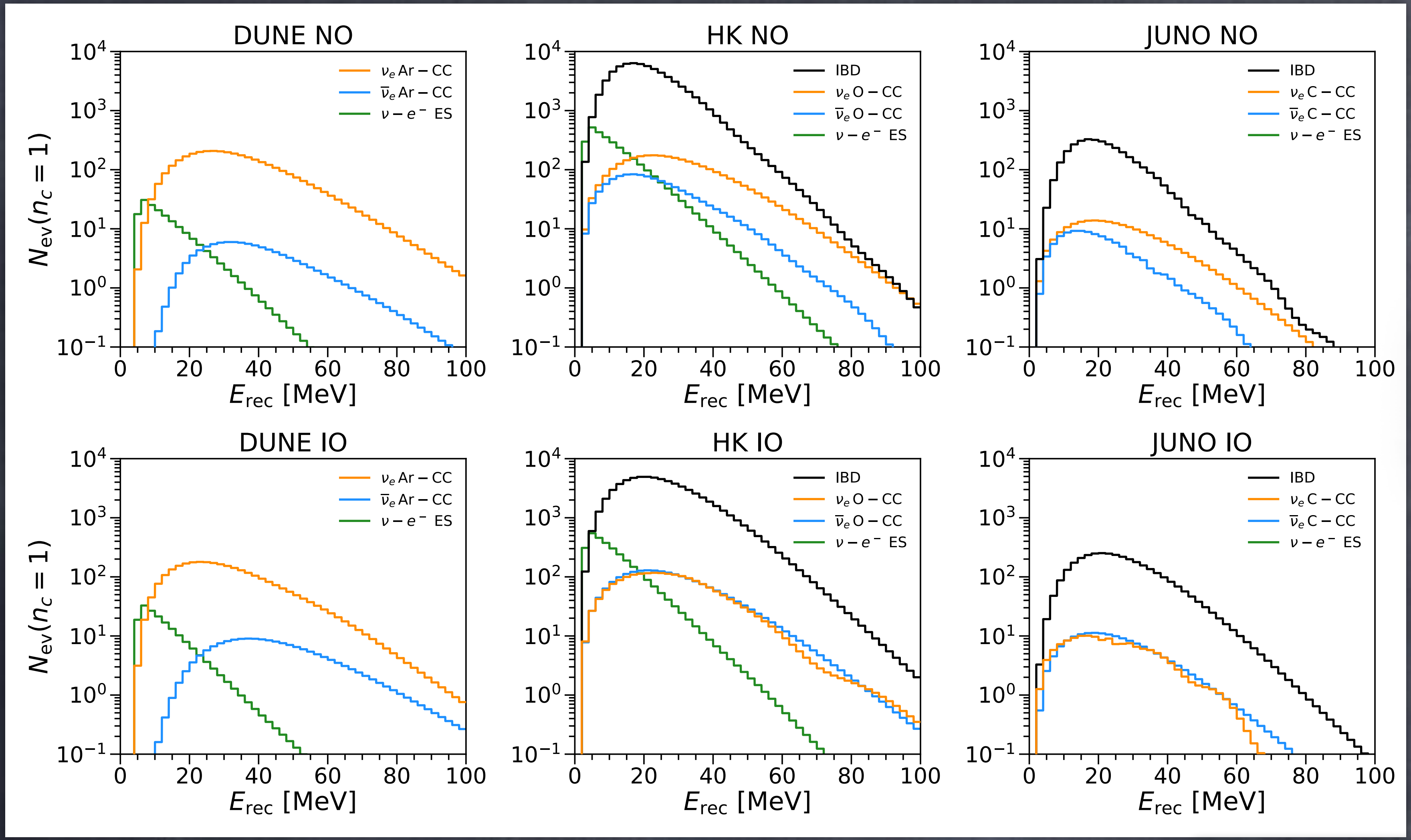


20 kton liquid scintillator

$\sigma_{\mathrm{JUNO}}/E_e \sim 0.01$

$$\mathrm{IBD}: \quad \bar{\nu}_e + p \to e^+ + n$$
$$\nu_e \mathrm{C-CC}: \quad \nu_e + {}^{12}\mathrm{C} \to e^- + X$$
$$\bar{\nu}_e \mathrm{C-CC}: \quad \bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + X$$
$$\nu - e^- \ \mathrm{ES}: \quad \nu + e^- \to \nu + e^-$$

Event distributions (for W20 simulation at 10 kpc)

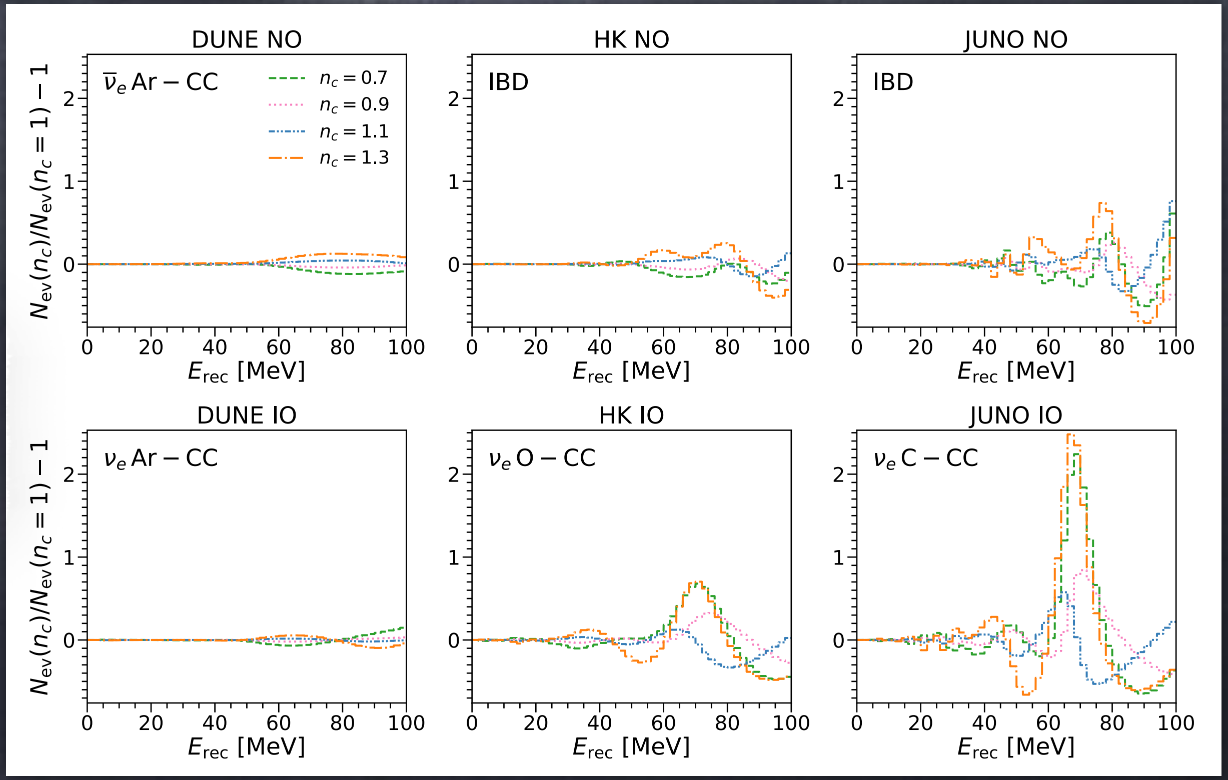


NO: matter effects for antineutrinos

Search for spectral distortions along the tails

IO: matter effects for neutrinos

R. Hajjar, O. Mena and SPR, arXiv:2303.09369

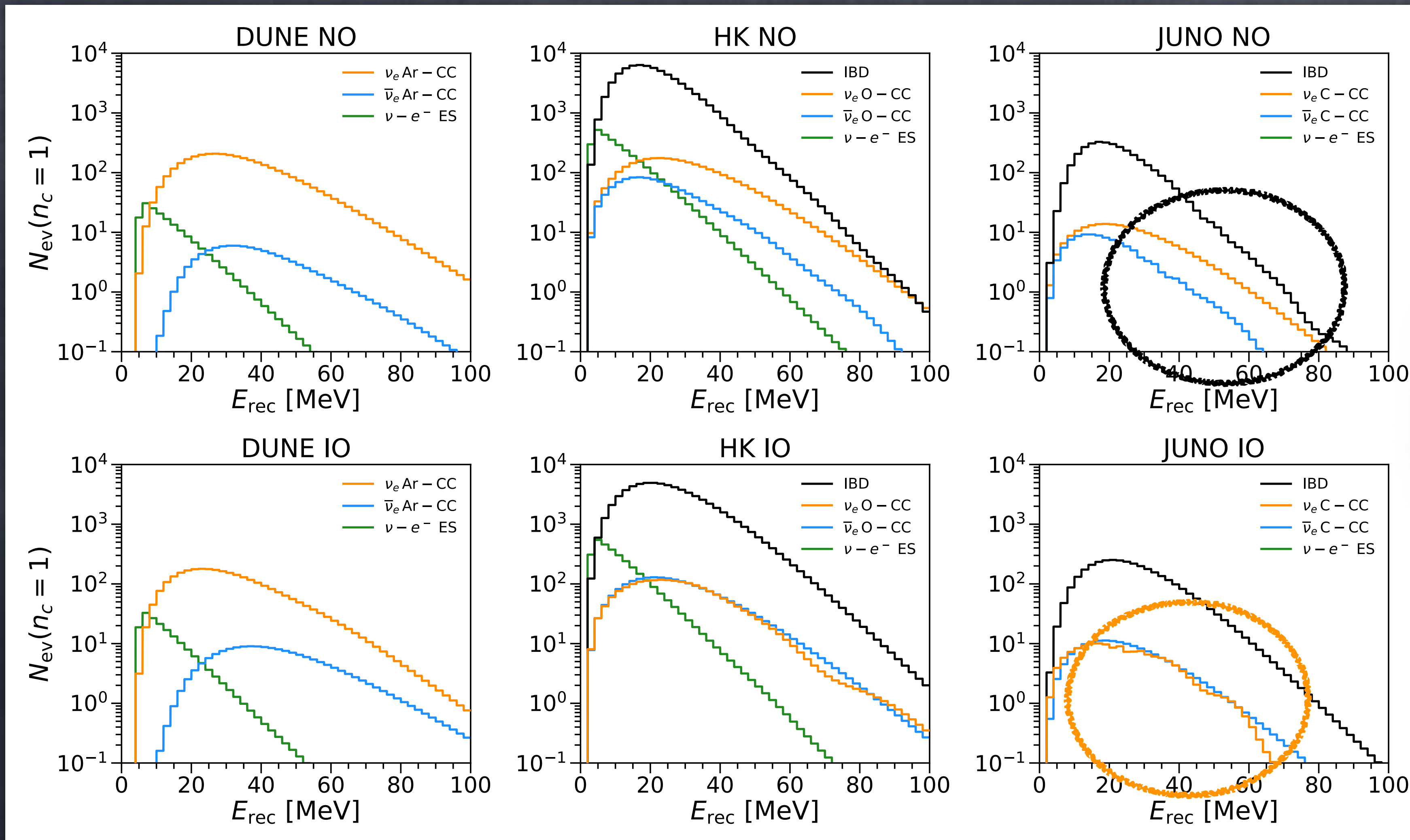


Two-layer Earth model imposing the Earth mass:
n_c = core density normalization
[$n_c = 1$ (PREM)]

energy resolution is critical for Earth tomography

Event distributions

(for W20 simulation at 10 kpc)



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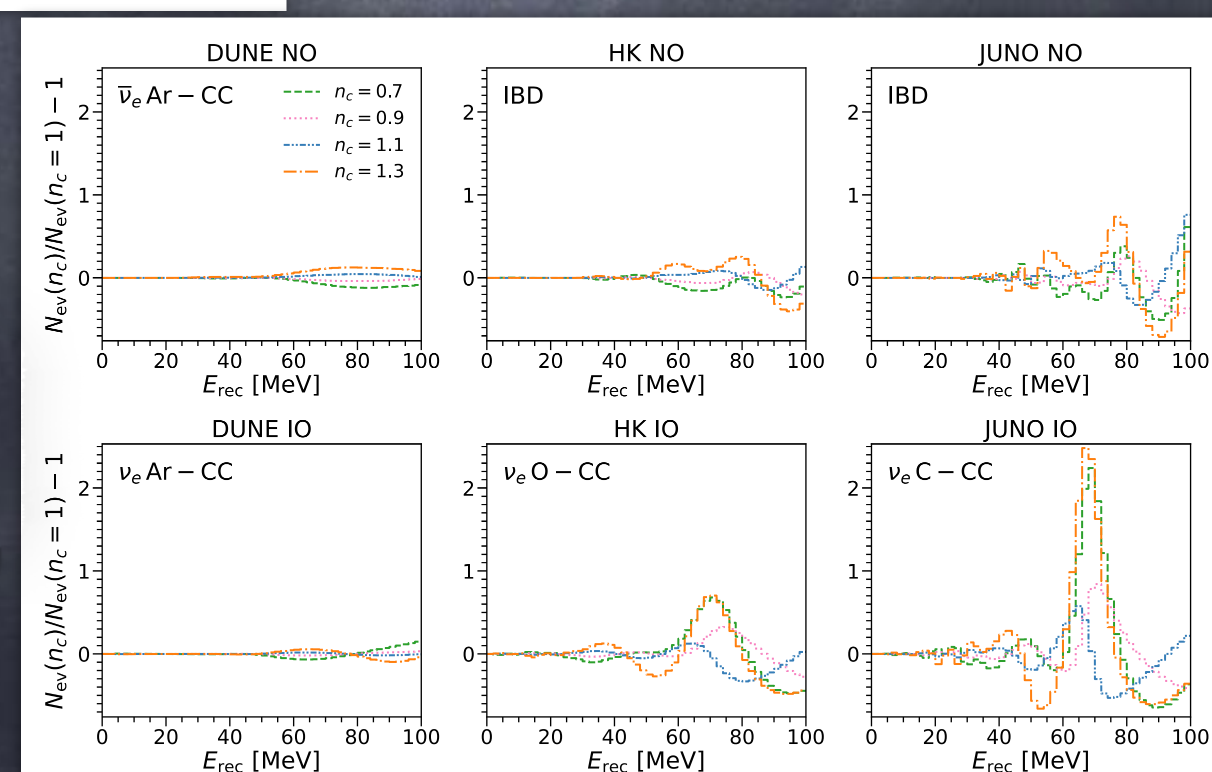
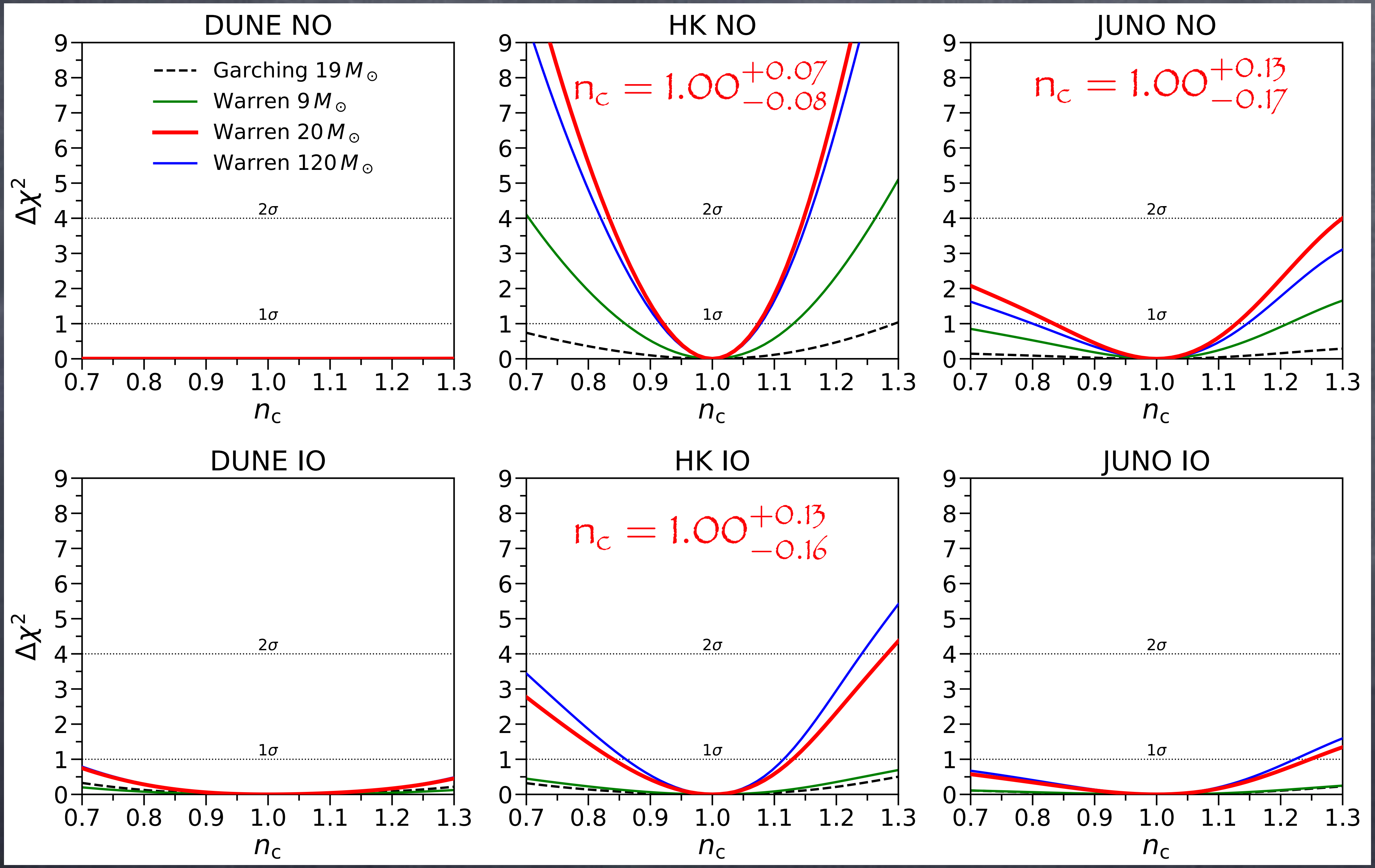


Dependence on the SN neutrino spectra

(in all analyses we assume a two-layer Earth model and we impose the constraint on the Earth mass)



R. Hajjar, O. Mena and SPR, arXiv:2303.09369

only if initial spectra are sufficiently different, Earth tomography would be possible

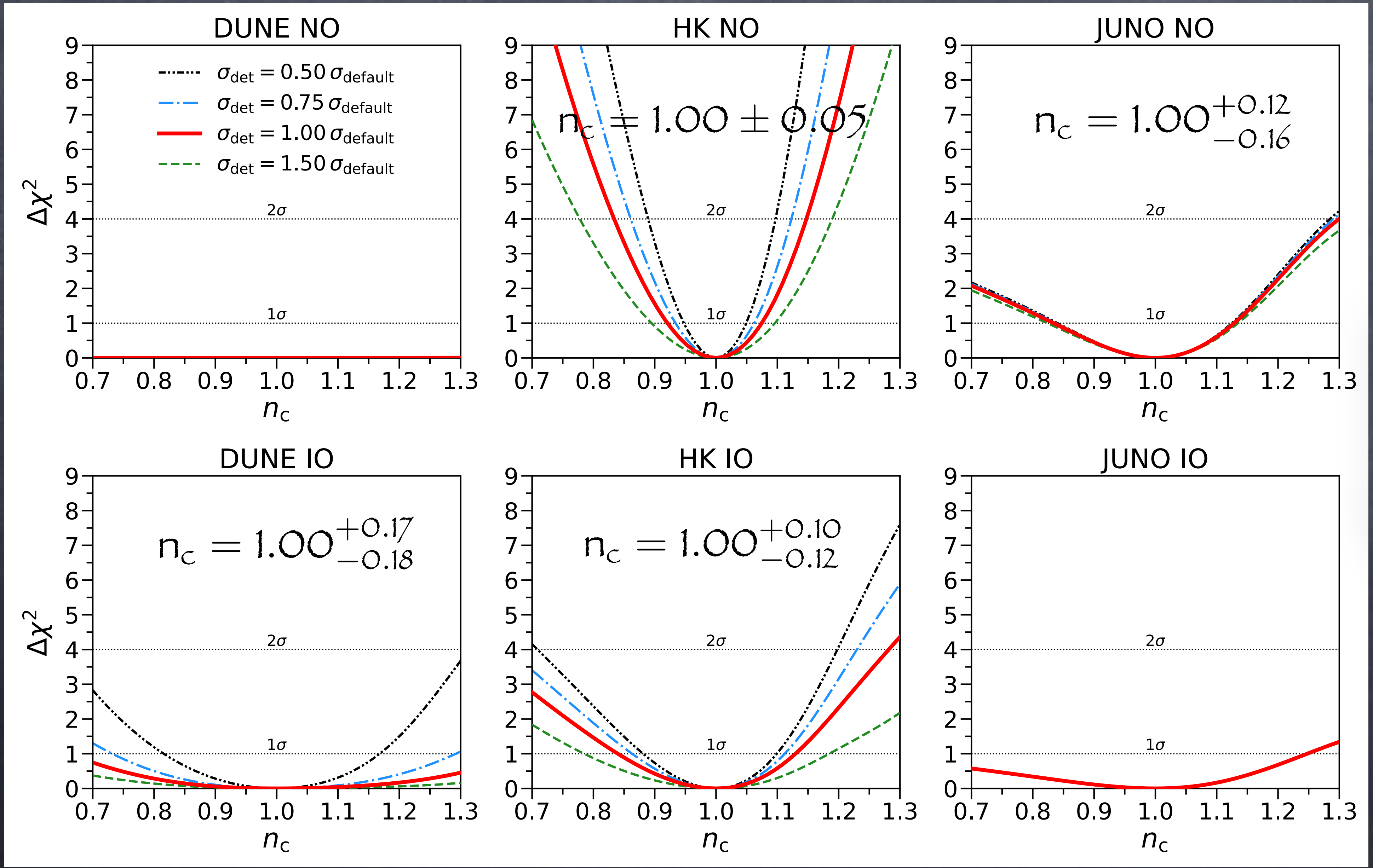
Dependence on the energy resolution

Attenuation (wash out) effect

A. N. Ioannisian and A Yu. Smirnov, Phys. Rev. Lett. 93:241801, 2004

A. N. Ioannisian, N. A. Kazarian, A Yu. Smirnov and D. Wyler, Phys. Rev. D71:033006, 2005

$$\lambda_{\rm att} \equiv \ell_0 \left(\frac{E_\nu}{\pi\, \sigma_E}\right) = 4209\ {\rm km} \left(\frac{E_\nu}{40\ {\rm MeV}}\right) \left(\frac{7.5\times 10^{-5}\ {\rm eV}^2}{\Delta m^2_{21}}\right) \left(\frac{0.1}{\sigma_E/E_\nu}\right)$$



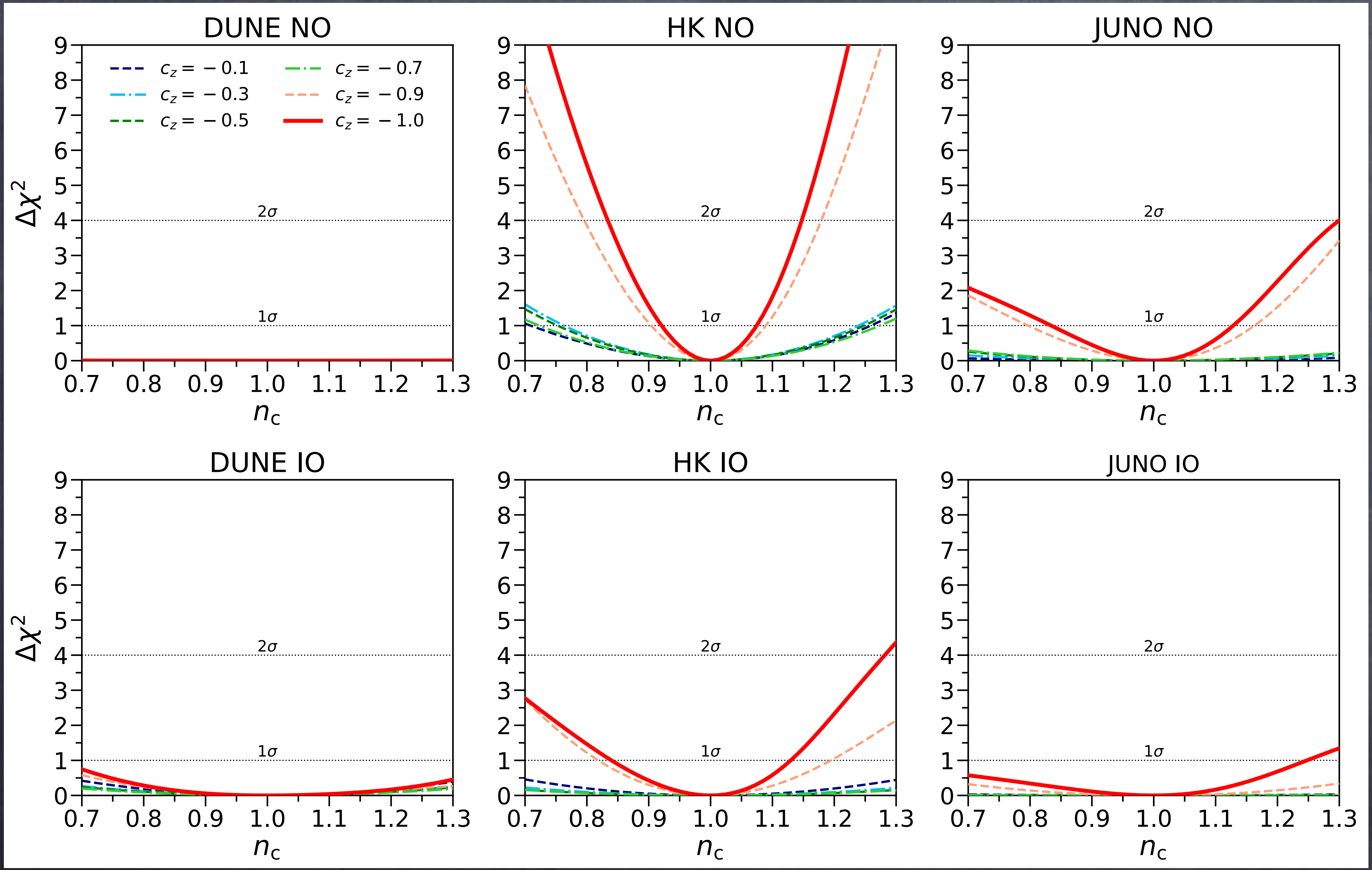
(for W20 simulation at 10 kpc)

Very little impact in JUNO: dominated by the neutrino energy spread in IBD

R. Hajjar, O. Mena and SPR, arXiv:2303.09369

Dependence on the SN direction

(for W20 simulation at 10 kpc)



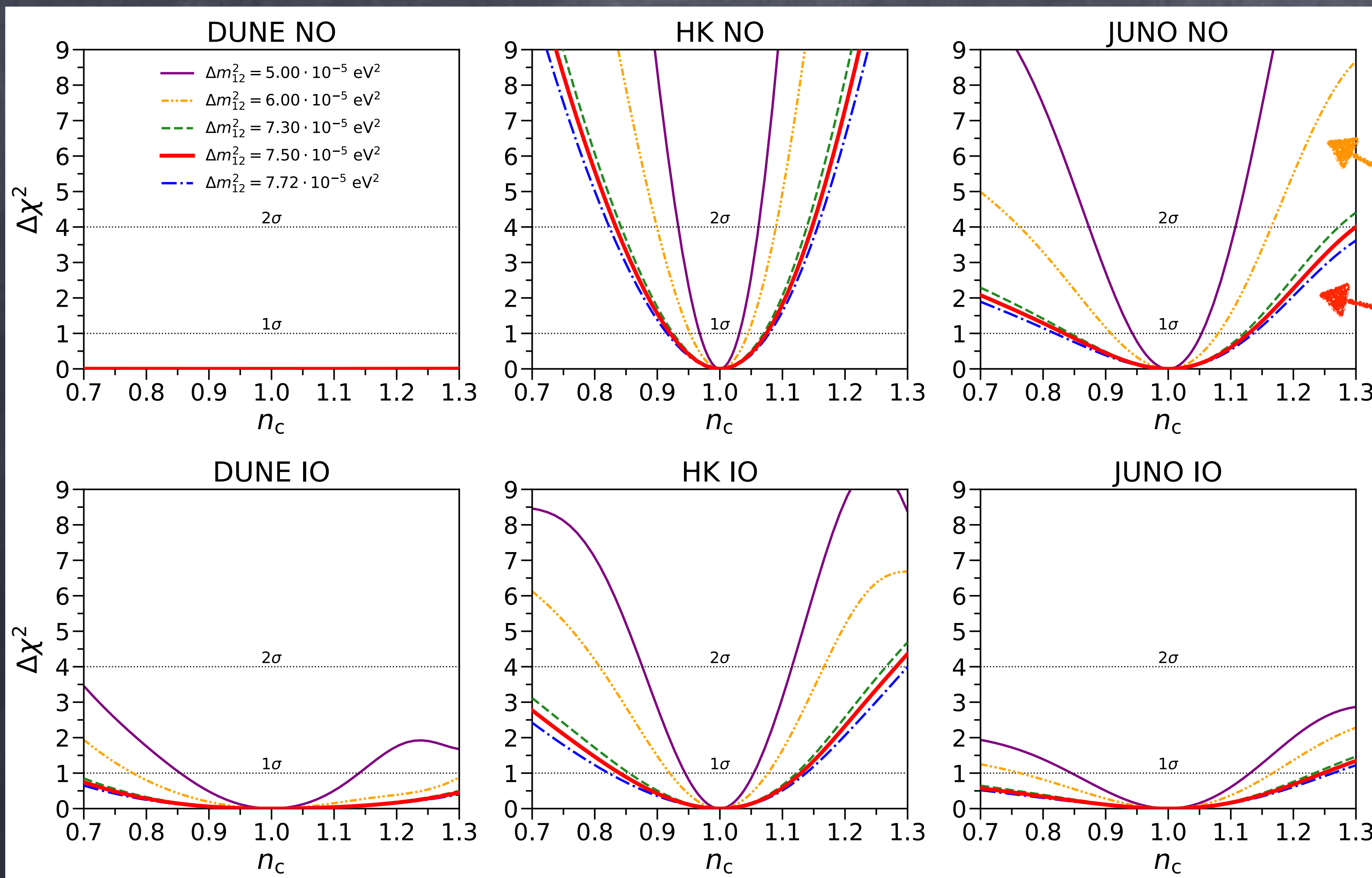
core-crossing is required

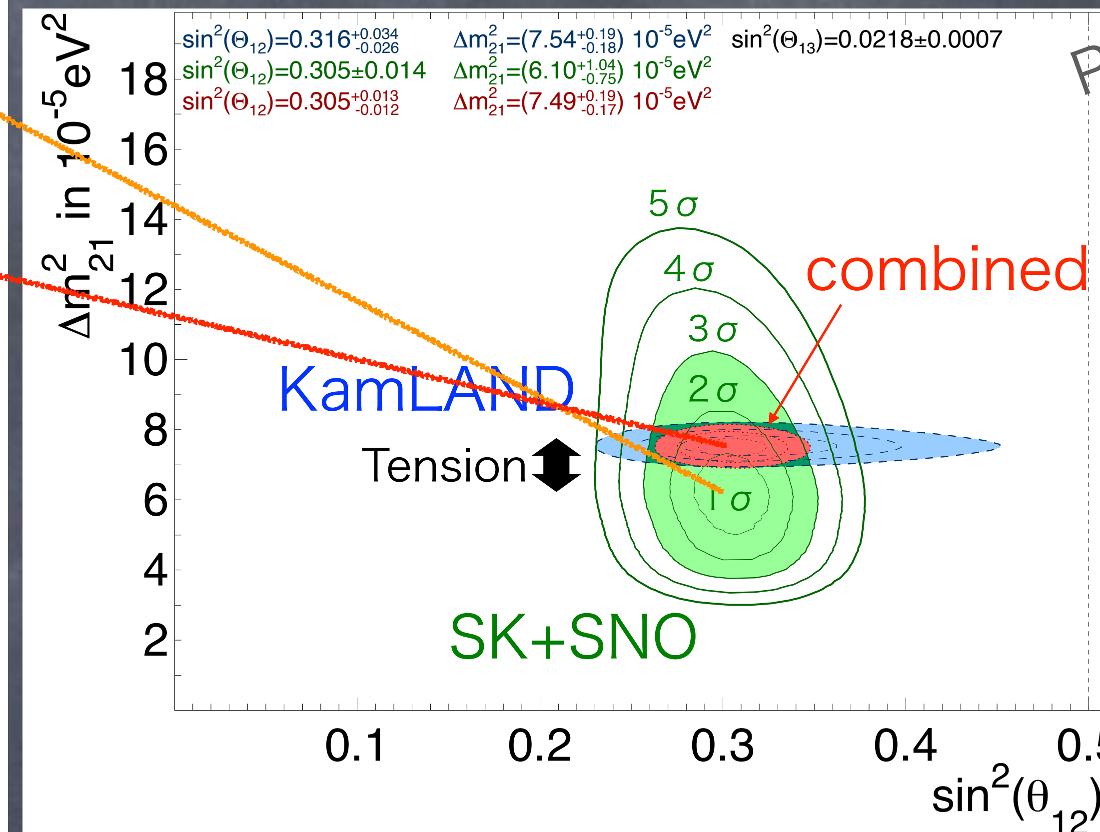
R. Hajjar, O. Mena and SPR, arXiv:2303.09369

Dependence on neutrino mixing parameters

Δm^2_{21}

(for W20 simulation at 10 kpc)

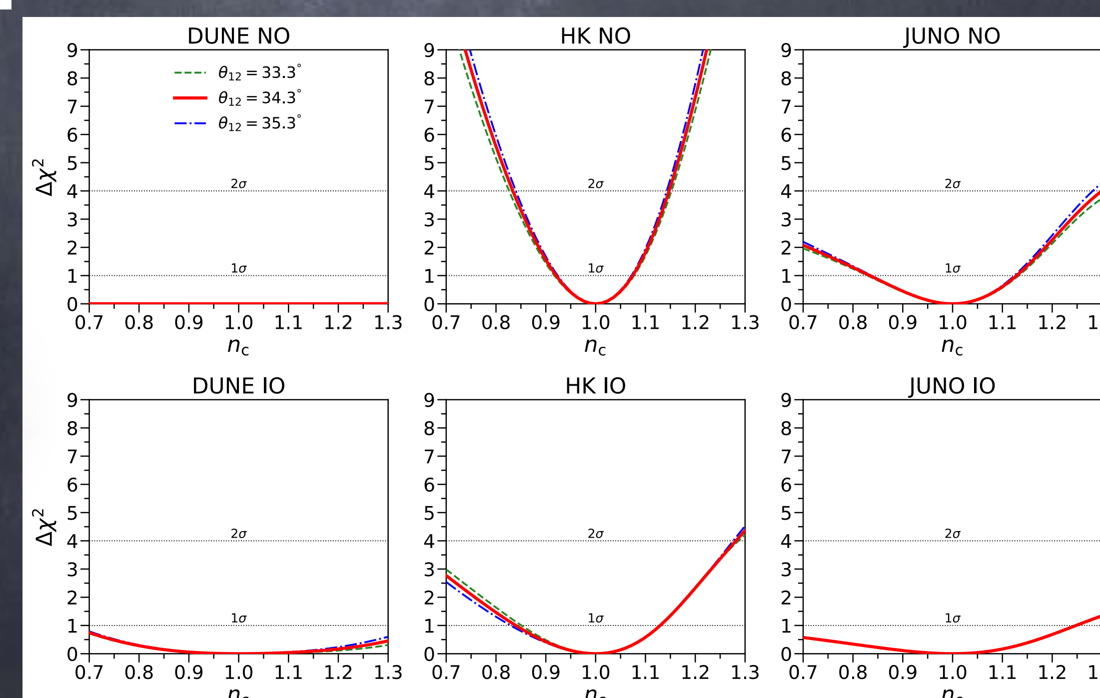




Y. Koshio, Talk at Neutrino 2022

R. Hajjar, O. Mena and SPR, arXiv:2303.09369

θ_{12}



very mild effect due to uncertainties

Conclusions

Neutrinos allow us to look inside the Earth in a completely different manner from standard techniques

Main neutrino tomography approaches:
oscillation and absorption tomography

After 45 years of being proposed, we performed the first Earth (absorption) tomography with neutrinos:
first measurement of the Earth's mass using only the weak force!

Analysis with 1 year of data,
but 10 years of data already collected by IceCube
… and other future experiments: KM3NeT, Baikal-GVD

Promising prospects with future detectors for neutrino oscillation tomography using atmospheric and supernova neutrinos

Edmund Halley,

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

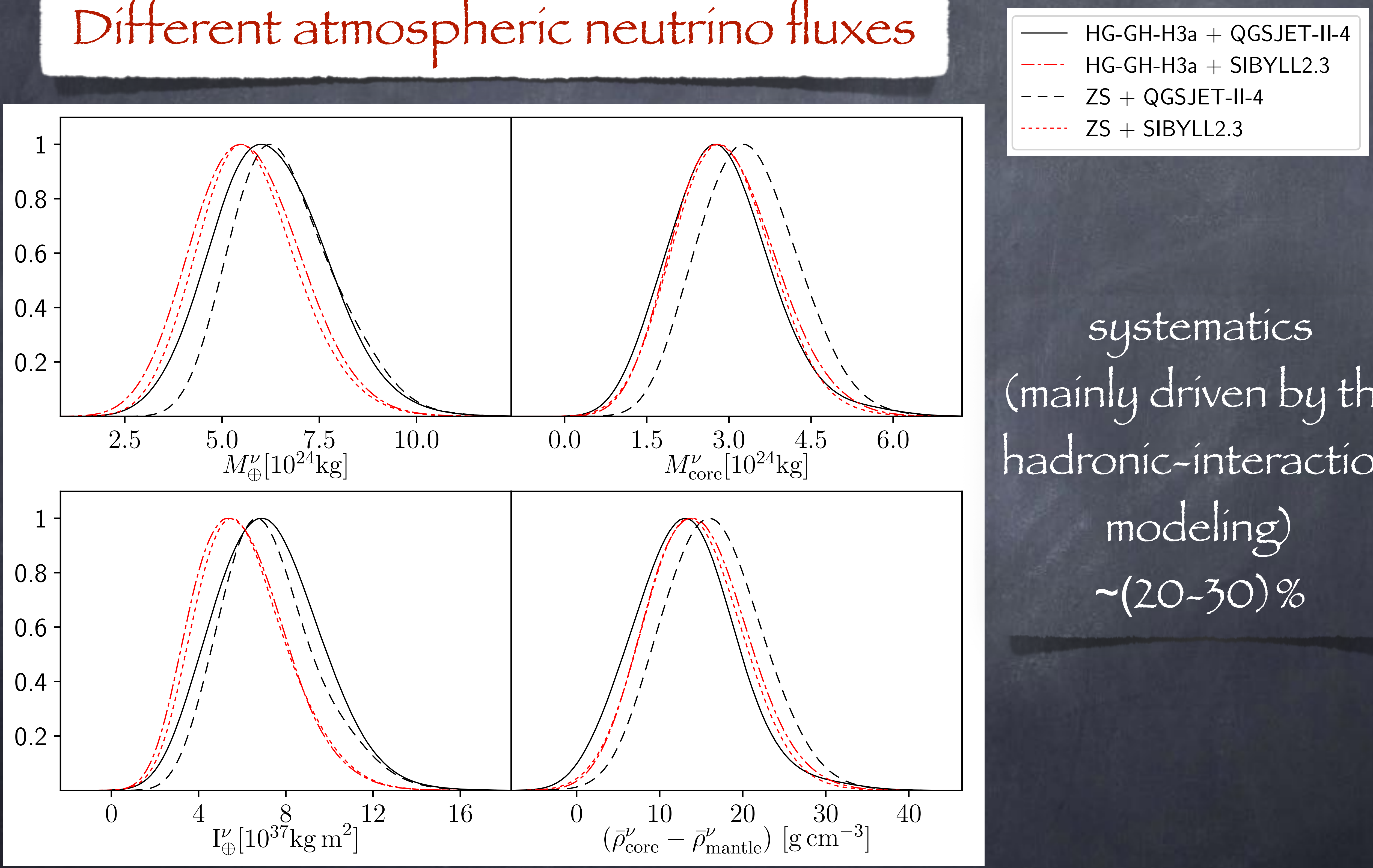
"what curiosity in the structure, what accuracy in the mixture and composition of the parts, ought not we to expect in the fabric of this globe"

Thanks!

Extras

Impact of discrete systematics

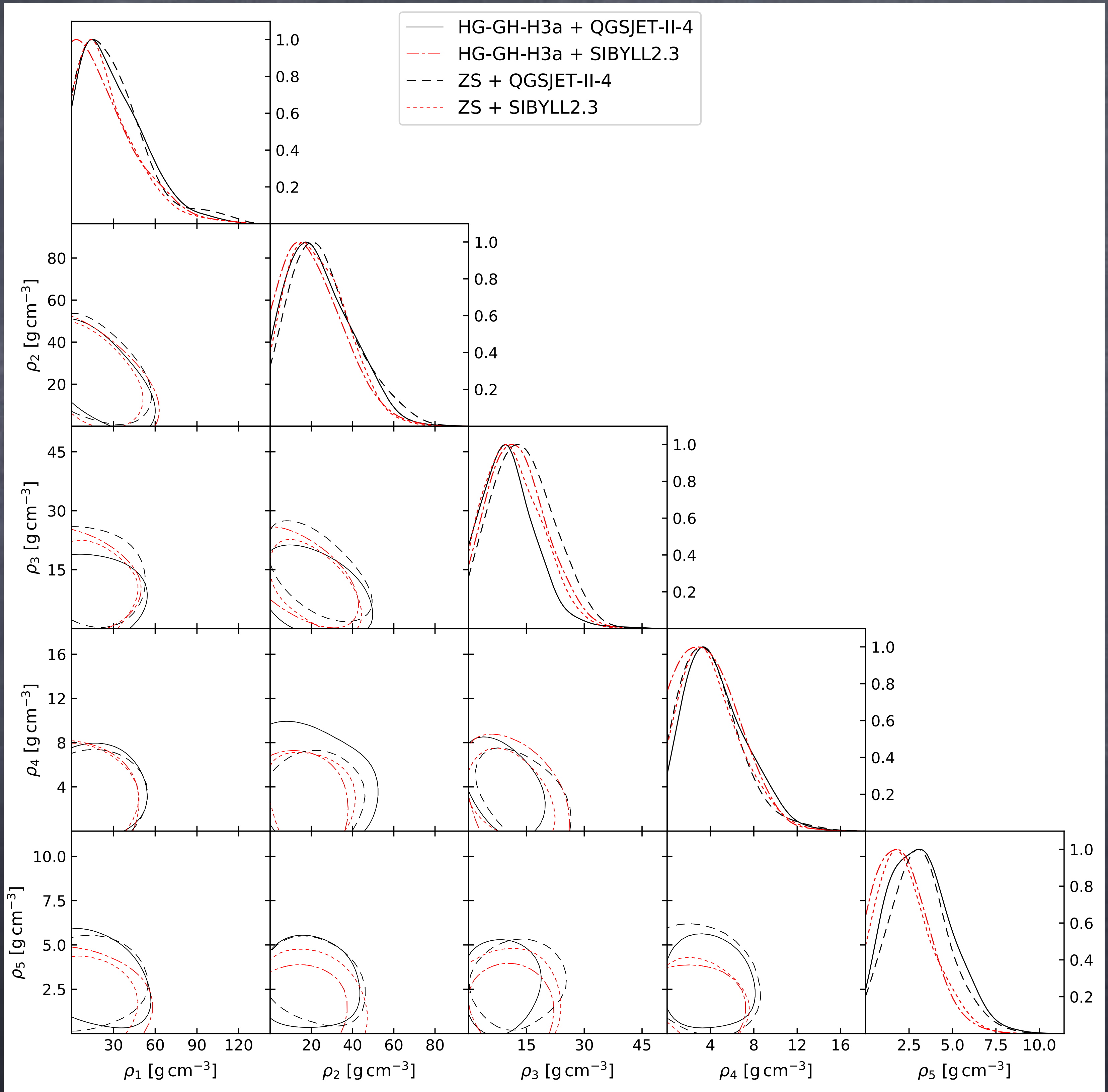
Different atmospheric neutrino fluxes



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

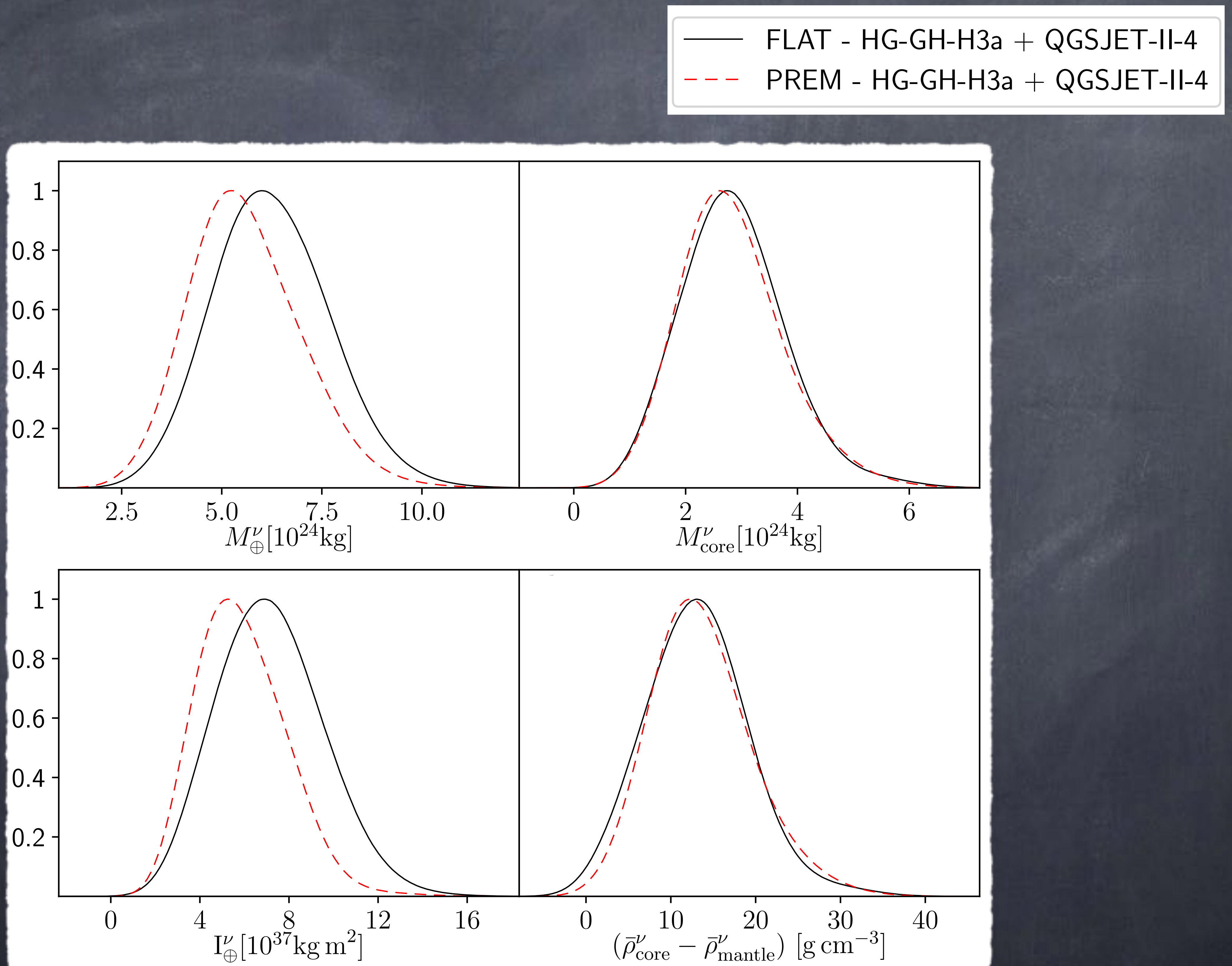
A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

neutrino fluxes: Correlations



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

Impact of density profile



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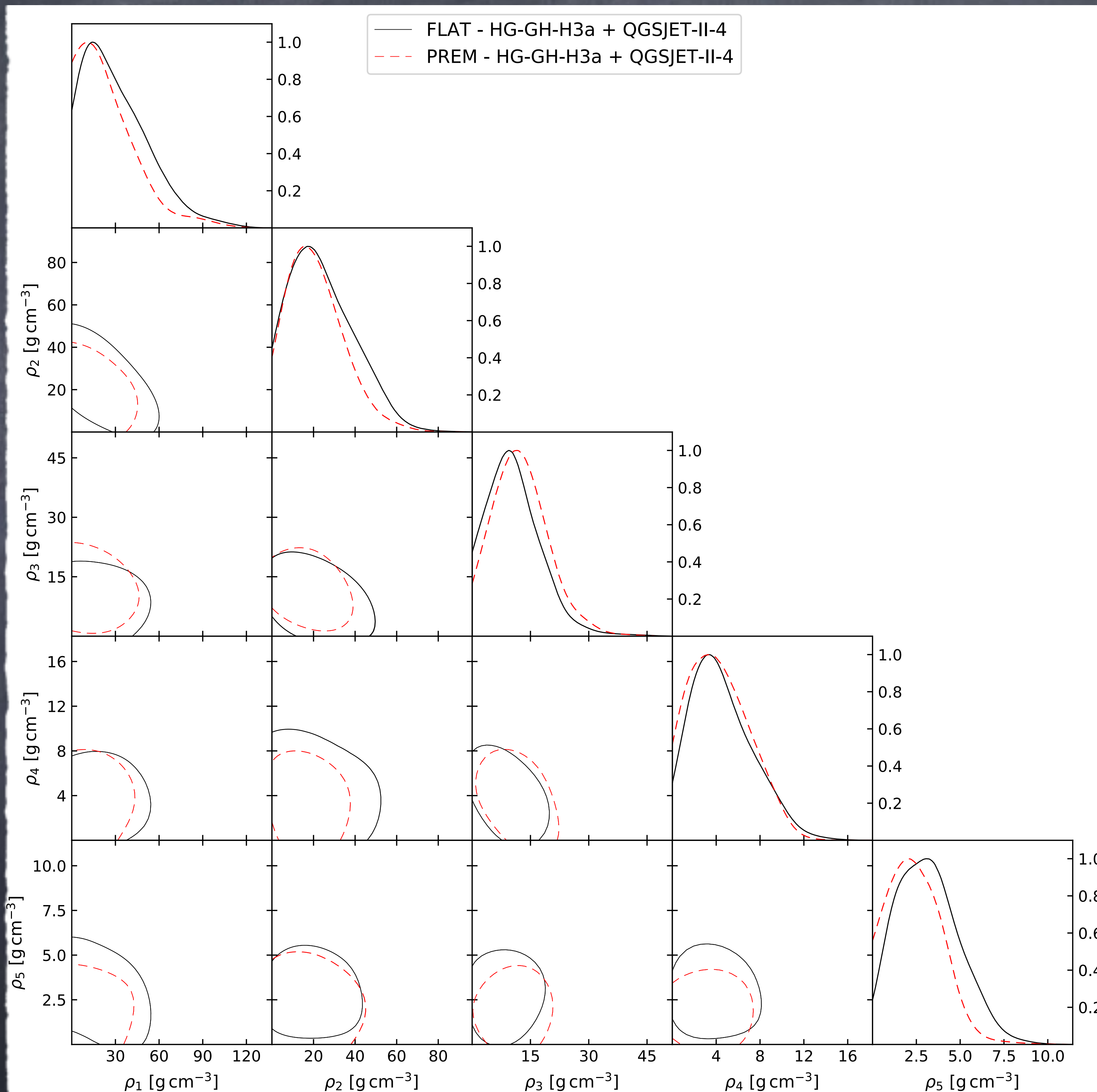
Impact of density profile:Correlations



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Impact of systematics

	Piecewise flat Earth's profile				PREM Earth's profile
	HG-GH-H3a + QGSJET-II-04	HG-GH-H3a + SIBYLL2.3	ZS + QGSJET-II-04	ZS + SIBYLL2.3	HG-GH-H3a + QGSJET-II-04
$M_{\oplus}^{\nu}$ [10^{24} kg]	$6.0^{+1.6}_{-1.3}$	$5.5^{+1.5}_{-1.3}$	$6.2^{+1.4}_{-1.2}$	$5.5^{+1.3}_{-1.2}$	$5.3^{+1.5}_{-1.3}$
$M_{\rm core}^{\nu}$ [10^{24} kg]	$2.72^{+0.97}_{-0.89}$	$2.79^{+0.98}_{-0.85}$	$3.27^{+0.92}_{-0.89}$	$2.84^{+0.89}_{-0.88}$	$2.62^{+0.97}_{-0.84}$
$I_{\oplus}^{\nu}$ [10^{37} kg cm^2]	6.9 ± 2.4	$5.4^{+2.3}_{-1.9}$	$6.7^{+2.3}_{-2.0}$	$5.5^{+2.2}_{-1.9}$	$5.3^{+2.3}_{-1.7}$
$\bar{\rho}_{\rm core}^{\nu} - \bar{\rho}_{\rm mantle}^{\nu}$ [g/cm^3]	$13.1^{+5.8}_{-6.3}$	$14.0^{+6.0}_{-5.9}$	$15.9^{+6.0}_{-5.9}$	$13.5^{+6.1}_{-5.5}$	$12.3^{+6.3}_{-5.4}$
$p -$ value mantle denser than core	1.1×10^{-2}	2.4×10^{-3}	9.4×10^{-4}	4.6×10^{-3}	3.8×10^{-3}

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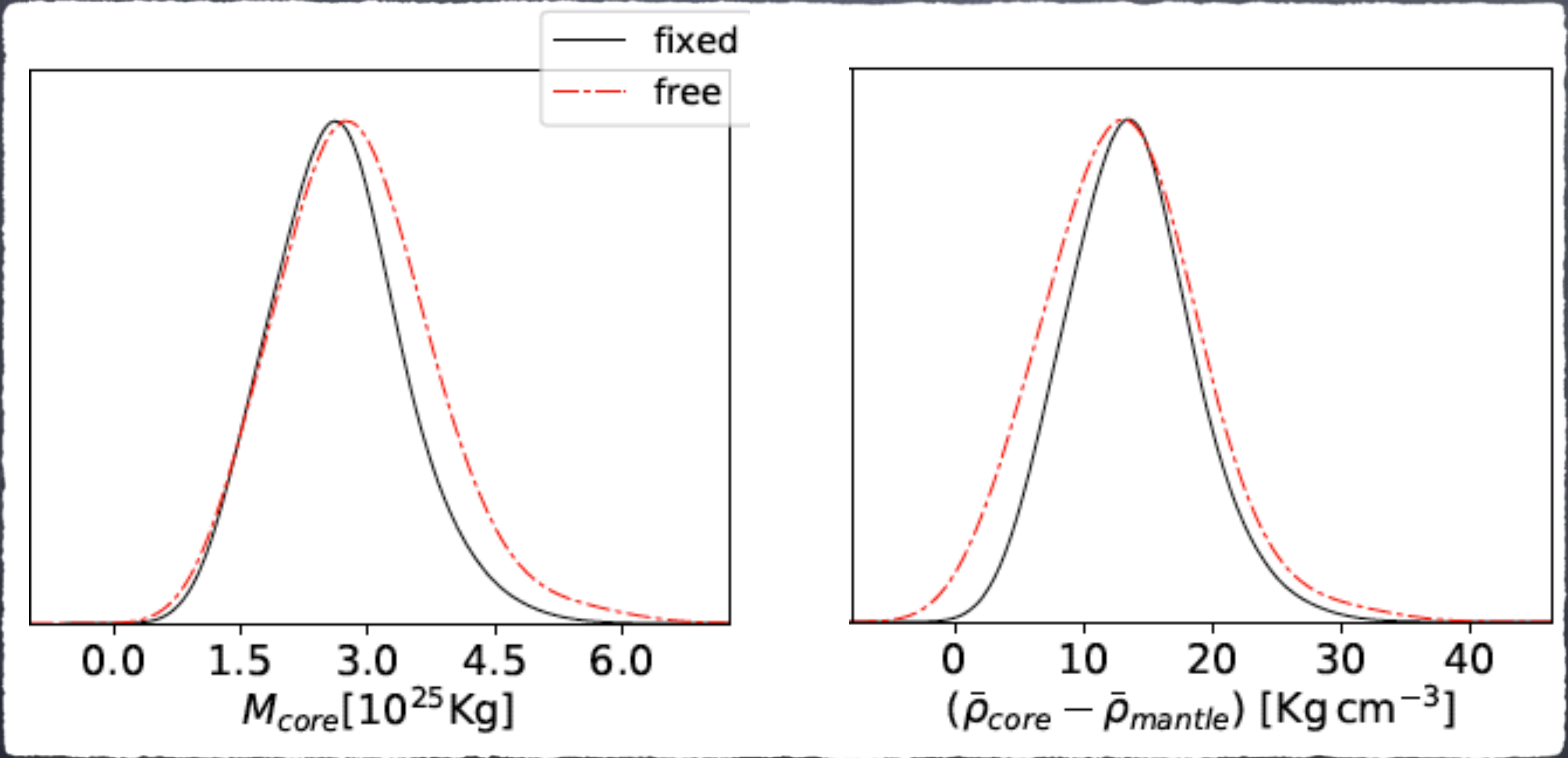
Adding gravity constraints



Density of the mantle determined at ~4%