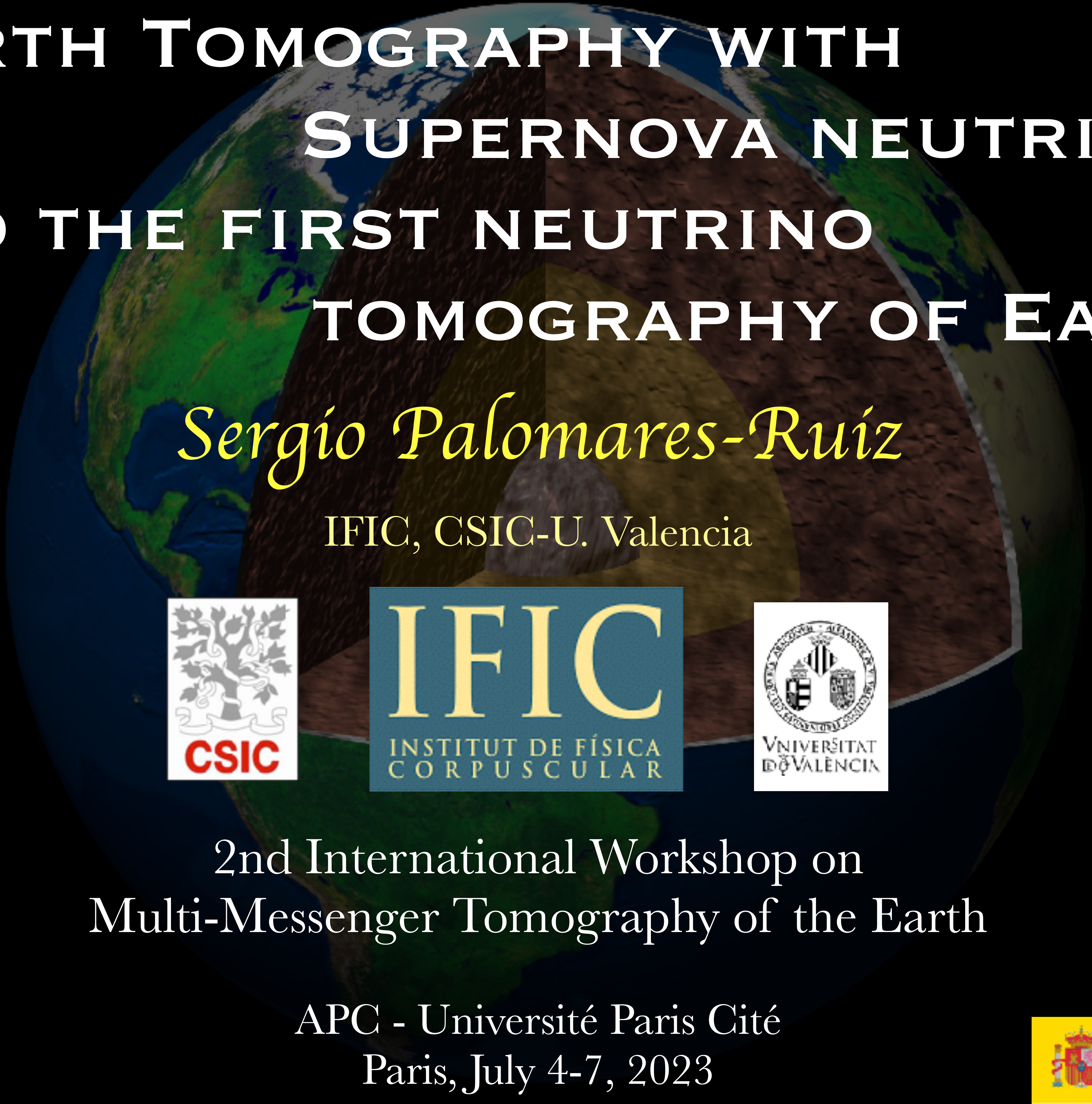


Earth Tomography with Supernova neutrinos and the first neutrino tomography of Earth

Sergio Palomares-Ruiz

IFIC, CSIC-U. Valencia

2nd International Workshop on
Multi-Messenger Tomography of the Earth

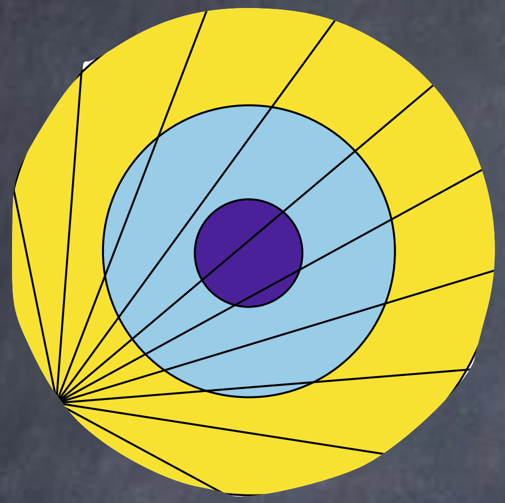
APC - Université Paris Cité
Paris, July 4-7, 2023

MINISTERIO DE CIENCIA E INNOVACIÓN

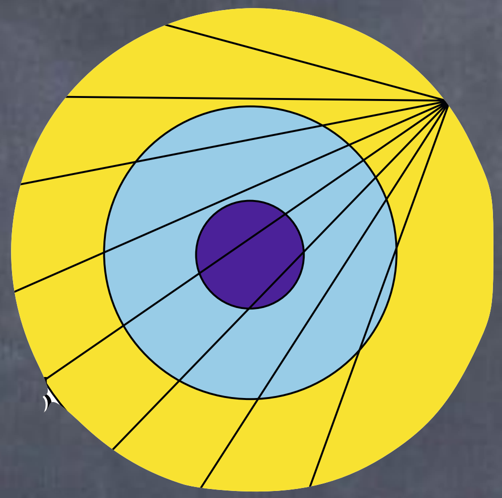
Review: W. Winter, Earth, Moon and Planets 99:285, 2006

NEUTRINO EARTH TOMOGRAPHY: APPROACHES

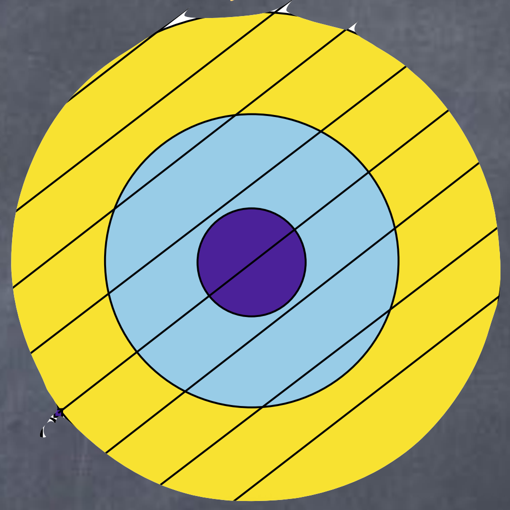
(quasi) isotropic flux



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

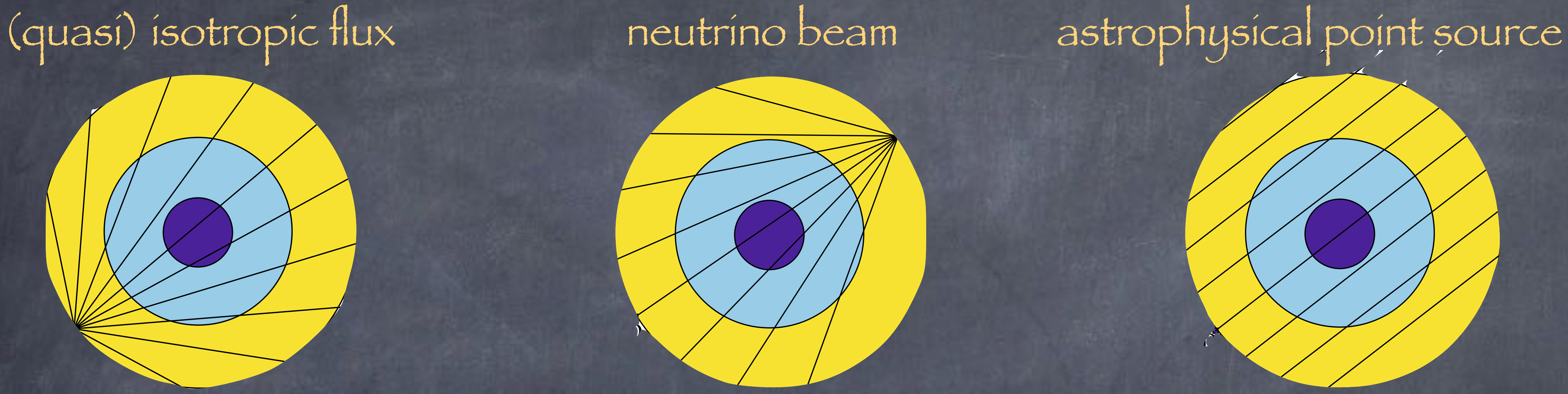
sensitive to nucleon density

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

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

Review: W. Winter, Earth, Moon and Planets 99:285, 2006

NEUTRINO EARTH TOMOGRAPHY: APPROACHES



oscillation 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

absorption tomography

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

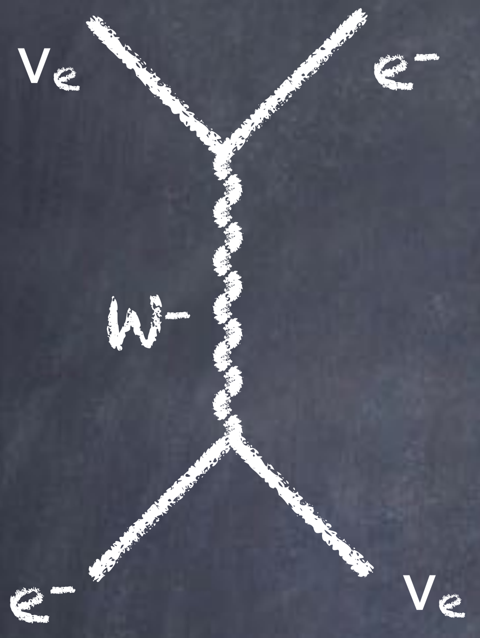
Atmospheric neutrinos
M. C. González-García, F. Halzen, M. Maltoni and H. K. M. Tanaka, Phys. Rev. Lett. 100:061802, 2008

Man-made beams
A. Placci and E. Zavattini, CERN report 1973
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

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

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

coherent forward scattering

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

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

phase shift

incoherent scattering

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

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

$$\sigma \propto G_F^2$$

absorption

NEUTRINO MATTER EFFECTS

tiny Δn: a matter of scales

coherent forward scattering

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

absorption

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

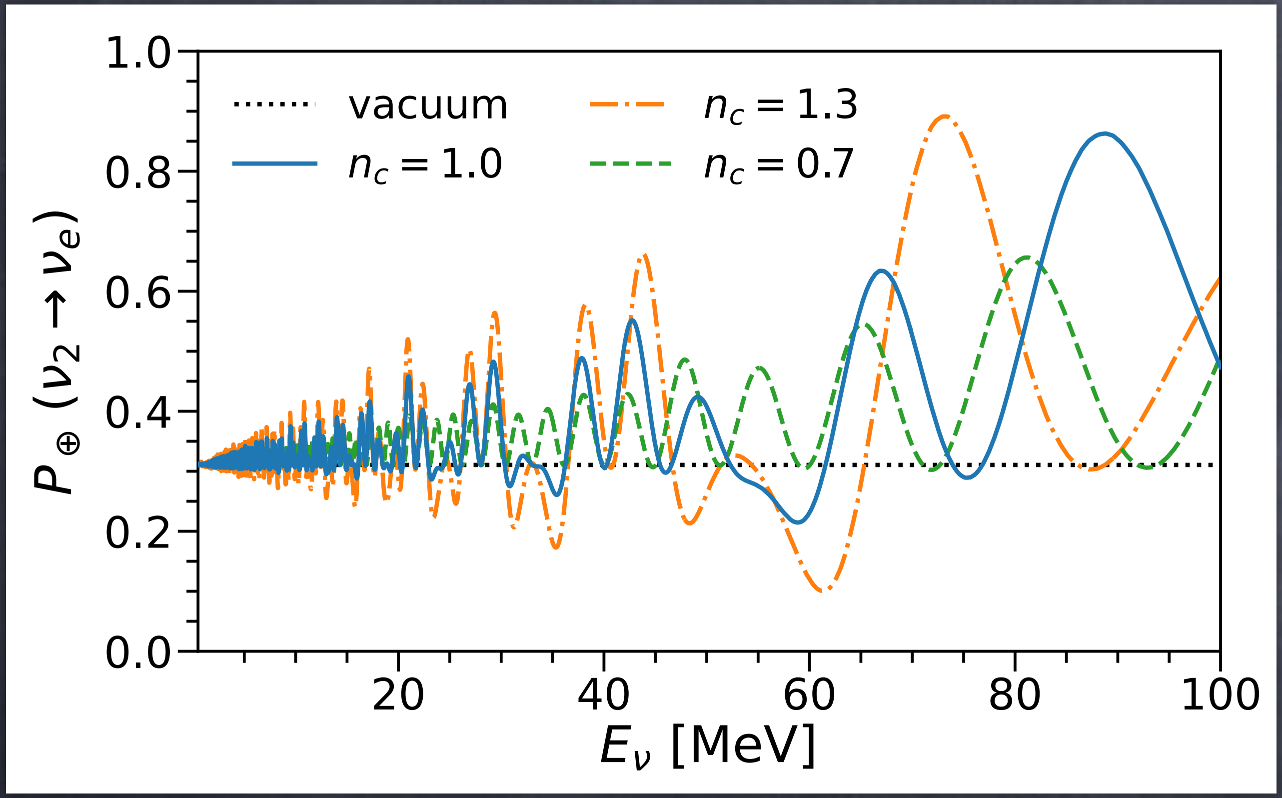
NEUTRINO OSCILLATION TOMOGRAPHY

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

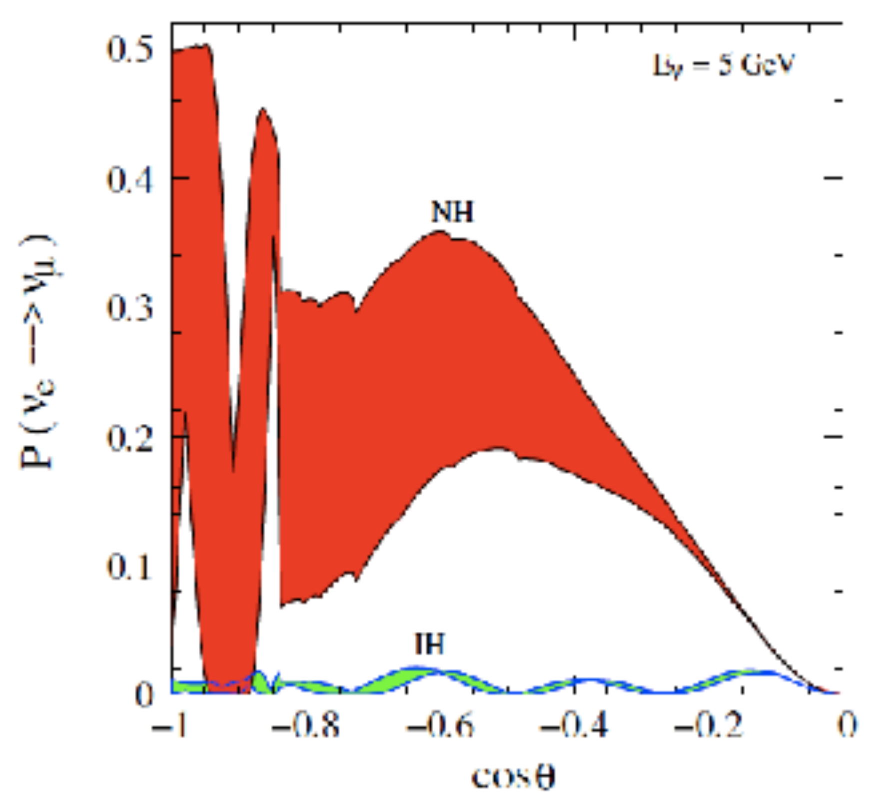
(solar and supernova neutrinos)



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

Δm^2_{31} – driven matter effect

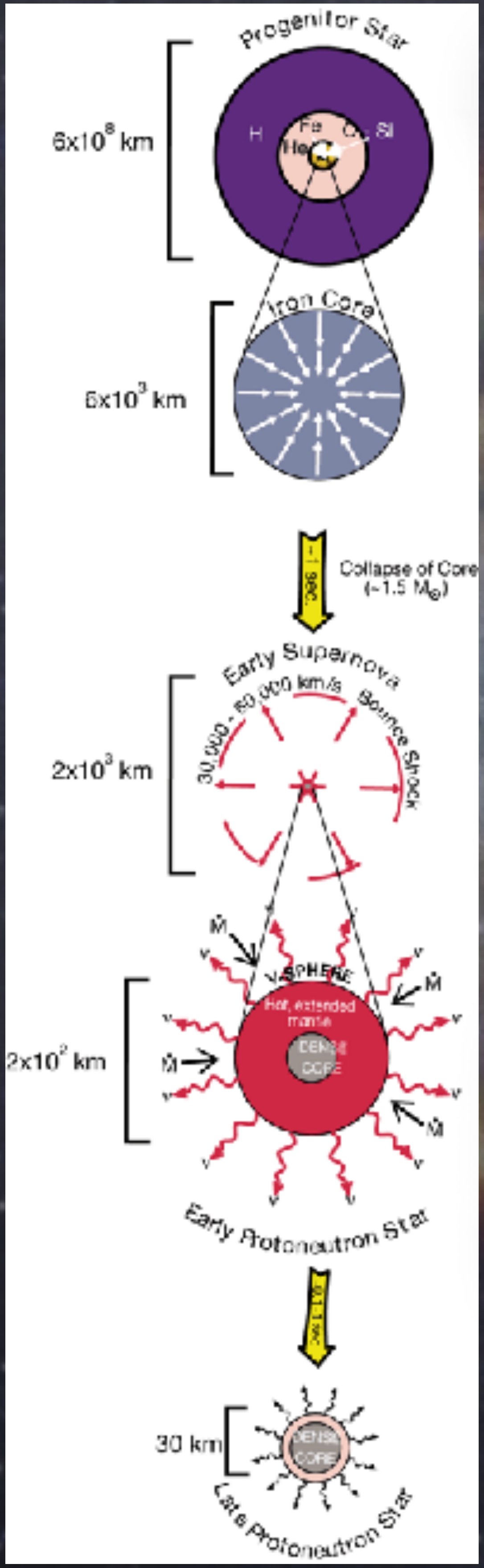
(atmospheric neutrinos)



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

Matter effect can be resonant for different directions and energies

CORE-COLLAPSE SUPERNOVA



Gravitational instability

Neutrino trapping

Core bounce and shock formation

Shock propagation and ν_e burst

Shock stagnation and revival by neutrino heating

PNS cooling

Neutrinos are the death rattles of massive stars: they carry 99% of the released energy ($\sim 10^{53}$ erg)

Average neutrino energy ~ 10-15 MeV …with long tails

Neutrino emission time ~ 10 s

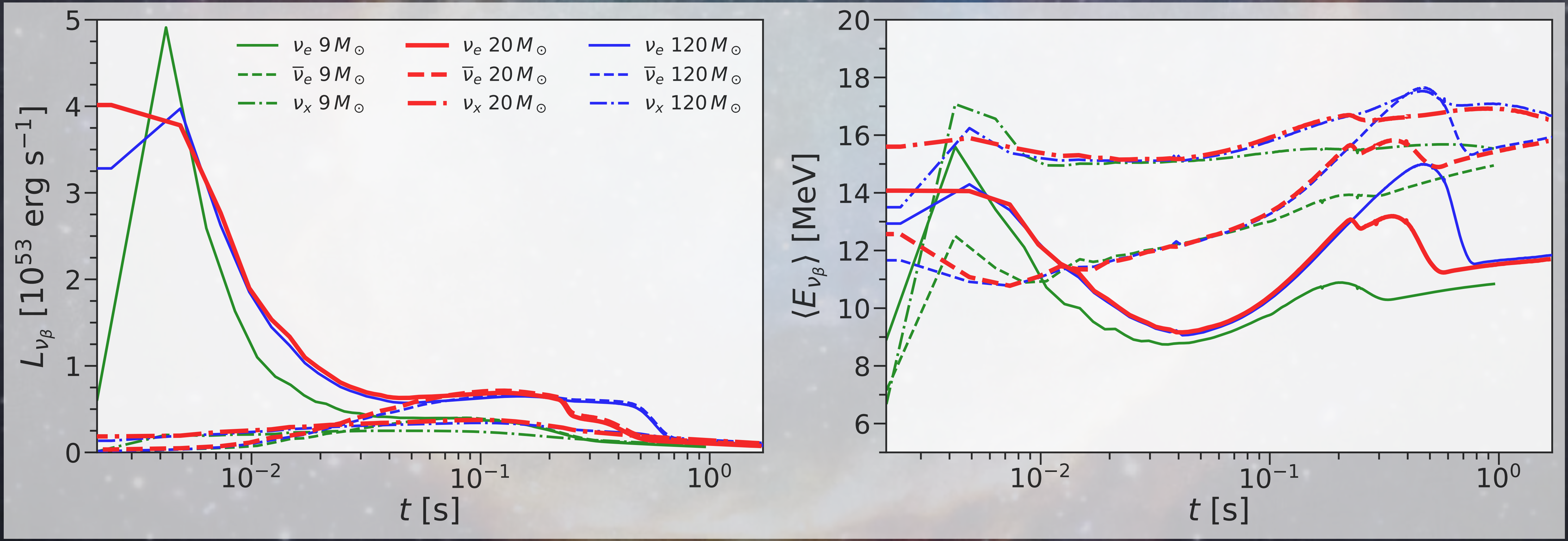
A. Burrows, Nature 403, 727 (2000)

SUPERNOVA NEUTRINOS (MeV)

Tomography first considered in M. Lindner, T. Ohlsson, R. Tomàs and W. Winter, Astropart. Phys. 19:755, 2003

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

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



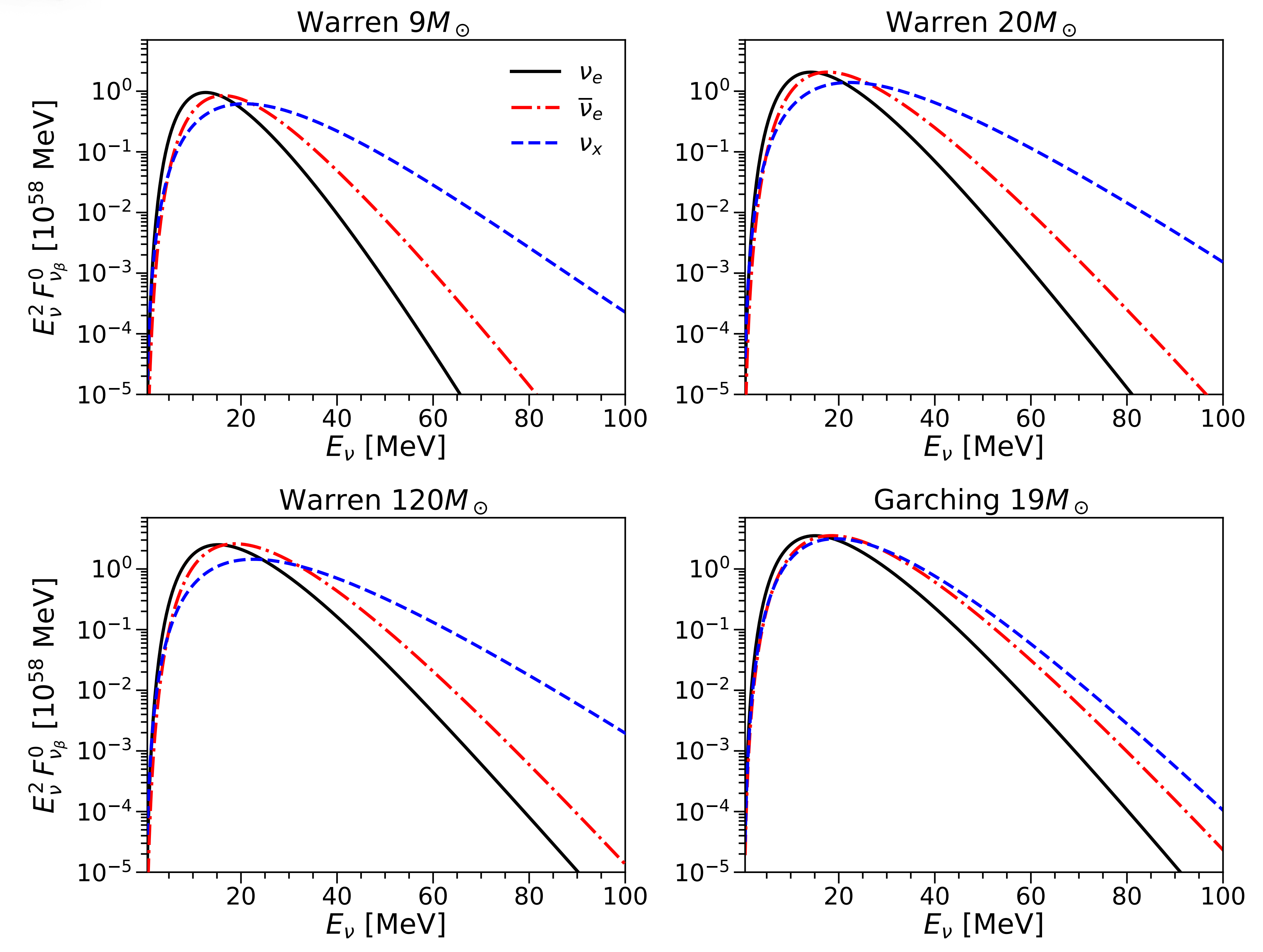
From the simulations of M. L. Warren, S. M. Couch, E. P. O'Connor and V. Morozova, Astrophys. J. 898:139, 2020

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

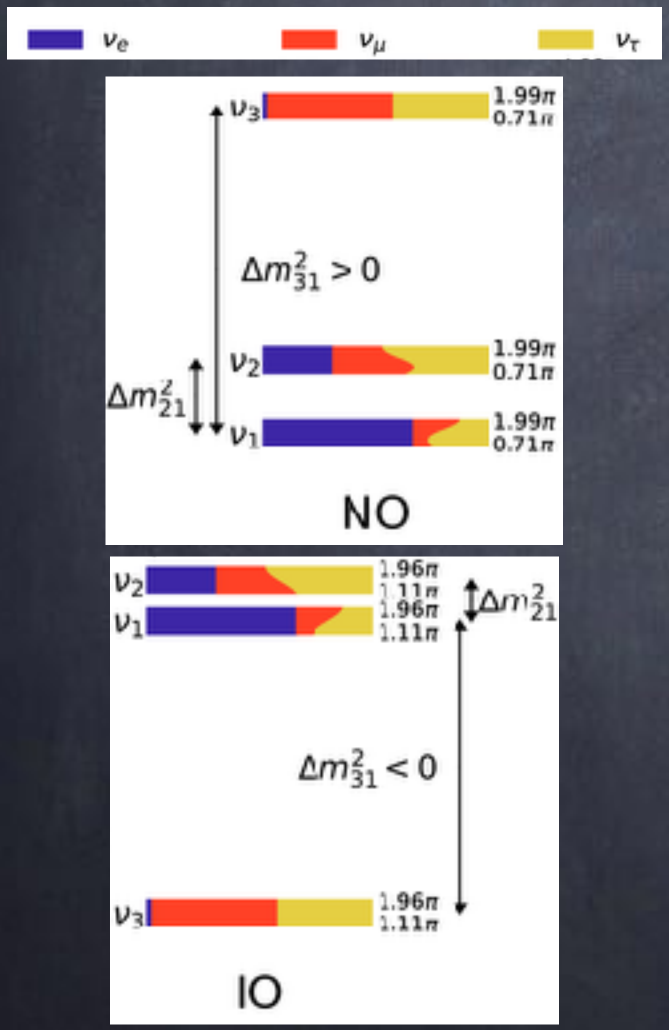
SUPERNOVA NEUTRINO SPECTRA AT EARTH

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,

which depends on the neutrino mass ordering



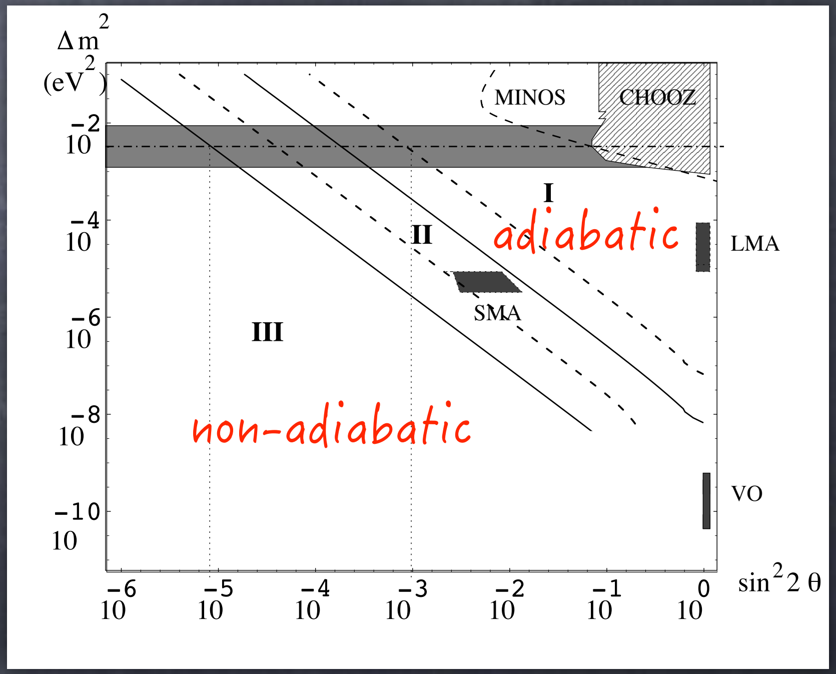
P. F. Salas et al., JHEP 02:071, 2021

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

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

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

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



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

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

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

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

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

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

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

2-neutrino probability for constant density:

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

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

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

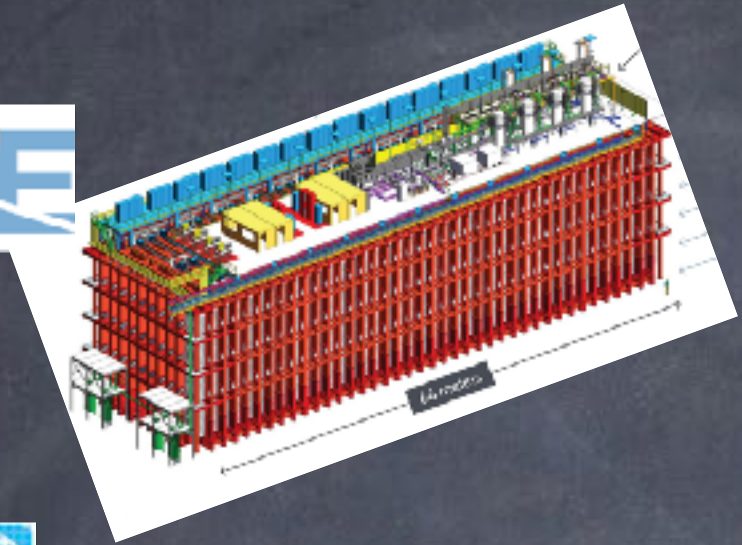
$$\boxed{\epsilon \equiv \frac{2 E_\nu V}{\Delta m^2_{21}} \simeq 0.12 \left(\frac{E_\nu}{20\ \mathrm{MeV}}\right) \left(\frac{Y_e \rho}{3\ \mathrm{g/cm^3}}\right) \left(\frac{7.5\times 10^{-5}\ \mathrm{eV}^2}{\Delta m^2_{21}}\right)}$$

Regeneration factor:

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

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

FUTURE NEUTRINO DETECTORS



40 kton liquid Argon

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

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

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

$$\nu - e^-\ \mathrm{ES}: \quad \nu + e^- \to \nu + e^-$$

Important to use the differential IBD cross section: $\Delta E_e \sim 2\, E_\nu / m_p$

2x187 kton water Cherenkov
with Gadolinium

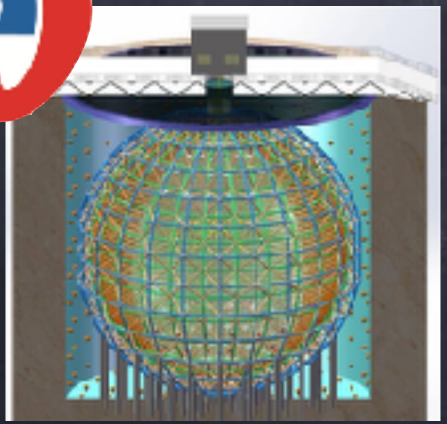
$\sigma_{\mathrm{HK}}/E_e \sim 0.08$

$$\mathrm{IBD}: \quad \bar{\nu}_e + p \to e^+ + n$$

$$\nu_e\mathrm{O}-\mathrm{CC}: \quad \nu_e + {}^{16}\mathrm{O} \to e^- + X$$

$$\bar{\nu}_e\mathrm{O}-\mathrm{CC}: \quad \bar{\nu}_e + {}^{16}\mathrm{O} \to e^+ + X$$

$$\nu - e^-\ \mathrm{ES}: \quad \nu + e^- \to \nu + e^-$$



20 kton liquid scintillator

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

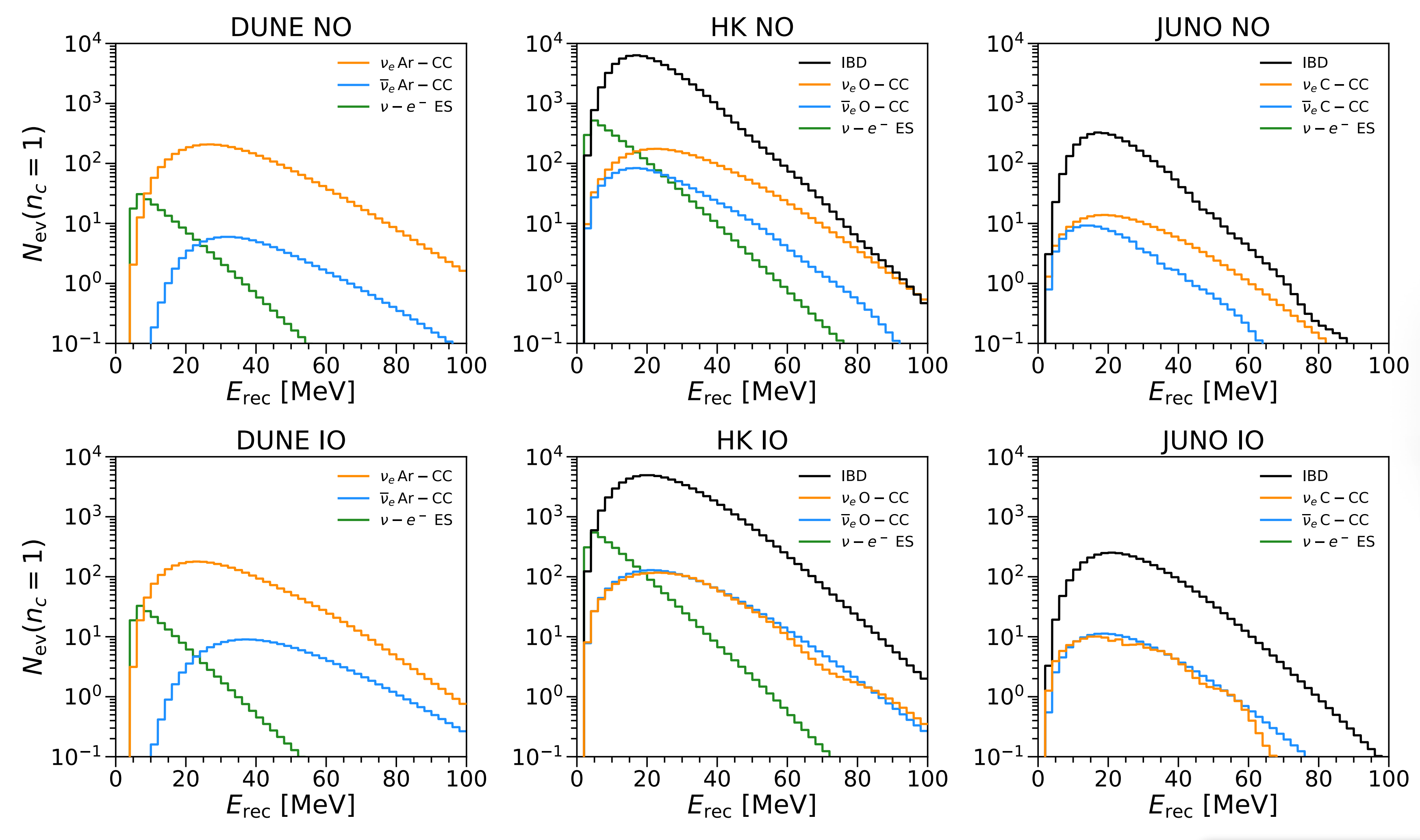
$$\mathrm{IBD}: \quad \bar{\nu}_e + p \to e^+ + n$$

$$\nu_e\mathrm{C}-\mathrm{CC}: \quad \nu_e + {}^{12}\mathrm{C} \to e^- + X$$

$$\bar{\nu}_e\mathrm{C}-\mathrm{CC}: \quad \bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + X$$

$$\nu - e^-\ \mathrm{ES}: \quad \nu + e^- \to \nu + e^-$$

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

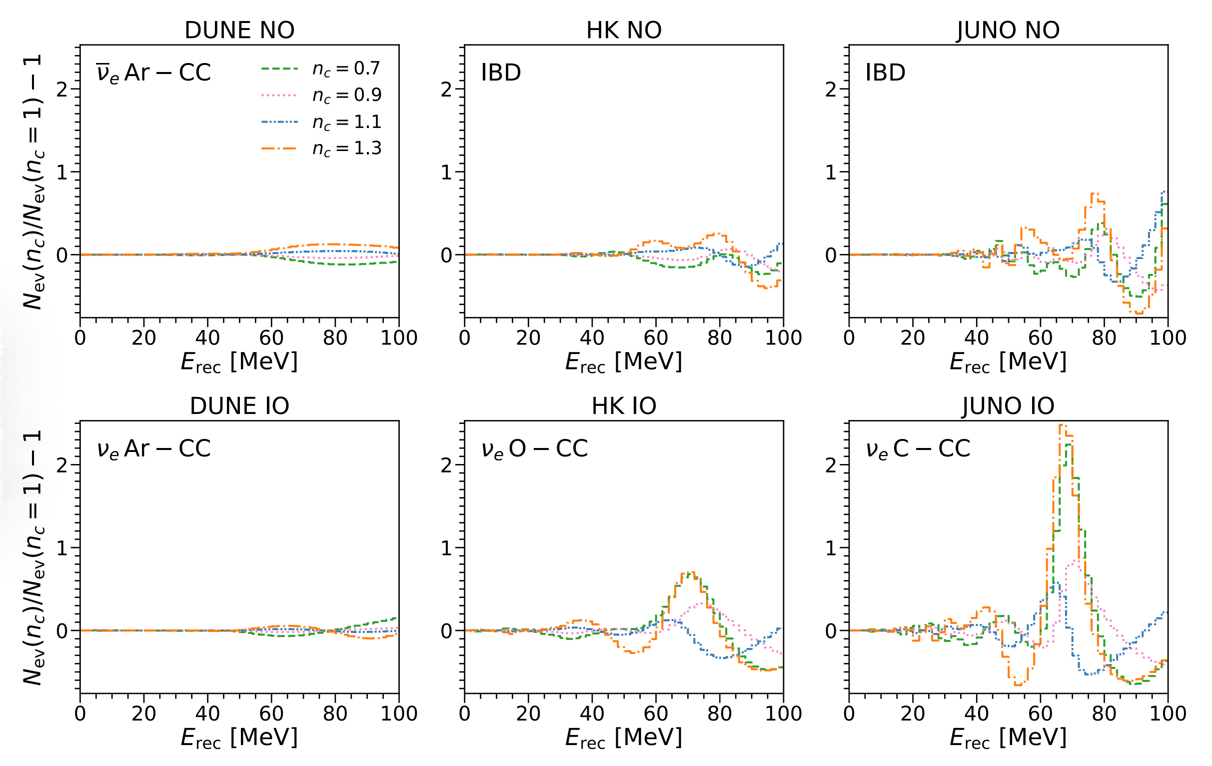
R. Hajjar, O. Mena and SPR, arXiv:2303.09369

Two-layer (core-mantle) Earth model imposing the Earth mass:

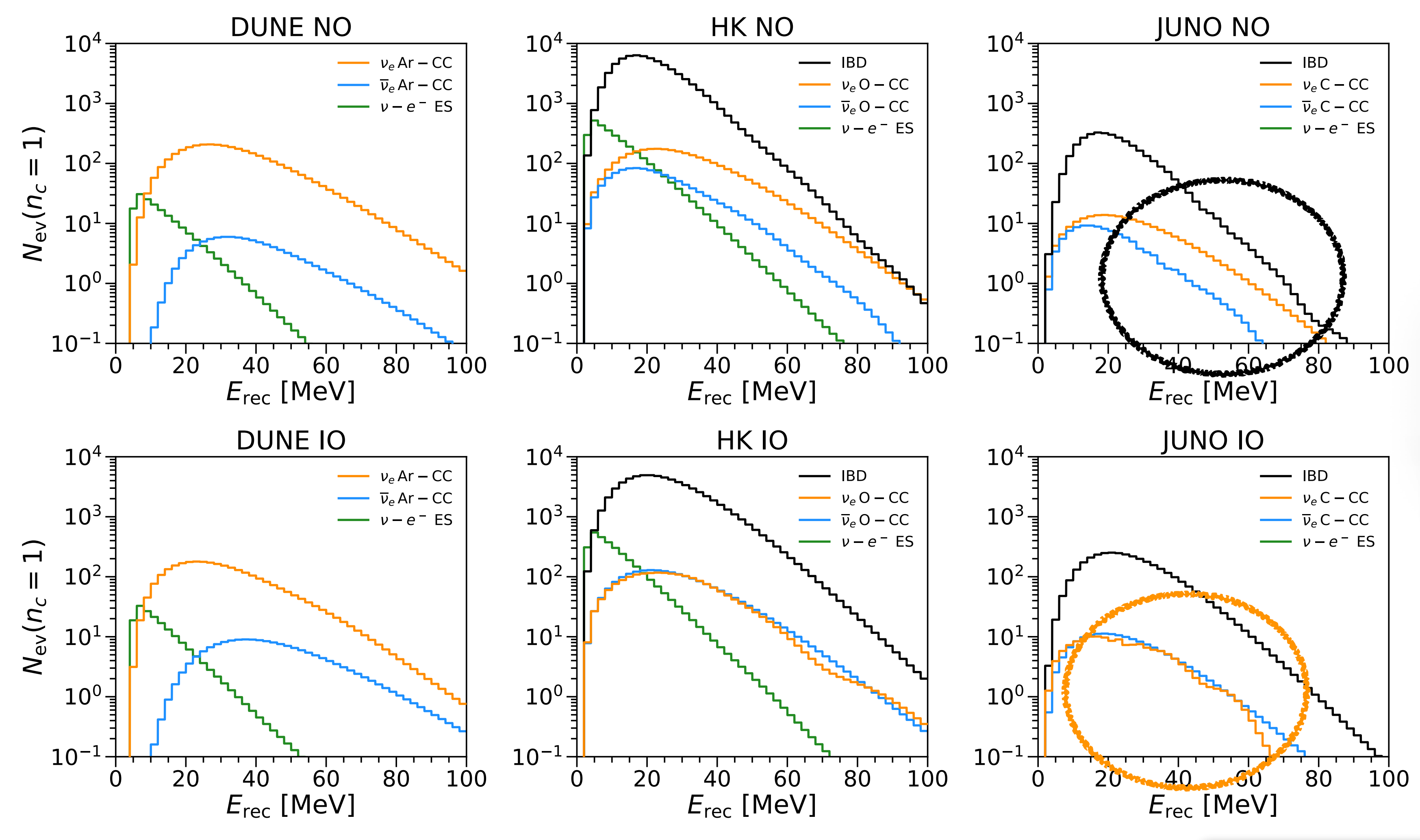
n_c = core density normalization

[$n_c = 1$ (PREM)]

energy resolution is critical for Earth tomography



EVENT DISTRIBUTIONS (for W20 simulation at 10 kpc)



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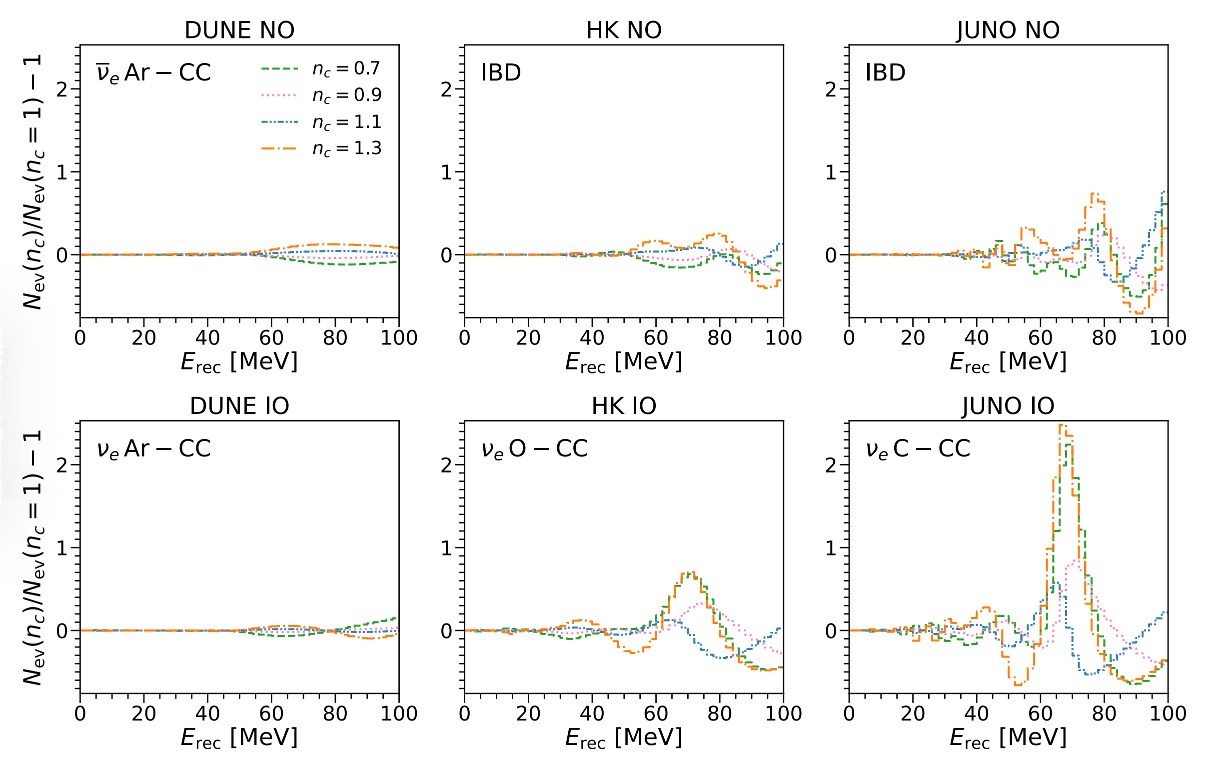
R. Hajjar, O. Mena and SPR, arXiv:2303.09369



Two-layer (core-mantle) Earth model imposing the Earth mass:

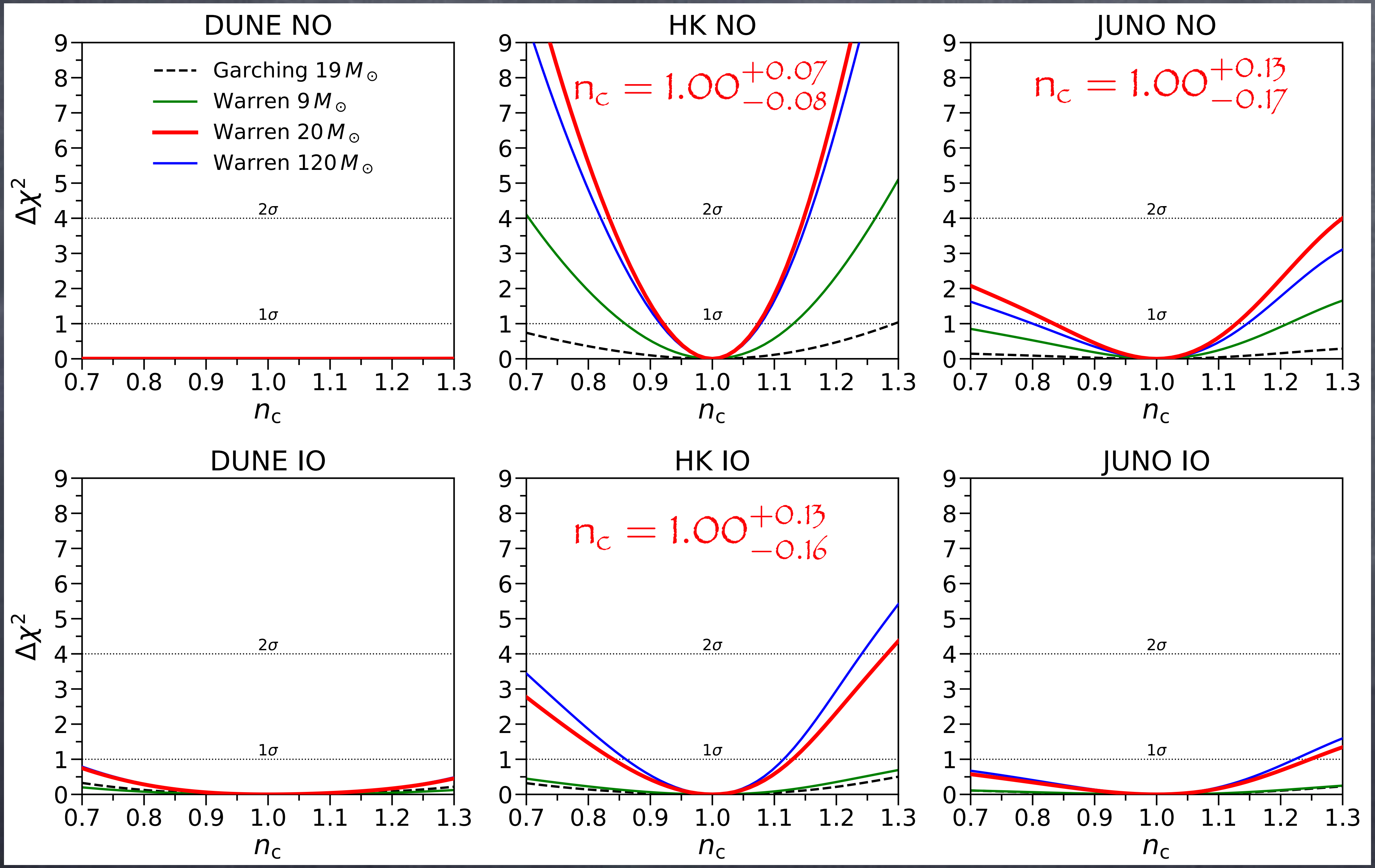
n_c = core density normalization

[$n_c = 1$ (PREM)]

energy resolution is critical for Earth tomography

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 could be possible

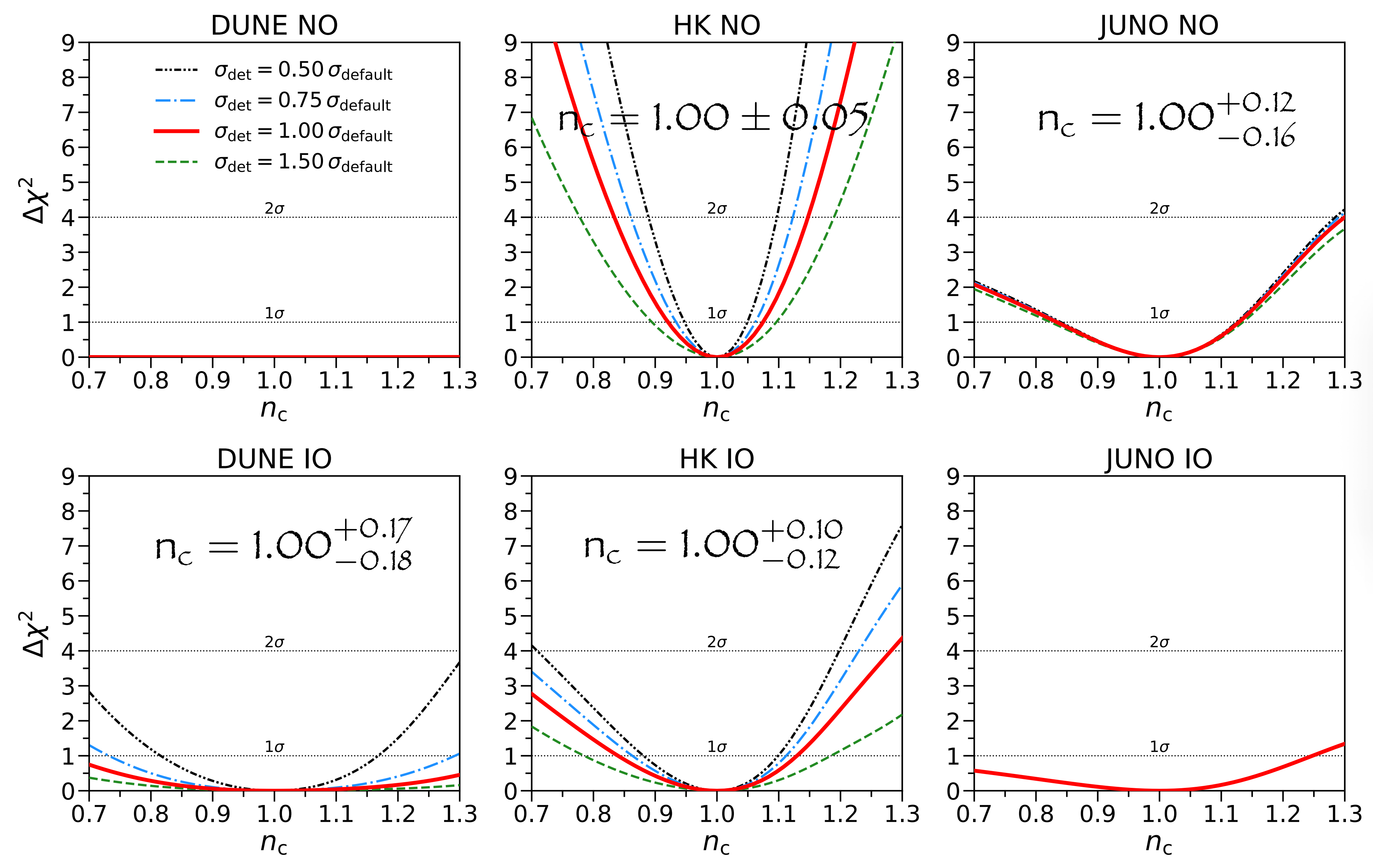
DEPENDENCE ON THE ENERGY RESOLUTION

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

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



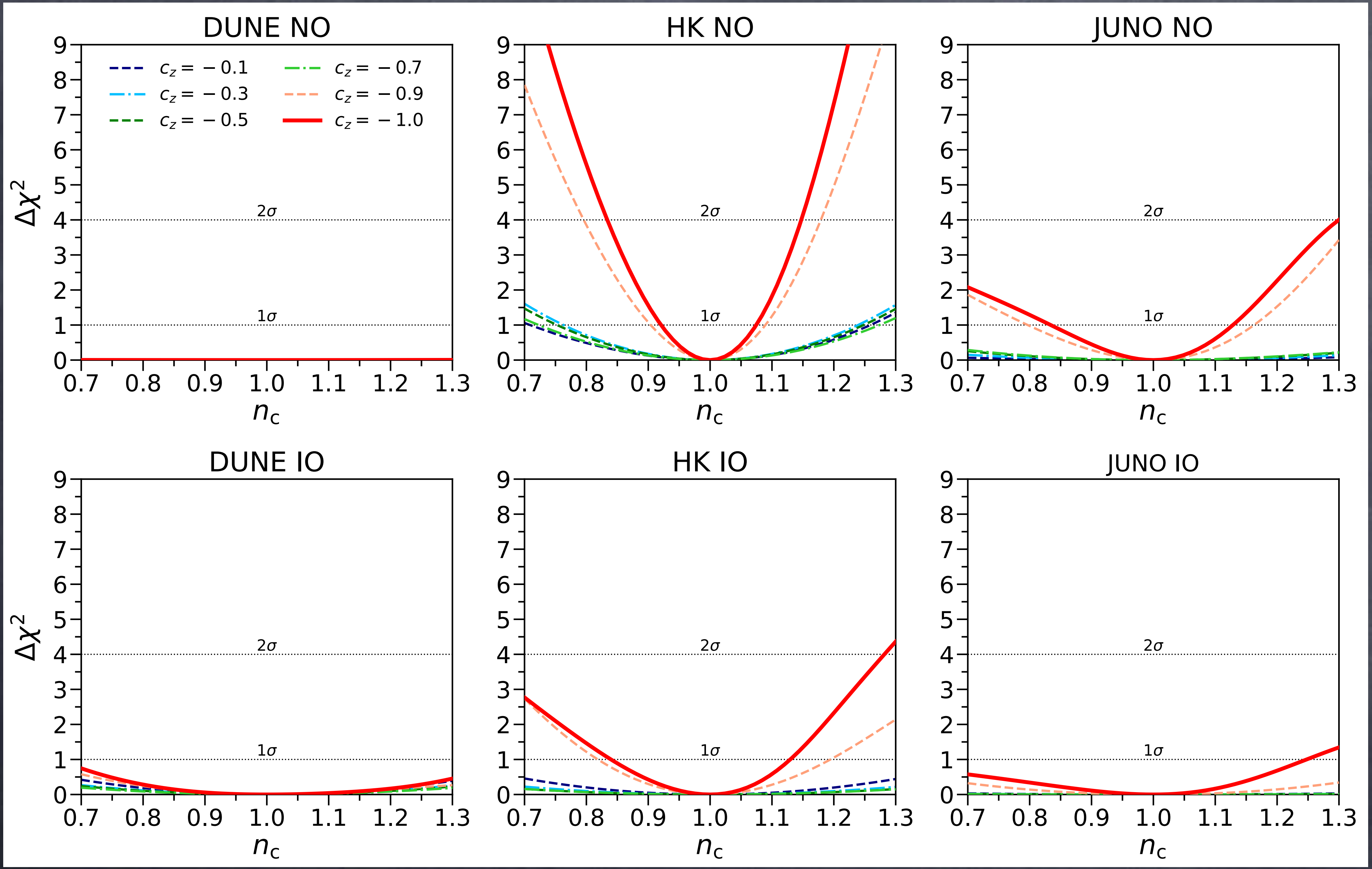
(for W20 simulation at 10 kpc)

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

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

DEPENDENCE ON THE SN DIRECTION

(for W20 simulation at 10 kpc)



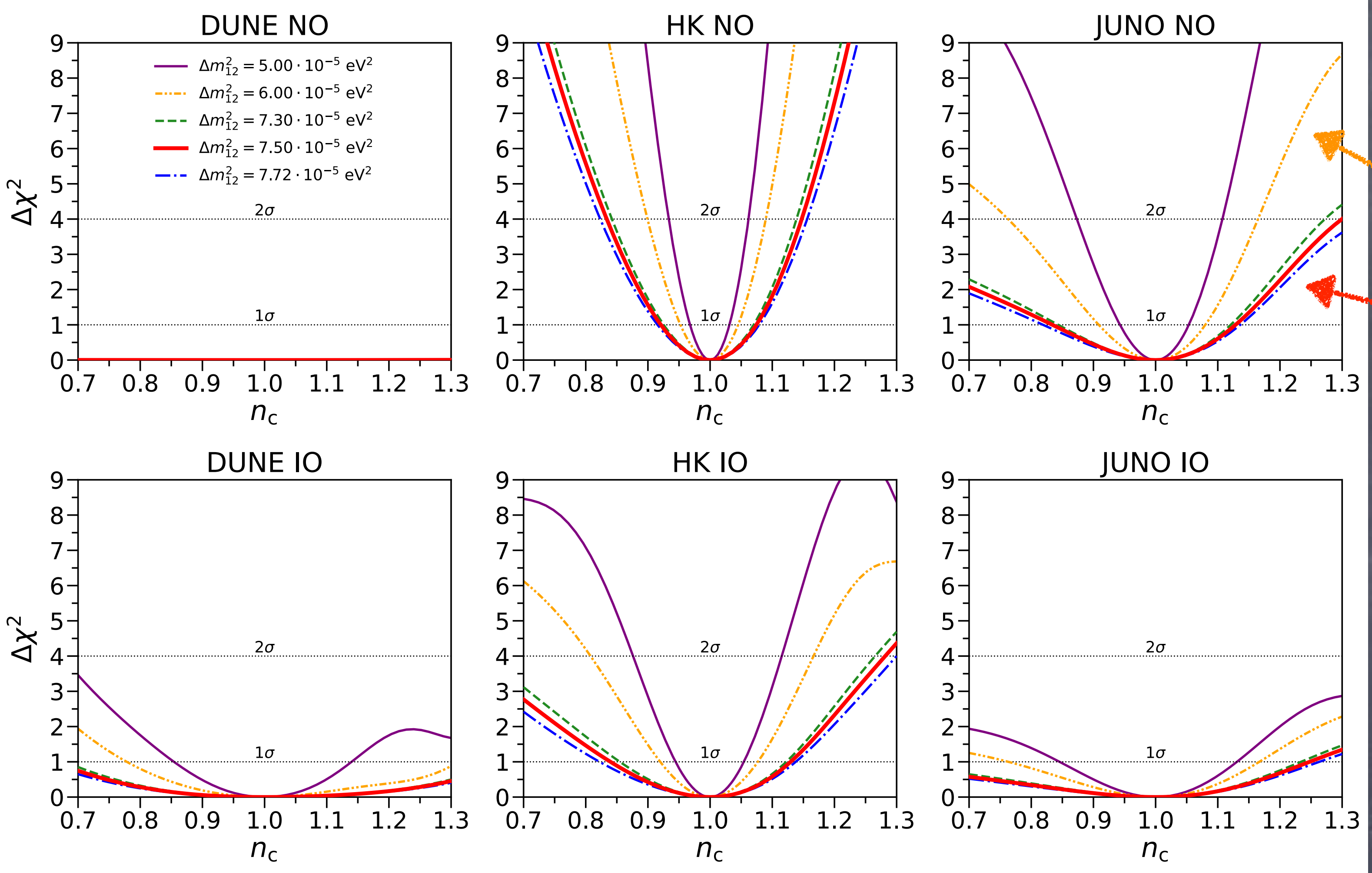
core-crossing
is required

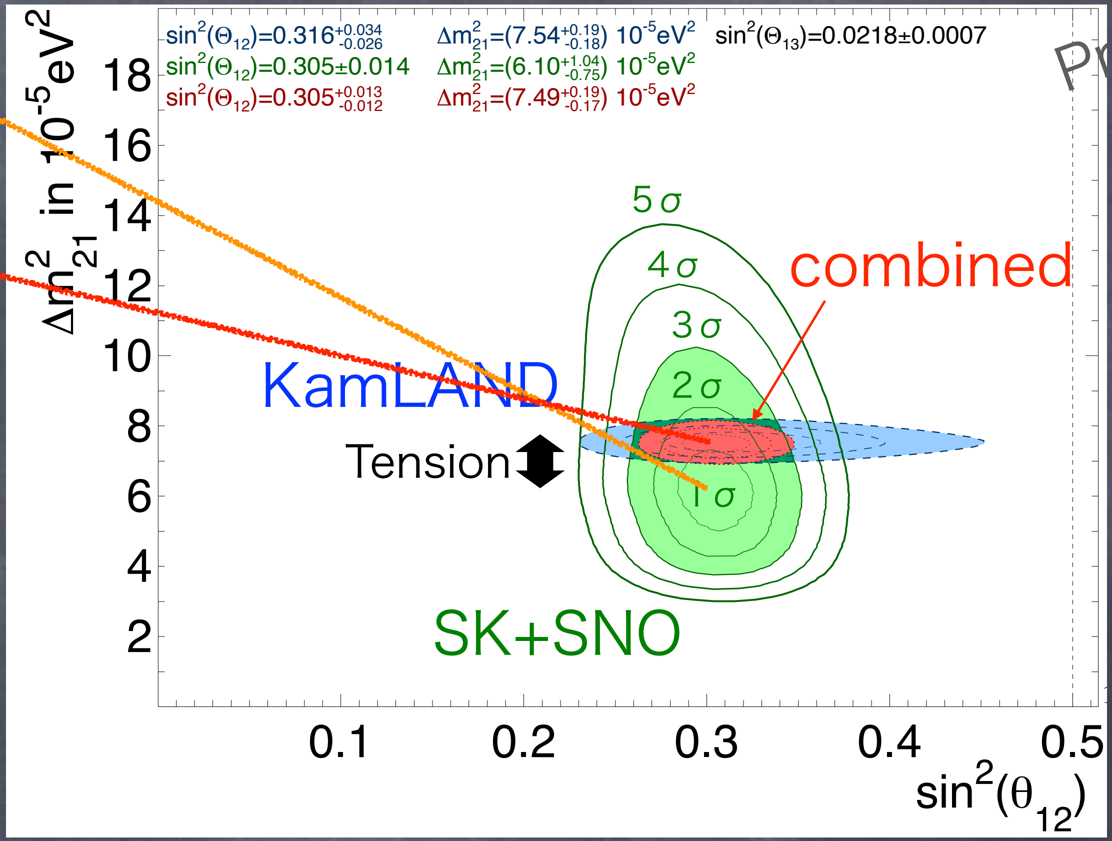
R. Hajjar, O. Mena and SPR, arXiv:2303.09369

DEPENDENCE ON NEUTRINO MIXING PARAMETERS

Δm^2_{21}

(for W20 simulation at 10 kpc)

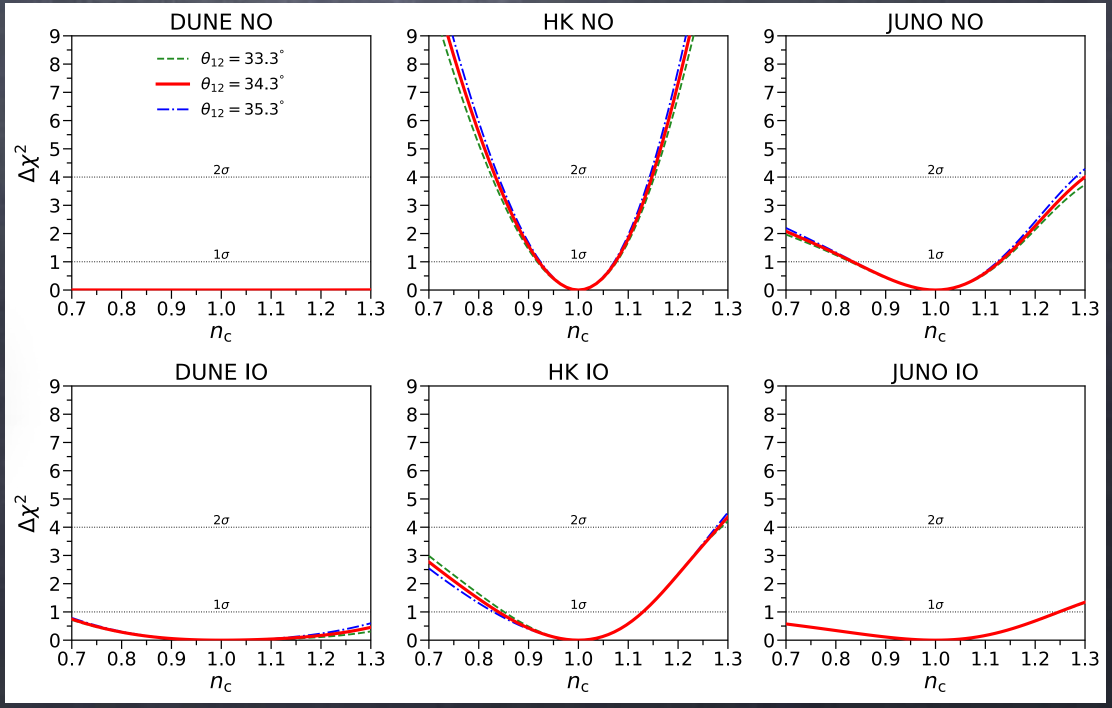




Y. Koshio, Talk at Neutrino 2022

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

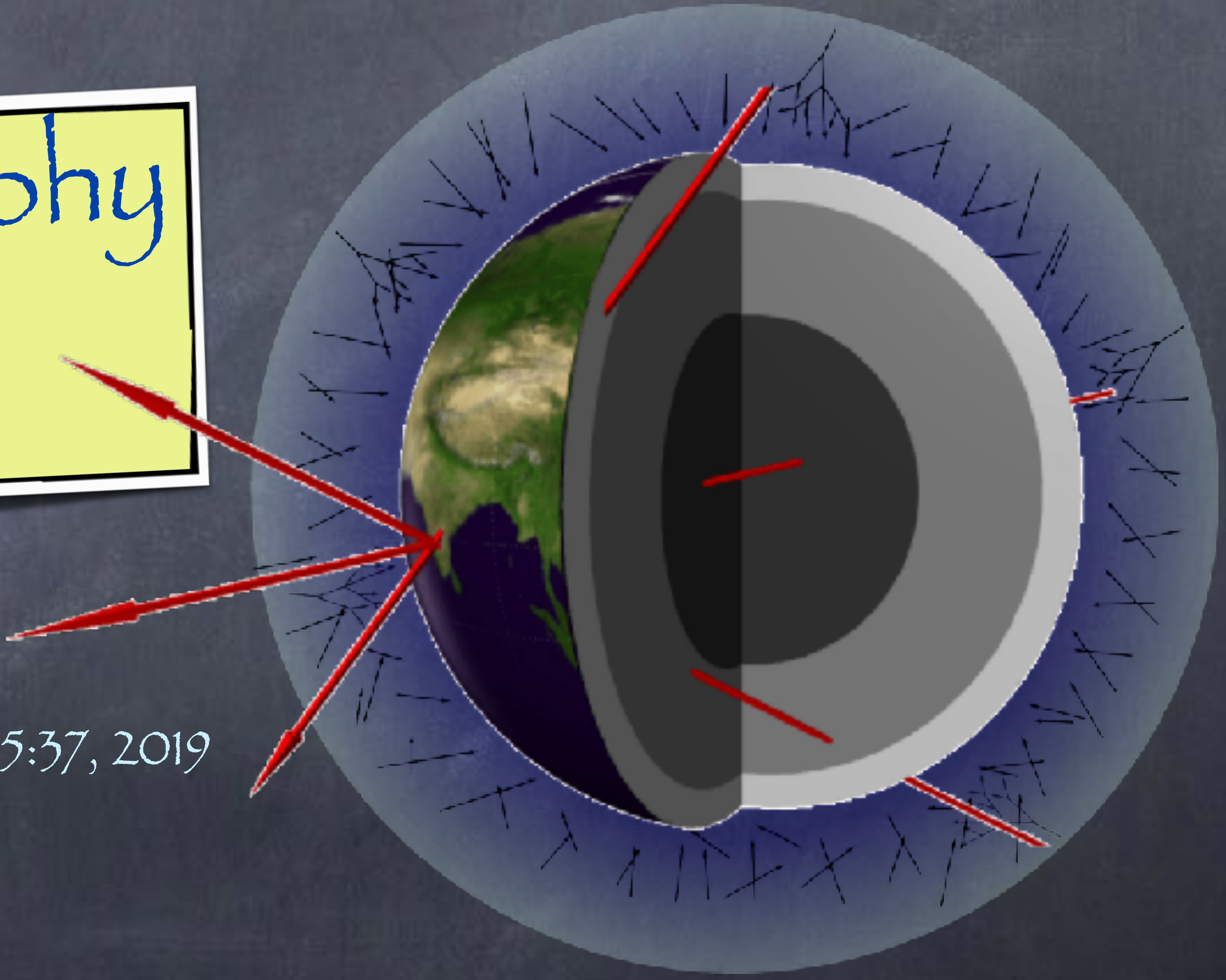
θ_{12}



very mild effect due to uncertainties

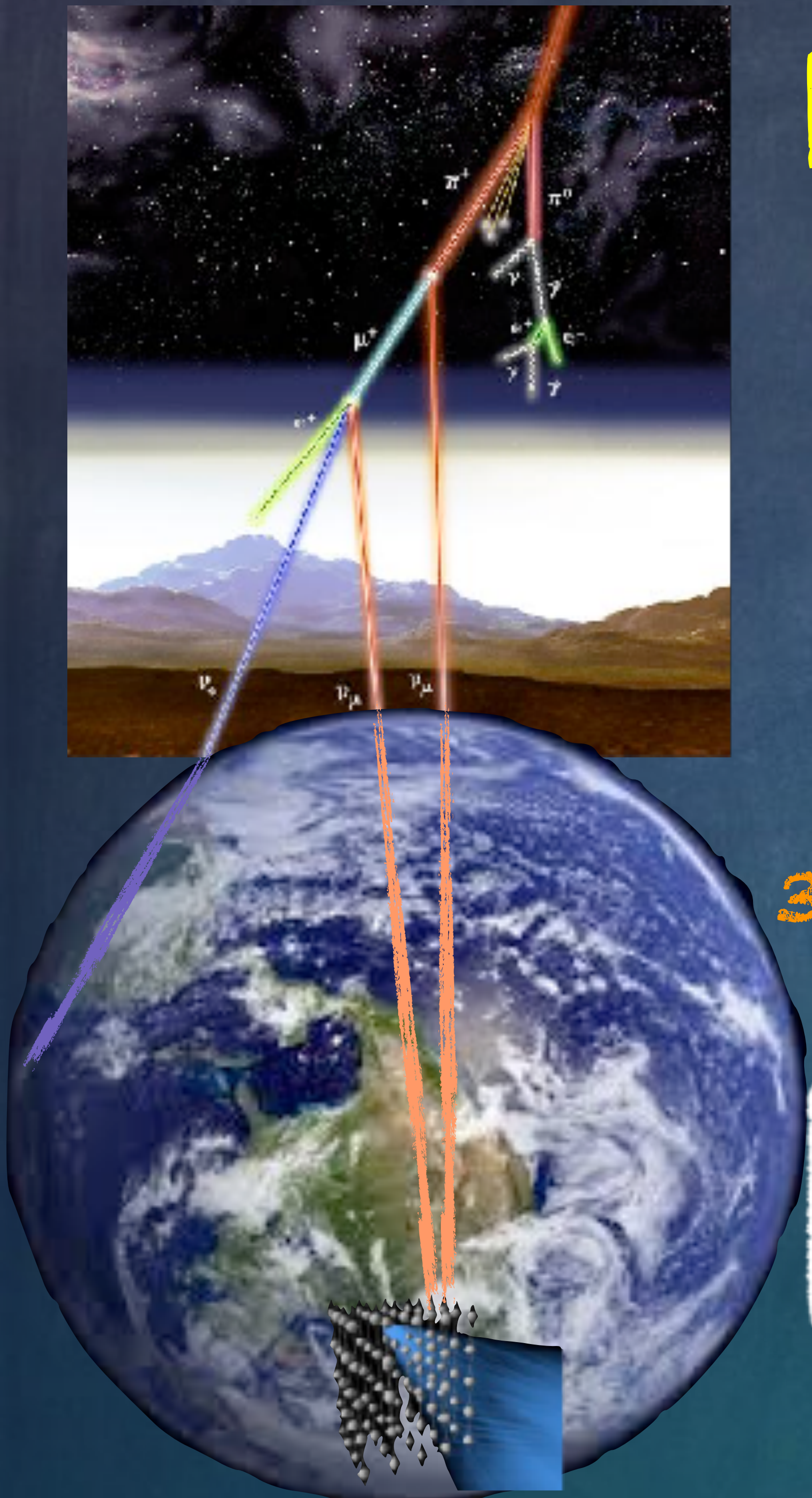
Neutrino absorption tomography

First Earth tomography with neutrinos!



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

ATMOSPHERIC NEUTRINOS



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

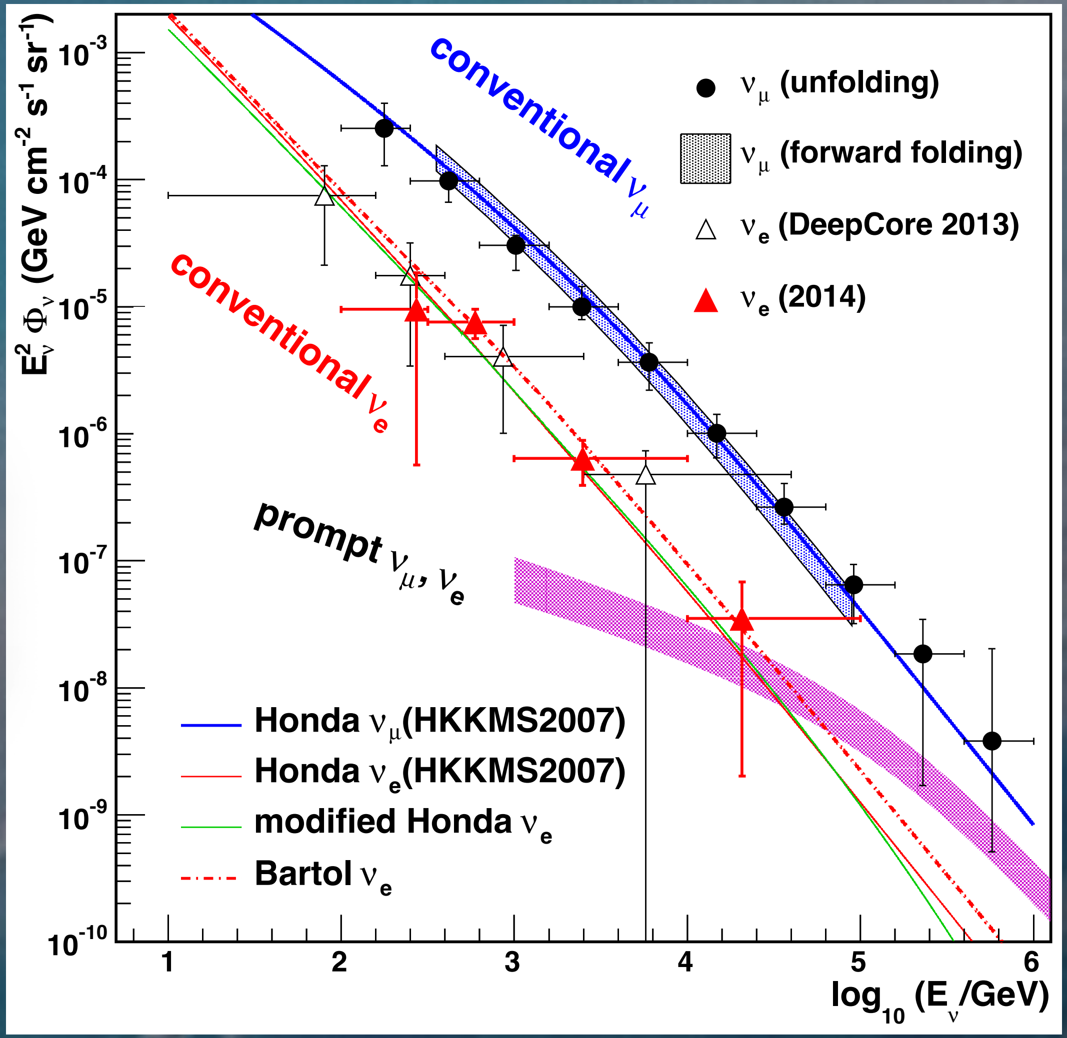
$$\mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

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

Interactions of cosmic rays in the atmosphere

30 MeV < E < 100 TeV

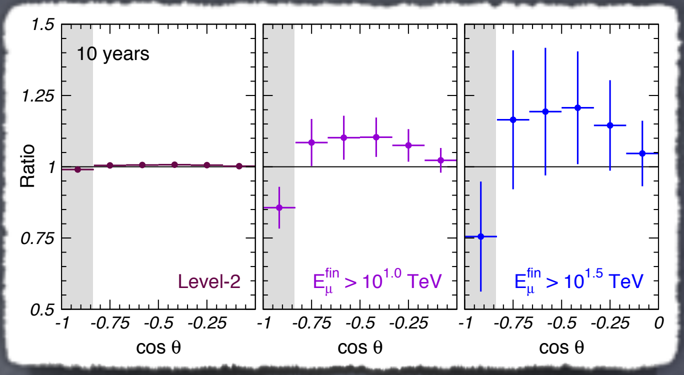
Huge range of energies and baselines



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

PREVIOUS STUDIES

First forecast of neutrino absorption 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

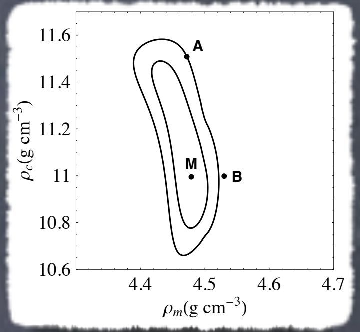
Non-homogeneity at (3.4-4.7)σ after 10 years

First forecast for KM3NeT

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

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

few percent error after 10 years



Study of lateral heterogeneities (with IceCube)

Needs ~300 years

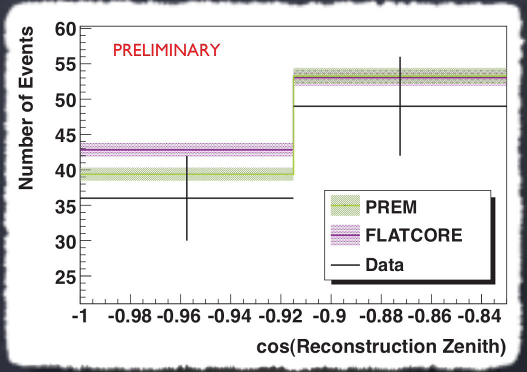
N. Takeuchi, Earth Planets Space 62:215, 2010

Another study of Earth non-homogeneity (with IceCube)

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

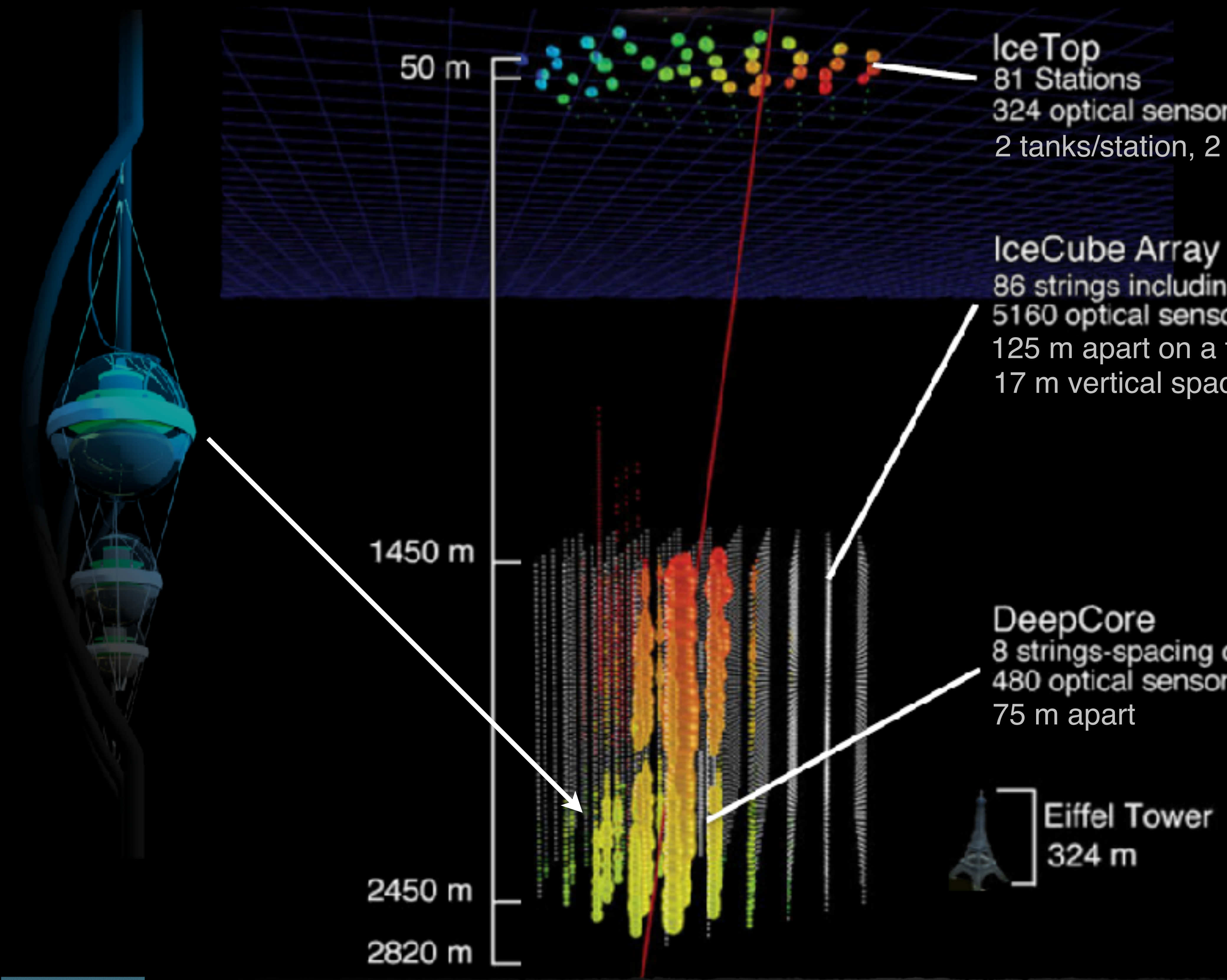
First attempt using 1 year of IC-40 data

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



THE ICECUBE NEUTRINO TELESCOPE

At the South Pole



IceTop
81 Stations
324 optical sensors
2 tanks/station, 2 DOMs/tank

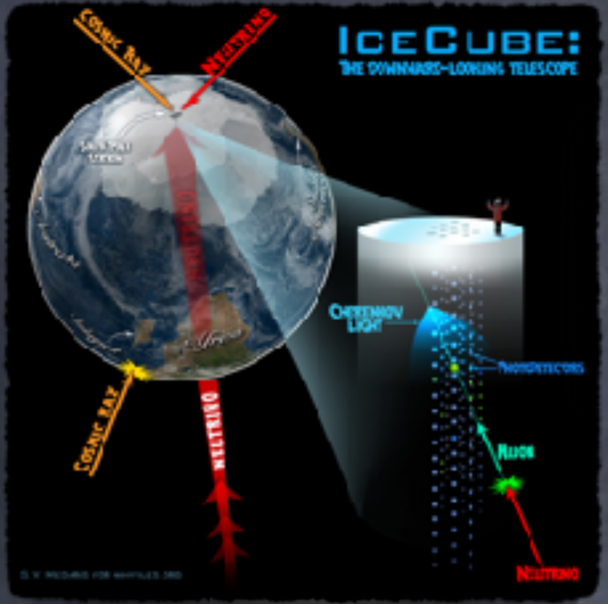
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
125 m apart on a triangular grid
17 m vertical spacing between PMTs

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
75 m apart

completed in 2010

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

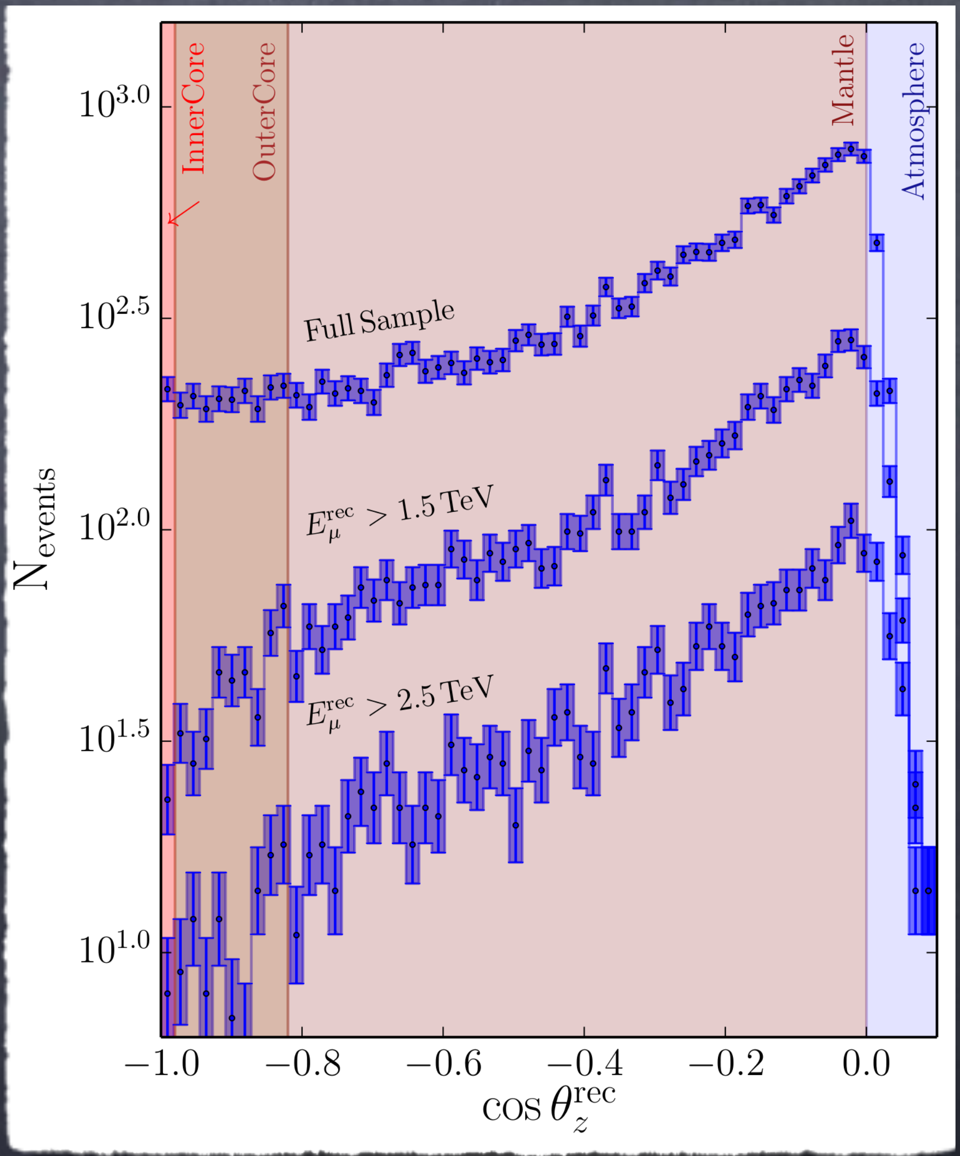
Energy range: ~ 400 GeV - 20 TeV

Zenith angle range: cos θ = [-1, 0.2]

Number of events: 20145 (343.7 days)

>99.9% muon neutrino purity

Publicly available!

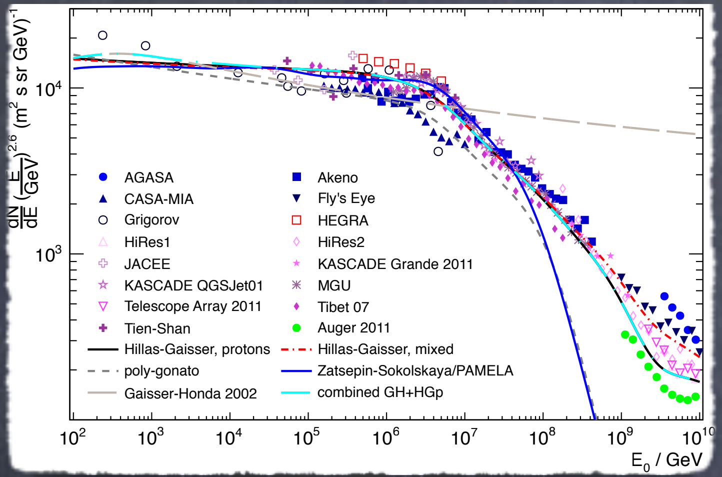


A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

ANALYSIS INGREDIENTS

Primary cosmic-ray spectrum

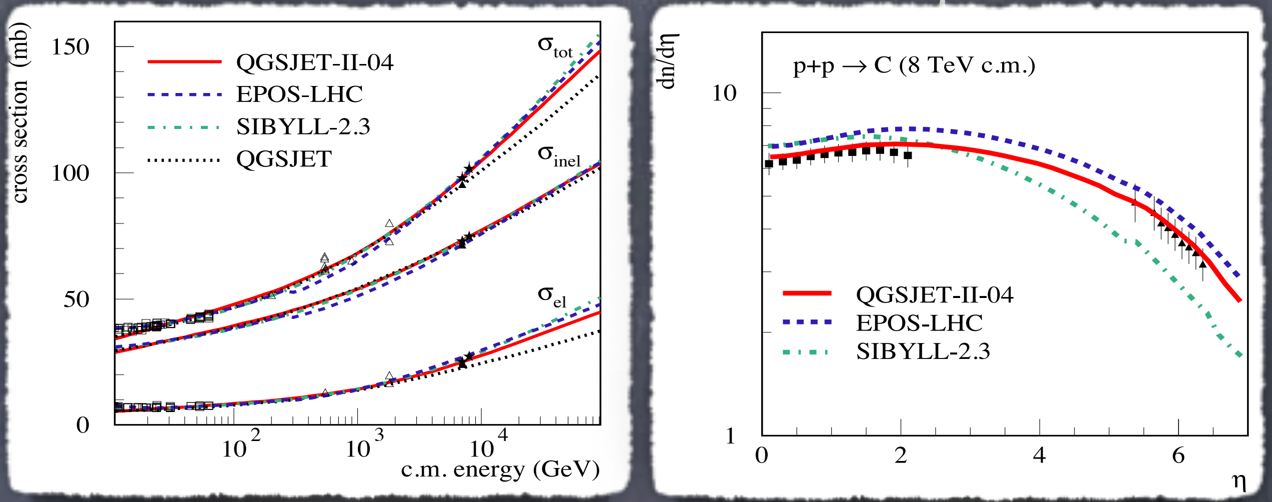
3-population models to fit cosmic-ray data



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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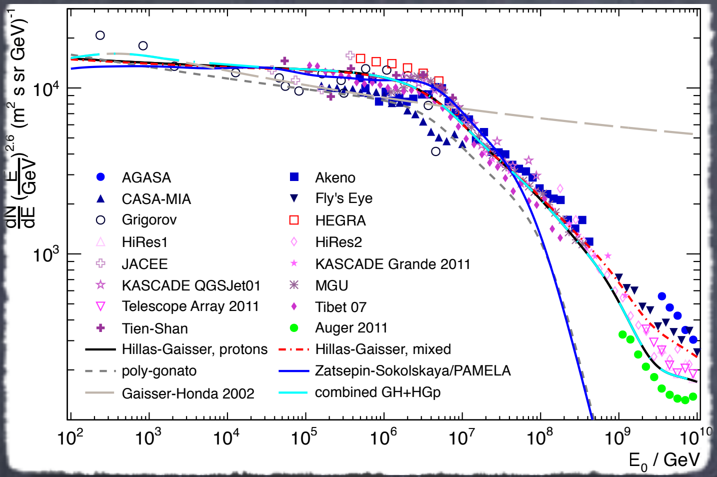

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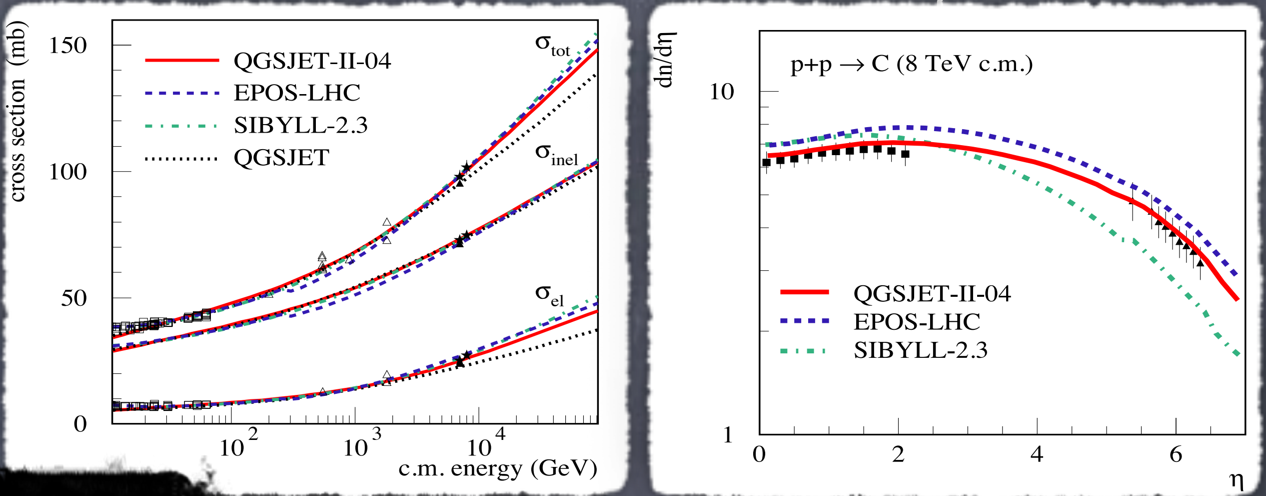
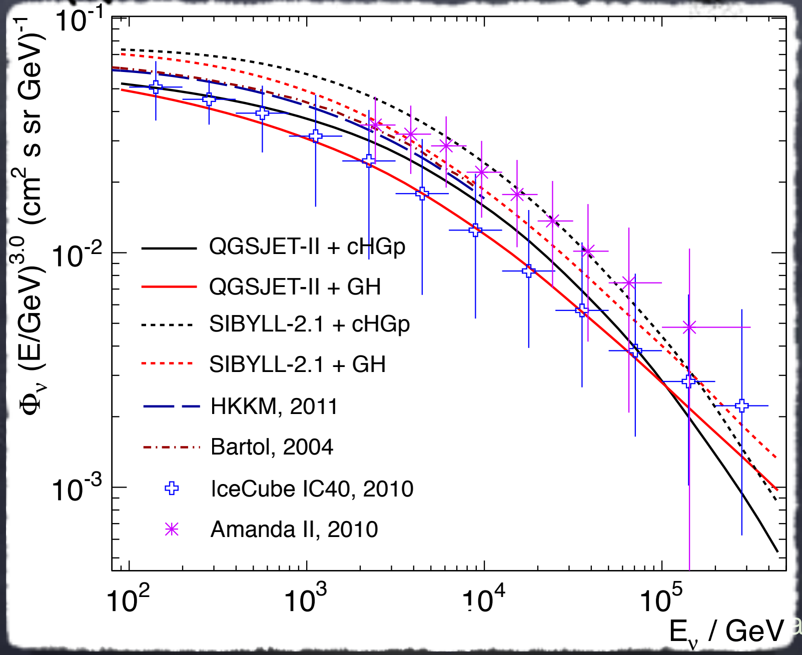


S. Ostapchenko, ECRS 2016, arXiv:1612.09461

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

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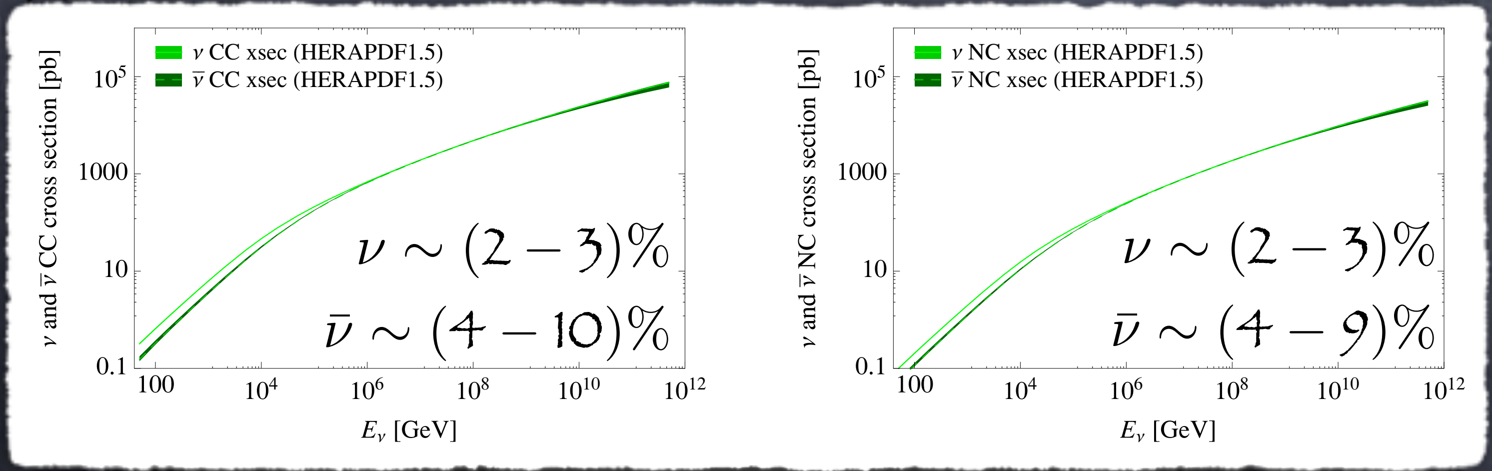
Neutrino interactions with nucleons



$\nu \sim (2-3)\%$
$\bar{\nu} \sim (4-10)\%$

$\nu \sim (2-3)\%$
$\bar{\nu} \sim (4-9)\%$

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

< 100 TeV, nuclear effects increase the cross sections by <2%

S. R. Klein, S. A. Robertson and R. Vogt, Phys. Rev. C102:015808, 2020

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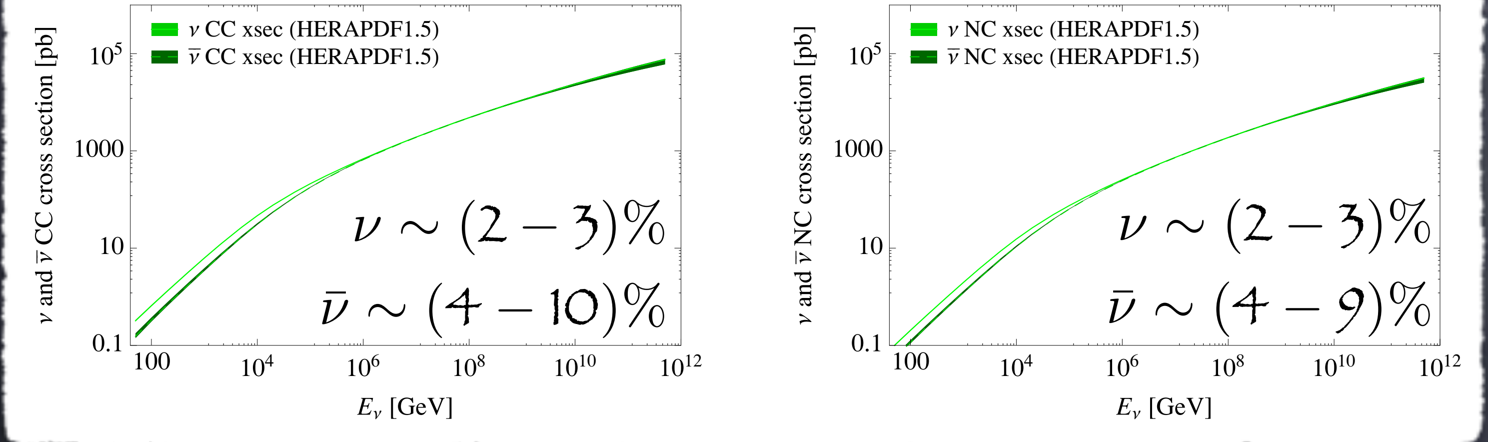

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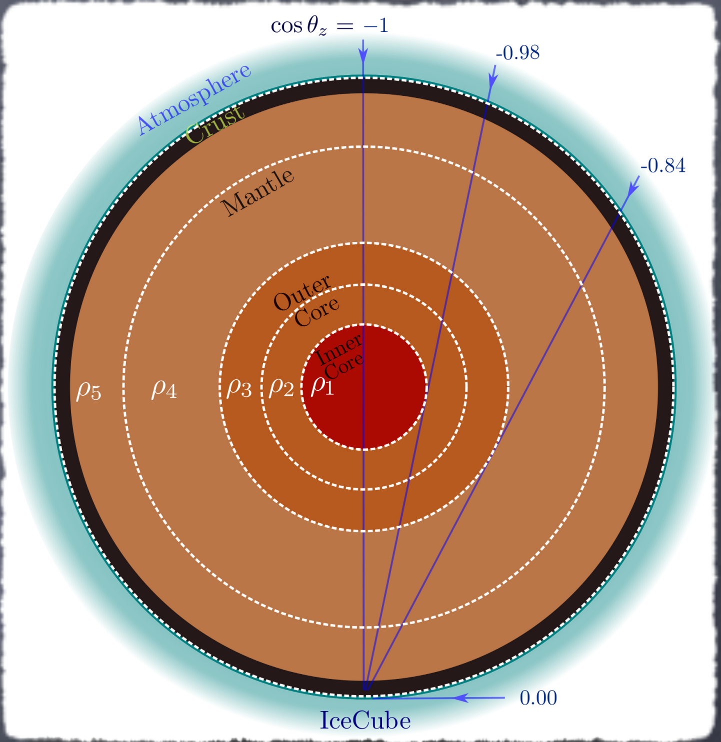
Earth model



5 spherical layers:

1 for the inner core

2 for the outer core

2 for the mantle

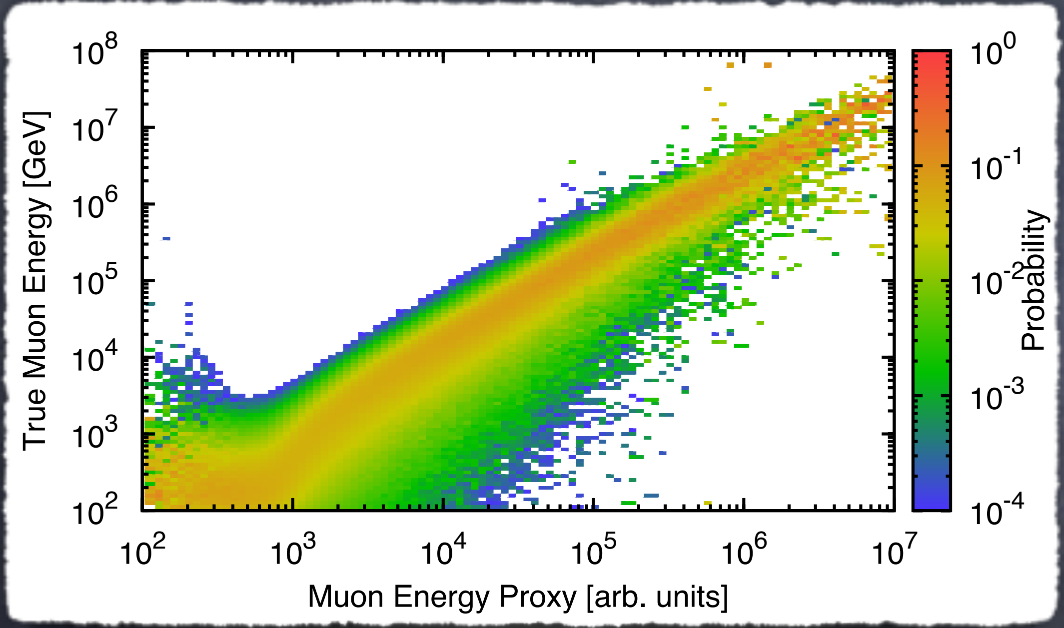
ANALYSIS INGREDIENTS

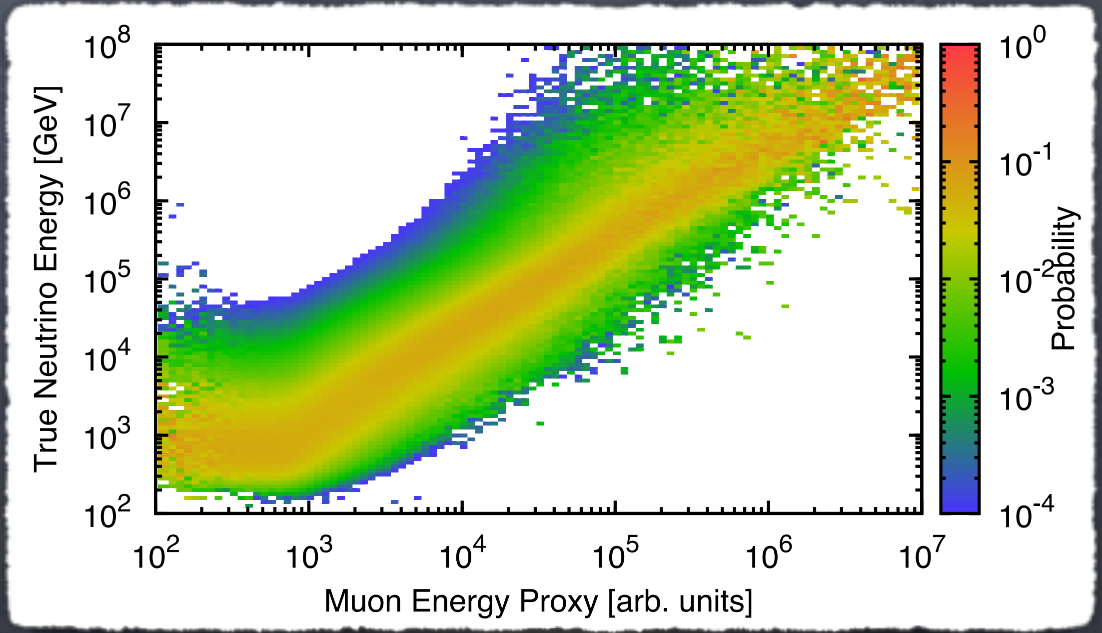
Detector simulation

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

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

STATISTICAL ANALYSIS

densities of the 5 Earth layers

Binned maximum likelihood analysis

$$\ln \mathcal{L}(\vec{\rho};\vec{\eta}) = \sum_{i\in \mathrm{bins}} \left(N_i^{\mathrm{data}} \ln N_i^{\mathrm{th}}(\vec{\rho};\vec{\eta}) - N_i^{\mathrm{th}}(\vec{\rho};\vec{\eta}) \right) - \sum_j \frac{\left(\eta_j - \eta_j^{0}\right)^2}{2\sigma_j^2}$$

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

Binned maximum likelihood analysis

$$\ln \mathcal{L}(\vec{\rho};\vec{\eta}) = \sum_{i\in\text{bins}} \left(N_i^{\text{data}} \ln N_i^{\text{th}}(\vec{\rho};\vec{\eta}) - N_i^{\text{th}}(\vec{\rho};\vec{\eta})\right) - \sum_j \frac{\left(\eta_j - \eta_j^{0}\right)^2}{2\sigma_j^2}$$

4 nuisance parameters

DOM efficiency

Flux continuous parameters:

- overall normalization
- pion/kaon ratio
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other systematics

Primary CR spectra

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Neutrino cross sections

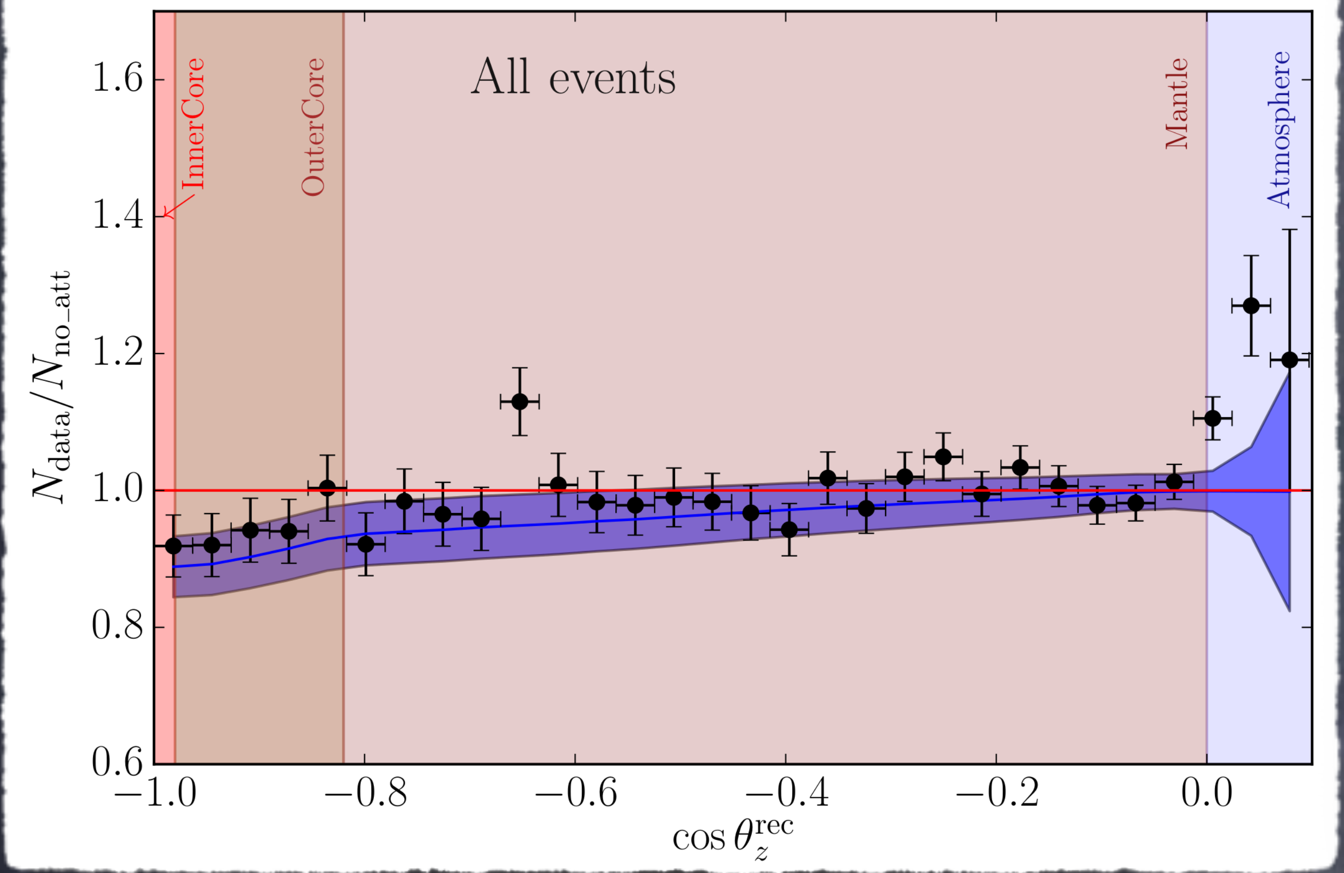
Optical properties
of ice not included!

We use MultiNest for parameter inference

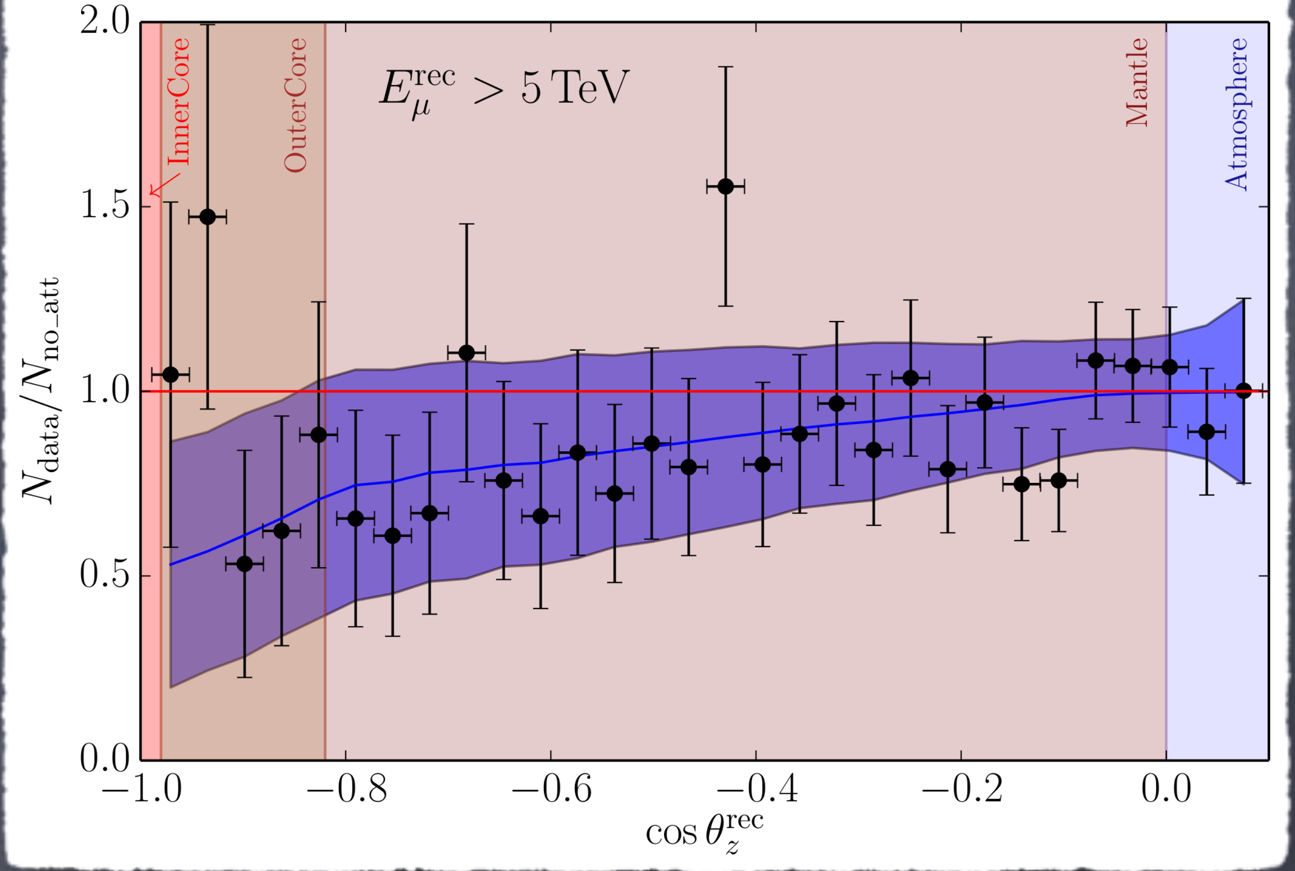
F. Feroz and M. Robson, https://github.com/farhanferoz/MultiNest

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)

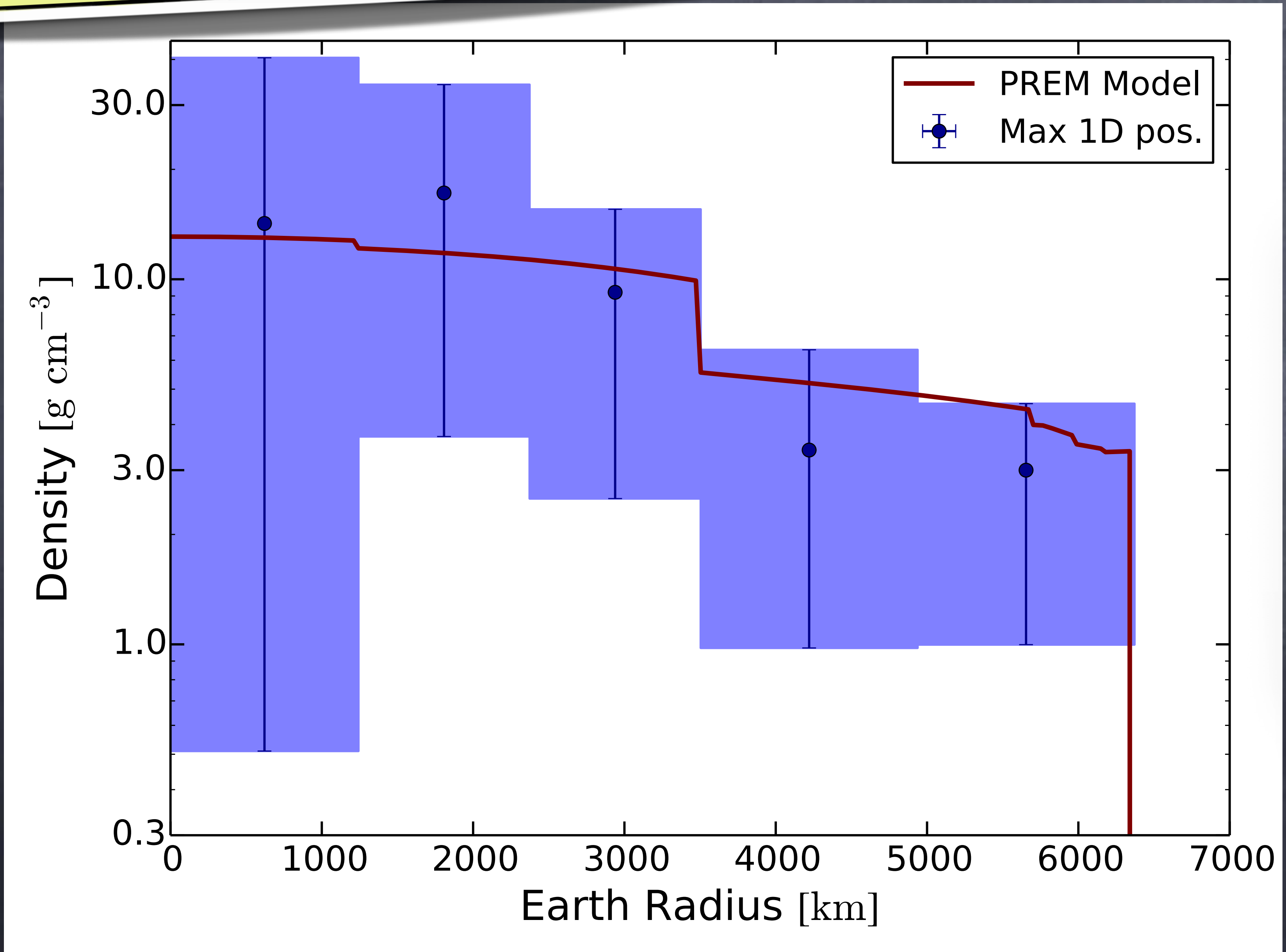
MAIN RESULT: 1-D DENSITY PROFILE

First Earth tomography with neutrinos!

nature physics

Neutrino tomography of Earth

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

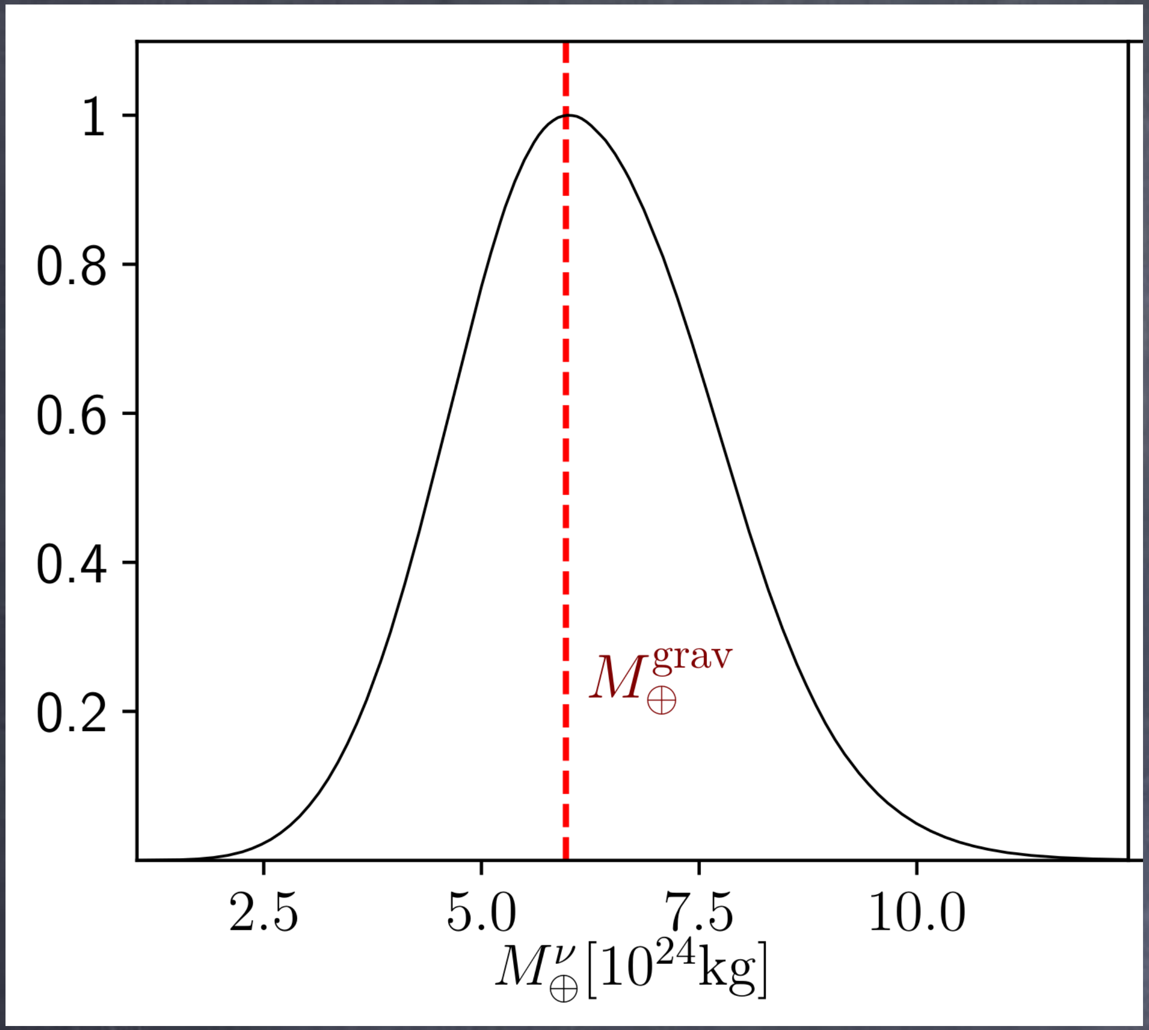


NO constraint on the Earth mass or moment of inertia…

pure weak interaction measurement

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

EARTH'S MASS



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

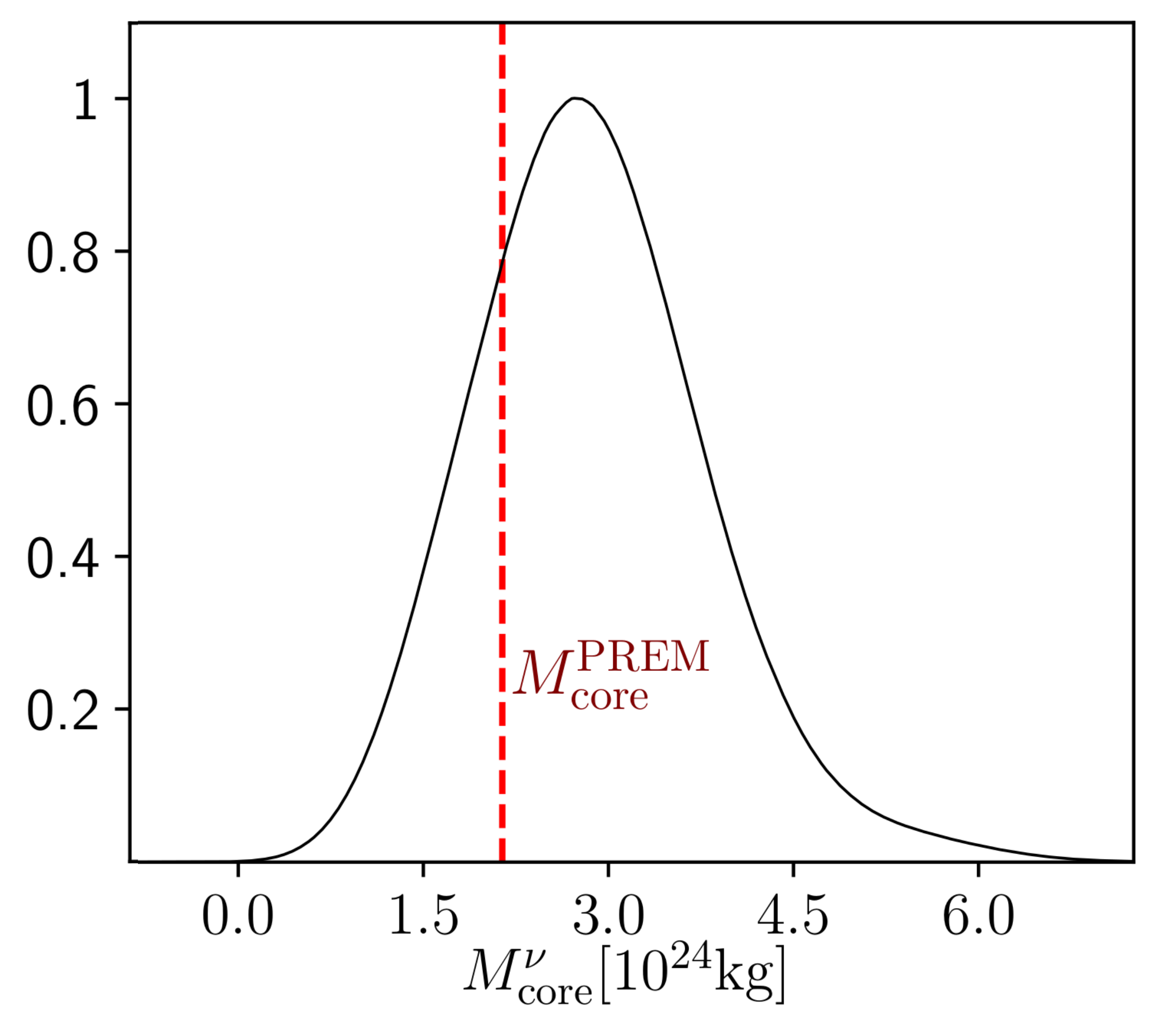
$$M_\nu = \left(6.0^{+1.6}_{-1.3}\right)\times 10^{24}\ \text{kg}$$

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

Gravitational measurement

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

EARTH'S CORE MASS



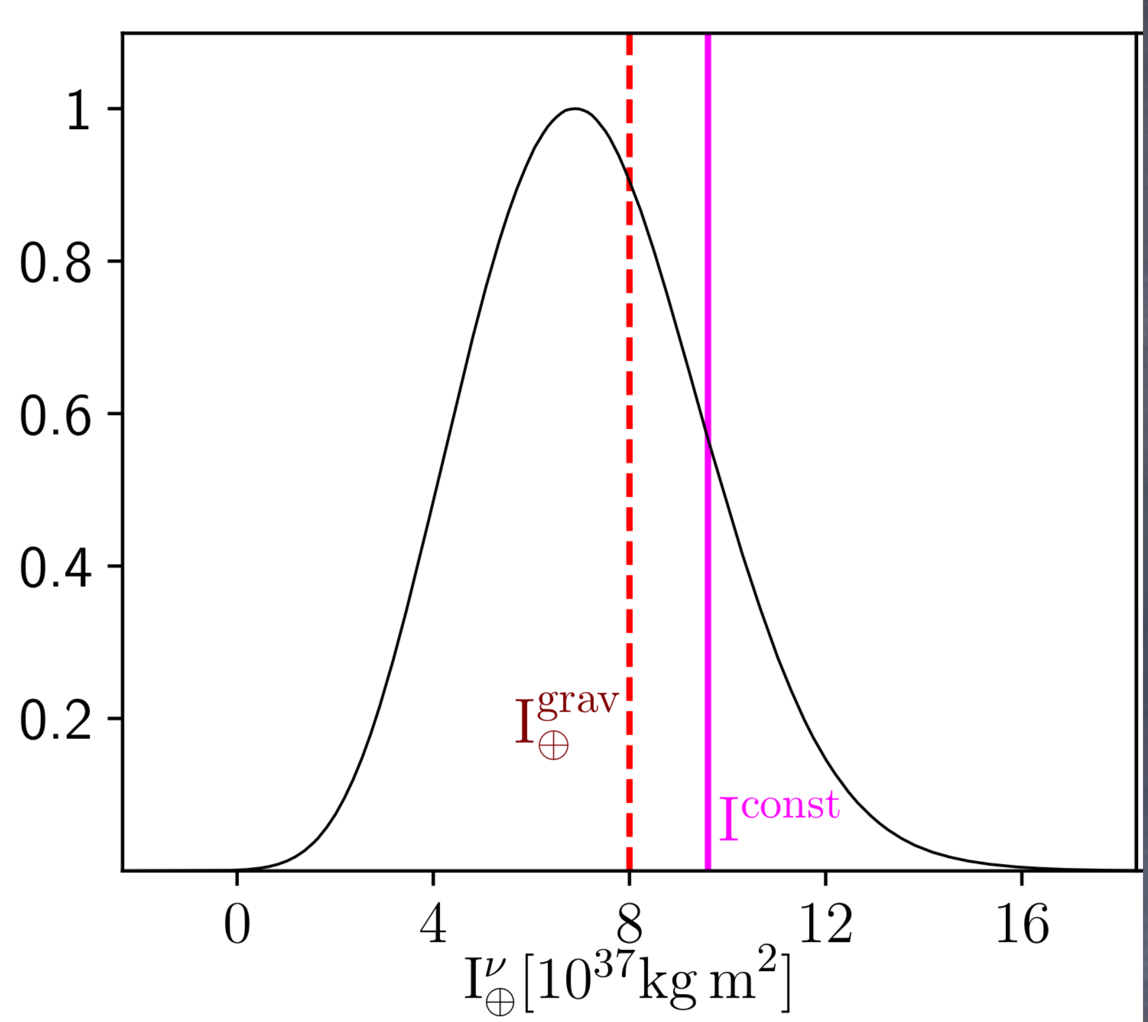
A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

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

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

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

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!

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

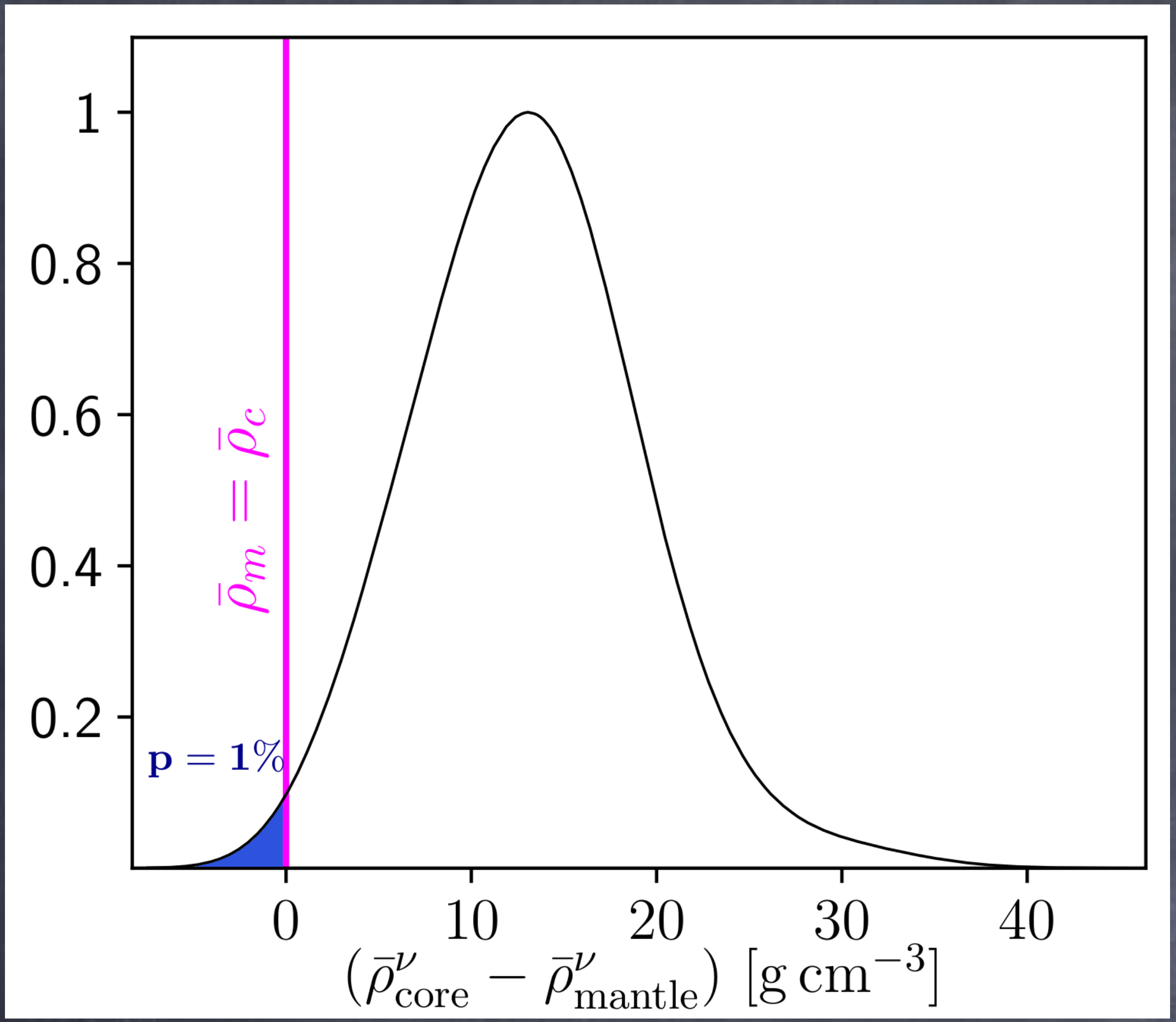
$$\frac{I_\nu}{I_{sphere-\nu}} = 0.7 \pm 0.3$$

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



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

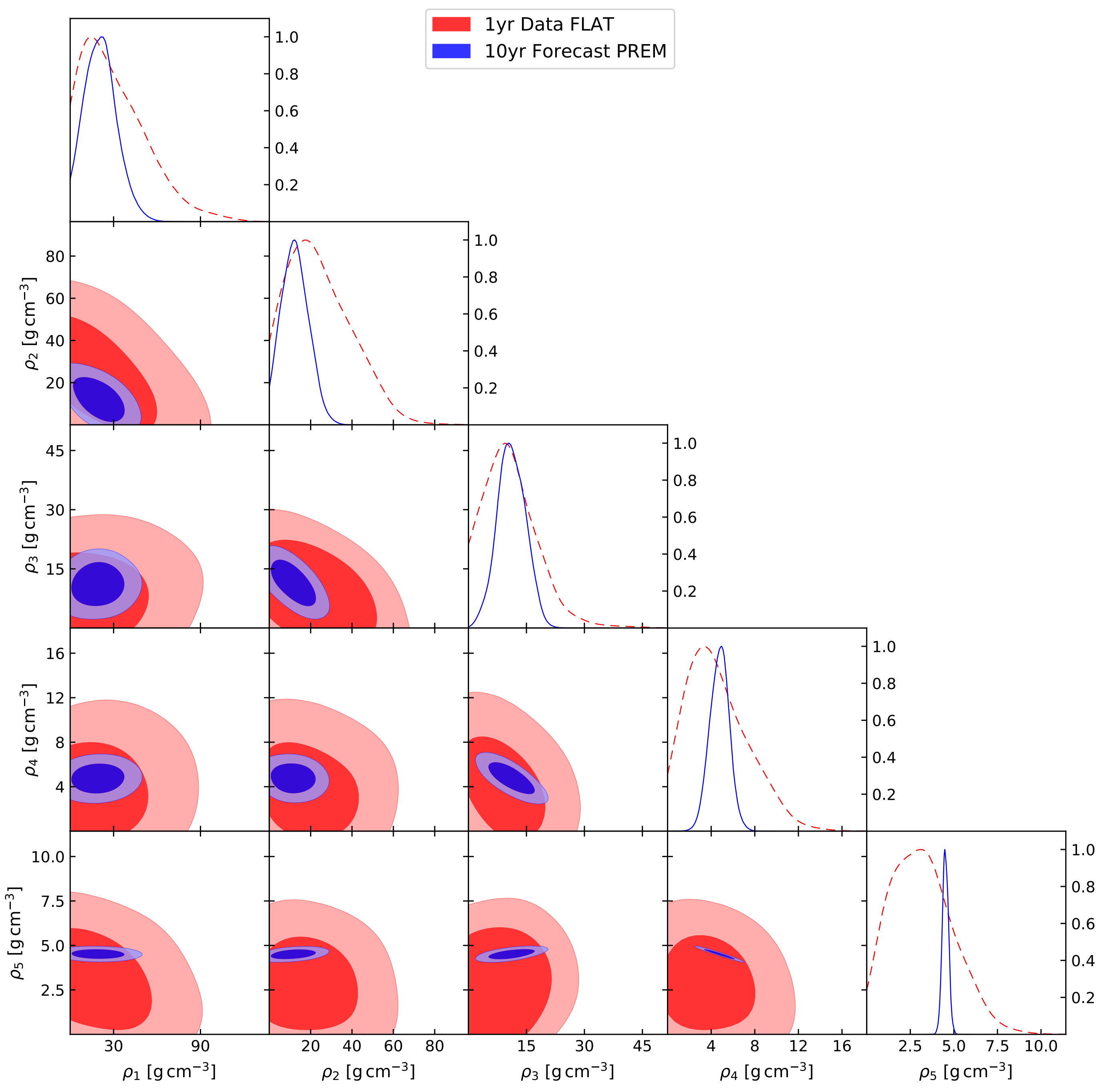
First measurement of the Earth's core-mantle discontinuity using the weak force!

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

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

WHAT ABOUT THE FUTURE?
… ACTUALLY THE PRESENT

Forecast for 10 years of data



Few per cent error in the mantle

A finer modeling can be considered

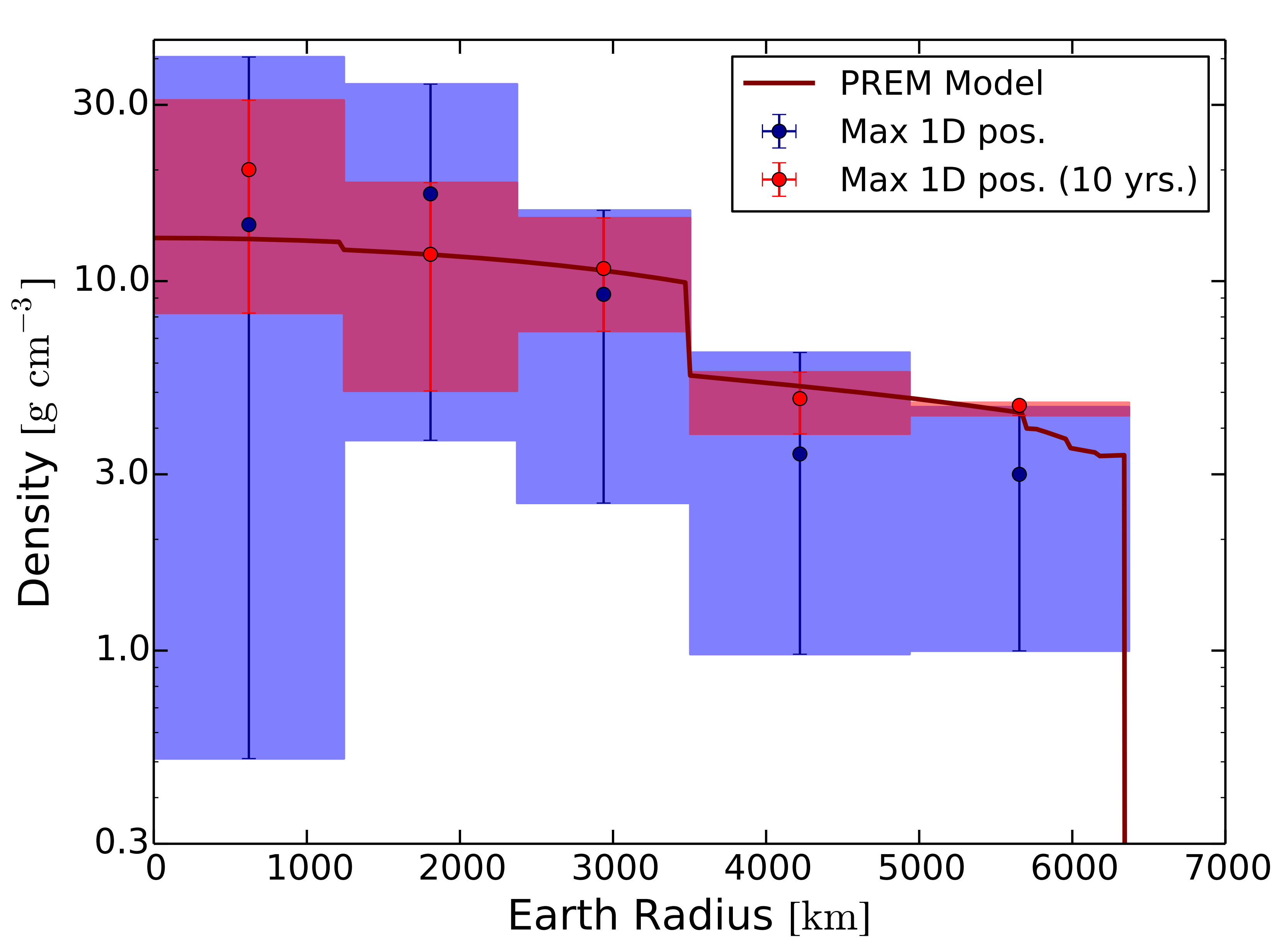
Test of discontinuities

Knowledge of hadronic-interaction model impacts systematics

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

WHAT ABOUT THE FUTURE?
... ACTUALLY THE PRESENT

Forecast for 10 years of data

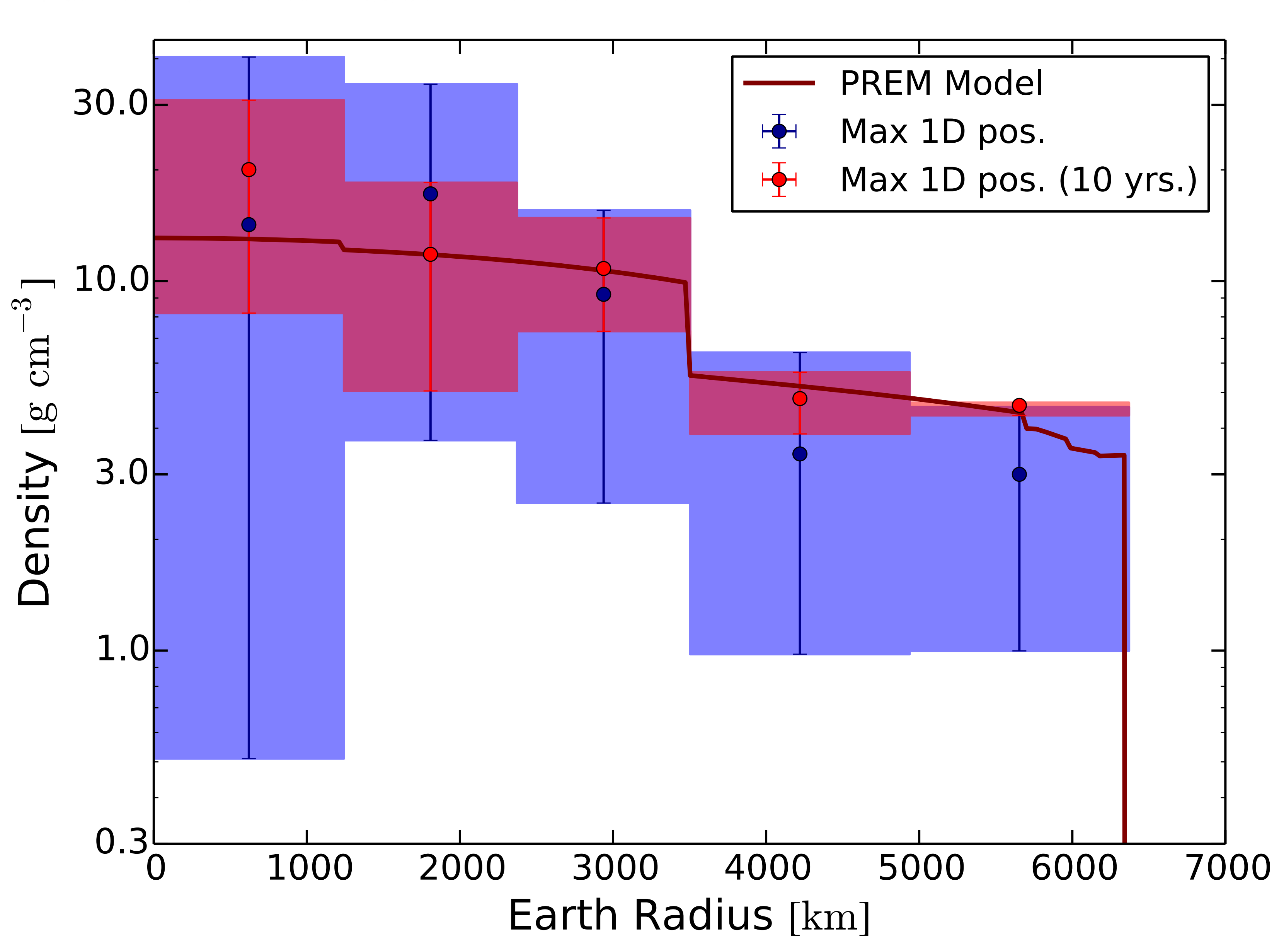


A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

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

CONCLUSIONS

Neutrinos allow us to do Earth (oscillation and absorption) tomography
complementary to standard techniques

Interesting prospects with future detectors for
oscillation tomography using supernova neutrinos…
let's hope we don't have to wait much for the next galactic SN

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!

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

Keep in mind we are at the infant stages of neutrino tomography of Earth,
seismological tomography is a century older!

Edmund Halley,

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

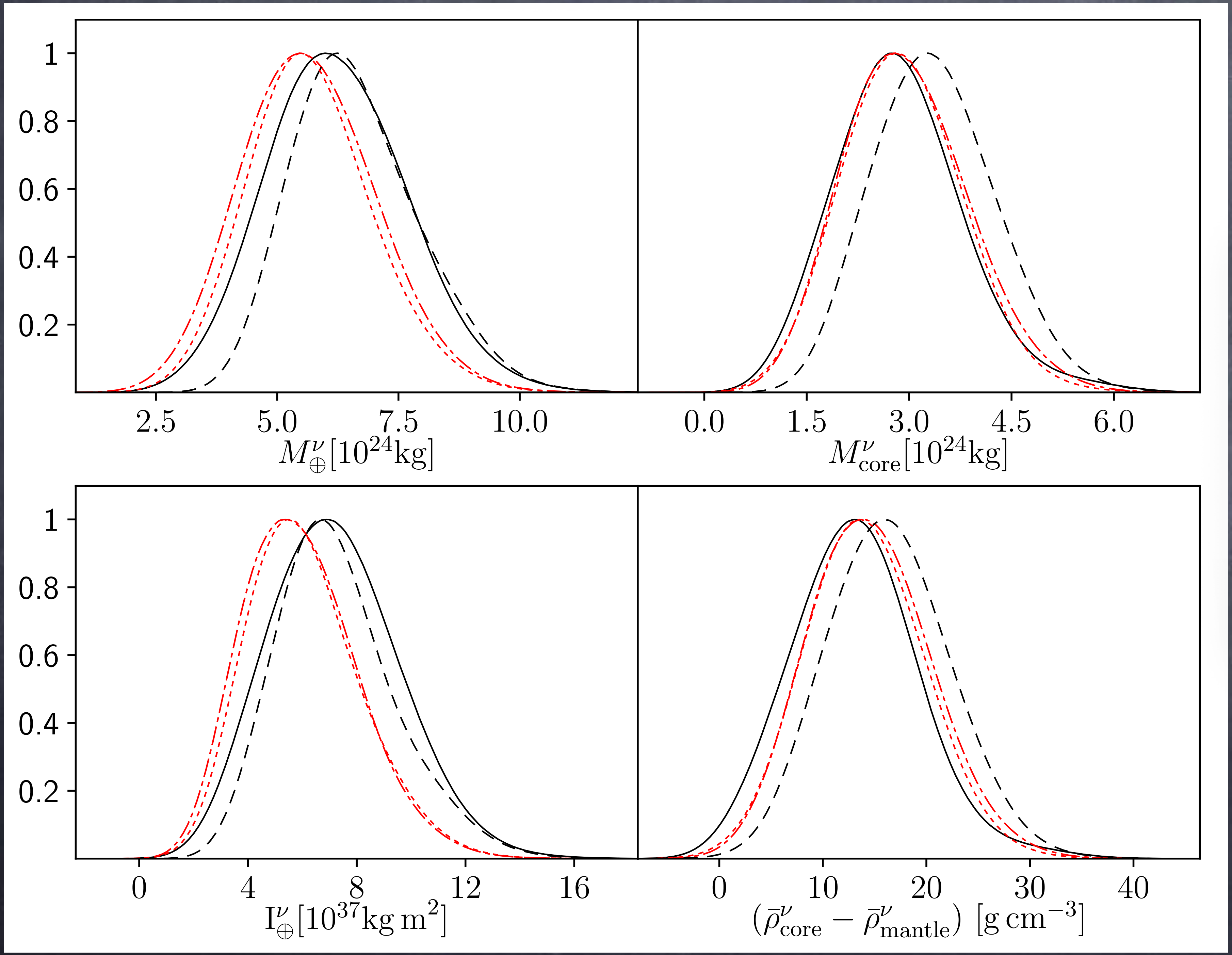
"what curiosity in the structure, what accuracy in the mixture and composition of the parts, ought not we to expect in the fabric of this globe"

Thanks!

Extras

IMPACT OF DISCRETE SYSTEMATICS

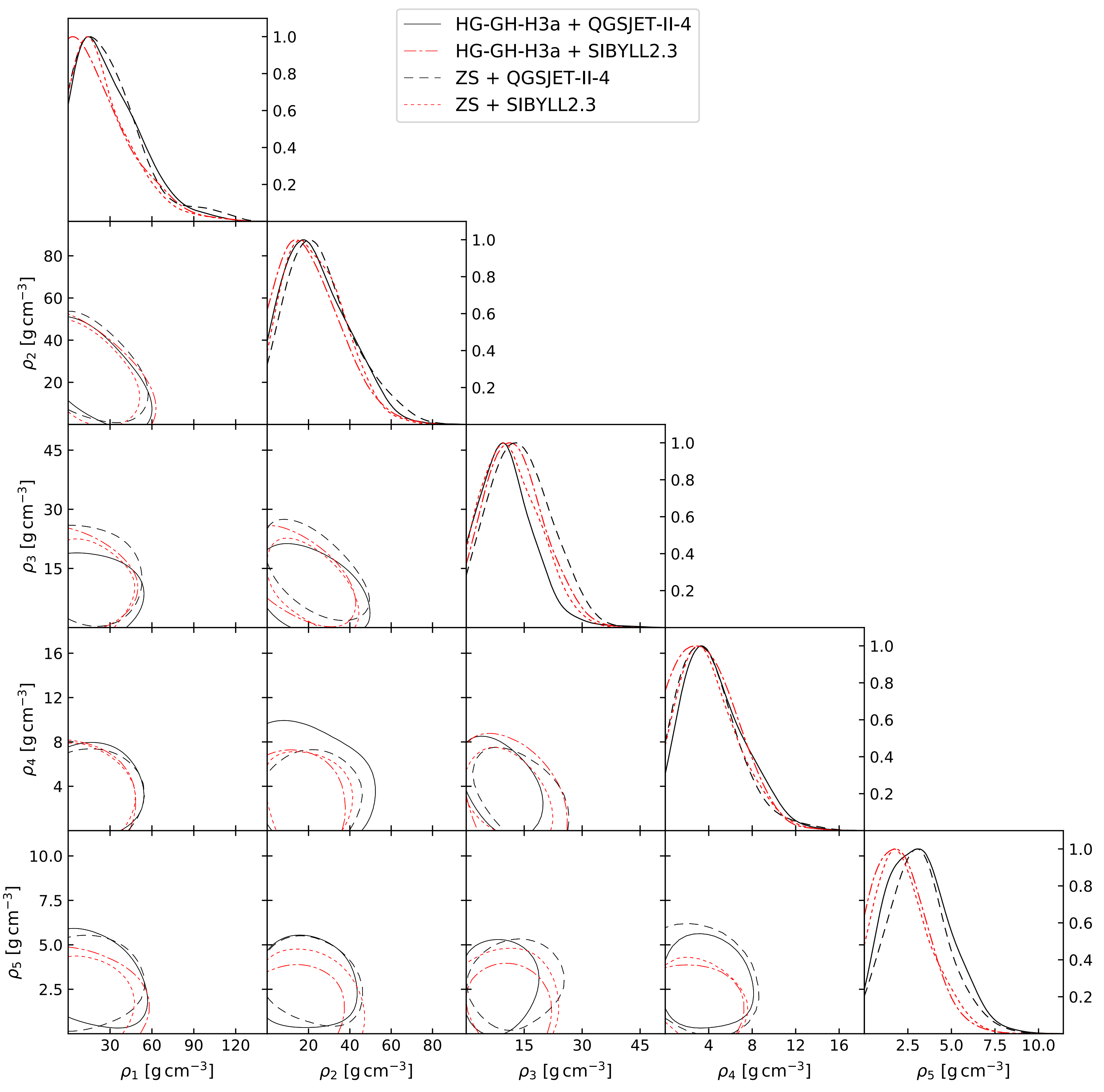
Different atmospheric neutrino fluxes



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

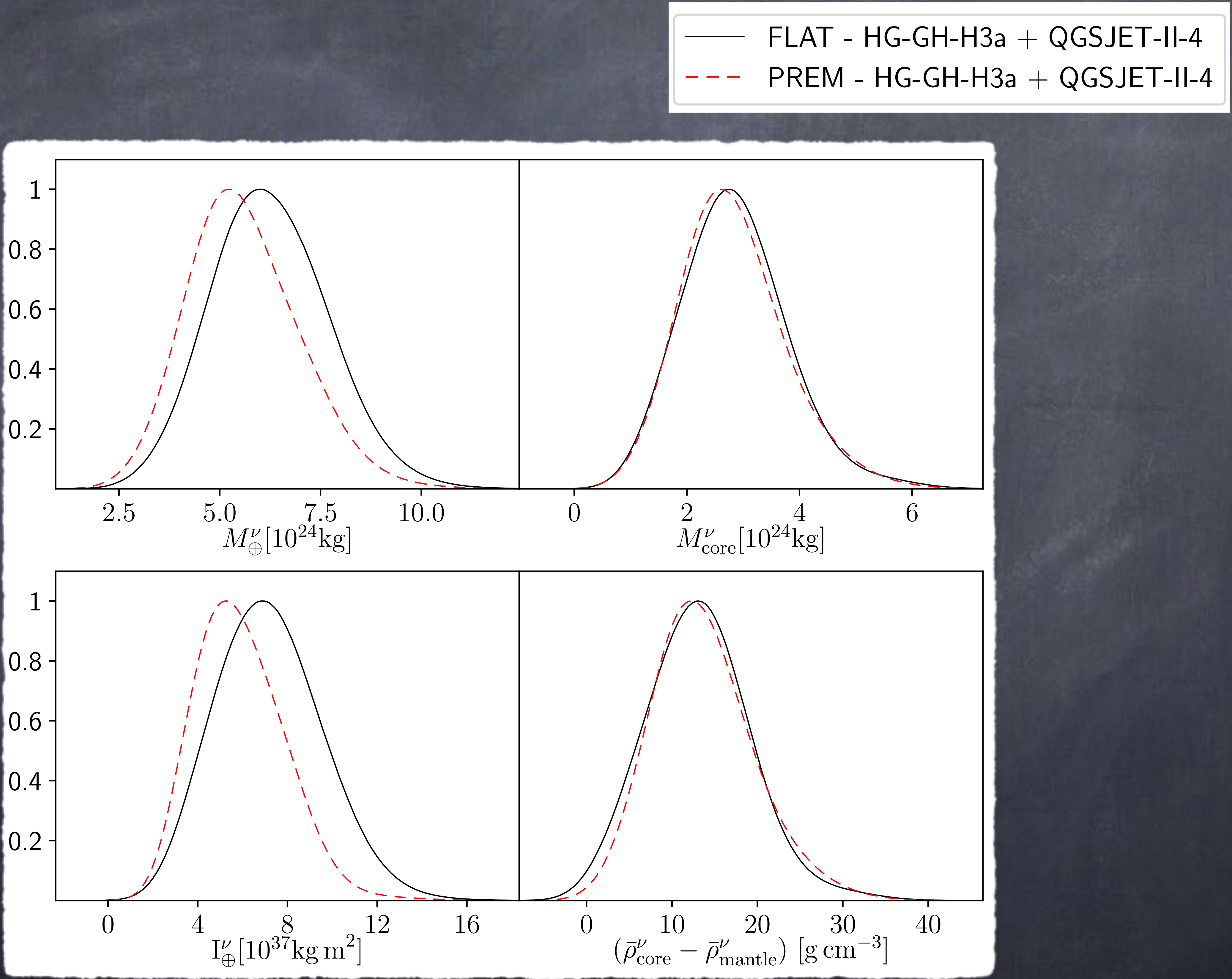
A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

NEUTRINO FLUXES: CORRELATIONS



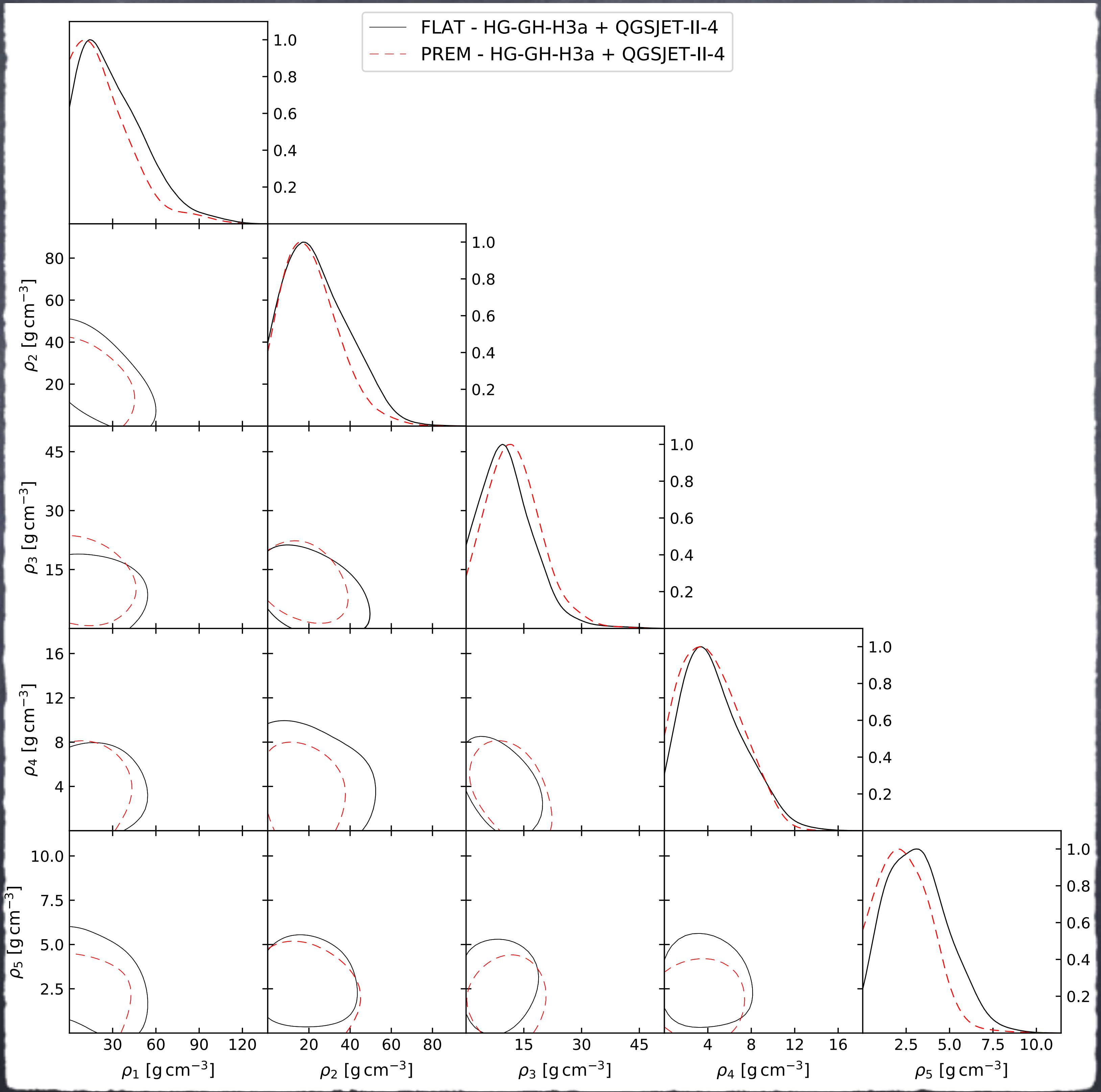
A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

Impact of density profile



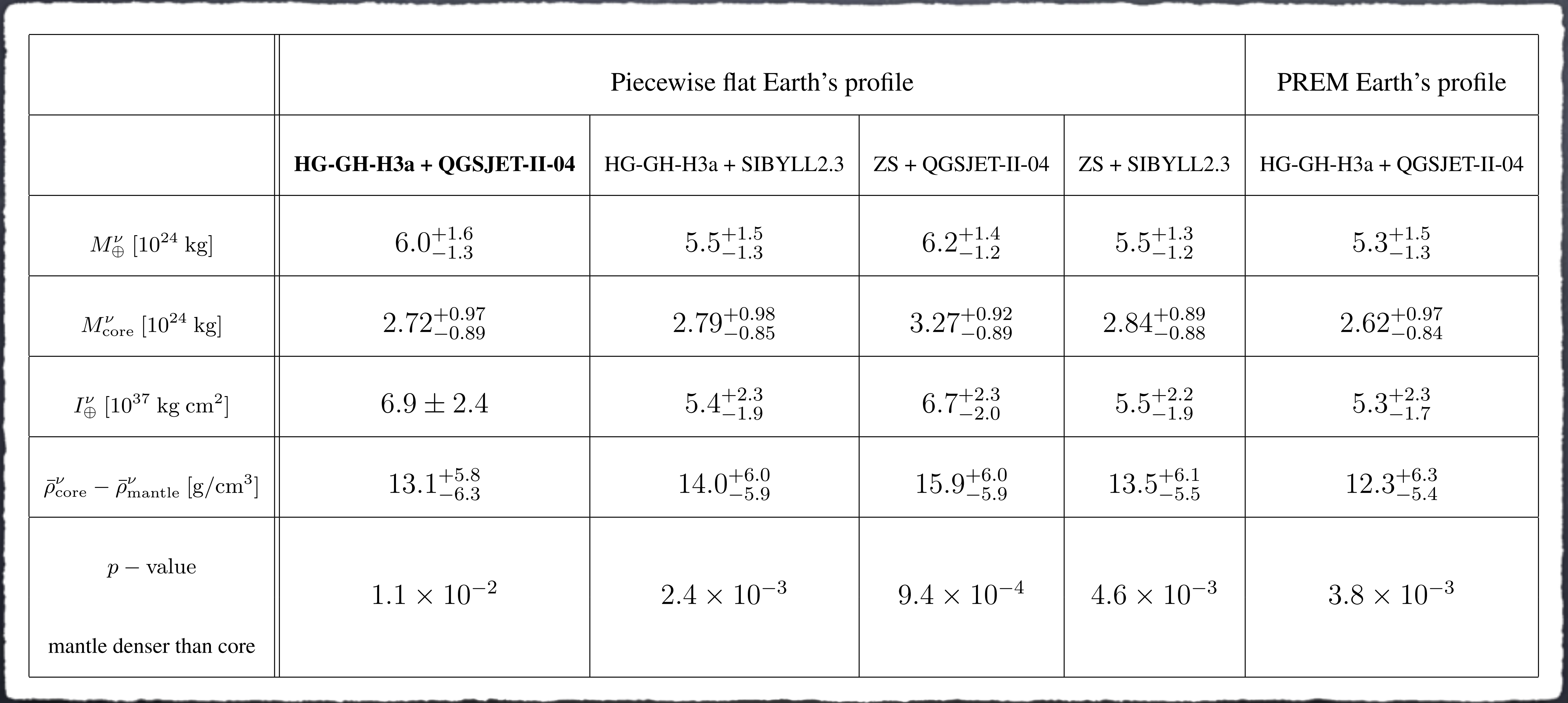
A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

Impact of density profile:Correlations



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

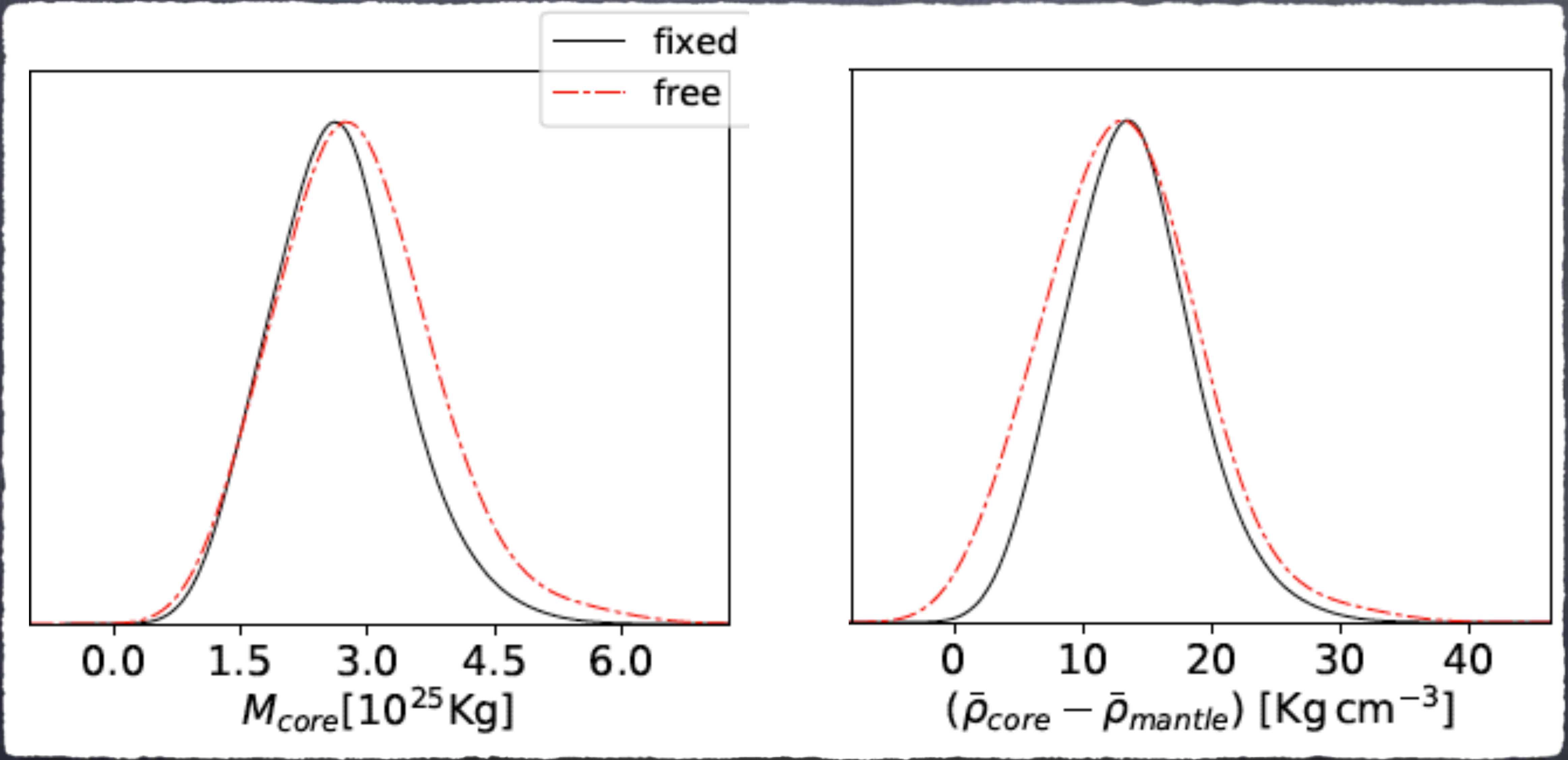
Impact of systematics



	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	$5.4^{+2.3}_{-1.9}$	$6.7^{+2.3}_{-2.0}$	$5.5^{+2.2}_{-1.9}$	$5.3^{+2.3}_{-1.7}$
$\bar\rho_{\rm core}^\nu - \bar\rho_{\rm mantle}^\nu$ $[{\rm g/cm^3}]$	$13.1^{+5.8}_{-6.3}$	$14.0^{+6.0}_{-5.9}$	$15.9^{+6.0}_{-5.9}$	$13.5^{+6.1}_{-5.5}$	$12.3^{+6.3}_{-5.4}$
$p -$ 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}

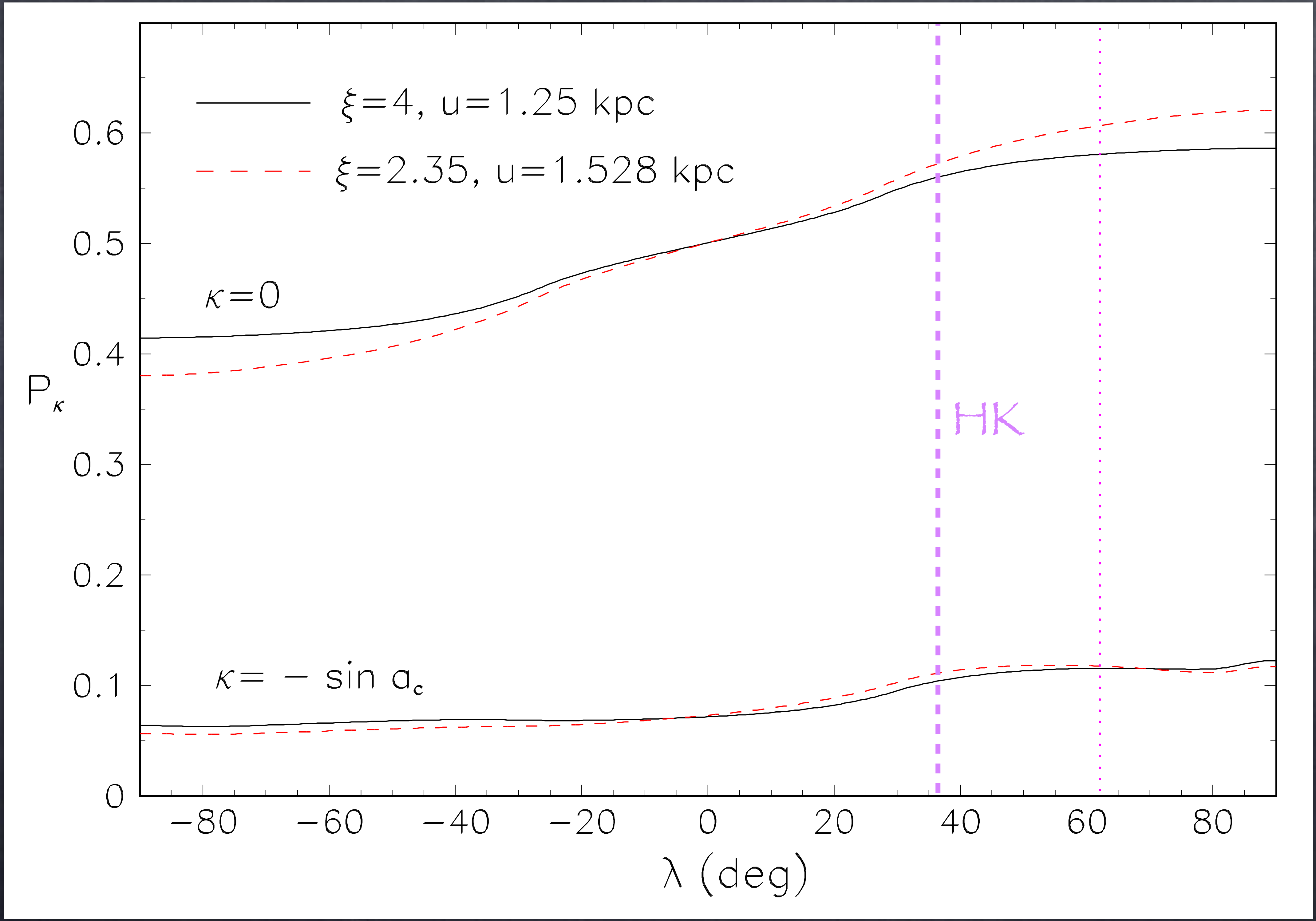
A. Donini, SPR and J. Salvado, Nature Physics 15:37, 2019

ADDING GRAVITY CONSTRAINTS



Density of the mantle determined at ~4%

PROBABILITY OF EARTH/CORE SHADOWING FOR A GALACTIC SN



A. Mirizzi, G. G. Raffelt and P. D. Serpico, JCAP 05:012, 2006