

Neutrino Earth tomography in DUNE

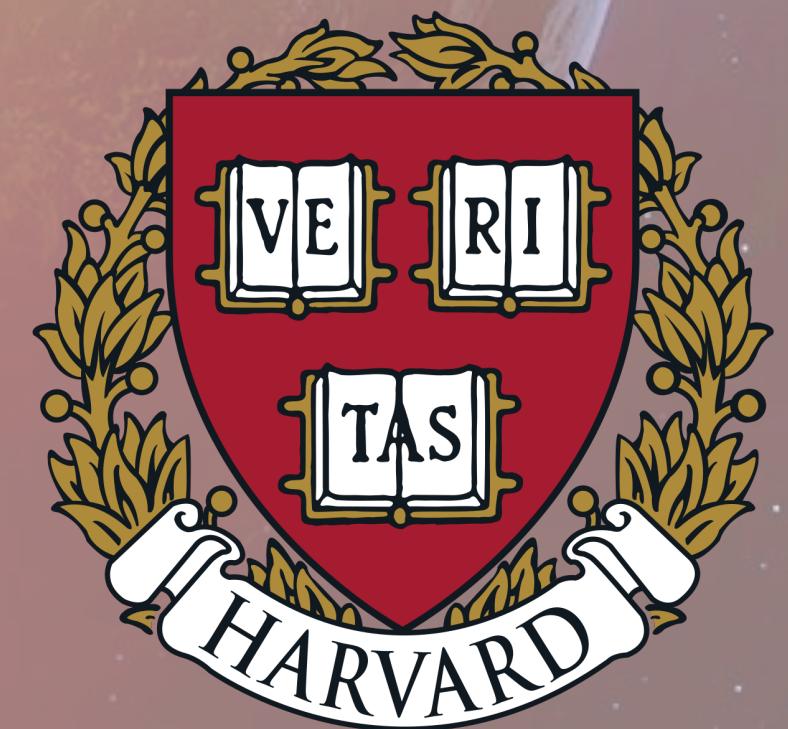
MMTE

Ivan Martinez-Soler

In collaboration with Kevin J. Kelly, Pedro A.N. Machado, and Yuber F. Perez-Gonzalez

Based on JHEP 05 (2022) 187 arXiv: 2110.00003

July 31, 2022

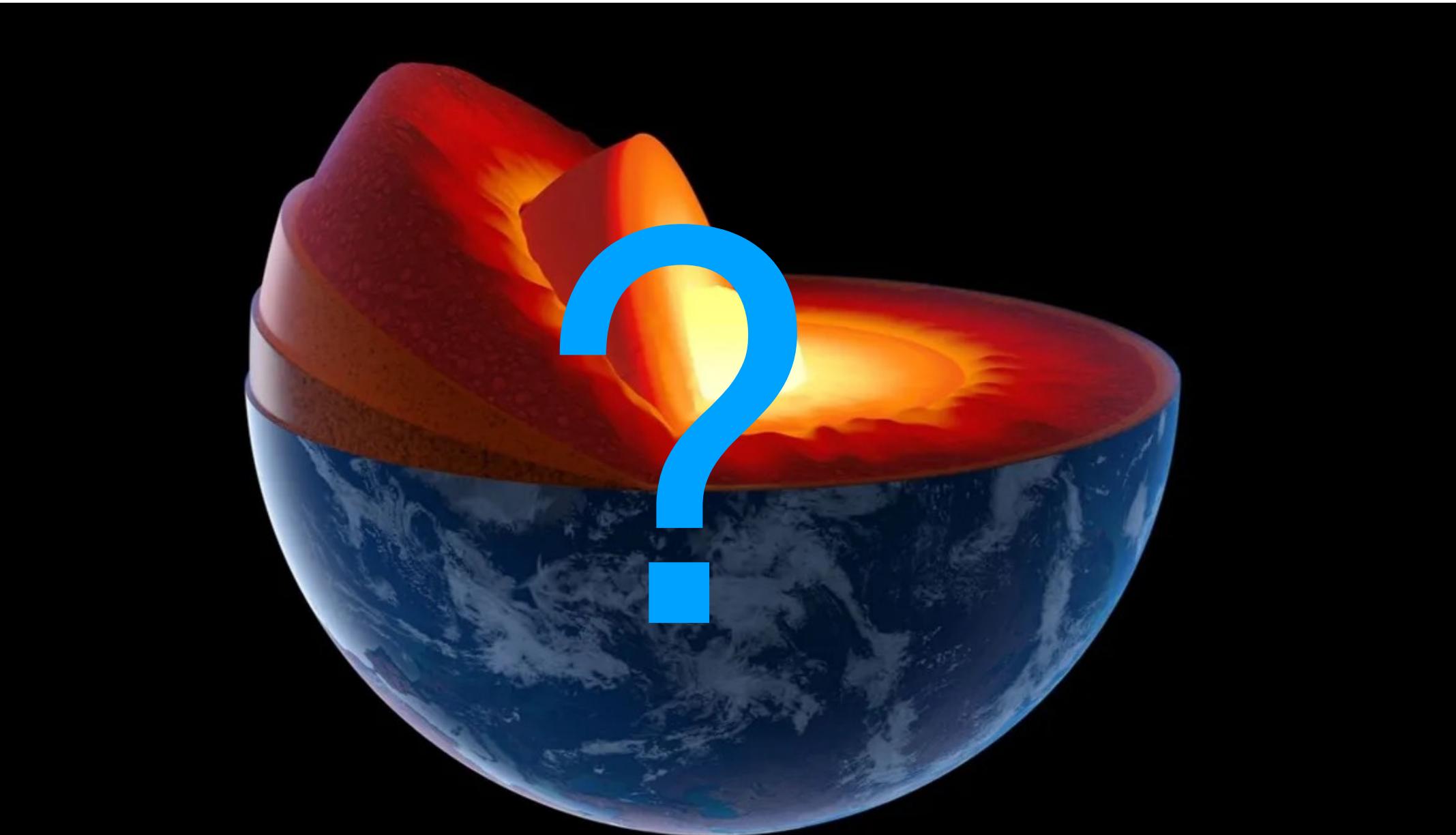


Earth tomography

See William McDonough's Talk

There are several open questions about our planet:

- Composition of the Earth (N/A)
- Amount of water in the mantle
- Mass of the Core
- Cooling mechanism

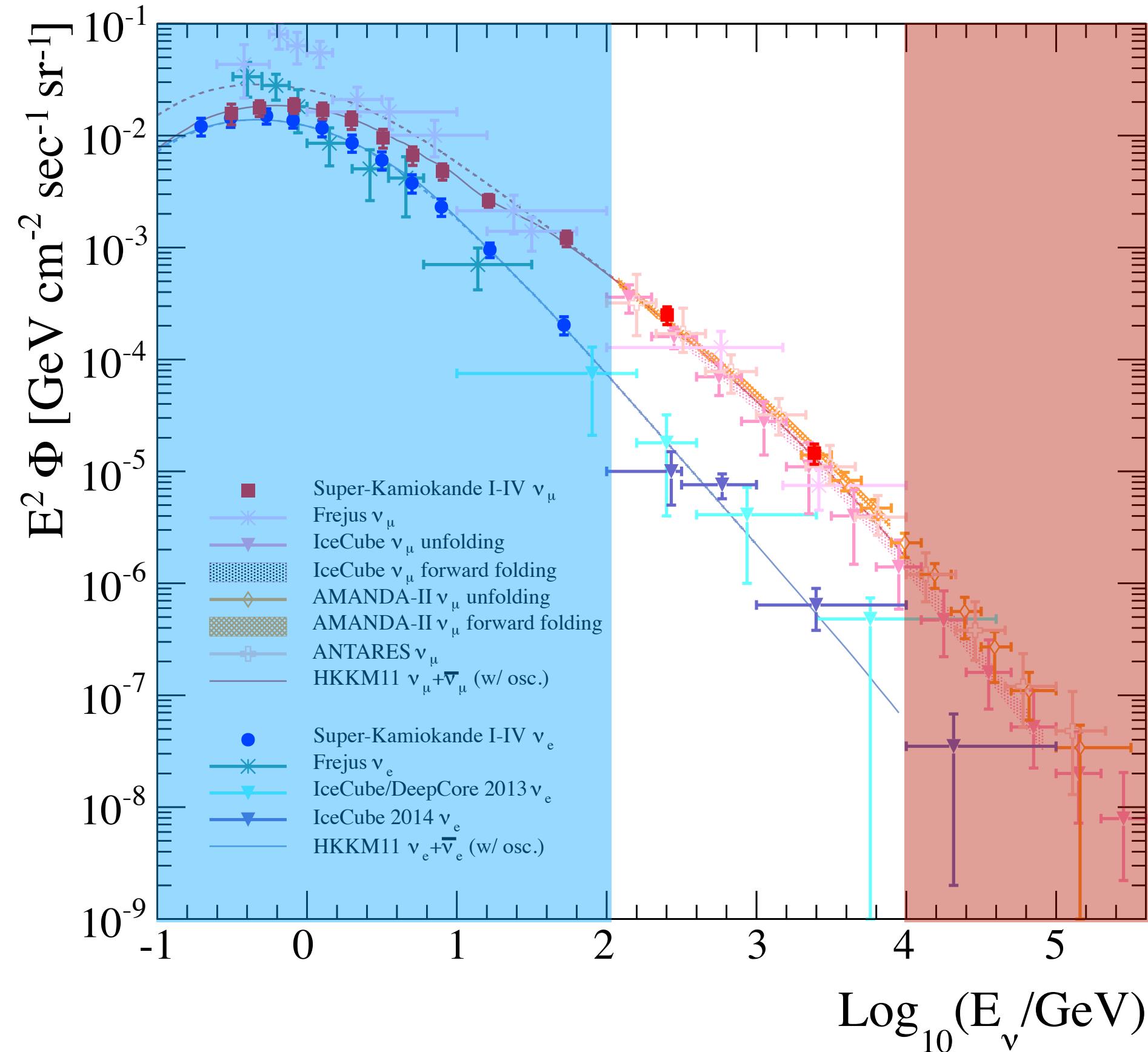


The most traditional measurements are based seismology

Alternative method: atmospheric neutrinos

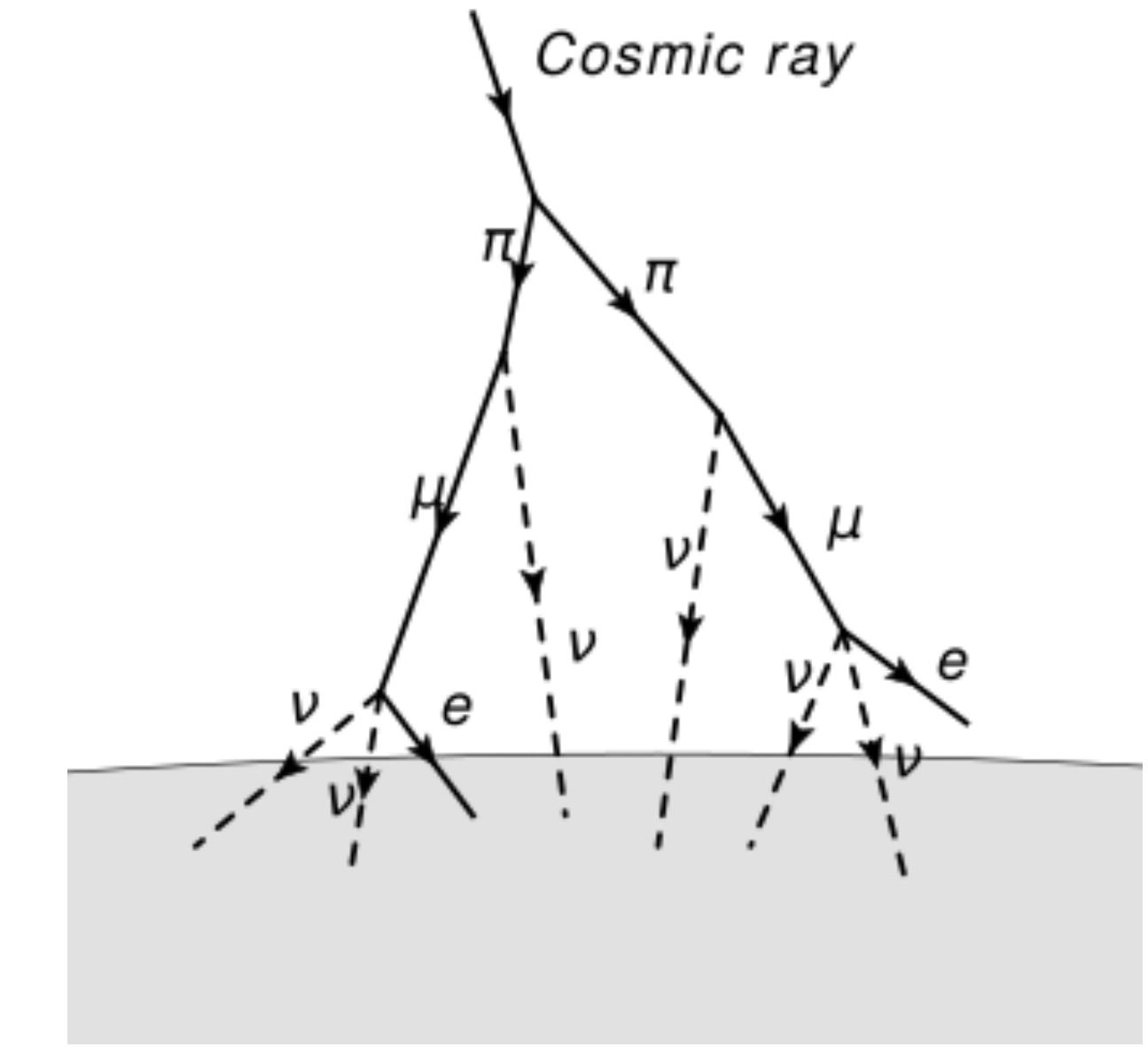
Atmospheric neutrinos

Atmospheric neutrinos are created in the collision of cosmic rays with the atmospheric nuclei



$$\begin{aligned}\pi &\rightarrow \mu \nu_\mu \\ K &\rightarrow \mu \nu_\mu \\ \mu &\rightarrow e \bar{\nu}_e \bar{\nu}_\mu\end{aligned}$$

- We focus on neutrino energies around the **GeV scale**
- At very high energy, neutrinos get absorbed in their path through the Earth

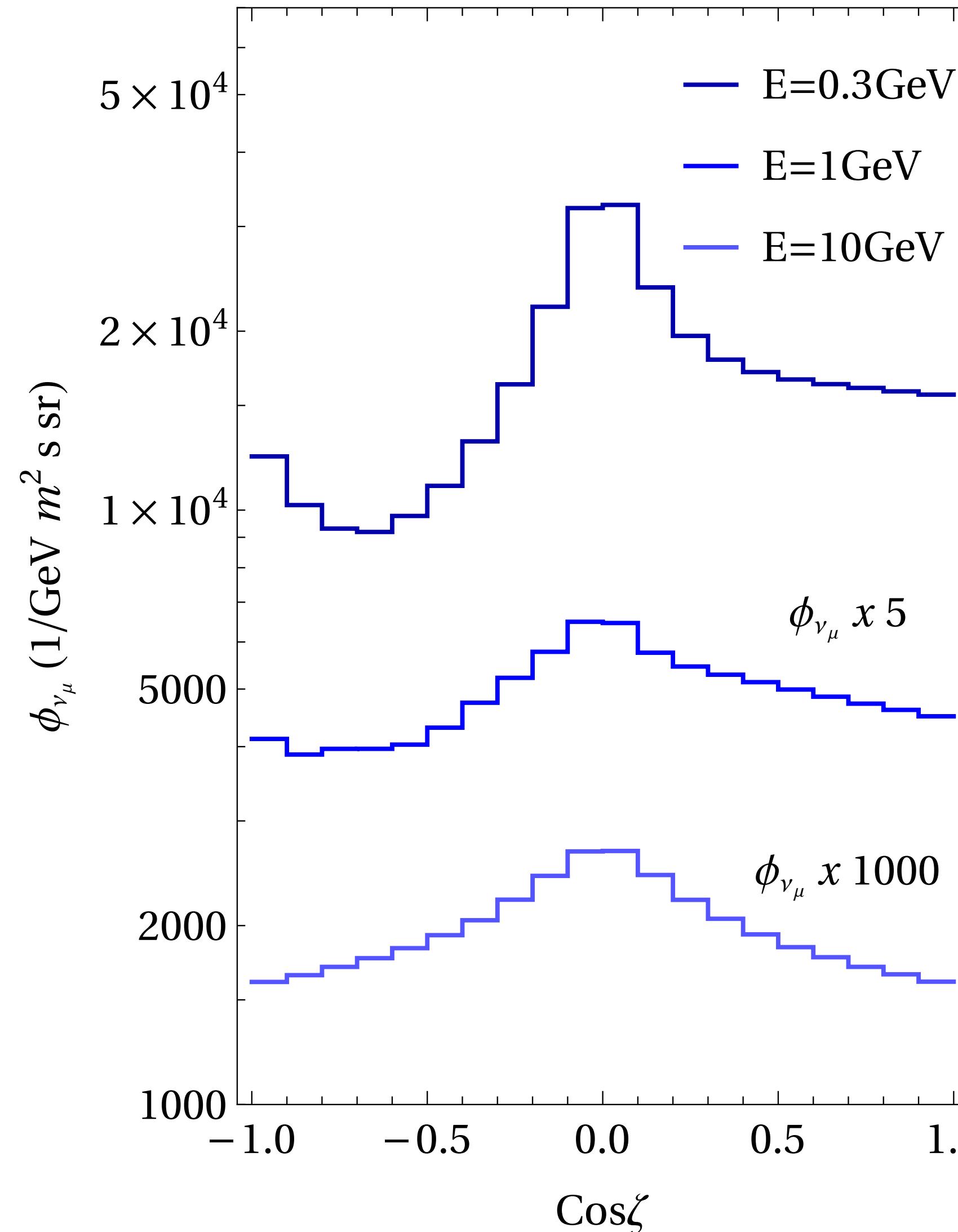


See Andrea Donini and
Kotayo Hoshina Talks

E. Richard et al. (SK), Phys.Rev.D 94 (2016) 5, 052001

Atmospheric neutrinos

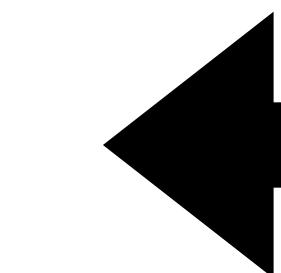
The most recent atmospheric neutrino flux estimations are based on 3D-MC simulation



$$\phi_{\nu_i} = \phi_p \otimes R_p \otimes Y_{p \rightarrow \nu_i} + \sum_A \phi_A \otimes R_A \otimes Y_{A \rightarrow \nu_i}$$

The main components in the flux calculations are:

- Cosmic ray flux (ϕ_p)
- Geomagnetic effects (R)
- Hadronic interactions (Y)



See Edward Kearns's Talk

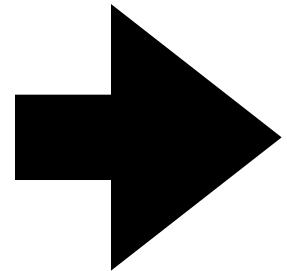
Honda, Sajjad Athar, Kajita, Kasahara,
Midorikawa Phys.Rev.D 92 (2015)

Atmospheric neutrinos

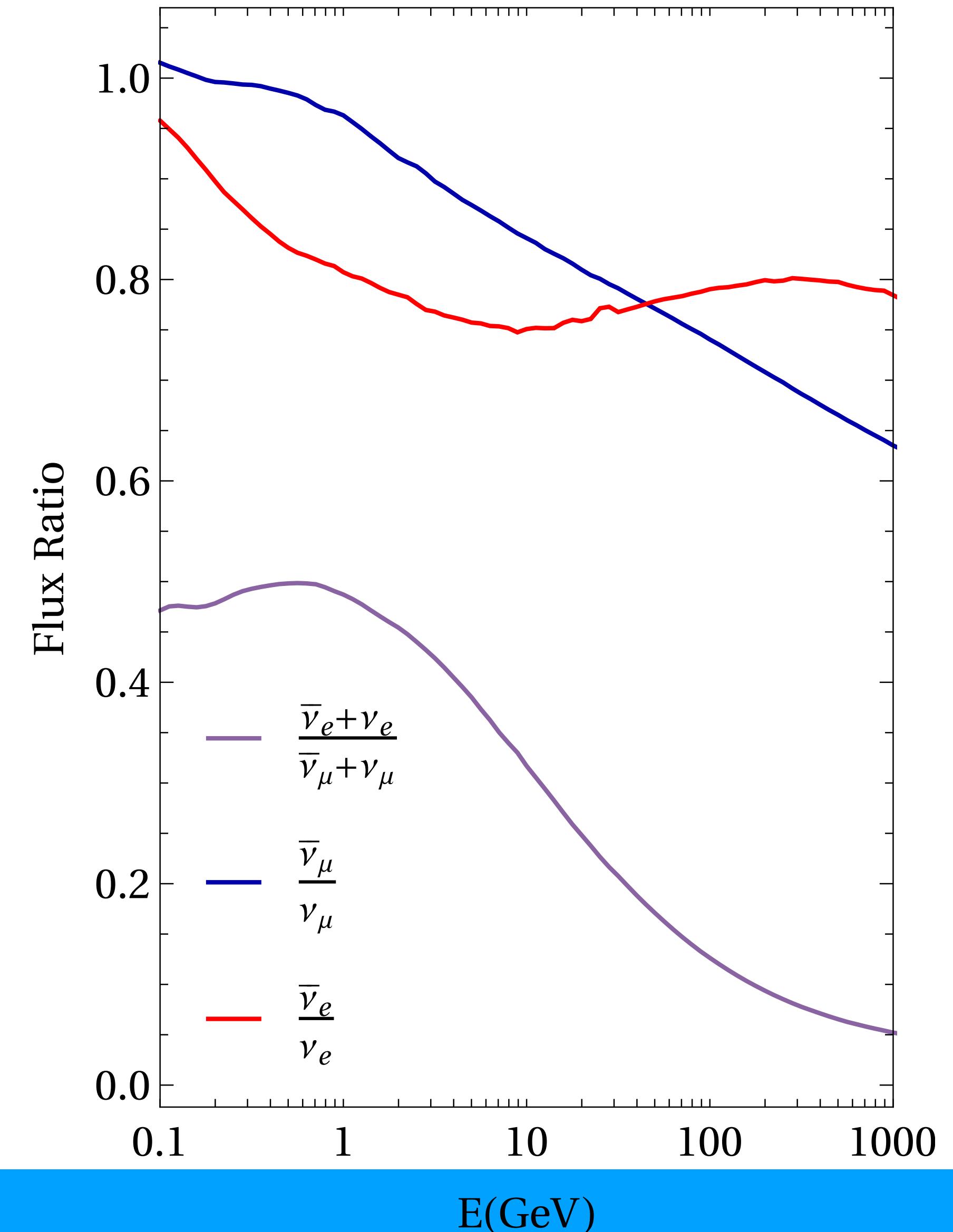
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$$\phi_{\nu_i} = \phi_p \otimes R_p \otimes Y_{p \rightarrow \nu_i} + \sum_A \phi_A \otimes R_A \otimes Y_{A \rightarrow \nu_i}$$

The atmospheric flux **composition changes** with the energy



Honda, Sajjad Athar, Kajita, Kasahara,
Midorikawa Phys.Rev.D 92 (2015)



3ν mixing

In the **3v scenario**, neutrino evolution is described by six parameters

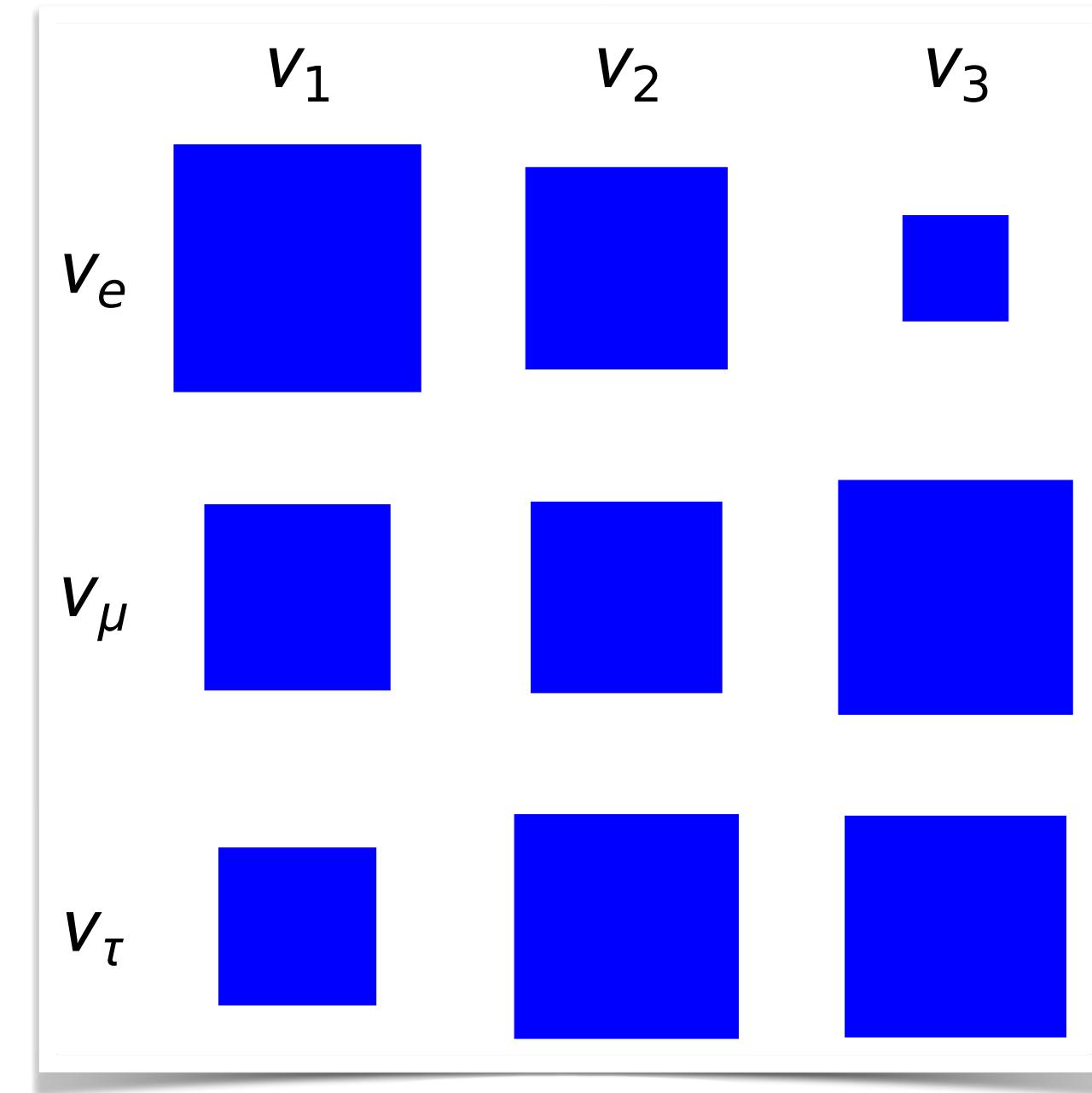
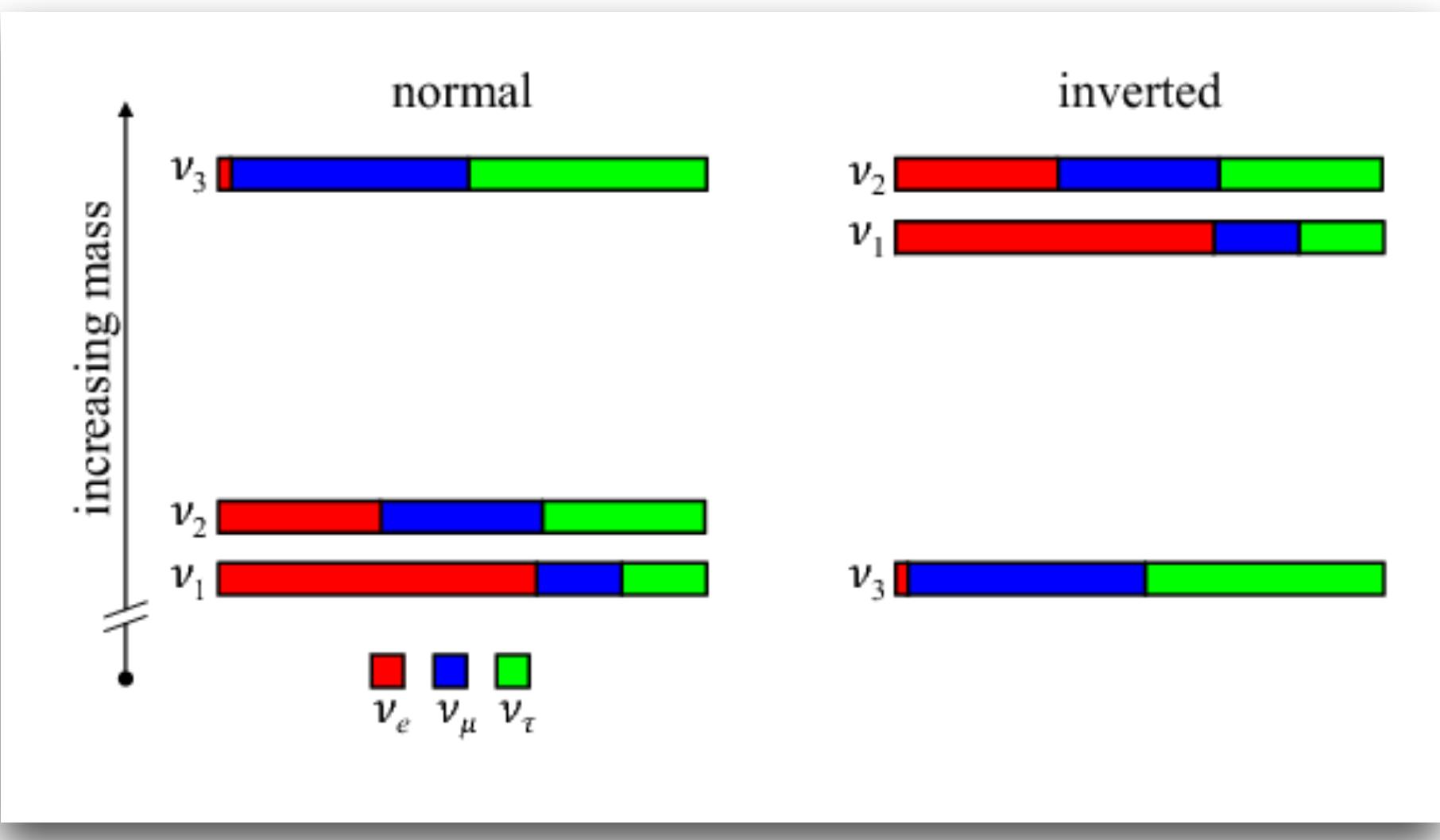
See Sanjib Kumar's Talk

$$i \frac{d\nu}{dE} = \frac{1}{2E} \left(U^\dagger \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U \right) \nu$$

Mixing between massive and massive states

$$\nu_\alpha = \sum U_{\alpha i} \nu_i \quad U = U(\theta_{23}) U(\theta_{13}, \delta_{cp}) U(\theta_{12})$$

Mass ordering



3ν mixing in matter

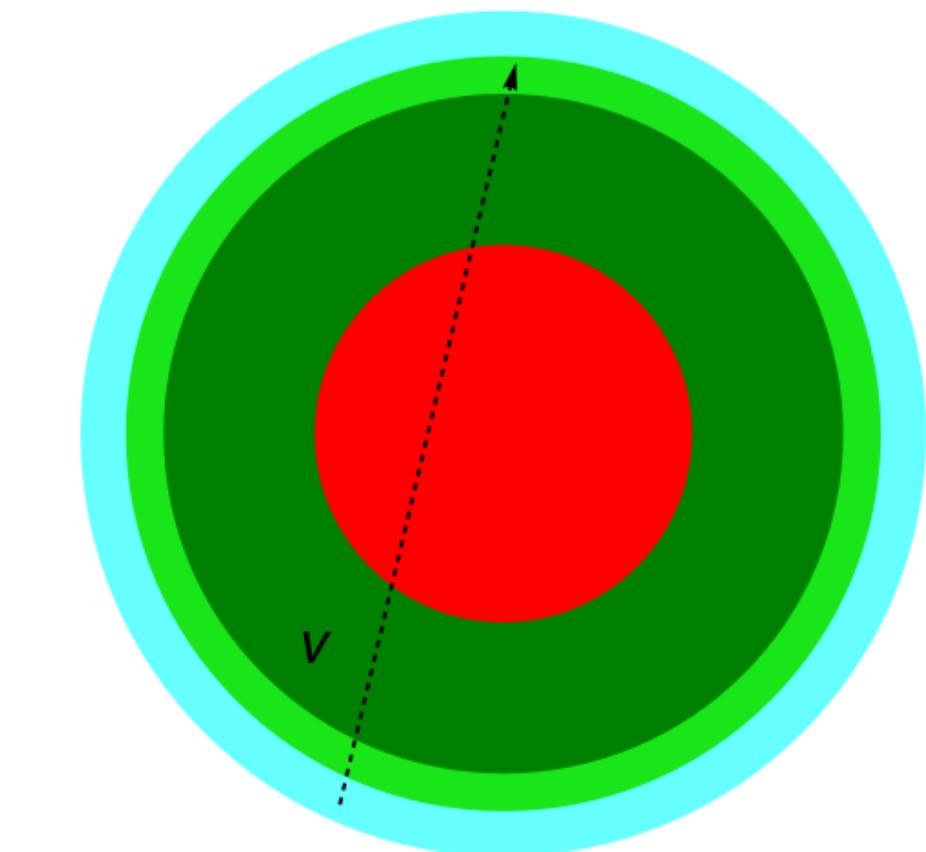
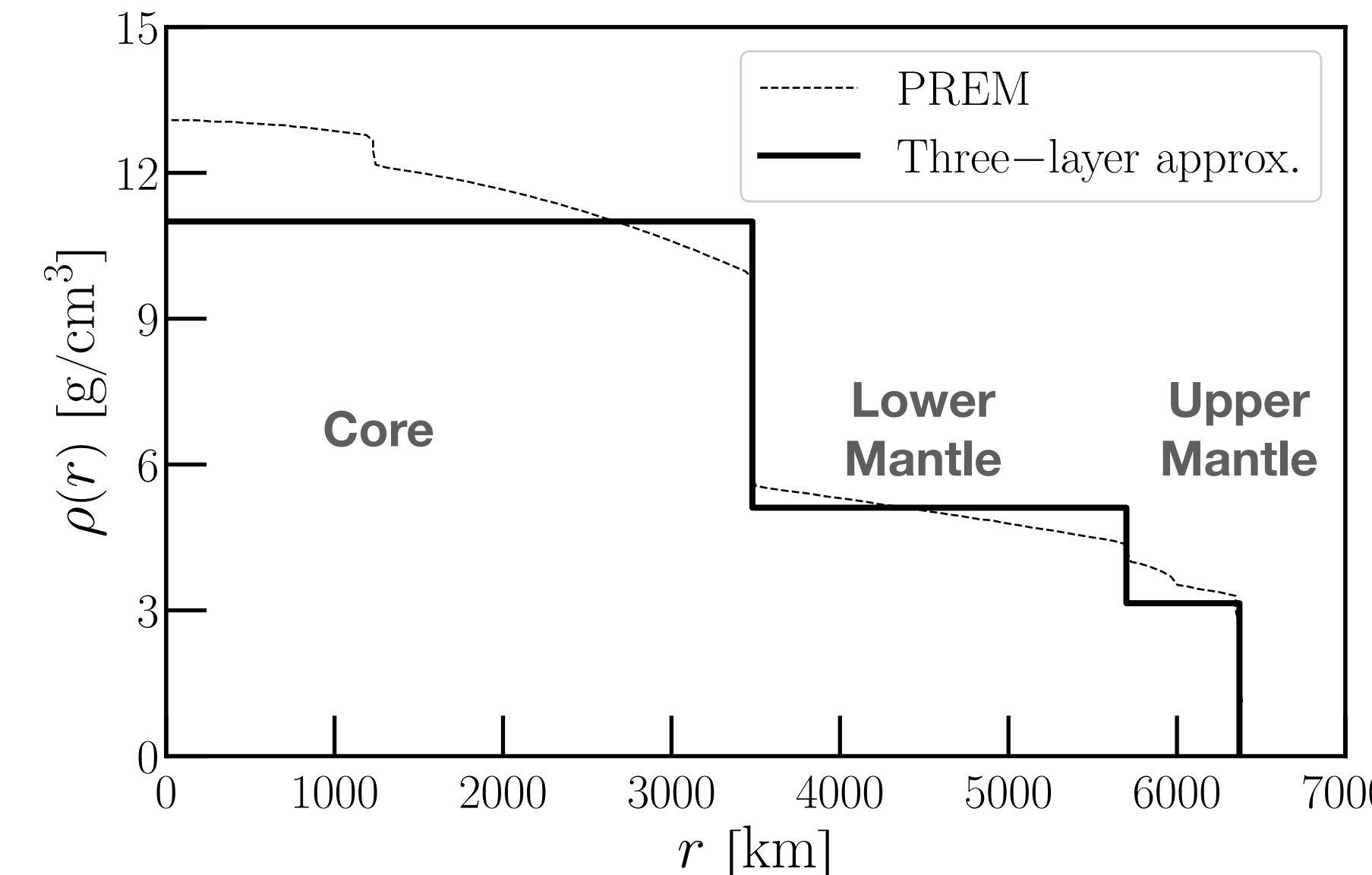
In matter, the evolution is affected by the matter potential

$$i \frac{d\nu}{dE} = \frac{1}{2E} (U^\dagger \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U \pm V_{mat}) \nu$$

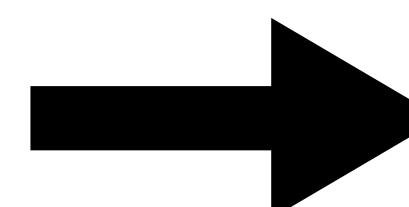
$$V_{mat} = \sqrt{2} G_F N_e \text{diag}(1, 0, 0)$$

Electron density along the neutrino trajectory

For neutrinos crossing the Earth



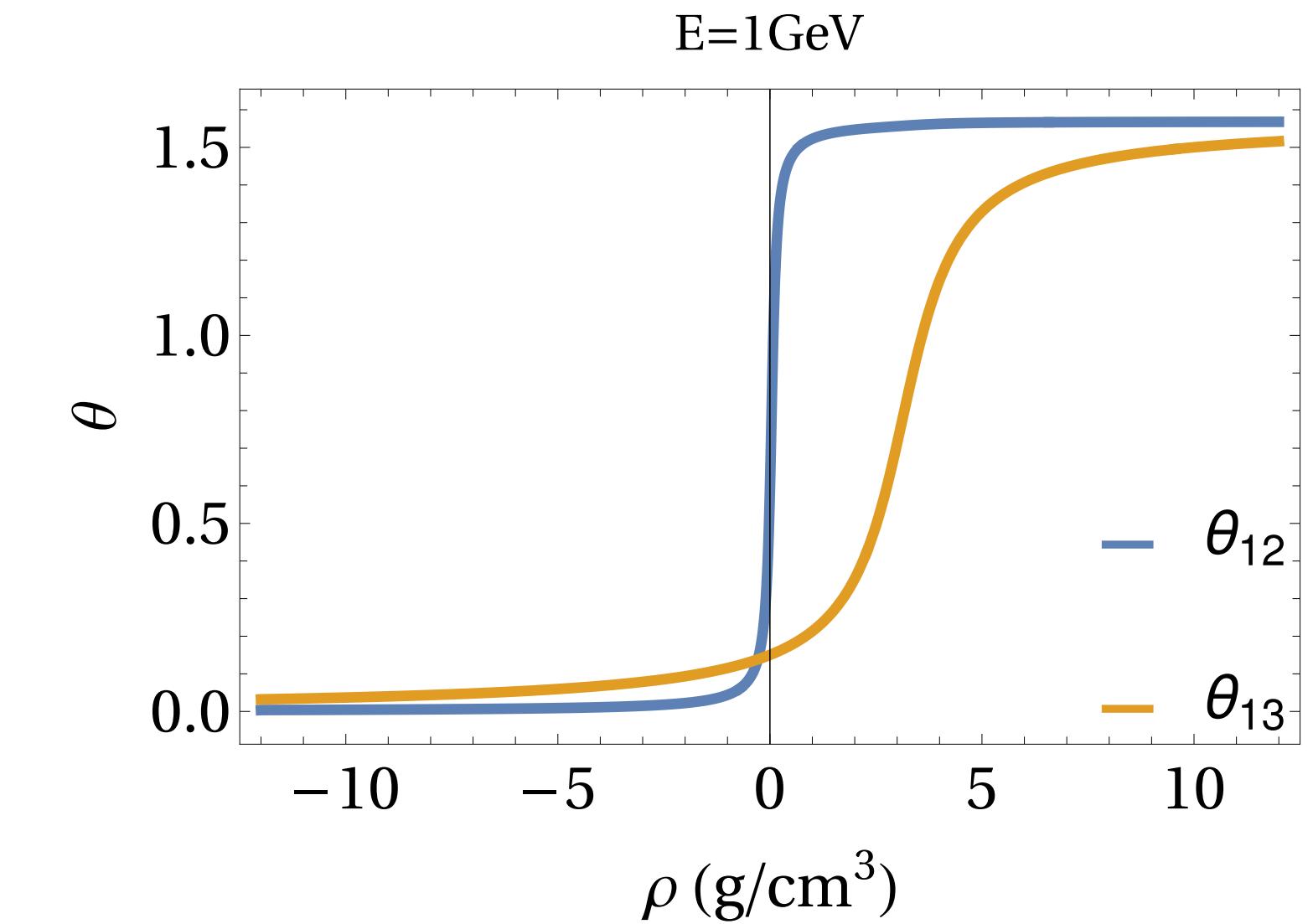
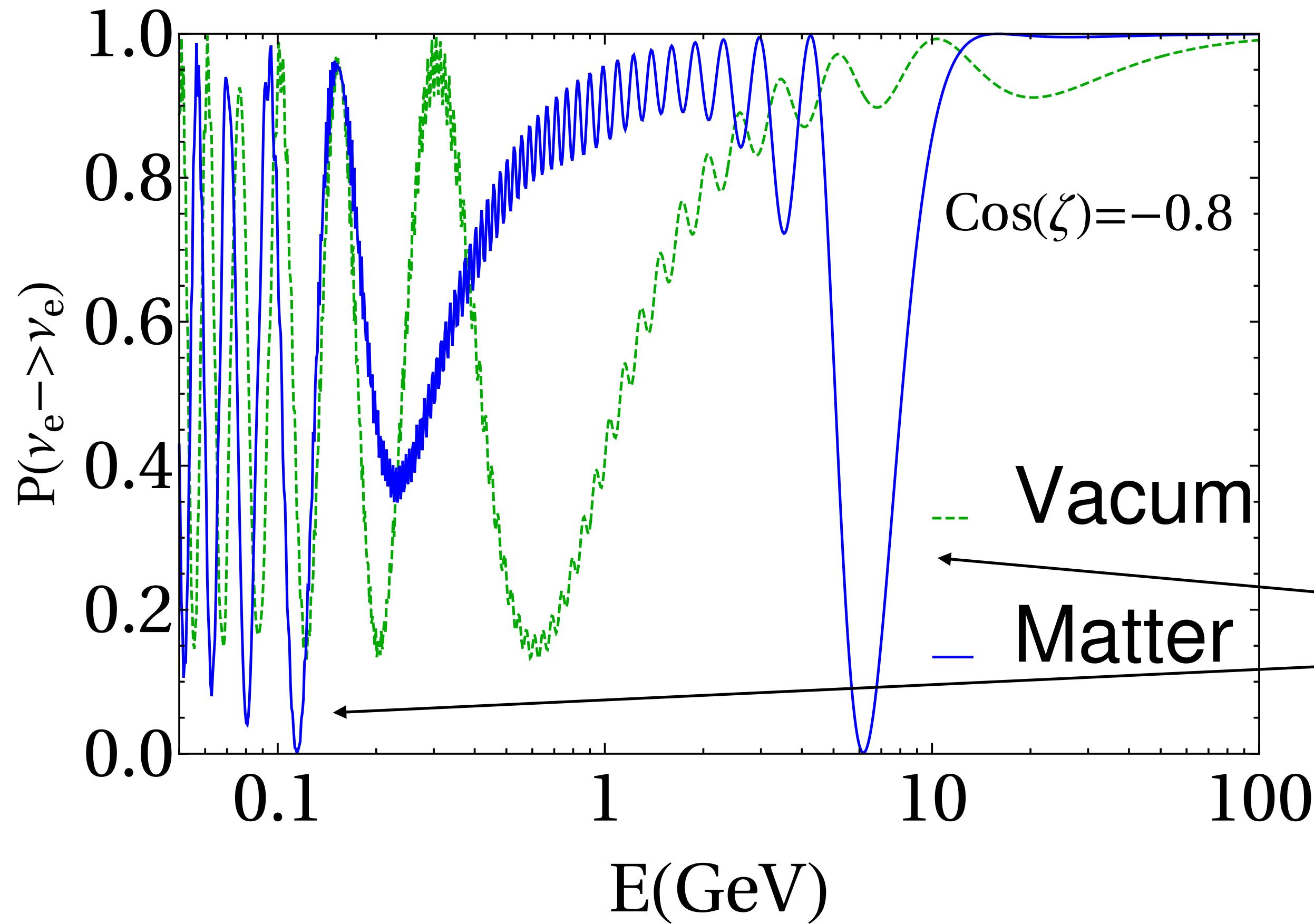
Complementarity among the different measurements



Seismology	Total density and state of matter
Absorption	Atomic number
Oscillations	Electron number (thus proton number)

MSW resonance

In the presence of matter, the **mixing angle** can get **enhanced**, leading to a **maximal flavor oscillation**



Those resonances happen for a specific neutrinos energy and density

$$E_{\text{MSW}} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F N_A N_e}$$

Parametric resonance

See Serguey Petcov's Talk

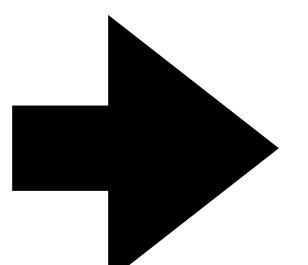
The neutrino evolution across several layers is described by the product of the amplitudes of each layer

$$S = S_M S_C S_M$$

The amplitude in each layer depends on the neutrino phase

$$S_x = \cos \phi_x \mathbf{1}_2 - i \sin \phi_x \vec{\sigma} \cdot \vec{n}_x$$

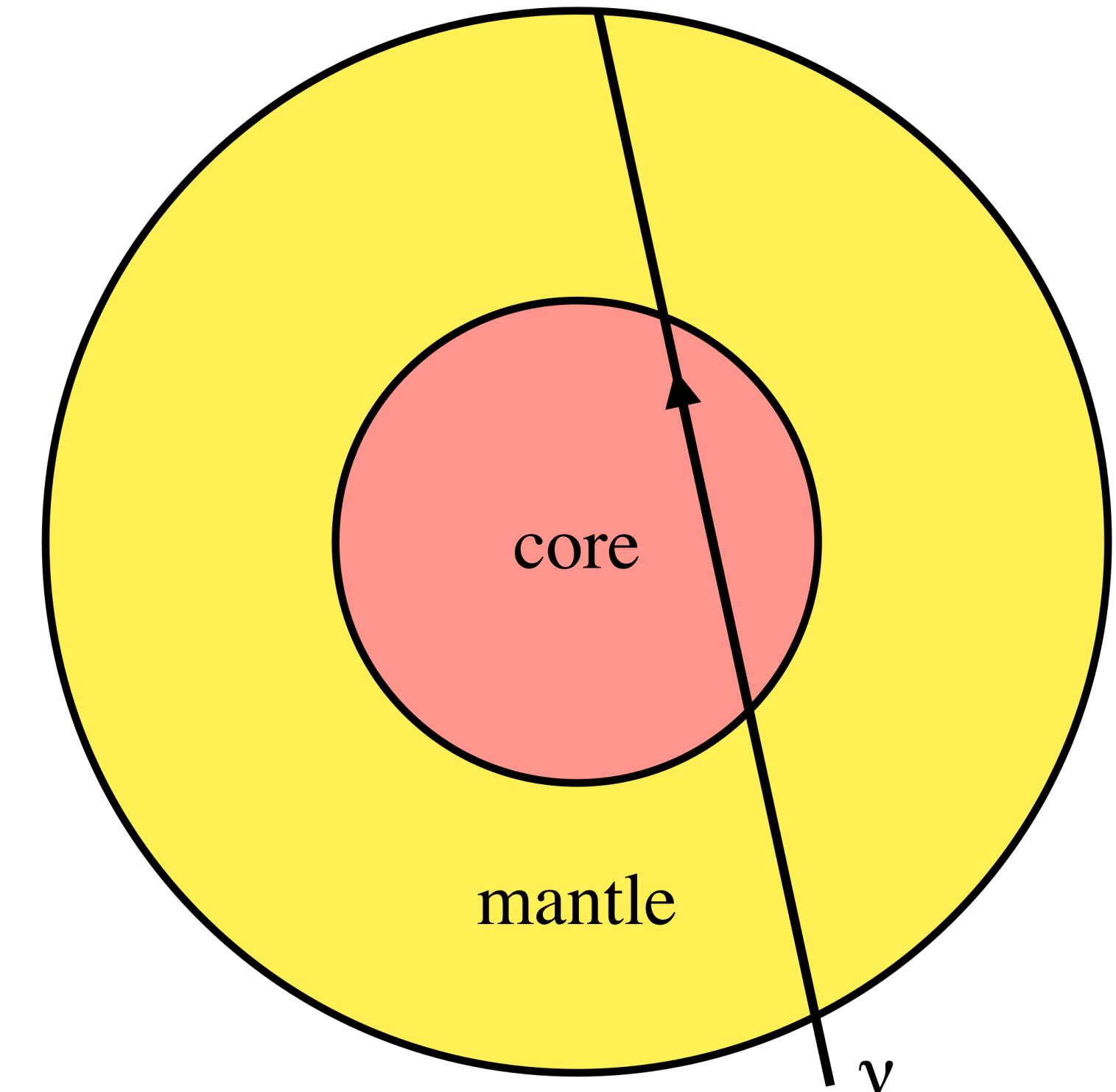
$$\vec{n}_x = (\sin 2\theta_x, 0, -\cos 2\theta_x)$$



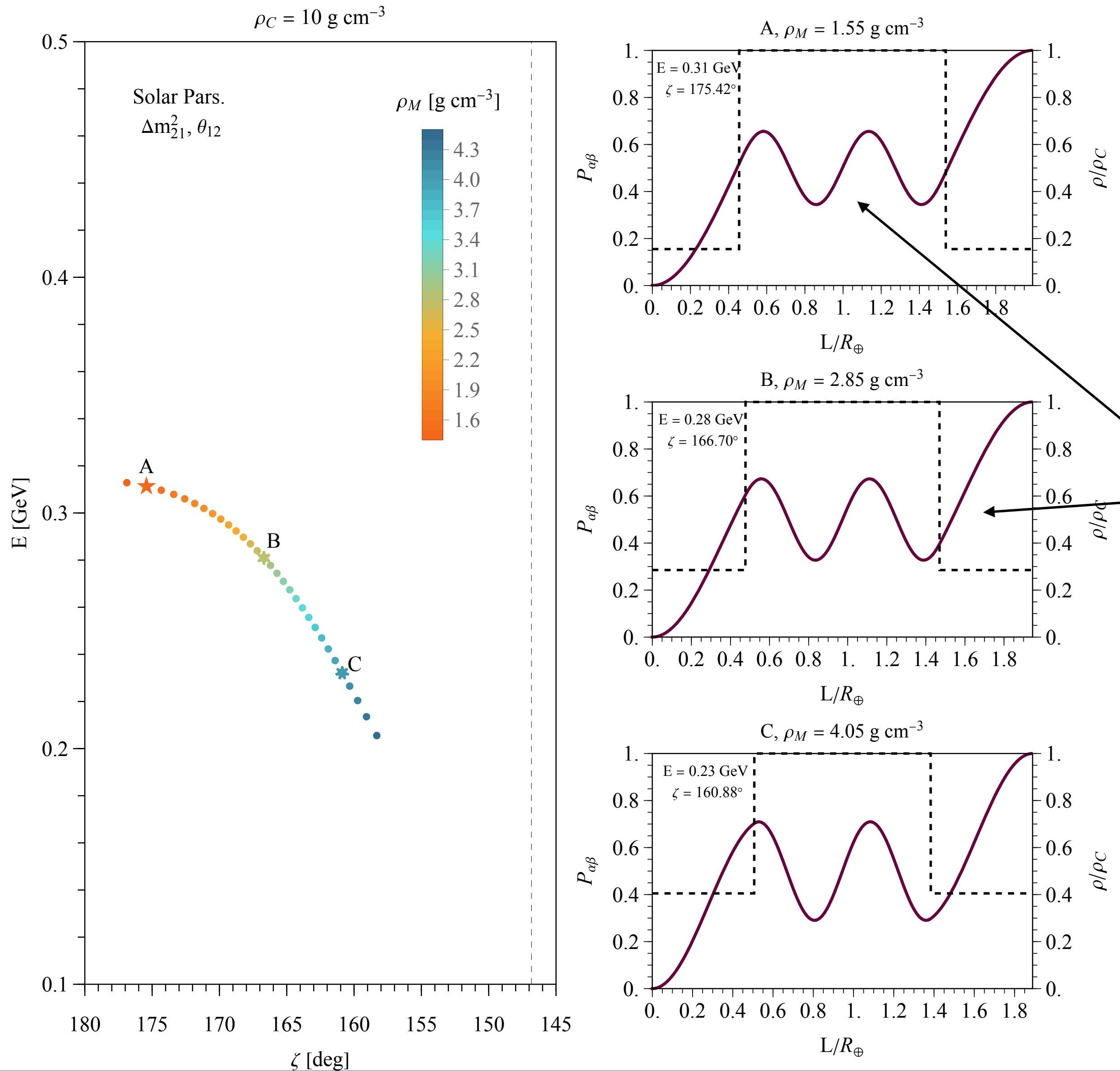
The phase (ϕ_x) and the mixing (θ_x) depends on the neutrino energy, the baseline and the density

$$\phi_x = \frac{\Delta m_x^2 L_x}{4E}$$

Petcov, Phys.Lett.B 434 (1998), Chizhov, Maris and Petcov, hep-ph/9810501, Akhmedov Nucl.Phys.B 538 (1999)



Parametric resonance



A complete flavor transition ($P_{\alpha\beta} = 1$) can be obtained under a constructive interference between the amplitudes of different layers

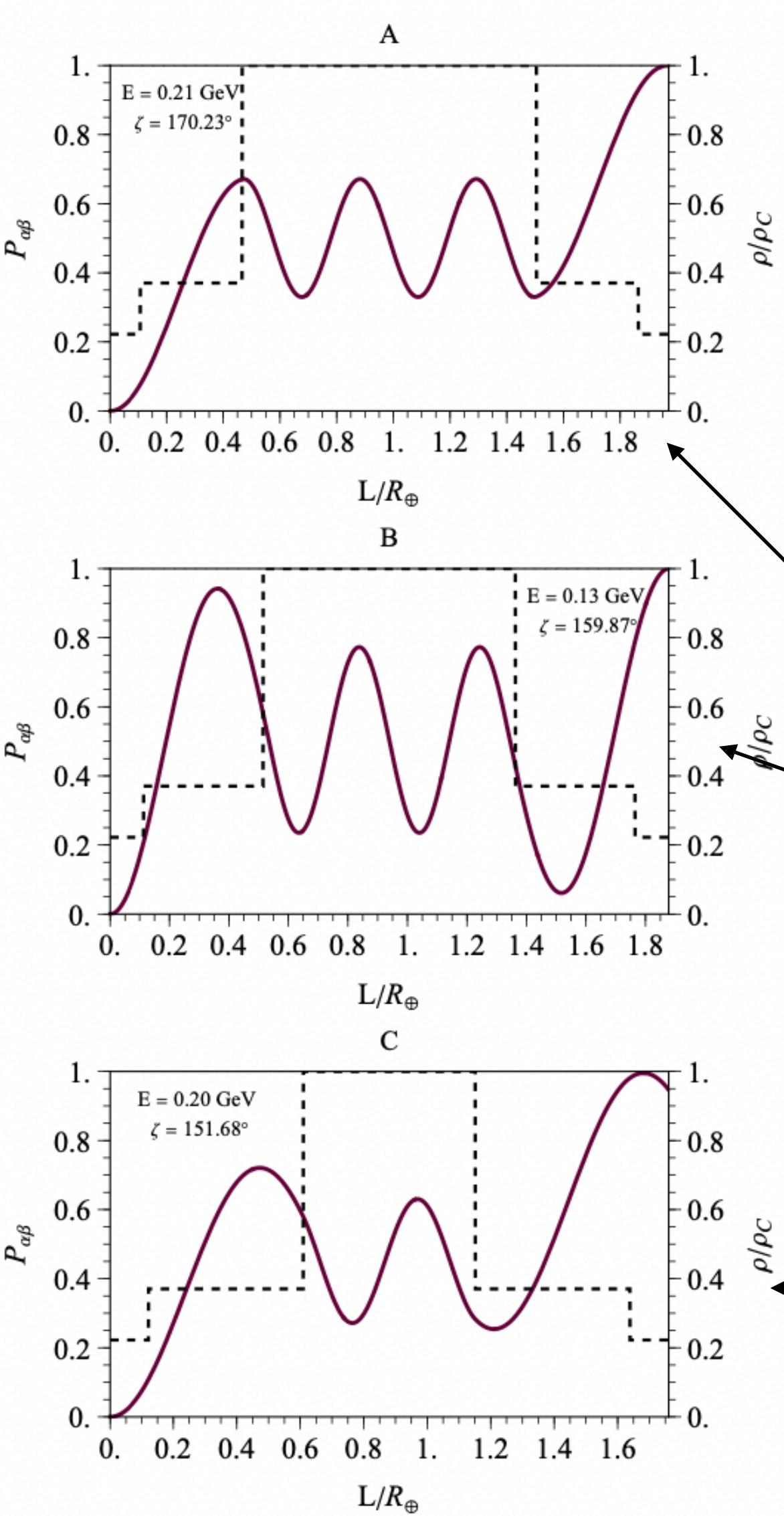
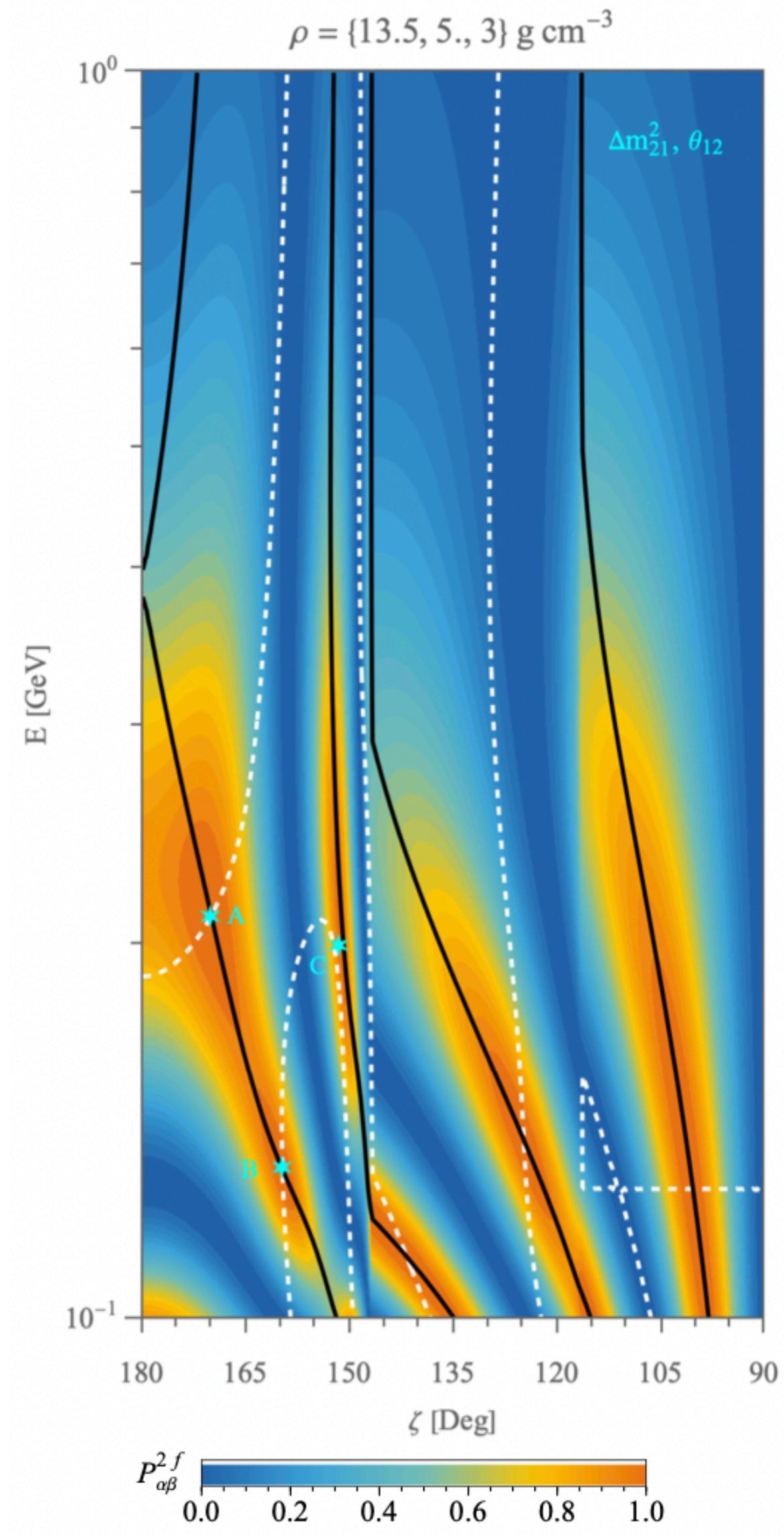
θ_x in each layer is not maximal

Relation between the mixing angles in each layer

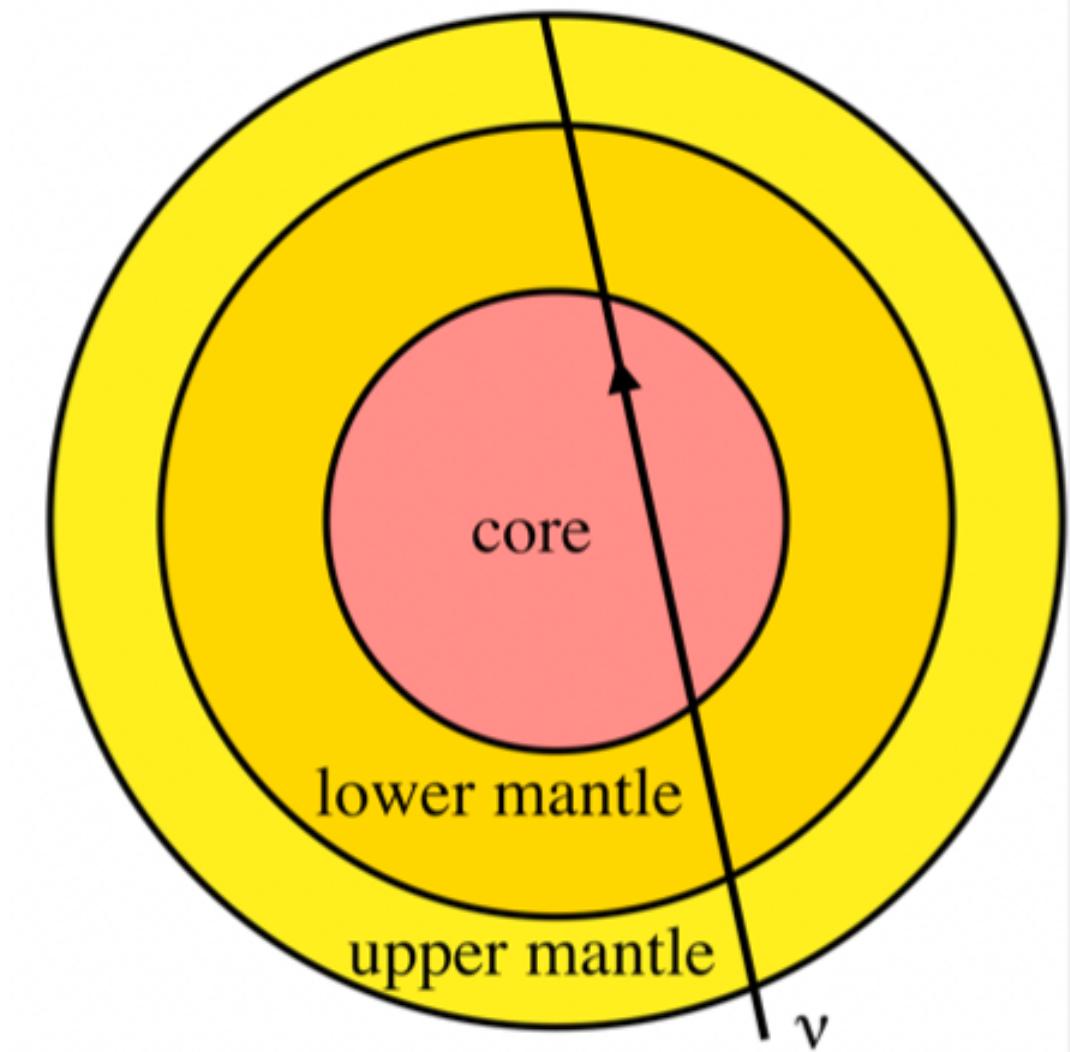
$$\cos 2\theta_c \leq 0, \cos 2(2\theta_M - \theta_c) \geq 0$$

$$\cos 2\theta_c \geq 0, \cos 2(2\theta_M - \theta_c) \leq 0$$

Parametric resonance



In a **3 layer** scenario, the evolution includes the amplitudes through the **upper mantle**, the **lower mantle**, and the **core**



$$S = S_{UM} S_{LM} S_C S_{LM} S_{UM}$$

For several energies and directions a full parametric conversion happens

The phases along the three layers also lead to **parametric enhancements** (almost a maximal flavor conversion)

Detection of atmospheric neutrinos

At present, several experiments have measured the neutrino flux at different energy scales:

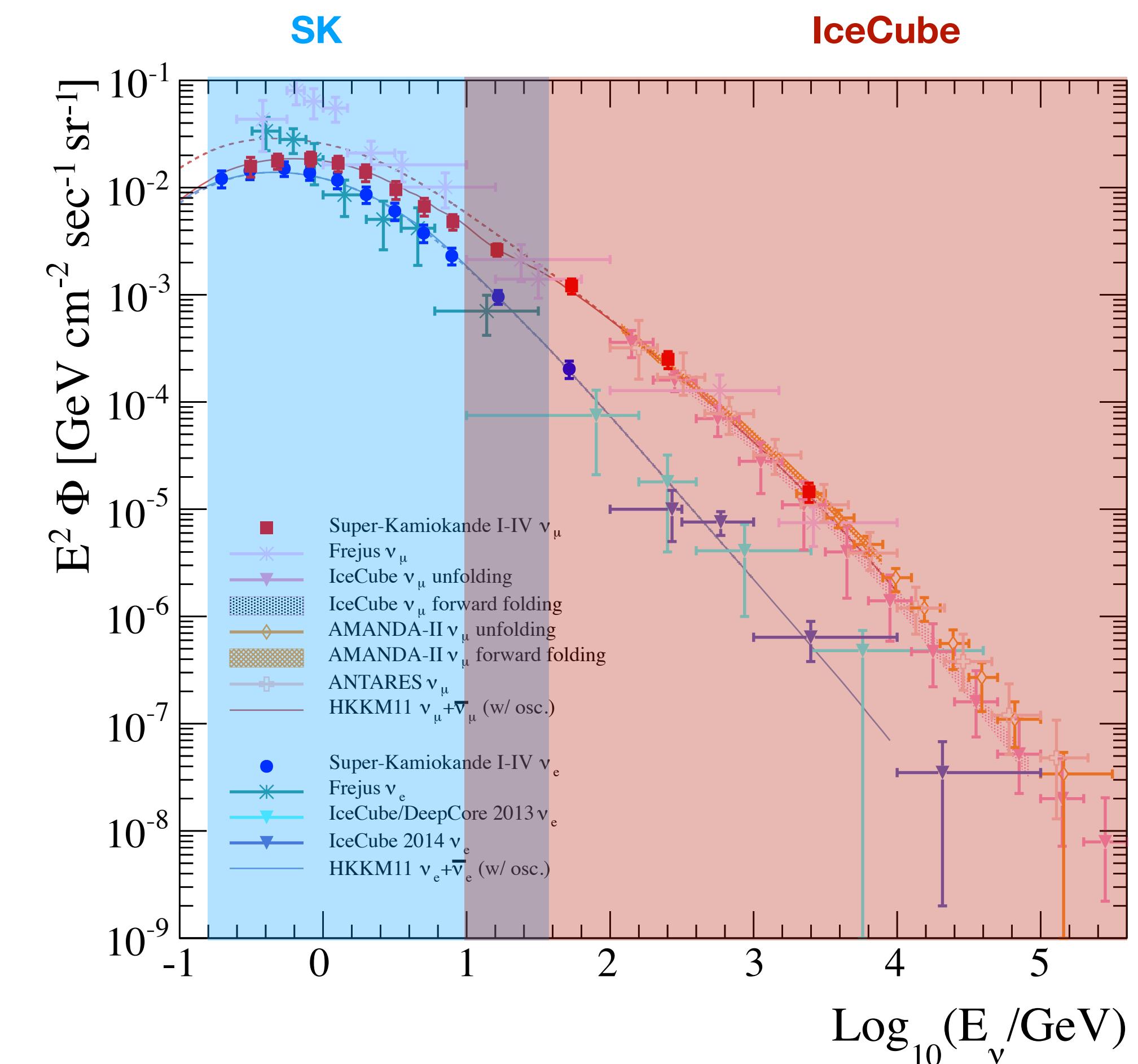
Super-Kamiokande (SK)

- 22.5 kton water Cherenkov
- Measures the atmospheric flux from the sub-GeV region
- Small sample at multi-GeV due to the volume
- The event sample is divided into FC, PC, and Up- μ
- Low directionality for sub-GeV ν

IceCube

- $\sim 1\text{ km}^3$ ice Cherenkov
- Measures the atmospheric flux from the multi-GeV region
- The event sample is divided into tracks and cascades

See Francis Halzen's Talk



Next generation experiments: DUNE

In the future, the atmospheric neutrino flux will be measured with high precision

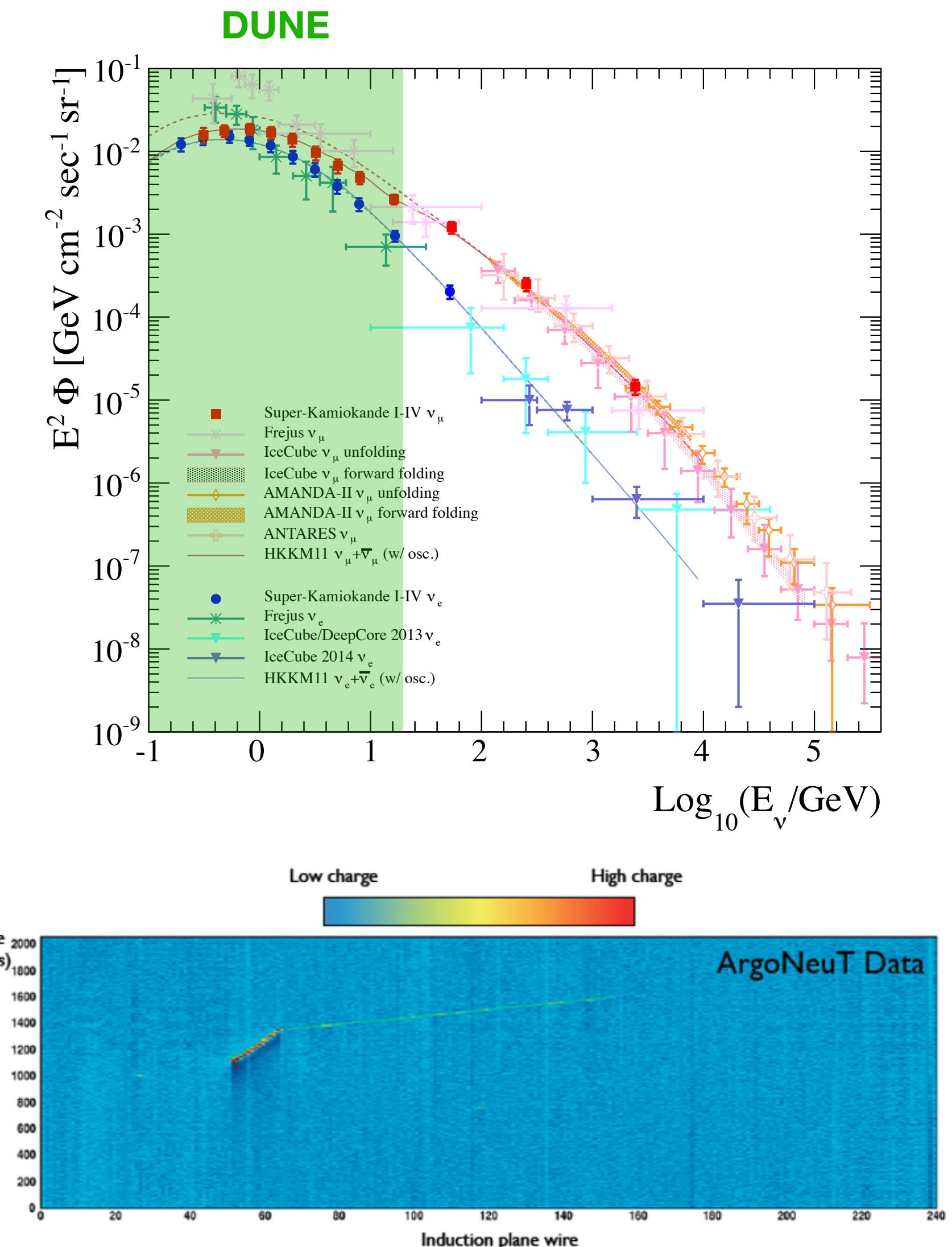
DUNE

- 40 kton LArTPC
- Measures the atmospheric flux from the sub-GeV region
- Good event topology reconstruction at low energies

LArTPCs:

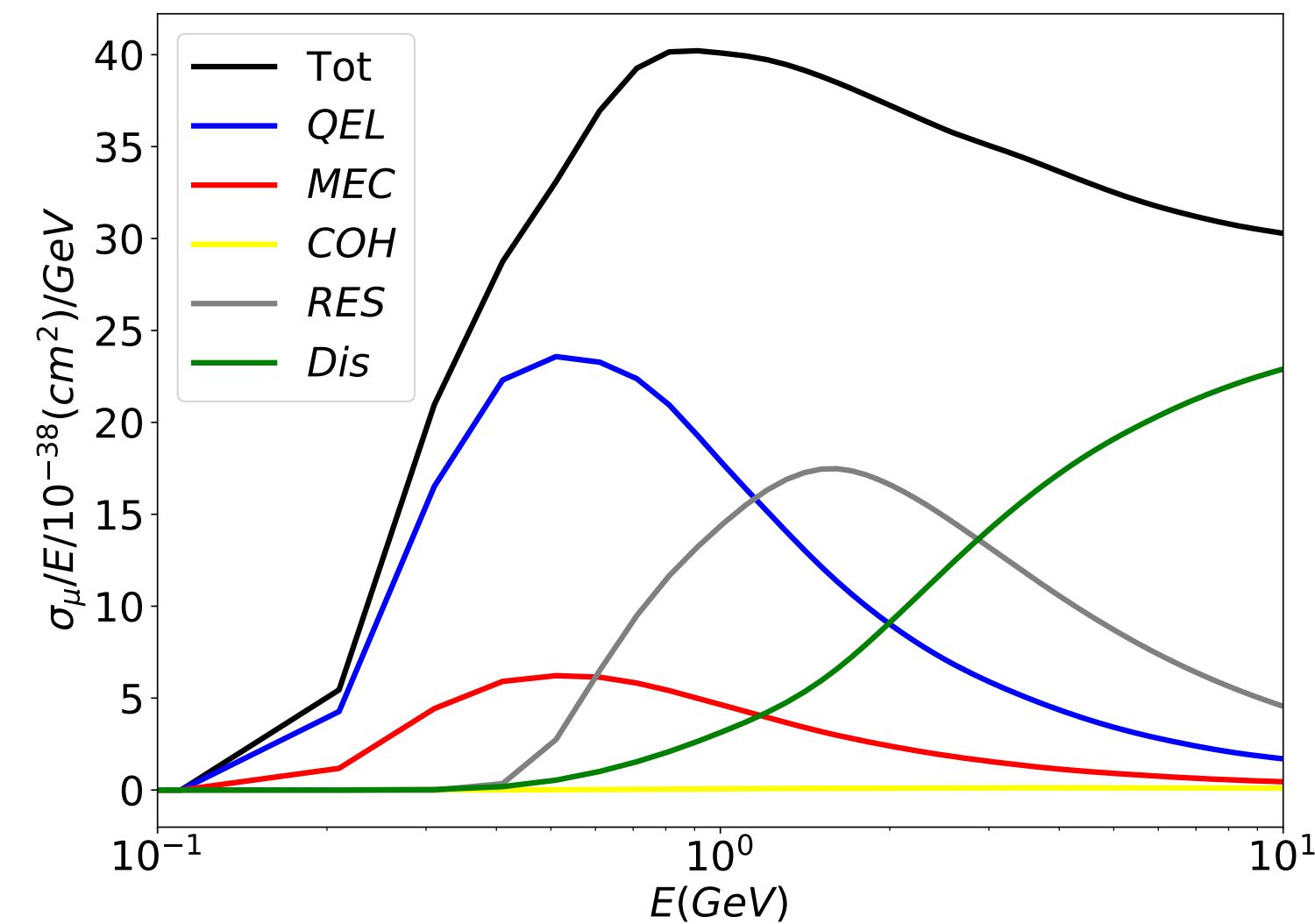
- Excellent capabilities to **identify charged particles**.
- Precise measurement of the **energy and the direction** of low-energy charged particles
- Neutrino energy and direction are reconstructed from the event topology.

$$E_{\nu}^{dep} = E_l + K_p + \dots$$



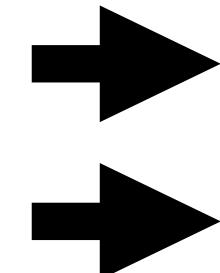
Next generation experiments: DUNE

We simulate neutrino scattering on Argon using **NuWro** event generator.



$\bar{\nu}$ dominated

ν dominated



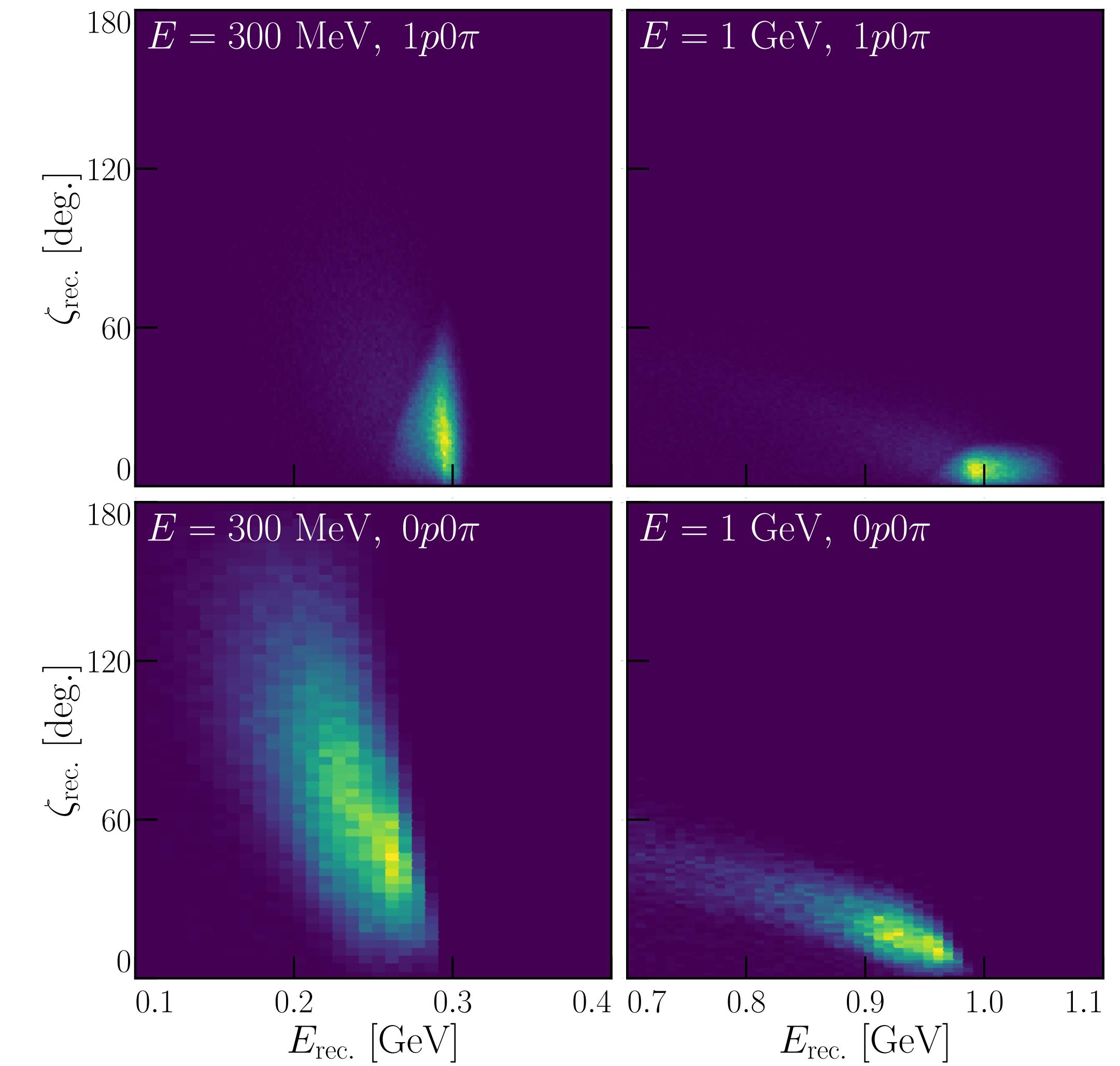
We consider **events topologies** based on the **number of visible protons and pions** in the final state (CC – NpM π).

Np	Events/400 kton year
CC-0p0π	~7000
CC-1p0π	~12000
CC-2p0π	~500
CC-0p1π	~200

DUNE: Event reconstruction

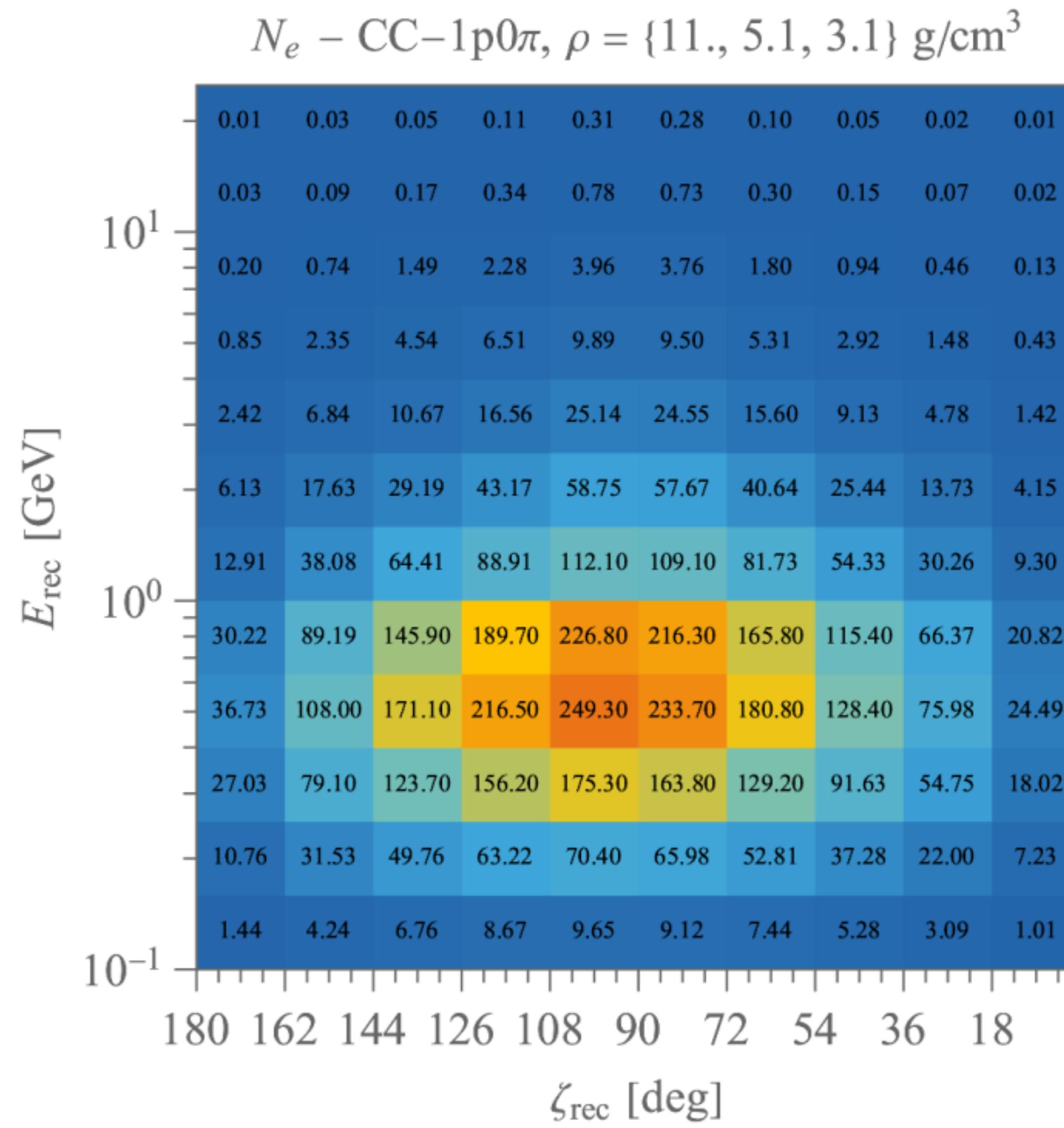
To simulate the event reconstruction, we consider a minimum kinetic energy and a finite energy and direction resolutions

	K.E.	Ang.	E
P	30MeV	10	10%
π	30MeV	10	10%
Λ	30MeV	10	10%
μ^\pm	5MeV	2	5%
e	10MeV	2	5%

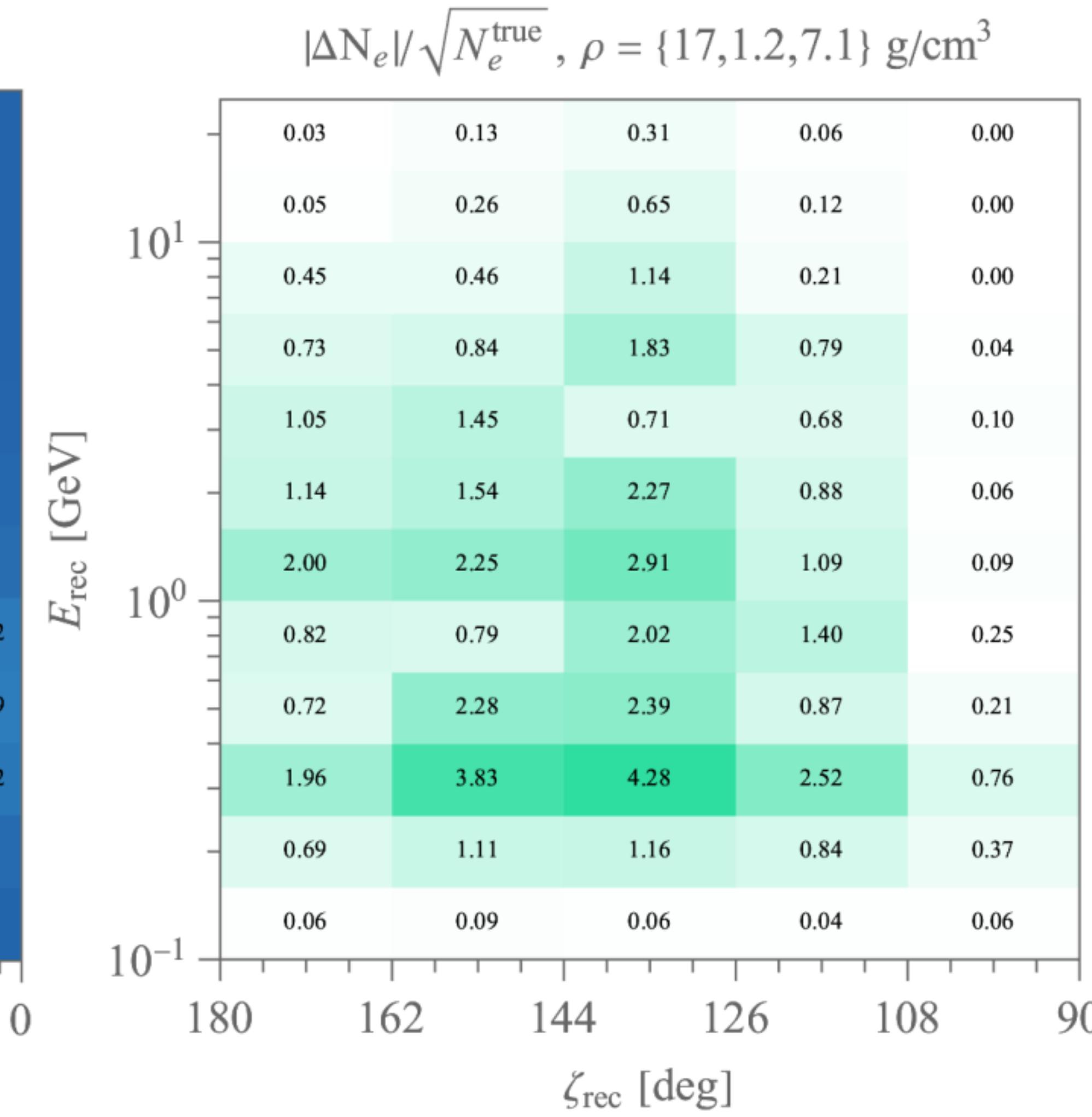


Event distribution in DUNE

Most of the events in DUNE have energies below 1GeV



The largest sensitivity to the matter potential comes from the trajectories crossing the mantle and the crust



Flux uncertainties

The uncertainties on the atmospheric neutrino flux reduce the sensitivity to the mixing parameters.

$$\Phi_\alpha(E, \cos \zeta) = f_\alpha(E, \cos \zeta) \Phi_0 \left(\frac{E}{E_0} \right)^\delta \eta(\cos \zeta)$$

These systematics are common to both experiments

- Φ_0 normalization
- Flavor ratio (ν_e/ν_μ)
- Neutrino to antineutrino ratio ($\bar{\nu}/\nu$)
- Energy distortion (δ)
- Zenit distortion ($\eta(\cos \zeta)$)
- Honda's tables ($f_\alpha(E, \cos \zeta)$)

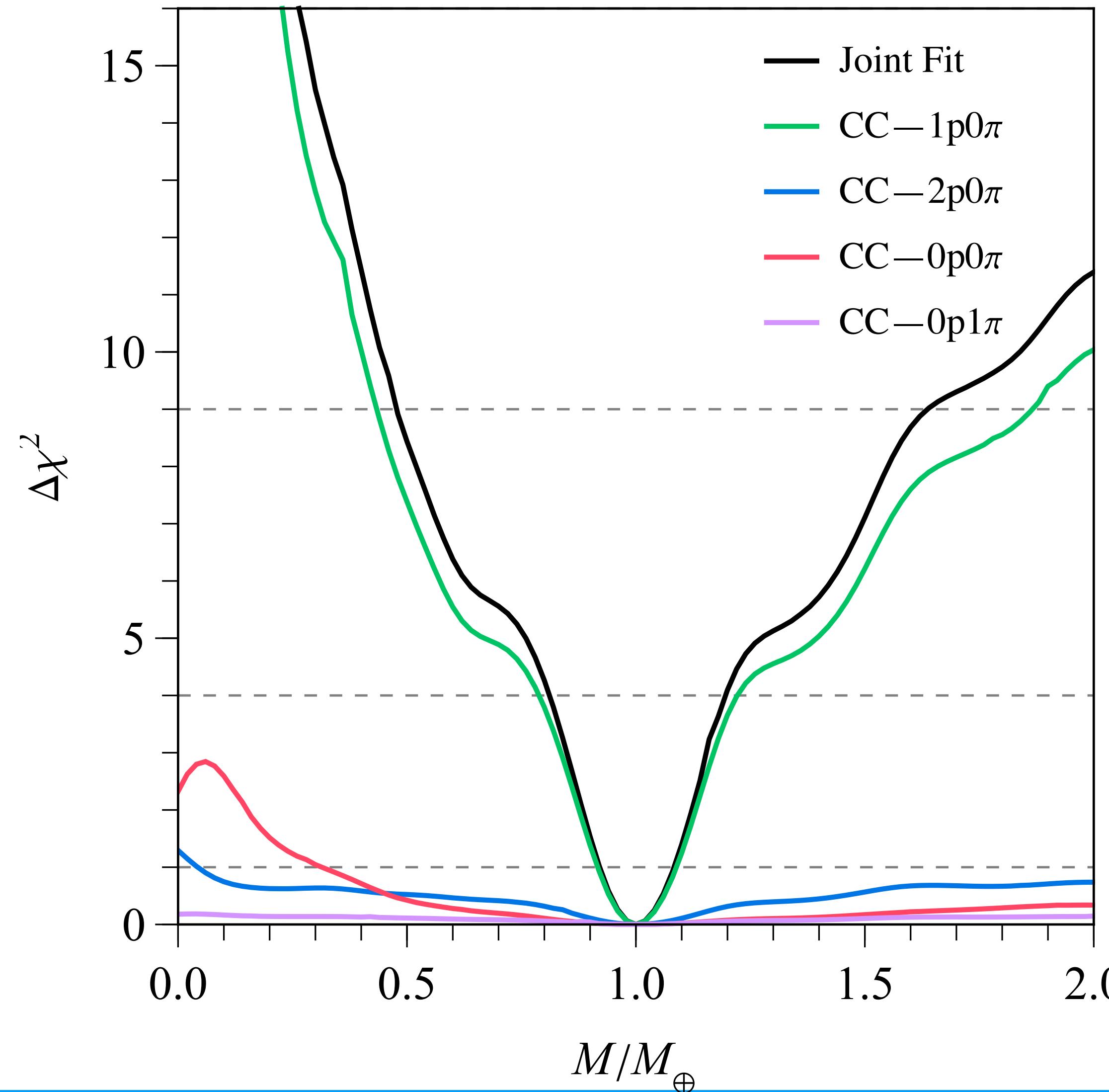
$$\eta(\cos \zeta) \equiv [1 - C_u \tanh(\cos \zeta)^2] \Theta(\cos \zeta) + [1 - C_d \tanh(\cos \zeta)^2] \Theta(-\cos \zeta)$$

Systematic	Uncert./Priors
Φ_0	40%
ν_e/ν_μ	5%
$\bar{\nu}/\nu$	2%
δ	20%
$C_{u,d}$	20%

Barr, Gaisser, Robbins and Stanev, PRD 74 (2006) 094009

Overall Earth Mass Measurement

Normal Ordering



DUNE can measure the total mass of the Earth
using atmospheric neutrinos

$$M = (1 \pm 0.084)M_\oplus$$

400 kton-year

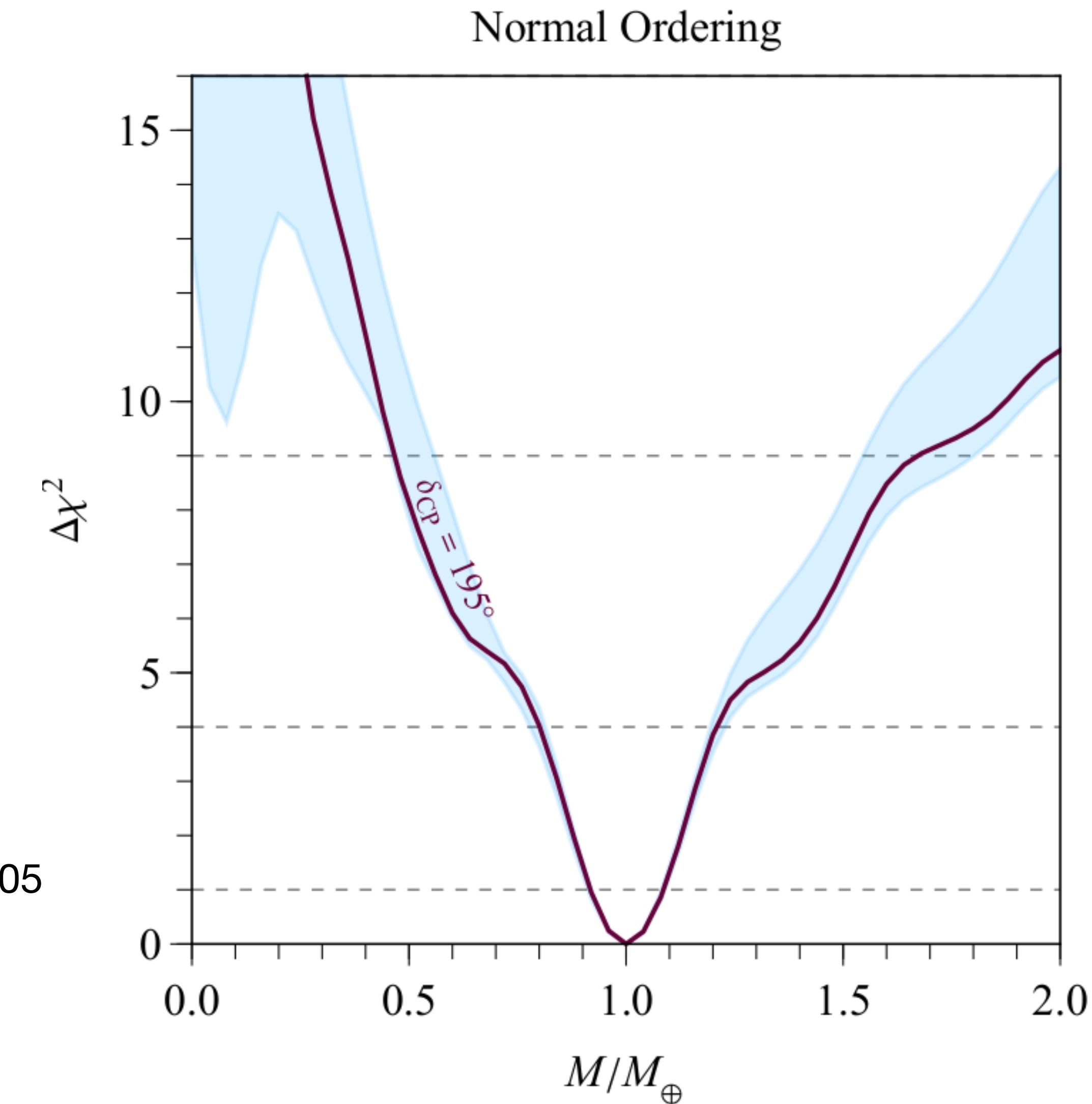
$$M = (1^{+0.48}_{-0.43})M_\oplus$$

60 kton-year

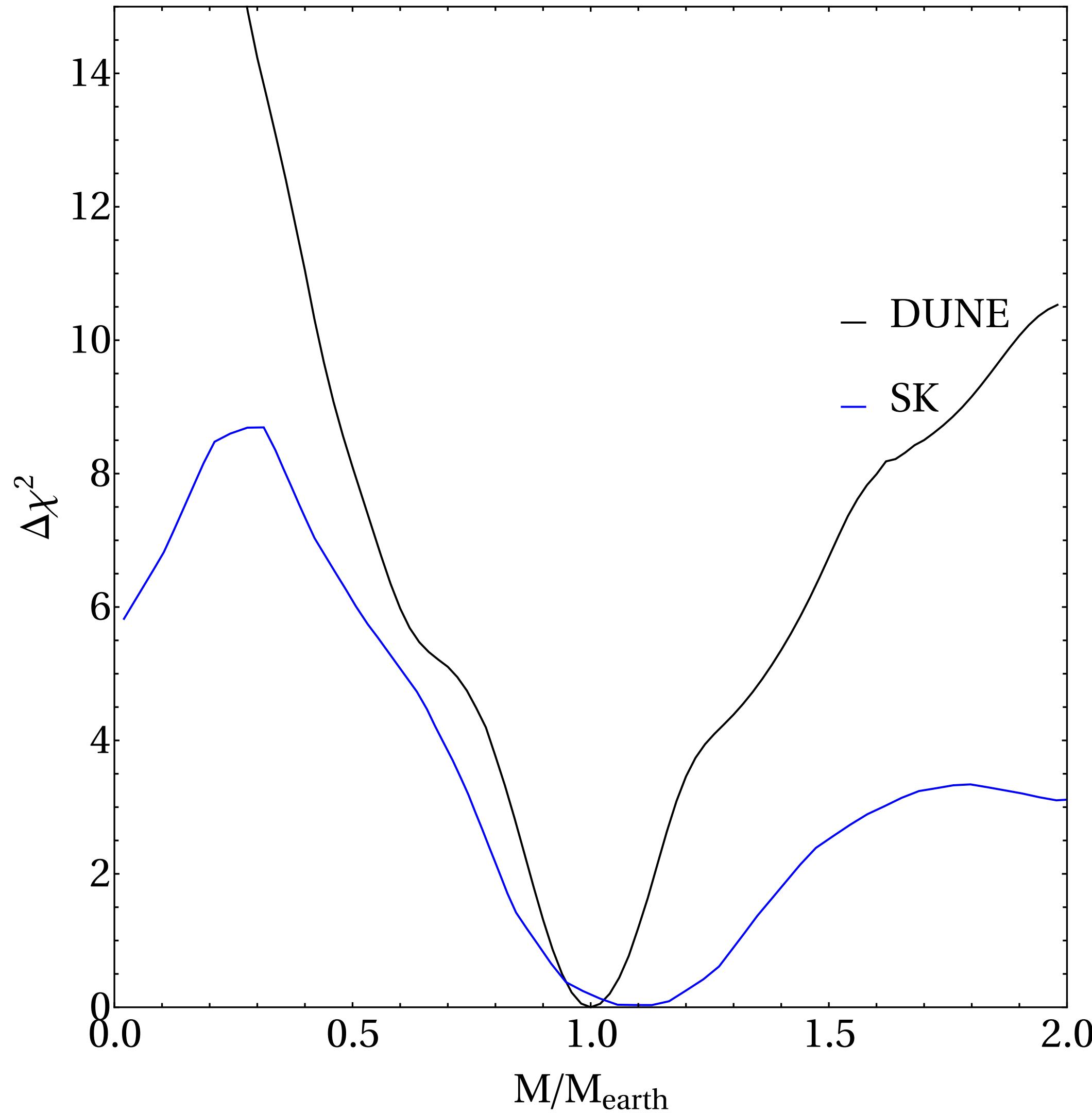
Impact of mixing parameters

The oscillation parameters have a negligible impact on the measurement of M/M_{\oplus}

K.J.K, P.A.N.M, I.M.S., Y.F.P-G, JHEP 05
(2022) 187 arXiv: 2110.00003



Total mass of the Earth



$\Delta M \sim 8.5 \%$

DUNE

$\Delta M \sim 21 \%$

SK

SuperKamiokande, Phys.Rev.D97 (2018)

$M/M_{\oplus} > 0$ ($\sim 1\sigma$)

IceCube

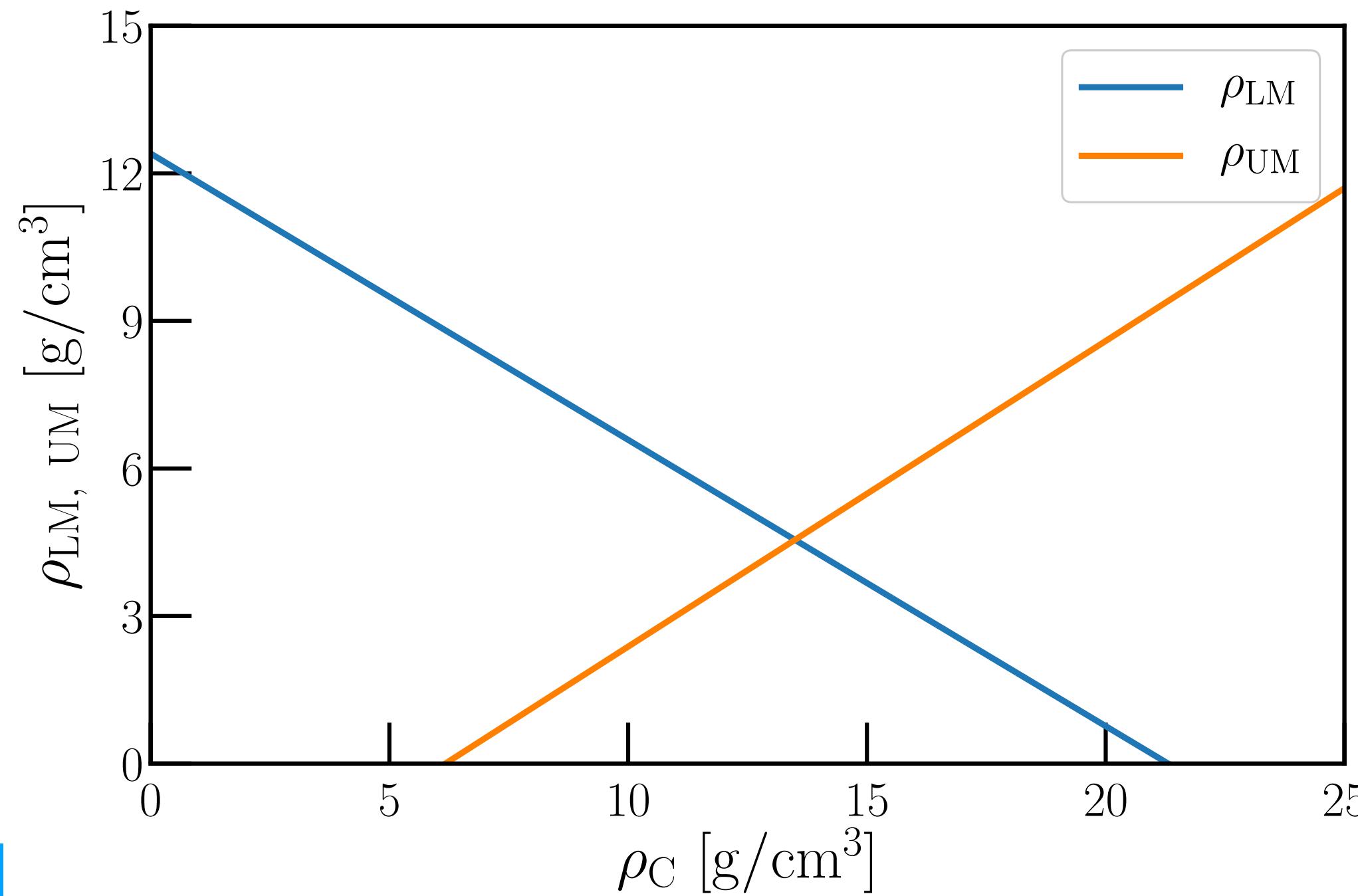
IceCube, Eur.Phys.J.C. 80 (2020)

Sensitivity to the Earth's core

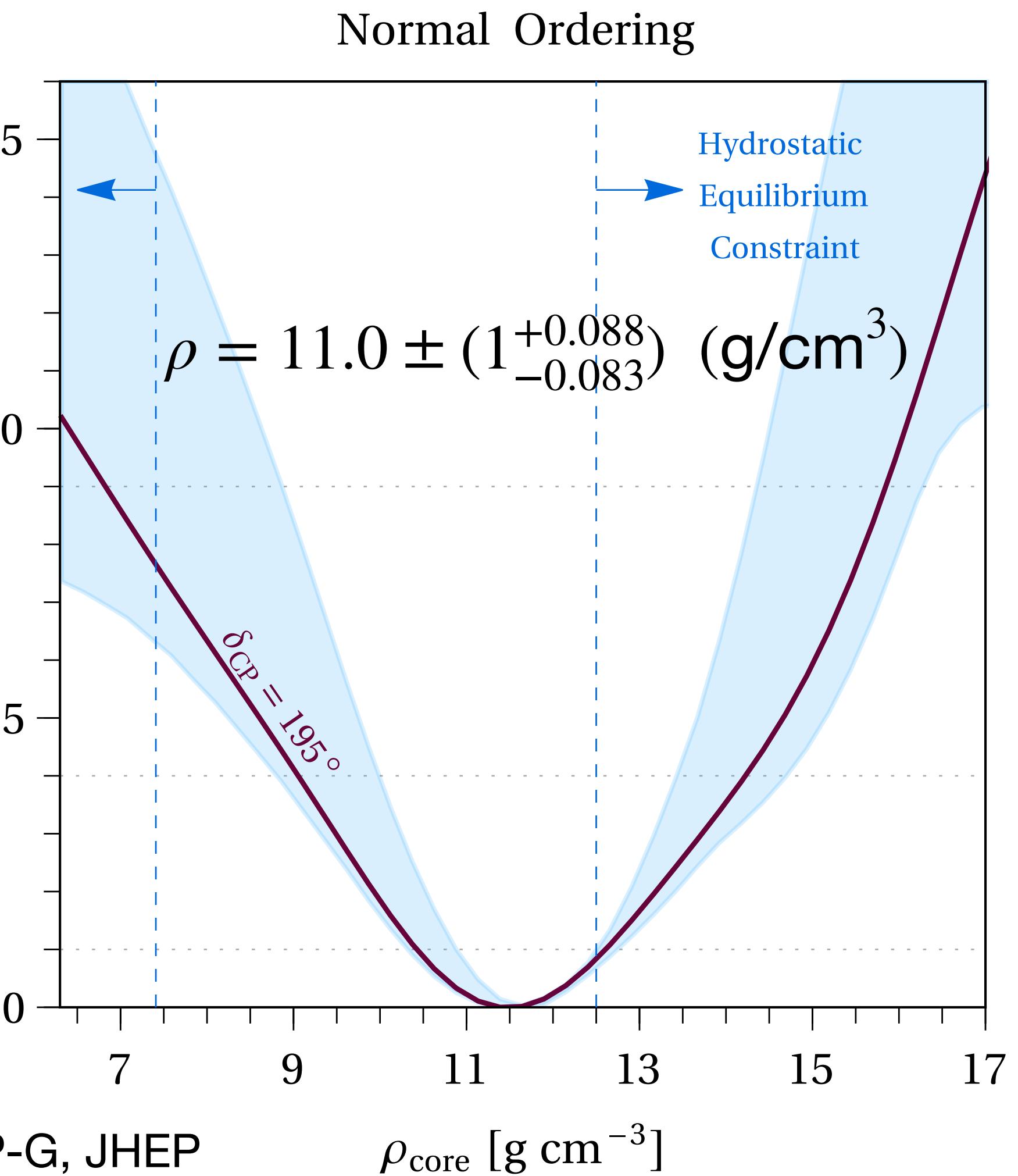
Additional measurements of the **total mass** and the **momentum of inertial** can provide information about the **matter distribution**

$$M_{\oplus} = \frac{4\pi}{3} \left[\rho_C R_C^3 + \rho_{LM} (R_{LM}^3 - R_C^3) + \rho_{UM} (R_{\oplus}^3 - R_{LM}^3) \right]$$

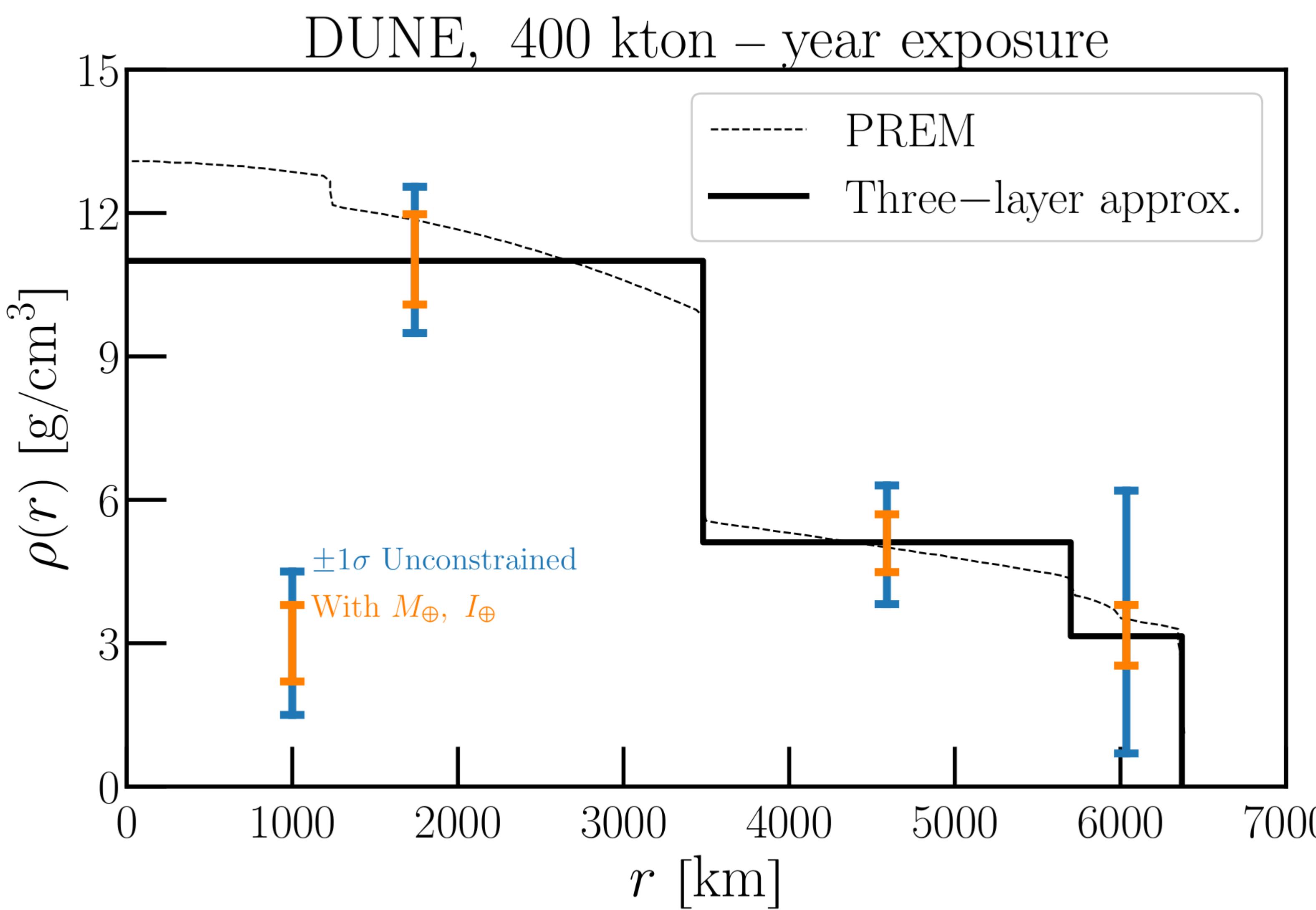
$$I_{\oplus} = \frac{8\pi}{15} \left[\rho_C R_C^5 + \rho_{LM} (R_{LM}^5 - R_C^5) + \rho_{UM} (R_{\oplus}^5 - R_{LM}^5) \right]$$



K.J.K, P.A.N.M, I.M.S., Y.F.P-G, JHEP
05 (2022) 187 arXiv: 2110.00003



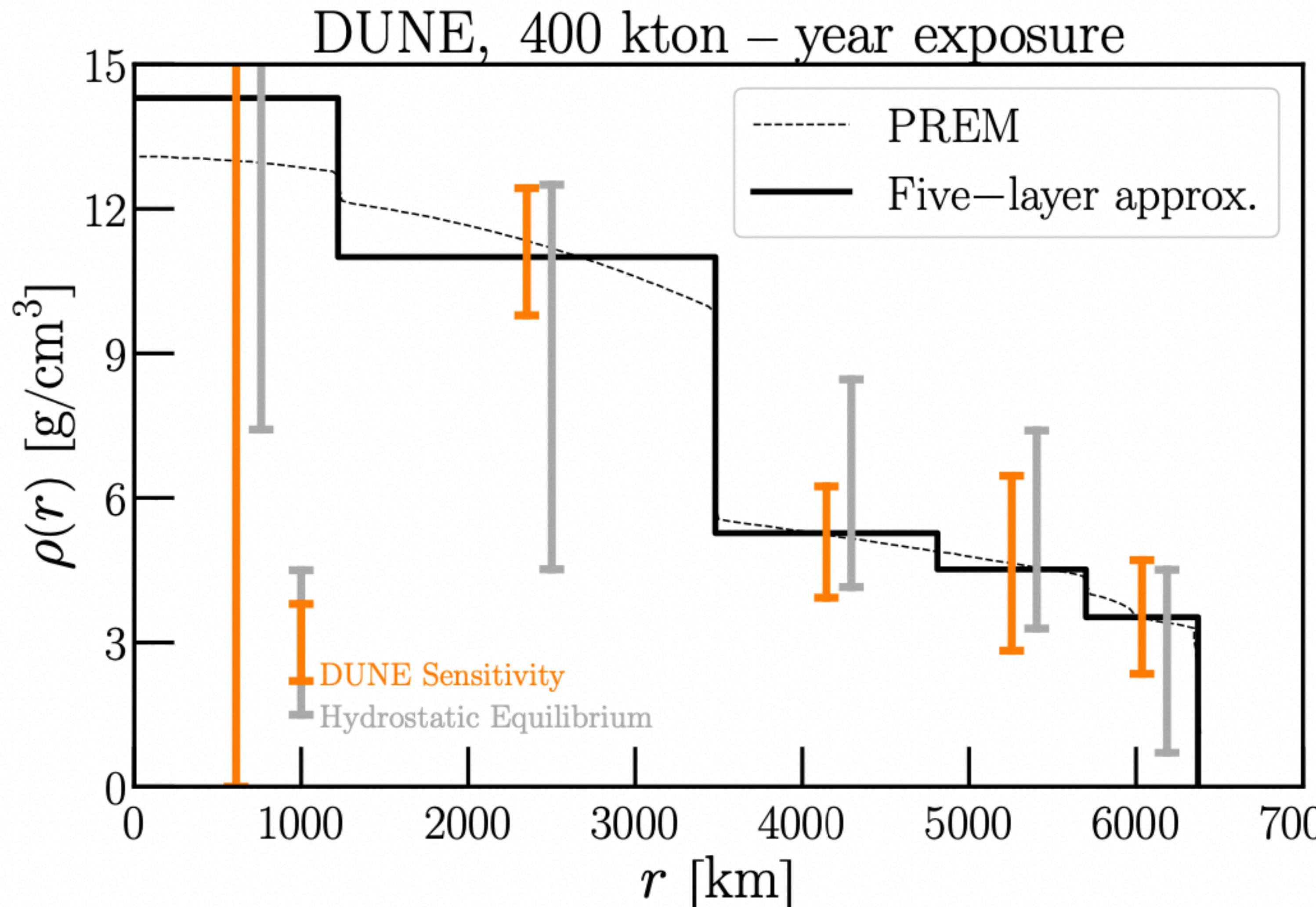
Earth's matter profile sensitivity



We explored the sensitivity to the three layers without additional constraints

The main sensitivity is obtained for the **core** and the **lower mantle**

Earth's matter profile sensitivity: 5 layers



This analysis can complement other measurements of the Earth matter distribution.

See: A. Donini, S. Palomares-Ruiz and J. Salvado Nature Phys. 15 (2019) 1, 37-40

Conclusions

- **Atmospheric neutrinos** give us access to the Earth's matter profile in different ways. In this talk, we focused on measuring the flavor of the neutrinos after crossing the Earth.
- In the future, **DUNE** will measure the atmospheric neutrino flux from the **sub-GeV to the multi-GeV** with great precision.
- We have developed a detector simulation using an **event generator** that accounts for the uncertainties in reconstructing events and the **systematics** related to the flux.
- Dune will be able to measure M_{\oplus} **at the 8.4%**
- Combining DUNE with other measurements is possible to determine the core, the lower mantle and the upper mantle at 8.6%, 12.3% and 21%.
- The precision obtained is rather independent of the present uncertainties of the mixing parameters.

A cluster of colorful, glowing spheres against a dark background. The spheres are primarily yellow and orange, with some red and white highlights, resembling stylized galaxies or nebulae. They are arranged in a loose, overlapping group.

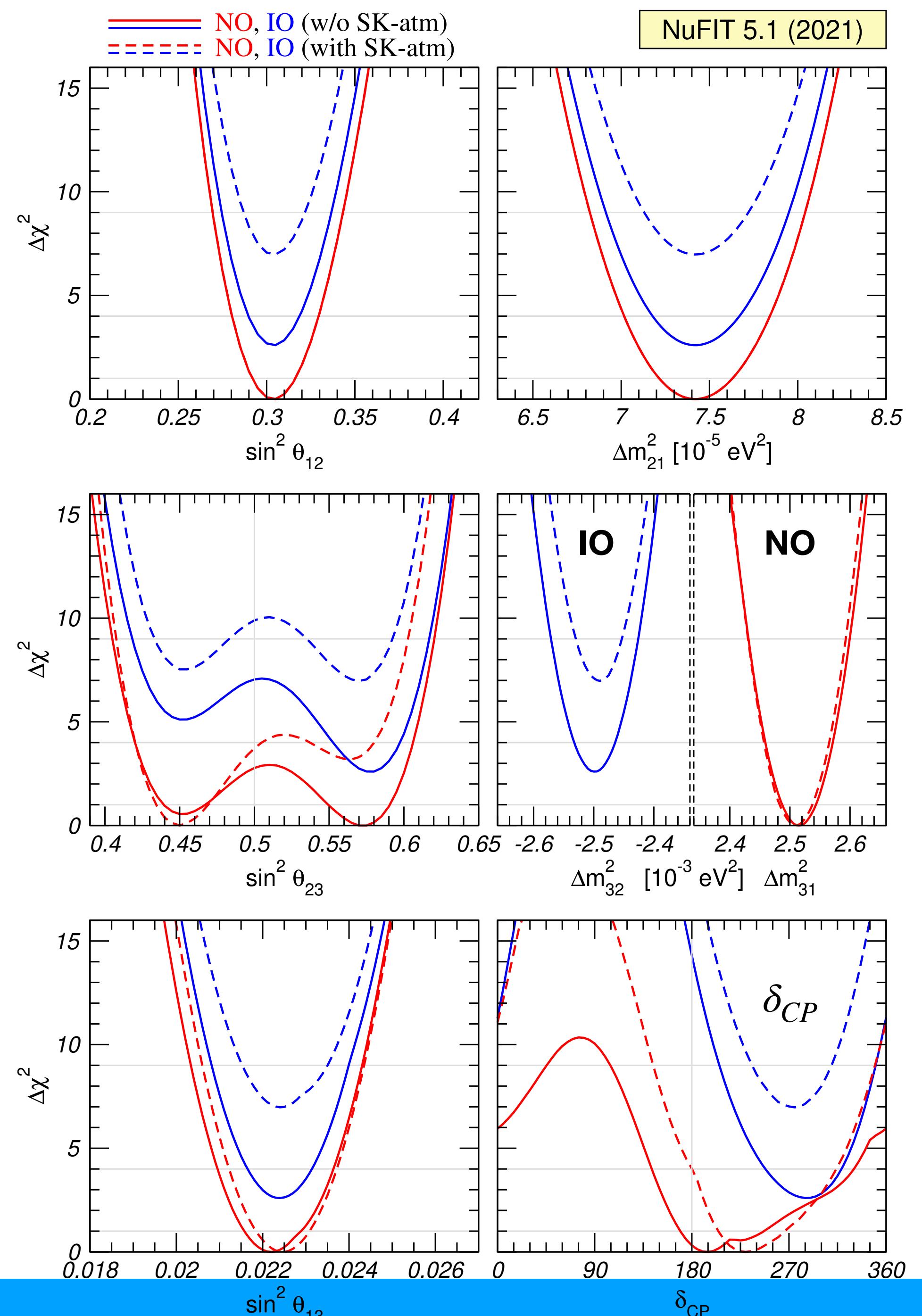
Thanks!

3ν mixing

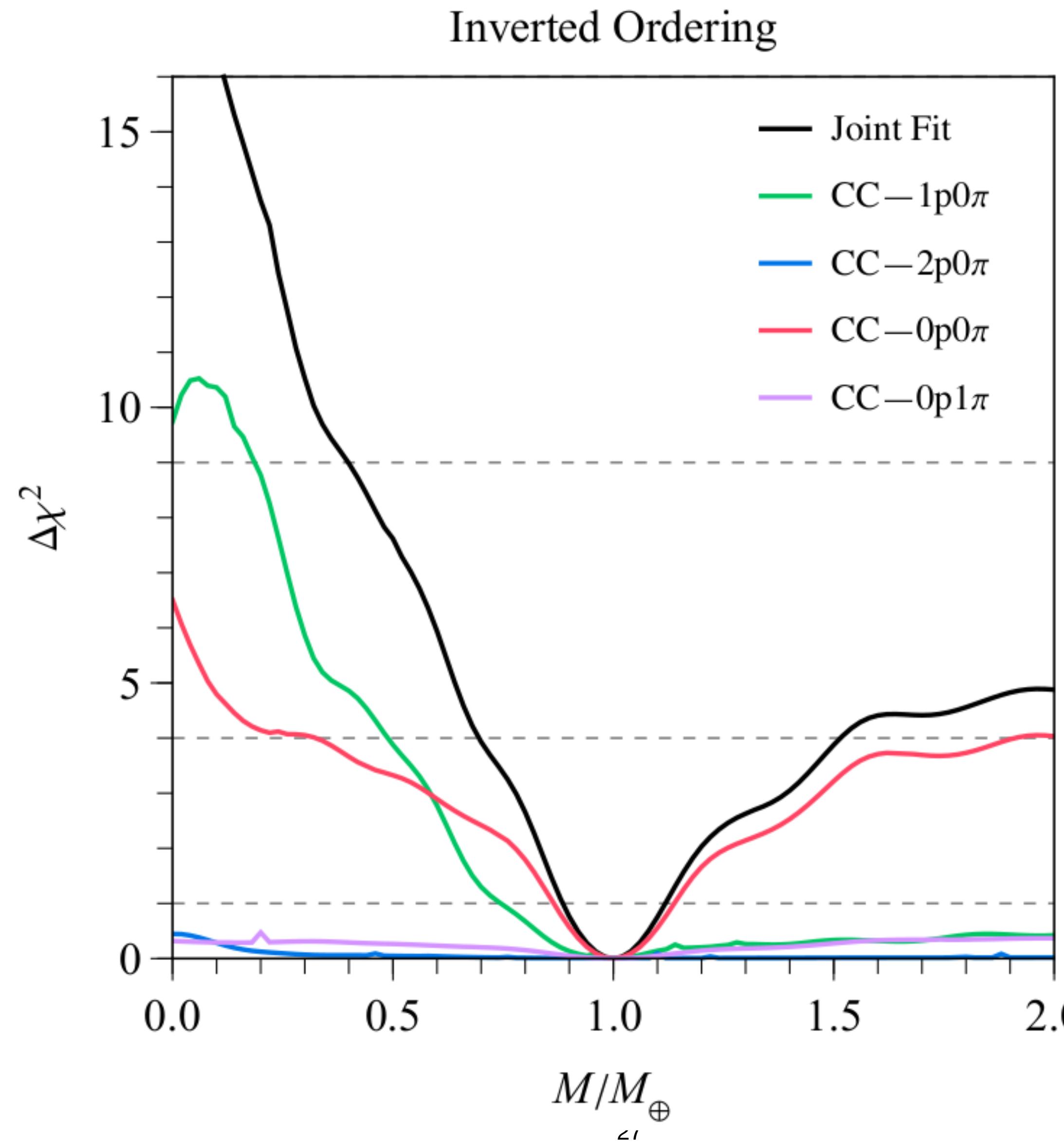
Present sensitivity to the 3ν scenario

Param	Value	Precision
θ_{12}	33.44	~4%
θ_{13}	8.57	~2.8%
θ_{23}	49.2	~2.8%
δ_{cp}	197	
Δm_{21}^2	$7.42 \times 10^{-5} \text{ eV}^2$	~3%
Δm_{31}^2	$2.52 \times 10^{-3} \text{ eV}^2$	~1%

- The less constrained parameters are:
- Mass ordering
 - Octant of θ_{23}
 - CP-phase

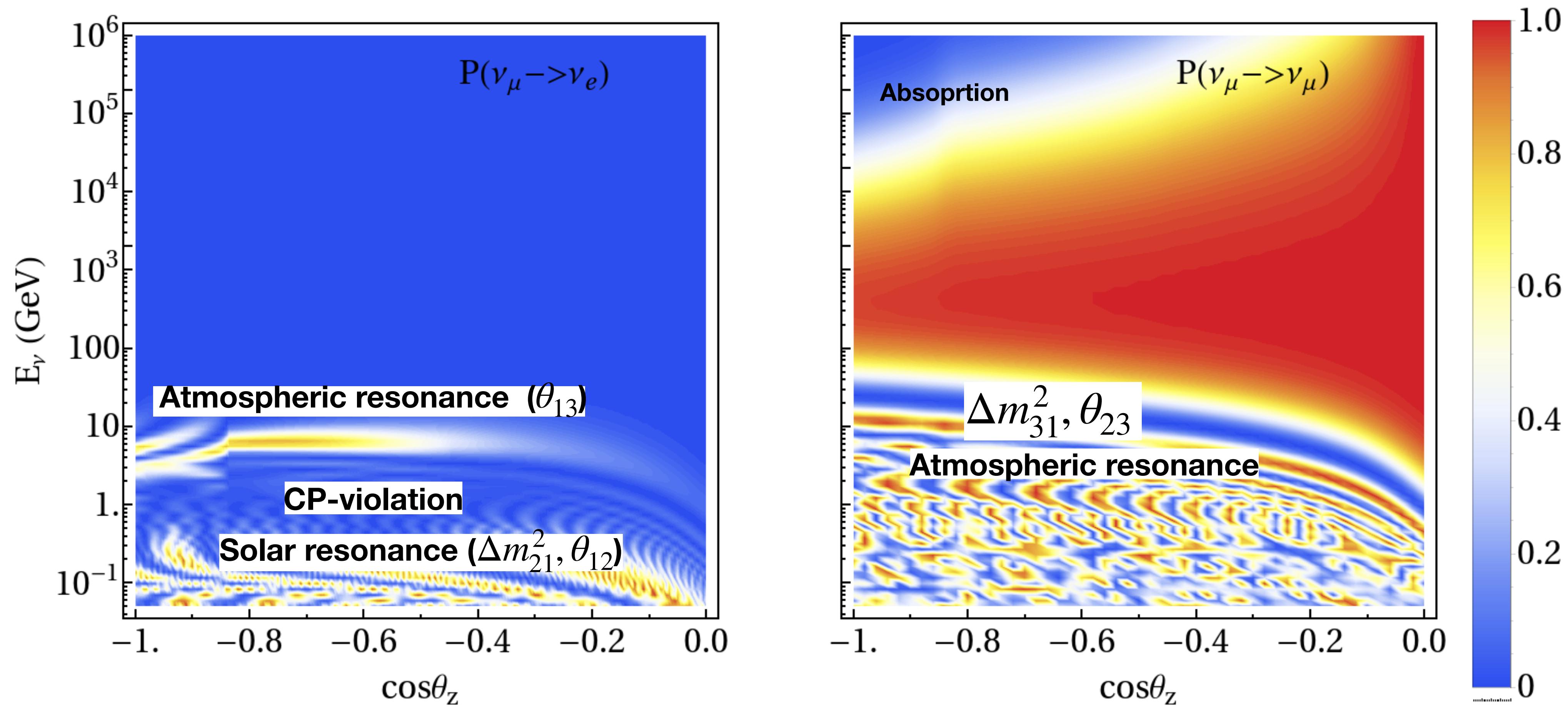


Bakup: Total mass of the Earth and IO



3ν mixing through the Earth

A rich phenomenology is accessible using atmospheric neutrinos



Sub-GeV atmospheric neutrinos

For $E < 1\text{GeV}$, the CP-violation term is enhanced due to the development of the solar oscillation

$$P_{CP} = -8J_{CP}^{max} \sin(\delta_{cp}) \sin(\Delta_{21}) \sin(\Delta_{31}) \sin(\Delta_{32})$$

- For $E > 1$, $\sin(\Delta_{21}) \ll 1$
- For $E < 1$, $\sin(\Delta_{31}) \sin(\Delta_{32}) \sim 1/2$

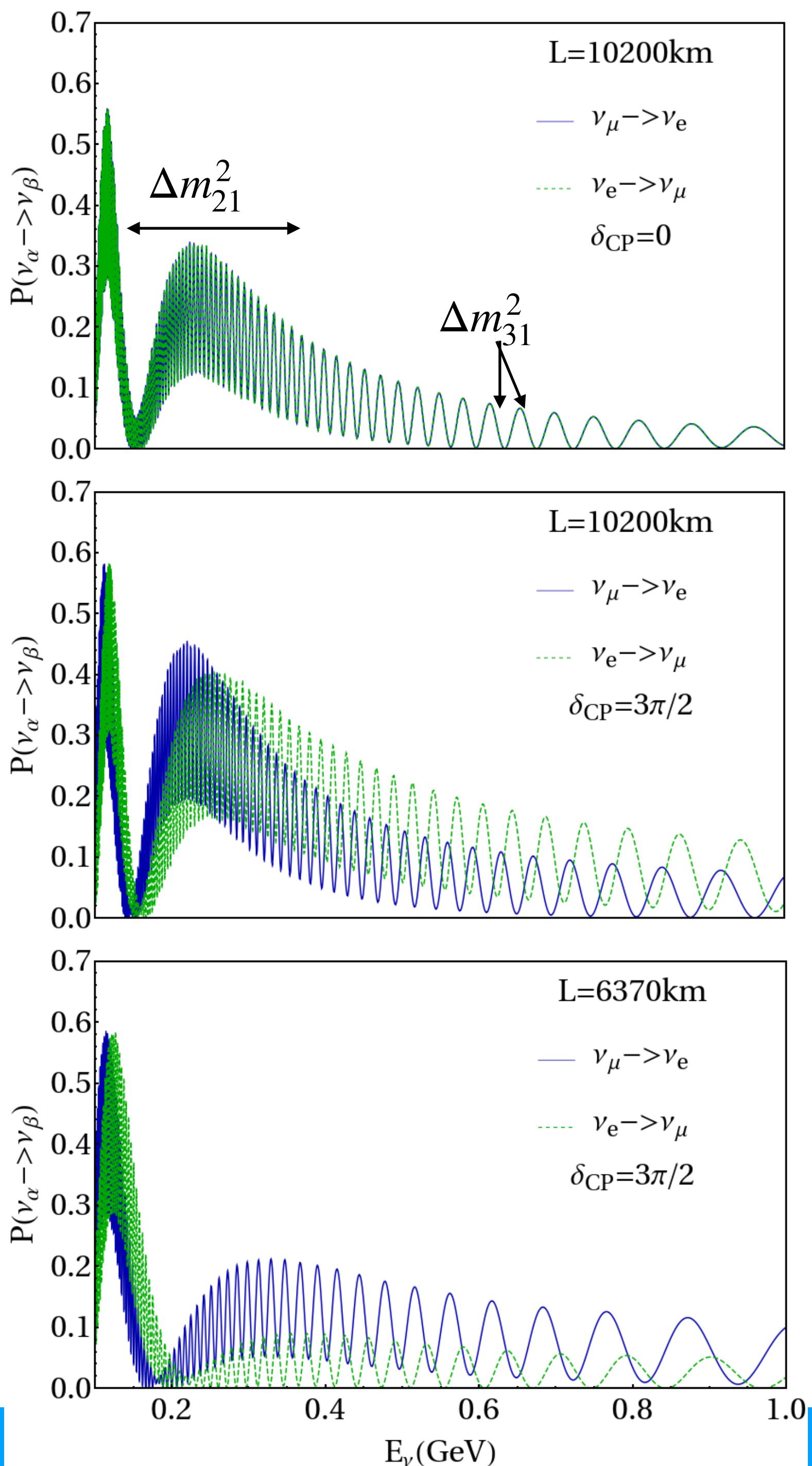
For $\delta_{cp} \neq 0$, the CPT conservation implies

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\nu_e \rightarrow \nu_\mu)$$

- The impact δ_{cp} depends on the neutrino direction and it is independent of the neutrino energy.

I. Martinez-Soler, H. Minakata, PTEP (2019) 7, 073B07

K.J. Kelly, P.A.N. Machado, I. Martinez-Soler, S.J. Parke Y.F.Perez-Gonzalez, Phys.Rev.Lett 123 (2019) 8, 081801



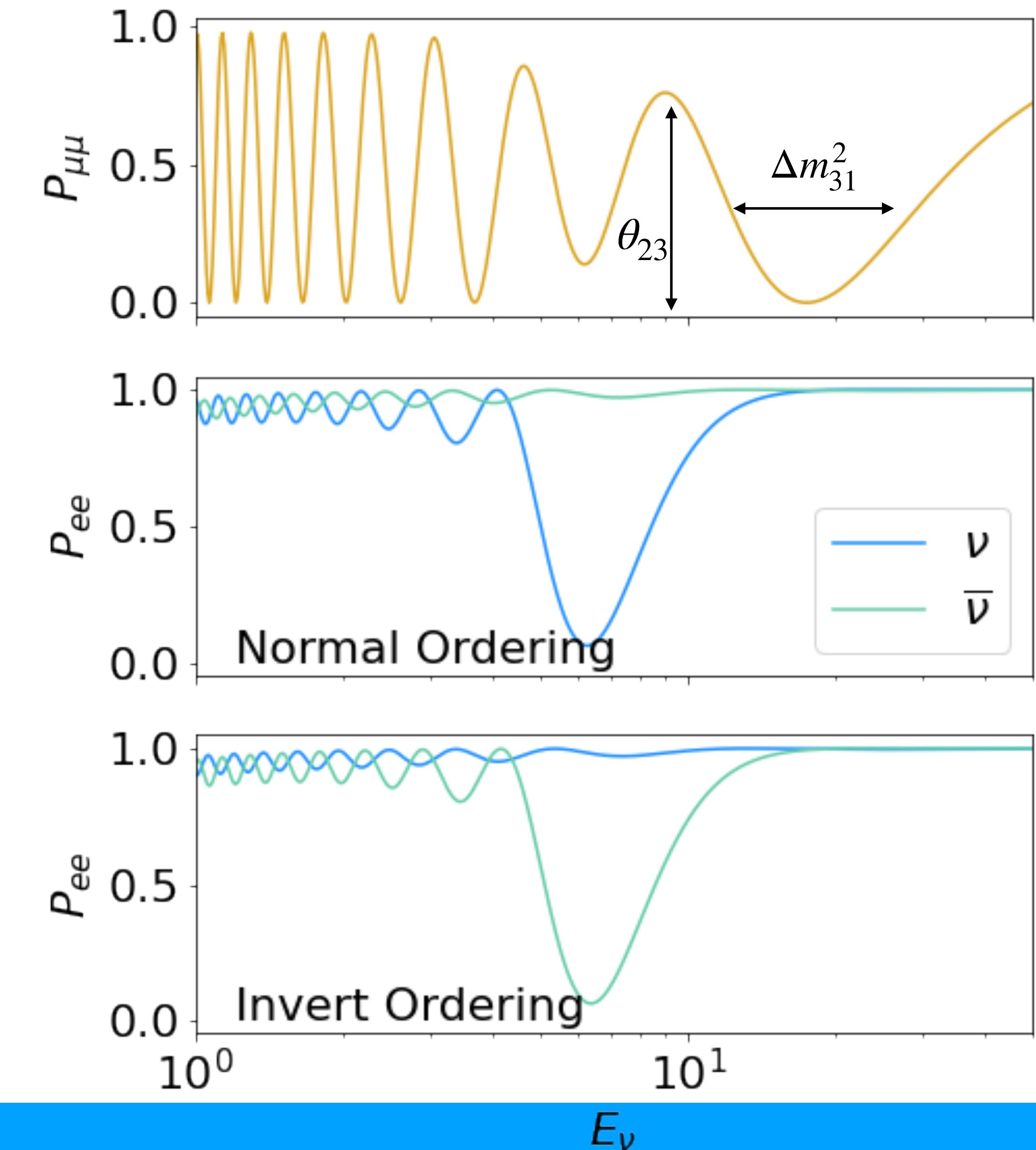
Multi-GeV atmospheric neutrinos

In the multi-GeV region, atmospheric neutrinos become sensitive to Δm_{31}^2 and θ_{23} .

At the GeV scale, there is resonant flavor conversion.
Neutrinos are sensitive to the **mass ordering**:

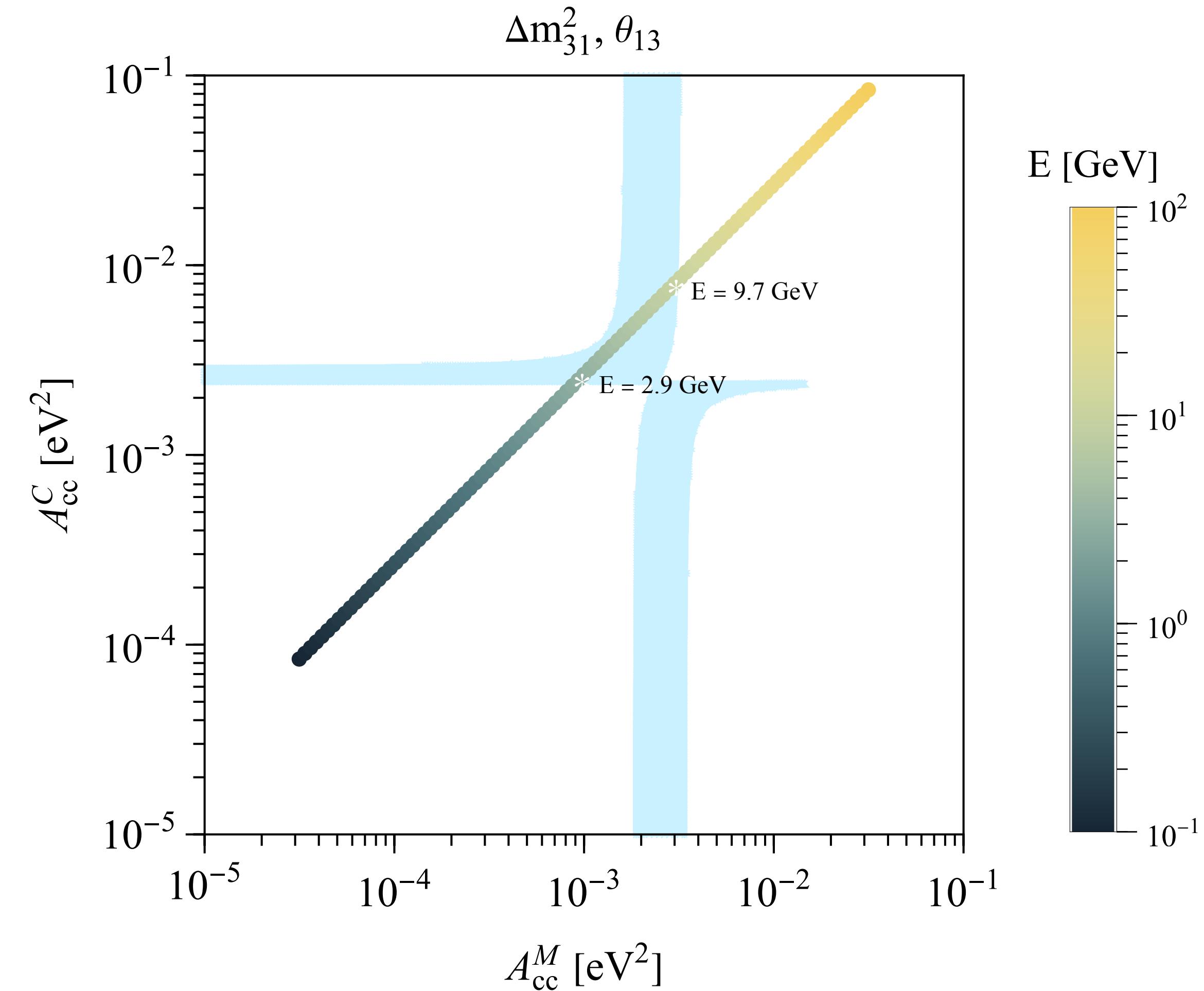
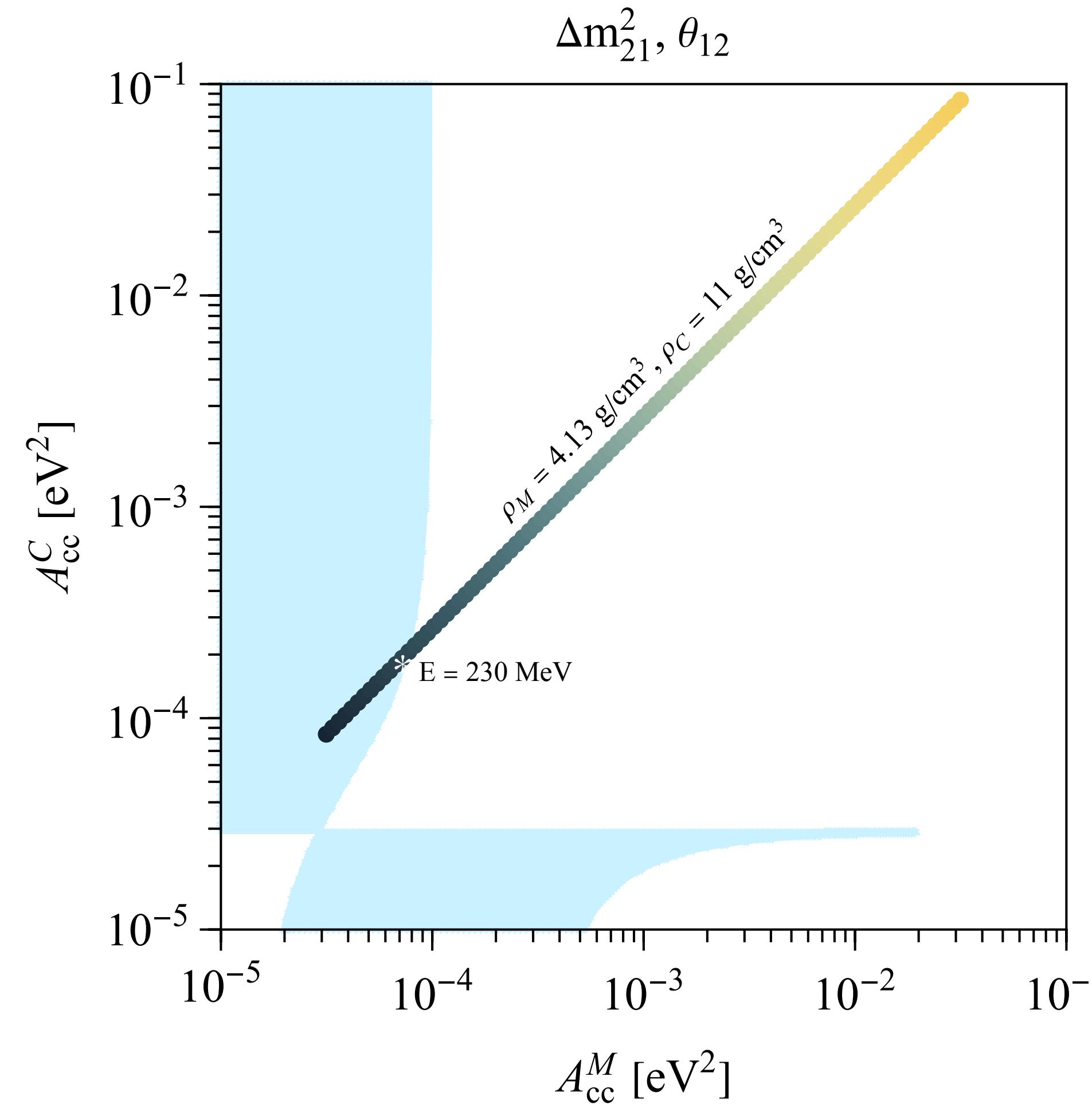
- The matter effect enhances the oscillation of neutrinos (anti-neutrinos) for NO (IO)
- The enhancement of the effective θ_{13} . MSW resonance.

$$E_r \simeq 5.3 \text{ GeV} \left(\frac{\Delta m_{31}^2}{2.5 \times 10^{-3} \text{ eV}^2} \right) \left(\frac{\cos 2\theta}{0.95} \right) \left(\frac{\rho}{6 \text{ g/cc}} \right)$$

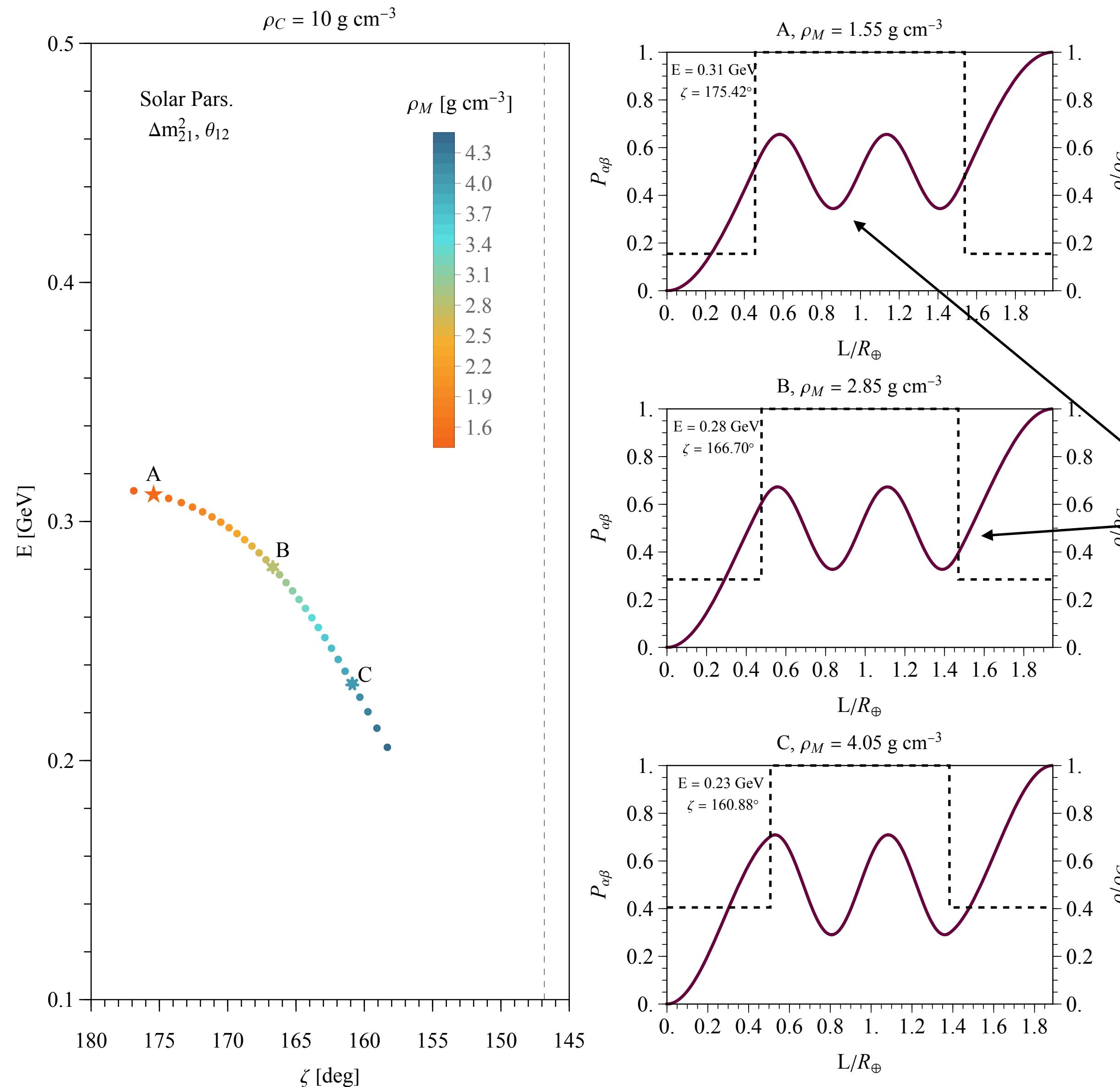


Backup: Parametric resonance

An extensive set of values of the core and the mantle matter potential fulfill the parametric resonance condition



Parametric resonance in the multi-GeV region



A complete flavor transition ($P_{\alpha\beta} = 1$) can be obtained under a constructive interference between the amplitudes of different layers

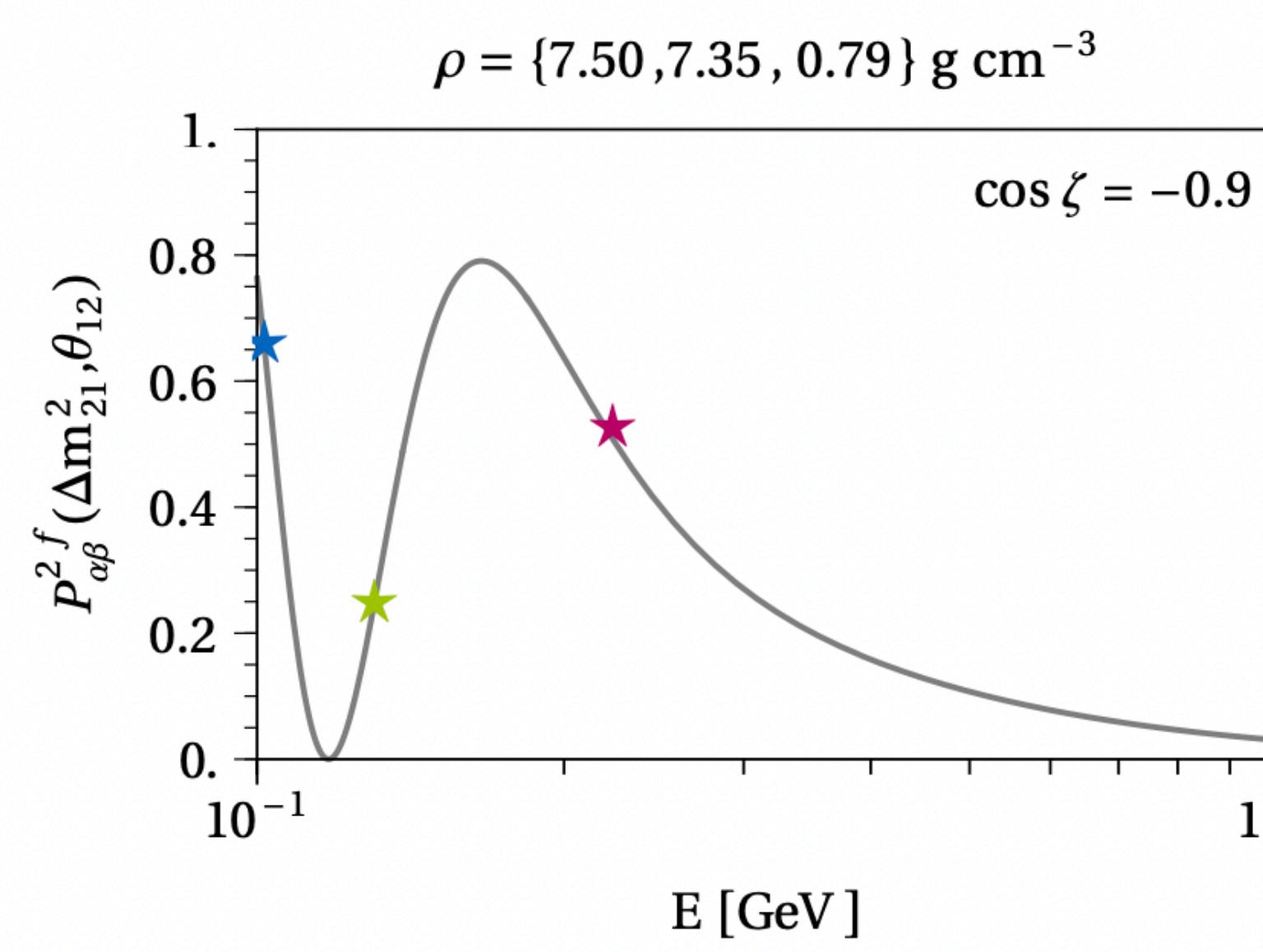
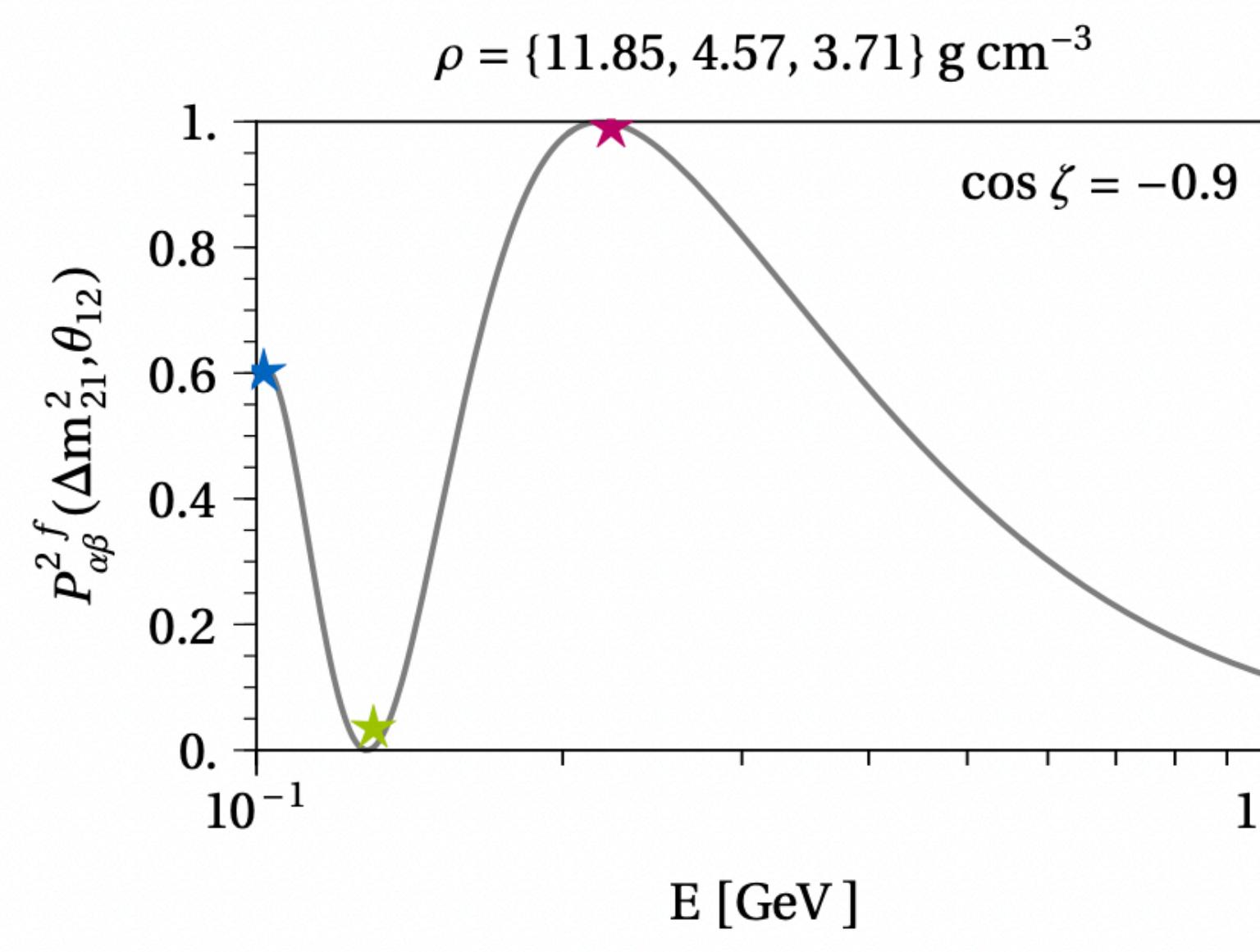
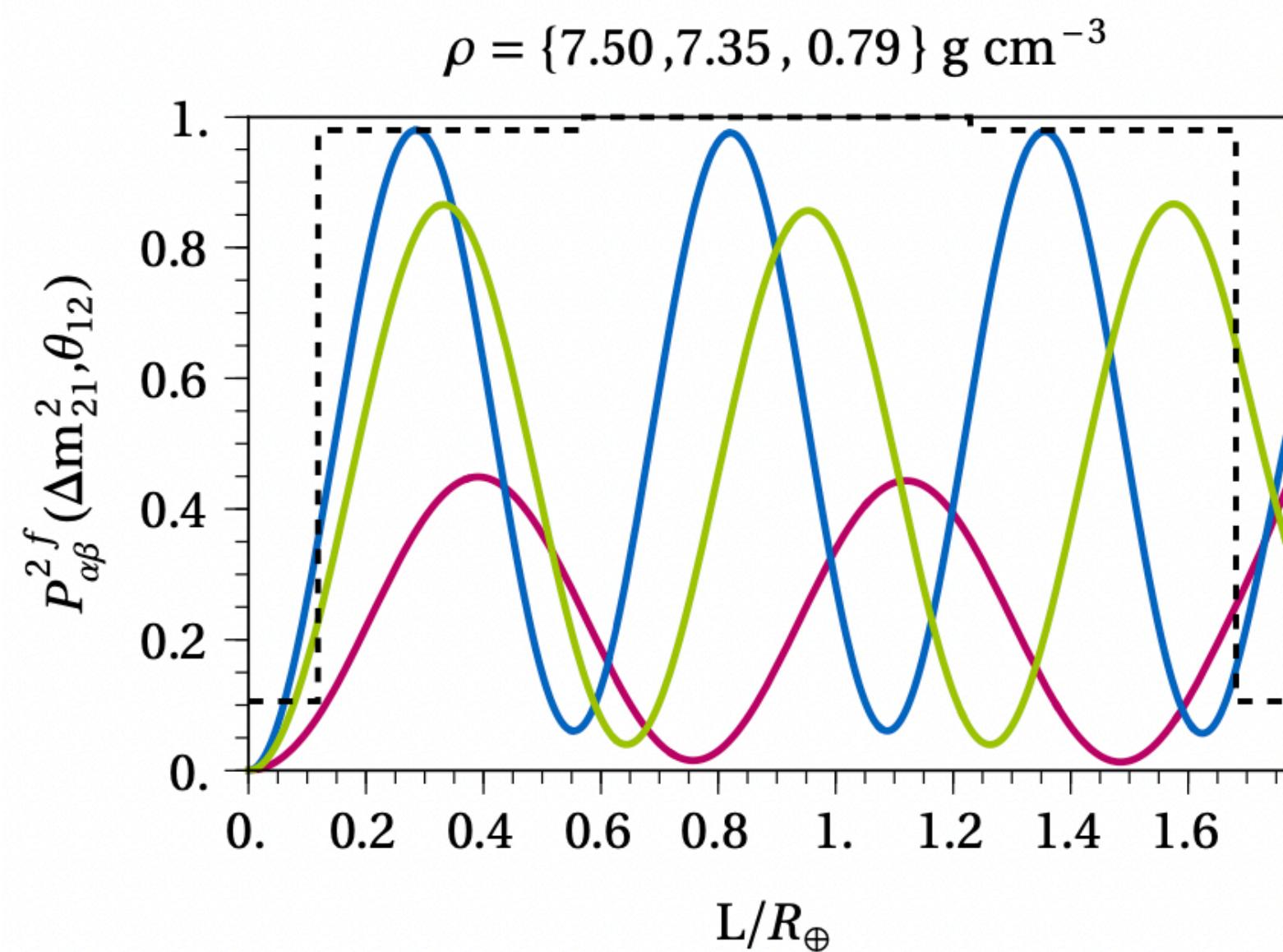
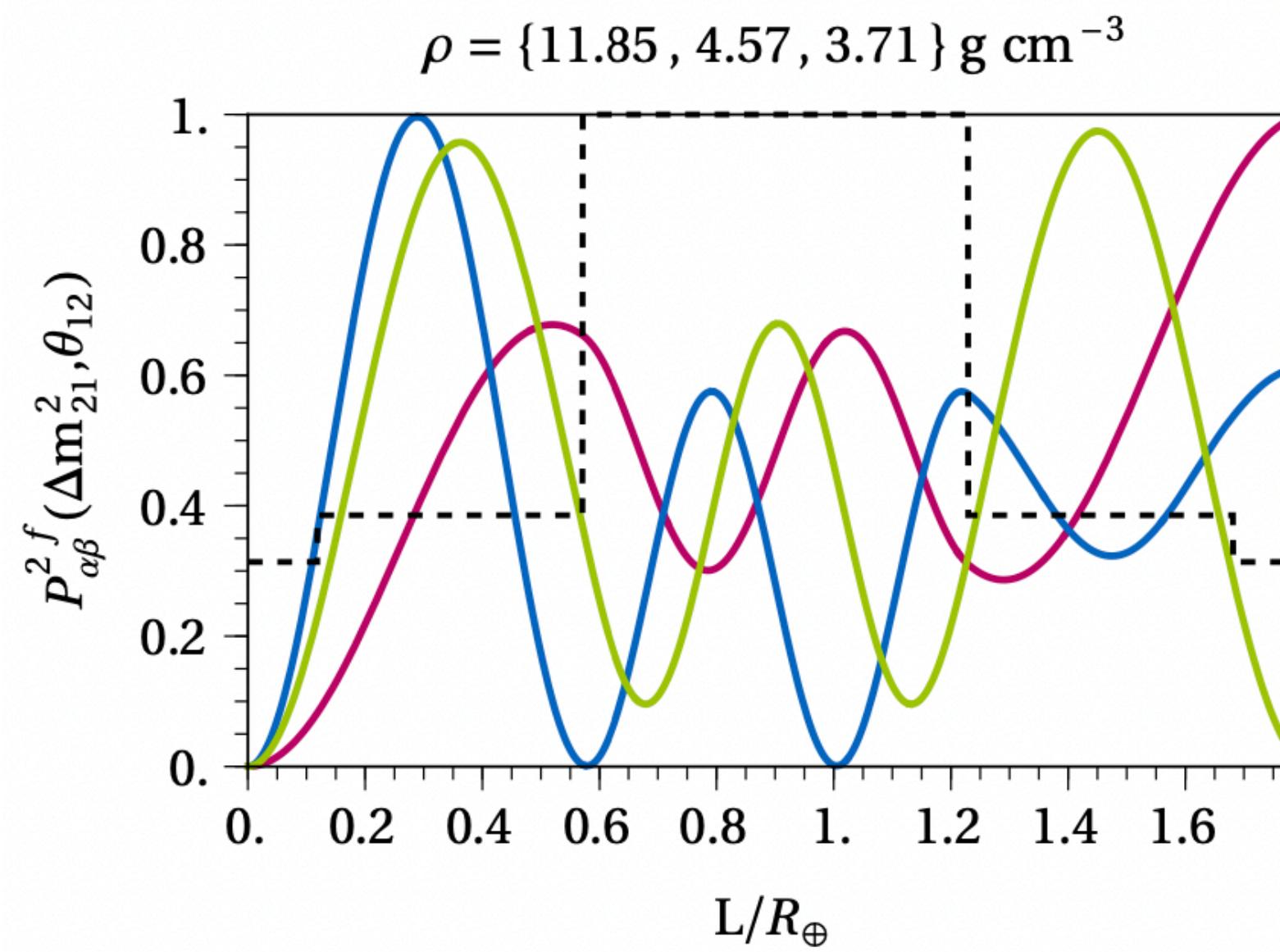
θ_x in each layer is not maximal

Relation between the mixing angles in each layer

$$\cos 2\theta_c \leq 0, \cos 2(2\theta_M - \theta_c) \geq 0$$

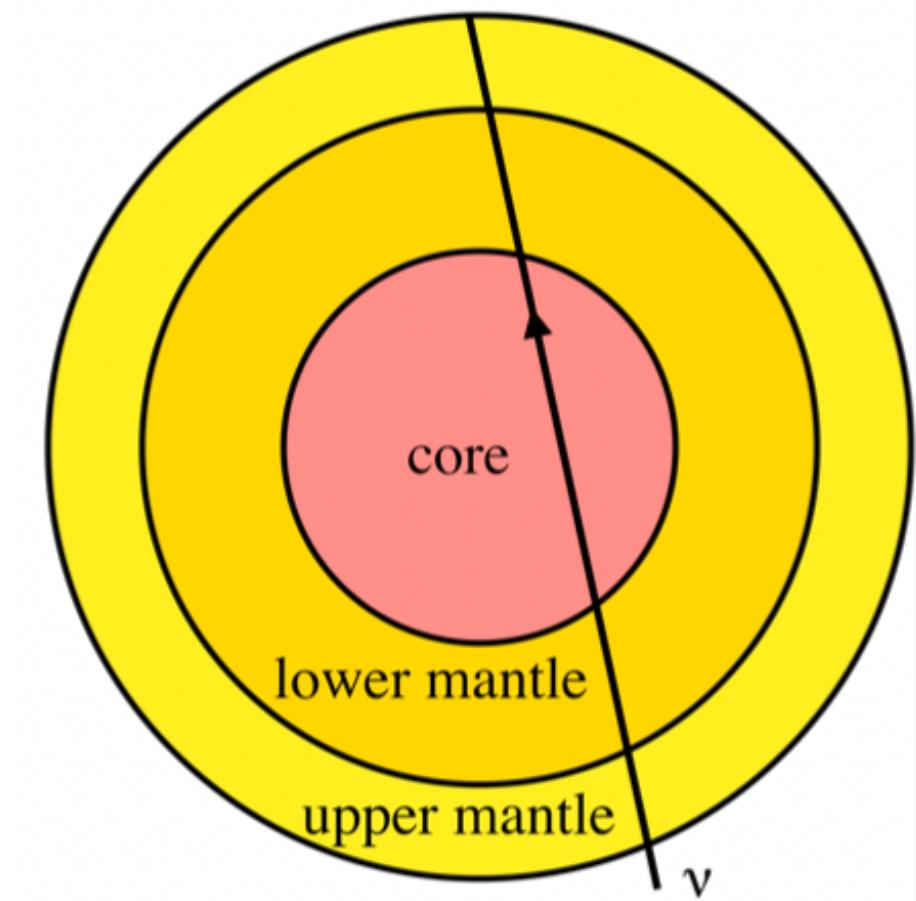
$$\cos 2\theta_c \geq 0, \cos 2(2\theta_M - \theta_c) \leq 0$$

Parametric resonance: 3 layers

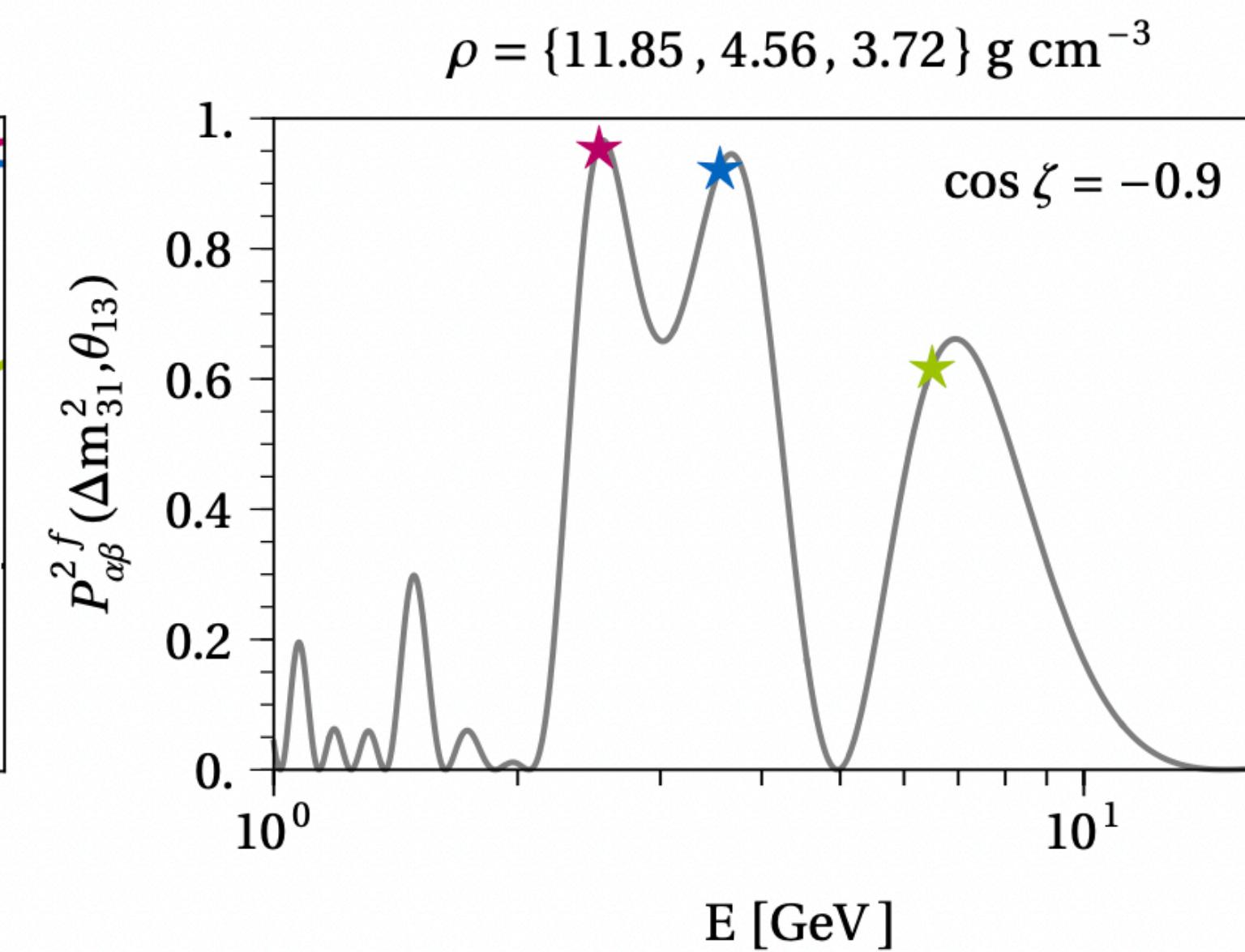
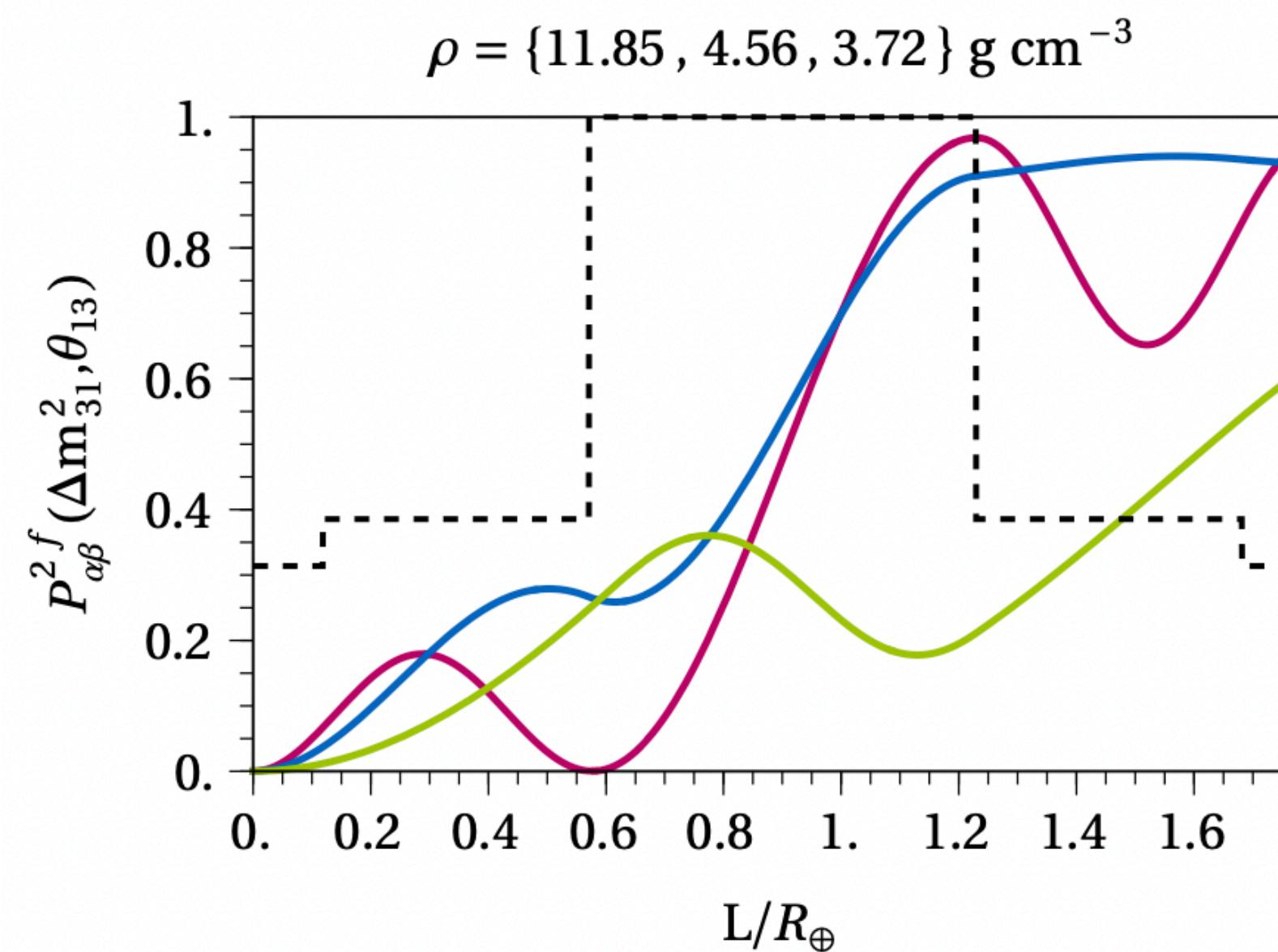


Sub-GeV

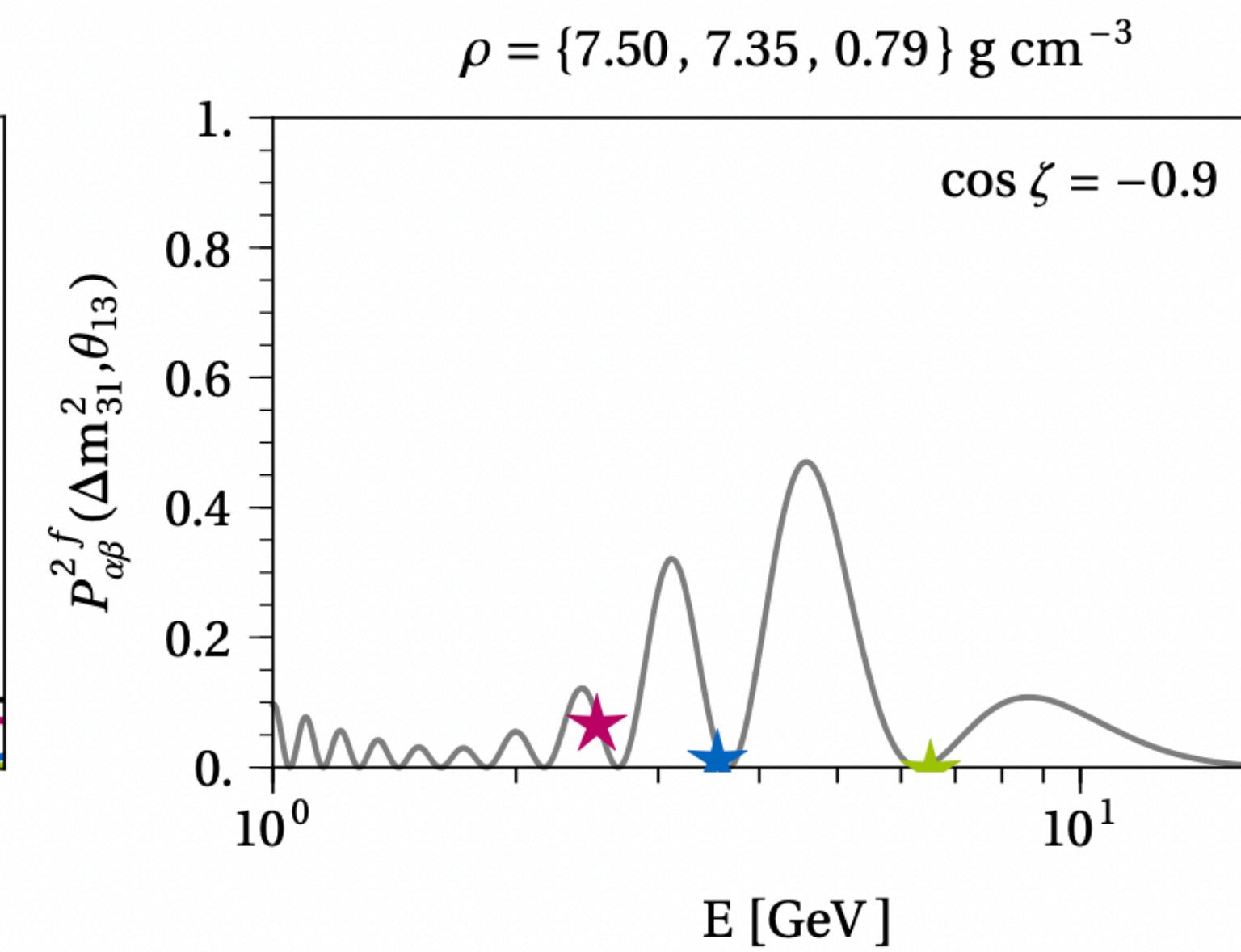
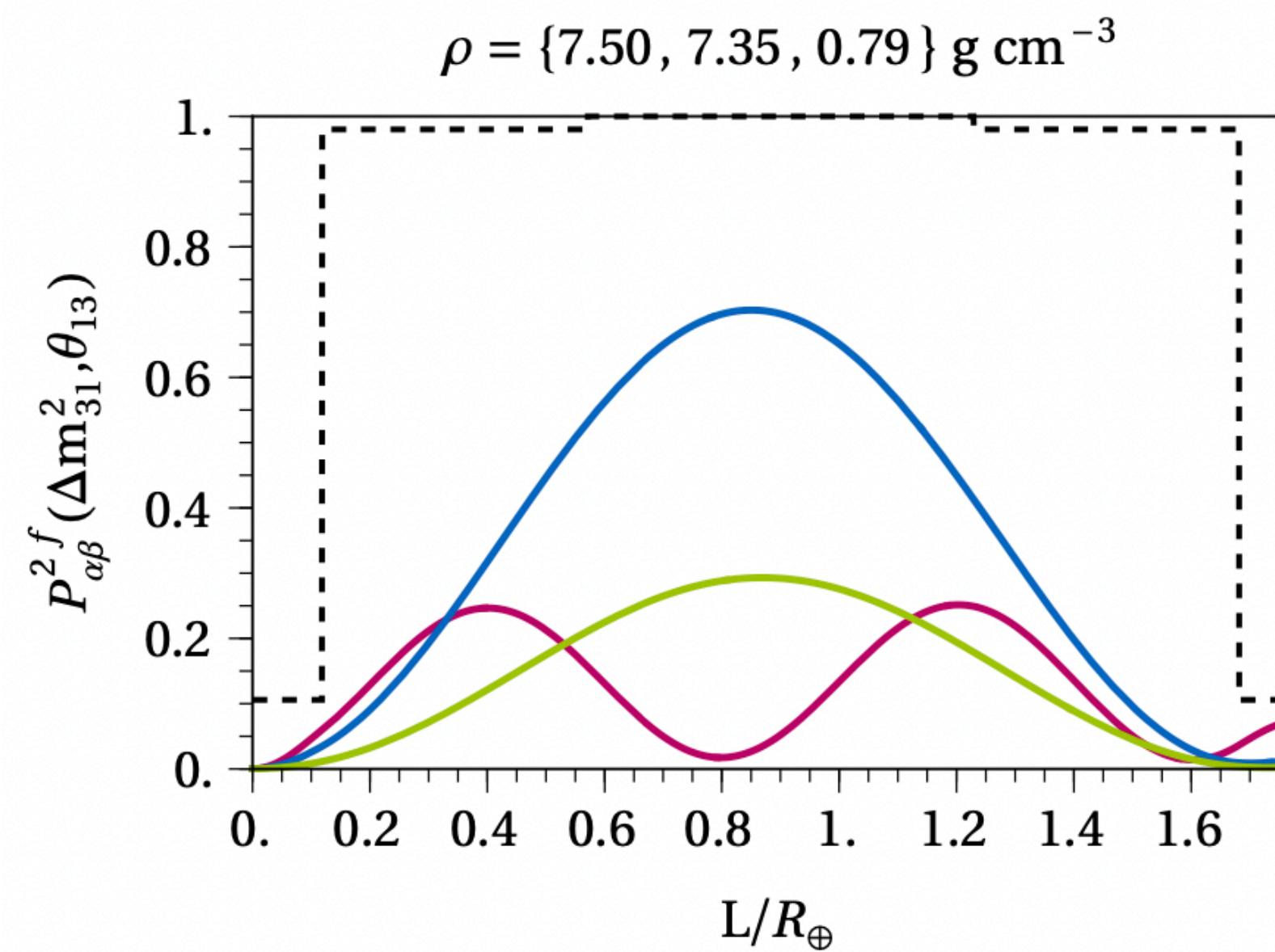
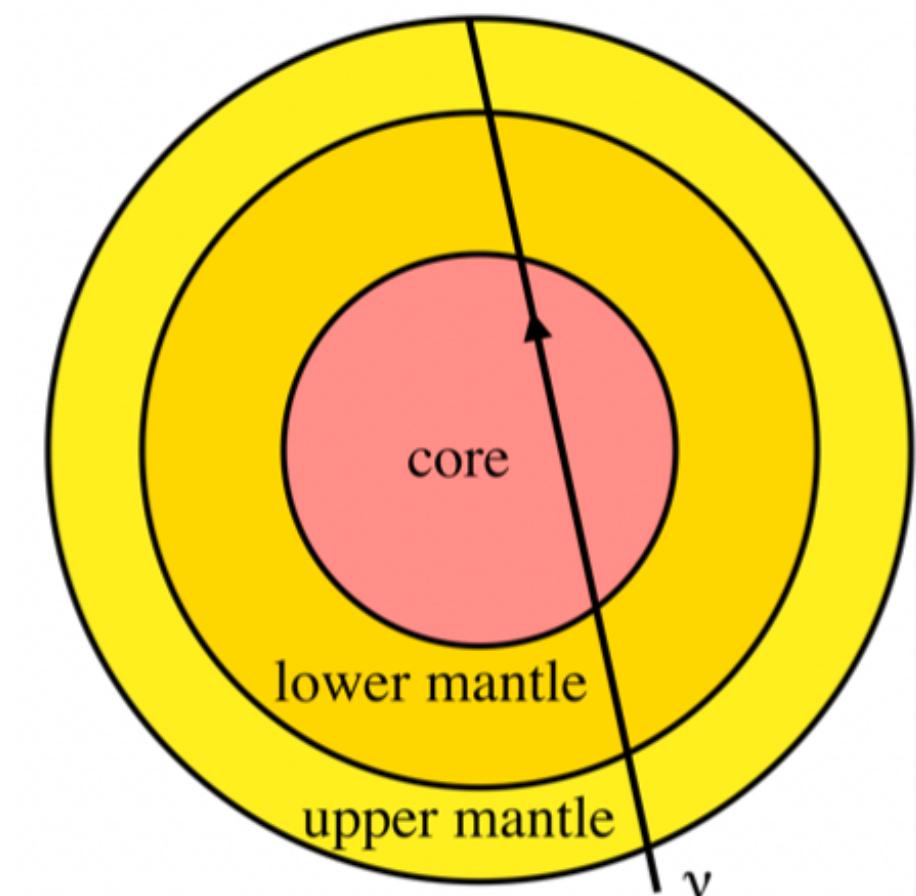
In the three-layer scenario, we found several local maxima coming from the phase interference



Parametric resonance: 3 layers

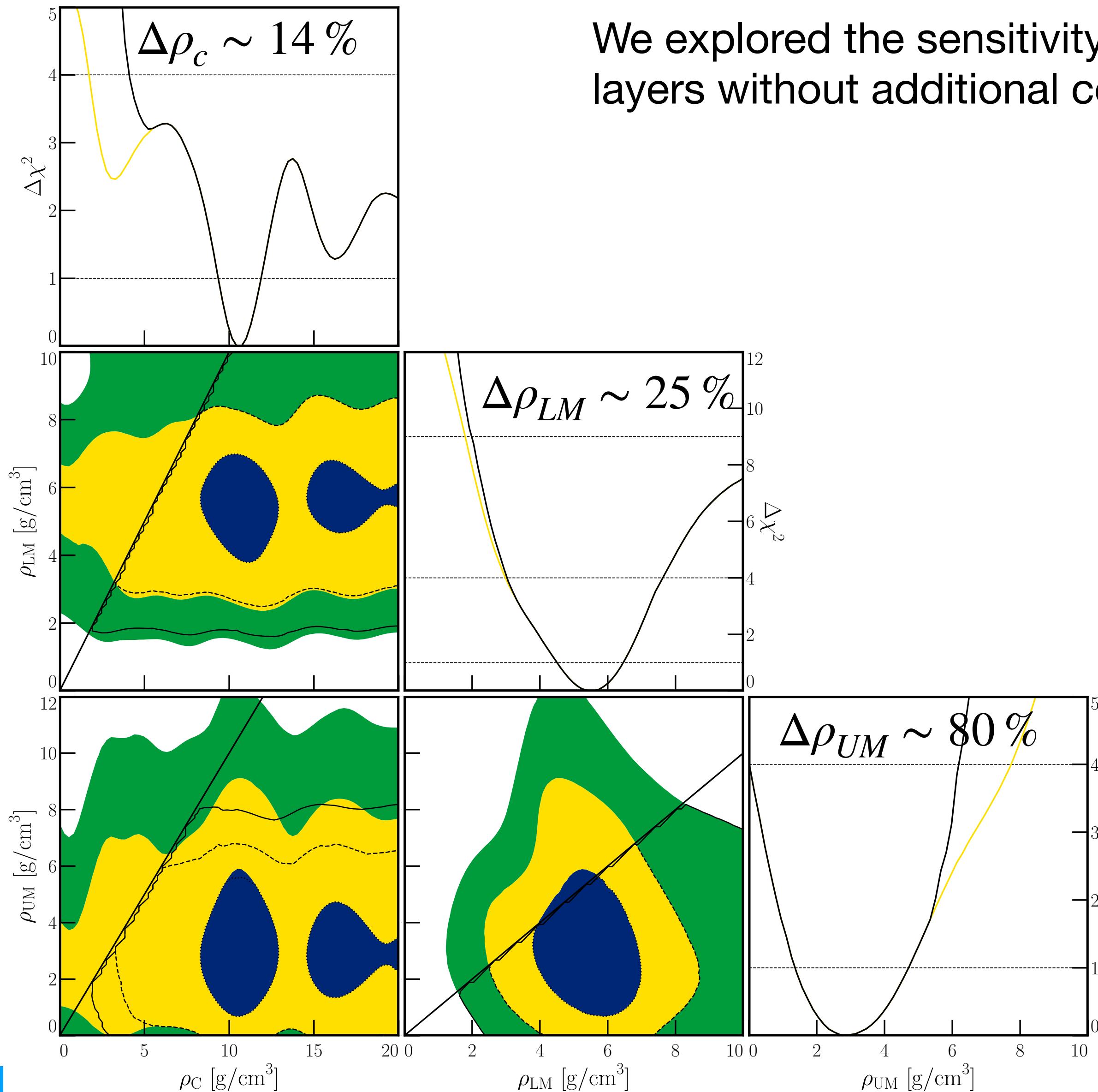


Multi-GeV

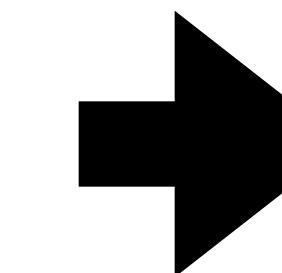


In the three-layer scenario, we found several local maxima coming from the phase interference

Earth's matter profile without constraints



We explored the sensitivity to the three layers without additional constraints



The main sensitivity is obtained for the **core** and the **lower mantle**

K.J.K, P.A.N.M, I. M. S., Y.F.P-G, JHEP 05 (2022) 187 arXiv:
2110.00003