Neutrino oscillations with a million of atmospheric neutrinos

NUTs

Ivan Martinez-Soler

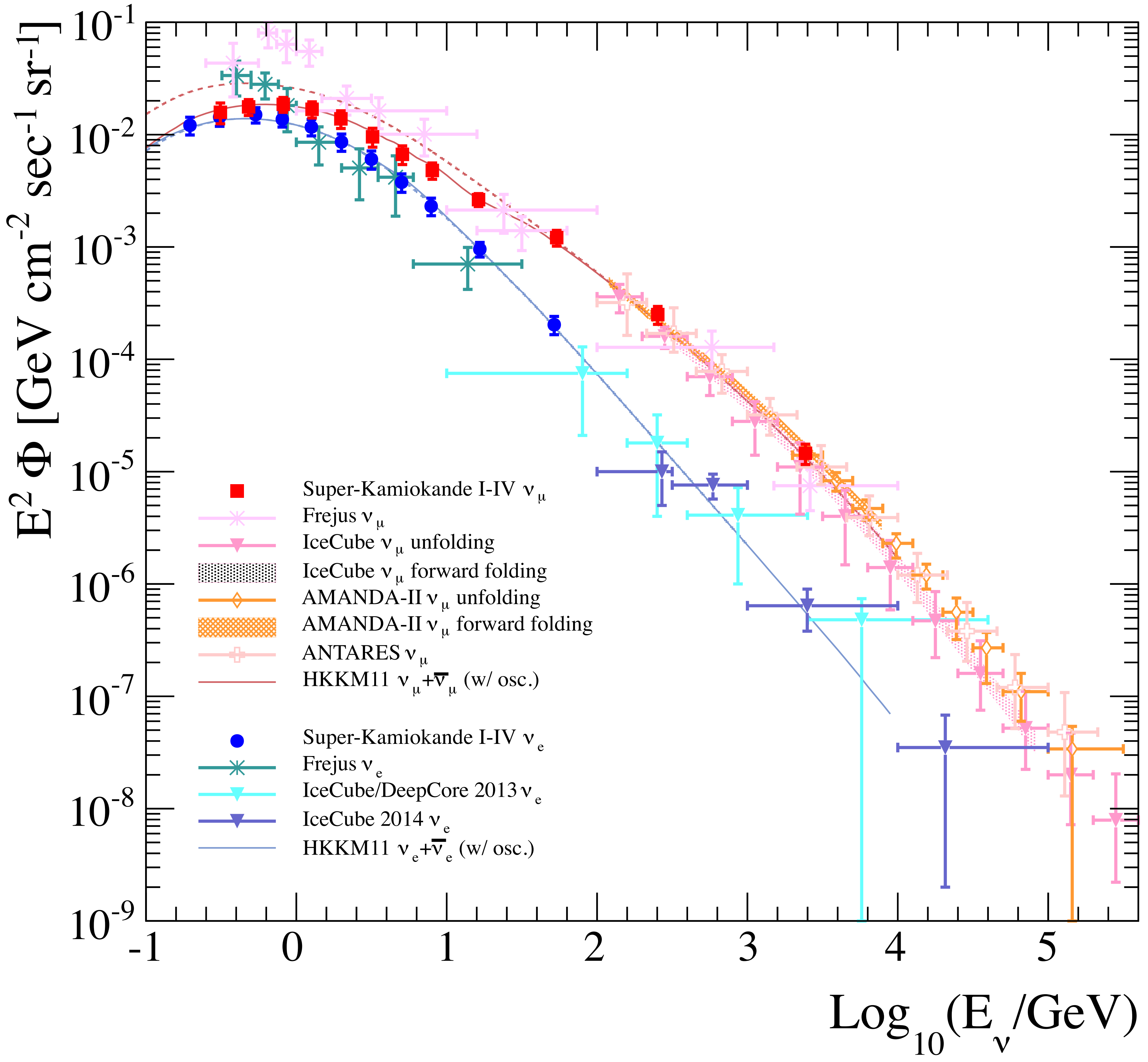
June 3, 2022

Outline

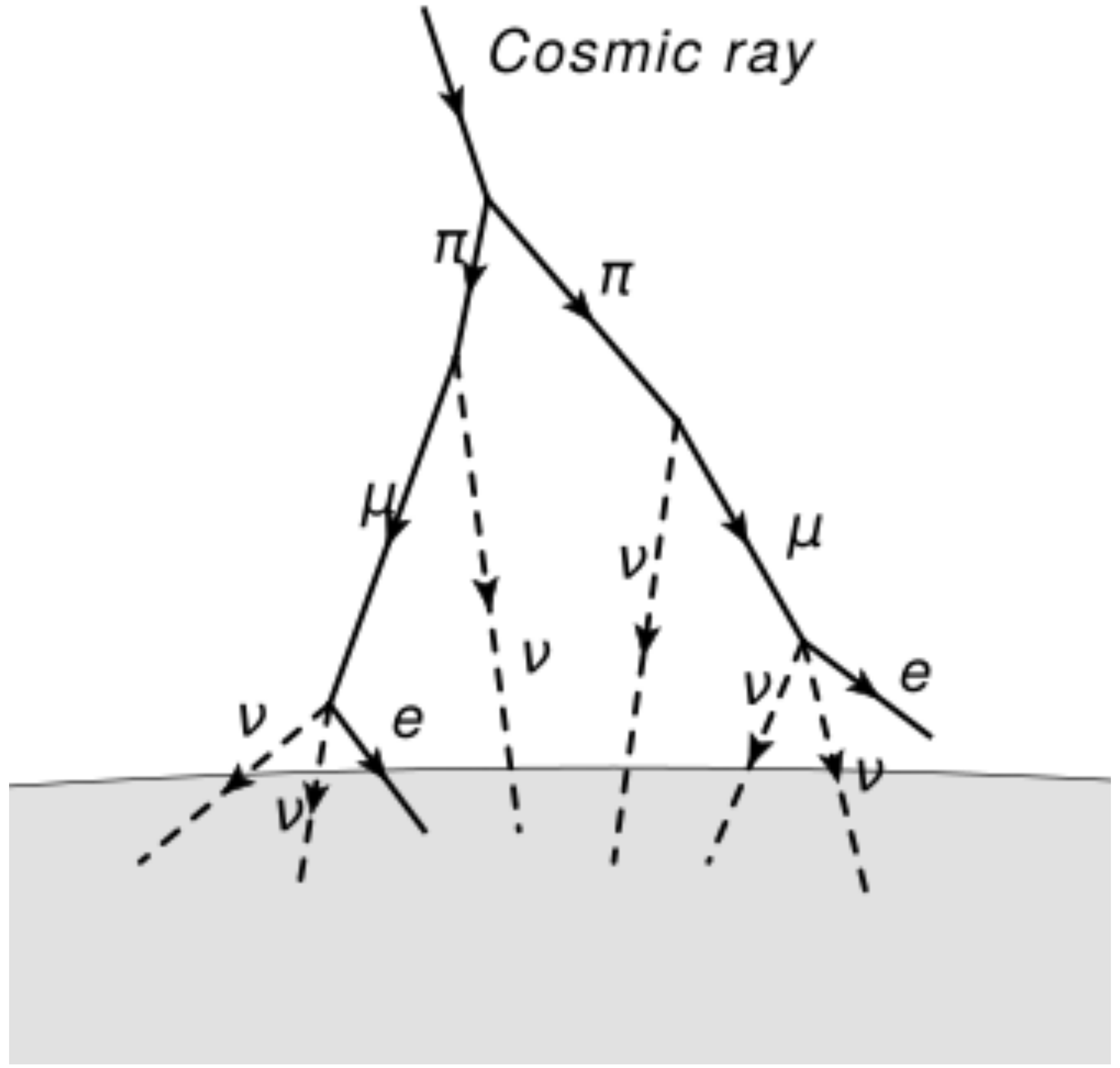
- Atmospheric neutrinos.
- Status of the 3ν mixing scenario. How atmospheric neutrinos can contribute?
- Next-generation of experiments: DUNE
- Neutrinos can weight the Earth: Tomography!
- Conclusions

Atmospheric neutrinos

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



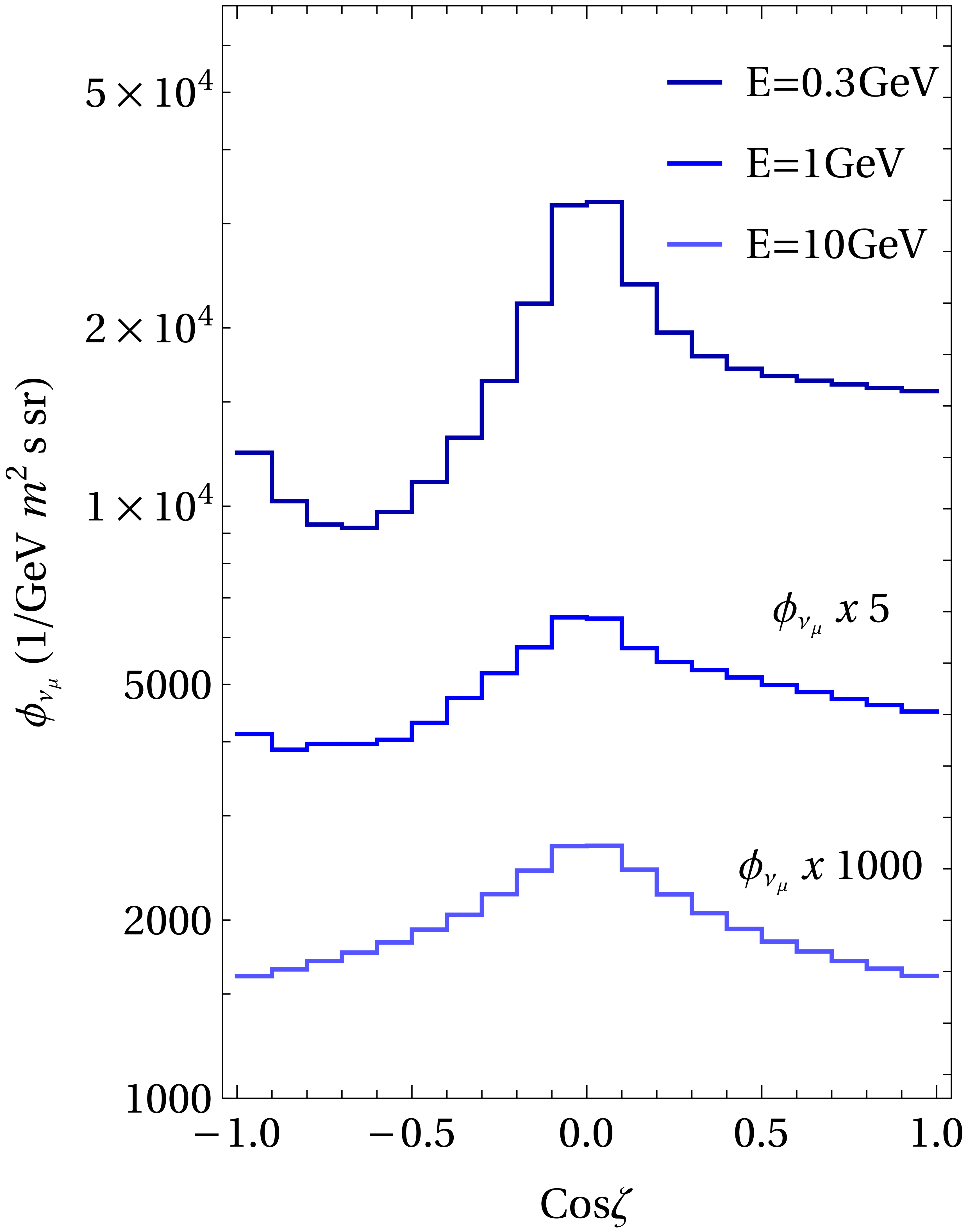
E. Richard et al. (SK), Phys.Rev.D 94 (2016) 5, 052001



$$\pi \to \mu\nu_\mu$$
$$K \to \mu\nu_\mu$$
$$\mu \to e\bar{\nu}_e\bar{\nu}_\mu$$

Atmospheric neutrinos

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



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

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

The main components in the flux calculations are:

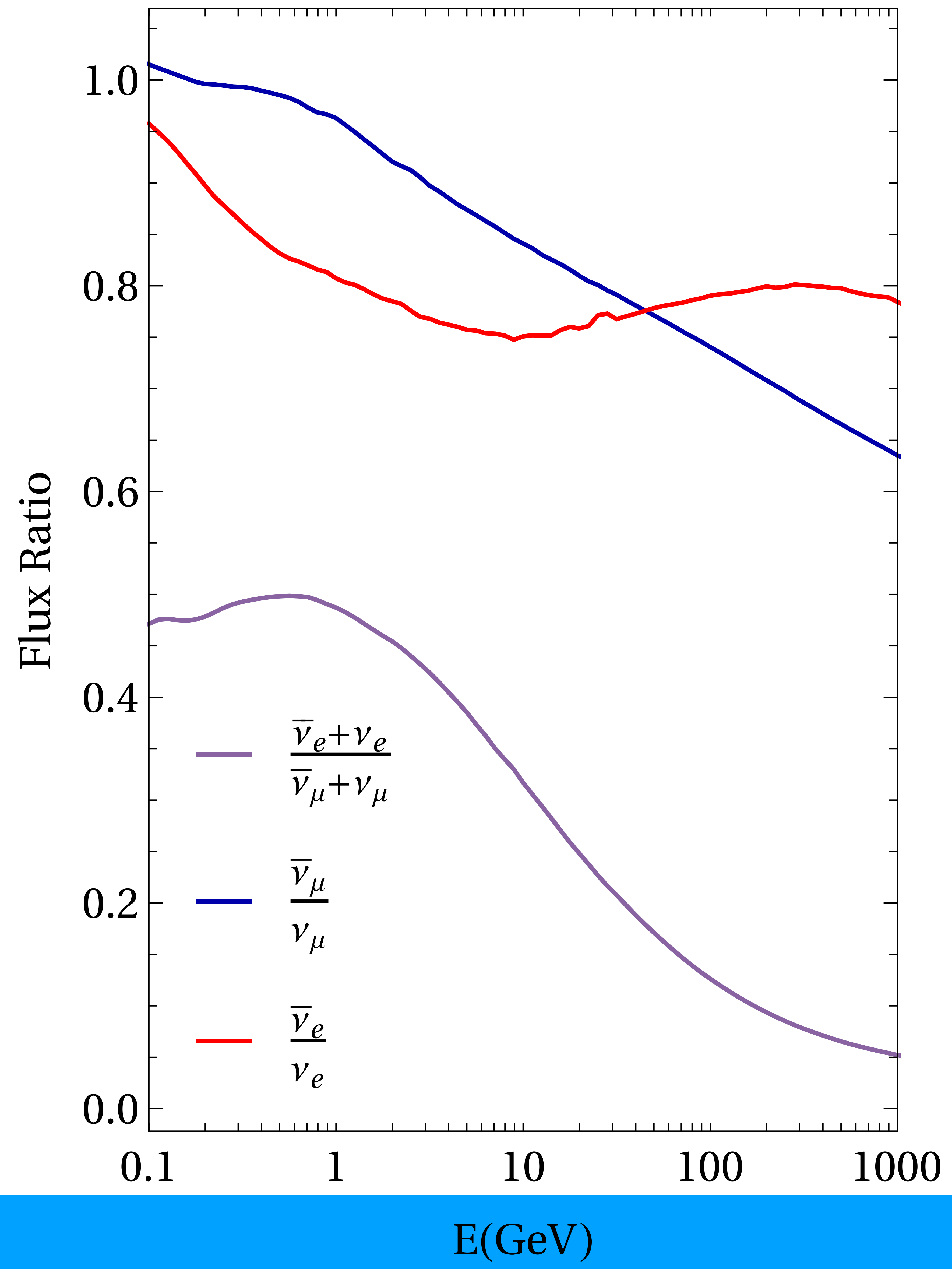
- Cosmic ray flux (ϕ_p)
- Geomagnetic effects (R)
- Hadronic interactions (Y)

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 atmospheric flux **composition changes** with the energy



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

The 3ν scenario

3ν mixing

See Michele’s Talk

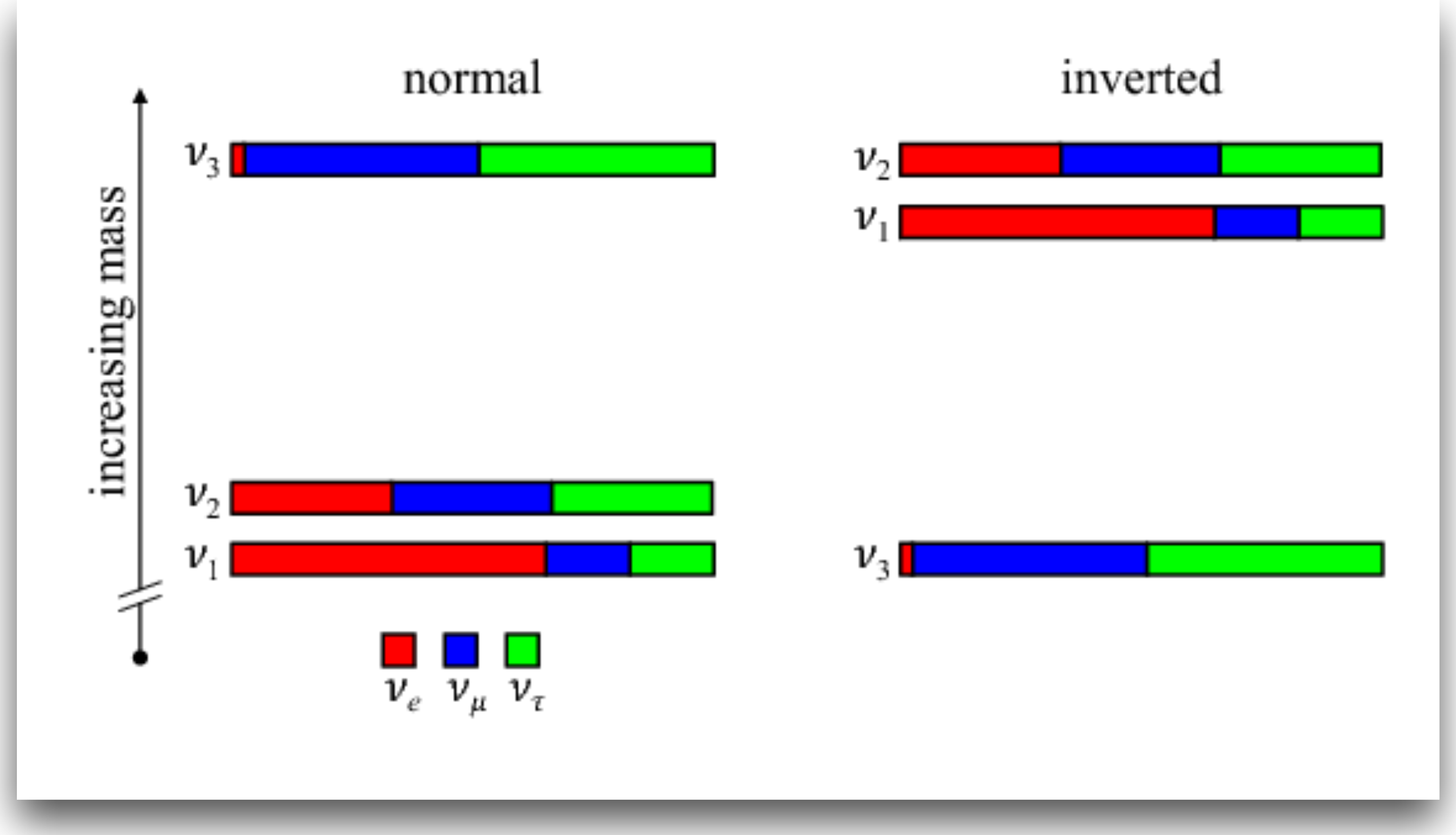
In the **3ν scenario**, neutrino evolution is described by six parameters

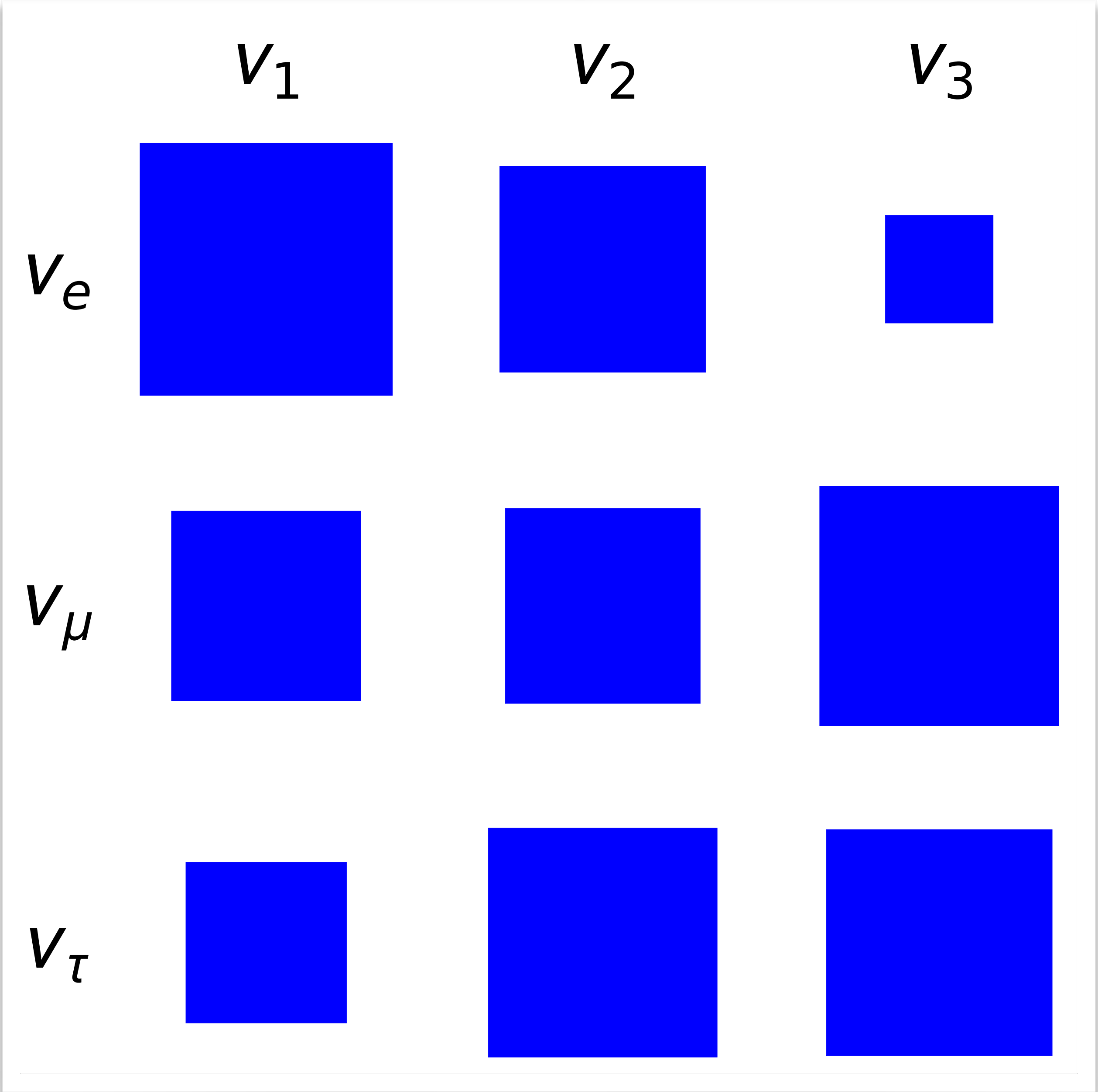
$$i\frac{d\nu}{dE} = \frac{1}{2E}\left(U^{\dagger}\text{diag}(0,\Delta m^2_{21}, \Delta m^2_{31})U\right)\nu$$

Mixing between massive and massive states

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

Mass ordering





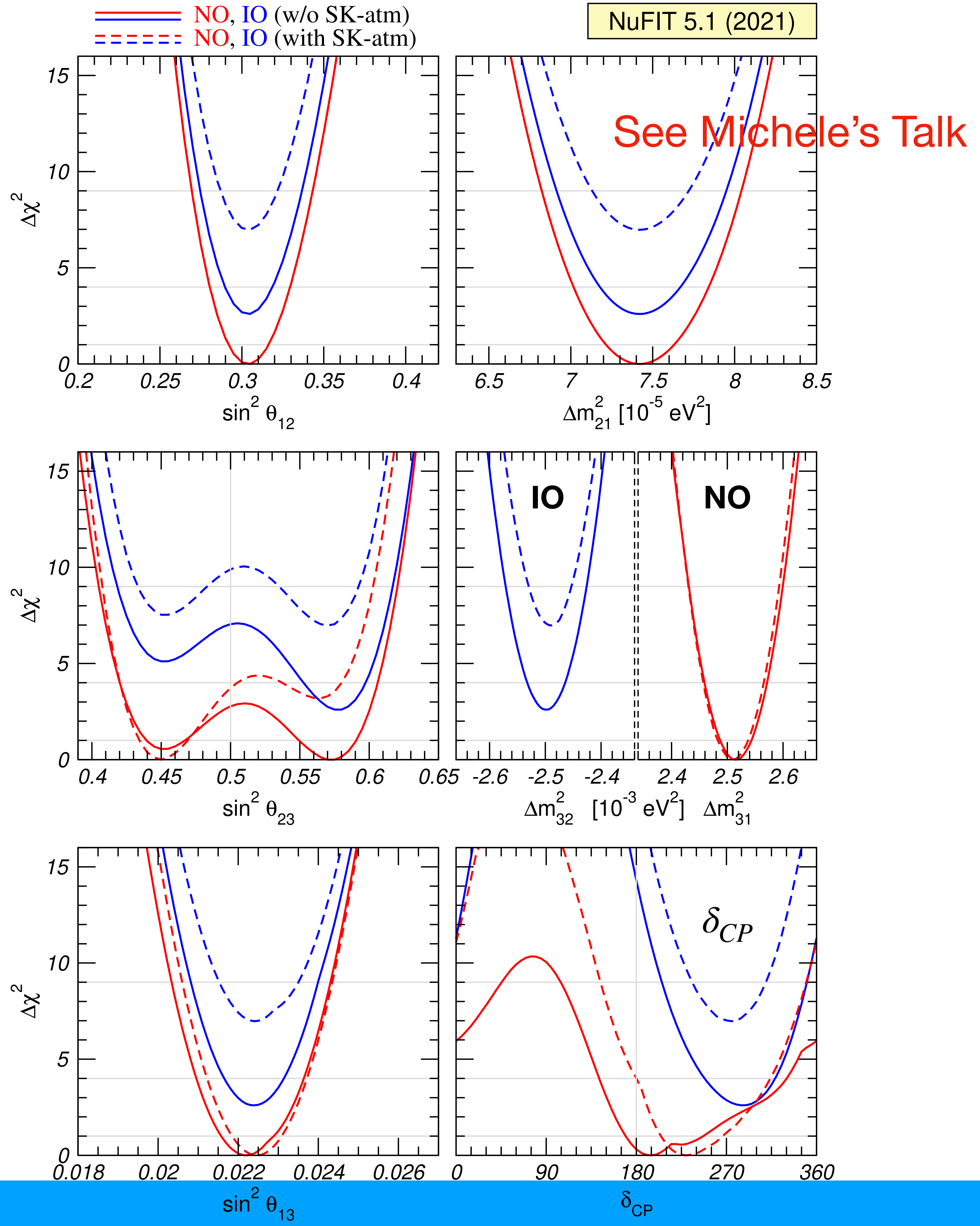
3ν mixing

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^2_{21}	$7.42 \times 10^{-5}\mathrm{eV}^2$	~3%
Δm^2_{31}	$2.52 \times 10^{-3}\mathrm{eV}^2$	~1%

The less constrained parameters are:

- Mass ordering
- Octant of θ_{23}
- CP-phase



See Michele's Talk

3ν mixing in matter

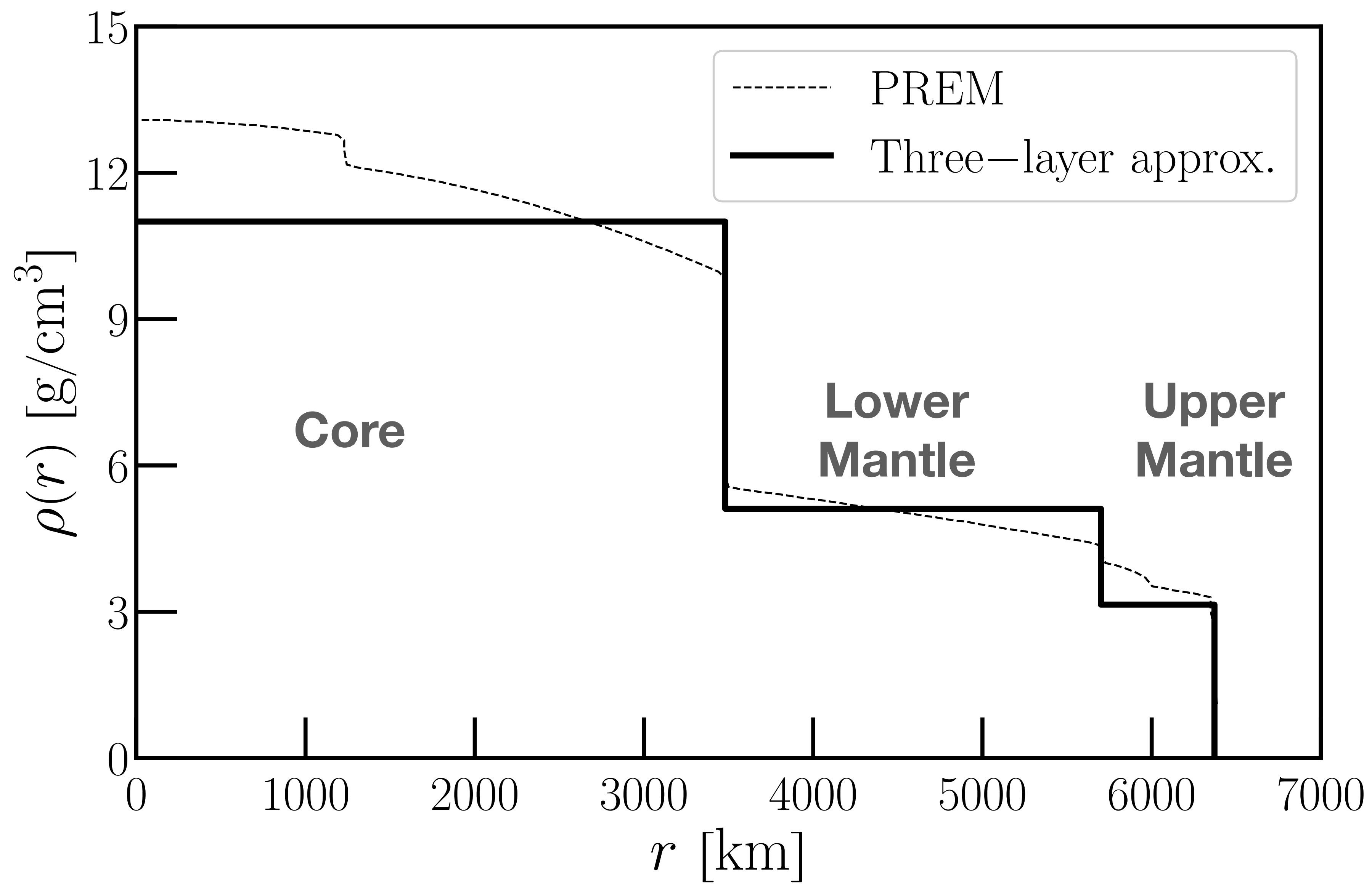
In matter, the evolution is affected by the matter potential

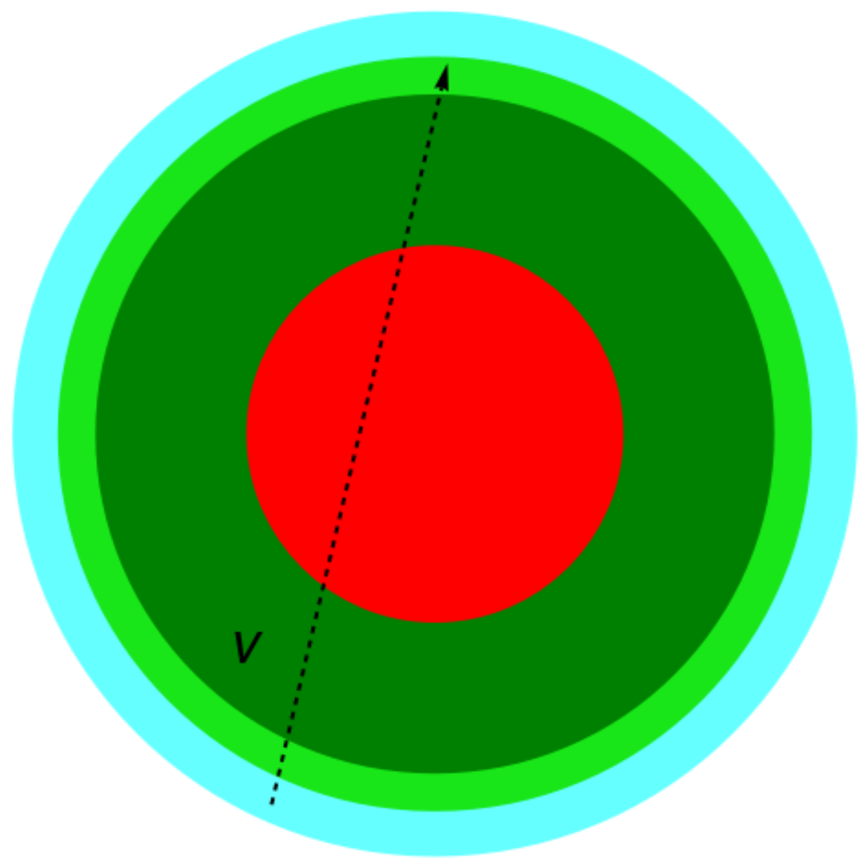
$$i\frac{d\nu}{dE} = \frac{1}{2E}\left(U^\dagger \mathrm{diag}(0,\Delta m^2_{21}, \Delta m^2_{31})U \pm \boxed{V_{mat}}\right)\nu$$

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

Electron density along the neutrino trajectory

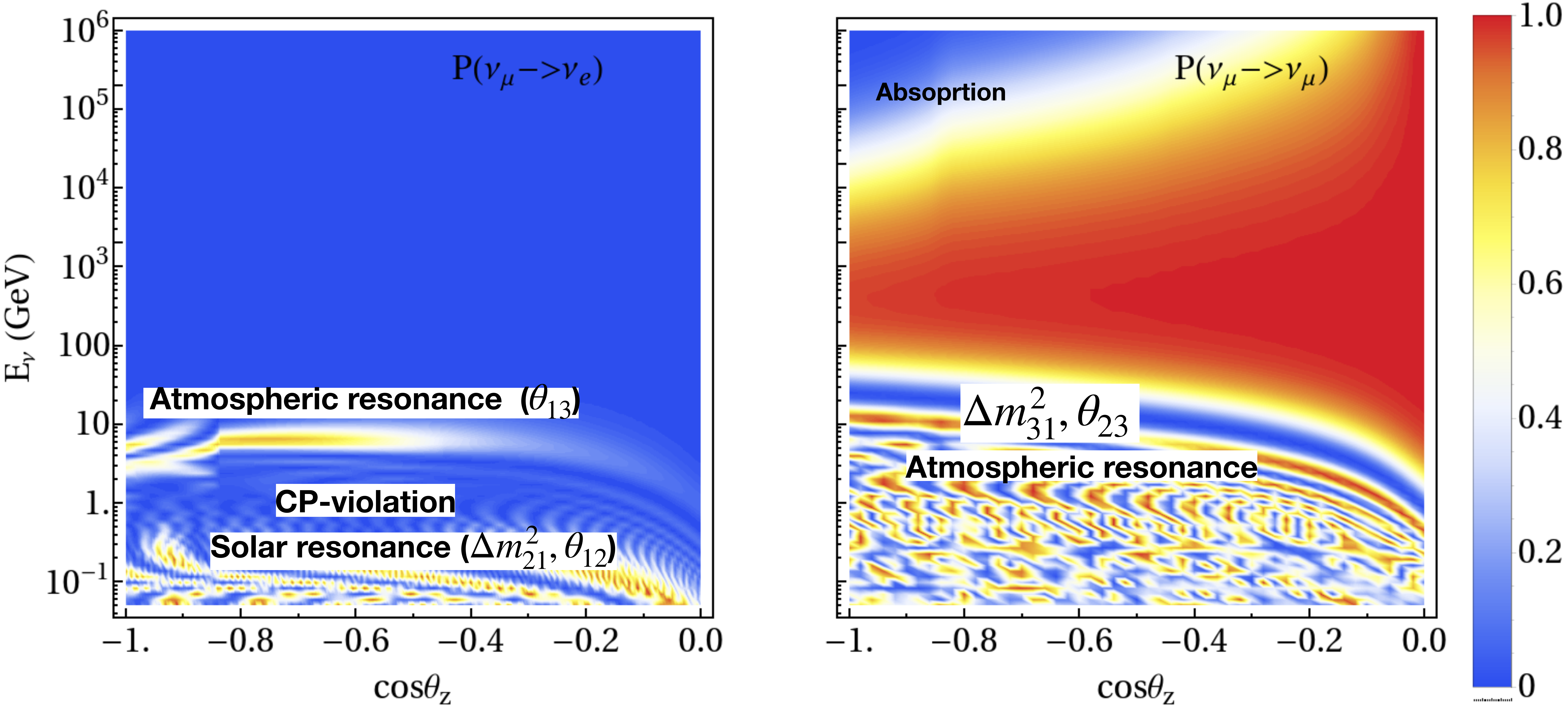
For neutrinos crossing the Earth





3ν mixing through the Earth

A reach phenomenology is accessible using atmospheric neutrinos



Sub-GeV atmospheric neutrinos

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

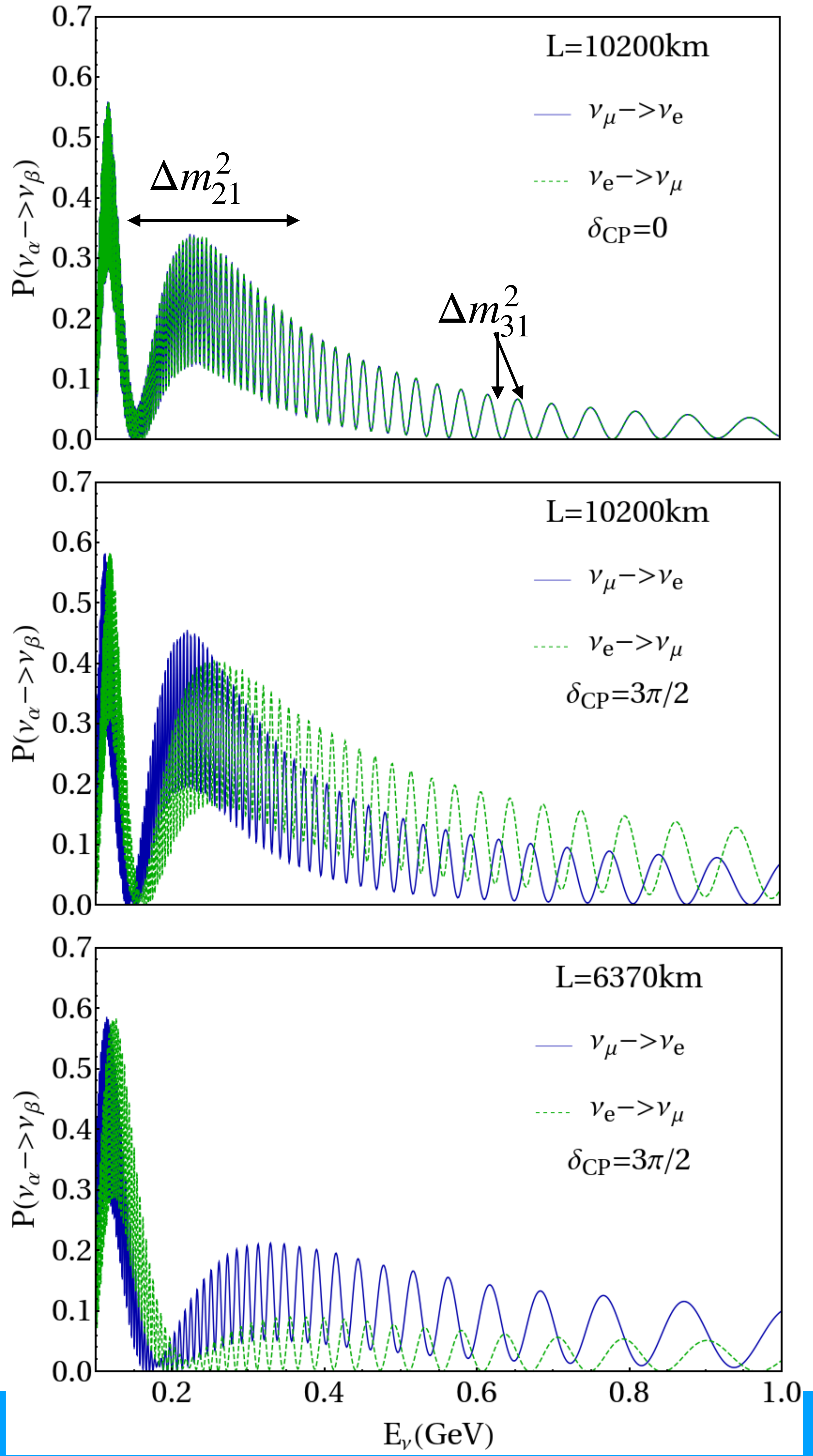
For $\delta_{cp} \neq 0$, the CPT conservation implies

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

- 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

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



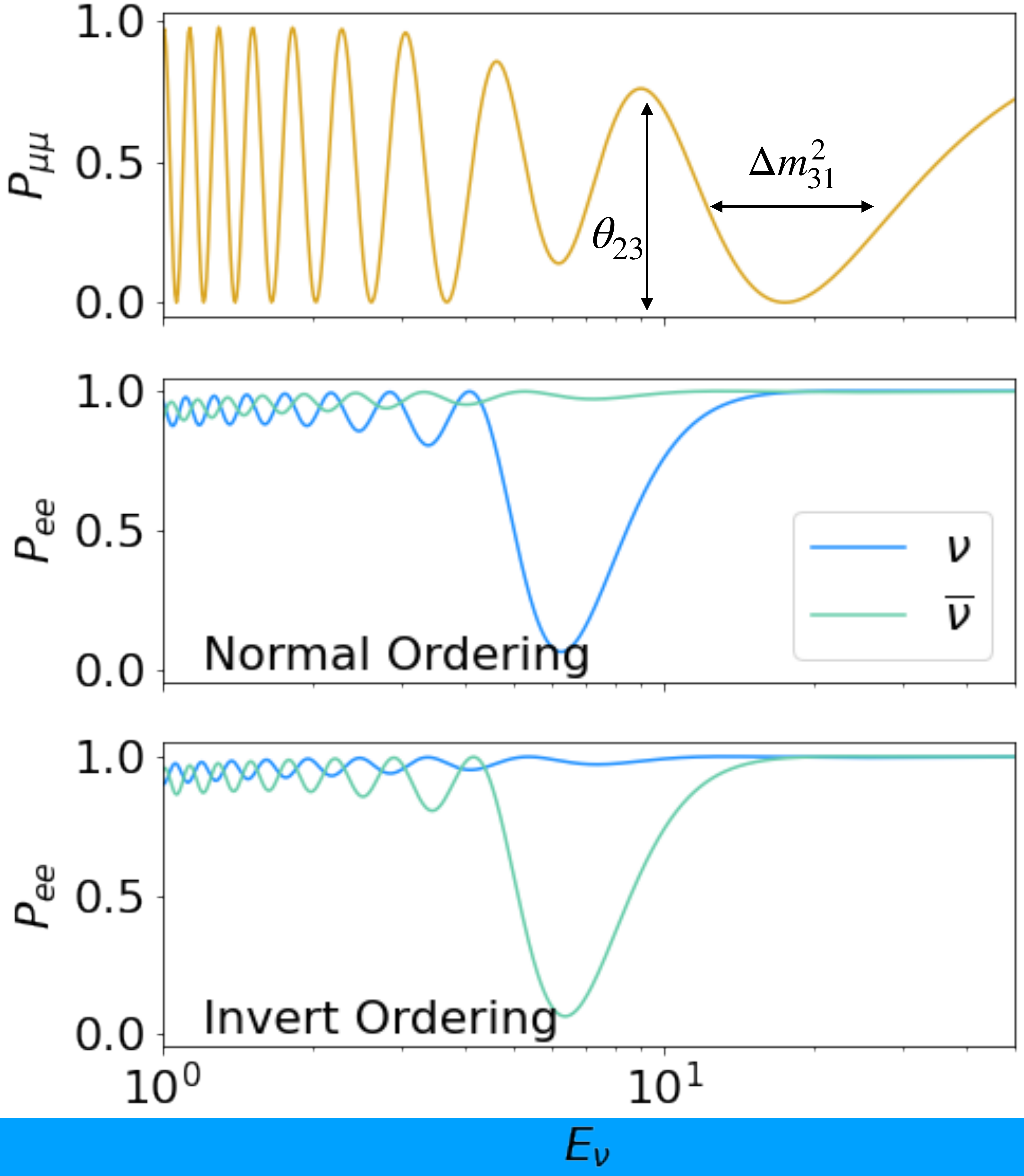
Multi-GeV atmospheric neutrinos

In the multi-GeV region, atmospheric neutrinos become sensitive to Δm^2_{31} 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.

$$E_r \simeq 5.3\text{GeV}\left(\frac{\Delta m^2_{31}}{2.5\times 10^{-3}\text{eV}^2}\right)\left(\frac{cos2\theta}{0.95}\right)\left(\frac{\rho}{6\text{g/cc}}\right)$$

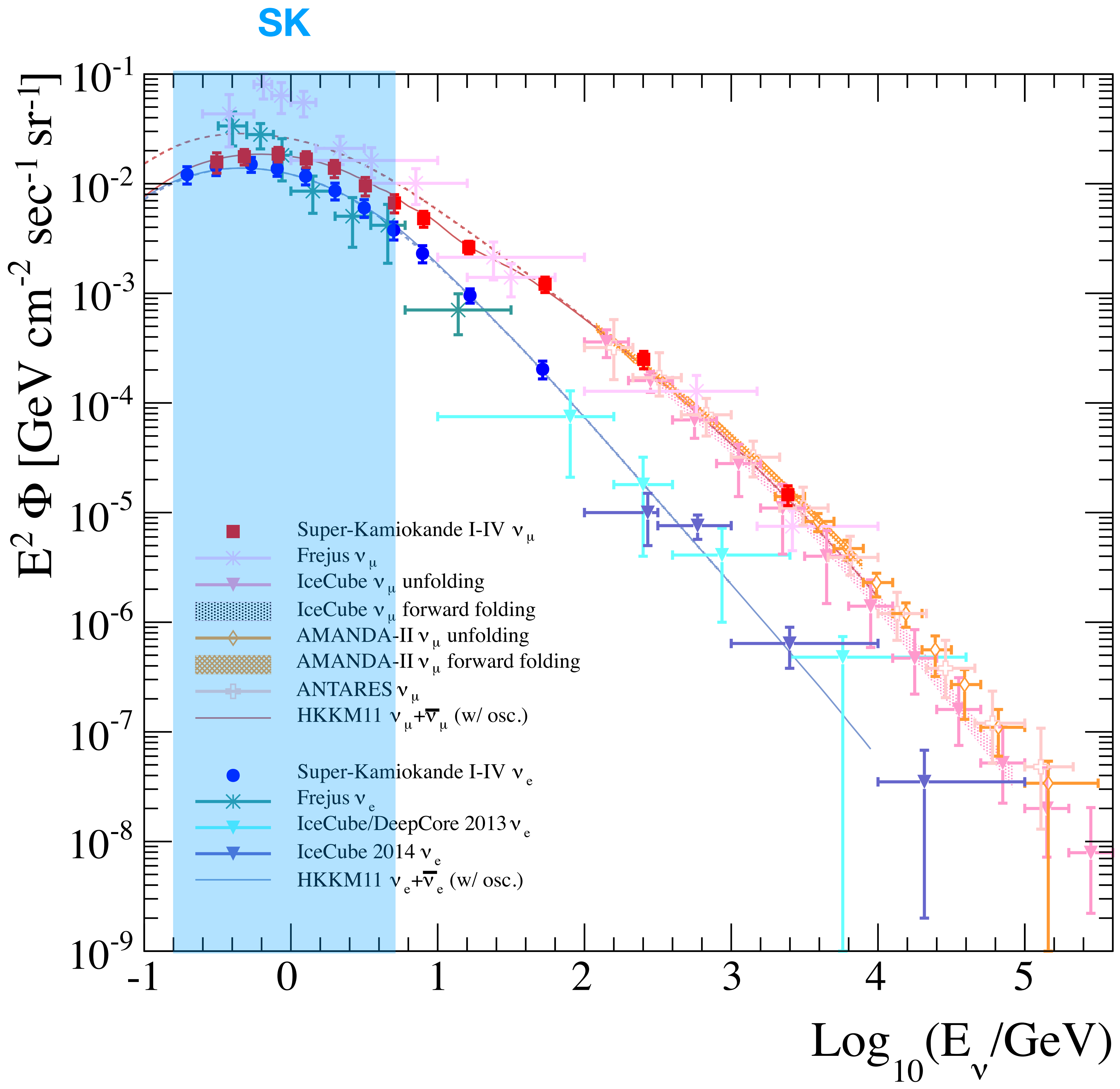


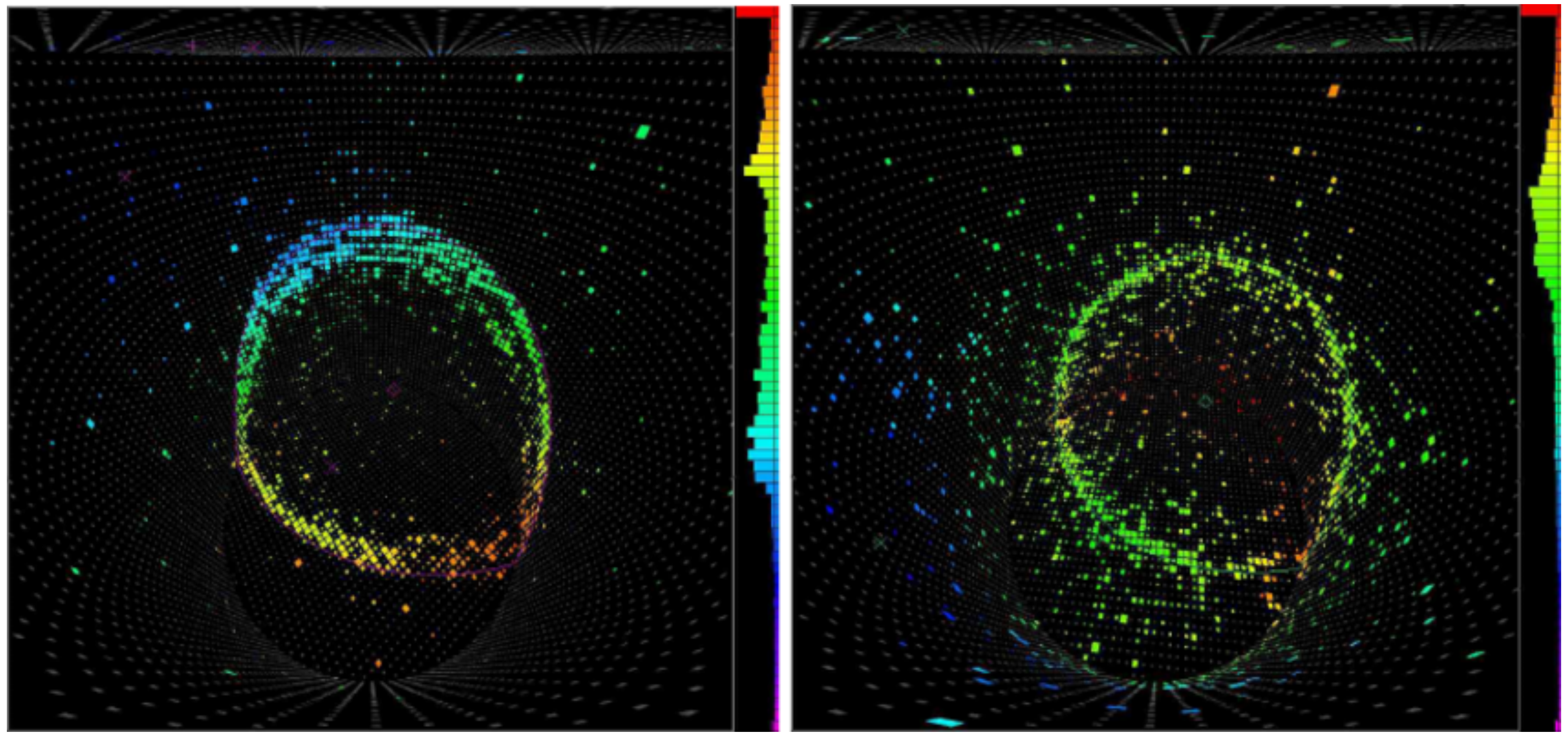
Detection of atmospheric neutrinos

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
- Event sample is divided in FC, PC and Up-μ

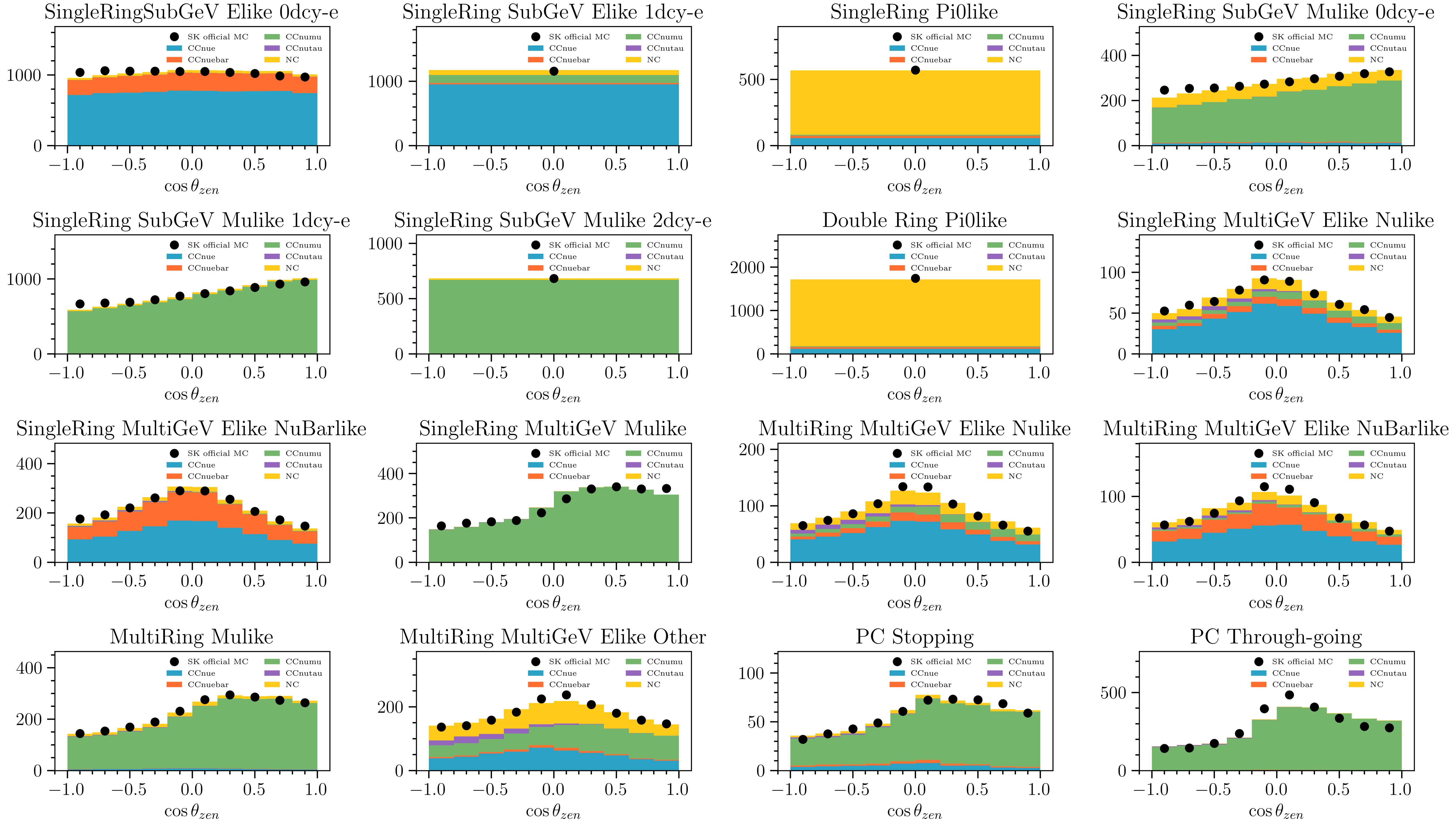




C.A. Argüelles, P. Fernandez, I. Martinez-Soler and M. Jin, in preparation

Super-Kamiokande

Preliminary



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We have developed a simulation of SK that includes:

- The measurement up to 2008
- H-tagging from 2008 to 2018
- Gd-tagging from 2018

In the simulation, we included all the detector systematics from Super-Kamiokande I-IV analysis

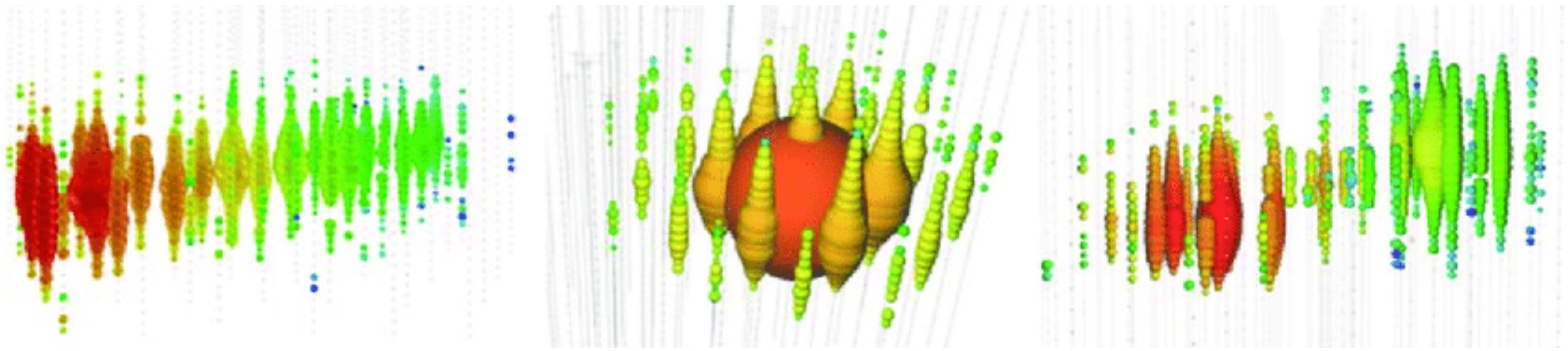
For a detailed description of the detector systematics see K. Abe et al. (Super-Kamiokande), Phys.Rev.D97 (2018) 7, 072001

Detection of atmospheric neutrinos

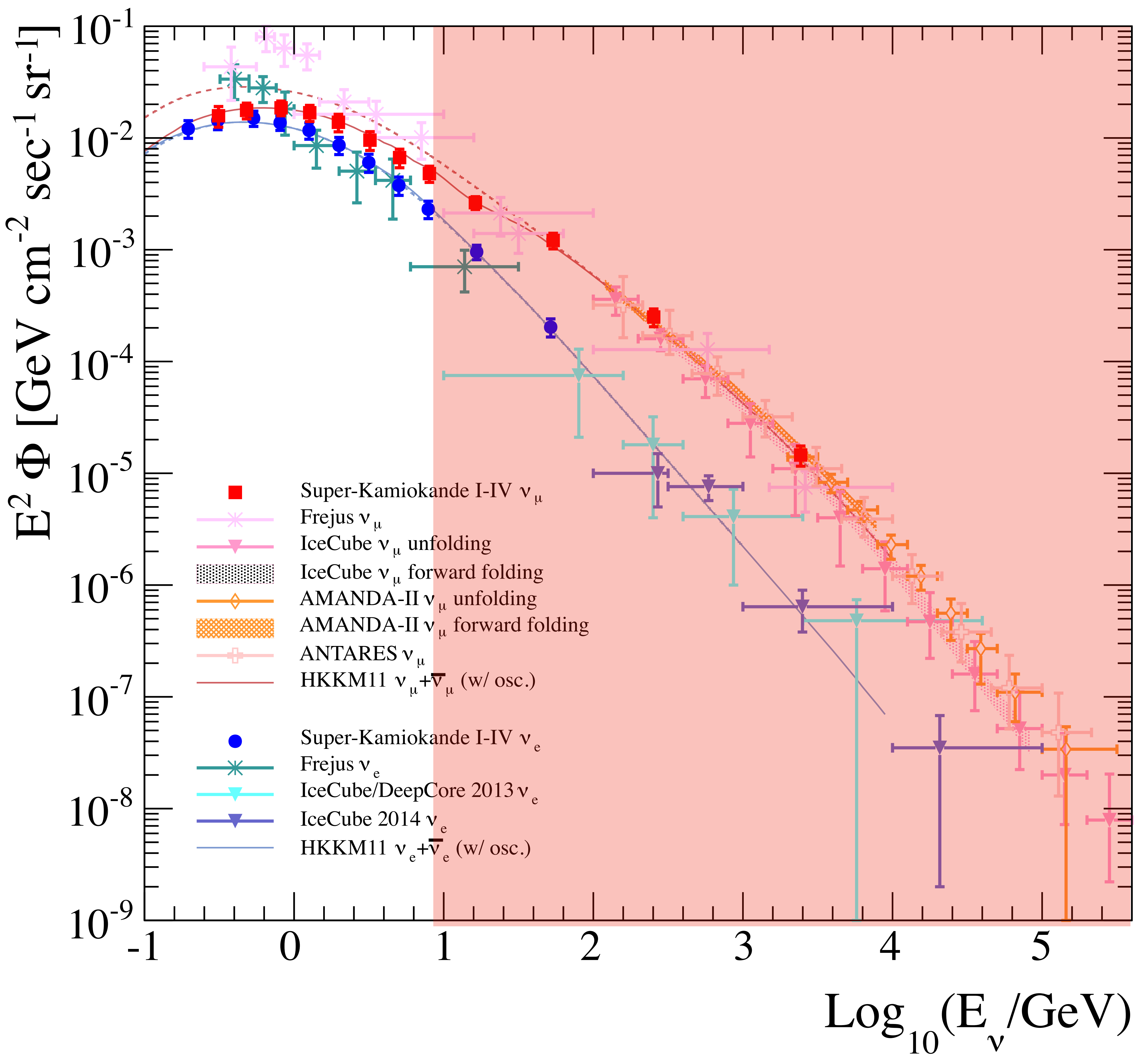
The high-energy part of the flux is measured by IceCube

IceCube

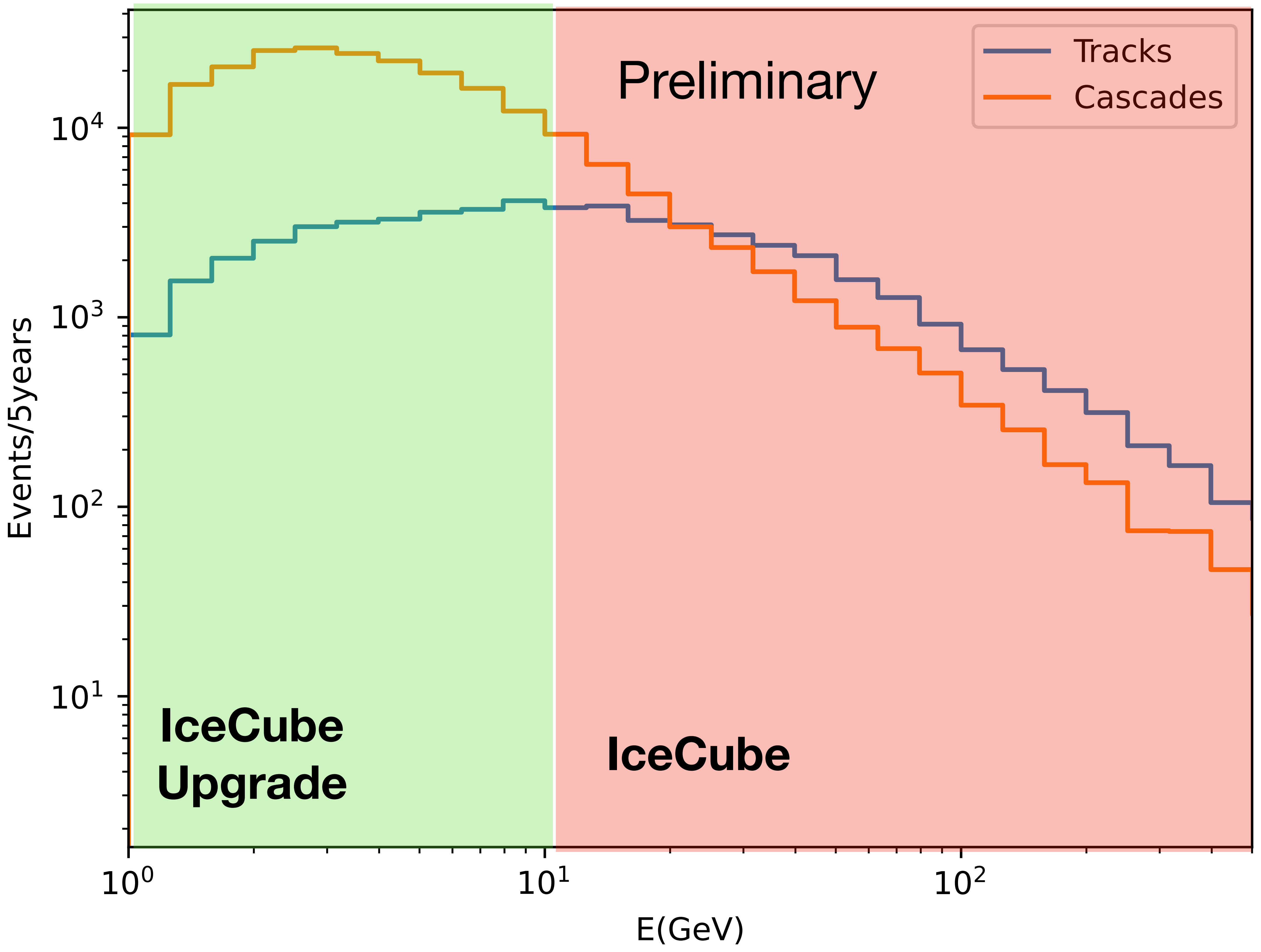
- $\sim 1\text{km}^3$ ice Cherenkov
- Measures the high-energy part of the flux
- The sample is divided into tracks and cascades



IceCube



IceCube-upgrade



C.A. Argüelles, P. Fernandez, I. Martinez-Soler and M. Jin, in preparation

In this analysis, we have focused on the IceCube upgrade:

- 7 additional strings with a denser distribution of high-effieciency photosensors
- Lower energy threshold ($E > 1 GeV$)

To estimate the detector sensitivity, we have included all the detector systematics:

- Ice absorption
- Ice scattering
- Optical headon
- Optical efficiency
- Optical lateral

M. G. Aartsen et al.. Phys. Rev., D99(3),032007

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

Systematic	Uncert./Priors
$\Phi_0(E < 1$ GeV$)$	25%
$\Phi_0(E > 1$ GeV$)$	15%
ν_e/ν_μ	2%
$\overline{\nu}/\nu$	2%
δ	20%
$C_{u,d}$	2%

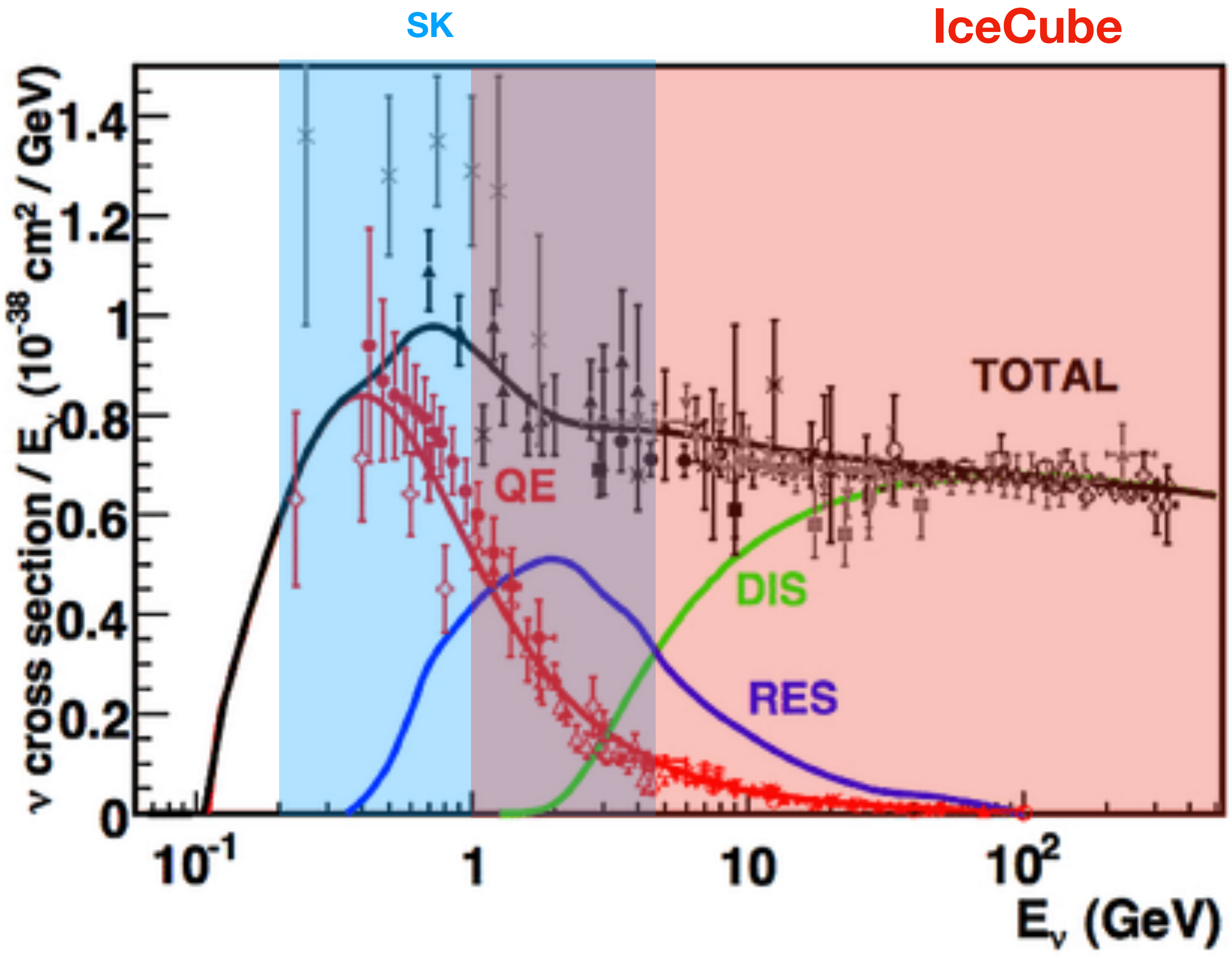
- Φ_0 normalization
- Flavor ratio (ν_e/ν_μ)
- Neutrino to antineutrino ratio ($\overline{\nu}/\nu$)
- Energy distortion (δ)
- Zenit distortion ($\eta(cos\zeta)$)
- Honda's tables ($f_\alpha(E, \cos\zeta)$)

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

K. Abe et al. (Super-Kamiokande), Phys.Rev.D97 (2018) 7, 072001

Cross-section uncertainties

- Atmospheric neutrinos are detected under several different types of interactions.
- The uncertainties in the interaction model also reduce the sensitivity.



K. Abe et al. (Super-Kamiokande),
Phys.Rev.D97 (2018) 7, 072001 for a

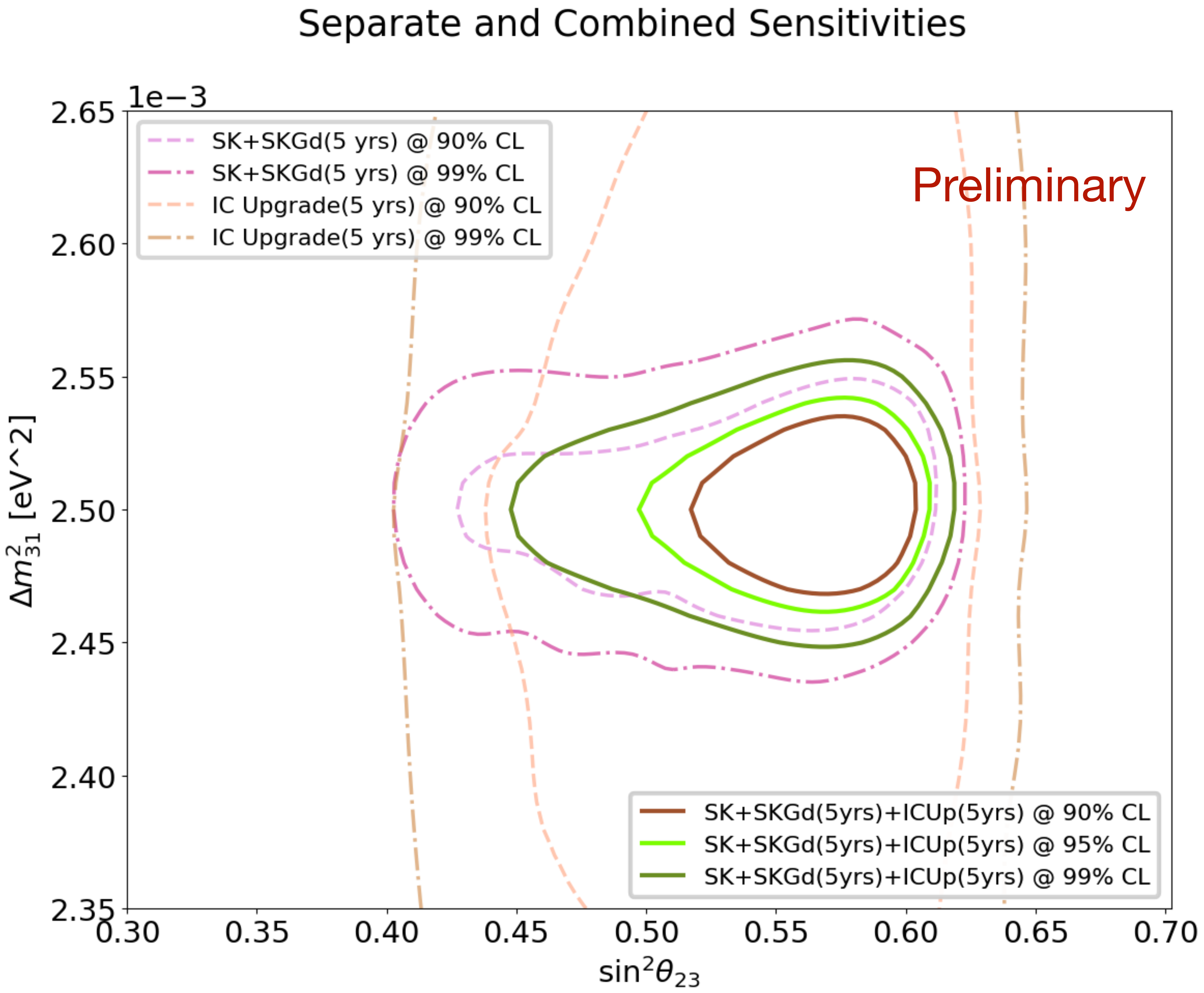
Systematic	Uncer./Prior
CCQE	10%
CCQE $\nu/\bar{\nu}$	10%
CCQE e/μ	10%
CC1 π	10%
CC1π $\pi^0/\pi^\pm$	40%
CC1π $\nu_e/\bar{\nu}_e$	10%
CC1π $\nu_\mu/\bar{\nu}_\mu$	10%
Coh.π	100%
Axial Mass	10%
NC hadron prod.	5%
NC over CC	10%
ν_τ	25%
Neutron prod. (SK)	15%
DIS	10%

Combined analysis: θ_{23} and Δm^2_{31}

Making a **combined analysis** of **SK** and **IceCube-upgrade,** we have estimated the sensitivity to δ_{cp}**,** θ_{23} and the **mass ordering**

- Adding both experiments, we can resolve the **octant of** θ_{23} at 2σ
- The measurement of Δm^2_{31} is dominated by IC.

- $\sin^2\theta_{13} =$ 0.022 (fixed)
- Profiled over δ_{cp}

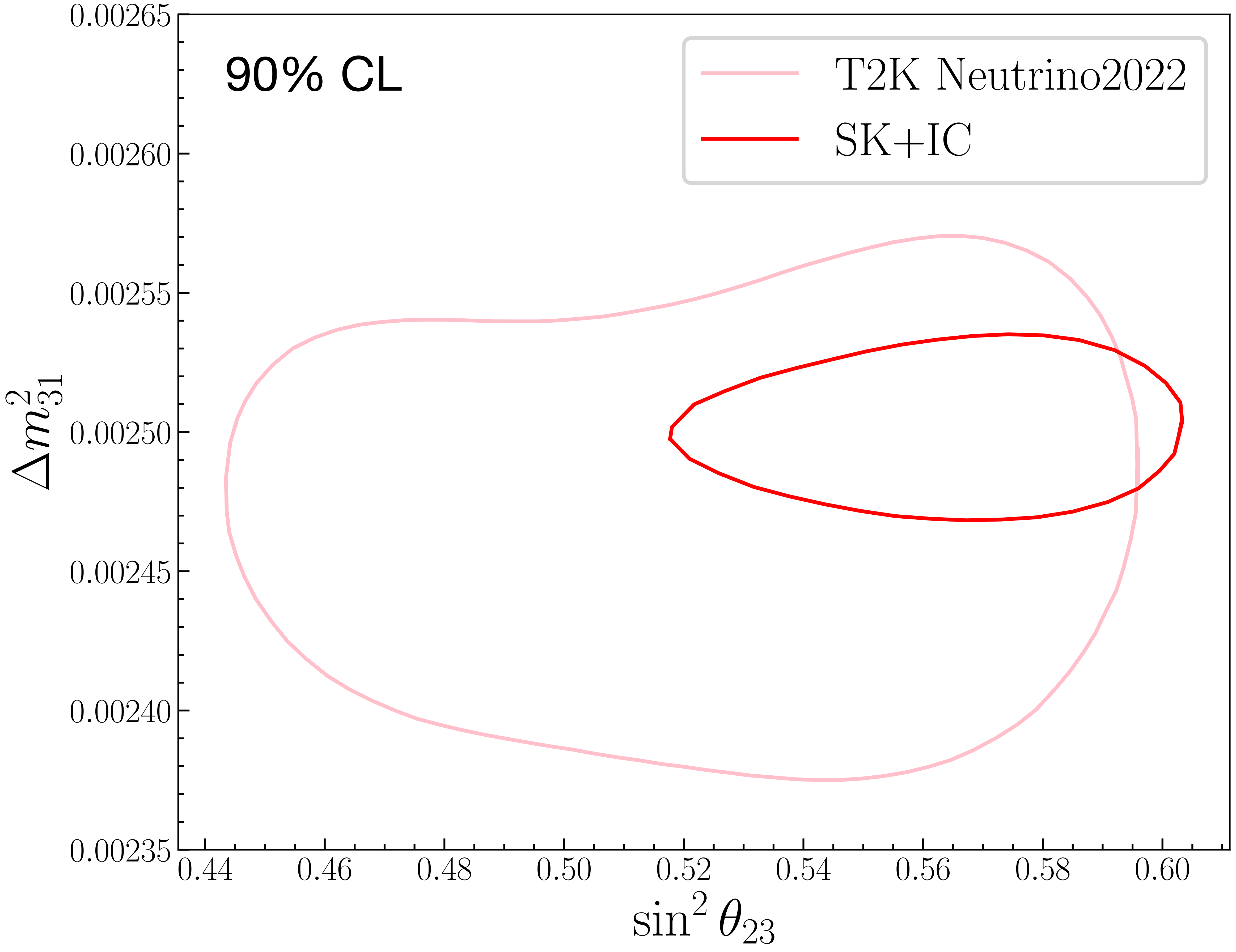


C.A. Argüelles, P. Fernandez, **I. Martinez-Soler** and M. Jin, in preparation

Combined analysis: θ_{23} and Δm^2_{31}

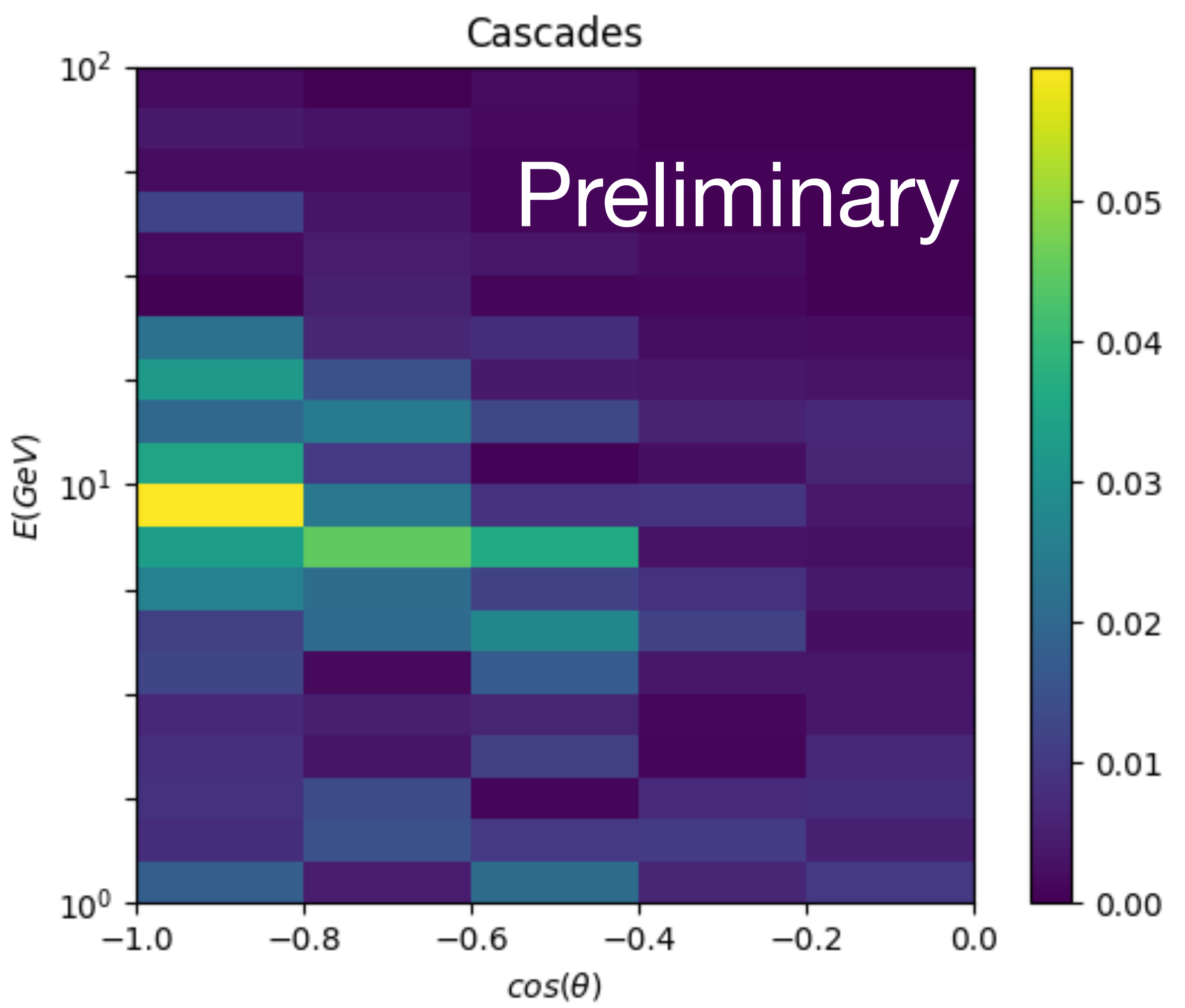
The **SK+IC-upgrade** will have better sensitivity than **LBL** and **reactor** experiments.

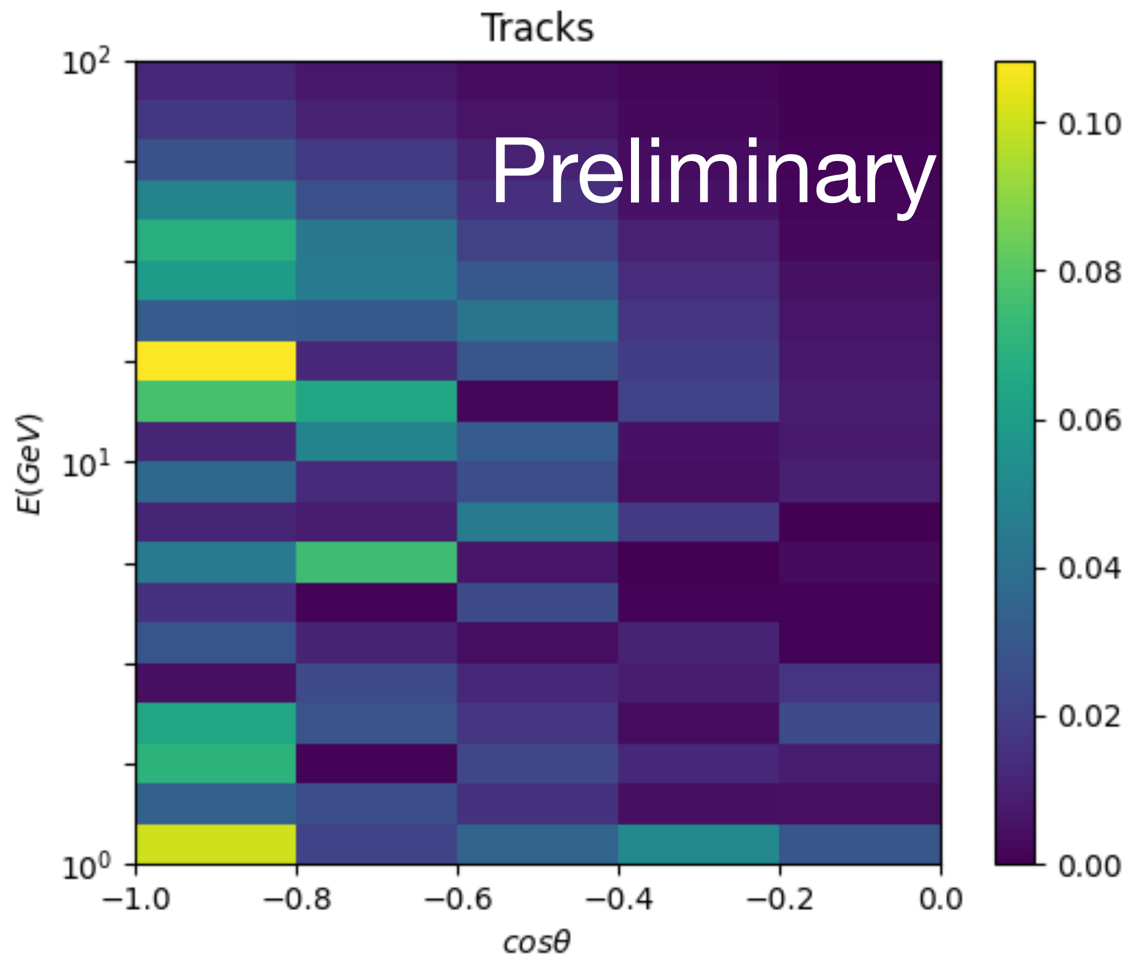
- $\sin^2\theta_{13}$ = 0.022 (fixed)
- Profiled over δ_{cp}



Combined analysis: mass ordering

- The **sensitivity** to the ordering is dominated by the tracks crossing the core in IC-upgrade around the GeV.
- We expect to reach 5σ by the end of the decade.





- $\sin^2\theta_{13}$ = 0.022 (fixed)
- Profiled over δ_{cp}

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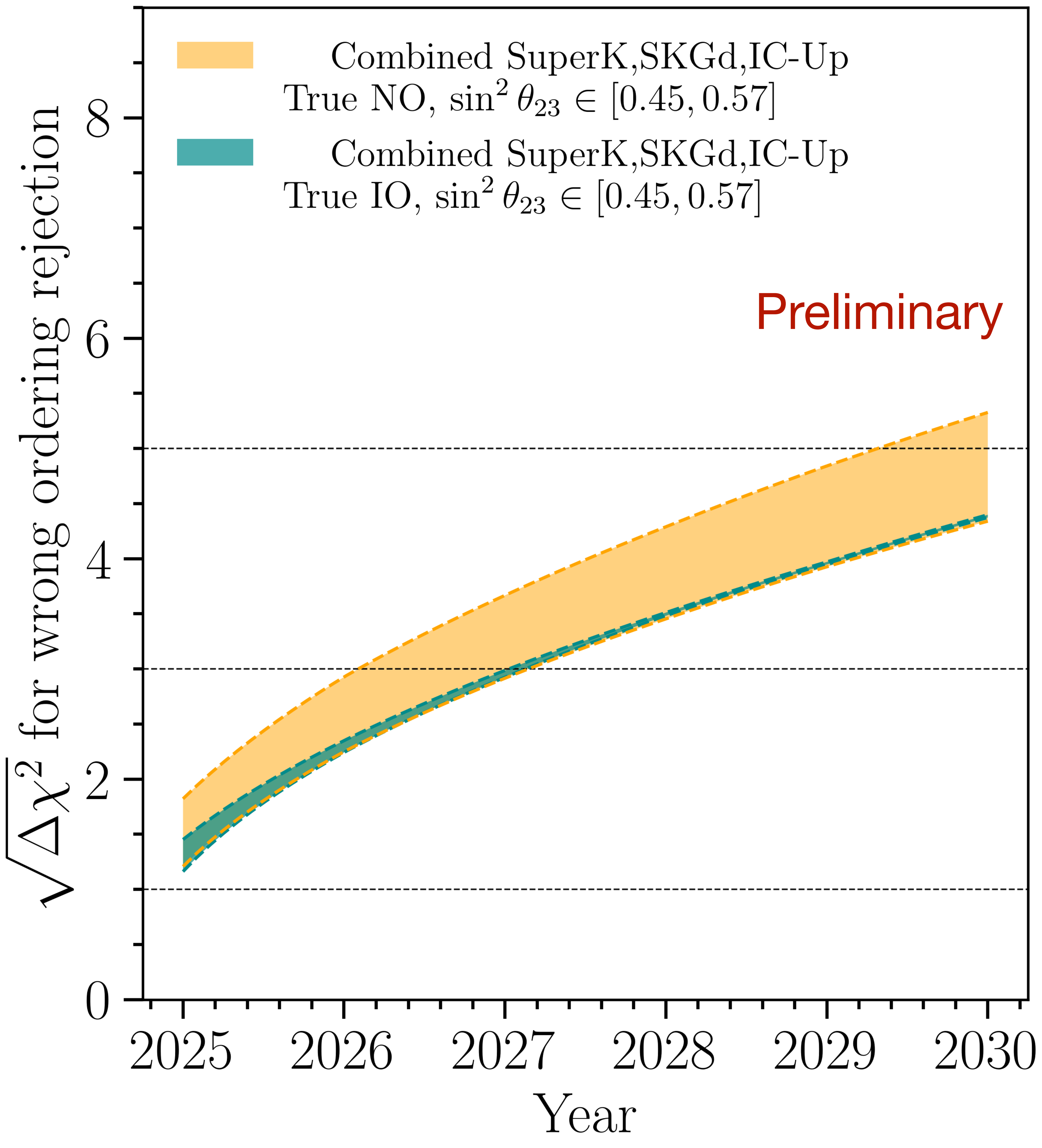
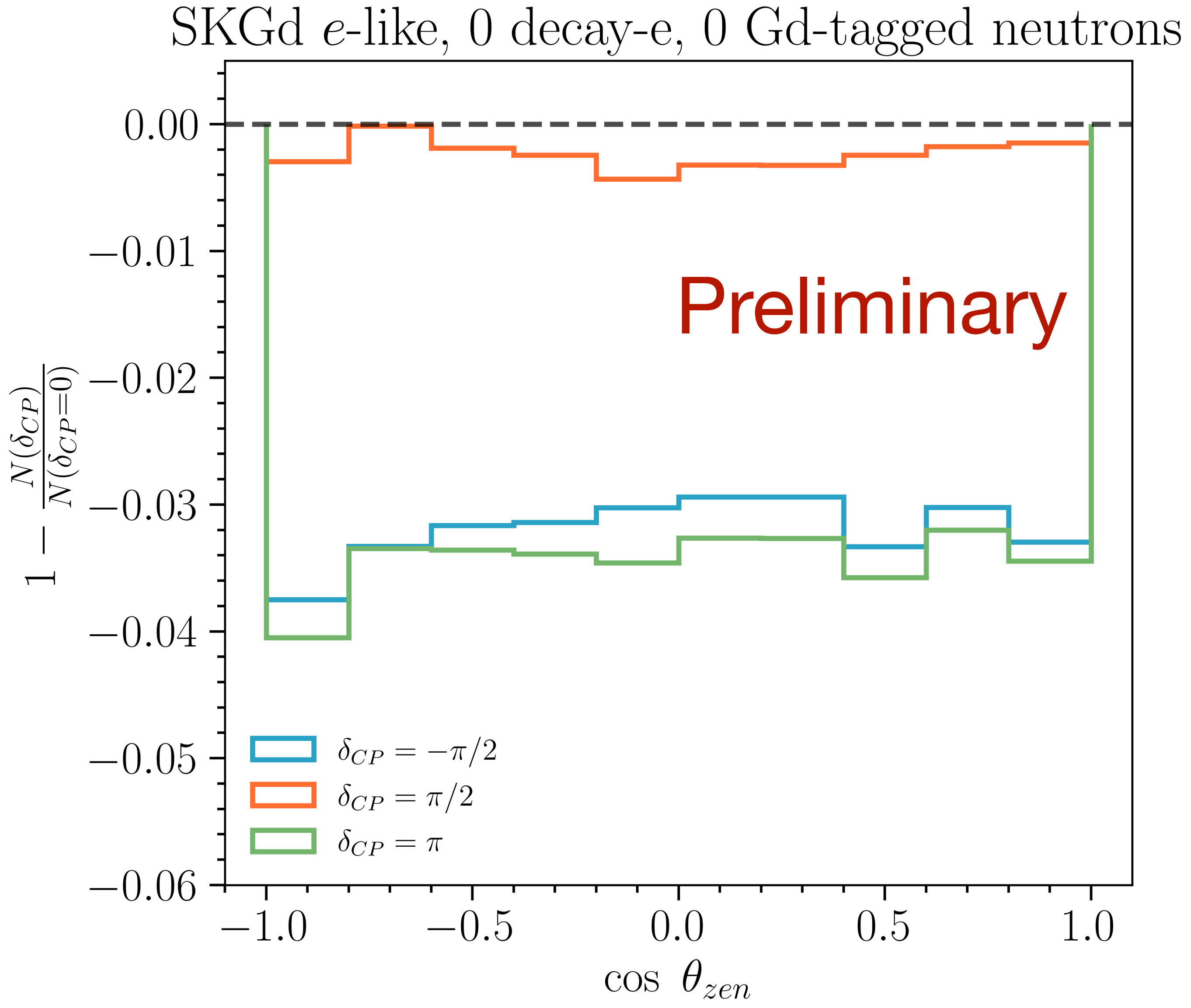
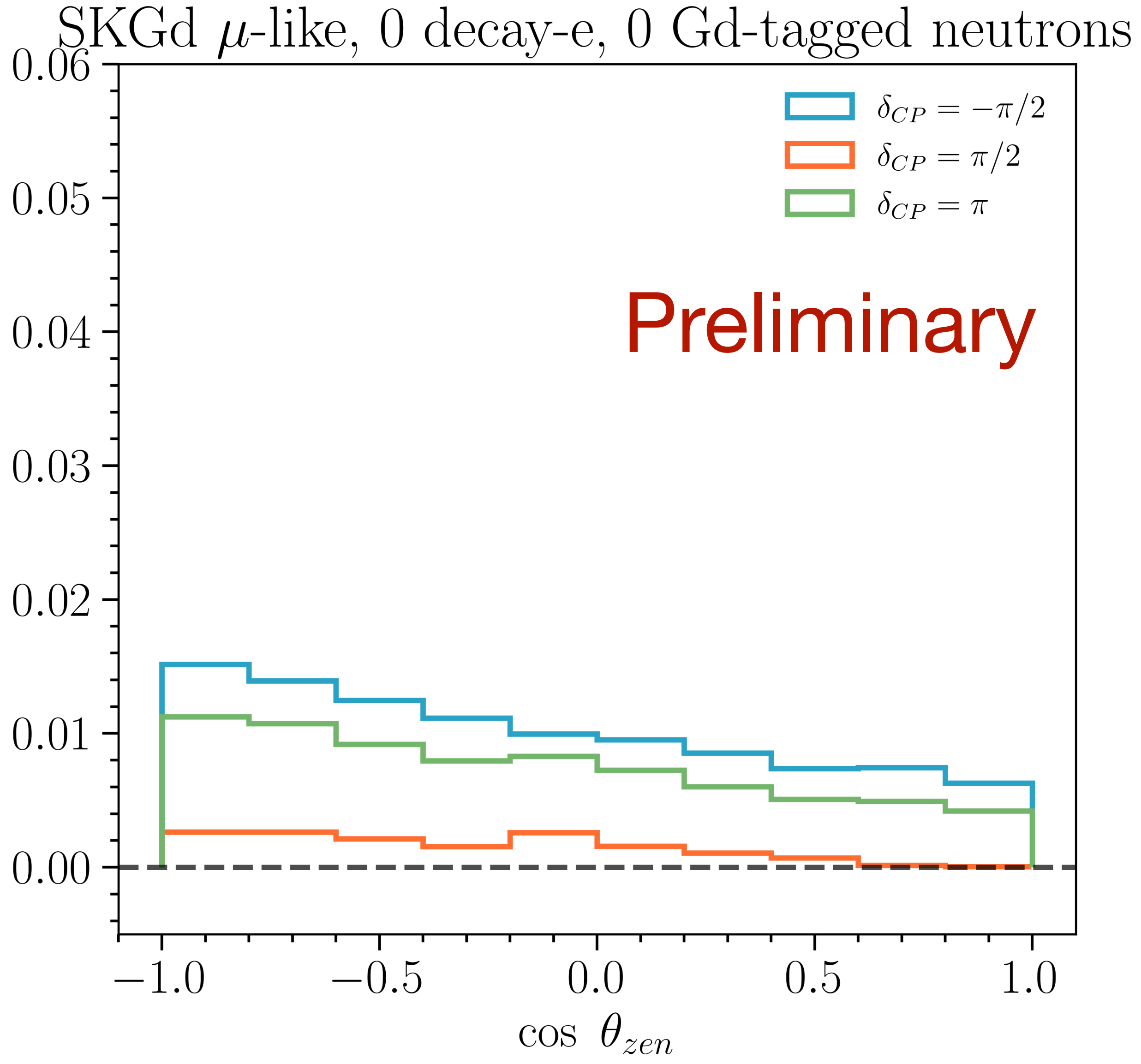


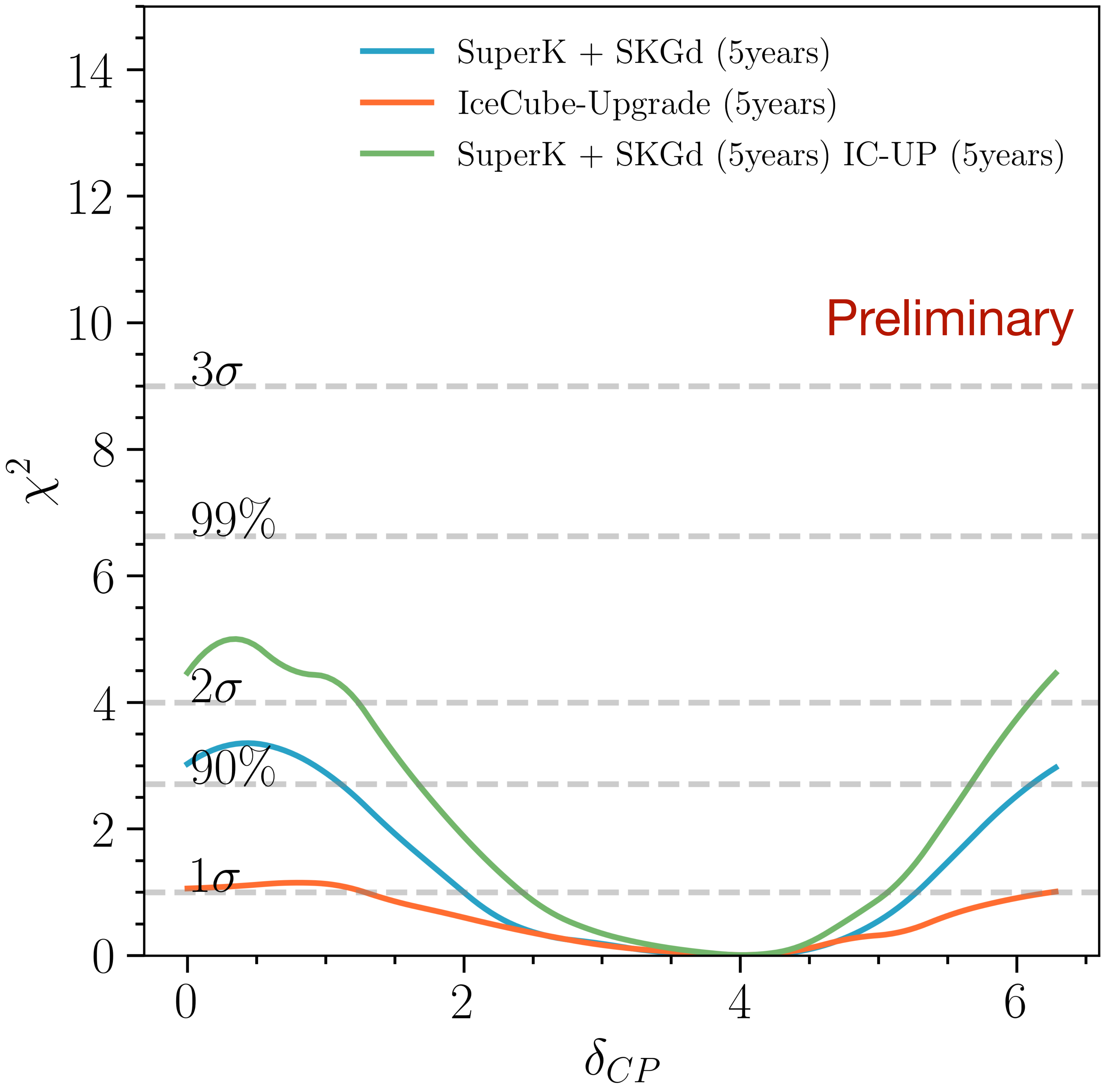
Combined analysis: δ_{cp}

The sensitivity to δ_{cp} is dominated by Super-Kamiokande

- The samples that dominate the sensitivity are the e-like and μ-like with no neutron tagged
- We can get a sensitivity larger than 2σ by the end of the decade using just atmospheric neutrinos.







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Systematic impact

What systematic has a larger impact? By the moment, we have studied the systematics related to the flux

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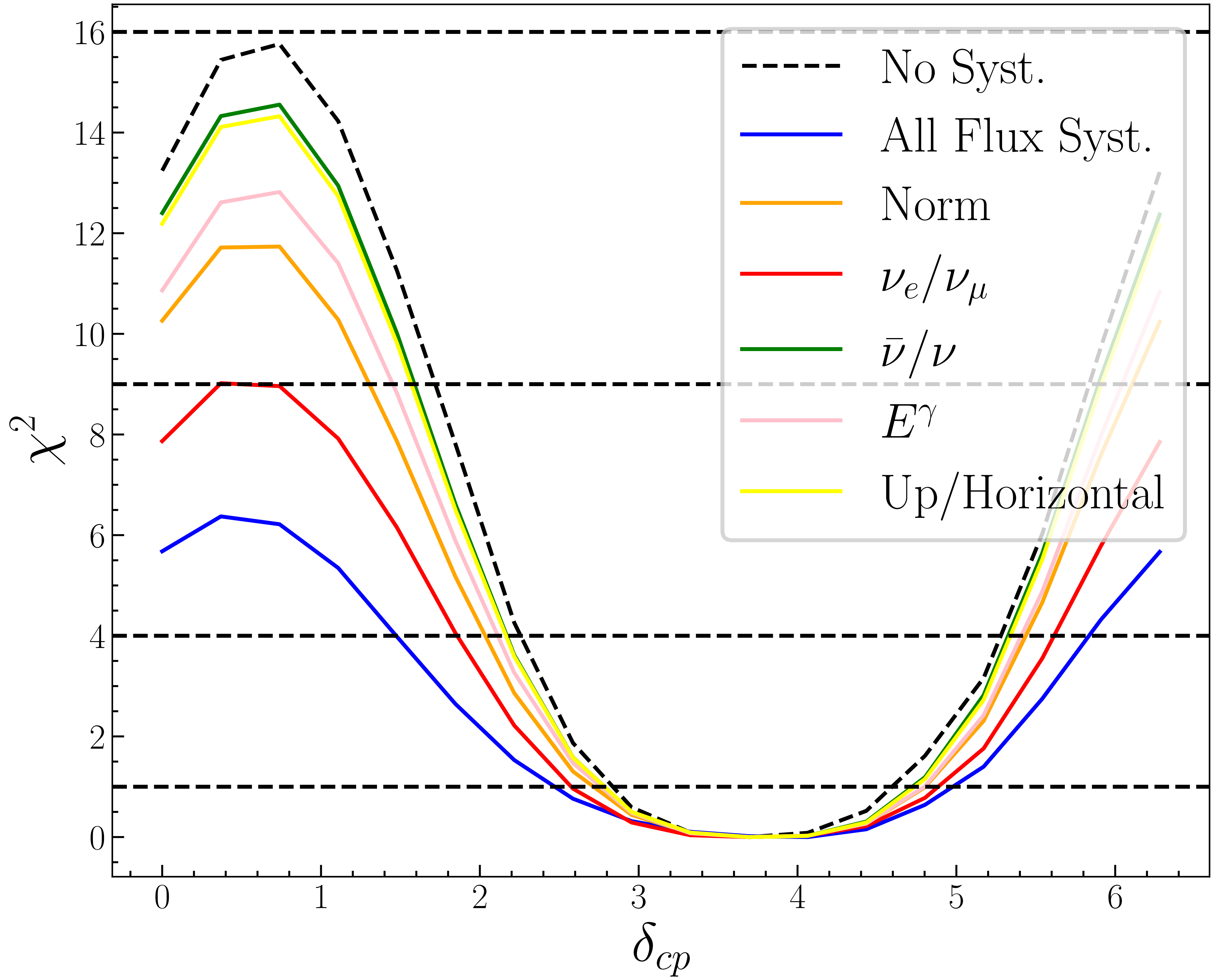
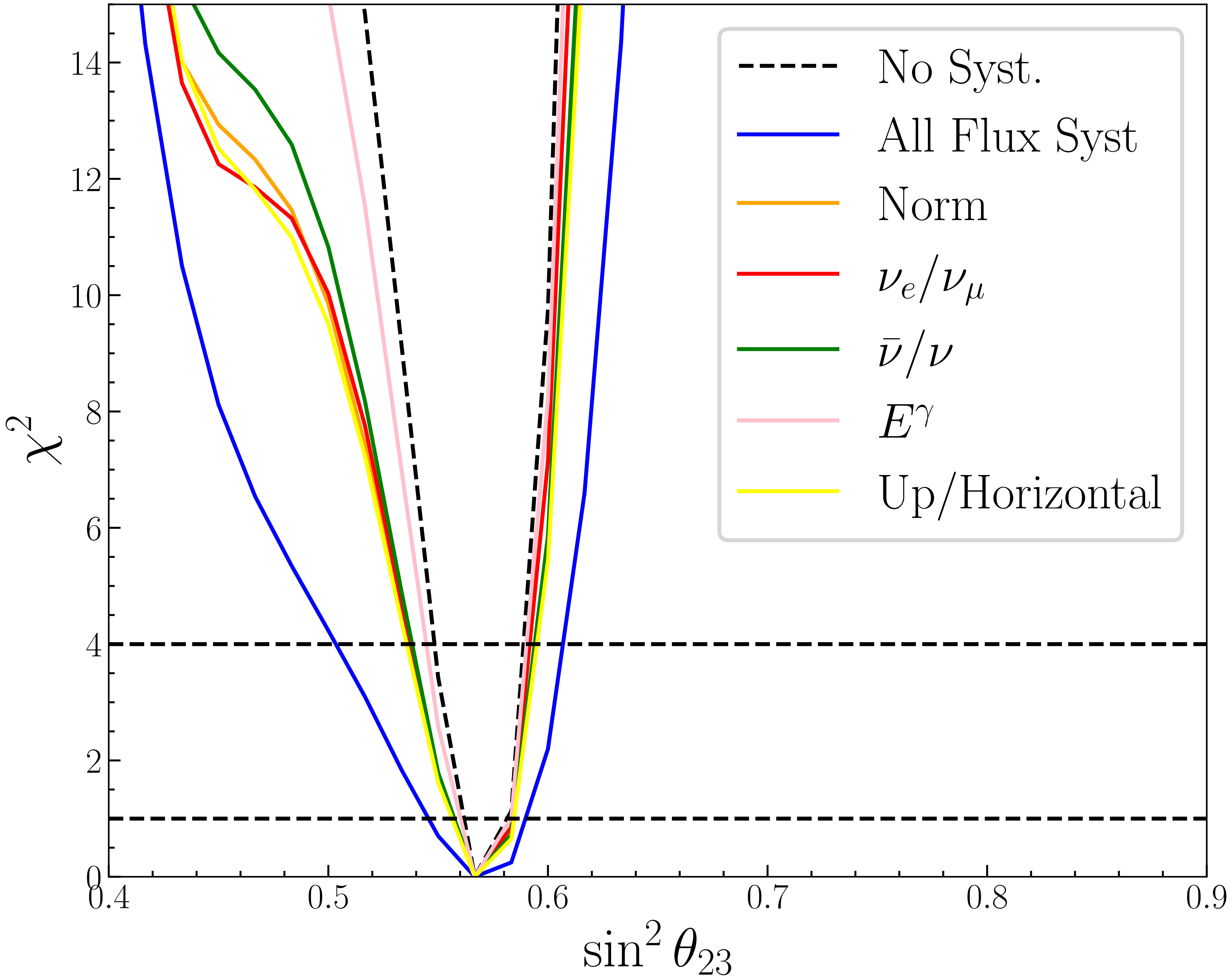
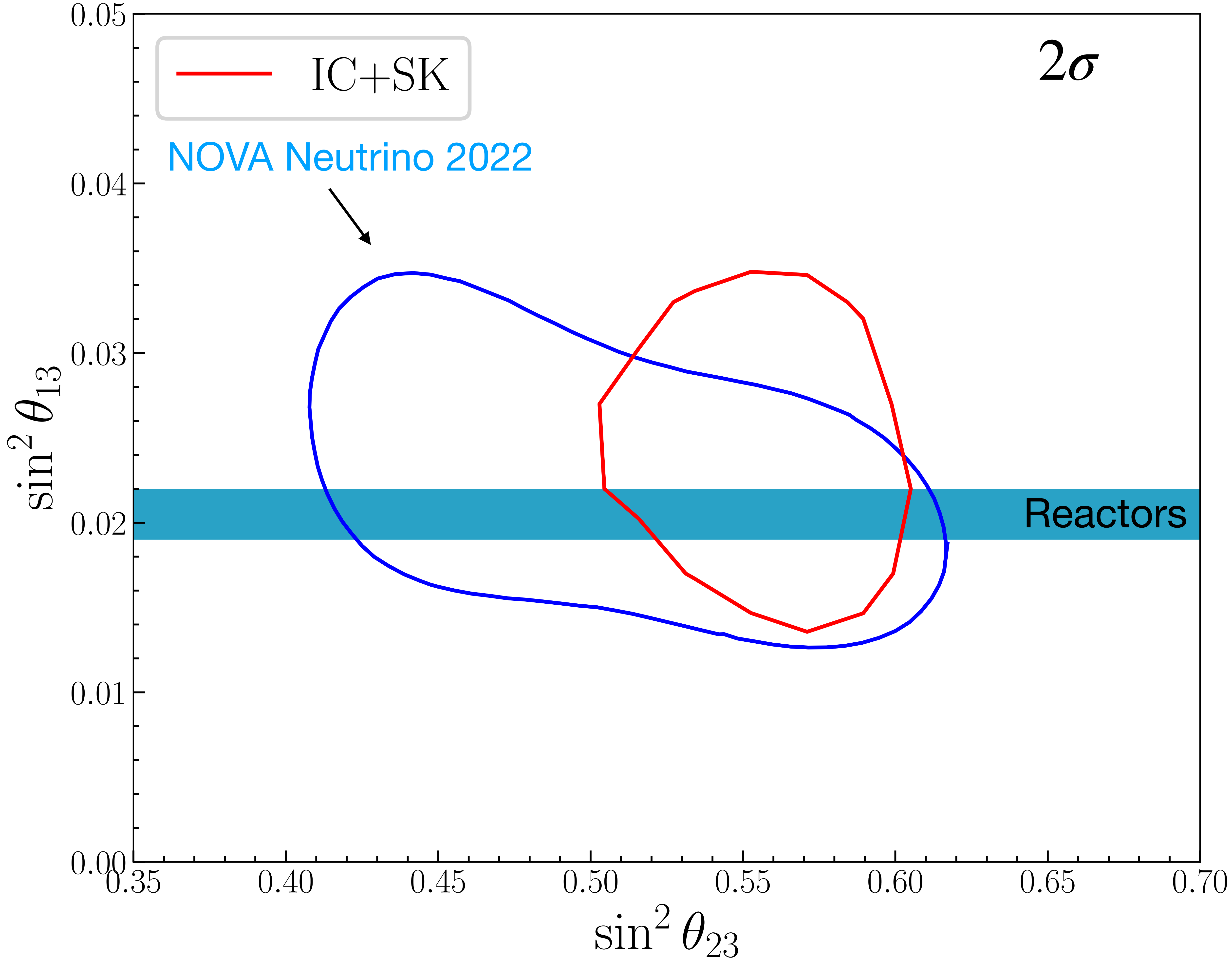




Bonus: sensitivity over θ_{13}

The measurement of the atmospheric resonance also gives us a sensitivity to $\sin^2\theta_{13}$



ORCA will improve the precision

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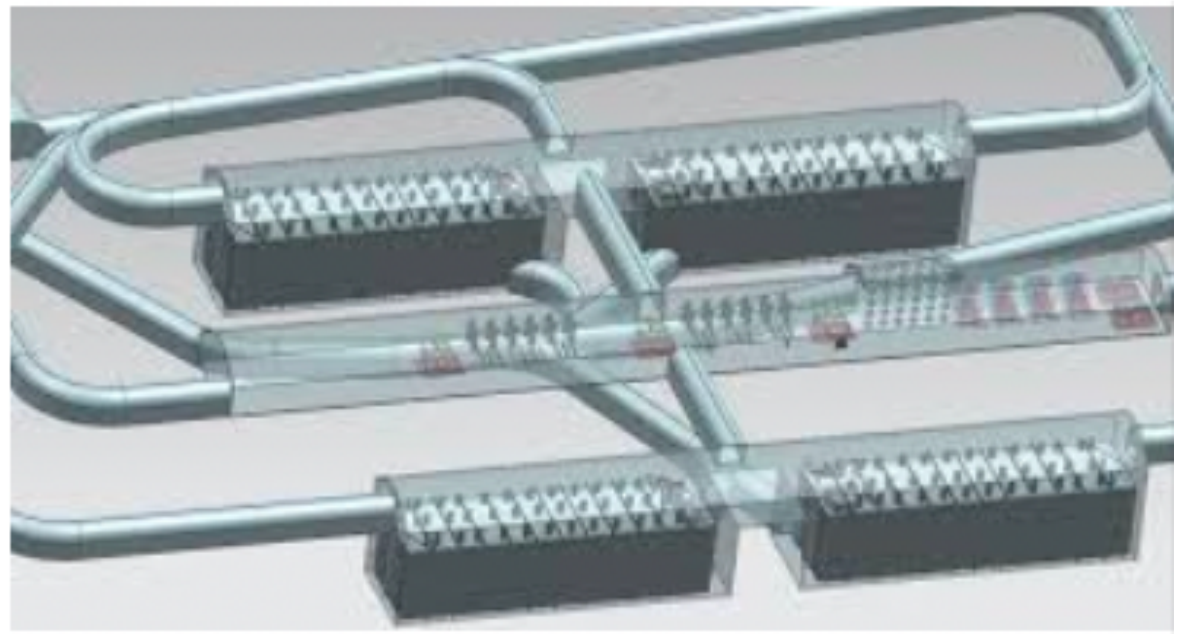
Next-generation of experiments: DUNE

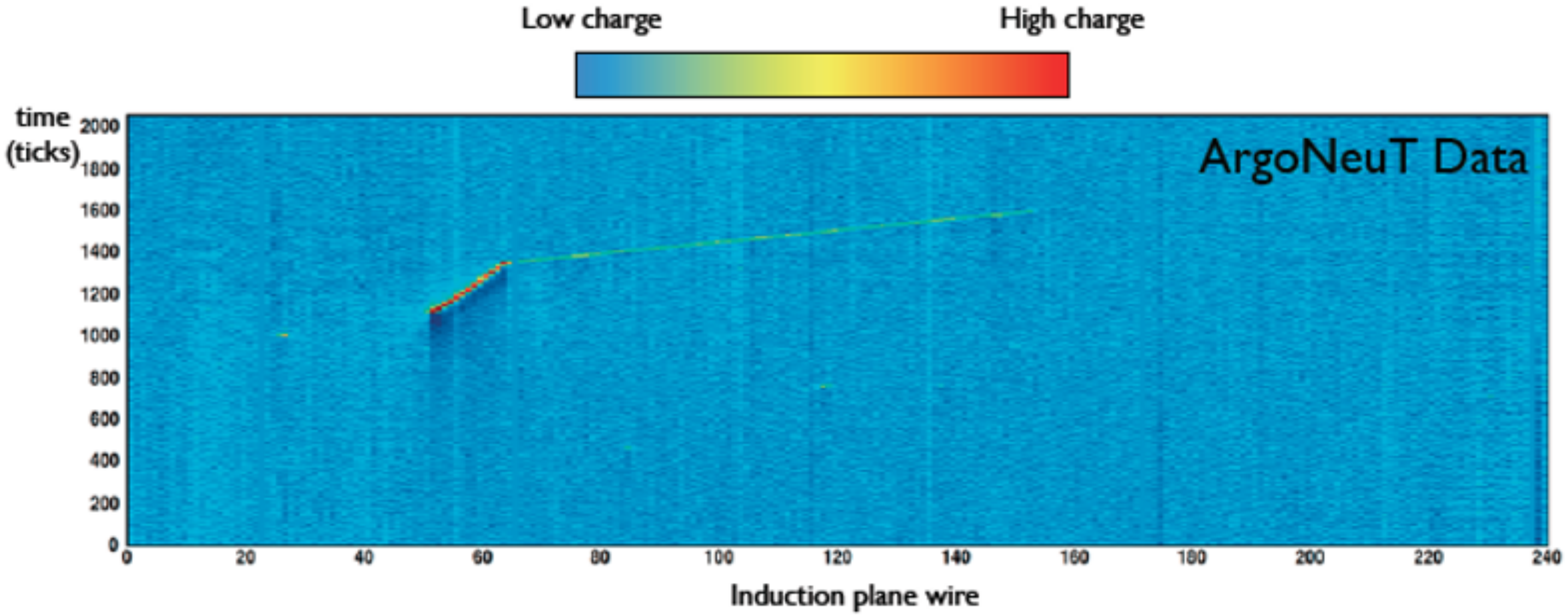
Next generation experiments: DUNE



LArTPCs:

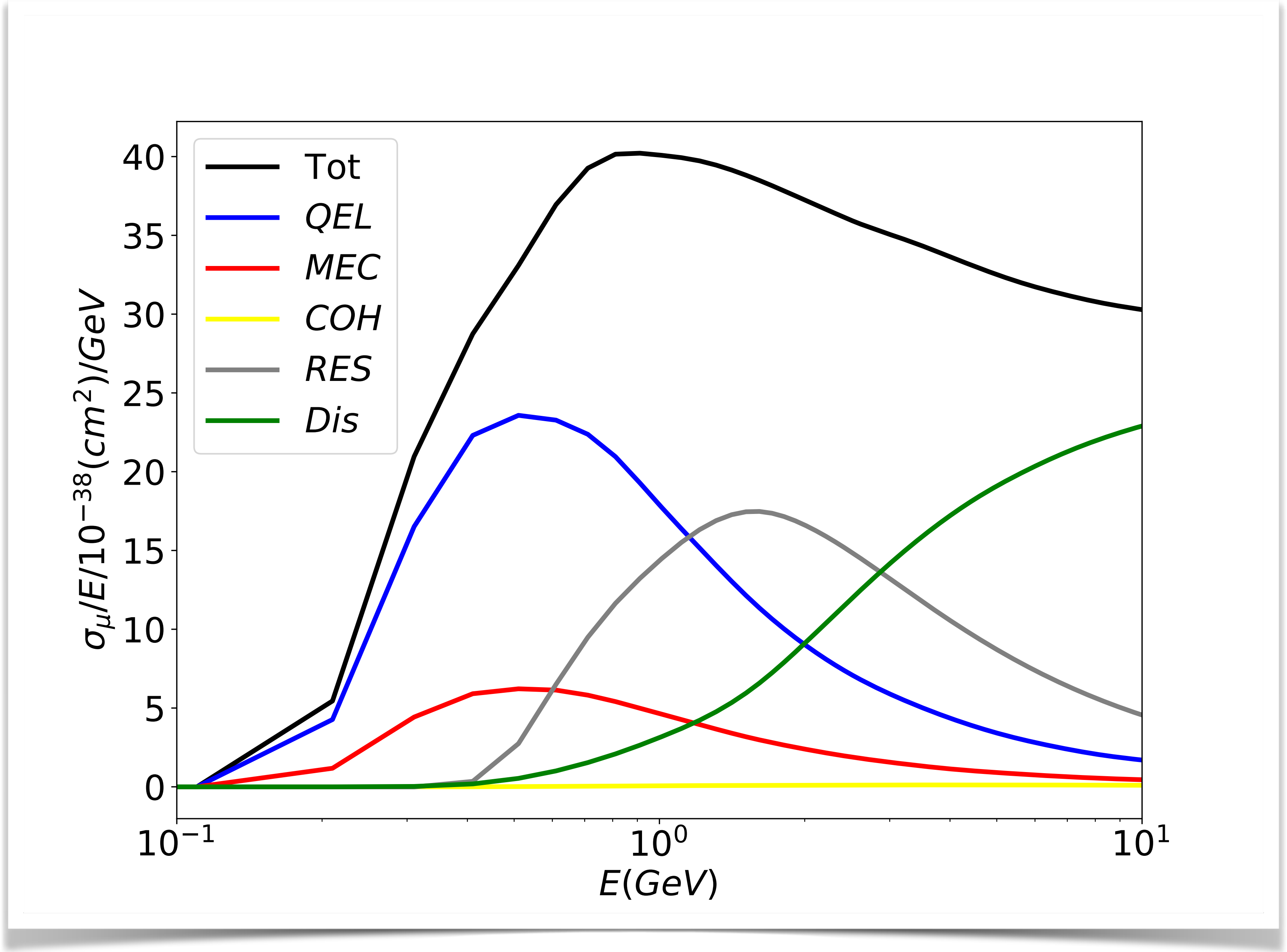
- Excellent capabilities to **identify charged particles**.
- Precise measurement of the **energy and the direction** of low-energy charged particles
- Neutrino energy and direction are reconstructed from the event topology.

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



Next generation experiments: DUNE

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



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

$\bar{\nu}$ dominated → CC-0p0π

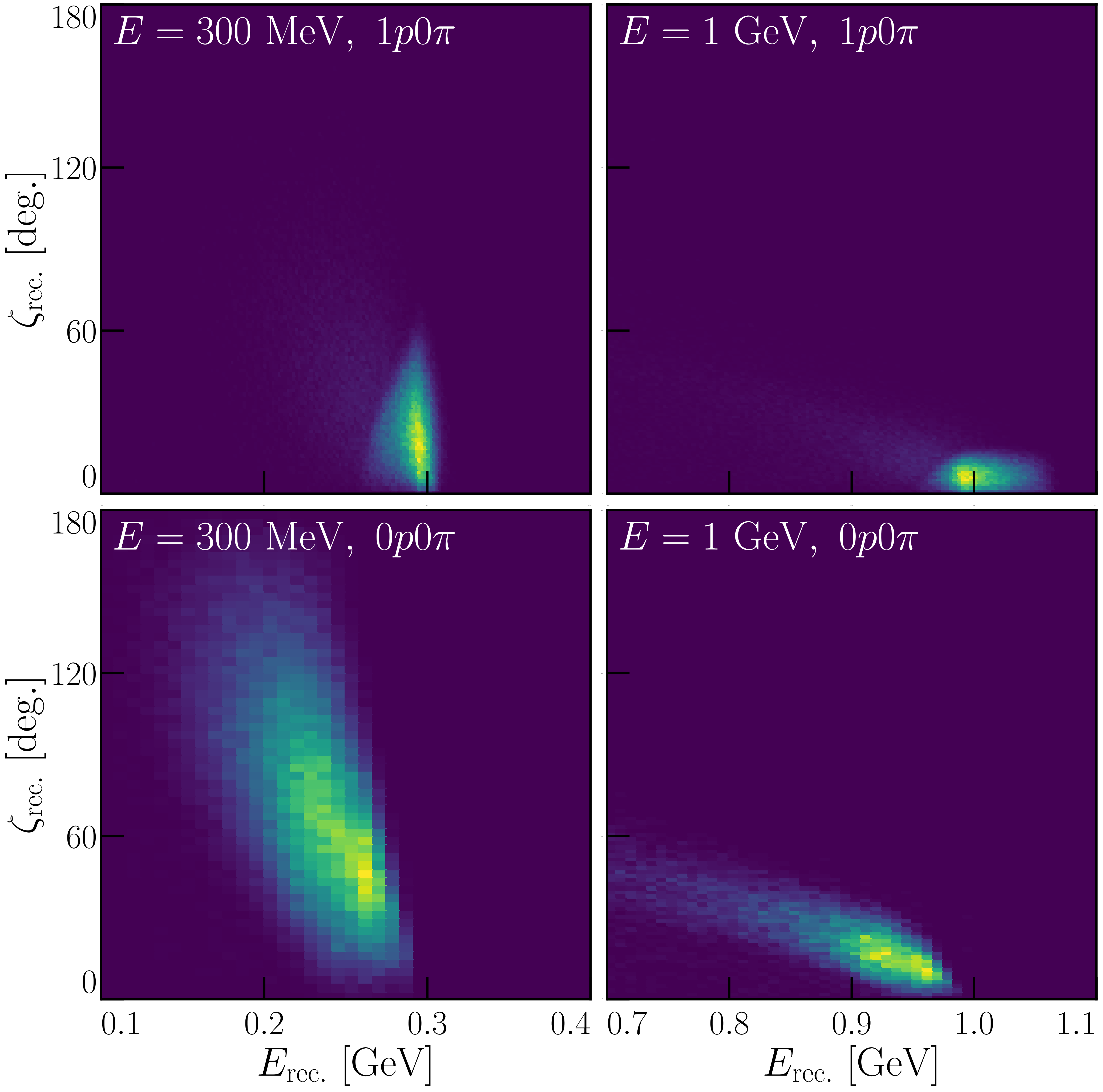
ν dominated → CC-1p0π

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

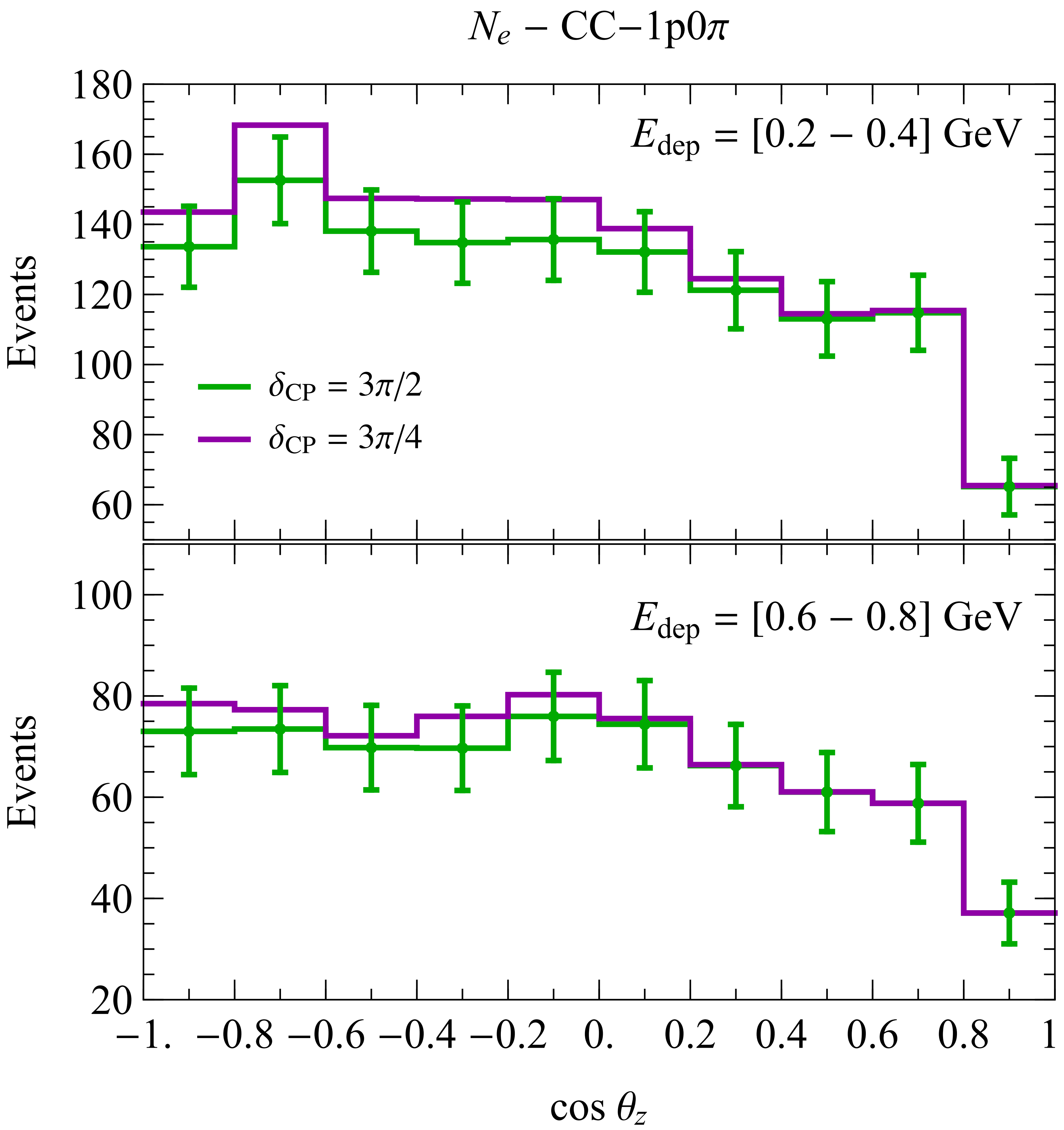
	K.E.	Ang.	E
P	30MeV	10	10%
π	30MeV	10	10%
Λ	30MeV	10	10%
$\mu^{\pm}$	5MeV	2	5%
e	10MeV	2	5%



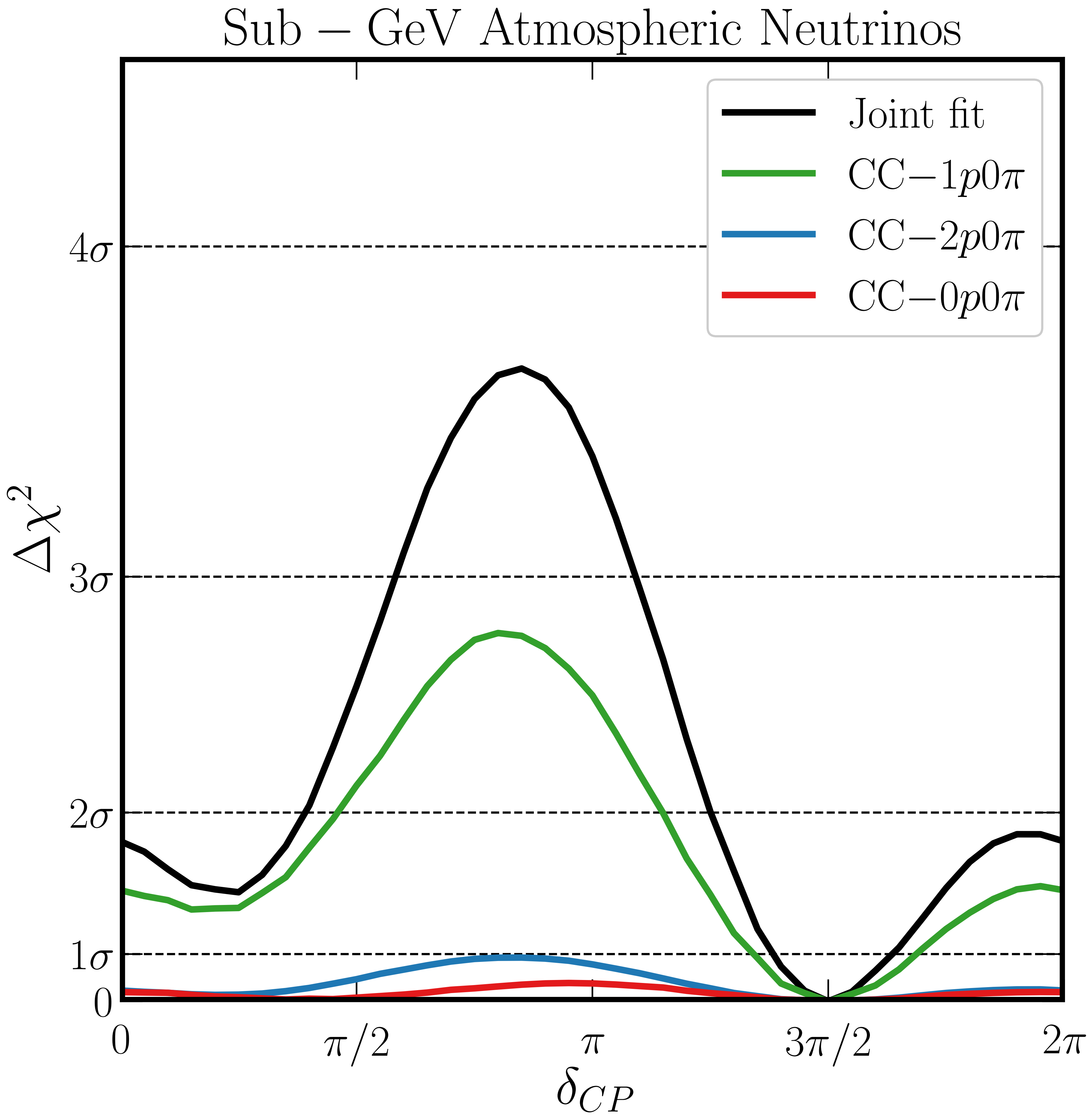
KJ.K, P.A.N.M, I. Martinez-Soler, S.J.P Y.F.P-G, Phys.Rev.Lett 123 (2019) 8

DUNE sensitivity

δ_{cp} induces a large deviation in the number of expected events for DUNE



DUNE can exclude some values of δ_{cp} to more than 3σ



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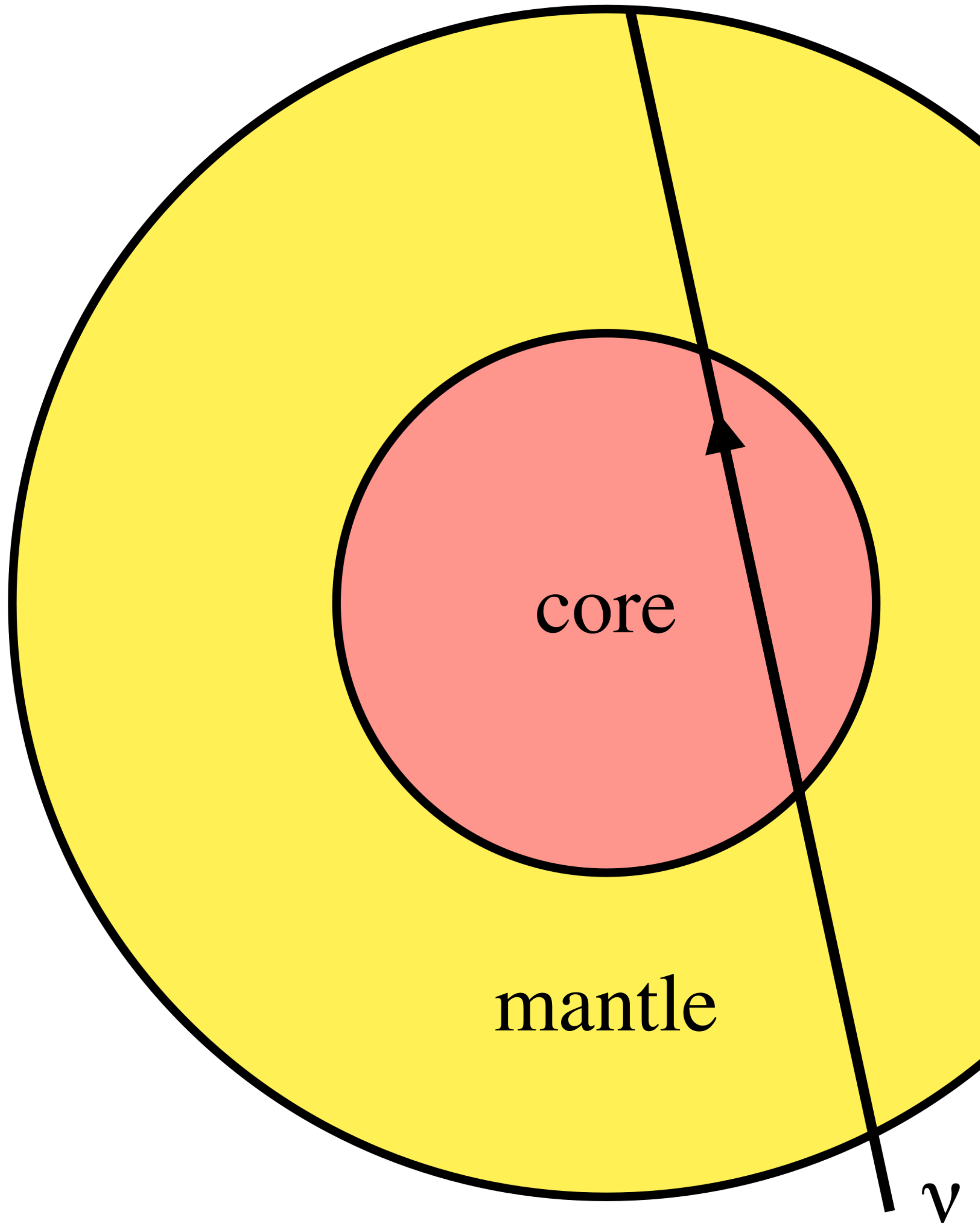
Tomography

Parametric resonance



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

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

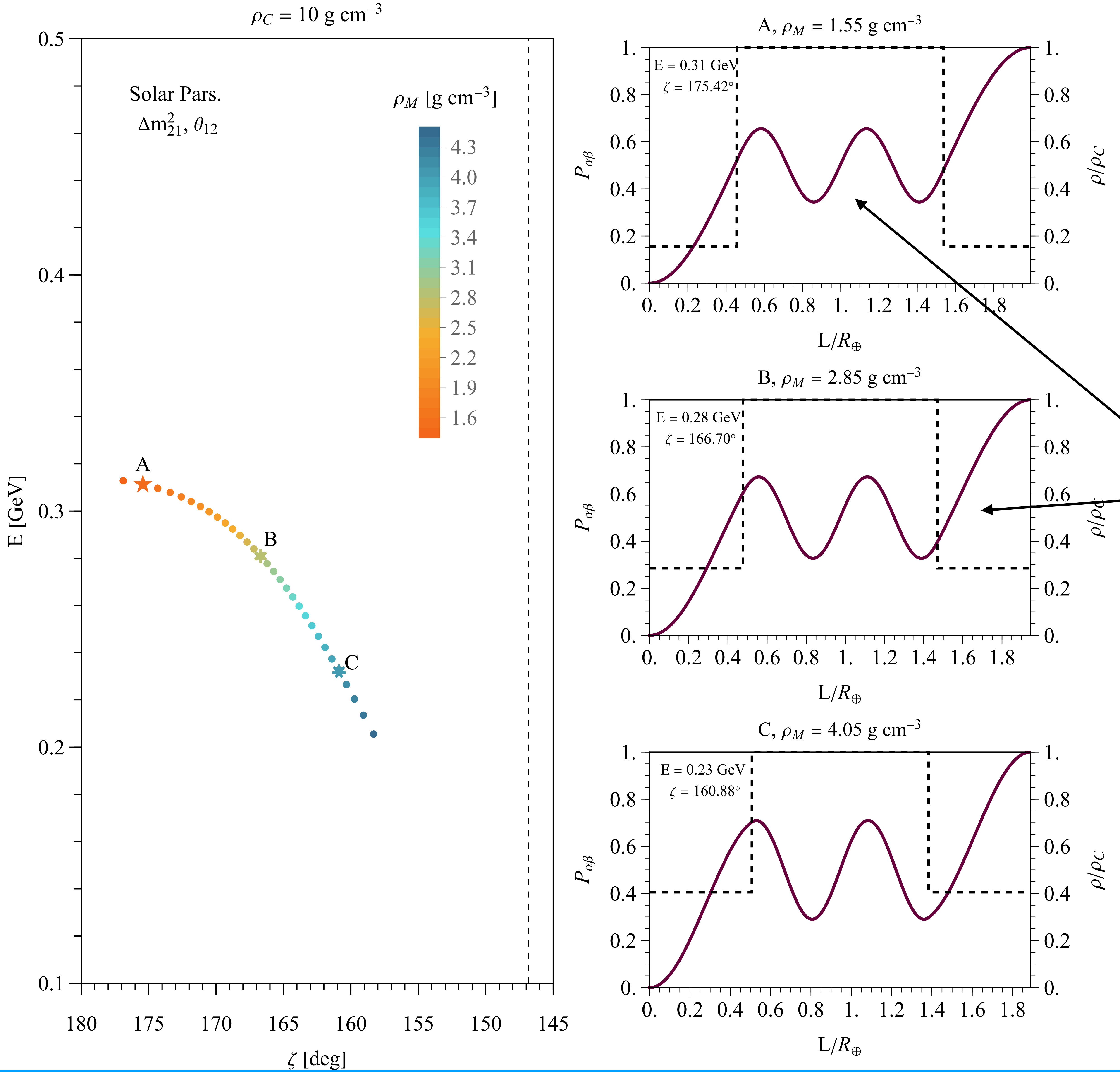
$$\vec{n}_x = (\sin 2\theta_x, 0, -\cos 2\theta_x)$$

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

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

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

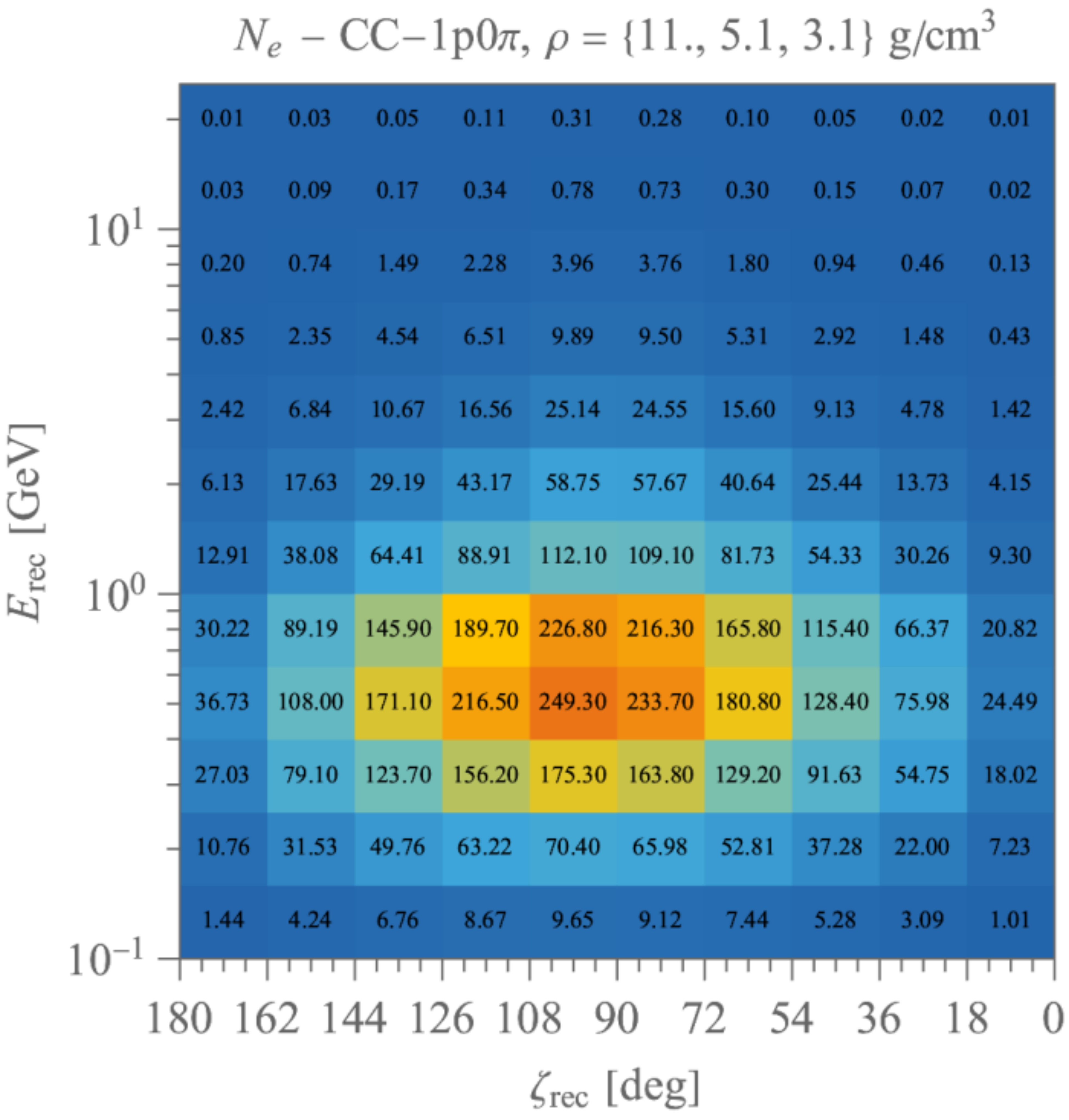
$$\cos 2\theta_c \leq 0, \cos 2(2\theta_M - \theta_c) \geq 0$$

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

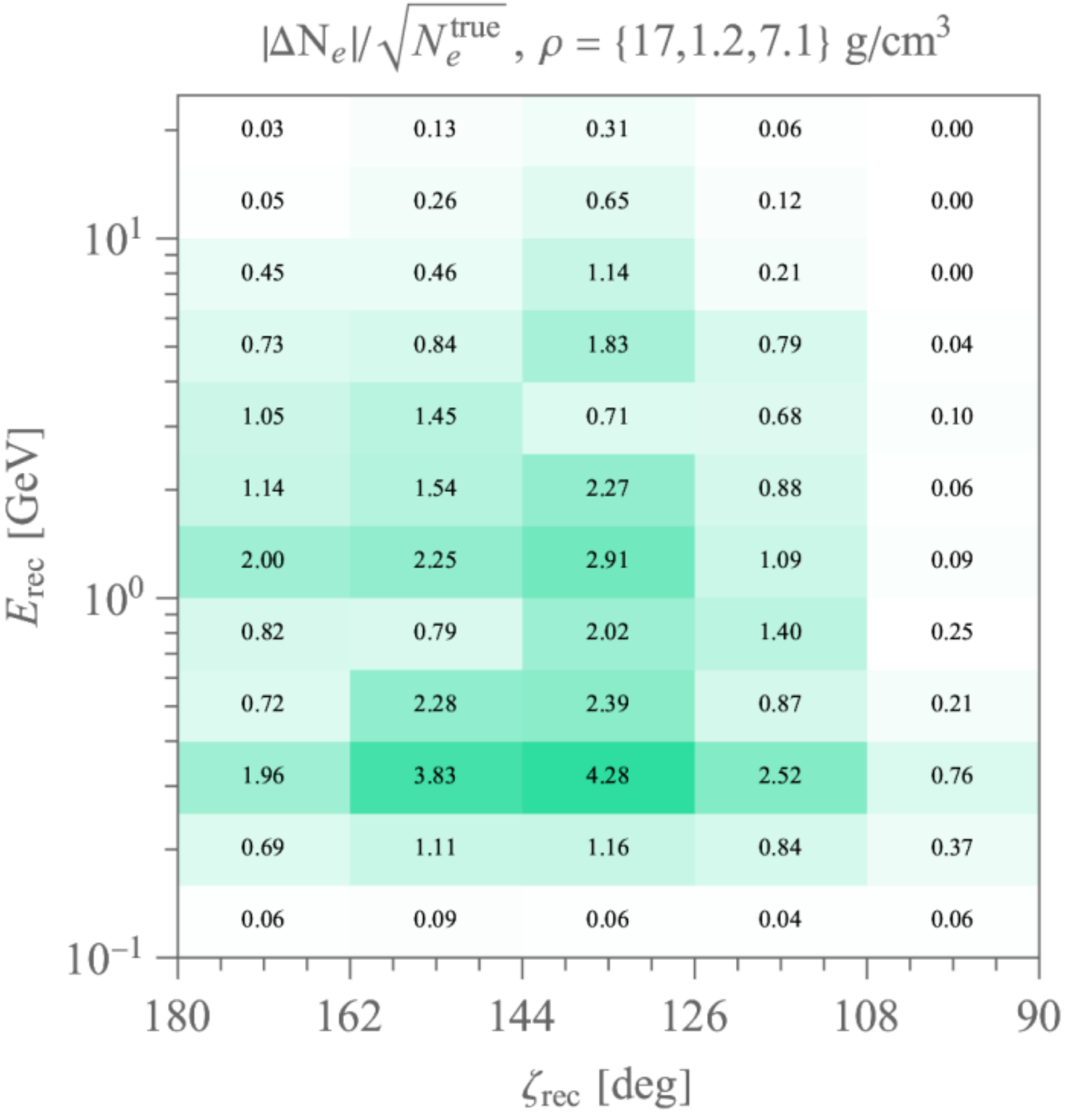
KJ.K, P.A.N.M, I. Martinez-Soler, Y.F.P-G, accepted in JHEP

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



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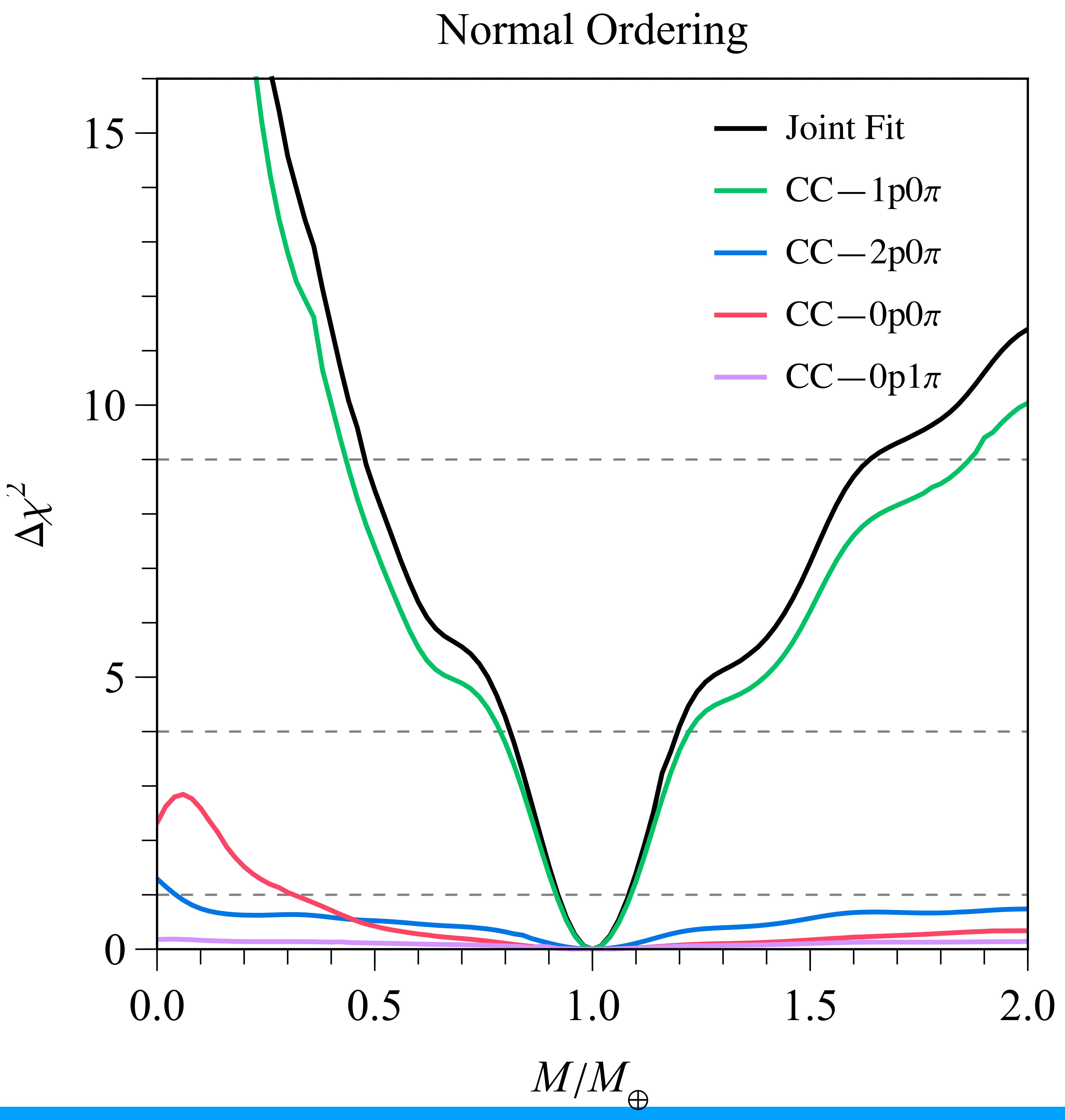
Overall Earth Mass Measurement



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

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Impact of mixing parameters

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

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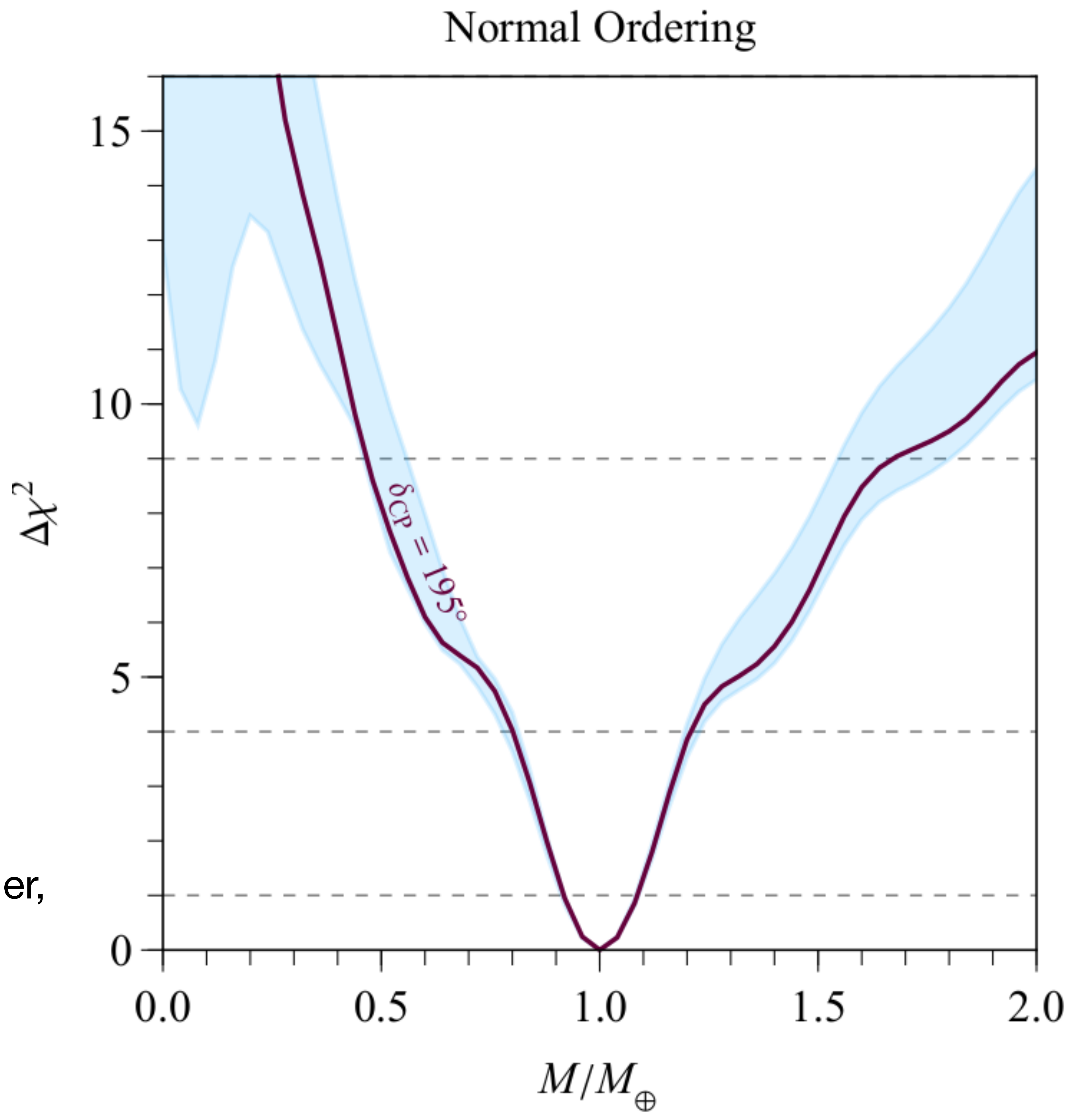
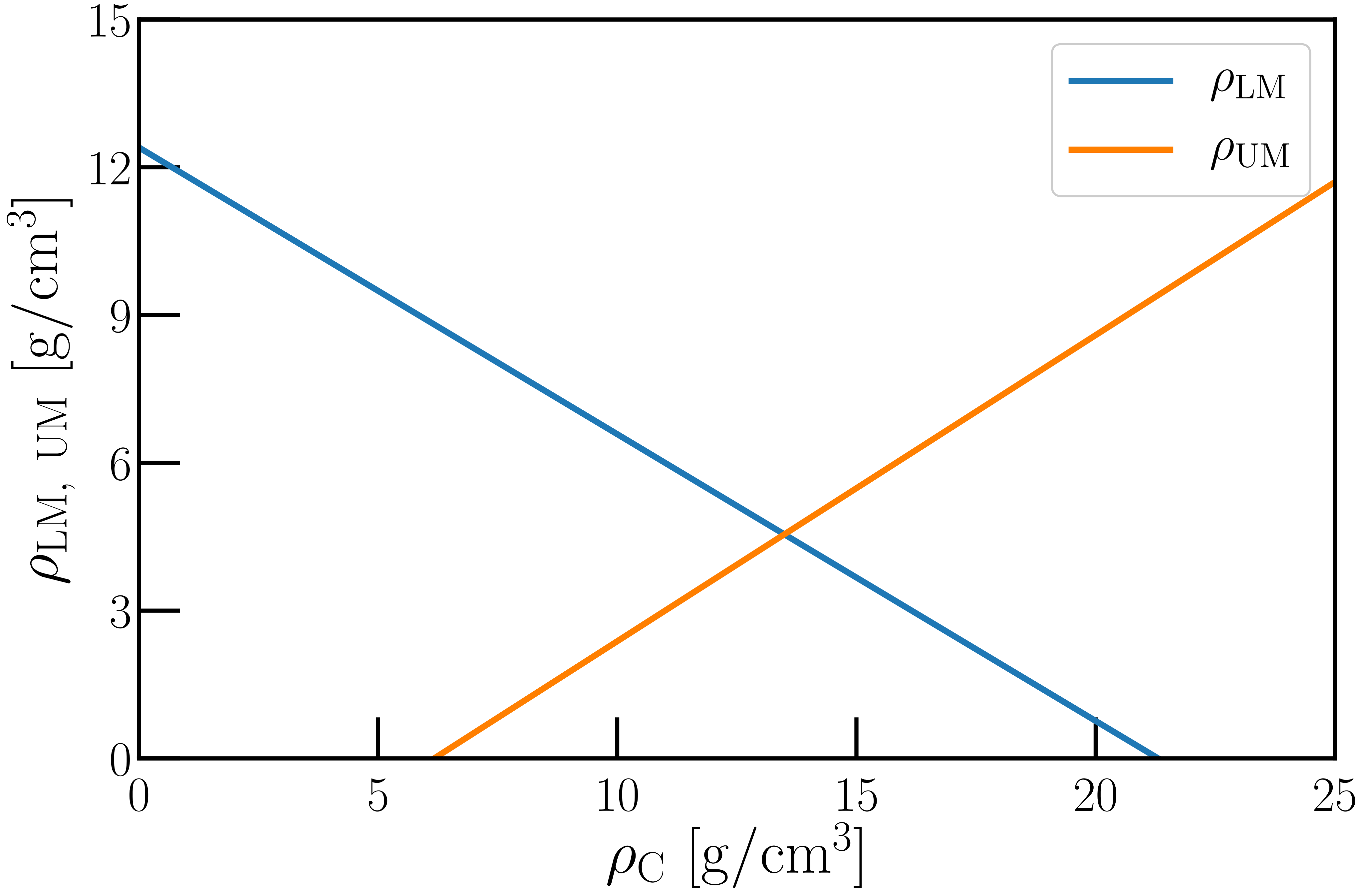


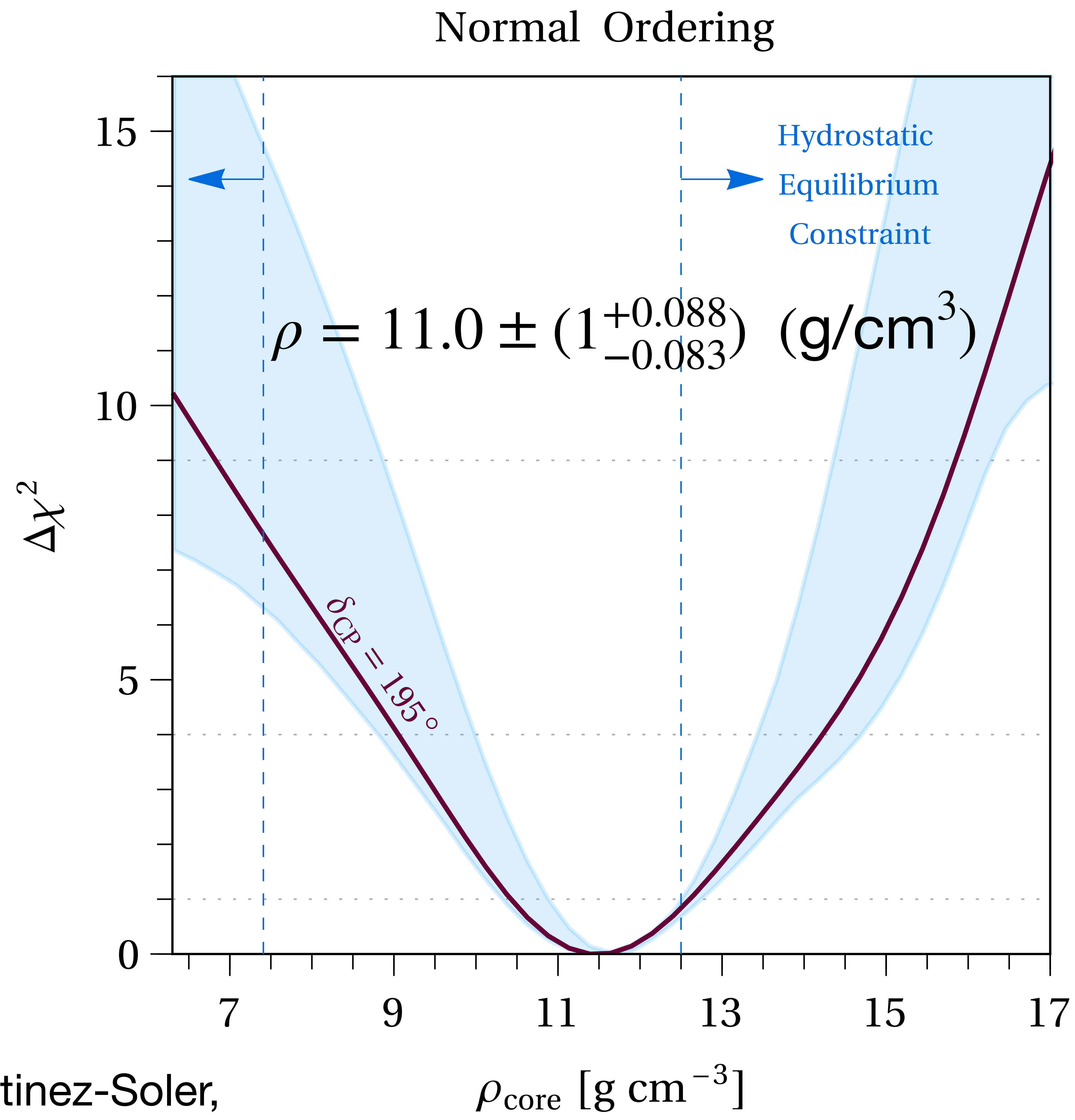
Sensitivity to the Earth's core

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

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

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





$\rho = 11.0 \pm (1^{+0.088}_{-0.083})$ (g/cm^3)

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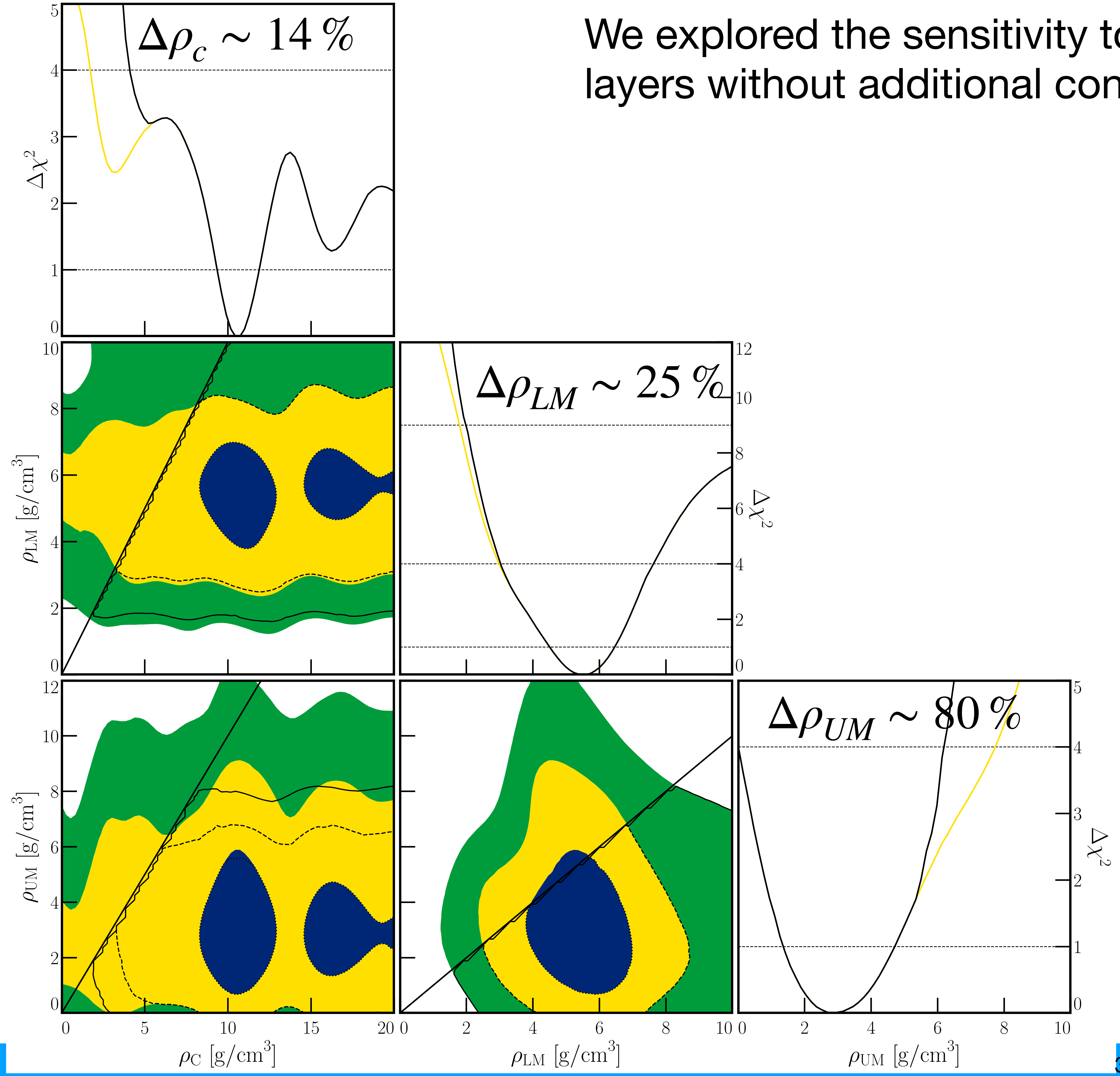
Earth’s matter profile without constraints



We explored the sensitivity to the three layers without additional constraints

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

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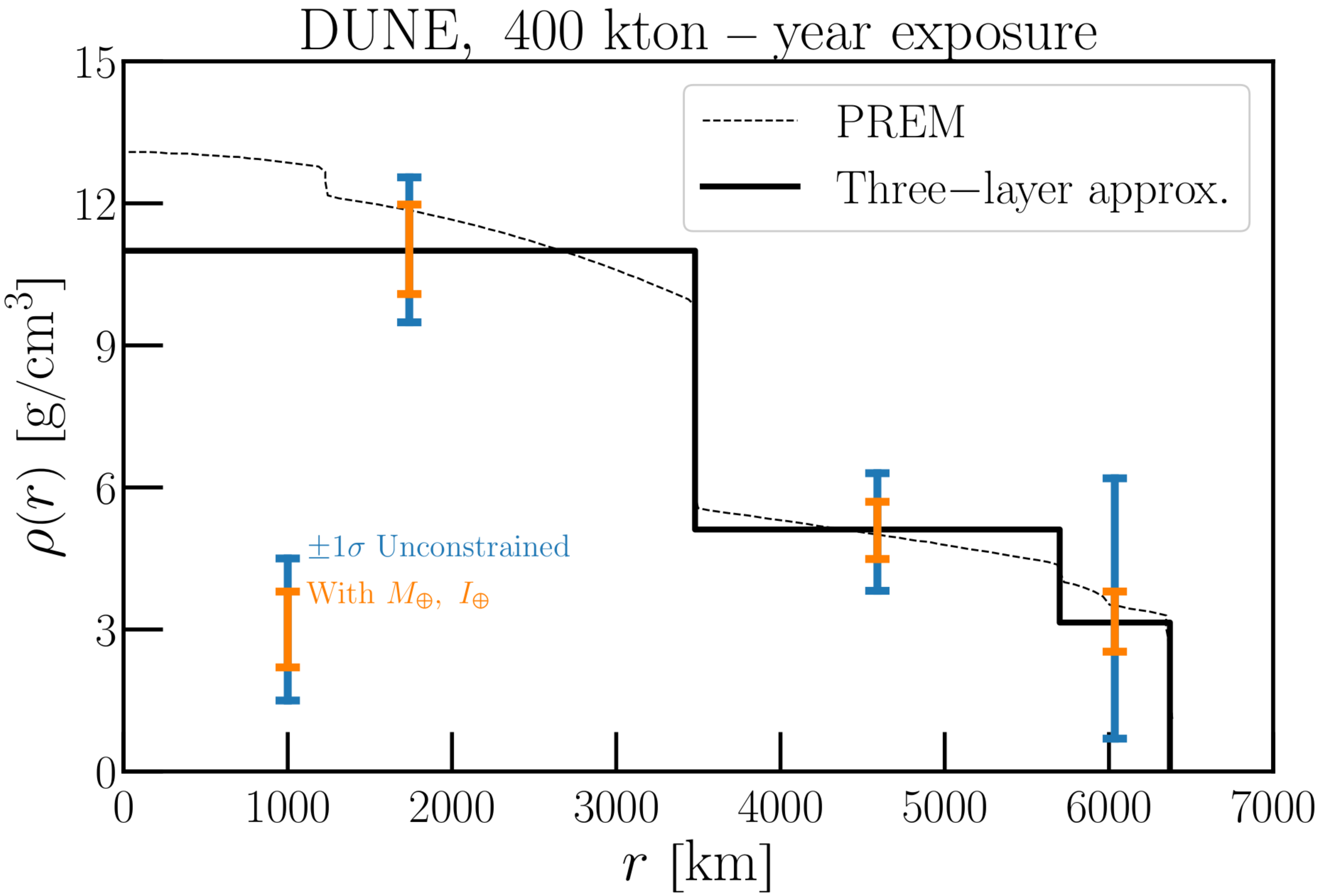
Earth’s matter profile sensitivity



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** are a unique source for exploring the **neutrino properties.** Also, they can complement **other research areas.**

- By the end of this decade, **atmospheric neutrinos** will contribute to some of the open questions in neutrino physics: the **mass ordering**, the **octant of** θ_{23} , and the **CP-violation phase.**
    - For θ_{23} it is possible to get more than 2σ significance over the octant
    - It is possible to discriminate the mass ordering at 5σ using just atmospheric neutrinos
    - δ_{cp} can be measured at more than 2σ thanks to Super-Kamiokande with Gd

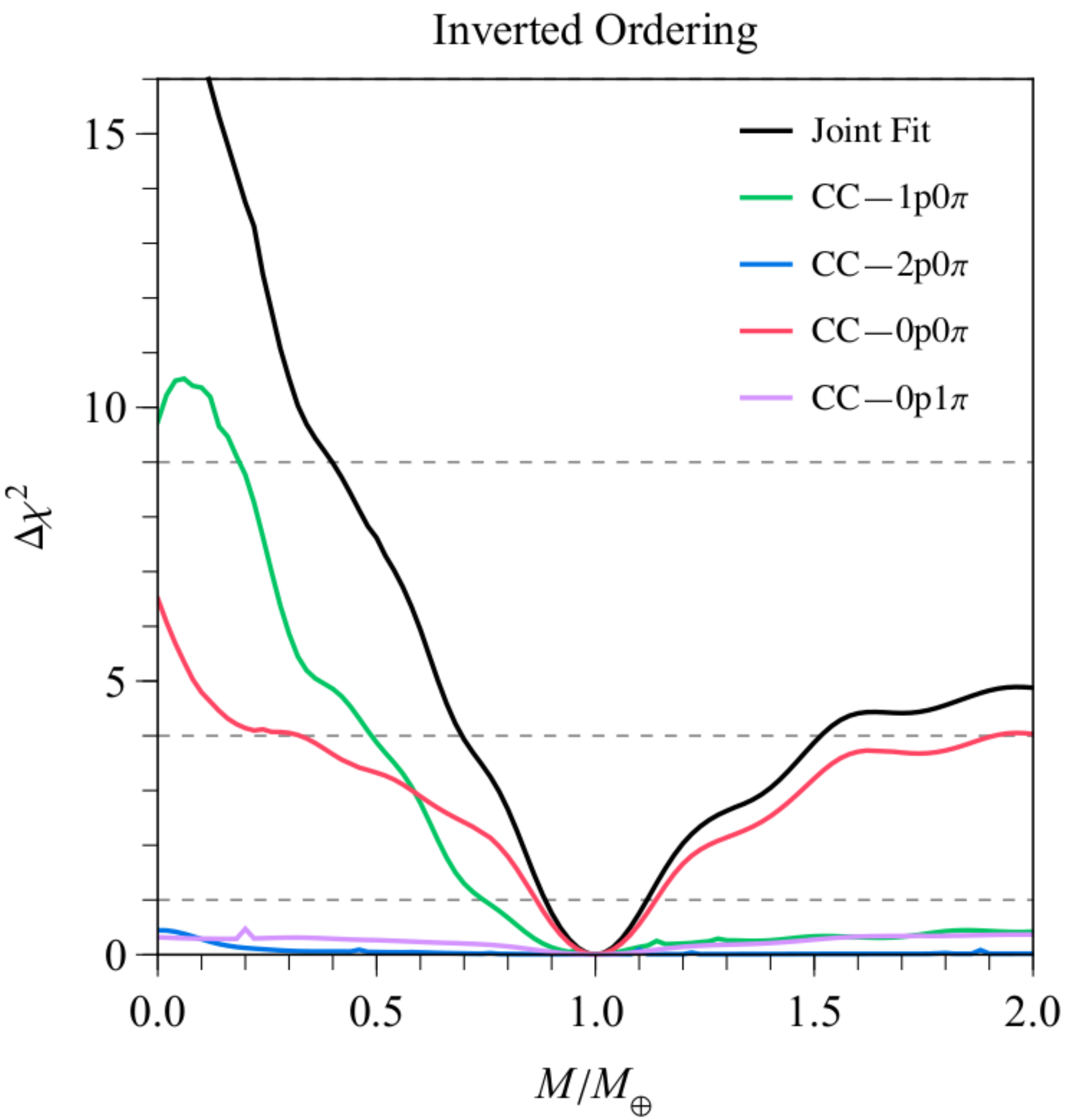
- The next generation of experiments will contribute with a precise measurement of the atmospheric flux. In particular, **DUNE** will be sensitive to some values of δ_{cp} at than 3σ**.**

- The flavor distribution of the atmospheric neutrinos will also help in the determination of the **inner structure of the Earth.**

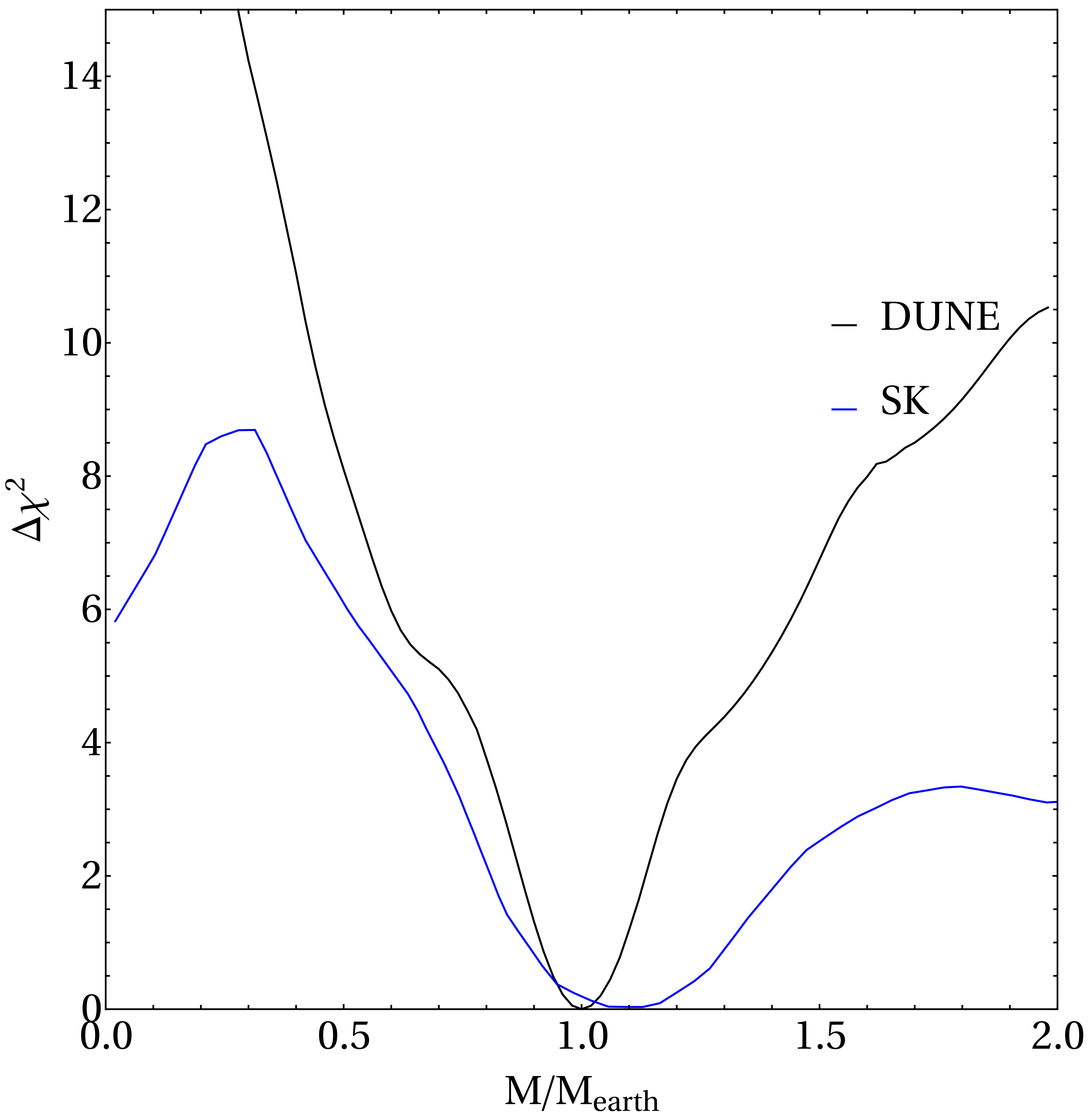
- Neutrino oscillation can provide a good determination of the **core** and the **lower-mantle.**

¡Gracias!

Bakup: Total mass of the Earth and IO



Bakup: Total mass of the Earth and IO



$\Delta M \sim 8.5\,\%$ DUNE

$\Delta M \sim 21\,\%$ SK

SuperKamiokande, Phys.Rev.D97 (2018)

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

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

BAckup: DUNE sensitivity to θ_{23}