CP-violation and the Earth's Interior: Through the Atmospheric Neutrino Looking-Glass

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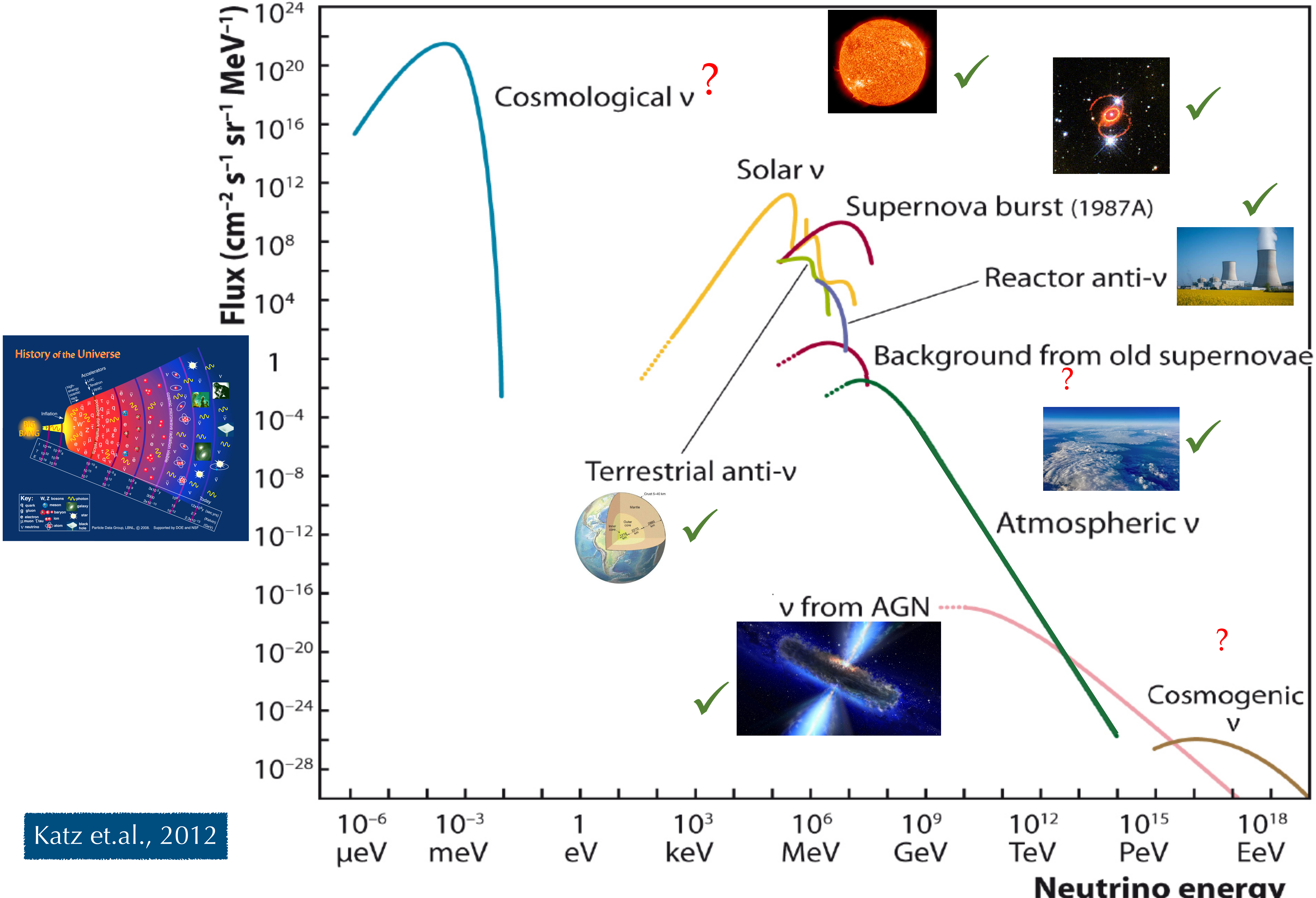
IPPP, Durham U

Opportunities with Atmospheric Neutrinos
Institute of Physics
November 10th, 2021

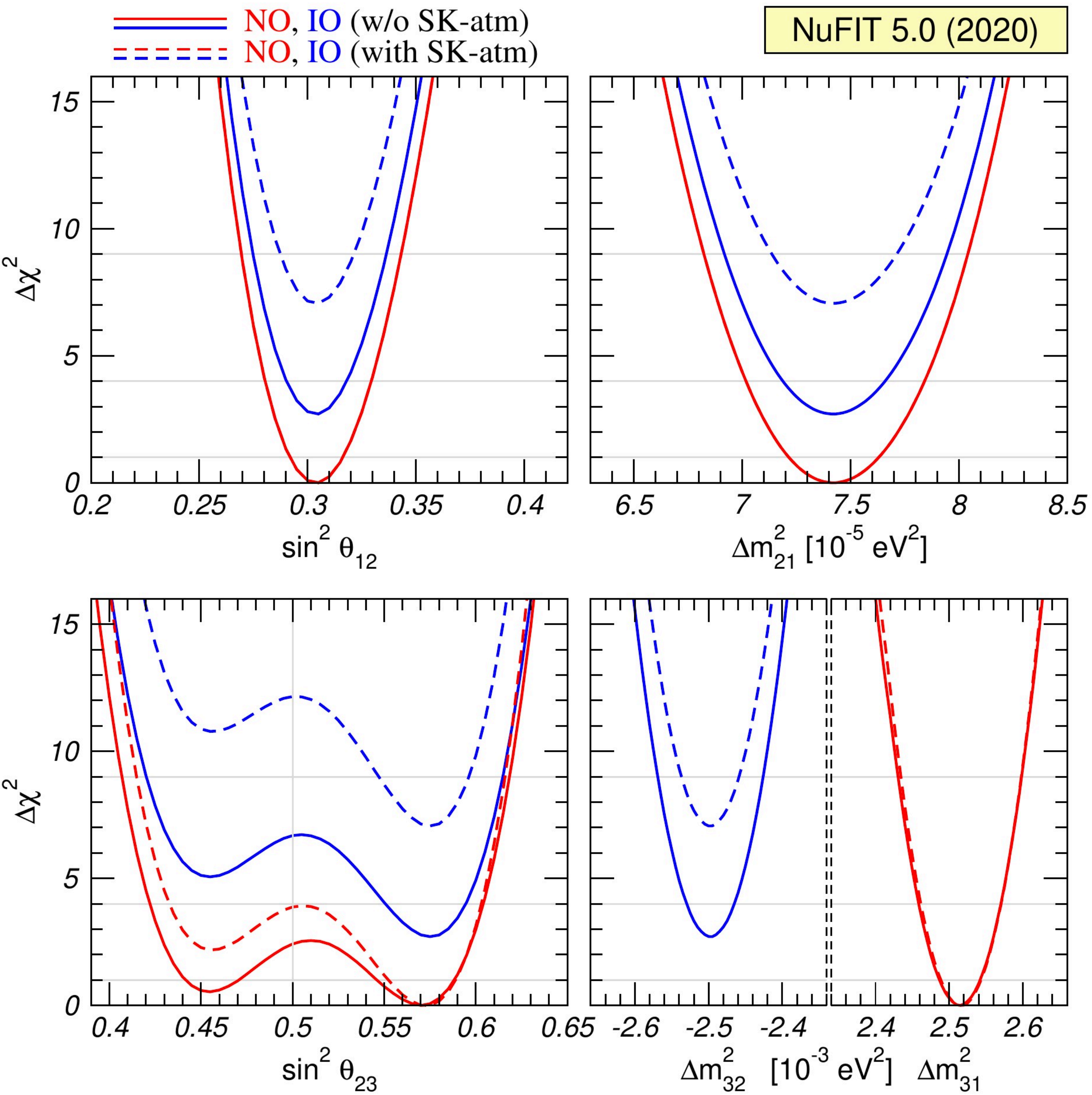
Durham University

IP3



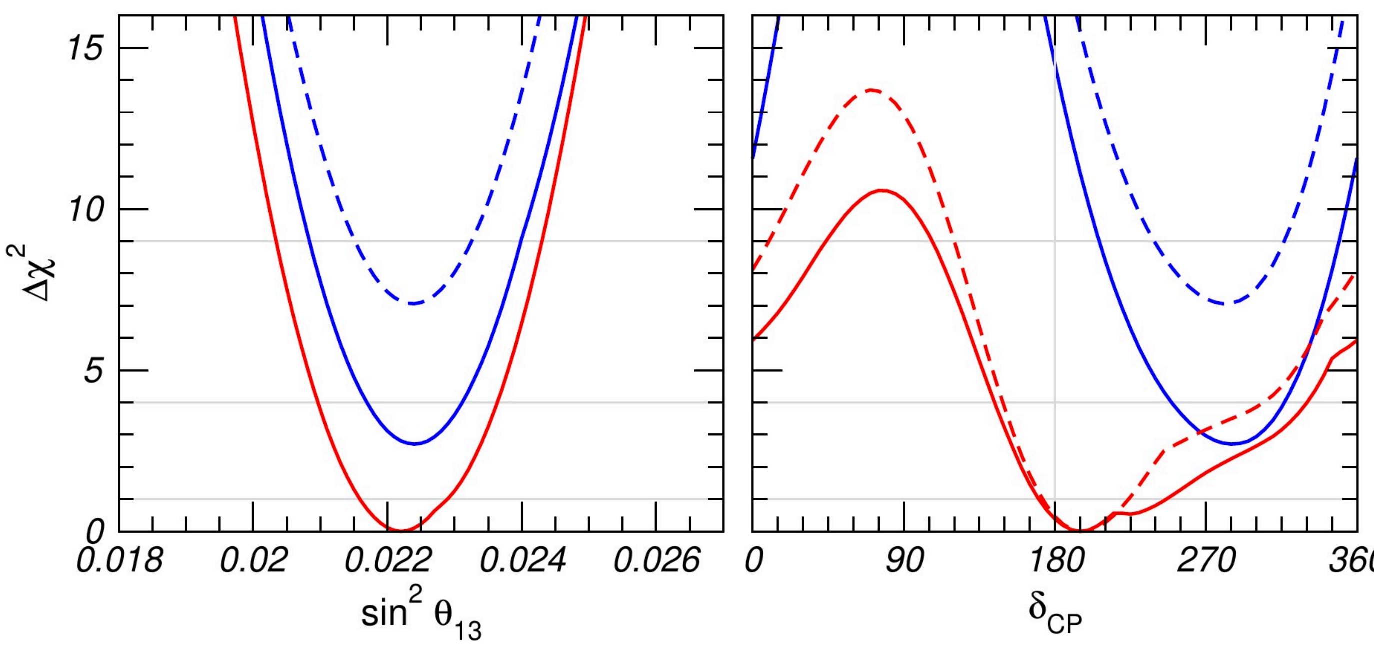
Katz et.al., 2012

What do we know about neutrino masses and mixing?



$$P(\nu_\alpha \to \nu_\beta) = \sum_{a,b} \widetilde{U}^*_{\alpha a} \widetilde{U}_{\beta a} \widetilde{U}_{\alpha b} \widetilde{U}^*_{\beta b}\, e^{i\Delta_{ab} L}$$

- 3 mixing angles
- 2 quadratic mass differences



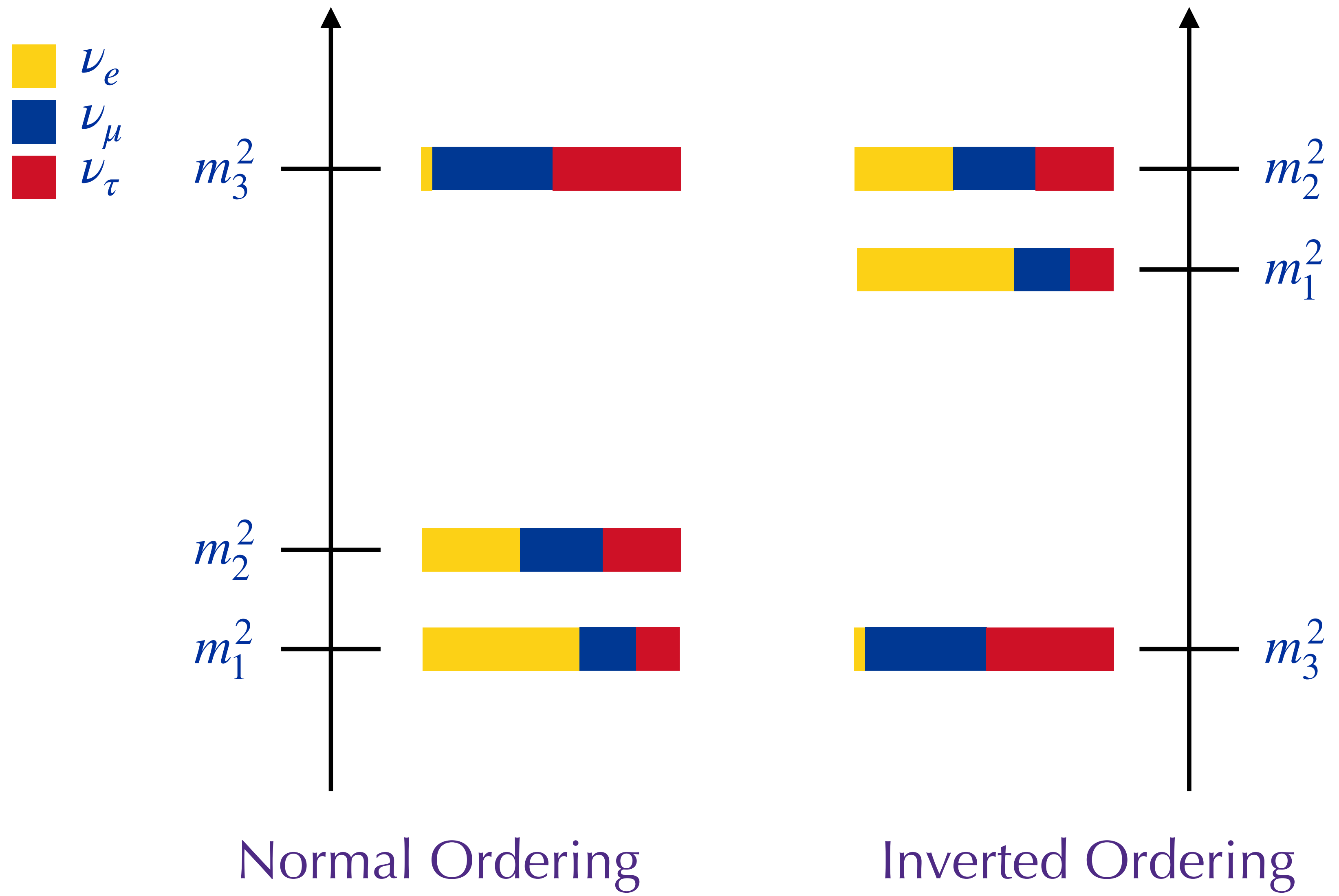
NuFit
JHEP 09 (2020) 178

Other global fits

Valencia group
2006.11237

Bari group
2003.08511

What do we not know about neutrino masses and mixing?



$|\nu_a\rangle = \tilde{U}_{\alpha a}|\nu_\alpha\rangle$

T2K ⟶ NO
NOvA ⟶ NO
T2K + NOvA ⟶ IO

Kelly, Machado, Parke, YFPG, and Funchal
2007.08526

Denton, Gehrlein, Pestes
PRL 126 (2021) 5, 051801

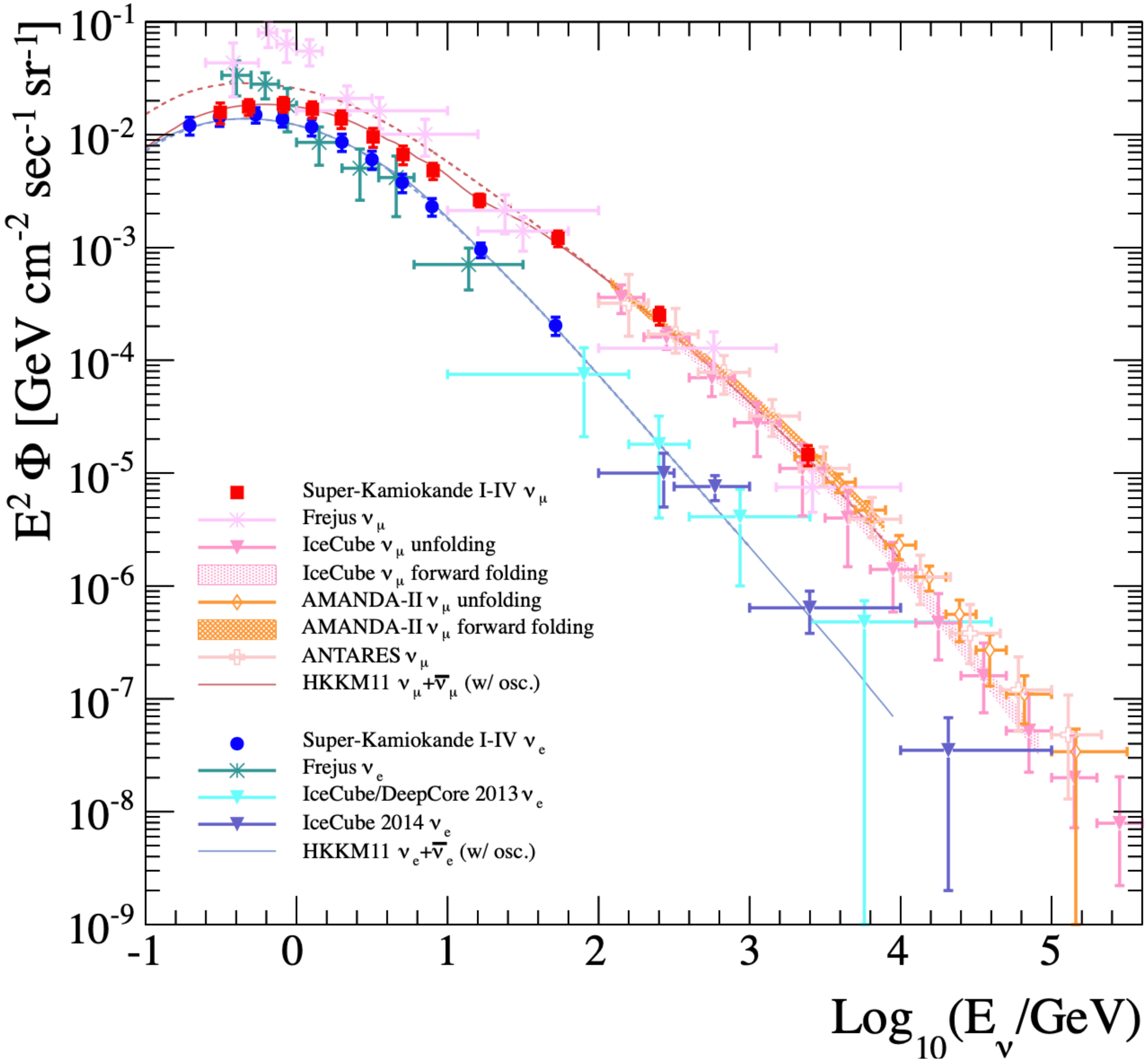
Chatterjee, Palazzo
PRL 126 (2021) 5, 051802

- CP phase - CP violation
- Absolute mass values
- Dirac vs Majorana nature

Atmospheric Neutrinos

- Decay of instable mesons produces a flux of neutrinos

$$\pi^{\pm} \to \mu^{\pm} + \nu_\mu(\overline{\nu}_\mu)$$
$$K^{\pm} \to \mu^{\pm} + \nu_\mu(\overline{\nu}_\mu)$$
$$\mu^{\pm} \to e^{\pm} + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$$



- Neutrino spectrum spans many orders of magnitude in energy (~10 MeV - 100 TeVs)

- Flux ratios are energy-dependent

$$\frac{\nu_e + \overline{\nu}_e}{\nu_\mu + \overline{\nu}_\mu} \sim \frac{1}{2} \qquad E \lesssim 1 \text{ GeV}$$

E. Richard et al. (SK),
PRD 94 (2016) 5, 052001.

See this morning talks

Oscillation Probabilities — MSW and Parametric

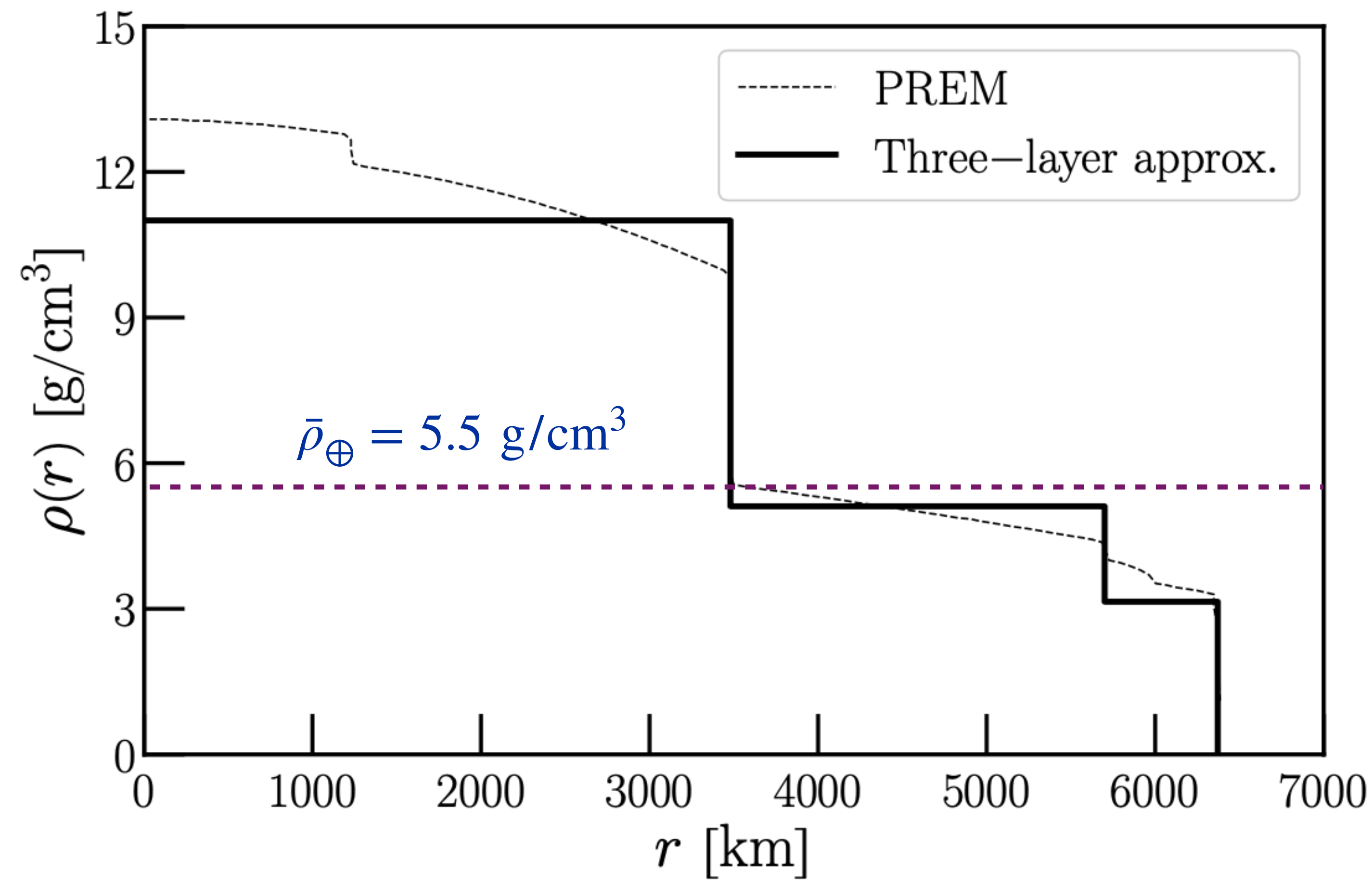
Neutrino propagation in matter:

$$i\frac{d\vec{\nu}}{dt} = H\vec{\nu}$$

$$H = \frac{1}{2E}U^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U + \begin{pmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$V_{CC} = \sqrt{2}G_F n_e$$

Electron density $n_e = N_A Y_e \rho$



MSW resonance

Matter effects matter

Constant Density!

$$E_{\rm MSW} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F N_A Y_e \rho} \simeq \begin{cases} 5.3\ \text{GeV} \left(\frac{\Delta m^2}{2.5\times 10^{-3}\ \text{eV}^2}\right)\left(\frac{\cos 2\theta}{0.95}\right)\left(\frac{0.5}{Y_e}\right)\left(\frac{6\ \text{g/cm}^3}{\rho}\right) & \text{(atmospheric pars.)} \\ 68\ \text{MeV} \left(\frac{\Delta m^2}{7.5\times 10^{-5}\ \text{eV}^2}\right)\left(\frac{\cos 2\theta}{0.41}\right)\left(\frac{0.5}{Y_e}\right)\left(\frac{6\ \text{g/cm}^3}{\rho}\right) & \text{(solar pars.)} \end{cases}$$

Oscillation Probabilities — MSW and Parametric

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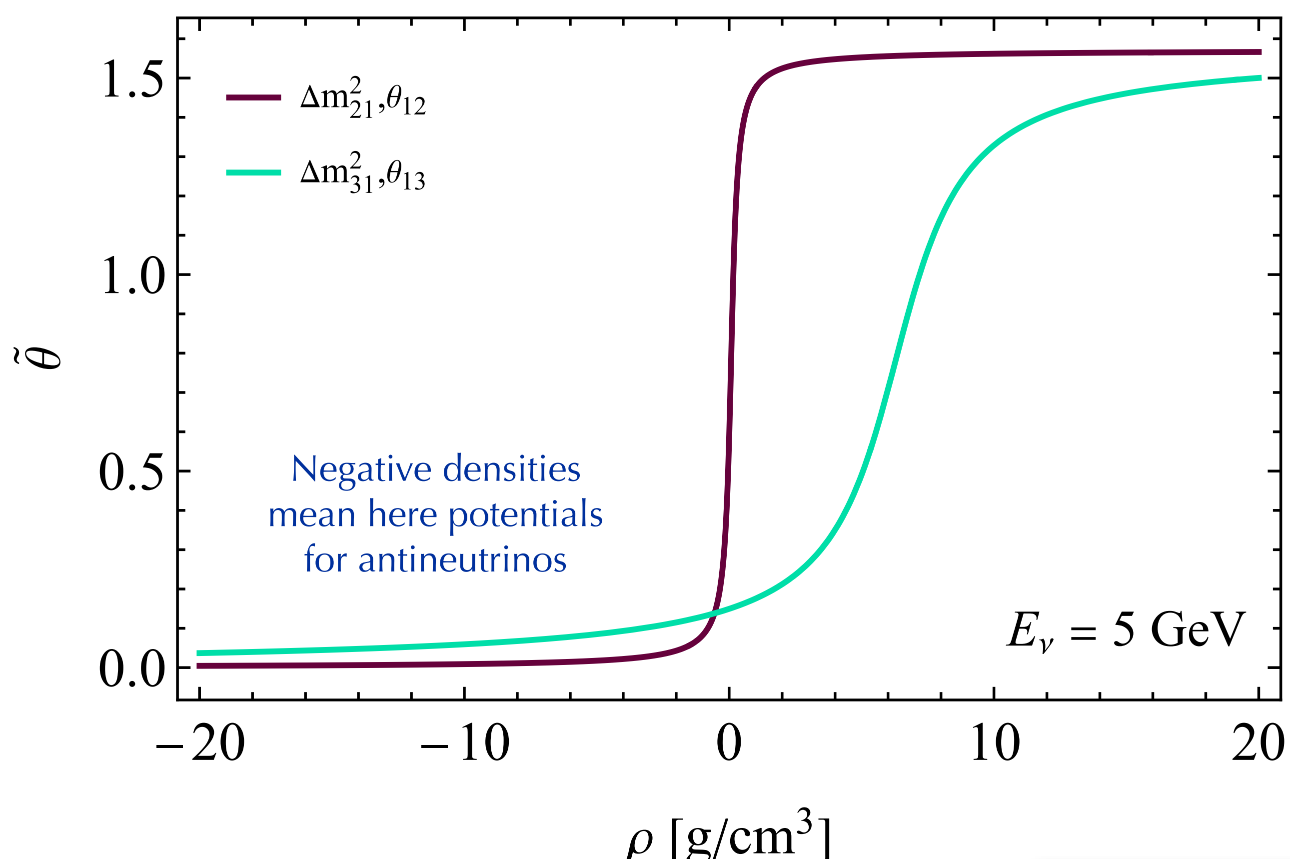
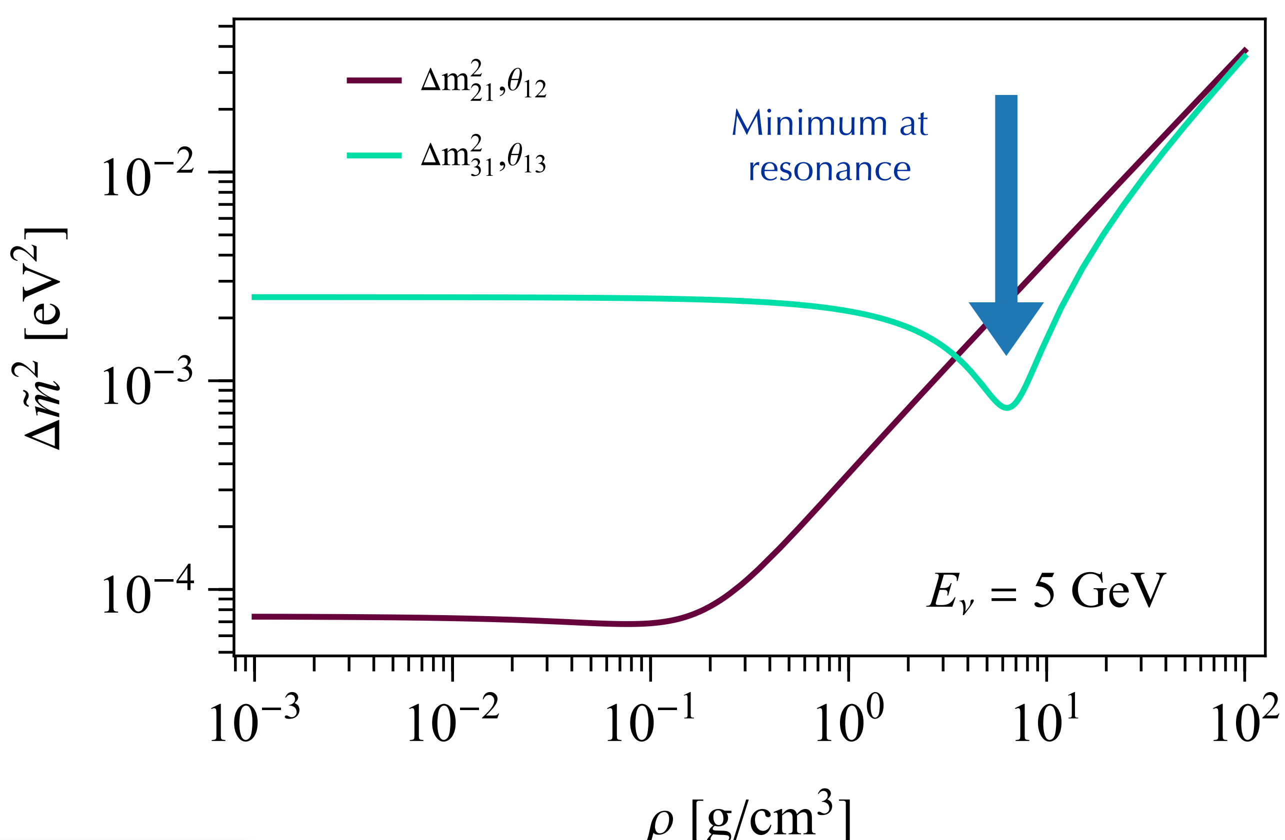
Angle in matter



Mass difference in matter



Constant Density!

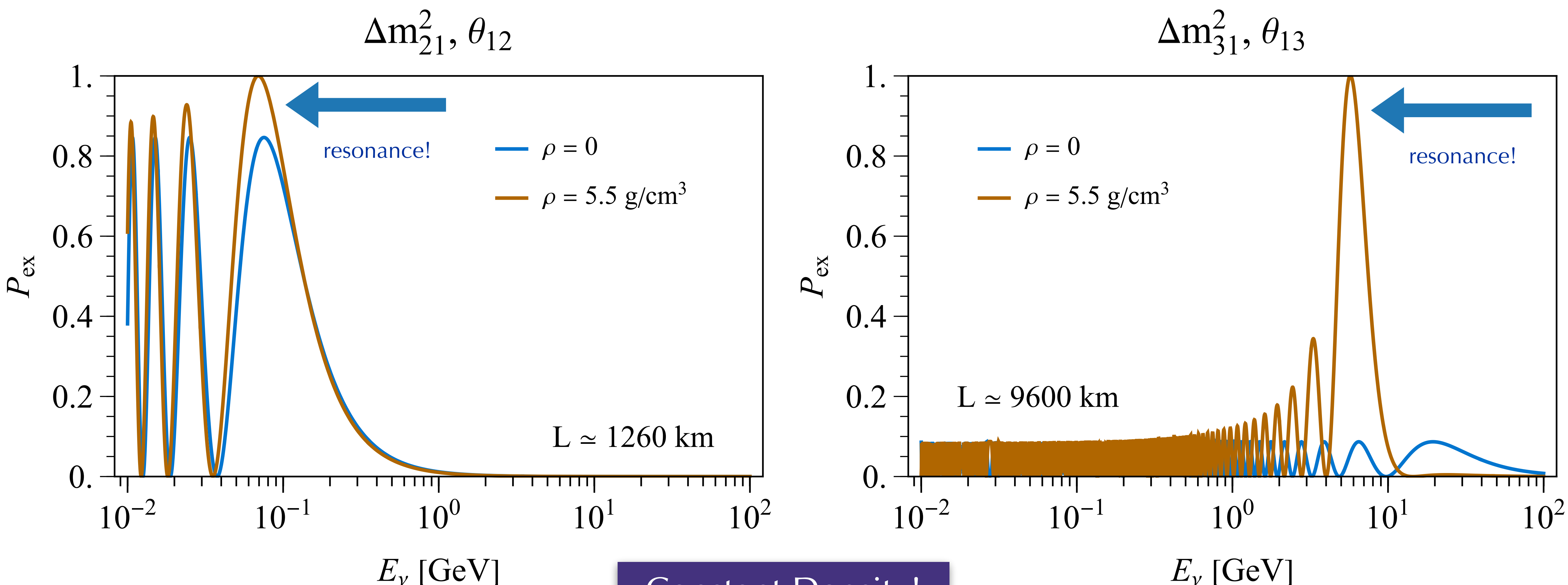
2-flavours

Oscillation Probabilities — MSW and Parametric

MSW resonance

Matter effects matter

$$E_{\rm MSW} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N_A Y_e \rho} \simeq \begin{cases} 5.3\ \text{GeV} \left(\frac{\Delta m^2}{2.5\times 10^{-3}\ \text{eV}^2}\right)\left(\frac{\cos 2\theta}{0.95}\right)\left(\frac{0.5}{Y_e}\right)\left(\frac{6\ \text{g/cm}^3}{\rho}\right) & \text{(atmospheric pars.)} \\ 68\ \text{MeV} \left(\frac{\Delta m^2}{7.5\times 10^{-5}\ \text{eV}^2}\right)\left(\frac{\cos 2\theta}{0.41}\right)\left(\frac{0.5}{Y_e}\right)\left(\frac{6\ \text{g/cm}^3}{\rho}\right) & \text{(solar pars.)} \end{cases}$$



Constant Density!

Pex →2-flavour appearance probability

Oscillation Probabilities — MSW and Parametric

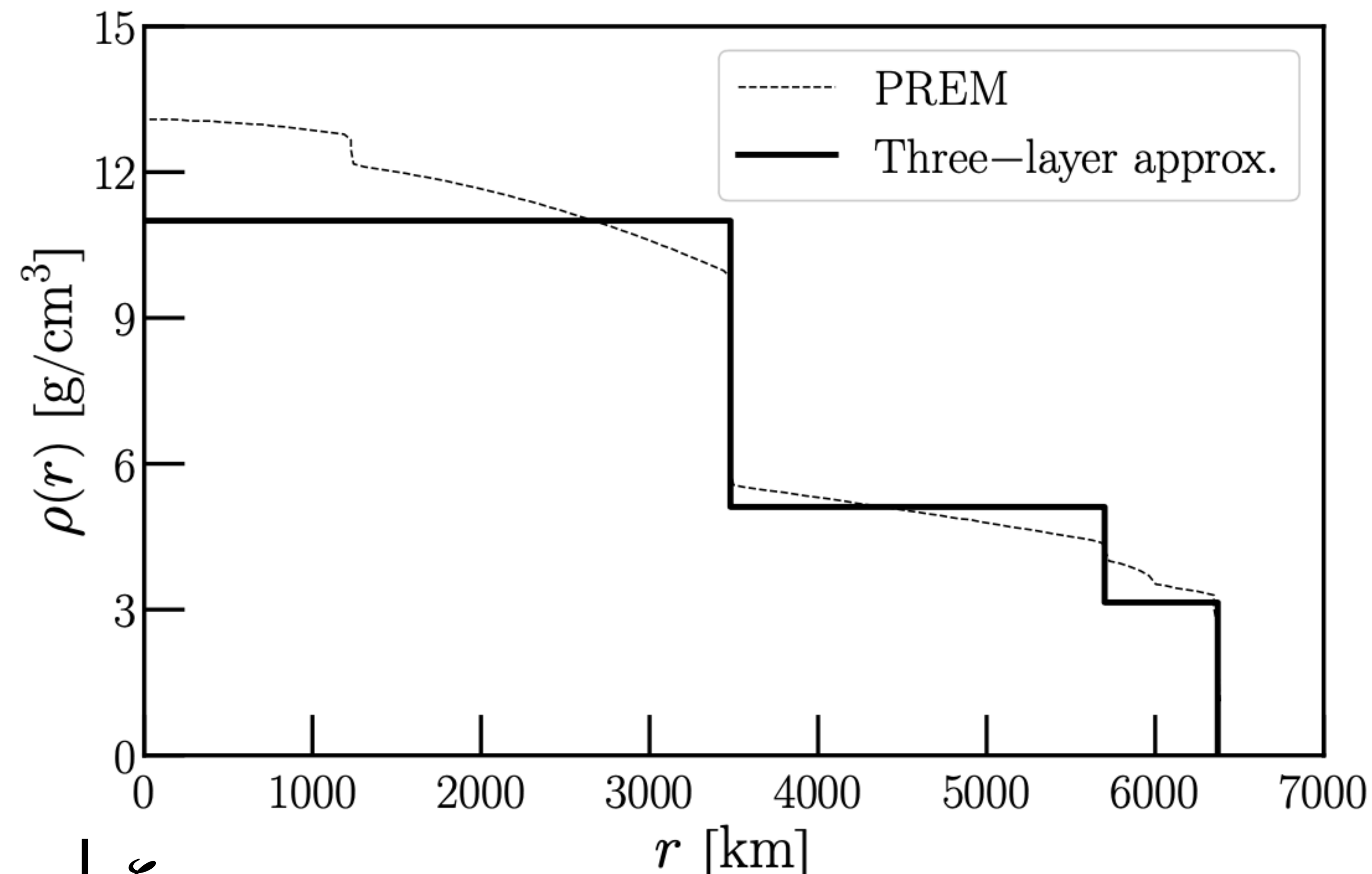
Let's assume a three-layered Earth

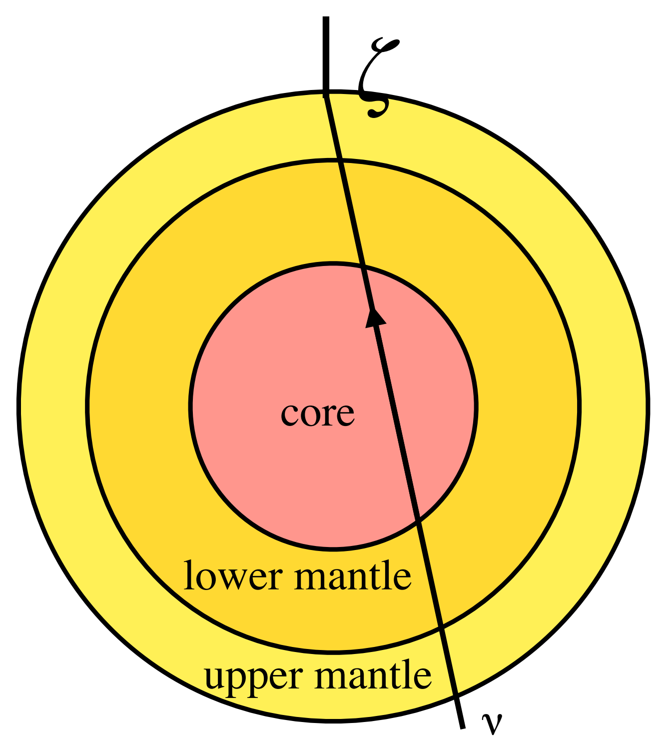
$$i\frac{d\vec{\nu}}{dt} = H\vec{\nu}$$

$$H = \frac{1}{2E}U^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U + \begin{pmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$V_{CC} = \sqrt{2}G_F n_e$$ → Electron density $n_e = N_A Y_e \rho$

$$\rho = \rho(\zeta)$$

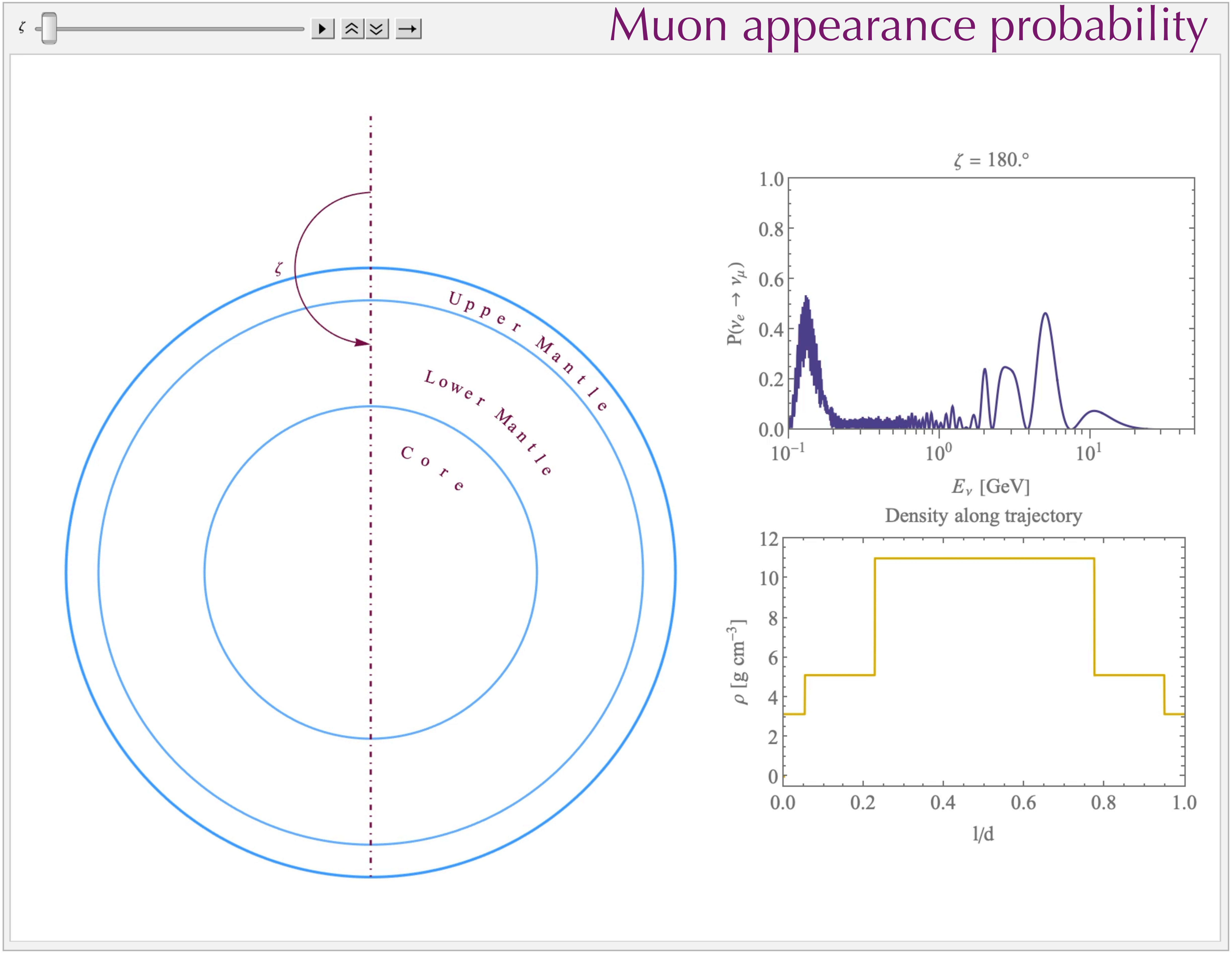




- $\zeta \gtrsim 147^\circ \longrightarrow$ Neutrinos cross the core and mantle
- $116^\circ \lesssim \zeta \lesssim 147^\circ \longrightarrow$ Neutrinos cross the lower and upper mantle

Not only the matter effects are important, but also the abrupt change in the densities

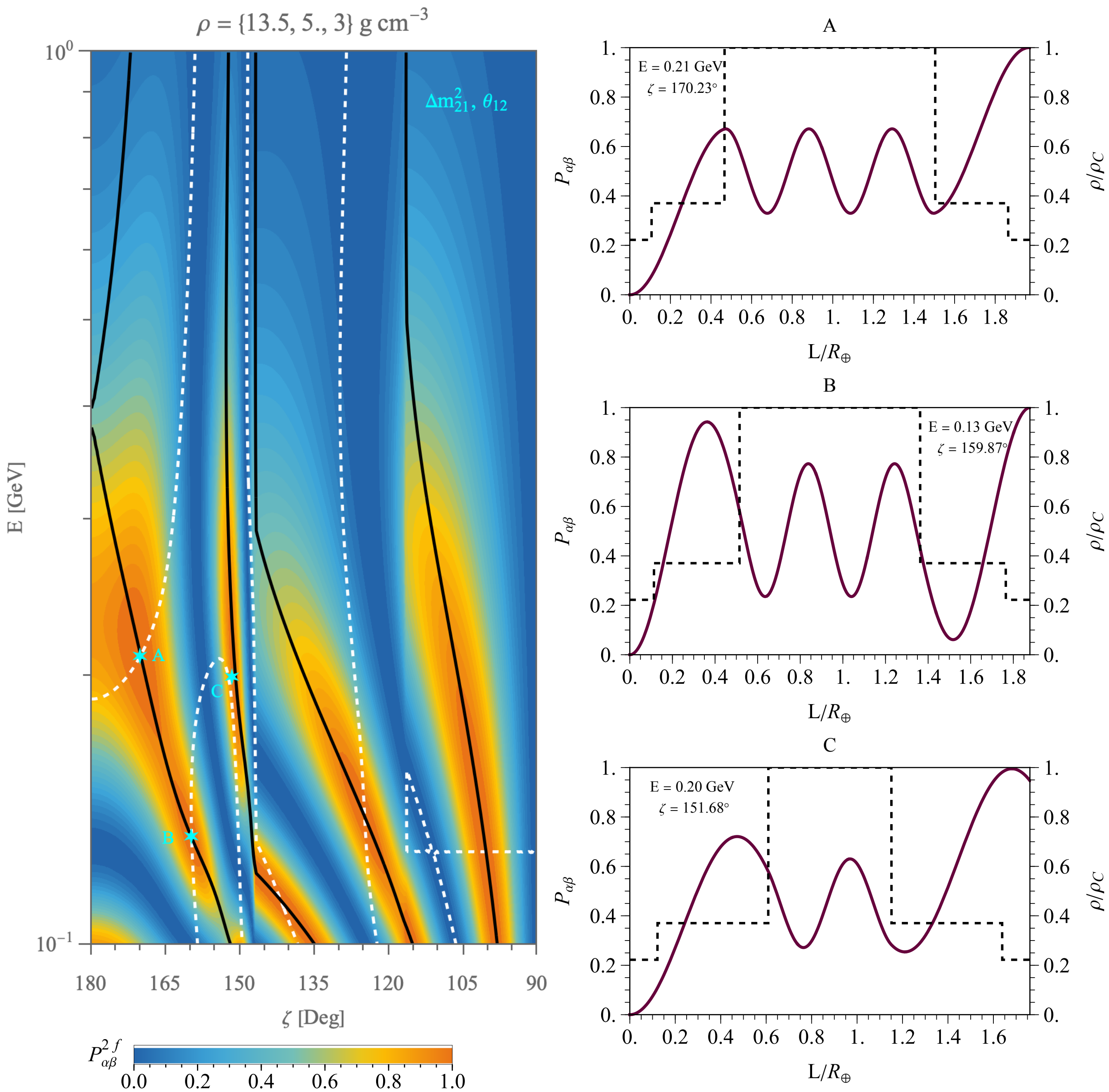
Muon appearance probability

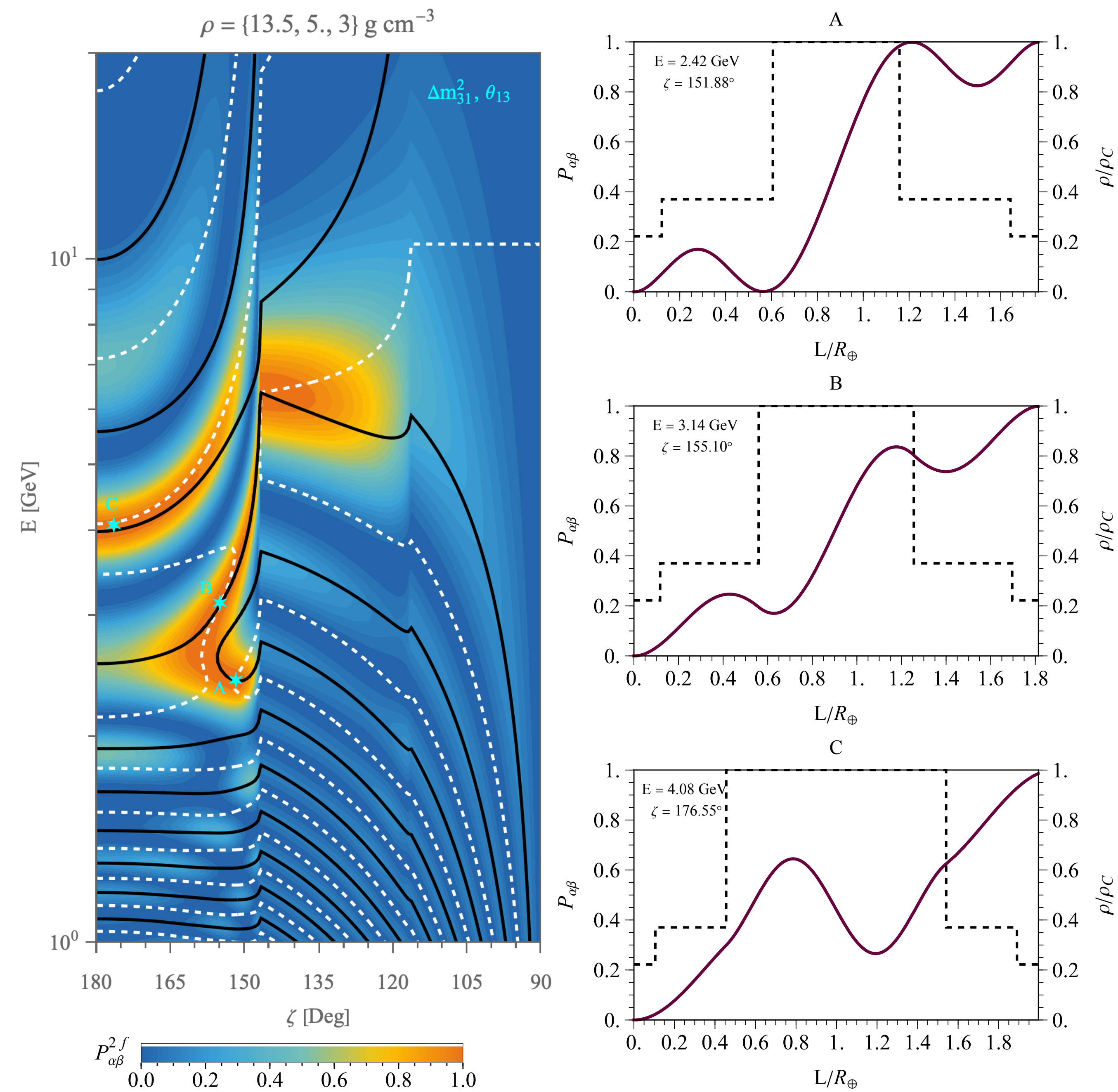


Oscillation Probabilities — MSW and Parametric

Parametric Enhancement!

Serendipitous relations between angles and phases





Different conditions lead to an enhancement of the oscillation probability, see, e.g. 2110.00003

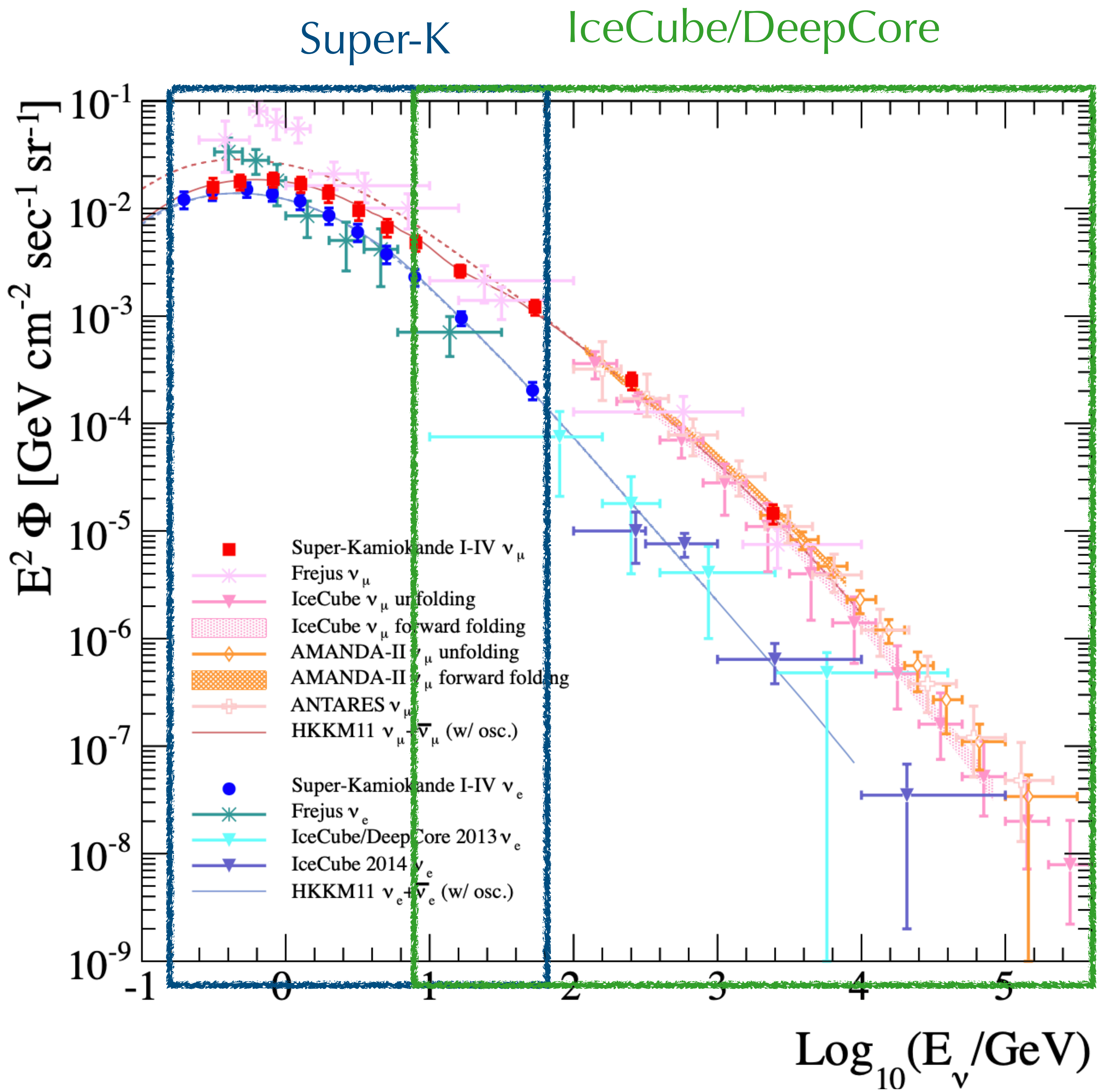
Measuring Atmospheric Neutrinos

Super-K:

- 22.5 kton Water Cherenkov
- Samples divided in FC, PC, Up, μ -like rings
- Low directionality for sub-GeV νs

IceCube/DeepCore:

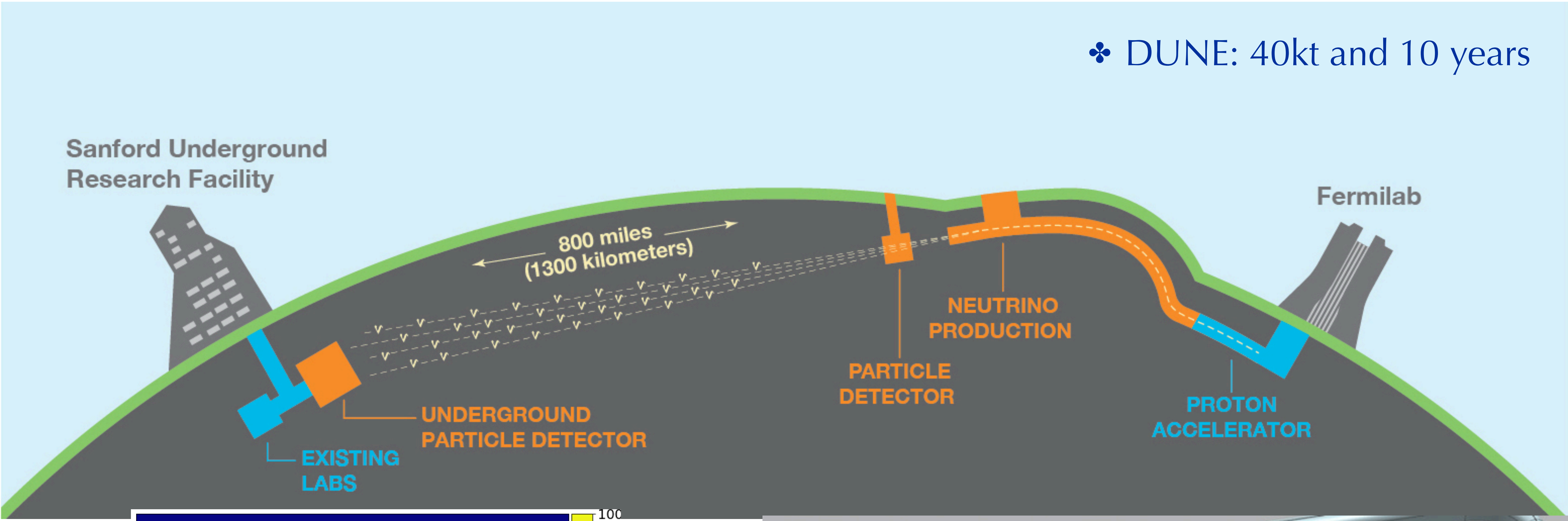
- ~ 1 km^3 Ice Cherenkov
- Samples divided cascades and tracks
- Measures the high energy ($E \gtrsim 5$ GeV) part of the flux

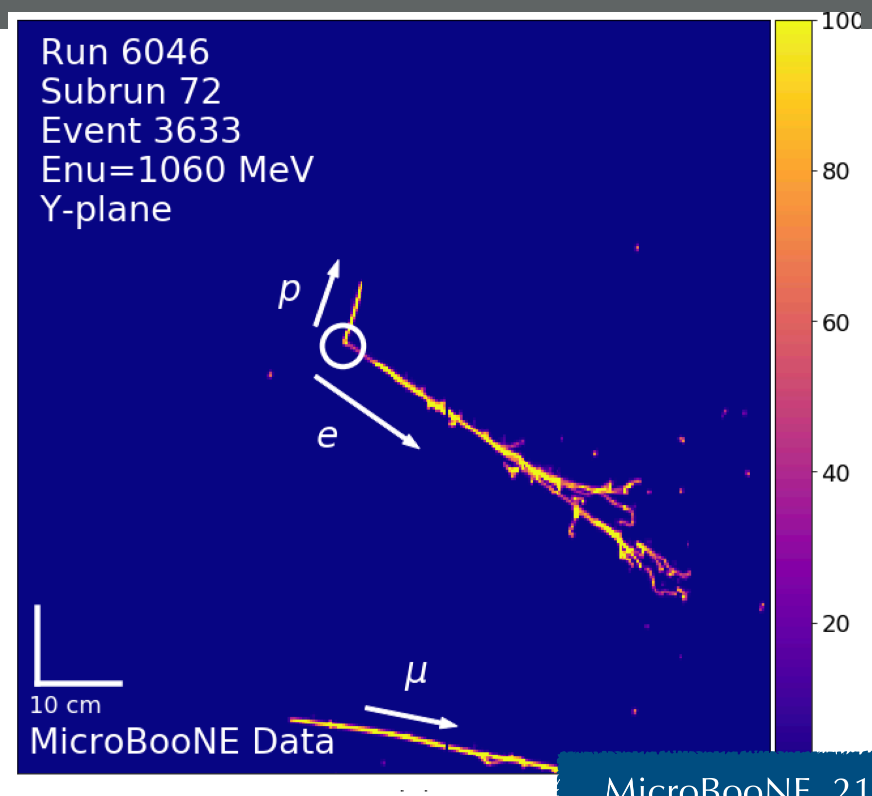


Other possibilities to measure atmospheric neutrinos??

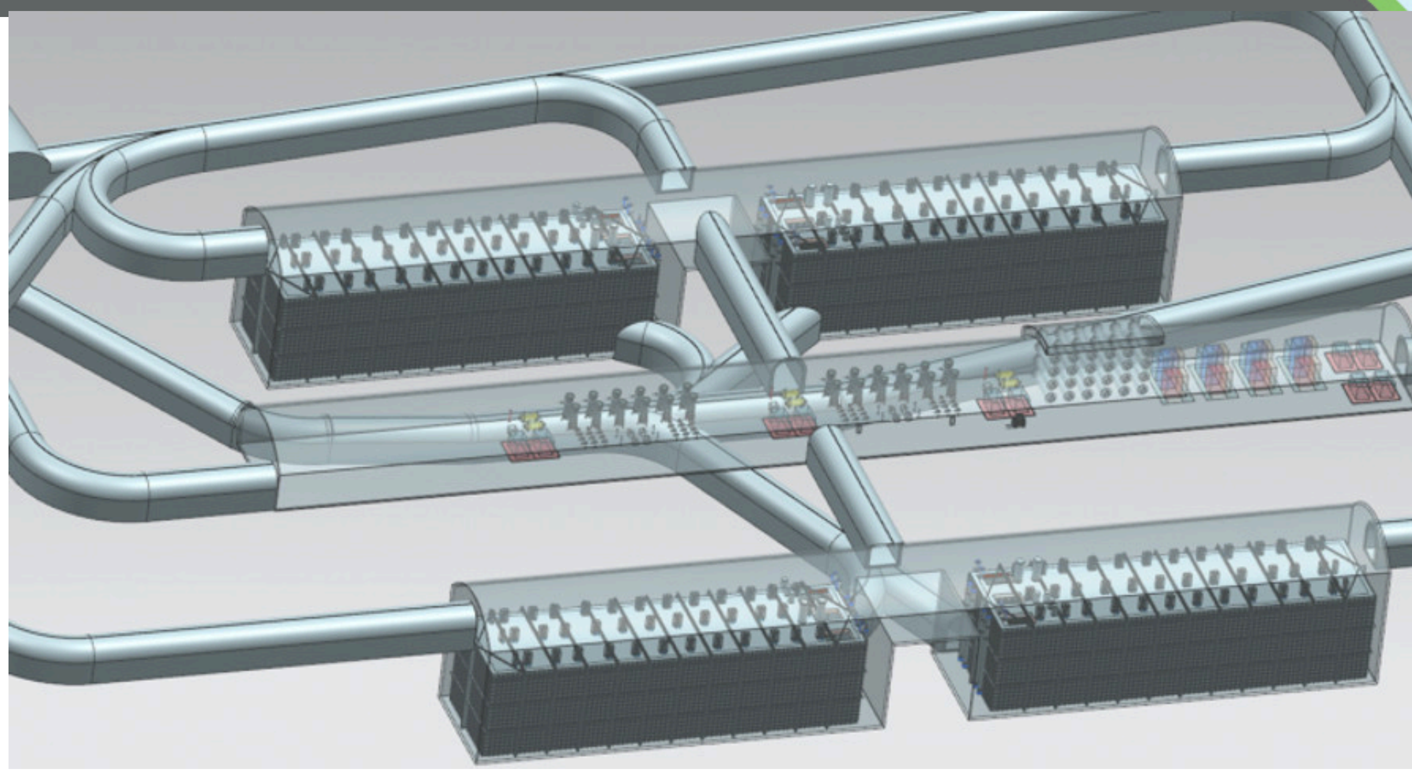
Deep Underground Neutrino Experiment (DUNE)

- DUNE: 40kt and 10 years





MicroBooNE, 2110.14080



DUNE — Reconstruction Capabilities

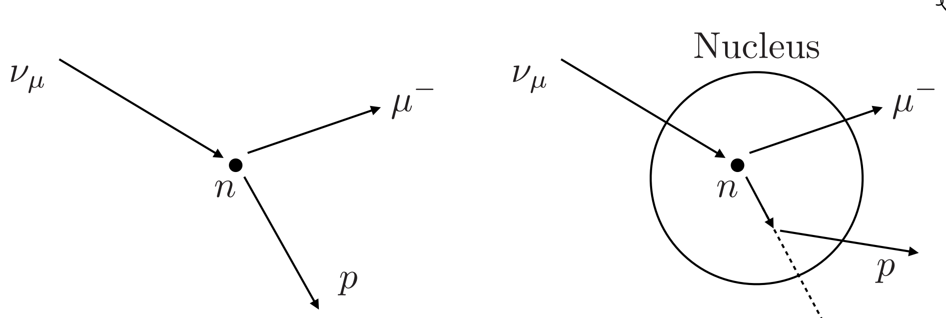
- Capability of identifying different types of particles
- Low-energy protons!
- Precise energy/direction measurement of their trajectories
- Distinguish between topologies

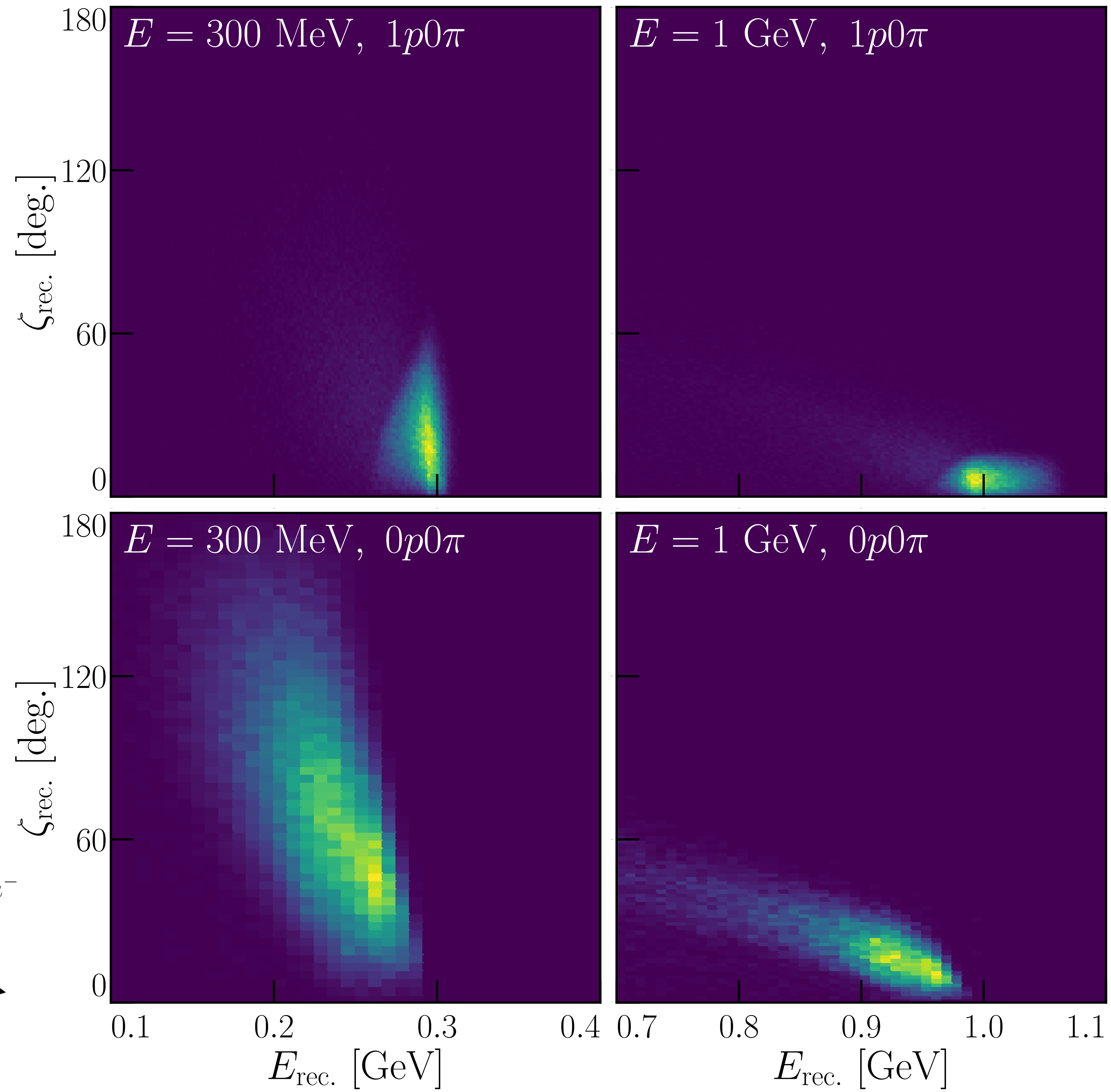
  1lepton + *n*-protons + *m*-pions

Reconstruction of energy ***and*** direction

↓

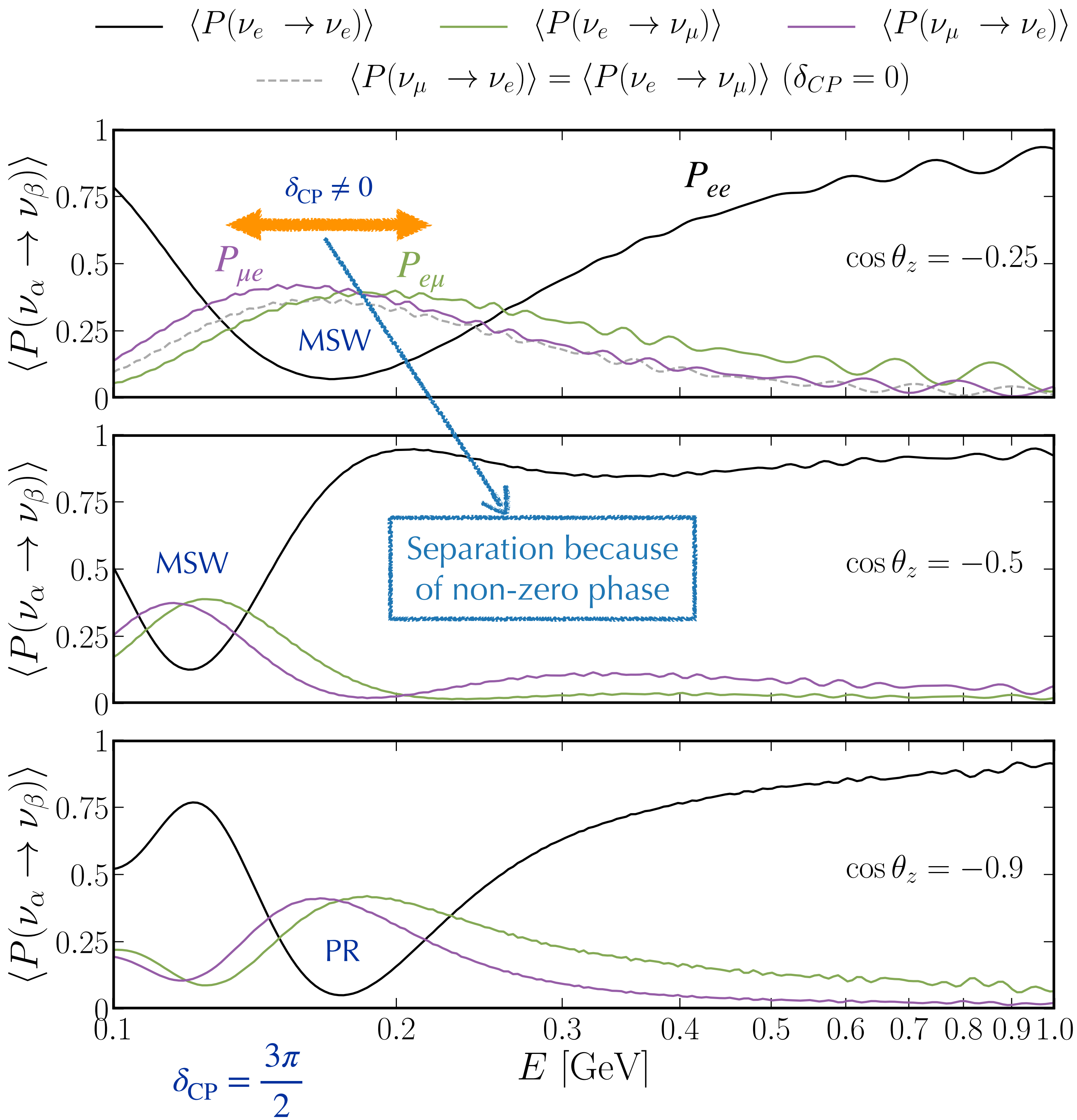
Nuclear physics is tough!!



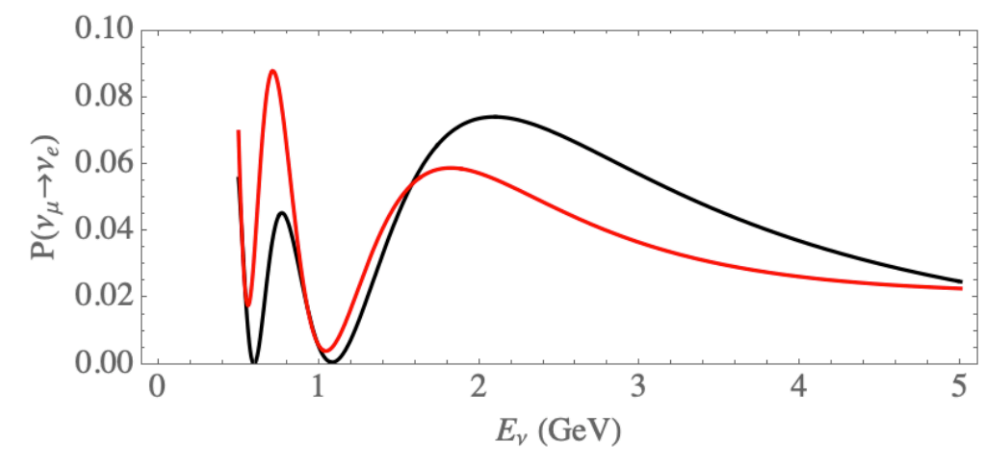


We use `NuWro` to simulate neutrino interactions

CP violation — Sub-GeV neutrinos



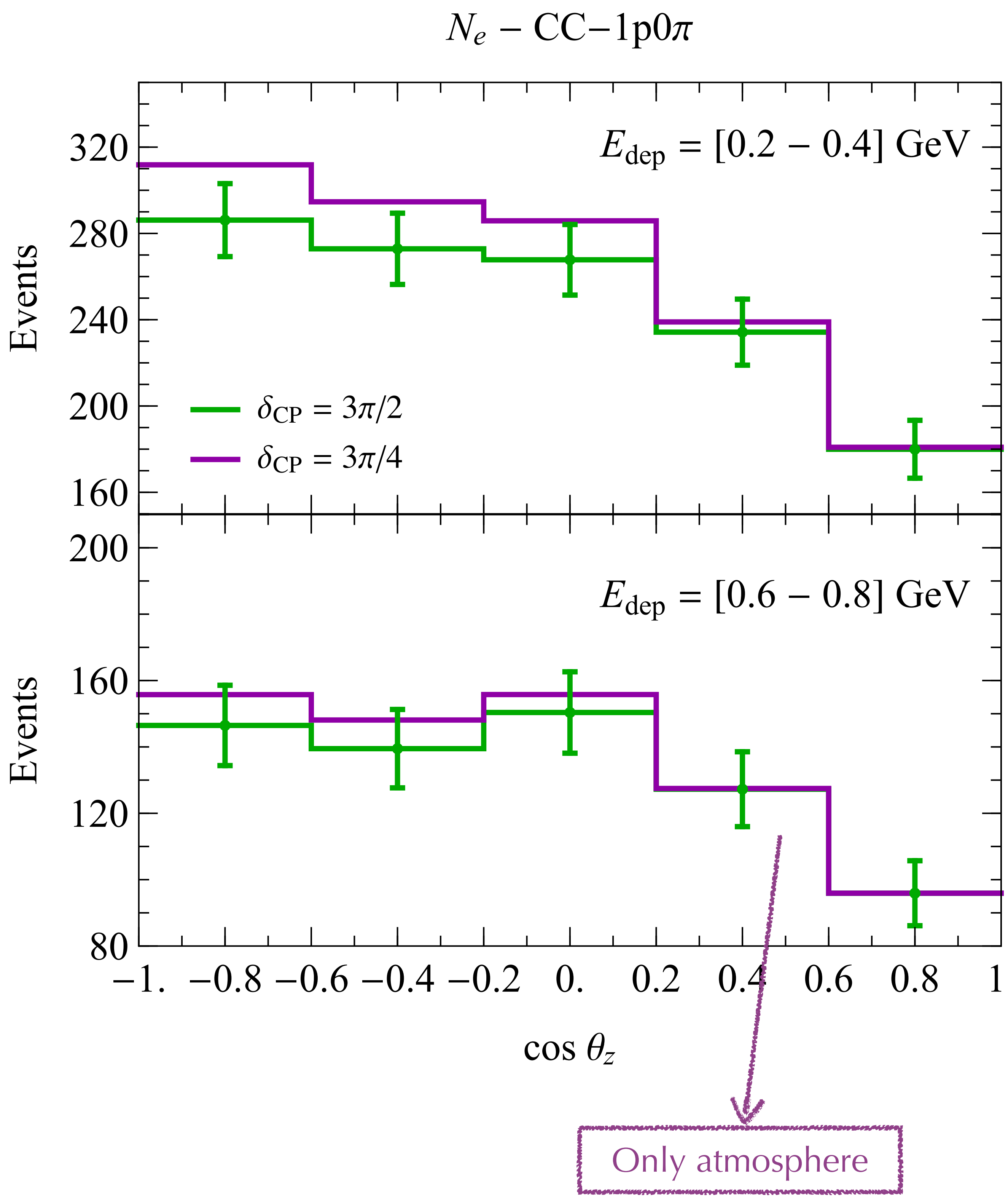
The main goal of DUNE is to measure leptonic CP violation
For DUNE's beam, CP will be a small effect (few %)

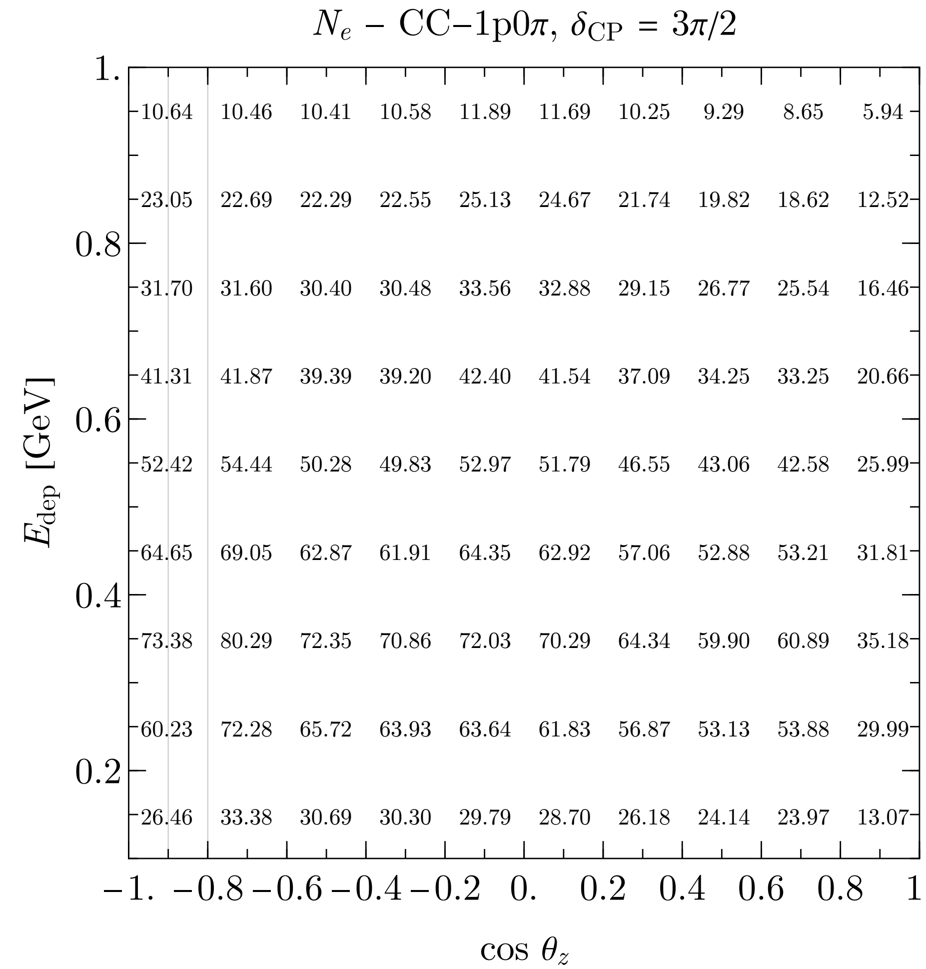


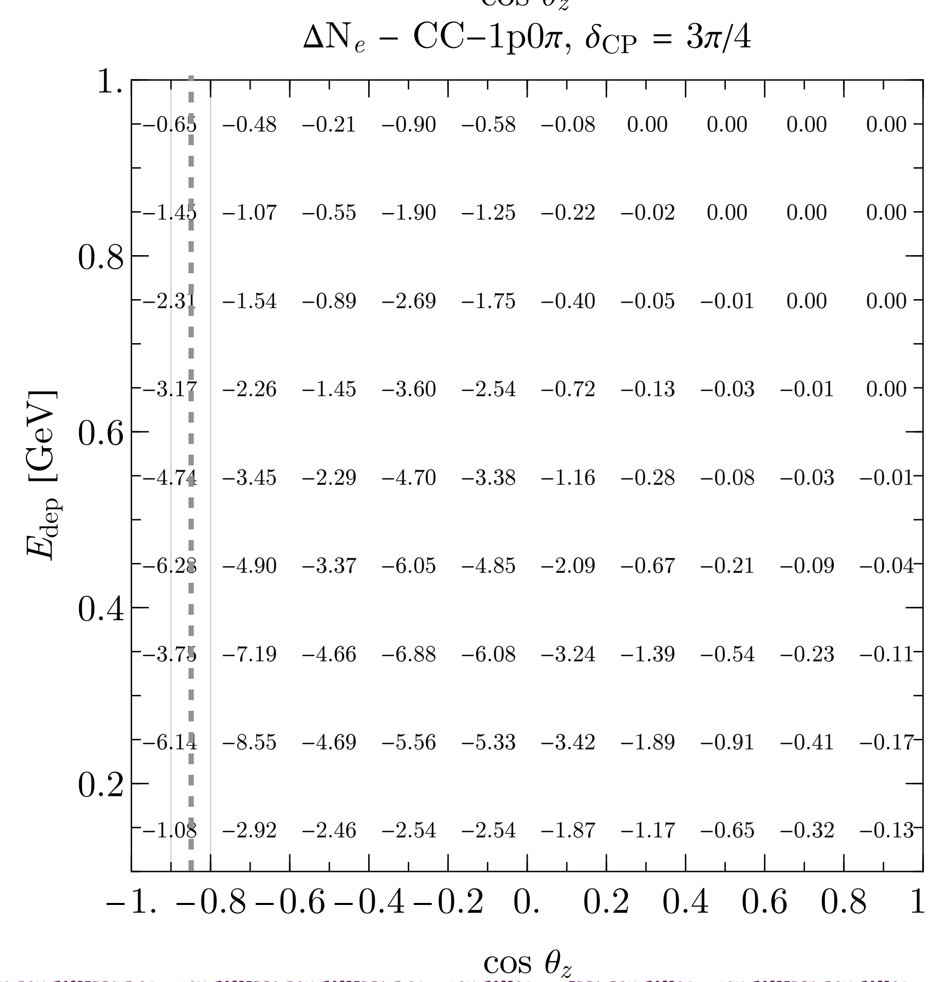
From Pedro Machado's talk on IceDUNE

CP Violation effects are "huge" in the Sub GeV Sample

Sub-GeV neutrinos







DUNE — Analysis

	K.E.	Ang.	E
p	30 MeV	10°	10%
π	30 MeV	10°	10%
Λ	30 MeV	10°	10%
$\mu^\pm$	5 MeV	2°	5%
$e^\pm$	10 MeV	2°	5%

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

Honda's Tables

Systematics

Systematic	Uncertainties/Priors
Normalization (Φ_0)	40%
Flavor ratio (ν_e/ν_μ)	5%
Neutrino to antineutrino ratio ($\overline{\nu}/\nu$)	2%
Energy distortion (δ)	0 ± 0.2
Zenith distortion ($C_{u,d}$)	0 ± 0.2

Test statistics:

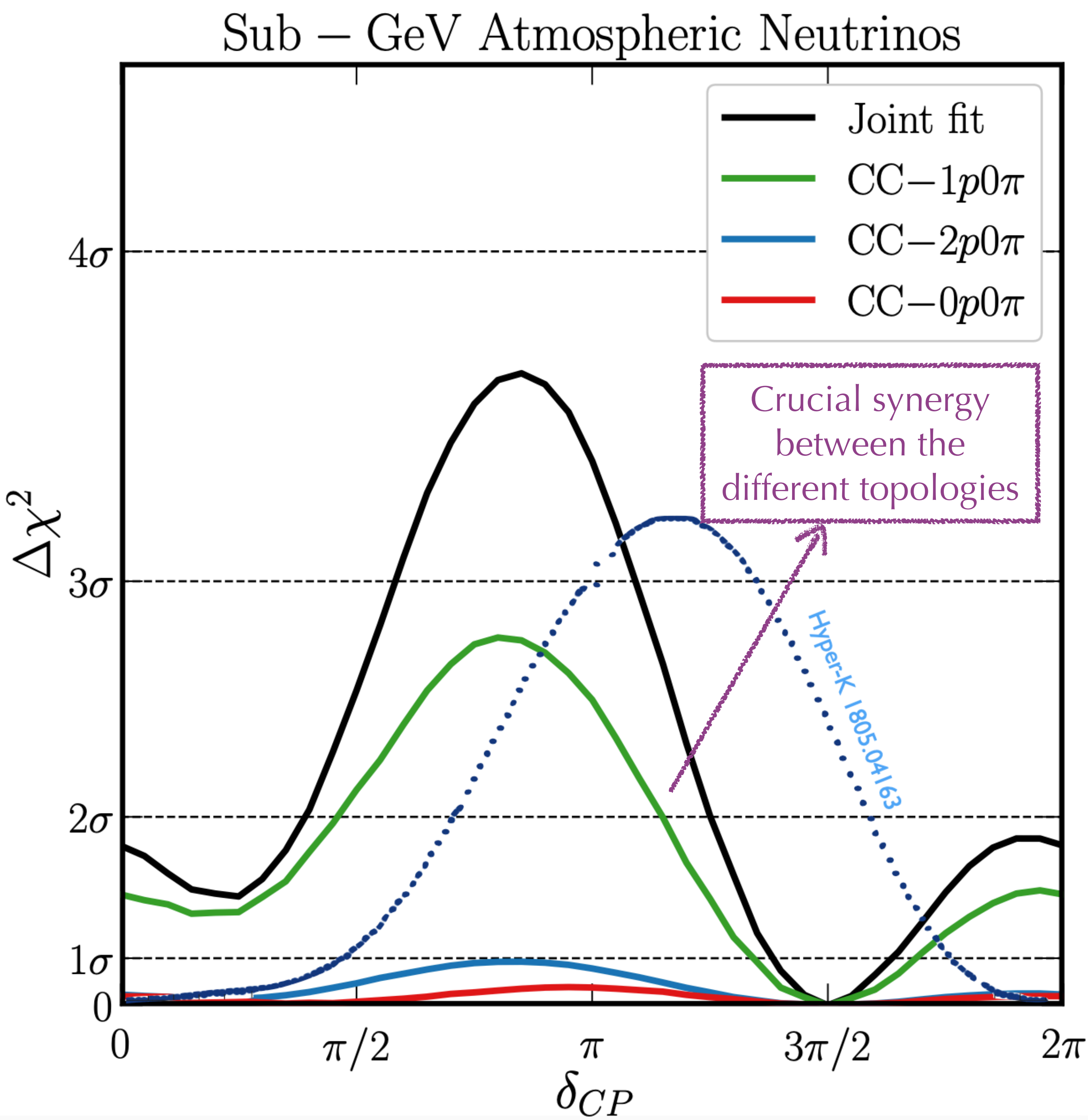
Systematics

Oscillation pars.

$$\Delta\chi^2 = \min_{\vec{q},\vec{\theta}} \left\{ 2 \sum_{m=0,1,2} \sum_{\alpha=e,\mu} \sum_i N^\alpha_{i,m} - N^{\alpha,\mathrm{bf}}_{i,m} + N^{\alpha,\mathrm{bf}}_{i,m} \log\left(\frac{N^\alpha_{i,m}}{N^{\alpha,\mathrm{bf}}_{i,m}}\right) + \sum_j \frac{\left(q_j - q_j^{\mathrm{bf}}\right)^2}{\sigma^2_{q_j}} + \sum_l \frac{\left(\theta_l - \theta_l^{\mathrm{bf}}\right)^2}{\sigma^2_{\theta_l}} \right\}$$

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

CP violation — Sub-GeV neutrinos



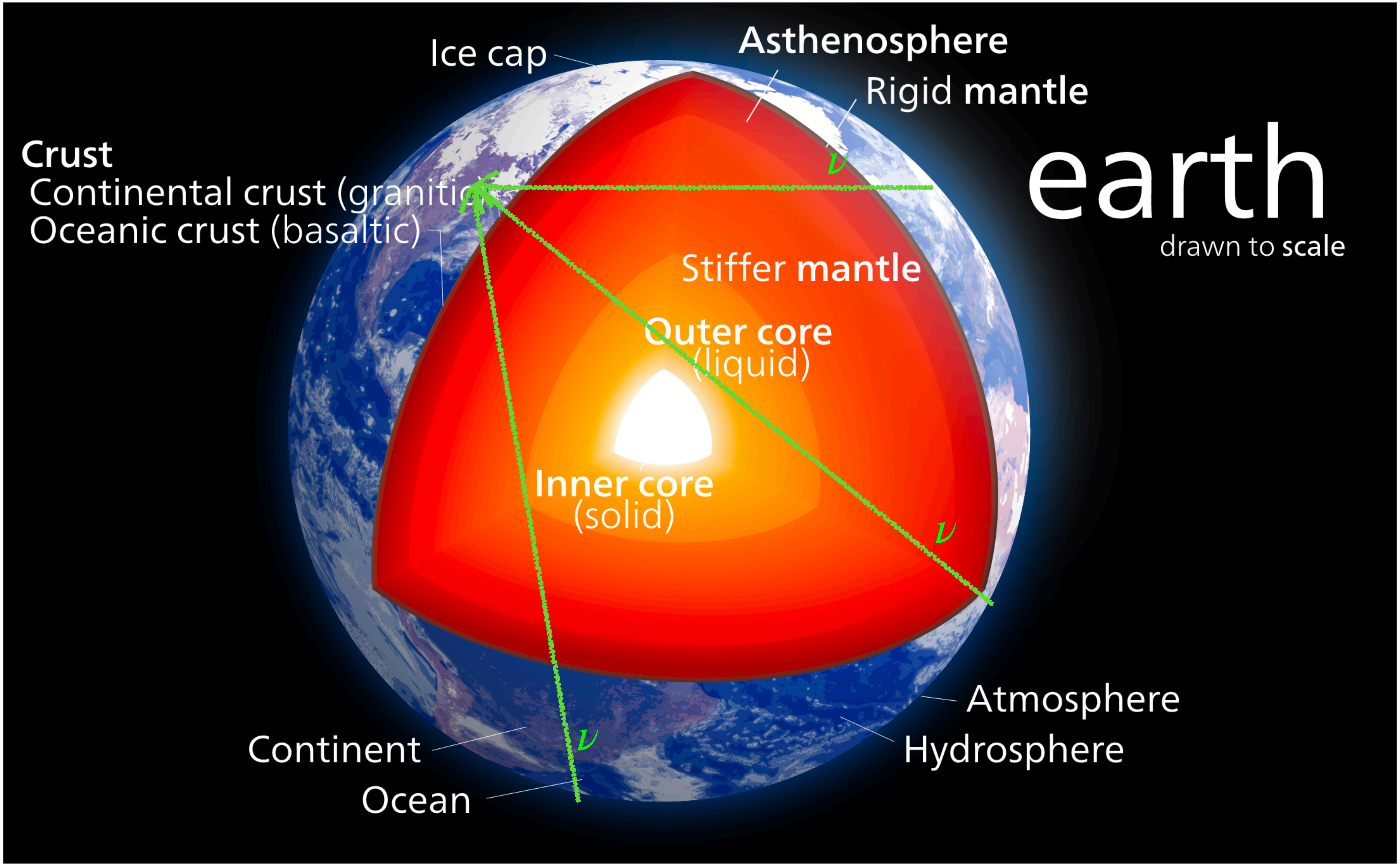
Kelly, Machado, Martinez-Soler, Parke, and YFPG, PRL 123 (2019) 8, 081801

- Assume as true value $\delta_{\rm CP} = 3\pi/2$
- $1\ell 1p0\pi \longrightarrow$ Coming mainly from neutrinos
- $1\ell 0p0\pi \longrightarrow$ Coming mainly from antineutrinos

Topologies help to separate *statistically* neutrinos from antineutrinos

"Free" measurement, and a cross-check of beam results

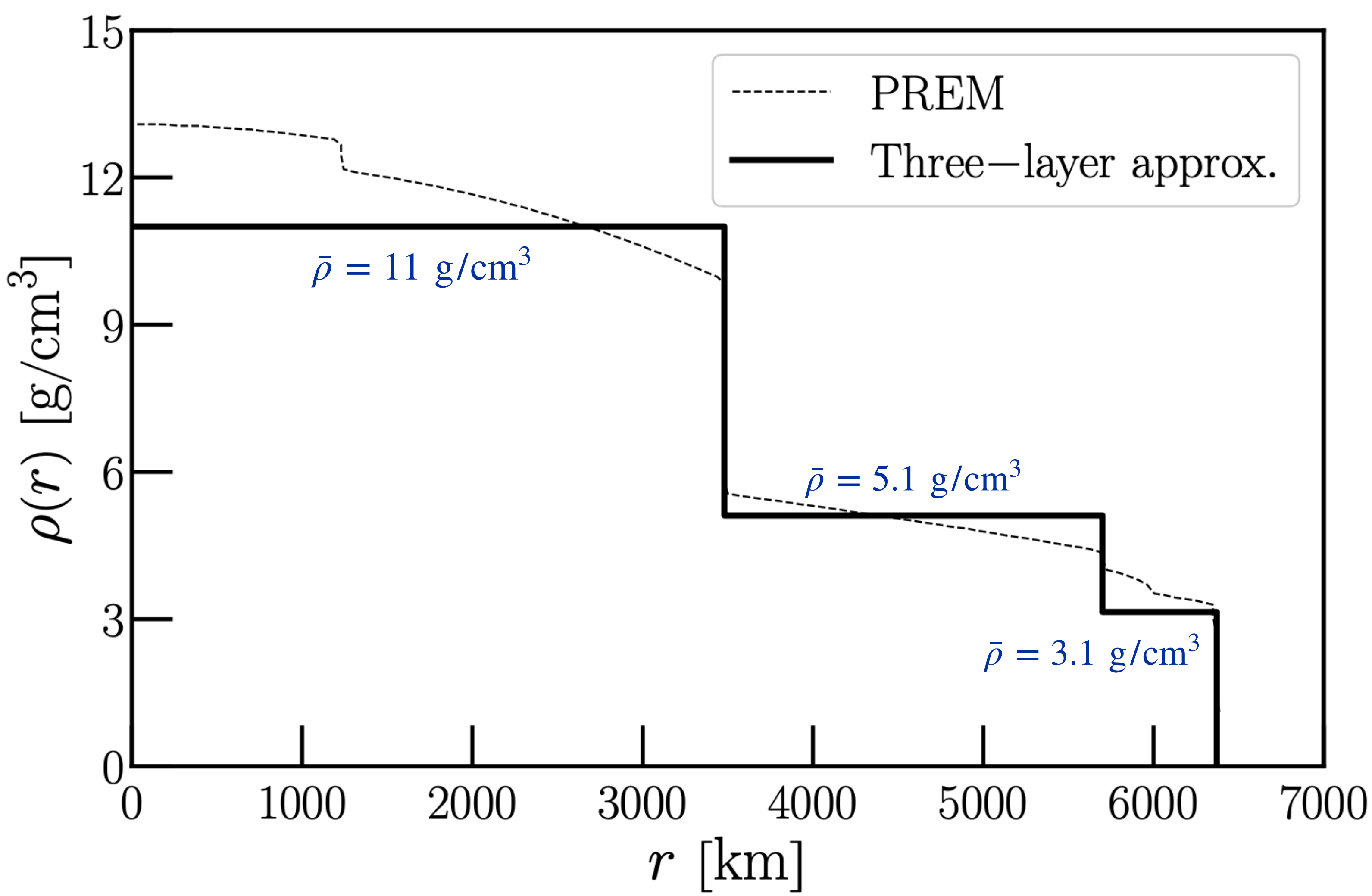
Earth Matter Profile

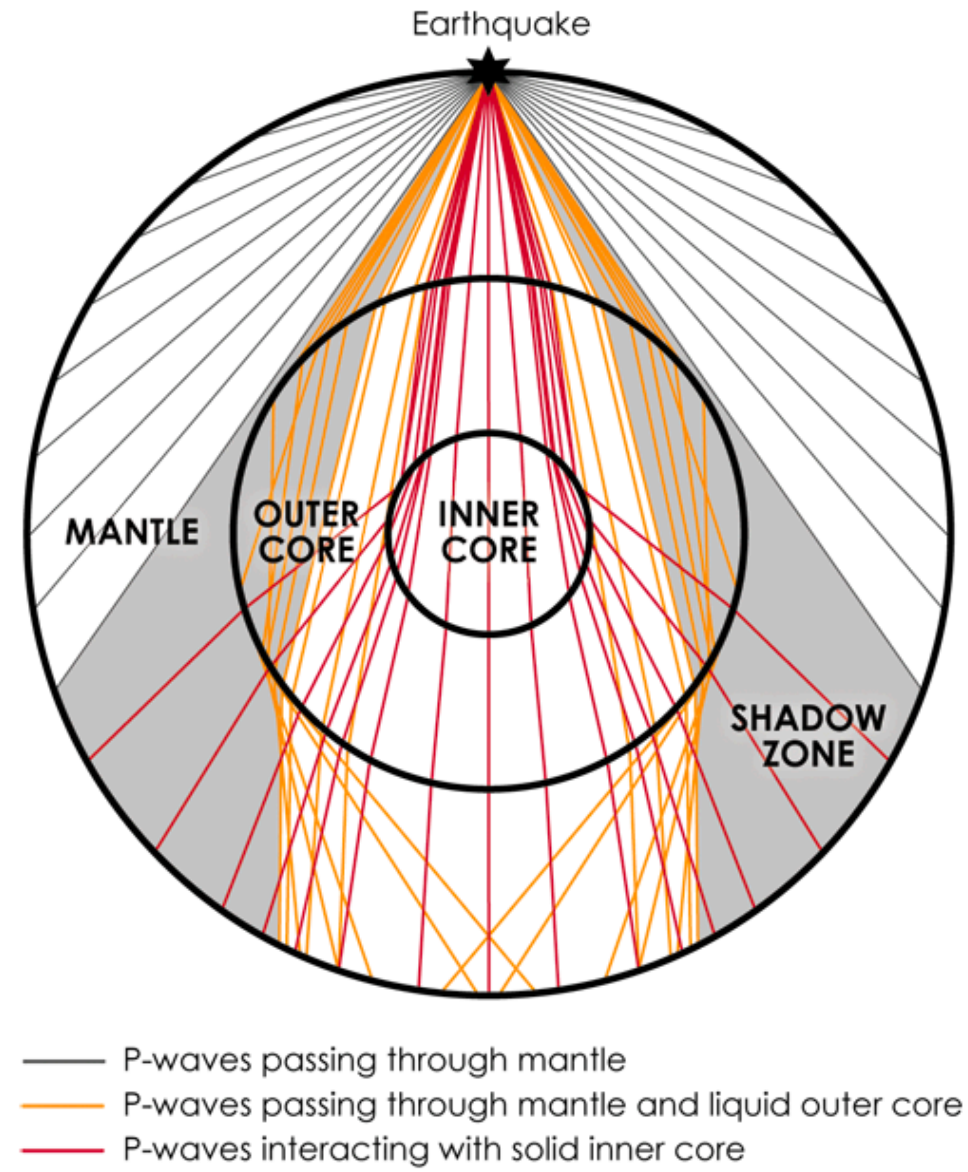


✤ How well do we know the density profile?

Earth Matter Profile

How well do we know the density profile?





HE neutrinos: absorption

$$\frac{\lambda}{R_\oplus} \sim 3.7 \left(\frac{10\ \mathrm{g/cm^3}}{\rho}\right)\left(\frac{10\ \mathrm{TeV}}{E}\right)$$

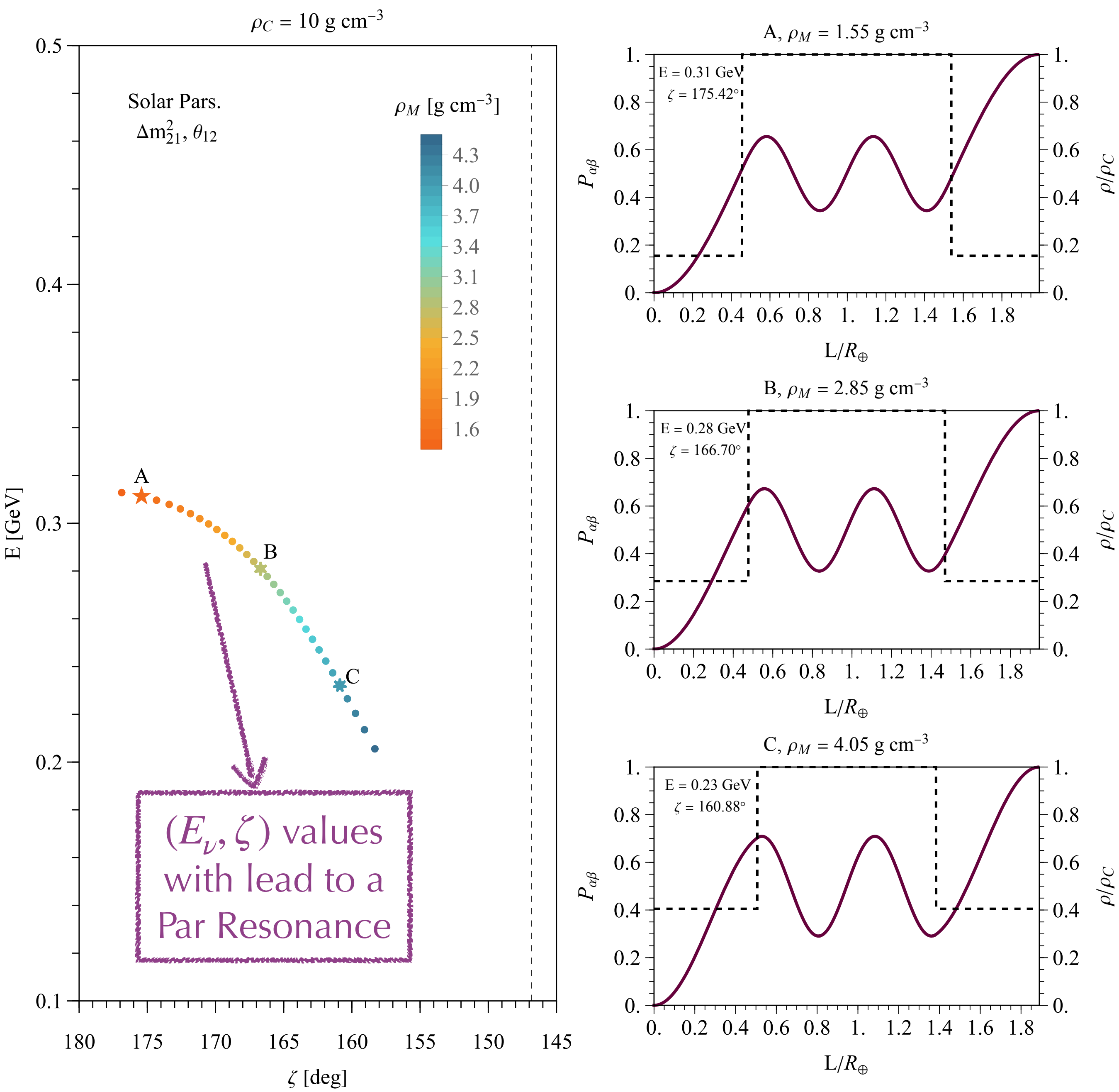
Seismology tell us the radii and density of the layers → Mass + Moment of Inertia

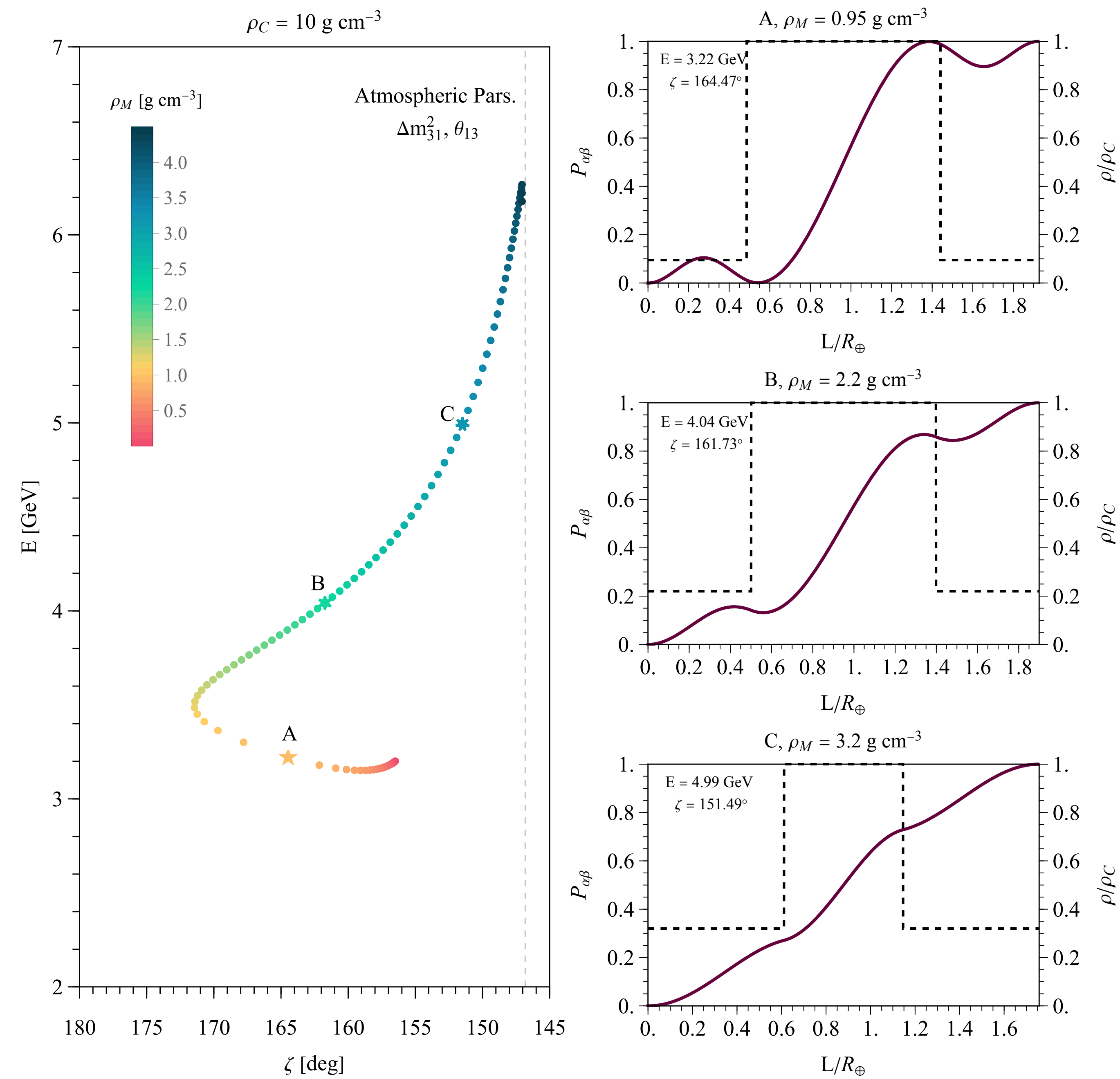
De Rujula, Glashow, Wilson and Charpak, Phys. Rept. 99 (1983) 341.

Donini, Palomares-Ruiz and Salvado, Nature Phys. 15 (2019) 37 [1803.05901]

Oscillation Probabilities — MSW and Parametric

Parametric Enhancement!



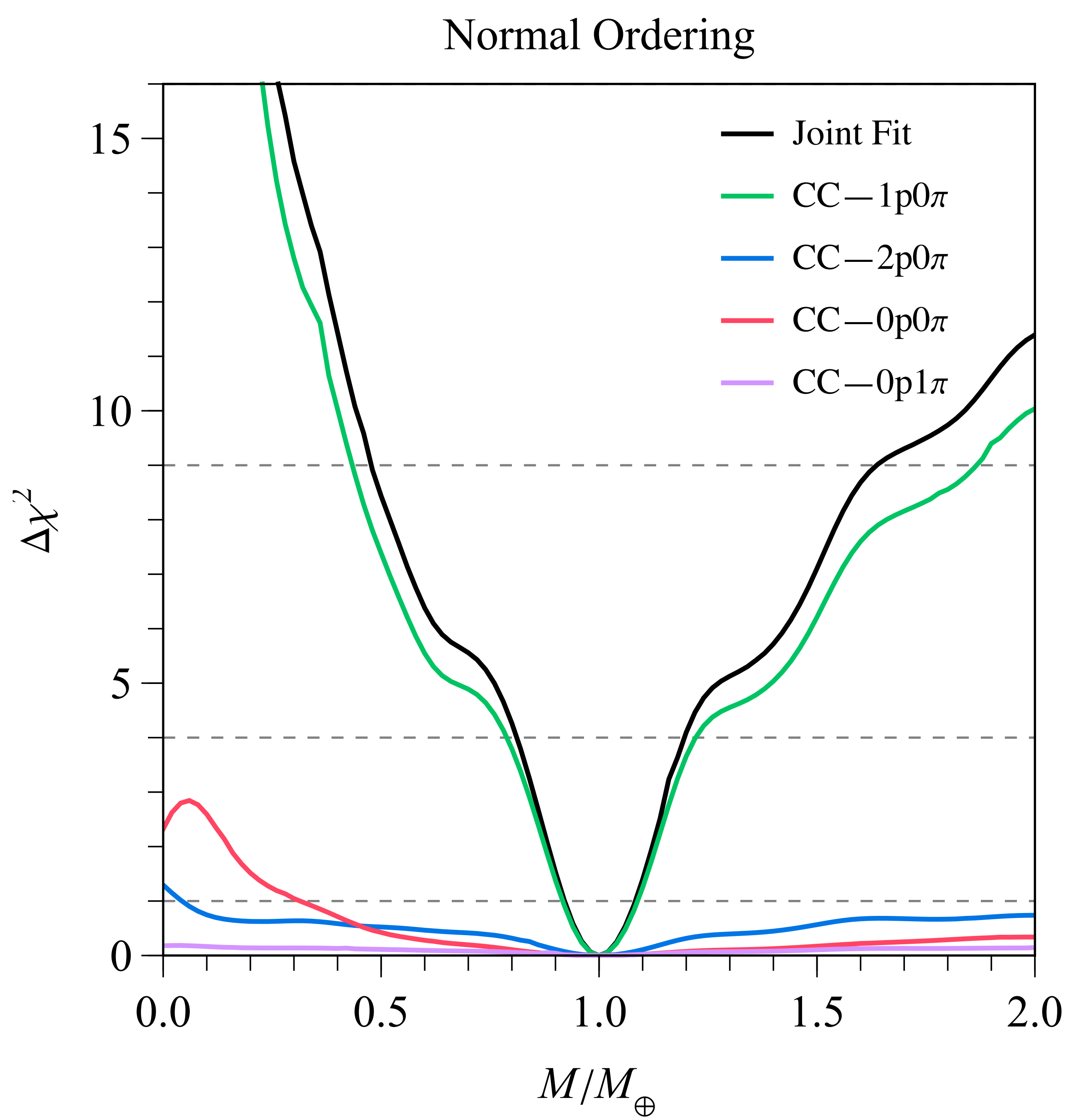


Different conditions lead to an enhancement of the oscillation probability, see, e.g. 2110.00003

Extremely dependent on the densities of the layers

There are other solutions besides these ones

Earth Matter Profile I: Total mass*



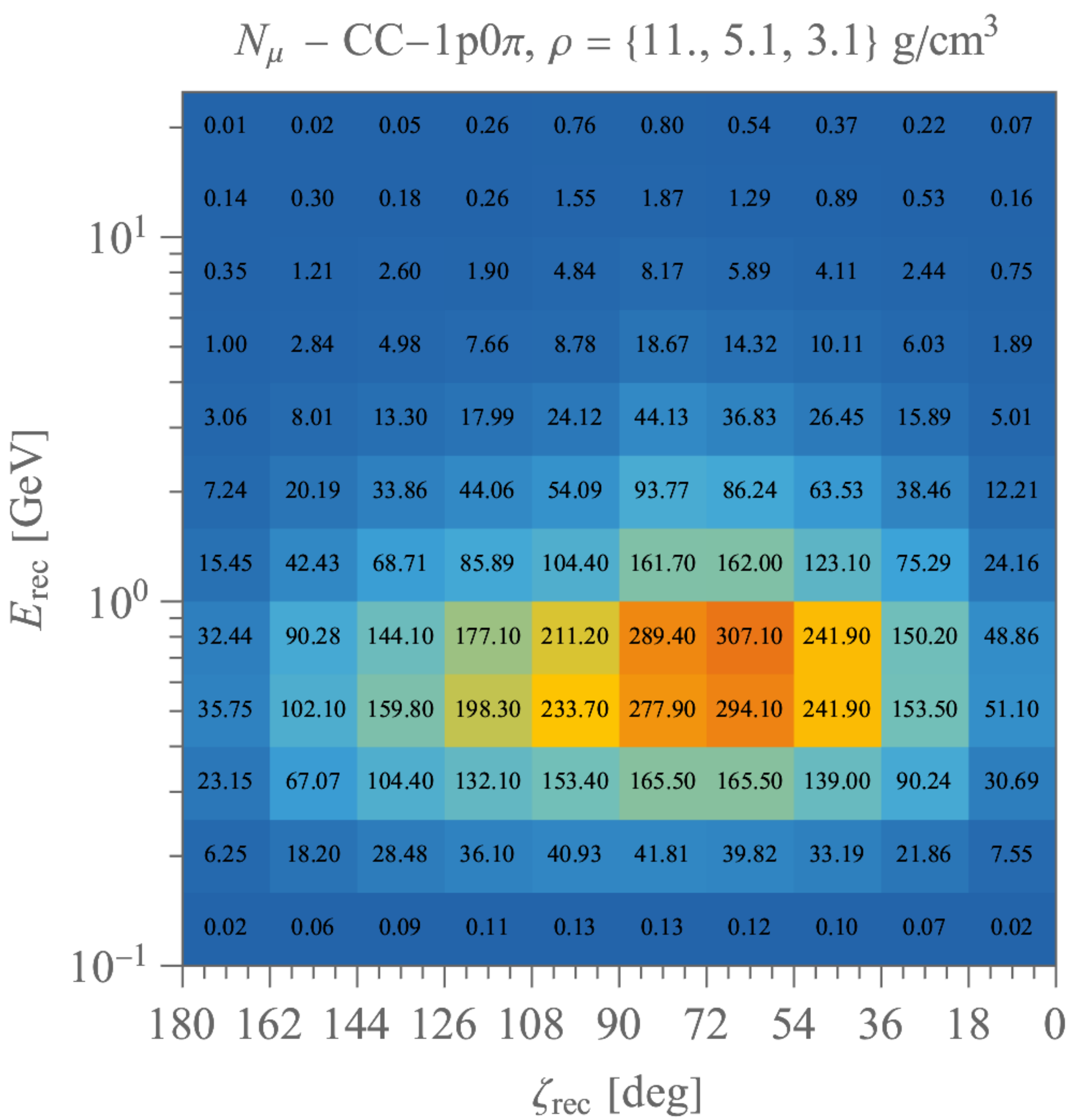
$$M = (1 \pm 0.084) M_\oplus \qquad \text{(400 kton-year exposure)}$$

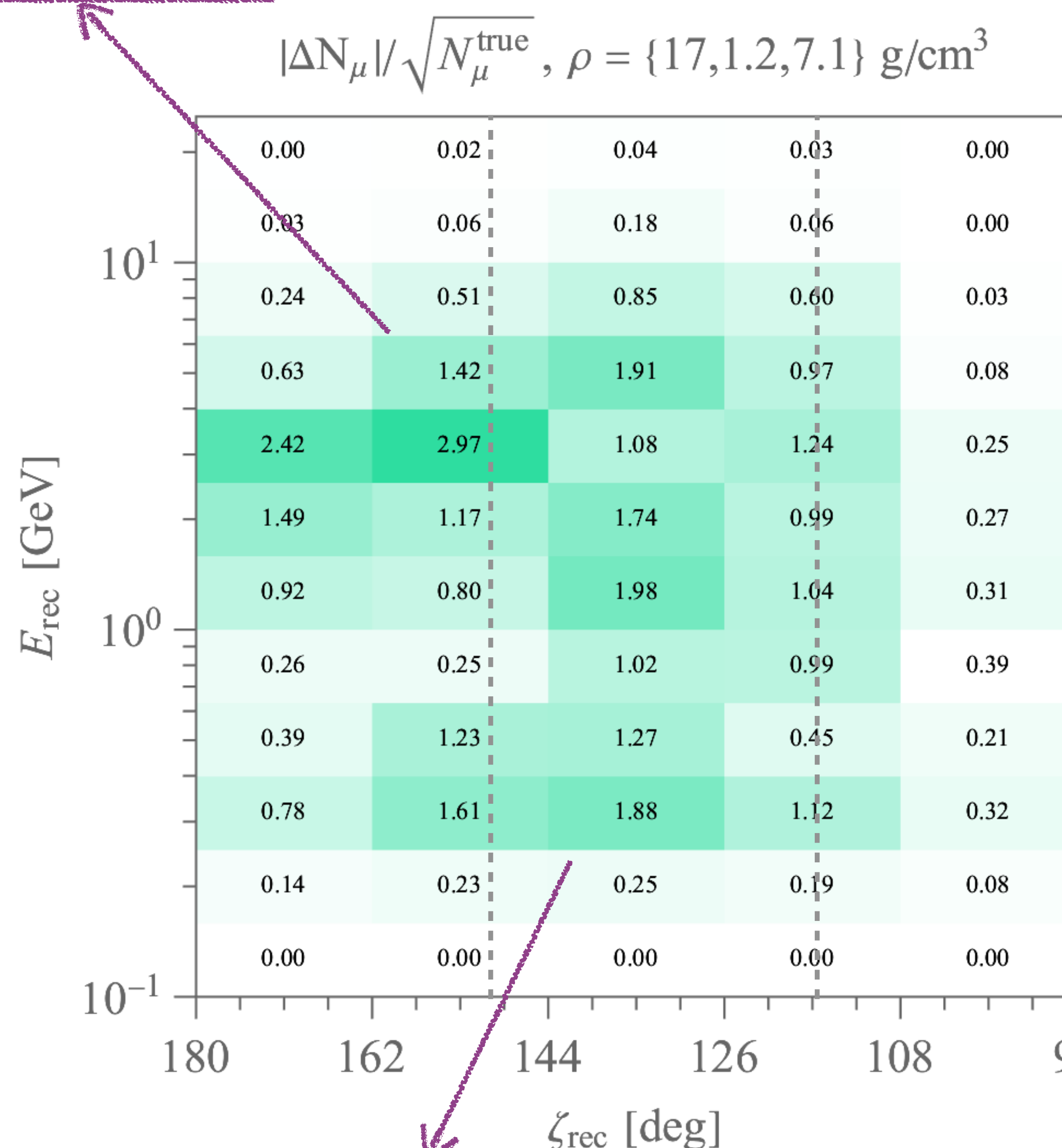
Kelly, Machado, Martinez-Soler, and YFPG, 2110.00003

*recall that oscillations are sensitive to the electron density, thus we can extract the chemical composition as well

DUNE — Reconstruction Capabilities

Parm Enhancement at core-mantle @ multi GeV





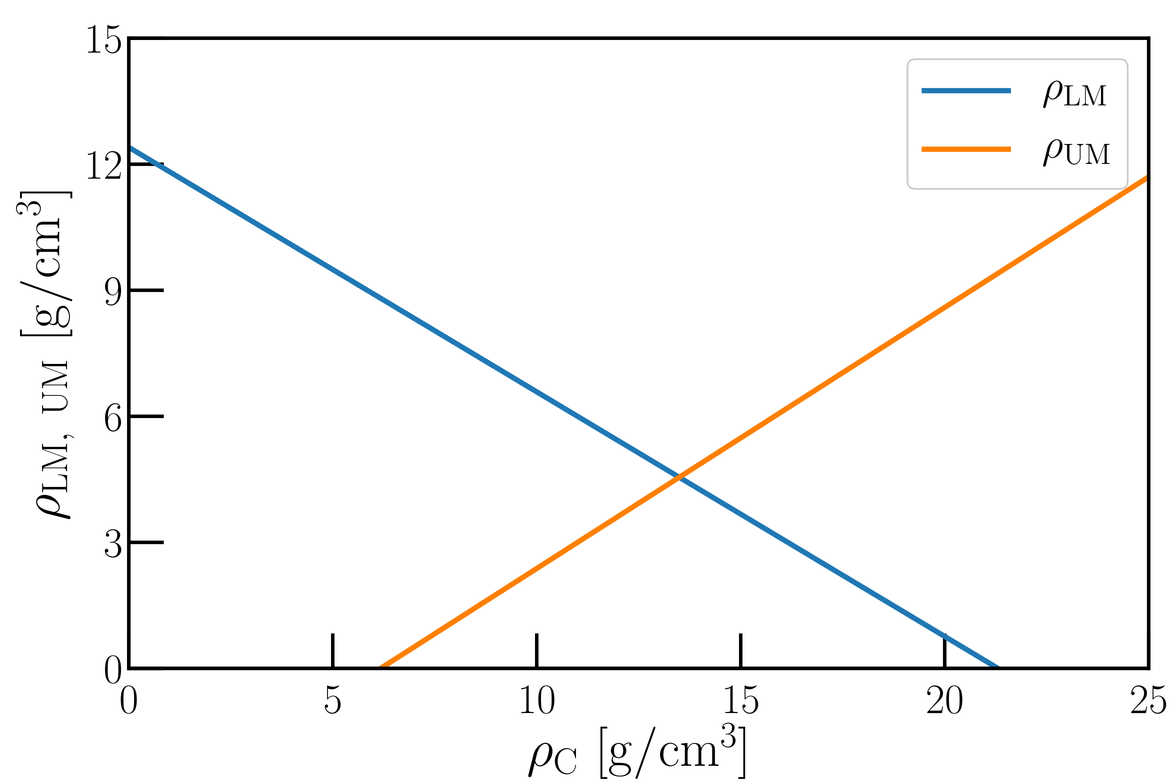
SubGeV MSW in the mantle

Earth Matter Profile II: Core density

Mass and Moment of Inertia constraints

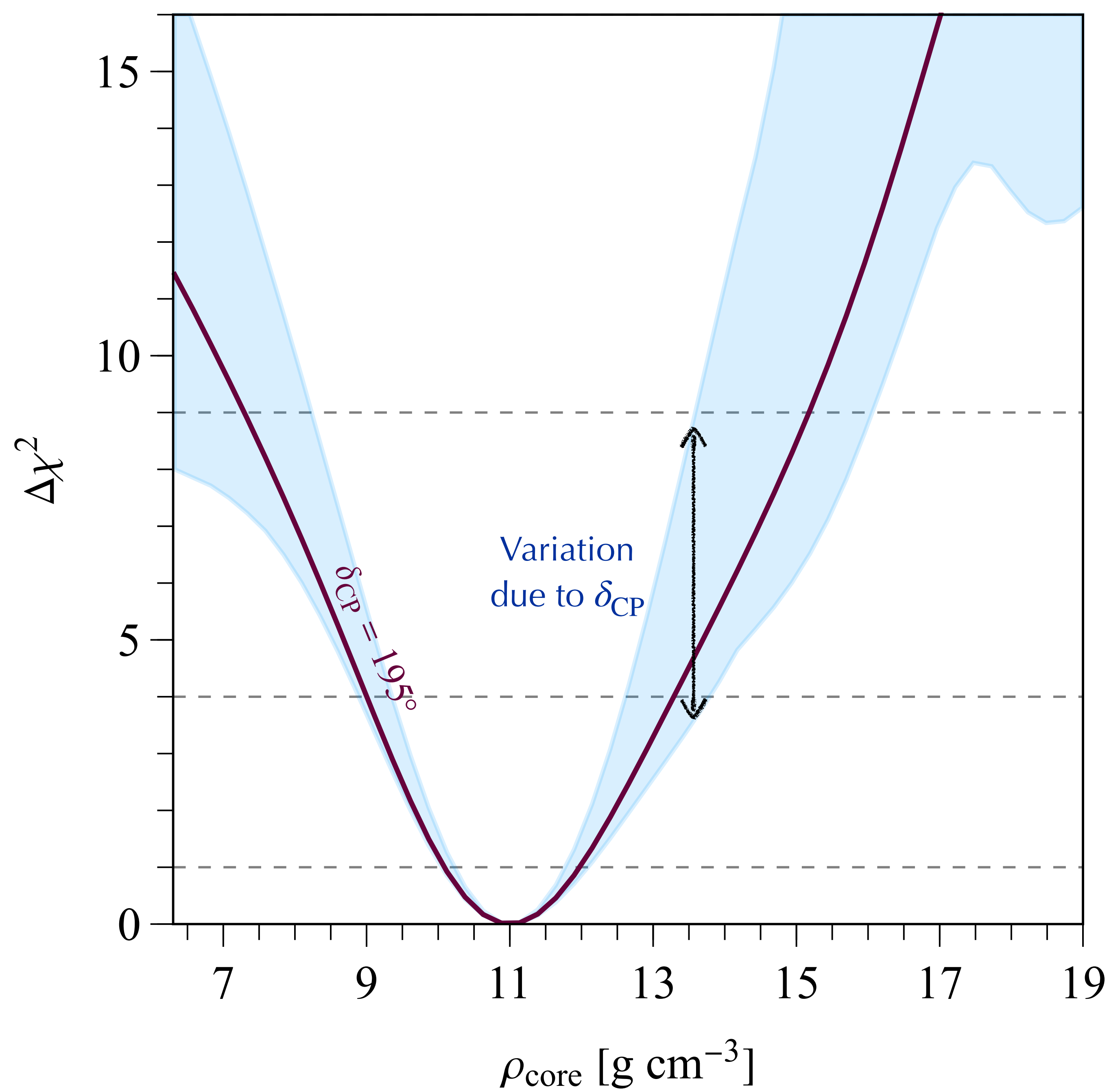
$$M_\oplus = 5.9722 \times 10^{24}\ \text{kg}$$
$$I_\oplus = 8.01738 \times 10^{37}\ \text{kg m}^2$$

$$M_\oplus = \frac{4\pi}{3}\left[\rho_C R_C^3 + \rho_{LM}\left(R_{LM}^3 - R_C^3\right) + \rho_{UM}\left(R_\oplus^3 - R_{LM}^3\right)\right],$$
$$I_\oplus = \frac{8\pi}{15}\left[\rho_C R_C^5 + \rho_{LM}\left(R_{LM}^5 - R_C^5\right) + \rho_{UM}\left(R_\oplus^5 - R_{LM}^5\right)\right].$$



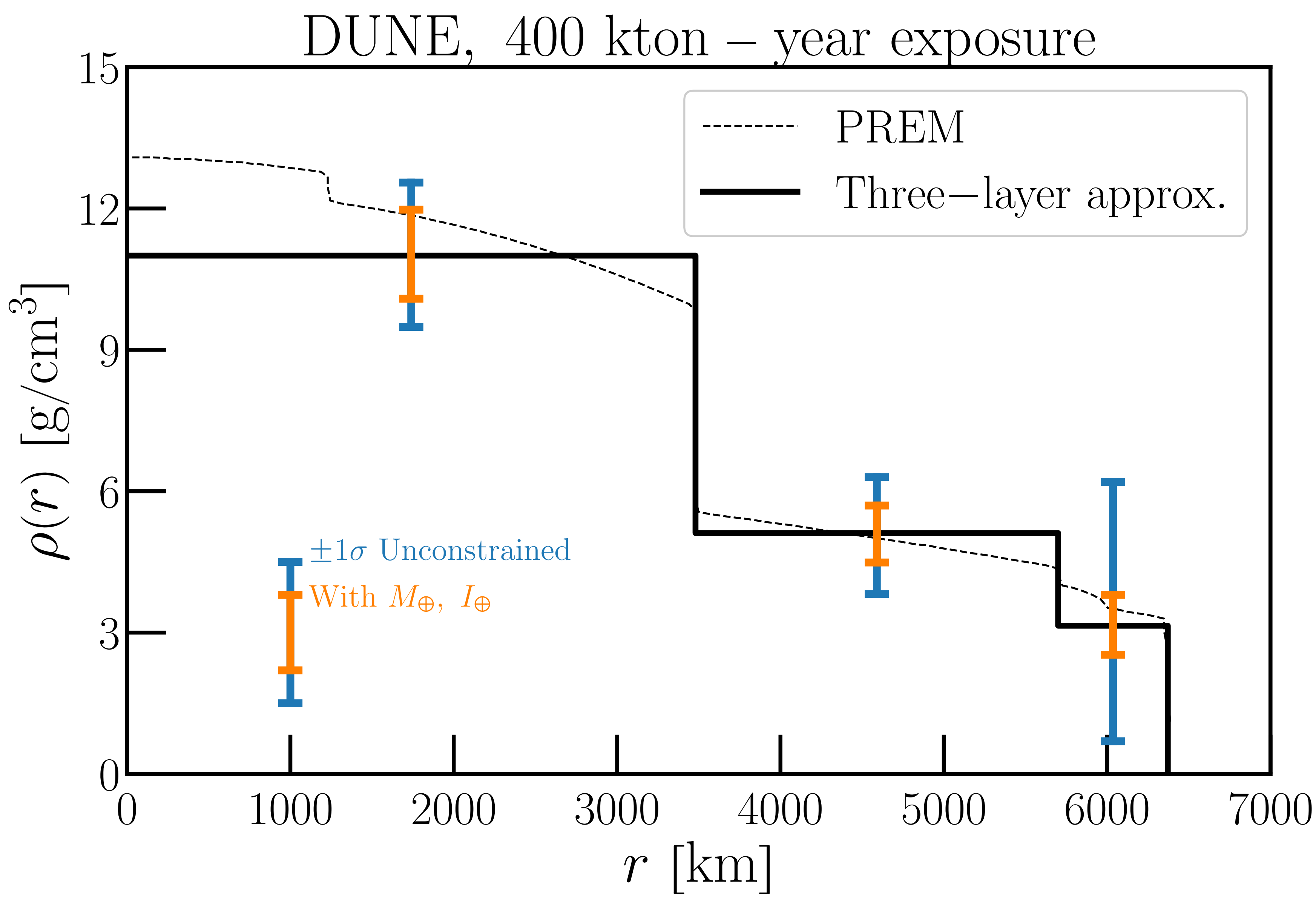
$$\rho_C = 11.0 \times (1^{+0.088}_{-0.083})\ \text{g/cm}^3$$

Normal Ordering



Kelly, Machado, Martinez-Soler, and YFPG, 2110.00003

Earth Matter Profile III: No Constraints



At 1σ C.L.:

$$\rho_C = 11.0 \times (1 \pm 0.14)\ \mathrm{g/cm^3}$$
$$\rho_{LM} = 5.11 \times (1^{+0.23}_{-0.25})\ \mathrm{g/cm^3}$$
$$\rho_{UM} = 3.15 \times (1^{+0.97}_{-0.78})\ \mathrm{g/cm^3}$$

Exclude a “coreless” Earth at $\sim 2\sigma$

Exclude a “mantleless” Earth at $\gtrsim 3\sigma$

Kelly, Machado, Martinez-Soler, and YFPG, 2110.00003

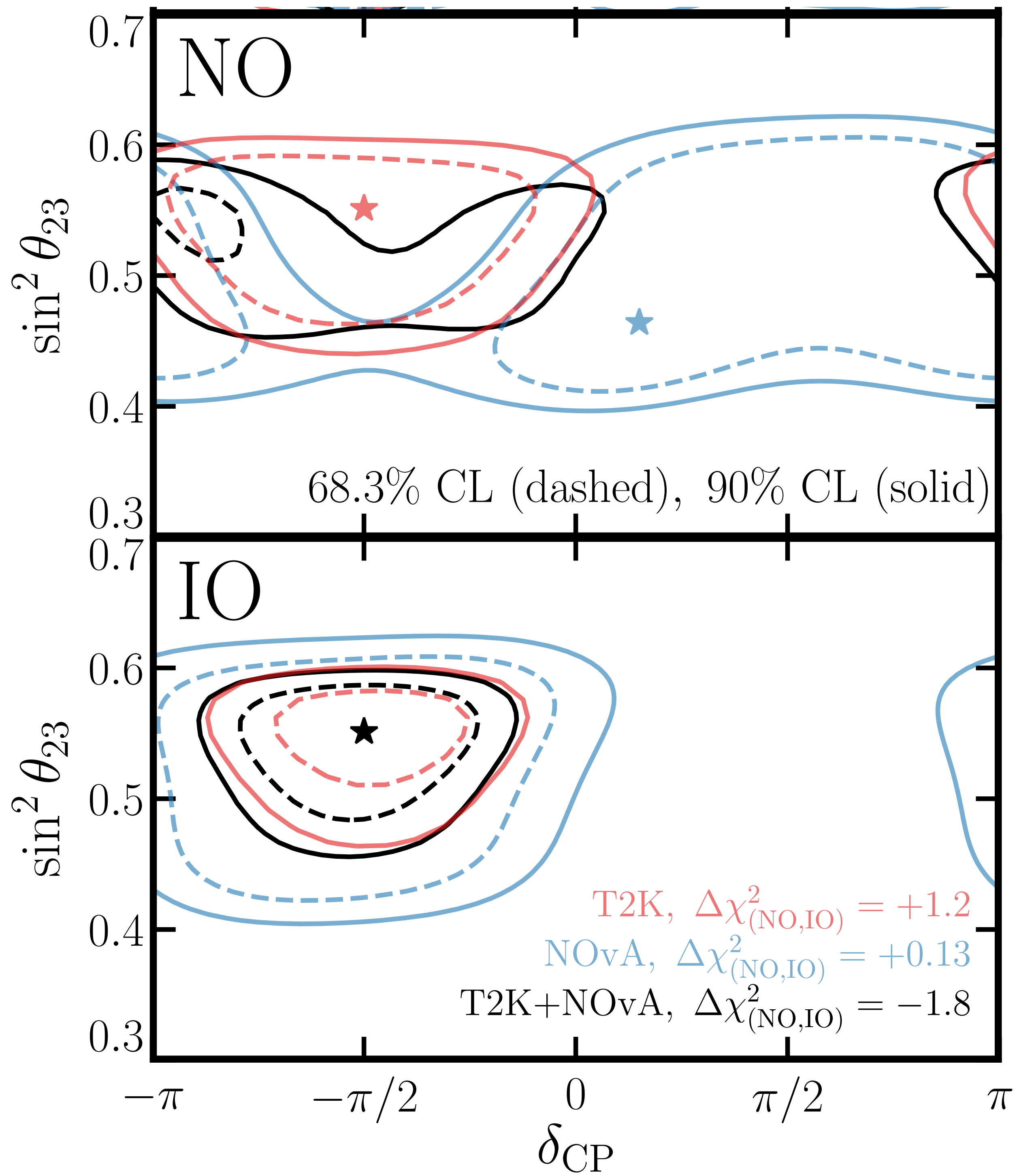
Conclusions

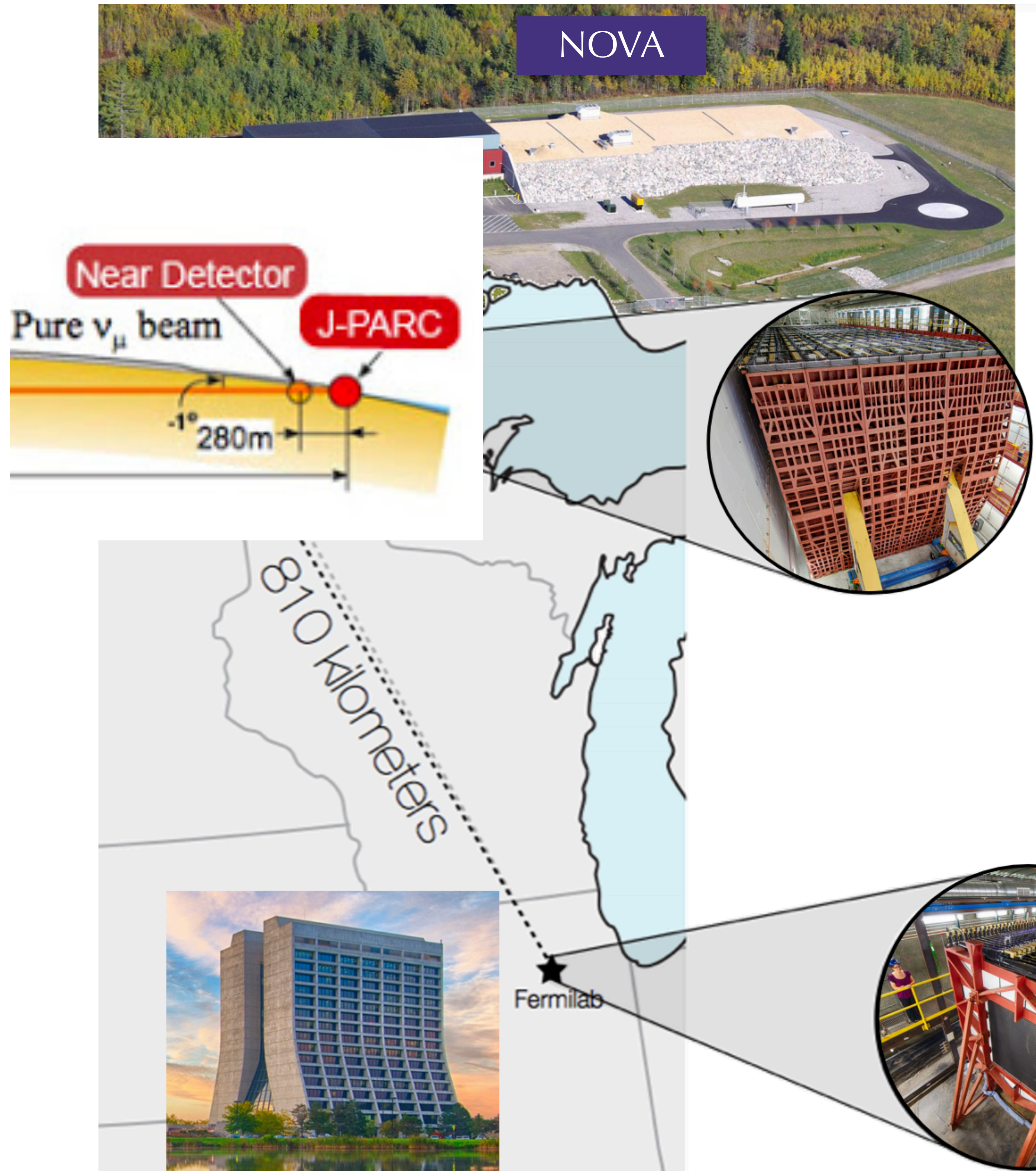
- Atmospheric neutrinos and their oscillations through the Earth present a whole new phenomena, yet to be fully explored.
- Expected capabilities of LArTPC offer a unique laboratory to measure atmospheric neutrinos from ~100 MeVs up to ~30 GeV.
- Assuming realistic resolutions for different particles and topologies, we have demonstrated that DUNE will be able to constrain the CP violation phase using sub-GeV atmospheric neutrinos, excluding some regions with $\gtrsim 3\sigma$.
- Moreover, DUNE has the capability to determine the total Earth's mass at the 10% after 10 years, and the density profile, i.e., the densities of the Core and Mantle at a 9% (25%) with (without) constraints on the mass and moment of inertia
- BSM??

Thank you!

Backup

Accelerator Neutrinos





Alex Himmel, Neutrino 2020

Kelly, Machado, Parke, YFPG, and Funchal 2007.08526

MINOS, T2K, NOvA… DUNE

Measurement of Δm^2_{3j}, θ_{23} and δ_{CP}

What do we know about neutrino masses and mixing?

Neutrinos oscillate!!

Mixing

$$|\nu_\alpha\rangle = \widetilde{U}^*_{\alpha a}|\nu_a\rangle$$

$$\Delta_{ab} = \frac{\Delta m^2_{ab}}{2E}.$$

$$P(\nu_\alpha \to \nu_\beta) = \sum_{a,b} \widetilde{U}^*_{\alpha a}\widetilde{U}_{\beta a}\widetilde{U}_{\alpha b}\widetilde{U}^*_{\beta b}\, e^{i\Delta_{ab}L}$$

$$\Delta m^2_{ab} = m^{\nu\,2}_a - m^{\nu\,2}_b$$

Neutrinos are usually ultrarelativistic

PMNS Mixing matrix

$$\widetilde{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\,e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\,e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}\,e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}\,e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}\,e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

2 more phases if neutrinos are Majorana

$c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij}$

2 to 3 flavor probabilities

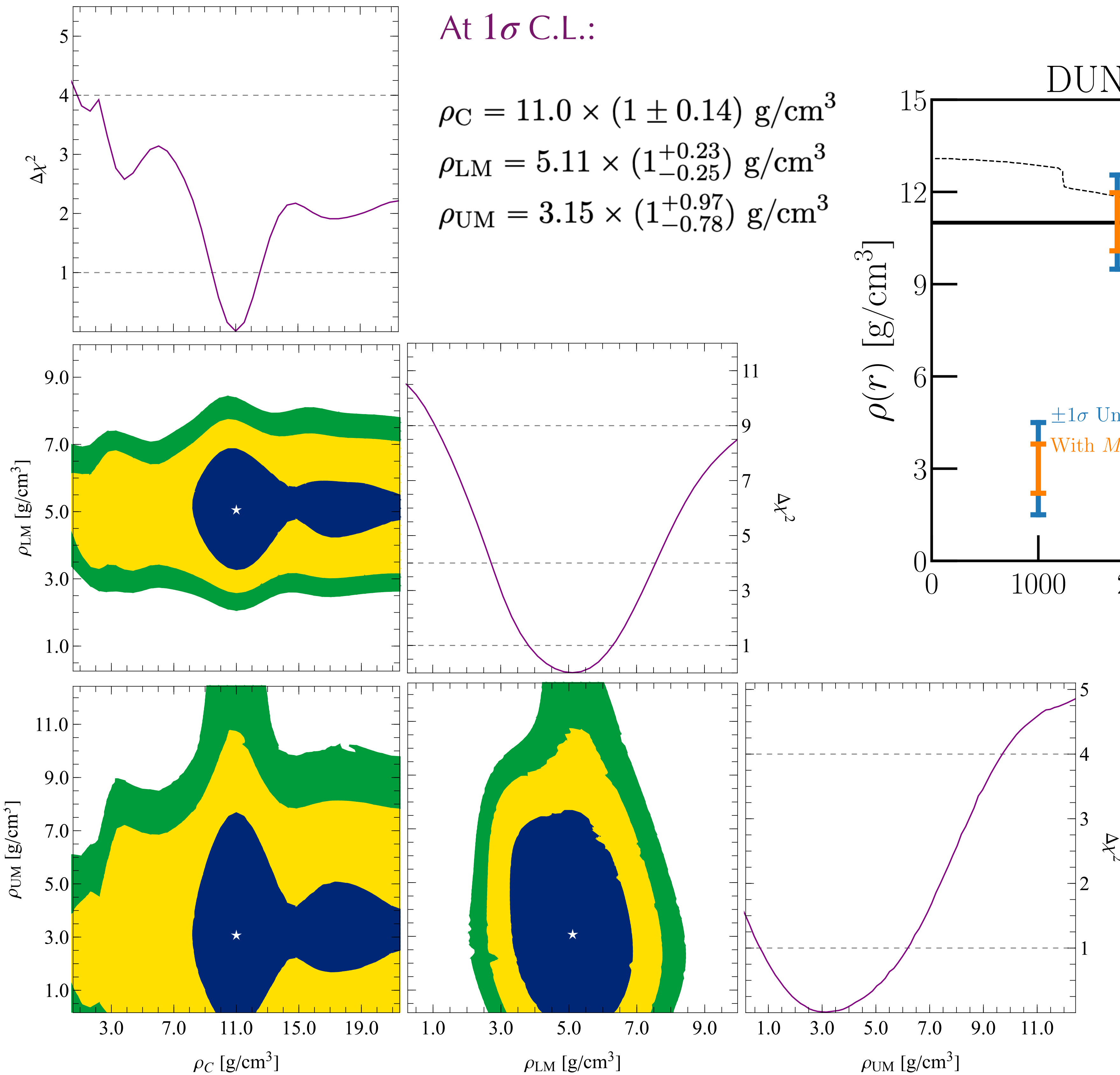
- Solar limit $E \ll E^{\rm atm}_{\rm MSW}$ $\sin^2\theta_{13} \to 0$

$$P_{\nu_\mu \to \nu_e} \approx \cos^2\theta_{23} P^{\rm 2f}_{\alpha\beta}(\Delta m^2_{21}, \theta_{12})$$

- Atmospheric limit $\Delta m^2_{21} \to 0$ and/or $\theta_{12} \to 0$

$$P_{\nu_\mu \to \nu_e} \approx \sin^2\theta_{23} P^{\rm 2f}_{\alpha\beta}(\Delta m^2_{31}, \theta_{13})$$

Earth Matter Profile III: No Constraints

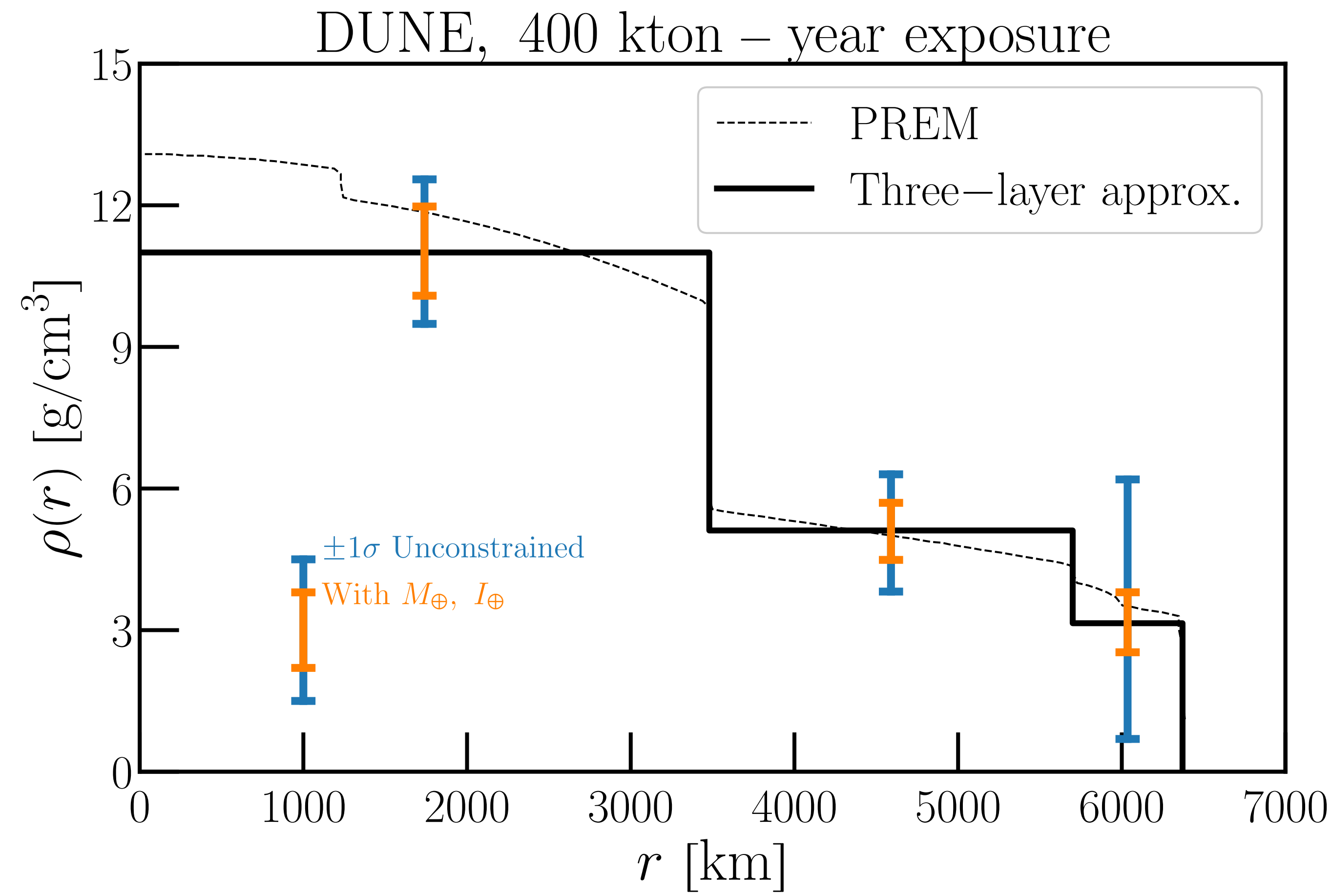


At 1σ C.L.:

$$\rho_C = 11.0 \times (1 \pm 0.14)\ \mathrm{g/cm^3}$$

$$\rho_{LM} = 5.11 \times (1^{+0.23}_{-0.25})\ \mathrm{g/cm^3}$$

$$\rho_{UM} = 3.15 \times (1^{+0.97}_{-0.78})\ \mathrm{g/cm^3}$$



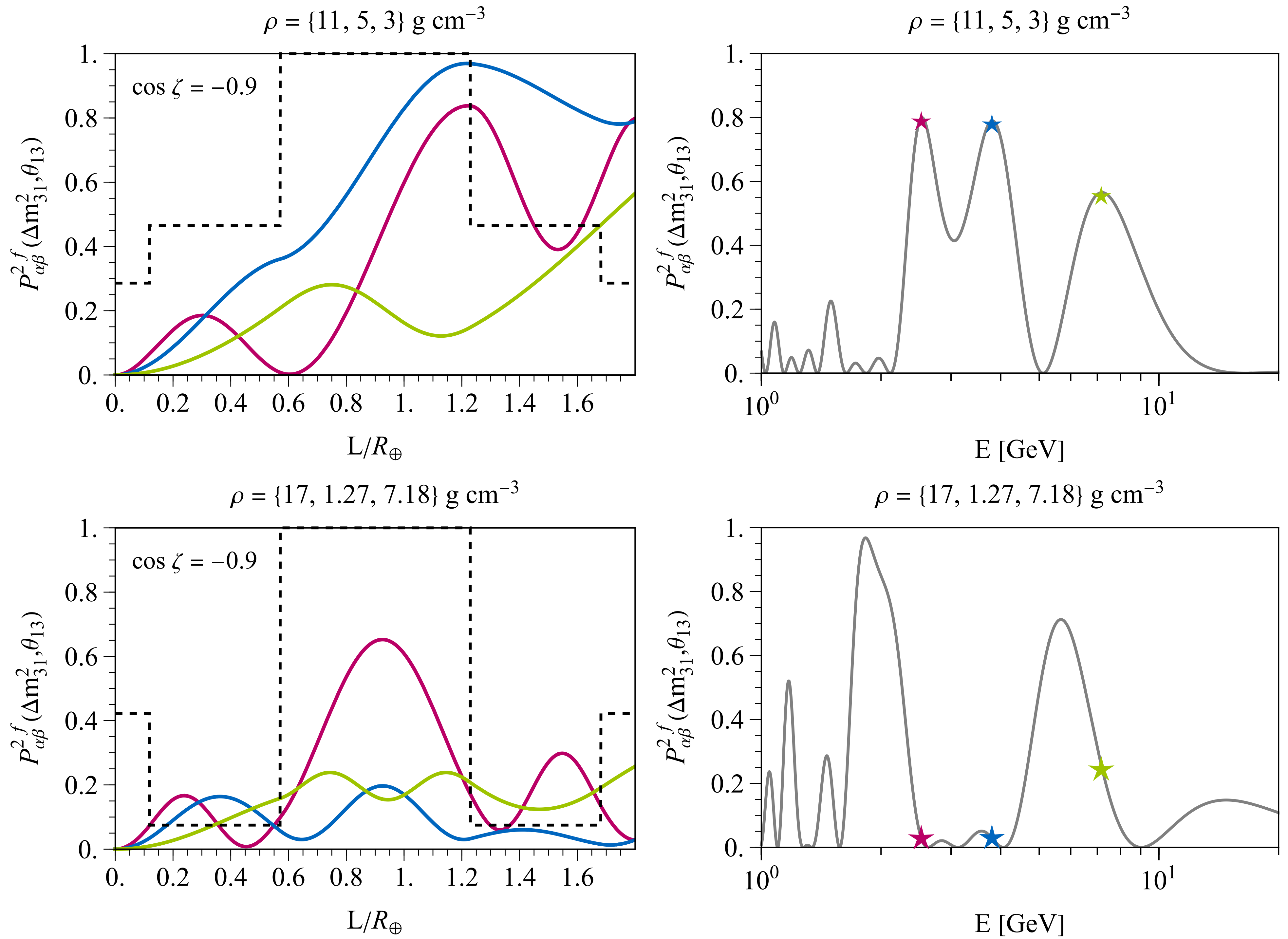
Exclude a "coreless" Earth at $\sim 2\sigma$

Exclude a "mantleless" Earth at $\gtrsim 3\sigma$

Kelly, Machado, Martinez-Soler, and YFPG, 2110.00003

Oscillation Probabilities — MSW and Parametric

Parametric Enhancement!



Oscillation Probabilities — MSW and Parametric

Parametric Enhancement!