

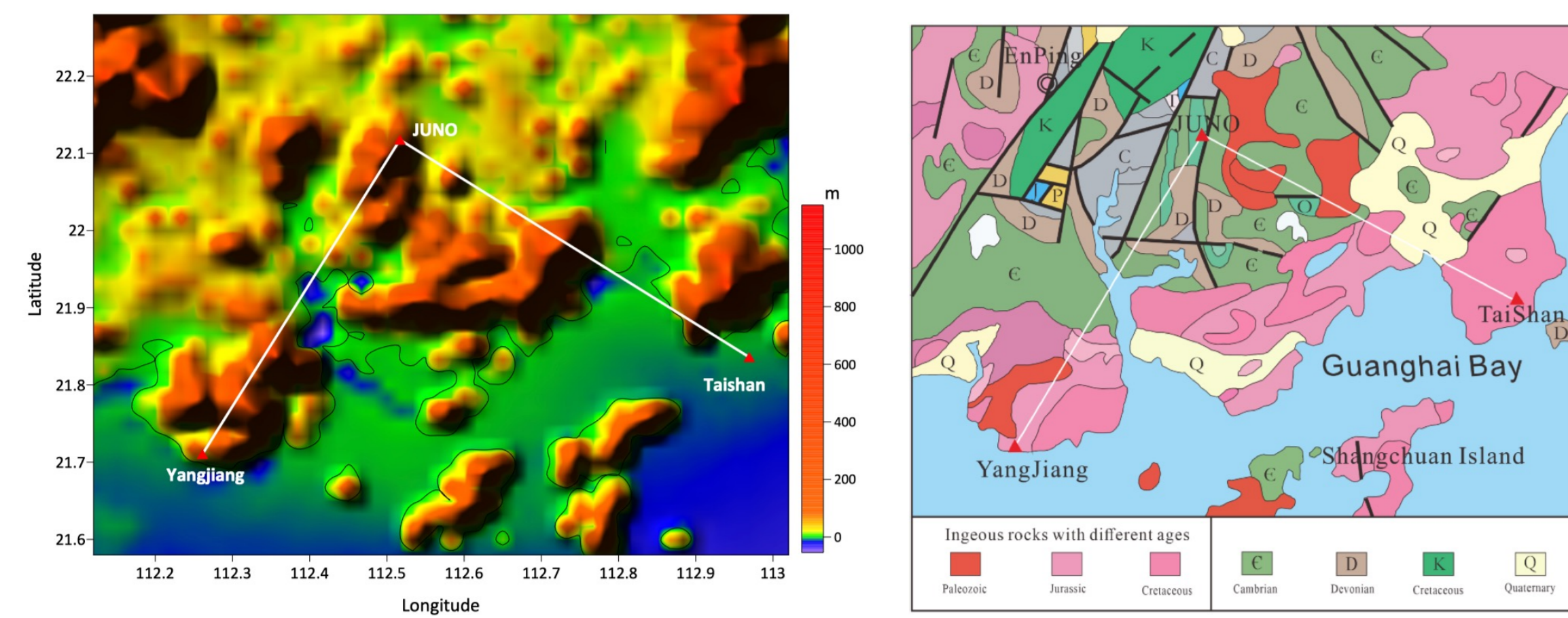
1 Motivation: why matter effects matter

- JUNO has entered the precision era, where matter effects are no longer negligible.
- In Ref. [1], the authors have pointed out:
 - Terrestrial matter effects at JUNO are small but non-negligible.
 - Including matter effects can reduce the mass-ordering (MO) sensitivity by $\Delta\chi_{MO}^2 \approx 0.6$.
 - Neglecting matter effects can shift the fitted θ_{12} and Δm_{21}^2 by about 1σ – 2σ .



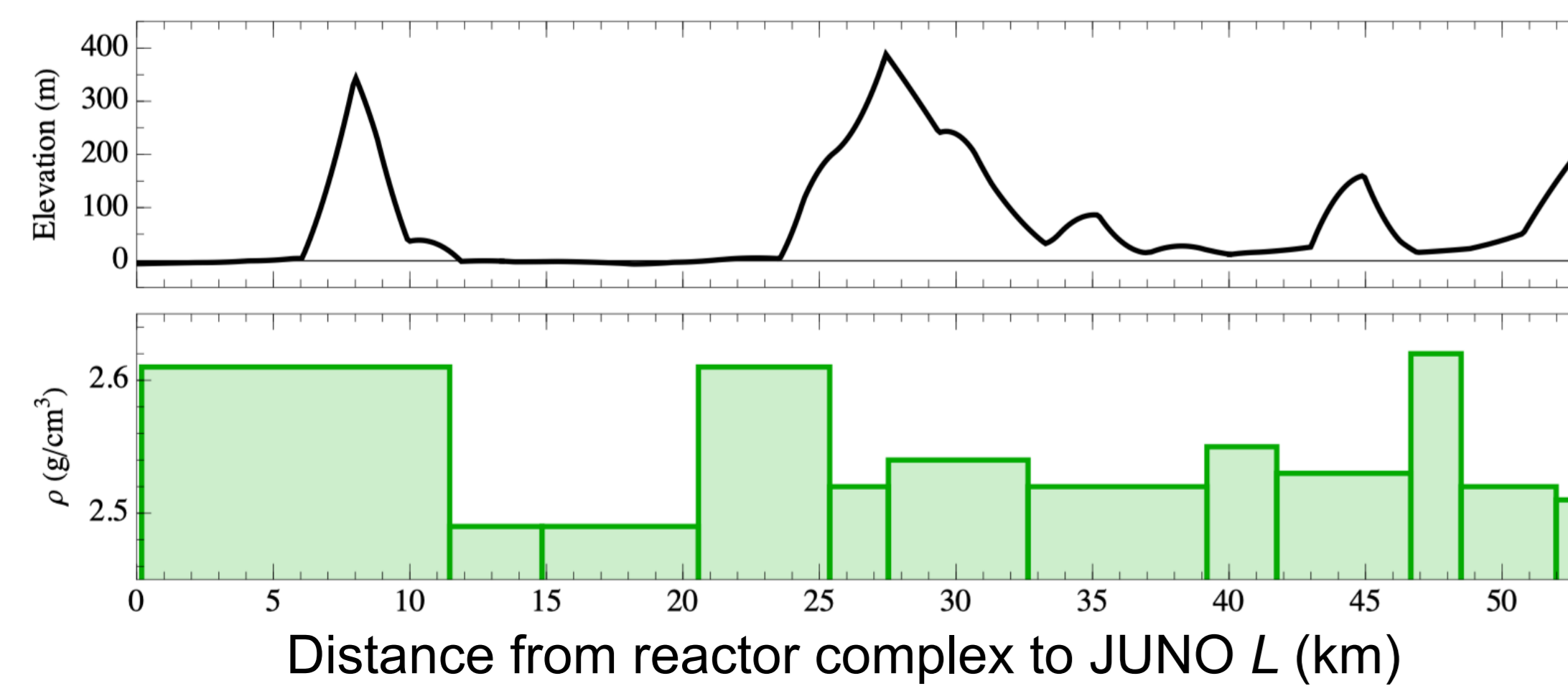
If matter effects themselves must be included, does the realistic variation of the shallow-crust density profile also affect the extracted physics results?

2 Model from local geology



Below we use the Taishan (TS) baseline as the main example; Yangjiang (YJ) gives similar conclusions.

Segmented shallow-crust density profile (TS)



- Effective profiles:** TS has 13 segments and YJ has 15 segments, including the initial air segment.
- Average densities:** $\bar{\rho}_{TS} \approx 2.541 \text{ g cm}^{-3}$ and $\bar{\rho}_{YJ} \approx 2.554 \text{ g cm}^{-3}$.

3 Conservative density fluctuations

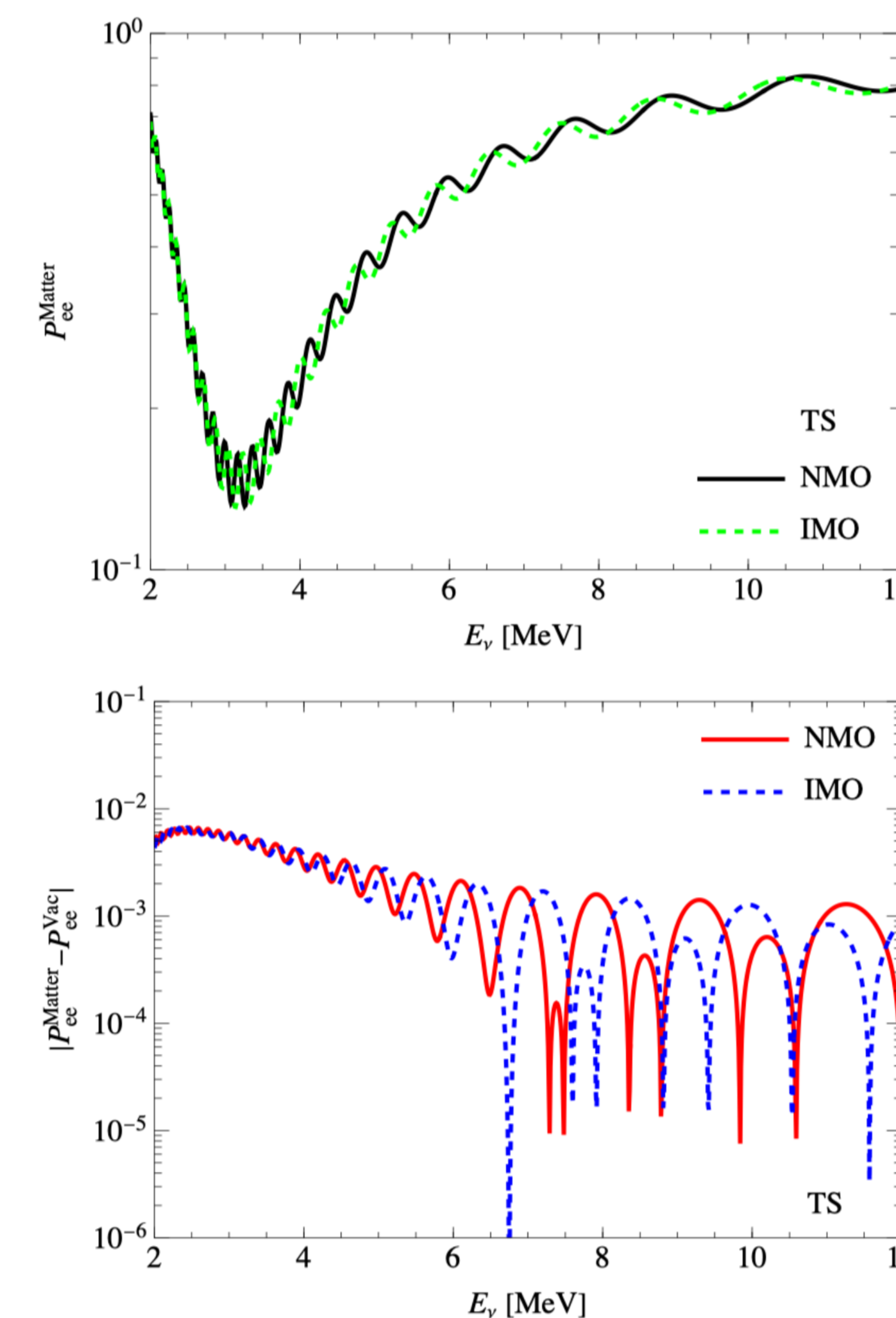
We adopt conservative, geologically motivated fluctuation treatments with a $\pm 10\%$ amplitude.

- Scenario A (coherent shift):** all rock-segment densities are coherently rescaled by $\pm 10\%$.
- Scenario B (independent fluctuations):** each rock-segment density and effective length fluctuates independently within $\pm 10\%$, while the total baseline length is fixed.

Average-density stability

- Scenario A:** tests the extreme coherent density shift.
- Scenario B:** represents fine-structure fluctuations.
 - For the TS baseline, the baseline-averaged density remains very stable: one-sigma spread $\approx 1.5\%$.
 - About 95% of random realizations stay within $\pm 3\%$ of the reference value.
 - Length fluctuations alone have a tiny impact on the average density.

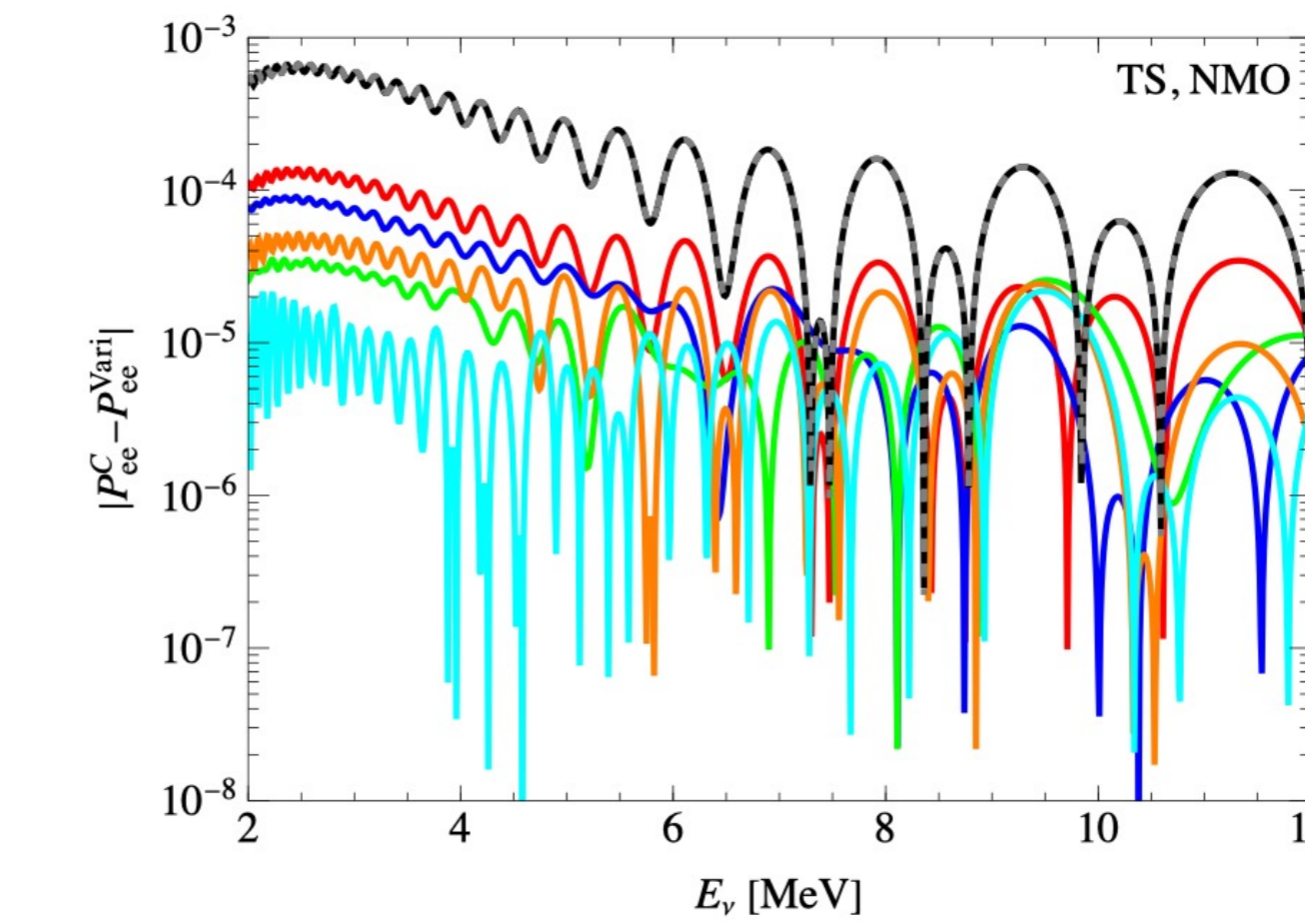
4 Matter effect versus vacuum (TS only)



The matter effect itself produces an $O(1\%)$ spectral distortion relative to the vacuum expectation and is already comparable to JUNO's precision goals.

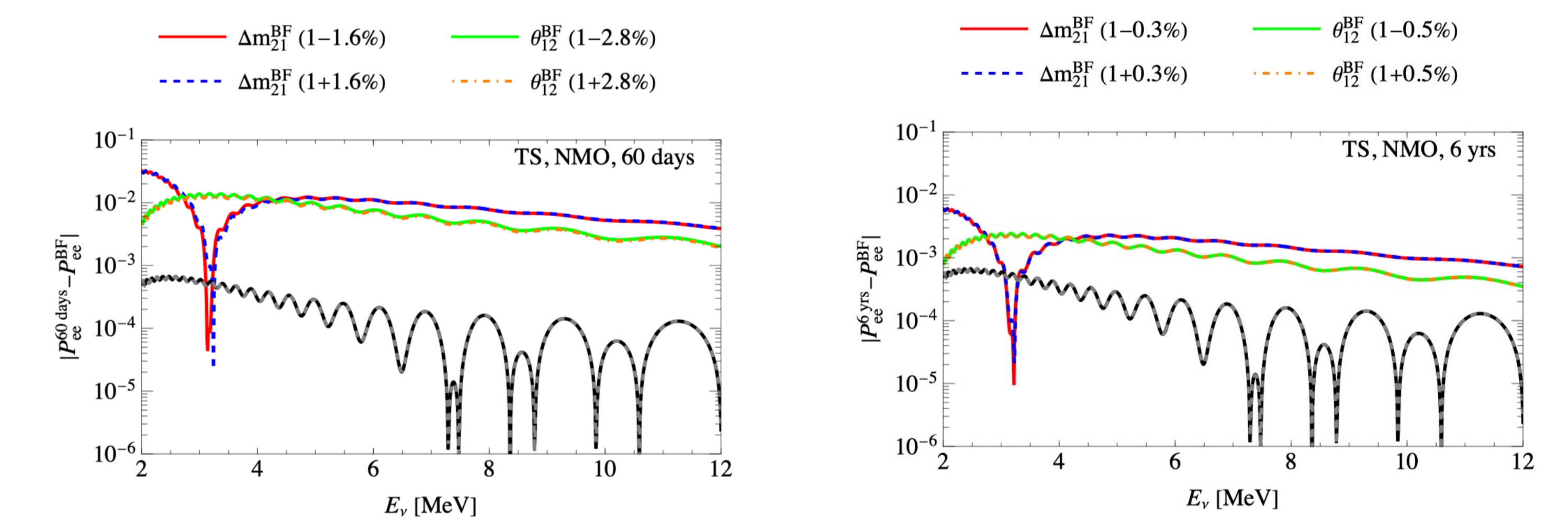
5 Constant vs. fluctuated profiles (TS only)

A Difference between constant and variable profiles



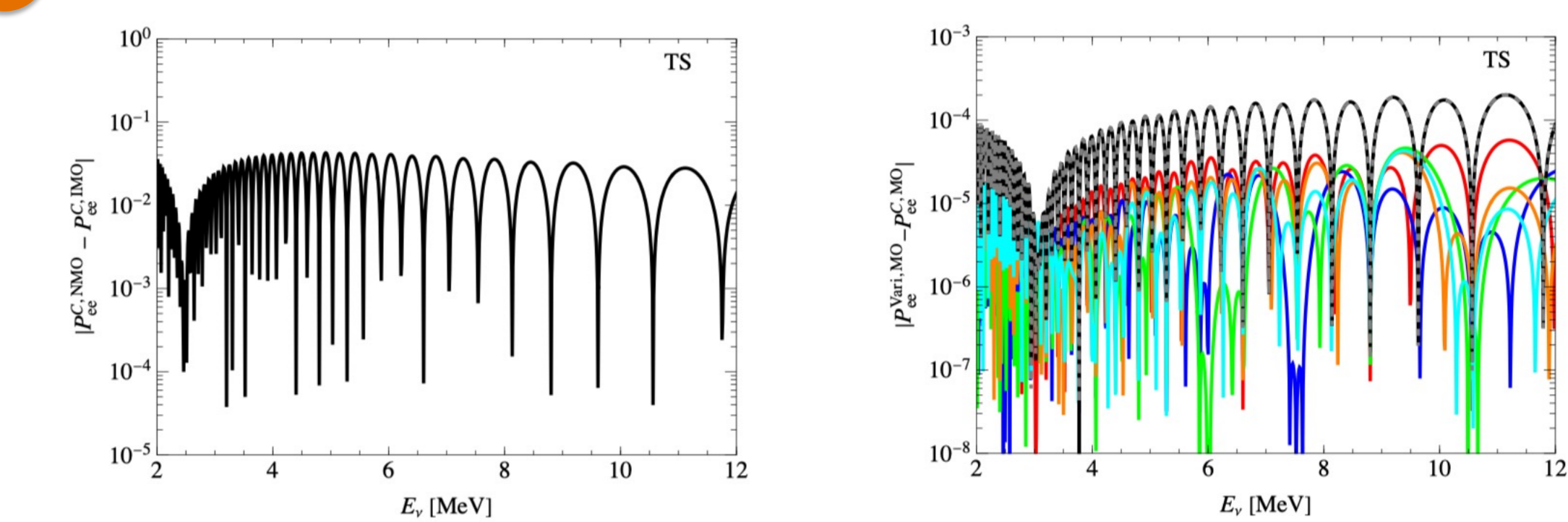
Scenario A (coherent shift, black and gray lines) reaches $\sim 10^{-3}$, whereas Scenario B (independent fluctuations, colored curves) is mostly $\leq 10^{-4}$ thanks to statistical averaging.

B Density-profile vs. oscillation-parameter uncertainties



Density-profile uncertainties are more than one order of magnitude smaller than current parameter-induced uncertainties, but become increasingly relevant as JUNO precision improves.

C Impact on mass-ordering discriminator



Profile variations modify the mass-ordering discriminator only at $\sim 10^{-4}$, i.e. $\sim 1\%$ of the overall NMO–IMO separation. The mass-ordering determination remains robust.

6 Outlook / take-home message

Localized shallow-crust density anomalies induce only tiny additional corrections, so JUNO's oscillation measurements remain robust against realistic anomalous density structures.

Take-home message

- ✓ Matter effects themselves must be modeled in JUNO precision analyses.
- ✓ A constant average density is adequate for current MO sensitivity.
- ✓ Realistic density-profile variations are subleading but nonzero and should be modeled explicitly for future per-mille precision oscillation physics.