The Present and Future of CP Violation in Neutrinos at DUNE

Julia Gehrlein

Physics Department
Colorado State University

Decades of Discovery at Brookhaven National Laboratory

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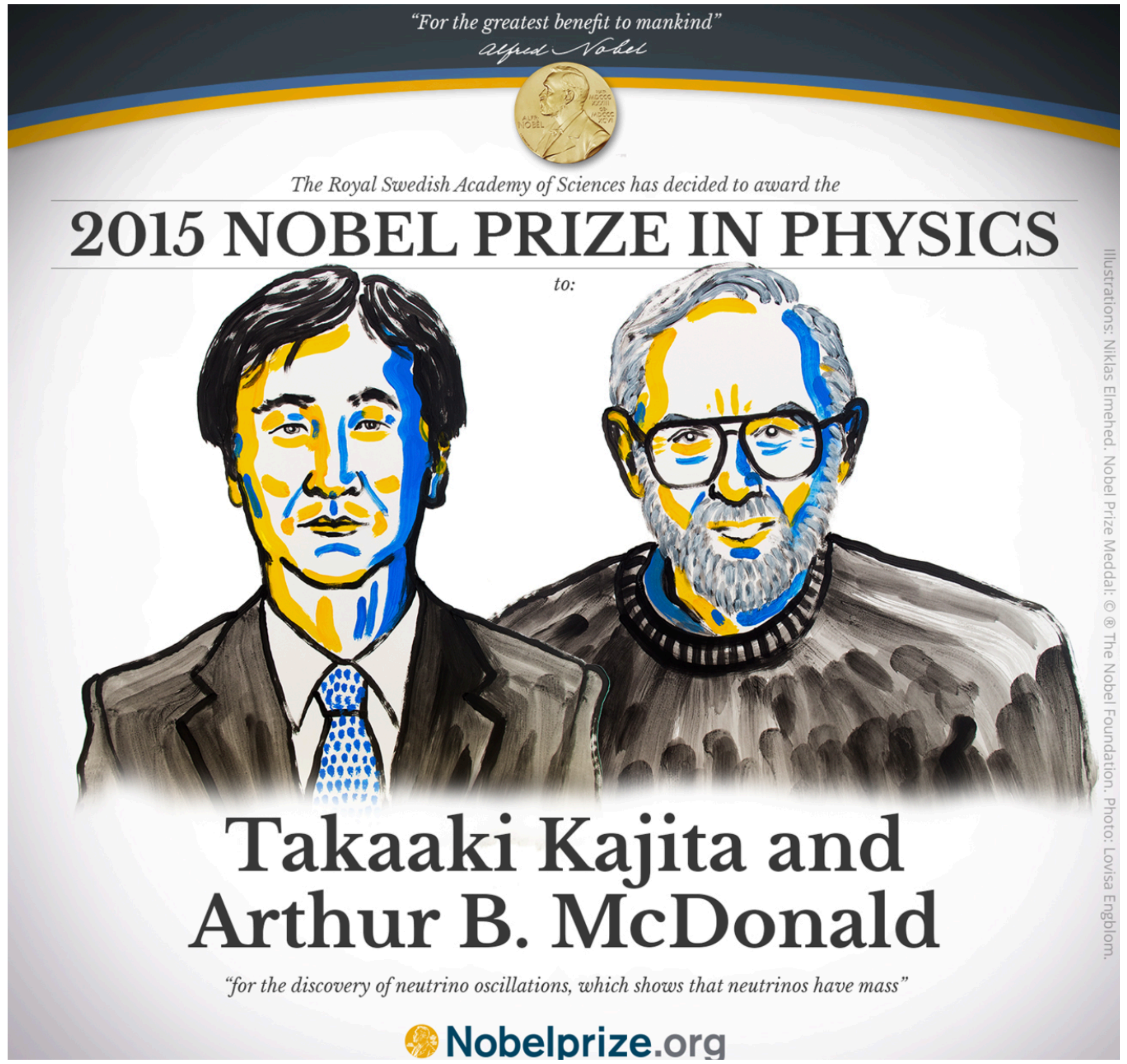
COLORADO STATE UNIVERSITY

Neutrino oscillations

Study of neutrino oscillations in past decades

Coherent picture of 3-flavor neutrino oscillation has emerged

(Although some anomalies still unresolved)



Neutrino oscillations

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Observation of neutrino oscillations

neutrino masses:
At least two neutrinos have non-zero mass
→ have to go beyond SM

Introduce at least 7 new parameters to model
→ want to measure them

Neutrino mixing parameters

All three neutrino mixing angles are non-zero

$\rightarrow$ possibility for CP violation in the lepton sector

Amount of CP violation in mass matrices quantified via Jarlskog invariant

$$J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta$$

[Jarlskog '85]

$$J_{CP}^{\max} = 1/(6\sqrt{3}) \approx 0.096$$

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[Jarlskog '85]

Known

Need to measure δ

If $\delta = 0,\ \pi$: CP conservation

If $\delta = \pm\,\pi/2$: maximal CP violation

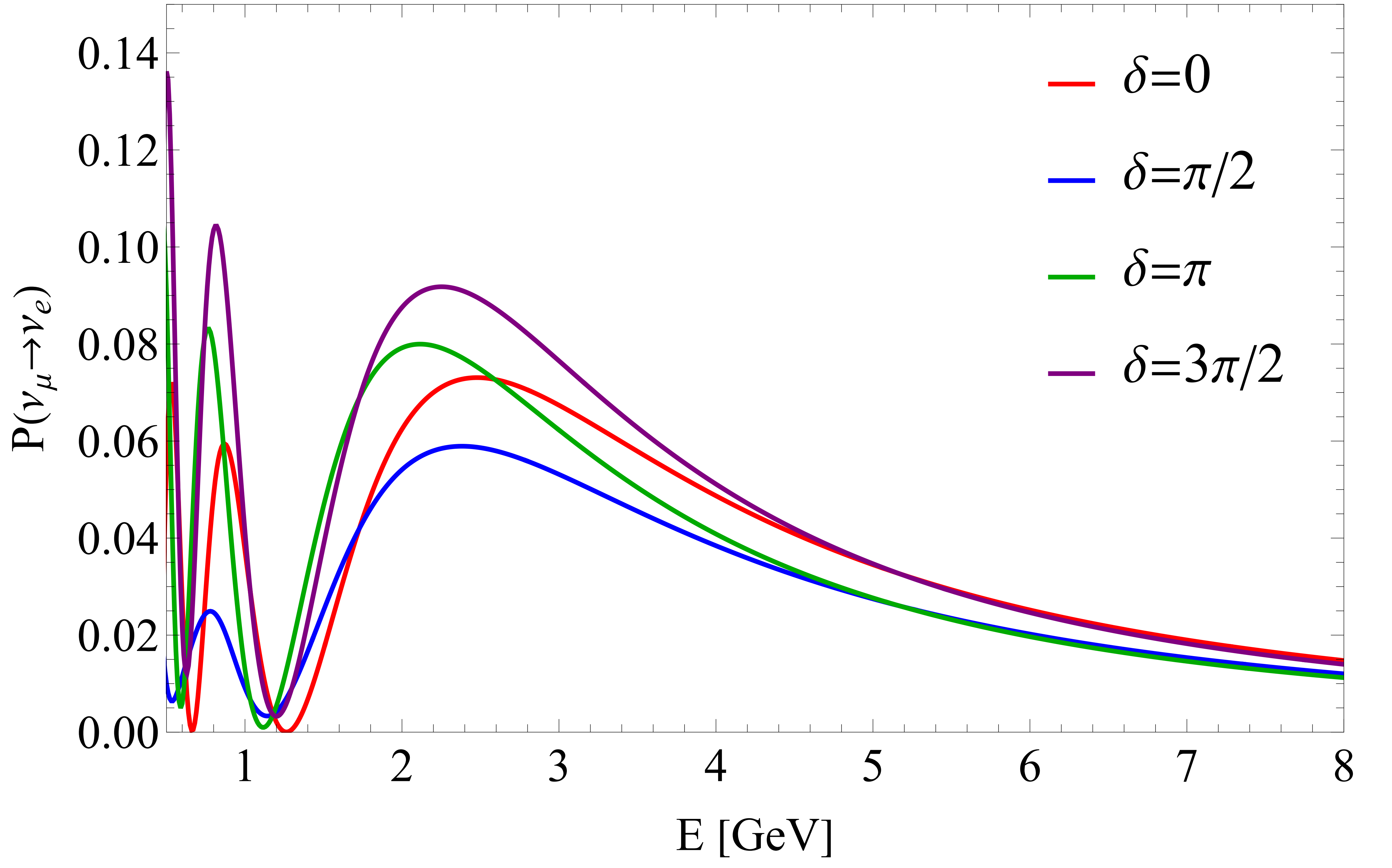
Measuring CP in neutrinos

How do we measure δ?

Use long-baseline experiments:

$\overset{(-)}{\nu}_e$ appearance probability in $\overset{(-)}{\nu}_\mu$ beam depends on δ

(However also dependence on mass ordering, other oscillation parameters)



To alleviate effects of systematics uncertainties:
Compare neutrino to anti-neutrino channel

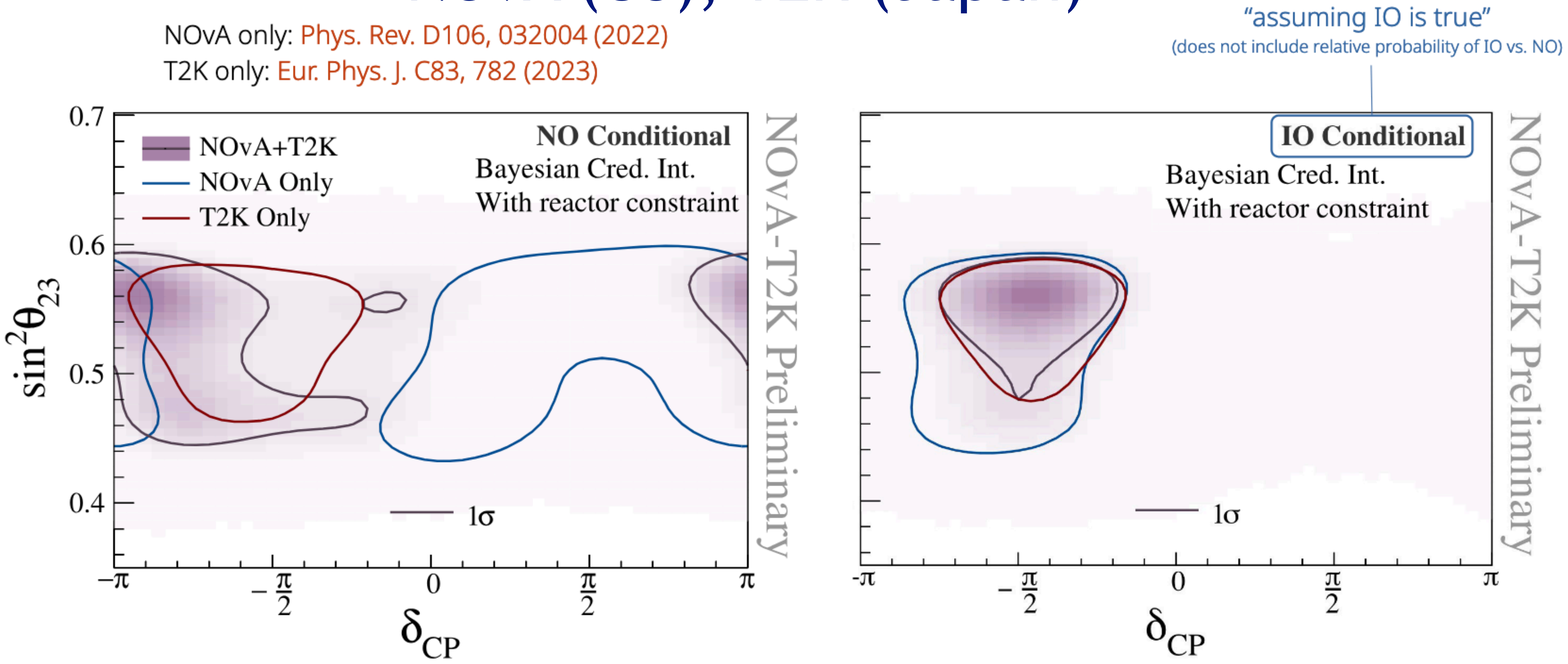
If they behave differently
$\rightarrow$ CP violation

Measuring CP in neutrinos

Current status of the measurement of δ

Current experiments long-baseline experiments:
NOvA (US), T2K (Japan)

NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)



[Wolcott Neutrino 2024]

In normal ordering: slight disagreement

In inverted ordering: improvement on constraints

Measuring CP in neutrinos

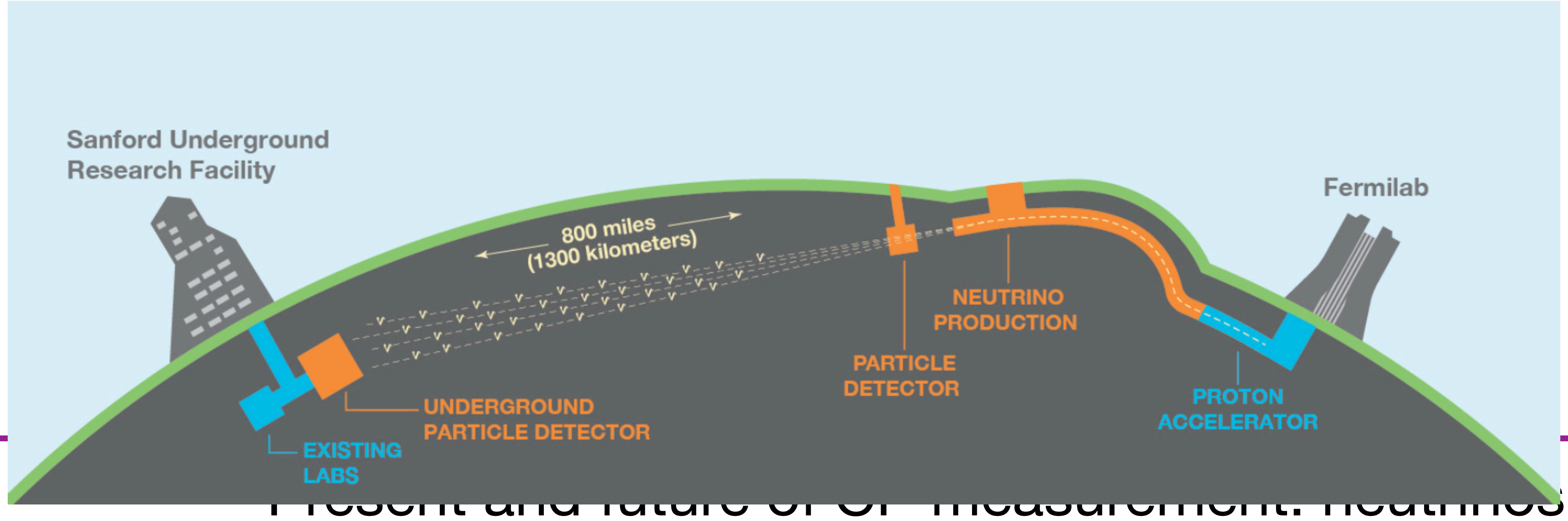
Current status of CP measurement: not measured yet

→ need future experiments

Requirement:

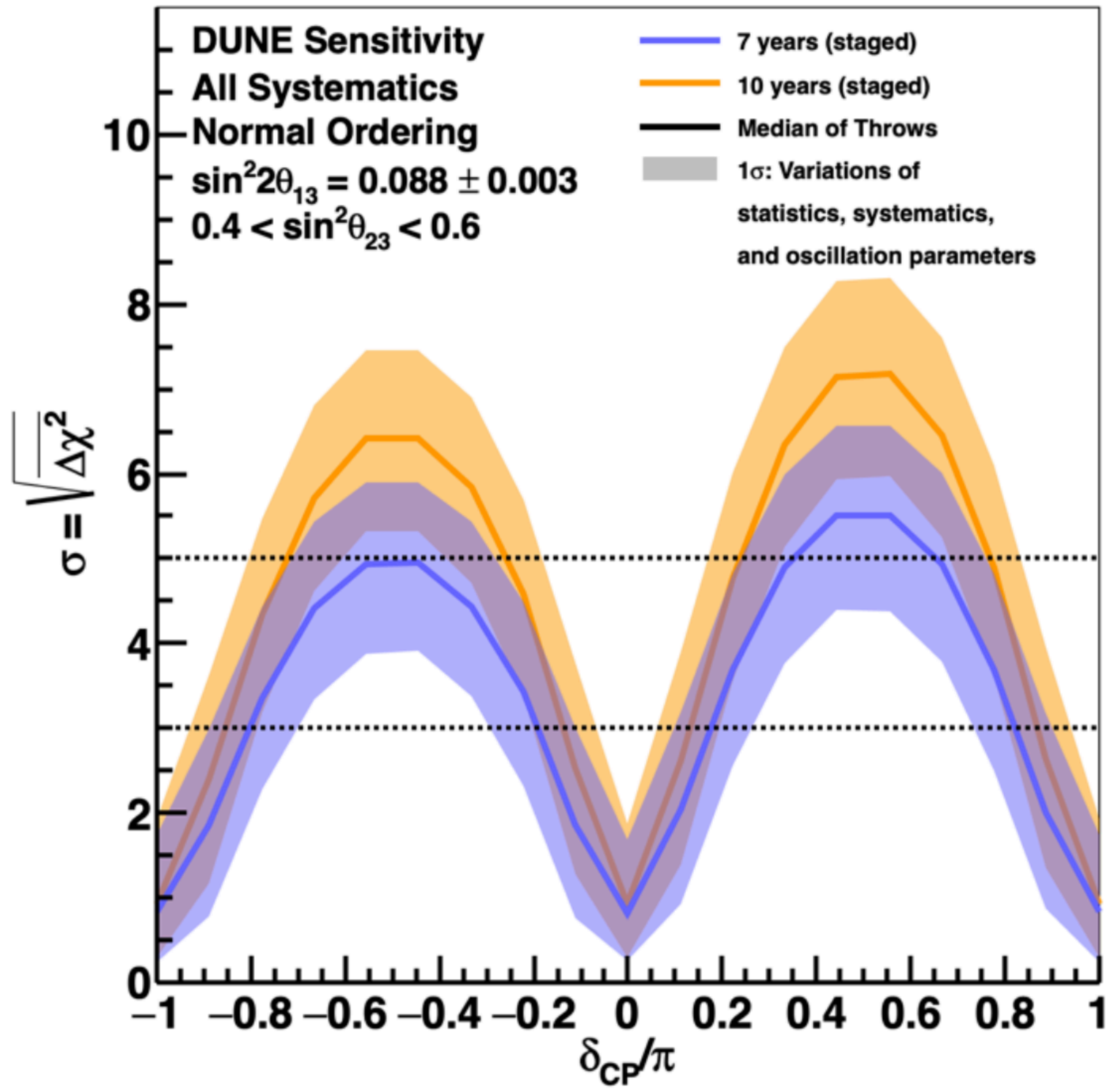
- Very large to increase statistics
- Very good energy reconstruction
- Improved knowledge on systematics
- Excellent team

Satisfied by DUNE (Deep Underground Neutrino Experiment) and research team at BNL



Measuring CP in neutrinos at DUNE

Sensitivity to CP violation at DUNE



Experiment in Japan: HK with similar sensitivity

[DUNE TDR]

Theoretical expectation

Do we have any expectation for the CP measurement of DUNE?
Current knowledge: $|J_{\text{PMNS}}| < 0.033$

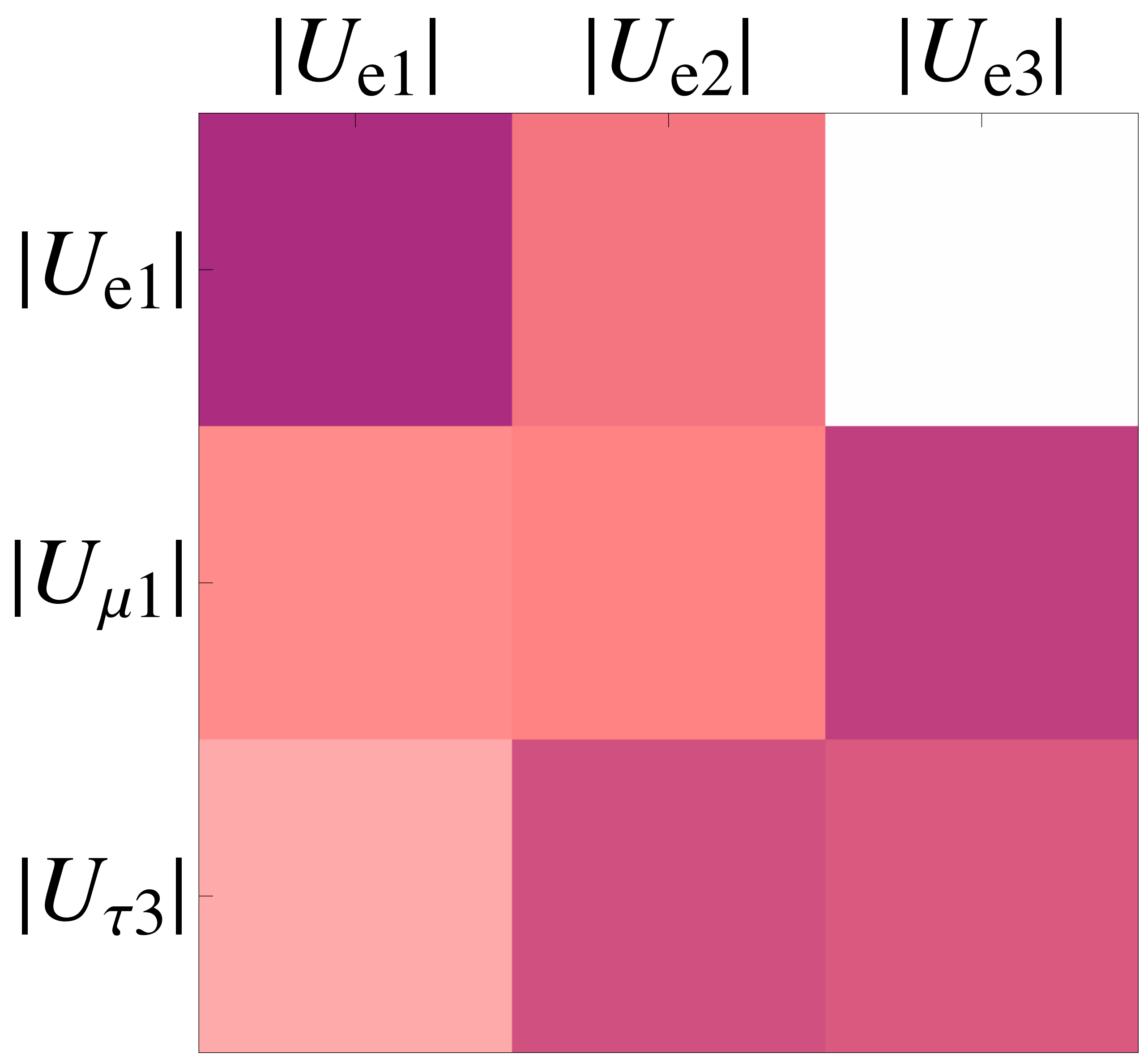
- Use guidance from quark sector?
  $$J_{\text{CKM}} = 2.7 \cdot 10^{-5}$$
- Guidance from the strong sector?
  $$\theta_{QCD} \lesssim 10^{-10}$$
- Is CP broken differently in different sectors? Why?
- Does a large J_{PMNS} point towards the existence of a new symmetry in the lepton sector?

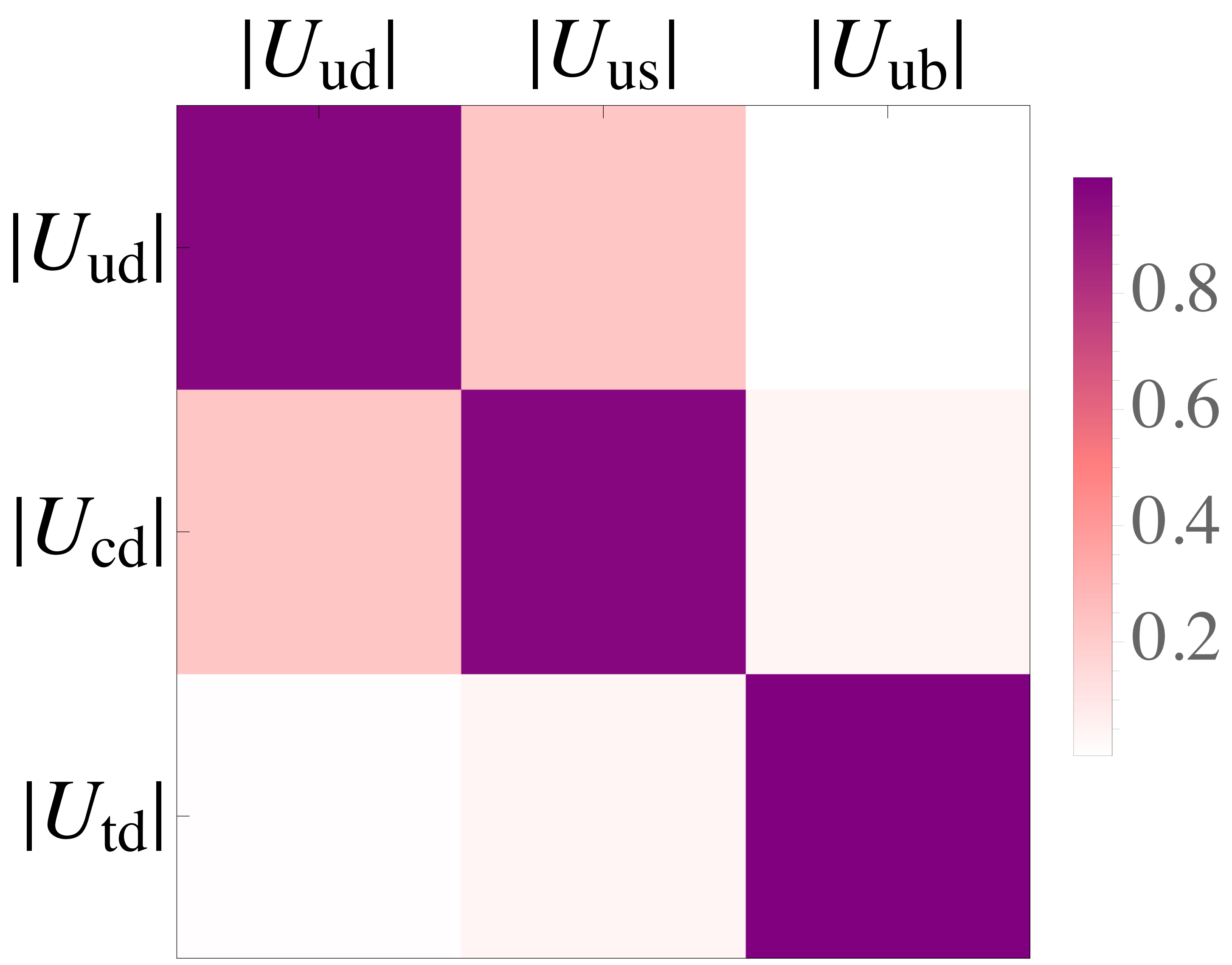
Theoretical expectation

Is there a new symmetry in the neutrino sector?

- CP symmetry: broken at different degrees in different sectors
- Flavor symmetry: could also provide rationale between difference in mixings in quark sector and lepton sector

Leptons





Quarks

Theoretical expectation

Predictions from new symmetries

- CP symmetry: $\delta = 0,\ \pi$
- Flavor symmetry: depends on model

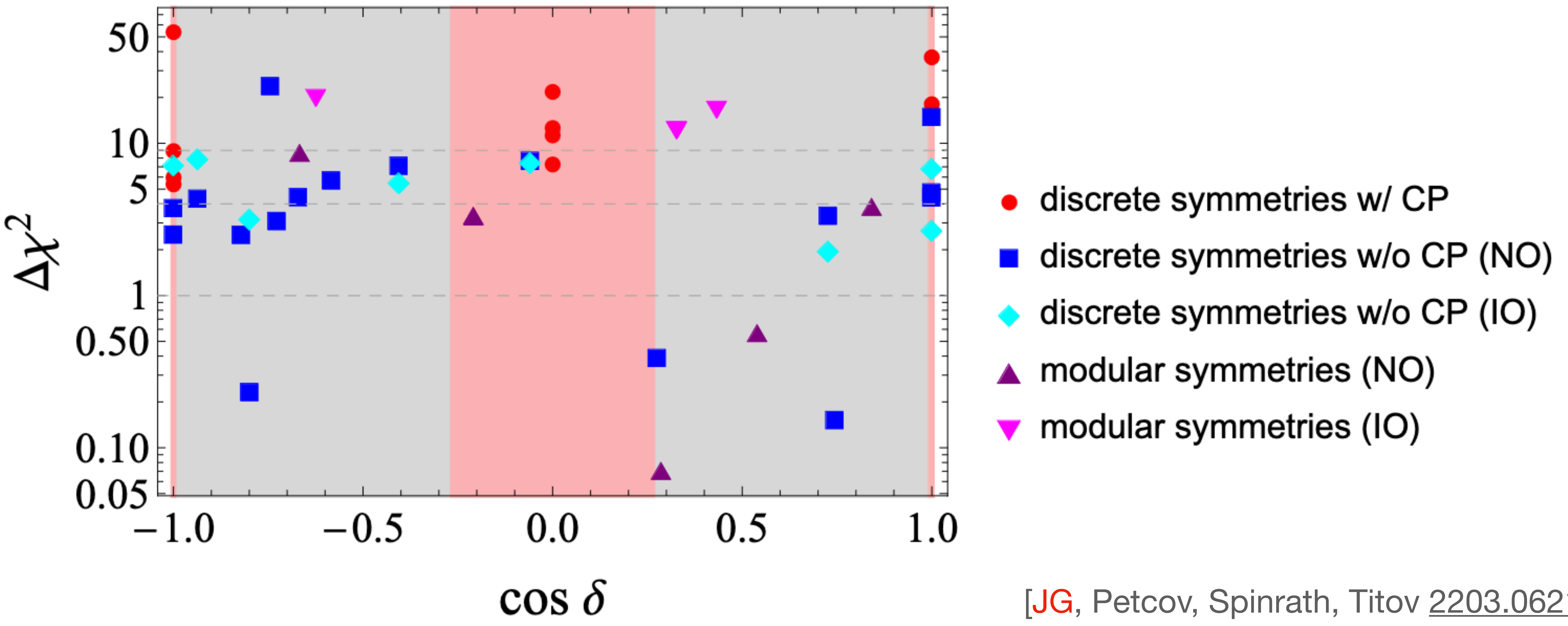
Most predictive flavor models predict relations between mixing parameter like $\theta_{12}^{\text{PMNS}} - \theta_{12}^{\nu} \approx \theta_{13}^{\text{PMNS}} \cos\delta$

Also prediction for other mixing parameters and masses

Learning about symmetries

If we measure δ precisely enough we can learn something about new symmetries in the lepton sector

→ provides target sensitivity for DUNE

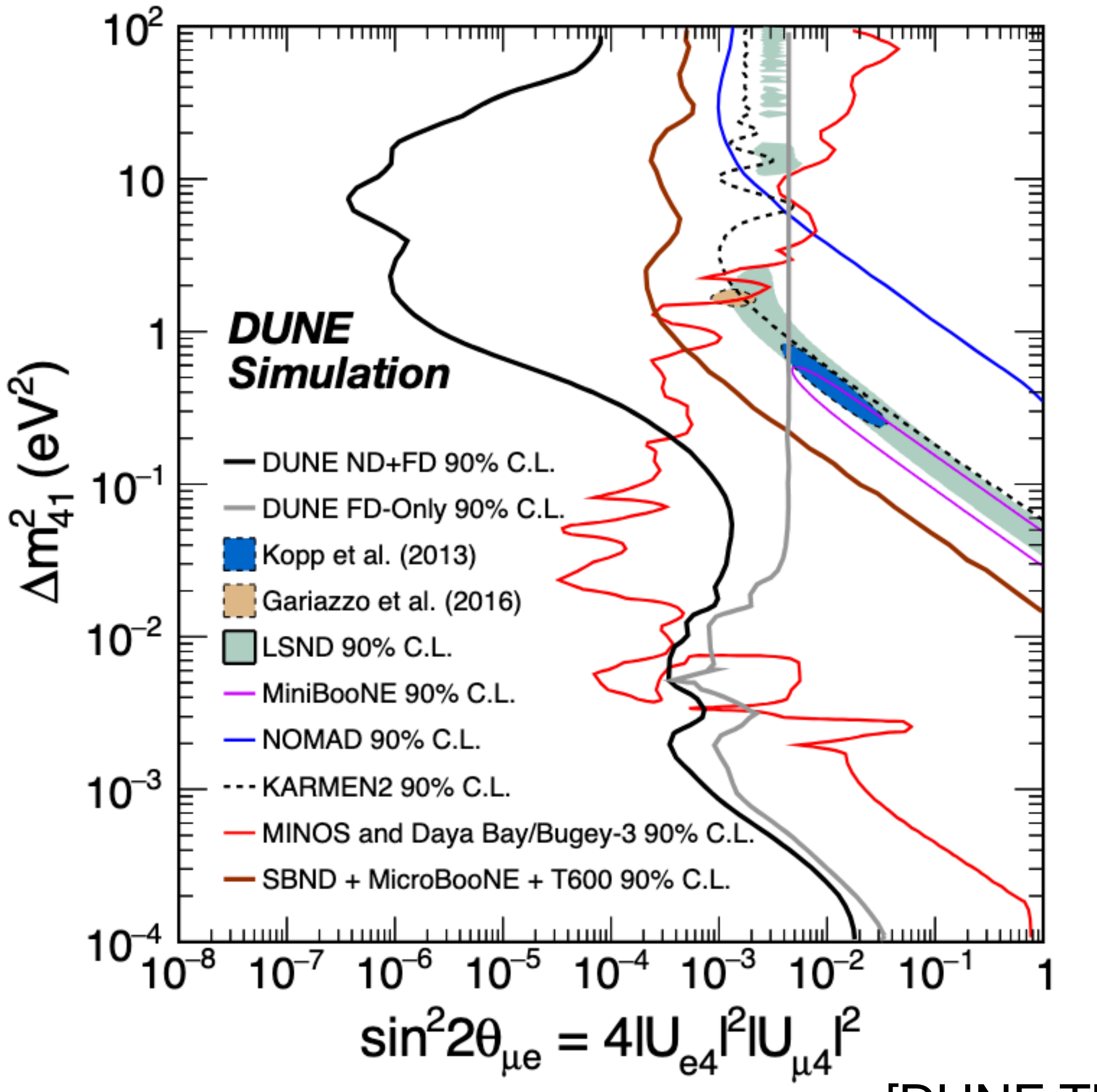


[JG, Petcov, Spinrath, Titov 2203.06219]

Learning about new physics

Very precise measurements of oscillation parameters could open window to explore new physics in the neutrino sector beyond neutrino oscillations

- Existence of additional neutrino generations
- New neutrino-matter interactions
- Violation of CPT



[DUNE TDR]

Conclusions

- CP violation is possible in the lepton sector
- Have not measured CP phase δ yet but DUNE will measure δ in the future
- Measurement of δ will allow us to test symmetries of nature: CP symmetry, existence of a flavor symmetry in the lepton sector
- Probe of possible new physics in the neutrino sector

Thanks for your attention!

Learning about symmetries

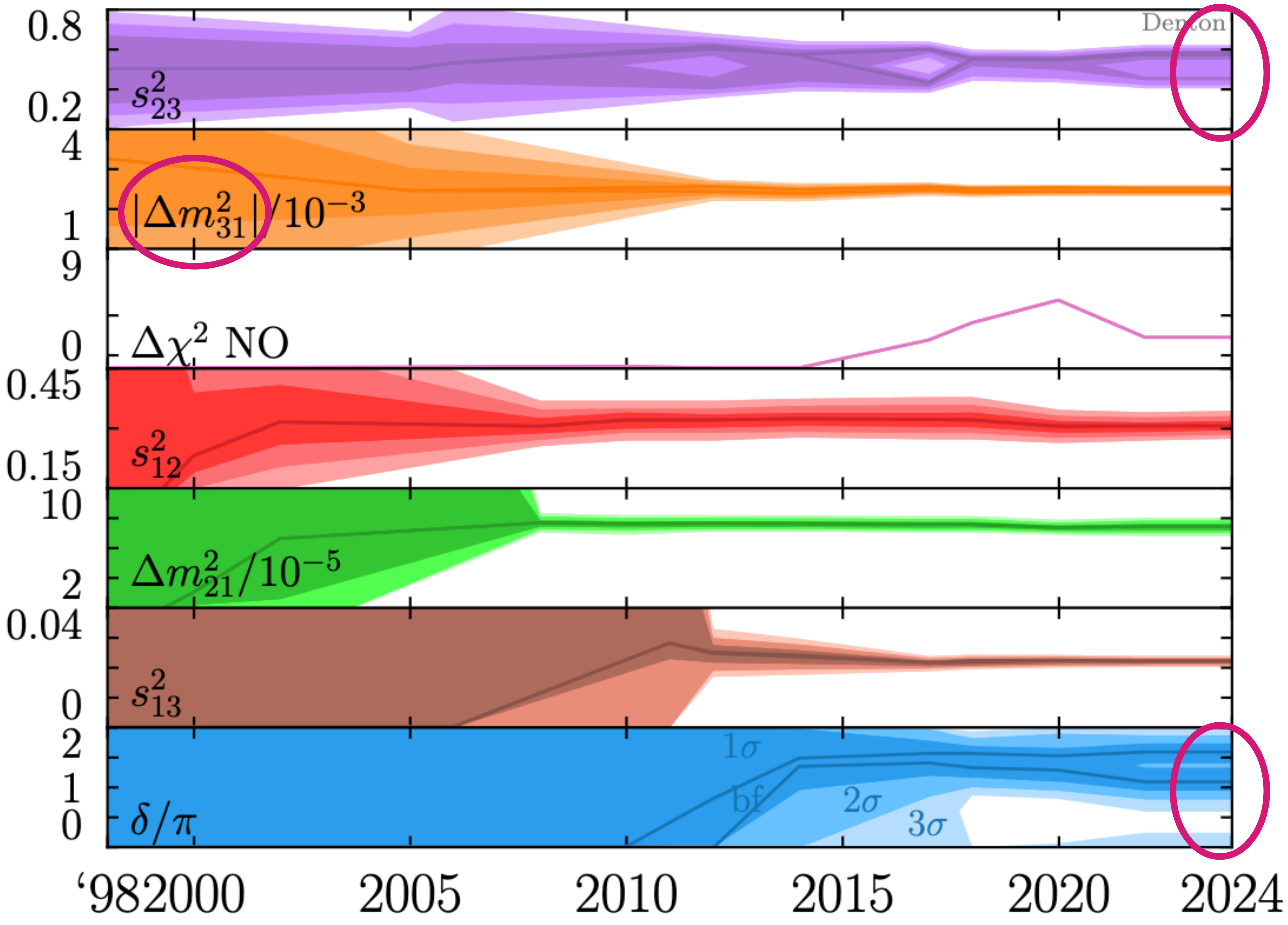
What is the connection of δ to the matter-antimatter asymmetry of the universe?

No 1-to-1 correspondence between δ and amount of CPV in early universe

To explain the matter-antimatter asymmetry need new particles that lead to additional sources of CPV

If neutrinos are Majorana particles: additional phases are physical
No access to Majorana phases in oscillations: requires complementary program

Appendix: Neutrino oscillations



[update from
Denton et al 2212.00809]

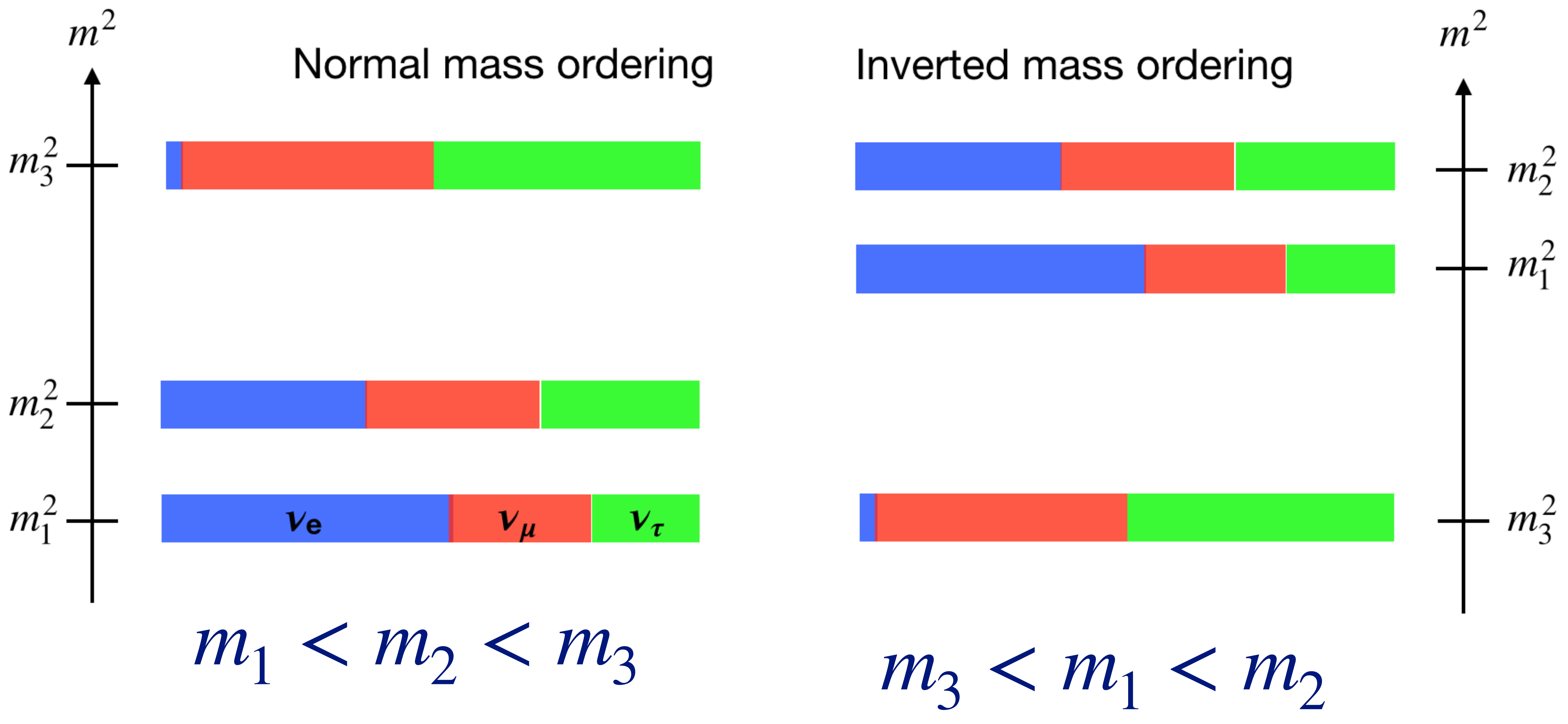
Appendix: Neutrino oscillations

Global fits to oscillation data:

Information on mixing angles, mass splittings

mass splittings: $|\Delta m_{32}^2| = 2.5 \cdot 10^{-3}\ \mathrm{eV}^2,\ \Delta \mathrm{m}_{21}^2 = 7.4 \cdot 10^{-5}\ \mathrm{eV}^2$

mass ordering unknown



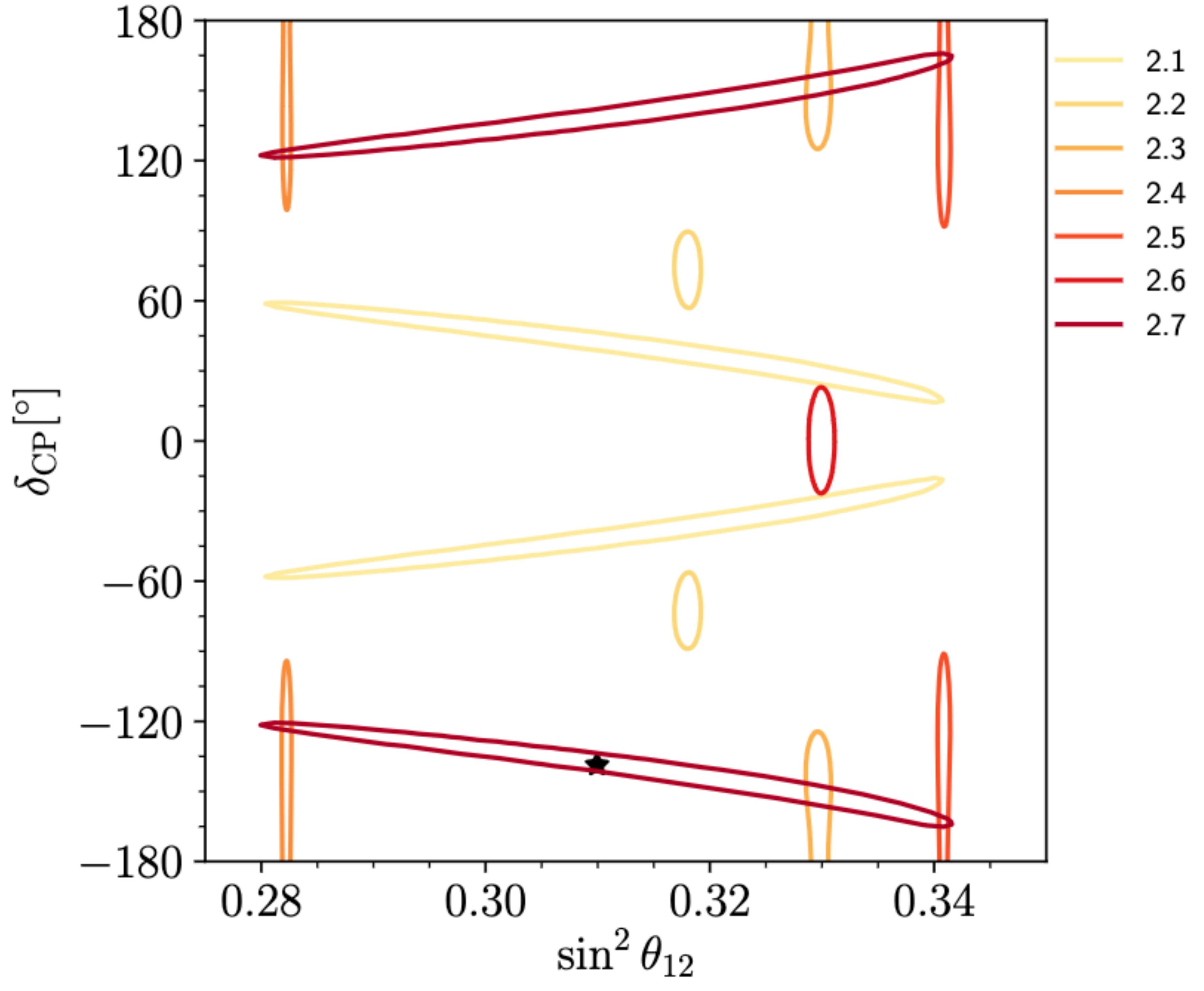
Appendix: Flavor models

- Distinguish different flavor models with precision oscillation measurements

Sum rules can be used to distinguish different mixing pattern

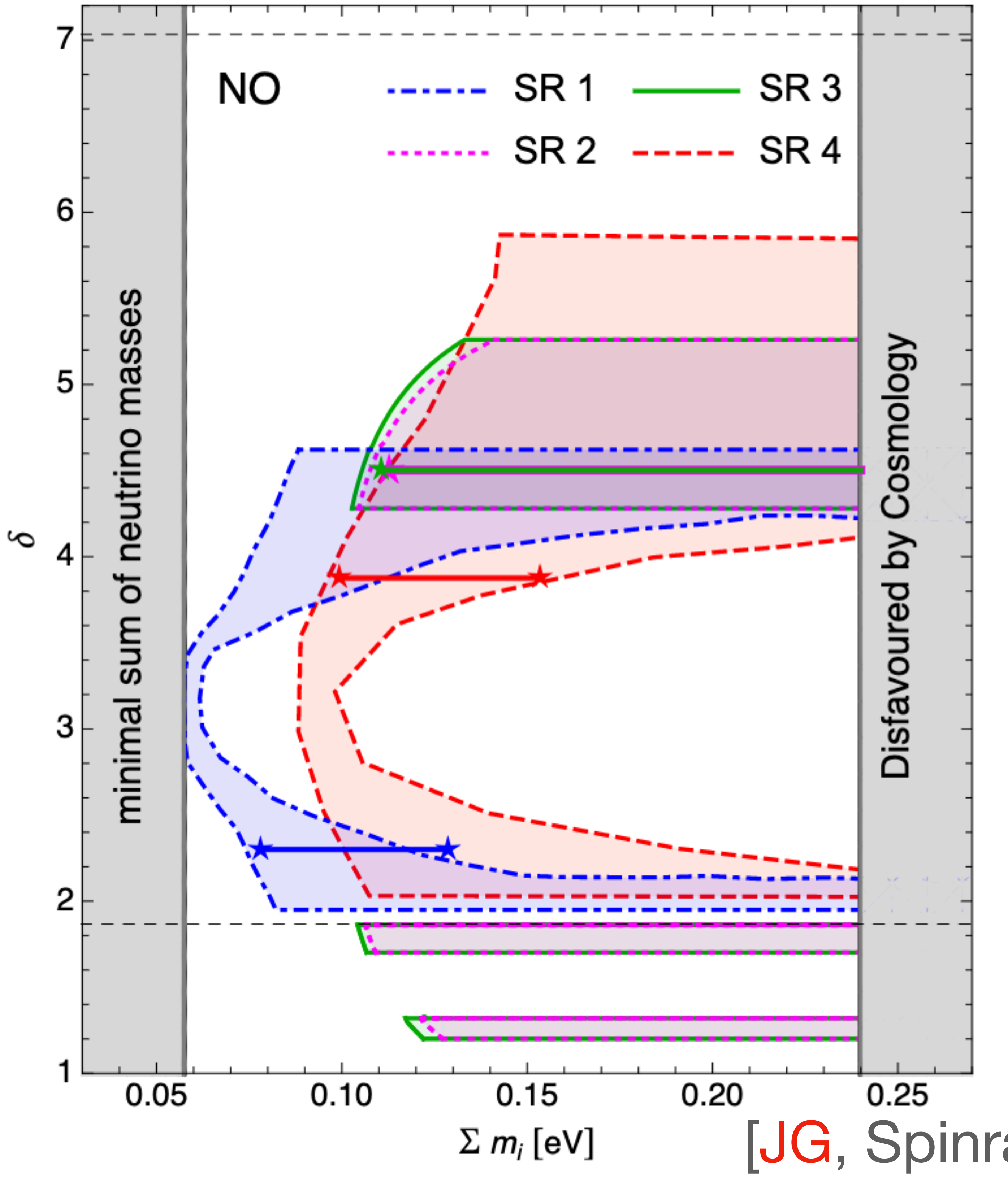
Future experiments can disentangle different models

at $>5\sigma$!



[Blennow, Ghosh, Ohlsson, Titov 2004.00017]

Correlations can be probed!



[JG, Spinrath 2012.04131]

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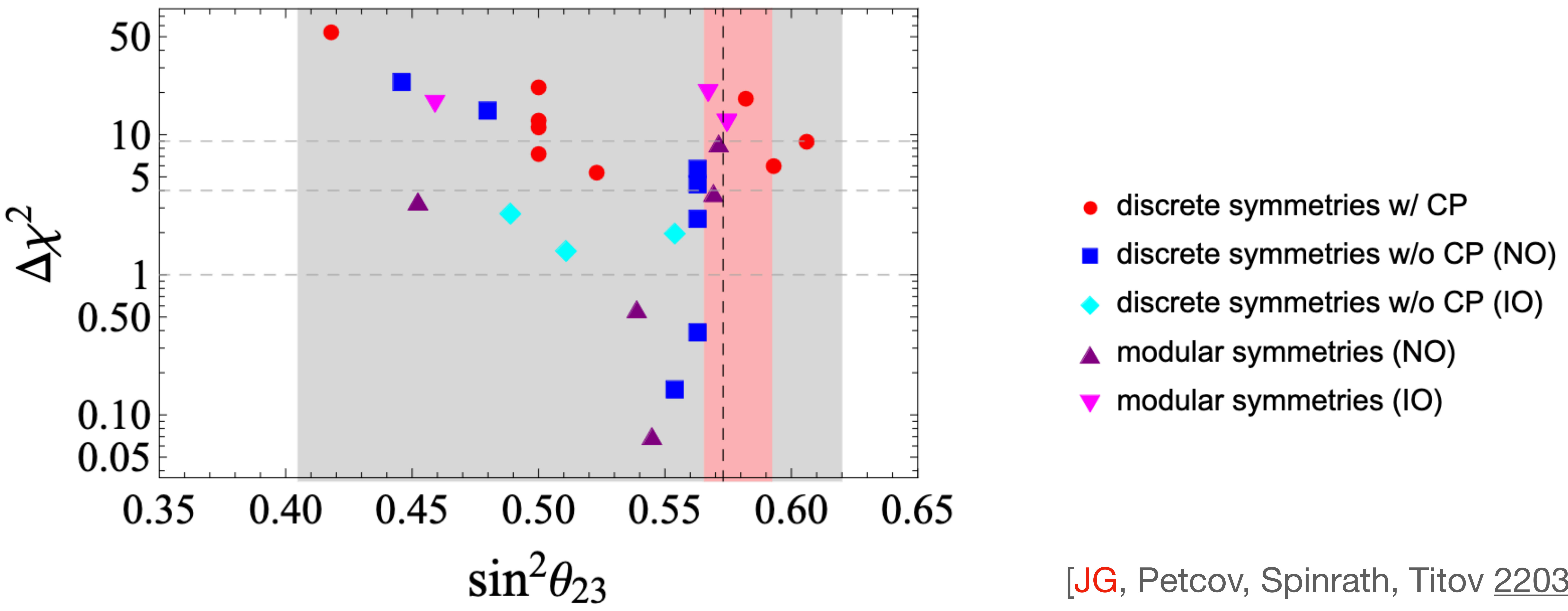

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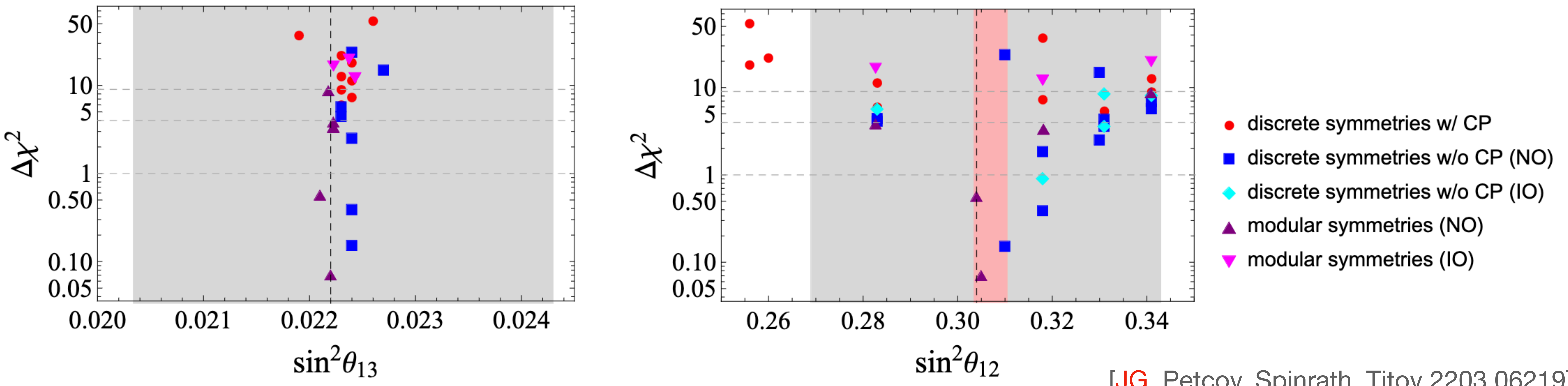

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