How will we first measure the Neutrino Mass Ordering?

João Coelho

IJCLab - Orsay

12 February 2021

Mostly based on…

Earliest Resolution to the Neutrino Mass Ordering?

Anatael Cabrera*[1,2,4], Yang Han†[1,2], Michel Obolensky[1], Fabien Cavalier[2], João Coelho[2], Diana Navas-Nicolás[2], Hiroshi Nunokawa‡[2,7], Laurent Simard[2], Jianming Bian[3], Nitish Nayak[3], Juan Pedro Ochoa-Ricoux[3], Bedřich Roskovec[3], Pietro Chimenti[5], Stefano Dusini[6a], Marco Grassi[6b], Mathieu Bongrand[8,2], Rebin Karaparambil[8], Victor Lebrin[8], Benoit Viaud[8], Frederic Yermia[8], Lily Asquith[9], Thiago J. C. Bezerra[9], Jeff Hartnell[9], Pierre Lasorak[9], Jiajie Ling[10], Jiajun Liao[10], and Hongzhao Yu[10]

[1]APC, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité University, 75205 Paris Cedex 13, France
[2]IJCLab,, Université Paris-Saclay, CNRS/IN2P3, 91405 Orsay, France
[3]Department of Physics and Astronomy, University of California at Irvine, Irvine, California 92697, USA
[4]LNCA Underground Laboratory, CNRS/IN2P3 - CEA, Chooz, France
[5]Departamento de Física, Universidade Estadual de Londrina, 86051-990, Londrina – PR, Brazil
[6a]INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy
[6b]Dipartimento di Fisica e Astronomia, Università di Padova, via Marzolo 8, I-35131 Padova, Italy
[7]Department of Physics, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, RJ, 22451-900, Brazil
[8]SUBATECH, CNRS/IN2P3, Université de Nantes, IMT-Atlantique, 44307 Nantes, France
[9]Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom
[10]Sun Yat-sen University, NO. 135 Xingang Xi Road, Guangzhou, China, 510275

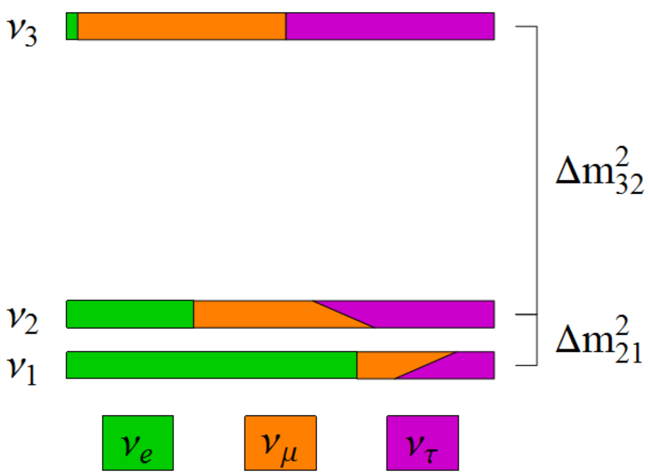
August 27, 2020 – v3.5

We hereby illustrate and numerically demonstrate via a simplified *proof of concept* calculation tuned to the latest average neutrino global data that the combined sensitivity of JUNO with NOvA and T2K experiments has the potential to be the first fully resolved ($\geq 5\sigma$) measurement of neutrino Mass Ordering (MO) around 2028; tightly linked to the JUNO schedule. Our predictions account for the key ambiguities and the most relevant $\pm 1\sigma$ data fluctuations. In the absence of any concrete MO theoretical prediction and given its intrinsic binary outcome, we highlight the benefits of having such a resolved measurement in the light of the remarkable MO resolution ability of the next generation of long baseline neutrino beams experiments. We motivate the opportunity of exploiting the MO experimental framework to scrutinise the standard oscillation model, thus, opening for unique discovery potential, should unexpected discrepancies manifest. Phenomenologically, the deepest insight relies on the articulation of MO resolved measurements via at least the two possible methodologies *matter effects* and purely *vacuum* oscillations. Thus, we argue that the JUNO vacuum MO measurement may feasibly yield full resolution in combination to the next generation of long baseline neutrino beams experiments.

https://inspirehep.net/literature/1813376

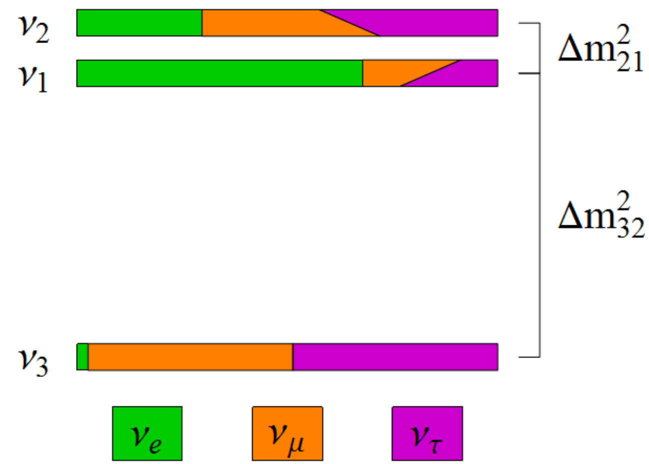
What’s all this about NMO?

Normal Ordering



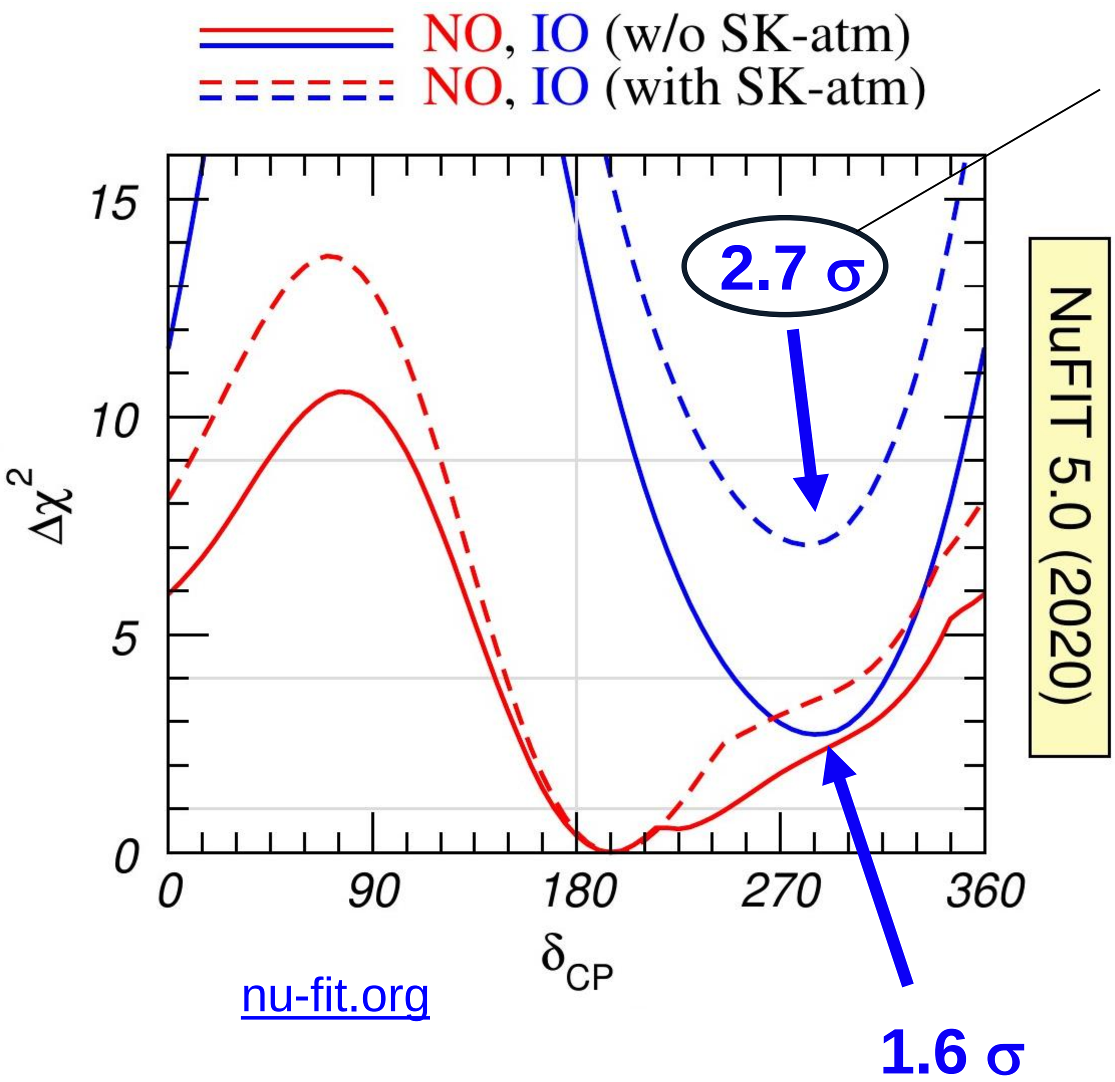
Which one is it?

Inverted Ordering



- Neutrino mass implies new physical interactions
- Determining the mass hierarchy rules out ~½ of the models of mass generation
- Also important consequences for cosmology, $0\nu\beta\beta$ decay, super-nova astronomy, earth tomography, etc.

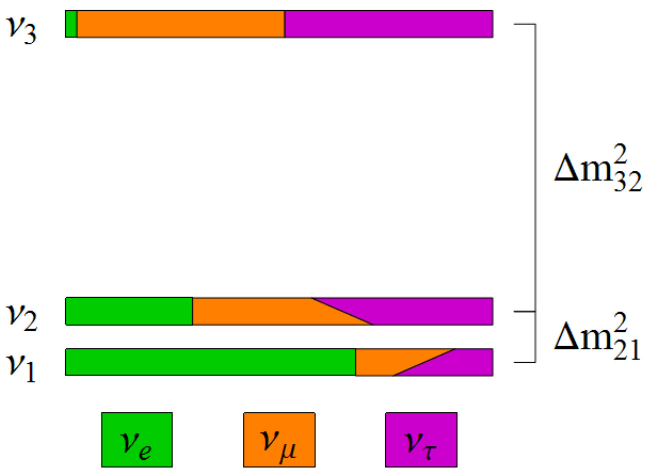
What's the status of NMO?

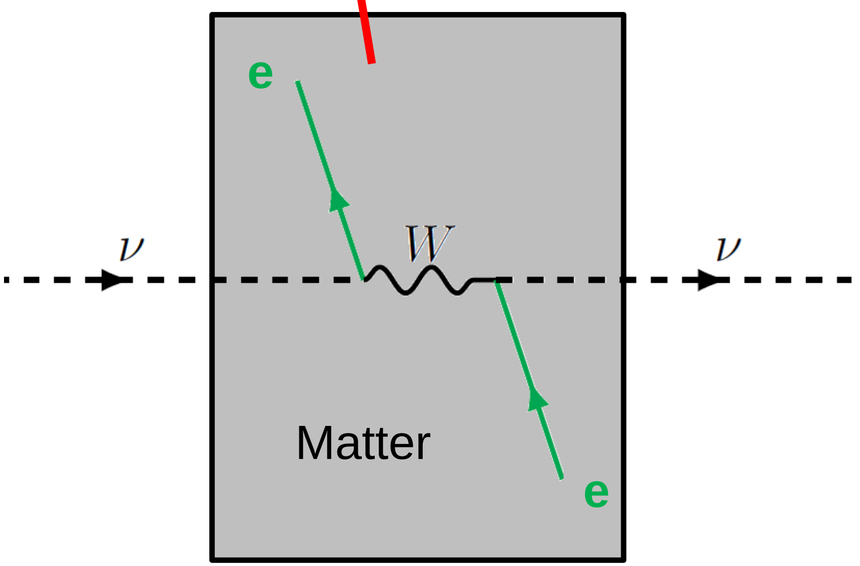


New SK data will push this down to ~2.5 σ

How do we know this?

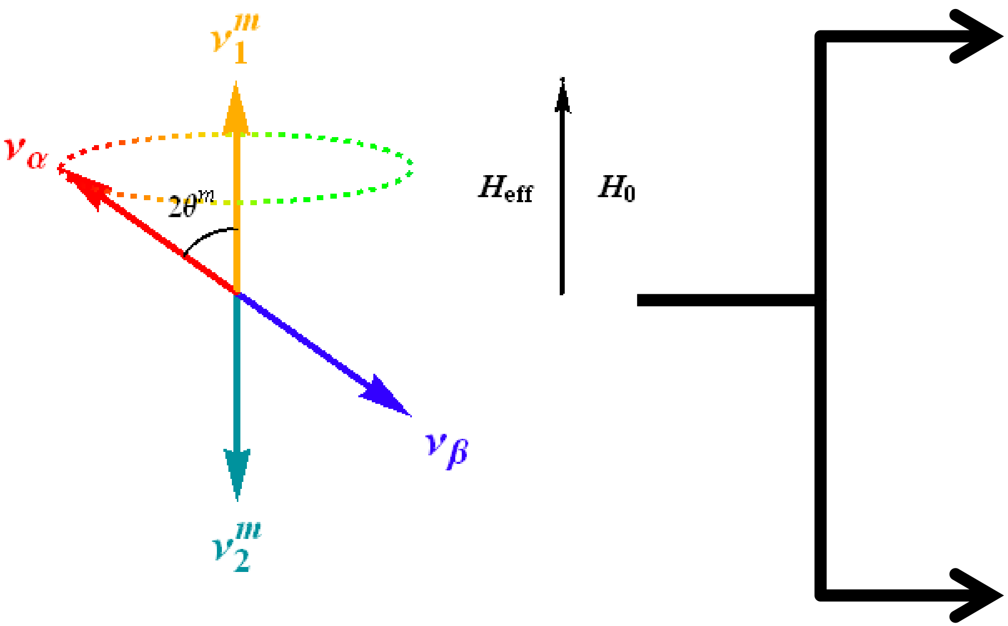
$$H_{eff} = \underbrace{U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger}_{\mathbf{H_0}} + \underbrace{V_e \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}}_{\mathbf{V}}$$

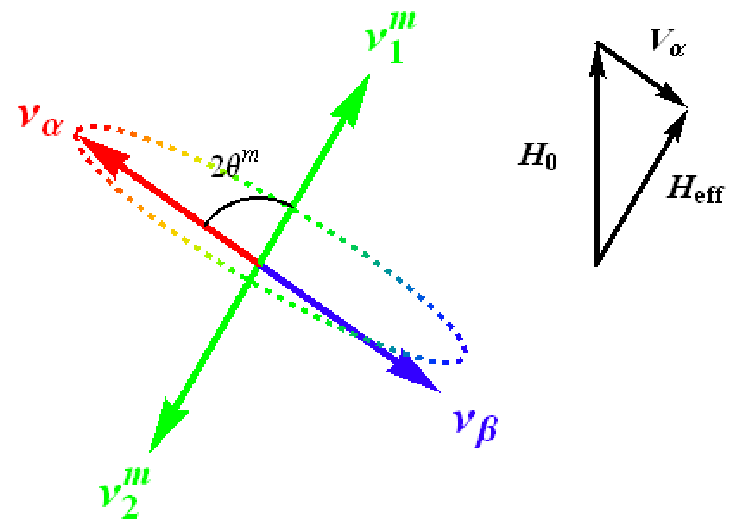


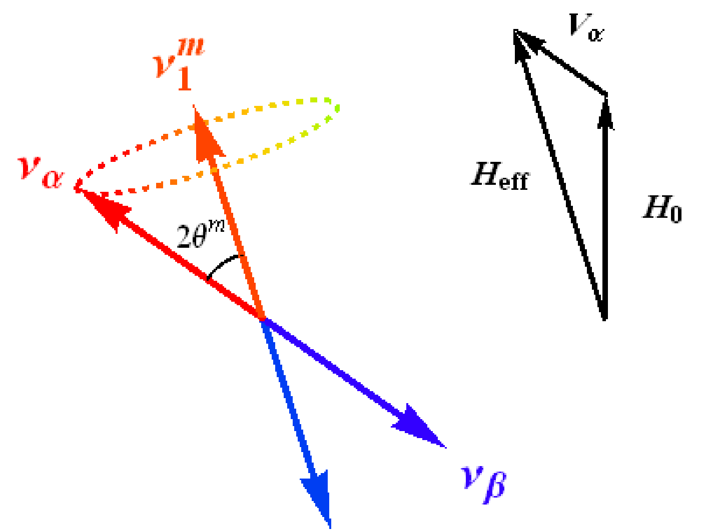


Tilted Oscillations

$$H_{eff} = H_0 - V_\alpha$$

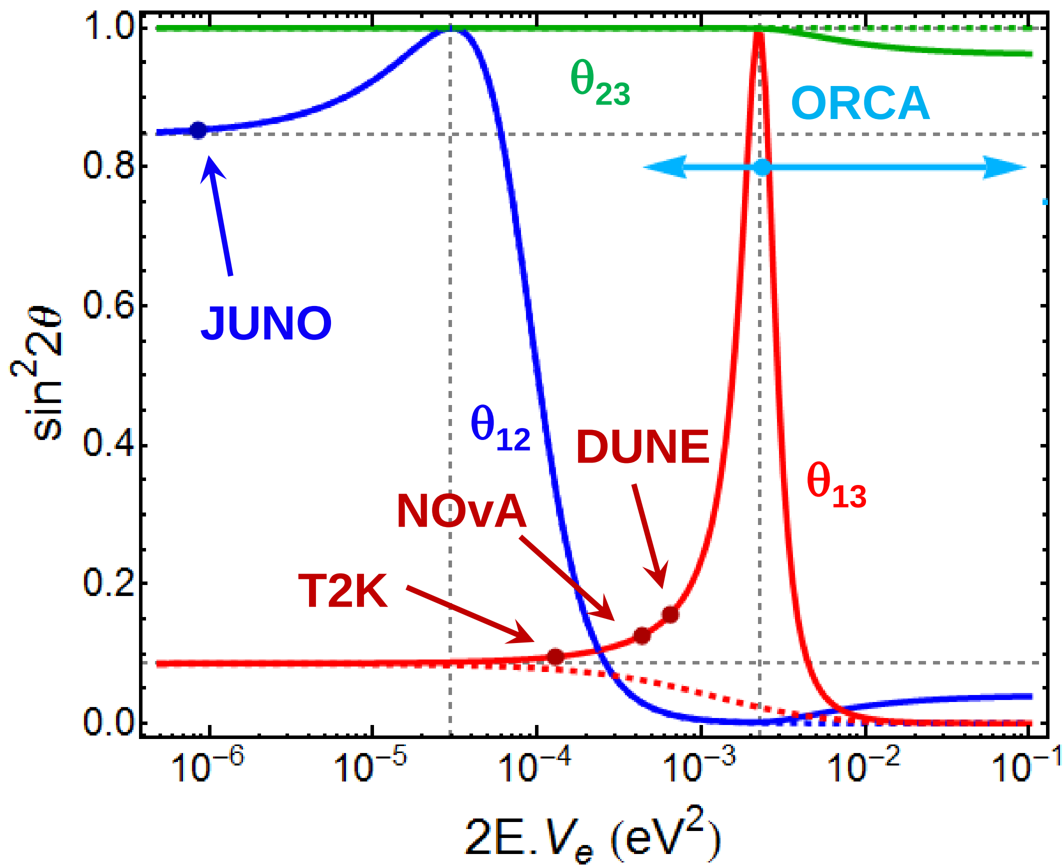






$$H_{eff} = H_0 + V_\alpha$$

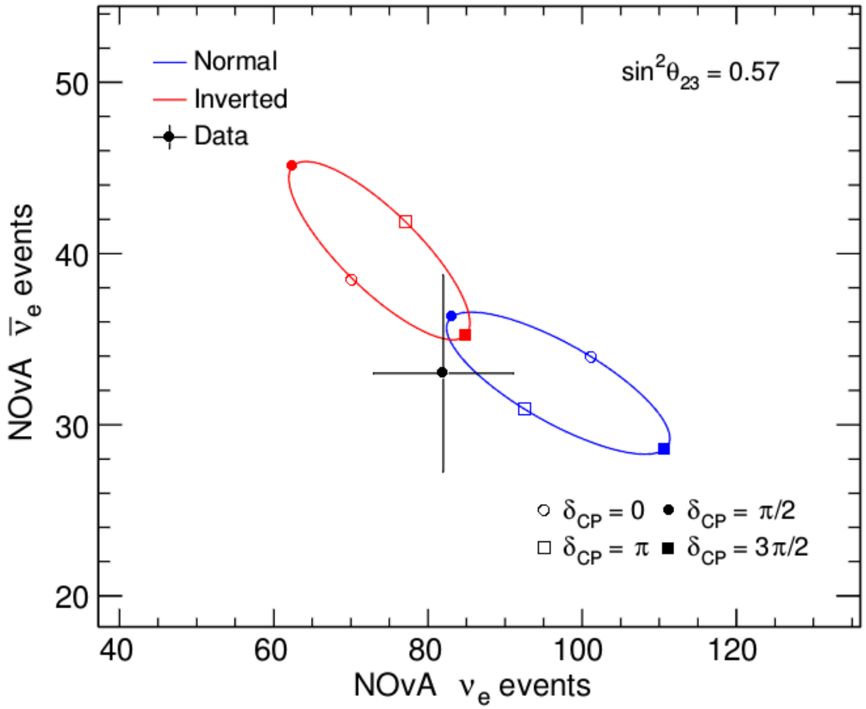
Resonances



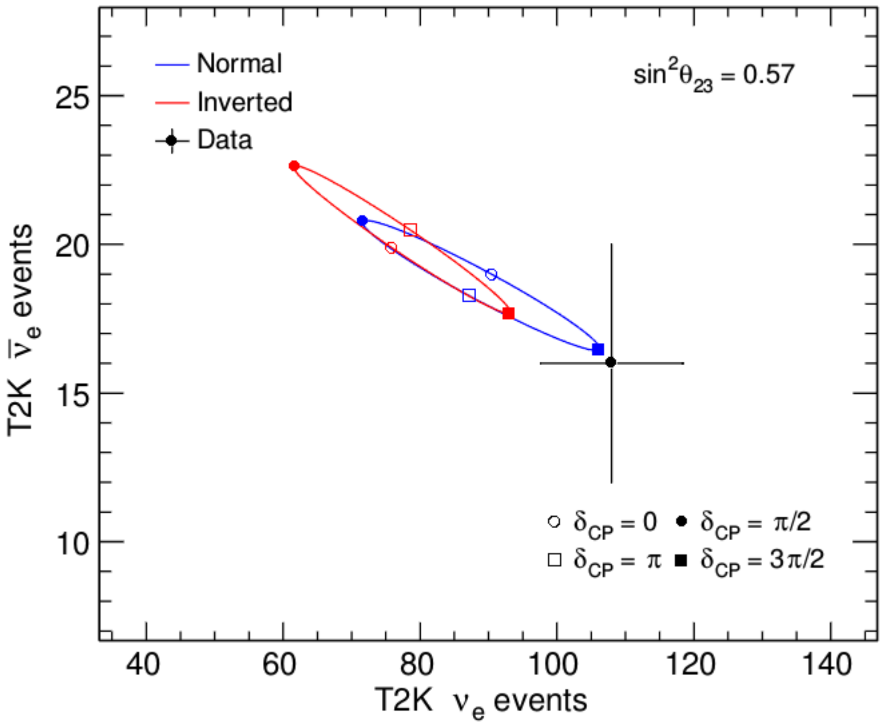
$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Effect on LBL ν_e appearace

NOvA

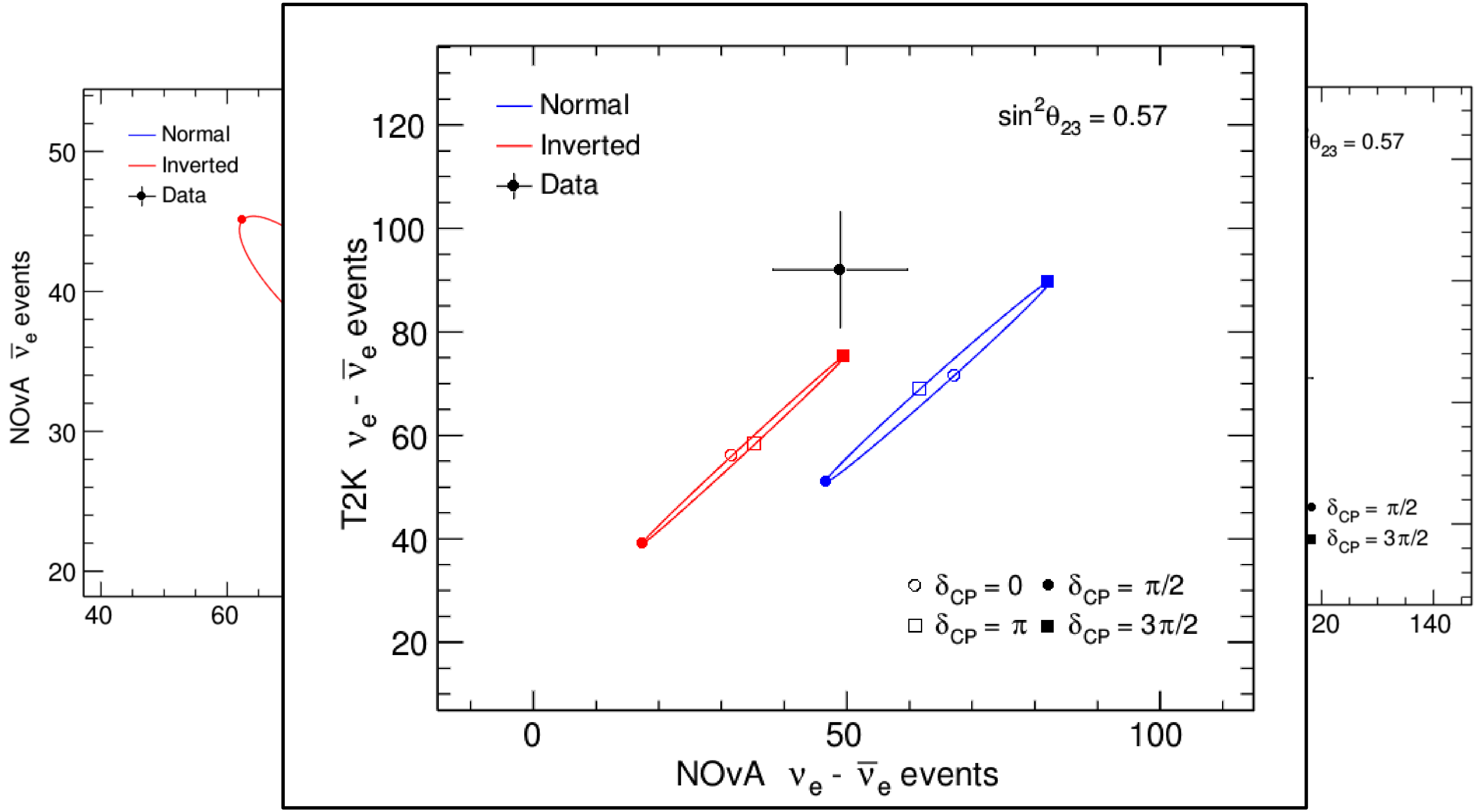


T2K

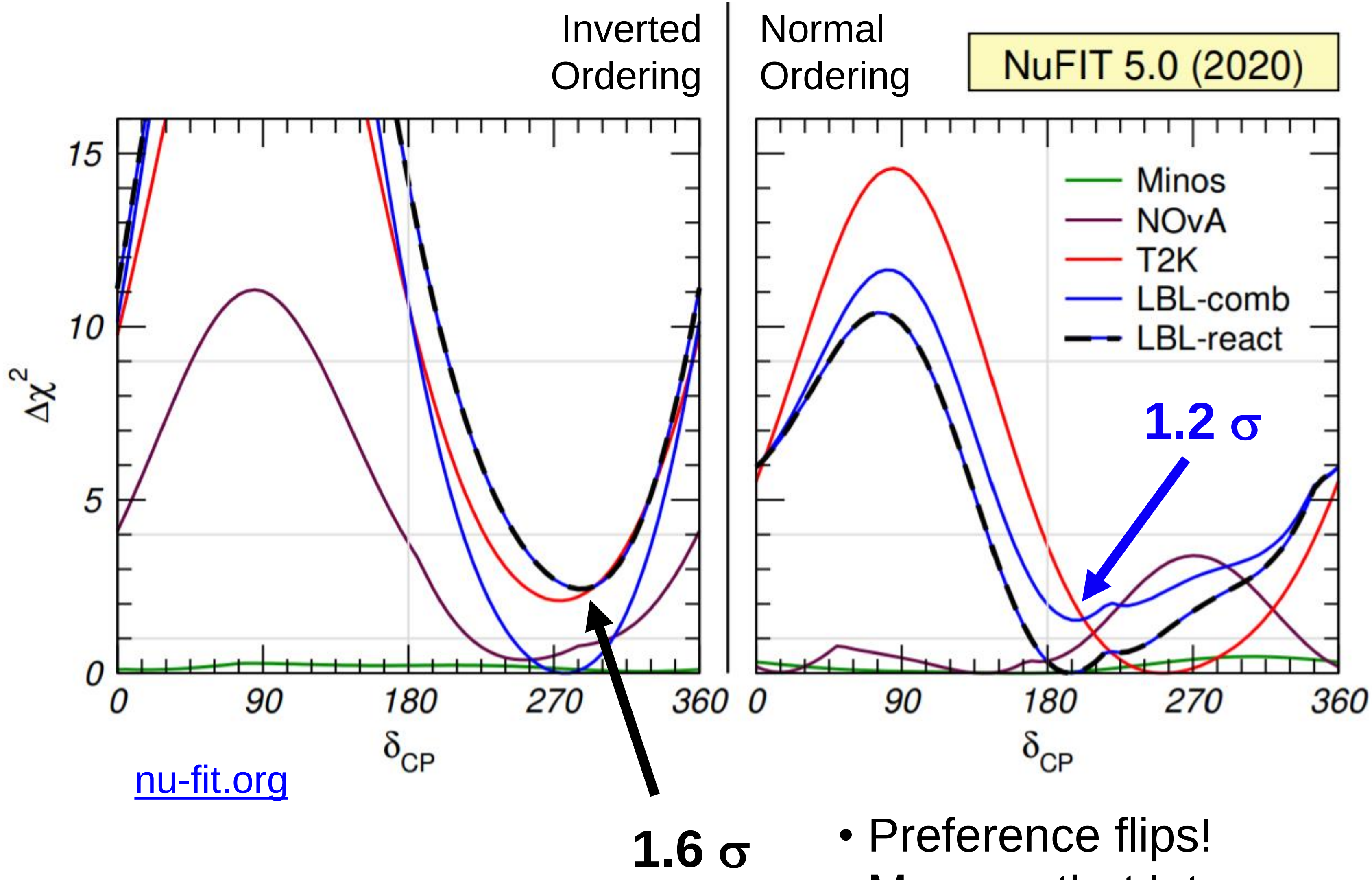


Effect on LBL ν_e appearace

Joint view



How come NuFIT says Normal?

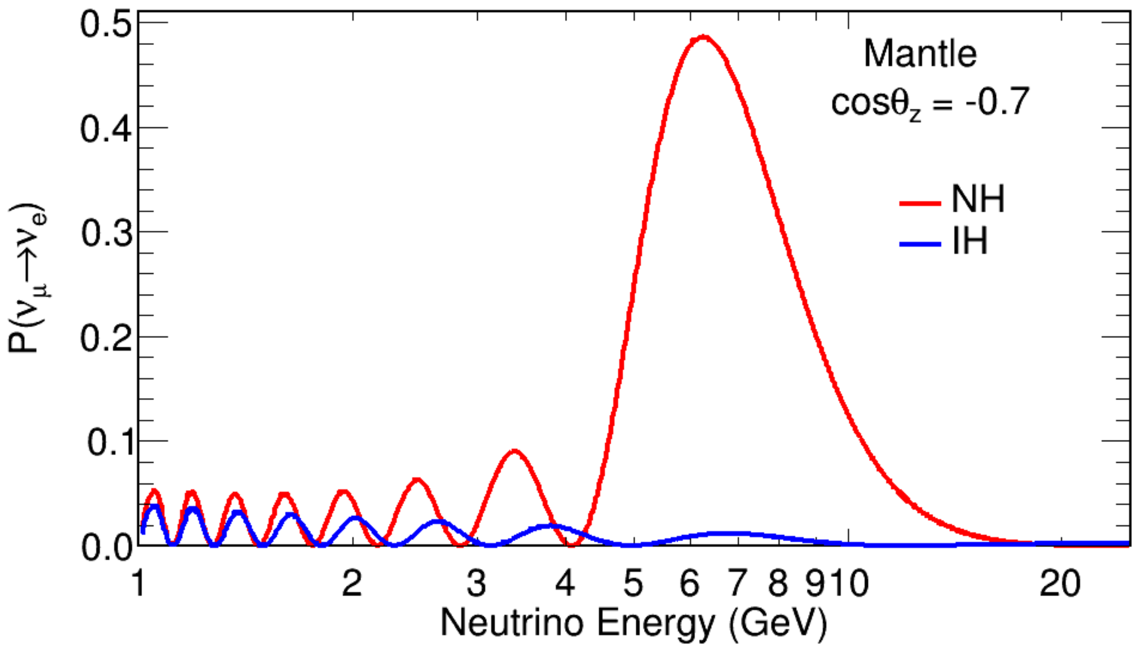


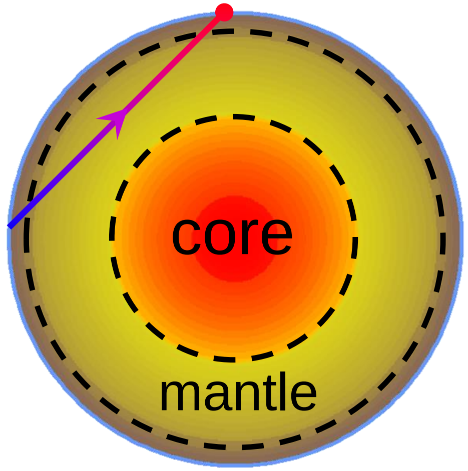
nu-fit.org

- Preference flips!
- More on that later…

What about atmospherics?

- Huge effect for mantle-crossing neutrinos

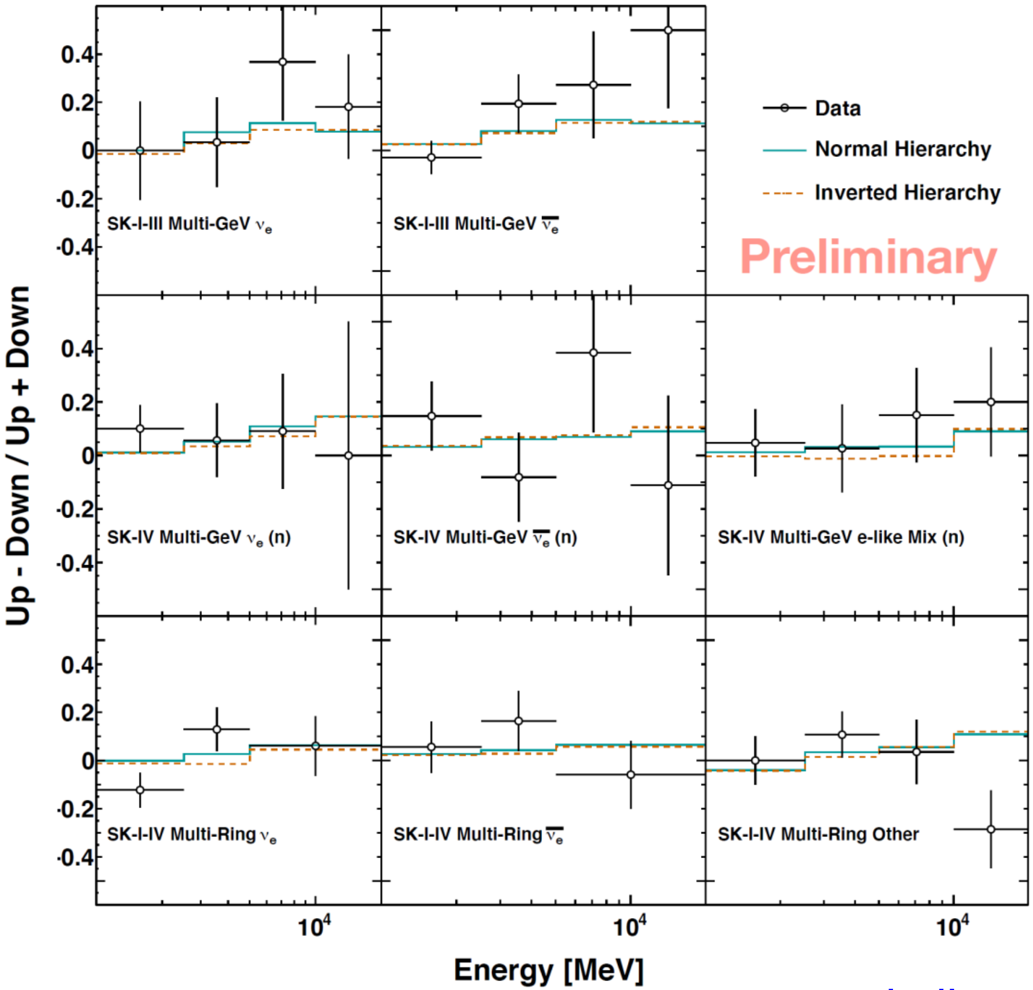




What about atmospherics?

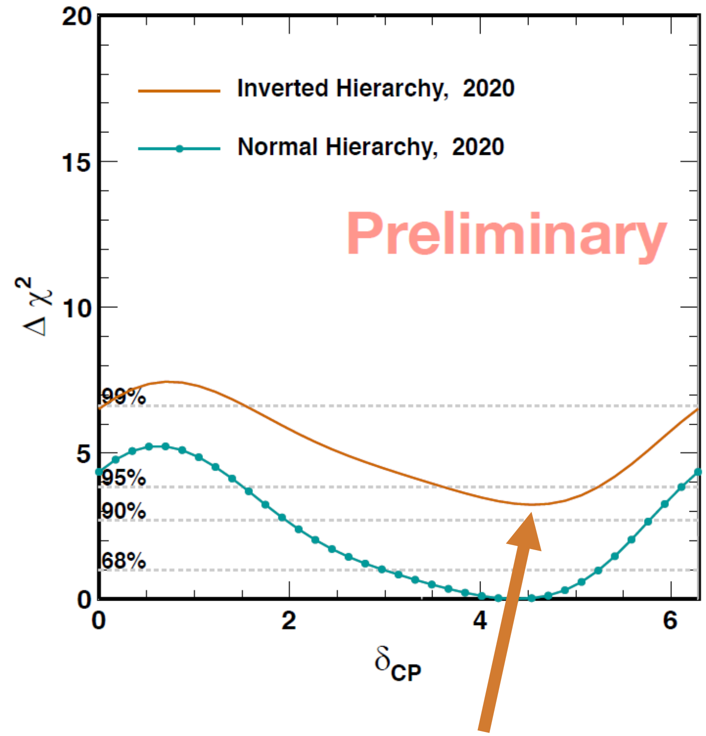
- But reality is a lot more complicated

Up: cosθ < -0.4, Down: cosθ > 0.4



Exposure: 364.8 kton-years
(~16 years)

Super-Kamiokande

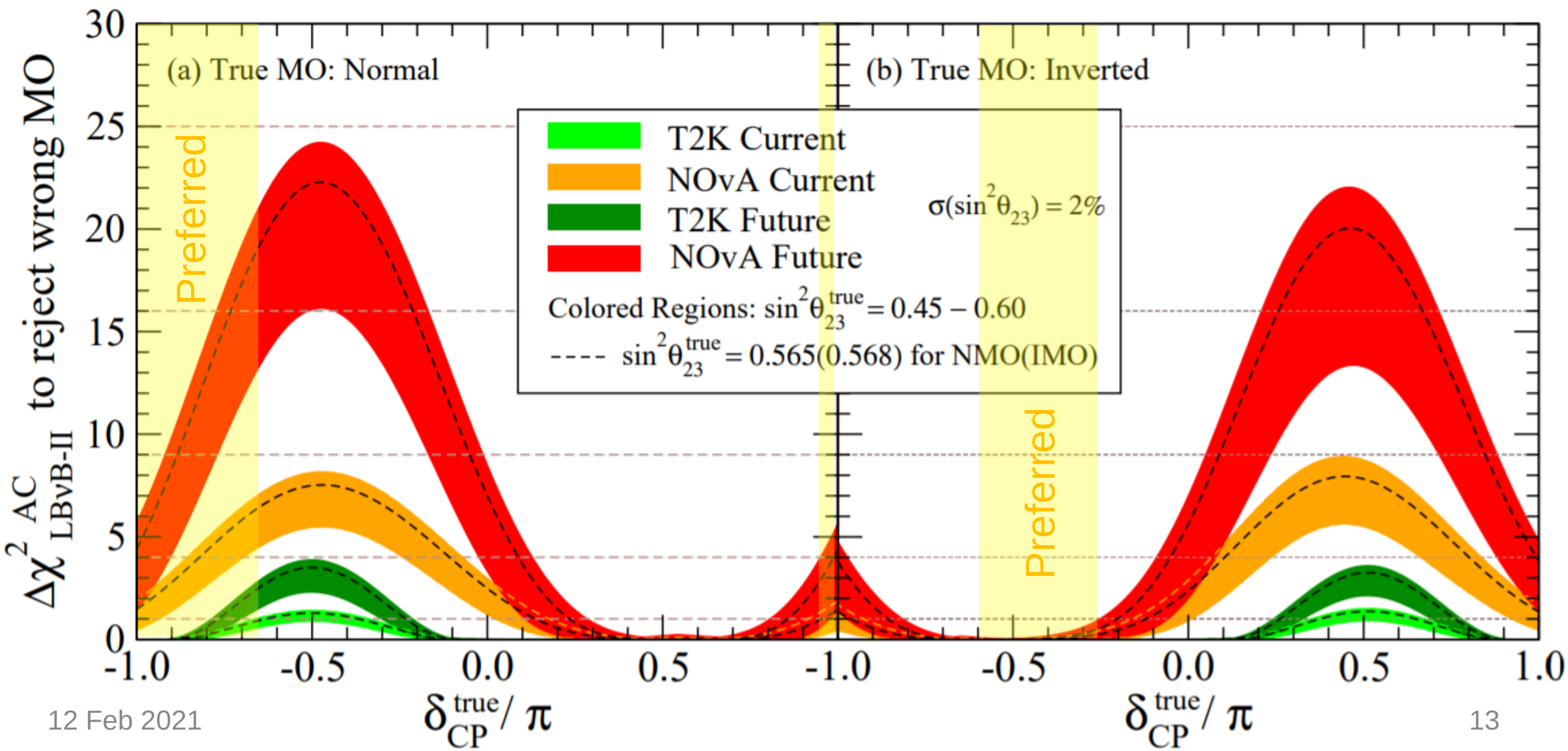


1.8 σ

Y. Nakajima – Neutrino 2020

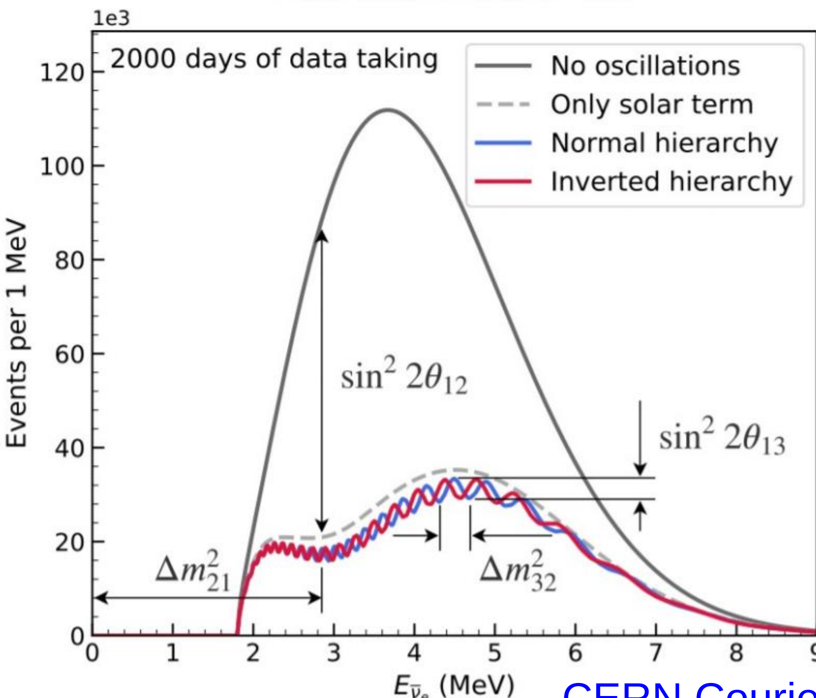
What to expect before DUNE?

- Super-K gets diminishing returns after 25 years running
- NOvA dominates from LBL, but T2K plays important role
- Combined 5σ potential, but not in current preferred region
- Max $\Delta\chi^2$: NOvA ~ 23 units, T2K ~ 3 units, SK ~ 3 units



What about the near future?

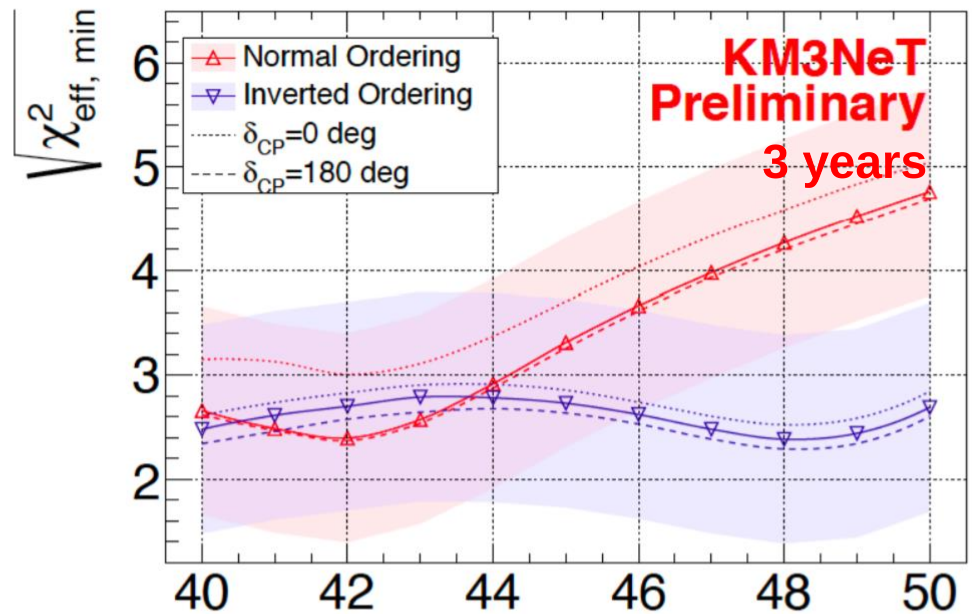
JUNO ~ 3 σ



[CERN Courier]

ORCA ~ 2.5 – 4.5 σ

(Depending on true ordering)

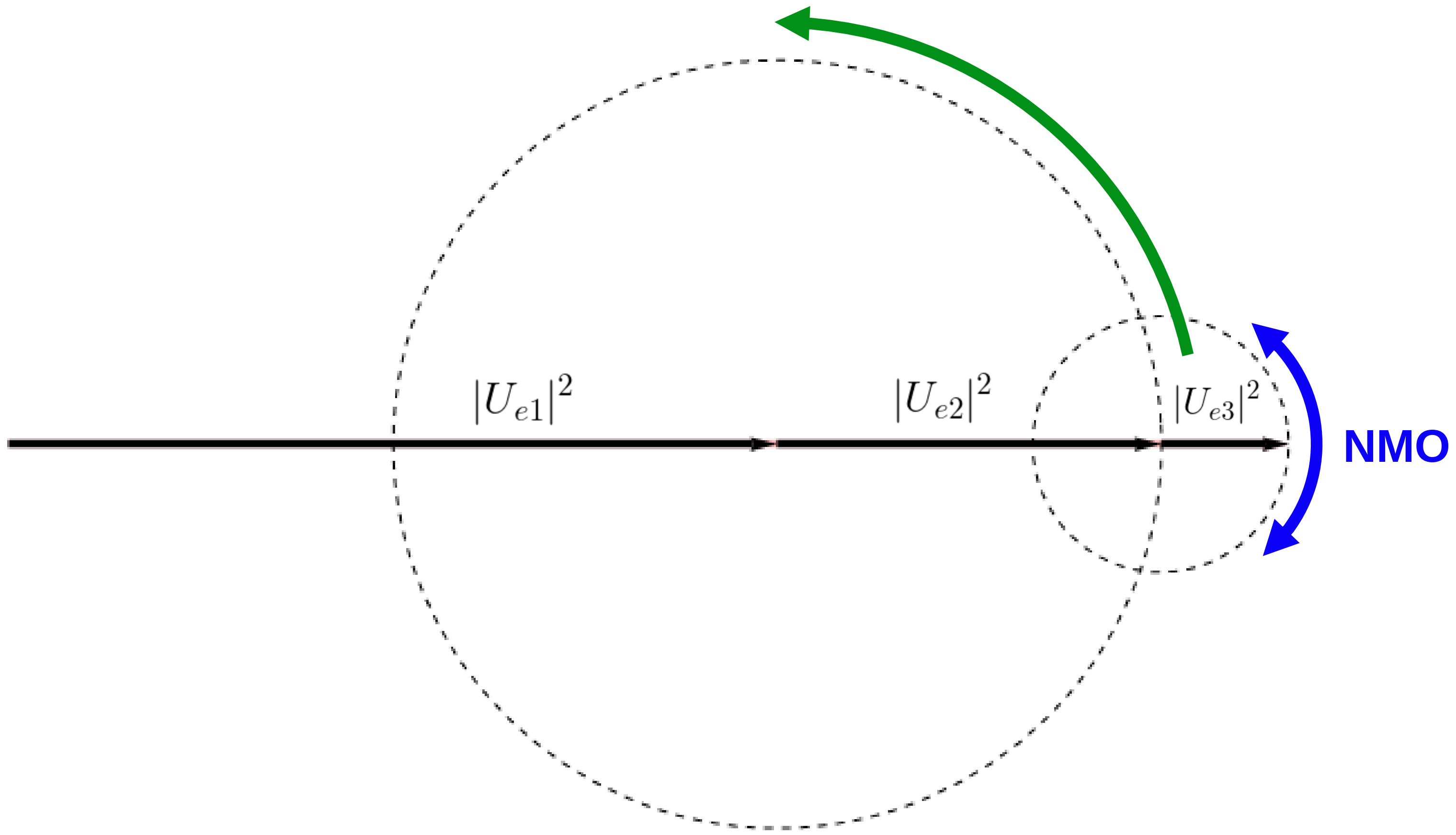


[D. Samtleben – Neutrino 2020]

- At face value, if the true ordering is inverted, **not 5σ**
- $\Delta\chi^2$: NOvA+T2K ~ 0 units, SK ~ 3 units?,
  JUNO ~ 9 units, ORCA ~ 6-9 units
  Total ~ 20 units (4.5 σ)

A closer look at NMO in vacuum

$$P(\nu_e \to \nu_e) = \left| \, |U_{e1}|^2 + |U_{e2}|^2 e^{-i\frac{\Delta m^2_{21} L}{2E}} + |U_{e3}|^2 e^{-i\frac{\Delta m^2_{31} L}{2E}} \right|^2$$



A closer look at NMO in vacuum

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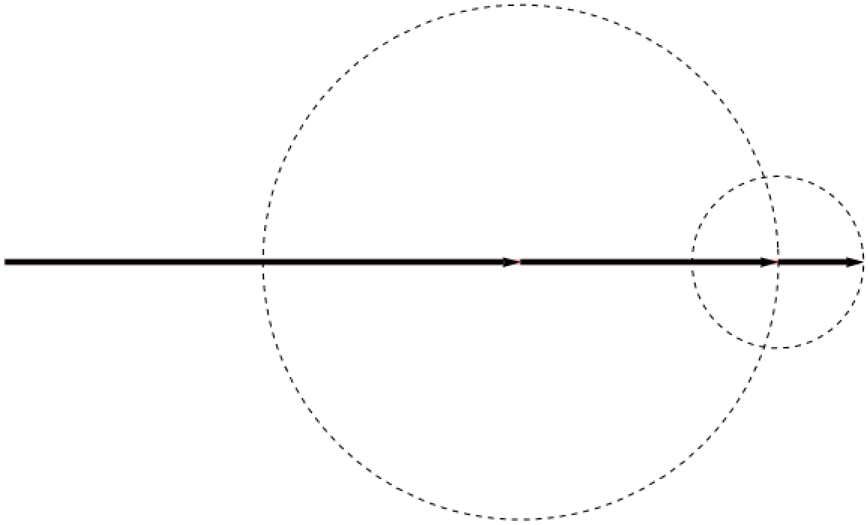

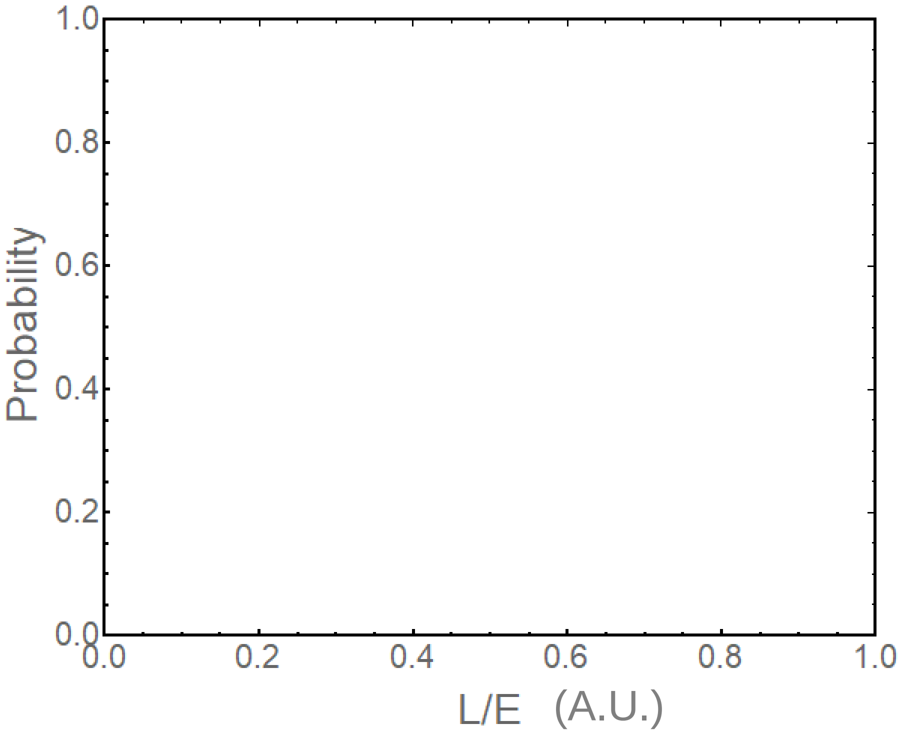

A closer look at NMO in vacuum

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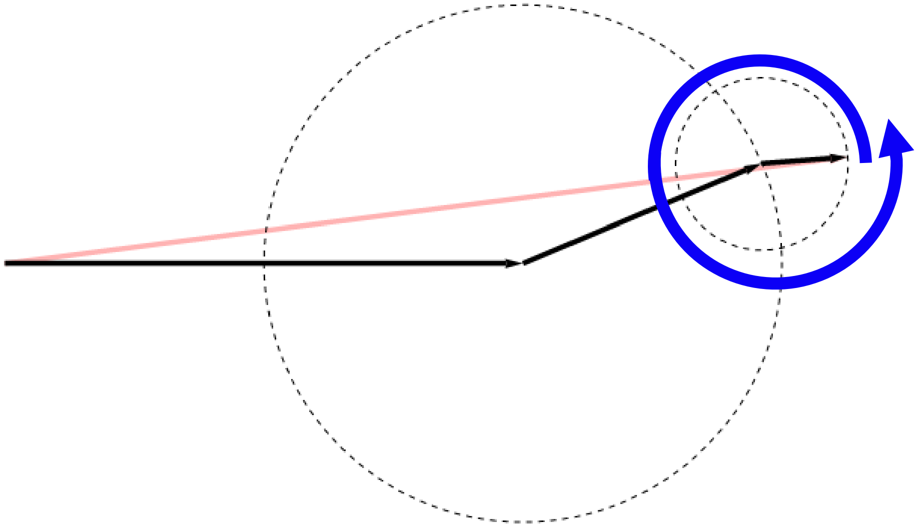
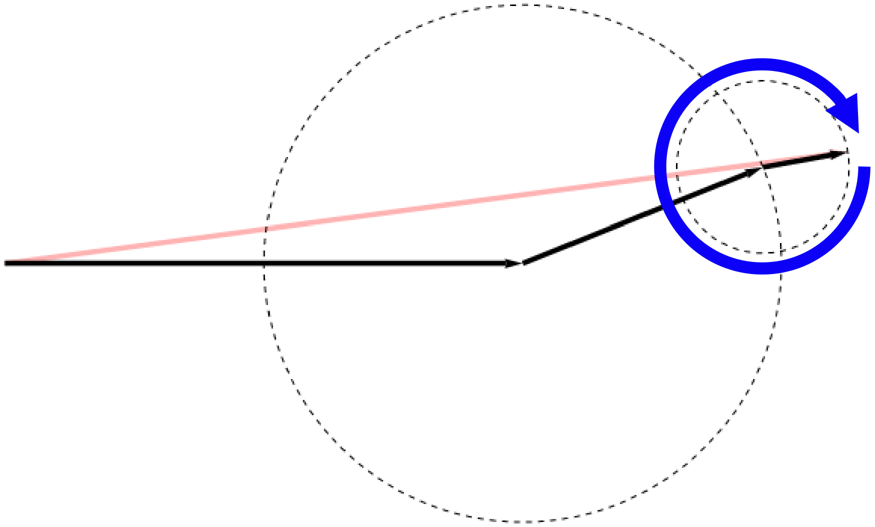
Normal Ordering

Inverted Ordering



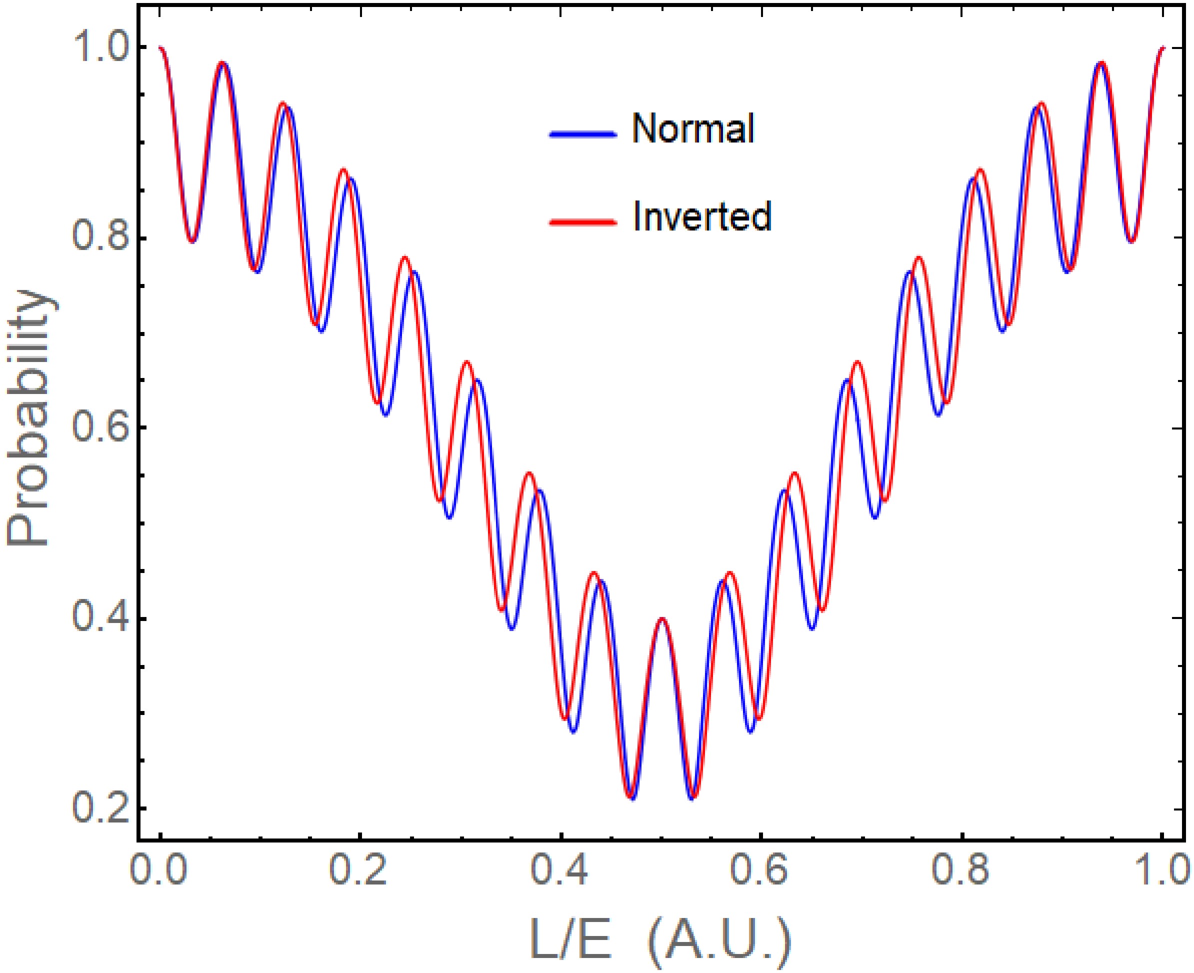


Slower
More than one turn
to reach maximum

Faster
Less than one turn
to reach maximum

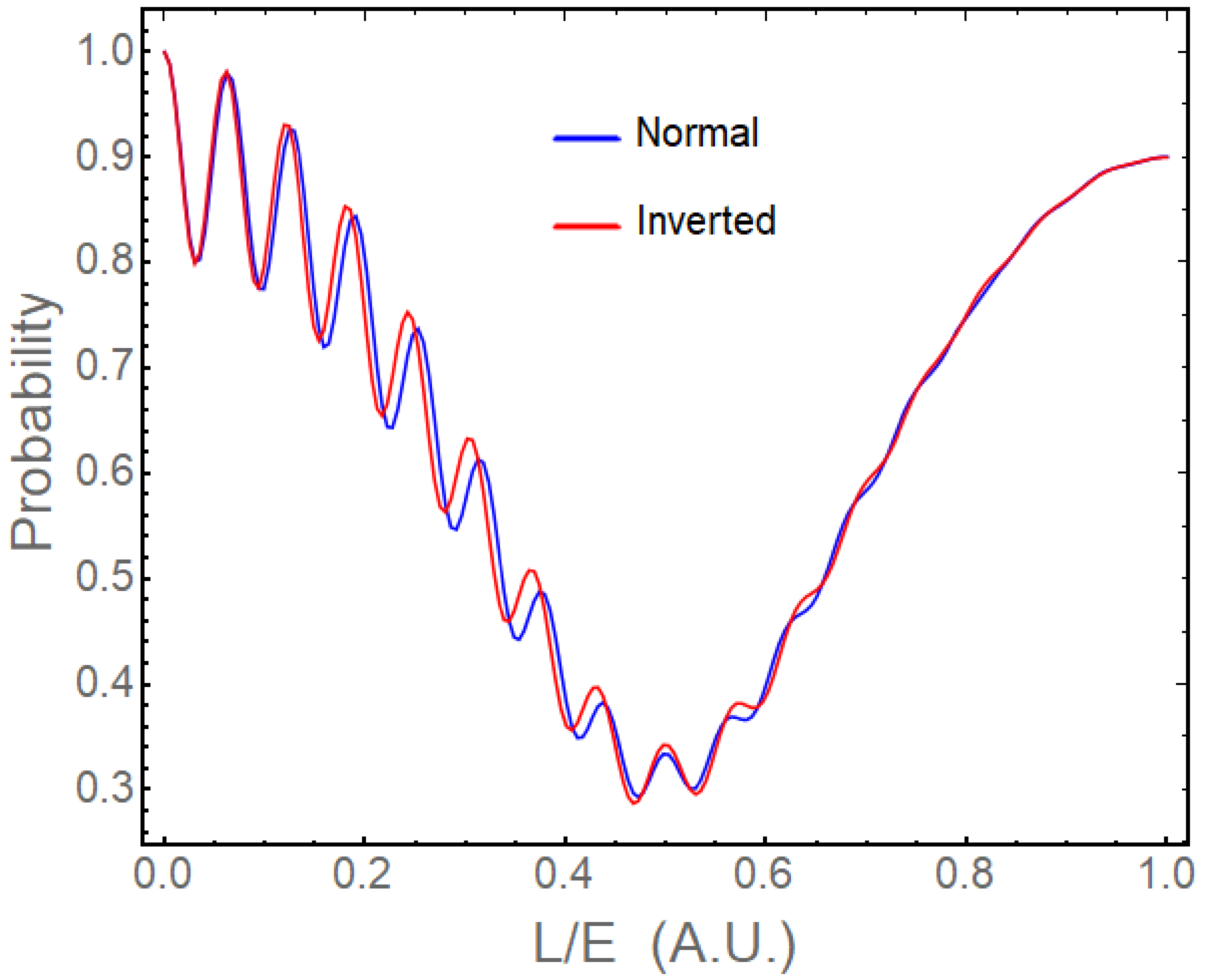
A closer look at NMO in vacuum

- NMO can be determined by oscillation frequency
- However…



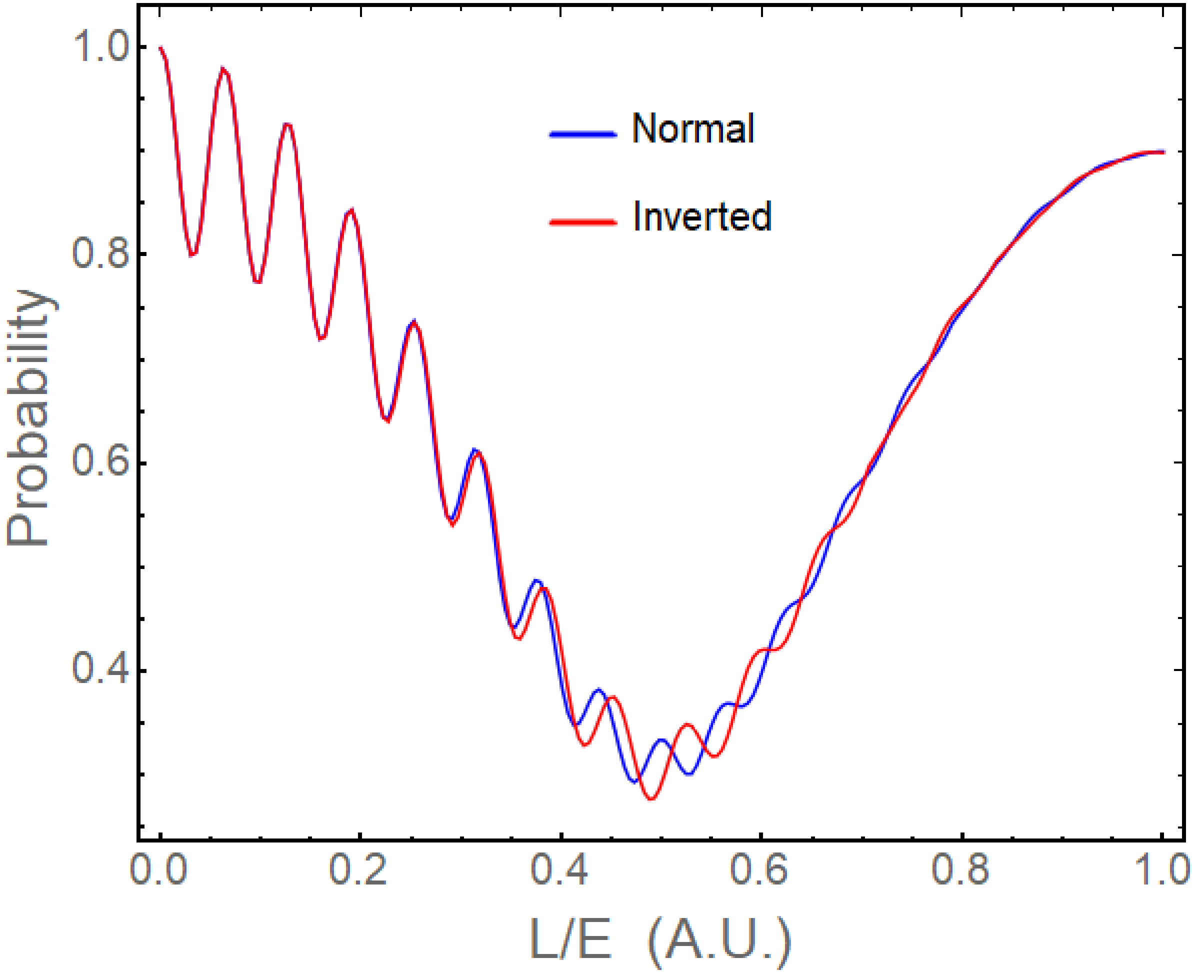
A closer look at NMO in vacuum

- NMO can be determined by oscillation frequency
- However… energy resolution and…



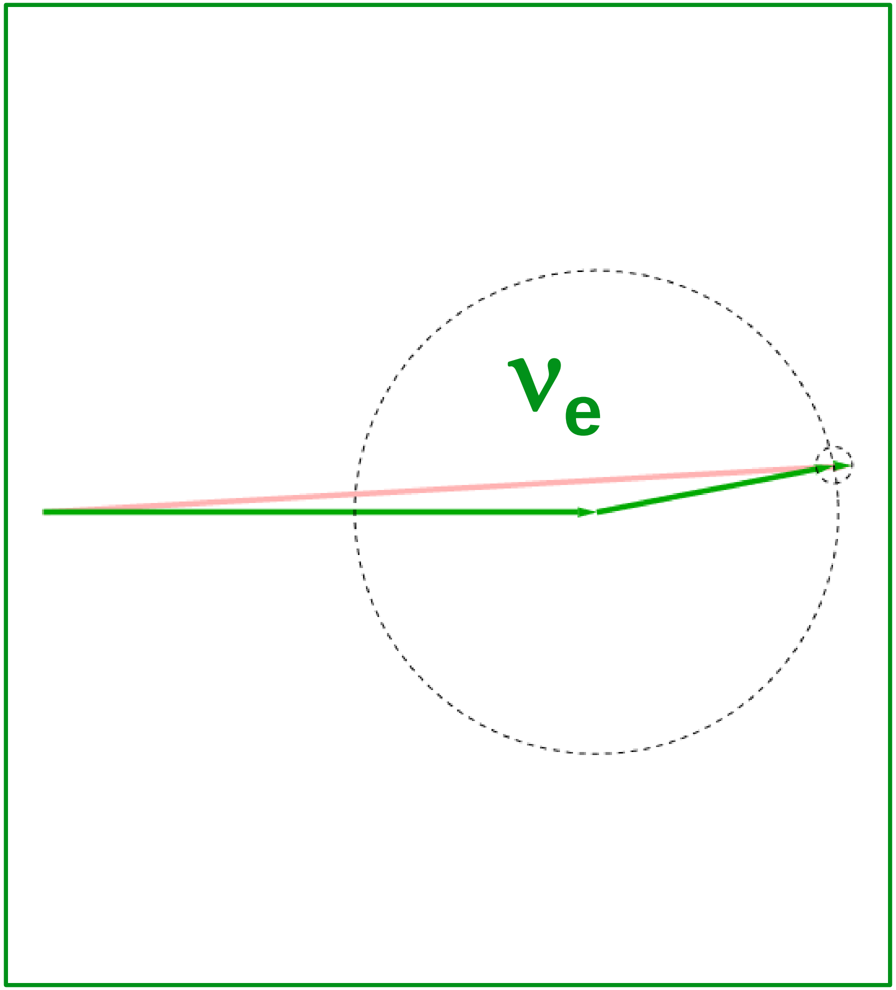
A closer look at NMO in vacuum

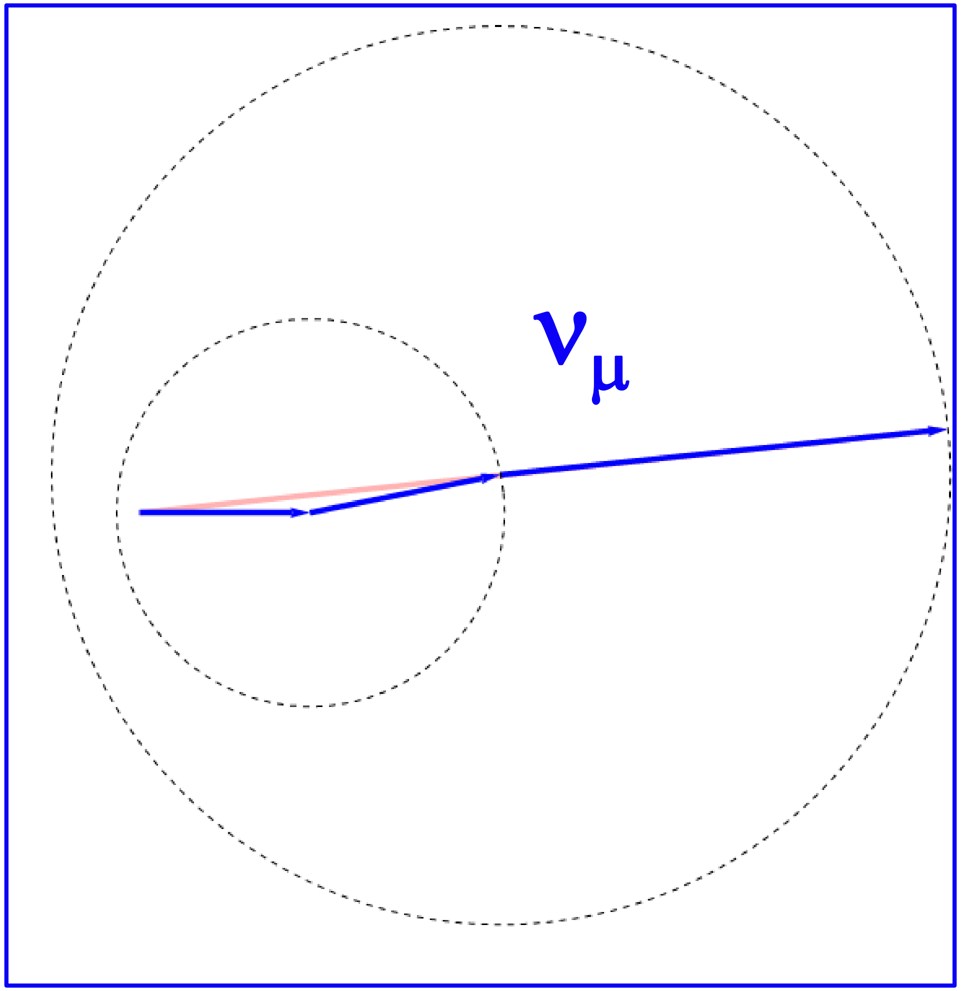
- NMO can be determined by oscillation frequency
- However… energy resolution and… unknown freq. scale



$\nu_\mu \leftrightarrow \nu_e$ synergy

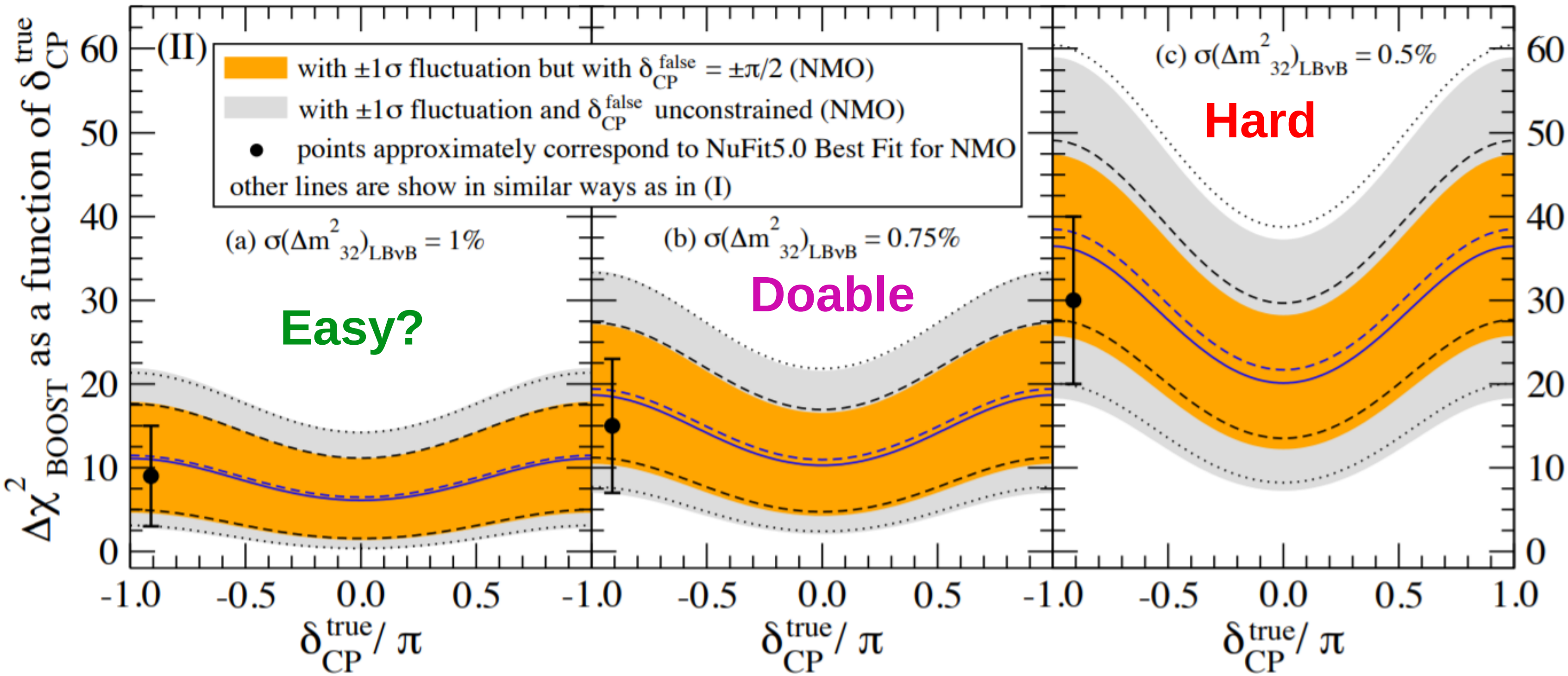
- Mixing structure leads to different effective frequencies





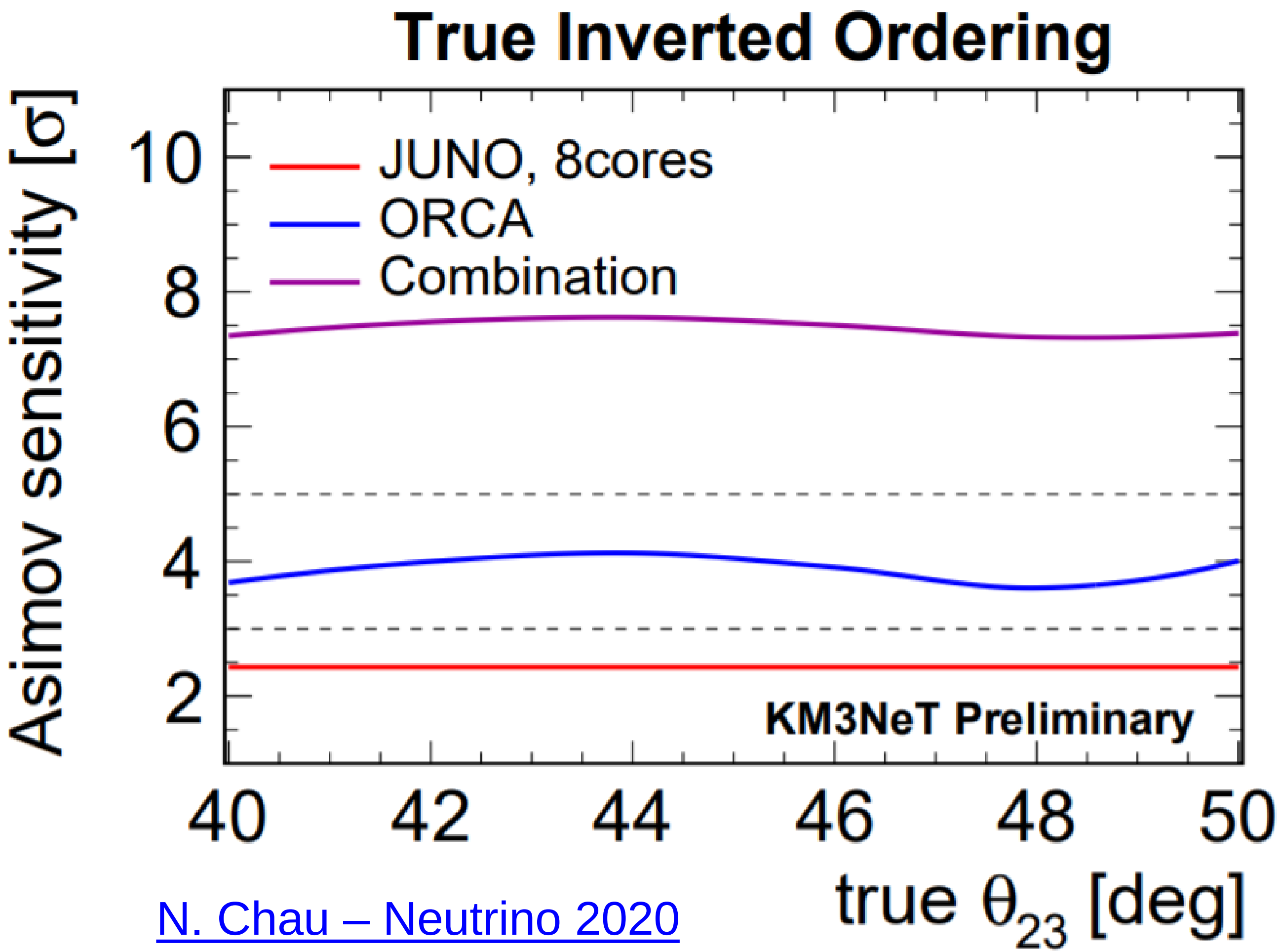
How much do we stand to gain?

- Synergy between JUNO and LBL can add **10 – 40 units of χ^2**
- Exploits extra data from LBL disappearance to probe NMO
- Effect highly dependent on precision of LBL on Δm^2_{32}



And it's not just LBL either

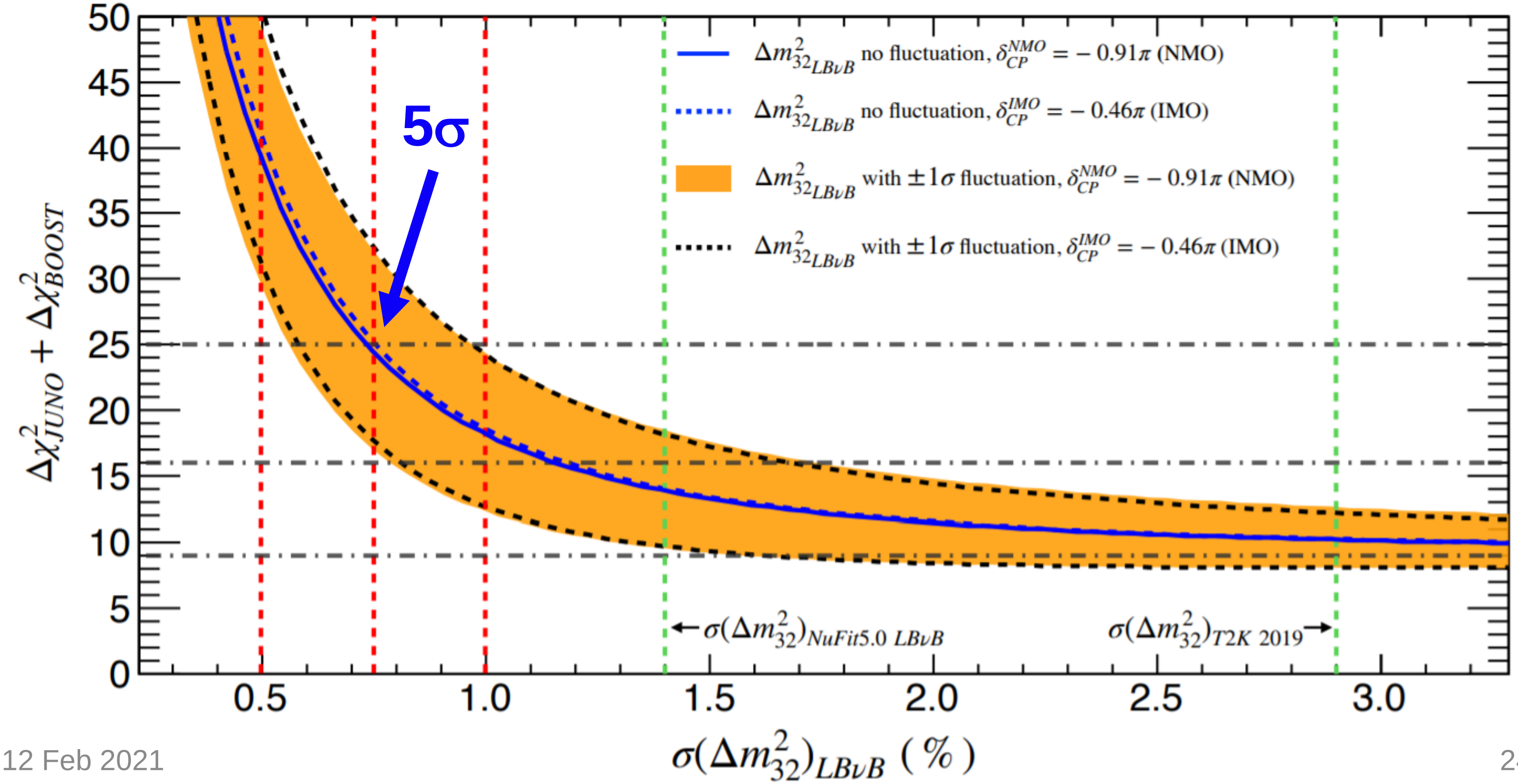
- **Synergies** between **JUNO** and **ORCA**, for example, can add even more boosting to the NMO determination (**~40 units of χ^2**)



[N. Chau – Neutrino 2020]

What's the lesson here?

- No single experiment is likely to reach 5σ on NMO by 2028
- The ν_μ disapp. channel may provide the extra boost needed
- LBL and atmospheric experiment should keep in mind the **importance of Δm^2_{32} resolution** in their future planning



Thank you!

ν
BSM
ββ
solar
reactor
accelerator
atmospheric
coherent scattering
P2IO