

Juno ≠ the Neutrino Mass Ordering

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[based on arXiv:2107.12410 by David V. Forero, Stephen J. Parke, Christoph A. Ternes and RZF]



NuCo 2021: Neutrinos en Colombia

28-30 July 2021

We do not know the Neutrino Mass Ordering

Normal Ordering

$$\Delta m_{21}^2$$



3

$$|\Delta m_{31}^2| > |\Delta m_{32}^2|$$



2

1

$$\Delta m_{\text{atm}}^2$$

$$\Delta m_{21}^2$$



2

1

$$|\Delta m_{31}^2| < |\Delta m_{32}^2|$$

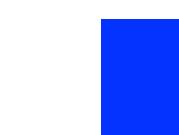


3

ν_e



ν_μ



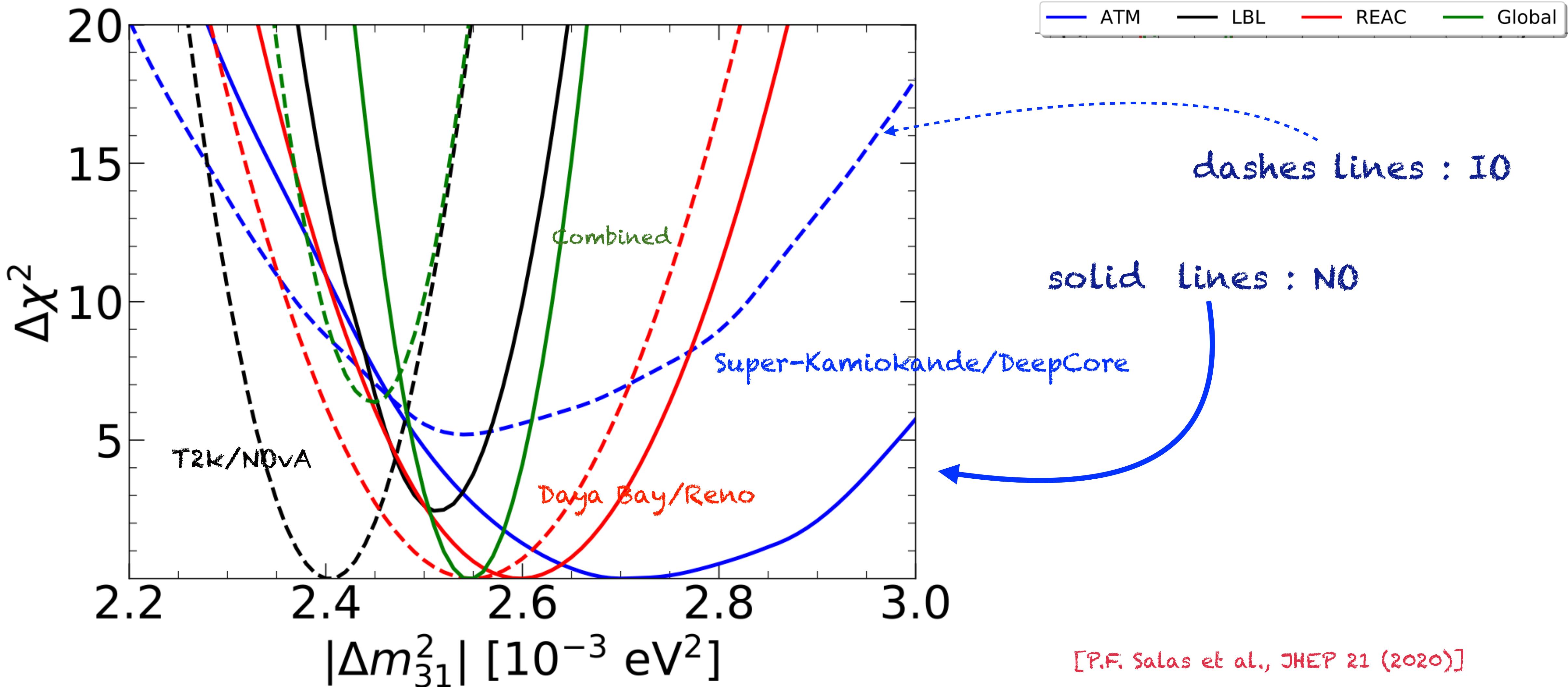
ν_τ



using flavor content

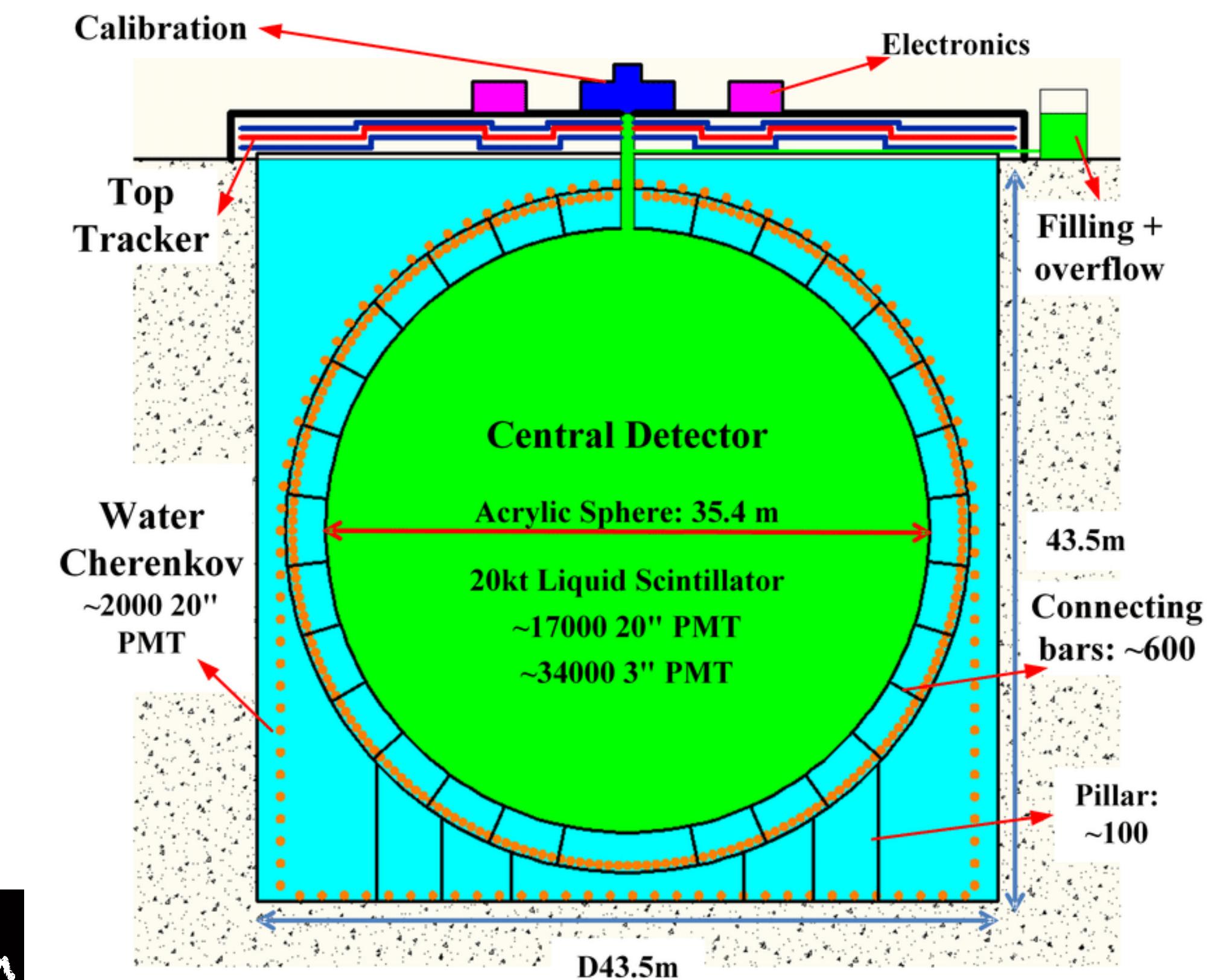
$$|U_{e1}^\nu| > |U_{e2}^\nu| > |U_{e3}^\nu|$$

What do we know about the Neutrino Mass Ordering ?



The Jiangmen Underground Neutrino Observatory (JUNO)

Jiangmen Underground Neutrino Observatory is a 20 kton liquid scintillator detector located @ 53 km from Yangjiang & Taishan Nuclear Power Plants in China - medium baseline reactor neutrino detector

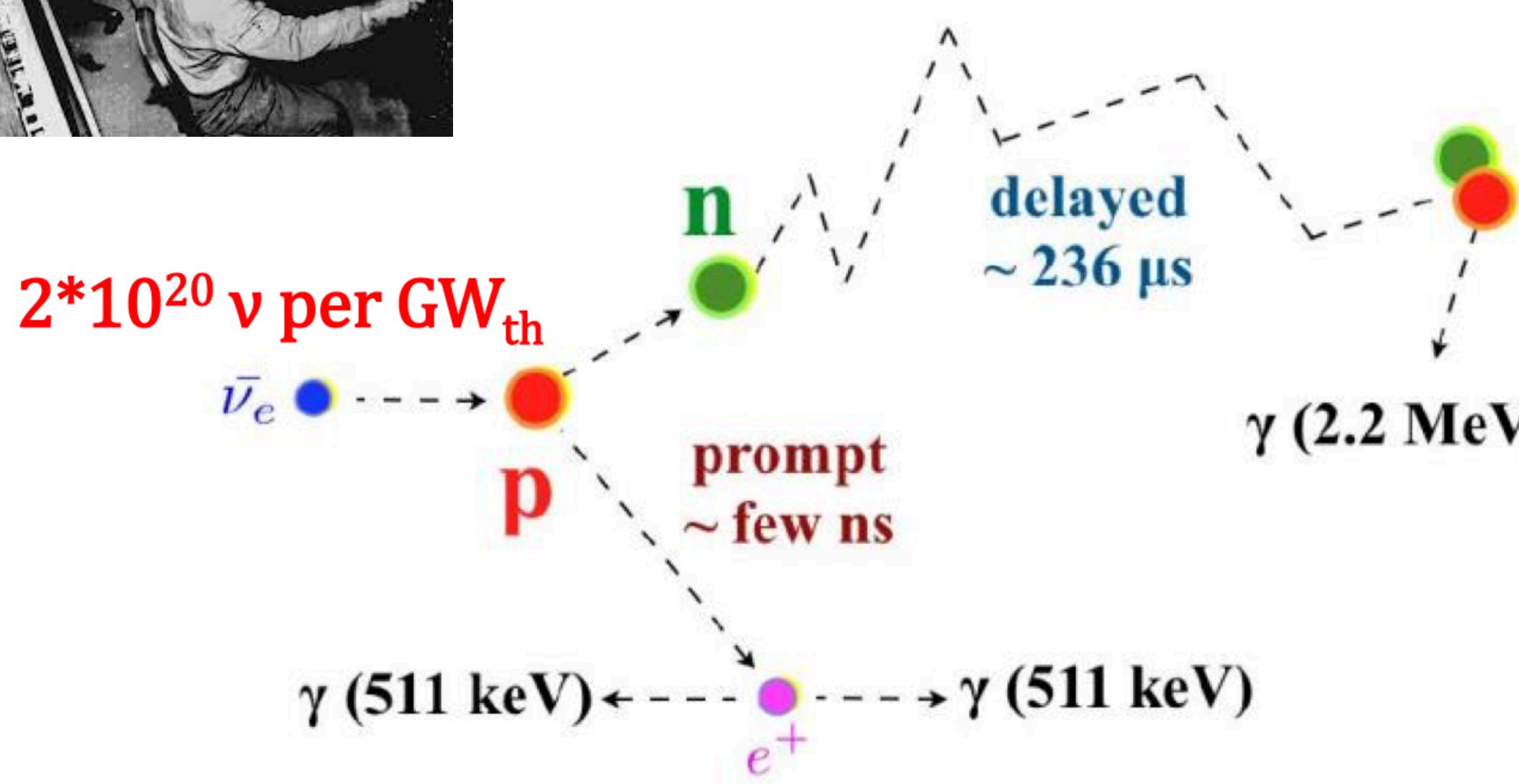


[Take from Z. Yu talk on behalf of JUNO Collab.]

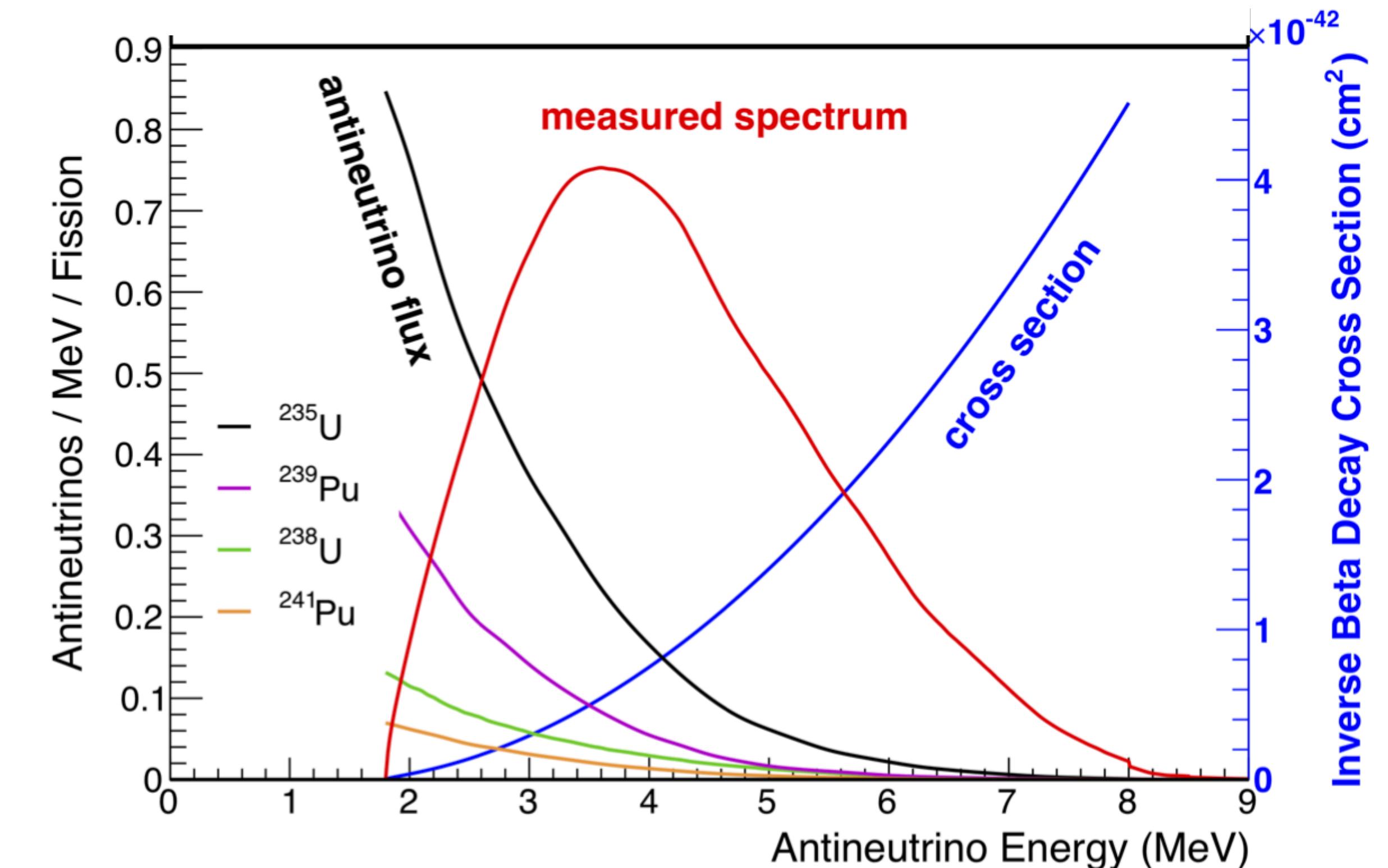
The Jiangmen Underground Neutrino Observatory (JUNO)



Reactor Antineutrino Oscillation Experiment



Inverse Beta Decay X-Section:
prompt & delayed signal coincidence

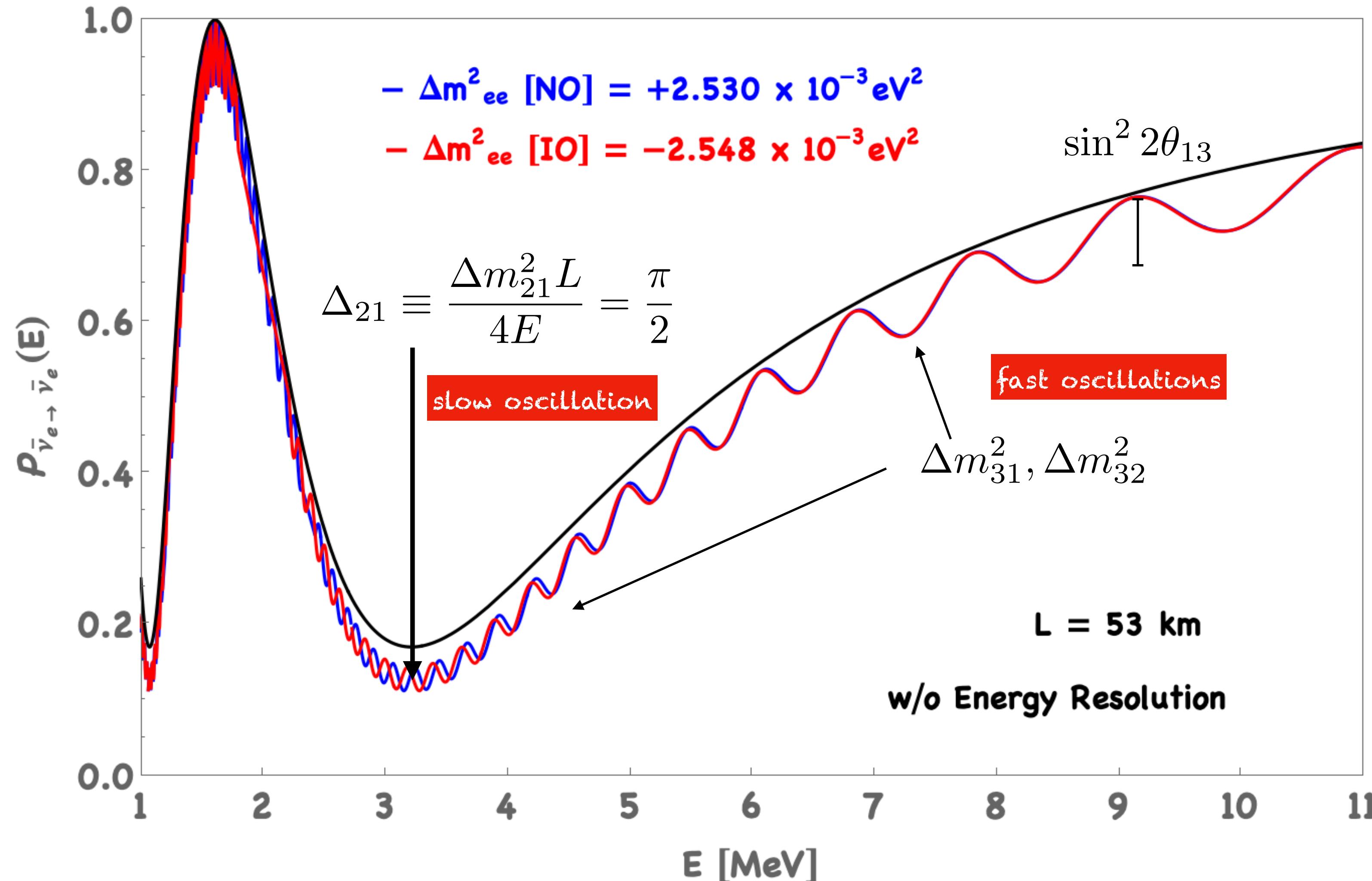


[taken from Vogel, Wen, Zhang, 2015]



JUNO's Flagship Measurement Strategy

medium baseline reactor neutrino detector



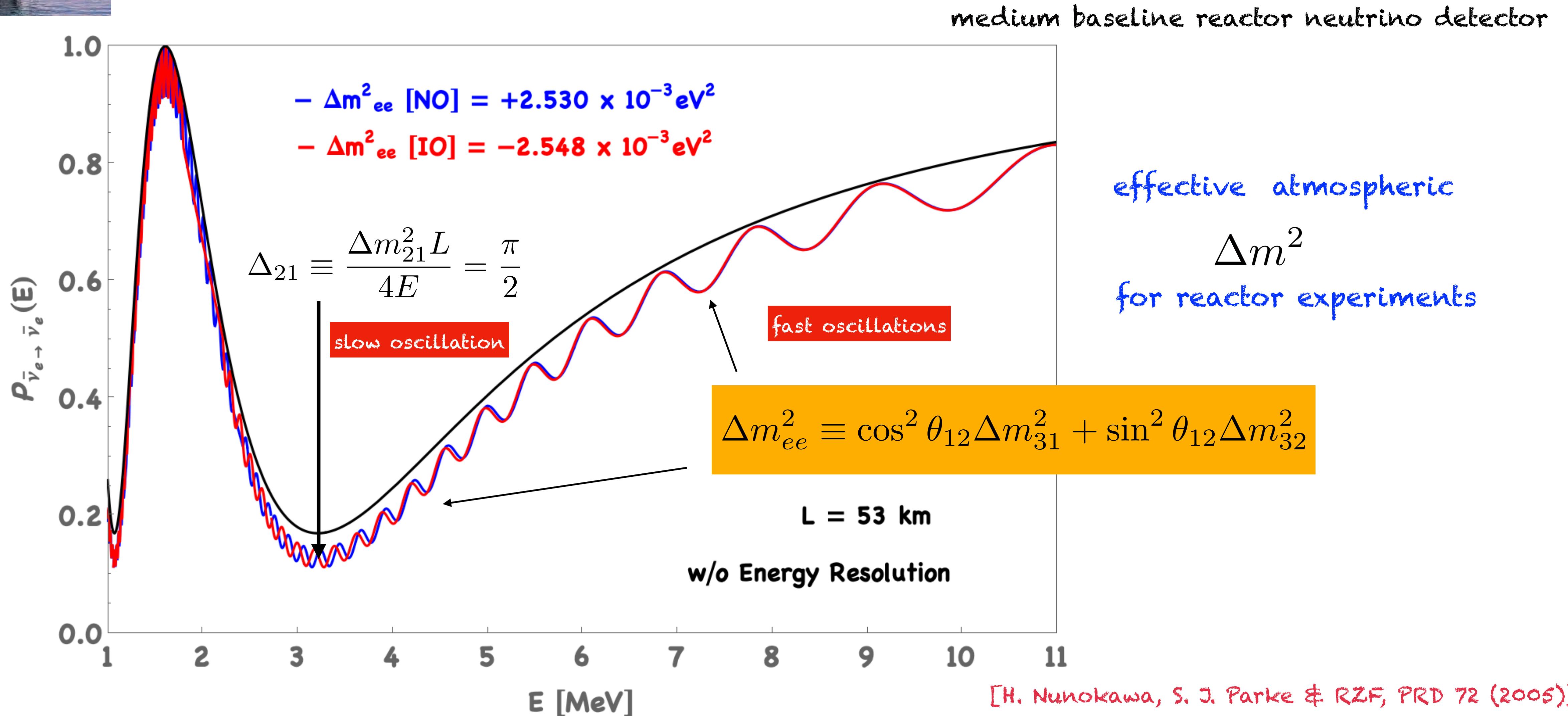
Low and high frequency
modes present

[S.T.Petcov & M.Piai, PLB 533 (2002)
&

S. Choubey et al., PRD 68 (2003)]



JUNO's Flagship Measurement Strategy



Neutrino Survival Probability @ JUNO

in vacuum

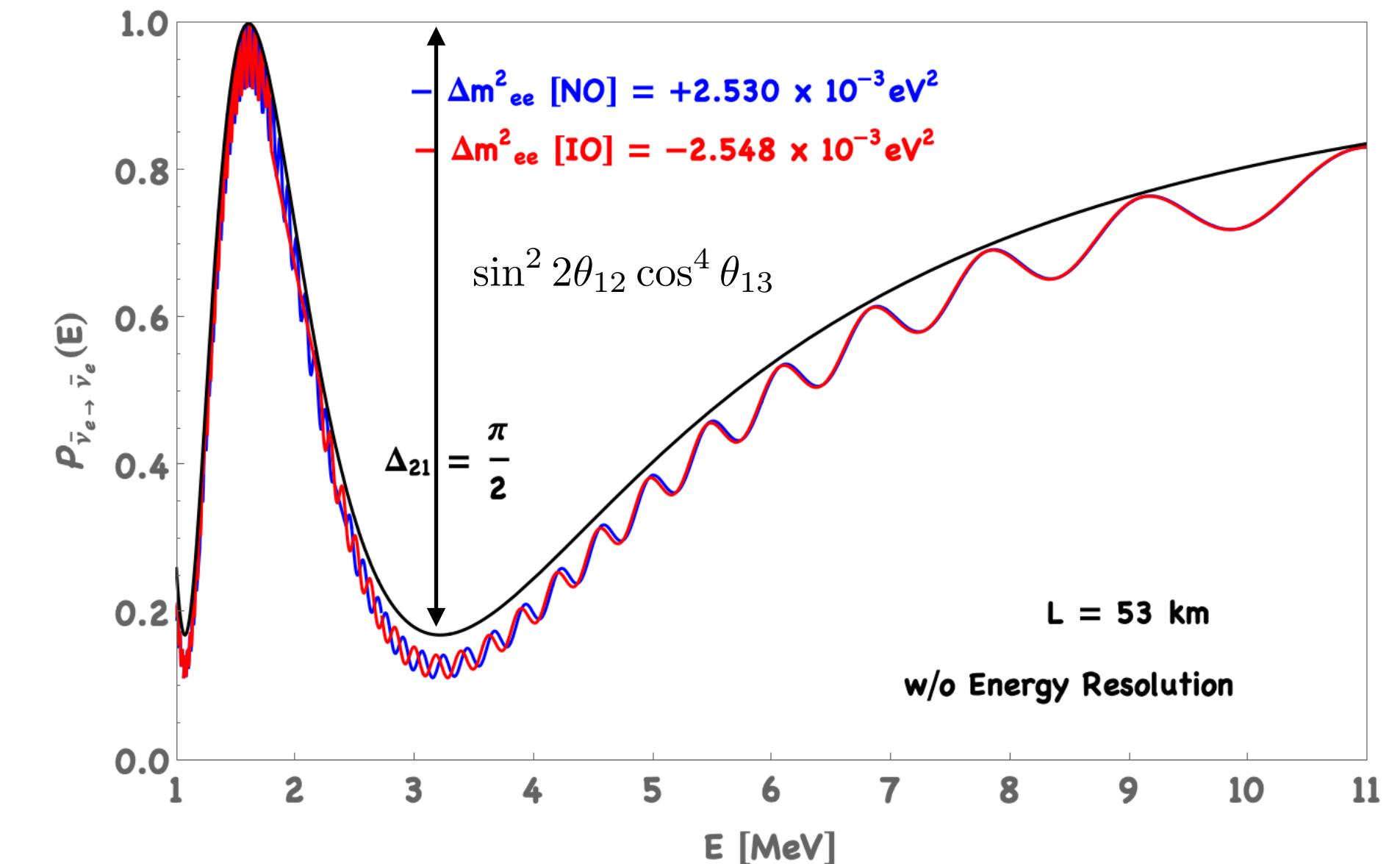
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \frac{1}{2} \sin^2 2\theta_{13} \left[1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}} \cos(2|\Delta_{ee}| \pm \Phi_\odot) \right] - P_\odot$$

[H. Minakata, H. Nunokawa, S. J. Parke & RZF, PRD 76 (2007)]

$$P_\odot = \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \Delta_{21}$$

solar term

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$



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$$P_\odot = \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \Delta_{21} \quad \text{solar term}$$

$$\Phi_\odot = \arctan(\cos 2\theta_{12} \tan \Delta_{21}) - \Delta_{21} \cos 2\theta_{12}$$

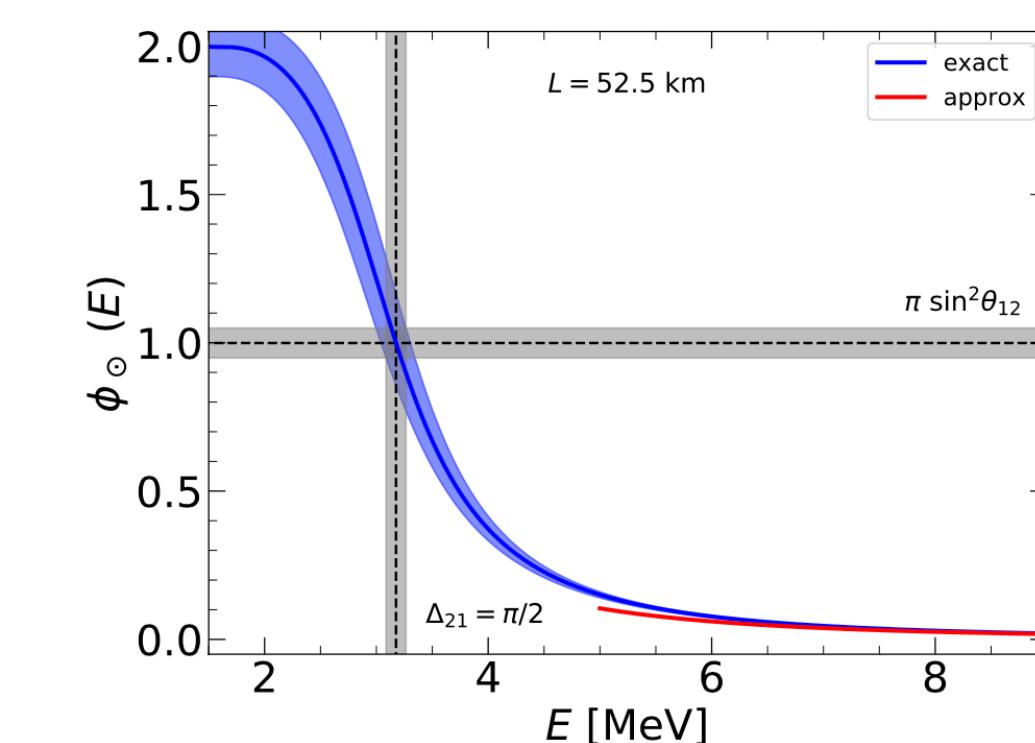
effective atmospheric Δm^2 for reactor experiments

$$\Delta m_{ee}^2 \equiv \cos^2 \theta_{12} \Delta m_{31}^2 + \sin^2 \theta_{12} \Delta m_{32}^2$$

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advance/retardation phase

+NO | - IO



Neutrino Survival Probability @ JUNO

in vacuum

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$\Delta m_{21}^2, \sin^2 \theta_{12}, \sin^2 \theta_{13}, \Delta m_{ee}^2, \pm$ sign

Neutrino Survival Probability @ JUNO

in vacuum

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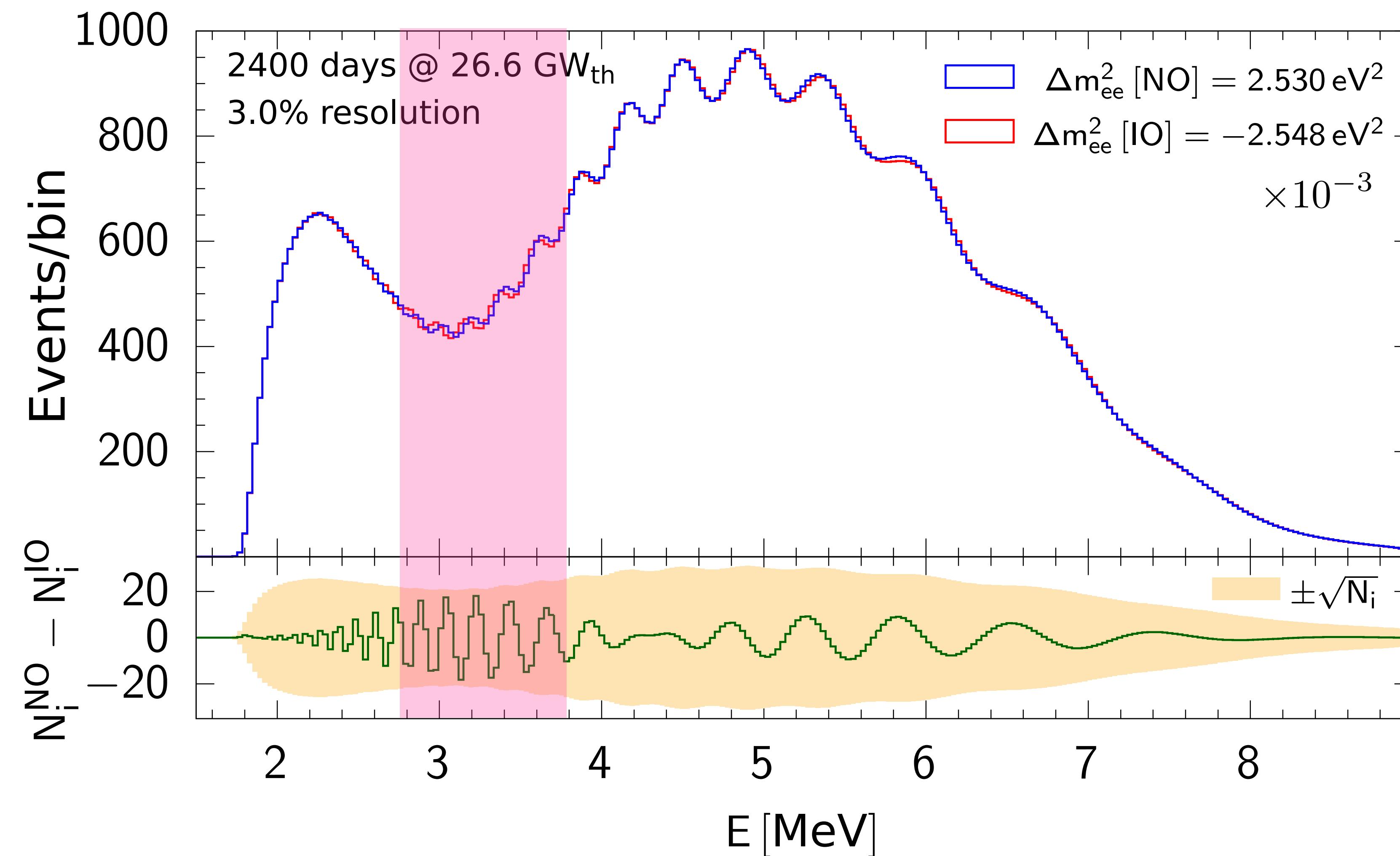
$\Delta m_{21}^2, \sin^2 \theta_{12}, \sin^2 \theta_{13}, \Delta m_{ee}^2, \pm \text{sign}$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

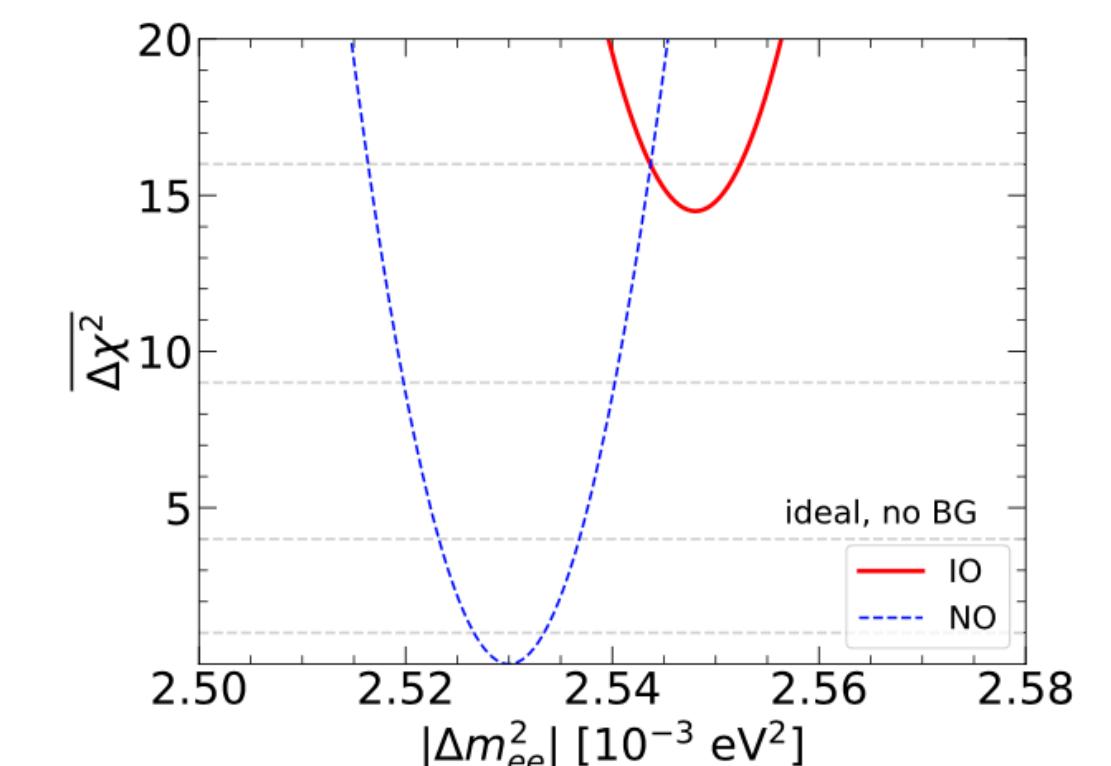
 $|\Delta m_{ee}^2[\text{IO}]| > |\Delta m_{ee}^2[\text{NO}]|$

retardation/advancement of the phase result in a change
of the "effective fast oscillation scale"

JUNO's Challenging Measurement

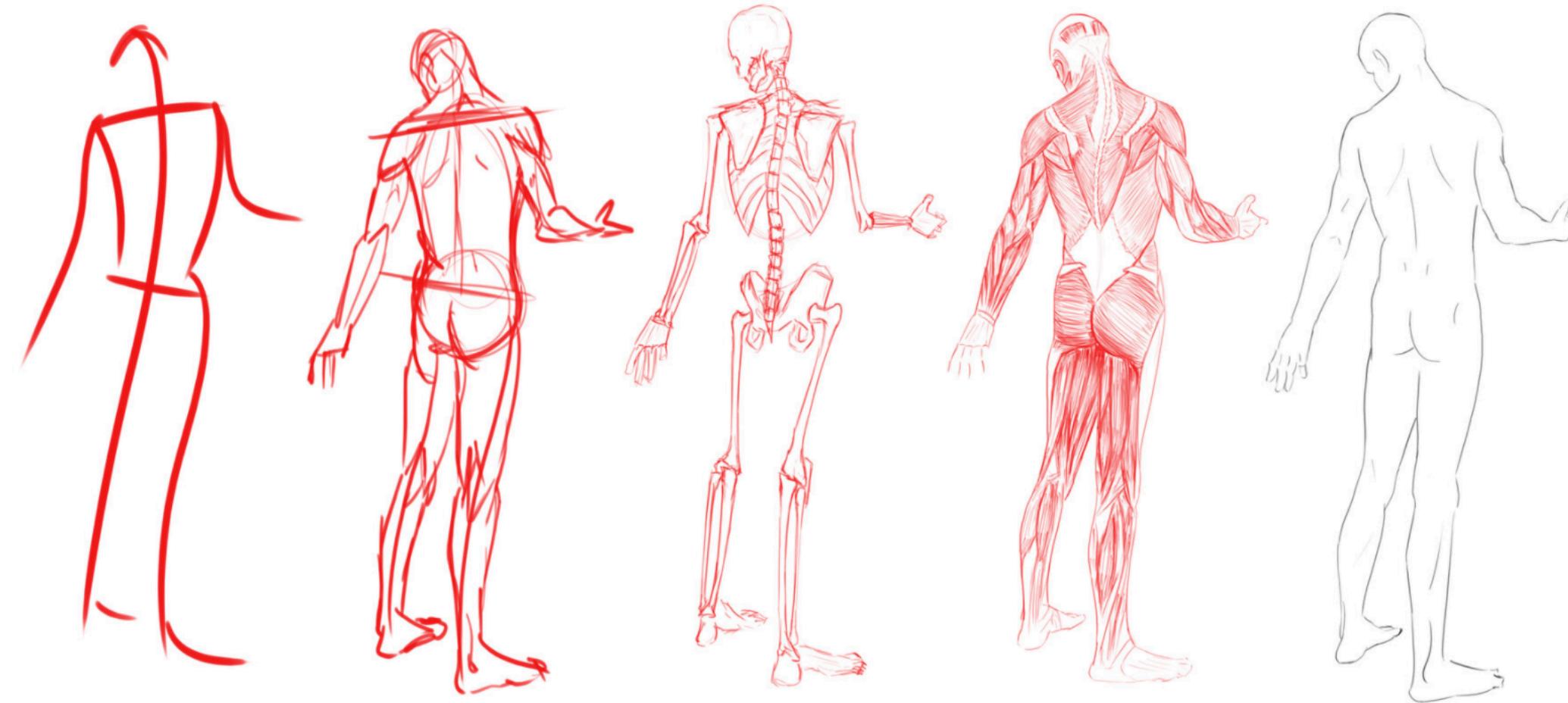


$$|\Delta m_{ee}^2[\text{IO}]| > |\Delta m_{ee}^2[\text{NO}]|$$



single core
no other systematics
no background events

every single effect counts !



Anatomy of a Measurement

updated reactors configuration & backgrounds

updated detector live time & systematic effects

[JUNO Collab., arXiv:2104.02565]

updated knowledge of neutrino oscillation parameters

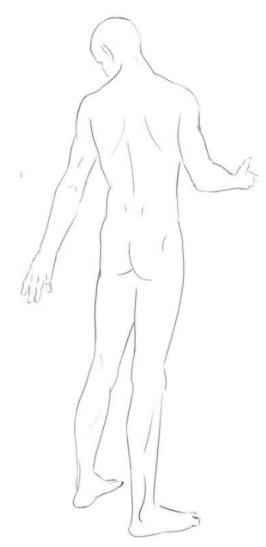
We assume

[See David V. Forero, Stephen J. Parke, Christoph A. Ternes and RZF, arXiv:2107.12410]

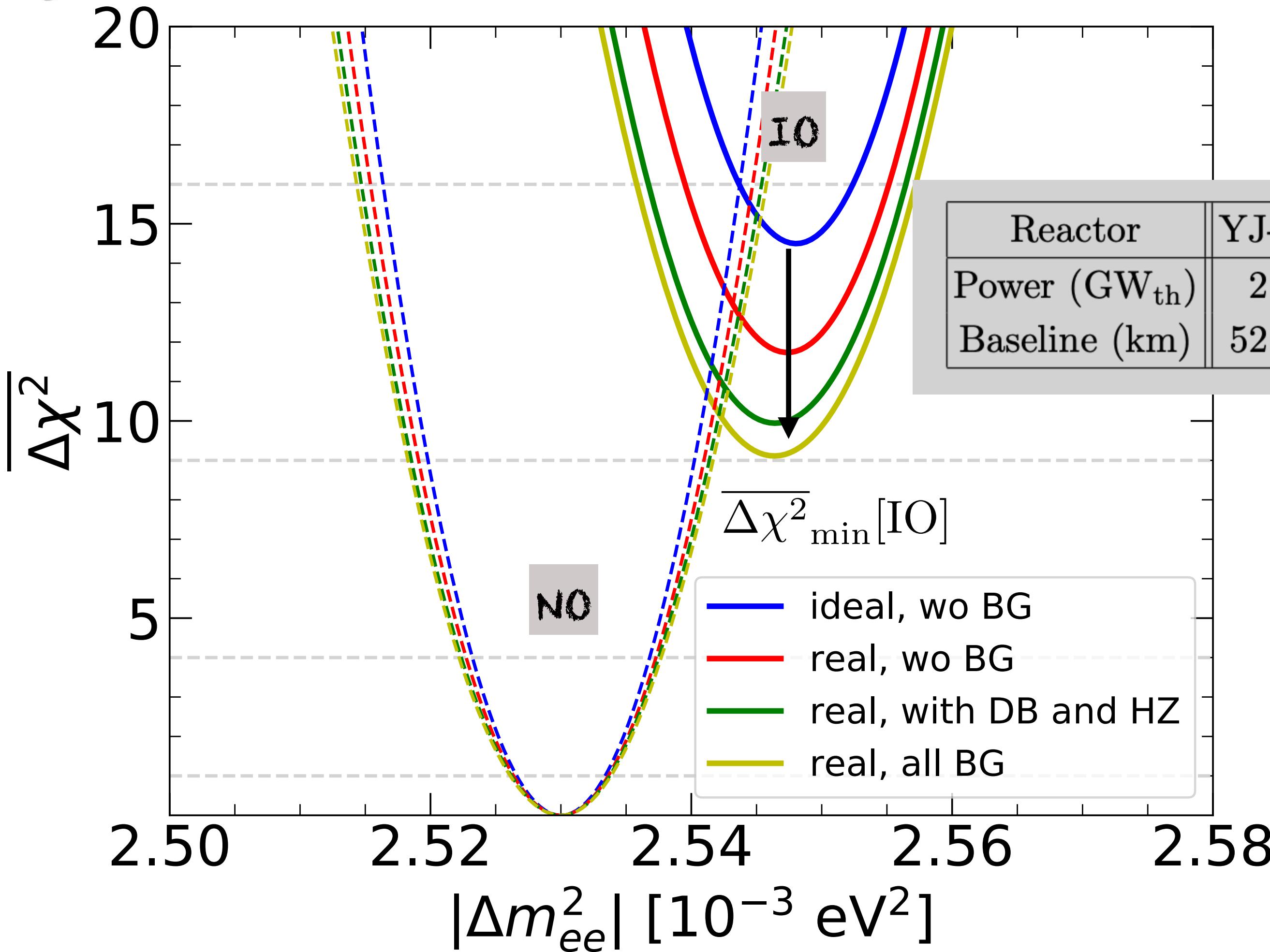
Normal Ordering		
Parameter	Nominal Value	1σ
$\sin^2 \theta_{12}$	0.318	± 0.016
$\Delta m_{21}^2 [10^{-5} \text{eV}^2]$	7.50	± 0.21
$\sin^2 \theta_{13}$	0.02200	± 0.00065
$\Delta m_{ee}^2 [10^{-3} \text{eV}^2]$	2.53	$+0.03/-0.02$

+ total exposure of 26.6 GW_{th} for 2400 days (8 years @ 82% live time)
+ 200 energy bins & 3% energy resolution

★ we do not consider matter effect here (we only interested here in sensitivity)



From single to multiple cores + backgrounds



$\overline{\Delta \chi^2}_{min}[\text{IO}]$

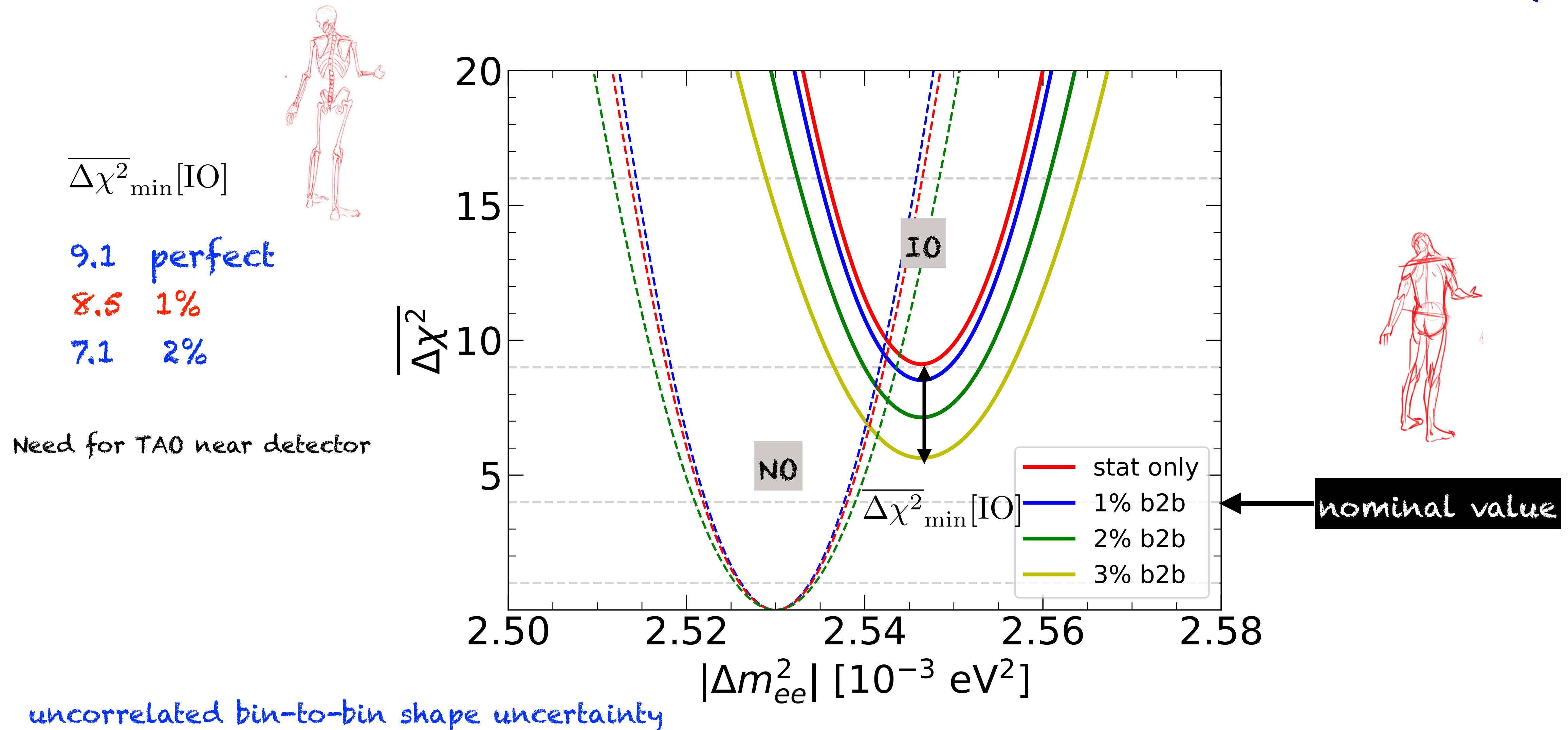
14.5 ideal single core no bckg

11.7 real core distribution

9.1 real core distribution + all bckg



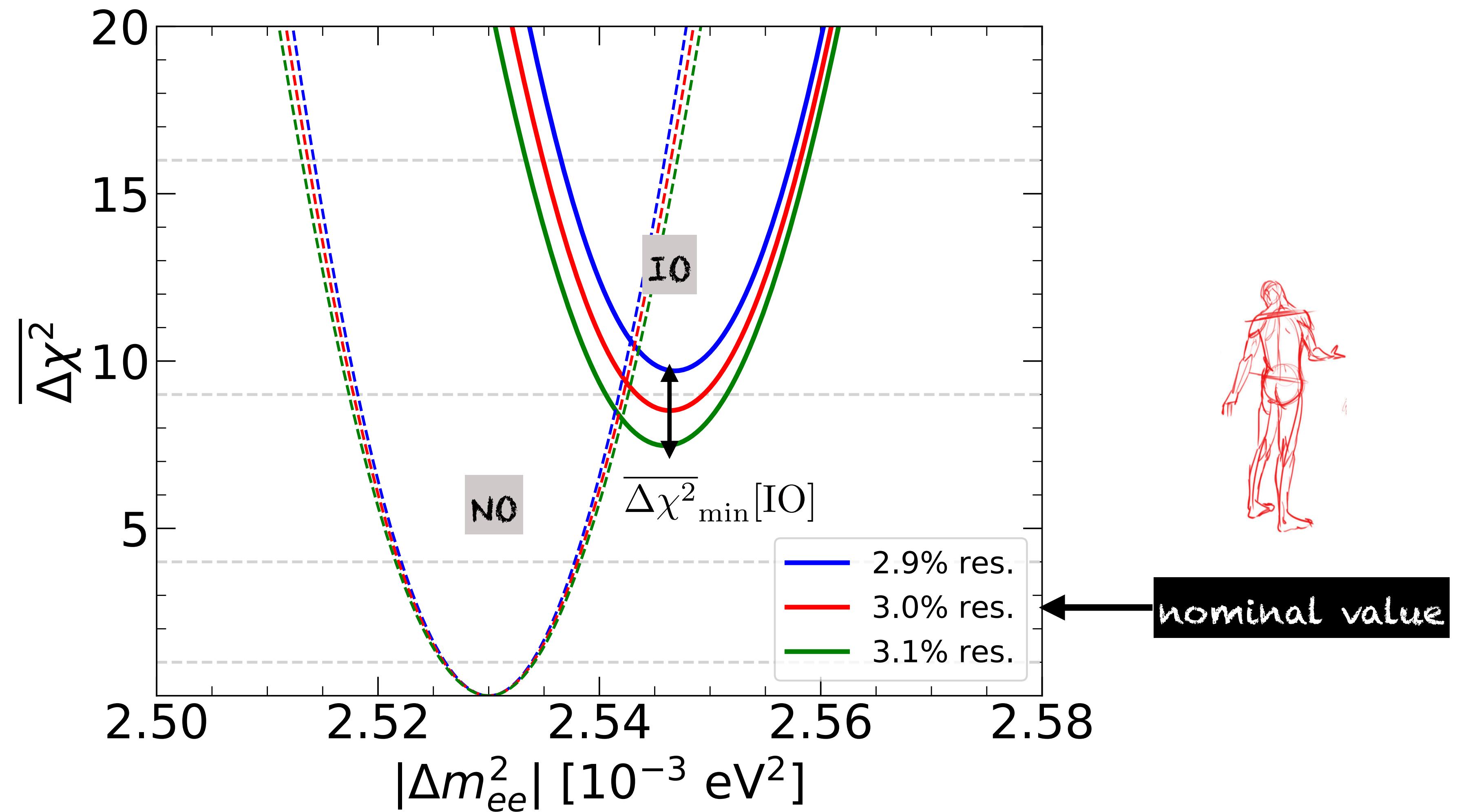
How well do we know the $\overline{\nu}_e$ Flux Shape?



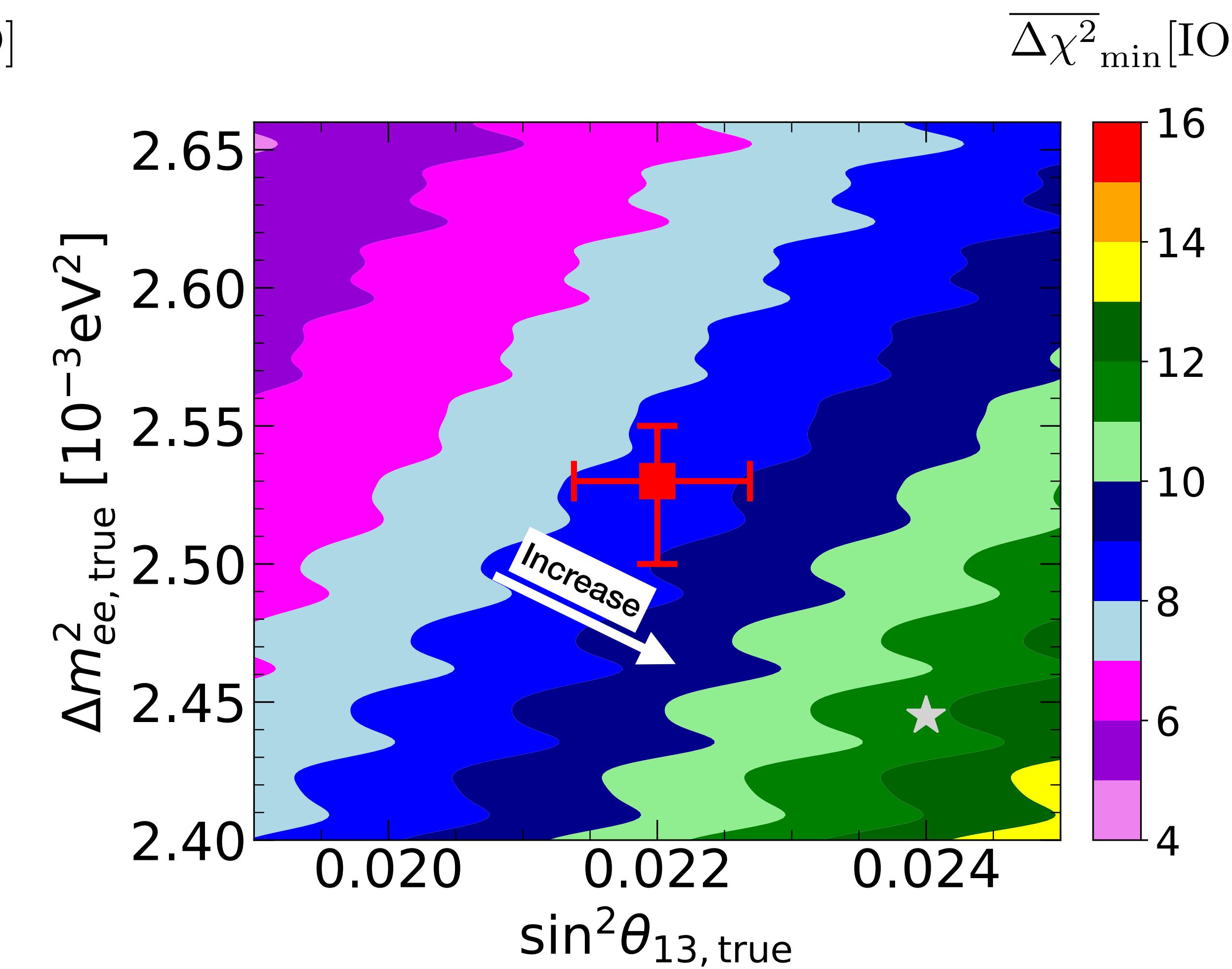
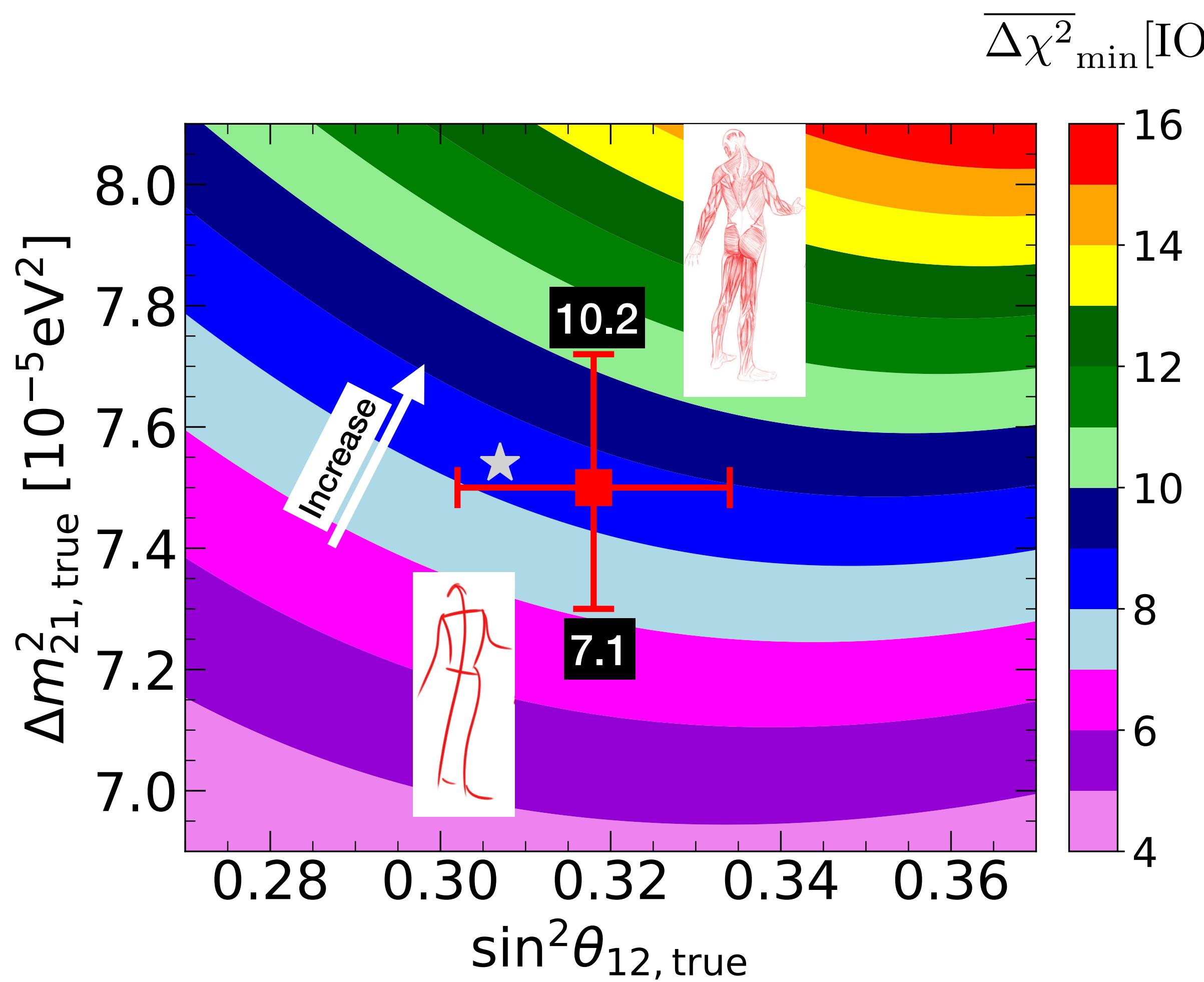
JUNO Energy Resolution

$\overline{\Delta\chi^2}_{\min}[\text{IO}]$

9.7	2.9%
8.5	3.0%
7.5	3.1%



True Value of the Oscillation Parameters



Non-Linearity of the Energy Scale

intrinsic + instrumental non-linearity of the detector can be model by

$$E_p = E - 0.78 \text{ MeV}$$

$$E_p = \frac{E^{\text{vis}}}{f_{\text{NL}}}$$

$$f_{\text{NL}}(a_1, a_2, a_3, a_4; E_p) \equiv \frac{a_1 + a_2 E_p}{1 + a_3 e^{-a_4 E_p}}$$

penalty

$$\chi^2_{\text{NL}} = \max_{E_p} \left(\frac{f_{\text{NL}}(\bar{a}_1, \bar{a}_2, \bar{a}_3, \bar{a}_4; E_p)}{f_{\text{NL}}(a_1, a_2, a_3, a_4; E_p)} - 1 \right)^2 / (\sigma_{\text{bias}})^2$$

calibration values [JUNO Collab., JHEP 03 (2021)]

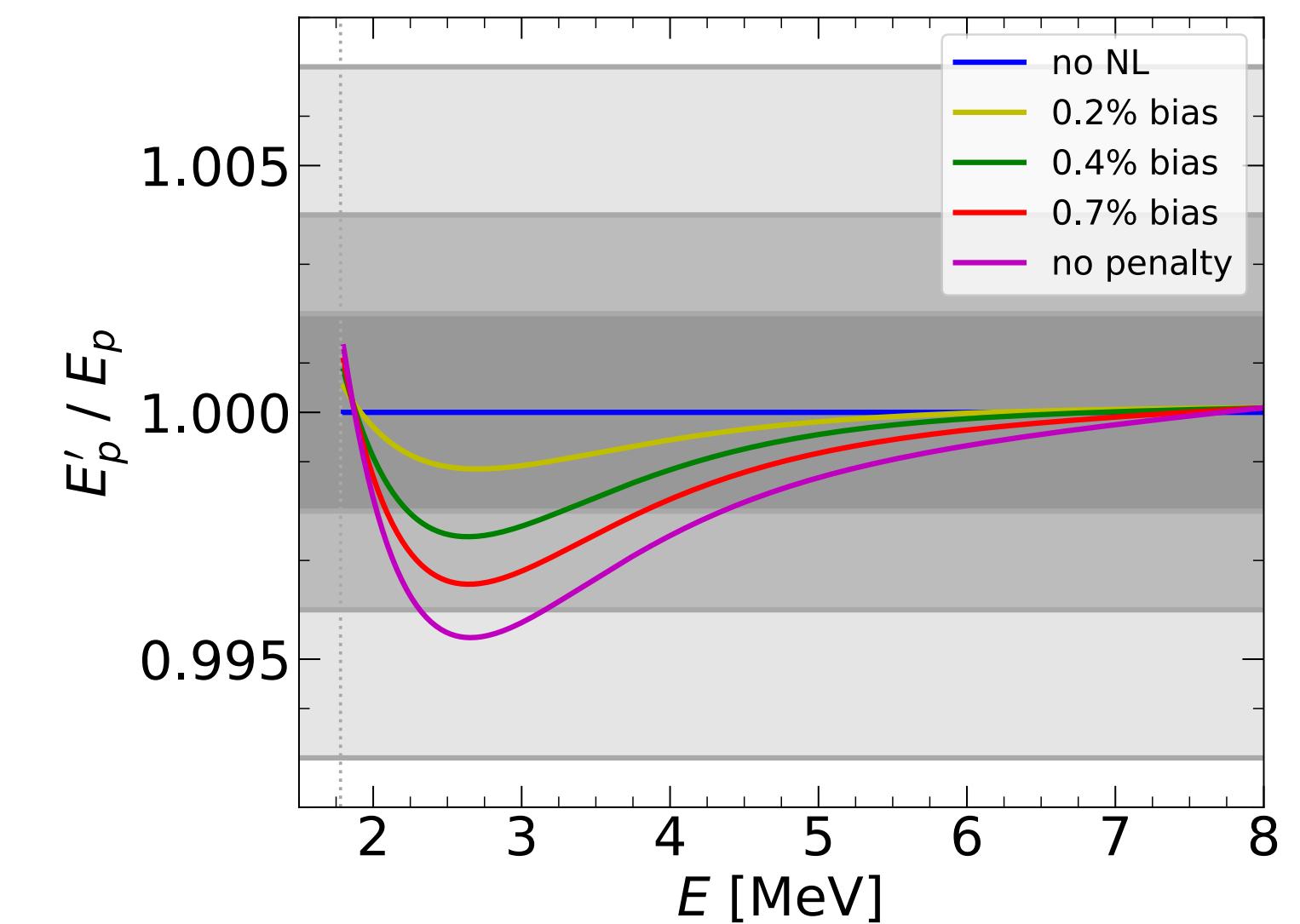
[F. Capozzi, E. Lisi & A. Marrone, PRD 92 (2015)]

$$\bar{a}_1 = 1.049 \quad \bar{a}_2 = 2.062 \times 10^{-4} \quad \bar{a}_3 = 9.624 \times 10^{-2} \quad \bar{a}_4 = 1.184$$

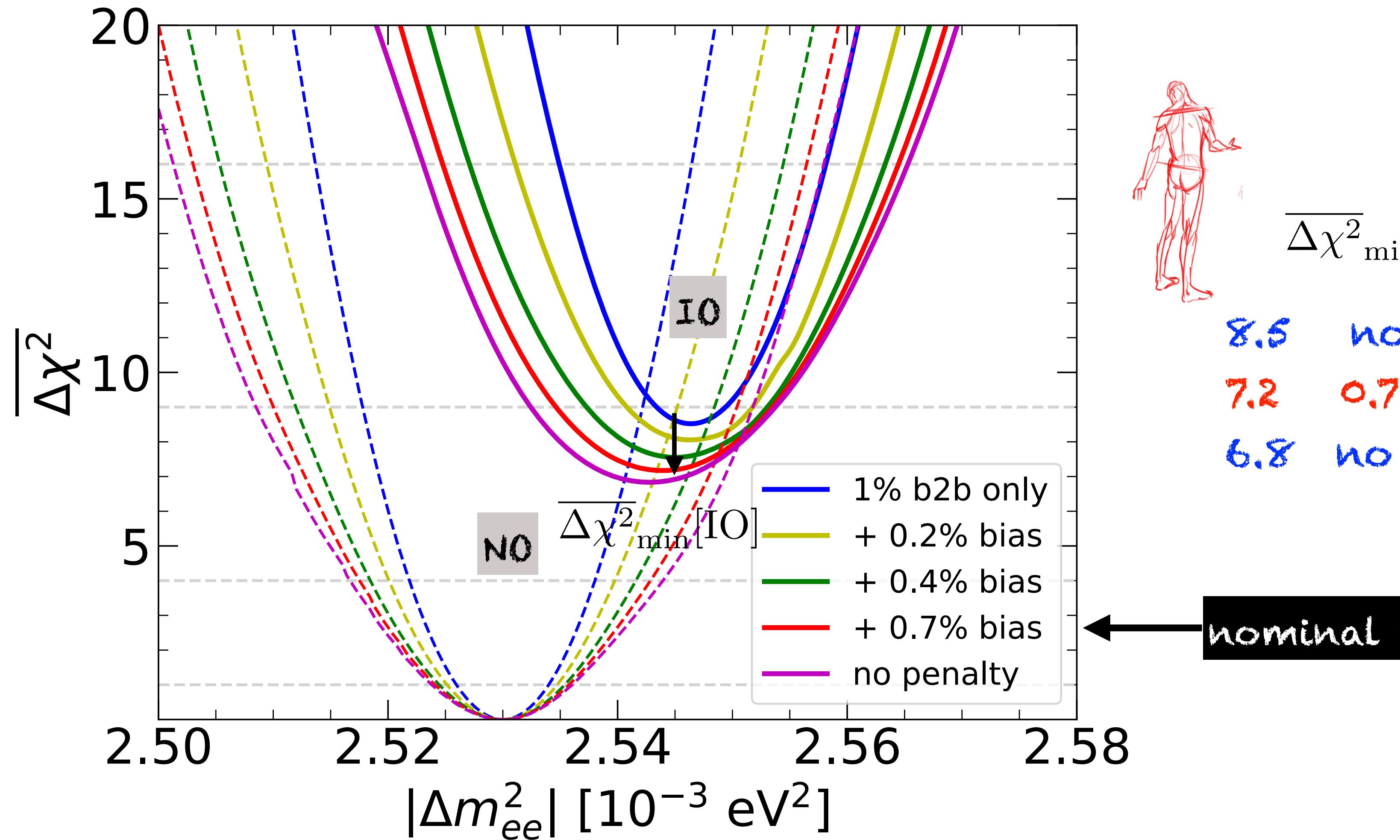
reconstructed prompt energy

$$\frac{E'_p}{E_p} = \frac{f_{\text{NL}}(\bar{a}_1, \bar{a}_2, \bar{a}_3, \bar{a}_4; E_p)}{f_{\text{NL}}(a_1, a_2, a_3, a_4; E_p)}$$

true prompt energy



Non-Linearity of the Energy Scale



$\overline{\Delta\chi^2}_{\min}[\text{IO}]$

8.5 no NL effect

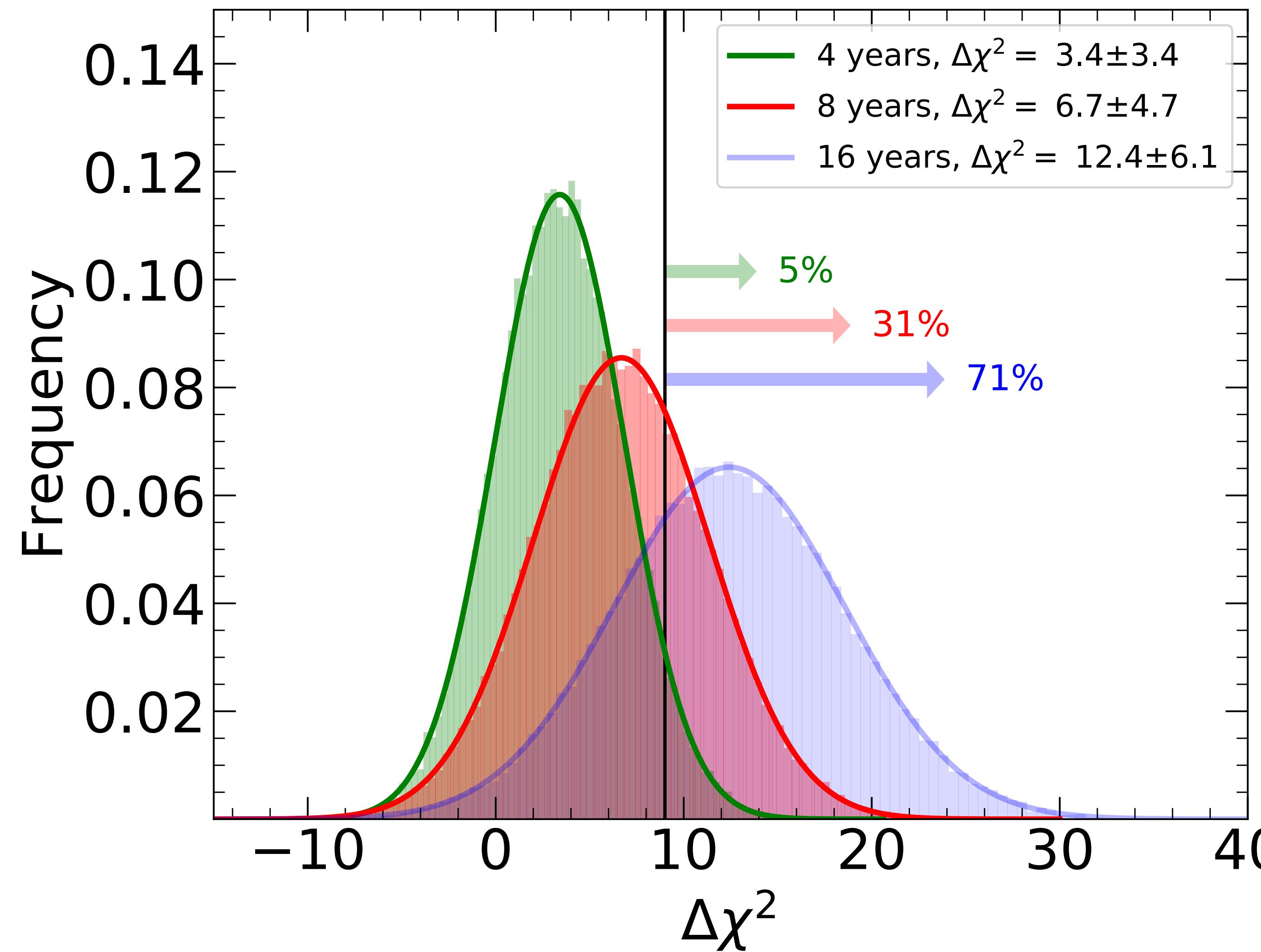
7.2 0.7% bias

6.8 no penalty



nominal value

Statistical Fluctuations



60 k JUNO pseudo-experiments simulated fluctuating spectrum

$$N_i \pm \sqrt{N_i}$$

only for 31% of the experiments
JUNO can determine the mass ordering
@ 3σ CL of better in 8 years



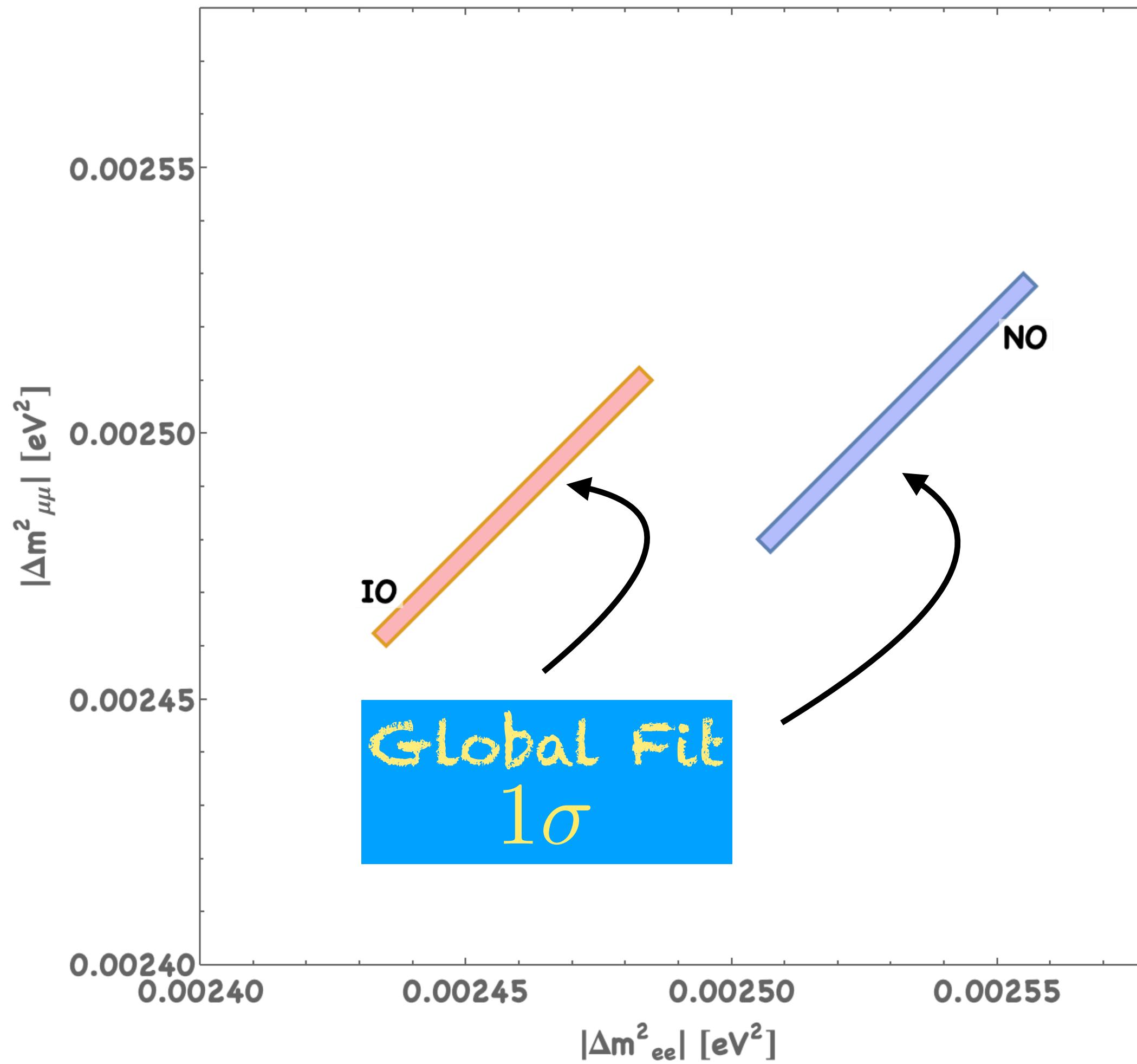
$$\Delta\chi^2 \equiv \chi^2_{\min}[\text{IO}] - \chi^2_{\min}[\text{NO}]$$

$$\Delta m_{ee}^2$$



$$\Delta m_{\mu\mu}^2$$

- NO ■ IO – Global Fit Allowed Region



Synergism

[H. Nunokawa, S. J. Parke & RZF, PRD 72 (2005)]

effective atmospheric Δm^2 for accelerator experiments

$$\Delta m_{\mu\mu}^2 \equiv \sin^2 \theta_{12} \Delta m_{31}^2 + \cos^2 \theta_{12} \Delta m_{32}^2$$

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$$|\Delta m_{ee}^2[\text{NO}]| > |\Delta m_{ee}^2[\text{IO}]|$$

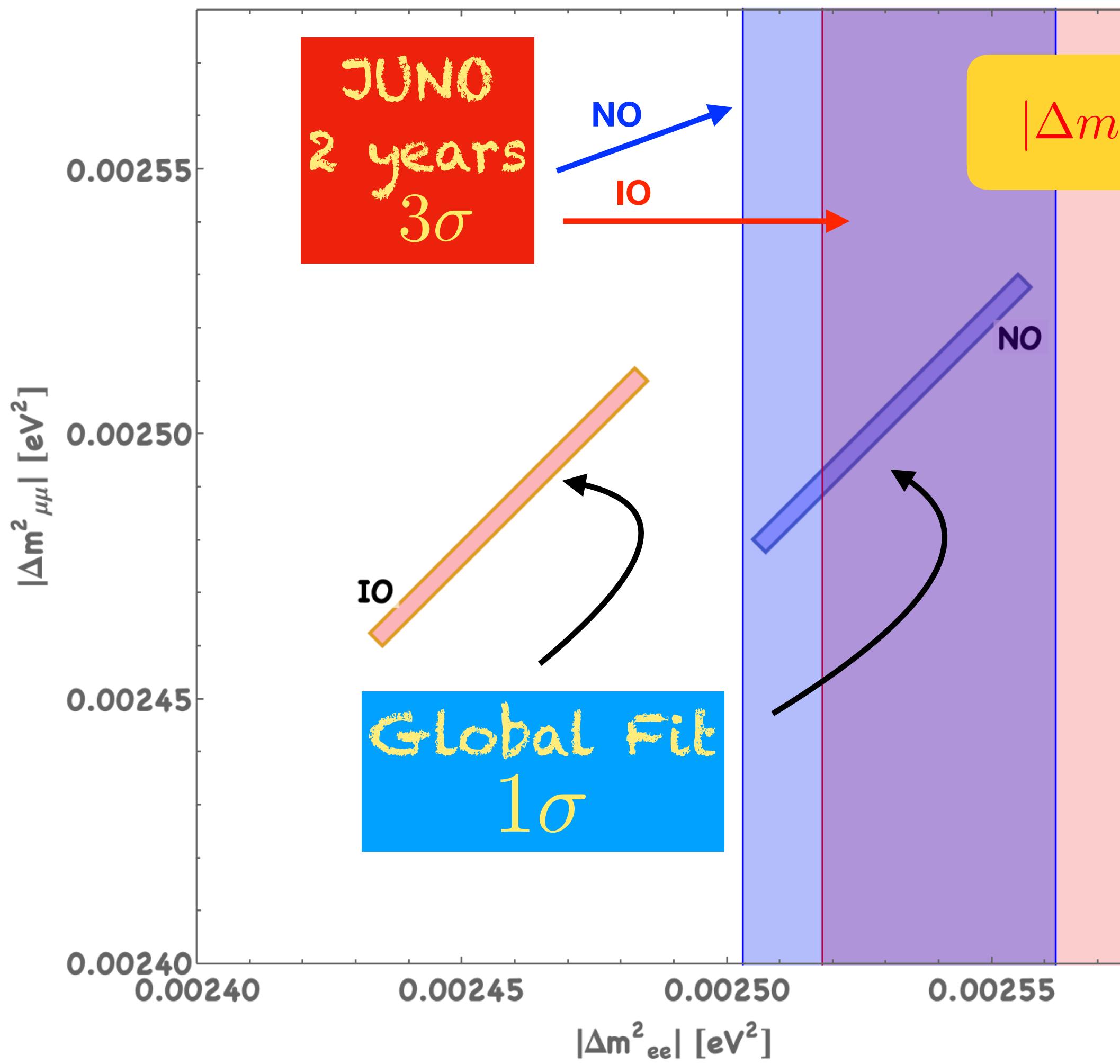
(accelerator experiments – T2K/NOvA)

$$\Delta m_{ee}^2$$



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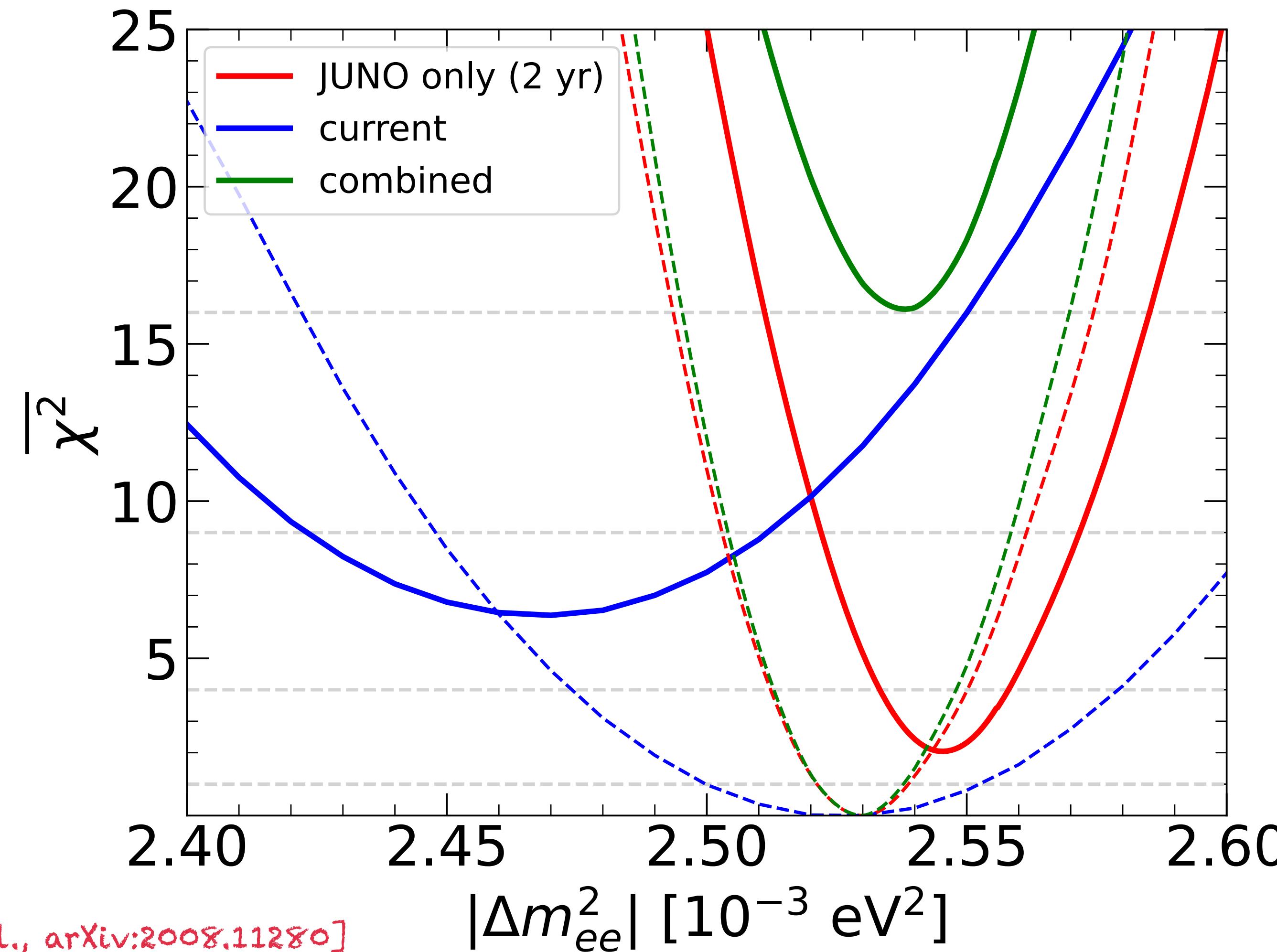
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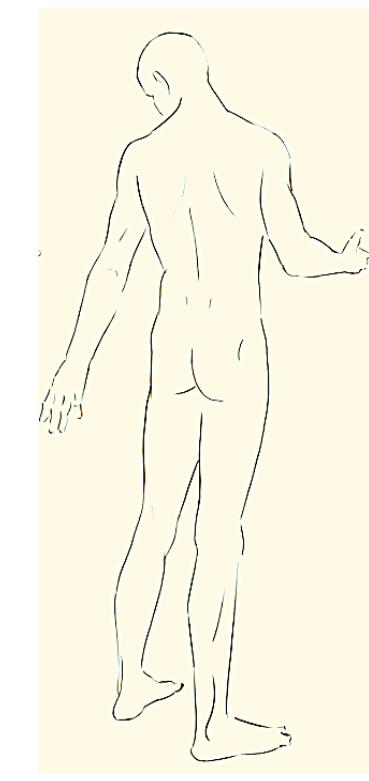
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JUNO & Global Fit Combined

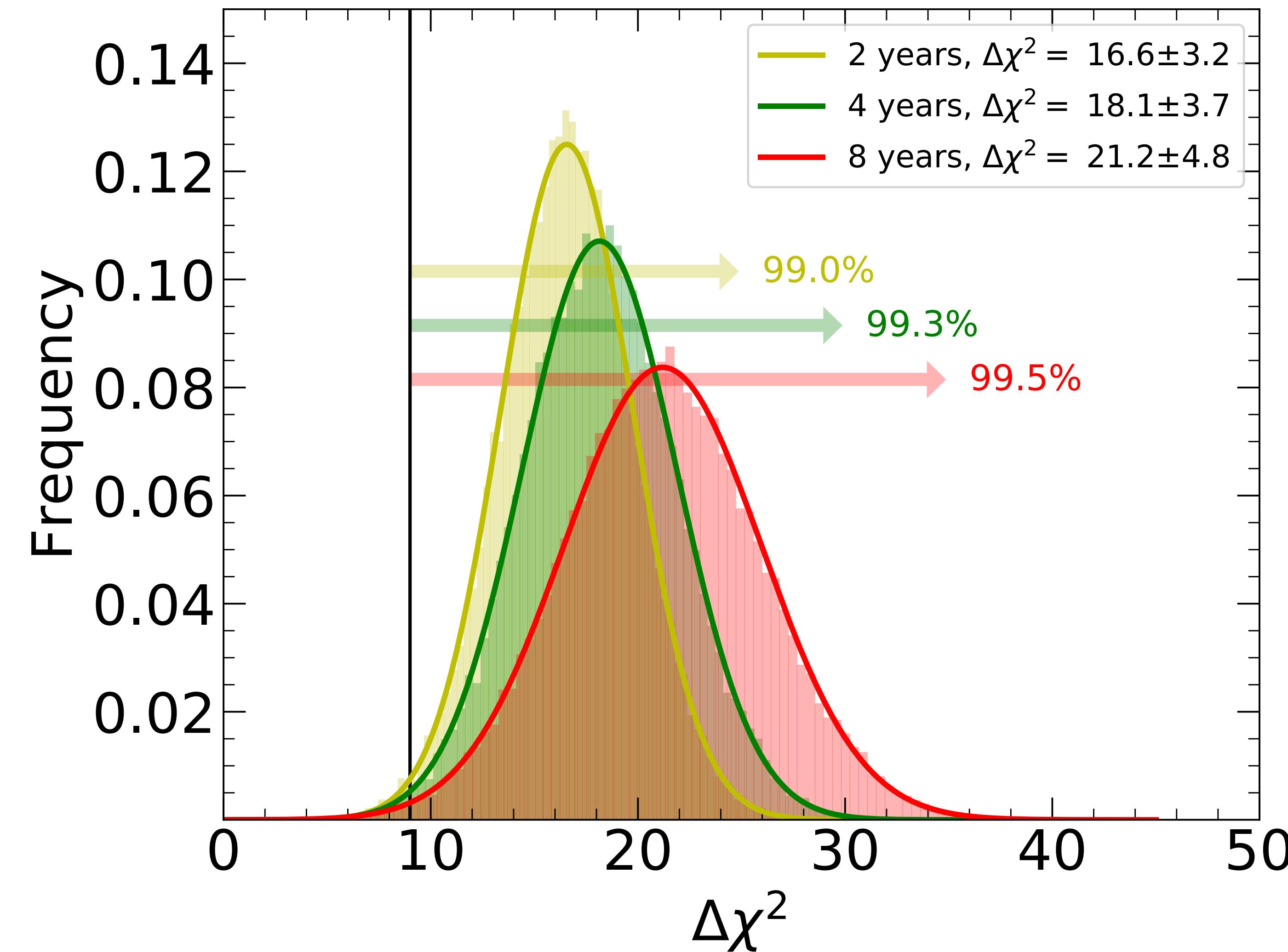


[Conf. A. Cabrera et al., arXiv:2008.11280]

$\overline{\Delta\chi^2}_{\min}[\text{IO}]$
2.0 JUNO
16 JUNO + Global Fit



JUNO & Global Fit Combined



Final Conclusions:

- JUNO's strategy to determine the neutrino mass ordering is very challenging
- The true value of the neutrino oscillation parameters may make the job easier or even more difficult
- JUNO will most probably not determine the neutrino mass ordering @ 3σ CL alone
- The synergy between JUNO's $|\Delta m_{ee}^2|$ measurement and the constraint from $|\Delta m_{\mu\mu}^2|$ sensitive experiments will most probably allow for the determination of the neutrino mass ordering after 2 years of JUNO @ 3σ CL or more

Another possible way to determine the neutrino mass hierarchy

Hiroshi Nunokawa, Stephen Parke, and Renata Zukanovich Funchal
Phys. Rev. D **72**, 013009 – Published 29 July 2005



ν_e

ν_μ

ν_τ