Global Neutrino Oscillation Fits

Renata Zukanovich Funchal
Universidade de São Paulo

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Neutrino Factories and
Future Neutrino Facilities

SHAPING THE GLOBAL PICTURE

A Successful Scenario

flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathbf{U} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\mathbf{U} = \mathbf{V}\,\mathrm{diag}(1, \mathrm{e}^{\imath\alpha_2/2}, \mathrm{e}^{\imath\alpha_3/2})$$

Extra CP Violating phases only if Majorana

mass eigenstates

Pontecorvo-Maki-Nakagawa-Sakata Mixing Matrix

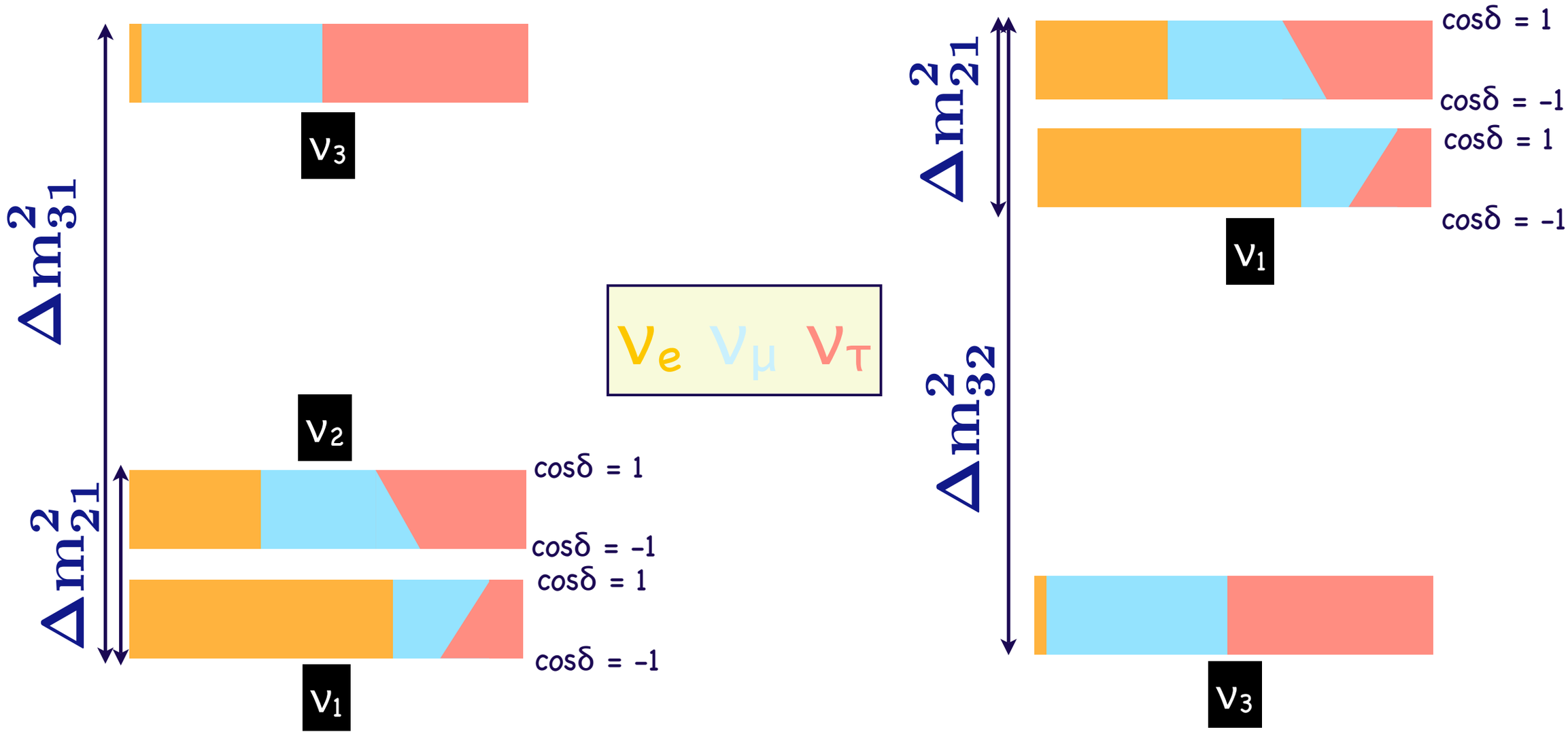
$$\mathbf{V} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \mathrm{c}_{23} & \mathrm{s}_{23} \\ 0 & -\mathrm{s}_{23} & \mathrm{c}_{23} \end{bmatrix} \begin{bmatrix} \mathrm{c}_{13} & 0 & \mathrm{s}_{13}\,\mathrm{e}^{-\mathrm{i}\delta} \\ 0 & 1 & 0 \\ -\mathrm{s}_{13}\,\mathrm{e}^{\mathrm{i}\delta} & 0 & \mathrm{c}_{13} \end{bmatrix} \begin{bmatrix} \mathrm{c}_{12} & \mathrm{s}_{12} & 0 \\ -\mathrm{s}_{12} & \mathrm{c}_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\mathrm{c}_{\mathrm{ij}} \equiv \cos\theta_{\mathrm{ij}} \quad \mathrm{s}_{\mathrm{ij}} \equiv \sin\theta_{\mathrm{ij}} \quad \theta_{\mathrm{ij}} \in [0, \pi/2] \quad \delta \in [0, 2\pi] \quad \alpha_{\mathrm{i}} \in [0, 2\pi]$$

known : θ_{23} θ_{13} θ_{12} unknown : δ α_2 α_3

A Successful Scenario

The Squared Mass Spectrum



Normal Ordering

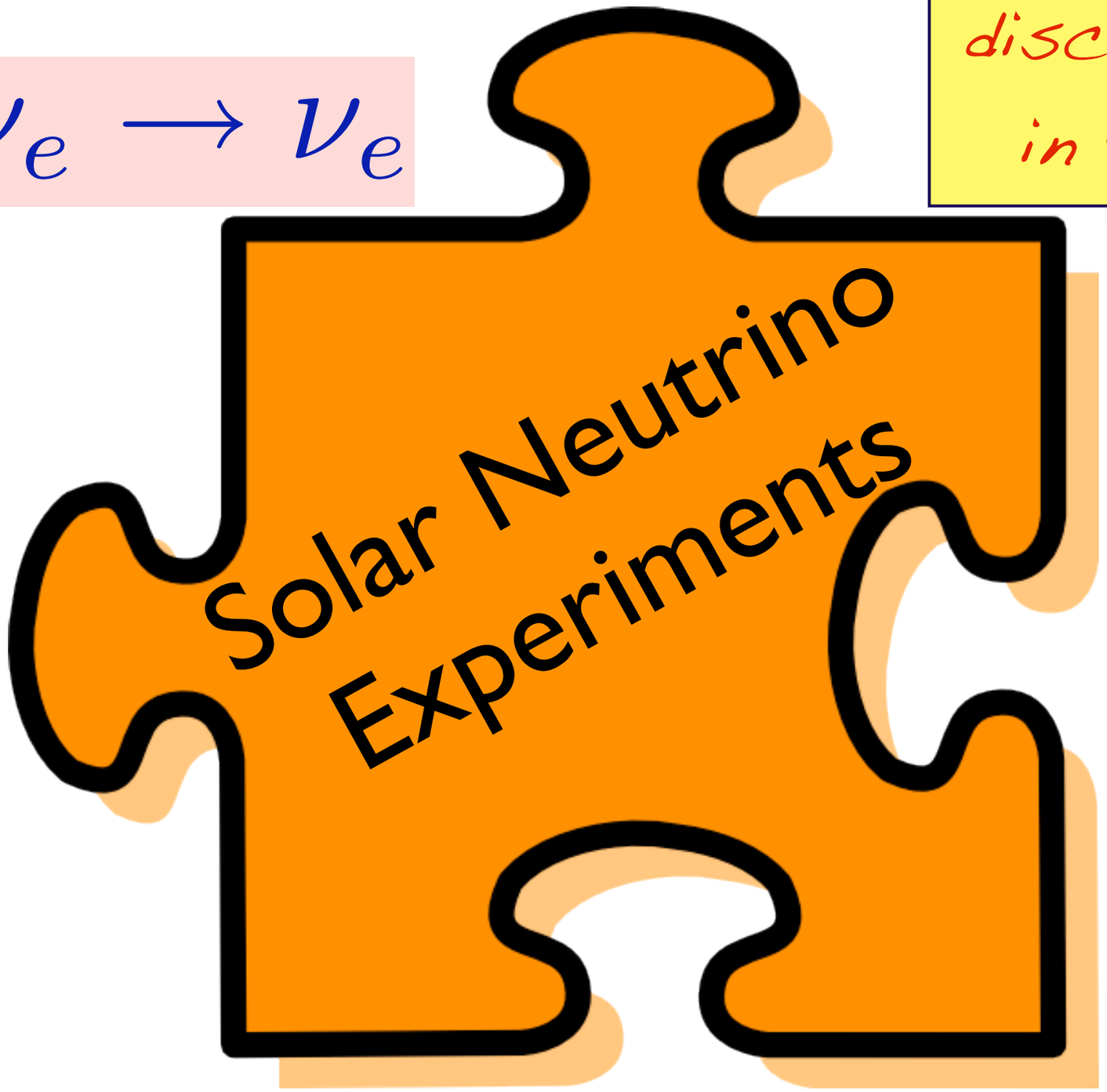
Inverse Ordering

Ordering not known !

FROM DISCOVERY TO PRECISION

Data: Pieces of the Puzzle

$\nu_e \longrightarrow \nu_e$



discovered oscillations
in vacuum & matter

Chlorine

Gallex/GNO

SAGE

SK1-SK2-SK3-SK4

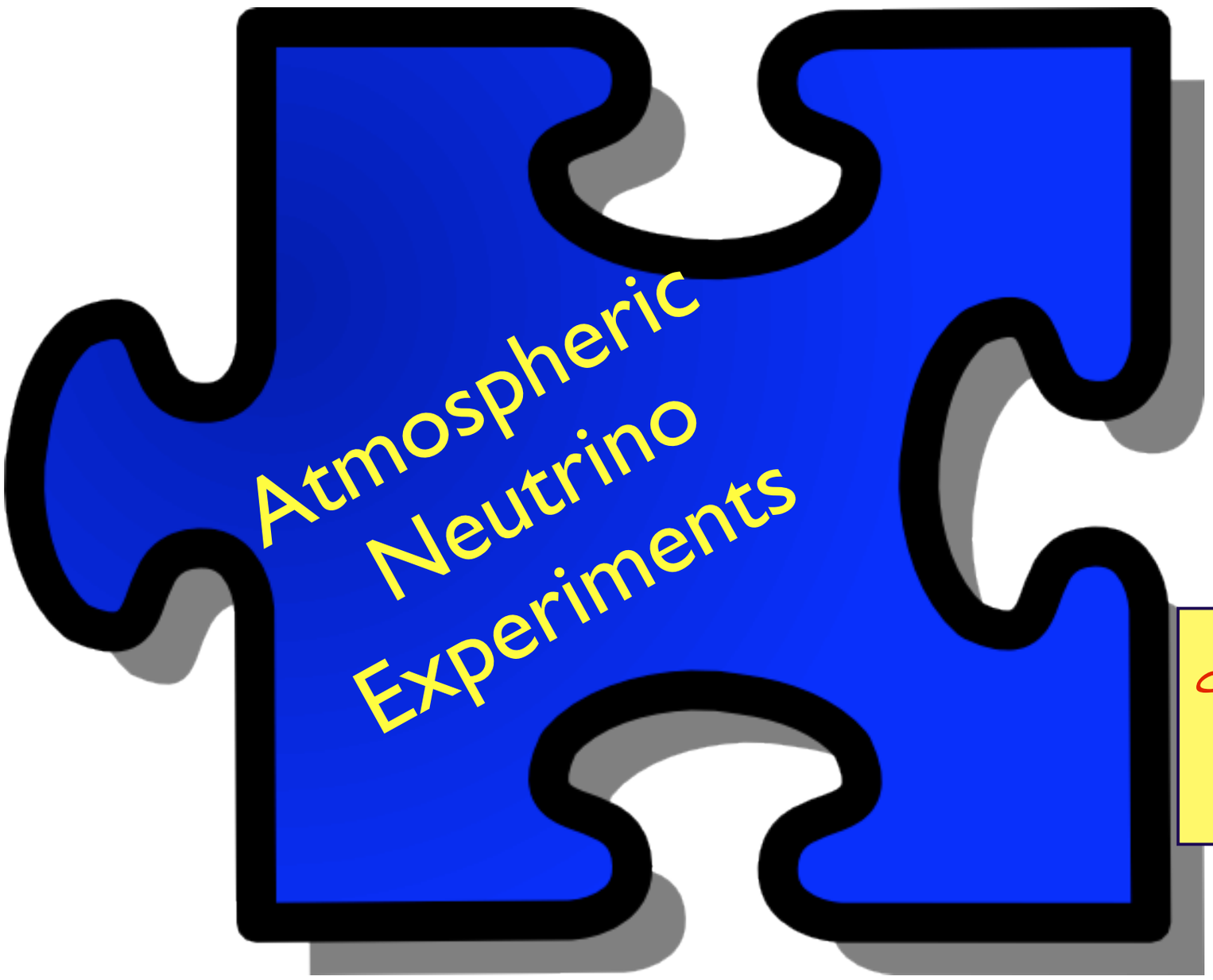
SNO

Borexino

Δm^2_{21}

$\sin^2\theta_{21}$

Data: Pieces of the Puzzle



$$\nu_\mu \longrightarrow \nu_\mu$$

$$\nu_e \longrightarrow \nu_e$$

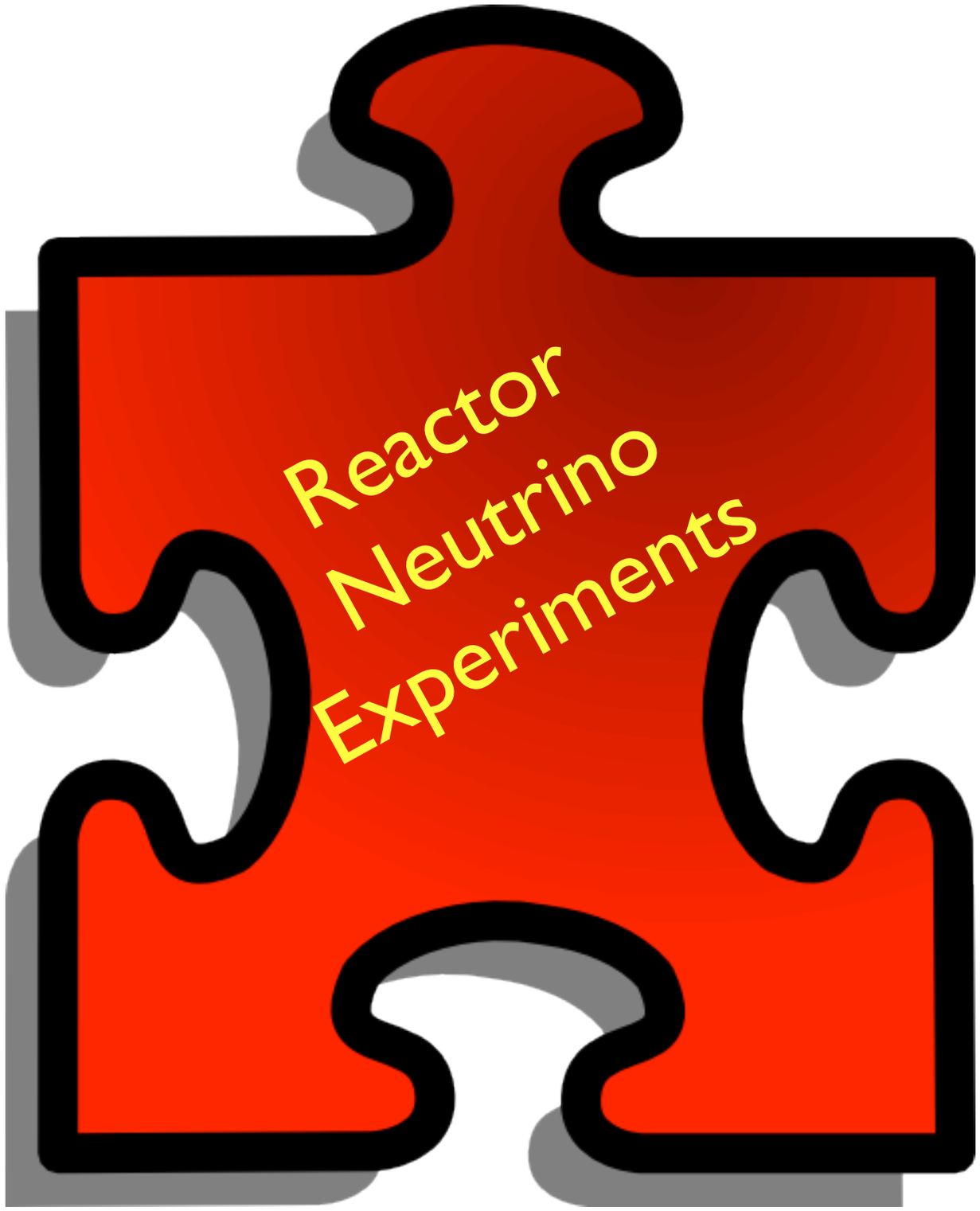
SK1-SK2-SK3-SK4

discovered oscillations in vacuum

$$\Delta m^2_{3\ell}$$

$$\sin^2\theta_{23}$$

Data: Pieces of the Puzzle



$$\nu_e \longrightarrow \nu_e$$

KamLAND
CHOOZ/Palo-Verde
Double-CHOOZ
Daya-Bay
Reno

discovered oscillations in vacuum

Δm^2_{21} $\Delta m^2_{3\ell}$

$\sin^2\theta_{21}$ $\sin^2\theta_{13}$

Data: Pieces of the Puzzle

$$\nu_\mu \longrightarrow \nu_\mu$$
$$\nu_\mu \longrightarrow \nu_e$$
$$\nu_\mu \longrightarrow \nu_\tau$$

K2K

MINOS

T2K

OPERA

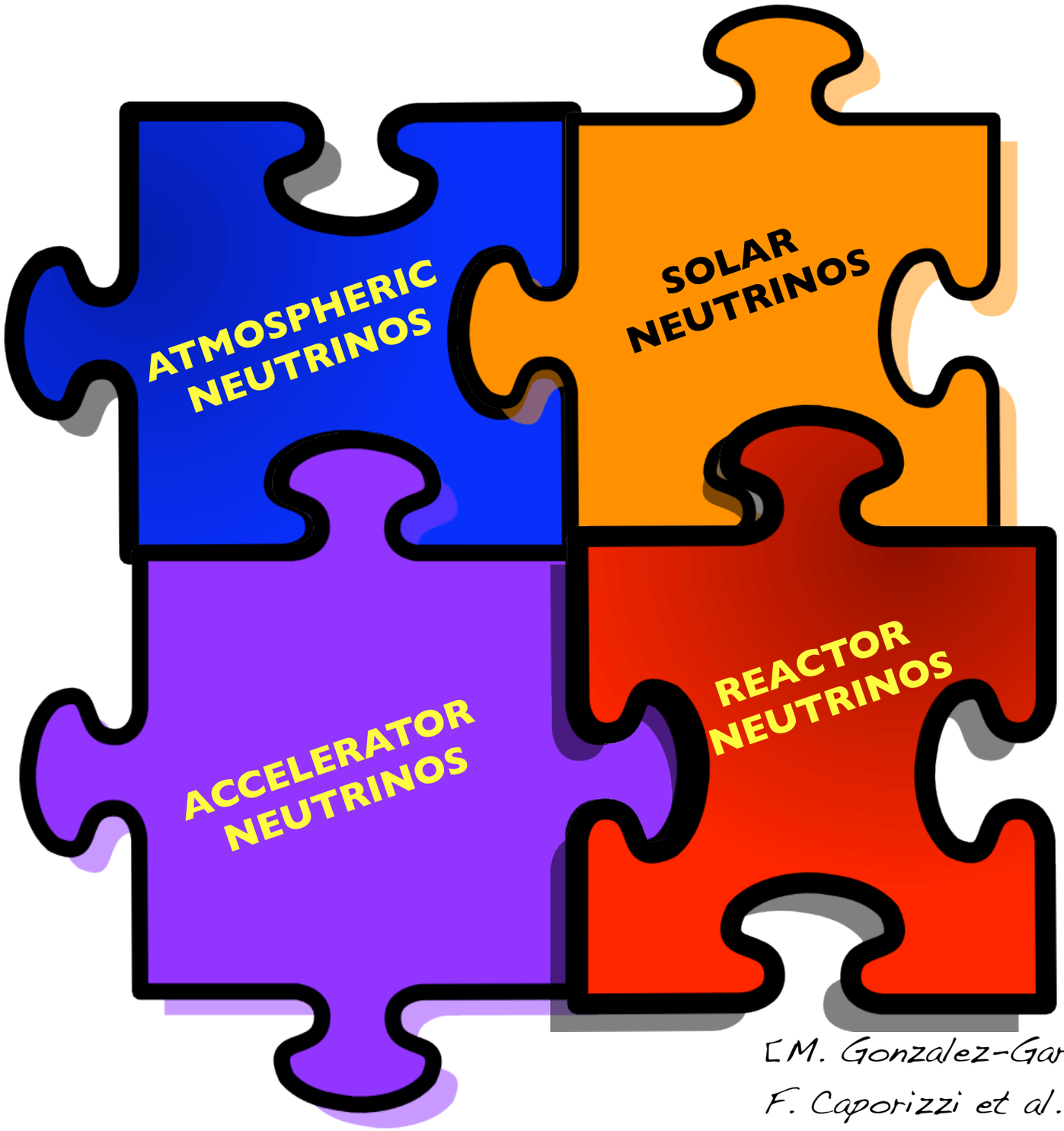
(+ NOvA)

observed oscillations

$\mathbf{\Delta m^2_{3\ell}}$ $\sin^2\theta_{13}$

$\sin^2\theta_{23}$

Global Analyses



by combining data we can

- Find Best Estimates
- Test Consistency of the Framework
- Find Correlations
- Find hints on unknown parameters
- Useful for guidance

[M. Gonzalez-Garcia et al. arXiv:1409.5439 & arXiv:1507.04366 ; F. Caporizzi et al. arXiv:1312.2878; D. Forero et al. arXiv:1405.7540]

$$\Delta m^2_{21}$$

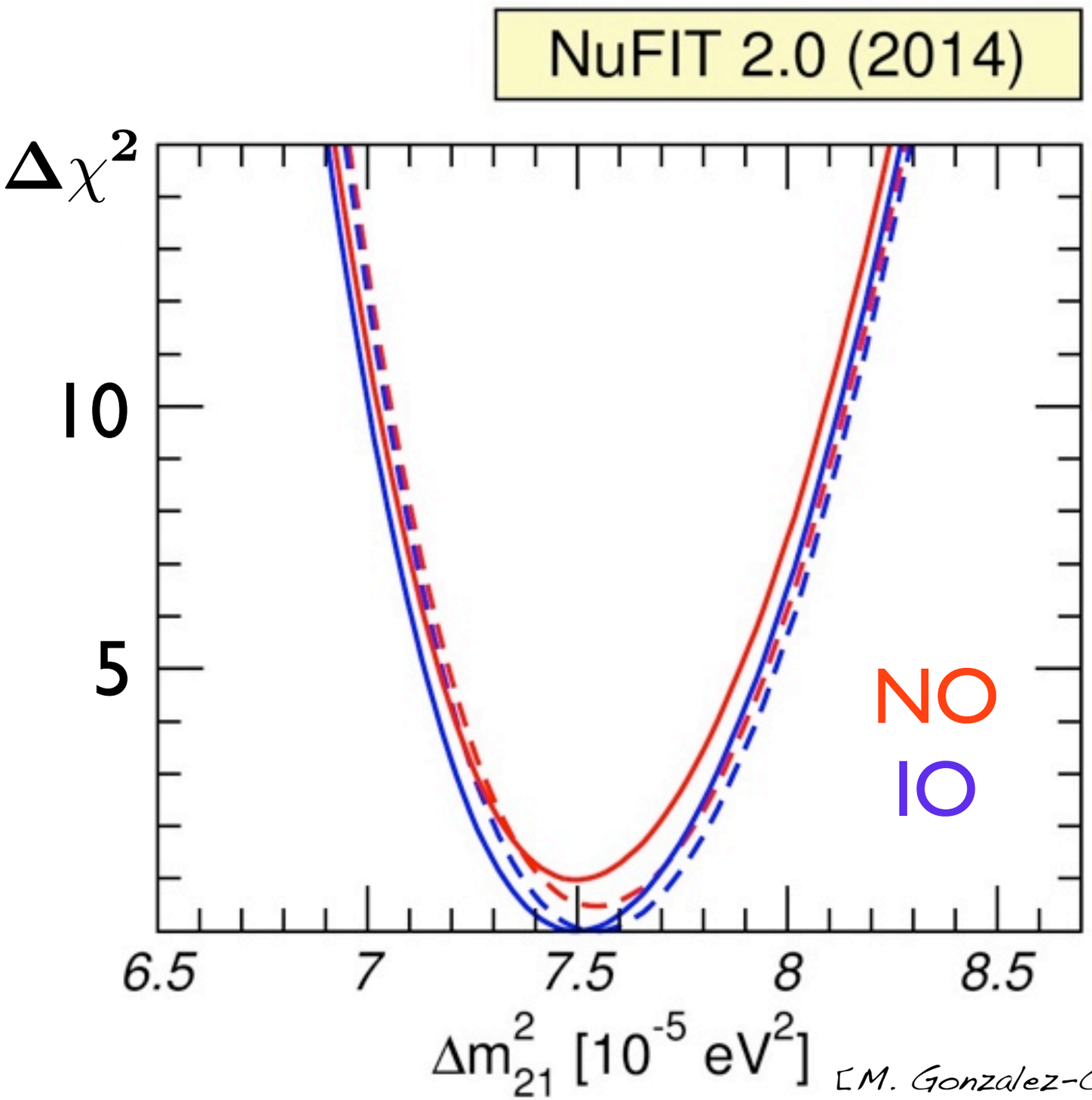
$$\sin^2\theta_{21}$$

$$|\Delta m^2_{3\ell}|$$

$$\sin^2\theta_{13}$$

ROBUST MEASUREMENTS

Δm^2_{21}



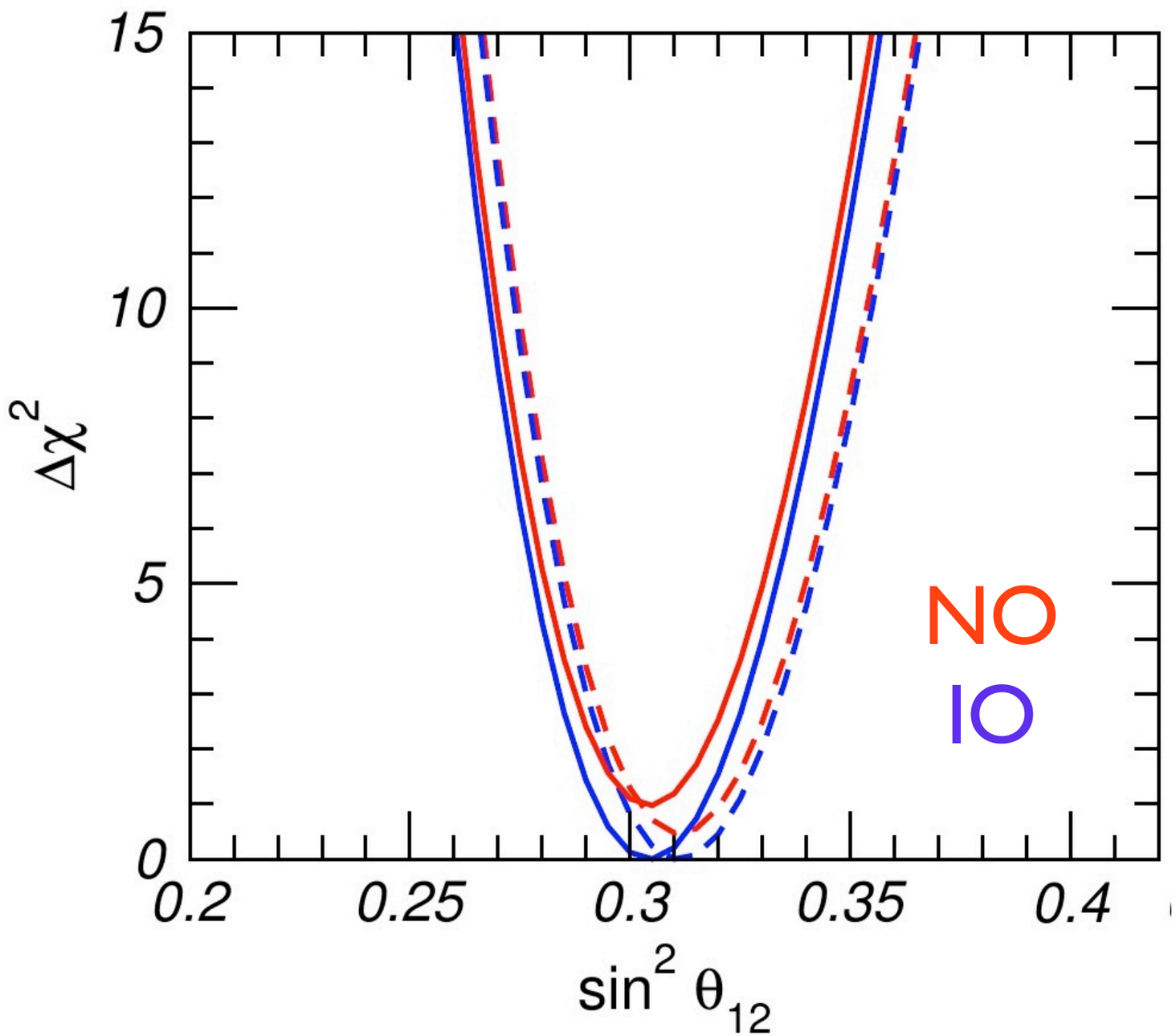
Frequentist or Bayesian Equivalent

$$(7.50 \pm 0.19) \times 10^{-5} \mathrm{eV}^2$$

2.5 %

[M. Gonzalez-Garcia et al. arXiv:1409.5439 & arXiv:1507.04366]

$\sin^2\theta_{21}$



Frequentist or Bayesian Equivalent

$$0.304 \pm 0.013$$

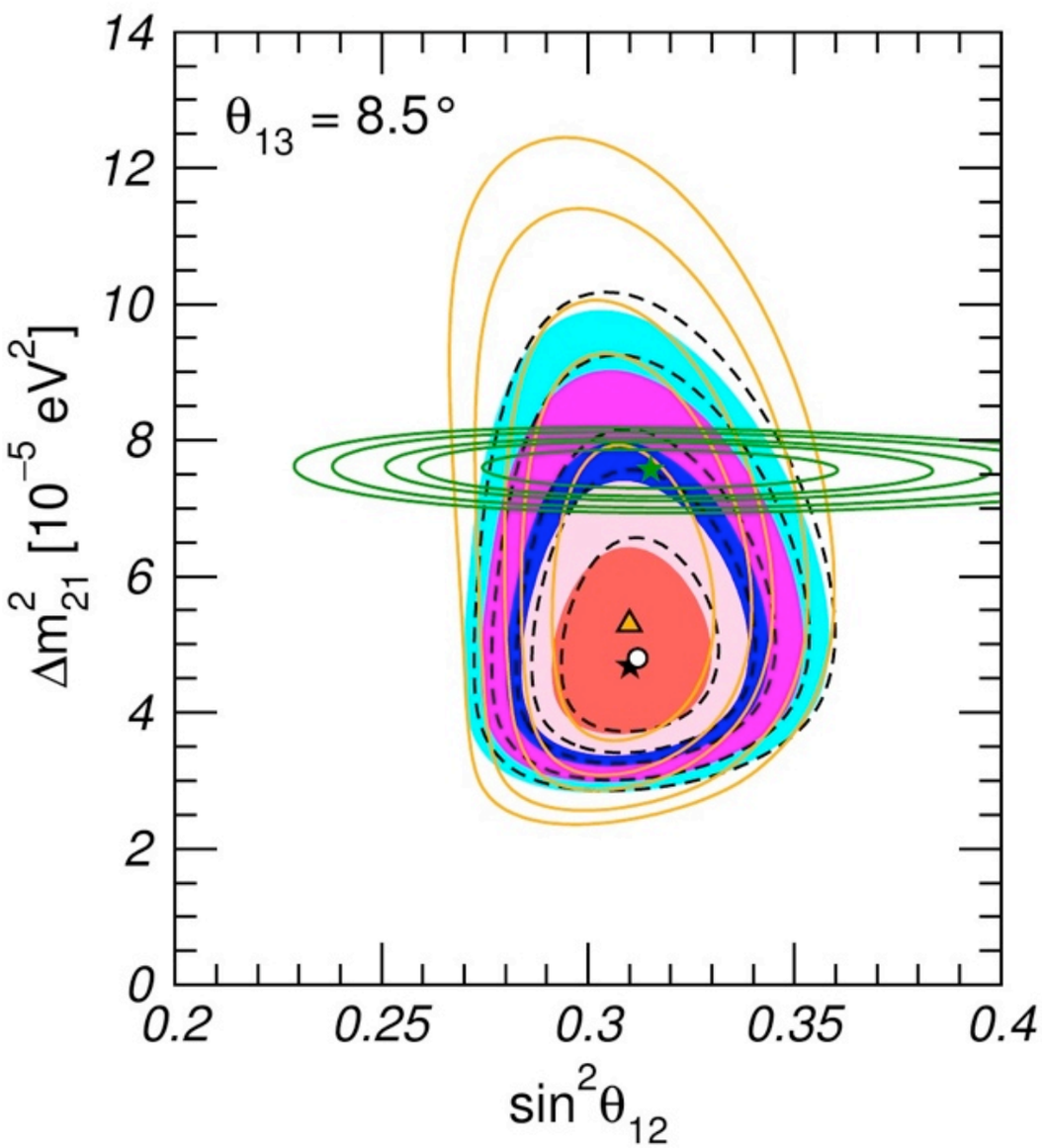
4.3 %

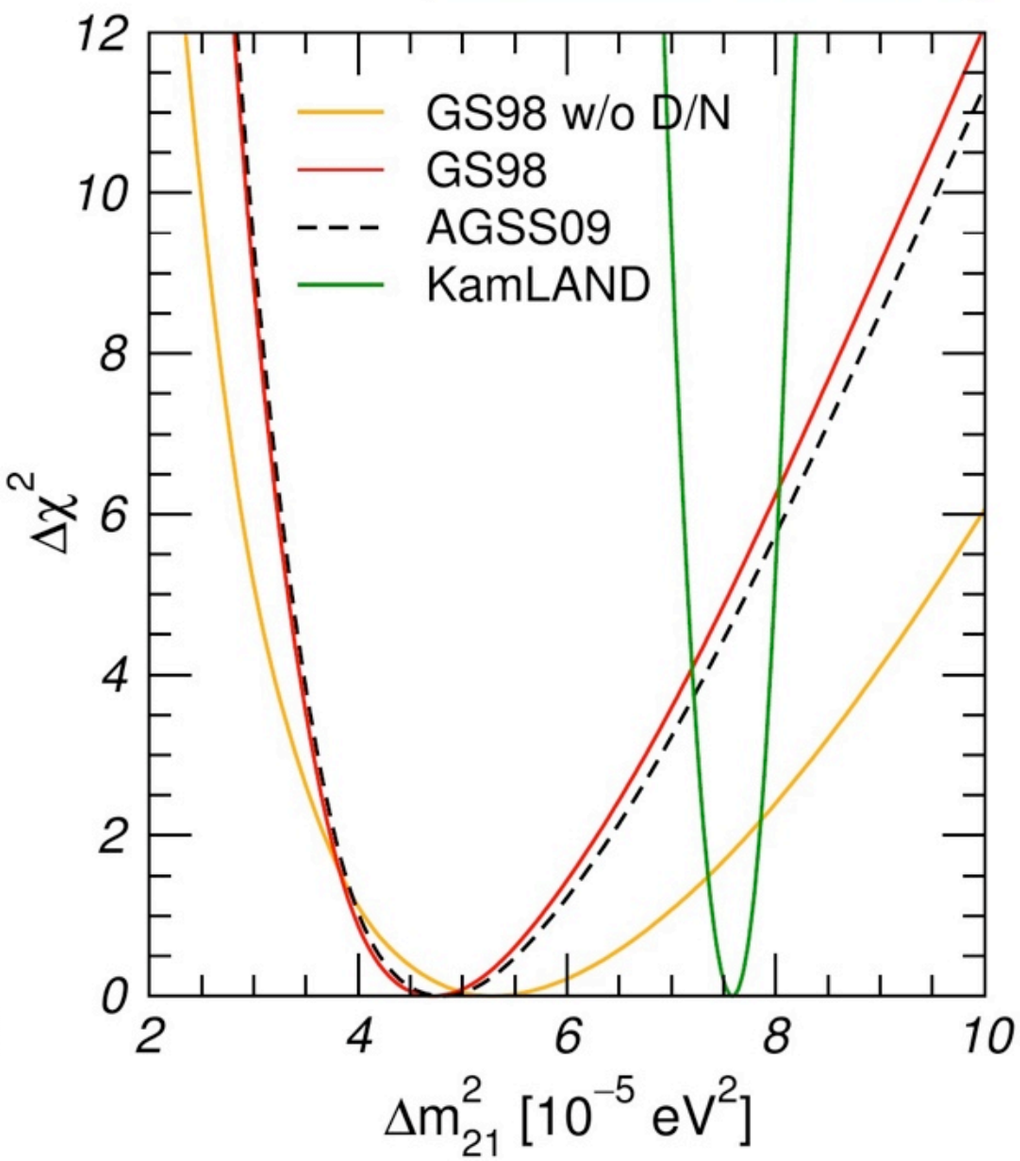
[M. Gonzalez-Garcia et al. arXiv:1409.5439 & arXiv:1507.04366]

Δm^2_{21}

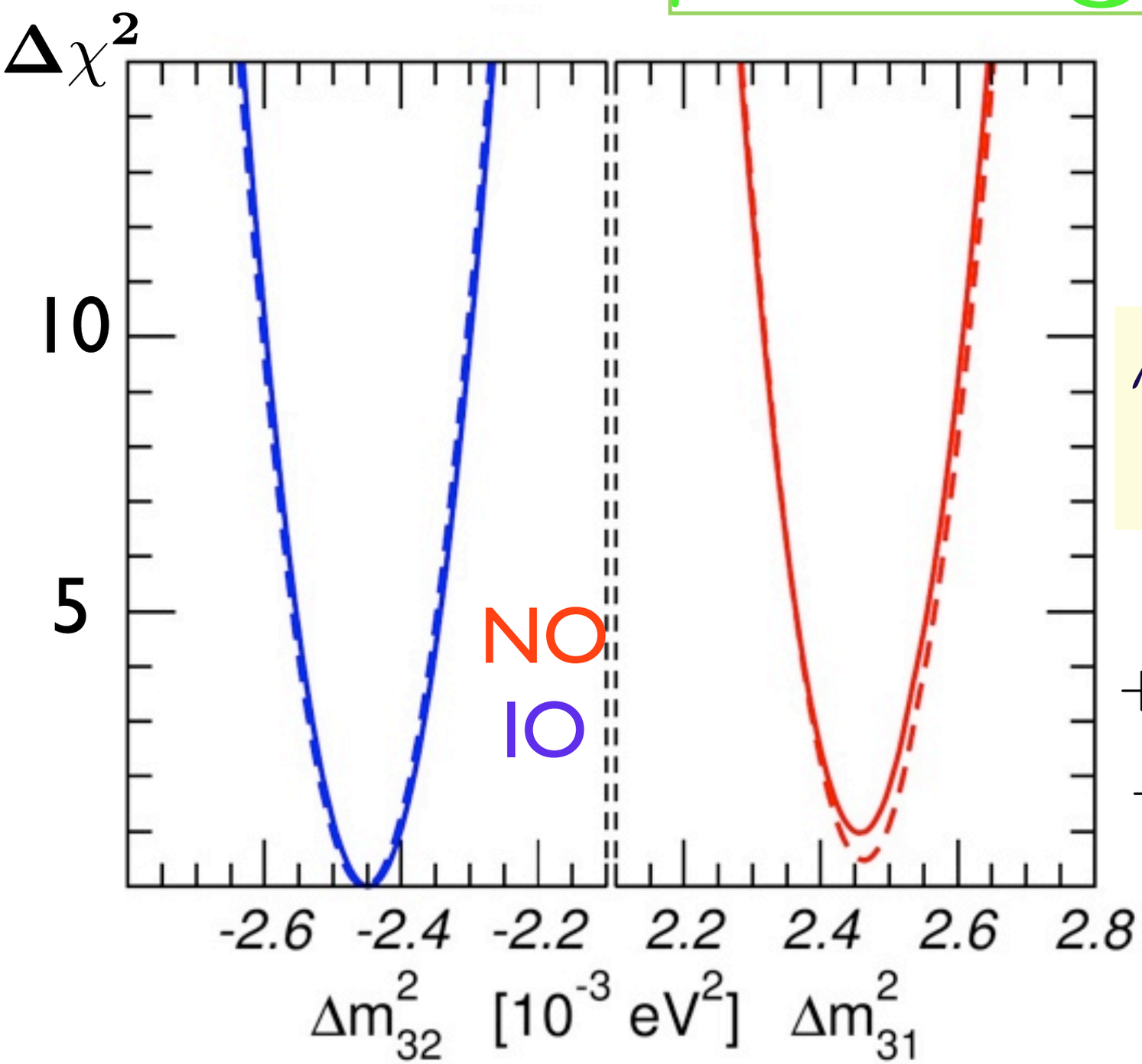
Tension between Solar and KamLAND

NuFIT 2.0 (2014)





$\Delta m^2_{3\ell}$



Frequentist or Bayesian Equivalent

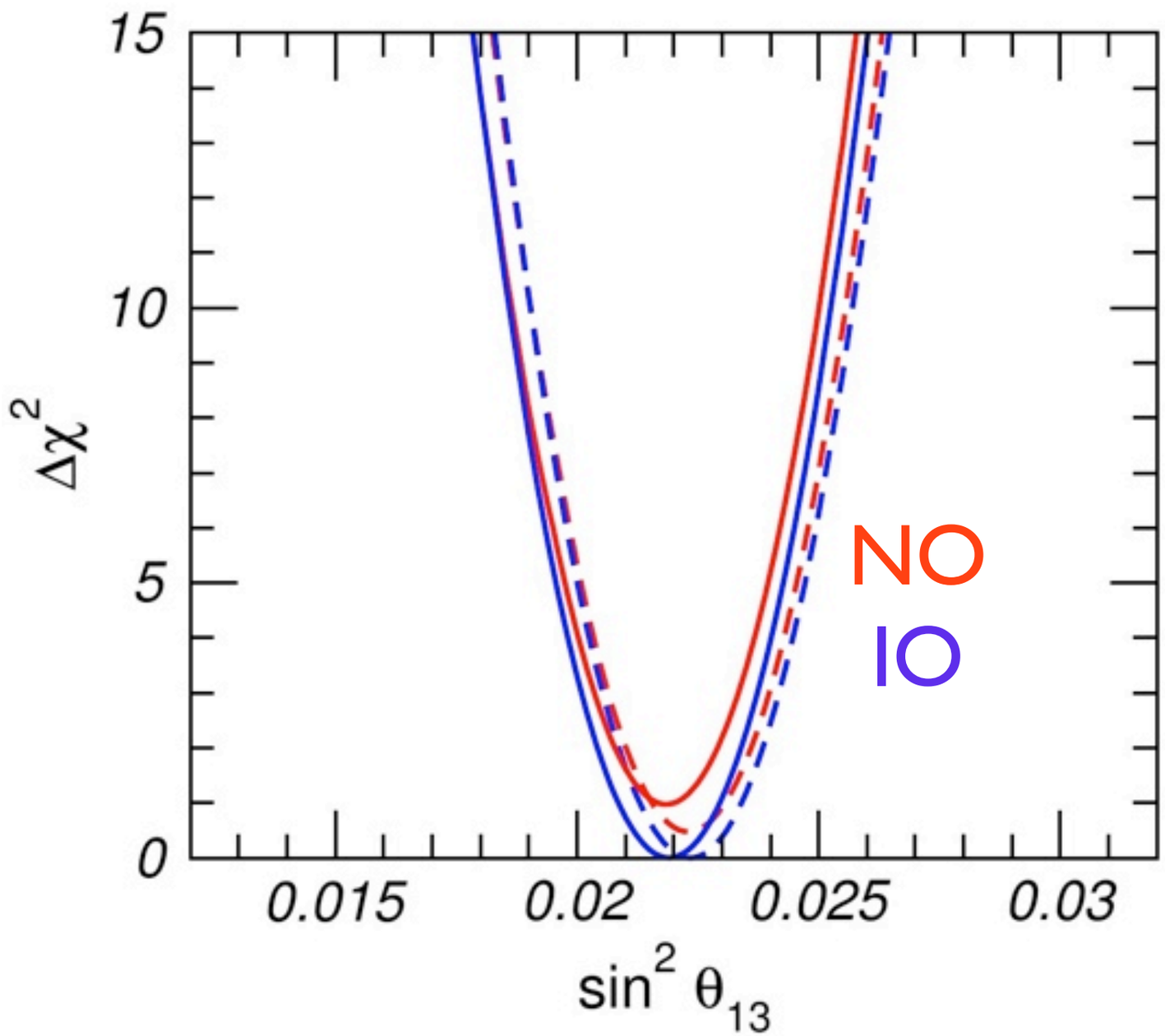
$$+(2.457 \pm 0.047) \times 10^{-3}\mathrm{eV}^2$$

$$-(2.449 \pm 0.047) \times 10^{-3}\mathrm{eV}^2$$

1.9 %

[M. Gonzalez-Garcia et al. arXiv:1409.5439 & arXiv:1507.04366]

$\sin^2\theta_{13}$



Frequentist or Bayesian Equivalent

$$0.0218 \pm 0.0010$$

4.6 %

[M. Gonzalez-Garcia et al. arXiv:1409.5439 & arXiv:1507.04366]

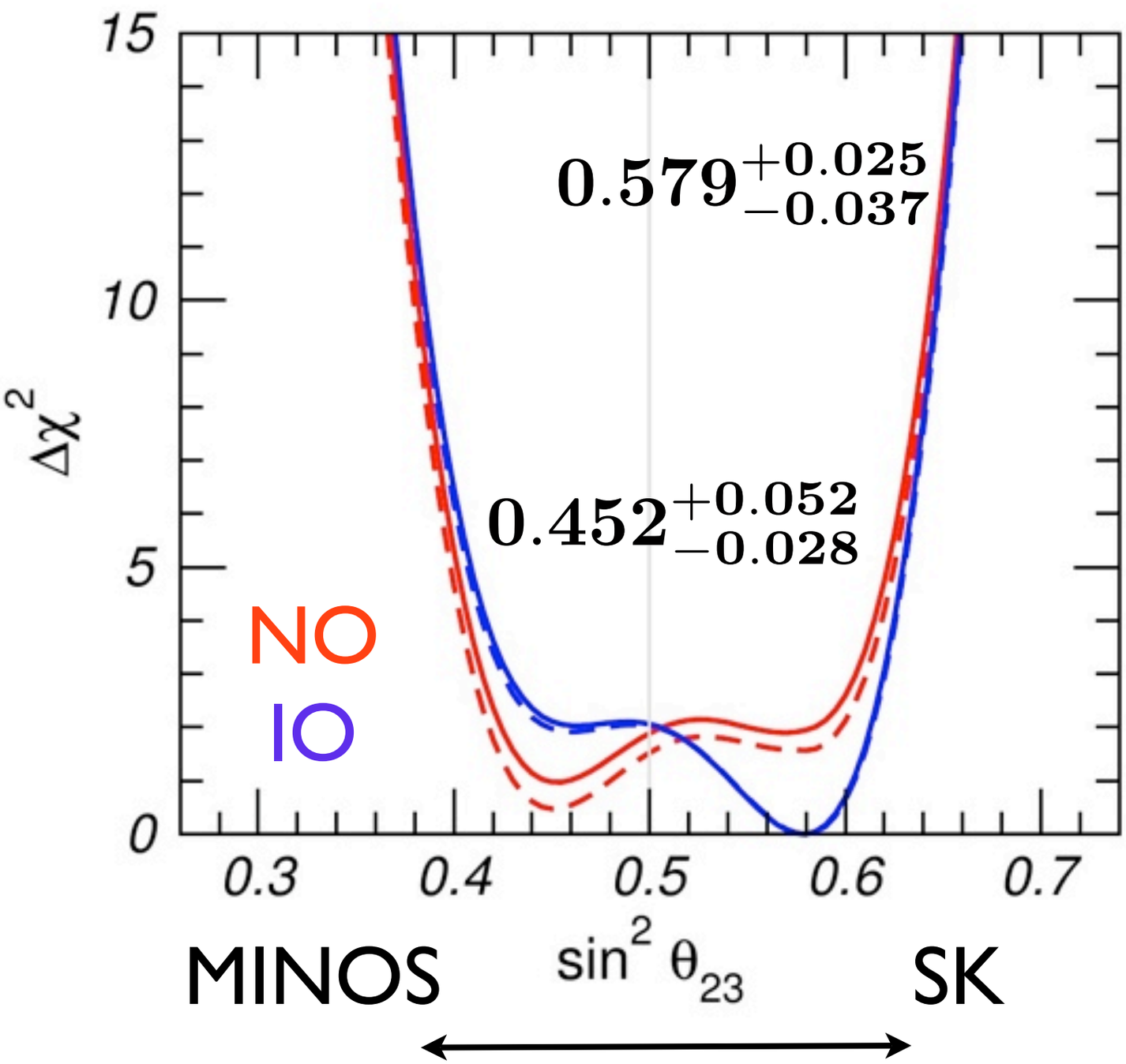
θ_{23} octant

mass ordering

δ

HINTS OF AN UNCHARTED TERRITORY

θ_{23}



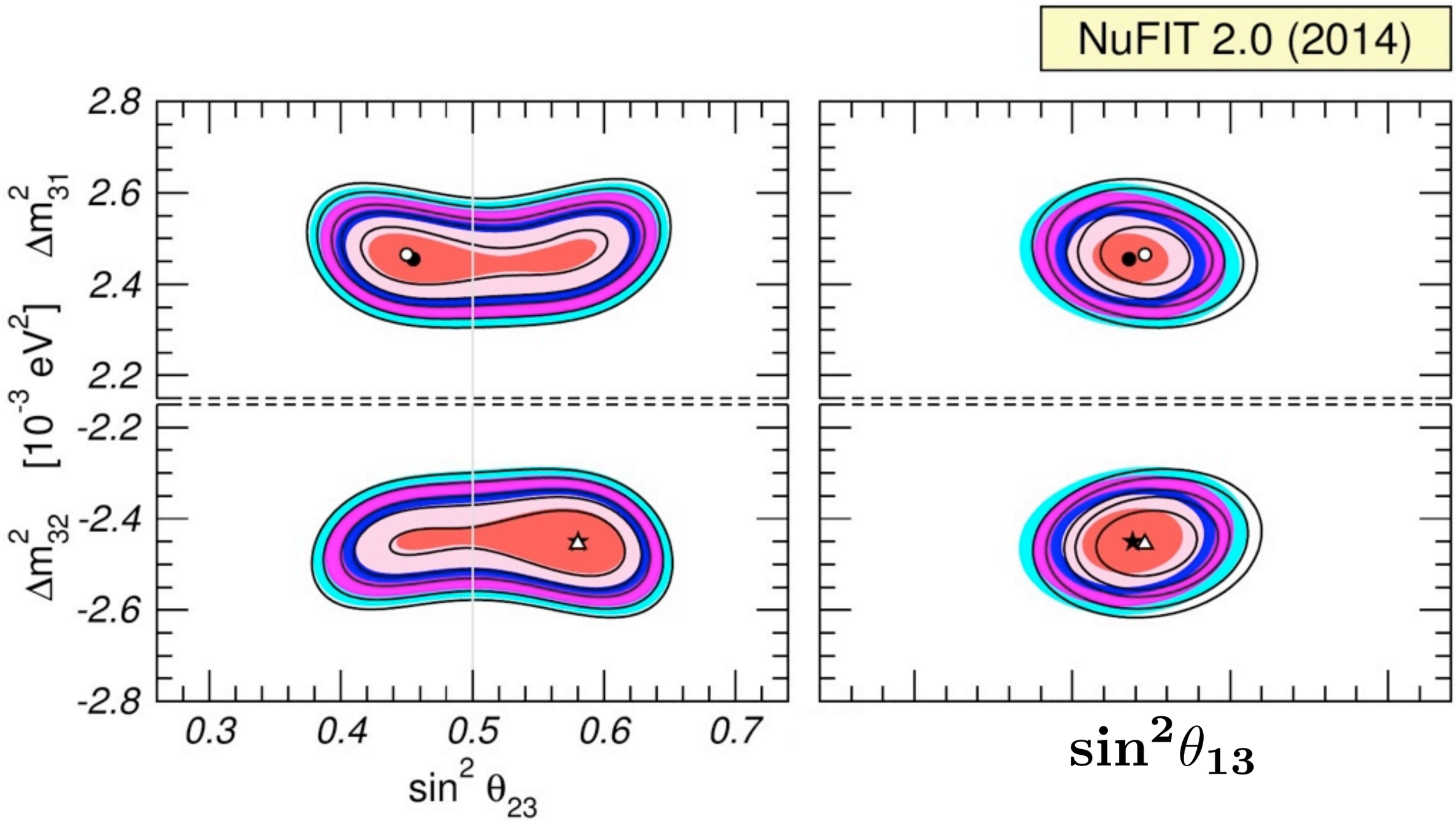
Bayesian Analysis
Weakly Prefer 2nd
(IO)

unstable/fragile

tug-of-war

[M. Gonzalez-Garcia et al. arXiv:1409.5439 & arXiv:1507.04366]

No Prefered Mass Ordering

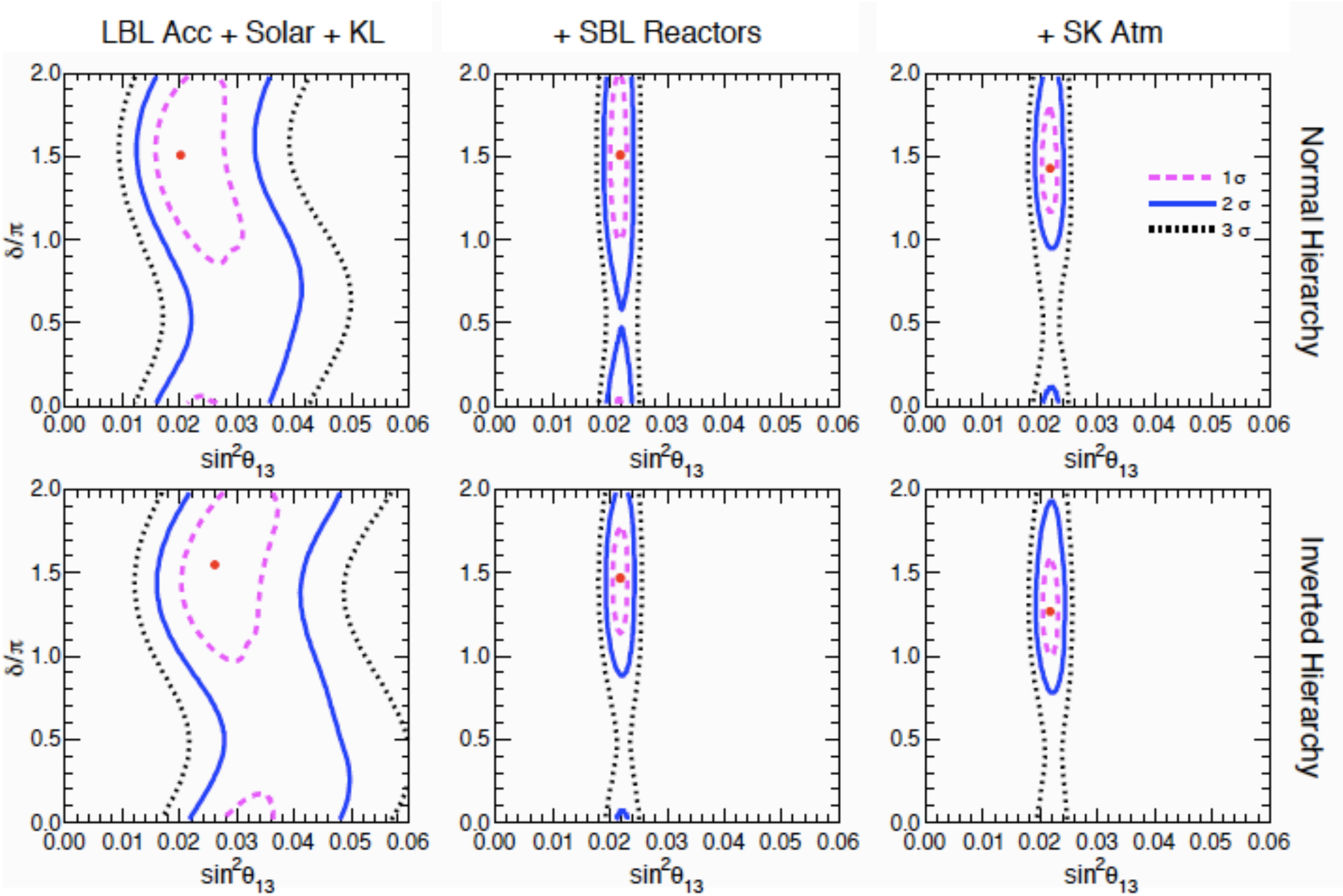


Bayesian Analysis
Weakly Prefer IO
Not Significant

[M. Gonzalez-Garcia et al. arXiv:1507.04366]

δ

[E. Lisi, Moriond 2015]

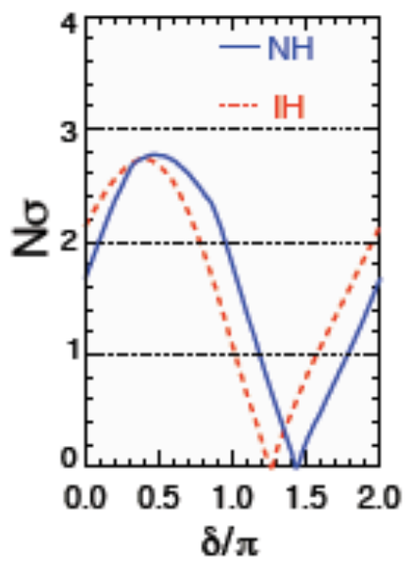


δ

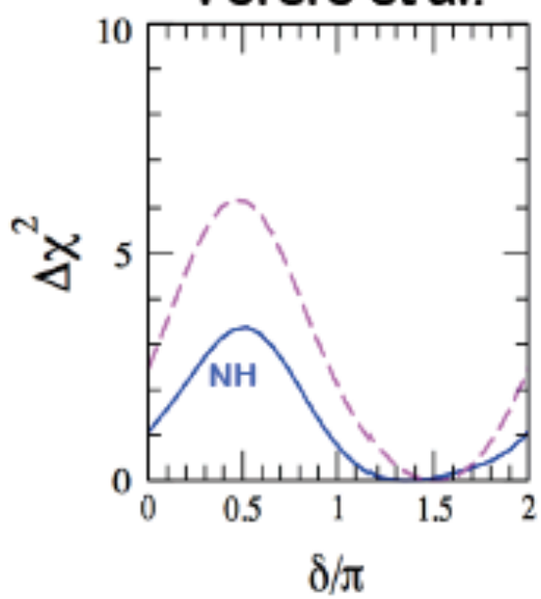
[E. Lisi, Moriond 2015]

For comparison:

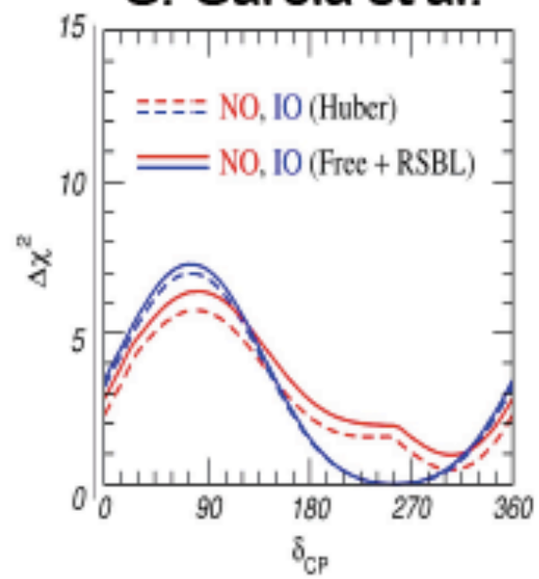
Lisi et al.



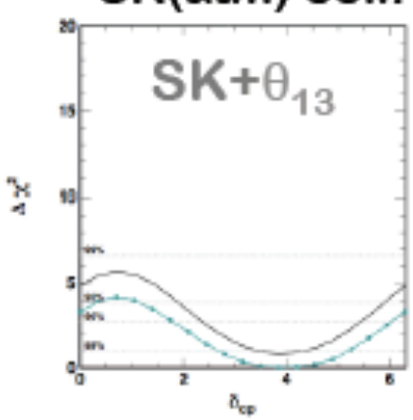
Forero et al.



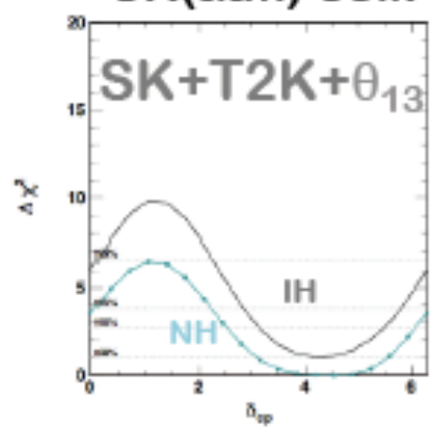
G.-Garcia et al.



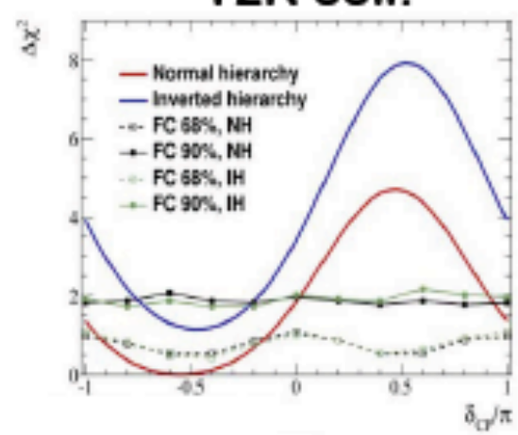
SK(atm) coll.



SK(atm) coll.



T2K coll.

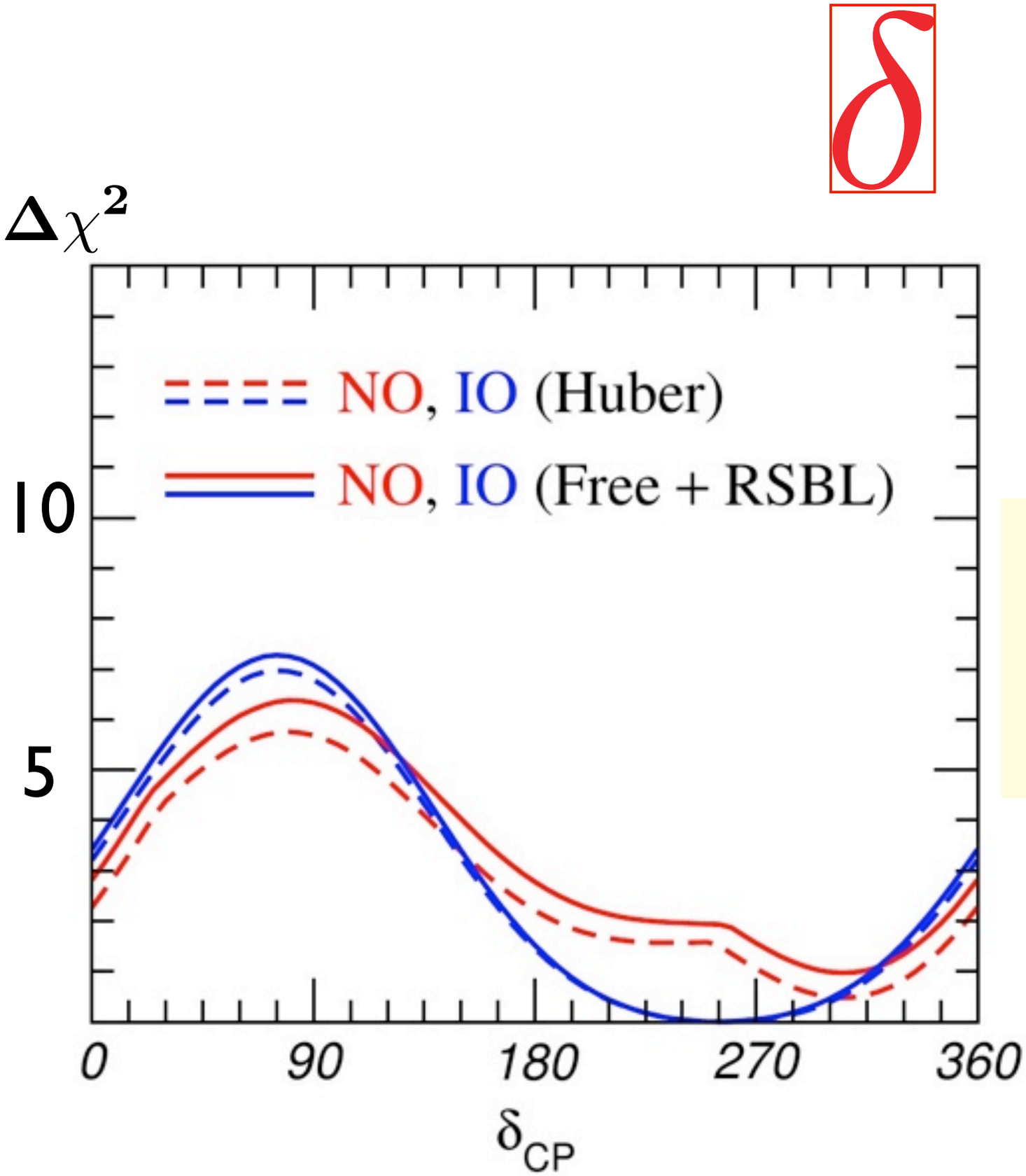


Status of representative CP phase values (in various fits):

δ/π ~ 3/2: preferred (nearly maximal CPV with sinδ ~ −1)

δ/π ~ 1/5: disfavored (by ~2-2.6 sigma w.r.t. to preferred value)

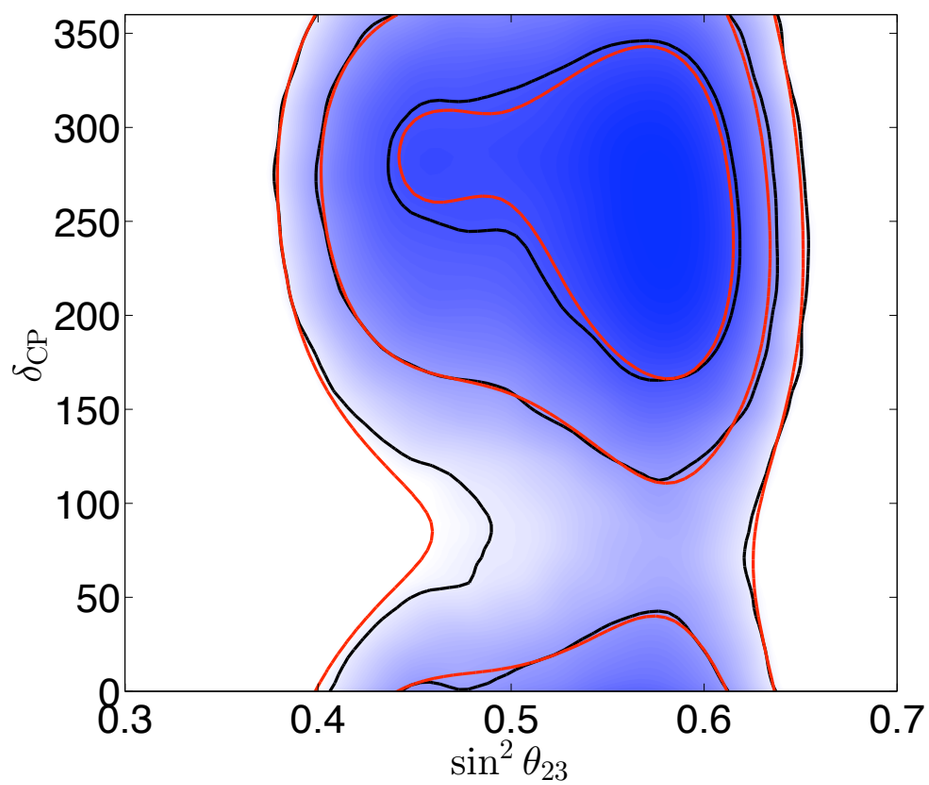
δ/π ~ 0 or ~1: in between (~1-1.3 sigma away from best fit)



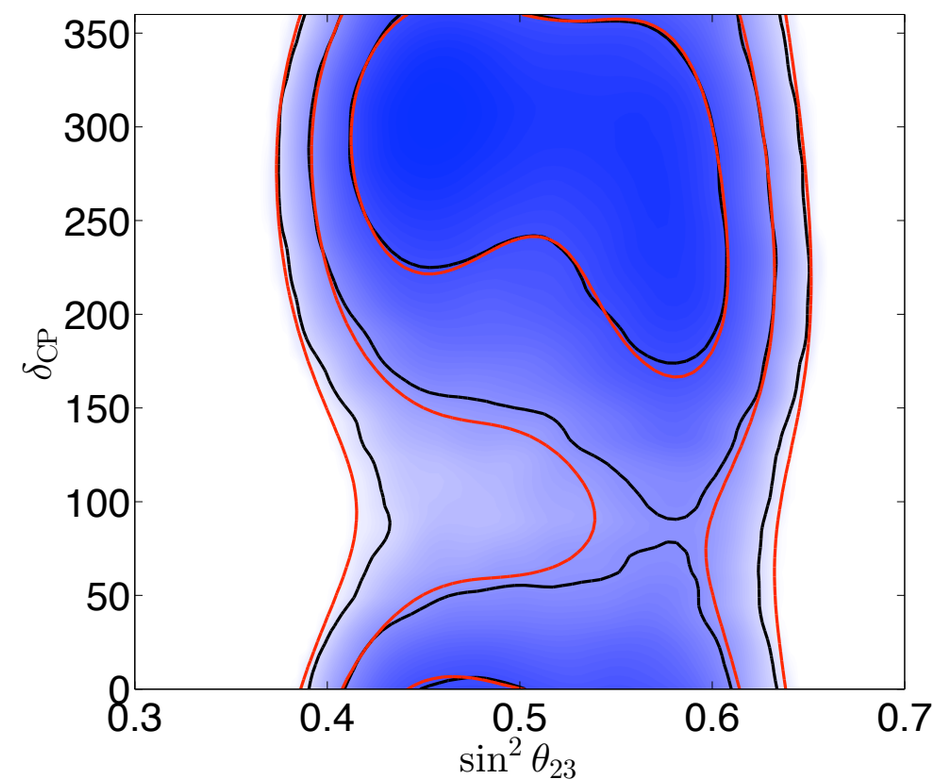
Bayesian Analysis
Prefer CPV over CPC
But Not Significant

[M. Gonzalez-Garcia et al. arXiv:1409.5439 & arXiv:1507.04366]

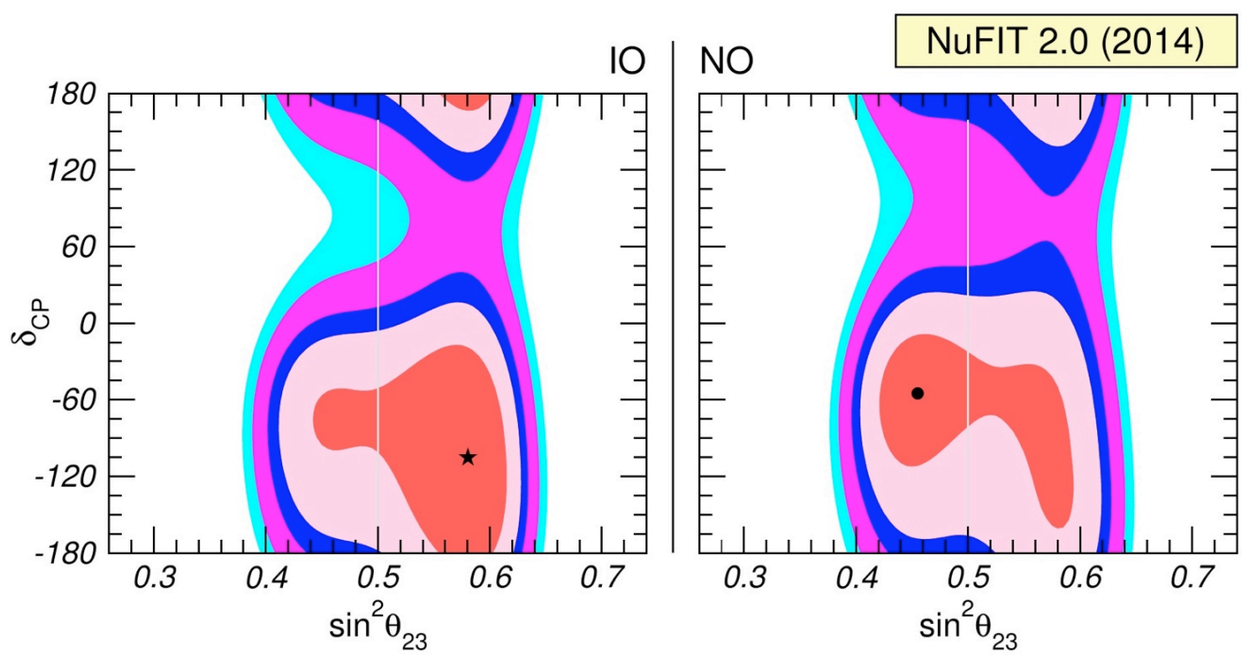
IO



NO



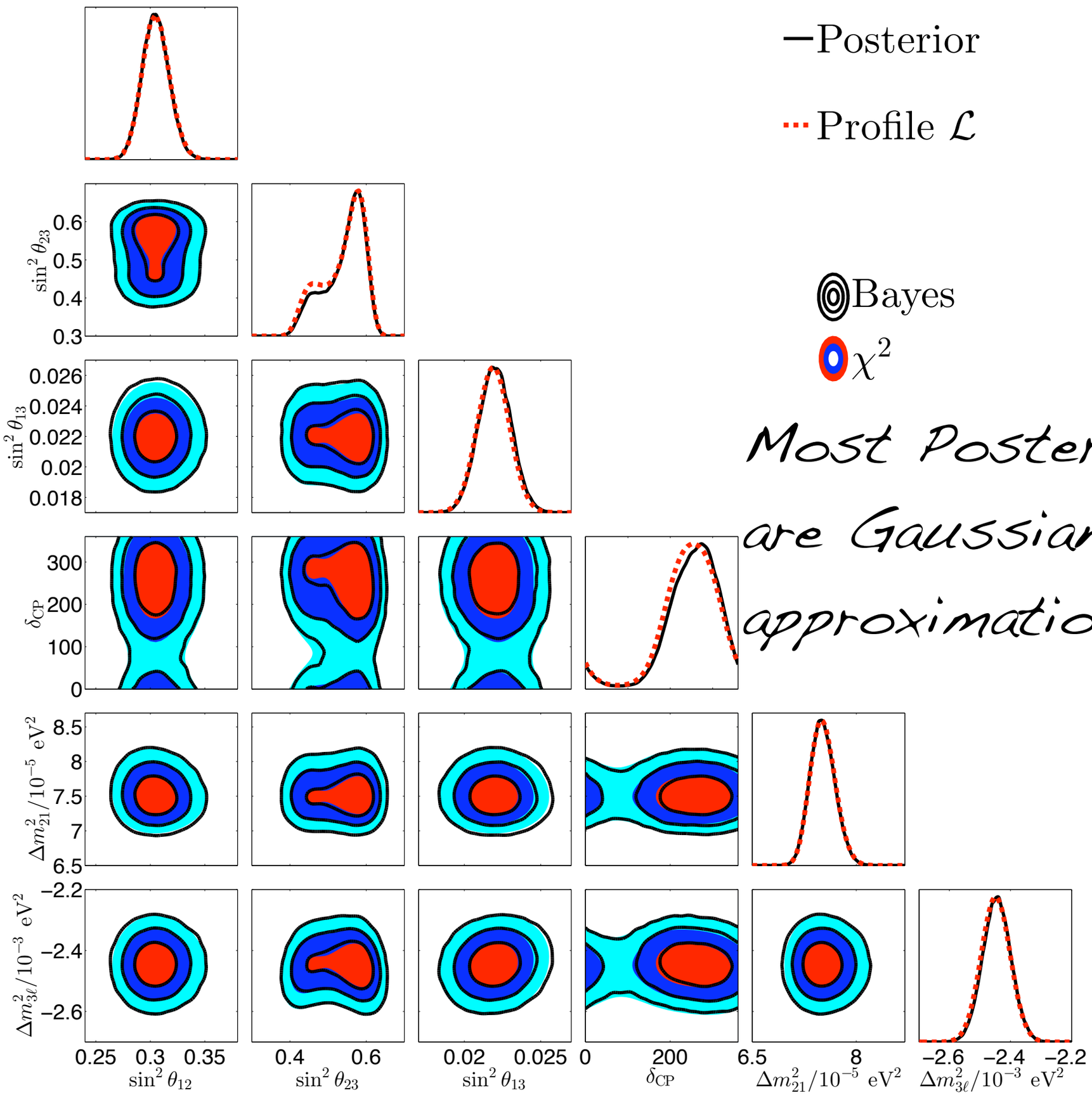
quantitatively stronger in NO



Correlation between

$$\sin^2\theta_{23} \times \delta$$

[M. Gonzalez-Garcia et al. arXiv:1409.5439 & arXiv:1507.04366]



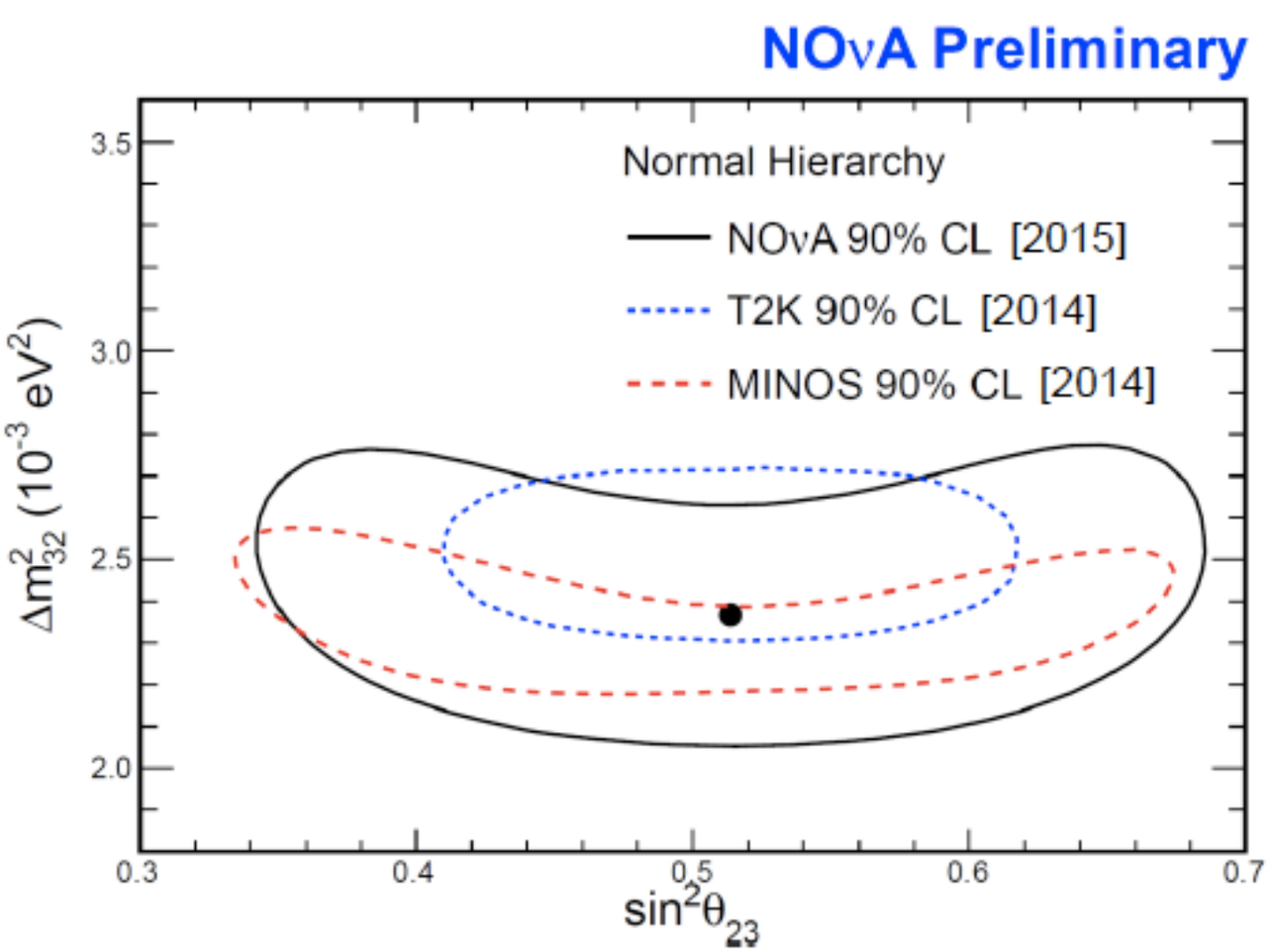
Most Posterior Distributions are Gaussians to a very good approximation

[M. Gonzalez-Garcia et al. arXiv:1507.04366]

NOVAS DE NOVA

$$\nu_\mu \longrightarrow \nu_\mu$$

[R. Patterson, Fermilab JETP Aug. 6, 2015]

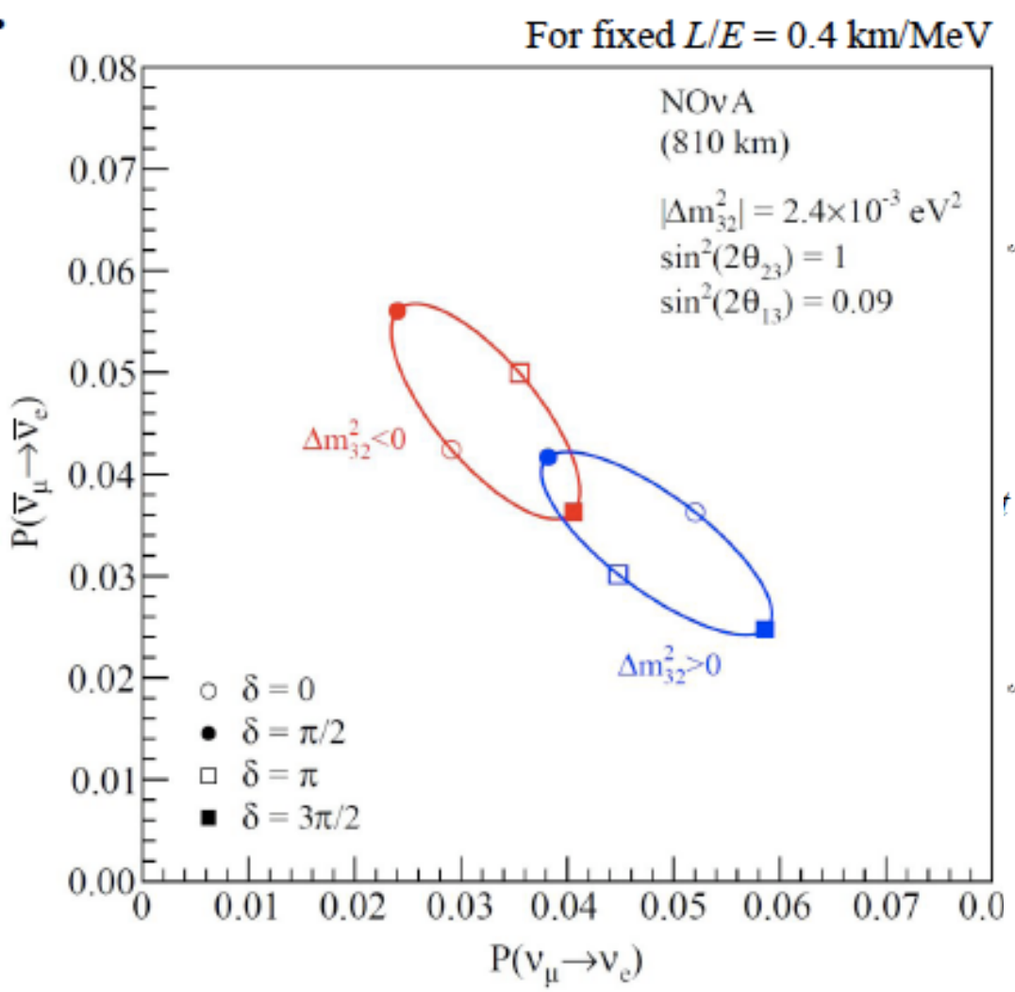


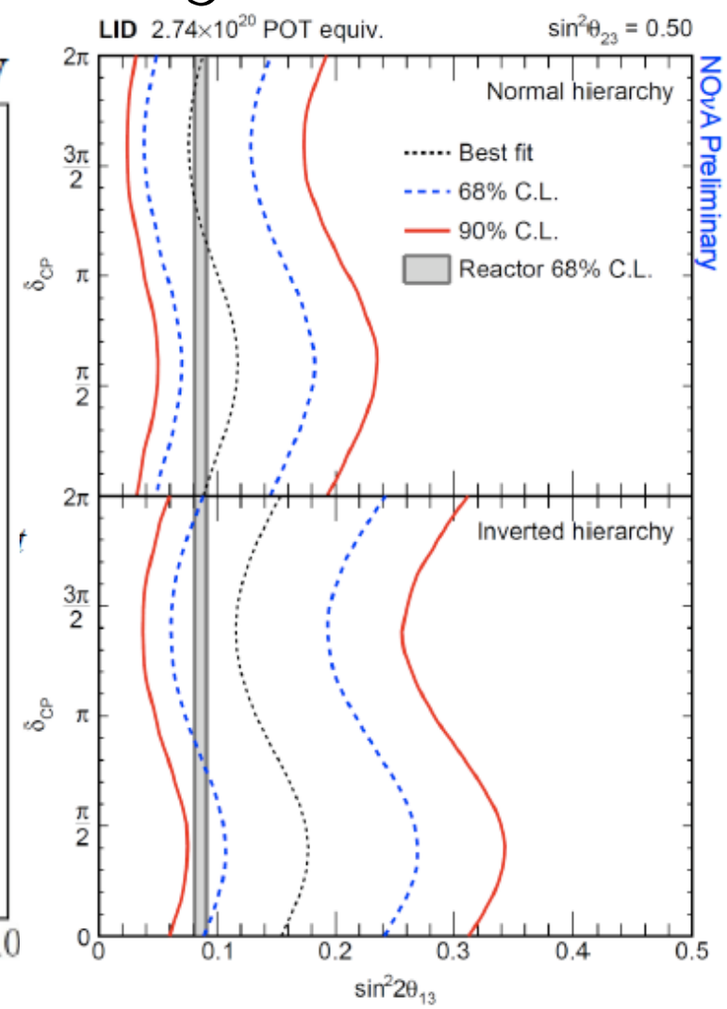
Allowed regions consistent with other experiments

this should not change global results

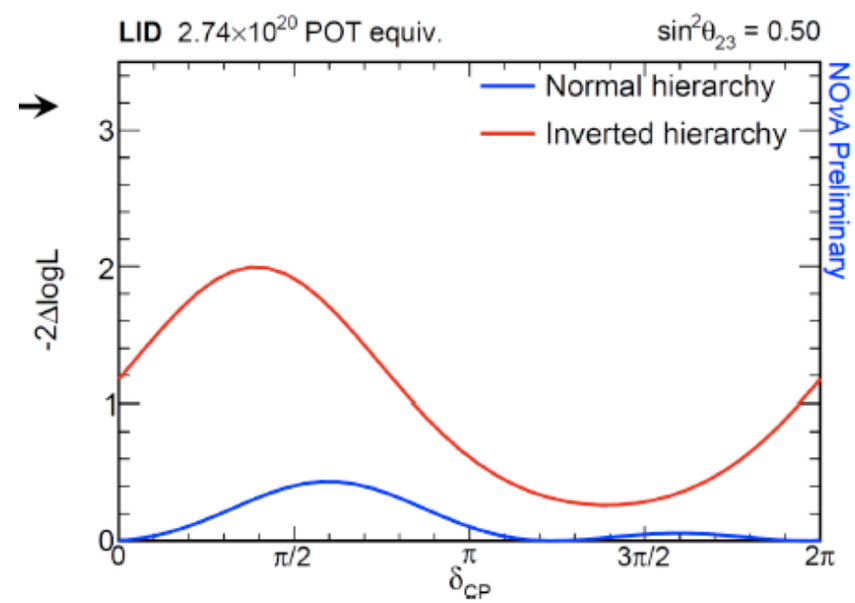
$\nu_\mu \longrightarrow \nu_e$

[R. Patterson, Fermilab JETP Aug. 6, 2015]





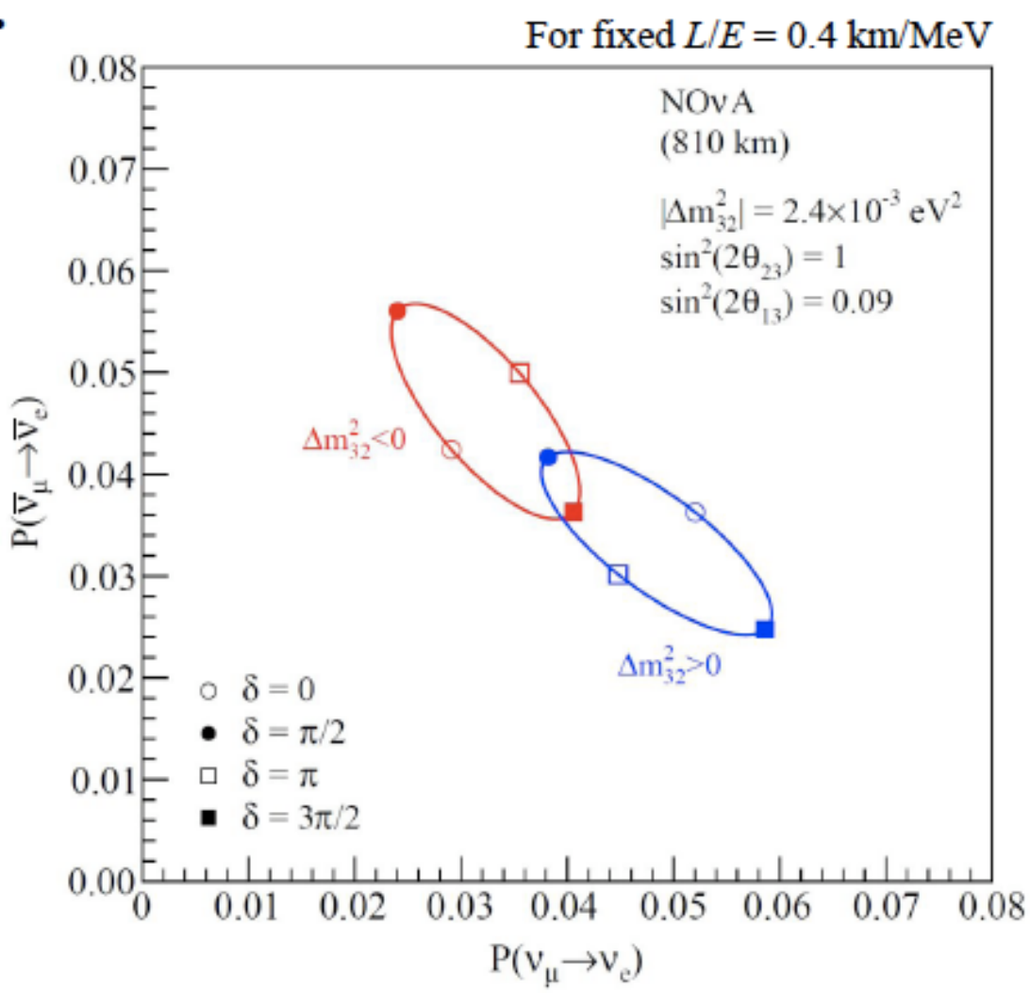
6 events

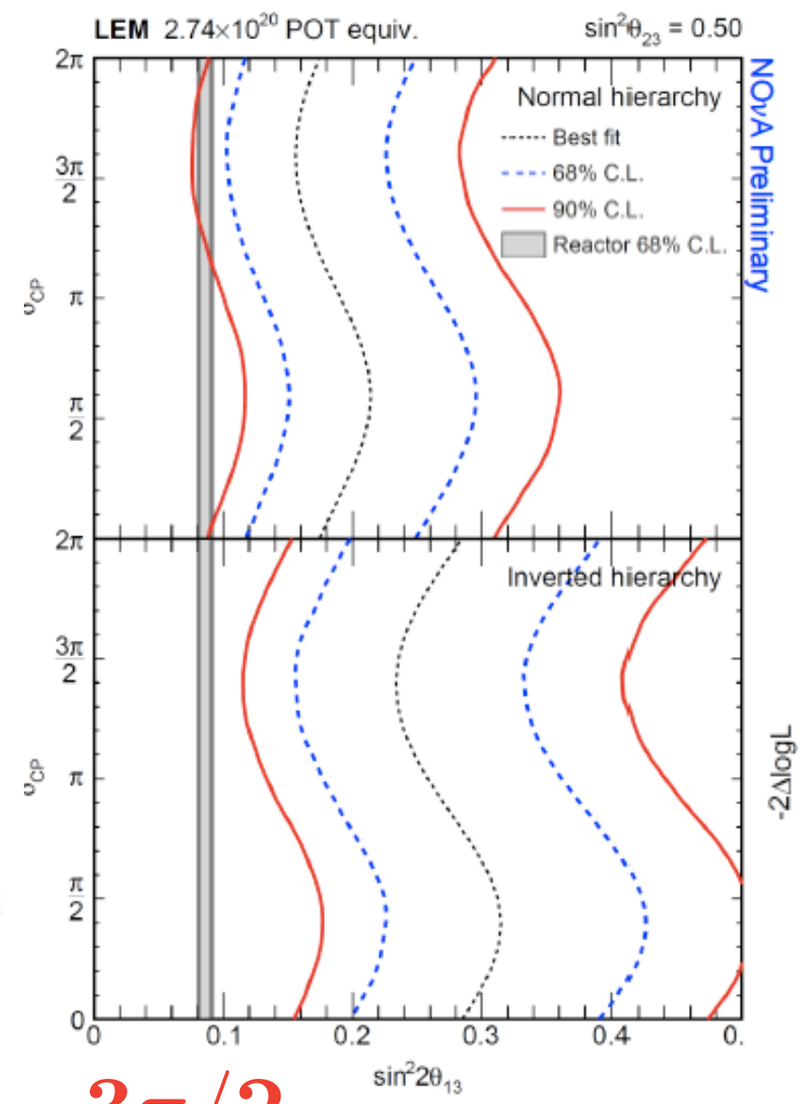


prefer NO & $\delta \sim 3\pi/2$

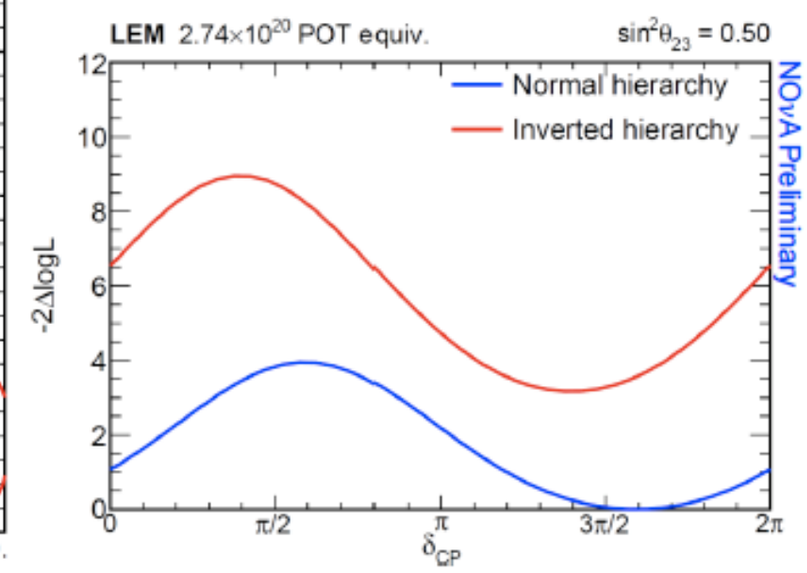
$\nu_\mu \longrightarrow \nu_e$

[R. Patterson, Fermilab JETP Aug. 6, 2015]





11 events



prefer NO & $\delta \sim 3\pi/2$

AN AUSPICIOUS FUTURE ?

CODA

$\sin^2\theta_{12} \sim 0.3$

$\sin^2\theta_{23} \sim 0.5$

$\sin^2\theta_{13} \sim 0.02$

$\Delta m^2_{21} \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2$

$|\Delta m^2_{31,32}| \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$

all known to better than 5%

CODA

$\sin^2\theta_{12} \sim 0.3$

$\sin^2\theta_{23} \sim 0.5$

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$|\Delta m^2_{31,32}| \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$

all known to better than 5%

Undetermined quantities

δ

mass ordering

θ_{23} octant

all data seem to prefer CPV

$\delta \sim 3\pi/2$

CODA

$\sin^2\theta_{12} \sim 0.3$

$\sin^2\theta_{23} \sim 0.5$

$\sin^2\theta_{13} \sim 0.02$

$\Delta m^2_{21} \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2$

$|\Delta m^2_{31,32}| \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$

all known to better than 5%

Undetermined quantities

δ

mass ordering

θ_{23} octant

NOvA seems to prefer NO

Global Fits prefer IO

But Still not statistically significant. Stay tuned!

CODA

$\sin^2\theta_{12} \sim 0.3$

$\sin^2\theta_{23} \sim 0.5$

$\sin^2\theta_{13} \sim 0.02$

$\Delta m^2_{21} \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2$

$|\Delta m^2_{31,32}| \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$

all known to better than 5%

Undetermined quantities

δ

mass ordering

θ_{23} octant

Global Fit prefer 2nd octant slightly for IO

This may change with NOvA

PMNS

NuFIT 2.0 (2014)

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

CKM

still a long way to go ...

$$|V_{CKM}| = \begin{pmatrix} 0.97425 \pm 0.00022 & 0.2253 \pm 0.0008 & (4.13 \pm 0.49) \times 10^{-3} \\ 0.225 \pm 0.008 & 0.986 \pm 0.016 & (41.1 \pm 1.3) \times 10^{-3} \\ (8.4 \pm 0.6) \times 10^{-3} & (40.0 \pm 2.7) \times 10^{-3} & 1.021 \pm 0.032 \end{pmatrix}$$

Beyond Oscillations: Absolute Mass Observables

Cosmology:

$$\Sigma = m_1 + m_2 + m_3$$

Effective electron neutrino mass:

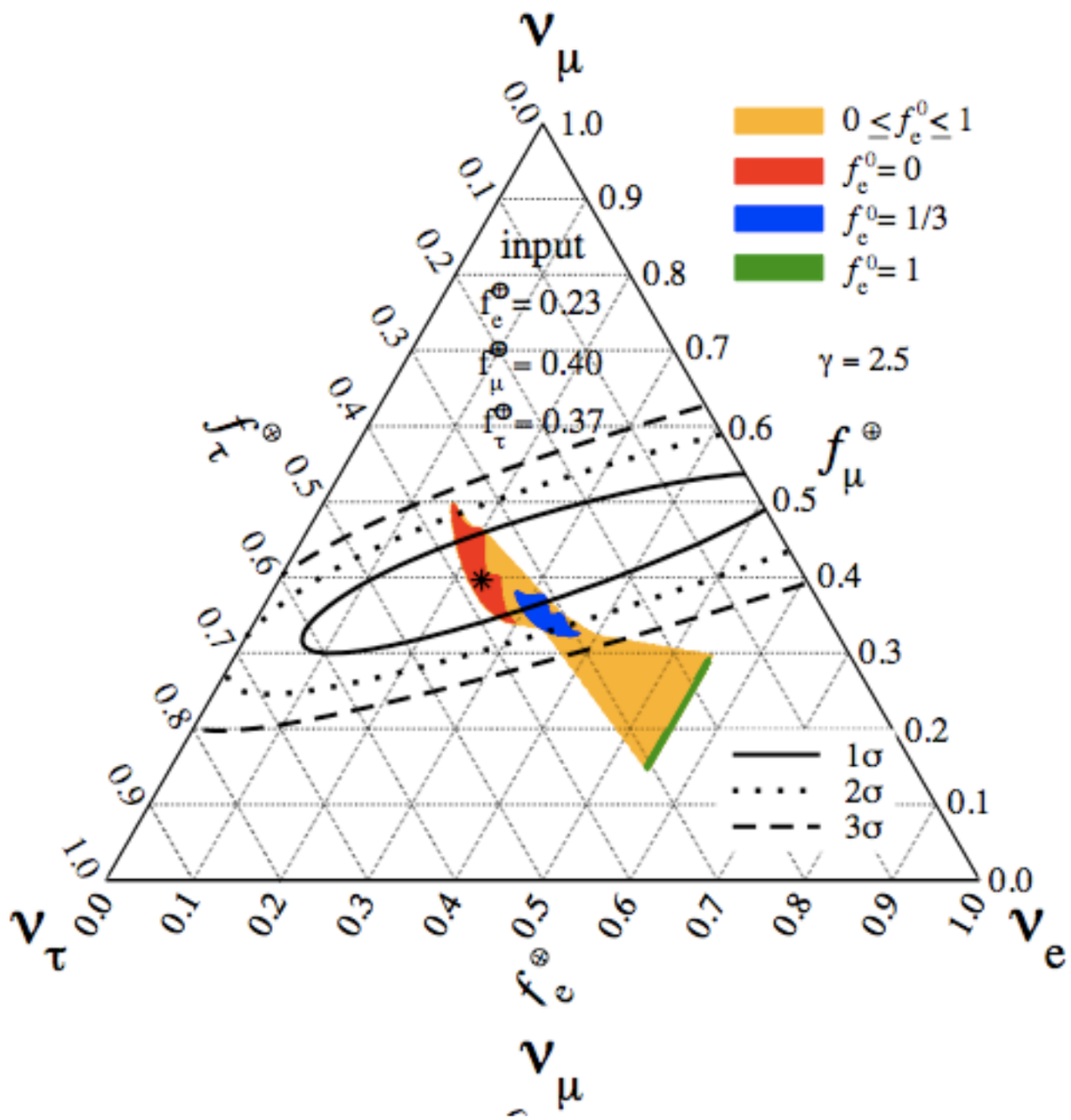
$$m_\beta^2 = [c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]$$

Effective Majorana mass:

$$m_{\beta\beta} = |c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\alpha_2} + s_{13}^2 m_3 e^{i\alpha_3}|$$

These observables are correlated by oscillation data

Effect on IceCube Data Interpretation



Keep an open mind for possible new states...

or new subleading effects...

Thank you