Recent status of neutrino oscillation phenomenology

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1. Introduction

2. The standard 3 flavor scenario

3. Oscillation vs non-oscillation experiments

4. Beyond the standard 3 flavor framework
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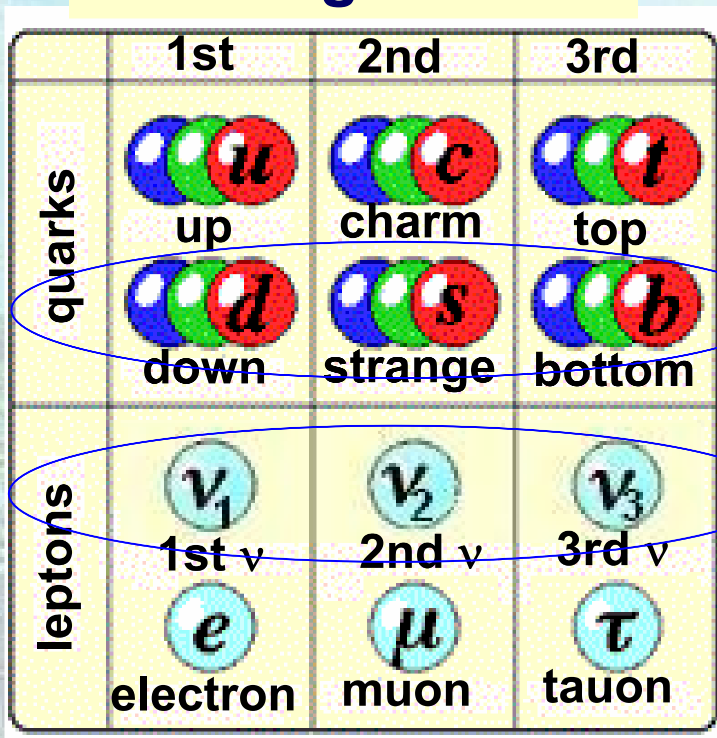
5. Summary

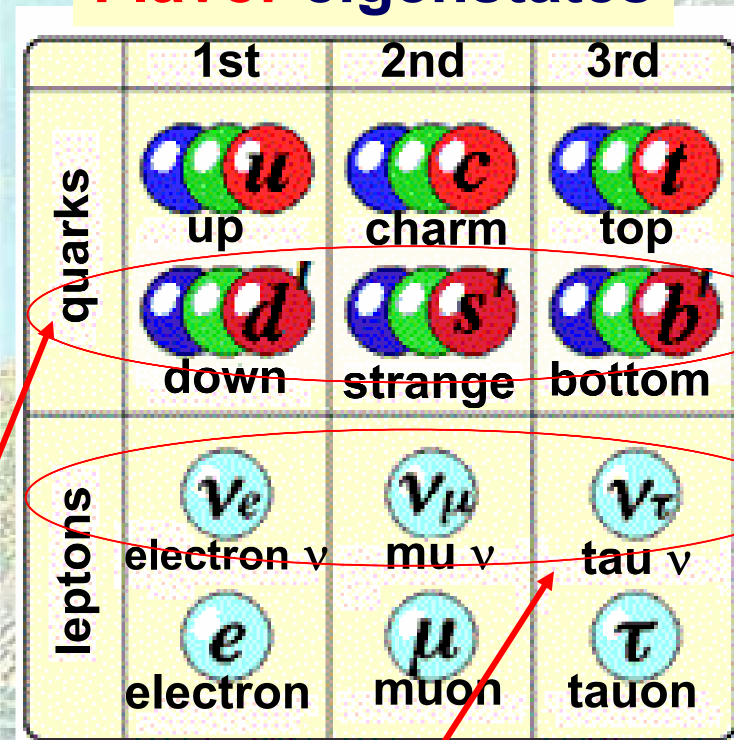
1. Introduction

Flavor and mass eigenstates in massive ν SM

Mass eigenstates

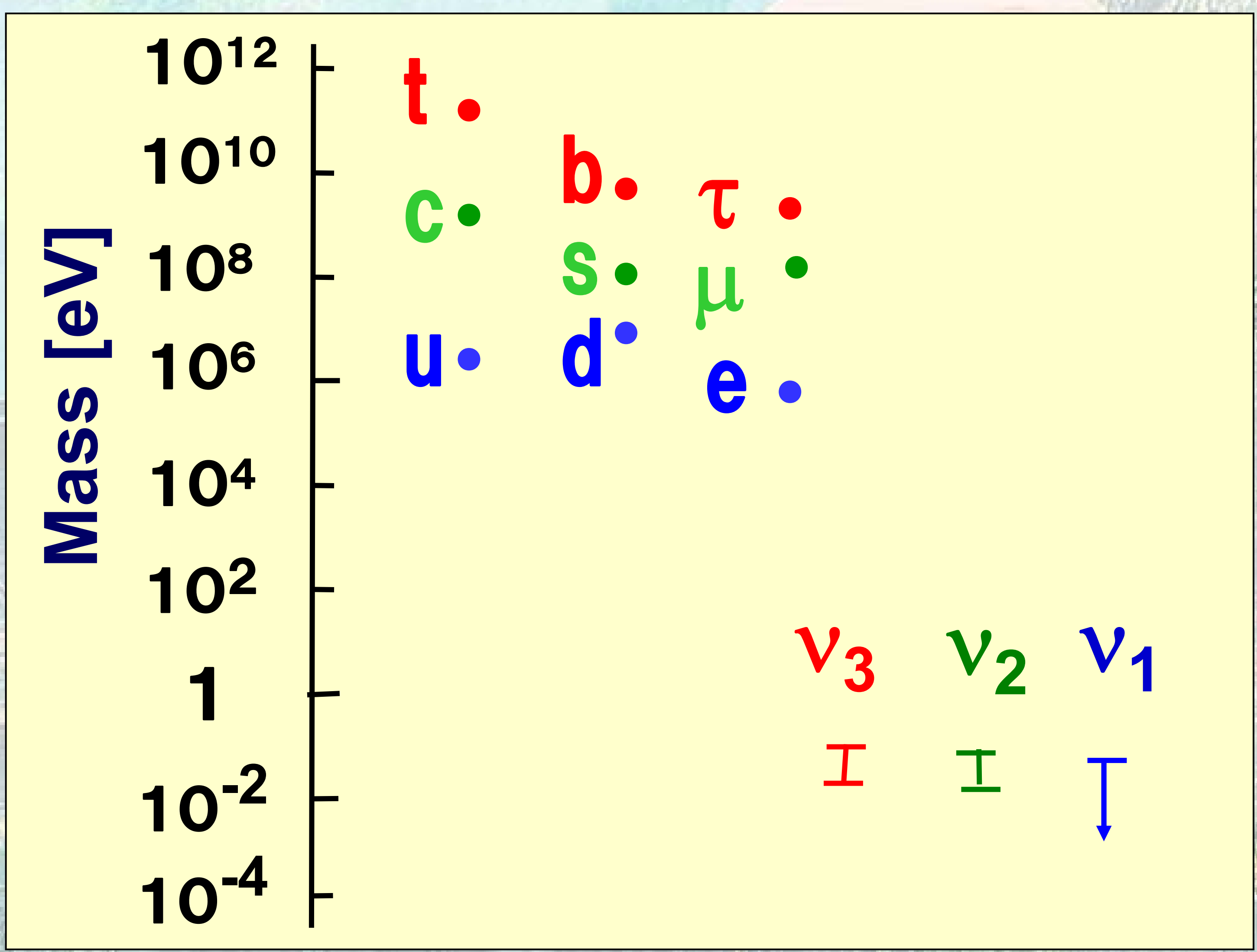


Flavor eigenstates



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Masses of Quarks & Leptons → Neutrinos are not heavy



Tiny neutrino mass

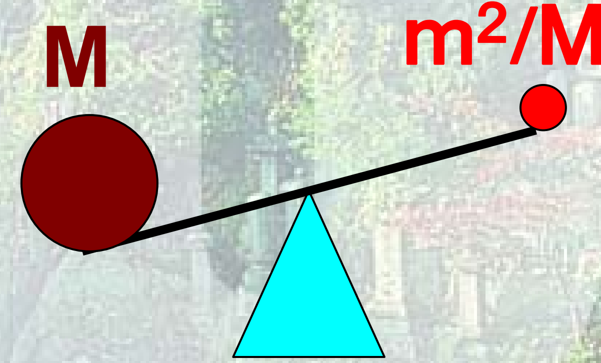
Seesaw mechanism

1977 Minkowski; 1979 Yanagida; 1979 Gell-Mann, Ramond, Slansky

$$\left(\overline{(\nu_L)^c},\ \bar{\nu}_R\right) \underbrace{\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}}_{\simeq\, U\, \mathrm{diag}(-m^2/M,\, M)\, U^{-1}} \begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix} + h.c.$$

$$U \simeq \begin{pmatrix} 1 & m/M \\ -m/M & 1 \end{pmatrix}$$

If m=1GeV and m^2/M gives m_ν,
then $m_\nu = m^2/M \sim 0.05$ eV
→ $M \sim 10^{10}$GeV

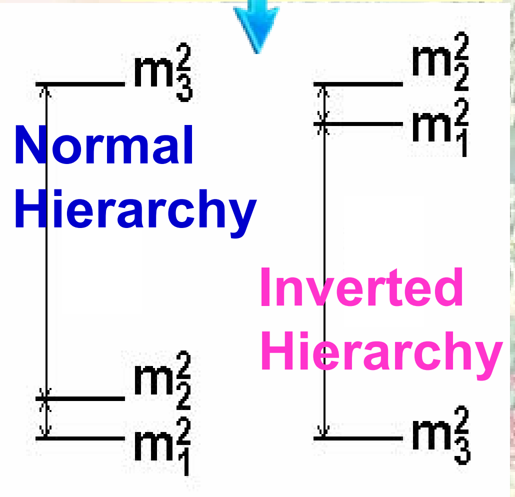


Tiny ν mass may be a hint for new physics at high energy

→ Reason why ν may be discussed in this Conference

2. Framework of 3 flavor ν oscillation

Both hierarchy patterns are allowed



Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Functions of mixing angles θ_{12}, θ_{23}, θ_{13}, and CP phase δ

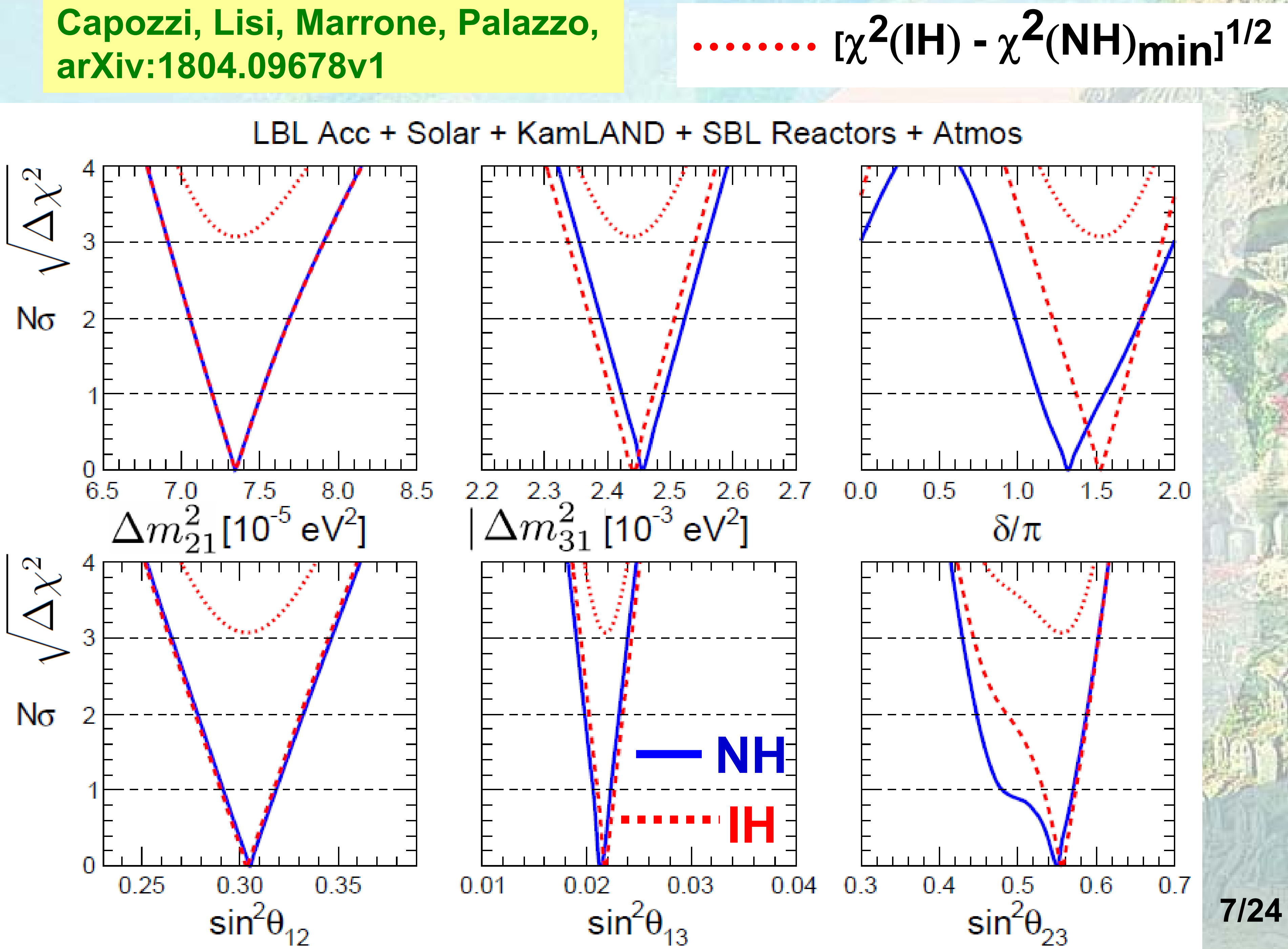
All 3 mixing angles have been measured:

ν_{solar}+KamLAND → $\theta_{12} \cong \frac{\pi}{6}$, $\Delta m_{21}^2 \cong 8 \times 10^{-5}\,\mathrm{eV}^2$

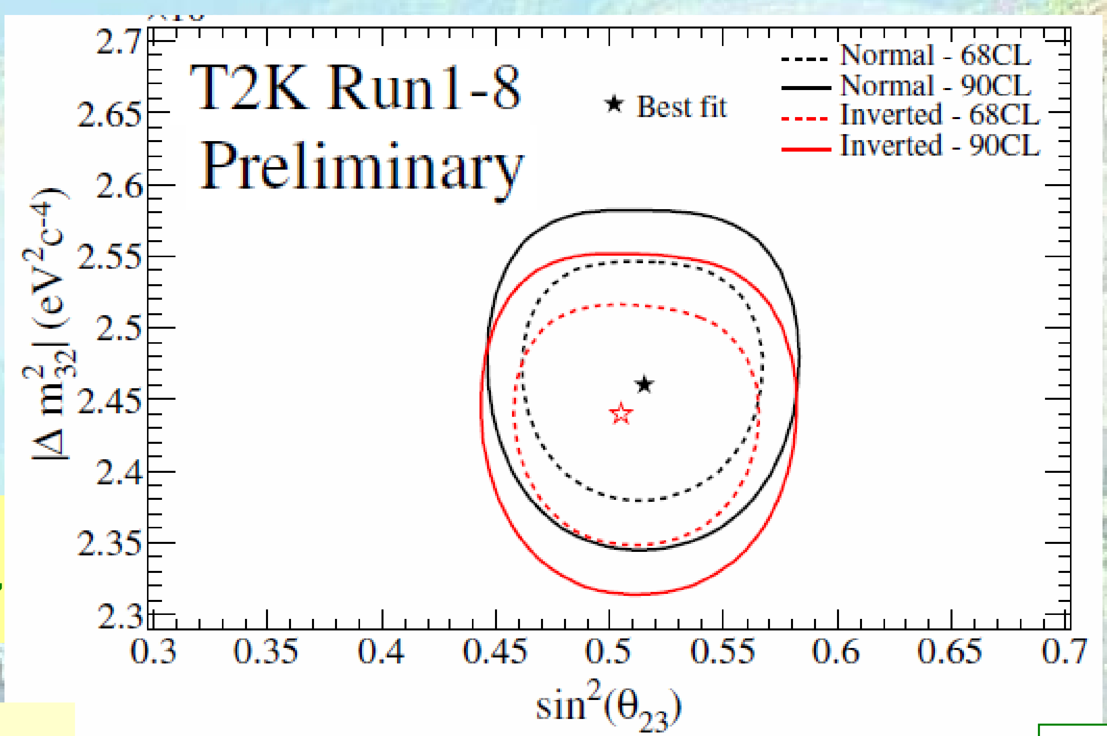
ν_{atm}(Ito), T2K (Zsoldos), NOvA (Suter) → $\theta_{23} \cong \frac{\pi}{4}$, $|\Delta m_{32}^2| \cong 2.5 \times 10^{-3}\,\mathrm{eV}^2$

D-CHOOZ (Kaneda), Daya Bay (Hu, He), Reno (Shin), T2K, NOvA, etc. → $\theta_{13} \cong \pi / 20$

Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1

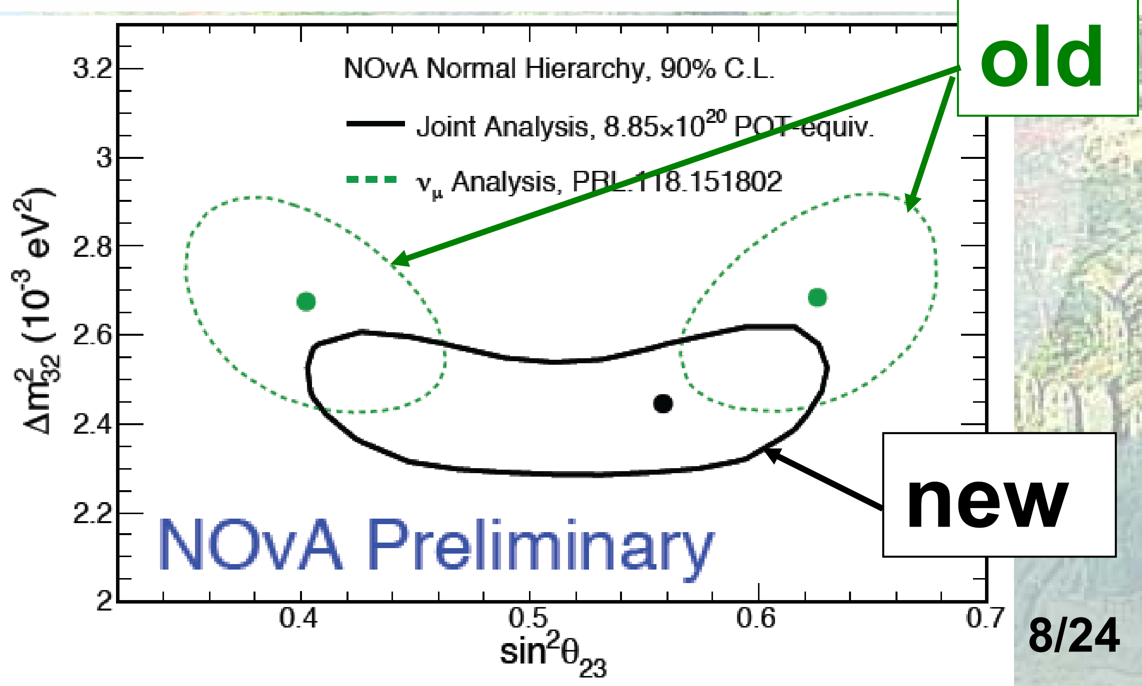


T2K vs NOvA: θ_{23}



S. V. Cao (T2K), arXiv:1805.05917

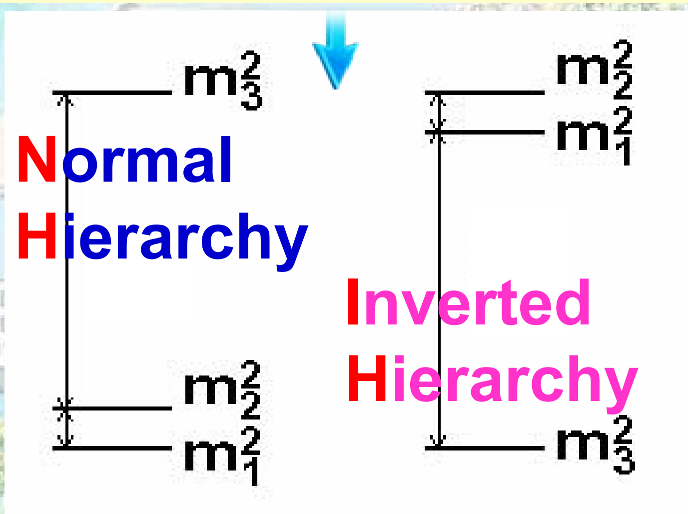
The discrepancy in θ_{23} between T2K & NOvA seemed to be solved in Jan. 2018.



A. Radovic, Fermilab JETP seminar, Jan. 12, 2018

Next task is to measure $\text{sign}(\Delta m^2_{31})$, $\pi/4-\theta_{23}$ and δ

Both hierarchy patterns are allowed

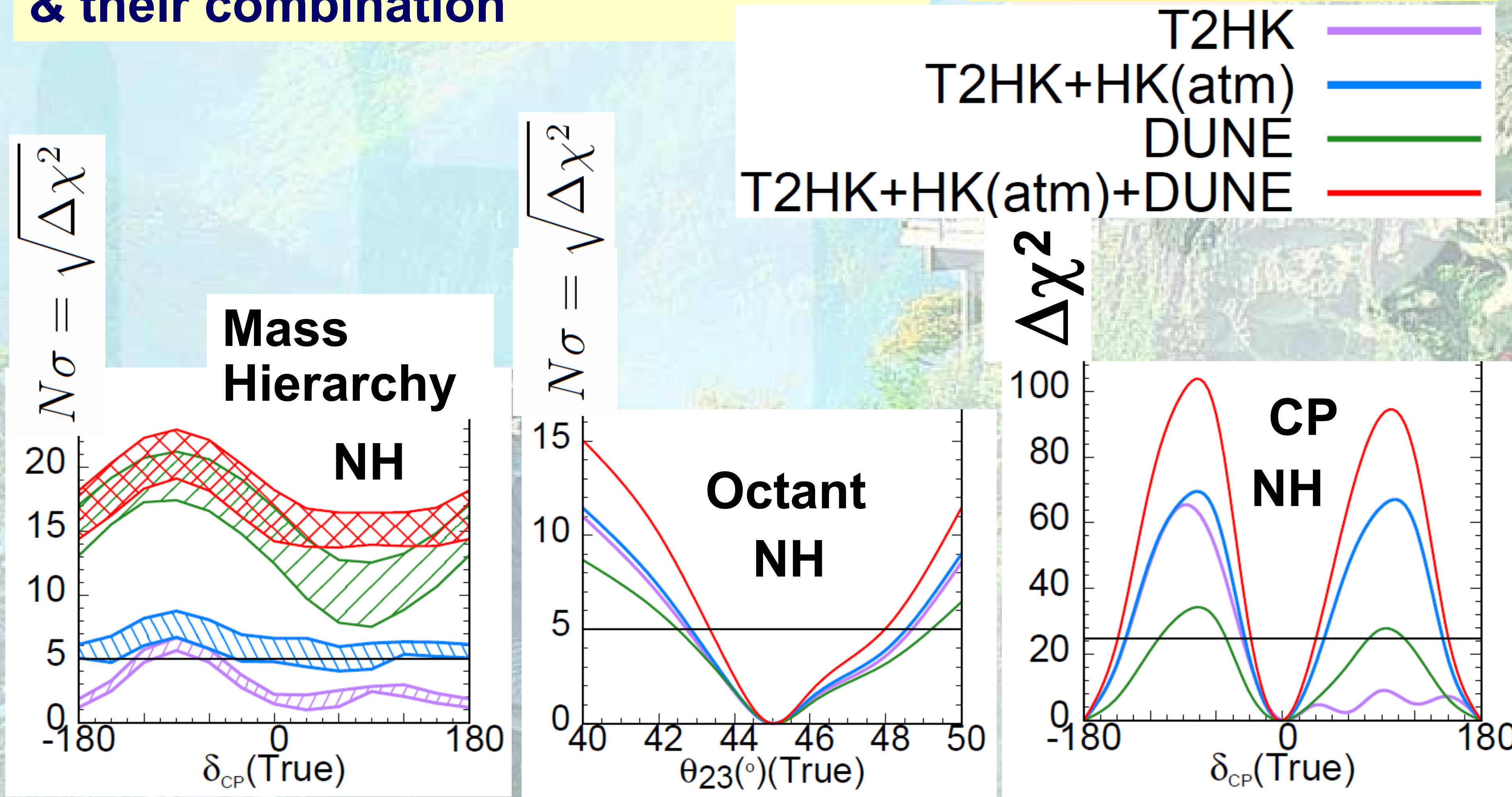


Proposed experiments

- T2HK(JP, JPARC-->HK)
  L=295km, E~0.6GeV
- DUNE (US, FNAL-->Homestake, SD)
  E~2GeV, L=1300km
- T2HKK(JP+KR, JPARC-->HK+Korea)
  L=295km+1100km, 0.5GeV<E<1.5GeV

Sensitivity of T2HK, ν_{atm}@HK, DUNE & their combination

Fukasawa, Ghosh, Yasuda, NPB918 ('17) 337



T2HK & DUNE experiments are expected to determine sign(Δm^2_{31}) , $\pi/4-\theta_{23}$ and δ

3. Oscillation vs non-oscillation experiments

- **neutrino oscillation**

  $\Delta m^2_{jk}=m^2_j - m^2_k$

- **neutrinoless double beta decay** ← Only when ν has Majorana mass

  $m_{ee}=|\Sigma(U_{ej})^2 m_j \exp(i\phi_j)|$ ← Majorana phases

- **direct measurement**

  $m_\beta=(\Sigma|U_{ej}|^2 m^2_j)^{1/2}$

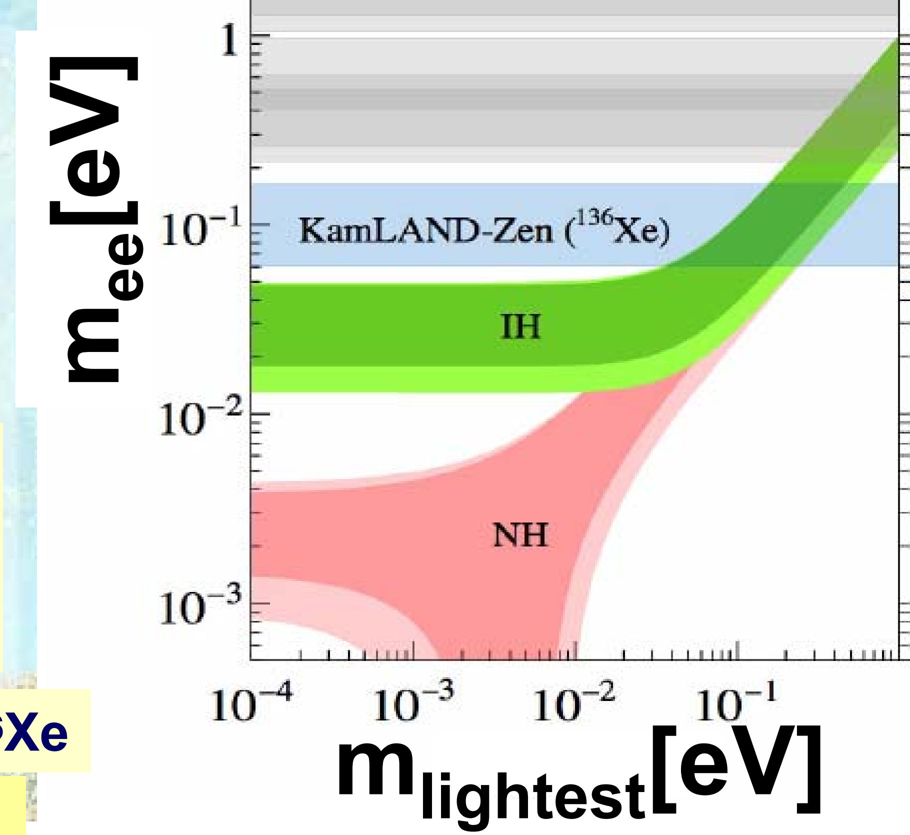
- **cosmology**

  Σm_j

3.1 neutrinoless double beta decay

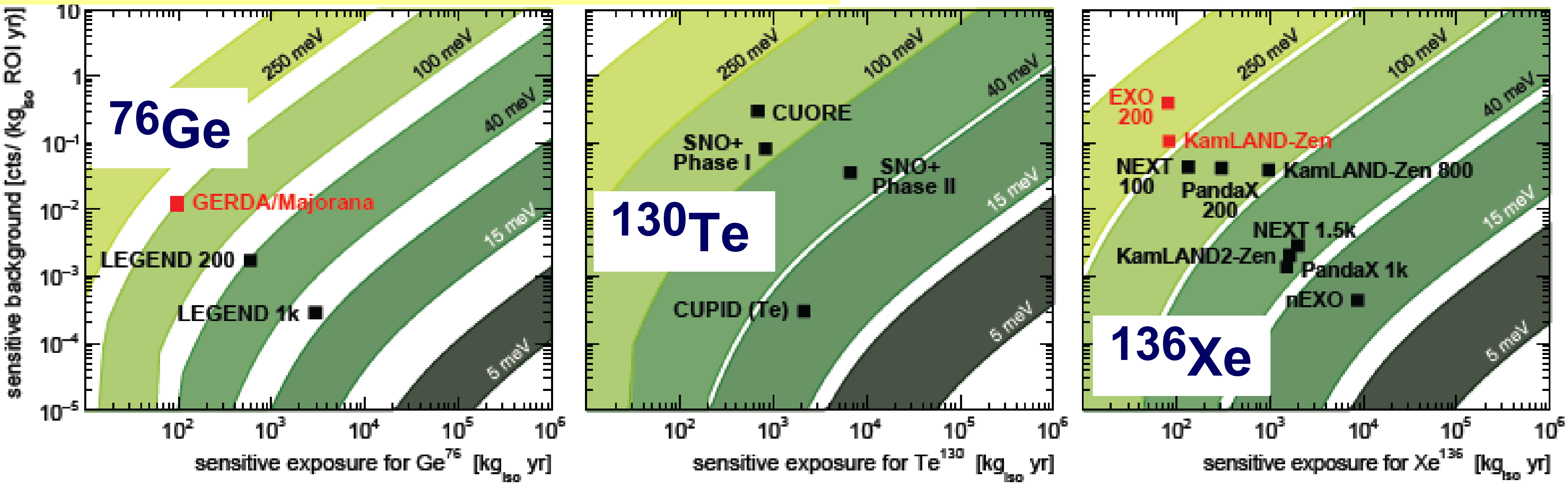
$m_{ee}=|\Sigma(U_{ej})^2 m_j \exp(i\phi_j)|$

See talks by Shirai, Cao, Marini, von Strum, Buuck on May 31 (Thu)



Discovery sensitivity for ^{76}Ge, ^{130}Te, ^{136}Xe

Agostini, Benato, Detwiler, arXiv:1705.02996v3

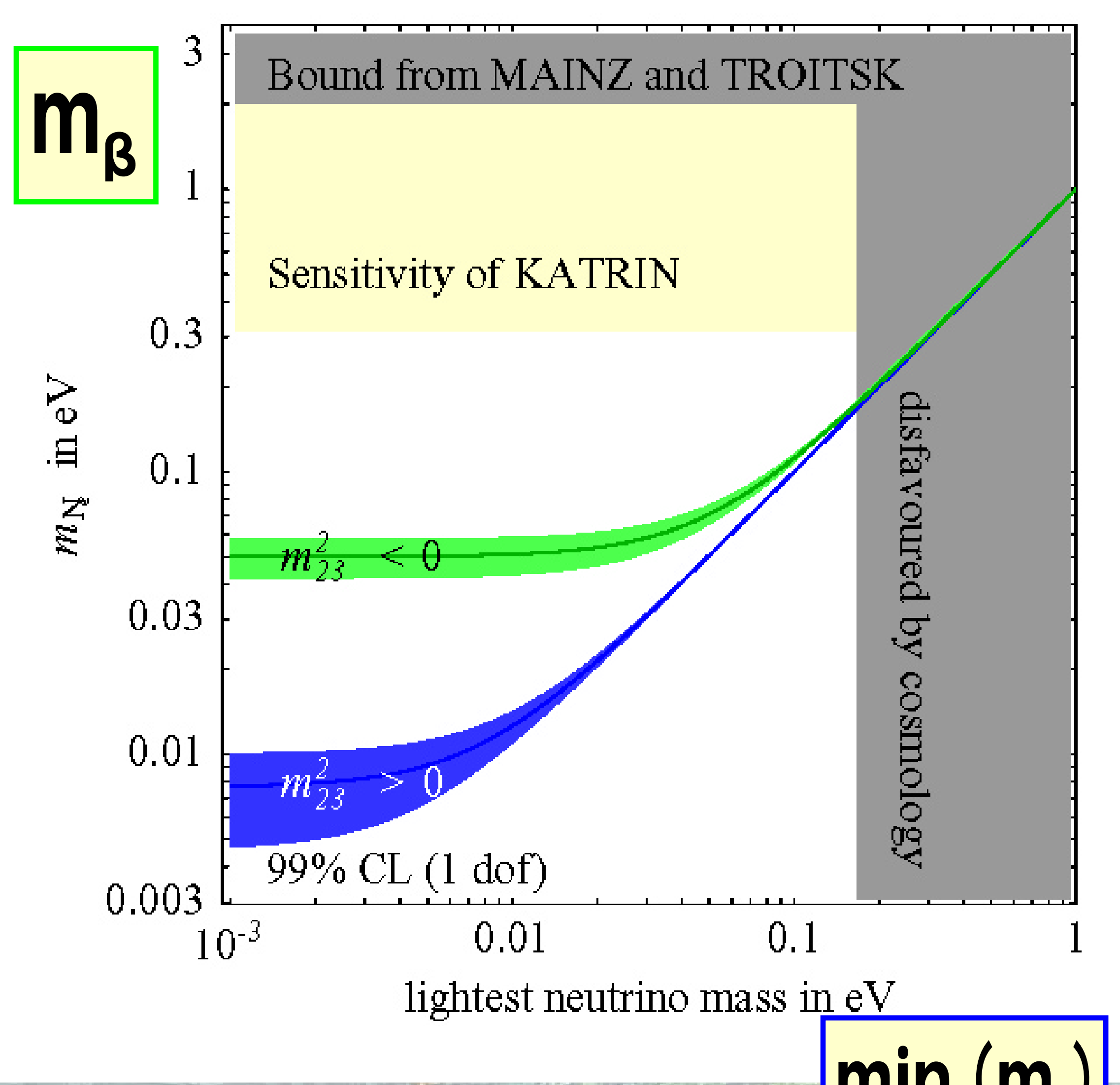


3.2 direct measurement

Strumia-Vissani: hep-ph/0606054

$$m_\beta = (\Sigma |U_{ej}|^2 m_j^2)^{1/2}$$

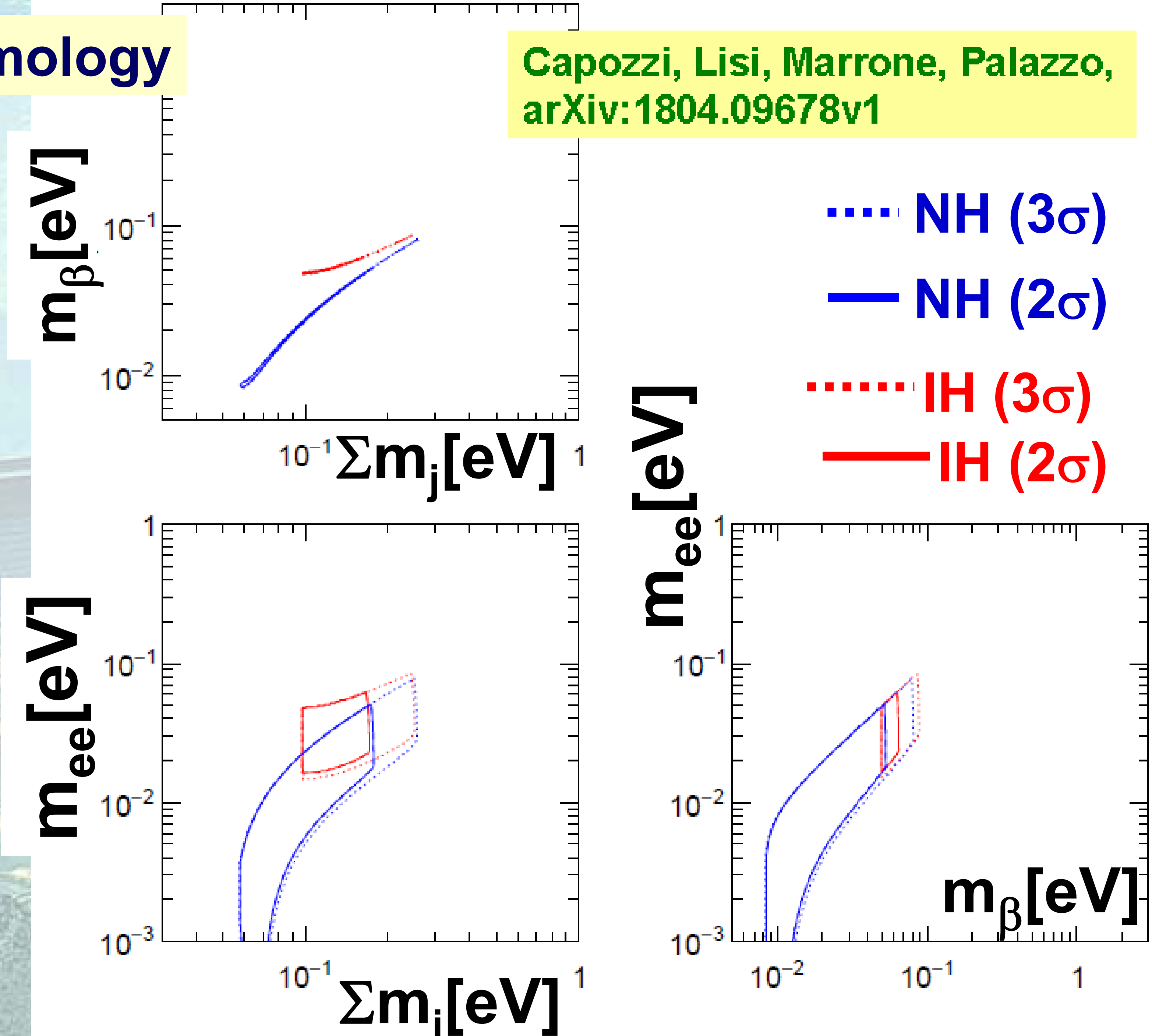
m_β



min (m_j)

3.3 cosmology

Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1



4. Beyond the standard 3 flavor framework

4.1 Light sterile neutrinos (ν_s)

Light sterile neutrinos have been phenomenologically motivated by:

- LSND anomaly
- Reactor anomaly
- Galium anomaly

4.2 Flavor dependent Non-Standard Interaction in propagation

NSI has been phenomenologically motivated by:

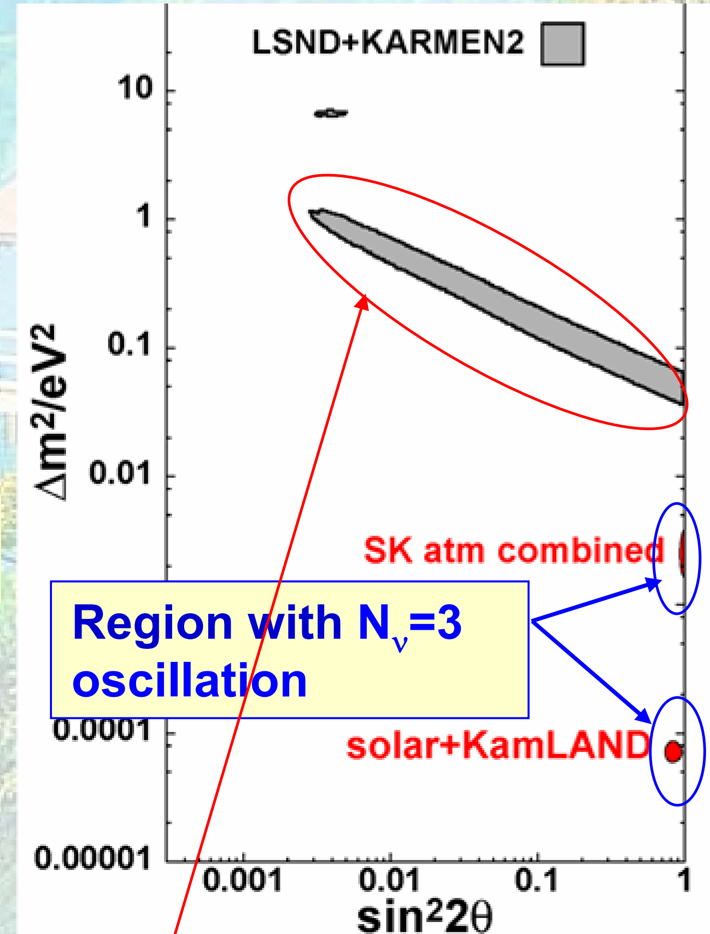
- Tension between Δm^2_{21}(solar) & Δm^2_{21}(KamLAND)

4.1.1 LSND anomaly

● **LNSD experiment @LANL**

$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

$\Delta m^2 \cong O(1)eV^2, \sin^2 2\theta \cong O(10^{-2})$ **??**



It cannot be explained by N_ν=3 oscillation

→ LEP data

→ N_ν=3 active light ν

→ 4th ν must be sterile

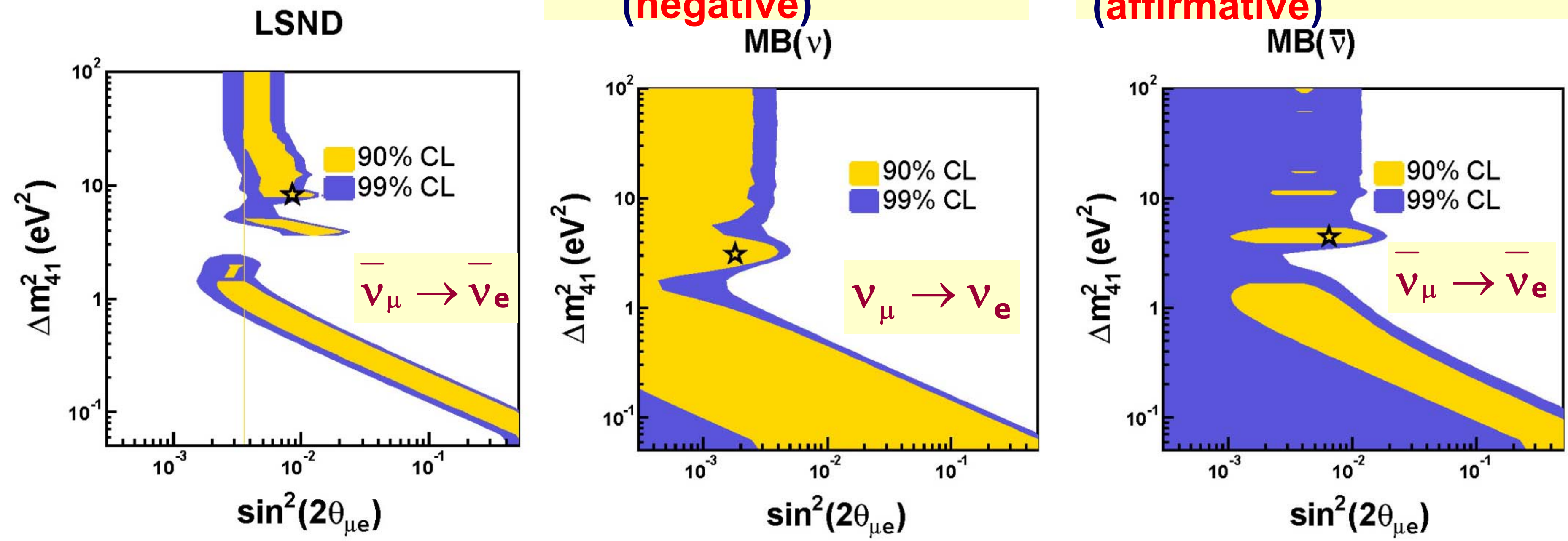
MiniBooNE @FNAL

Experiment which tests LSND

E～1GeV, L～1km, $(L/E)_{MB}=(L/E)_{LSND}$

ν mode(2007) (negative)

anti-ν mode(2010) (affirmative)



1995
LSND was true?

2007 (ν)
LSND was wrong!

2010
LSND was right？

Sterile ν oscillations!?

4.1.2 Reactor ν anomaly

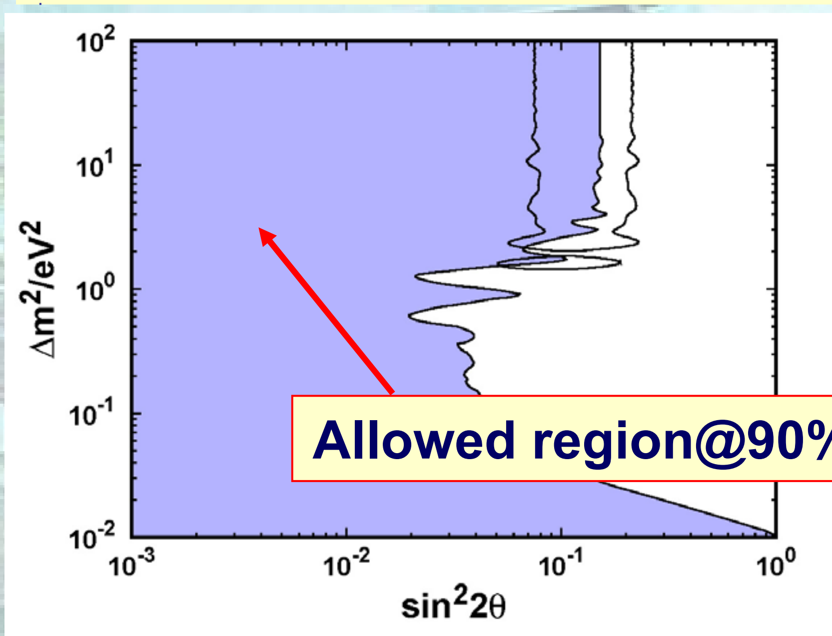
Mention et al (2011); Huber (2011)

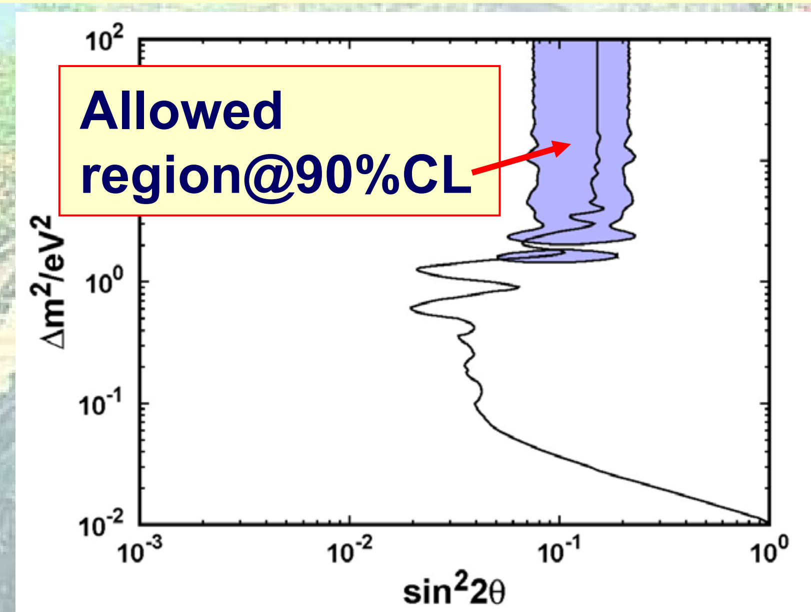
Recent reevaluation of reactor ν flux suggests affirmative interpretation of $\bar{\nu}_e \to \bar{\nu}_e$ oscillation at short distances

(new flux)= (old flux) x 1.03

Bugey(reactor $\bar{\nu}_e \to \bar{\nu}_e$):
Negative w/ old flux

Bugey(reactor)+etc:
Affirmative w/ new flux?



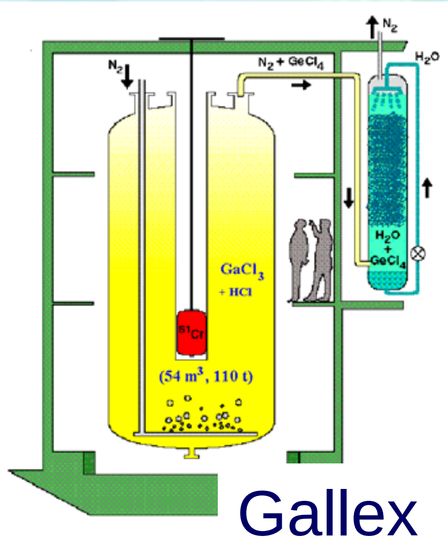


No ν oscillation for $\Delta m^2_{41} = O(1)\ eV^2$

ν oscillation may exist for $\Delta m^2_{41} = O(1)\ eV^2$

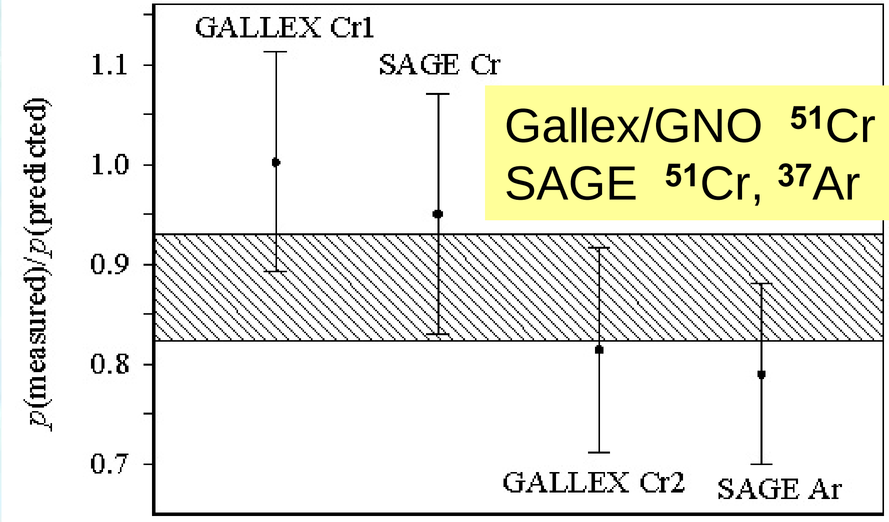
4.1.3 Gallium anomaly

Gallium radioactive source experiments



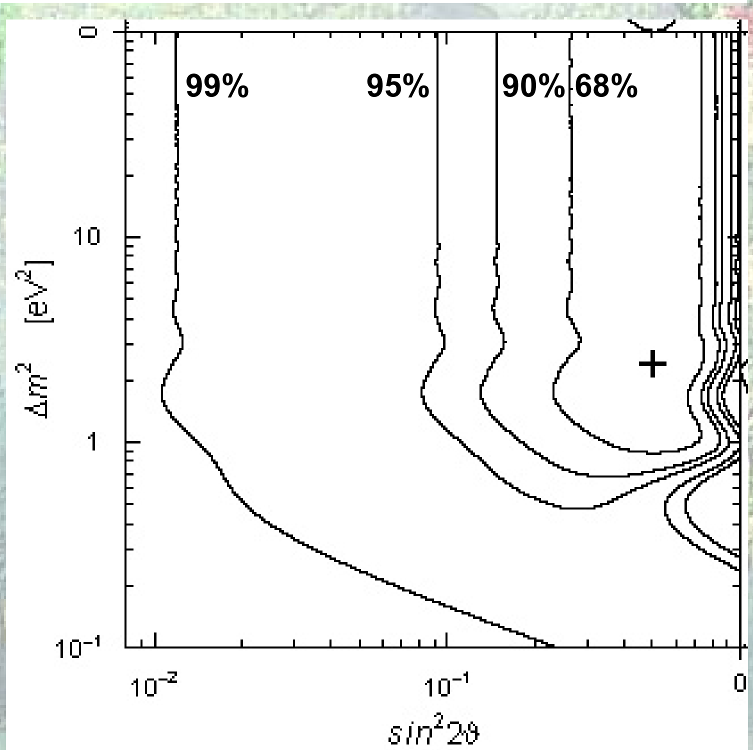
$$R \equiv \frac{\mathrm{p(measured)}}{\mathrm{p(predicted)}} = 0.88 \pm 0.05 (1\sigma)$$

SAGE, nucl-ex/0512041



Giunti-Laveder, 1006.3244v3 [hep-ph]

Results of the Ga radioactive source calibration experiments may be interpreted as an indication of the disappearance of ν_e due to active-sterile oscillations.



4.2 Nonstandard Interaction in propagation

Flavor-dependent Non Standard Interactions:

$$\mathcal{L}_{eff} = G_{NP}^{\alpha\beta}\,\bar{\nu}_\alpha\gamma^\mu\nu_\beta\,\bar{f}\gamma_\mu f'$$

neutral current non-standard interaction

f = e, u or d

Modification of matter effect

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\,\mathrm{diag}\,(E_1, E_2, E_3)\,U^{-1} + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

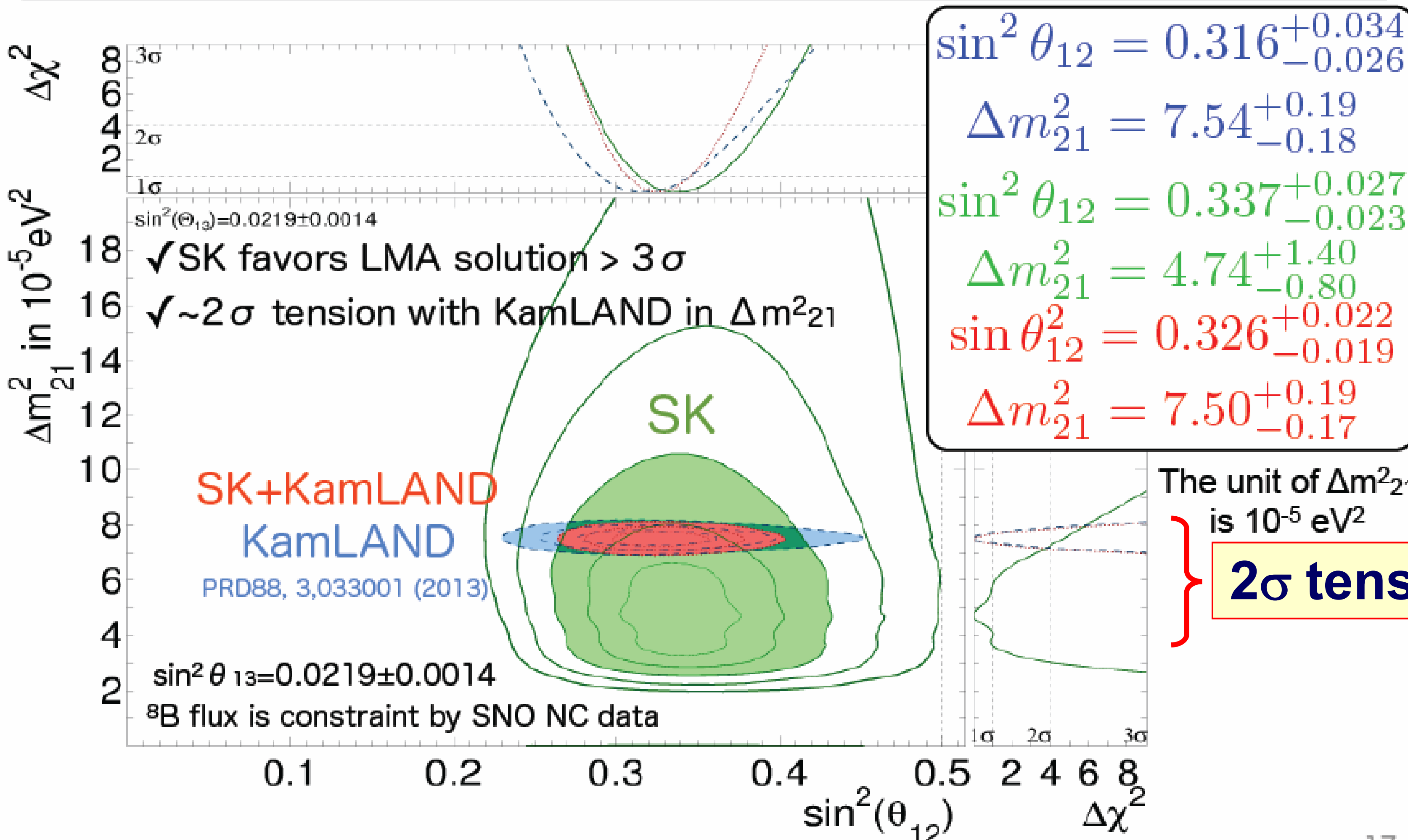
NP

$A \equiv \sqrt{2}G_F N_e$ $\quad N_e \equiv$ electron density

- **Tension between Δm^2_{21}(solar) & Δm^2_{21}(KamLAND)**

SK I - IV combined

Koshio@ NOW2016

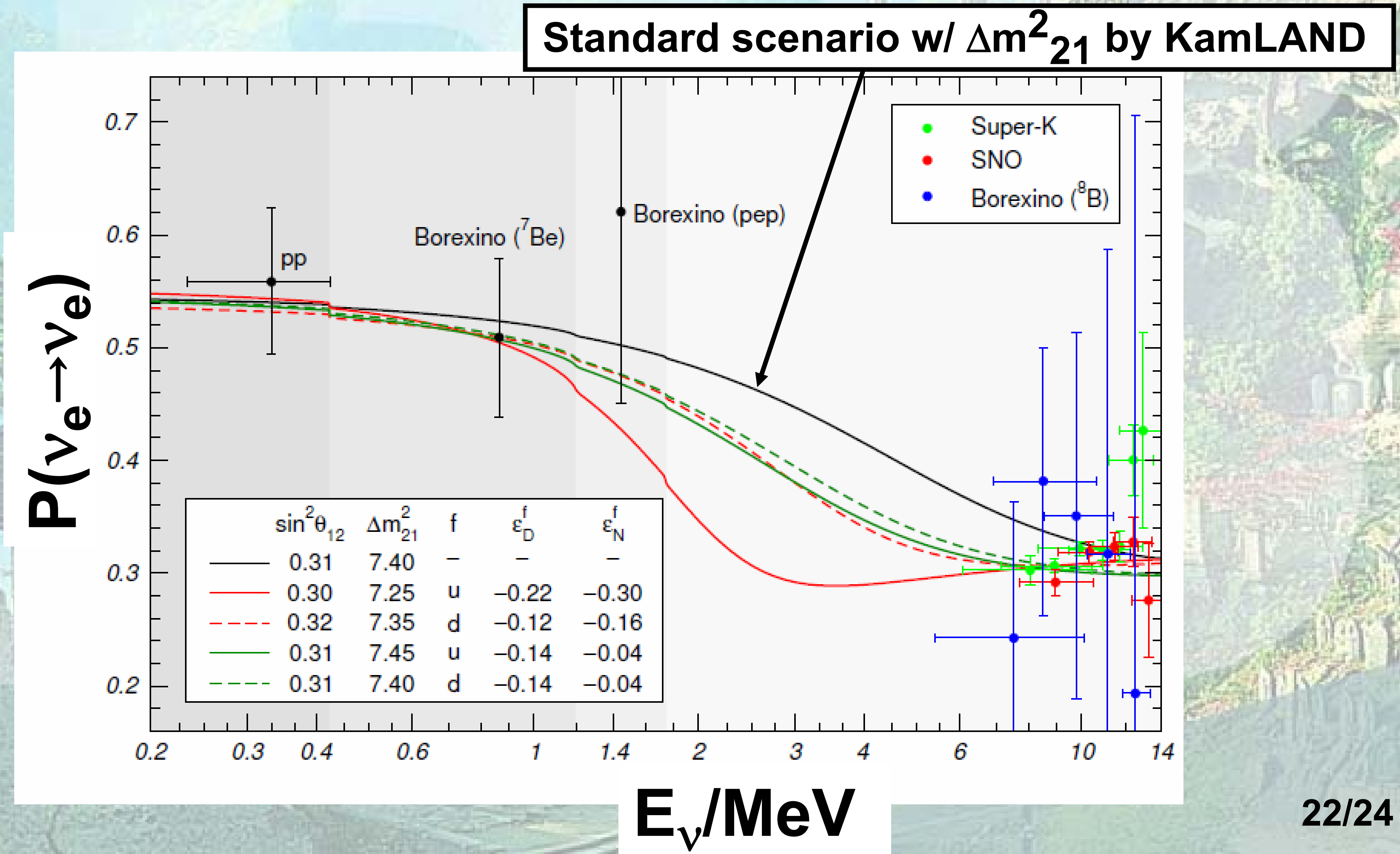


The unit of Δm^2_{21} is 10^{-5} eV^2

2σ tension

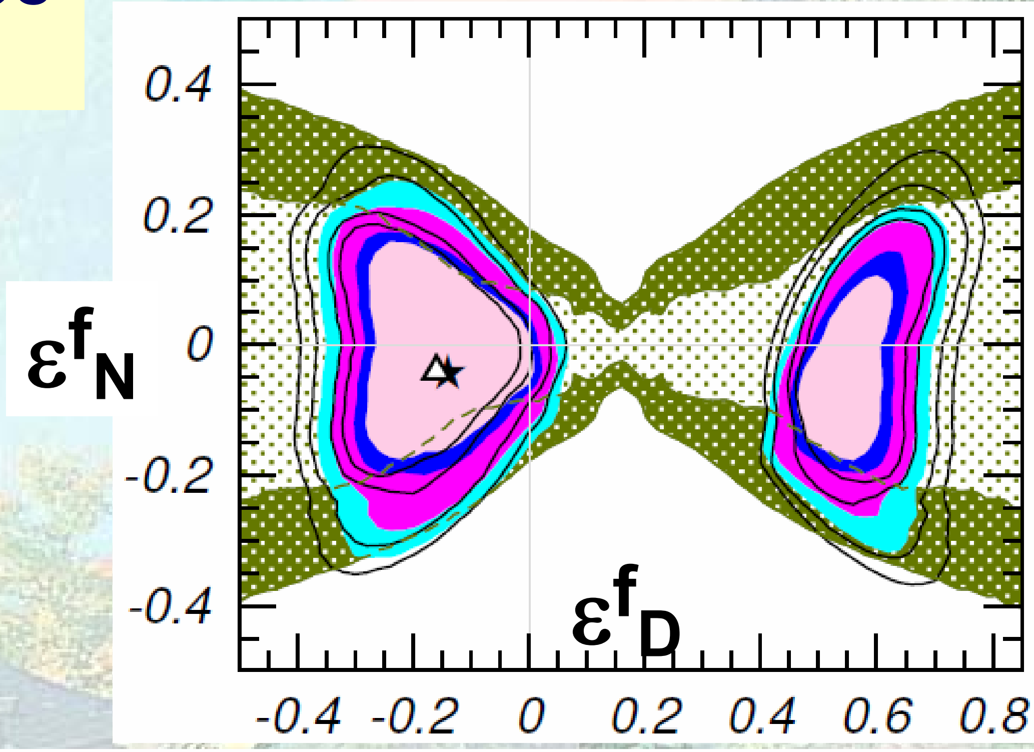
Tension between solar ν & KamLAND data comes from little observation of upturn by SK & SNO

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152



Tension between solar ν & KamLAND data can be solved by NSI

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152



$$\epsilon_D^f = c_{13}s_{13}\mathrm{Re}\left[e^{i\delta_{\rm CP}}\left(s_{23}\epsilon_{e\mu}^f + c_{23}\epsilon_{e\tau}^f\right)\right] - \left(1+s_{13}^2\right)c_{23}s_{23}\mathrm{Re}\left[\epsilon_{\mu\tau}^f\right] - \frac{c_{13}^2}{2}\left(\epsilon_{ee}^f - \epsilon_{\mu\mu}^f\right) + \frac{s_{23}^2 - s_{13}^2c_{23}^2}{2}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right)$$

$$\epsilon_N^f = c_{13}\left(c_{23}\epsilon_{e\mu}^f - s_{23}\epsilon_{e\tau}^f\right) + s_{13}e^{-i\delta_{\rm CP}}\left[s_{23}^2\epsilon_{\mu\tau}^f - c_{23}^2\epsilon_{\mu\tau}^{f*} + c_{23}s_{23}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right)\right]$$

f = e, u or d

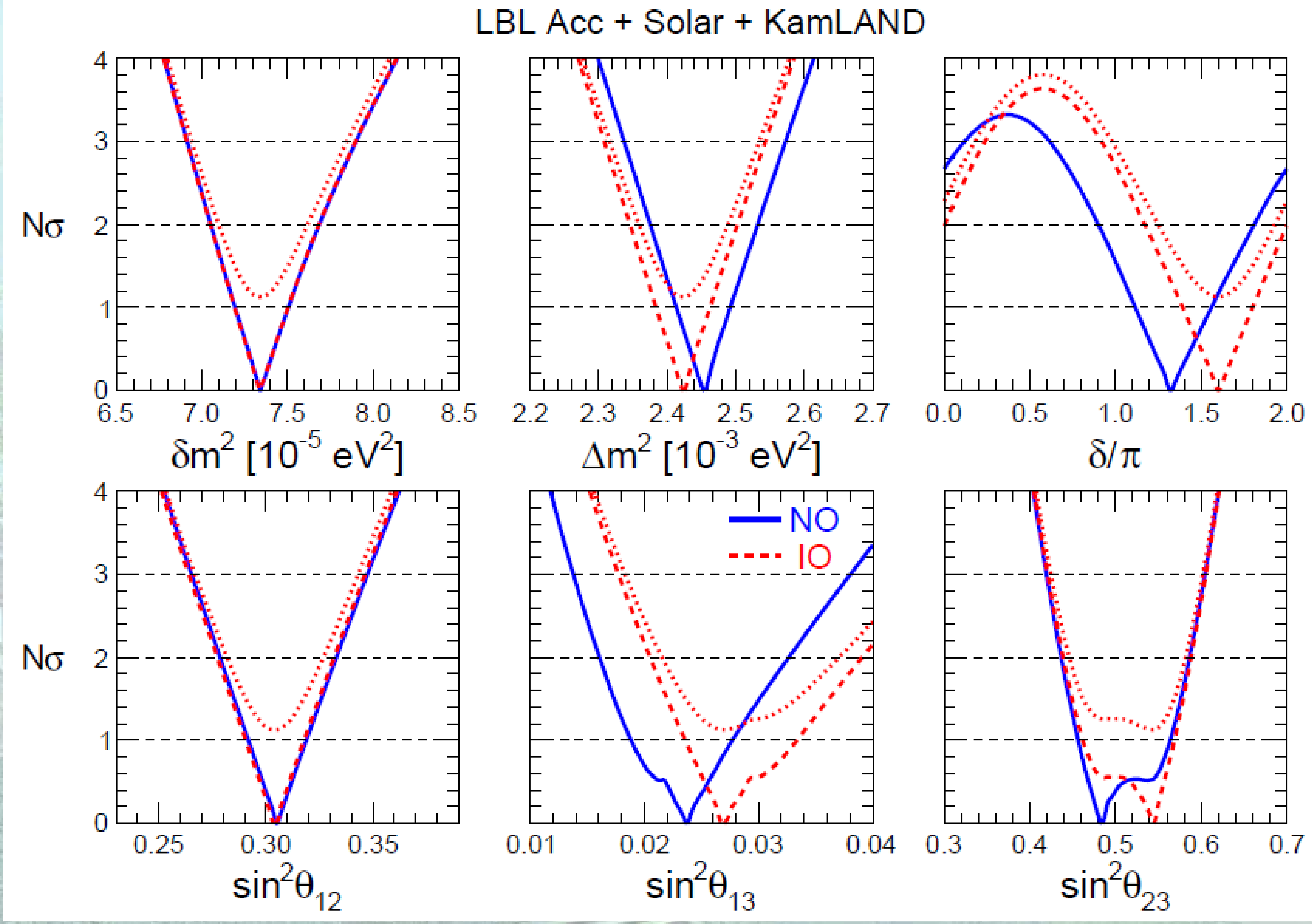
5. Summary

1. To complete the standard 3 flavor scenario, we still have to determine:
   - Mass hierarchy (important to determine δ)
   - $\theta_{23}-\pi/4$
   - δ

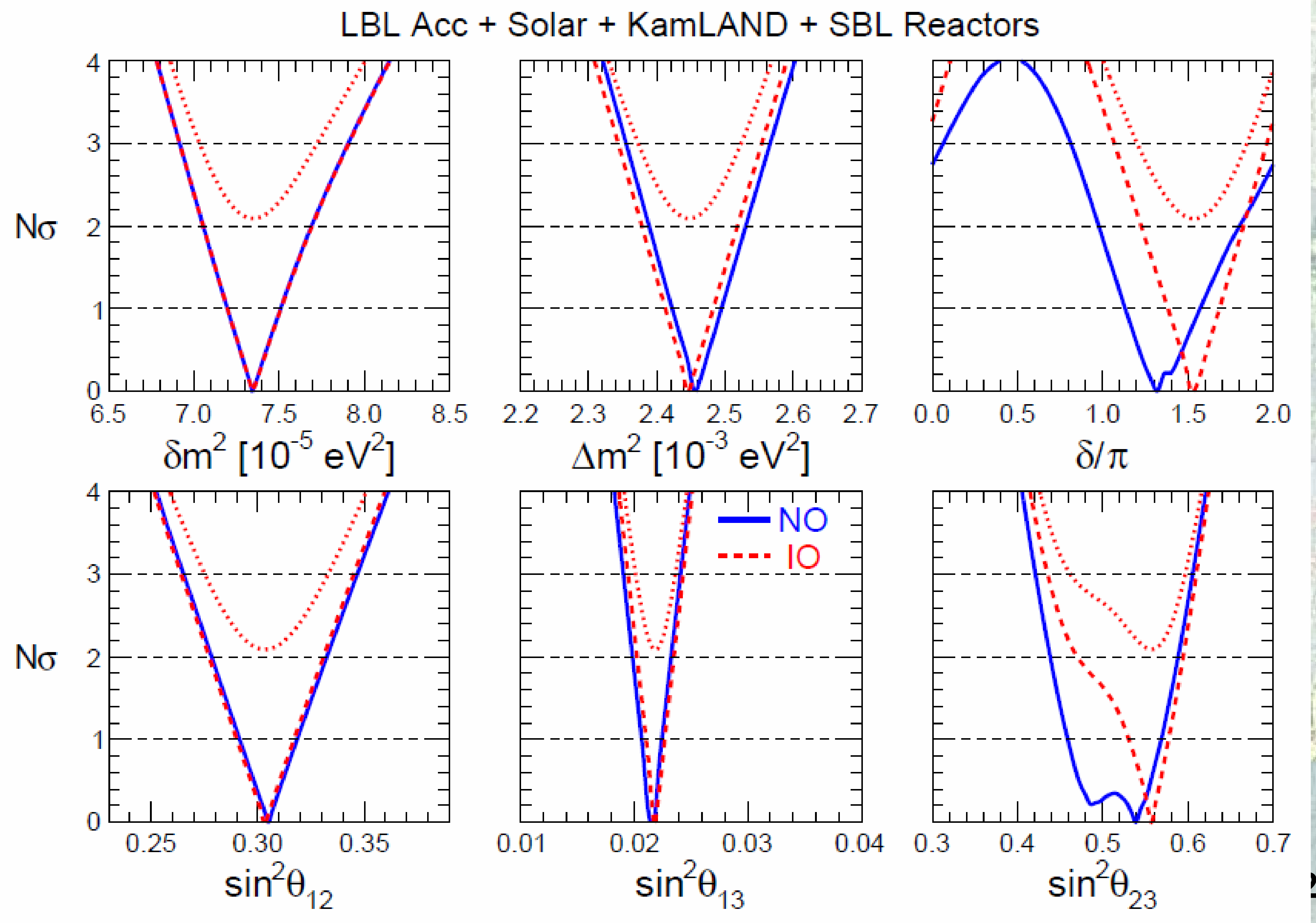
   Future LBL experiments are expected to determine these parameters.
2. Currently there are several hints for deviation from the standard 3 flavor scenario. Research on sterile neutrinos and NSI is in progress and it may give us a hint for physics beyond SM + 3 massive ν.

Backup slides

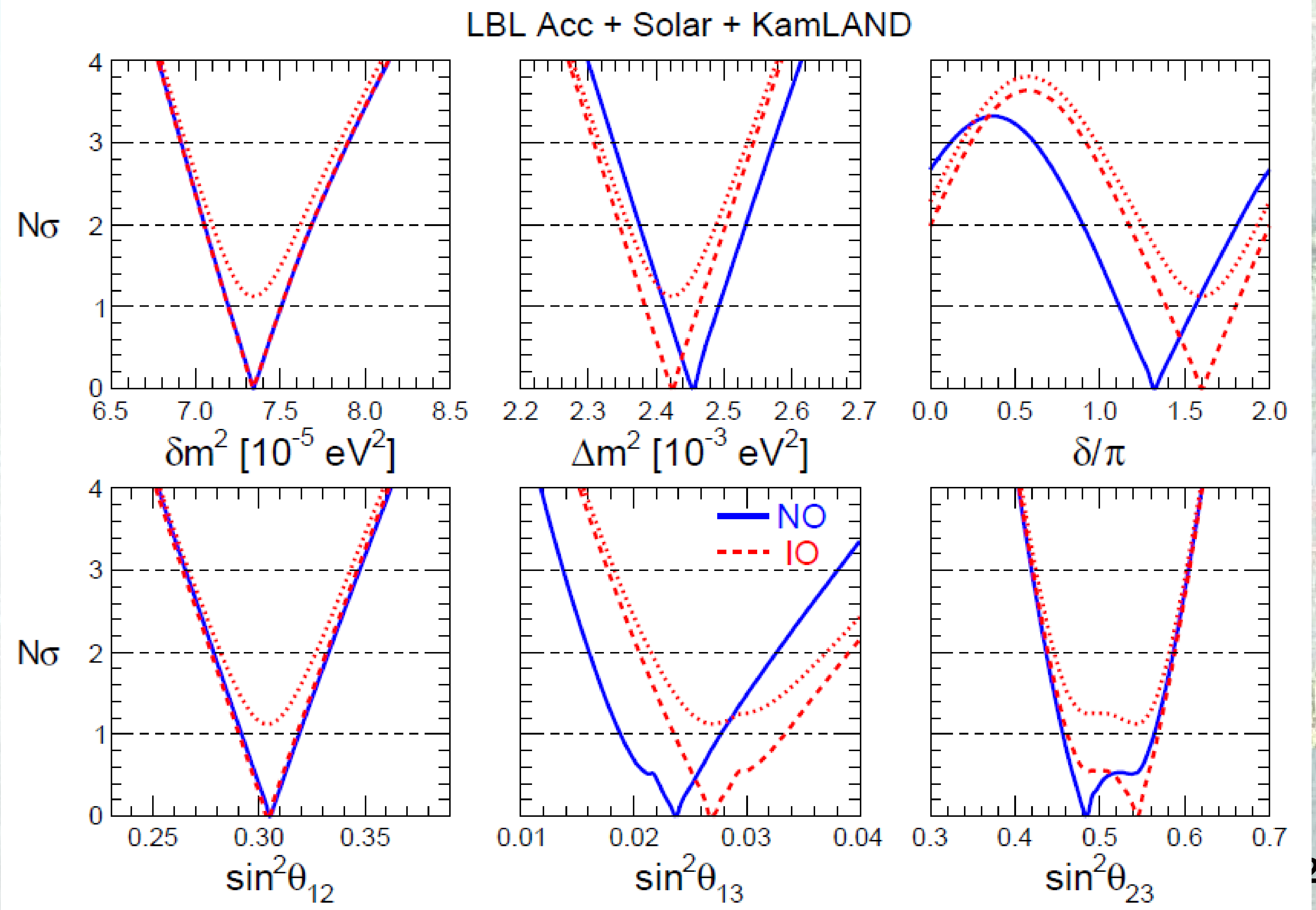
Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1



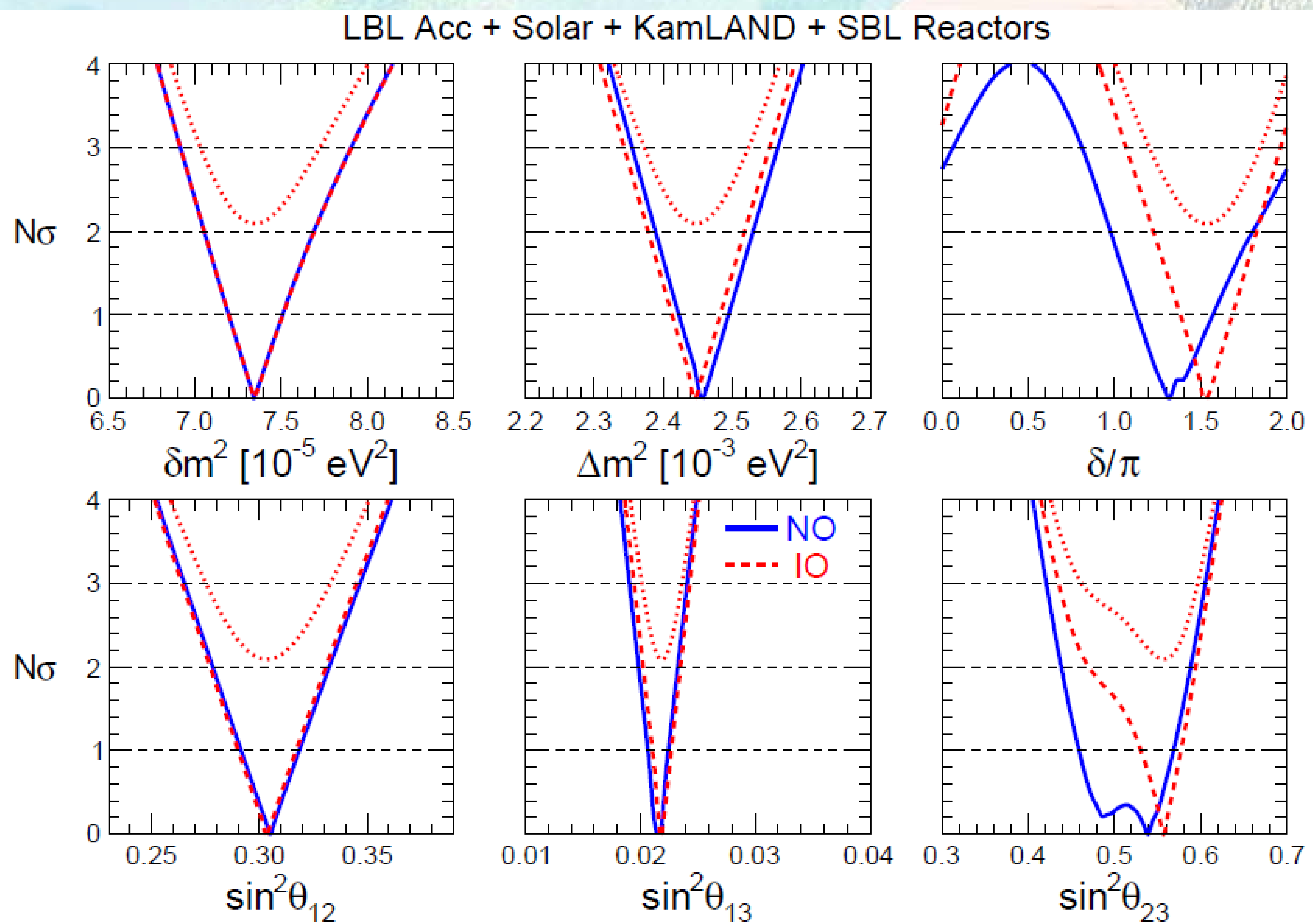
Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1



Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1



Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1

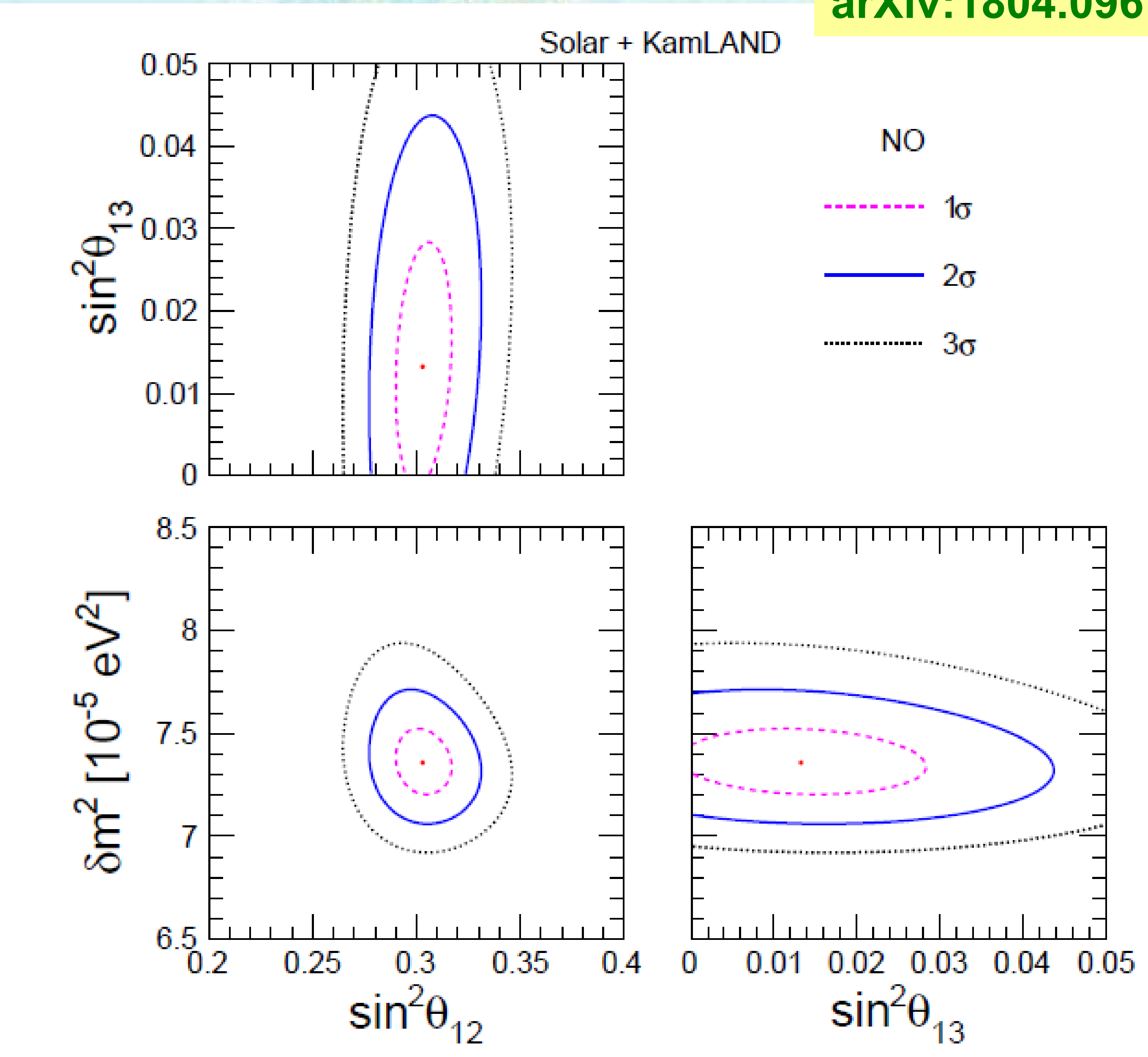


Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1

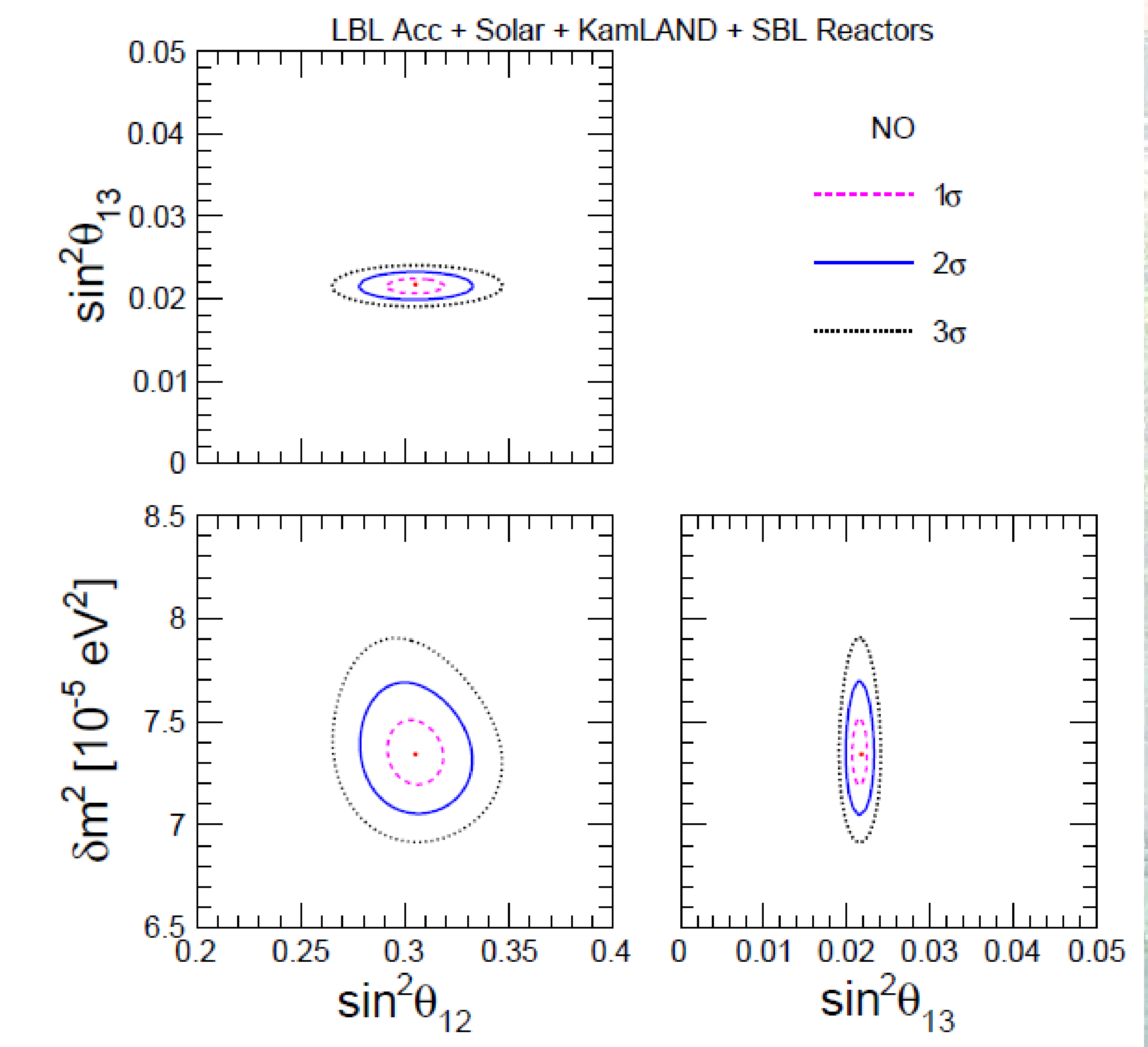
Table 1: Best fit values and allowed ranges at $N\sigma = 1, 2, 3$ for the 3ν oscillation parameters, in either NO or IO. The latter column shows the formal "1σ accuracy" for each parameter, defined as 1/6 of the 3σ range divided by the best-fit value (in percent).

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
	IO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
$\sin^2\theta_{12}$	NO	3.04	2.91 – 3.18	2.78 – 3.32	2.65 – 3.46	4.4
	IO	3.03	2.90 – 3.17	2.77 – 3.31	2.64 – 3.45	4.4
$\sin^2\theta_{13}/10^{-2}$	NO	2.14	2.07 – 2.23	1.98 – 2.31	1.90 – 2.39	3.8
	IO	2.18	2.11 – 2.26	2.02 – 2.35	1.95 – 2.43	3.7
$\|\Delta m^2\|/10^{-3}$ eV^2	NO	2.455	2.423 – 2.490	2.390 – 2.523	2.355 – 2.557	1.4
	IO	2.441	2.406 – 2.474	2.372 – 2.507	2.338 – 2.540	1.4
$\sin^2\theta_{23}/10^{-1}$	NO	5.51	4.81 – 5.70	4.48 – 5.88	4.30 – 6.02	5.2
	IO	5.57	5.33 – 5.74	4.86 – 5.89	4.44 – 6.03	4.8
δ/π	NO	1.32	1.14 – 1.55	0.98 – 1.79	0.83 – 1.99	14.6
	IO	1.52	1.37 – 1.66	1.22 – 1.79	1.07 – 1.92	9.3

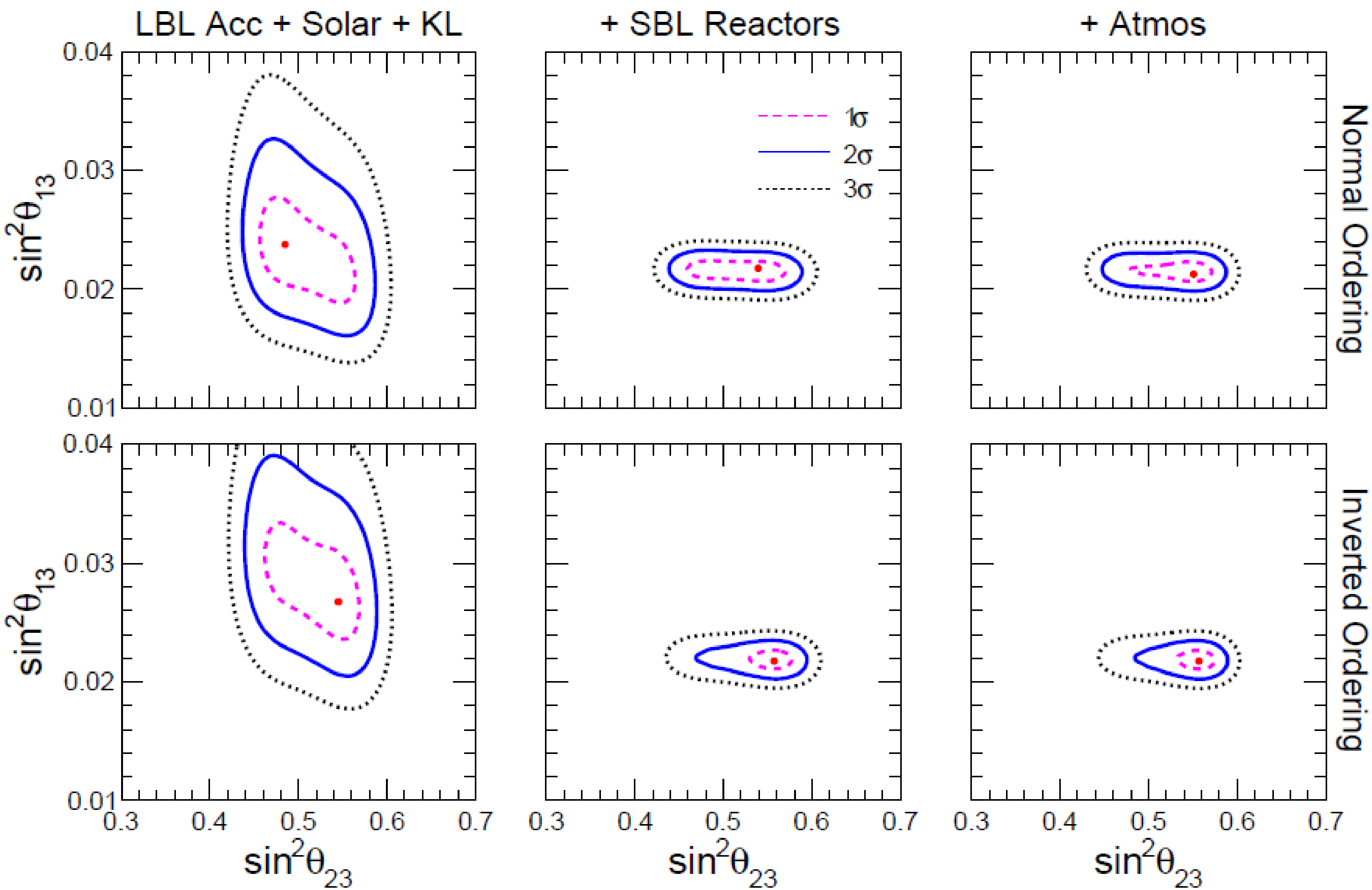
Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1



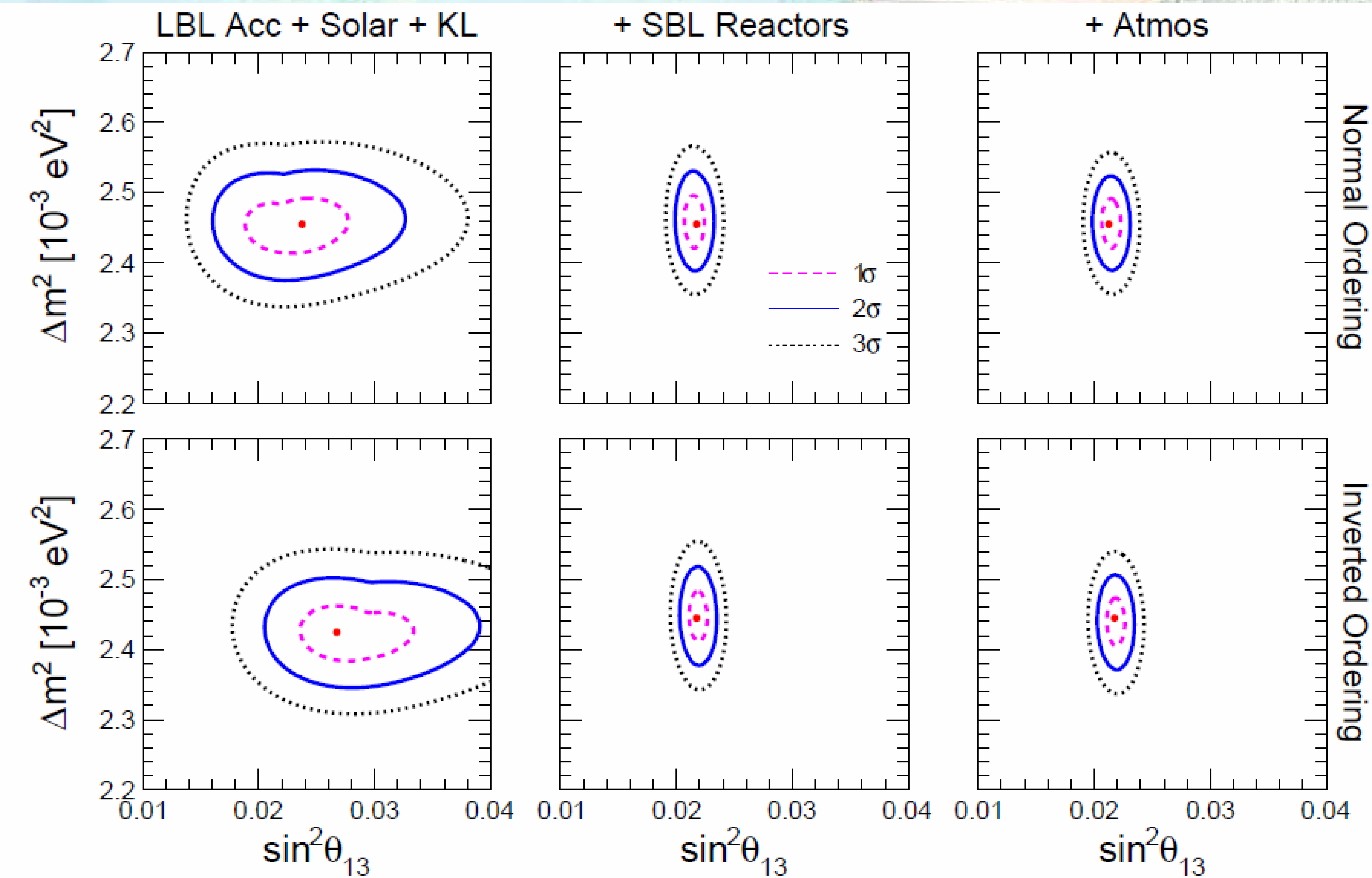
Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1



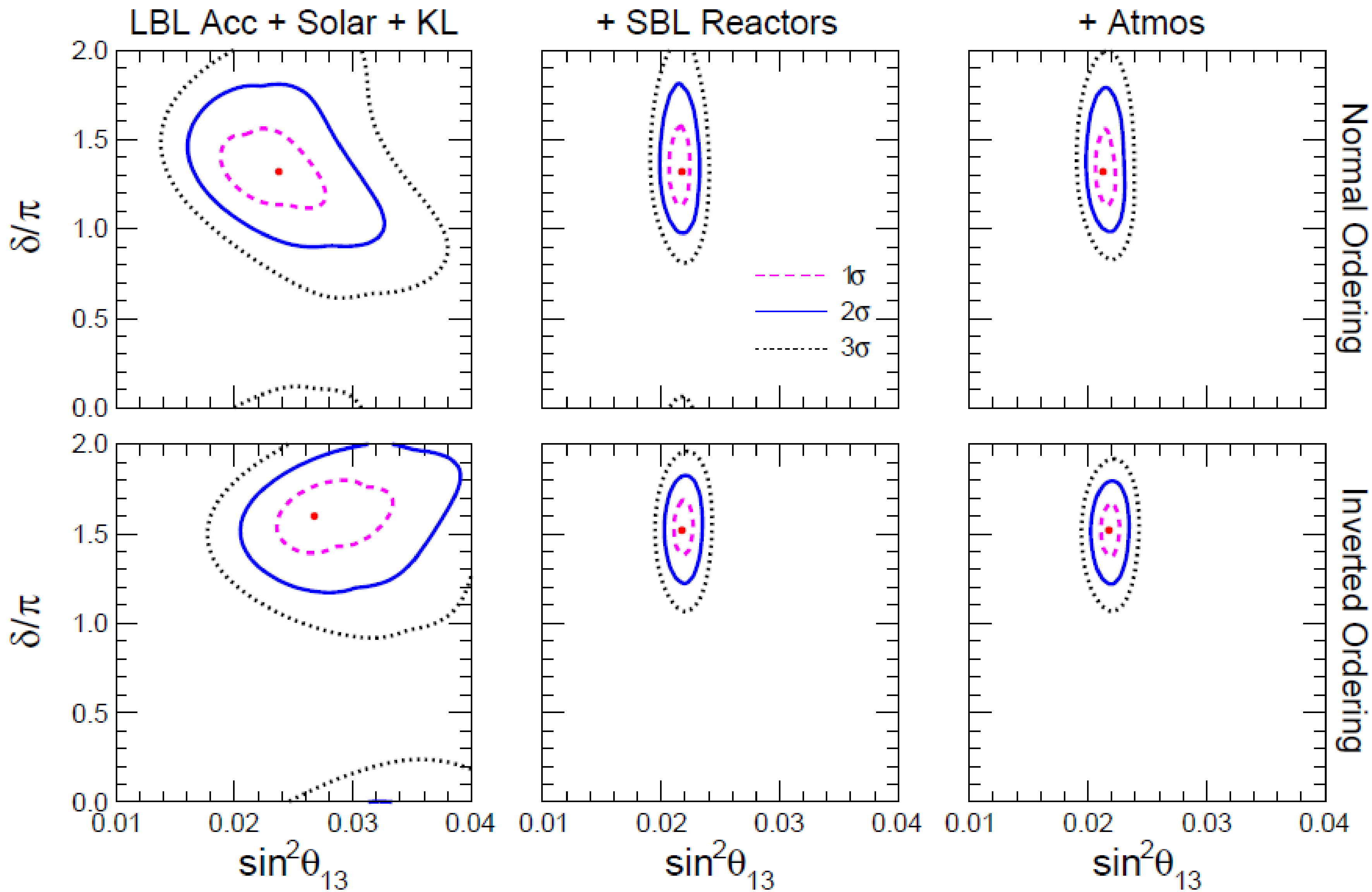
Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1



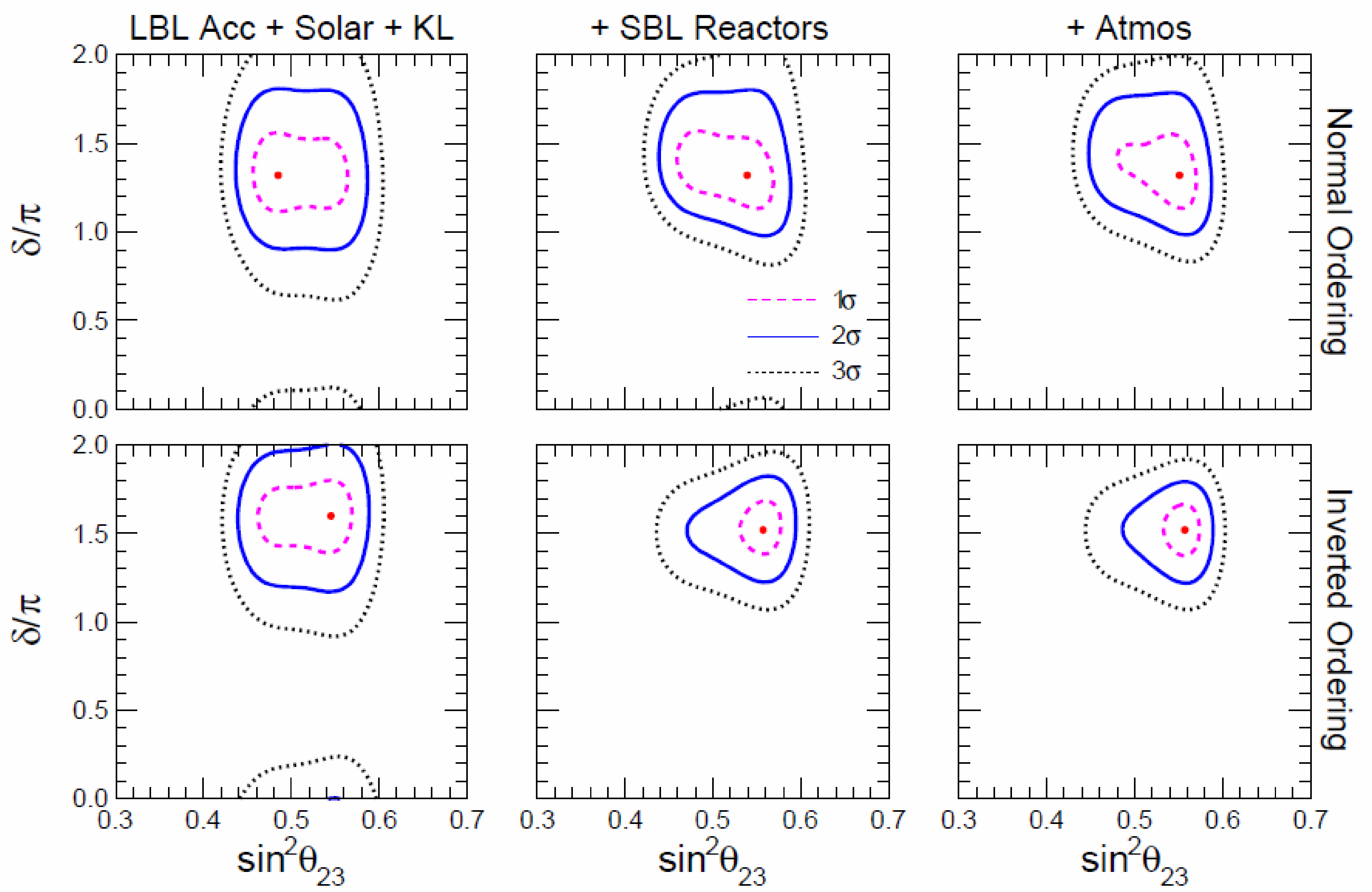
Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1



Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1



Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1



Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1