Neutrino oscillations: phenomenological overview

Neutrinos at the forefront of elementary particle physics and astrophysics, Lyon, 22-24 Oct 2012

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Outline

- Introduction
- Three-flavour analysis based on post-Neutrino2012 data
    - θ_{13} (dependence on reactor fluxes)
    - non-maximality and octant of θ_{23}

  C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T.S., 1209.3023

  www.nu-fit.org

- SBL anomalies and eV-scale sterile neutrinos

  work in prep. with J. Kopp, M. Maltoni, P. Machado

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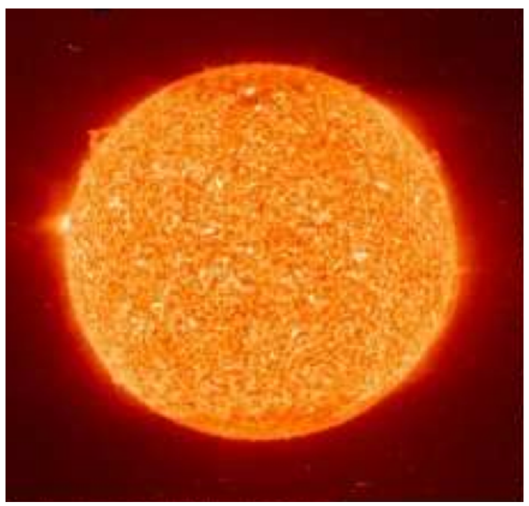
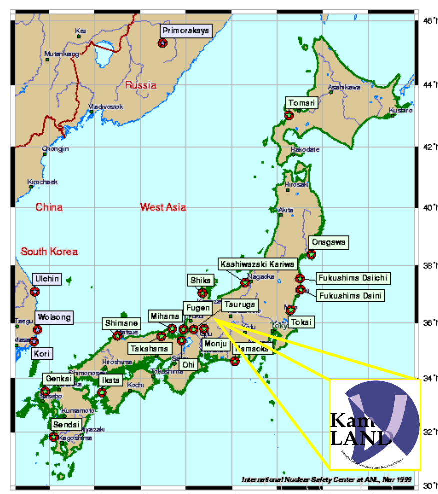
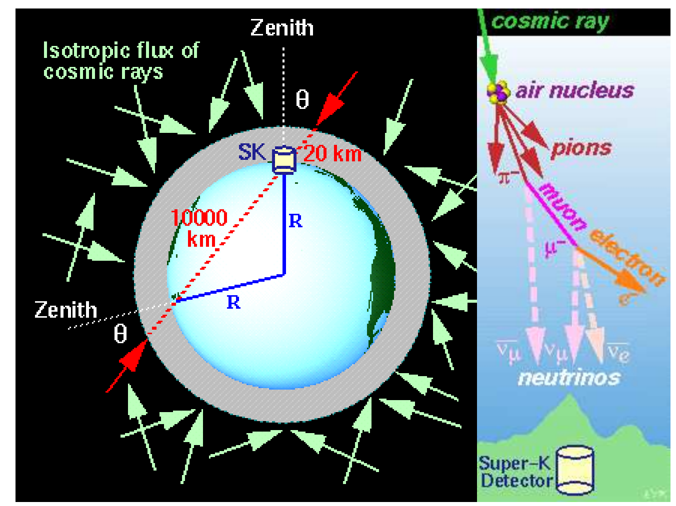
- Better trust high-significant result.

- A. Rubbia (quoting E. Lisi): "Global fits cannot replace real data."

- Global fits do not attempt to replace real data but get out the most of data.

Global data on neutrino oscillations

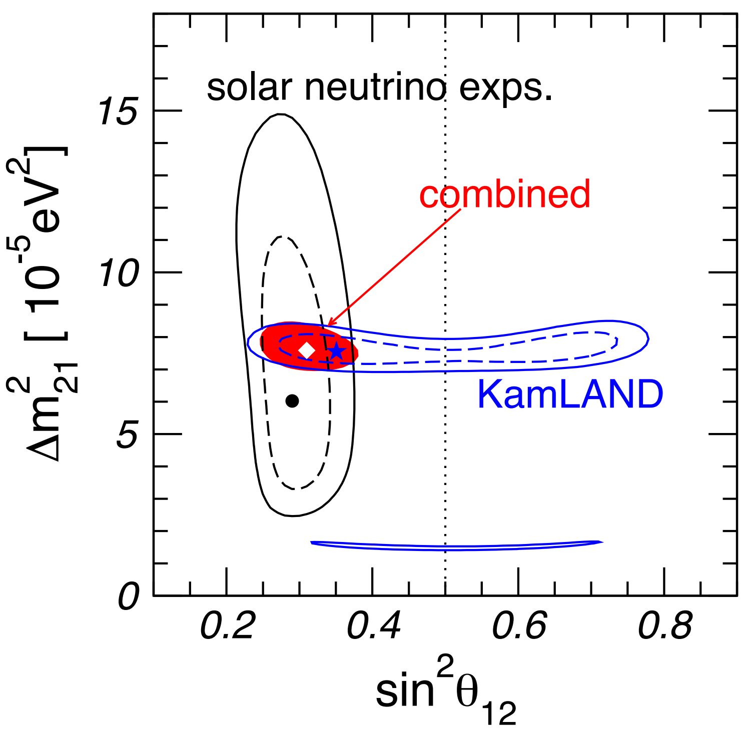
from various neutrino sources and
vastly different energy and distance scales:

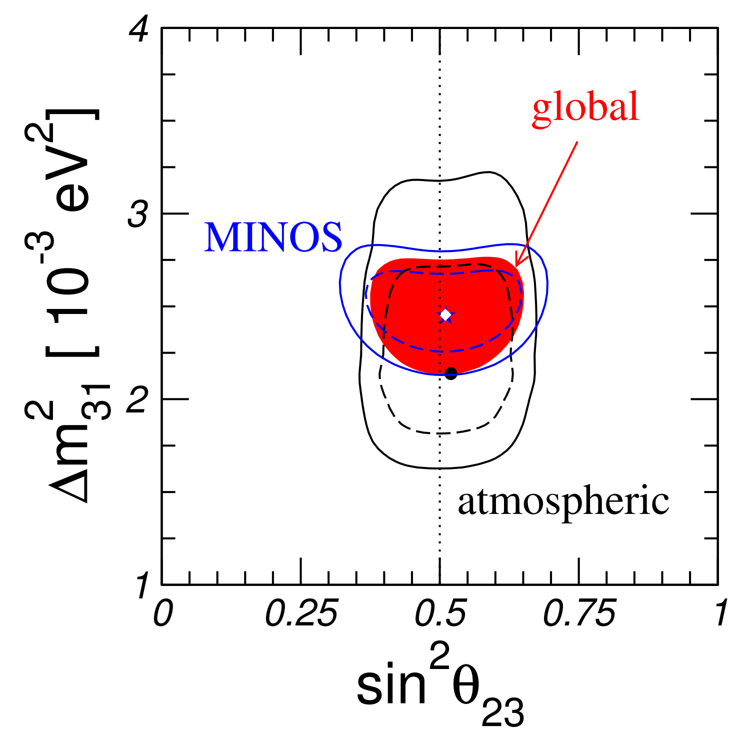
sun	reactors	atmosphere	accelerators
			
Homestake,SAGE,GALLEX SuperK, SNO, Borexino	KamLAND, CHOOZ	SuperKamiokande	K2K, MINOS, T2K

- global data fits nicely with the 3 neutrinos from the SM
- a few "anomalies" at 2-3 σ: LSND, MiniBooNE, reactor anomaly, no LMA MSW up-turn of solar neutrino spectrum

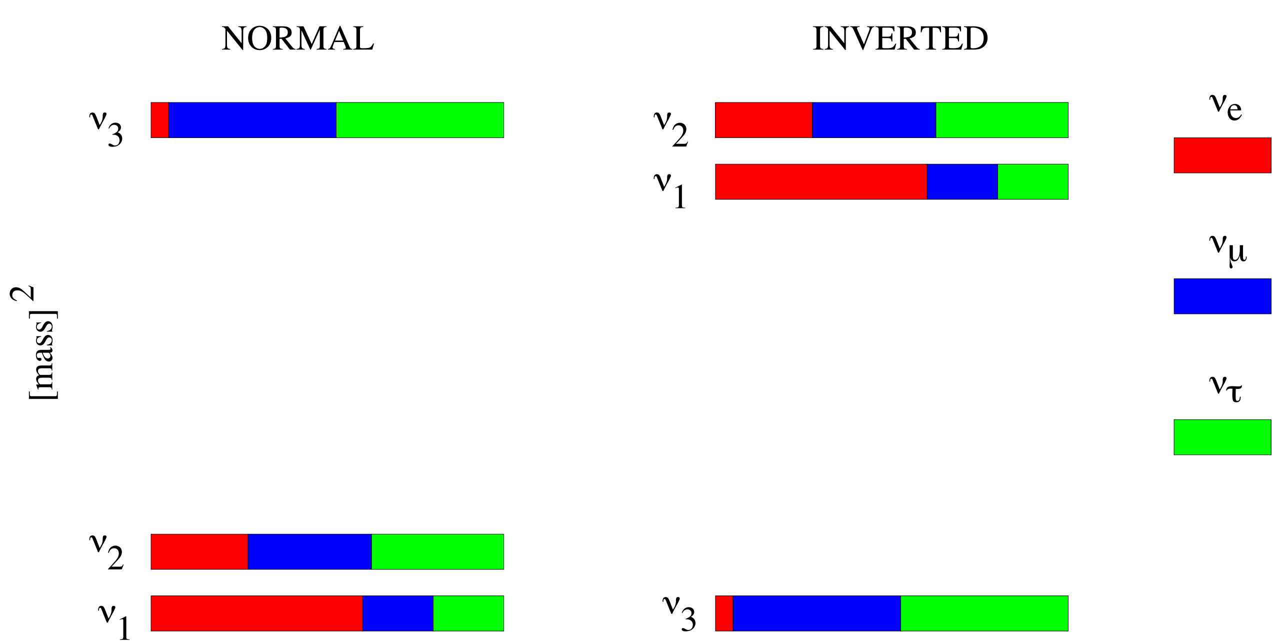
Leading order oscillation picture

Dominant effective 2-flavour oscillation modes:





schematic picture of 3-flavour oscillation parameters:

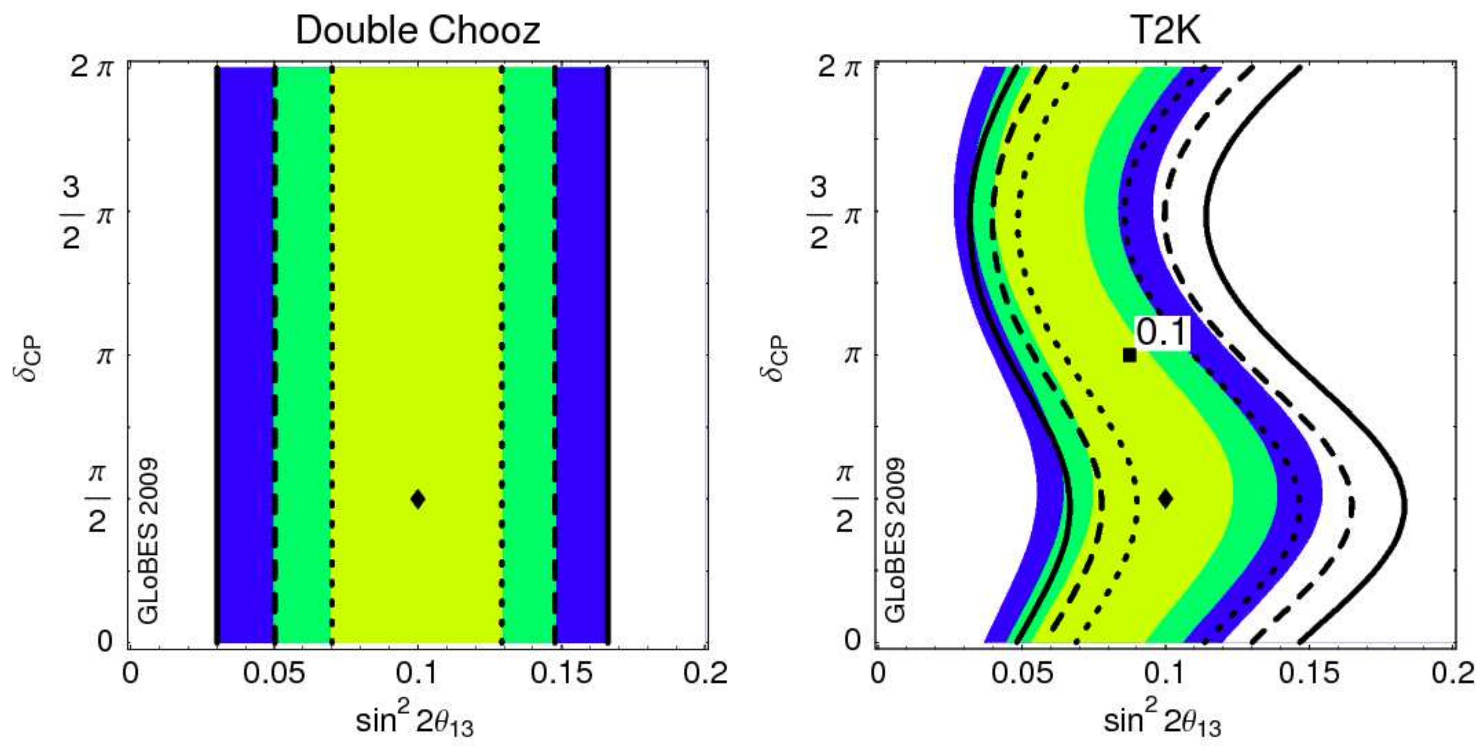


Effects of non-zero θ_{13}

transitions of ν_e involving Δm^2_{31}:

- $\bar{\nu}_e$ disappearance at reactors with $L \simeq 1$ km
  "clean" measurment of θ_{13}: $P \approx 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{31} L/4E)$
- $\nu_\mu \to \nu_e$ transitions at accelerator experiments
  complicated function of all osc parameters (CP phase δ)

simulation: assume $\sin^2 2\theta_{13} = 0.1$, $\delta = \pi/2$



Huber, Lindner, TS, Winter, 09

The θ_{13} revolution see talks by D. Wark, A. Cabrera

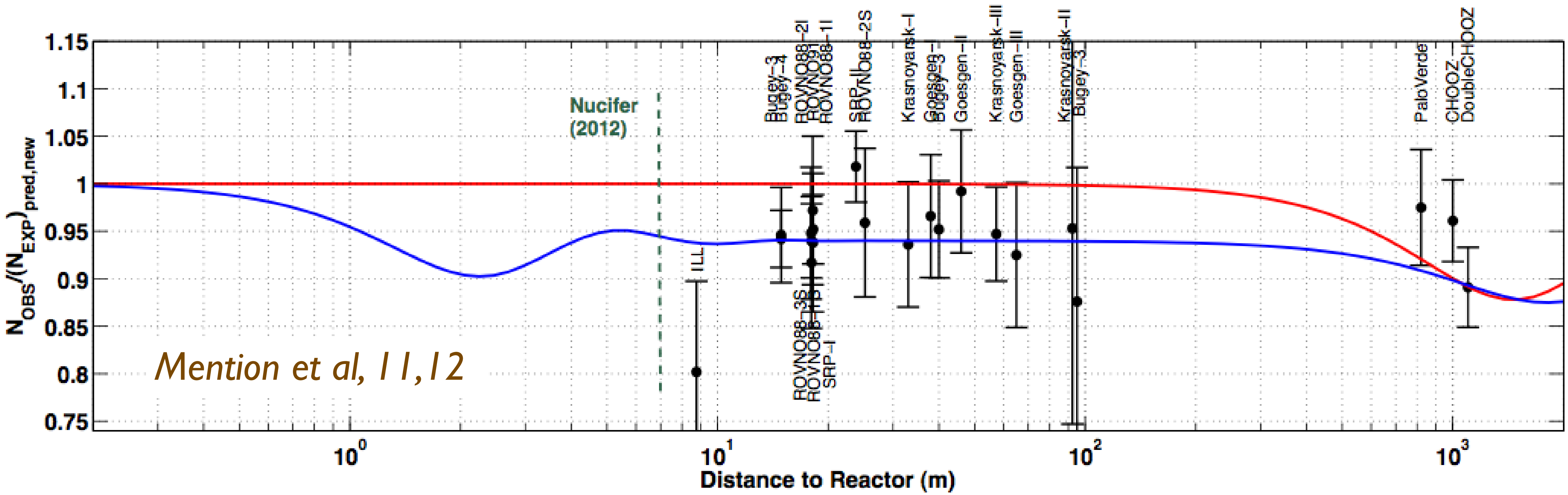
- *Around June 2011: 6 events in T2K (1.5 ± 0.3 bkg for $\theta_{13} = 0$): 2.5σ*
  - *global fits gave >3σ for the first time*
    Fogli et al, 1106.6028; TS, Tortola, Valle 1108.1376
  - *after ICHEP2012:*
    11 events in T2K (3.2 ± 0.4 bkg for $\theta_{13} = 0$): 3.2σ
- *DoubleChooz (11.12), DayaBay (12.03), RENO (12.04)*
- *post-Neutrino2012:*
  $\theta_{13} = 0$ disfavored at $\Delta\chi^2 \approx 100$ in the global fit

The reactor anomaly

- to predict the $\bar{\nu}_e$ flux from nuclear reactors one has to convert the measured e^- spectra from ^{235}U, ^{239}Pu, ^{241}Pu into neutrino spectra
  Schreckenbach et al., 82, 85, 89
- recent improved calculation Mueller et al., 1101.2663 $\sim$ 3% higher fluxes (ab initio calculations + virtual branches for missing part)
- confirmed by independent calculation P. Huber, 1106.0687 (virtual branches)
- increase of predicted number of neutrino-induced events compared to old flux calculations:

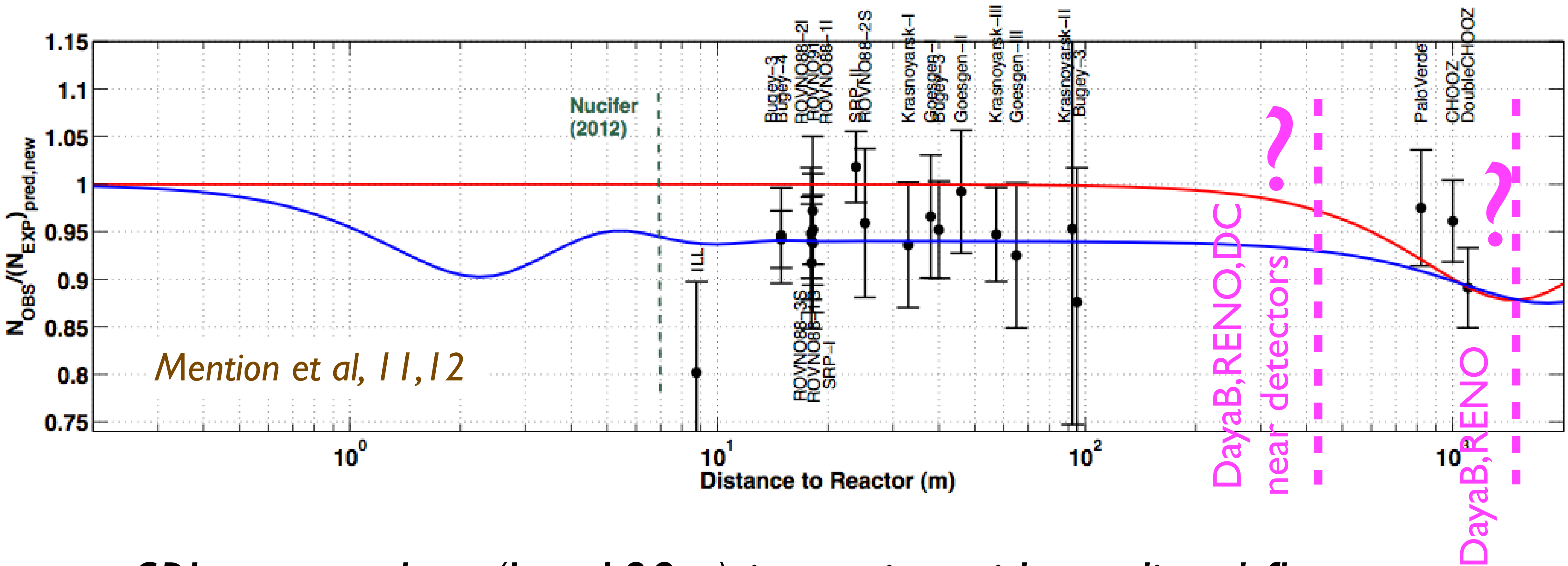
^{235}U	^{239}Pu	^{241}Pu	^{238}U
3.7%	4.2%	4.7%	9.8%

The reactor anomaly



- *SBL reactor data (L < 100m) in tension with predicted flux $f = 0.935 \pm 0.024$ (different from 1 @ 2.7σ)*
- *systematics?*
  - *normalization of ILL electron spectra*
  - *neutron lifetime (use 2012 PDG value)*
- *sterile neutrinos at the eV scale?*

The reactor anomaly



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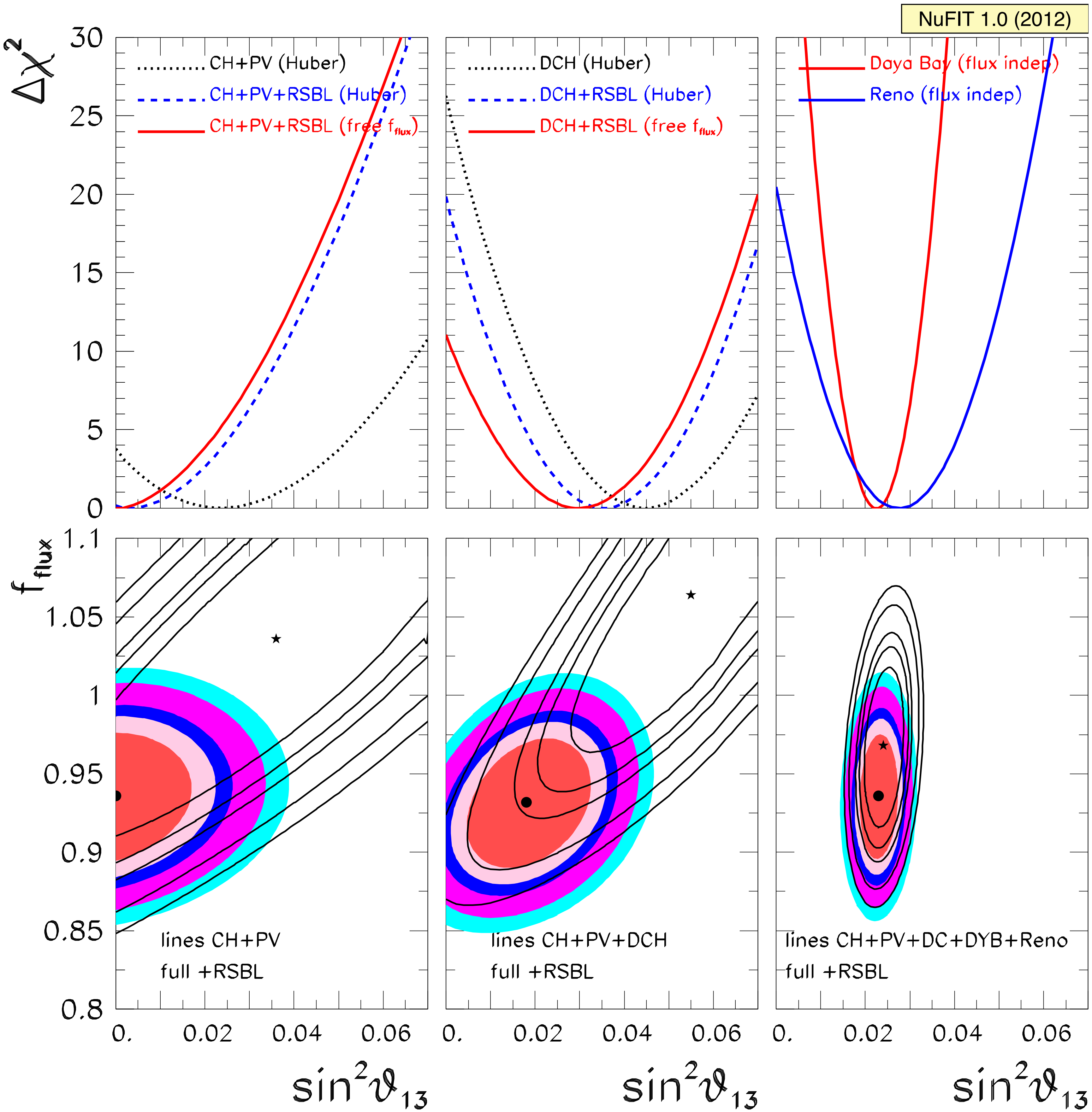
The reactor anomaly and the θ_{13} determination



θ_{13} summary

two extreme assumptions on reactor fluxes:

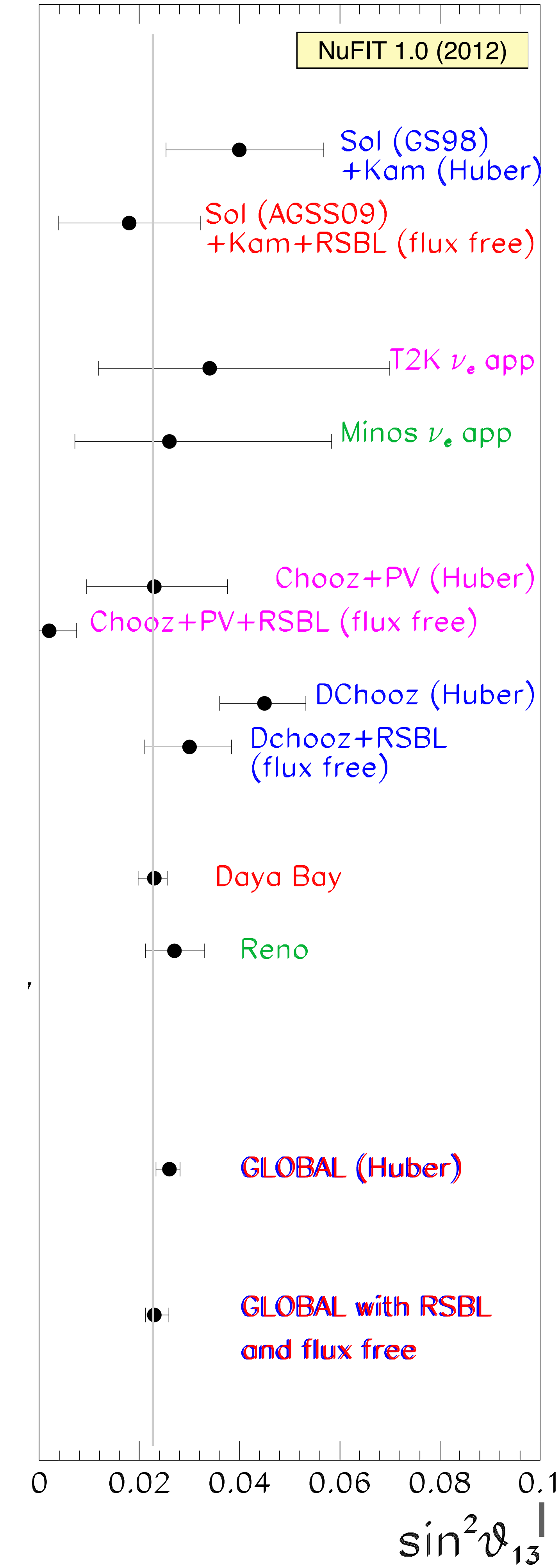
- *use fluxes from Huber, 1106.0687 without SBL reactor data*

$\sin^2\theta_{13} = 0.025 \pm 0.0023 \quad \theta_{13} = (9.2^{+0.42}_{-0.45})^\circ \quad \sin^2 2\theta_{13} = 0.099 \pm 0.009$

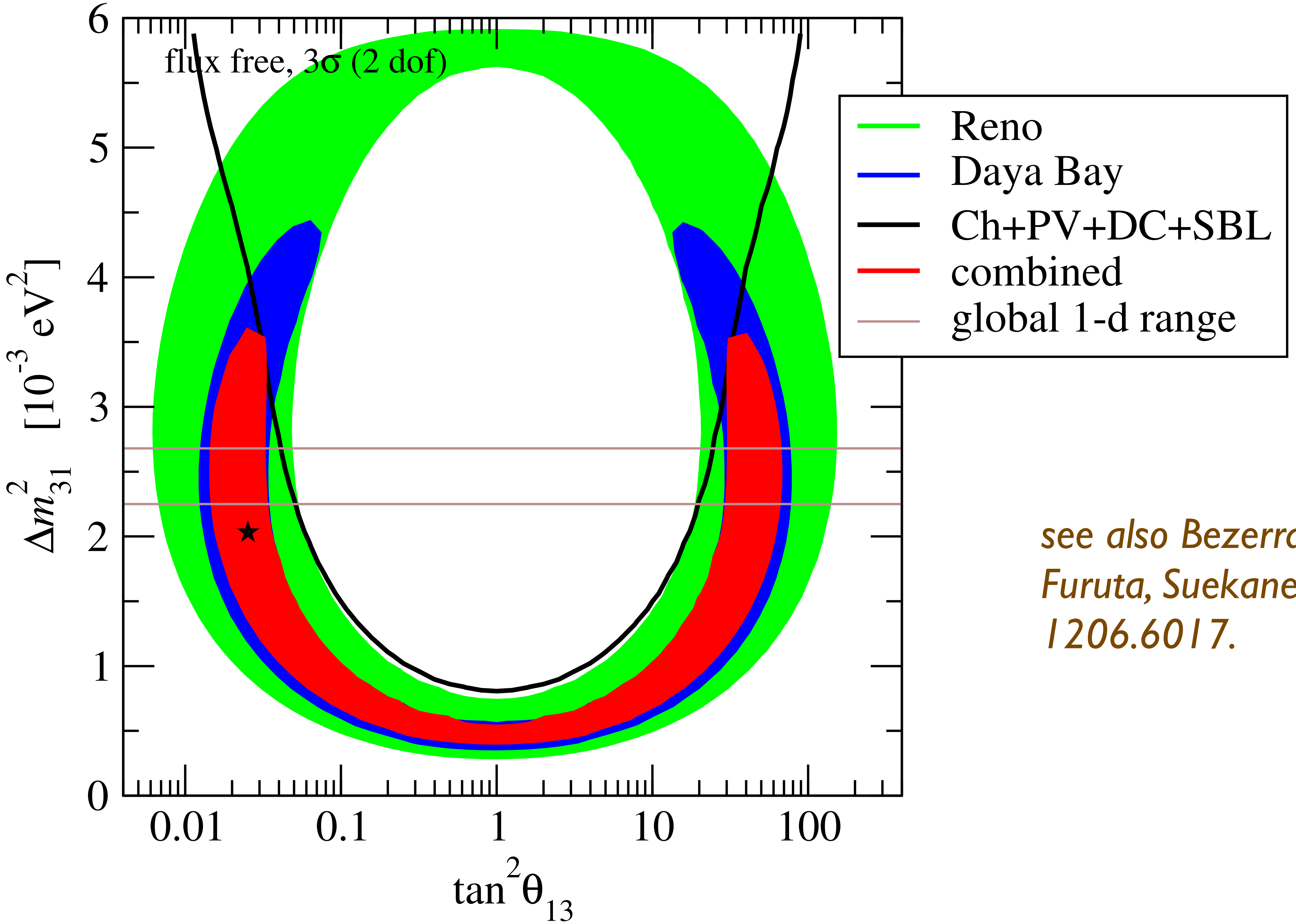
- *leave react flux free and include SBL data*

$\sin^2\theta_{13} = 0.023 \pm 0.0023 \quad \theta_{13} = (8.6^{+0.44}_{-0.46})^\circ \quad \sin^2 2\theta_{13} = 0.088 \pm 0.009$

- *affect global fit result at the 1σ level*
- *dependence on solar model is not visible in the global fit*
- *$\theta_{13} = 0$ disfavored at $\Delta\chi^2 \approx 100$ in global fit!*



Measuring $\Delta m^2{}_{31}$ with reactors



see also Bezerra, Furuta, Suekane, 1206.6017.

will improve with spectral data from DayaBay / RENO

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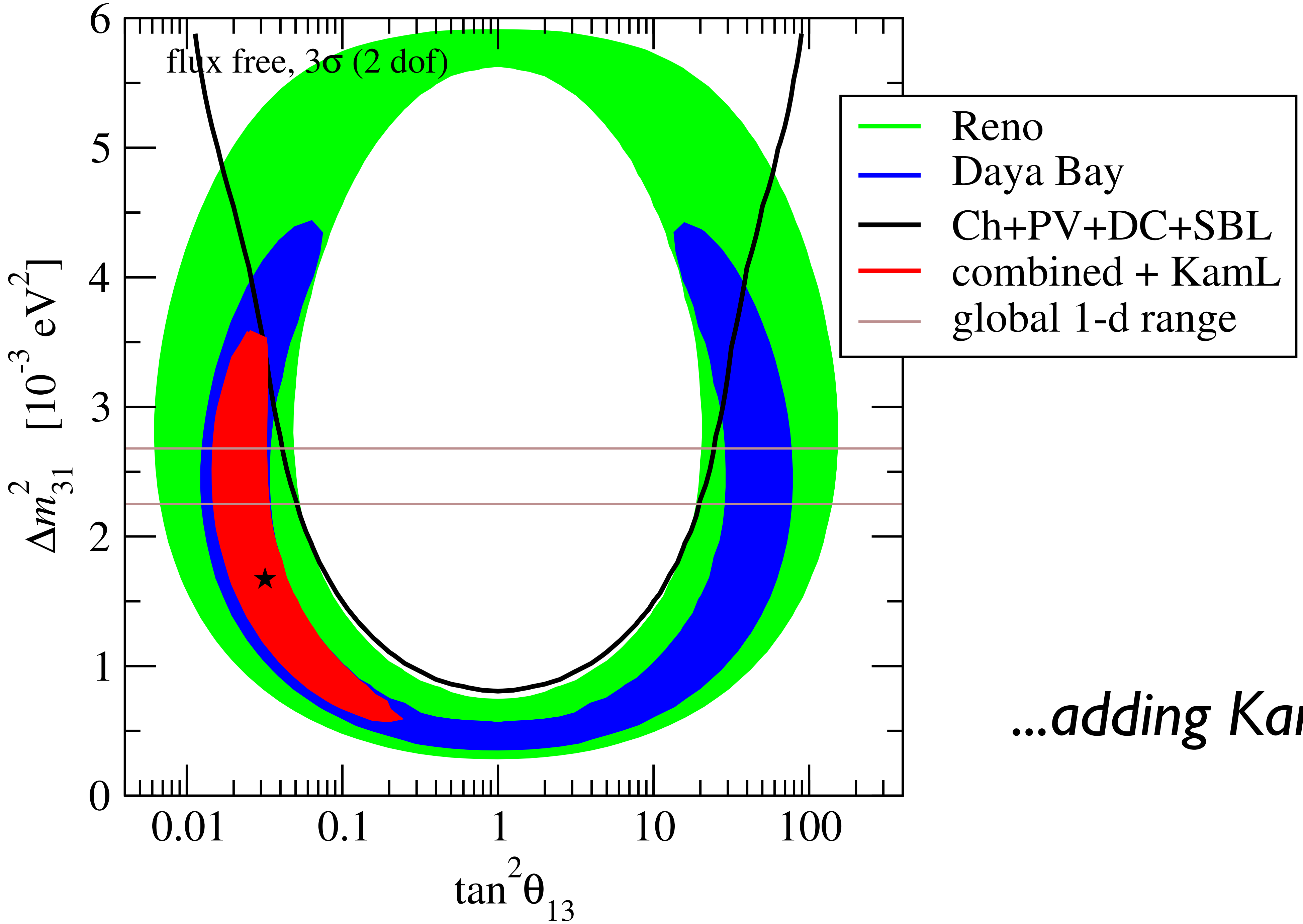
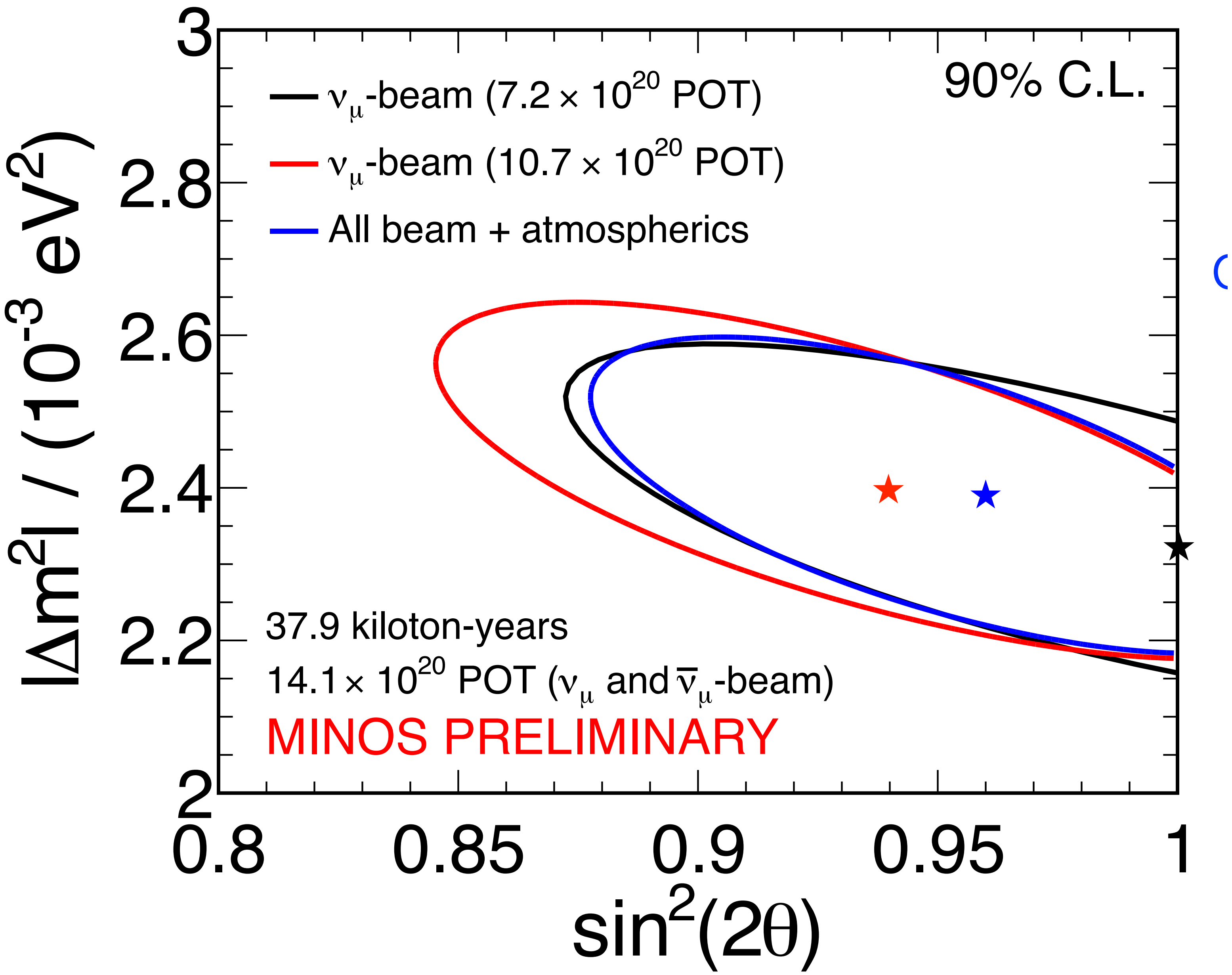


...adding KamLAND

will improve with spectral data from DayaBay / RENO

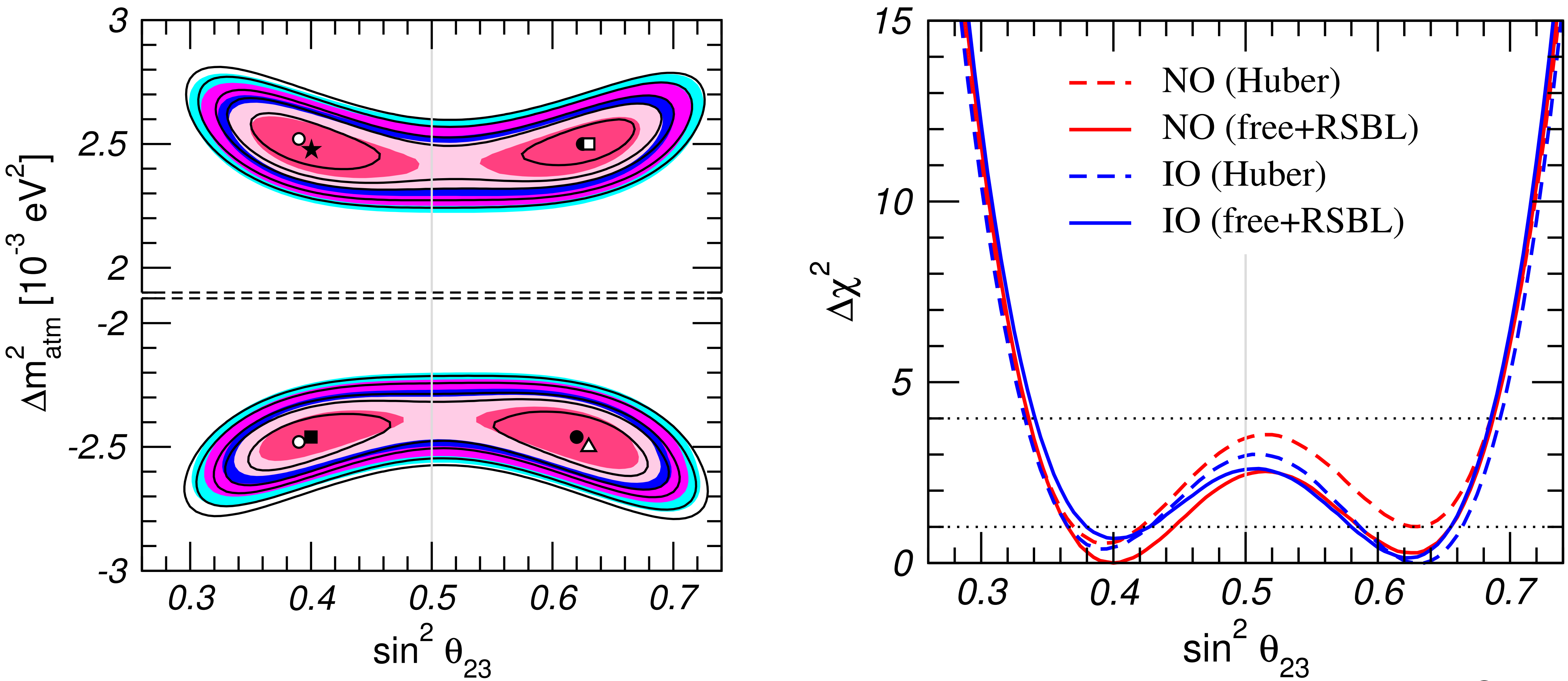
On non-maximal 23 mixing



Nichol (MINOS), talk at Neutrino2012

On non-maximal 23 mixing

global data without atmospheric (MINOS and T2K disappearance most important)



degeneracy between the two θ_{23} octants

$\sin^2\theta_{23} \approx 0.40$
$\sin^2\theta_{23} \approx 0.62$

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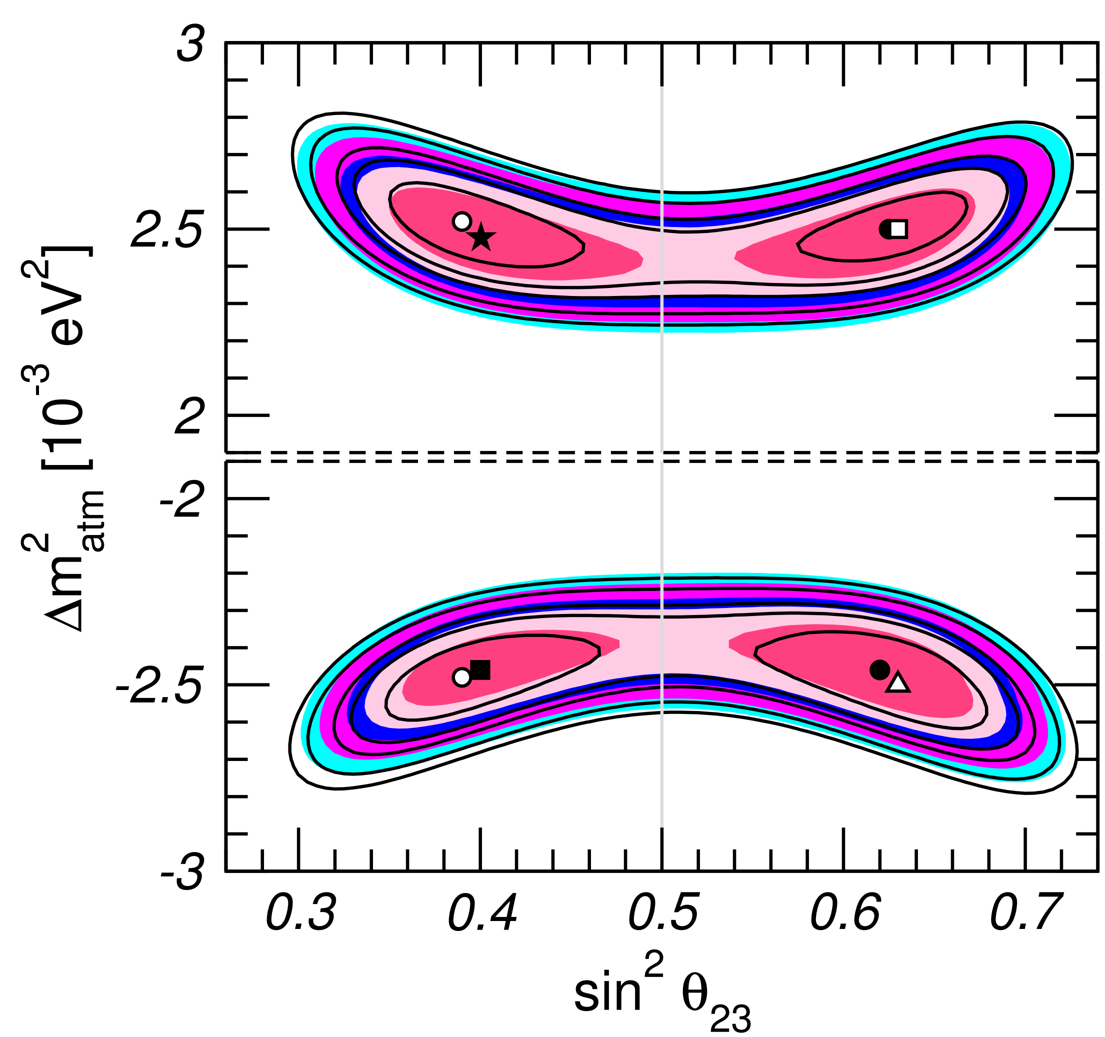
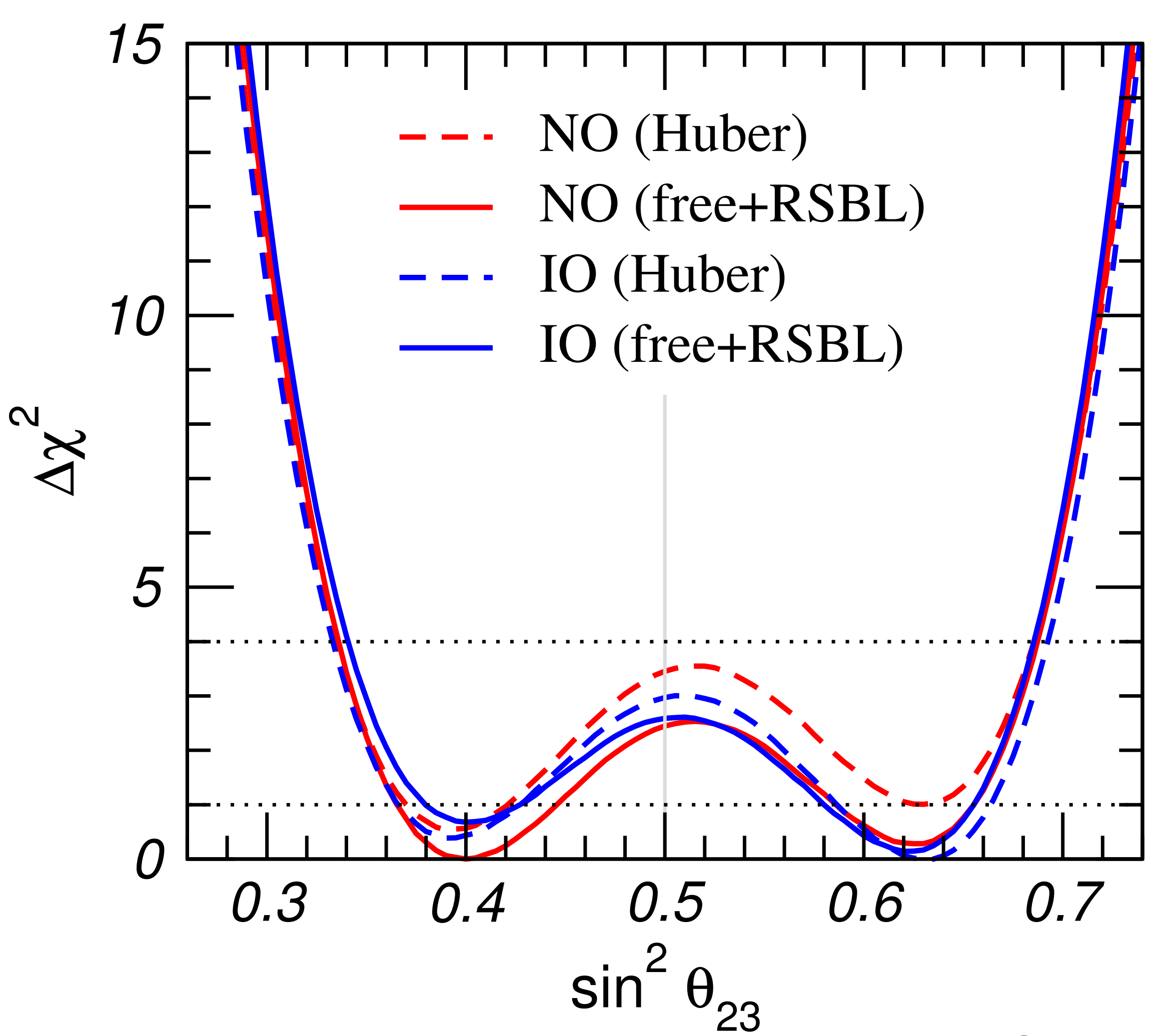




degeneracy between the two θ_{23} octants

$\sin^2\theta_{23} \approx 0.40$
$\sin^2\theta_{23} \approx 0.62$

neglecting Δm^2_{21}: $P_{\mu\mu} \approx 1 - 4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)\sin^2\frac{\Delta m^2_{\rm atm}L}{4E} \quad \Rightarrow \quad \sin^2\theta_{23} = \frac{|U_{\mu 3}|^2}{\cos^2\theta_{13}}$

slight shift to larger values of $\sin^2\theta_{23}$

Octant degeneracy and LBL appearance

Fogli, Lisi, hep-ph/9604415

$$P_{\mu e} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(1-A)\Delta}{(1-A)^2}$$
$$+ \sin 2\theta_{13}\, \hat\alpha\, \sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A}\frac{\sin A\Delta}{A}\cos(\Delta+\delta_{CP})$$
$$+ \hat\alpha^2 \cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2}$$

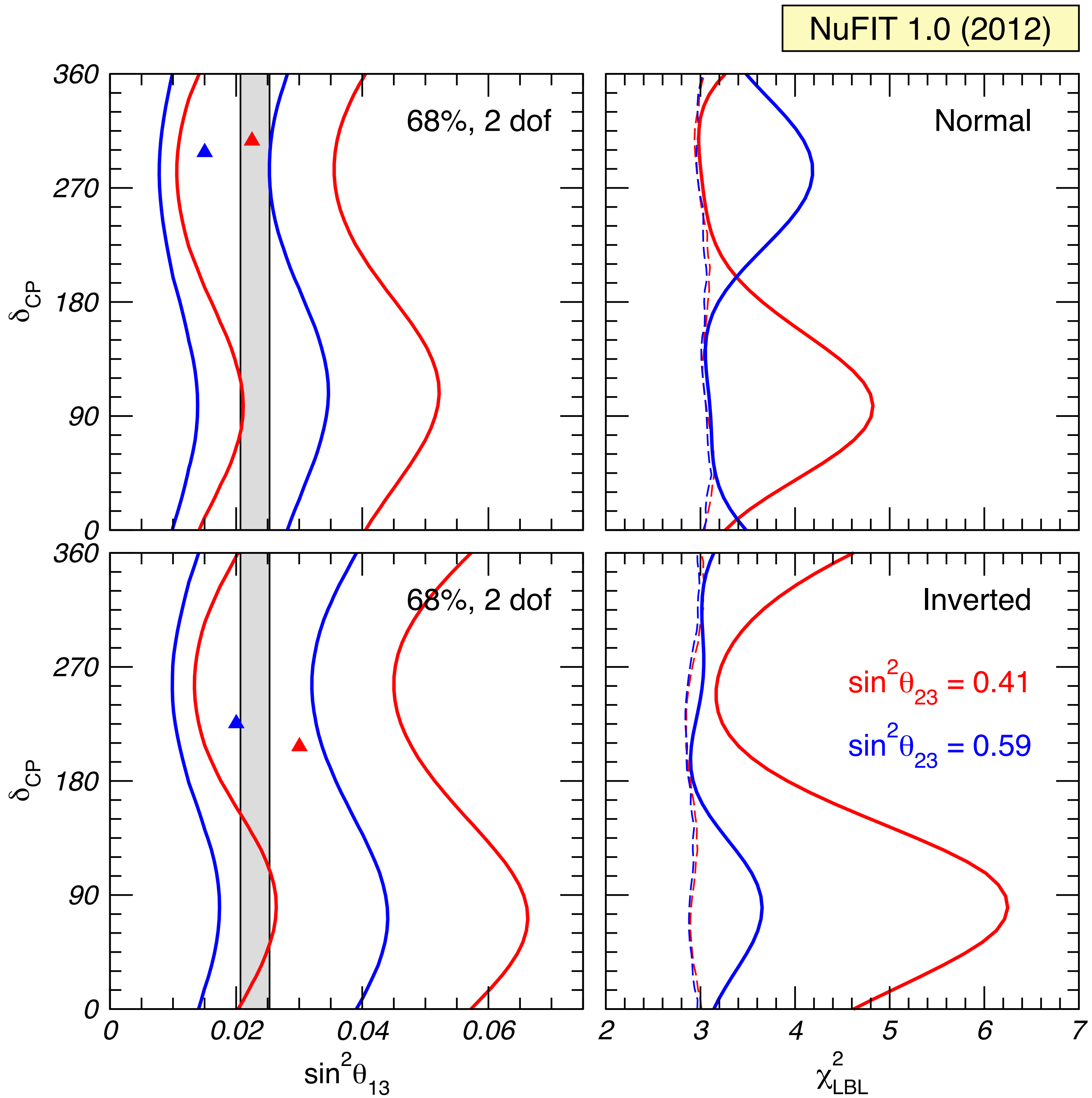
with

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}, \quad \hat\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}\sin 2\theta_{12}, \quad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}}$$

- *for large θ_{13} the leading term depends on octant*
- *beam+reactor combination may be sensitive to octant*

Minakata et al. hep-ph/0211111; McConnel, Shaevitz, hep-ex/0409028

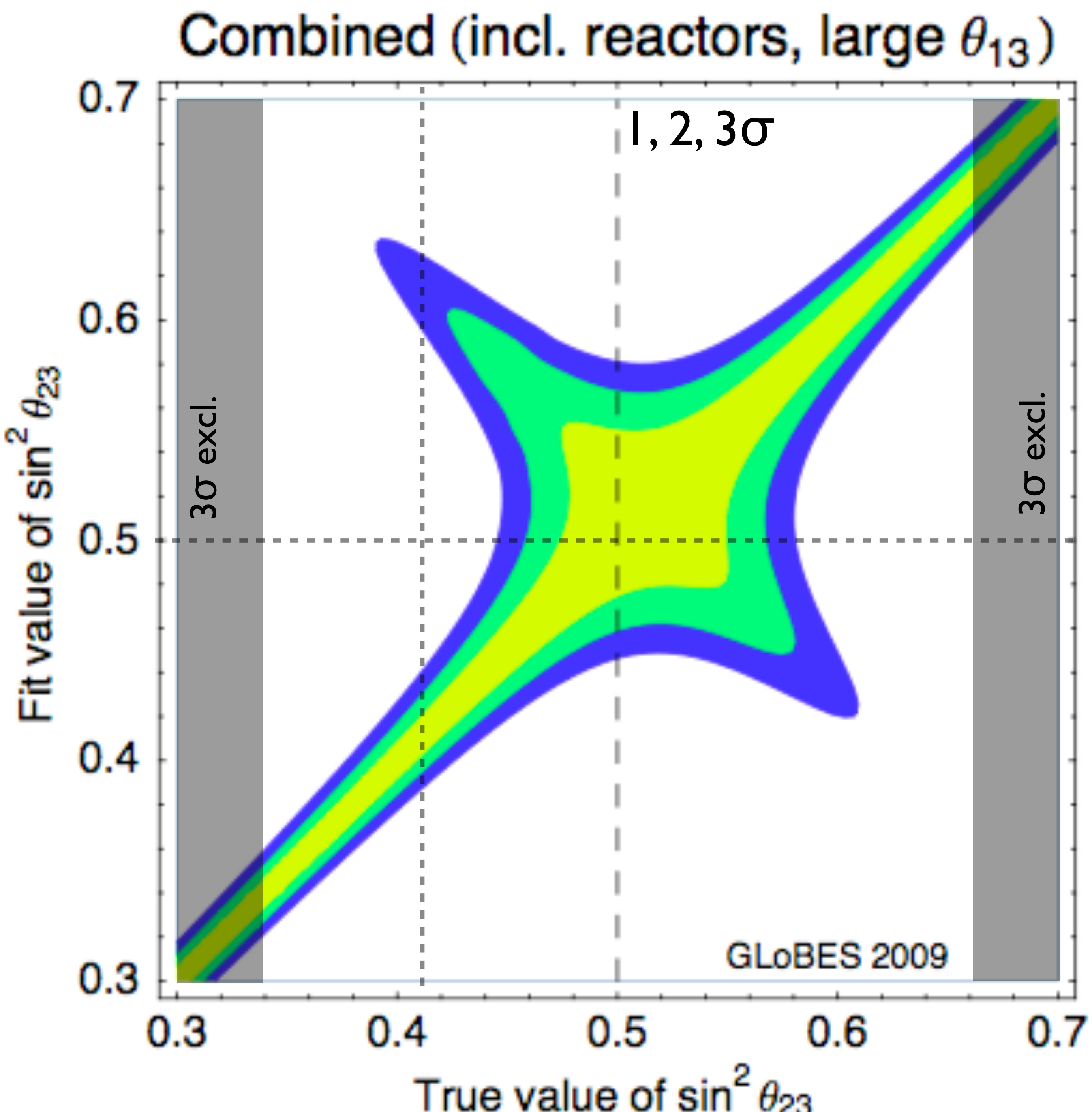
Octant degeneracy and LBL appearance



present data from LBL appearance versus reactor cannot discriminate between the octants

Global fit ~2020 - θ_{23} octant

final exposure of T2K, NOvA, DayaBay combined



$\sin^2 2\theta_{13} = 0.1$
$\delta = 0$

Huber, Lindner, TS, Winter, 0907.1896

3-flavor effects in atmospheric neutrinos

excess in electron-like events:

$$\frac{N_e}{N_e^0} - 1 \simeq (r\, s_{23}^2 - 1)\, P_{2\nu}(\Delta m_{31}^2, \theta_{13}) \qquad \theta_{13}\text{-effects}$$

$$+ \; (r\, c_{23}^2 - 1)\, P_{2\nu}(\Delta m_{21}^2, \theta_{12}) \qquad \Delta m_{21}^2\text{-effects}$$

$$- \; 2 s_{13} s_{23} c_{23}\, r\, \mathrm{Re}(A_{ee}^* A_{\mu e}) \qquad \text{interference: } \delta_{\mathrm{CP}}$$

$$r = r(E_\nu) \equiv \frac{F_\mu^0(E_\nu)}{F_e^0(E_\nu)}$$

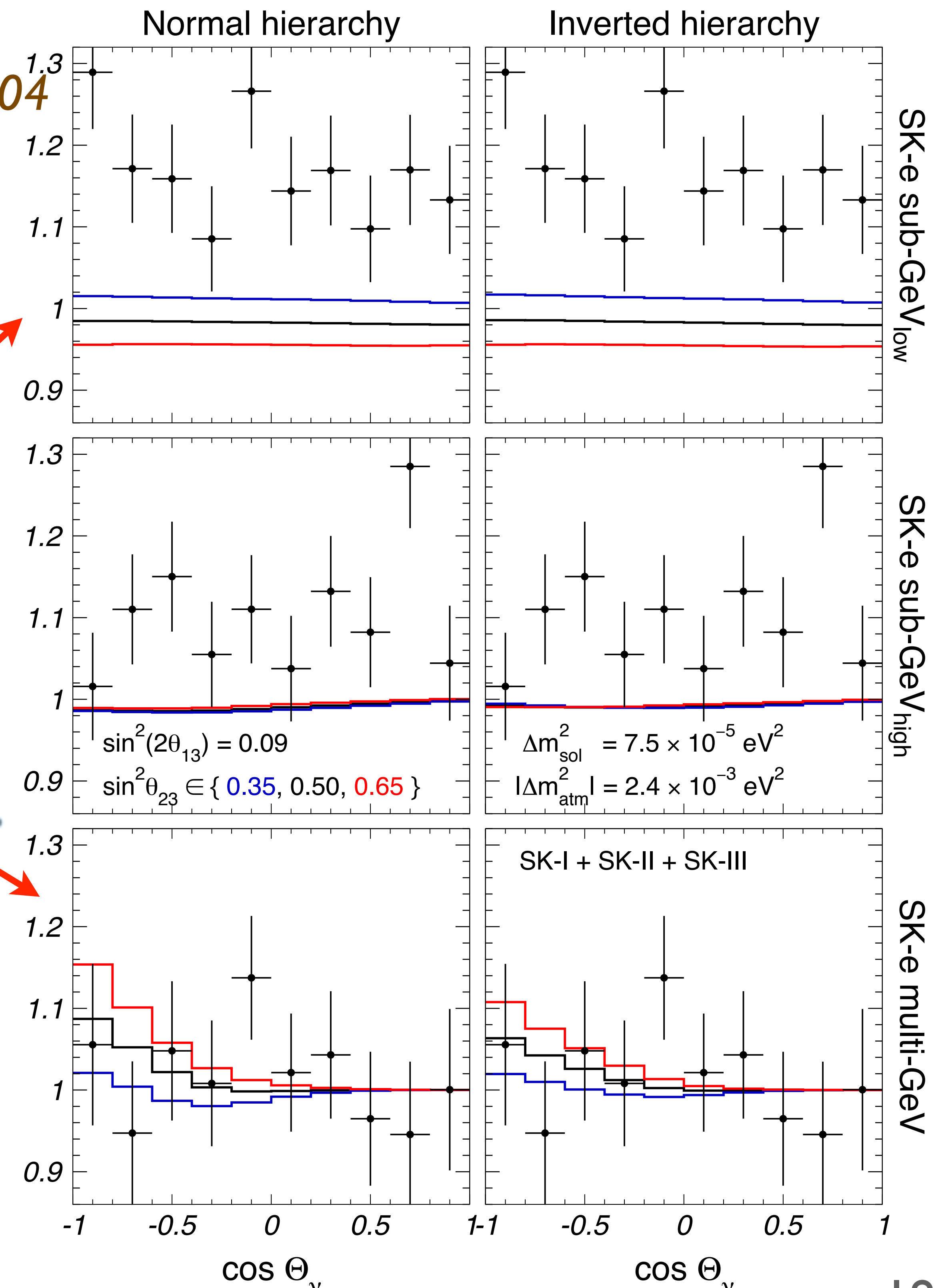
$r \approx 2$ (sub-GeV)

$r \approx 2.6 - 4.5$ (multi-GeV)

3-flavor effects in atmospheric neutrinos

Peres, Smirnov, 99;
Gonzalez-Garcia, Maltoni, Smirnov, 04

SK1-3 data



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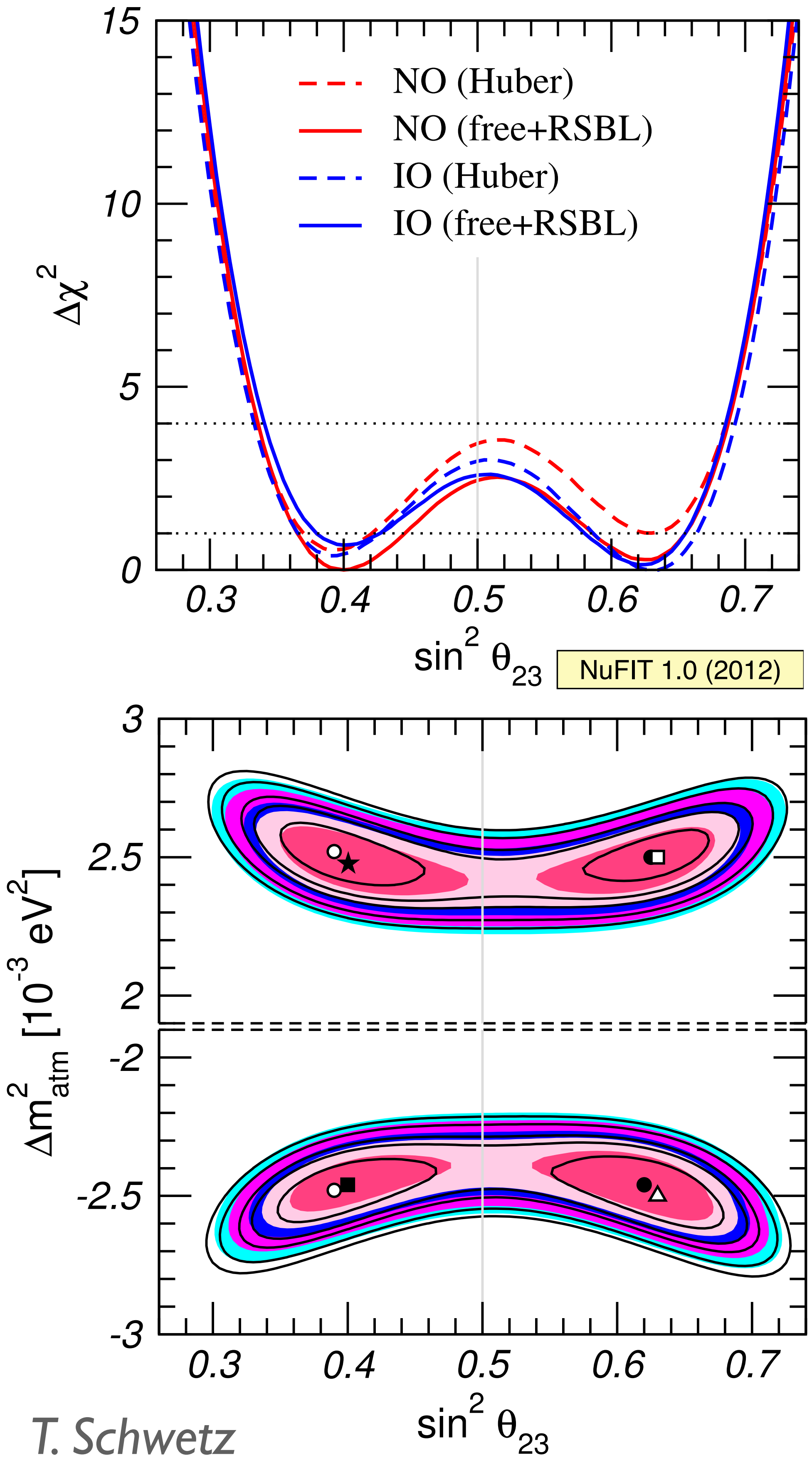
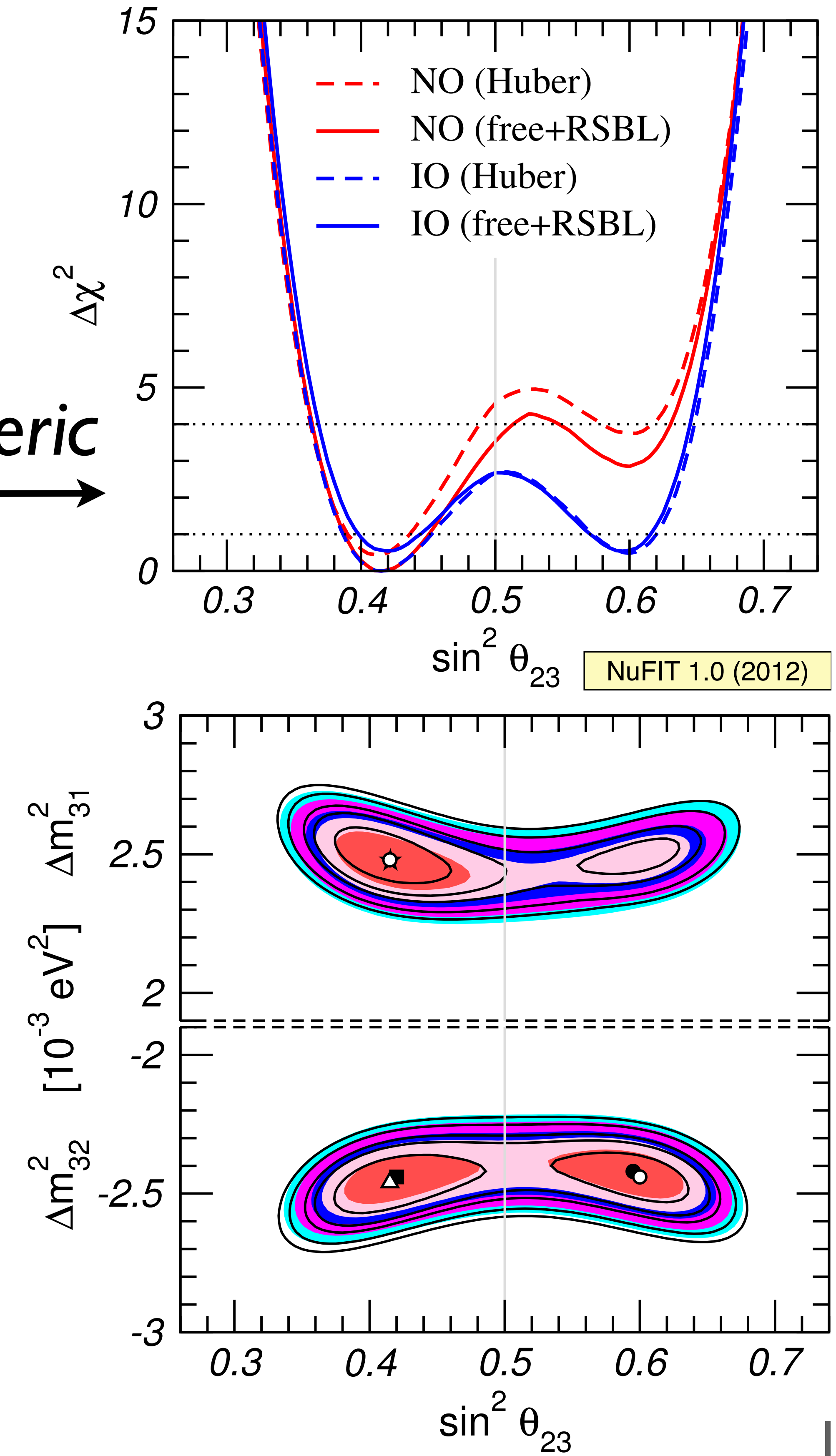
The octant and atmospheric neutrino data

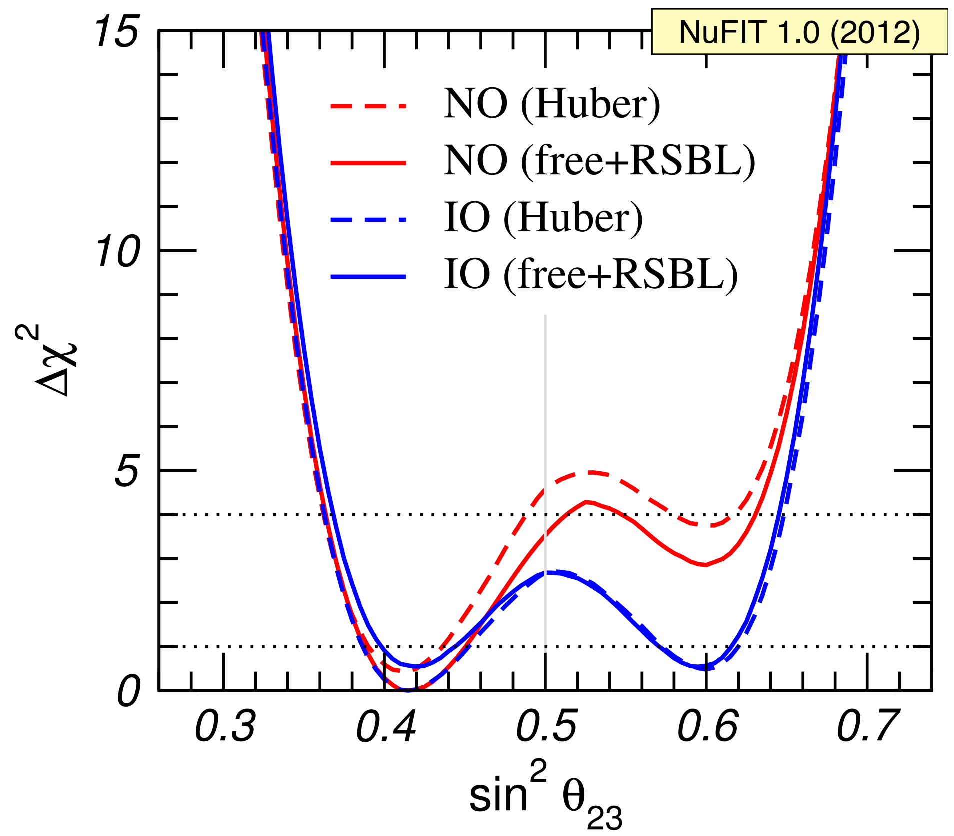


adding atmospheric →



The octant and atmospheric neutrino data

	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$

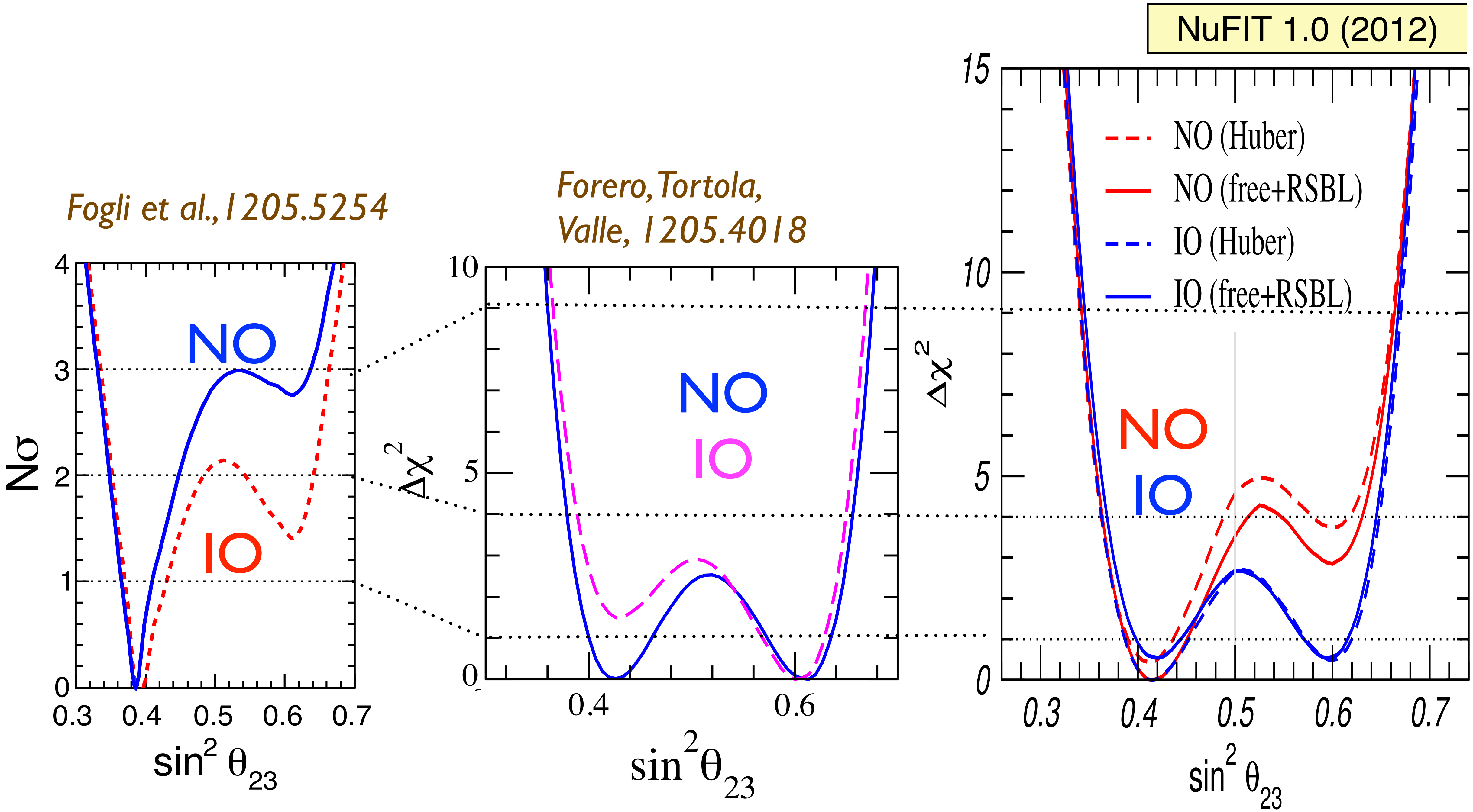


- *preference for non-maximality: 2σ (NO) or 1.5σ (IO)*
- *preference for 1st octant: 1.5σ (NO) or <0.9σ (IO)*

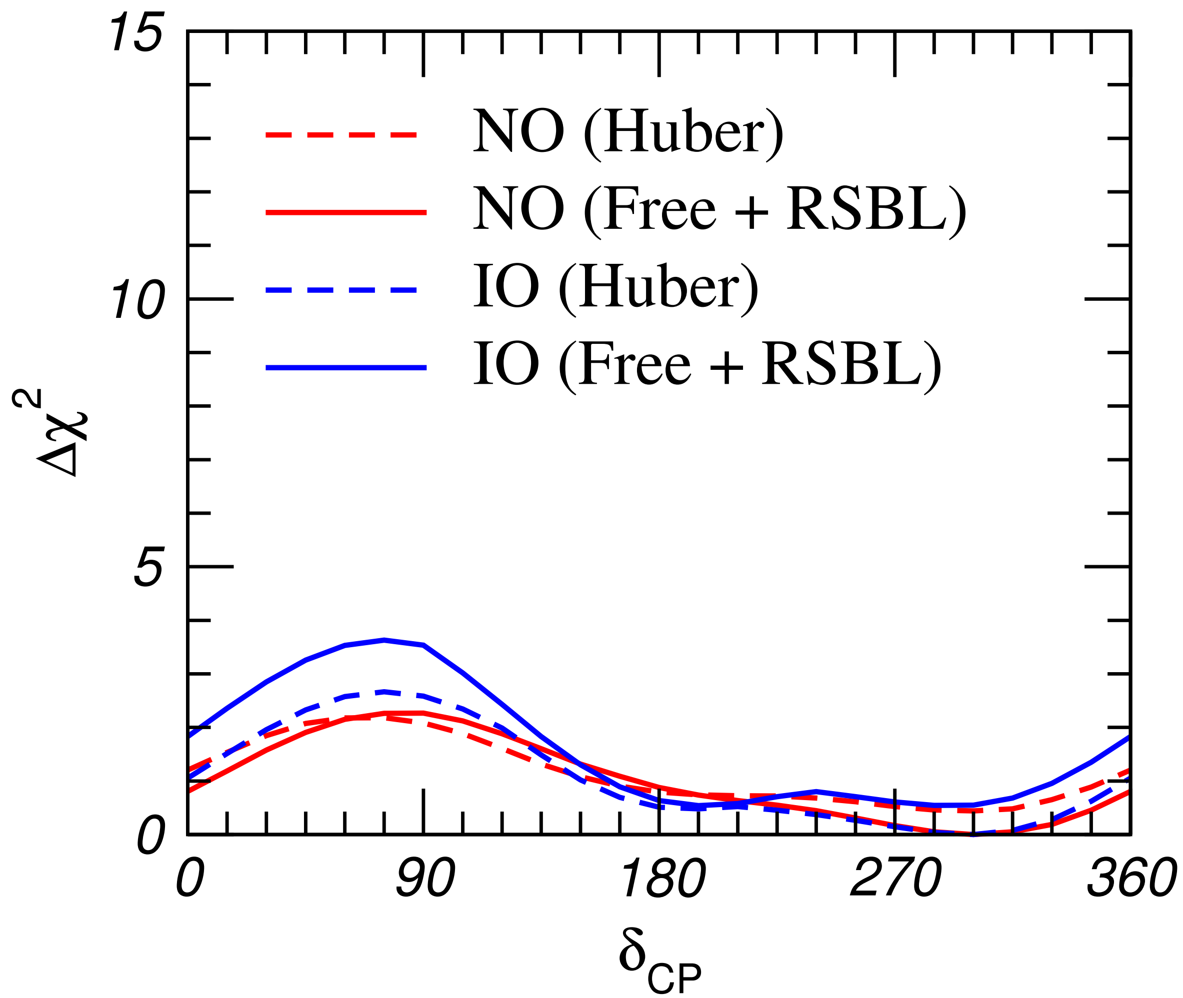
Comparison with other global fits

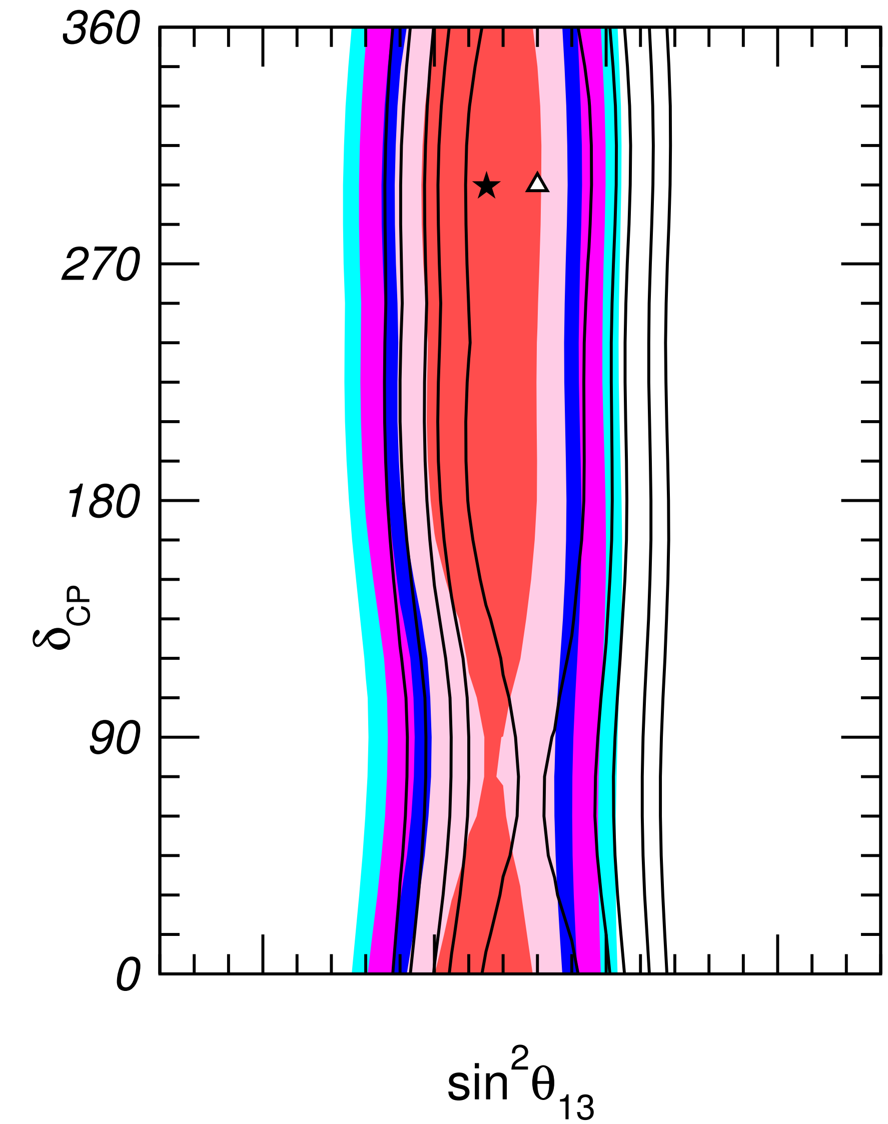
Fogli et al., 1205.5254

Forero, Tortola, Valle, 1205.4018



The CP phase

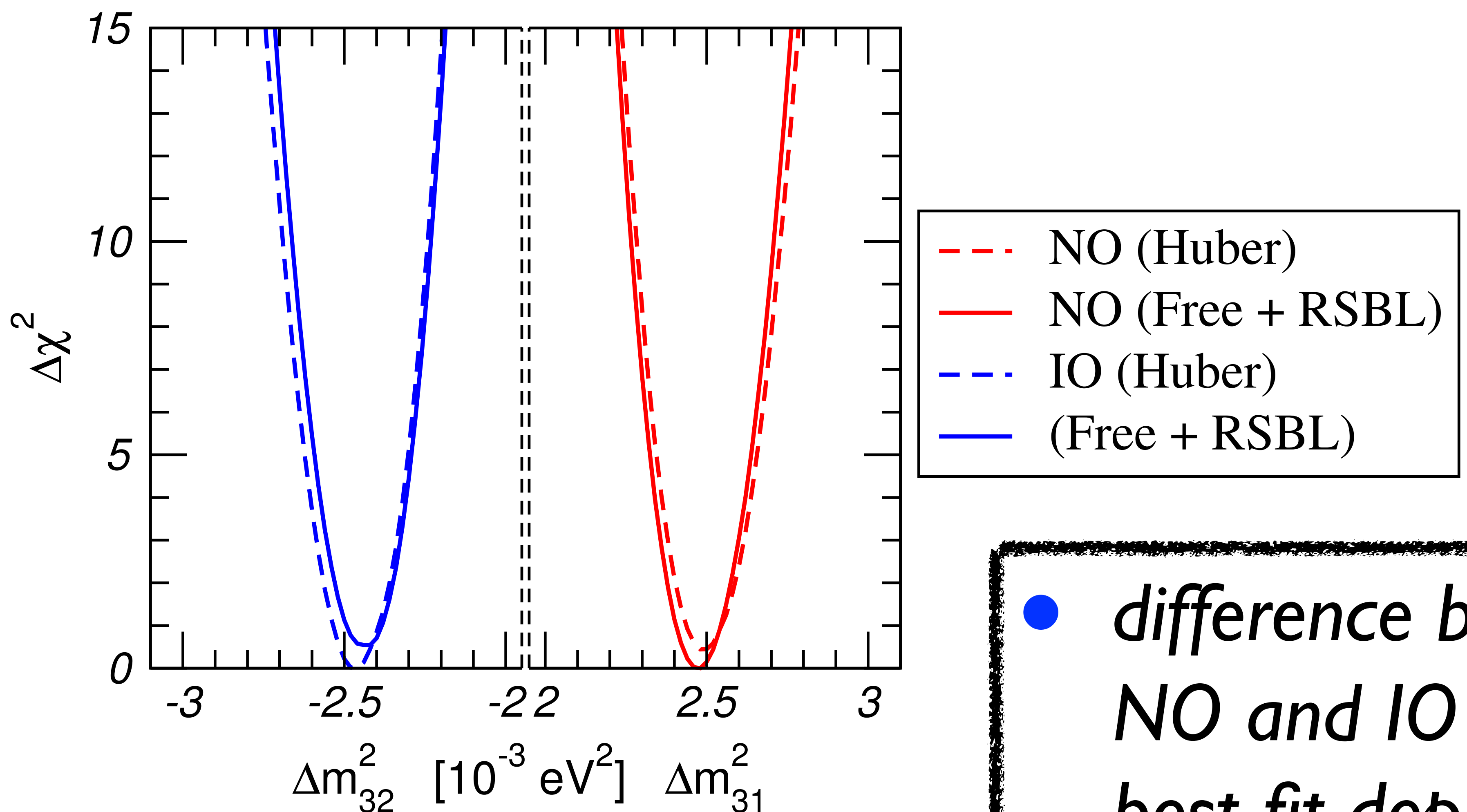




- *"preferred" regions for δ~ 300° at 1σ (everything allowed at 2σ)*

$\Delta m^2{}_{31,32}$ and the mass ordering

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$	$2.49^{+0.055}_{-0.051}$	$2.29 \to 2.71$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.43^{+0.042}_{-0.065}$	$-2.65 \to -2.24$	$-2.47^{+0.073}_{-0.064}$	$-2.68 \to -2.25$



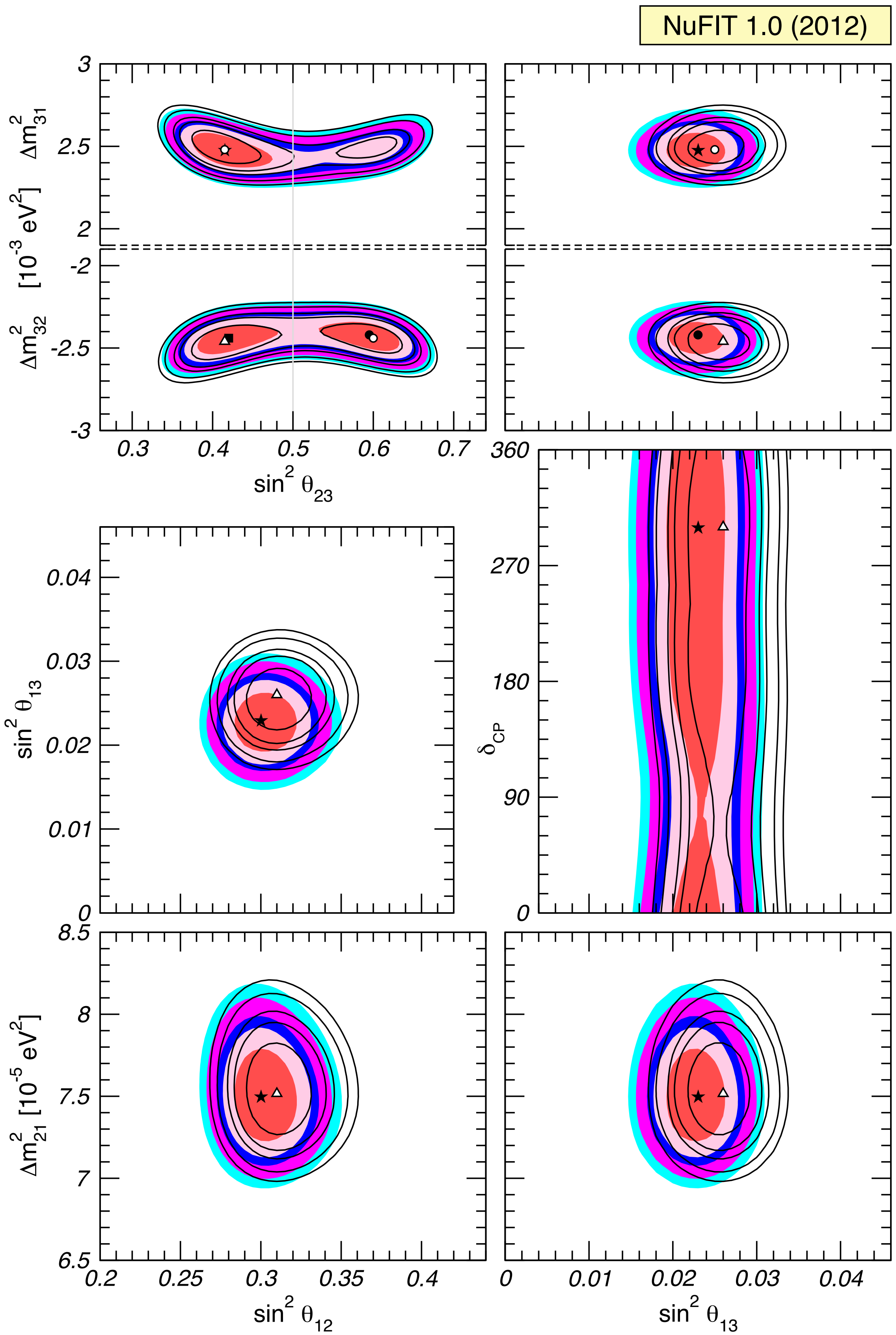
- *difference between NO and IO of $\Delta\chi^2 \approx 0.5$ best fit depends on the assumption of reactor fluxes*

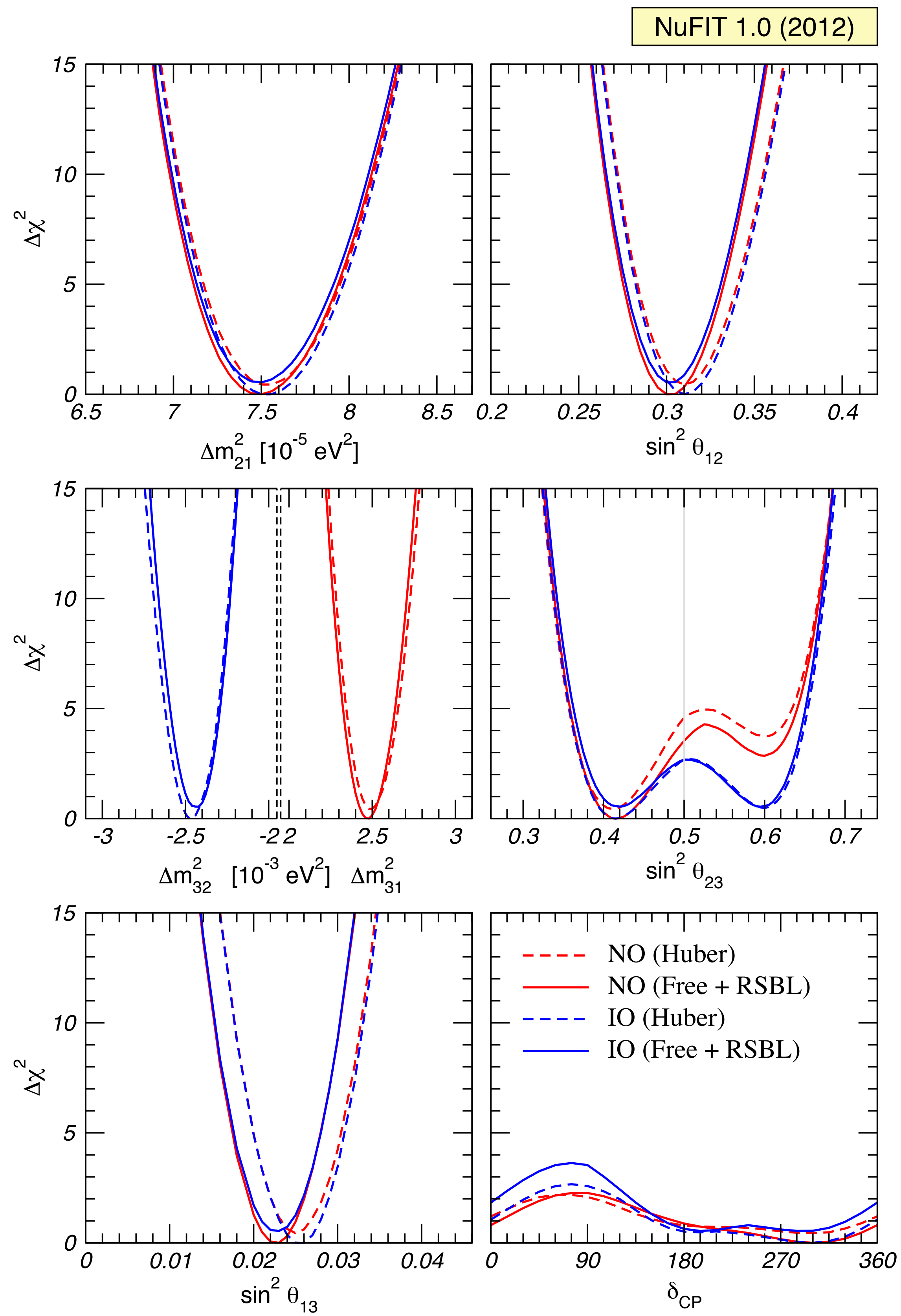
Prospects for mass ordering

Relatively large value of θ_{13} opens exciting possibilities maybe even before experiments like HyperK, LAGUNA/LBNO, LBNE

- *atmospheric neutrinos in PINGU*
  Akhmedov, Razzaque, Smirnov, 1205.7071
  talk by Ken Clark
- *large-scale reactor experiment at ~50 km*
  e.g. Petcov, Piai, hep-ph/0112074
  DayaBay-II related studies
- *atmospheric neutrinos in magnetized detector*
  INO project; Blennow, TS, 1203.3388
- *Supernova?* *talk by Pasquale Serpico tomorrow*

Three-neutrino summary





NuFIT 1.0 (2012)

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \rightarrow 0.34$	0.31 ± 0.013	$0.27 \rightarrow 0.35$
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \rightarrow 36$	33.9 ± 0.8	$31 \rightarrow 36$
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \rightarrow 0.67$	$0.41^{+0.030}_{-0.029} \oplus 0.60^{+0.020}_{-0.026}$	$0.34 \rightarrow 0.67$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \rightarrow 55$	$40.1^{+2.1}_{-1.7} \oplus 50.7^{+1.1}_{-1.5}$	$36 \rightarrow 55$
$\sin^2\theta_{13}$	0.023 ± 0.0023	$0.016 \rightarrow 0.030$	0.025 ± 0.0023	$0.018 \rightarrow 0.033$
$\theta_{13}/^\circ$	$8.6^{+0.44}_{-0.46}$	$7.2 \rightarrow 9.5$	$9.2^{+0.42}_{-0.45}$	$7.7 \rightarrow 10.$
$\delta_{\rm CP}/^\circ$	300^{+66}_{-138}	$0 \rightarrow 360$	298^{+59}_{-145}	$0 \rightarrow 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	7.50 ± 0.185	$7.00 \rightarrow 8.09$	$7.50^{+0.205}_{-0.160}$	$7.04 \rightarrow 8.12$
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C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T.S., 1209.3023

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www.nu-fit.org

- *Continously updated results at www.nu-fit.org*
- *provided by the NuFIT group:*
  C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T.S.

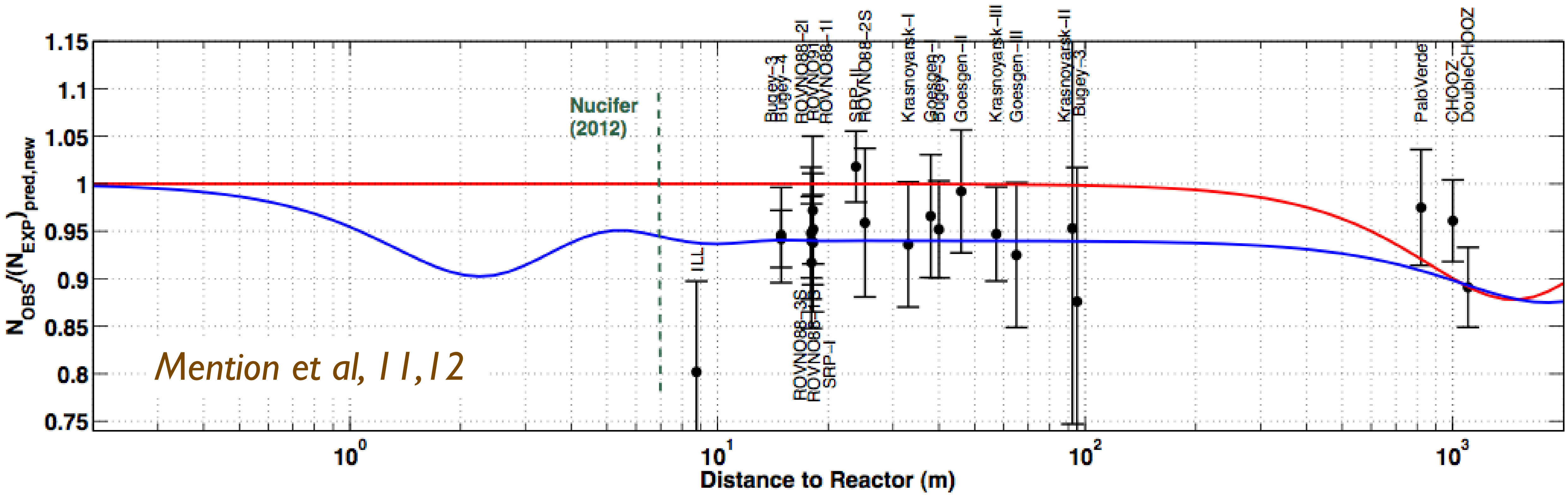
Hints for eV sterile neutrinos

- Reactor anomaly ($\bar{\nu}_e$ disappearance)
- Gallium anomaly (ν_e disappearance)
- LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ appearance)
- MiniBooNE ($\bar{\nu}_\mu \to \bar{\nu}_e$, $\nu_\mu \to \nu_e$ appearance)

Can they all be consistent and respect bounds on eV-scale oscillations?

will not speak about cosmological implications,
see talks by G. Miele, N. Saviano, L. Verde, C. Giunti on Wed

The reactor anomaly



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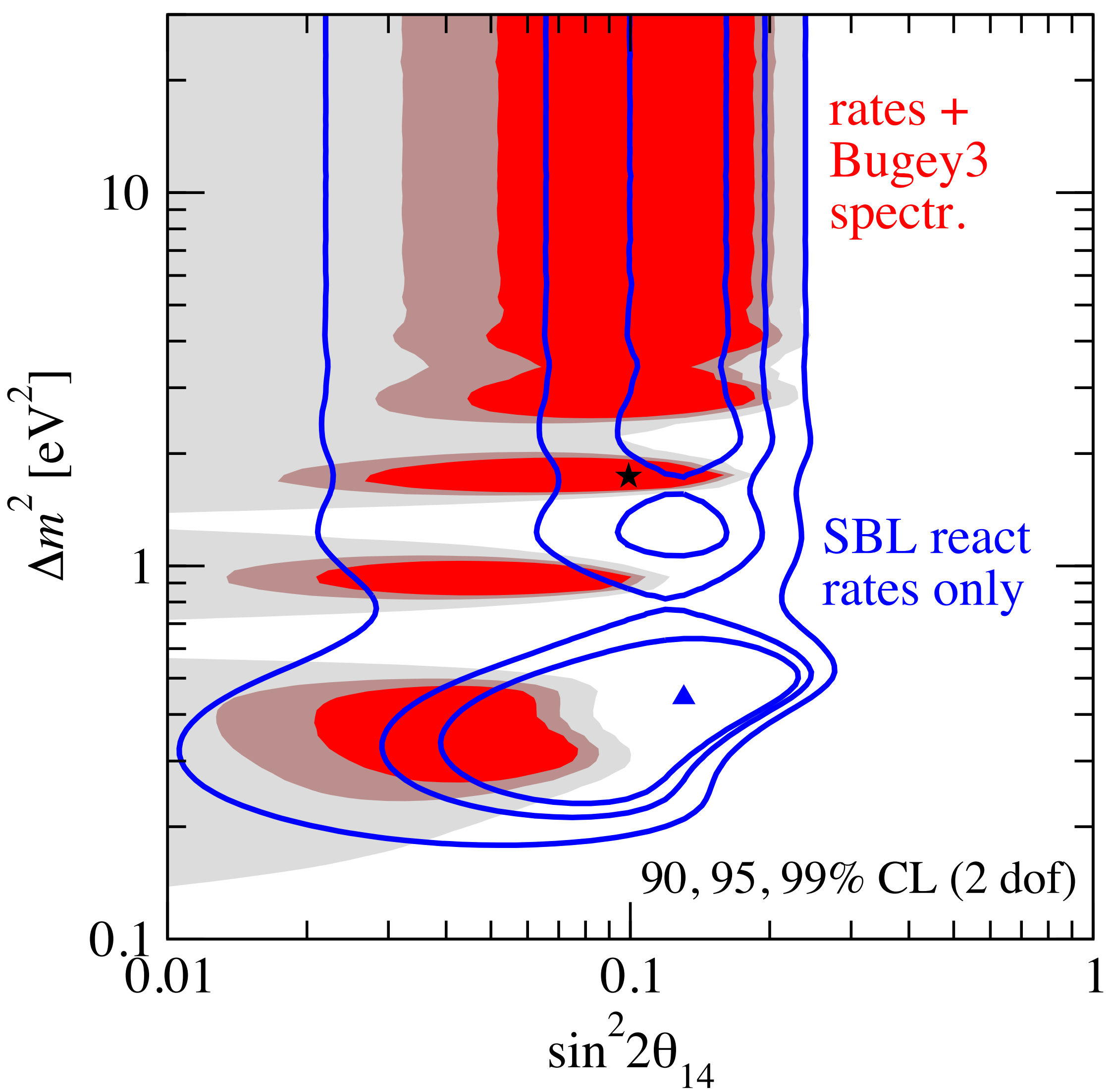
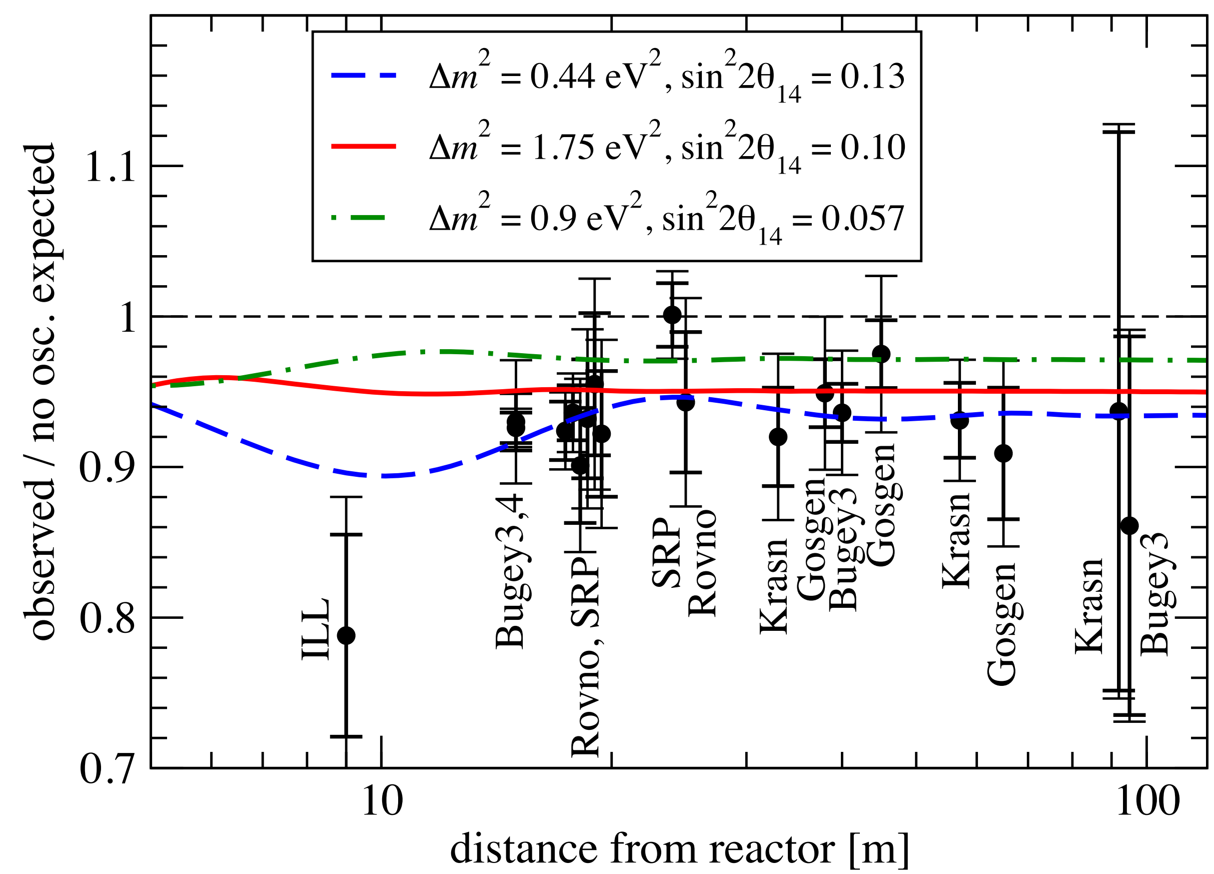
- *sterile neutrinos at the eV scale?*

The reactor anomaly and sterile neutrinos



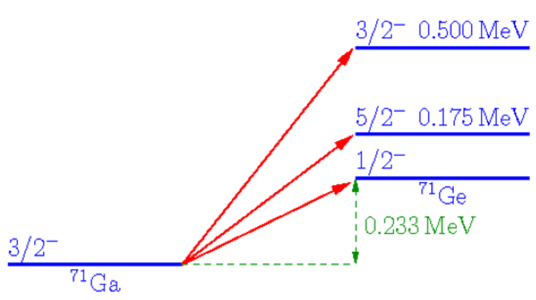


	$\sin^2 2\theta_{14}$	Δm^2_{41} [eV^2]	$\chi^2_{\min}$/dof (GOF)	$\Delta\chi^2_{\text{no-osc}}$ (CL)
SBLR rates only	0.13	0.44	11.5/17 (83%)	11.4/2 (99.7%)
SBLR incl. Bugey3 spectr.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)

The Gallium anomaly

Callibration data of Ga solar neutrino experiments with radio active sources show a deficit compared to expectations.

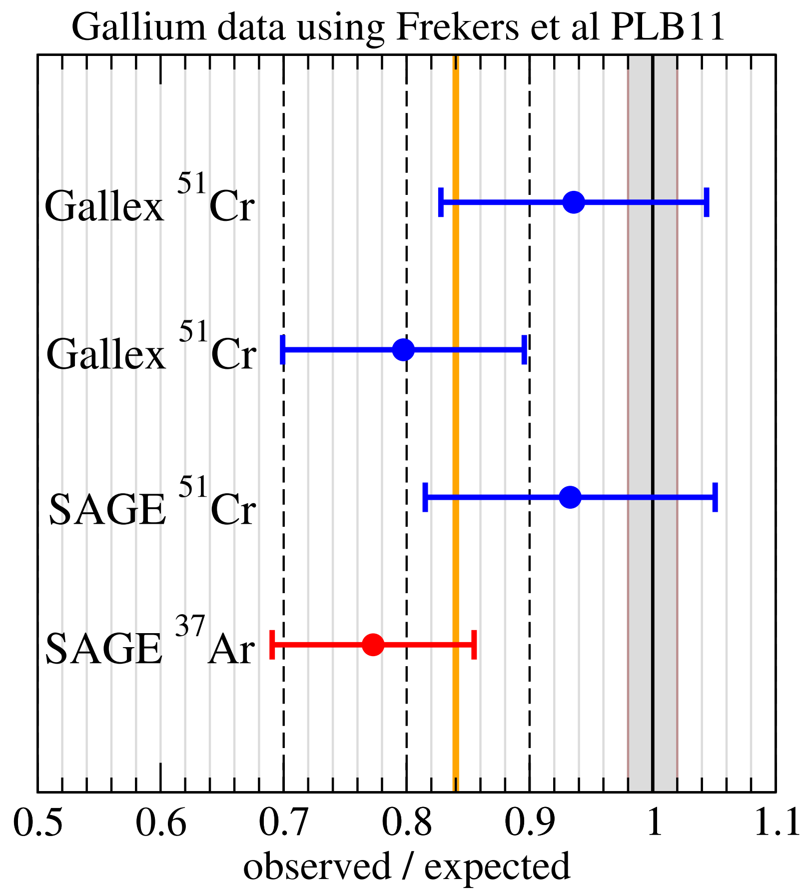
the reaction $\nu_e + ^{71}\text{Ga} \to ^{71}\text{Ge} + e^-$ can proceed to the ground state or through excited states of ^{71}Ge



recent measurement of $^{71}\text{Ga}(^3\text{He}, t)^{71}\text{Ge}$ D. Frekers et al., PLB 706, 134

$$\frac{\text{BGT}_{175}}{\text{BGT}_{\text{g.s.}}} = 0.0399 \pm 0.0305 \qquad \frac{\text{BGT}_{500}}{\text{BGT}_{\text{g.s.}}} = 0.207 \pm 0.016$$

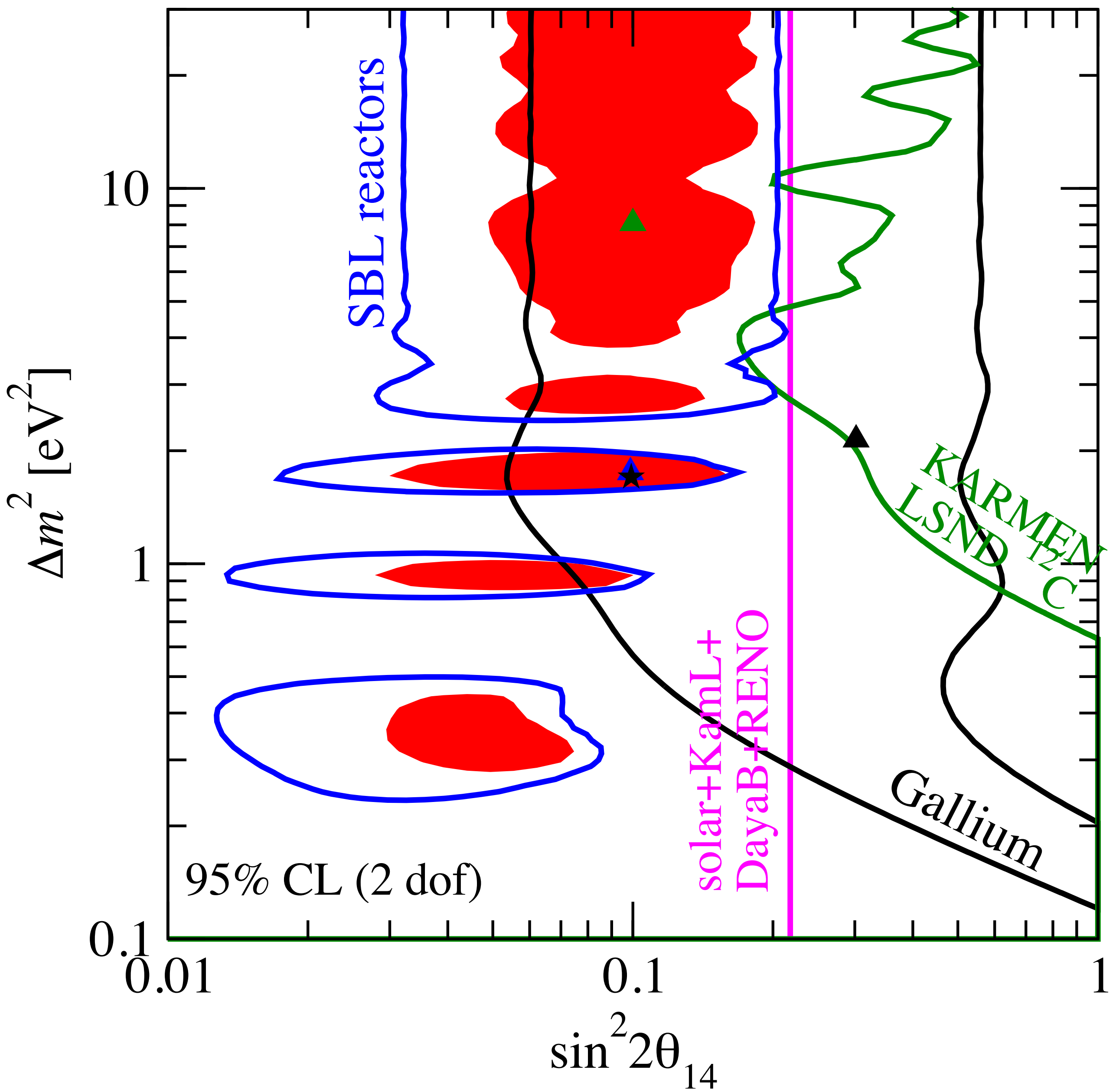
$\Rightarrow$ contribution of $7.2 \pm 2.0\%$ from excited states (for ^{51}Cr)



combined fit: $\chi^2_{\text{min}} = 2.3/3\,\text{dof} \quad r = 0.84^{+0.054}_{-0.051} \quad \Delta\chi^2_{r=1} = 8.7\,(2.9\sigma)$

see also Giunti, Laveder, 1006.3244

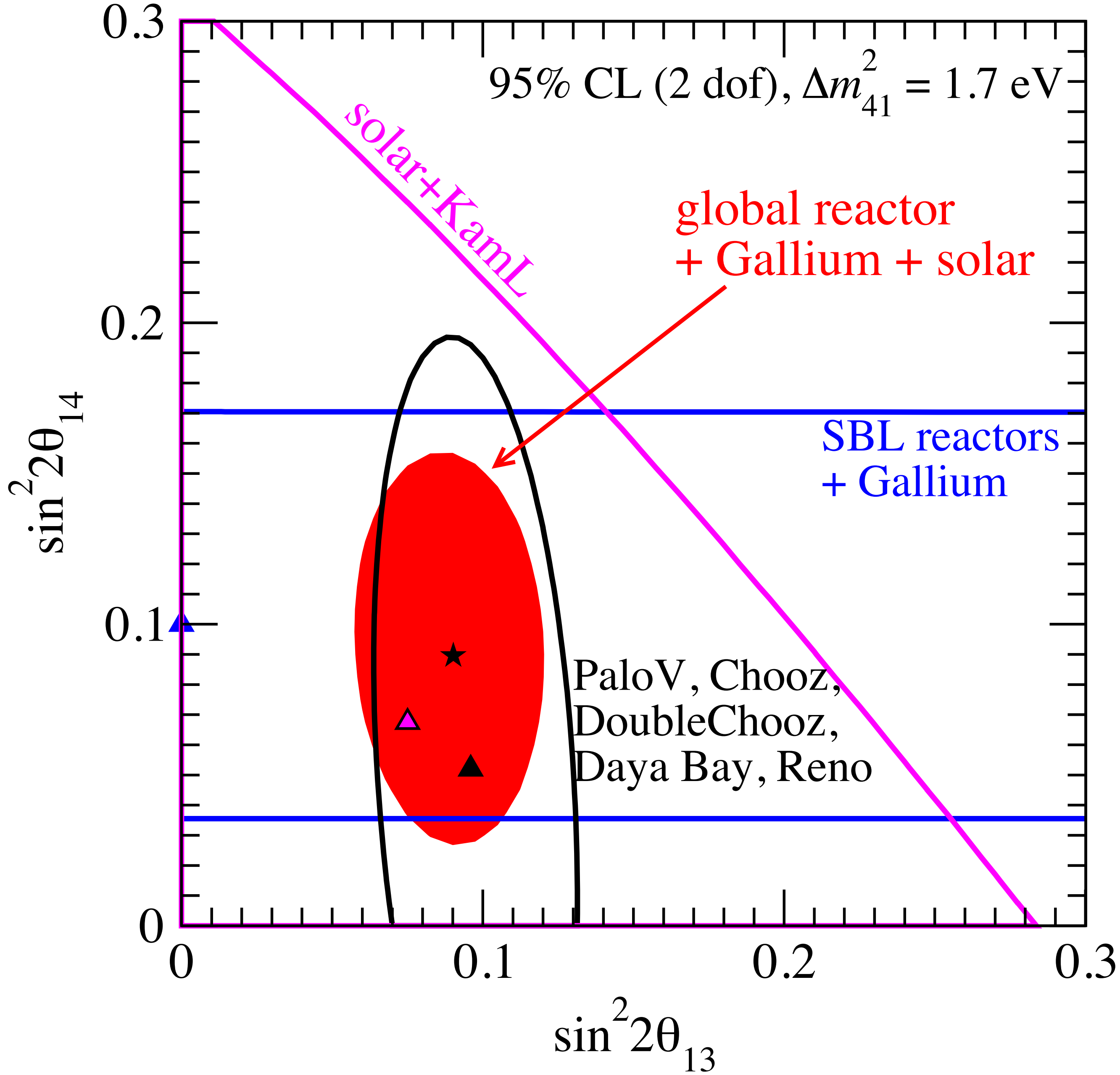
Global data on ν_e disappearance

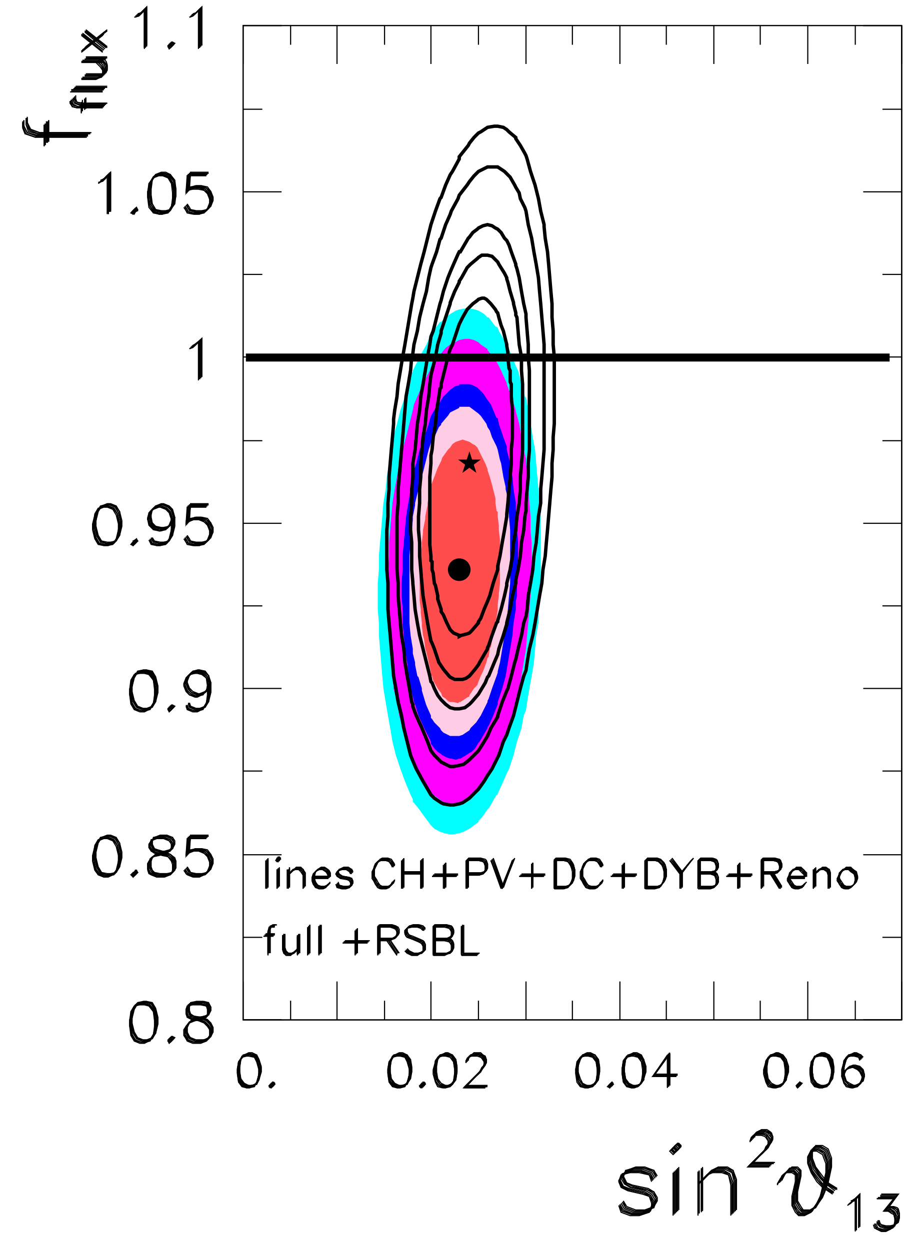


- ν_e disappearance constraints from LSND and KARMEN
  LSND and KARMEN measure the cross section for $\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N} + e^-$ consistent with expectations $\to$ limit on ν_e disappearance Conrad, Shaevitz, 1106.5552
- solar neutrinos
  degeneracy between θ_{13} and θ_{14} e.g., Palazzo, 1105.1705

no oscillations excluded at 99.8% CL

Global data on ν_e disappearance



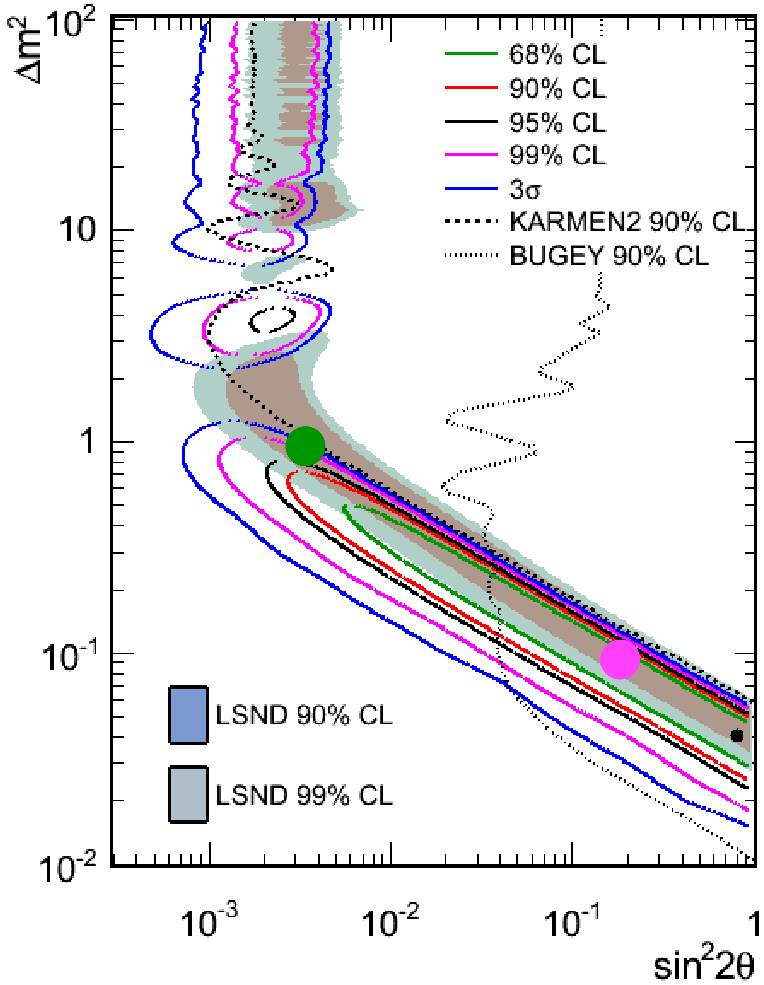


impact of eV oscillations on θ_{13} determination

Appearance results from MiniBooNE

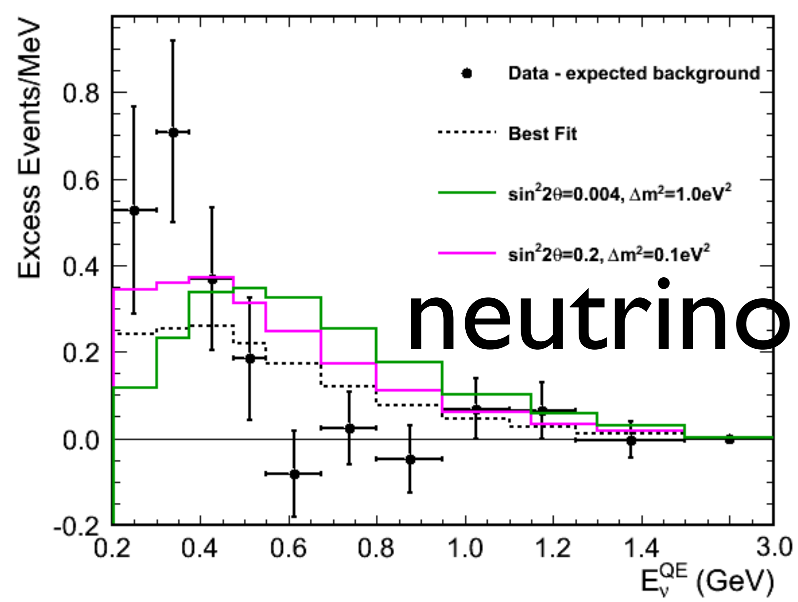
Chris Polly @ Neutrino2012, 1207.4809

Simultaneous 3+1 fit to ν and anti-ν data



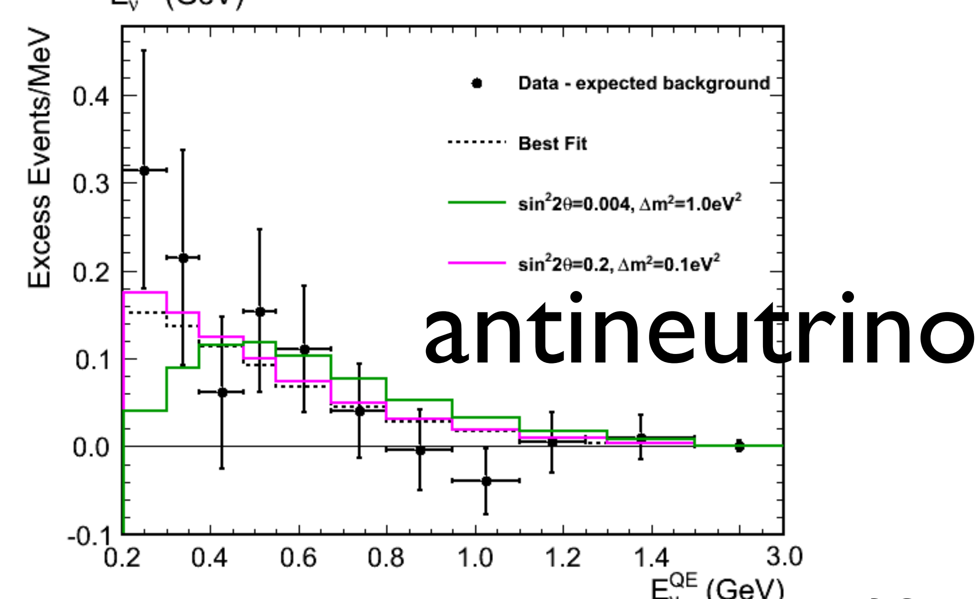
- WS accounted for properly
- Construction of correlated systematic error matrix (Z. Pavlovic)
- E>200 MeV BF preferred at 3.8σ over null

Total Excess: 240.3 +/- 34.5 +/- 52.6



* Simultaneous fit (E>200 MeV) with fully-correlated systematic to entire MB neutrino and anti-neutrino data

combined	E > 200 MeV	E > 475 MeV
χ^2(null)	42.53	12.87
Prob(null)	0.1%	35.8%
χ^2(bf)	24.72	10.67
Prob(bf)	6.7%	35.8%



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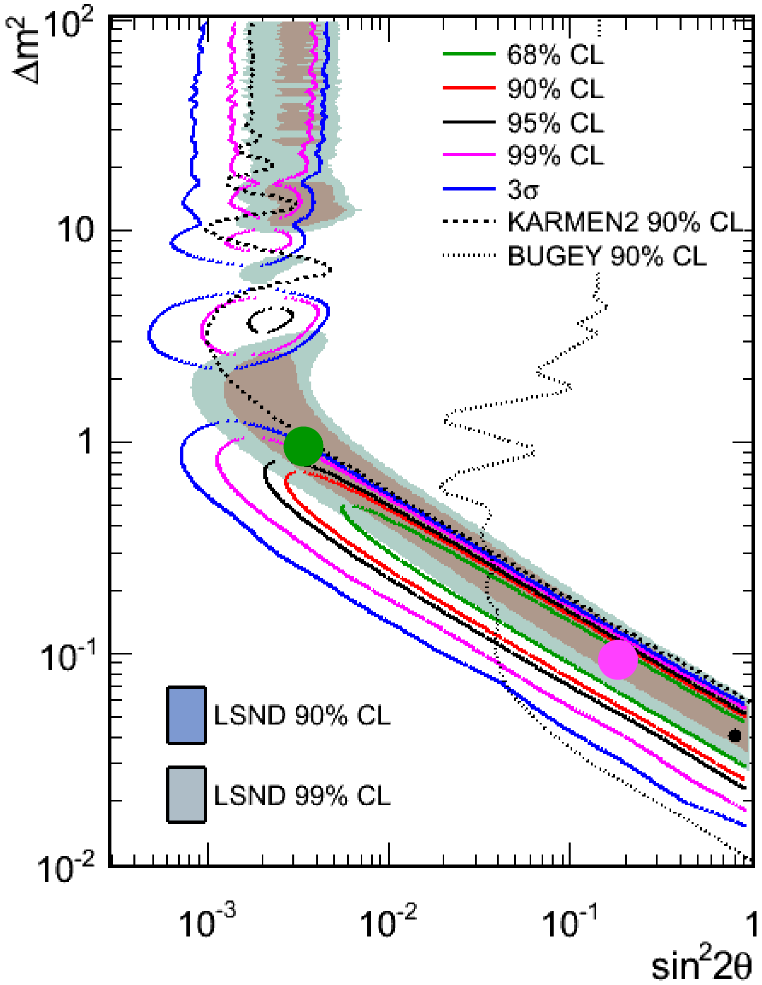

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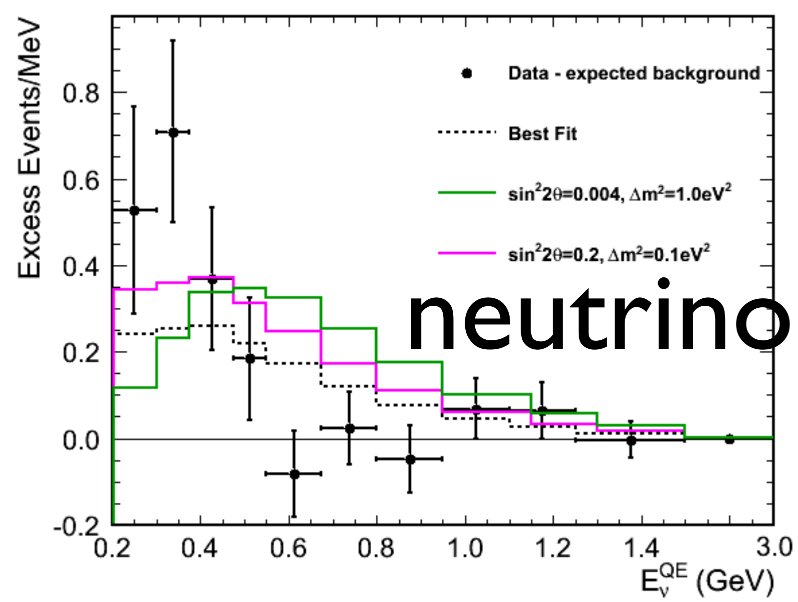

LSND: 3.8σ

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combined	E > 200 MeV	E > 475 MeV
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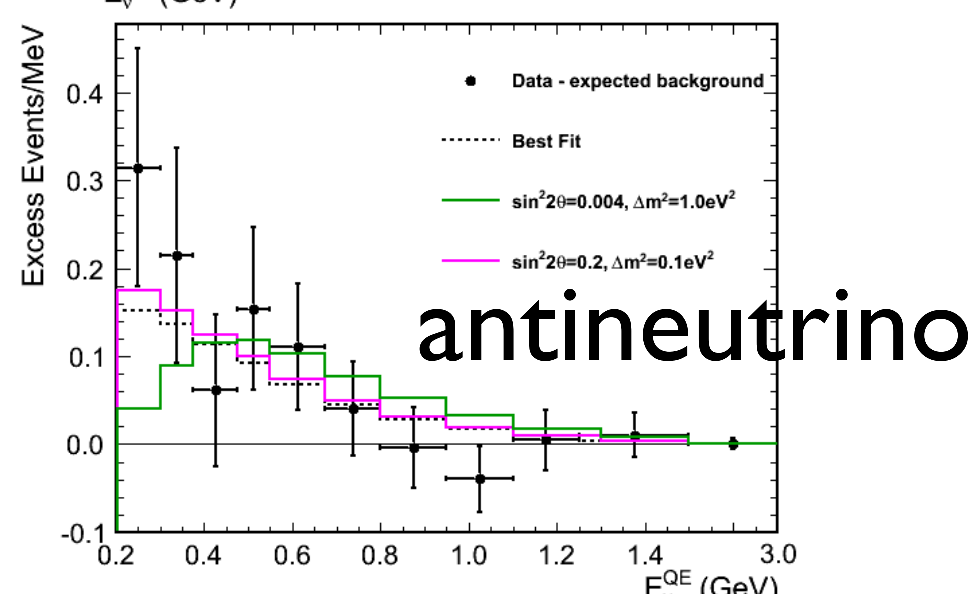


Fitting all together?

3+1 SBL oscillations

appearance

$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

disappearance ($\alpha = e, \mu$)

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

- effective 2-flavour oscillations
- no CP violation $\longrightarrow$ same results for $\bar{\nu}$ (LSND, MB) and ν (MB) data

Fitting all together?

3+1 SBL oscillations

appearance

$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2 |U_{\mu 4}|^2$$

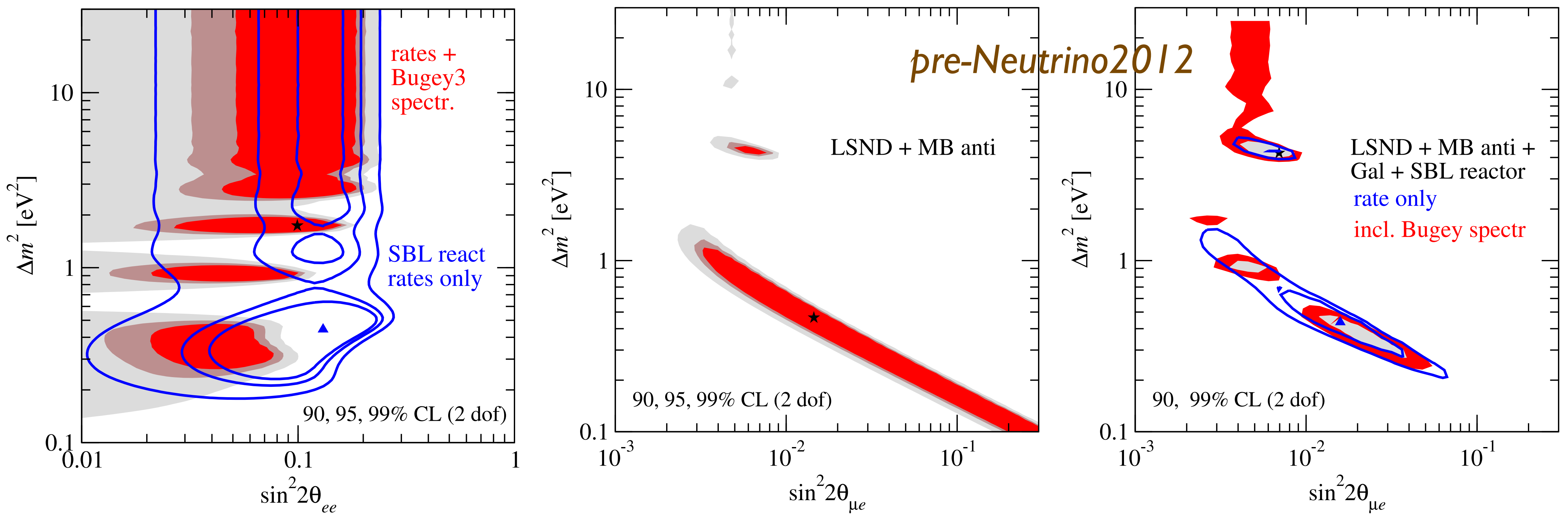
disappearance ($\alpha = e, \mu$)

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

$$\boxed{\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}}$$

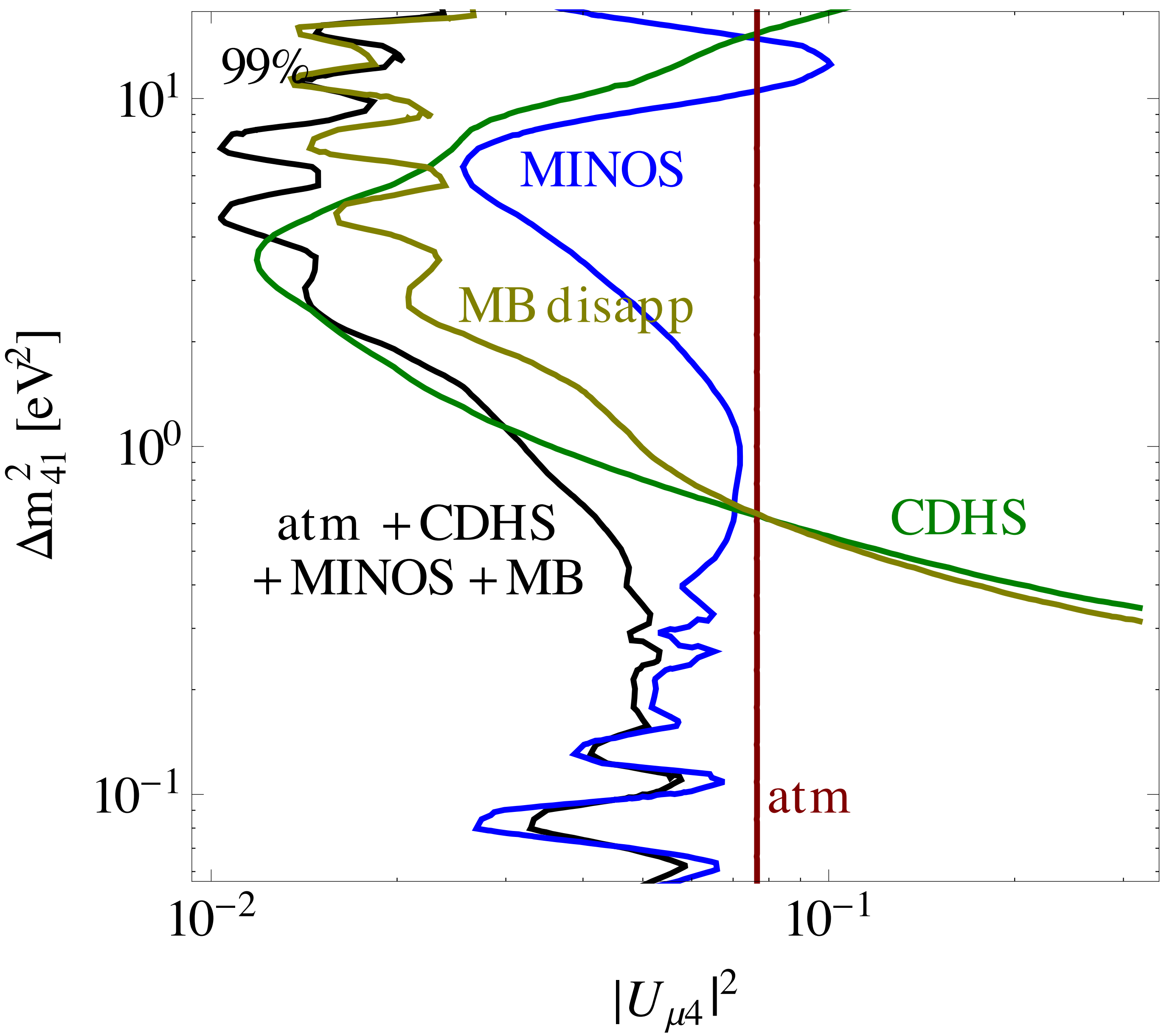
$\nu_\mu \to \nu_e$ app. signal requires also signal in both, ν_e and ν_μ disappearance (appearance mixing angle quadratically suppressed)

ν_e disap vs $\nu_\mu \rightarrow \nu_e$ appearance



- *reactor+Ga anomalies and LSND+MB hints are perfectly consistent, BUT...*

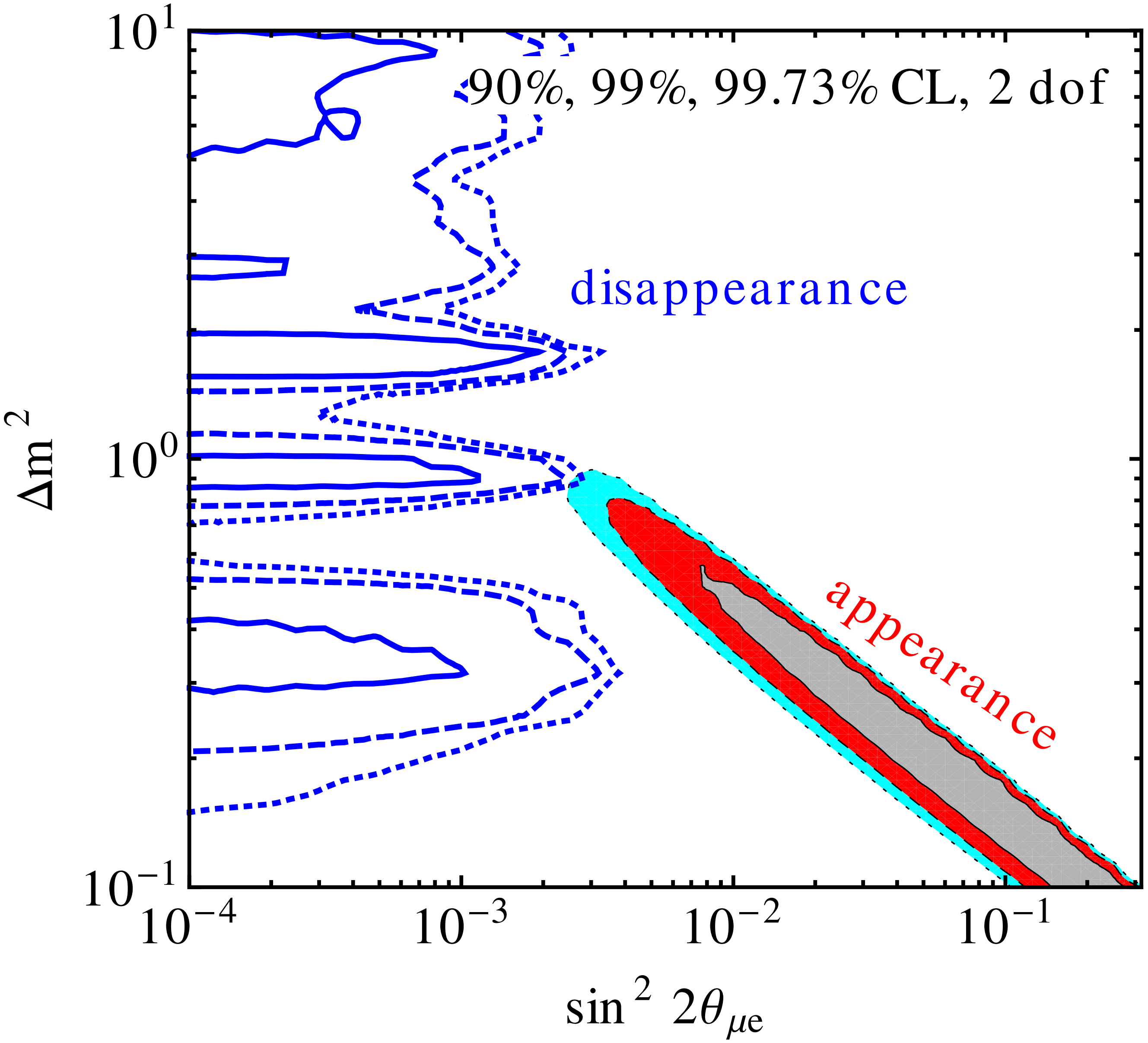
Constrains on ν_μ disappearance



- *CDHS, atmospheric neutrinos, MINOS, MiniBooNE*
- *additional constraints from IceCube (not used)*

Nunokawa, Peres, Zukanovich, 03, Coubey, 07, Razzaque, Smirnov, 11, 12, Esmaili, Halzen, Peres, 12

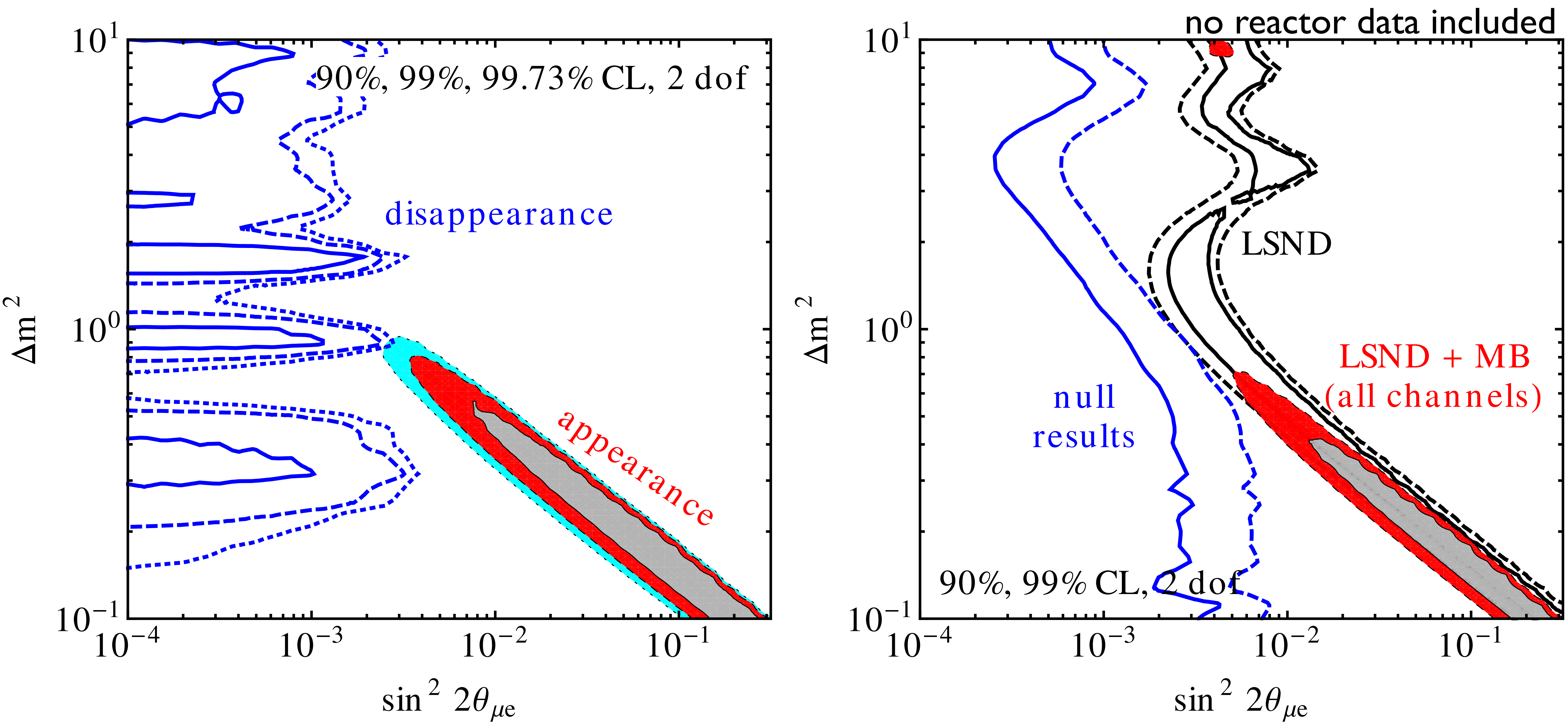
Strong tension in global data



$\chi^2/\text{dof (all)}$	$= 603.2 / 573$	18%
$\chi^2/\text{dof (disapp)}$	$= 486.3 / 505$	72%
$\chi^2/\text{dof (app)}$	$= 97.4 / 68$	1.1%
$\chi^2_{\text{PG}}/\text{dof (dis/app)}$	$= 19.6 / 2$	0.06%

J. Kopp, P. Machado, M. Maltoni, TS (to appear)

Strong tension in global data



J. Kopp, P. Machado, M. Maltoni, TS (to appear)

Strong tension in global data

there are three classes of data:

$\nu_e \to \nu_e$ disappearance $\quad \sin^2 2\theta_{ee}$

$\nu_\mu \to \nu_\mu$ disappearance $\quad \sin^2 2\theta_{\mu\mu}$

$\nu_\mu \to \nu_e$ appearance $\quad \sin^2 2\theta_{\mu e}$

$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

- each combination of two sets is consistent (they depend on different mixing parameters)
- BUT: strong tension if all three of them are combined

Adding more sterile neutrinos?

3+2 SBL oscillations:

appearance:

$$
\begin{aligned}
P_{\nu_\mu\to\nu_e} &= 4\,|U_{e4}|^2|U_{\mu4}|^2\sin^2\phi_{41} + 4\,|U_{e5}|^2|U_{\mu5}|^2\sin^2\phi_{51} \\
&+ 8\,|U_{e4}U_{\mu4}U_{e5}U_{\mu5}|\sin\phi_{41}\sin\phi_{51}\cos(\phi_{54}-\delta)
\end{aligned}
$$

disappearance:

$$
P_{\nu_\alpha\to\nu_\alpha} \approx 1 - 4\sum_{i=4,5}|U_{\alpha i}|^2\sin^2\phi_{i1} - 4\,|U_{\alpha4}|^2|U_{\alpha5}|^2\sin^2\phi_{54}
$$

$$[\phi_{ij} \equiv \Delta m^2_{ij} L/4E]$$

- phase $\delta \equiv \arg\left(U^*_{e4}U_{\mu4}U_{e5}U^*_{\mu5}\right) \to$ CP violation
  Karagiorgi et al. 06; Maltoni, TS 07

Adding more sterile neutrinos?

3+2 SBL oscillations:

appearance:

$$\begin{aligned} P_{\nu_\mu \to \nu_e} &= 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} + 4\,|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} \\ &+ 8\,|U_{e4} U_{\mu 4} U_{e5} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta) \end{aligned}$$

disappearance:

$$P_{\nu_\alpha \to \nu_\alpha} \approx 1 - 4 \sum_{i=4,5} |U_{\alpha i}|^2 \sin^2 \phi_{i1} - 4\,|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \phi_{54}$$

$$[\phi_{ij} \equiv \Delta m^2_{ij} L / 4E]$$

- BUT: constrain $|U_{ei}|$ and $|U_{\mu i}|$ $(i = 4, 5)$ from disappearance to be reconciled with appearance amplitudes $|U_{ei} U_{\mu i}|$

Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz, 1207.4765

3+1 vs 3+2
$\Delta\chi^2$=12.4
4 dof
98.6 % CL

3+2 vs 3+3
$\Delta\chi^2$=3.3
5 dof

	χ^2_{min} (dof)	χ^2_{null} (dof)	P_{best}	P_{null}	χ^2_{PG} (dof)	PG (%)
3+1						
All	233.9 (237)	286.5 (240)	55%	2.1%	54.0 (24)	0.043%
App	87.8 (87)	147.3 (90)	46%	0.013%	14.1 (9)	12%
Dis	128.2 (147)	139.3 (150)	87%	72%	22.1 (19)	28%
ν	123.5 (120)	133.4 (123)	39%	25%	26.6 (14)	2.2%
$\overline{\nu}$	94.8 (114)	153.1 (117)	90%	1.4%	11.8 (7)	11%
App vs. Dis	-	-	-	-	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	-	-	-	-	15.6 (3)	0.14%
3+2						
All	221.5 (233)	286.5 (240)	69%	2.1%	63.8 (52)	13%
App	75.0 (85)	147.3 (90)	77%	0.013%	16.3 (25)	90%
Dis	122.6 (144)	139.3 (150)	90%	72%	23.6 (23)	43%
ν	116.8 (116)	133.4 (123)	77%	25%	35.0 (29)	21%
$\overline{\nu}$	90.8 (110)	153.1 (117)	90%	1.4%	15.0 (16)	53%
App vs. Dis	-	-	-	-	23.9 (4)	0.0082%
ν vs. $\overline{\nu}$	-	-	-	-	13.9 (7)	5.3%
3+3						
All	218.2 (228)	286.5 (240)	67%	2.1%	68.9 (85)	90%
App	70.8 (81)	147.3 (90)	78%	0.013%	17.6 (45)	100%
Dis	120.3 (141)	139.3 (150)	90%	72%	24.1 (34)	90%
ν	116.7 (111)	133.4 (123)	34%	25%	39.5 (46)	74%
$\overline{\nu}$	90.6 (105)	153 (117)	84%	1.4%	18.5 (27)	89%
App vs. Dis	-	-	-	-	28.3 (6)	0.0081%
ν vs. $\overline{\nu}$	-	-	-	-	110.9 (12)	53%

Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz, 1207.4765

	χ^2_{min} (dof)	χ^2_{null} (dof)	P_{best}	P_{null}	χ^2_{PG} (dof)	PG (%)
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App vs. Dis	-	-	-	-	28.3 (6)	0.0081%
ν vs. $\overline{\nu}$	-	-	-	-	110.9 (12)	53%

T. Schwetz

Adding more sterile neutrinos?

- *Motivation for CP violation no longer there (MB neutrino and antinu are consistent)*
- *More neutrinos cannot solve the appearance-disappearance tension*
- *Fit to MiniB low-E data not improved in global fit*
- *May create more problems with cosmology*

Summary - three flavour

- *global fit gives determination of θ_{13} with $\Delta\chi^2 \approx 100$, small dependence on reactor anomaly remains*
- *indications of non-maximal value of θ_{23} at 2σ (driven my MINOS), octant sensitvity from atmospheric data (below 1.5σ, depends on mass ordering)*
- *certain regions of δ_{CP} "disfavoured" at 1σ*
- *no sensitivity to mass ordering ($\Delta\chi^2 \approx 0.5$)*

Summary - sterile neutrinos

- *hints from reactor and Ga anomalies at ~3σ (not in tension with other data)*
- *hints from LSND, MiniBooNE ~3.8σ*
  low-E MiniB data not well fitted (few% prob)
- *strong tension in global fit (constraints from ν_μ disappearance experiments)*
- *no significant improvement by more sterile neutrinos*

Thanks...

- ...to my NuFIT collaborators
  C. Gonzalez-Garcia,
  M. Maltoni, J. Salvado

www.nu-fit.org

- ...to my sterile-nu collaborators

  J. Kopp, M. Maltoni, P. Machado (to appear)

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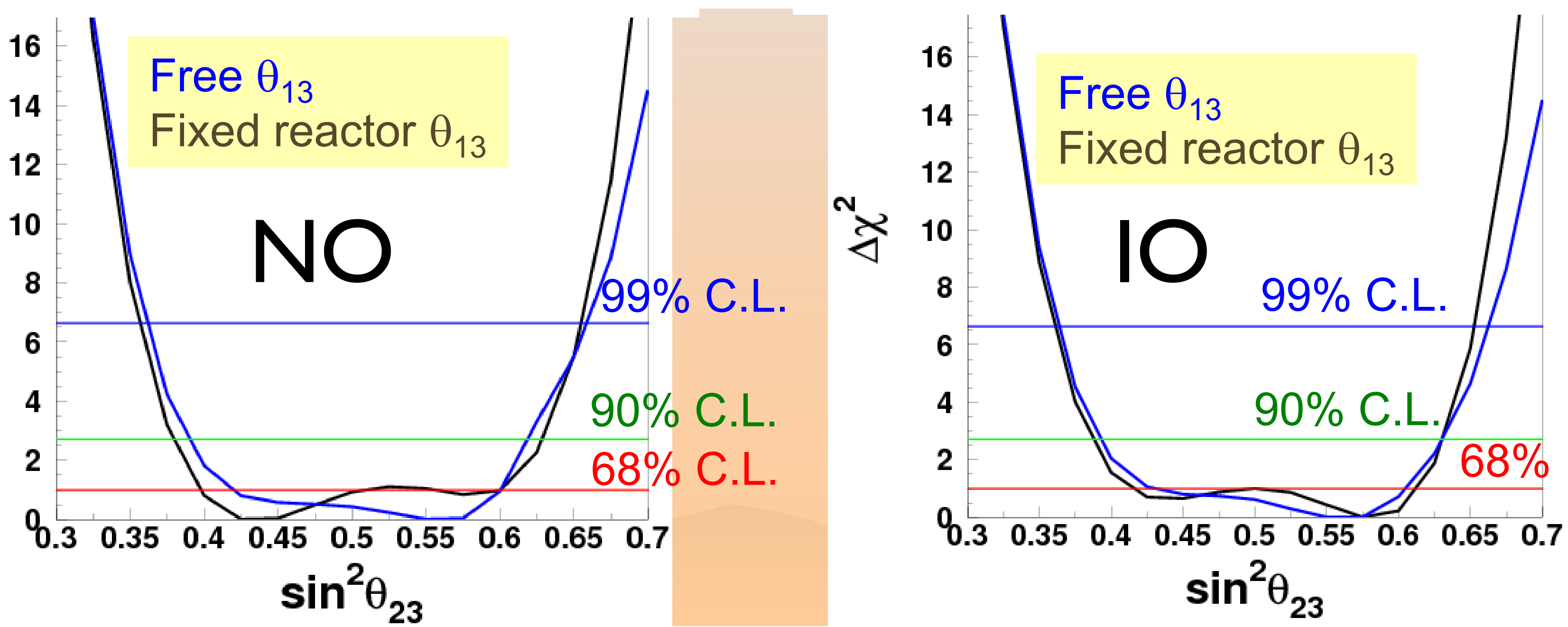
- ...to my sterile-nu collaborators

  J. Kopp, M. Maltoni, P. Machado (to appear)

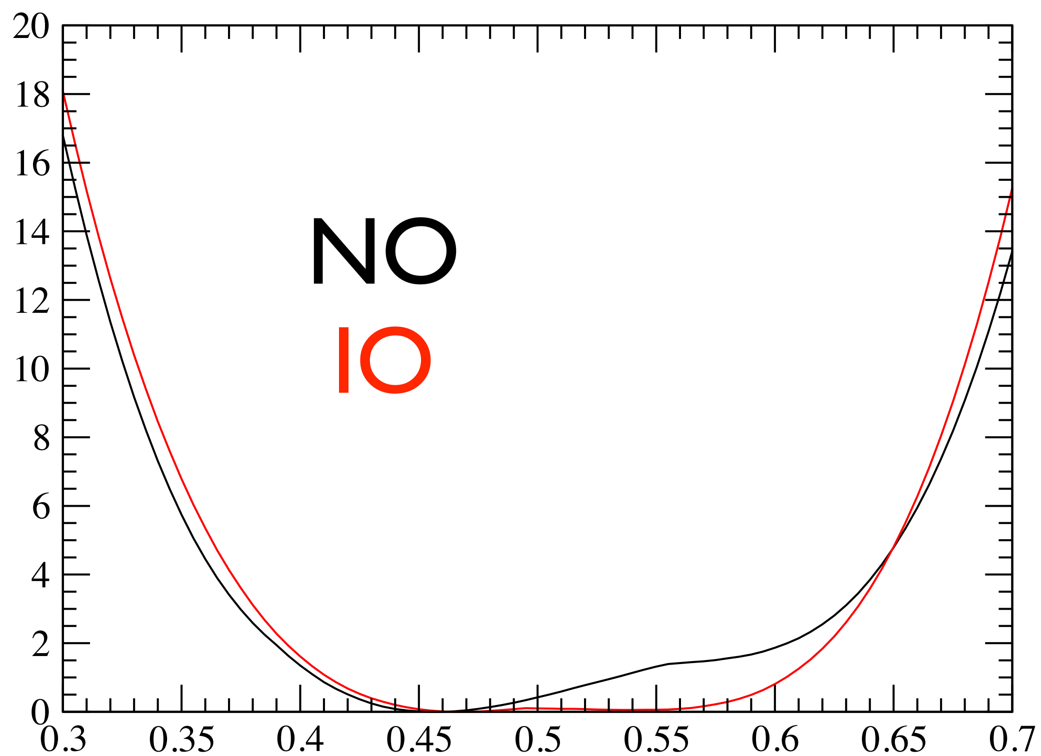
- ...**to you, for your attention!**

additional slides

Comparison with SuperK



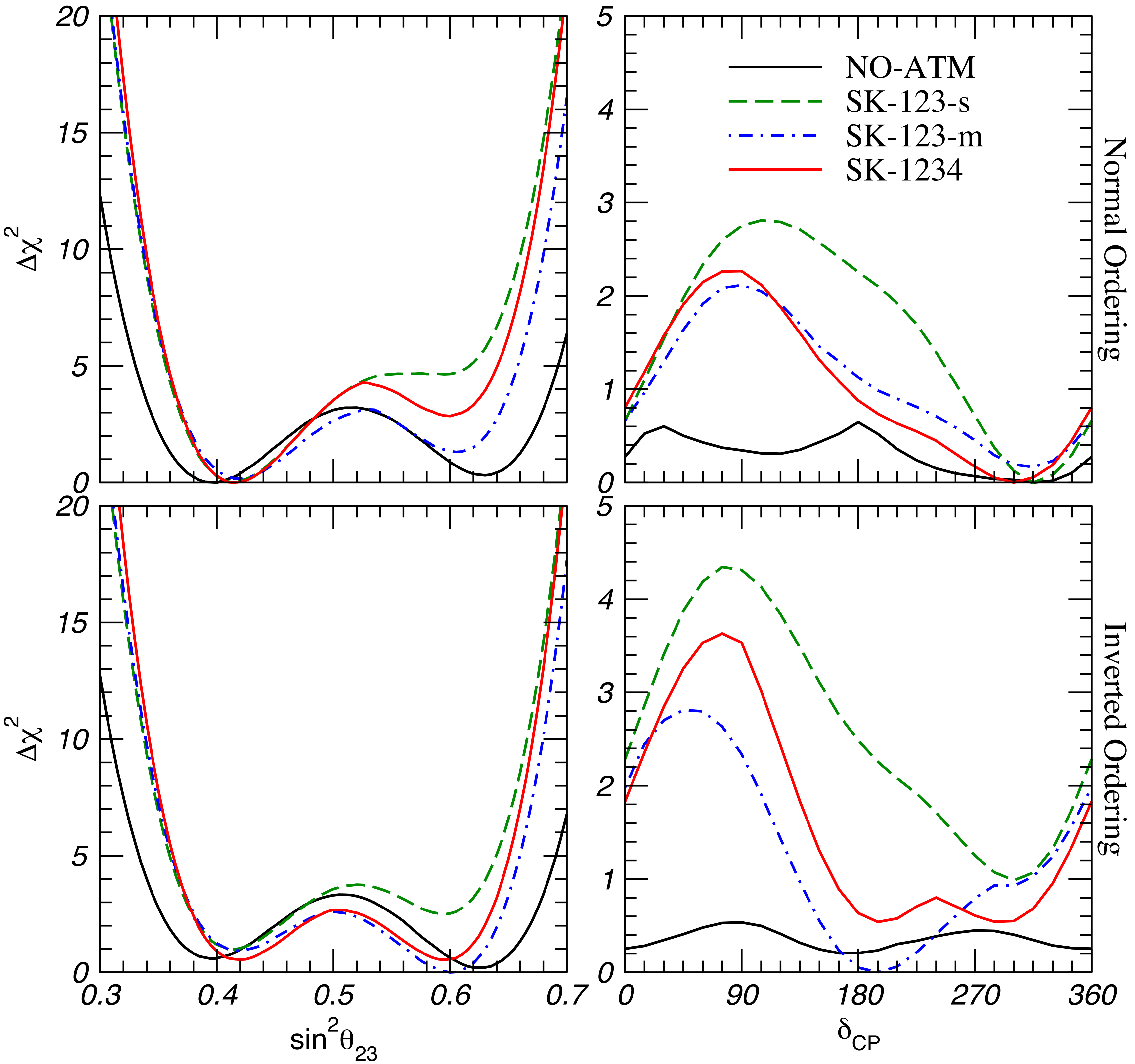
Itow (SuperK), talk at Neutrino2012



our SK1-4 only fit
θ_{13} fixed

→sensitivity to octant manifests itself only together with the MINOS hint for non-maximality

Impact of latest SK1-4 data in global fit



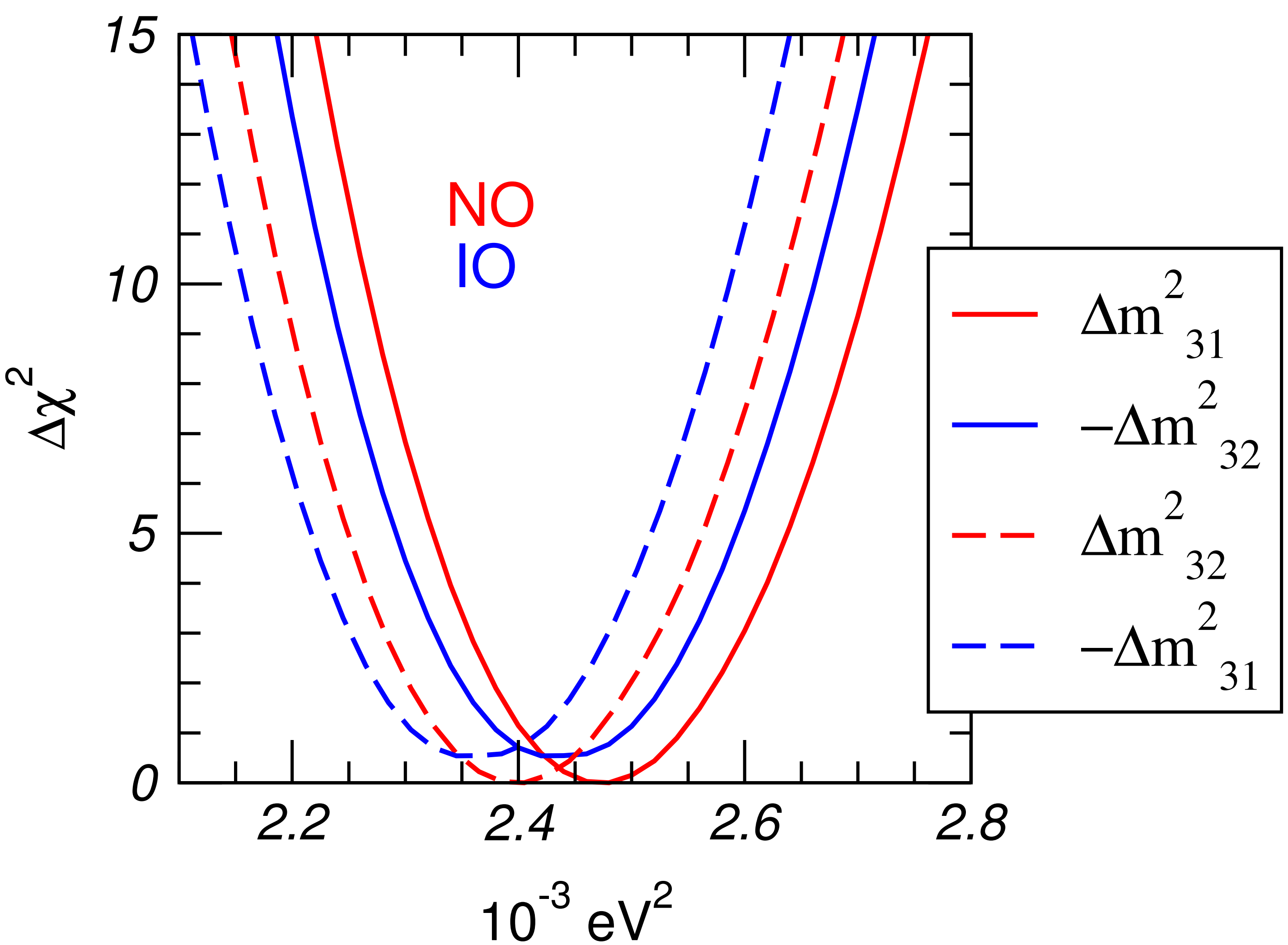
previous SK1-3 analysis by Maltoni et al.

same data but sub-GeV sample merged

adding SK4 data (+1097 days) and using new flux predictions (Honda et al 11)

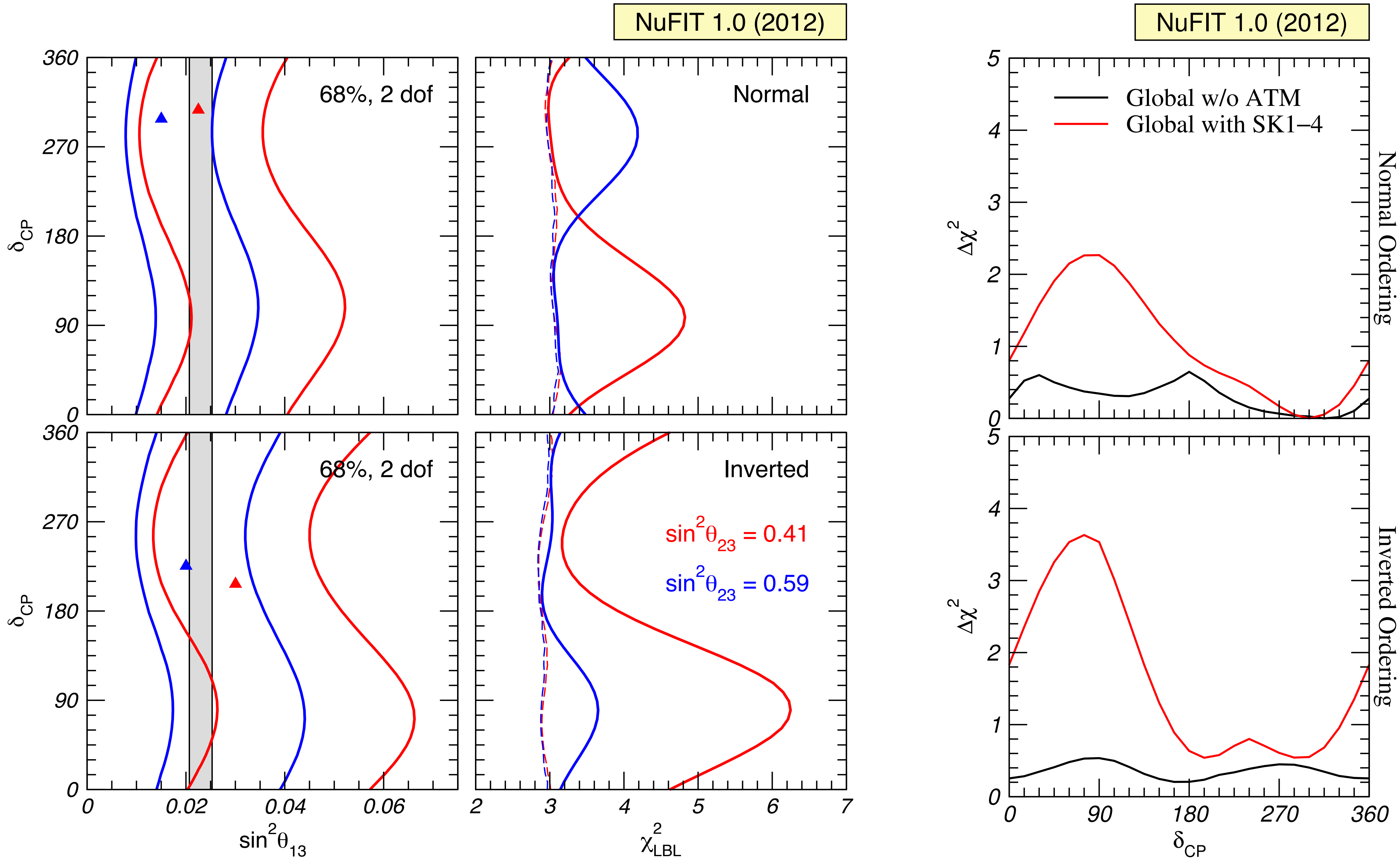
$\Delta m^2{}_{31,32}$ and the mass ordering

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\frac{\Delta m^2_{31}}{10^{-3}\ \text{eV}^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$	$2.49^{+0.055}_{-0.051}$	$2.29 \to 2.71$
$\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$ (I)	$-2.43^{+0.042}_{-0.065}$	$-2.65 \to -2.24$	$-2.47^{+0.073}_{-0.064}$	$-2.68 \to -2.25$



- *difference between $|\Delta m^2{}_{31}|$ and $|\Delta m^2{}_{32}|$ at the level of 1σ*

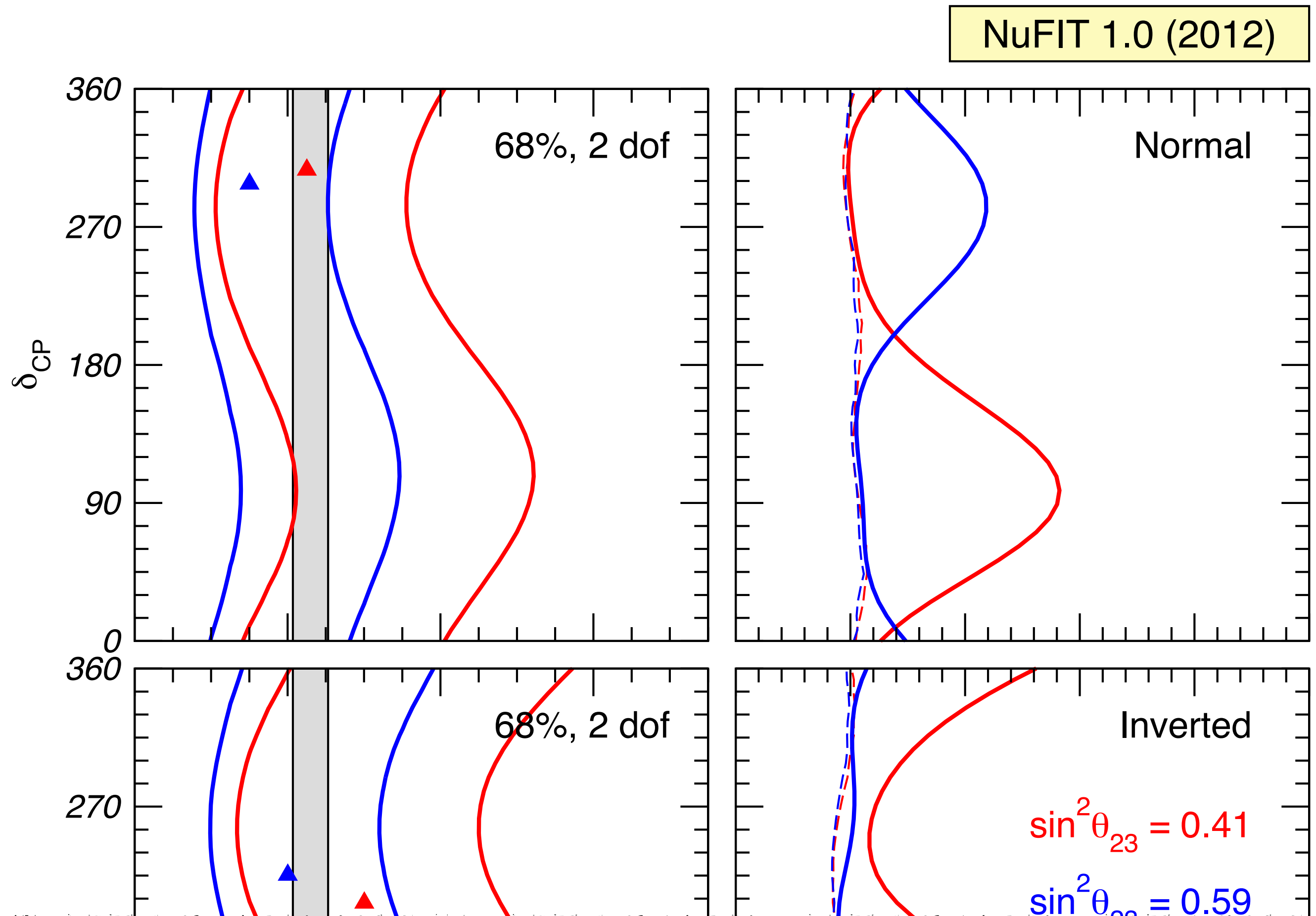
The CP phase and atmospheric neutrino data

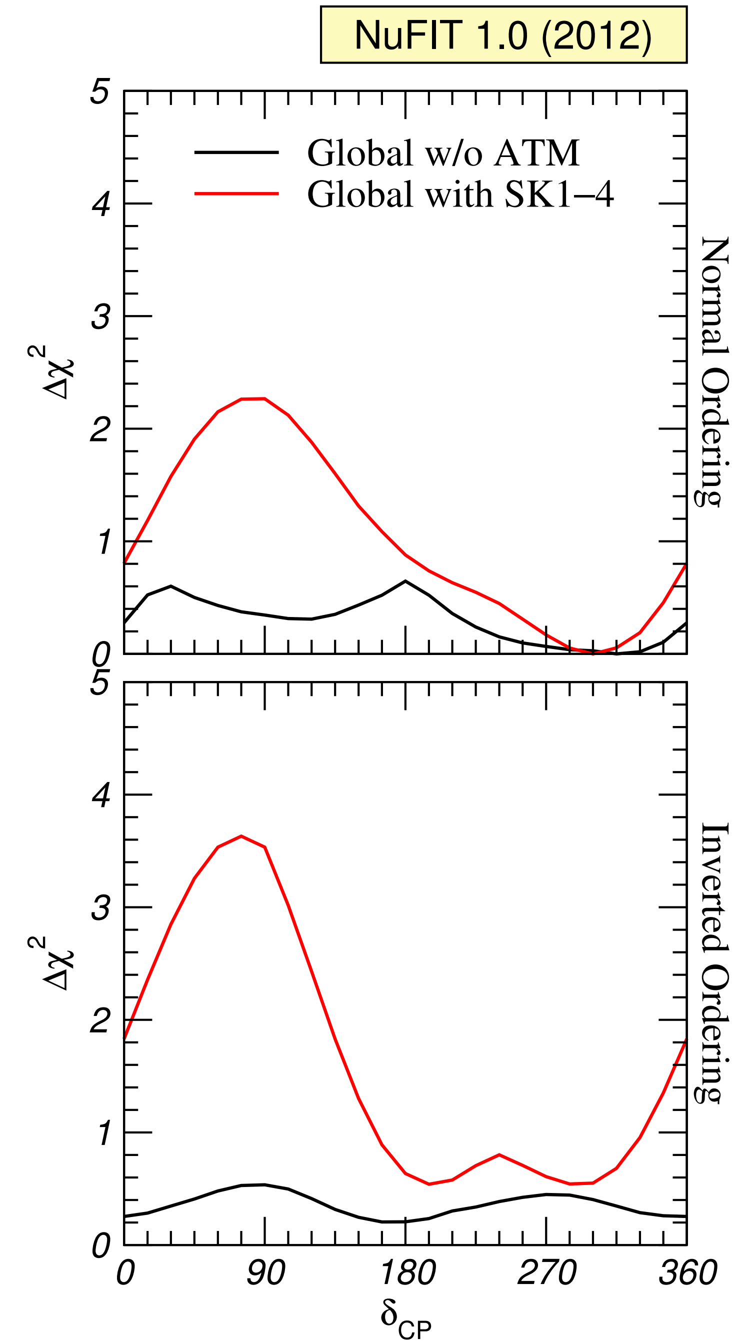


LBL app + react

adding atmospheric

The CP phase and atmospheric neutrino data





- *non-maximality from LBL disapp*
- *preference for 1st octant from atm*
- *sensitivity to δ from LBL appearance + reactors*

adding atmospheric