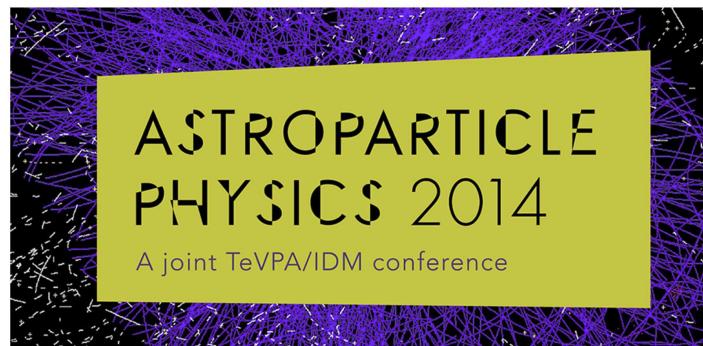


PHENOMENOLOGY WITH MASSIVE NEUTRINOS

Concha Gonzalez-Garcia

(YITP Stony Brook & ICREA U. Barcelona)



June 25, 2014

PHENOMENOLOGY OF MASSIVE NEUTRINOS

Concha Gonzalez-Garcia

(ICREA U. Barcelona & YITP Stony Brook)

$3\nu'$ s: Lepton Flavour Parameters. Neutrino Mass Scale

Beyond: Light Sterile Neutrinos. Non Standard Interactions

ν in the SM

The SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

$(1, 2)_{-\frac{1}{2}}$	$(3, 2)_{\frac{1}{6}}$	$(1, 1)_{-1}$	$(3, 1)_{\frac{2}{3}}$	$(3, 1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u_R^i	d_R^i
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c_R^i	s_R^i
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t_R^i	b_R^i

There is no ν_R

ν in the SM

The SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

$(1, 2)_{-\frac{1}{2}}$	$(3, 2)_{\frac{1}{6}}$	$(1, 1)_{-1}$	$(3, 1)_{\frac{2}{3}}$	$(3, 1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u_R^i	d_R^i
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c_R^i	s_R^i
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t_R^i	b_R^i

There is no ν_R

↓

Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau$

↓

ν strictly massless

The New Minimal Standard Model

- Minimal Extensions to give Mass to the Neutrino:

- * Introduce ν_R AND impose L conservation \Rightarrow Dirac $\nu \neq \nu^c$:

$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

- * NOT impose L conservation \Rightarrow Majorana $\nu = \nu^c$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_\nu \overline{\nu_L} \nu_L^C + h.c.$$

The New Minimal Standard Model

- Minimal Extensions to give Mass to the Neutrino:

* Introduce ν_R AND impose L conservation \Rightarrow Dirac $\nu \neq \nu^c$:

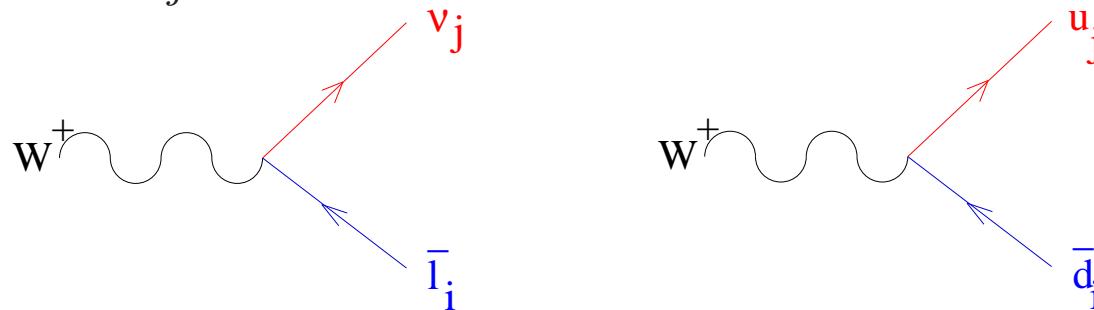
$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

* NOT impose L conservation \Rightarrow Majorana $\nu = \nu^c$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_\nu \overline{\nu_L} \nu_L^C + h.c.$$

- The charged current interactions of leptons are not diagonal (same as quarks)

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} (U_{\text{LEP}}^{ij} \overline{\ell^i} \gamma^\mu L \nu^j + U_{\text{CKM}}^{ij} \overline{U^i} \gamma^\mu L D^j) + h.c.$$



The New Minimal Standard Model

- Minimal Extensions to give Mass to the Neutrino:

* Introduce ν_R AND impose L conservation \Rightarrow Dirac $\nu \neq \nu^c$:

$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

* NOT impose L conservation \Rightarrow Majorana $\nu = x\nu^c$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_\nu \overline{\nu_L} \nu_L^C + h.c.$$

- The charged current interactions of leptons are not diagonal (same as quarks)

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} (U_{LEP}^{ij} \overline{\ell^i} \gamma^\mu L \nu^j + U_{CKM}^{ij} \overline{U^i} \gamma^\mu L D^j) + h.c.$$

- In general for $N = 3 + m$ massive neutrinos U_{LEP} is $3 \times N$ matrix

$$U_{LEP} U_{LEP}^\dagger = I_{3 \times 3} \quad \text{but in general} \quad U_{LEP}^\dagger U_{LEP} \neq I_{N \times N}$$

- U_{LEP} : $3(N - 2)$ angles + $2N - 5$ Dirac phases + $N - 1$ Majorana phases

Effects of ν Mass: Oscillations

- If neutrinos have mass, a weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \rightarrow \nu_\alpha + N'$

is a linear combination of the mass eigenstates ($|\nu_i\rangle$) : $|\nu_\alpha\rangle = \sum_{i=1}^n U_{\alpha i} |\nu_i\rangle$

- After a distance L it can be detected with flavour β with probability

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{j \neq i} \text{Re}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin^2 \left(\frac{\Delta_{ij}}{2} \right) + 2 \sum_{j \neq i} \text{Im}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin(\Delta_{ij})$$

$$\frac{\Delta_{ij}}{2} = \frac{(E_i - E_j)L}{2} = 1.27 \frac{(m_i^2 - m_j^2)}{\text{eV}^2} \frac{L/E}{\text{Km/GeV}}$$

Effects of ν Mass: Oscillations

- If neutrinos have mass, a weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \rightarrow \nu_\alpha + N'$ is a linear combination of the mass eigenstates ($|\nu_i\rangle$) : $|\nu_\alpha\rangle = \sum_{i=1}^n U_{\alpha i} |\nu_i\rangle$
- After a distance L it can be detected with flavour β with probability

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{j \neq i} \text{Re}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin^2 \left(\frac{\Delta_{ij}}{2} \right) + 2 \sum_{j \neq i} \text{Im}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin(\Delta_{ij})$$

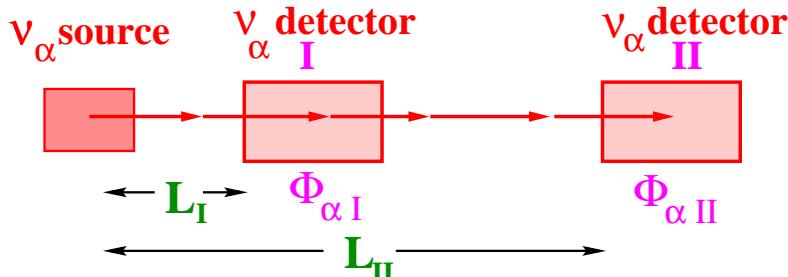
$$\frac{\Delta_{ij}}{2} = \frac{(E_i - E_j)L}{2} = 1.27 \frac{(m_i^2 - m_j^2)}{\text{eV}^2} \frac{L/E}{\text{Km/GeV}}$$

No information on ν mass scale nor Majorana versus Dirac

ν Oscillations: Experimental Probes

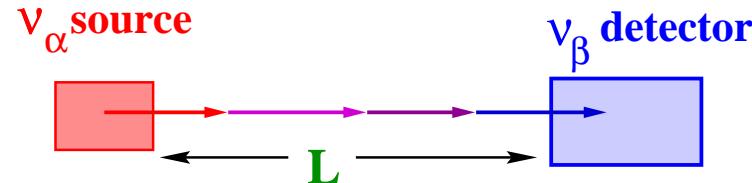
- Generically there are two types of experiments to search for ν oscillations :

Disappearance Experiment



Compares $\Phi_{\alpha I}$ and $\Phi_{\alpha II}$ to look for loss

Appearance Experiment

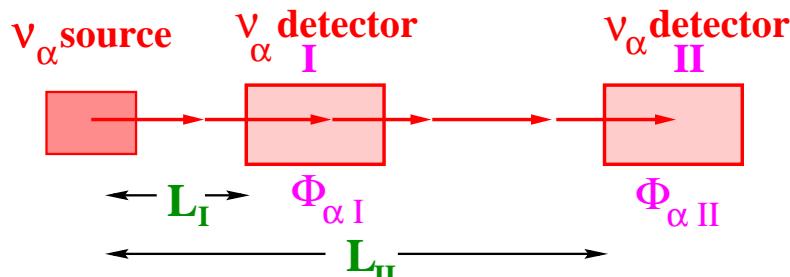


Searches for
 β diff α

ν Oscillations: Experimental Probes

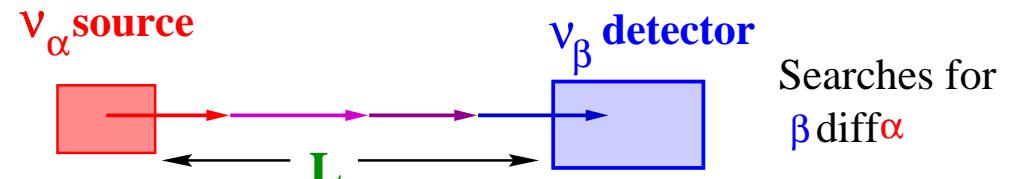
- Generically there are two types of experiments to search for ν oscillations :

Disappearance Experiment

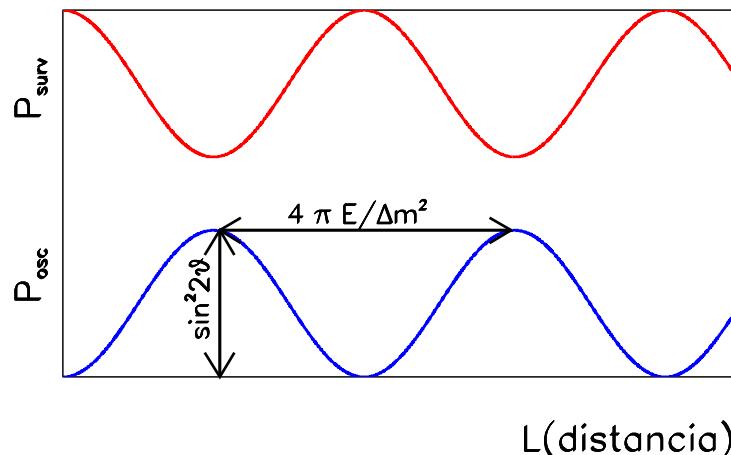


Compares $\Phi_{\alpha I}$ and $\Phi_{\alpha II}$ to look for loss

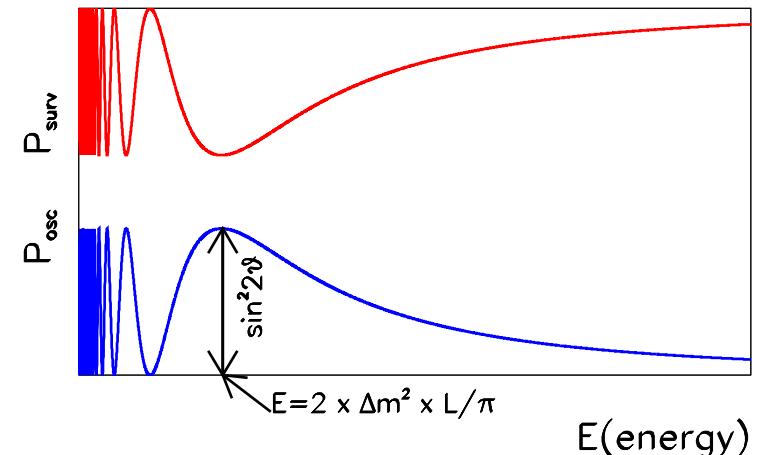
Appearance Experiment



- To detect oscillations we can study the neutrino flavour as function of the Distance to the source



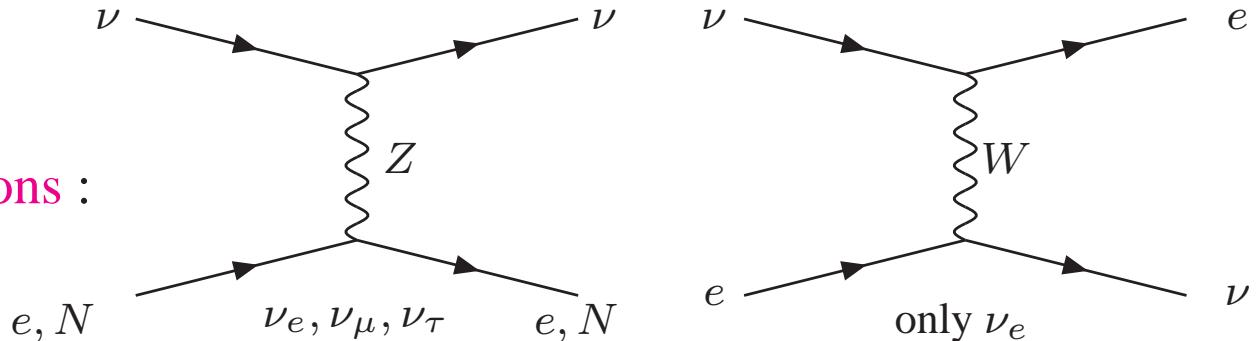
As function of the neutrino Energy



Matter Effects

- If ν cross matter regions (Sun, Earth...) it interacts *coherently*

- But Different flavours
have different interactions :



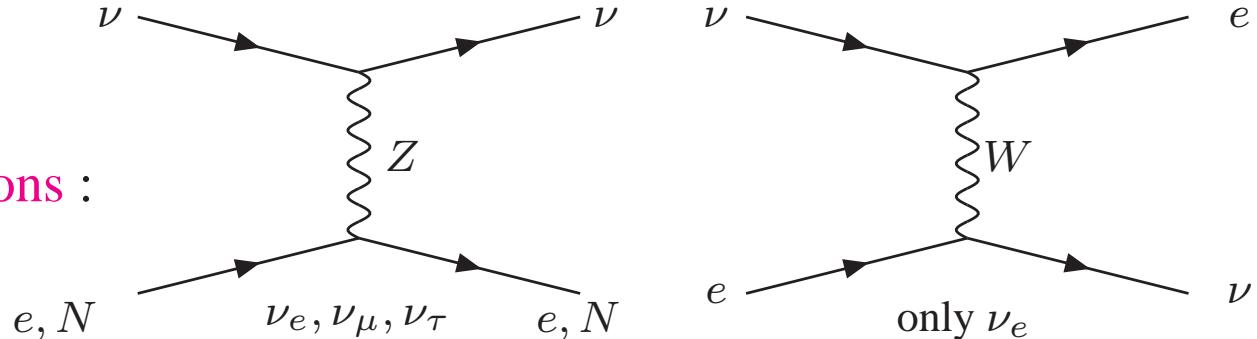
- To include this effect: potential in the evolution equation: $V_e \neq V_\mu$

\Rightarrow *Modification of mixing angle and oscillation wavelength*

Matter Effects

- If ν cross matter regions (Sun, Earth...) it interacts *coherently*

- But Different flavours have different interactions :



- To include this effect: potential in the evolution equation: $V_e \neq V_\mu$

\Rightarrow *Modification of mixing angle and oscillation wavelength*

- The mixing angle in matter

$$\sin(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\sqrt{(\Delta m^2 \cos(2\theta) - A)^2 + (\Delta m^2 \sin(2\theta))^2}}$$

$$A = 2 E (V_\alpha - V_\beta)$$

- When $\Delta m^2 \cos(2\theta) \sim A \Rightarrow$ Enhancement of Oscillation (MSW Effect)

- By 2014 we have observed with high (or good) precision:

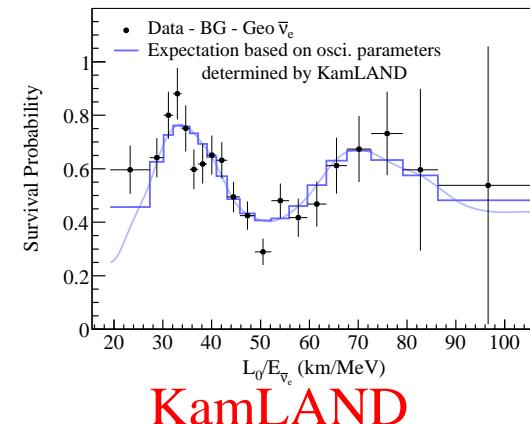
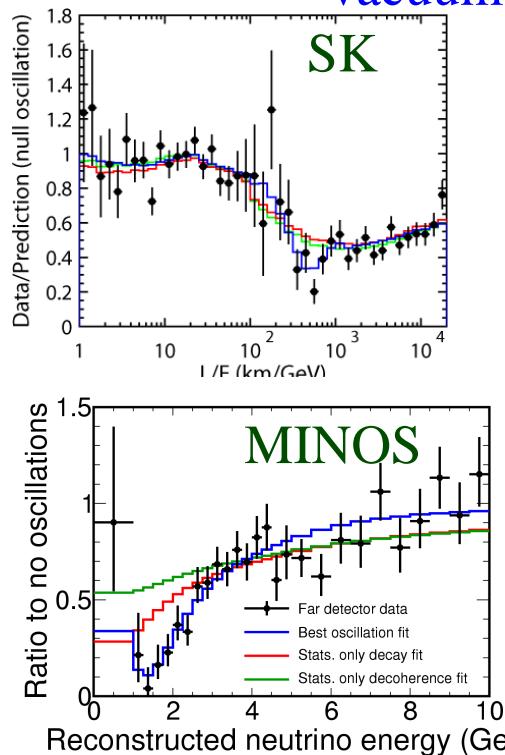
- * Solar ν_e convert to ν_μ/ν_τ (**Cl, Ga, SK, SNO, Borexino**)
- * Reactor $\overline{\nu}_e$ disappear at $L \sim 200$ Km (**KamLAND**)
- * Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK,MINOS**)
- * Accelerator ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 250[700]$ Km (**K2K,T2K, [MINOS]**)
- * Some accel ν_μ appear as ν_e at $L \sim 250[700]$ Km (**T2K [MINOS]**)
- * Reactor $\overline{\nu}_e$ disappear at $L \sim 1$ Km (**D-Chooz, Daya-Bay, Reno**)

- By 2014 we have observed with high (or good) precision:

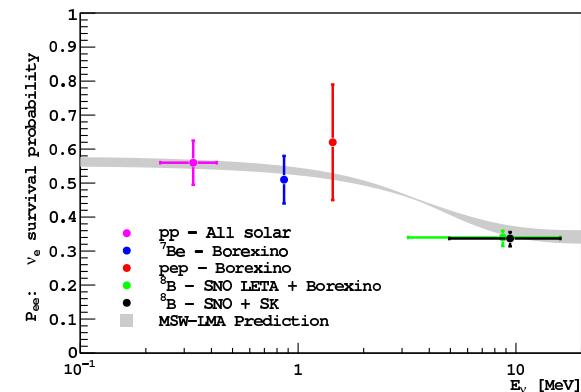
- * Solar ν_e convert to ν_μ/ν_τ (**Cl, Ga, SK, SNO, Borexino**)
- * Reactor $\bar{\nu}_e$ disappear at $L \sim 200$ Km (**KamLAND**)
- * Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK, MINOS**)
- * Accelerator ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 250[700]$ Km (**K2K, T2K, [MINOS]**)
- * Some accel ν_μ appear as ν_e at $L \sim 250[700]$ Km (**T2K [MINOS]**)
- * Reactor $\bar{\nu}_e$ disappear at $L \sim 1$ Km (**D-Chooz, Daya-Bay, Reno**)

- We have confirmed:

Vacuum oscillation L/E pattern



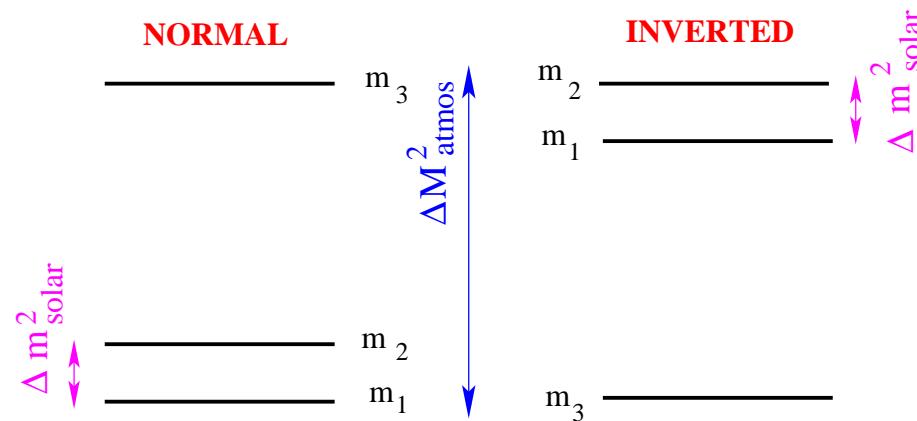
MSW conversion in Sun



3 ν Flavour Parameters

- For 3 ν 's : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

$$U_{\text{LEP}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

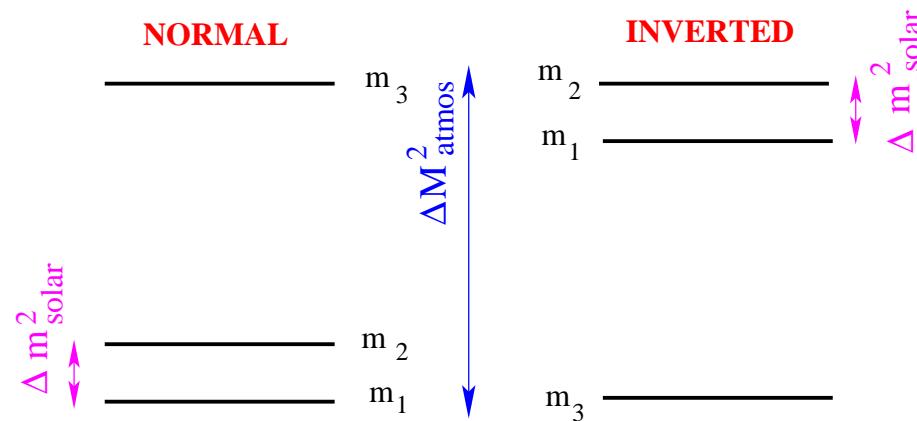


- Two Possible Orderings

3 ν Flavour Parameters

- For 3 ν 's : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

$$U_{\text{LEP}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



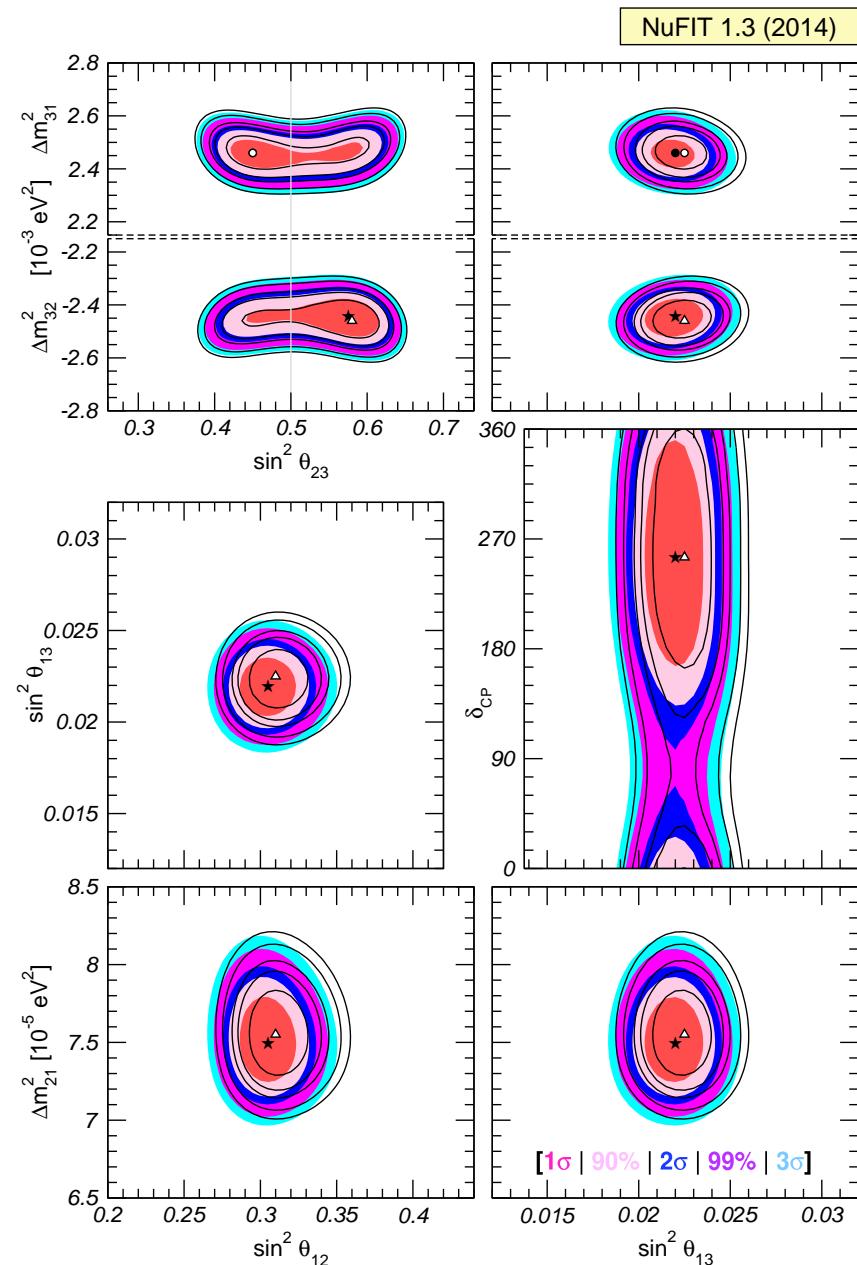
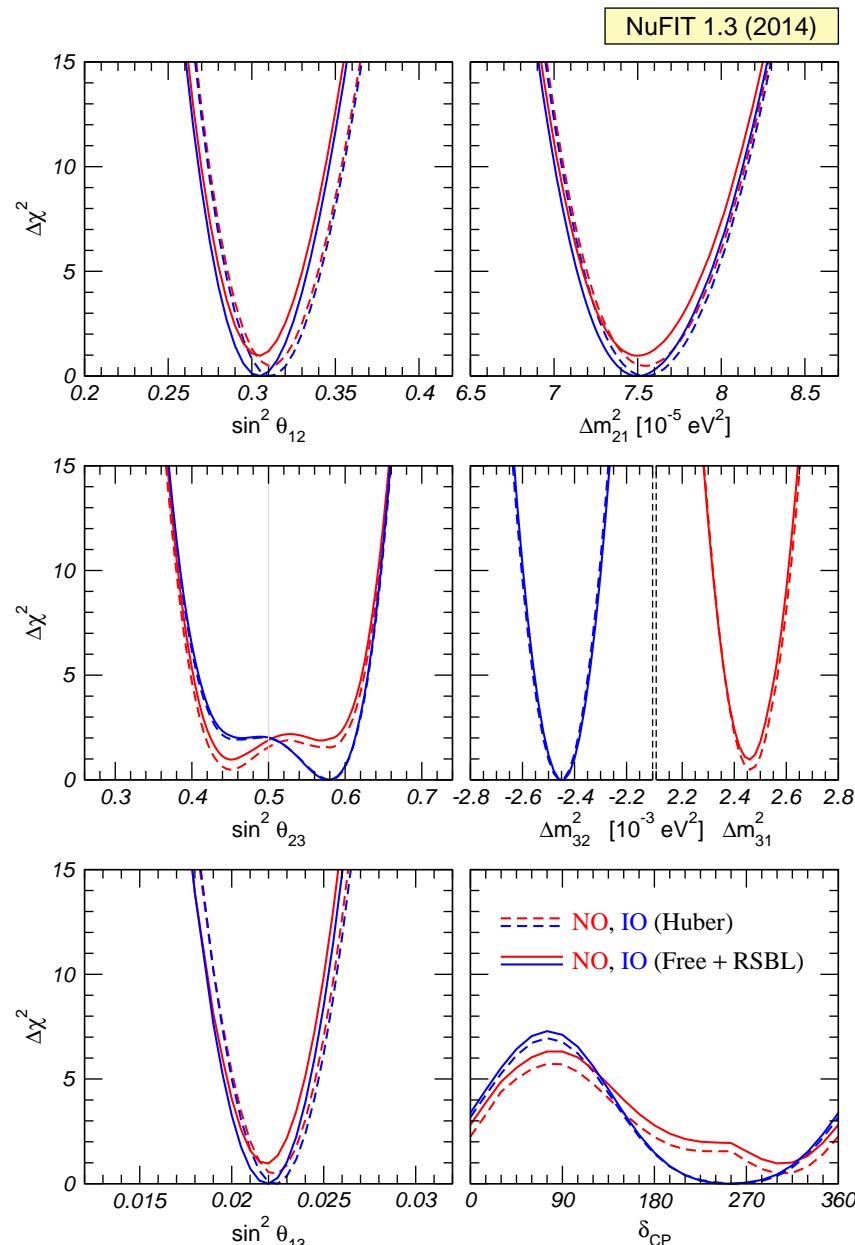
- Two Possible Orderings

Experiment	Dominant Dependence	Important Dependence
Solar Experiments	$\rightarrow \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\rightarrow \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	$\rightarrow \theta_{13}$	Δm^2_{atm}
Atmospheric Experiments	$\rightarrow \theta_{23}$	Δm^2_{atm} , θ_{13} , δ_{CP}
Accelerator LBL ν_μ Disapp (Minos)	$\rightarrow \Delta m^2_{\text{atm}}$	θ_{23}
Accelerator LBL ν_e App (Minos, T2K)	$\rightarrow \theta_{13}$	δ_{CP} , θ_{23}

3 ν Flavour Parameters: Present Status

Global 6-parameter fit <http://www.nu-fit.org>

Maltoni, Schwetz, Salvado, MCGG

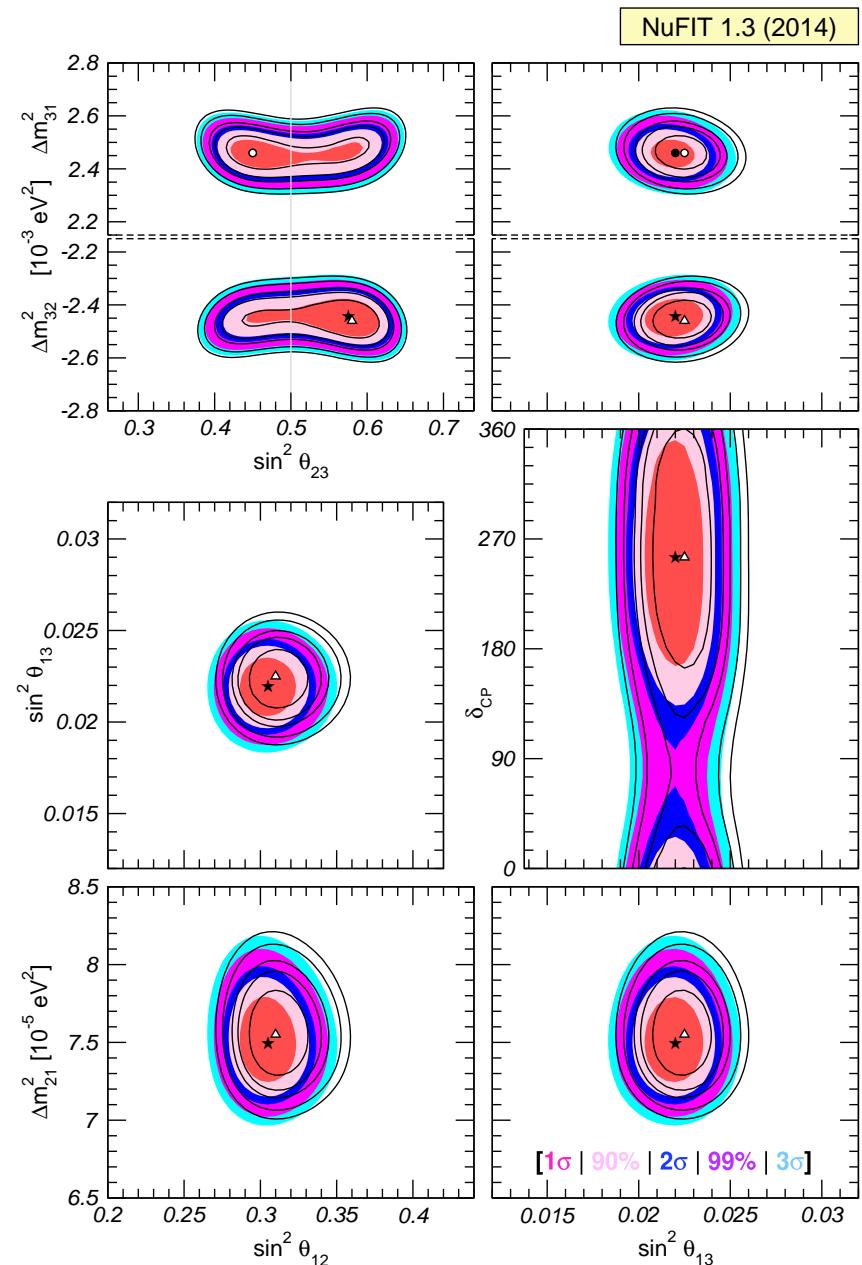
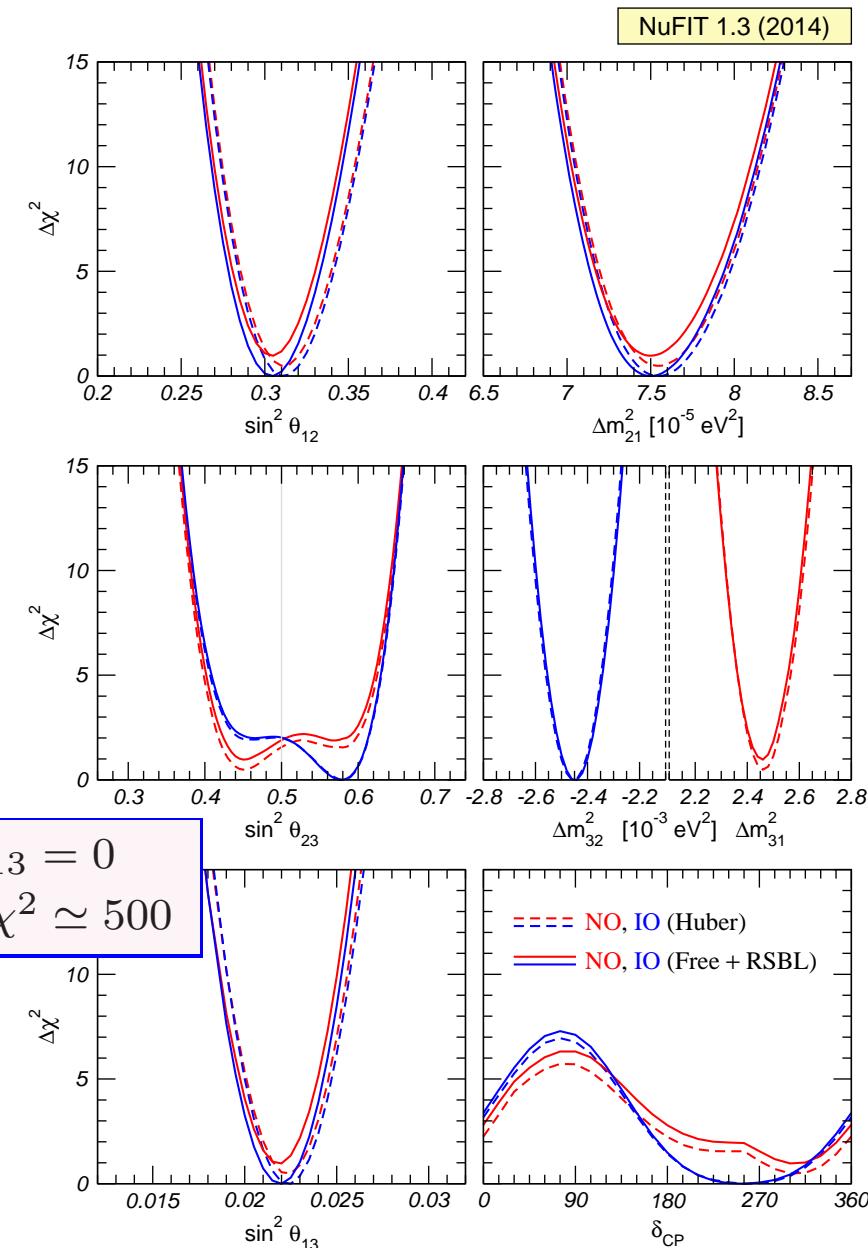


Other analysis: Capuzzi et al arXiv:1312.2878; Forero et al, arXiv:1405.7540; (Talk by A. Palazzo)

3 ν Flavour Parameters: Present Status

Global 6-parameter fit <http://www.nu-fit.org>

Maltoni, Schwetz, Salvado, MCGG

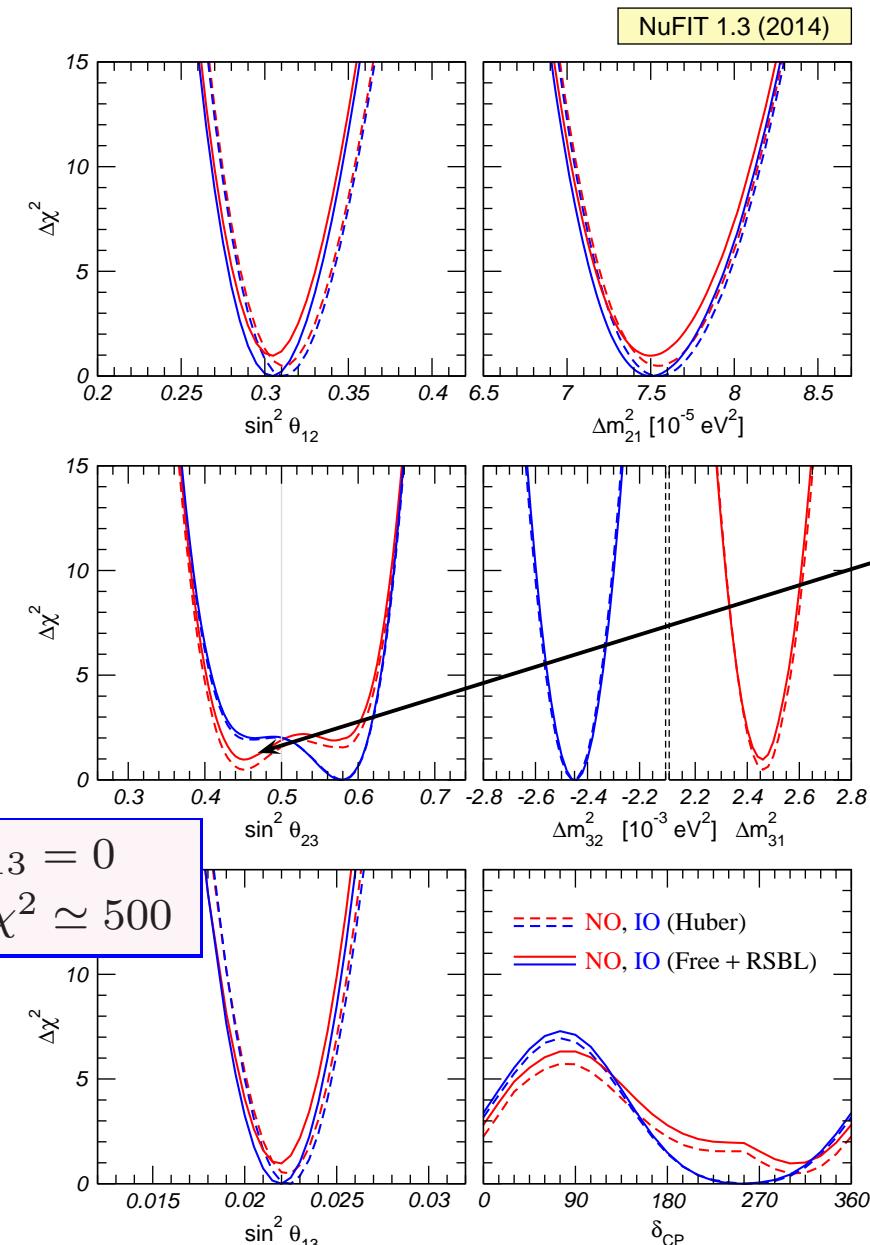


Other analysis: Capuzzi et al arXiv:1312.2878; Forero et al, arXiv:1405.7540; (Talk by A. Palazzo)

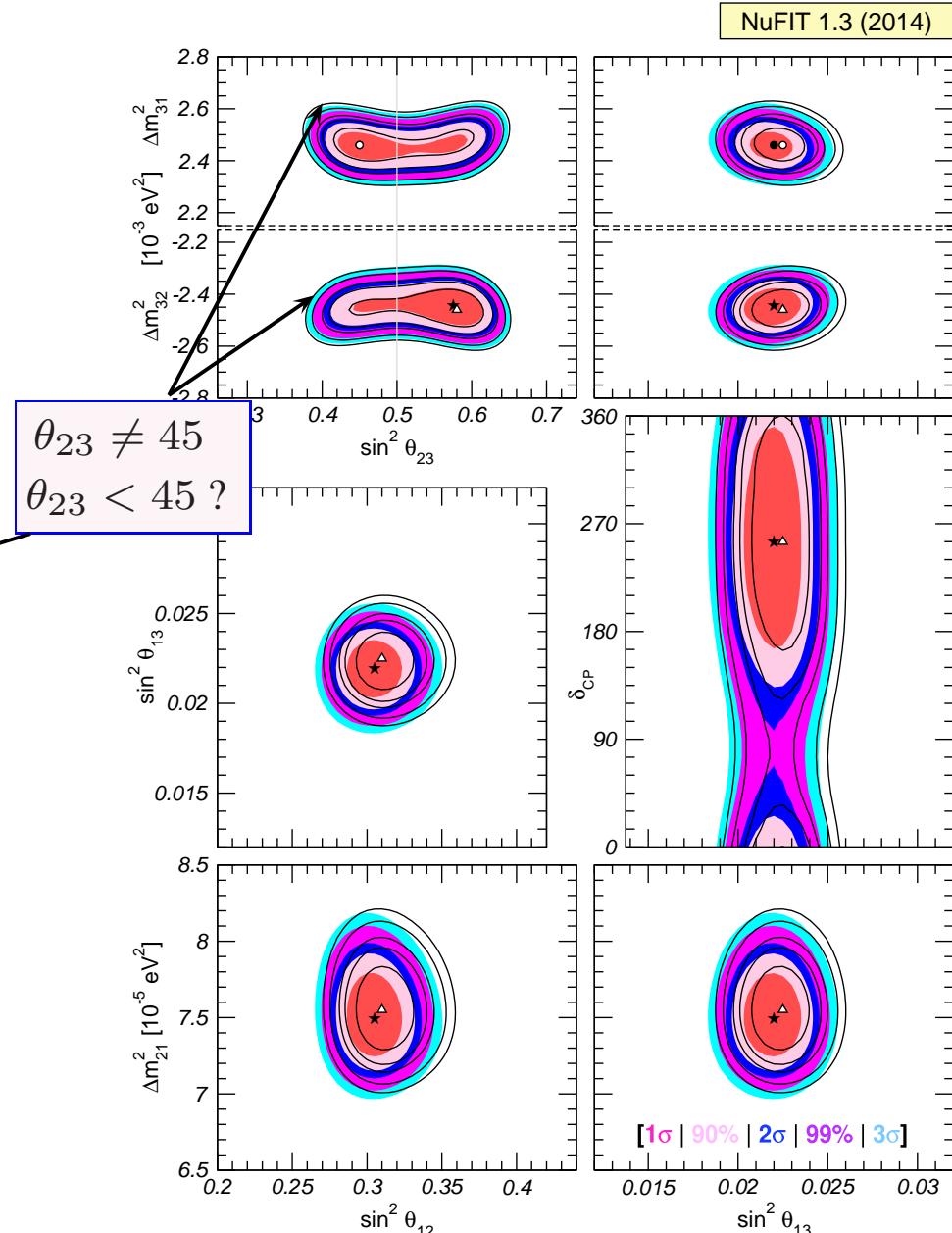
3 ν Flavour Parameters: Present Status

Global 6-parameter fit <http://www.nu-fit.org>

Maltoni, Schwetz, Salvado, MCGG



$\theta_{23} \neq 45^\circ$
 $\theta_{23} < 45^\circ ?$

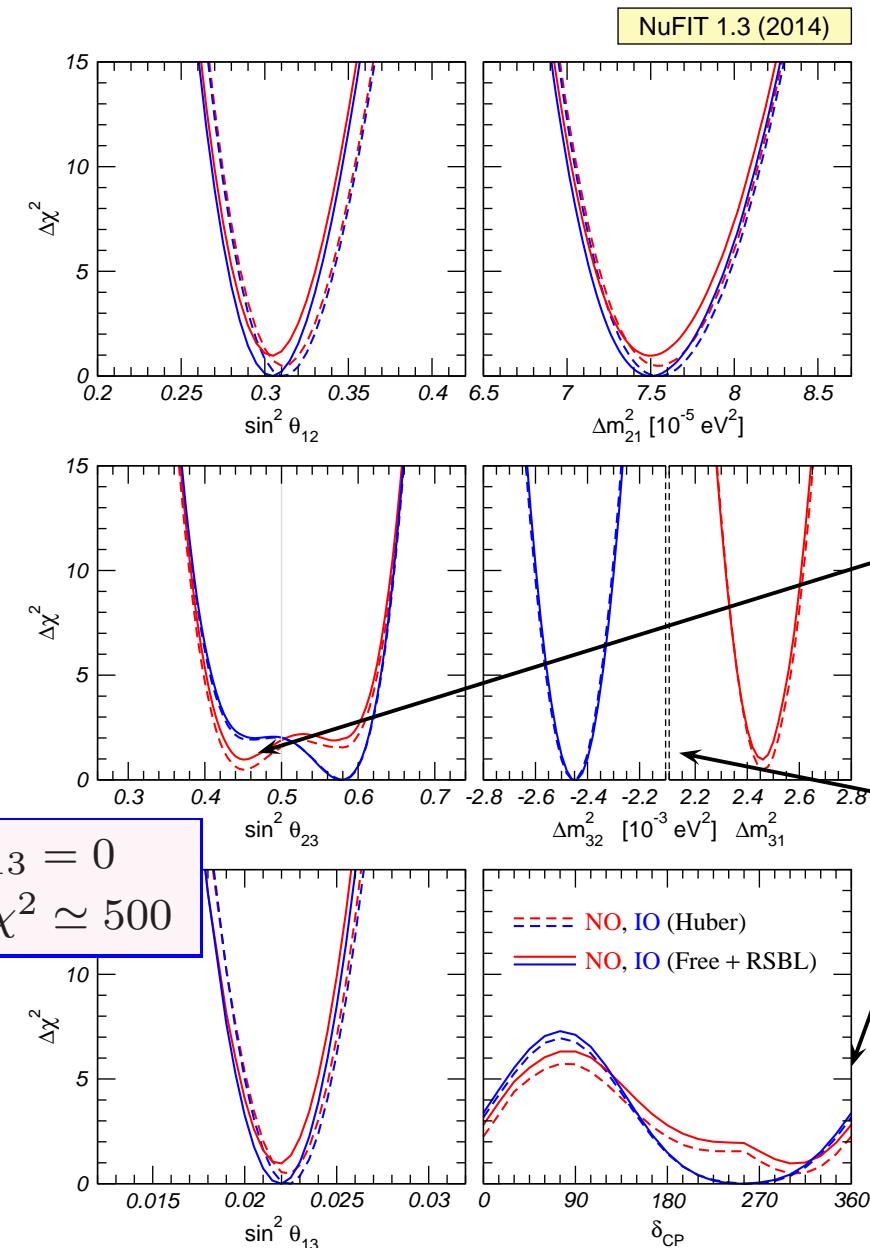


Other analysis: Capuzzi et al arXiv:1312.2878; Forero et al, arXiv:1405.7540; (Talk by A. Palazzo)

3 ν Flavour Parameters: Present Status

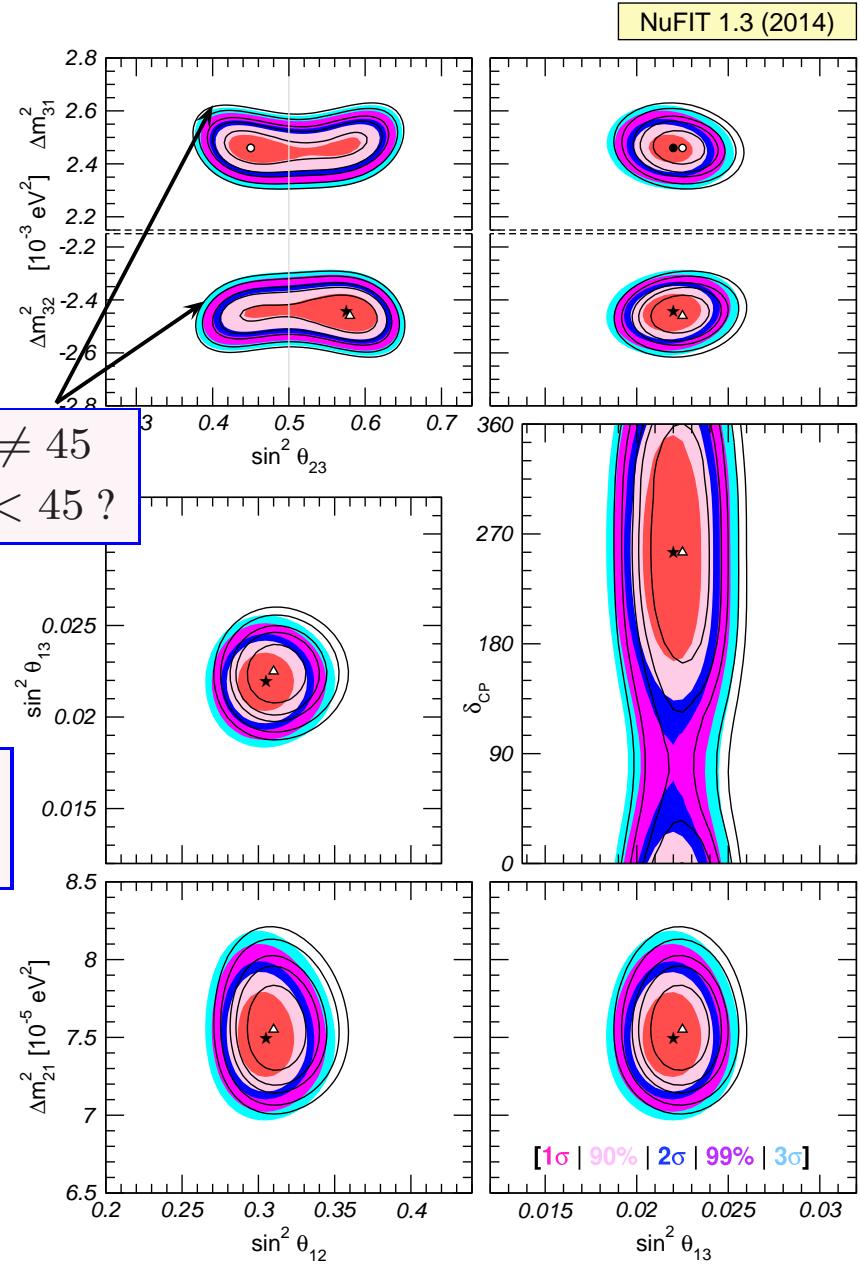
Global 6-parameter fit <http://www.nu-fit.org>

Maltoni, Schwetz, Salvado, MCGG



$\theta_{23} \neq 45^\circ$
 $\theta_{23} < 45^\circ ?$

N/I
 δ_{CP}



Other analysis: Capuzzi et al arXiv:1312.2878; Forero et al, arXiv:1405.7540; (Talk by A. Palazzo)

3 ν Flavour Parameters: Present Status

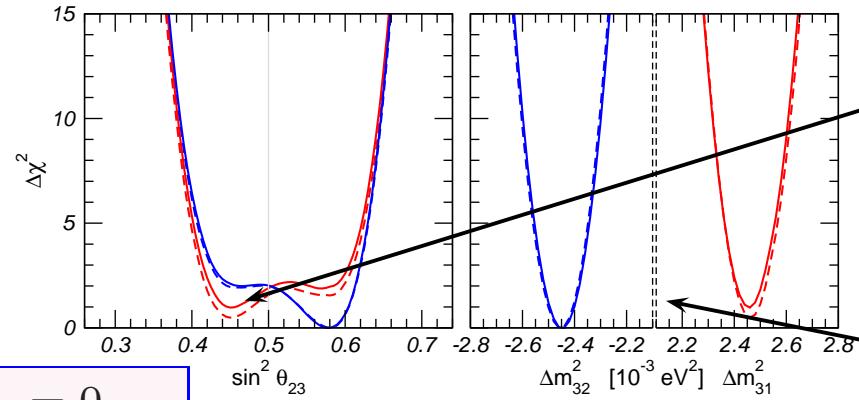
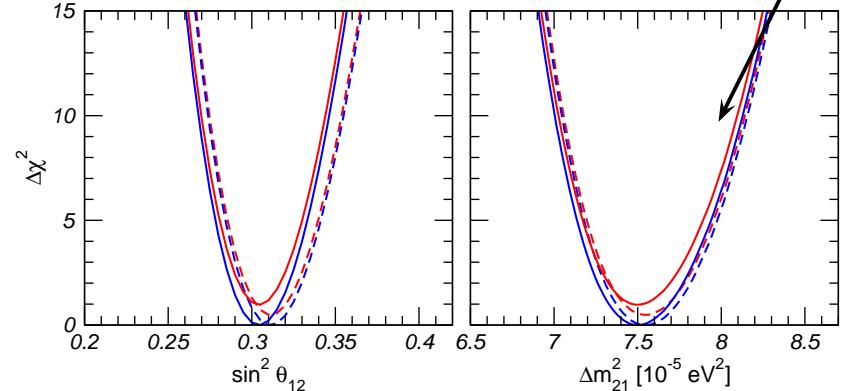
Global 6-parameter fit <http://www.nu-fit.org>

Maltoni, Schwetz, Salvado, MCGG

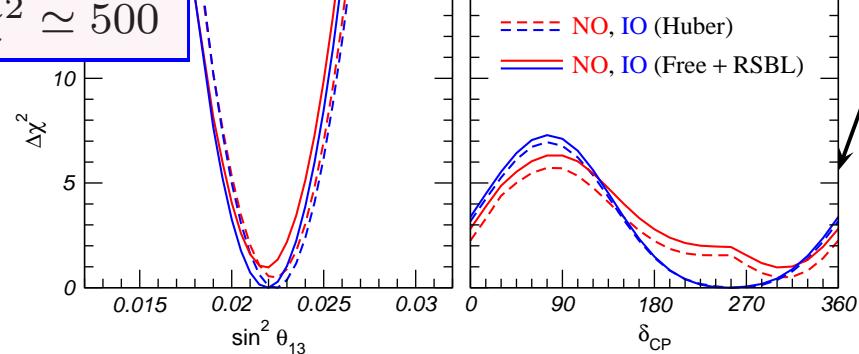
Curves = uncertainty on reactor fluxes

NuFIT 1.3 (2014)

NuFIT 1.3 (2014)

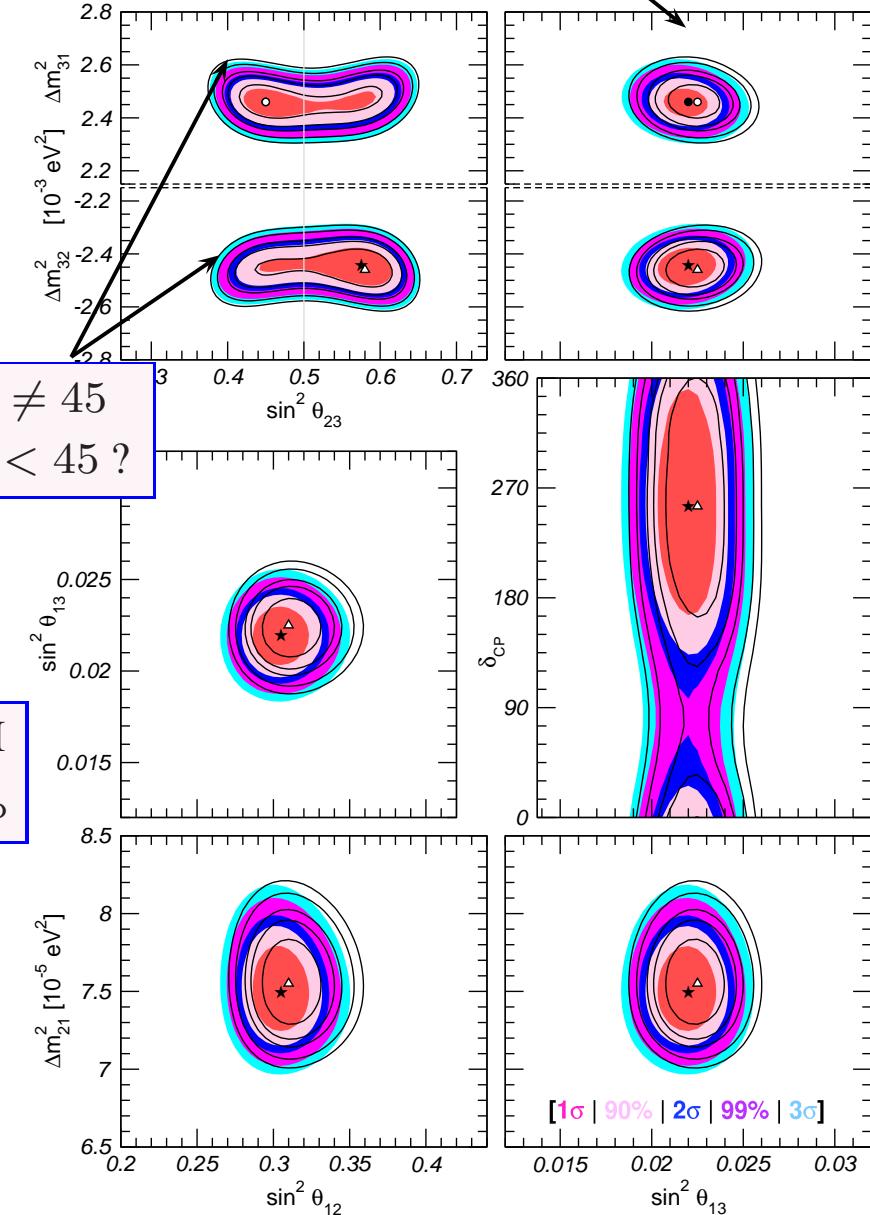


$\theta_{13} = 0$
 $\Delta\chi^2 \approx 500$



$\theta_{23} \neq 45^\circ$
 $\theta_{23} < 45^\circ ?$

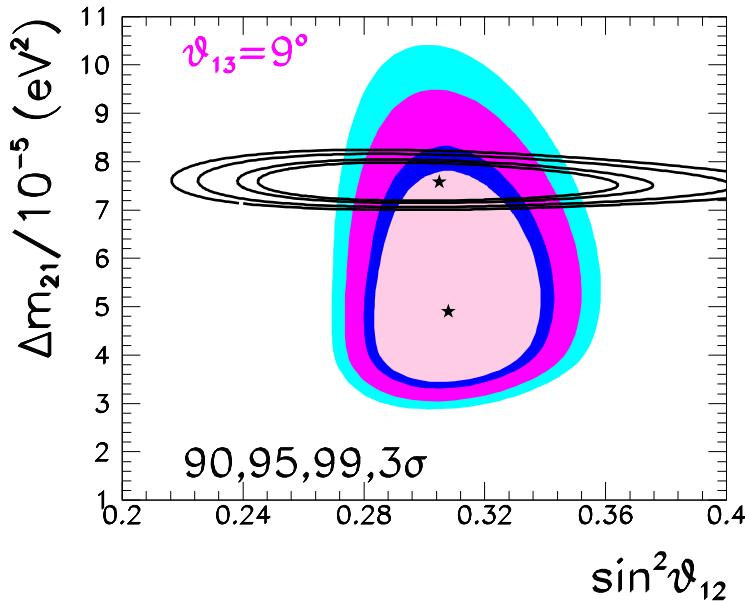
N/I
 δ_{CP}



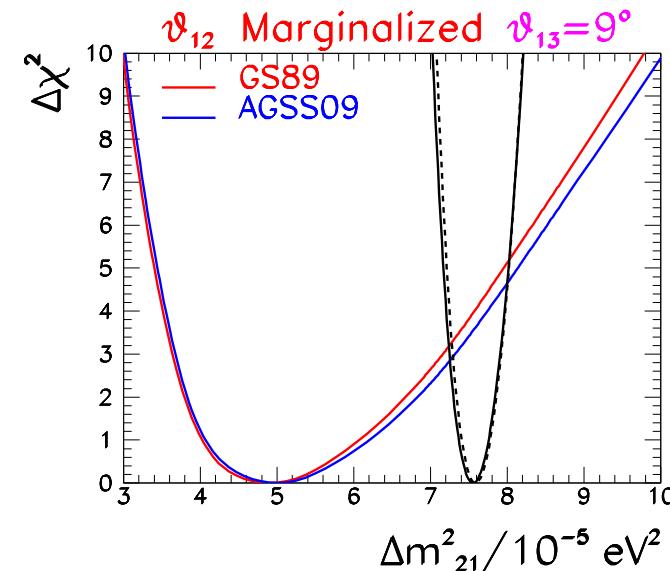
Other analysis: Capuzzi et al arXiv:1312.2878; Forero et al, arXiv:1405.7540; (Talk by A. Palazzo)

“12” sector: KamLAND and SOLAR

For $\theta_{13} \simeq 9^\circ$: θ_{12} OK.

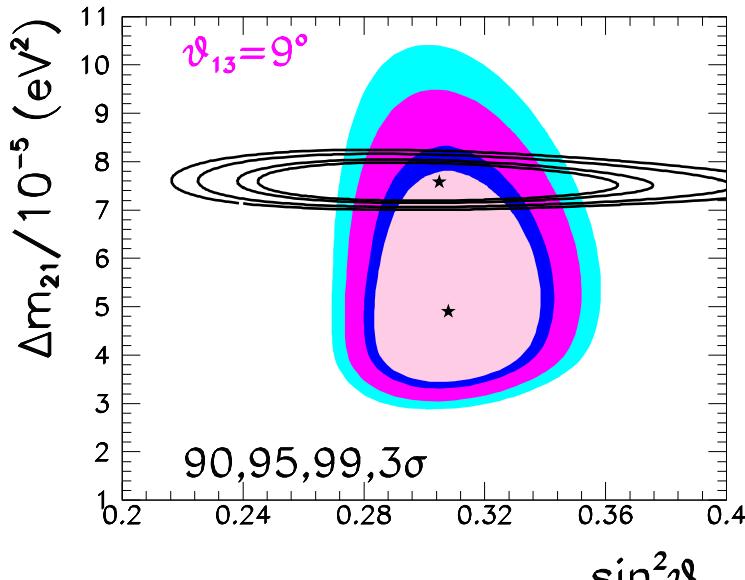


But residual tension on Δm_{12}^2

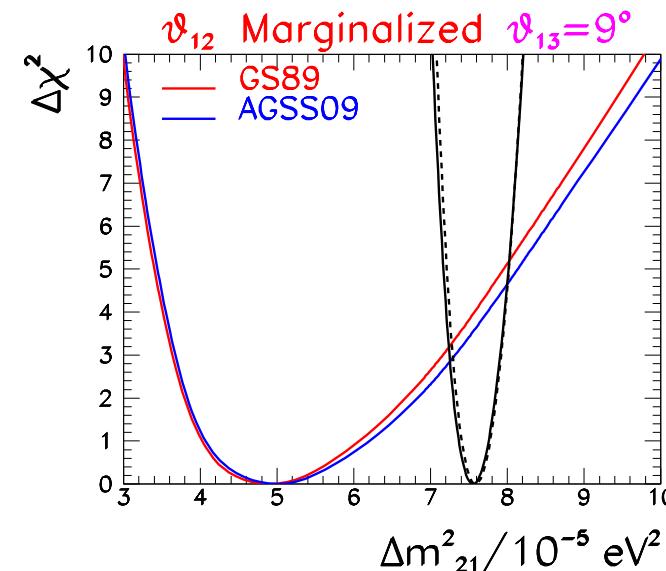


“12” sector: KamLAND and SOLAR

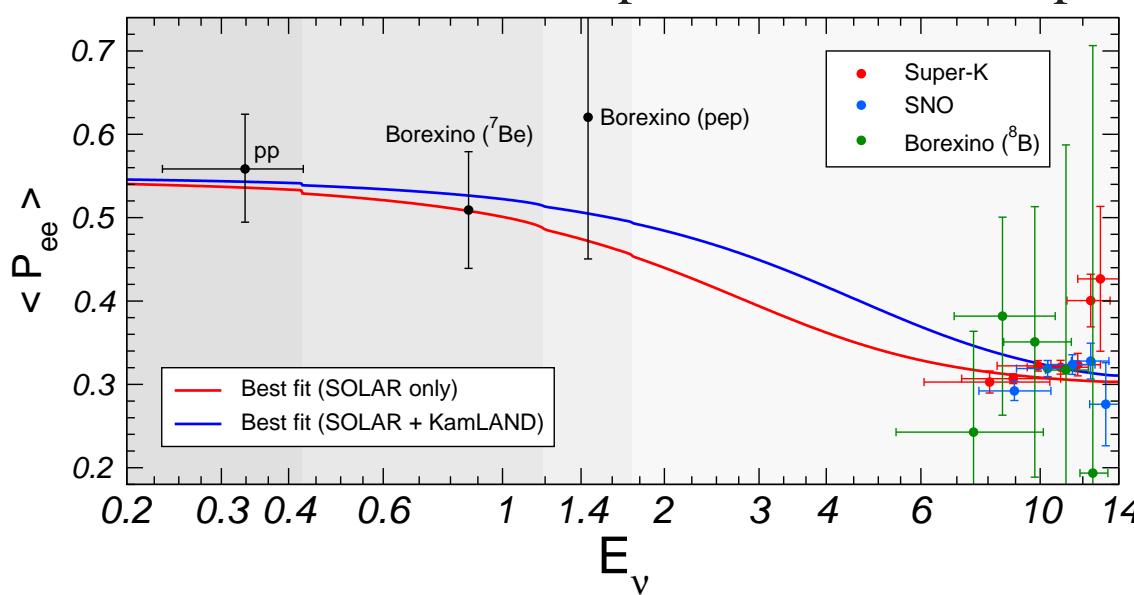
For $\theta_{13} \simeq 9^\circ$: θ_{12} OK.



But residual tension on Δm_{12}^2



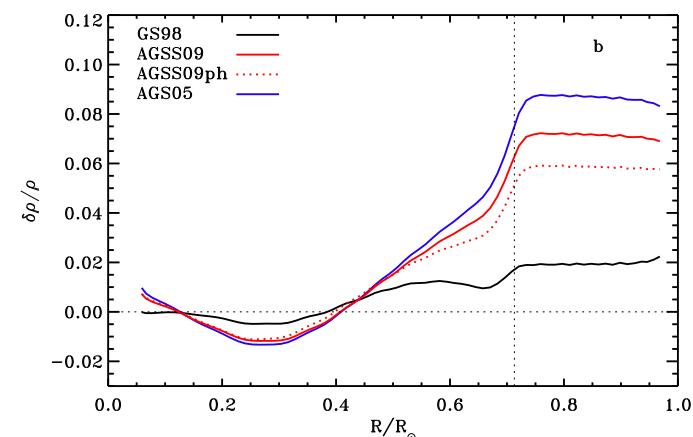
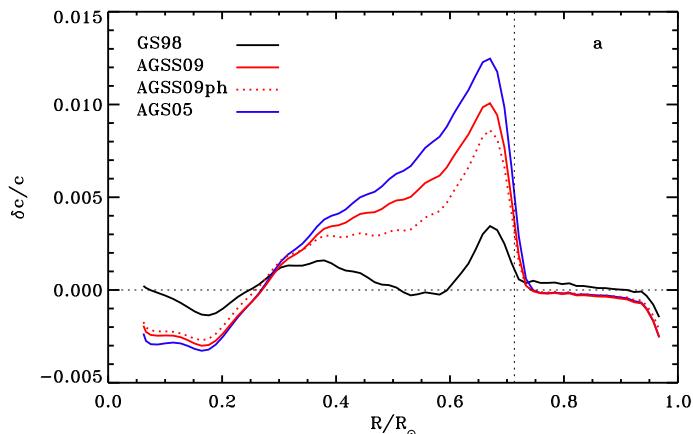
Tension related to smaller-than-expected low-E turn up from MSW at best global fit



More latter...

“12” Sector and the Solar Fluxes

- Newer determination of abundance of heavy elements in solar surface give lower values
- Solar Models with these lower metalicities fail in reproducing helioseismology data
- Two sets of SSM:
Starting from Bahcall *etal* 05, Serenelli *etal* 0909.2668
- GS98** uses older metalicities
- AGSSX** uses newer metalicities



Flux $\text{cm}^{-2} \text{s}^{-1}$	GS98	AGSS09	Diff (%)
pp/ 10^{10}	5.97	6.03 (1 ± 0.005)	0.8
pep/ 10^8	1.41	1.44 (1 ± 0.010)	2.1
hep/ 10^3	7.91	8.18 (1 ± 0.15)	3.4
$^7\text{Be}/10^9$	5.08	4.64 (1 ± 0.06)	8.8
$^8\text{B}/10^6$	5.88	4.85 (1 ± 0.12)	17.7
$^{13}\text{N}/10^8$	2.82	$2.07(1^{+0.14}_{-0.13})$	26.7
$^{15}\text{O}/10^8$	2.09	$1.47(1^{+0.16}_{-0.15})$	30.0
$^{17}\text{F}/10^{16}$	5.65	$3.48(1^{+0.17}_{-0.16})$	38.4

Most difference in CNO fluxes

“12” Sector and the Solar Fluxes

– Two sets of SSM:

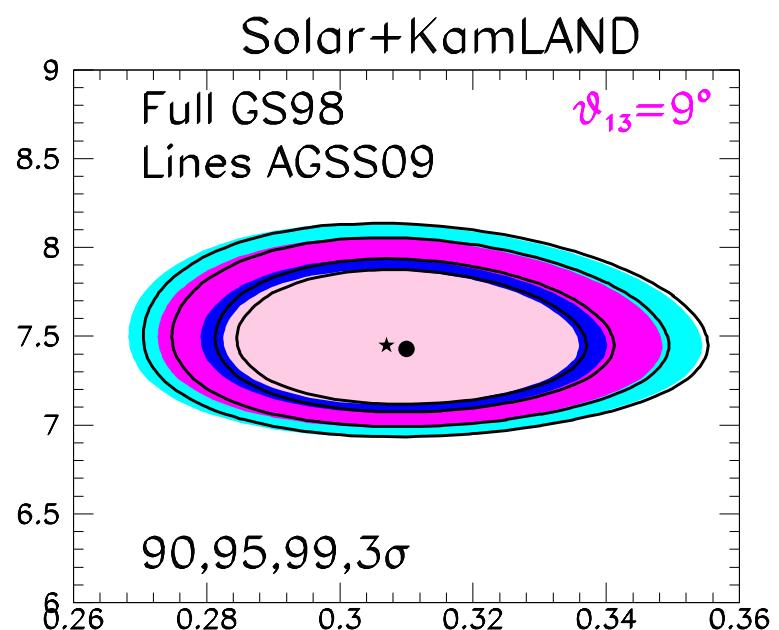
GS98 uses older metallicities

AGSXX uses newer metallicities

* What is the effect on the determination
of oscillation parameters?

Very small

Impact in Parameter Determination



“12” Sector and the Solar Fluxes

– Two sets of SSM:

GS98 uses older metalicities

AGSXX uses newer metalicities

* What is the effect on the determination of oscillation parameters?

Very small

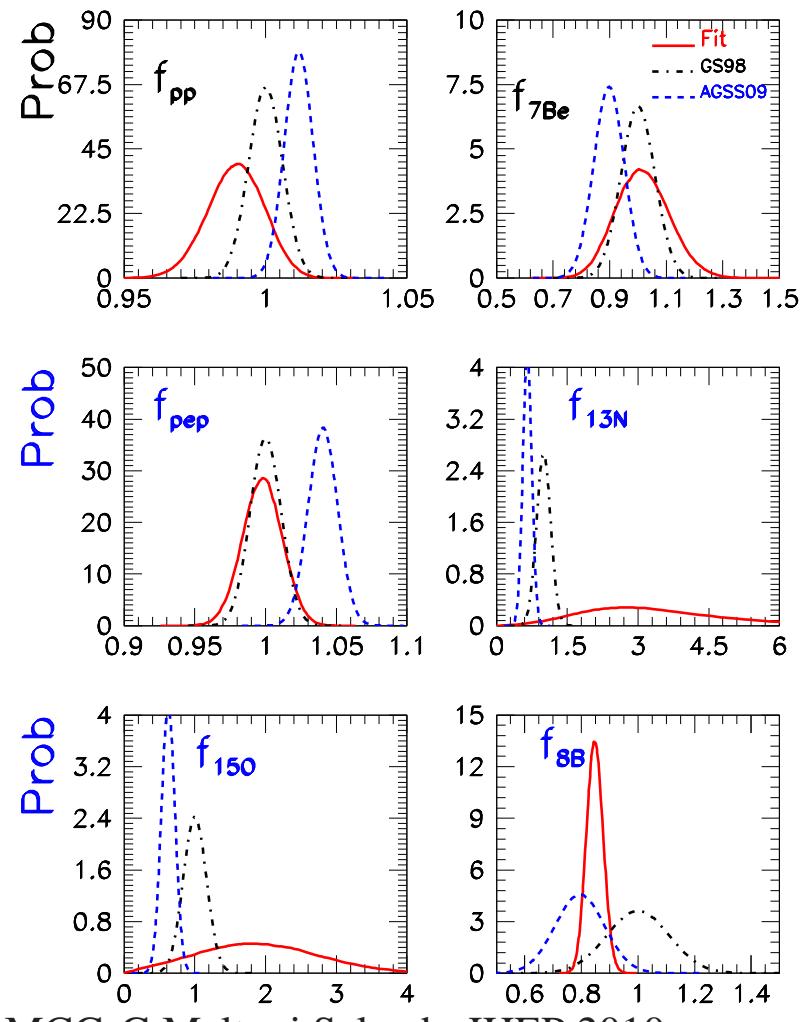
* Which SSM does the solar data favour?
Both model statistically equally prob

Future CNO determined:

Cleaner Borexino, SNO+ (Talk by Meyer)

3ν oscillation fit with solar fluxes free:
(within luminosity constraint)

Comparison with Models



“12” Sector and the Solar Fluxes

– Two sets of SSM:

GS98 uses older metallicities

AGSXX uses newer metallicities

* What is the effect on the determination of oscillation parameters?

Very small

* Which SSM does the solar data favour?
Both model statistically equally prob

Future CNO determined:

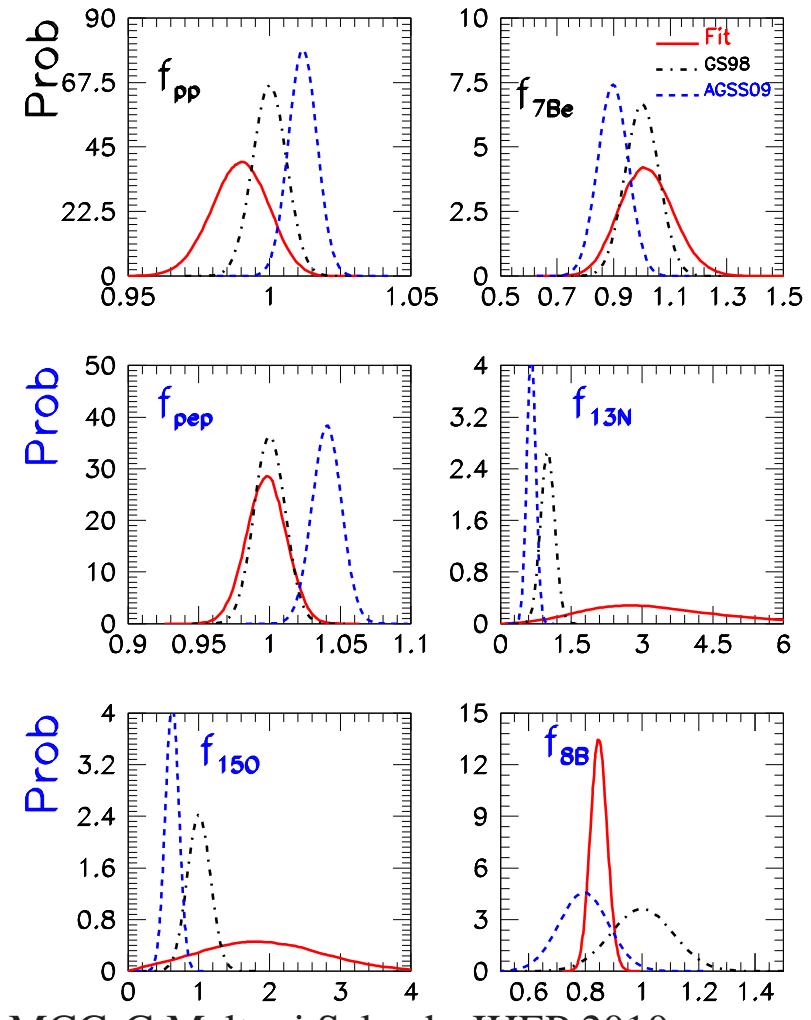
Cleaner Borexino, SNO+ (Talk by Meyer)

– Test of Solar Luminosity:

$$\frac{L_{\odot}(\nu - \text{inferred})}{L_{\odot}} = 1.0 \pm 0.14$$

3ν oscillation fit with solar fluxes free:
(within luminosity constraint)

Comparison with Models

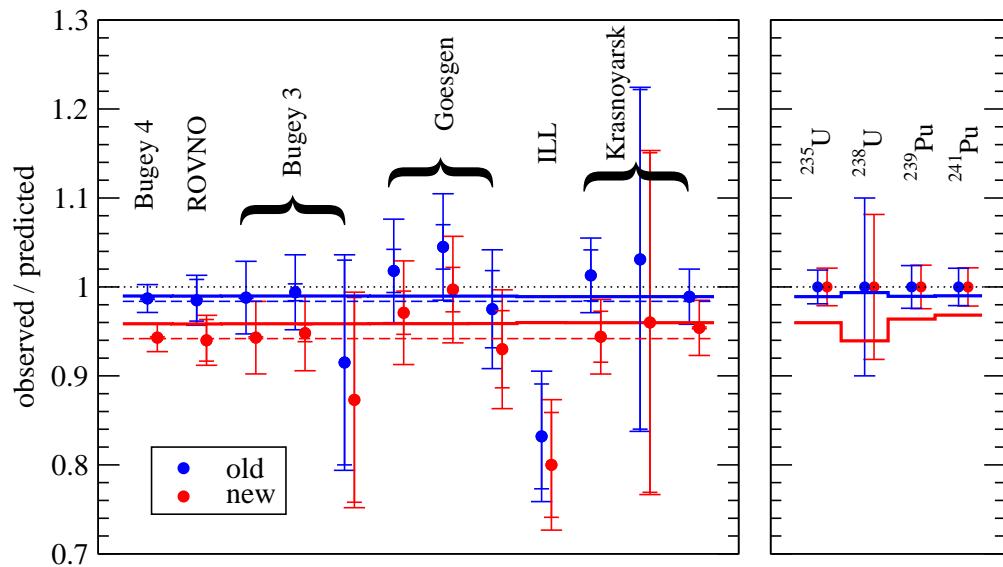


3 ν Analysis: θ_{13} from Reactors and Flux anomaly

- Recently the reactor $\bar{\nu}_e$ fluxes have been recalculated
T.A. Mueller et al., [arXiv:1101.2663].; P. Huber, [arXiv:1106.0687].

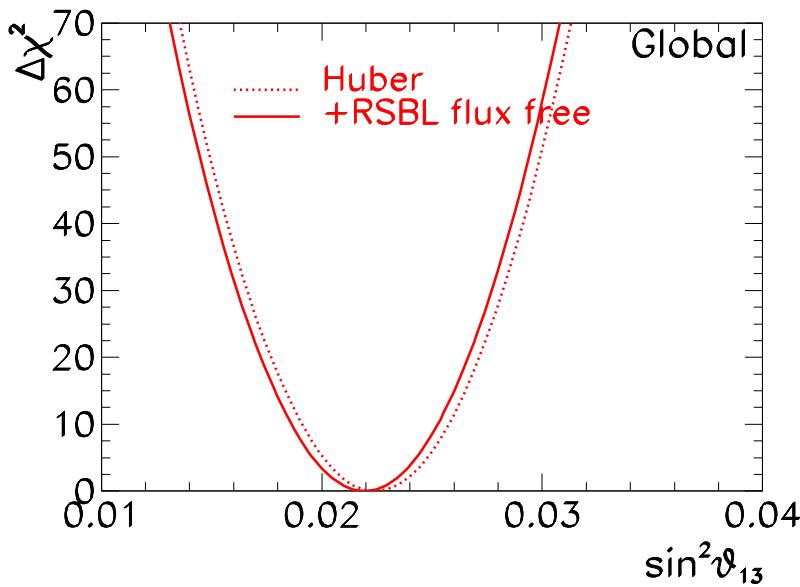
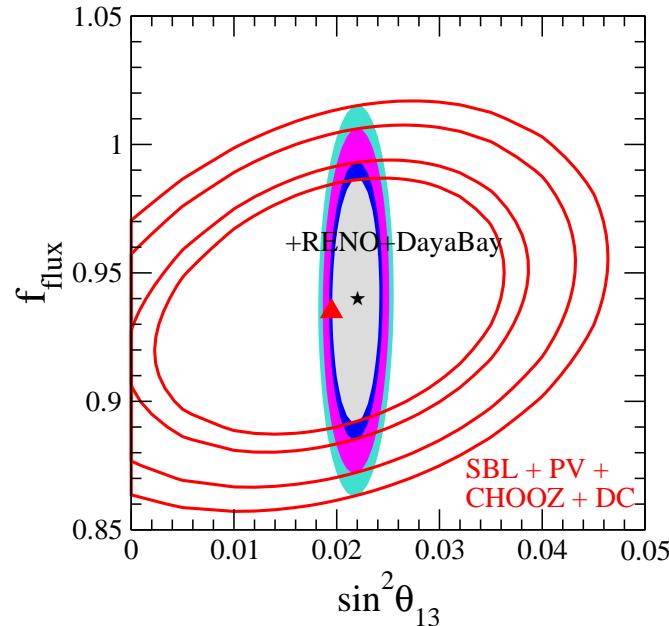
- Both reevaluations find higher fluxes by about 3.5 %

- So *negative* reactor experiments at short baselines (RSBL) indeed observed a deficit



- For 3ν analysis a consistent approach (T. Schwetz et. al. [arXiv:1103.0734]):
- Fit oscillation parameters and reactor fluxes simultaneously
- Use theoretical calculation and/or RSBL data as priors

3 ν Analysis: θ_{13} from Reactors and Flux anomaly



- Experiments without near detector (**CHOOZ, Palo-Verde, D-CHOOZ**) sensitive to the flux assumptions
- **DAYA-BAY and RENO**
Near-Far comparison
⇒ results flux independent
- Two extreme priors :
 - a) Use fluxes from **Huber 1106.0687** without RSBL data
 $\sin^2 \theta_{13} = 0.0223 \pm 0.001$
 - b) Leave flux free and include RSBL
 $\sin^2 \theta_{13} = 0.0219 \pm 0.001$
 Uncertainty at $\sim 0.5\sigma$ level

3 ν Analysis: θ_{13} in Long Baseline vs REACT

- In LBL APP $\nu_\mu \rightarrow \nu_e$

$$P_{\mu e} \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_{\mp}} \right)^2 \sin^2 \left(\frac{B_{\mp} L}{2} \right) + \tilde{J} \frac{\Delta_{12}}{V_E} \frac{\Delta_{31}}{B_{\mp}} \sin \left(\frac{V_E L}{2} \right) \sin \left(\frac{B_{\mp} L}{2} \right) \cos \left(\frac{\Delta_{31} L}{2} \pm \delta_{CP} \right)$$

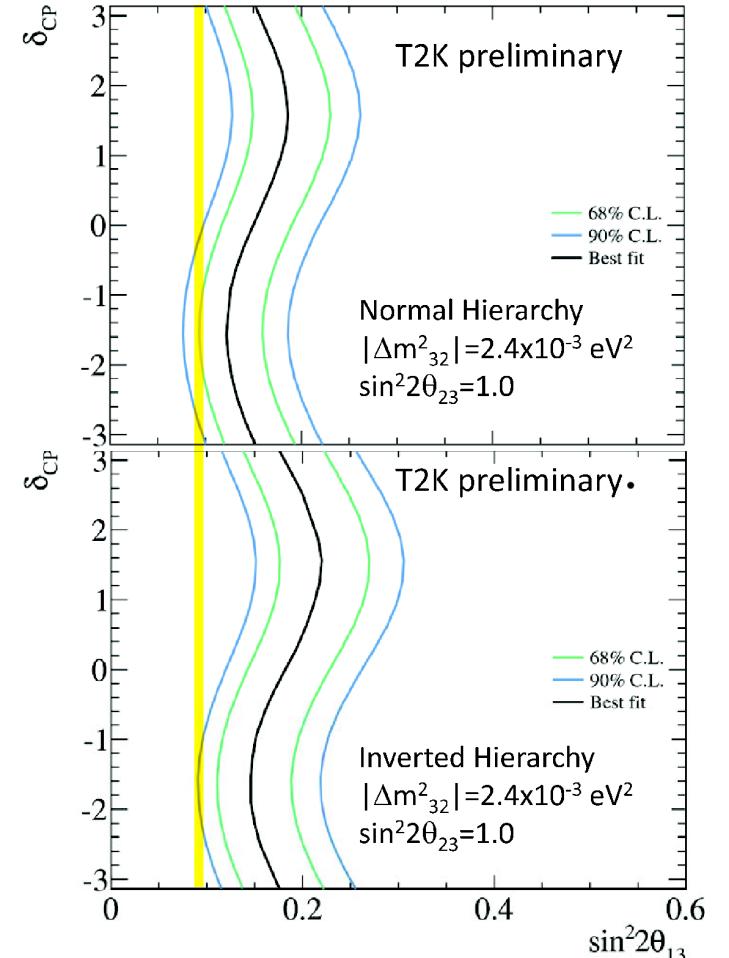
$$B_{\pm} = \Delta_{31} \pm V_E \quad \tilde{J} = c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$

So $\sin^2 2\theta_{APP} = 2 \sin^2 \theta_{23} \sin^2 2\theta_{13}$

- In Reactor $P_{ee} \simeq \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta_{31} L}{2} \right)$

So $\sin^2 2\theta_{REAC} = \sin^2 2\theta_{13}$

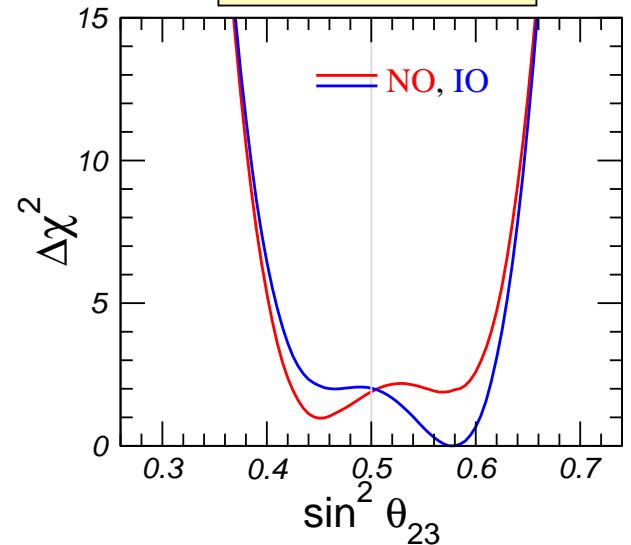
If $\begin{cases} \sin^2 2\theta_{REAC} \leq \sin^2 2\theta_{APP} & \Rightarrow \theta_{23} \geq \frac{\pi}{4} \text{ favoured} \\ \sin^2 2\theta_{REAC} \geq \sin^2 2\theta_{APP} & \Rightarrow \theta_{23} \leq \frac{\pi}{4} \text{ favoured} \end{cases}$



3 ν : θ_{23} Octant and Mass Ordering

NuFIT 1.3 (2014)

- Determination of Octant of θ_{23} :
 - Maximal $\theta_{23} = 45^\circ$ Disfavoured at 1.5σ level
Now mostly driven by MINOS ν_μ DIS
 - NO: $\theta_{23} < 45^\circ$ Favoured at 1.5σ level
Driven by SK I-IV ATM Sub-GeV ν_e excess
Also in MINOS-APP+REACT
 - IO: $\theta_{23} > 45^\circ$ Favoured at 1.7σ level
Driven by T2K-APP+REACT

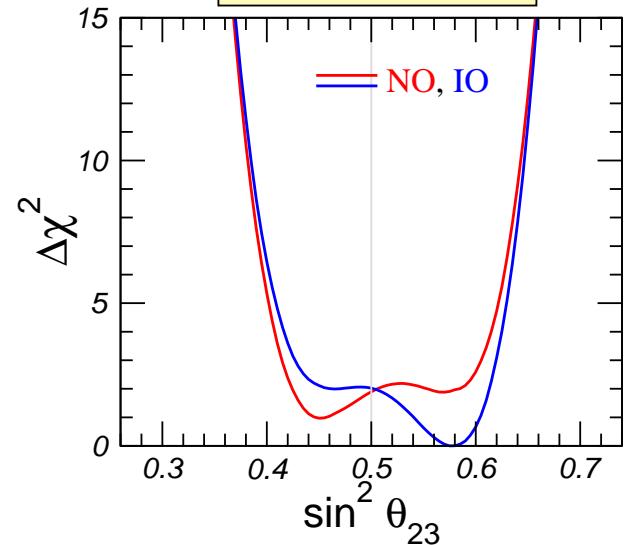


- Determination of Mass Ordering:
 - No significant difference Normal versus Inverted
IO favoured at $0-1\sigma$ level
- Sign and size of these $1-1.5\sigma$ “hints”
vary among analysis

3 ν : θ_{23} Octant and Mass Ordering

NuFIT 1.3 (2014)

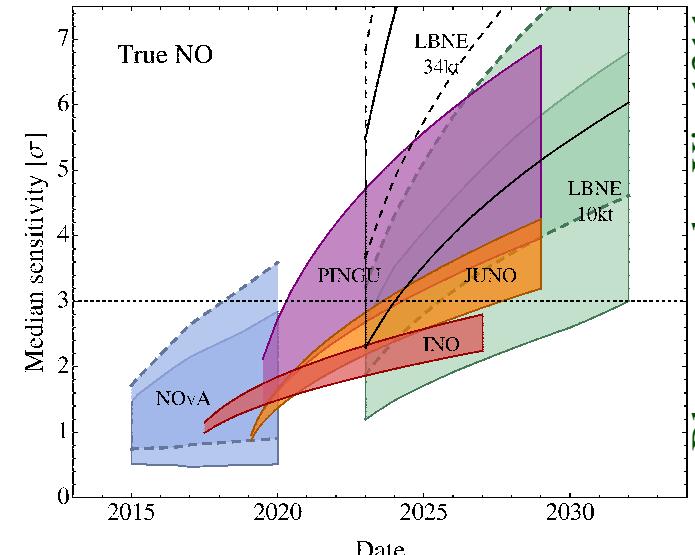
- Determination of Octant of θ_{23} :
 - Maximal $\theta_{23} = 45^\circ$ Disfavoured at 1.5σ level
Now mostly driven by MINOS ν_μ DIS
 - NO: $\theta_{23} < 45^\circ$ Favoured at 1.5σ level
Driven by SK I-IV ATM Sub-GeV ν_e excess
Also in MINOS-APP+REACT
 - IO: $\theta_{23} > 45^\circ$ Favoured at 1.7σ level
Driven by T2K-APP+REACT



- Determination of Mass Ordering:
 - No significant difference Normal versus Inverted
IO favoured at $0-1\sigma$ level
- Sign and size of these $1-1.5\sigma$ “hints”
vary among analysis

Talks by Kearns, Palazzo, Maltoni

Ordering: Future

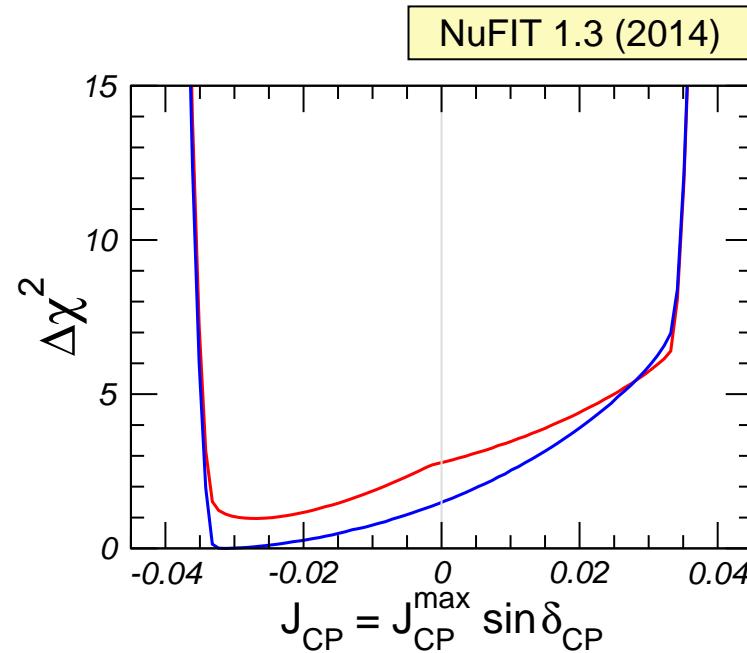
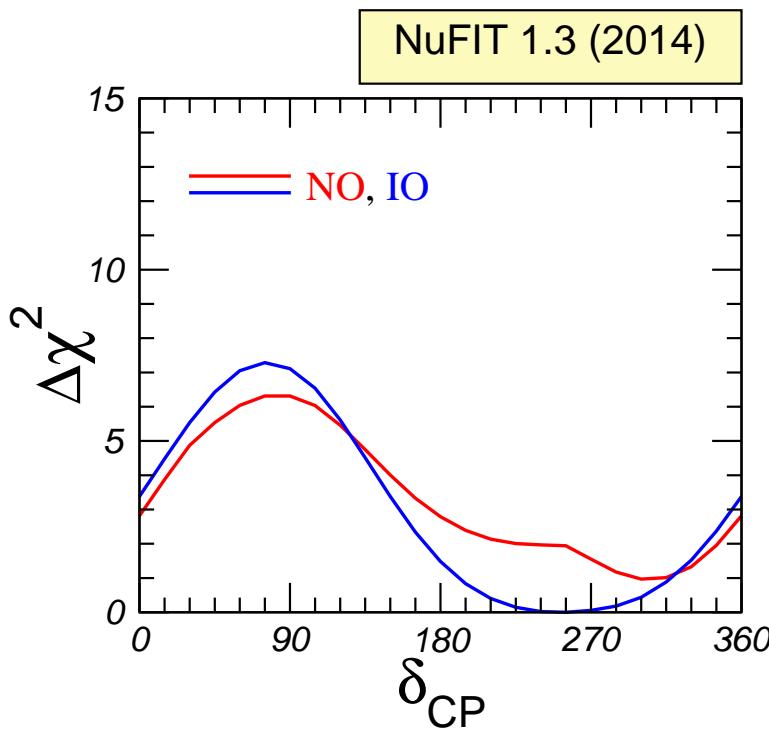


Talks by Sekiya, Cowen

3 ν Analysis: Leptonic CP violation

- Driven by the LBL-APP vs REACT θ_{13} with slight influence of ATM
- Projection over leptonic Jarkskog param

$$J \equiv \sin_{12} \cos_{12} \sin_{23} \cos_{23} \sin_{13} \cos_{13}^2 \sin \delta_{CP}$$



- $\sim 2\sigma$ “Hint” CP phase around $\delta_{CP} = \frac{3\pi}{2}$?
(beware of diff notation for δ_{CP} in literature)

Flavour Parameters: Present Status 1σ (3σ):

$$\begin{aligned}
 \Delta m_{21}^2 &= 7.5 \pm 0.18 \left({}^{+0.56}_{-0.47} \right) \times 10^{-5} \text{ eV}^2 & \theta_{12} &= 33.5^\circ {}^{+0.77}_{-0.74} \left({}^{+2.4}_{-2.2} \right) \\
 \Delta m_{31}^2 (\text{N}) &= 2.46 {}^{+0.05}_{-0.05} \left({}^{+0.14}_{-0.14} \right) \times 10^{-3} \text{ eV}^2 & \theta_{23} &= \begin{cases} (\text{N}) 42.1^\circ {}^{+3.2^\circ}_{-1.5^\circ} \left({}^{+11.1^\circ}_{-3.7^\circ} \right) \\ (\text{I}) 49.4^\circ {}^{+1.6^\circ}_{-2.0^\circ} \left({}^{+3.9^\circ}_{-11.0^\circ} \right) \end{cases} \\
 |\Delta m_{32}^2|(\text{I}) &= 2.49 {}^{+0.05}_{-0.05} \left({}^{+0.14}_{-0.14} \right) \times 10^{-3} \text{ eV}^2 & \theta_{13} &= 8.5^\circ {}^{+0.19}_{-0.17} \left({}^{+0.6^\circ}_{-0.5^\circ} \right) \\
 && \delta_{\text{CP}} &= \begin{cases} (\text{N}) 300^\circ {}^{+45^\circ}_{-45^\circ} \left({}^{+60^\circ}_{-300^\circ} \right) \\ (\text{I}) 251^\circ {}^{+67^\circ}_{-59^\circ} \left({}^{+109^\circ}_{-251^\circ} \right) \end{cases}
 \end{aligned}$$

$$|U|_{\text{LEP}(3\sigma)} = \begin{pmatrix} 0.801 \rightarrow 0.845 & 0.514 \rightarrow 0.580 & 0.137 \rightarrow 0.158 \\ 0.225 \rightarrow 0.517 & 0.441 \rightarrow 0.700 & 0.614 \rightarrow 0.793 \\ 0.246 \rightarrow 0.529 & 0.464 \rightarrow 0.713 & 0.590 \rightarrow 0.776 \end{pmatrix}$$

Flavour Parameters: Present Status 1σ (3σ):

$$\begin{aligned}
 \Delta m_{21}^2 &= 7.5 \pm 0.18 \left({}^{+0.56}_{-0.47} \right) \times 10^{-5} \text{ eV}^2 & \theta_{12} &= 33.5^\circ {}^{+0.77}_{-0.74} \left({}^{+2.4}_{-2.2} \right) \\
 \Delta m_{31}^2(\text{N}) &= 2.46 {}^{+0.05}_{-0.05} \left({}^{+0.14}_{-0.14} \right) \times 10^{-3} \text{ eV}^2 & \theta_{23} &= \begin{cases} (\text{N}) 42.1^\circ {}^{+3.2^\circ}_{-1.5^\circ} \left({}^{+11.1^\circ}_{-3.7^\circ} \right) \\ (\text{I}) 49.4^\circ {}^{+1.6^\circ}_{-2.0^\circ} \left({}^{+3.9^\circ}_{-11.0^\circ} \right) \end{cases} \\
 |\Delta m_{32}^2|(\text{I}) &= 2.49 {}^{+0.05}_{-0.05} \left({}^{+0.14}_{-0.14} \right) \times 10^{-3} \text{ eV}^2 & \theta_{13} &= 8.5^\circ {}^{+0.19}_{-0.17} \left({}^{+0.6^\circ}_{-0.5^\circ} \right) \\
 && \delta_{\text{CP}} &= \begin{cases} (\text{N}) 300^\circ {}^{+45^\circ}_{-45^\circ} \left({}^{+60^\circ}_{-300^\circ} \right) \\ (\text{I}) 251^\circ {}^{+67^\circ}_{-59^\circ} \left({}^{+109^\circ}_{-251^\circ} \right) \end{cases}
 \end{aligned}$$

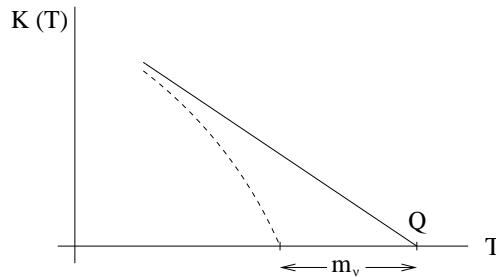
$$|U|_{\text{LEP}(3\sigma)} = \begin{pmatrix} 0.801 \rightarrow 0.845 & 0.514 \rightarrow 0.580 & 0.137 \rightarrow 0.158 \\ 0.225 \rightarrow 0.517 & 0.441 \rightarrow 0.700 & 0.614 \rightarrow 0.793 \\ 0.246 \rightarrow 0.529 & 0.464 \rightarrow 0.713 & 0.590 \rightarrow 0.776 \end{pmatrix}$$

- Good progress but still precision very far from:

$$|V|_{\text{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2 {}^{+1.1}_{-5}) \times 10^{-3} \\ (8.67 {}^{+0.29}_{-0.31}) \times 10^{-3} & (40.4 {}^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146 {}^{+0.000021}_{-0.000046} \end{pmatrix}$$

Neutrino Mass Scale

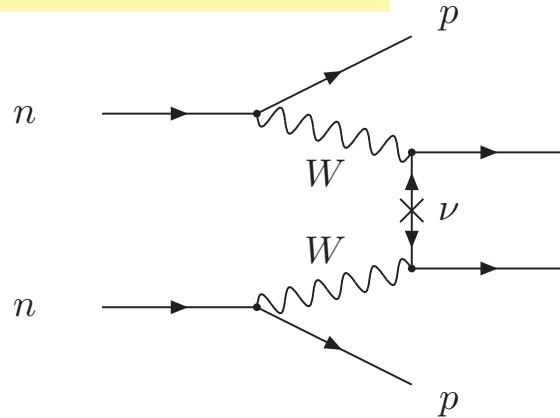
Single β decay : Dirac or Majorana ν mass modify spectrum endpoint



$$m_{\nu_e}^2 = \sum m_j^2 |U_{ej}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2$$

ν -less Double- β decay: \Leftrightarrow Majorana ν' s sensitive to Majorana phases

If m_ν only source of ΔL $(T_{1/2}^{0\nu})^{-1} \propto (m_{ee})^2$



$$\begin{aligned} m_{ee} &= \left| \sum U_{ej}^2 m_j \right| \\ &= \left| c_{13}^2 c_{12}^2 m_1 e^{i\eta_1} + c_{13}^2 s_{12}^2 m_2 e^{i\eta_2} + s_{13}^2 m_3 e^{-i\delta_{CP}} \right| \end{aligned}$$

COSMO Neutrino mass (Dirac or Majorana) modify the growth of structures

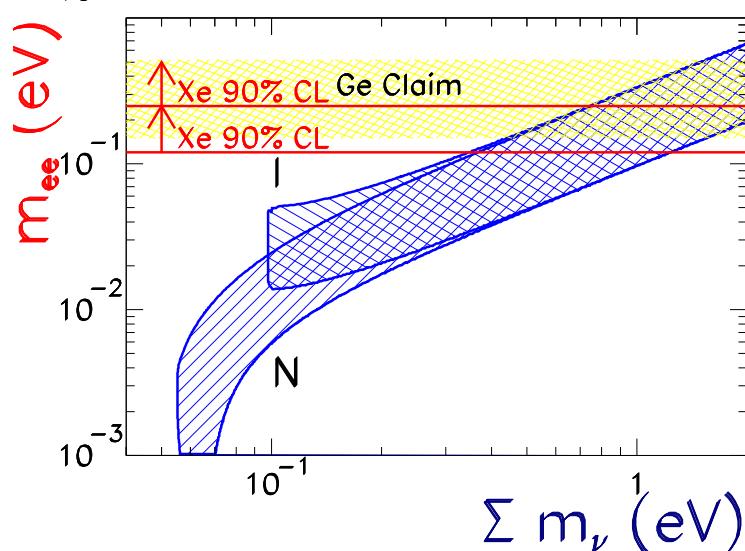
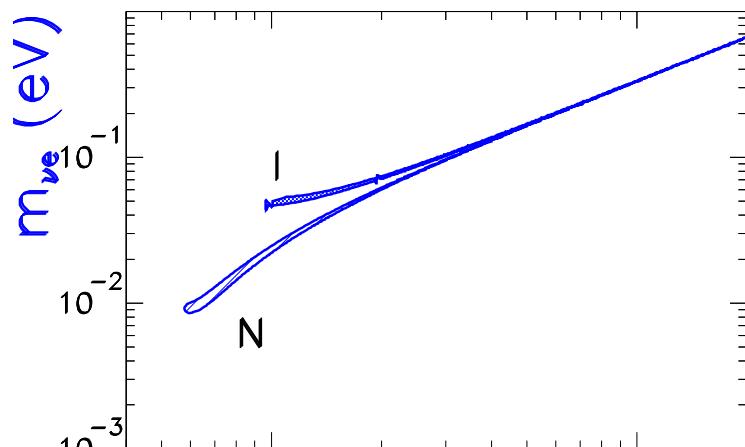
$$\sum m_i$$

Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis

⇒ Correlations m_{ν_e} , m_{ee} and $\sum m_\nu$
(Fogli et al (04))

Maltoni, Schwetz, Salvado, MCGG (95%)

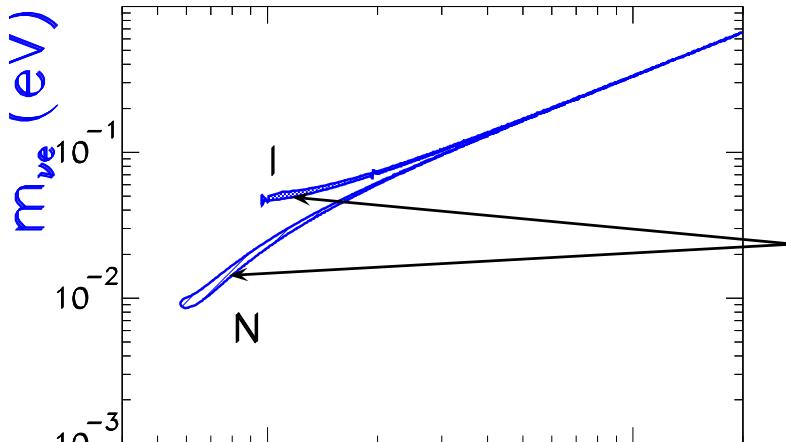


Neutrino Mass Scale: The Cosmo-Lab Connection

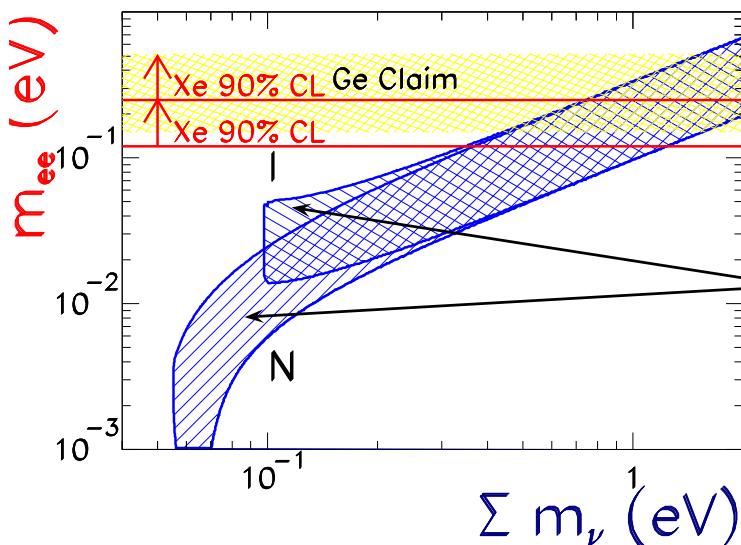
Global oscillation analysis

⇒ Correlations m_{ν_e} , m_{ee} and $\sum m_\nu$
(Fogli et al (04))

Maltoni, Schwetz, Salvado, MCGG (95%)



Width due to range in oscillation parameters very narrow
High precision determination of m_{ν_e} and $\sum m_i$ can give information on ordering



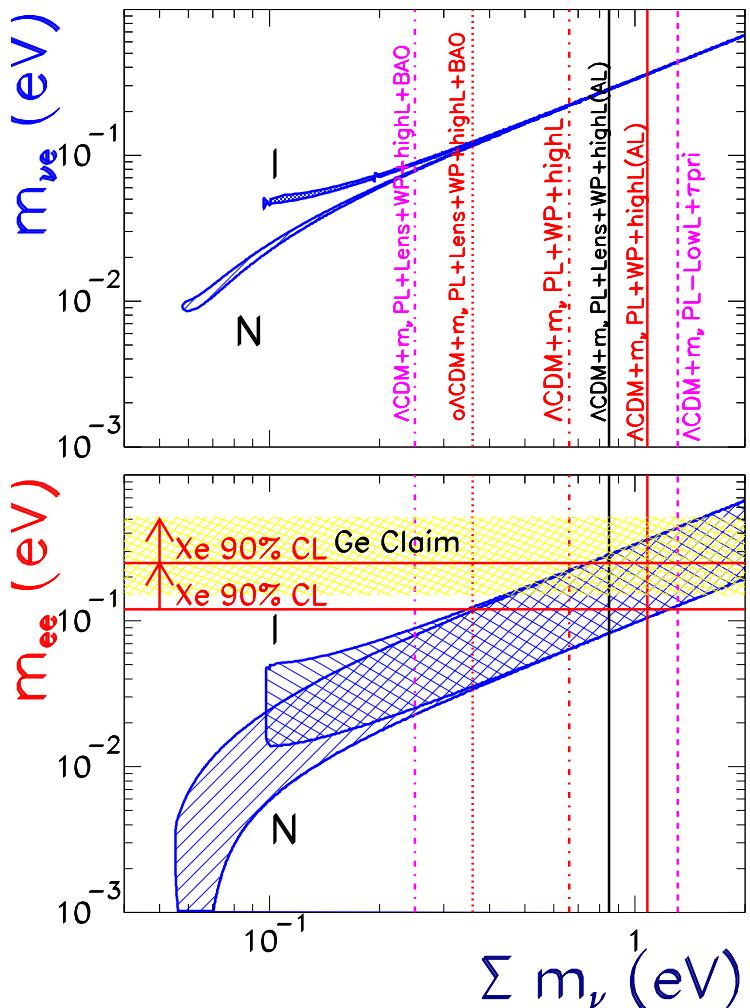
Wide band due to unknown Majorana phases

Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis

⇒ Correlations m_{ν_e} , m_{ee} and $\sum m_\nu$
 (Fogli *et al* hep-ph/0408045)

Maltoni, Schwetz, Salvado, MCGG (95%)



Presently only Bounds

- From Tritium β decay (Mainz & Troisk expe)
 $m_{\nu_e} < 2.2$ eV (95%)
 Katrin (2016?) Sensitivity to $m_{\nu_e} \sim 0.2$ eV
- From $0\nu\beta\beta$ decay (EXO, KL and ZEN...):
 $m_{ee} < 0.14 - 0.45$ eV (90%)
 In 5-10 yr Experiments $\Rightarrow m_{ee} \sim 0.015$ eV
- From Analysis of Cosmological data
 Bound on $\sum m_\nu$ changes with:
 cosmo parameters fix in analysis
 cosmo observables considered

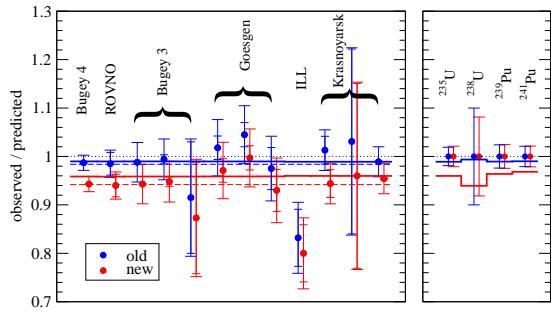
Model	Observables	Σm_ν (eV) 95%
Λ CDM + m_ν	Planck-lowL+ τ prior	≤ 1.31
Λ CDM + m_ν	Planck+WP+highL(A_L)	≤ 1.08
Λ CDM + m_ν	Planck+Lens+WP+highL(A_L)	≤ 0.85
Λ CDM + m_ν	Planck+WP+highL	≤ 0.66
$o\Lambda$ CDM + m_ν	Planck+WP+highL	≤ 0.98
Λ CDM + m_ν	Planck+Lens+WP+highL+BAO	≤ 0.25
$o\Lambda$ CDM + m_ν	Planck+Lens+WP+highL+BAO	≤ 0.36

Light Sterile Neutrinos

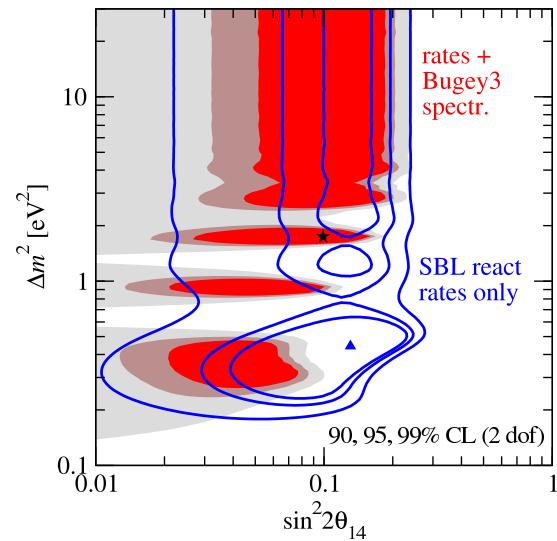
- Several Observations which can be Interpreted as Oscillations with $\Delta m^2 \sim \text{eV}^2$

Reactor Anomaly

New reactor flux calculation
 \Rightarrow Deficit in data at $L \lesssim 100 \text{ m}$



Explained as ν_e disappearance

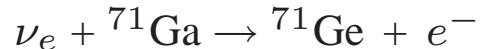


Kopp et al, ArXiv 1303.3011

Gallium Anomaly

Acero, Giunti, Laveder, 0711.4222
 Giunti, Laveder, 1006.3244

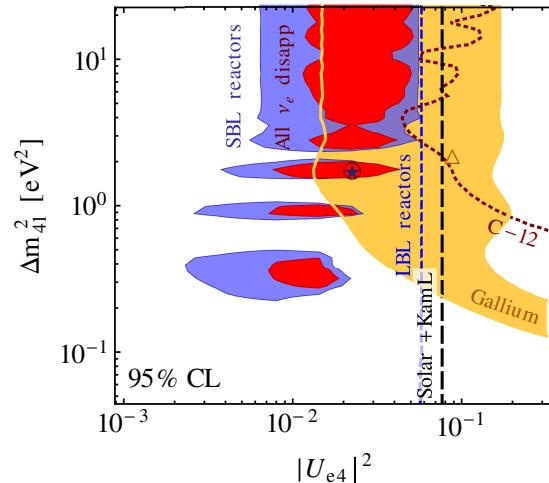
Radioactive Sources (^{51}Cr , ^{37}Ar)
 in calibration of Ga Solar Exp;



Give a rate lower than expected

$$R = \frac{N_{\text{obs}}}{N_{\text{th}}^{\text{Bahc}}} = 0.86 \pm 0.05 \quad (2.8\sigma)$$

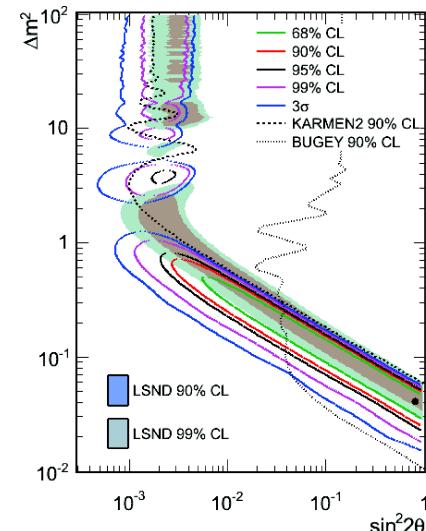
Explained as ν_e disappearance



Kopp et al, ArXiv 1303.3011
 Talk by T. Schwetz

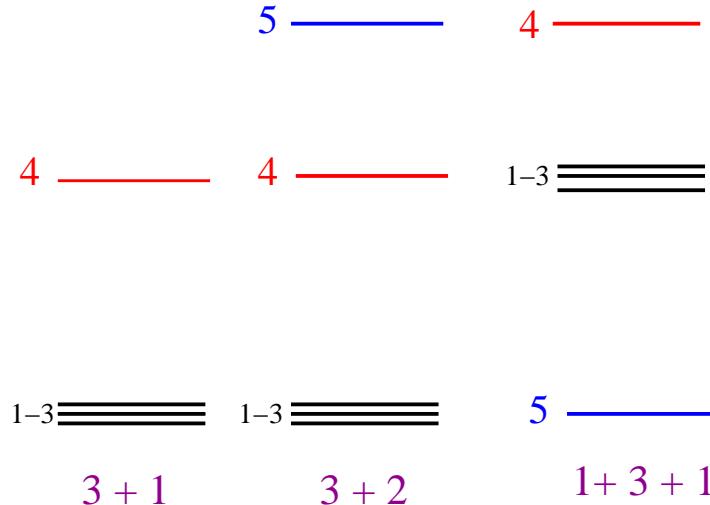
LSND, MiniBoone

$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



Light Sterile Neutrinos

- These explanations require $3+N_s$ mass eigenstates $\rightarrow N_s$ sterile neutrinos



$\nu_e \rightarrow \nu_e$ **disapp** (REACT,Gallium,Solar, LSND/KARMEN)

• Problem: fit together $\nu_\mu \rightarrow \nu_e$ **app** (LSND,KARMEN,NOMAD,MiniBooNE,E776,ICARUS)

$\nu_\mu \rightarrow \nu_\mu$ **disapp** (CDHS,ATM,MINOS,MiniBooNE)

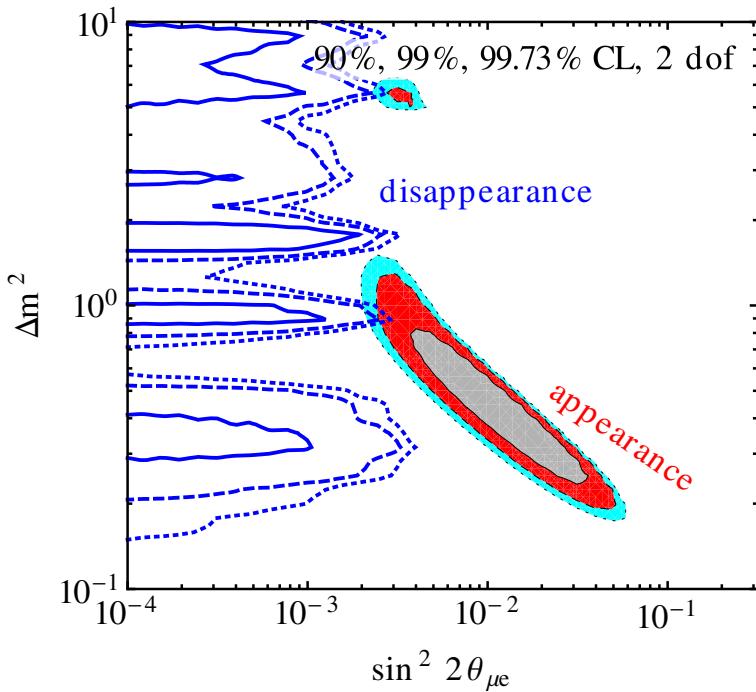
- Generically: $P(\nu_e \rightarrow \nu_\mu) \sim |U_{ei}^* U_{\mu i}|$ [i =heavier state(s)]

But $|U_{ei}|$ constrained by $P(\nu_e \rightarrow \nu_e)$ disappearance data
 And $|U_{\mu i}|$ constrained by $P(\nu_\mu \rightarrow \nu_\mu)$ disappearance data } \Rightarrow Severe tension

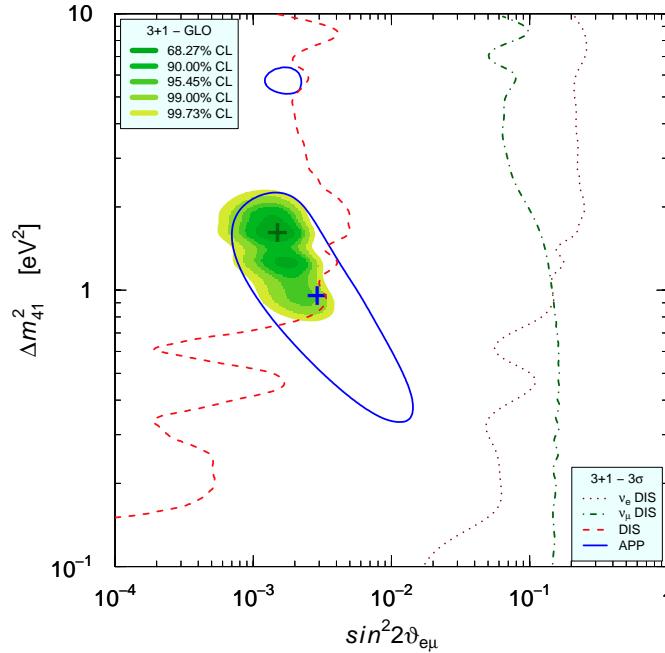
Light Sterile Neutrinos: 3+1

- Comparing the parameters required to explain signals with bounds from disappearance

Kopp et al, ArXiv 1303.3011



Giunti et al, ArXiv 1308.5288



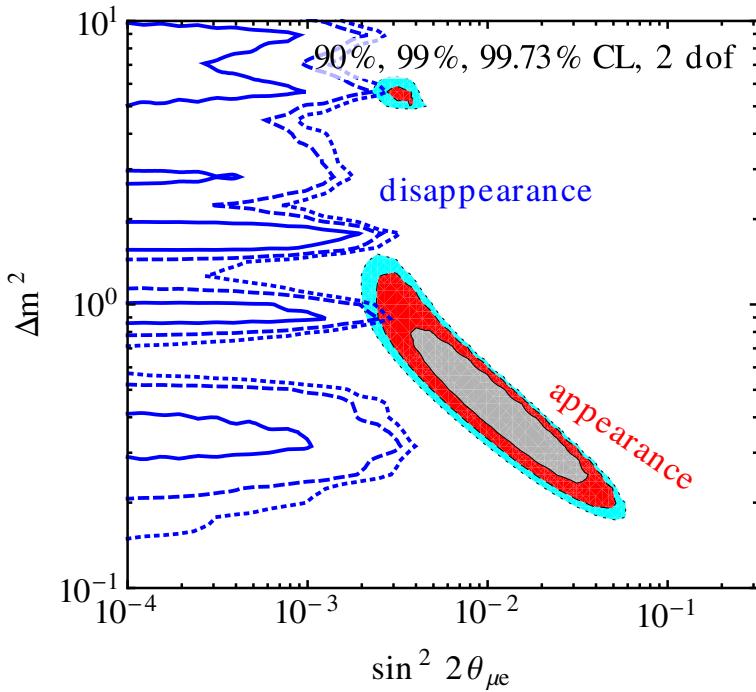
- Difference in the analysis of both appearance and disappearance
- Somewhat different conclusions

Talk by T. Schwetz

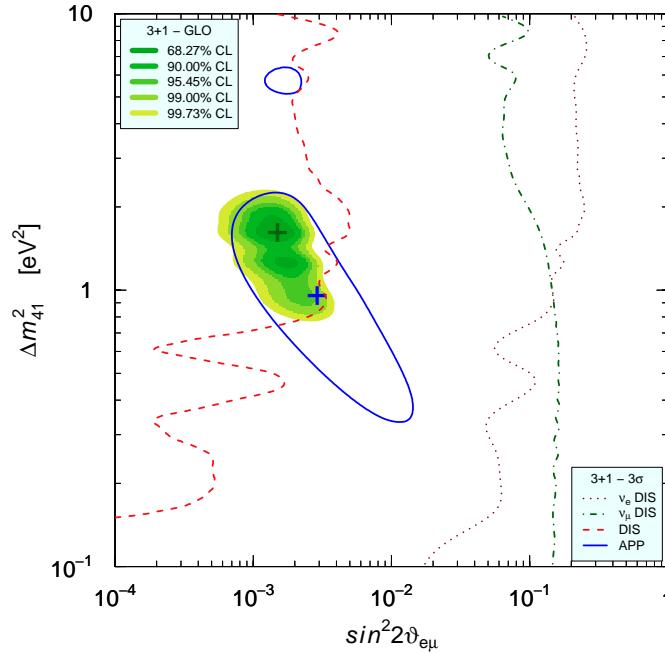
Light Sterile Neutrinos: 3+1

- Comparing the parameters required to explain signals with bounds from disappearance

Kopp et al, ArXiv 1303.3011



Giunti et al, ArXiv 1308.5288



- Difference in the analysis of both appearance and disappearance
- Somewhat different conclusions
- Adding more steriles (3+2 or 1+3+1): not much improvement
- Also tension with cosmology

Talk by T. Schwetz

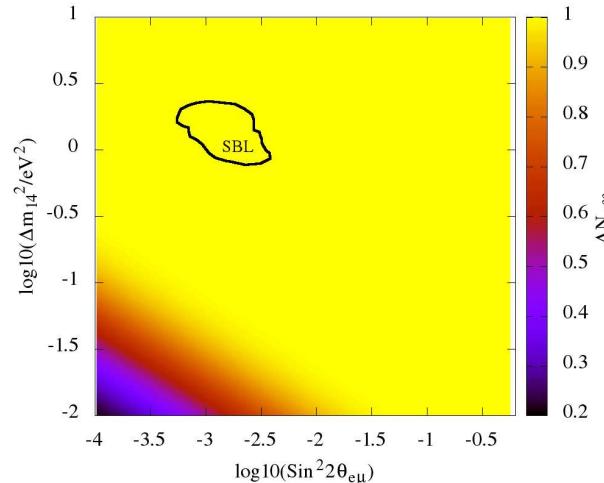
Light Sterile Neutrinos in Cosmology

One light ν_s mixed with 3 ν'_a s contributes to ρ as N_{eff} .

From evol eq for 3 + 1 ensemble one finds

⇒ So if “explanation” to SBL anomalies

1 ν_s contributes as much as 1 ν_a



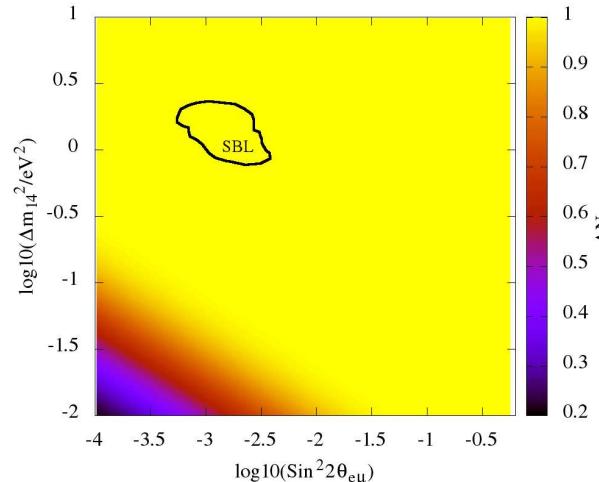
Light Sterile Neutrinos in Cosmology

One light ν_s mixed with 3 ν'_a s contributes to ρ as N_{eff} .

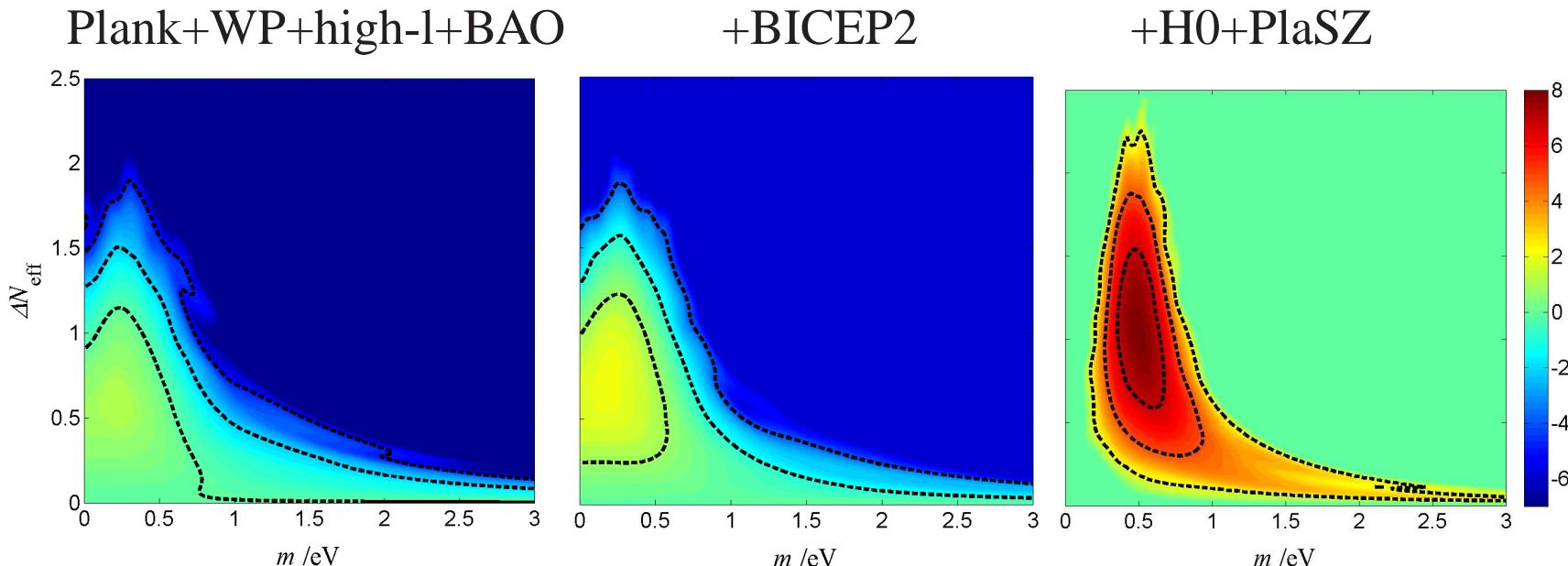
From evol eq for 3 + 1 ensemble one finds

\Rightarrow So if “explanation” to SBL anomalies

1 ν_s contributes as much as 1 ν_a



But presently cosmo data tells us



\Rightarrow No compatibility with SBL unless NP at work to prevent fully ν_s thermalization

Determination of Matter Potential: Non Standard ν Int

- In the three-flavor oscillation picture, the neutrino evolution equation reads:

$$i \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = H^\nu \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \quad \text{with } H^\nu = H_{\text{vac}} + H_{\text{mat}} \quad \text{and} \quad H^{\bar{\nu}} = (H_{\text{vac}} - H_{\text{mat}})^*$$

- The most general matter potential can be parametrized

$$H_{\text{mat}} = \sqrt{2} G_F N_e(r) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2} G_F \sum_{f=e,u,d} N_f(r) \begin{pmatrix} \varepsilon_{ee}^f & \varepsilon_{e\mu}^f & \varepsilon_{e\tau}^f \\ \varepsilon_{e\mu}^{f*} & \varepsilon_{\mu\mu}^f & \varepsilon_{\mu\tau}^f \\ \varepsilon_{e\tau}^{f*} & \varepsilon_{\mu\tau}^{f*} & \varepsilon_{\tau\tau}^f \end{pmatrix}$$

Deviations from $H_{\text{mat}}^{\text{SM}} = \sqrt{2} G_F N_e(r) \text{diag}(1, 0, 0)$ can be due to **NSI**

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\mu \nu_\beta) (\bar{f} \gamma_\mu P f), \quad P = L, R$$

$$\text{with } \varepsilon_{\alpha\beta}^f = \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$$

- The 3ν evolution depends on 6 (vac) + 8 (mat)= 14 Parameters

Matter Potential/NSI in Solar and KamLAND

- Solar ν' s: 2 relevant combinations of NSI

$$\begin{aligned} \varepsilon_D^f &= c_{13}s_{13}\text{Re} \left[e^{i\delta_{\text{CP}}} \left(s_{23} \varepsilon_{e\mu}^f + c_{23} \varepsilon_{e\tau}^f \right) \right] \\ &\quad - \left(1 + s_{13}^2 \right) c_{23}s_{23}\text{Re} \left(\varepsilon_{\mu\tau}^f \right) \\ &\quad - \frac{c_{13}^2}{2} \left(\varepsilon_{ee}^f - \varepsilon_{\mu\mu}^f \right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2} \left(\varepsilon_{\tau\tau}^f - \varepsilon_{\mu\mu}^f \right) \\ \varepsilon_N^f &= c_{13} \left(c_{23} \varepsilon_{e\mu}^f - s_{23} \varepsilon_{e\tau}^f \right) \\ &\quad + s_{13}e^{-i\delta_{\text{CP}}} \left[s_{23}^2 \varepsilon_{\mu\tau}^f - c_{23}^2 \varepsilon_{\mu\tau}^{f*} \right. \\ &\quad \left. + c_{23}s_{23} \left(\varepsilon_{\tau\tau}^f - \varepsilon_{\mu\mu}^f \right) \right] \end{aligned}$$

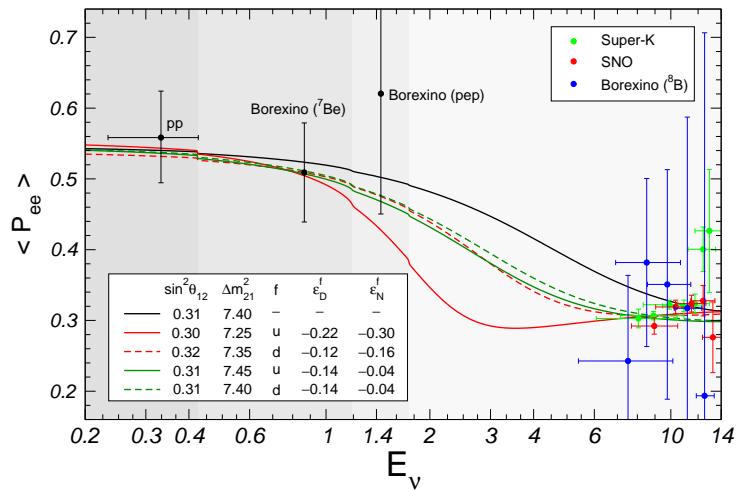
Matter Potential/NSI in Solar and KamLAND

- Solar ν' s: 2 relevant combinations of NSI

$$\begin{aligned}\varepsilon_D^f &= c_{13}s_{13}\text{Re} \left[e^{i\delta_{\text{CP}}} \left(s_{23}\varepsilon_{e\mu}^f + c_{23}\varepsilon_{e\tau}^f \right) \right] \\ &- \left(1 + s_{13}^2 \right) c_{23}s_{23}\text{Re} \left(\varepsilon_{\mu\tau}^f \right) \\ &- \frac{c_{13}^2}{2} \left(\varepsilon_{ee}^f - \varepsilon_{\mu\mu}^f \right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2} \left(\varepsilon_{\tau\tau}^f - \varepsilon_{\mu\mu}^f \right)\end{aligned}$$

$$\begin{aligned}\varepsilon_N^f &= c_{13} \left(c_{23}\varepsilon_{e\mu}^f - s_{23}\varepsilon_{e\tau}^f \right) \\ &+ s_{13}e^{-i\delta_{\text{CP}}} \left[s_{23}^2\varepsilon_{\mu\tau}^f - c_{23}^2\varepsilon_{\mu\tau}^{f*} \right. \\ &\quad \left. + c_{23}s_{23} \left(\varepsilon_{\tau\tau}^f - \varepsilon_{\mu\mu}^f \right) \right]\end{aligned}$$

- Better fit with NSI ($\Delta\chi^2_{\text{OSC}} \simeq 5\text{--}7$)



Due to no observation of MSW up-turn

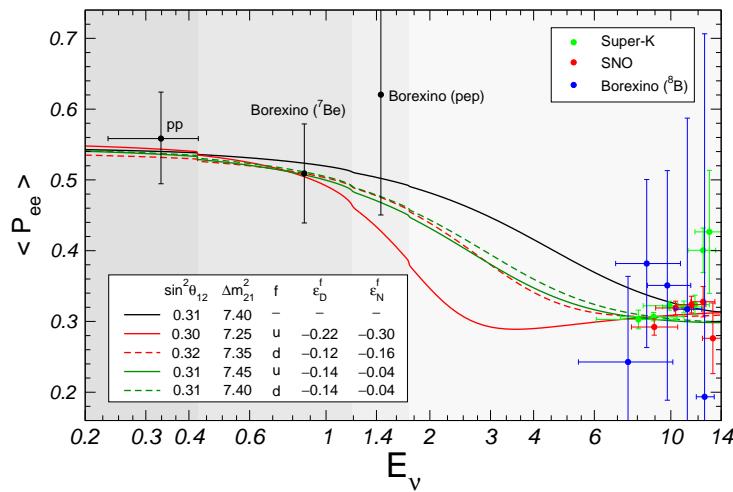
Matter Potential/NSI in Solar and KamLAND

- Solar ν' s: 2 relevant combinations of NSI

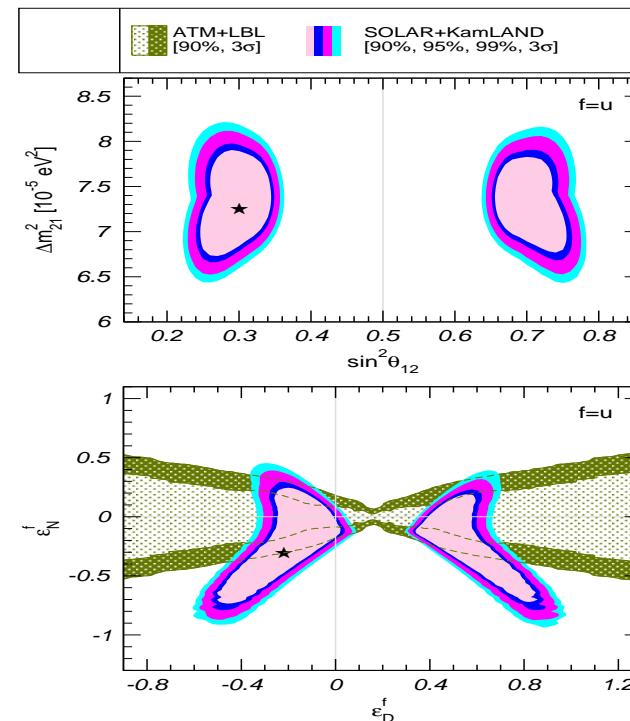
$$\begin{aligned} \varepsilon_D^f &= c_{13}s_{13}\text{Re} \left[e^{i\delta_{\text{CP}}} \left(s_{23}\varepsilon_{e\mu}^f + c_{23}\varepsilon_{e\tau}^f \right) \right] \\ &- \left(1 + s_{13}^2 \right) c_{23}s_{23}\text{Re} \left(\varepsilon_{\mu\tau}^f \right) \\ &- \frac{c_{13}^2}{2} \left(\varepsilon_{ee}^f - \varepsilon_{\mu\mu}^f \right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2} \left(\varepsilon_{\tau\tau}^f - \varepsilon_{\mu\mu}^f \right) \end{aligned}$$

$$\begin{aligned} \varepsilon_N^f &= c_{13} \left(c_{23}\varepsilon_{e\mu}^f - s_{23}\varepsilon_{e\tau}^f \right) \\ &+ s_{13}e^{-i\delta_{\text{CP}}} \left[s_{23}^2\varepsilon_{\mu\tau}^f - c_{23}^2\varepsilon_{\mu\tau}^{f*} \right. \\ &\quad \left. + c_{23}s_{23} \left(\varepsilon_{\tau\tau}^f - \varepsilon_{\mu\mu}^f \right) \right] \end{aligned}$$

- Better fit with NSI ($\Delta\chi^2_{\text{OSC}} \simeq 5-7$)



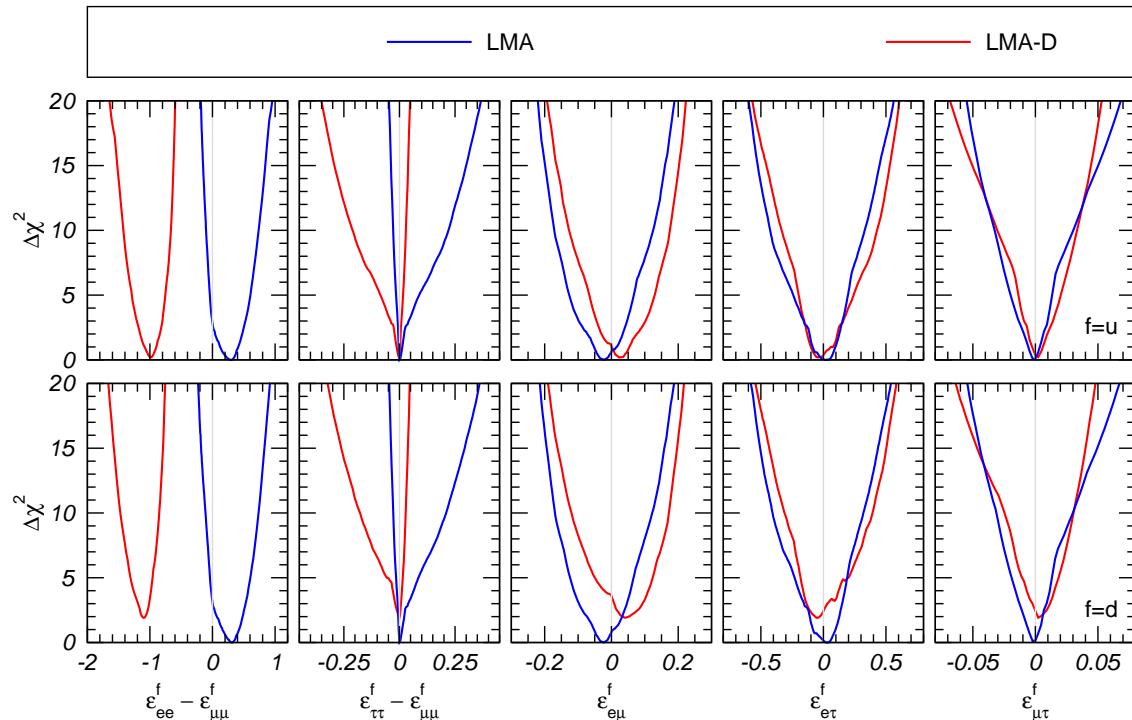
- LMA and LMA-D ($\theta_{12} > \frac{\pi}{4}$) allowed



Due to no observation of MSW up-turn

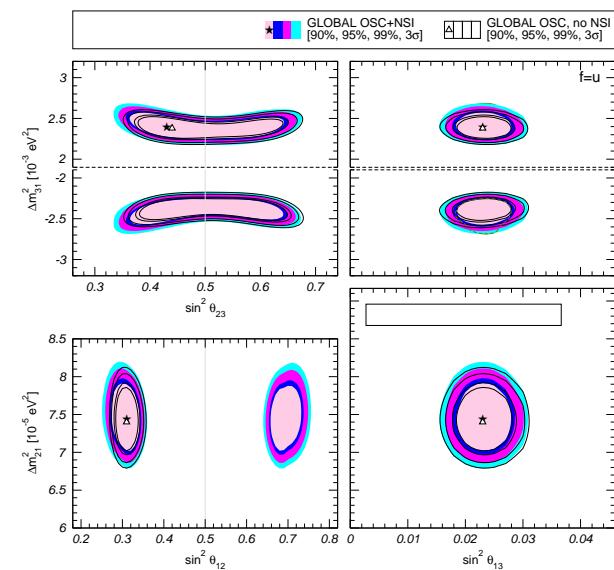
Matter Potential/NSI: Global Analysis

- Parameter space of matter potential is bounded



	90% CL			90% CL	
Param.	OSC	SCATT	Param.	OSC	SCATT
$ \varepsilon_{ee}^u $	0.51–1.19	0.7–1	$ \varepsilon_{ee}^d $	0.51–1.17	0.3–0.7
$ \varepsilon_{ττ}^u $	0.03	1.4–3	$ \varepsilon_{ττ}^d $	0.03	1.1–6
$ \varepsilon_{eμ}^u $	0.09	0.05	$ \varepsilon_{eμ}^d $	0.09	0.05
$ \varepsilon_{eτ}^u $	0.15	0.5	$ \varepsilon_{eτ}^d $	0.14	0.5
$ \varepsilon_{μτ}^u $	0.01	0.05	$ \varepsilon_{μτ}^d $	0.01	0.05

Osc parameter robust
(but solar dark side)



Bounds from global osc fit
stronger than scattering ones
for $\varepsilon_{τβ}^{u,d}$

Summary

- Finally we have the three leptonic mixing angles determined (at $\pm 3\sigma/6$)

$$\Delta m_{21}^2 = 7.50 \times 10^{-5} \text{ eV}^2 \quad (2.3\%) \quad \begin{array}{ll} \Delta m_{31}^2 = 2.46 \times 10^{-3} \text{ eV}^2 & \text{NO} \\ |\Delta m_{32}^2| = 2.45 \times 10^{-3} \text{ eV}^2 & \text{IO} \end{array} \quad (1.9\%)$$

$$\sin^2 \theta_{12} = 0.3 \quad (4\%) \quad \sin^2 \theta_{23} = \begin{array}{ll} 0.58 & \text{IO} \\ 0.44 & \text{NO} \end{array} \quad (8.5\%) \quad \sin^2 \theta_{13} = 0.0219 \quad (4.8\%)$$

- Still ignore or not significantly determined

Majorana or Dirac? θ_{23} Octant (But interesting interplay LBL/REACT)

Absolute ν mass Normal or Inverted ? CP violation in leptons?

- Sterile ν 's: Not satisfactory description of SBL anomalies. Tension with Cosmo

- Much more physics in this data than masses and mixings

Tests of solar models, of ATM fluxes, reactor fluxes ...

New Physics: NSI, Lorentz Invariance, Tests of CPT ...