LEPTON FLAVOUR FROM NEUTRINO OSCILLATIONS

Concha Gonzalez-Garcia

(YITP Stony Brook & ICREA U. Barcelona)

Invisibles 14 Workshop, July 15, 2014

Global fit to neutrino oscillation data
http://www.nu-fit.org

invisibles
neutrinos, dark matter & dark energy physics

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$3\nu' s$: 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^i_R	d^i_R
$\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L$	$\begin{pmatrix}c^i\\ s^i\end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$	$\begin{pmatrix}t^i\\ b^i\end{pmatrix}_L$	τ_R	t^i_R	b^i_R

There is no ν_R

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There is no ν_R

$$\Downarrow$$

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

$$\Downarrow$$

ν *strictly* massless

The New Minimal Standard Model

- Minimal Extensions to give Mass to the Neutrino:

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

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

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

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

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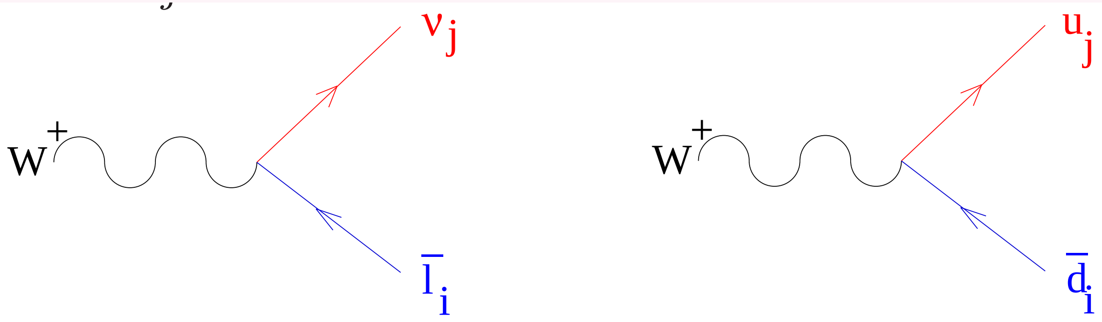
- The charged current interactions of leptons are not diagonal (same as quarks)

$$\frac{g}{\sqrt{2}} W^+_\mu \sum_{ij} \left(U^{ij}_{\rm LEP}\, \overline{\ell^i}\, \gamma^\mu\, L\, \nu^j \;+\; U^{ij}_{\rm CKM}\, \overline{U^i}\, \gamma^\mu\, L\, D^j \right) \;+\; h.c.$$



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

$U_{LEP} U_{LEP}^\dagger = I_{3\times3}$ but in general $U_{LEP}^\dagger U_{LEP} \neq I_{N\times N}$

- 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 $l_\alpha + N \to \nu_\alpha + N'$

  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

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

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

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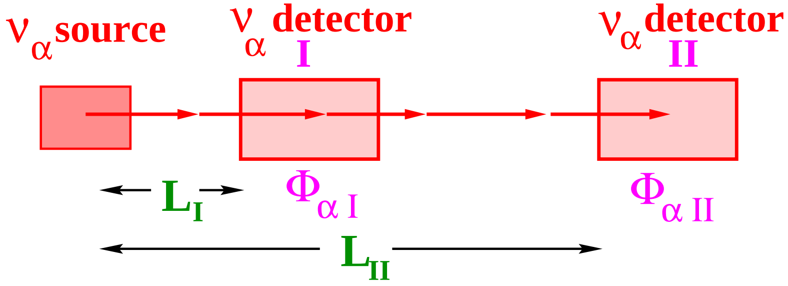
No information on ν mass scale nor Majorana versus Dirac

ν Oscillations: Experimental Probes

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

Disappearance Experiment



ν_α **source**

ν_α **detector I**

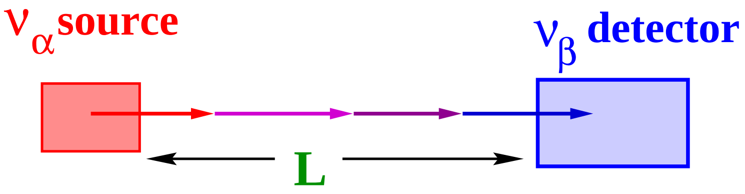
ν_α **detector II**

L_I $\Phi_{\alpha\ I}$ $\Phi_{\alpha\ II}$

L_{II}

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

Appearance Experiment



ν_α **source**

ν_β **detector**

L

Searches for β diffα

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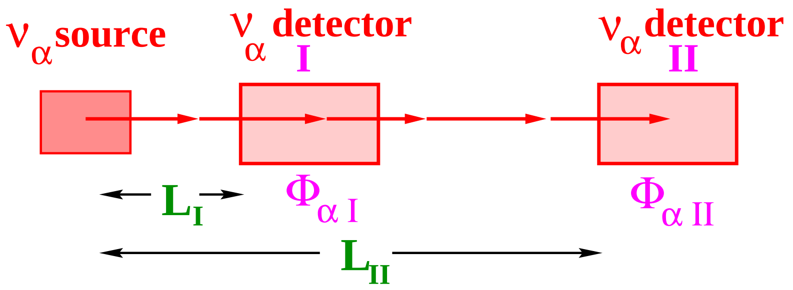

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ν_α detector I

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$\Phi_{\alpha\,I}$

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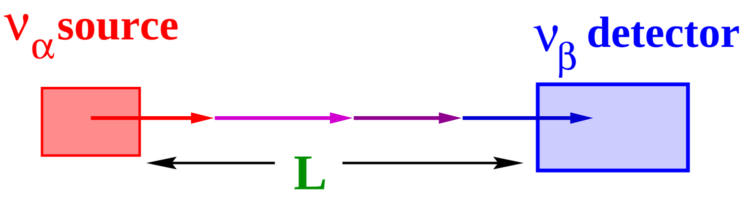


ν_α source

ν_β detector

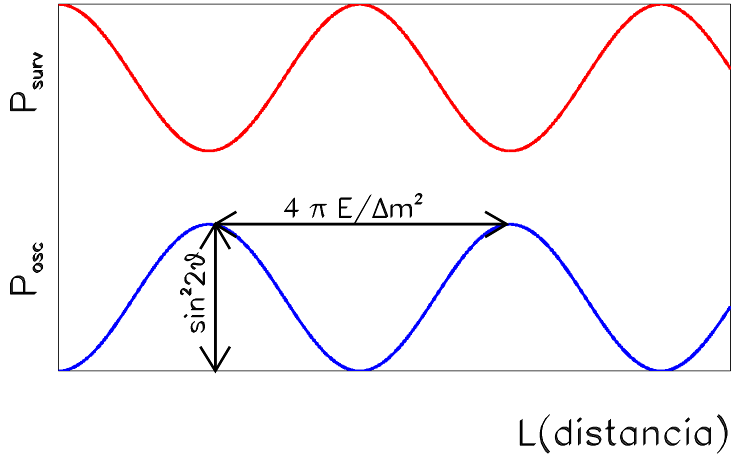
L

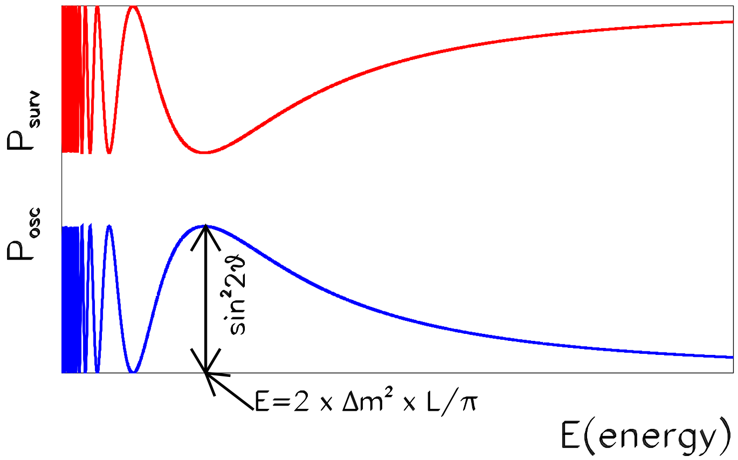
Searches for
β diff α

- To detect oscillations we can study the neutrino flavour

as function of the Distance to the source

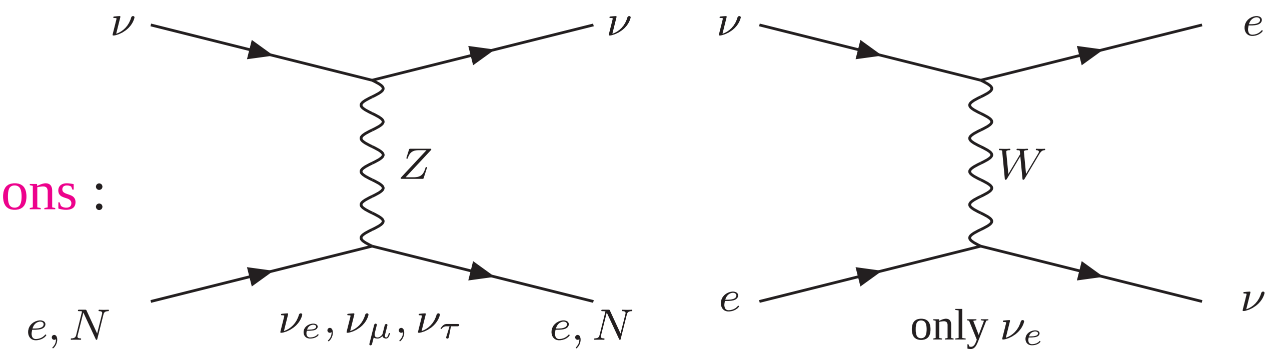
As function of the neutrino Energy





Matter Effects

- If ν cross matter regions (Sun, Earth...) it interacts *coherently*
  - But Different flavours have different interactions :



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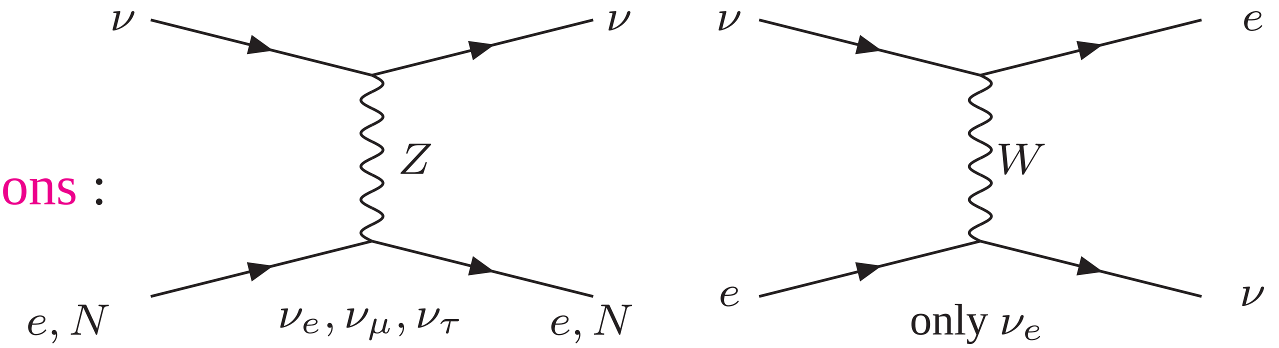

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- The mixing angle in matter

$$\sin(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\sqrt{(\Delta m^2 \cos(2\theta) - A)^2 + (\Delta m^2 \sin(2\theta))^2}} \qquad A = 2\,E\,(V_\alpha - V_\beta)$$

  - 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])
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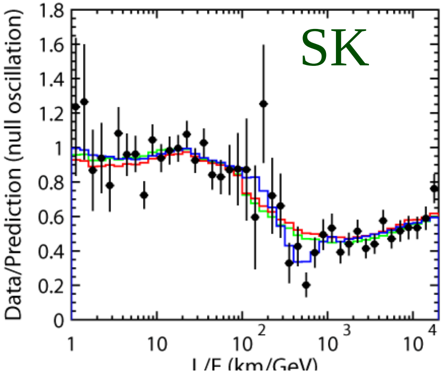
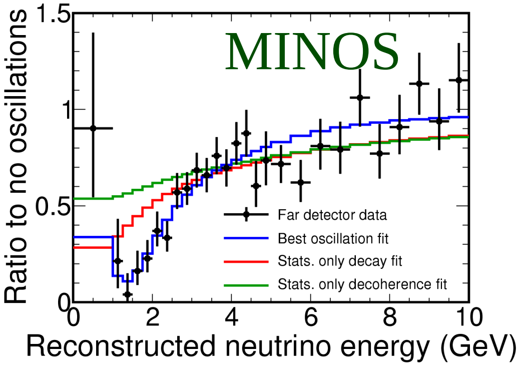
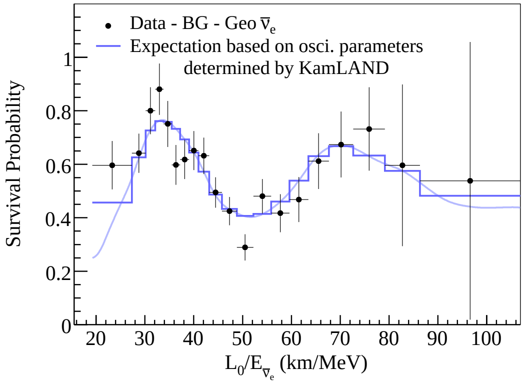
- We have confirmed:

Vacuum oscillation L/E pattern

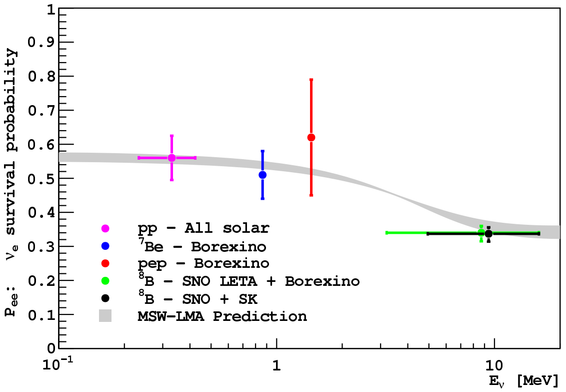






KamLAND

MSW conversion in Sun



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All this implies that neutrinos are massive

and There is Physics Beyond SM

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All this implies that neutrinos are massive

and There is Physics Beyond SM

- The *important* question:

What is the BSM theory?

- The *difficult* path:

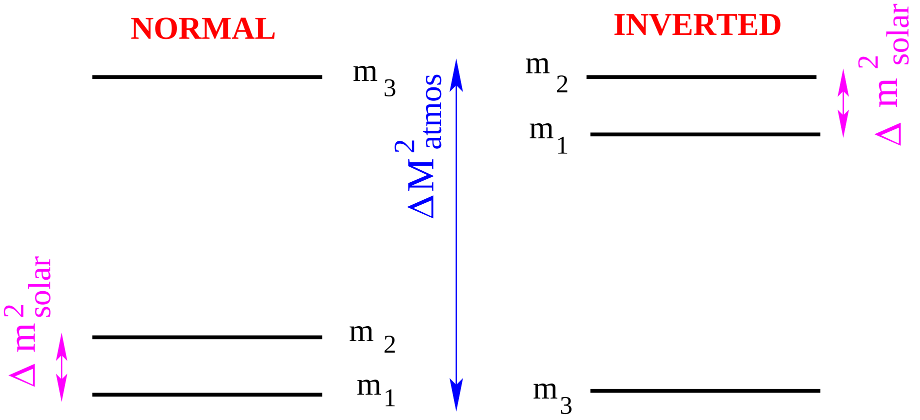
Detailed determination of the new low energy parametrization

3ν Flavour Parameters

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

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

- Two Possible Orderings



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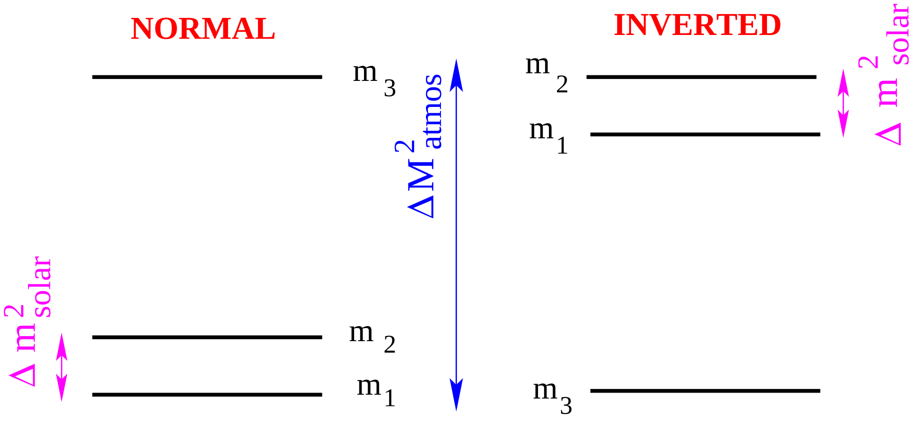
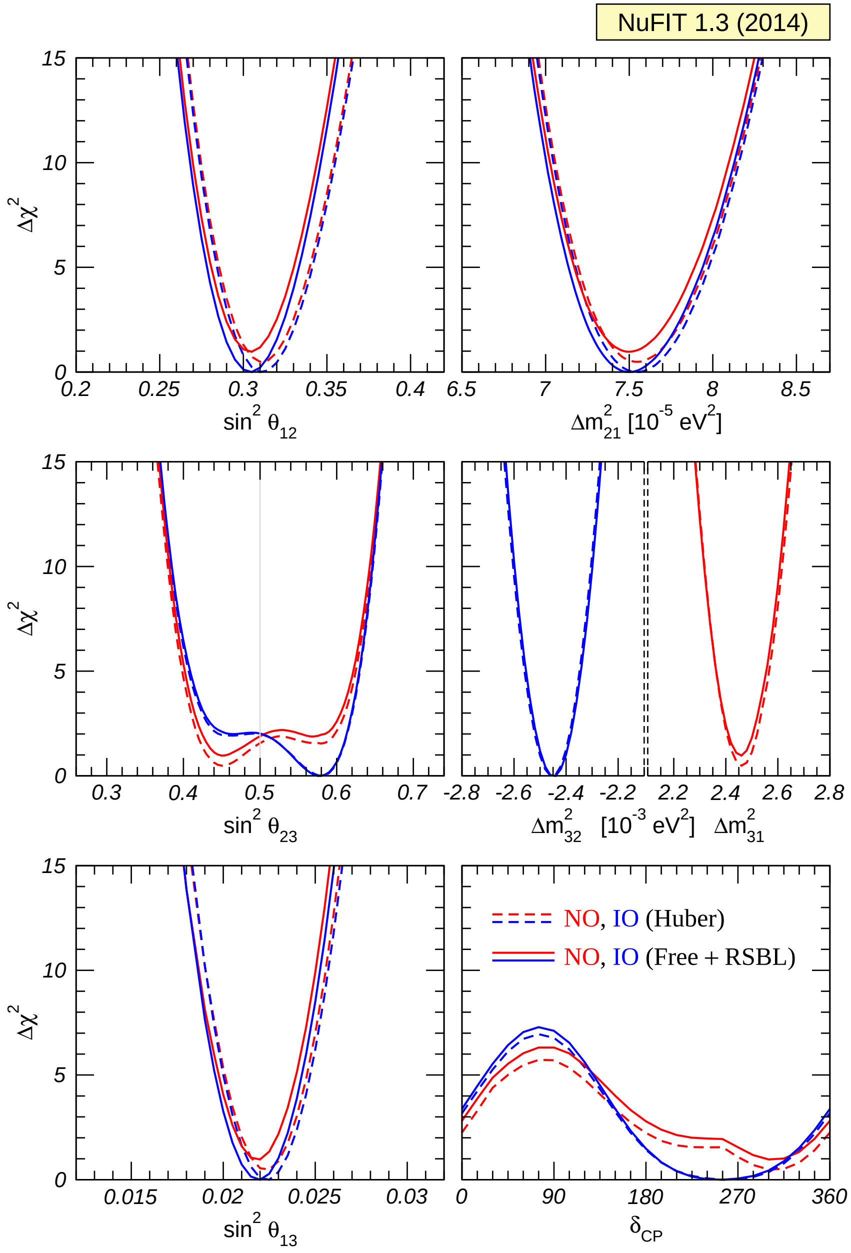


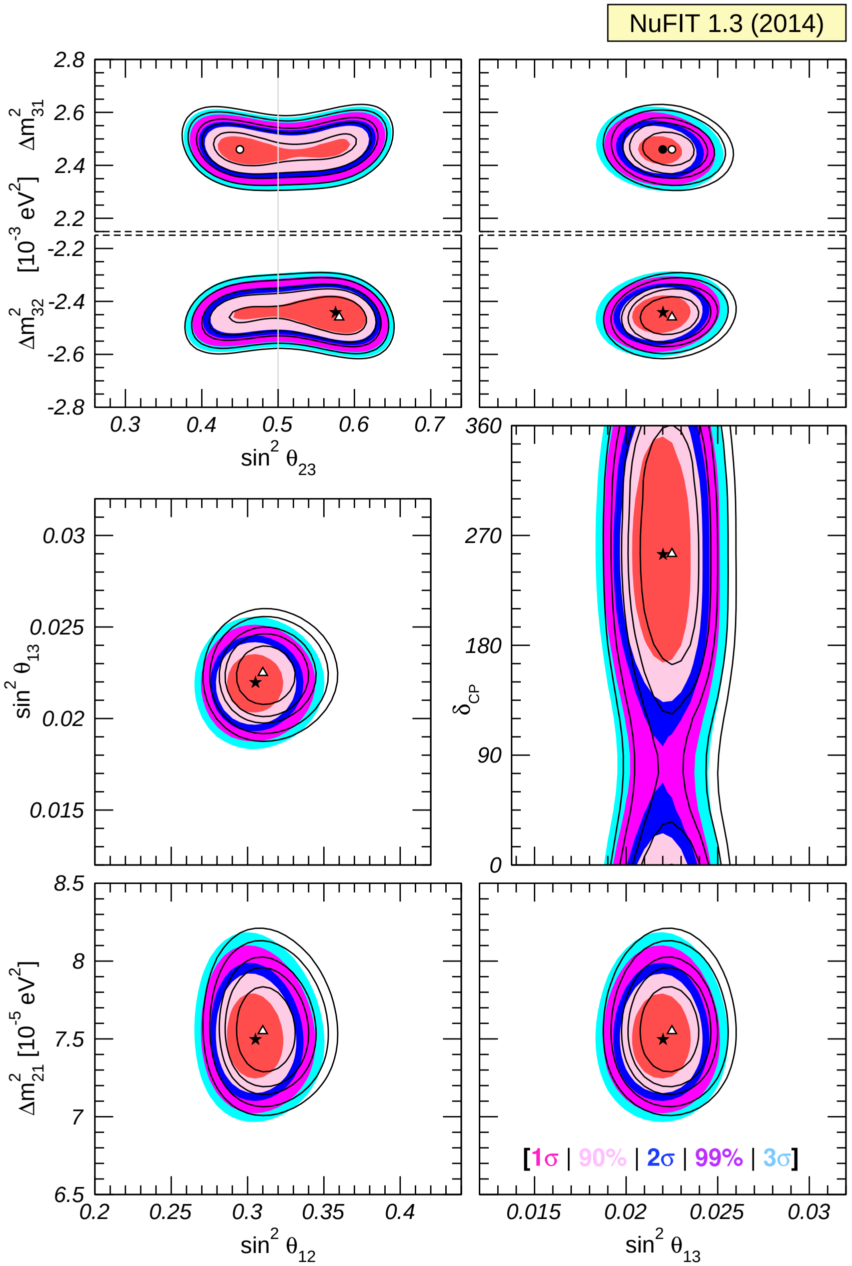
Experiment	Dominant Dependence	Important Dependence
Solar Experiments	$\rightarrow \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\rightarrow \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	$\rightarrow \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\rightarrow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

3 ν Flavour Parameters: Present Status

Global 6-parameter fit http://www.nu-fit.org (updated after ν2014)

Maltoni, Schwetz, Salvado, MCGG





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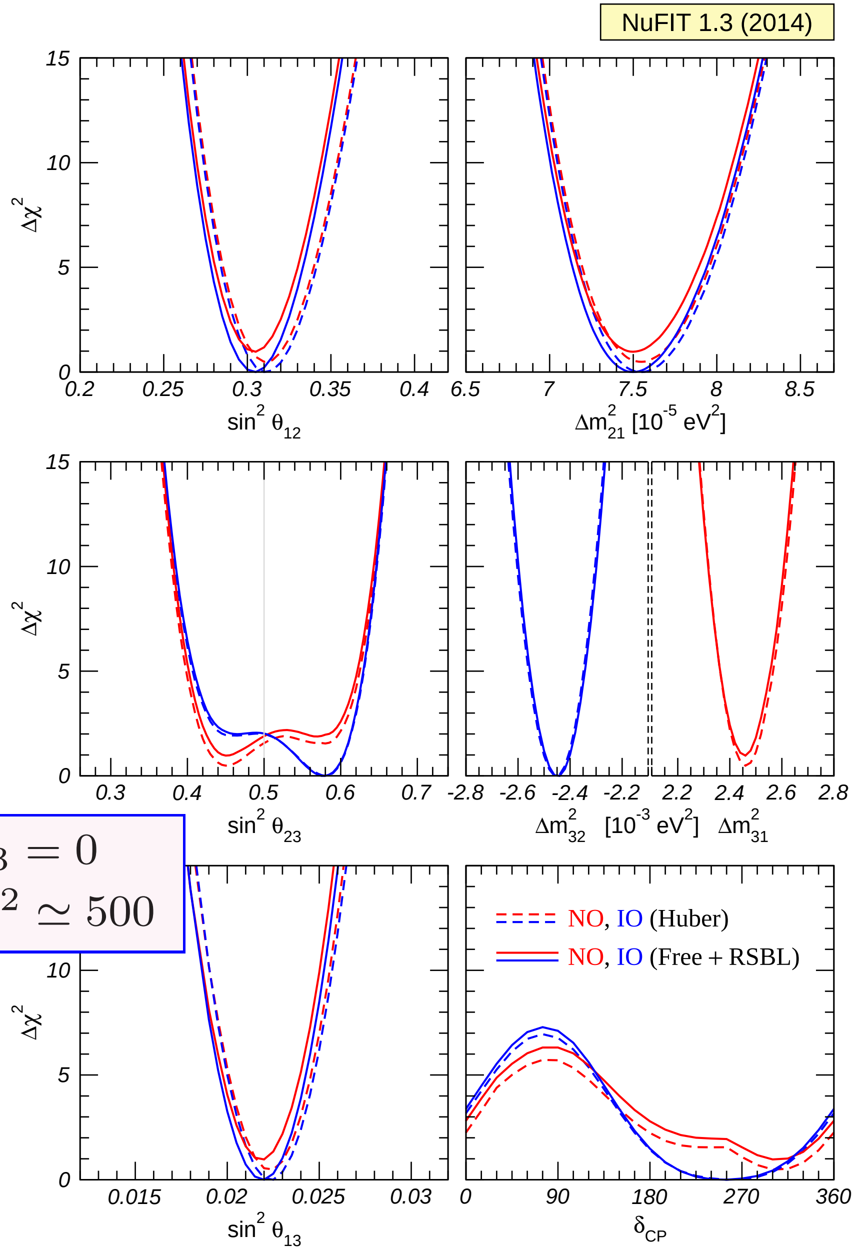
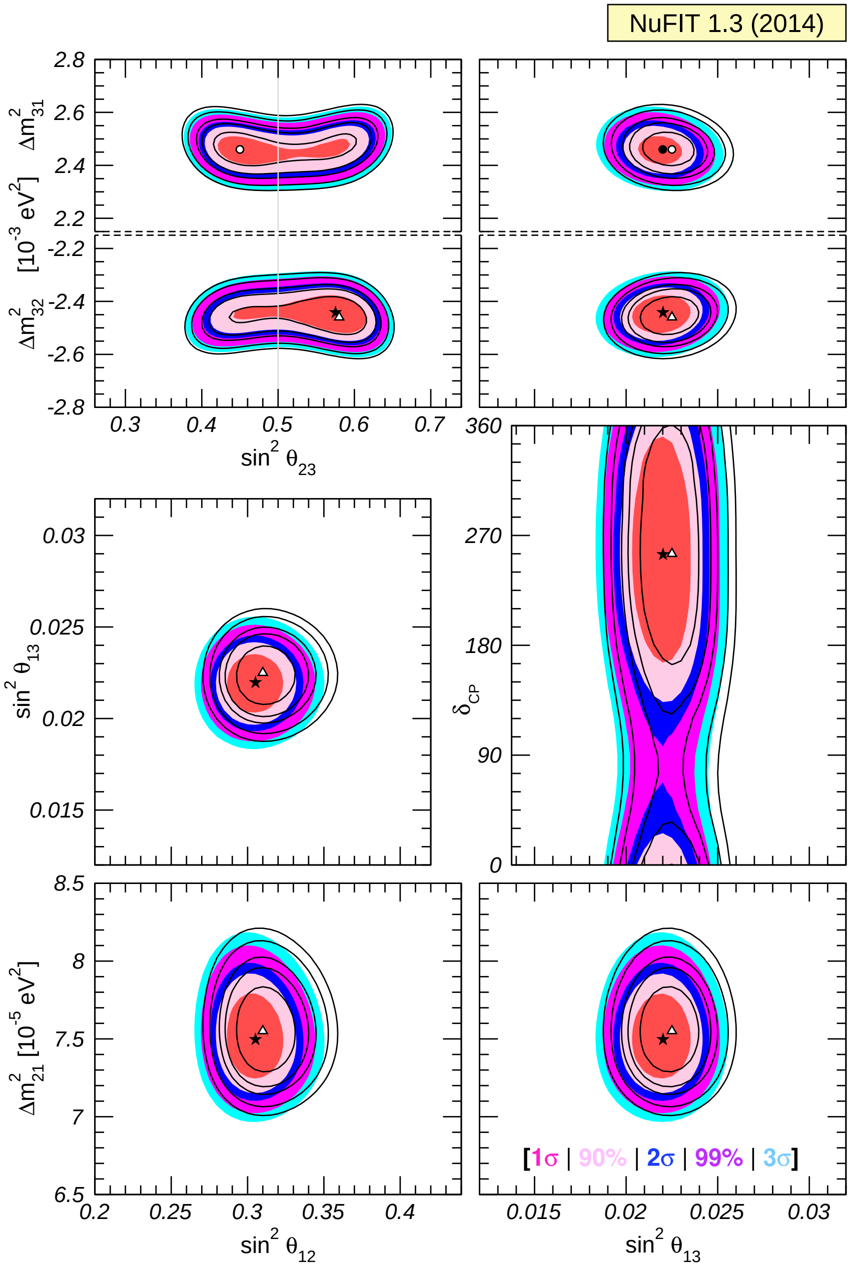


$\theta_{13} = 0$

$\Delta\chi^2 \simeq 500$



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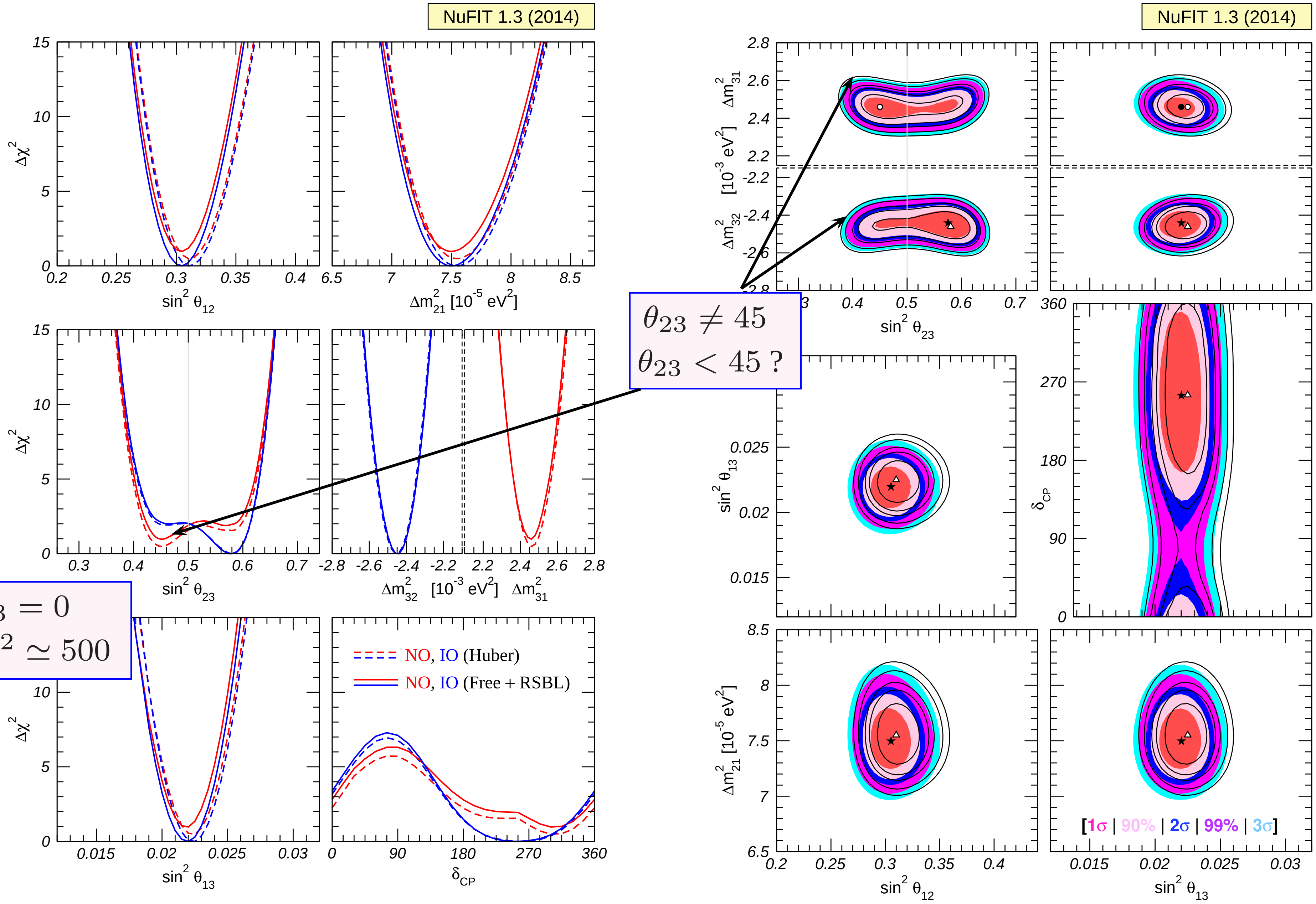

$\theta_{23} \neq 45$

$\theta_{23} < 45$?

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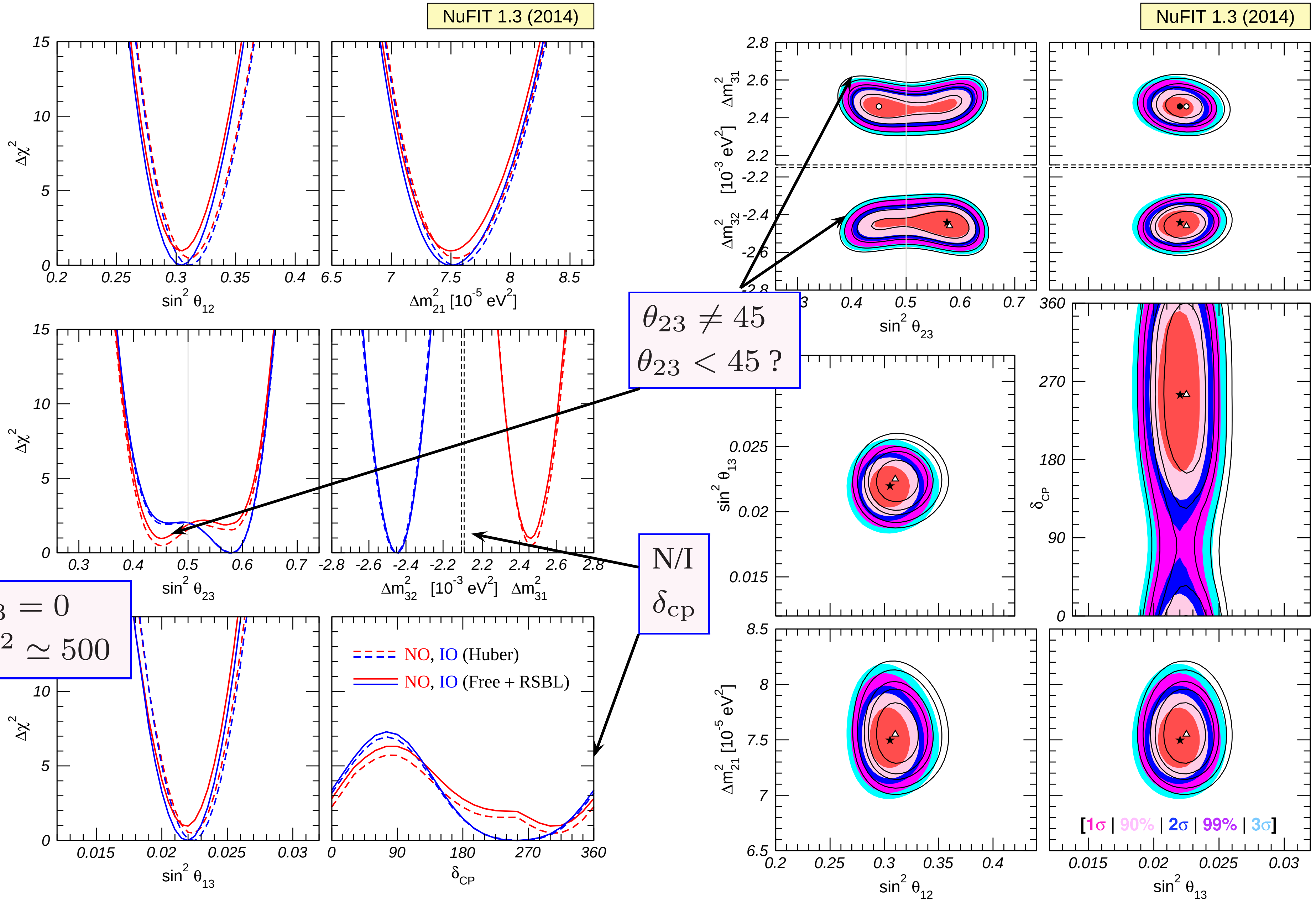

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N/I

δ_{cp}

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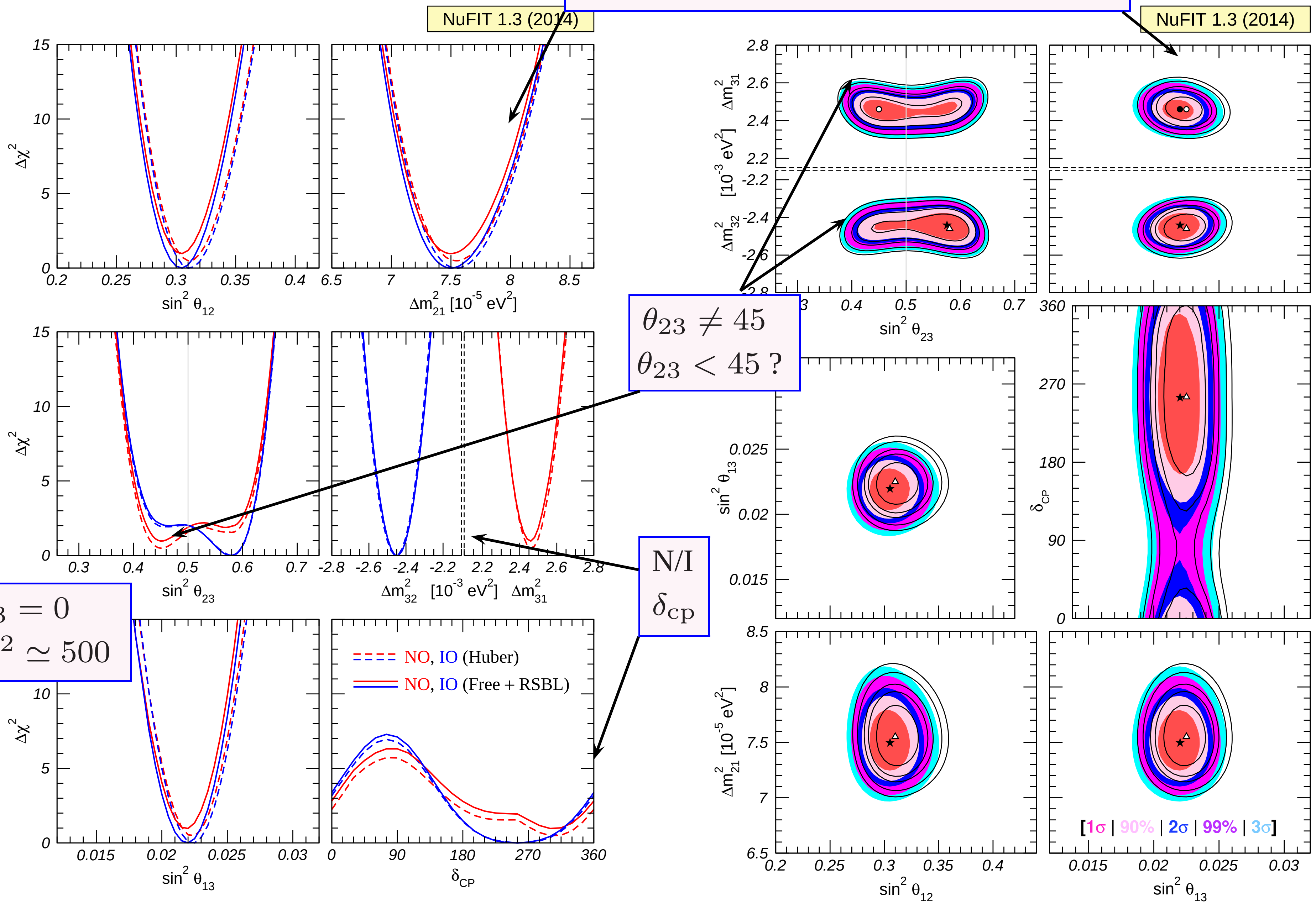

Curves = uncertainty on reactor fluxes

$\theta_{23} \neq 45$

$\theta_{23} < 45$?

N/I

$\delta_{\rm cp}$

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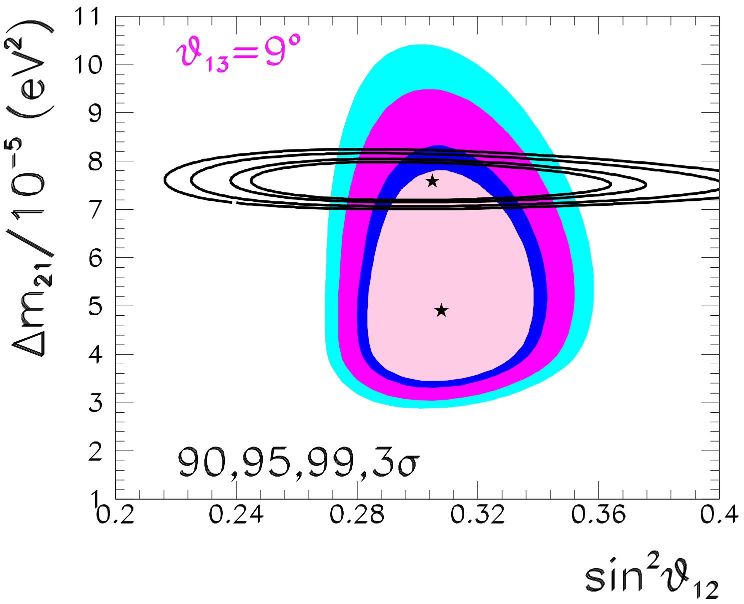
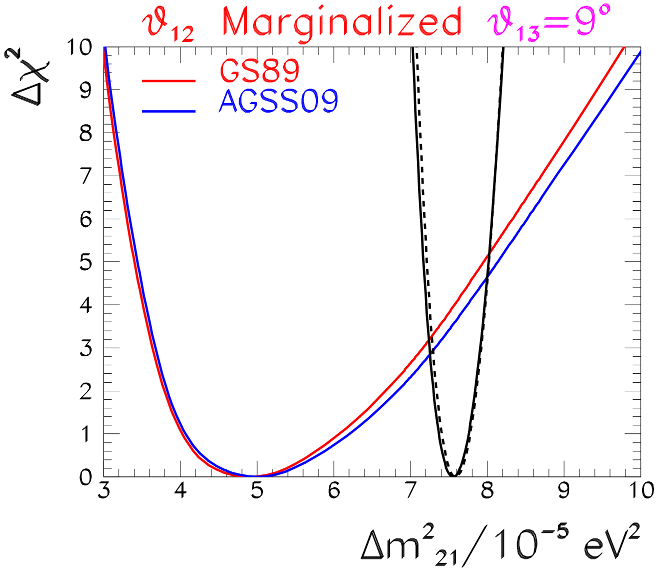
“12” sector: KamLAND and SOLAR

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

But residual tension on Δm^2_{12}





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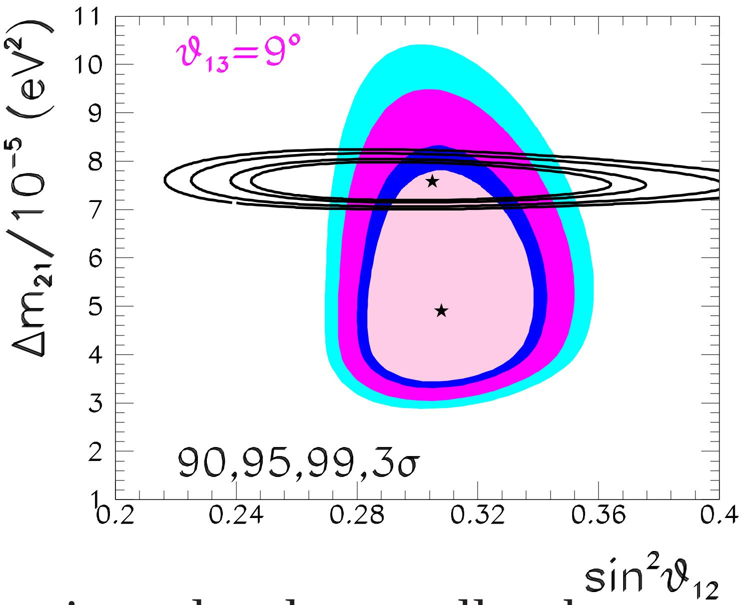

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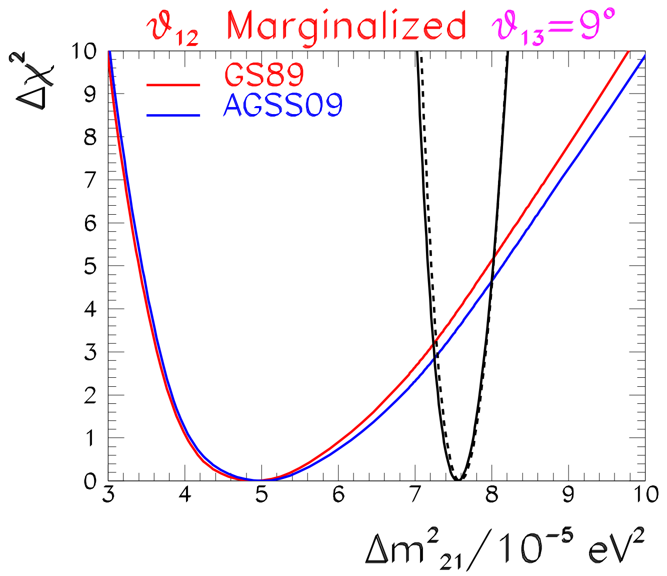
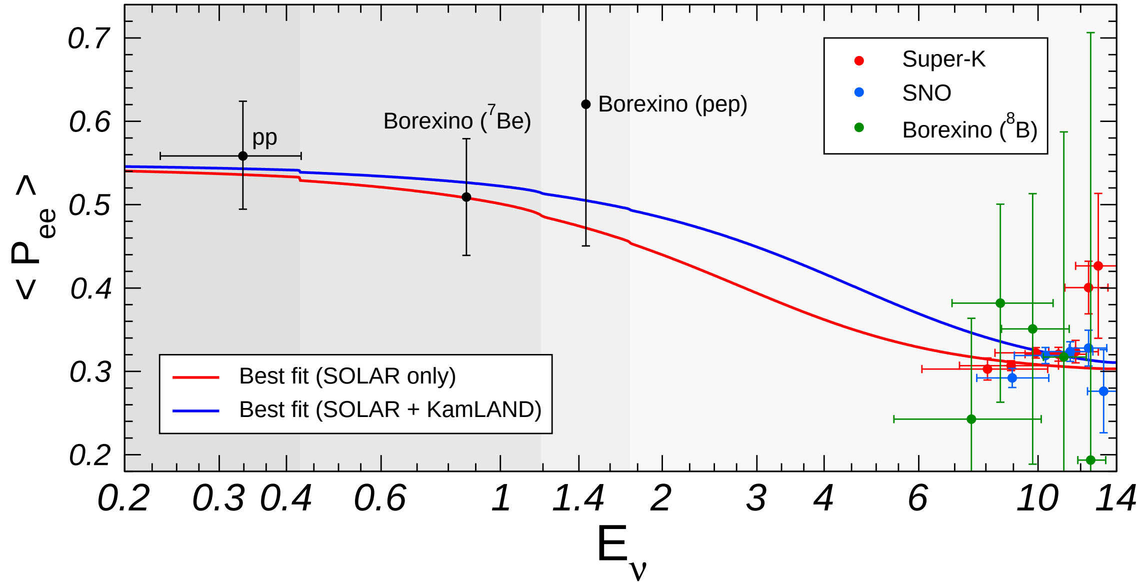


Tension related to smaller-than-expected low-E turn up from MSW at best global fit



NSI? More latter. . .

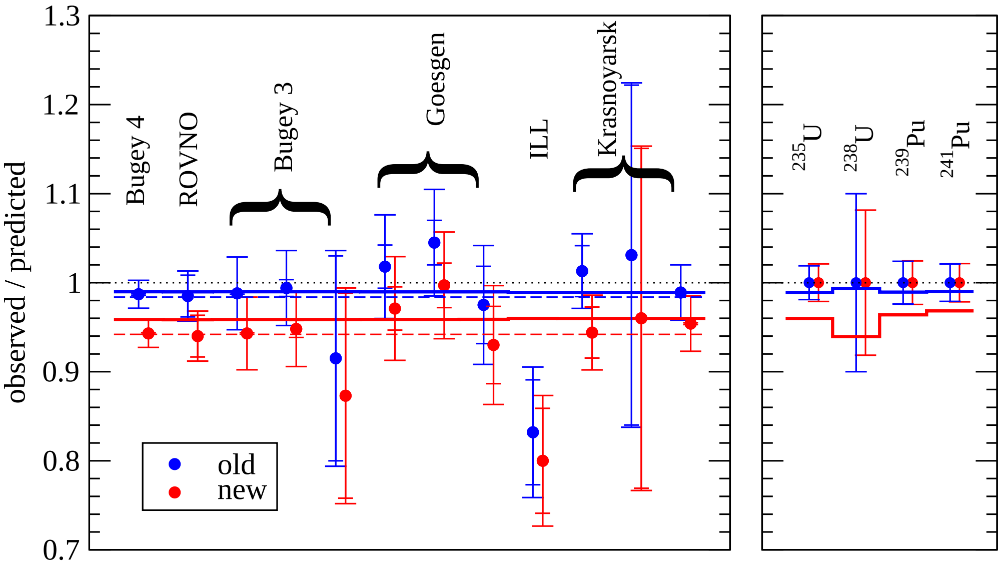
3 ν Analysis: θ_{13} from Reactors and Flux anomaly

- Recently the reactor $\bar{\nu}_e$ fluxes have been recalculated

  T.A. Mueller et al.,[arXiv:1101.2663].;P. Huber, [arXiv:1106.0687].

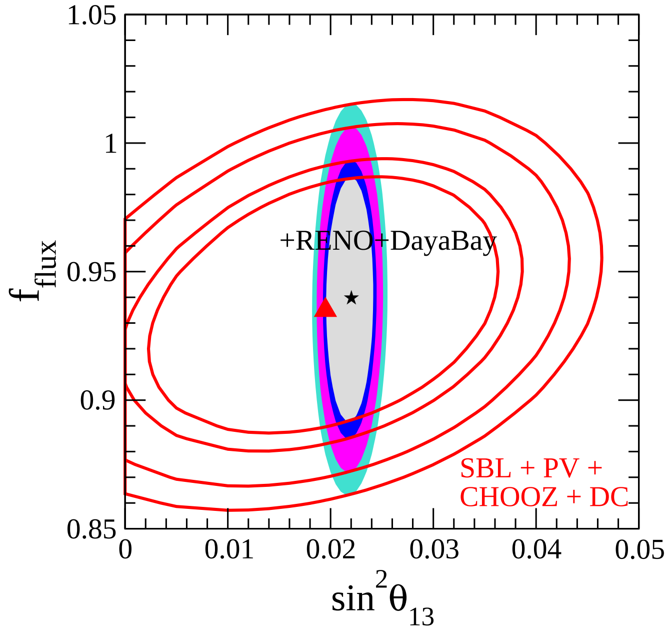
- Both reevaluations find higher fluxes by about 3.5 %

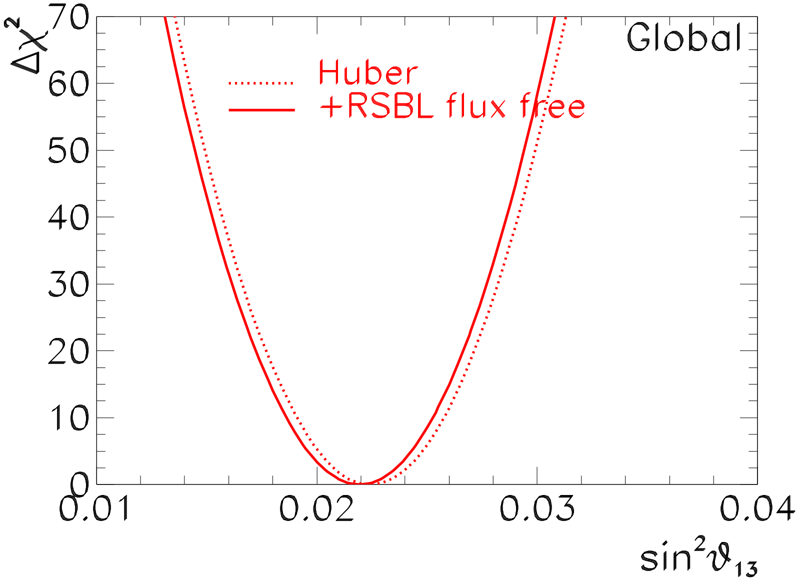
- So *negative* reactor experiments at short baselines (RSBL) indeed observed a deficit



- 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 $\Rightarrow$ 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: Long Baseline vs REACT

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

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

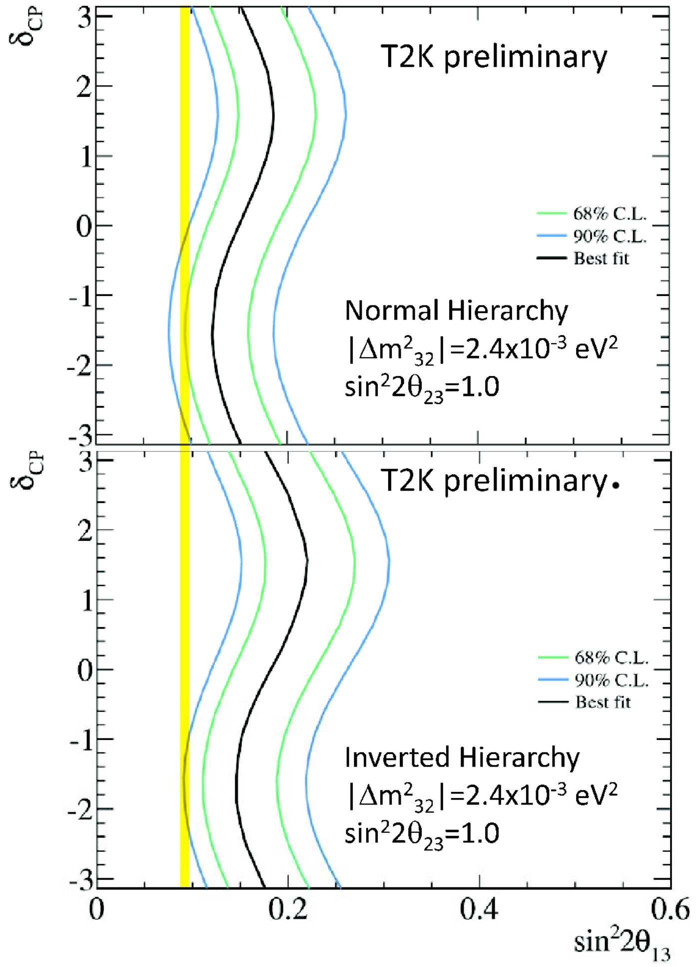
$B_\pm = \Delta_{31} \pm V_E$ $\tilde{J} = c_{13}\sin^2 2\theta_{13}\sin^2 2\theta_{23}\sin^2 2\theta_{12}$

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

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

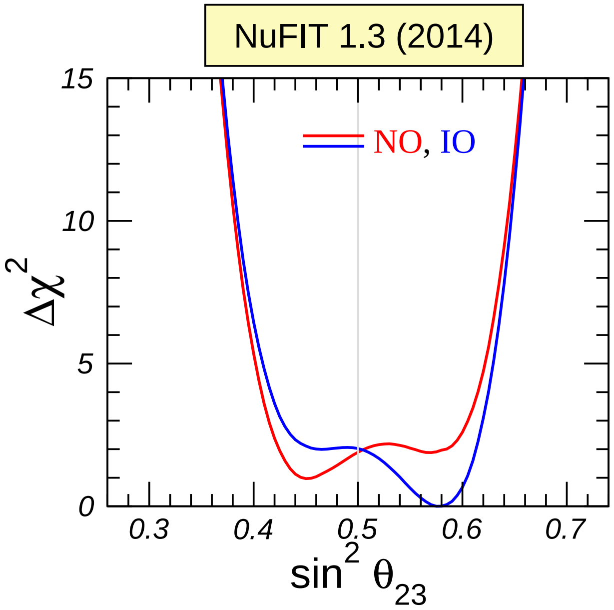
So $\sin^2 2\theta_{\rm REAC} = \sin^2 2\theta_{13}$

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



3 ν: θ_{23} Octant and Mass Ordering

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

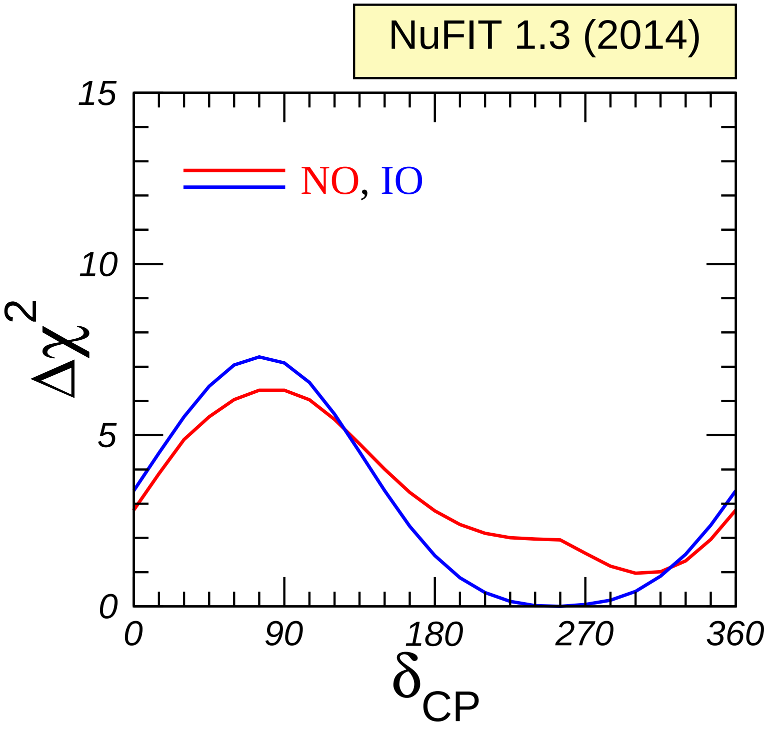


- Determination of Mass Ordering:
  - No significant difference Normal versus Inverted
    IO favoured at 0-1 σ level

- Sign and size of these 1-1.5σ “hints”
  vary among analysis

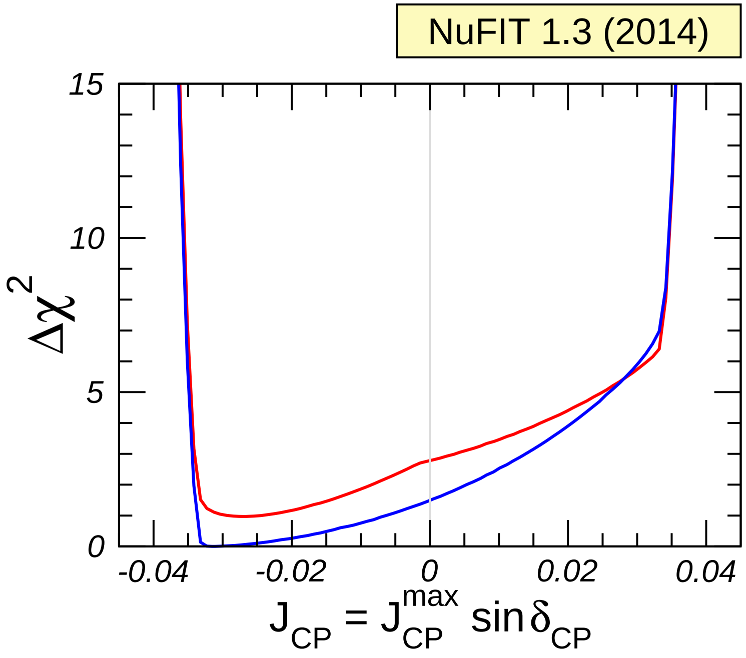
3ν Analysis: Leptonic CP violation

- Driven by the LBL-APP vs REACT θ_{13} with slight influence of ATM



- Projection over leptonic Jarkskog param

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



- $\sim 2\sigma$ "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):

$$\Delta m^2_{21} = 7.5 \pm 0.18 \left({}^{+0.56}_{-0.47}\right) \times 10^{-5}\,\mathrm{eV}^2 \qquad \theta_{12} = 33.5^{\circ}{}^{+0.77}_{-0.74} \left({}^{+2.4}_{-2.2}\right)$$

$$\Delta m^2_{31}(\mathrm{N}) = 2.46^{+0.05}_{-0.05} \left({}^{+0.14}_{-0.14}\right) \times 10^{-3}\,\mathrm{eV}^2 \qquad \theta_{23} = \begin{cases} (\mathrm{N})\ 42.1^{\circ}{}^{+3.2^{\circ}}_{-1.5^{\circ}} & \left({}^{+11.1^{\circ}}_{-3.7^{\circ}}\right) \\ (\mathrm{I})\ 49.4^{\circ}{}^{+1.6^{\circ}}_{-2.0^{\circ}} & \left({}^{+3.9^{\circ}}_{-11.0^{\circ}}\right) \end{cases}$$

$$|\Delta m^2_{32}|(\mathrm{I}) = 2.49^{+0.05}_{-0.05} \left({}^{+0.14}_{-0.14}\right) \times 10^{-3}\,\mathrm{eV}^2 \qquad \theta_{13} = 8.5^{\circ}{}^{+0.19}_{-0.17} \left({}^{+0.6^{\circ}}_{-0.5^{\circ}}\right)$$

$$\delta_{\mathrm{CP}} = \begin{cases} (\mathrm{N})\ 300^{\circ}{}^{+45^{\circ}}_{-45^{\circ}} & \left({}^{+60^{\circ}}_{-300^{\circ}}\right) \\ (\mathrm{I})\ 251^{\circ}{}^{+67^{\circ}}_{-59^{\circ}} & \left({}^{+109^{\circ}}_{-251^{\circ}}\right) \end{cases}$$

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

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- Good progress but still precision very far from:

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

Lepton Mixing Unitarity

- Previous results assume $U_{\rm LEP}$ to be unitary
- If ν_L mixed with m extra states $U_{\rm LEP} = (K_{l,3\times 3}\,, K_{h,3\times m})$ Schechter, Valle (1980)

  And $U_{\rm LEP} U^\dagger_{\rm LEP} = I_{3\times 3}$ but in general $U^\dagger_{\rm LEP} U_{\rm LEP} \neq I_{(3+m)\times(3+m)}$
- If m states are heavy ($M >> E_\nu$) oscillations measure $K_{L,3\times 3}$ (not unitary)

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- If m states are heavy ($M >> E_\nu$) oscillations measure $K_{L,3\times3}$ (not unitary)
- But this unitarity violation ⇒ Flavour Changing Neutral Currents
  Flavour Violation in Charged Lepton Processes
  Universality Violation of Charge Current …
- Constraints on these processes limit leptonic unitarity violation to

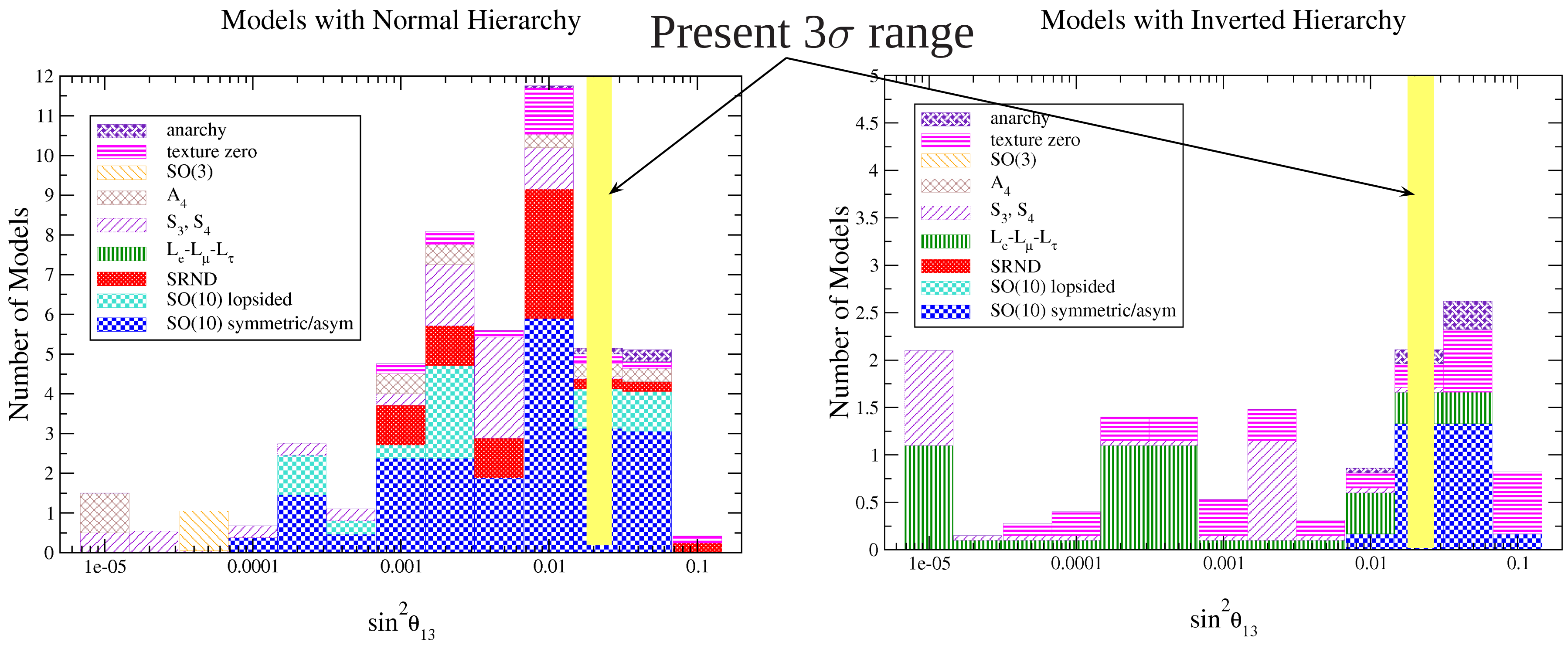
$$|K_l K_l^\dagger| = \begin{pmatrix} 0.994 \pm 0.005 & < 7.0 \times 10^{-5} & < 1.6 \times 10^{-2} \\ < 7.0 \times 10^{-5} & 0.995 \pm 0.005 & < 1.0 \times 10^{-2} \\ < 1.6 \times 10^{-2} & < 1.0 \times 10^{-2} & 0.995 \pm 0.005 \end{pmatrix}$$

Antusch *et al* hep-ph/0607029

or equivalently $K_l \simeq (I + \epsilon) U(\theta_{ij}, \delta, \eta_i)$ with $|\epsilon_{\alpha j}| \leq \text{few} \times 10^{-3}$ while $K_h \sim \mathcal{O}(\epsilon)$

Modeling Lepton Flavour: 2006 to 2014

- Survey of 63 ν mass models in 2006 (Albright, M-C Chen,hep-ph/0608136)

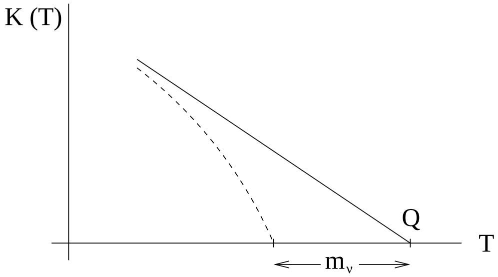

Present 3σ range

– Determination of θ_{13} has given us important handle in flavour modeling

– Next *frontiere* is the ordering (see talk by T. Schwetz)

Neutrino Mass Scale

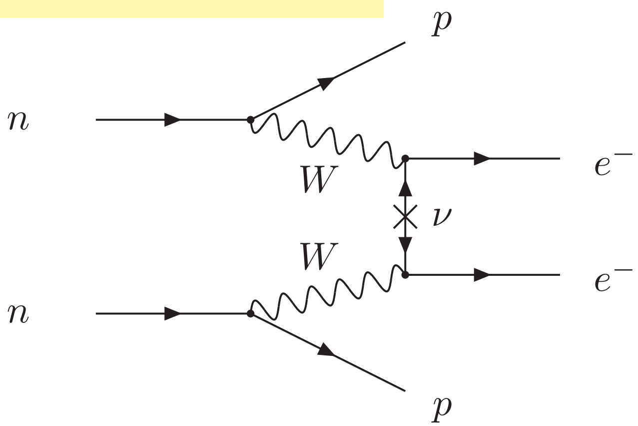
Single β decay : Dirac or Majorana ν mass modify spectrum endpoint



$$m^2_{\nu_e} = \sum m^2_j |U_{ej}|^2 = c^2_{13} c^2_{12} m^2_1 + c^2_{13} s^2_{12} m^2_2 + s^2_{13} m^2_3$$

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

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



$$m_{ee} = |\sum U^2_{ej} m_j|$$

$$= \left| c^2_{13} c^2_{12} m_1 \, e^{i\eta_1} + c^2_{13} s^2_{12} m_2 \, e^{i\eta_2} + s^2_{13} m_3 \, e^{-i\delta_{CP}} \right|$$

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

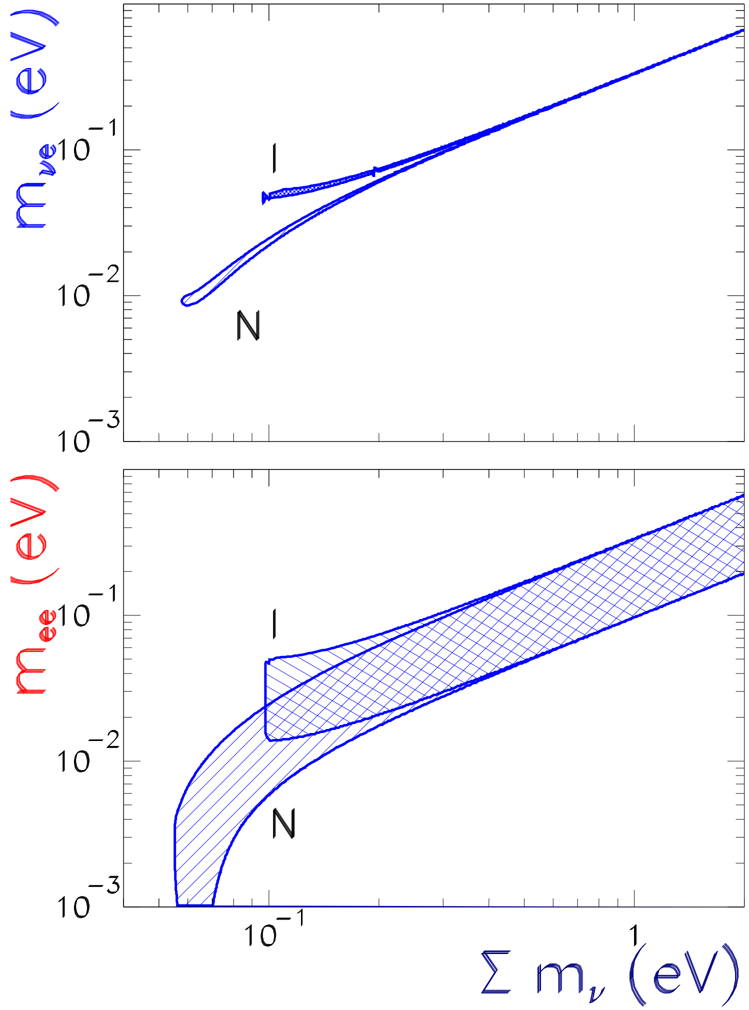
$$\sum m_i$$

Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis

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

Maltoni, Schwetz,Salvado, MCGG (95%)



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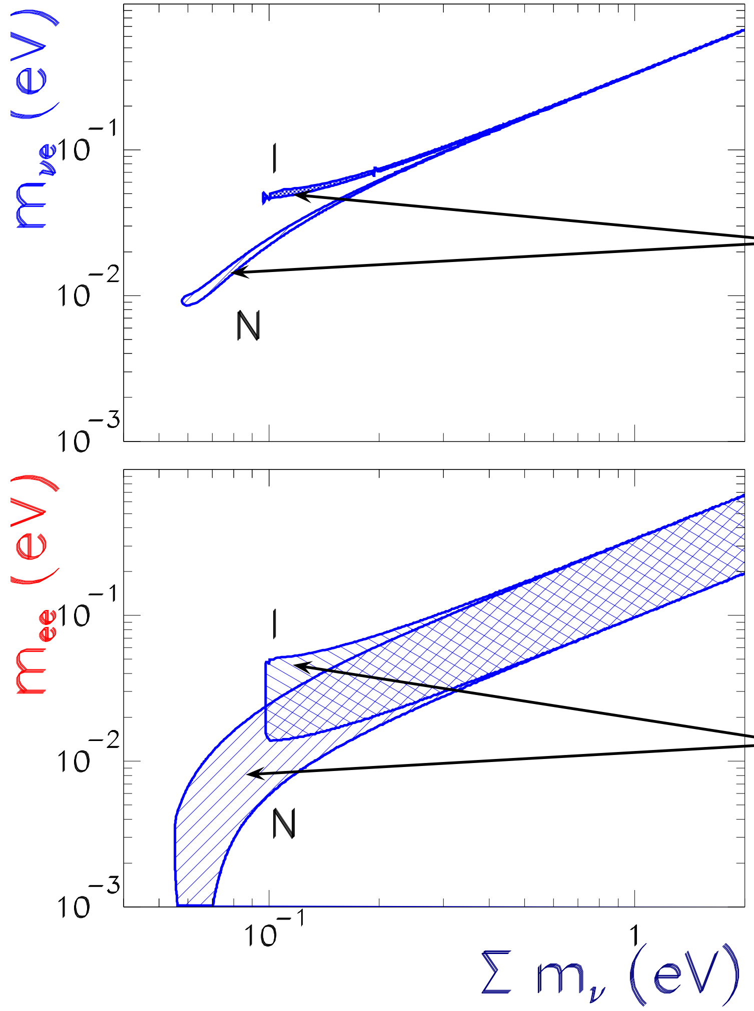

Width due to range in oscillation parameters very narrow

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)

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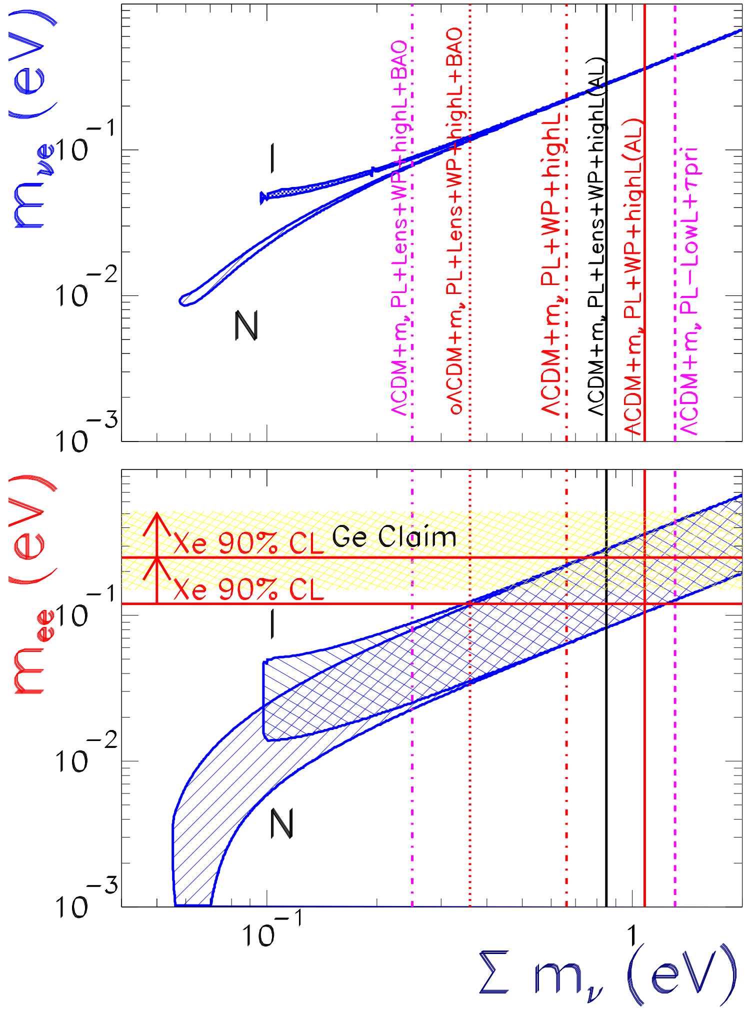


Presently only Bounds

- 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, KLandZEN,Gerda…) :

  $m_{ee} < 0.14 - 0.45$ eV (90%)

  In 5-10 yr Experiments ⇒ $m_{ee} \sim 0.015\,$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%
ΛCDM $+ m_\nu$	Planck-lowL+τprior	≤ 1.31
ΛCDM $+ m_\nu$	Planck+WP+highL(A$_L$)	≤ 1.08
ΛCDM $+ m_\nu$	Planck+Lens+WP+highL(A$_L$)	≤ 0.85
ΛCDM $+ m_\nu$	Planck+WP+highL	≤ 0.66
$o\Lambda$CDM $+ m_\nu$	Planck+WP+highL	≤ 0.98
ΛCDM $+ m_\nu$	Planck+Lens+WP+highL+BAO	≤ 0.25
$o\Lambda$CDM $+ m_\nu$	Planck+Lens+WP+highL+BAO	≤ 0.36

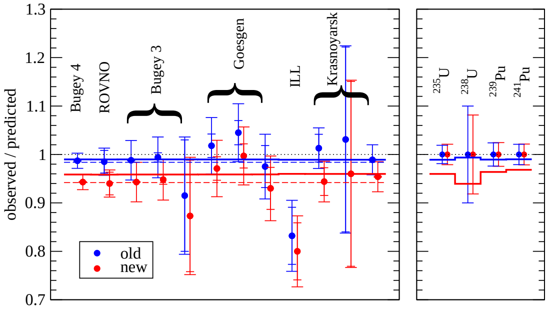
Light Sterile Neutrinos

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

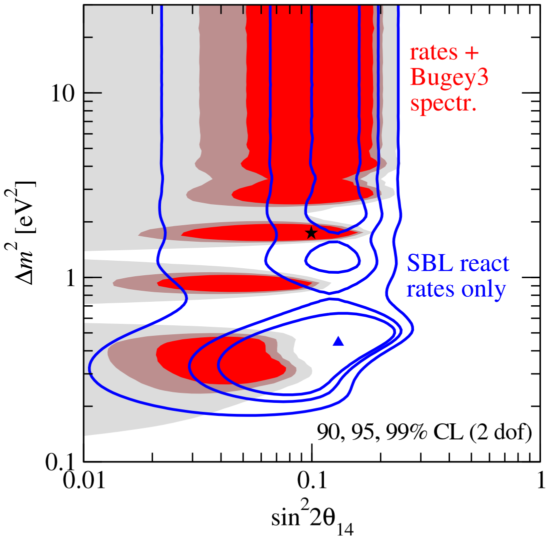
Reactor Anomaly

New reactor flux calculation

$\Rightarrow$ Deficit in data at $L \lesssim 100$ m



Explained as ν_e disappearance



Kopp etal, ArXiv 1303.3011

Gallium Anomaly

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

Radioactive Sources (^{51}Cr, ^{37}Ar)

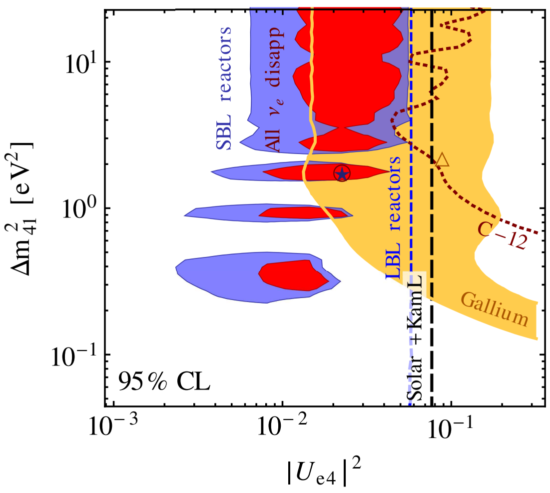
in callibration of Ga Solar Exp;

$$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$$

Give a rate lower than expected

$$R = \frac{N_{\rm obs}}{N^{\rm th}_{\rm Bahc}} = 0.86 \pm 0.05 \ (2.8\sigma)$$

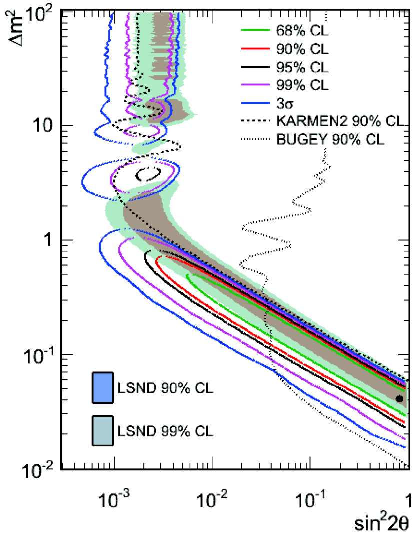
Explained as ν_e disappearance



Kopp etal, ArXiv 1303.3011

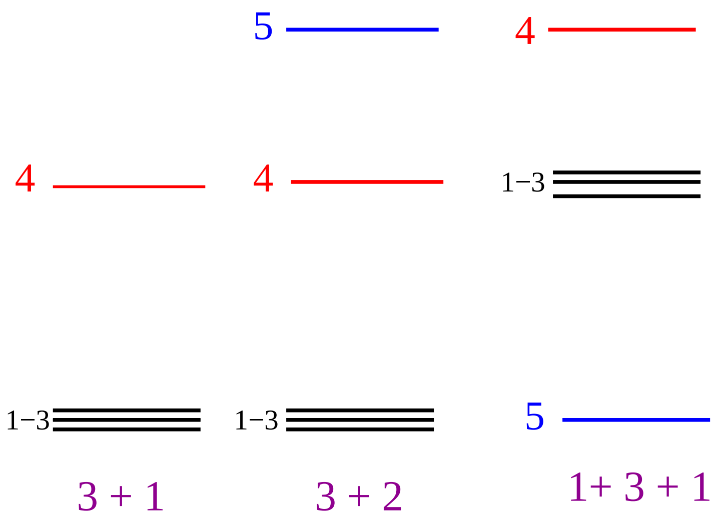
LSND, MiniBoone

$\nu_\mu \to \nu_e$ and $\bar\nu_\mu \to \bar\nu_e$



Light Sterile Neutrinos

- These explanations require 3+N_s mass eigenstates → N_s sterile neutrinos



- Problem: fit together
  $\nu_e \to \nu_e$ disapp (REACT,Gallium,Solar, LSND/KARMEN)
  $\nu_\mu \to \nu_e$ app (LSND,KARMEN,NOMAD,MiniBooNE,E776,ICARUS)
  $\nu_\mu \to \nu_\mu$ disapp (CDHS,ATM,MINOS,MiniBooNE)

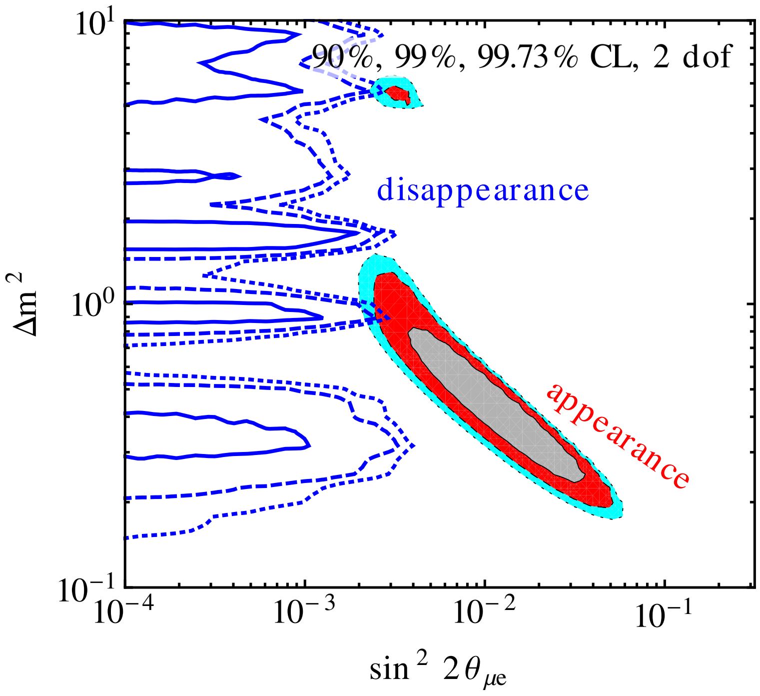
- Generically: $P(\nu_e \to \nu_\mu) \sim |U^*_{ei} U_{\mu i}|$ [i =heavier state(s)]

$$\left.\begin{array}{l} \text{But } |U_{ei}| \text{ constrained by } P(\nu_e \to \nu_e) \text{ disappearance data} \\ \text{And } |U_{\mu i}| \text{ constrained by } P(\nu_\mu \to \nu_\mu) \text{ disappearance data} \end{array}\right\} \Rightarrow \text{Severe tension}$$

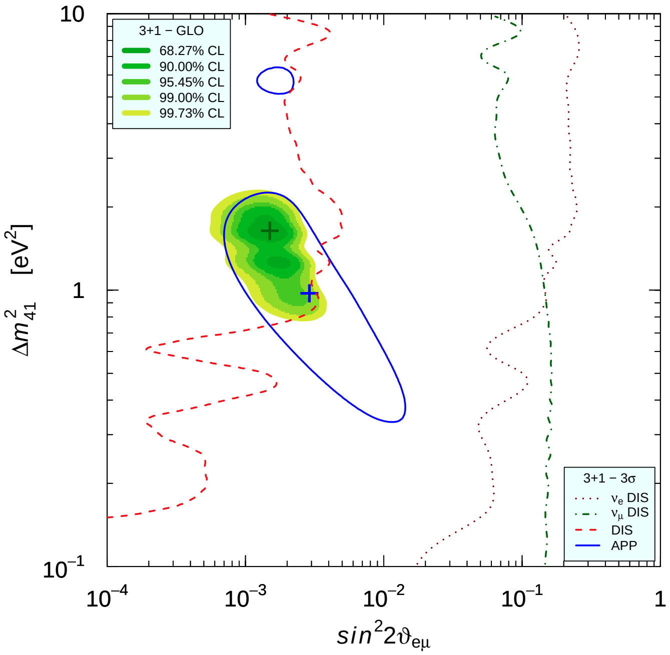
Light Sterile Neutrinos:3+1

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

Kopp etal, ArXiv 1303.3011



Giunti etal, ArXiv 1308.5288



– Difference in the analysis of both appearance and disappearance

– Somewhat different conclusions

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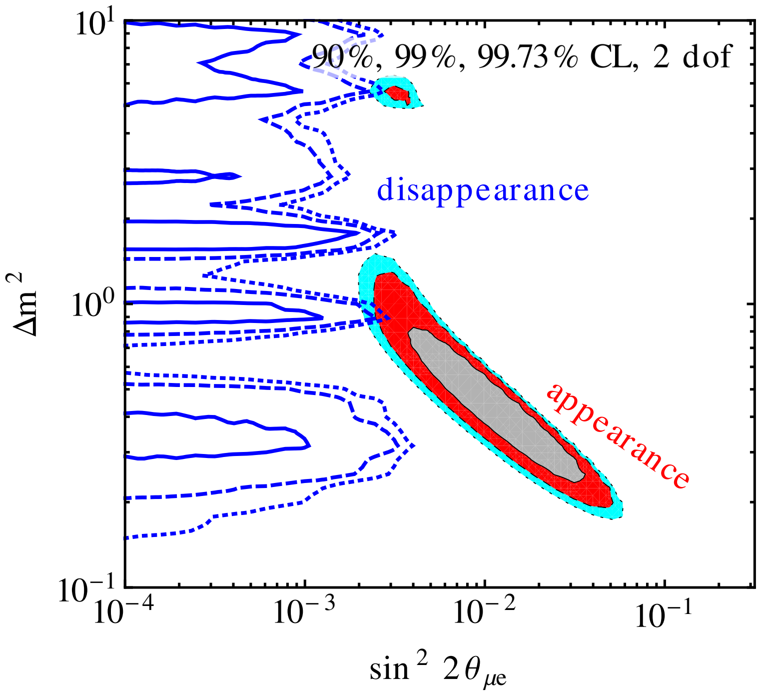
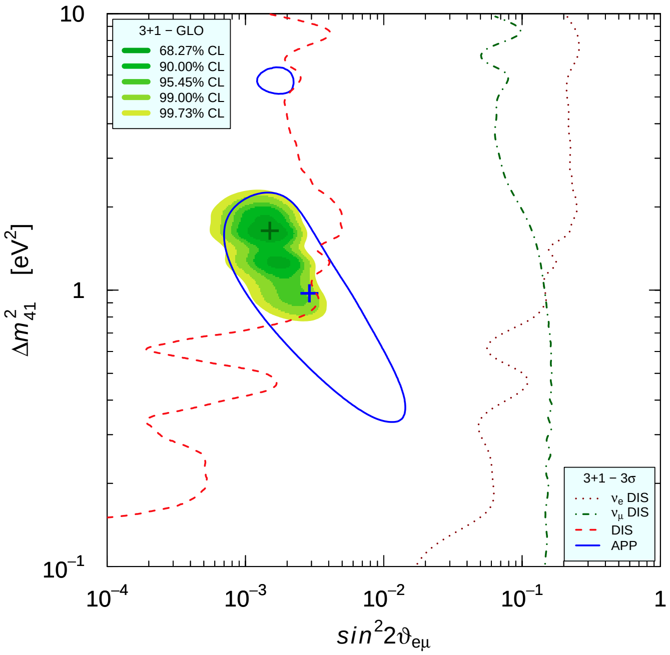
Kopp etal, ArXiv 1303.3011



Giunti etal, ArXiv 1308.5288



– Difference in the analysis of both appearance and disappearance

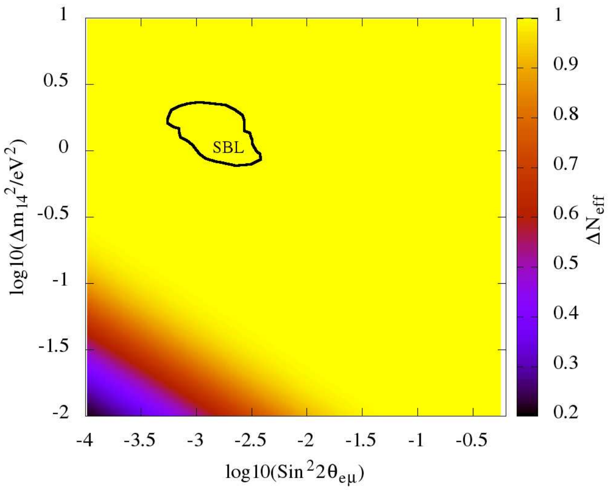
– Somewhat different conclusions

- Adding more steriles (3+2 or 1+3+1): not much improvement

  Also tension with cosmology

Light Sterile Neutrinos in Cosmology

One light ν_s mixed with 3 $\nu_a^\prime s$ contributes to ρ as N_{eff}.



From evol eq for $3+1$ esemble one finds

$\Rightarrow$ So if "explaination" to SBL anomalies

1 ν_s contributes as much as 1 ν_a

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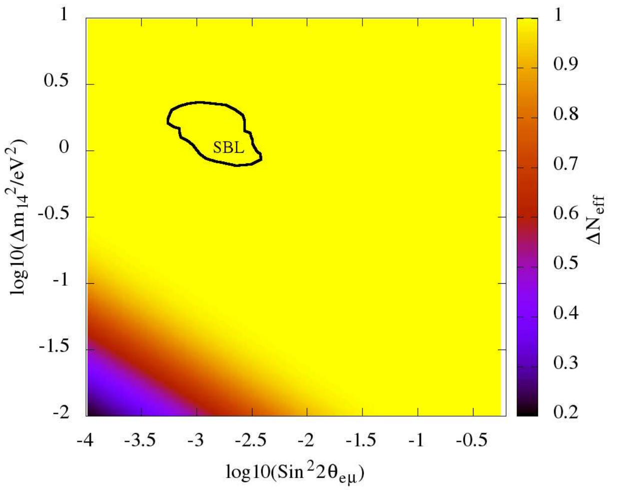
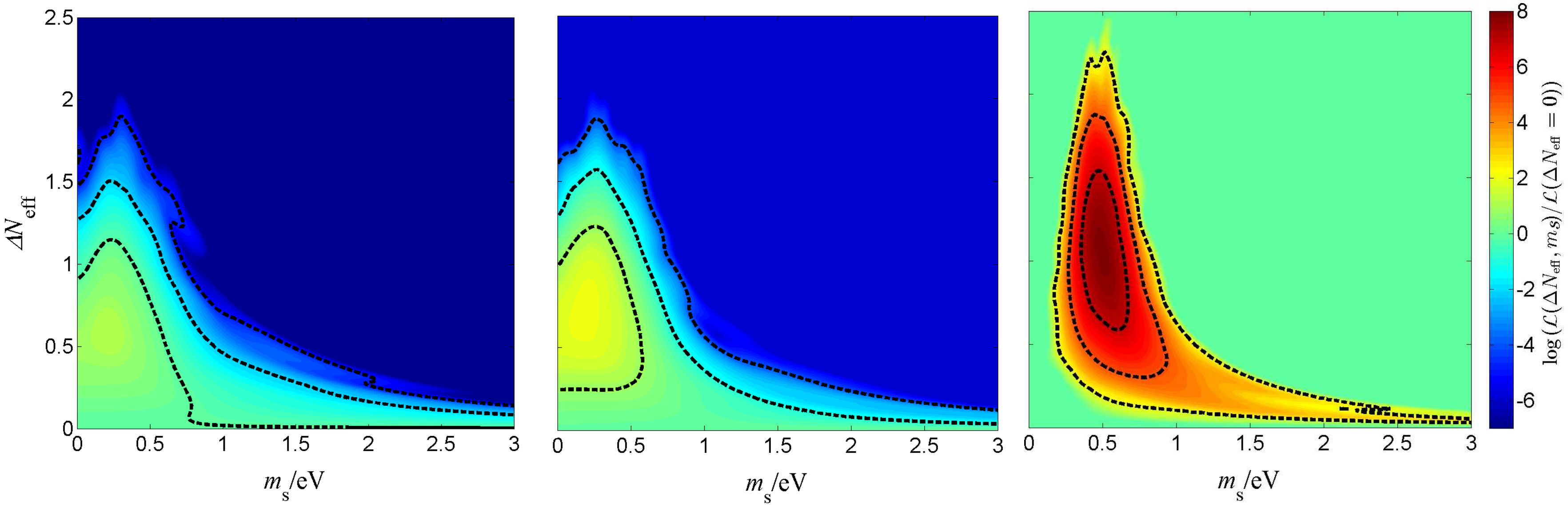


But analysis of cosmo data in ΛCDM+$r+\nu_s$ tells us

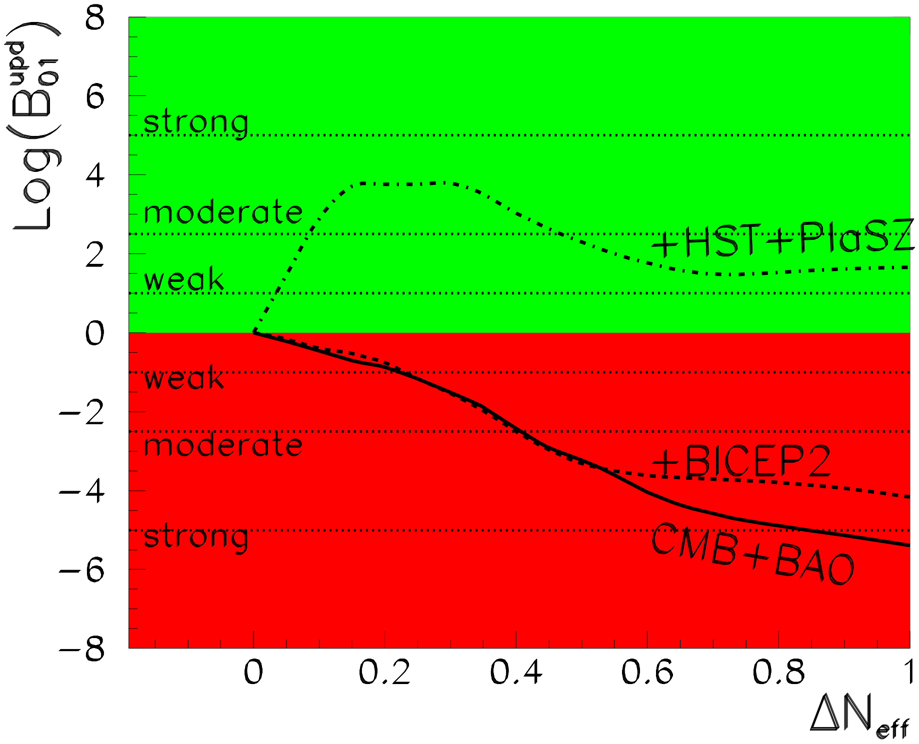
Plank+WP+high-l+BAO +BICEP2 +H0+PlaSZ



J. Bergstrom, M.C.G-G, V. Niro, J. Salvado, ArXiv:1407.XXXX

Light Sterile Neutrinos in Cosmology

Bayes factor for 3+1 vs 3+0 from cosmology $B_{10}^{\mathrm{upd}} = \frac{Pr(\mathrm{Cosmo}|3{+}1 \text{ for SBL})}{Pr(\mathrm{Cosmo}|3{+}0)}$



J. Bergstrom, M.C.G-G, V. Niro, J. Salvado, ArXiv:1407.XXXX

Results in qualitative agreement with f.e. Archidiacono *et. al.* ArXiv:1404.1794

Non Standard ν Int:Determination of Matter Potential

- Including non-standard neutrino NC interactions with fermion f

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

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

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

with most general matter potential

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

with $\varepsilon^f_{\alpha\beta} = \varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}$

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

Matter Potential/NSI in Solar and KamLAND

- Solar $\nu' s$: 2 relevant combinations of NSI

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

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

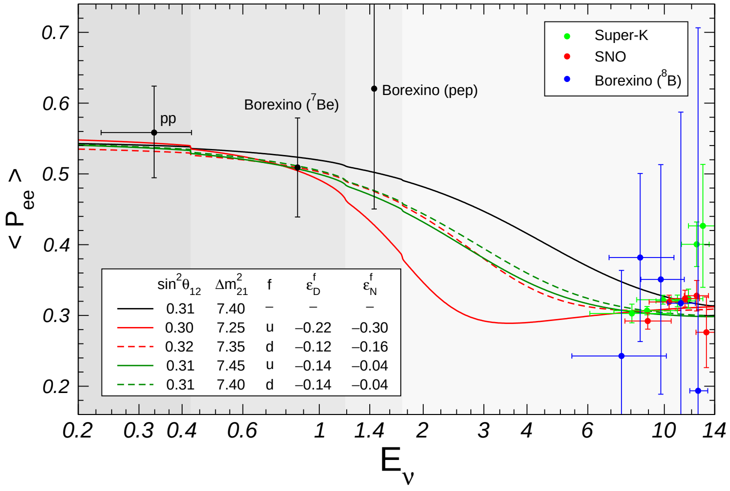
Matter Potential/NSI in Solar and KamLAND

- Solar $\nu' s$: 2 relevant combinations of NSI

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

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

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



Due to no observation of MSW up-turn

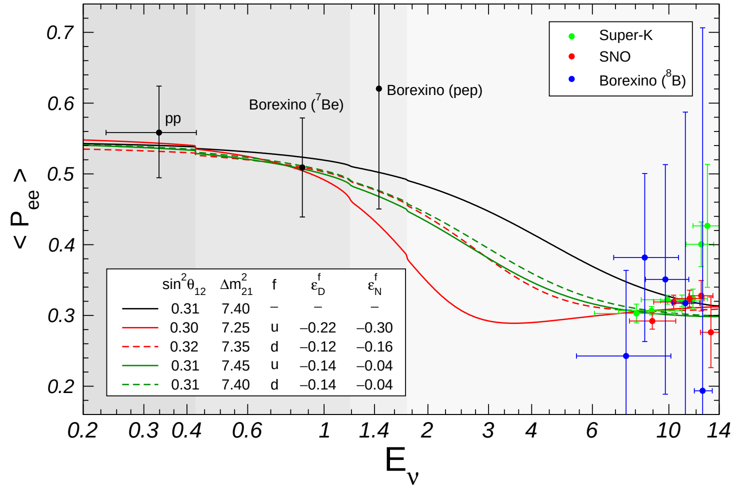
Matter Potential/NSI in Solar and KamLAND

- Solar $\nu' s$: 2 relevant combinations of NSI

$$\begin{aligned}\varepsilon^f_D &= c_{13} s_{13} \mathrm{Re}\left[e^{i\delta_{\rm CP}}\left(s_{23}\,\varepsilon^f_{e\mu} + c_{23}\,\varepsilon^f_{e\tau}\right)\right] \\ &-\left(1+s^2_{13}\right) c_{23} s_{23} \mathrm{Re}\left(\varepsilon^f_{\mu\tau}\right) \\ &-\frac{c^2_{13}}{2}\left(\varepsilon^f_{ee} - \varepsilon^f_{\mu\mu}\right) + \frac{s^2_{23}-s^2_{13}c^2_{23}}{2}\left(\varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu}\right)\end{aligned}$$

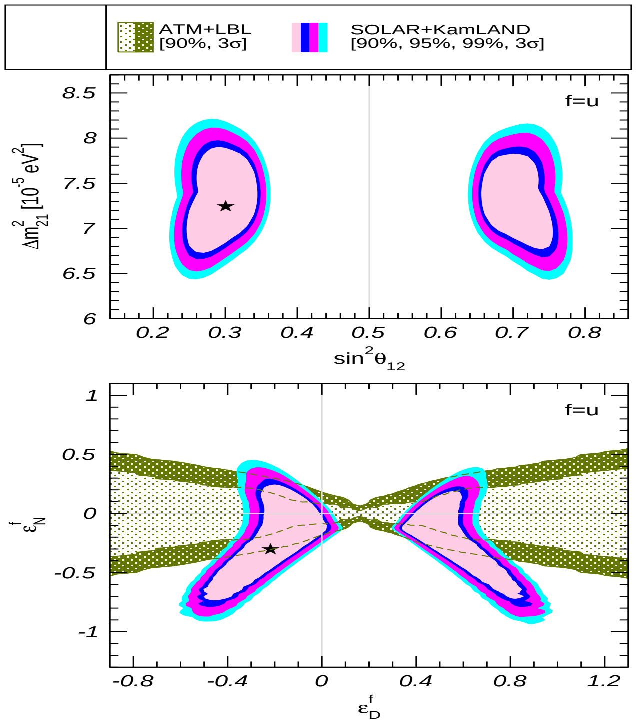
$$\begin{aligned}\varepsilon^f_N &= c_{13}\left(c_{23}\,\varepsilon^f_{e\mu} - s_{23}\,\varepsilon^f_{e\tau}\right) \\ &+ s_{13} e^{-i\delta_{\rm CP}}\left[s^2_{23}\,\varepsilon^f_{\mu\tau} - c^2_{23}\,\varepsilon^{f\,*}_{\mu\tau}\right. \\ &\left. + c_{23} s_{23}\left(\varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu}\right)\right]\end{aligned}$$

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



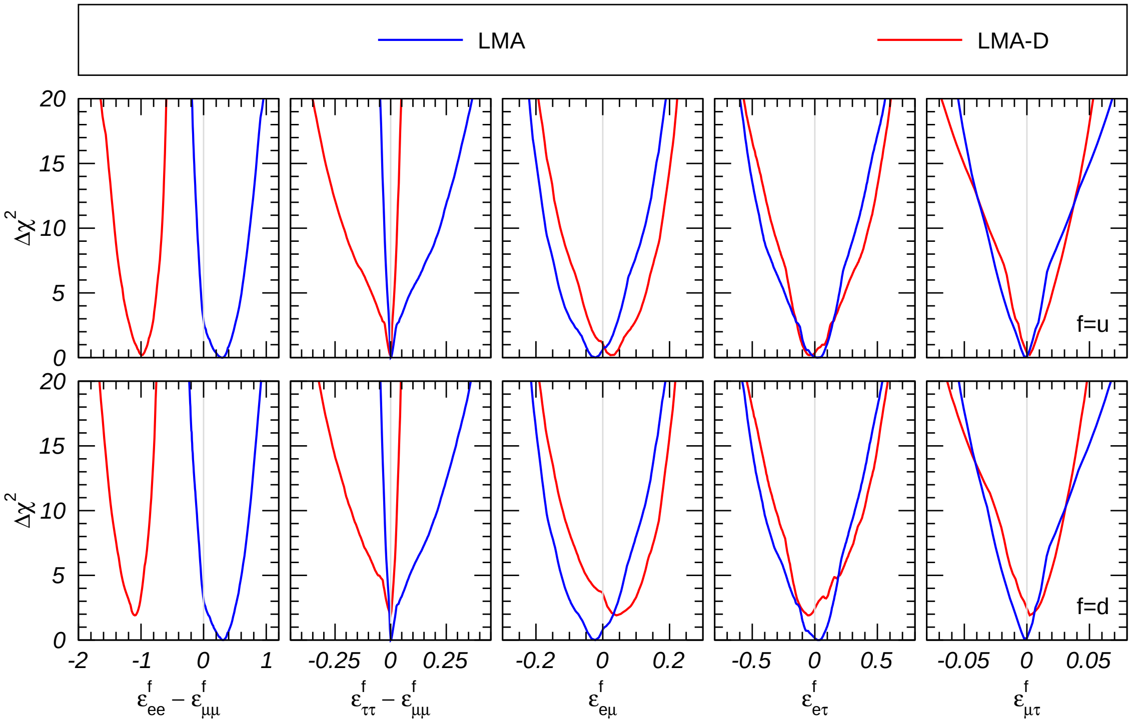
Due to no observation of MSW up-turn

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



Matter Potential/NSI: Global Analysis

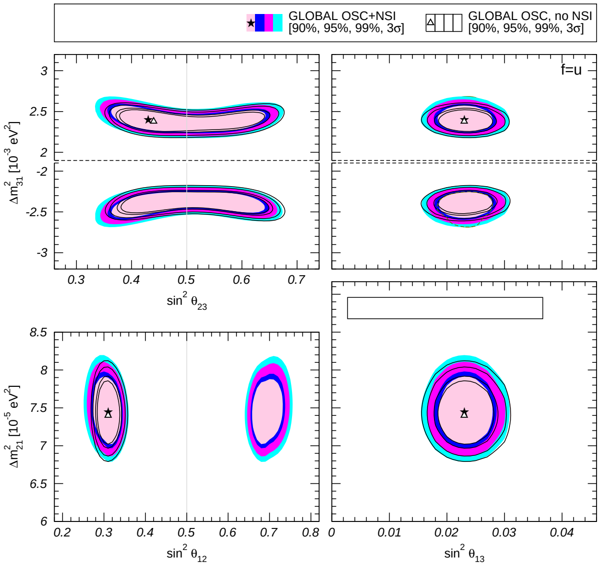
- Parameter space of matter potential is bounded



	90% CL	
Param.	OSC	SCATT
$\lvert\varepsilon^u_{ee}\rvert$	0.51–1.19	0.7–1
$\lvert\varepsilon^u_{\tau\tau}\rvert$	0.03	1.4–3
$\lvert\varepsilon^u_{e\mu}\rvert$	0.09	0.05
$\lvert\varepsilon^u_{e\tau}\rvert$	0.15	0.5
$\lvert\varepsilon^u_{\mu\tau}\rvert$	0.01	0.05

	90% CL	
Param.	OSC	SCATT
$\lvert\varepsilon^d_{ee}\rvert$	0.51–1.17	0.3–0.7
$\lvert\varepsilon^d_{\tau\tau}\rvert$	0.03	1.1–6
$\lvert\varepsilon^d_{e\mu}\rvert$	0.09	0.05
$\lvert\varepsilon^d_{e\tau}\rvert$	0.14	0.5
$\lvert\varepsilon^d_{\mu\tau}\rvert$	0.01	0.05

Osc parameter robust
(but solar dark side)



Bounds from global osc fit stronger than scattering ones for $\varepsilon^{u,d}_{\tau\beta}$

Maltoni, MCG-G, ArXiv:1307.3092

Summary

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

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

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

- 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 Invarance, Tests of CPT …