NEUTRINO MASSES AND MIXING CIRCA 2016

Concha Gonzalez-Garcia

(ICREA U. Barcelona & YITP Stony Brook)

Neutrino GdR, June 16th, 2016

Global fit to neutrino oscillation data

http://www.nu-fit.org

elusives

neutrinos, dark matter & dark energy physics

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OUTLINE

Determination of 3ν Lepton Flavour Parameters

Extensions: Light Sterile $\nu's$, Non-standard ν 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

- By 2016 we have observed with high (or good) precision:

  - $*$ Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK**,MINOS, ICECUBE)
  - $*$ Accel. ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K, MINOS, NOνA**)
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- The *important* question:

What is the BSM theory?

- The *starting* path:

Precise determination of the low energy parametrization

The New Minimal Standard Model

- Minimal extension to introduce L_α violation $\Rightarrow$ 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 $\nu = \nu^c$

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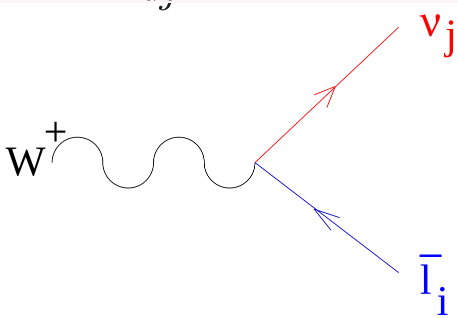
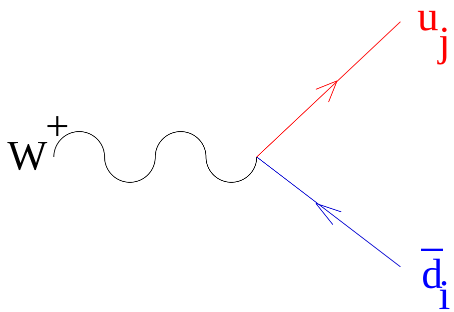
- The charged current interactions of leptons are not diagonal (same as quarks)

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





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

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

- 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

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

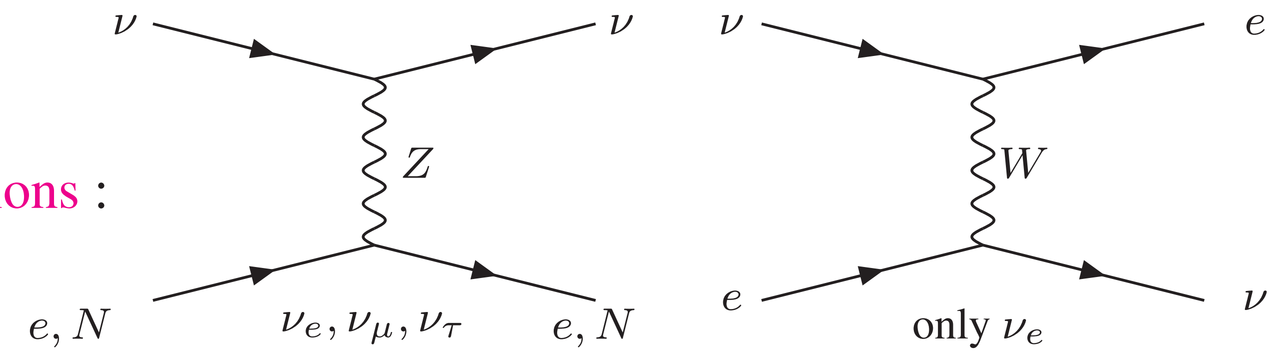
$$\frac{\Delta_{ij}}{2} = \frac{(E_i - E_j)L}{2} = 1.27 \frac{(m_i^2 - m_j^2)}{\mathrm{eV}^2} \frac{L/E}{\mathrm{Km/GeV}}$$

No information on ν mass scale nor Majorana versus Dirac

Matter Effects

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

  – But Different flavours have different interactions :



$\Rightarrow$ Effective potential in ν evolution : $V_e \neq V_{\mu,\tau} \Rightarrow \Delta V^\nu = -\Delta V^{\bar\nu} = \sqrt{2} G_F N_e$

$\Rightarrow$ *Modification of mixing angle and oscillation wavelength* $\equiv$ MSW effect

- The mixing angle in matter

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

- For solar neutrinos in adiabatic regime $P(\nu_e \to \nu_e) = \frac{1}{2}\left[1 + \cos(2\theta_m)\cos(2\theta)\right]$

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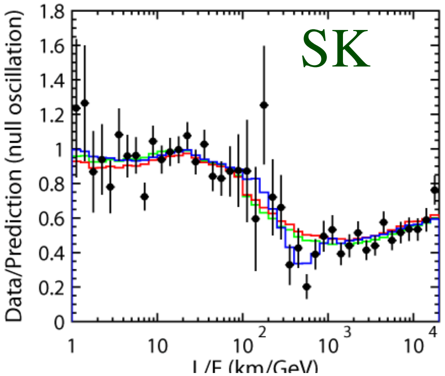
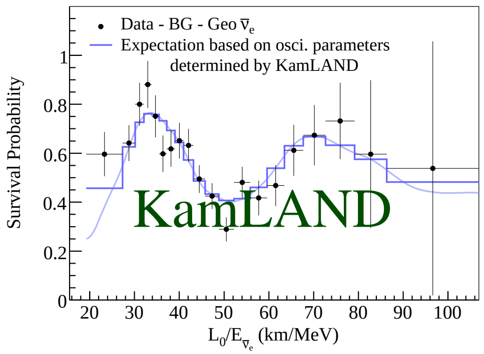
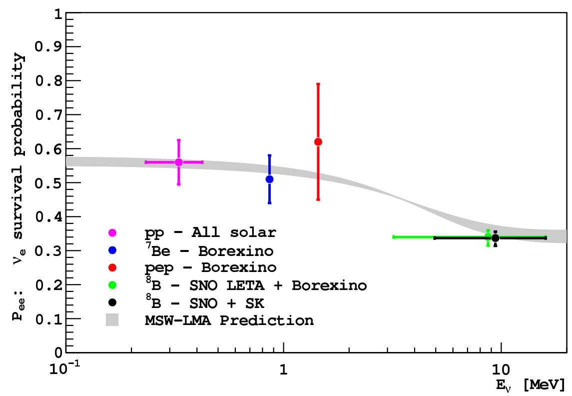
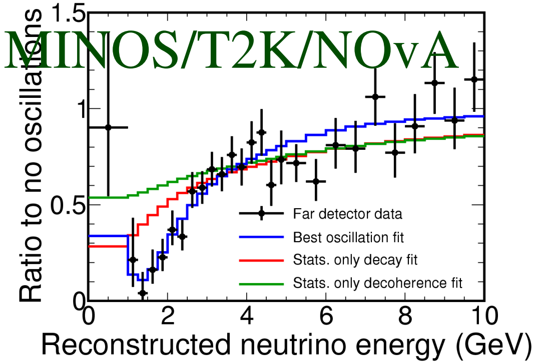
- Confirmed: Vacuum oscillation L/E pattern with 2 frequencies

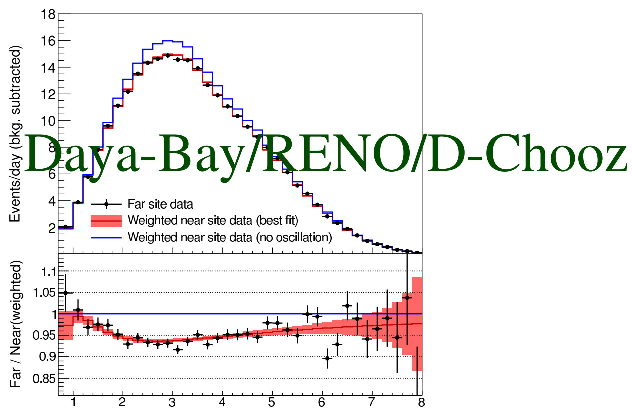
MSW conversion in Sun









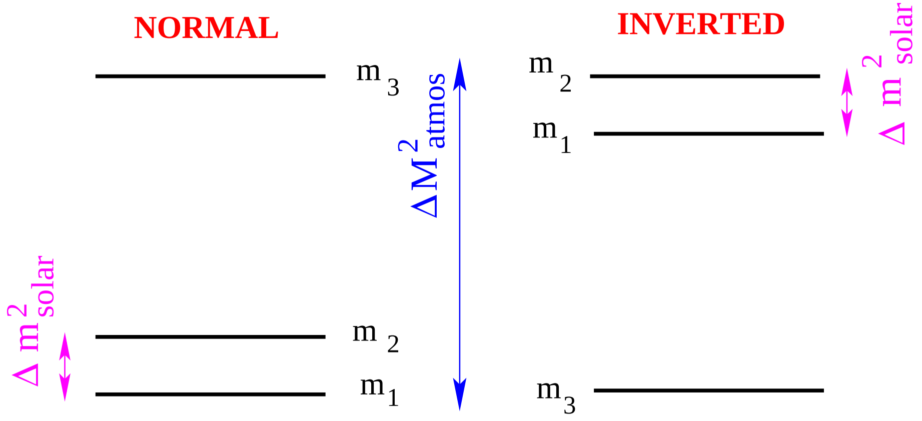


3ν Flavour Parameters

- 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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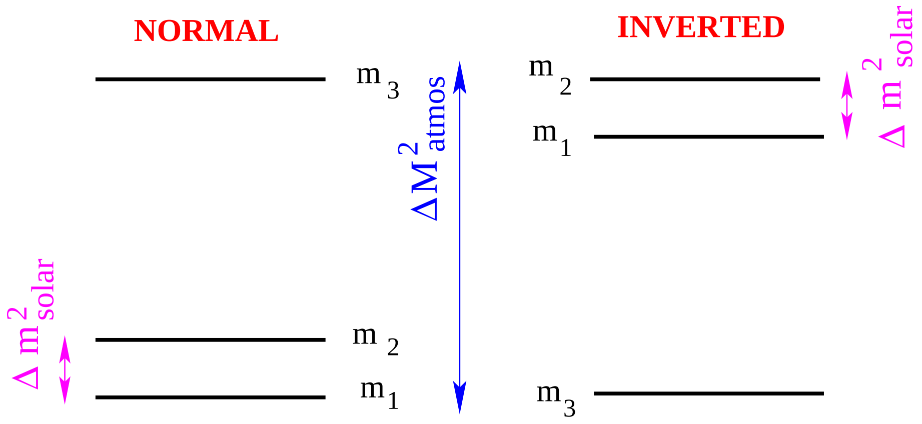
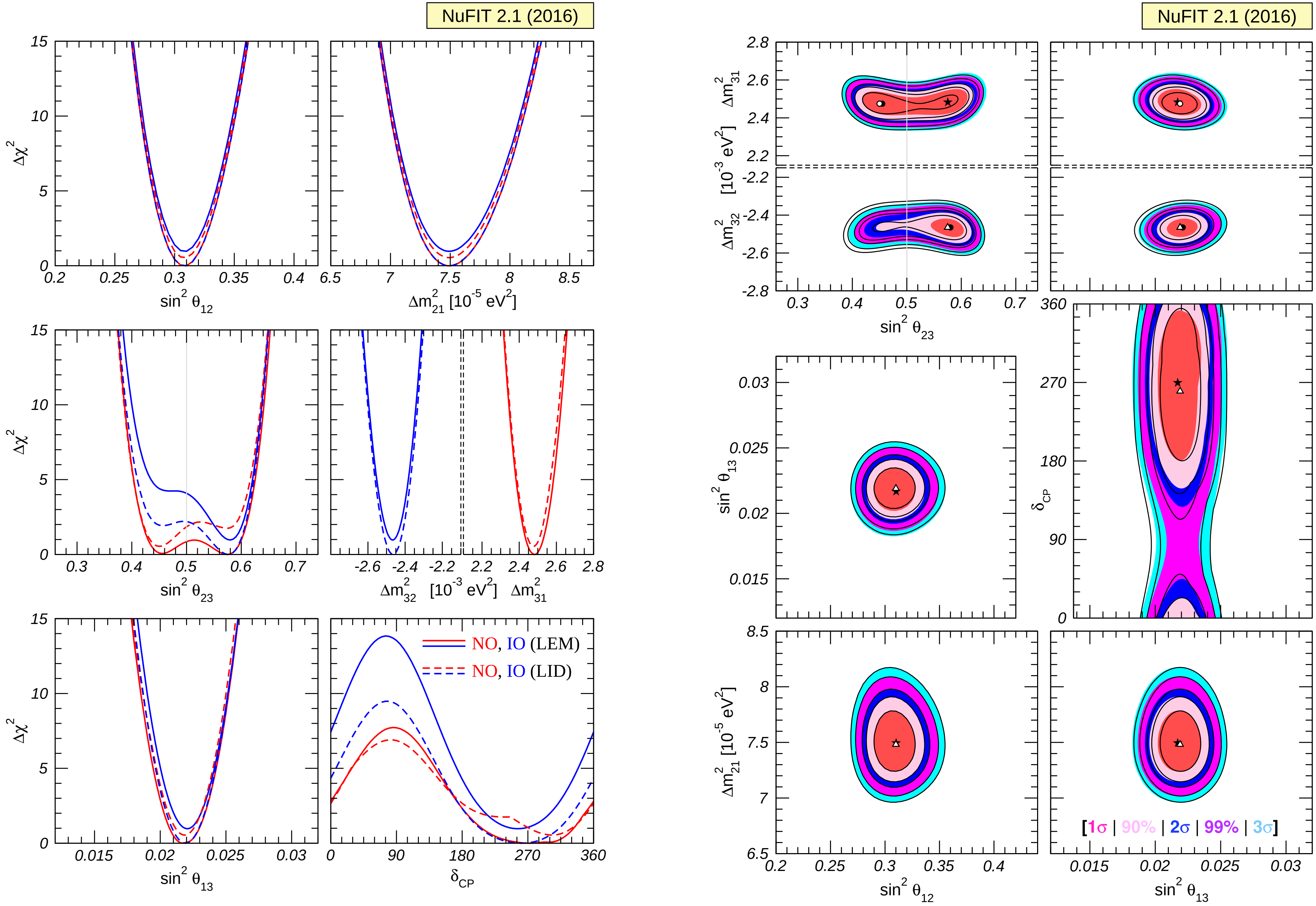


Experiment	Dominant Dependence	Important Dependence
Solar Experiments	$\to \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\to \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	$\to \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\to \theta_{23}$	$\Delta m^2_{\rm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

3 ν Flavour Parameters: Status in 6/2016

Global 6-parameter fit http://www.nu-fit.org (ArXiv:1409.5439)

Maltoni, Schwetz, Martinez-Soler, Esteban, MCG-G



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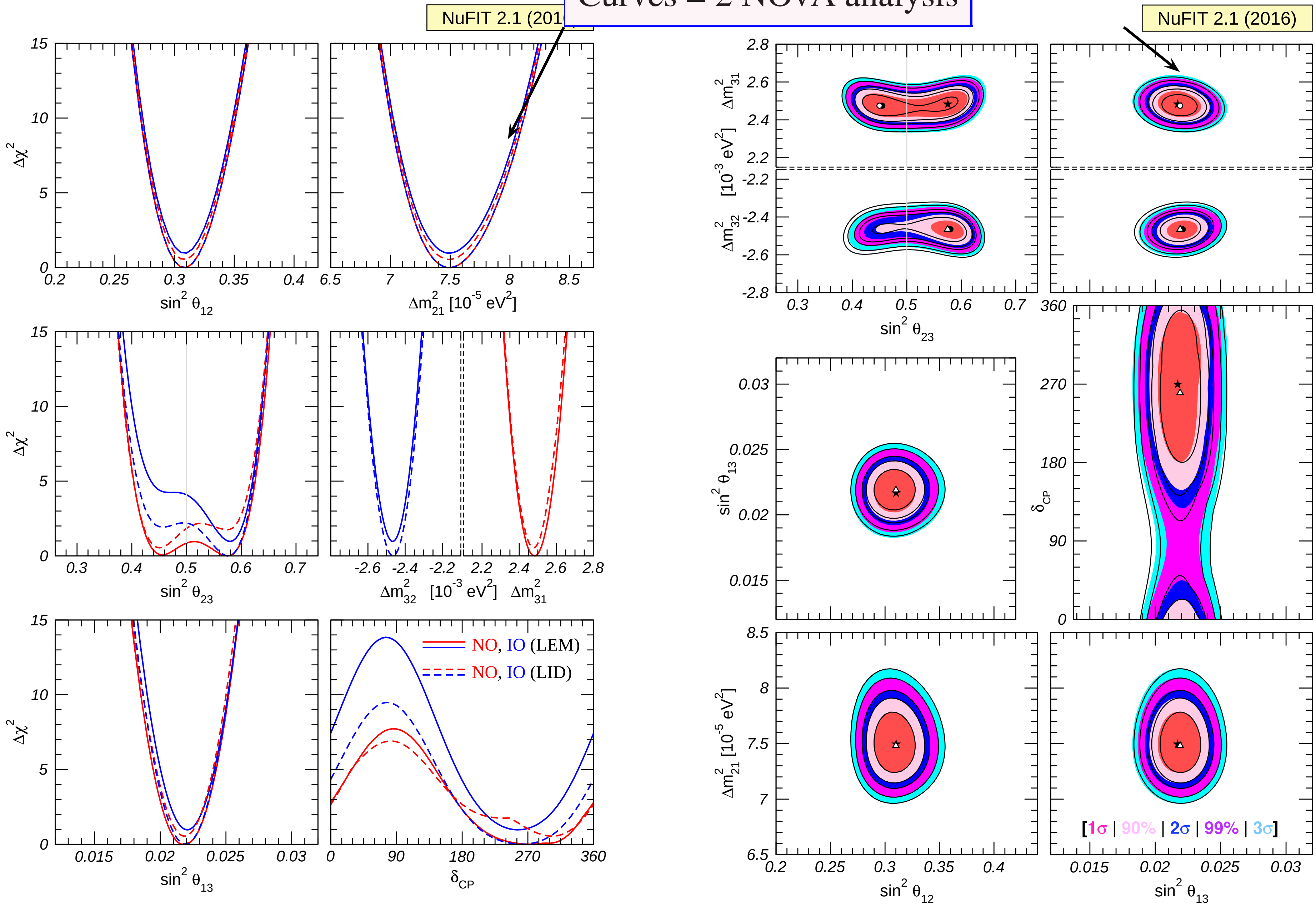
Curves = 2 NOvA analysis



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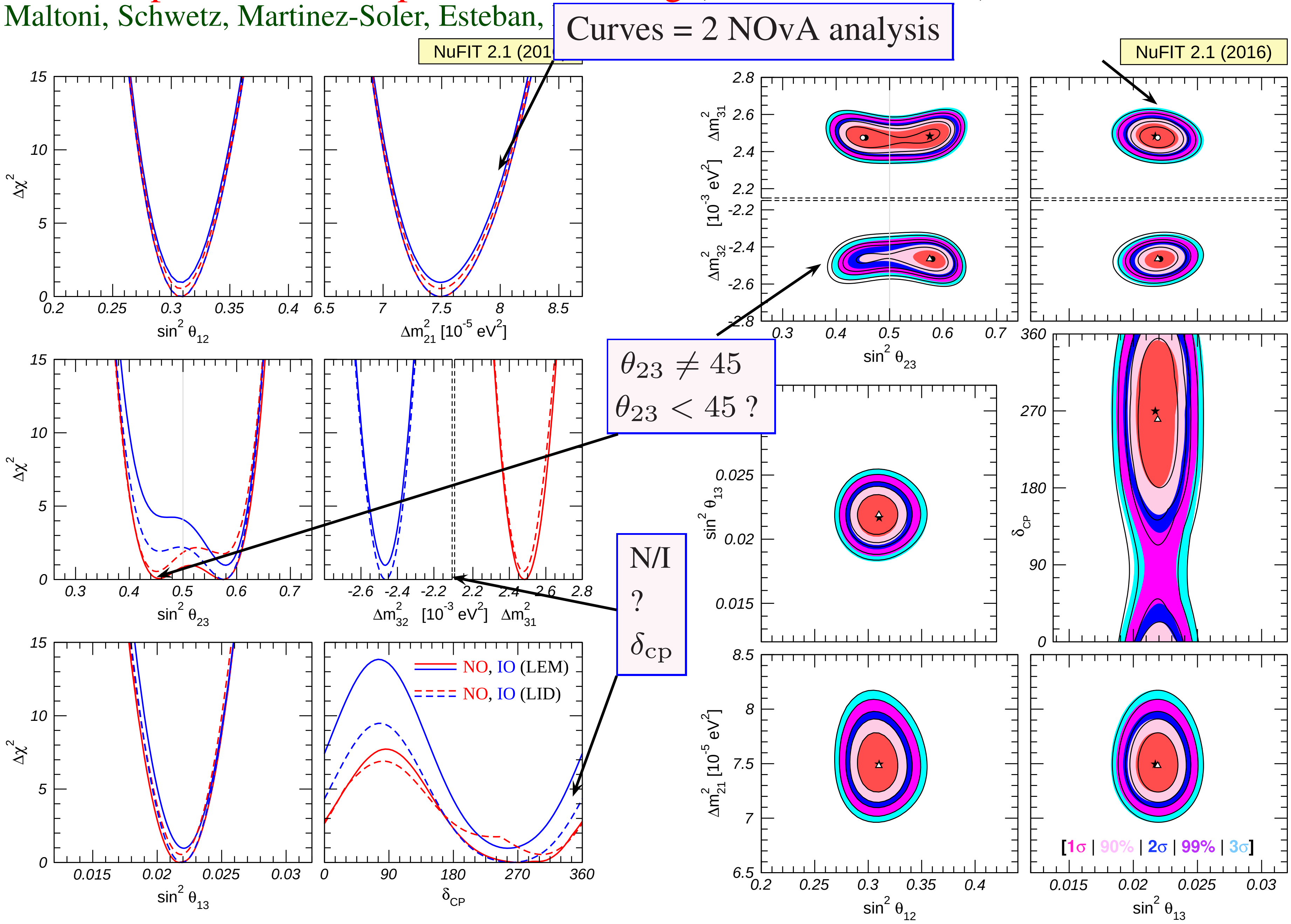
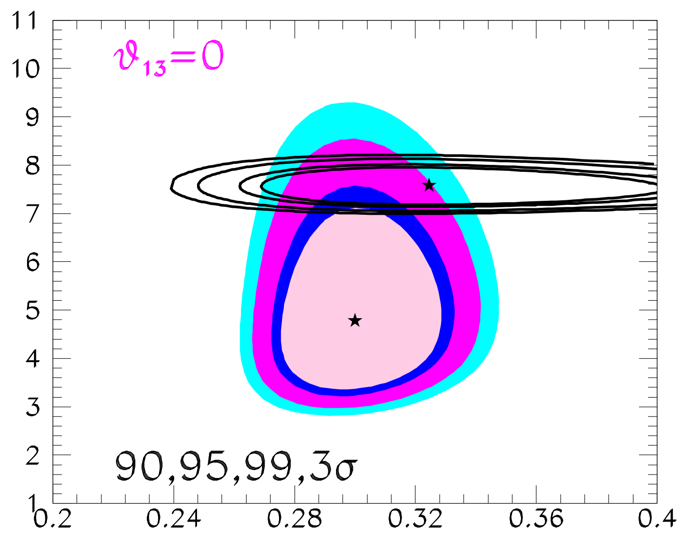


3 ν Analysis: "12" Sector and θ_{13}

- For $\theta_{13} = 0$



$$\sin^2\theta_{12} = \begin{cases} 0.3 \text{ From Solar} \\ 0.325 \text{ From KLAND} \end{cases}$$

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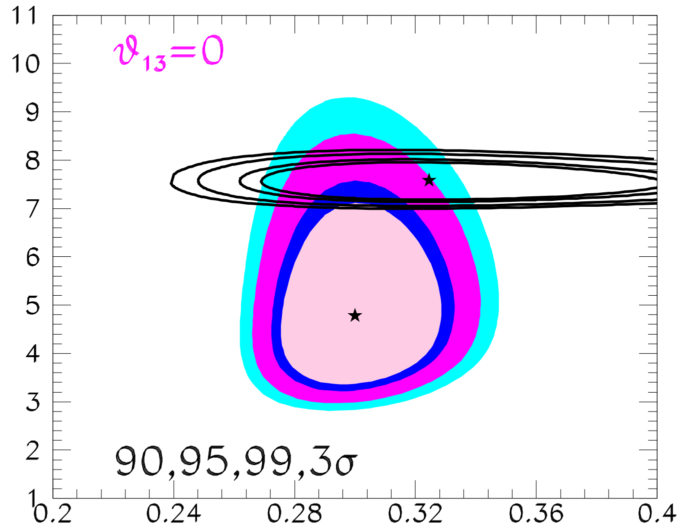


$$\sin^2\theta_{12} = \begin{cases} 0.3 \text{ From Solar} \\ 0.325 \text{ From KLAND} \end{cases}$$

• When θ_{13} increases

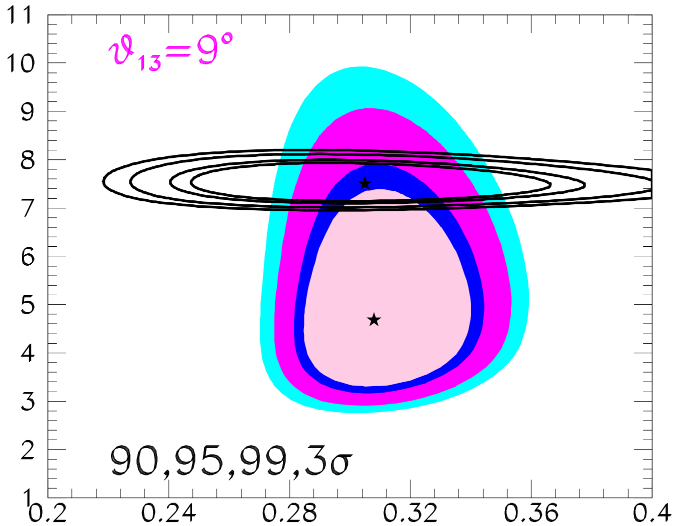
$$P_{ee} \simeq \begin{cases} \text{Solar High E} : c_{13}^4 \sin^2 2\theta_{12} \\ \text{Solar Low E} : c_{13}^4 \left(1 - \sin^2 2\theta_{12}/2\right) \\ \text{Kam} : c_{13}^4 \left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{21}^2 L}{4E}\right) \end{cases}$$

$\Rightarrow$ KamLAND region shifts left

$\Rightarrow$ Solar slight shifts right (due to High E)

3 ν Analysis: "12" Sector and θ_{13}

- For $\theta_{13} \simeq 9^\circ$



⇒ Good match of best fit θ_{12}

⇒ Residual tension on Δm^2_{21}

- When θ_{13} increases

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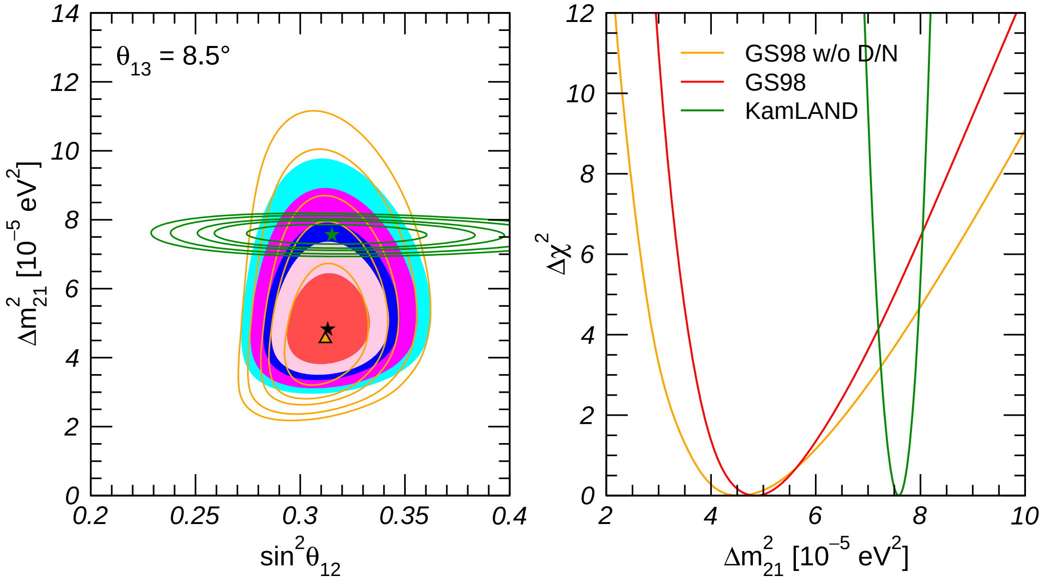
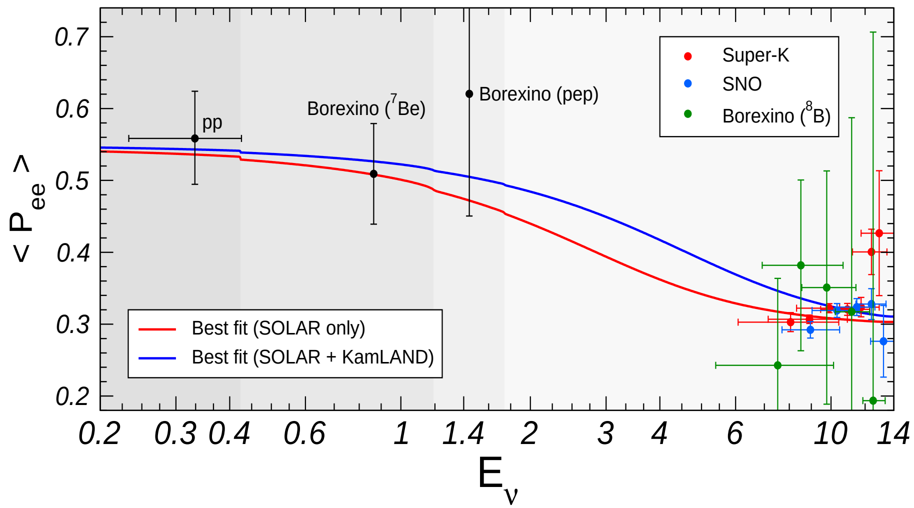
Issues in 3 ν Analysis: Δm^2_{21} KamLAND vs SOLAR

For $\theta_{13} \simeq 9°$ θ_{12} OK. But residual tension on Δm^2_{12}

NuFIT 2.1 (2016)



Tension related to: a)"too large" of Day/Night at SK



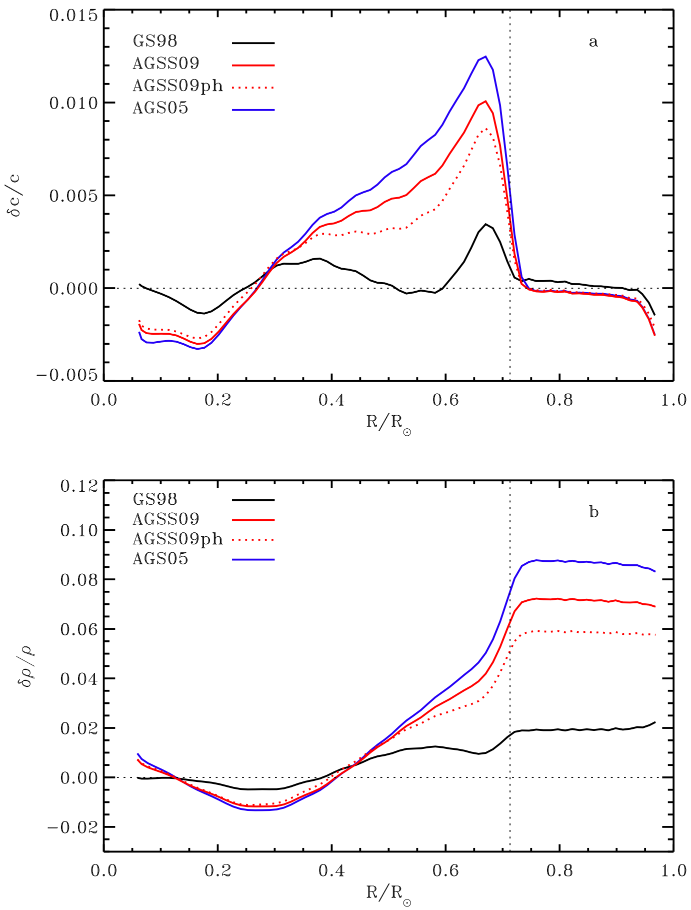
b) smaller-than-expected low-E turn up from MSW at best global fit

Modified matter potential?

Issues with 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

AGSXX uses newer metalicities

Flux $cm^{-2}\ s^{-1}$	GS98	AGSS09	Diff (%)
$pp/10^{10}$	5.97	$6.03\ (1 \pm 0.005)$	0.8
$pep/10^{8}$	1.41	$1.44\ (1 \pm 0.010)$	2.1
$hep/10^{3}$	7.91	$8.18\ (1 \pm 0.15)$	3.4
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Most difference in CNO fluxes

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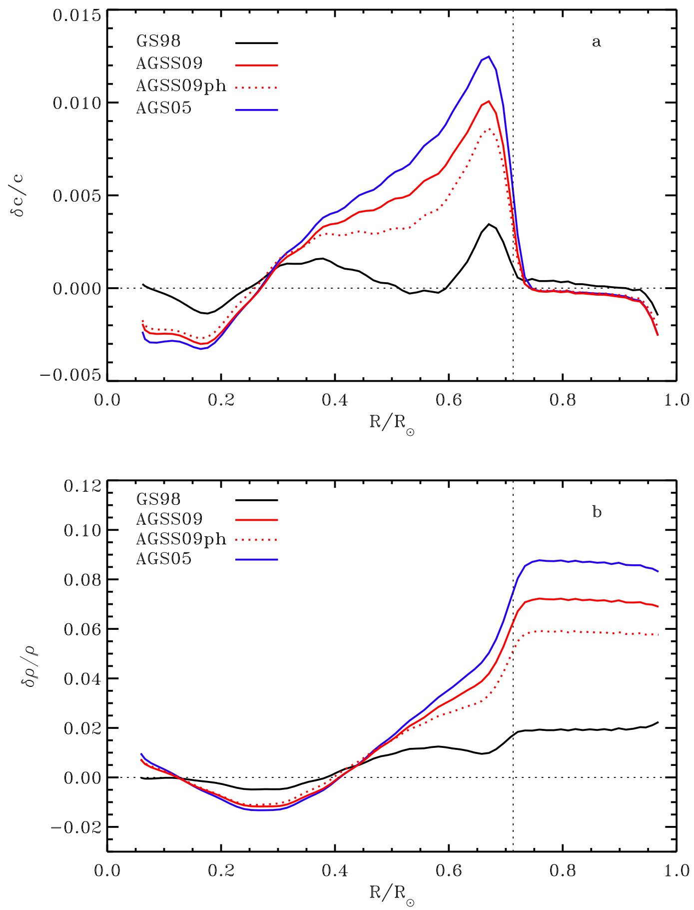

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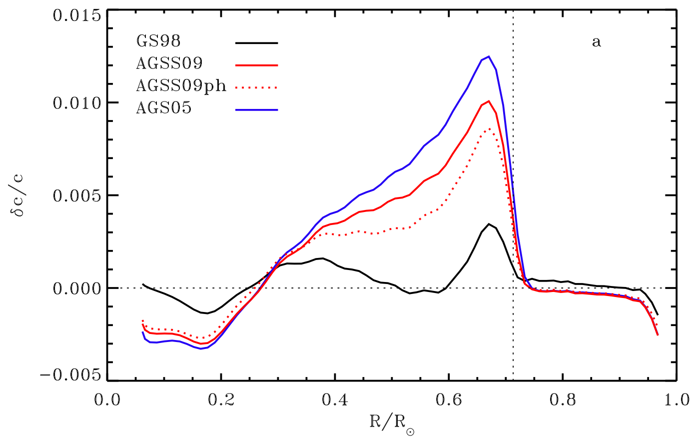

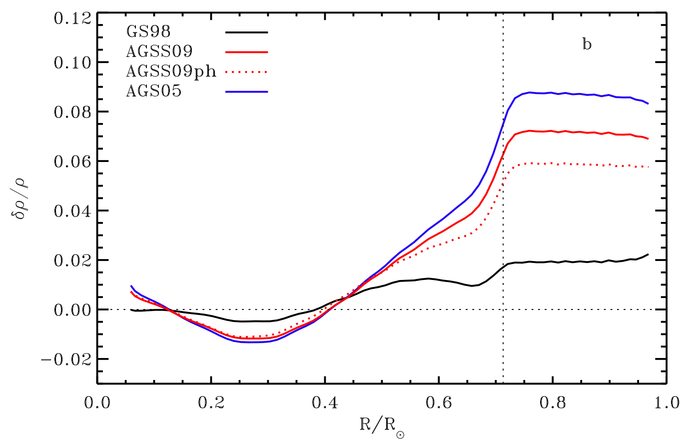

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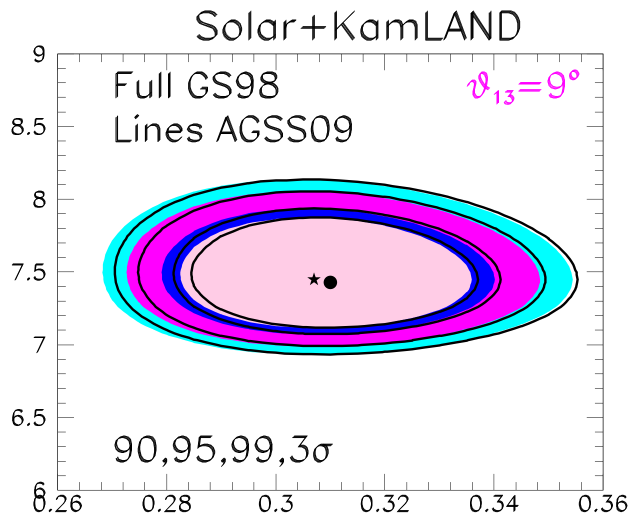
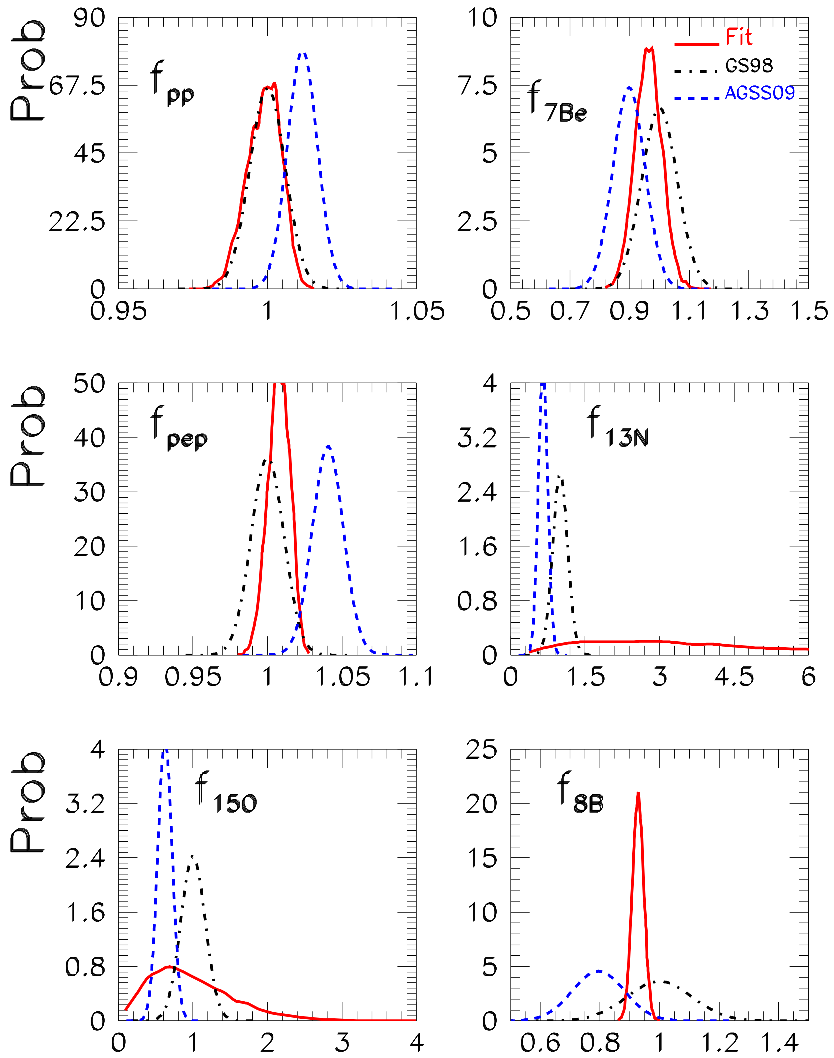
–Impact in Osc Parameter Determination



Neglegeable ⇒ Possible to Invert and Extract Fluxes from Data.

Learning how the Sun Shines with $\nu's$

Results of Oscillation analysis with solar flux normalizations free: $f_i = \frac{\Phi_i}{\Phi_i^{GS98}}$



Bergstrom,MCG-G,Maltoni,Peña-Garay,Serenelli, Song, ArXiv:1601:00972

Present limit on CNO:

$$\frac{L_{\rm CNO}}{L_\odot} < 2\,\%\ (3\sigma)$$

Test of Luminosity Constraint:

$$\frac{L_\odot(\nu - \text{inferred})}{L_\odot} = 1.04 \pm 0.07$$

Comparing with the Models:

Both statistically equally probable

New experiments needed
more sensitive to CNO fluxes

New models with new Nuclear Rates
New problems with Helioseismology

Bergstrom,MCG-G,Maltoni,
Peña-Garay,Serenelli,Song, in preparation

3 ν Analysis: "23" Sector ATM and LBL Disapp

$*\Delta m^2_{3\ell}$ consistent in all experiments

$*$ slightly better by T2K-DIS

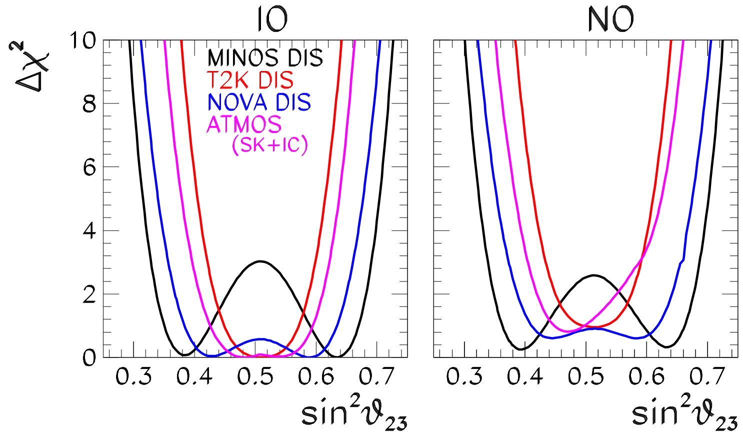
$*$ Minos-DIS slight favour non-maximal θ_{23}

$*$ T2K-DIS favours maximal (best precision)

$*$ $\theta_{31} \neq 0 \Rightarrow$

$*$ATM sensitivity to octant θ_{23} & sign Δm^2_{31}

Slight preference $\theta_{13} < 45°$ in ATMOS NO



(In all curves $\theta_{13}, \Delta m^2_{21}, \theta_{12}$ minimized over SOLAR+REACTOR)

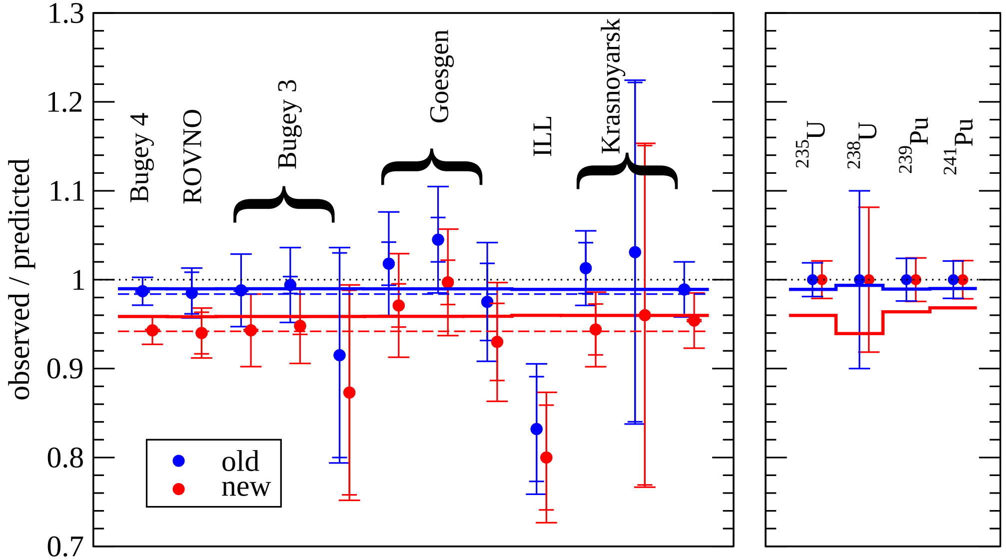
Issues in 3 ν Analysis: Reactor Flux anomaly and θ_{13}

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

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

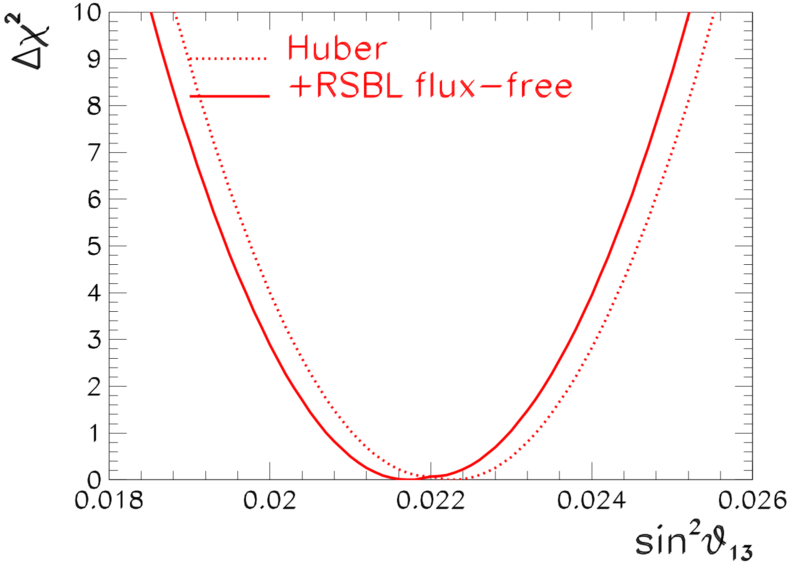
- Both reevaluations find higher fluxes by about 3.5 %

- 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

Issues in 3 ν Analysis: Reactor Flux anomaly and θ_{13}



- Experiments without near detector (CHOOZ, Palo-Verde) sensitive to the flux assumptions
- DAYA BAY, RENO, D-CHOOZ Near-Far comparison $\Rightarrow$ results flux independent
- Two extreme priors :

  a) Use fluxes from Huber 1106.0687 without RSBL data

  $$\sin^2\theta_{13} = 0.0217^{+0.0013}_{-0.001}$$

  b) Leave flux free and include RSBL

  $$\sin^2\theta_{13} = 0.0223^{+0.0013}_{-0.001}$$

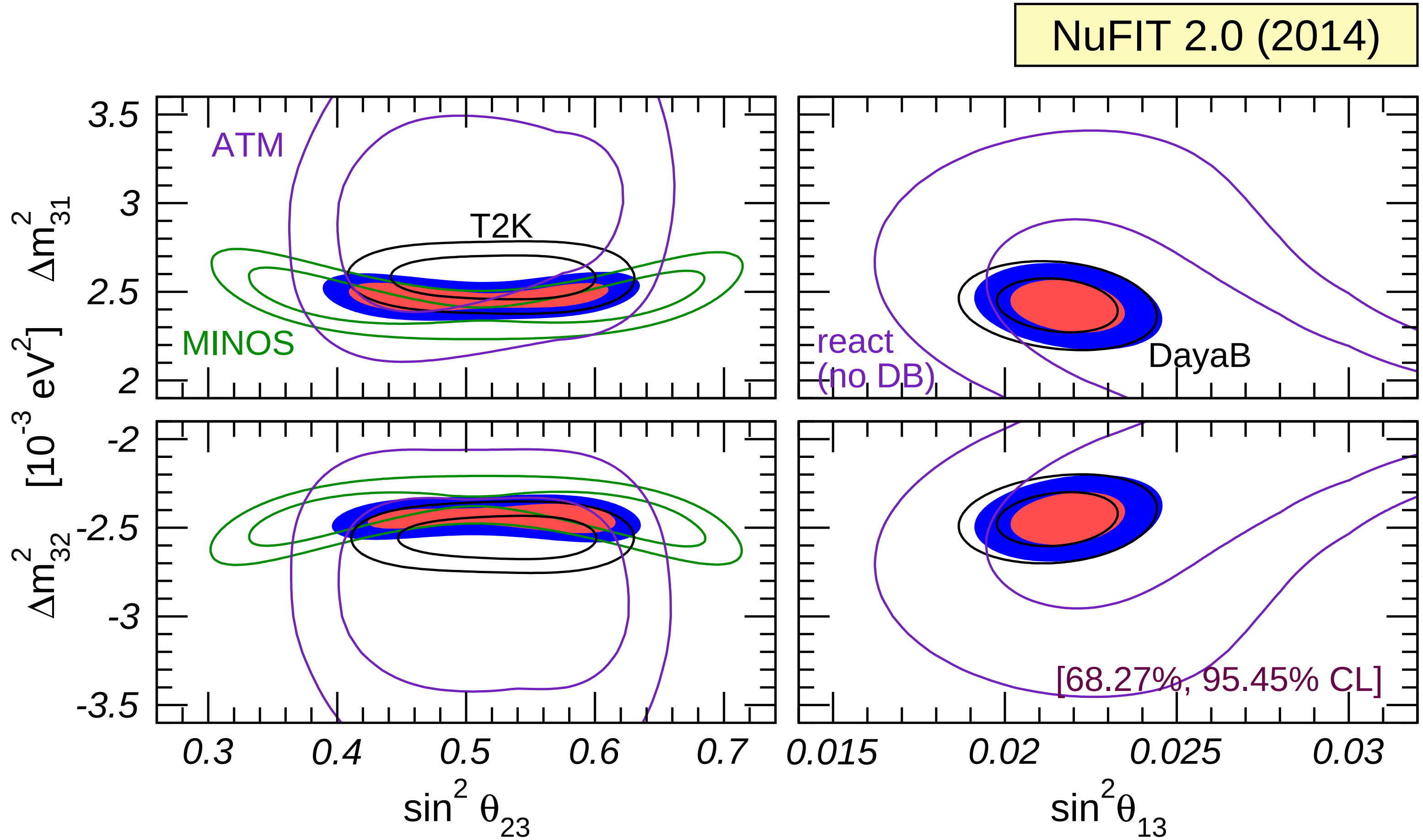
  Uncertainty at $\lesssim 0.5\sigma$ level

  $\chi^2_{min,a} - \chi^2_{min,b} \sim 7$

3 ν Analysis: Long Baseline vs REACT and $|\Delta m^2_{3l}|$

Independent and consistent determination of $|\Delta m^2_{3l}|$ from MBL reactor data

In particular from Daya Bay (also Reno and DC) near/far E Spectrum



3 ν Analysis: LBL vs REACT and θ_{23}, Ordering, $\delta_{\rm CP}$

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

$$P_{\mu e} \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{\Delta_{31} \pm V}\right)^2 \sin^2\left(\frac{\Delta_{31} \pm V\; L}{2}\right)$$
$$+8\, J_{\rm CP}^{\rm max} \frac{\Delta_{12}}{V} \frac{\Delta_{31}}{\Delta_{31} \pm V} \sin\left(\frac{V L}{2}\right) \sin\left(\frac{\Delta_{31} \pm V L}{2}\right) \cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

$$J_{\rm CP}^{\rm max} = c_{13}^2 s_{13} c_{23} s_{23} c_{12} s_{12}$$

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

–So from first term in $P_{\mu e}$:

$\sin^2 2\theta_{\rm REAC} \leq \sin^2 2\theta_{\rm APP} \quad \Rightarrow \theta_{23} \geq \frac{\pi}{4}$ favoured

–Or from second term in $P_{\mu e}$:

$\Rightarrow \delta \sim \frac{3\pi}{2} (\equiv -\frac{\pi}{2})$ favoured

3 ν Analysis: LBL vs REACT and θ_{23}, Ordering, $\delta_{\rm CP}$

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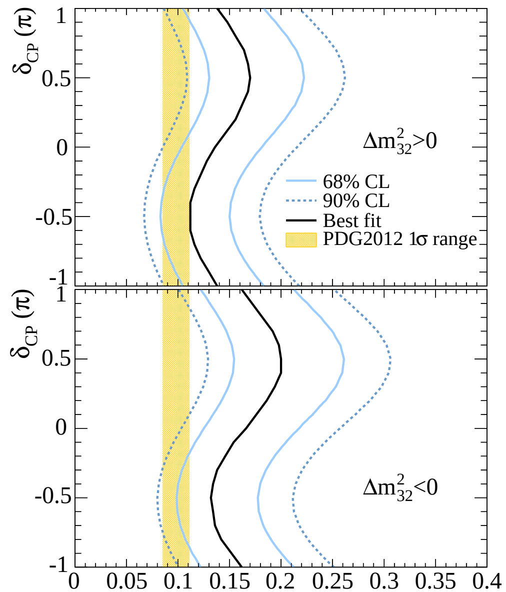

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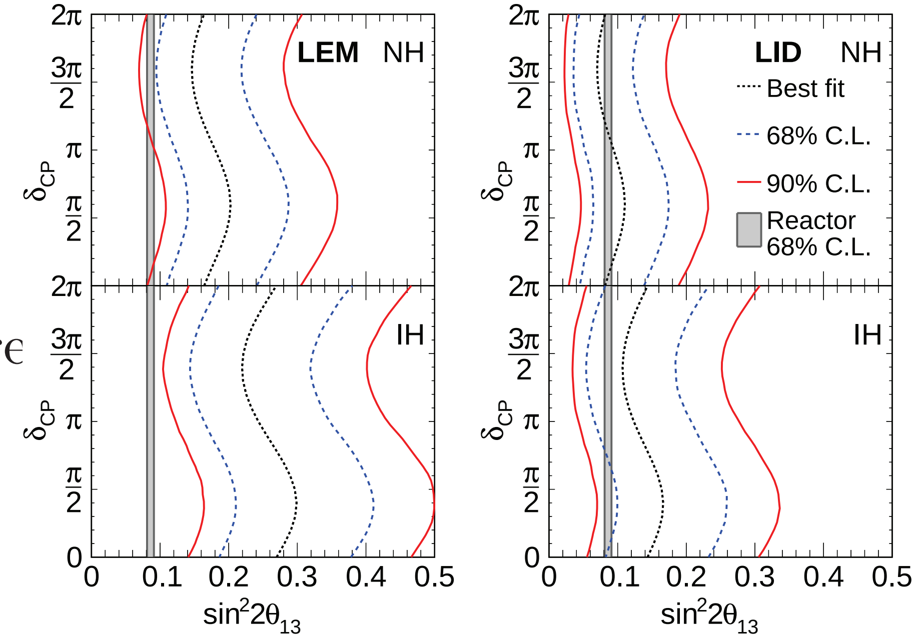

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$$+8\, J^{\rm max}_{\rm CP} \frac{\Delta_{12}}{V} \frac{\Delta_{31}}{\Delta_{31} \pm V} \sin\left(\frac{V L}{2}\right) \sin\left(\frac{\Delta_{31} \pm V L}{2}\right) \cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

$$J^{\rm max}_{\rm CP} = c^2_{13} s_{13} c_{23} s_{23} c_{12} s_{12}$$

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

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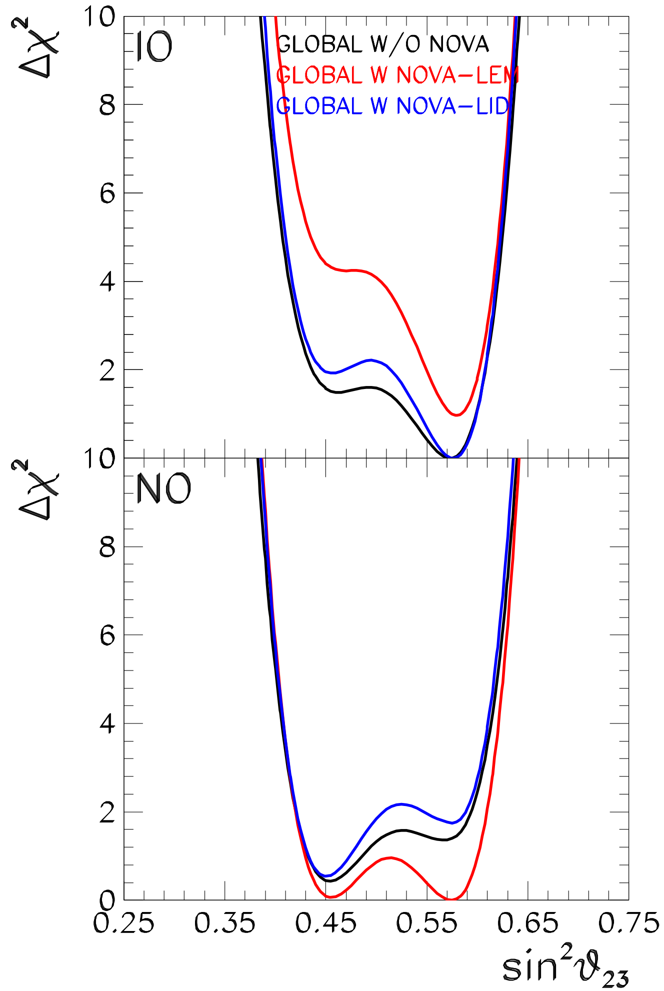
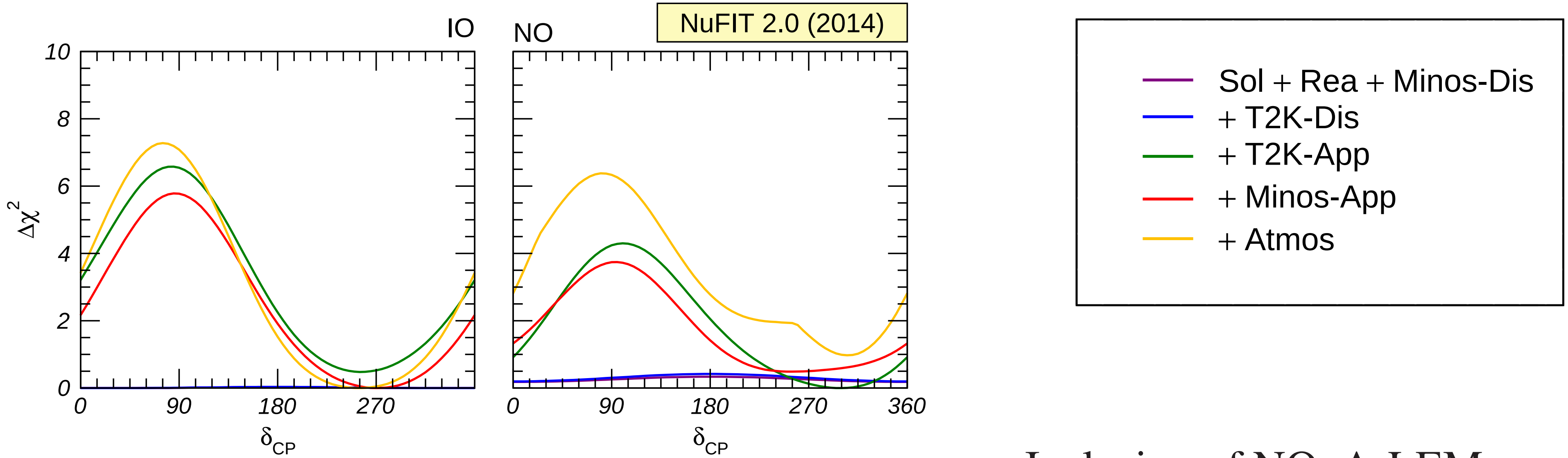
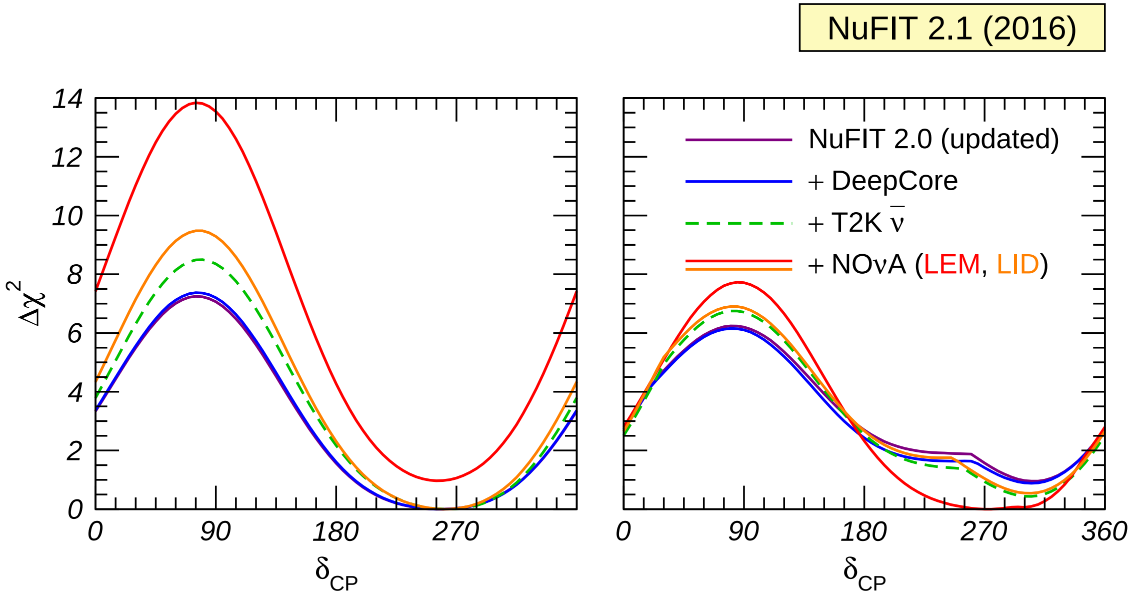


Inclusion of NOvA-LEM

$\Rightarrow$ shift in favoured order

3ν Analysis: Leptonic CP violation





Inclusion of NOvA-LEM:

∗ Stronger CP "hint" for IO

∗ But NO globally favoured

⇒ Present significance of CPV

NO: $\delta_{CP} = 272^{+61}_{-64}$

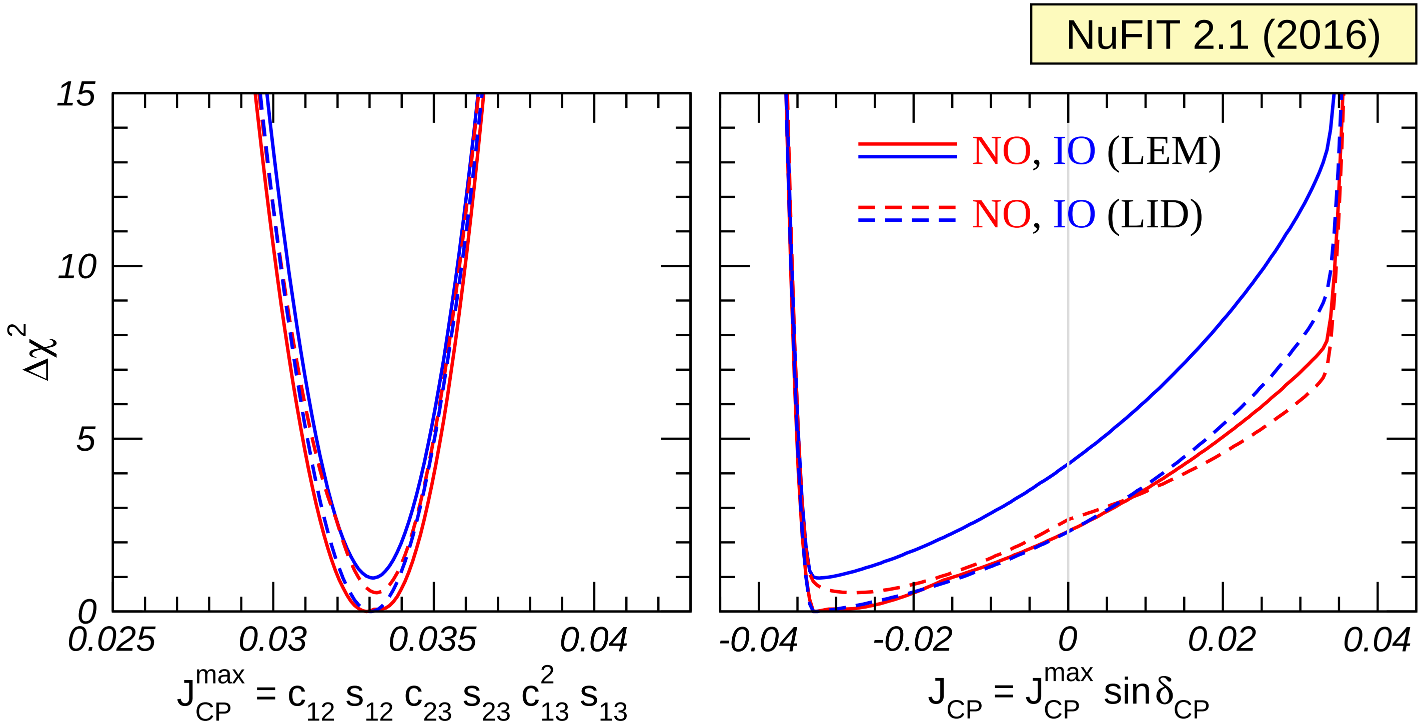
(0 → 360 allowed at 3σ)

IO: $\delta_{CP} = 256 \pm 43$

(21 → 131 excluded at 3σ)

3ν Analysis: Leptonic CP violation

Leptonic Jarlskog determinant $J_{\rm CP} = c_{12} s_{12} c_{23} s_{23} c_{13}^2 s_{13} \sin\delta_{\rm CP}$



Compared to the quark sector $J_{\rm CMK} = \left(3.06^{+0.21}_{-0.20}\right) \times 10^{-5}$

Near Future for CP and Ordering: Strategies

- $\nu/\bar{\nu}$ comparison with or without Earth matter effects in $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ at LBL: DUNE (wide band beam, L=1300 km), HK (narrow band beam, L=300 km)

$$P_{\mu e} \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{\Delta_{31} \pm V}\right)^2 \sin^2\left(\frac{\Delta_{31} \pm V\,L}{2}\right)$$
$$+8\,J_{\rm CP}^{\rm max}\,\frac{\Delta_{12}}{V}\,\frac{\Delta_{31}}{\Delta_{31} \pm V}\,\sin\left(\frac{VL}{2}\right)\sin\left(\frac{\Delta_{31} \pm VL}{2}\right)\cos\left(\frac{\Delta_{31}L}{2} \pm \delta_{CP}\right)$$

$$J_{\rm CP}^{\rm max} = c_{13}^2 s_{13} c_{23} s_{23} c_{12} s_{12}$$

– Challenge: Parameter degeneracies, Normalization uncertainty, E_ν reconstruction

- Earth matter effects in large statistics ATM ν_μ disapp : HK,INO, PINGU,ORCA …

– Challenge: ATM flux contains both ν_μ and $\bar{\nu}_\mu$, ATM flux uncertainties

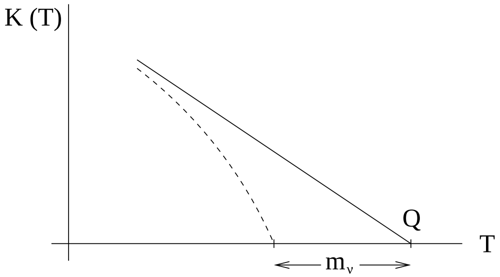
- Reactor experiment at $L \sim 60$ km (vacuum) able to observe the difference between oscillations with Δm_{31}^2 and Δm_{32}^2: JUNO, RENO-50

$$P_{\nu_e,\nu_e} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + s_{12}^2 \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)\right]$$

– Challenge: Energy resolution

Neutrino Mass Scale

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

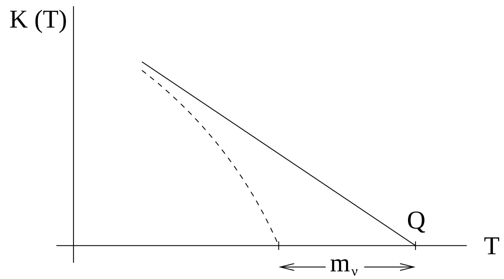


$$m^2_{\nu_e} = \sum m^2_j |U_{ej}|^2 = c^2_{13} c^2_{12} m^2_1 + c^2_{13} s^2_{12} m^2_2 + s^2_{13} m^2_3$$

Present bound: $m_{\nu_e} \leq 2.2$ eV (at 95 % CL)

Neutrino Mass Scale

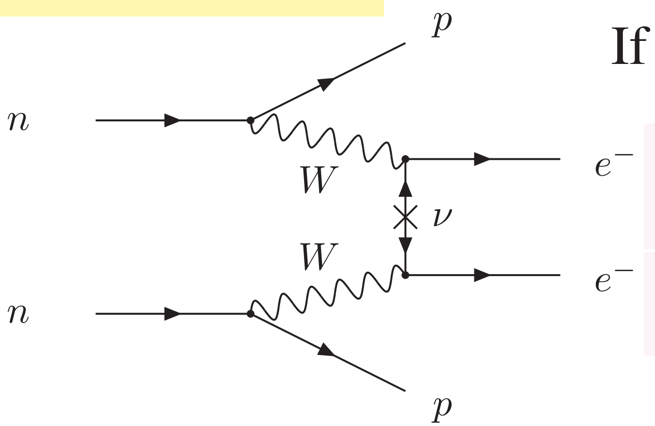
Single β decay : Dirac or Majorana ν mass modify spectrum endpoint



$$m^2_{\nu_e} = \sum m_j^2 |U_{ej}|^2 = c^2_{13} c^2_{12} m_1^2 + c^2_{13} s^2_{12} m_2^2 + s^2_{13} m_3^2$$

Present bound: $m_{\nu_e} \leq 2.2$ eV (at 95 % CL)

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



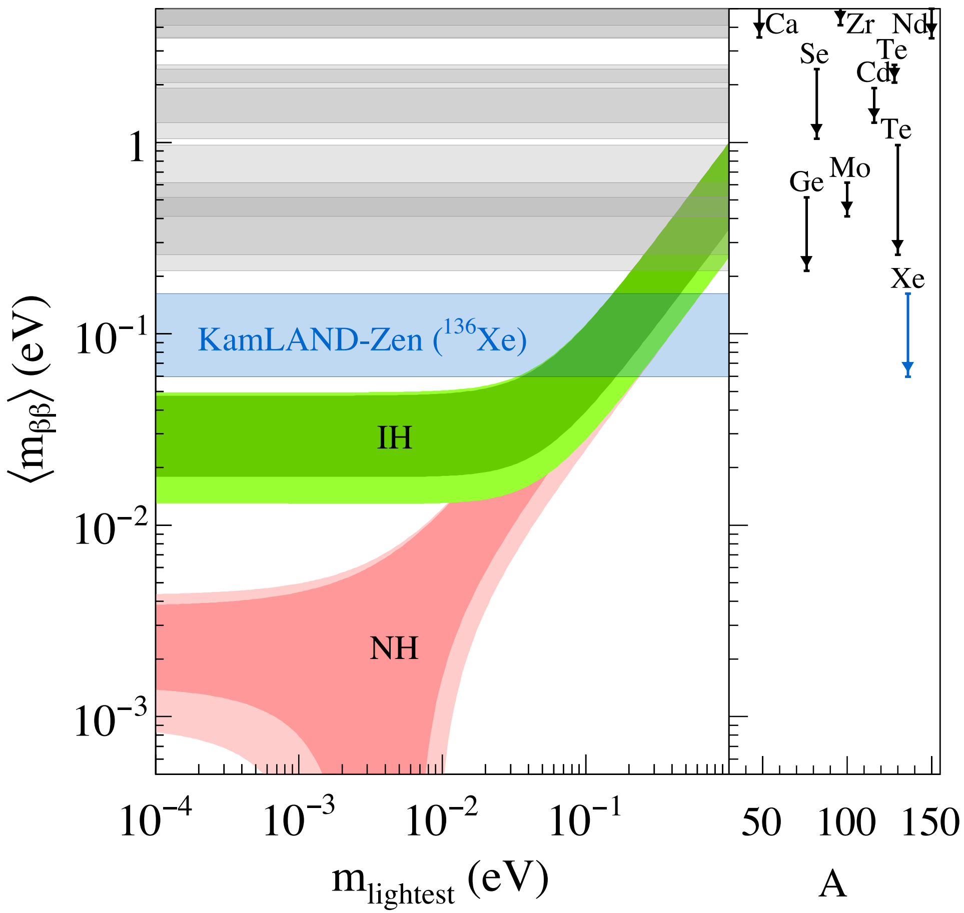
If m_ν only source of ΔL $\quad T^{0\nu}_{1/2} = \dfrac{m_e}{G_{0\nu}\, M^2_{\text{nucl}}\, m^2_{ee}}$

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

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

$0\nu\beta\beta$ Decay: Present

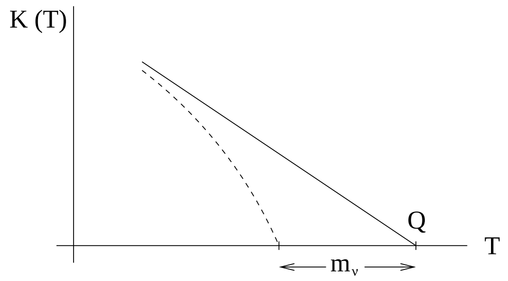
Bounds from ^{136}Xe (EXO and KamLAND-ZEN), ^{76}Ge (Gerda) and ^{130}Te (Cuore-0)



KamLAND-Zen Coll. ArXiv:1505.02889

Neutrino Mass Scale

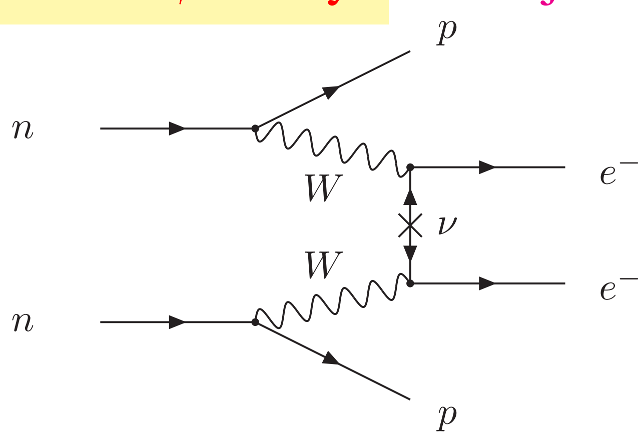
Single β decay : Dirac or Majorana ν mass modify spectrum endpoint



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

Present bound: $m_{\nu_e} \leq 2.2$ eV (at 95 % CL)

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



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

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

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

Present Bounds: $m_{ee} < 0.06$–0.76 eV

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

$$\sum m_i$$

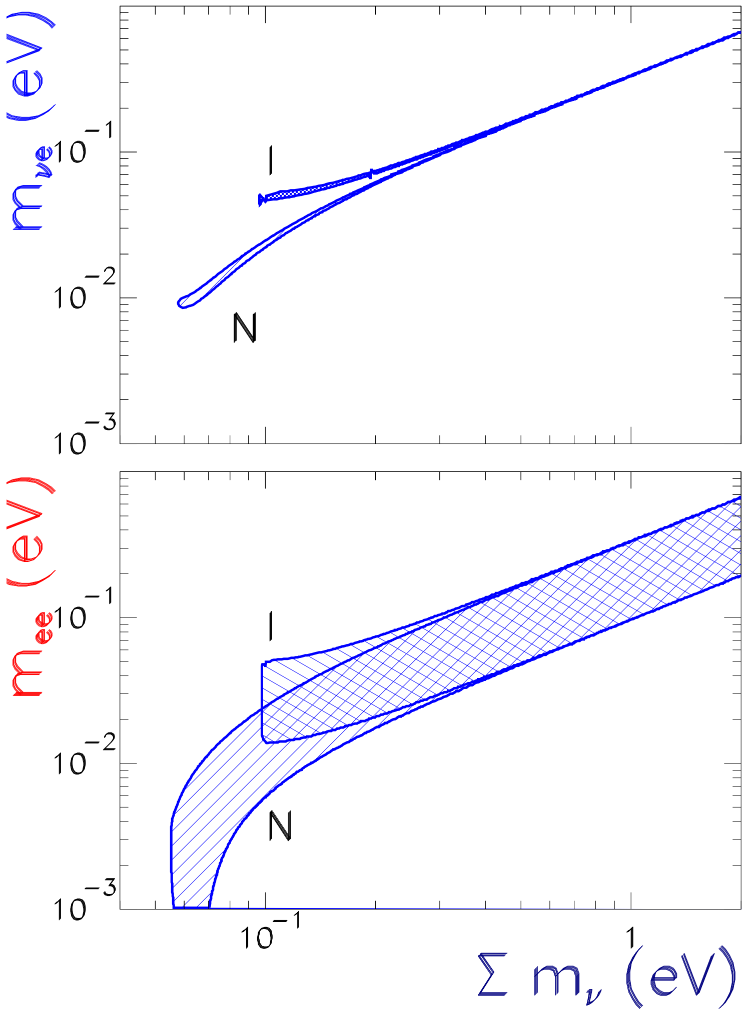
Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis

$\Rightarrow$ Correlations m_{ν_e}, m_{ee} and $\sum m_\nu$

(Fogli *et al* (04))

Nufit (95%)



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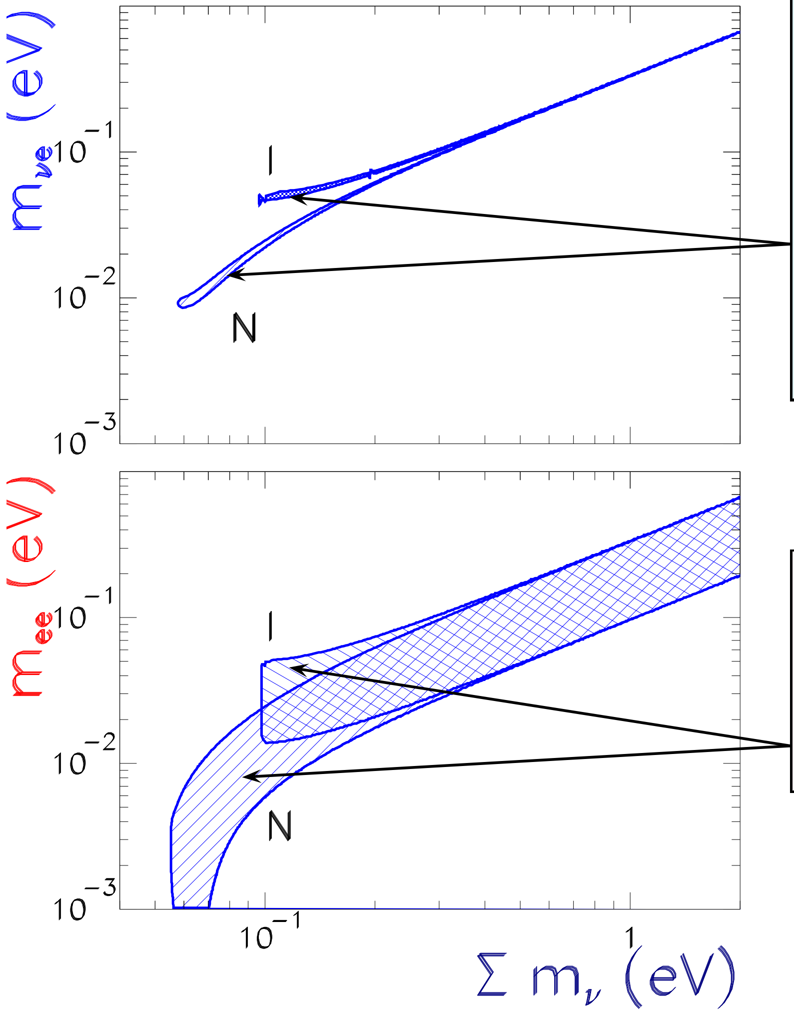


Width due to range in oscillation parameters very narrow

High precision determination of m_{ν_e} and $\sum m_i$ can give information on ordering

Wide band due to unknown Majorana phases $\Rightarrow$ Possible Det of Maj phases

If Matrix Element Uncertainty Reduced

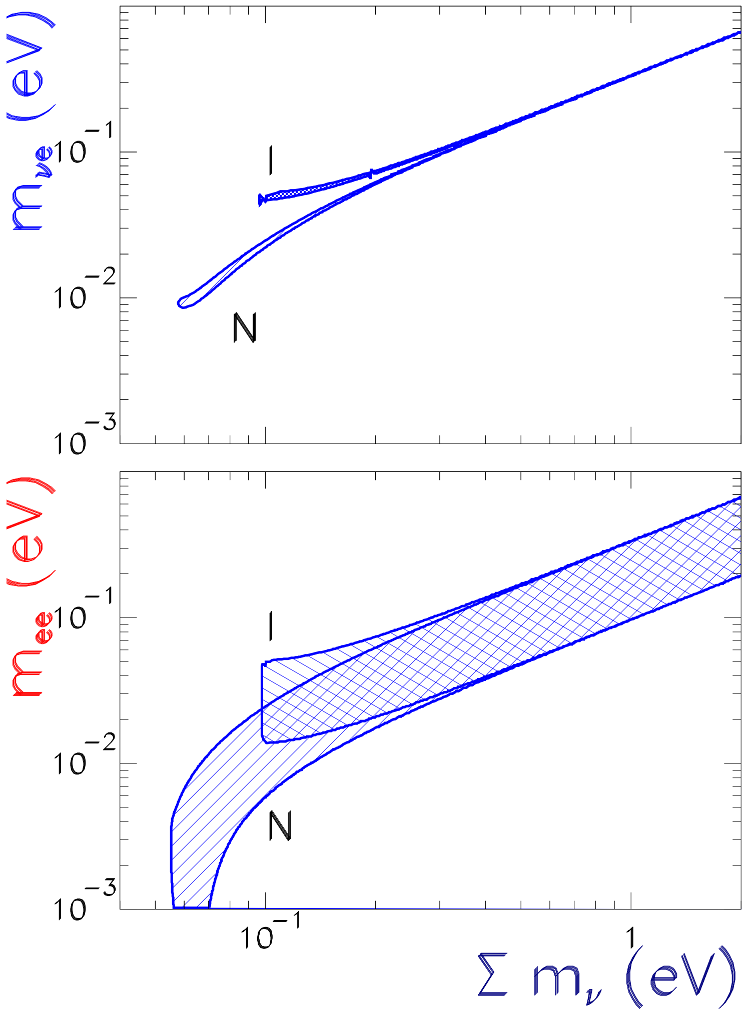
Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis

$\Rightarrow$ Correlations m_{ν_e}, m_{ee} and $\sum m_\nu$

(Fogli *et al* hep-ph/0408045)

Nufit (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 for Majorana Neutrinos

  $m_{ee} < 0.06 - 0.15$ eV (90%)

  Goal of Next Decade $\Rightarrow$ m_{ee} at IO

- 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_ν	Planck TT + lowP	≤ 0.72
ΛCDM + m_ν	Planck TT + lowP + lensing	≤ 0.68
ΛCDM + m_ν	Planck TT,TE,EE + lowP+lensing	≤ 0.59
ΛCDM + m_ν	Planck TT,TE,EE + lowP	≤ 0.49
ΛCDM + m_ν	Planck TT + lowP + lensing + BAO + SN + H_0	≤ 0.23
ΛCDM + m_ν	Planck TT,TE,EE + lowP+ BAO	≤ 0.17

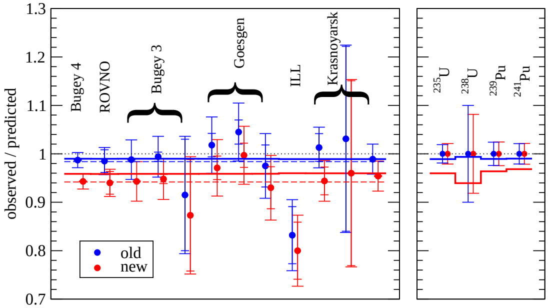
Light Sterile Neutrinos

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

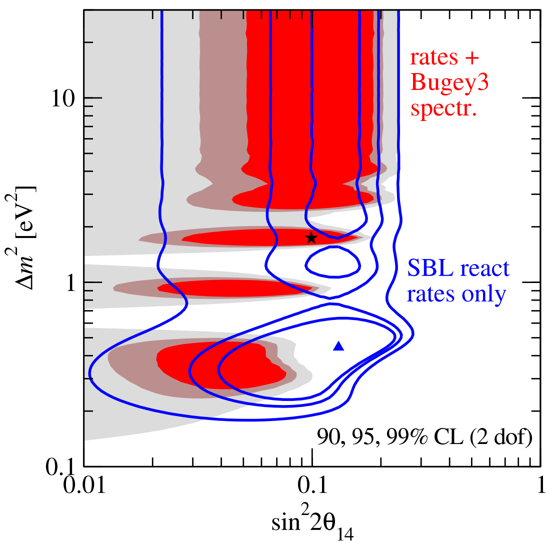
Reactor Anomaly

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)

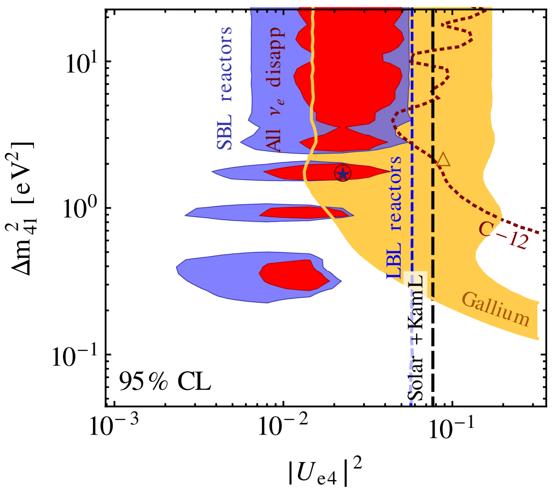
in calibration of Ga Solar Exp;

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

Give a rate lower than expected

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

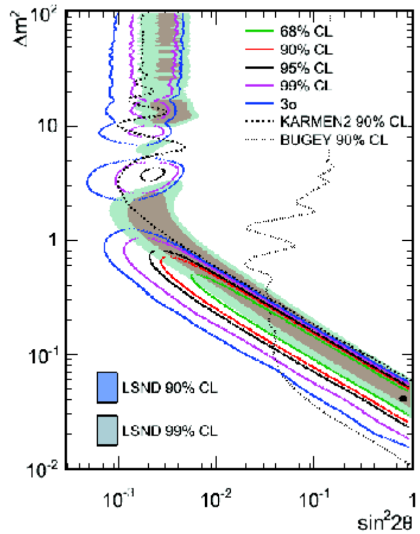
Explained as ν_e disappearance



Kopp etal, ArXiv 1303.3011

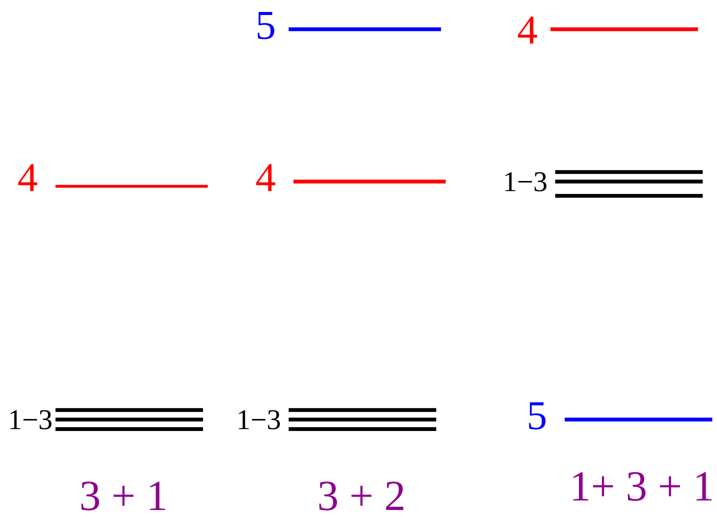
LSND, MiniBoone

$\nu_\mu \rightarrow \nu_e$ and $\bar\nu_\mu \rightarrow \bar\nu_e$



Light Sterile Neutrinos

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



- Problem: fit together
  $\nu_e \rightarrow \nu_e$ disapp (REACT,Gallium,Solar, LSND/KARMEN)
  $\nu_\mu \rightarrow \nu_e$ 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)]

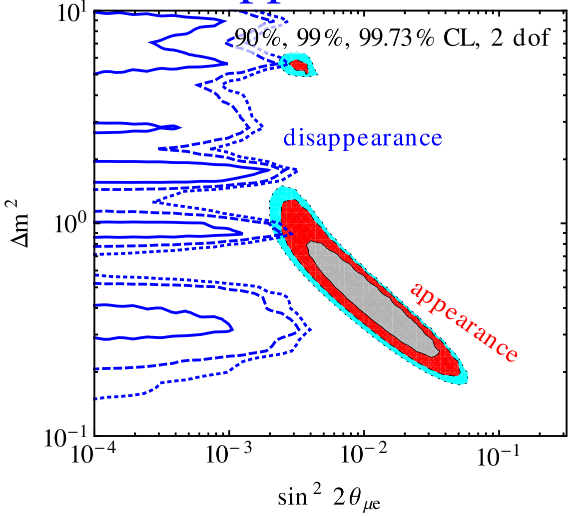
  But $|U_{ei}|$ constrained by $P(\nu_e \rightarrow \nu_e)$ disappearance data
  And $|U_{\mu i}|$ constrained by $P(\nu_\mu \rightarrow \nu_\mu)$ disappearance data
  $\Rightarrow$ Severe tension

Light Sterile Neutrinos:3+1

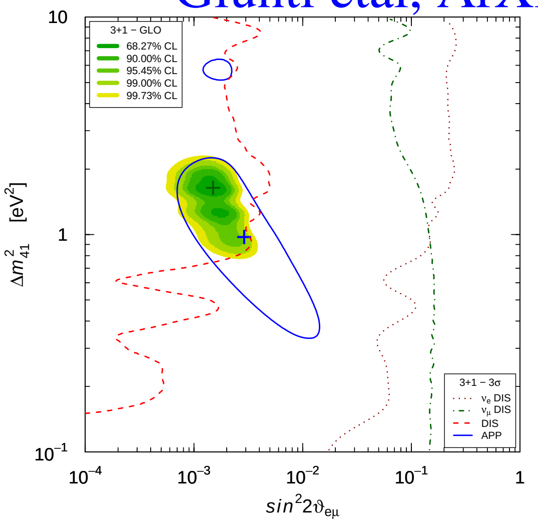
- Comparing the parameters required to explain signals with bounds from disapp

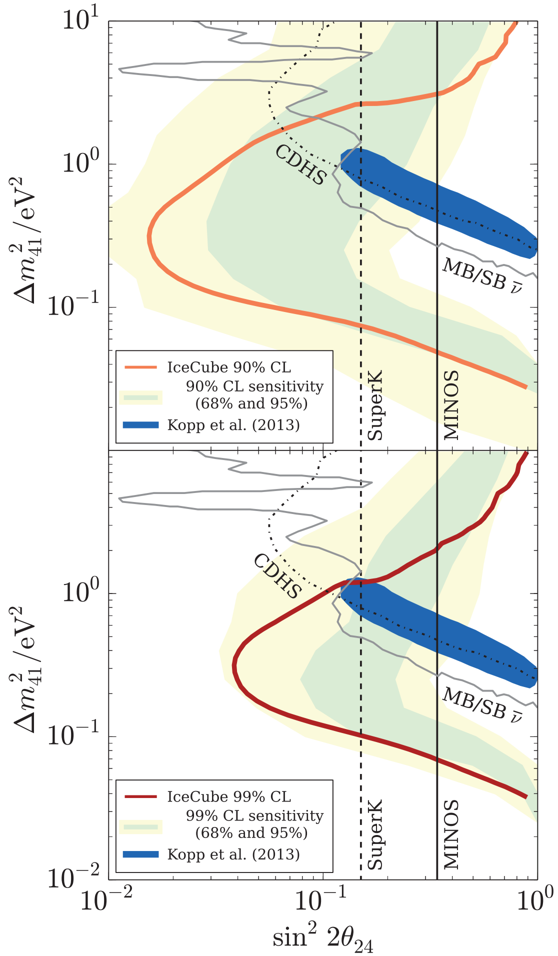
Further Disfavoured by ICECUBE

Kopp etal, ArXiv 1303.3011



Giunti etal, ArXiv 1308.5288



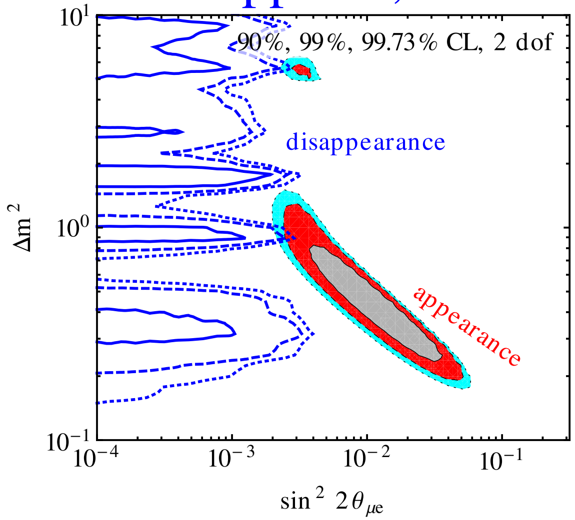


Somewhat different conclusions

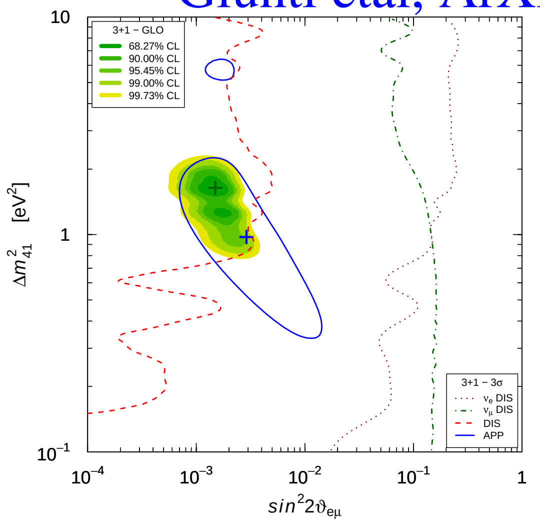
Light Sterile Neutrinos:3+1

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

Kopp etal, ArXiv 1303.3011

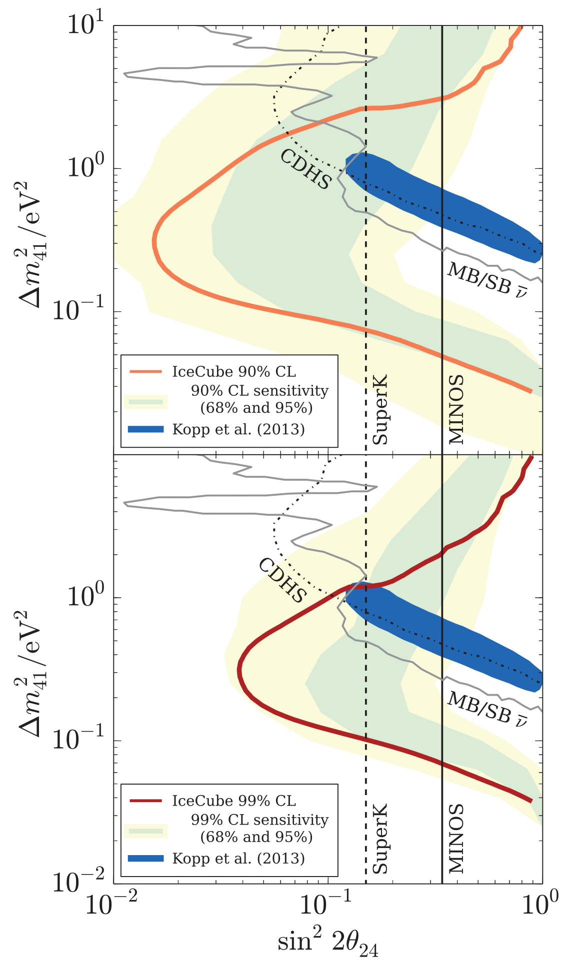


Giunti etal, ArXiv 1308.5288



Somewhat different conclusions

Further Disfavoured by ICECUBE



More steriles help? Arguelles etal ArXiv:1602.00671

Though disfavoured by Cosmology

Massive ν in Cosmology

Relic $\nu's$: Effects in several cosmological observations at several epochs

<table>
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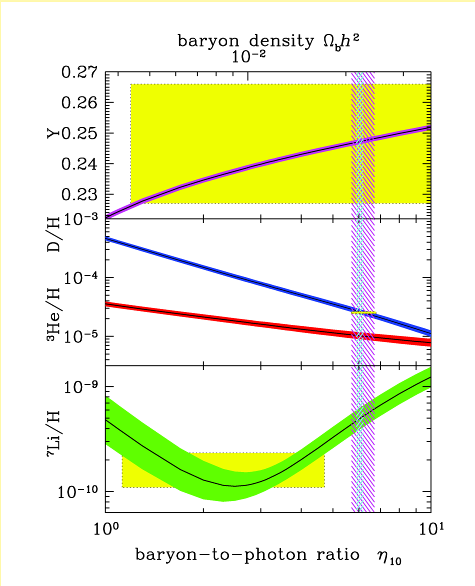
<td>
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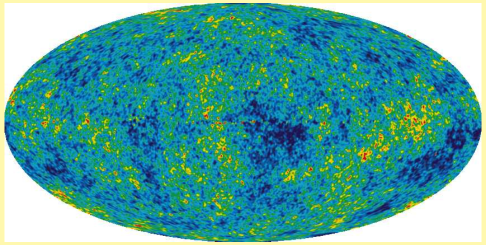
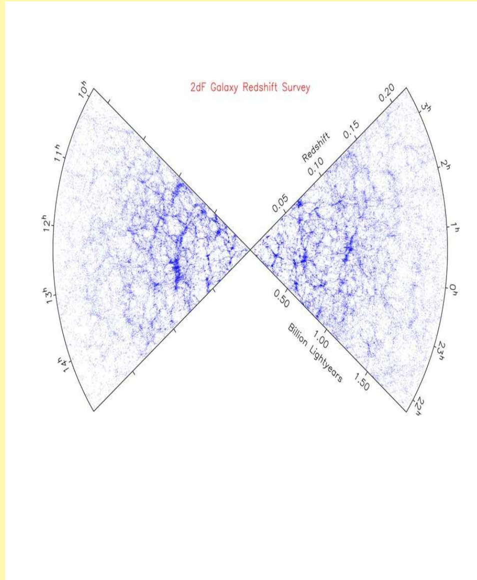
<td></td>
<td>
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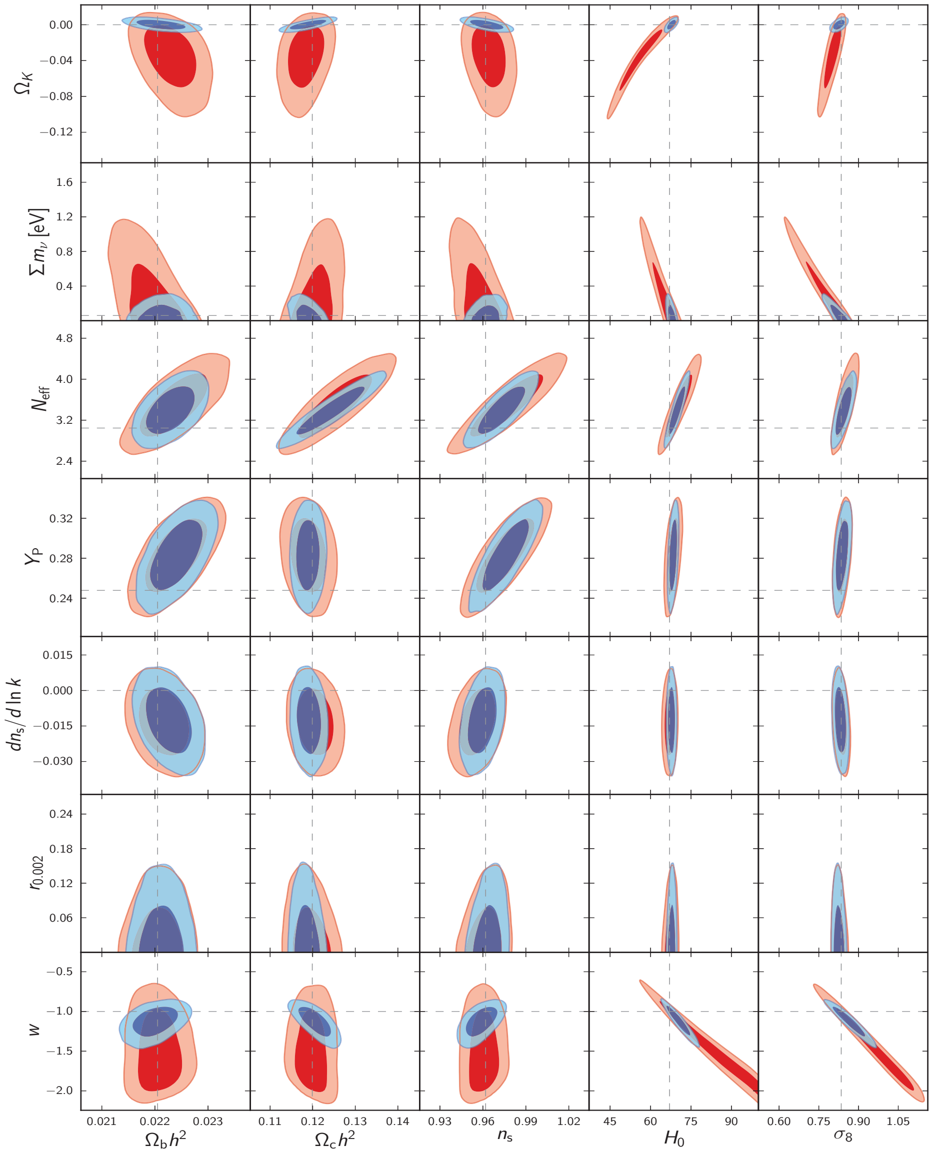
</tr>
<tr>
<td>Primordial
Nucleosynthesis
BBN</td>
<td>Cosmic Microwave
Background
CMB</td>
<td>Large Scale
Structure Formation
LSS</td>
</tr>
<tr>
<td>$T \sim$ MeV</td>
<td colspan="2">$T \lesssim$ eV</td>
</tr>
<tr>
<td>Number of $\nu's$ ($N_{\rm eff}$)</td>
<td colspan="2">$N_{\rm eff}$ and $\sum m_\nu$</td>
</tr>
</table>

Observables also depend on all other cosmological parameters

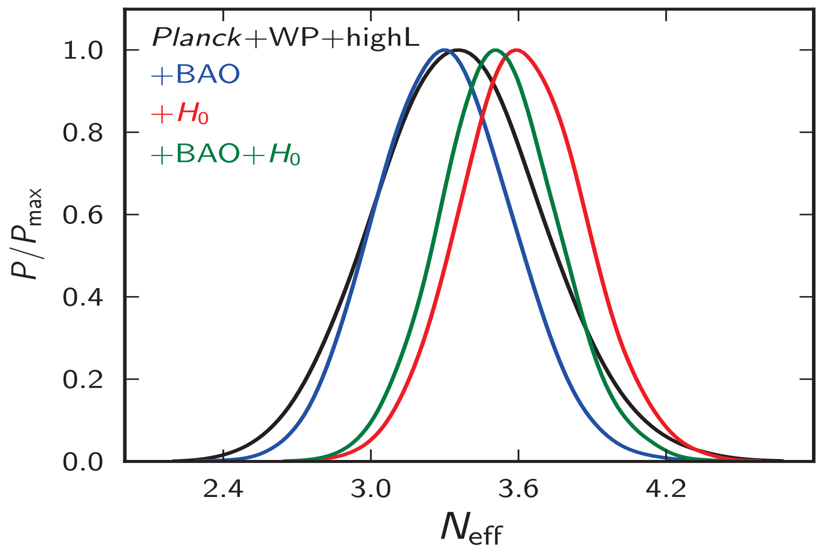
Cosmological Analysis by Planck

arXiv:1502.01589



Range of Bounds

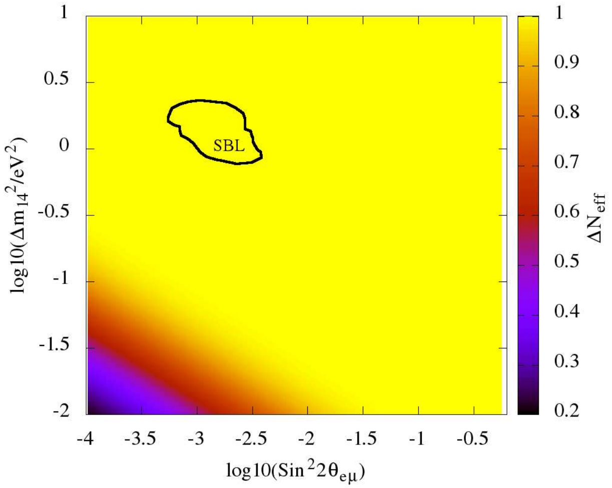
Model	Observables	Σm_ν (eV) 95%
ΛCDM + m_ν	Planck TT + lowP	≤ 0.72
ΛCDM + m_ν	Planck TT + lowP + lensing	≤ 0.68
ΛCDM + m_ν	Planck TT,TE,EE + lowP+lensing	≤ 0.59
ΛCDM + m_ν	Planck TT,TE,EE + lowP	≤ 0.49
ΛCDM + m_ν	Planck TT + lowP + lensing + BAO + SN + H_0	≤ 0.23
ΛCDM + m_ν	Planck TT,TE,EE + lowP+ BAO	≤ 0.17



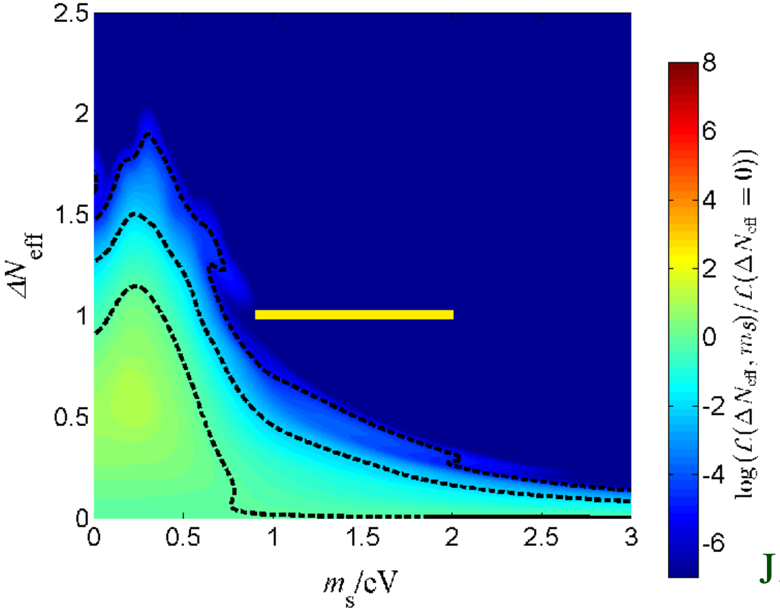
Light Sterile Neutrinos in Cosmology

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

From evol eq for $3+1$ ensemble one finds
$\Rightarrow$ So if "explaination" to SBL anomalies
1 ν_s contributes as much as 1 ν_a



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



J. Bergstrom, etal, ArXiv:1407.3806

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:

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

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

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

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

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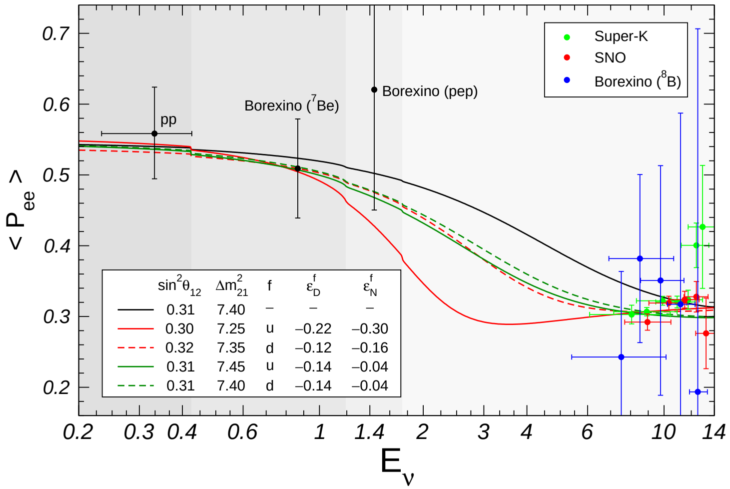
- Better fit with NSI ($\Delta\chi^2_{\rm OSC} \simeq 5$–$7$)



Due to no observation of MSW up-turn

Matter Potential/NSI in Solar and KamLAND

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

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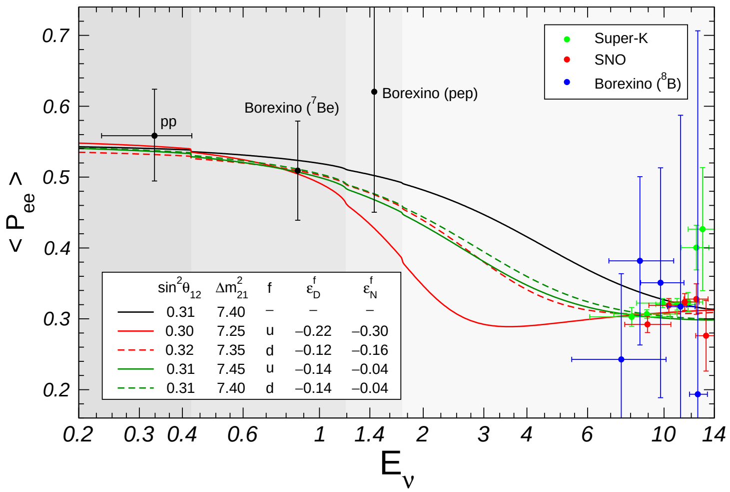
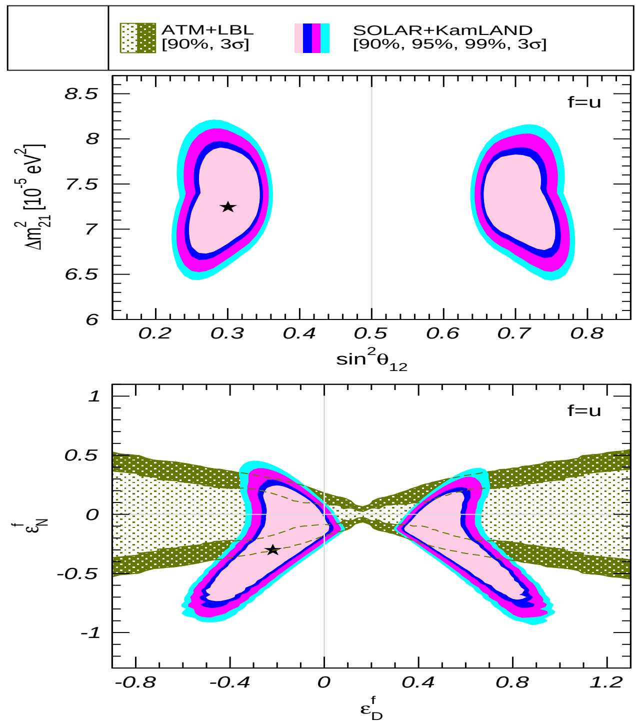


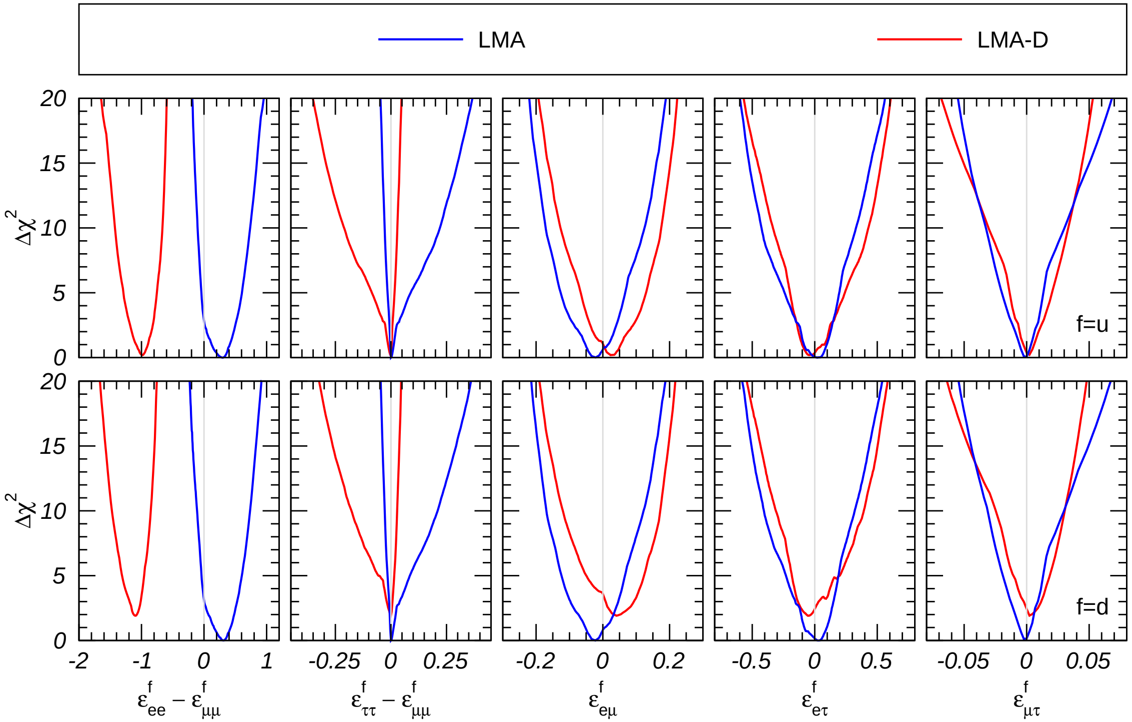
Due to no observation of MSW up-turn

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



Matter Potential/NSI: Global Analysis

- Parameter space of matter potential is bounded

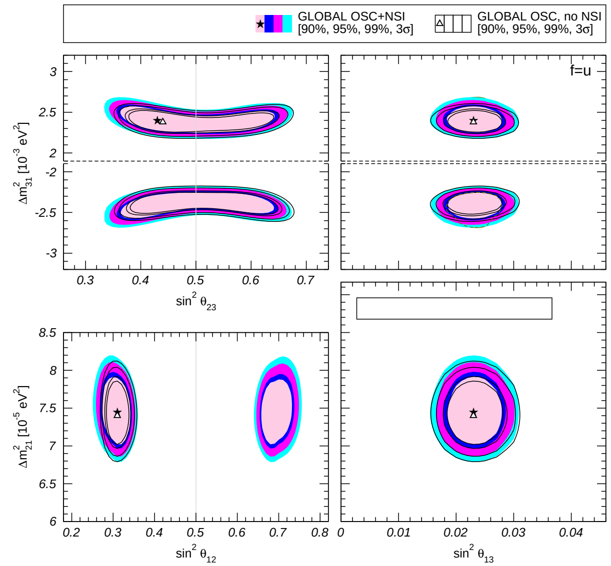


	90% CL	
Param.	OSC	SCATT
$\vert\varepsilon^u_{ee}\vert$	0.51–1.19	0.7–1
$\vert\varepsilon^u_{\tau\tau}\vert$	0.03	1.4–3
$\vert\varepsilon^u_{e\mu}\vert$	0.09	0.05
$\vert\varepsilon^u_{e\tau}\vert$	0.15	0.5
$\vert\varepsilon^u_{\mu\tau}\vert$	0.01	0.05

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

The Emerging Picture

- At least two neutrinos are massive $\Rightarrow$ There is NP

- Oscillations DO NOT determine the lightest mass but β decay:

$$\sum m_{\nu_i} \leq 2 \text{ eV/c}^2$$

$\Rightarrow$ Heaviest ν is at least 1 millon de times lighter than the electron

- Dirac or Majorana?: We do not know

- Three mixing angles are non-zero (and relatively large) $\Rightarrow$ very different from CKM

– The two arising questions

  * Why are neutrinos so light?

    The Origin of Neutrino Mass

  * Why are lepton mixing so different from quark's?

    The Flavour Puzzle

Bottom-up: Light ν from *Generic* New Physics

If SM is an effective low energy theory, for $E \ll \Lambda_{\rm NP}$

– The same particle content as the SM and same pattern of symmetry breaking

– But there can be non-renormalizable (dim>4) operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_n \frac{1}{\Lambda_{\rm NP}^{n-4}} \mathcal{O}_n$$

First NP effect $\Rightarrow$ dim=5 operator

There is only one!

$$\mathcal{L}_5 = \frac{Z_{ij}^{\nu}}{\Lambda_{\rm NP}} \left(\overline{L_{L,i}} \tilde{\phi} \right) \left(\tilde{\phi}^T L_{L,j}^C \right)$$

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which after symmetry breaking

induces a ν Majorana mass

$$(M_\nu)_{ij} = Z^\nu_{ij} \frac{v^2}{\Lambda_{\rm NP}}$$

Implications:

– It is natural that ν mass is the first evidence of NP

– Naturally $m_\nu \ll$ other fermions masses $\sim \lambda^f v$ if $\Lambda_{\rm NP} >> v$

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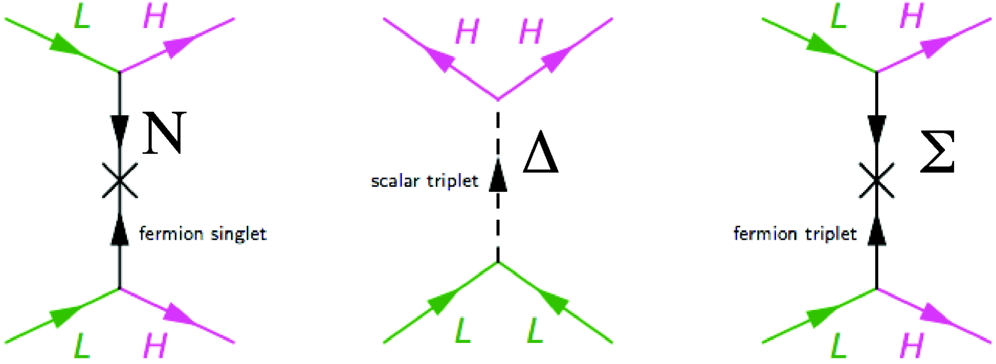
– $m_\nu > \sqrt{\Delta m^2_{\rm atm}} \sim 0.05$ eV for $Z^\nu \sim 1 \Longrightarrow \Lambda_{\rm NP} \sim 10^{15}{\rm GeV} \Longrightarrow$ $\Lambda_{\rm NP} \sim$ GUT scale

⇒ Leptogenesis possible

[But if $Z^\nu \sim (Y_e)^2 \Rightarrow \Lambda_{\rm NP} \sim$ TeV scale]

Model Degeneracy at Low Energy

$\mathcal{O}_5$ is generated for example by tree-level exchange of singlet ($N_i \equiv (1,1)_0$) (Type-I) or triplet fermions ($N_i \equiv \Sigma_i \equiv (1,3)_0$) (Type-III) or a scalar triplet $\Delta \equiv (1,3)_1$ (Type-II)



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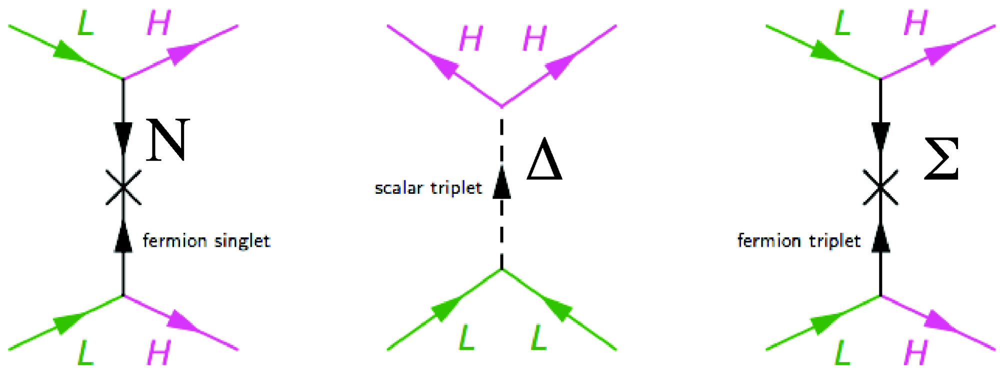


- For fermionic see-saw $-\mathcal{L}_{\rm NP} = -i\overline{N_i}\partial\!\!\!/ N_i + \frac{1}{2} M_{N ij}\overline{N_i^c} N_j + \lambda^\nu_{\alpha j}\overline{L_\alpha}\tilde{\phi} N_j [.\tau]$

$$\Rightarrow \mathcal{O}_5 = \frac{(\lambda^{\nu T}\lambda^\nu)_{\alpha\beta}}{\Lambda_{\rm NP}}\left(\overline{L_\alpha}\tilde{\phi}\right)\left(\tilde{\phi}^T L^C_\beta\right) \quad \text{with} \quad \Lambda_{\rm NP} = M_N$$

- For scalar see-saw $-\mathcal{L}_{\rm NP} = f_{\Delta\alpha\beta}\overline{L_\alpha}\,\Delta\, L^C_\beta + M^2_\Delta\,|\Delta|^2 + \kappa\,\phi^T\,\Delta^\dagger\,\phi\ \ldots$

$$\Rightarrow \mathcal{O}_5 = \frac{f_{\Delta\alpha\beta}}{\Lambda_{NP}}\left(\overline{L_\alpha}\tilde{\phi}\right)\left(\tilde{\phi}^T L^C_\beta\right) \quad \text{with} \quad \Lambda_{\rm NP} = \frac{M^2_\Delta}{\kappa}$$

Very different physics, but same ν parameters: How to proceed?

Model Degeneracy at Low Energy

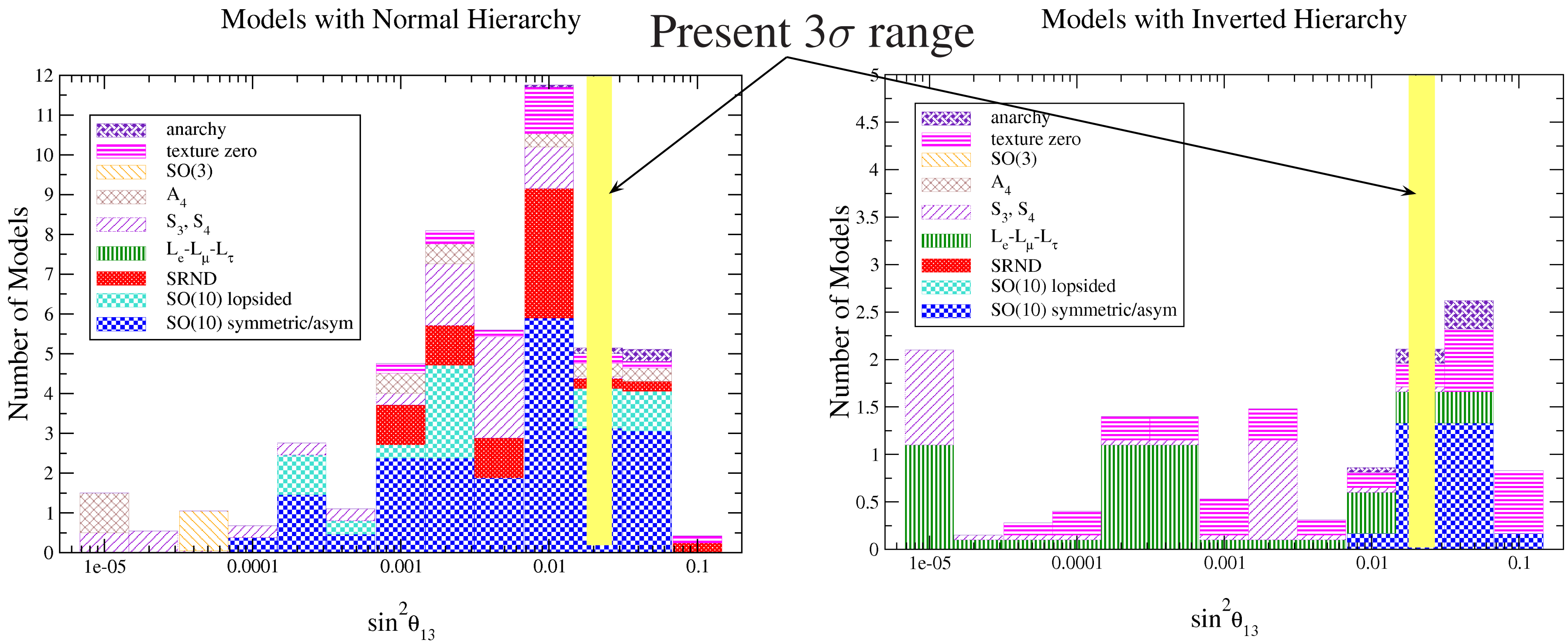
Same $\mathcal{O}_5$ can be generated by very different High Energy physics

Very different physics, but same ν parameters: How to proceed?

– Top-down: Assume some specific model and work out the relations

Modeling Lepton Flavour: 2006 to 2016

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



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

– Next *frontier* is the ordering

Model Degeneracy at Low Energy

Same $\mathcal{O}_5$ can be generated by very different High Energy physics

Very different physics, but same ν parameters: How to proceed?

– Top-down: Assume some specific model and work out the relations

– Hope/Wait for additional information from charged LFV, collider signals . . .

Summary

- 3ν parameter determination (at $\pm 3\sigma/6$)

$$\Delta m^2_{21} = 7.49\times 10^{-5}\ \text{eV}^2\ (2.3\%) \qquad \begin{array}{l}\Delta m^2_{31} = 2.48\times 10^{-3}\ \text{eV}^2 \quad \text{NO} \\ \Delta m^2_{32} = -2.47\times 10^{-3}\ \text{eV}^2 \quad \text{IO}\end{array}\ (1.8\%)$$

$$\sin^2\theta_{12} = 0.308\ (4\%) \qquad \sin^2\theta_{23} = \begin{array}{ll}0.579 & \text{IO} \\ 0.479 & \text{NO}\end{array}\ (7.2\%) \qquad \sin^2\theta_{13} = 0.022\ (4.8\%)$$

- Still not significantly determined: Ordering θ_{23} Octant

CPV? $\text{NO}: \delta_{CP} = 256^{\pm}43\ (0 \to 360 \text{ allowed at } 3\sigma)$
$\text{IO}: \delta_{CP} = 272^{+61}_{-64}\ (21 \to 131 \text{ excluded at } 3\sigma)$ (with NOvA-LEM)

Ignored: Majorana or Dirac Absolute ν mass

- $$|U|_{\text{LEP}(3\sigma)} = \begin{pmatrix} 0.789 \to 0.843 & 0.517 \to 0.584 & 0.137 \to 0.158 \\ 0.231 \to 0.518 & 0.441 \to 0.693 & 0.617 \to 0.790 \\ 0.251 \to 0.530 & 0.468 \to 0.711 & 0.595 \to 0.773 \end{pmatrix}$$

- Sterile ν's: Not satisfactory description of SBL anomalies. Tension with Cosmo
- Much more physics in this data than masses and mixings

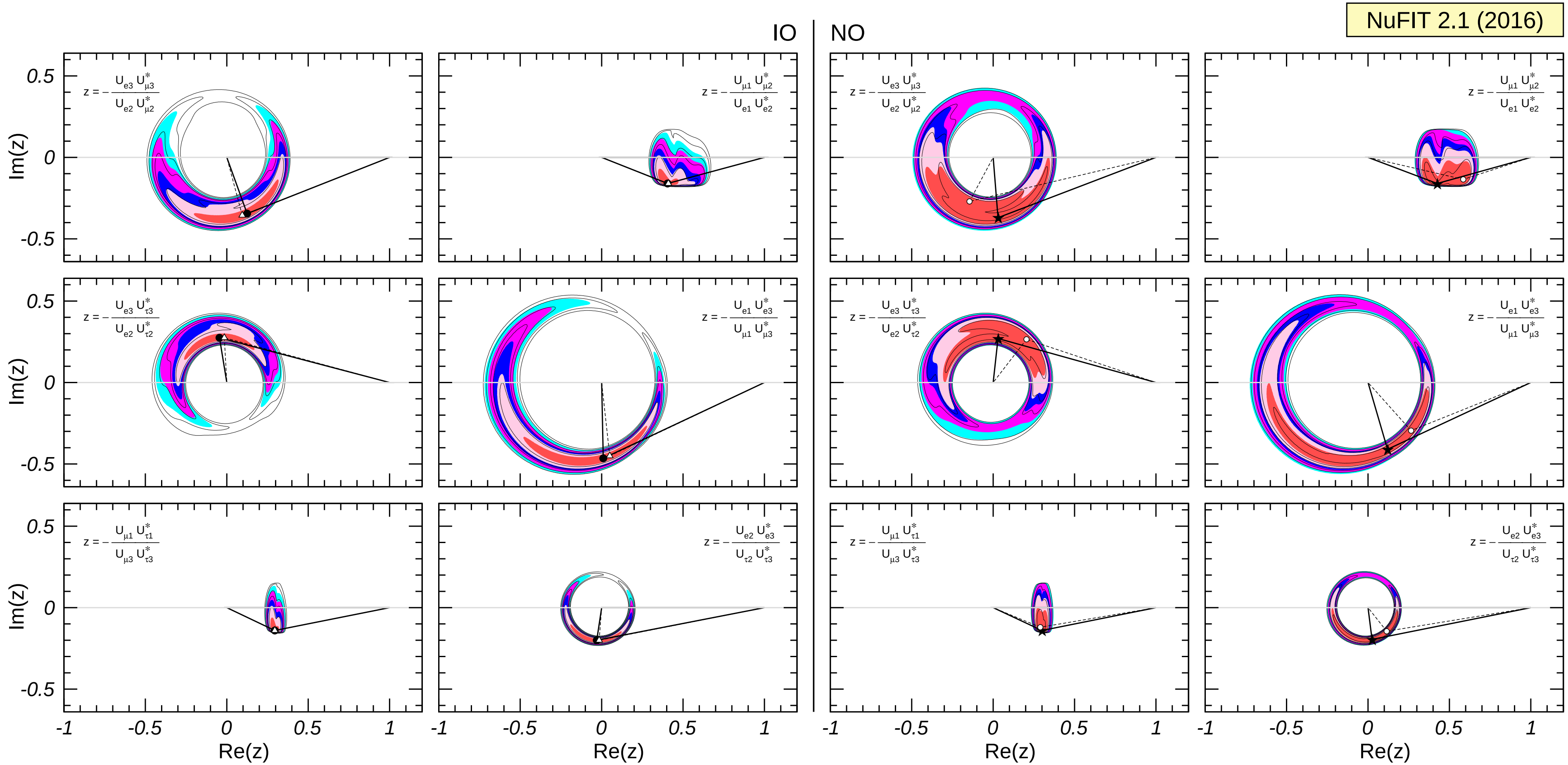
  Tests of solar models, of ATM fluxes, reactor fluxes ...

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

LEM	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.97$)		Any Ordering
$\sin^2\theta_{12}$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.273 \to 0.349$
$\theta_{12}/^\circ$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.19$	$31.52 \to 36.18$
$\sin^2\theta_{23}$	$0.574^{+0.026}_{-0.144}$	$0.390 \to 0.639$	$0.579^{+0.022}_{-0.029}$	$0.400 \to 0.637$	$0.390 \to 0.639$
$\theta_{23}/^\circ$	$49.3^{+1.5}_{-8.3}$	$38.6 \to 53.1$	$49.6^{+1.3}_{-1.7}$	$39.2 \to 53.0$	$38.6 \to 53.1$
$\sin^2\theta_{13}$	$0.0217^{+0.0013}_{-0.0010}$	$0.0187 \to 0.0250$	$0.0221^{+0.0010}_{-0.0010}$	$0.0190 \to 0.0251$	$0.0187 \to 0.0250$
$\theta_{13}/^\circ$	$8.47^{+0.24}_{-0.20}$	$7.86 \to 9.11$	$8.54^{+0.19}_{-0.20}$	$7.93 \to 9.12$	$7.86 \to 9.11$
$\delta_{CP}/^\circ$	272^{+61}_{-64}	$0 \to 360$	256^{+43}_{-43}	$131 \to 381$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.02 \to 8.08$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.484^{+0.045}_{-0.048}$	$+2.351 \to +2.618$	$-2.467^{+0.041}_{-0.042}$	$-2.595 \to -2.341$	$\begin{bmatrix}+2.351 \to +2.618 \\ -2.588 \to -2.348\end{bmatrix}$
LID	**Normal Ordering ($\Delta\chi^2 = 0.55$)**		**Inverted Ordering (best fit)**		**Any Ordering**
$\sin^2\theta_{12}$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.273 \to 0.349$
$\theta_{12}/^\circ$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$31.52 \to 36.18$
$\sin^2\theta_{23}$	$0.451^{+0.038}_{-0.025}$	$0.387 \to 0.634$	$0.576^{+0.023}_{-0.033}$	$0.393 \to 0.636$	$0.389 \to 0.636$
$\theta_{23}/^\circ$	$42.2^{+2.2}_{-1.4}$	$38.5 \to 52.8$	$49.4^{+1.4}_{-1.9}$	$38.8 \to 52.9$	$38.6 \to 52.9$
$\sin^2\theta_{13}$	$0.0219^{+0.0010}_{-0.0010}$	$0.0188 \to 0.0249$	$0.0219^{+0.0010}_{-0.0010}$	$0.0189 \to 0.0250$	$0.0189 \to 0.0250$
$\theta_{13}/^\circ$	$8.50^{+0.19}_{-0.20}$	$7.87 \to 9.08$	$8.51^{+0.20}_{-0.20}$	$7.89 \to 9.10$	$7.89 \to 9.10$
$\delta_{CP}/^\circ$	303^{+39}_{-50}	$0 \to 360$	262^{+51}_{-57}	$98 \to 416$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.02 \to 8.08$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.477^{+0.042}_{-0.042}$	$+2.351 \to +2.610$	$-2.465^{+0.041}_{-0.043}$	$-2.594 \to -2.339$	$\begin{bmatrix}+2.355 \to +2.606 \\ -2.594 \to -2.339\end{bmatrix}$
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range

3ν Analysis: Leptonic CP violation

Leptonic Unitarity Triangles



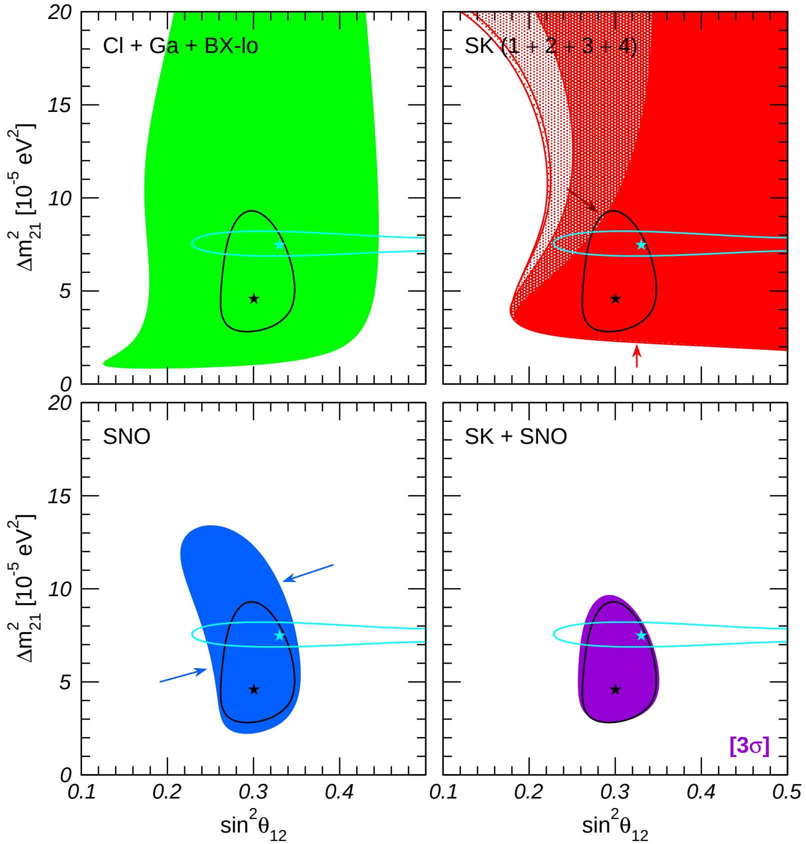
3 ν Analysis: "12" Sector

- $\Delta m^2_{13} \gg E/L \Rightarrow$ $P^{3\nu}_{ee} = c^4_{13} P_{2\nu} + s^4_{13}$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_a\end{pmatrix} = \left[\frac{\Delta m^2_{21}}{4E}\begin{pmatrix}-\cos 2\theta_{12} & \sin 2\theta_{12}\\ \sin 2\theta_{12} & \cos 2\theta_{12}\end{pmatrix} \pm \sqrt{2} G_F N_e \begin{pmatrix} c^2_{13} & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_a\end{pmatrix}$$

With $\theta_{13} = 0$

$$P_{ee} \simeq \begin{cases} \text{Solar High E}: c^4_{13} \sin^2 2\theta_{12} \\ \text{Solar Low E}: c^4_{13} \left(1 - \sin^2 2\theta_{12}/2\right) \\ \text{Kam}: c^4_{13} \left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}\right) \end{cases}$$



$*$ Solar region determined by High E data

$*$ Param's $\begin{cases} \theta_{12} \text{ SNO most sensitivity} \\ \Delta m^2_{21} \text{ by KamLAND} \end{cases}$

$*$ Tension in best fit between

Solar and KamLAND $\Rightarrow \theta_{13}$ and ...?