MASSIVE NEUTRINOS CIRCA 2017

Concha Gonzalez-Garcia

(YITP Stony Brook & ICREA U. Barcelona)

PASCOS, June 19th, 2017

Global fit to neutrino oscillation data

http://www.nu-fit.org

elusives neutrinos, dark matter & dark energ

invisiblesPlus neutrinos, dark matter & dark energy physics

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Neutrino Flavour Transition: Data and Interpretation

Some comments on Status of :

- *Leptonic CP violation*
- *Determination of mass Ordering*
- *Degeneracies with NC-NSI*
- *Light Sterile neutrinos*
- *Mass scale*

Neutrinos in the Standard Model

The SM is a gauge theory based on the symmetry group

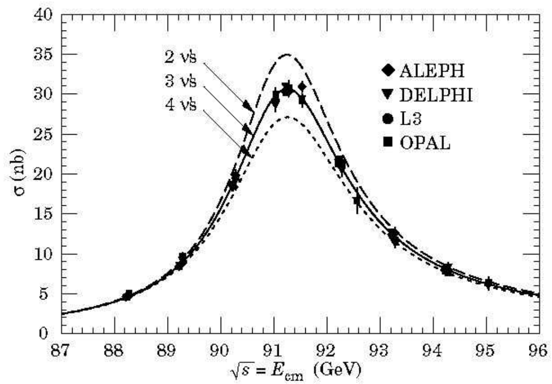
$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

With three generation of fermions

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	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

Three and only three



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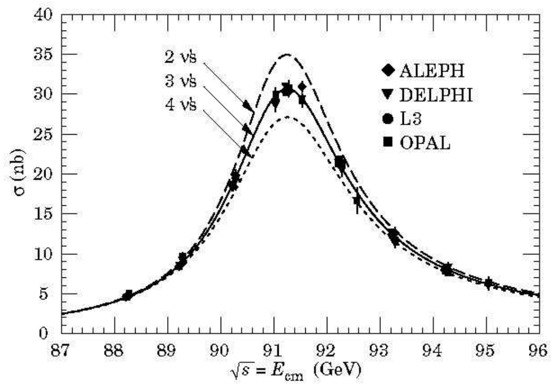

There is no ν_R

$\Downarrow$

Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau$ (hence $L = L_e + L_\mu + L_\tau$)

$\Downarrow$

ν *strictly* massless

- By 2017 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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All this implies that L_α are violated

and There is Physics Beyond SM

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and There is Physics Beyond SM

- The *starting* path:

Precise determination of the low energy parametrization

The New Minimal Standard Model

- Minimal Extension to allow for LFV $\Rightarrow$ 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 $\nu = \nu^c$

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

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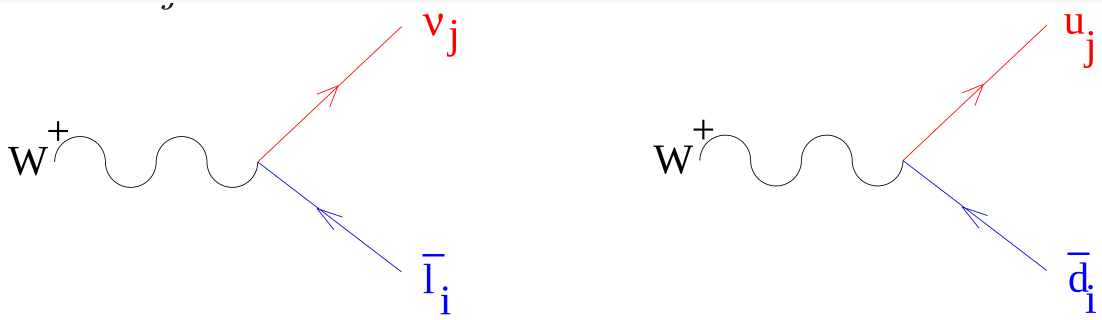
- The charged current interactions of leptons are not diagonal (same as quarks)

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



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

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

- $U_{\rm LEP}$: $3 + 3s$ angles + $2s + 1$ Dirac phases + $s + 2$ Majorana phases

ν Mass Oscillations in Vacuum

- 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

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- When osc between 2-ν dominates:

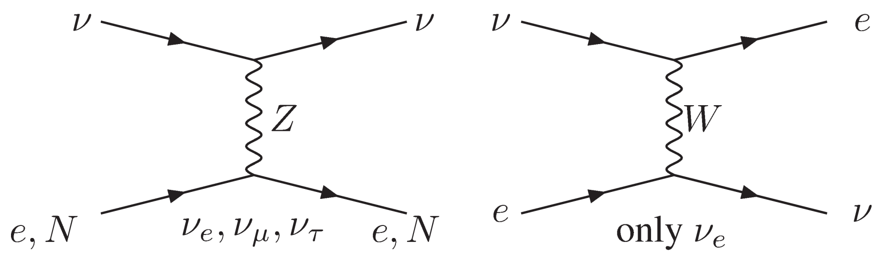
$$P_{\alpha\alpha} = 1 - P_{osc} \qquad \text{Disappear}$$

$$P_{osc} = \sin^2(2\theta)\, \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right) \qquad \text{Appear}$$

Matter Effects

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

  – But Different flavours have different interactions :



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

$$-i \frac{\partial}{\partial x} \begin{pmatrix} \nu_e \\ \nu_X \end{pmatrix} = \Big[\big[- \begin{pmatrix} V_e - V_X - \frac{\Delta m^2}{4E} \cos 2\theta & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} \Big] \begin{pmatrix} \nu_e \\ \nu_X \end{pmatrix}$$

$\Rightarrow$ *Modification of mixing angle and oscillation wavelength* (MSW)

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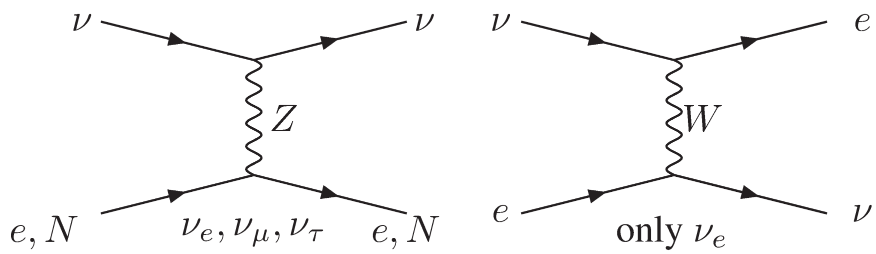

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$\Rightarrow$ *Modification of mixing angle and oscillation wavelength* (MSW)

- Mass difference and mixing in matter:

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

$$\sin(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\Delta m^2_{mat}}$$

$\Rightarrow$ For solar $\nu' s$ in adiabatic regime

$$P_{ee} = \frac{1}{2}\left[1 + \cos(2\theta_m)\cos(2\theta)\right]$$

Dependence on θ octant

$\Rightarrow$ In LBL terrestrial experiments

Dependence on sign of Δm^2 and θ octant

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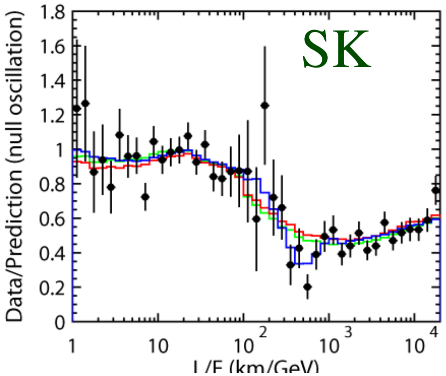
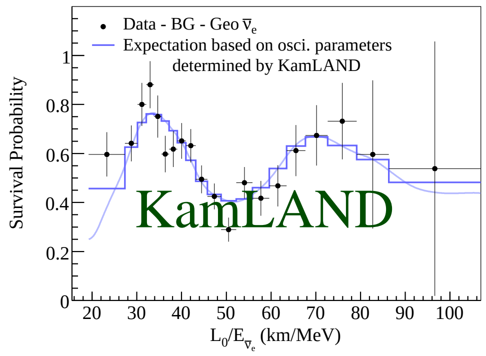
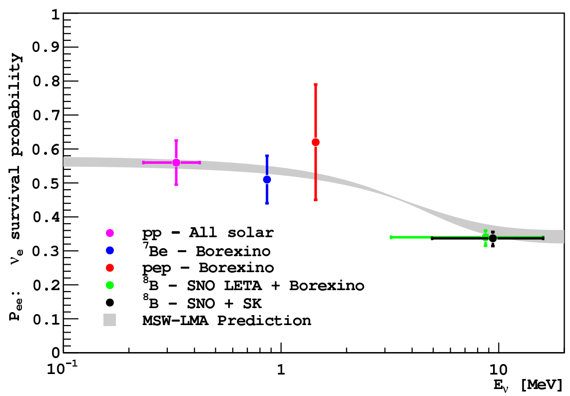
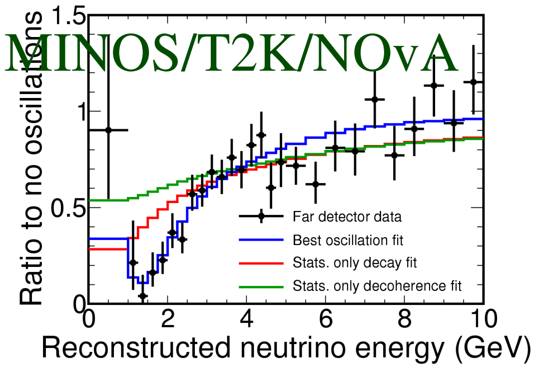
- Confirmed: Vacuum oscillation L/E pattern with 2 frequencies

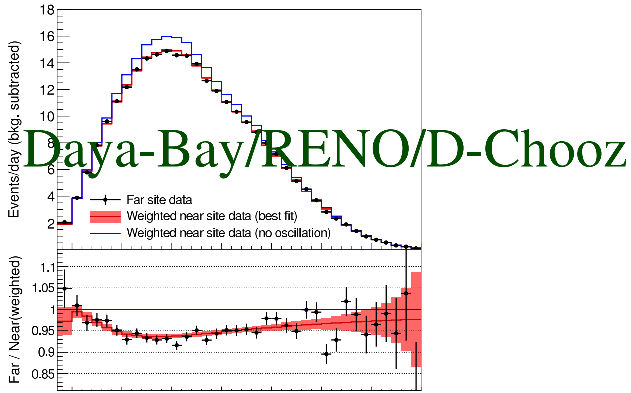




MSW conversion in Sun





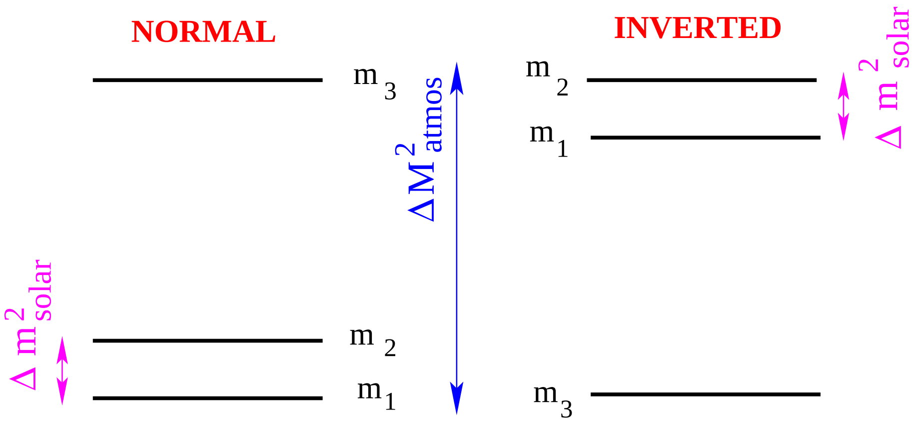


3ν Flavour Parameters

- 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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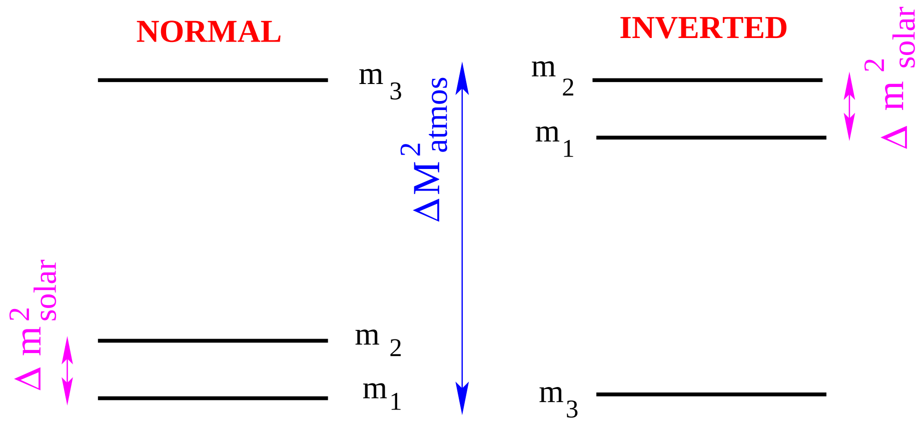
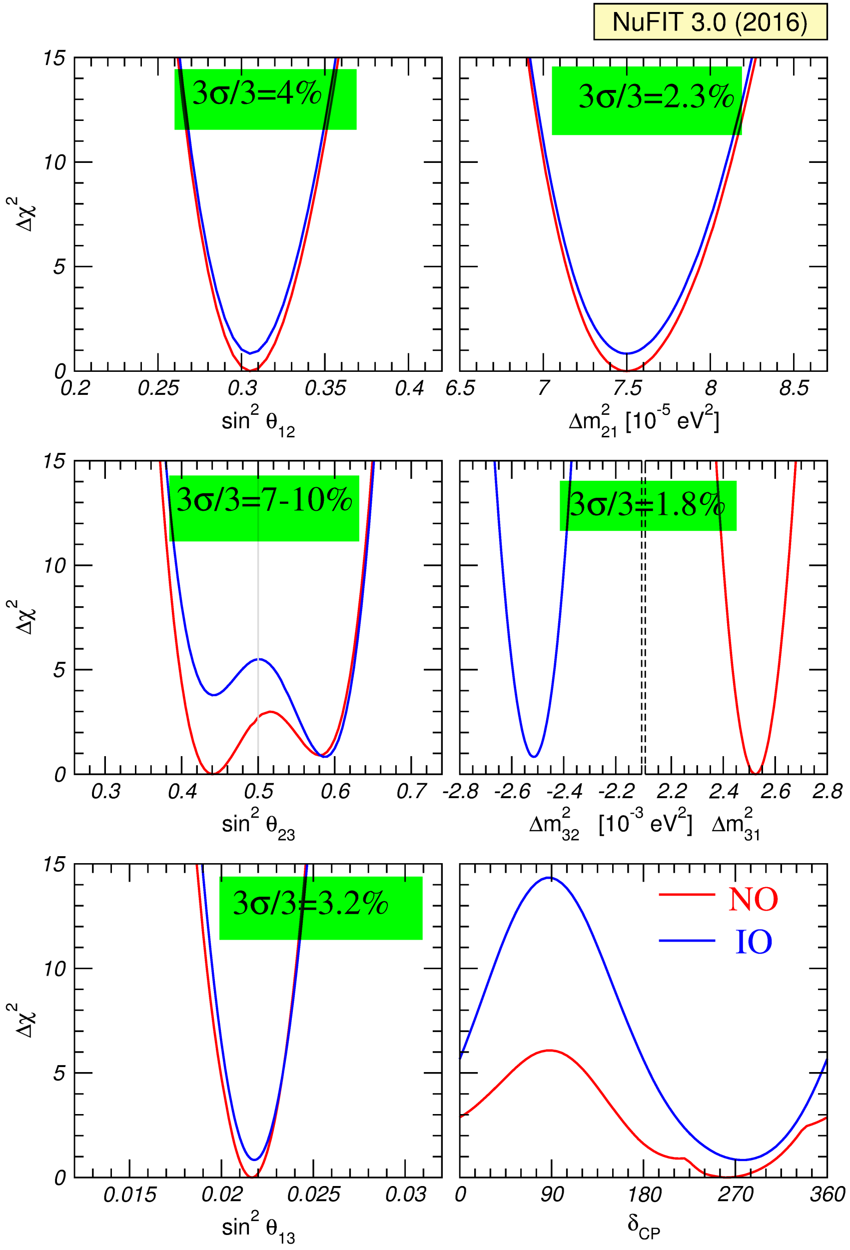


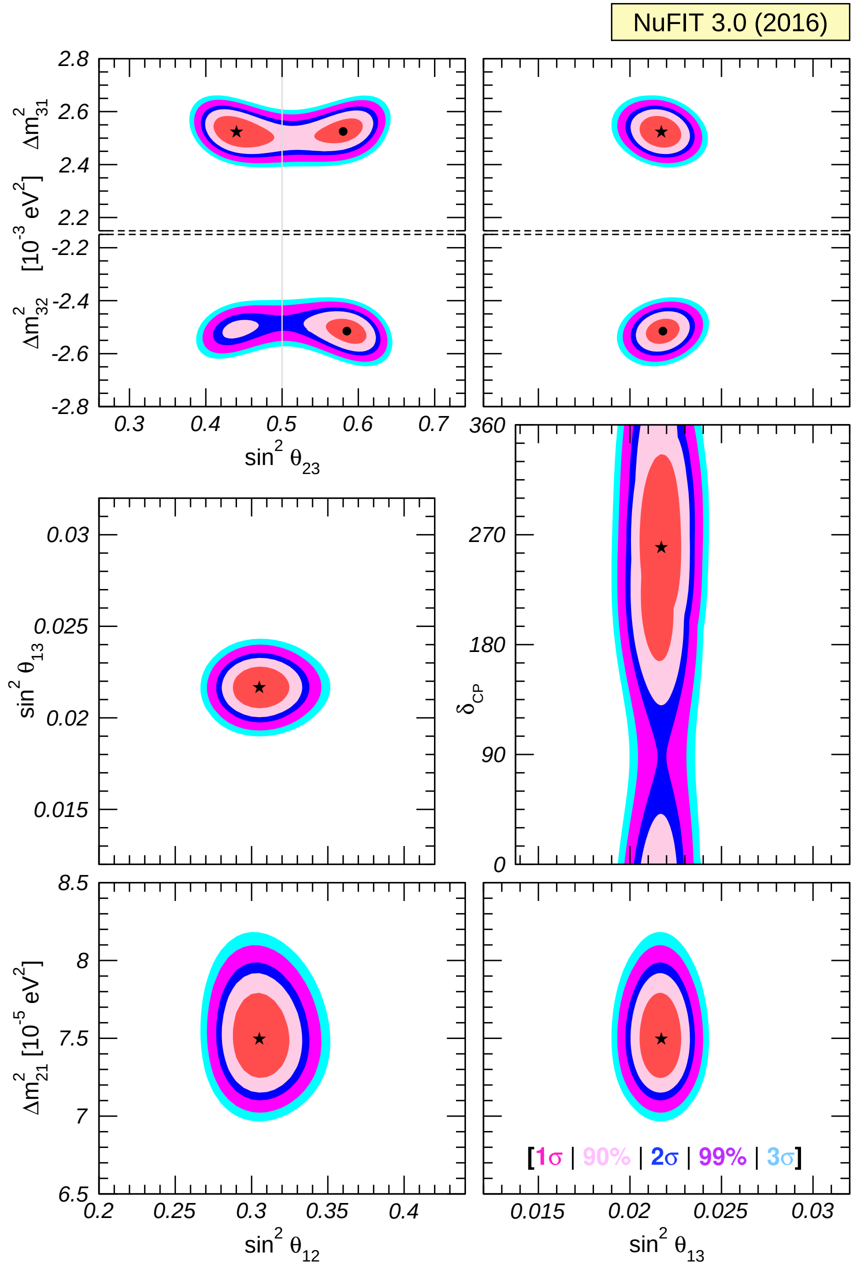
Experiment	Dominant Dependence	Important Dependence
Solar Experiments	$\rightarrow \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\rightarrow \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	$\rightarrow \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\rightarrow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

3 ν Flavour Parameters: Status in 6/2017

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

Esteban, Maltoni, Martinez-Soler, Schwetz, MCG-G ArXiv:1611:01514





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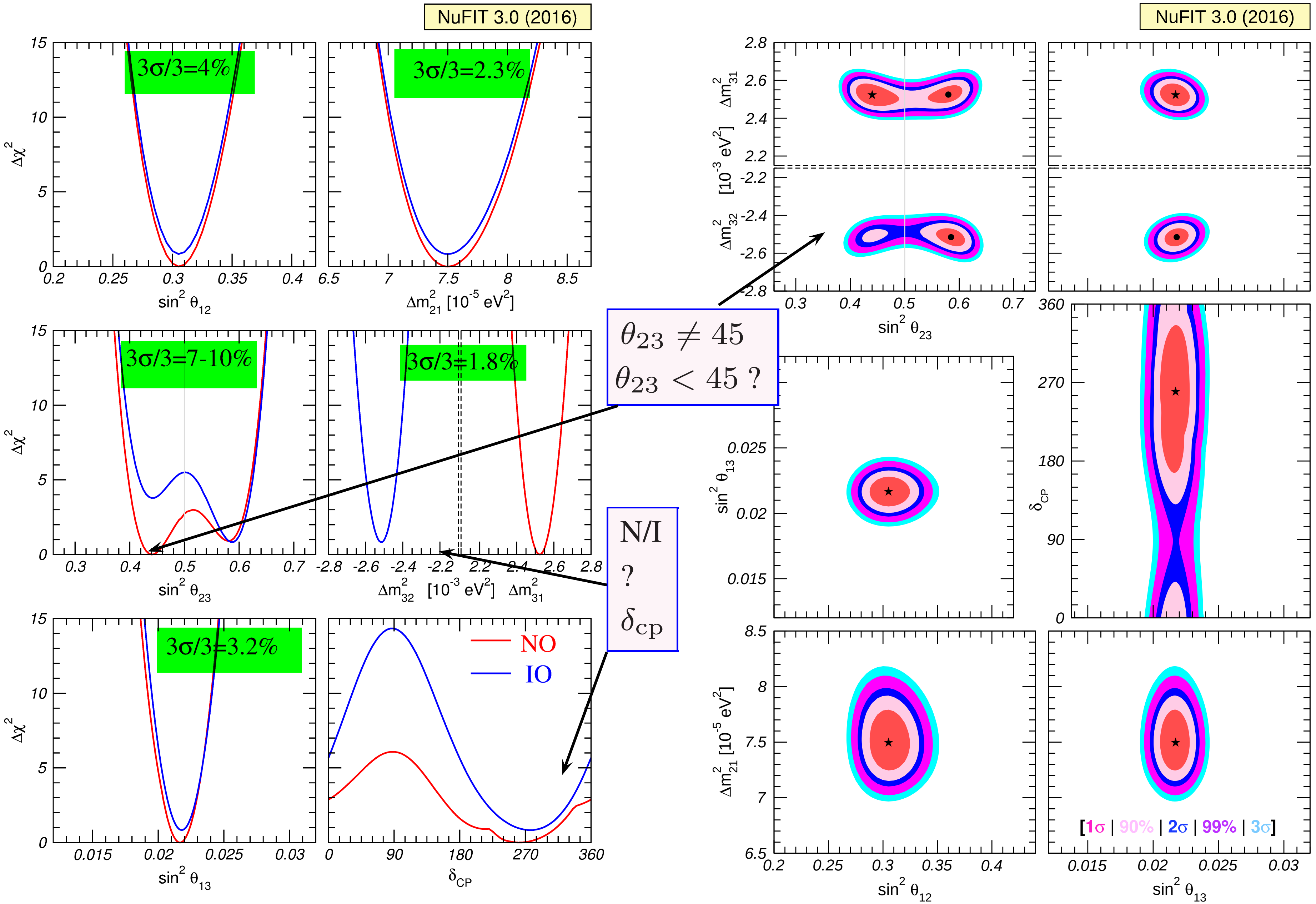


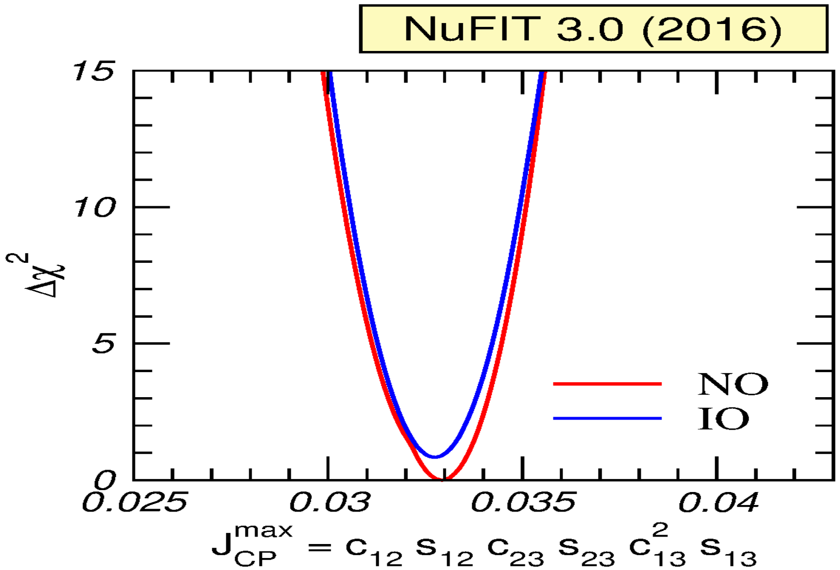
Leptonic CP Violation

- Leptonic $\not{C}P \Rightarrow P_{\nu_\alpha \to \nu_\beta} \neq P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}$:

$$P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} \propto J = \mathrm{Im}(U_{\alpha 1} U^*_{\alpha_2} U_{\beta 2} U^*_{\beta_1}) = J^{\max}_{\mathrm{LEP,CP}} \sin \delta_{\mathrm{CP}}$$

$$J^{\max}_{\mathrm{LEP,CP}} = \frac{1}{8} c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$

- Maximum Allowed Leptonic CPV:



$J^{\max}_{\mathrm{LEP,CP}} = (3.29 \pm 0.07) \times 10^{-2}$

to compare with

$J_{\mathrm{CKM,CP}} = (3.04 \pm 0.21) \times 10^{-5}$

$\Rightarrow$ Leptonic CPV may be largest CPV in New Minimal SM

if $\sin \delta_{\mathrm{CP}}$ not too small

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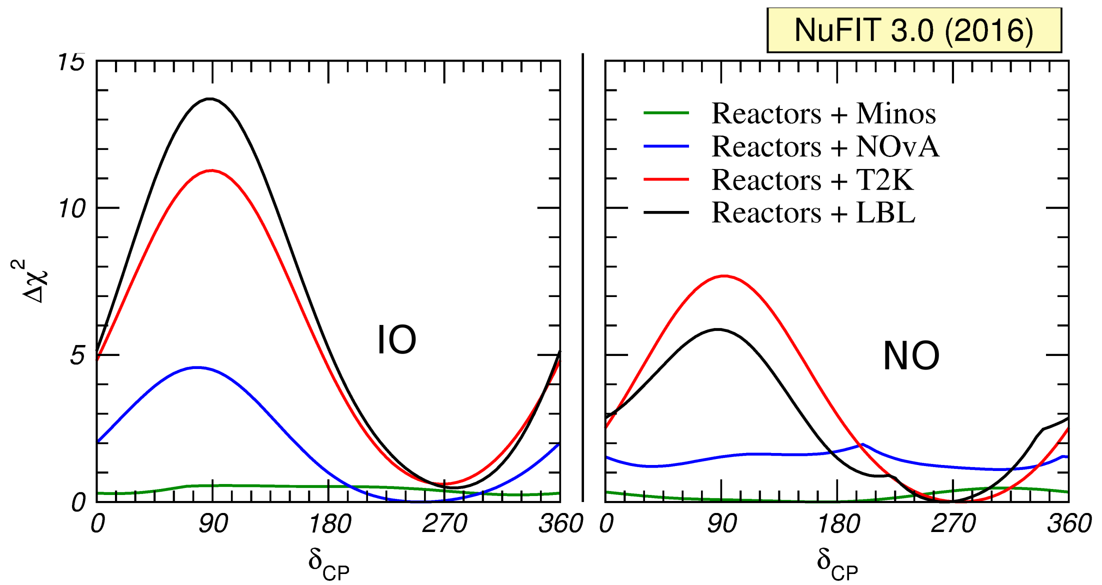
- Leptonic CPV Phase: Mainly from $\nu_\mu \to \nu_e$ in LBL (complicated by matter effects)

$$P_{\mu e} \simeq s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) + 8\, J^{\max}_{\mathrm{LEP,CP}} \frac{\Delta_{12}}{V_E} \frac{\Delta_{31}}{B_\mp} \sin\left(\frac{V_E L}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad J^{\max}_{\mathrm{LEP,CP}} = \tfrac{1}{8} c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$



– Best fit $\delta_{\mathrm{CP}} \sim 270°$

– CP conservation at 70% (NO), 97% (IO)

– Driven by "fluctuation" in T2K

Mass hierarchy	ν_e Normal	ν_e Inverted	$\bar{\nu}_e$ Normal	$\bar{\nu}_e$ Inverted
$\delta_{CP} = -\pi/2$	28.8	25.5	6.0	6.5
$\delta_{CP} = 0$	24.2	21.2	6.9	7.4
$\delta_{CP} = \pi/2$	19.7	17.2	7.7	8.4
$\delta_{CP} = \pm\pi$	24.2	21.6	6.8	7.4
Data	32		4	

$\Rightarrow$ Significance may not grow soon

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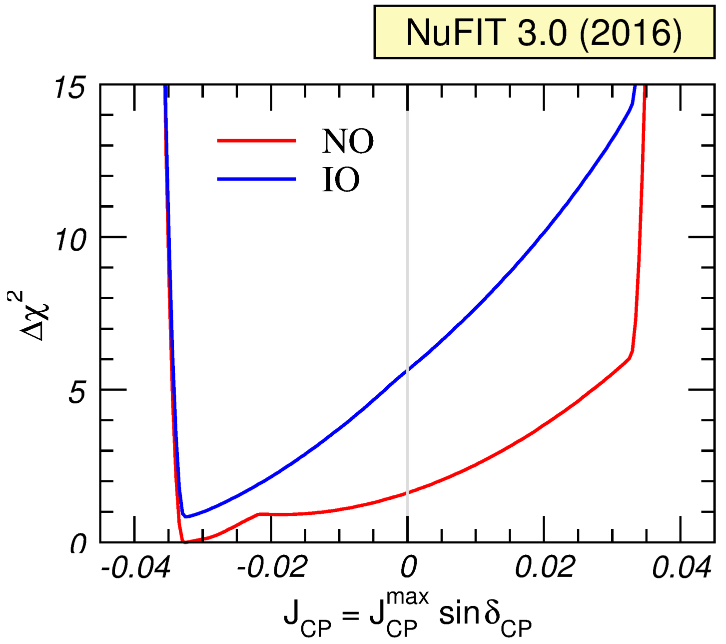
- Leptonic Jarlskog Invariant



Best fit $J_{\mathrm{LEP,CP}} = -0.033$

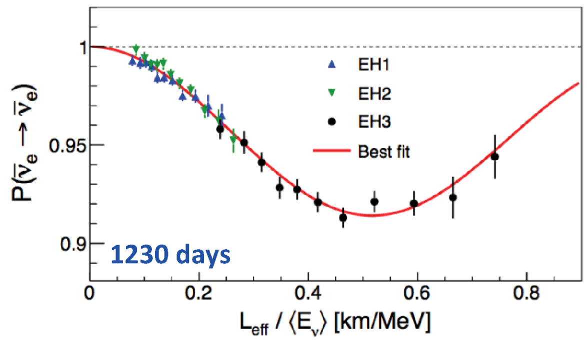
Redundancy: Δm^2_{23} in LBL vs Reactors

- At LBL determined in ν_μ and $\bar\nu_\mu$ disappearance spectrum

$$P_{\mu\mu} \simeq 1 - (c^4_{13}\sin^2 2\theta_{23} + s^2_{23}\sin^2 2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \mathcal{O}(\Delta m^2_{21})$$

- At MBL Reactors (Daya-Bay, Reno, D-Chooz) determined in $\bar\nu_e$ disapp spectrum

$$P_{ee} \simeq 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) - c^4_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$



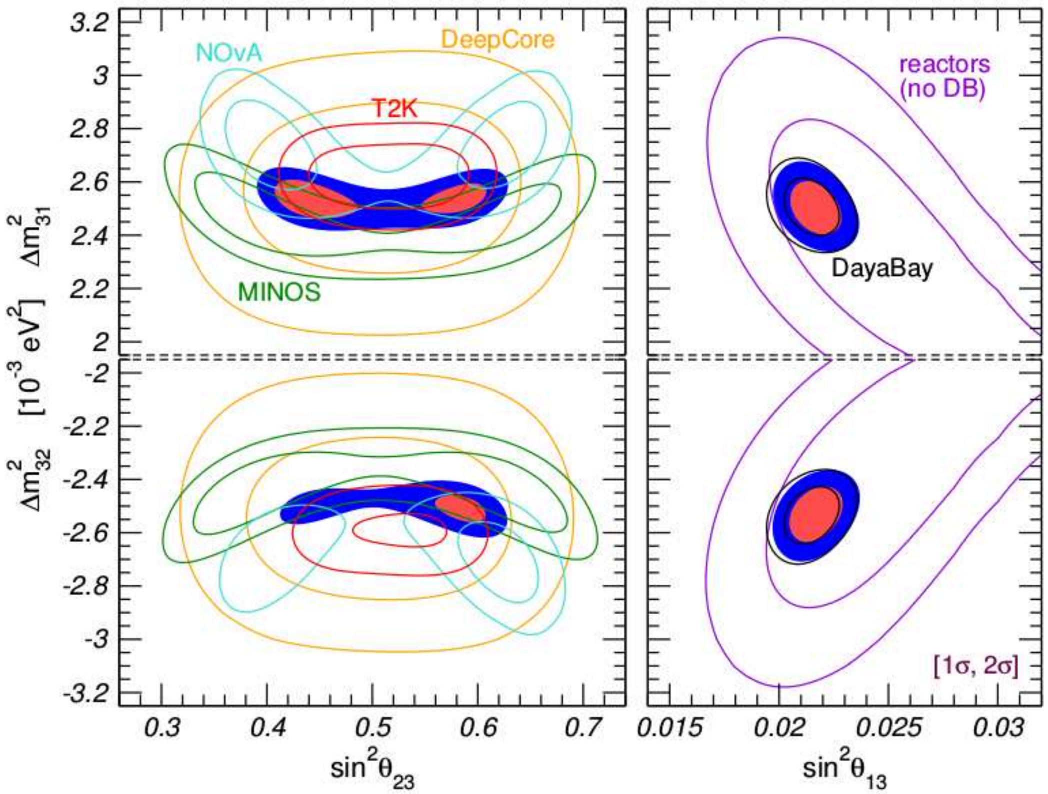
$$\Delta m^2_{ee} \simeq |\Delta m^2_{32}| \pm c^2_{12}\Delta m^2_{21} \simeq |\Delta m^2_{32}| \pm 0.05 \times 10^{-3}\ \mathrm{eV}^2$$

Nunokawa,Parke,Zukanovich (2005)

Δm^2_{23} in LBL vs Reactors: Consistency

- At LBL determined in ν_μ and $\bar{\nu}_\mu$ disappearance spectrum
- At MBL Reactors (Daya-Bay, Reno, D-Chooz) determined in $\bar{\nu}_e$ disapp spectrum

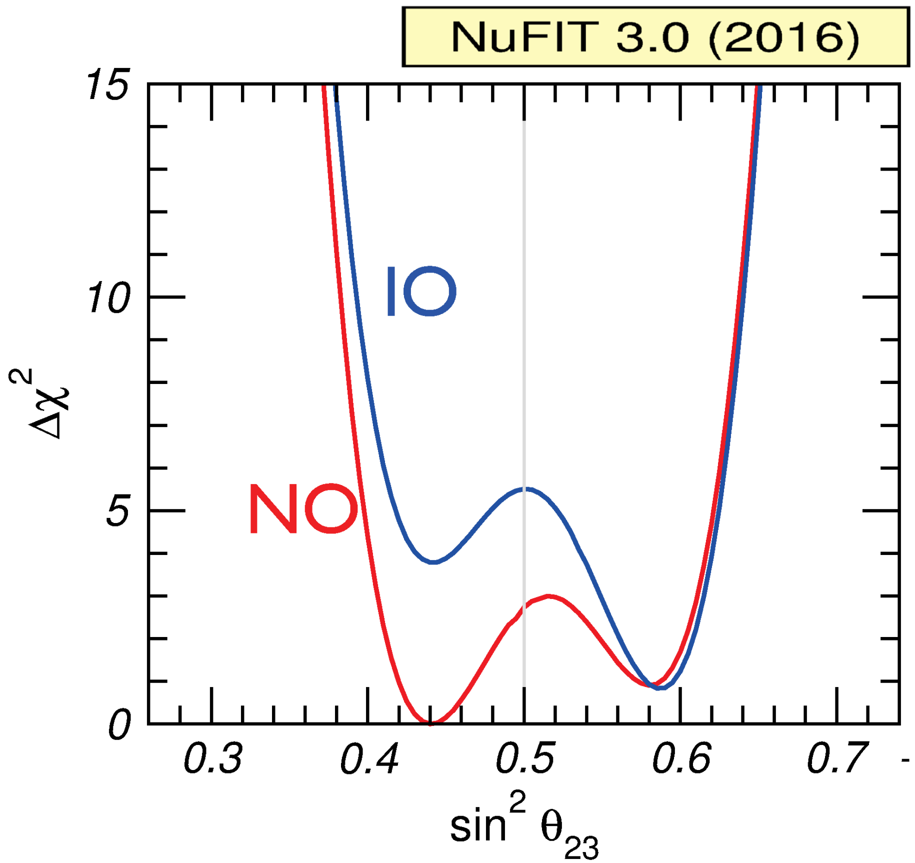
LBL ν_μ disappearance REAC ν_e disappearance



– Consistent determination of $|\Delta m^2_{32}|$

– Hint for non-maximal θ_{23} driven by NOνA and MINOS

Ordering and θ_{23}



– No significance preference Normal vs Inverted Ordering: $\Delta\chi^2 \sim 1$

– Favoured Octant of θ_{23} depends on ordering

– CL of maximal mixing at 91%(NO) or 98% (IO)

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)

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

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

– 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^2_{31} and Δm^2_{32}: JUNO, RENO-50

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

– Challenge: Energy resolution

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Alternative Oscillation Mechanisms

- Oscillations are due to:
  - Misalignment between CC-int and propagation states: Mixing $\Rightarrow$ Amplitude
  - Difference phases of propagation states $\Rightarrow$ Wavelength. For Δm^2-OSC $\lambda = \dfrac{4\pi E}{\Delta m^2}$

Alternative Oscillation Mechanisms

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  - Difference phases of propagation states $\Rightarrow$ Wavelength.

For Δm^2-OSC $\lambda = \frac{4\pi E}{\Delta m^2}$

- ν masses are not the only mechanism for oscillations

Violation of Equivalence Principle (VEP): Gasperini 88, Halprin,Leung 01

Non universal coupling of neutrinos $\gamma_1 \neq \gamma_2$ *to gravitational potential* ϕ

$$\lambda = \frac{\pi}{E|\phi|\delta\gamma}$$

Violation of Lorentz Invariance (VLI): Coleman, Glashow 97

Non universal asymptotic velocity of neutrinos $c_1 \neq c_2 \Rightarrow E_i = \frac{m_i^2}{2p} + c_i p$

$$\lambda = \frac{2\pi}{E\Delta c}$$

Interactions with space-time torsion: Sabbata, Gasperini 81

Non universal couplings of neutrinos $k_1 \neq k_2$ *to torsion strength* Q

$$\lambda = \frac{2\pi}{Q\Delta k}$$

Violation of Lorentz Invariance (VLI) Colladay, Kostelecky 97; Coleman, Glashow 99

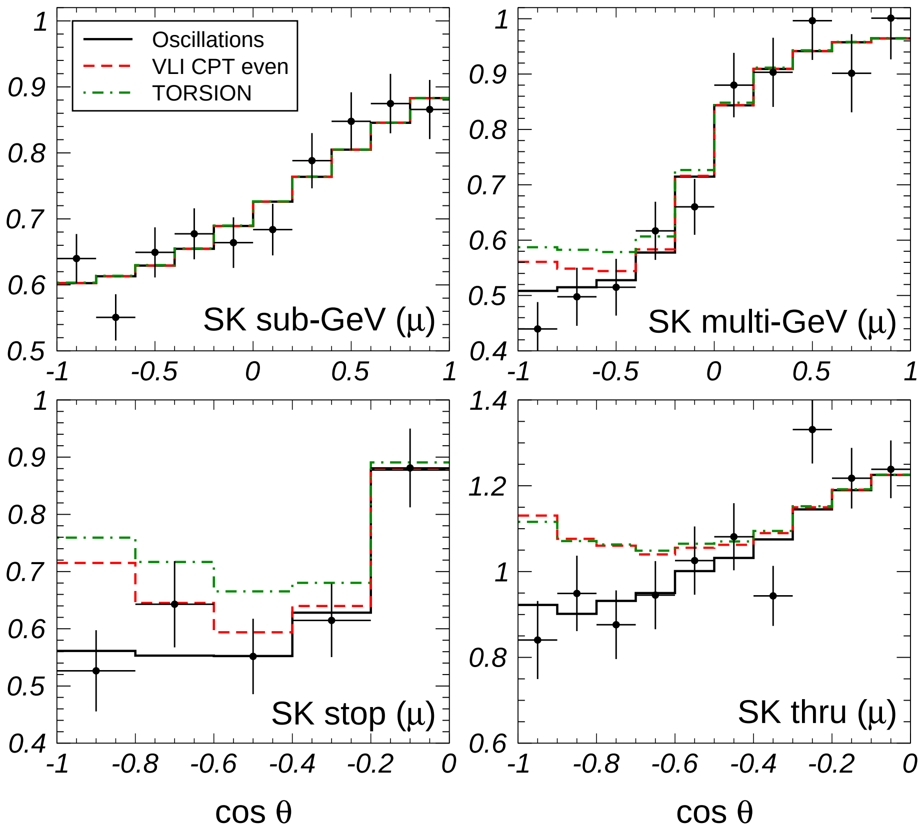
due to CPT violating terms: $\bar{\nu}_L^\alpha b_\mu^{\alpha\beta}\gamma_\mu \nu_L^\beta \Rightarrow E_i = \frac{m_i^2}{2p} \pm b_i$

$$\lambda = \pm\frac{2\pi}{\Delta b}$$

ATM ν's: Subdominant NP Effects

- Using atmospheric neutrino data these effects can be constrained

MCG-G, M. Maltoni hepp-ph,0404085,0704.1800



At 90% CL:

$$\frac{|\Delta c|}{c} \leq 1.2 \times 10^{-24}$$

$$|\phi\,\Delta\gamma| \leq 5.9 \times 10^{-25}$$

$$|Q\,\Delta k| \leq 4.8 \times 10^{-23}\ \text{GeV}$$

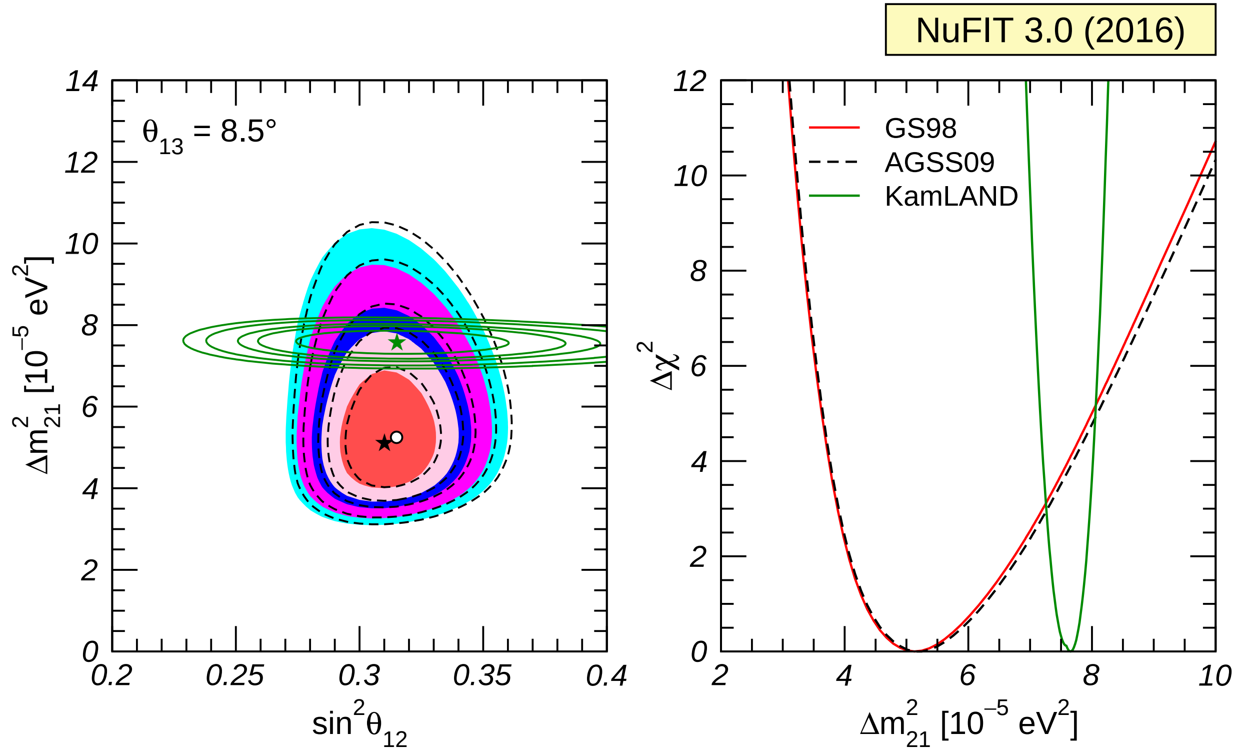
$$|\Delta b| \leq 3.0 \times 10^{-23}\ \text{GeV}$$

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

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

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

- With $\theta_{13} \simeq 9^\circ$ θ_{12} OK. But $\sim 2\sigma$ tension on Δm^2_{12}



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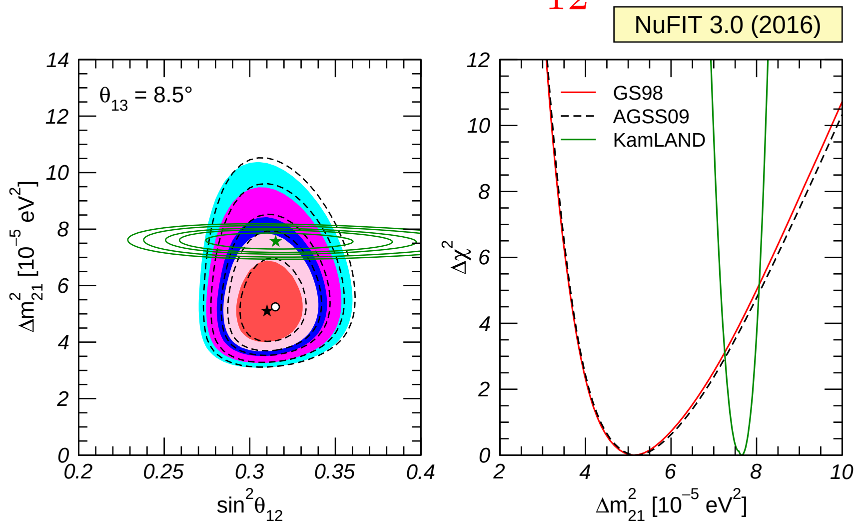
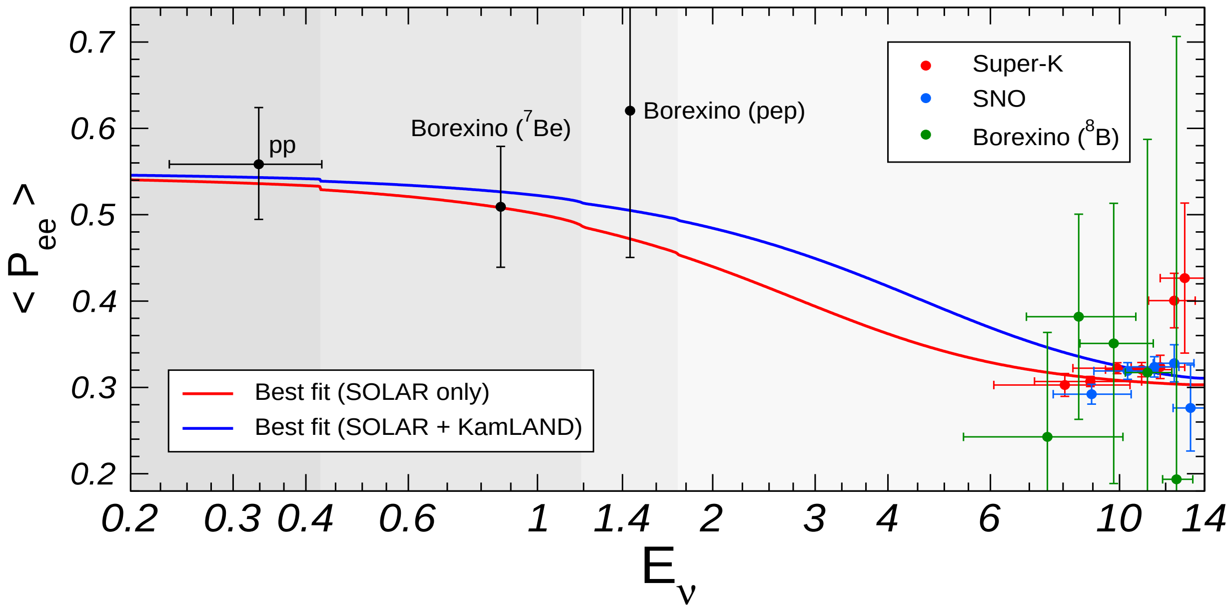


Tension related to: a)"too large" of Day/Night at SK



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

Modified matter potential?

Non Standard ν Interactions

- Including non-standard neutrino NC interactions with fermion f

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

- In flavour basis $\vec\nu = (\nu_e, \nu_\mu, \mu_\tau)^T$ the neutrino evolution eq.:

$$i\frac{d}{dx}\vec\nu = H^\nu\vec\nu \quad \text{with} \quad H^\nu = H_{\rm vac} + H_{\rm mat} \quad \text{and} \quad H^{\bar\nu} = (H_{\rm vac} - H_{\rm mat})^*$$

- The most general matter potential can be parametrized

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

Deviations from $H^{\rm SM}_{\rm mat} = \sqrt{2}G_F N_e(r){\rm diag}(1,0,0)$ induced by **NSI**

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Deviations from $H^{\rm SM}_{\rm mat} = \sqrt{2} G_F N_e(r) {\rm diag}(1,0,0)$ induced by **NSI**

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

$\Rightarrow$ Parameters degeneracies (some well-known but being rediscovered lately ...)

In particular CPT $\Rightarrow$ invariance under simultaneously:

$$\theta_{12} \leftrightarrow \frac{\pi}{2} - \theta_{12}\,, \qquad (\varepsilon_{ee} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{ee} - \varepsilon_{\mu\mu}) - 2\,,$$

$$\Delta m^2_{31} \to -\Delta m^2_{32}\,, \qquad (\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu})\,,$$

$$\delta \to \pi - \delta\,, \qquad \varepsilon_{\alpha\beta} \to -\varepsilon^*_{\alpha\beta} \qquad (\alpha \neq \beta)\,,$$

NSI: Bounds from Oscillation data

		90% CL	
Param.	best-fit	LMA	LMA $\oplus$ LMA – D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus\ [-1.19, -0.81]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$

– Bounds $\mathcal{O}(1-10\%)$

– Except $\varepsilon_{ee} - \varepsilon_{\mu\mu}$

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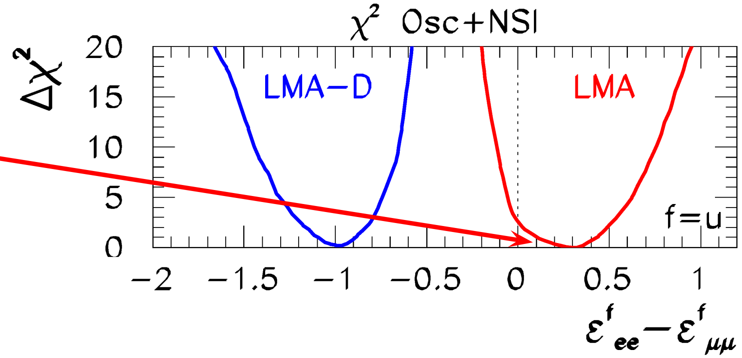
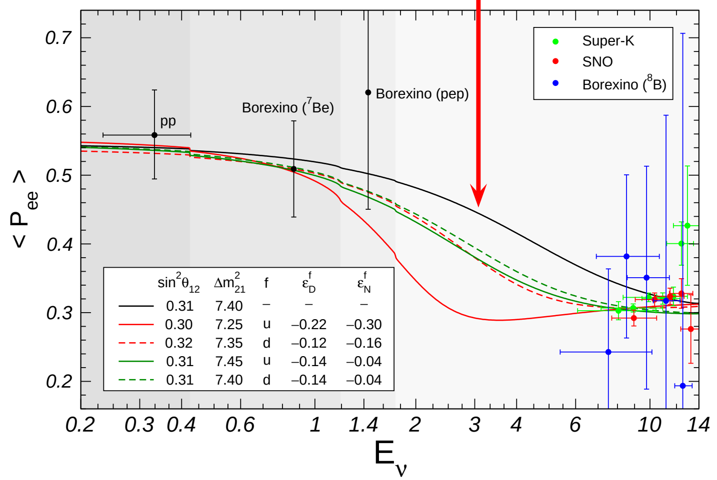
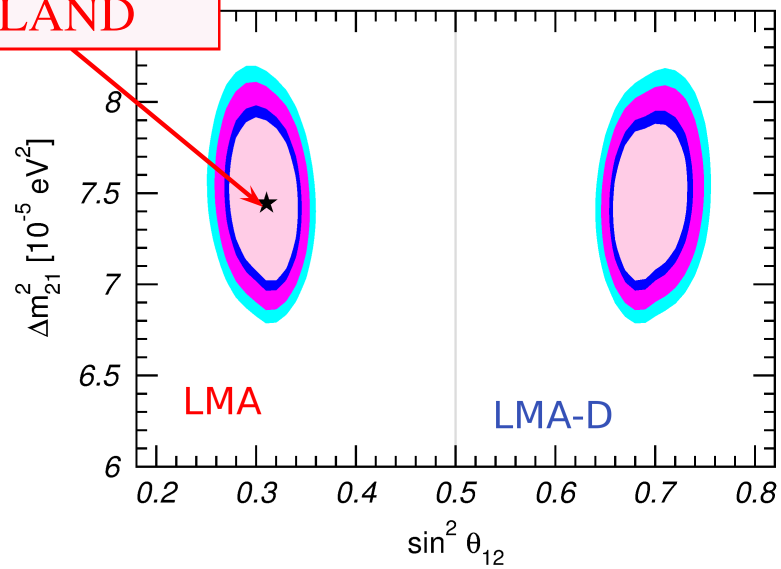


– Bounds $\mathcal{O}(1-10\%)$

– Except $\varepsilon_{ee} - \varepsilon_{\mu\mu}$

LMA: Improved fit
to Solar+KamLAND





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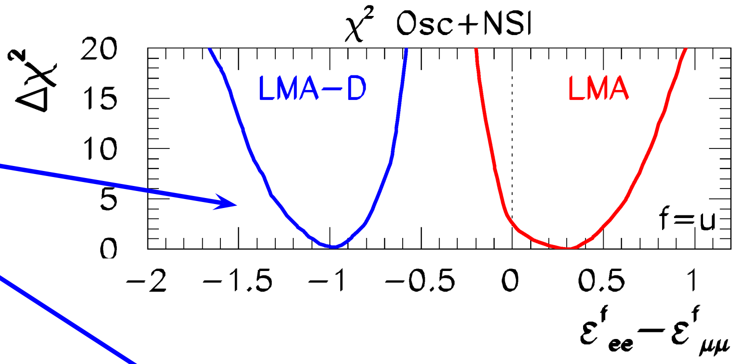


– Bounds $\mathcal{O}(1-10\%)$

Except [...]

Degenerate solution LMA-D ($\theta_{12} > 45°$)

Miranda,Tortola, Valle, hep-ph/0406280

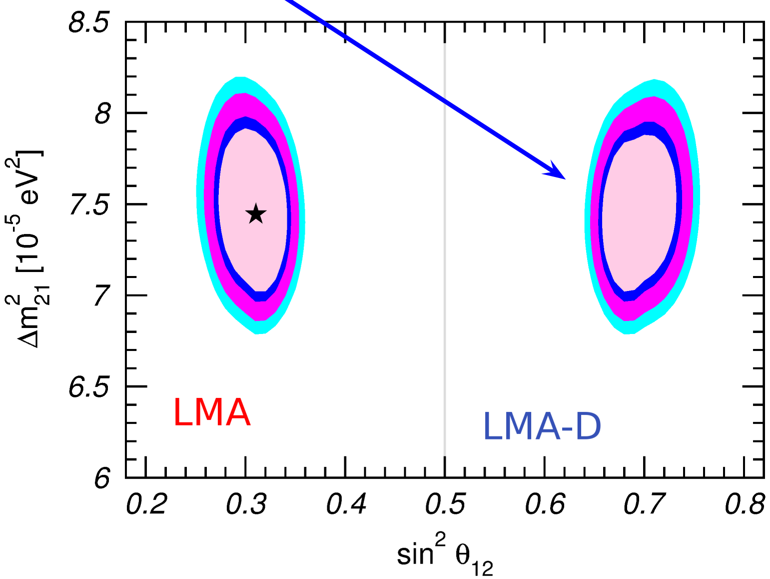
Cannot be resolved with osc-experiments

Requires NC scattering experiments

Coloma etal 1701.04828

Requires NSI $\sim G_F$ (light mediators?)

Farzan 1505.06906, and Shoemaker 1512.09147



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- Other NP at play? Large NSI interactions still allowed in ν oscillations

  But challenging model building
- Only three light states?

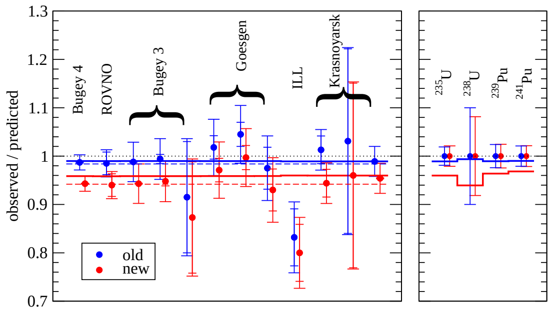
Beyond 3ν's: Light Sterile Neutrinos

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

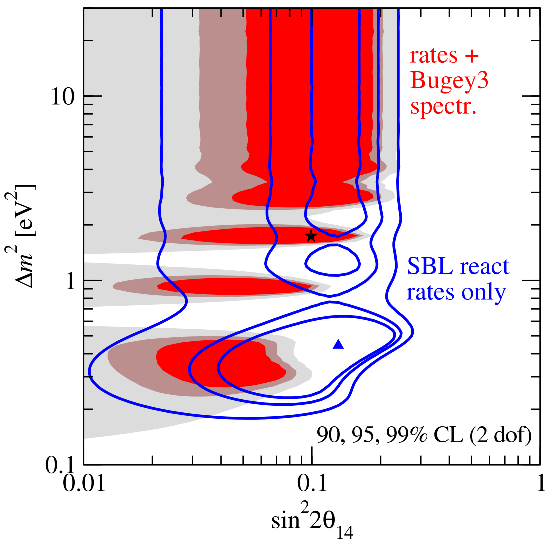
Reactor Anomaly

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

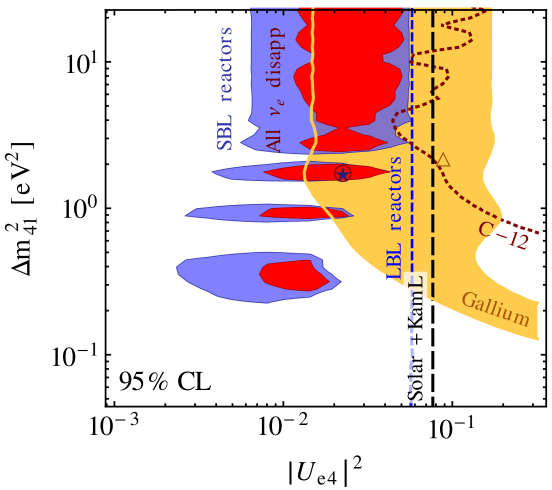
Radioactive Sources (^{51}Cr, ^{37}Ar) in calibration of Ga Solar Exp;

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

Give a rate lower than expected

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

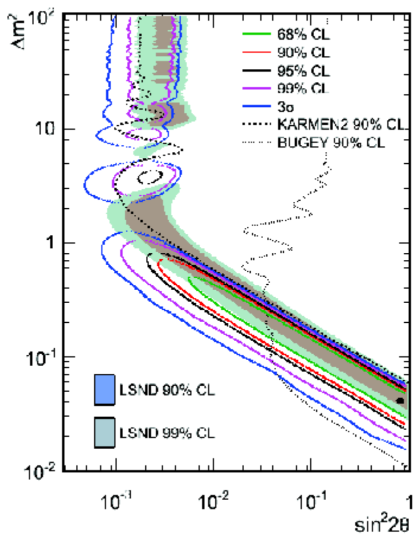
Explained as ν_e disappearance



Kopp etal, ArXiv 1303.3011

LSND, MiniBoone

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



Light Sterile Neutrinos

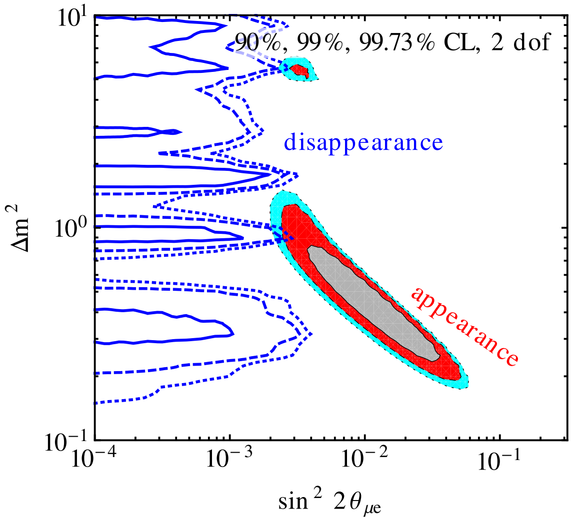
- These explanations require 3+N_s mass eigenstates $\rightarrow$ N_s sterile neutrinos

- 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,ICECUBE)

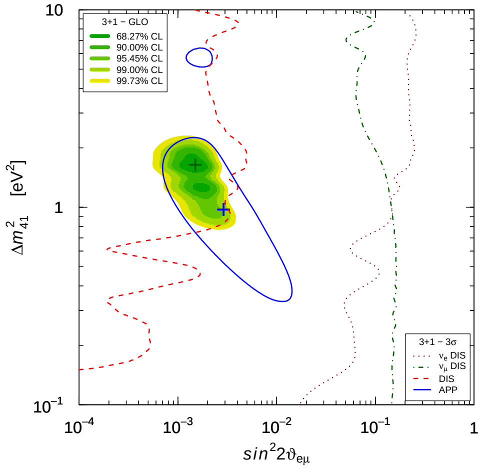
- Generically: $P(\nu_e \rightarrow \nu_\mu) \sim |U^*_{ei} U_{\mu i}|$ [i =heavier state(s)]

  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

Kopp etal, ArXiv 1303.3011

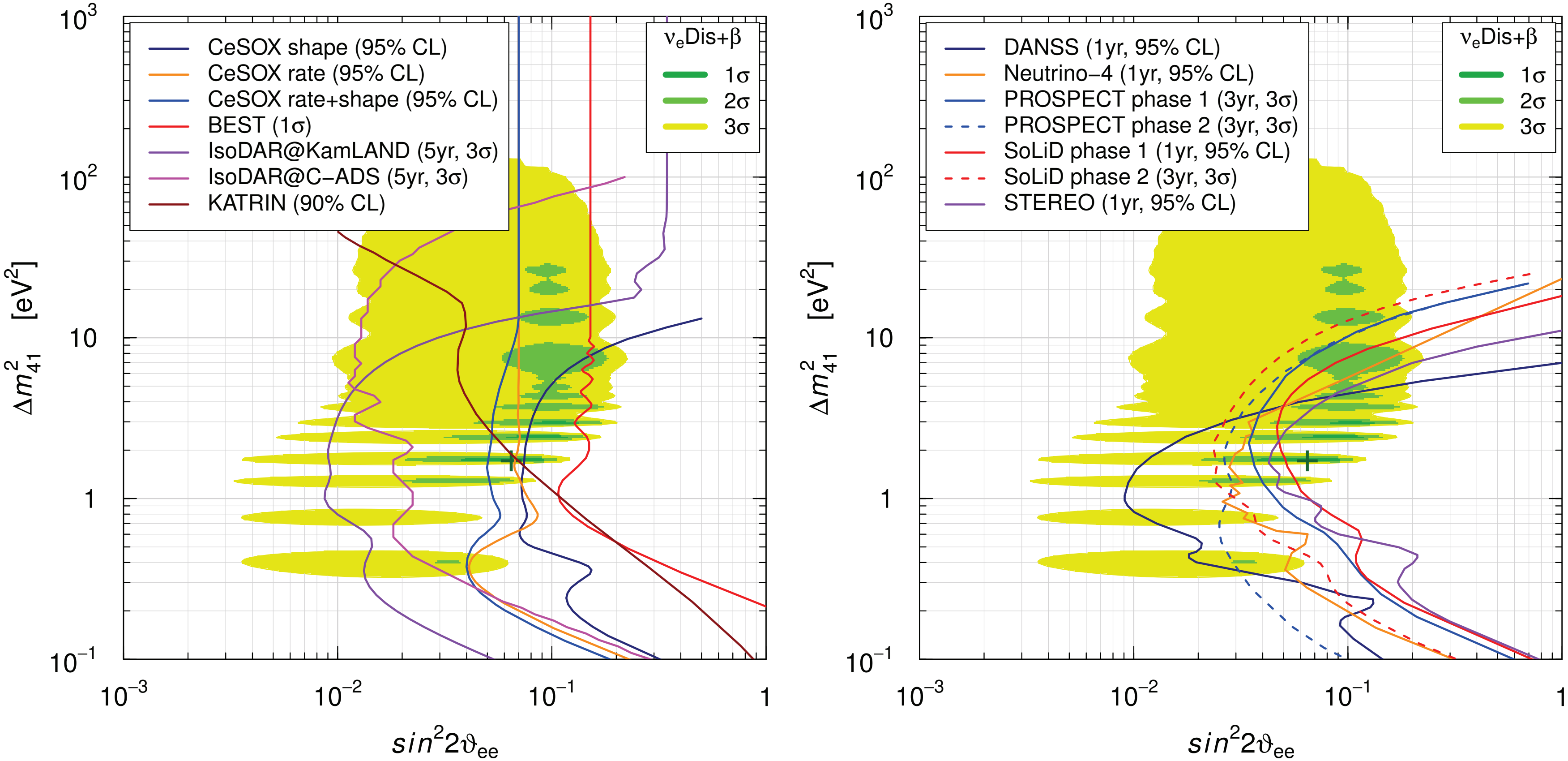


Giunti etal, ArXiv 1308.5288



- New generation of ν_e disappearance experiments $\Rightarrow$ adding to the tension

The Race for ν_e and $\bar{\nu}_e$ Disappearance



CeSOX (Gran Sasso, Italy) $^{144}\text{Ce} \to \bar{\nu}_e$
BOREXINO: $L \simeq$ 5-12m [Vivier@TAUP2015]

BEST (Baksan, Russia) $^{51}\text{Cr} \to \nu_e$
$L \simeq$ 5-12m [PRD 93 (2016) 073002]

IsoDAR@KamLAND (Kamioka, Japan)
$^{8}\text{Li} \to \bar{\nu}_e$ $L \simeq$ 16m [arXiv:1511.05130]

IsoDAR@C-ADS (Guangdong, China)
$^{8}\text{Li} \to \bar{\nu}_e$ $L \simeq$ 15m [JHEP 1601 (2016) 004]

DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]
Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]
SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

KATRIN (Karlsruhe, Germany) $^{3}\text{H} \to \bar{\nu}_e$ [Drexlin@NOW2016]

$\Rightarrow$ Fit with 3+N steriles severely disfavoured unless some data is dropped

Giunti etal 1703.00860

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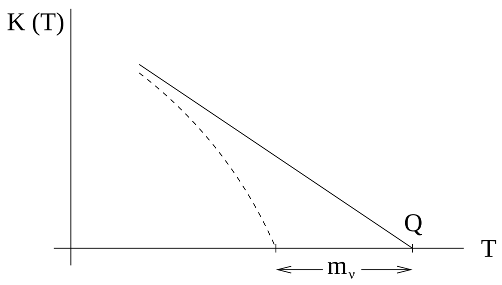
- Other NP at play? Large NSI interactions still allowed in ν oscillations
  But challenging model building
- Only three light states?
  Standing anomalies in app and disapp channels in severe tension with bounds
  New results from ν_e disappearance further disfavour $\mathcal{O}(\rm eV)$ ν_s interpretation
- Oscillations DO NOT determine the lightest mass
- Oscillations DO NOT distinguish Dirac/Majorana

Neutrino Mass Scale: β Decay

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



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

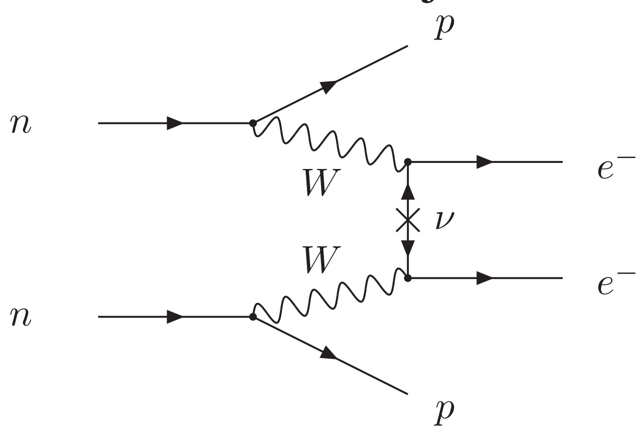
Present bound: $m_{\nu_e} \leq 2.2$ eV (at 95 % CL)

Katrin (201X???!!) Sensitivity to $m_{\nu_e} \sim 0.2\,\text{eV}$

Purely kinematics $\Rightarrow$ Only model independent probe ν-mass scale

Majorana or Dirac: $0\nu\beta\beta$ Decay

$0\nu\beta\beta \Rightarrow$ L violation $\Leftrightarrow$ Majorana ν



If m_ν only source of ΔL

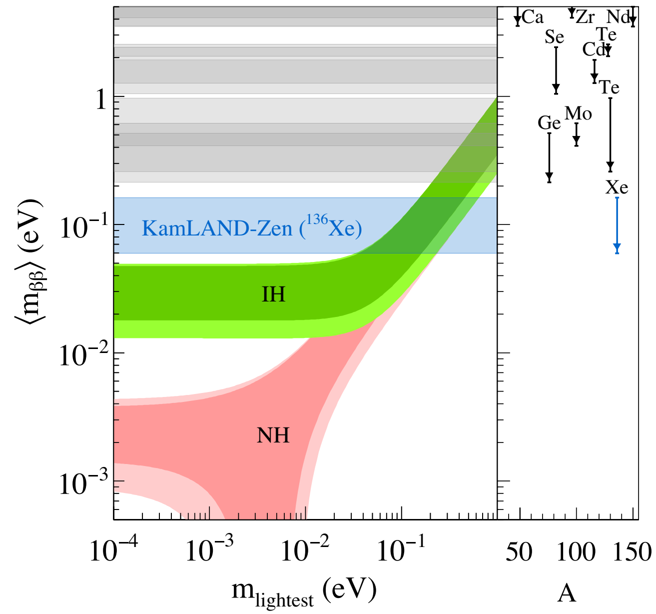
$$T_{1/2}^{0\nu} = \frac{m_e}{G_{0\nu}\, M_{\rm nucl}^2\, m_{ee}^2}$$

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

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

$= f(m_\ell$, order, maj phases$)$

At present only bounds from ^{136}Xe (EXO and KamLAND-ZEN) ^{76}Ge (Gerda) and ^{130}Te (Cuore-0)



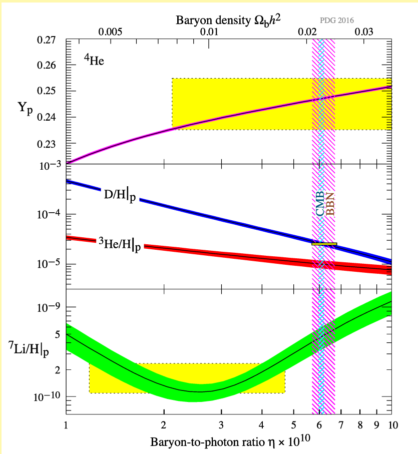
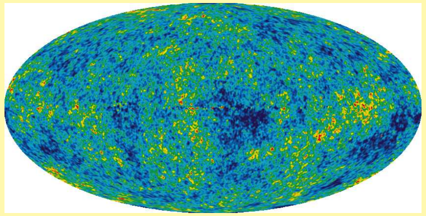
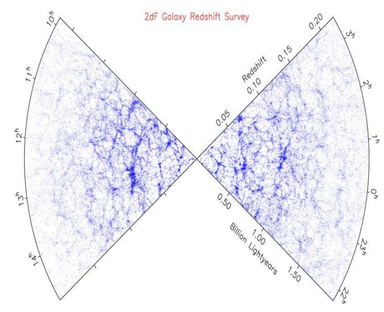
KamLAND-Zen Coll. ArXiv:1605.02889

$m_{ee} \lesssim 0.061 - 0.165$ (90% CL)

Light massive ν in Cosmology

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

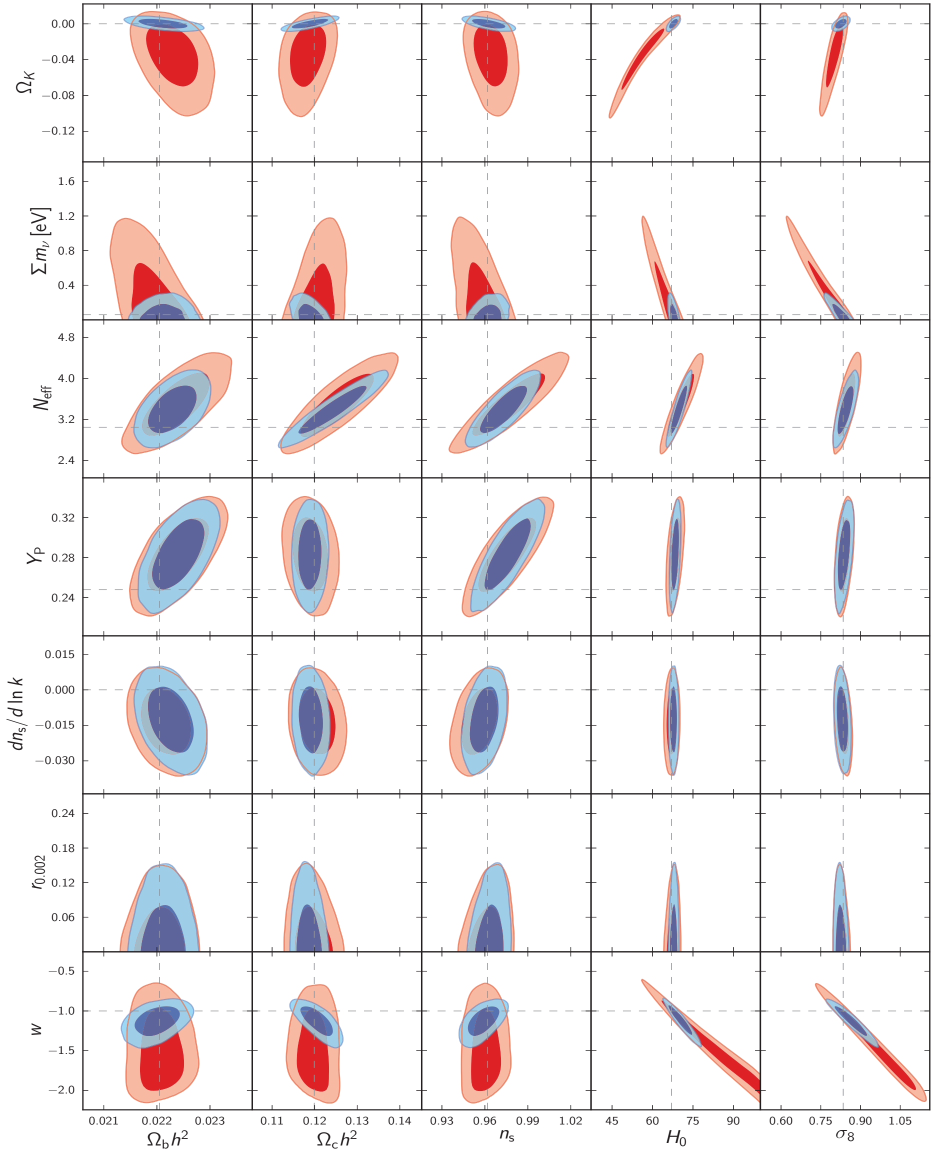
Mainly via two effects: $\rho_r = \left[1 + \frac{7}{8} \times \left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\text{eff}}\right] \rho_\gamma$ and $\sum_i m_{\nu_i}$

		
Primordial Nucleosynthesis BBN	Cosmic Microwave Background CMB	Large Scale Structure Formation LSS
$T \sim$ MeV	$T \lesssim$ eV	
Number of $\nu' s$ (N_{eff})	N_{eff} and $\sum m_\nu$	

BUT: Observables also depend on all other cosmo parameters (and assumptions)

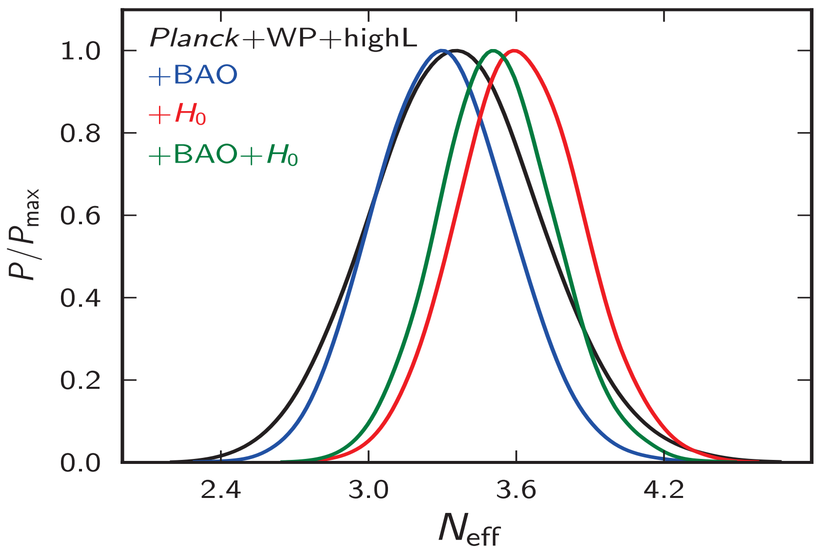
Example: Cosmological Analysis by Planck

arXiv:1502.01589



Range of Bounds in ΛCDM

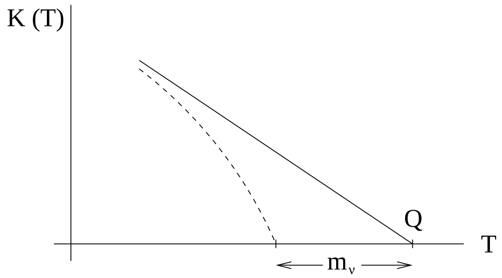
Model	Observables	Σm_ν (eV) 95%
$\Lambda\mathrm{CDM} + m_\nu$	Planck TT + lowP	≤ 0.72
$\Lambda\mathrm{CDM} + m_\nu$	Planck TT + lowP + lensing	≤ 0.68
$\Lambda\mathrm{CDM} + m_\nu$	Planck TT,TE,EE + lowP+lensing	≤ 0.59
$\Lambda\mathrm{CDM} + m_\nu$	Planck TT,TE,EE + lowP	≤ 0.49
$\Lambda\mathrm{CDM} + m_\nu$	Planck TT + lowP + lensing + BAO + SN + H_0	≤ 0.23
$\Lambda\mathrm{CDM} + m_\nu$	Planck TT,TE,EE + lowP+ BAO	≤ 0.17



Neutrino Mass Scale

Concha Gonzalez-Garcia

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

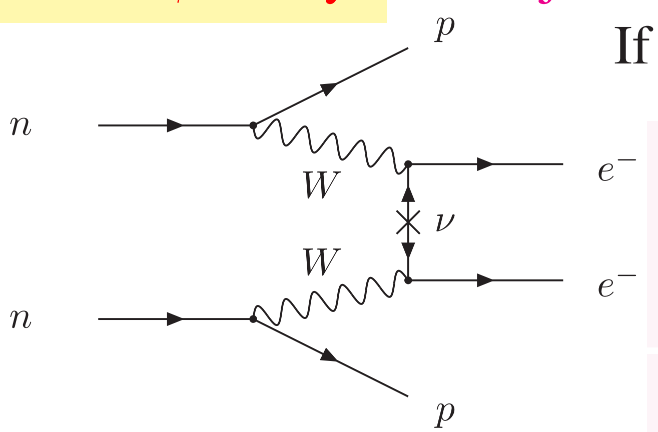


$$m^2_{\nu_e} = \sum m_j^2 |U_{ej}|^2 = \begin{cases} \text{NO}: \; m_\ell^2 + \Delta m^2_{21} c^2_{13} s^2_{12} + \Delta m^2_{31} s^2_{13} \\ \text{IO}: \; m_\ell^2 + \Delta m^2_{21} c^2_{13} s^2_{12} - \Delta m^2_{31} c^2_{13} \end{cases}$$

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

Katrin (20XX???) Sensitivity to $m_{\nu_e} \sim 0.2$ eV

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



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

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

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

$$= f(m_\ell, \text{order}, \text{maj phases})$$

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

COSMO for Dirac or Majorana m_ν affect growth of structures

$$\sum m_i = \begin{cases} \text{NO}: \; \sqrt{m_\ell^2} + \sqrt{\Delta m^2_{21} + m^2_\ell} + \sqrt{\Delta m^2_{31} + m^2_\ell} \\ \text{IO} \; \sqrt{m^2_\ell} + \sqrt{-\Delta m^2_{31} - \Delta m^2_{21} - m^2_\ell} + \sqrt{-\Delta m^2_{31} - m^2_\ell} \end{cases}$$

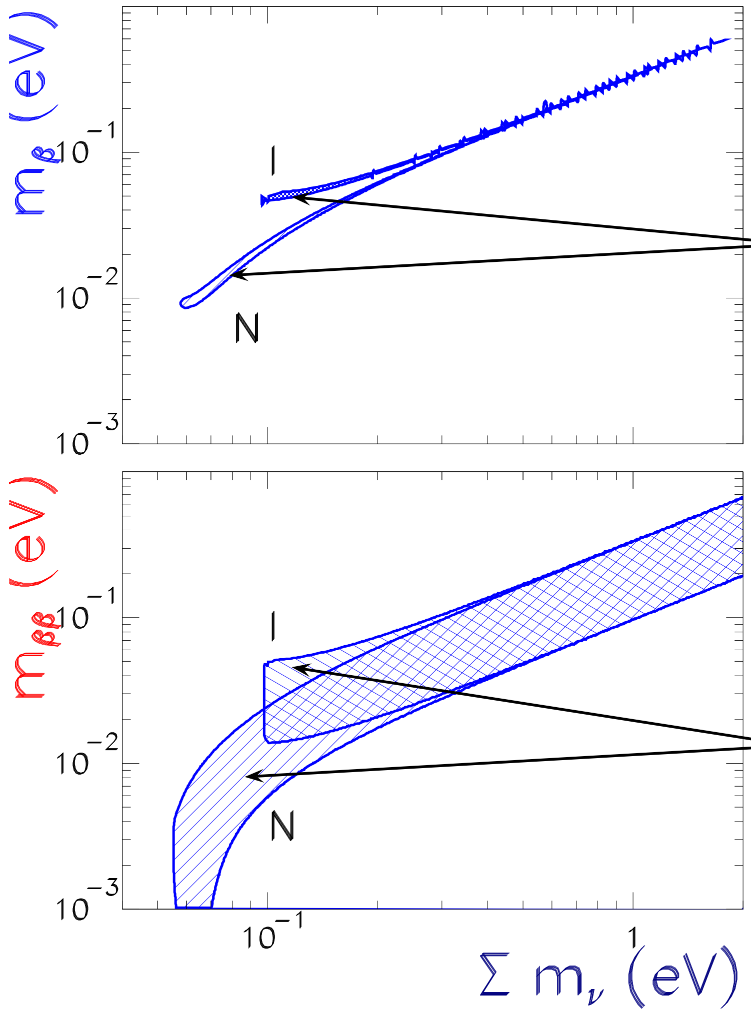
Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis

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

(Fogli *et al* (04))

Nufit (95%)



Width due to range in oscillation parameters very narrow

Lower bound on $\sum m_i$ depends on ordering

Wide band due to unknown Majorana phases $\Rightarrow$

Possible Det of Maj phases?

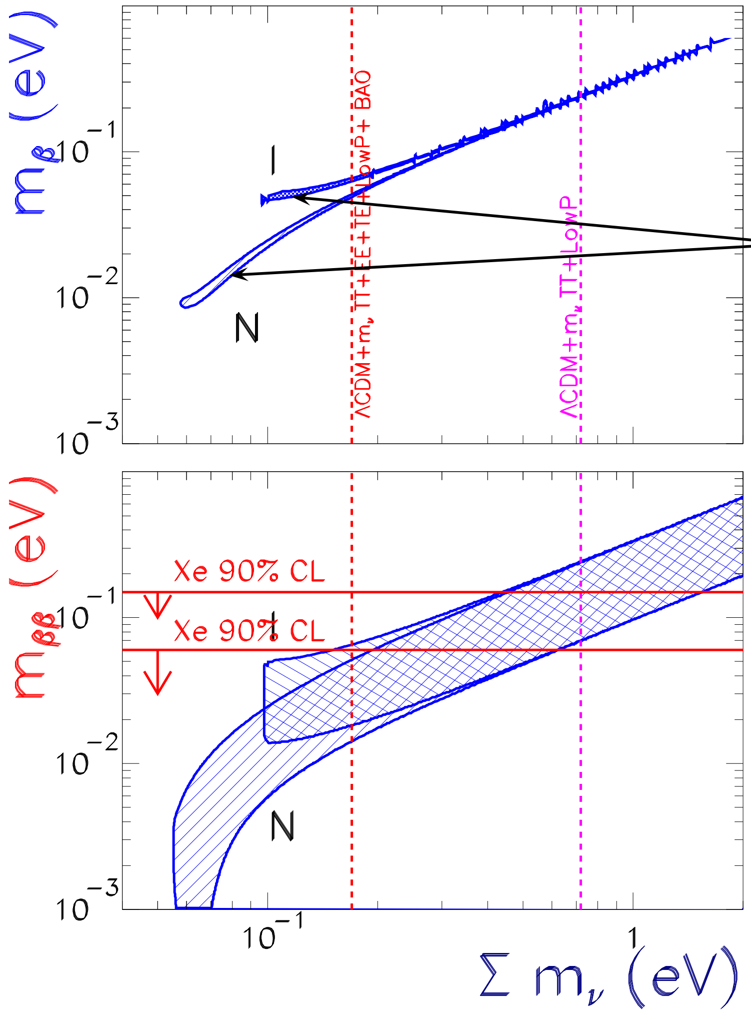
Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis

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

(Fogli *et al* (04))

Nufit (95%)



Lower bound on $\sum m_i$ depends on ordering

Precision determination/bound of $\sum m_i$ can give information on ordering ?

Hannestad, Schwetz 1606.04691, Simpson etal 1703.03425, Capozzi etal 1703.04471 …

Or much ado about nothing?

Cosmo data will only add to N/I likelihood when accuracy on Σm_ν better than 0.02 eV (to see a 2σ N/I difference between 0.06 and 0.1)

Hannestad, Schwetz 1606.04691

Confirmed Low Energy Picture and MY List of Q&A

- At least two neutrinos are massive ⇒ There is NP
- Three mixing angles are non-zero (and relatively large) ⇒ very different from CKM
- Leptonic CP: Best fit $J_{\rm Lep,CP} = -0.033$. CP conservation at 70% CL
  Significance likely to grow slowly with present experiments
- Ordering: No significant preference in our global fit
  Requires new oscillation experiments
- Other NP at play? Large NSI interactions still allowed in ν oscillations
  But challenging model building
- Only three light states?
  Standing anomalies in app and disapp channels in severe tension with bounds
  New results from ν_e disappearance further disfavour $\mathcal{O}(\rm eV)$ ν_s interpretation
- Oscillations DO NOT determine the lightest mass
  Only model independent probe of m_ν β decay: $\sum m_i^2 |U_{ei}|^2 \leq (2.2 \text{ eV})^2$
  Anxiously waiting for Katrin
- Dirac or Majorana?: We do not know, *anxiously* waiting for ν-less $\beta\beta$ decay
- Cosmological effects?: Still missing a “signal” and will we ever be convinced it is $\nu' s$?

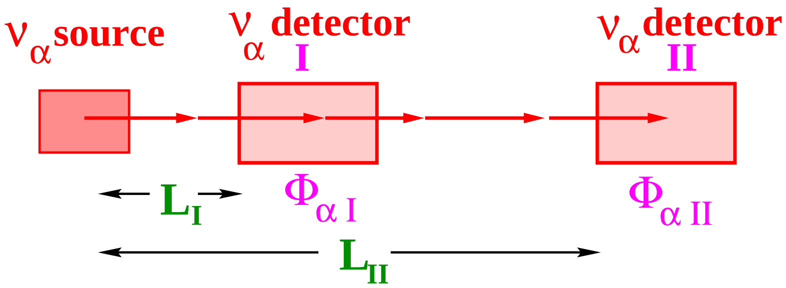
THANK YOU

Back-up Slides

ν Oscillations: Experimental Probes

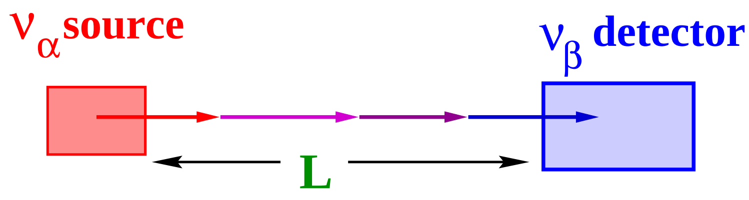
- Generically there are two types of experiments to search for ν oscillations :

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

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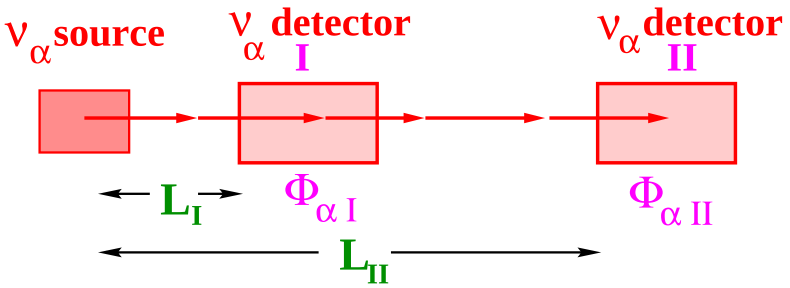

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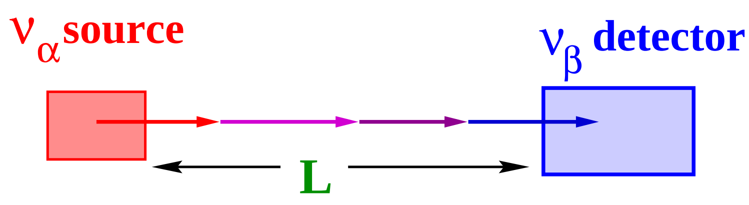
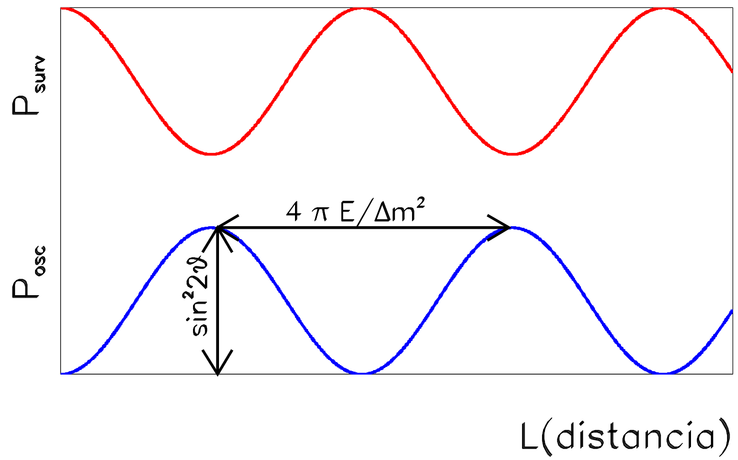


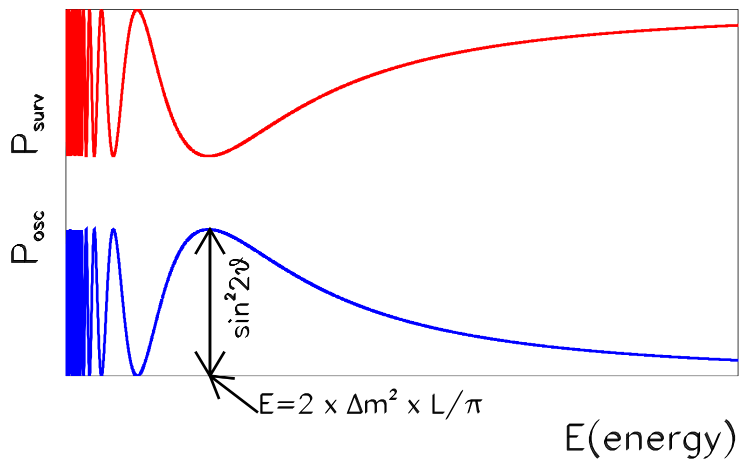
Searches for β diff α

• To detect oscillations we can study the neutrino flavour

as function of the Distance to the source



As function of the neutrino Energy



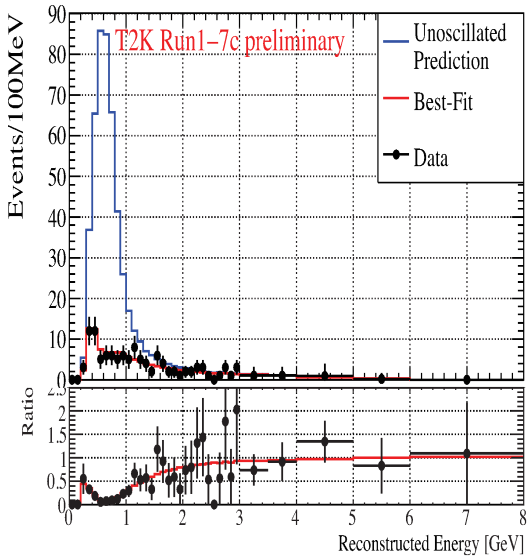
3 ν Analysis: θ_{23}

- Best determined in ν_μ and $\bar\nu_\mu$ disapperance in LBL

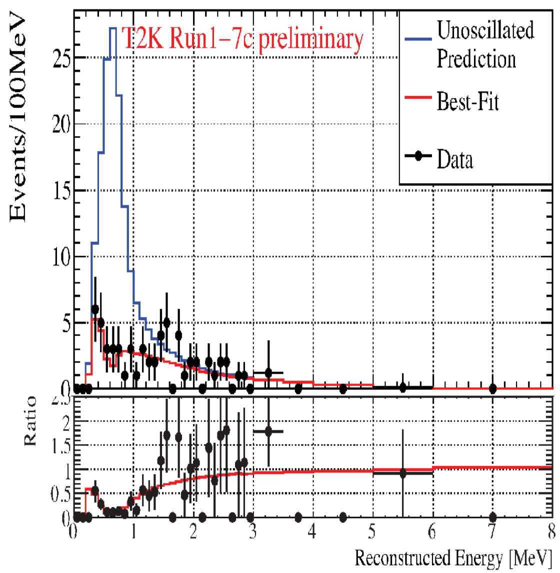
$$P_{\mu\mu} \simeq 1 - (c_{13}^4 \sin^2 2\theta_{23} + s_{23}^2 \sin^2 2\theta_{13}) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + \mathcal{O}(\Delta m_{21}^2)$$

- At osc maximum $\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) = 1 \Rightarrow P_{\mu\mu} \simeq 0$ for $\theta_{23} \simeq \frac{\pi}{4}$

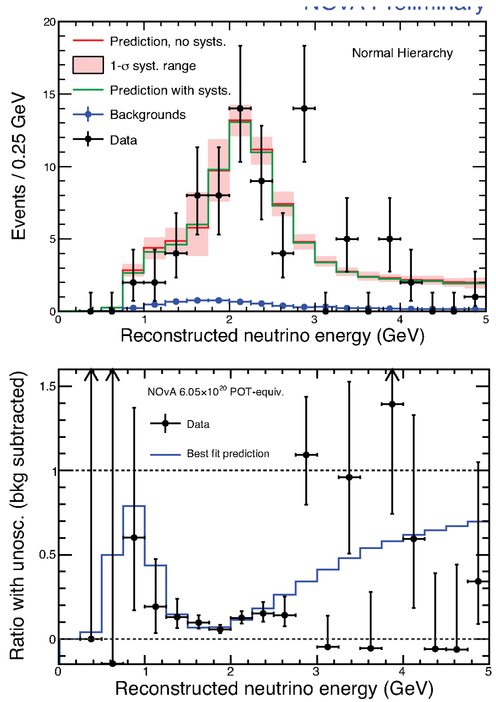
T2K $\nu_\mu \to \nu_\mu$



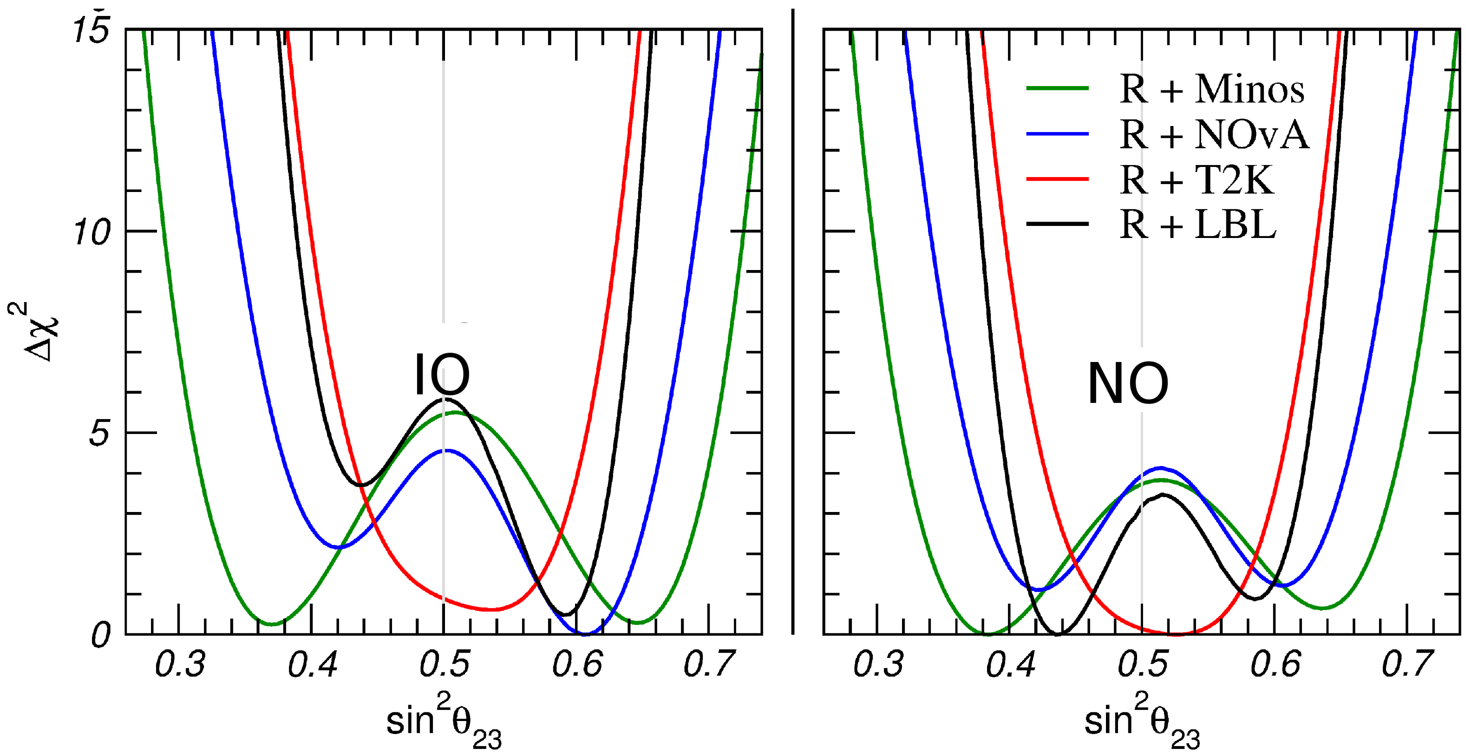
T2K $\bar\nu_\mu \to \bar\nu_\mu$



NOvA $\nu_\mu \to \nu_\mu$



Ordering and θ_{23}



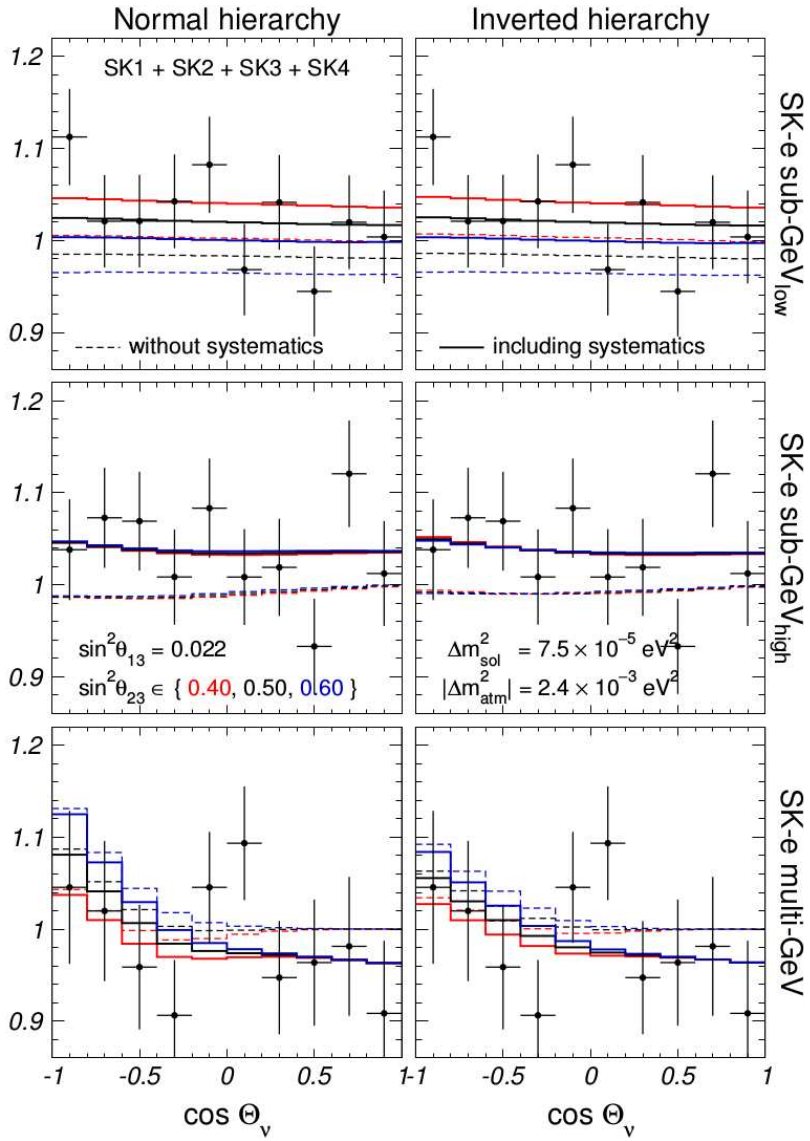
– Favoured Octant of θ_{23} depends on ordering – CL of maximal mixing at 91%(NO) 98% (IO)

3 ν Analysis: Ordering, $\delta_{\rm CP}$ in ATM

- For $\theta_{31} \neq 0$ ATM sensitivity to octant θ_{23} & ordering & $\delta_{\rm CP}$

$$\frac{N_e}{N_e^0} - 1 \simeq (\bar r\, c_{23}^2 - 1) P_{2\nu}(\Delta m^2_{21}, \theta_{12}) \quad [\Delta m^2_{21} \text{ term}]$$
$$+(\bar r\, s_{23}^2 - 1) P_{2\nu}(\Delta m^2_{31}, \theta_{13}) \quad [\theta_{13} \text{ term}]$$
$$-2\bar r\, s_{13} s_{23} c_{23} Re(A^*_{ee} A_{\mu e}) \quad [\delta_{CP} \text{ term}]$$

$$\bar r \equiv \Phi^0_\mu / \Phi^0_e \simeq 2(\text{subG}),\ 2.6\text{–}4.6(\text{multiG})$$



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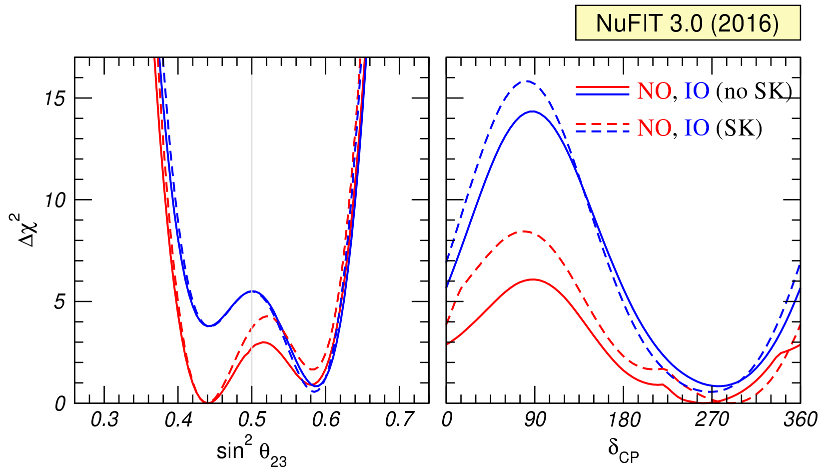
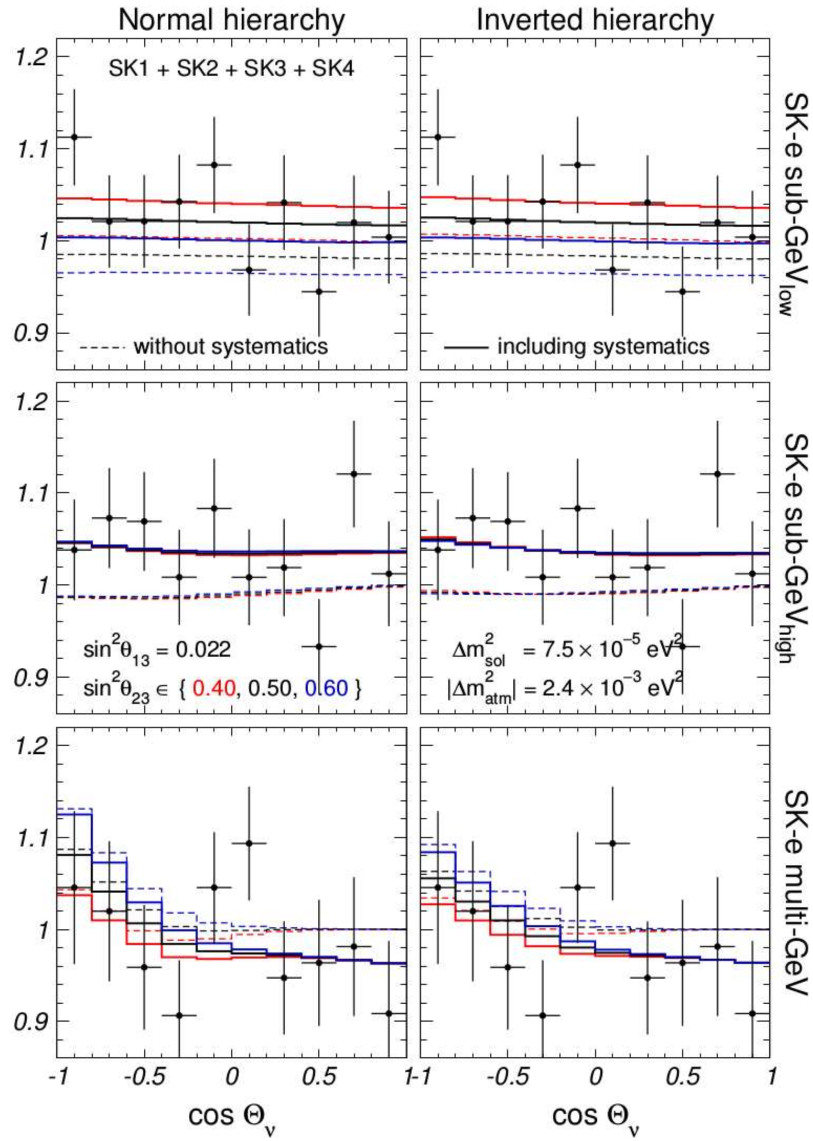
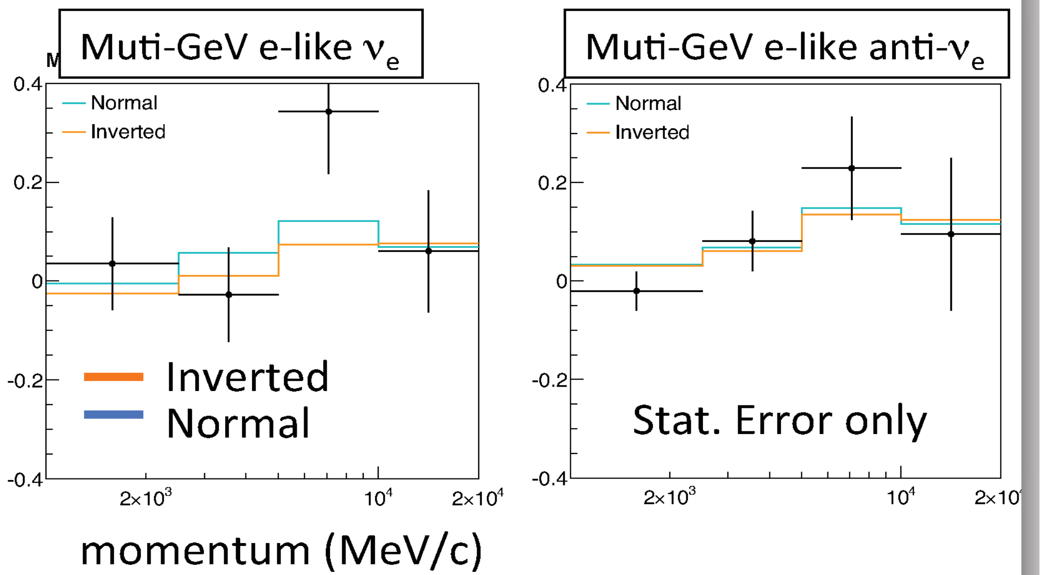
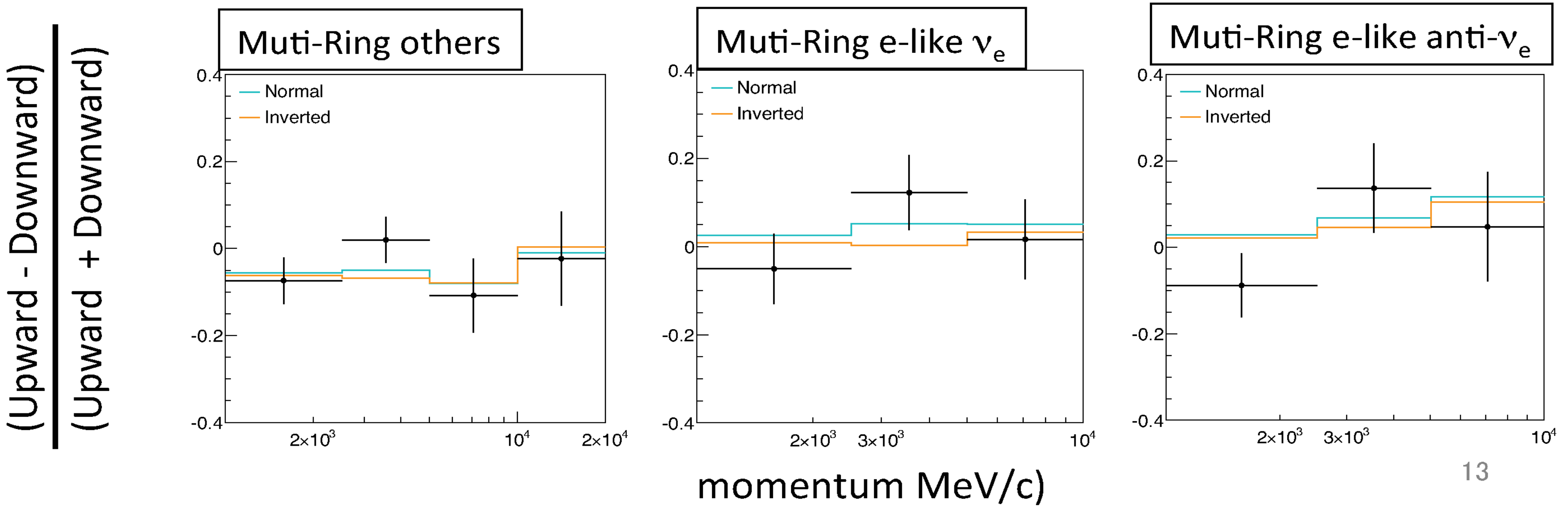




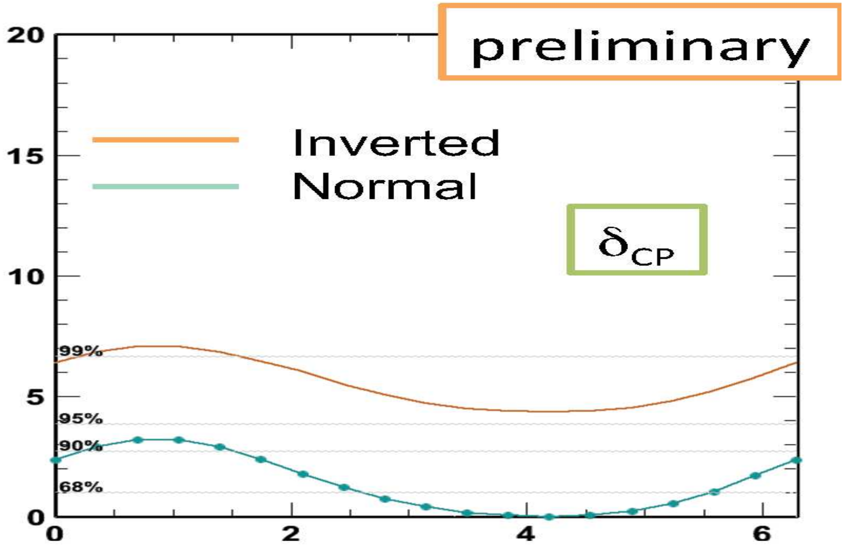
- **Normal** hierarchy favored at:
  - $\chi^2_{NH} - \chi^2_{IH} =$ **-4.3**
    (-3.1 expected)
- Driven by excess of upward-going e-like events:
  - Primarily in SK-IV data
  - consistent with the effects of θ_{13} driven ν oscillation.

Upward/Downward asymmetry in energetic electron samples (νe/anti-νe enriched)





J. Kameda (SK) talk at Nufact 2016



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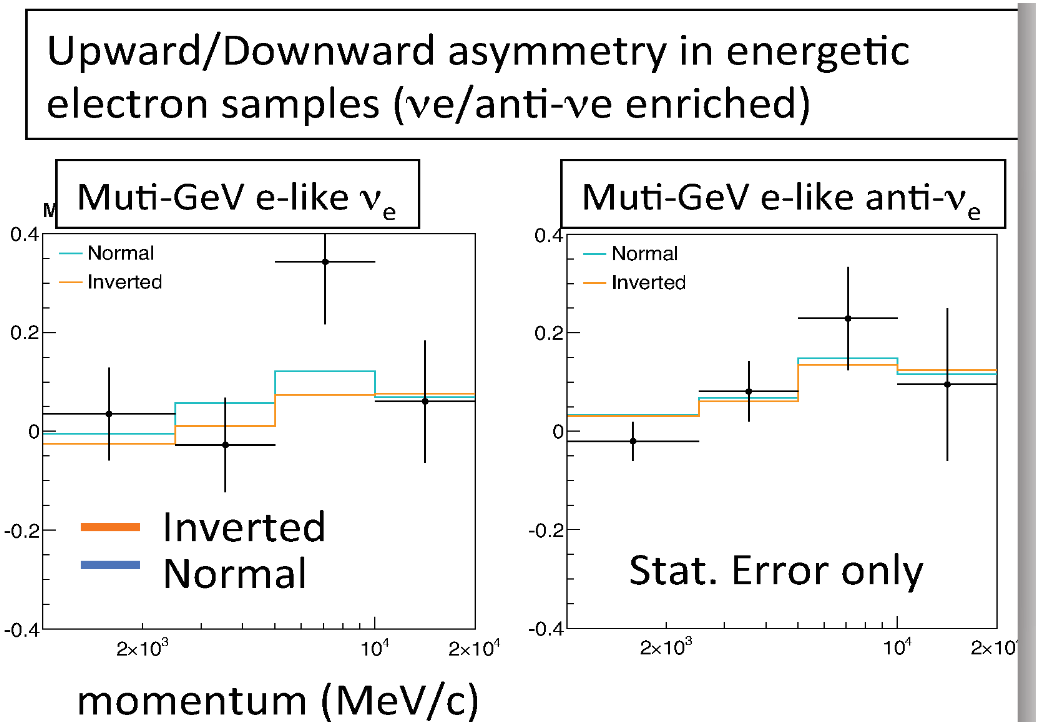
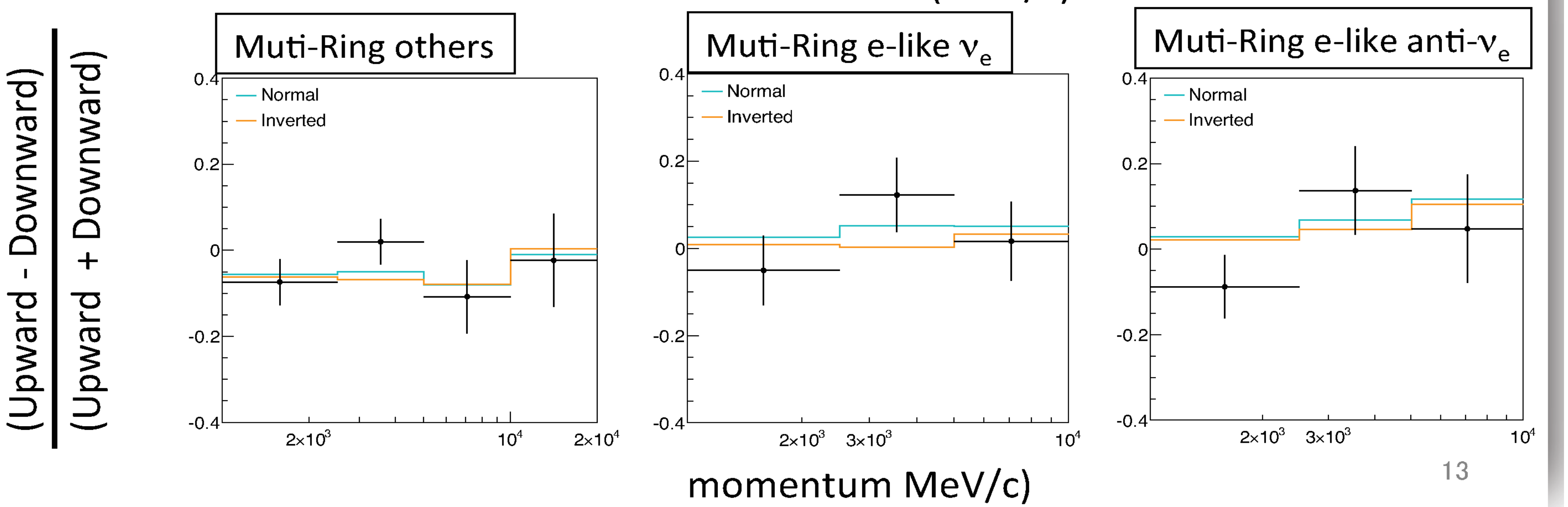
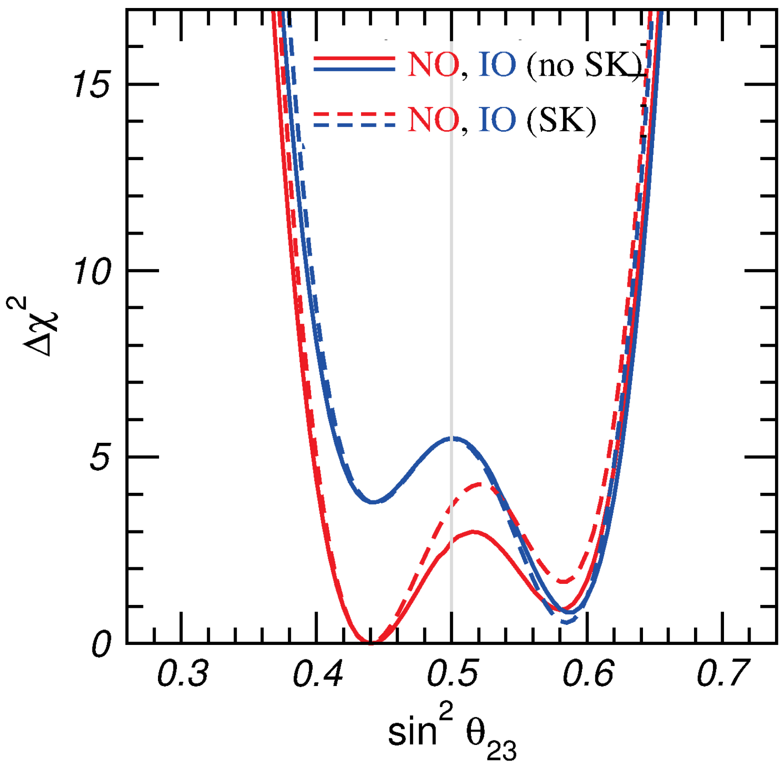




J. Kameda (SK) talk at Nufact 2016

Comparison with Bari group

NuFIT 3.0, Esteban et al., 1611.01514



Cappozzi et al., 1703.04471

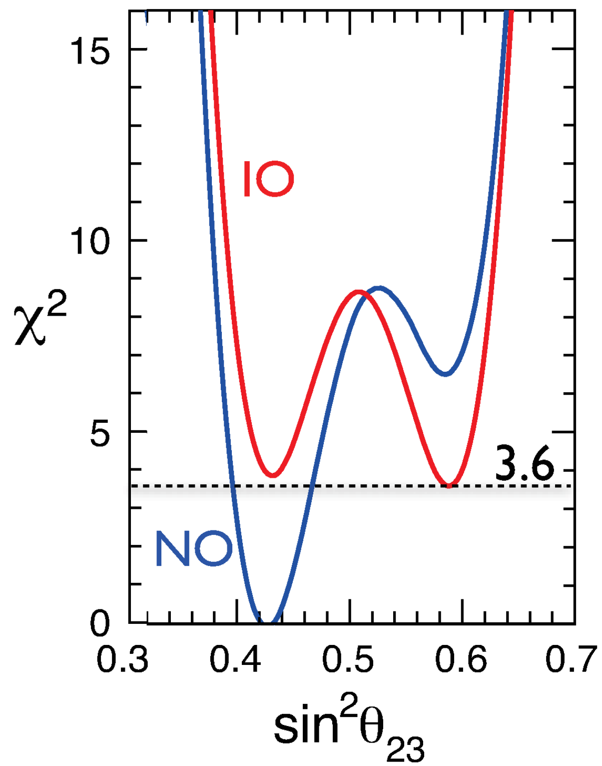


Figure display "borrowed" from T. Schwetz Moriond 17 talk

Main Difference in ATM sensitivity

Both groups use the same reduced number of atm data subsamples

Using these data subsamples SK never found a $\theta_{13} \neq 0$ effect

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 $K_{L,3\times 3}$ (not unitary)
- But this unitarity violation $\Rightarrow$ Flavour Changing Neutral Currents
  Flavour Violation in Charged Lepton Processes
  Universality Violation of Charge Current ...
- Constraints on these processes limit leptonic unitarity violation to

$$|K_l K_l^\dagger| = \begin{pmatrix} 0.9979 - 0.9998 & < 10^{-5} & < 0.0021 \\ < 10^{-5} & 0.9996 - 1.0 & < 0.0008 \\ < 0.0021 & < 0.0008 & 0.9947 - 1.0 \end{pmatrix}$$

Antusch *et al* ArXiv:1407.6607

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

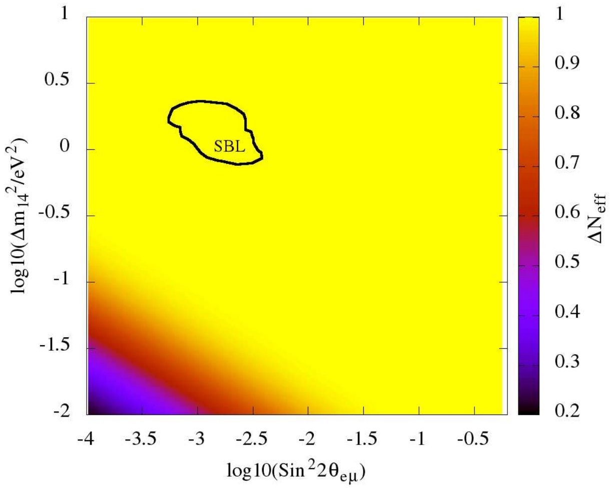
Mixed Light Sterile Neutrinos in Cosmology

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

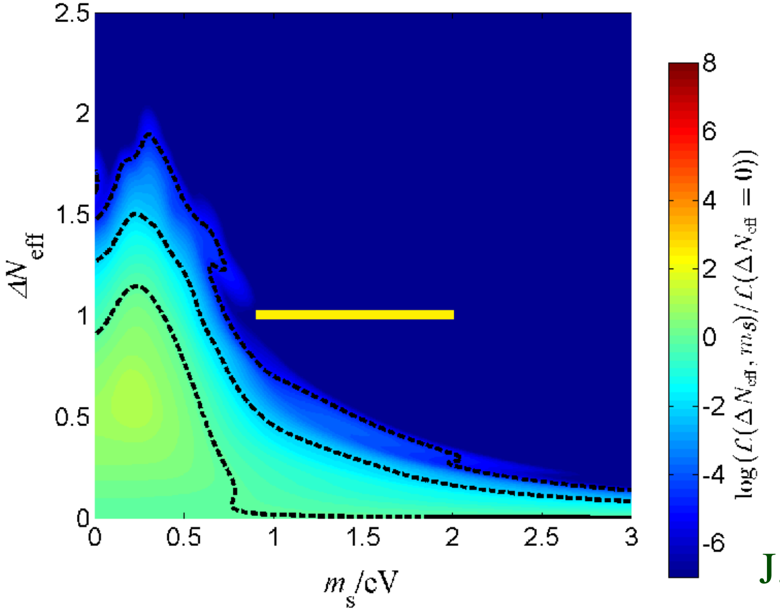
$\Rightarrow$ So if "explaination" to SBL anomalies

1 ν_s contributes as much as 1 ν_a



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

Plank+WP+high-l+BAO



J. Bergstrom, etal, ArXiv:1407.3806

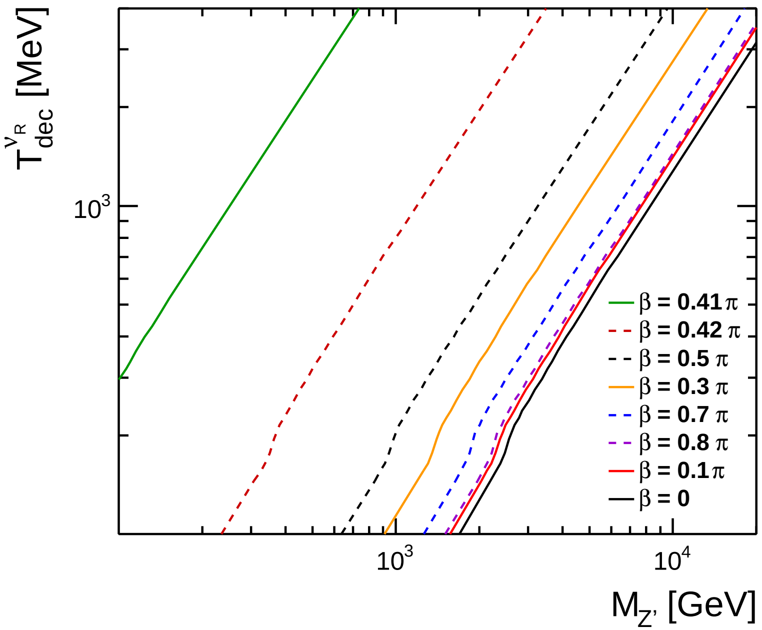
Light Sterile $\nu's$ in Cosmology and New Interactions

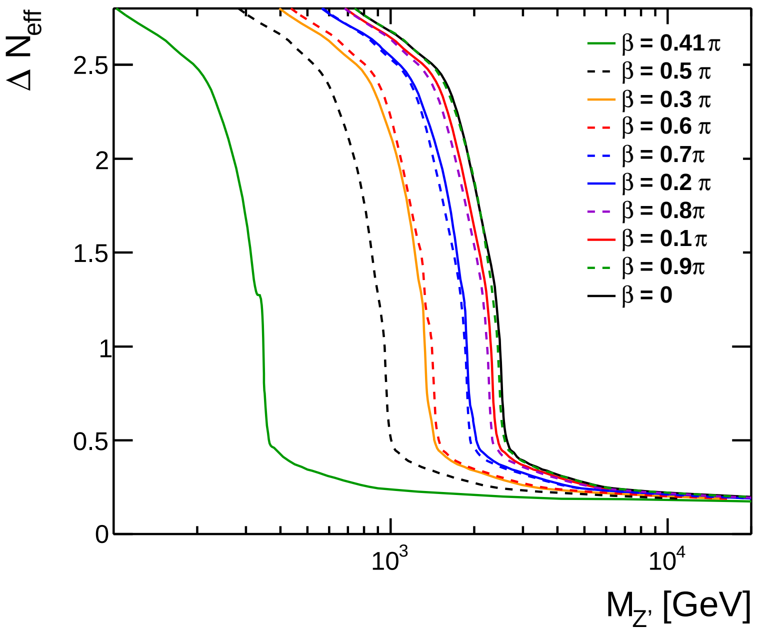
- In string inspired E_6 models, 3 light ν_R's with new interactions

$$(Z' \text{ with coupling } Y_{Z'}^{\nu_R} = \cos\beta \frac{5}{\sqrt{40}} - \frac{1}{\sqrt{24}} \sin\beta)$$

- In these scenarios $\Delta N_{\rm eff} = 3 \times \left(\frac{T_{\nu_R}}{T_{\nu_L}}\right)^4 = 3 \times \left(\frac{g(T^{\rm dec}_{\nu_R})}{g(T^{\rm dec}_{\nu_R})}\right)^{\frac{4}{3}}$

Determined by $\sigma(\bar\nu_R \nu_R \to \bar f f)$ mediated by Z' (ie $M_{Z'}$ and coupling parameter β)





A. Solaguren-Beascoa, MCG-G
arXiv:1210.6350

⇒ Interplay between cosmological determination of $\Delta N_{\rm eff}$ and Z' LHC searches