NEUTRINO MASSES AND MIXING: A LITTLE HISTORY FOR A LOT OF FUN

Concha Gonzalez-Garcia

(ICREA U. Barcelona & YITP Stony Brook)

History of the Neutrino, Paris Sept 2018

νfit Global fit to neutrino oscillation data

elusiνes
neutrinos, dark matter & dark energ

inνisiblesPlus
neutrinos, dark matter & dark energy physics

- By 2018 we have observed with high (or good) precision:

  $\ast$ Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK**,MINOS, ICECUBE)

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  $\ast$ Some accelerator ν_μ appear as ν_e at $L \sim 300/800$ Km (**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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- The *starting* path:

  Precise determination of the low energy parametrization

The New Minimal Standard Model

- Minimal Extension to allow for LFV ⇒ give Mass to the Neutrino

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

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

  - $*$ NOT impose L conservation ⇒ 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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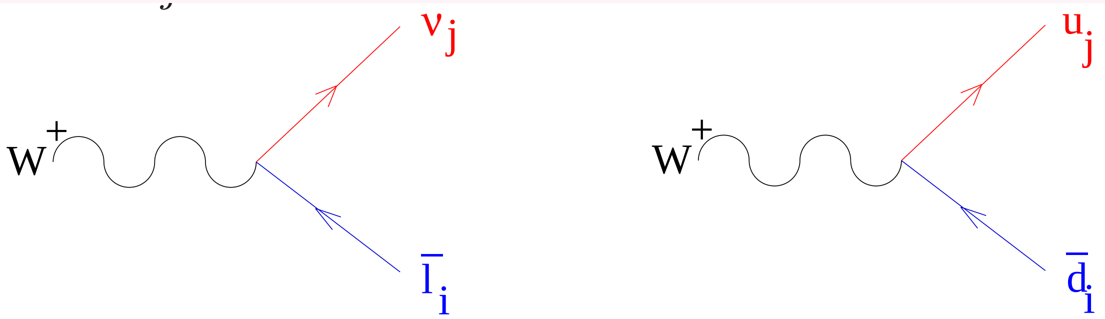
- The charged current interactions of leptons are not diagonal (same as quarks)

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



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

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

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

The New Minimal Standard Model

- Minimal Extension to allow for LFV $\Rightarrow$ give Mass to the Neutrino

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

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$\Rightarrow$ Flavour Oscillations:

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

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

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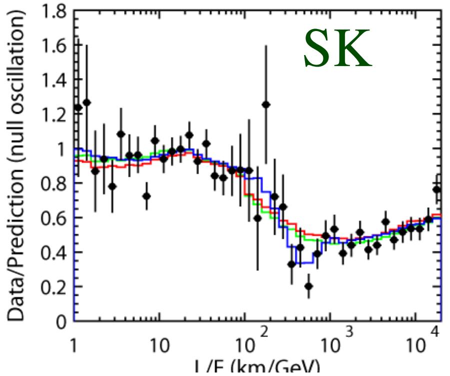
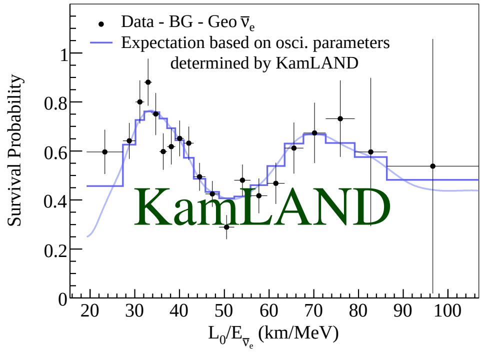
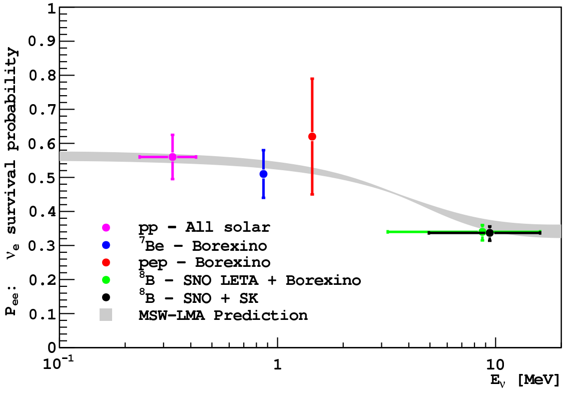
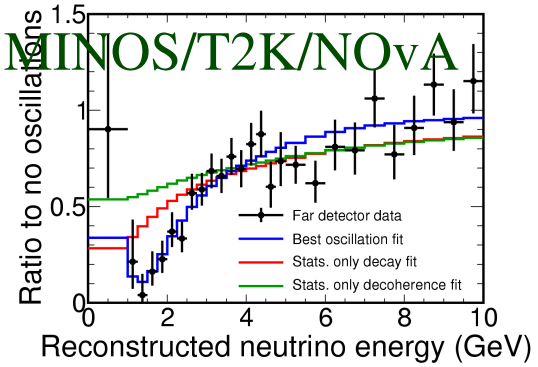
- Confirmed: Vacuum oscillation L/E pattern with 2 frequencies

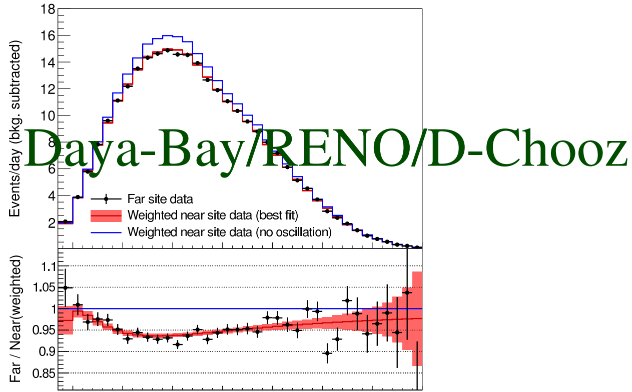
MSW conversion in Sun









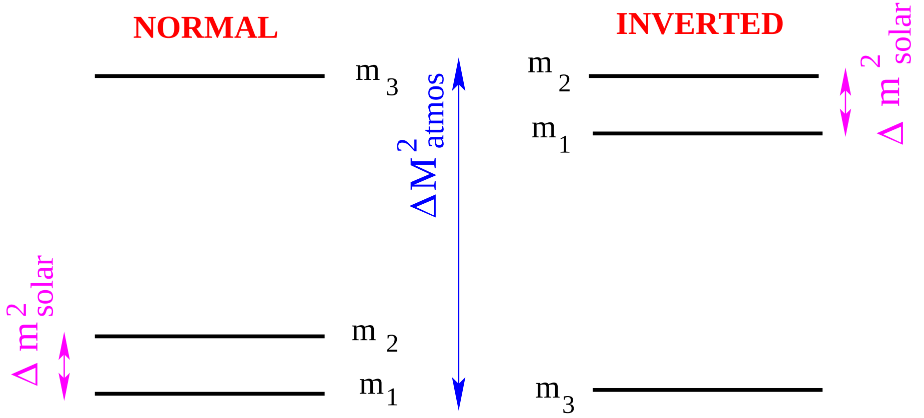


3ν Flavour Parameters

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

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

- Two Possible Orderings

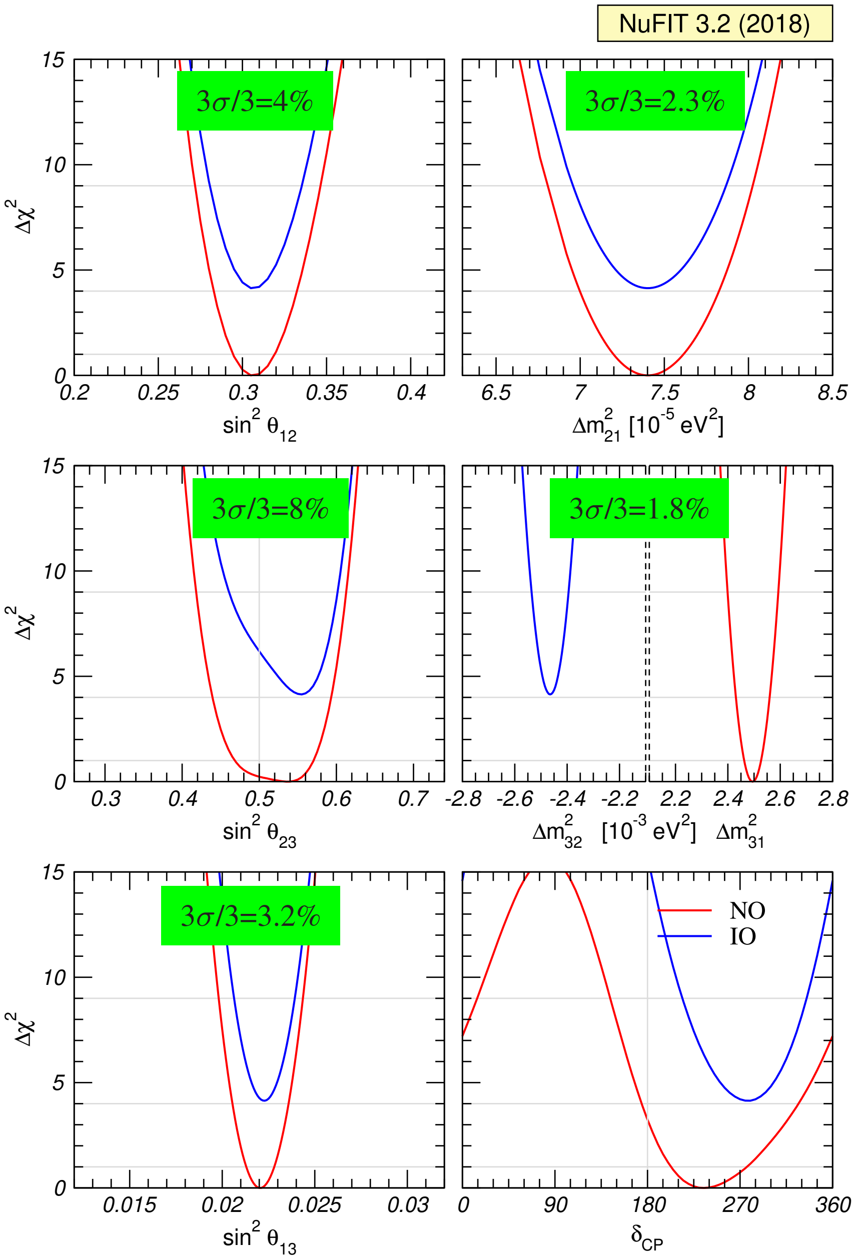


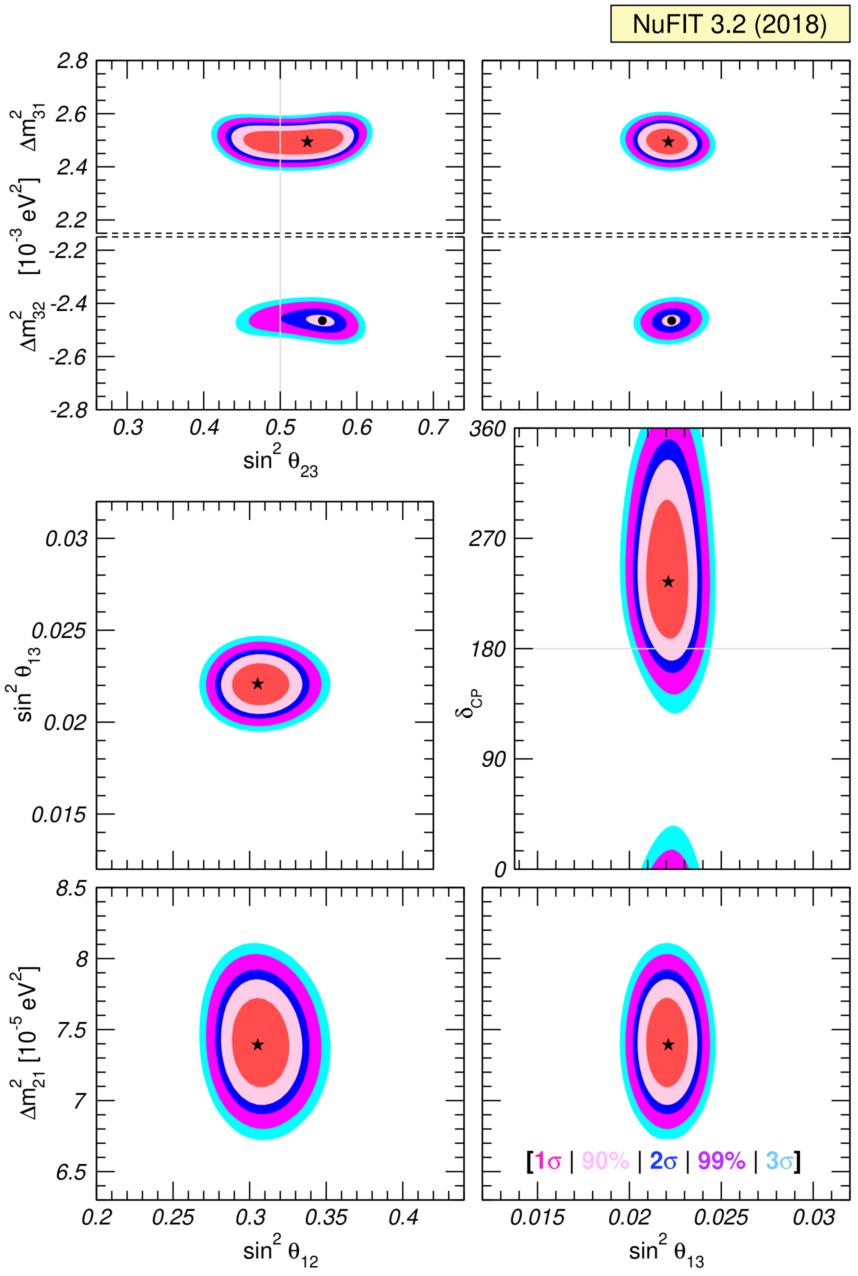
Experiment	Dominant Dependence	Important Dependence
Solar Experiments	$\to \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\to \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	$\to \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\to \theta_{23}$	$\Delta m^2_{\rm atm}$, 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 June 2018

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

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





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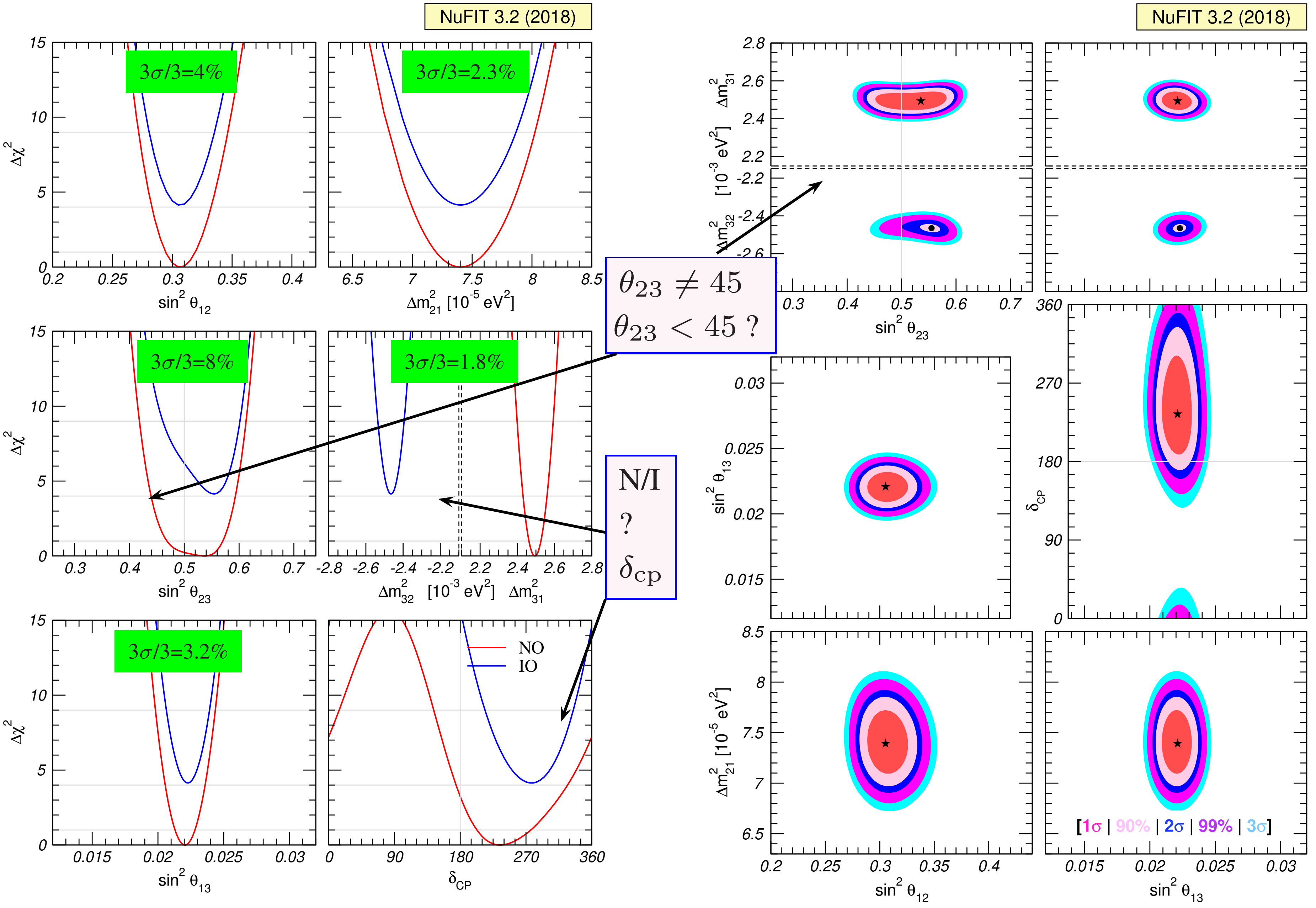


$\theta_{23} \neq 45$

$\theta_{23} < 45$?

N/I

?

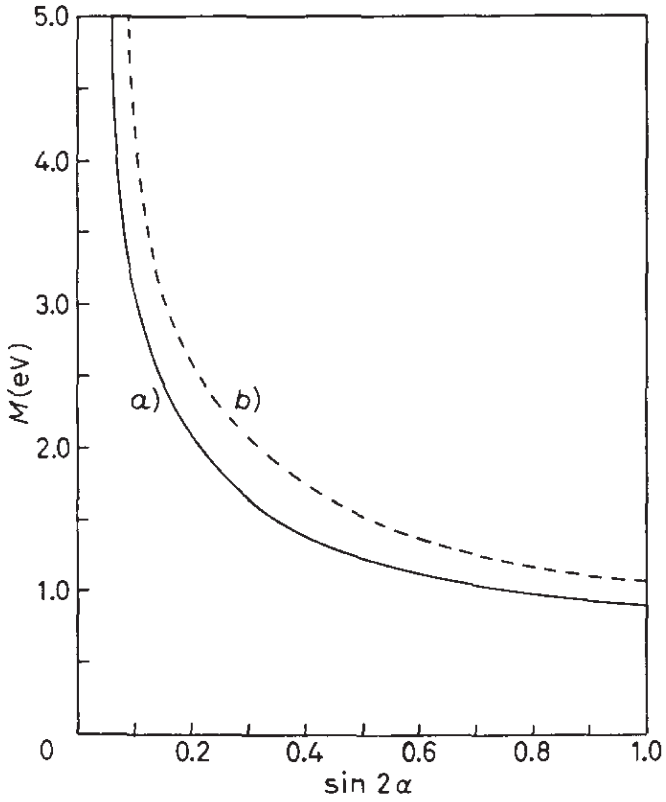
$\delta_{\rm cp}$

Early Neutrino Parameter Plots

- The First?

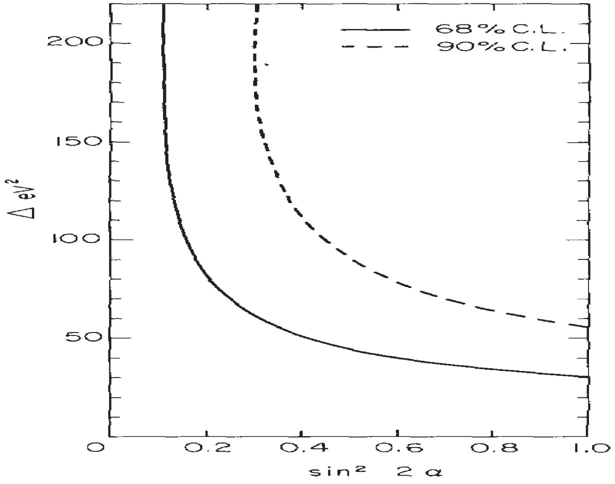
Data From Gargamelle $\nu_\mu \to \nu_e$

Belloti, Cavalli, Fiorini, Rollier, Nov. Cim. Dec 76

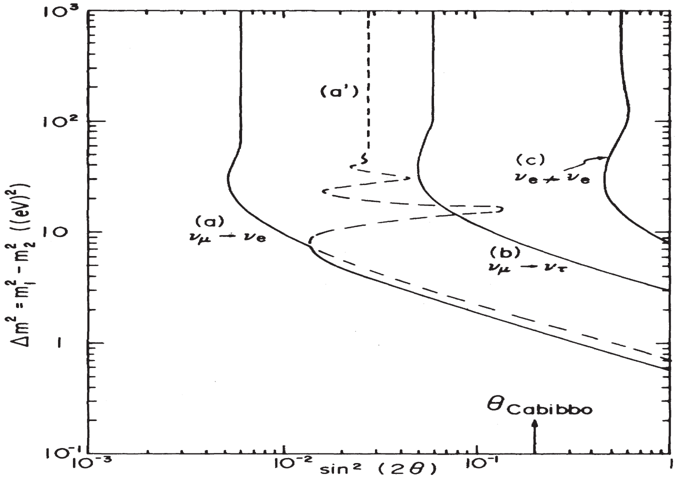


- From BEBC at CERN Deden *etal*, PLB Jan 81

$\nu_e \to \nu_e$



- FNAL Bubble Chamber Baker *etal*, PRL Nov 81



Early "Global Analysis"

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- Barger,Whisnant,Cline,Phillips, PLB Jun 80
- De Rujula,Lusignoli,Maiani,Petcov,Petronzio, NPB May 80

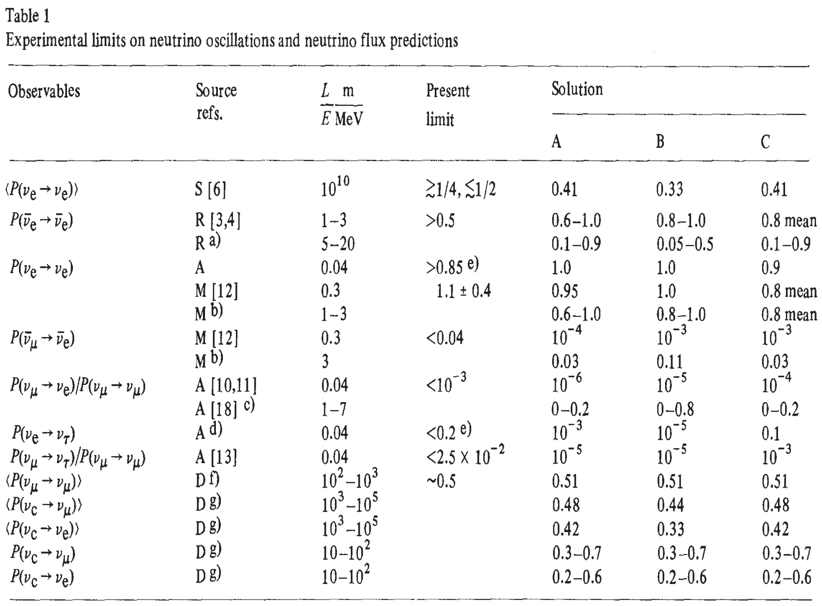
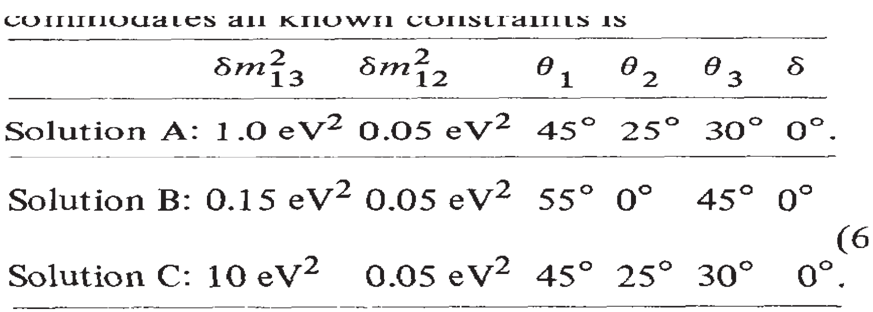


Table 1
Experimental limits on neutrino oscillations and neutrino flux predictions

Observables	Source refs.	$\frac{L}{E}\frac{\mathrm{m}}{\mathrm{MeV}}$	Present limit	Solution		
				A	B	C
$\langle P(\nu_e\to\nu_e)\rangle$	S [6]	10^{10}	$\gtrsim 1/4, \lesssim 1/2$	0.41	0.33	0.41
$P(\bar\nu_e\to\bar\nu_e)$	R [3,4]	1–3	>0.5	0.6–1.0	0.8–1.0	0.8 mean
	R a)	5–20		0.1–0.9	0.05–0.5	0.1–0.9
$P(\nu_e\to\nu_e)$	A	0.04	>0.85 e)	1.0	1.0	0.9
	M [12]	0.3	1.1 ± 0.4	0.95	1.0	0.8 mean
	M b)	1–3		0.6–1.0	0.8–1.0	0.8 mean
$P(\bar\nu_\mu\to\bar\nu_e)$	M [12]	0.3	<0.04	10^{-4}	10^{-3}	10^{-3}
	M b)	3		0.03	0.11	0.03
$P(\nu_\mu\to\nu_e)/P(\nu_\mu\to\nu_\mu)$	A [10,11]	0.04	$<10^{-3}$	10^{-6}	10^{-5}	10^{-4}
	A [18] c)	1–7		0–0.2	0–0.8	0–0.2
$P(\nu_e\to\nu_\tau)$	A d)	0.04	<0.2 e)	10^{-3}	10^{-5}	0.1
$P(\nu_\mu\to\nu_\tau)/P(\nu_\mu\to\nu_\mu)$	A [13]	0.04	$<2.5\times10^{-2}$	10^{-5}	10^{-5}	10^{-3}
$\langle P(\nu_\mu\to\nu_\mu)\rangle$	D f)	10^2–10^3	~0.5	0.51	0.51	0.51
$\langle P(\nu_c\to\nu_\mu)\rangle$	D g)	10^3–10^5		0.48	0.44	0.48
$\langle P(\nu_c\to\nu_e)\rangle$	D g)	10^3–10^5		0.42	0.33	0.42
$P(\nu_c\to\nu_\mu)$	D g)	10–10^2		0.3–0.7	0.3–0.7	0.3–0.7
$P(\nu_c\to\nu_e)$	D g)	10–10^2		0.2–0.6	0.2–0.6	0.2–0.6



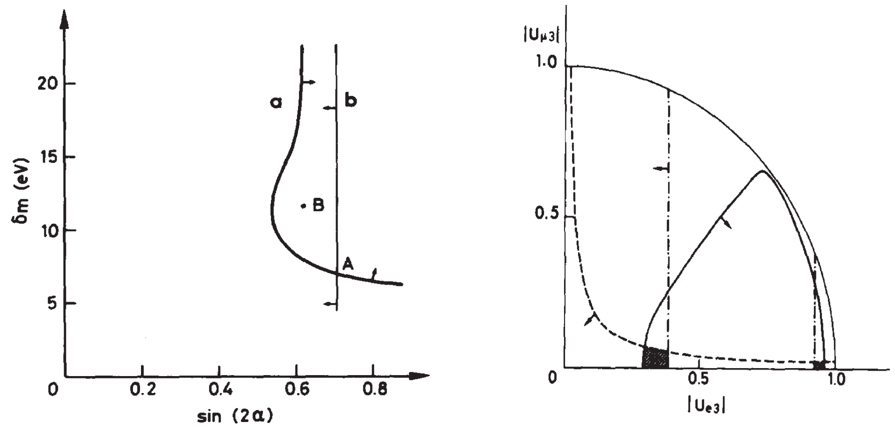
commodates all known constraints is

	δm^2_{13}	δm^2_{12}	θ_1	θ_2	θ_3	δ
Solution A:	1.0 eV^2	0.05 eV^2	45°	25°	30°	0°.
Solution B:	0.15 eV^2	0.05 eV^2	55°	0°	45°	0°
Solution C:	10 eV^2	0.05 eV^2	45°	25°	30°	0°.

(6

KM-like mixing convention

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}c_1 & s_1c_3 & s_1s_3\\ -s_1c_2 & c_1c_2c_3+s_2s_3e^{i\delta} & c_1c_2s_3-s_2c_3e^{i\delta}\\ -s_1s_2 & c_1s_2c_3-c_2s_3e^{i\delta} & c_1s_2s_3+c_2c_3e^{i\delta}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix},$$



$$U=\begin{pmatrix}0.65 & 0.65 & -0.38\\ [-0.71e^{i\delta}\mp|<0.021|] & [0.71e^{i\delta}\mp|<0.02|] & \mp|<0.06|\\ [0.27\mp e^{i\delta}|<0.04|] & [0.27\pm e^{i\delta}|<0.04|] & 0.92\end{pmatrix}, \qquad (6.2)$$

with mass differences in the ranges

$$10^{-5}\,\mathrm{eV}\lesssim\sqrt{|m_1^2-m_2^2|}\lesssim 1\,\mathrm{eV}\,,$$
$$\sqrt{|m_3^2-m_1^2|}\sim 10\,\mathrm{eV}\,.$$

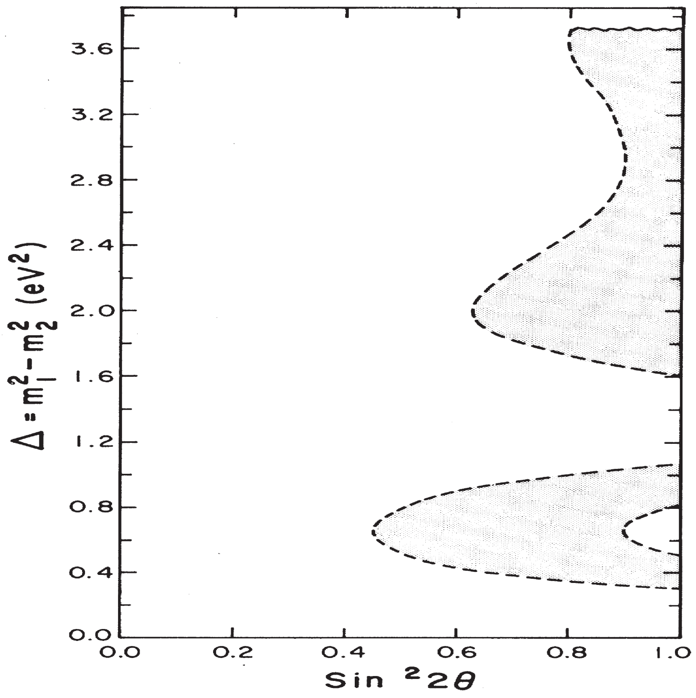
Early Reactor $\mathcal{O}(eV)$ "hints"

- Data from Savannah River Plant

Nezrick and Reines, PR Feb 66 L=6 m

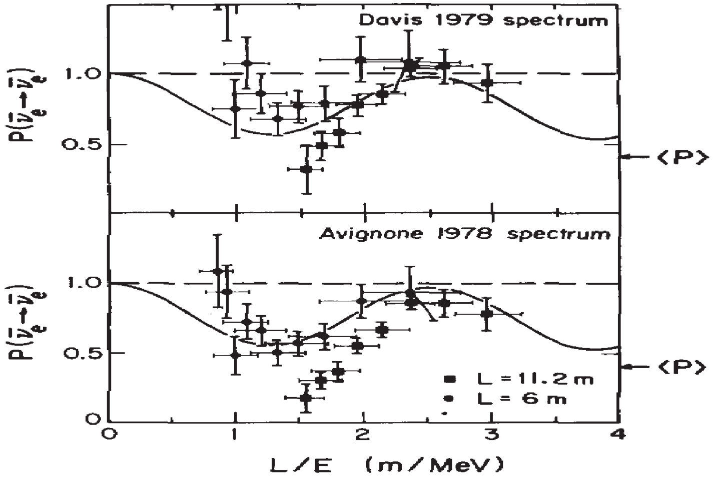
$$\frac{\bar{\sigma}_{\rm exp}}{\bar{\sigma}_{\rm th}} = 0.88 \pm 0.13$$

Reines,Sobel,Pasierb PRL Oct 80 L=11.2 m



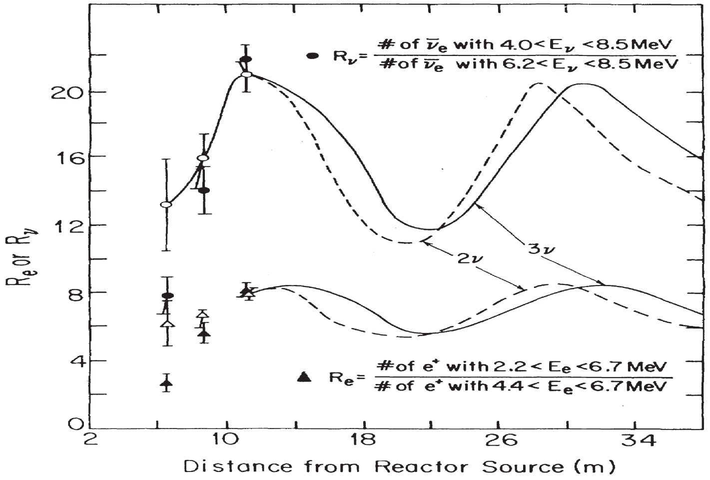
- Early Pheno Analysis

Barger,Whisnant,Cline,Phillips, PLB Jun 80

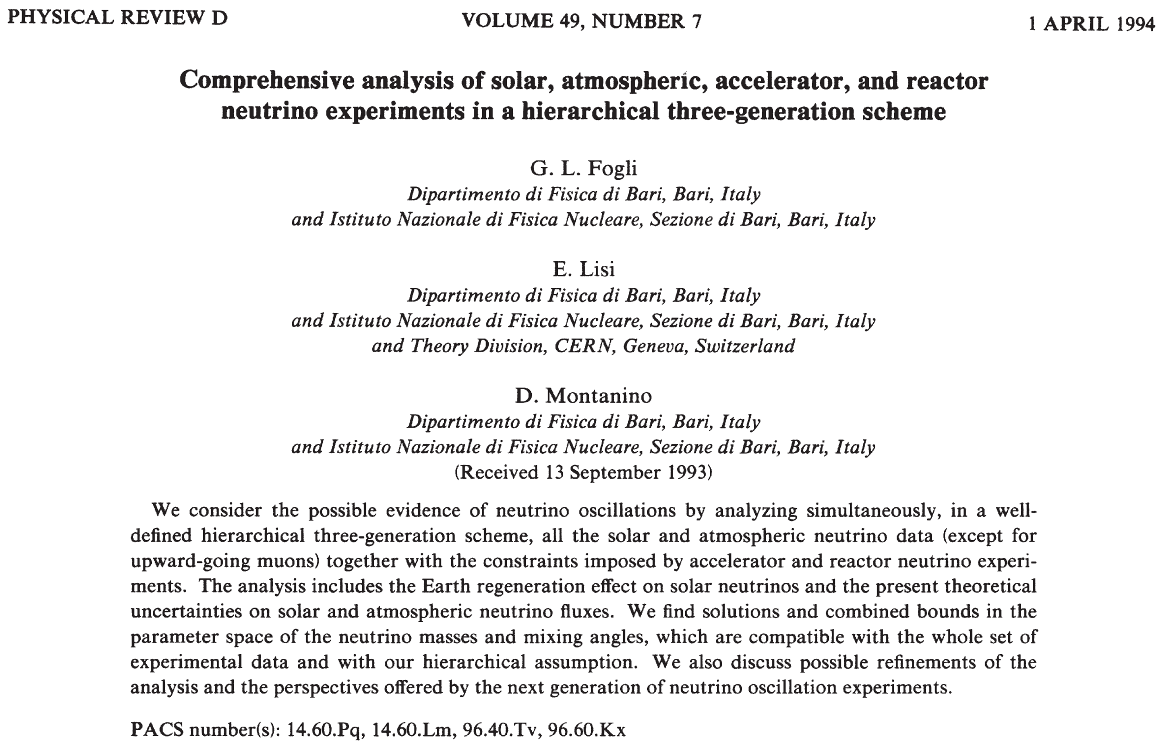


- Even Flux Independent Analysis !!!

Silverman and Soni , PRL Feb 81



- Global Analysis: State of the Art by mid 90's



PHYSICAL REVIEW D VOLUME 49, NUMBER 7 1 APRIL 1994

Comprehensive analysis of solar, atmospheric, accelerator, and reactor neutrino experiments in a hierarchical three-generation scheme

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(Received 13 September 1993)

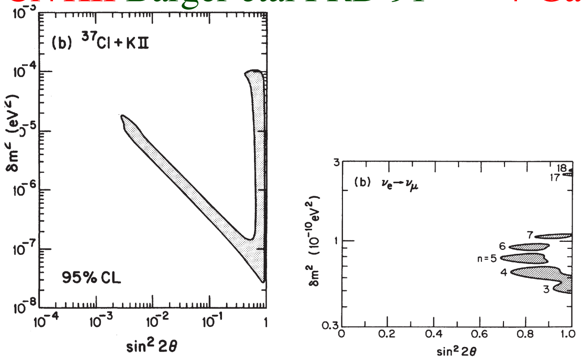
We consider the possible evidence of neutrino oscillations by analyzing simultaneously, in a well-defined hierarchical three-generation scheme, all the solar and atmospheric neutrino data (except for upward-going muons) together with the constraints imposed by accelerator and reactor neutrino experiments. The analysis includes the Earth regeneration effect on solar neutrinos and the present theoretical uncertainties on solar and atmospheric neutrino fluxes. We find solutions and combined bounds in the parameter space of the neutrino masses and mixing angles, which are compatible with the whole set of experimental data and with our hierarchical assumption. We also discuss possible refinements of the analysis and the perspectives offered by the next generation of neutrino oscillation experiments.

PACS number(s): 14.60.Pq, 14.60.Lm, 96.40.Tv, 96.60.Kx

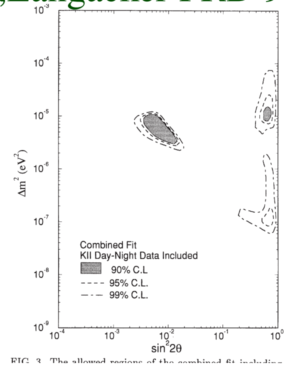
“12” Sector at a Glance

Concha Gonzalez-Garcia

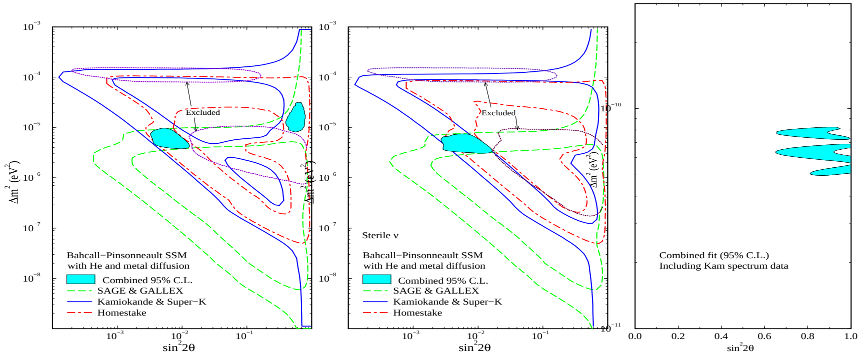
Cl+KII Barger *etal* PRD 91



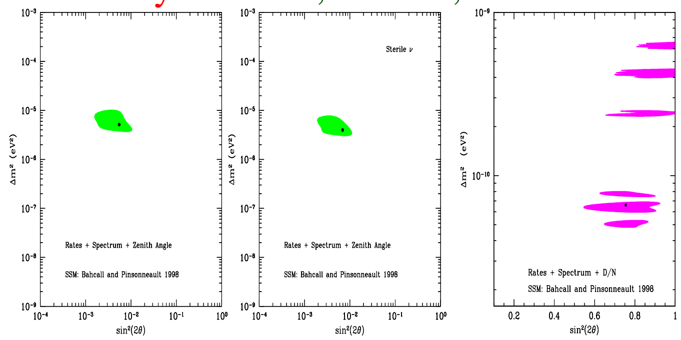
\+ Ga Hata,Langacker PRD 94



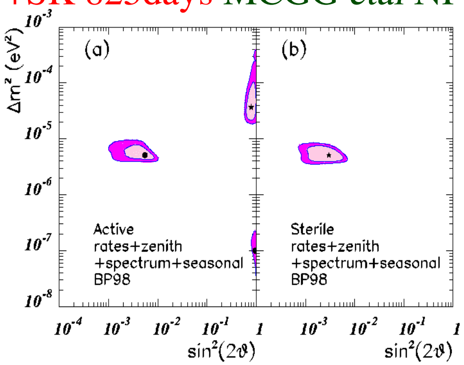
\+SK 100days Hata,Langacker PRD 97



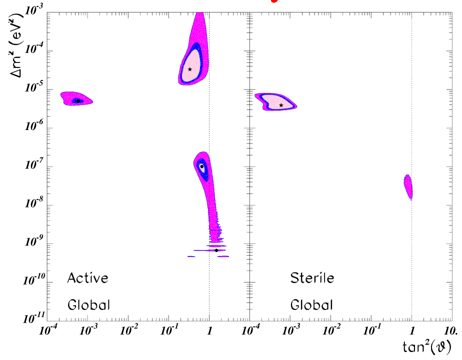
\+SK 505days Bahcall, Krastev, Smirnov PRD 98



\+SK 825days MCGG *etal* NPB 00



\+SK 1117days MCGG *etal*



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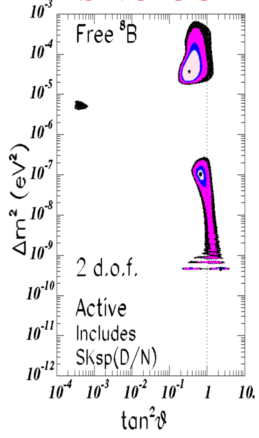

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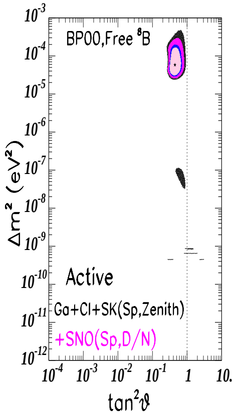
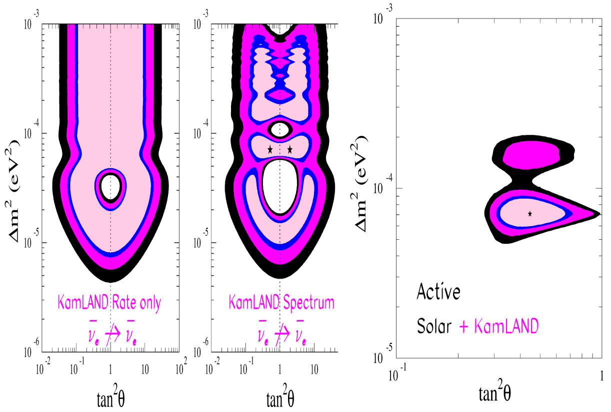
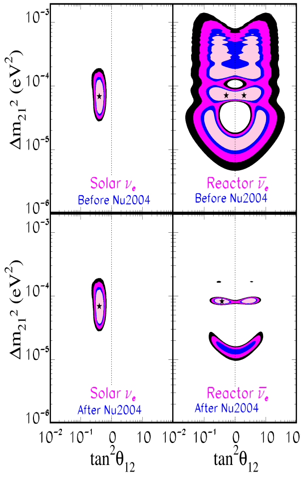
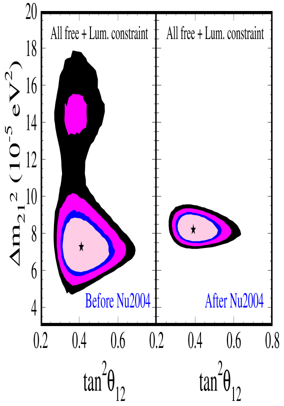


\+KamLAND 02





By 2004



Bahcall, MCGG,Peña-Garay JHEP 01 JHEP 02 JHEP 03 JHEP 04

Concha Gonzalez-Garcia

3 ν Analysis: “12” Sector

- $\Delta m^2_{13} \gg E/L \Rightarrow$ $P^{2\nu}_{ee}$ obtained by solving

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_a\end{pmatrix} = \left[\frac{\Delta m^2_{21}}{4E}\begin{pmatrix}-\cos 2\theta_{12} & \sin 2\theta_{12}\\ \sin 2\theta_{12} & \cos 2\theta_{12}\end{pmatrix} \pm \sqrt{2}G_F N_e \begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_a\end{pmatrix}$$

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

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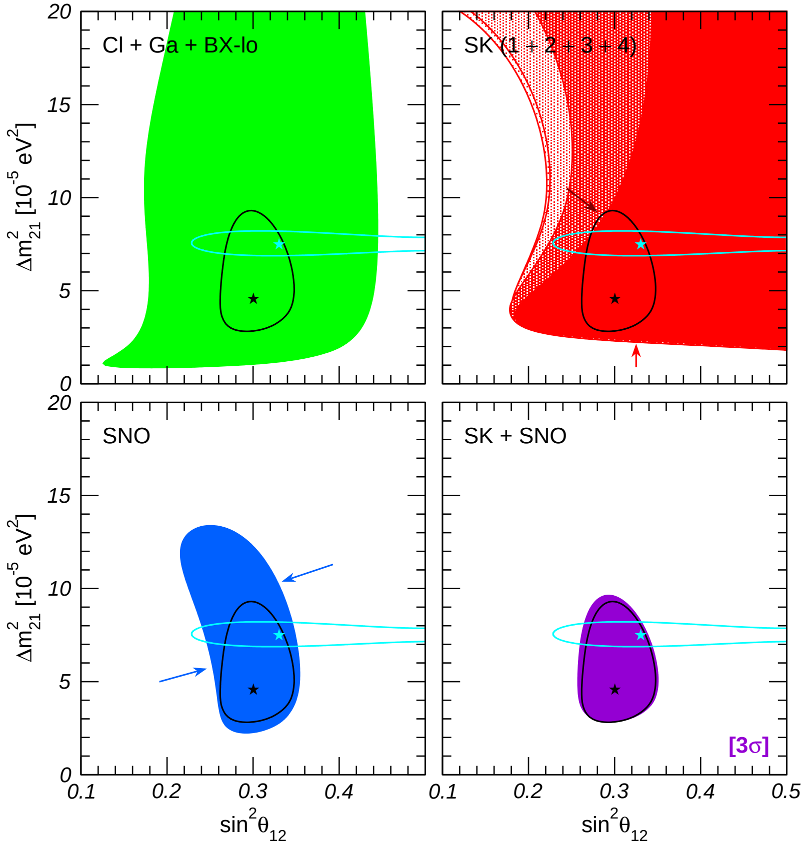
For 2ν’s



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$*$ Solar region determined by High E data

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

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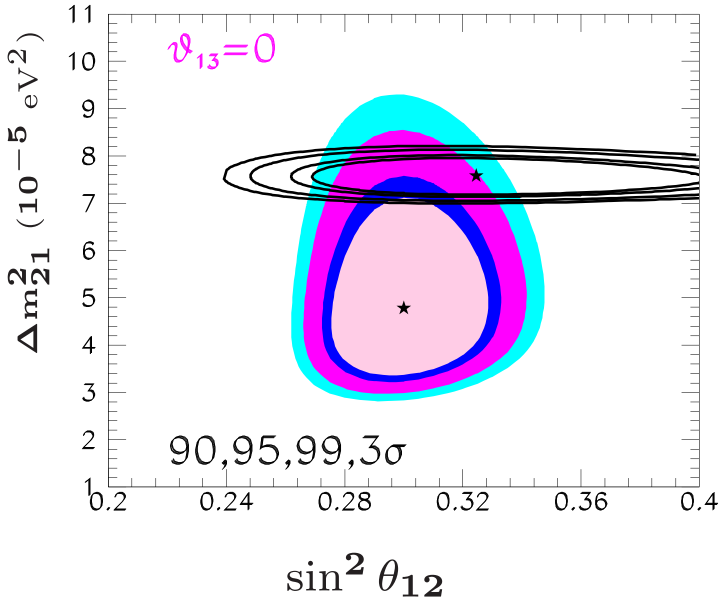

$*$ Solar region determined by High E data

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

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

3 ν Analysis: “12” Sector and θ_{13}

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

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

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

⇒ KamLAND region shifts left

⇒ Solar slight shifts right (due to High E)

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

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

⇒ KamLAND region shifts left

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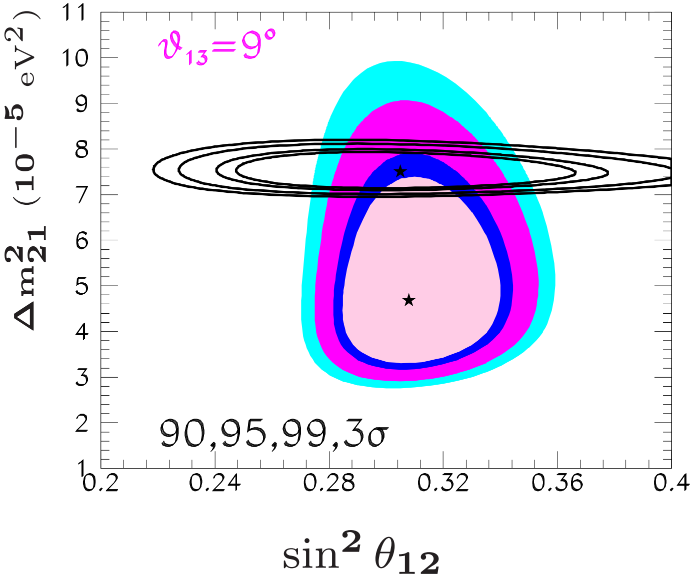


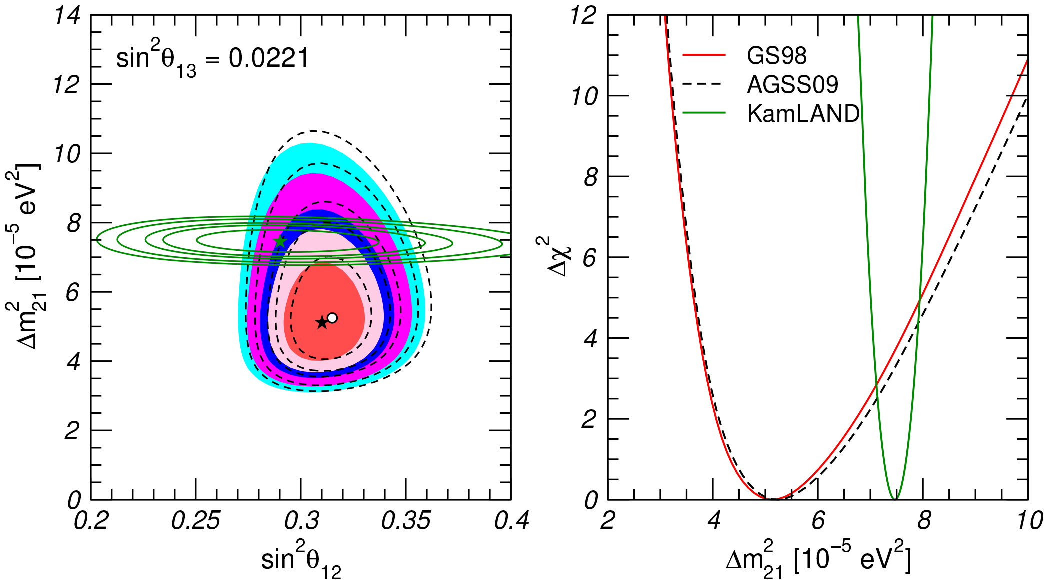
⇒ Good match of best fit θ_{12}

⇒ Residual tension on Δm^2_{21}

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

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

NuFIT 3.2 (2018)



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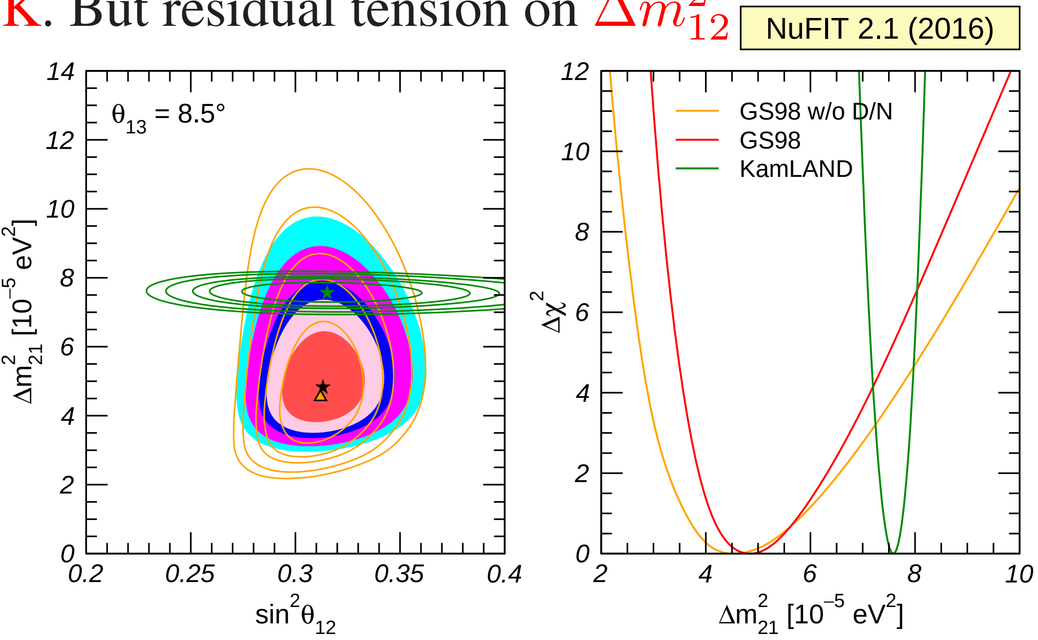
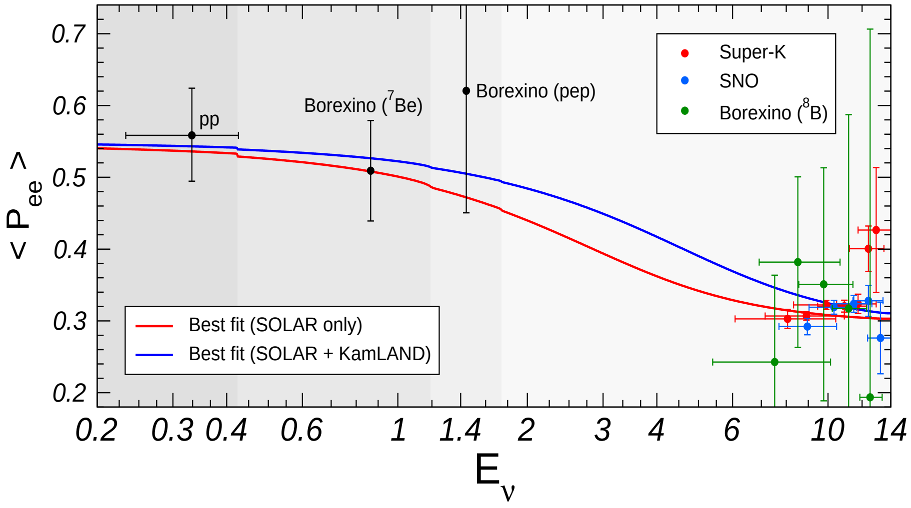
For $\theta_{13} \simeq 9^\circ$ θ_{12} OK. But residual tension on Δm^2_{12}



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



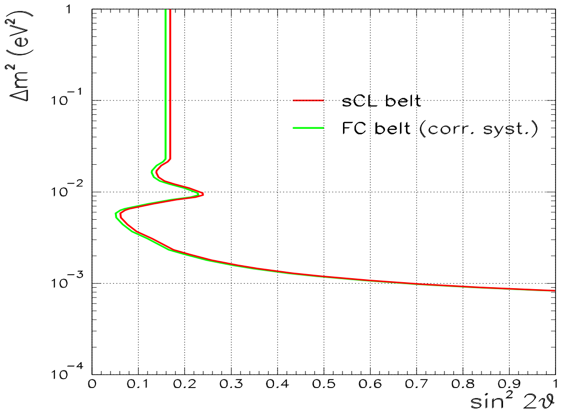
b) smaller-than-expected
low-E turn up from MSW
at best global fit

Modified matter potential? More latter …

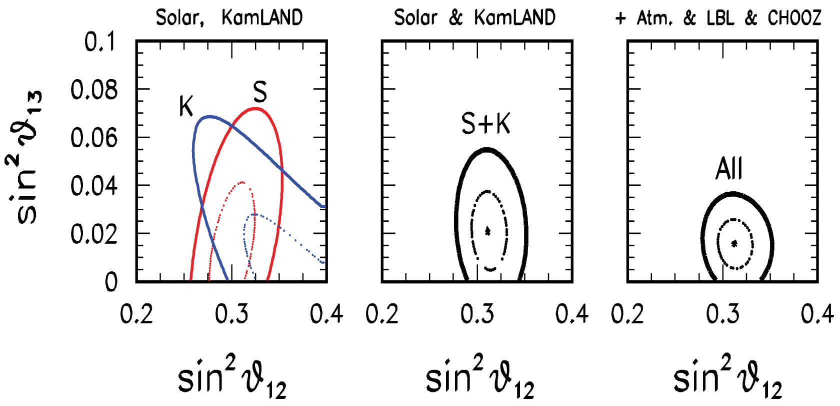
θ_{13} at a Glance

Concha Gonzalez-Garcia

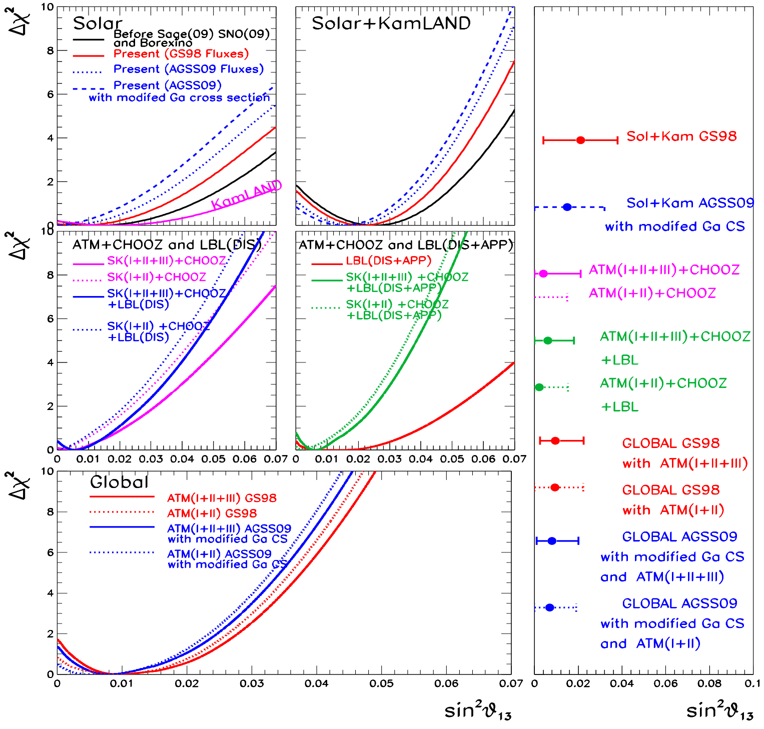
Final Chooz bounds PRD 03



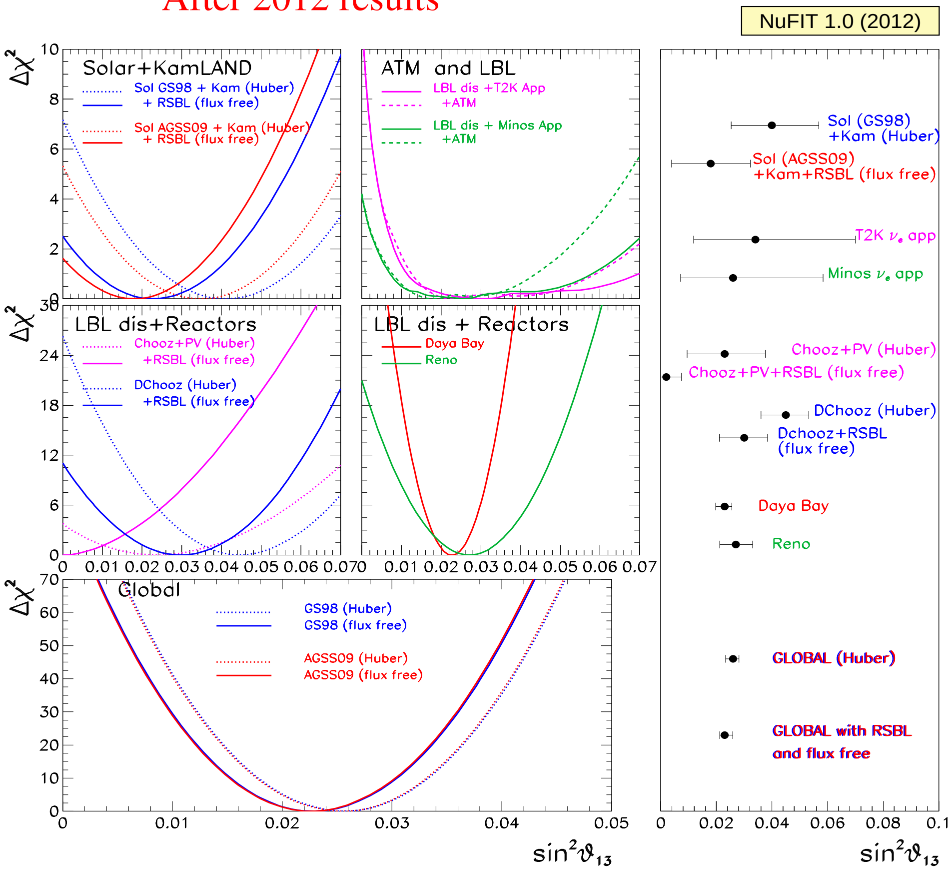
"First Hints" Fogli *etal* PRL 08



" Status Hints 2011" MCGG *etal* JHEP 11



After 2012 results

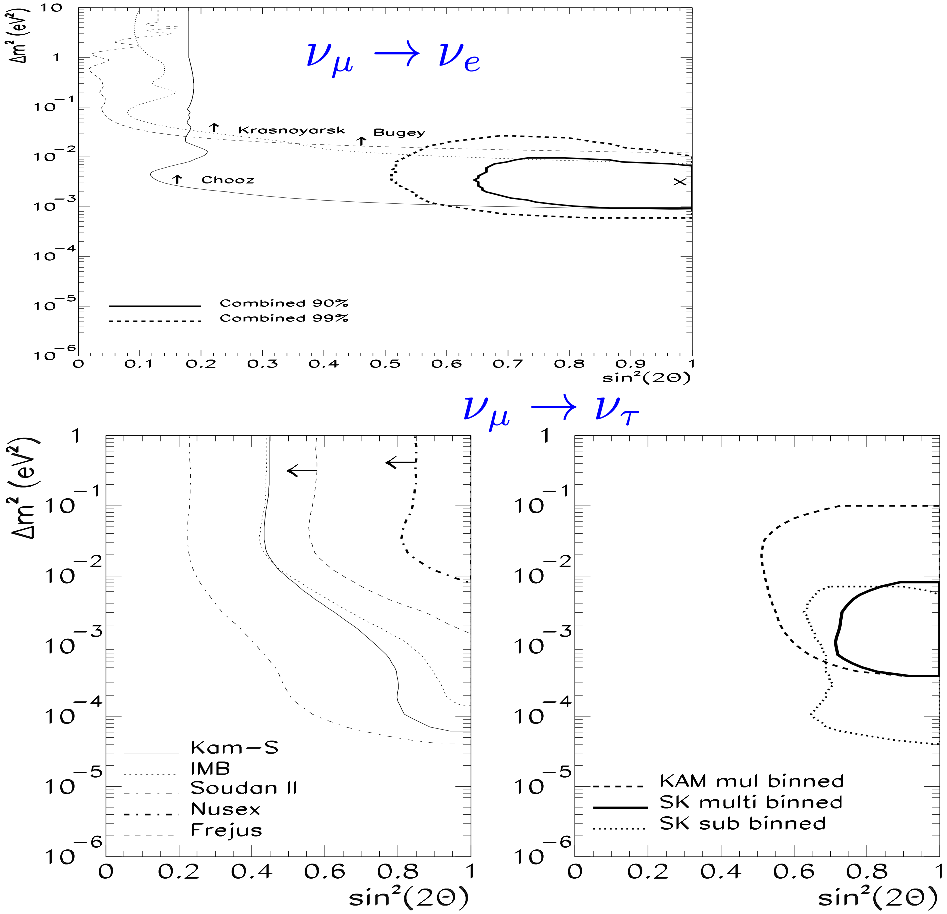


“32” Sector

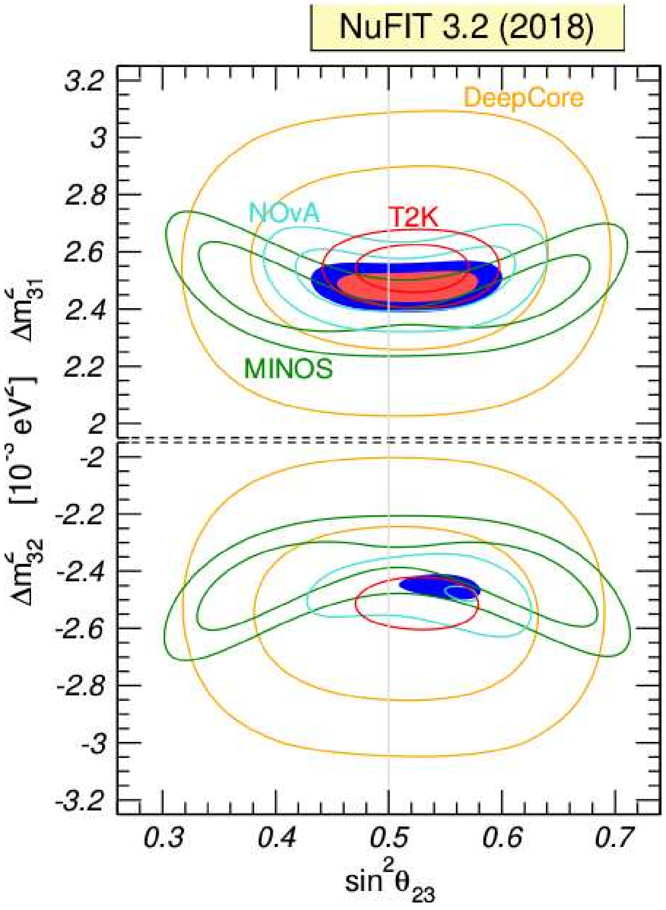
- Originally best determined in ν_μ and $\bar{\nu}_\mu$ disapperance in ATM → LBL

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

In 1998



In 2018



M.C G-G *etal* PRD Jun 98

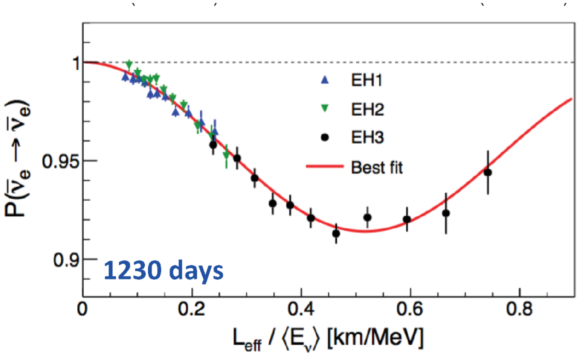
Δm^2_{23} in Reactors

- 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

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



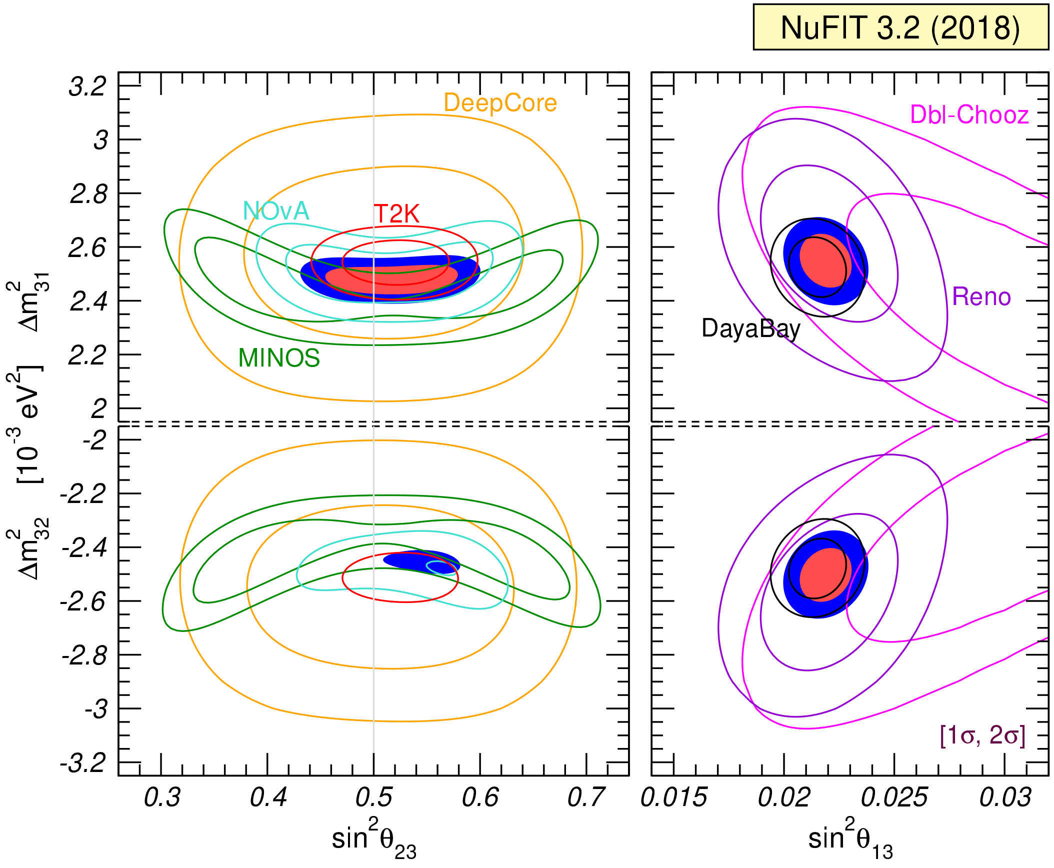
$$\Delta m^2_{ee} \simeq |\Delta m^2_{32}| \pm c^2_{12}\Delta m^2_{21} \simeq |\Delta m^2_{32}| \pm 0.05\times 10^{-3}\ \mathrm{eV}^2$$

Nunokawa,Parke,Zukanovich (2005)

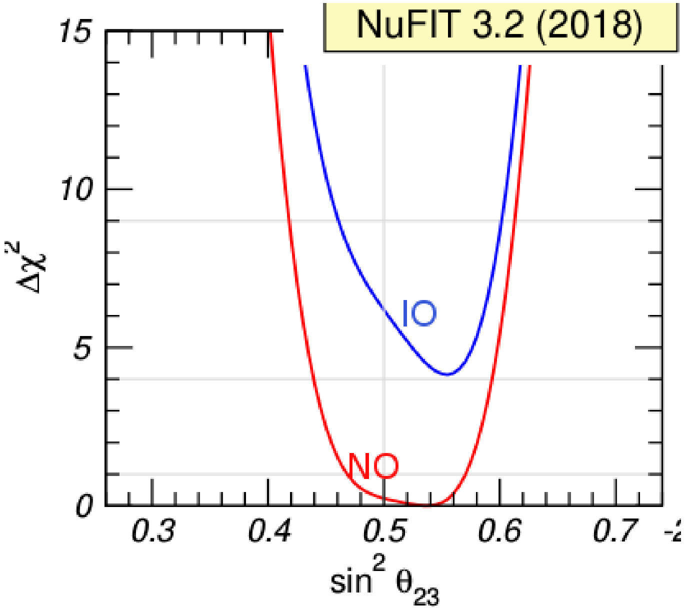
LBL & Reactors: Consistency

LBL ν_μ disapp

REAC ν_e disapp



- Consistent values of $|\Delta m^2_{32}|$
- "Oscillating hint" for non-max θ_{23} driven by NOνA and MINOS
- Slight fav $\theta_{23} > 45$
- Final θ_{23} range depends on how Reac data is included



LBL & Reactors: Consistency

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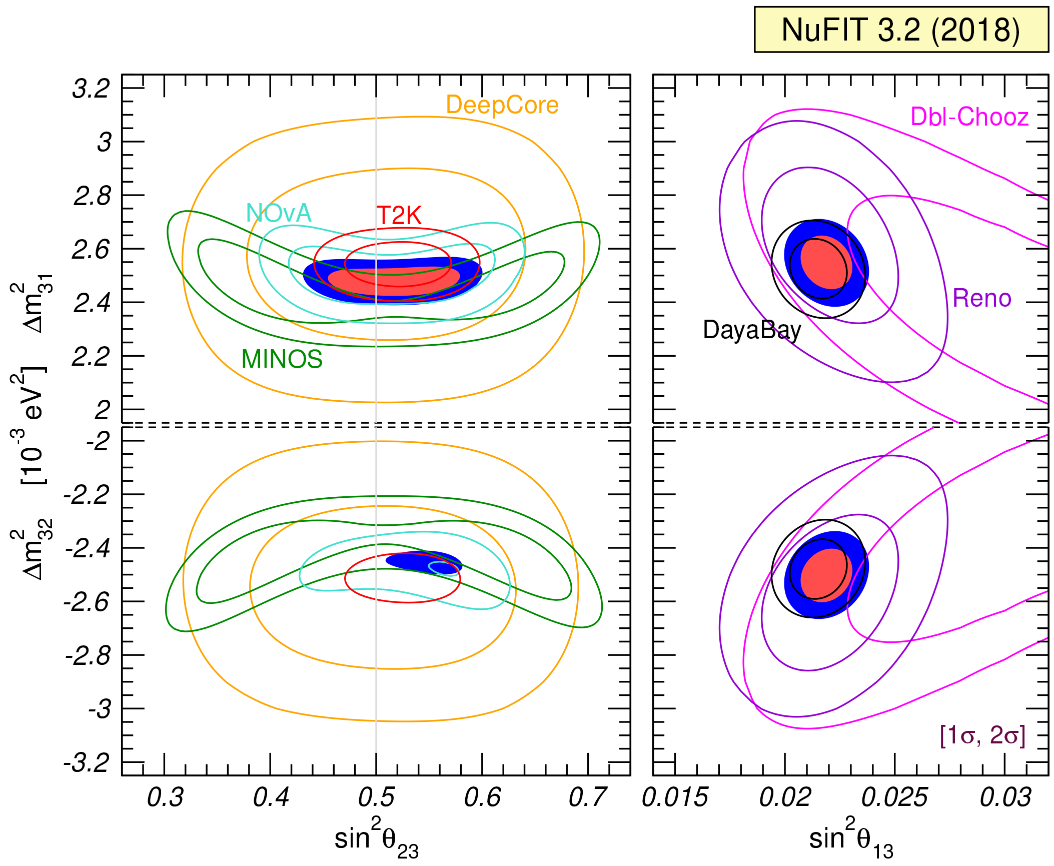

- Consistent values of $|\Delta m^2_{32}|$
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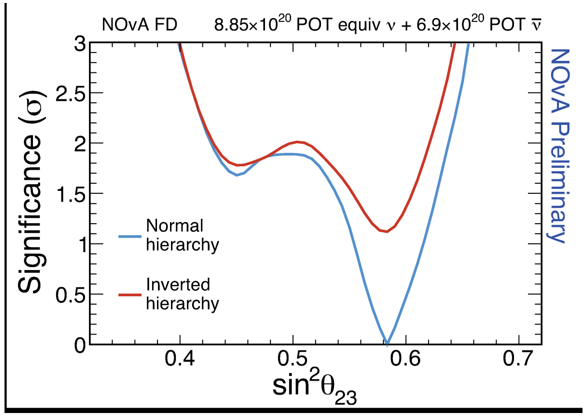
- Slight fav $\theta_{23} > 45$
  - Final θ_{23} range depends on how Reac data is included
  - More $\theta_{23} > 45$ with NOνA $\bar{\nu}$?



Ordering

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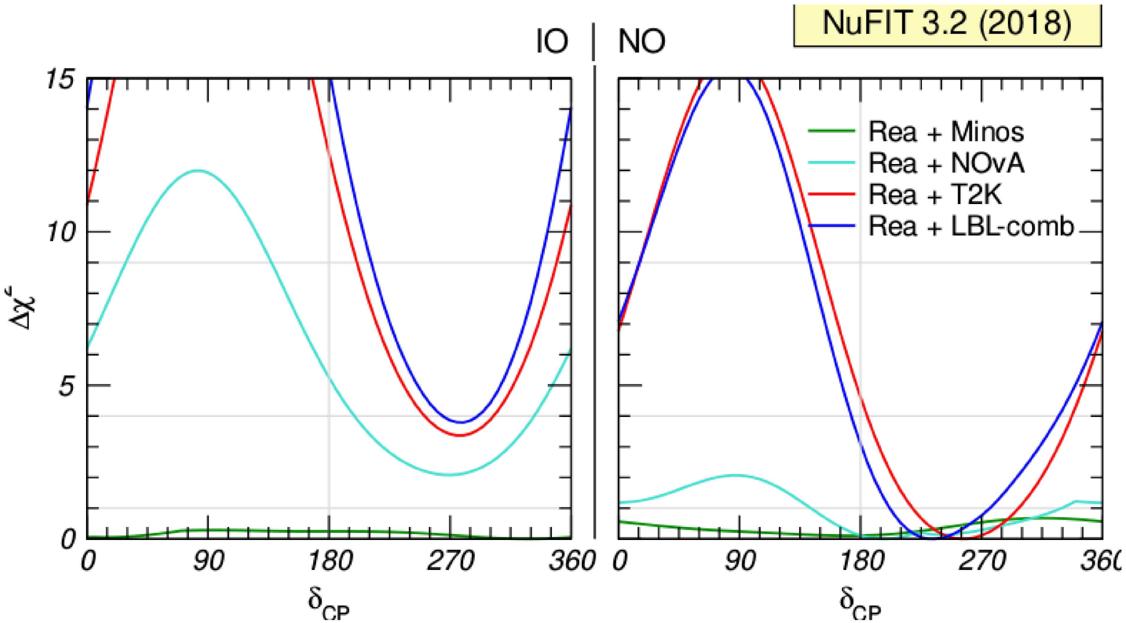
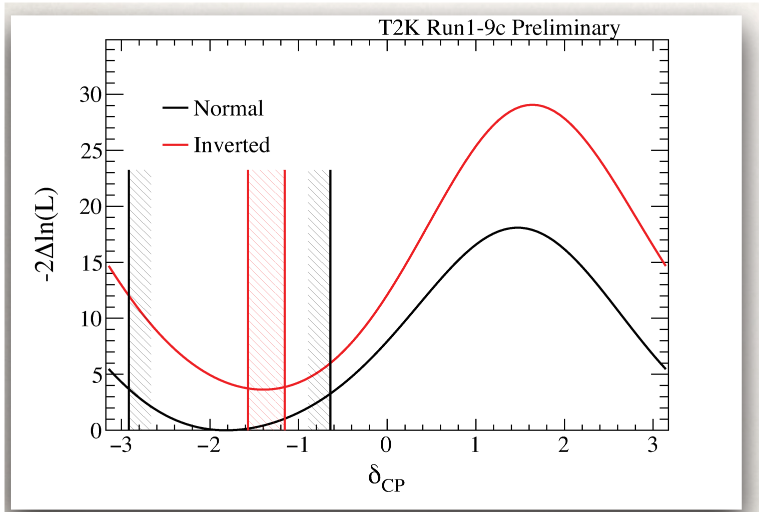
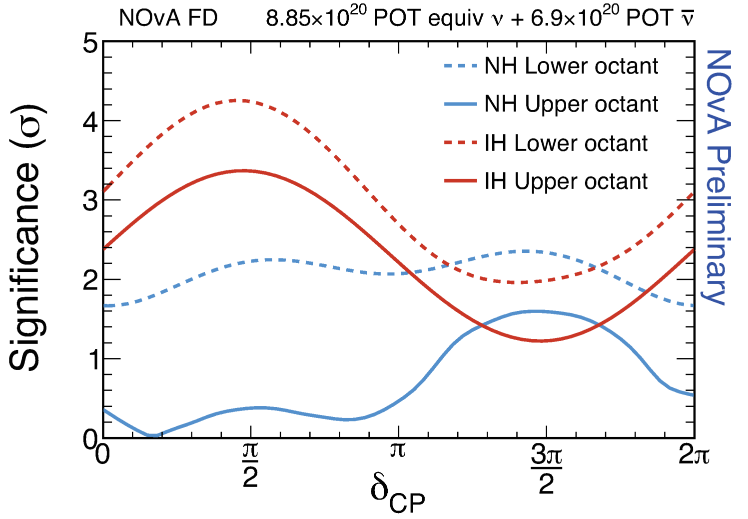


IO disfavoured at $\sim 2\sigma$

T2K nu2018 results: consistent

NOνA nu2018:consistent





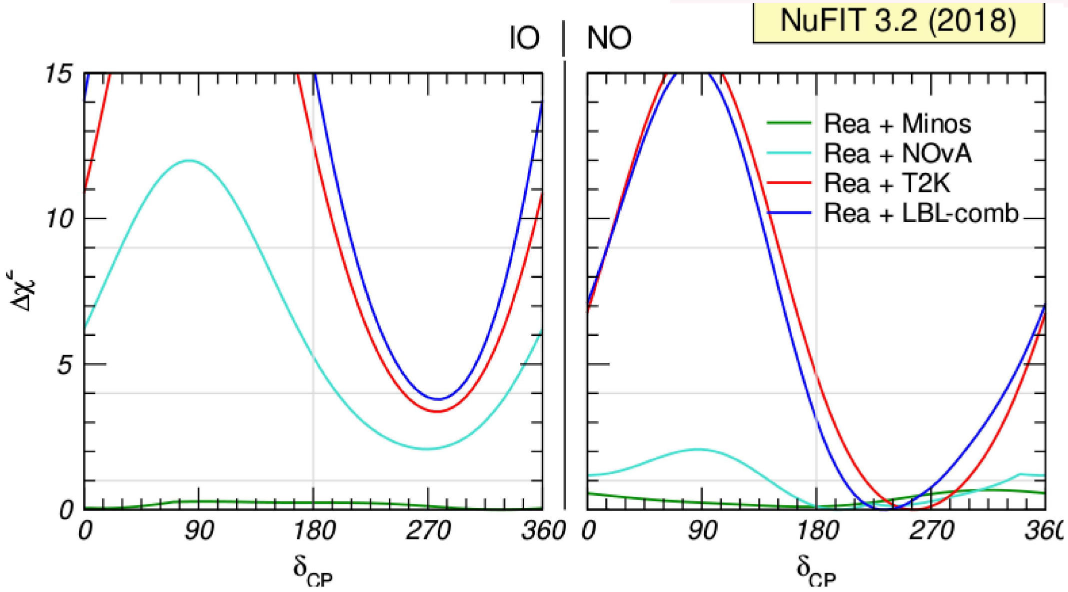
Leptonic CP Phase

Concha Gonzalez-Garcia

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

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

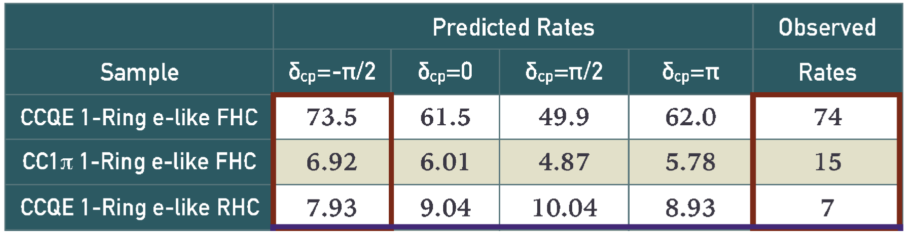
$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad J_{\rm LEP,CP}^{\rm max} = \frac{1}{8} c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12} = (3.32 \pm 0.07) \times 10^{-2}$$



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

– CP conserv at 2σ (NO), 3σ (IO)

– Mainly Driven by “fluctuation” in T2K



Sample	Predicted Rates				Observed
	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7

– NOνA 2017 ν data consistent

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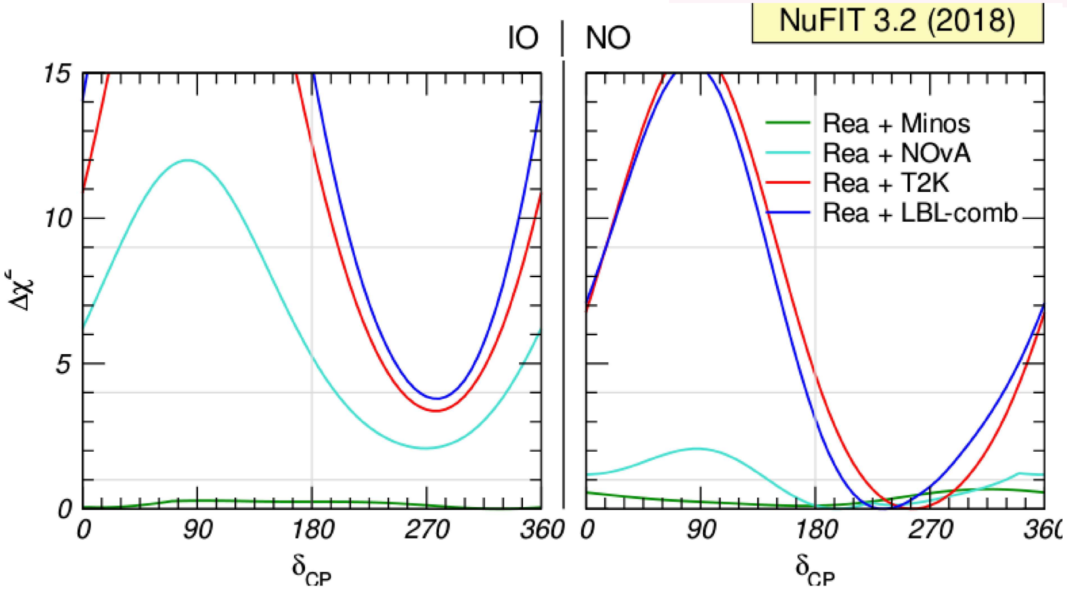
$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad J^{\rm max}_{\rm LEP,CP} = \frac{1}{8} c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12} = (3.32 \pm 0.07) \times 10^{-2}$$



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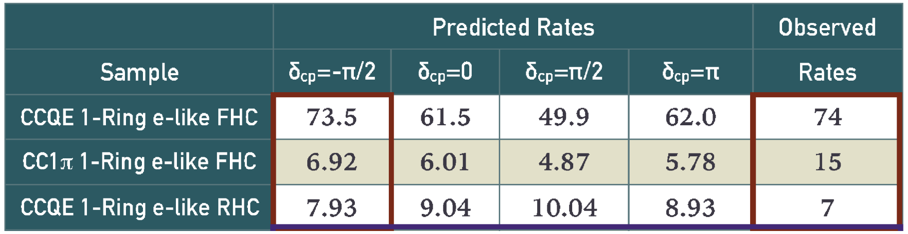

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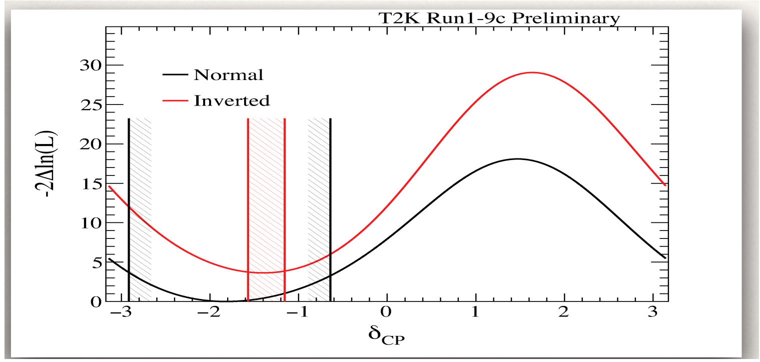
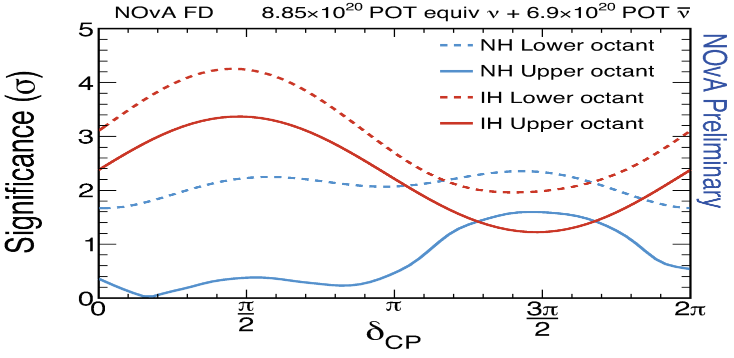
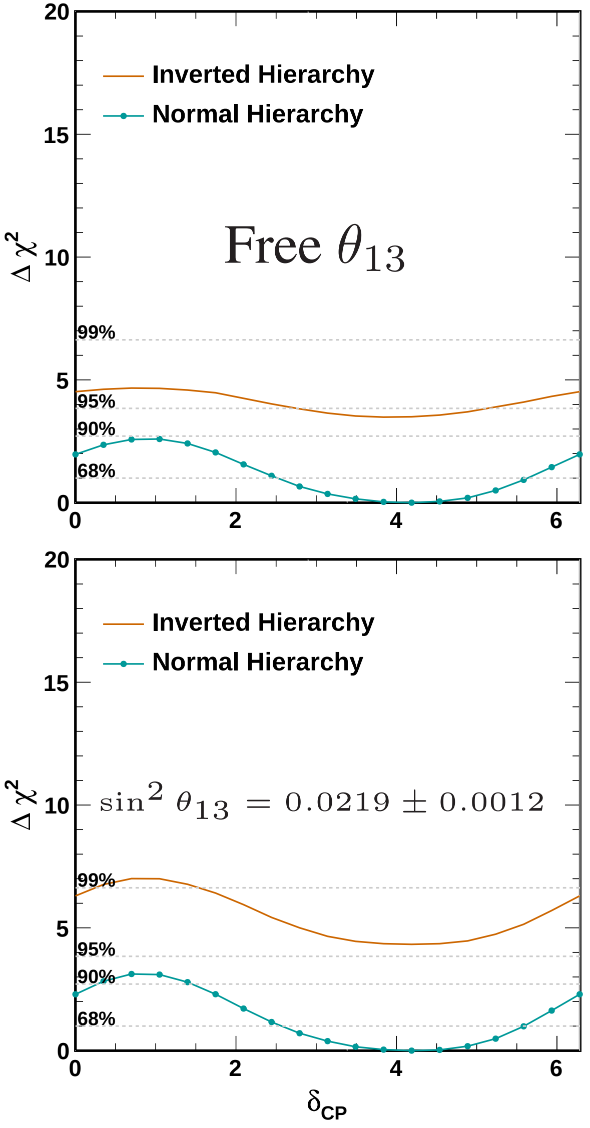


But NOνA nu2018 results??

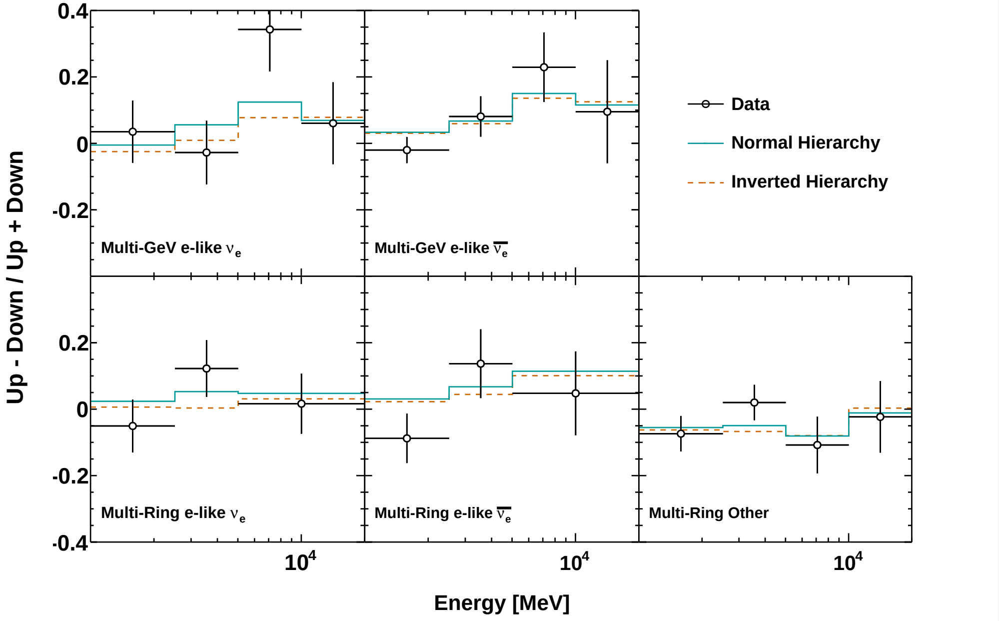


θ_{23}, CP & Ordering: Effect in SK ATM

Latest SK analysis (PRD 2018) yelds:



From SK paper: *"Small excesses seen between a few and ten GeV in the Multi-GeV e-like ν_e and the Multi-Ring e-like ν_e and $\bar{\nu}_e$ samples drive these preferences"*.



– No pheno group reproduces SK analysis

– Only possibility is combine with SK χ^2 tables

θ_{23}, CP & Ordering: Effect in SK ATM

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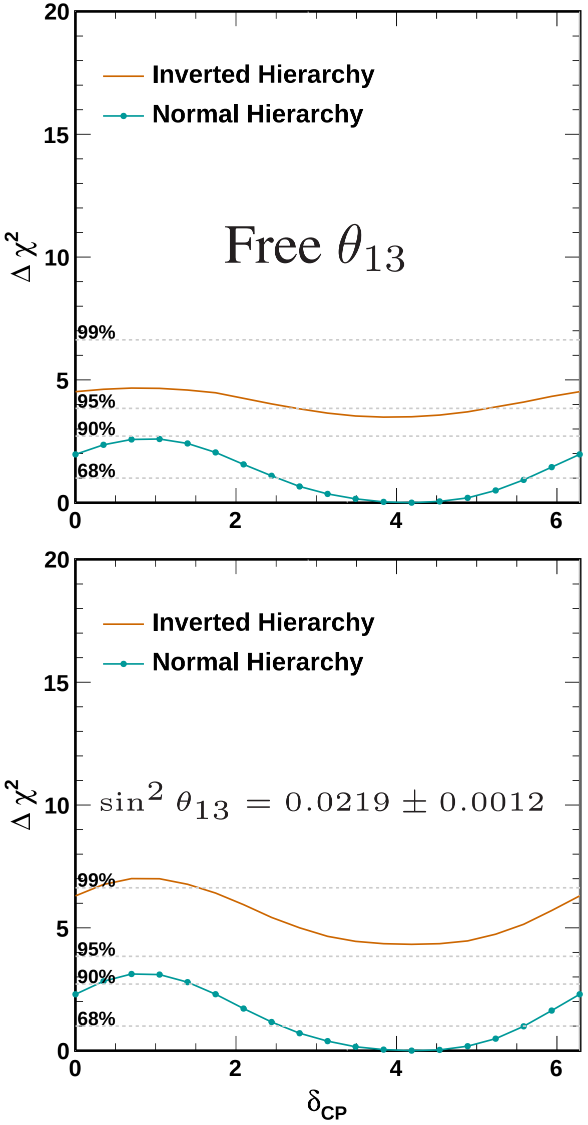

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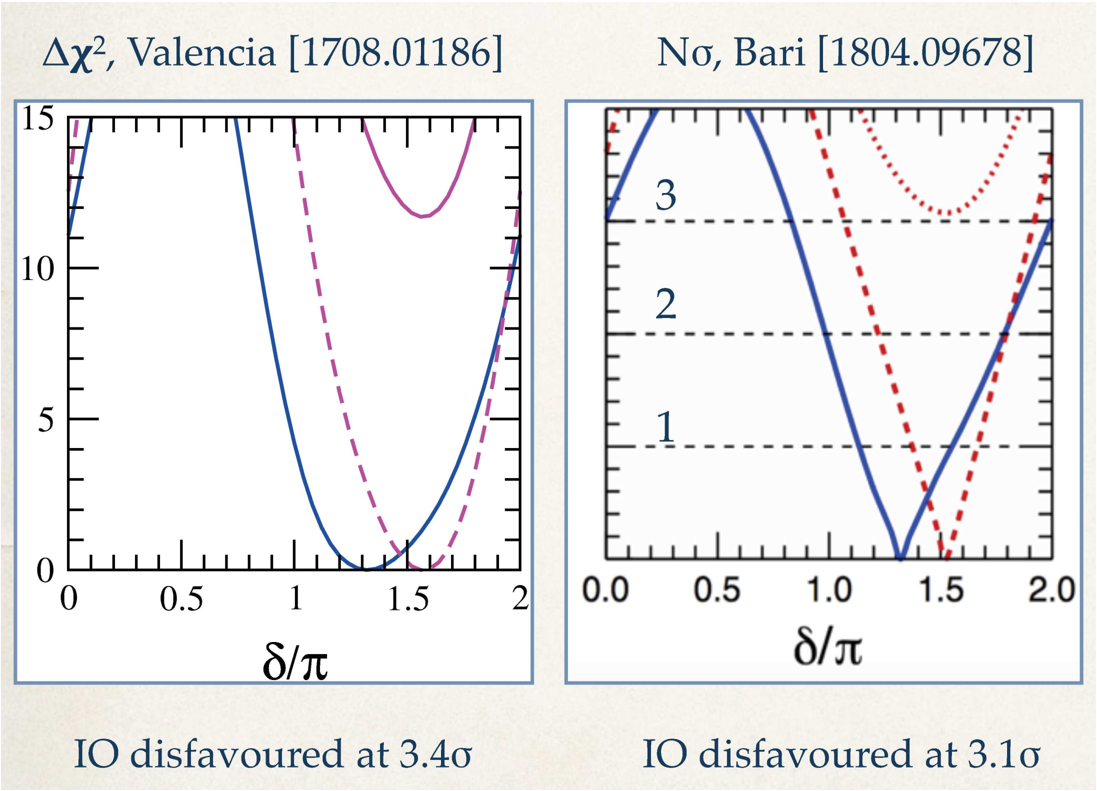

$\Delta\chi^2$, Valencia [1708.01186]

Nσ, Bari [1804.09678]

IO disfavoured at 3.4σ

IO disfavoured at 3.1σ

Alternative Oscillation Mechanisms

- Oscillations are due to:
  - Misalignment between CC-int and propagation states: Mixing ⇒ Amplitude
  - Difference phases of propagation states ⇒ Wavelength.

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

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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

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

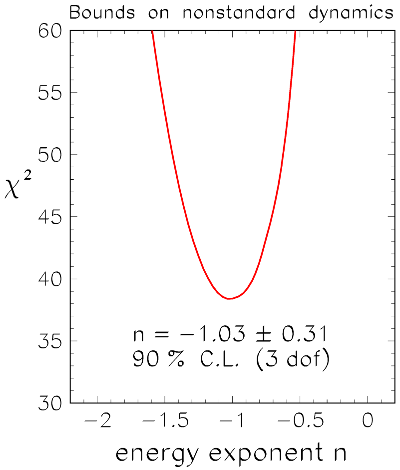
Violation of Lorentz Invariance (VLI) Colladay, Kostelecky 97; Coleman, Glashow 99

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

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

Alternative Mechanisms vs ATM ν's

- With early SK ATM's they could be rule out as dominant



Fogli, Lisi and Marrone hep-ph/0105139

Different L/E dependence:

$P_{\mu\tau} = \alpha \sin^2(\beta L E^n)$

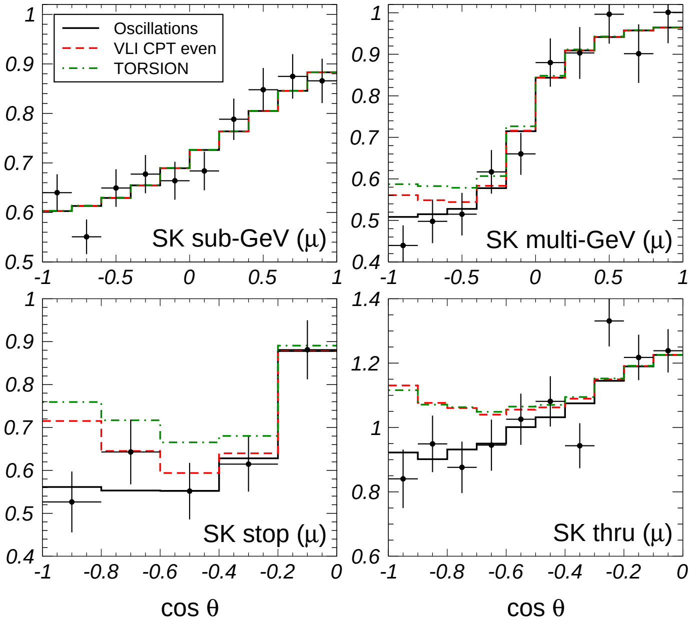
$n = -1$ oscillations

$n = 1$ Viol Equiv. Principle

$n = 1$ Viol Lorentz invariance

Fit : $n = -1.03 \pm 0.31$ 90%CL

- And soon after severly constrained (MCG-G, M. Maltoni PRD 04,07)



At 90% CL:

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

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

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

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

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.:

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

$$H_{\rm mat} = \sqrt{2} G_F N_e(r) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2} G_F N_e(r) \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

$\varepsilon_{\alpha\beta}(r) \equiv \sum_{f=ued} \frac{N_f(r)}{N_e(r)} \varepsilon^{fV}_{\alpha\beta}$ $\Rightarrow$ 3ν evolution depends on 6 (vac) + 8 per f (mat)

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$\Rightarrow$ Parameters degeneracies (some well-known but being rediscovered lately …)
In particular CPT $\Rightarrow$ invariance under simultaneously:

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

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

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

NSI: Bounds/Degeneracies from/in Oscillation data

M.C G-G, M.Maltoni JHEP 1307.3092

		90% CL	
Param.	best-fit	LMA	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 $\varepsilon^{q,V}_{ee} - \varepsilon^{q,V}_{\mu\mu}$

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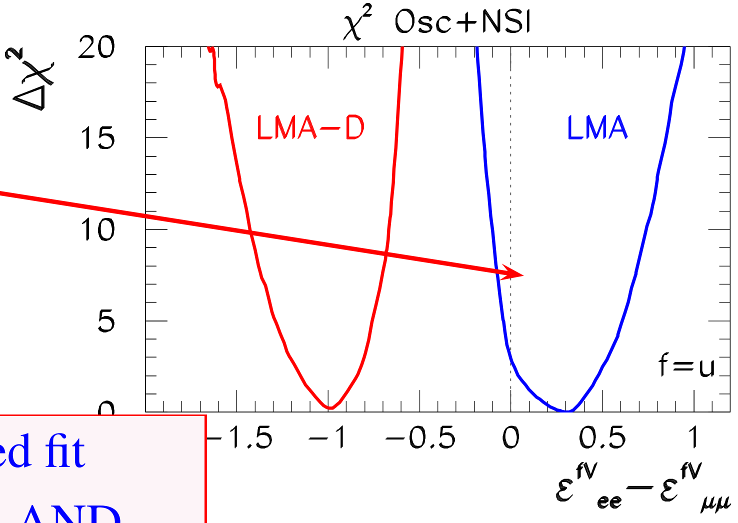

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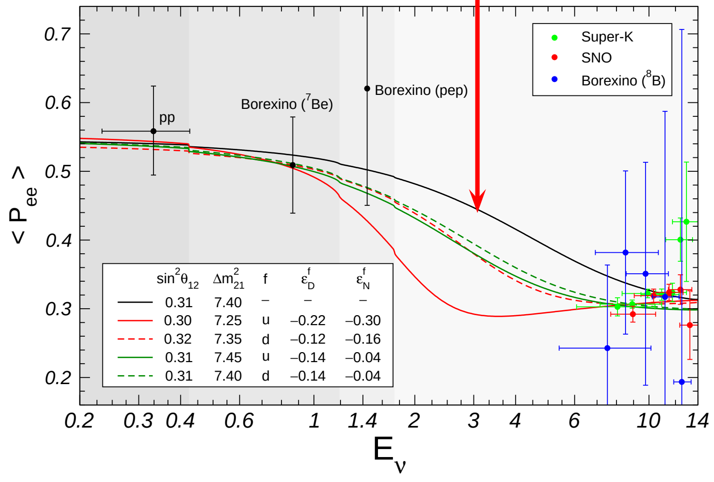
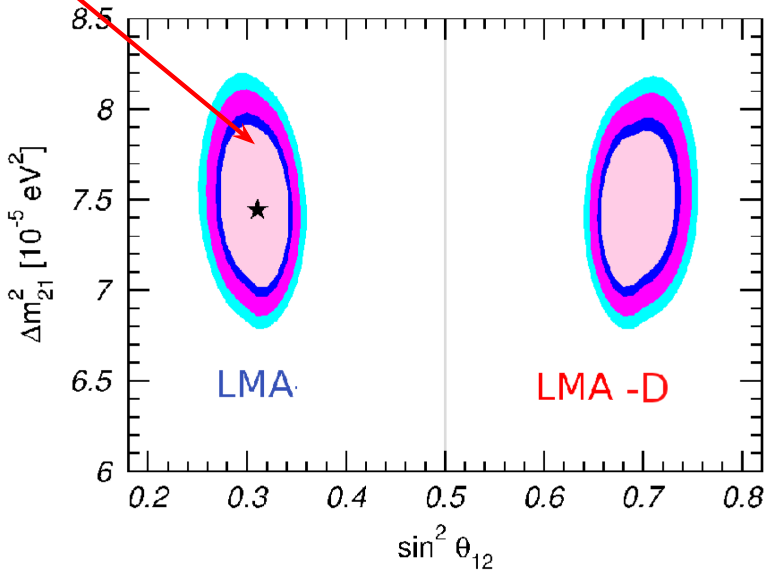
LMA: Improved fit
to Solar+KamLAND





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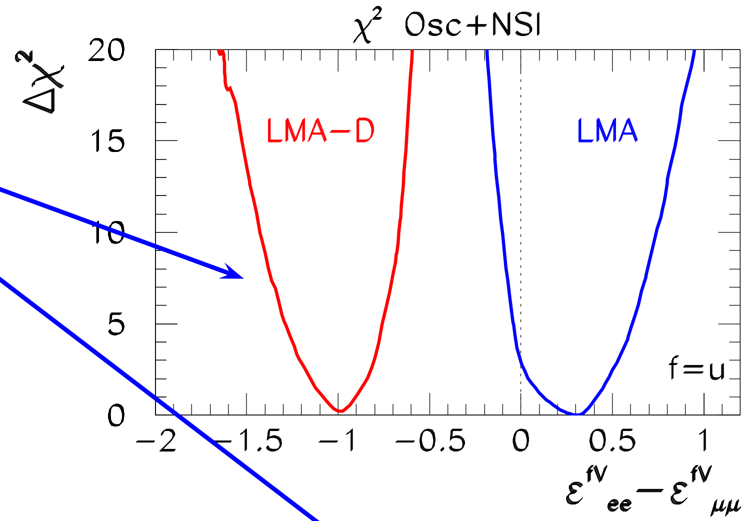

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– Except $\varepsilon^{q,V}_{ee} - \varepsilon^{q,V}_{\mu\mu}$

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

Miranda,Tortola, Valle, hep-ph/0406280

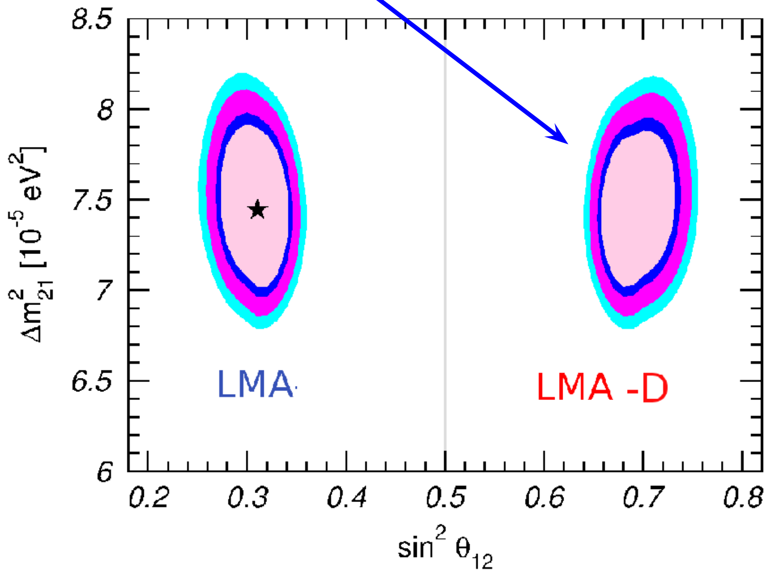
Cannot be resolved with osc-experiments

Requires NC scattering experiments

Coloma etal 1701.04828

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

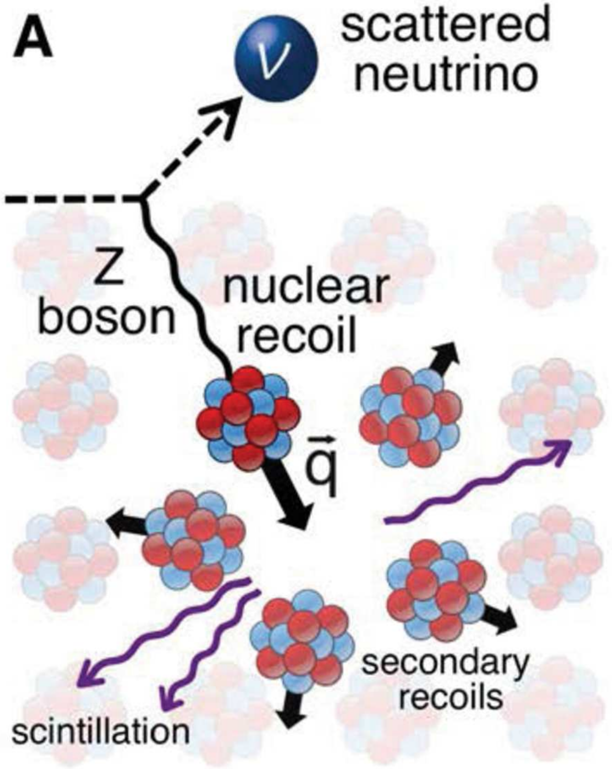
Farzan 1505.06906, and Shoemaker 1512.09147



COHERENT EXPERIMENT

Science 2017 [ArXiv:1708.01294]

- observation of coherent neutrino-nucleus scattering at 6.7σ at CsI[Na] detector
- neutrinos from stopped pion source at Oak Ridge NL
- 142 events observed, in agreement with Standard Model



NSI: Combination with COHERENT data

Coloma, MCGG, Maltoni,Schwetz ArXiv:1708.02899

- COHERENT has detected for first time Coherent νN scattering 1708.01294:
  142(1± 0.28(sys)) observed events over a steady bck of 405
  136(SM) + 6(1± 0.25(sys) beam-on bck) expected

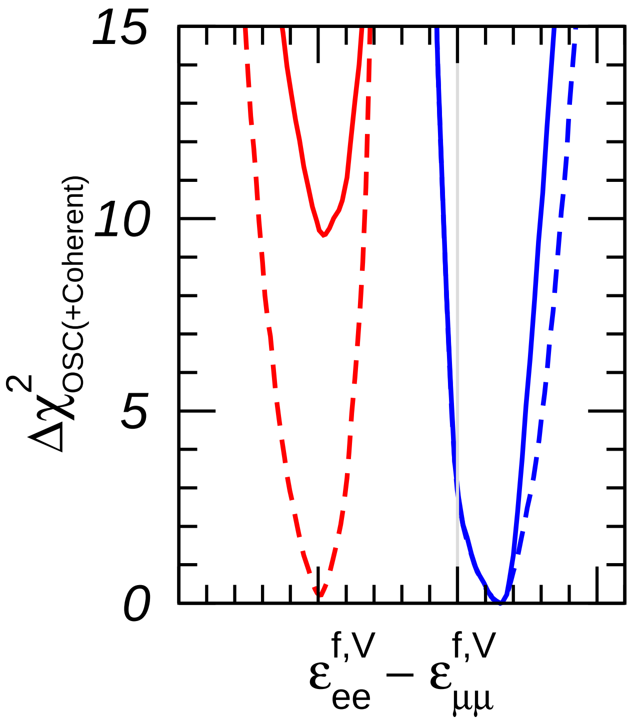
- In presence of NSI: $N_{\rm NSI}(\varepsilon) = \gamma \left[f_{\nu_e} Q^2_{we}(\varepsilon) + (f_{\nu_\mu} + f_{\bar{\nu}_\mu}) Q^2_{w\mu}(\varepsilon) \right]$

$$Q^2_{w\alpha} \propto \left[Z(g_p^V + 2\varepsilon^{u,V}_{\alpha\alpha} + \varepsilon^{d,V}_{\alpha\alpha}) + N(g_n^V + \varepsilon^{u,V}_{\alpha\alpha} + 2\varepsilon^{d,V}_{\alpha\alpha})\right]^2 + \sum_{\beta\neq\alpha}\left[Z(2\varepsilon^{u,V}_{\alpha\beta} + \varepsilon^{d,V}_{\alpha\beta}) + N(\varepsilon^{u,V}_{\alpha\beta} + 2\varepsilon^{d,V}_{\alpha\beta})\right]^2$$

- OSCILLATION + COHERENT ⇒ LMA-D excluded at more than 3.1 σ
  for NSI with f=up or f=down

All NSI's constrained

	$f=u$	$f=d$
$\epsilon^{f,V}_{ee}$	$[0.028, 0.60]$	$[0.030, 0.55]$
$\epsilon^{f,V}_{\mu\mu}$	$[-0.088, 0.37]$	$[-0.075, 0.33]$
$\epsilon^{f,V}_{\tau\tau}$	$[-0.090, 0.38]$	$[-0.075, 0.33]$
$\epsilon^{f,V}_{e\mu}$	$[-0.073, 0.044]$	$[-0.07, 0.04]$
$\epsilon^{f,V}_{e\tau}$	$[-0.15, 0.13]$	$[-0.13, 0.12]$
$\epsilon^{f,V}_{\mu\tau}$	$[-0.01, 0.009]$	$[-0.009, 0.008]$



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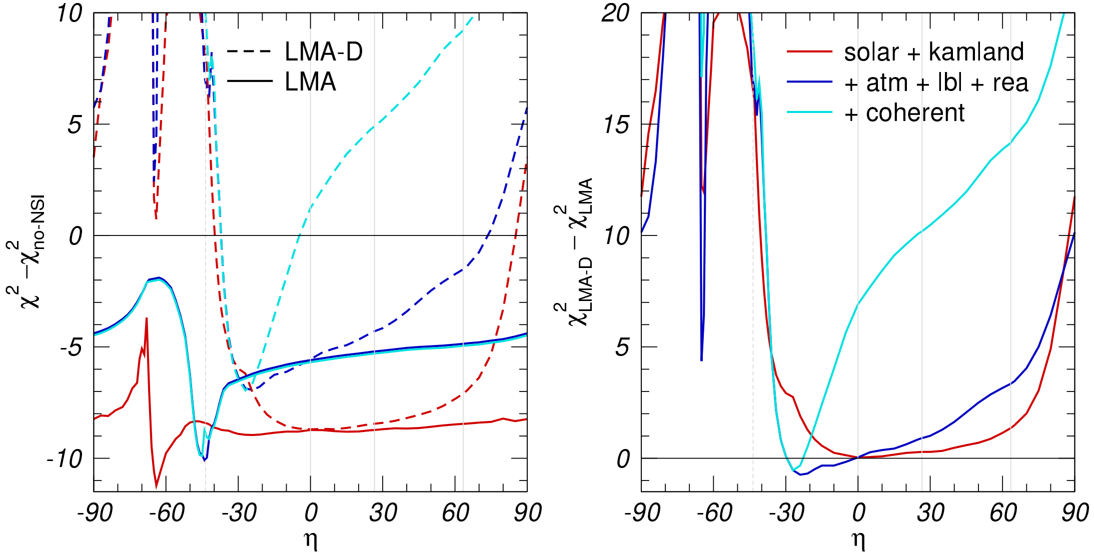
- OSCILLATION + COHERENT:

  Update with more general NSI's: $\varepsilon^u_{\alpha\beta} \propto (2\cos\eta - \sin\eta)\varepsilon^\eta_{\alpha\beta}$ $\quad \varepsilon^d_{\alpha\beta} \propto (2\sin\eta - \cos\eta)\varepsilon^\eta_{\alpha\beta}$



LMA-D Still allowed at 3σ for

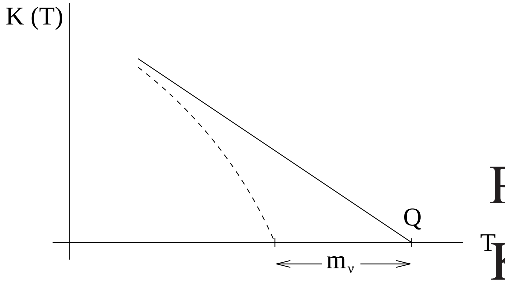
$$-40^\circ \lesssim \eta \lesssim 15^\circ$$

Esteban etal, ArXiv:1805.04530

Neutrino Mass Scale

Concha Gonzalez-Garcia

Single β decay : Pure kinematics, Dirac or Majorana ν's, only model independent

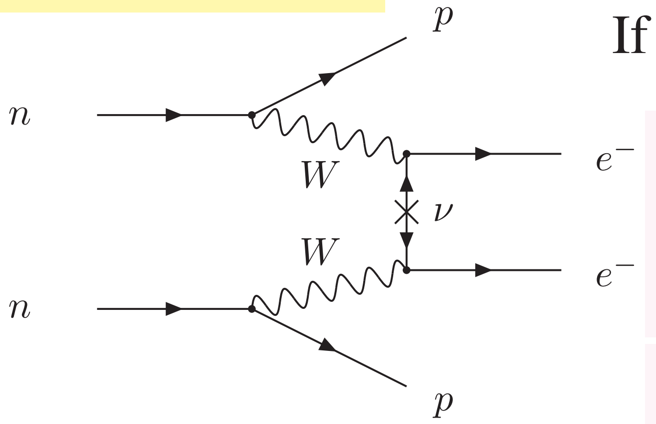


$$m^2_{\nu_e} = \sum m^2_j |U_{ej}|^2 = \begin{cases} \mathrm{NO}: \; m^2_\ell + \Delta m^2_{21} c^2_{13} s^2_{12} + \Delta m^2_{31} s^2_{13} \\ \mathrm{IO}: \; m^2_\ell + \Delta m^2_{21} c^2_{13} s^2_{12} - \Delta m^2_{31} c^2_{13} \end{cases}$$

Present bound: $m_{\nu_e} \leq 2.0$ eV (95% CL Mainz&Troisk exp)

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

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



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

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

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

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

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

COSMO for Dirac or Majorana

m_ν affect growth of structures

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

Neutrino Mass Scale: Other Channels

Muon neutrino mass

- From the two body decay at rest

$$\pi^- \to \mu^- + \overline{\nu}_\mu$$

- Energy momentum conservation:

$$m_\pi = \sqrt{p_\mu^2 + m_\mu^2} + \sqrt{p_\mu^2 + m_\nu^2}$$
$$m_\nu^2 = m_\pi^2 + m_\mu^2 - 2 + m_\mu \sqrt{p^2 + m_\pi^2}$$

- Measurement of p_μ plus the precise knowledge of m_π and $m_\mu \Rightarrow m_\nu$
- The present experimental result bound:

$$\boxed{m_{\nu_\mu}^{eff} \equiv \sqrt{\sum m_j^2 |U_{\mu j}|^2} < 190 \text{ KeV}}$$

Tau neutrino mass

- The τ is much heavier $m_\tau = 1.776$ GeV

$\Rightarrow$ Large phase space $\Rightarrow$ difficult precision for m_ν

- The best precision is obtained from hadronic final states

$$\tau \to n\pi + \nu_\tau \quad \text{with } n \geq 3$$

- Lep I experiments obtain:

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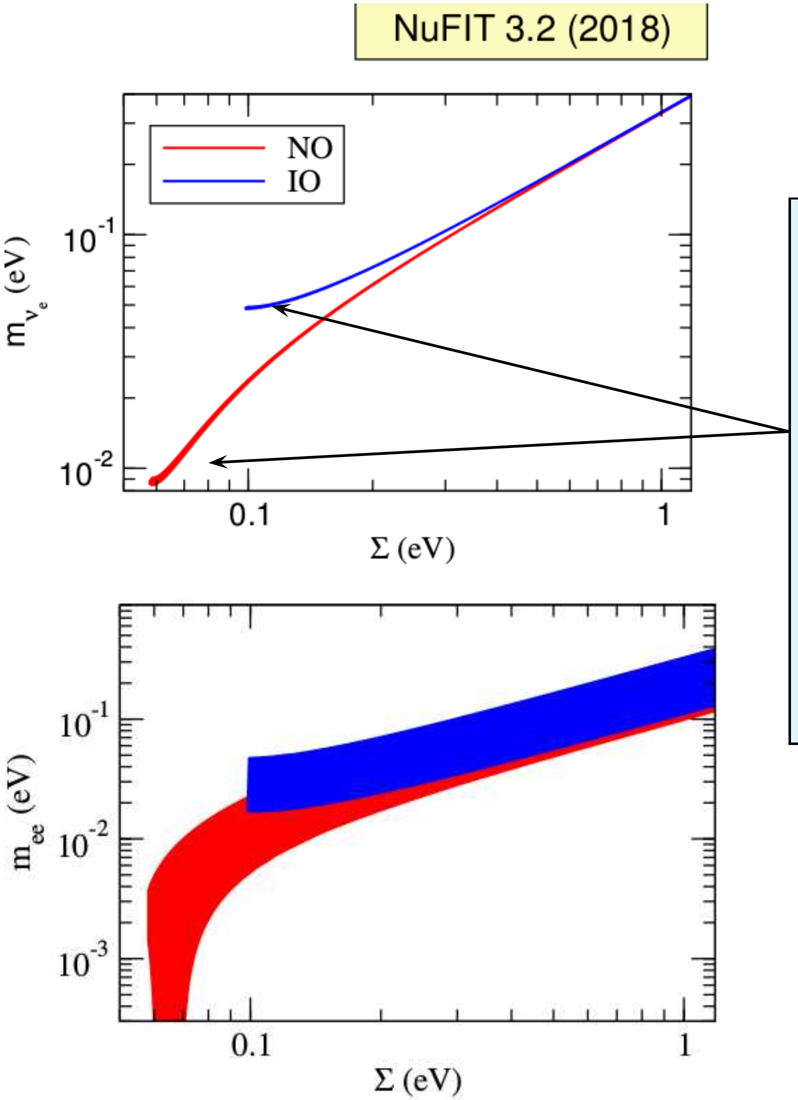
⇒ Mixing angles U_{ej} are not negligible

Best kinematic limit on Neutrino Mass Scale comes from Tritium Beta Decay

Purely kinematics ⇒ Only model independent probe ν-mass scale

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))



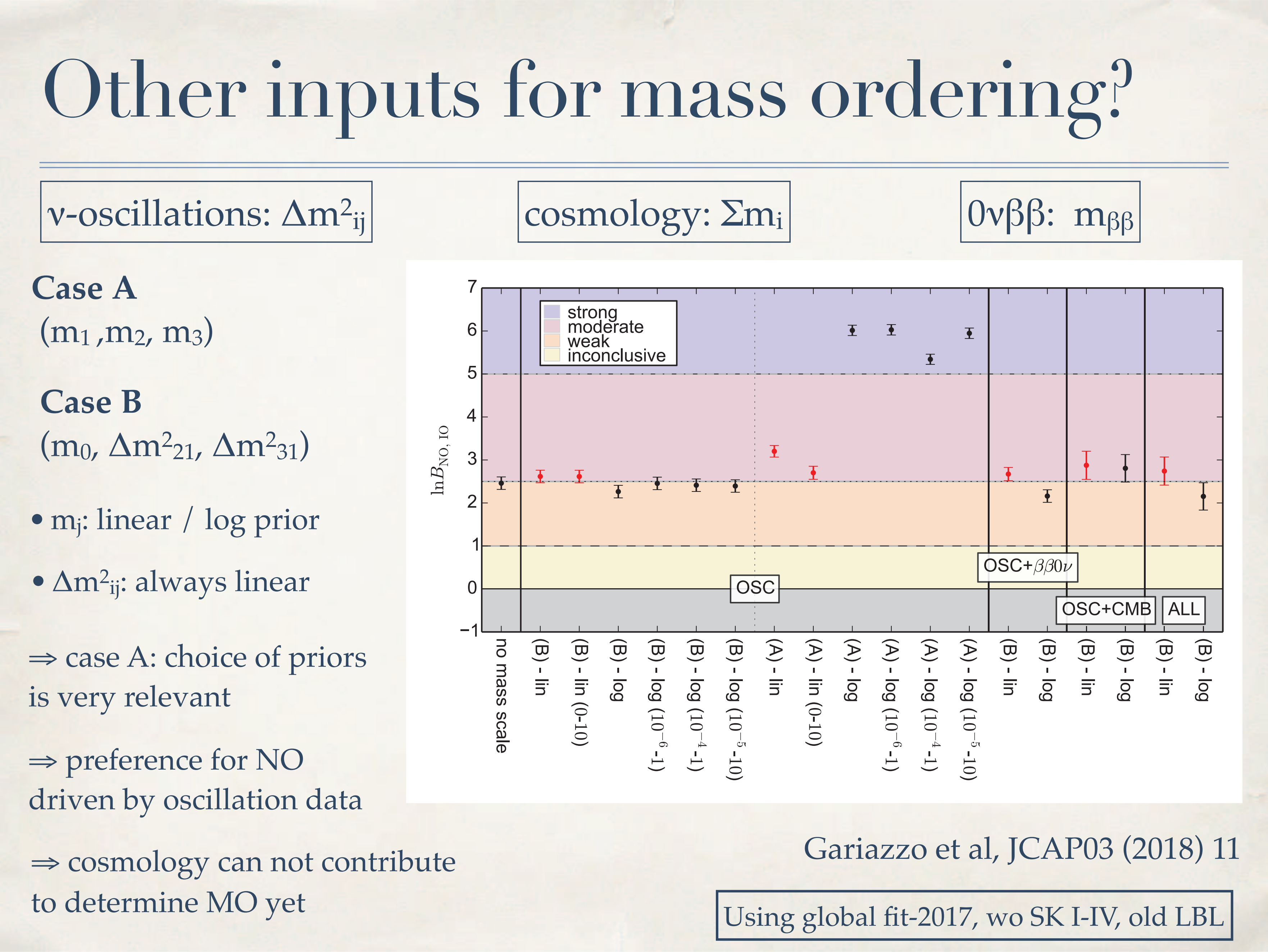
Lower bound on $\sum m_i$ depends on ordering

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?

Ordering: The Cosmo-Lab Connection



Other inputs for mass ordering?

ν-oscillations: Δm^2_{ij}

cosmology: Σm_i

0νββ: $m_{\beta\beta}$

Case A
(m_1, m_2, m_3)

Case B
(m_0, Δm^2_{21}, Δm^2_{31})

- m_j: linear / log prior
- Δm^2_{ij}: always linear

⇒ case A: choice of priors is very relevant

⇒ preference for NO driven by oscillation data

⇒ cosmology can not contribute to determine MO yet

Gariazzo et al, JCAP03 (2018) 11

Using global fit-2017, wo SK I-IV, old LBL

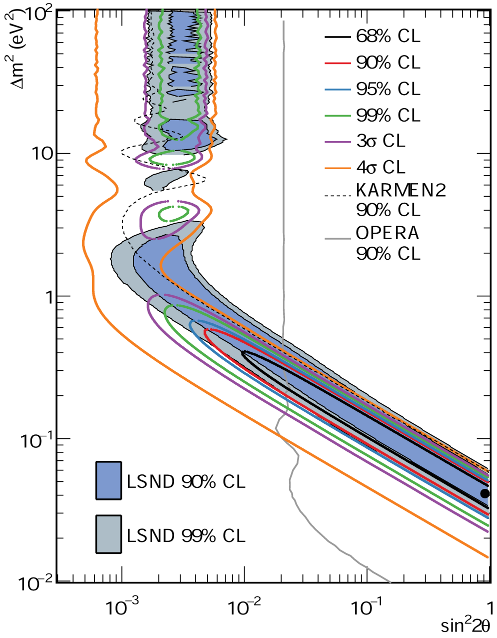
Slide from M. Tortola Talk at ν2018

Beyond 3ν's: Light Sterile Neutrinos

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

LSND, MiniBoone

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



From LSND mid 90's
to MiniBoone 1805.12028

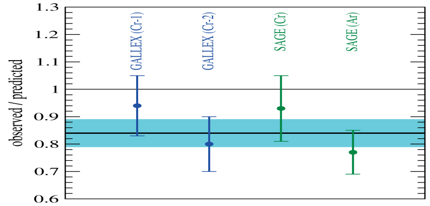
Gallium Anomaly

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

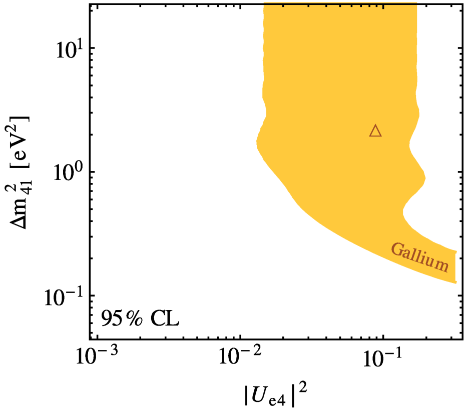
Radioactive Sources (^{51}Cr, ^{37}Ar)
in calibration of Ga Solar Exp;

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

Give a rate lower than expected



Explained as ν_e disappearance

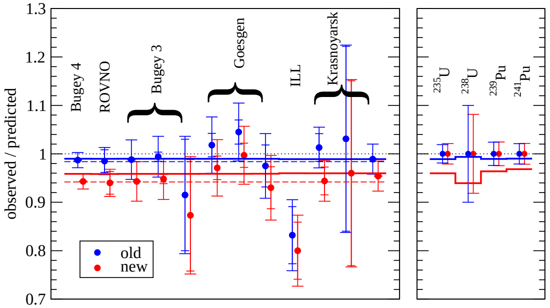


Reactor Anomaly

Huber, 1106.0687
Mention *etal* ,1101.2755

New reactor flux calculation

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



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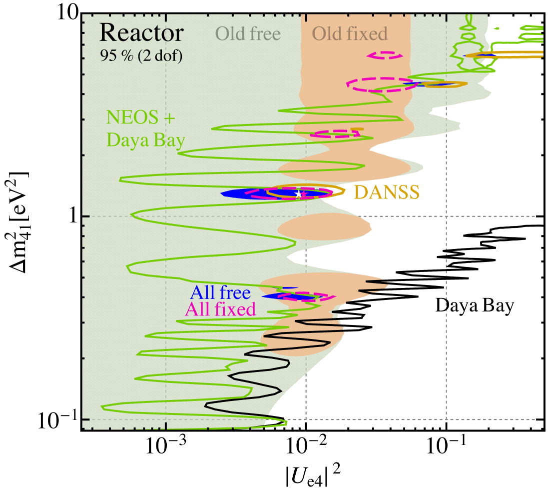
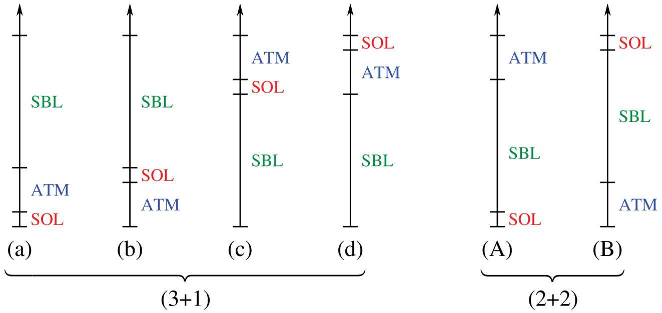


Denler etal, 1803.10661

Light Sterile Neutrinos

- These explanations require $\mathcal{O}$(eV) mass ν_s



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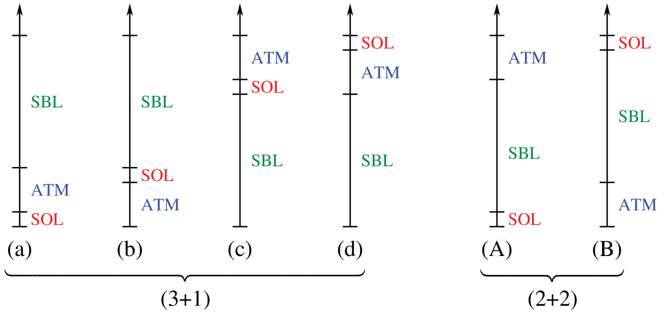
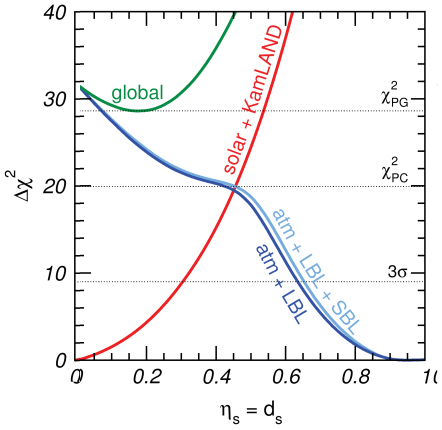


- 2+2:



Ruled out by solar and atm data ($\gtrsim 5\sigma$)

Maltoni *etal* NPB 02

Light Sterile Neutrinos

Concha Gonzalez-Garcia

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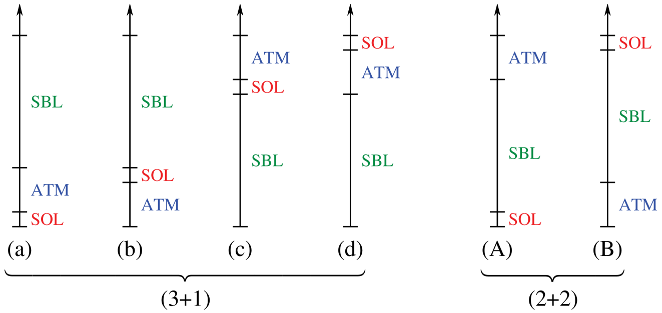

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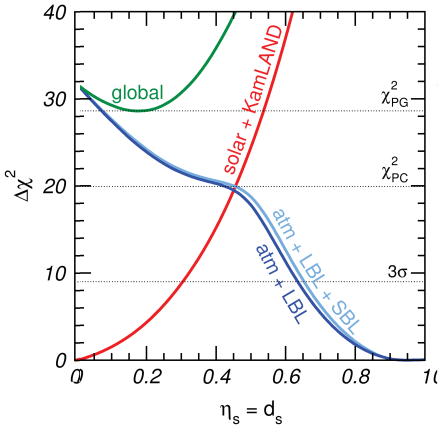
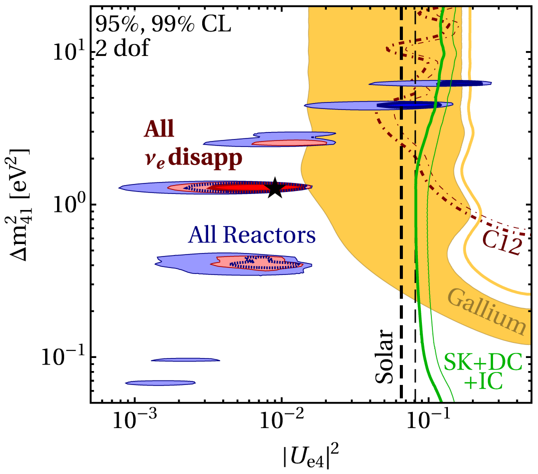


Ruled out by solar and atm data ($\gtrsim 5\sigma$)

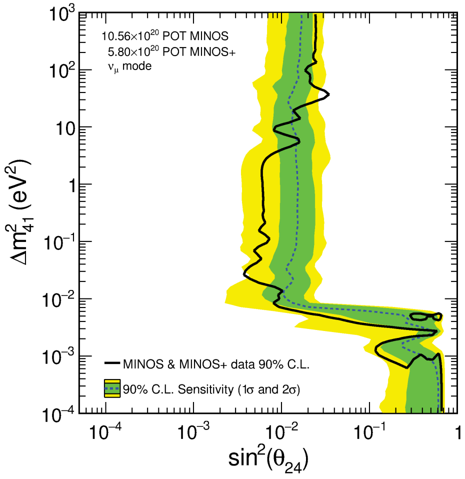
Maltoni *etal* NPB 02

- 3+1: Generically appearance $P_{e\mu} \sim |U^*_{ei} U_{\mu i}| \begin{cases} |U_{ei}| \text{ constrained by } P_{ee} \text{ disapp data} \\ |U_{\mu i}| \text{ constrained by } P_{\mu\mu} \text{ disapp data} \end{cases}$

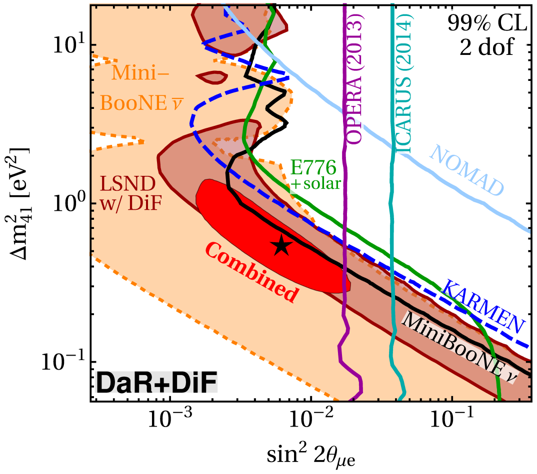
ν_e disapp



ν_μ disapp



ν_e app



III. Sterile neutrino models and ν_μ disappearance

(3+1): robustness of the result

- The tension cannot be eliminated by discarding any *individual* experiment.

Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	χ^2_{PG}/dof	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.7×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$-dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$-dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$-dis+solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

Conclusions at ICHEP02

- Big experimental effort: flavor conversion proved

  Solar $\nu' s$: Verification of Flavour Conversion ν_e to ν_μ or ν_τ at 5 σ
  Atmospheric ν_μ's disappear ($> 15\sigma$) most likely to ν_τ

- Most likely explanation is neutrino oscillation and soon this will be tested with “man-made” neutrino beams from reactor and accelerators

- ν masses imply physics beyond the standard model

- Further advance requires more and more precise data

Conclusions at ICHEP12

- First ICHEP with the three leptonic mixing angles determined (at $\pm 3\sigma/6$)

$\Delta m^2_{21} = 7.5 \times 10^{-5}$ eV^2 (2.4%)

$\Delta m^2_{31} = 2.45 \times 10^{-3}$ eV^2
$|\Delta m^2_{32}| = 2.43 \times 10^{-3}$ eV^2 (2.8%)

$\sin^2\theta_{12} = 0.3$ (4%) $\sin^2\theta_{23} = 0.42$ (11%) $\sin^2\theta_{13} = 0.023$ (10%)

- Still ignore or not significantly seen
  - Majorana or Dirac?
  - Absolute ν mass
  - CP violation in leptons?
  - Normal or Inverted Ordering?
  - θ_{23} Octant

$\Rightarrow$ New experiments beyond approved needed to answer these questions

ν masses are BSM physics effects to be put together with *all other NP effects*:
from charged LFV, Collider signals, Cosmo-astroparticle…to establish
the Next Standard Model