MASSIVE NEUTRINOS CIRCA 2017

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INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS

Neutrinos in Cosmology, Astro-, Particle- and Nuclear Physics

Erice-Sicily: September 16-24, 2017

OUTLINE

The confirmed picture: 3ν Lepton Flavour Parameters

A partial list of Q&A

http://www.nu-fit.org

Neutrinos in the Standard Model

The SM is a gauge theory based on the symmetry group

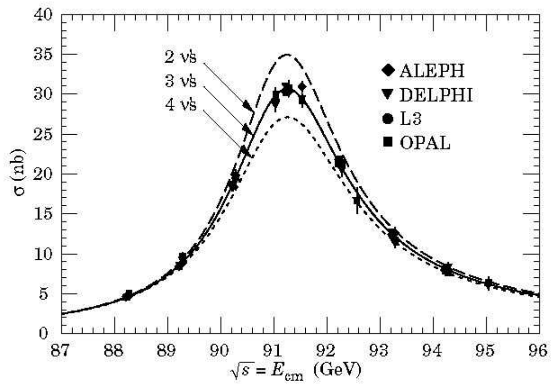
$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

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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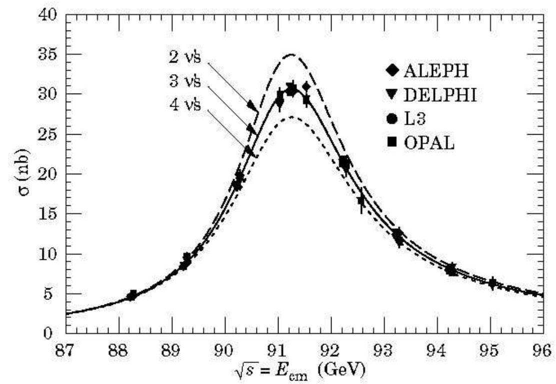

There is no ν_R

$\Downarrow$

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**)
  - $*$ Some accelerator ν_μ appear as ν_e at $L \sim 300/800$ Km (**T2K**, MINOS,NOνA)
  - $*$ Solar ν_e convert to ν_μ/ν_τ (Cl, Ga, **SK, SNO, Borexino**)
  - $*$ Reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km (**KamLAND**)
  - $*$ Reactor $\overline{\nu_e}$ disappear at $L \sim 1$ Km (D-Chooz, **Daya Bay, Reno**)

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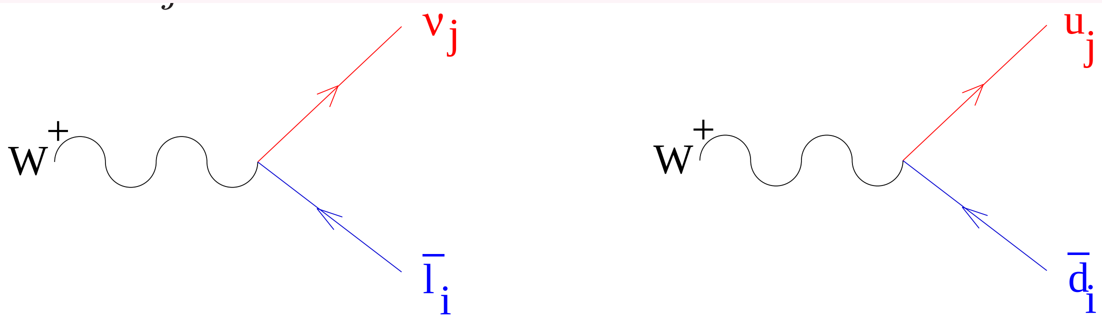
- The charged current interactions of leptons are not diagonal (same as quarks)

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



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

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

- $U_{\rm LEP}$: $3 + 3s$ 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:

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

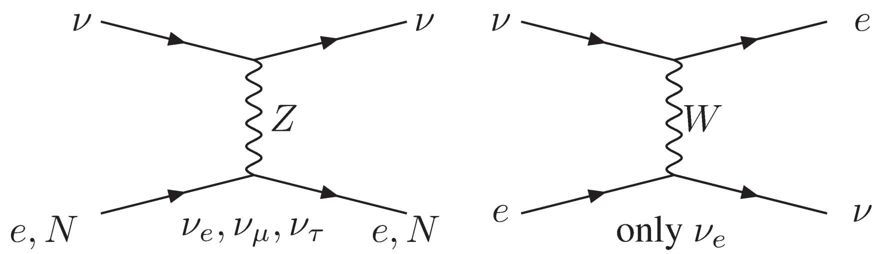
$$P_{osc} = \sin^2(2\theta)\, \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right) \qquad \text{Appear}$$

$\Rightarrow$ No info on sign of Δm^2 and θ octant

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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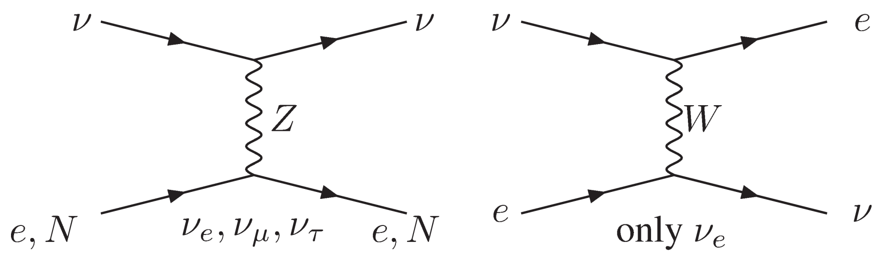

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$\Rightarrow$ *Modification of mixing angle and oscillation wavelength* (MSW)

- 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

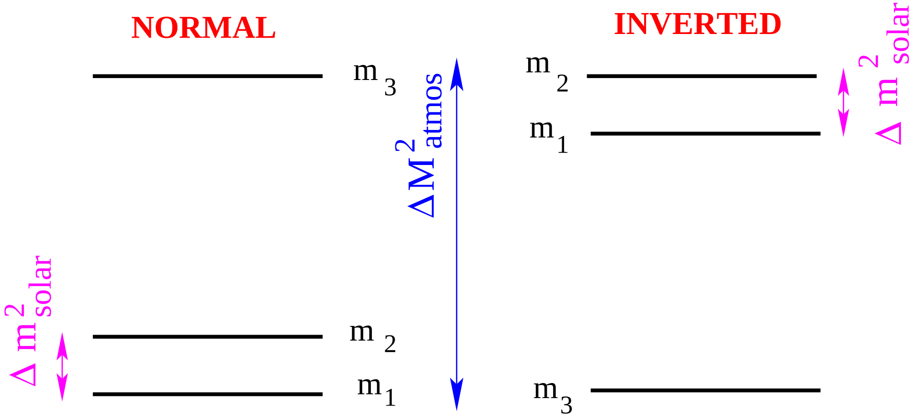
and θ octant

3ν Flavour Parameters

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

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

- Two Possible Orderings



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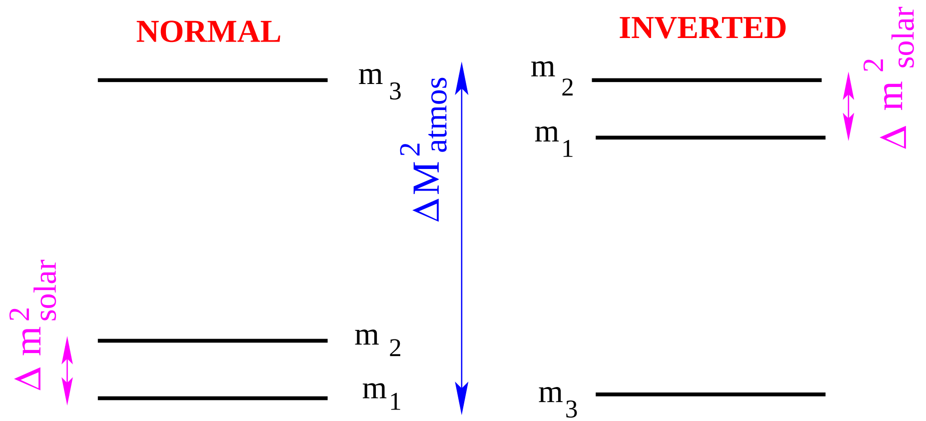
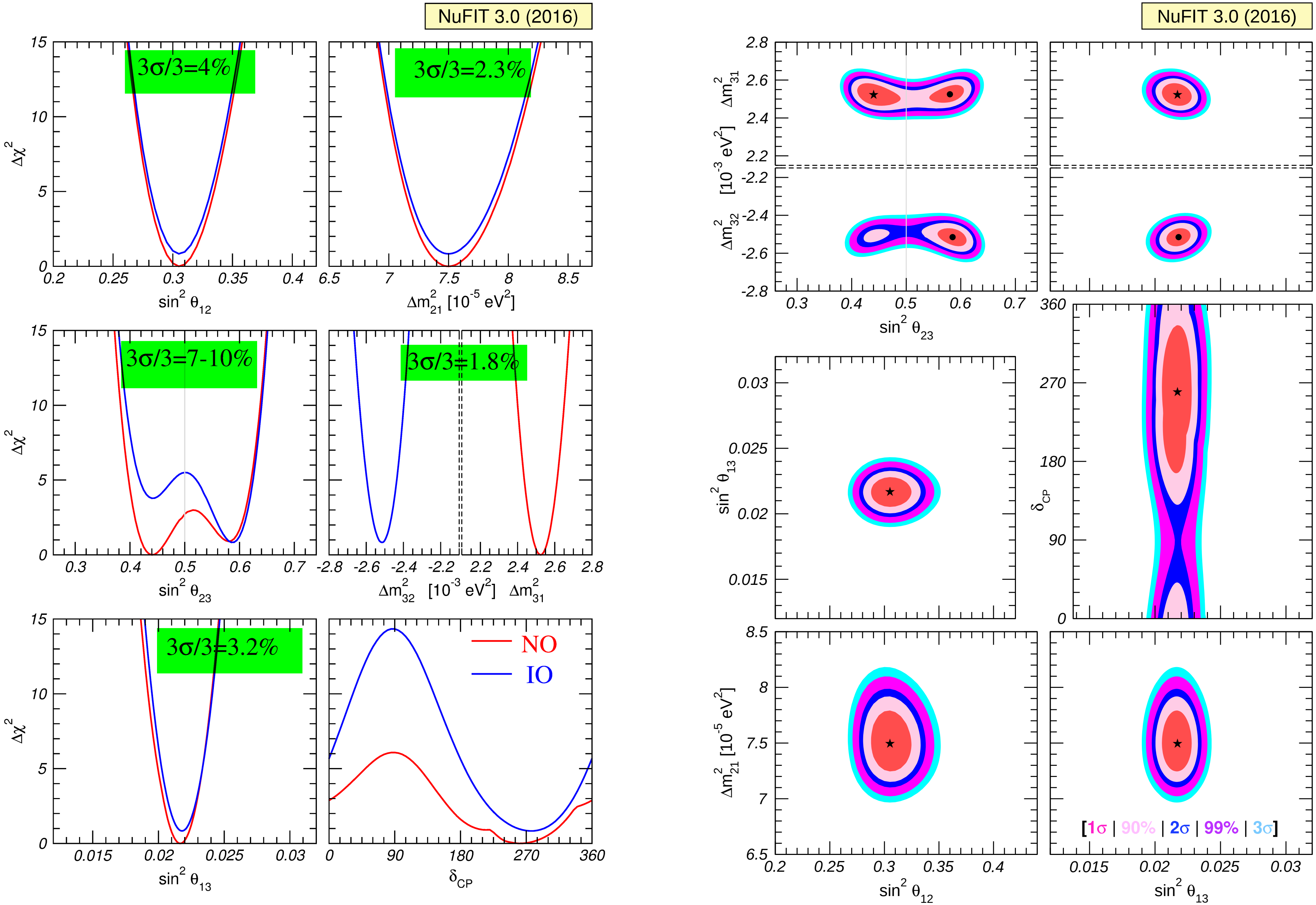


Experiment	Dominant Dependence	Important Dependence
Solar Experiments	$\to \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\to \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	$\to \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\to \theta_{23}$	$\Delta m^2_{\rm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

3 ν Flavour Parameters: Status June 2017

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

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



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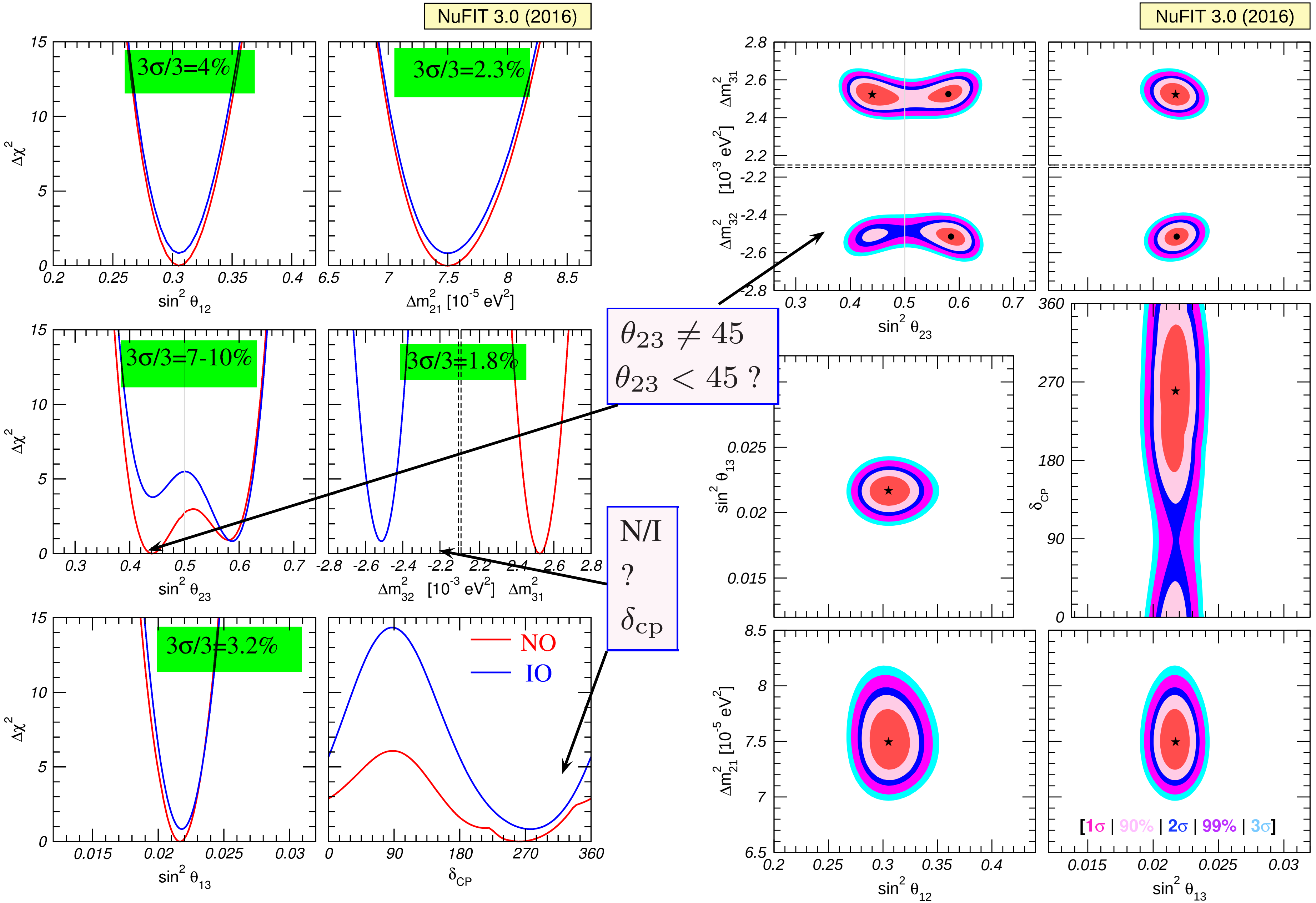

3 ν Flavour Parameters: Status Sept 2017

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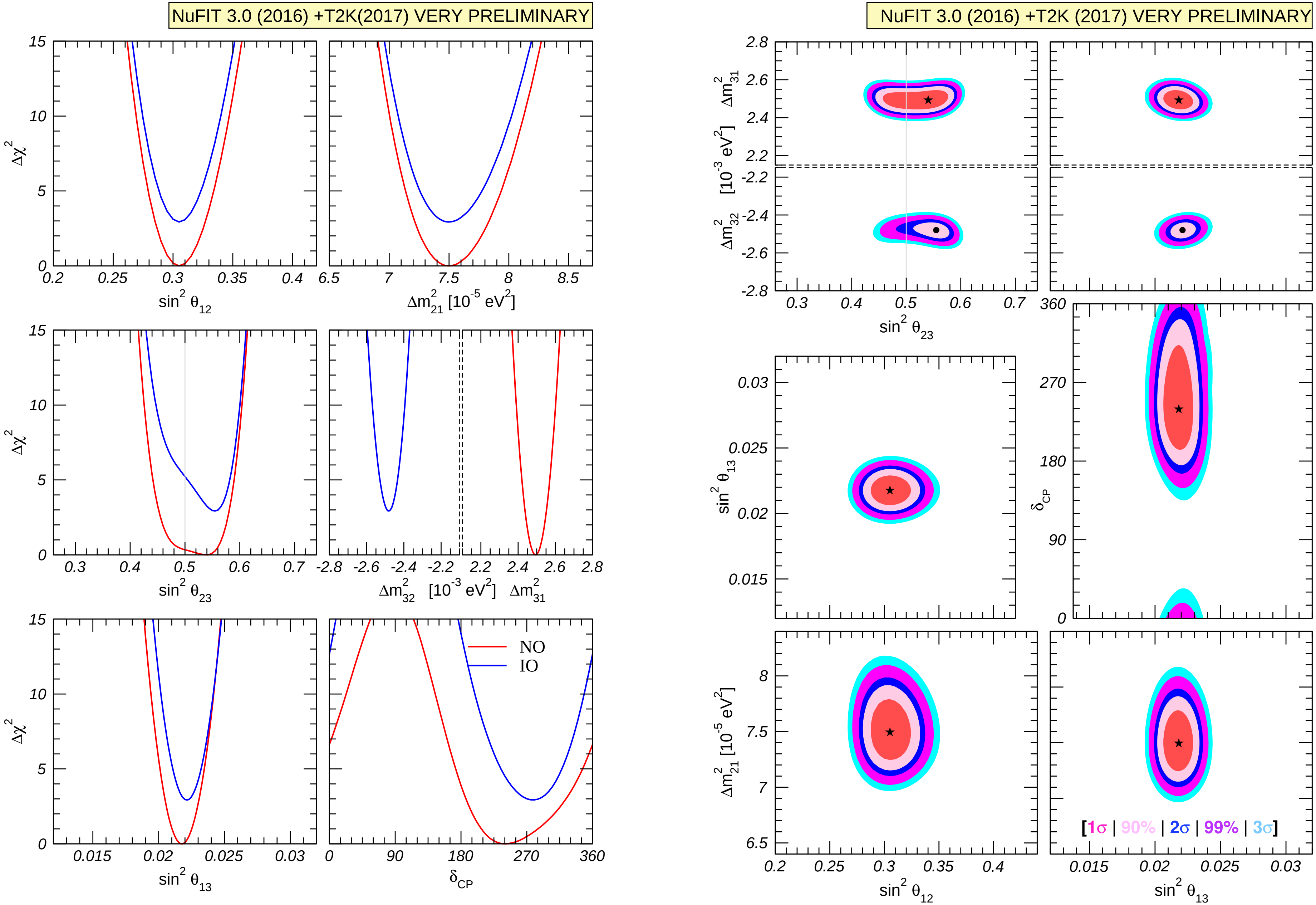
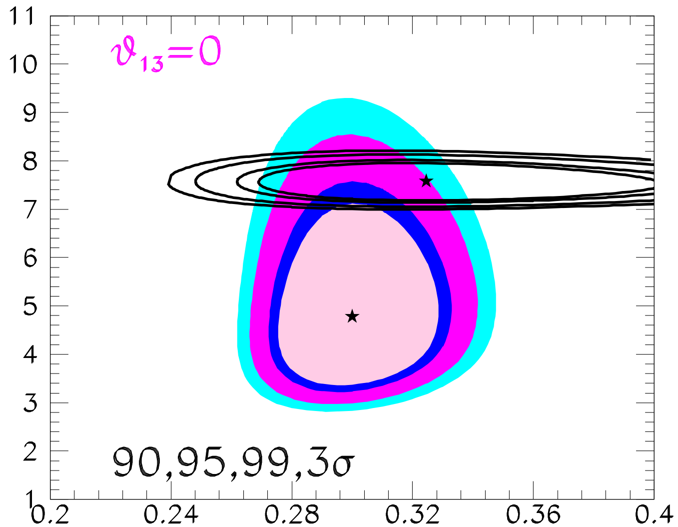
Esteban, Maltoni, Martinez-Soler, Schwetz, MCG-G effect OF T2K (2017) VERY PRELIMINARY



3 ν Analysis: "12" Sector and θ_{13}

• For $\theta_{13} = 0$



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

• When θ_{13} increases

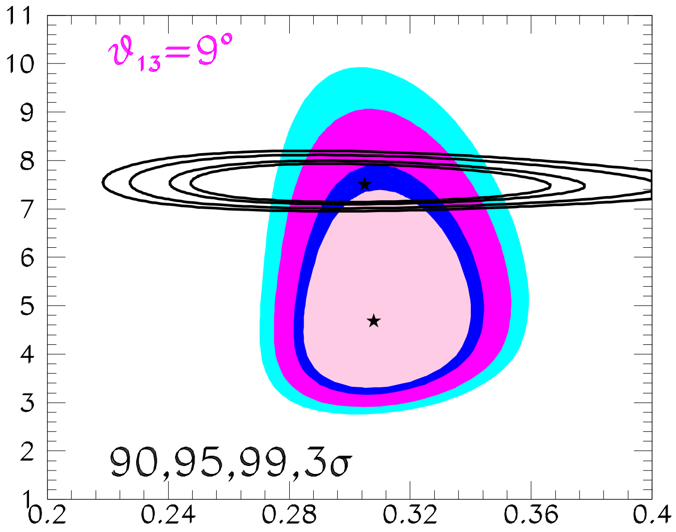
$$P_{ee} \simeq \begin{cases} \text{Solar High E}: c_{13}^4 \sin^2 2\theta_{12} \\ \text{Solar Low E}: c_{13}^4 \left(1 - \sin^2 2\theta_{12}/2\right) \\ \text{Kam}: c_{13}^4 \left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{21}^2 L}{4E}\right) \end{cases}$$

$\Rightarrow$ KamLAND region shifts left

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

3 ν Analysis: "12" Sector and θ_{13}

- For $\theta_{13} \simeq 9°$



⇒ Good match of best fit θ_{12}

⇒ Residual tension on Δm^2_{21}

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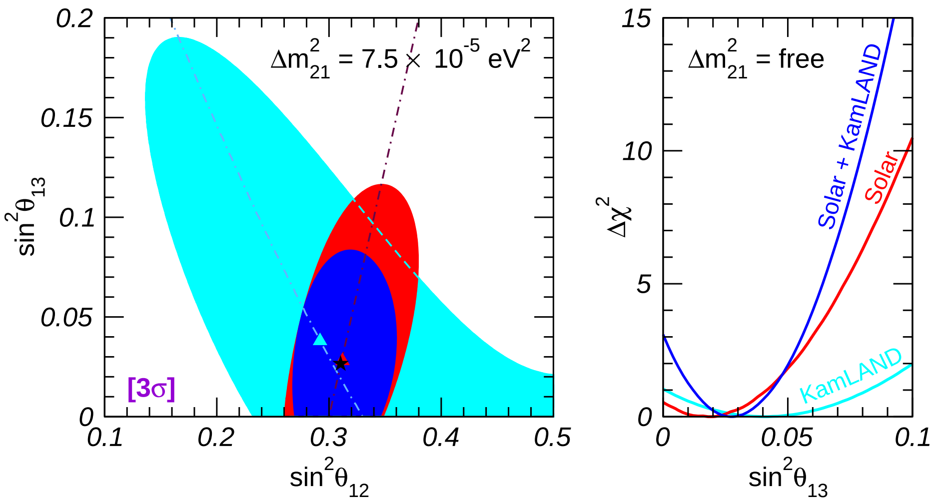
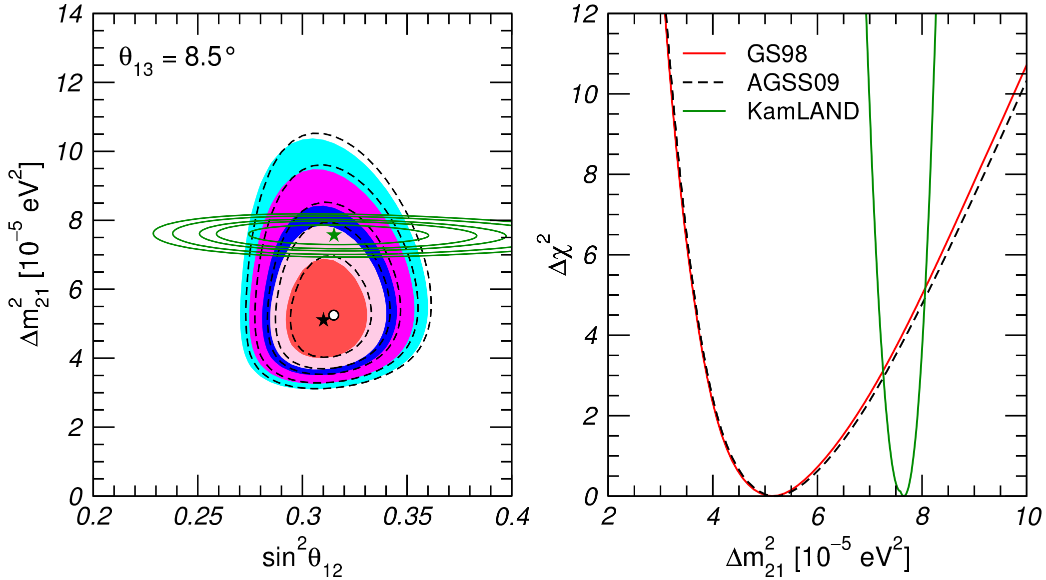


3 ν Analysis: Δm^2_{21} KamLAND vs SOLAR

For $\theta_{13} \simeq 9^\circ$ θ_{12} OK. But residual tension on Δm^2_{12} NuFIT 3.0 (2016)



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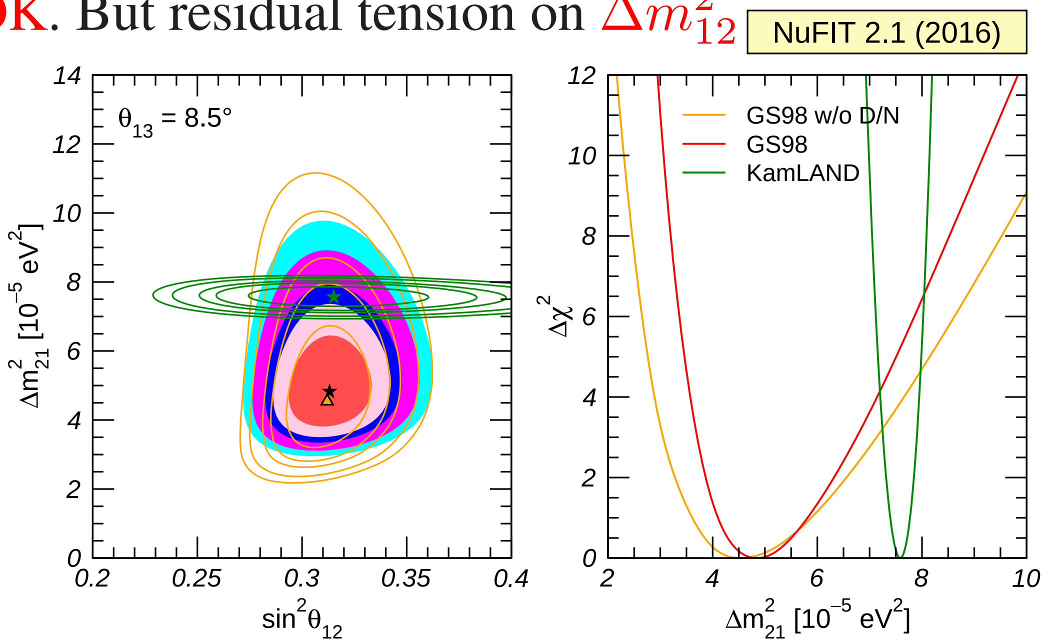
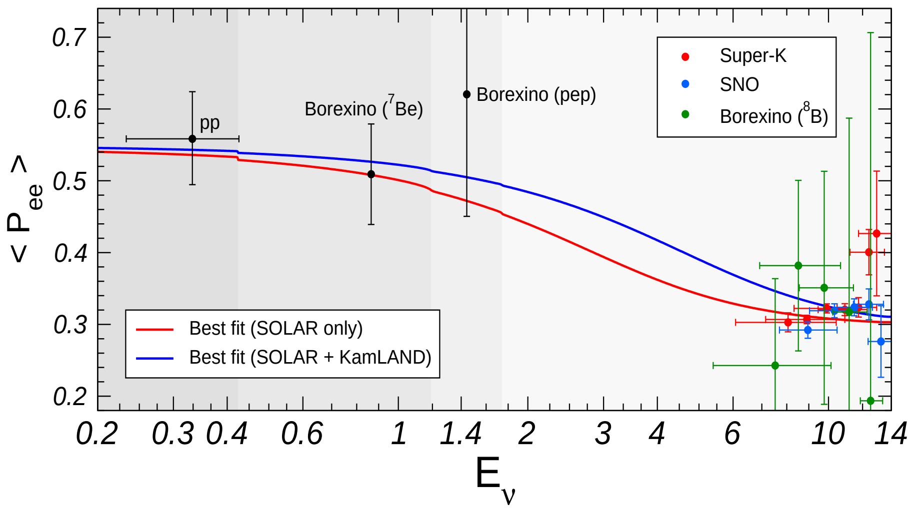


Tension related to: a)“too large” of Day/Night at SK



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

Modified matter potential? More latter . . .

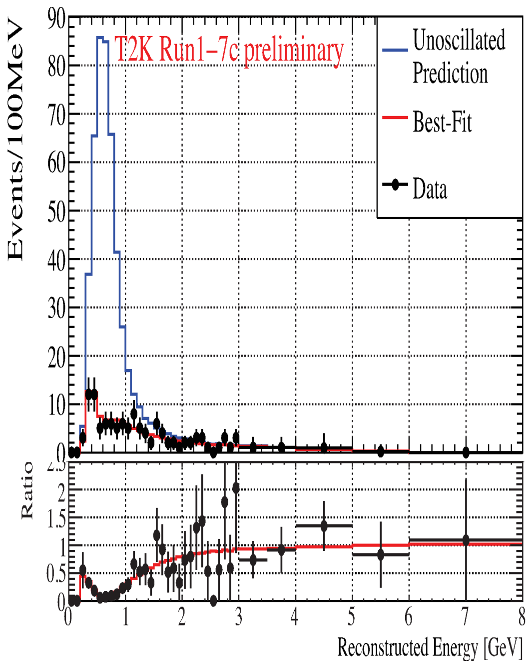
3 ν Analysis: θ_{23}

- Best determined in ν_μ and $\bar{\nu}_\mu$ disapperance in LBL

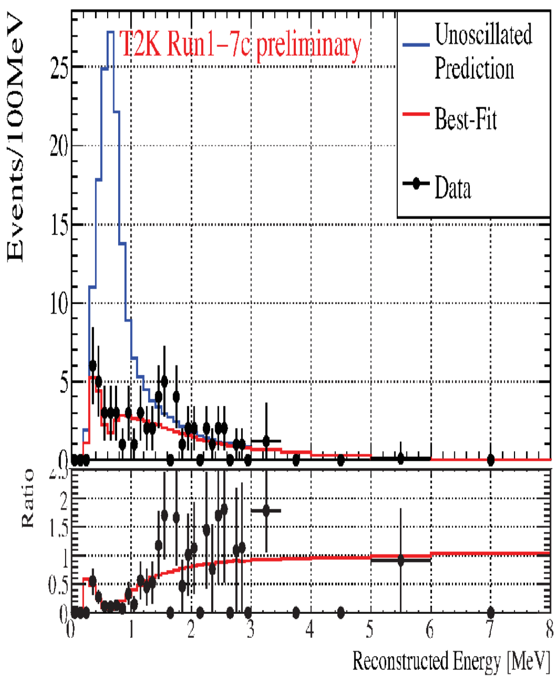
$$P_{\mu\mu} \simeq 1 - (c_{13}^4 \sin^2 2\theta_{23} + s_{23}^2 \sin^2 2\theta_{13}) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + \mathcal{O}(\Delta m_{21}^2)$$

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

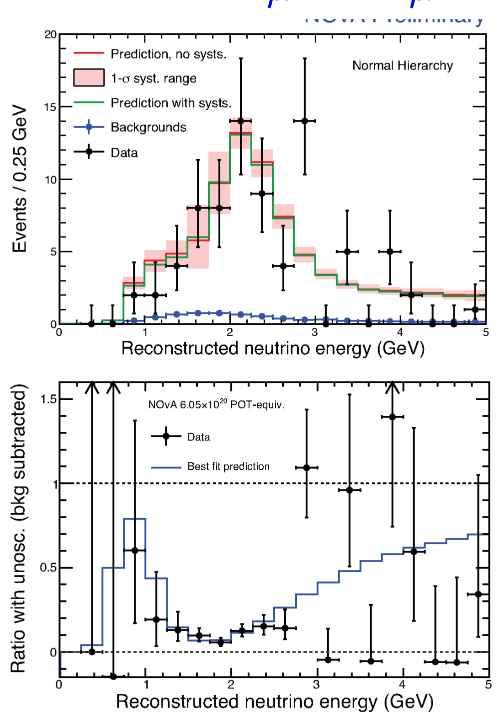
T2K $\nu_\mu \to \nu_\mu$



T2K $\bar{\nu}_\mu \to \bar{\nu}_\mu$



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



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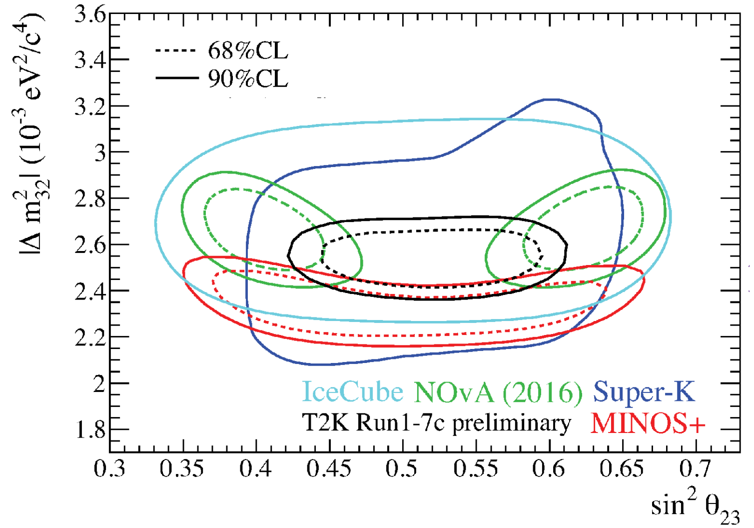
- Allowed regions by the different experiments:



In making this figure θ_{13} is constrained by prior from reactor data

Caution: Not the same using θ_{13} reactor prior than combining with reactor results (because of Δm_{32}^2 in reactors)

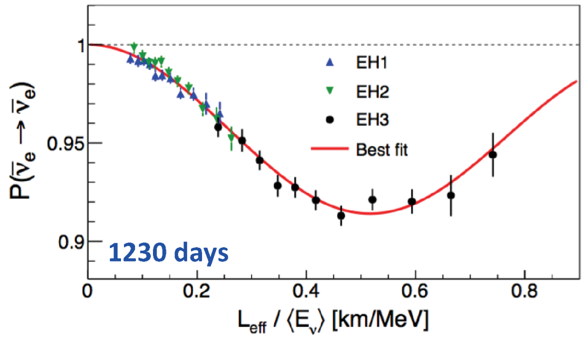
Δm^2_{23} in LBL vs Reactors

• 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

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



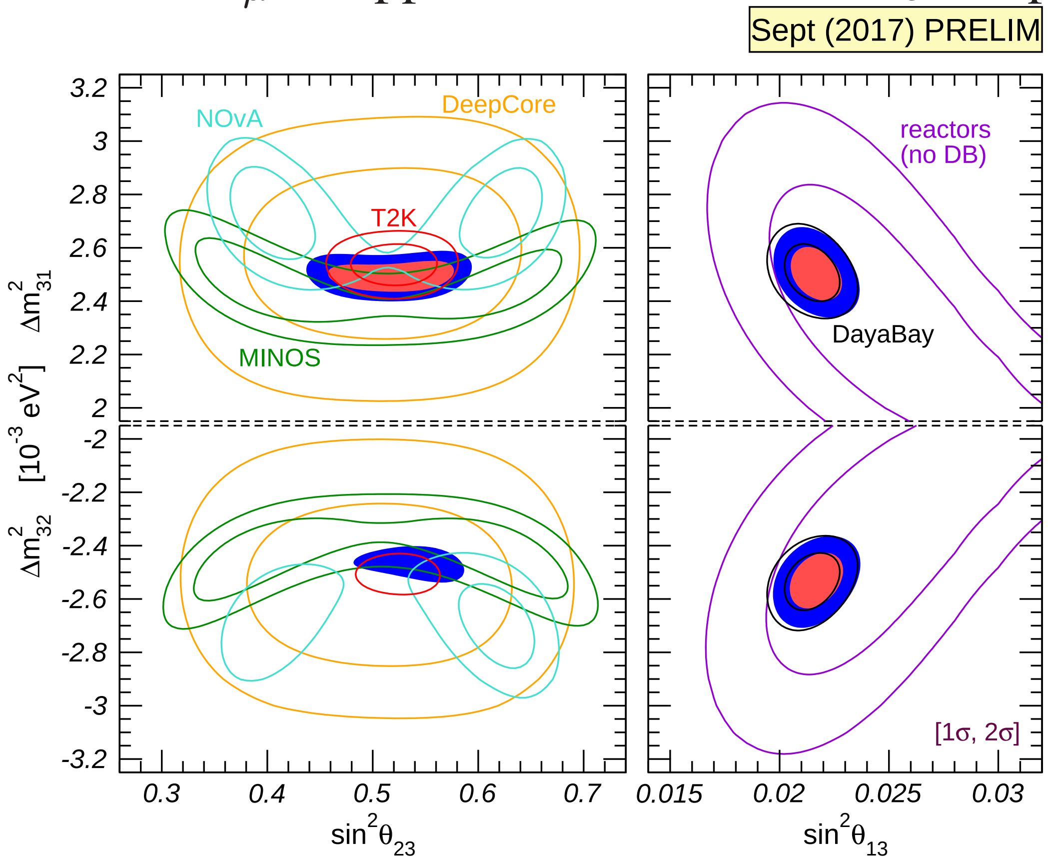
$$\Delta m^2_{ee} \simeq |\Delta m^2_{32}| \pm c^2_{12}\Delta m^2_{21} \simeq |\Delta m^2_{32}| \pm 0.05 \times 10^{-3}\ \mathrm{eV}^2$$

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 values of $|\Delta m^2_{32}|$

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

– T2K (2017) slight fav $\theta_{23} > 45$

Leptonic CP Violation

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

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

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

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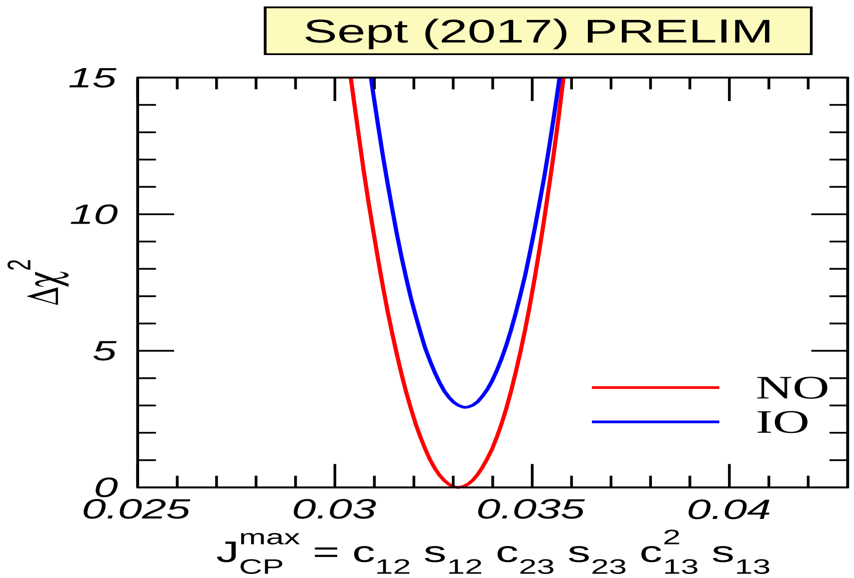
$$J^{\max}_{\text{LEP,CP}} = \frac{1}{8} c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$

- Maximum Allowed Leptonic CPV:



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

to compare with

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

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

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

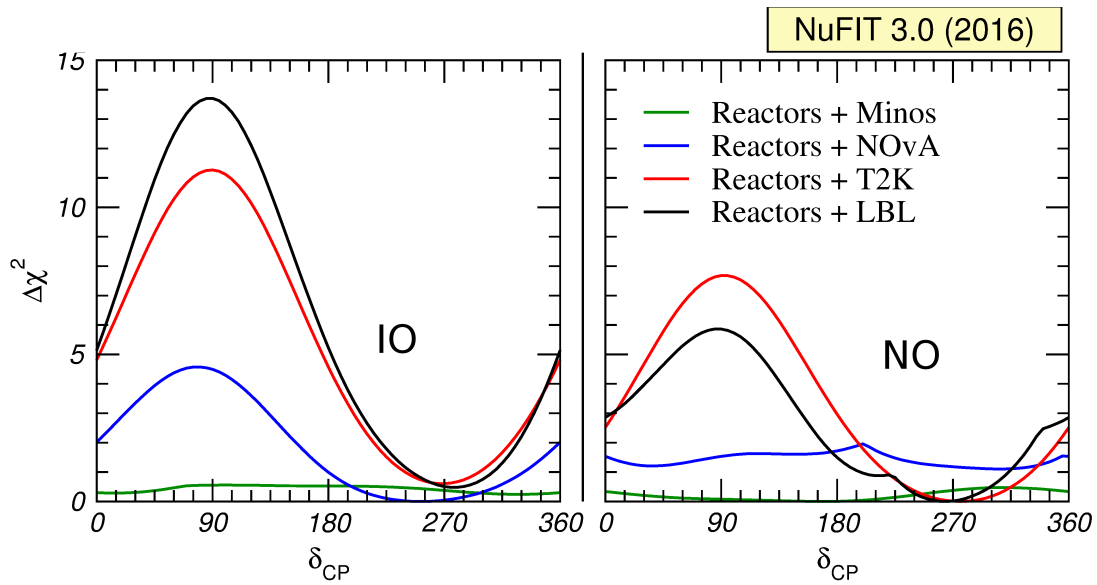
Leptonic CP Phase

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

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

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

Before T2K (2017)



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

– CP conserv at 70% (NO), 97% (IO)

– Driven by "fluctuation" in T2K

	ν_e		$\bar\nu_e$	
Mass hierarchy	Normal	Inverted	Normal	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	

$\Rightarrow$ One concluded :

Significance may not grow soon

Leptonic CP Phase:T2K 2017

Accumulated **14.7x10^{20}** protons-on-target (POT) in neutrino mode and **7.6x10^{20}** POT in antineutrino mode - full data set presented here

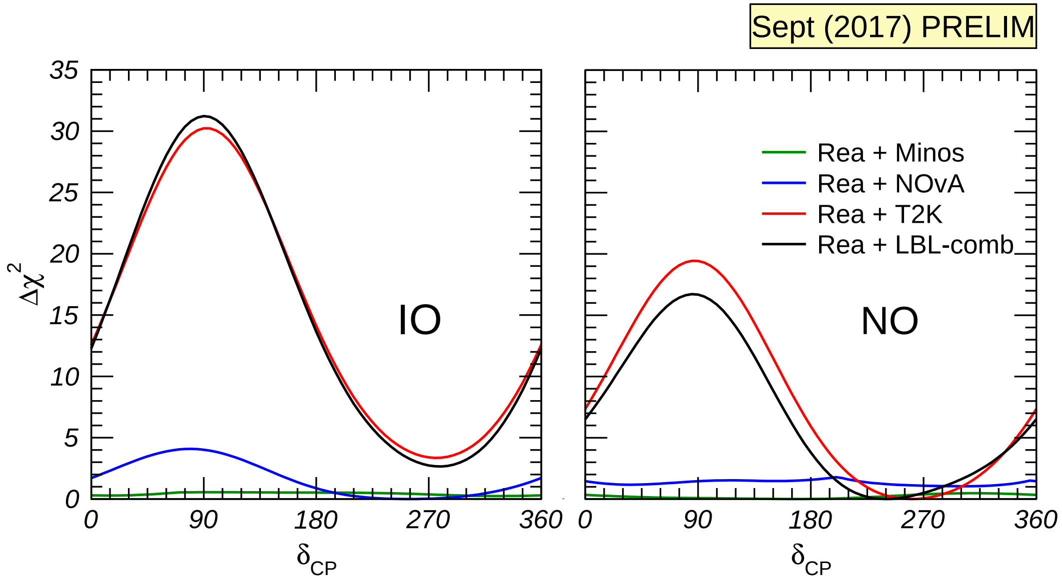
- **29% of the approved** T2K POT

	Sample	Predicted Rates				Observed
		$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
ν_e	CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
ν_e	CC1π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
$\overline{\nu_e}$	CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
ν_μ	CCQE 1-Ring μ-like FHC	267.8	267.4	267.7	268.2	240
$\overline{\nu_\mu}$	CCQE 1-Ring μ-like RHC	63.1	62.9	63.1	63.1	68

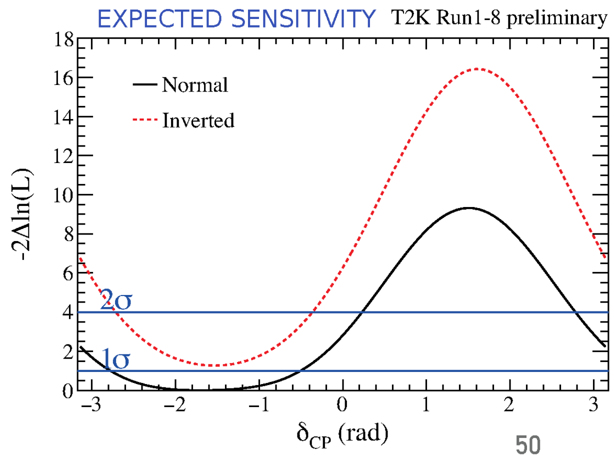
M. Hartz, KeK colloquim, August 2017

Leptonic CP Phase

Including T2K (2017) PRELIMINARY



– Best fit at $\delta_{CP} \sim 240°$
– CP conserv at 95% (NO)
– 15°–160° disfavoured at $\Delta\chi^2 > 9$
– Sill more than expected sensitiv in T2K
–$\chi^2_{min,IO} - \chi^2_{min,NO} \simeq 3$



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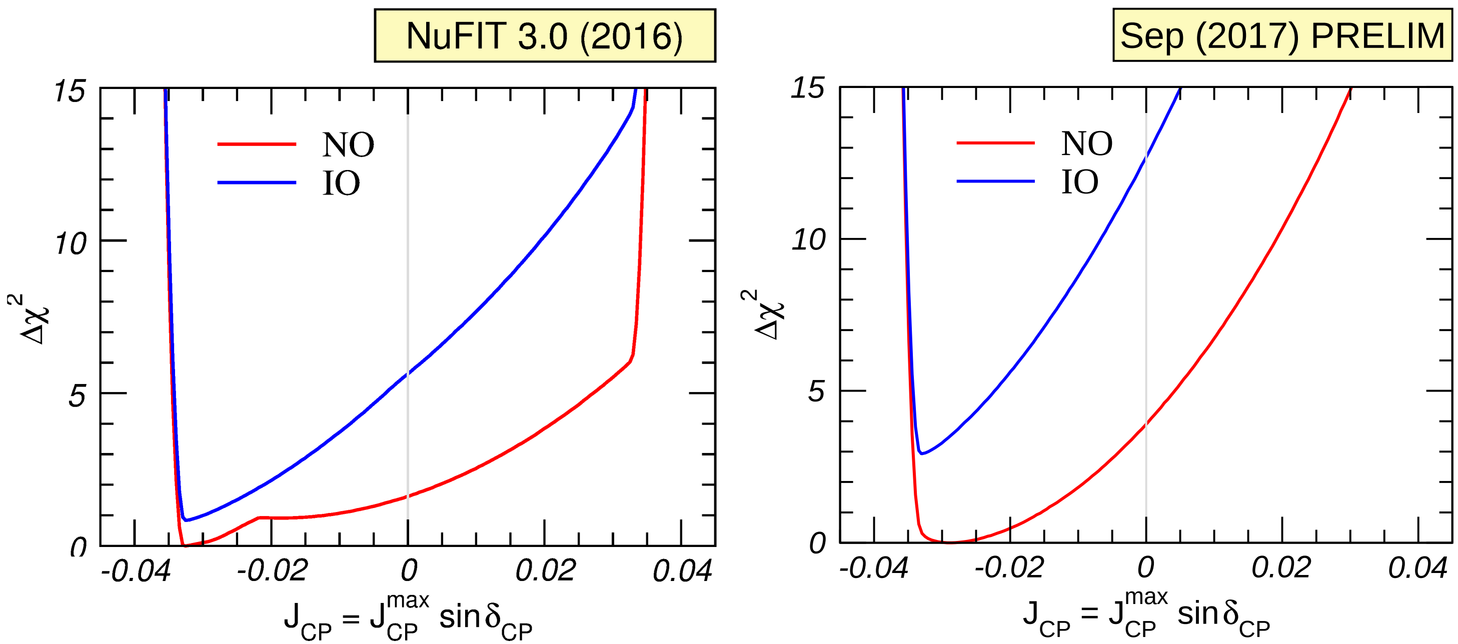
- Leptonic Jarlskog Invariant : Best fit $J_{\mathrm{LEP,CP}} = -0.030$



Confirmed Low Energy Picture and MY List of Q&A

- At least two neutrinos are massive $\Rightarrow$ There is NP
- Three mixing angles are non-zero (and relatively large) $\Rightarrow$ very different from CKM
- Leptonic CP: Best fit $J_{\rm Lep,CP} = -0.033$. CP conservation at 95% CL
- Ordering: No significant preference yet

  Requires new oscillation experiments
- 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
- Only three light states?

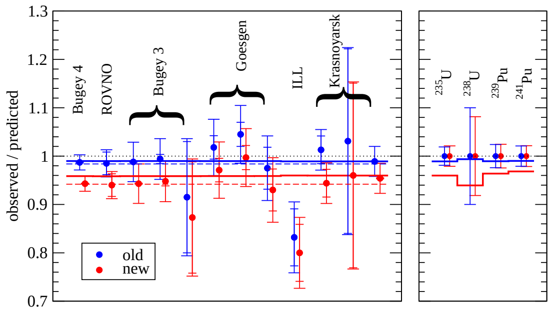
Beyond 3ν's: Light Sterile Neutrinos

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

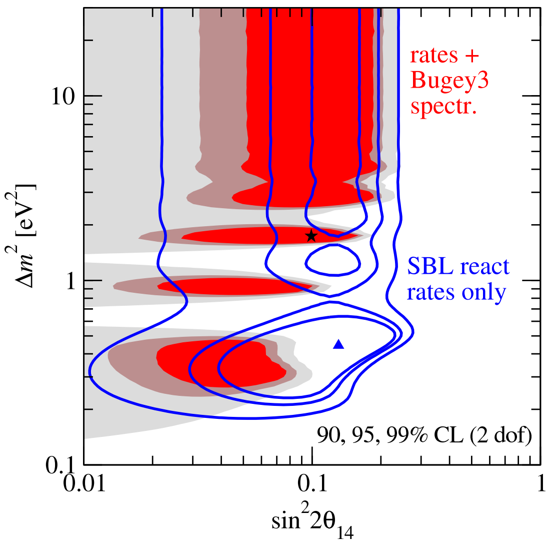
Reactor Anomaly

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

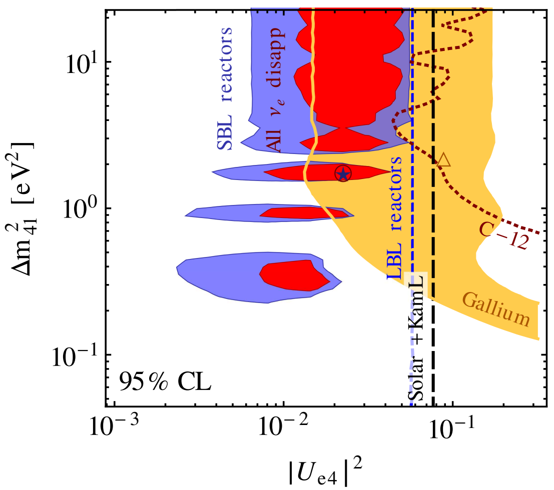
Radioactive Sources (^{51}Cr, ^{37}Ar)
in calibration of Ga Solar Exp;

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

Give a rate lower than expected

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

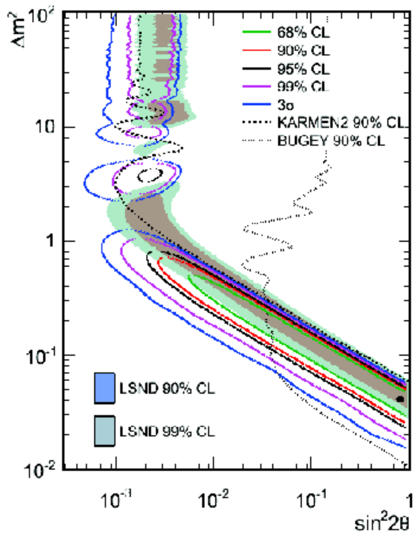
Explained as ν_e disappearance



Kopp etal, ArXiv 1303.3011

LSND, MiniBoone

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



Light Sterile Neutrinos

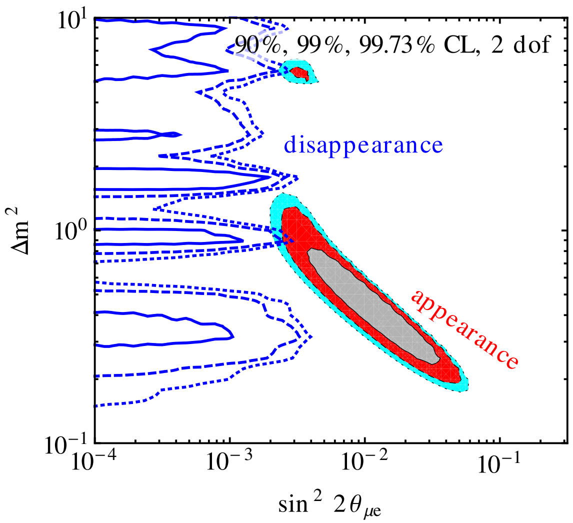
- These explanations require 3+N_s mass eigenstates $\to$ N_s sterile neutrinos

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

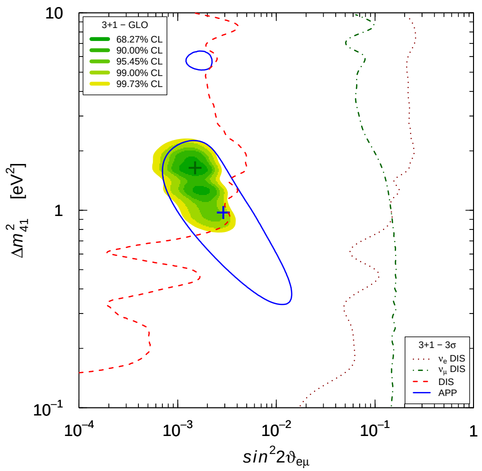
- Generically: $P(\nu_e \to \nu_\mu) \sim |U_{ei}^* U_{\mu i}|$ [i =heavier state(s)]

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

Kopp etal, ArXiv 1303.3011

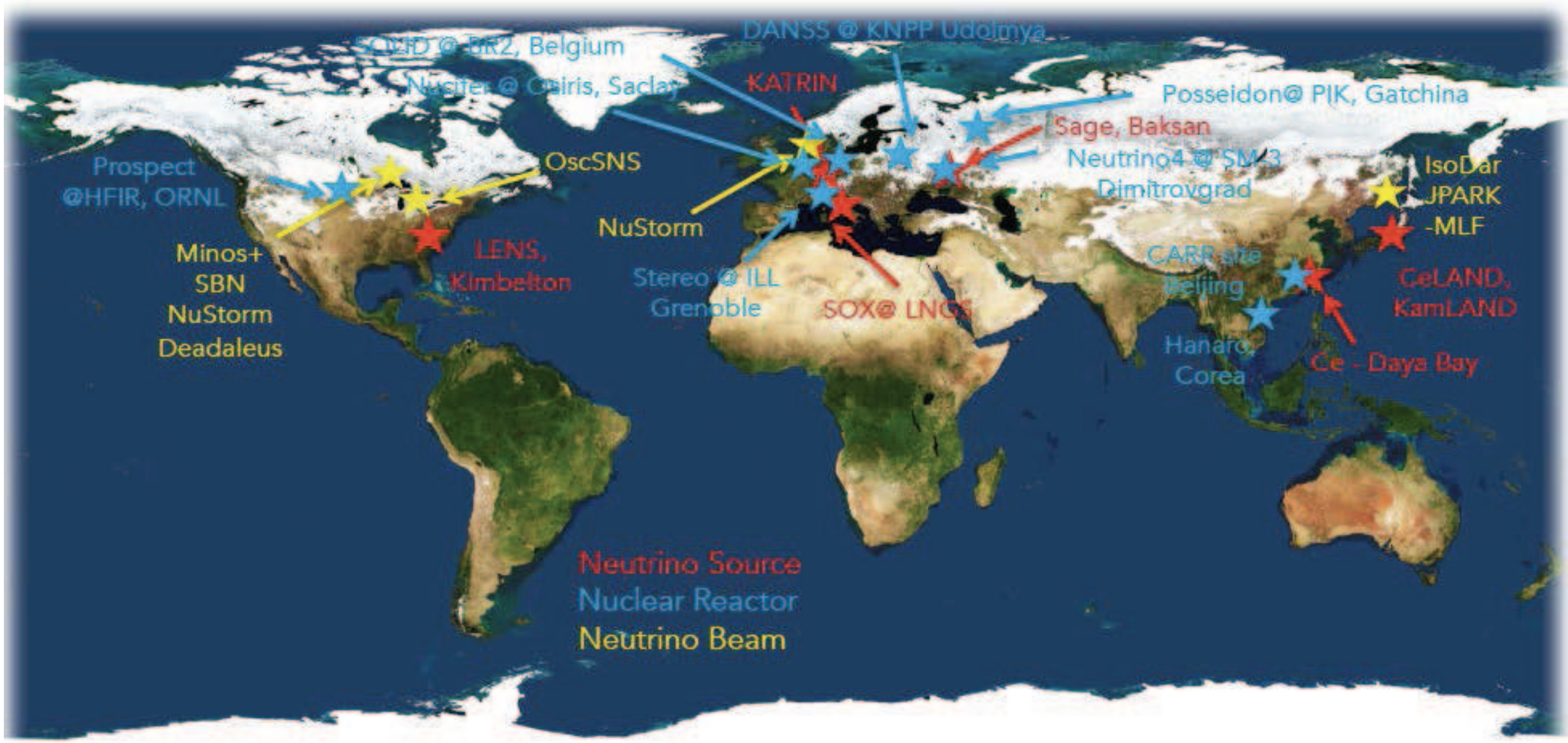


Giunti etal, ArXiv 1308.5288



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

Searches for eV sterile neutrinos



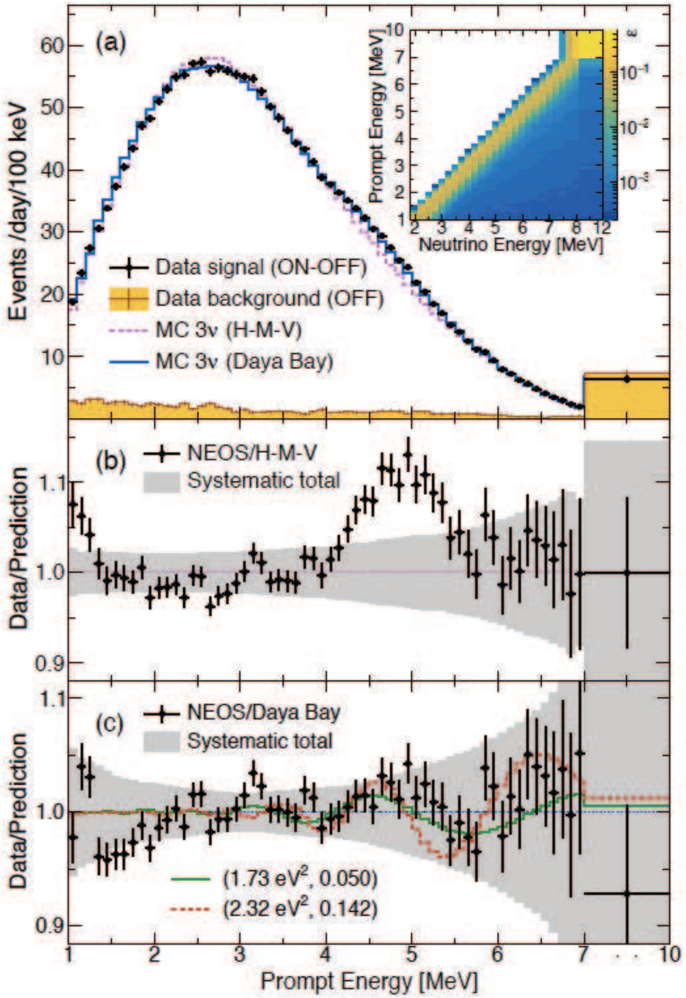
This talk: (anti-) ν_e disapearance only

$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{ee} = |U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$

Slides from S Schoener 's talk, Borex10 Workshop, Gran Sasso Sept 2017

NEOS @ Hanbit (Korea)

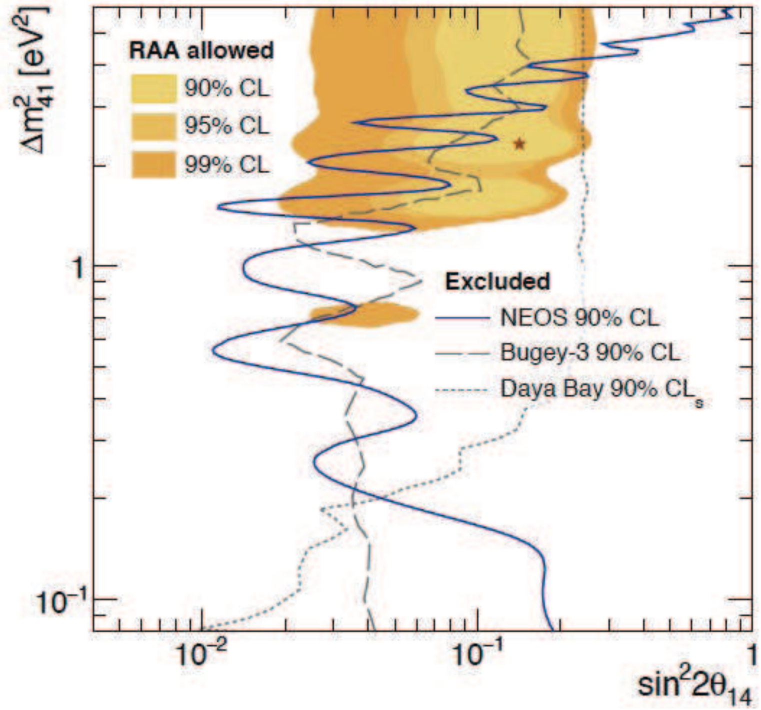
arXiv:1610.05134v4 [hep-ex] 21 Mar 2017



Single detector / single distance

Analysis done with Daya Bay spectrum as reference

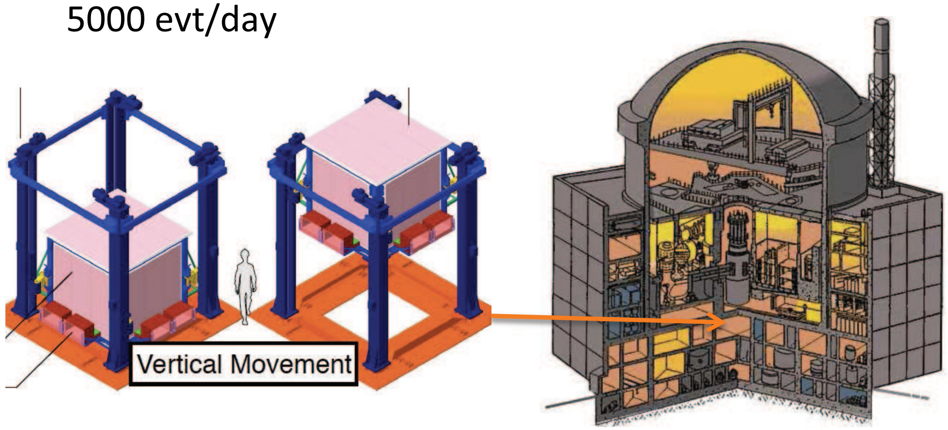
Relies on 5 MeV bumb!

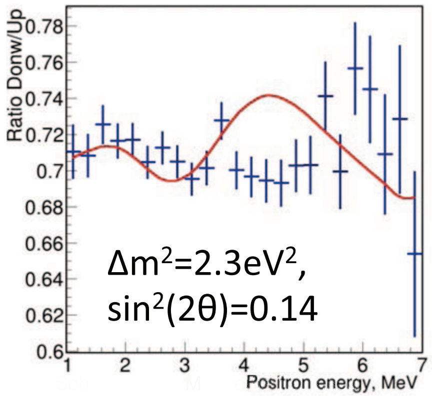


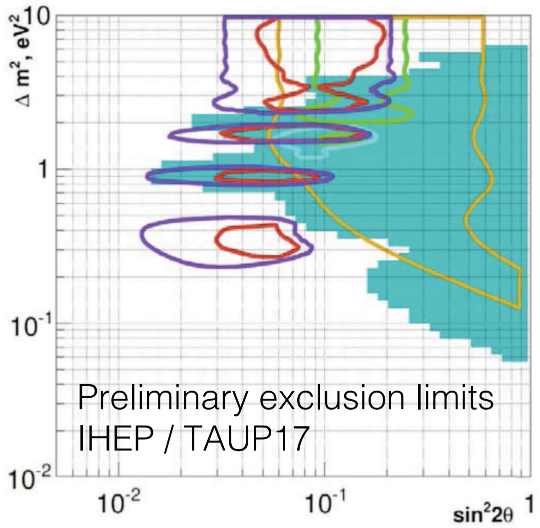
DANSS @ Kalinin

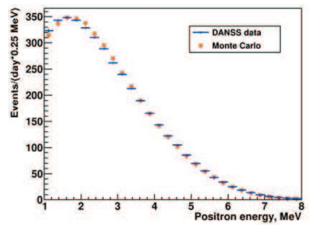
- 3 GW extended core (5000 ev/day)
- Plastic strips with Gd-loaded interlayer, WLS fibers
- Vertical motion of the detector (9.7-12.2 m)
- Independent of burn-up or spectral feature

5000 evt/day









No 5 MeV bump

⇒ Decrease of the signifcance of the reactor anomaly

Dentler etal 1709.04294

⇒ Global fit with 3+N steriles severely disfavoured unless some data is dropped

Giunti etal 1703.00860

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  Anxiously waiting for Katrin
- Dirac or Majorana?: We do not know, *anxiously* waiting for ν-less $\beta\beta$ decay
- Only three light states? Tension between hints and bounds

  New results from $\bar\nu_e$ disappearance further disfavour $\mathcal{O}(\text{eV})$ ν_s interpretation
- Other NP at play?

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 $\lambda = \frac{4\pi E}{\Delta m^2}$

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- ν masses are not the only mechanism for oscillations

Violation of Equivalence Principle (VEP): Gasperini 88, Halprin,Leung 01 $\lambda = \frac{\pi}{E|\phi|\delta\gamma}$

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

Violation of Lorentz Invariance (VLI): Coleman, Glashow 97 $\lambda = \frac{2\pi}{E\Delta c}$

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

Interactions with space-time torsion: Sabbata, Gasperini 81 $\lambda = \frac{2\pi}{Q\Delta k}$

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

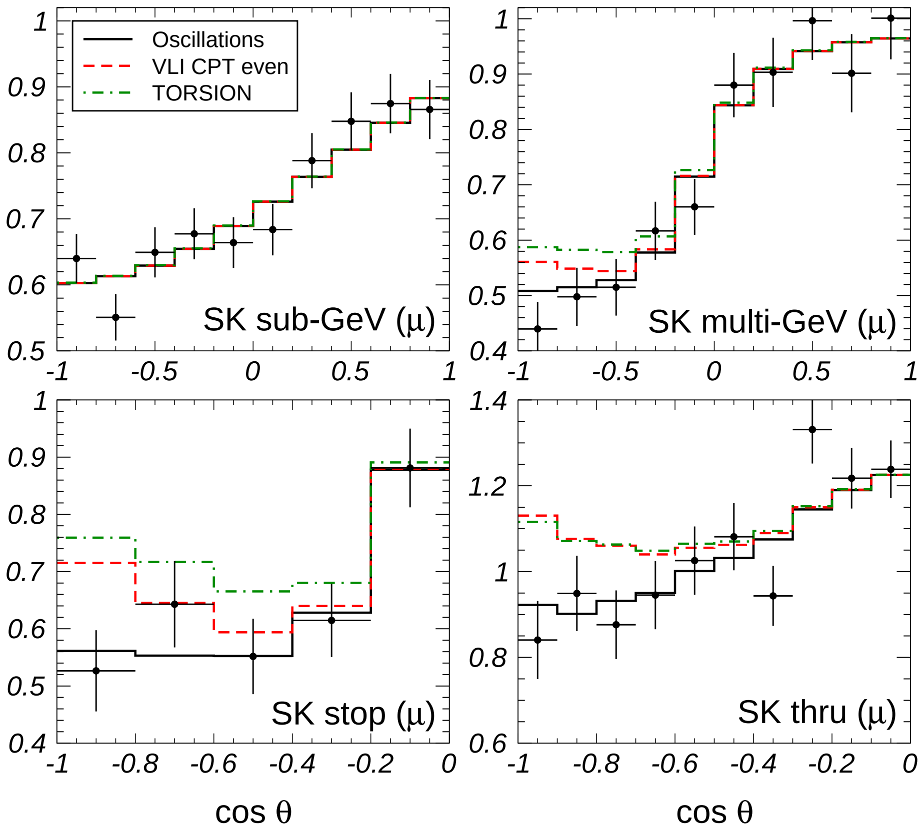
Violation of Lorentz Invariance (VLI) Colladay, Kostelecky 97; Coleman, Glashow 99

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:

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

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

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

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

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.:

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

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

$$\varepsilon_{\alpha\beta}(r) \equiv \sum_{f=ued}\frac{N_f(r)}{N_e(r)}\varepsilon^{fV}_{\alpha\beta}$$ $\Rightarrow$ 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 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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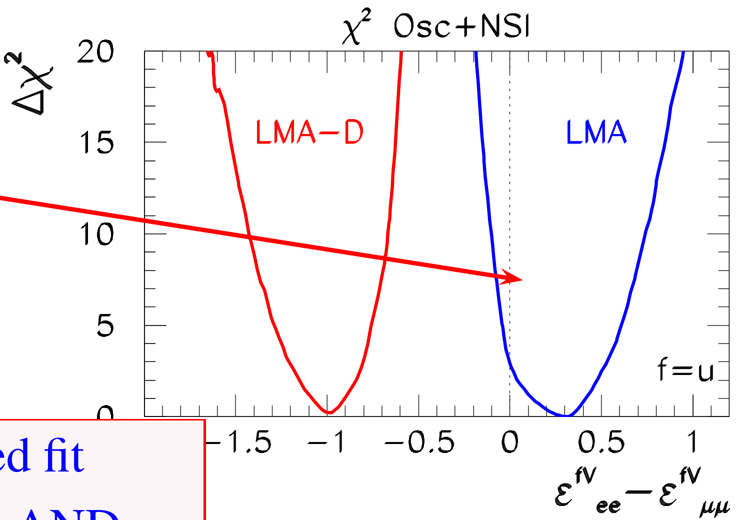
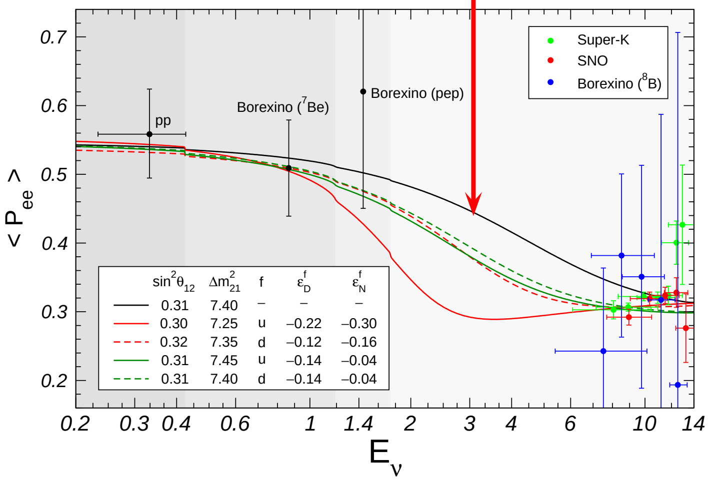
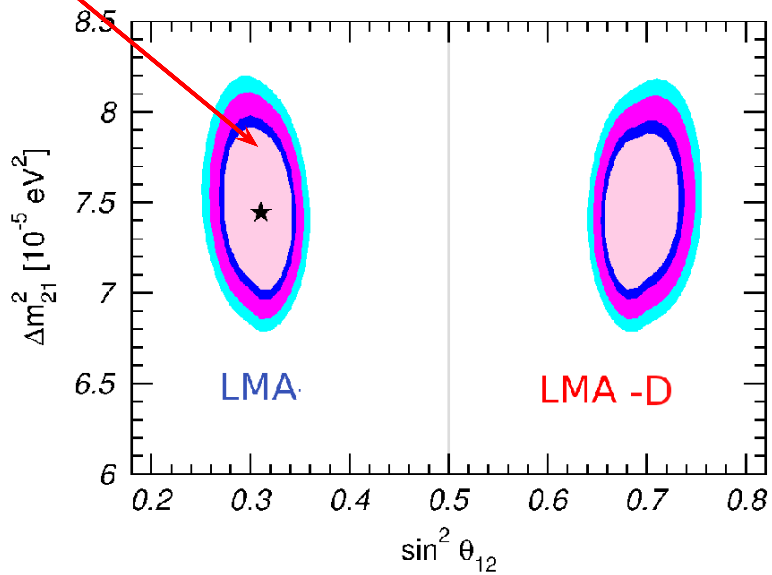


– Bounds $\mathcal{O}(1-10\%)$

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

LMA: Improved fit to Solar+KamLAND





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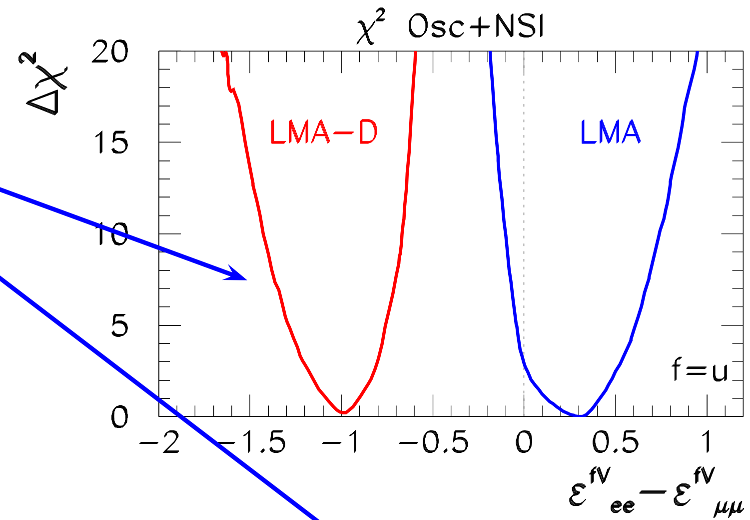
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$



– Bounds $\mathcal{O}(1-10\%)$

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

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

Miranda,Tortola, Valle, hep-ph/0406280

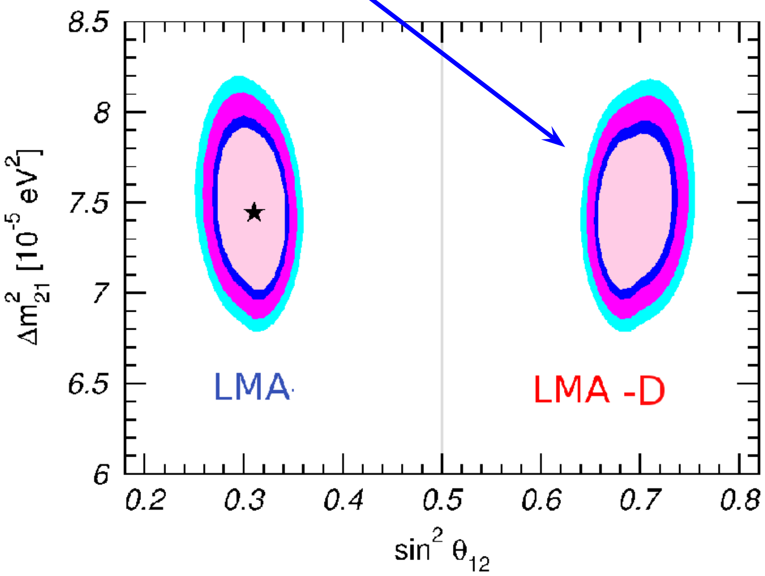
Cannot be resolved with osc-experiments

Requires NC scattering experiments

Coloma etal 1701.04828

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

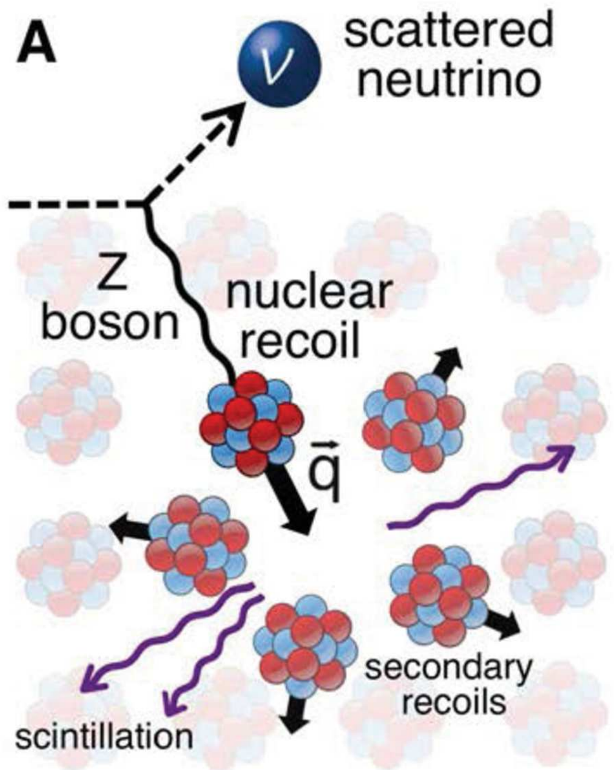
Farzan 1505.06906, and Shoemaker 1512.09147



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

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

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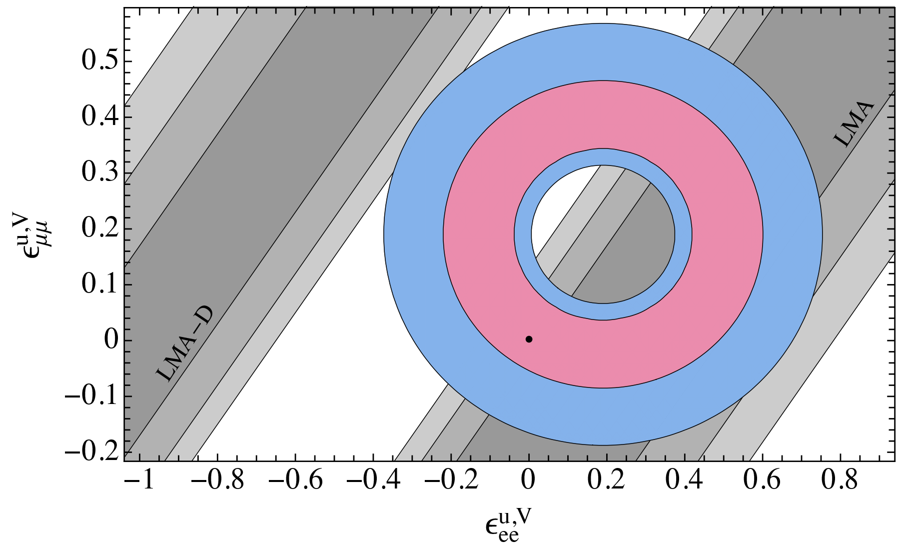
- Impact on LMA-D: Allowed COHERENT region vs LMA-D required range



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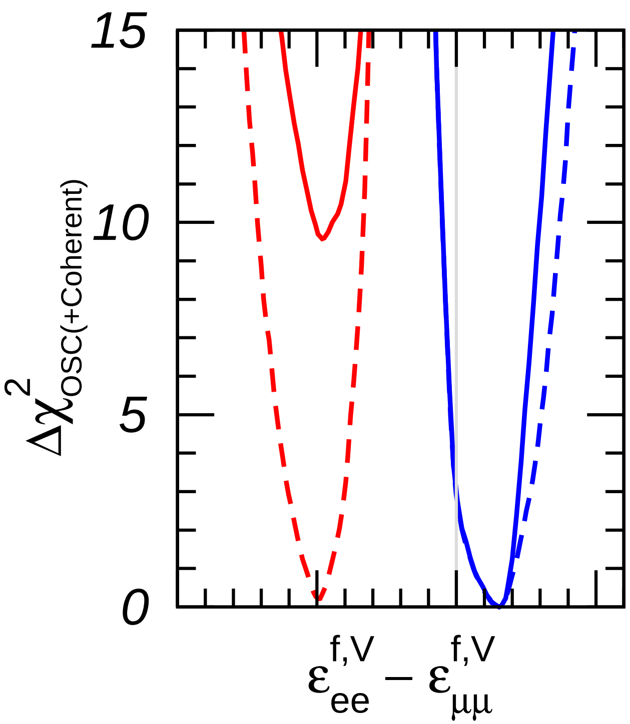
- OSCILLATION + COHERENT $\Rightarrow$ LMA-D excluded at more than 3.1 σ

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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- Learning about the Sun with $\nu' s$?

A Detour in the Sun

- Sun=Main sequence star
- Solar Models describes the Sun based on:

Mass:	$M_\odot = 2 \times 10^{33}$ gr
Radius:	$R_\odot = 7 \times 10^5$ km
Surf Lum:	$L_\odot = 3.842 \times 10^{33}(1 \pm 0.004)$ erg/sec
Age:	$\tau_\odot = 4.57 \times 10^9(1 \pm 0.0044)$ yr

- Basic assumptions:

- The Sun is spherically symmetric
- Some Equation of State

- Incorporate:

- Transport of Energy: Radiative and Convective

$\Rightarrow$ Model of opacities

- Chemical Evolution by Nuclear Reactions

$\Rightarrow$ pp-chain and CNO cycles

- Microscopic Diffusion

- Using inputs from:

- Lab Measurements of Nuclear Rates
- Element Abundance Determination By

$\Rightarrow$ Spectroscopy of Photosphere: C, N, O

$\Rightarrow$ Meteorites: Mg,Si,S,Fe

$\Rightarrow$ Other methods: Ne, Ar

- They Predict Observables:

- Neutrino Flux Spectrum
- Relevant to Helioseismology :

$\Rightarrow$ Surface He Abundance

$\Rightarrow$ Inner Radius of Convective Zone

$\Rightarrow$ Sound Speed Profile

The Solar Composition Problem

– Newer determination of abundances in solar surface give lower values

$\log \epsilon_i \equiv \log N_i/N_H + 12$

Element	GS98	AGSS09met
C	8.52 ± 0.06	8.43 ± 0.05
N	7.92 ± 0.06	7.83 ± 0.05
O	8.83 ± 0.06	8.69 ± 0.05
Mg	7.58 ± 0.01	7.53 ± 0.01
Si	7.56 ± 0.01	7.51 ± 0.01
S	7.20 ± 0.06	7.15 ± 0.02
Fe	7.50 ± 0.01	7.45 ± 0.01
Ar	6.40 ± 0.06	6.40 ± 0.13
Ne	8.08 ± 0.06	7.93 ± 0.10

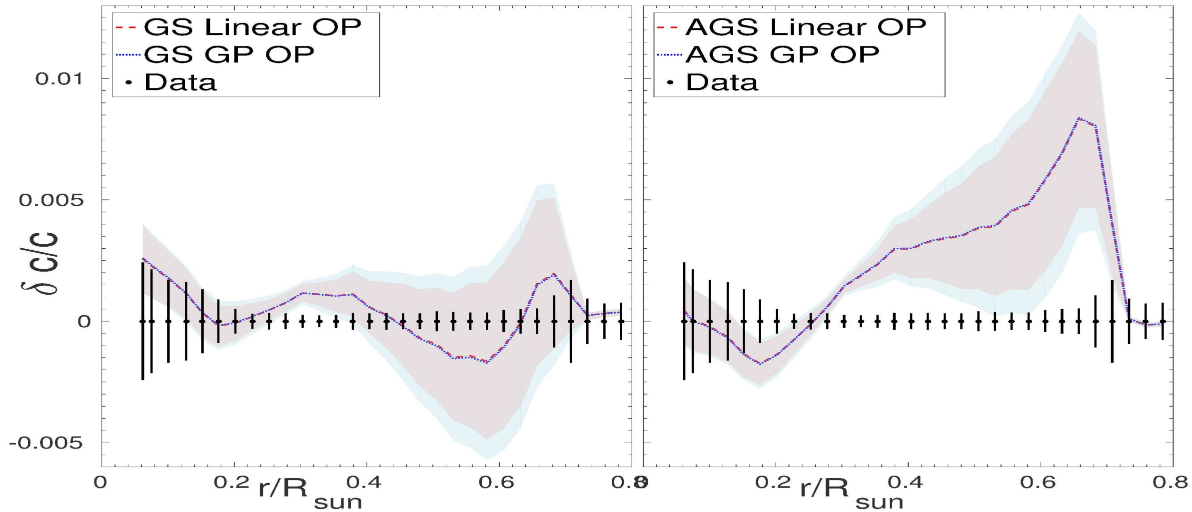
$\Rightarrow$ Two sets of SSM:

Starting from Bahcall *etal* 05, Serenelli *etal* 2016

B16-GS98 with old abund

B16-AGSS09met with new abund

– Solar Models with lower metalicities fail in reproducing helioseismology data



Predictions very strongly correlated

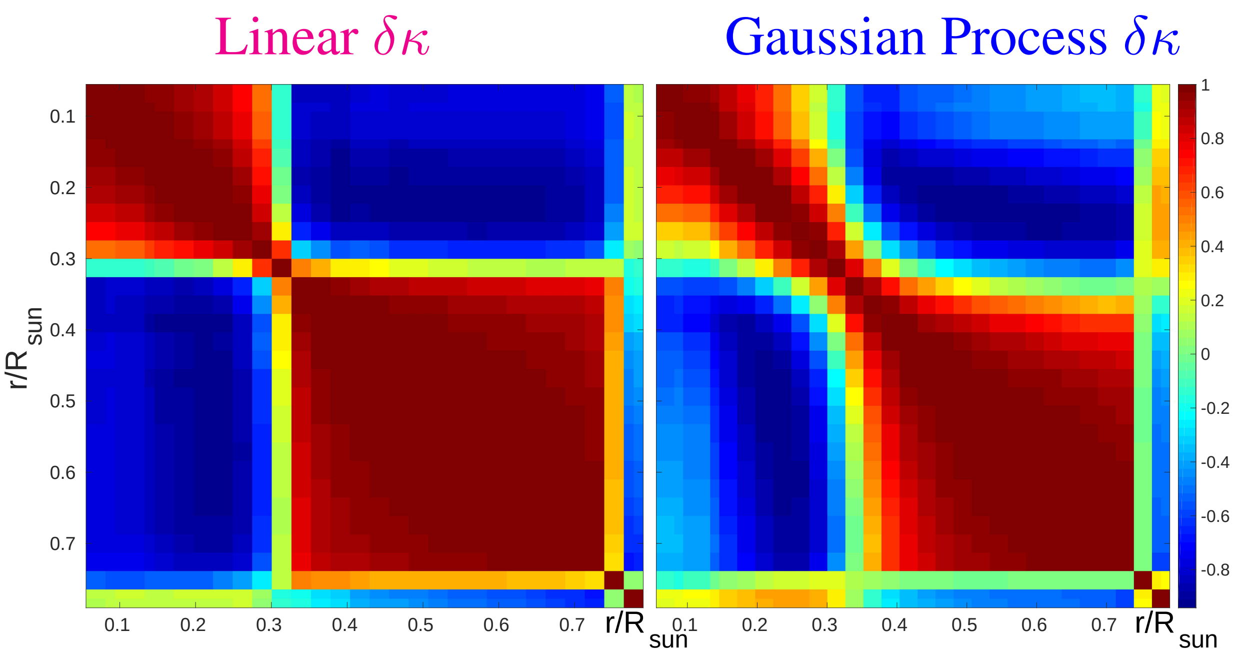
– B16-GS98 (dis)agreement at 2.5 σ

– B16-AGSS09 disagreement 4.7 σ

– Bayes factor B16-AGSS09/B16-GS98<-13 (very strong disfavouring)

Modeling the uncertainty in the opacity profile

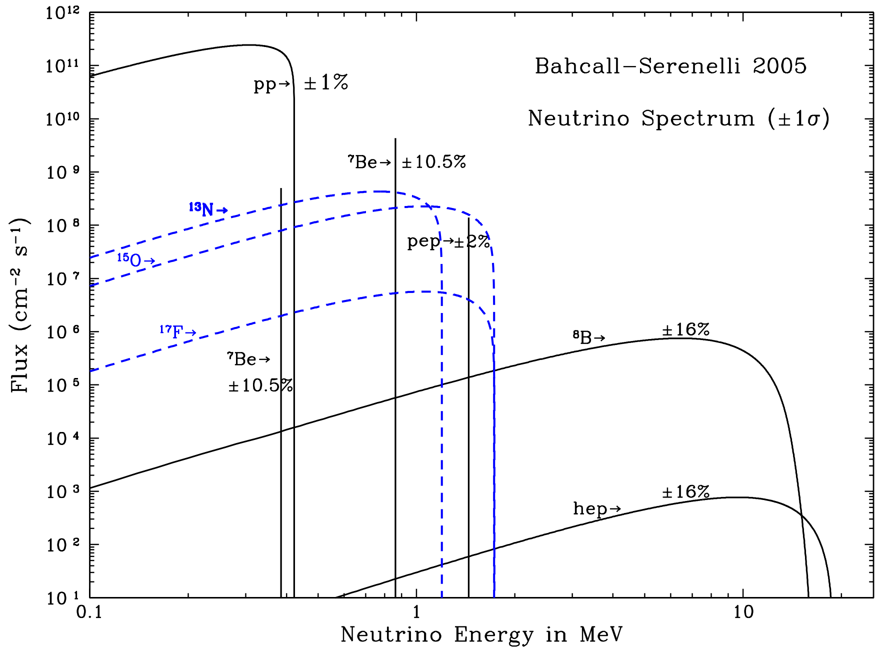
- Opacity is a function $\kappa(T, \rho, X_i = N_i/N_H)$. How to parametrize its uncertainty?
- Generically $(1 + \delta\kappa(T))\langle\kappa(T, \rho, X_i)\rangle$
  $\Rightarrow$ Most studies $\delta\kappa(T) = C$ or $\delta\kappa(T) = a + b\log T$ with prior for σ_C (or σ_a,σ_b)
  $\Rightarrow$ only very rigid variations allowed
- Alternative: Gaussian Process anszat with same $\sigma(T)$ but correlation length $L < 1$



Song, MCG-G,Serenelli,Villante (17)

Still, even with GP opacity uncertainty Bayes factor B16-AGSS09/B16-GS98=-4.1
(Moderate to strong disfavour)

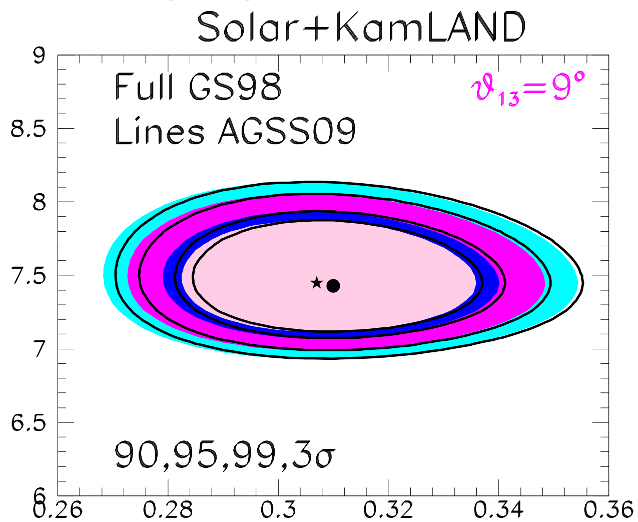
The Neutrino Fluxes



Flux cm^{-2} s^{-1}	B16GS98	B16-AGSS09met	Diff (%)
pp/10^{10}	5.98	$6.03\ (1 \pm 0.005)$	0.8
pep/10^8	1.44	$1.46\ (1 \pm 0.01)$	2.1
hep/10^3	7.98	$8.25\ (1 \pm 0.30)$	3.4
^{7}Be/10^9	4.93	$4.40\ (1 \pm 0.06)$	8.8
^{8}B/10^6	5.46	$4.50\ (1 \pm 0.12)$	17.7
^{13}N/10^8	2.78	$2.04(1 \pm 0.14)$	**26.7**
^{15}O/10^8	2.05	$1.44\ (1 \pm 0.16)$	**30.0**
^{17}F/10^{16}	5.29	$3.26\ (1 \pm 0.18)$	**38.4**

Most difference in CNO fluxes

– Neglegeable Impact in Osc Parameter Determination



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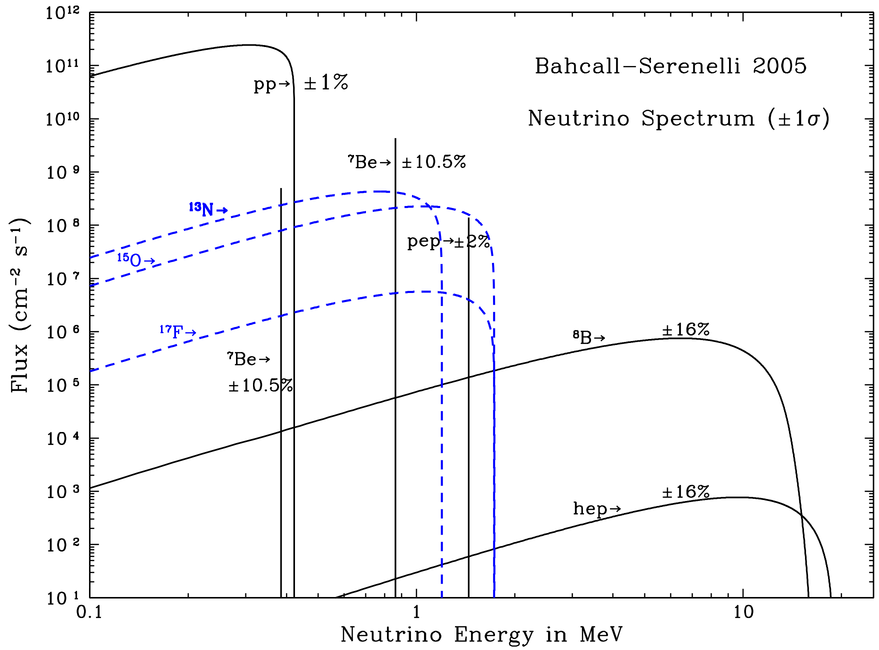

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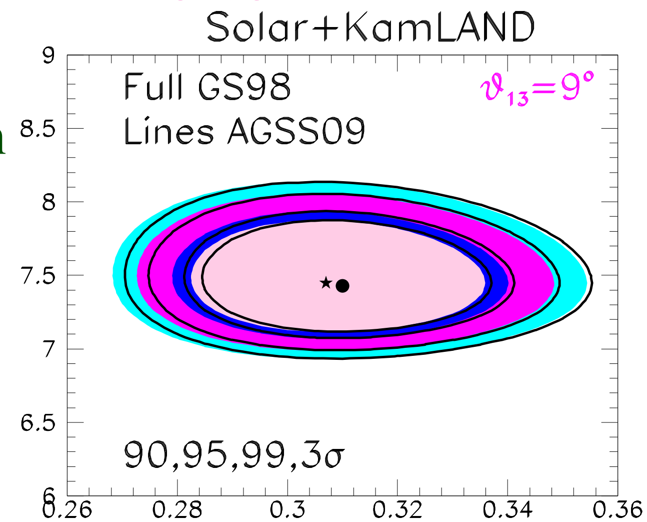
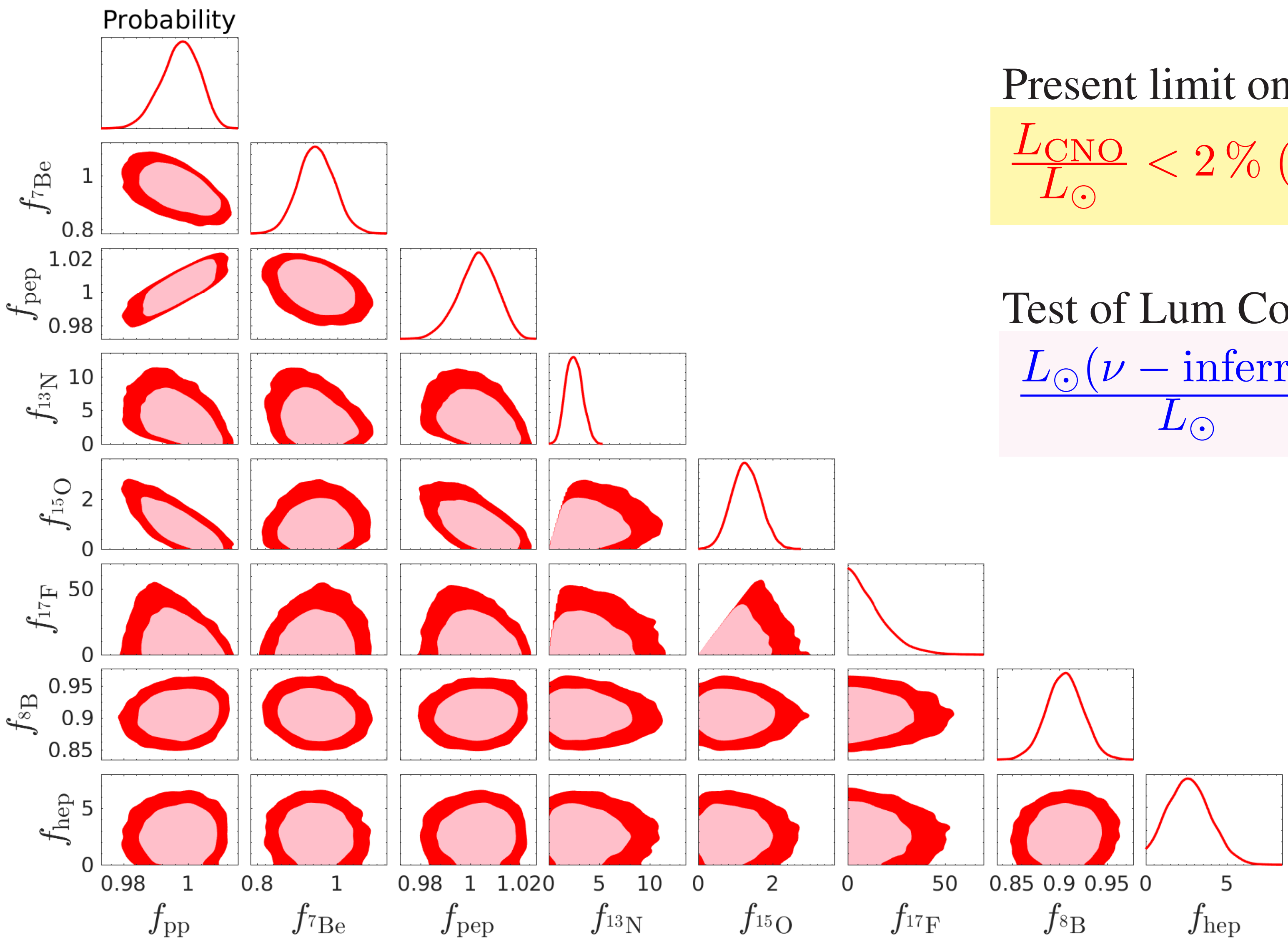


– Neglegeable Impact in Osc Parameter Determination

$\Rightarrow$ Possible to extract fluxes for data

Testing How the Sun Shines with $\nu' s$

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



Present limit on CNO:

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

Test of Lum Constraint:

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

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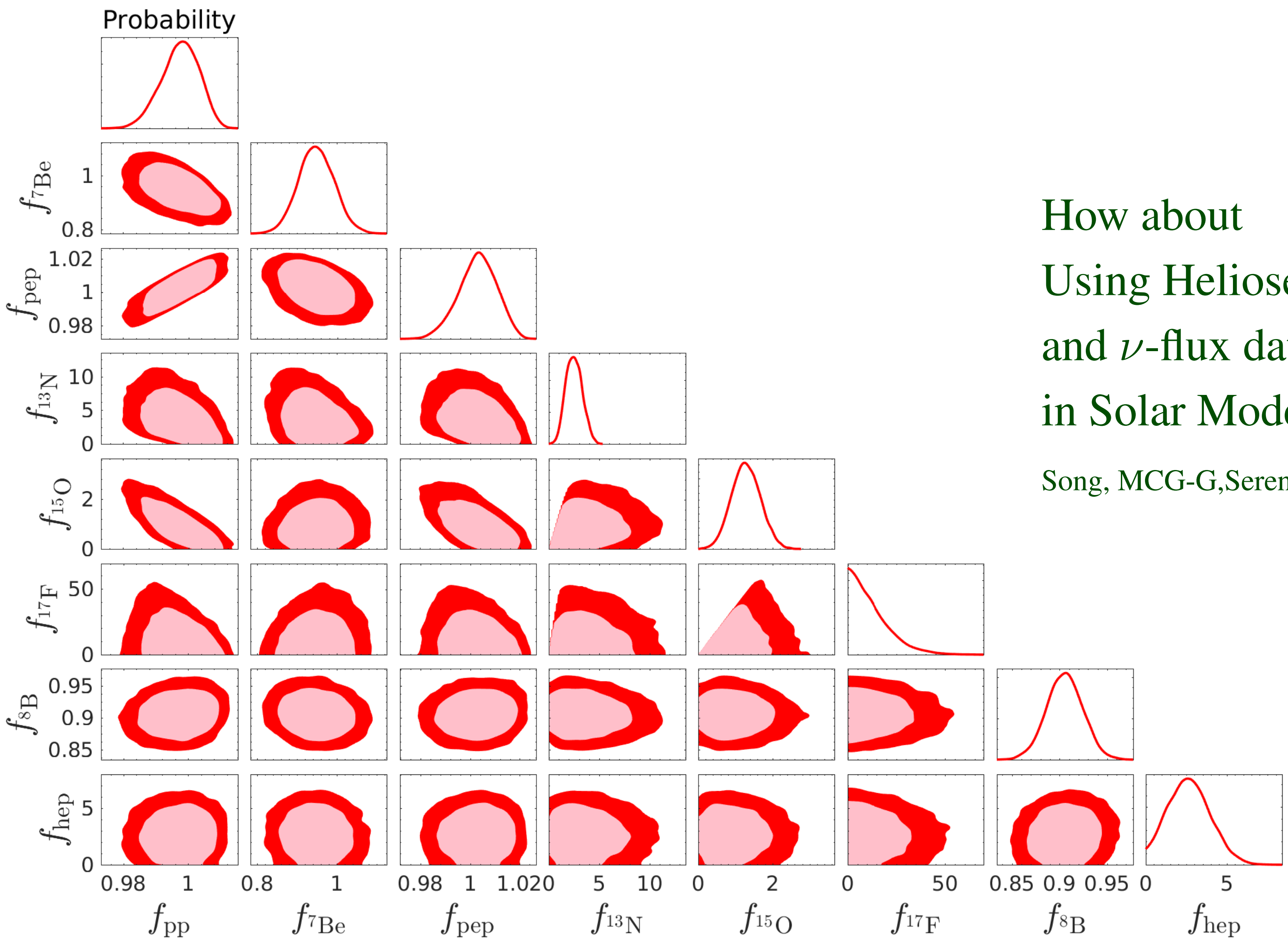


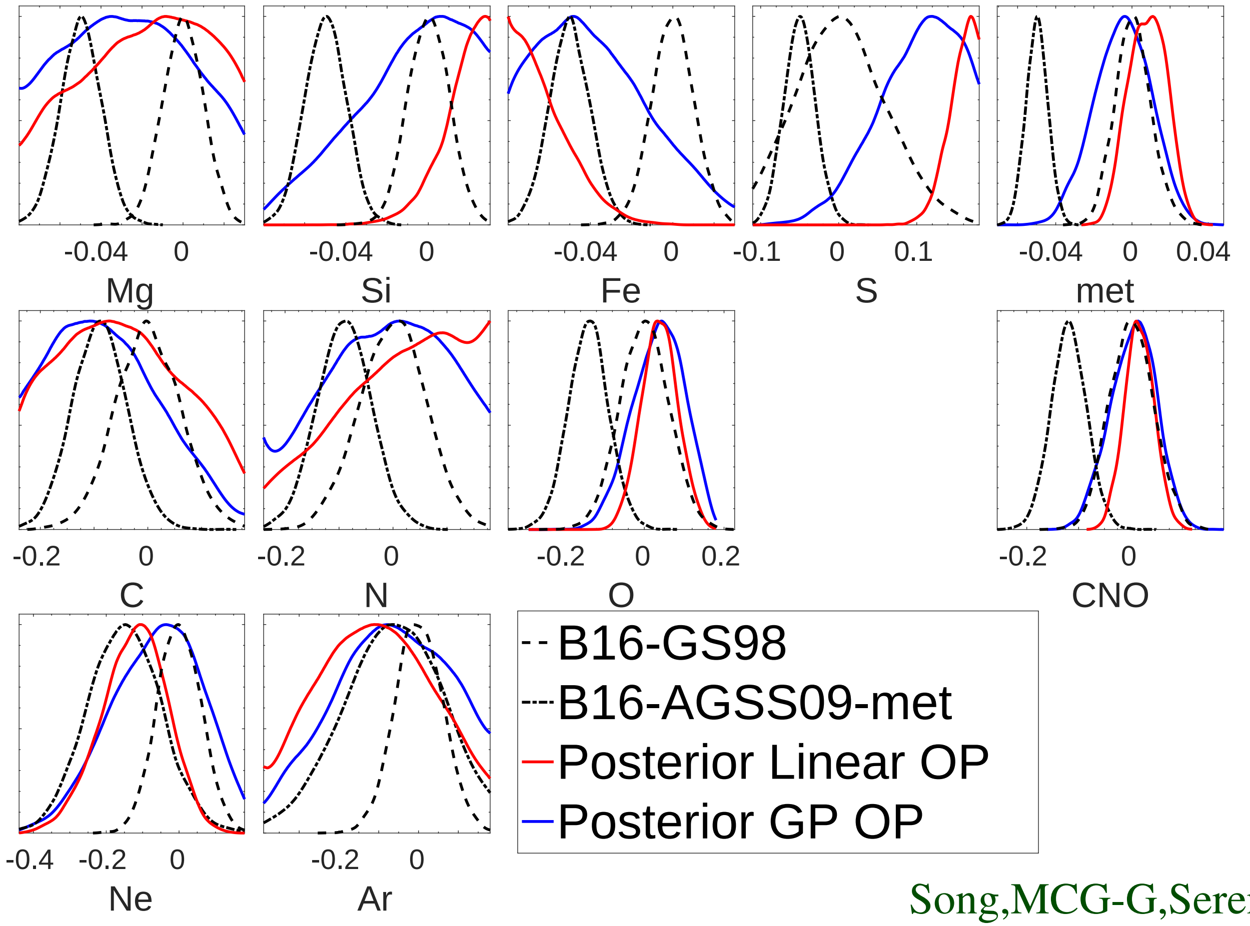
How about
Using Helioseismic
and ν-flux data
in Solar Modeling?

Song, MCG-G,Serenelli,Villante (17)

Using ν and Helioseismic Data in Sun Modeling

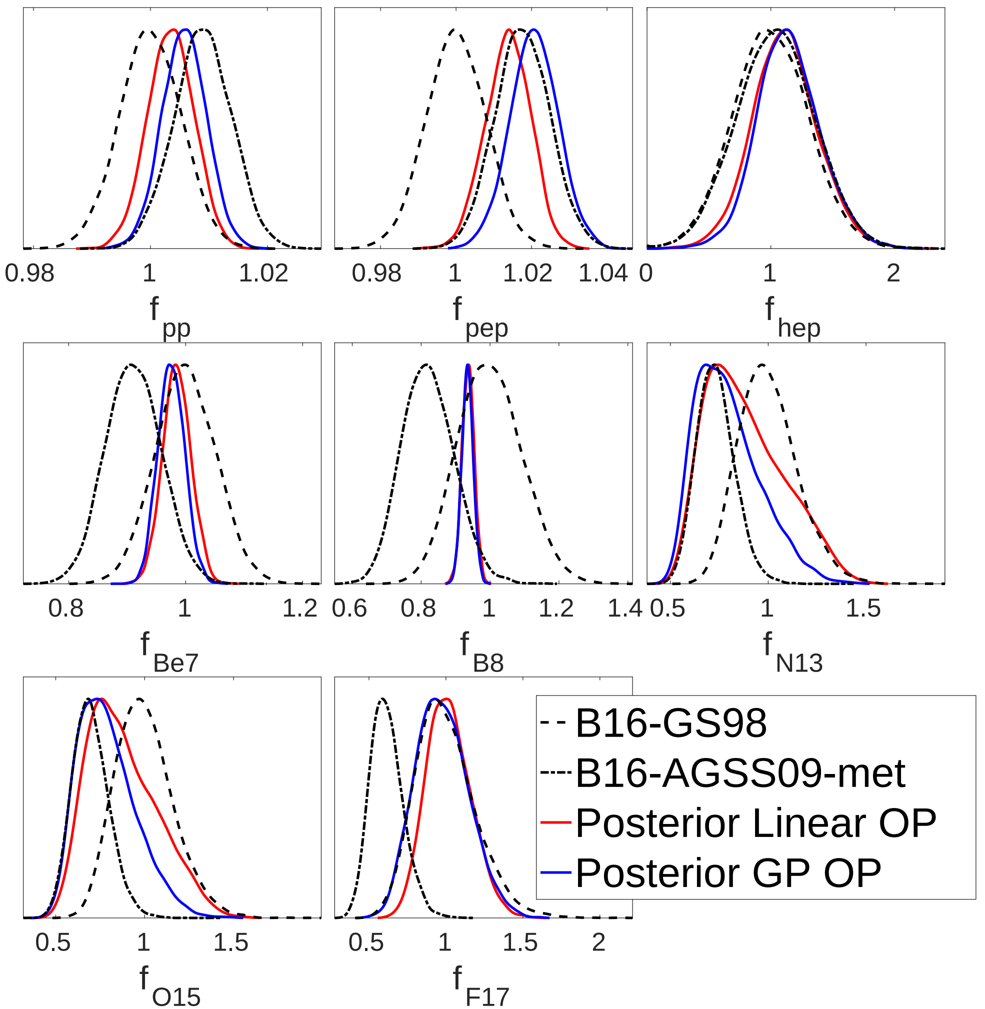
- Proposal: Invert approach and use the ν and helioseismic data in construction of SSM
- Method: Bayesian Inference of Abundance Posterior Distrib (from Uniform Priors)
- Test effects of effects of other modeling aspects (f.e. opacity uncertainty profiles)

$$x = \ln \frac{N_i}{N_H} - \langle \ln \frac{N_i}{N_H} \rangle_{GS98}$$



Song,MCG-G,Serenelli,Villante (17)

ν fluxes from ν+helioseismic data



MCG-G,Serenelli, Song,Villante in preparation

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- Learning about the Sun with $\nu' s$? Improvements on Solar Modeling

Thank You

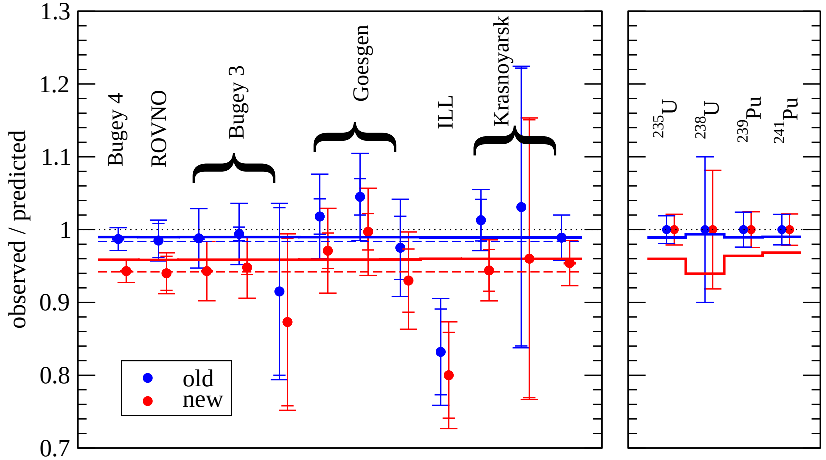
3 ν Analysis: Reactor Flux anomaly and θ_{13}

- The reactor $\bar{\nu}_e$ fluxes was recalculated about 6 yrs ago

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

- Both found higher fluxes ~ 3.5 %

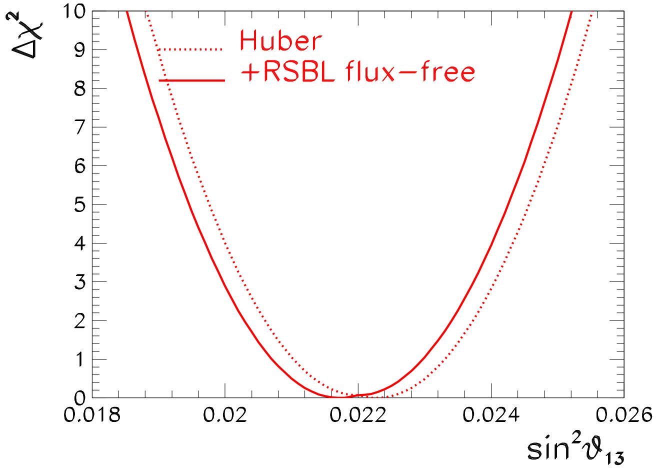
$\Rightarrow$ *negative* reactor experiments at short baselines (RSBL) indeed observed a deficit



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

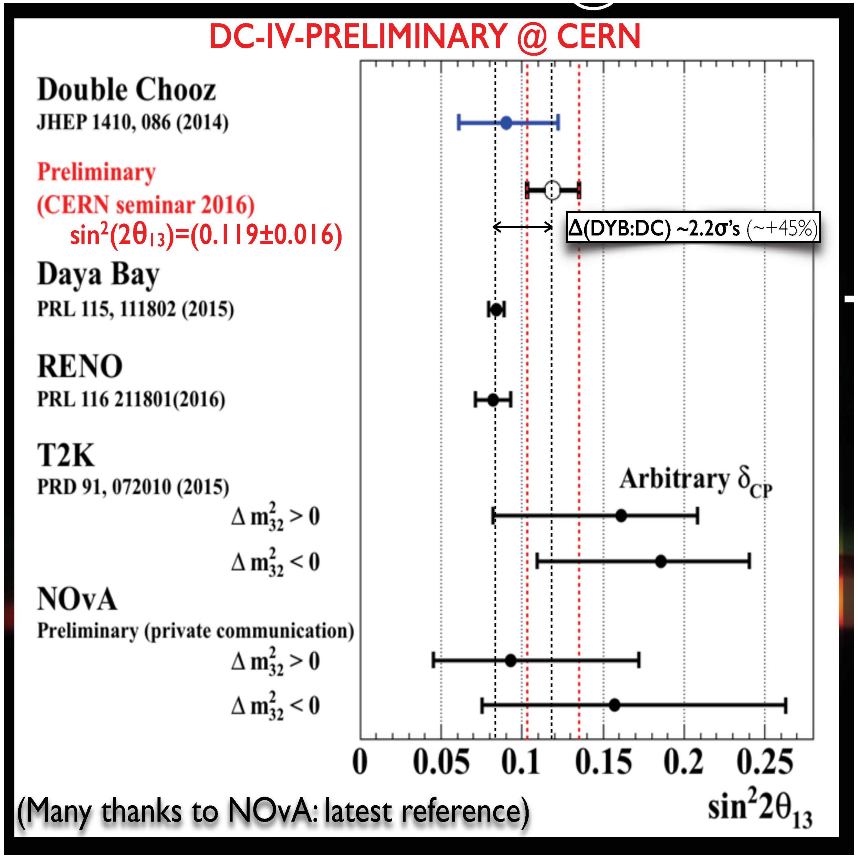
Difference at $\lesssim 0.3\sigma$ level

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



Issues in 3 ν Analysis: Consistency of θ_{13}

Daya Bay vs Double Chooz?



From DC (Anatael Cabrera) Talk CERN Sep 16

Allowed regions of DC vs Daya Bay

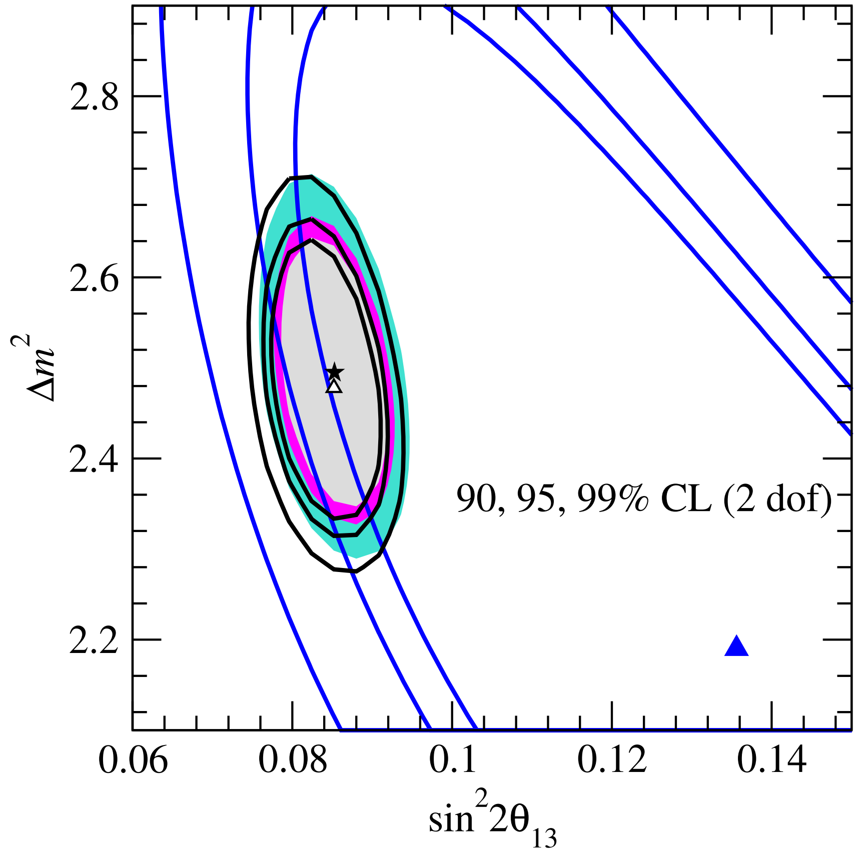


Fig. Courtesy of T. Schwetz

No significant discrepancy

Lepton Mixing Unitarity

- Previous results assume $U_{\rm LEP}$ to be unitary
- If ν_L mixed with m extra states $U_{\rm LEP} = (K_{l,3\times3}\,, K_{h,3\times m})$ Schechter, Valle (1980)

  And $U_{\rm LEP}U^\dagger_{\rm LEP} = I_{3\times3}$ 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 $K_{L,3\times3}$ (not unitary)

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- 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

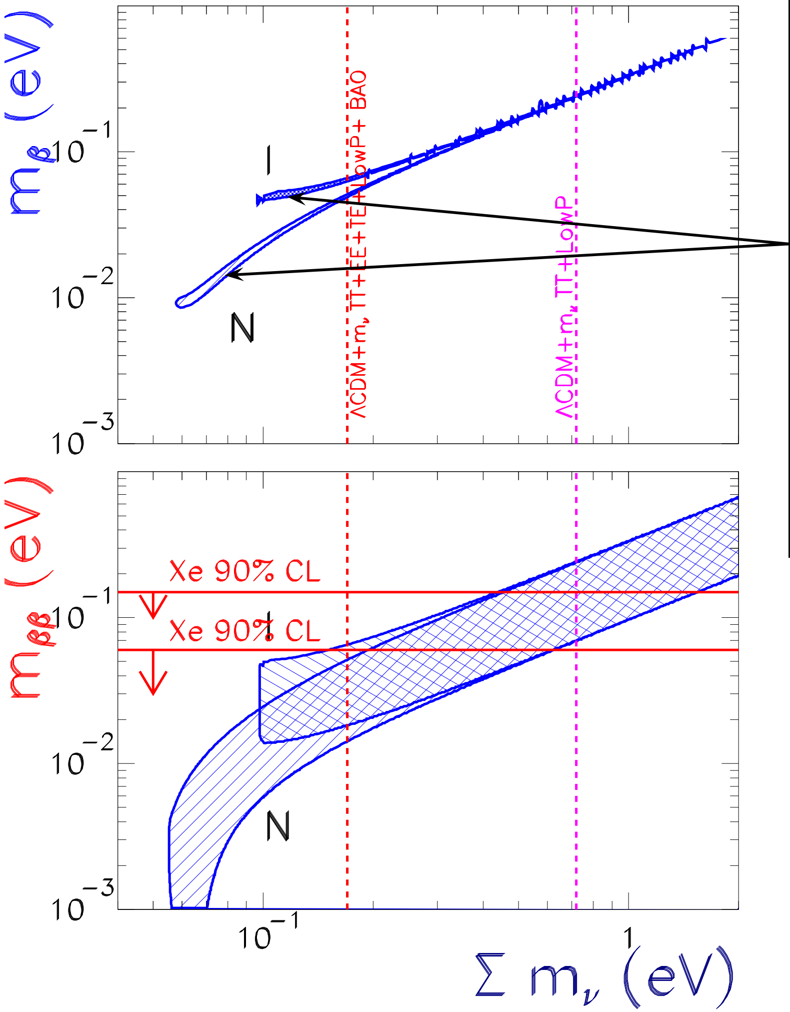
or equivalently $K_l \simeq (I+\epsilon) U(\theta_{ij},\delta,\eta_i)$ with $|\epsilon_{\alpha j}| \leq \text{few} \times 10^{-3}$ while $K_h \sim \mathcal{O}(\epsilon)$

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