Minimal Models with Light Sterile Neutrinos

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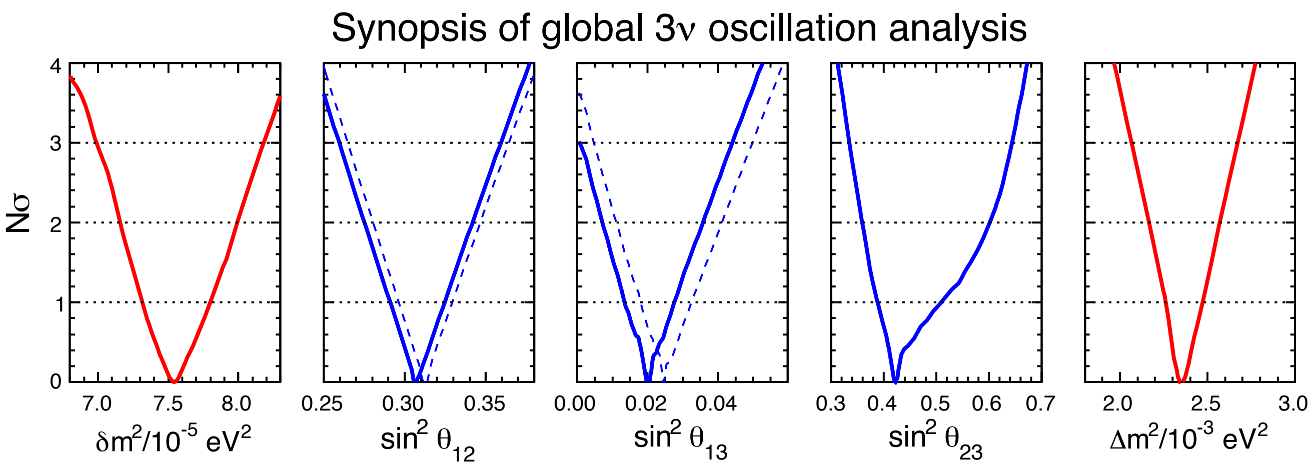
Based on A. Donini, P.H., J. López-Pavón, M. Maltoni, arXiv: 1106.0064

SM + massive ns

After the decennium mirabilis of neutrino physics:



Fogli et al (after T2K and MINOS)

CKM seems to work also for the leptons (although CP violation is still to be found !)

3n mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Outlier I: LSND anomaly

LSND vs KARMEN

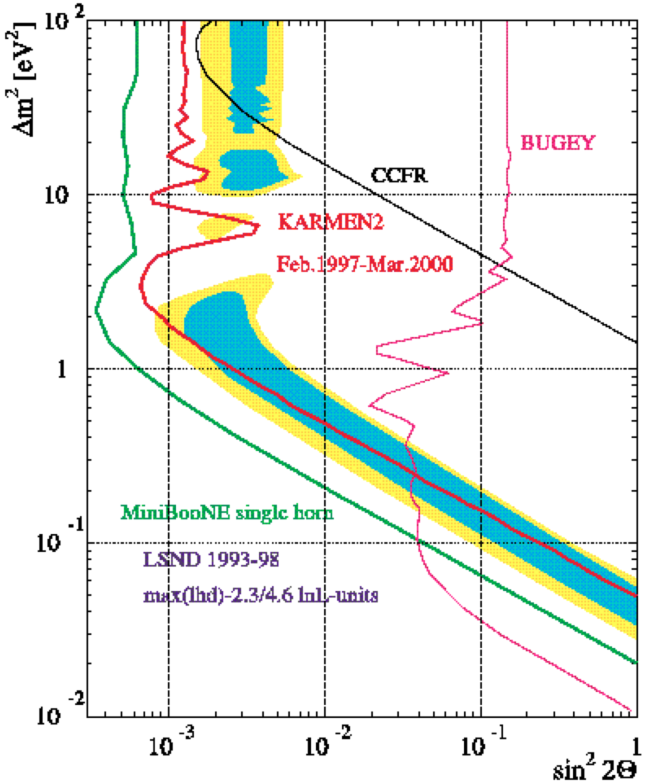
$$\pi^+ \to \quad \mu^+ \quad \nu_\mu$$
$$\nu_\mu \quad \to \nu_e \text{ DIF } (28 \pm 6/10 \pm 2)$$

$$\mu^+ \to \quad e^+ \quad \nu_e \, \bar{\nu}_\mu$$
$$\bar{\nu}_\mu \quad \to \bar{\nu}_e \text{ DAR } (64 \pm 18/12 \pm 3)$$

Appearance signal with very different

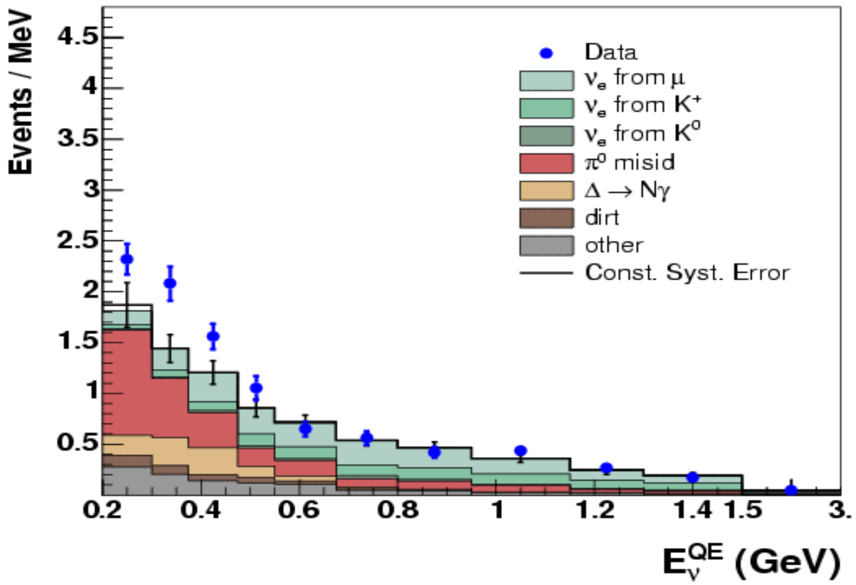
$$|\Delta m^2| \gg |\Delta m^2_{atm}|$$

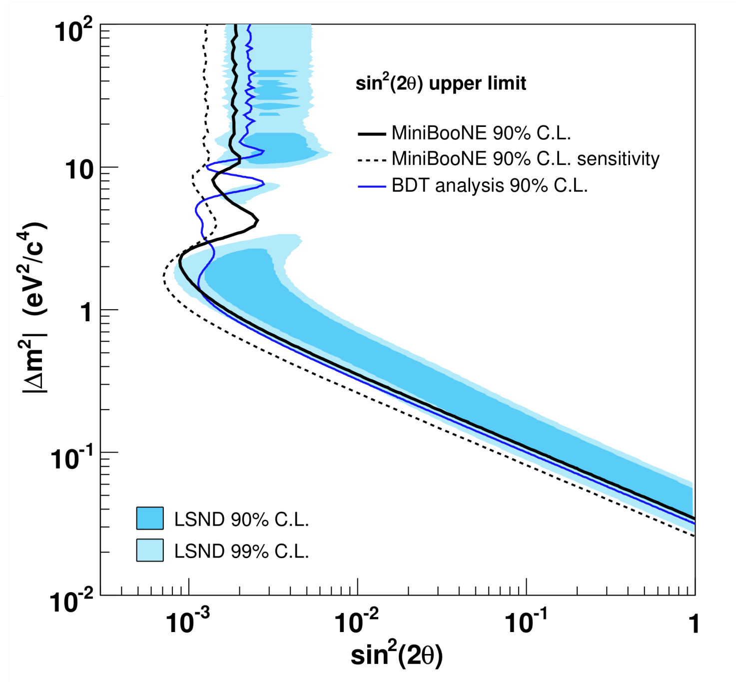
20 MeV ≤ E_n ≤ 200 MeV



MiniBOONE-n

Neutrino run   200 MeV ≤ E_n ≤ 3 GeV





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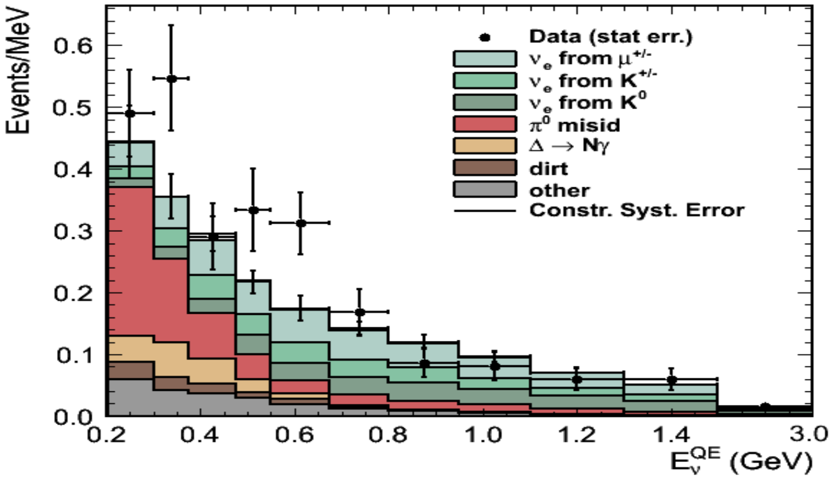
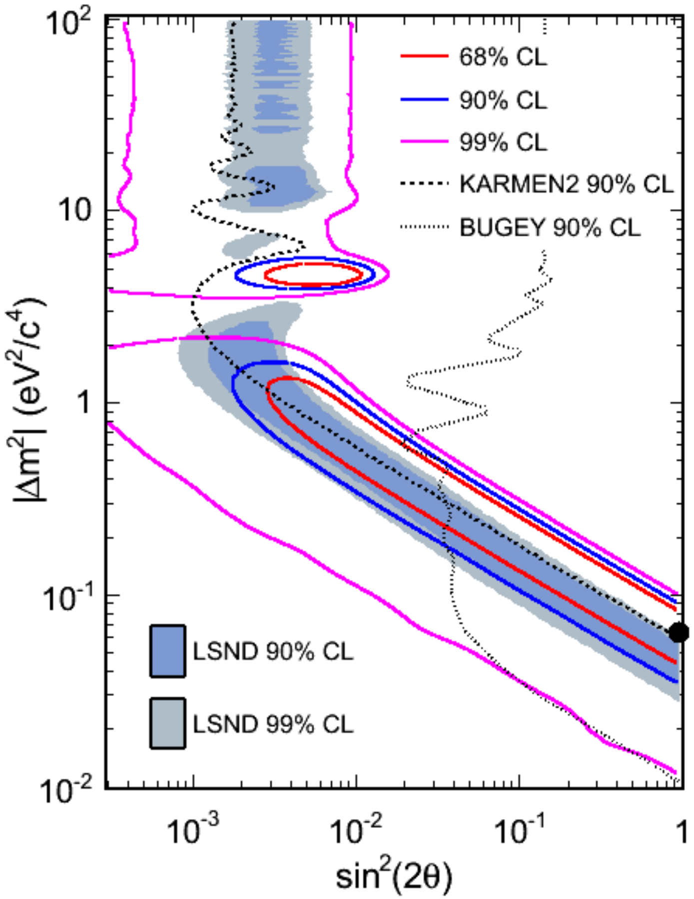
Low energy excess…but not expected if LSND right

MiniBOONE-n̄

Anti-Neutrino run





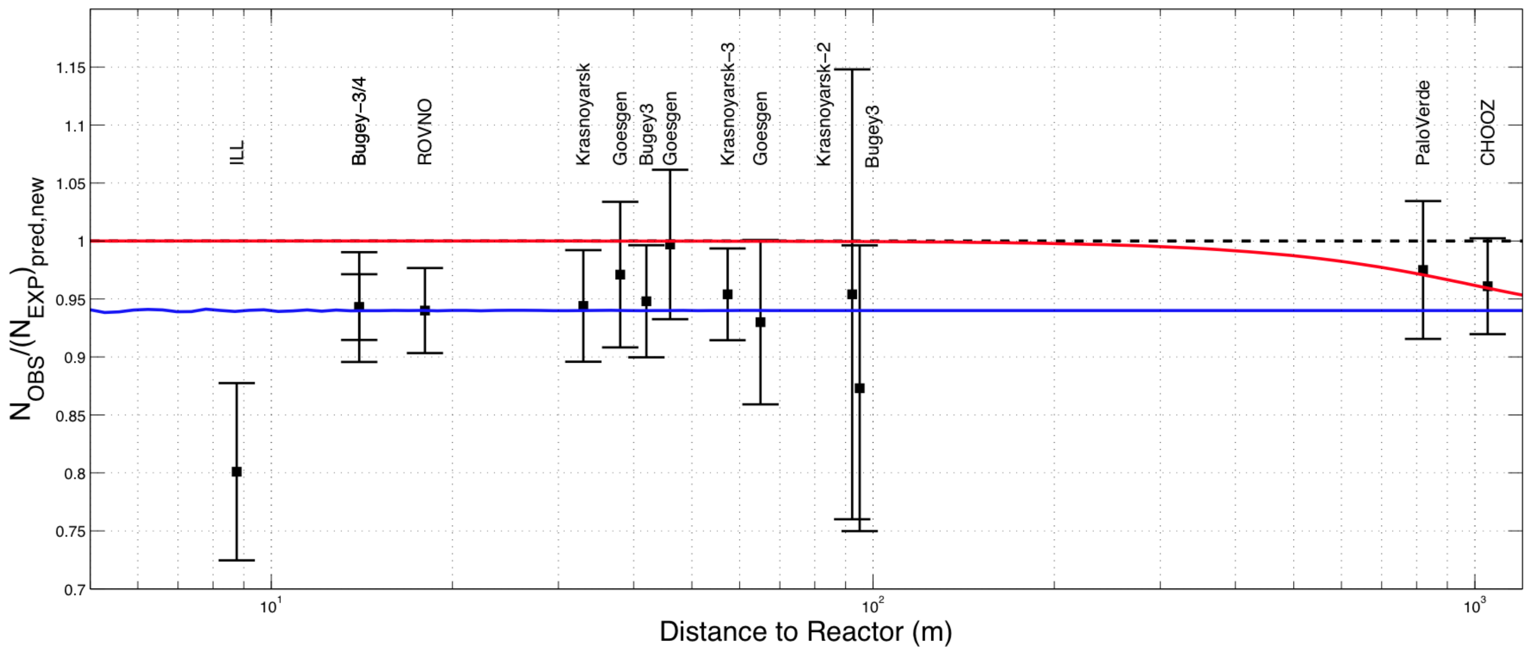
Compatible with LSND !

	475-1250MeV	1250-3000MeV
Excess	20.9 ±13.9	3.8±5.8
LSND-best fit	22	3.5

In order to accommodate a new $|\Delta m^2_{LSND}| \simeq \mathcal{O}(1eV)$

- Need at least four ($n_s \geq 1$) distinct eigenstates
- Apparently CP violating effect needed (signal LSND/MB anti-n not MB n)
  $n_s \geq 2$ Sorel, Conrad, Shaevitz
- Tension appearance (signal) and disappearance (no signal) ?
- Tension with cosmology ?

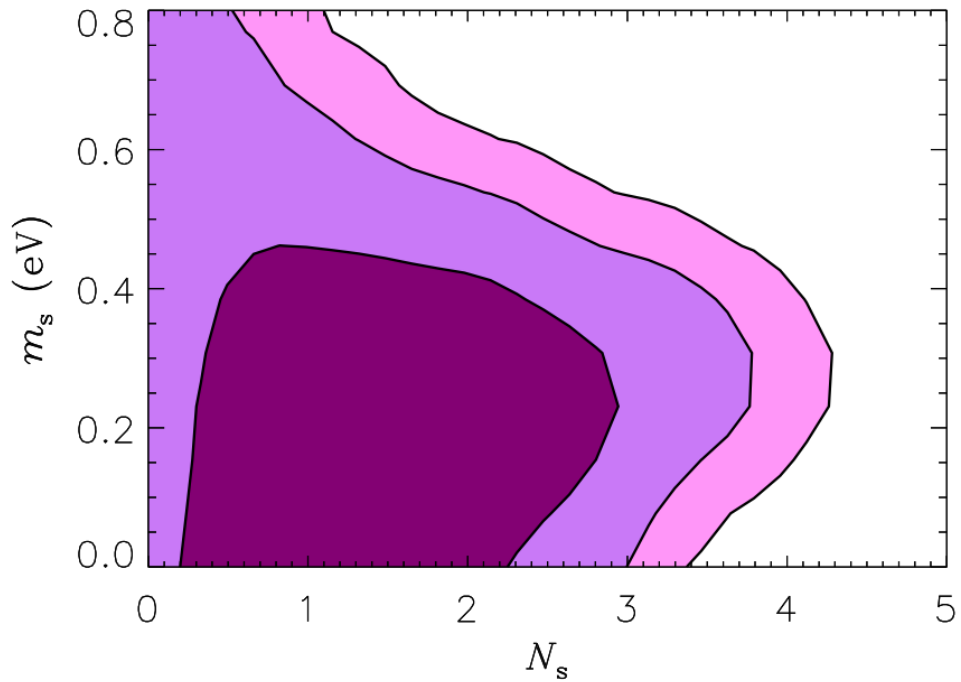
Outlier II: reactor anomaly



Re-calculation of reactor fluxes: old fluxes underestimated by 3%:

Mueller et al, ArXiv: 1101.2663

Outlier III: Cosmology



Hamann et al, ArXiv: 1006.5276

Sterile species favoured by LSS and CMB

Nucleosynthesis:

$$N_s = 0.68^{+0.80}_{-0.70}$$

Izotov, Thuan

3+2 neutrino mixing model

Parametrized in terms of a general unitary 5x5 mixing matrix
(9 angles, >6 phases physical)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_s' \end{pmatrix} = U_{5\times5} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \end{pmatrix}$$

	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

Kopp, Maltoni, Schwetz (KMS) arXiv:1103.4570

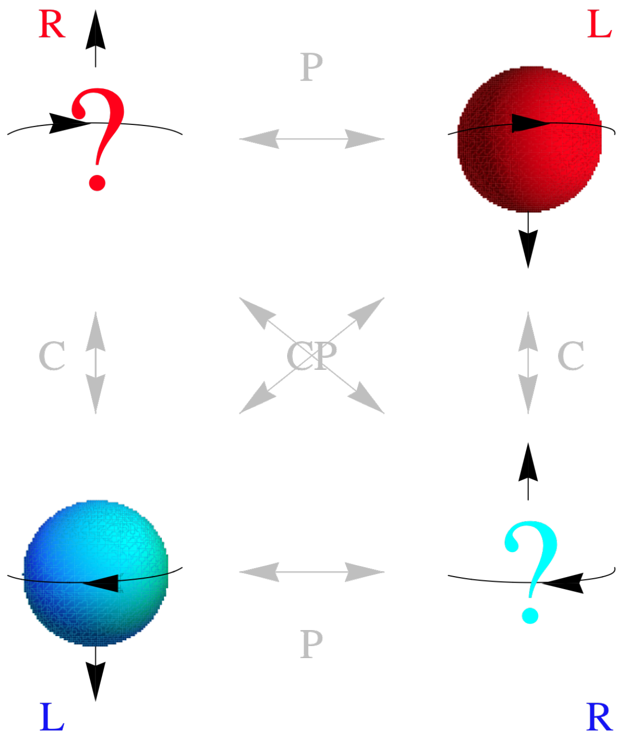
	3+1	3+2
$\chi^2_{\rm min}$	100.2	91.6
NDF	104	100
GoF	59%	71%
Δm^2_{41} [eV^2]	0.89	0.90
$\lvert U_{e4}\rvert^2$	0.025	0.017
$\lvert U_{\mu4}\rvert^2$	0.023	0.018
Δm^2_{51} [eV^2]		1.60
$\lvert U_{e5}\rvert^2$		0.017
$\lvert U_{\mu5}\rvert^2$		0.0064
η		1.52π
$\Delta\chi^2_{\rm PG}$	24.1	22.2
NDF$_{\rm PG}$	2	5
PGoF	6×10^{-6}	5×10^{-4}

Giunti, Laveder, (GL) arXiv:1107.1452

Significant improvement over 3n scenario, but tension appearance/disappearance remains

SM + massive ns

Neutrinos are massive -> need to add the other helicity states



New elementary dofs -> sterile n

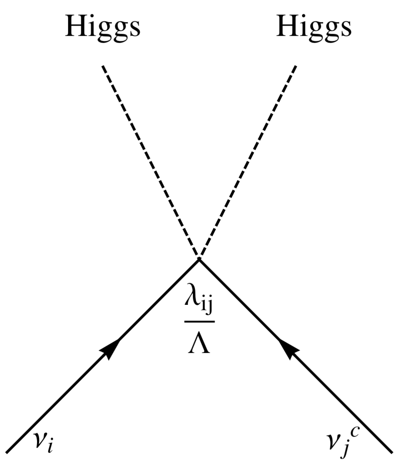
or

Majorana mass terms

SM + massive ns

Majorana neutrinos + gauge invariance

Weinberg's operator (d=5)



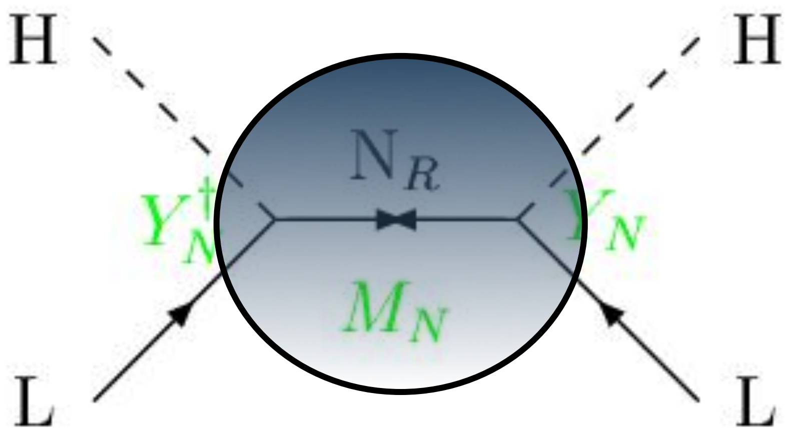
-> new dofs at L

$$m_\nu \sim \lambda \frac{v^2}{\Lambda}$$

But model dependent...

SM + sterile ns

Massive majorana singlet neutrinos



Many models (Type I Seesaw, Inverse Seesaw, Direct Seesaw) involve sterile n

Minkowski; Gell-Mann, Ramond Slansky; Yanagida, Glashow…

SM + sterile ns

Most general (renormalizable) Lagrangian compatible with SM gauge symmetries:

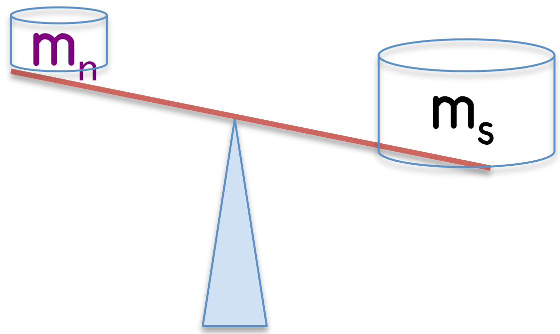
$$\mathcal{L} = \mathcal{L}_{SM} - \sum_{i=1}^{n_R} \bar{l}_L^{\alpha} Y^{\alpha i} \tilde{\Phi} \nu_R^i - \sum_{i,j=1}^{n_R} \frac{1}{2} \bar{\nu}_R^{ic} M_N^{ij} \nu_R^j + h.c.$$

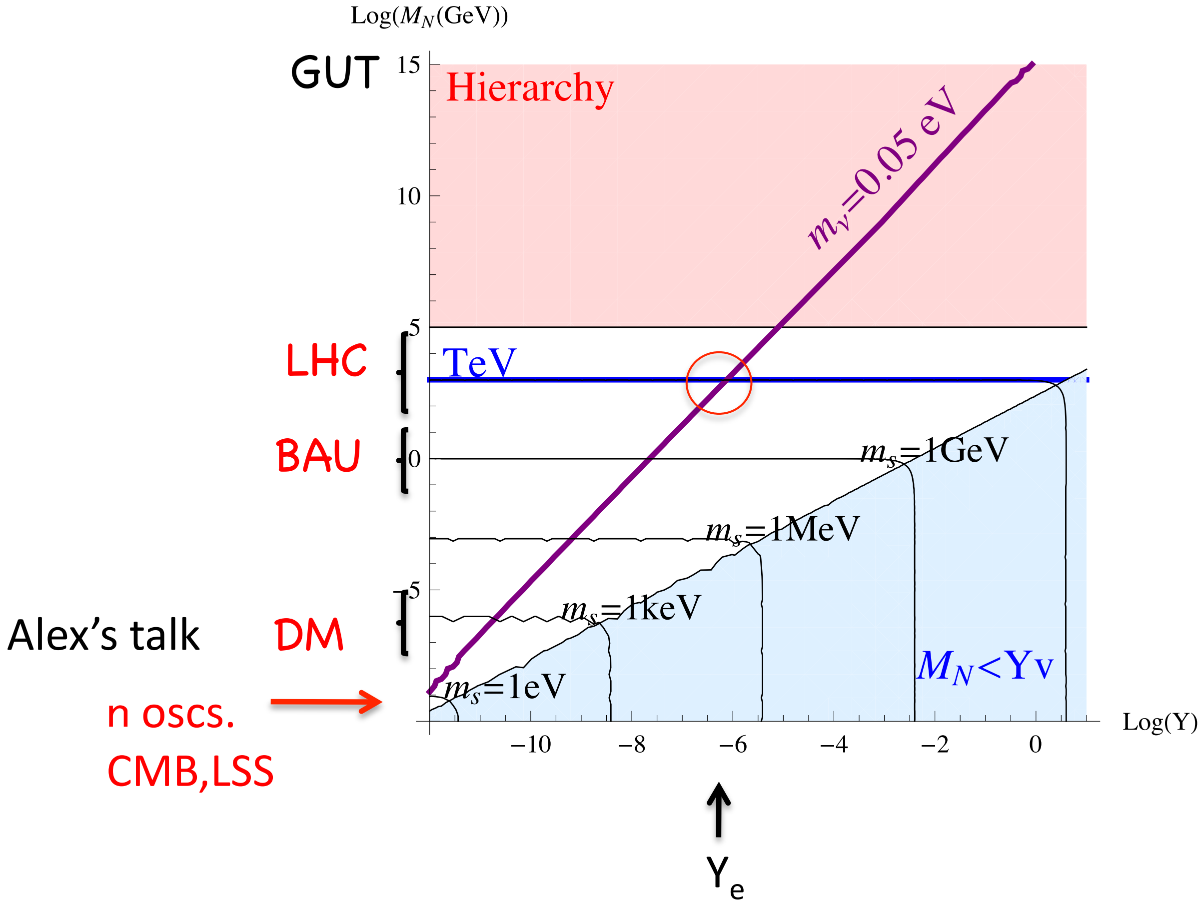
Y: 3 x n_R M_N: n_Rx n_R

$$M_\nu = \begin{pmatrix} 0 & Yv \\ Yv & M_N \end{pmatrix}$$

Phenomenology and cosmo implications strongly depend on n_{R}, M_N and global symmetries (patterns in Y and M_N)

Type I seesaw: $M_N >> Y v$





$$m_\nu = Y^T \frac{v^2}{M_N} Y$$

$$m_s \sim M_N$$

$$\theta_{s\alpha} \sim \sqrt{\frac{m_\nu}{M_N}}$$

Important to understand how data breaks this Y, M_N degeneracy

Type I + (approx) Lepton number

Wyler, Wolfenstein; Mohapatra, Valle;
Branco, Grimus, Lavoura, Malinsky, Romao,…

n_R

$$\begin{pmatrix} 0 & Yv & 0 \\ Yv & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix}$$

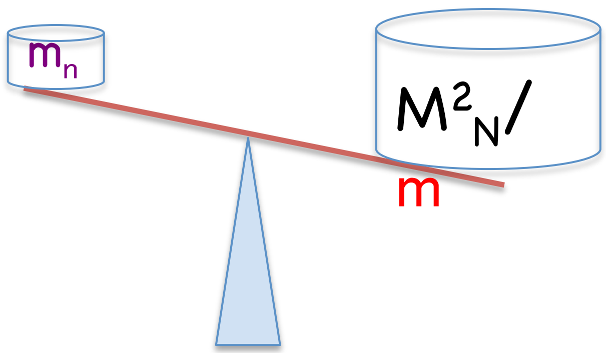
L= +1 -1 +1

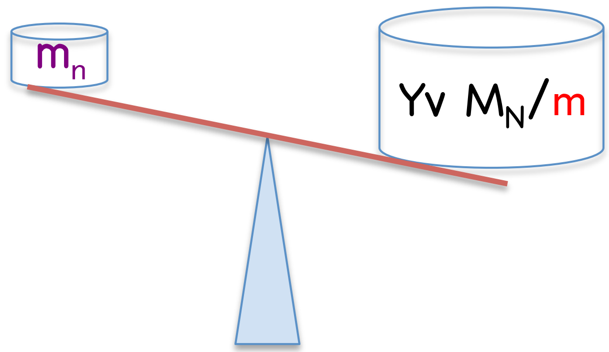
Inverse Seesaw

$$\begin{pmatrix} 0 & Yv & 0 \\ Yv & 0 & M_N \\ 0 & M_N & \mu \end{pmatrix}$$

Direct Seesaw

$$\begin{pmatrix} 0 & Yv & \mu \\ Yv & 0 & M_N \\ \mu & M_N & 0 \end{pmatrix}$$





Y unsuppressed: -> LFV effects at LHC, large m-> e g, etc
-> heavier spectrum M_N, Y v

Cirigliano et al; Kersten,Smirnov; Abada et al; Gavela,et al

Most models of neutrino masses involve sterile neutrinos…

- what are the minimal models that can explain confirmed neutrino masses ie 3 n mixing scenario ?
- what are those that can account for any of the neutrino anomalies eg. 3+2 n mixing model ?

Minimal models

Most general (renormalizable) Lagrangian compatible with SM gauge symmetries:

$$\mathcal{L} = \mathcal{L}_{SM} - \sum_{i=1}^{n_R} \bar{l}_L^{\alpha} Y^{\alpha i} \tilde{\Phi} \nu_R^i - \sum_{i,j=1}^{n_R} \frac{1}{2} \bar{\nu}_R^{ic} M_N^{ij} \nu_R^j + h.c.$$

Y: 3 x n_R $\qquad$ M_N: n_R x n_R

Number of Physical Parameters

n_R	L_i	# zero modes	# masses	# angles	# CP phases
1	-	2	2	2	0
	+1	2	1	2	0
2	-	1	4	4	3
	(+1,+1)	1	2	3	1
	(+1,-1)	3	1	3	1
3	-	0	6	6	6
	(+1,+1,+1)	0	3	3	1
	(+1,-1,+1)	2	2	6	4
	(+1,-1,-1)	4	1	4	1

Complexity (↓) predictivity (↑)

1 Dirac (→ n_R = 1, L_i = +1)

2 Dirac (→ n_R = 2, L_i = (+1,+1))

3 Dirac (→ n_R = 3, L_i = (+1,+1,+1))

Minimal models

Most general (renormalizable) Lagrangian compatible with SM gauge symmetries:

$$\mathcal{L} = \mathcal{L}_{SM} - \sum_{i=1}^{n_R} \bar{l}_L^{\alpha} Y^{\alpha i} \tilde{\Phi} \nu_R^i - \sum_{i,j=1}^{n_R} \frac{1}{2} \bar{\nu}_R^{ic} M_N^{ij} \nu_R^j + h.c.$$

Y: $3 \times n_R$ $\qquad$ M_N: $n_R \times n_R$

Complexity ↓ $\qquad$ predictivity ↑

Number of Physical Parameters

n_R	L_i	# zero modes	# masses	# angles	# CP phases	
1	-	2	2	2	0	→ 3+1 minimal
	~~+1~~	~~2~~	~~1~~	~~2~~	~~0~~	→ 1 Dirac
2	-	1	4	4	3	→ 3+2 minimal
	(+1,+1)	1	2	3	1	→ 2 Dirac
	~~(+1,-1)~~	~~3~~	~~1~~	~~3~~	~~1~~	
3	-	0	6	6	6	
	(+1,+1,+1)	0	3	3	1	→ 3 Dirac
	(+1,-1,+1)	2	2	6	4	
	~~(+1,-1,-1)~~	~~4~~	~~1~~	~~4~~	~~1~~	

Pheno 3+n_s mixing models ?

They assume a general mass matrix for 3+n_s neutrinos: what is that model ?

Example 1:

$$\begin{pmatrix} M_{LL} & \overbrace{M_{LR}}^{3\mathrm{x}n_s} \\ M_{LR}^T & M_{RR} \end{pmatrix}$$

Pheno 3+n_s mixing models ?

They assume a general mass matrix for 3+n_s neutrinos:

Example 1: Gauge invariance

$$\begin{pmatrix} M_{LL} & M_{LR} \\ M_{LR}^T & M_{RR} \end{pmatrix}$$

↓

Effective theory: M_{LL} parametrizes our ignorance about the underlying dynamics (eg. a model with n_R > n_s, where the heavier states are integrated out)

Pheno 3+n_s mixing models ?

Example 2: Dirac

$$\overbrace{\phantom{M_{LR}}}^{(3+n_{s)}x(3+n_s)}$$

$$\begin{pmatrix} 0 & M_{LR} \\ M^T_{LR} & 0 \end{pmatrix}$$

requires to add 3+2 n_s Weyl sterile fermions to the SM, with specific lepton number assigments (3+n_s:+1, n_s:-1) !

These cannot be the minimal models...

$3+n_s$ pheno vs $3+n_R$ minimal ?

For the same $n_s=n_R$ many more parameters…less predictive

	# Angles	# CP Phases	# Dm^2
3+1 pheno	6	3	3
3+1 minimal	2	0	2
3+2 pheno	9	6	4
3+2 minimal	4	3	4

This work: Minimal 3+1, 3+2 confronted with data (neutrino experiments)

Earlier work: De Gouvea, hep-ph/0501039
De Gouvea, J. Jenkins, Vasudevan hep-ph/0608147

On parametrizations

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

- Physical parameters only
- Convenient to impose existing constraints

M_N =diag(M_1,M_2,...)

General

3+1

$$m_D = U^*(\theta_{13}, \theta_{23}) \begin{pmatrix} 0 \\ 0 \\ m \end{pmatrix}$$

3+2

$$m_D = U^*(\theta_{12}, \theta_{13}, \theta_{23}, \delta) \begin{pmatrix} 0 & 0 \\ m_2 & 0 \\ 0 & m_3 \end{pmatrix} V^\dagger(\theta_{45}, \alpha_1, \alpha_2)$$

↓

Standard PMNS only if Dirac/degenerate N

Casas-Ibarra (m_D << M_N)

3+2

$$\mathcal{M}_\nu = \begin{pmatrix} U & \epsilon \\ -\epsilon^\dagger U & 1 \end{pmatrix} Diag(0, m_2, m_3, M_1, M_2) \begin{pmatrix} U & \epsilon \\ -\epsilon^\dagger U & 1 \end{pmatrix}^T$$

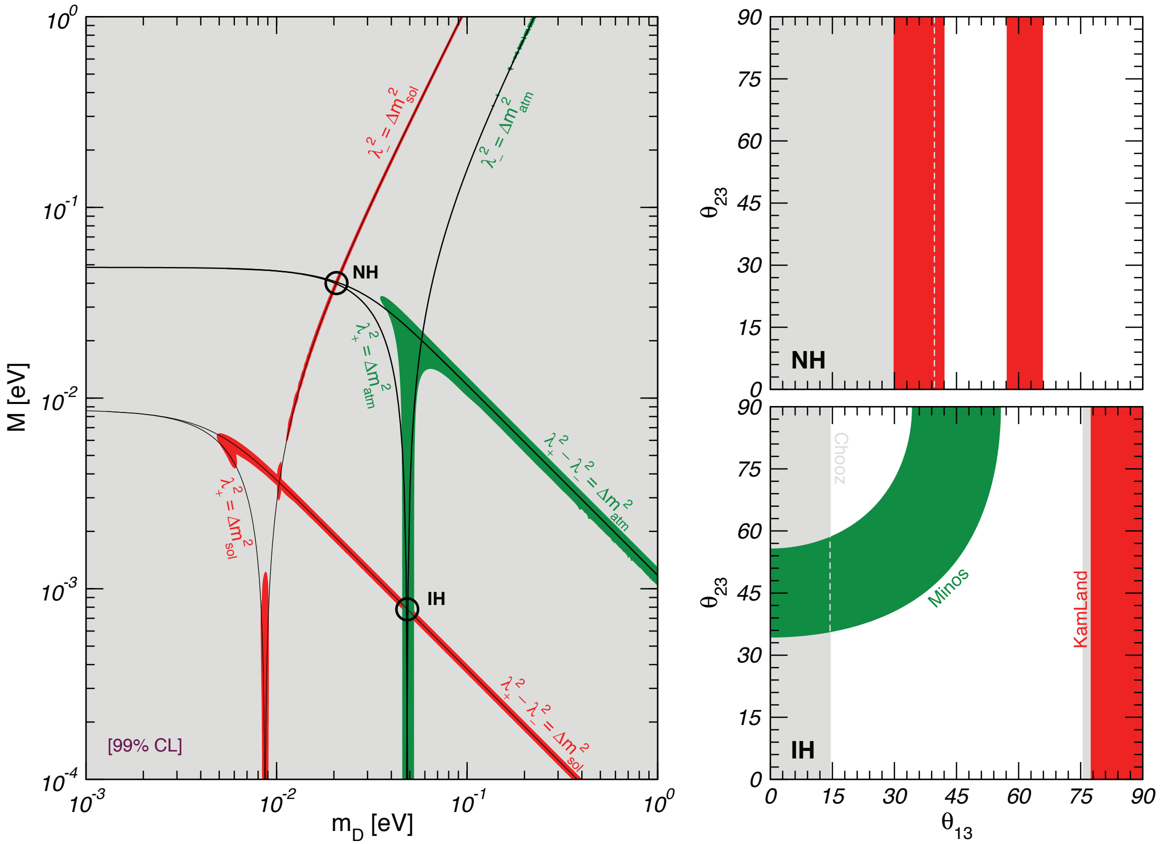
$$\epsilon = U \begin{pmatrix} 0 & 0 \\ m_2^{1/2} & 0 \\ 0 & m_3^{1/2} \end{pmatrix} R^\dagger(\theta_{45}) M_N^{-1/2}$$

↓

standard PMNS

Minimal 3+1

Two massless +two massive eigenstates, only two physical angles, no CP violation

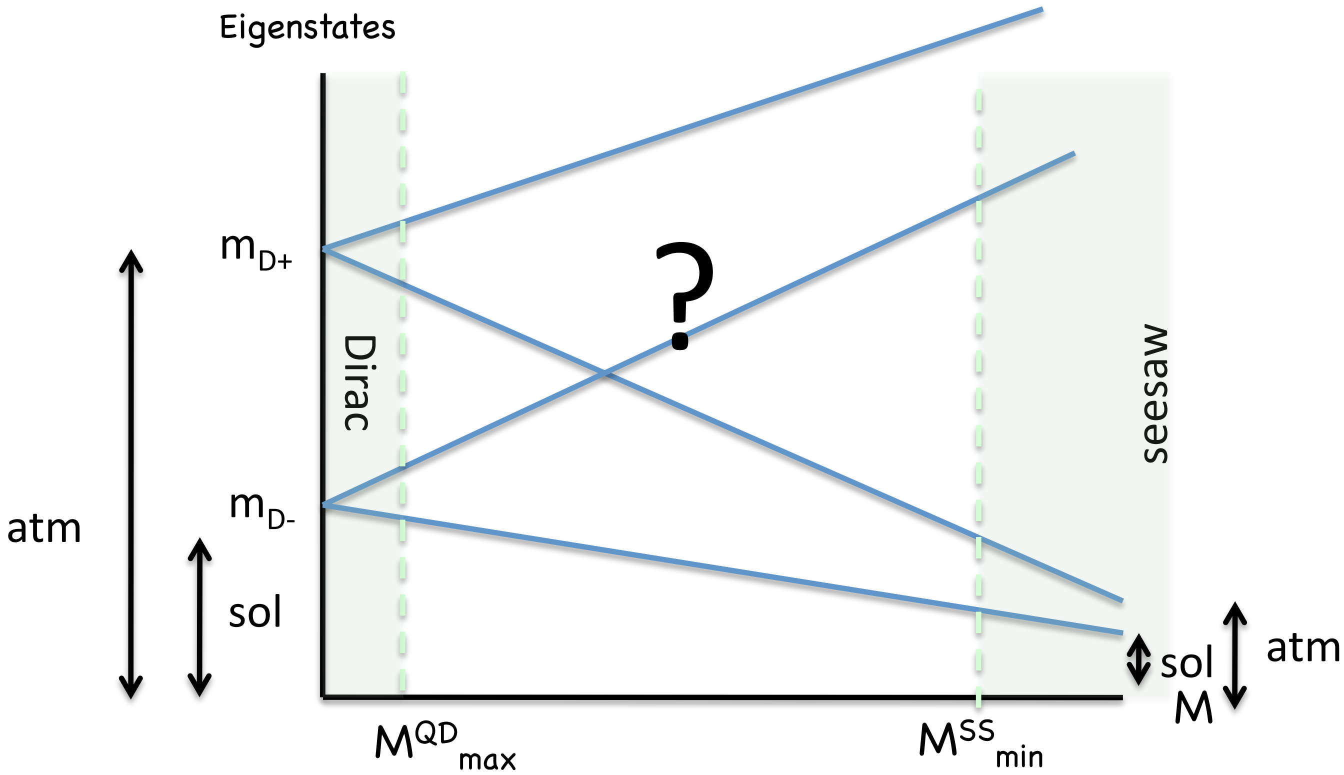


Strong incompatibility between Chooz+KamLAND vs Chooz+MINOS

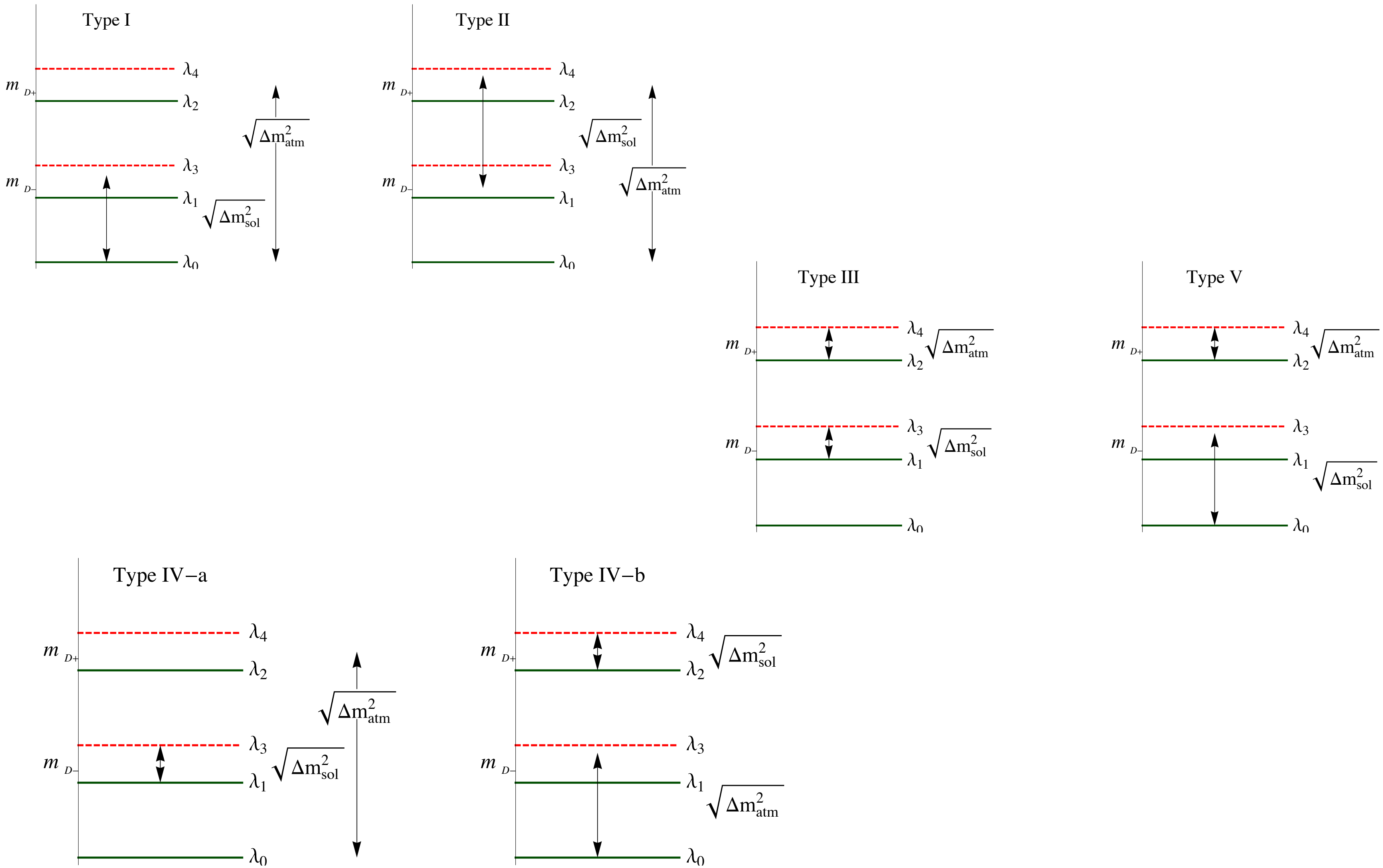
Minimal 3+2

Parameters: 1 massless, 4 massive eigenstates, 4 angles, 2 CP phases

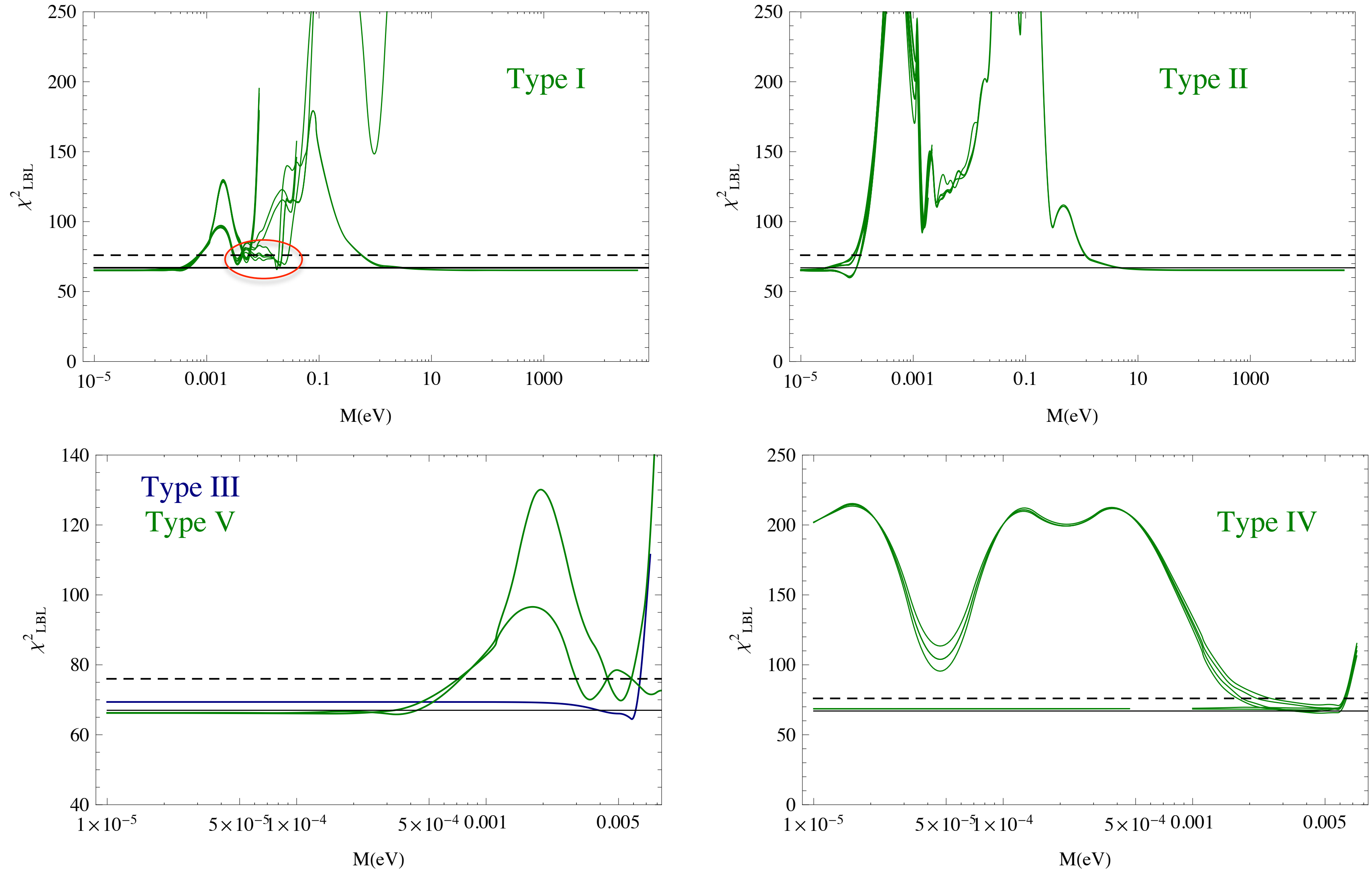
Simplification: degenerate case $M_1 = M_2 = M$, 3 angles, no CP violation



$$|\lambda_i^2 - \lambda_j^2| = \Delta m_{atm}^2, |\lambda_k^2 - \lambda_l^2| = \Delta m_{sol}^2,\ \ i,j,k,l = 0,...,4$$



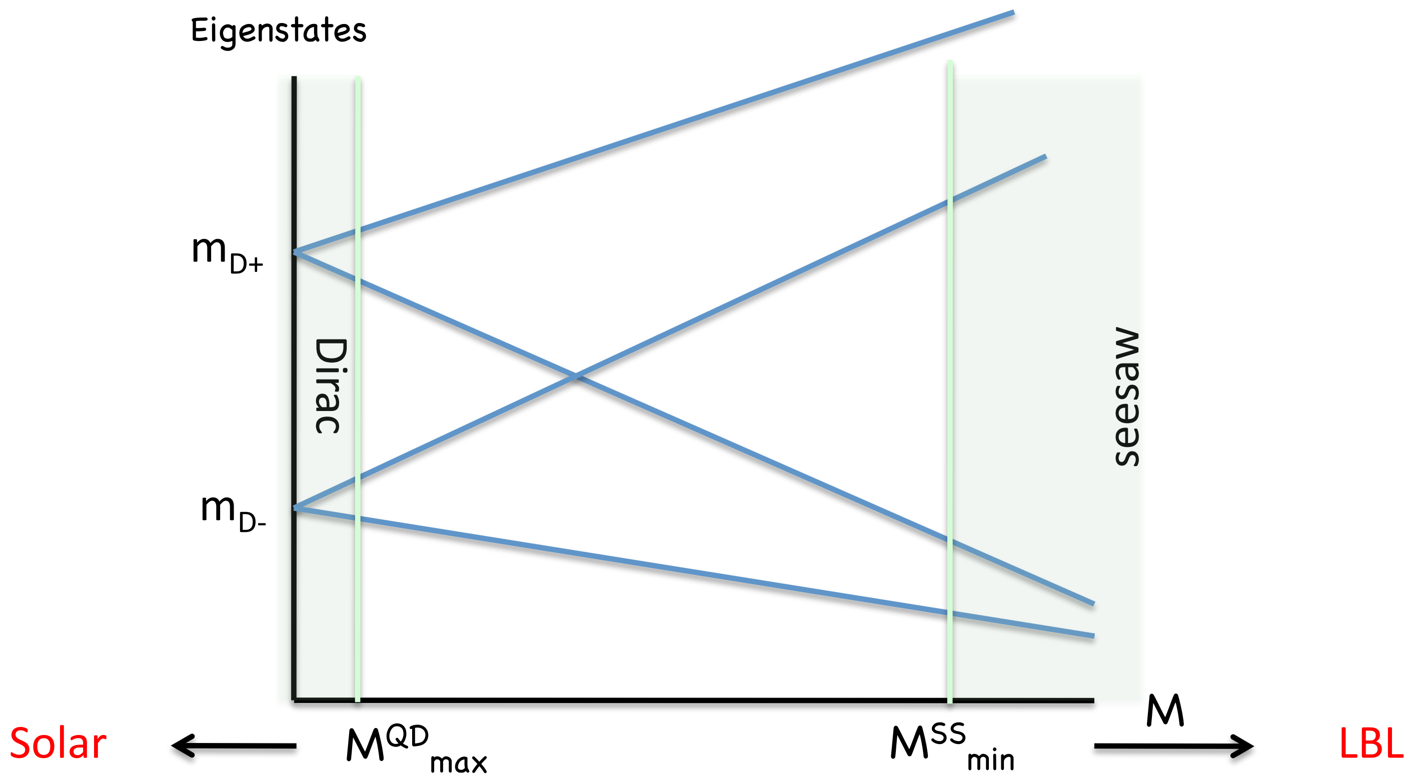
MINOS+KamLAND+CHOOZ



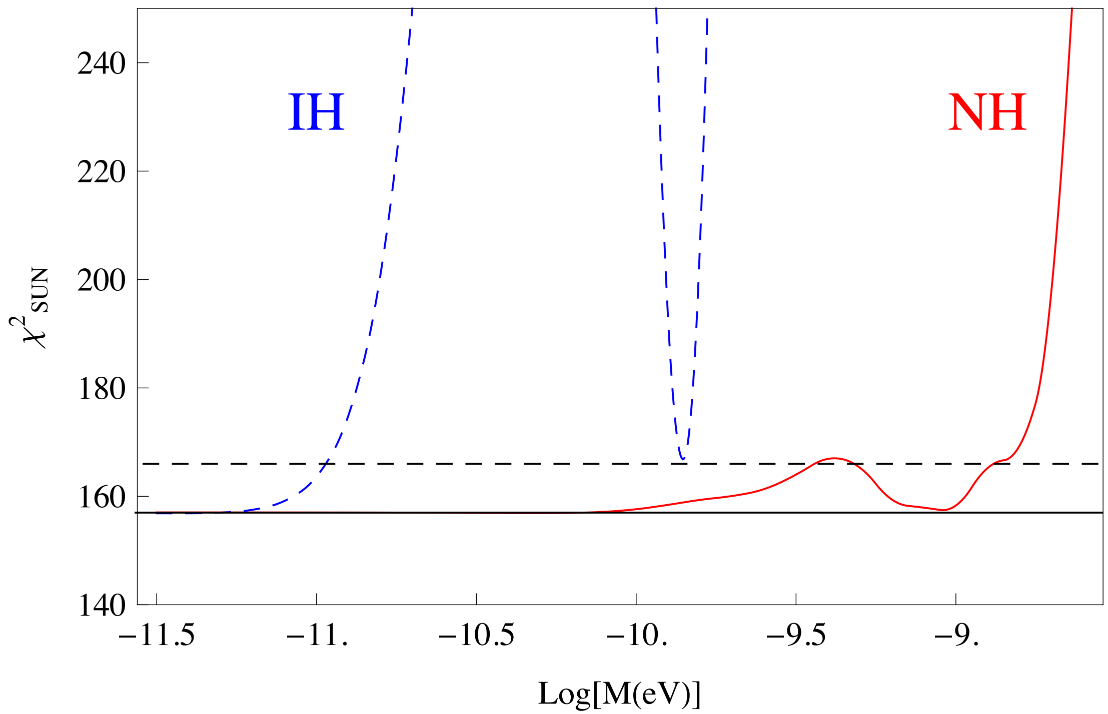
SOLAR data

Excludes all exotic Type III, IV, V solutions

Excludes all the intermediate Type I solutions



SOLAR data: $M^{QD}{}_{max}$



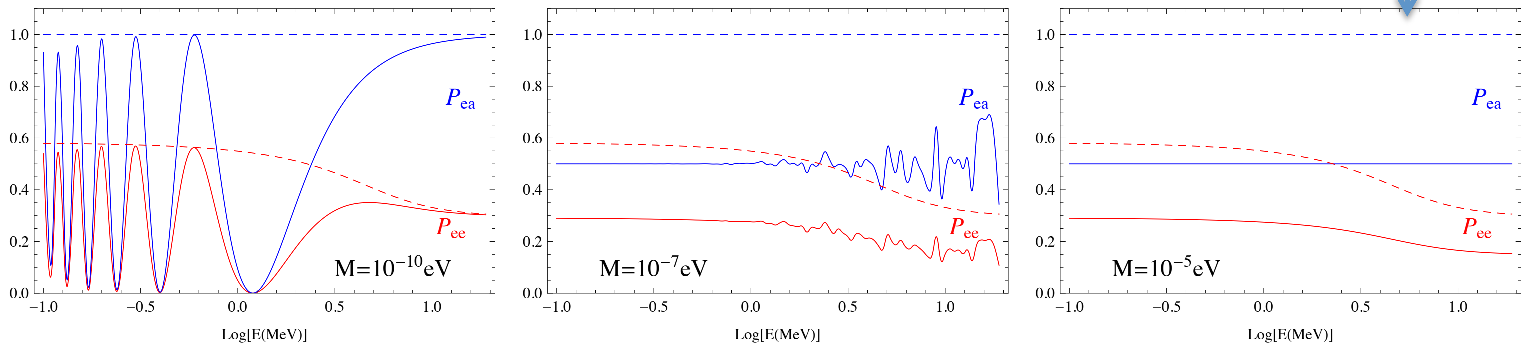
Impressive sensitivity of solar neutrinos to tiny departures from diracness!

See also De Gouvea, Huang, Jenkins arXiv: 0906.1611

SOLAR data: $M^{QD}{}_{max}$

IH

Adiabatic approx.

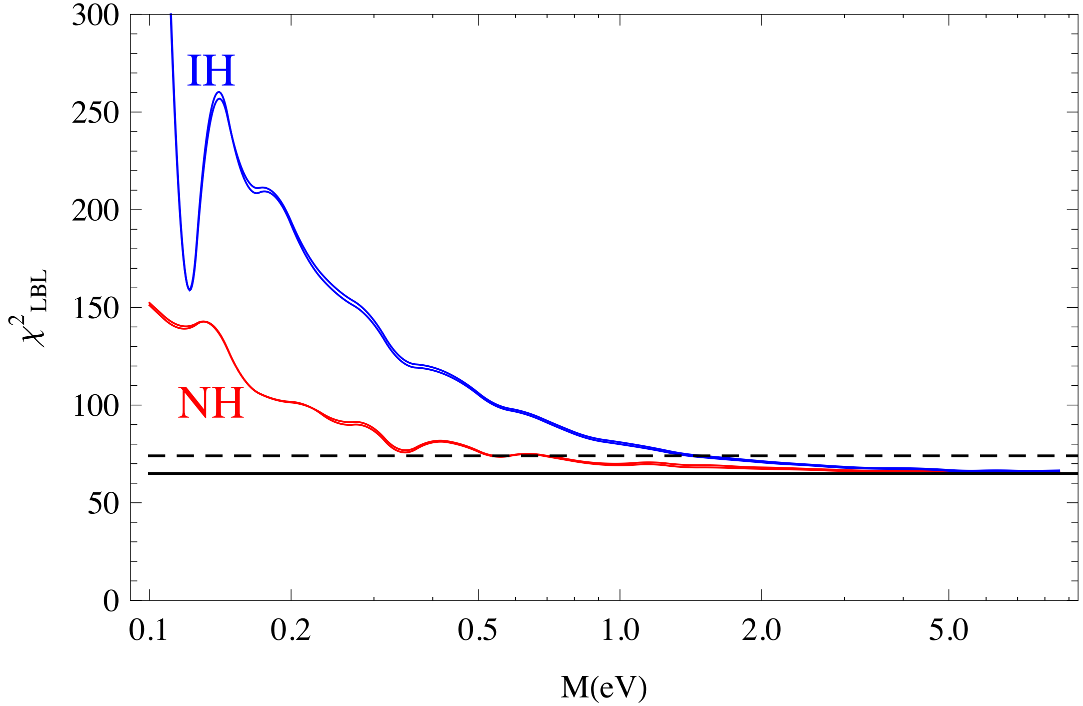


Adiabaticity limit:

$$M(\mathrm{eV}) < \begin{cases} 10^{-7} \times E_\nu(\mathrm{MeV}) & \mathrm{NH}, \\ 2 \times 10^{-8} \times E_\nu(\mathrm{MeV}) & \mathrm{IH}. \end{cases}$$

Vaccuum oscillations: $$L_{osc} \sim \frac{E_\nu}{M m_{D^-}}$$

LBL data: M^{SS}_{min}



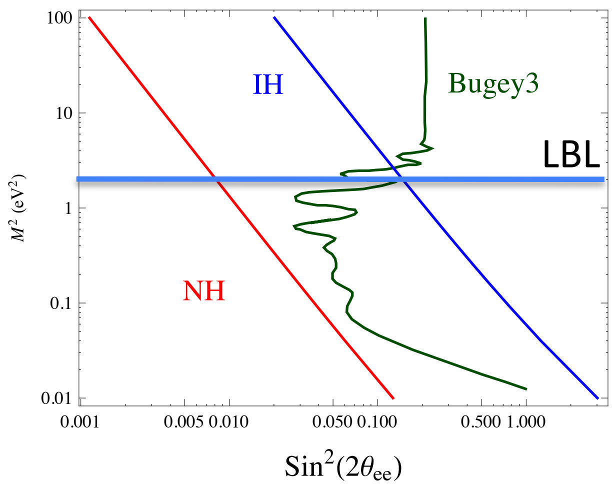
M > 0.6 eV (NH), 1.4eV (IH) as good fits as 3n scenario

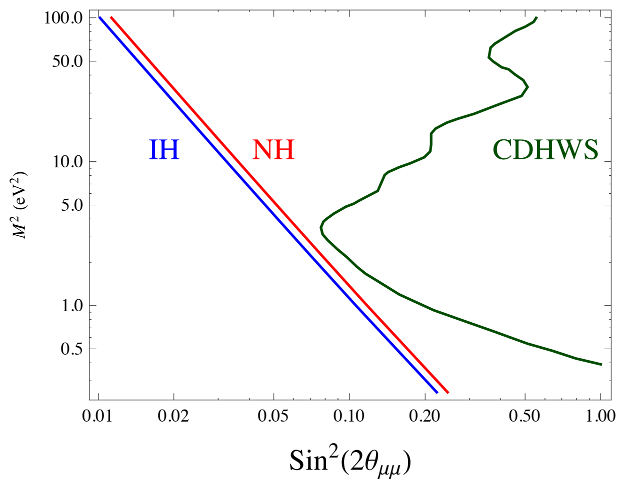
Other constraints on M^{SS}_{min} ?

Neutrinoless double-beta decay: $m_{ee} = 0$ ($M \ll 100MeV$)

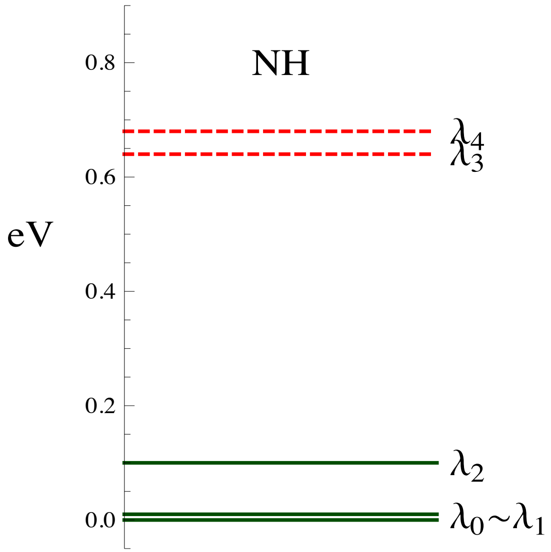
Tritium: presently no constraint (small mixing of heavy states)

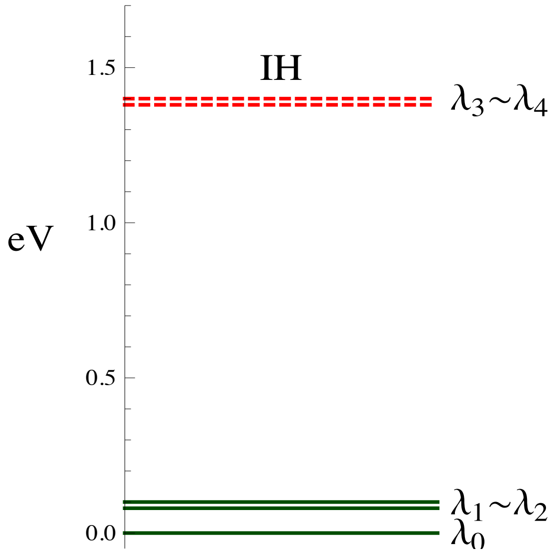
SBL reactor:





LSND/MB + reactor anomaly ?





Matching to 3+2 pheno model:

NH:

$$
\begin{aligned}
(U_{\rm mix})_{e4} &= s_{13} s_{34}, \\
(U_{\rm mix})_{e5} &= c_{13} s_{12} s_{25}, \\
(U_{\rm mix})_{\mu 4} &= c_{13} s_{23} s_{34}, \\
(U_{\rm mix})_{\mu 5} &= (c_{12} c_{23} - s_{12} s_{13} s_{23}) s_{25},
\end{aligned}
$$

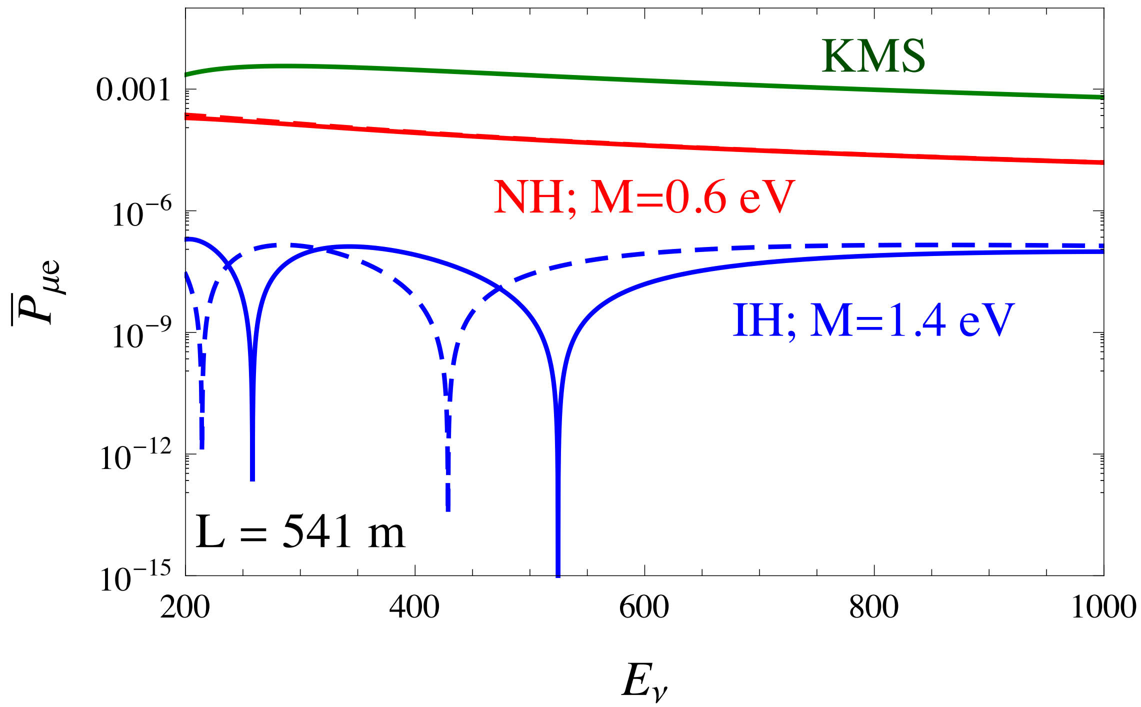
U ~0.1 (right ballpark for IH) !

	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

Kopp, Maltoni, Schwetz

$$s_{25} \approx m_{D-}/M, \qquad s_{34} \approx -m_{D+}/M,$$

No, for degenerate case



Beyond the degenerate case

In Casas&Ibarra parametrization: (θ_{13}, θ_{23}, θ_{12}, δ, $m_1=0$, m_2, m_3, θ_{45}^r, θ_{45}^i, M_1, M_2)

Eg: NH

$$|U_{e4}| \simeq \left|\sqrt{\frac{m_2}{M_1}} s_{12} c_{13} \cos(\theta_{45}^r - i\theta_{45}^i) + \sqrt{\frac{m_3}{M_1}} e^{-i\delta} s_{13} \sin(\theta_{45}^r - i\theta_{45}^i)\right| \quad \Delta m_{41}^2 \simeq M_1^2$$

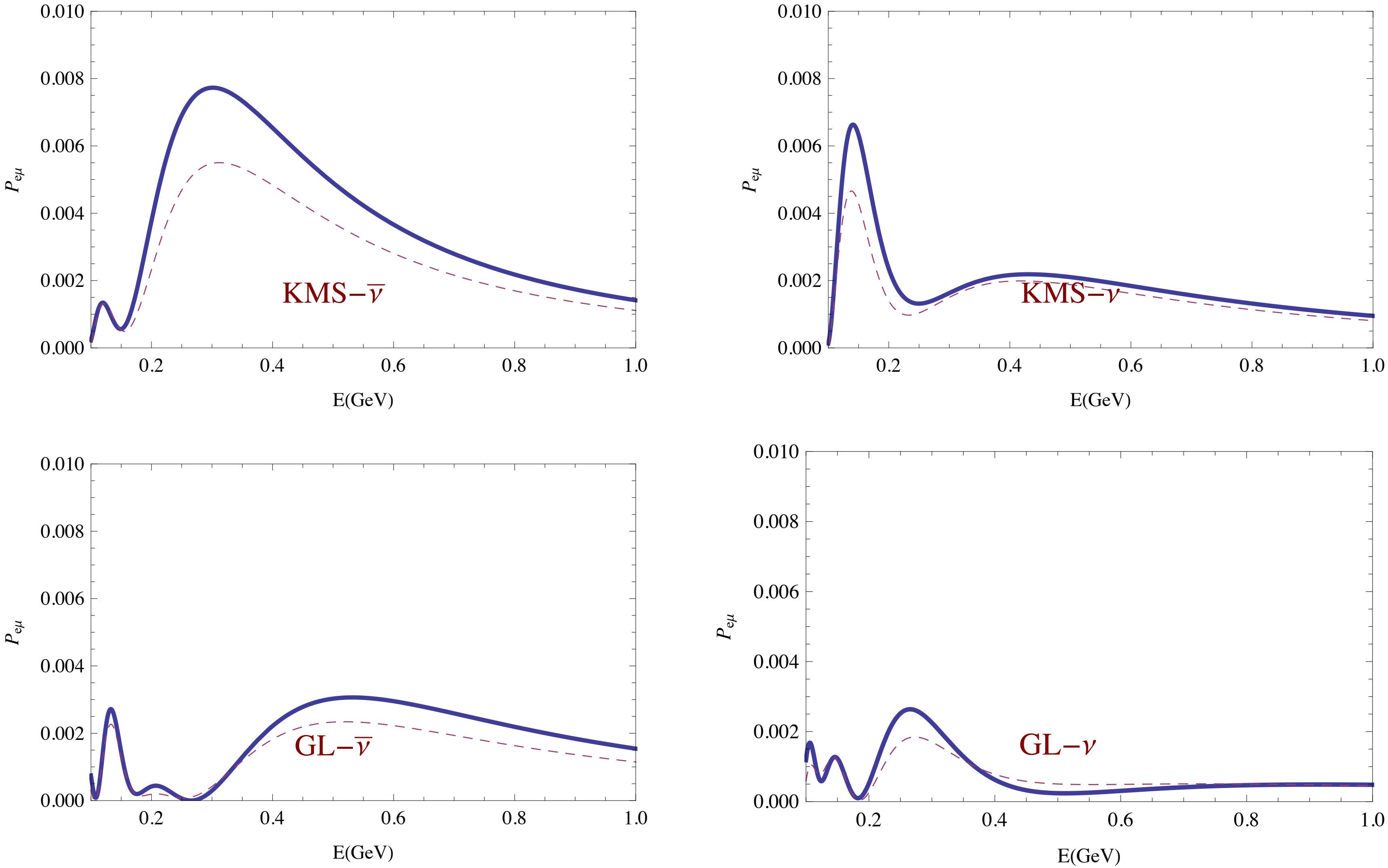
$$|U_{e5}| \simeq \left|-\sqrt{\frac{m_2}{M_2}} s_{12} c_{13} \sin(\theta_{45}^r - i\theta_{45}^i) + \sqrt{\frac{m_3}{M_2}} e^{-i\delta} s_{13} \cos(\theta_{45}^r - i\theta_{45}^i)\right| \quad \Delta m_{51}^2 \simeq M_2^2$$

	|Ue4|	|Um4|	|Ue5|	|Um5|	f
3+2 KMS	0.128	0.165	0.138	0.148	1.62 p
3+2 (IH)	0.136	0.20	0.162	0.14	1.59 p
3+2 (NH)	0.095	0.17	0.082	0.149	1.74 p

3+2 GL	**0.130**	**0.134**	**0.130**	**0.08**	1.52 p
3+2 (IH)	0.133	0.137	0.167	0.09	1.44 p

A detailed fit to the data is underway…

3+2 minimal (IH) vs KMS/GL best fits



Conclusions

- Most models of neutrino masses add sterile Weyl fermions to the SM (seesaw type I, inverse, direct…)
- Complexity/predictivity of those models depend on n_R and global (e.g. lepton number) symmetry
- $n_R=1$ excluded by reactor and accelerator LBL data
- $n_R=2$ (in degenerate limit), excluded for

  10^{-9} (10^{-11}) eV $< M <$ 1.4 eV NH (IH)
- $n_R=2$ with two masses ~eV could explain LSND/MiniBOONE at similar level as 3+2 pheno (if IH !) with less free parameters ? (all mixings determined in terms of one complex angle and d)
- It is important to exclude simpler models before going to more complex ones…