On Minimal Models with Light Sterile Neutrinos

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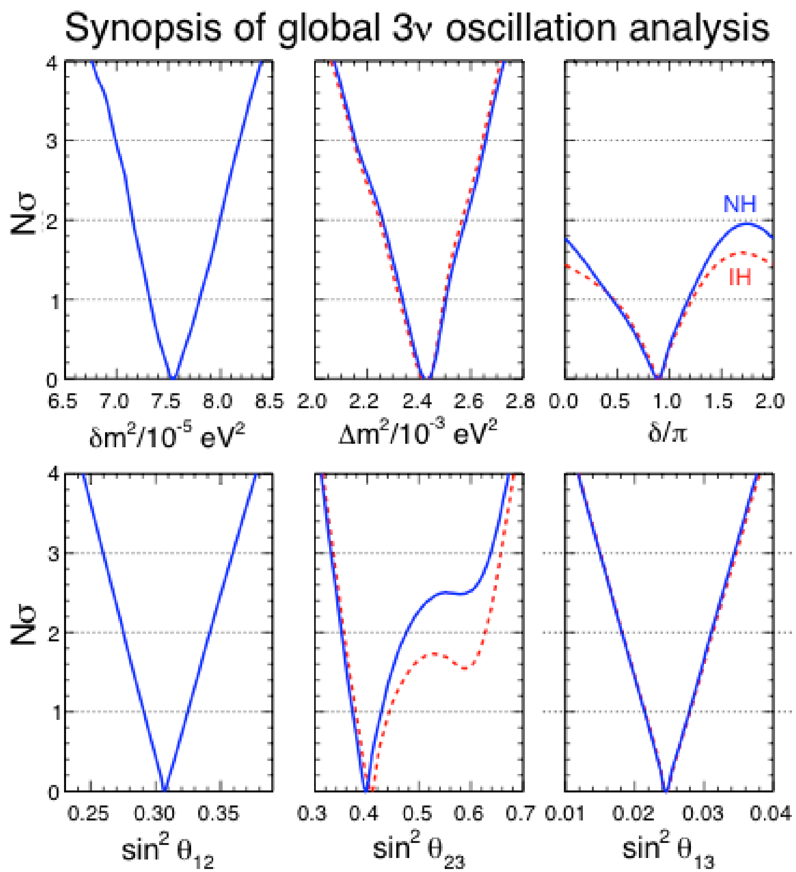
Donini, López-Pavón, PH, Maltoni arXiv:1106.0064
Donini, López-Pavón, PH, Maltoni, Schwetz arXiv:1205.5230

SM + massive ν_s

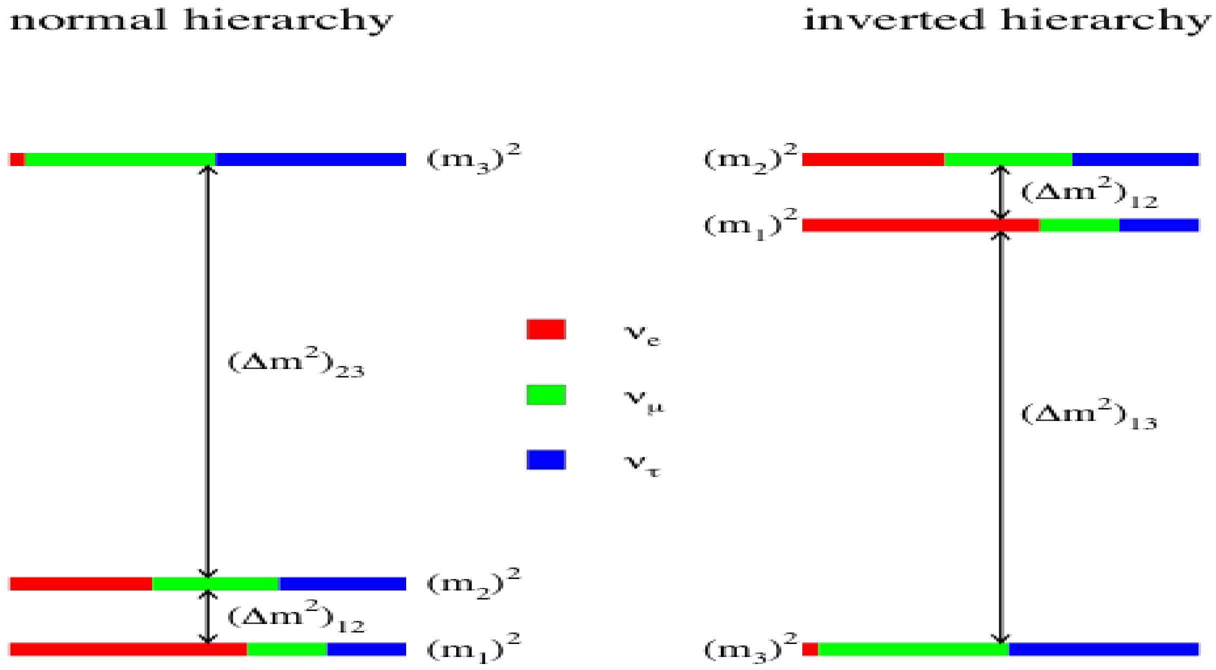


Fogli et al 2012
(after T2K,
Double-CHOOZ, Daya Bay, RENO)

3ν mixing:

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

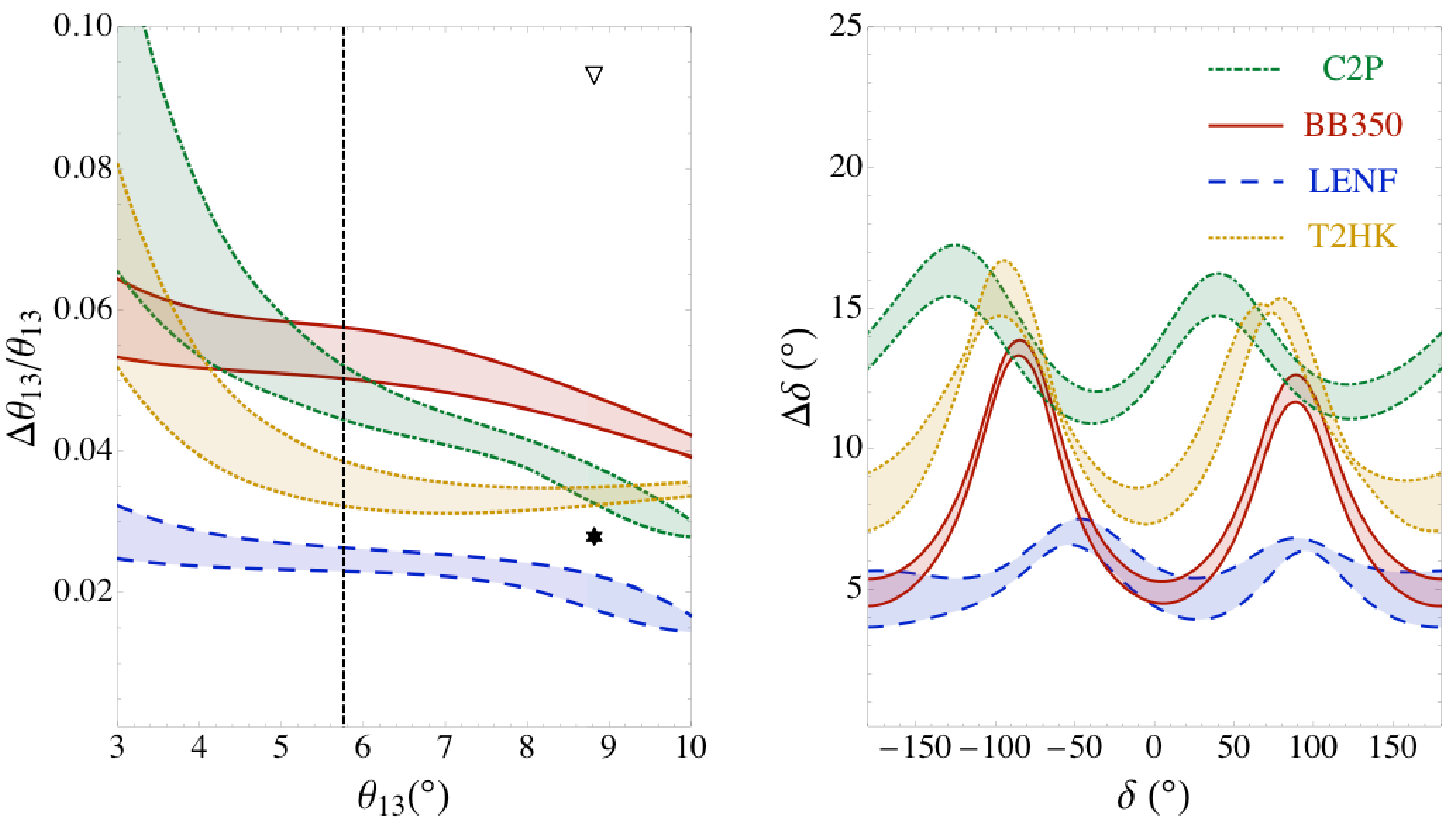
Standard 3ν scenario



The flavour observables:

Masses	Angles	CP-phases
$m_1^2 < m_2^2, m_3^2$	$\theta_{12}, \theta_{23}, \theta_{13}$	$\delta, \alpha_1, \alpha_2$

Good prospects for CP volation

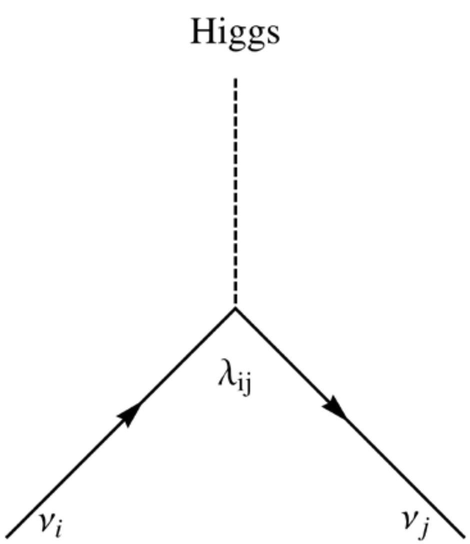


Coloma, Donini, Fernandez-Martinez,PH arXiv:1203.5651

New dofs needed !

Neutrinos are massive -> there must be new dofs in the SM

$$-\mathcal{L}_{\rm Dirac} = \bar{\nu}_L m_\nu \nu_R + h.c. \;\leftrightarrow \bar{L}\tilde{\Phi}\lambda\nu_R + h.c.$$



$$m_\nu \sim \lambda v$$

New dofs needed

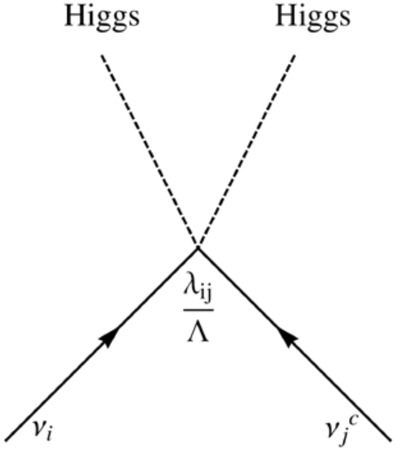
Neutrinos are massive -> there must be new dofs in the SM

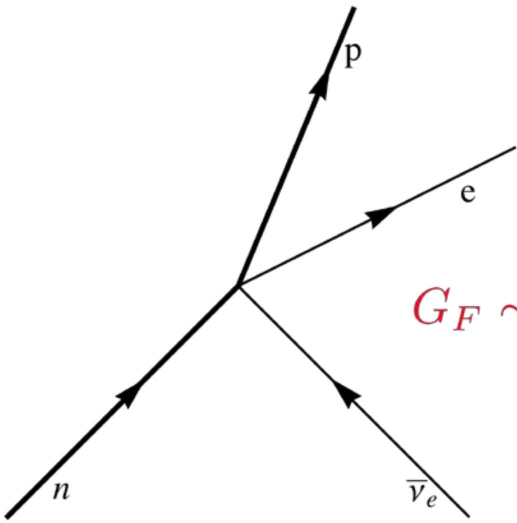
$$-\mathcal{L}_{\mathrm{Majorana}} = \bar{\nu}_L m_\nu \nu_L^c + h.c. \;\leftrightarrow\; \bar{L}\tilde{\Phi}\; \alpha \; \tilde{\Phi} L^c + h.c.$$

Weinberg

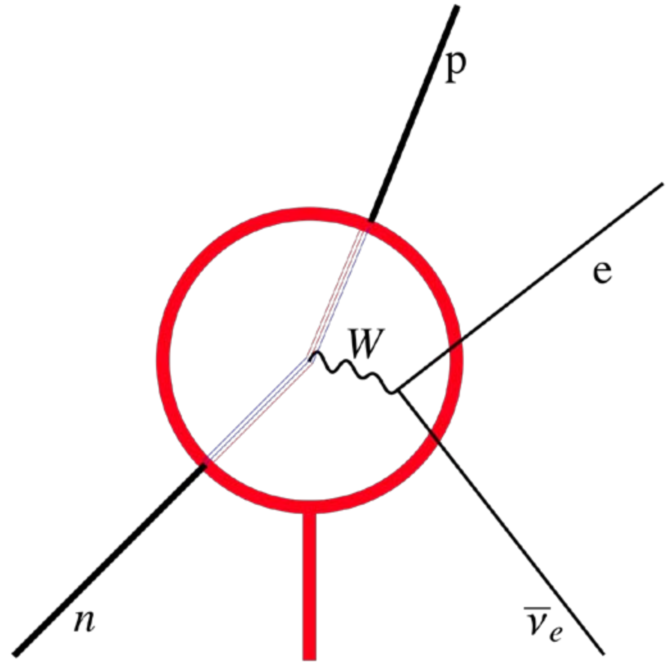
$$[\alpha] = -1$$

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

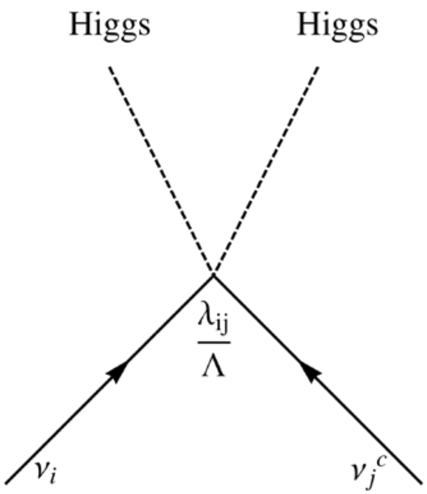




$$G_F \sim \frac{1}{M_W^2}$$



SM



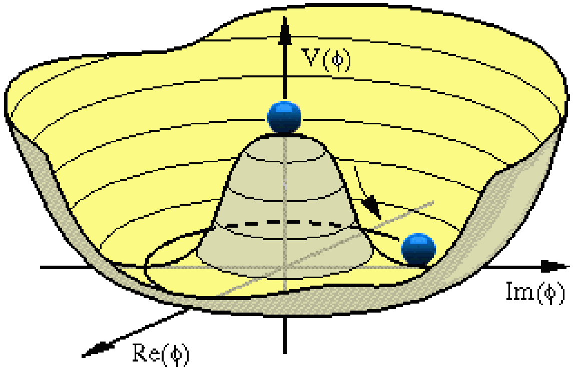
νSM ?

The good νSM

- How does the ν scale relates to the EW scale ?

The good νSM

- New scale versus EWSB ?

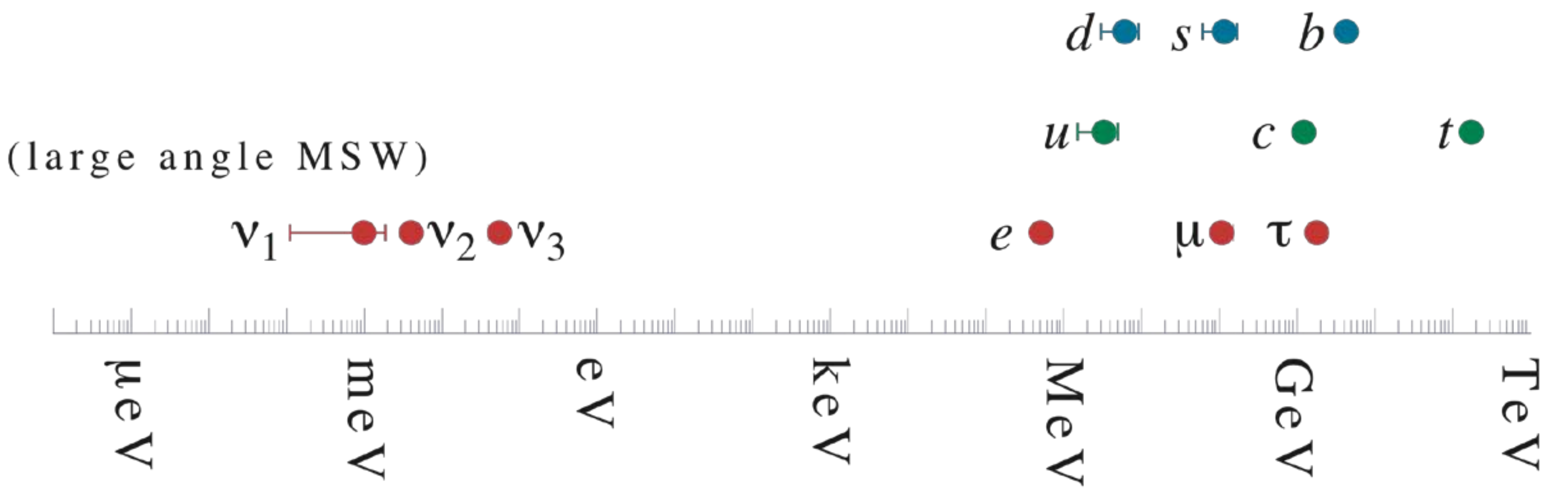


Besides the consistency of SM, now the Higgs…where does the new scale fit in this picture ?

The good νSM

- New scale versus EWSB ?
- Explanation for the neutrino-charged lepton hierarchy

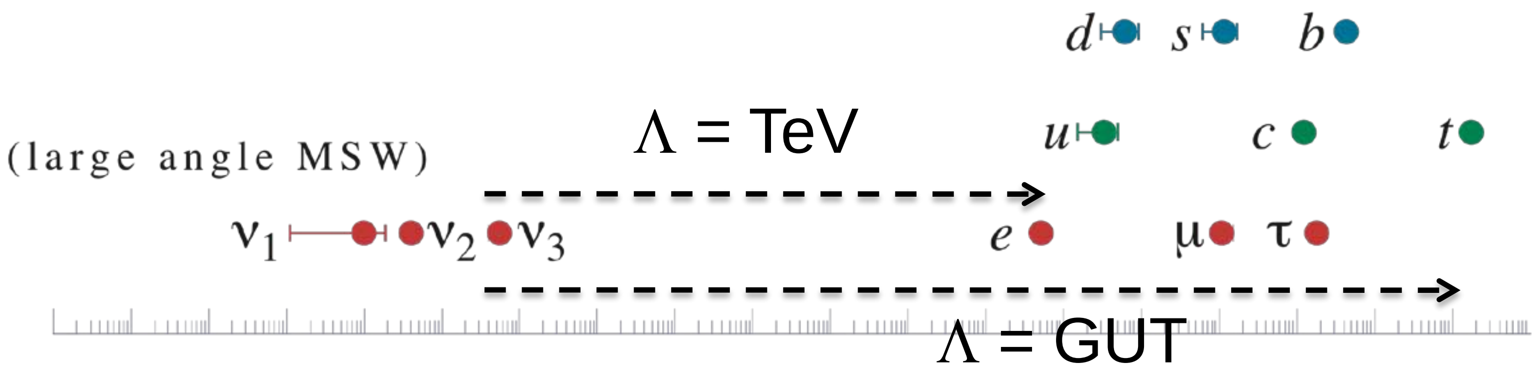
The ν flavour puzzle I



Why are neutrino masses so light ?

Seesaw of type I

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



Yukawa

The good νSM

- New scale versus EWSB ?
- Explanation for the neutrino-charged lepton hierarchy
- Explain difference lepton/quark mixing

CKM

The ν flavour puzzle II

V_{CKM} =

$$\begin{pmatrix} 0.97383(24) & 0.2272(10) & 3.96(9)\times 10^{-3} \\ 0.2271(10) & 0.97296(24) & 42.21^{+0.10}_{-0.80}\times 10^{-3} \\ 8.14^{+0.32}_{-0.64}\times 10^{-3} & 41.61^{+0.12}_{-0.78}\times 10^{-3} & 0.999100^{+0.000034}_{-0.000004} \end{pmatrix}$$

PDG 2007

PMNS

$$|U|_{3\sigma} = \begin{pmatrix} 0.77 \to 0.86 & 0.50 \to 0.63 & 0.0 \to 0.22 \\ 0.22 \to 0.56 & 0.44 \to 0.73 & 0.57 \to 0.80 \\ 0.21 \to 0.55 & 0.40 \to 0.71 & 0.59 \to 0.82 \end{pmatrix}$$

Gonzalez-Garcia, Maltoni

Differences are striking!

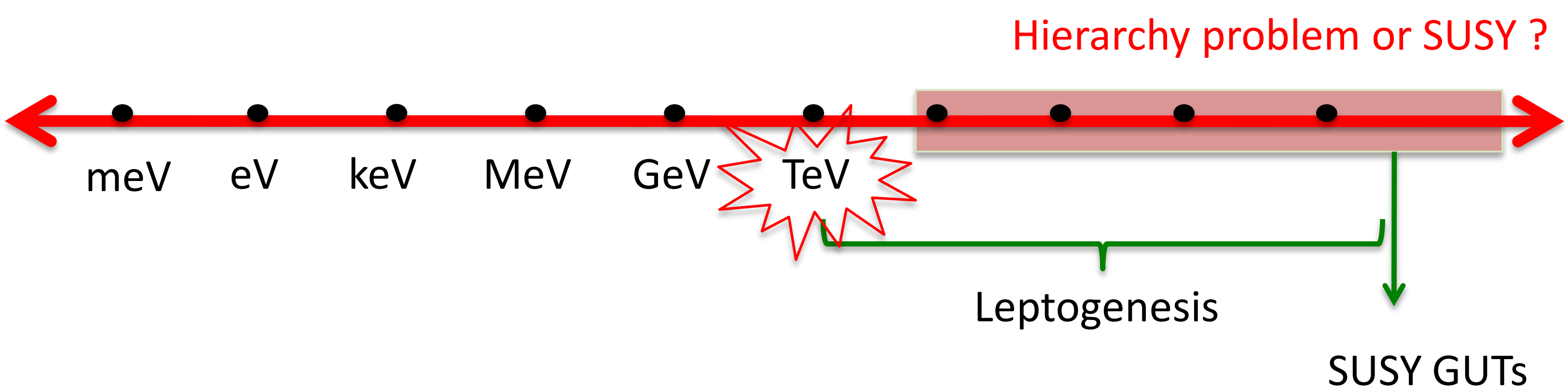
The good νSM

- New scale versus EWSB ?
- Explanation for the neutrino-charged lepton hierarchy
- Explain the difference lepton/quark mixing(probably a very relevant question is how many ν dofs)
- Explain other open problems: DM, matter-antimatter, oscillation anomalies, cosmology anomalies…

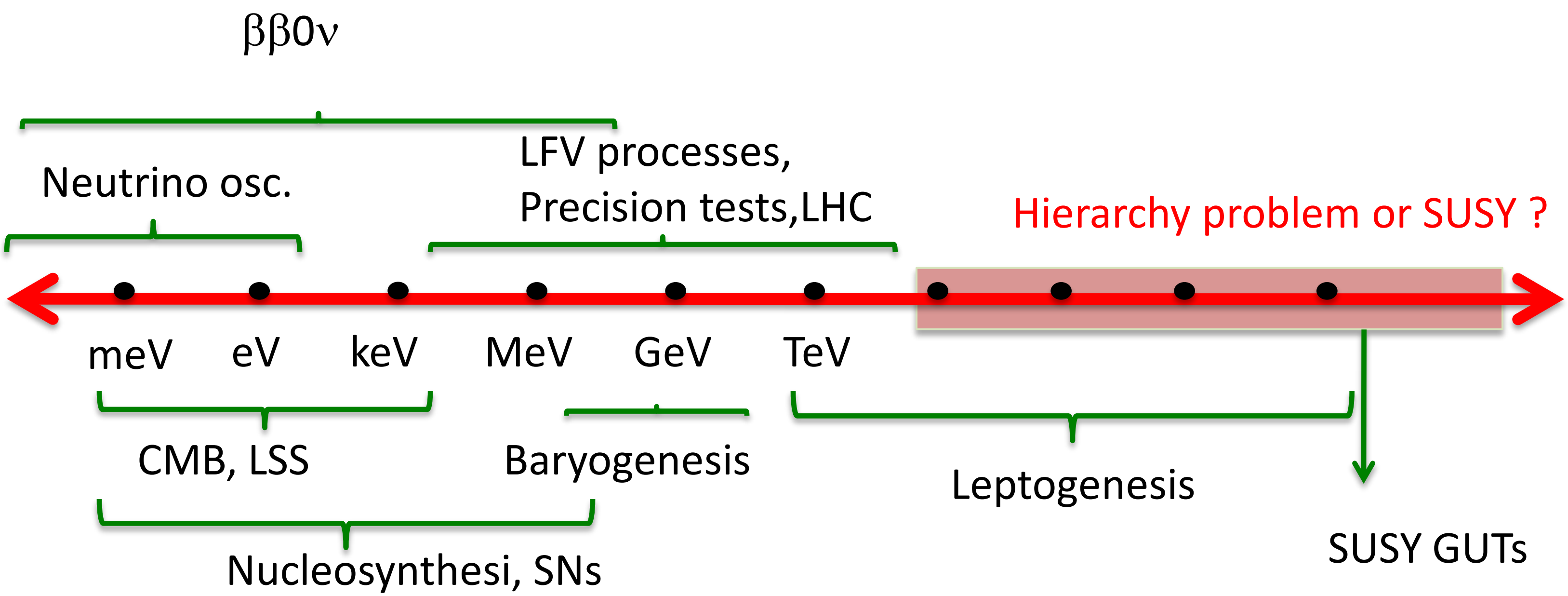
The good νSM

- New scale versus EWSB ?
- Explanation for the neutrino-charged lepton hierarchy
- Explain the difference lepton/quark mixing
- Explain other open problems: DM, matter-antimatter, oscillation anomalies, cosmology anomalies…
- Do so, in a predictable and testable way !

Pinning down the New physics scale

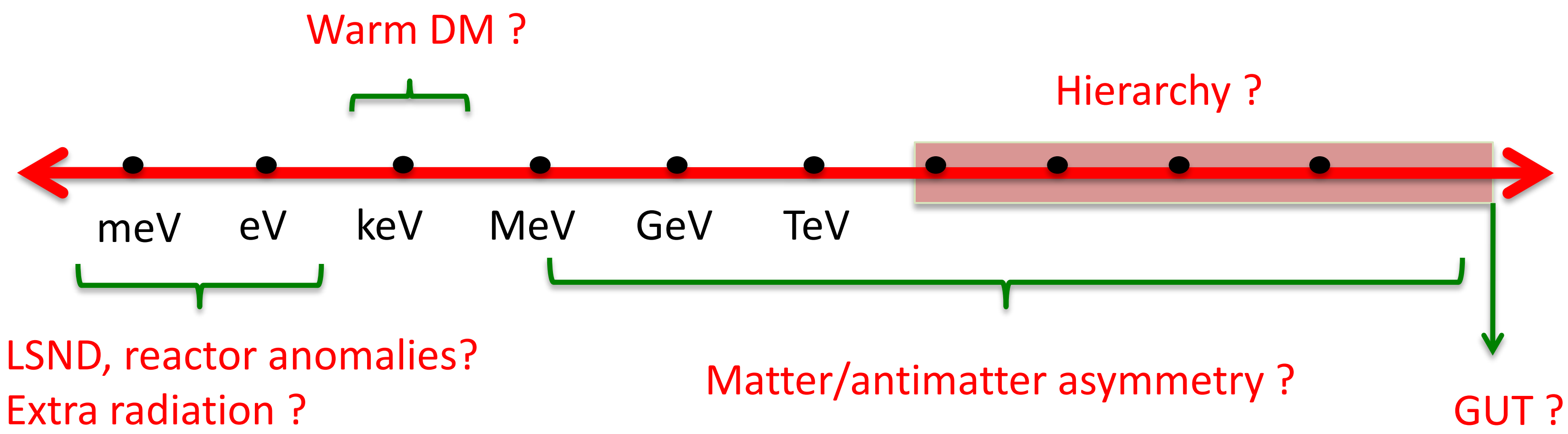


Pinning down the New physics scale



Light Sterile Neutrinos White Paper, Abazajian et al arXiv: 1204.5379 and refs. therein

Other uses of the New physics scale(s)



New dofs might help resolve open problems…or be excluded by observations

Outlier I: LSND anomaly

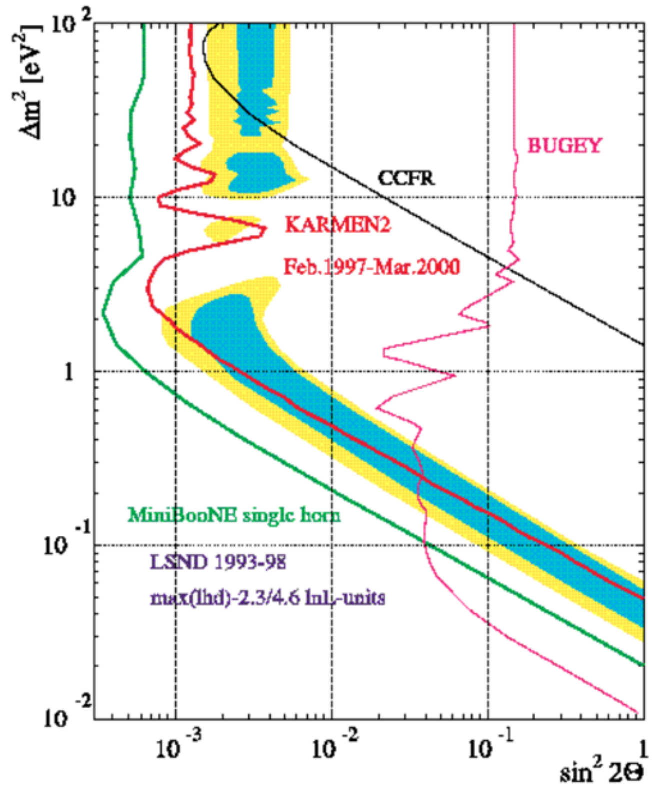
$$\pi^+ \to \mu^+ \quad \nu_\mu$$
$$\nu_\mu \to \nu_e \ \mathrm{DIF}\ (28 \pm 6/10 \pm 2)$$

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

Appearance signal with very different

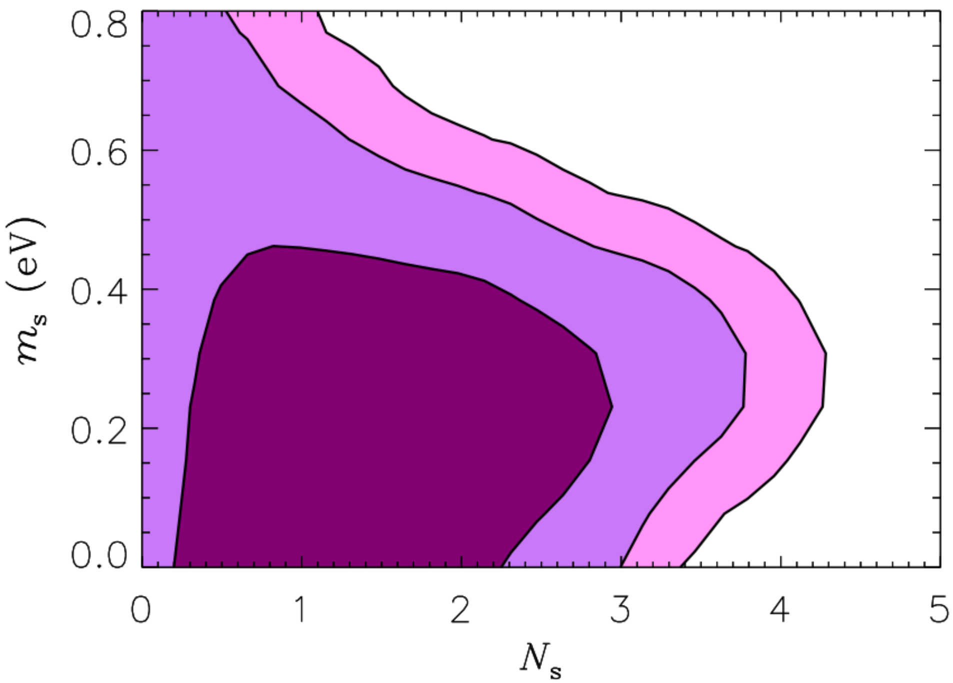
$$|\Delta m^2| \gg |\Delta m^2_{atm}|$$

LSND vs KARMEN



Not yet disproved at an acceptable level of confidence…

Outlier II: 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

LSND anomaly

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-ν not MB ν) $n_s \geq 2$
(seems not the case with new MiniBOONE data…)

- Tension appearance (signal) and disappearance (no signal) ?

- Tension with cosmology ?

Oscillation terms associated with the larger mass splittings…

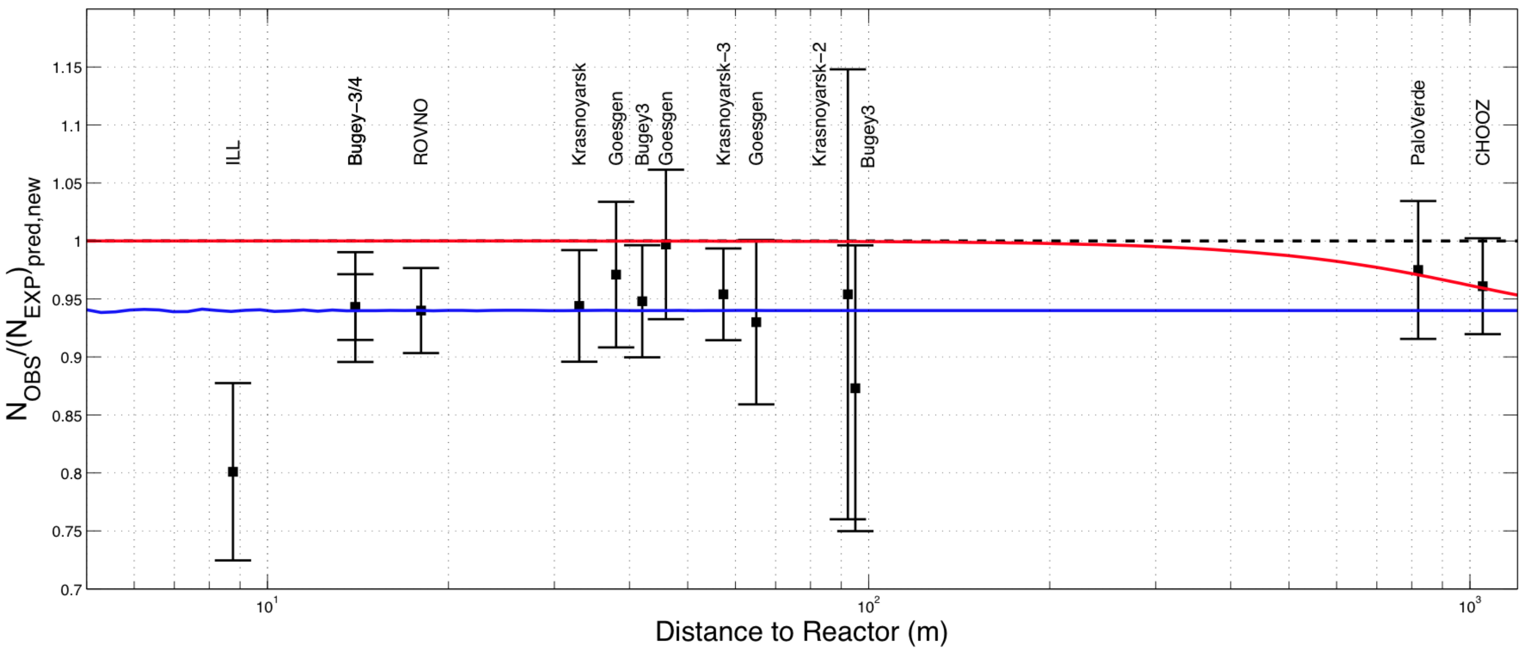
$$P(\nu_e \rightarrow \nu_\mu) = O(|U_{ei}|^2 \, |U_{\mu i}|^2)$$

$$P(\nu_\mu \rightarrow \nu_\mu) = O(|U_{\mu i}|^2)$$

$$P(\nu_e \rightarrow \nu_e) = O(|U_{ei}|^2)$$

A convincing signal would be to find it in all the three…

Outlier III: reactor anomaly



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

Mueller et al, ArXiv: 1101.2663

Still to be confirmed by the new reactor experiments !

3+2 neutrino mixing model

Parametrized in terms of a general unitary 5x5 mixing matrix
(9 angles, 5 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
χ^2_{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
$\Delta\chi^2_{PG}$	24.1	22.2
NDF_{PG}	2	5
PGoF	6×10^{-6}	5×10^{-4}

Giunti, Laveder, (GL) arXiv:1107.1452

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

What is this Pheno 3+n_s mixing model ?

Assumes a general mass matrix for 3+n_s neutrinos:

$$\begin{array}{cc} \overbrace{\phantom{M_{LL}}}^{3x3} & \overbrace{\phantom{M_{LR}}}^{3xn_s} \\ \end{array}$$

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

What is this Pheno 3+n_s mixing models ?

Assumes a general mass matrix for 3+n_s neutrinos:

Gauge invariance

$$\left(\begin{array}{cc} \cancel{M_{LL}} & M_{LR} \\ M_{LR}^T & M_{RR} \end{array} \right)$$

$\downarrow$

Effective theory: M_{LL} parametrizes our ignorance about the underlying dynamics

UV extension 1: a model with $n_R >= 3+n_s$, where 3 heavier states are integrated out
UV extension 2: a model with $n_R = 3 + 2\ n_s$ and an exact lepton number....

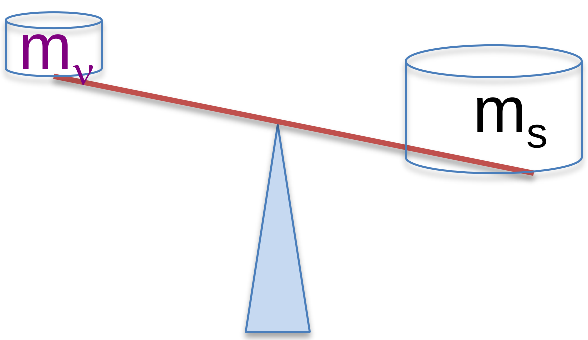
Type I Seesaw

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 $\quad$ M_N: n_Rx n_R

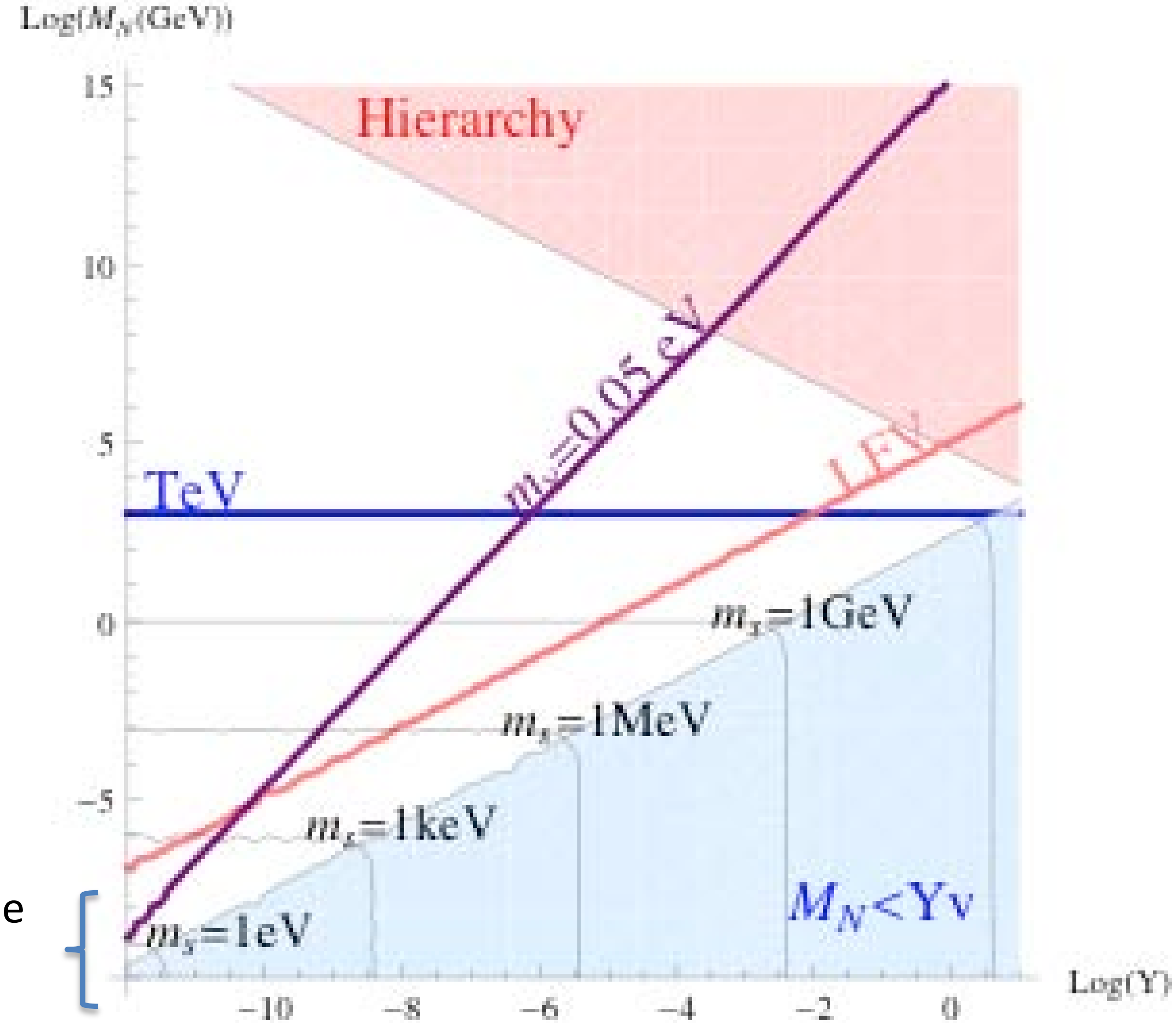
$$M_\nu = \begin{pmatrix} 0 & Yv \\ Yv & M_N \end{pmatrix}$$



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

$$LFV \sim Y^\dagger \frac{v^2}{M_N^2} Y$$

One scale see-saw models



Light sterile neutrinos

Y_e

3+n_R Minimal Models

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

3+2 Minimal Model much more predictive than 3+2 Phenomenological Model

Model	# Δm^2	# Angles	# Phases
3 ν	2	3	1 -3
3+2 MM	4	4	3
3+2 PM	4	9	5

Mini-seesaw models De Gouvea & coll. hep-ph/0501039, hep-ph/0608147

On parametrizations

$$\mathcal{M}_\nu = \left(\begin{array}{cc} 0 & m_D \\ m_D^T & M_N \end{array} \right)$$

- Independent (physical) parameters only
- Convenient to impose existing constraints

$$\mathcal{M}_\nu = U^* \mathrm{Diag}(0, m_2, m_3, M_1, M_2) U^T$$

$$U = \left(\begin{array}{cc} U_{aa} & U_{as} \\ U_{sa} & U_{ss} \end{array} \right),$$

Casas-Ibarra parametrization

For $m_i << M_j$

$$U_{aa} \simeq U_{\rm PMNS} \qquad U_{as} \simeq iU_{\rm PMNS} \begin{pmatrix} 0 \\ m_l^{1/2} R^\dagger M_h^{-1/2} \end{pmatrix}$$

$$U_{PMNS}(\theta_{12}, \theta_{13}, \theta_{23}, \delta, \alpha)$$ Unitary

$$R(\theta_{45}, \gamma_{45}) = \begin{pmatrix} \cos(\theta_{45} + i\gamma_{45}) & \sin(\theta_{45} + i\gamma_{45}) \\ -\sin(\theta_{45} + i\gamma_{45}) & \cos(\theta_{45} + i\gamma_{45}) \end{pmatrix}$$ Complex orthogonal

If M ≤ O(eV) corrections are important !

Beyond Casas-Ibarra

More generally (extended Casas-Ibarra)

$$U_{aa} = U_{PMNS} \begin{pmatrix} 1 & 0 \\ 0 & H \end{pmatrix}, \; U_{as} = iU_{PMNS} \begin{pmatrix} 0 \\ H m_l^{1/2} R^\dagger M_h^{-1/2} \end{pmatrix}$$

$$H^{-2} = I + m_l^{1/2} R^\dagger M_h^{-1} R m_l^{1/2}$$

Donini, et al 1205.5230

Incorporates the expected non-unitarity effects in the light sector

Alternative parametrization same philosophy

Blennow, Fernandez-Martinez arXiv:1107.3992

Heavy-Light Mixings

Heavy-light mixings are predicted up to a complex angle z_{45} and two CP phases !

Normal Hierarchy

Ex: $$U_{e4} \simeq i\left(\sqrt{\frac{m_3}{M_1}}e^{i(\alpha-\delta)}s_{13}\sin z_{45} + \sqrt{\frac{m_2}{M_1}}c_{13}s_{12}\cos z_{45}\right)$$

Suppressed in $\sqrt{\frac{m_i}{M_j}}$ and θ_{reactor} or $\sqrt{\frac{\Delta m^2_{\text{sol}}}{\Delta m^2_{\text{atm}}}}$

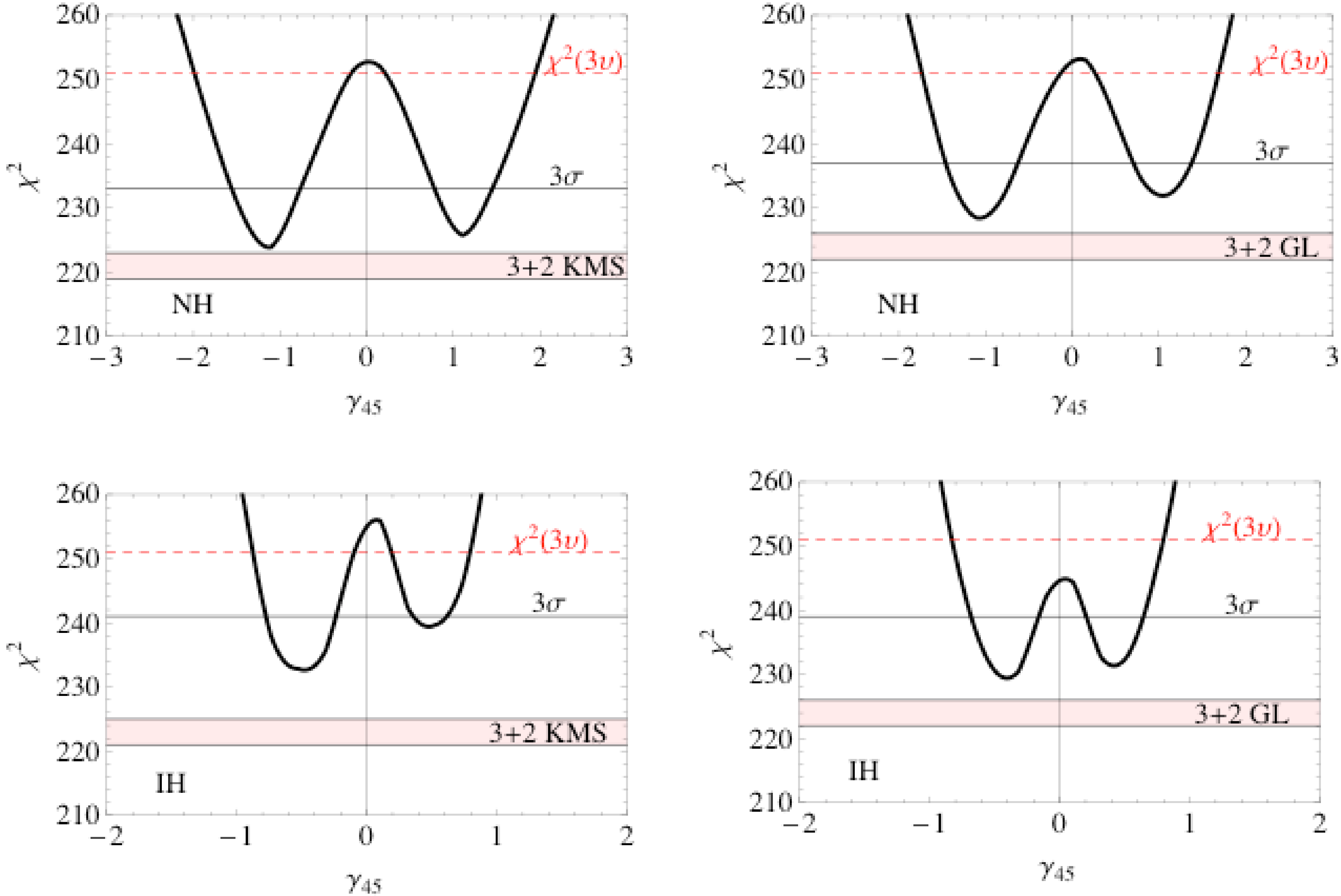
Inverse Hierarchy Suppressed only in $\sqrt{\frac{m_i}{M_j}}$ Right ballpark!

Donini, et al 1106.0064; de Gouvea, Huang 1110:6122;Fan,Langacker 1201:6662

Global fits

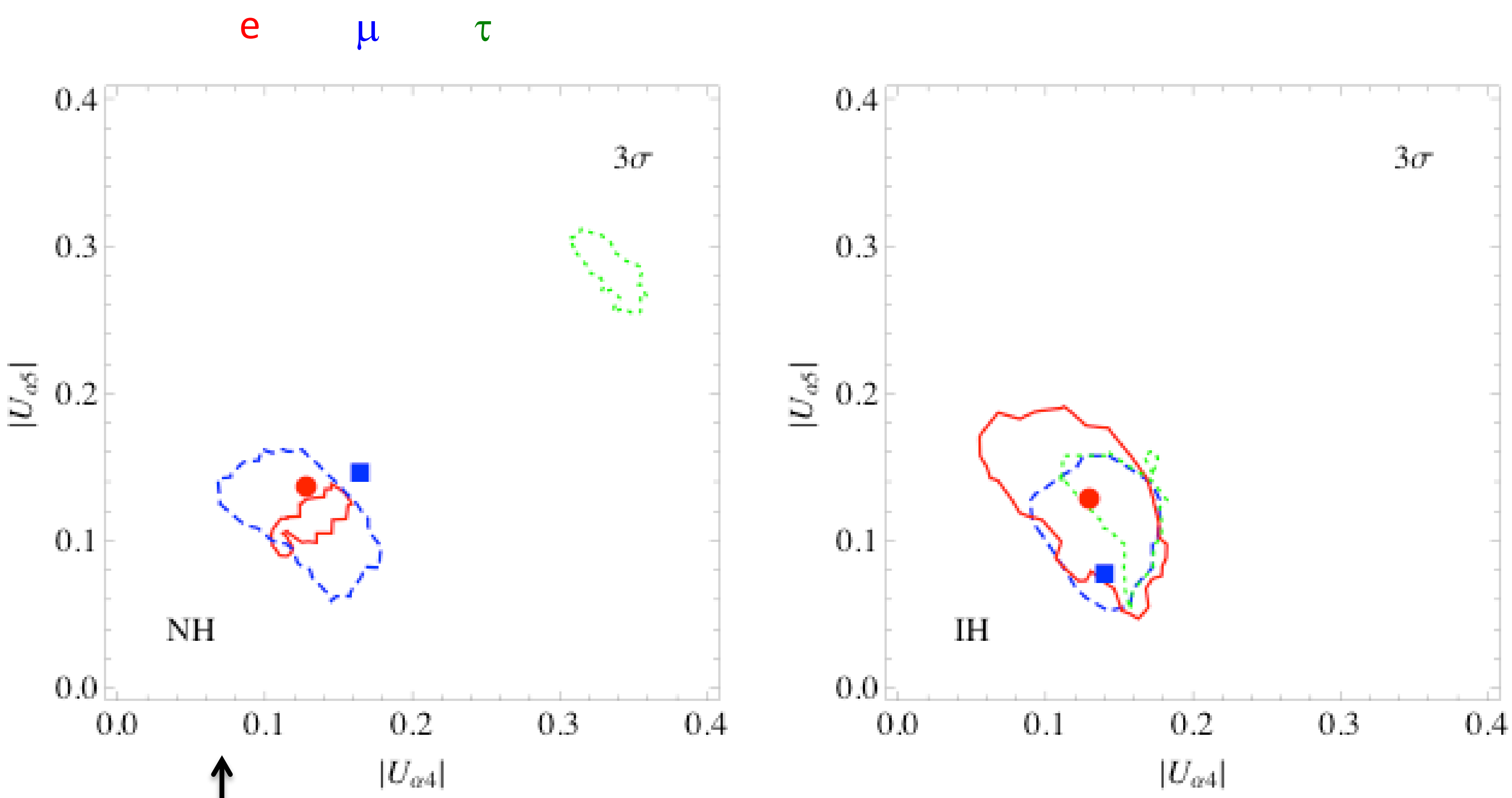
- Not possible to decouple LBL and SBL analyses: too large correlations in U_{aa} and U_{as}
- Need to include corrections to Casas-Ibarra-> more general parametrization
- Use M_1, M_2 from KMS and GL fits

3+2 MM vs 3+2 PM vs 3ν



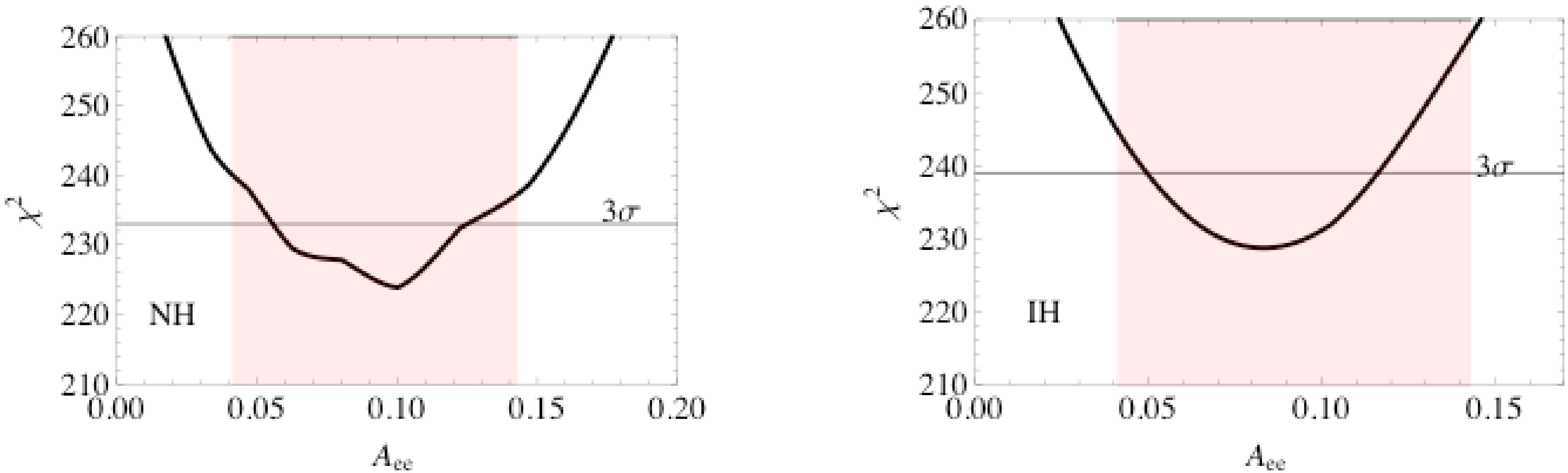
$$z_{45} = \theta_{45} + i\gamma_{45}$$

Heavy-Light Mixings

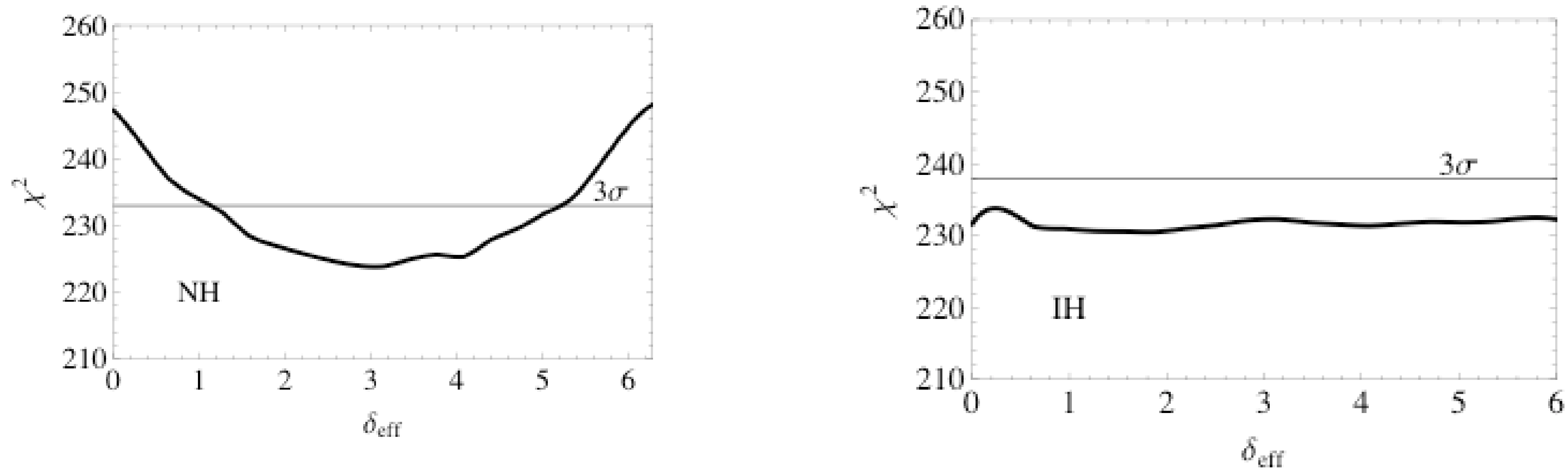


Large tau mixings to heavy states

Constraint on $\sin^2 2\theta_{\mathrm{reactor}}$



Constraint on δ_{eff}

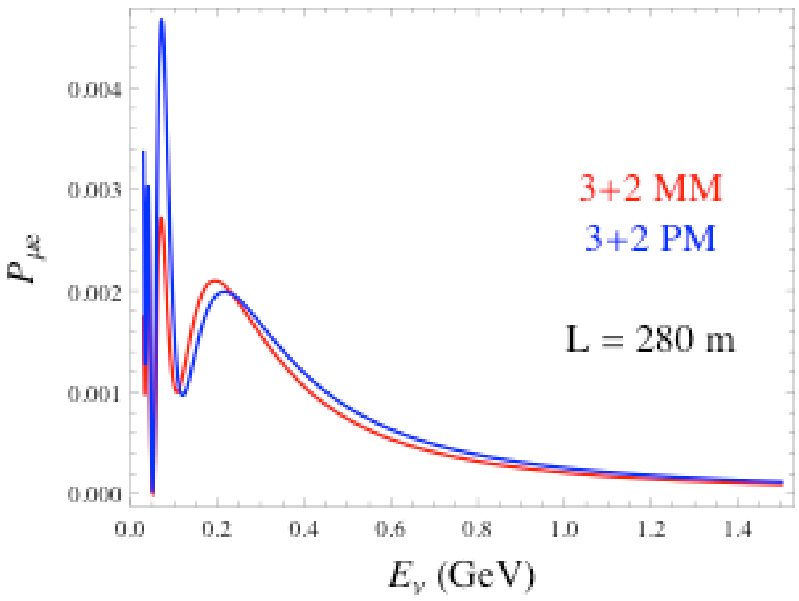


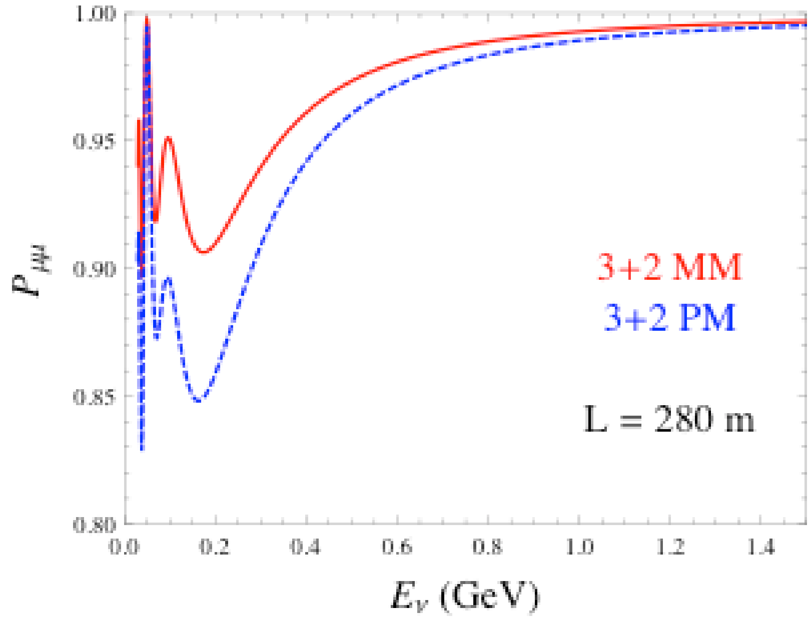
BUT….

Significant improvement over 3ν scenario, but large tension appearance/disappearance in μ sector remains (MINOS CC high energy)

Tension with cosmology that favours extra but lighter states

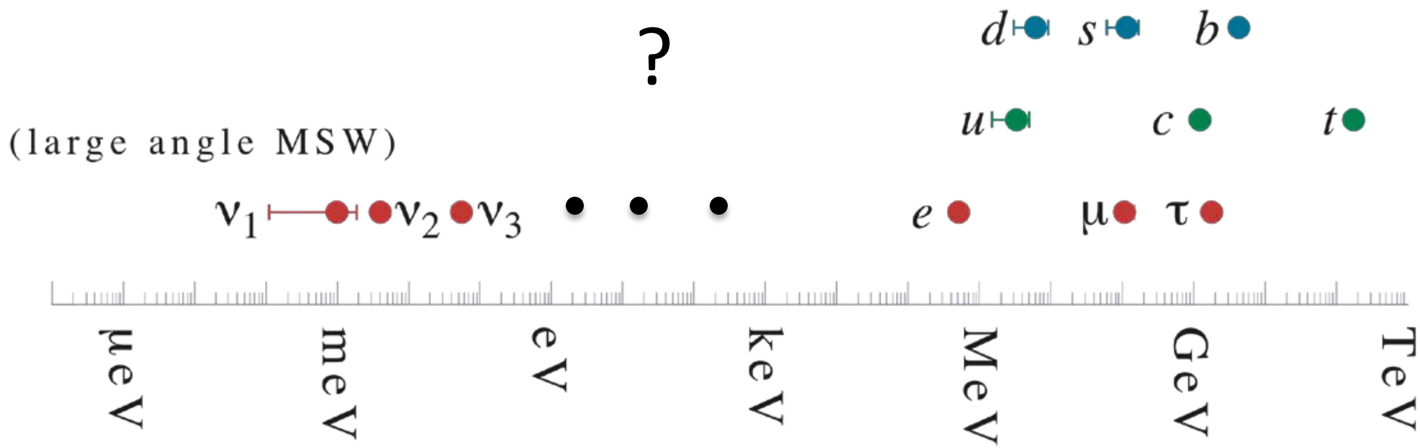
Should be easy to clarify…





T2K ND

Even if LSND not correct we should clarify whether the picture does not look like …



Hierarchy ?

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 M$_N$: n_Rx n_R

Number of Physical Parameters

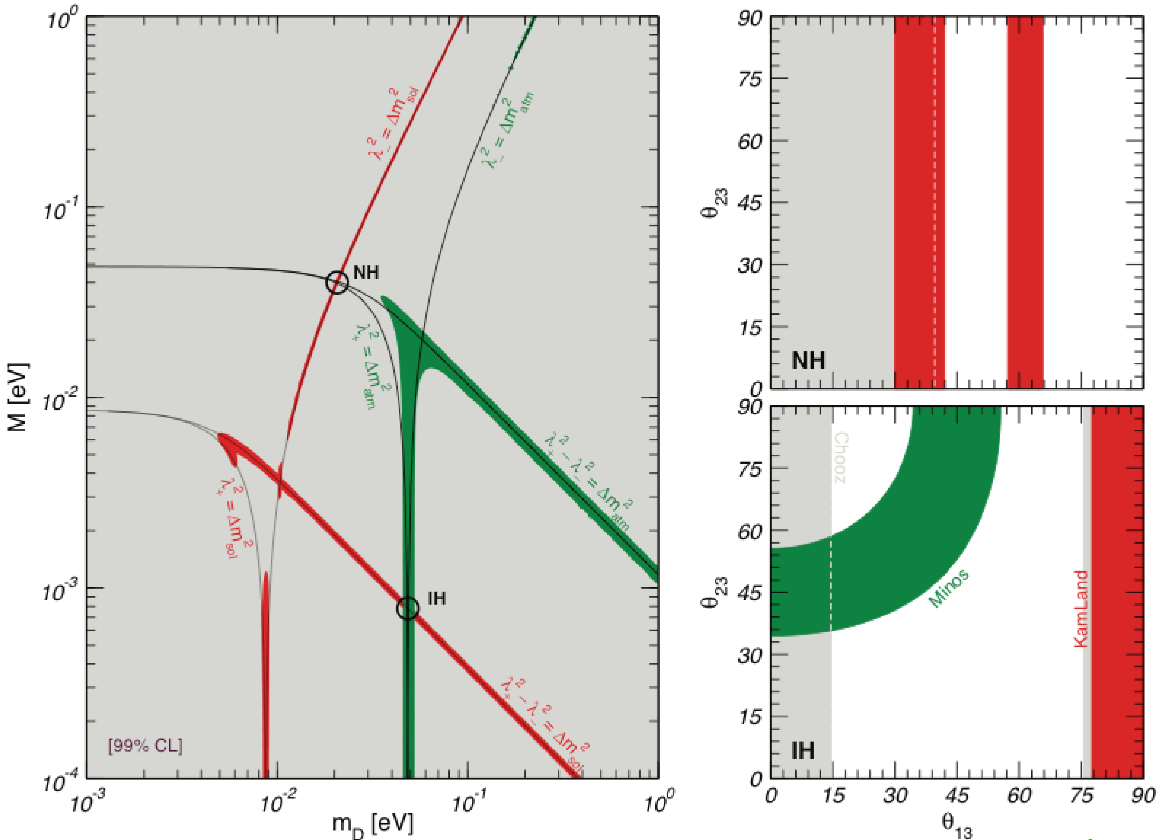
Complexity

predictivity

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~~	

Minimal 3+1

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

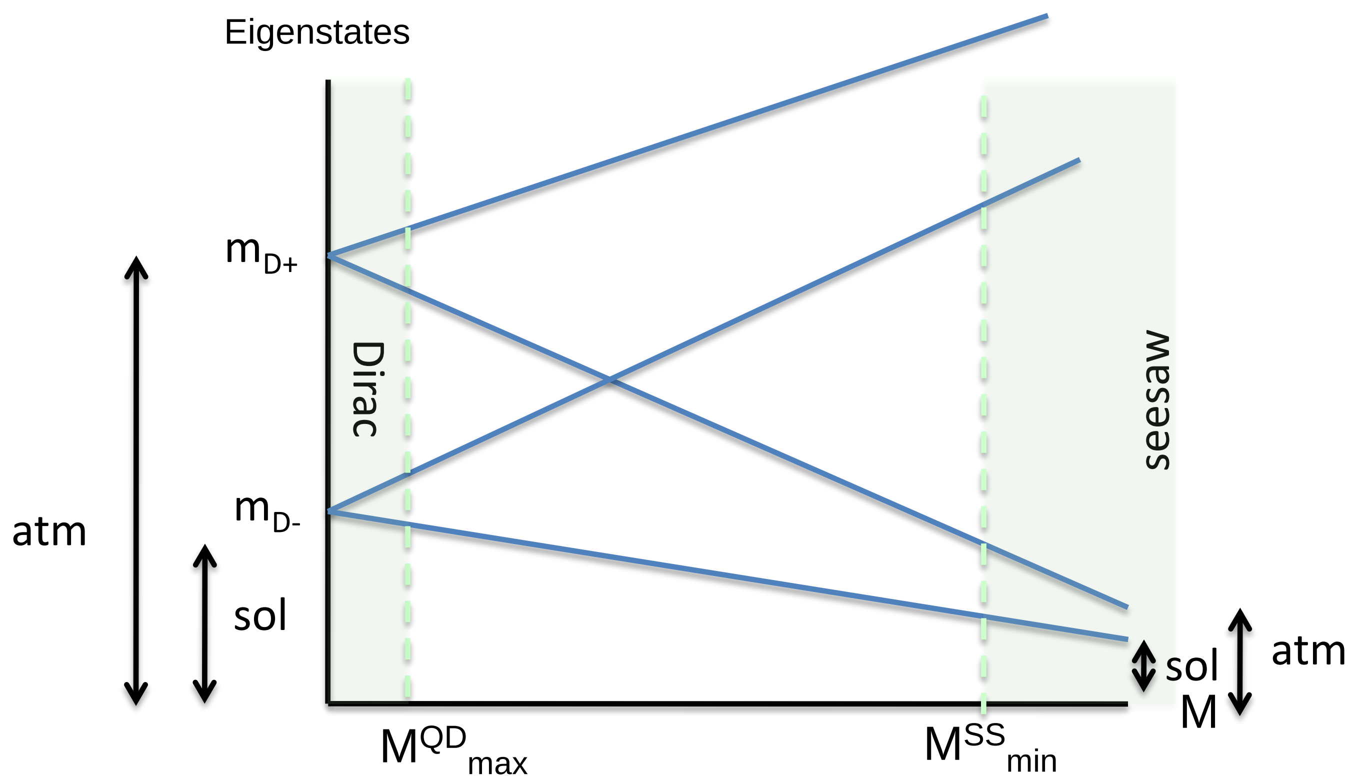


Donini et al 1106.0064

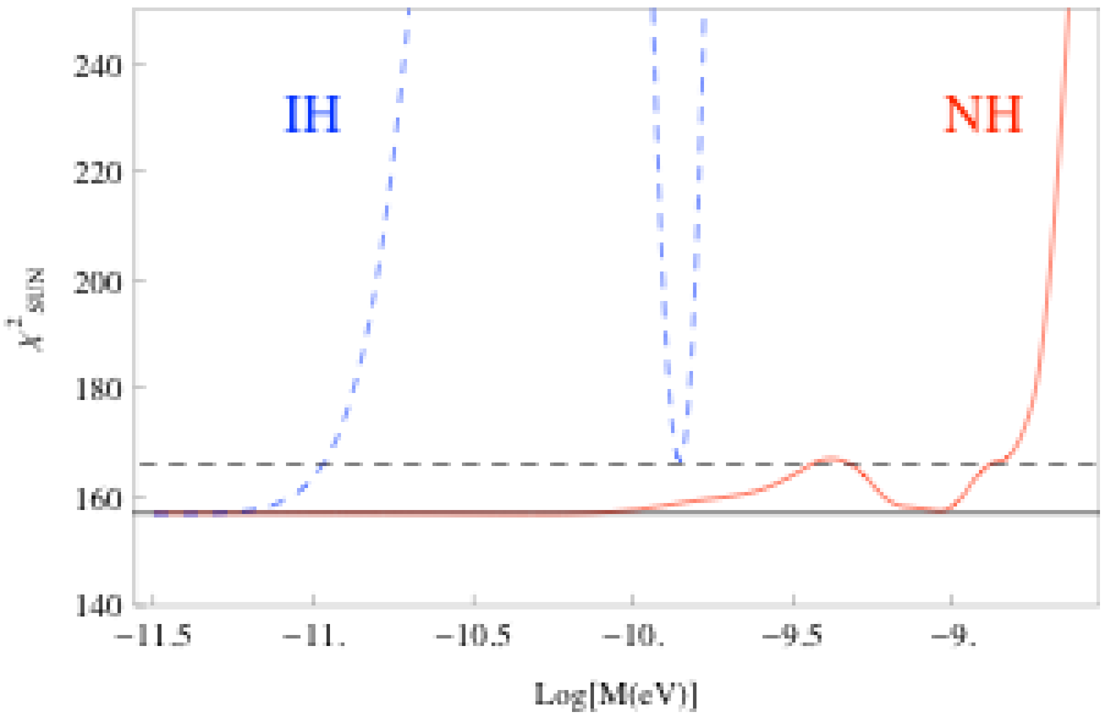
Strong incompatibility between Chooz+KamLAND vs Chooz+MINOS

Minimal 3+2

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



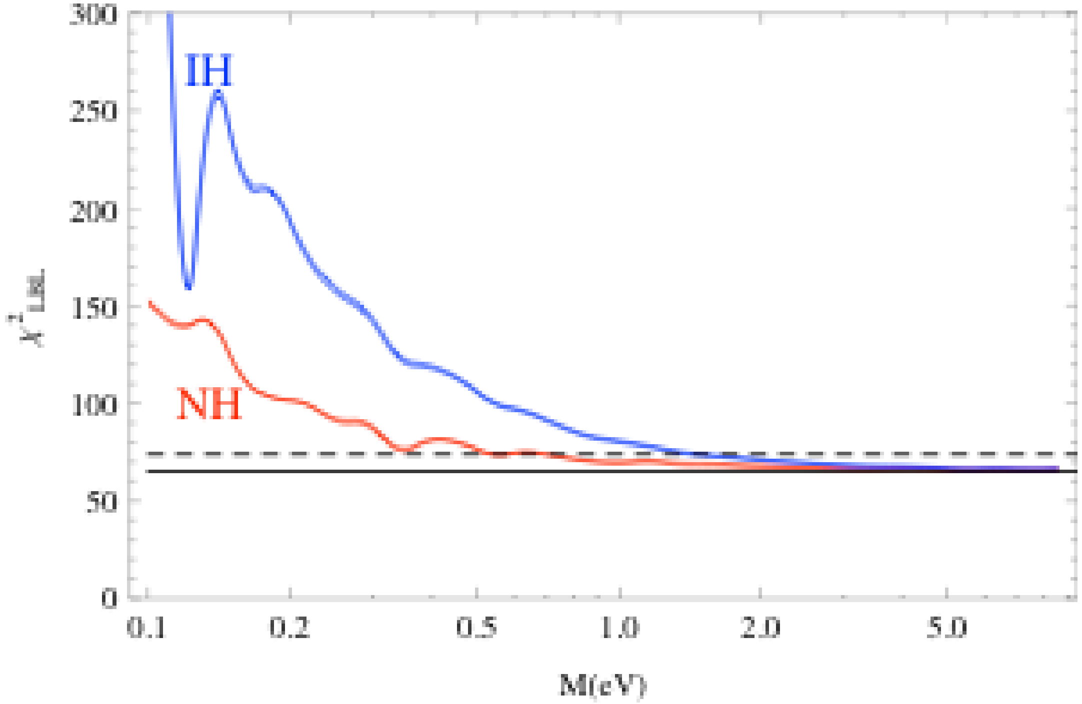
SOLAR data: M^{QD}_{max}



Impressive sensitivity of solar neutrinos to tiny departures from diracness!

See also De Gouvea, Huang, Jenkins arXiv: 0906.1611

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



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

Conclusions

- Minimal models of neutrino masses are also models with extra sterile states but ones that are much more constrained/predictive than those used in phenomenological fits

- They have a rich phenomenology if their mass is below the EW scale

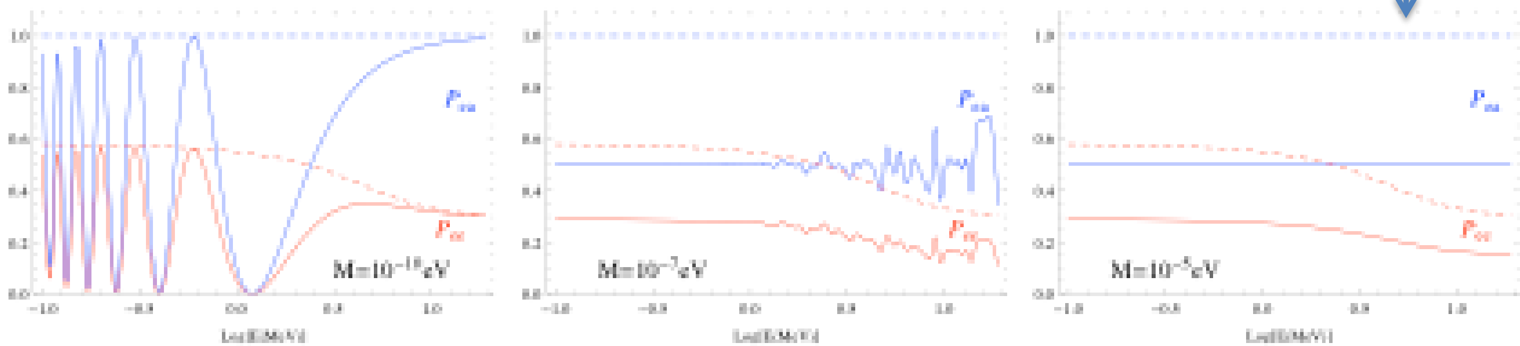
- This phenomenology has to be explored systematically

- Optimistically we might solve some other problem…or at least severely constraint the ν physics scale

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

IH

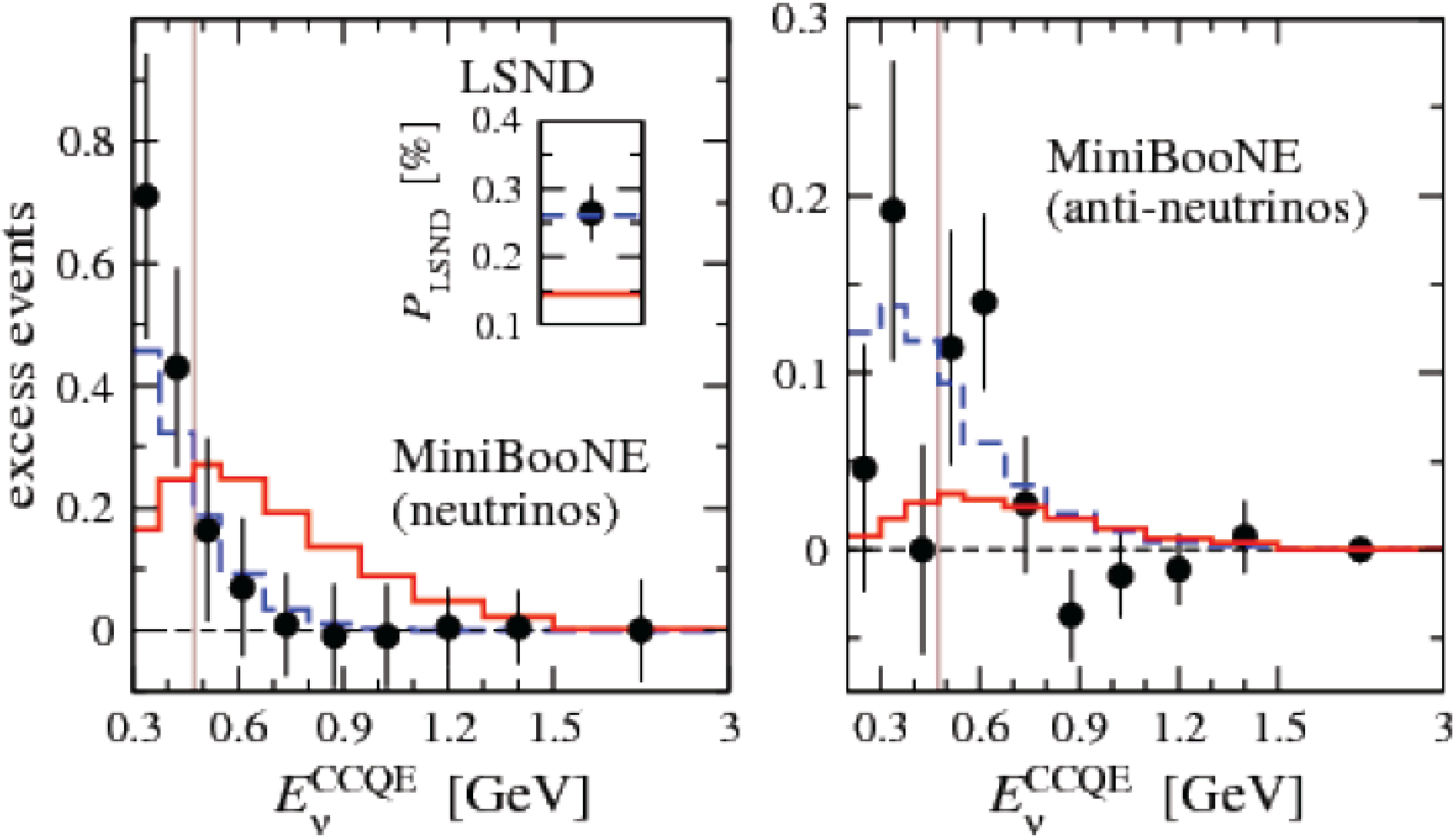
Adiabatic approx.



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


excess events
0.8
0.6
0.4
0.2
0
0.3
0.6
0.9
1.2
1.5
3
E_ν^{CCQE} [GeV]
LSND
0.4
0.3
0.2
0.1
P_{LSND} [%]
MiniBooNE
(neutrinos)
0.3
0.2
0.1
0
MiniBooNE
(anti-neutrinos)
0.3
0.6
0.9
1.2
1.5
3
E_ν^{CCQE} [GeV]

3+2 PM, KMS fit