Sterile Neutrinos for Warm Dark Matter and the Reactor Anomaly in Flavour Symmetry Models

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FLASY12, Dortmund, 2 July 2012

ν

$m_\nu = m_L - m_D^T\, M_R^{-1}\, m_D$

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MANITOP

Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

Based on JB, W. Rodejohann, H. Zhang, JHEP 1107, 091 (2011); JCAP 1201, 052 (2012)

Outline

- Motivations for keV & eV scale sterile neutrinos
  - *keV WDM*
  - *SBL anomalies, N_{eff} from cosmology*
- $0\nu\beta\beta$ phenomenology
- Sterile neutrinos in $A_4 \times Z_3 \times U(1)_{FN}$ flavour models
  - *Effective model*
  - *Seesaw model*
- NLO corrections and θ_{13}

Quick recap: why "sterile"?

- Z-boson decay width means $N_{active} = 3$, i.e. only three active neutrinos with $m_\nu < m_Z/2$
- Sterile/singlet/right-handed neutrino is SU(2) singlet
  - *Only interacts via mixing with active sector*
  - *Can interact with Higgs and/or BSM physics*
- Mass of sterile neutrino is unprotected and can be large (GUT scale) or small (pseudo-Dirac case)
- From phenomenology alone: "low-energy seesaw"?

(de Gouvêa et al)

Max-Planck-Institut für Kernphysik

WDM and keV sterile neutrinos

- Standard ΛCDM cosmological model:
  - *non-relativistic DM with WIMP DM candidate*
- keV WDM also compatible with observations, solves problems with small scale structure
  - *Reduces number of Dwarf satellite galaxies*
  - *Smoothes cusps in DM halos*
- Sterile neutrino is good candidate
  - *Appears in usual seesaw model*
  - *Need a mechanism to produce correct relic abundance, e.g. Dodelson-Widrow scenario:*

$$\Omega_{\mathrm{DM}} \simeq 0.2 \left(\frac{\theta_s^2}{3 \times 10^{-9}} \right) \left(\frac{M_s}{3\ \mathrm{keV}} \right)^{1.8}$$

WDM and keV sterile neutrinos

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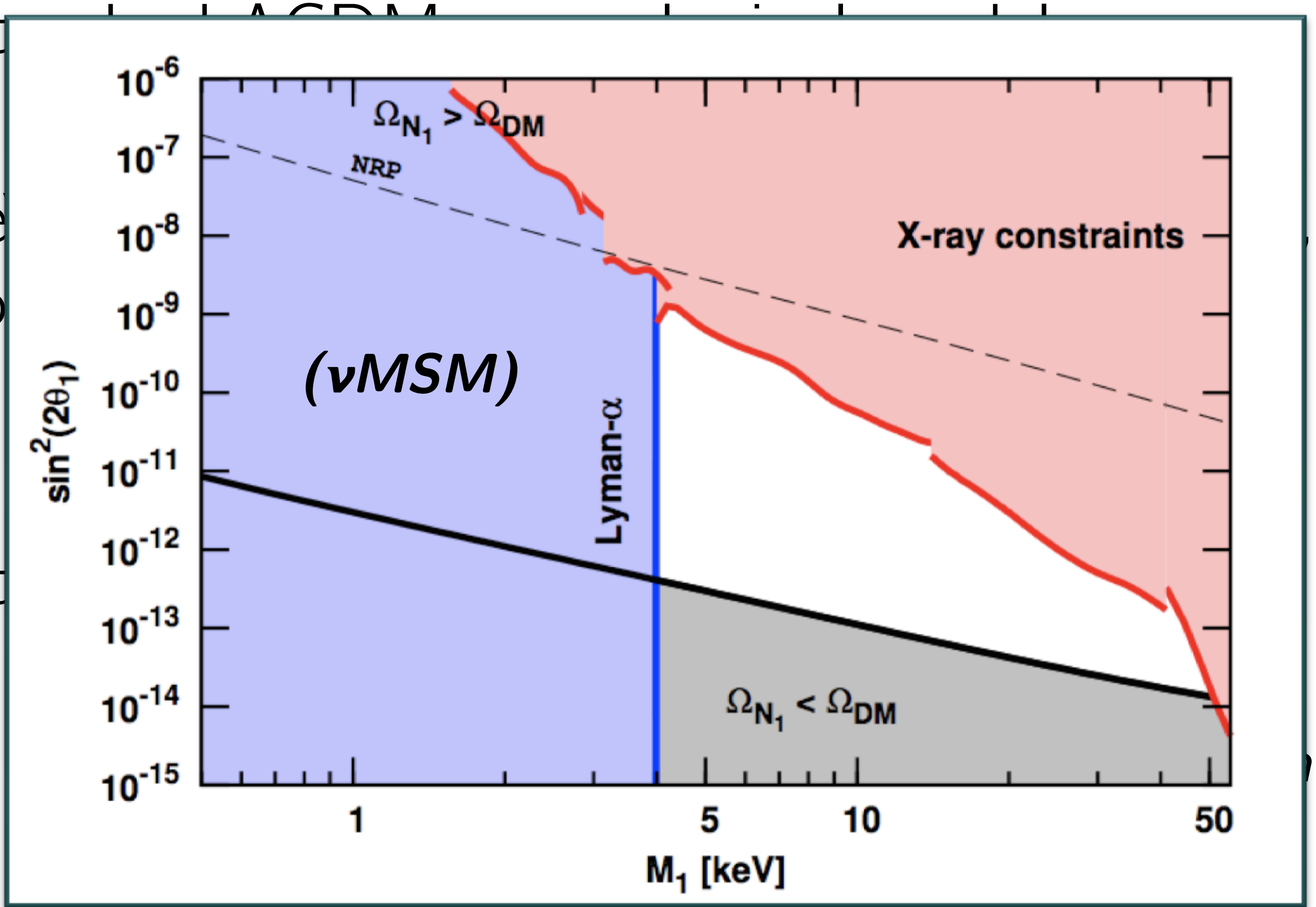
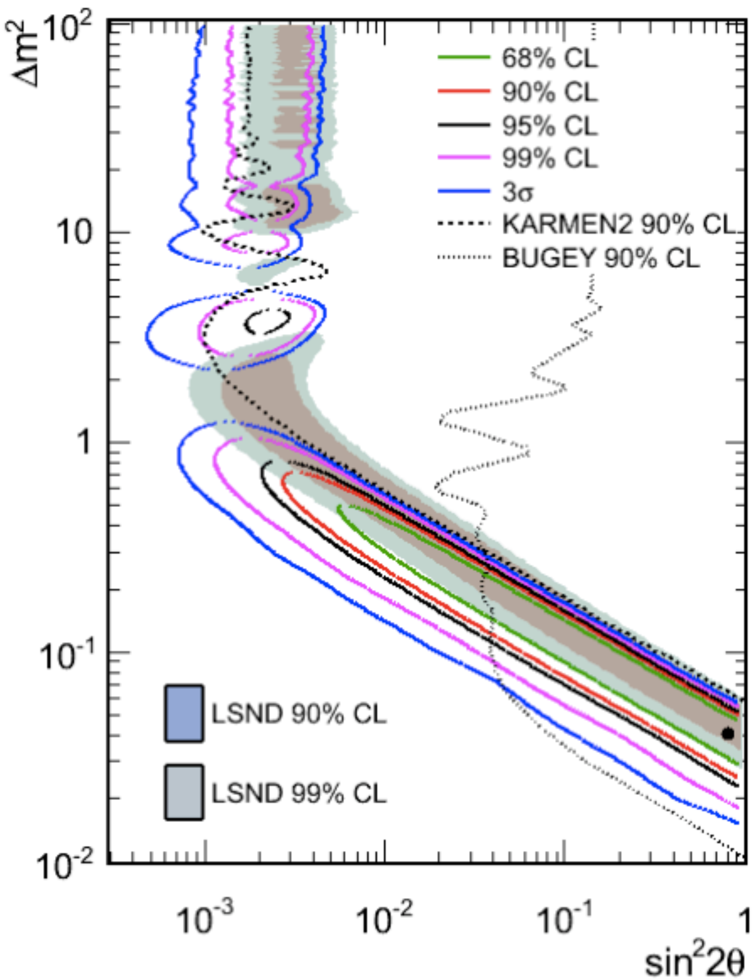


Bezrukov 2011

$$\Omega_{\rm DM} \simeq 0.2 \left(\frac{\theta_s^2}{3 \times 10^{-9}}\right) \left(\frac{M_s}{3\ \text{keV}}\right)^{1.8}$$

eV-scale sterile neutrinos



- LSND
  - $\overline{\nu}_\mu \to \overline{\nu}_e \ (3.8\sigma)$
  - $\Delta m^2 \simeq 1$ eV^2

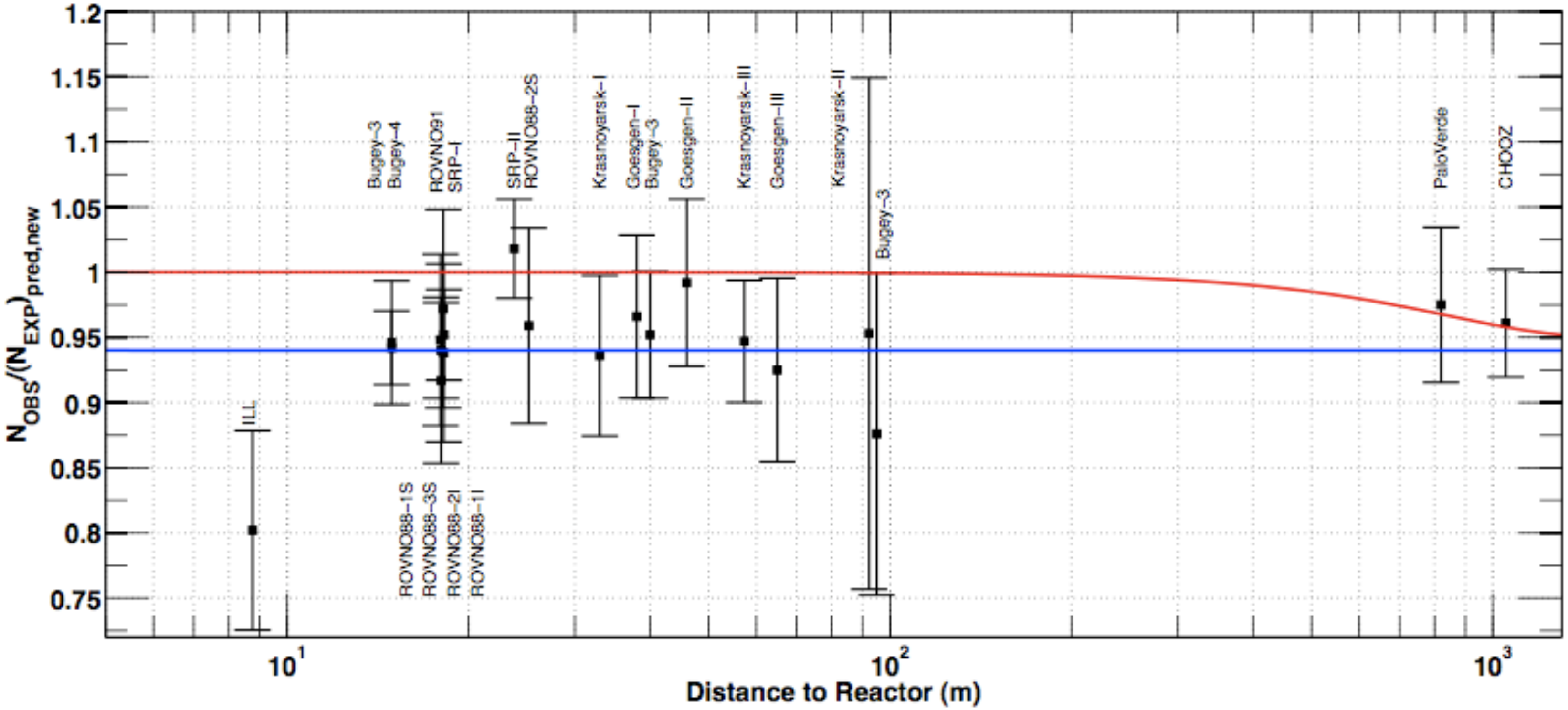
$\Longrightarrow$ 3+1 scenario

- MiniBooNE $(\nu_\mu$ and $\bar{\nu}_\mu)$
  - *Combined low energy (200-1250 MeV) excess of 3.8σ*
  - *Excesses not well understood*

Polly, Neutrino 2012

eV-scale sterile neutrinos

- Re-evaluation of beta decay spectra shows a 6% increase in antineutrino flux (reactor anomaly)



	Best-fit	1σ	3σ
$\lvert\Delta m^2_{\text{new}}\rvert$ (eV^2)	2.35	2.25–2.45	> 1.2
$\sin^2\theta_{\text{new}}$	0.043	0.032–0.054	0.0091–0.067

Mention et al., 2011

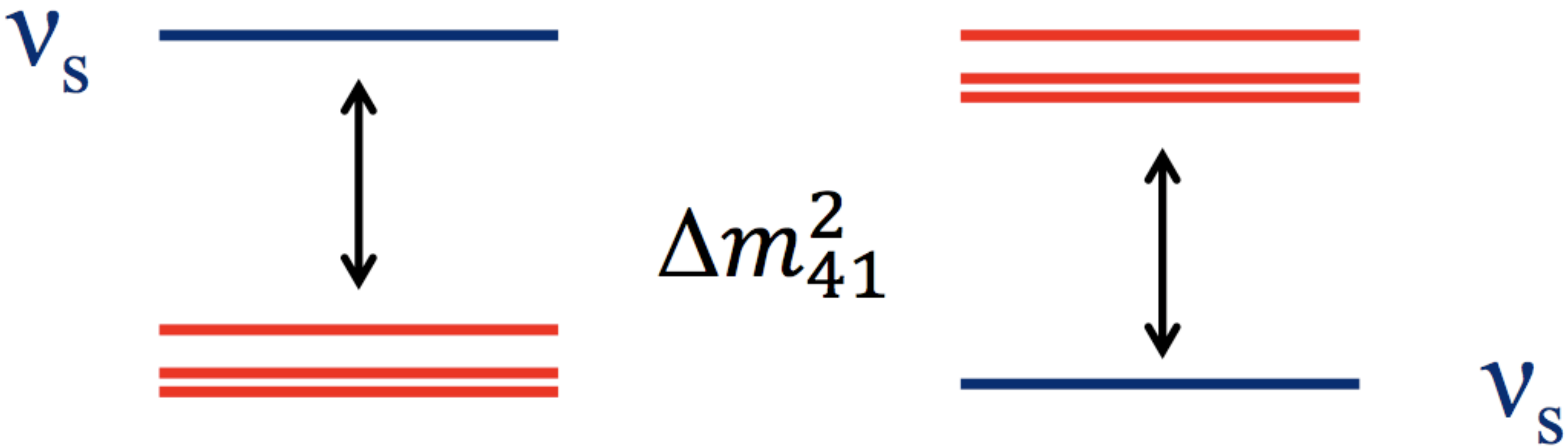
eV-scale sterile neutrinos

Table 1: Best-fit and estimated 2σ values of the sterile neutrino parameters.

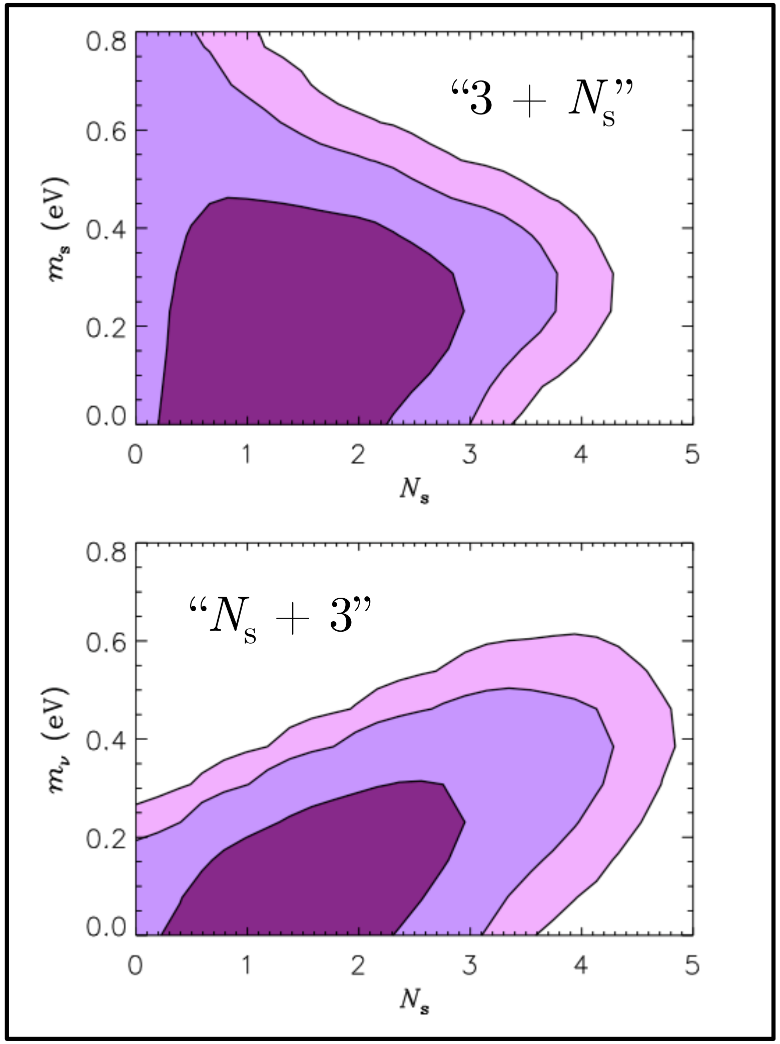
	parameter	Δm^2_{41} [eV]	$\|U_{e4}\|^2$	Δm^2_{51} [eV]	$\|U_{e5}\|^2$
3+1/1+3	best-fit	1.78	0.023		
	2σ	1.61–2.01	0.006–0.040		
3+2/2+3	best-fit	0.47	0.016	0.87	0.019
	2σ	0.42–0.52	0.004–0.029	0.77–0.97	0.005–0.033
1+3+1	best-fit	0.47	0.017	0.87	0.020
	2σ	0.42–0.52	0.004–0.029	0.77–0.97	0.005–0.035

Kopp et al, 2011

3+1 vs 1+3



Cosmology & eV sterile neutrinos



Hamann et al., 2010

- Some extra radiation preferred by CMB, SDSS, HST
- N_{eff} consistent with 3 (but also with 4) at 2σ:
- 3+2 excluded from HDM limit
- Expect PLANCK to clarify the issue soon

Neutrino mixing with sterile neutrinos

- Phenomenological approach (1 sterile neutrino):

$$U = R_{34}\tilde{R}_{24}\tilde{R}_{14}R_{23}\tilde{R}_{13}R_{12}P$$

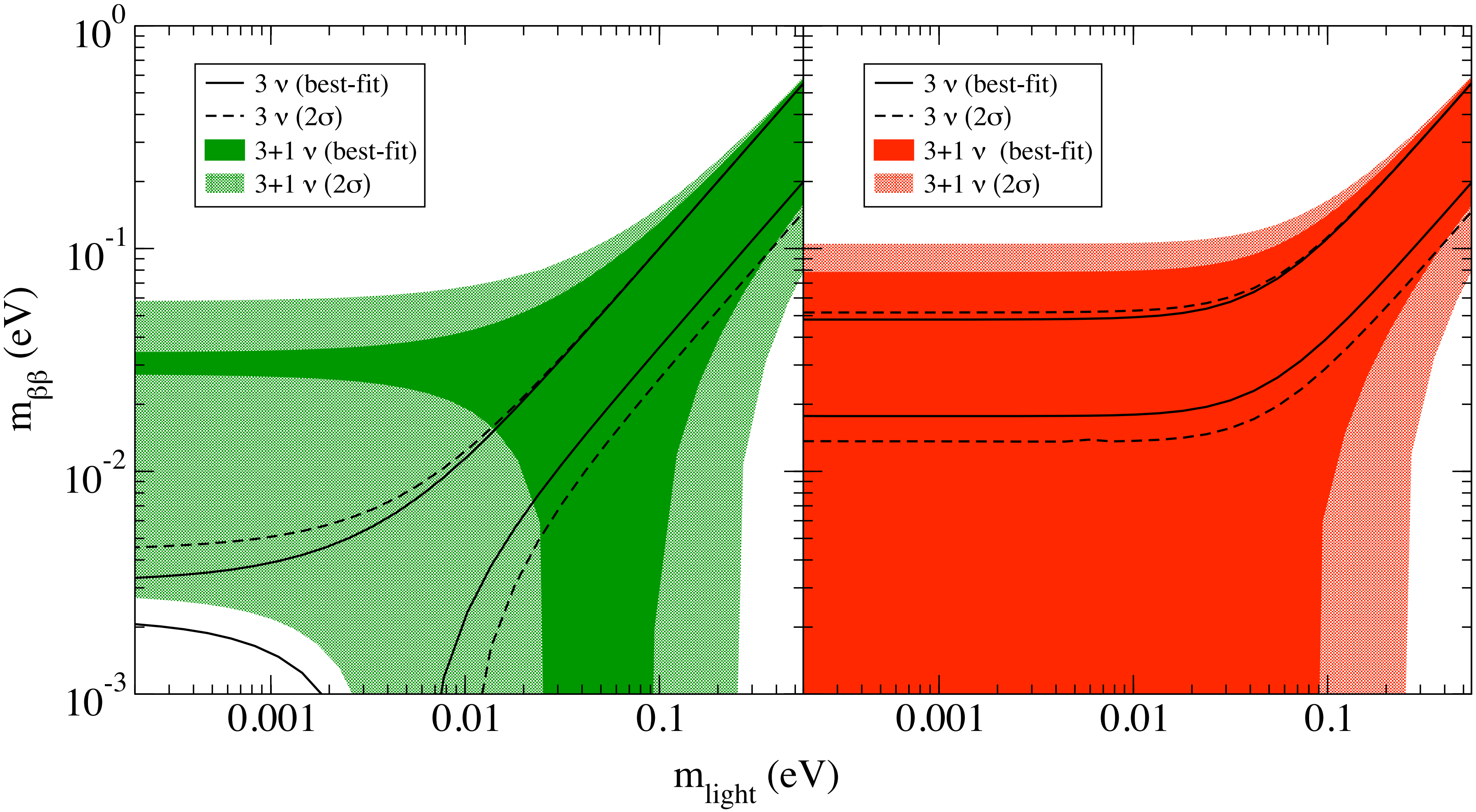
$$R_{34} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_{34} & s_{34} \\ 0 & 0 & -s_{34} & c_{34} \end{pmatrix} \quad \text{or} \quad \tilde{R}_{14} = \begin{pmatrix} c_{14} & 0 & 0 & s_{14}e^{-i\delta_{14}} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_{14}e^{i\delta_{14}} & 0 & 0 & c_{14} \end{pmatrix}$$

$$P = \text{diag}\left(1, e^{i\alpha/2}, e^{i(\beta/2+\delta_{13})}, e^{i(\gamma/2+\delta_{14})}\right)$$

$\Rightarrow$ 3 Dirac, 3 Majorana phases

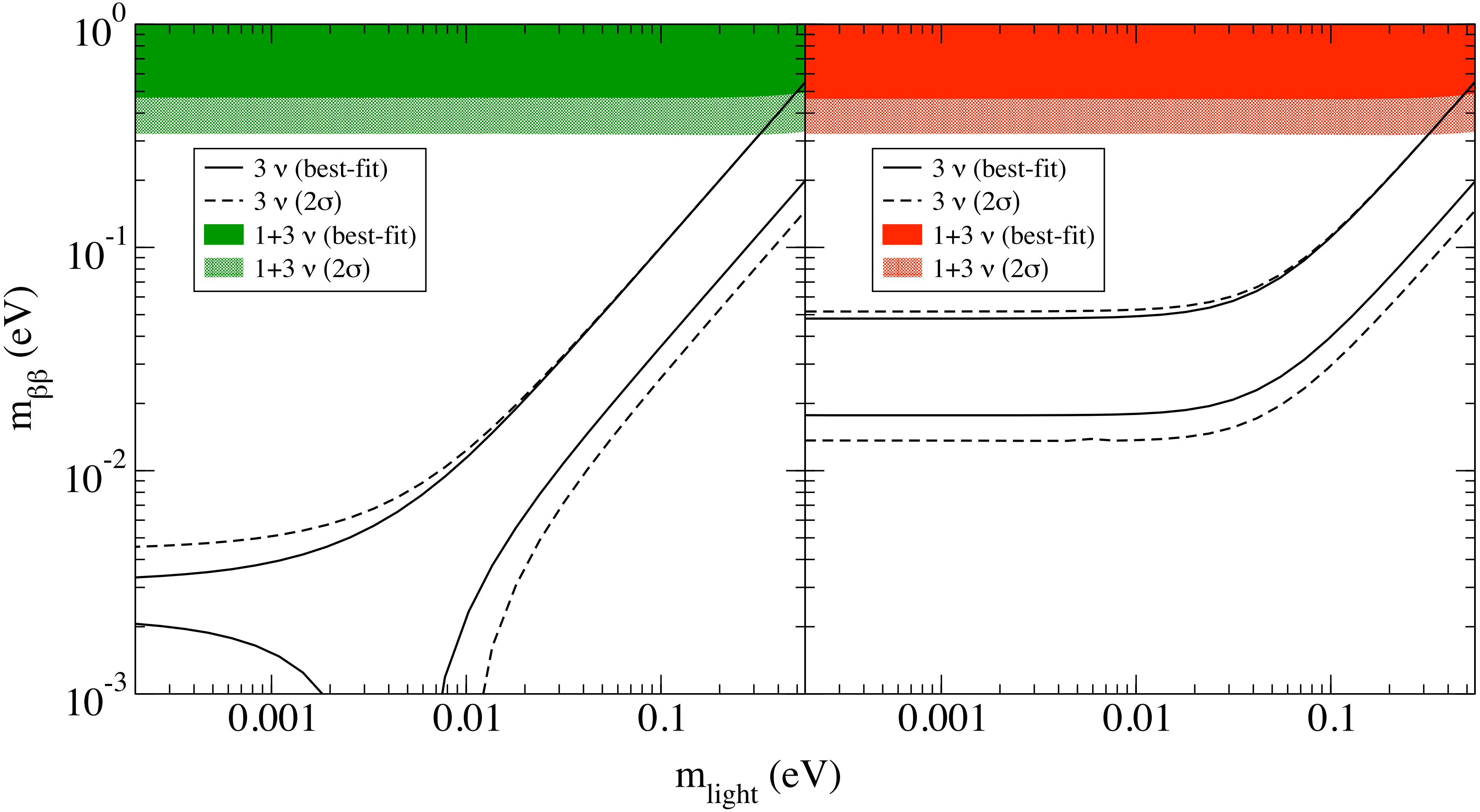
- New effects in neutrinoless double beta decay...

0νββ phenomenology



$$\langle m_{ee} \rangle_{(3+1)\nu} \simeq \left| c_{14}^2 \langle m_{ee} \rangle_{3\nu} + s_{14}^2 \sqrt{\Delta m_{41}^2} e^{i\gamma} \right|$$

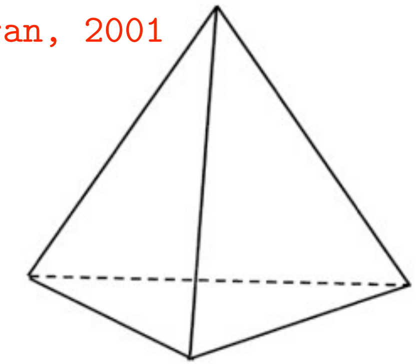
0νββ phenomenology



$$\langle m_{ee} \rangle_{(1+3)\nu} \simeq \sqrt{\Delta m^2_{41}} \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \alpha/2}$$

A_4 symmetry

Ma, Rajasekaran, 2001

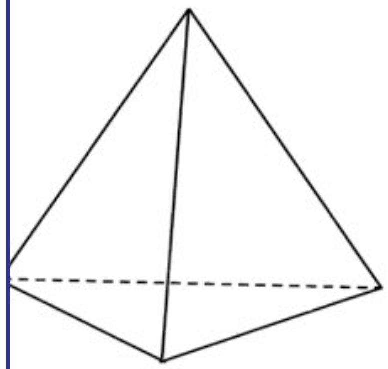


- Symmetry group of the tetrahedron
- Even permutations of four objects
- Twelve elements
- Four irreducible representations: $\underline{1}$, $\underline{1}'$, $\underline{1}''$ and $\underline{3}$
- Product rules:

$$\underline{1} \times \underline{1} = \underline{1}$$
$$\underline{1}' \times \underline{1}'' = \underline{1}$$
$$\underline{1}'' \times \underline{1}' = \underline{1}$$
$$\underline{1}' \times \underline{1}' = \underline{1}''$$
$$\underline{1}'' \times \underline{1}'' = \underline{1}'$$
$$\underline{3} \times \underline{3} = \underline{1} + \underline{1}' + 1'' + \underline{3}_{as} + \underline{3}_s$$

- Symme
- Even p
- Twelve
- Four ir … , $\underline{1}''$ and $\underline{3}$
- Produc … $\underline{3}_{as} + \underline{3}_s$

Type	L_i	ℓ^c_i	ν^c_i	Δ	References
A1				-	[1–14] [15]#
A2	$\underline{3}$	$1, 1', 1''$	-	$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$	[16–18]
A3				$\underline{1}, \underline{3}$	[19]
B1	3	$1, 1', 1''$	3	-	[4, 20–27]# [28–30]* [31–48]
B2				$\underline{1}, \underline{3}$	[49]#
C1				-	[2, 50, 51] [52]#
C2	$\underline{3}$	$\underline{3}$	-	1	[53, 54] [55]#
C3				$\underline{1}, \underline{3}$	[56]
C4				$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$	[57]
D1				-	[58, 59]# [60, 61]* [62]
D2	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{1}$	[63] [64]*
D3				$\underline{1}'$	[65]*
D4				$\underline{1}', \underline{3}$	[66]*
E1	3	3	$1, 1', 1''$	-	[67, 68]
E2				$\underline{1}$	[69]
F	$1, 1', 1''$	3	3	1 or $1'$	[70]
G	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}', \underline{1}''$	-	[71]
H	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	-	-	[72]
I	3	$1, 1, 1$	1	-	[73]*
J	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}$	-	[74]* [75]
K	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}, \underline{1}$	-	[76]*
L	3	$1, 1, 1$	$1, 1', 1''$	-	[77]
M	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{3}$	-	[12, 39, 78, 79]
N	3	$1, 1, 1$	$1, 1$	1	[80]*
O	$1, 1', 1''$	$1, 1', 1''$	$\underline{3}$	-	[81]
P	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}'', \underline{1}'$	$\underline{3}, \underline{1}$	-	[82, 83]
Q	$1, 1', 1''$	$1, 1'', 1'$	$3, 1', 1''$	-	[84]



JB, Rodejohann, 2010.
Updated regularly at
www.mpi-hd.mpg.de/
personalhomes/jamesb/
(see also Ding, 2011)

Model with effective operators

Effective model with sterile neutrino

Table 2: Altarelli-Feruglio effective A_4 model, including a sterile neutrino ν_s

Field	L	e^c	μ^c	τ^c	$h_{u,d}$	φ	φ'	ξ	Θ	ν_s
$SU(2)_L$	2	1	1	1	2	1	1	1	1	1
A_4	$\underline{3}$	$\underline{1}$	$\underline{1}''$	$\underline{1}'$	$\underline{1}$	$\underline{3}$	$\underline{3}$	$\underline{1}$	$\underline{1}$	$\underline{1}$
Z_3	ω	ω^2	ω^2	ω^2	1	1	ω	ω	1	1
$U(1)_{\mathrm{FN}}$	-	F_e	F_μ	F_τ	-	-	-	-	-1	F_ν

$$\mathcal{L}_{\mathrm{Y},\ell} = \frac{y_e}{\Lambda}\lambda^{F_e} e^c(\varphi L)h_d + \frac{y_\mu}{\Lambda}\lambda^{F_\mu}\mu^c(\varphi L)' h_d + \frac{y_\tau}{\Lambda}\lambda^{F_\tau}\tau^c(\varphi L)'' h_d$$

$$\mathcal{L}_{\mathrm{Y},\nu} = \frac{x_a}{\Lambda^2}\xi(Lh_u Lh_u) + \frac{x_d}{\Lambda^2}(\varphi' Lh_u Lh_u) + \frac{x_e}{\Lambda^2}\lambda^{F_\nu}\xi(\varphi' Lh_u)\nu_s + m_s\lambda^{2F_\nu}\nu_s^c\nu_s^c + \text{h.c.}$$

$$\lambda \equiv \frac{\langle\Theta\rangle}{\Lambda} < 1 \quad \Longrightarrow \text{FN suppression factor}$$

Masses & mixing

$$\langle\xi\rangle = u,\ \langle\varphi\rangle = (v,0,0) \text{ and } \langle\varphi'\rangle = (v',v',v')$$

$$\Rightarrow M_\ell \text{ diagonal} \Rightarrow m_\alpha = y_\alpha v_d \frac{v}{\Lambda}\lambda^{F_\alpha}$$

$$M_\nu^{4\times 4} = \begin{pmatrix} a+\frac{2d}{3} & -\frac{d}{3} & -\frac{d}{3} & e \\ \cdot & \frac{2d}{3} & a-\frac{d}{3} & e \\ \cdot & \cdot & \frac{2d}{3} & e \\ \cdot & \cdot & \cdot & m_s \end{pmatrix}$$

$$\begin{aligned} a &= 2x_a\frac{uv_u^2}{\Lambda^2} \\ d &= 2x_d\frac{v'v_u^2}{\Lambda^2} \\ e &= \sqrt{2}x_e\frac{uv'v_u}{\Lambda^2} \end{aligned}$$

Mixing matrix:

$\theta_{13} = 0$

$$U \simeq \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 & \frac{e}{m_s} \\ 0 & 0 & 0 & \frac{e}{m_s} \\ 0 & 0 & 0 & \frac{e}{m_s} \\ 0 & -\frac{\sqrt{3}e}{m_s} & 0 & 0 \end{pmatrix} + \mathcal{O}\left(\frac{e^2}{m_s^2}\right)$$

Numerical example

Mass eigenvalues:

$$m_1 = a + d\,, \quad m_2 = a - \frac{3e^2}{m_s}\,, \quad m_3 = -a + d\,, \quad m_4 = m_s + \frac{3e^2}{m_s}$$

For $F_\nu = 6$, $\langle\Theta\rangle = v = v' = u = 10^{11}$ GeV, $\Lambda = 10^{12.5}$ GeV

$$a \sim d \simeq 0.1 \left(\frac{u}{10^{11}\ \mathrm{GeV}}\right)\left(\frac{v_u}{10^2\ \mathrm{GeV}}\right)^2\left(\frac{10^{12.5}\ \mathrm{GeV}}{\Lambda}\right)^2 \ \mathrm{eV}$$

$$e \simeq 0.1 \left(\frac{\lambda}{10^{-1.5}}\right)^6\left(\frac{u}{10^{11}\ \mathrm{GeV}}\right)\left(\frac{v'}{10^{11}\ \mathrm{GeV}}\right)\left(\frac{v_u}{10^2\ \mathrm{GeV}}\right)\left(\frac{10^{12.5}\ \mathrm{GeV}}{\Lambda}\right)^2 \ \mathrm{eV}$$

Sterile neutrino mass & mixing:

$$\left(\frac{x_s}{\Lambda}(\varphi\varphi) + \frac{x_{s'}}{\Lambda^2}\xi\xi\xi + \frac{x_{s''}}{\Lambda^2}(\varphi'\varphi')\xi\right)\nu_s^c\nu_s^c \Longrightarrow \left(x_s\frac{v^2}{\Lambda} + x_{s'}\frac{u^3}{\Lambda^2} + x_{s''}\frac{3v'^2u}{\Lambda^2}\right)\lambda^{2F_\nu}$$

$$m_s \simeq 10^{0.5}\left(\frac{\lambda}{10^{-1.5}}\right)^{12}\left(\frac{v}{10^{11}\ \mathrm{GeV}}\right)^2\left(\frac{10^{12.5}\ \mathrm{GeV}}{\Lambda}\right) \ \mathrm{eV}$$

$$\theta_{14} \simeq e/m_s \simeq 0.1$$

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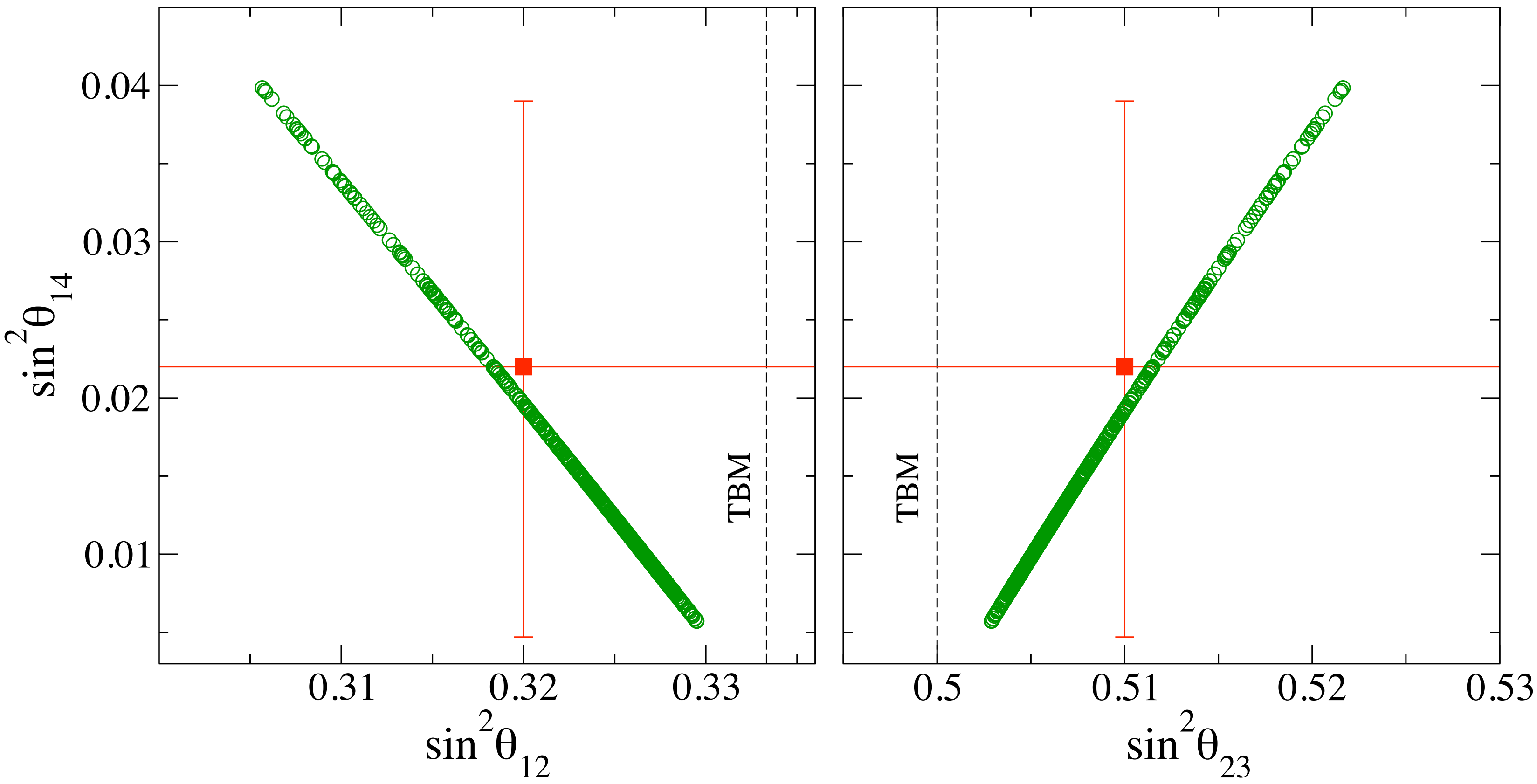
Deviations from TBM with sterile ν



$$\sin^2\theta_{12} \simeq \frac{1}{3}\left[1 - 2\sin^2\theta_{14}\right] \,, \quad \sin^2\theta_{23} \simeq \frac{1}{2}\left[1 + \sin^2\theta_{14}\right]$$

Non-zero θ_{13}?

- Sterile neutrino causes deviations to solar and atmospheric angles, but reactor angle remains zero
- Need charged lepton correction terms from dim-7 operators:

Altarelli, Feruglio, 2006

$$\text{e.g., } \eta_i \propto \langle\varphi\rangle\langle\varphi'\rangle\langle h_u\rangle^2/\Lambda^3$$

$$\Rightarrow \sin^2\theta_{13} \simeq \frac{(\eta_1 - \eta_2)^2}{8a^2}$$

$\Rightarrow$ non-zero θ_{13} possible with NLO operators

Seesaw model

Sterile neutrinos in seesaw models

- Split seesaw mechanism

  Kusenko; Adulpravitchai et al

- Symmetries (eg. L_e-L_μ-L_τ)

  Shaposhnikov; Lindner et al

- Froggatt-Nielsen mechanism

  Merle & Niro; JB, Rodejohann, Zhang

- Extended seesaw mechanisms

  Mohapatra; Smirnov; Zhang

- ....?

NLO seesaw corrections

Full neutrino mass matrix is: $M_\nu^{6\times 6} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$

$$U_\nu \simeq \begin{pmatrix} 1 - \frac{1}{2}BB^\dagger & B \\ -B^\dagger & 1 - \frac{1}{2}B^\dagger B \end{pmatrix} \begin{pmatrix} V_\nu & 0 \\ 0 & V_R \end{pmatrix}$$

Schechter & Valle, 1982; Grimus & Lavoura, 2000; Hettmansperger, Lindner, Rodejohann 2011

$$M_\nu = -M_D M_R^{-1} M_D^T = V_\nu \, \mathrm{diag}(m_1, m_2, m_3) V_\nu^T$$

$$M_R = V_R \, \mathrm{diag}(M_1, M_2, M_3) V_R^T$$

NLO corrections governed by

$$B = M_D M_R^{-1} + \mathcal{O}\left(M_D^3 (M_R^{-1})^3\right)$$

$$B \simeq \sqrt{M_\nu / M_R}$$

$\Rightarrow$ can be significant if $M_R \simeq 1$ eV

Active-sterile mixing & 0νββ

- Active-sterile mixing is

$$\theta_{\alpha i} \equiv [U_\nu]_{\alpha,3+i} = [BV_R]_{\alpha i} \simeq \frac{[M_D V_R^*]_{\alpha i}}{M_i}$$

$\Rightarrow$ mixing is a ratio of two scales

- 0νββ amplitude vanishes if all sterile neutrinos light

$$\langle m_{ee} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i + \sum_{i=1}^{3} U_{e,3+i}^2 M_i \right| = \left[M_\nu^{6\times 6} \right]_{ee} = 0$$

- In addition, in certain flavour symmetry models

$$M_D = V_\nu \,\mathrm{diag}\left(\sqrt{-m_1 M_1}, \sqrt{-m_2 M_2}, \sqrt{-m_3 M_3} \right) V_R^T$$

Chen, King 2009; Choubey et al 2010

$$U_{e,3+i}^2 M_i = \left[-(V_\nu^2)_{ei} \frac{m_i}{M_i} \right] M_i = -U_{ei}^2 m_i \,, \quad (i = 1, 2, 3)$$

$\Longrightarrow$ pairwise cancellation!

Seesaw model

A_4 singlets

Table 3: A_4 type I seesaw model, with three right-handed sterile neutrinos

Field	L	e^c	μ^c	τ^c	$h_{u,d}$	φ	φ'	φ''	ξ	ξ'	ξ''	Θ	ν_1^c	ν_2^c	ν_3^c
$SU(2)_L$	2	1	1	1	2	1	1	1	1	1	1	1	1	1	1
A_4	$\underline{3}$	$\underline{1}$	$\underline{1}''$	$\underline{1}'$	$\underline{1}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{1}$	$\underline{1}'$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{1}'$	$\underline{1}$
Z_3	ω	ω^2	ω^2	ω^2	1	1	ω	ω^2	ω^2	ω	1	1	ω^2	ω	1
$U(1)_{\rm FN}$	-	3	1	0	-	-	-	-	-	-	-	-1	F_1	F_2	F_3

$$-\mathcal{L}_{\mathrm{Y},\nu} = \frac{y_1}{\Lambda}\lambda^{F_1}(\varphi L h_u)\nu_1^c + \frac{y_2}{\Lambda}\lambda^{F_2}(\varphi' L h_u)''\nu_2^c + \frac{y_3}{\Lambda}\lambda^{F_3}(\varphi'' L h_u)\nu_3^c$$
$$+ \frac{1}{2}\left[w_1\lambda^{2F_1}\xi\nu_1^c\nu_1^c + w_2\lambda^{2F_2}\xi'\nu_2^c\nu_2^c + w_3\lambda^{2F_3}\xi''\nu_3^c\nu_3^c\right] + \mathrm{h.c.}$$

- FN charge drops out of leading order seesaw term
- Different scenarios possible, vary F_i
- Active sterile mixing depends on FN charge, e.g.

$$\theta_{e1} \simeq \frac{y_1 v v_u}{w_1 u \Lambda}\lambda^{-F_1}$$

Reminder: motivations/mass scales

- Three (observed) phenomena to explain, with three distinct mass scales:
  - *eV – SBL oscillation anomalies*
  - *keV – Warm Dark Matter*
  - *GeV – Resonant leptogenesis / νMSM*
  - *$> 10^9$ GeV – Standard leptogenesis*

$\Longrightarrow$ with three RH neutrinos one cannot explain all three phenomena!

Model I: eV, eV, keV
Model II: eV, keV, $\simeq$ GeV
Model III: keV, $\gtrsim$ GeV, $\gtrsim$ GeV

Seesaw model

Table 4: Summary of possible model scenarios

	$F_1,\ F_2,\ F_3$	Mass spectrum	$\lvert U_{\alpha 4}\rvert$	$\lvert U_{\alpha 5}\rvert$	$\langle m_{ee}\rangle$ NO	$\langle m_{ee}\rangle$ IO	Phenomenology
I	9, 10, 10	$M_{2,3}=\mathcal{O}(\mathrm{eV})$,	$\mathcal{O}(0.1)$	$\mathcal{O}(0.1)$	0	0	$3+2$ mixing
IIA	9, 10, 0	$M_2=\mathcal{O}(\mathrm{eV})$ $M_3=\mathcal{O}(10^{11}\,\mathrm{GeV})$	$\mathcal{O}(0.1)$	$\mathcal{O}(10^{-11})$	0	$\frac{2\sqrt{\Delta m_\mathrm{A}^2}}{3}$	$3+1$ mixing
IIB	9, 0, 10	$M_2=\mathcal{O}(10^{11}\,\mathrm{GeV})$ $M_3=\mathcal{O}(\mathrm{eV})$	$\mathcal{O}(10^{-11})$	$\mathcal{O}(0.1)$	$\frac{\sqrt{\Delta m_\mathrm{S}^2}}{3}$	$\frac{\sqrt{\Delta m_\mathrm{A}^2}}{3}$	
III	9, 5, 5	$M_{2,3}=\mathcal{O}(10\,\mathrm{GeV})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-6})$	$\frac{\sqrt{\Delta m_\mathrm{S}^2}}{3}$	$\sqrt{\Delta m_\mathrm{A}^2}$	Leptogenesis

Choose $F_1=9 \Rightarrow M_1 \simeq 1$ keV, $\theta_1^2 \simeq 10^{-8}$

Negligible contribution to neutrino mass, $\theta_1^2 M_1 \simeq 10^{-5}$ eV

$\Longrightarrow$ Decouple ν_1^c, get 5×5 mass matrix

For example, with $\langle\varphi'\rangle=(v',v',v')$ and $\langle\varphi''\rangle=(0,v'',-v'')$

$$M_D^{(\mathrm{NO})}=\frac{v_u}{\Lambda}\begin{pmatrix} y_2 v'\lambda^{F_2} & 0 \\ y_2 v'\lambda^{F_2} & -y_3 v''\lambda^{F_3} \\ y_2 v'\lambda^{F_2} & y_3 v''\lambda^{F_3}\end{pmatrix} \qquad M_R=\begin{pmatrix} w_2 u'\lambda^{2F_2} & 0 \\ 0 & w_3 u''\lambda^{2F_3}\end{pmatrix}$$

$\Longrightarrow$ TBM at leading order

Seesaw model

Table 4: Summary of possible model scenarios

	F_1, F_2, F_3	Mass spectrum	$\lvert U_{\alpha 4}\rvert$	$\lvert U_{\alpha 5}\rvert$	$\langle m_{ee}\rangle$ NO	$\langle m_{ee}\rangle$ IO	Phenomenology
I	9, 10, 10	$M_{2,3}=\mathcal{O}(\mathrm{eV})$,	$\mathcal{O}(0.1)$	$\mathcal{O}(0.1)$	0	0	$3+2$ mixing
IIA	9, 10, 0	$M_2=\mathcal{O}(\mathrm{eV})$ $M_3=\mathcal{O}(10^{11}\,\mathrm{GeV})$	$\mathcal{O}(0.1)$	$\mathcal{O}(10^{-11})$	0	$\frac{2\sqrt{\Delta m^2_{\mathrm{A}}}}{3}$	$3+1$ mixing
IIB	9, 0, 10	$M_2=\mathcal{O}(10^{11}\,\mathrm{GeV})$ $M_3=\mathcal{O}(\mathrm{eV})$	$\mathcal{O}(10^{-11})$	$\mathcal{O}(0.1)$	$\frac{\sqrt{\Delta m^2_{\mathrm{S}}}}{3}$	$\frac{\sqrt{\Delta m^2_{\mathrm{A}}}}{3}$	
III	9, 5, 5	$M_{2,3}=\mathcal{O}(10\,\mathrm{GeV})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-6})$	$\frac{\sqrt{\Delta m^2_{\mathrm{S}}}}{3}$	$\sqrt{\Delta m^2_{\mathrm{A}}}$	Leptogenesis

$$|U_{e3}|^2 \simeq \frac{r_1^2}{2}\left[\boxed{\left(\frac{y'_\mu}{y_\mu}-\frac{y'_\tau}{y_\tau}\right)^2}\right]+\frac{1}{2}\boxed{(\chi-\rho_3)^2-(\chi-\rho_3)}\,r_1\boxed{\left(\frac{y'_\mu}{y_\mu}-\frac{y'_\tau}{y_\tau}\right)},$$

$$|U_{e2}|^2 \simeq \frac{1}{3}\left[1-3\epsilon_1^2-\boxed{2\rho_2}-2r_1\boxed{\left(\frac{y'_\mu}{y_\mu}+\frac{y'_\tau}{y_\tau}\right)}\right],$$

$$|U_{\mu 3}|^2 \simeq \frac{1}{2}\left[1-2\epsilon_2^2+2\boxed{\frac{y'_\tau}{y_\tau}}r_1+\frac{2}{3}\boxed{\sigma_+^N R}\right],$$

$$|U_{e,\mu 4}|^2 \simeq \epsilon_1^2\left[1\mp\boxed{2\rho_2}\mp 2r_1\boxed{\left(\frac{y'_\mu}{y_\mu}\pm\frac{y'_\tau}{y_\tau}\right)}\right]$$

NLO seesaw corrections

corrections from NLO operators

$\Longrightarrow$ non-zero θ_{13} possible from charged leptons

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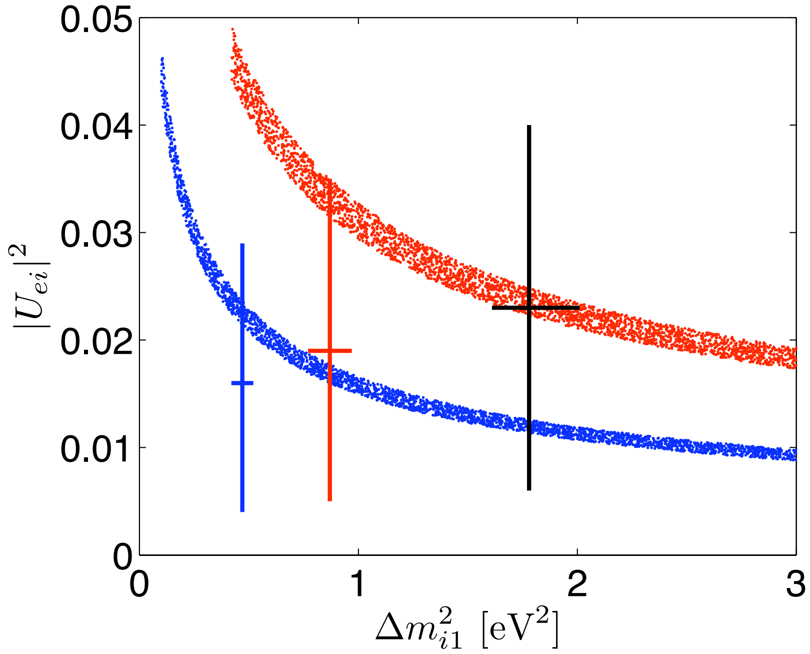
Seesaw model

- Inverted ordering:

$$\underline{|U_{e,\mu 4}|^2} \simeq \epsilon_1^2 \left[1 - 2\rho_2 \mp 2r_1 \left(\frac{y'_\mu}{y_\mu} \pm \frac{y'_\tau}{y_\tau}\right)\right],$$

$$\underline{|U_{e5}|^2} \simeq 4\epsilon_2^2 \left[1 + r_1 \left(\frac{y'_\mu}{y_\mu} + \frac{y'_\tau}{y_\tau}\right) - (\chi - \rho_3)\right],$$



Scenario I:
$\Rightarrow$ 3+2 mixing

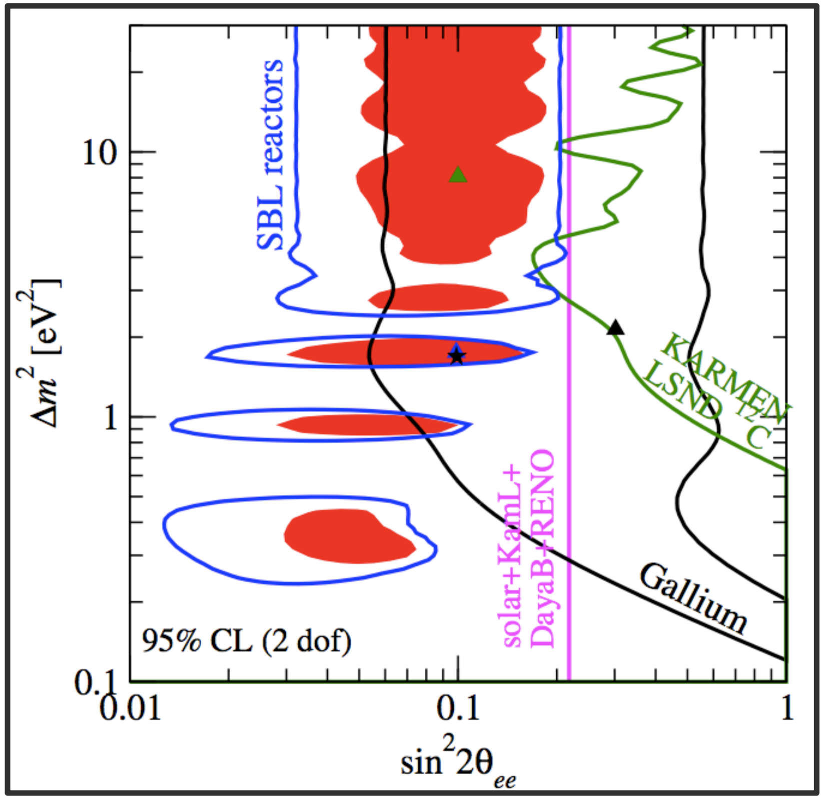
Scenario IIB:
$\Rightarrow$ 3+1 mixing

Conclusion

- "Light" sterile neutrinos exhibit distinct phenomenological signatures
- The FN mechanism is one way to suppress the sterile neutrino mass
- Flavour symmetry models can be extended to include light sterile neutrinos
- NLO seesaw terms need to be considered for eV-scale sterile neutrinos
- Deviations from TBM due to sterile neutrinos, but large reactor angle requires NLO operators

Latest global fits

ν_e disappearance data

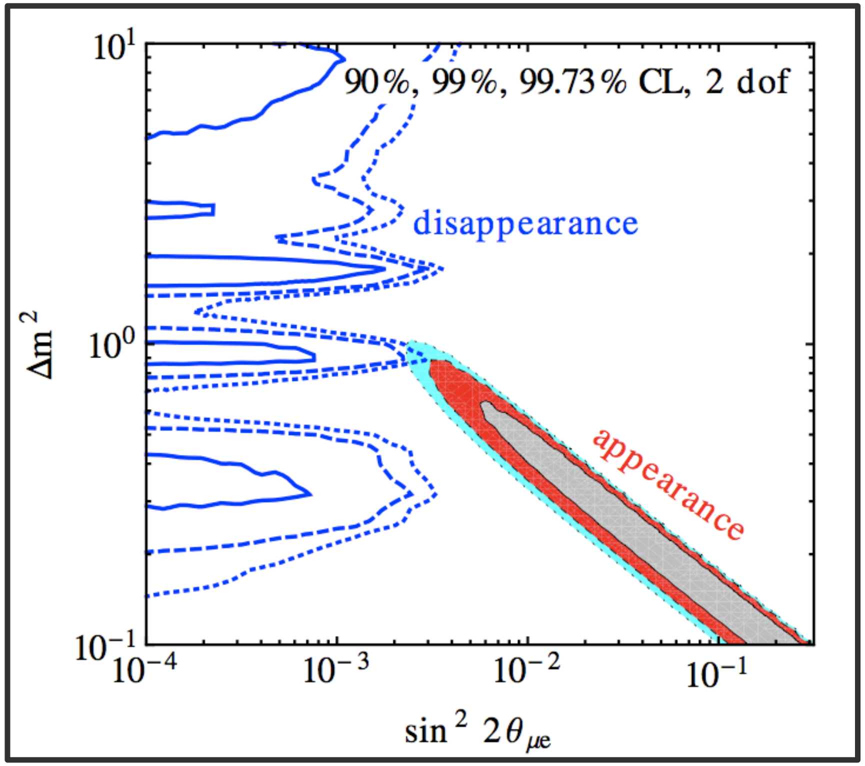


$$|U_{e4}|^2 = 0.025$$

$$\Delta m^2_{41} = 1.71 \text{ eV}^2$$

taken from Schwetz, Neutrino 2012

ν_e & ν_μ disapp. / ν_μ app.



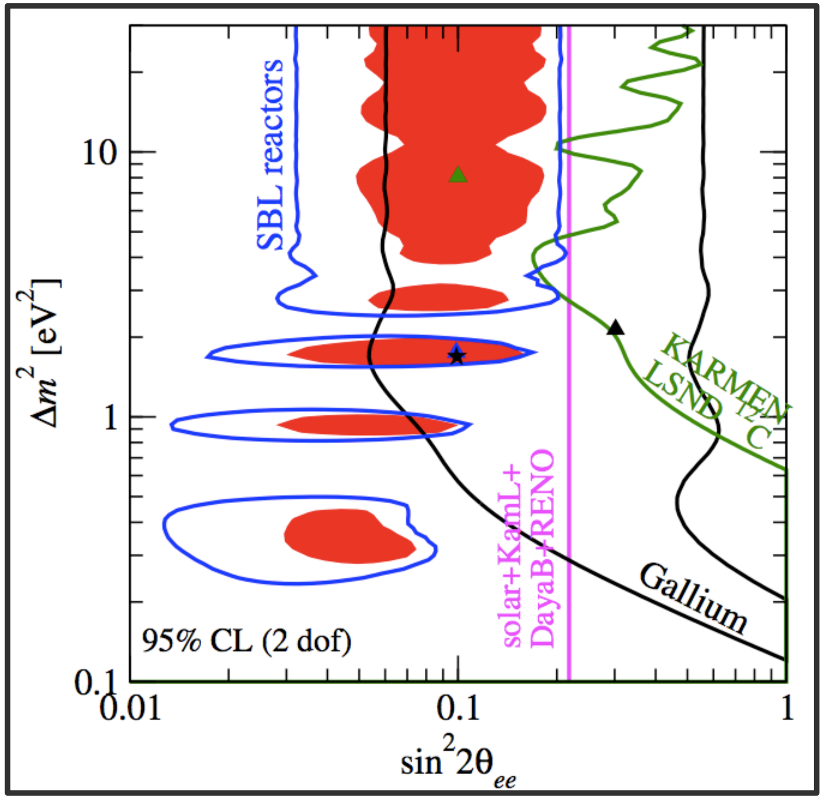
$$|U_{e4}|^2 = 0.022, \ |U_{\mu 4}|^2 = 0.030$$

$$\sin^2 2\theta_{\mu e} = 0.0026$$

$$\Delta m^2_{41} = 0.92 \text{ eV}^2$$

Latest global fits

ν_e disappearance data



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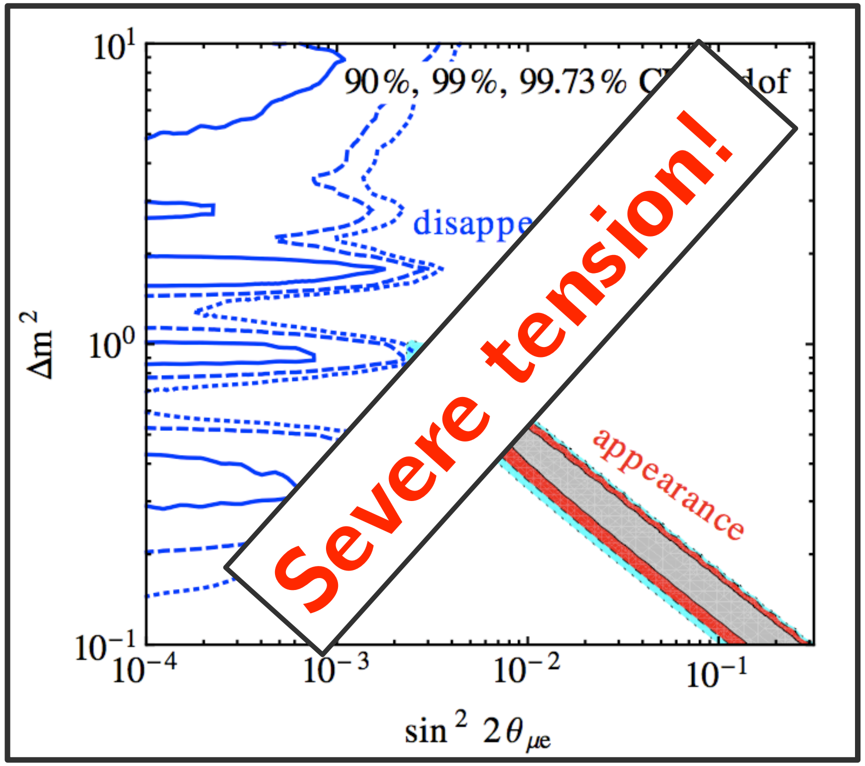

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