Sterile Neutrinos in Models

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(ICHEP 2016)

05/08/16

MANITOP

Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

38th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

AUGUST 3 - 10, 2016

CHICAGO

ICHEP2016CHICAGO

Heisenberg-Programm

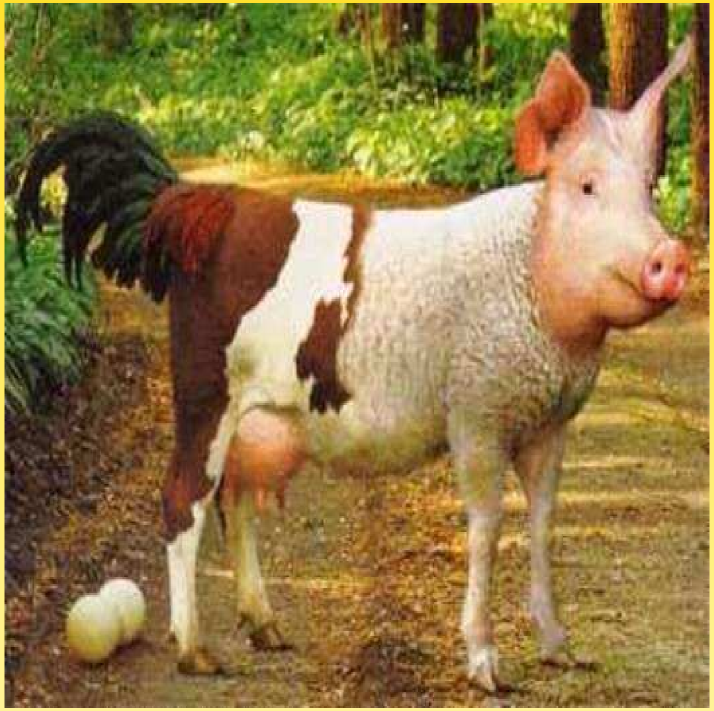
DFG Deutsche Forschungsgemeinschaft

What are Sterile Neutrinos?

fermions transforming as $(1, 0)$ under $SU(2)_L \times U(1)_Y$, call them N_R

- second simplest addition to the Standard Model
- show up in most theories beyond the Standard Model
- are "sterile", but
  - mix with active neutrinos $\nu_\alpha \leftrightarrow N_R^c$
  - couple to the Higgs $\overline{L}\, \tilde{\Phi}\, N_R$
  - could have new interactions ($B - L$, left-right,...)
- mass scale in principle arbitrary
- are used to explain several things...

Sterile Neutrinos



- $\ll$ eV: missing upturn of $P_{ee}^{\odot}$
- eV: SBL Anomalies
- eV: $N_{\rm eff}$ (Cosmology, BBN, H_0)
- eV: r-process
- keV: Warm Dark Matter
- TeV: Z-width, NuTeV
- 10^{10} GeV: Leptogenesis
- 10^{15} GeV: Seesaw Mechanism

What is the Mass of a sterile Neutrino?

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

special cases:

- $m_D = 0$; **pure Majorana case**
- $M_R = 0$; **pure Dirac case**
- $M_R \gg m_D$; **seesaw case**
- $m_D \gg M_R$; **pseudo-Dirac case**
- $M_D \sim M_R$; **ugly case**

stay in seesaw limit in this talk

Formalism

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

6×6 (?) mass matrix diagonalized by

$$\mathcal{U}_\nu \simeq \begin{pmatrix} 1 - \frac{1}{2}BB^\dagger & B \\ -B^\dagger & 1 - \frac{1}{2}B^\dagger B \end{pmatrix} \begin{pmatrix} U & 0 \\ 0 & V_R \end{pmatrix} \quad \text{with } B = m_D M_R^{-1}$$

light neutrino mass matrix:

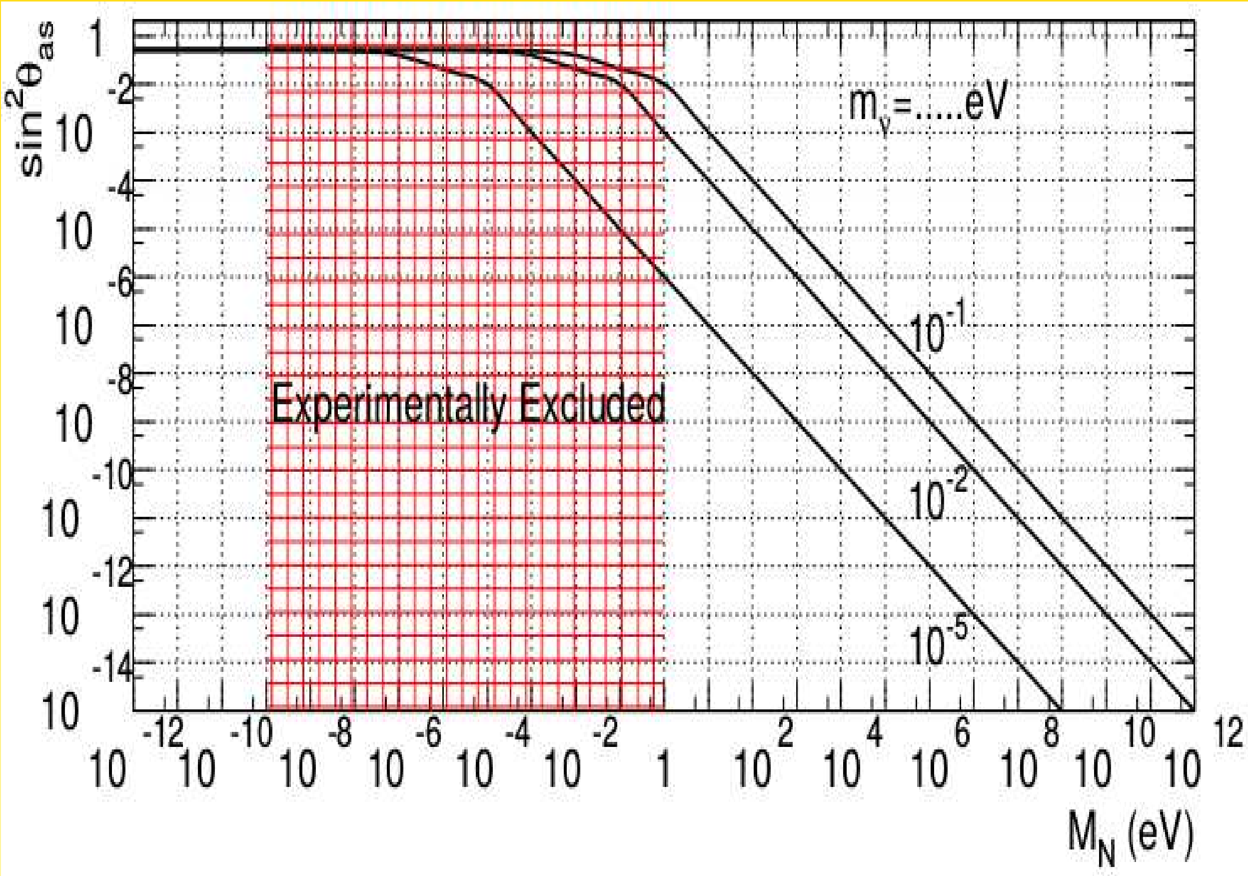
$$m_\nu = -m_D\, M_R^{-1}\, m_D^T = U\, \mathrm{diag}(m_1, m_2, m_3)\, U^T$$

heavy neutrino mass matrix:

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

non-unitary 3×3 PMNS matrix $N = (1 - \frac{1}{2}BB^\dagger)\, U$

in seesaw limit, naively, active-sterile mixing = $m_D/M_R = \sqrt{m_\nu/M_R}$



(plot by Andre de Gouvea)

(but: these are all matrices. . .)

Seesaw Scale

can make M_R TeV, but then mixing $\sqrt{m_\nu/M_R} \simeq 10^{-7}$

not necessarily correct, m_D and M_R are matrices...

$$m_D = v \begin{pmatrix} h_1 & h_2 & h_3 \\ \omega\, h_1 & \omega\, h_2 & \omega\, h_3 \\ \omega^2\, h_1 & \omega^2\, h_2 & \omega^2\, h_3 \end{pmatrix}, \quad M_R = M_0 \mathbb{1} \quad (\text{here } \omega = e^{2i\pi/3})$$

gives $m_\nu = 0$, add small corrections...

$m_D = v$, $M_R =$ TeV, mixing m_D/M_R large

(corresponds to large $\mathrm{Im}\{\omega_{ij}\}$ in Casas-Ibarra)

GUTs

heavy N_R appear naturally in $SO(10)$ as part of 16-dim spinor rep.,

$$16 \times 16 = 10 + 126 + 120$$

Yukawa structure depends on Higgs representations, e.g.

$$m_D \propto (H_{10} - 3sF_{126} + it_D\, G_{120}),\ m_{\rm up} \propto (H_{10} + sF_{126} + it_u\, G_{120}),\ M_R \propto F_{126}$$

Higgses	Authors	M_1 [GeV]
$\mathbf{45}, \mathbf{10}, \mathbf{16}, \overline{\mathbf{16}}$	Babu, Pati, Wilczek	10^{10}
$\mathbf{10}, \mathbf{126}, \overline{\mathbf{126}}$	Goh, Mohapatra, Ng; Bajc, Senjanovic, Vissani	10^{13}
$\mathbf{45}, \mathbf{10}, \mathbf{16}, \overline{\mathbf{16}}$	Ji, Li, Mohapatra	$3.8 \cdot 10^{10}$
$\mathbf{10}, \mathbf{126}, \overline{\mathbf{126}}, \mathbf{120}$	Dutta, Mimura, Mohapatra	10^{13}
$\mathbf{45}, \mathbf{10}, \mathbf{16}, \overline{\mathbf{16}}$	Albright, Barr	$5.4 \cdot 10^{8}$

Recent fit including RG, Higgs, θ_{13}

Dueck, W.R.

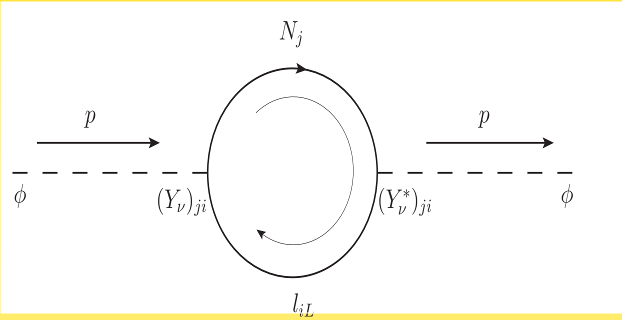
Mod	Comments	$\sin^2\theta^l_{23}$	m_0 [meV]	M_3 [GeV]	M_2 [GeV]	M_1 [GeV]	$\chi^2_{\rm min}$
MN	no RGE, NH	0.406	3.03	5.5×10^{12}	7.2×10^{11}	1.5×10^{10}	1.10
MN	RGE, NH	0.346	2.40	3.6×10^{12}	2.0×10^{11}	1.2×10^{11}	23.0
MS	no RGE, NH	0.387	2.58	3.9×10^{12}	7.2×10^{11}	1.6×10^{10}	9.41
MS	RGE, NH	0.410	6.83	1.1×10^{12}	5.7×10^{10}	1.5×10^{10}	3.29
FN	no RGE, NH	0.410	8.8	1.9×10^{13}	2.8×10^{12}	2.2×10^{10}	6.6×10^{-5}
FN	RGE, NH	0.410	1.54	9.9×10^{14}	7.3×10^{13}	1.2×10^{13}	11.2
FS	no RGE, NH	0.410	1.16	1.5×10^{13}	5.3×10^{11}	5.7×10^{10}	9.0×10^{-10}
FS	RGE, NH	0.410	3.17	4.2×10^{13}	4.9×10^{11}	4.9×10^{11}	6.9×10^{-6}
FN	no RGE, IH	0.590	35.85	2.2×10^{13}	4.9×10^{12}	9.2×10^{11}	2.5×10^{-4}
FN	RGE, IH	0.590	30.24	1.1×10^{13}	3.5×10^{12}	5.5×10^{11}	13.3
FS	no RGE, IH	0.590	6.27	1.2×10^{13}	4.2×10^{11}	3.5×10^{7}	3.9×10^{-8}
FS	RGE, IH	0.590	11.97	1.2×10^{13}	3.1×10^{11}	2.0×10^{3}	0.602

M have $10_H + \overline{126}_H$, F have $10_H + 120_H + \overline{126}_H$, S = SUSY, N = no SUSY

Problems with heavy N_R

With $\overline{L}\,\tilde{\Phi}\,Y_\nu\,N_R$:

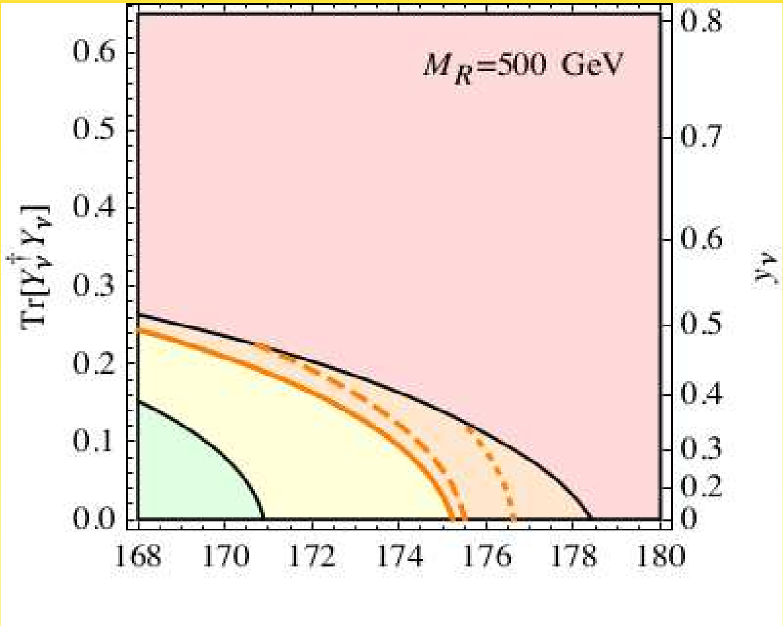
Naturalness:



$$\delta m_h^2 \propto m_\nu\, M_N^3$$
$$\Rightarrow M_N \lesssim 10^7\ \text{GeV}$$

Vissani; Clarke, Foot, Volkas

Vacuum stability:

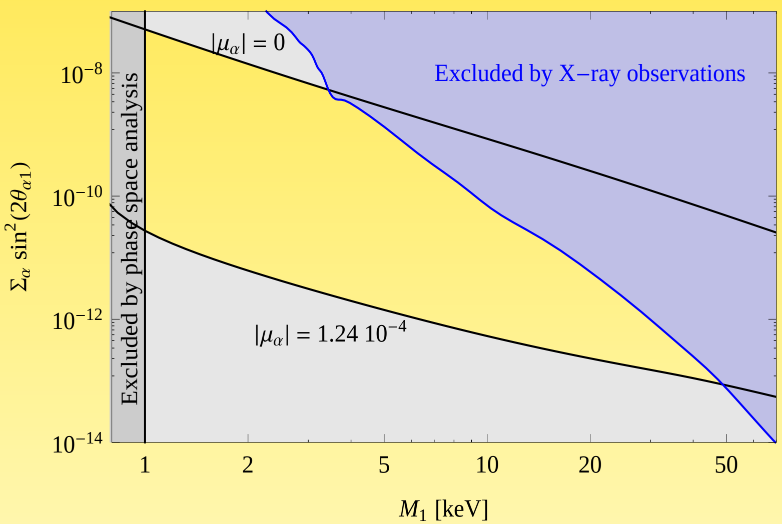


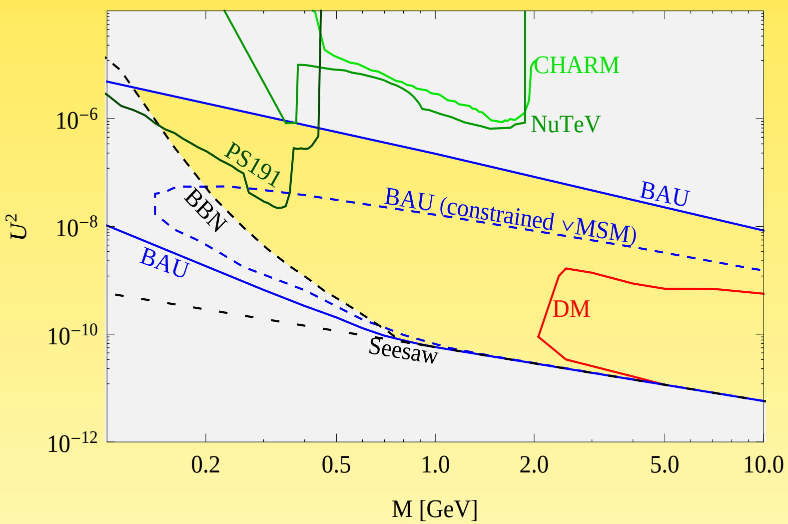
$$\dot{\lambda} \propto -\left(y_{\rm top}^4 + \tfrac{1}{3} Y_\nu^4\right)$$

W.R., Zhang; Lindner, Patel, Radovcic

νMSM

- no new scale beyond v and Planck scale
- no new particles except 3 right-handed neutrinos
  - one is keV and is Warm Dark Matter
  - two are few GeV, almost degenerate, and do leptogenesis via oscillations





Shaposhnikov *et al.*; talks by van Herwijnen, Drewes

Seesaw Extensions

extend (ν_L^c, N_R) to (ν_L^c, N_R, S)

$$\mathcal{M} = \begin{pmatrix} 0 & m_D^T & m_{DS}^T \\ m_D & M_R & m_{RS}^T \\ m_{DS} & m_{RS} & M_S \end{pmatrix}$$

most often considered variants

name	entries	m_ν
double	$m_D, m_{RS} \ll M_S$ $m_D \ll m_{RS}^2/M_S$	$\left(\frac{m_D}{10^2\,\mathrm{GeV}}\right)^2 \left(\frac{10^{16}\,\mathrm{GeV}}{m_{RS}}\right)^2 \left(\frac{M_S}{10^{19}\,\mathrm{GeV}}\right)$ eV
inverse	$M_S \ll m_D \ll m_{RS}$	$\left(\frac{m_D}{10^2\,\mathrm{GeV}}\right)^2 \left(\frac{\mathrm{TeV}}{m_{RS}}\right)^2 \left(\frac{M_S}{0.1\,\mathrm{keV}}\right)$ eV
linear	$m_{RS} \gg m_D \sim m_S$	$\left(\frac{m_D}{10^2\,\mathrm{GeV}}\right) \left(\frac{m_{DS}}{10^2\,\mathrm{GeV}}\right) \left(\frac{10^{13}\,\mathrm{GeV}}{m_{RS}}\right)$ eV

Inverse Seesaw

$$\mathcal{M} = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & m_{RS}^T \\ 0 & m_{RS} & M_S \end{pmatrix}$$

with $M_S \ll m_D < m_{RS}$

$$m_\nu \simeq \left(\frac{m_D}{10^2\,\mathrm{GeV}}\right)^2 \left(\frac{\mathrm{TeV}}{m_{RS}}\right)^2 \left(\frac{M_S}{0.1\,\mathrm{keV}}\right) \mathrm{eV}$$

unitarity violation large

$$BB^\dagger \simeq 10^{-2} \left(\frac{m_D}{10^2\,\mathrm{GeV}}\right)^2 \left(\frac{\mathrm{TeV}}{m_{RS}}\right)^2$$

Pseudo-Dirac pair of TeV-scale singlets $m_{RS} \pm M_S$ (no LNV); sizable LFV

$\rightarrow$ *desirable features without Yukawa tuning*

Another Extension

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_R & m_{RS}^T \\ 0 & m_{RS} & 0 \end{pmatrix}$$

with $M_R \gg m_{RS} > m_D$ and only one S (Zhang)

results in one massless active neutrino with

$$m_\nu = m_D M_R^{-1} m_{RS}^T (m_{RS} M_R^{-1} m_{RS}^T)^{-1} m_{RS} (M_R^{-1})^T m_D^T - m_D M_R^{-1} m_D^T$$

and sterile state

$$m_4 = -m_{RS} M_R^{-1} m_{RS}^T$$

(essentially $m_D M_R^{-1} m_D^T$ and $m_{RS} M_R^{-1} m_{RS}^T$)

active-sterile mixing:

$$U_{\alpha 4} = m_D M_R^{-1} m_{RS}^T (M_S M_R^{-1} m_{RS}^T)^{-1} = \mathcal{O}(m_D/m_{RS})$$

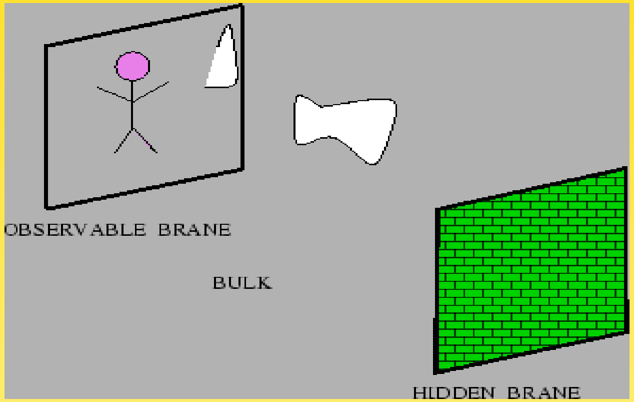
Models for light sterile Neutrinos

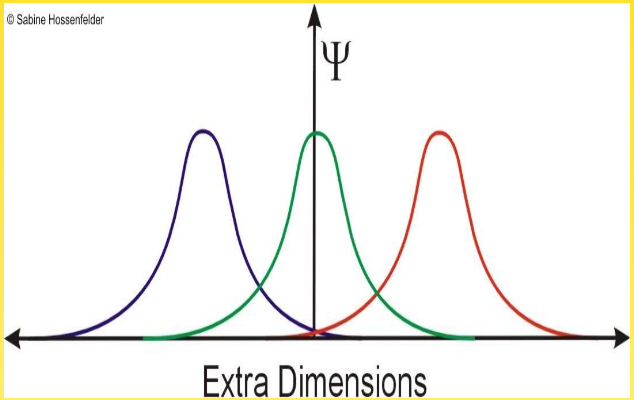
how to bring one (or all) of the singlet neutrinos down to (k)eV ?

- extra dimensions (Kusenko, Takahashi, Yanagida)
- zero mass plus corrections (Mohapatra; Shaposhnikov; Lindner, Merle, Niro; Araki, Li)
- Froggatt-Nielsen (Merle, Niro; Barry, W.R., Zhang)

Light sterile neutrinos from extra dimensions: "Split Seesaw"

localize one heavy neutrino N_1 on distant brane, separated from the SM brane





5D theory compactified on S_1/Z_2 with coordinate $y \in [0, l]$; $M_{\rm Pl}^2 = M_{\rm 5D}^3 \, l$

small wave function overlap between this field and our world:

$$M_1 \propto e^{-2m\,l} \;, \quad m_D \propto e^{-m\,l}$$

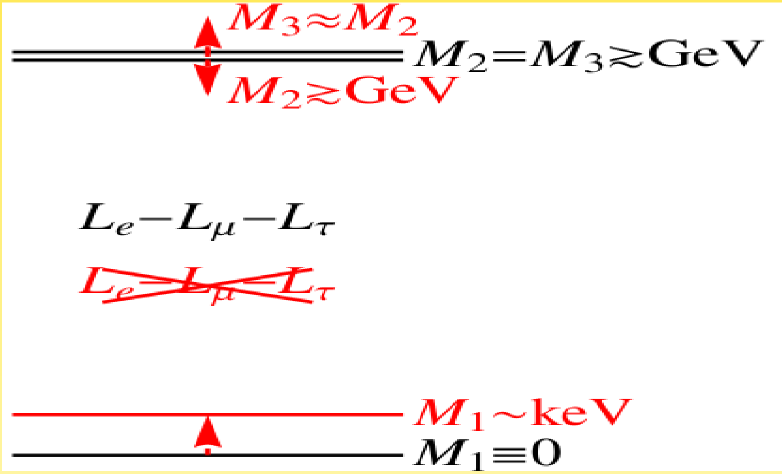
(m mass of 5D spinor)

Kusenko, Takahashi, Yanagida; flavor model: Adulpravitchai, Takahashi

Light sterile neutrinos from slightly broken flavor symmetry

introduce flavor symmetry leading to one massless 'heavy' neutrino, e.g.

$$M_R^{L_e-L_\mu-L_\tau} = \begin{pmatrix} 0 & a & b \\ \cdot & 0 & 0 \\ \cdot & \cdot & 0 \end{pmatrix} \Rightarrow M_1 = 0\,, \quad M_{2,3} = \pm\sqrt{a^2+b^2}$$



small breaking to lift M_1

Mohapatra; Shaposhnikov; Lindner, Merle, Niro; Araki, Li

Flavor Symmetries

'role model' (Altarelli, Feruglio)

Field	l	e^c	μ^c	τ^c	$h_{u,d}$	φ	φ'	ξ
A_4	3	1	$1''$	$1'$	1	3	3	1
Z_3	ω	ω^2	ω^2	ω^2	1	1	ω	ω
$U(1)_{\rm FN}$	0	4	2	0	0	0	0	0

and simply modify to (Barry, W.R., Zhang)

Field	L	e^c	μ^c	τ^c	$h_{u,d}$	φ	φ'	ξ	ν_s
A_4	3	1	$1''$	$1'$	1	3	3	1	1
Z_3	ω	ω^2	ω^2	ω^2	1	1	ω	ω	1
$U(1)_{\rm FN}$	-	4	2	0	-	-	-	-	6

$m_s \simeq {\rm eV}$, $\delta m_\nu \simeq \theta_{as}^2\, m_s$, generates non-zero θ_{13}, non-maximal θ_{23}

A_4 Seesaw Model with light steriles (Barry, W.R., Zhang)

Field	L	e^c	μ^c	τ^c	$h_{u,d}$	ν_1^c	ν_2^c	ν_3^c
A_4	3	1	$1''$	$1'$	1	1	$1'$	1
Z_3	ω	ω^2	ω^2	ω^2	1	ω^2	ω	1
$U(1)$	-	3	1	0	0	F_1	F_2	F_3

various possibilities for the FN-charges (M_1 is keV):

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

Contribution to active neutrino physics

- if sterile with mixing θ and mass M exists, contributes to active neutrino mass matrix as

$$\delta m_\nu \simeq \theta^2 \, M$$

can be used to generate θ_{13}, $\theta_{23-\pi/4}$, etc. (Smirnov, Funchal; Barry, W.R., Zhang; Merle, Morisi, Winter; Rivera-Agueldo, Perez-Lorenzana; Borah)

- contribution to effective mass can cancel inverted hierarchy contribution to double beta decay (pheno opposite to active case) (Barry, W.R., Zhang; Giunti)

- sterile mixing and phases can disturb determination of mass ordering and CPV in LBL experiments (Gandhi, Kayser; deGouvea, Kelly; Agarwalla, Chatterjee, Palazzo)

Conformal Ideas

forbid mass terms by conformal symmetry, generate mass terms by Coleman-Weinberg from hidden sector, including new scalars Φ (Higgs portal)

$\lambda\, v^2 \simeq \lambda_{\rm P}\, \langle\Phi\rangle^2$: implies for new scalars TeV-scale VEVs

scalars can be responsible for neutrino mass, e.g.

- $B-L$, thus TeV-ish neutrinos (`Khoze, Ro`)
- modified inverse seesaw generating keV singlets (`Humbert, Lindner, Smirnov`)
- connect scalar complex imaginary part ('Majoron') to 'axion' (`Meissner, Nicolai`)

Summary

- steriles well motivated scenario for many issues
- mass scale arbitrary
- many ideas to accomodate in models
- many experiments coming up to test sterile hypothesis