Model building with sterile neutrinos

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Outline

- Status of experimental indications for sterile neutrinos ν_s
- Model building with eV-scale ν_s
- Model building with keV-scale ν_s
- Four generations of (all) leptons?
- Model building with ν_s in GUTs
- Summary

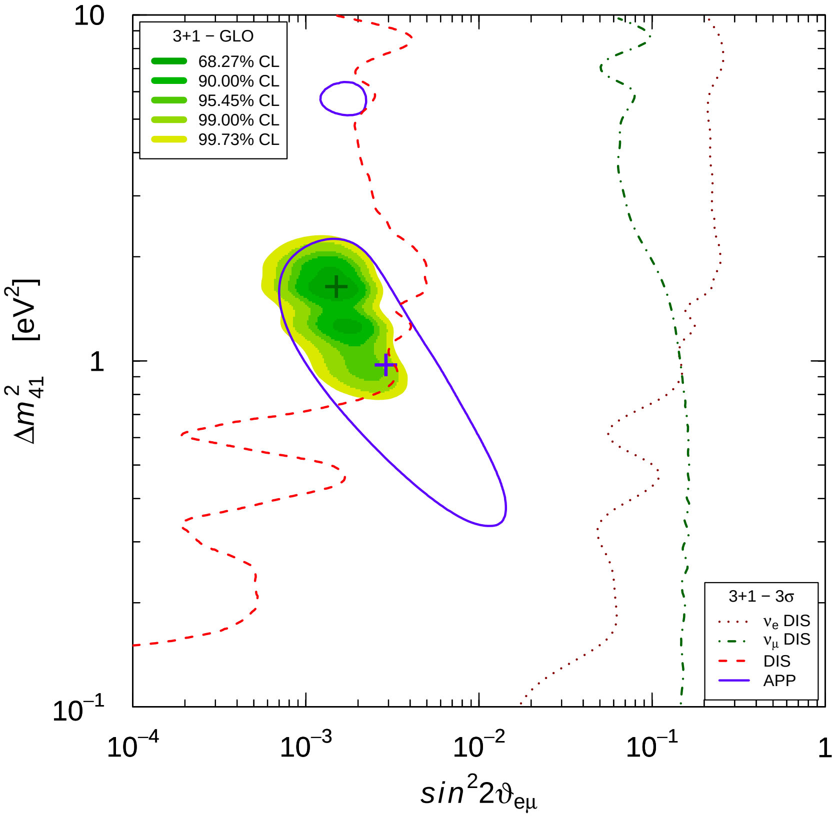
Experimental indications for eV-scale ν_s

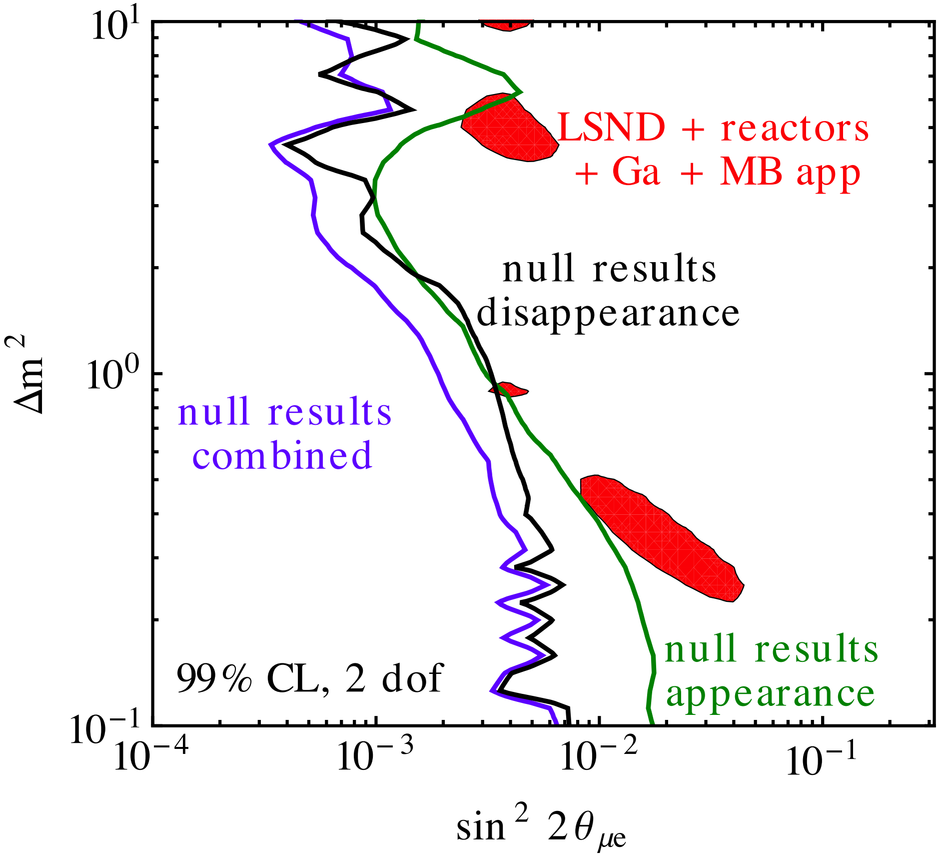
Several experiments observe anomalies

- LSND, MiniBooNE
- reactor neutrino fluxes
- Gallium anomaly
- however, ν_μ disappearance experiments do not seem to be compatible with anomalies
- however, standard cosmology seems to be fine with only three light states

Experimental indications for eV-scale ν_s

Results of two different global fits ***(Giunti et al. ('13), Kopp et al. ('13))***

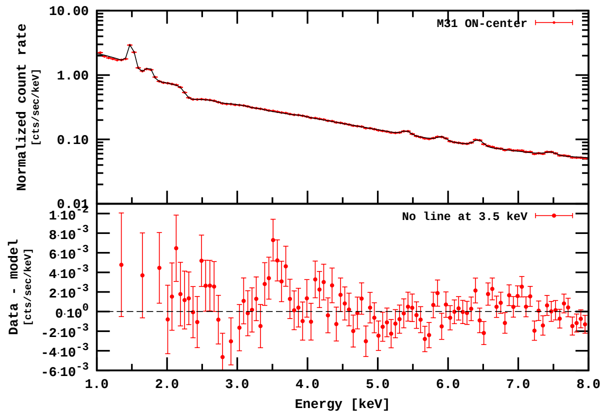


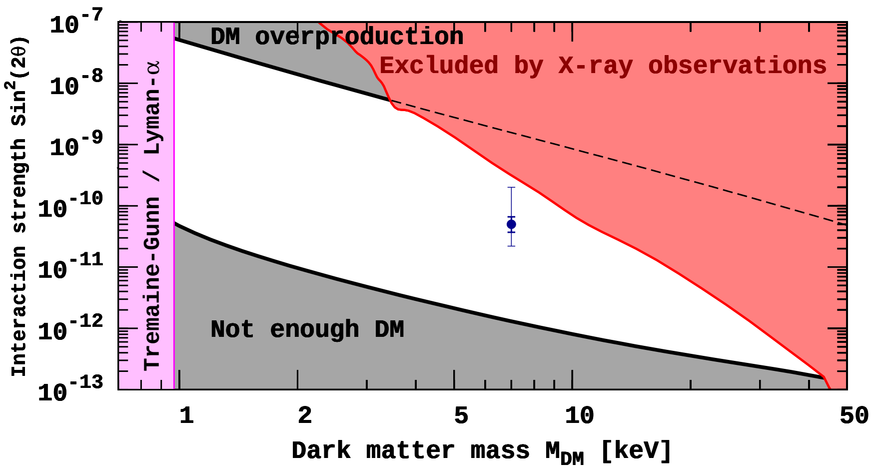


Experimental indications for keV-scale ν_s

3.5 keV line?

(Boyarsky et al. ('14))

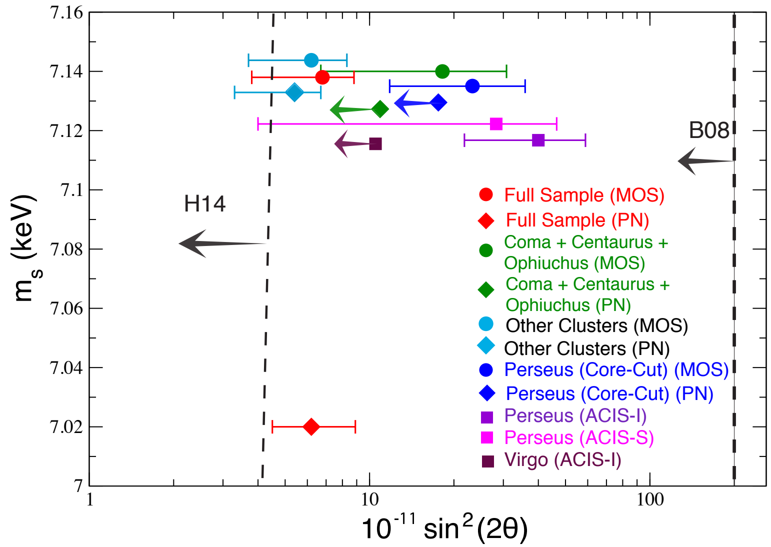


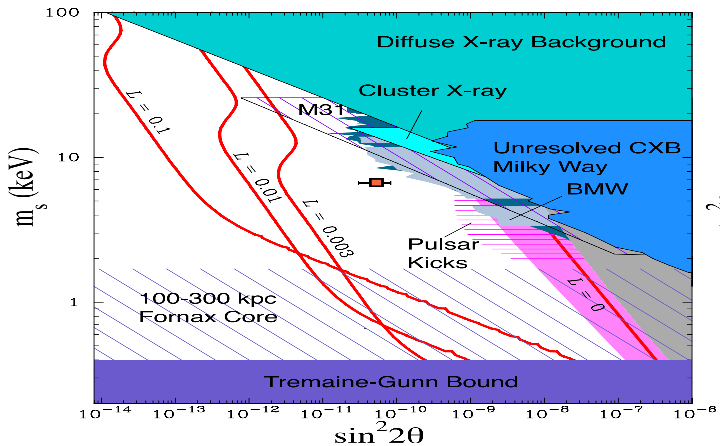


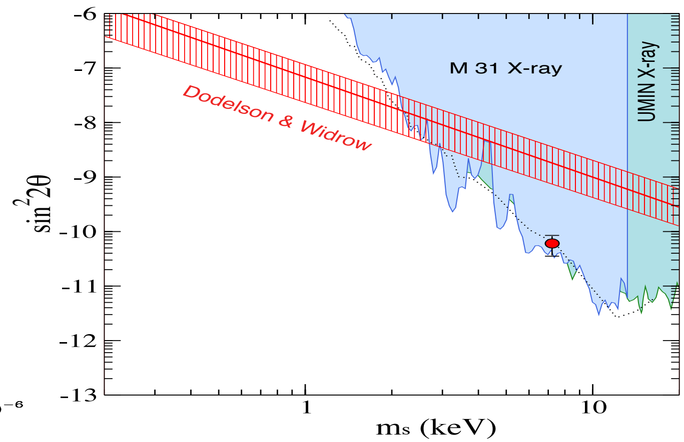
Experimental indications for keV-scale ν_s

3.5 keV line?

(Bulbul et al. ('14))







Model building with $\boldsymbol{\nu_s}$

- in principle you can just add a new state to an existing model
- however, you should be able to give reason for mass as well as mixing of the new state
- according to the experimental indications the latter are
  - eV-scale ν_s: $m_s \sim 1\,\mathrm{eV}$ and $\theta \sim 10^{-1}$
  - keV-scale ν_s: $m_s \sim 7\,\mathrm{keV}$ and $\theta \sim 10^{-5}$
- probably you should also address the question why there is just one such (neutral) state and not three
- possible reasons: symmetry protects one state, additional state is really different (under flavor group)

eV-scale $\boldsymbol{\nu_s}$ in $\boldsymbol{A_4}$ model

Idea and main features *(Barry et al. ('11))*

- starting point is A_4 model leading to tri-bimaximal mixing *(Altarelli/Feruglio ('05))*
  - neutrino masses come from Weinberg operator
  - charged lepton mass hierarchy is explained with Froggatt-Nielsen symmetry $U(1)_{FN}$
  - lepton mixing is predicted, independent from neutrino mass spectrum
- add one gauge singlet ν_s^c that is a singlet of A_4 and only carries FN charge

$$\nu_s^c \sim (\mathbf{1}, 1, 6) \quad \text{under} \quad (A_4, Z_3, U(1)_{FN})$$

eV-scale ν_s in A_4 model

Details about the flavor group A_4

- this group is isomorphic to the group of even permutations of four different objects
- it has 12 elements
- it possesses four irreducible representations:
  $\mathbf{1}$ is real; $\mathbf{1}'$, $\mathbf{1}''$ are complex conjugated;
  $\mathbf{3}$ is real
- it is a subgroup of $SO(3)$
- it belongs to a series of groups A_n, $n = 1, 2, ...$ of which, however, only A_4 and A_5 are "useful" for flavor model building

eV-scale ν_s in A_4 model

Particle content of the model $(\omega = e^{2\pi i/3})$

Field	L	e^c	μ^c	τ^c	ν_s^c
A_4	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}''$	$\mathbf{1}'$	$\mathbf{1}$
Z_3	ω	ω^2	ω^2	ω^2	1
$U(1)_{FN}$	0	3	1	0	6

Field	$h_{u,d}$	φ	φ'	ξ	θ
A_4	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$
Z_3	1	1	ω	ω	1
$U(1)_{FN}$	0	0	0	0	-1

eV-scale $\boldsymbol{\nu_s}$ in $\boldsymbol{A_4}$ model

Lagrangian involving ν_s^c

$$\mathcal{L}_{\nu_s^c} = \frac{x_e}{\Lambda^2}\left(\frac{\theta}{\Lambda}\right)^6 \xi(\varphi' L h_u)\,\nu_s^c \quad \left(+\frac{x_f}{\Lambda^2}\left(\frac{\theta}{\Lambda}\right)^6 (\varphi'\varphi' L h_u)\,\nu_s^c\right)$$

$$+\theta\left(\frac{\theta}{\Lambda}\right)^{11} \nu_s^c \nu_s^c + \text{h.c.}$$

- take as expansion parameter $\mathrm{VEV}/\Lambda \approx 0.03$
- mass of ν_s^c appropriately suppressed by large FN charge: $m_s \sim \langle\theta\rangle\,\lambda^{11} \approx \langle\theta\rangle\,10^{-17} \sim 1\,\mathrm{eV}$
- coupling of ν_s^c also suppressed: $e \sim v_u\,\lambda^8 \approx 0.1\,\mathrm{eV}$
- lepton mixing also gets perturbed

eV-scale ν_s in A_4 model

Mass matrix of neutrinos and ν_s

$$\mathcal{M}_\nu^{4\times 4} = \begin{pmatrix} a+2d/3 & -d/3 & -d/3 & e \\ . & 2d/3 & a-d/3 & e \\ . & . & 2d/3 & e \\ . & . & . & m_s \end{pmatrix}$$

We can extract as mixing matrix

$$U = \begin{pmatrix} & & & 0 \\ & \text{TB} & & 0 \\ & & & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} & & & e/m_s \\ & 0 & & e/m_s \\ & & & e/m_s \\ 0 & -\sqrt{3}e/m_s & 0 & 0 \end{pmatrix} + \ldots$$

eV-scale ν_s in A_4 model

$$\cdots + \begin{pmatrix} 0 & -\sqrt{3}e^2/(2m_s^2) & 0 & 0 \\ 0 & -\sqrt{3}e^2/(2m_s^2) & 0 & 0 \\ 0 & -\sqrt{3}e^2/(2m_s^2) & 0 & 0 \\ 0 & 0 & 0 & -3e^2/(2m_s^2) \end{pmatrix}$$

We find

$$\theta_{13} = 0 \ , \ \sin^2\theta_{12,23} \text{ are corrected at } \mathcal{O}((e/m_s)^2)$$

and

$$U_{e4} = U_{\mu 4} = U_{\tau 4} \quad \text{and} \quad \sin^2\theta_{i4} = \mathcal{O}((e/m_s)^2) \sim 10^{-2} \ \text{ with } \ i = 1, 2, 3$$

eV-scale $\boldsymbol{\nu_s}$ and induced $\boldsymbol{\theta_{13}}$

The preceding model could not give rise to θ_{13} sufficiently large.
This problem can be solved, if one uses a more general structure of vacuum of the field coupling ν_s^c to L ***(Merle et al. ('14))***.
In particular, one can find the relation ***(Merle et al. ('14))***

$$\sin\theta_{14}\,\left(\sin\theta_{24}\,e^{-i\beta}+\sin\theta_{34}\,e^{-i\gamma}\right)\approx\frac{\sqrt{2\,\Delta m_{31}^2}}{m_s}\,e^{-i\,(\alpha-\delta_2)}\,\sin\theta_{13}\,\cos\theta_{13}$$

See also very recent paper ***(Rivera-Agudelo/Perez-Lorenzana ('15))***.

keV-scale $\boldsymbol{\nu_s}$ in $\boldsymbol{A_4}$ model

A side remark:

instead of an eV-scale ν_s one can easily implement a keV-scale ν_s that can play the role of Warm Dark Matter ***(Barry et al. ('11))***.

For this to work FN charge of ν_s^c as well as scales in the model (VEVs, Λ) need to be adjusted.

νMSM: characteristics

(Asaka et al. ('05), Asaka/Shaposhnikov ('05))

- add three right-handed (RH) neutrinos N_I, $I = 1, 2, 3$, to Standard Model (SM)

$$\delta\mathcal{L} = \overline{N}_I i\,\partial_\mu\,\gamma^\mu\,N_I - F_{\alpha I}\,\overline{L}_\alpha N_I\,\Phi - \frac{M_I}{2}\,\overline{N}^c_I N_I + \mathrm{h.c.}$$

  with L_α, $\alpha = e,\ \mu,\ \tau$, lepton doublets and Φ Higgs field

- 15 free parameters in $F_{\alpha I}$

νMSM: characteristics

(Asaka et al. ('05), Asaka/Shaposhnikov ('05))

Phenomenology

- Dark Matter candidate N_1 with $M_1 \sim$ few keV
- two heavier states, $1\,\mathrm{GeV} \lesssim M_{2,3} \lesssim 10\,\mathrm{GeV}$ that are highly degenerate in mass $\Delta M/M \sim 10^{-6}$ can explain baryon asymmetry of the Universe
- Yukawa couplings $F_{\alpha I}$ must be very suppressed and exhibit hierarchy
- light neutrino masses are strongly hierarchical, both orderings are admitted

νMSM: characteristics

(Asaka et al. ('05), Asaka/Shaposhnikov ('05))

Experimental tests

- experimental indications for N_1, keV-scale ν_s, have been found in 2014 ***(Boyarsky et al. ('14), Bulbul et al. ('14))***
- states $N_{2,3}$ with masses of a few GeV can be tested at SHiP ***(Alekhin et al. ('15))***

νMSM with global lepton number

Idea and main features *(Shaposhnikov ('06))*

- assume global lepton number with the following assignment

  $$N_1 \ : \ q \quad , \quad N_2 \ : \ -1 \quad , \quad N_3 \ : \ 1 \quad , \quad L_i \ : \ -1 \quad \text{and} \quad E_k \ : \ -1$$

  with $q \neq 0, \pm 1$
- state N_1 is massless
- states $N_{2,3}$ have same mass: $M \, \overline{N}_2^c N_3$
- no mixing of state N_1 with active neutrinos, only $h_{k2} \, \overline{L}_k \, N_2 \, \Phi$
- masses of active neutrinos all vanish,
  lepton mixing is undetermined

νMSM with global lepton number

Explicit breaking of global lepton number

$$L_{\text{break}} = -\frac{1}{2}\,\overline{N}^c \Delta M\, N - \overline{L}\,\Delta F\, N\,\Phi$$

$$\Delta M = \begin{pmatrix} m_{11}\, e^{i\,\alpha} & m_{12} & m_{13} \\ m_{12} & m_{22}\, e^{i\,\beta} & 0 \\ m_{13} & 0 & m_{33}\, e^{i\,\gamma} \end{pmatrix} \quad \text{and} \quad \Delta F = \begin{pmatrix} h_{11} & 0 & h_{13} \\ h_{21} & 0 & h_{23} \\ h_{31} & 0 & h_{33} \end{pmatrix}$$

with $m_{ij} \ll M$ and $h_{i1}\,,\ h_{j3} \ll h_{k2}$.

The order of the lepton number breaking terms should be suppressed by $\epsilon \sim (10^{-4} \div 10^{-3})$ relative to the invariant terms.

If $m_{ij} \sim \epsilon^n\, M$, then $|M_2 - M_3| \sim M_1$.

Lepton mixing is adjusted correctly by choice of parameters h_{ij}.

Version of νMSM with $L_e - L_\mu - L_\tau$

Idea and main features *(Lindner et al. ('10))*

- neutrino masses receive in this model also a contribution from type-II seesaw mechanism *(Bezrukov et al. ('09))*
- assume $L_e - L_\mu - L_\tau$ as exact symmetry at leading order

$$L_{eL} \ : 1 \ , \ L_{\mu L} \ : -1 \ , \ L_{\tau L} \ : -1 \ , \ e_R \ : 1 \ , \ \mu_R \ : -1 \ , \ \tau_R \ : -1 \ ,$$

$$N_{1R} \ : 1 \ , \ N_{2R} \ : -1 \ , \ N_{3R} \ : -1$$

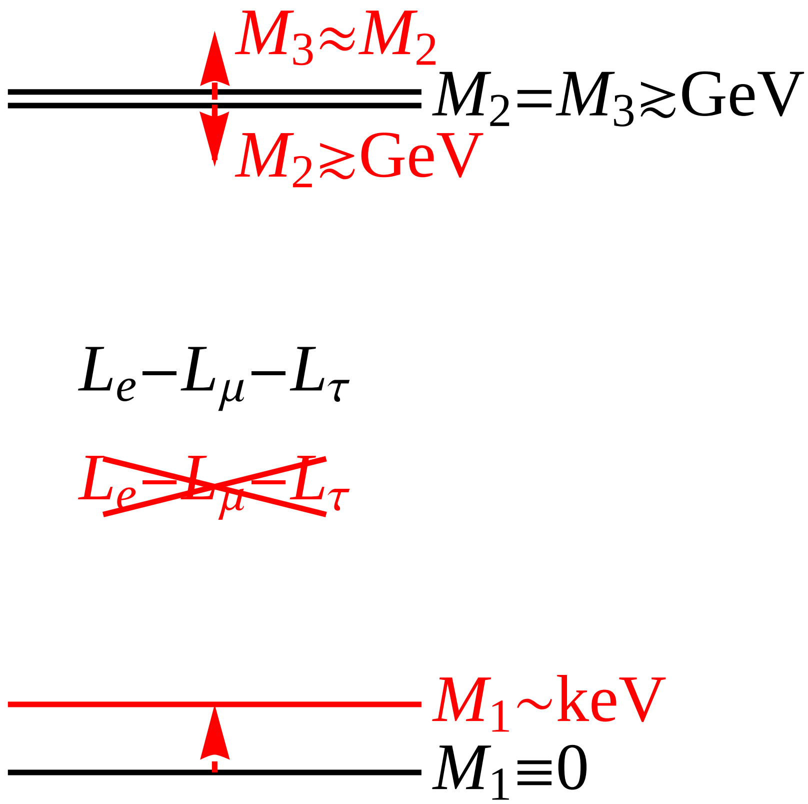
- scalar fields ϕ and Δ do not transform under $L_e - L_\mu - L_\tau$
- model leads to realistic results, if $L_e - L_\mu - L_\tau$ is explicitly (softly) broken

Version of νMSM with $L_e - L_\mu - L_\tau$

Phenomenology

- if $L_e - L_\mu - L_\tau$ is unbroken, one neutrino is massless and two have degenerate masses (active as well as sterile ones)
- breaking $L_e - L_\mu - L_\tau$ leads to keV-scale ν_s and active neutrino masses with inverted ordering
- if $L_e - L_\mu - L_\tau$ is unbroken, lepton mixing angles are fixed: $\theta_{13} = 0$, $\theta_{23} = \pi/4$ and $\theta_{12} = \pi/4$
- breaking $L_e - L_\mu - L_\tau$ introduces corrections to mixing, in particular coming from the charged lepton sector (most relevant for the solar mixing angle)

Version of νMSM with $L_e - L_\mu - L_\tau$



(Merle/Niro ('11))

νMSM with flavor symmetry Q_6

Idea and main features *(Araki/Li ('11))*

- use finite, discrete, non-abelian symmetry $Q_6 \simeq D_3'$, because it is smallest group with complex singlet and real doublet
- assign sterile neutrinos to particular representations of Q_6:
  - keV-scale ν_s separated from others: singlet; choose complex singlet in order to suppress mass term
  - GeV-scale ν_s have almost same mass: doublet; choose real doublet in order to have mass unsuppressed
  - hierarchy of mixing between active and different sterile states N_1 and $N_{2,3}$ is explained

$\boldsymbol{\nu}$MSM with flavor symmetry $\boldsymbol{Q_6}$

Details about the flavor group Q_6

- this group has 12 elements
- it possesses six irreducible representations:
  $\mathbf{1}$, $\mathbf{1}'$ are real; $\mathbf{1}''$, $\mathbf{1}'''$ are complex conjugated;
  $\mathbf{2}$ is pseudo-real and $\mathbf{2}'$ is real
- it is a subgroup of $SU(2)$
- it belongs to a series of groups $Q_{2n} \simeq D'_n$, $n = 1, 2, ...$, that all have similar properties

νMSM with flavor symmetry Q_6

Particle content of the model ($\omega = e^{2\pi i/3}$)

Field	L_1	L_D	E_1	E_D	N_1	N_D
Q_6	$\mathbf{1}$	$\mathbf{2}'$	$\mathbf{1}'$	$\mathbf{2}$	$\mathbf{1}''$	$\mathbf{2}'$
Z_3	1	1	ω^2	ω	1	1
Z_2	$+$	$+$	$+$	$+$	$+$	$-$

Field	H	S_x	S_y	S_z	D
Q_6	$\mathbf{1}$	$\mathbf{1}''$	$\mathbf{1}'''$	$\mathbf{1}$	$\mathbf{2}'$
Z_3	1	ω^2	ω^2	1	1
Z_2	$+$	$+$	$+$	$-$	$-$

$\boldsymbol{\nu}$MSM with flavor symmetry $\boldsymbol{Q_6}$

Lagrangian of sterile neutrinos

$$\mathcal{L}_M = m_a\,(N_D N_D)_{\mathbf{1}} + \frac{m_b}{\Lambda^2}\,(N_D N_D)_{\mathbf{2}'}(DD)_{\mathbf{2}'} + \frac{m_c}{\Lambda^2}\,N_1 N_1 S_x S_y^{\star} + \text{h.c.}$$

leads to mass matrix

$$M_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & m_a \\ 0 & m_a & 0 \end{pmatrix} + \frac{1}{\Lambda^2}\begin{pmatrix} m_c\,\langle S_x S_y\rangle & 0 & 0 \\ 0 & m_b\,\langle D_2\rangle^2 & 0 \\ 0 & 0 & m_b\,\langle D_1\rangle^2 \end{pmatrix}$$

$\boldsymbol{\nu}$MSM with flavor symmetry $\boldsymbol{Q_6}$

Lagrangian of sterile neutrinos

$$\mathcal{L}_M = m_a\,(N_D N_D)_{\mathbf{1}} + \frac{m_b}{\Lambda^2}\,(N_D N_D)_{\mathbf{2'}}(DD)_{\mathbf{2'}} + \frac{m_c}{\Lambda^2}\,N_1 N_1 S_x S_y^\star + \text{h.c.}$$

- assume $m_{a,b,c} \sim \mathcal{O}(\text{GeV})$
- masses $M_{2,3}$ almost degenerate and of order GeV
- $M_1 \ll M_{2,3}$ suppressed by $\langle S_x S_y \rangle / \Lambda^2 \sim 10^{-6}$: $M_1 \sim \mathcal{O}(\text{keV})$
- splitting $M_{2,3}$ is of order $\langle D_{1,2} \rangle^2 / \Lambda^2 \sim 10^{-6}$
- if $\langle D_1 \rangle = \langle D_2 \rangle$, maximal 2-3 mixing

νMSM with flavor symmetry Q_6

Charged leptons

- all arise at the non-renormalizable level

$$m_e \sim \frac{\langle S_x \rangle^2}{\Lambda^2} v \, , \quad m_{\mu,\tau} \sim \frac{\langle S_x \rangle}{\Lambda} v \, , \; \frac{\langle S_y \rangle}{\Lambda} v$$

- explanation of $m_e \ll m_\mu$ via hierarchy in operators
- instead $m_\mu \ll m_\tau$ is fine-tuned
- $m_\tau \ll v$ is explained
- estimate

$$\frac{\langle S_x \rangle}{\Lambda} \, , \; \frac{\langle S_y \rangle}{\Lambda} \sim (10^{-3} \div 10^{-2})$$

νMSM with flavor symmetry Q_6

Terms generating Dirac mass matrix

$$\mathcal{L}_\nu = \frac{\alpha}{\Lambda}\overline{L}_1\tilde{H}\,(N_D D)_{\mathbf{1}} + \frac{\beta}{\Lambda}\,(\overline{L}_D\tilde{H}\,N_D)_{\mathbf{2}'}\,D + \frac{\gamma}{\Lambda}\,(\overline{L}_D\tilde{H}\,N_D)_{\mathbf{1}}S_z + \frac{\delta}{\Lambda^3}\,\overline{L}_1\tilde{H}\,N_1 S_x^3 \;\left(+\frac{\epsilon}{\Lambda^3}\,(\overline{L}_D\tilde{H}\,N_D)_{\mathbf{1}'}S_x S_y^\star S_z\right) \; + \mathrm{h.c.}$$

leads to mass matrix

$$M_D = \frac{v}{\Lambda}\begin{pmatrix} 0 & \alpha\,\langle D_2\rangle & \alpha\,\langle D_1\rangle \\ 0 & \beta\,\langle D_1\rangle & \gamma\,\langle S_z\rangle \\ 0 & \gamma\,\langle S_z\rangle & \beta\,\langle D_2\rangle \end{pmatrix} + \frac{v}{\Lambda^3}\begin{pmatrix} \delta\,\langle S_x\rangle^3 & 0 & 0 \\ 0 & 0 & ... \\ 0 & ... & 0 \end{pmatrix}$$

νMSM with flavor symmetry Q_6

- if $\langle D_1 \rangle = \langle D_2 \rangle$, lepton mixing angles $\theta_{23} = \pi/4$ and $\theta_{13} = 0$
- relative suppression of coupling of N_1 to light neutrinos compared to couplings of $N_{2,3}$
- however, suppression of all couplings is not sufficient: $\langle S_i, D_i \rangle / \Lambda \sim 10^{-3}$; thus, we need small couplings α, ..., δ of order $10^{-4.5}$
- mixing of keV-scale ν_s with active neutrinos depends on δ; can be different from α, ..., γ

$\boldsymbol{\nu}$MSM with flavor symmetry $\boldsymbol{Q_6}$

Phenomenology of light neutrinos

- strongly hierarchical neutrino masses with normal ordering and $m_1 \approx 0$
- atmospheric and reactor mixing angles

$$\tan\theta_{23} \approx 1 + \mathcal{O}\left(\frac{\langle D_1\rangle - \langle D_2\rangle}{\langle D_1\rangle + \langle D_2\rangle}\right) \quad \text{and} \quad \sin\theta_{13} \approx \mathcal{O}\left(\frac{\langle D_1\rangle - \langle D_2\rangle}{\langle D_1\rangle + \langle D_2\rangle}\right)$$

- no prediction for solar mixing angle; is function of α, β and γ

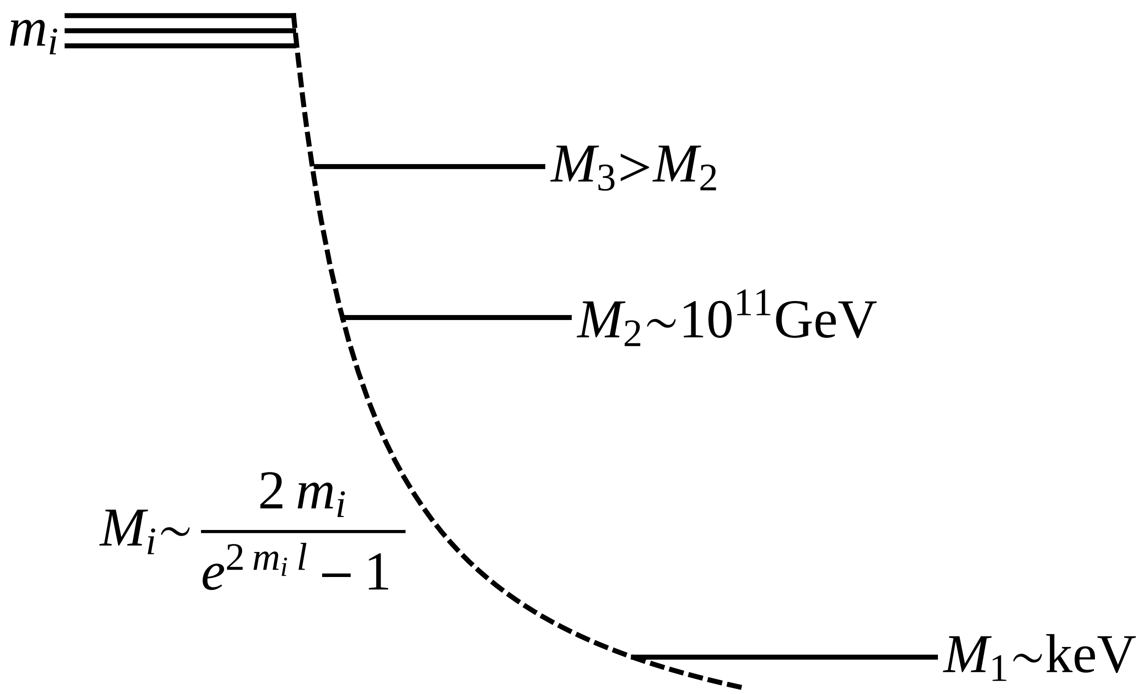
keV-scale ν_s more general

- using a "general" global $U(1)$ symmetry (Froggatt-Nielsen symmetry) one can achieve a spectrum with one keV-scale ν_s, two states with much larger masses as well as describe light neutrino masses and lepton mixing correctly

  (Merle/Niro ('11))

- alternative idea: "split seesaw mechanism" ***(Kusenko et al. ('10))***
  use extra dimension and different localization of RH neutrinos in order to achieve split spectrum; exponential suppression of masses is possible ($M_i \sim e^{-2m_i l}$), also of couplings ($\lambda_i \sim e^{-m_i l}$)
  [numerical example: $m_2 \simeq 2.3\, l^{-1}$ leads to $M_2 \sim 10^{12}\,\mathrm{GeV}$, whereas $m_1 \simeq 24\, l^{-1}$ leads to $M_1 \sim \mathrm{keV}$]

Split seesaw mechanism



(Merle/Niro ('11))

Split seesaw mechanism with A_4

(Adulpravitchai/Takahashi ('11))

- challenge 1: RH neutrino masses should be split, but in traditional A_4 models *(Altarelli/Feruglio ('05))* these are assigned to $\mathbf{3}$ of A_4 in order to achieve (close to) tri-bimaximal mixing
- splitting of RH neutrino masses achieved via new particle assignment

$$N_{R1} \sim \mathbf{1} \;\; , \;\; N_{R2} \sim \mathbf{1}' \;\; , \;\; N_{R3} \sim \mathbf{1}''$$

- lepton mixing angles are partly predicted

$\theta_{13} = 0$, $\theta_{23} = \pi/4$ and θ_{12} arbitrary

Split seesaw mechanism with A_4

- challenge 2: lightest RH neutrino with mass of order keV can only be Dark Matter candidate, if additional contribution to light neutrino masses exists
- so, neutrino masses arise from type I+II seesaw mechanism
- predictions for lepton mixing angles are maintained

In case you do not like extra dimensions:
a similar model has also been considered in four dimensions only with the flavor symmetry A_4 ***(Barry et al. ('11))***.
The main features are the same: RH neutrinos in singlets of A_4 and mass hierarchy among these is achieved via Froggatt-Nielsen symmetry.

Four generations of (all) leptons?

- A_5 model with four chiral lepton generations, three vector-like charged leptons and six RH neutrinos

  (Chen et al. ('10))

- models with four chiral families and four RH neutrinos

  (Schmidt/Smirnov ('11))

  - main purpose of this study: analysis of different contributions to light neutrino masses
  - sketches of models with flavor group $\mathrm{SG}(20, 3)$:
    $L \sim \mathbf{4}$, $e_R \sim \mathbf{1_2} + \mathbf{1_3} + \mathbf{1_4} + \mathbf{1_1}$
    and RH neutrinos transform either as
    $N_R \sim \mathbf{1_2} + \mathbf{1_3} + \mathbf{1_4} + \mathbf{1_1}$ or $N_R \sim \mathbf{4}$

Model building with $\boldsymbol{\nu_s}$ in GUTs

In $SU(5)$ RH neutrinos appear in different GUT multiplets:

$$\Psi_{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^c & -u_2^c & u^1 & d^1 \\ -u_3^c & 0 & u_1^c & u^2 & d^2 \\ u_2^c & -u_1^c & 0 & u^3 & d^3 \\ -u^1 & -u^2 & -u^3 & 0 & e^c \\ -d^1 & -d^2 & -d^3 & -e^c & 0 \end{pmatrix} \qquad \Psi_{\bar{5}} = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{pmatrix} \qquad \Psi_1 = \nu^c$$

$$\mathcal{L} = y_u \Psi_{10}\Psi_{10}H_5 + y_{d,1}\Psi_{\bar{5}}\Psi_{10}H_{\bar{5}} + y_{d,2}\Psi_{\bar{5}}\Psi_{10}H_{\overline{45}} + y_\nu \Psi_{\bar{5}}\Psi_1 H_5 + M\Psi_1\Psi_1$$

In $SO(10)$ they are naturally included in the representation $\mathbf{16}$:

$$\Psi_{16} = \mathbf{10}_{SU(5)} + \bar{\mathbf{5}}_{SU(5)} + \mathbf{1}_{SU(5)}$$

Model building with ν_s in GUTs

However, there can be additional singlets S_i in $SO(10)$:
double seesaw mechanism ***(Mohapatra ('86), Mohapatra/Valle ('86))***.
This mechanism is interesting, since it can explain the difference between charged fermions and neutrinos;
in particular, the huge difference between the up quark and light neutrino mass matrix. ***(H et al. ('08))***

$$\Psi_{16} = \mathbf{10}_{SU(5)} + \overline{\mathbf{5}}_{SU(5)} + \mathbf{1}_{SU(5)} \quad \text{and gauge singlets } S_i$$

$$\mathcal{L} = y_u \Psi_{16} \Psi_{16} H_{10} + y_{16S} \Psi_{16} S H_{\overline{16}} + M_{SS} S S$$

$$m_D = y_u \langle H_{10} \rangle \propto M_u \;,\; M_{NS} = y_{16S} \langle H_{\overline{16}} \rangle$$

$$\langle H_{\overline{16}} \rangle \propto M_{GUT} \quad \text{and} \quad M_{SS} \propto M_{Planck}$$

Model building with $\boldsymbol{\nu_s}$ in GUTs

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$$(\nu_L, N, S) \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_{NS} \\ 0 & M_{NS}^T & M_{SS} \end{pmatrix} \begin{pmatrix} \nu_L \\ N \\ S \end{pmatrix}$$

$$m_\nu^{DS} = m_D \, (M_{NS}^{-1\,T} \, M_{SS} \, M_{NS}^{-1}) \, m_D^T$$

Model building with ν_s in GUTs

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$$m_\nu^{DS} = m_D \, (M_{NS}^{-1\,T} \, M_{SS} \, M_{NS}^{-1}) \, m_D^T$$

If $M_{NS} \propto m_D^T$, then

$m_\nu^{DS} \propto M_{SS}$ and thus hierarchy is (partly) cancelled ***(H et al. ('08))***

Examples for suitable flavor symmetries: T_7 and $\Sigma(81)$.

Summary

- some ideas exist in the literature for explaining properties of eV-scale or keV-scale ν_s
- however, model building is very challenging and by now no satisfactory model has been proposed
- ν_s can also have interesting effects in GUTs
- surely, more work on symmetries and models is needed

Thanks for your attention.