Multicomponent Dark Matter and Light Sterile Neutrinos

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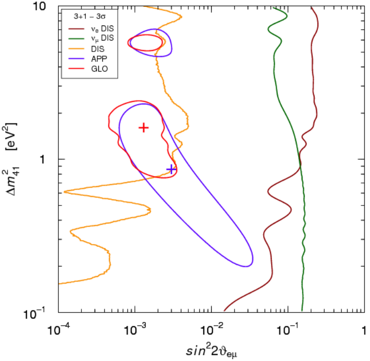
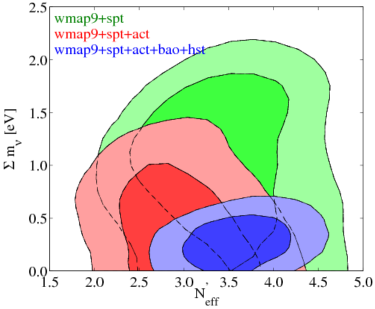
based on
JH, He Zhang,
arXiv:1211.0538.

Hints for eV sterile neutrino(s)

Short-baseline neutrino experiments hint at sterile neutrino(s) with mass $m_4 \sim 1\,\mathrm{eV}$ and active–sterile mixing $|U_{as}| \sim \mathcal{O}(0.1)$.





Cosmology likes extra d.o.f., but with smaller masses. . .

[Archidiacono et al., *1302.6720*]

Full disclosure

- Appearance vs. disappearance:
  - Reactor and Gallium: ν_e disappearance.
  - LSND and MiniBooNE: $\nu_\mu \to \nu_e$ appearance.
  - No ν_μ disappearance. . . ?

  $\Rightarrow$ Tension in global fit. $1+3+1$ preferred over $3+1$ and $3+2$. . .
  [Kopp et al., *1303.3011*]

- Planck @ 95% C.L.:

$$N_{\text{eff}} < 3.84\,, \qquad\qquad \sum m_\nu < 0.23\,\mathrm{eV}\,,$$

  depending on the combination of data sets. [Planck coll., *1303.5076*]
  $\Rightarrow$ Tension between SBL and cosmology. [Mirizzi et al., *1303.5368*]

Very puzzling. Let's embrace the hints!

How to make ν_s light?

Isn't new physics always at TeV?

- Use seesaw partners ν_R as steriles: eV-seesaw

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

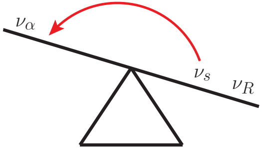
with $m_D \sim 0.1\,\mathrm{eV}$, $M_R \sim 1\,\mathrm{eV}$. [de Gouvêa, *PRD (2005)*]

- Active–sterile mixing automatically large: $U_{as} \sim m_D/M_R \sim \sqrt{m_\nu/m_s} \sim 0.1$.
- Minimal $3+2$ scheme: two ν_R at eV scale, works fine. [Donini, Schwetz et al., *JHEP (2012)*]
- Just throw in random $\mathcal{O}(1)$ couplings: sterile neutrino anarchy. [JH, Rodejohann, *PRD (2013)*]

$\Rightarrow$ The "heavy" eV-scale suppresses the "light" 0.1 eV?

How to make ν_s light? II

- Put ν_s on the other side of the seesaw:



- Suppressed *BY* seesaw: need additional right-handed singlet S and mass matrix for $(\nu_\alpha,\, \nu_{R,j}^c,\, S^c)$

$$\mathcal{M}_{\rm MES} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_R & m_S \\ 0 & m_S^T & 0 \end{pmatrix} .$$

  Minimal Extended Seesaw (MES) [Chun, Joshipura, Smirnov, *PLB (1995)*, Babu, Seidl, *PRD,PLB (2004)*, Barry, Rodejohann, Zhang, *JHEP (2011)*, Zhang, *PLB (2012)*]

- Works also for $3+2$, $3+3, \ldots$, just add more singlets.

Minimal extended seesaw

$$\mathcal{M}_{\mathrm{MES}} = \begin{pmatrix} 0^{3\times 3} & m_D & 0 \\ m_D^T & M_R^{3\times 3} & m_S \\ 0 & m_S^T & 0^{1\times 1} \end{pmatrix}$$

Assume $M_R \gg m_D, m_S$, usual seesaw:

$$\mathcal{M}_\nu^{4\times 4} \simeq - \begin{pmatrix} (m_D M_R^{-1} m_D^T)^{3\times 3} & m_D M_R^{-1} m_S \\ m_S^T M_R^{-1} m_D^T & (m_S^T M_R^{-1} m_S)^{1\times 1} \end{pmatrix} .$$

- all masses suppressed by seesaw scale $M_R \sim 2 \times 10^{14}\,\mathrm{GeV}$. ✓
- sterile mass $m_4 \sim 1$ eV for $m_S \sim 5$–$10 m_D$.
- active–sterile mixing $U_{as} = \mathcal{O}(m_D/m_S)$ automatically right. ✓

$\Rightarrow$ SBL sterile neutrinos. ✓

Great, but how to get MES structure?

How to get MES

Need

$$\overline{L}\langle H\rangle\nu_R\,, \qquad m_S\overline{S^c}\nu_R\,, \qquad M_R\overline{\nu_R^c}\nu_R$$

and forbid couplings

$$\overline{L}\langle H\rangle S\,, \qquad \overline{S^c}S\,.$$

- Flavor symmetry $A_4 \otimes \mathbb{Z}_4$ (messy...). [Zhang, *PLB (2012)*]
- Abelian gauge symmetry $U(1)'$: simple, but need additional fermions to cancel anomalies. [Babu, Seidl, *PLB (2004)*]
  - Cancel anomalies, make new fermions massive, and not disturb MES structure? With few scalars? *Yes!*

Magic numbers

	$\nu_{R,1}$	$\nu_{R,2}$	$\nu_{R,3}$	S_1	S_2	S_3	S_4	S_5	S_6	S_7	ϕ
Y'	0	0	0	11	-5	-6	1	-12	2	9	11

Mass matrix has nice block structure:

$$\mathcal{M} = \begin{pmatrix} (\mathcal{M}_{\mathrm{MES}})_{7\times 7} & 0 \\ 0 & (\mathcal{M}_S)_{6\times 6} \end{pmatrix}$$

with

$$\mathcal{M}_S = \begin{pmatrix} 0 & y_1\langle\phi\rangle & 0 & 0 & 0 & 0 \\ y_1\langle\phi\rangle & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & y_2\langle\phi\rangle & 0 & 0 \\ 0 & 0 & y_2\langle\phi\rangle & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & y_3\langle\phi\rangle \\ 0 & 0 & 0 & 0 & y_3\langle\phi\rangle & 0 \end{pmatrix} .$$

$\Rightarrow$ S_1 gives MES, $S_{2,3,4,5,6,7}$ decouple and form 3 Dirac fermions $\Psi_{1,2,3}$!

More numbers

- Happy "accident": ϕ breaks $U(1)'$ to $\mathbb{Z}_{11}$.
  $\Rightarrow$ all three Ψ_j stable!
- Active–sterile mixing $V_{4j} \sim \mathcal{O}(m_D/m_S) \overset{!}{=} \mathcal{O}(0.1)$.
- For $\mathcal{O}(1)$ Yukawas $\Rightarrow$ $U(1)'$ breaking at $\langle\phi\rangle \sim 10\langle H\rangle \sim \mathrm{TeV}$.

  $\Rightarrow$ masses for Z', $\mathrm{Re}(\phi)$, $\Psi_{1,2,3}$ around $100\,\mathrm{GeV}$–TeV.

$\Rightarrow$ Multicomponent stable dark matter.

Breakdown of neutral fermions:

$$\underbrace{\nu_e, \nu_\mu, \nu_\tau, S_1, \overbrace{\nu_{R,1}, \nu_{R,2}, \nu_{R,3}}^{\text{seesaw/leptogenesis}}}_{\text{(3+1) MES}},\ \underbrace{\overbrace{S_2, S_3}^{\Psi_1}, \overbrace{S_4, S_5}^{\Psi_2}, \overbrace{S_6, S_7}^{\Psi_3}}_{\text{DM}}$$

Dark matter interactions

Lagrangian:

$$\sum_j \left[\mathrm{i}\overline{\Psi}_j \gamma^\mu \partial_\mu \Psi_j - M_j \left(1 + \frac{\mathrm{Re}(\phi)}{\langle \mathrm{Re}(\phi) \rangle} \right) \overline{\Psi}_j \Psi_j + \frac{g'}{2} Z'_\mu \overline{\Psi}_j \gamma^\mu \left(g_j^V + g_j^A \gamma_5 \right) \Psi_j \right]$$

with $g_1^V = 1$, $g_2^V = 13$, $g_3^V = -7$, $g_1^A = -11$, $g_2^A = -11$, $g_3^A = 11$.

Connection to the Standard Model just like all other $U(1)_{\mathrm{DM}}$ models:

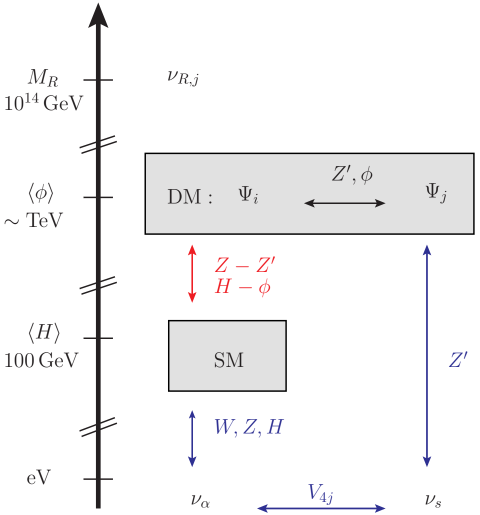
- Scalar mixing (Higgs portal): $\mathcal{L} \supset \delta\, |H|^2 |\phi|^2$
  $\Rightarrow \Psi_j$ couple to Higgs. [Lopez-Honorez et al., *PLB (2012)*]
- Vector mixing (kinetic-mixing portal): $\mathcal{L} \supset \sin\xi\ F_Y^{\mu\nu} F'_{\mu\nu}$
  $\Rightarrow \Psi_j$ couple to Z boson. [Mambrini, *JCAP (2011)*]

New:

- Fermion mixing (neutrino portal):

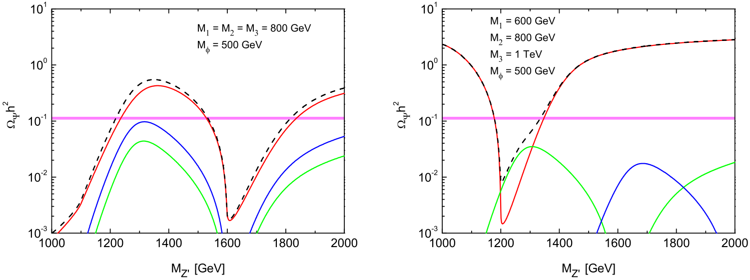
$$\mathcal{L} \supset \frac{11 g'}{2} Z'_\mu \sum_{i,j=1}^{4} V_{4i}^* V_{4j} \ \left(\overline{\nu}_i \gamma^\mu \gamma_5 \nu_j + \overline{\nu}_i \gamma^\mu \nu_j \right) .$$

Neutrino portal



Relic density via neutrino portal

- Relic density via annihilation $\Psi\Psi \to Z' \to \nu_s \nu_s$ into sterile neutrinos.



- Direct detection is loop-suppressed: $\sim \Delta m_{41}^2/(100\,\mathrm{GeV})^2 \sim 10^{-22}$.
- Indirect detection: $\mathrm{BR}(\Psi\Psi \to \nu\nu) \simeq 100\%$ gives monochromatic neutrinos from Galactic halo. Too small for IceCube...
- Including Higgs portal and kinetic-mixing portal gives the usual measurable effects.

Summary

- Additional right-handed neutrinos with exotic charges under a broken $U(1)'$ can generate structure in neutral fermions.
- Here: generate seesaw-suppressed sterile neutrino.
- Magic numbers: necessary anomaly-cancelling fermions form multicomponent DM.
- Gauge interactions open new SM–DM portal through sterile neutrinos.

$\Rightarrow$ Huge unexplored playground!

Other charges: $3+2$, $3+3$, Majorana DM, unstable DM, ...

Minimal extended seesaw

$$\mathcal{M}_{\text{MES}} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_R & m_S \\ 0 & m_S^T & 0 \end{pmatrix}$$

Assume $M_R \gg m_D, m_S$, usual seesaw:

$$\mathcal{M}_\nu^{4\times 4} \simeq -\begin{pmatrix} m_D M_R^{-1} m_D^T & m_D M_R^{-1} m_S \\ m_S^T M_R^{-1} m_D^T & m_S^T M_R^{-1} m_S \end{pmatrix} .$$

For $m_S \gg m_D$, one more seesaw:

$$\mathcal{M}_\nu^{3\times 3} \simeq -m_D M_R^{-1} m_D^T + m_D M_R^{-1} m_S \, (m_S^T M_R^{-1} m_S)^{-1} m_S^T M_R^{-1} m_D^T$$

and

$$m_4 \simeq m_s \simeq -m_S^T M_R^{-1} m_S \, .$$

Active–sterile mixing

- Diagonalize $\mathcal{M}_\nu^{4\times 4}$ with

$$V \simeq \begin{pmatrix} (1-\frac{1}{2}RR^\dagger)U_{\mathrm{PMNS}} & R \\ -R^\dagger U_{\mathrm{PMNS}} & 1-\frac{1}{2}R^\dagger R \end{pmatrix},$$

  active–sterile mixing vector
  $R = m_D M_R^{-1} m_S \, (m_S^T M_R^{-1} m_S)^{-1} \sim \mathcal{O}(m_D/m_S)$.

- $m_D \sim 100\,\mathrm{GeV}$, $m_S \sim 500\,\mathrm{GeV}$ and $M_R \sim 2\times 10^{14}$ GeV give
  $m_\nu \sim 0.05$ eV, $m_s \sim 1.3$ eV, $R \simeq 0.2$

$\Rightarrow$ SBL sterile neutrinos. ✓

Neutrino anarchy

- Anarchy: complete absence of any symmetry in lepton mixing.
  [Hall, Murayama, Weiner, *PRL (2000)*, de Gouvêa, Murayama, *PLB (2003)*]

$$\mathcal{M}_R = M_R \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix} , \quad \mathcal{M}_D = m_D \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix}$$

$\Rightarrow$ Lepton mixing angles follow Haar measure – all $U_{ij} \sim \mathcal{O}(1)$.

- Linear measure for masses: statistical distribution of $\frac{\Delta m^2_{21}}{\Delta m^2_{31}}$. ✓

- Sterile Anarchy: $3+2$ eV-seesaw with anarchic entries. ✓

$\Rightarrow$ One massless neutrino, no $0\nu\beta\beta$, no discovery at KATRIN.
[JH, Rodejohann, *PRD (2013)*]