RADIATIVE ACTIVE-STERILE NEUTRINO MASS WITH DARK MATTER

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Outline

Active Neutrinos: Present Status

Parameters	Normal Hierarchy (NH)	Inverted Hierarchy (IH)
$\frac{\Delta m^2_{21}}{10^{-5}\text{eV}^2}$	$7.02 - 8.09$	$7.02 - 8.09$
$\frac{\lvert\Delta m^2_{31}\rvert}{10^{-3}\text{eV}^2}$	$2.317 - 2.607$	$2.307 - 2.590$
$\sin^2\theta_{12}$	$0.270 - 0.344$	$0.270 - 0.344$
$\sin^2\theta_{23}$	$0.382 - 0.643$	$0.389 - 0.644$
$\sin^2\theta_{13}$	$0.0186 - 0.0250$	$0.0188 - 0.0251$
δ	$0 - 2\pi$	$0 - 2\pi$

TABLE: Global fit 3σ values of neutrino oscillation parameters (M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, JHEP 2014)

Active Neutrinos: Present Status

Parameters	Normal Hierarchy (NH)	Inverted Hierarchy (IH)
$\frac{\Delta m^2_{21}}{10^{-5}\text{eV}^2}$	$7.11 - 8.18$	$7.11 - 8.18$
$\frac{\lvert\Delta m^2_{31}\rvert}{10^{-3}\text{eV}^2}$	$2.30 - 2.65$	$2.20 - 2.54$
$\sin^2\theta_{12}$	$0.278 - 0.375$	$0.278 - 0.375$
$\sin^2\theta_{23}$	$0.393 - 0.643$	$0.403 - 0.640$
$\sin^2\theta_{13}$	$0.0190 - 0.0262$	$0.0193 - 0.0265$
δ	$0 - 2\pi$	$0 - 2\pi$

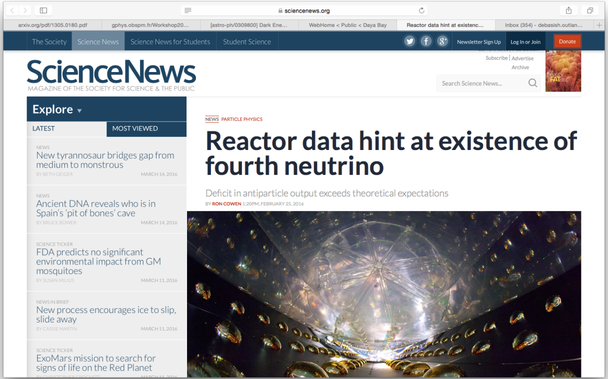
Table: Global fit 3σ values of neutrino oscillation parameters (D. V. Forero, M. Tortola and J. W. F. Valle, PRD 2014)

Active Neutrinos: Known Unknowns

- The lightest neutrino mass.
- The neutrino mass hierarchy: Normal ($m_1 < m_2 < m_3$) or Inverted ($m_3 < m_1 < m_2$).
- Octant of atmospheric mixing angle: $\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$.
- Leptonic Dirac CP phase δ [1].
- Majorana or Dirac.

[1] Recent hint from T2K: $\delta \approx -\pi/2$ (K. Abe et al, PRD 2015)

Existence of a fourth light neutrino?



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[2] Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay, PRL 116, 061801 (2016)

Existence of a fourth light neutrino?

Searches for Sterile Neutrinos with the IceCube Detector

The IceCube Collaboration

(Submitted on 6 May 2016)

The IceCube neutrino telescope at the South Pole has measured the atmospheric muon neutrino spectrum as a function of zenith angle and energy in the approximate 320 GeV to 20 TeV range, to search for the oscillation signatures of light sterile neutrinos. No evidence for anomalous ν_μ or $\bar{\nu}_\mu$ disappearance is observed in either of two independently developed analyses, each using one year of atmospheric neutrino data. New exclusion limits are placed on the parameter space of the 3+1 model, in which muon antineutrinos would experience a strong MSW-resonant oscillation. The exclusion limits extend to $\sin^2 2\theta_{24} \leq 0.02$ at $\Delta m^2 \sim 0.3$ eV^2 at the 90\% confidence level. The allowed region from global analysis of appearance experiments, including LSND and MiniBooNE, is excluded at approximately the 99\% confidence level for the global best fit value of $|U_{e4}|^2$.

Comments: 9 pages, 5 figures
Subjects: **High Energy Physics - Experiment (hep-ex)**; High Energy Astrophysical Phenomena (astro-ph.HE)
Cite as: **arXiv:1605.01990 [hep-ex]**
(or **arXiv:1605.01990v1 [hep-ex]** for this version)

[3]

[3] Also see Danny's talk tomorrow

Hint of a light sterile neutrino

- LSND (Liquid Scintillator Neutrino Detector) accelerator experiment, designed to study $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions, reported an excess of $\bar{\nu}_e$ events at 3.8σ level (PRD 64, 112007; PRL 75, 2650).
- Such accelerator experiments with baseline L of few tens of meters and neutrino energies E of few tens of MeV are sensitive to neutrino oscillations occurring at $\Delta m^2 \sim 1\text{eV}^2$.
- MiniBooNE also observed excess of $\bar{\nu}_e$ and ν_e events at 3.8σ level consistent with neutrino oscillations in the range $0.01 < \Delta m^2 < 1\text{eV}^2$ (PRL 110, 161801).
- LSND, KARMEN, MiniBooNE and ICARUS data restrict the allowed mass-mixing parameters to a small region around $\Delta m^2 \sim 0.5\text{eV}^2, \sin^2 2\theta \sim 5 \times 10^{-3}$

[4]

[4] Light Sterile Neutrinos: A White Paper, arXiv:1204.5379; Also see C. Giunti, arXiv:1512.04758

Hint of a light sterile neutrino

- Short baseline reactor neutrino experiments also observed similar anomalies, about 2.8σ deficit of the rate of $\bar{\nu}_e$ (PRD 83, 073006).
- The Gallium neutrino anomaly was also observed in short baseline disappearance of ν_e in GALLEX and SAGE experiments with statistical significance of about 2.9σ (PRC 73, 045805; PRC 83, 065504; PRC 80, 015807).
- The nine year WMAP data also suggested additional light species $N_{\rm eff} = 3.84 \pm 0.40$ (95% CL)(arXiv:1212.5226).
- The 2013 Planck data however, favour the standard three neutrino picture $N_{\rm eff} = 3.30^{+0.54}_{-0.51}$ (95% CL)(arXiv:1303.5076) which gets updated to 3.15 ± 0.23 in 2015 Planck data (arXiv:1502.01589).
- Global fit data of sterile neutrinos can be found in arXiv:1303.3011 (Kopp et al).

Sterile Neutrino Global Fit

	$\sin^2 2\theta_{14}$	Δm^2_{41} [eV^2]	χ^2_{min}/dof (GOF)	$\Delta\chi^2_{\text{no-osc}}$/dof (CL)
SBL rates only	0.13	0.44	11.5/17 (83%)	11.4/2 (99.7%)
SBL incl. Bugey3 spectr.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)
SBL + Gallium	0.11	1.80	64.0/78 (87%)	14.0/2 (99.9%)
SBL + LBL	0.09	1.78	93.0/113 (92%)	9.2/2 (99.0%)
global ν_e disapp.	0.09	1.78	403.3/427 (79%)	12.6/2 (99.8%)

Table 4. Best fit oscillation parameters and χ^2_{min} values as well as $\Delta\chi^2_{\text{no-osc}} \equiv \chi^2_{\text{no-osc}} - \chi^2_{\text{min}}$ within a 3+1 framework. Except in the row labeled "SBL rates only", we always include spectral data from Bugey3. The row "global ν_e disapp." includes the data from reactor experiments (see Tab. 3) as well as Gallium data, solar neutrinos and the LSND/KARMEN ν_e disappearance data from ν_e–^{12}C scattering. The CL for the exclusion of the no oscillation hypothesis is calculated assuming 2 degrees of freedom ($|U_{e4}|$ and Δm^2_{41}).

Figure: Global fit from Kopp et. al., 1303.3011

Light sterile neutrino

- Global fit data however, suffer from the tension between antineutrino appearance signals and bounds from antineutrino appearance experiments (NPB 643, 321; PLB 539, 91; NPB 708, 215). A consistent interpretation of all experimental data suggesting a sub-eV sterile neutrino is still missing!
- IceCube also rules out most part of Global fit data in their latest results (arXiv:1605.01990).

Hint of a light sterile neutrino

- Even if all the anomalies at neutrino experiments go away in future, a light keV sterile neutrino can still be interesting from Cosmology point of view [5].
- keV sterile neutrinos can give rise to Warm DM. This can provide a solution to the small scale structure problem.
- keV sterile neutrino DM can rise to the 3.55 keV X-ray line observed in the data taken by XMM-Newton and Chandra from several galaxy clusters (ApJ 789, 13; PRL 113, 251301; PRL 115, 161301).
- A 7.1 keV sterile neutrino having mixing with active neutrinos of the order $\sin^2 2\theta \approx 10^{-11} - 10^{-10}$ can fit the data.

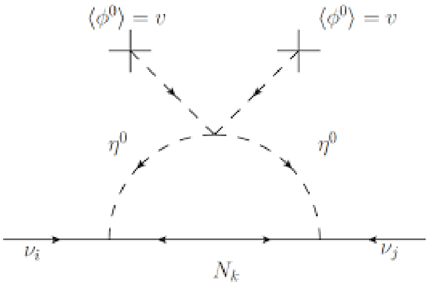
[5] Alex, Kevork and Marco's talks yesterday

Sterile Neutrino Model Building

- Generating a sub-eV to keV scale sterile neutrino in generic tree level seesaw models require some amount of fine-tuning.
- Several interesting possibilities have appeared recently: Merle & Niro'2011; Barry, Rodejohann & Zhang'2011-12; Bhupal Dev & Pilaftsis'2013 etc. For a review, see A. Merle, IJMPD 22, 1330020 (2013); White paper, 1602.04816.
- Our approach is to forbid the tree level active-sterile mixing term as well as bare mass term of sterile neutrino and allow them to be generated at one loop level.
- Consider a similar radiative mass generation mechanism for active neutrinos.
- Check if a stable dark matter candidate can also be embedded within such frameworks: in *scotogenic* fashion (E. Ma, PRD 73, 077301).

Scotogenic Model

The original *Scotogenic* model has an additional Higgs doublet η and three singlet neutrinos N_k odd under a Z_2 symmetry. The light neutrino mass arise only at one loop level:



The lightest Z_2 odd particle is stable and can be a dark matter candidate.

Abelian Version of Scotogenic Model

- In order to have light active and sterile neutrinos at one-loop level, a symmetry higher than Z_2 is required, as Z_2 itself can not prevent a tree level sterile neutrino mass term.
- We choose an extra $U(1)_X$ gauge symmetry which gets spontaneously broken down at a high scale to the standard model gauge symmetry.
- The extra fermion content is chosen in a *minimal* way required to cancel the gauge anomalies.
- The transformations of the fields under the $U(1)_X$ symmetry are chosen in such a way that three active and one sterile neutrino masses arise only at one loop level.
- It is also made sure that there remains an unbroken remnant Z_2 symmetry which stabilises the dark matter candidate.

Abelian Version of Scotogenic Model

- Let the $U(1)_X$ charges of $(u, d)_L$, u_R, d_R, $(\nu, e)_L$, e_R be $n_{1,2,3,4,5}$ respectively.
- Consider n_N copies of singlet fermion N and n_Σ copies of $SU(2)_L$ triplet fermions Σ such that $n_N + n_\Sigma = 3$, minimum required to give rise to three light active neutrinos in both tree level as well as radiative seesaw.
- Both N and Σ are assumed to transform as n_6 under $U(1)_X$ and have zero $U(1)_Y$ hypercharges.

Anomaly Cancelations

With this choice of $U(1)_X$ charges, one can write the anomaly cancelation conditions as (Adhikari, Erler, Ma, PLB 2009)

$$[SU(3)_c]^2 U(1)_X \quad : \quad 2n_1 - n_2 - n_3 = 0$$

$$[SU(2)_L]^2 U(1)_X \quad : \quad \frac{9}{2} n_1 + \frac{3}{2} n_4 - 2 n_\Sigma n_6 = 0$$

$$[U(1)_Y]^2 U(1)_X \quad : \quad \frac{1}{6} n_1 - \frac{4}{3} n_2 - \frac{1}{3} n_3 + \frac{1}{2} n_4 - n_5 = 0$$

$$U(1)_Y [U(1)_X]^2 \quad : \quad n_1^2 - 2n_2^2 + n_3^2 - n_4^2 + n_5^2 = 0$$

$$[U(1)_X]^3 \quad : \quad 3(6n_1^3 - 3n_2^3 - 3n_3^3 + 2n_4^3 - n_5^2) - (3n_\Sigma + n_N) n_6^3 = 0$$

$$[U(1)_X] \quad : \quad 3(6n_1 - 3n_2 - 3n_3 + 2n_4 - n_5) - (3n_\Sigma + n_N) n_6 = 0$$

Solving the first four equations allows one to write $n_{2,3,5,6}$ in terms of n_1 and n_4 with $3n_1 + n_4 \neq 0$.

Anomaly Cancelations

- All anomalies are cancelled if $n_N = 0, n_\Sigma = 3$. This gives rise to the usual type III seesaw model.
- If $n_N = 0, n_\Sigma = 2$, then in the units of $(3n_1 + n_4)/8$, the $[U(1)_X]^3$ anomaly gives -90 whereas $[U(1)_X]$ anomaly cancels out.
- This can be cancelled by three singlet fields with $U(1)_X$ charges $(3, 2, -5)$ or $(-6, 1, 5)$. Both of them allow the possibility of radiative neutrino mass and a remnant Z_2 symmetry.
- The other possibilities with $n_\Sigma \neq 2$ give tree level neutrino masses from a combination of type I and type III seesaw without any remnant Z_2 symmetry.

Models with $U(1)_X$ charges $(3, 2, -5)$

Particle	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$U(1)_X$	Z_2
$(u, d)_L$	$(3, 2, \frac{1}{6})$	n_1	$+$
u_R	$(\bar{3}, 1, \frac{2}{3})$	$\frac{1}{4}(7n_1 - 3n_4)$	$+$
d_R	$(\bar{3}, 1, -\frac{1}{3})$	$\frac{1}{4}(n_1 + 3n_4)$	$+$
$(\nu, e)_L$	$(1, 2, -\frac{1}{2})$	n_4	$+$
e_R	$(1, 1, -1)$	$\frac{1}{4}(-9n_1 + 5n_4)$	$+$
N_R	$(1, 1, 0)$	$\frac{3}{8}(3n_1 + n_4)$	-
$\Sigma_{1R,2R}$	$(1, 3, 0)$	$\frac{3}{8}(3n_1 + n_4)$	-
S_{1R}	$(1, 1, 0)$	$\frac{2}{8}(3n_1 + n_4)$	$+$
S_{2R}	$(1, 1, 0)$	$-\frac{5}{8}(3n_1 + n_4)$	-
$(\phi^+, \phi^0)_1$	$(1, 2, -\frac{1}{2})$	$\frac{3}{4}(n_1 - n_4)$	$+$
$(\phi^+, \phi^0)_2$	$(1, 2, -\frac{1}{2})$	$\frac{1}{4}(9n_1 - n_4)$	$+$
$(\phi^+, \phi^0)_3$	$(1, 2, -\frac{1}{2})$	$\frac{1}{8}(9n_1 - 5n_4)$	-
χ_1	$(1, 1, 0)$	$-\frac{1}{2}(3n_1 + n_4)$	$+$
χ_3	$(1, 1, 0)$	$-\frac{3}{8}(3n_1 + n_4)$	-
χ_4	$(1, 1, 0)$	$-\frac{3}{4}(3n_1 + n_4)$	$+$

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[6] DB, R Adhikari, PLB 2014

The Model

- The additional fermionic fields in the model are just sufficient to cancel anomalies.
- The vacuum expectation values (vev) of the Higgs fields are denoted as $\langle \phi^0_{1,2} \rangle = v_{1,2}$, $\langle \chi^0_{1,4} \rangle = u_{1,4}$.
- Assuming no mixing between the electroweak gauge bosons and the extra $U(1)_X$ boson gives rise to

$$3(n_4 - n_1)v_1^2 = (9n_1 - n_4)v_2^2$$

  which implies $1 < n_4/n_1 < 9$.
- For zero mixing, the $U(1)_X$ gauge boson mass is

$$M_X^2 = 2g_X^2\left(-\frac{3M_W^2}{8g_2^2}(9n_1 - n_4)(n_1 - n_4) + \frac{1}{16}(3n_1 + n_4)^2(4u_1^2 + 9u_4^2)\right)$$

The Yukawa Lagrangian

The relevant part of the Yukawa Lagrangian is

$$\mathcal{L}_Y \supset y\bar{L}\Phi_1^\dagger S_{1R} + h_N \bar{L}\Phi_3^\dagger N_R + h_\Sigma \bar{L}\Phi_3^\dagger \Sigma_R + f_N N_R N_R \chi_4 + f_S S_{1R} S_{1R} \chi_1$$
$$+ f_\Sigma \Sigma_R \Sigma_R \chi_4 + f_{12} S_{1R} S_{2R} \chi_3^\dagger \qquad (1)$$

Tree Level Neutrino Mass

The tree-level neutrino mass matrix in the basis $(\nu_e, \nu_\mu, \nu_\tau, S_{1R}, S_{2R}, N_R)$is

$$M_f = \begin{pmatrix} 0 & 0 & 0 & y_1 v_1 & 0 & 0 \\ 0 & 0 & 0 & y_2 v_1 & 0 & 0 \\ 0 & 0 & 0 & y_3 v_1 & 0 & 0 \\ y_1 v_1 & y_2 v_1 & y_3 v_1 & f_S u_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & f_N u_4 \end{pmatrix} \tag{2}$$

One of the light neutrinos will acquire a tree level mass given by

$$m_{\nu 3} \approx \frac{2y^2 v_1^2}{f_S u_1}$$

Active Neutrino Mass at loop level

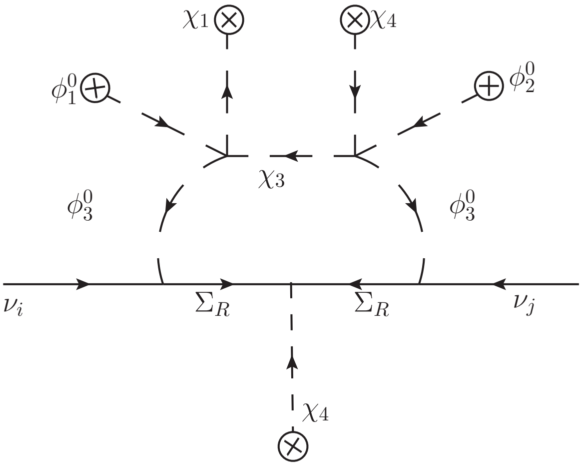


Figure: One-loop contribution to active neutrino mass

Active Neutrino Mass at loop level

The one-loop contribution $(M_\nu)_{ij}$ to 3×3 neutrino mass matrix is given by

$$(M_\nu)_{ij} \approx \frac{f_3 f_5 v_1 v_2 u_1 u_4}{16\pi^2} \sum_k h_{N,\Sigma_{ik}} h_{N,\Sigma_{jk}} \left(A_k + (B_k)_{ij} \right)$$

where $k = 1, 2, 3$ corresponds to different N_R

Active Neutrino Mass at loop level

$$A_k \;=\; (M_{N,\Sigma})_k \left[I\left(m_{\phi^0_{3R}}, m_{\phi^0_{3R}}, (M_{N,\Sigma})_k, m_{\chi_{3R}} \right) - I\left(m_{\phi^0_{3I}}, m_{\phi^0_{3I}}, (M_{N,\Sigma})_k, m_{\chi_{3R}} \right) \right],$$

$$(B_k)_{ij} = -(2-\delta_{ij})(M_{N,\Sigma})_k I\left(m_{\phi^0_{3R}}, m_{\phi^0_{3I}}, (M_{N,\Sigma})_k, m_{\chi_{3I}} \right),$$

$$I(a,a,b,c) = \frac{(a^4 - b^2c^2)\ln(a^2/c^2)}{(b^2-a^2)^2(c^2-a^2)^2} + \frac{b^2\ln(b^2/c^2)}{(c^2-b^2)(a^2-b^2)^2} - \frac{1}{(a^2-b^2)(a^2-c^2)},$$

$$\begin{aligned} I(a,b,c,d) \;=\; & \frac{1}{a^2-b^2}\left[\frac{1}{a^2-c^2}\left(\frac{a^2}{a^2-d^2}\ln(a^2/d^2) - \frac{c^2}{c^2-d^2}\ln(c^2/d^2) \right) \right. \\ - & \left. \frac{1}{b^2-c^2}\left(\frac{b^2}{b^2-d^2}\ln(b^2/d^2) - \frac{c^2}{c^2-d^2}\ln(c^2/d^2) \right) \right] \end{aligned}$$

Active Neutrino Mass at loop level

If all the scalar masses in the loop diagram are almost degenerate and written as m_{sc} then

$$A_k + (B_k)_{ij} \approx m_{2k} \left[\frac{m_{sc}^2 + m_{2k}^2}{m_{sc}^2 \left(m_{sc}^2 - m_{2k}^2\right)^2} - \frac{(2 - \delta_{ij})\; m_{2k}^2}{\left(m_{sc}^2 - m_{2k}^2\right)^3} \ln\left(m_{sc}^2 / m_{2k}^2\right) \right] ,$$

where $m_{2k} = (M_{N,\Sigma})_k$. And if all scalar and fermion masses in the loop are almost degenerate and written as m_{deg} then

$$A_k + (B_k)_{ij} \approx \frac{(2 - \delta_{ij})}{6 m_{deg}^3} \; .$$

Active Neutrino Mass at loop level

In this simplest approximation, the one loop contribution to neutrino mass is

$$(M_\nu)_{ij} \approx \frac{f_3 f_5 v_1 v_2 u_1 u_4}{16\pi^2} \sum_k h_{N,\Sigma_{ik}} h_{N,\Sigma_{jk}} \frac{(2-\delta_{ij})}{6 m_{deg}^3}$$

Taking $v_1, v_2 \sim 10^2$ GeV, one can have TeV scale $U(1)_X$ gauge symmetry $u_1 \sim u_4 \sim m_{deg} \sim 10^3$ GeV and correct order of neutrino mass $M_\nu \sim 0.1$ eV if

$$f_3 f_5 h_{N,\Sigma_{ik}} h_{N,\Sigma_{jk}} \sim 10^{-9}$$

Much better than TeV scale type I seesaw where Dirac Yukawa couplings are fine tuned to $Y_D Y_D \sim 10^{-11}$!

Sterile Neutrino Mass at loop level

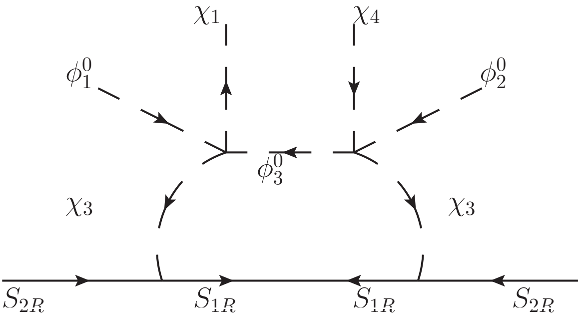


FIGURE: One-loop contribution to sterile neutrino mass

Sterile Neutrino Mass at loop level

Since S_{2R} corresponds to the fifth entry in the mass matrix shown earlier, we denote its mass term as $(M_f)_{55}$. The one-loop contribution to its mass can be written as

$$(M_f)_{55} \approx \frac{f_{12}^2 f_3 f_5 v_1 v_2 u_1 u_4}{16\pi^2} (A+B) \tag{3}$$

where A and B can be obtained by replacing $(M_{N,\Sigma})_k$ by $M_{S_{1R}}$ in A_k and B_k respectively. Constraints on the couplings are similar to the ones for active neutrinos.

Active-Sterile Mixing at loop level

- For the minimal field content shown earlier, the sterile neutrino S_{2R} acquires a small mass at loop level but does not have any mixing with the active neutrinos at tree/loop level.
- Such a sterile neutrino can still contribute to the radiation content of the Universe, but won't show up in neutrino oscillation experiments.
- Since S_{2R} is Z_2-odd, the only way it can mix with the active neutrinos is by breaking the remnant Z_2 symmetry.
- We introduce a new scalar singlet field ζ with $U(1)_X$ charge $\frac{5}{8}(3n_1 + n_4)$ which a tree level mixing term of N_R and S_{1R} which effectively allow one loop mixing between active and sterile neutrino.

Active-Sterile Mixing at loop level

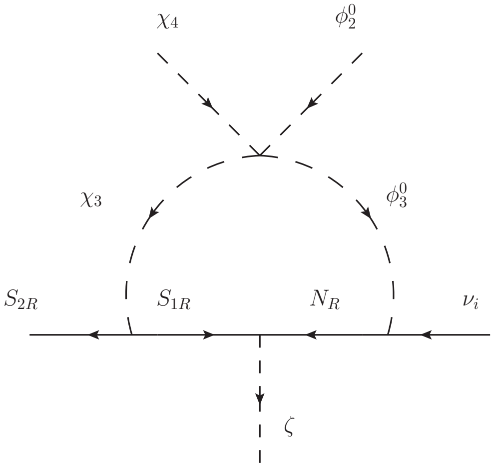


Figure: One-loop contribution to active-sterile neutrino mixing

Active-Sterile Mixing at loop level

The mixing term corresponding to the above diagram can be estimated as

$$(M_f)_{5j} = (M_f)^*_{j5} \approx \sum_k \frac{f_{12} f_5 v_2 u_4 (h_{N,\Sigma})_{kj} M_X}{16\pi^2} \left[I\left(m_{\chi_{3R}}, m_{\phi^0_{3R}}, M_X\right) - I\left(m_{\chi_{3I}}, m_{\phi^0_{3I}}, M_X\right)\right.$$

where $j, k = 1, 2, 3$ and k corresponds to different N_R. M_X is the $U(1)_X$ symmetry breaking scale and we have assumed $M_{S_{1R}} \sim M_{N_R} \sim M_{\Sigma_R} \sim M_X$ and

$$I(a, b, c) = \frac{a^2 b^2 \ln(a^2/b^2) + b^2 c^2 \ln(b^2/c^2) + c^2 a^2 \ln(c^2/a^2)}{(a^2 - b^2)(b^2 - c^2)(c^2 - a^2)}$$

Active-Sterile Mixing at loop level

If we consider $m_{\chi_{3R}} \sim m_{\phi^0_{3R}}$ and/or $m_{\chi_{3I}} \sim m_{\phi^0_{3I}}$ then to get $(M_f)_{5j}$ one is required to consider $I\,(a, a, c)$ which is given by

$$I\,(a, a, c) = \frac{1}{(a^2 - c^2)^2}\left(a^2 - c^2 - c^2 \ln(a^2/c^2)\right)$$

Assuming $m_{\chi_{3R}} \sim m_{\chi_{3I}} \ll M_X$, we have

$$(M_f)_{5j} \approx \sum_k \frac{f_{12} f_5 v_2 u_4 (h_{N,\Sigma})_{kj} M_X}{16\pi^2 M_X^4}\left[m^2_{\chi_{3R}} - m^2_{\chi_{3I}} - M_X^2 \ln(m^2_{\chi_{3R}}/m^2_{\chi_{3I}})\right]$$

Active-Sterile Mixing at loop level

Writing $m_{\chi_3} = (m_{\chi_{3R}} + m_{\chi_{3I}})/2$ and assuming the Yukawa couplings to be real

$$(M_f)_{15} \approx \sum_k \frac{f_{12} f_5 v_2 u_4 (h_{N,\Sigma})_{1k}}{16\pi^2 M_X m^2_{\chi_3}} \left[m^2_{\chi_{3R}} - m^2_{\chi_{3I}} \right]$$

For $(M_f)_{25}$ in the above expression $(h_{N,\Sigma})_{1k}$ will be replaced by $(h_{N,\Sigma})_{2k}$. As $A + B \approx 1/(m^2_{\chi_3} M_X)$

$$(M_f)_{55} \approx \frac{f^2_{12} f_3 f_5 v_1 v_2 u_1 u_4}{16\pi^2 m^2_{\chi_3} M_X}$$

If we consider $(h_{N,\Sigma})^2_{1k} \sim (h_{N,\Sigma})^2_{2k} \ll f^2_{12}$ then $(M_f)_{11} \sim (M_f)_{22} \ll (M_f)_{55}$ and we can write the active sterile mixing angles as

$$\tan 2\theta_{e5} = \frac{2(M_f)_{15}}{(M_f)_{55}}; \quad \tan 2\theta_{\mu 5} = \frac{2(M_f)_{25}}{(M_f)_{55}}$$

Active-Sterile Mixing at loop level

The $(1, 4)$ element of the mixing matrix as

$$|U_{e4}| \sim \sin\theta_{e5} \approx \frac{1}{2}\tan 2\theta_{e5} = \sum_k \frac{(h_{N,\Sigma})_{1k}}{f_{12} f_3 v_1 u_1}\left[m^2_{\chi_{3R}} - m^2_{\chi_{3I}}\right]$$

To get $|U_{\mu 4}|$ in the above expression $(h_{N,\Sigma})_{1k}$ is to be replaced by $(h_{N,\Sigma})_{2k}$. For $h_{N,\Sigma} \sim 1, f_{12} f_3 \sim 10^{-5}, v_1 \sim 10^2$ GeV, $u_1 \sim 1$ TeV, $(m^2_{\chi_{3R}} - m^2_{\chi_{3I}}) \approx 0.1$ GeV^2 one can get $|U_{e4}| \sim 0.1$ as required from global fit data.

Models with $U(1)_X$ charges $(-6, 1, 5)$

Particle	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$U(1)_X$	Z_2
N_R	$(1,1,0)$	$-\frac{6}{8}(3n_1+n_4)$	+
$\Sigma_{1R,2R}$	$(1,3,0)$	$\frac{3}{8}(3n_1+n_4)$	-
S_{1R}	$(1,1,0)$	$\frac{5}{8}(3n_1+n_4)$	-
S_{2R}	$(1,1,0)$	$\frac{1}{8}(3n_1+n_4)$	-
$(\phi^+,\phi^0)_1$	$(1,2,-\frac{1}{2})$	$\frac{3}{4}(n_1-n_4)$	+
$(\phi^+,\phi^0)_2$	$(1,2,-\frac{1}{2})$	$\frac{1}{4}(9n_1-n_4)$	+
$(\phi^+,\phi^0)_3$	$(1,2,-\frac{1}{2})$	$\frac{1}{8}(9n_1-5n_4)$	-
ξ	$(1,3,0)$	$\frac{9}{8}(3n_1+n_4)$	-
χ_1	$(1,1,0)$	$-\frac{1}{2}(3n_1+n_4)$	+
χ_2	$(1,1,0)$	$-\frac{1}{4}(3n_1+n_4)$	+
χ_3	$(1,1,0)$	$-\frac{3}{8}(3n_1+n_4)$	-
χ_4	$(1,1,0)$	$-\frac{3}{4}(3n_1+n_4)$	+
χ_5	$(1,1,0)$	$\frac{9}{4}(3n_1+n_4)$	+

[7]

[7] R Adhikari, DB, E Ma (2014)

Sterile Neutrino Mass

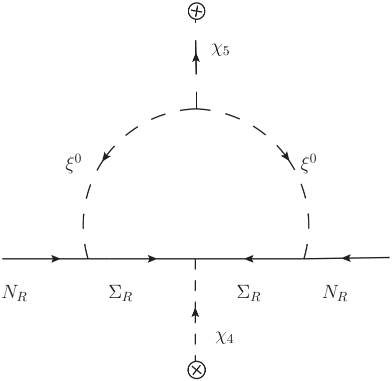


Figure: One-loop contribution to sterile neutrino mass

Active Sterile Neutrino Mixing

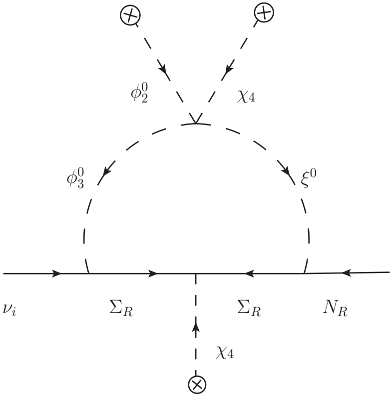


Figure: One-loop contribution to active-sterile neutrino mixing

Models with $U(1)_X$ charges $(-6, 1, 5)$

particle	a_1	a_4	Z_2
$(u,d)_L$	1	0	+
u_R	7/4	–3/4	+
d_R	1/4	3/4	+
$(\nu, l)_L$	0	1	+
l_R	-9/4	5/4	+
$\Sigma_{1R,2R}$	9/8	3/8	–
N_R	-18/8	-6/8	+
S_{1R}	3/8	1/8	–
S_{2R}	15/8	5/8	–
ϕ	3/4	–3/4	+
η_1	3/8	–7/8	–
η_2	9/8	–5/8	–
χ_1^0	3/4	1/4	+
χ_2^0	9/4	3/4	+
χ_3^0	3/8	1/8	–
χ_4^+	3/8	–15/8	–
$\xi^{(++,+,0)}$	9/8	–13/8	–

TABLE: Particle content of proposed model with $U(1)_X$ assignment given by $a_1 n_1 + a_4 n_4$ where $3n_1 + n_4 \neq 0$ (R Adhikari, DB, E Ma, PLB 2016)

Model with Radiative Lepton Masses

The relevant Yukawa couplings of the fermions can be written as a part of the Yukawa Lagrangian

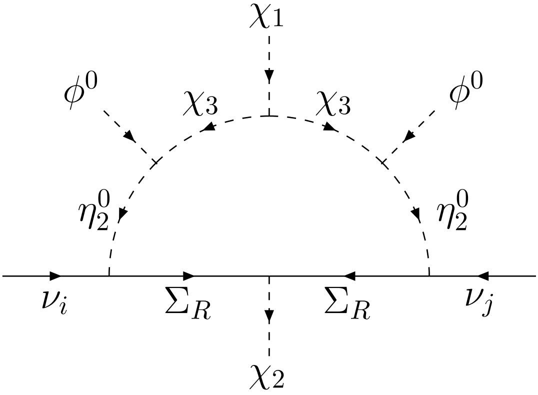
$$\mathcal{L}_Y \supset y_{1i}\bar{S_1}_R L_i \eta_1 + y_{2i}\bar{\Sigma}_R L_i \eta_2 + y_{3j} S_{2R} l_{jR} \chi_4 + y_{4j} \Sigma_R l_{jR} \xi + f_1 \Sigma_R \Sigma_R \bar{\chi}_2$$

$$+ f_2 S_{1R} S_{1R} \bar{\chi}_1 + f_3 S_{1R} S_{2R} \bar{\chi}_2 + f_4 N_R S_{2R} \chi_3$$

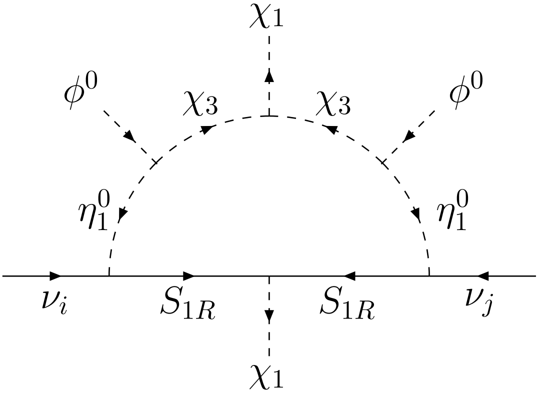
The part of the scalar Lagrangian relevant for discussion on lepton masses is

$$V_s \supset \mu_1 \Phi^\dagger \eta_2 \bar{\chi}_3 + \mu_2 \Phi^\dagger \eta_1 \chi_3 + \mu_3 \chi_3 \chi_3 \bar{\chi}_1 + \lambda_1 \Phi^\dagger \eta_1 \chi_1 \bar{\chi}_3 + \lambda_2 \Phi^\dagger \eta_1^\dagger \chi_4 \chi_1$$
$$+ \lambda_3 \Phi^\dagger \eta_2^\dagger \xi \chi_1$$

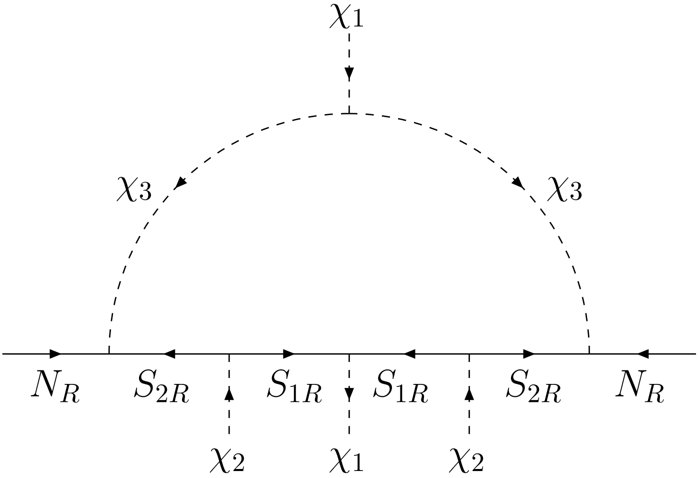
Active Neutrino Masses



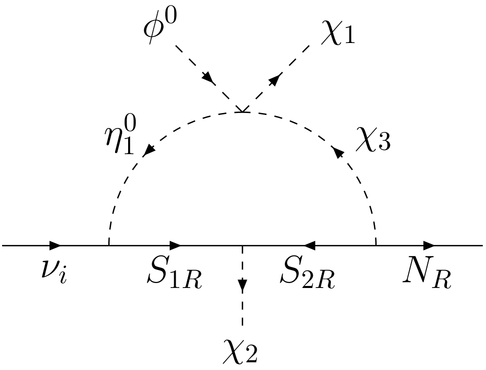
Active Neutrino Masses



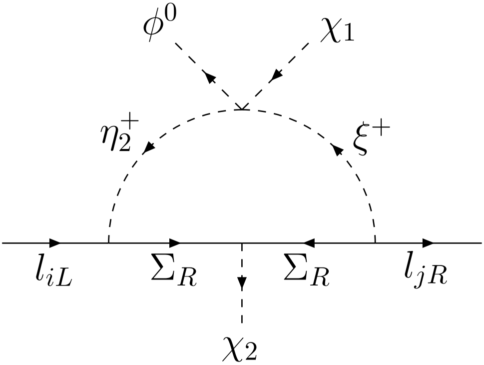
Sterile Neutrino Mass



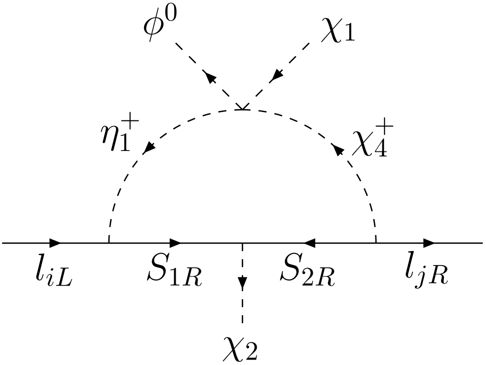
Active-Sterile Neutrino Mixing



Charged Lepton Masses



Charged Lepton Masses



Concluding Remarks

- Abelian versions of scotogenic models can naturally accommodate light sterile neutrinos and their mixing with active neutrinos at one loop level.
- Similar ideas can also be implemented in non-abelian gauge extensions of the standard model say, Left-Right Symmetric Models.
- The sterile neutrinos at eV scale can have interesting implications at neutrino oscillation experiments if they sufficiently mix with the active neutrinos.
- Sterile neutrinos at keV scale can be a good warm dark matter candidate.
- In both of these cases, the lightest Z_2 odd particle can always be a cold dark matter candidate.
- Such mixed dark matter scenario could be interesting from structure formation point of view.

Concluding Remarks

- Light Sterile neutrinos can significantly affect the predictions for neutrinoless double beta decay (Giradi, Meroni & Petcov'2013).
- Light Sterile neutrinos can also affect the predictions for usual thermal leptogenesis (Hannestad, Hansen & Tram'2013).
- Light Sterile neutrinos also allow more possibilities of texture zeros in the light neutrino mass matrix. For example, in the 3×3 active neutrino block, one can have three (Y. Zhang, PRD 2013) or four zero (arXiv:1606.02076) textures in the presence of sterile neutrinos whereas only upto two zero textures are allowed in three light neutrino scenarios.
- Scotogenic Models can also give new sources of lepton flavor violation (Toma & Vicente'2014; Vicente & Yaguna'2015)
- A viable model to implement TeV scale WIMPy Leptogenesis (arXiv:1605.01292).

Concluding Remarks

- Minimal scotogenic models suffer from a hierarchy type problem that can spoil the phenomenological success of the model: RGE contributions from heavy Majorana neutrinos to the mass parameters of the Z_2 odd scalar fields could turn them negative at some energy scale breaking the Z_2 symmetry and loss of CDM candidate (Merle & Platscher'2015).
- This can be prevented if the physical Z_2-odd scalar masses are restricted to a certain ranges, typically of the order of the heaviest Majorana neutrino: can be satisfied in our models as well.

THANK YOU