Sterile Neutrinos: Induced Mass Versus Direct Mixing Effects of Active Neutrinos

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Effects of New Neutrino States

Neutrino Neutrality Opens Unique Possibility
- can have Majorana mass terms
- can mix with singlets of the SM symmetry group

Effects of Mixing with Sterile
- **direct:** produce dynamical effects on $\nu$ conversion
- **indirect:** modify the mass matrix of active neutrinos

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No clear observational evidences exist. But . . .

There are some interesting hints . . .

- LSND result as (3+1) or (3+2) oscillations (MiniBooNE)
- keV neutrinos may be (Warm) Dark Matter
- Observed velocities of pulsars
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Suppose active neutrinos $\nu_a = (\nu_e, \nu_\mu, \nu_\tau)^T$ acquire (eg. via seesaw) the Majorana mass matrix

$$m_a = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\tau\mu} & m_{\tau\tau} \end{pmatrix}$$

Assume:

- $m_a \leq 1$ eV
- active $\nu$ mix with a single sterile $S$ via $m_{aS}^T = (m_{eS}, m_{\mu S}, m_{\tau S})$
- $S$: mass, mixing, new symmetries... (New Physics)
- $m_S \gg m_{\alpha S}, m_a$
Induced Mass Matrix

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Induced Mass Matrix

In the basis \((\nu_a, S)\)

\[
\begin{pmatrix}
  m_a & m_{aS} \\
  m^T_{aS} & m_S
\end{pmatrix}
\]

so since \(m_S \gg m_{\alpha S}, m_a\) after block diagonalization the light neutrinos mass matrix becomes

\[
m_\nu \approx m_a + m_I
\]

where

\[
m_I \equiv -\frac{1}{m_S} (m_{aS}) \times (m_{aS})^T
\]

is the induced mass matrix due to active-sterile mixing
Defining the active - sterile mixing angles

\[ \sin \theta_{jS} \approx \frac{m_{jS}}{m_S} \]

we can write the induced masses as

\[ (m_I)_{ij} = - \sin \theta_{iS} \sin \theta_{jS} m_S \]

combination of parameters which determines physical effects

For flavor blind mixing \( \Rightarrow m_I = - \sin^2 \theta_S m_S \)
Induced Mass Matrix

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For flavor blind mixing \( \Rightarrow \quad m_I = - \sin^2 \theta_S m_S \)
The neutrino mass matrix elements in the flavor basis:

\[ m_{\alpha\beta} = m_1 e^{-i2\lambda_1} U_{\alpha_1}^{*} U_{\beta_1}^{*} + m_2 U_{\alpha_2}^{*} U_{\beta_2}^{*} + m_3 e^{-i2\lambda_3} U_{\alpha_3}^{*} U_{\beta_3}^{*} \]

with \( \alpha, \beta = e, \mu, \tau \) and \( \Delta m^2_{ij} = m_i^2 - m_j^2 \)

CP-violating phases: \( 0 \leq \lambda_i \leq \pi \) and \( 0 \leq \delta \leq \pi/2 \)

\[ U_{\alpha i}(\theta_{12}, \theta_{13}, \theta_{23}, \delta) = \text{PMNS matrix elements} \]
Reconstructed Neutrino Mass Matrix

use best fit values to reconstruct mass matrix from data

\[ |\Delta m^2_{32}| = 2.4 \left(1.00 \pm 0.11\right) \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m^2_{21} = 7.92 \left(1.00 \pm 0.045\right) \times 10^{-5} \text{ eV}^2 \]

\[ \sin^2 \theta_{23} = 0.44 \left(1.00 \pm 0.21\right) \quad \sin^2 \theta_{12} = 0.314 \left(1.00 \pm 0.09\right) \]

\[ \sin^2 \theta_{13} = 0.9 \left(1.0 \pm 3.1\right) \times 10^{-2} \]

Normal Hierarchy (in meV)

\[ m_3 = \sqrt{\Delta m_{31}^2} > m_2 = \sqrt{\Delta m_{21}^2} > m_1 = 0 \]

<table>
<thead>
<tr>
<th>Best Fit</th>
<th>[ m_\nu = \begin{pmatrix} 3.2 &amp; 6.0 &amp; 0.6 \ 24.8 &amp; 21.4 &amp; 30.7 \end{pmatrix} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. Allowed (1σ)</td>
<td>[ m_\nu = \begin{pmatrix} 2.5 - 5.0 &amp; 2.7 - 9.8 &amp; 0. - 5.1 \ 19.9 - 30.3 &amp; 18.1 - 22.9 &amp; 24.5 - 34.0 \end{pmatrix} ]</td>
</tr>
<tr>
<td>Free CP phases</td>
<td>[ m_\nu = \begin{pmatrix} 0.3 - 5.0 &amp; 0. - 10.8 &amp; 0. - 11.1 \ 12.7 - 30.9 &amp; 18.5 - 29.4 &amp; 16.7 - 34.5 \end{pmatrix} ]</td>
</tr>
</tbody>
</table>

\[ \delta m_{ee} \sim 2.5 \text{ meV} \quad \delta m_{e\mu, e\tau, \mu\tau} \sim 5 \text{ meV} \quad \delta m_{\mu\mu, \tau\tau} \sim 10 \text{ meV} \]
### Inverted Hierarchy (in meV)

$$m_2 \sim m_1 \sim \sqrt{\left| \Delta m^2_{31} \right|} > m_3 = 0$$

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<tr>
<th>Best Fit</th>
<th>( m_\nu = \begin{pmatrix} 48.0 &amp; 2.8 &amp; 3.7 \ 27.4 &amp; 24.0 &amp; 21.7 \end{pmatrix} )</th>
</tr>
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<td>Exp. (1( \sigma ))</td>
<td>( m_\nu = \begin{pmatrix} 43.2 - 51.0 &amp; 0. - 8.6 &amp; 0. - 9.2 \ 21.3 - 31.9 &amp; 21.3 - 25.6 &amp; 17.8 - 28.2 \end{pmatrix} )</td>
</tr>
<tr>
<td>Free CP phases</td>
<td>( m_\nu = \begin{pmatrix} 11.4 - 51.0 &amp; 0. - 39.0 &amp; 0. - 36.7 \ 0. - 32.1 &amp; 4.6 - 26.7 &amp; 0. - 28.2 \end{pmatrix} )</td>
</tr>
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\( \delta m \sim (8 - 10)\) meV but \( \delta m_{\mu\tau} \sim 4\) meV
### Degenerate Mass Spectrum (in meV)

\[ m_1 \sim m_2 \sim m_3 \sim m_0 = 0.2 \text{ eV} \]

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<td><strong>Best Fit</strong></td>
<td>( \begin{pmatrix} 200.0 &amp; 0.5 &amp; 0.4 \ 202.7 &amp; 2.9 &amp; \ 203.5 &amp; \end{pmatrix} )</td>
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<td><strong>Exp. (1( \sigma ))</strong></td>
<td>( \begin{pmatrix} 200.1 - 200.3 &amp; 0.06 - 1.0 &amp; 0. - 1.0 \ 202.1 - 203.6 &amp; 2.4 - 3.3 &amp; \end{pmatrix} )</td>
</tr>
<tr>
<td><strong>Free CP phases</strong></td>
<td>( \begin{pmatrix} 60.0 - 200.3 &amp; 0. - 176.6 &amp; 0. - 170.3 \ 0.02 - 203.6 &amp; 0.5 - 200.3 &amp; \end{pmatrix} )</td>
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\[ \delta m \sim 1 \text{ meV} \quad \text{but strong effect of CP phases} \quad \delta m \sim m_0 \]
S Can Generate Tri-Bimaximal Mixing Matrix

Experimental Results are in good agreement with the so-called tri-bimaximal mixing matrix

$$U_{\text{tbm}} = U^{m}_{23} U^{12} = \frac{1}{\sqrt{6}} \begin{pmatrix} 2 & \sqrt{2} & 0 \\ -1 & \sqrt{2} & \sqrt{3} \\ 1 & -\sqrt{2} & \sqrt{3} \end{pmatrix}$$

$$\sin^2 \theta_{13} = 0$$
$$\sin^2 \theta_{23} = \cos^2 \theta_{23} = 1/2$$
$$\sin^2 \theta_{12} = 1/3$$
S Can Generate Tri-Bimaximal Mixing Matrix

mass matrix which generates tri-bimaximal in normal hierarchy

\[
m_{\nu} = \frac{\sqrt{|\Delta m_{32}^2|}}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix} + \frac{\sqrt{|\Delta m_{21}^2|}}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}
\]

both can be induced by $\nu - S$ mixing

dominant matrix by mixing with $S$

\[m_{\alpha S} = m_0(0, 1, -1)\]

so

\[m_S \sin^2 \theta_S = \frac{\sqrt{|\Delta m_{32}^2|}}{2} \approx 25 \text{ meV}\]

sub-dominant matrix by universal mixing with $S'$

\[m_{\alpha S'} = m'_0(1, 1, 1)\]

so

\[m'_S \sin^2 \theta'_S = \frac{\sqrt{|\Delta m_{21}^2|}}{3} \approx 3 \text{ meV}\]

$m_a$ should be very small $\sim v_{EW}^2 / M_{Pl}$
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both can be induced by \( \nu - S \) mixing
dominant matrix by mixing with \( S \)

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sub-dominant matrix by universal mixing with \( S' \)

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\]

\( m_a \) should be very small \( \sim v_{\text{EW}}^2/M_{\text{Pl}} \)
Single $S$: induced matrix $m_I$ is singular cannot reproduce the dominant structures for degenerate $(\det m \approx m_0^3)$ or inverted mass hierarchy (two dominant eigenvalues and determinant of 1-2 submatrix in non-zero)

S can be the origin of the dominant block only in the case of normal mass hierarchy!
S Can Switch Normal ⇔ Inverted Mass Hierarchy

\[ m_\nu^{\text{inv}} \sim \sqrt{2} m_\nu^{\text{norm}} - \sqrt{\frac{\Delta m^2_{32}}{2}} D \]

induced term \( D \) is close to the democratic matrix with all elements being nearly 1
Sterile Giving Negligible Contributions

\( m_1 \) becomes irrelevant if

\[ \frac{m_i S m_j S}{m_S} \ll (m_a)_{ij} \]

Effect of \( S \) below \( 1\sigma \) spread of matrix elements

### Normal Mass Hierarchy

\[
\sin^2 \theta_{eS} m_S < 2 \text{ meV} \quad \sin^2 \theta_{\mu S} m_S, \quad \sin^2 \theta_{\tau S} m_S < 5 \text{ meV}
\]

### Inverted Mass Hierarchy

\[
\sin^2 \theta_{eS} m_S < 8 \text{ meV} \quad \sin^2 \theta_{\mu S} m_S < 4 \text{ meV}
\]

but \( \sin^2 \theta_S m_S < 20 \text{ meV} \) (phase)

### Degenerate Spectrum

\[
\sin^2 \theta_{eS} m_S < 1 \text{ meV} \quad \text{but} \quad \sin^2 \theta_S m_S \sim 200 \text{ meV} \) (phase)
Some Benchmarks

\[ \sin^2 \theta_{\alpha S} m_S < 1 \text{ meV} \] (1)
below 1\(\sigma\) experimental uncertainties for hierarchical spectra can influence sub-leading structure in degenerate spectrum

\[ \sin^2 \theta_{\alpha S} m_S < 3 \text{ meV} \] (2)
can generate sub-leading structures in hierarchical spectra

\[ \sin^2 \theta_{\alpha S} m_S < 30 \text{ meV} \] (3)
can generate dominant structures in hierarchical spectra
Some Benchmarks

\[ \sin^2 \theta_{\alpha S} m_S < 0.5 \text{ eV} \quad (4) \]

maximal allowed value for matrix elements from data
Astrophysical, Cosmological and Laboratory Bounds on $\nu_e - \nu_S$ Mixing

$S$ thermalized before BBN

$m_S \sin^2 \theta_S > 0.6 \text{ meV}$

LSS: gives bound on $\rho_S(m_S)$

X-ray: $S \rightarrow \nu_a \gamma$ with $E_\gamma \approx m_S/2$

CMB: $N_\nu < 3.74$ (WMAP+LSS+SN)

BBN: low and high mass region

SN: $\bar{\nu}_e$-disapp. and star cooling

Accelerator: Violation of Lepton Universality + FCNC + LEP
Astrophysical, Cosmological and Laboratory Bounds on $\nu_\mu - \nu_S$ Mixing

$S$ thermalized before BBN

$m_S \sin^2 \theta_S > 0.4$ meV

LSS: gives bound on $\rho_S(m_S)$

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Accelerator: Violation of Lepton Universality + FCNC + LEP
Astrophysical, Cosmological and Laboratory Bounds on $\nu_{\tau} - \nu_S$ Mixing

- $S$ thermalized before BBN
  - $m_s \sin^2 \theta_S > 0.4$ meV

- LSS: gives bound on $\rho_S(m_S)$
- X-ray: $S \rightarrow \nu_a \gamma$ with $E_\gamma \approx m_S/2$
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$V_s \leftrightarrow \nu_{\tau}$
Regions where $m_I$ effect is greater than direct mixing:

**High Mass Window:** $m_S \gtrsim 300$ MeV and $\sin^2 \theta_S \lesssim 10^{-9}$

- restricted by CMB, meson decays and SN1987A cooling
- future measurements may improve bound by a factor 10
- $\nu_e - \nu_S$: $0\nu\beta\beta$ can probe the whole region
- other channels: $m_I$ gives the bound $(\sin^2 \theta_{\alpha S} m_S \lesssim 0.5$ eV)
- bounds dominant contribution to degenerate spectrum
- contributions out of control: can create ambiguity in implications of mass and mixing results
Confronting Benchmarks with Experimental Bounds

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**Low Mass Window:** $m_S \sim (0.1 - 0.3)$ eV and $\sin^2 \theta_S = 10^{-3} - 10^{-1}$

- closed for all channels by BBN $\Delta N_\nu < 1 \Rightarrow m_I < 1$ meV
- limited by LSS from above
- if $\Delta N_\nu = 1$ is allowed bounds depend on flavor
  - $\nu_e - \nu_S$: reactor & atmospheric $\nu$ exclude dominant $m_I$
  - $\nu_\mu - \nu_S$: atmospheric $\nu$ allow larger regions: e.g. $m_I \sim 10$ meV
  - $\nu_\tau - \nu_S$: bound weaker, allowing for dominant contributions $m_I \sim (30 - 250)$ meV
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- for $m_S = (10^{-3} - 10^5) \text{ keV}$ effects of direct mixing dominate

  $$m_I \lesssim 4 \cdot 10^{-2} \text{ meV}$$

  only very small corrections to $m_a$ can be produced

- for $m_S = (1 - 10^4) \text{ keV}$ bound even stronger

  $$m_I \lesssim 10^{-2} \text{ meV}$$
if $T_R << 100 \text{ MeV}$ the experimental bounds on $\nu - S$ mixing are relaxed


Sterile neutrino required to explain LSND result is allowed here
Stronger effects of $m_1$ possible
if \( S \) has a *soft mass* generated by a medium dependent VEV of some new scalar field \( A \) the experimental bounds on \( \nu - S \) mixing are relaxed


\[
m_S = \lambda \langle A \rangle \quad \text{and} \quad \langle A \rangle \propto n_\nu \quad \text{(number density of active \( \nu \))}
\]

\[
m_S = m_S^0 (1 + z)^3
\]

\[
m_I = \frac{m_{IS}^2}{m_S^0 (1 + z)^3} = m_I^0 (1 + z)^{-3}
\]

mixing mass \( m_{IS} \) is constant in time
if $S$ has a soft mass generated by a medium dependent VEV of some new scalar field $A$ the experimental bounds on $\nu - S$ mixing are relaxed.


So

$$\sin \theta_S = \frac{m_{iS}}{m_S^0(1 + z)^3} = \sin \theta_S^0(1 + z)^{-3}$$

$$\sin^2 \theta_S m_S = \frac{\sin^2 \theta_S^0 m_S^0}{(1 + z)^3}$$

in the past all cosmological bounds were satisfied.
Avoiding Bounds
Sterile Interacts with massless or low-mass Majoron

if $S \rightarrow \nu \phi$ (or annihilate) fast enough ($\tau_S \ll 1 \text{s}$) all astrophysical and cosmological bounds could be evaded

if $m_S \sim 1 \text{keV}$ such a fast decay can be achieved for the scalar coupling $g \sim 10^{-8}$

Summary

- $S - \nu$ mixing generate $m_I$ which can be the origin of dominant or sub-dominant structures in $m_\nu$
- Direct mixing effects of $S$ can be observed in cosmology, astrophysics and laboratory experiments
- For $m_S \gtrsim 300$ MeV $m_I$ effects dominate
- For $m_S \sim (10^{-3} - 10^5)$ keV direct mixing effects dominate
- For $m_S \sim (0.1 - 0.3)$ eV the two effects are comparable
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