Sterile Neutrinos:

Direct Mixing Effects Versus Induced Mass Matrix 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 ν conversion
- indirect: modify the mass matrix of active neutrinos

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Experimental Evidences of Sterile?

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
- Early reionization of the universe due S radiative decay

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Induced Mass Matrix

Suppose active neutrinos $\nu_a = (\nu_e, \nu_\mu, \nu_\tau)^T$ acquire (*eg.* via seesaw) the Majorana mass matrix

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

Assume:

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

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Induced Mass Matrix

In the basis (ν_a, S)

$$\begin{pmatrix} \mathbf{m_a} & m_{aS} \\ m_{aS}^T & m_S \end{pmatrix}$$

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

$$\mathbf{m}_\nu \approx \mathbf{m_a} + \mathbf{m_l}$$

where

$$\mathbf{m_l} \equiv -\frac{1}{m_S}(m_{aS}) \times (m_{aS})^T$$

is the induced mass matrix due to active-sterile mixing

Induced Mass Matrix

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 $\Rightarrow$ $m_I = -\sin^2\theta_S\, m_S$

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Reconstructed Neutrino Mass Matrix

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 $\Delta m^2_{ij} = m^2_i - m^2_j$

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

$U_{\alpha i}(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ = PMNS matrix elements

Reconstructed Neutrino Mass Matrix

use best fit values to reconstruct mass matrix from data

$$|\Delta m^2_{32}| = 2.4 \left(1.00 \ {}^{+0.11}_{-0.13}\right) \times 10^{-3}\ \mathrm{eV}^2$$

$$\Delta m^2_{21} = 7.92\,(1.00 \pm 0.045) \times 10^{-5}\ \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.44\,(1.00 \ {}^{+0.21}_{-0.11}) \qquad \sin^2\theta_{12} = 0.314 \left(1.00^{+0.09}_{-0.075}\right)$$

$$\sin^2\theta_{13} = 0.9 \left(1.0 \ {}^{+3.1}_{-0.9}\right) \times 10^{-2}$$

G.L. Fogli, E. Lisi, A. Marrone, A. Palazzo, arXiv:hep-ph/0506083

Normal Hierarchy (in meV)

$$m_3 = \sqrt{\Delta m^2_{31}} > m_2 = \sqrt{\Delta m^2_{21}} > m_1 = 0$$

Best Fit	$\mathbf{m}_\nu = \begin{pmatrix} 3.2 & 6.0 & 0.6 \\ & 24.8 & 21.4 \\ & & 30.7 \end{pmatrix}$
Exp. Allowed $(1\,\sigma)$	$\mathbf{m}_\nu = \begin{pmatrix} 2.5-5.0 & 2.7-9.8 & 0.-5.1 \\ & 19.9-30.3 & 18.1-22.9 \\ & & 24.5-34.0 \end{pmatrix}$
Free CP phases	$\mathbf{m}_\nu = \begin{pmatrix} 0.3-5.0 & 0.-10.8 & 0.-11.1 \\ & 12.7-30.9 & 18.5-29.4 \\ & & 16.7-34.5 \end{pmatrix}$

$$\delta m_{ee} \sim 2.5\,\text{meV} \quad \delta m_{e\mu,e\tau,\mu\tau} \sim 5\,\text{meV} \quad \delta m_{\mu\mu,\tau\tau} \sim 10\,\text{meV}$$

Inverted Hierarchy (in meV)

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

Best Fit	$\mathbf{m}_\nu = \begin{pmatrix} 48.0 & 2.8 & 3.7 \\ & 27.4 & 24.0 \\ & & 21.7 \end{pmatrix}$
Exp. $(1\,\sigma)$	$\mathbf{m}_\nu = \begin{pmatrix} 43.2-51.0 & 0.-8.6 & 0.-9.2 \\ & 21.3-31.9 & 21.3-25.6 \\ & & 17.8-28.2 \end{pmatrix}$
Free CP phases	$\mathbf{m}_\nu = \begin{pmatrix} 11.4-51.0 & 0.-39.0 & 0.-36.7 \\ & 0.-32.1 & 4.6-26.7 \\ & & 0.-28.2 \end{pmatrix}$

$\delta m \sim (8-10)\,\text{meV}$ but $\delta m_{\mu\tau} \sim 4\,\text{meV}$

Degenerate Mass Spectrum (in meV)

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

Best Fit	$\mathbf{m}_\nu = \begin{pmatrix} 200.0 & 0.5 & 0.4 \\ & 202.7 & 2.9 \\ & & 203.5 \end{pmatrix}$
Exp. $(1\,\sigma)$	$\mathbf{m}_\nu = \begin{pmatrix} 200.1 - 200.3 & 0.06 - 1.0 & 0. - 1.0 \\ & 202.1 - 203.6 & 2.4 - 3.3 \\ & & 202.5 - 204.1 \end{pmatrix}$
Free CP phases	$\mathbf{m}_\nu = \begin{pmatrix} 60.0 - 200.3 & 0. - 176.6 & 0. - 170.3 \\ & 0.02 - 203.6 & 0.5 - 200.3 \\ & & 0.02 - 204.1 \end{pmatrix}$

$\delta m \sim 1\,\text{meV}$ but strong effect of CP phases $\delta m \sim m_0$

S Can Generate Tri-Bimaximal Mixing Matrix

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

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

$\sin^2\theta_{13} = 0$
$\sin^2\theta_{23} = \cos^2\theta_{23} = 1/2$
$\sin^2\theta_{12} = 1/3$

S Can Generate Tri-Bimaximal Mixing Matrix

mass matrix which generates tri-bimaximal in normal hierarchy

$$\mathbf{m}_\nu = \frac{\sqrt{|\Delta m^2_{32}|}}{2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix} + \frac{\sqrt{\Delta m^2_{21}}}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

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

dominant matrix by mixing with S

$$m_{\alpha S} = m_0(0,1,-1) \quad \text{so} \quad m_S \sin^2\theta_S = \frac{\sqrt{|\Delta m^2_{32}|}}{2} \approx 25 \text{ meV}$$

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

$$m_{\alpha S'} = m'_0(1,1,1) \quad \text{so} \quad m'_S \sin^2\theta'_S = \frac{\sqrt{\Delta m^2_{21}}}{3} \approx 3 \text{ meV}$$

m_a should be very small $\sim v^2_{\rm EW}/M_{\rm Pl}$

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S Cannot Always Generate The Dominant Block

Single S: induced matrix $\mathbf{m}_I$ is singular

cannot reproduce the dominant structures for degenerate $(\mathrm{Det}\,\mathbf{m} \approx m_0^3)$ 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 $\Leftrightarrow$ Inverted Mass Hierarchy

$$\mathbf{m}_\nu{}^{\mathrm{inv}} \sim \sqrt{2}\,\mathbf{m}_\nu^{\mathrm{norm}} - \sqrt{\frac{|\Delta m^2_{32}|}{2}}\mathbf{D}$$

induced term **D** is close to the *democratic matrix* with all elements being nearly 1

Sterile Giving Negligeable Contributions

$\mathbf{m_I}$ becomes irrelevant if $\frac{m_{iS} m_{jS}}{m_S} \ll (m_a)_{ij}$

Effect of S below 1σ spread of matrix elements

Normal Mass Hierarchy

$\sin^2\theta_{eS}\, m_S < 2\ \mathrm{meV}$ $\quad$ $\sin^2\theta_{\mu S}\, m_S,\ \sin^2\theta_{\tau S}\, m_S < 5\ \mathrm{meV}$

Inverted Mass Hierarchy

$\sin^2\theta_{eS}\, m_S < 8\ \mathrm{meV}$ $\quad$ $\sin^2\theta_{\mu S}\, m_S < 4\ \mathrm{meV}$

but $\sin^2\theta_S\, m_S < 20\ \mathrm{meV}$ (phase)

Degenerate Spectrum

$\sin^2\theta_{eS}\, m_S < 1\ \mathrm{meV}$ but $\sin^2\theta_S\, m_S \sim 200\ \mathrm{meV}$ (phase)

Some Benchmarks

$\sin^2\theta_{\alpha S}\, m_S < 1\ \mathrm{meV}$ (1)

below 1σ experimental uncertainties for hierarchical spectra can influence sub-leading structure in degenerate spectrum

$\sin^2\theta_{\alpha S}\, m_S < 3\ \mathrm{meV}$ (2)

can generate sub-leading structures in hierarchical spectra

$\sin^2\theta_{\alpha S}\, m_S < 30\ \mathrm{meV}$ (3)

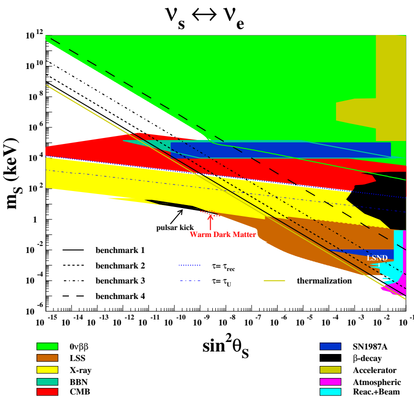
can generate dominant structures in hierarchical spectra

Some Benchmarks

$\sin^2\theta_{\alpha S}\, m_S < 0.5\ \mathrm{eV}$ (4)

maximal allowed value for matrix elements from data

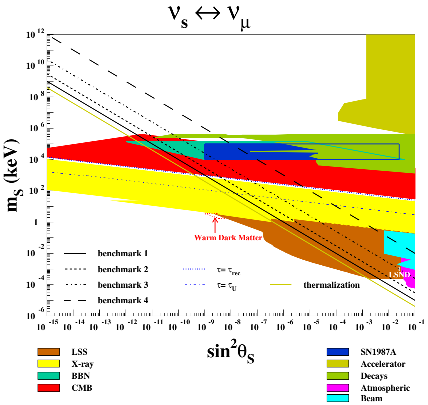
Astrophysical, Cosmological and Laboratory Bounds on $\nu_e - \nu_S$ Mixing



S thermalized before BBN
$m_S \sin^2\theta_S > 0.6$ meV

LSS: gives bound on $\rho_S(m_S)$
X-ray: $S \to \nu_a \gamma$ 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

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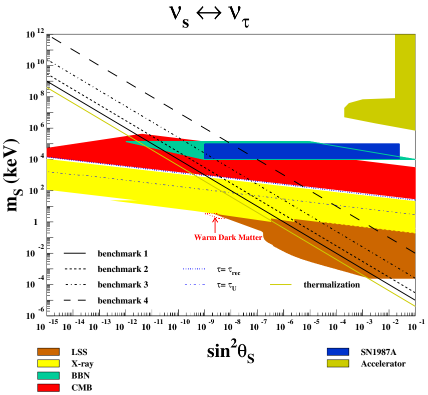

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Confronting Benchmarks with Experimental Bounds

Regions where **$\mathbf{m_I}$** 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: $\mathbf{m_I}$ gives the bound $(\sin^2\theta_{\alpha S}\, m_S \lesssim 0.5\ \mathrm{eV})$
- bounds dominant contribution to degenerate spectrum
- contributions out of control: can create ambiguity in implications of mass and mixing results

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Regions where $\mathbf{m_I}$ effect is greater than direct mixing:

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 $\Delta N_\nu < 1 \Rightarrow \mathbf{m_I} < 1\,\text{meV}$
- limited by LSS from above
- if $\Delta N_\nu = 1$ is allowed bounds depend on flavor
- $\nu_e - \nu_S$: reactor & atmospheric ν exclude dominant $\mathbf{m_I}$
- $\nu_\mu - \nu_S$: atmospheric ν allow larger regions: *e.g.* $\mathbf{m_I} \sim 10$ meV
- $\nu_\tau - \nu_S$: bound weaker, allowing for dominant contributions $\mathbf{m_I} \sim (30 - 250)$ meV

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

Confronting Benchmarks with Experimental Bounds

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Confronting Benchmarks with Experimental Bounds

- for $m_S = (10^{-3} - 10^5)$ keV effects of direct mixing dominate

$$m_l \lesssim 4 \cdot 10^{-2}\ \mathrm{meV}$$

  only very small corrections to $\mathbf{m}_a$ can be produced
- for $m_S = (1 - 10^4)$ keV bound even stronger

$$m_l \lesssim 10^{-2}\ \mathrm{meV}$$

Avoiding Bounds

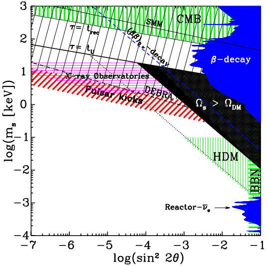
Low Reheating Temperature Cosmological Scenario

if $T_R << 100\ \mathrm{MeV}$ the experimental bounds on $\nu - S$ mixing are relaxed

G. Gelmini, S. Palomares-Ruiz and S. Pascoli, Phys. Rev. Lett. **93**, 081302 (2004) [arXiv:astro-ph/0403323]

Sterile neutrino required to explain LSND result is allowed here

Stronger effects of $\mathbf{m_I}$ possible



Avoiding Bounds
Mass-Varying Neutrino Scenario

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

R. Fardon, A. E. Nelson and N. Weiner, JCAP **0410**, 005 (2004) [astro-ph/0309800]

$m_S = \lambda\langle A\rangle$ and $\langle A\rangle \propto n_\nu$ (number density of active ν)

$$m_S = m_S^0(1+z)^3$$

$$m_l = \frac{m_{iS}^2}{m_S^0(1+z)^3} = m_l^0(1+z)^{-3}$$

mixing mass m_{iS} is constant in time

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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 where satisfied

Avoiding Bounds

Sterile Interacts with massless or low-mass Majoron

if $S \to \nu\phi$ (or annihilate) fast enough $(\tau_S << 1\,\mathrm{s})$ all astrophysical and cosmological bounds could be evaded

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

S. Palomares-Ruiz, S. Pascoli and T. Schwetz, JHEP **0509**, 048 (2005)

Summary

- $S - \nu$ mixing generate m_l which can be the origin of dominant or sub-dominant structures in m_ν
- Direct mixing effects of S can be observed in cosmology, astrophysics and laboratory experiments
- For $m_S \gtrsim 300$ MeV m_l 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
- New Physics can relax or even lift cosmological and astrophysical bounds

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