Theory and Phenomenology of Sterile Neutrinos

Joachim Kopp (University of Mainz)

June 7, 2014 @ Neutrino 2014, Boston
Outline

1 Sterile Neutrinos

2 Oscillation Anomalies: A Global Fit
   - $\nu_e$ Appearance
   - $\nu_e$ Disappearance
   - $\nu_\mu$ Disappearance
   - Sterile Neutrino Oscillations: The Global Picture

3 Sterile Neutrinos in Cosmology: Robustness of Constraints

4 Light Sterile Neutrinos and Dark Matter Searches
   - Sterile Neutrinos and Direct Dark Matter Searches
   - Sterile Neutrinos and Indirect Dark Matter Searches

5 Summary
Sterile Neutrinos
Sterile neutrinos

Definition

Sterile neutrino = SM singlet fermion

- Very generic extension of the SM
  - can be leftovers of extended gauge multiplets (e.g. GUT multiplets)
- Very useful in phenomenology:
  - Can explain smallness of neutrino mass
    (seesaw mechanism, $m \sim \text{TeV} \ldots M_{\text{Pl}}$)
  - Can explain baryon asymmetry of the Universe
    (leptogenesis, $m \gg 100 \text{ GeV}$)
  - Can explain dark matter
    ($m \sim \text{keV}$)
  - Can explain various neutrino oscillation anomalies
    ($m \sim \text{eV}$)
Example: The $\nu$MSM

- SM + $\geq 3$ sterile neutrinos $N_j$

$$\mathcal{L} \supset Y_{ij} \bar{L}_i H N_j + \frac{1}{2} M_{ij} \bar{N}_i \bar{N}_j$$

- Two of the sterile neutrino masses $> 10^{10}$ GeV
  - Seesaw mechanism
  - Leptogenesis

- One sterile neutrino at $\sim$ keV
  - Warm Dark Matter Candidate

Asaka Blanchet Shaposhnikov, hep-ph/0503065
Asaka Shaposhnikov, hep-ph/0505013
Asaka Eijima Ishida, arXiv:1101.1382

Possible extensions

- More sterile neutrinos $\rightarrow$ eV-scale neutrinos for short-baseline anomalies?
- Left-right symmetric extension: sterile neutrinos charged under $SU(2)_R$

Duerr Fileviez-Perez Lindner, arXiv:1306.0568
Oscillation Anomalies: A Global Fit
\( (\nu_e) \) appearance in the 3+1 scenario and beyond

Motivated by LSND and MiniBooNE: excess of \( (\nu_e) \) events in \( (\nu_\mu) \) beam.

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</tr>
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<td>KARMEN</td>
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<td>8.6/9</td>
<td>9.0/9</td>
</tr>
<tr>
<td>NOMAD</td>
<td>0.0/1</td>
<td>0.0/1</td>
<td>0.0/1</td>
</tr>
<tr>
<td>ICARUS</td>
<td>2.0/1</td>
<td>2.3/1</td>
<td>1.5/1</td>
</tr>
<tr>
<td>Combined</td>
<td>87.9/66</td>
<td>72.7/63</td>
<td>74.6/63</td>
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Global fit to all appearance data is consistent

Background oscillations important in MiniBooNE and E776

Significant improvement in 3 + 2 and 1 + 3 + 1

JK Machado Maltoni Schwetz, 1303.3011 see also fits by Giunti Laveder et al.
Conrad Ignarra Karagiorgi Shaevitz Spitz Djurcic Sorel
$\nu_e$ appearance in the 3+1 scenario and beyond

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MiniB \(\bar{\nu}\) & 10.7/11 & 9.6/11 & 12.7/11 \\
E776 & 32.4/24 & 29.2/24 & 31.3/24 \\
KARMEN & 9.8/9 & 8.6/9 & 9.0/9 \\
NOMAD & 0.0/1 & 0.0/1 & 0.0/1 \\
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$\bar{\nu}_e$ disappearance: reactor and gallium experiments

The reactor anomaly

- Reevaluation of reactor $\bar{\nu}_e$ flux is $\sim 3.5\%$ above previous prediction
  $\rightarrow$ systematic uncertainties or new physics?

Mueller et al. 1101.2663, Huber 1106.0687, Hayes et al. 1309.4146 & talk by G. Garvey

\begin{align*}
\Delta m^2 &= 0.44 \text{ eV}^2, \sin^2 2\theta_{14} = 0.13 \\
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\( \bar{\nu}_e \) disappearance: reactor and gallium experiments

### The reactor anomaly

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### The gallium anomaly

- Experiments with intense radioactive \( \nu_e \) sources (\( ^{51}\text{Cr} \) and \( ^{37}\text{Ar} \))
- Neutrino detection via \( ^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^- \)
- Observation: Neutrino deficit (\( \sim 3\sigma \))

Giunti Laveder 1006.3244
\(\bar{\nu}_e\) disappearance in the 3+1 scenario

\[\Delta m^2 = 0.44 \text{ eV}^2, \sin^2 2\theta_{14} = 0.13\]
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<table>
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<tr>
<th>Source</th>
<th>(\sin^2 2\theta_{14})</th>
<th>(\Delta m^2_{41} \text{ [eV}^2])</th>
<th>(\chi^2_{\text{min}}/\text{dof (GOF)})</th>
<th>(\Delta \chi^2_{\text{no osc}}/\text{dof (CL)})</th>
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<tr>
<td>SBL rates only</td>
<td>0.13</td>
<td>0.44</td>
<td>11.5/17 (83%)</td>
<td>11.4/2 (99.7%)</td>
</tr>
<tr>
<td>SBL incl. Bugey3 spect.</td>
<td>0.10</td>
<td>1.75</td>
<td>58.3/74 (91%)</td>
<td>9.0/2 (98.9%)</td>
</tr>
<tr>
<td>SBL + Gallium</td>
<td>0.11</td>
<td>1.80</td>
<td>64.0/78 (87%)</td>
<td>14.0/2 (99.9%)</td>
</tr>
<tr>
<td>global (\nu_e) disapp.</td>
<td>0.09</td>
<td>1.78</td>
<td>403.3/427 (79%)</td>
<td>12.6/2 (99.8%)</td>
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JK Machado Maltoni Schwetz, 1303.3011
Relation between appearance and disappearance

We find: $\bar{\nu}_e$ disappearance experiments consistent among themselves, $\nu_e$ appearance experiments consistent among themselves.

But:

3 + 1 neutrinos

At $L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$

\[ P_{ee} = 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2) \]
\[ P_{\mu\mu} = 1 - 2|U_{\mu4}|^2(1 - |U_{\mu4}|^2) \]
\[ P_{e\mu} = 2|U_{e4}|^2|U_{\mu4}|^2 \]

It follows

\[ 2P_{e\mu} \approx (1 - P_{ee})(1 - P_{\mu\mu}) \]

In the 3 + 1 case, at large enough baseline, there is a one-to-one relation between the appearance and disappearance probabilities.
Combining different oscillation channels provides the strongest, most robust constraints on sterile neutrinos
\(\nu_\mu\) disappearance in the 3+1 scenario

- Parameter regions favored by tentative hints are in tension with null results from \(\nu_\mu\) disappearance searches.

\[
\begin{align*}
\Delta m^2_{41} [\text{eV}^2] & \quad |U_{\mu 4}|^2 \\
10^{-2} & \quad 10^{-1} \\
10^0 & \quad 10^1
\end{align*}
\]

- Null results combined
- 99% CL

JK Machado Maltoni Schwetz, 1303.3011
Parameter regions favored by tentative hints are in tension with null results from $\nu_\mu$ disappearance searches.

$\Delta m_{41}^2$ vs. $|U_{\mu 4}|^2$
The global oscillation fit

3 + 1 Severe tension between appearance and disappearance and between exp’s with and without a signal.

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Parameter goodness of fit (PG) test:

Compares $\chi^2_{\text{min}}$ from global and separate fits to test compatibility of 2 data sets

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**The global oscillation fit**

3 + 1 Severe tension between appearance and disappearance and between exp’s with and without a signal

3 + 2 Tension remains for two sterile neutrinos

3 + 3 No significant improvement expected

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The MIT/Columbia fit

\( \overline{\nu}_\mu \rightarrow \overline{\nu}_e \) appearance data:
- LSND
- MiniBooNE
- KARMEN
- NOMAD

\( \nu_\mu \) disappearance data:
- MiniBooNE
- Minos CC \( \nu_\mu \)
- CDHS
- CCFR
- Atmospheric neutrinos

\( \nu_e \) disappearance data:
- Short baseline reactor experiments
- Gallium experiments
- \( \nu_e - ^{12}\text{C} \) CC scattering in KARMEN, LSND

\( \chi^2 / \text{dof} \) and PG test results in qualitative agreement with ours \( \rightarrow \) tension confirmed

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Theory and Phenomenology of Sterile Neutrinos
The GL$^4$ fit

$\bar{\nu}_\mu \to \bar{\nu}_e$ appearance data:
- LSND
- MiniBooNE
- E776
- KARMEN
- NOMAD
- ICARUS
- OPERA

$\bar{\nu}_\mu$ disappearance data:
- MiniBooNE/SciBooNE
- Minos NC+CC $\nu_\mu$
- CDHS
- CCFR
- Atmospheric neutrinos

$\bar{\nu}_e$ disappearance data:
- Reactor experiments
- Gallium experiments
- Solar neutrinos
- $\nu_e^{12}$C scattering in KARMEN, LSND

Conclusion

NO tension found
Conclusion from oscillation data: severe tension

My personal point of view

Anomalies are definitely interesting enough to be checked

- If mundane explanations are found, we will learn important lessons for future neutrino experiments
- If sterile neutrinos exist, this would be the discovery of the decade.

Questions for the future

- Is one (or all) of the positive results not due to sterile neutrinos?
- Are some of the exclusion limits too strong? (removing one from the fit is not enough!)
- Does new physics beyond the simple $3 + X$ scenarios help?
Hidden sector gauge forces and SBL oscillations

If sterile neutrinos have new interactions with SM fermions (e.g. in models with “baryonic sterile neutrinos”), new MSW potentials will influence oscillations.

How does this affect the tension in the SBL data?

Karagiorgi Shaevitz Conrad, arXiv:1202.1024
Pospelov, arXiv:1103.3261

\[
\chi^2 - \chi^2_{\text{min}} \\
90\% \text{ and } 99\% \text{ CL}
\]

- MINOS
- MiniBooNE
- Solar
- previous best fit

Preliminary

JK, Johannes Welter, in preparation
Sterile Neutrinos in Cosmology: Robustness of Constraints
Sterile neutrinos in cosmology

Models with $\mathcal{O}(\text{eV})$ sterile neutrino(s) constrained by cosmology:

- **Sum of neutrino masses**
  \[ \sum m_\nu \lesssim 0.23 \text{ eV} \]

- **# of relativistic species**
  \[ N_\nu = 4 \text{ mildly disfavored} \]

(This would change if BICEP-2 is included.)

Talks by Marta Spinelli, Daniel Eisenstein
Ade et al. (Planck), arXiv:1303.5076
Gonzalez-Garcia Maltoni Salvado, arXiv:1006.3795
Hamann Hannestad Raffelt Tamborra Wong, arXiv:1006:5276
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Hamann Hannestad Raffelt Tamborra Wong, arXiv:1006:5276

Question:

What does it take to evade these constraints?
Suppressed $\nu_s$ production from thermal MSW effect

- $\nu_s$ production in the early Universe through $\nu_{e,\mu,\tau} \rightarrow \nu_s$ oscillations
  
  - Assume $\nu_s$ charged under a hidden sector gauge group $U(1)_s$
  
  - Neutrino self energy:

- Tadpole diagram: conventional MSW potential: $V \propto n_f - n_{\bar{f}}$
  
  - Bubble diagram: thermal contribution $V \propto T^\alpha$
  
  - At high $T$: strong MSW-type potential even without lepton asymmetry

\[
\sin 2\theta_{\text{eff}} = \frac{\sin 2\theta}{\sqrt{\sin^2 2\theta + (\cos 2\theta - \frac{2EV}{\Delta m^2})^2}}
\]

- $\nu_s$ production through oscillations suppressed in the early Universe
  
  \[\rightarrow\] no cosmological constraints

Hannestad Hansen Tram arXiv:1310.5926

Dasgupta JK arXiv:1310.6337
Suppression of $\nu_s$ production by thermal MSW effect

For $\alpha' \sim 10^{-3}$ and $M_{A'} \lesssim 10$ MeV:

- effective potential $V_{\text{eff}} \gg$ oscillation frequency $\Delta m^2/(2E)$

until neutrino decoupling.

$\Rightarrow$ sterile neutrino production suppressed, no cosmological constraints

Hannestad Hansen Tram arXiv:1310.5926
Dasgupta JK arXiv:1310.6337
Hidden sector gauge forces and dark matter

Interesting connection to dark matter physics:

The same gauge force that suppressed sterile neutrino production can also solve small scale structure problems:

- Too big to fail problem
- Cusp vs. core problem
- Missing satellites problem

Dasgupta JK arXiv:1310.6337
Light Sterile Neutrinos and Dark Matter Searches
Neutrinos and direct dark matter detection

Solar neutrinos are a well-known background to future direct DM searches:

\[
\frac{d\sigma_{\text{SM}}(\nu N \rightarrow \nu N)}{dE_r} = \frac{G_F^2 m_N F^2(E_r)}{2\pi E^2_\nu} \left[ A^2 E^2_\nu + 2AZ(2E^2_\nu(s^2_w - 1) - E_r m_N s^2_w) + 4Z^2(E^2_\nu + s^4_w(2E^2_\nu + E_r^2 - E_r(2E_\nu + m_N)) + s^2_w(E_r m_N - 2E^2_\nu)) \right],
\]

see e.g. Gütlein et al. arXiv:1003.5530
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+ 4Z^2(E_{\nu}^2 + s_w^4(2E_{\nu}^2 + E_r^2 - E_r(2E_{\nu} + m_N)) + s_w^2(E_r m_N - 2E_{\nu}^2)) \right],
\]

SM signal will only become sizeable in multi-ton detectors
But: New physics can enhance the rate

Examples:
- Neutrino magnetic moments
- Sterile neutrinos + \( \lesssim \) GeV scale hidden sector gauge force
Low-energy scattering of neutrinos beyond the SM

A: \( \nu \) magnetic moment
B, C, D: kinetically mixed \( A' \) + sterile \( \nu_s \)

- **Enhanced scattering at low** \( E_r \) **for light** \( A' \)
- **Negligible** compared to SM scattering \( \sim g^4 m_T / M_W^4 \) at energies probed in dedicated neutrino experiments

\[ [\text{Pospelov 1103.3261, Pospelov Pradler 1203.0545}] \]

[Enhanced scattering at low \( E_r \) for light \( A' \)]

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Theory and Phenomenology of Sterile Neutrinos

25

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Sterile neutrinos and DM annihilation in the Sun

- Neutrino telescope limits on neutrinos from dark matter annihilation in the Sun depend crucially on oscillation physics.
- If sterile neutrinos exist, new MSW resonances can lead to strong conversion of active neutrinos into sterile neutrinos in the Sun.

Esmaili Peres, arXiv:1202.2869
Argüelles JK, arXiv:1202.3431
Oscillation probabilities for a 3+3 toy scenario

\[ P(\nu_e \rightarrow \nu_X) \quad P(\nu_\mu \rightarrow \nu_X) \quad P(\nu_\tau \rightarrow \nu_X) \]

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_X) \quad P(\bar{\nu}_\mu \rightarrow \bar{\nu}_X) \quad P(\bar{\nu}_\tau \rightarrow \bar{\nu}_X) \]

Thick red lines = active–sterile oscillations

plots from Argüelles JK, arXiv:1202.3431
see also Esmaili Peres, arXiv:1202.2869

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Theory and Phenomenology of Sterile Neutrinos
Impact on IceCube limits

plot from Carlos Argüelles JK, arXiv:1202.3431
see also Esmaili Peres, arXiv:1202.2869
Summary
Summary

- Sterile neutrinos are **theoretically well motivated** and **phenomenologically useful**
- **Tension** between **appearance** and **disappearance** searches
- **Neutrino 2014**: several interesting new limits
  - Will increase the tension
  - Qualitative conclusions strengthened
- **Cosmology disfavors** $N_\nu \geq 4$, especially for $m_{\nu_s} \gtrsim 0.23$ eV.
  (if BICEP-2 is included, this conclusion would change)
- **Many mechanisms** for making sterile neutrinos **fully consistent with cosmology**
  - Example: hidden sector gauge force
  - Can additionally **solve small scale structure problems**
    if coupled also to **dark matter**

- **Sterile neutrinos and dark matter searches**
  - Direct searches: **non-standard neutrino signals** in DM detectors
  - Indirect searches: limits on **DM annihilation in the Sun** modified by active–sterile oscillations
Thank you!
Data sets included in our fit

$\bar{\nu}_e$ disappearance
- SBL reactor experiments
- LBL reactor experiments
- KamLAND
- Radioactive source (Ga) experiments
- Solar neutrinos
- Atmospheric neutrinos
- $\nu_e - ^{12}\text{C}$ scattering in KARMEN, LSND

$\bar{\nu}_e$ appearance
- LSND
- MiniBooNE
- KARMEN
- NOMAD
- ICARUS
- E776

$\bar{\nu}_\mu$ disappearance
- Atmospheric neutrinos (includes either $\bar{\nu}_e$ disapp. or full matter effects)
- MiniBooNE (includes oscillations of backgrounds)
- MINOS CC+NC (full $n$-flavour oscillations in matter)
- CDHS
Relation between appearance and disappearance

3 + 2 neutrinos

At \( L \gg 4\pi E/\Delta m^2_{41} \), but \( L \ll 4\pi E/\Delta m^2_{31} \)

\[
P_{ee} = 1 - 2 \left| U_{e4} \right|^2 (1 - \left| U_{e4} \right|^2) + \left| U_{e5} \right|^2 (1 - \left| U_{e5} \right|^2) - \left| U_{e4} \right|^2 \left| U_{e5} \right|^2
\]

\[
P_{\mu\mu} = 1 - 2 \left| U_{\mu4} \right|^2 (1 - \left| U_{\mu4} \right|^2) + \left| U_{\mu5} \right|^2 (1 - \left| U_{\mu5} \right|^2) - \left| U_{\mu4} \right|^2 \left| U_{\mu5} \right|^2
\]

\[
P_{e\mu} = 2 \left( \left| U_{e4} \right|^2 \left| U_{\mu4} \right|^2 + \left| U_{e5} \right|^2 \left| U_{\mu5} \right|^2 + \text{Re}(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*) \right)
\]
Relation between appearance and disappearance

3 + 2 neutrinos

At \( L \gg 4\pi E/\Delta m_{41}^2 \), but \( L \ll 4\pi E/\Delta m_{31}^2 \)

\[ P_{ee} = 1 - 2 \left[ |U_{e4}|^2 (1 - |U_{e4}|^2) + |U_{e5}|^2 (1 - |U_{e5}|^2) - |U_{e4}|^2 |U_{e5}|^2 \right] \]

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It follows

\[ 2P_{e\mu} \simeq (1 - P_{ee})(1 - P_{\mu\mu}) \]

\[ + 4 \left[ \text{Re}(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*) + 4 |U_{e4}|^2 |U_{\mu5}|^2 + 4 |U_{e5}|^2 |U_{\mu4}|^2 \right] \]

\[ = (1 - P_{ee})(1 - P_{\mu\mu}) - 2 \left[ |U_{e4}|^2 |U_{\mu5}|^2 + |U_{e5}|^2 |U_{\mu4}|^2 \right] \]

\[ - 2 |U_{e4} U_{\mu5} - U_{e5} U_{\mu4}|^2 \]
Relation between appearance and disappearance

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It follows

\[ 2P_{e\mu} \leq (1 - P_{ee})(1 - P_{\mu\mu}) \]

Unlike in the 3 + 1 case, for 3 + 2 models, there is NO one-to-one relation between the appearance and disappearance probabilities.

However, there is an inequality, which can be used to set meaningful constraints.
Impact of $\theta_{13}$

- Sterile neutrinos do not impact $\theta_{13}$ measurement
- $\theta_{13} \neq 0$ does not impact sterile neutrino search

Antimatter $\bar{\nu}_\mu$ disappearance in the 3+1 scenario

- Parameter regions favored by tentative hints are in tension with null results.
$\bar{\nu}_\mu$ disappearance in the 3+1 scenario

- Parameter regions favored by tentative hints are in tension with null results
- Constraints on $|U_{\tau 4}| \sim \sin \theta_{34}$ possible due to NC events and matter effects

\( \nu_\mu \) disappearance in the 3+1 scenario

- Parameter regions favored by tentative hints are in tension with null results
- Constraints on \(|U_{\tau 4}| \sim \sin \theta_{34}\) possible due to NC events and matter effects
- Complex phases important

Differences between our fit and Giunti et al.

- **MiniBooNE fit**
  we use MB analysis based on official MC events, include BG oscillation

- **MINOS fit**
  we fit CC+NC data, including ND and FD, detector response matrices based on official MINOS MC

- **Reactor fit**
  minor differences in the data set, possibly different treatment of correlations among systematic uncertainties

- **LSND fit**
  Note that LSND spectral data is more constraining than the total count rate. We use this information; our fit is consistent with the numbers reported in hep-ex/0203023 (Church, Eitel, Mills, Steidl, combined LSND+KARMEN analysis)

- **Atmospheric neutrinos**
  Full fit vs. tabulated $\chi^2$
A combined fit of oscillation data and cosmology

Archidiacono Fornengo Giunti Hannestad Melchiori arXiv:1302.6720
A combined fit of oscillation data and cosmology

\[ \sin^2 \theta_e \mu \Delta m^4_{12}^{10^{-4} \ldots 10^{-1}} \]

Archidiacono Fornengo Giunti Hannestad Melchiori arXiv:1302.6720

Oscillation + Cosmology
Are light sterile neutrinos ruled out by cosmology?

$\nu_s$ production in the early Universe through $\nu_{e,\mu,\tau} \rightarrow \nu_s$ oscillations at $T \gtrsim \text{MeV}$

Dodelson Widrow 1994

Making sterile neutrinos fully consistent with cosmology

- $> 1$ new relativistic degrees of freedom + $\omega < -1$ + $\mu_\nu \neq 0$
  
  Hamann Hannestad Raffelt Wong, arXiv:1108.4136

- Entropy production after neutrino decoupling (e.g. due to late decay of heavy sterile neutrinos or other particles) $\rightarrow$ neutrinos diluted
  
  Fuller Kishimoto Kusenko 1110.6479, Ho Scherrer 1212.1689

- Very low reheating temperature
  
  Gelmini Palomares-Ruiz Pascoli, astro-ph/0403323

- Large lepton asymmetry ($\gtrsim 0.01$) $\rightarrow \nu_s$ production MSW-suppressed
  

- Couplings to a Majoron field $\rightarrow$ suppressed production
  
  Bento Berezhiani, hep-ph/0108064

- New gauge interaction in the $\nu_s$ sector $\rightarrow \nu_s$ production suppressed by thermal potential
  
  Hannestad et al. 1310.5926
  Dasgupta JK 1310.6337
Two further remarks

- If sterile and visible sectors have ever been in thermal equilibrium, $\nu_s$ will have been produced thermally very early on.
- But temperatures of the two sectors are very different:

$$T_{\text{visible}} > T_{\text{sterile}}$$

after the SM phase transitions.

→ $\nu_s$ abundance $\ll$ active neutrino abundance
Two further remarks

- If sterile and visible sectors have ever been in thermal equilibrium, $\nu_s$ will have been produced thermally very early on.
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after the SM phase transitions.

$\rightarrow \nu_s$ abundance $\ll$ active neutrino abundance

Mixing of $U(1)_s$-charged $\nu_s$ with active neutrinos:

$$\mathcal{L} \supset -\bar{L}Y_\nu \tilde{H} \nu_R - \bar{\nu}_s Y_s H_s \nu_R - \frac{1}{2}(\nu_R)^c M_R \nu_R + h.c.$$

($\tilde{H}$ = SM Higgs, $H_s$ = sterile sector Higgs)

see e.g. Harnik JK Machado arXiv:1202.6073
Example 1: Neutrino magnetic moments

Assume neutrinos carry an enhanced magnetic moment

\[ \mathcal{L}_{\mu\nu} \supset \mu_{\nu} \bar{\nu} \sigma^{\alpha\beta} \partial_{\beta} A_{\alpha\nu}, \quad \mu_{\nu} \gg \mu_{\nu,SM} = 3.2 \times 10^{-19} \mu_B \]

Cross section large at low energies due to photon propagator \( \propto q^{-2} \)

\[
\frac{d\sigma_{\mu}(\nu e \rightarrow \nu e)}{dE_r} = \mu_{\nu}^2 \alpha \left( \frac{1}{E_r} - \frac{1}{E_\nu} \right),
\]

![Graph showing electron and nuclear recoil data for different experiments with observed counts and energy values.](image)
Example: A not-so-sterile 4th neutrino

Introduce a new $U(1)'$ gauge boson $A'$ (hidden photon) and a light sterile neutrino $\nu_s$

Related model with gauged $U(1)_B$ first discussed in Pospelov 1103.3261
detailed studies in Harnik JK Machado 1202:6073 and Pospelov Pradler 1203.0545

- $\nu_s$ charged under $U(1)'$ → direct coupling to $A'$
- SM particles couple to $A'$ only through kinetic mixing

$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu \nu} F'^{\mu \nu} - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} - \frac{1}{2} \epsilon F'_{\mu \nu} F^{\mu \nu} + \bar{\nu}_s i \phi \nu_s + g' \bar{\nu}_s \gamma^\mu \nu_s A'_{\mu}$$

$$- (\nu_L)^c m_{\nu_L} \nu_L - (\nu_S)^c m_{\nu_S} \nu_S - (\nu_L)^c m_{\text{mix}} \nu_S$$

A small fraction of solar neutrinos can oscillate into $\nu_s$

$\nu_s$ scattering cross section in the detector given by

$$\frac{d\sigma_{A'}(\nu_s e \rightarrow \nu_s e)}{dE_r} = \frac{\epsilon^2 e^2 g'^2 m_e}{4\pi p^2_M (M^2_{A'} + 2E_r m_e)^2} \left[ 2E^2_\nu + E^2_r - 2E_r E_\nu - E_r m_e - m^2_\nu \right]$$
Temporal modulation of neutrino signals

Signals of new light force mediators and/or sterile neutrinos can show seasonal modulation:

- The Earth–Sun distance: Solar neutrino flux peaks in winter.
Temporal modulation of neutrino signals

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Harnik JK Machado, arXiv:1202.6073
Temporal modulation of neutrino signals

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- **Sterile neutrino absorption**: For strong \( \nu_s - A' \) couplings and not-too-weak \( A' - \text{SM} \) couplings, sterile neutrino cannot traverse the Earth. \( \rightarrow \) lower flux at night. And nights are longer in winter.
- **Earth matter effects**: An MSW-type resonance can lead to modified flux of certain neutrino flavors at night. And nights are longer in winter.
Hidden photons

$$\mathcal{L} \supset -\frac{1}{4} F_{\mu\nu}' F'^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \epsilon F_{\mu\nu}' F^{\mu\nu} + \bar{\nu}_s i \phi \nu_s + g' \bar{\nu}_s \gamma^\mu \nu_s A'_\mu$$

Constraints from Jaeckel Ringwald 1002.0329, Redondo 0801.1527, Bjorken Essig Schuster Toro 0906.0580, Dent Ferrer Krauss 1201.2683, Harnik JK Machado

Joachim Kopp

Theory and Phenomenology of Sterile Neutrinos
3+3 flavor toy model

Consider toy model with 3 sterile neutrinos, each of them mixing with only one of the active flavors:

\[ U = R_{14}(\theta) \, R_{25}(\theta) \, R_{36}(\theta) \, U_{PMNS} \], \quad R_{ij} = \text{rotation in } ij\text{-plane}. \]

Hamiltonian:

\[ \mathcal{H} \simeq E + \frac{1}{2E} U \mathcal{D} U^\dagger + V_{MSW}, \quad \mathcal{D} = \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2, \Delta m_{41}^2, \Delta m_{51}^2, \Delta m_{61}^2) \]

Mikheyev-Smirnov-Wolfenstein (MSW) potential:

\[ V_{MSW} = \sqrt{2} G_F \text{diag}(n_e - n_n/2, -n_n/2, -n_n/2, 0, 0, 0), \]

\[ n_e (n_n) = \text{electron (neutron) number density} \]

Oscillation probability:

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\beta | e^{-i\mathcal{H}t} | \nu_\alpha \rangle \right|^2 \]