Sterile neutrinos: to be or not to be?

Joachim Kopp (University of Mainz)

June 9, 2015 @ WIN 2015, Heidelberg
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

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 $= \text{SM singlet fermion}$

- 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
    ($m \sim \text{eV}$)
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.

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.

Collin Conrad Ignarra Karagiorgi Shaevitz Spitz Djurcic Sorel

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>LSND $\nu$</td>
<td>11.0/11</td>
<td>8.6/11</td>
<td>7.5/11</td>
</tr>
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<td>MiniB $\nu$</td>
<td>19.3/11</td>
<td>10.6/11</td>
<td>9.1/11</td>
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</tr>
<tr>
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<td>ICARUS</td>
<td>2.0/1</td>
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<td>1.5/1</td>
</tr>
<tr>
<td>Combined</td>
<td>87.9/66</td>
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appearance in the 3+1 scenario and beyond

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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 \( 1+3+1 \)

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$\nu_e$ disappearance in the 3+1 scenario

<table>
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<tr>
<th>sin$^2 2\theta_{14}$</th>
<th>$\Delta m^2_{41}$ [eV$^2$]</th>
<th>$\chi^2_{\text{min}}$/dof (GOF)</th>
<th>$\Delta \chi^2_{\text{no osc}}$/dof (CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBL rates only</td>
<td>0.13</td>
<td>0.44</td>
<td>11.5/17 (83%)</td>
</tr>
<tr>
<td>SBL incl. Bugey3 spect.</td>
<td>0.10</td>
<td>1.75</td>
<td>58.3/74 (91%)</td>
</tr>
<tr>
<td>SBL + Gallium</td>
<td>0.11</td>
<td>1.80</td>
<td>64.0/78 (87%)</td>
</tr>
<tr>
<td>global $\nu_e$ disapp.</td>
<td>0.09</td>
<td>1.78</td>
<td>403.3/427 (79%)</td>
</tr>
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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 $L \ll 4\pi E/\Delta m^2_{31}$

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

It follows

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

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
Parameter regions favored by tentative hints are in tension with null results from $\bar{\nu}_\mu$ disappearance searches.

$$\Delta m_{41}^2 [eV^2]$$

$|U_{\mu 4}|^2$

99% CL

MINOS (2011)

CDHS atm

MB disapp

MB app reactors+Ga

LSND

Null results combined

JK Machado Maltoni Schwetz, 1303.3011
$\nu_\mu$ disappearance in the 3+1 scenario

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

\[ \begin{array}{c}
10^{-2} \\
10^{-1} \\
10^{0} \\
10^{1}
\end{array} \]

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$|U_{\mu 4}|^2$

Null results combined

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MINOS (2011)

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CDHS

SK (2014)

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MB app reactors+Ga

Preliminary

JK Machado Maltoni Schwetz, 1303.3011
Neutrino Absorption (at TeV energies, neutrinos are absorbed by the earth)

Matter Signal antineutrino, because of the known hierarchy

\[ \nu_{\mu} \] oscillation parameters!

Big Resonance!

Hierarchy demands this be in antineutrino mode

Slide courtesy of Janet Conrad
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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Sterile Neutrinos in Cosmology
Sterile neutrinos in cosmology

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

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

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

Ade et al. (Planck), arXiv:1303.5076
Gonzalez-Garcia Maltoni Salvado, arXiv:1006.3795
Hamann Hannestad Raffelt Tamborra Wong, arXiv:1006:5276
**Sterile neutrinos in cosmology**

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**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
  Dodelson Widrow 1994
- Assume $\nu_s$ couple to $\gtrsim$ MeV gauge boson $A'$
- Neutrino self energy:
  \begin{equation*}
  \begin{aligned}
  A' \\
  \nu_s \rightarrow \nu_s \\
  \nu_s \\
  \end{aligned}
  \end{equation*}

- Leads to thermal MSW potential $V \propto T^4$
- At high $T$: mixing strongly suppressed

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

- No $\nu_s$ production through oscillations
  $\rightarrow$ no cosmological constraints

Hannestad Hansen Tram arXiv:1310.5926
Dasgupta JK arXiv:1310.6337
Two regions:

- **Weak coupling**: No $\nu_s$ production (see previous slide)
- **Strong coupling**: Lots of $\nu_s$ produced, but **not harmful** (see next slide)

Chu Dasgupta JK arXiv:1505.02795

Strongly self-interacting sterile neutrinos

- Large coupling $\rightarrow$ efficient conversion of $\nu_{e,\mu,\tau} \rightarrow \nu_s$ after neutrino freeze-out (Dodelson-Widrow mechanism)
  - conflict with neutrino mass bounds?
- But: self-interacting $\nu_s$ don’t free stream

Chu Dasgupta JK arXiv:1505.02795
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

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**Graphs:**

- **Left:** $\sin^2(2\theta_{14}) = 0.12$, $\Delta m^2_{21} = 0.2 \text{ eV}^2$
- **Middle:** $\sin^2(2\theta_{14}) = 0.12$, $\Delta m^2_{21} = 0.4 \text{ eV}^2$
- **Right:** $\sin^2(2\theta_{14}) = 0.12$, $\Delta m^2_{21} = 0.6 \text{ eV}^2$

JK, Johannes Welter, arXiv:1408.0289
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:

see e.g. Gütlein et al. arXiv:1003.5530
Neutrinos and direct dark matter detection

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**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 ($\sim g^4m_T/M_W^4$) at energies probed in dedicated neutrino experiments

[Joachim Kopp]

Enhanced scattering at low $E_r$ for light $A'$

Negligible compared to SM scattering ($\sim g^4m_T/M_W^4$) at energies probed in dedicated neutrino experiments
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

\[ P(\nu_e \to \nu_X) \]
\[ P(\nu_\mu \to \nu_X) \]
\[ P(\nu_\tau \to \nu_X) \]

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

Thick red lines = active–sterile oscillations

plots from Argüelles JK, arXiv:1202.3431
see also Esmaili Peres, arXiv:1202.2869
Summary
Four independent anomalies
  ▶ Consistent with each other

Tension in global fit
  ▶ Are the anomalies real?
  ▶ Are the null results real?

Cosmological limits: Avoided elegantly by self-interacting sterile $\nu_s$

With and without new interactions: rich phenomenology in dark matter detectors
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 $L \gg 4\pi E/\Delta m_{41}^2$, but $L \ll 4\pi E/\Delta m_{31}^2$

\[
\begin{align*}
P_{ee} &= 1 - 2 \left[ |U_{e4}|^2 (1 - |U_{e4}|^2) + |U_{e5}|^2 (1 - |U_{e5}|^2) - |U_{e4}|^2 |U_{e5}|^2 \right] \\
P_{\mu\mu} &= 1 - 2 \left[ |U_{\mu4}|^2 (1 - |U_{\mu4}|^2) + |U_{\mu5}|^2 (1 - |U_{\mu5}|^2) - |U_{\mu4}|^2 |U_{\mu5}|^2 \right] \\
P_{e\mu} &= 2 \left[ |U_{e4}|^2 |U_{\mu4}|^2 + |U_{e5}|^2 |U_{\mu5}|^2 + \text{Re}(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*) \right]
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\]

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

3 + 2 neutrinos

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

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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.
Sterile neutrinos do not impact $\theta_{13}$ measurement

$\theta_{13} \neq 0$ does not impact sterile neutrino search

$\nu_\mu$ 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

Joachim Kopp

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

The MIT/Columbia fit

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance data:
  - LSND
  - MiniBooNE
  - KARMEN
  - NOMAD

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

- $\bar{\nu}_e$ disappearance data:
  - Short baseline reactor experiments
  - Gallium experiments
  - $\nu_\mu - ^{12}\text{C}$ CC scattering in KARMEN, LSND

Poster by Gabriel Collin

$\chi^2$/dof and PG test results in qualitative agreement with ours $\rightarrow$ tension confirmed
The GL$^4$ fit

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 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
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 $\chi^2$
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 + $w < -1$ + $\mu_\nu \neq 0$
  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) → 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 ($\gtrsim 0.01$) → $\nu_s$ production MSW-suppressed

- Couplings to a Majoron field → suppressed production
  Bento Berezhiani, hep-ph/0108064

- New gauge interaction in the $\nu_s$ sector → $\nu_s$ 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.

$\rightarrow \nu_s$ 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.
- But **temperatures** of the two sectors are very different:

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

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
Suppression of $\nu_s$ production by thermal MSW effect

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

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

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

\[ \text{electron recoil} \]

\[ \text{Nuclear recoil – Ge} \]
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 $U(1)' \rightarrow$ direct coupling to $A'$
- SM particles couple to $A'$ only through kinetic mixing

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

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

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

$$\frac{d\sigma_{A'}(\nu_se \rightarrow \nu_se)}{dE_r} = \frac{\epsilon^2 e^2 g'^2 m_e}{4\pi p^2_{\nu}(M_{A'}^2 + 2E_r m_e)^2} \left[2E_{\nu}^2 + E_r^2 - 2E_r E_\nu - E_r m_e - m^2_{\nu}\right]$$
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.

- Active–sterile neutrino oscillations: For oscillation lengths $\lesssim 1$ AU, sterile neutrino appearance depends on the time of year.

- Sterile neutrino absorption: For strong $\nu_s - A'$ couplings and not-too-weak $A' - $SM couplings, sterile neutrino cannot traverse the Earth, leading to a 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.
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Harnik JK Machado, arXiv:1202.6073
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Hidden photons

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

Kinetic mixing \( \epsilon \)

Kinetic mixing \( \epsilon \) and Dark Photon Mass \( M_{A'}(\text{GeV}) \)

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

Sterile neutrinos: to be or not to be?
3+3 flavor toy model

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

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

Hamiltonian:

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

Mikheyev-Smirnov-Wolfenstein (MSW) potential:

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

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

Oscillation probability:

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

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