Phenomenology with sterile neutrinos

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based on work done in collaboration with
Carlos Arguëlles, Roni Harnik, Pedro Machado,
Michele Maltoni, Stephen Parke, Thomas Schwetz
Outline

1. Recent hints for sterile neutrinos
2. Global fit
3. Sterile neutrinos and direct dark matter detection
4. Sterile neutrinos and indirect dark matter detection
5. Conclusions
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Short baselines anomalies

An intriguing accumulation of inconclusive hints . . .
The reactor anti-neutrino anomaly

- Recent reevaluation of expected reactor $\bar{\nu}_e$ flux is $\sim 3.5\%$ higher than previous prediction Mueller et al. arXiv:1101.2663 vs. Schreckenbach 1985
- **Method:** Use measured $\beta$-spectra from $^{238}\text{U}$, $^{235}\text{U}$, $^{241}\text{Pu}$ fission at ILL and convert to $\bar{\nu}_e$ spectrum
- **Problem:** Requires knowledge of $Q$-values for all contributing decays.

<table>
<thead>
<tr>
<th>Old method</th>
<th>New method</th>
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<tbody>
<tr>
<td>30 effective branches</td>
<td>Uses nuclear databases (90% of $\bar{\nu}_e$ flux)</td>
</tr>
<tr>
<td></td>
<td>5 effective branches (remaining 10%)</td>
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<td></td>
<td>Error propagation, correlation matrix</td>
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<td>Off-equilibrium corrections</td>
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<td>(short irradiation time at ILL $\rightarrow$ not all $\beta$-branches in equilibrium)</td>
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Mueller et al.’s results recently confirmed using independent method: P. Huber, arXiv:1106.0687

...but also mentions possibly poorly understood nuclear effects (weak magnetism) in nuclei with large log $ft$ as a possible source of the anomaly.
The reactor anti-neutrino anomaly (2)

- Have short-baseline reactor experiments observed an event deficit?

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Mention et al. arXiv:1101.2755
Fit to reactor anti-neutrino data in a 3+1 model

Assume 3 active neutrinos + 1 sterile neutrino
($\nu_e$ can oscillate into sterile neutrinos)

\[
\begin{align*}
\sin^2 2\theta_{\text{react}} & \\
\Delta m_{41}^2 & \text{[eV}^2]\end{align*}
\]

90%, 99% CL (2 dof)
curves: old fluxes
colors: new fluxes

plot by Thomas Schwetz
LSND, KARMEN, MiniBooNE

- **LSND:**
  - $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam from stopped pion source

- **MiniBooNE:**
  - $\bar{\nu}_e$ appearance in accelerated $\bar{\nu}_\mu$ beam
  - No similar appearance in $\nu_e$ mode
  → CP violation?

- **KARMEN:**
  - Very similar to LSND, but no excess
The Gallium anomaly (not included in our fits)

- **Calibration** measurements for the GALLEX and SAGE solar neutrino detectors using intense radioactive $\nu_e$ sources ($^{51}$Cr and $^{37}$Ar)
- Neutrino detection via $^{71}$Ga + $\nu_e \rightarrow ^{71}$Ge + e$^-$
- **Result:** Measurements consistently lower than expectation from other calibration methods

**Question:** How well are efficiencies of the radiochemical method understood?

Mention et al. Moriond 2011 talk
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Fit to SBL data in a 3+1 model

- Short baseline: Standard oscillations ineffective ($\Delta m^2$ too small)
- Add extra (sterile) neutrino → 3+1 model (effectively a 2-flavor problem)
- Fit does not work well (no CP violation)

![Graph showing oscillation parameters](image)
Global fit in a 5-flavor framework

Why 5 flavors?

- Need at least 2 sterile neutrinos to have CP violation at short baseline for MiniBooNE $\nu_e$ vs. $\bar{\nu}_e$ (in 3+1, SBL oscillations are effectively 2-flavor)

Parameter goodness of fit: Test compatibility of 2 data sets by comparing global $\chi^2_{\text{min}}$ to $\chi^2_{\text{min}}$ for separate fits
Global fit in a 5-flavor framework

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 Parameter goodness of fit test: Test compatibility of 2 data sets by comparing global $\chi^2_{\text{min}}$ to $\chi^2_{\text{min}}$ for separate fits

JK Maltoni Schwetz, arXiv:1103.4570; see Giunti Laveder arXiv:1107.1452 for another global fit
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Sterile neutrinos and direct dark matter detection

- **Solar and atmospheric neutrinos** are a well-known **background** to future direct dark matter searches

  - See e.g. Gütlein et al. arXiv:1003.5530

- **If low-energy neutrino interactions** are **enhanced** by new physics, this background can be **significantly enhanced**
  - → **Possible explanation of DM anomalies?**

  - Pospelov arXiv:1103.3261, Harnik JK Machado (work in progress)

- Phenomenologically, this is **easiest to achieve** in models with **sterile neutrinos**
Introduce a sterile neutrino + a light ($\ll 1$ eV) gauge boson, weakly coupled to electrons, but not too weakly coupled to sterile neutrinos.

Sterile neutrinos and direct dark matter detection (2)

- Introduce a sterile neutrino + a light ($\ll 1$ eV) gauge boson, weakly coupled to electrons, but not too weakly coupled to sterile neutrinos.

- Can potentially explain CoGeNT excess through $\nu_s - e^-\text{scattering}$.

- The diagram illustrates the phase space for sterile neutrino masses $m_{A'}$ and electron coupling $g_e$, with constraints from various experiments such as CMB, Coulomb, Rydberg, Borexino, SN, and Sun.

- The region of interest lies in the lower left portion of the plot, where sterile neutrinos are produced in the Sun through oscillation.

- The coupling constant $g_e$ is varied on the vertical axis, and $m_{A'}$ is varied on the horizontal axis.

- The plot includes constraints from the cosmic microwave background (CMB), Coulomb, Rydberg, and Borexino.

- The green region represents the allowed parameter space, with constraints from Firas and CAST.

- The red line indicates the fixed target region.

- The purple region shows the constraints from Borexino, where $g_{\nu}=g_e$.

- The gray region is the Sun, and the blue region is the HB region.

- The diagram is preliminary, as indicated by the text at the bottom of the page.

Ringwald et al., Harnik JK Machado (work in progress)
Sterile neutrinos and direct dark matter detection (2)

- Introduce a sterile neutrino + a light ($\ll 1$ eV) gauge boson, weakly coupled to electrons, but not too weakly coupled to sterile neutrinos
- $O$(MeV) sterile neutrinos produced in the Sun through oscillation
- Can potentially explain CoGeNT excess through $\nu_s$–$e^-$ scattering

With several sterile neutrinos, oscillations can lead to annual modulation
Sterile neutrinos and direct dark matter detection (3)

An alternative model

- Assume mass of sterile neutrino to be slightly below the solar Be-7 line
  - Easier to avoid Borexino constraint
  - Xenon-100 electron background may still be a problem

![Graph showing electron recoil count rate versus energy](image)

\[ M_{\nu} = 10 \text{ keV} \]

\[ g_{\nu} g_T = 5 \times 10^{-11} \]

\[ c_V = 1, \ c_A = 0 \]

\[ m_{\nu} = 855 \text{ keV} \]

Harnik JK Machado (work in progress)
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Sterile neutrinos and indirect dark matter search

- IceCube and Super-Kamiokande 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.

![Graph showing the probability of sterile neutrino conversions](image)

Arguëlles JK (work in progress)
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Conclusions

- Several interesting, but inconclusive hints for sterile neutrinos
  - LSND and MiniBooNE
  - Reactor anti-neutrino anomaly
  - Gallium anomaly

- Global fit favors $3 + 2$ scenario with $\Delta m_{41}^2 \sim 0.47 \text{ eV}^2$, $\Delta m_{51}^2 \sim 0.87 \text{ eV}^2$

- But tension remains in the fit

- We need a conclusive $\geq 5\sigma$ result in short-baseline neutrino physics

Far-reaching implications of existence of sterile neutrinos. For instance:

- Potential new signals in direct dark matter searches. Possible explanation for CoGeNT excess in terms of sterile neutrinos + new light gauge force?

- Limits on neutrinos from dark matter annihilation in the Sun can become much weaker
Thank you!
Our fitting procedure

- **Atmospheric neutrinos:** Eight classes of events: Sub-GeV $e, \mu$ ($p < 400$ GeV/c), Sub-GeV $e, \mu$ ($p > 400$ GeV/c), Multi-GeV $e, \mu$, Upward stopping $\mu$, upward throughgoing $\mu$, 10 zenith angle bins each

- **Reactor experiments:** Bugey 3 (incl. spectrum), Bugey 4, Chooz (incl. spectrum), Goesgen 1–3, ILL, Krasnoyarsk 1–3, Palo Verde, Rovno

- **SBL $\nu_e$ appearance experiments:** LSND, KARMEN, MiniBooNE ($\nu$ and $\bar{\nu}$, consider only $E > 475$ MeV, i.e. low-$E$ excess in $\nu_e$ sample not included)

- **Gallium anomaly not included**

- **SBL $\nu_\mu$ disappearance experiments:** CDHS, NOMAD

- All codes reproduce the individual fits from the respective experiments and have been used and tested in many previous projects.