Sterile Neutrino Searches

Carlos Argüelles

NuFact
September, 2021
Cagliari, Italy
Outline

• The need for more than three neutrinos and more
• The garden of forking paths
• Outlook
Outline

- The need for more than three neutrinos and *more*
- The garden of forking paths
- Outlook
The short-baseline anomalies

**LSND (3.8σ)**

These experiments observe $\nu_e$ appearance at $L/E \sim 1 \text{ km/GeV}$!

**MiniBooNE (4.8σ)**

This points to $\Delta m^2 \sim 1 \text{ eV}^2$
These are not alone, other interesting observations

<table>
<thead>
<tr>
<th>Neutrino</th>
<th>$\nu_\mu \rightarrow \nu_e$</th>
<th>$\nu_\mu \rightarrow \nu_\mu$</th>
<th>$\nu_e \rightarrow \nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MiniBooNE (BNB) *</td>
<td>SciBooNE/MiniBooNE</td>
<td></td>
<td>KARMEN/LSND Cross Section</td>
</tr>
<tr>
<td>MiniBooNE(NuMI)</td>
<td>CCFR</td>
<td></td>
<td>Gallium *</td>
</tr>
<tr>
<td>NOMAD</td>
<td>CDHS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MINOS IceCube</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Antineutrino</td>
<td></td>
<td>SciBooNE/MiniBooNE</td>
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<tr>
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</table>

* $\Rightarrow >2\sigma \text{ "signal"}$
The anomalies lie ~ in a line

\[ E_\nu [\text{GeV}] \]

\[ L [\text{km}] \]

- MINOS (Far)
- MINOS (Near)
- CCFR84
- NOMAD
- CDHS
- LSND
- GALLEX
- SAGE
- PROSPECT
- Bugey
- NEOS
- DANSS
- MiniBooNE (BNB)
- MiniBooNE (NuMI)

First oscillation maxima \( \Delta m^2_{13} = 1.32 \text{ eV}^2 \)

Second oscillation maxima \( \Delta m^2_{23} = 1.32 \text{ eV}^2 \)
Vanilla solution: light sterile neutrino

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_s
\end{pmatrix} = 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4
\end{pmatrix}
\]

Assuming Normal Ordering

\[\Delta m^2_{41}\]
Results from electron-neutrino disappearance

Wiggles or fluctuations?
See C. Giunti arXiv:2101.06785

See poster by A. Minotti for a recent summary

See talk by d Galbinski for sensitivity of the Solid experiment
Results from muon-neutrino disappearance

See talk by J. Hewes for recent results from Nova
Global-fit solution

Data strongly prefers a model with a sterile neutrino.

Appearance and Disappearance signals should be related!

\[ P_{\nu_e \to \nu_e} = 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2 (1.27 \Delta m_{41}^2 L/E) \]
\[ P_{\nu_\mu \to \nu_e} = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2 (1.27 \Delta m_{41}^2 L/E) \]
\[ P_{\nu_\mu \to \nu_\mu} = 1 - 4(1 - |U_{\mu4}|^2)|U_{\mu4}|^2 \sin^2 (1.27 \Delta m_{41}^2 L/E) \]

\[ \sin^2 2\theta_{ee} = 4(1 - |U_{e4}|^2)|U_{e4}|^2 \]
\[ \sin^2 2\theta_{\mu\mu} = 4(1 - |U_{\mu4}|^2)|U_{\mu4}|^2 \]
\[ \sin^2 2\theta_{\mu e} = 4|U_{\mu4}|^2|U_{e4}|^2 \]
Appearance and disappearance “preference regions” don’t overlap!

\[ \nu_{\mu} \rightarrow \nu_e \]

\[ \nu_e \rightarrow \nu_e, \quad \nu_{\mu} \rightarrow \nu_{\mu} \]

Appearance and disappearance “preference regions” don’t overlap!

3+1 model severely disfavored by tension between appearance and disappearance

Let’s not forget cosmology!

Dasgupta & Kopp 2014; Chu, Dasgupta & Kopp 2015; Saviano et al. 2014; Mirrizi et al. 2015; Cherry, Friedland & Shoemaker 2016; Chu et al. 2018

See talk by Yvonne Y. Y. Wong at Neutrino 2020 for summary
Outline

• The need for more than three neutrinos and more
• The garden of forking paths
• Outlook
From here: The Garden of Forking Paths*

- Do we understand all SM background/process well enough?
- Are all the anomalies (MB, LSND, reactors) related? Or only some of them? E.g., are LSND and MiniBooNE observing the same physics?
- Since null results are not scrutinized as carefully as anomalous ones. Are all null results reliable?
- Is there a significant signal of electron-neutrino disappearance (e.g. reactors)?
- Is IceCube seeing hints of the missing muon-neutrino disappearance?
- If the anomalies are confirmed as new physics, in what theories are they embedded?

*Garden of Forking Paths is spy/mystery short story by Jorge Luis Borges
Stepping back: What do we know?

- LSND saw an excess of electron-antineutrino events.
- MiniBooNE saw an excess of electron-like events in neutrino and antineutrino modes.
- Reactor experiments using ratios see hints of oscillations at large mass-square-differences.
- Muon-neutrino disappearance has resulted in weak signals at large mass-square-differences.
- Anomalous observations are on a line on L/E.
- Standard cosmological scenarios disfavor an additional neutrino. Though tensions in the Hubble parameter indicate that something is missing.

Indications of new neutrino oscillations

Indications of additional new physics
Stepping back: What do we know?

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Many elements suggest something like 3+1, but something else is hinted by observations and tensions in the data sets.
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Many elements suggest something like 3+1, but something else is hinted by observations and tensions in the data sets.
IceCube Hints

- Best fit:
  \[ \Delta m^2_{41} = 4.47^{+3.53}_{-2.08} \text{eV}^2 \]
  \[ \sin^2(2\theta_{24}) = 0.10^{+0.10}_{-0.07} \]

- Sterile neutrino hypothesis is preferred to null

- Null is rejected at 8% p-value
We measure two things:
- length (direction)
- energy
We extract two parameters:
- squared mass difference
- mixing angle

How does the IceCube analysis work?
Comparison to global-fit solutions

IceCube Preliminary

IceCube muon-neutrino disappearance result is in a very interesting part of parameter space, but has low significance.
Reexamining IceCube

IceCube muon-neutrino disappearance result is in a very interesting part of parameter space, but has low significance.

Is IceCube significance low because we are not looking for the right model?
“Sterile” Neutrino Decay

Decay can be visible or invisible.

If neutrinos are Dirac -> invisible
If neutrinos are Majorana -> visible

\[ \tau = \frac{16\pi}{g^2 m_4} \]
Sterile Neutrino Decay
(3+1+Invisible-Decay)

Global data prefers 3+1+Decay! Does IceCube prefer it?
Results of 3+1+Decay in IceCube

Does IceCube prefer it? YES!

See talk by G. Parker for details
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- Anomalous observations are on a line on L/E.
- Standard cosmological scenarios disfavor an additional neutrino. Though tensions in the Hubble parameter indicate preference for additional radiation/secret interactions.

Many elements suggest something like 3+1, but something else is hinted by observations and tensions in the data sets.
Reexamining MiniBooNE

3+1 oscillation best-fit point does a good job in high-energy region

Low-energy part is not fully explained by 3+1

Indications of additional new physics?

Indications of new neutrino oscillations?
Switching gears: Changing how we look at things

This is useful if we are after an oscillation explanation

In other cases we need to fit these two!

MiniBooNE event identification

Three typical event signatures:
- Muon-neutrino CCQE produces sharp photon ring on PMTS,
- Electron-neutrino CCQE events produces fuzzy ring,
- Muon-neutrino NC can produce pi0: two gammas -> two fuzzy rings.

Cannot distinguish between electrons and photons!
Menu of other explanations

**New signatures**

Gninenko 1107.0279  
Magill et al 1803.03262  
Heavy neutrino $O$(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916,  
CA, Hostert, Tsai et al 1812.08768  
Heavy neutrino $O$(1-100MeV), light $Z'$, decay

**Heavy Neutrino Decay**

Bai et al 1512.05357

Dentler et al 1911.01427,  
de Gouvea et al 1911.01447,  
Hostert & Pospelov 2008.11851

Heavy $O$(100MeV) decay to $\nu_e$

Fisher et al 1909.0956,  
CA, Foppiani, Hostert 2109.03831

Heavy $O$(100MeV) decay to photon

**Oscillations+X**

Assadi et al 1712.08019  
Resonant matter effect

Moss et al 1711.05921, Moulai et al 1910.13456  
Steriles + decay

Liao et al 1810.01000  
Steriles + NCNSI + CCNSI

**More than one at a time**

S. Vergani et al arXiv:2105.06470  
Light Sterile + Heavy neutrino $O$(100MeV),  
magnetic moment
Menu of other explanations

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S. Vergani et al arXiv:2105.06470  
Light Sterile + Heavy neutrino \( O(100\text{MeV}) \), magnetic moment
Non-Minimal HNL: di-electron scenario

E. Bertuzzo et al., PhysRevLett.121.241801
P. Ballett, M. Ross-Lonergan, S. Pascoli,
PhysRevD.99.071701
A. Abdullah, M. Hostert, S. Pascoli,
Non-Minimal HNL: di-electron scenario

Good fit to the energy and angular distribution.

E. Bertuzzo et al., PhysRevLett.121.241801
Non-Minimal HNL: di-electron scenario

In tension with measurements of electron-neutrino scattering
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JSNS\(^2\)@J-PARC will directly test LSND

Pion decay at rest beam and IBD detection
Short Baseline Program@FNAL

M. Bonesini

SBND@FNAL Program

Will test the MiniBooNE low-energy excess &
Perform new searches for electron neutrino appearance

See upcoming talk by V. Gustavo
See talk by M. Bonesini for SBN Program Summary
See talk by M. Torti for plans for ICARUS
See talk by Kathryn Sutton for uBooNE photon analysis

\[ \Delta m_{41}^2 (eV^2) \]

\[ \sin^2 2\theta_{\mu e} \]
IsoDAR@Yemilab will conclusively rule out the 3+1 model, but also due to its ability to trace the oscillation wave see variants on this model such as 3+1+Decay.
IceCube will continue improving muon neutrino disappearance searches. “Low energy” sample (<100 GeV) still not studied.

See talk by K. Leonard DeHolton for more details.
Take home messages

• 3+1 model is disfavored as a global solution.

• Alternative explanations of the short baseline anomalies have been proposed: 3+1+Decay, 3+1+NSI, non-minimal heavy neutral leptons, etc.

• The low-energy part of the MiniBooNE hints points to a non-oscillation explanation.

• Lots of ideas out there. We need more data to solve the short-baseline puzzle.
Thanks!
Bonus slides
Menu of other explanations

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Light Sterile + Heavy neutrino $O$(100MeV),
magnetic moment
Non-Minimal HNL: photon scenario

\[
\sum_{j=1}^{3} \bar{N}_j (i \phi - M_j) N_j + \sum_{i=1}^{3} (d_{ij} \bar{\nu}_i \sigma_{\mu\nu} F^{\mu\nu} N_j + h.c.)
\]

\[
\begin{align*}
\{d, m_N\} &= \{2.8 \times 10^{-7} \text{ GeV}^{-1}, 376 \text{ MeV}\} \\
\text{MiniBooNE Data}
\end{align*}
\]

\[
\begin{align*}
\nu(p, n) &\rightarrow N(p, n) \\
\nu A &\rightarrow NA \\
\nu_\mu &\rightarrow \nu_e \\
\{\Delta m^2, \sin^2(2\theta)\} &= \{1.3 \text{ eV}^2, 6.9 \times 10^{-4}\} \\
\text{MiniBooNE Data}
\end{align*}
\]
A global solution: 3+1+HNL-photon

<table>
<thead>
<tr>
<th>Used to Test</th>
<th>References (Flux Type)</th>
<th>Type of Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e$ disappearance</td>
<td>[39–43] (Reactor)</td>
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</tr>
<tr>
<td>$\nu_e$ disappearance</td>
<td>[44–46] (Source)</td>
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</tr>
<tr>
<td>$\bar{\nu}_\mu \to \bar{\nu}_e$ appearance</td>
<td>[47, 48] ($\pi/\mu$ DAR)</td>
<td>$3+1$-only</td>
</tr>
<tr>
<td>$\nu_\mu \to \nu_e$ appearance</td>
<td>[49] ($\pi/\mu$ DIF)</td>
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<tr>
<td>$\bar{\nu}_\mu$ disappearance</td>
<td>[50–53] ($\pi/\mu$ DIF)</td>
<td></td>
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<tr>
<td>$\nu_\mu$ disappearance</td>
<td>[51, 54–56] ($\pi/\mu$ DIF)</td>
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3+1 + $\mathcal{N}$

Explained by eV-sterile

Explained by MeV-HNL

<table>
<thead>
<tr>
<th>Fit type:</th>
<th>3+1-only</th>
<th>3+1-complete</th>
</tr>
</thead>
<tbody>
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<td>$\chi^2_{app}$</td>
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<td>$\chi^2_{dis}$</td>
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<td>$N_{glob}$</td>
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<td>$\chi^2_{PG}$</td>
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<td>28</td>
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<tr>
<td>$N_{PG}$</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

$p$-value: 7E-03, $N\sigma$: 2.7$\sigma$, 4.8$\sigma$

Tension

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Light sterile parameter space

Heavy "sterile" parameter space

3+1+Decay In IceCube

3+1+Decay model compared to 3+1 produces broader and smoother muon-neutrino disappearance.
Phenomenological implications of 3+1+Decay


- Reactor experiments experience reduced oscillations features.
- Oscillation probability at MiniBooNE slightly shifted to higher energies.
Reactor Antineutrino Anomaly (RAA)

Nuclear reactors: electron spectra from $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$ are translated to $\bar{\nu}_e$ flux

A recalculation of fluxes lead to $\sim 6\%$ discrepancy with $2\%$ error bars

Berryman & Huber
Phys. Rev. D 101, 015008

3σ significance, but fully driven by theoretical prediction.

Constraints from Direct Mass Measurements

Compare to other muon-neutrino disappearance results
Best-fit point (data) and signal shape (Monte Carlo)

$$\Delta m^2_{41} = 4.47^{+3.53}_{-2.08} \text{eV}^2$$

$$\sin^2(2\theta_{24}) = 0.10^{+0.10}_{-0.07}$$
Event distribution (data) and best-fit shape (Monte Carlo)

- Best-fit shape effect is in a low-statistics regime
- Hard to see by eye in the data
- But the result does not seem to be a statistical fluctuation
- Consistent year-to-year

< 100 events/bin $\rightarrow$ > 10% stat. error

< 6% shape effect
Best-fit shape effect is in a low-statistics regime
- Hard to see by eye in the data
- But the result does not seem to be a statistical fluctuation
- Consistent year-to-year

Event distribution (data) and best-fit shape (Monte Carlo)
Sterile Neutrino Decay  
(3+1+Visible-Decay)


Neutrino Decay as a Solution to the Short-Baseline Anomalies  
Sterile Neutrino Decay
(3+1+Visible-Decay)

Visible decay predicts emission of antineutrinos from the Sun!

Neutrino Decay as a Solution to the Short-Baseline Anomalies
Non-Minimal HNLs - Testability

Photon-like signatures
neutrino-electron scattering
(MINERvA, CHARM-II)

$\mu_{\nu,1} = 30 \text{ MeV}, \alpha^2 = 2 \times 10^{-10}, \alpha_B = 1/4$


More data from: MINERvA, NOvA, and SBN program to come soon!

Rare kaon decays

P. Ballet, M. Hostert, S. Pascoli,

Double cascades in IceCube

P. Coloma et al, arxiv:1707.08573,
P. Coloma arxiv:1906.02106

KOTO & muon (g-2) anomalies

B. Dutta, S. Ghosh, T. Li, PhysRevD.102.055017

BSM Physics at the Electron Ion Collider: Searching for Heavy Neutral Leptons

(https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF7_EF0-NF2_NF3-RF4_RF0_Brian_Batell-114.pdf)

Dark Sector With Neutrino Beams


Opportunities and signatures of non-minimal Heavy Neutral Leptons

Non-Standard Matter Effects
(3+1+NSI)

J. Liao et al

See also Denton et al
Bhupal Dev et al

Direct Probes of Matter Effects In Neutrino Oscillations
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF1_NF3-TF0_TF0_Peter_Denton-010.pdf)
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Position of resonance maps onto sterile parameter space

We measure two things:
- length (direction)
- energy

We extract two parameters:
- squared mass difference
- mixing angle