Overview: Neutrino Experimental Anomalies (NF02)

July 21, 2022

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This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.
Standard Model Neutrino Oscillations

- Have a beautiful picture of three oscillating Standard Model neutrinos coming into focus
  - Three mass differences define the relative weights of the different neutrinos
    - Also defines the travel distance required for flavor change to occur
  - Three angles define which flavors are in each mass state
    - Also defines magnitude of flavor changing

\[
\begin{align*}
\Delta m^2_{\text{atm}} & \approx 2.5 \times 10^{-3} \text{ eV}^2 \\
\Delta m^2_{\text{solar}} & \approx 8.3 \times 10^{-5} \text{ eV}^2 \\
\tan^2 \theta_{13} & \approx 0.002
\end{align*}
\]
Sampling Neutrino Flavors

• We got here by sampling neutrino flavors.
  • Want to make sure I taste the flavor that was produced: stout, amber, pilsner?
• For neutrinos, charged current interactions enable this
  • Want to make sure I detect the flavor that was produced: e, μ, or τ?
Many detector technologies can help us taste that flavor:

- Electron = shower-like
- Muon = track-like

MicroBooNE: a liquid argon TPC in a $\nu_\mu$ beamline
Neutrino Oscillations: L and E

- Have a beautiful picture of three oscillating Standard Model neutrinos coming into focus
- Took many experiments to get us here!
- Baselines (L): >km-scale
- Energies (E): MeV to GeV++!

Example: OPERA

Example: KamLAND
Neutrino Oscillations: L and E

- Have a beautiful picture of three oscillating Standard Model neutrinos coming into focus
- Took many experiments to get us here!
- Baselines (L): >km-scale

- Let’s go HERE!
- WHY go here?
Neutrino Anomalies

- Neutrino fluxes and energies measured at < km disagree with state-of-the-art neutrino predictions
- Indications of something odd beyond ‘SM oscillation’?!
Reactor and Gallium Anomalies

- Deficits in neutrino detection rates at electron-flavor sources
- Sources host only lower (MeV-scale) energy scale processes

\[ \bar{\nu}_e \]

Daya Bay: liquid scintillator inverse beta decay detectors

SM neutrino oscillations

Daya Bay, CPC 41 (2016)
MiniBooNE and LSND Anomalies

- Excesses of electron-like events in ~muon-flavor sources
- Sources host some higher (GeV-scale) energy scale processes

MiniBooNE Anomaly
- MiniBooNE (2002-2019) observed low-energy excess (LEE) with 4.8σ (systematics limited) significance
- If LEE is interpreted as ν_e appearance in the primarily ν_µ beam, would suggest 4th (sterile) neutrino

Phys. Rev. D103, 052002

Too many fuzzy rings in MiniBooNE!

Electron Cherenkov ring event in MiniBooNE

MiniBooNE: an oil Cherenkov detector
New Neutrino Mass States?

- Neutrino fluxes and energies measured at < km disagree with state-of-the-art neutrino predictions
- Indications of new physics beyond ‘SM oscillations’?(!)
- New flavor transformations (like sterile osc)? New dark sector interactions?
New Neutrino Mass States?

- Other good reasons to look for new mass states, too
  - Dark matter: could heavy neutral leptons be a viable candidate?
  - See-saw mechanism: heavier neutral leptons help explain why SM neutrinos are so light?

- ``Ultralight'' DM: non-thermal bosonic fields
- ``Light'' DM: dark sectors sterile $\nu$ can be thermal
- WIMP
- Composite DM (Q-balls, nuggets, etc)
- Primordial black holes

<table>
<thead>
<tr>
<th>Mass State</th>
<th>Window</th>
<th>Limit</th>
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<tbody>
<tr>
<td>$10^{-22}$ eV</td>
<td>QCD axion classic window</td>
<td>WDM limit</td>
</tr>
<tr>
<td>$10^6 - 10^4$ eV</td>
<td>GeV</td>
<td>unitarity limit</td>
</tr>
<tr>
<td>$100$ TeV</td>
<td>$M_{pl}$</td>
<td>$10 M_\odot$</td>
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Outline For This Session

• In the Neutrino Frontier, we are excited about these anomalies!

• Our plan for this session:
  • 2 talks summarizing what we’ve learned about anomalies in the last P5 period
  • 1 talk recent describing developments in theory/pheno views of the anomalies
  • A panel discussion aimed at what the next P5 period holds for the sub-field

<table>
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<tr>
<th>Time</th>
<th>Session Title</th>
<th>Speaker</th>
<th>Duration</th>
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<tbody>
<tr>
<td>10:15 AM</td>
<td>Experimental Status: Atmospheric/Accelerator DIF and DAR</td>
<td>Mark Ross-Lonergan</td>
<td>15m</td>
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<tr>
<td>10:30 AM</td>
<td>Experimental Status: Radioactive Sources and Reactors over the Past 10 Years</td>
<td>Pranava Teja Surukuchi (Yale University)</td>
<td>15m</td>
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<td>10:45 AM</td>
<td>Recent Theory Progress and Interpretation(s)</td>
<td>Matheus Hostert (Perimeter Institute)</td>
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<td>11:05 AM</td>
<td>Panel: Path to Resolution through Neutrino Experiments and Beyond</td>
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