Prospects for the Search for Sterile Neutrinos

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Big questions

What is the origin of the neutrino masses?

What is the optimal strategy towards a complete set of measurements of neutrino oscillation parameters and towards a precision global fit of the PMNS matrix?

Is the existing experimental program (reactor, SBL) sufficient to confirm or exclude the existence of sterile neutrino states with masses in the eV/c² range?

How to search for heavy neutral leptons with present and future facilities?

Is gravity described by the Einstein theory of general relativity?

How do gravitational waves help to understand Dark Sector of the universe?

What is the proton-proton cross section at ultra-high energies?

How can cosmic neutrino’s help to pin-down their properties oscillations and mass hierarchy?
**Big questions**

What is the origin of the neutrino masses?

What is the optimal strategy towards a complete set of measurements of neutrino oscillation parameters and towards a precision global fit of the PMNS matrix?

Is the existing experimental program (reactor, SBL) sufficient to confirm or exclude the existence of sterile neutrino states with masses in the eV/c² range?

• Motivation: Hints from short baseline experiments suggesting new physics
• Reactor and SBL accelerator dedicated searches → new results now and coming soon….
• Results from other experiments, and limits from cosmology
• Putting it all together: Global fits and implications for long baseline measurements

How can cosmic neutrino's help to pin down their properties oscillations and mass hierarchy?
Accelerator Anomalies: Evidence of excess of electron neutrino events ($\nu_e$ appearance?) from the LSND and MiniBooNE experiments

**LSND**
- Liquid Scintillator detector
- $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam
- $L/E \sim 1$ ($E_\nu \sim 40$ MeV)

**MiniBooNE**
- Oil Cerenkov detector
- $\nu_e$ appearance in $\nu_\mu$ beam
- $L/E \sim 1$ ($E_\nu \sim 800$ MeV)

New results in 2018
Experiments at very short baselines for reactors for many years reported some deviation from prediction – not significant

Re-calculation of flux changed interpretation of this data...
At short baselines experiments see fewer neutrinos than expected (red line)
Electron neutrinos disappearing

Source measurements....

The Gallium Anomaly

\[ R = N_{\text{exp}} / N_{\text{no osc}} \]

\[ R = 0.84 \pm 0.05 \]

Signals at SBL are at the 2-4σ level. All pointing in the same direction.

Taken individually, each anomaly is not significant enough to be convincing…. But they are all pointing toward the same thing….

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>DAR</td>
<td>$\bar{\nu}_\mu \to \bar{\nu}_e$ CC</td>
<td>3.8σ</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>SBL accelerator</td>
<td>$\nu_\mu \to \nu_e$ CC</td>
<td>4.5σ</td>
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</tr>
<tr>
<td>GALLEX/SAGE</td>
<td>Source - e capture</td>
<td>$\nu_e$ disappearance</td>
<td>2.8σ</td>
</tr>
<tr>
<td>Reactors</td>
<td>Beta-decay</td>
<td>$\bar{\nu}_e$ disappearance</td>
<td>3.0σ</td>
</tr>
</tbody>
</table>

Most commonly interpreted as hint for one or more new “sterile” neutrino (oscillates but does not interact weakly) at large $\Delta m^2_{\text{new}}$ ($\sim1\text{eV}^2$) and small mixing.
Short Baseline Results cannot be explained by three neutrinos responsible for long baseline oscillations.

$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} \sin^2 (1.27 \Delta m^2_{ij} \frac{L}{E})$

Need a fourth (or more) “sterile” state

3+1 model
Number of experimental efforts with or near first results:

- Dedicated searches
  - SBL reactor experiments
    - New searches for nuebar disappearance
    - New measurements informing reactor flux predictions
  - SBL Accelerator experiments: SBN program at Fermilab
- Limits from other experiments
  - MINOS+, ICECUBE
- Limits from cosmology
- Experiments in planning stages

Will discuss recent results...
Reactor experiments:

Pure $\bar{\nu}_e$ source produced by fissions in $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$

$\bar{\nu}_e$ disappearance baseline $\sim$ m
Reactor experiments:

Pure $\nu_e$ source produced by fissions in $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$
NEOS: “Neutrino Experiment for Oscillation at Short baseline”

- 23.7m from reactor core at Hanbit Nuclear Power Plant, Korea
- 1 ton Gd-LS active target
- Phase I: 180 days live --> no strong evidence of sterile neutrino (PRL 118.121803)
- Phase II: underway as of Sept 2018
DANSS: Detector of the reactor AntiNeutrino Solid State

- Movable detector (10.7-12.7 m)
- Results based on comparison of rated at two different baselines
- Independent of predicted reactor flux
• Segmented liquid scintillator Gd loaded cells
• Movable detector (6-12m)
• Data takings since June 2016

Report oscillation at large $\Delta m^2$ and large mixing ($1\sigma$ contour $\rightarrow$ blue) ...
SoLid

BR2 nuclear site
- Compact research reactor
  - Fuel 93.5% $^{235}$U
  - Thermal power 50-80 MW
  - Duty cycle 150 days/year (~1 month cycles)
  - SoLid at baseline 6-9 m
  - Segmented solid scintillator
  - First physics data in 2018
STEREO at ILL

- ILL: Research reactor (58MW)
- Pure 235U fission spectrum
- Movable location 9-11m from reactor core
- Relative measurement in 6 identical cells
- Phase I: Nov 2016-March 2017
- Phase II: October 2017-2020
Segmented, $^6$Li loaded, movable detector at HFIR at Oakridge
Look for oscillation signature vs distance (flat ratio consistent with no oscillations)
1st results from 33 days livetime $\rightarrow$ 95% exclusion curve disfavors RAA at 2.2$\sigma$
Continued running underway
Reactor Measurements...

- Segmented, 6 Li loaded, movable detector
- Look for oscillation signature vs distance (flat ratio consistent with no oscillations)
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PROSPECT Physics
A Precision Oscillation and Spectrum Experiment

Spectral Distortion vs Baseline

- Sensitivity: 3σ CL
- Phase-I (1 yr), Multiple Positions
- Phase-I (3 yr), Multiple Positions
- SBL Anomaly (Kopp), 95% CL
- All ν, Disappearance Exps (Kopp), 95% CL
- SBL + Gallium Anomaly (RAA), 95% CL
- Daya Bay Exclusion, 95% CL

3σ, 3 yrs
3σ, 1 yr

Daya Bay
**Predicting the reactor flux...**

Measure spectrum of $^{235}$U to test model predictions of reactor flux from Daya Bay, Prospect, ...

Example:

**Prompt Energy Spectrum**

- **Improvement on ILL**
  - ~100k events per year
  - ~4.5%/\sqrt{E}
  - ~5000 events

- **Testing models of $^{235}$U $\bar{\nu}_e$ spectrum**
  - 2018 ILL
  - PROSPERT - Phase 1
  - $\beta$-Conversion, Huber, 1-$\sigma$
  - $\beta$-Conversion, Huber, 1-$\sigma$
  - Nuclear Calculation, Daya Bay, Langed, 1-$\sigma$
  - PROSPERT, near 3Y, 1-$\sigma$
  - PROSPERT, near 3Y, 1-$\sigma$

- **Ratio to Huber**
  - Huber
  - Best-fit excess

- **$\chi^2$ Contribution**
  - Local P-Value

- **Reconstructed Visible Energy (MeV)**

![Graph showing improvement on ILL and testing models of $^{235}$U $\bar{\nu}_e$ spectrum.](image)
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New results in 2018

3.8 $\sigma$

4.5 $\sigma$
Fermilab: Three detector Short Baseline Neutrino (SBN) program on the Booster Neutrino Beamline
Muon neutrino beam (same as MiniBooNE) sampled at SBND near detector (no oscillations), far detectors: MicroBooNE, ICARUS

- MicroBooNE: Address the MiniBooNE Low Energy Excess: Is it electrons or photons?
- SBND: Is there a baseline dependent effect?
- ICARUS: With large detector, span all allowed regions in parameter space at 5σ
$\nu_e$ appearance sensitivity with three detector SBN experiment
Physics reach of the SBN Program

- Definite test (>5σ) of the currently allowed oscillation parameter regions
- In addition to $\nu_e$ appearance, SBN also has sensitivity to $\nu_\mu$ disappearance
  - Needed to confirm an oscillation interpretation of any observed appearance signal
  - Providing a more robust result on sterile-neutrino-induced oscillations
Experiments capitalize on topology and calorimetry capabilities of LArTPCs

Critical for SBN experiments → Resolve size and \textit{NATURE} of excess
Phase 1: MicroBooNE → data taking

- 14 papers, 33 public notes
- Final year of data taking for 1st oscillation results

2015
- Detector turn on (October)
- Cosmic and beam data
- Immediate identification of neutrinos

2016
- First MC release of automated LArTPC reconstruction (MCC7)
- Performance results and Data/MC discrepancies
- “Open development” phase, investigate novel ideas, major effort on low level and high level reconstruction

2017
- CRT installation
- Converging on a new robust MC (MCC8), first MC using data as input
- Efforts on modelling, first calibrations, particle ID, 1st systematics, computing speed up

2018
- Exploiting MCC8 for 1st physics results
- Identified limitations in signal processing and efficiencies
- 1st iteration on calibrations, systematics → targeted development of a new MC (MCC9)

2019-2020
- Flagship results with flagship MC that makes extensive use of uB data as a constraint

Public notes
- 2/7/19 Princeton Colloquium, 2018

Publications:
- JINST 12, P07006 (2017)
- JINST 12, P07007 (2017)
- JINST 12, P08003 (2017)
- JINST 12, P10010 (2017)
- JINST 12, P12030 (2017)
- JINST 12, P03011 (2017)
- JINST 13, P02017 (2017)
- JINST 13, P07006 (2018)
- JINST 13, P07007 (2018)
- JINST 13, P08003 (2018)
- arXiv:1805.06887
- arXiv:1805.06887
- arXiv:1805.06887
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- arXiv:1805.06887
Phase 2: SBND + ICARUS

SBND:
- Detector design finalized
- Installation is going to happen in 2019

SBND Detector Hall: Test installation of CRT panels

TPC and other components under construction

Planned data taking 2020

ICARUS:
- Currently in the installation phase
- Cosmic Ray Taggers are being installed and tested

ICARUS Warm vessel completed

ICARUS Cold shield recently installed

Planned data taking 2019
Developing technology (hardware and software) en route to DUNE

89 tonnes of active mass

MicroBooNE

ProtoDUNE single phase
CERN Neutrino Platform
Limits from LBL measurements for 4 neutrino oscillations (MINOS+)

- Different oscillation signatures in near and far detectors based on mass splitting (left)
- MINOS+ combines LBL limits on $\theta_{24}$ with reactor limits on $\theta_{14}$ to compare to miniboone allowed region (right)
Global Fits

- Each of the anomalies can be explained by sterile neutrinos
- Global fits consider 3+1 models (most conventional) but also more exotic…
- Problems with global fits to all data…
- Strong tension between appearance and disappearance experiments (not new...)
- Discrepancies between reactor neutrino results (eg: PROSPECT rules out Neutrino4)

*Other future measurements will inform hints and limits:*

- BEST (source experiment)
- KATRIN and $^{163}$Ho neutrino mass experiments also sensitive to sterile neutrinos
- JSNS2: direct test of LSND
- Continued measurements from IceCube DeepCore
Summary:

Is the existing experimental program (reactor, SBL) sufficient to confirm or exclude the existence of sterile neutrino states with masses in the eV/c² range?

We will know a lot more in the next couple of years!

- Reactors:
  - results can be interpreted as hints or limits. As limits, consistent with no oscillations at ~2σ level, ... some inconsistencies amongst all experiments (ie: Neutrino 4)
  - Analysis of predicted flux informed by spectral measurements from experiments
    - (Spectral feature at 5 MeV still not understood)
- SBN accelerator program
  - Phase 1: First results from MicroBooNE
  - Phase 2: with SBND and ICARUS
    - 5σ coverage of allowed region
    - Near/Far comparison in same technology for both appearance and disappearance