NF02 Status Report

~~Sterile Neutrinos~~ → Understanding Experimental Anomalies

Snowmass Neutrino Frontier Community Feedback Meeting - Feb. 9, 2022

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NF02 Scope: Understanding Experimental Anomalies

What is our scope:

- Current neutrino experimental anomalies: LSND, MiniBooNE, reactor and gallium anomalies
- Solving the anomalies: standard and BSM origins, current and future experimental input
- The solutions for these anomalies are likely to drive a large fraction of the effort in our field (e.g. SBN program and recent/upcoming μB results)

What is NOT our scope:

- Broader/more general BSM physics (NF03), general neutrino-nucleus interactions (NF06)
- Identifying which experiments to build or which theories to test first

NF02 Scope: Understanding Experimental Anomalies

There are clear connections to other working groups

- NF01: CPV is a O(1%) effect. Solutions to the anomaly could affect precision CP determination (not now, but, e.g. in DUNE)
- NF03: Large overlap; our BSM focus is on "BSM that can address the current anomalies." How to disentangle models? Where can we probe different solutions?
- NF06: ν-N interaction model play a major role in interpreting the anomalies (Gallium, MiniBooNE)
- NF09: A better understanding of the Reactor Antineutrino Anomaly (RAA) requires interrogating reactor flux calculations
- NF10: Different solutions can be probed in different detectors, e.g. MicroBooNE's NC Δ to Nγ search, e^+e^- signals in LArTPCs, up-scattering events in IceCube

Strategy

Solicited Community Input → A total of 47 LOIs relevant to NF02 (links to LOIs are available here: https://www.snowmass21.org/neutrino/sterile/start)

Inspired by last Snowmass process → a single "encyclopedia" of experimental neutrino anomalies, within the context of light sterile neutrino oscillations **and beyond**, in **a single White Paper**

More expansive review, serve as guidance and motivation for follow-up tests/ultimate resolution

This area of neutrino physics will continue to evolve, given anticipated experimental results in the next 5 years with relevant sensitivity to proposed interpretations. Need to think **beyond current/planned experiments**, in anticipation of what can be learned (theory+experiment).

Emphasis on **needs and options for future**.

→ **NF02 Report will be heavily inspired by White Paper Summary**

NF02-Wide White Paper: In a nutshell!

WHITE PAPER ON LIGHT STERILE NEUTRINO SEARCHES AND RELATED PHENOMENOLOGY
NF02 CONTRIBUTED PAPER TO SNOWMASS 2021

1. **Introduction and Motivation**: Neutrinos as a portal to new physics
2. **Experimental Anomalies**: review of LSND, MiniBooNE, RAA and Gallium Anomaly
3. **Interpretations of the Anomalies**:
   a. BSM with flavor conversion: 3+1
   b. BSM with flavor conversion: 3+1 with variations
   c. New particles in neutrino scattering, e.g. dark neutrinos, magnetic moment
   d. New particles in the beam, e.g. HNLs and dark matter
   e. Conventional explanations, e.g. single photon emission, reactor flux modeling, xsec uncertainties
4. **Broader Experimental Landscape**: Putting the anomalies and interpretations in context with other results, e.g. from null decay-at-rest and decay-in-flight experiments (SBL experiments, MINOS/MINOS+, etc.), recent SBL reactor experiments, atmospheric neutrino experiments, etc.
5. **Indirect Probes**: Cosmology (BBN, CMB, LSS), astrophysics, direct neutrino mass measurements
6. **Future Prospects**: Long list of planned and proposed experiments
7. **Summary of Requirements**: requirements for future experiments, theory developments (e.g. BSM in generators), analysis/statistical data treatment in order to address the anomalies, including discussion on experimental data releases

Emphasis is on “beyond 3+1” + conventional

NF02-Wide White Paper Contributions

- We currently have 4 lead editors; plus an additional ~10 editors who are responsible for specific sections/subsections; and multiple contributors who have provided input in specific topics (e.g., 3+1 global fits, experimental prospects, etc.)

- Majority of editors are early-career
- Contributors span all levels of seniority and a healthy admixture of theorists and Experimentalists

- Incomplete author list shown here; **co-authorship is open to the community** (sign up here, see last slide for details)

White Paper on Light Sterile Neutrino Searches and Related Phenomenology

NF02 Contributed Paper to Snowmass 2021

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NF02-Wide White Paper Walkthrough

1. Introduction and Motivation

Three-neutrino picture now established as Extended SM, following the discovery of neutrino oscillation, which stands as one of few **indisputable pieces of evidence for new physics "beyond the SM"**

Neutrino mass generation mechanism is qualitatively different from that of other fermions. Generally **requires addition of new particle content to SM**, but no experimental indication of scale of new physics. **Neutrinos are a promising portal to new physics**, where we can look for deviations from ESM phenomenology, or search for other particle production in neutrino beams/detectors.

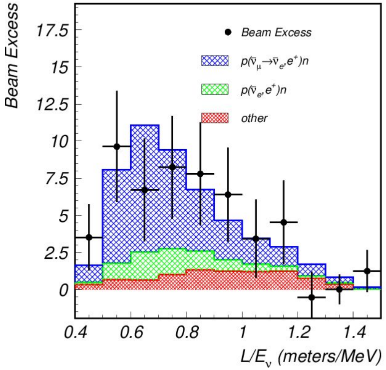
Interest in this direction further fanned by a series of experimental anomalies, suggesting the existence of new neutrino states. An **expansive and dedicated scientific program has been launched** over the past two decades to address them.

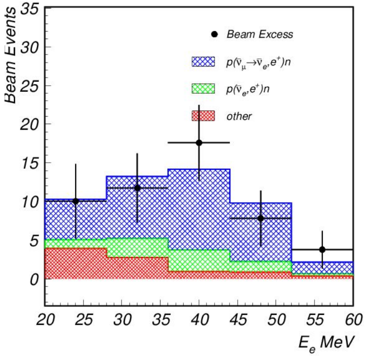
One of the most widely examined theoretical frameworks is that of **light sterile neutrino oscillations (broadly, 3+N).** While it can accommodate all short-baseline anomalies to date, it **fails** to accommodate the lack of corresponding signals in other short-baseline, long-baseline, and atmospheric measurements. The need to interpret compelling experimental results has **given rise to extensive experimental neutrino program and substantial body of related phenomenological work**, including many viable interpretations, which we review.

BSM physics which may be responsible for observed experimental neutrino anomalies will **continue to compel particle physicist toward further experimentation in this area for years to come**. Discovery of new physics would be **groundbreaking**; implications for particle physics, astrophysics, cosmology. A **clear null result/(E)SM explanation(s)** would bring a welcome resolution to a **long-standing puzzle**, and clarify current neutrino picture, paving the way toward "clean" neutrino measurements at future facilities.

NF02-Wide White Paper Walkthrough

2. Experimental Anomalies



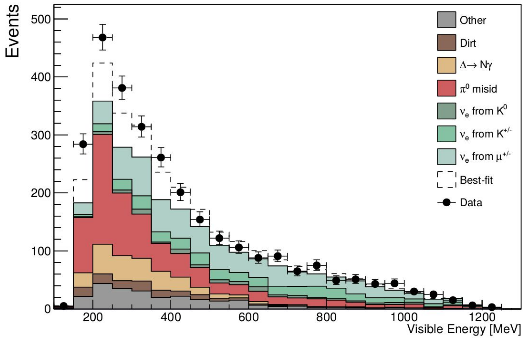


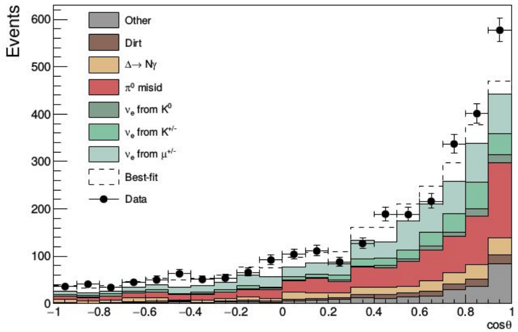
LSND

- Introduction of the long standing LSND anomaly, both detector technology and how the signal was detected.
- Brief mention of the primary backgrounds and how they were reduced.
- Excess described both in terms of traditional 3+1 sterile oscillation paradigm (including final allowed region) but also in terms of visible energy and a brief description of the other variables in which the excess was fit

NF02-Wide White Paper Walkthrough

2. Experimental Anomalies





MiniBooNE

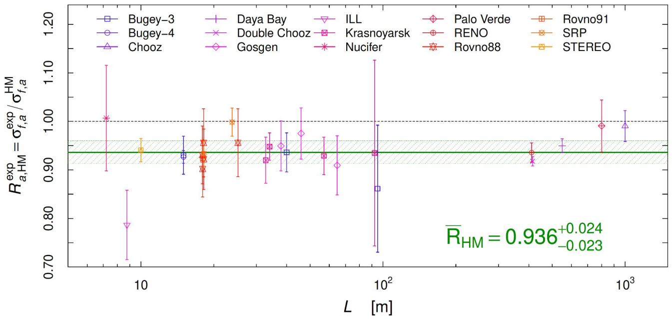
- Introduction to the MiniBooNE detector, with a focus on the various backgrounds to the primary $\nu_\mu \rightarrow \nu_e$ oscillation search.
- Excess described not only in terms of reconstructed neutrino energy (which is primarily relevant for oscillatory solutions) but also in terms of visible energy, angle, detector radius, and timing.
- Discussion of cherenkov detection methods, and how electrons and photons (and co-linear e+e-) are irreducible backgrounds. This motivates recent theoretical interpretations in Sec. 3.

NF02-Wide White Paper Walkthrough

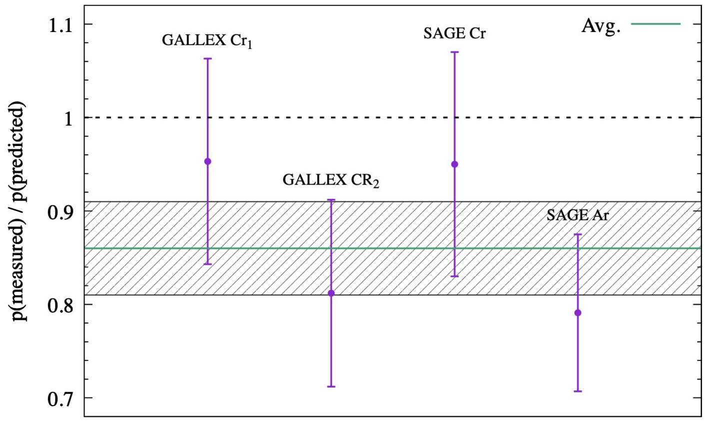
2. Experimental Anomalies

Reactor Antineutrino Anomaly

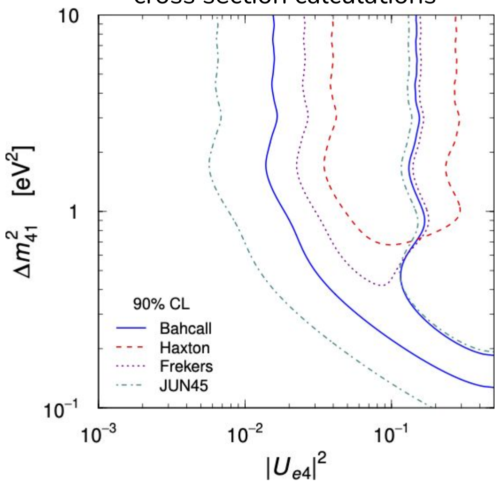
- Until early 2000s, reactor neutrino experiments that measured fluxes agreed with the predicted flux
- In 2011, updated reactor models and neutron lifetime increased the predicted fluxes
- Observed a global deficit **5-6%** in measured fluxes: Reactor Antineutrino Anomaly (RAA)
- Sterile neutrinos at ~eV scale could explain RAA
- Experiments measuring fluxes post-RAA also observed the deficit
- Oscillation frequencies in general agreement with the sterile neutrino suggested by LSND, MiniBooNE, and Gallium anomalies



NF02-Wide White Paper Walkthrough
2. Experimental Anomalies



GALLEX and SAGE - Different cross section calculations



[J. Kostensalo *et al.* PLB(2019)]

Gallium Anomaly

- GALLEX, SAGE detected electron neutrinos from radioactive sources (^{51}Cr and ^{37}Ar) using ^{71}Ga as the detector.
- The ratio of the measurement and expected ^{71}Ge event rates were found to be less than one.
- Limited by uncertainties on the cross section.
- But, hint of electron neutrino disappearance (short-baseline) under a 3+1 scenario
- All experiments are compatible with light sterile neutrino scenario (3+1)
- Significance of the gallium anomaly is larger than 2σ, depending on the cross section

NF02-Wide White Paper Walkthrough

3. Interpretations of the Anomalies

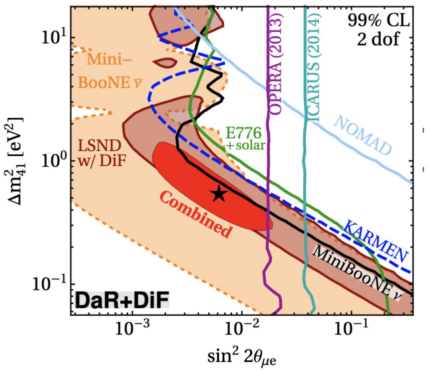
- **A large number of contributions on this section from the community. Thank you!**

NF02-Wide White Paper Walkthrough
3. Interpretations of the Anomalies

Historically, short-baseline data was interpreted mostly in terms of oscillations, but recent years have seen a shift towards other types of physics at low-scales.

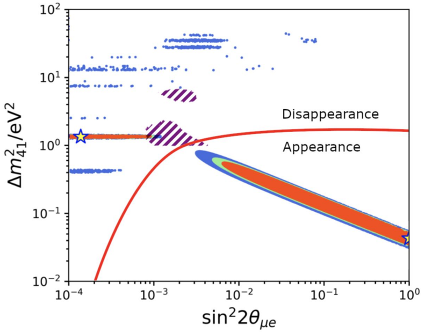
Discussion of flavor conversion models begins with 3+1

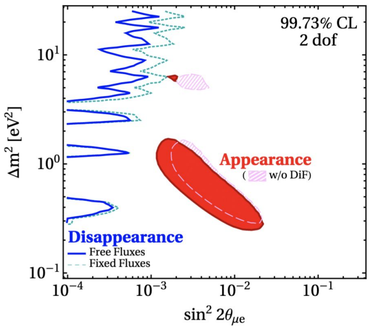
- Global fits to short-baseline data showing strong tension between appearance and disappearance data sets. Caveats: statistics, interpretation of CLs, theory uncertainties



Prompts consideration of alternative flavor-conversion explanations beyond (3+1) oscillations:

- (3+1) + wavepacket decoherence
- (3+N)
- (3+1) + NSI
- (3+1) + decay
- Flavor-violating μ decays
- Large extra dimensions and altered dispersion relations
- Lorentz violation





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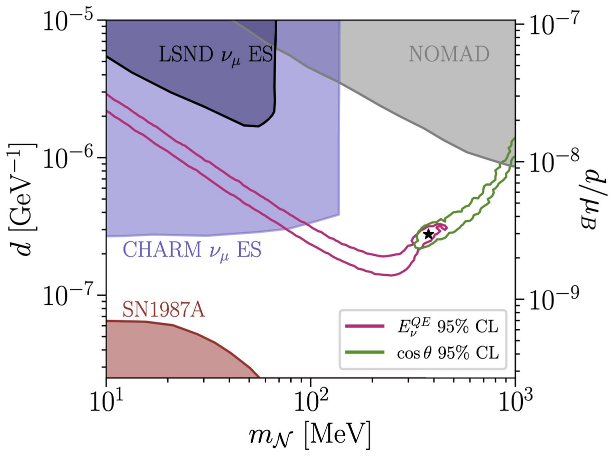
3. Interpretations of the Anomalies

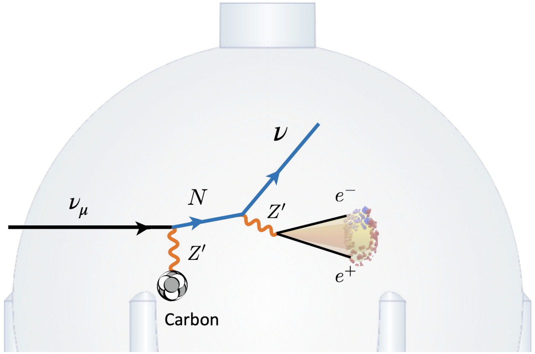
3.2.1 Transition Magnetic Moment

- Electromagnetic and weak production of N, followed by **N** → **vγ** decay via magnetic moment.
- Single photon showers.



3.2.2 Dark Neutrinos

- Scattering and decay via new forces, such as a dark photon or scalar:
  - **N → v(Z' → e+e-) or N → v(S→e+e-)**
  - **N → v(S→ γγ)**
- Mimic single showers when overlapping



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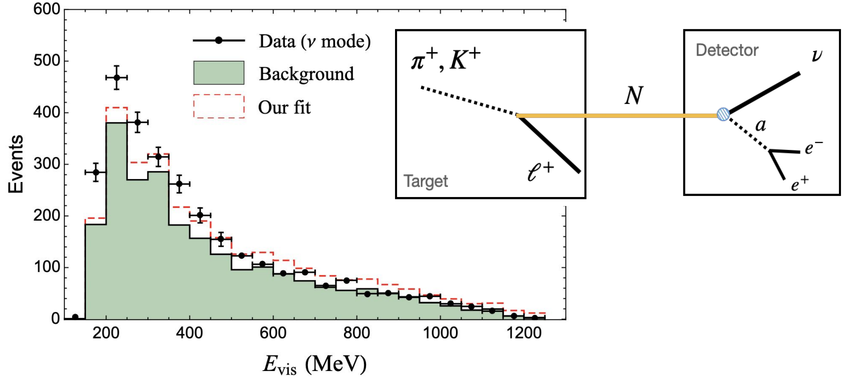
3. Interpretations of the Anomalies

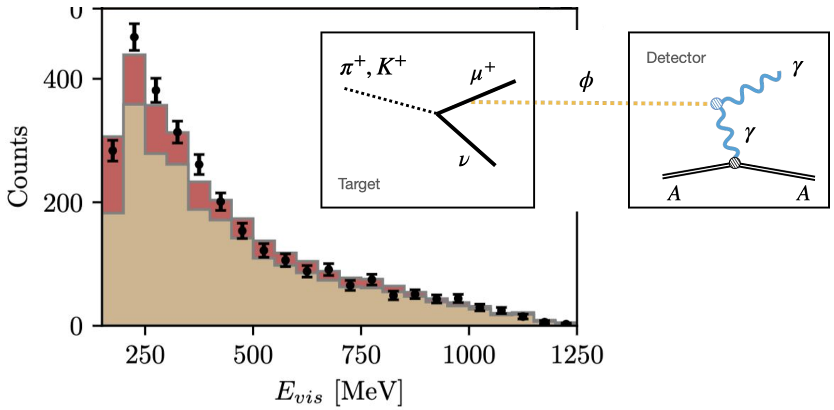
3.2.3 Long-Lived Heavy Neutrinos

- Decay-in-flight signatures of HNLs with new interactions (e.g. with axion-like particle).



3.2.4 Dark Matter Particles

- New particles produced in charged meson decays, which then interact inside the detector to produce e+e- or single photons.



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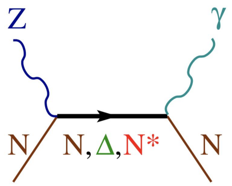
3. Interpretations of the Anomalies

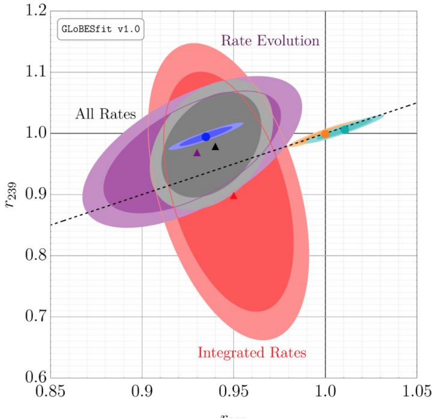
3.3.1 Single Photon Production

- An irreducible background in MiniBooNE at low energy; could have contributed to the excess (independently of possibility of BSM) if mis-modeled/underestimated
- SM calculation by Alvarez-Ruso et al. finds a rate much in agreement with MiniBooNE estimates.
  - Main contribution from Delta(1232) (w/ propagator in nuclear medium).
  - Coherent photons are a small component.



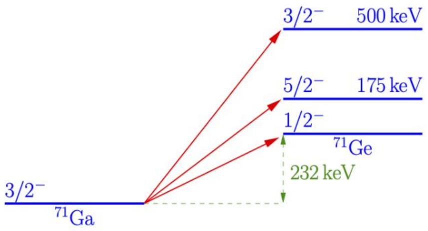
3.3.2 Reactor Flux Modeling

- Database-driven flux predictions deviate substantially from beta-driven conversion predictions
- Conversion predictions using new beta measurements don't match well with previous conversion predictions
- Sizeable uncertainties still appear to leave room for steriles.



3.3.3 The Gallium Anomaly and Interaction Cross-Section Uncertainties

- Is nu-Ga x-section over-estimated?
- Early nu-Ga x-sections calcs only consider GS → GS transition, didn't include error bands
- New calculations all seem to agree an anomaly is present.



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4. Broader Experimental Landscape

4.1 Flavor Conversion
4.1.1 Pion Decay at Rest Accelerator Experiments
4.1.2 Pion Decay in Flight Accelerator Experiments
4.1.3 Reactor Neutrino Experiments
4.1.4 Atmospheric Neutrino Experiments
4.1.5 Radioactive Source Experiments
4.2 Dark Sectors in Scattering and In the Beam
4.2.1 Neutrino-electron Scattering Measurements
4.2.2 Heavy Neutral Lepton Searches
4.3 Conventional Explanations and Other Searches
4.3.1 Constraints on Single Photon Production
4.3.2 Reactor Flux Models
4.3.3 MicroBooNE nue CC Search

- **A large number of contributions on this section from the community. Thank you!**
- The experimental results reviewed include:
  - 4.1.1 **KARMEN**
  - 4.1.2 SBL: **MiniBooNE, MiniBooNE/SciBooNE, MiniBooNE-NuMI, MicroBooNE nue CC, NOMAD, CCFR, CDHS;** LBL: **MINOS/MINOS+, NOvA, T2K, OPERA and ICARUS**
  - 4.1.3 SBL: **DANSS, NEOS, Neutrino-4, PROSPECT, STEREO** MBL: **Daya Bay, Double Chooz, RENO** Also, joint fits of Reactor experimental results, and joint analysis with Accelerator experiments
  - 4.1.4 **IceCube,** Super-K, ANTARES
  - 4.1.5 **BEST**
  - 4.2.1 **MINERvA, CHARM-II**
  - 4.2.2 **T2K**
  - 4.3.1 **MicroBooNE NC Delta radiative decay search**
  - 4.3.2 **Daya Bay, RENO, HM model**
  - 4.3.3 **MicroBooNE nue CC**
- **Key messages:**
  - Over the past 10 years, these results have, at minimum, rendered the simplest 3+1 interpretation as inadequate.
  - On the other hand, they have served as valuable probes of other, more extended scenarios described in Sec. 3.
  - No clear picture has emerged yet.

We would very much welcome and greatly appreciate a contribution on **Super-K and ANTARES atmospheric** neutrino measurements with relevance to SBL anomalies!

NF02-Wide White Paper Walkthrough

5. Indirect Probes: Astrophysics, Cosmology, Direct Mass Measurements

5.1 Cosmology
5.2 Astrophysics/Supernovae
5.3 Direct Mass Measurements

- In standard cosmology, complete thermalization of an eV-mass scale light sterile state (with oscillation parameters required to explain the short-baseline anomalies) is inevitable
  - This runs into problem with the measured primordial elemental abundances, notably, Deuterium and Helium-4.
  - CMB and large-scale structure also disfavour strongly a fully-thermalized neutrino-like particle species (although incomplete thermalization of a 1 eV mass species is compatible with observations).

- A number of mechanisms involving new physics have been proposed to suppress thermalization.
  - E.g., large neutrino asymmetries, secret interactions, low reheating temperature, etc.
  - Some of these appear problem-free. Some, however, have undesirable side effects on the observables that render them not very effective.

- This section is being finalized...

- Coupling to sterile neutrinos can be kinematically constrained by high precision measurements of beta/electron capture decay products
  - Kinematic constraint is clean with limited model dependence
  - Naturally covers higher Δm^2 parameter space than SBL experiments

NF02-Wide White Paper Walkthrough

6. Future Experimental Prospects

6.1 Decay-At-Rest Accelerator Experiments
6.2 Decay-In-Flight Accelerator Experiments
6.3 Reactor Neutrino Experiments
6.4 Radioactive Source Experiments
6.5 Atmospheric Experiments
6.6 Kaon Factories
6.7 Collider Experiments
6.8 Direct Mass Measurements/Beta Decay

- **A large number of contributions on this section from the community. Thank you!**
- The experimental results reviewed include:
  - 6.1 **JSNS2, JSNS2-II, COHERENT at the SNS, Coherent CAPTAIN Mills, GeV proton beam dump at Fermilab, IsoDAR, K-Pipe**
  - 6.2 **SBN, NuStorm, DUNE, Hyper-K, ESSnuSB**
  - 6.3 **DANSS upgrade, JUNO-TAO, NEOS-II, Neutrino-4 Upgrade, PROSPECT-II**
  - 6.4 **BEST-II, Neutrino Oscillometry with Jinping**
  - 6.5 **IceCube upgrade, DUNE, Hyper-K, THEIA, KM3Net, ORCA, ARCA**
  - 6.6 **NA-62**
  - 6.7 **FASERnu, FLArE**
  - 6.8 **KATRIN/TRISTAN, Project 8, HUNTER, DUNE (Ar39)**

We would very much welcome and greatly appreciate a contribution on **K-Pipe**, **NuStorm**, and **DUNE, Hyper-K and THEIA atmospheric** neutrino measurements with relevance to SBL anomalies!

- **Key messages:**
  - New experiments coming online, with unprecedented sensitivity reach within the context of 3+N oscillations
  - Beyond just pion DAR and DIF, other sources including Kaon DAR, muon storage ring, isotope DAR, …
  - Proliferation of sources, detection methods, interaction channels, but also differentiation capability between different interpretations is both exciting opportunity and crucial for resolving SBL anomalies

NF02-Wide White Paper Walkthrough
7. Summary of Requirements

- This section is being finalized...

7. Summary of Requirements

c. <u>2012</u>: Requirements for resolving SBL anomalies were driven by the **goal to establish or refute the existence of sterile neutrinos**:

- Multiple and orthogonal approaches in the same spirit as employed for neutrino oscillations (short-baseline + reactor short baseline + source) → all of these now realized as ongoing or about to become online experimental programs
- Decay-at-Rest experiments: A stopped pion source
- Multi-detector approach for accelerator-based experiments
- Emphasis on Short Baselines for reactor experiments
- Development of radioactive sources for Source-based experiments
- Multi-channel approach (elastic, NC, CC scattering)
- Coordinated pheno approach in global analyses within a given theory framework: ability to compare not only signal but also background and systematic assumptions across different measurements; publication of experimental response functions; global analyses including cosmological and beta decay measurements

Your input on this topic is welcome, and important!

c. <u>2022</u>: Requirements for resolving SBL anomalies are driven by the goal of disentangling between different interpretations and solidifying our understanding of the neutrino picture. Regardless of what the upcoming experiments observe (any deviation from three-neutrino picture, or not), how do we put these anomalies to rest/how do we disentangle between different interpretations? What other channels/sectors can or should be explored?

We welcome everyone’s feedback!

This week

- On the **key highlighted points** in these slides (which will serve as basis of report)
  - Please use this google form for feedback: https://forms.gle/zJHh3WBsaPZs66jr5
  - Example feedback: “<Exciting proposed experiment A/interpretation B> does not seem to be represented in the whitepaper; I suggest reaching out to <Firstname Lastname, email> for a contribution.”
  - **Deadline: Friday, Feb. 11, 11:59pm ET**

Next week

- On the **draft white paper** to be circulated to NF02 mailing list on Feb. 14, 2022
  - Please use the following google form for feedback: https://forms.gle/P1sPE16rziS3Us2B7
  - Example input:
    - Missing key references (bibtex format), and relevant section/line number/text
    - Corrections/edits/comments, and relevant section/line number/text
  - **Deadline: Monday, Feb. 21, 11:59pm ET**

Before Feb. 28

- We will be formally extending an invitation to the entire community for co-authorship on this paper. We **welcome anyone who wishes to be listed as co-author to add their name** directly to the author list, here: `https://www.overleaf.com/7519841165hmcnbtrgbqkj`