Decay-at-Rest (DAR) / Short Baseline Accelerator (SBL) Searches

Neutrino Frontier Sterile Neutrinos working group mini-workshop

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09/25/2020

LOIs (I)

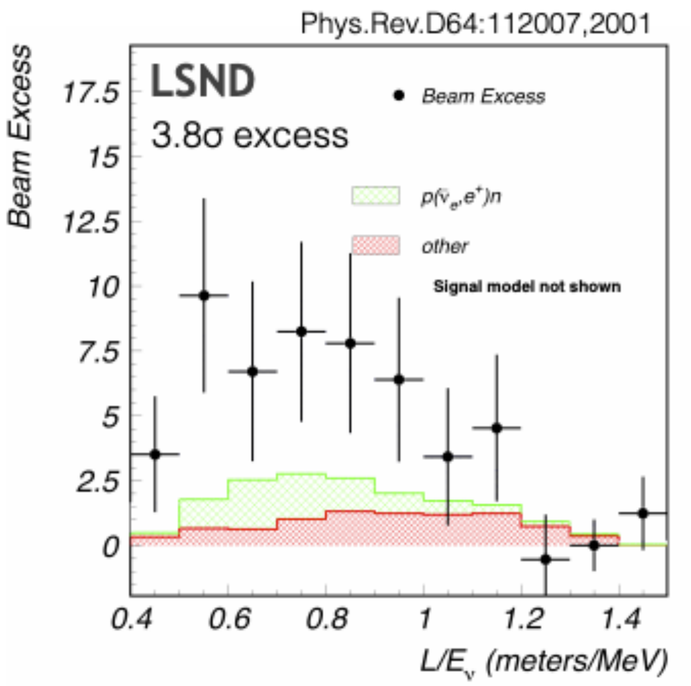
- AF215: LANSCE-PSR Short-Pulse Upgrade for Improved Dark Matter and Sterile Neutrino Searches
- NF080: Neutrino Physics with IsoDAR
- NF128: The JSNS^2 Experiment
- NF067: Far-Future COHERENT physics program at the SNS
- NF142: Directional detectors for CEvNS and physics beyond the Standard Model
- NF139: Inelastic Neutrino-Nucleus Interaction Measurements with COHERENT
- NF161: Neutrino Opportunities at the ORNL Second Target Station
- RF099: Fixed-Target Searches for New Physics with O(1 GeV) Proton Beams at Fermi National Accelerator Laboratory
- NF002: Coherent Elastic Neutrino-Nucleus Scattering: Theoretical and experimental impact

LOIs (II)

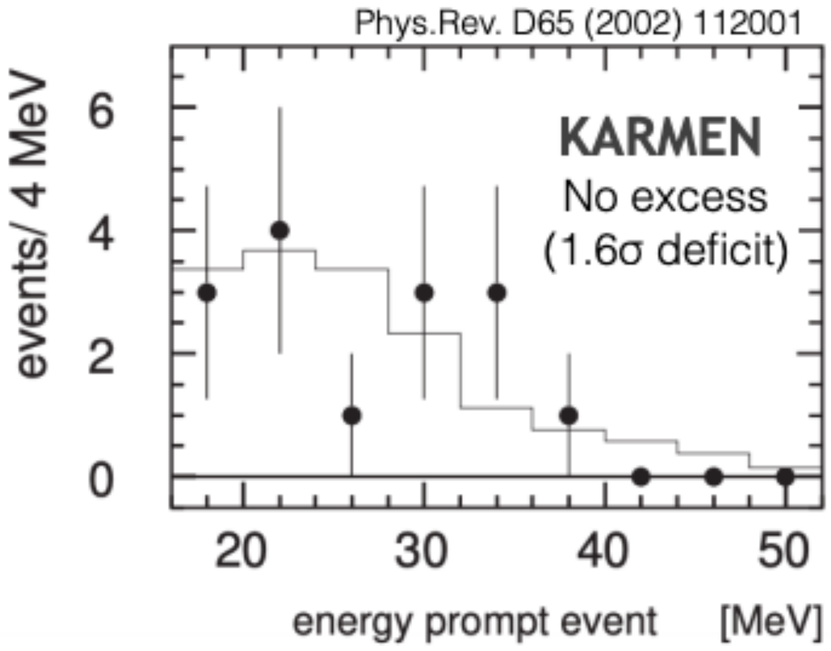
- NF062: The ESS neutrino Super Beam Design Study (ESSnuSB) and the High Intensity Frontier Initiative (HIFI)
- NF164: Sensitive Tests for Sterile Neutrino Oscillations at the Short-Baseline Neutrino Program at Fermilab
- NF160: Physics Opportunities for detection and study of Heavy Neutral Leptons at Accelerator Neutrino Experiments
- NF079: ICARUS in the Next Decade
- NF189: Follow up of anomalies measured in short baseline neutrino experiments
- NF082: Neutrinos from stored muons; nuSTORM

Short Baseline Observations of ν_e's

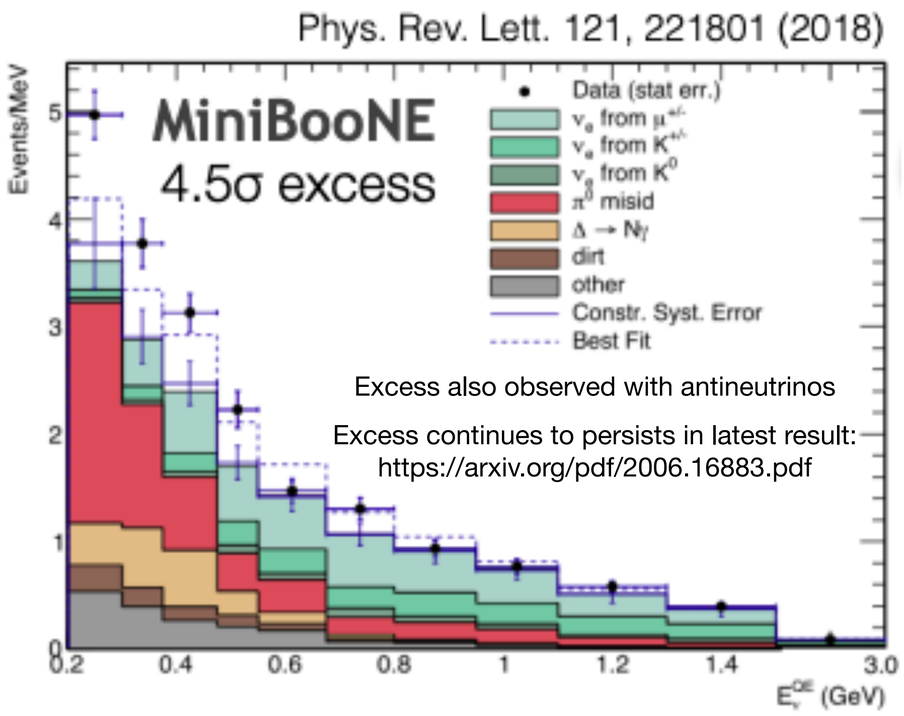
- Data-driven field, primarily focused on following up on LSND/MiniBooNE excesses



π decay-at-rest



μ decay-at-rest



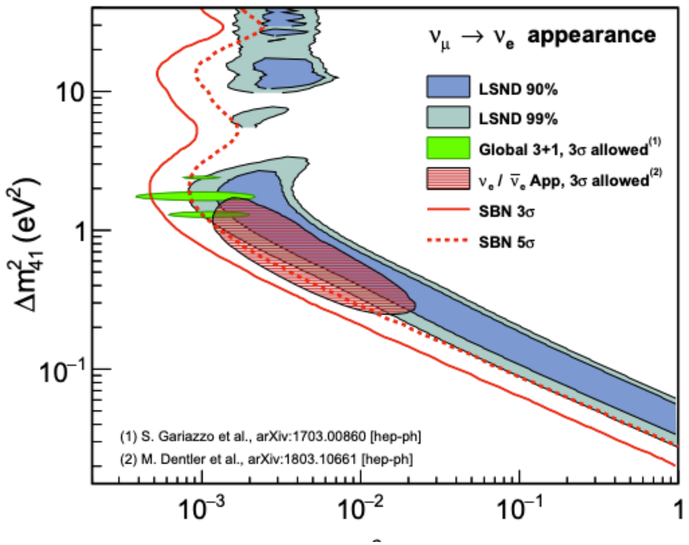
π decay-in-flight

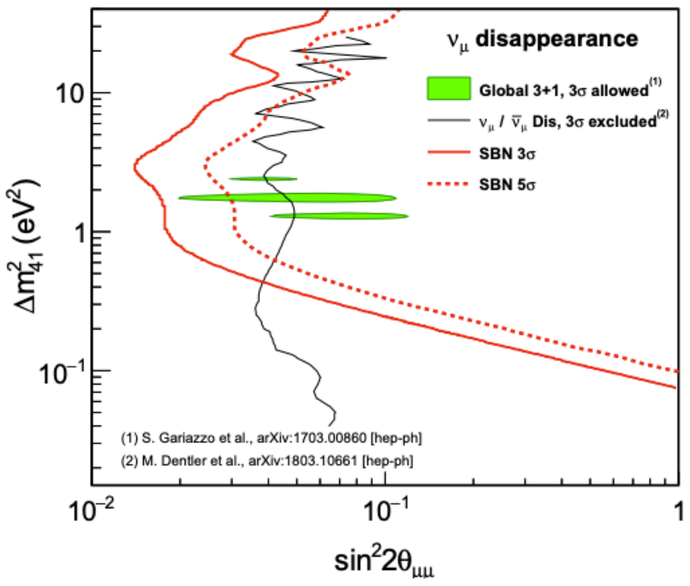
Connection to Sterile Neutrinos

- Interpretation has mostly focused on testing 3+N models of "vanilla” sterile neutrinos
  - Spurred on by observations of ν_e disappearance that could also be interpreted in terms of vanilla sterile neutrinos of similar masses
- Lots of interest recently in exploring richer set of models, but this is challenging:
  - Models must describe excesses seen at different energy and length scales, observations in other kinematic variables (e.g. angle), and explain non-observation of excess in e.g. MiniBooNE dump mode
- But “vanilla” sterile neutrinos have trouble explaining the data too, when considering the global context
  - Tension between appearance and disappearance, in particular with no observation of ν_μ disappearance
  - Tension with cosmological data
- Nonetheless expect a much clearer picture on the vanilla sterile neutrino interpretation of the DAR/SBL ν_e appearance anomalies in the next ~5 years

Fermilab Short Baseline Neutrino Program[NF164,NF079]

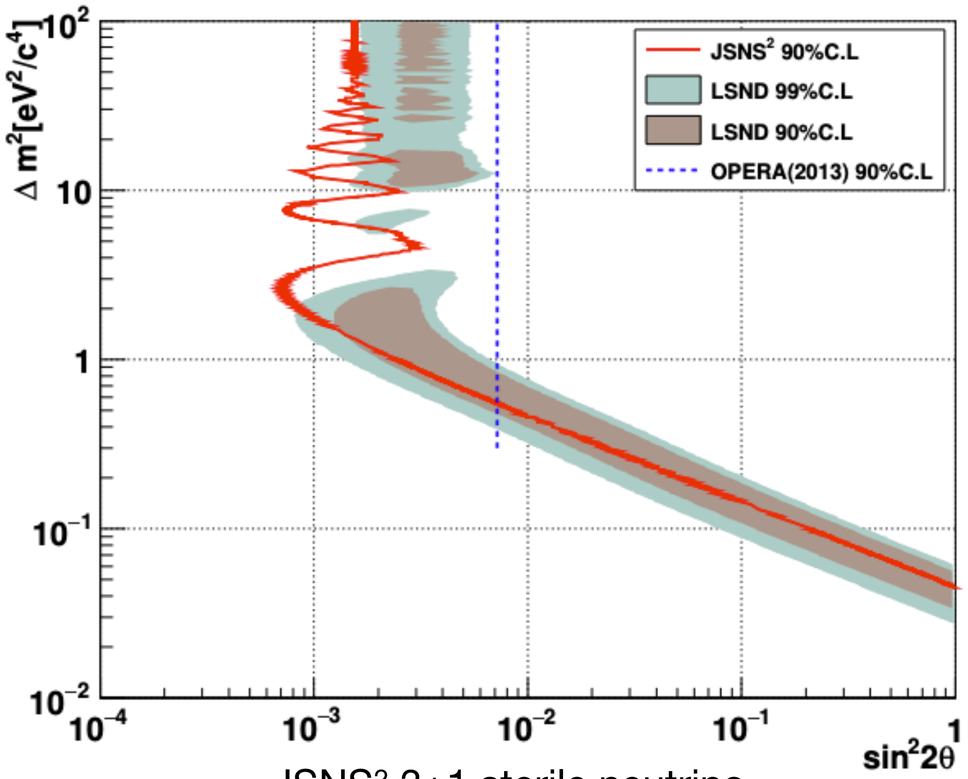
- π decay-in-flight SBL experiment using same beam as MiniBooNE
- LArTPC-based program consisting of:
  - MicroBooNE (started data-taking in 2015), 85 tons, 470 m
  - ICARUS (commissioning now), 476 tons, 600 m
  - SBND (detector assembly underway; operations in early 2022), 112 tons, 110 m
- Both ν_e appearance and ν_μ disappearance 3+1 sterile searches
- World-leading 3+1 sterile neutrino search that can cover the parameters allowed by past anomalies at ≥ 5σ significance
  - At larger values of $\Delta m^2 \sim 7 eV^2$ hinted at by other experiments, ICARUS could resolve the oscillation pattern in the ν_μ disappearance probability for sufficiently large mixings
- Both far detectors also see neutrinos (both off-axis and from the hadron absorber) from the NuMI beam line serving NOvA, which can serve as an independent source to confirm any observed signals





The JSNS^2 Experiment[NF128]

- μ DAR experiment at the Materials and Life Science Experimental Facility at J-PARC
  - 3 GeV 610 kW (with 1 MW upgrade expected soon) proton beam incident on Hg target
- 50 ton (17 ton fiducial) Gd-doped liquid scintillator detector 24 m from neutrino source
- Electron antineutrino appearance search will be direct test of LSND
- Initial data taking run performed in Summer 2020; results currently being analyzed
- Second detector is now also funded to provide improved coverage of LSND allowed region



JSNS^2 3+1 sterile neutrino appearance sensitivity for 3 years of data-taking with 1 detector

What's Next?

- Definitive confirmation (observation) of a ν_e (ν_μ) appearance (disappearance) signal would be a monumental particle physics discovery
- Major world-wide experimental program should then be launched to characterize the signal[NF189]
  - Leverage existing and already-planned experiments
    - SBN: Cross-check with NuMI events, run in anti-neutrino mode, etc.
    - Not just DAR/SBL—will need input from the entire neutrino program
  - Test sterile neutrino hypothesis in new ways
    - active-to-sterile searches, ν_μ appearance, map out oscillation probability to discriminate 3+1 vs. 3+2, etc.
    - Upgrade existing facilities, build new sources, detectors, and facilities

New Developments

- Recent theoretical work has highlighted that sterile neutrinos are just one of a plethora of interesting, phenomenologically viable new physics scenarios that can be probed at DAR / SBL experiments
    - To highlight a specific example, rich theory landscape and phenomenology associated with Heavy Neutral Leptons (for example can distinguish Majorana vs. Dirac) that can be searched for both at the near detectors of long baseline experiments such as DUNE and SBL experiments, such as the SBN[NF160]
- Observation of coherent elastic neutrino-nucleus scattering (CEvNS) by the COHERENT experiment provides a novel experimental tool that can now be utilized to search for BSM physics in new ways[NF002], including e.g.
    - NC active-to-sterile neutrino oscillation searches, which would provide smoking-gun evidence for the existence of sterile neutrinos and
    - Light dark matter, up-scattered heavy neutrinos and dark matter, axion-like particles (ALPs), especially when coupled to a directional CEvNS detector, such as a low-pressure, Negative Ion Time Projection Chamber (NITPC) such as a νBDX-DRIFT, which can distinguish between backgrounds and various BSM signatures[NF142]
- Can a future DAR/SBL program provide broad sensitivity to interesting new physics scenarios and add to the overall sterile neutrino picture beyond the current program?

COHERENT and the SNS[NF067,NF139,NF161]

- The SNS at ORNL impinges 1.4 MW of 1 GeV protons compressed into few hundred ns pulses on a Hg target at the first target station at 60 Hz to produce a bright source of DAR neutrinos

- COHERENT collaboration made first-ever measurements of CEvNS on CsI and Ar 16-25 m away in “Neutrino Alley”, which provides 8 m.w.e. of overburden and substantial shielding from beam-related neutrons

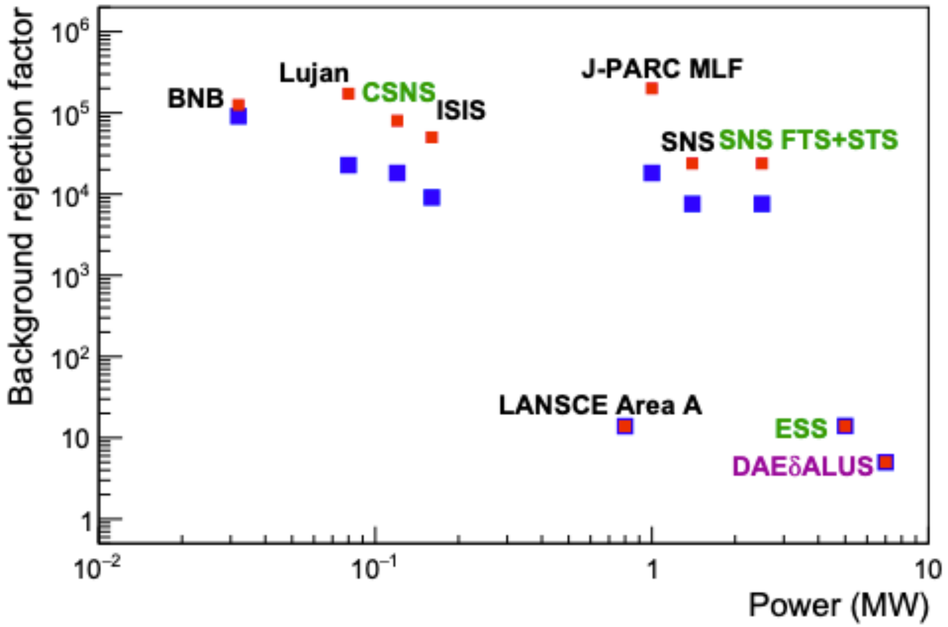
  - In the long-term, precision-capable (<1%) experimental program of CEvNS measurements opens the door to a diverse array of BSM searches, including for e.g. NSIs, ALPs, light dark matter, sterile neutrinos, as well as precision electroweak and neutrino EM properties and cross section measurements

- Planned Proton Power Upgrade (PPU) project at the SNS will double the power of the existing accelerator. A Second Target Station (STS) will be added with a new neutron-production W target along with a new experimental hall

  - The beam power is expected to be 1.7 MW in 2022 and 2.0 MW in 2024. In 2028, after STS construction is completed, the FTS will receive 2.0 MW at 45 Hz, and the STS will receive 0.7 MW at 15 Hz

- Detectors sited in between the STS and FTS, at tens of meter baselines, will receive flux from both. It will be technically feasible to site 10-ton-scale detectors at the STS (for example, in a hall of 4.5 m × 10 m × 4 m height)

  - Presents a clear opportunity for future sterile neutrino searches (see next slide)



LANSCE-PSR Short-Pulse Upgrade[AF215]

- The Lujan spallation W target at LANL is fed by 800-MeV protons from the Proton Storage Ring (PSR), providing a high-average power (~100 kW), 20-Hz, short-pulse (< 300 nsec) beam

- The Coherent CAPTAIN-Mills (CCM) detector is a 10-ton, liquid argon (LAr) fast detector instrumented with 120 photomultiplier tubes and 500 MHz readout electronics. In 2019 it was built and ran for four months at the Lujan center

  - Initial measurements demonstrated that the detector can achieve ~1 ns timing resolution, ~20 cm spatial resolution, and an energy threshold of 50 keV (nuclear recoil). Analysis has identified that (LAr) purification is required to achieve 10-20 keV thresholds and will be included for the 2021 beam run

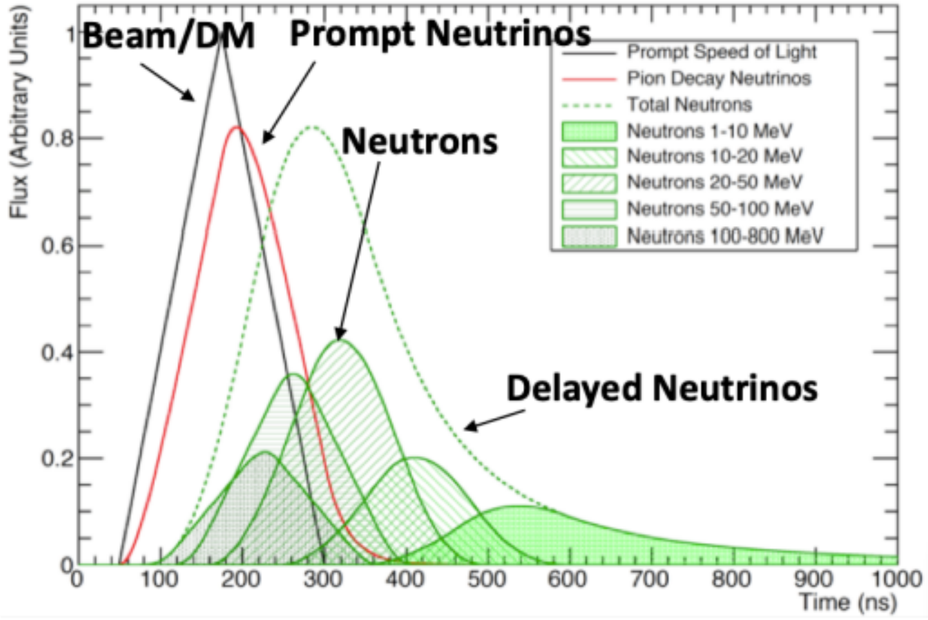
  - This would then enable a CEvNS-based sterile neutrino search

- However, moderated neutrons arrive through extensive bulk shielding about ~125 ns after the arrival of the neutrino beam, so CCM can only measure less than 50% of the generated neutrino signal before the wave of beam neutrons arrives.

- If the proton beam pulse width can be shortened to less than 100 ns, then about a factor of two improvement can be achieved in efficiency. Further, shorter pulses also reduce the steady-state random backgrounds by one third (100/300), which delivers a combined signal-to-background (S/B) improvement of six times greater for the same charge on target. If the proton beam could be reduced to 30 ns while still maintaining the same charge per pulse, then a S/B improvement of ~ 2/(30/300), or 20 can be achieved.

  - Also implementing PID techniques could then result in a combined S/B improvement of >100.

- Once designed, expected that the PSR upgrades to achieve 30 ns timing could be implemented in 2-3 years



HEP-Dedicated GeV Proton Beam Dump Facility at Fermilab[RF099]

- CW-capable PIP-II LINAC at Fermilab can simultaneously provide sufficient protons to drive MW-class O(GeV) beams as well as the multi-MW LBNF/DUNE beamline

- New Booster-sized, permanent magnet accumulator ring (in a new or existing beam enclosure) could compress beam into pulses suitable for a proton beam dump facility (~320 ns goal with a O(10^{-5}) duty factor)

  - Initial operation at 100 kW with 800 MeV protons could be realized within the decade, with an upgrade path to MW-class proton beams in the GeV range

- Beam dump facility can be optimized and designed from the ground-up for HEP (neutron suppression, large detectors, flexible locations), including sensitive dark sector and CEvNS-based active-to-sterile searches

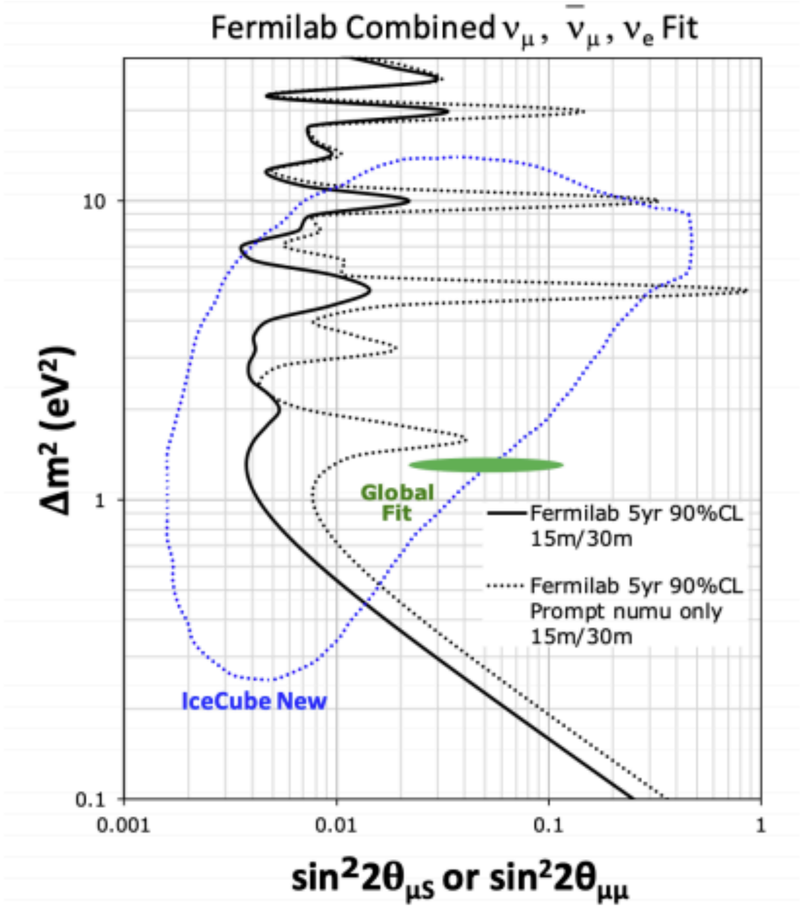


FIG. 2. Fermilab beam dump facility 90% confidence limits on active-to-sterile neutrino mixing assuming a 5 year run. Also shown are the 90% confidence limits for $\nu_\mu \to \nu_\mu$ disappearance, assuming the $\bar{\nu}_\mu$ and ν_e can be detected with similar assumptions as for the ν_μ, the 90% confidence limit from IceCube [19], and a recent global fit [20].

The ESS neutrino Super Beam Design Study (ESSnuSB) and the High Intensity Frontier Initiative (HIFI)[NF062]

- ESS is under construction and roughly 70% complete; first science will start in 2023 and full accelerator power should be reached around 2026

- 5 MW, 2.5 GeV proton beam, 3 ms beam pulse with 4% duty factor

- EU-supported ESSnuSB neutrino Super Beam project performing Design Study (CDR expected in Dec. 2021) to double duty factor to 8% and add 400 m accumulator ring to compress proton pulses to ~1 μs for a long-baseline neutrino oscillation experiment with a 1 megaton water Cerenkov far detector targeting CP-violation sensitivity using the ν_e appearance second oscillation maximum

- Such a facility could also support a High Intensity Frontier Physics program, including

  - CEvNS-based DAR sterile neutrino searches

  - Other DAR sterile neutrinos searches, including mono-energetic ν_μ disappearance from kaon DAR

  - Muon storage ring SBL sterile neutrino searches (see next slide)

Neutrinos from stored muons; nuSTORM[NF082]

- Store muon beams at CERN with central momentum from 1 GeV/c to 6 GeV/c with a momentum acceptance of 16% from pion decay
- Provides extremely well-understood beam of electron neutrinos and muon antineutrinos (or vice versa)
  - Muon beam energy and flux can be understood at the 1% level or better
- Serve a definitive neutrino-nucleus scattering program
- Provide the technology test-bed required for the development of muon beams capable of serving as the basis for a multi-TeV lepton-antilepton (muon) collider
- Allows searches for 3+1 sterile neutrinos with the exquisite sensitivity necessary to go beyond the reach of the FNAL Short Baseline Neutrino program
  - Sensitivities based on near (50 m) / far (2 km) setup with a 1.3 kt magnetized iron-scintillator calorimeter
  - Both ν_μ appearance and disappearance sterile neutrino searches possible

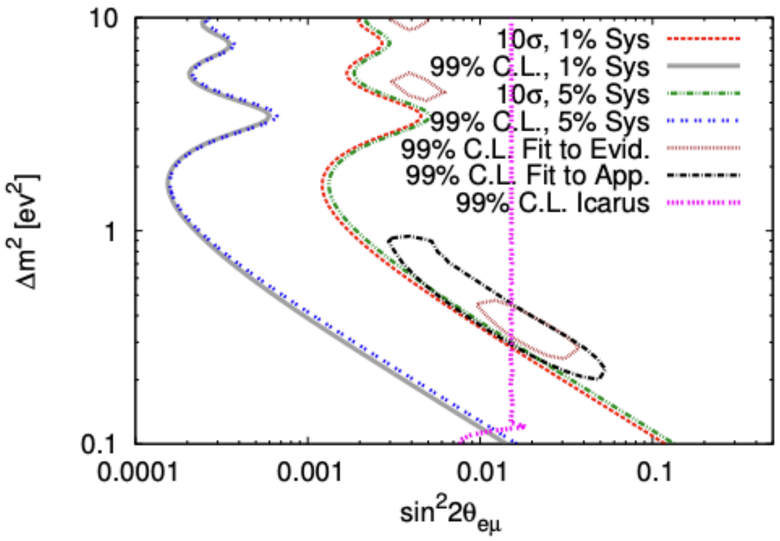


FIG. 4. Sensitivity of nuSTORM to the $\nu_e \to \nu_\mu$ appearance oscillation due to the presence of sterile neutrinos assuming a (3+1) model with anticipated and inflated systematics, compared to 99% confidence contours from global fits to the evidence for sterile neutrinos and to all available appearance experiments generated by Kopp *et. al.* [24] (filled contours) and limits set by ICARUS [34].

IsoDAR @ KamLAND[NF080]

- Proposal to bring compact cyclotron to large underground detector such as KamLAND
  - Impinge 600 kW, 60 MeV proton beam on ^{9}Be target to produce copious neutron flux, which then captures on 99.99% isotopically pure ^{7}Li sleeve
- Electron antineutrino disappearance search using intense ^{8}Li DAR source
- Mapping out disappearance probability can distinguish between different scenarios

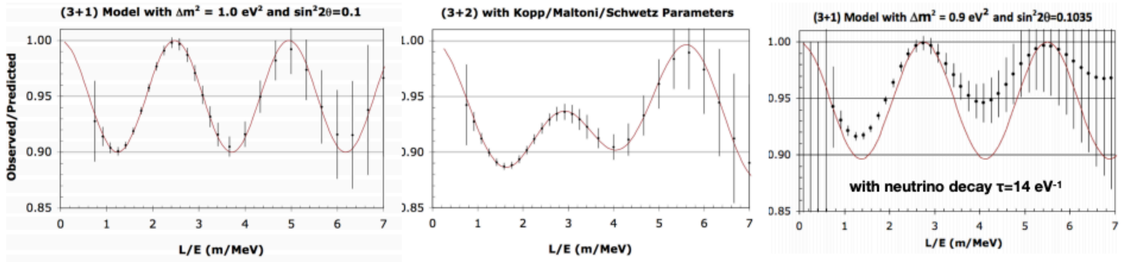


Figure 1: *IsoDAR@KamLAND L/E dependence, 5 years of running, for 3+1 (left) and 3+2 (middle) sterile neutrinos, and 3+1 with decay (right). Solid curve shows no smearing in the reconstructed position and energy. Data points with error bars include smearing.*

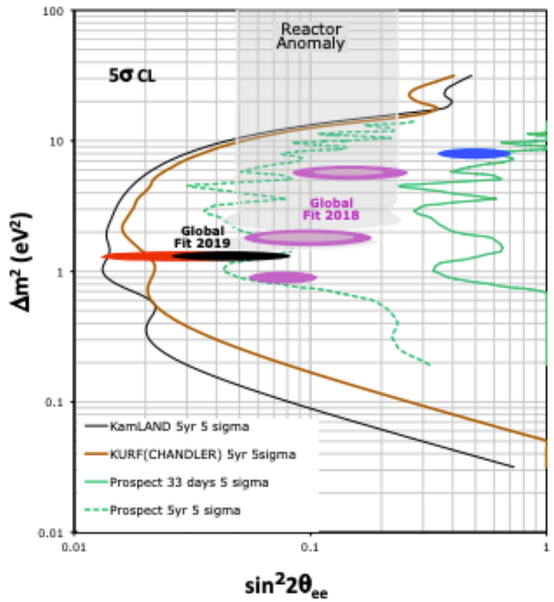


Figure 2: *Black line: IsoDAR@KamLAND capability at 5σ. Gray area: RAA signal; Magenta area: Global fit allowed signal; Red area: DANSS/NEOS combined signal; Blue area: Neutrino-4 signal. Green lines: PROSPECT at 5σ, solid–present, dashed – 5 year projection.*

Summary

- HEP community is searching for hints of where to look to find new physics — follow the data!
- Excess ν_e's at DAR and SBL experiments could be pointing us to exciting physics beyond the Standard Model
- Vanilla sterile neutrinos should be understood as one of a constellation of new physics scenarios accessible at DAR and SBL experiments
    - These can be searched for as an explanation for the anomalous ν_e excess or as interesting and relevant BSM models in their own right
- The recently-measured CEvNS process (also coupled to new detectors) can be utilized as a novel tool to probe BSM scenarios, including sterile neutrinos at DAR sources.
- Tremendous and timely opportunity at a variety of different accelerator facilities to make a major HEP investment at a DAR source to go after this physics as a part of this community planning process

Thank you