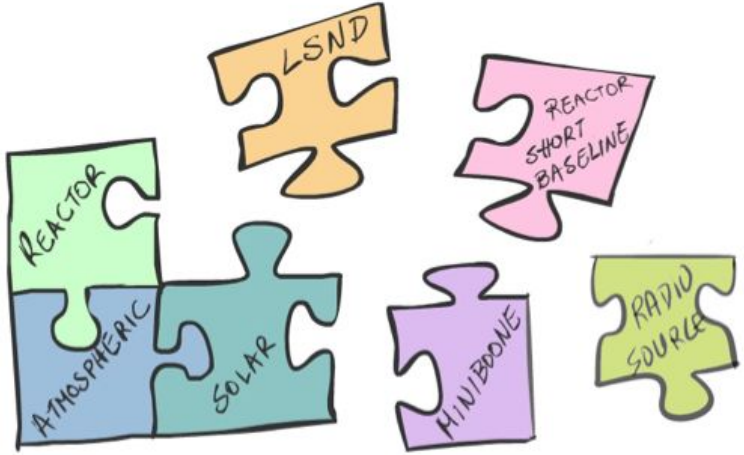
Future 8 GeV Short-Baseline Neutrino Program at Fermilab



Georgia Karagiorgi, Columbia University
ACE Workshop, Fermilab

June 14, 2023

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(1) Multiple, interesting **anomalies** in the field of experimental neutrino physics

(2) A broad and diverse program to address them under way, including a **powerful program** right here at Fermilab about to turn on, with unique capabilities

(3) Exciting **opportunity** to expand beyond this program, and, if we are lucky, follow up on interesting signals about to be seen/discovered!

SNOWMASS NEUTRINO FRONTIER:
NF02 TOPICAL GROUP REPORT
UNDERSTANDING EXPERIMENTAL NEUTRINO ANOMALIES

SUBMITTED TO THE PROCEEDINGS OF THE US COMMUNITY STUDY ON THE FUTURE OF PARTICLE PHYSICS (SNOWMASS 2021)

arXiv:2209.05352v1 [hep-ex] 12 Sep 2022

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[4]DEPARTMENT OF PHYSICS, UNIVERSITY OF CINCINNATI, CINCINNATI, OH 45221, USA

*This report is based on the NF02-contributed *White Paper on Light Sterile Neutrino Searches and Related Phenomenology* [1].

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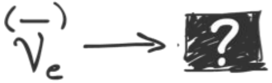
*Although pertaining to the ongoing SBN program at Fermilab,
the work, statements, and conclusions presented in this talk are not to be considered as results or statements from that program.

(Short-baseline) Experimental Neutrino Anomalies

i.e. very close to neutrino production, before any (three-neutrino) oscillations "turn on" (at experimental neutrino L/E ~ 1m/MeV)

Two categories of anomalous signals:

"appearance" of electron (anti)neutrinos in very pure **accelerator-based** muon (anti)neutrino beams from pion decay-in-flight (DIF) or pion decay-at-rest (DAR)



"disappearance" of electron (anti)neutrinos in pure sources of electron (anti)neutrinos, including reactors* and electron-capture radioactive sources

*now understood as limitations in neutrino flux modeling

Leading theoretical interpretation c. 2010

"Vanilla" light sterile neutrino oscillations

$\Delta m^2 \sim 1\ eV^2 \rightarrow$ oscillations at L/E ~ 1 m/MeV

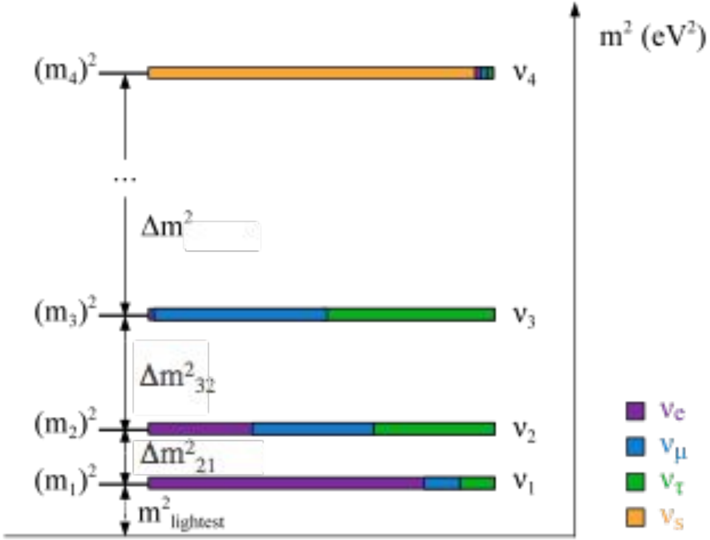
Expect:

✓ Electron anti/neutrino disappearance ~ O(10%)

? Muon anti/neutrino disappearance ~ O(10%)

✓ Muon to electron anti/neutrino appearance ~O(1%)

Probability amplitudes are approx. proportional to electron and/or muon flavor content(s) of new mass states



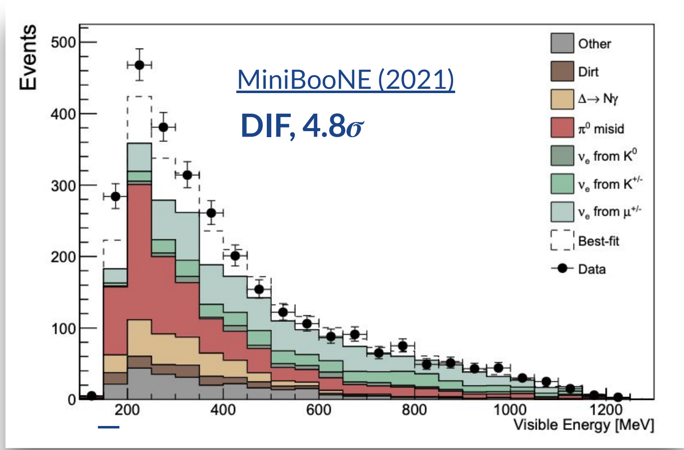
increasing sterile neutrino mass → decreasing mixing

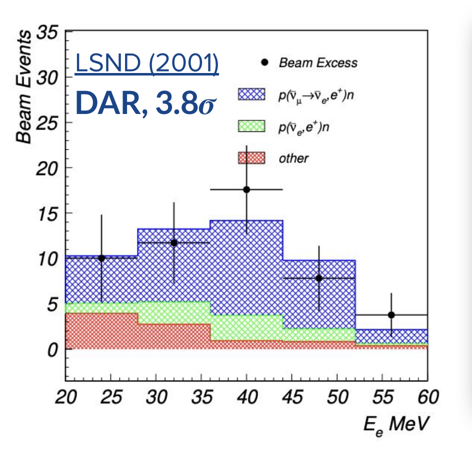
meV eV keV MeV GeV TeV

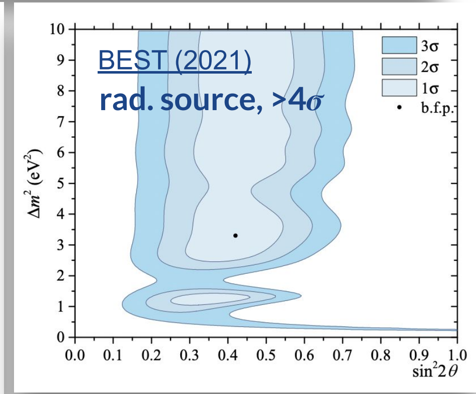
Leading theoretical interpretation c. 2010 ⤚ 2020

"Vanilla" light sterile neutrino oscillations

✓ Compelling theoretical interpretation to each experimental signal when considered independently







Leading theoretical interpretation c. 2010 ⤔ 2020

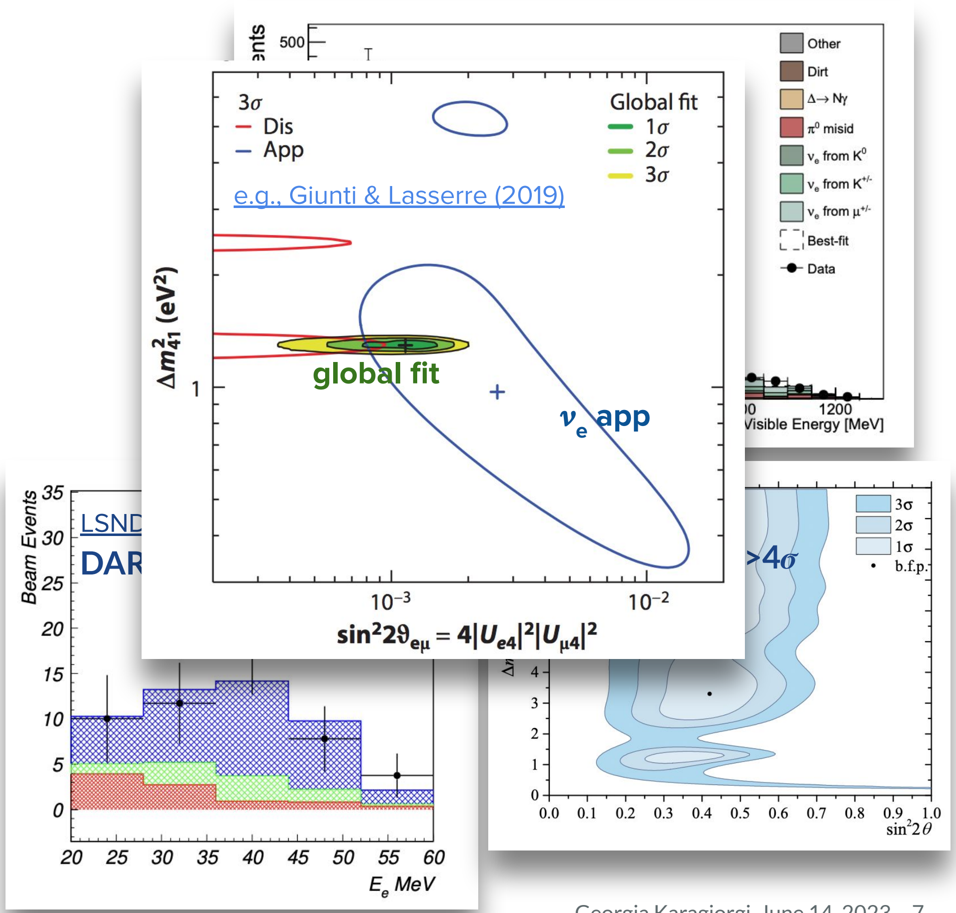
“Vanilla” light sterile neutrino oscillations

✓ Compelling theoretical interpretation to each experimental signal when considered independently

✗ A contrived solution to all anomalies when considered collectively with muon neutrino disappearance constraints

Significant tensions in global data sets exist for any scenario: 3+1, 3+2, 3+3

**Caveat: treatment of all global data sets using consistent assumptions (e.g. flux, cross-section) is challenging → comprehensive, multi-channel searches are needed that account for flux and cross-section correlations across different flavor measurements to put the “vanilla” 3+N model eternally to rest*



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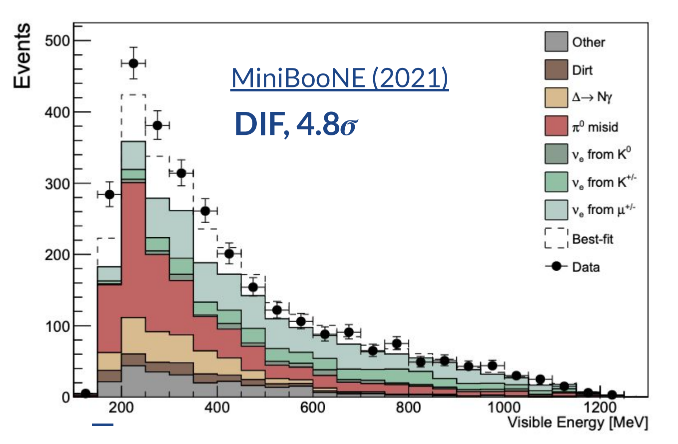
Leading theoretical interpretation c. 2010 ↣ 2020

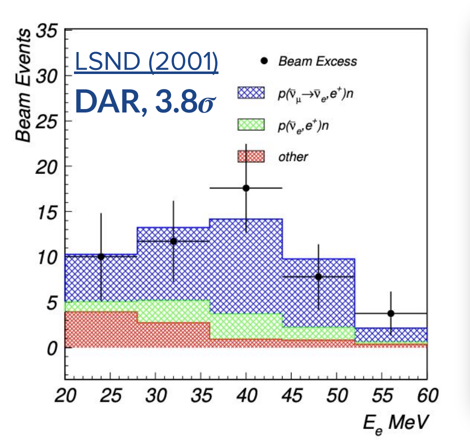
"Vanilla" light sterile neutrino oscillations

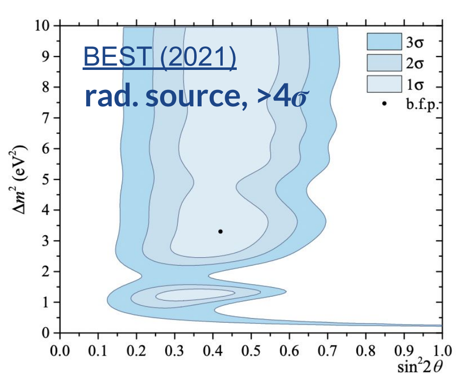
✓ Compelling theoretical interpretation to each experimental signal when considered independently

✗ A contrived solution to all anomalies when considered collectively with muon neutrino disappearance constraints

! Anomalies still stand, unexplained, and represent tantalizing indications for new physics beyond the three-neutrino framework







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Leading interpretations today

Three broad categories of theoretical interpretations:

- **Flavor conversion** models
- **Dark sector** portal models
- **"Standard Model" or "conventional"** interpretations

Category	Model	Signature	Anomalies: LSND	MiniBooNE	Reactor	Gallium	References
Flavor Conversion: Transitions	$3{+}N$ oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [103–106]
	$3{+}N$ w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[46, 47]
	$3{+}N$ w/ sterile decay	$\nu_4 \to \phi \nu_e$	✓	✓	✓ (orange)	✓ (orange)	[44, 45, 48–50]
Flavor Conversion: Matter Effects	$3{+}N$ w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[38–42]
	$3{+}N$ w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓ (orange)	✓ (orange)	[43]
Flavor Conversion: Flavor Violation	lepton-flavor-violating μ decays	$\mu^+ \to e^+ \nu_\alpha \bar{\nu}_e$	✓	✗	✗	✗	[51–53]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e \phi A$	✓	✓	✗	✗	[54]
Dark Sector: Decays in Flight	transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[75]
	dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[73]
Dark Sector: Neutrino Scattering	neutrino-induced up-scattering	$\nu A \to NA$, $N \to \nu e^+ e^-$ or $N \to \nu\gamma\gamma$	✓ (orange)	✓	✗	✗	[63–72]
	neutrino dipole up-scattering	$\nu A \to NA$, $N \to \nu\gamma$	✓ (orange)	✓	✗	✗	[55–62]
Dark Sector: Dark Matter Scattering	dark particle-induced up-scattering	γ or e^+e^-	✗	✓	✗	✗	[74]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[74]

✓ – the model can naturally explain the anomaly, ✓ (orange) – the model can partially explain the anomaly, ✗ – the model cannot explain the anomaly.

For an up to date review, and list of references, see the Snowmass NF02-wide White Paper: https://arxiv.org/abs/2203.07323

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Putting interpretations to the test

- A broad experimental program is being pursued by the community

<table>
<tr><th>Source</th><th>Flavor Conversion:
3+N Oscillations</th><th>Flavor Conversion:
Anomalous Matter Effects</th><th>Flavor Conversion:
Lepton Flavor Violation</th><th>Dark Sector:
Decays in Flight</th><th>Dark Sector:
Neutrino-induced Up-scattering</th><th>Dark Sector:
Dark-particle-induced Up-scattering</th></tr>
<tr><td>Reactor</td><td>DANSS Upgrade, JUNO-TAO, NEOS-II, Neutrino-4 Upgrade, PROSPECT-II</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Radioactive Source</td><td>BEST-2, IsoDAR, THEIA, Jinping</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Atmospheric</td><td colspan="2">IceCube Upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-Kamiokande, THEIA</td><td></td><td></td><td colspan="2">IceCube Upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-Kamiokande, THEIA</td></tr>
<tr><td>Pion/Kaon Decay-At-Rest</td><td>JSNS^2, COHERENT, Coherent CAPTAIN-Mills, KPIPE</td><td></td><td>JSNS^2, COHERENT, Coherent CAPTAIN-Mills, KPIPE, PIP2-BD</td><td></td><td></td><td>COHERENT, Coherent CAPTAIN-Mills, KPIPE, PIP2-BD, SBN-BD</td></tr>
<tr><td>Beam Short Baseline</td><td>SBN</td><td></td><td></td><td colspan="3">SBN, FASERν, SND@LHC, FLArE</td></tr>
<tr><td>Beam Long Baseline</td><td colspan="3">DUNE, Hyper-Kamiokande, ESSnuSB</td><td colspan="3">DUNE, Hyper-Kamiokande, ESSnuSB</td></tr>
<tr><td>Muon Decay-In-Flight</td><td colspan="3">nuSTORM</td><td></td><td>nuSTORM</td><td></td></tr>
<tr><td>Beta Decay and Electron Capture</td><td>KATRIN/TRISTAN, Project-8, HUNTER, BeEST, DUNE (^{39}Ar), PTOLEMY, $2\nu\beta\beta$</td><td></td><td></td><td></td><td></td><td></td></tr>
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Putting interpretations to the test

- A broad experimental program is being pursued by the community
- Including dedicated accelerator-based short-baseline neutrino program at Fermilab

Source	Flavor Conversion: 3+N Oscillations ✓	Flavor Conversion: Anomalous Matter Effects	Flavor Conversion: Lepton Flavor Violation	Dark Sector: Decays in Flight ✓	Dark Sector: Neutrino-induced Up-scattering ✓	Dark Sector: Dark-particle-induced Up-scattering ✓
Reactor	DANSS Upgrade, JUNO-TAO, NEOS-II, Neutrino-4 Upgrade, PROSPECT-II					
Radioactive Source	BEST-2, IsoDAR, THEIA, Jinping					
Atmospheric	IceCube Upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-Kamiokande, THEIA				IceCube Upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-Kamiokande, THEIA	
Pion/Kaon Decay-At-Rest	JSNS^2, COHERENT, Coherent CAPTAIN-Mills, KPIPE		JSNS^2, COHERENT, Coherent CAPTAIN-Mills, KPIPE, PIP2-BD			COHERENT, Coherent CAPTAIN-Mills, KPIPE, PIP2-BD, SBN-BD
Beam Short Baseline	SBN			SBN, FASERν, SND@LHC, FLArE		
Beam Long Baseline	DUNE, Hyper-Kamiokande, ESSnuSB			DUNE, Hyper-Kamiokande, ESSnuSB		
Muon Decay-In-Flight	nuSTORM				nuSTORM	
Beta Decay and Electron Capture	KATRIN/TRISTAN, Project-8, HUNTER, BeEST, DUNE (^{39}Ar), PTOLEMY, $2\nu\beta\beta$					

For an up to date review, and list of references, see the Snowmass NF02-wide White Paper: https://arxiv.org/abs/2203.07323

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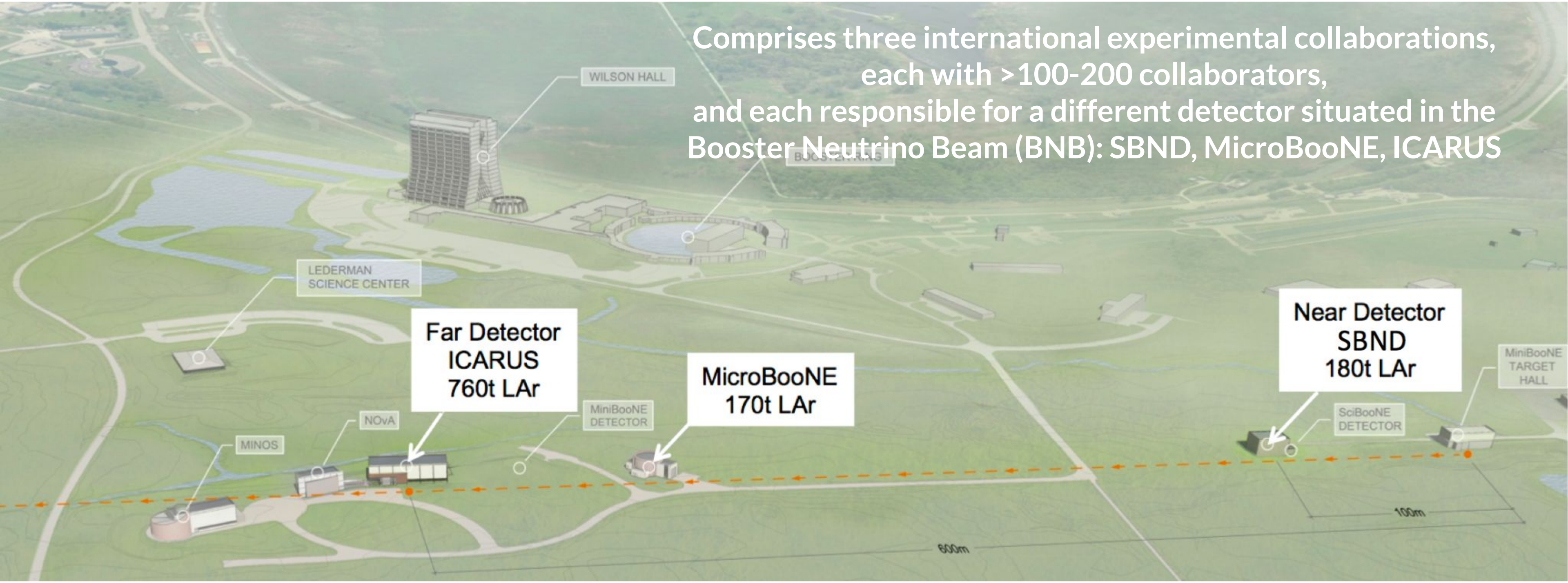
SBN @ Fermilab

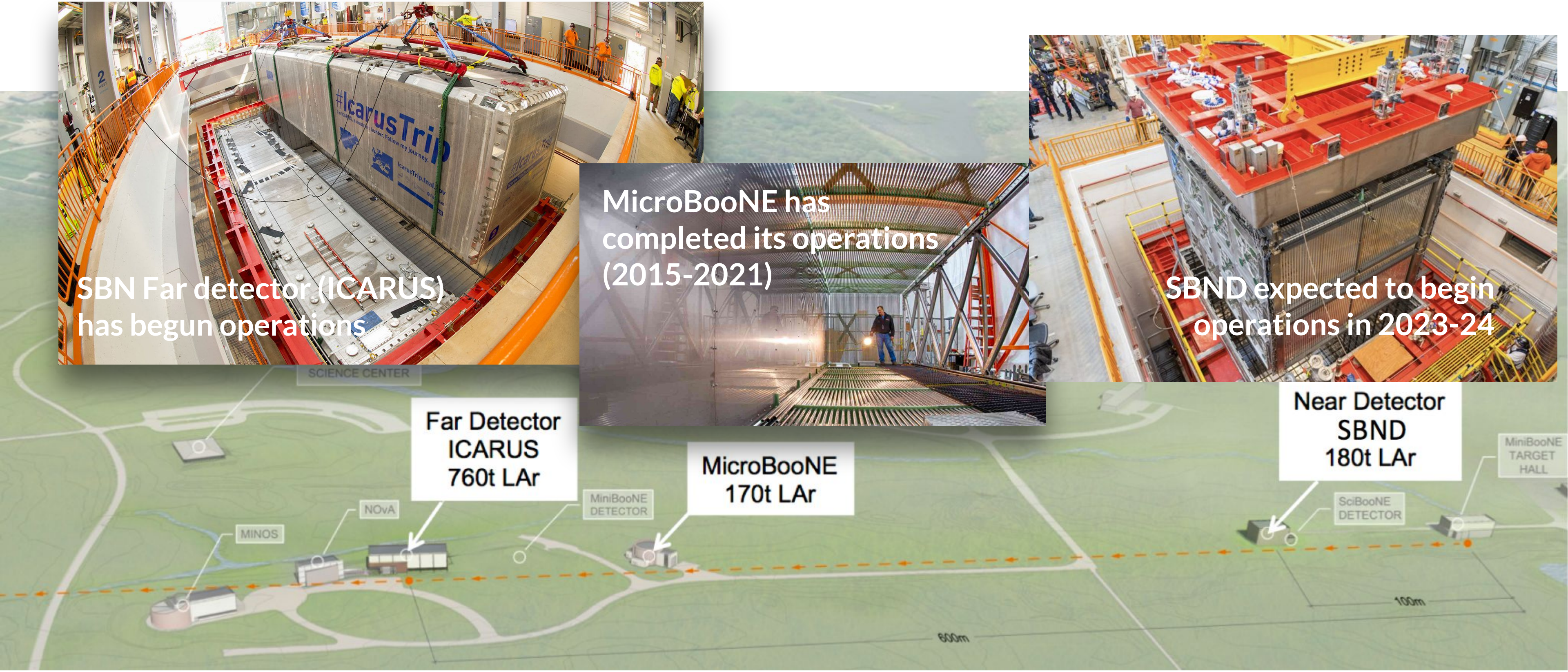
Currently ongoing **Short Baseline Neutrino (SBN) Program**: can directly test a vast array of MiniBooNE Anomaly interpretations, ranging from conventional origins, to flavor transformation, and to new particle production in the beam or in neutrino scattering

Comprises three international experimental collaborations, each with >100-200 collaborators, and each responsible for a different detector situated in the Booster Neutrino Beam (BNB): SBND, MicroBooNE, ICARUS



SBN @ Fermilab

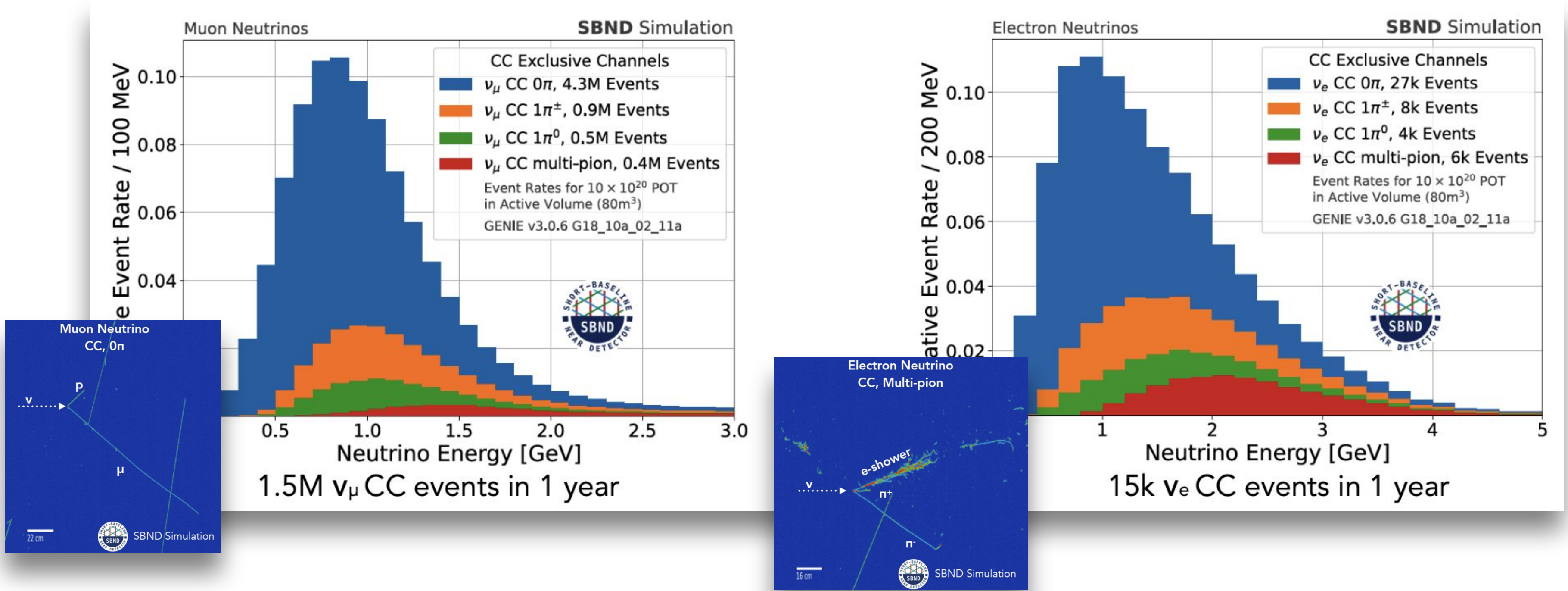
All three detectors share the same technology
(also the same as future DUNE FD1): Liquid Argon TPC



SBN @ Fermilab

Expected to run until the planned accelerator long-shutdown (2027), delivering a diverse physics program:

(1) Neutrino interactions measurements (increasing available data by more than an order of magnitude)



1.5M ν_μ CC events in 1 year

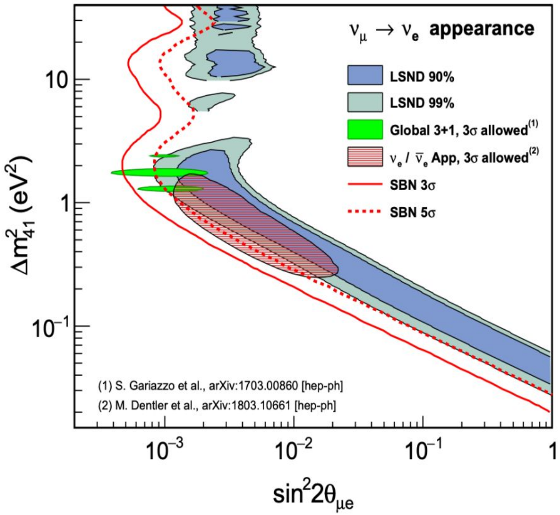
15k ν_e CC events in 1 year

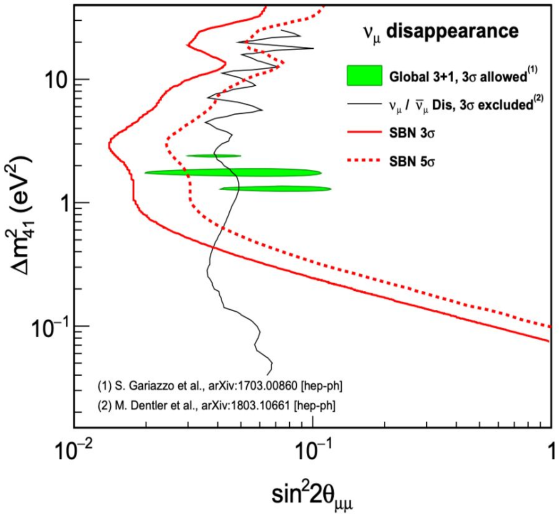
SBN @ Fermilab

Expected to run until the planned accelerator long-shutdown (2027), delivering a diverse physics program:

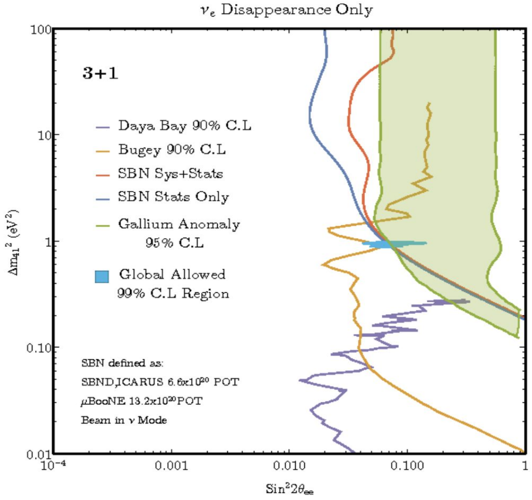
(1) Neutrino interactions measurements (increasing available data by more than an order of magnitude)
(2) eV-scale sterile neutrino searches (ν_e appearance, ν_μ and ν_e disappearance, and NC rate disappearance)

SBN Collab, arXiv:1503.01520, also
Machado, Palamara, Schmitz, Ann.Rev.Nucl.Part.Sci. 69 (2019) 363-387





D. Cianci, et al, Phys.Rev.D 96 (2017) 5, 055001



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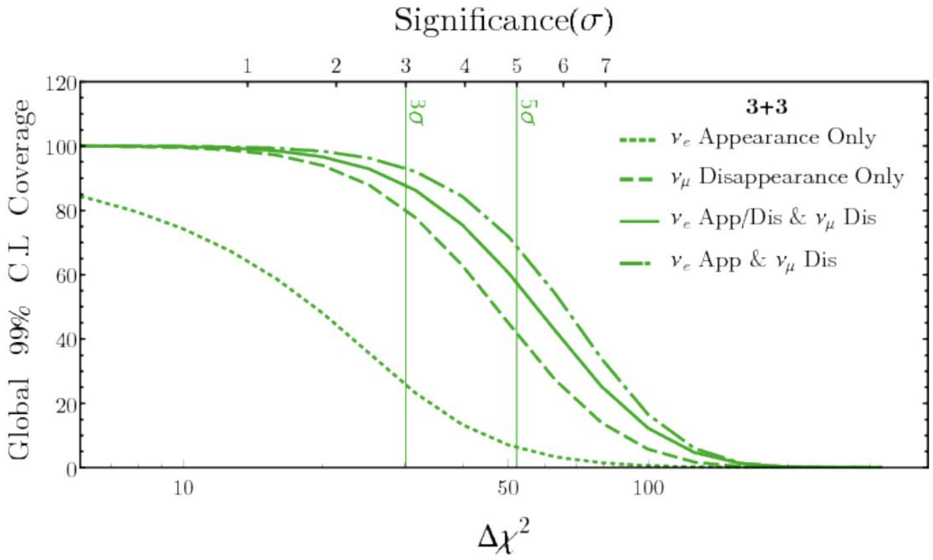


SBN can probe, with 5σ sensitivity, more than 50% of the globally-allowed (at 99% CL) 3+3 sterile neutrino oscillation parameter space

D. Cianci, et al, Phys.Rev.D 96 (2017) 5, 055001

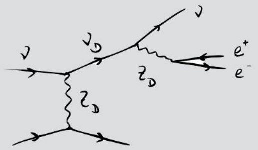
SBN @ Fermilab

Expected to run until the planned accelerator long-shutdown (2027), delivering a diverse physics program:

(1) Neutrino interactions measurements (increasing available data by more than an order of magnitude)
(2) eV-scale sterile neutrino searches (ν_e appearance, ν_μ and ν_e disappearance, and NC rate disappearance)
(3) Conventional and alternative explanations of MiniBooNE anomaly, and other new physics scenarios:

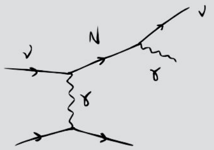
- Dark neutrinos
- Transition magnetic moment
- Axion-like particles
- Heavy neutral leptons
- Higgs portal scalars
- Light dark matter
- Millicharged particles
- …

Dark Neutrinos



Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

Transition Magnetic Moment

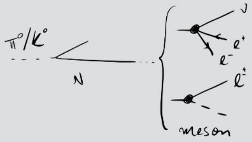


Gninenko PRL 2009
Coloma Machado Soler Shoemaker PRL 2017
Atkinson et al 2021 Vergani et al 2021

Axion-like Particles

Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

Heavy Neutral Leptons

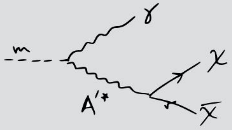


Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Higgs Portal Scalar

Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

Light Dark Matter



Romeri Kelly Machado PRD 2019

Millicharged Particles

Magill, Plestid, Pospelov, Tsai, PRL 2019
Harnik Liu Palamara, JHEP 2019

Note: not an exhaustive list!

Image credit P. Machado and M. Del Tutto

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What could be done beyond SBN?

Possible SBN running configurations beyond accelerator long-shutdown:

…

Dedicated beam dump experiments

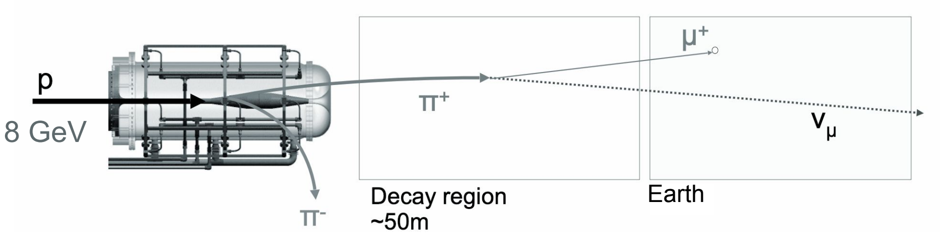
Antineutrino running mode and detector upgrades
(e.g. magnetized detectors for sign differentiation)

Antineutrino running mode

Increased statistics in neutrino running mode

E.g. scenario: antineutrino running at SBN

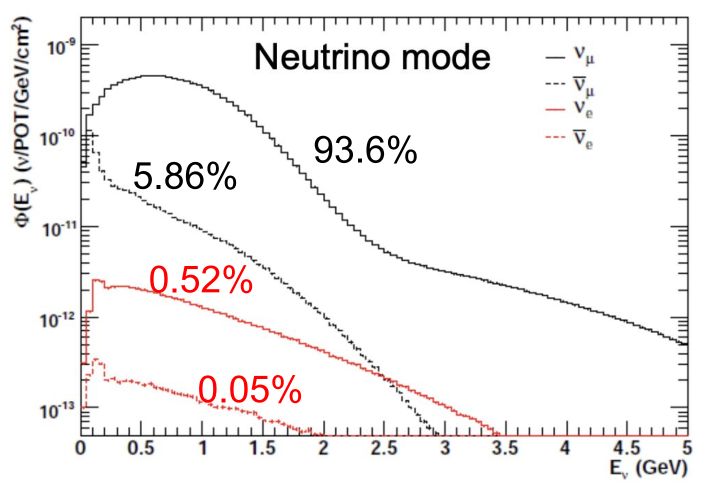
Magnetic horn polarity flip → defocuses π+, focuses π-

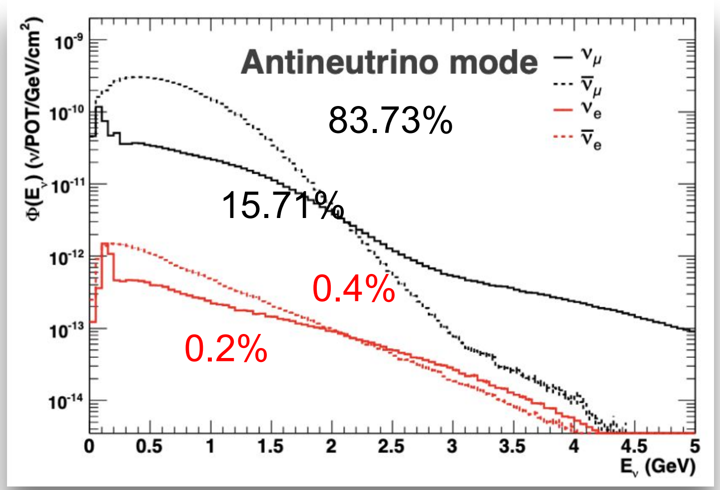


→ detectors …

higher wrong-sign fraction, amplified by anti/neutrino relative cross sections

Well-understood flux content; leverages experience and expertise from extended MiniBooNE antineutrino running Phys.Rev.D 79 (2009) 072002





E.g. scenario: antineutrino running at SBN

SBN antineutrino running and 3+N:

From [D. Cianci, et al, Phys.Rev.D 96 (2017) 5, 055001](#) *

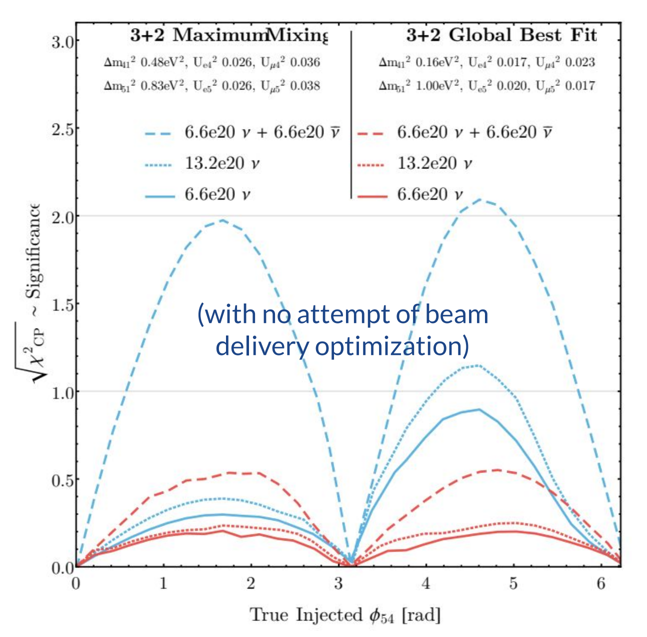
**This study projected only 6.6e20 POT in neutrino mode for SBN, and similar projections for antineutrino mode. Current neutrino mode projections are ~2x higher.*

Overall, **"coverage" of 3+N globally-allowed regions improves** with added antineutrino running (though not as rapidly as it would by additional proton beam delivery in neutrino mode).

On the other hand, **observable differences in neutrino and antineutrino oscillation probabilities provide access to leptonic CP violation** associated with the sterile sector:

E.g., 3+2:

$$P(\nu_\alpha \to \nu_\beta) = 4|U_{\alpha4}|^2|U_{\beta4}|^2\sin^2 x_{41} + 4|U_{\alpha5}|^2|U_{\beta5}|^2\sin^2 x_{51} + 8|U_{\alpha4}||U_{\beta4}||U_{\alpha5}||U_{\beta5}| \times \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{54}), \qquad x_{ij} \equiv 1.27\Delta m^2_{ij} L/E$$



Under this assumption, it is possible to observe maximal CP violation with SBN, depending on underlying parameters and beam delivery!

E.g. scenario: antineutrino running at SBN

SBN antineutrino running and MiniBooNE Anomaly investigations (I):

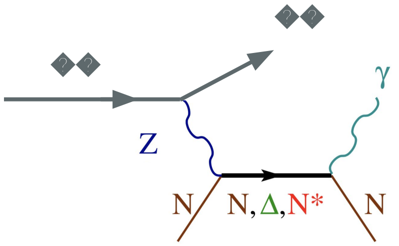
E.g., a conventional interpretation of MiniBooNE Anomaly involves **rare, never-before-measured SM processes** involving single-photon production in neutrino scattering below 1 GeV, e.g.:

- NC coherent single-photon production
- NC Delta production followed by radiative decay

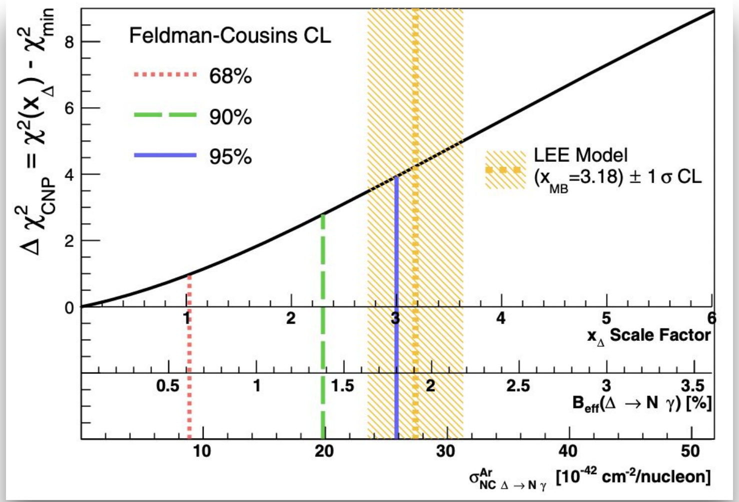
It will be important to **study and confirm that the rates** of these processes scale as predicted **for SM neutrinos and antineutrinos**.

Important **input also for long-baseline neutrino oscillation measurements**, where SM single-photon processes can contribute as background.

Statistics is key!



MicroBooNE, Phys.Rev.Lett. 128 (2022) 111801



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E.g. scenario: antineutrino running at SBN

SBN antineutrino running and MiniBooNE Anomaly investigations (II):

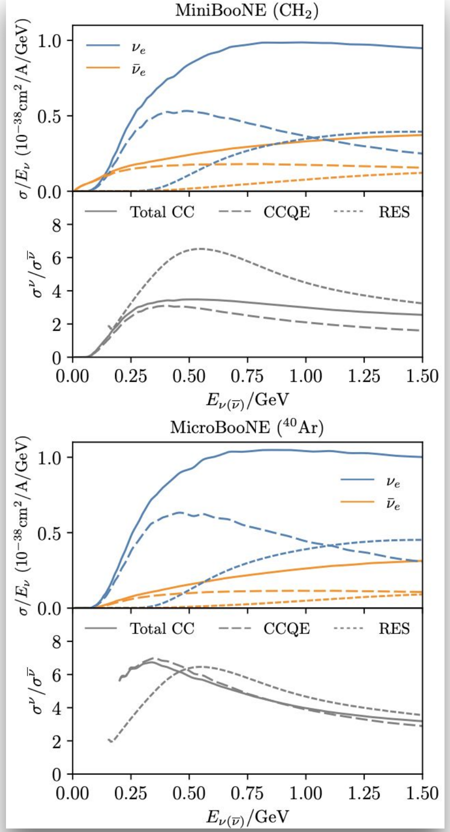
E.g., another recently suggested possibility is that the MiniBooNE Anomaly is **sourced entirely of electron antineutrinos**, evading present MicroBooNE constraints, due to

- Choice of interaction final states for current analyses
- Under-reconstruction of electron antineutrino energy
- Lower antineutrino cross-section for argon vs. carbon

In principle, if the excess scales with flux, SBND should be able to observe a higher rate of antineutrino interactions than MicroBooNE, but measurement will be overwhelmed by right-sign (neutrino) rates with no proton in final state.

Dedicated antineutrino running would provide **higher purity and statistics** to test this hypothesis with improved sensitivity.

N. Kamp, et al. Phys.Rev.D 107 (2023) 9, 092002



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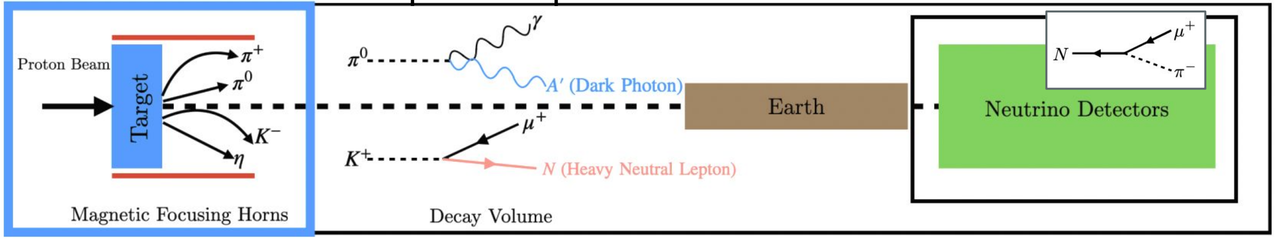
E.g. scenario: antineutrino running at SBN

SBN antineutrino running and Dark Sector physics searches:

E.g. **Heavy Neutral Lepton (HNL) searches**

“new particle” production in the beam

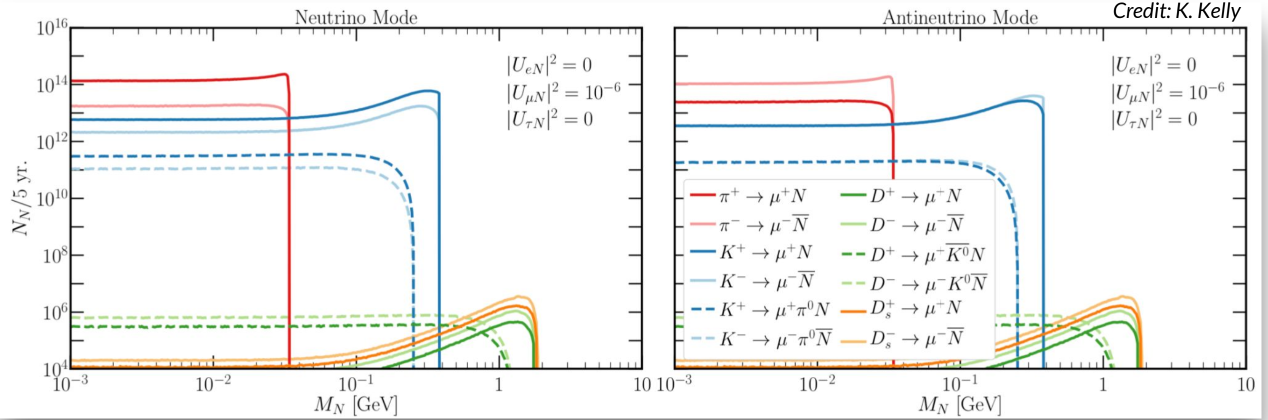
Credit: K. Kelly



Comparable rate of HNL production, but composition of N and anti-N changes between neutrino and antineutrino mode, while the neutrino beam background is also reduced in antineutrino running.

Are N production and decay chain rates to leptons and anti-leptons the same?

Credit: K. Kelly



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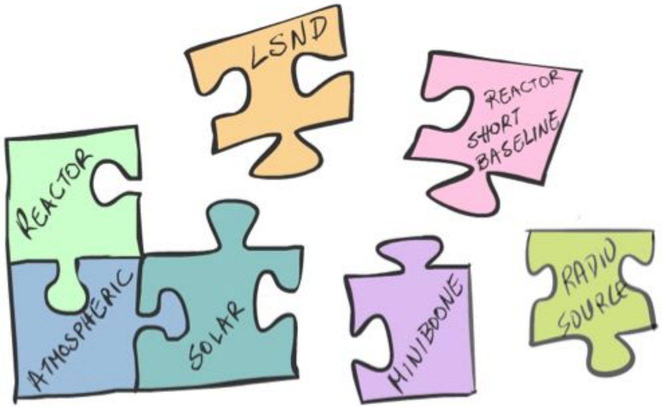
Summary (I)

Evidence for new physics beyond the three-neutrino framework is accumulating, all at neutrino short-baseline experiments, but **as of yet, no single, definitive experimental result in favor of eV-scale sterile neutrinos**.

Alongside efforts to search for potentially unidentified sources of systematic effects, strong tension between measurements has led to recent **shift toward more "exotic" interpretations, with plethora of models and rich phenomenology**.

Implications span multiple frontiers and multiple fields.



Summary (II)

A **premier accelerator-based short-baseline neutrino program** is underway at Fermilab

- Neutrino-argon interaction measurements
- Neutrino flavor conversion
- Dark sector physics

Enabled by an **over-performing Booster Neutrino Beam facility,** and thanks to decades of experimental users in the beamline (MiniBooNE, SciBooNE, ANNIE, MicroBooNE, and now SBN) contributing to a well-understood beam (BNB flux prediction paper has >400 citations).

Booster upgrades/running beyond the 2027 accelerator long-shutdown provide an **opportunity to significantly stretch or enhance the science value** of a short-baseline neutrino program.

A new physics signal at SBN would be a game changer! It would <u>necessitate</u> follow-up with either additional neutrino running, or antineutrino running!

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Summary (III)

It would be extremely valuable for our field to further explore the possibility of additional neutrino vs. antineutrino running enabled by a future booster upgrade, and in tandem with upcoming first results from the SBN program, as well as possible complementary detector upgrades.