Short-Baseline Neutrino Experiments

Georgia Karagiorgi, Columbia University

2024 Aspen Winter Conference

Aspen Center for Physics
March 24-29, 2024

ALFRED P. SLOAN FOUNDATION

*Disclaimers

1. This talk will focus on only **(a subset of) accelerator- based** short-baseline neutrino experiments.

   For a comprehensive review of experimental (and theoretical) landscape:

Snowmass White Paper by NF02 Topical Group: Understanding Experimental Neutrino Anomalies

White Paper on Light Sterile Neutrino Searches and Related Phenomenology

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*Disclaimers

1. This talk will focus on only **(a subset of) accelerator- based** short-baseline neutrino experiments.

   For an abbreviated summary:

   Snowmass Report by NF02 Topical Group

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)

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1. This talk will focus on only **(a subset of) accelerator- based** short-baseline neutrino experiments.

2. I will present primarily **my own views**.

A Century of Experimental Neutrino Anomalies

Early 1930s: Missing energy in beta decay

1960s…+: **Solar** neutrino deficit

1970s…+: **Atmospheric** neutrino deficit

1990s…+: LSND, MiniBooNE **accelerator** neutrino excesses

1990s…+: Gallium **radioactive source** neutrino deficit

*There are more anomalies, e.g. reactor short-baseline (flux uncertainties?), ANITA cosmic neutrino (complex ice modeling?), Neutrino-4 (dubious systematics?) → not in this talk

A Century of Experimental Neutrino Anomalies
… and Triumphs!

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Neutrino discovery in 1956s!

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Neutrino oscillation discoveries in 1998 and 2002!

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A Century of Experimental Neutrino Anomalies

Early 1930s: Missing energy in beta decay

Neutrino ... scovery in 1956s!

1960s ... ar neutrino deficit

... tmospheric neutrino deficit

Neutrino osc... nd 2002!

"Anomalous": Each signal is consistent with (unexpected) oscillations at $L \sim 0$ (at "short baseline"). Beyond 3 neutrinos!?

1990s…+: LSND, MiniBooNE **accelerator** neutrino excesses

1990s…+: Gallium **radioactive source** neutrino deficit

… quo vadis ???

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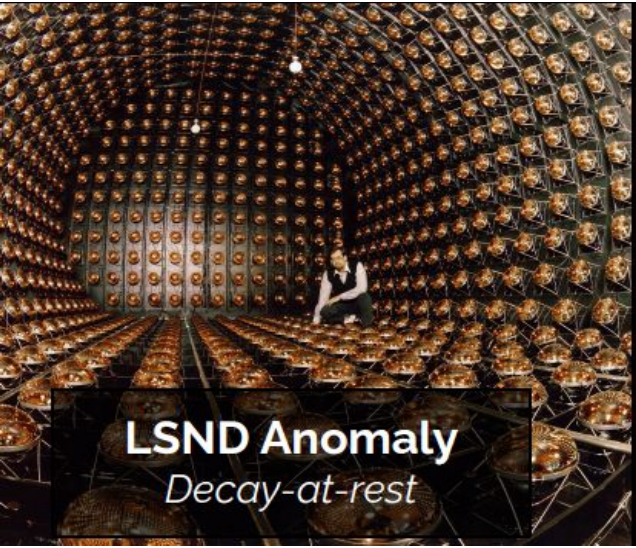
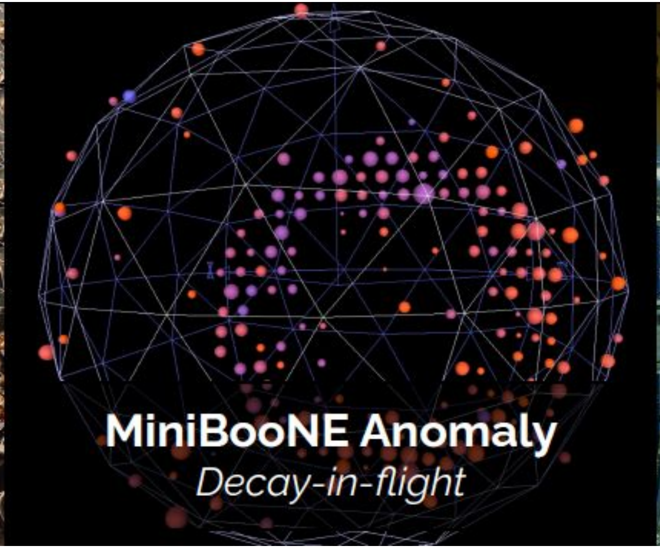
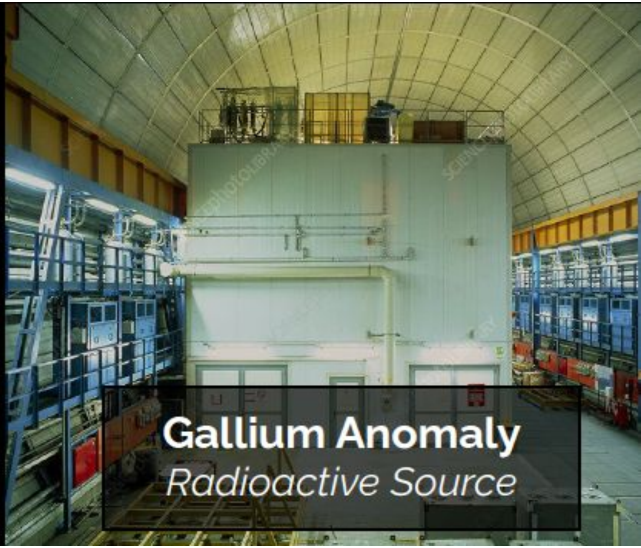
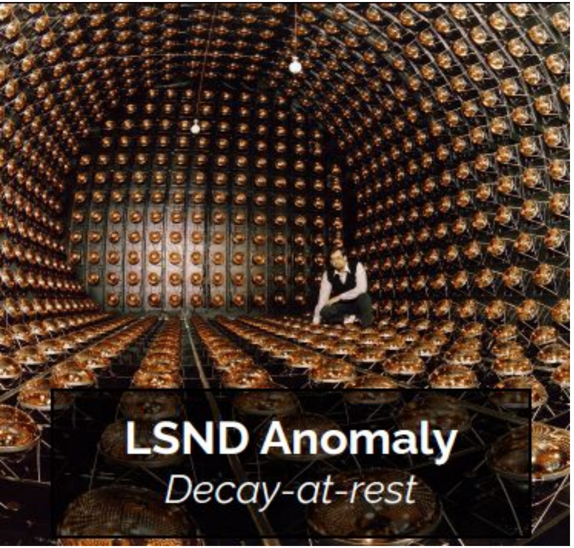
LSND, MiniBooNE, and Gallium Anomalies







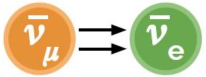
LSND Anomaly

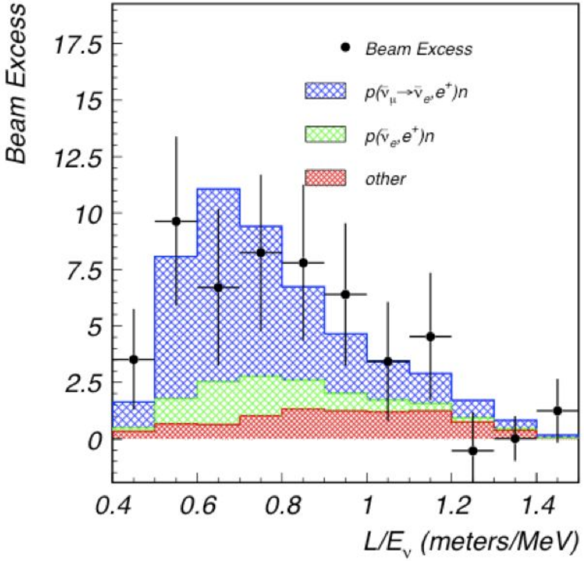


Studied a beam of muon neutrinos from **muon decay-at-rest**, using a liquid scintillator detector.

Well-understood neutrino production and detection processes.

Observed a **3.8σ** excess electron antineutrinos at L~30m **(L/E ~1m/MeV).**

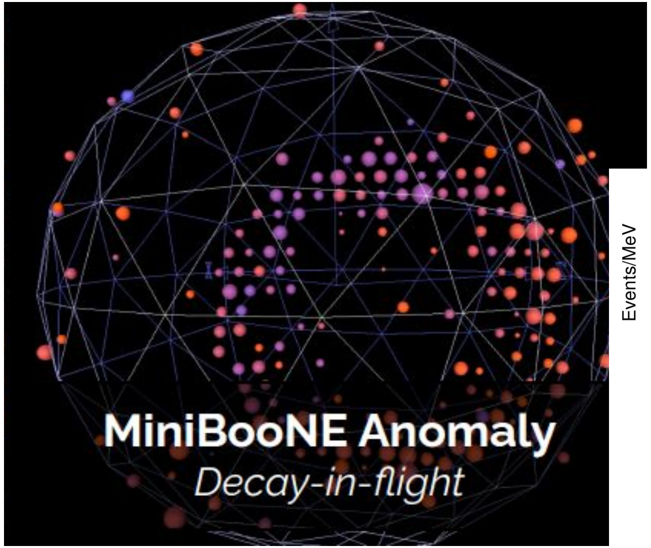


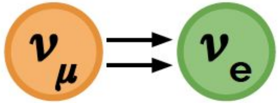


MiniBooNE Anomaly

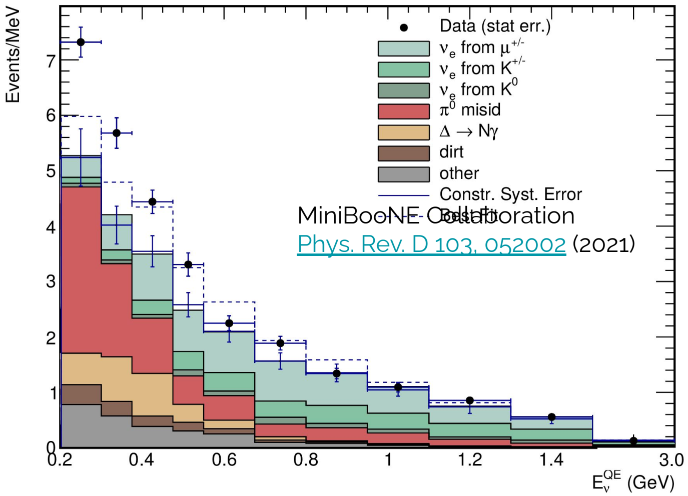
Studied neutrinos from a meson decay-in-flight source (~few hundred MeV mean neutrino energy) using a cherenkov detector.

Employed *in situ* constraints of flux/cross-section uncertainties and backgrounds.





Saw at **4.8σ** evidence of excess electron neutrinos at L~500m **(L/E ~1m/MeV)**.

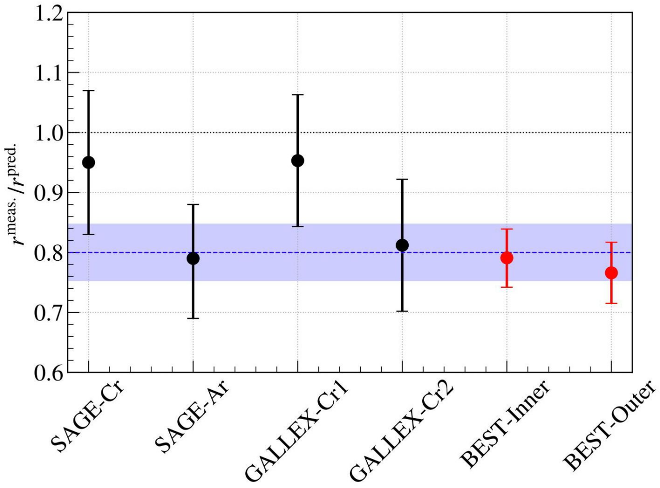


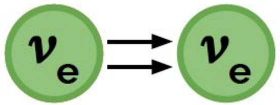
MiniBooNE Collaboration
Phys. Rev. D 103, 052002 (2021)

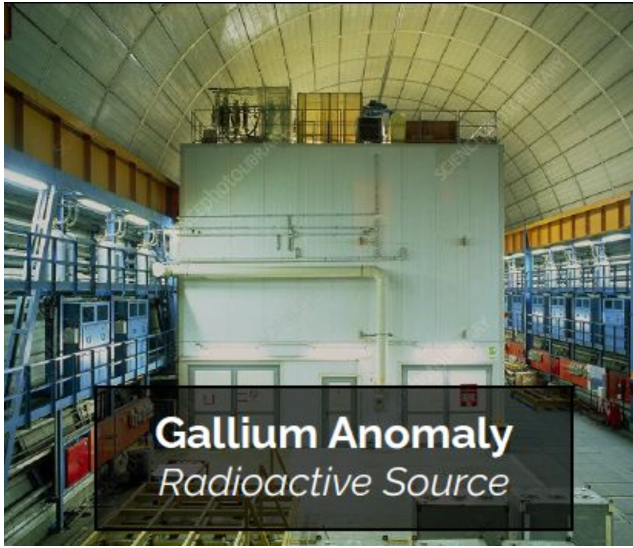
Gallium Anomaly

SAGE and **GALLEX** experiments studied electron neutrinos from intense radioactive sources of ^{51}Cr and ^{37}Ar deployed within their detectors.

Saw deficits of electron neutrinos as a function of detector radius **(L/E ~1m/MeV)**.





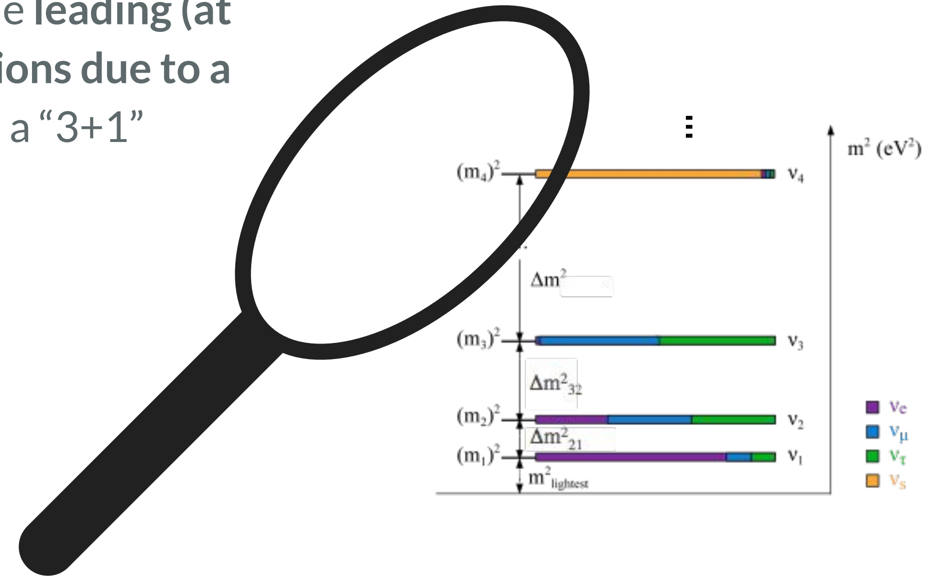


Recently confirmed by **BEST** experiment
[Phys. Rev. Lett. **128**, 232501 (2022)]

Combined ~**4.0σ** effect.

The Last Decade

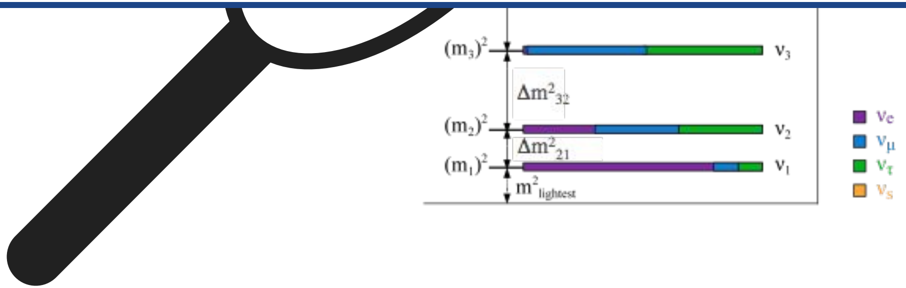
Following the previous P5 Recommendations, the community has successfully mounted **"a diverse program of small-experiments** aimed at directly addressing these anomalies and probing the **leading (at the time) theoretical explanation: oscillations due to a single eV-scale, mostly sterile neutrino**, or a "3+1" scenario.



The Last Decade

Following the previous P5 Recommendations,
the community has successfully mounted “a diverse

- Reactor short-baseline anomaly now understood as limitations in our understanding of reactor fluxes
- Gallium anomaly strikingly confirmed by direct test with BEST experiment
- Further MiniBooNE running and MicroBooNE results have revealed a complex picture seemingly at odds with 3+1… (more on this later)
- JSNS^2 and SBN accelerator-based programs initiated and now online, promising powerful tests of MiniBooNE and LSND… (more on this later)



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Community efforts beyond P5 Recommendations:

- Complementary data sets from non-short-baseline experiments including MINOS/MINOS+, IceCube, T2K, NOvA, SuperK, KATRIN… have been used to confront 3+1 oscillations
- A rich array of additional new physics models—from exotic flavor transformation to hidden sector couplings—that represent viable interpretations of the anomalies have been developed

The Last Decade >>>>>>>> Today

Following the previous P5 Recommendations,
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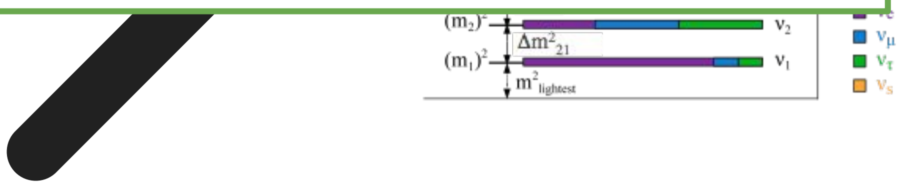
Community efforts beyond P5 Recommendations:

- Complementary data sets from non-short-baseline experiments including MINOS/MINOS+, IceCube, T2K, NOvA, SuperK, KATRIN... have been used to confront
-

Though much has been learned, the LSND, MiniBooNE and Gallium short-baseline anomalies still stand unexplained, and serve as compelling reasons to probe deeper and wider toward more "exotic" theoretical interpretations.
Experimental and theory communities are both actively engaged in this endeavor!



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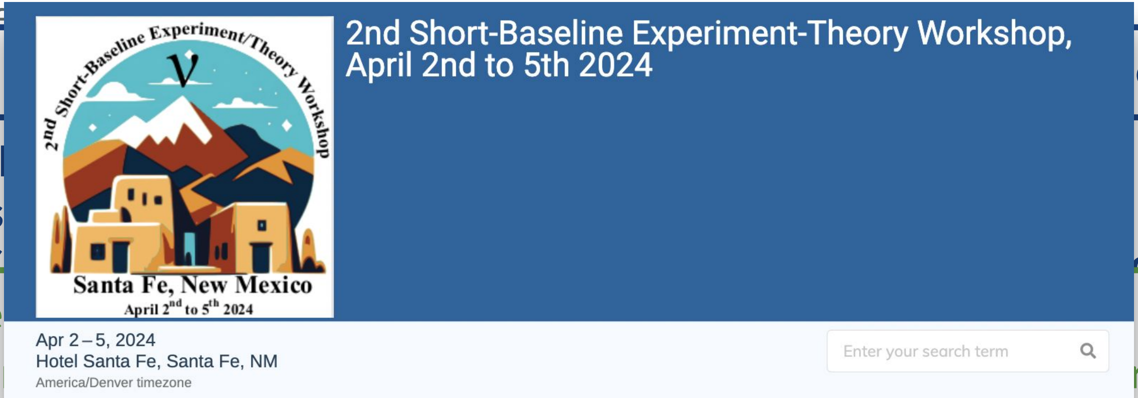

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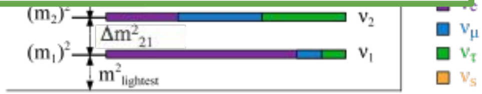

Revelations within Theoretical Community

Three broad categories of theoretical interpretations have emerged over the past ~5-10 years:

1. Flavor conversion models
2. Dark sector portals
3. Standard Model or “conventional” explanations

1. Flavor Conversion Models

"Vanilla" 3+1 (also 3+2 and 3+3) light sterile neutrino oscillations?

Significant tensions in global data sets disfavor this interpretation

***Caveat: Treatment of all global data sets** using consistent assumptions (e.g. flux, cross-section) is challenging

[lots of work by Giunti, Schwetz, Conrad, Diaz, Kamp, GK, Arguelles, Kopp, Machado, Maltoni, …]

NEEDED, in order to put this model to rest:

1. Comprehensive, multi-channel oscillation searches that account for oscillation effects and systematic correlations across different flavor measurements
2. Resolution of MiniBooNE low-energy excess (cannot be entirely vanilla 3+N oscillations)

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Efforts in this front already well underway!
(more on this later)

1. Flavor Conversion Models

"Vanilla" 3+1 (also 3+2 and 3+3) light sterile neutrino oscillations?

Overlooked, or other new physics?

- (3+1) + non-standard interactions (e.g. quasi-sterile neutrinos)
- (3+1) + sterile neutrino decay
- Lepton-flavor-violating μ decays
- Large extra dimensions and altered dispersion relations affecting neutrino propagation
- Lorentz violation
- …

[lots of work by Ballet, Pascoli, Bertuzzo, Conrad, De Gouvea, Dentler, Gariazzo, Giunti, Gninenko, Hostert, Ross-Lonergan, Kopp, Lavender, Li, Maltoni, Alves, Palomares-Ruiz, Babu, Martinez-Soler, Pascoli, Peres, Schwetz, Shaevitz, Spitz, Stenico, Tsai, Zukanovich, …]

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- Lorentz violation
- ...

All of these models can be tested with current and upcoming experiments!

For further details, see Snowmass NF02 White Paper: https://arxiv.org/abs/2203.07323

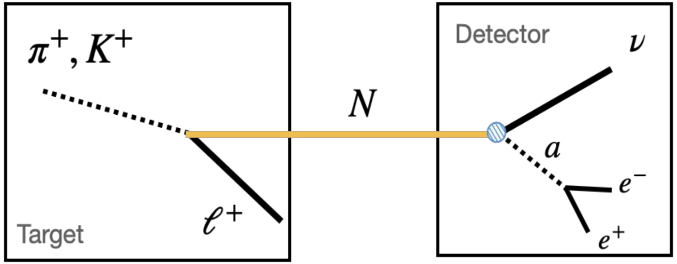
Category	Model	Signature	Anomalies			
			LSND	MiniBooNE	Reactor	Gallium
Flavor Conversion: Transitions	(3+1) oscillations	oscillations	✓	✓	✓	✓
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓
	(3+1) w/ sterile decay	$\nu_4 \to \phi\nu_e$	✓	✓	✓ (partial)	✓ (partial)
Flavor Conversion: Matter Effects	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓ (partial)	✓ (partial)
Flavor Conversion: Flavor Violation	lepton-flavor-violating μ decays	$\mu^+ \to e^+\nu_\alpha\overline{\nu_e}$	✓	✗	✗	✗
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e\phi A$	✓	✓	✗	✗

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

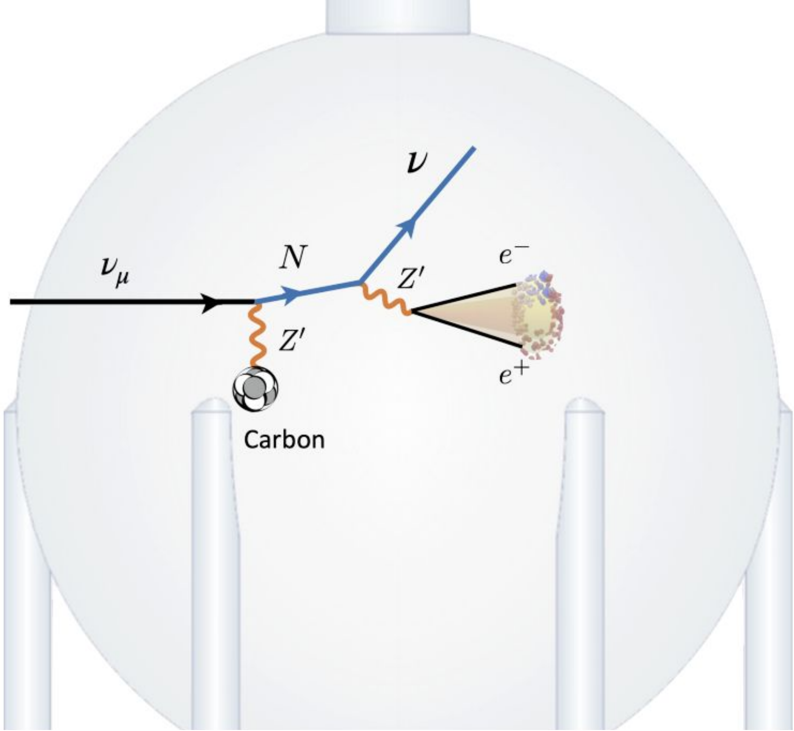
2. Dark Sector Portals

Associated with new particle production, and provide LSND/MiniBooNE interpretations:

in "neutrino beams", e.g.:



or, in neutrino scattering, e.g.:



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Category	Model	Signature	Anomalies			
			LSND	MiniBooNE	Reactor	Gallium
Dark Sector: Decays in Flight	transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗
	dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗
Dark Sector: Neutrino Scattering	neutrino-induced up-scattering	$\nu A \to NA$, $N \to \nu e^+e^-$ or $N \to \nu\gamma\gamma$	✓ (partial)	✓	✗	✗
	neutrino dipole up-scattering	$\nu A \to NA$, $N \to \nu\gamma$	✓ (partial)	✓	✗	✗
Dark Sector: Dark Matter Scattering	dark particle-induced up-scattering	γ or e^+e^-	✗	✓	✗	✗
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗

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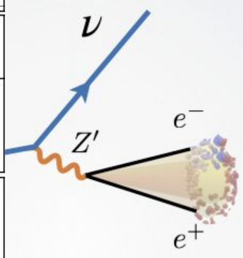

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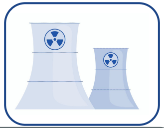
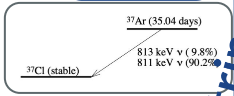
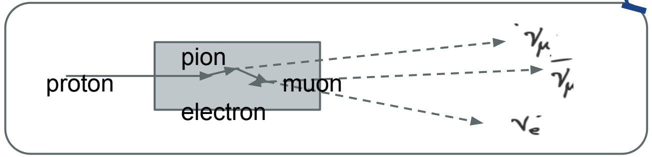
Anticipated Experimental Tests

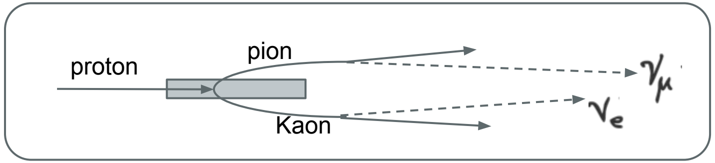
theoretical interpretations

neutrino source









Source	**Flavor Conversion:** 3+1 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
Beam Short Baseline	SBN	SBN		SBN, FASERν, SND@LHC, FLArE		
Beam Long Baseline	DUNE, Hyper-Kamiokande, ESSnuSB			DUNE, Hyper-Kamiokande, ESSnuSB		
Muon Decay-In-Flight	νSTORM				νSTORM	
Beta Decay and Electron Capture	KATRIN/TRISTAN, Project-8, HUNTER, BeEST, DUNE (^{39}Ar), PTOLEMY, $2\nu\beta\beta$					

For further details, see Snowmass NF02 White Paper: https://arxiv.org/abs/2203.07323

Anticipated Experimental Tests

theoretical interpretations

neutrino source

Source	Flavor Conversion: 3+1 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
Beam Short Baseline	SBN	SBN		SBN, FASERν, SND@LHC, FLArE		
Beam Long Baseline	DUNE, Hyper-Kamiokande, ESSnuSB			DUNE, Hyper-Kamiokande, ESSnuSB		
Muon Decay-In-Flight	νSTORM				νSTORM	
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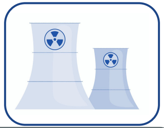
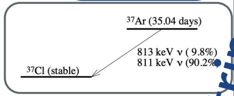
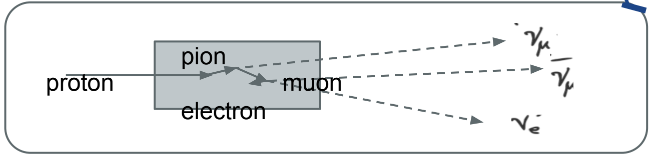
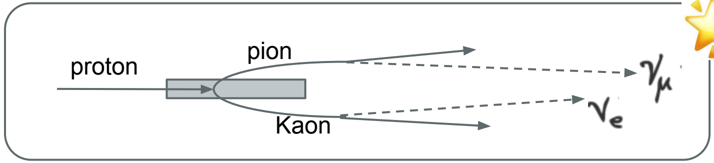




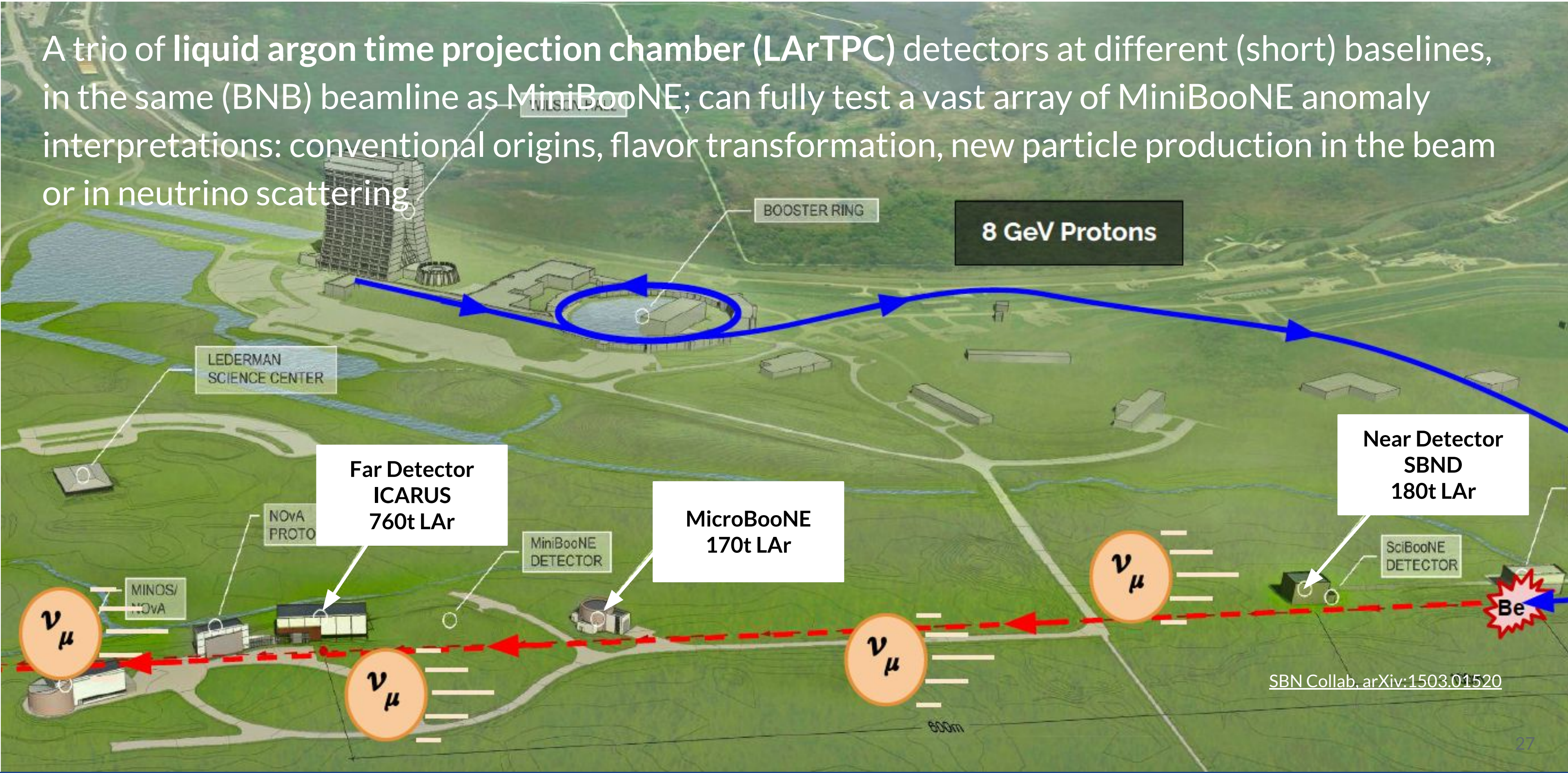




For further details, see Snowmass NF02 White Paper:
https://arxiv.org/abs/2203.07323

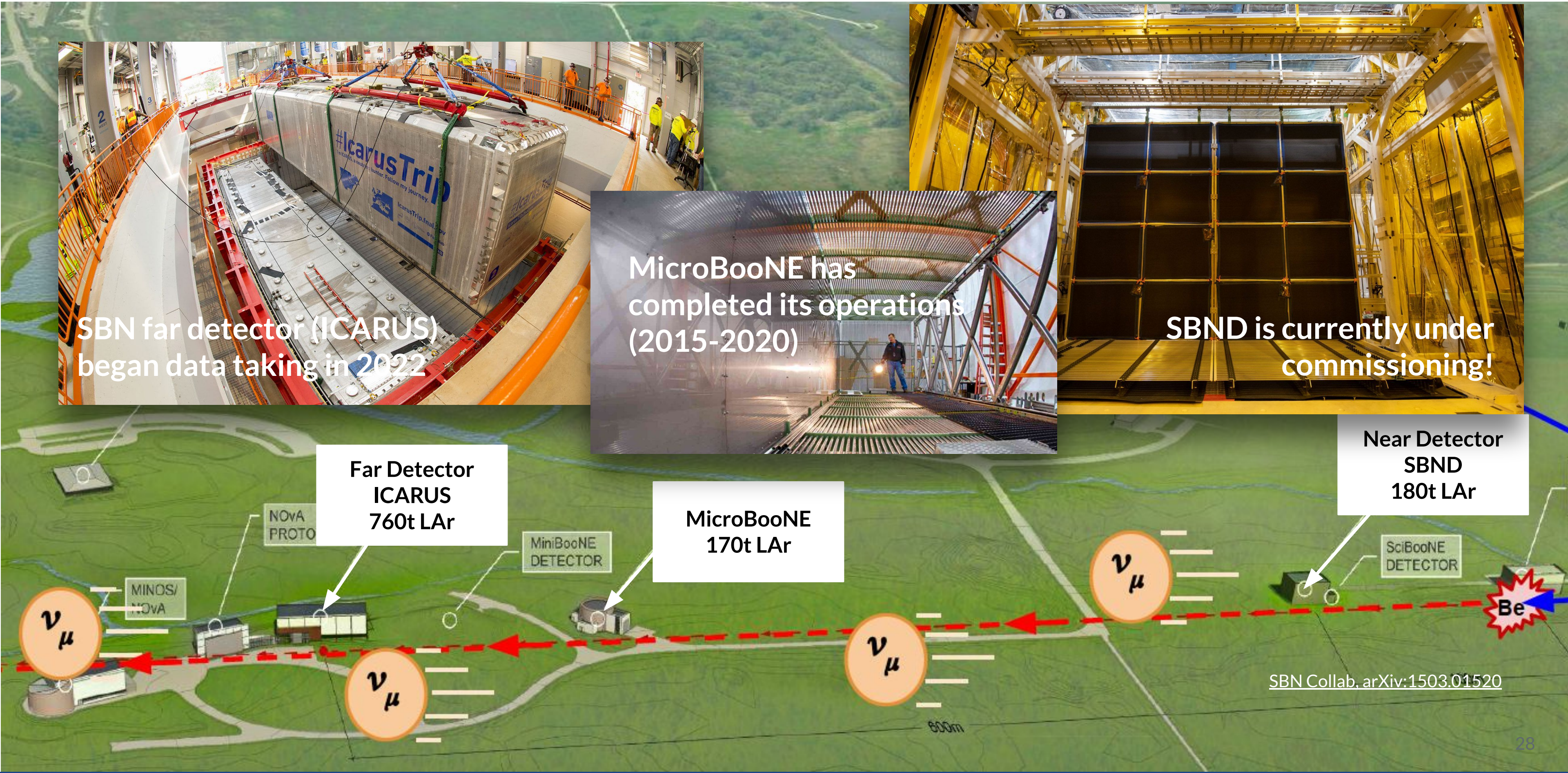
Short-Baseline Neutrino (SBN) Program at Fermilab

A trio of **liquid argon time projection chamber (LArTPC)** detectors at different (short) baselines, in the same (BNB) beamline as MiniBooNE; can fully test a vast array of MiniBooNE anomaly interpretations: conventional origins, flavor transformation, new particle production in the beam or in neutrino scattering



SBN Collab, arXiv:1503.01520

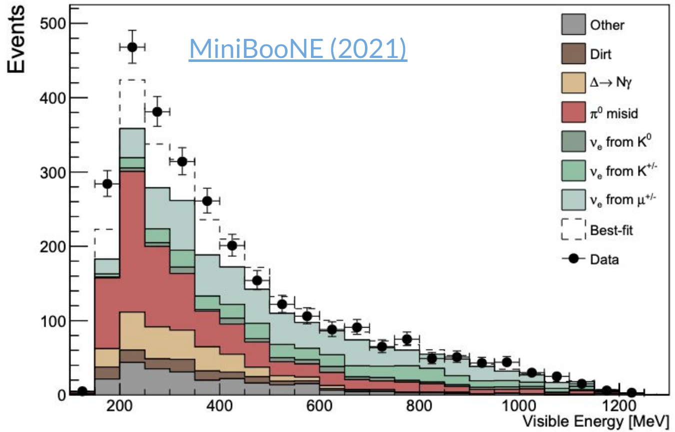
Short-Baseline Neutrino (SBN) Program at Fermilab

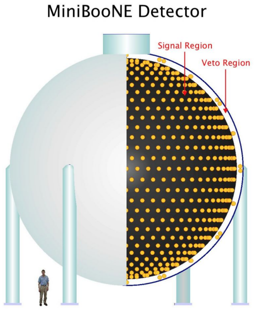


SBN Collab. arXiv:1503.01520

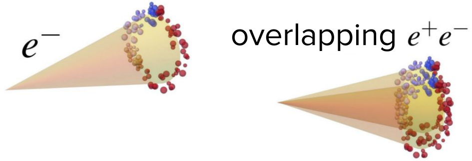
MicroBooNE Weighs In!

Key MiniBooNE challenge:

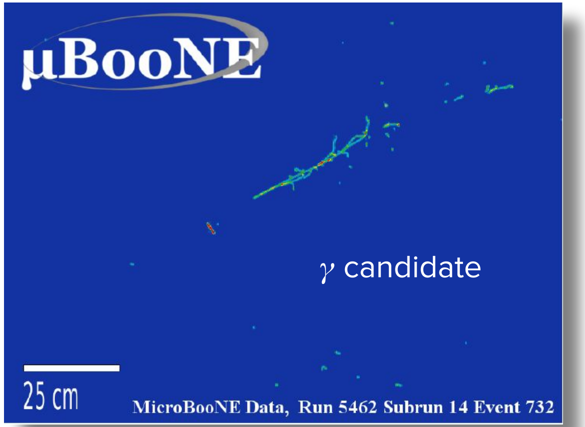




$e^{\mp}$ from $\overset{(-)}{\nu}_e$ interaction and
$\gamma \rightarrow e^+e^-$ are indistinguishable



Overcome, thanks to LArTPC imaging detector technology!



MicroBooNE Weighs In!

Direct tests of the MiniBooNE anomaly so far, using half of the MicroBooNE data set:

“Conventional” (SM) photon background?

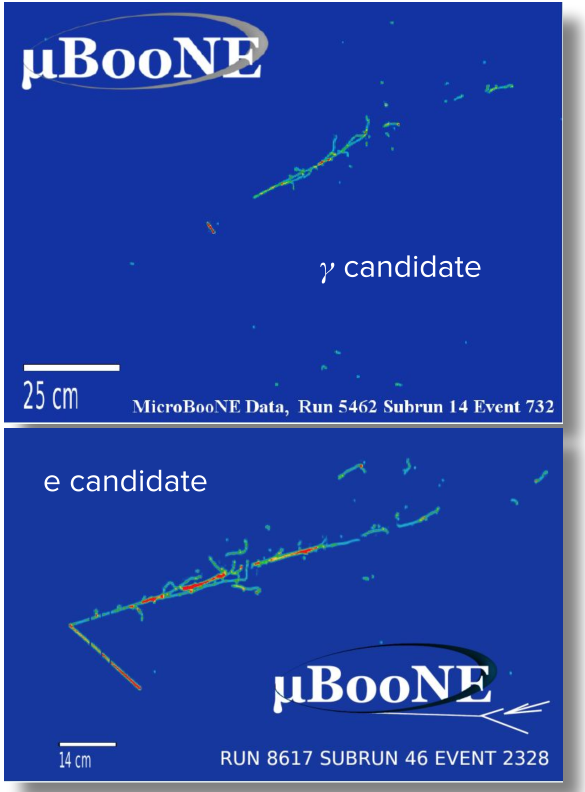
Dominant SM source of single-photons: neutrino-induced neutral-current Delta baryon production followed by Delta radiative decay
$\longrightarrow$ ruled out at >95% CL

[Phys.Rev.Lett. 128 (2022) 111801]

Energy-dependent enhancement of nue event rate?

Three separate, independent analyses rule it out as the sole source of the MiniBooNE anomaly

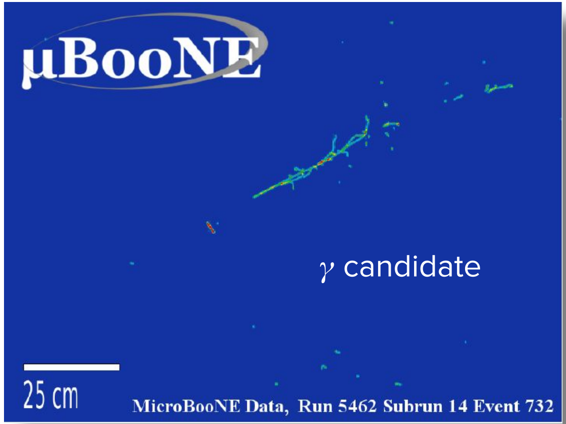
[Phys.Rev.Lett. 128 (2022) 24, 241801]



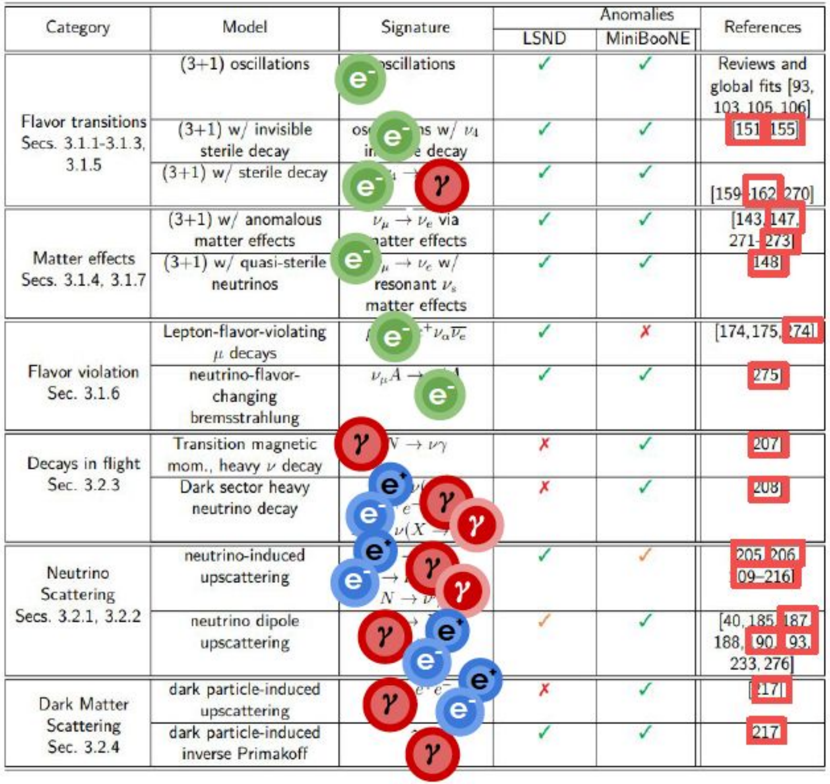
MicroBooNE Weighs In!

Anticipated new results:

- Enhanced-sensitivity photon searches (with improved reconstruction and 2x increase in statistics)
- Searches for 3+1 oscillations using BNB and NuMI-off-axis neutrinos
- **“Dark sector” physics searches**



Dark Sector Searches with LArTPCs



Category	Model	Signature	Anomalies: LSND	Anomalies: MiniBooNE	References
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	[151–155]
	(3+1) w/ sterile decay	$\nu_4 \to$	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \to e^+\nu_\alpha\overline{\nu_e}$	✓	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to$	✓	✓	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	[207]
	Dark sector heavy neutrino decay	$\nu(X \to$	✗	✓	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$N \to \nu$	✓	✓	[205, 206, 209–216]
	neutrino dipole upscattering		✓	✓	[40, 185–187, 188, 190–193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	e^+e^-	✗	✓	[217]
	dark particle-induced inverse Primakoff		✓	✓	[217]

Table modified from Snowmass White Paper on Light Sterile Neutrino Searches and Related Phenomenology

25+ dark-sector models in last 5 years

Incredibly rich and varied phenomenology containing

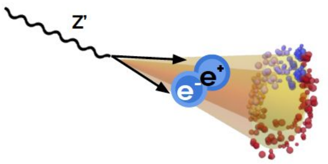
- Electron signals
- Photon signals
- Di-Photon signals
- e+e- signals

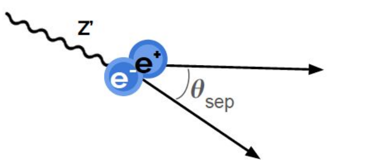
Image credit: Mark Ross-Lonergan

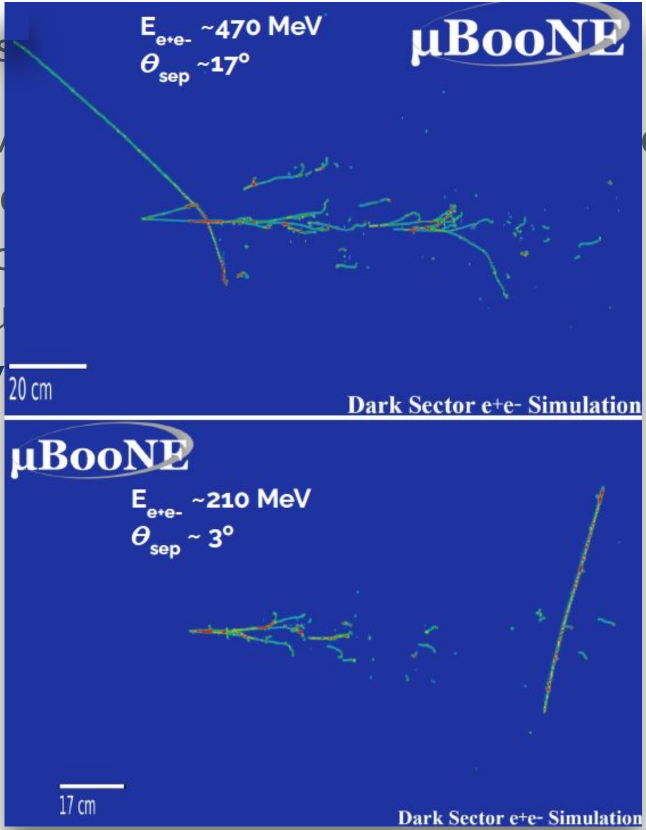
MicroBooNE Weighs In!

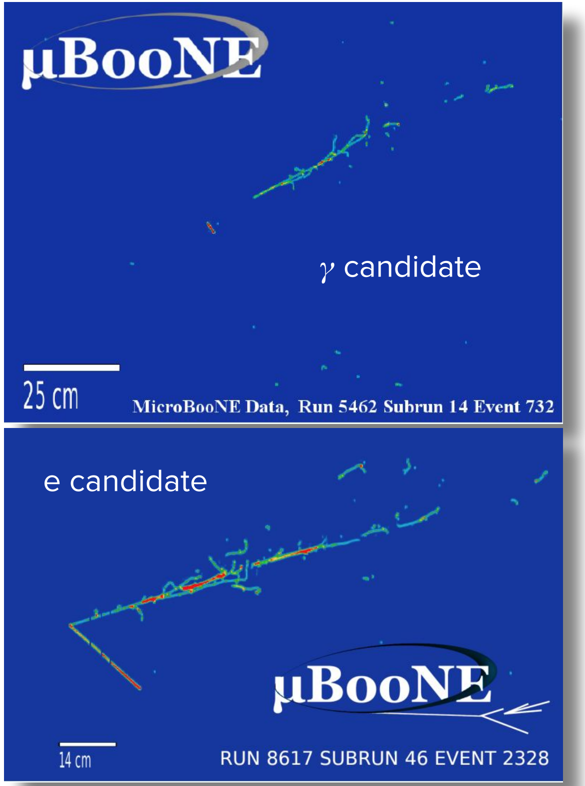
Anticipated new results

- Enhanced-sensitiv ... d
  reconstruction an
- Searches for 3+1 c
  NuMI-off-axis neu
- **"Dark sector" phy**









An Exciting New Era for Neutrino Physics!

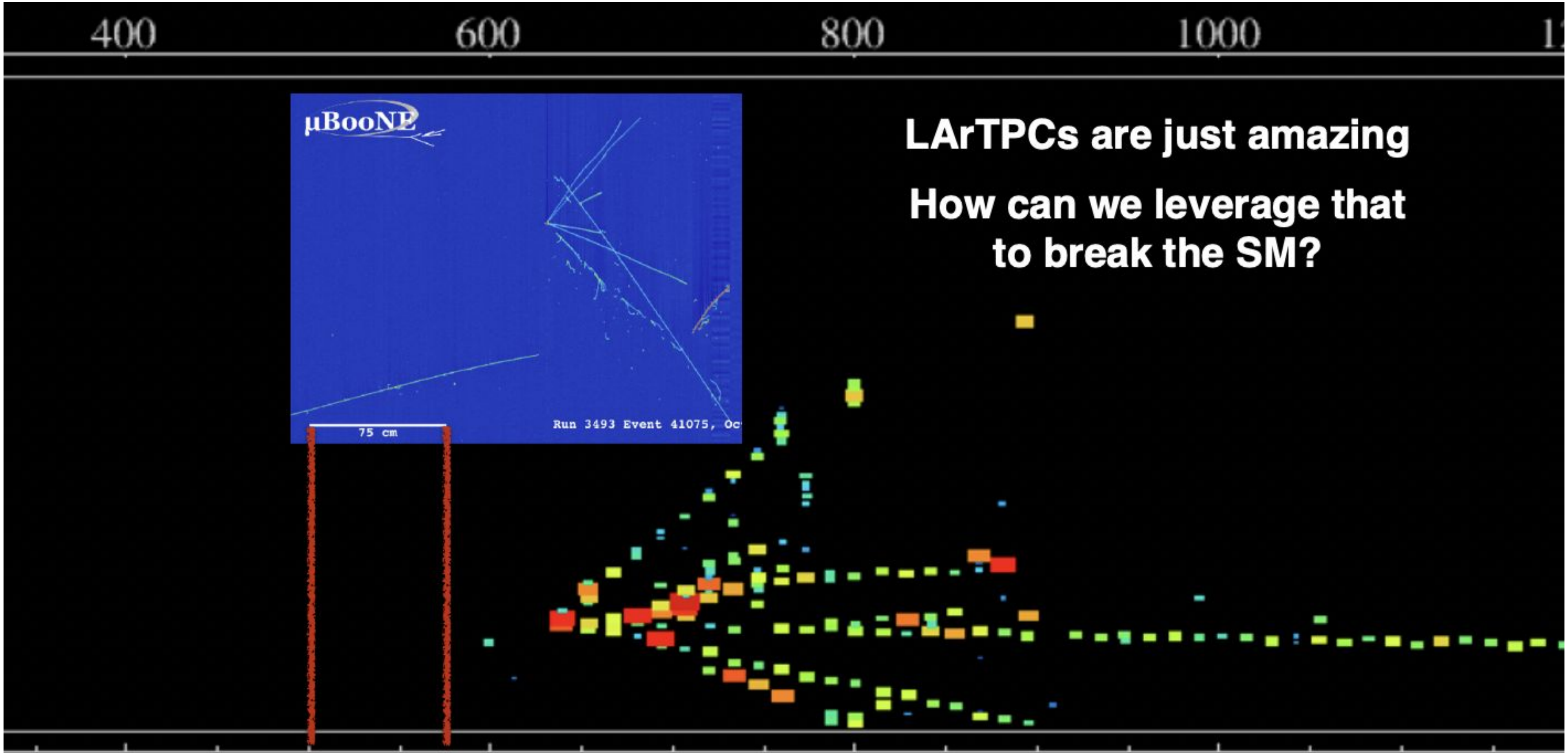


Image credit: Pedro Machado

Prospects at SBND

SBND expects to record O(10M) neutrino interactions on argon in just 3 years of running, about 20x the statistics already collected by MicroBooNE!

First-ever measurements of yet-undetected SM neutrino scattering processes:

- Coherent single-photon production in neutrino-nucleus neutral current scattering
- Delta and higher-mass resonance production in neutrino scattering followed by radiative decays
- ...

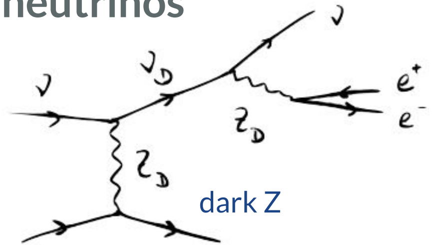
What's a discovery in particle physics
- Detecting for the first time a new fundamental process
- Discovering new particles (indirectly or directly)

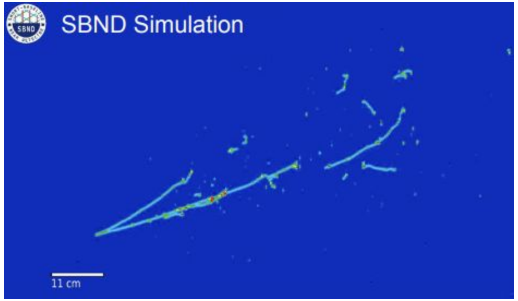
S. Gori

Prospects at SBND

High-sensitivity tests of MiniBooNE anomaly interpretations (SM and BSM models):

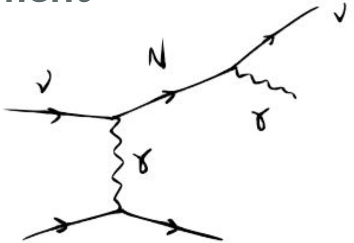
e.g., **dark neutrinos**

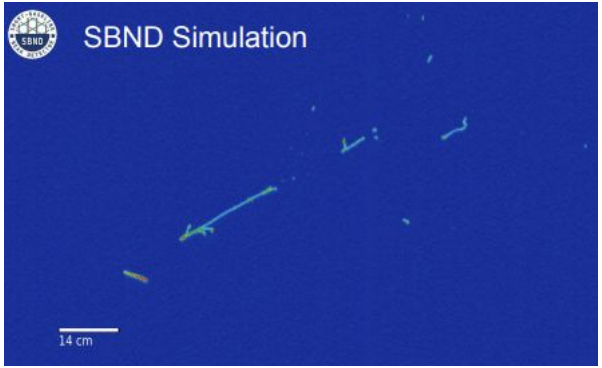




signature: e+e- pair with or without hadronic activity

e.g., **transition magnetic moment**

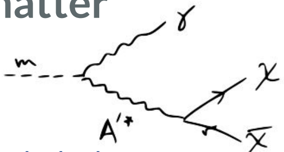




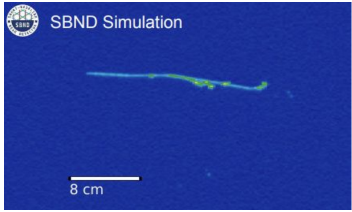
signature: photon shower with or without hadronic activity

Prospects at SBND

e.g., **light dark matter**



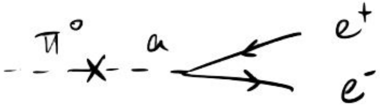
dark photon

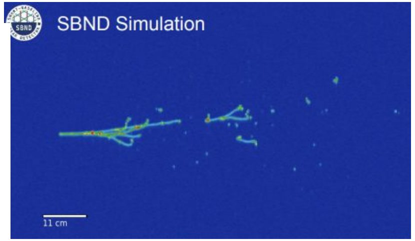


electron scattering

Broader tests of BSM scenarios:

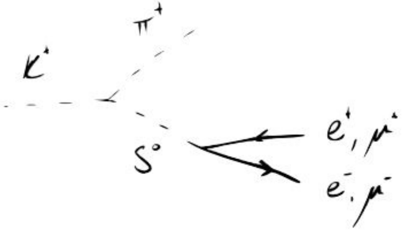
e.g., **axion-like particles**

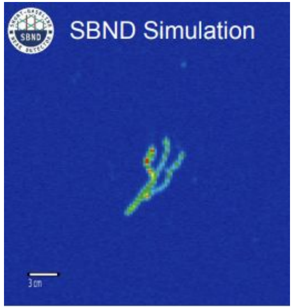




high-energy e+e- or μ+μ-

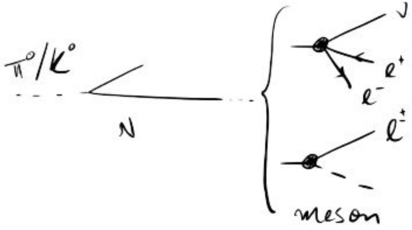
e.g., **Higgs portal scalars**

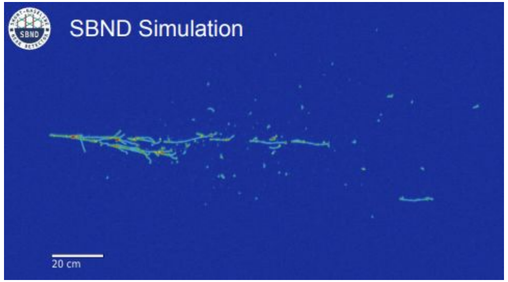




e+e- or μ+μ-, no hadronic activity

e.g., **heavy neutral leptons**

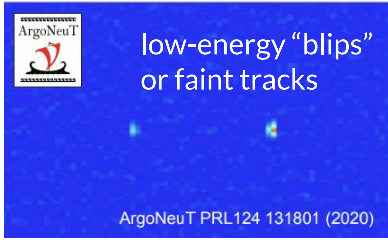




e+e-, μ+μ- or $\mu\pi$

e.g., **millicharged particles**

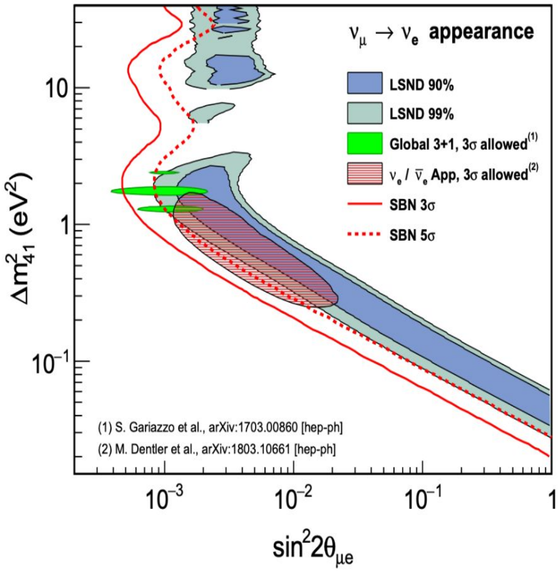
dark photon

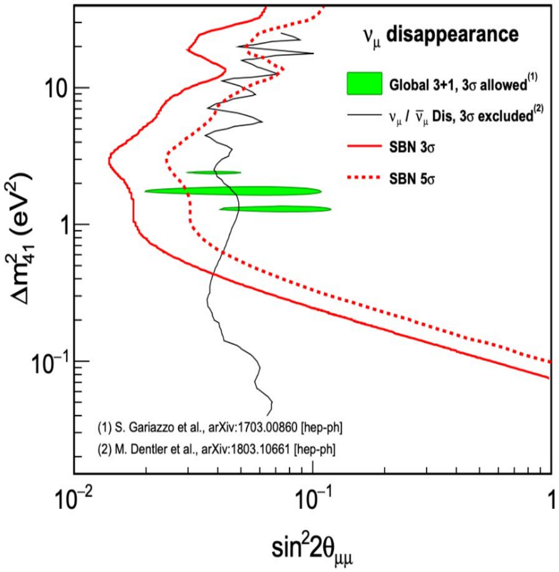


SBN Prospects: "Vanilla" 3+N models

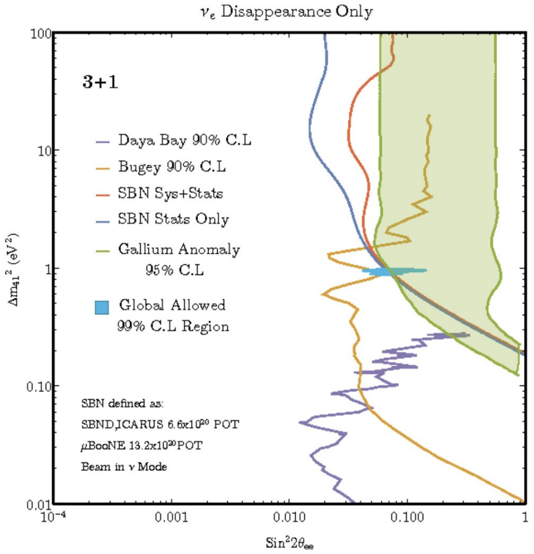
L-dependent search for ν_e appearance, ν_e disappearance, and ν_μ disappearance (no evidence thus far with atmospheric neutrinos or past accelerator experiments), and also **neutral current rate (combined all-active-flavor) disappearance** (smoking-gun signature of sterile neutrino oscillations)

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



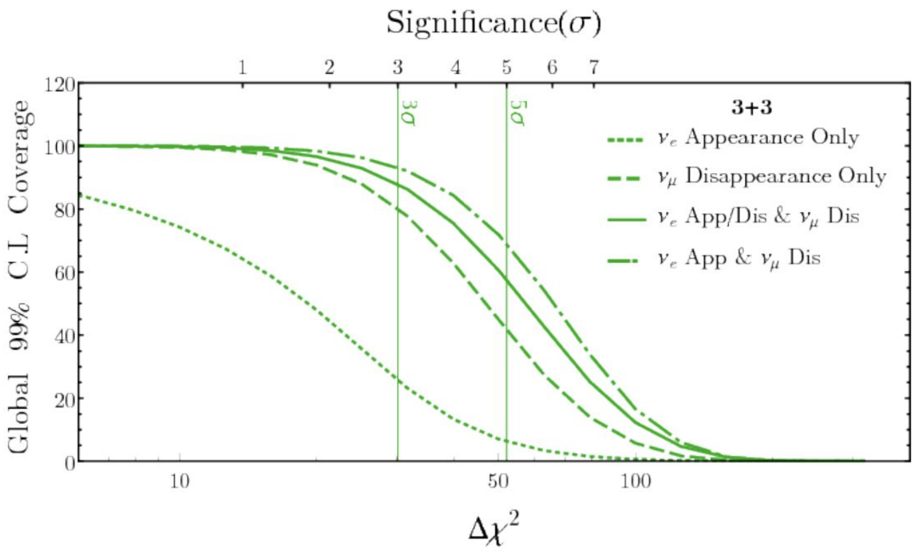


D. Cianci, et al, Phys.Rev.D 96 (2017) 5, 055001



SBN Prospects: "Vanilla" 3+N models

SBN can exhaustively probe 3+1, 3+2, and 3+3 oscillations through inclusive, multi-channel searches:



E.g., 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

An Exciting New Era for Neutrino Physics!

Thanks to unprecedented resolution and statistics provided by MicroBooNE and SBN, we are **on the cusp of major physics breakthroughs**:

- unprecedented studies of neutrino interactions and neutrino properties
- addressing long-standing experimental anomalies
- probing new parameter space for BSM theories

A new generation of scientists is **(re-)mastering this technology**:

- adapting new technological advancements to tackle new instrumentation challenges

An Exciting New Era for Neutrino Physics!

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E.g., unprecedented computing challenges:

Colliders: large number of interactions to be recorded and analyzed

LArTPC's: large size of interaction to be recorded and analyzed

Requires **innovation in hardware and software**, starting from low-level data processing, as close to detector as possible, and calls for a **new computing paradigm** with much greater focus on heterogeneous computing resources (GPUs, FPGAs, mixed architectures) both at high-performance computing facilities and on-device.

Leverages and benefits from **advances in artificial intelligence for image processing**.

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- unprecedented studies of neutrino interactions and neutrino properties
- addressing long-standing experimental anomalies
- probing new parameter space for BSM theories

A new generation of scientists is **(re-)mastering this technology**:

- adapting new technological advancements to tackle new instrumentation challenges
- using this new technology as a platform for innovative ideas and long-term R&D that will have a broad impact on high energy physics and beyond…

An Exciting New Era for Neutrino Physics!

Thanks to unprecedented resolution and statistics provided by MicroBooNE and SBN, we are **on the cusp of major physics breakthroughs**:

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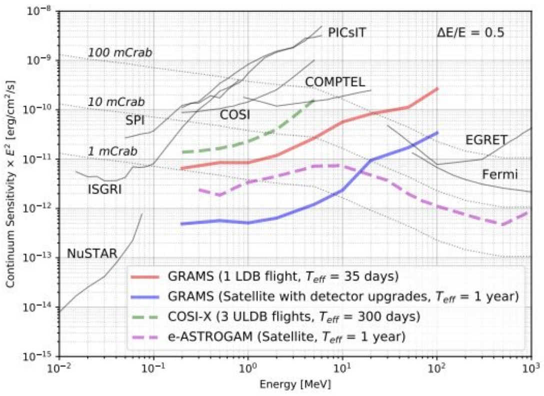
E.g., for astro-particle physics: Given sufficiently low energy threshold (keV), high resolution, and power-efficient charge readout design, technology can be flown for **MeV gamma-ray observations** and **indirect dark matter searches**

Gamma-Ray and AntiMatter Survey (GRAMS) has been funded by NASA for a technology-demonstration balloon flight in 2025-26.

GAMMA-RAY AND ANTIMATTER SURVEY



T. Aramaki, G.K., et al., [Astropart.Phys. 114 (2020) 107-114]

Short-Baseline Neutrino Experiments: Beyond-Standard Model, and Beyond-Neutrinos!

In recent decades, motivated by short-baseline experimental neutrino anomalies that have survived decades of testing and remain compelling, pushing us to innovate in both theory and experiment to better probe the neutrino sector.

Community now fully embraces that lack of constraints on neutrino properties, and their weakly-interacting nature, render them a **uniquely sensitive tool** for probing the physics of a wide range of dark matter models and generic searches for low-scale new physics.

Accelerator-based, short-baseline neutrino experiments offer high-luminosity (neutrinos, photons, nuclear and meson decays) and very sensitive, large detectors:

Discovery-class facilities for neutrino science, BSM physics, and innovative R&D!