Searches for New Physics Through Neutrino Experiments

Georgia Karagiorgi, Columbia University

Neutrino Frontiers Workshop - Focus Week

Galileo Galilei Institute for Theoretical Physics
Florence, Italy
July 1-5, 2024

ALFRED P. SLOAN
FOUNDATION

Neutrino Experiments:
Beyond Standard Model, and Beyond Neutrinos!

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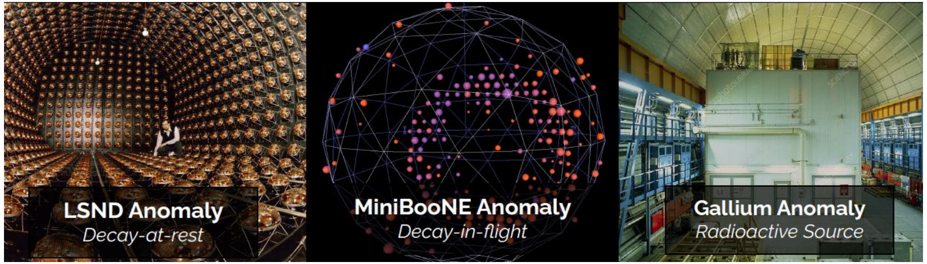

SNOWMASS NEUTRINO FRONTIER:
NF02 TOPICAL GROUP REPORT
UNDERSTANDING EXPERIMENTAL NEUTRINO ANOMALIES

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

G. KARAGIORGI[1], B. R. LITTLEJOHN[2], P. MACHADO[3], A. SOUSA[4], ON BEHALF OF THE NF02 TOPICAL GROUP COMMUNITY[*]

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NF02 Report: https://inspirehep.net/literature/2150479

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

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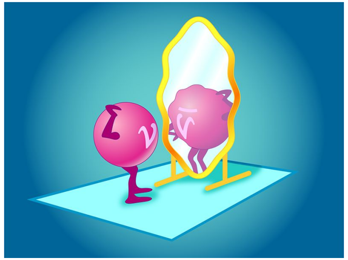
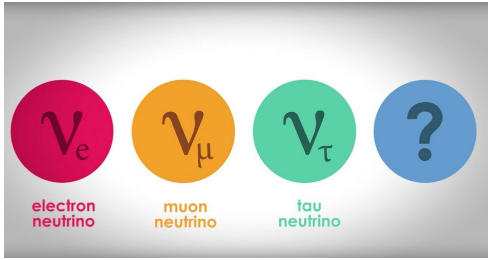
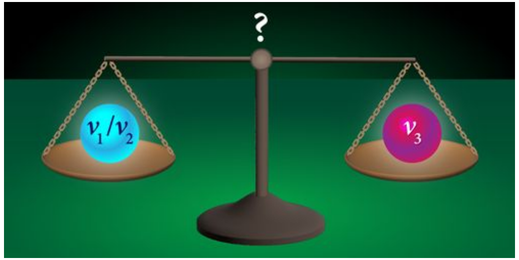
Yet to be measured neutrino parameters, undetermined neutrino properties, and the weakly-interacting nature of neutrinos render them a **uniquely sensitive tool** for generic searches for low-scale new physics, and even probing the physics of a wide range of dark matter models







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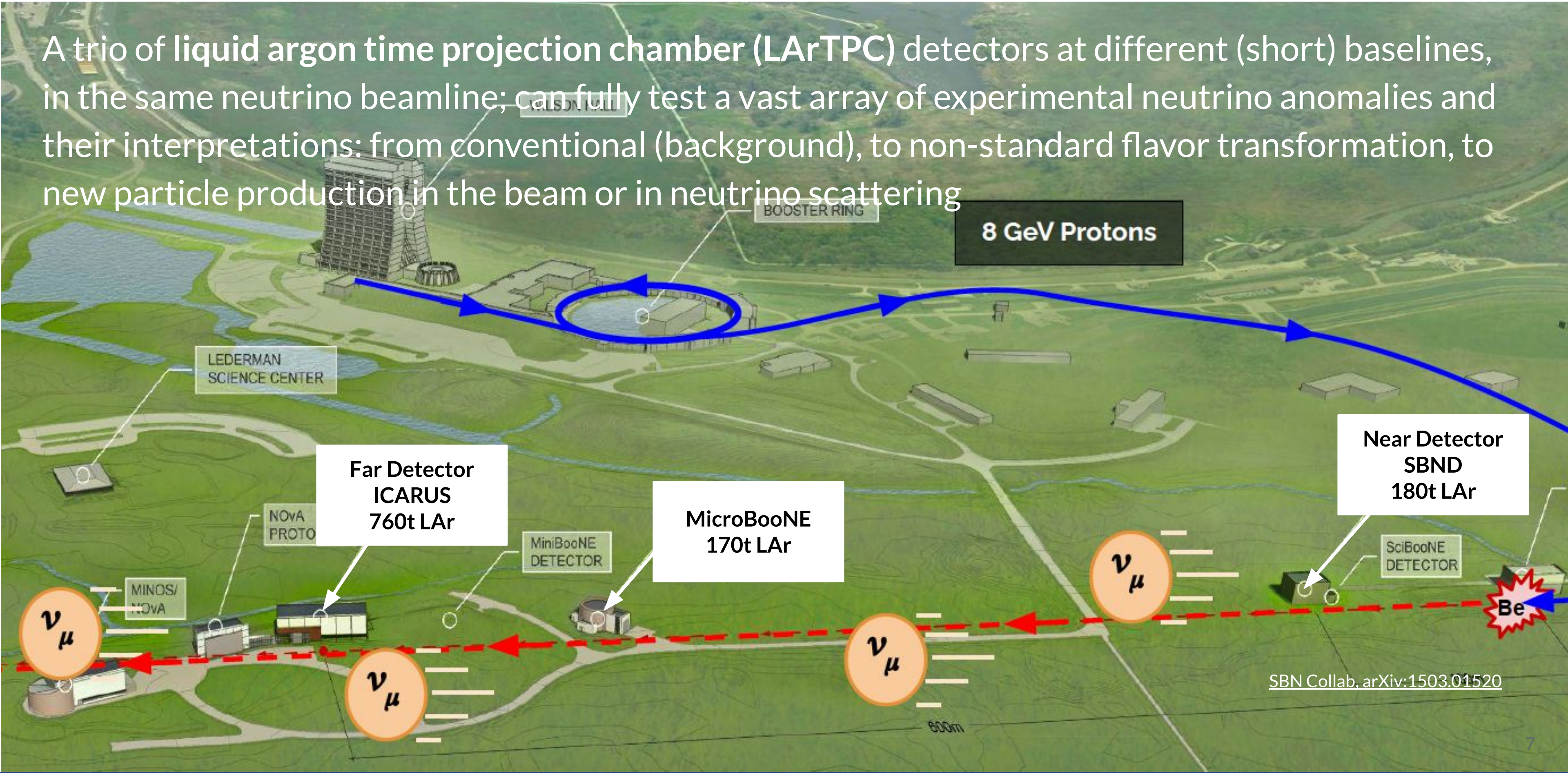
In this talk: **accelerator-based, short-baseline** neutrino experiments as **discovery-class facilities for neutrino science and BSM physics**: high-intensity (neutrinos, photons, meson decays) and high-precision (very sensitive, large detectors)

Short-Baseline Neutrino (SBN) Program at Fermilab

A trio of **liquid argon time projection chamber (LArTPC)** detectors at different (short) baselines, in the same neutrino beamline; can fully test a vast array of experimental neutrino anomalies and their interpretations: from conventional (background), to non-standard flavor transformation, to new particle production in the beam or in neutrino scattering



SBN Collab, arXiv:1503.01520

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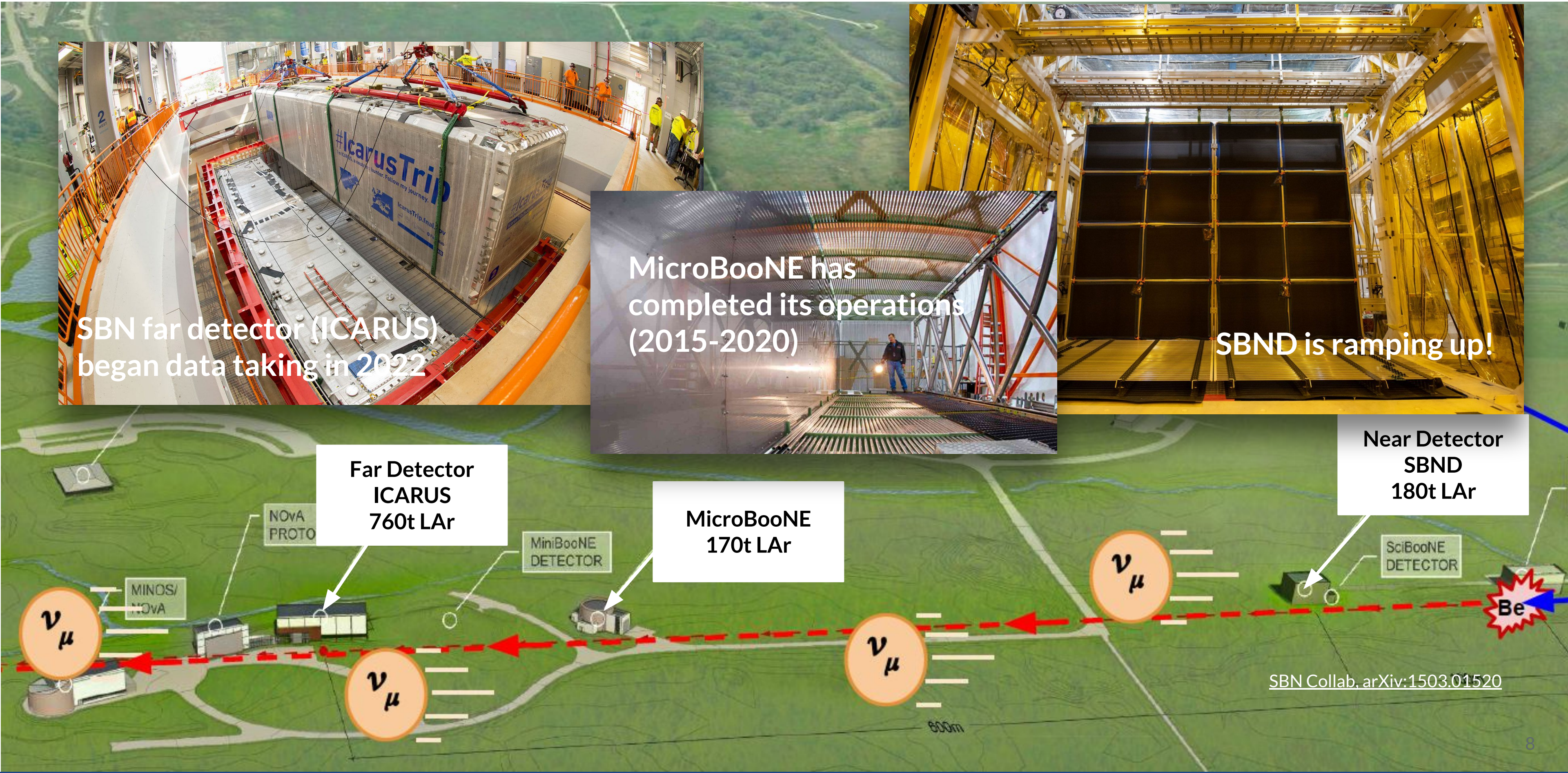
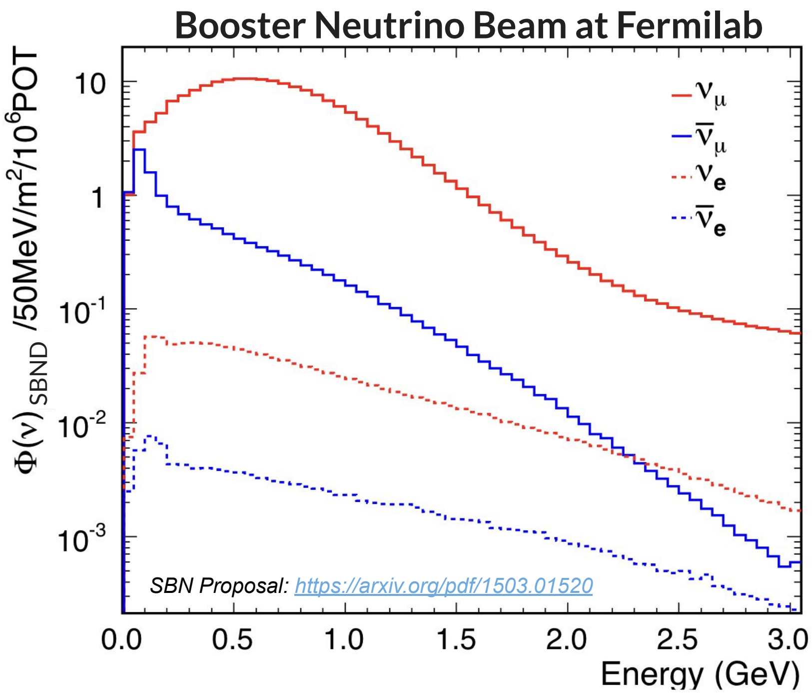


Accelerator-based, short-baseline experiments

High flux: *E.g., at SBND, O(2M) muon neutrino charged-current interactions per year!*



Flavor-pure: >99% muon neutrino flavor, ~0.5% electron neutrino flavor

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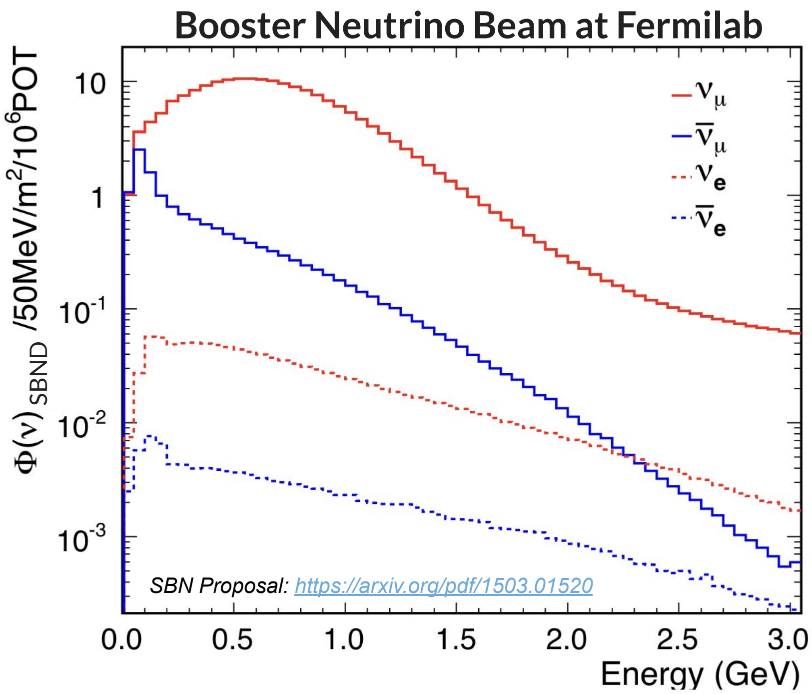

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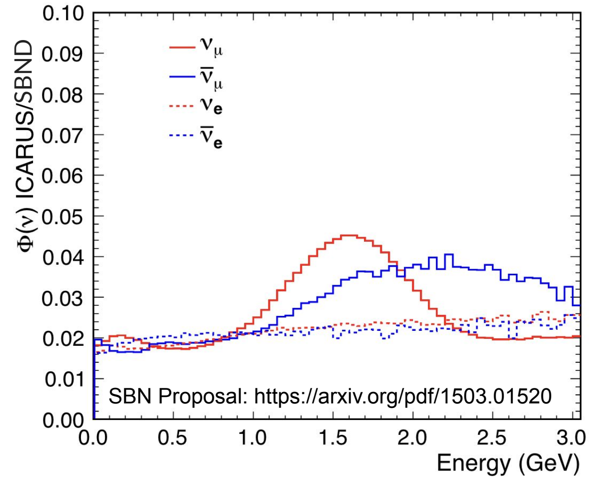

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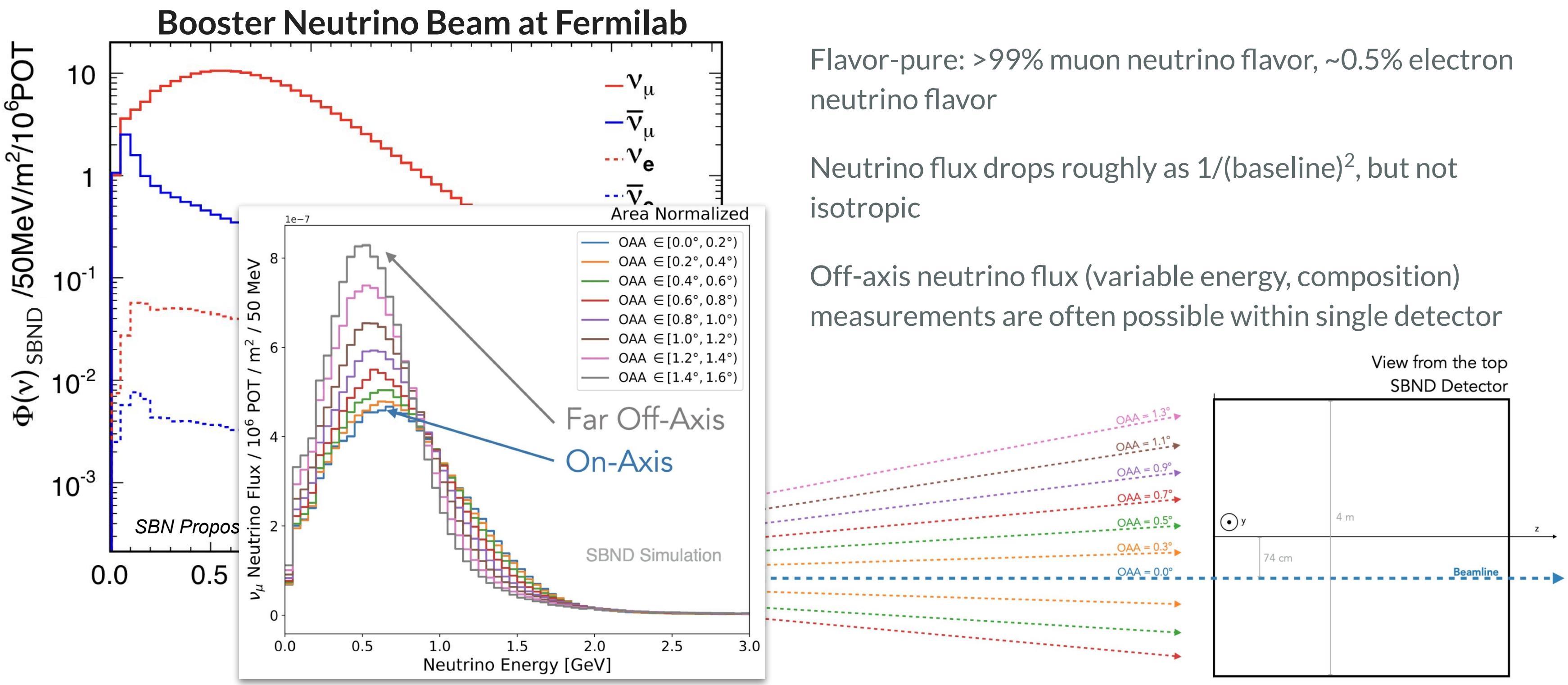

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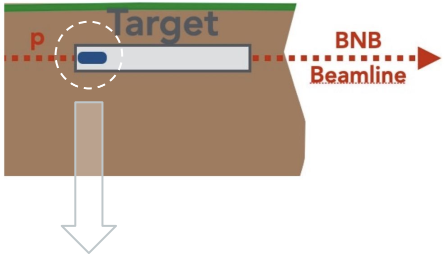
Off-axis neutrino flux (variable energy, composition) measurements are often possible within single detector

Figure courtesy of M. Del Tutto

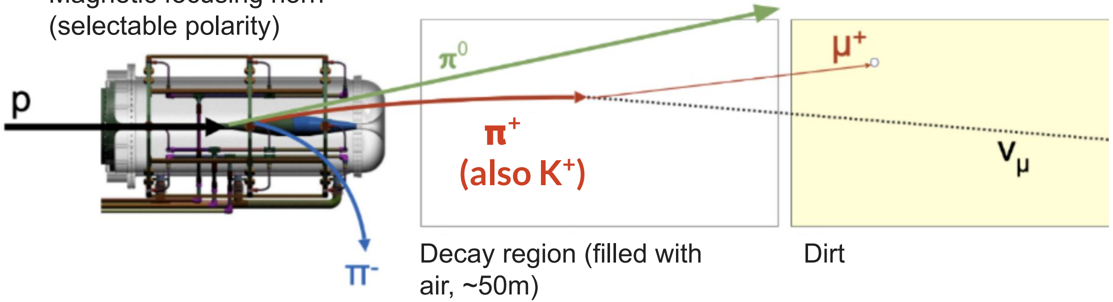
Accelerator-based, short-baseline experiments

High flux:** Neutrinos and **new particles

High-intensity, pulsed (1.6 μs beam spill),
8 GeV proton beam on Be target



Magnetic focusing horn
(selectable polarity)



Decay region (filled with air, ~50m)

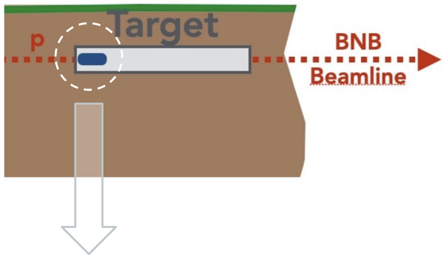
Dirt

Feebly-interacting particle searches:
Heavy neutral leptons
Long-lived particles
Higgs portal scalar
Dark trident
Millicharged particles
Dark matter particles (axion-like)

Accelerator-based, short-baseline experiments

High flux: *Neutrinos and* ***new particles***

High-intensity, pulsed (1.6 μs beam spill), 8 GeV proton beam on Be target



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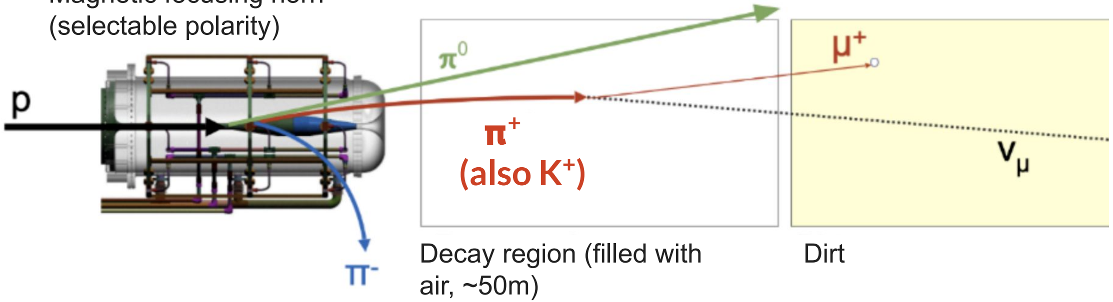

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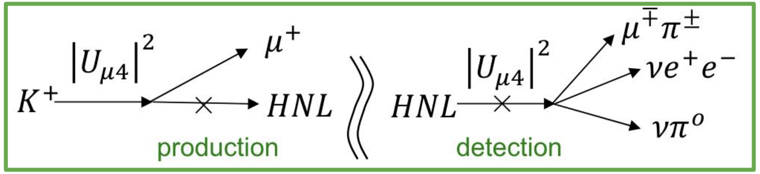
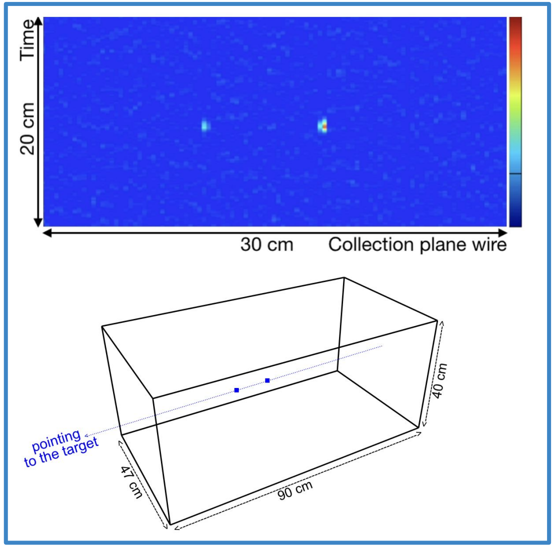
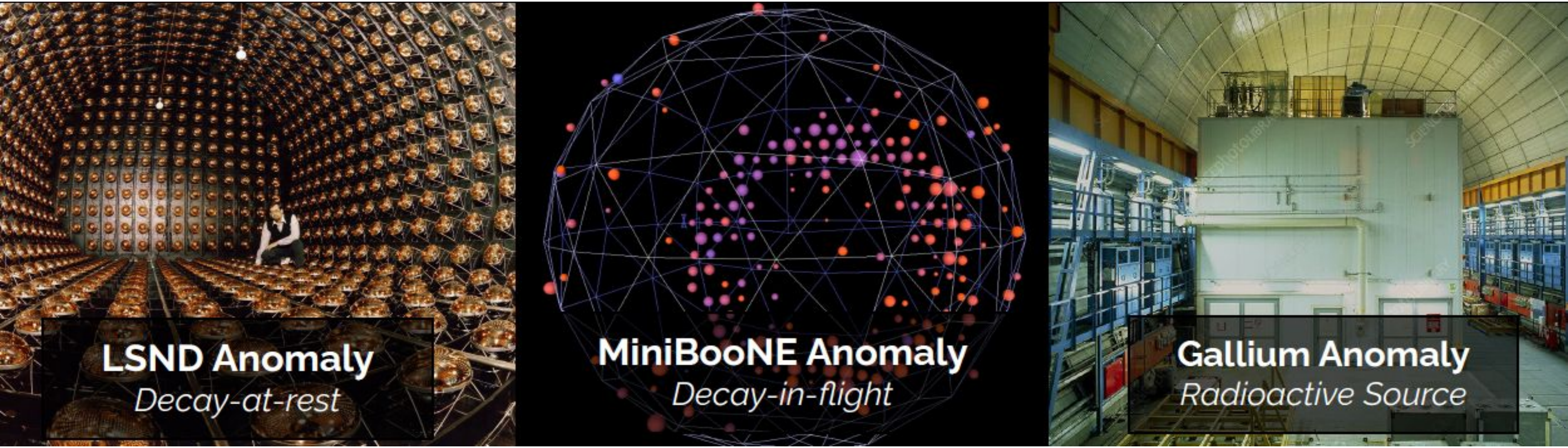




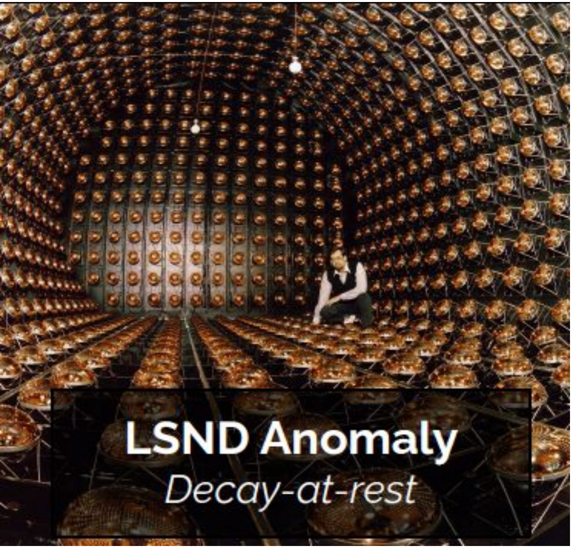
ArgoNeut, https://arxiv.org/pdf/1911.07996

A Key Driver:
LSND, MiniBooNE, and Gallium Anomalies



For a recent, thorough review of short-baseline anomalies, see [Neutrino 2024 talk]() by M. Maltoni.

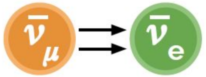
LSND Anomaly

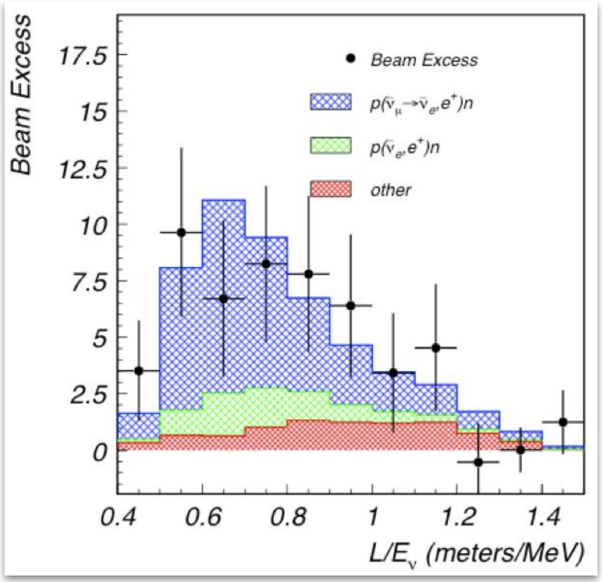


Studied a beam of muon neutrinos from **muon decay-at-rest**, using a liquid scintillator detector.

Well-understood neutrino production and detection processes.

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

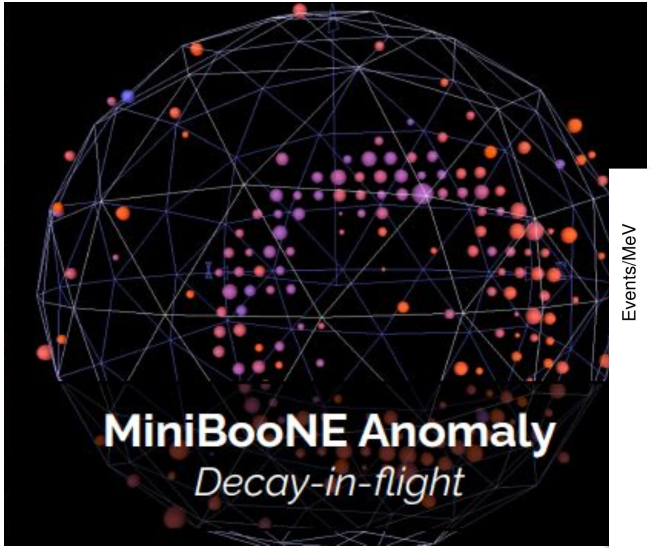


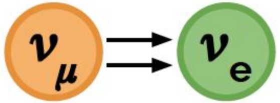


MiniBooNE Anomaly

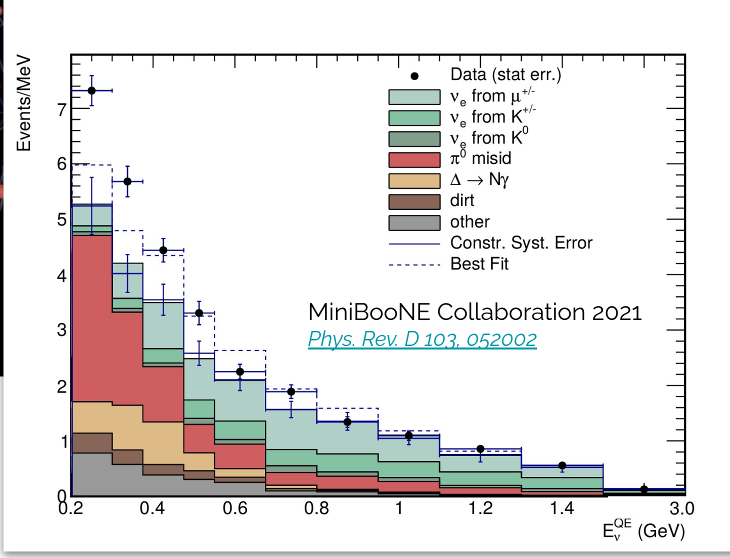
Studied neutrinos from a meson decay-in-flight source (~few hundred MeV mean neutrino energy) using a cherenkov detector.

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





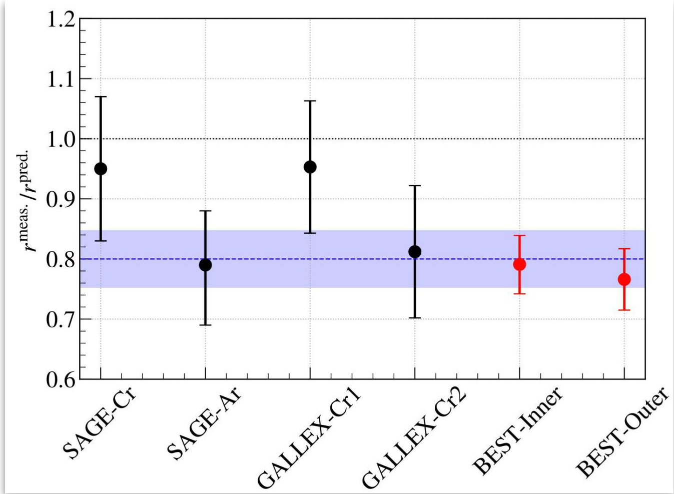
Saw at **4.8σ** evidence of excess electron neutrinos at L~500m **(L/E ~1m/MeV)**.

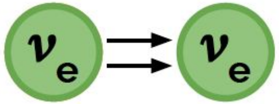


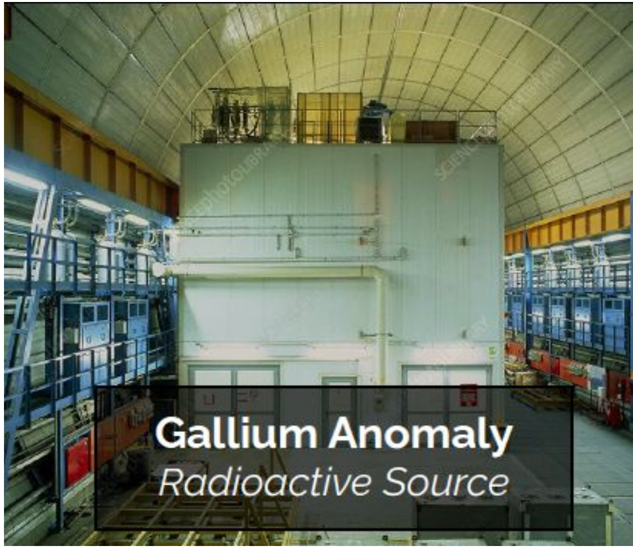
Gallium Anomaly

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)**.





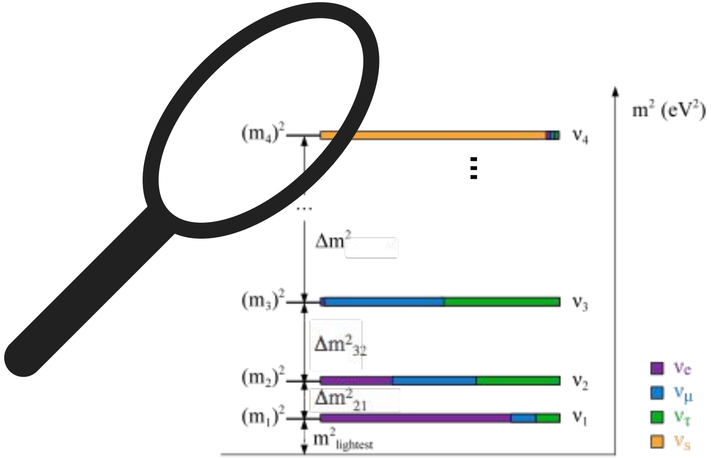


Recently confirmed by **BEST** experiment
[Phys. Rev. Lett. **128**, 232501 (2022)]

Combined ~**4.0σ** effect.

Short-baseline Anomalies: What We Know Now

Over the past decade, **a diverse program of small-experiments was mounted,** aimed at directly addressing these anomalies and probing the **leading (c. 2010) theoretical explanation: oscillations due to a single eV-scale, mostly sterile neutrino**, or a “3+1” scenario.



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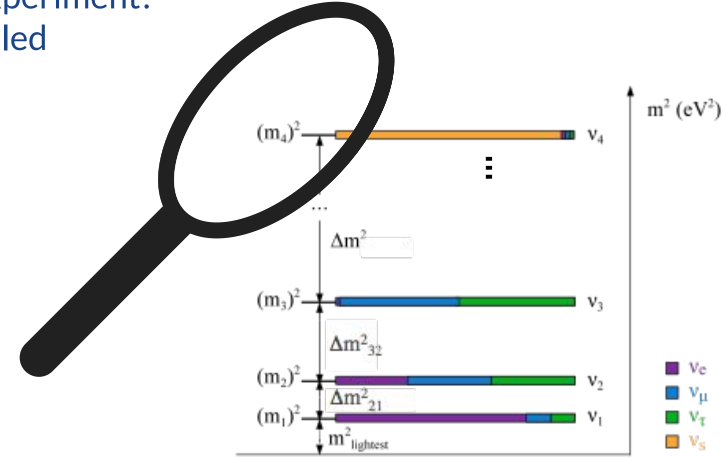
- Gallium anomaly strikingly confirmed by direct test with BEST experiment!
- Further MiniBooNE running and MicroBooNE results have revealed a complex picture seemingly at odds with 3+1…
- JSNS^2 and SBN accelerator-based programs initiated and now online, promising powerful tests of MiniBooNE and LSND…



- Reactor short-baseline anomaly now understood as limitations in our understanding of reactor fluxes (more on this by B. Littlejohn)

- Beyond direct tests, complementary data sets from non-accelerator and/or 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** theoretical interpretations

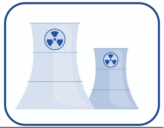
Flavor Conversion: 3+1 Oscillations	Flavor Conversion: Anomalous Matter Effects	Flavor Conversion: Lepton Flavor Violation	Dark Sector: Decays in Flight	Dark Sector: Neutrino-induced Up-scattering	Dark Sector: Dark-particle-induced Up-scattering

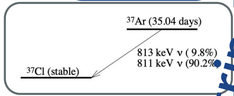
Anticipated Experimental Tests

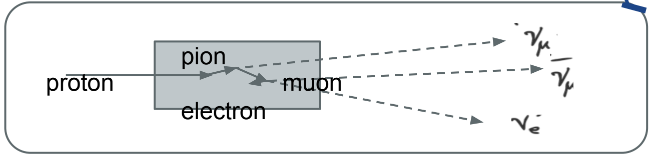
theoretical interpretations

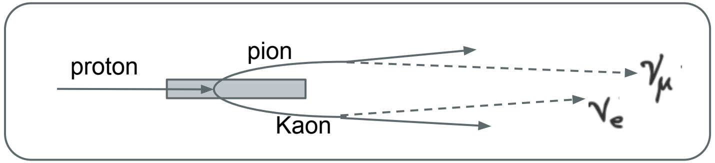
neutrino source

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						
Radioactive Source						
Atmospheric						
Pion/Kaon Decay-At-Rest						
Beam Short Baseline						
Beam Long Baseline						
Muon Decay-In-Flight						
Beta Decay and Electron Capture						









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

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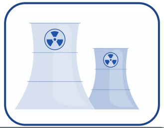

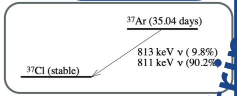

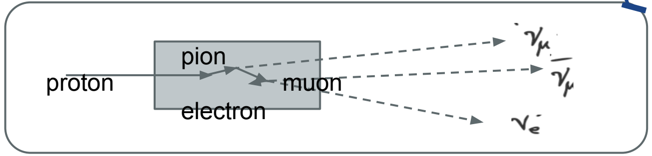

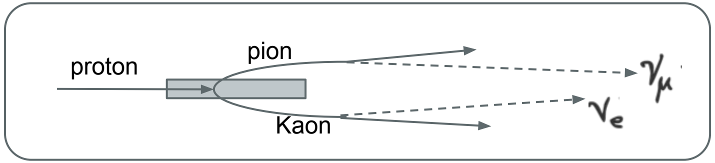

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Reactor	DANSS Upgrade, JUNO-TAO, NEOS-II, Neutrino-4 Upgrade, PROSPECT-II					
Radioactive Source	BEST-2, IsoDAR, THEIA, Jinping					
Atmospheric	IceCube Upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-Kamiokande, THEIA				IceCube Upgrade, KM3NET, ORCA 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, $2\nu\beta\beta$					

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Anticipated Experimental Tests

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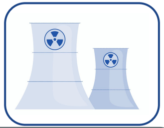

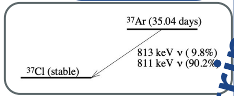

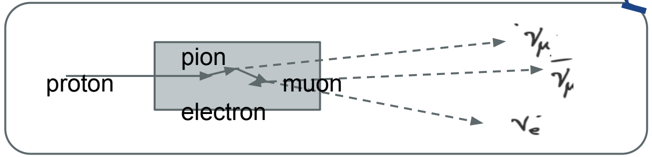

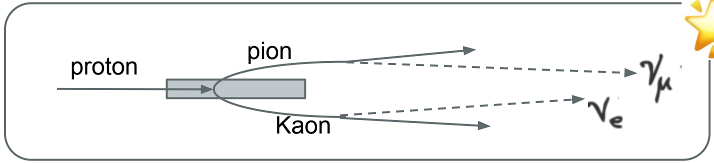

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1. Flavor Conversion @ SBN

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, …]

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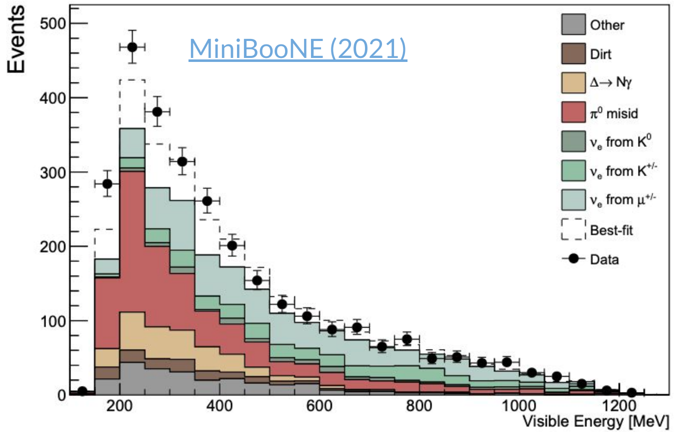
NEEDED, in order to exhaustively test this model:

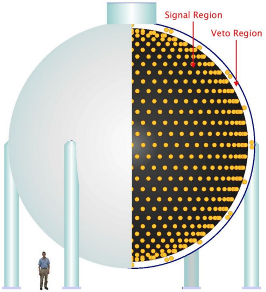
(a) Resolution of MiniBooNE low-energy excess (cannot be entirely vanilla 3+N oscillations; conventional/background origin?)

(b) Comprehensive, multi-channel oscillation searches that account for oscillation effects and systematic correlations across different flavor measurements

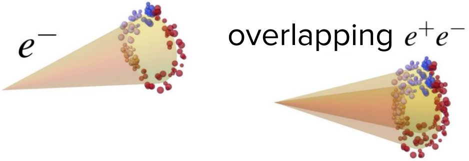
(a) A Closer Look at MiniBooNE Anomaly

Is the MiniBooNE excess electron- or photon-like?





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



Can be resolved using LArTPC technology!

(a) MicroBooNE Weighs In!

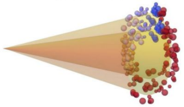
Direct tests of the MiniBooNE anomaly under a **photon** hypothesis:

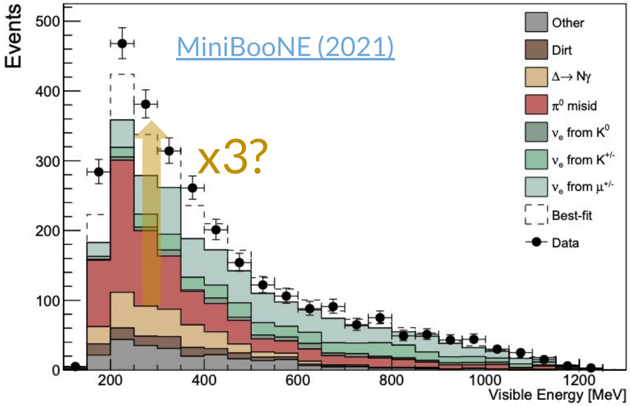
“Conventional” (SM) photon background?

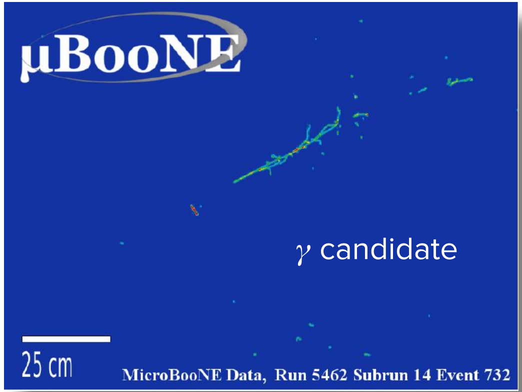
Dominant SM source of single-photons: **neutrino-induced neutral-current Delta baryon production followed by Delta radiative decay $\rightarrow$ ruled out at >95% CL**

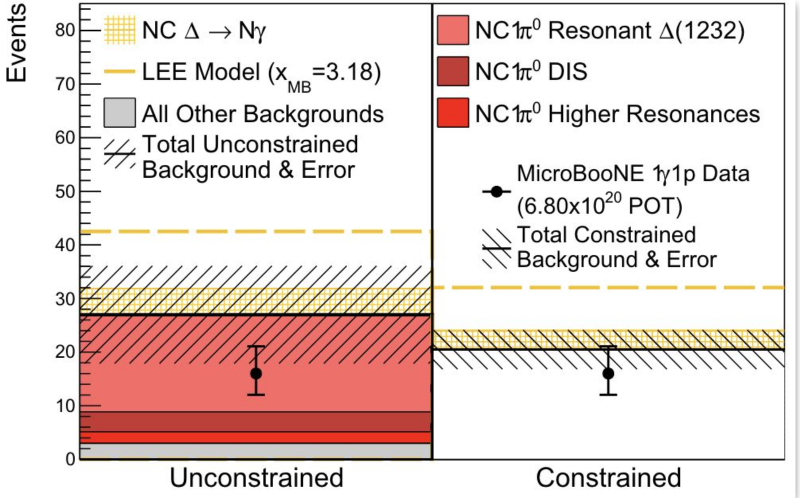
[Phys.Rev.Lett. 128 (2022) 111801](https://doi.org/10.1103/PhysRevLett.128.111801)

overlapping e^+e^-









Updated search in progress

[MicroBooNE Public Note 1126]()

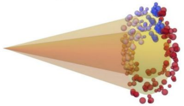
(a) MicroBooNE Weighs In!

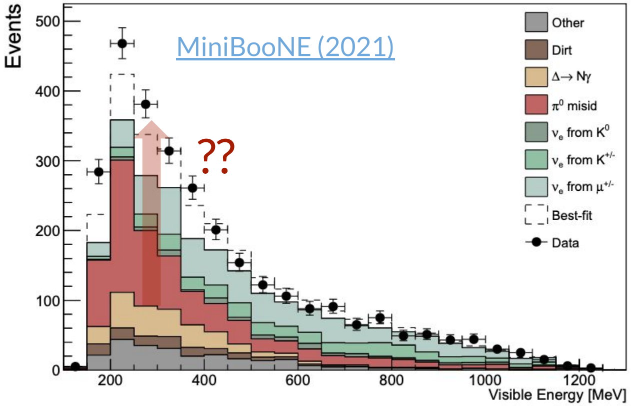
Direct tests of the MiniBooNE anomaly under a **photon** hypothesis:

"Conventional" (SM) photon background?

Inclusive and exclusive sub-dominant photon background searches are in progress

overlapping e^+e^-

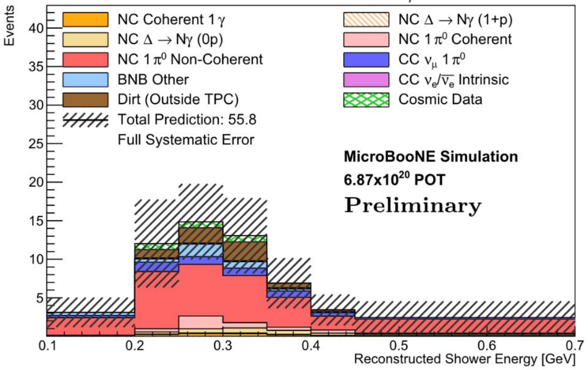




Neutral-current neutrino-nucleus coherent single-photon production

[MicroBooNE Public Note 1131](#)

Semi-final selection



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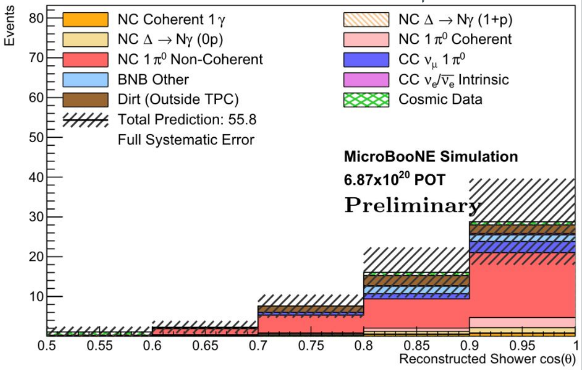
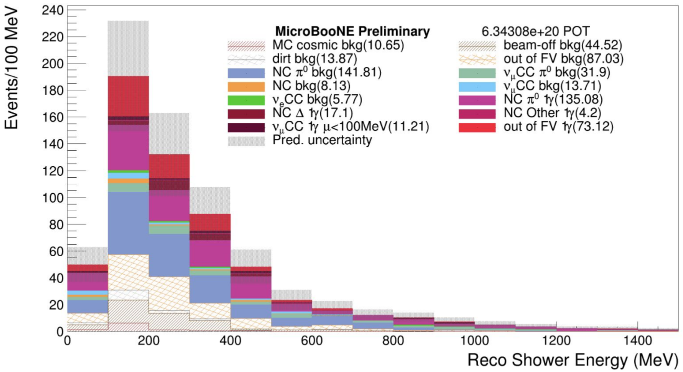


Inclusive single-photon search

[MicroBooNE Public Note 1125](#)



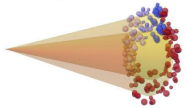
(a) Prospects at SBND

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

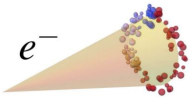
First-ever measurements of yet-undetected SM neutrino scattering processes and more powerful tests of the MiniBooNE excess:

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

overlapping e^+e^-



(a) MicroBooNE Weighs In!

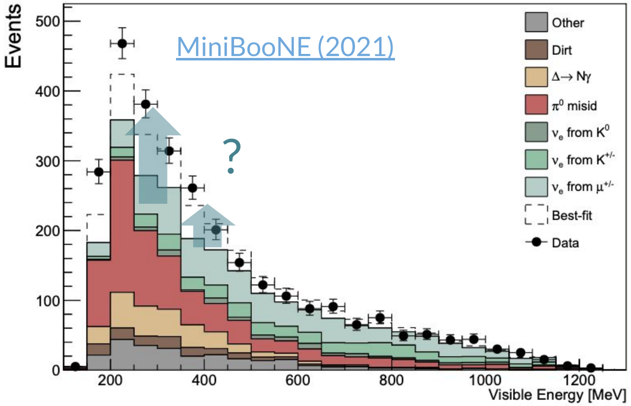


Direct tests of the MiniBooNE anomaly under an **electron** hypothesis:

Energy-dependent enhancement of electron neutrino event rate?

Half dataset (2021): Three separate, independent analyses rule it out as the sole source of the MiniBooNE anomaly

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



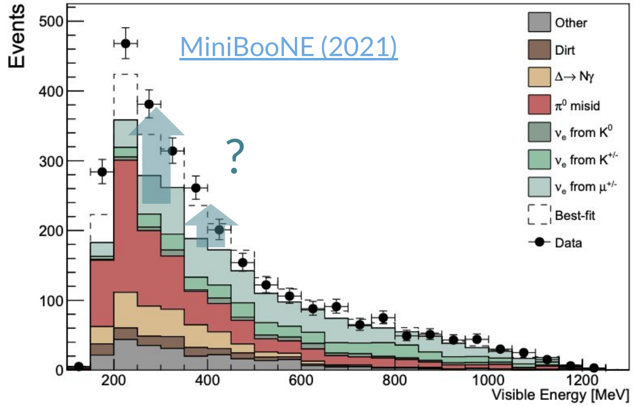
(a) MicroBooNE Weighs In!

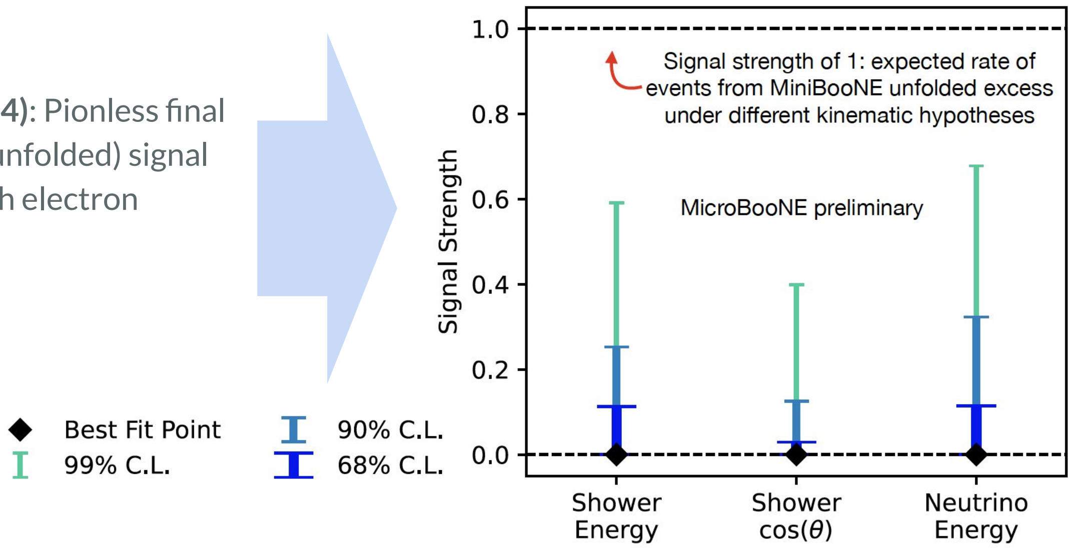
Direct tests of the MiniBooNE anomaly under an **electron** hypothesis:

Energy-dependent enhancement of electron neutrino event rate?

Half dataset (2021): Three separate, independent analyses rule it out as the sole source of the MiniBooNE anomaly
Phys.Rev.Lett. 128 (2022) 24, 241801

NEW! Full dataset (Neutrino 2024): Pionless final state analysis and improved (2D-unfolded) signal from MiniBooNE inconsistent with electron neutrino-like excess at >99% CL
MicroBooNE Public Note 1127





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, …]

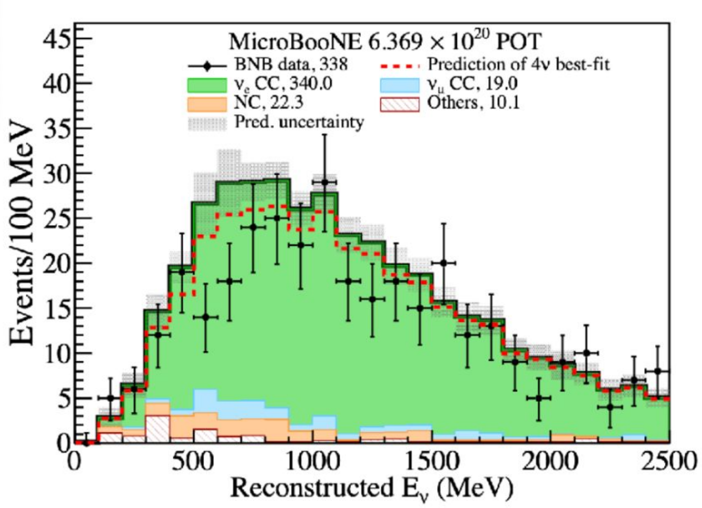
NEEDED, in order to exhaustively test this model:

(a) Resolution of MiniBooNE low-energy excess (cannot be entirely vanilla 3+N oscillations; conventional/background origin?)

(b) Comprehensive, multi-channel oscillation searches that account for oscillation effects and systematic correlations across different flavor measurements

(b) MicroBooNE Weighs In!

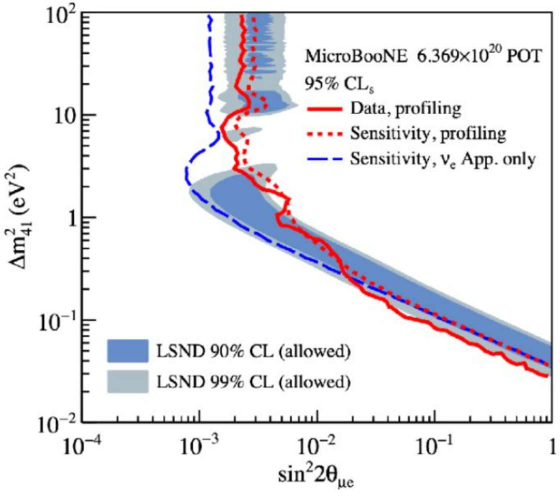
Searches for 3+1 oscillations in MicroBooNE, considering simultaneous appearance and disappearance effects!



ν_e ? $\longrightarrow$ ν_s ?

Reinterpret LEE ν_e analysis under 3+1 sterile neutrino oscillation framework

MicroBooNE PRL 130 (2023) 1, 01180

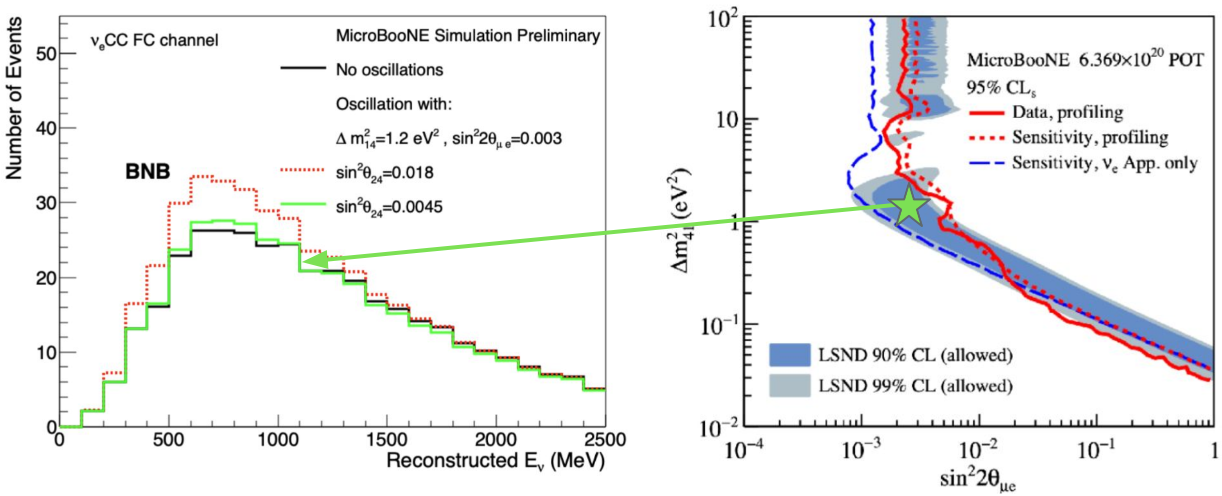


First results (2022) made use of half the MicroBooNE BNB data set.

(b) MicroBooNE Weighs In!

Cancellation of electron neutrino appearance and disappearance limits sensitivity in a single-detector measurement.

MicroBooNE PRL 130 (2023) 1, 01180



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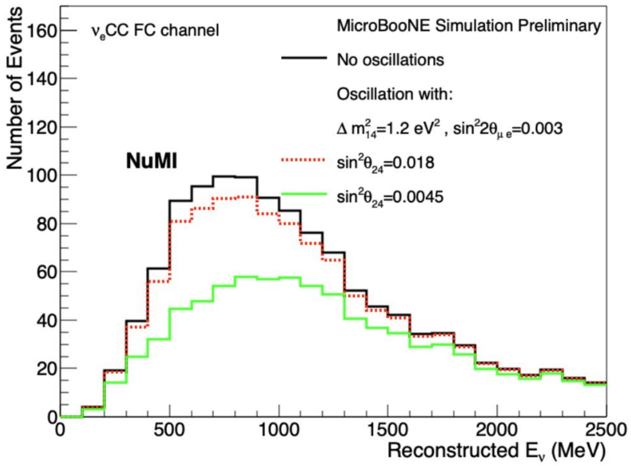
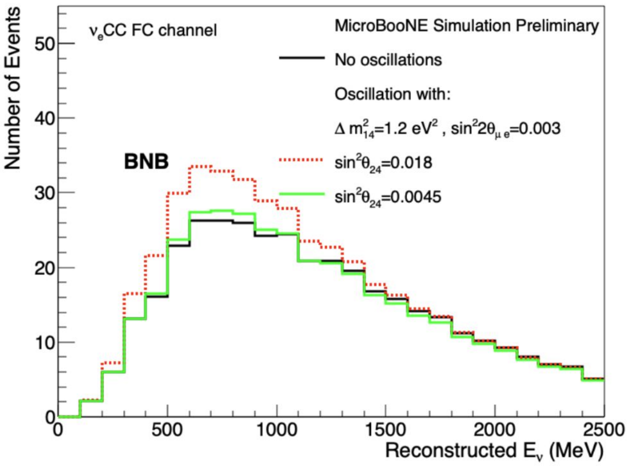
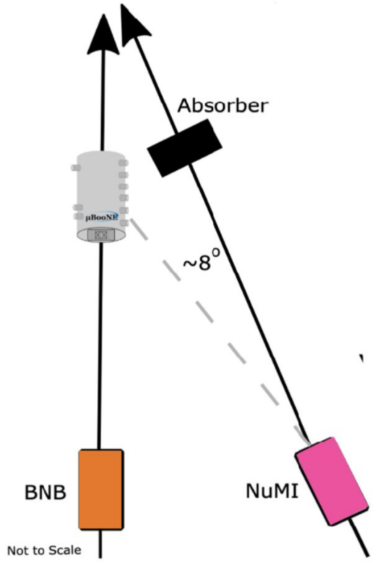
(b) MicroBooNE Weighs In!

Cancellation of electron neutrino appearance and disappearance limits sensitivity in a single-detector measurement.

Off-axis NuMI beam at MicroBooNE provides different electron to muon neutrino flux ratio, and helps break degeneracies → enhanced sensitivity!







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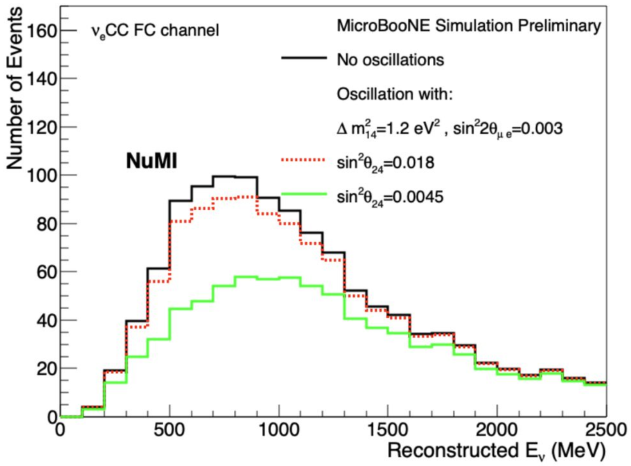
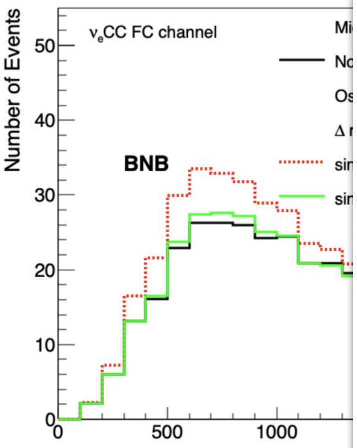
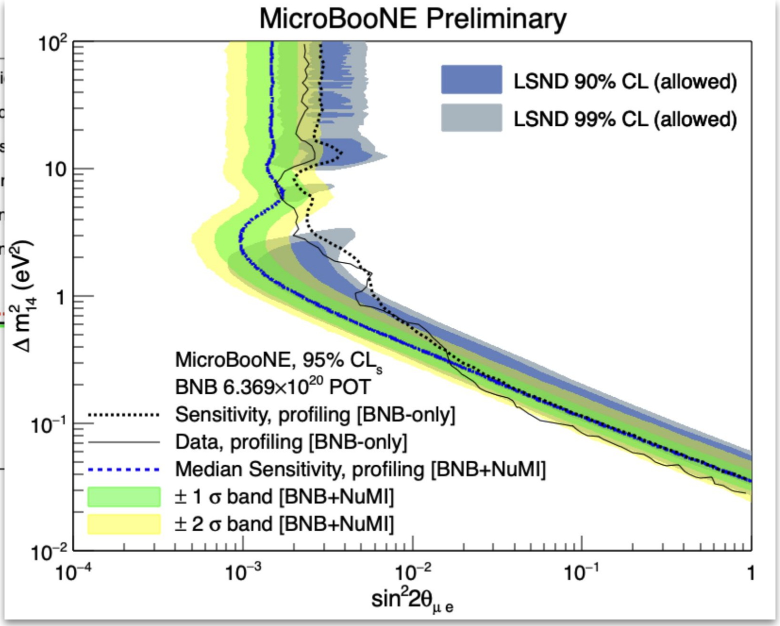




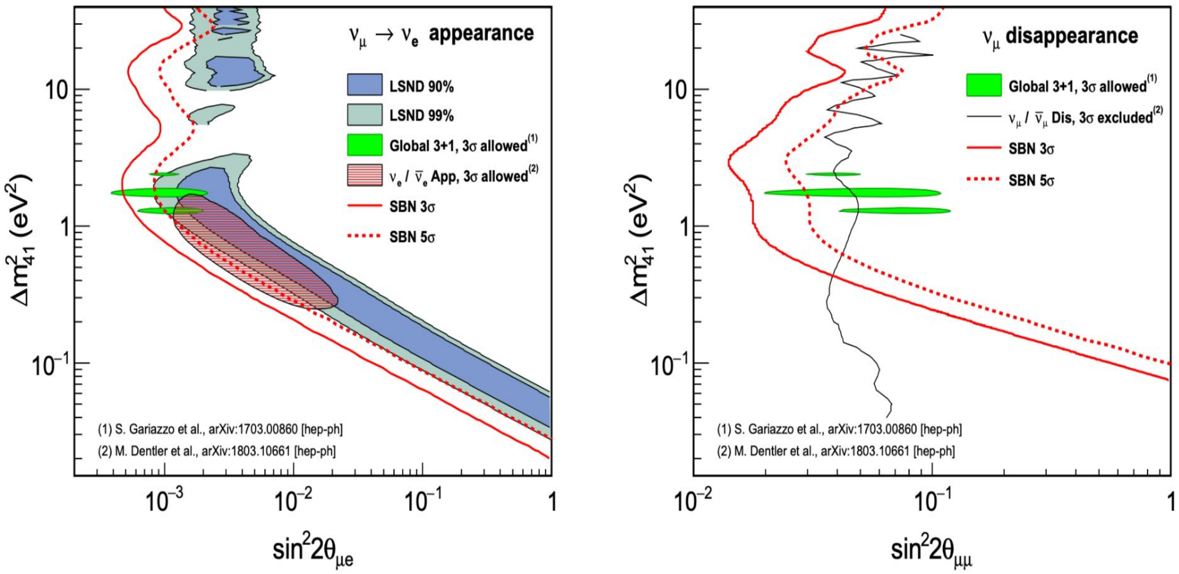


Results anticipated soon! [MicroBooNE Public Note 1132]

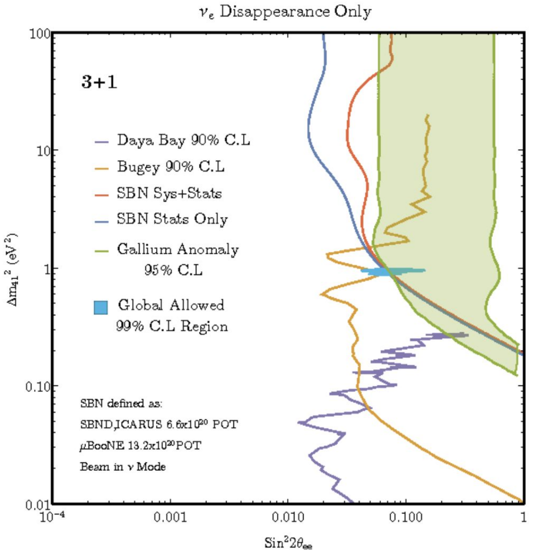
(b) SBN Prospects: "Vanilla" 3+N models

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

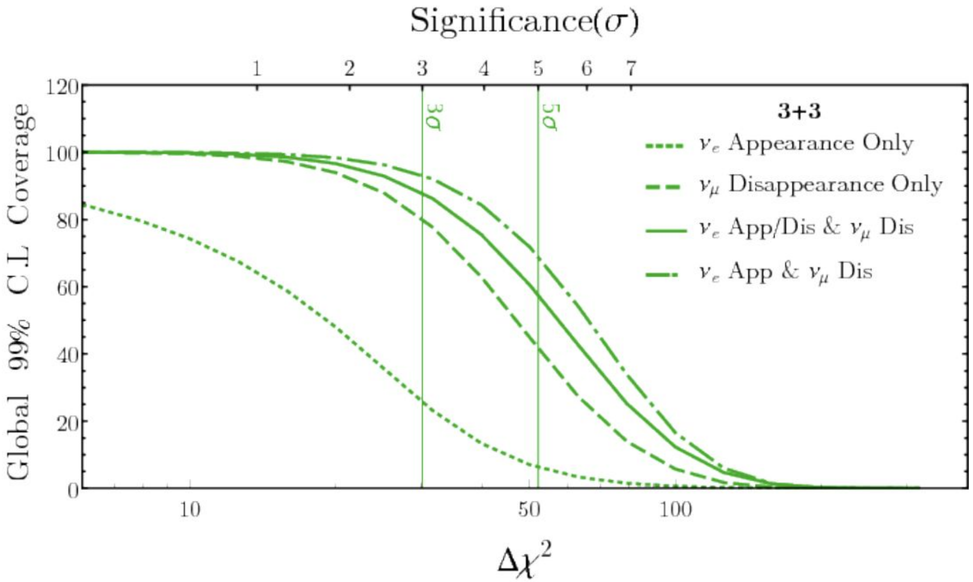


D. Cianci, et al, Phys.Rev.D 96 (2017) 5, 055001



(b) 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

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
- …

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

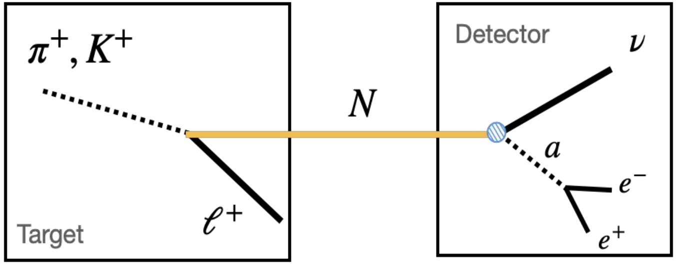
[lots of work by Ballet, Pascoli, Bertuzzo, Conrad, De Gouvea, Dentler, Gariazzo, Giunti, Gninenko, Hostert, Ross-Lonergan, Kopp, Lavender, Li, Maltoni, Alves, Palomares-Ruiz, Babu, Martinez-Soler, Pascoli, Peres, Schwetz, Shaevitz, Spitz, Stenico, Tsai, Zukanovich, …]

2. Dark Sectors @ SBN

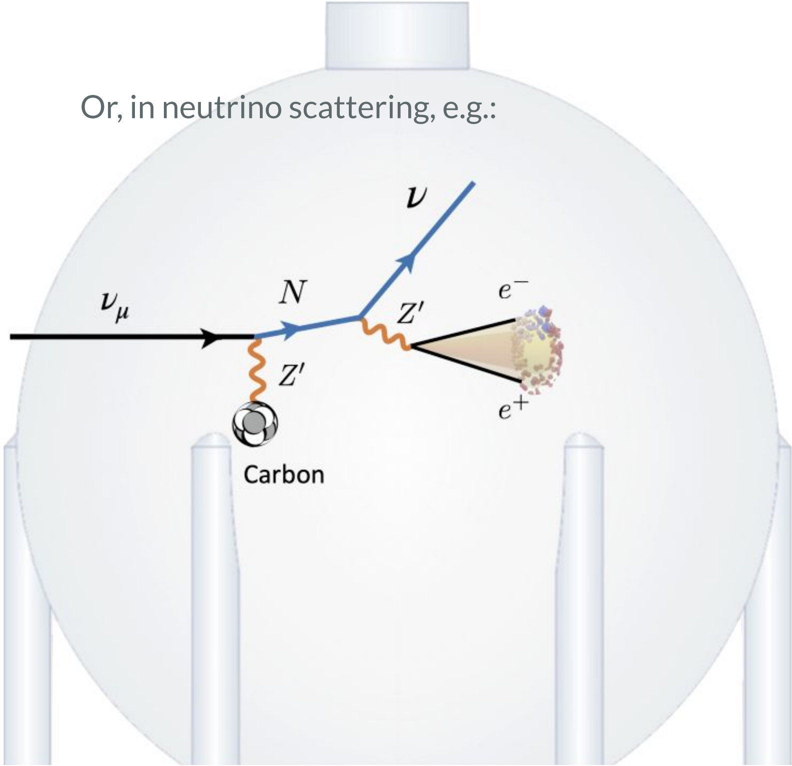
2. Dark Sector Portals

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

Production in the neutrino beam, e.g.:



Or, in neutrino scattering, e.g.:

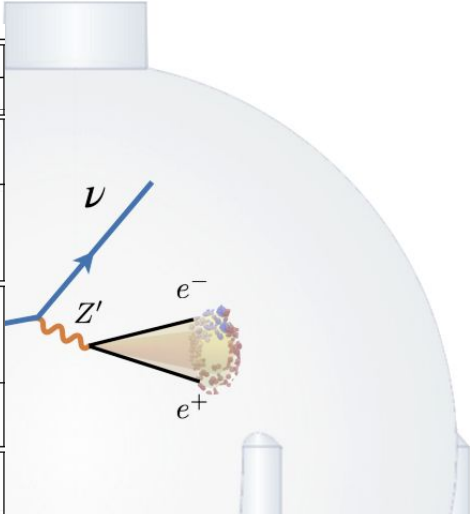


2. Dark Sector Portals

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

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	$\nu A \to N A$, $N \to \nu e^+ e^-$ or $N \to \nu\gamma\gamma$	✓ (partial)	✓	✗	✗
	neutrino dipole up-scattering	$\nu A \to N A$, $N \to \nu\gamma$	✓ (partial)	✓	✗	✗
Dark Sector: Dark Matter Scattering	dark particle-induced up-scattering	γ or e^+e^-	✗	✓	✗	✗
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗

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



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

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	[illegible]	✓	✓	[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	$\nu_\mu A \to$ [illegible]	✓	✓	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	[207]
	Dark sector heavy neutrino decay	[illegible]	✗	✓	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	[illegible] $N \to \nu$ [illegible]	✓	✓	[205, 206, 209–216]
	neutrino dipole upscattering	[illegible]	✓	✓	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	[illegible] e^+e^-	✗	✓	[217]
	dark particle-induced inverse Primakoff	[illegible]	✓	✓	[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

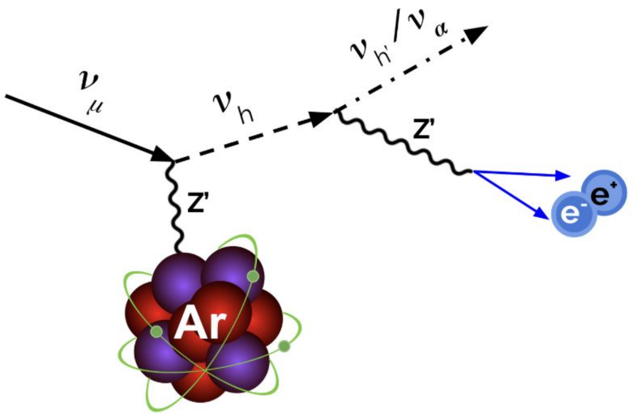
- e⁻ Electron signals
- γ Photon signals
- γ γ Di-Photon signals
- e⁺ e⁻ e+e- signals

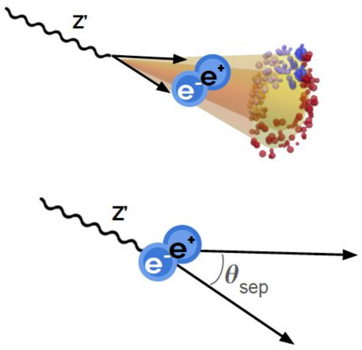
Image credit: Mark Ross-Lonergan

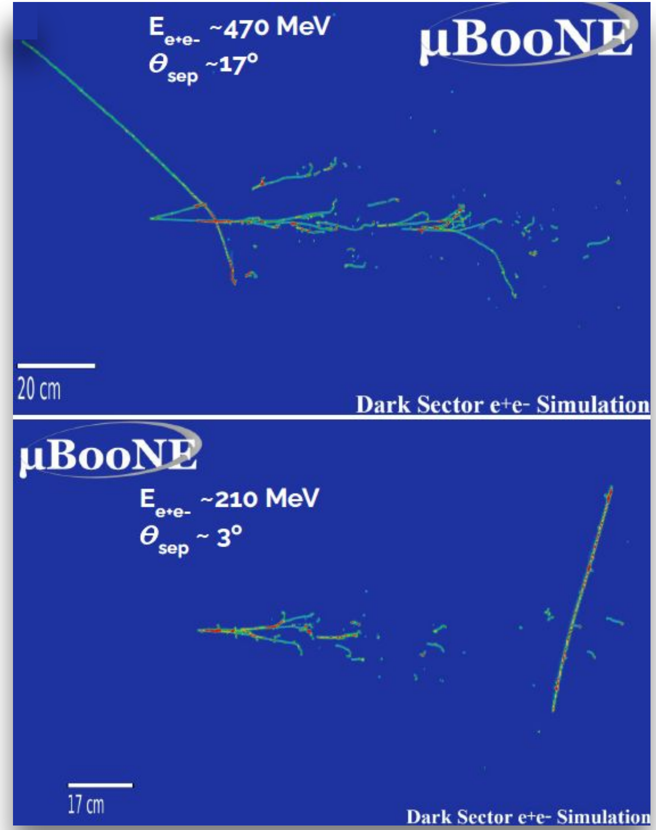
MicroBooNE e+e- Searches

Anticipated new results on searches for dark neutrinos decaying to e+e- pair:

Based on: Ballet et al. PRD 99 (2019) 071701
Bertuzzo et al. PRL 121 (2018) 24, 241801







Results anticipated soon! [MicroBooNE Public Note 1124]

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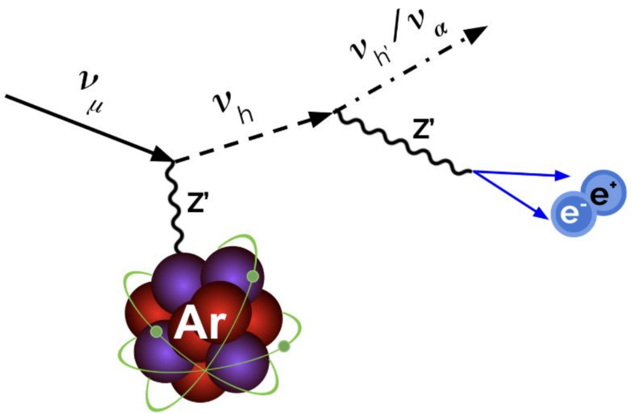
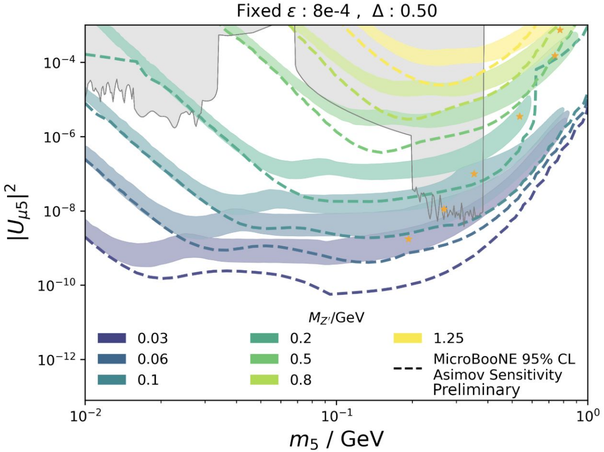
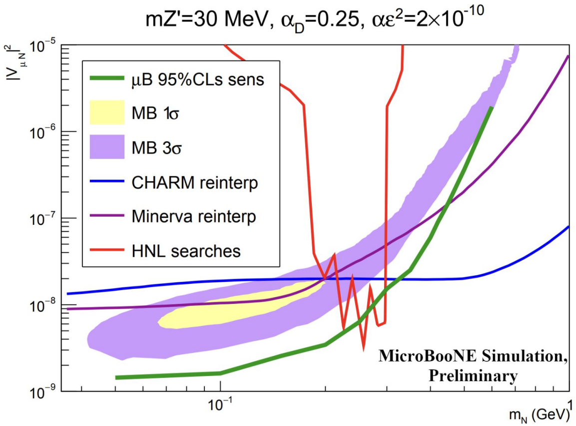


A broad 3+1 and 3+2 dark sector search



A focused light Z′ dark sector search

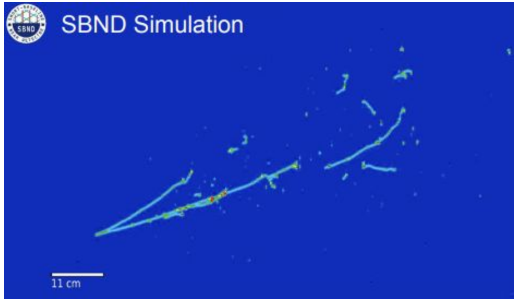


Results anticipated soon! [MicroBooNE Public Note 1124]

Prospects at SBND

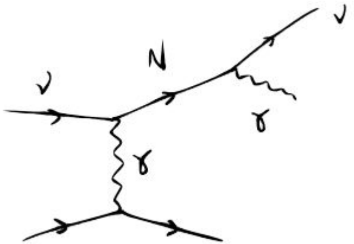
Higher-sensitivity tests of MiniBooNE anomaly interpretations:

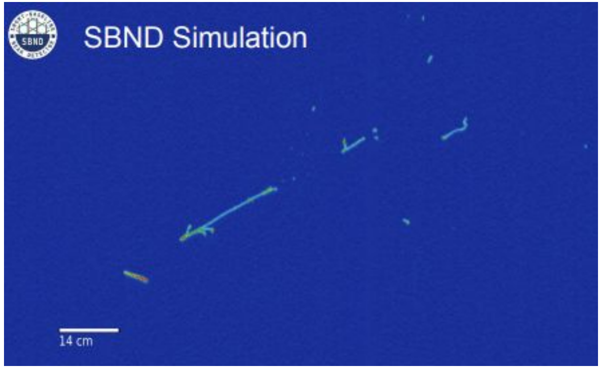
dark neutrinos



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

transition magnetic moment



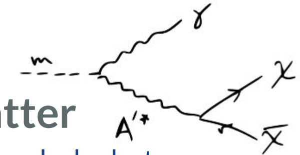


signature: photon shower with or without hadronic activity

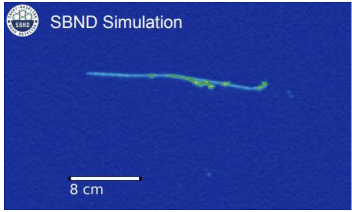
Other BSM Searches with LArTPCs

Broader tests of BSM scenarios:

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

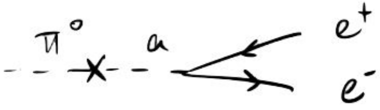


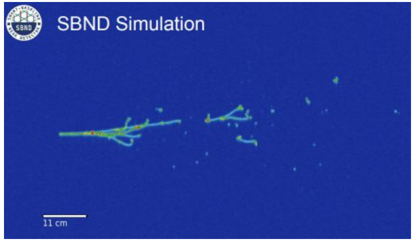
dark photon



electron scattering

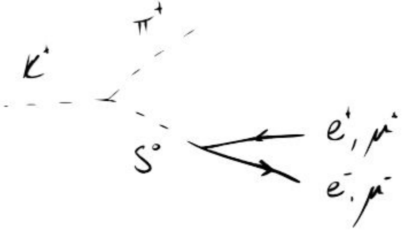
e.g., **axion-like particles**

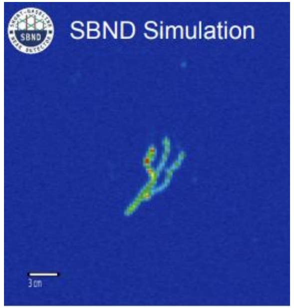




high-energy e+e- or μ+μ-

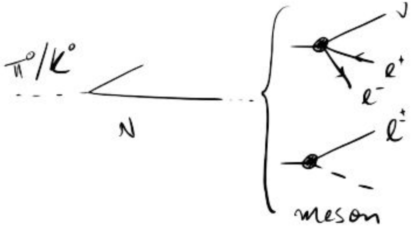
e.g., **Higgs portal scalars**

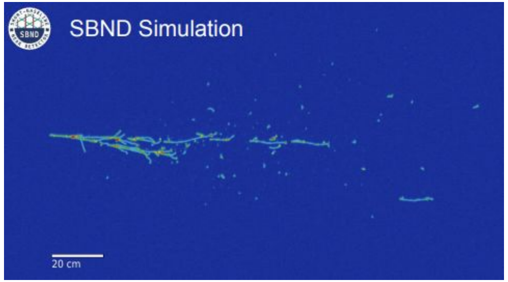




e+e- or μ+μ-, no hadronic activity

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

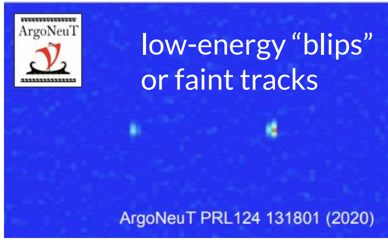




e+e-, μ+μ- or $\mu\pi$

e.g., **millicharged particles**

dark photon



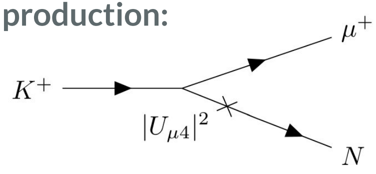
Other BSM Searches with LArTPCs

Results from MicroBooNE:

Heavy Neutral Leptons (HNLs):

- Making use of NuMI off-axis beam
- Improvements over past MicroBooNE search (2022)
- Leading limits (2024) at low HNL mass through HNL e+e- or π^0 decays

production:



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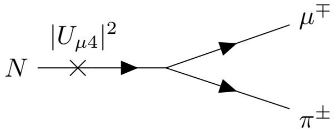

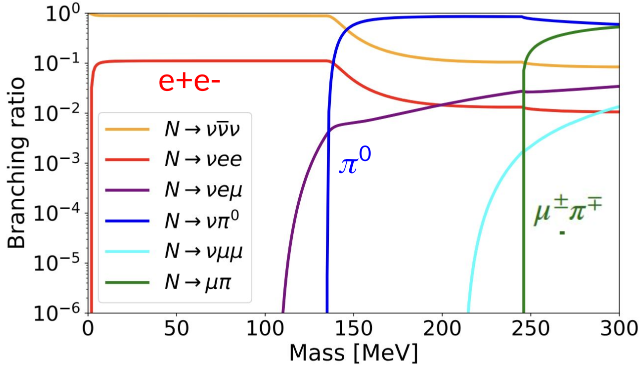

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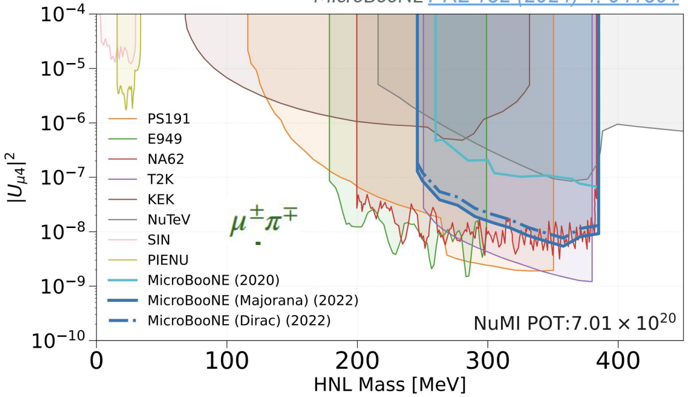

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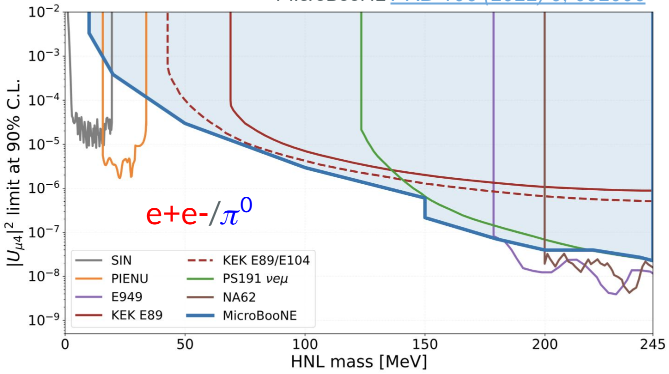


Thanks to LArTPCs' Exquisite Particle Imaging Capability

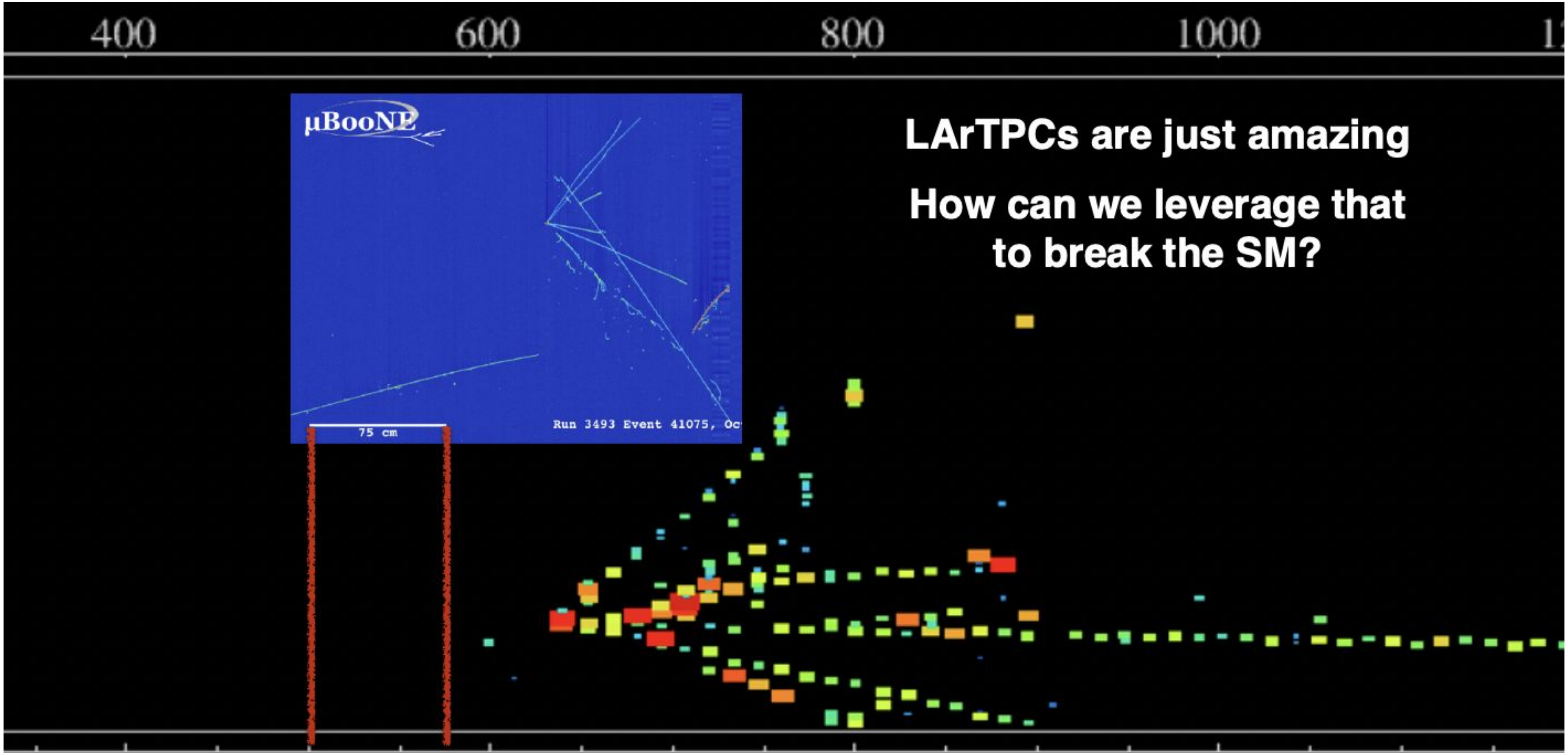


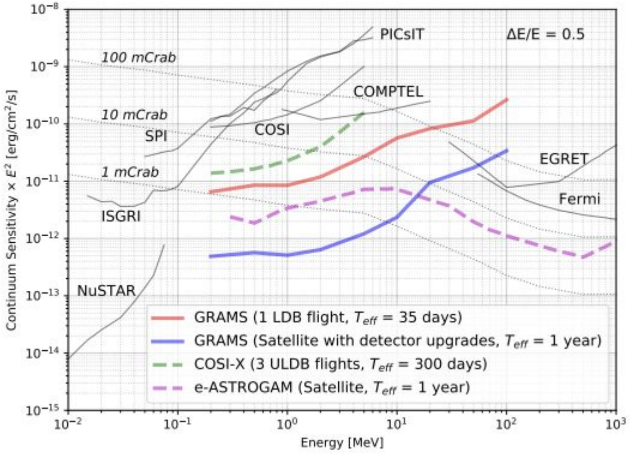
Image credit: Pedro Machado

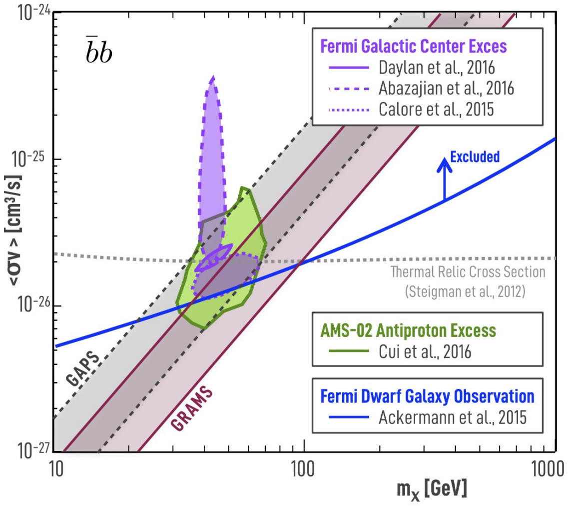
LArTPCs for Astro-particle Physics

- **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 **cosmic MeV gamma-ray observations** and **indirect dark matter searches**

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

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





An Exciting Time for Searches for New Physics

Thanks to huge strides in theory and detector technology over the past decade, **accelerator-based, short-baseline** neutrino experiments now serve as **discovery-class facilities for neutrino science and BSM physics**

The SBN Program (MicroBooNE, ICARUS and SBND) is already providing **ground-breaking results:**

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