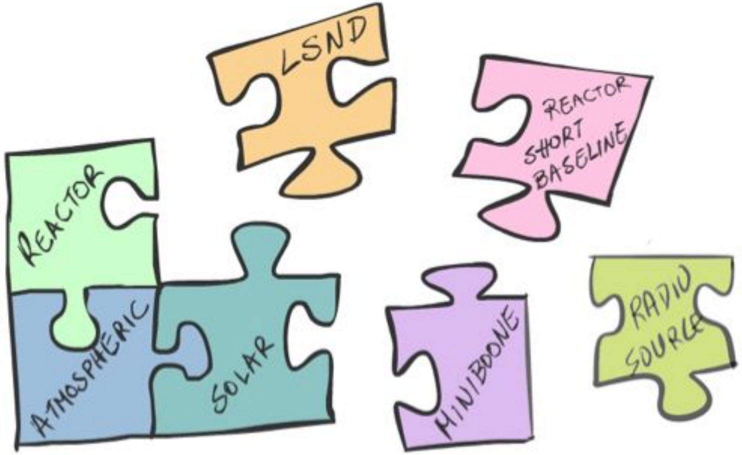
Beyond the Standard Model in the Neutrino Program:
II. Understanding Neutrino Anomalies



Georgia Karagiorgi, Columbia University
Snowmass Neutrino Colloquium

April 20, 2022

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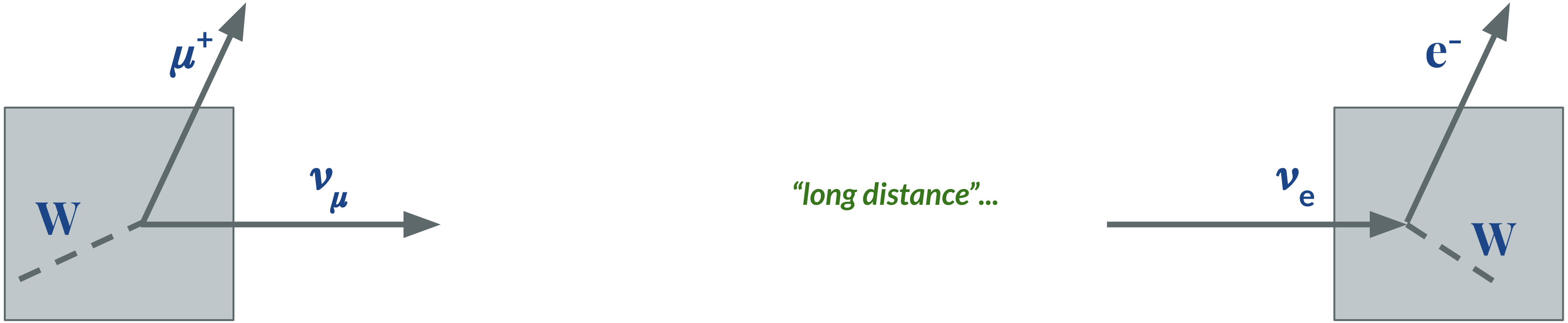
Your typical neutrino oscillation experiment…

Probing the well-established three-neutrino oscillation framework



“long distance”…

neutrino source

large detector measuring
ν_e, ν_μ, ν_τ

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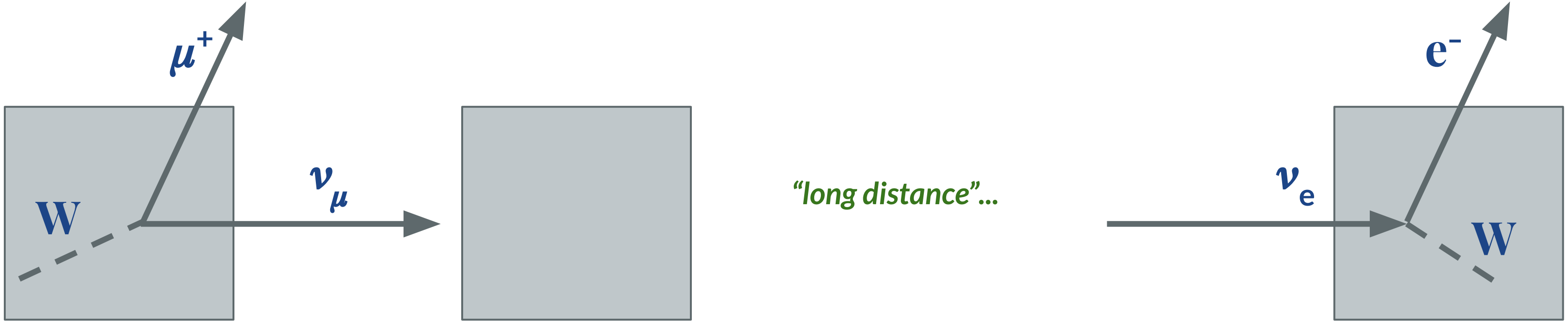

neutrino source

detector at L~0 measures “unoscillated” rates

large detector measuring ν_e, ν_μ, ν_τ

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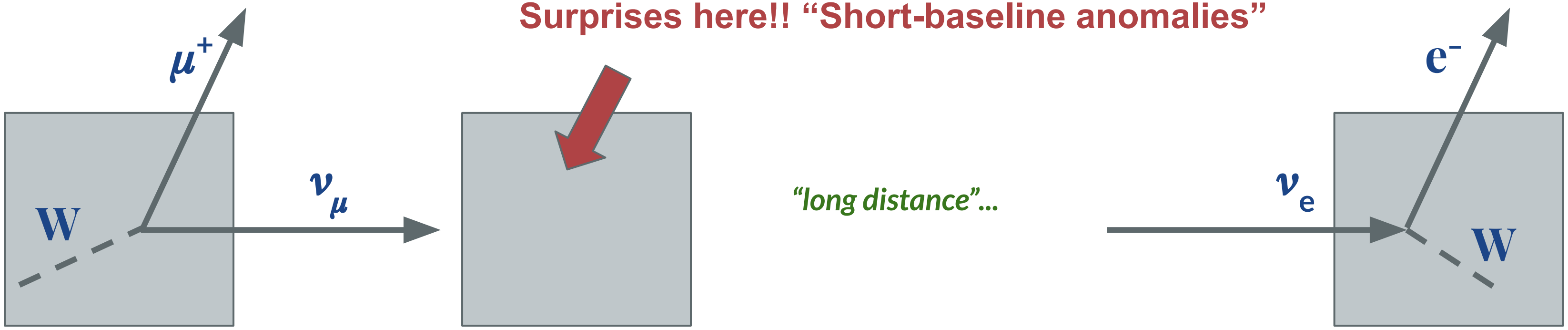
Your typical neutrino oscillation experiment…

Probing the well-established three-neutrino oscillation framework



Surprises here!! “Short-baseline anomalies”

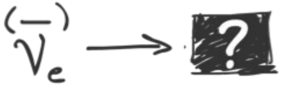
“long distance”…

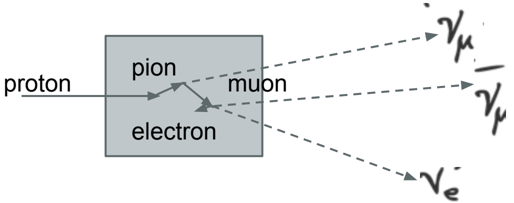
neutrino source

detector at L~0 measures
“unoscillated” rates

large detector
measuring
ν_e, ν_μ, ν_τ

(Short-baseline) Neutrino Anomalies

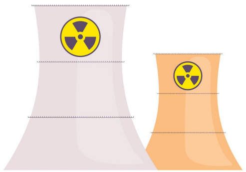




Decay At Rest

E_ν ~ 30 MeV

→ **excess $\bar{\nu}_e$**

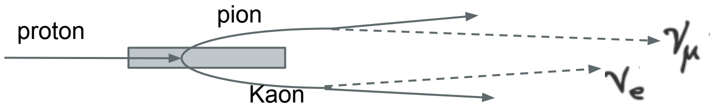


Reactor

^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu fission

E_ν ~ few MeV

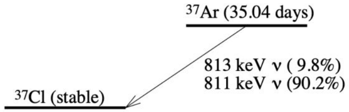
→ **$\bar{\nu}_e$ deficit**



Decay In Flight

E_ν ~ 600 MeV

→ **excess ν_e**



Radioactive Source

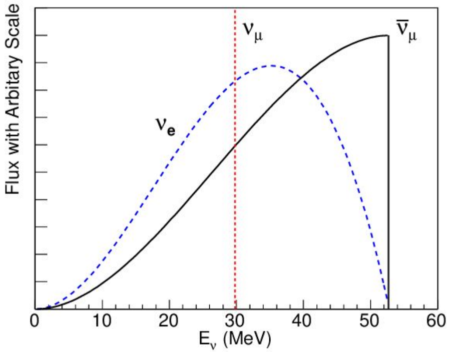
Electron capture decay

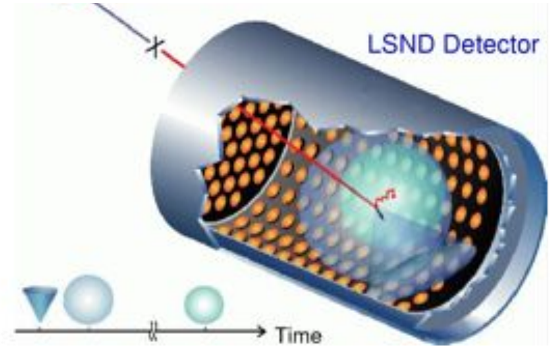
E_ν ~ 1 MeV

→ **ν_e deficit**

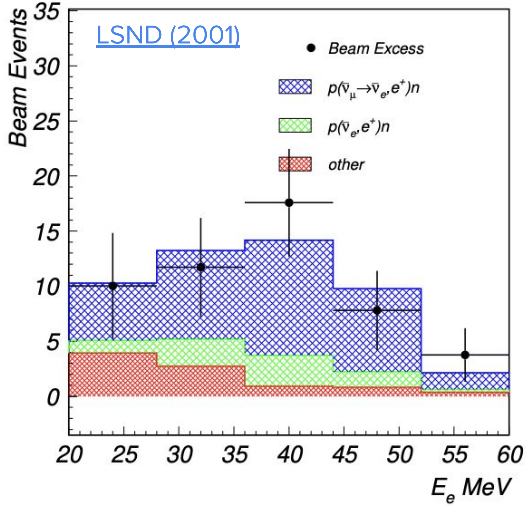
LSND Anomaly (1990's)

Well-understood beam from $\pi^+ \rightarrow \mu^+$ decay at rest





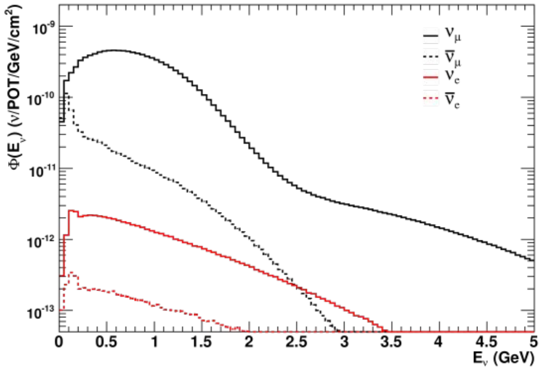
excess $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ dominated beam, 3.8σ



A direct test of the LSND Anomaly using an improved decay-at-rest beam facility and experimental arrangement has just begun in the form of the JSNS^2 experiment.

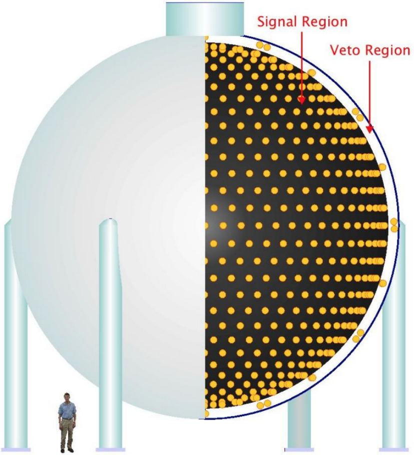
MiniBooNE Anomaly (2000's)

Beam from $\pi^{\pm} \to \mu^{\pm}$ decay in flight

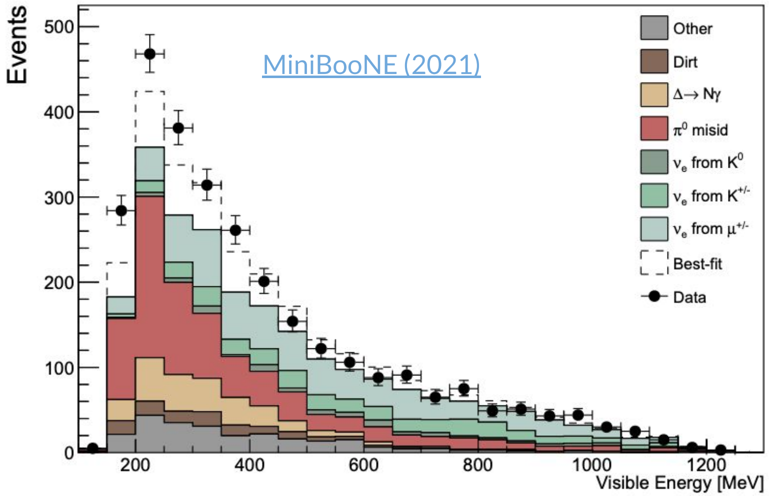


The community has just begun a comprehensive accelerator-based short-baseline program that is capable of directly testing MiniBooNE (and LSND) Anomaly interpretations

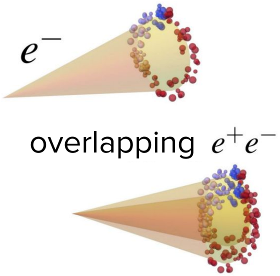
MiniBooNE Detector



excess $\overset{(-)}{\nu}_e$ in a $\overset{(-)}{\nu}_\mu$ dominated beam, 4.8σ



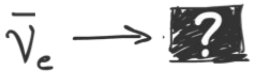
MiniBooNE (2021)



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

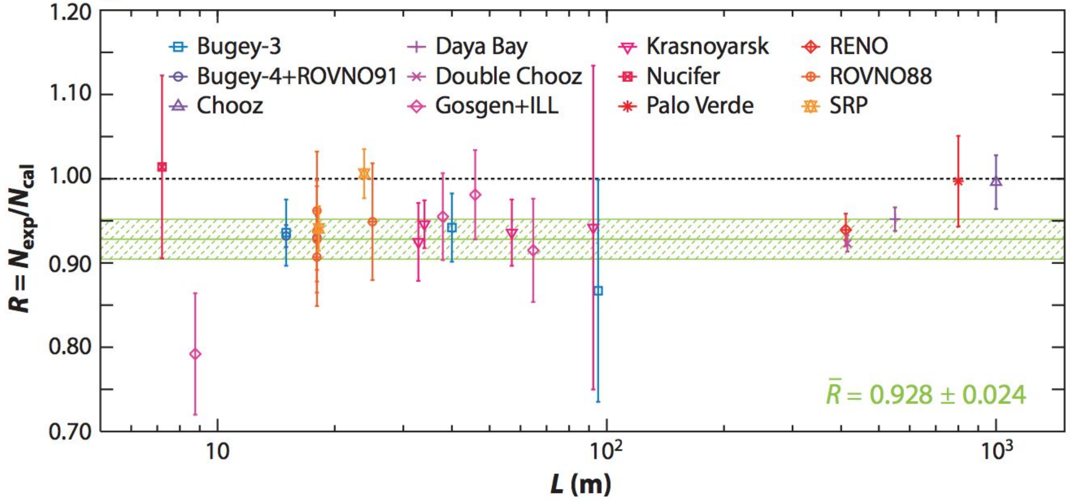
Reactor Anomaly (2010's)

Re-analysis of reactor antineutrino data from several experiments at 10-100m from reactor(s), after **new theoretical predictions** [Mueller *et al.*, *Huber*] of reactor antineutrino fluxes in 2011



deficit of reactor $\bar{\nu}_e$ event rate, ~2σ

Giunti & Lasserre (2019)



The Reactor Antineutrino Anomaly and subsequent reactor-based activities and new results have placed a required emphasis on experiments that **directly test Reactor Anomaly interpretations** as well as **improve our understanding of reactor neutrino fluxes.**

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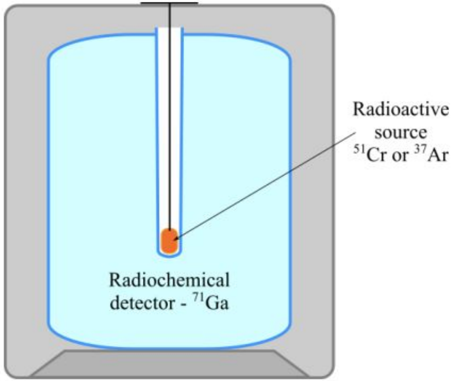
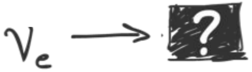
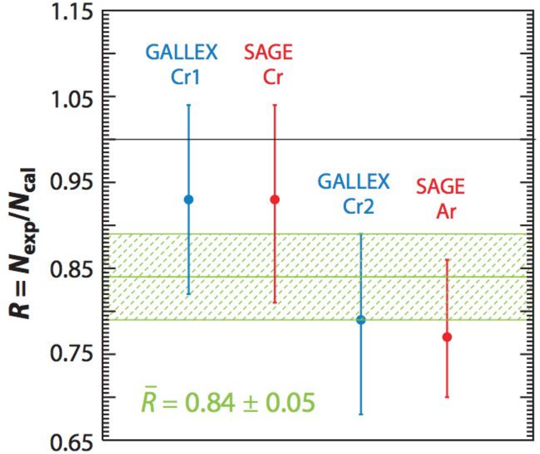
Gallium Anomaly (1990's-...)

SAGE/GALLEX experiments used ^{51}Cr and ^{37}Ar radioactive sources (producing ν_e) for calibration of their Gallium detectors





deficit of radioactive source ν_e event rate



Giunti & Lasserre (2019)

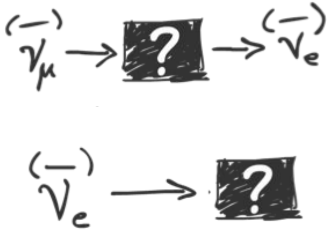
The development of new radioactive sources and detectors for improved direct tests of the Gallium Anomaly has been pursued and realized in the form of the BEST experiment (which **confirmed** the anomaly).

BEST (2021)

Interpretations

What the four Anomalies have in common:

- Electron (anti)neutrino observations which deviate from expectation, from either electron or muon (anti)neutrino sources
- L/E of 0.1-10 m/MeV



Collectively they represent tantalizing indications for new physics beyond the three-neutrino framework, and are the topic of Snowmass Neutrino Frontier Topical Group on “Understanding Experimental Neutrino Anomalies”

Three broad categories of theoretical interpretations:

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

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

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Interpretations: Flavor conversion models

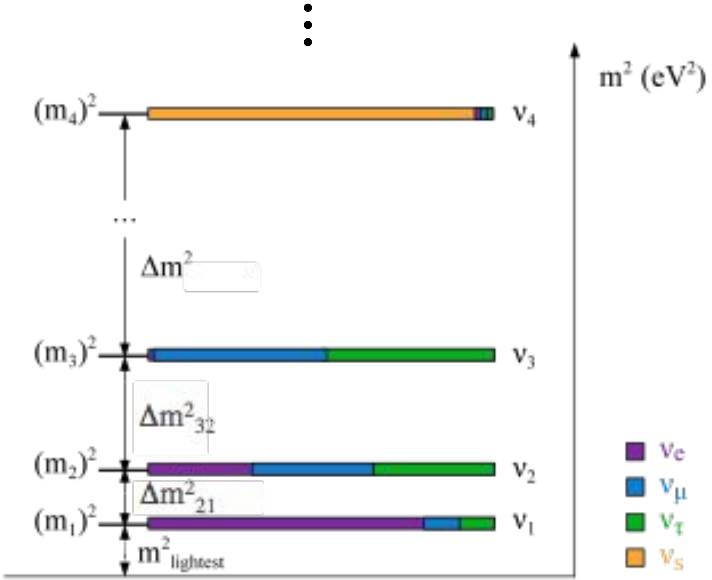
"Vanilla" light sterile neutrino oscillations

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

Expect:

✓ Electron neutrino disappearance ~ O(10%)
? Muon neutrino disappearance ~ O(10%)
✓ Muon to electron neutrino appearance ~O(1%)

Probability amplitudes are 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

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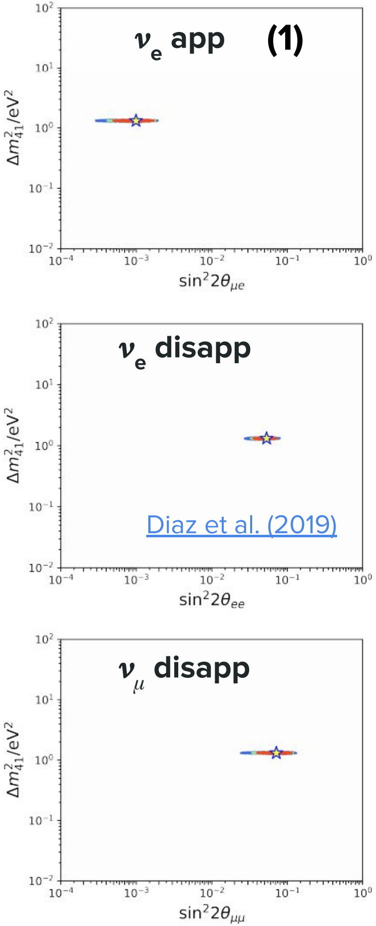
Interpretations: Flavor conversion models

Sterile Neutrino Global Picture

Findings after combining anomalies in global fits with other relevant experimental constraints

1. The “3+1” scenario is much **more preferred than null**



Diaz et al. (2019)

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Interpretations: Flavor conversion models

Sterile Neutrino Global Picture

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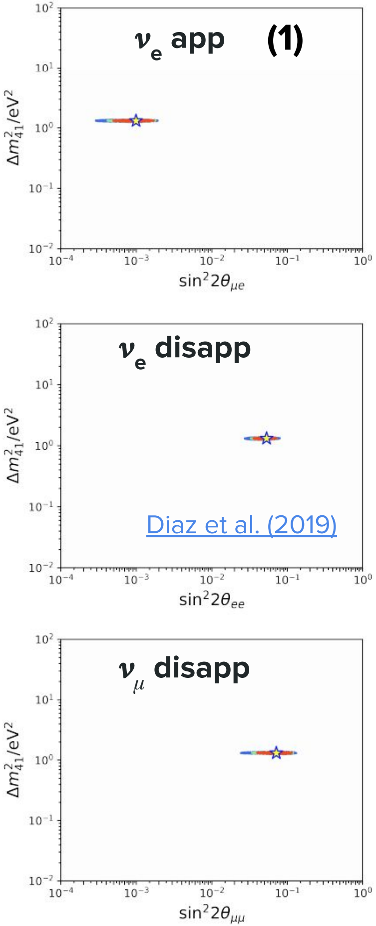
1. The “3+1” scenario is much **more preferred than null**
2. There is a large **tension** between appearance and disappearance data sets, and incompatibility of parameters preferred by appearance vs. disappearance experiments



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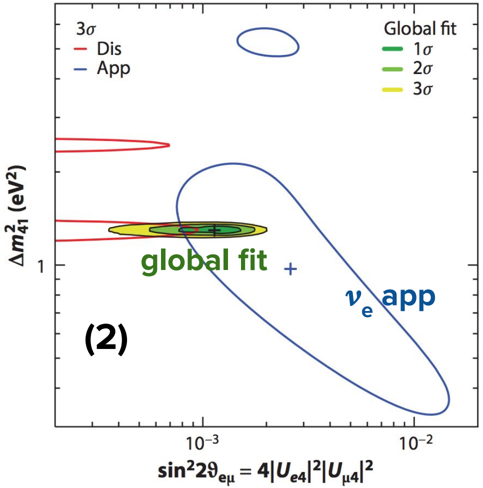


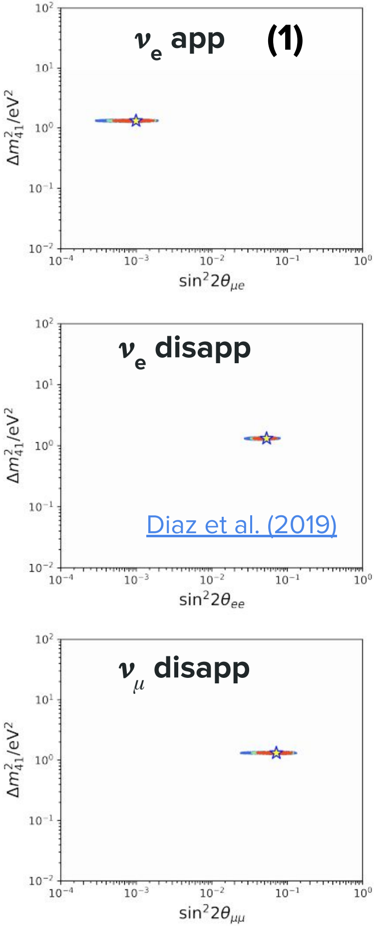
Giunti & Lasserre (2019)

Interpretations: Flavor conversion models

Sterile Neutrino Global Picture

Findings after combining anomalies in global fits with other relevant experimental constraints

1. The "3+1" scenario is much **more preferred than null**
2. There is a large **tension** between appearance and disappearance data sets, and incompatibility of parameters preferred by appearance vs. disappearance experiments
3. Some of this tension can be relieved with omission of **MiniBooNE low-energy excess**



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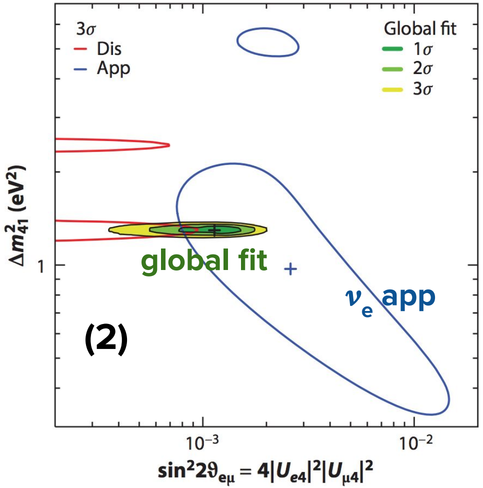

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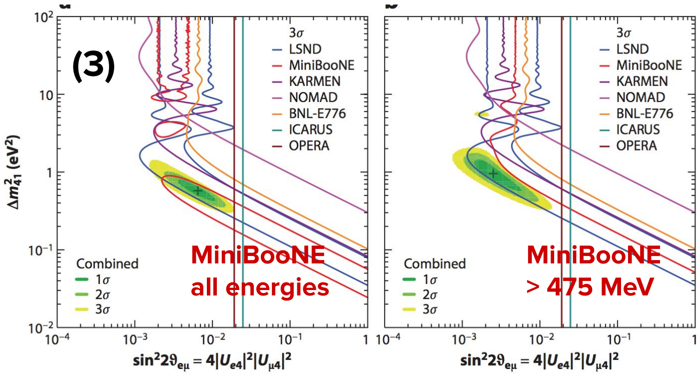


Interpretations: Flavor conversion models

3+1 (also 3+2 and 3+3) light sterile neutrino oscillations → significant tensions in global data sets.

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

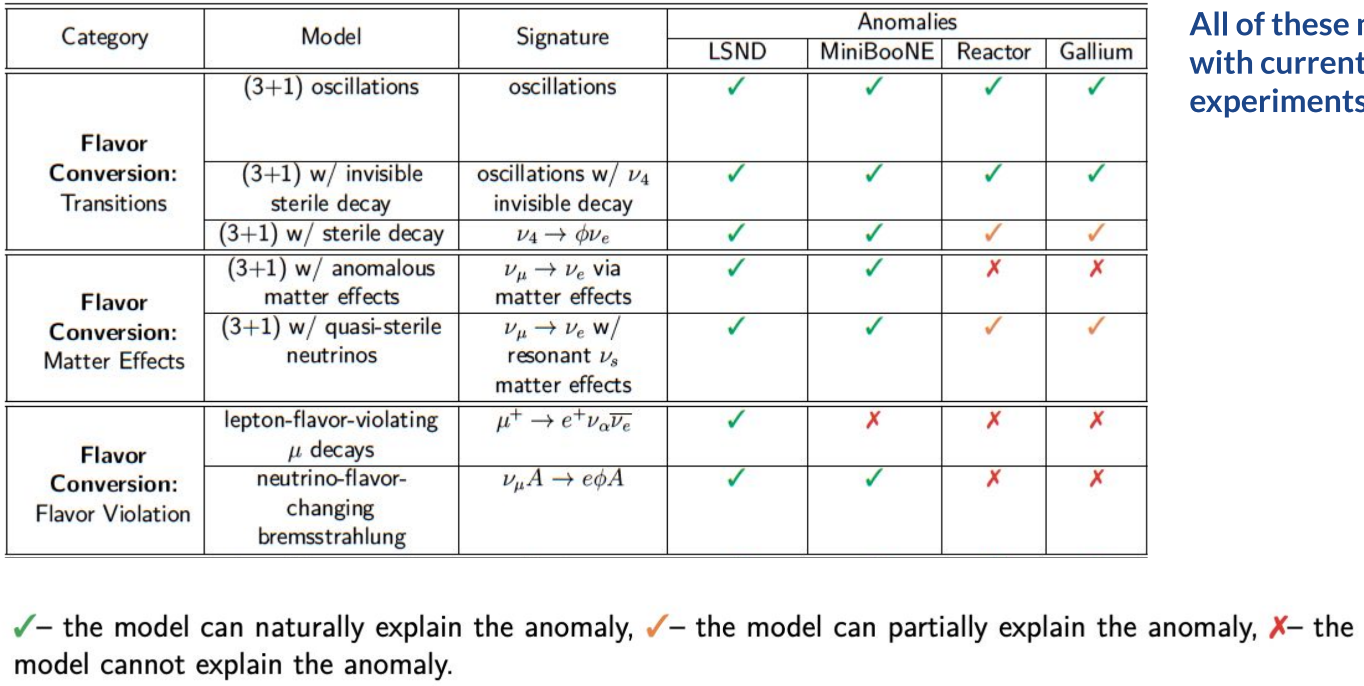
Or, overlooked or new physics ?

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

Plethora of models!

- (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
- …

Interpretations: Flavor conversion models



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	$\nu_4 \to \phi\nu_e$	✓	✓	✔	✔
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	✓	✓	✔	✔
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, ✔– 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!

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

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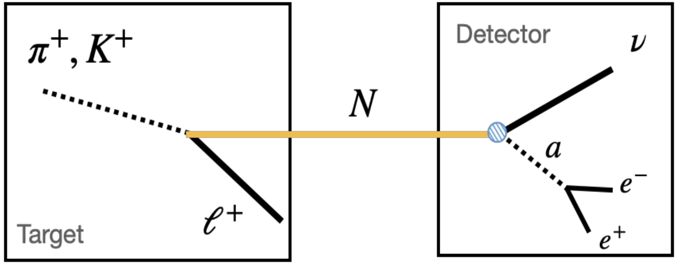
Interpretations: Dark sector portal models

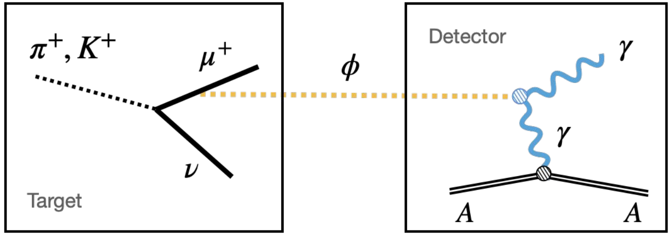
Associated with new particles produced

- **in “neutrino beams”**

  E.g. transition magnetic moment,
  long-lived heavy neutrinos decaying
  to single photons or axion-like particles,
  dark matter in the beam

Inspired by the theoretical observation that neutrinos are excellent candidates to be portals to dark sectors…





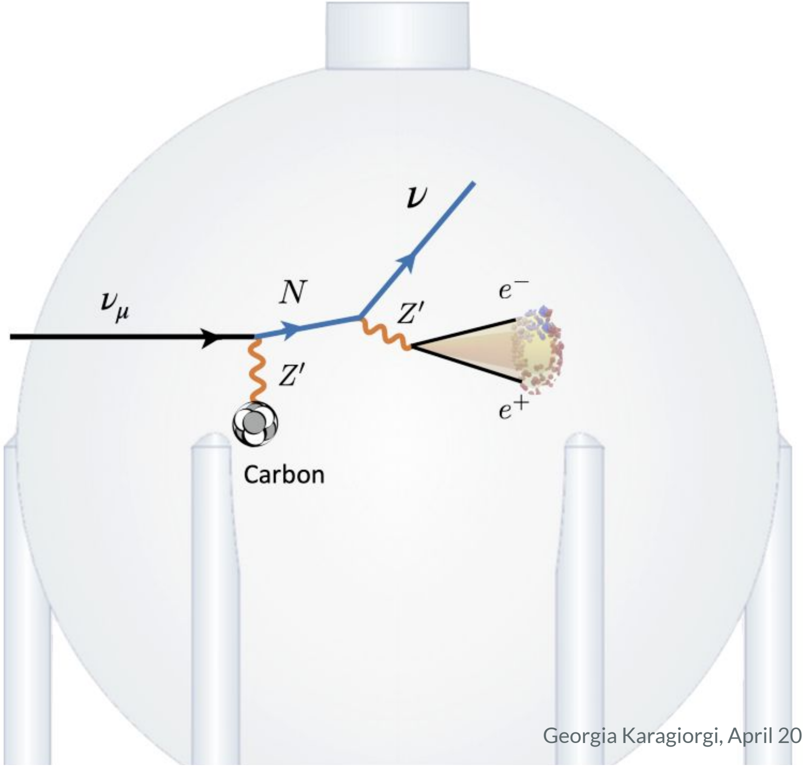
Interpretations: Dark sector portal models

Associated with new particles produced

- **in "neutrino beams", or**
- **in neutrino scattering (in detectors)**

E.g. MeV-GeV "dark neutrinos",
mixing with Standard Model neutrinos and
a dark photon or dark scalar

Inspired by the theoretical observation that neutrinos are excellent candidates to be portals to dark sectors…



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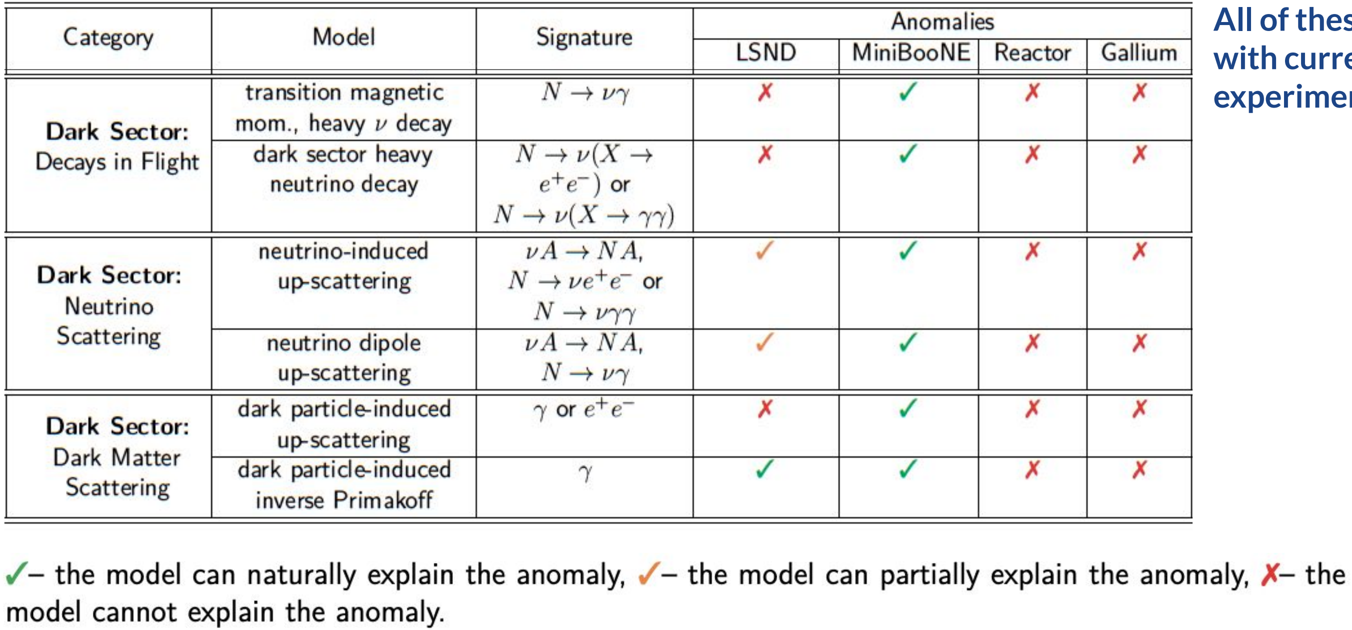
Interpretations: Dark sector portal models



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

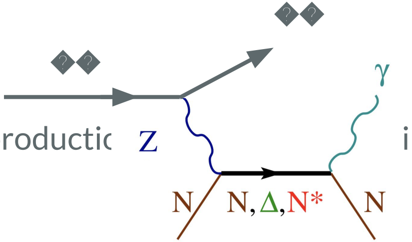
✓– the model can naturally explain the anomaly, ✓– the model can partially explain the anomaly, ✗– the model cannot explain the anomaly.

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

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

Interpretations: “Standard Model”

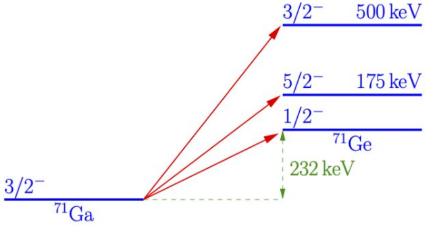
Flux, cross-section, or background mis-estimation

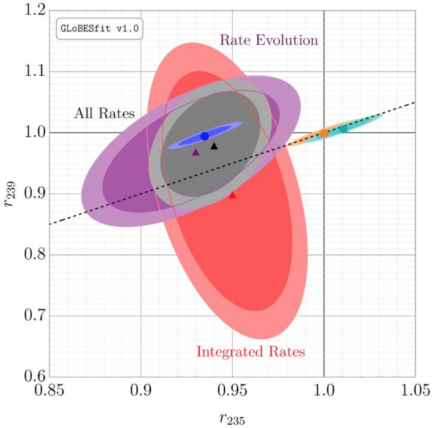


E.g., MiniBooNE: rare, never-before-measured SM processes such as single-photon productio ing below 1 GeV

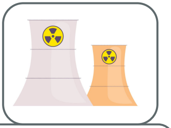
E.g., Reactor: studies on inclusion of forbidden beta transitions suggest underestimated uncertainties or unaccounted spectral deviations

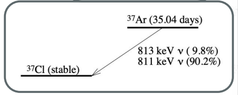
E.g., Gallium: uncertainty in ν_e detection cross section

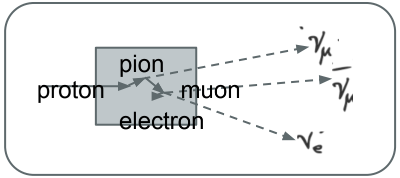


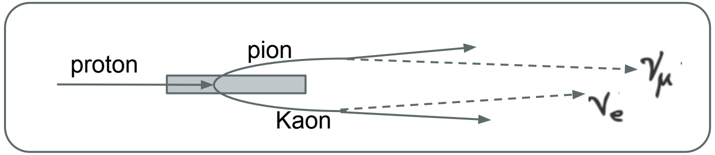


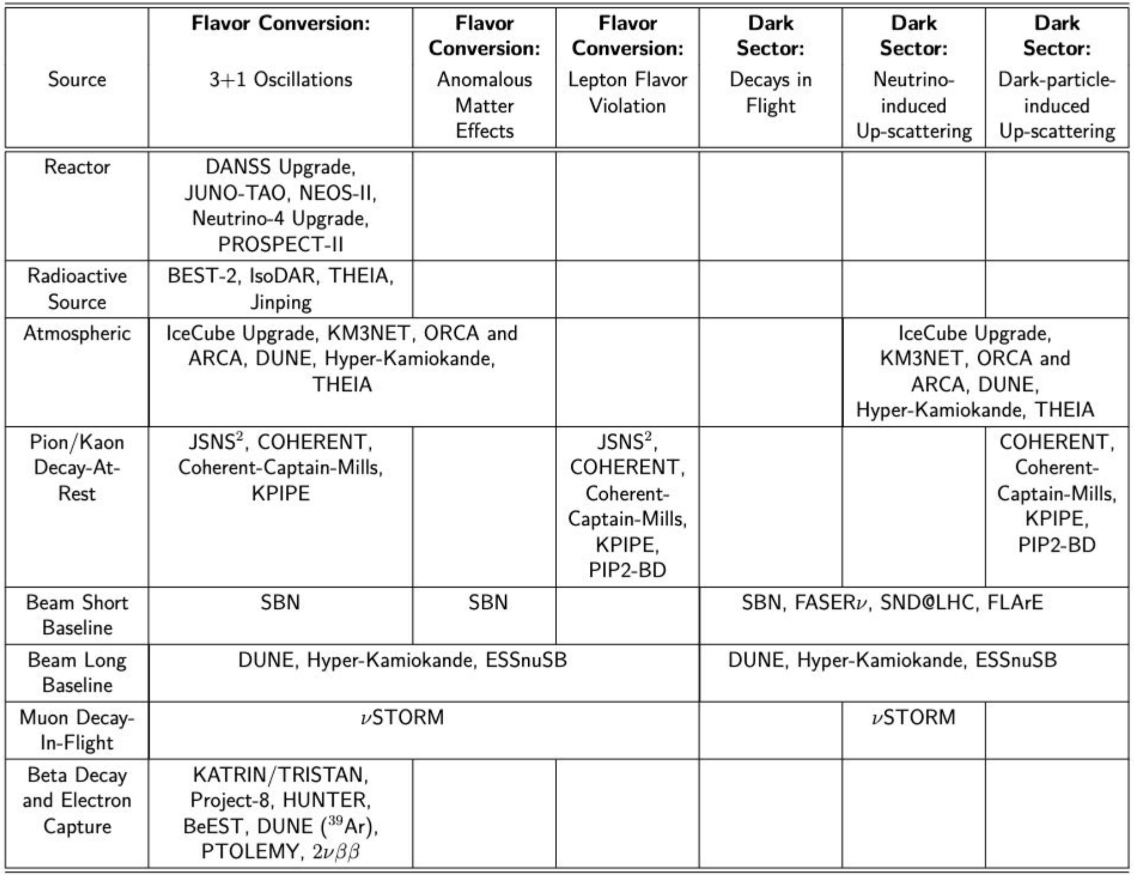
Anticipated Experimental Tests: Summary











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, $2\nu\beta\beta$					

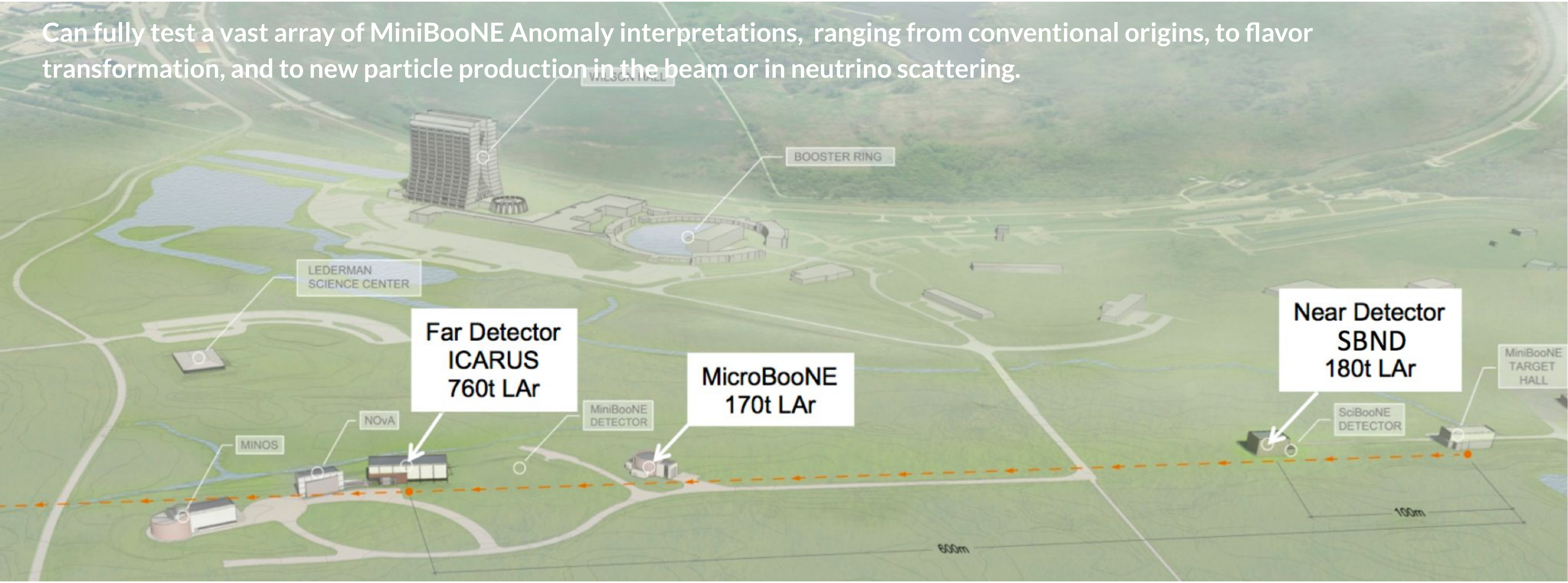
For further details, see Snowmass NF02 White Paper: https://arxiv.org/abs/2203.07323

Anticipated Experimental Tests: I. Decay In Flight

Fermilab-based MicroBooNE (2015-2020) and the Short-Baseline Neutrino Program (2022-...)

SBN Collab, arXiv:1503.01520

Can fully 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.



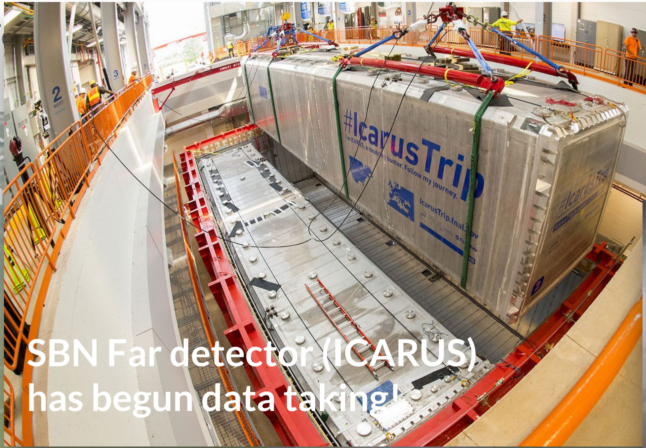
Anticipated Experimental Tests: I. Decay In Flight

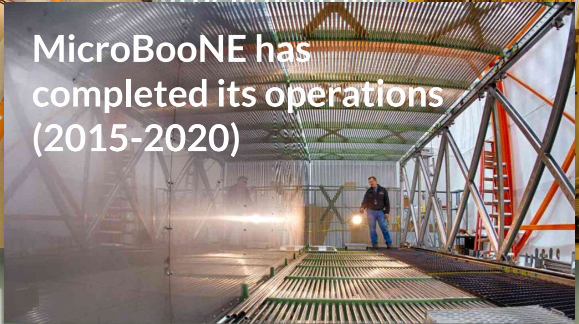
F Baseline Neutrino F

20

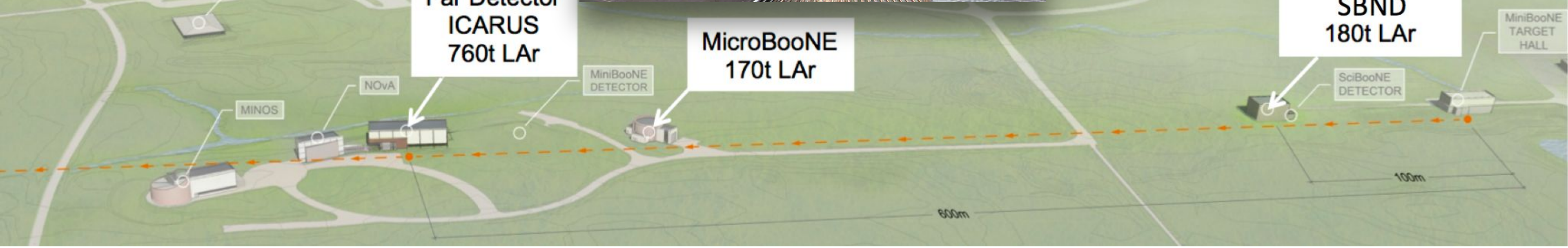
C etations, ranging

tr m or in neutrino s


SBN Far detector (ICARUS) has begun data taking!


MicroBooNE has completed its operations (2015-2020)


SBND expected to begin operations in 2023



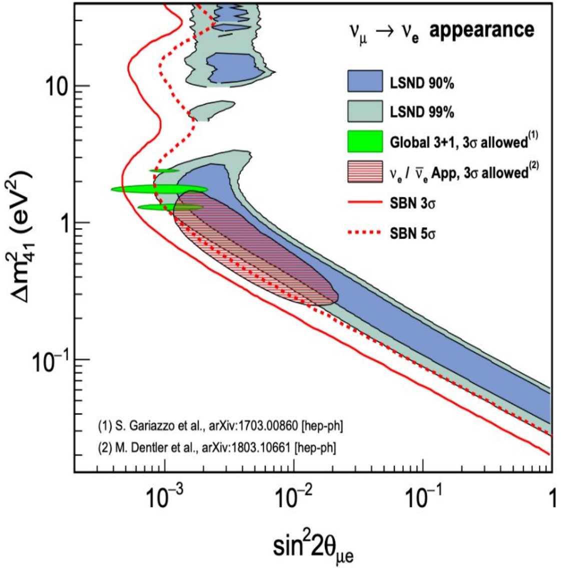
Anticipated Experimental Tests: I. Decay In Flight

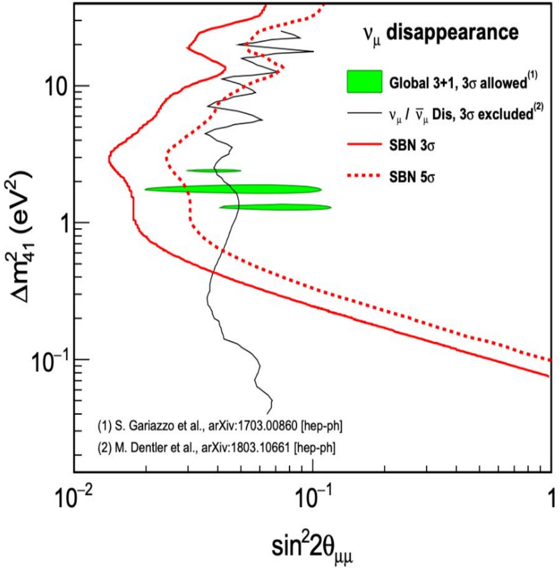
L-dependent search for ν_e appearance and ν_e disappearance

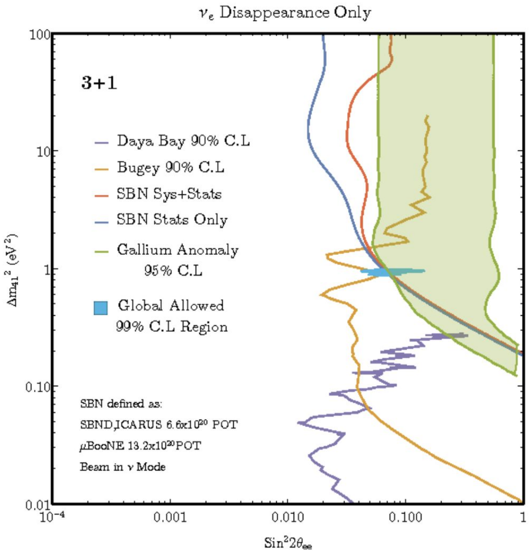
- \+ **ν_μ disappearance** (no evidence ever observed with atmospheric neutrinos or past accelerator experiments)
- \+ **neutral current rate (combined all-active-flavor) oscillations** (smoking gun signature of sterile neutrino oscillations)

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

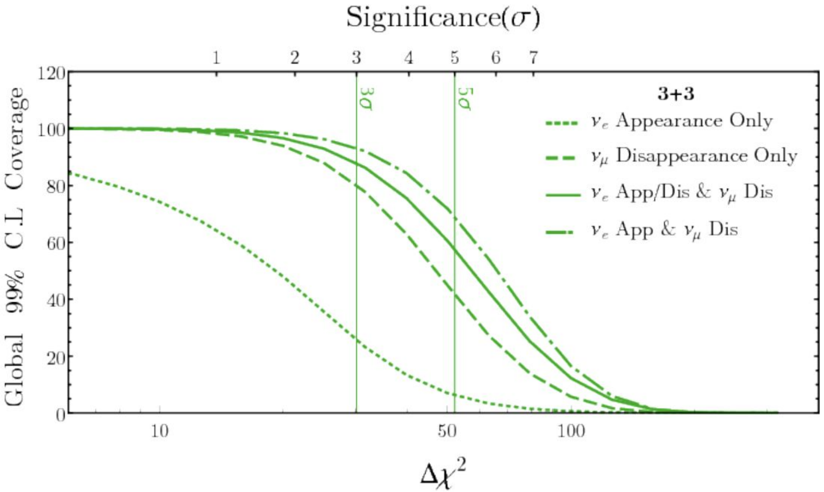






Anticipated Experimental Tests: I. Decay In Flight

SBN can exhaustively probe 3+N oscillations through inclusive, multi-channel searches!



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

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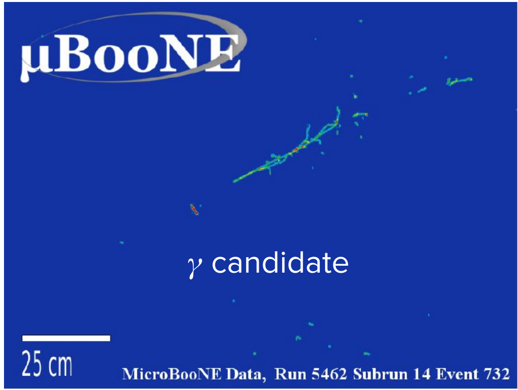
Anticipated Experimental Tests: I. Decay In Flight

First results from MicroBooNE in 2021!



Direct tests of MiniBooNE using half of total collected data:

Photon and electron searches →
Measurements **consistent with Standard Model predictions**, **ruling out the leading photon background interpretation** of the MiniBooNE Anomaly at >95% CL,

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

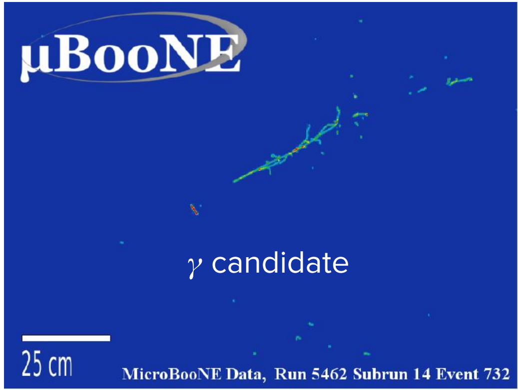
and **ruling out an enhancement of low-energy ν_e event rate** as the sole source of the MiniBooNE Anomaly!

MicroBooNE Collab, arXiv:2110.14080
MicroBooNE Collab, arXiv:2110.14065
MicroBooNE Collab, arxiv:2110.13978
MicroBooNE Collab, arXiv:2110.14054

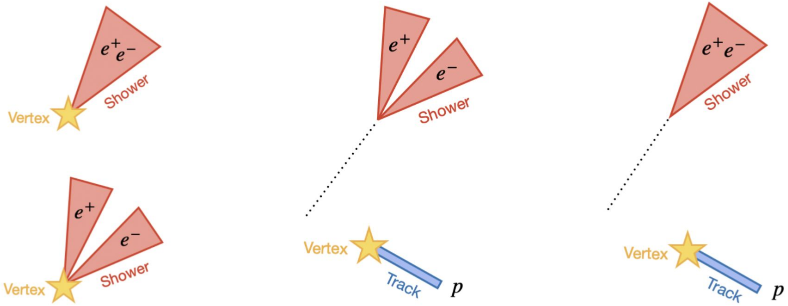
MicroBooNE sterile neutrino oscillation searches are in progress, based on these measurements!

Anticipated Experimental Tests: I. Decay In Flight

First results from MicroBooNE in 2021!



Also, anticipated sensitivity to "dark sector" models:



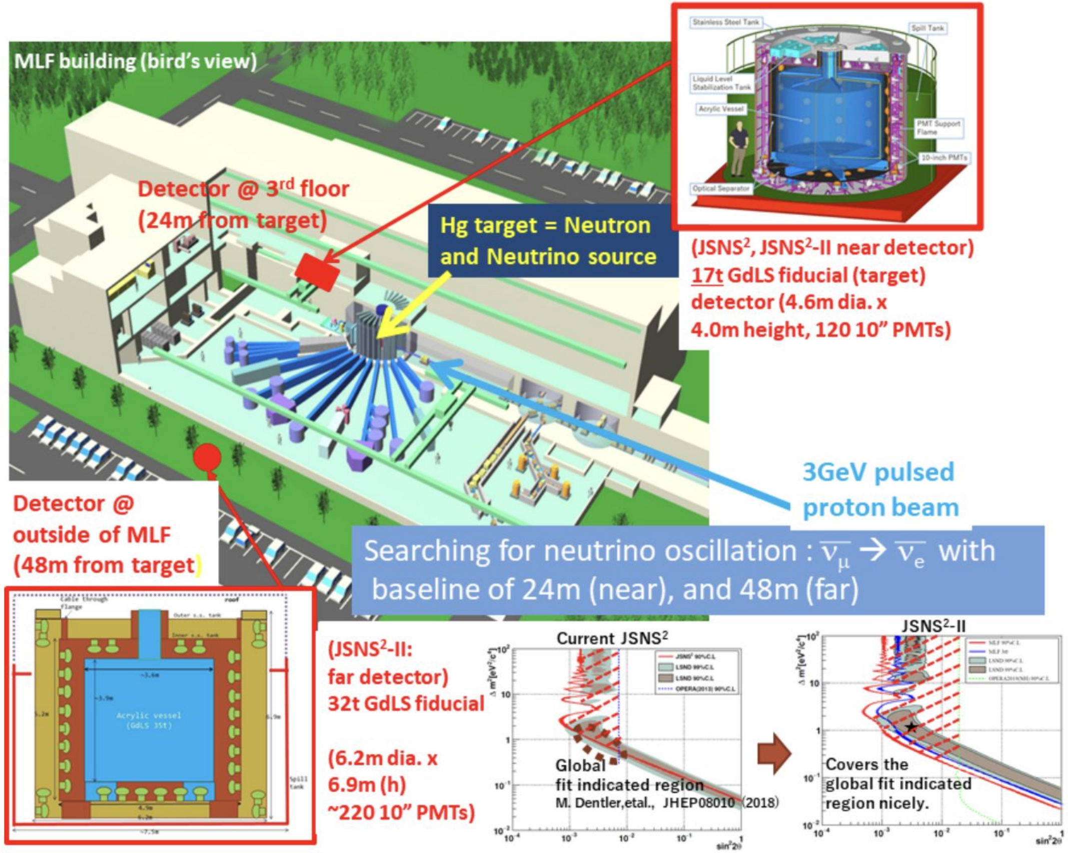
Other future/proposed experiments: SBND, FASERnu, SND@LHC, FLArE, nuSTORM; also CHARM-II and MINERvA (dark sector models)

Anticipated Experimental Tests: II. Decay At Rest

JPARC-based JSNS^2 and JSNS^2-II

JSNS^2/JSNS^2-II can test the full suggested sterile oscillation parameter space from the LSND Anomaly, as well as many lepton flavor violation interpretations

JSNS^2 Collab, arXiv:1310.1437, arXiv:2012.10807



Detector @ 3rd floor (24m from target)

Hg target = Neutron and Neutrino source

(JSNS^2, JSNS^2-II near detector)
17t GdLS fiducial (target) detector (4.6m dia. x 4.0m height, 120 10" PMTs)

3GeV pulsed proton beam

Searching for neutrino oscillation : $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ with baseline of 24m (near), and 48m (far)

Detector @ outside of MLF (48m from target)

(JSNS^2-II: far detector) 32t GdLS fiducial

(6.2m dia. x 6.9m (h) ~220 10" PMTs)

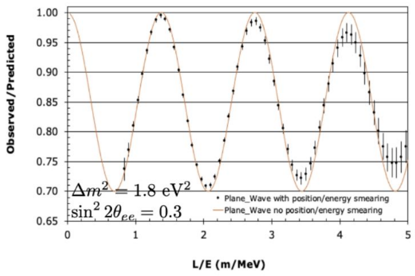
Global fit indicated region
M. Dentler,etal., JHEP08010 (2018)

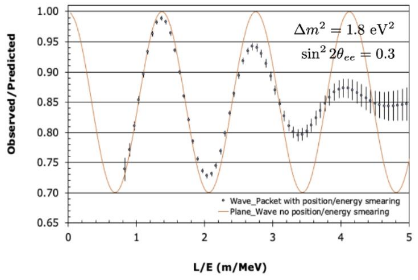
Covers the global fit indicated region nicely.

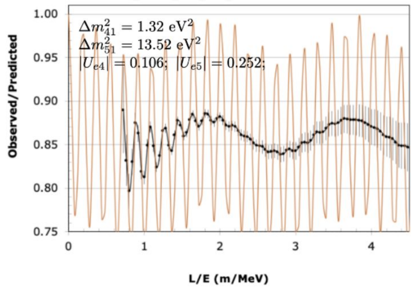
Other future/proposed experiments:
K-PIPE, COHERENT, Coherent-Captain-Mills, PIP2-BD

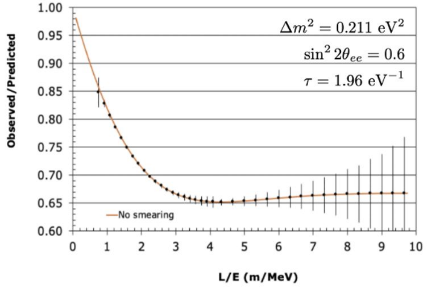
Anticipated Experimental Tests: III. Radioactive Source

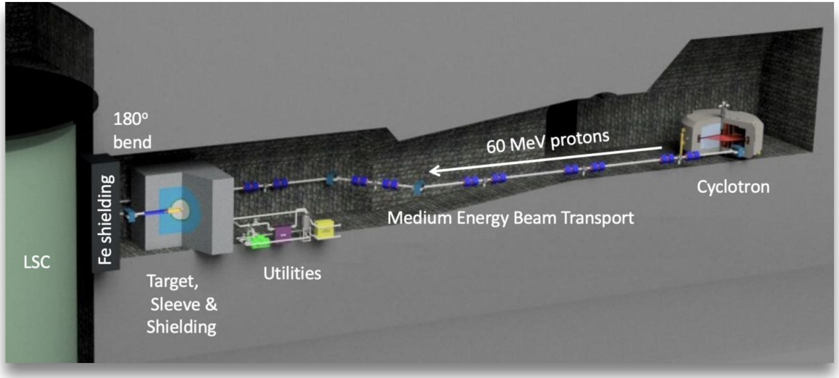
IsoDAR @ Yemilab, Korea









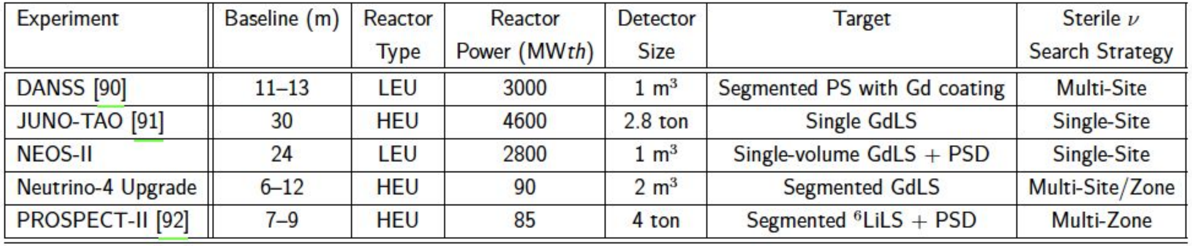


IsoDAR Collab, [arXiv:2111.09480](https://arxiv.org/abs/2111.09480)

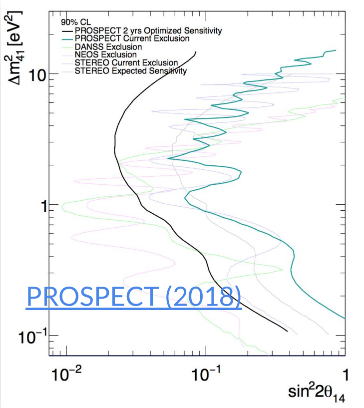
Other future/proposed experiments:
BEST-2, THEIA, Jinping

Anticipated Experimental Tests: IV. Reactor

Currently underway or planned for the next 5 years:



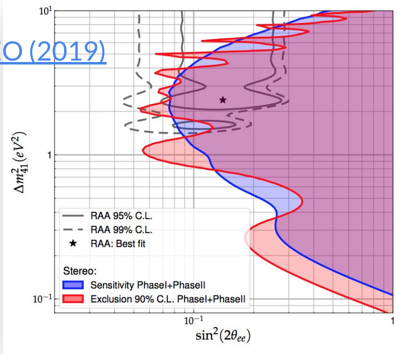
Experiment	Baseline (m)	Reactor Type	Reactor Power (MWth)	Detector Size	Target	Sterile ν Search Strategy
DANSS [90]	11–13	LEU	3000	1 m³	Segmented PS with Gd coating	Multi-Site
JUNO-TAO [91]	30	HEU	4600	2.8 ton	Single GdLS	Single-Site
NEOS-II	24	LEU	2800	1 m³	Single-volume GdLS + PSD	Single-Site
Neutrino-4 Upgrade	6–12	HEU	90	2 m³	Segmented GdLS	Multi-Site/Zone
PROSPECT-II [92]	7–9	HEU	85	4 ton	Segmented ^{6}LiLS + PSD	Multi-Zone



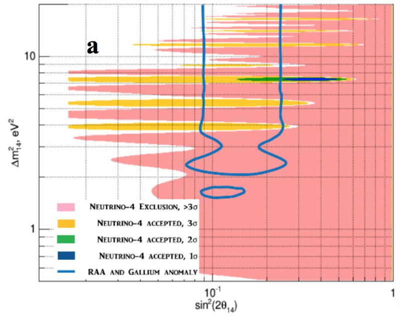
PROSPECT (2018)

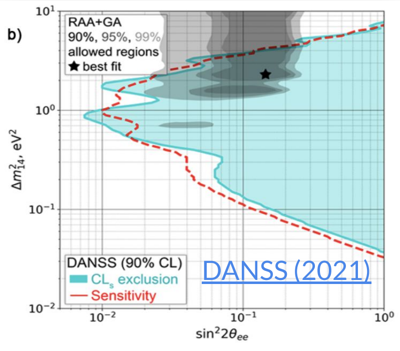
Most recent searches have ruled out majority of low Δm^2 region

STEREO (2019)

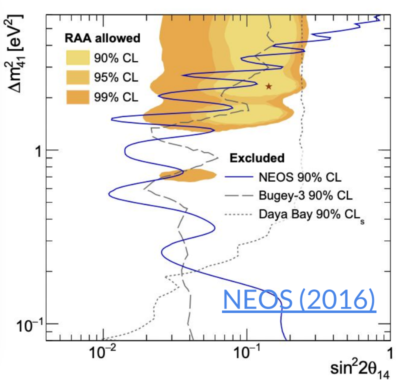


Neutrino-4 (2018)





DANSS (2021)

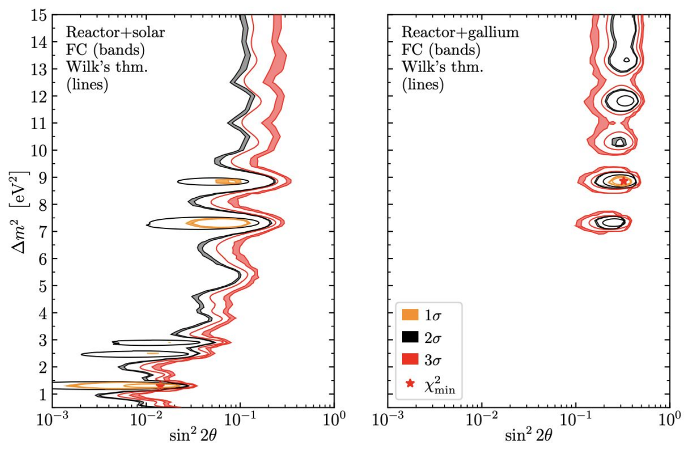


NEOS (2016)

Anticipated Experimental Tests: V. Solar Neutrinos

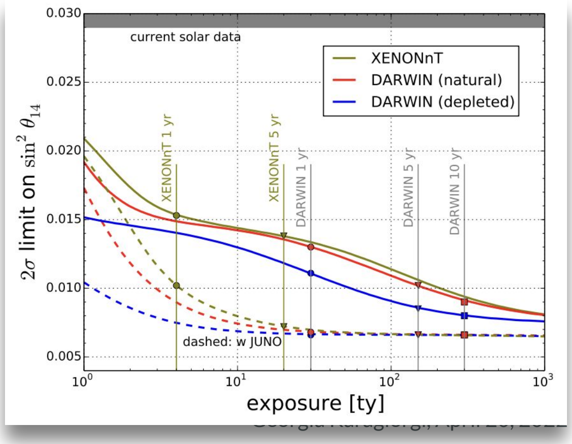
Reactor + radioactive source experiments are still compatible, and allow for high-Δm^2 oscillations.

However, **solar neutrino measurements** comparing high-energy and low-energy solar neutrino rates **place strong constraints to large $|U_{e4}|^2$ and are in significant tension with radioactive source experiments.**



Berryman et al, 2021

Future solar neutrino measurements (in combination with JUNO reactor neutrino measurements) are expected to improve over current limit by x4.5.



Goldhagen et al, 2021

Anticipated Experimental Tests: VI. Other types

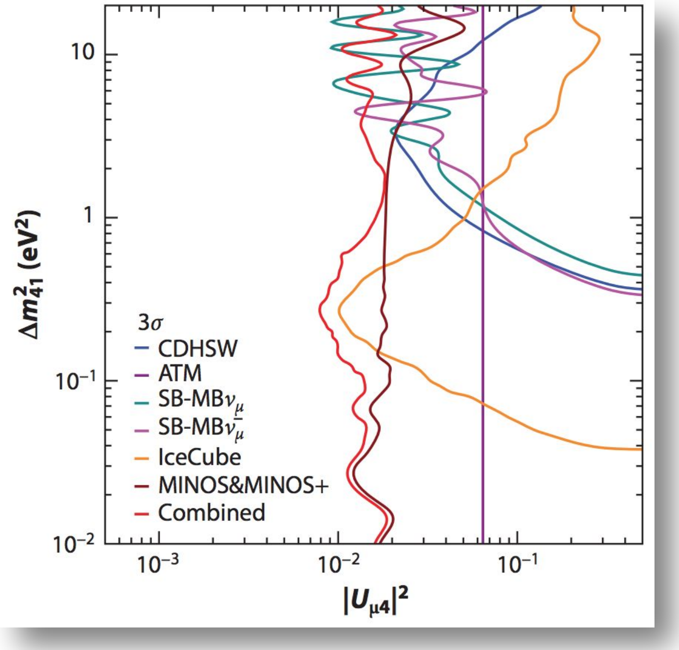
Other existing/ongoing searches for sterile neutrinos and other flavor conversion models include:

Atmospheric neutrino measurements with IceCube, Super-K, and **long-baseline neutrino** oscillation measurements with OPERA, MINOS/MINOS+, MINOS+/Daya-Bay, NOvA, T2K.

→ can be combined with reactor measurements; mostly sensitive to ν_μ disappearance (subdominant $\nu_\mu \rightarrow \nu_\tau$ sensitivity)

Future/proposed experiments: IceCube Upgrade, DUNE, Hyper-K, THEIA, KM3NET, ORCA and ARCA, ESSnuB

Giunti & Lasserre (2019)

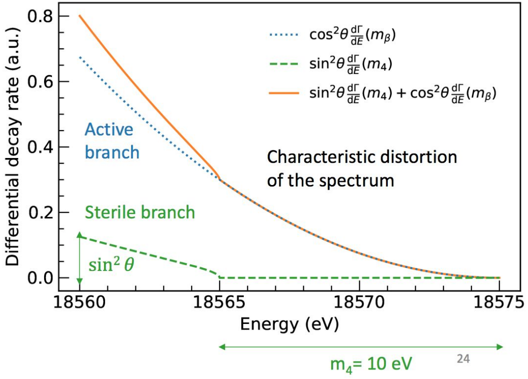


Anticipated Experimental Tests: VI. Other types

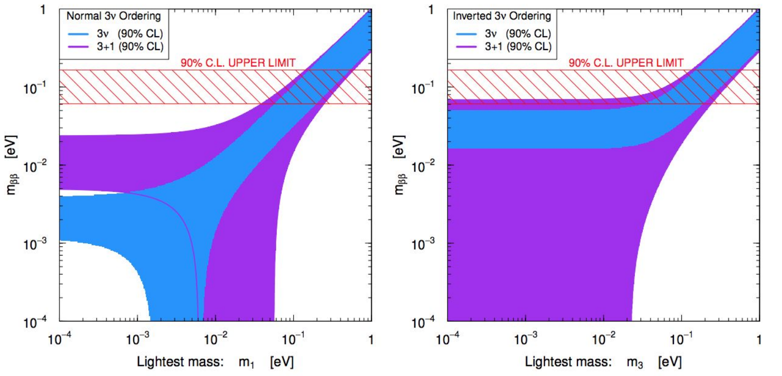
Complementary searches for eV-scale sterile neutrinos: searches for kinematic effects in **beta decay experiments** (KATRIN), **neutrinoless double beta decay experiments**, and **electron capture experiments.**

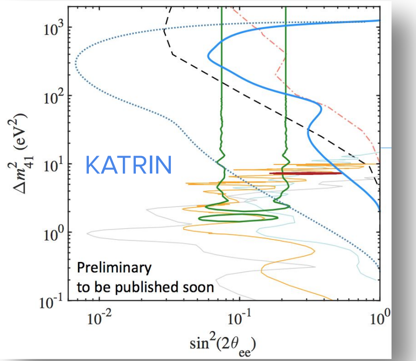
Future/proposed: KATRIN/TRISTAN, Project-8, HUNTER, BeEST, DUNE (39Ar), PTOLEMY

S. Marteens, Neutrino 2020



$$m_{\beta\beta} = \Big| |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3 + |U_{e4}|^2 e^{i\alpha_4} m_4 \Big|$$





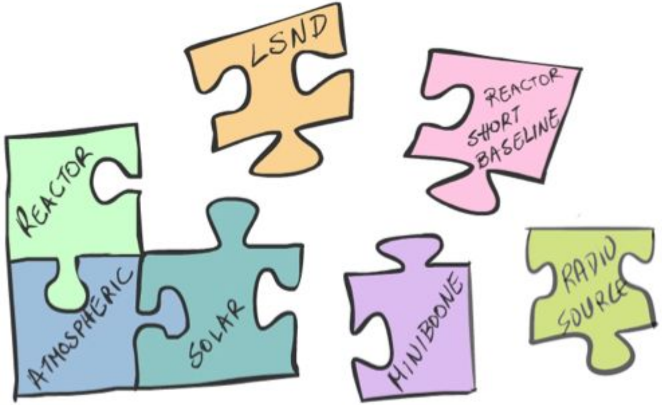
Where we stand, and prospects for discovery

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

Besides efforts to search for potentially as-of-yet-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.

With close collaboration between theory+experiment, it is likely that upcoming/new experiments will reach a verdict in the very near future.



Possible Outcomes and Future Opportunities

By seeing ongoing and planned experimental efforts through to completion, we will be able to point to the origin of each anomaly.

Expect that any imminent shift in the short-baseline experiment and theory landscape will define future priorities and programs for the field, depending heavily on identified origins of the anomalies.

E.g., anomalous flavor transformation at SBN → SBN antineutrino running, IsoDAR, additional DAR…

cross-section mis-modeling issue → impacts on the future neutrino oscillation programs will need to be mitigated with enhanced near detector facilities…

couplings to a new hidden sector, then an expansive, global program of New Physics research taking advantage of the world's foremost proton and electron beam facilities will need to be coordinated…

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Questions?

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