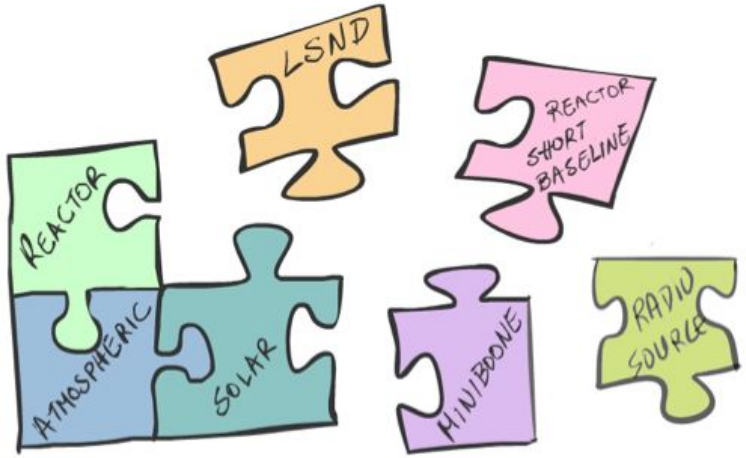
Overview of Light Sterile Neutrino Searches

Georgia Karagiorgi, Columbia University

NuFact 2022
Salt Lake City, Utah

ALFRED P. SLOAN FOUNDATION

Why talk about light sterile neutrinos?

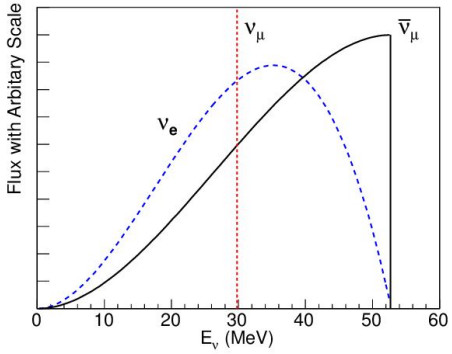


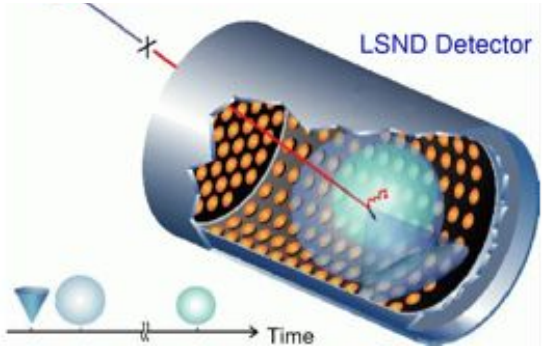
increasing sterile neutrino mass → decreasing mixing

meV | eV | keV | MeV | GeV | TeV

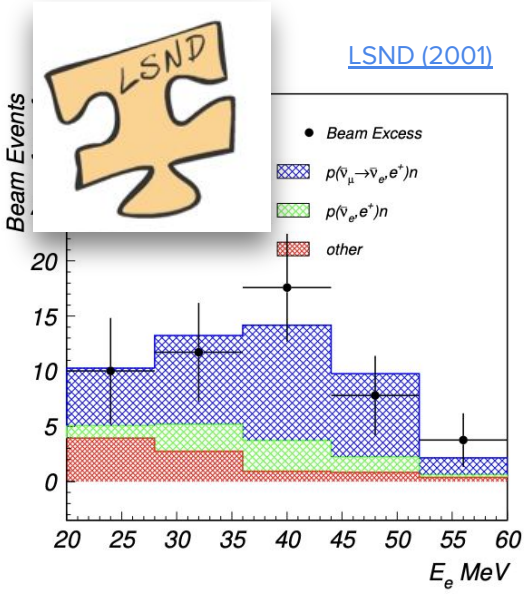
LSND Anomaly (1990's)

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





LSND (2001)



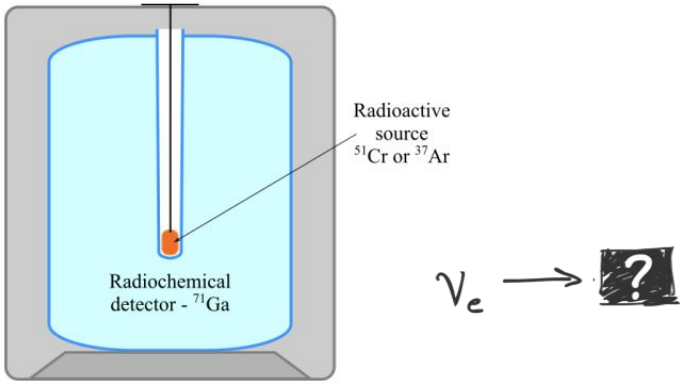
excess $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ dominated beam, 3.8σ

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.

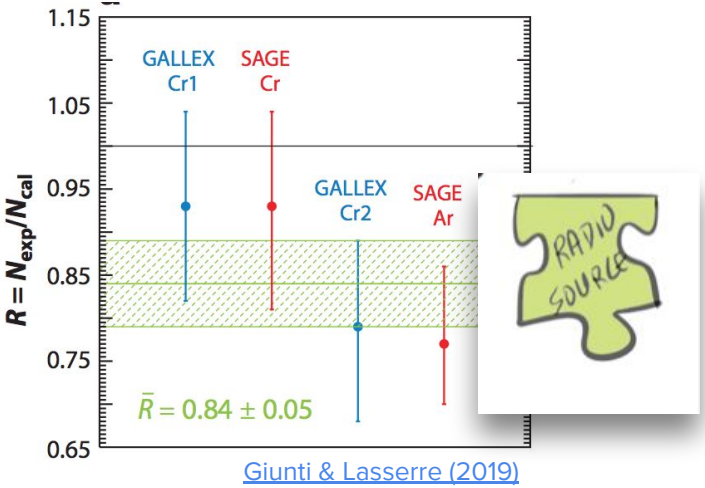
See talk by Jungsic Park

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

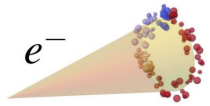


Giunti & Lasserre (2019)

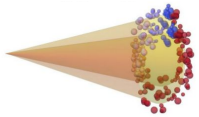
The development of new radioactive sources and detectors for improved direct tests of the Gallium Anomaly has been pursued and realized in the form of the BEST experiment (which **confirmed** the anomaly).

BEST (2021)

MiniBooNE Anomaly (2000's)

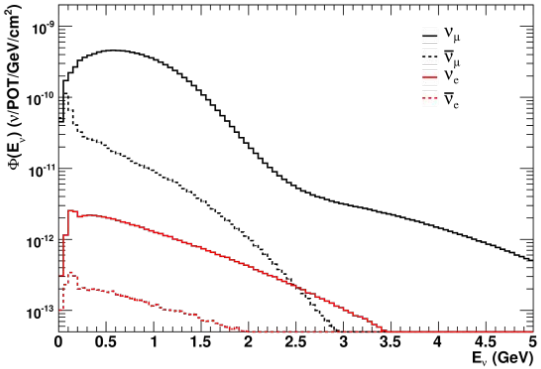


overlapping e^+e^-

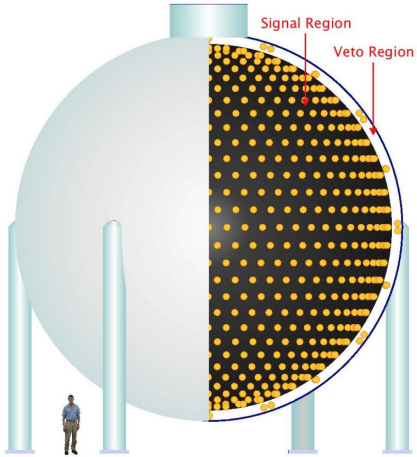


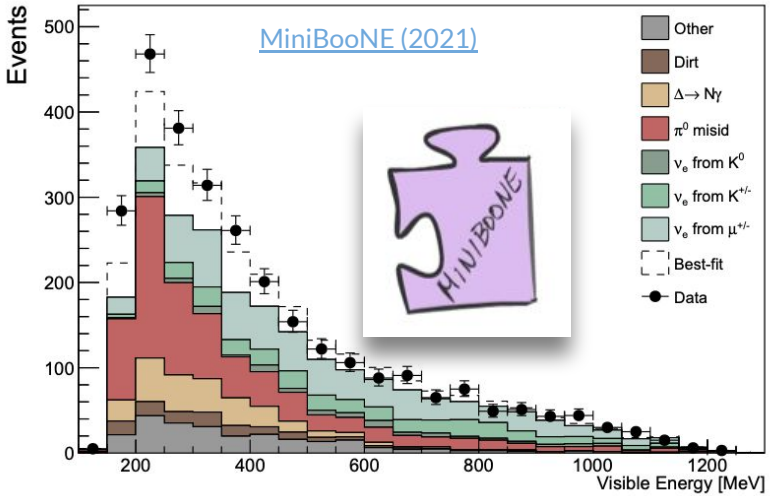
$e^{\mp}$ from $\overset{(-)}{\nu}_e$ interaction and $\gamma \to e^+e^-$ are indistinguishable to MiniBooNE

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



MiniBooNE Detector



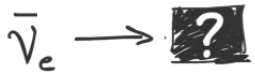


excess $\overset{(-)}{\nu}_e$ in a $\overset{(-)}{\nu}_\mu$ dominated beam, 4.8σ

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

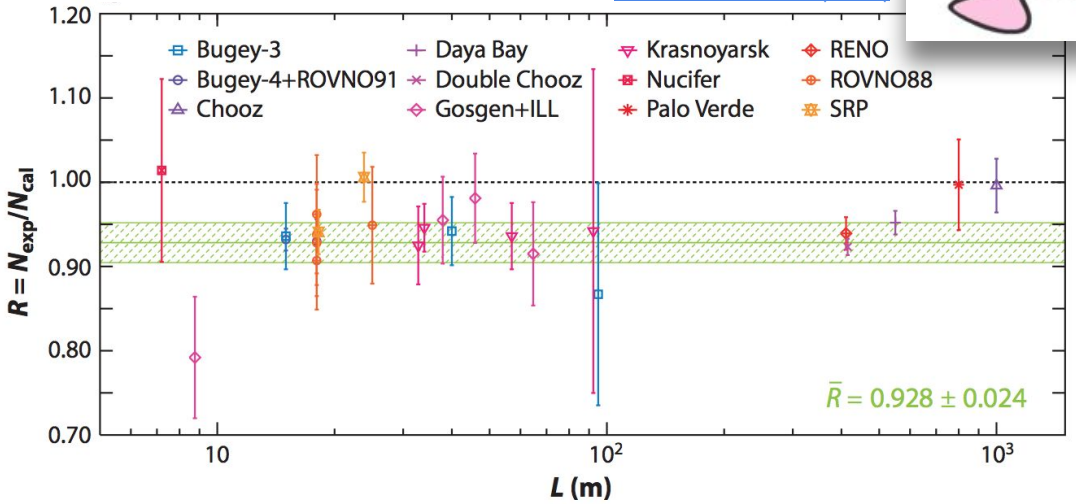
Reactor Anomaly (2010's)

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.**

What the four anomalies have in common:

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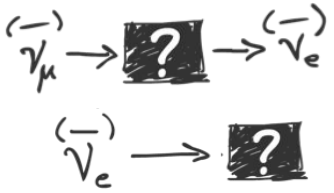
- Electron (anti)neutrino observations which deviate from expectation, from either electron or muon (anti)neutrino sources
- L/E of 0.1-10 m/MeV



Leading interpretation

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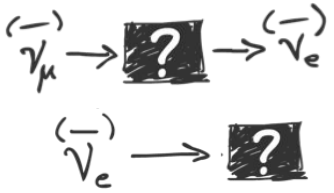


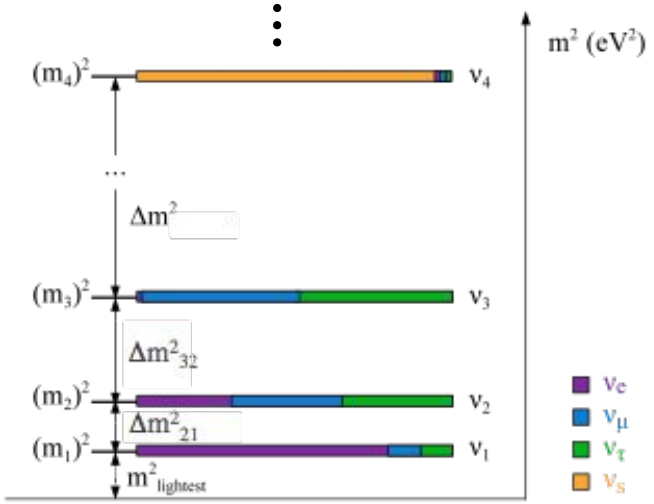
"Vanilla" light sterile neutrino oscillations

$\Delta m^2 \sim 1\ eV^2 \rightarrow$ 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%)

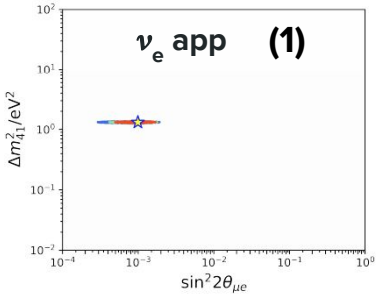
Probability amplitudes are proportional to electron and/or muon flavor content(s) of new mass states

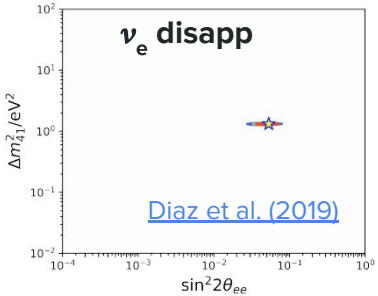


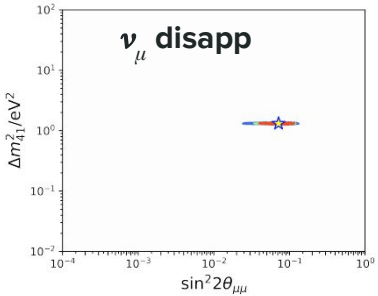
“Vanilla” light sterile neutrinos: Global picture

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

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







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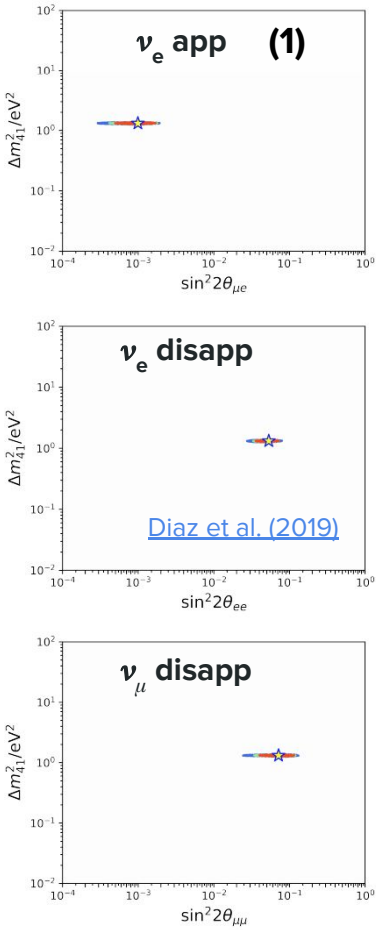

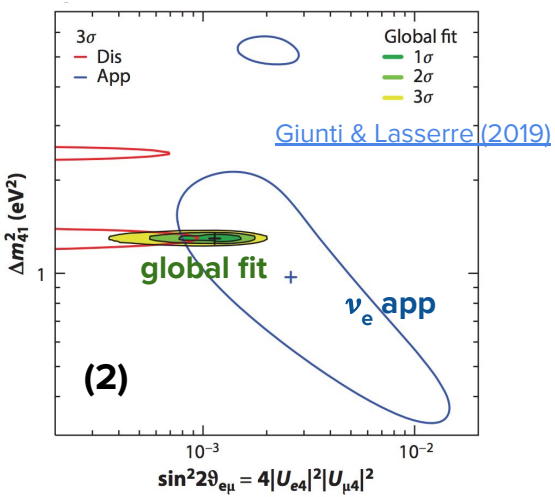

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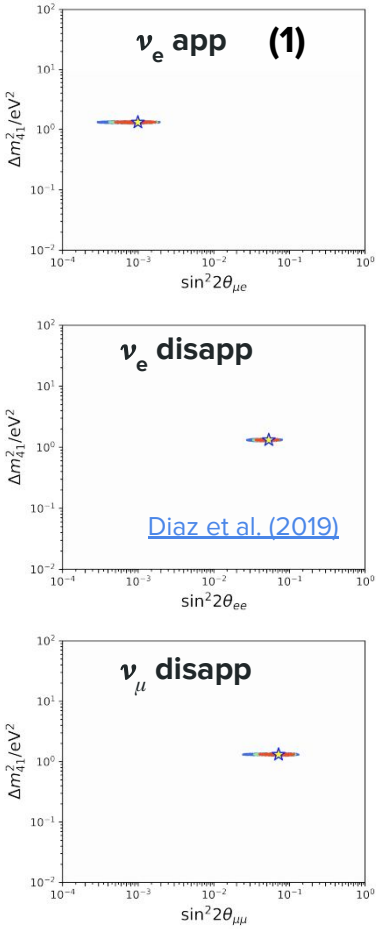
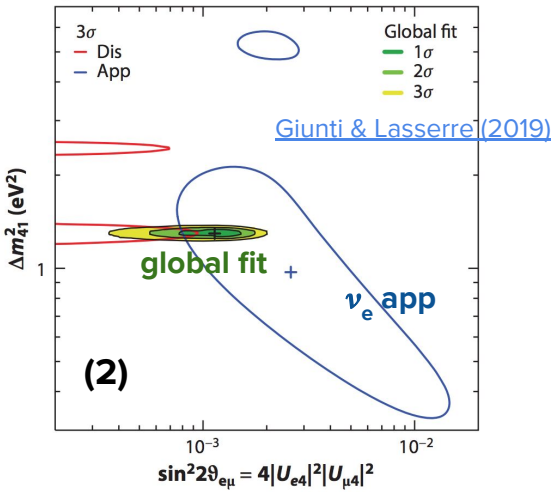
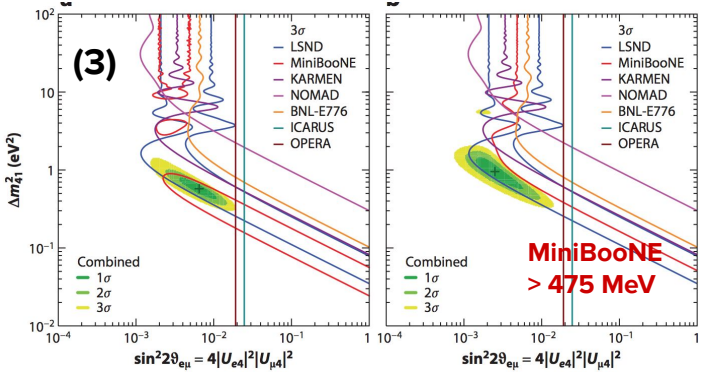
1. The “3+1” scenario is much **more preferred than null**
2. There is a large **tension** between appearance and disappearance data sets, and incompatibility of parameters preferred by appearance vs. disappearance experiments
3. Some of this tension can be relieved with omission of **MiniBooNE low-energy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





MiniBooNE all energies



“Vanilla” light sterile neutrinos: Global picture

Caveats!

1. For a while, global fits had been carried out with not very rigorous statistical treatment of data, e.g. no Feldman-Cousins corrections
2. Multiple experimental data sets share systematic correlations; are these properly treated in global fits?
3. Individual data sets are treated assuming appearance-only or disappearance-only signal predictions—an assumption valid only for small mixing amplitudes
4. What is the source of the MiniBooNE anomaly? Should it be interpreted as flavor transitions, or something else?

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Over the past decade, an extensive experimental program has been mounted delivering more sensitive tests to this interpretation:

Accelerator-based searches:

Decay-at-Rest:
LSND, KARMEN
Decay-in-Flight:
MiniBooNE, NOMAD, CDHS, CCFR

OPERA, NOvA, T2K, MINOS/MINOS+, NOvA MicroBooNE

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Searches with radioactive sources and at reactors:

Reactors:
Bugey, Chooz

NEW in ~last 10 years

DoubleChooz,
RENO, Daya-Bay,
DANSS, NEOS, Neutrino-4
PROSPECT, STEREO

Sources:
SAGE, GALLEX

BEST

“Vanilla” light sterile neutrinos: Global picture

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Atmospheric/solar neutrino-based searches:

Atmospheric:
Super-K

NEW in ~last 10 years

IceCube/DeepCore, ANTARES, Super-K

Solar:

Recent re-analyses

Accelerator-based searches

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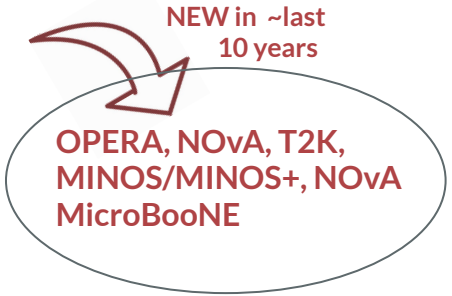


Some highlights in next slides…

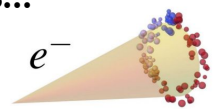
Accelerator-based searches

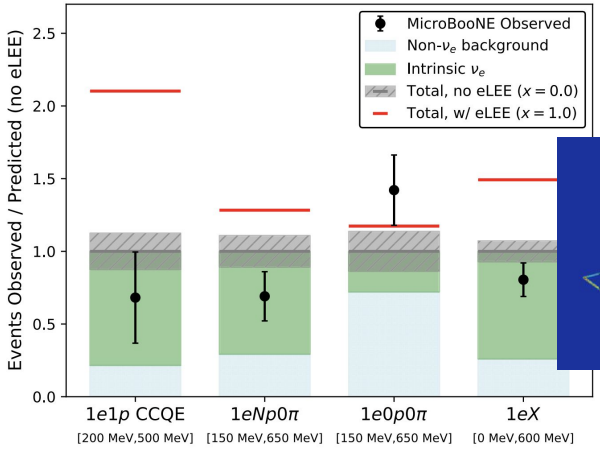
See talks by Kathryn Sutton and Xiangpan Ji

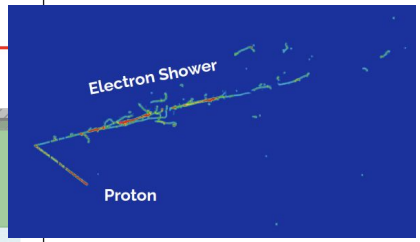
MicroBooNE: A direct test of the MiniBooNE anomaly:

No evidence of electron excess…

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





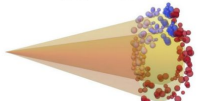


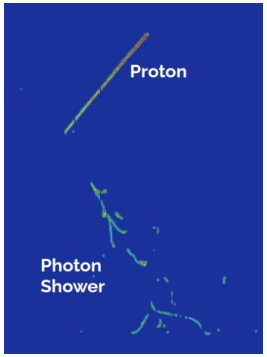
e/γ?

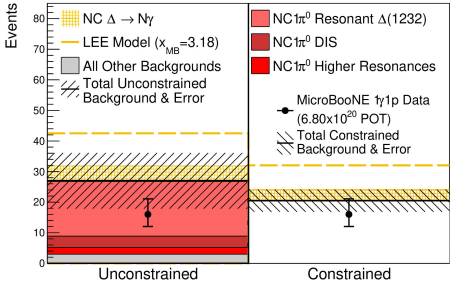
or photon excess!

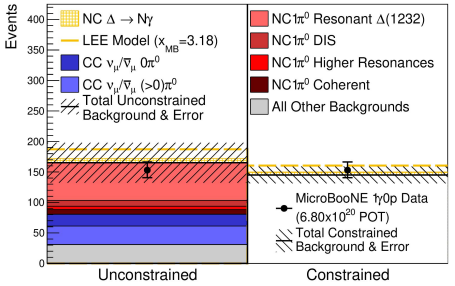
Phys. Rev. Lett. 128, 111801 (2022)

overlapping e^+e^-









Ruled out the possibility of mis-understood/enhanced leading backgrounds as an interpretation of the MiniBooNE excess

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Accelerator-based searches

See talks by Kathryn Sutton and Xiangpan Ji

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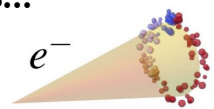

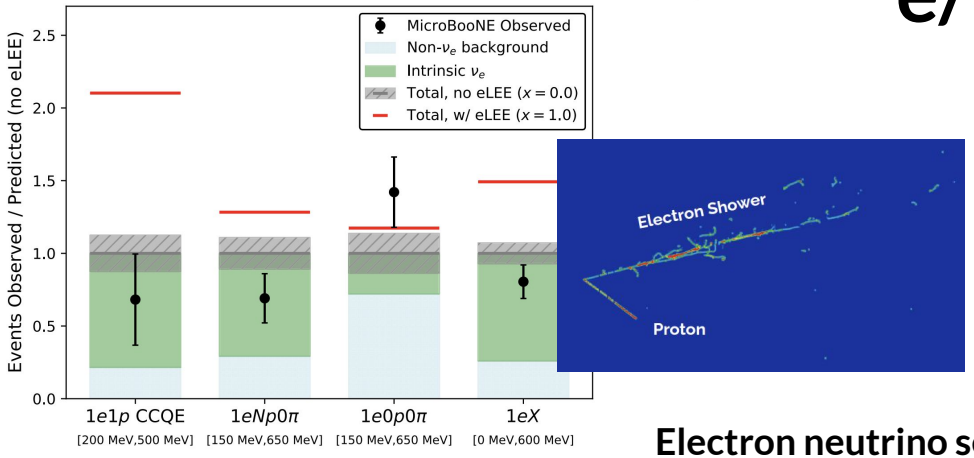

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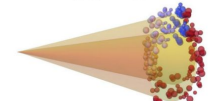

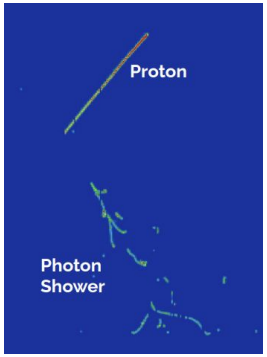

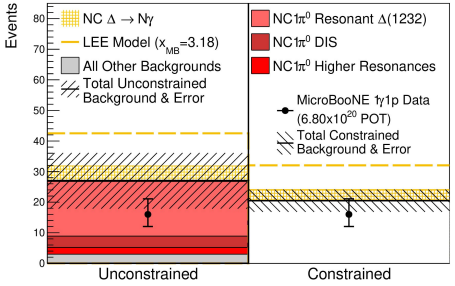

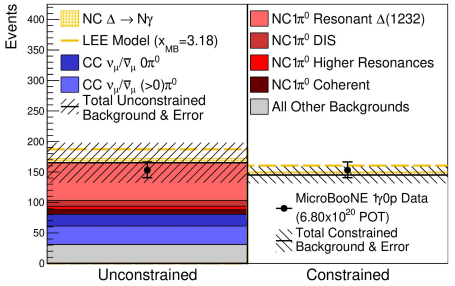

Electron neutrino search has also been reinterpreted as a search for light sterile neutrino oscillations; see e.g., MICROBOONE-NOTE-1116-PUB

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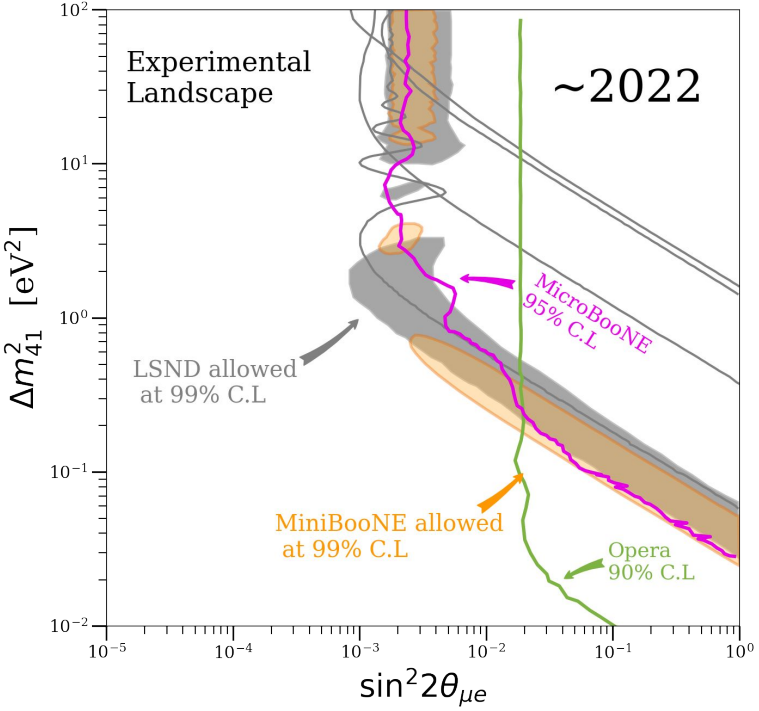
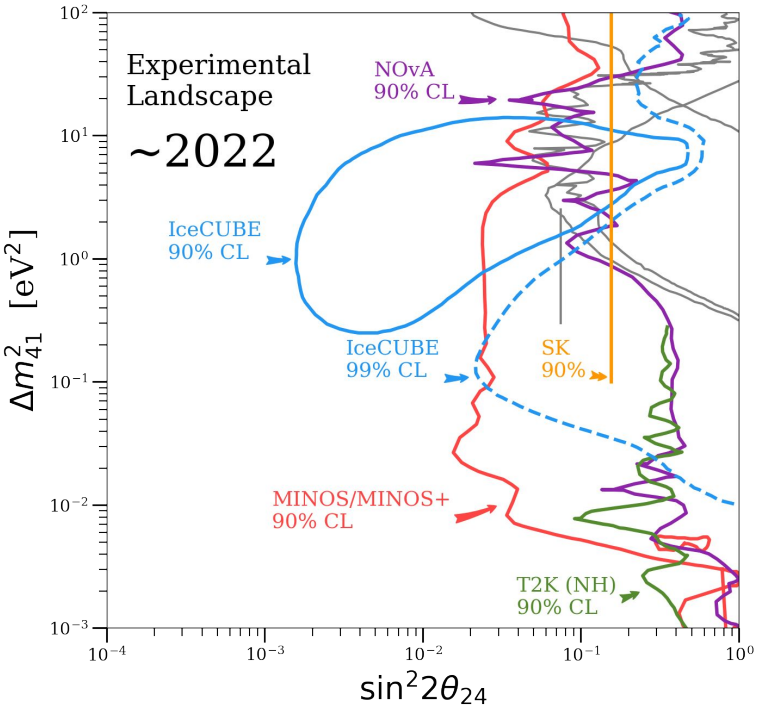
Accelerator-based searches

Closing in on 3+1 parameter space:



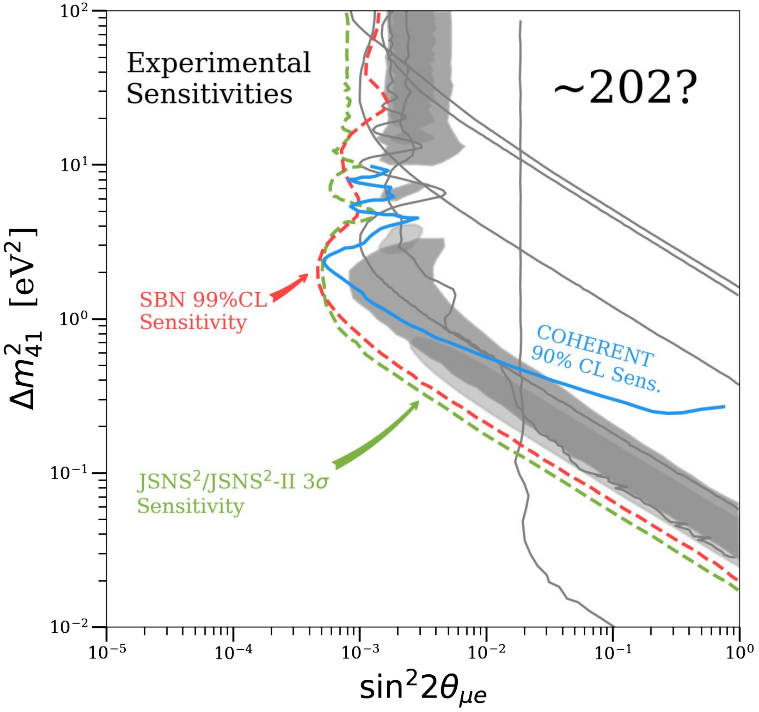


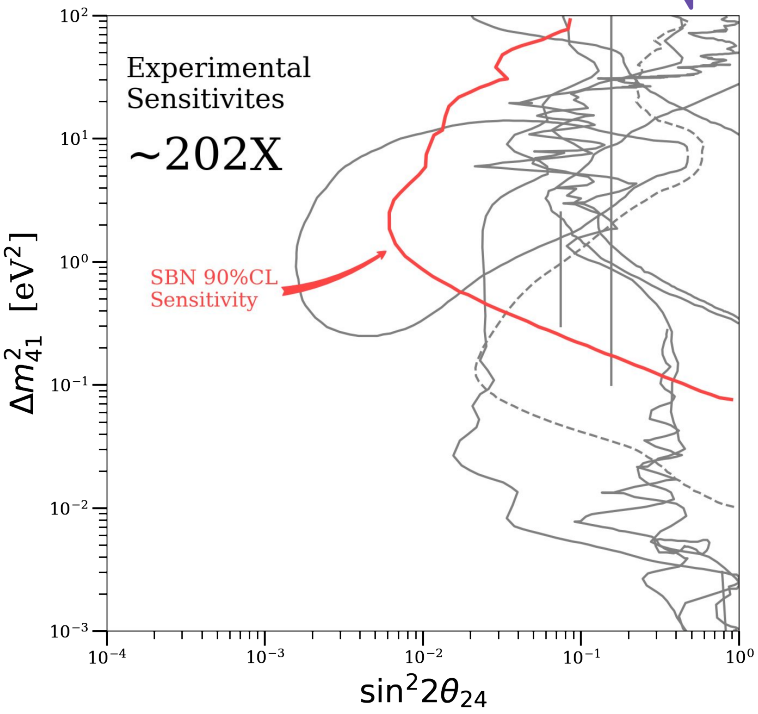
Credit: M. Ross-Lonergan, Snowmass 2022

Accelerator-based searches

See talks by Mark Ross-Lonergan, Jungsic Park, Samuel Hedges

Upcoming experimental searches: SBN, JSNS^2/JSNS^2-II, COHERENT





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Searches with radioactive sources and at reactors

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Bugey, Chooz

NEW in ~last 10 years

DoubleChooz, RENO, Daya-Bay, DANSS, NEOS, Neutrino-4 PROSPECT, STEREO

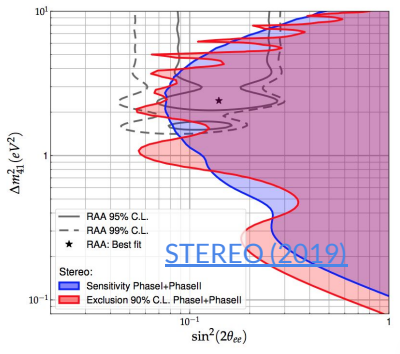
Sources:
SAGE, GALLEX

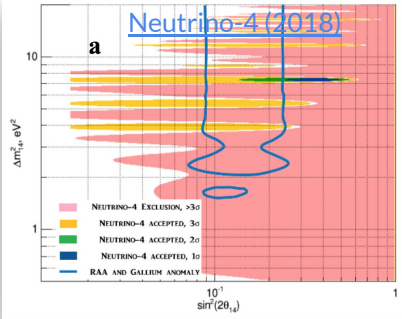
BEST

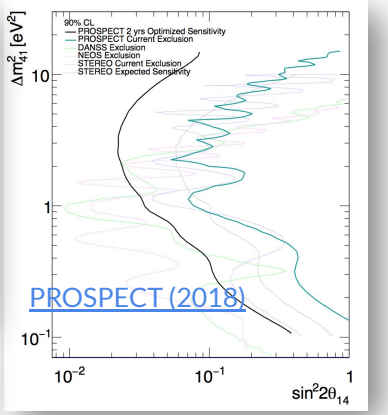
Some highlights in next slides…

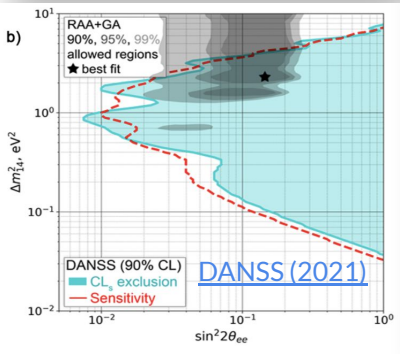
Searches with radioactive sources and at reactors

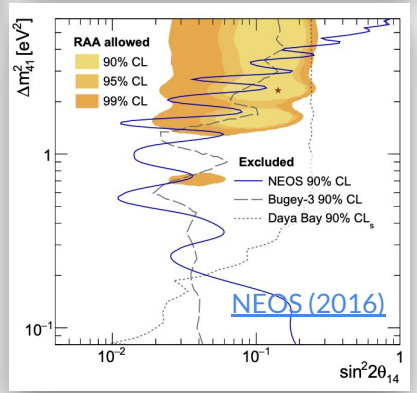
Majority of recent reactor-based short-baseline oscillation searches have excluded the majority of low-Δm^2 region









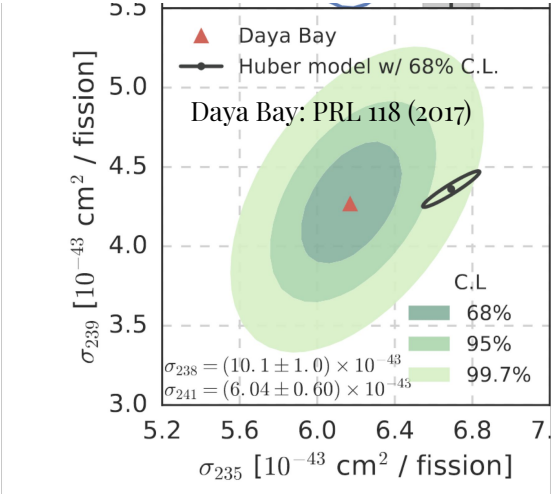


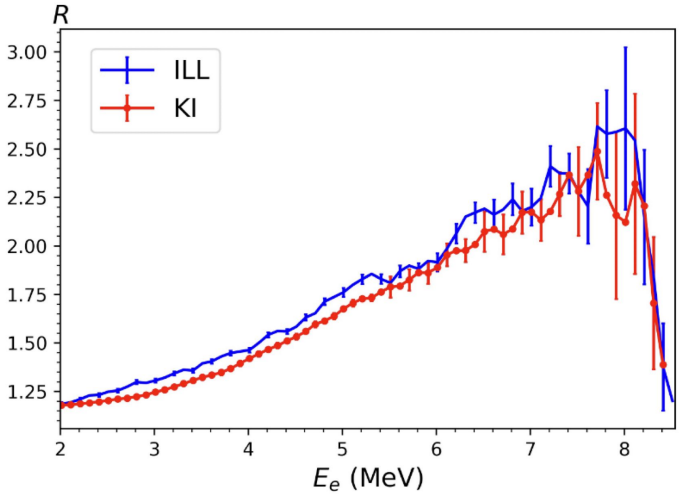
Searches with radioactive sources and at reactors

Majority of recent reactor-based short-baseline oscillation searches have excluded the majority of low-Δm^2 region

In combination with reactor-based long-baseline experimental measurements, have revealed clear deficiencies in reactor flux modeling that seem to contribute significantly to reactor anomaly

Single-isotope IBD yield extractions disagree with flux model predictions, e.g. ^{235}U



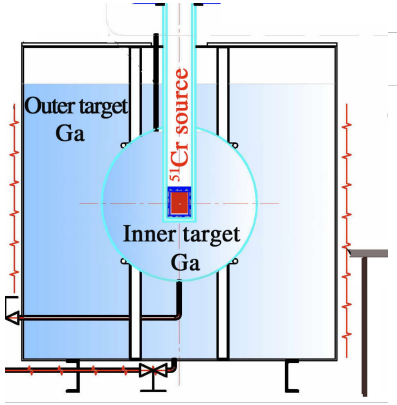


New $^{235}U/^{239}Pu$ beta-decay spectral measurements at Kurchatov Institute suggest possible calibration issue with previous ILL measurements

Searches with radioactive sources and at reactors

BEST: A direct test of the Gallium anomaly:

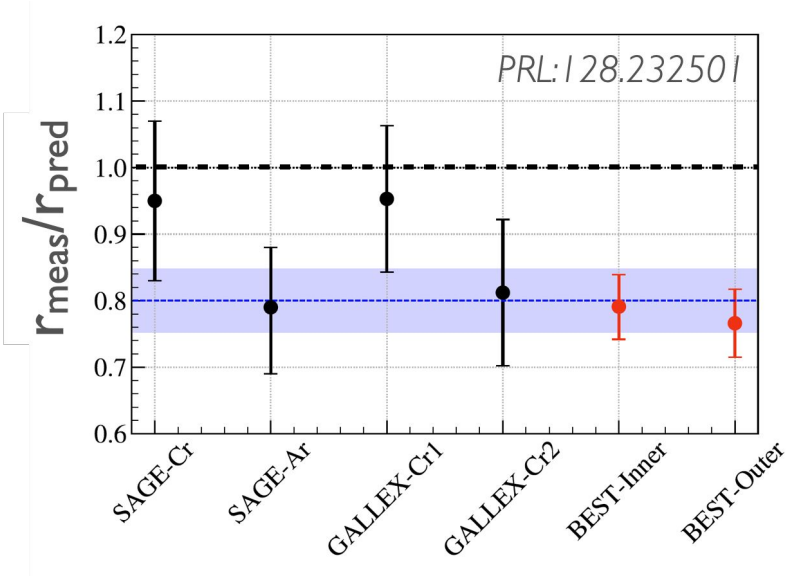
- Gallium source experiment, similar to GALLEX
- ^{51}Cr source (3 MCi)
- Two zones for flux cross-checks:
  - Inner sphere (L~0.660m)
  - Outer sphere (L~1.096m)
- ^{71}Ge production at each L measured separately



$$e^- + {}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_e \quad (^{51}\mathrm{Cr}\ 27.7\ \mathrm{days})$$

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + \mathrm{e}^-$$

Measured rate lower than expected in both volumes; confirms Gallium anomaly at >5σ !



Atmospheric and solar neutrino based searches

Caveats!

1. For a while, global fits had been carried out with not very rigorous statistical treatment of data, e.g. no Feldman-Cousins corrections
2. Multiple experimental data sets share systematic correlations; are these properly treated in global fits?
3. Individual data sets are treated assuming appearance-only or disappearance-only signal predictions—an assumption valid only for small mixing amplitudes
4. What is the source of the MiniBooNE anomaly? Should it be interpreted as flavor transitions, or something else?

Over the past decade, an extensive experimental program has been mounted delivering more sensitive tests to this interpretation:

Atmospheric/solar neutrino-based searches:

Atmospheric:
Super-K

NEW in ~last 10 years

IceCube/DeepCore, ANTARES, Super-K

Solar:

Recent re-analyses

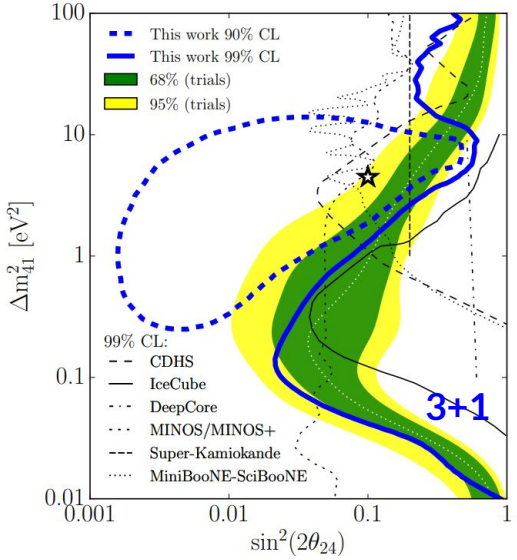
Some highlights in next slides…

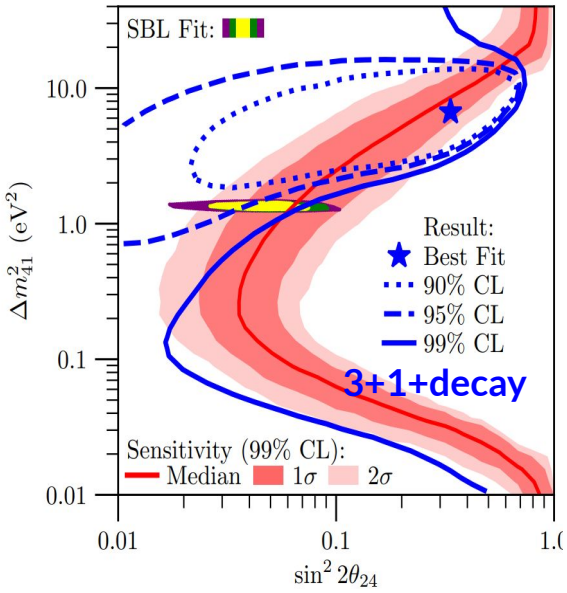
Atmospheric and solar neutrino based searches

IceCube/DeepCore:

Sensitivity to eV-scale sterile neutrinos due to matter-enhanced resonant disappearance for atmospheric neutrinos traveling through the Earth, and fast oscillations that average out at lower energies

https://arxiv.org/abs/2204.00612

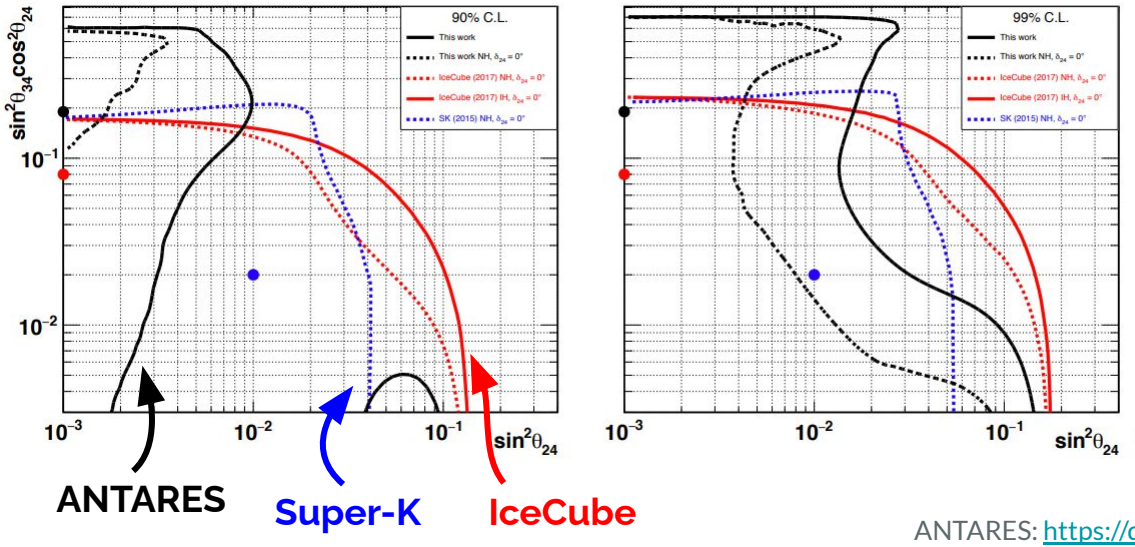




Closed contour at 90% CL but still consistent with three-neutrino paradigm

Atmospheric and solar neutrino based searches

IceCube/DeepCore + ANTARES + Super-K



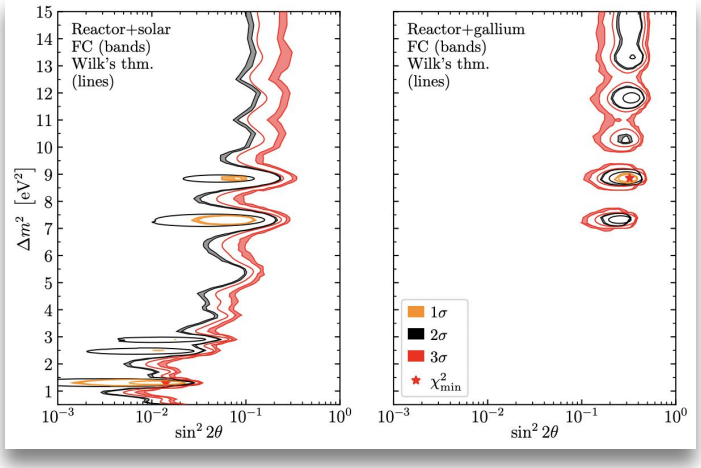
Insensitive to Δm^2, but can place constraint on the tau and muon content of a fourth mass eigenstate

ANTARES: https://doi.org/10.48550/arXiv.1812.08650
Super-K: https://doi.org/10.1103/PhysRevD.91.052019

Atmospheric and solar neutrino based searches

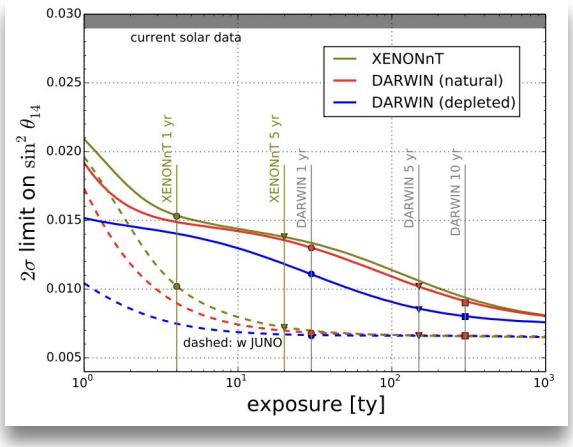
Solar neutrino measurements comparing high-energy and low-energy solar neutrino rates **place strong constraints to large electron neutrino disappearance, and are in significant tension with radioactive source experiments.**

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.

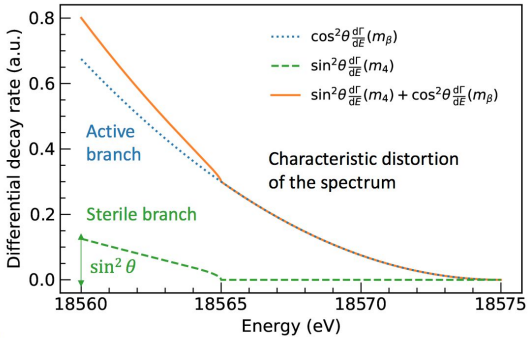
Goldhagen et al, 2021



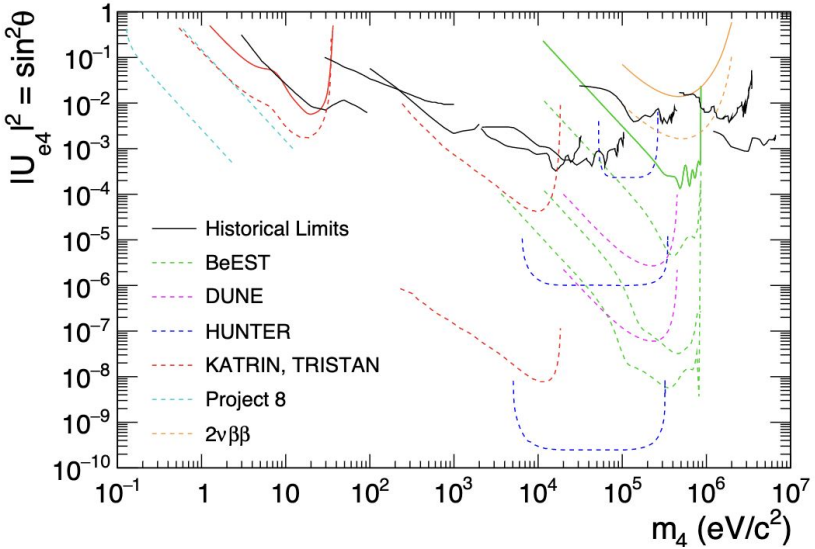
Other, complementary searches for eV-scale neutrinos

Searches for kinematic effects in **beta decay experiments** (KATRIN), **neutrinoless double beta decay experiments**, and **electron capture experiments.**

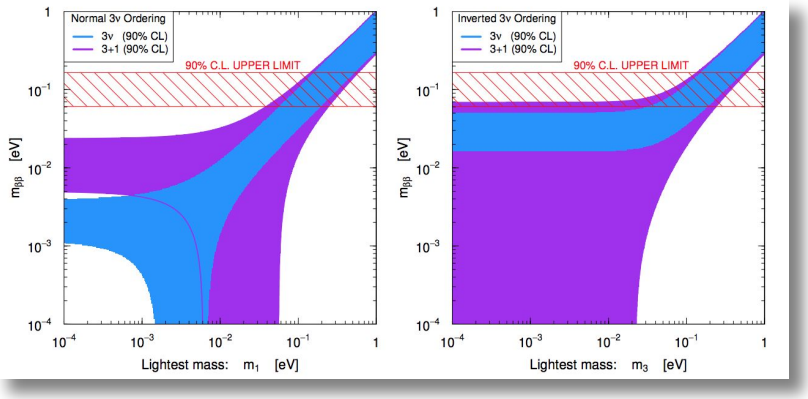
S. Marteens, Neutrino 2020



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



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



Closing in on “vanilla” sterile neutrinos

- At this point, the most persistent/compelling evidence for light sterile neutrino oscillations comes exclusively from LSND, MiniBooNE, and Gallium experiments (BEST)
- Interpretation in terms of “vanilla” sterile neutrinos seems challenging, due to relatively large mixings needed to describe observed signals
    - More definitive tests are anticipated in the very near future by MicroBooNE, SBN, and JSNS^2
- IceCube/DeepCore shows interesting hints for more extended light sterile neutrino scenarios
- The possibility of other conventional or new physics as underlying source(s) of the anomalies remains, and needs to be explored with equal priority

Where next?

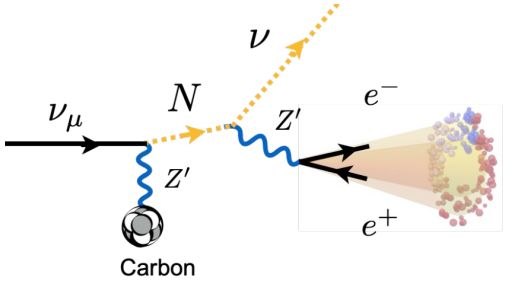
Beyond “vanilla” scenarios!

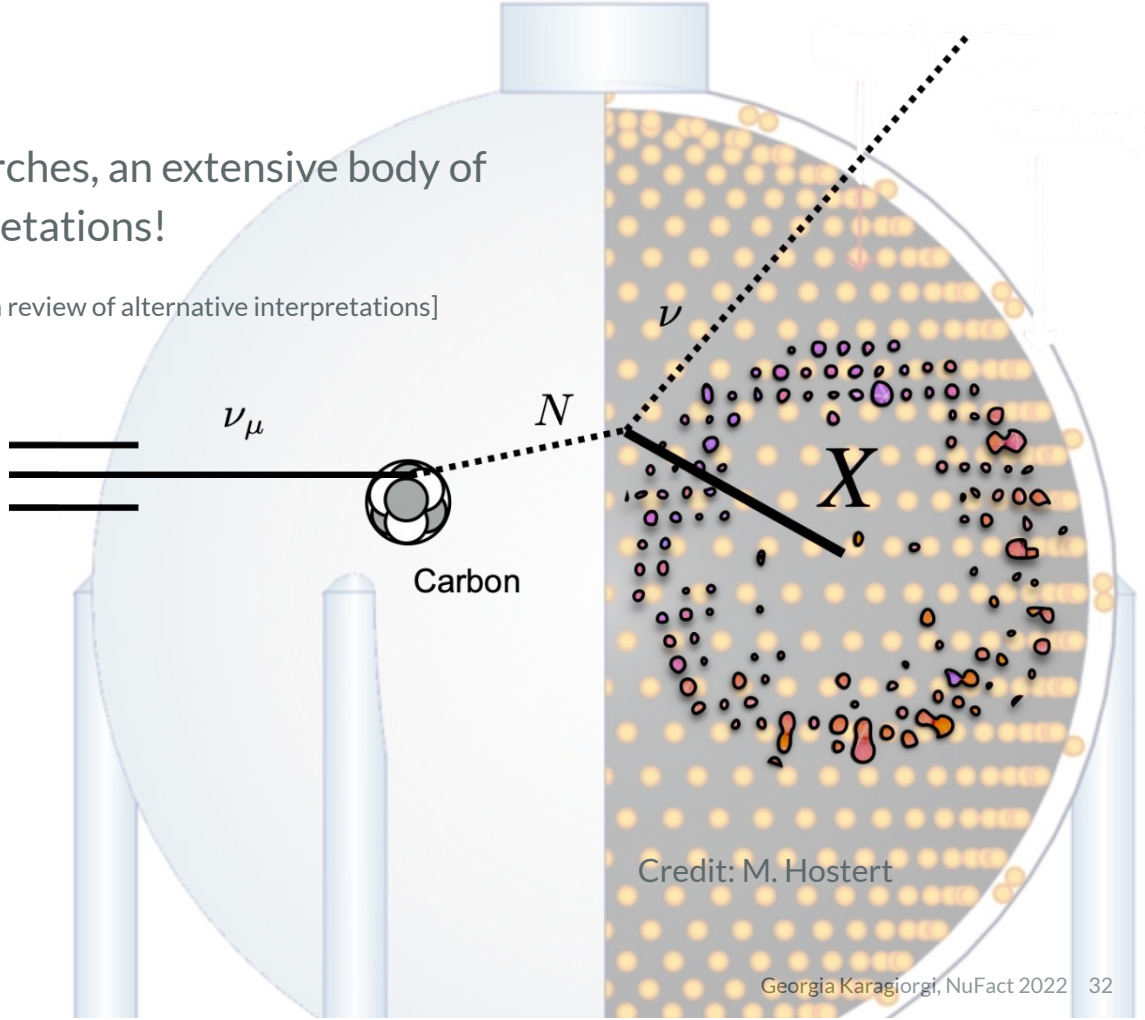
Where next?

Commensurate with experimental searches, an extensive body of theoretical work on alternative interpretations!

[See Snowmass 2022 talk by M. Hostert for a recent, thorough review of alternative interpretations]

Of particular interest, “Dark Sector” physics models, e.g. neutrino scattering to heavy neutrino through dark photon





Credit: M. Hostert

Promising upcoming probes:

Disclaimer: Views are my own

Promising upcoming probes: 1. CEvNS

Disclaimer: Views are my own

Coherent Elastic ν-Nucleus Scattering (CEvNS):
A new, promising probe of all-active to sterile flavor oscillations
Unique in that it makes use of a well-understood, SM neutral-current (NC) process

COHERENT at the Spallation Neutron Source plans to search for NC-based all-active-flavor disappearance using multiple detectors:

- 610 kg LAr calorimeter at 28 m
- 50 kg germanium PPC detector at 22 m
- 10-kg CsI scintillation detector at 19.3 m

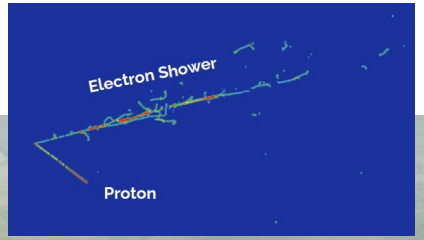
Coherent CAPTAIN-Mills at the Los Alamos Neutron Science Center also explores **CEvNS** to probe the LSND result by both measuring ν_μ's from π+ **decay-at-rest** as well as using π^0 **decay in flight** to probe complementary dark sector physics [PhysRevD.106.012001]

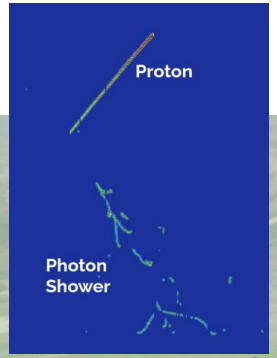
See talks by Samuel Hedges, Matteo Cadeddu

Promising upcoming probes: 2. Multi-channel searches

Disclaimer: Views are my own

Highly-capable Liquid Argon Time Projection Chamber (LArTPC) technology revolutionizing νBSM searches





Short-Baseline Neutrino Program at Fermilab is capable of multi-channel searches with enhanced sensitivity to light sterile neutrino oscillations and unique opportunities for dark sector searches

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

Promising upcoming probes: 2. Multi-channel searches

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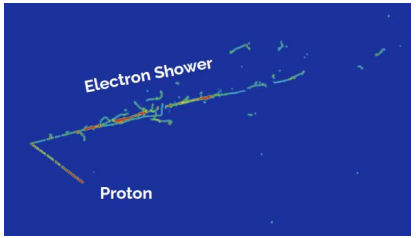
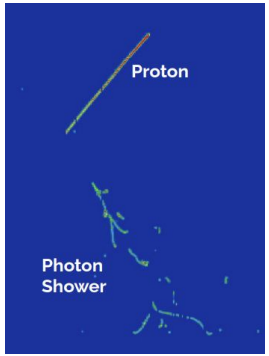
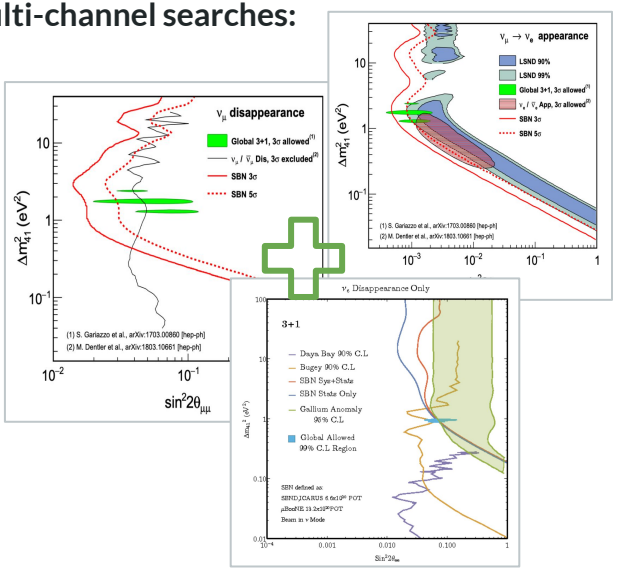
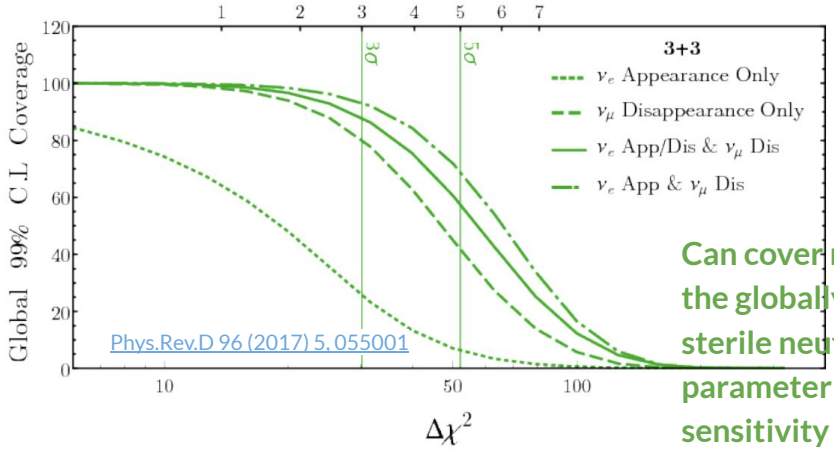




Sensitivity to 3+N oscillations through multi-channel searches:



Can inclusively and exhaustively probe 3+N oscillations:



Phys.Rev.D 96 (2017) 5, 055001

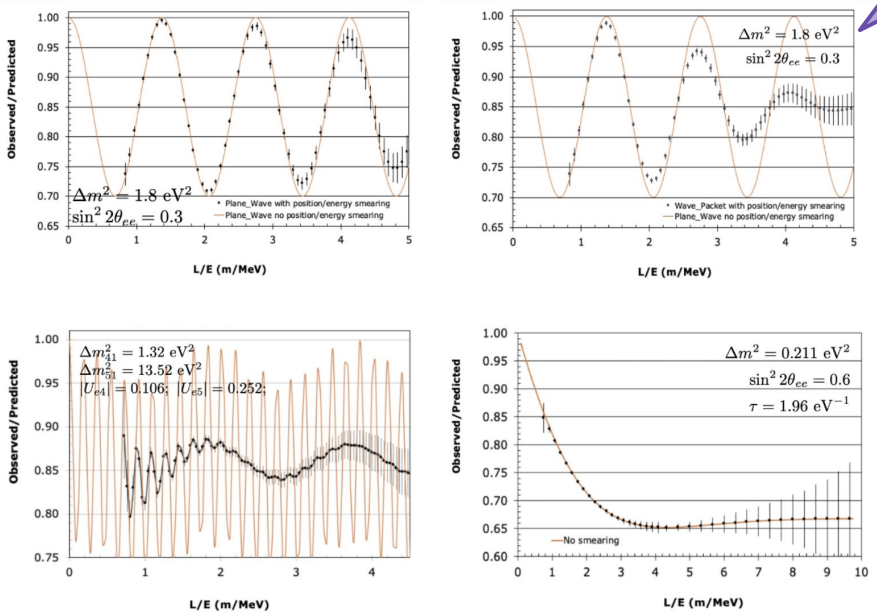
Can cover more than 50% of the globally-allowed 3+3 sterile neutrino oscillation parameter space with 5σ sensitivity

Promising upcoming probes: 3. Isotope DAR source

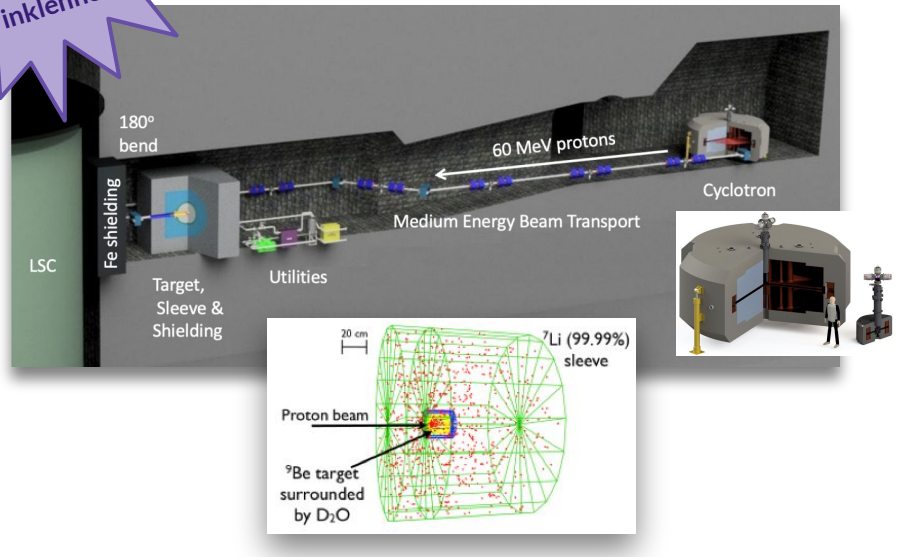
Disclaimer: Views are my own

IsoDAR @ Yemilab, Korea

IsoDAR Collab, arXiv:2111.09480



See talk by Daniel Winklehner

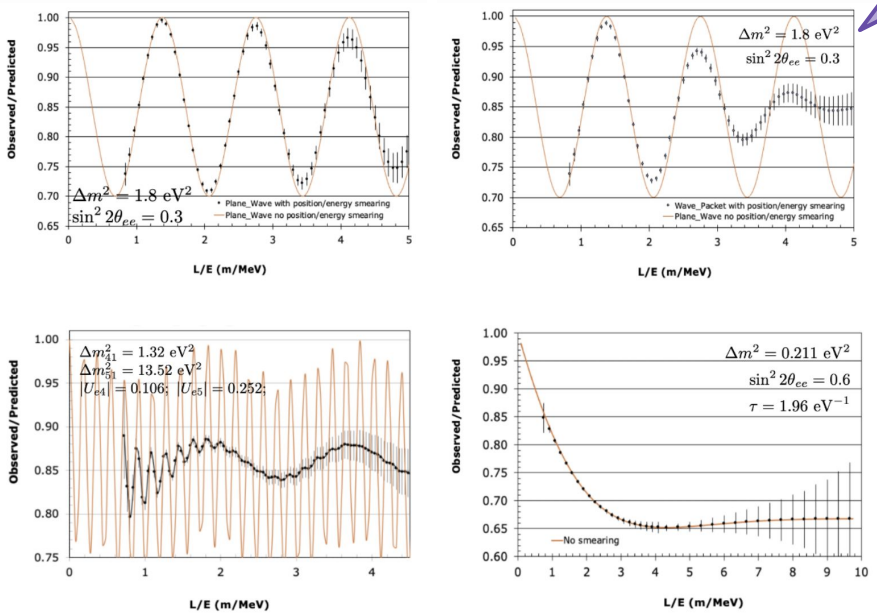


An alternative, well-understood source of **electron antineutrinos**, to probe reactor and radioactive source anomalies

Promising upcoming probes: 3. Isotope DAR source

IsoDAR @ Yemilab, Korea

IsoDAR Collab, arXiv:2111.09480



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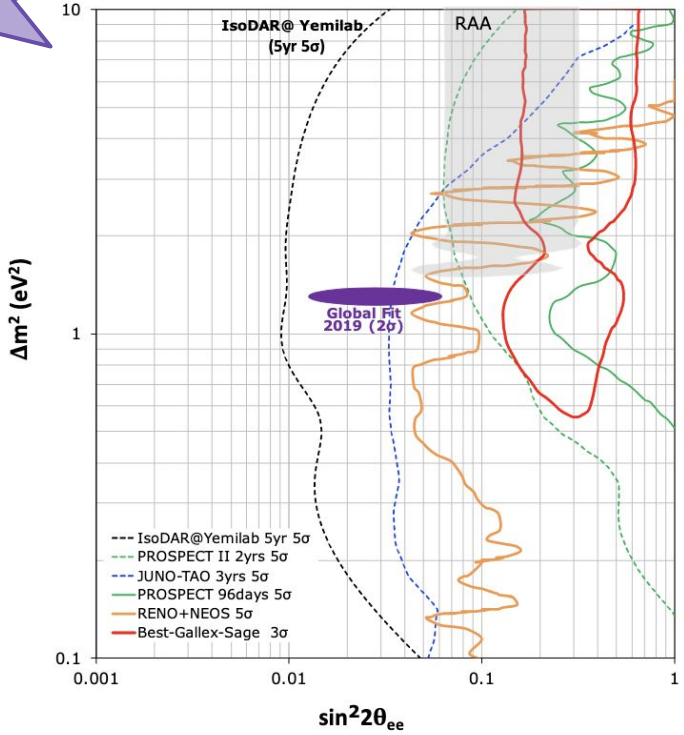

The future is bright!

The next few to five years will be exciting, with new results anticipated from MicroBooNE, SBN, JSNS2, and new probes:

> Light sterile neutrino oscillations will be put through stressful tests, but not clear if they will prevail as the underlying source of short-baseline anomalies.

At the same time, a plethora of new BSM interpretations will be the focus of upcoming and proposed highly-capable experimental facilities!

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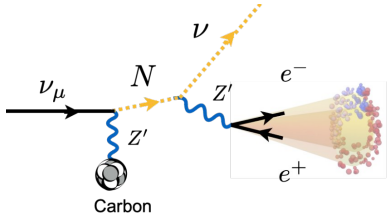

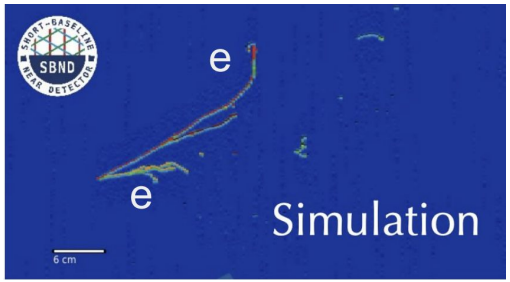

… or dark!?

Thank you!

ALFRED P. SLOAN FOUNDATION