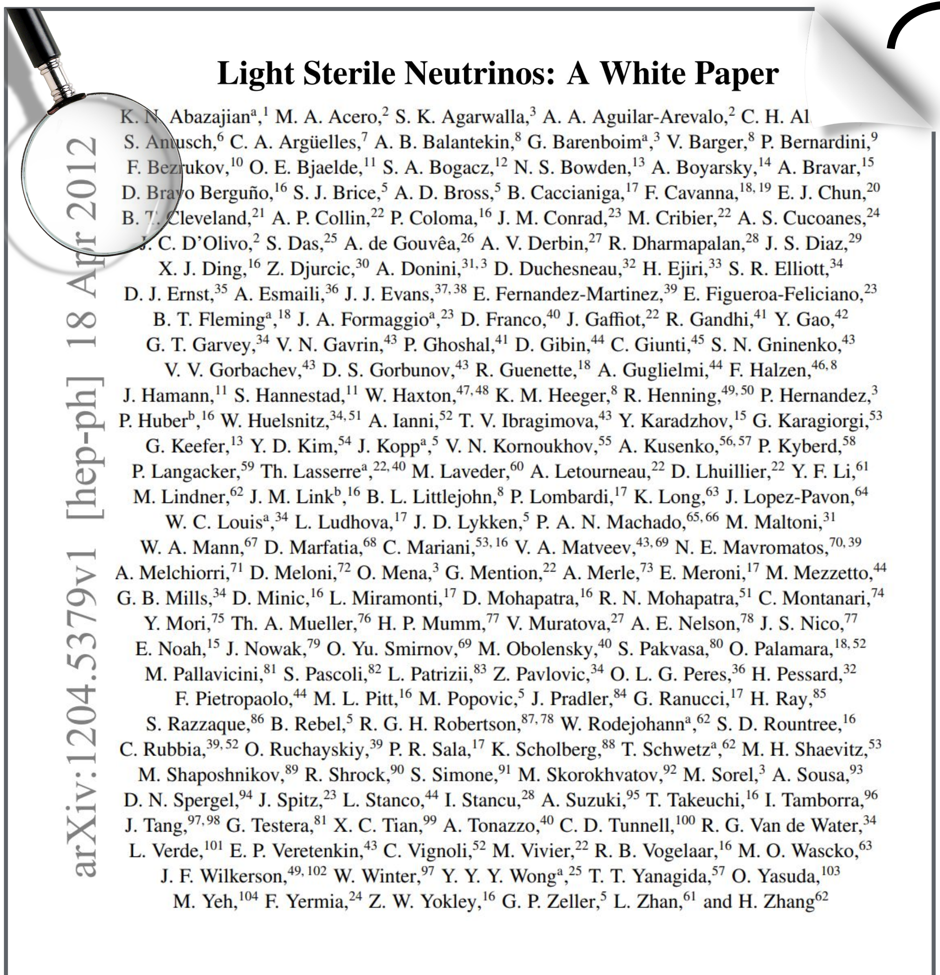

arXiv:1204.5379v1 [hep-ph] 18 Apr 2012

Light Sterile Neutrinos: A White Paper

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S. Antusch,[6] C. A. Argüelles,[7] A. B. Balantekin,[8] G. Barenboim[a],[3] V. Barger,[8] P. Bernardini,[9]
F. Bezrukov,[10] O. E. Bjaelde,[11] S. A. Bogacz,[12] N. S. Bowden,[13] A. Boyarsky,[14] A. Bravar,[15]
D. Bravo Berguño,[16] S. J. Brice,[5] A. D. Bross,[5] B. Caccianiga,[17] F. Cavanna,[18,19] E. J. Chun,[20]
B. T. Cleveland,[21] A. P. Collin,[22] P. Coloma,[16] J. M. Conrad,[23] M. Cribier,[22] A. S. Cucoanes,[24]
J. C. D'Olivo,[2] S. Das,[25] A. de Gouvêa,[26] A. V. Derbin,[27] R. Dharmapalan,[28] J. S. Diaz,[29]
X. J. Ding,[16] Z. Djurcic,[30] A. Donini,[31,3] D. Duchesneau,[32] H. Ejiri,[33] S. R. Elliott,[34]
D. J. Ernst,[35] A. Esmaili,[36] J. J. Evans,[37,38] E. Fernandez-Martinez,[39] E. Figueroa-Feliciano,[23]
B. T. Fleming[a],[18] J. A. Formaggio[a],[23] D. Franco,[40] J. Gaffiot,[22] R. Gandhi,[41] Y. Gao,[42]
G. T. Garvey,[34] V. N. Gavrin,[43] P. Ghoshal,[41] D. Gibin,[44] C. Giunti,[45] S. N. Gninenko,[43]
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J. Hamann,[11] S. Hannestad,[11] W. Haxton,[47,48] K. M. Heeger,[8] R. Henning,[49,50] P. Hernandez,[3]
P. Huber[b],[16] W. Huelsnitz,[34,51] A. Ianni,[52] T. V. Ibragimova,[43] Y. Karadzhov,[15] G. Karagiorgi,[53]
G. Keefer,[13] Y. D. Kim,[54] J. Kopp[a],[5] V. N. Kornoukhov,[55] A. Kusenko,[56,57] P. Kyberd,[58]
P. Langacker,[59] Th. Lasserre[a],[22,40] M. Laveder,[60] A. Letourneau,[22] D. Lhuillier,[22] Y. F. Li,[61]
M. Lindner,[62] J. M. Link[b],[16] B. L. Littlejohn,[8] P. Lombardi,[17] K. Long,[63] J. Lopez-Pavon,[64]
W. C. Louis[a],[34] L. Ludhova,[17] J. D. Lykken,[5] P. A. N. Machado,[65,66] M. Maltoni,[31]
W. A. Mann,[67] D. Marfatia,[68] C. Mariani,[53,16] V. A. Matveev,[43,69] N. E. Mavromatos,[70,39]
A. Melchiorri,[71] D. Meloni,[72] O. Mena,[3] G. Mention,[22] A. Merle,[73] E. Meroni,[17] M. Mezzetto,[44]
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S. Razzaque,[86] B. Rebel,[5] R. G. H. Robertson,[87,78] W. Rodejohann[a],[62] S. D. Rountree,[16]
C. Rubbia,[39,52] O. Ruchayskiy,[39] P. R. Sala,[17] K. Scholberg,[88] T. Schwetz[a],[62] M. H. Shaevitz,[53]
M. Shaposhnikov,[89] R. Shrock,[90] S. Simone,[91] M. Skorokhvatov,[92] M. Sorel,[3] A. Sousa,[93]
D. N. Spergel,[94] J. Spitz,[23] L. Stanco,[44] I. Stancu,[28] A. Suzuki,[95] T. Takeuchi,[16] I. Tamborra,[96]
J. Tang,[97,98] G. Testera,[81] X. C. Tian,[99] A. Tonazzo,[40] C. D. Tunnell,[100] R. G. Van de Water,[34]
L. Verde,[101] E. P. Veretenkin,[43] C. Vignoli,[52] M. Vivier,[22] R. B. Vogelaar,[16] M. O. Wascko,[63]
J. F. Wilkerson,[49,102] W. Winter,[97] Y. Y. Y. Wong[a],[25] T. T. Yanagida,[57] O. Yasuda,[103]
M. Yeh,[104] F. Yermia,[24] Z. W. Yokley,[16] G. P. Zeller,[5] L. Zhan,[61] and H. Zhang[62]

What have we learned since 2012?

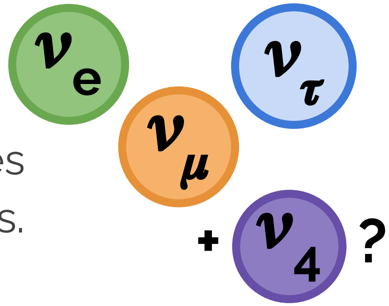
DIF & DAR neutrinos from Accelerator & Atmospheric sources over the past decade

Mark Ross-Lonergan

NF02: Understanding Experimental Neutrino Anomaly @ Snowmass
July 21st 2022

Los Alamos NATIONAL LABORATORY

Introduction



- For a lot of the past decade, focus of results surrounding the anomalies remained on the more **"traditional" 3+1 sterile neutrino** interpretations.
  - While this is definitely **shifting in recent years** to include **more exotic scenarios**, the majority of results I'll discuss today were still focused this way
  - Despite its shortcoming in stitching together global data, "3+1" sterile neutrino analyses (and 2-ν approximations) provides an excellent benchmark to paint a picture of the global landscape
  - 10 years in 15 mins is tough, so I very much apologize in advance if I skip over some experiments. Focus also on experimental publications, and not independent re-analyses

Decay-at-Rest

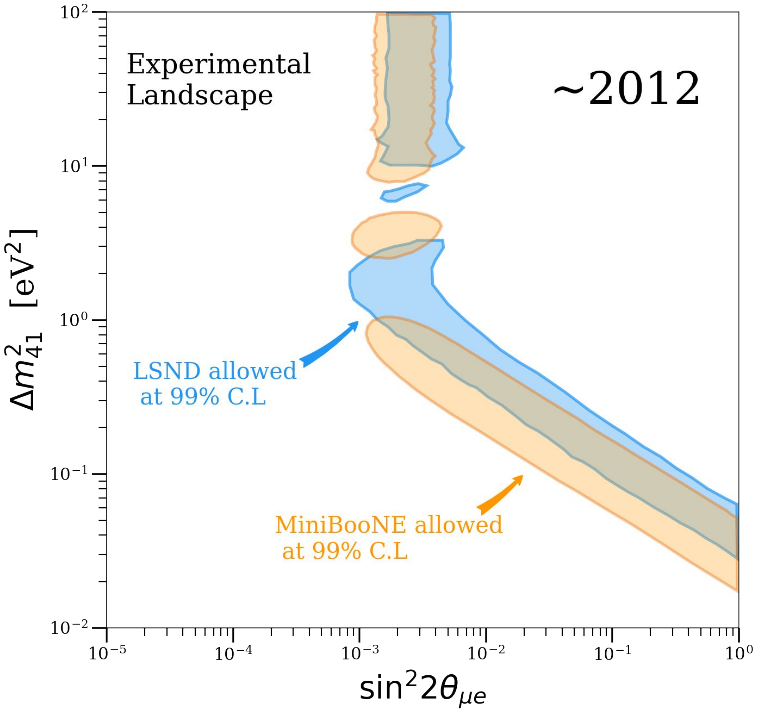
LSND

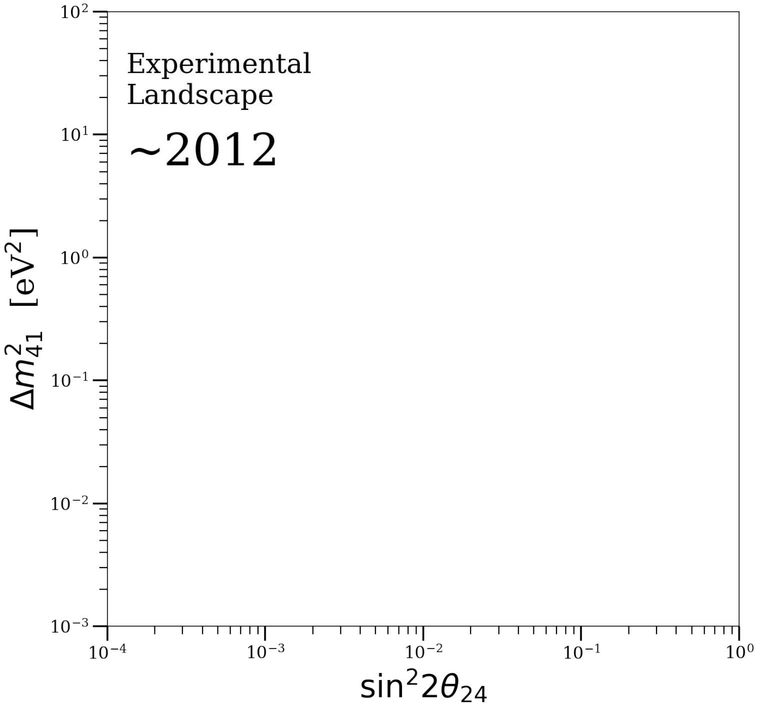
Decay-in-Flight
(Atmospheric)

Decay-in-Flight
(Accelerator)

MiniBooNE

The experimental anomalies in 2012





The experimental landscape in 2012

Decay-at-Rest

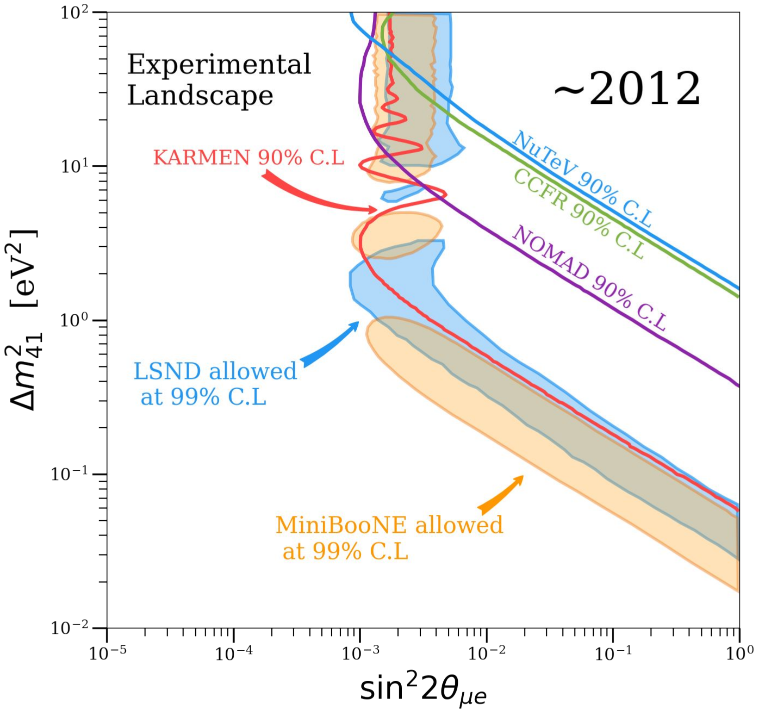
- LSND
- KARMEN

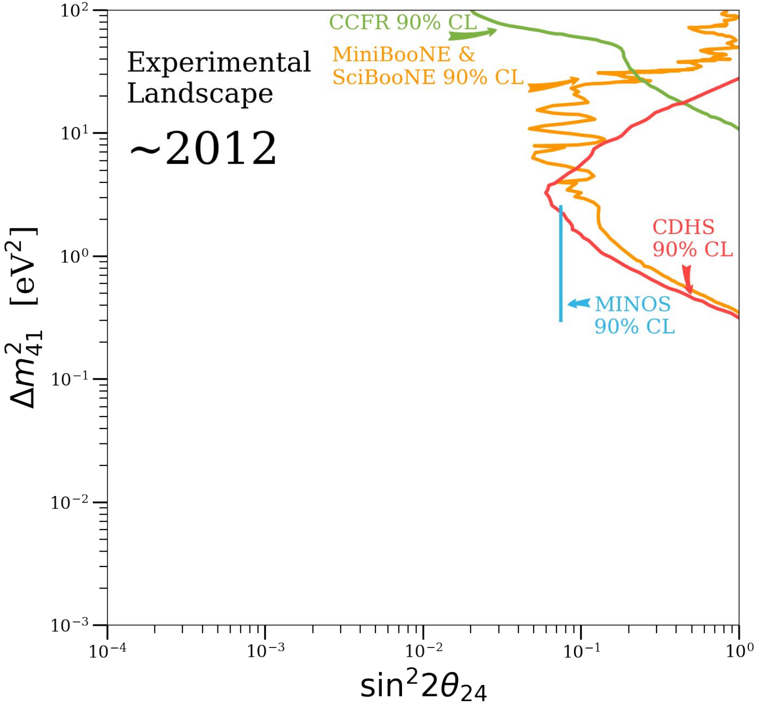
Decay-in-Flight
(Atmospheric)

- Super-Kamiokande

Decay-in-Flight
(Accelerator)

- MiniBooNE
- CDHS
- NOMAD
- CCFR
- MINOS





Caveat: In the interest of time, this is not a 100% comprehensive list, Apologies!

Decay-at-Rest

LSND
KARMEN

No new DAR results yet

Decay-in-Flight (Atmospheric)

Super-Kamiokande
IceCube/DeepCore
ANTARES

Big increase in atmospheric results

What's new in 2022?

Decay-in-Flight (Accelerator)

MiniBooNE
CDHS
NOMAD
CCFR
OPERA
MINOS/MINOS+
NOvA
T2K
uBooNE

A huge increase in both long and short baseline results

IceCube/DeepCore

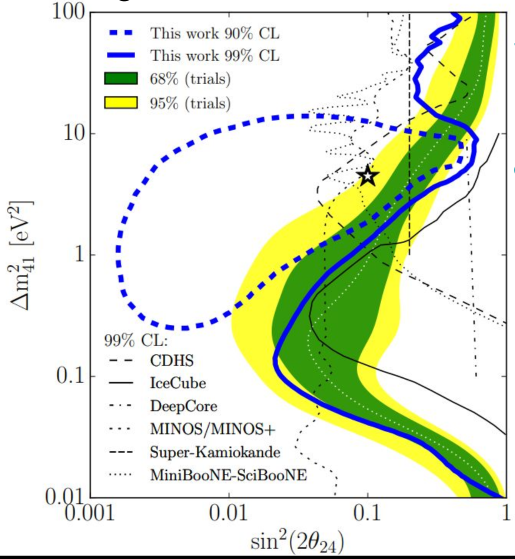
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Detects atmospheric neutrinos whose energies span over **5 orders of magnitude**, baselines of **20-12,750 km**, with over a **Gigaton** of polar ice.

IceCube proves very sensitive to eV scale sterile neutrinos due to the **matter enhanced resonant disappearance** when crossing the Earth's core, as well as searching for fast oscillations that have average out at lower energies

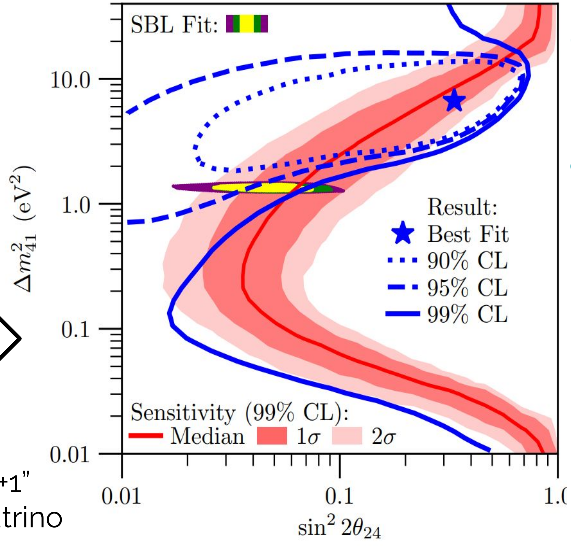
A closed contour at the 90% level, but results overall consistent with standard 3ν paradigm

3+1 Sterile Neutrino Model



https://arxiv.org/abs/2005.12942

Unstable 3+1 Sterile Neutrino Model



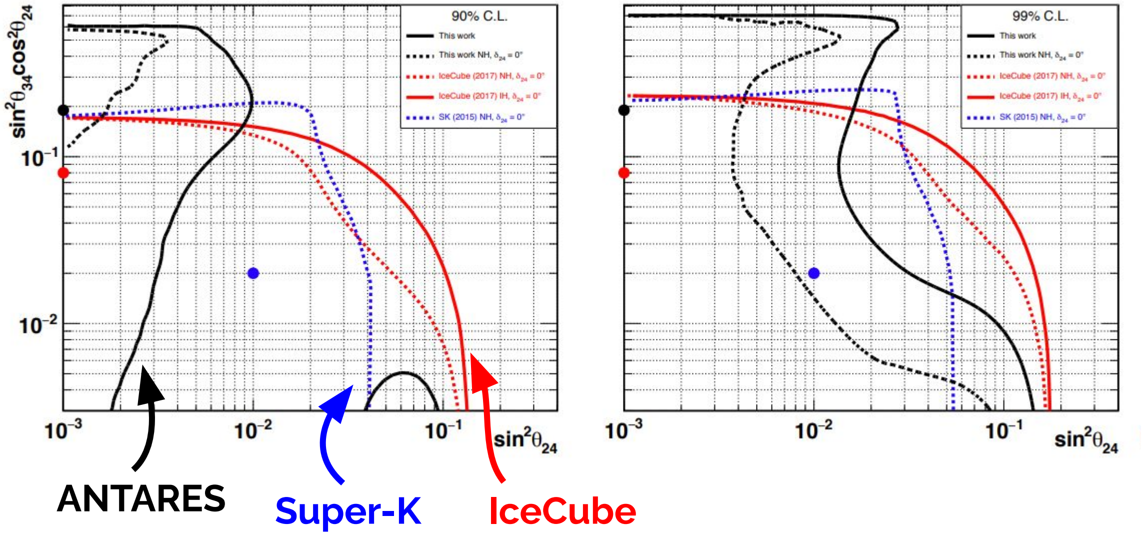
https://arxiv.org/abs/2204.00612

Beyond "3+1" sterile neutrino

ANTARES & Updated Super-Kamiokande

In addition to ice, atmospheric neutrinos are well probed by water Cherenkov detectors, both ultra-pure water in **Super-Kamiokande** and salt-water in the **ANTARES** neutrino telescope.

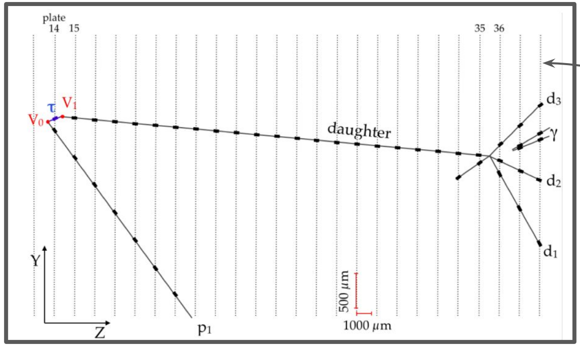
These are insensitive to mass squared differences, and so constraints placed on the $|U_{\tau 4}|^2$ vs. $|U_{\mu 4}|^2$ parameter space



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

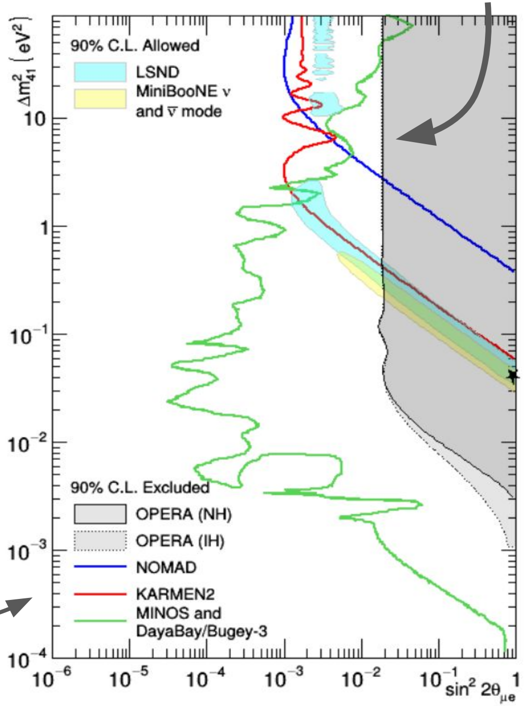
Adding tau's to the mix with OPERA

In this past decade **OPERA** experiment has conclusively observed the **appearance of ν_τ** in the primarily ν_μ neutrino CNGS beam in 2015, using nuclear emulsion cloud chamber detectors **(sub micro-meter resolution)** [1507.01417]



Event display showing tau appearance candidate

OPERA 90%



In 2019, they released their final 3+1 sterile results utilizing various channels [1904.05686]

- CC ν_μ Disappearance
- **CC ν_e and CC ν_τ appearance used jointly**
- Neutral current

Decay-at-Rest

LSND
KARMEN

Decay-in-Flight
(Atmospheric)

Super-Kamiokande
IceCube/DeepCore
ANTARES

Decay-in-Flight
(Accelerator)

MiniBooNE
CDHS
NOMAD
CCFR
OPERA
MINOS/MINOS+
NOvA
T2K
uBooNE

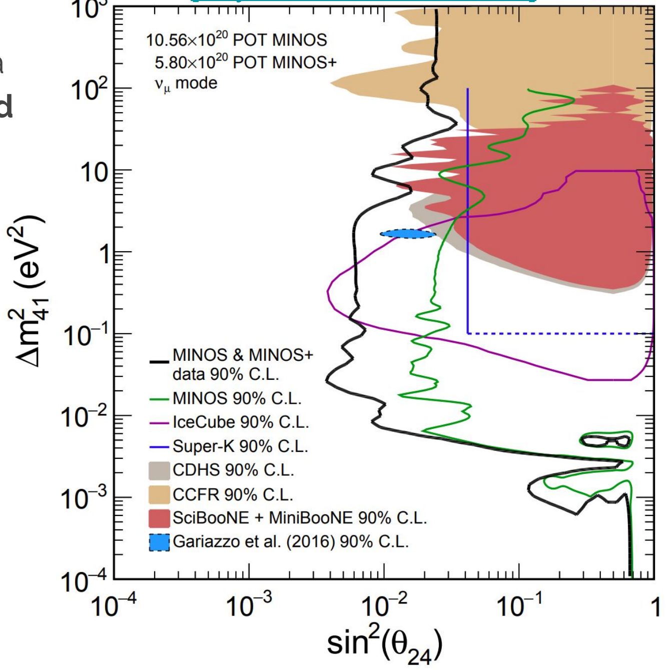
Addition of MINOS+

While first **MINOS** searches for sterile neutrinos were pre-2012, the last decade saw both a large re-analysis and the addition of the higher energy **MINOS+** dataset

- Analysis combined **both charged muon and neutral current selections** and saw no evidence for 3+1 sterile neutrinos

- Stringent constraints on ν_μ disappearance across a wide range of Δm^2 was achieved by this **combined short and long baseline**, **two detector fit.**

[PhysRevLett.122.091803]



Decay-at-Rest

LSND
KARMEN

Decay-in-Flight
(Atmospheric)

Super-Kamiokande
IceCube/DeepCore
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Decay-in-Flight
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NOvA
T2K
uBooNE

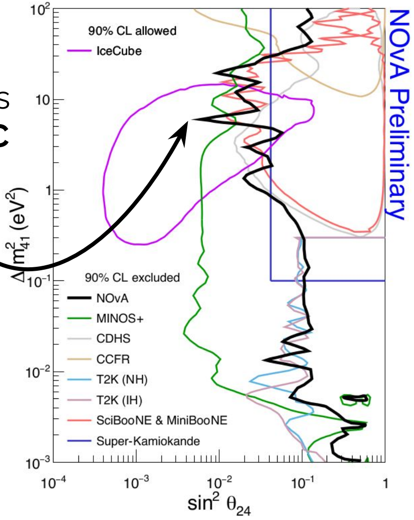
Off-axis & long-baseline experiments

- 300 ton near detector @ 1km
- 14,000 ton far detector @ 810km
- 0.8 Degrees off-axis

Two previous sterile neutrino searches using both neutrino[Ref] and anti-neutrino mode [Ref] **neutral current** searches show no evidence for sterile neutrinos

This year, preliminary results of a **combined NC and CC** analysis were shown.

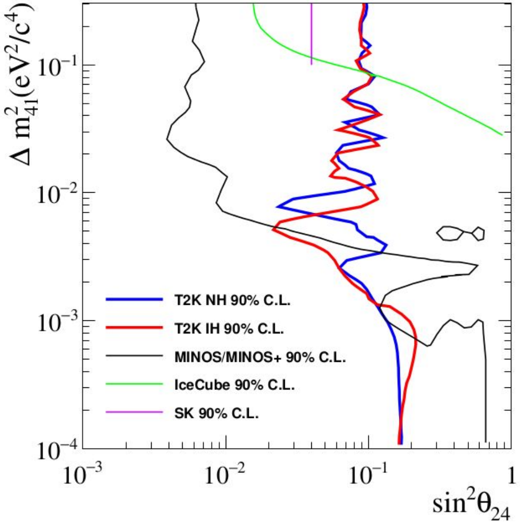
No evidence for sterile neutrinos observed.



- Multi-detector complex @ 280m
- Super-K as far detector @ 295km
- 2.5 Degrees off-axis

Searches for sterile neutrinos have been performed with both Near and Far detectors (Super-K) separately over the past decade.

Far Detector fit

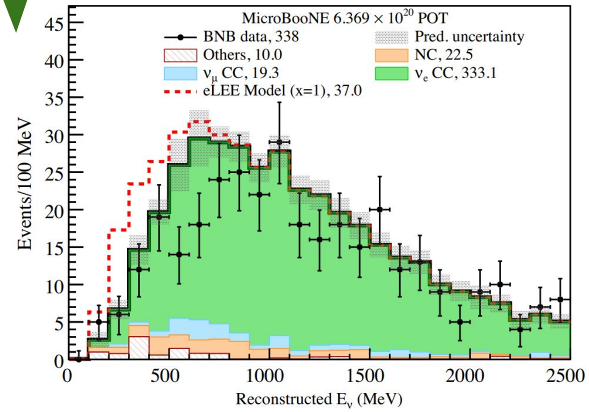


Probing Low-Energy Excess Anomaly

μBooNE

MicroBooNE is a Liquid Argon Time Projection Chamber (**LArTPC**) neutrino detector.
In the same Booster Neutrino Beam as MiniBooNE, ~50m upstream.

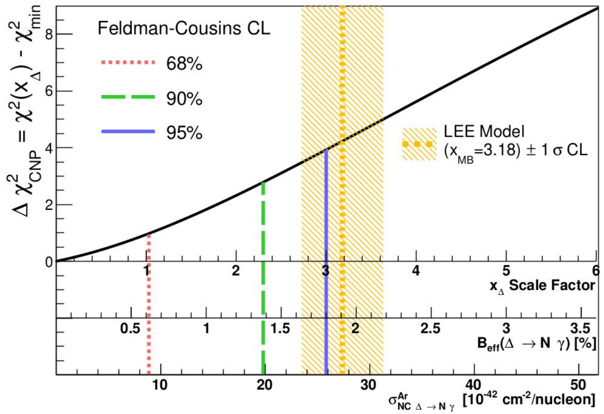
Its primary goal is to identify the source of the MiniBooNE low-energy excess, if it's truly **electron in origin**, or **mis-identified photons**



MicroBooNE observed **no excess of electrons** that could explain the MiniBooNE excess. Subsequent re-analysis of this data has placed **a direct bound on 3+1 $\nu_\mu \rightarrow \nu_e$ appearance** (see next slides..)

https://doi.org/10.1103/PhysRevLett.128.241801

First results have ruled out one of the leading photon interpretations, **NC Δ radiative decay**, at the **~95% CL**



https://doi.org/10.1103/PhysRevLett.128.111801

The experimental landscape in 2012

Decay-at-Rest

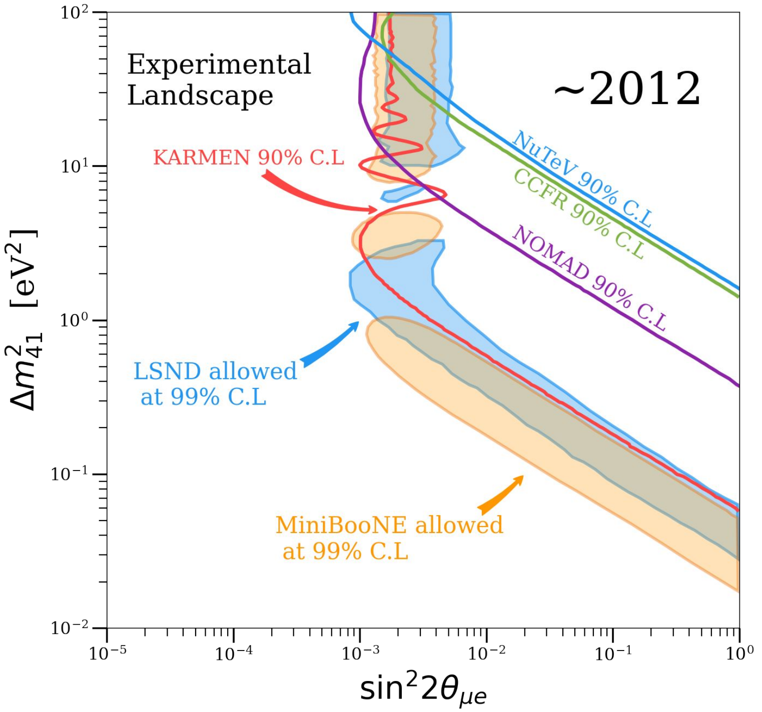
- LSND
- KARMEN

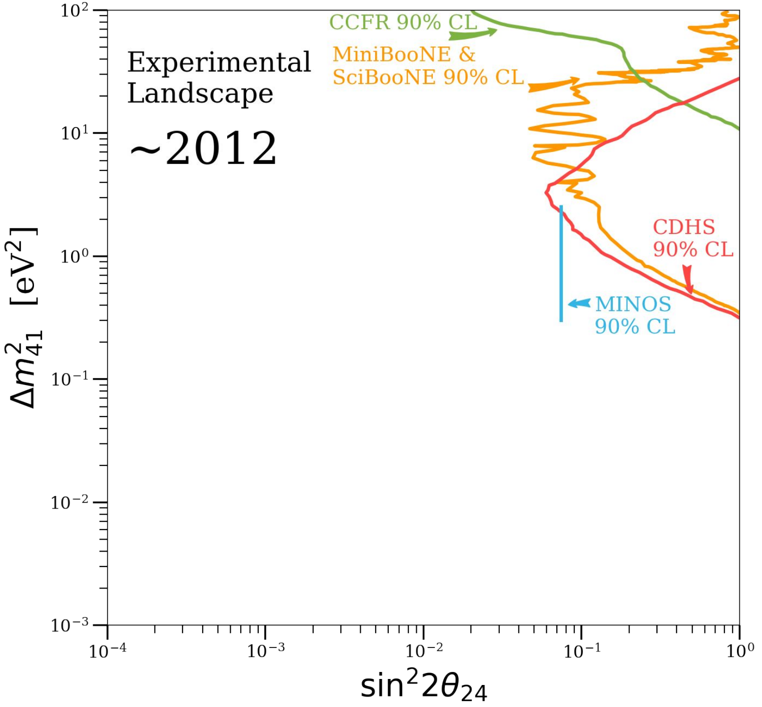
Decay-in-Flight
(Atmospheric)

- Super-Kamiokande

Decay-in-Flight
(Accelerator)

- MiniBooNE
- CDHS
- NOMAD
- CCFR
- MINOS





Reminder, where we stood a decade ago

The experimental landscape in ~~2012~~ 2022

Decay-at-Rest

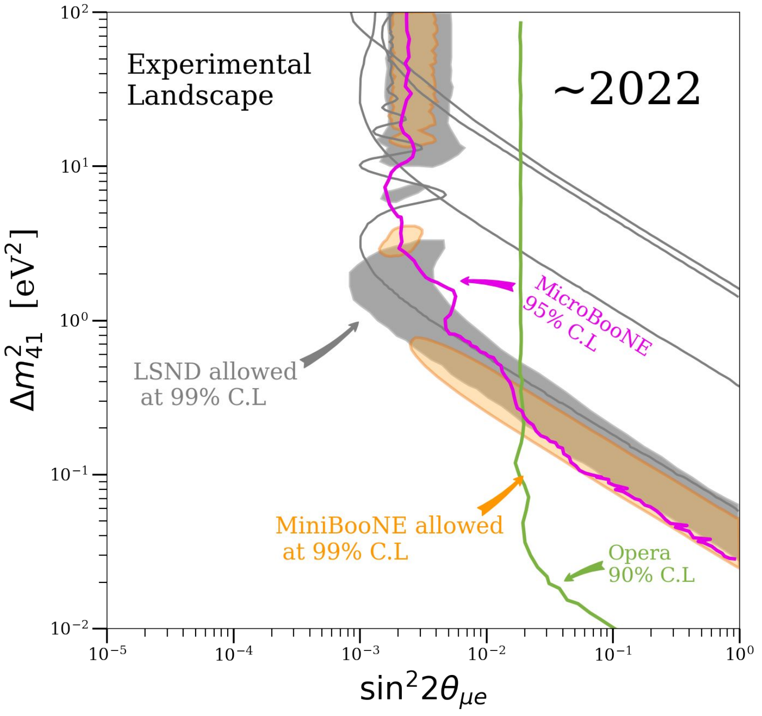
- LSND
- KARMEN

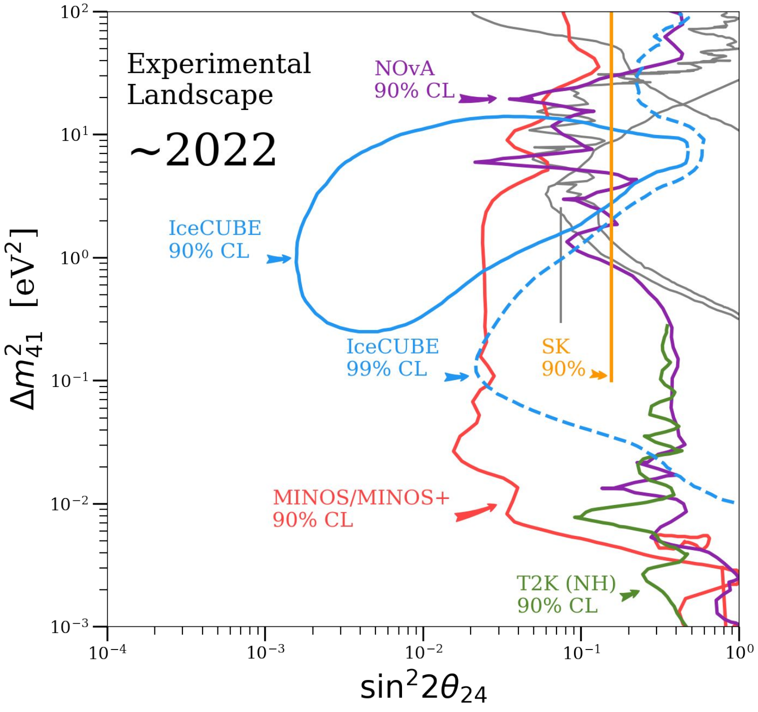
Decay-in-Flight (Atmospheric)

- Super-Kamiokande
- IceCube/DeepCore
- ANTARES

Decay-in-Flight (Accelerator)

- MiniBooNE
- CDHS
- NOMAD
- CCFR
- OPERA
- MINOS/MINOS+
- NOvA
- T2K
- uBooNE





Decay-at-Rest

LSND
KARMEN
JSNS² / JSNS²-II
Coherent
Coherent CAPTAIN-Mills
IsoDAR

Decay-in-Flight (Atmospheric)

Super-Kamiokande
IceCube/DeepCore
ANTARES

Decay-in-Flight (Accelerator)

MiniBooNE
CDHS
NOMAD
CCFR
OPERA
MINOS/MINOS+
NOvA
T2K
uBooNE
SBN (SBND & ICARUS)

On the cusp of a DAR revolution

2022 … and beyond

Upcoming full SBN short-baseline program

Direct probe of LSND

JSNS^2: J-PARC **S**terile **N**eutrino **S**earch at the **J**-PARC **S**pallation **N**eutron **S**ource

- Proposed in 2013, JSNS^2 provides a **clean** and **direct test of the LSND anomaly.**
- Uses the **same neutrino source** (μ^+ decay-at-rest) , **same target** , and **same detection principle** (Inverse-beta-decay) as LSND.
- Combination of low-duty factor beam, and Gadolinium doped liquid scintillator gives excellent signal/noise ratio

1st Phase: JSNS^2 [1310.1347]

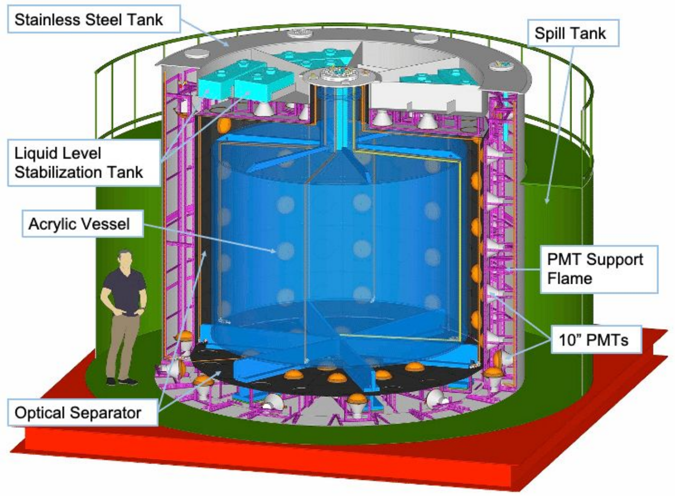
- Commissioned 2020, First physics data in 2021
- By May 2022, already has 23 % of the approved POT!

2nd Phase: JSNS^2-II [2012.10807]

Upgrade to two detectors, Has been granted stage-2 approval

- Near@24m (17 tons, 120 10'' PMTs
- Far @ 28m (32 tons, 220 10'' PMTs)

Greatly improves 3+1 sensitivity. **Data taking aim to start around the end of 2023**



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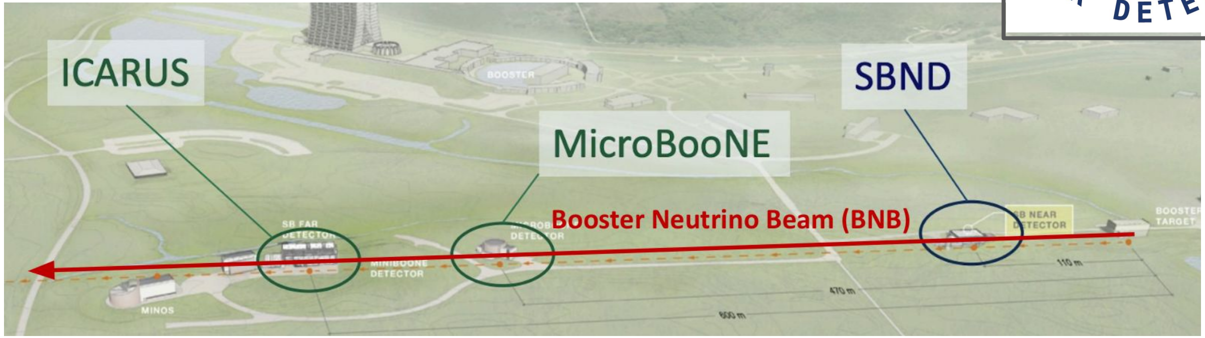
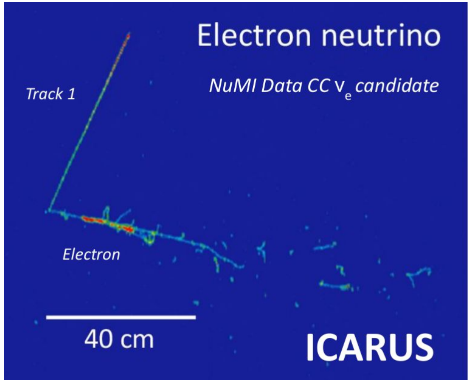
- OPERA
- MINOS/MINOS+
- NOvA
- T2K
- uBooNE
- **SBN (SBND & ICARUS)**

The Fermilab Short-Baseline Program

Three detectors in the same neutrino beam. All with the same nuclear target (Ar) and detector technology (LArTPC). Goal is **discovery** or **definitive exclusion** of ~1 eV scale sterile neutrino mass region





ICARUS is fully operational and is taking physics data from BNB and NuMI beams as of 9th June 2022!

SBND TPC installation is complete and aiming to fill by June 2023

Decay-at-Rest

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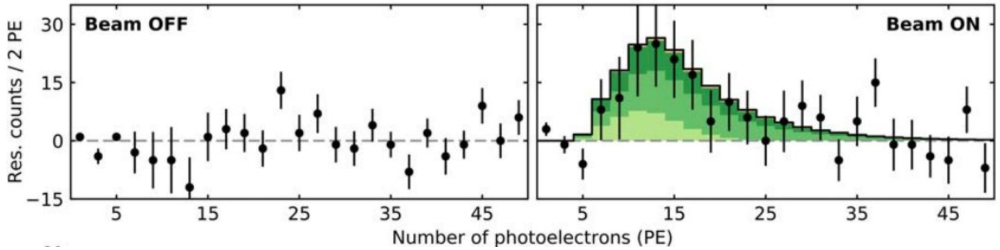
- OPERA
- MINOS/MINOS+
- NOvA
- T2K
- uBooNE
- SBN (SBND & ICARUS)

Emergence of a new probe, CEvNS

The discovery of **C**oherent **e**lastic **n**eutrino-**n**ucleus **s**cattering (**CEvNS**) in 2017 opened up an entire new field to probe these anomalies.

- After decades of searching, **COHERENT** using Spallation Neutron Source at Oak Ridge found **6.7σ evidence for CEvNS** with rate consistent with SM

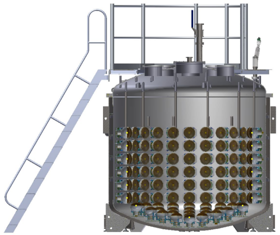
https://arxiv.org/pdf/1708.01294.pdf



By building multiple detectors at the SNS, COHERENT plans to search for sterile neutrinos through NC CEvNS disappearance

- 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 explores this space of **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: https://doi.org/10.1103/PhysRevD.106.012001



Decay-at-Rest

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SBN (SBND & ICARUS)

Towards Isotope Decay-at-Rest sources

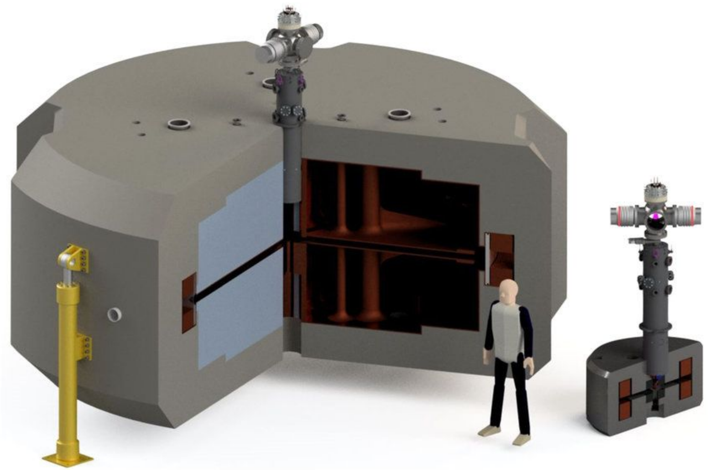
Goal is a extremely well known and very high intensity **isotope DAR source** by developing a compact isochronous cyclotron

- Cyclotron gives 600kW, continuous wave 60 MeV protons
- Proton beam strikes Be target → n → captures on ^{7}Li → ^{8}Li → ν_e
- **Prototype cyclotron under construction**

This is just the neutrino source, needs to be paired with a kTon scale detector.

- Preliminary approval has been granted to run **isoDAR@YemiLab**, where could be paired with the planned Liquid Scintillation Counter detector (2110.10635)

Compact Isochronous Cyclotron



Decay-at-Rest

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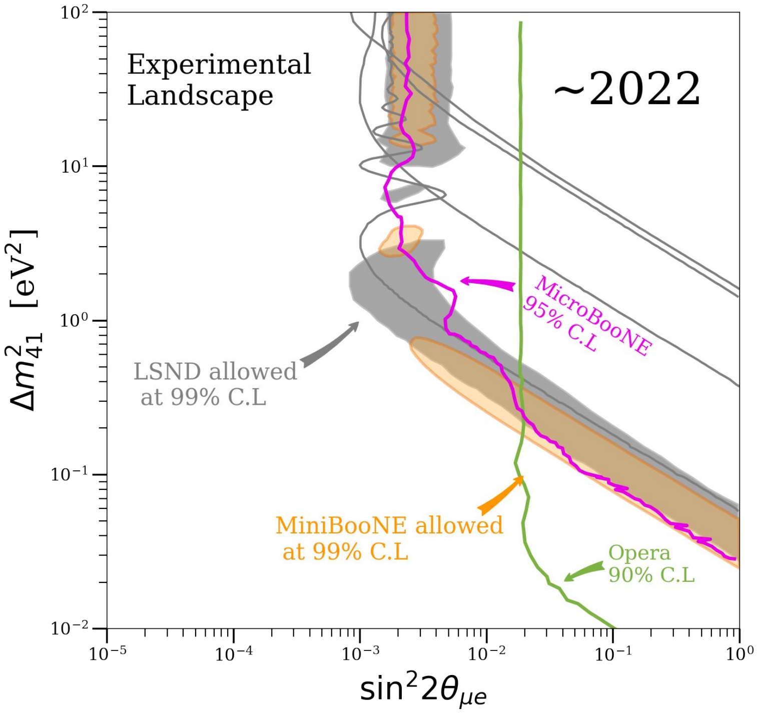
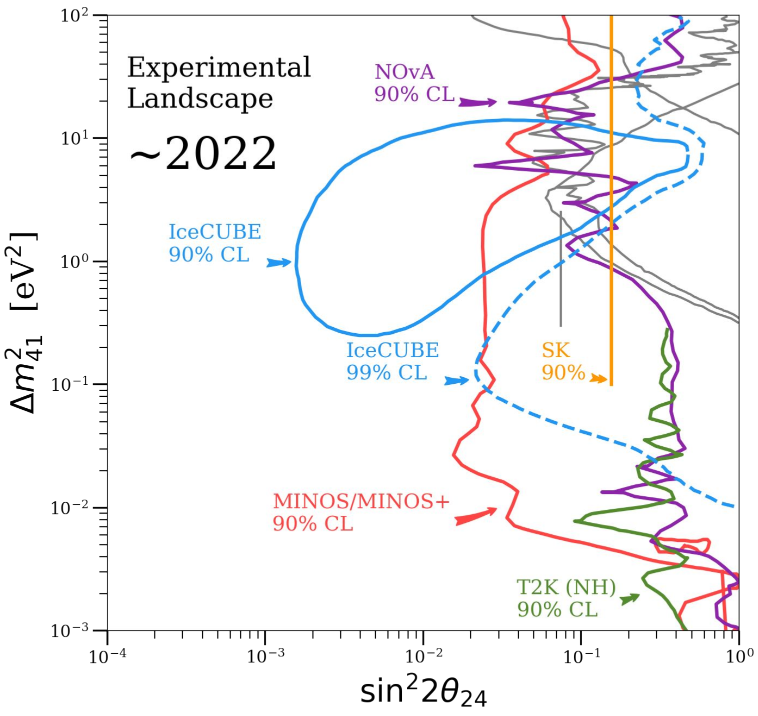
uBooNE

The experimental landscape in ~~2012~~ 2022





Reminder, where we stand as of today

The experimental landscape in ~~2012~~ ~~2022~~ 202x?

Decay-at-Rest

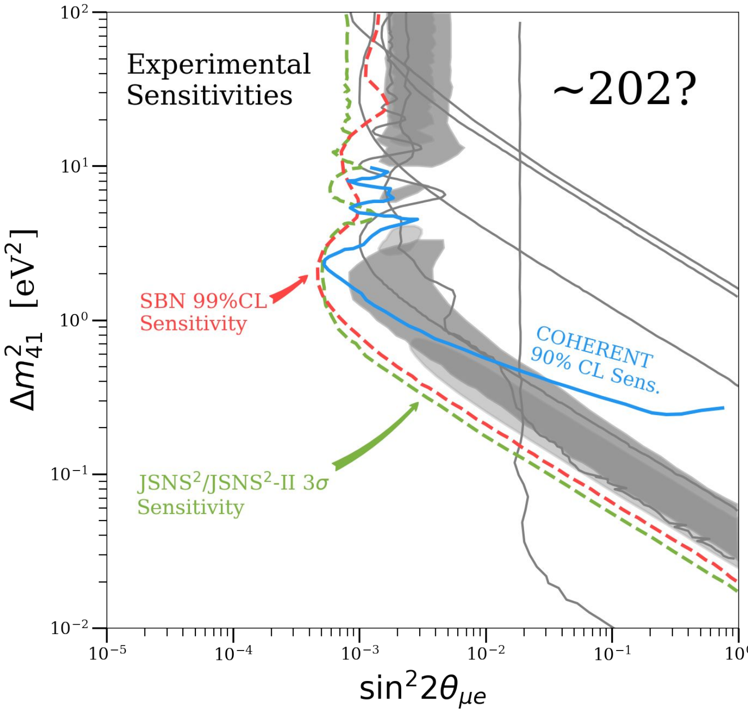
- LSND
- KARMEN
- **JSNS² / JSNS²-II**
- **Coherent**
- Coherent CAPTAIN-Mills
- IsoDAR

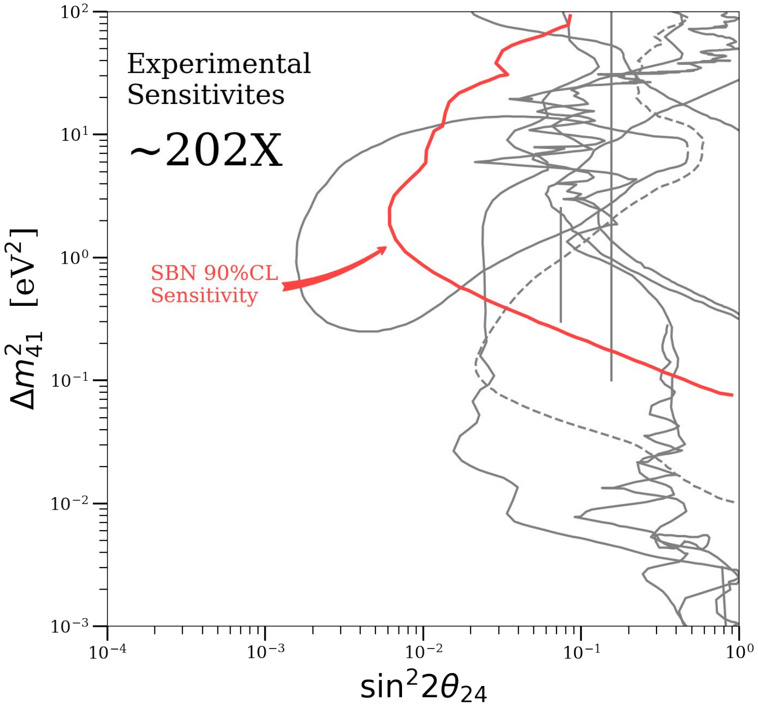
Decay-in-Flight (Atmospheric)

- Super-Kamiokande
- IceCube/DeepCore
- ANTARES

Decay-in-Flight (Accelerator)

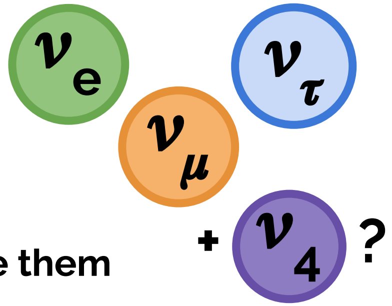
- MiniBooNE
- CDHS
- NOMAD
- CCFR
- OPERA
- MINOS/MINOS+
- NOvA
- T2K
- uBooNE
- **SBN (SBND & ICARUS)**



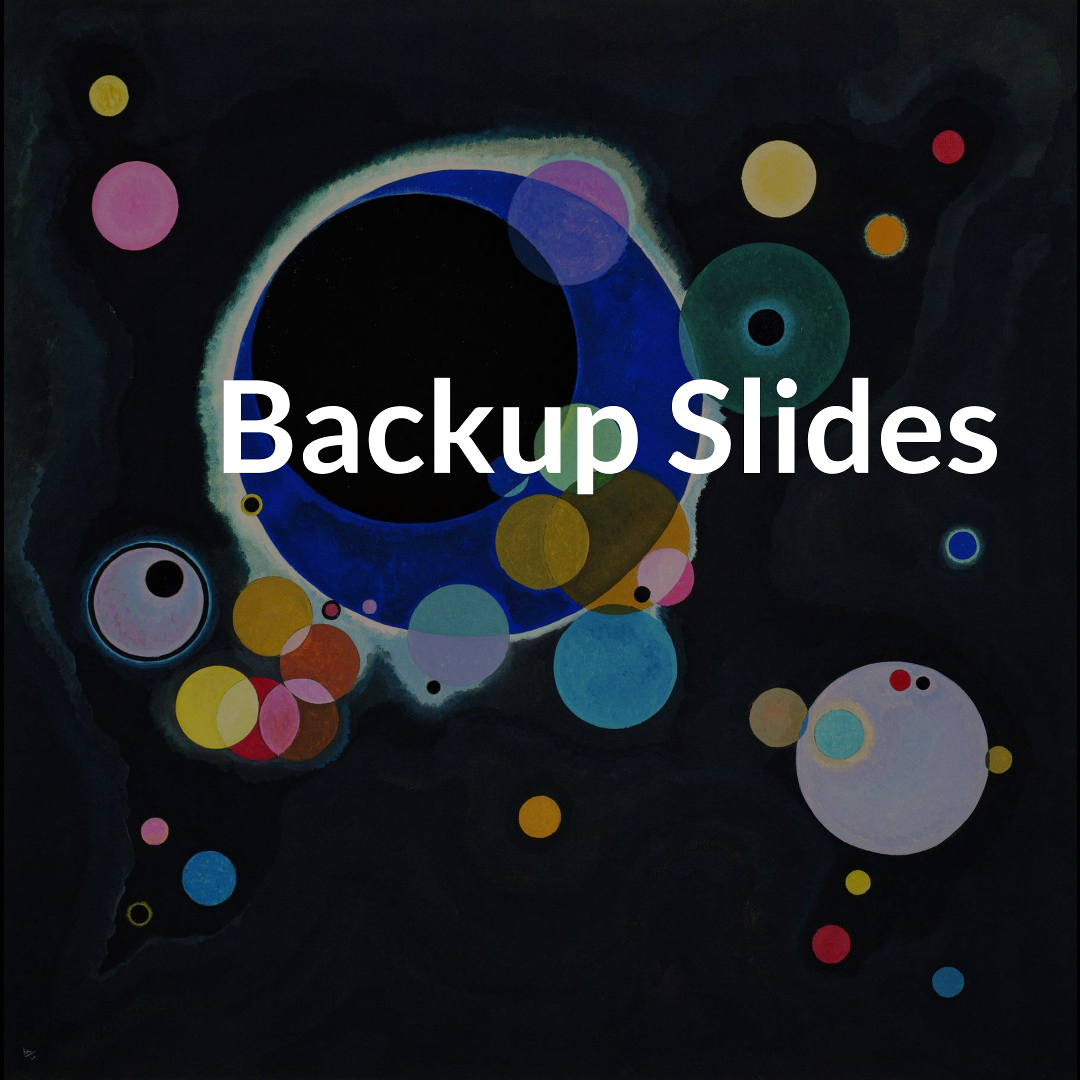


*Note, different CL's on these plots

Summary



- We have learned a lot in the past decade, but the "decay-at-rest" LSND and "decay-in-flight" MiniBooNE anomalies are as of yet unexplained
- We are on the cusp, however, of a plethora of results that will **directly probe them**
  - 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 **JSNS²/JSNS²-II experiment**.
  - A direct test of **MiniBooNE** has already begun with **MicroBooNE**, and will continue once the **full SBN program at Fermilab** comes online
- **Increased atmospheric sector** gives access to many orders of magnitude of neutrino energies & baselines with which to probe the SBL anomalies
- **Isotope decay-at-rest sources** are close to becoming a reality that delivers powerful probes of relevant sterile parameter space
- Entire new direction to search are opening up with the use of **CEvNS** to search for sterile neutrinos and dark-sector particles



Backup Slides

The experimental landscape in 2012

Decay-at-Rest

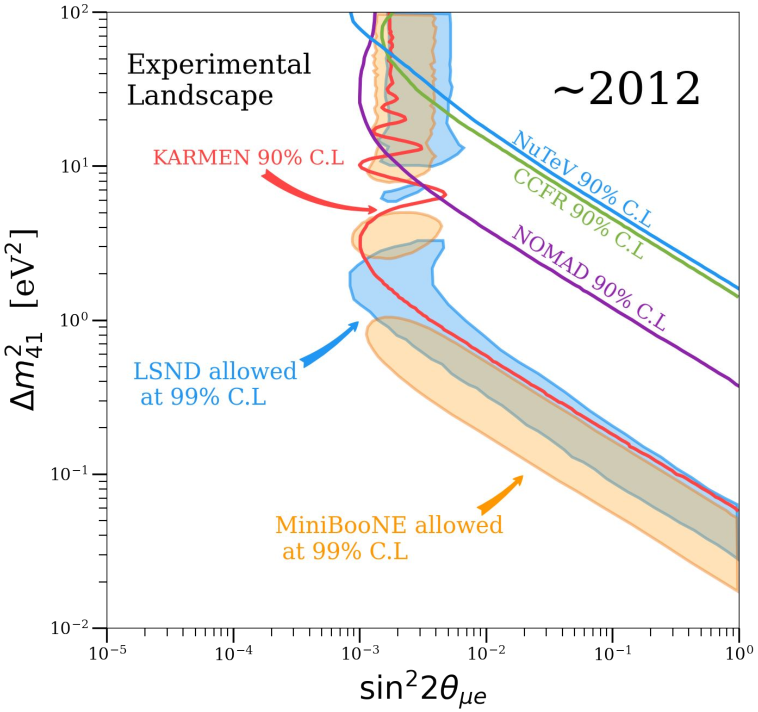
- LSND
- KARMEN

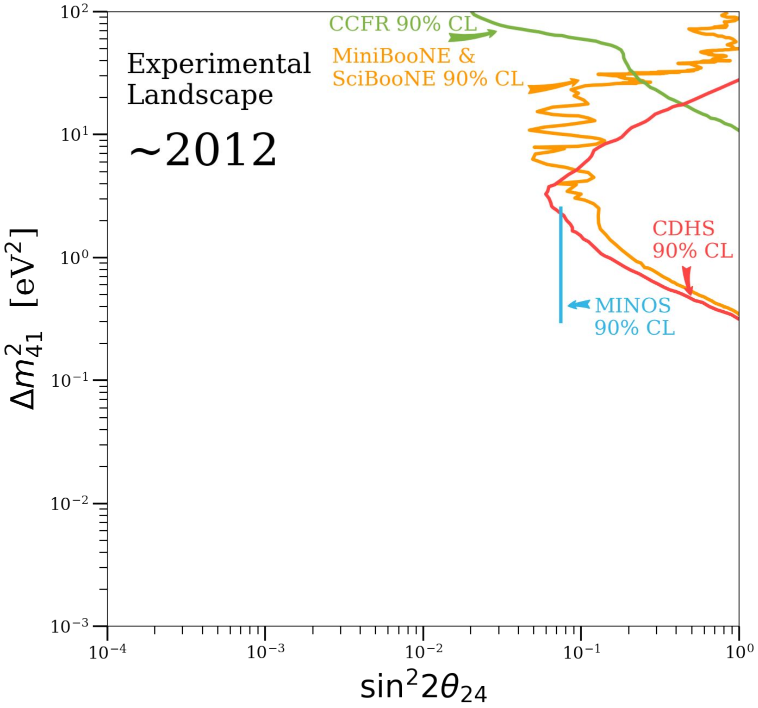
Decay-in-Flight (Atmospheric)

- Super-Kamiokande

Decay-in-Flight (Accelerator)

- MiniBooNE
- CDHS
- NOMAD
- CCFR
- MINOS





Decay-at-Rest

LSND
KARMEN

Decay-in-Flight
(Atmospheric)

Super-Kamiokande
IceCube/DeepCore
ANTARES

Decay-in-Flight
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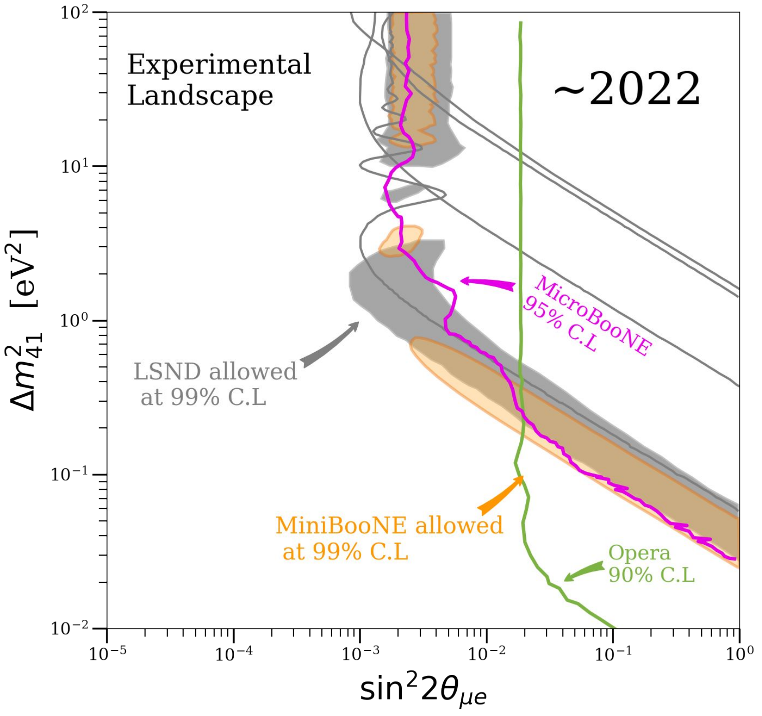
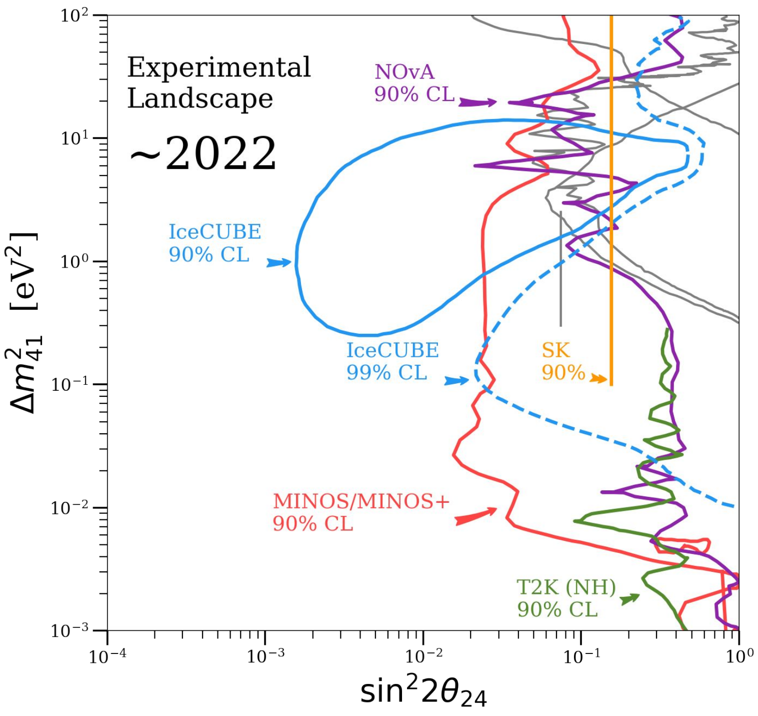
The experimental landscape in ~~2012~~ 2022





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