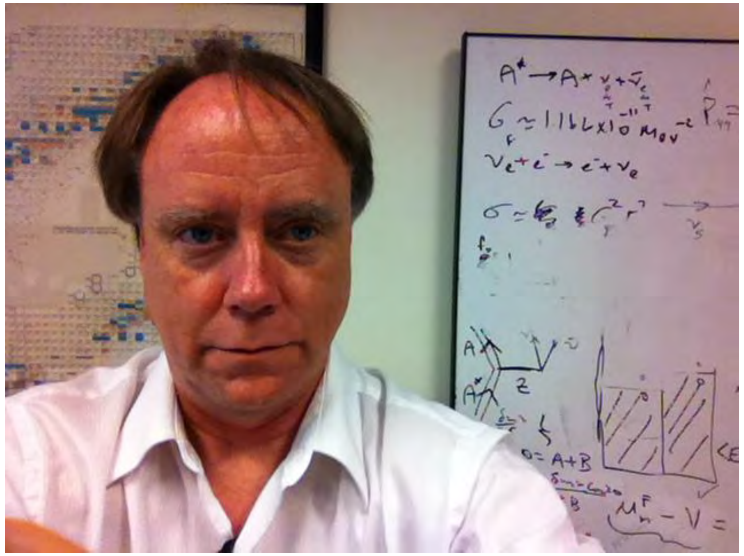
Thanks to George & Baha for Their Interest & Support in Sterile Neutrinos Over the Past 30 Years!

- I first met George at a Gordon Conference in 1995
- And I first met Baha shortly later at ORNL
- I blame them both for whetting my interest in sterile neutrinos!



LA-UR-25-20278

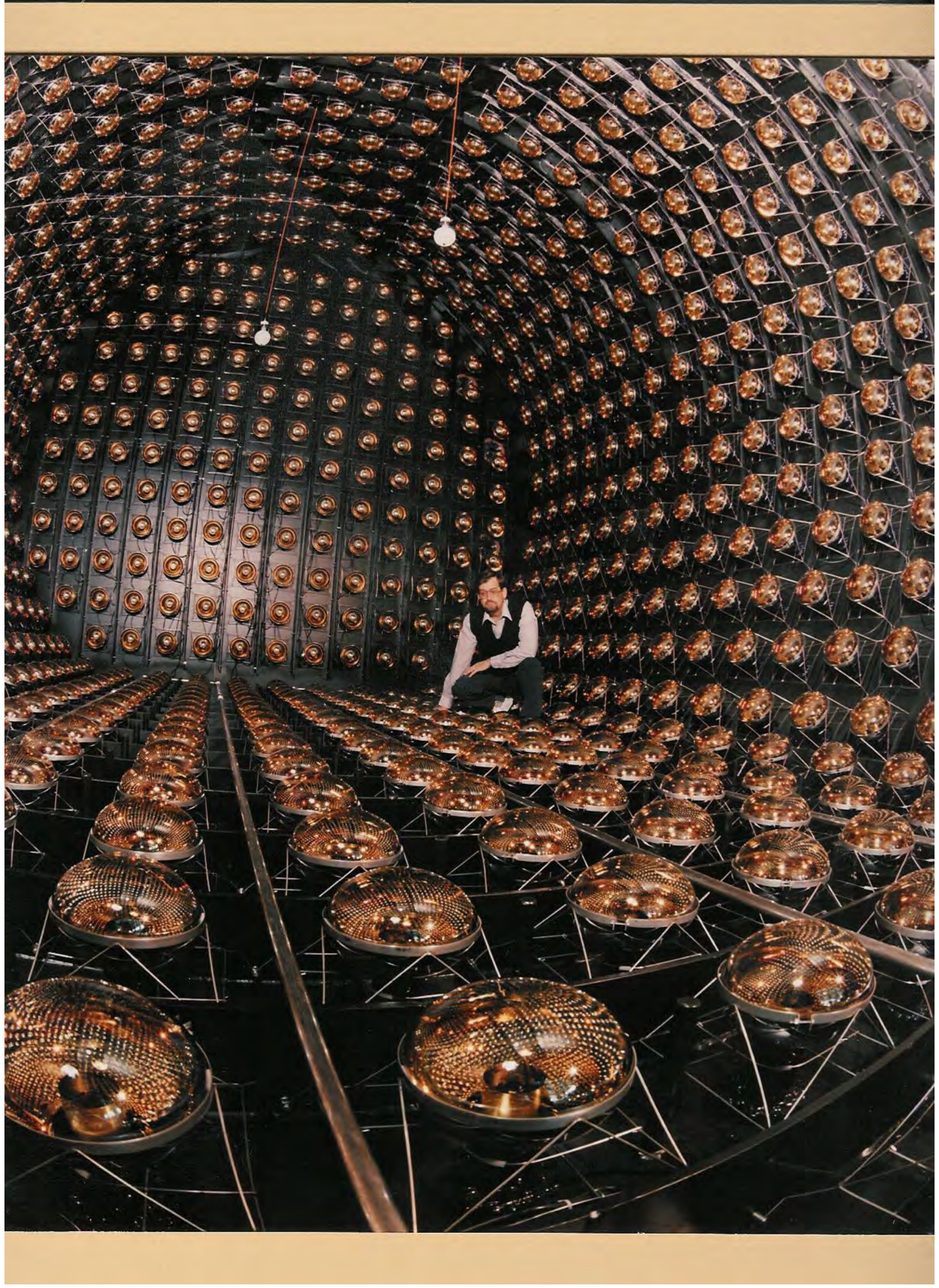
Evidence for Sterile Neutrinos

W. C. Louis, January 17, 2025

- Sterile Neutrino Evidence (>3σ)
- Sterile Neutrino Indications/Hints (~2σ) & Tensions in the Data
- Quasi-sterile Neutrinos & Apparent CPT Violation
- Upcoming Experiments
- Conclusions

Sterile Neutrino Evidence (>3σ)

- LSND
- MiniBooNE
- Gallium Anomaly



LSND Liquid Cherenkov/Scintillation Detector (1993-1998)

Located 30m from the beam dump

167 tons of Mineral Oil (CH_2) with 0.031 g/l of b-PBD & 1240 8” PMTs

Events are reconstructed from the charge/time of each hit PMT

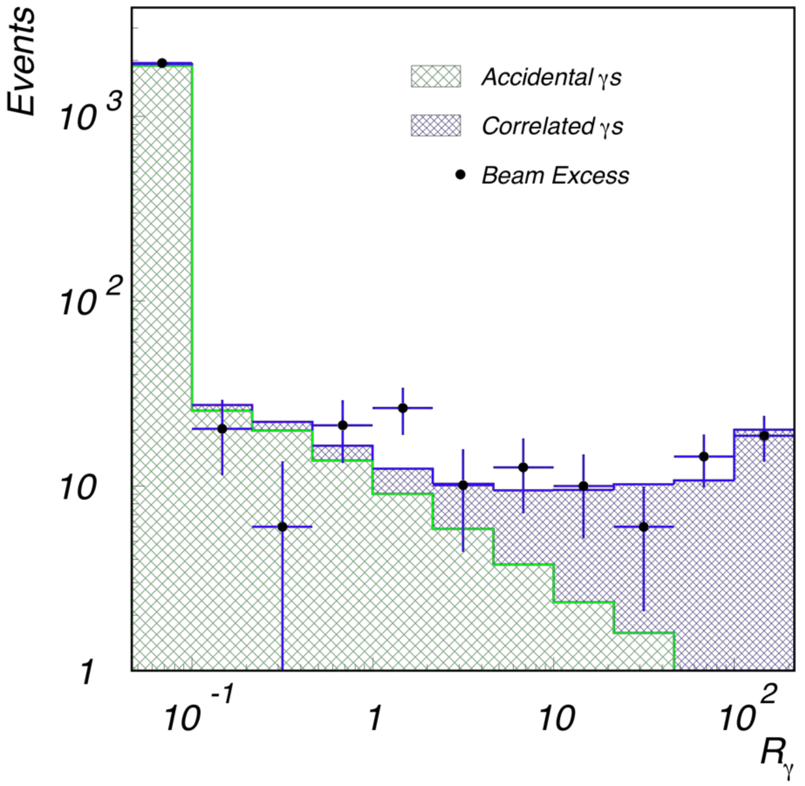
Designed to search for
$\overline{\nu}_\mu \to \overline{\nu}_e$

$\overline{\nu}_e$ p -> e^+ n, n p -> d γ(2.2 MeV)

LSND Event Excess

A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)

Correlated γ = 117.9+-22.4 events
Excess = 87.9+-22.4+-6.0 events



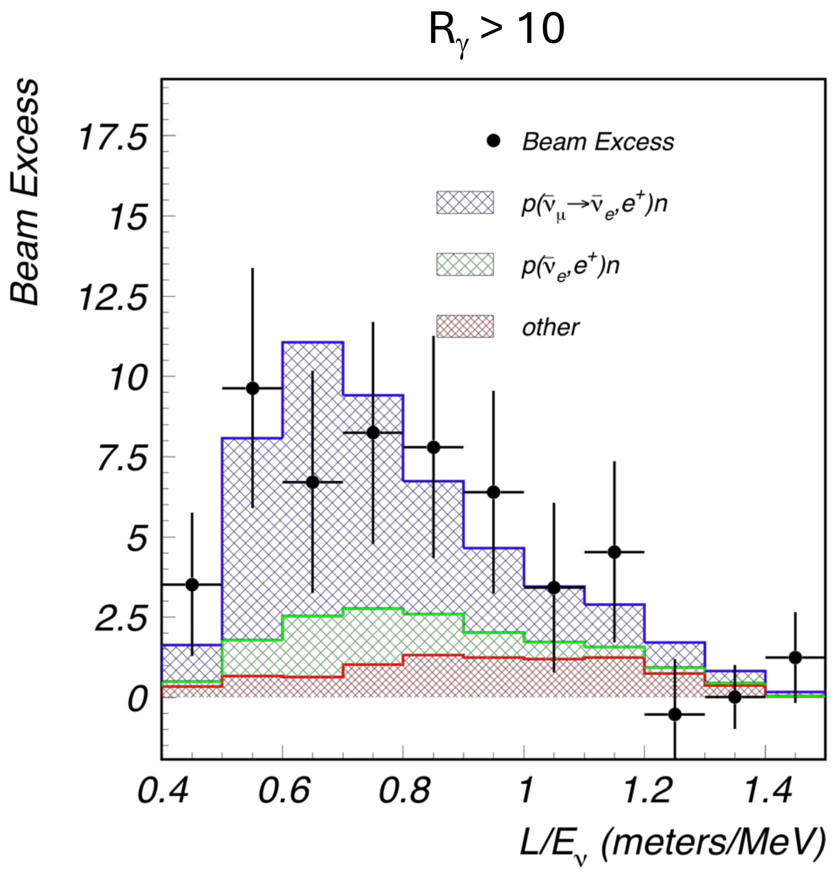
$\overline{\nu}_e$ p -> e^+ n, n p -> d γ(2.2 MeV)

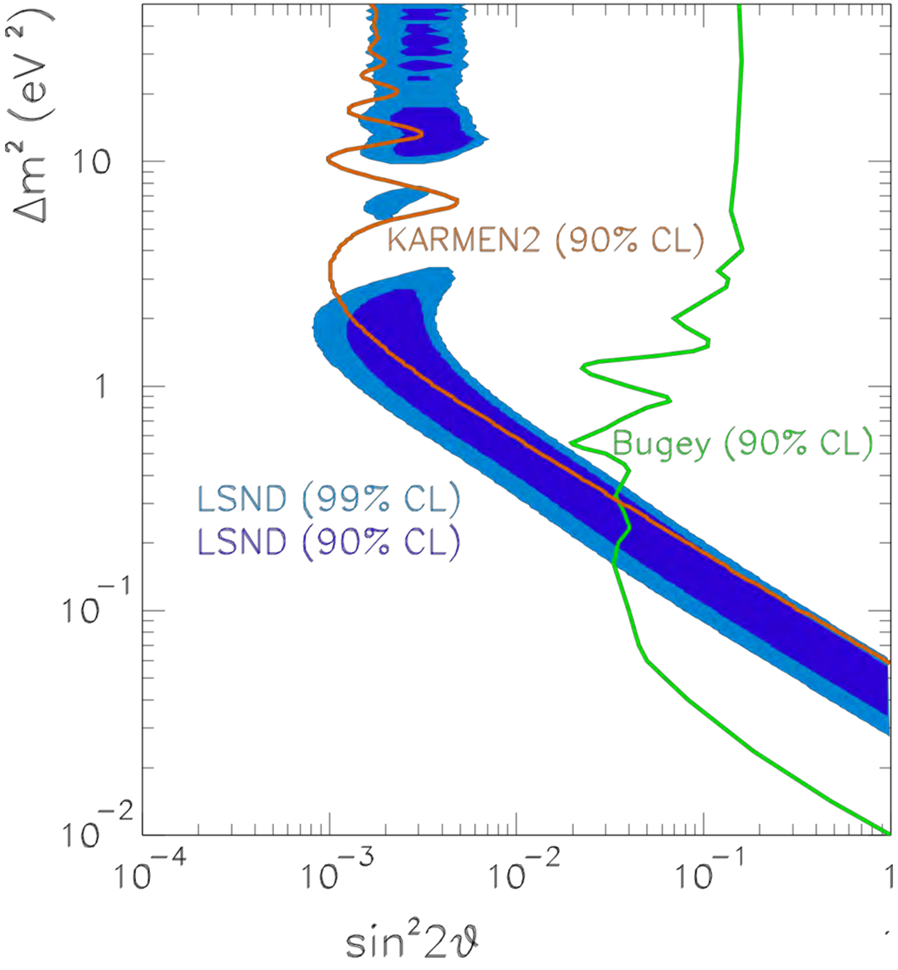
Selection	On Events	Off Events	ν Background	Excess	Significance
$R_\gamma > 1$	205	106.8+-2.5	39.2+-3.1	59.0+-12.7	4.6σ
$R_\gamma > 10$	86	36.9+-2.3	16.9+-2.3	32.2+-8.0	4.0σ
$R_\gamma > 100$	27	8.3+-0.7	5.4+-1.0	13.3+-3.9	3.4σ

LSND collected 1.9×10^{23} (0.3g) protons on target and observed a 3.8 σ excess of events.
Consistent with $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations, corresponding to P_{osc} = (0.264+-0.067+-0.045)%.

LSND Event Excess

A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)

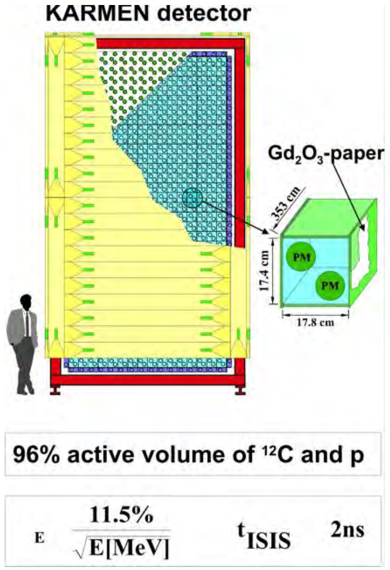




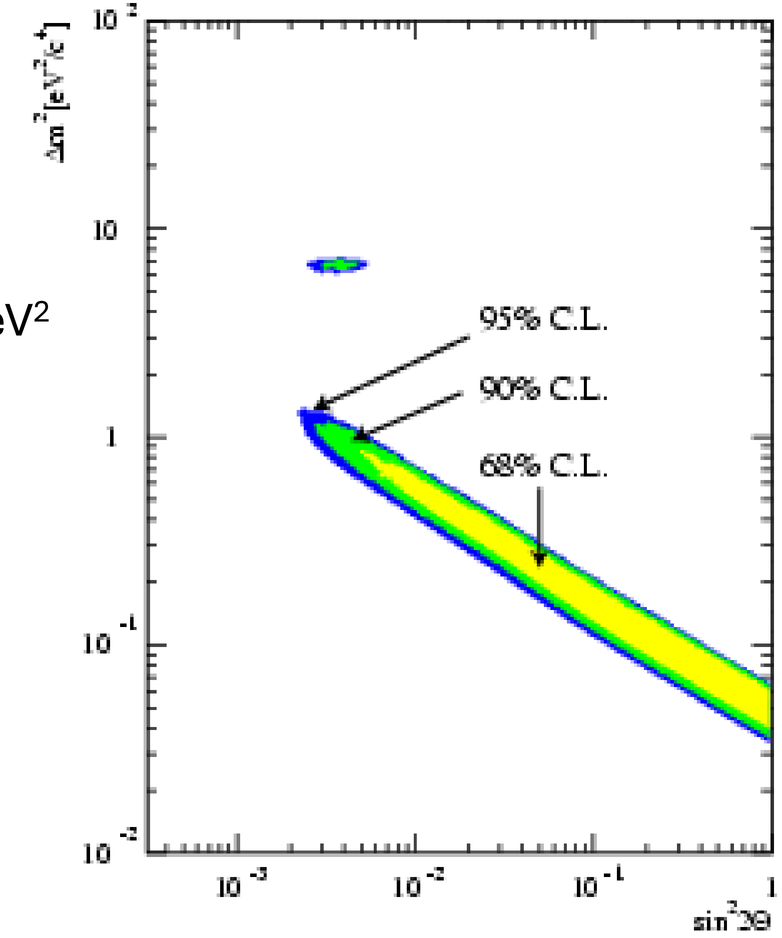
The LSND best fit at 1.2 eV^2 is favored over null by ~5σ ($\Delta\chi^2 = 29$).
LSND had very low intrinsic $\overline{\nu_e}$ background (0.07%) and is hardly affected by $\overline{\nu_e}$ disappearance.

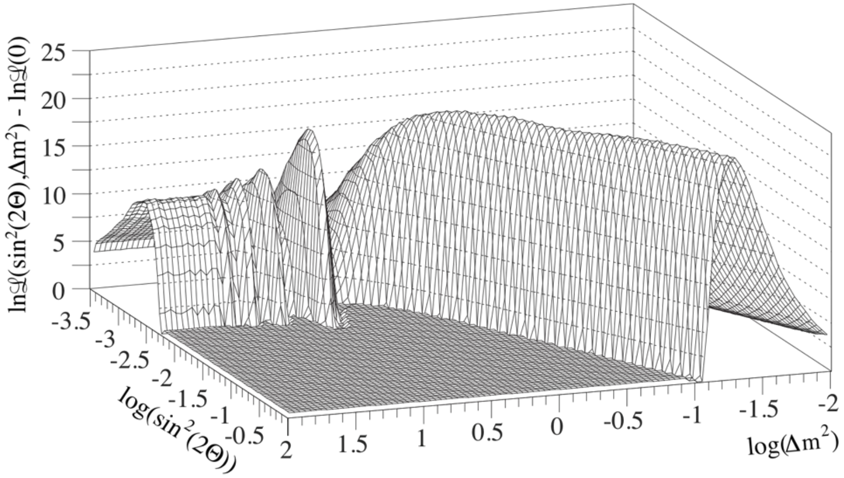
Joint LSND/KARMEN Analysis

E. D. Church, K. Eitel, G. B. Mills, and M. Steidl, Phys. Rev. D66, 013001, (2002)

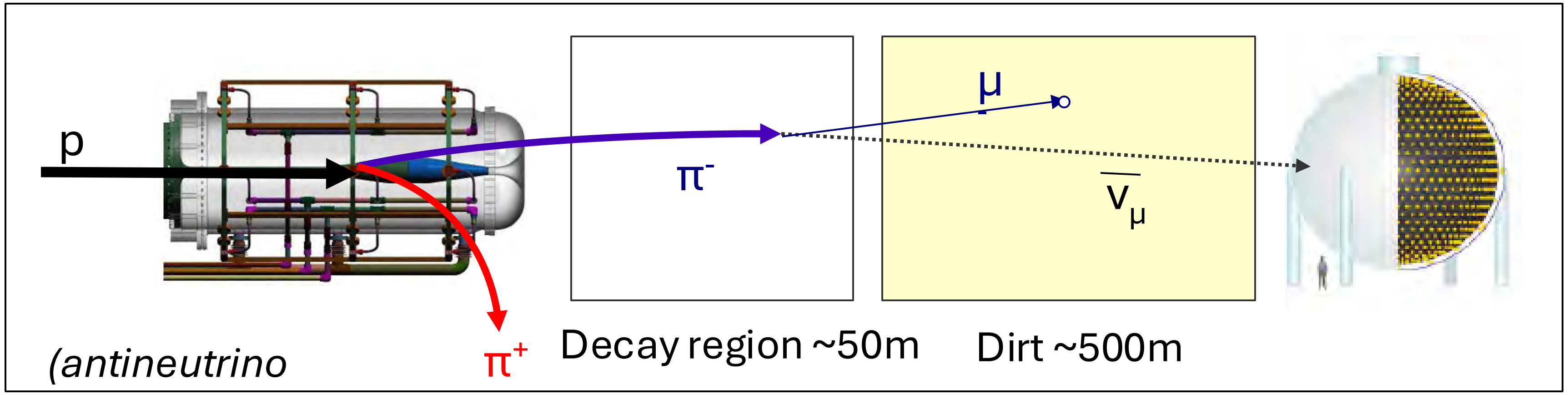


KARMEN observed no event excess; however, a joint analysis of KARMEN (17.7m) & LSND (30m) reveals a favored region of $\Delta m^2 < 2$ eV^2 and $\Delta m^2 \sim 7$ eV^2





MiniBooNE Experiment



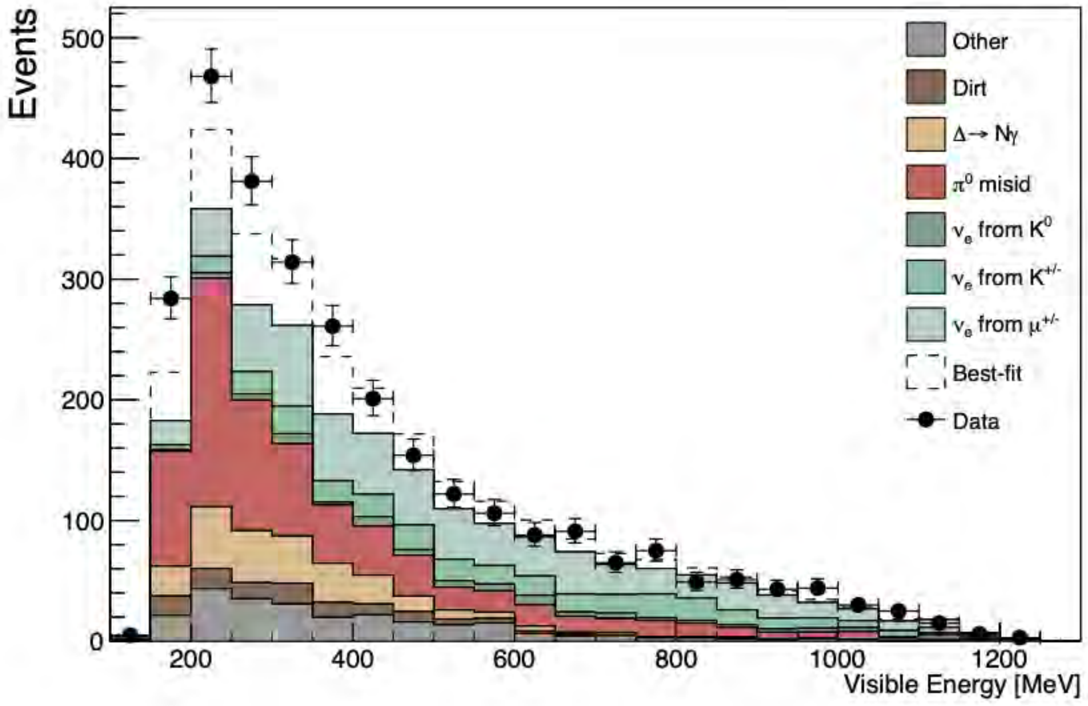
(antineutrino mode)

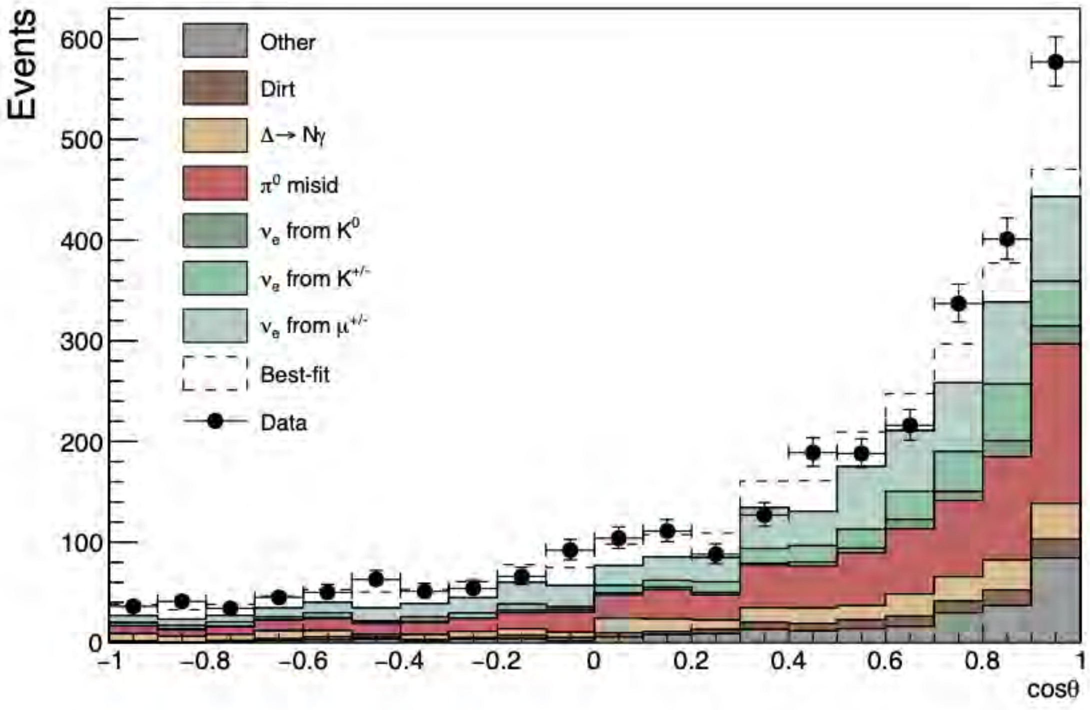
- Similar L/E as LSND for ν_μ -> ν_e & $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ oscillations
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

Total Neutrino Data

18.75 x 10^{20} POT

Phys. Rev. D **103, 052002 (2021)**





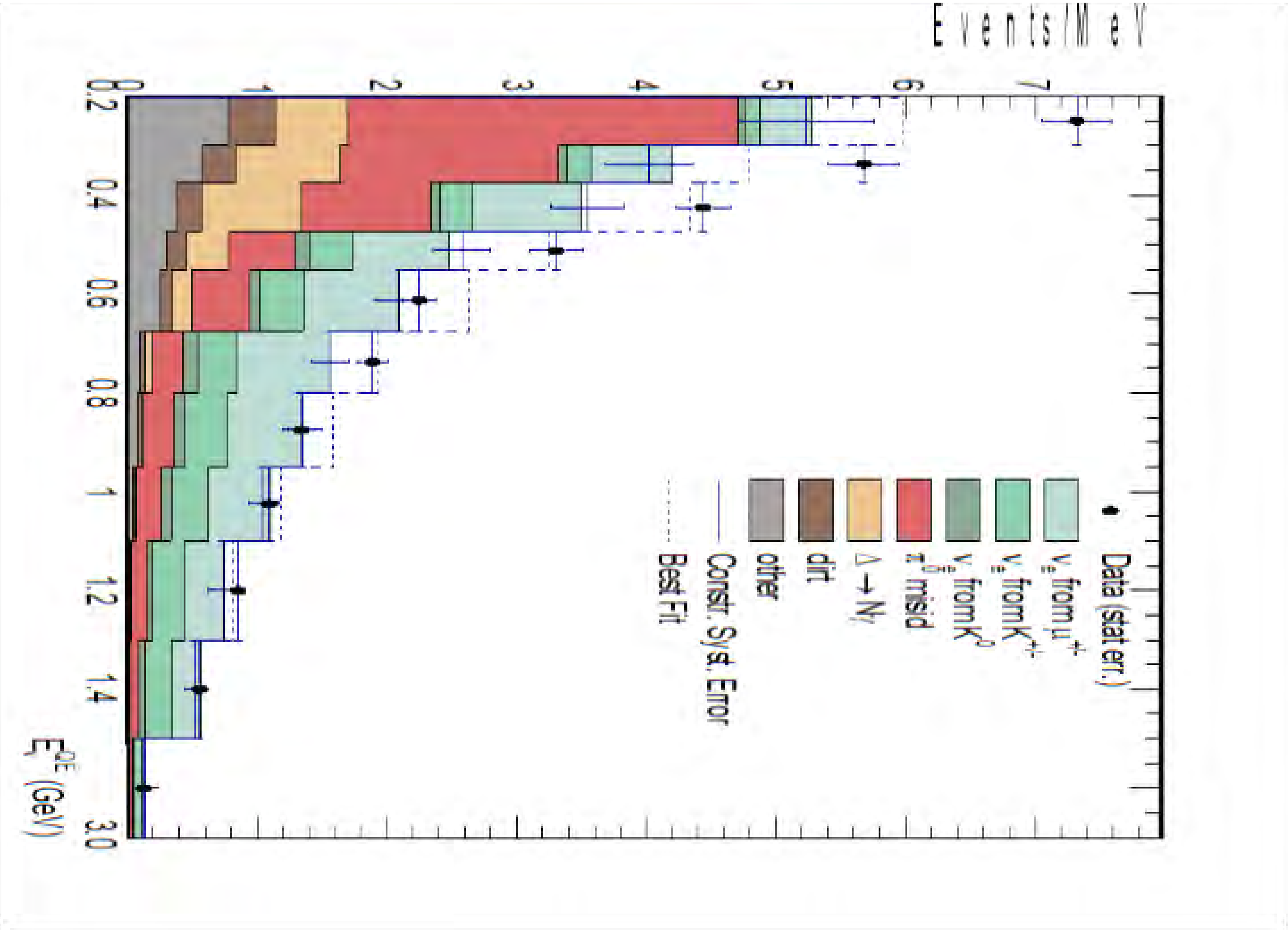
Neutrino Excess = 560.6 +- 119.6 events (4.7σ) with 200<E<1250 MeV

Excess is larger than LSND at low energies & high cosθ

Total Neutrino Data

18.75 x 10^{20} POT

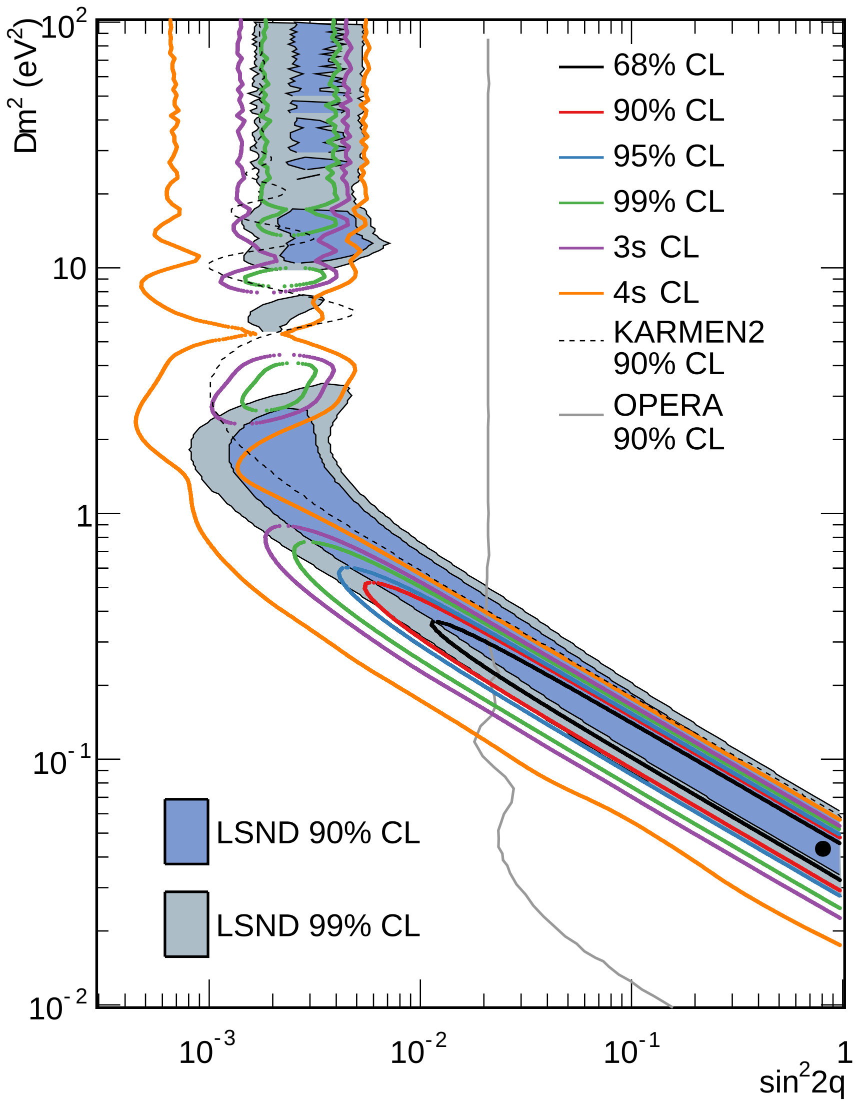
***Phys.Rev.D* 103, 052002 (2021)**



Neutrino Excess = 560.6 +- 119.6 events (4.7σ) with 200<E<1250 MeV

Allowed Regions

Phys.Rev.D **103, 052002 (2021)**



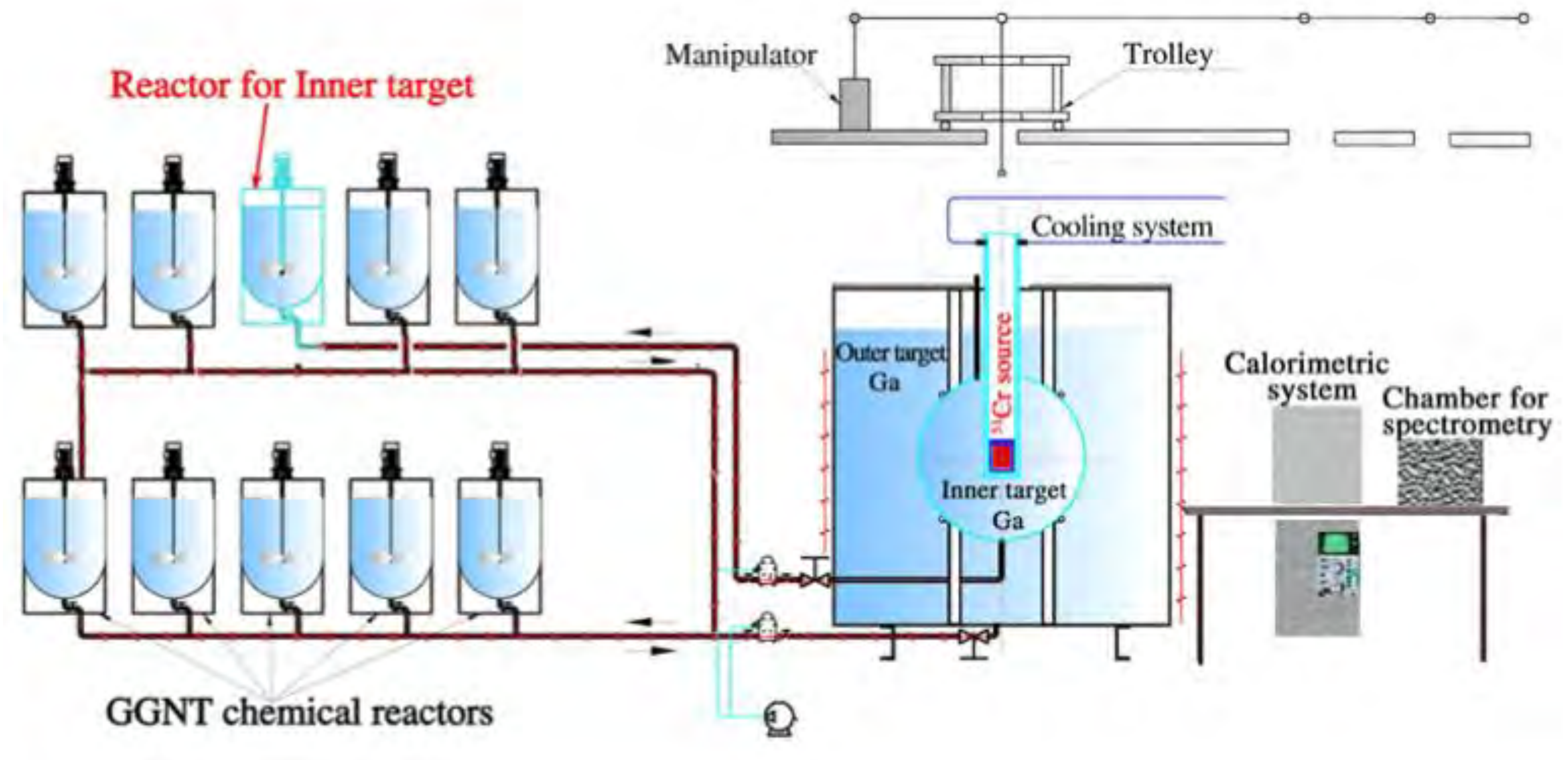
Neutrino + Anti-Neutrino Mode

$(\Delta m^2, \sin^2 2\theta) = (0.043\ \mathrm{eV}^2, 0.807)$

$\chi^2/ndf = 21.7/15.5\ (\mathrm{prob} = 12.3\%)$

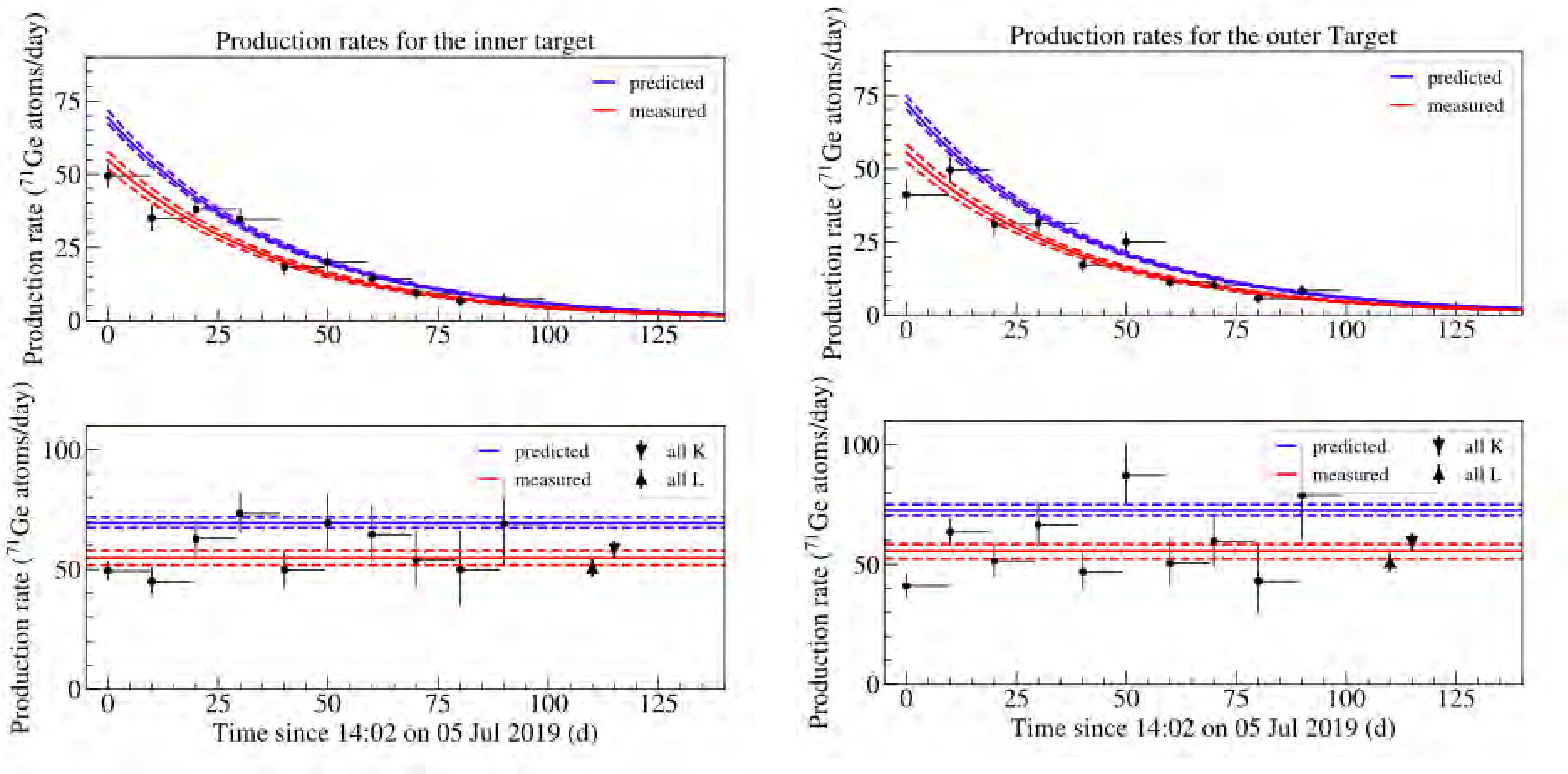
Total Excess = 638.0 +- 132.8 events (4.8σ) with 200<E<1250 MeV

Search for electron-neutrino transitions to sterile states in the BEST experiment : PRC 105, 065502 (2022)

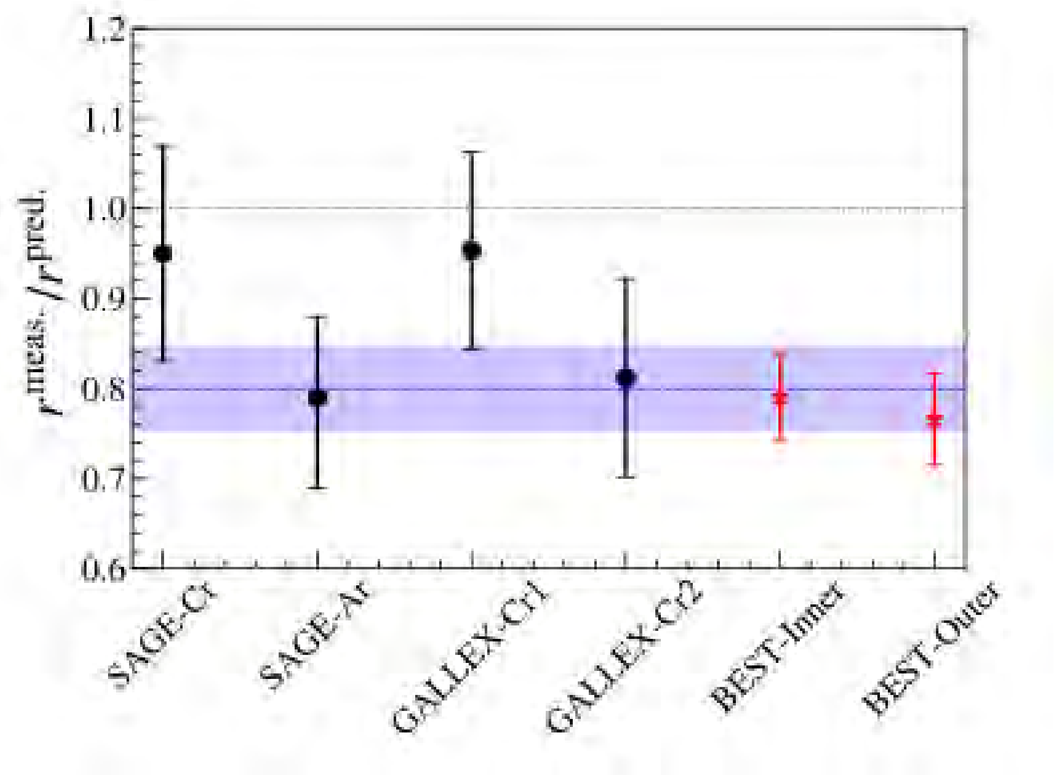


A 3.4 Mci 51Cr source was placed inside a vat containing 40 tons of Ga - 69Ga (0.6) & 71Ga (0.4)
The 51Cr source ($\tau_{1/2}$ = 11.43 d) produces 0.7 MeV ν_e that interact with 71Ga to produce 71Ge
The 71Ge atoms are extracted periodically and counted

Search for electron-neutrino transitions to sterile states in the BEST experiment : PRC 105, 065502 (2022)



Search for electron-neutrino transitions to sterile states in the BEST experiment : PRC 105, 065502 (2022)



The Gallium experiments measure a relative event rate = 0.80+-0.05 **(4σ deficit!)**
The best fit for the Gallium anomaly is $\sin^2 2\theta = 0.34$, $\Delta m^2 = 1.25$ eV^2

Search for electron-neutrino transitions to sterile states in the BEST experiment : PRC 105, 065502 (2022)

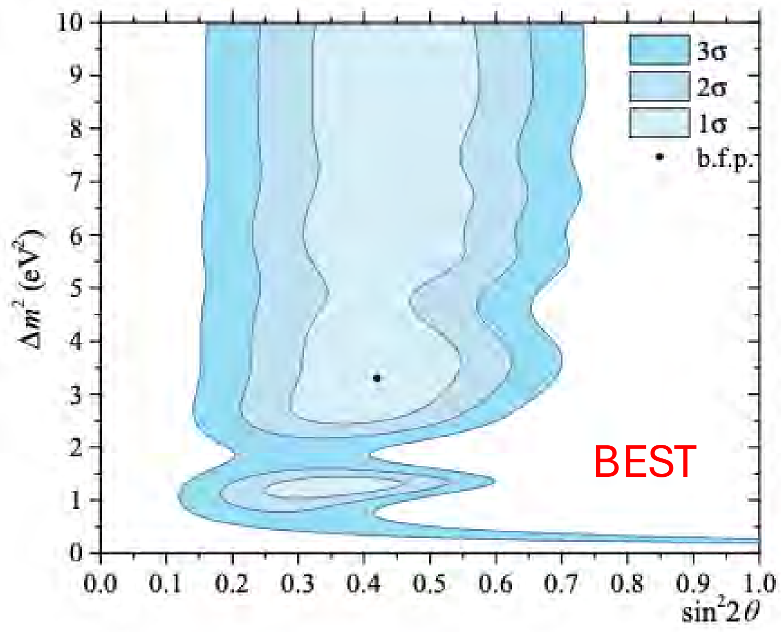


FIG. 10. Allowed regions for two BEST results. The best-fit point is $\sin^2 2\theta = 0.42^{+0.15}_{-0.17}$, $\Delta m^2 = 3.3^{+\infty}_{-2.3}$ eV^2 and is indicated by a point.

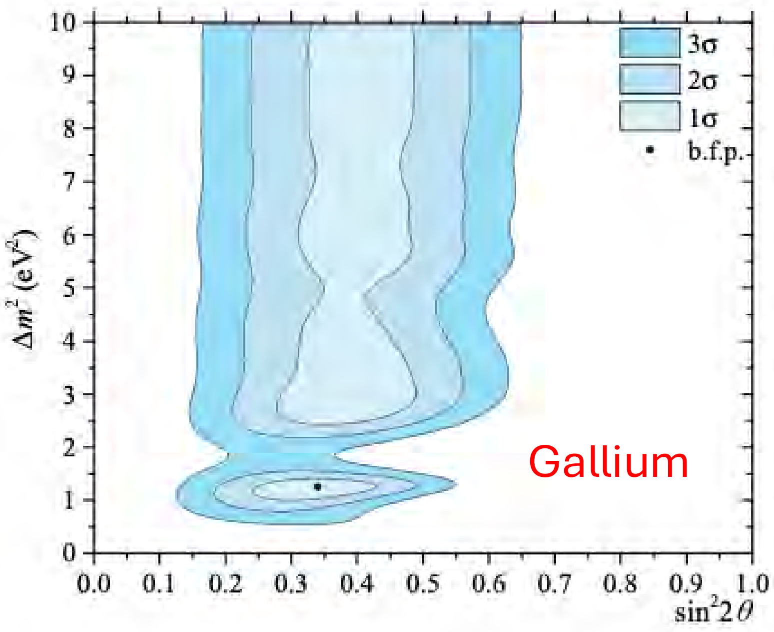


FIG. 12. Allowed regions for two GALLEX, two SAGE and two BEST results. The best-fit point is $\sin^2 2\theta = 0.34^{+0.14}_{-0.09}$, $\Delta m^2 = 1.25^{+\infty}_{-0.25}$ eV^2 and is indicated by a point.

The Gallium experiments have the **best** determination of the absolute event rate of any neutrino experiment!

Comparison of LSND, MB, & Gallium Anomaly

- LSND **3.8σ** Sensitive almost entirely to ν_μ -> ν_e
- MiniBooNE **4.8σ** Sensitive to both ν_μ -> ν_e and ν_e -> ν_x
- Gallium **4.0σ** Sensitive entirely to ν_e -> ν_x

The signals from these experiments are all model independent! (They do not depend, e.g., on a 3+1 model)

Sterile Neutrino Indications/Hints (~2σ) & Tensions

- IceCube vs MINOS+
- MicroBooNE vs MiniBooNE
- Reactors vs Gallium Anomaly

Indication of ν_μ Disappearance from IceCube

Phys. Rev. Lett. 133, 201804 (2024)

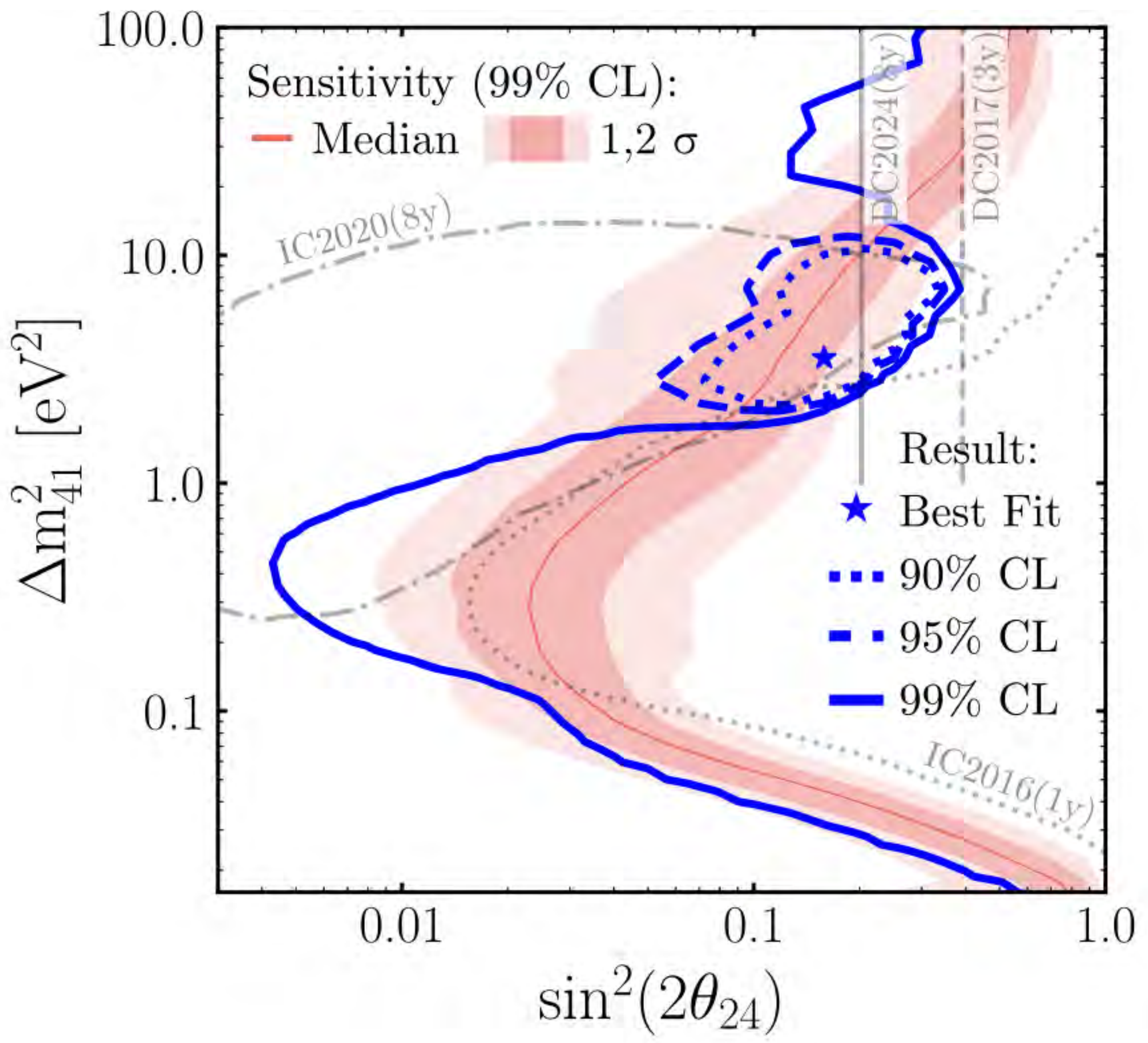
IceCube is sensitive to $\bar{\nu}_\mu$ disappearance from matter effects at an L/E ~ 1!

IceCube does observe a closed 95% contour consistent with disappearance.

This is the first hint of ν_μ disappearance at short baseline.

Upcoming results from IceCube will have lower systematic uncertainties and better sensitivity.

Best fit at $\Delta m^2 = 3.5$ eV^2, $\sin^2 2\theta = 0.16$



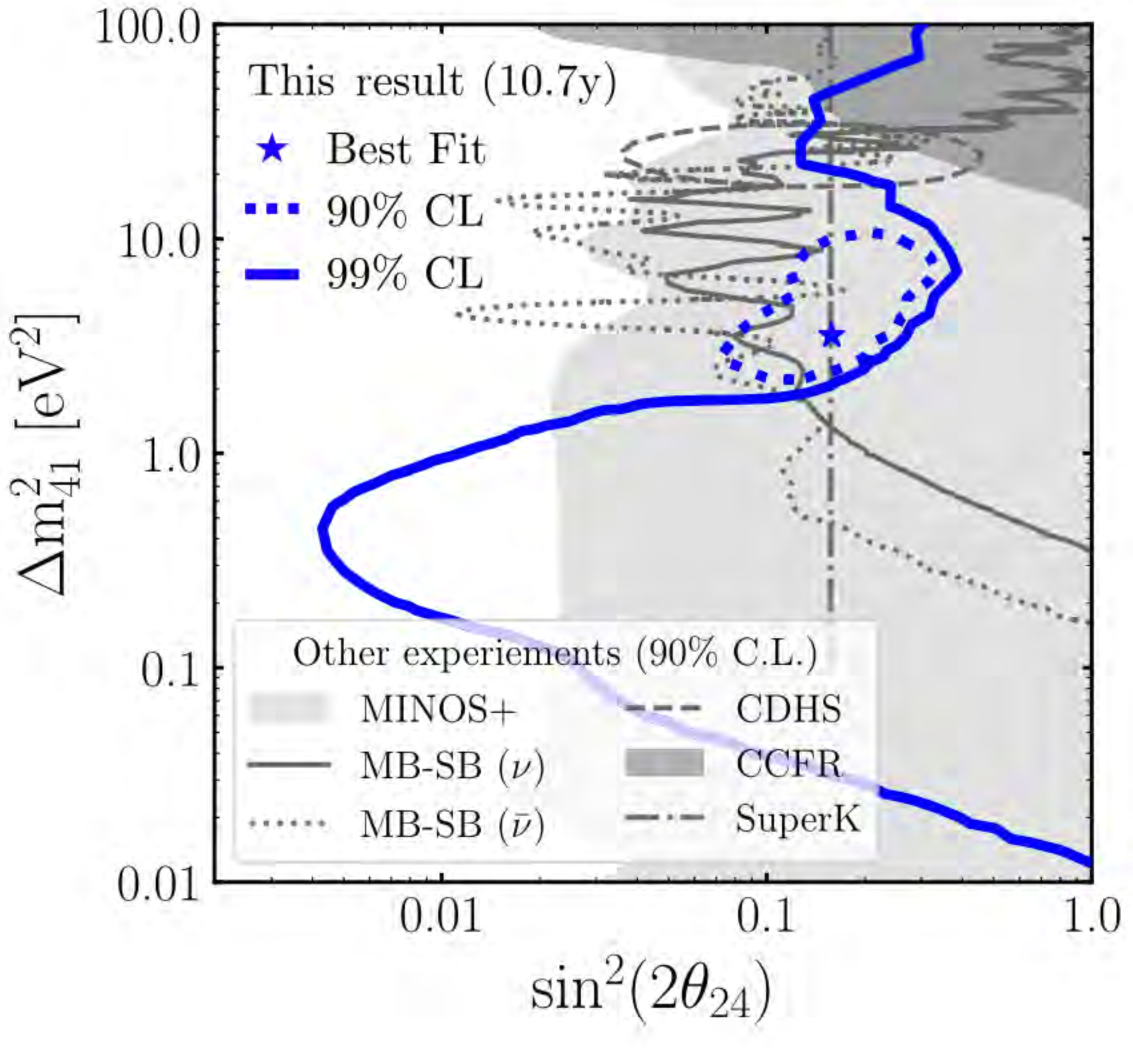
Indication of ν_μ Disappearance from IceCube

Phys. Rev. Lett. 133, 201804 (2024)

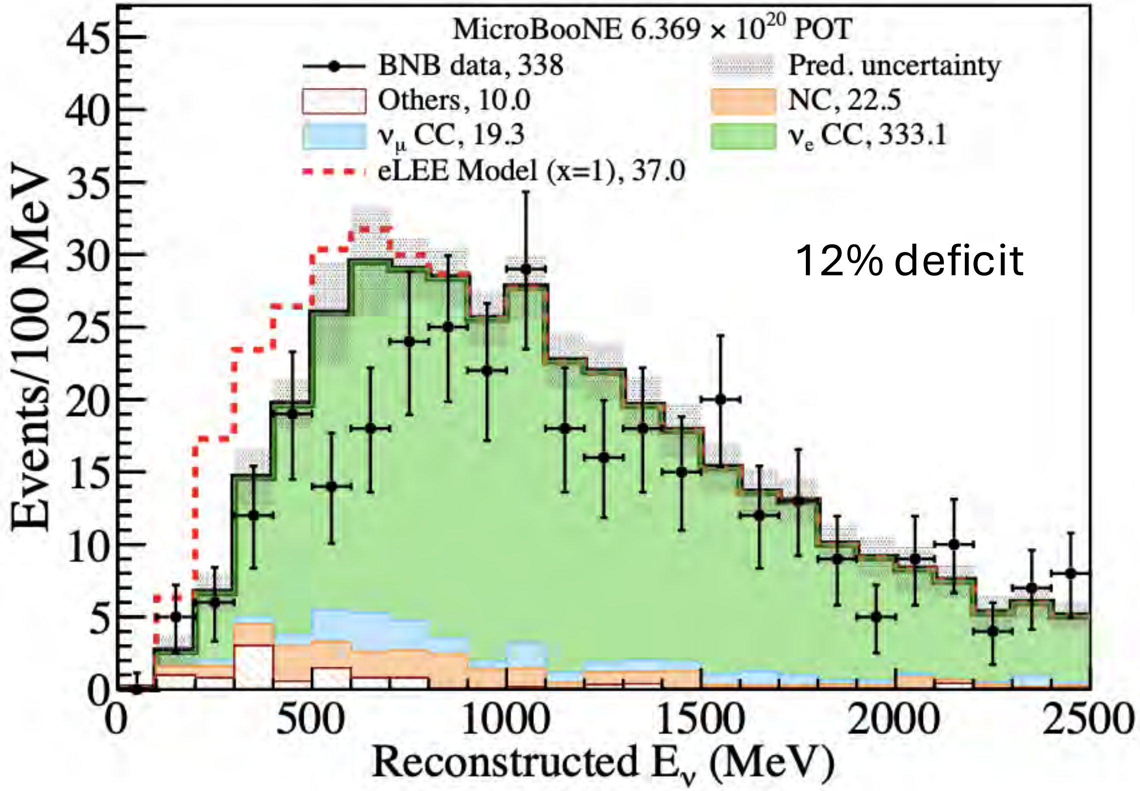
However, IceCube ($\bar{\nu}$) is in strong tension with MINOS+ (ν)

The MINOS+ limit is 2x better than the sensitivity; Is the limit too good?

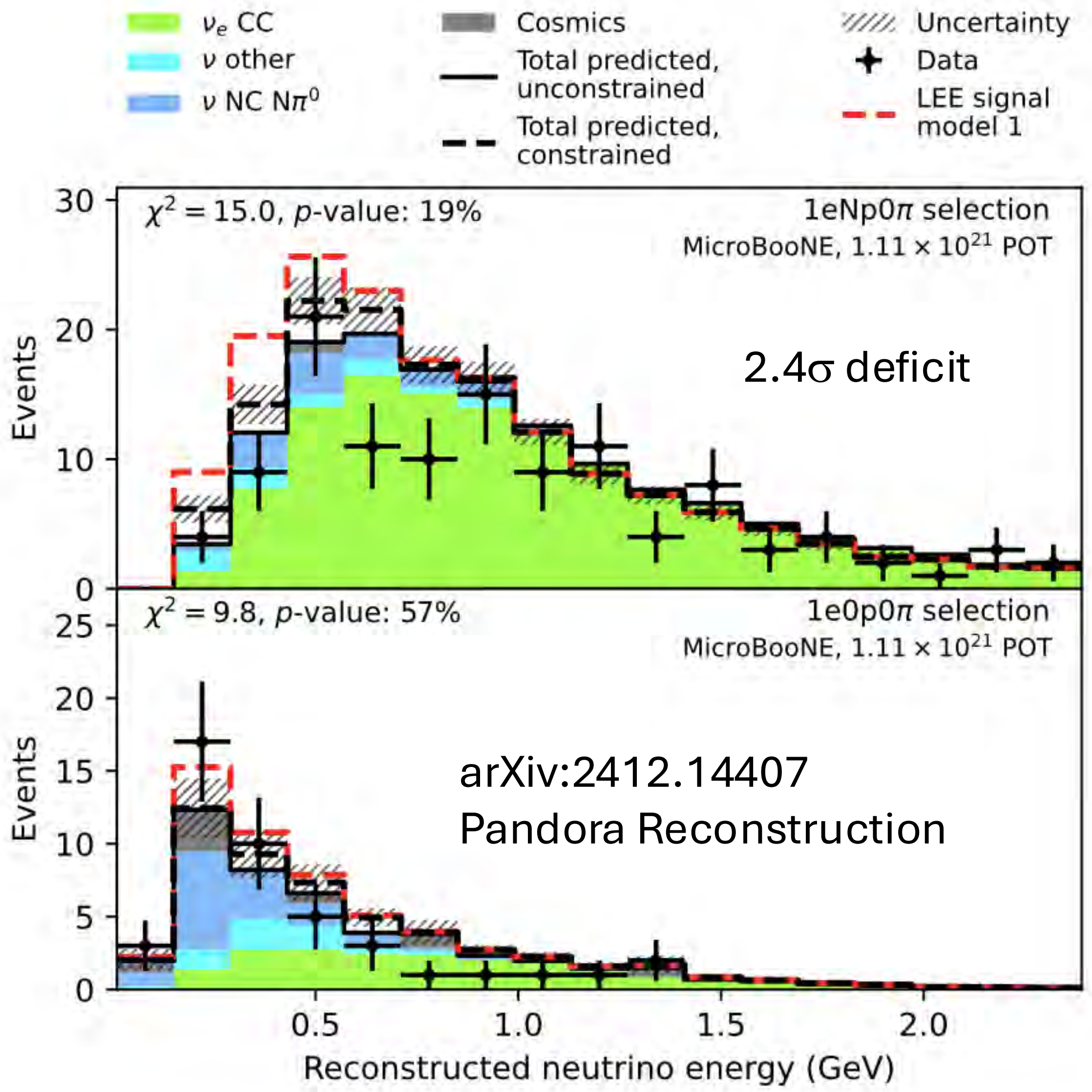
Apparent CPT Violation?



MicroBooNE Observes a ν_e Deficit Consistent with the Gallium Anomaly!

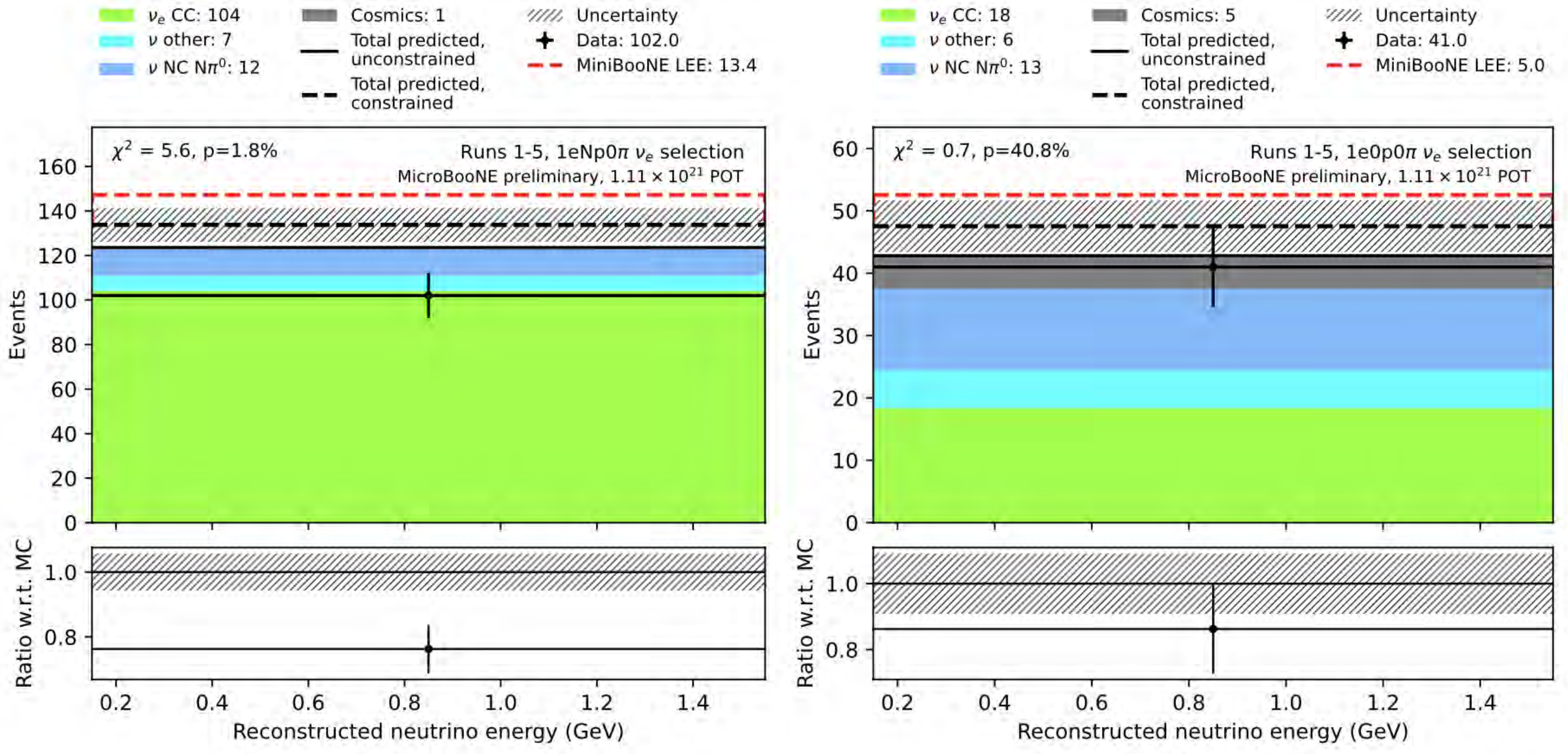


Phys.Rev.Lett. 128, 241801 (2022)
WireCell Reconstruction



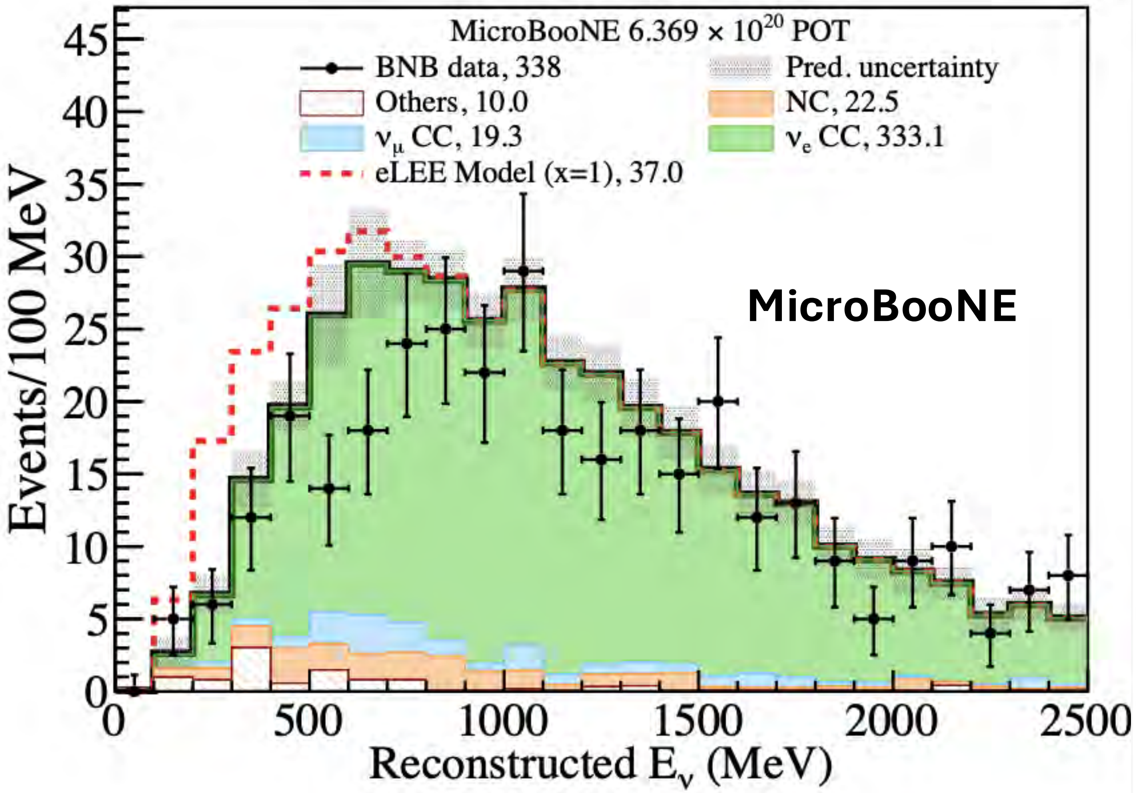
The Elephant in the room!

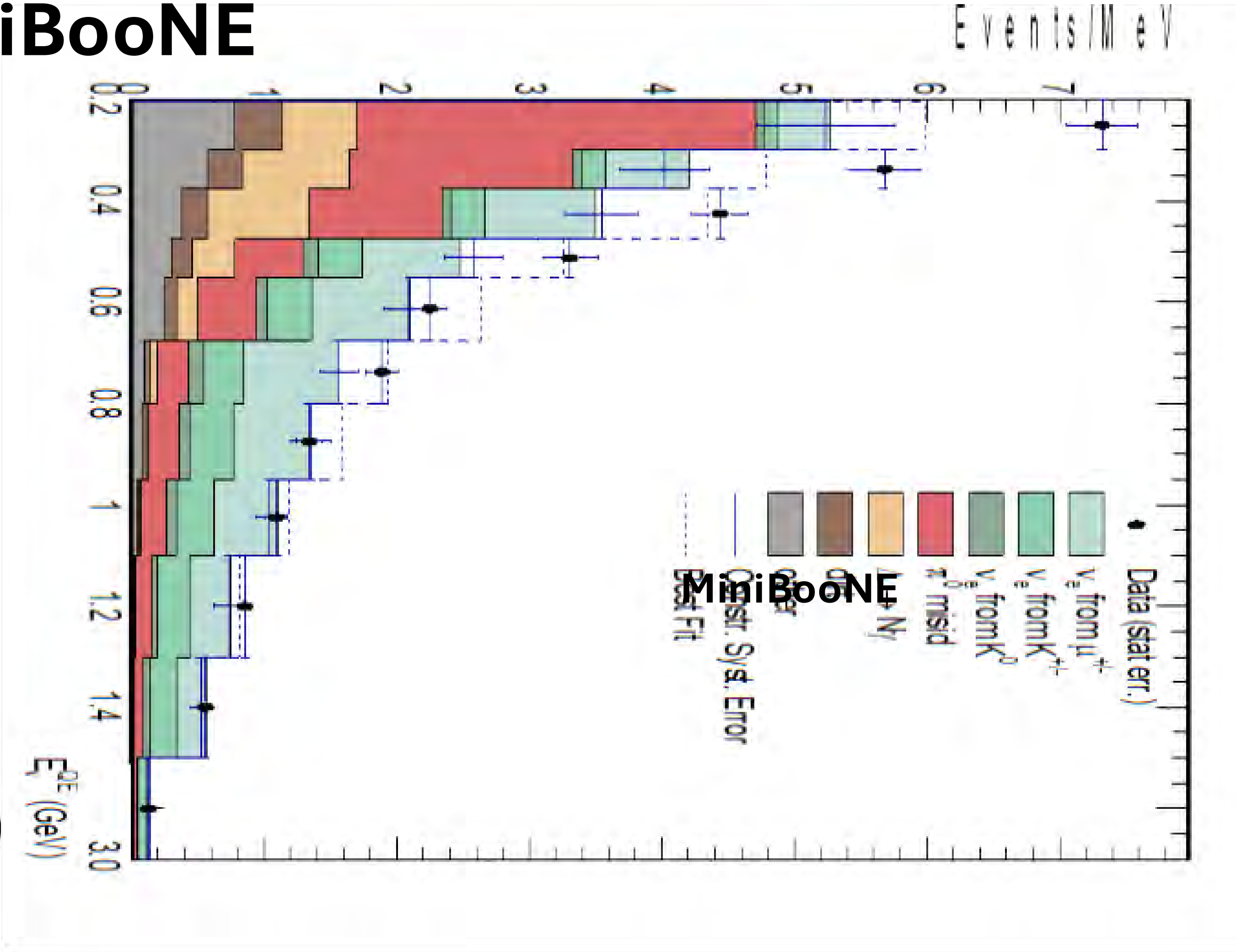
MicroBooNE Observes a ν_e Deficit Consistent with the Gallium Anomaly!



(a) (b)

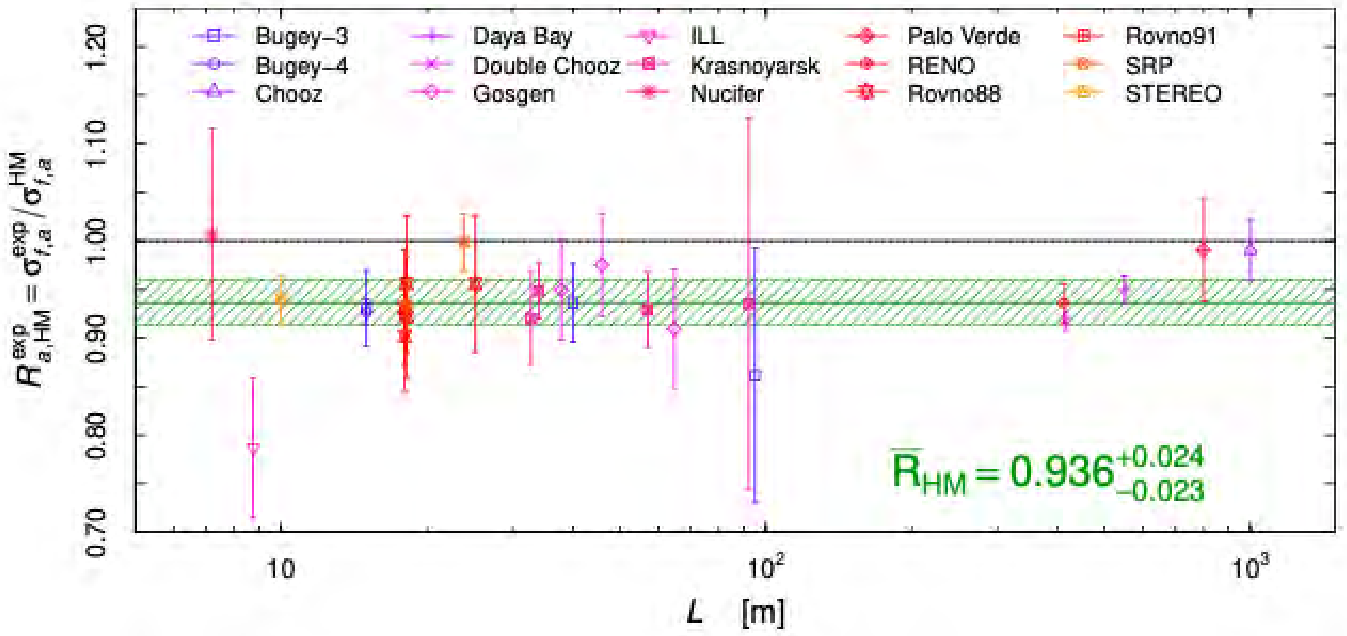
MicroBooNE vs MiniBooNE

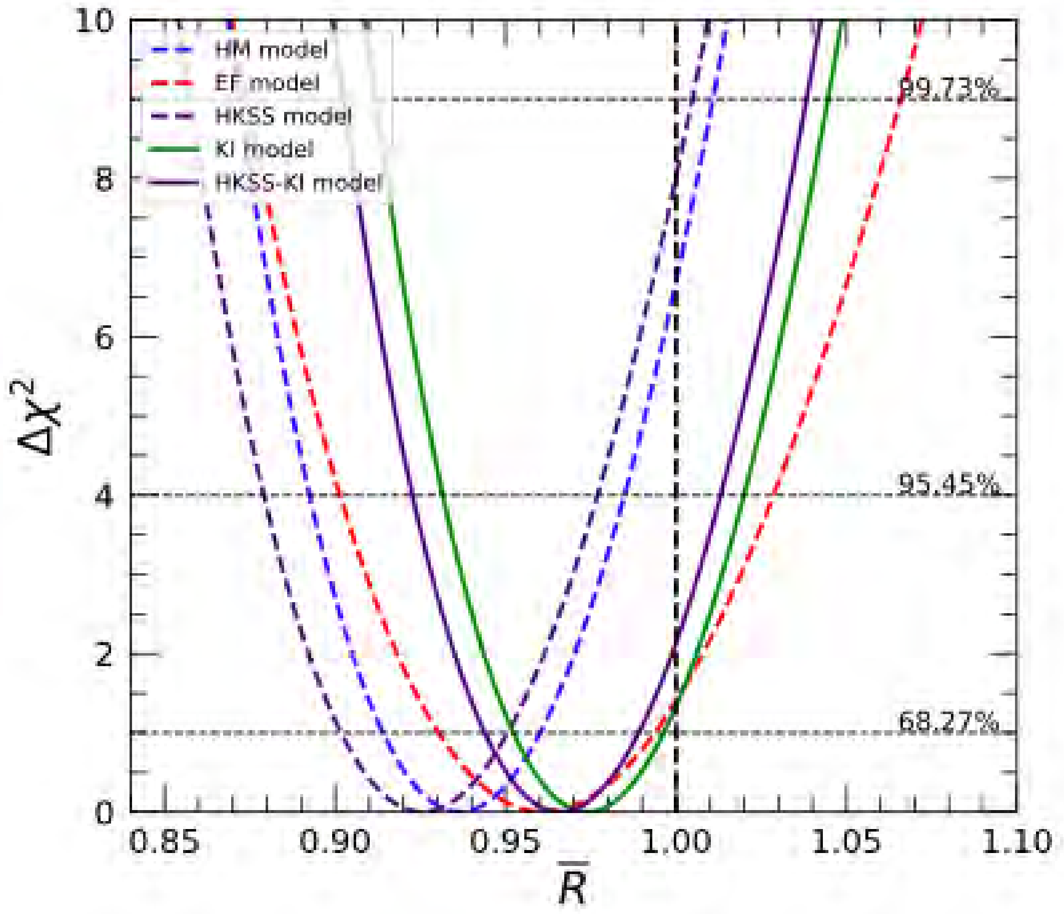




- Is some of the MiniBooNE excess due to BSM photon or e^+e^- production? (but antineutrino excess should be higher)
- Is difference due to different distances for MicroBooNE (470m) & MiniBooNE (541m)?
- Data suggest a more complicated 3+N model with uB and MB observing both ν_e appearance and ν_e disappearance with uB dominated by ν_e disappearance and MB dominated by ν_e appearance.

Reactor Neutrino Anomaly Phys.Lett.B 829 (2022)

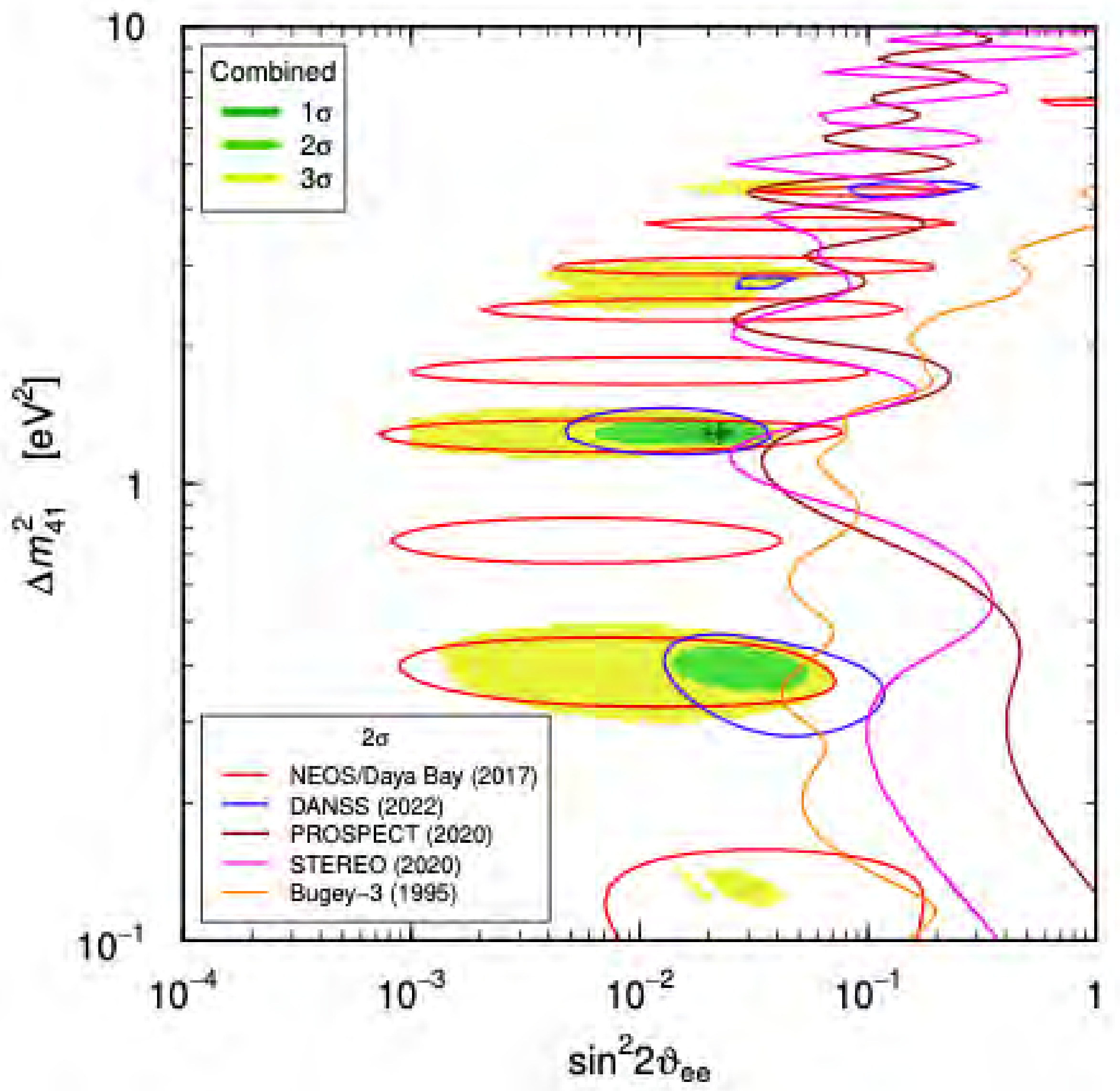


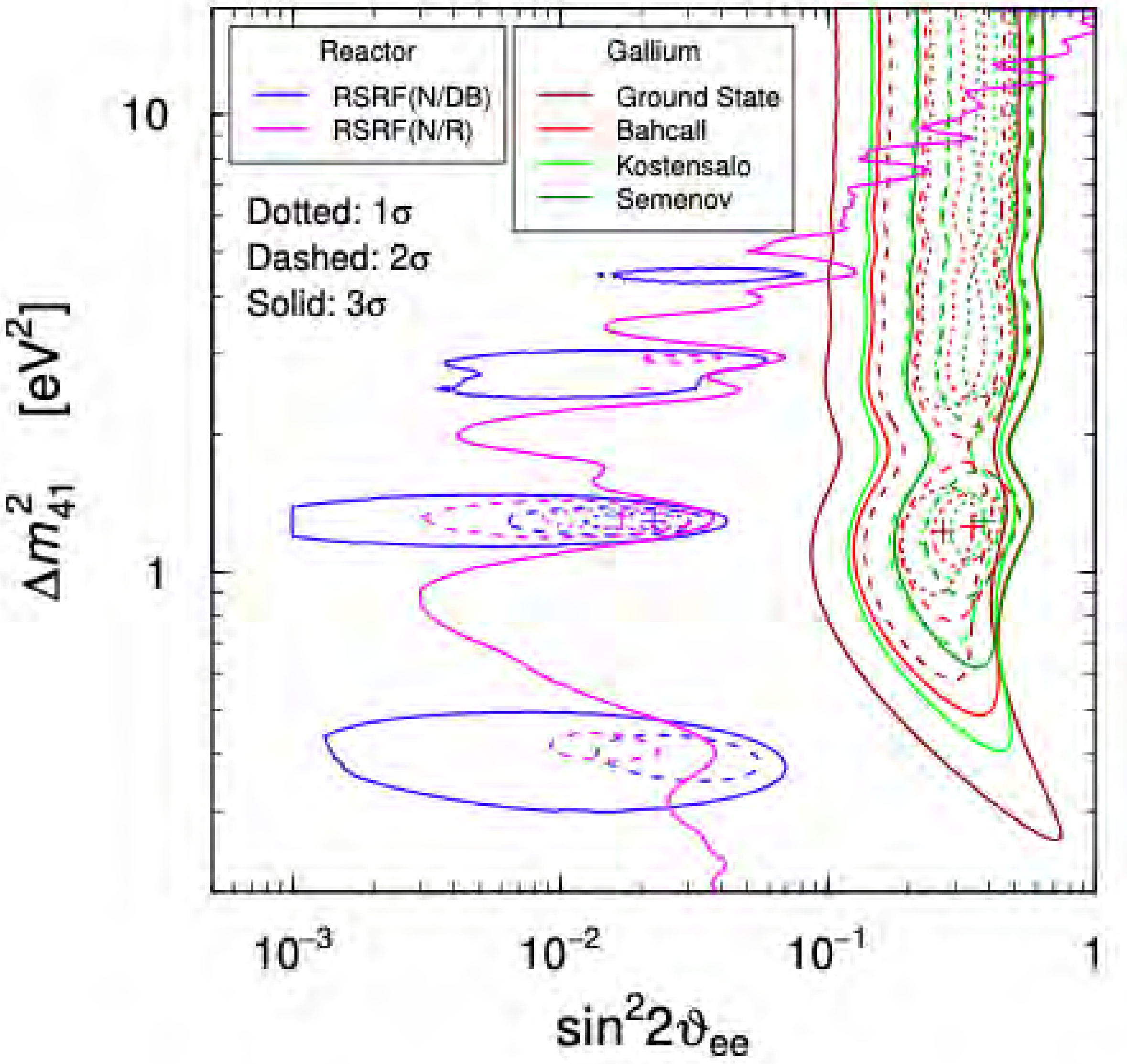


- Reactor ν Experiments measure fewer events than expected.
- However, the systematic uncertainties are large.
- The deficits are not significant.

Difference Between Reactor & Gallium Anomalies

arXiv:2209.00916 3+N Model? Apparent CPT Violation?





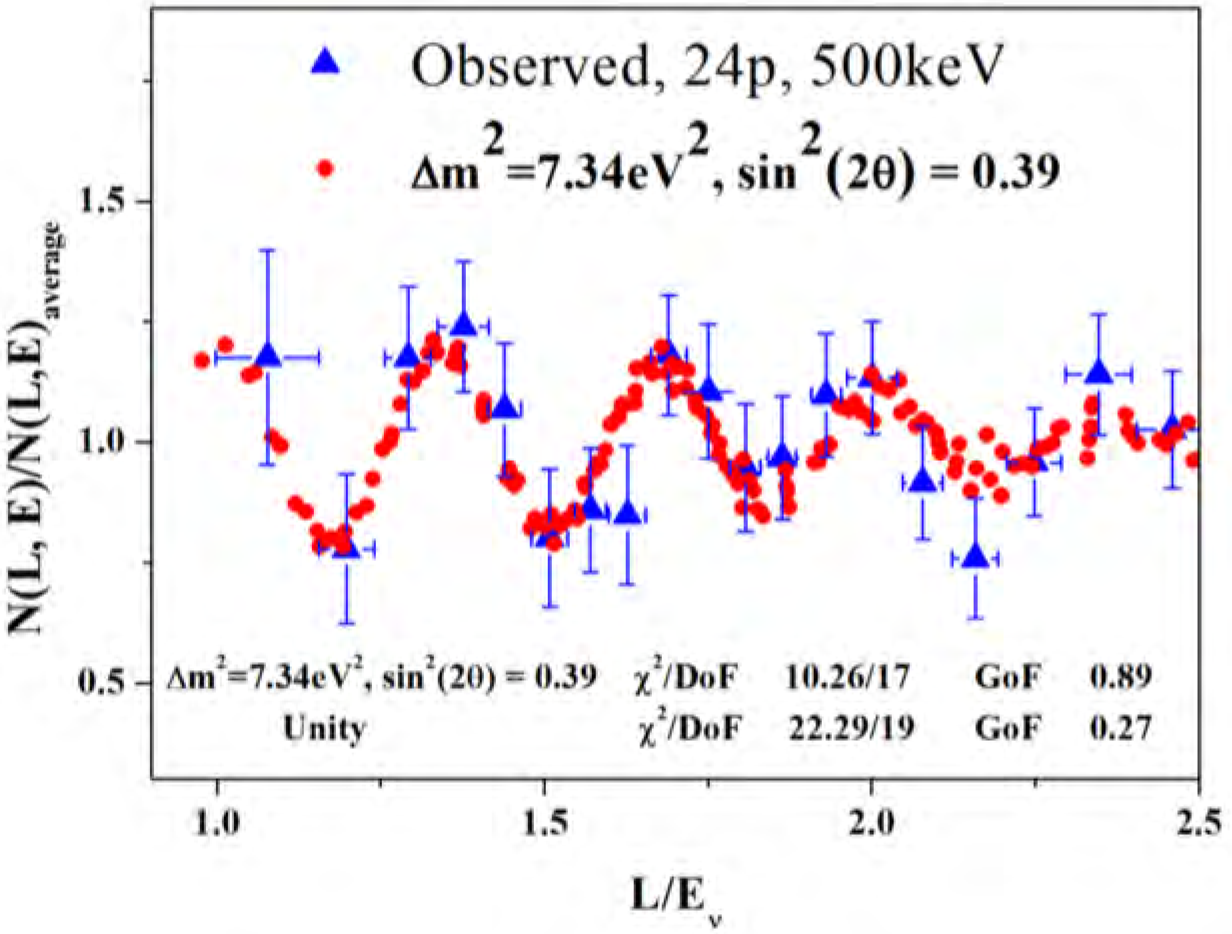
Neutrino 4 Evidence for Sterile Neutrinos

arXiv:2005.05301

- Neutrino-4 observes wiggles, Corresponding to $\Delta m^2 = 7.3$ eV^2 & $\sin^2 2\theta = 0.39$ & consistent with the Gallium anomaly

- Are these wiggles due to statistics or to ν oscillations?

- However, taking into account energy resolution, $\sin^2 2\theta \sim 1$



Quasi-sterile Neutrinos & Apparent CPT Violation

- BSM Matter Effects can cause apparent CPT violation

Quasi-sterile neutrinos from dark sectors. Part I. BSM matter effects in neutrino oscillations and the short-baseline anomalies.

Daniele S. M. Alves, WCL, and Patrick G. deNiverville JEHP 08, 034 (2022)

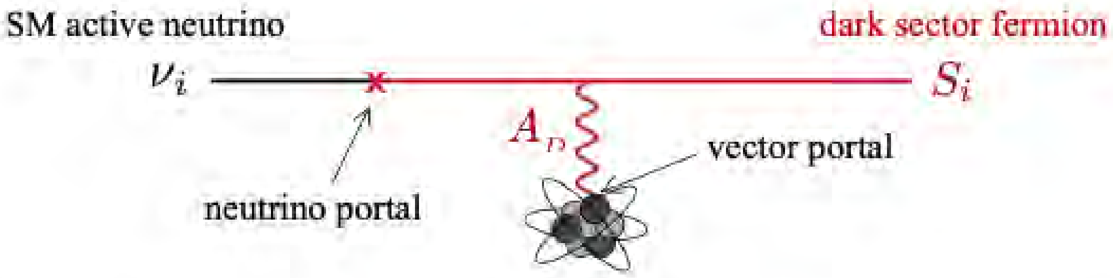


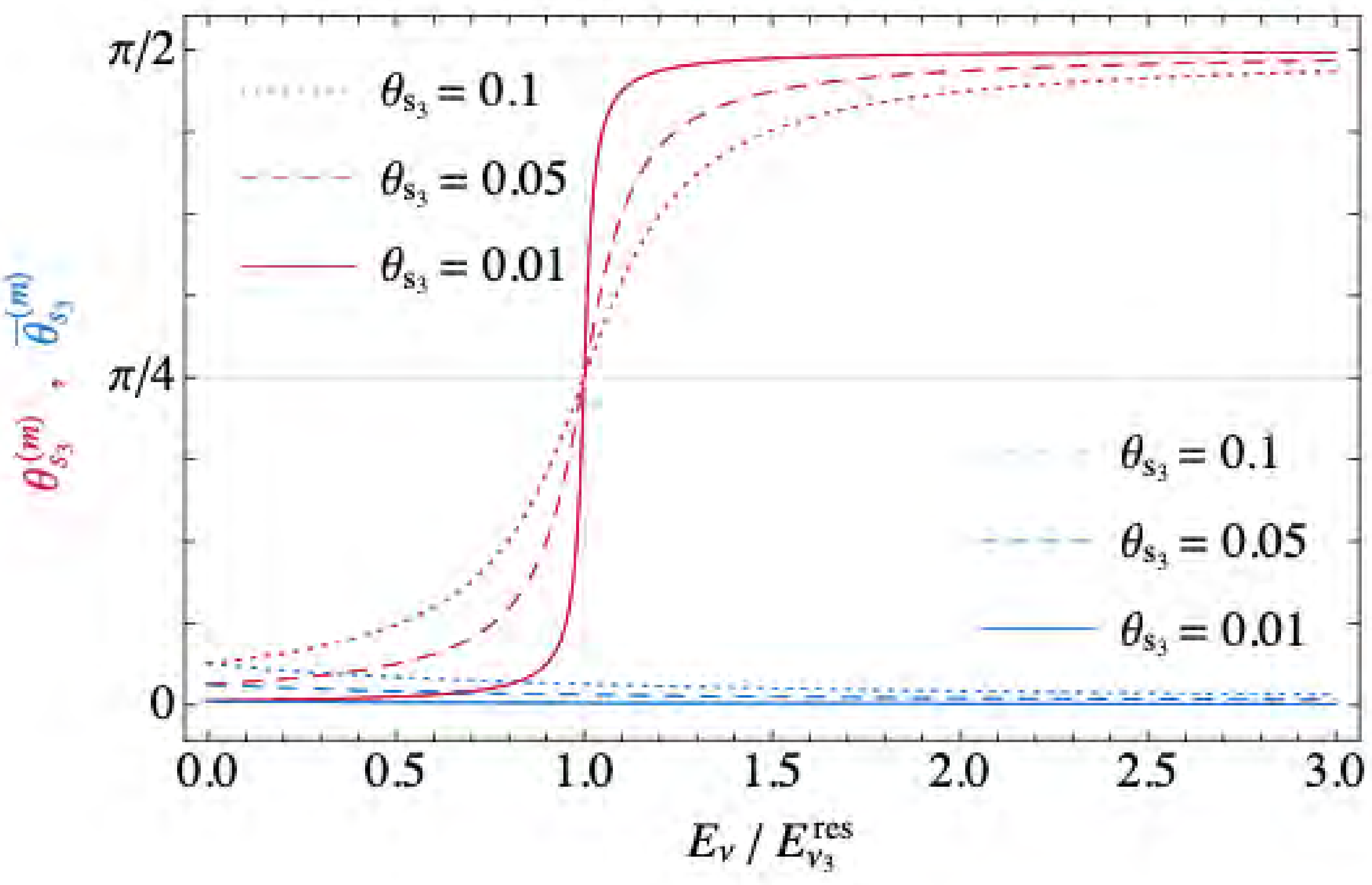
Figure 1. A generic consequence of dark sectors with neutrino- and vector-portals are quasi-sterile neutrinos. The BSM matter potential generated by the dark vector interactions can alter neutrino oscillations in matter.

Quasi-sterile neutrinos from dark sectors. Part I. BSM matter effects in neutrino oscillations and the short-baseline anomalies.

Daniele S. M. Alves, William C. Louis and Patrick G. deNiverville JEHP 08, 034 (2022)

Maximal neutrino oscillations occur at the resonant neutrino energy!

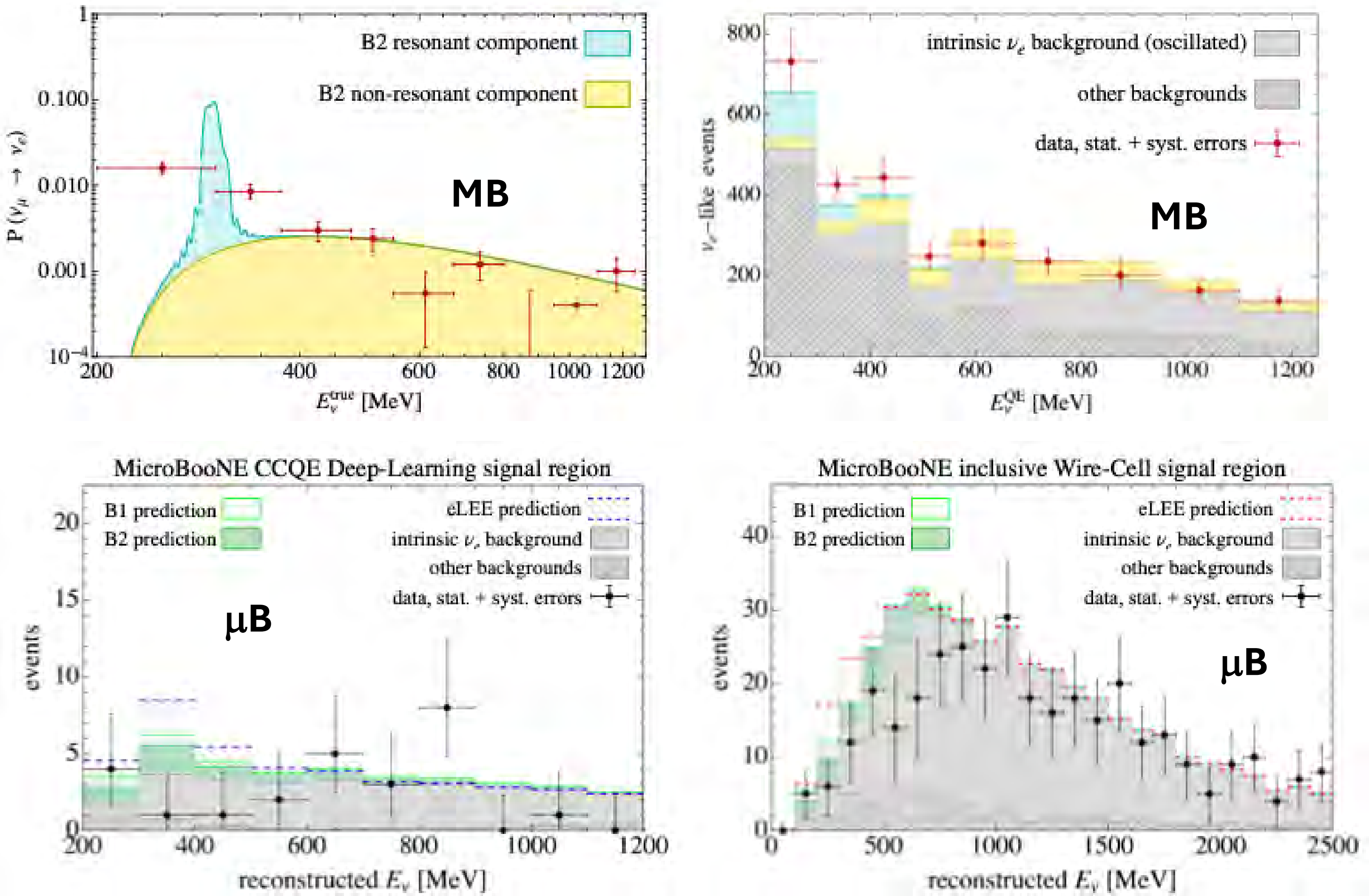
However, there is no resonance for antineutrinos.



Quasi-sterile neutrinos from dark sectors. Part I. BSM matter effects in neutrino oscillations and the short-baseline anomalies.

Daniele S. M. Alves, William C. Louis and Patrick G. deNiverville **JEHP 08, 034 (2022)**

The Quasi-sterile ν model explains the MiniBooNE excess well & is consistent with MicroBoone.



The Quasi-sterile ν model predicts a strong distance dependence near the resonance.

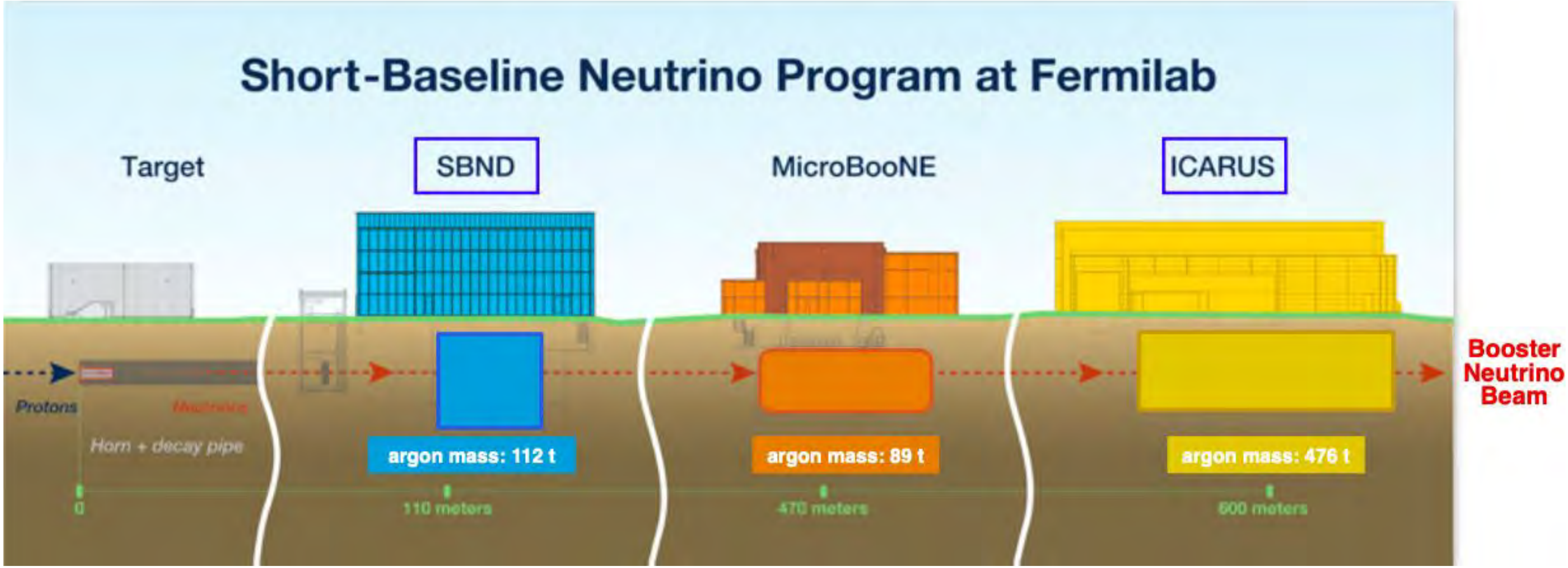
This fit is not optimized!

Upcoming Experiments

- SBN
- JSNS^2
- KATRIN

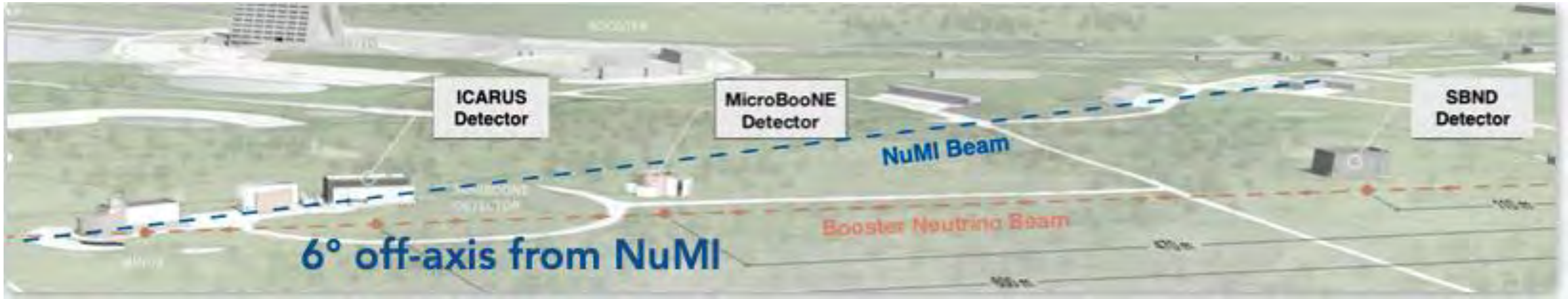
Short-Baseline Neutrino program

Short Baseline Neutrino (SBN) Program



MicroBooNE took data from 2015-2020
ICARUS started data taking in 2021
SBND began data taking in 2024

Short Baseline Neutrino (SBN) Program Has Two ν Beams



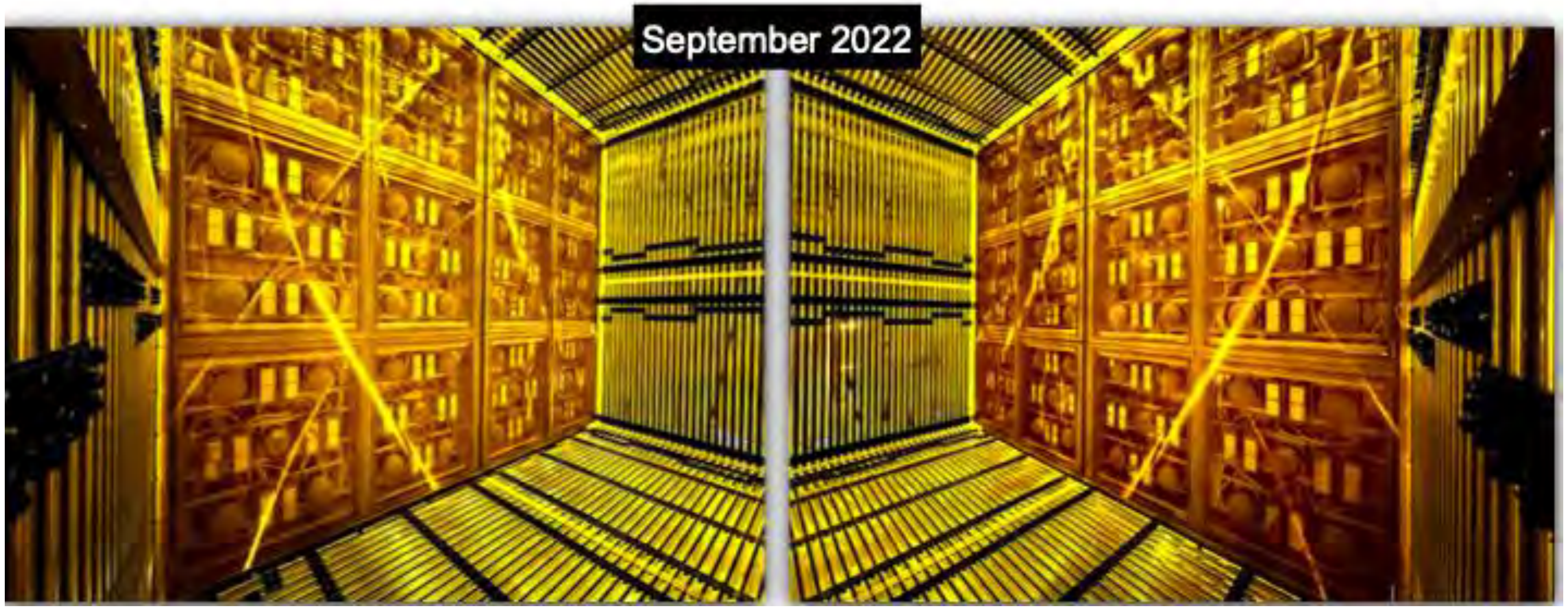
SBN has 3 LAr TPC detectors and 2 beamline (BNB & NuMI)
This yields 5 different baselines:
SBND: 110m (BNB)
ICARUS: 600m (BNB) & 810m (NuMI)
MicroBooNE: 470m (BNB) & 680m (NuMI)

ICARUS

Four TPCs in two modules
Each module is 3m x 4m x 18m
Steady data taking since March 2021

ICARUS has Cosmic Ray Tracker (CRT)
& concrete overburden

SBND

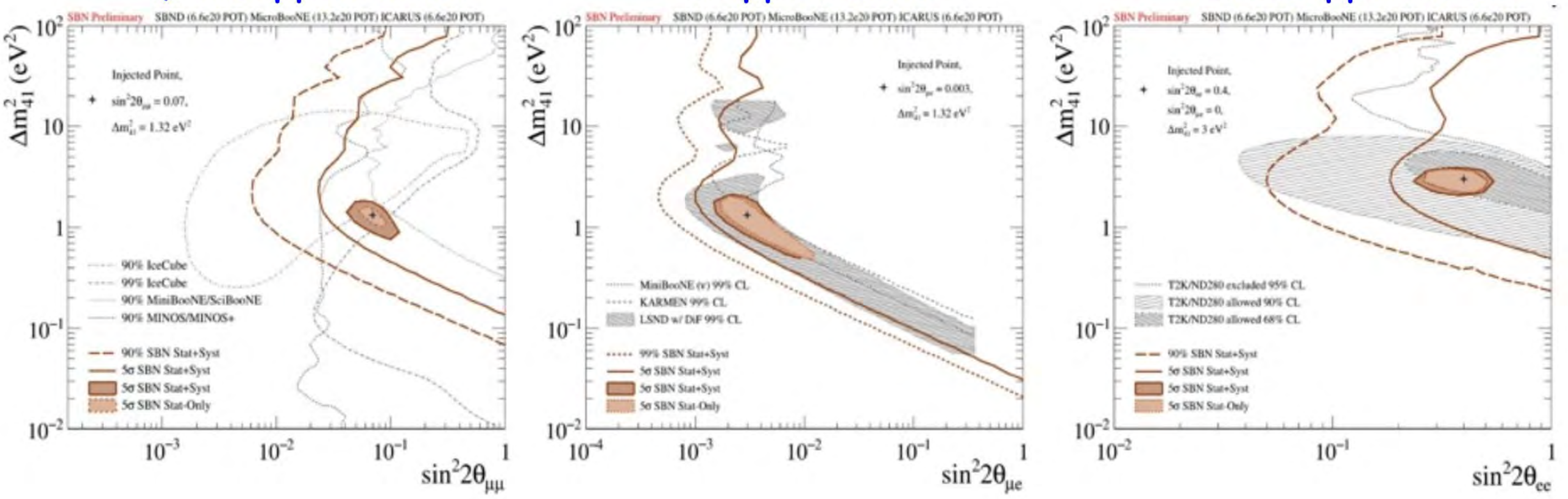


Detector installed in December 2022
Two Time Projection Chambers with Total dimension: 4m x 4m x 5m
APA – Anode wire planes with ~11000 wires
CPA - Cathode covered with TPB coated reflectors
Photon Detection System: 120 PMTs, 192 X-Arapucas

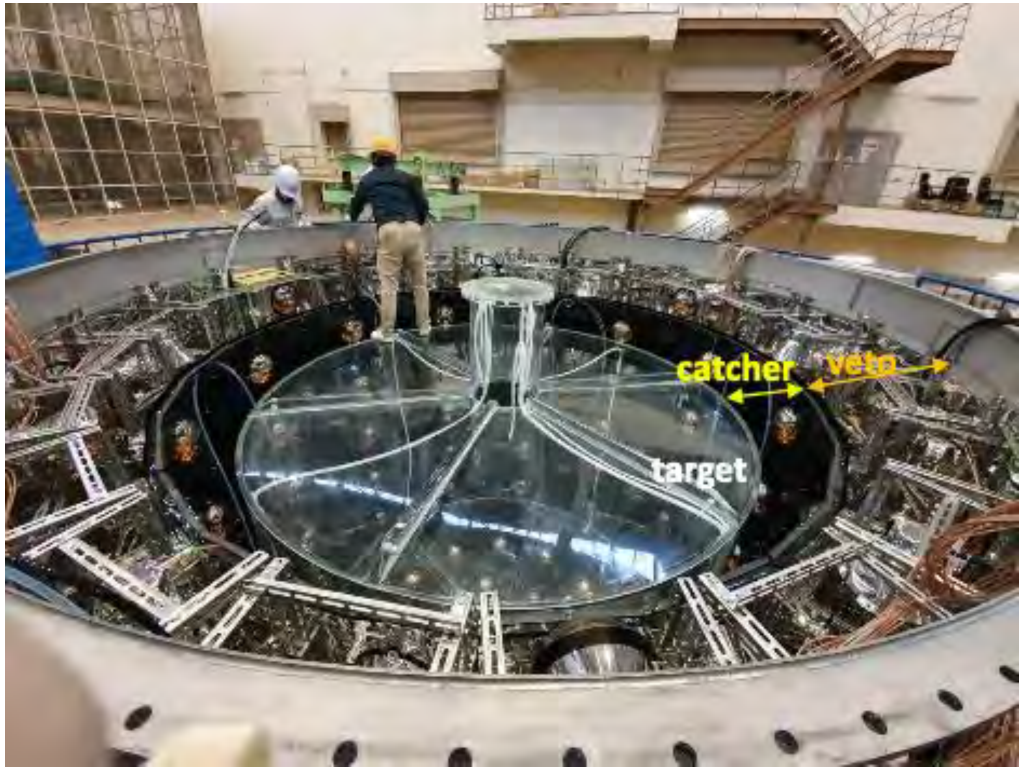
Membrane cryostat
Completed in October 2022

SBN Will have 5σ Coverage of the Short-Baseline ν Anomalies!

νμ disappearance | νe appearance | νe disappearance



JSNS^2



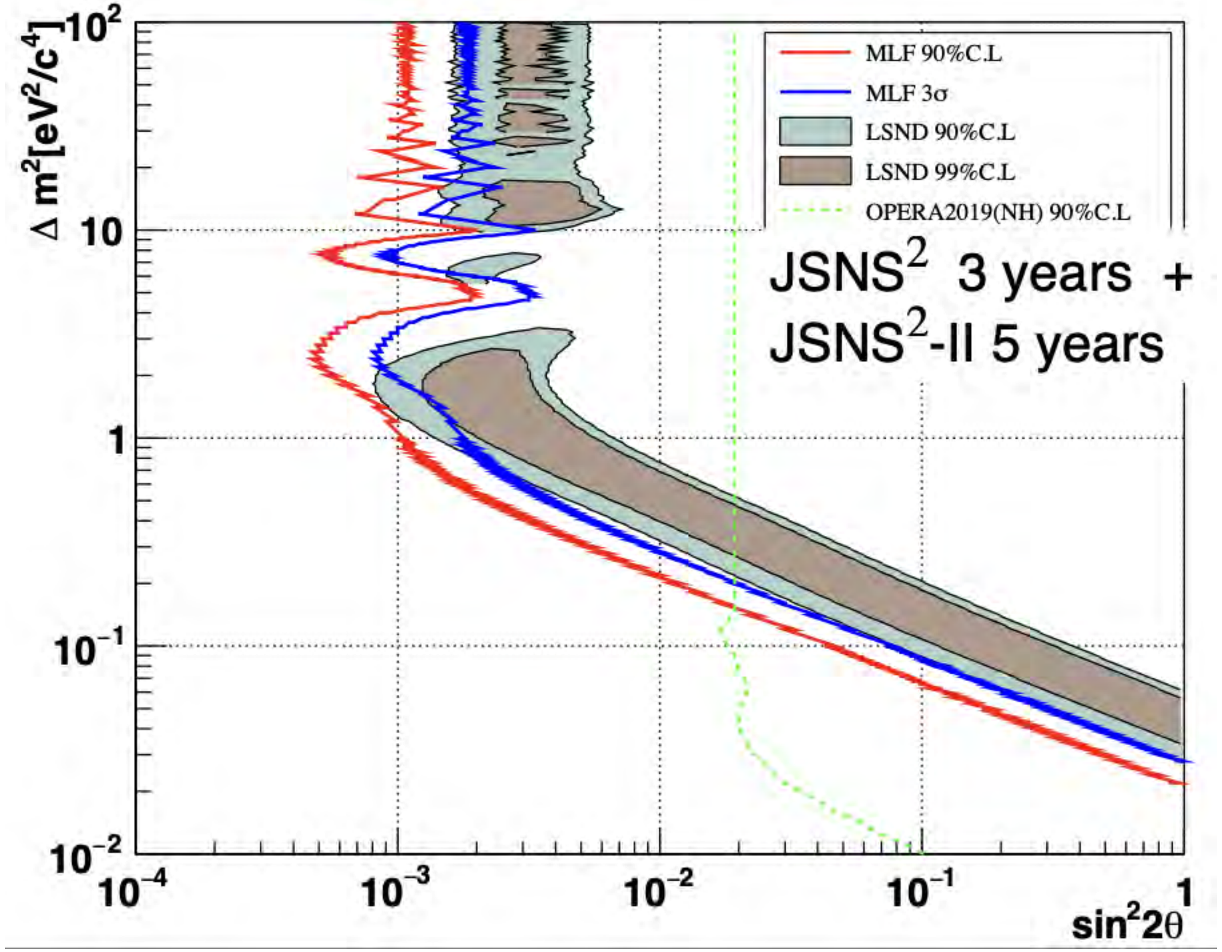
JSNS2 will provide a direct test of the LSND Signal
J-PARC MLF facility: 25 Hz, 1 MW, 3 GeV RCS
Each pulse consists of 2x100 ns buckets, 600 ns apart

50t (Gd-loaded + unloaded) liquid scintillator detector (4.6m diameter x 4.0m height)
120 10” PMTs

$JSNS^2$ vs. LSND

	LSND	$JSNS^2$	Notes
Detector Mass	167t	17t	-
Baseline	30m	24m	-
Beam Proton Energy	0.8GeV	3GeV	Allows for KDAR measurement. Expect ~10x higher pion production
Beam Power	800kW	1MW	-
Beam Duty Factor	600μs x120Hz	100ns(x2) x25Hz	Expect ~300x fewer ambient IBD backgrounds
Detector Medium	Dilute LS	Gd-LS	-
Neutron Capture	Hydrogen, ~0.2ms, 2.2MeV	Gadolinium, ~26μs, 8MeV	Shorter capture time & higher energy mean fewer backgrounds
Particle ID	Cherenkov	PSD	-

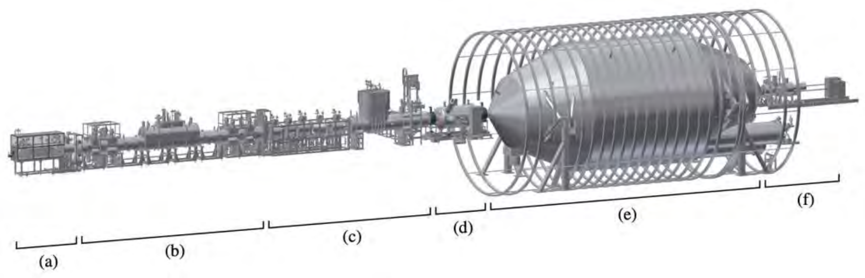
JSNS^2 Will Cover the LSND Signal at 3σ



Near Detector: 17 tons, 120 10-inch PMTs, 24 m
Far Detector: 32 tons, 220 10-inch PMTs, 48 m

KATRIN Tritium Beta Decay Experiment

Phys.Rev. D 105, 072004 (2022)

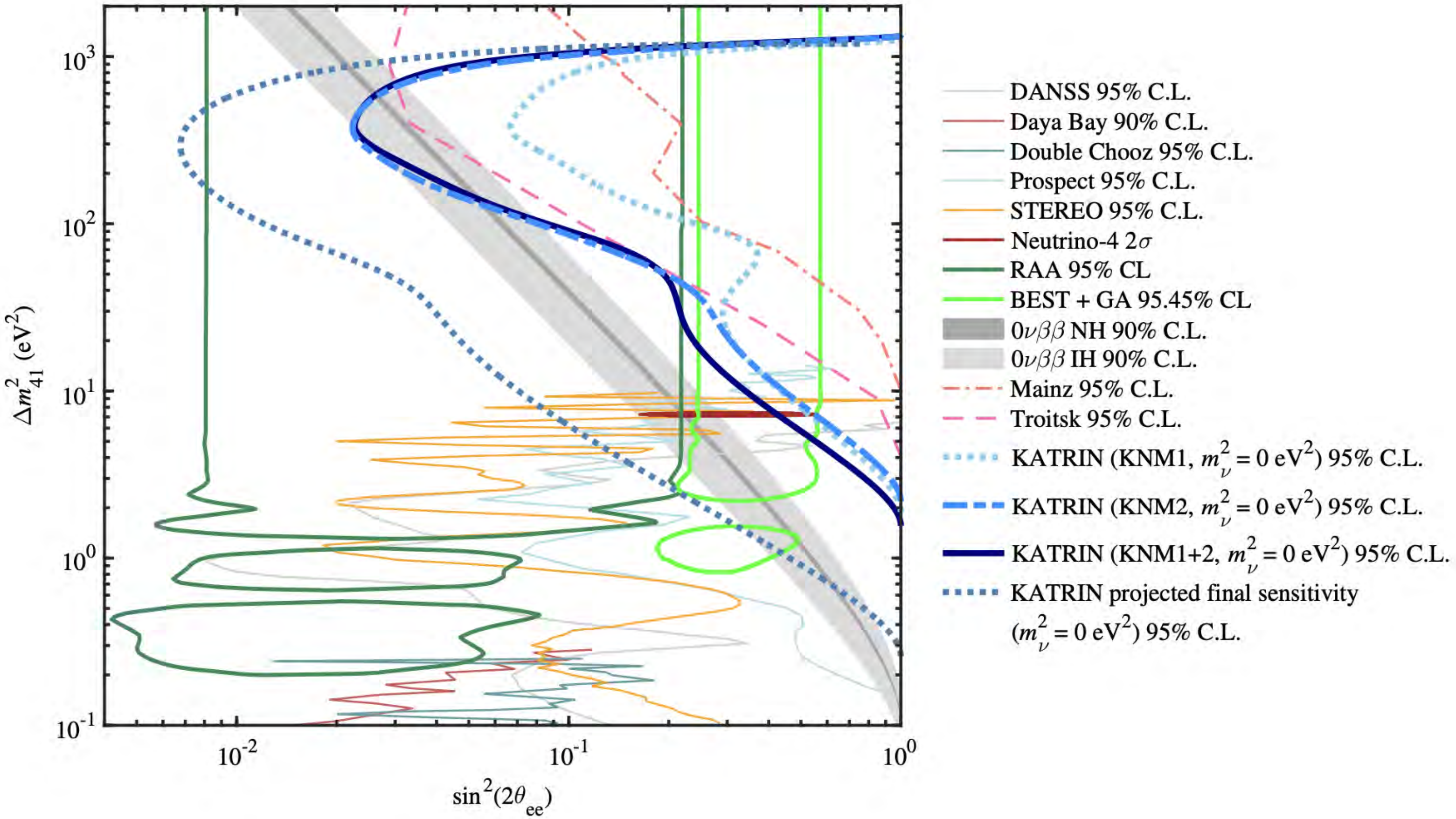


KATRIN has set a limit on the ν_1 mass of ~0.45 eV, with an ultimate sensitivity of <0.3 eV.

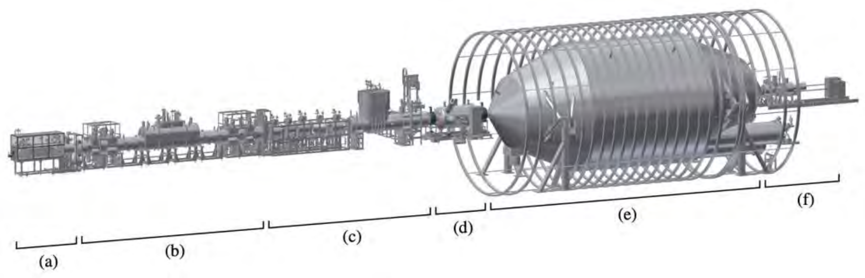
KATRIN has also set limits on the mass of ν_4 which is mostly sterile.

KATRIN has sensitivity to fully cover the Neutrino 4 signal.

Nexus of ββ decay, tritium β decay, reactors, & radioactive source expts.



KATRIN Tritium Beta Decay Experiment



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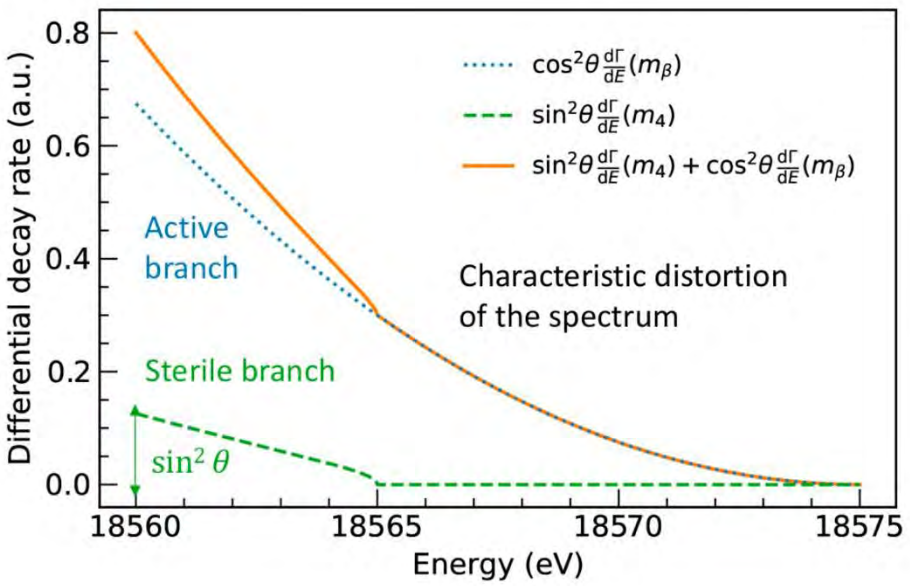
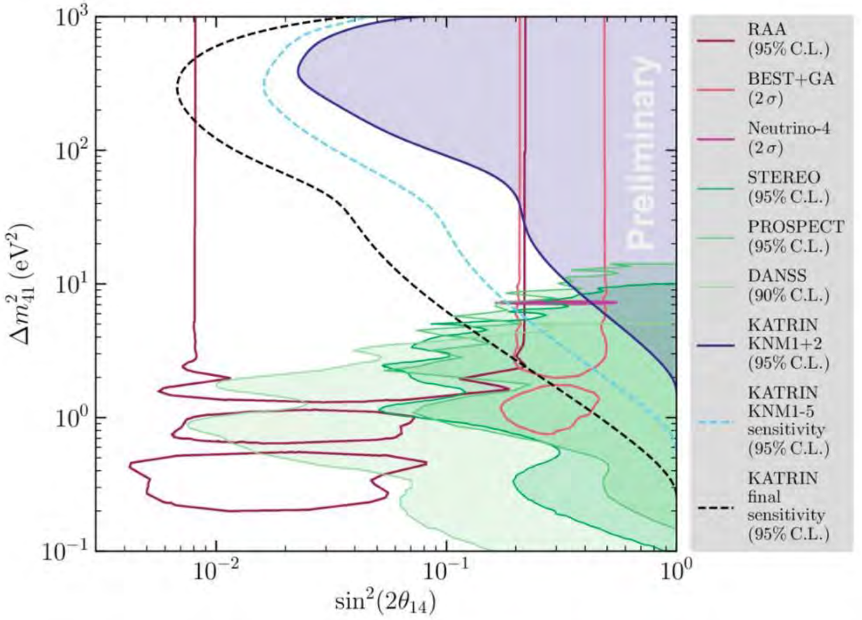
KATRIN has sensitivity to fully cover the Neutrino 4 signal





Conclusions

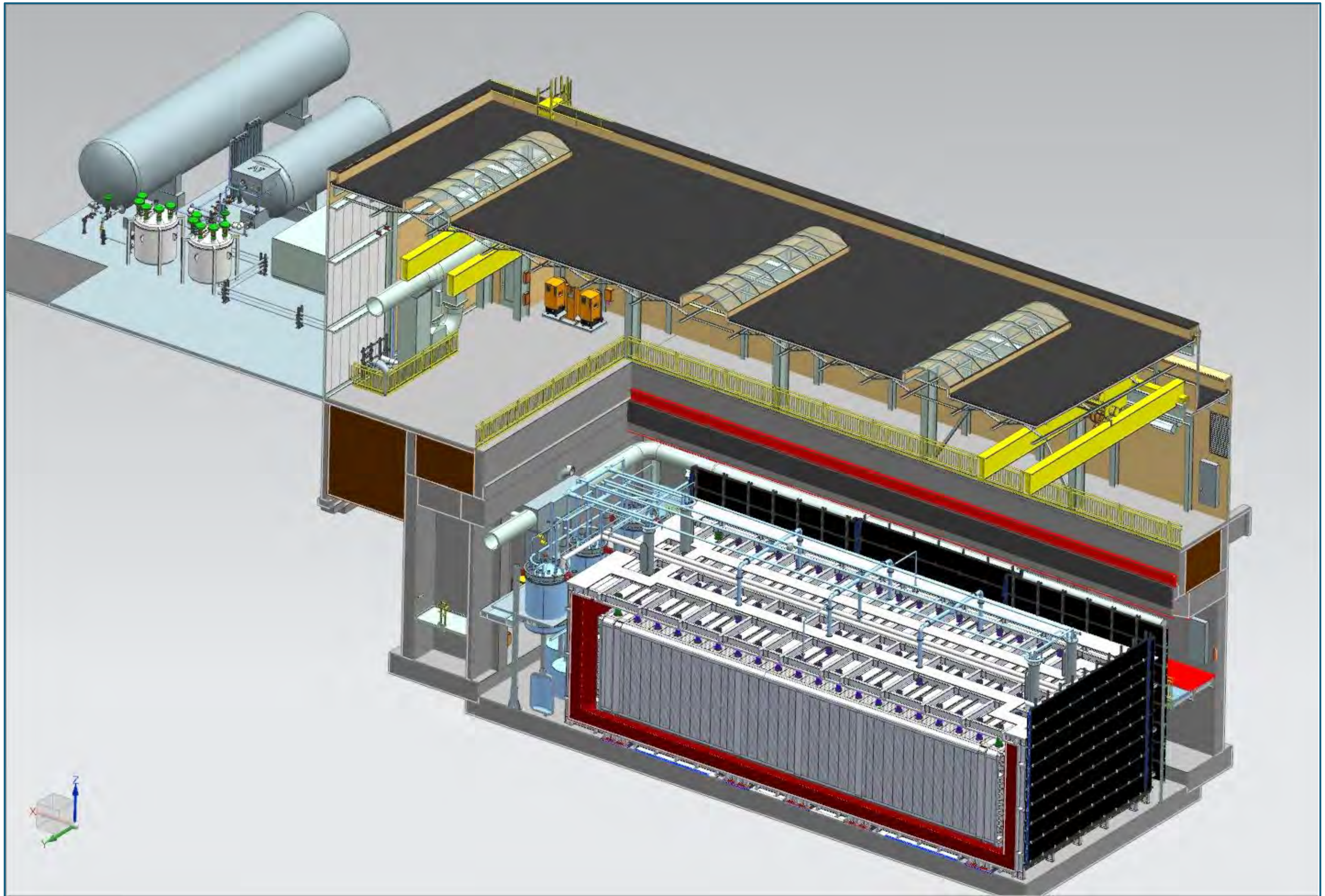
- Strong evidence for sterile neutrinos, although the 3+1 model is probably too simplistic
- Sterile neutrinos are great dark matter candidates and could help explain the Hubble Constant discrepancy
- Upcoming experiments (SBN, $JSNS^2$, KATRIN) may be able to prove overwhelmingly the existence of sterile neutrinos

MicroBooNE Observes a ν_e Deficit Consistent with the Gallium Anomaly!

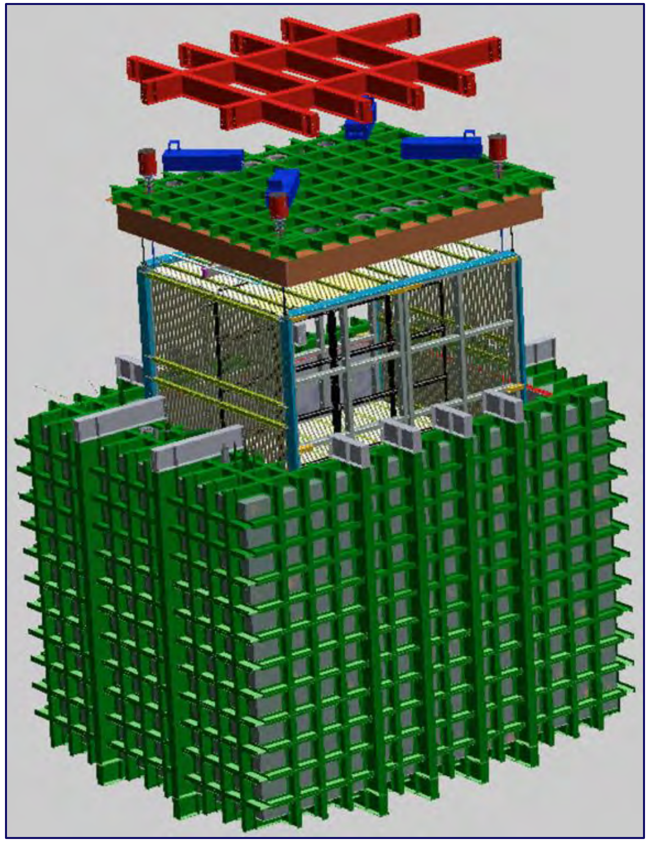
Number of events

	Signal channel	
	$1eNp0\pi$	$1e0p0\pi$
Data counts	102	41
Total H_0 prediction (constrained)	133.5 ± 7.4	47.6 ± 3.7
Total H_1 prediction (constrained, signal model 1)	151.7 ± 8.2	55.3 ± 3.9
Total H_1 prediction (constrained, signal model 2)	168.5 ± 9.3	57.7 ± 4.1
Total H_0 prediction (unconstrained)	123.6 ± 17.1	42.8 ± 7.6
Cosmics (unconstrained)	0.8	5.3
ν_e CC (unconstrained)	104.1	18.4
ν other (unconstrained)	6.8	6.1
ν NC π^0 (unconstrained)	11.9	13.1
MiniBooNE LEE Signal Model 1 (unconstrained)	13.4	5.0
MiniBooNE LEE Signal Model 2 (unconstrained)	29.9	7.5

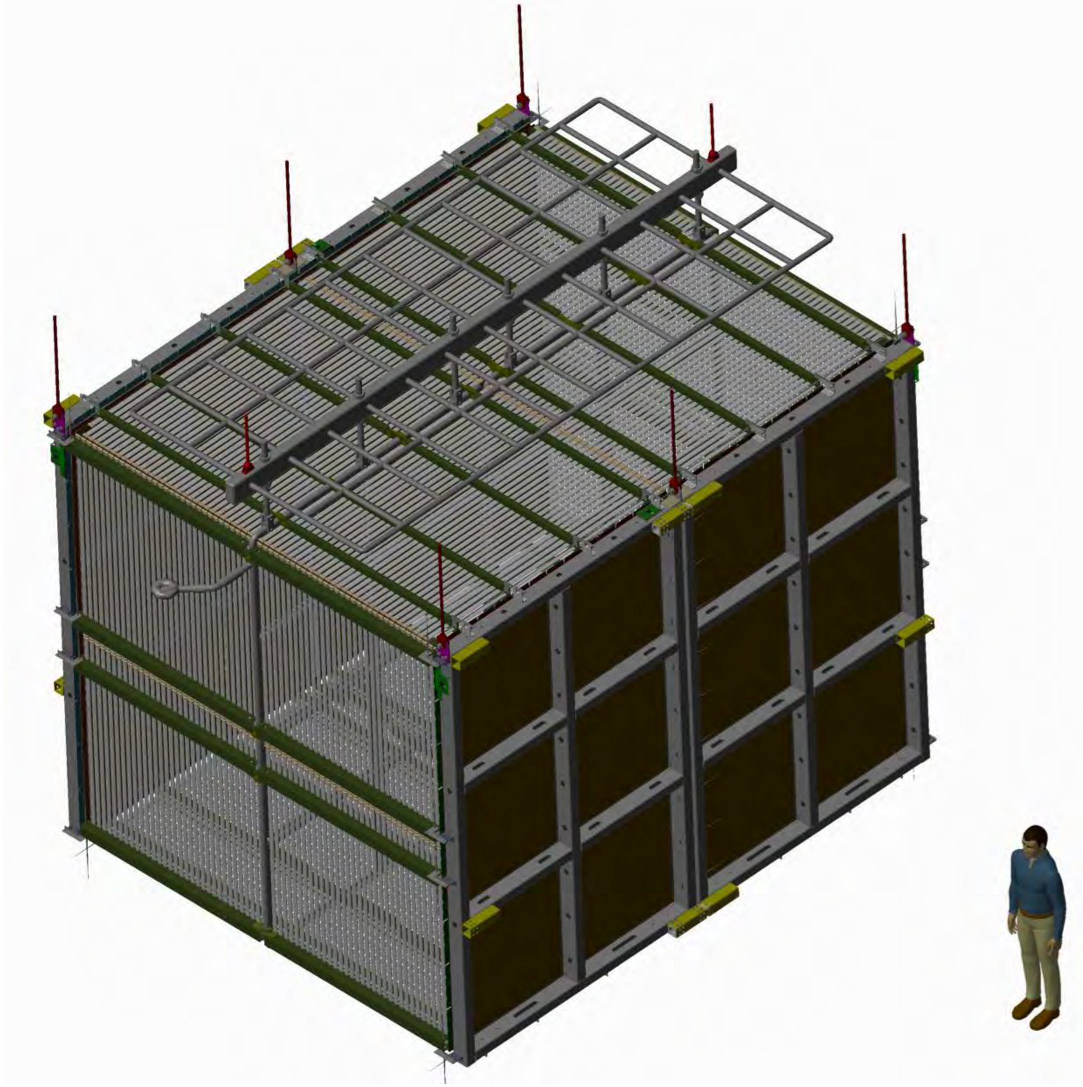
ICARUS



SBND



Membrane cryostat
constructed inside an outer
warm steel structure



Central cathode
with two 2m drift regions

Two 4m x 2.5m
Anode Plane Assemblies
(APAs) per side (drift region)