# Sterile neutrino searches at Fermilab

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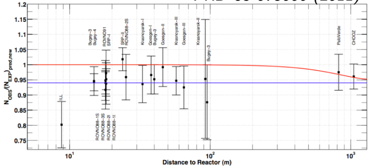
*(showing recent results from MINOS+, MiniBooNE, and the SBN experiments)*

SLAC NATIONAL ACCELERATOR LABORATORY

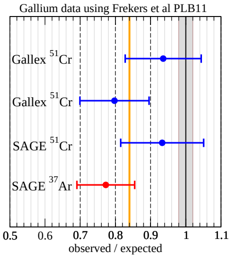
Fermilab 53rd Annual Users Meeting, August 13, 2020

# Anomalies from the electron neutrino world

PRD 83 073006 (2011)

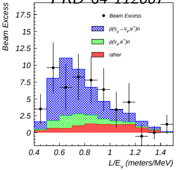



"reactor anomaly" unexpectedly low rate (−6%?) of positrons from reactor $\bar{\nu}_e$ (U and Pu decays)



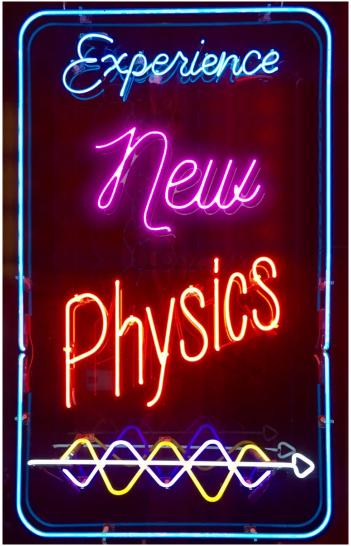

"gallium anomaly" unexpectedly low rate of electron from radioactive $\nu_e$ sources

PRD 64 112007



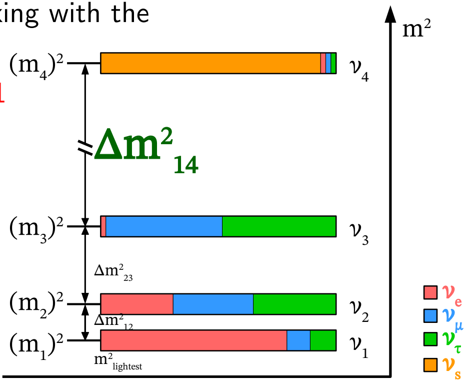

"LSND excess" unexpectedly high rate of electrons from $\mu$ decays at rest

# Accommodating anomalies: *enter* sterile neutrinos




A way out: postulate $N$ new "sterile" neutrinos

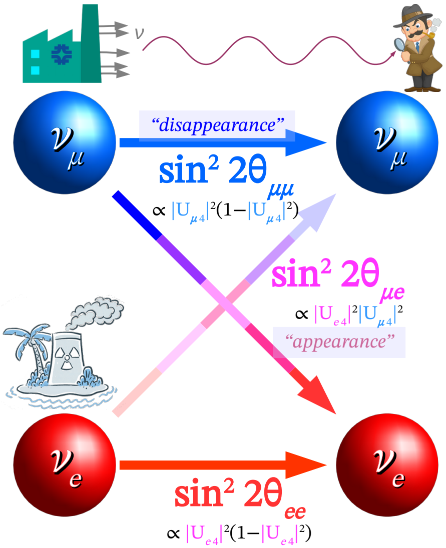
- from 3 to $(3 + N)$
- no electric, no strong, no weak charge
- realised by quantum mixing with the 3 "standard" neutrinos
- simplest scenario: $N = 1$
  $\rightarrow$ observable: $\Delta m^2_{41}$



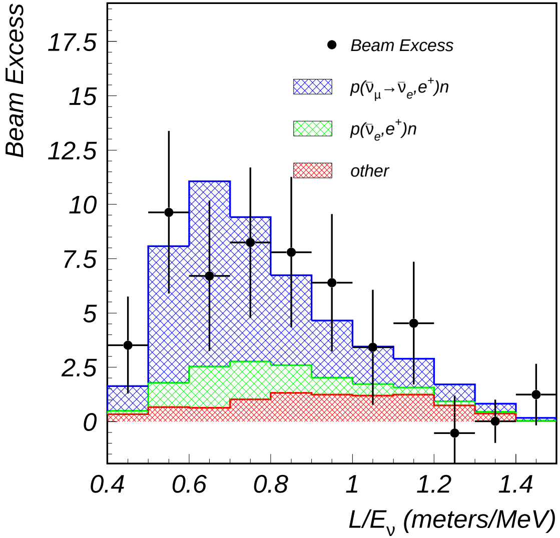
A practical, simplified view:
only $\nu_e$ and $\nu_\mu$ (the ones we probe) mix

Three measurements ( $\sin^2 2\theta_{\mu e}$, $\sin^2 2\theta_{\mu\mu}$, $\sin^2 2\theta_{ee}$) for two parameters ($|U_{e4}|^2$, $|U_{\mu 4}|^2$): self-consistency check!

*(Plenty of shortcuts: $\Delta m^2_{41} \gg \Delta m^2_{31}$, ignoring $\nu_\tau$, same probability for $\nu$ and $\bar{\nu}$, ...)*



# LSND result

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* *See A. Mastbaum's talk.*

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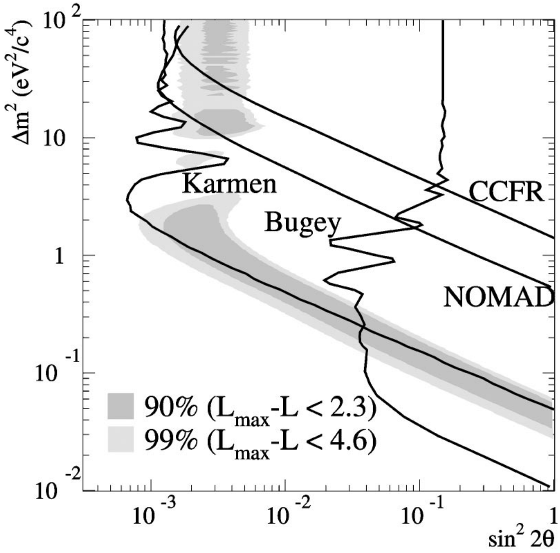


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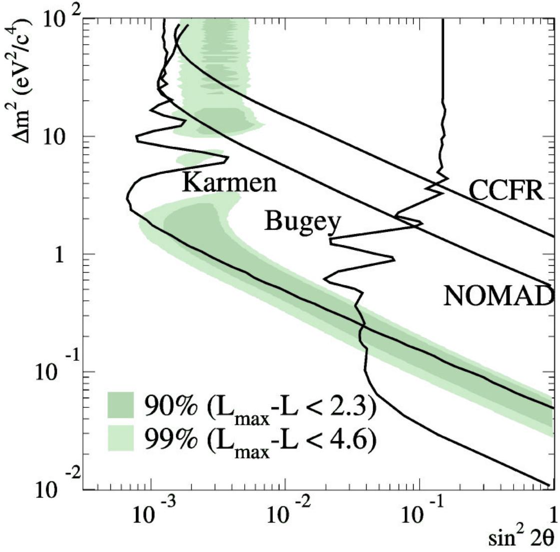


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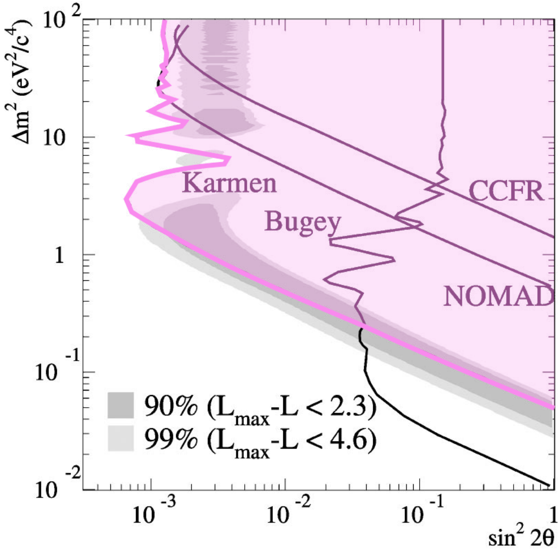


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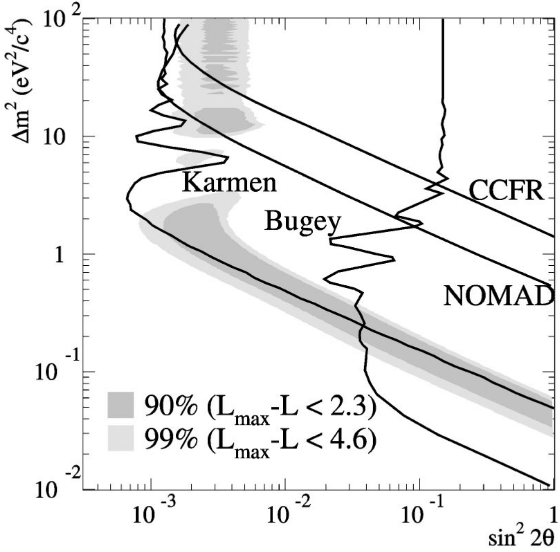


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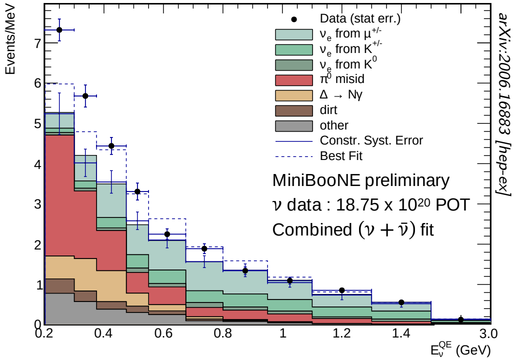
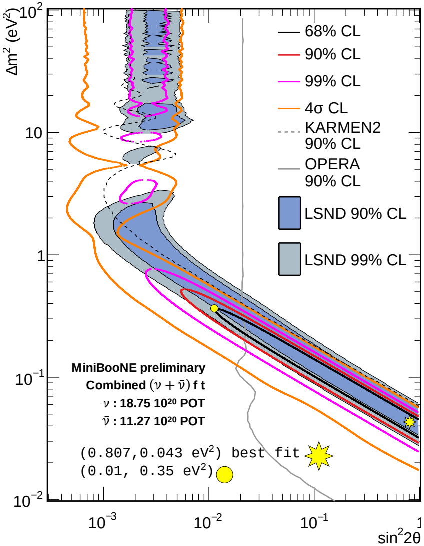
# Confirmation of the excess: MiniBooNE

MiniBooNE was proposed to solve the riddle...

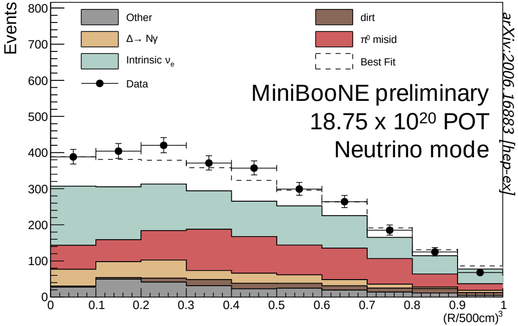
- $E_\nu \approx 500$ MeV, $L \approx 500$ m $\rightarrow$ again $\frac{L}{E} \approx 1$ m/MeV
- collected data (both $\nu$ and $\bar{\nu}$) in 2002–2019
- and *did* observe an excess of events! but...



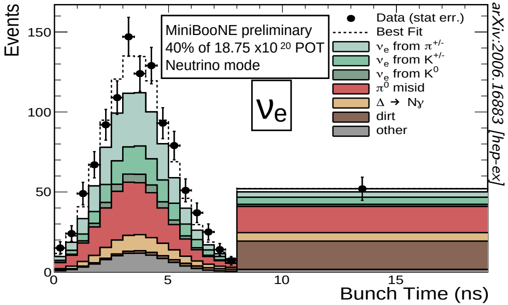



How to interpret those events? are those really electrons, or photons? some recent checks:

- $\gamma$ leaking in from outside the detector?
  $\Rightarrow$ excess is not concentrated at borders



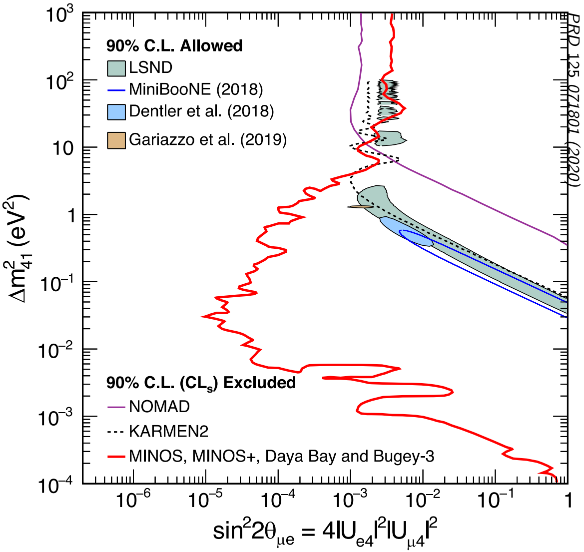

- some external, unrelated background?
  $\Rightarrow$ excess matches time of arrival of beam




MiniBooNE is publishing observed 2D distributions that may help model builders.

# The other side of the oscillation: MINOS+

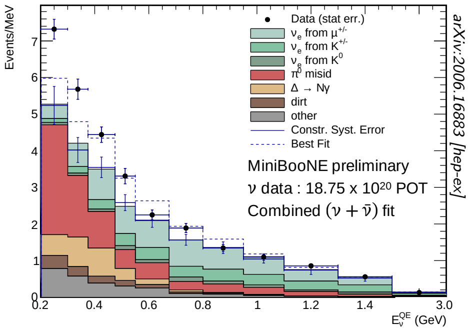
- $\nu_\mu \leftrightarrow \nu_e$ oscillations imply "disappearance" of both $\nu_\mu$ and $\nu_e$
- results from MINOS+ and ICECUBE set *limits on $\nu_\mu$ disappearance*
- combination of (Daya Bay + Bugey 3) (reactor experiments) and MINOS+ strengthens the exclusion of LSND/MiniBooNE signal as due to sterile neutrino within "3+1" model

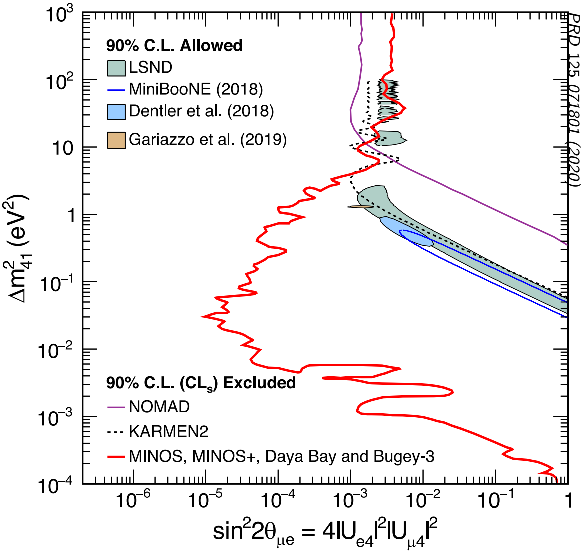


# Contradicting observations?

- $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$ results "in tension"

… and "3+1" model does not fit MiniBooNE data that well at low neutrino energy *(dashed line ↓)*:



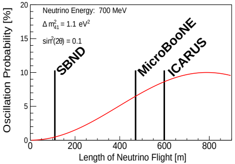



# The SBN program components

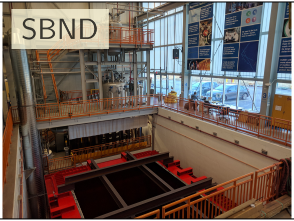
Fermilab Short Baseline Neutrino (SBN) program:

- designed to address the open questions on $\approx 1\,\text{eV}^2$ sterile neutrinos

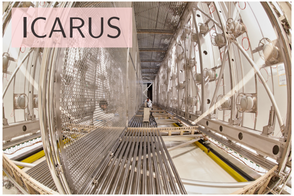
→ measure $\nu_\mu$ *and* $\nu_e$ oscillations, resolve electrons from photons




Booster Neutrino Beam, average: $E_\nu \approx 700\,\text{MeV}$

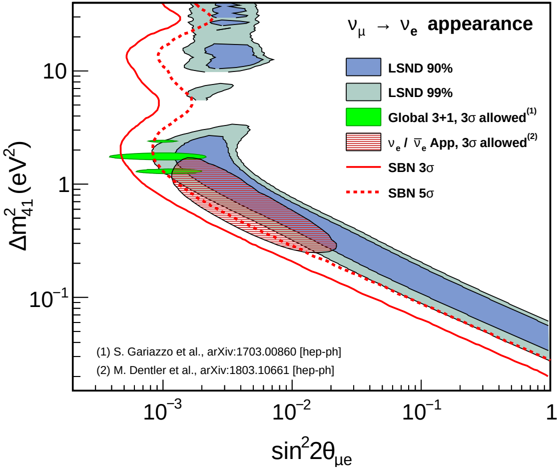


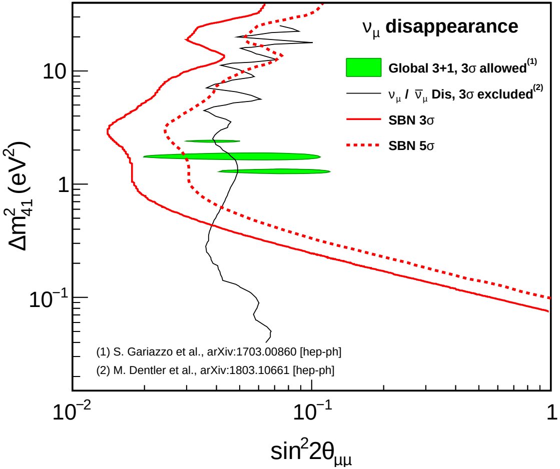





| | | | |
|---|---|---|---|
| active argon | 112 ton | 85 ton | 470 ton |
| $L$ | 110 m | 470 m | 600 m |
| $p$ on target | $6 \cdot 10^{20}$ | $12 \cdot 10^{20}$ | $6 \cdot 10^{20}$ |
| first data | 2021 | 2015 | 2020 |

# SBN expected sensitivity

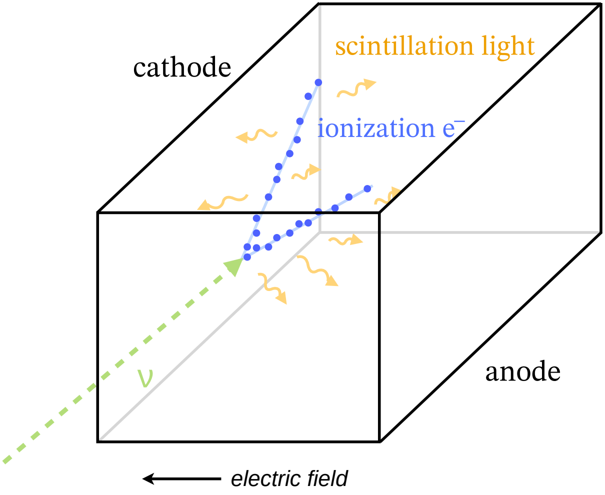



Expected sensitivity at 3 SD covers MiniBooNE and LSND

*(Annu. Rev. Nucl. Part. Sci.* 69, *363 (2019))*

# Liquid Argon Time Projection Chamber (LArTPC) is good for you




*drawing by Y.-T. Tsai*

How does it work:

- pioneered by ICARUS (@Italy)

1. beam interacts with $^{40}Ar$
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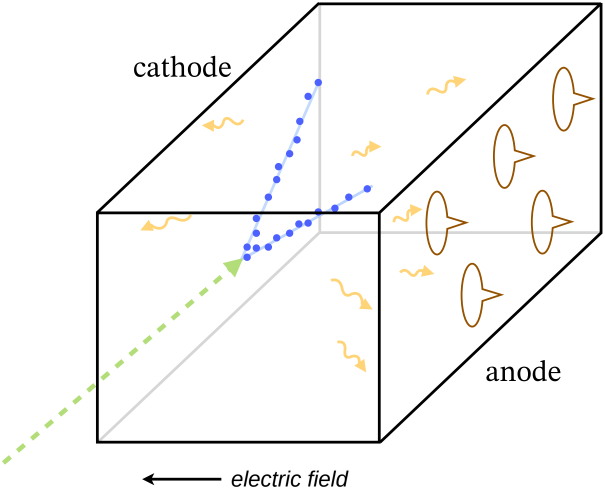


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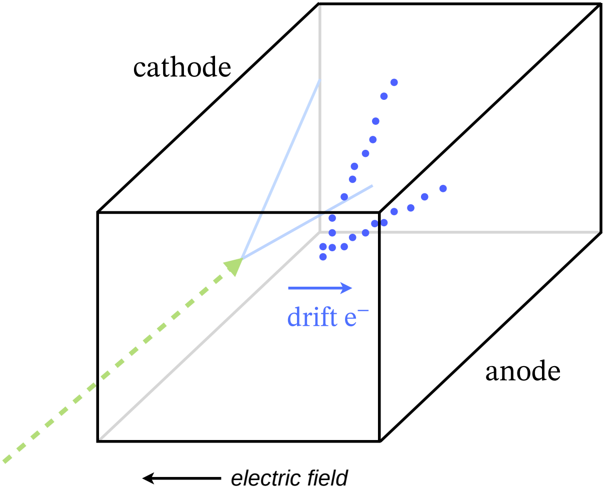


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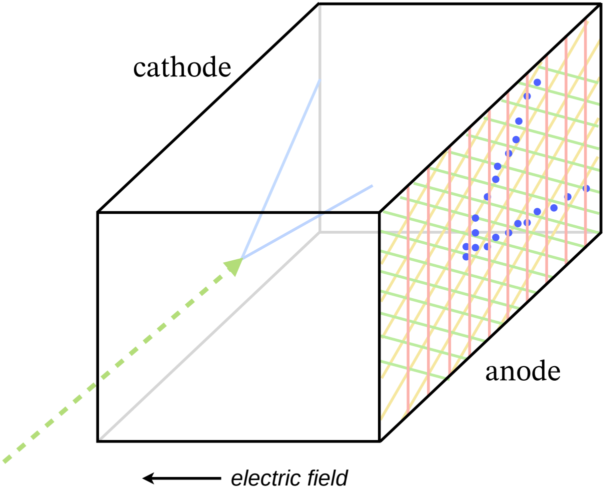


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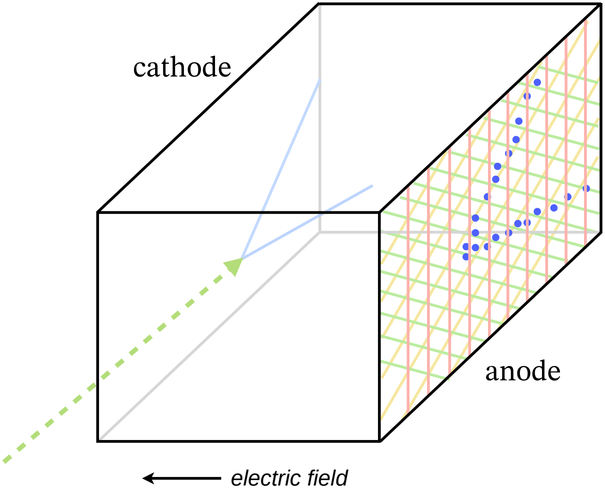


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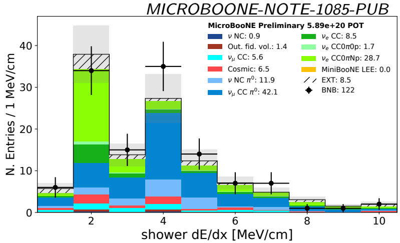
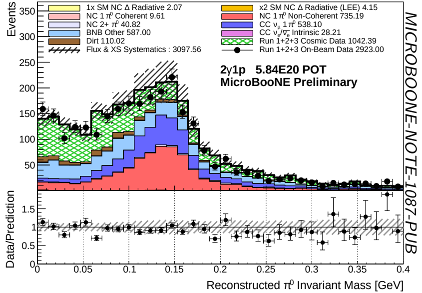
5. (three) wire sets sense them arriving
6. we get three detailed projections of the tracks and mildly localised light flashes

# The avant-garde: MicroBooNE




- designed to address the open questions on $\approx 1\,\mathrm{eV}^2$ sterile neutrinos
- same location as MiniBooNE $\rightarrow \frac{L}{E} \approx 1\,\mathrm{m/MeV}$
- can resolve photons from electrons $\nearrow$
- with good energy resolution for $E_\nu$ $\rightarrow$
- just completed the 5th year of data taking: $12 \cdot 10^{20}$ "protons on target" in the vault

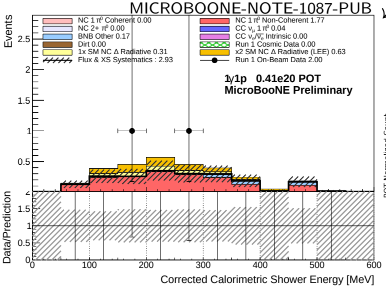
# MicroBooNE pushing forward

MicroBooNE looks for data excess at energy 200 – 600 MeV:

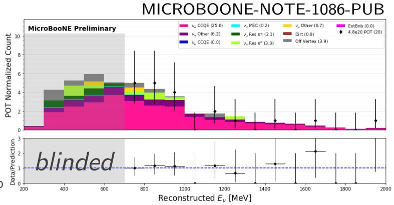
- low energy photons: $\nu$ Ar $\rightarrow \nu\ \gamma + X$ (MicroBooNE note 1087)
  $\rightarrow$ "side product": $\nu$ Ar $\rightarrow \nu\ \pi^0$ measurement useful for theory
- low energy electrons: three approaches (MicroBooNE notes 1085, 1086, 1088)
- analysis of $5 \cdot 10^{20}$ PoT ongoing: now checking side bands before full unblinding

$\swarrow$ $\gamma + p$: 5% open data

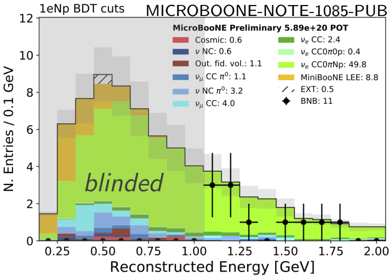
$e + p$: side bands $\downarrow \searrow$




$\gamma + p$ analysis: reconstructed $E_\gamma$




$e + p$ analysis: reconstructed $E_e$



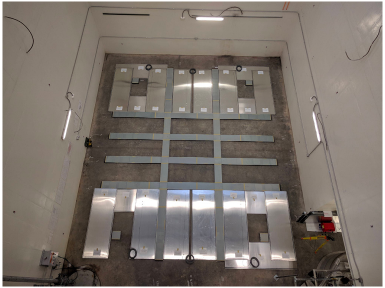

$e + N \times p$ analysis: reconstructed $E_e$

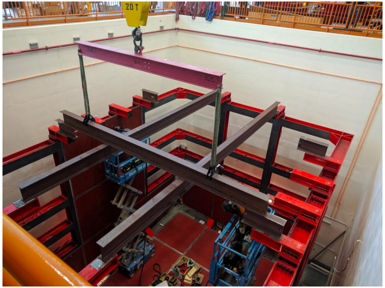
# Status of SBND construction highlights

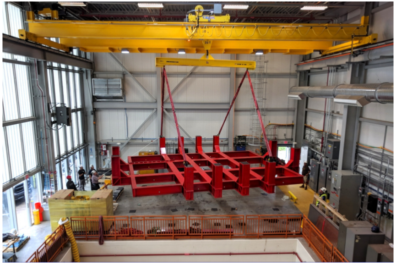
detector building →

↓ bottom side of cosmic ray detector installed

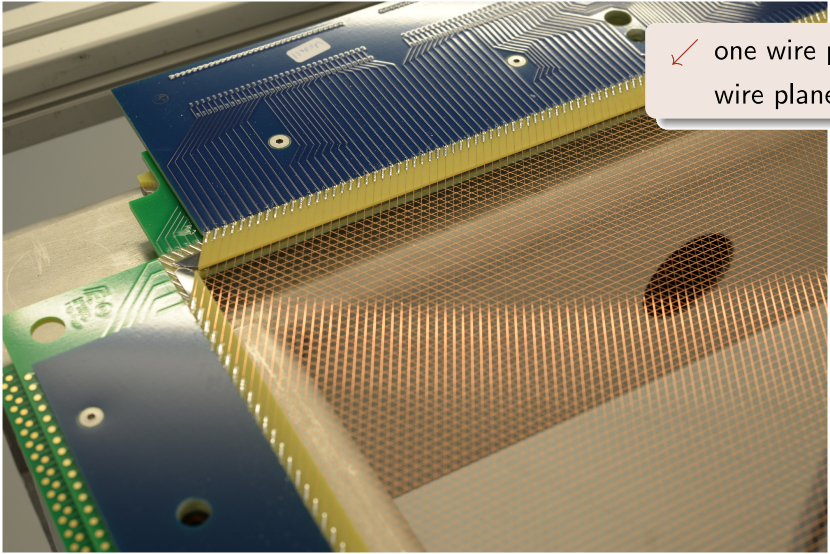
cryostat warm vessel installed ↓↘







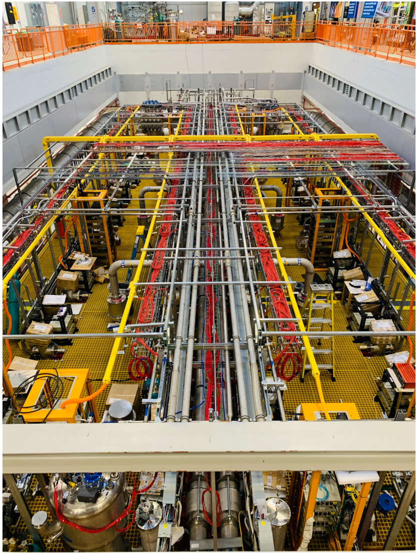
# Status of SBND construction: wire planes



↙ one wire plane (3 wire orientations)

wire plane support to FNAL DAB ↓

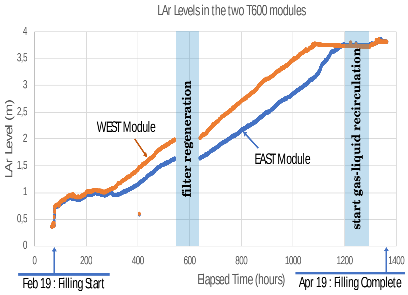
# Status of ICARUS commissioning (I)

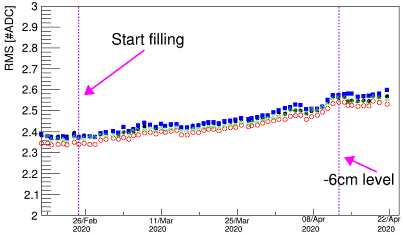


- cryogenic system installed and fully operational
- optical detector and TPC wire readout ready
- trigger distribution system being installed
- study of electronics noise ongoing
- 3-year data taking expected to start in autumn 2020

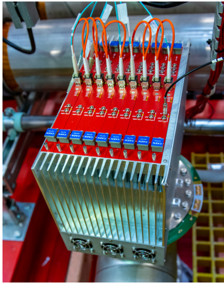
Cosmic ray tagging detectors and concrete overburden will be completed along the way. *(shown here bottom and side panels already installed)*

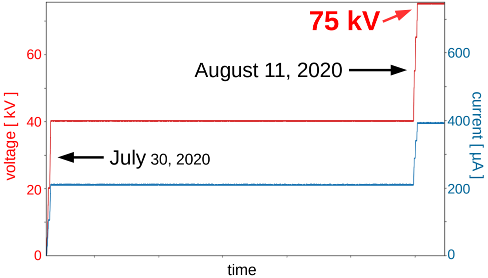
# Status of ICARUS commissioning (II)



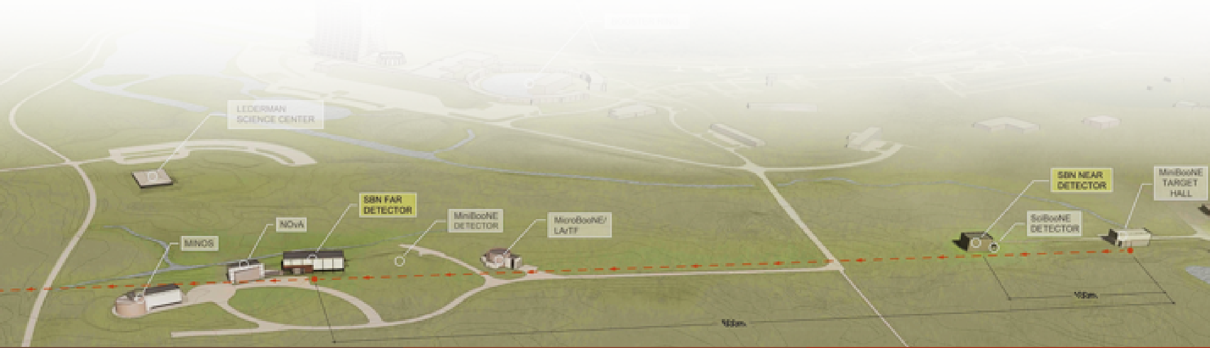

- readout cabling completed days ago →
- filling with liquid argon completed in April 2020 (readout noise was monitored)
- noise studies ongoing
- cathode voltage ramped up to the nominal 75 kV ↓





# After SBN

- observations hint to a sterile neutrino at 1 $\text{eV}^2$, but…
  $\rightarrow$ "3+N" models are having a hard time; others have been outright excluded
  $\rightarrow$ more complex models seem to be necessary to explain *the existing data*…
- information-rich LArTPC is solid foundation to cover studies we don't know yet we need
- with SBN, in five years from now we look forward for the resolution of these anomalies, or the confirmation of discovery of new phenomena



# Additional material

# Neutrinos, oscillations and their probabilities


- each charged lepton comes with a "flavour", and it keeps it for all its life
- neutrinos also come with a flavour, but they may *change* it
- quantum effect → probability of change "oscillates" in time:

$$P(\nu_e \to \nu_\mu) \propto P_{e\mu}^{max} \sin^2 \omega_{e\mu} t$$

- three flavour (e $\mu$, $\tau$) → six independent parameters:

| | | | |
|---|---|---|---|
| $\Delta m^2_{21}$ | $(7.53 \pm 0.18) \cdot 10^{-5}\ \text{eV}^2$ | $\sin^2\theta_{12}$ | $(0.307 \pm 0.013)$ rad |
| $\Delta m^2_{31}$ | $(2.453 \pm 0.034) \cdot 10^{-3}\ \text{eV}^2$ | $\sin^2\theta_{13}$ | $(0.0218 \pm 0.0007)$ rad |
| $\delta_{CP}$ | ? | $\sin^2\theta_{23}$ | $(0.545 \pm 0.021)$ rad |

… *or so we thought.*

# Approximate 2-neutrino oscillation probabilities in 3+1 model

Simplified view:

- only one sterile neutrino ($N = 1$)...
- .. and only $\nu_e$ and $\nu_\mu$ (the ones we probe)
- $\Delta m^2_{41} \gg \Delta m^2_{31}$, ignoring $\nu_\tau$, same probability for $\nu$ and $\bar{\nu}$, ...

$$P(\nu_\mu \to \nu_e) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41}}{4} \frac{L}{E}$$

$$P(\nu_\mu \to \nu_\mu) = 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) \sin^2 \frac{\Delta m^2_{41} L}{4E} = \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{41}}{4} \frac{L}{E}$$

$$P(\nu_e \to \nu_e) = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \sin^2 \frac{\Delta m^2_{41} L}{4E} = \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4} \frac{L}{E}$$

(the oscillation argument is actually $\sin^2\left(1.27 \cdot \Delta m^2_{41} \frac{L}{E}\right)$ using $\Delta m^2_{41}$ in eV$^2$, $L$ in metres and $E$ in MeV)

1. Source packs five $\nu_\mu$ for us…

⇒

2. … they are sent express par avion…

⇒

3. … and we open the box looking for:

… muons! expect five, find five.

nothing is missing.

Also, no oscillation occurred.

… muons! we find ONLY THREE?!

Some $\mu$ have **disappeared**!

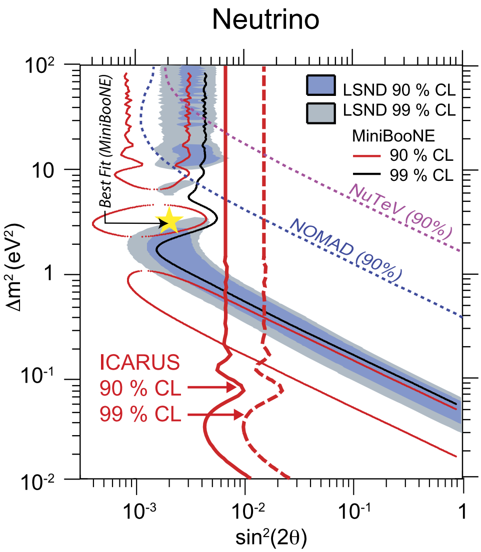
(actually, two $\nu_\mu$ "oscillated away" from $\mu$ flavour)

… electrons! expect 0… find TWO?!

"I would give 0 stars if I could!"

Some $e^-$ have **appeared**! (actually, two $\nu_\mu$ "oscillated" to $\nu_e$ flavour)

# ICARUS@LNGS: exclusion




EPJ C(2013) 73: 2599:

- mostly $\nu_\mu$ beam (CNGS) from CERN to Gran Sasso (LNGS)
- on the axes: $\Delta m^2_{41}$ and $\sin^2 2\theta_{\mu e}$

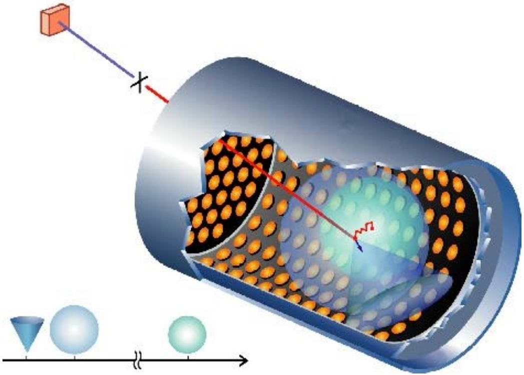
# Recent results from short baseline reactor experiments

- Reactor antineutrino anomaly (RAA): best fit at $\Delta m^2_{41} \approx 2.3\,\text{eV}^2$, $\sin^2 2\theta_{\mu e} = 0.5$
- Neutrino-4 (RU) (Jetp Lett. 109 (2019) 213; A.P. Serebrov et al. arXiv:2005.05301): oscillations at $\Delta m^2_{41} = 7.25\,\text{eV}^2$, $\sin^2 2\theta_{\mu e} = 0.26$ (2.8 s.d.)
- PROSPECT(US): disfavours RAA at 2.2 s.d. (PRL 121 (2018) 251802)
- STEREO (FR): disfavours RAA at 99.9% CL (arXiv:1912.06582 and 2004.04075)
- DANSS (RU): excludes plenty (arXiv:1911.10140v1)
- NEOS (KR): excludes RAA at 4.3 s.d. (PRL 118 (2017) 121802)
- Solid (UK, FR, BE, US): ...

# Excess from antimuon neutrino: LSND

LSND took data at Los Alamos National Laboratory on 1993–1998:

- detector: 167 tons of mineral oil with scintillator
- antimuons decay at rest 30 m upstream
  $\rightarrow$ decay $\bar{\nu}_\mu$ spectrum well known, $E < 52\,\text{MeV}$
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\bar{\nu}_e p \rightarrow e^+ n$ ("inverse $\beta$ decay"), neutron captured emits photon
- look for a $e^+$ (scintillation + Cherenkov light) and a 2.2 MeV $\gamma$ after $\approx$ 180 ns
- tests $E_{\bar{\nu}_e} \approx 20 - 60$ GeV, $L \approx 25 - 35$ m $\Rightarrow$
  $L/E = \mathcal{O}\left(0.5 - 1.5\,\text{eV}^2\right)$

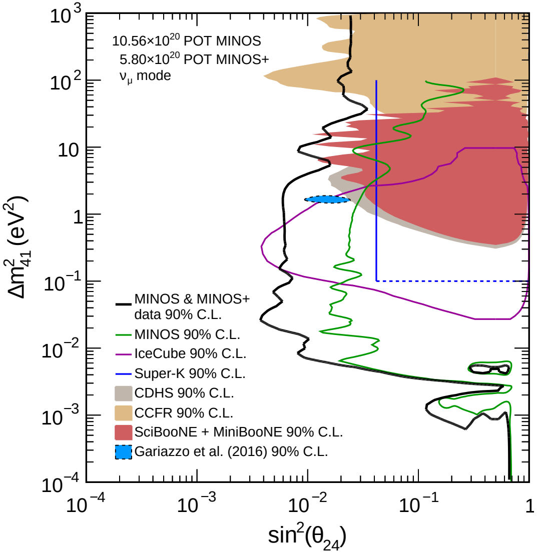


back to LSND results

# MINOS+ disappearance result

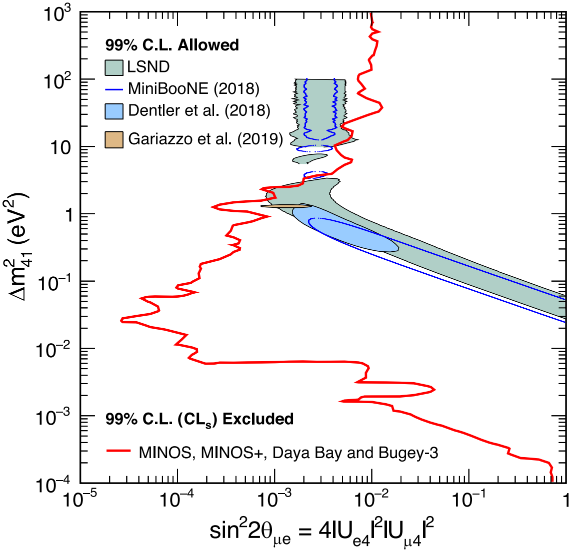
- results from MINOS+ set *limits on $\nu_\mu$ disappearance* (PRL **122** (2017) 091803)
- MINOS+: $L = 735$ km, $E_\nu = 7$ GeV (newest data) $\rightarrow \frac{L}{E} \approx 100$ m/MeV

*(the blue global fit in the plot is dated 2016 ↗)*

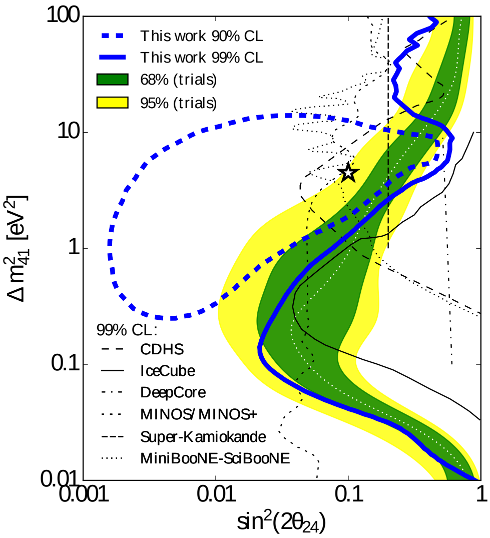


# The other side of the oscillation: MINOS+

Same result as shown before, but with CL=99%
*PRL* 125, *071801 (2020)*



# $\nu_\mu$ disappearance limits from ICECUBE




arXiv:2005.12942 (June 2020):

- exclusion "band" at confidence level 99%
- closed contour at confidence level 90% (null hypothesis — no disappearance — *p*-value 8%)
- quote: *"best-model location is at* $\Delta m^2 \approx 4.5\,\text{eV}^2$ *and* $\sin^2 2\theta_{24} \approx 0.9$ *and is strongly preferred, by a factor of 10.7, to the no sterile neutrino hypothesis"*