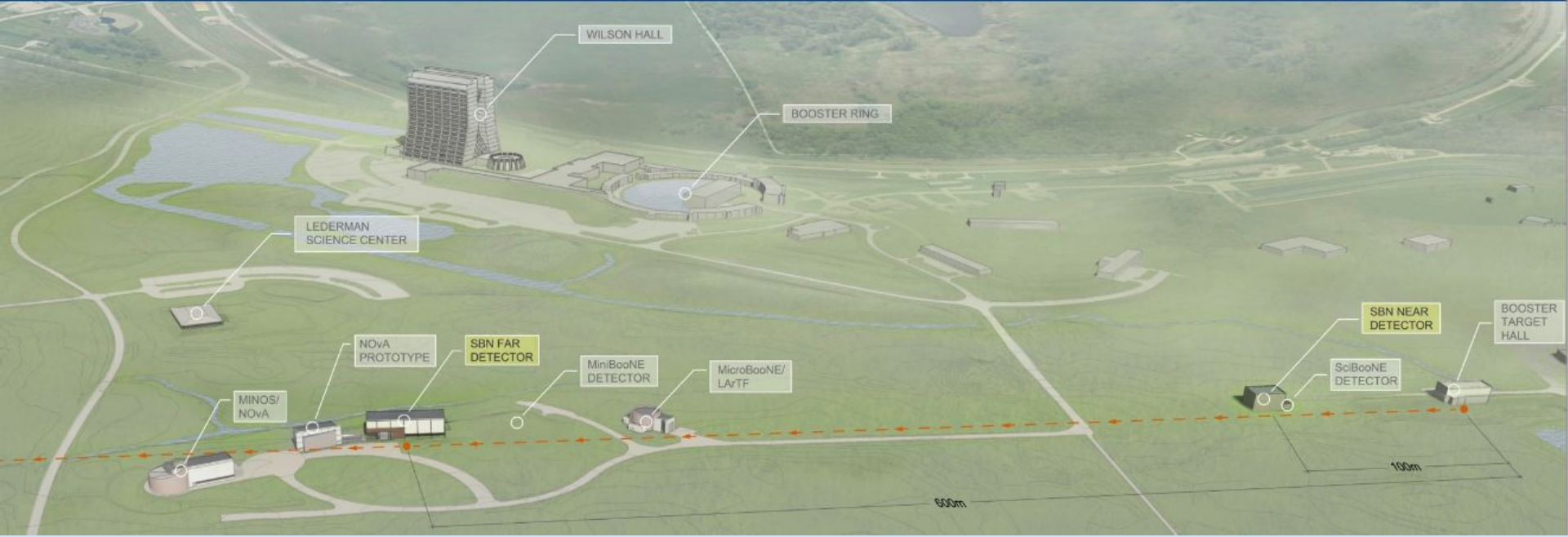


ICARUS at SBN

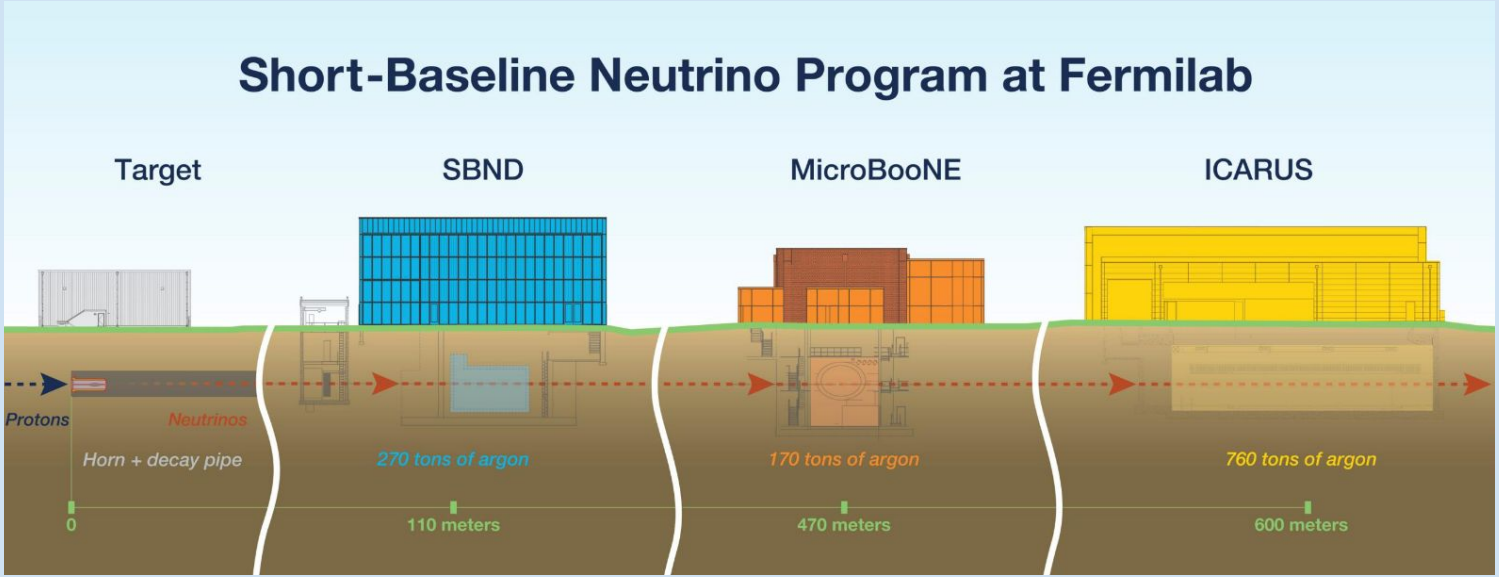
Tyler Boone, for the ICARUS collaboration
Colorado State University
6/17/22

Sterile Neutrinos

- There have been several anomalies observed in different neutrino experiments
- One possible solution to anomalous measurements is to propose a fourth, “sterile” neutrino state
- New mixing angles would be small
- Recent data from the Neutrino 4 experiment may point to steriles at ~7 eV^2
- ICARUS (as part of the SBN program) is perfectly situated to search for this anomalous neutrino at the 1 eV^2 mass scale

Anomaly name	**Neutrino source**	**Anomalous finding**
Gallium	Solar	Deficit of ν_e, Nobs/Npred = 0.84 to 2σ
"Reactor"	Nuclear reactors	Deficit of ν_e, Nobs/Npred = 0.93 ± 0.023
LSND	Decay-at-rest pion beam	Excess of ν_e to 3σ
MiniBooNE	Accelerator	Excess of ν_e to 3.4σ, excess of ν_e to 2.8σ

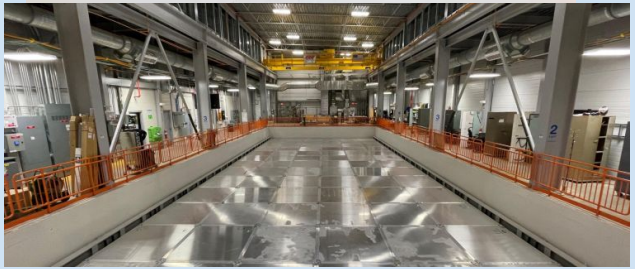
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

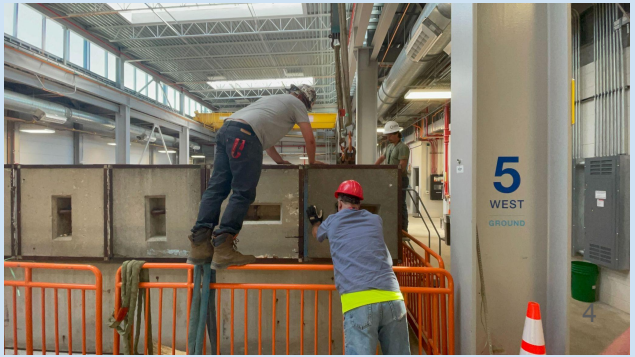


- MicroBooNE's goal: understand the MiniBooNE anomaly
  - Completed data taking in 2020, exciting results published in 2021
- SBND+ICARUS will search for short baseline neutrino oscillations which point to sterile neutrinos
- Dark matter searches will be conducted with NuMI off-axis beam
- Build expertise and understanding of liquid argon TPCs in neutrino beams, measure v-Ar cross sections at energies useful for DUNE

The ICARUS detector

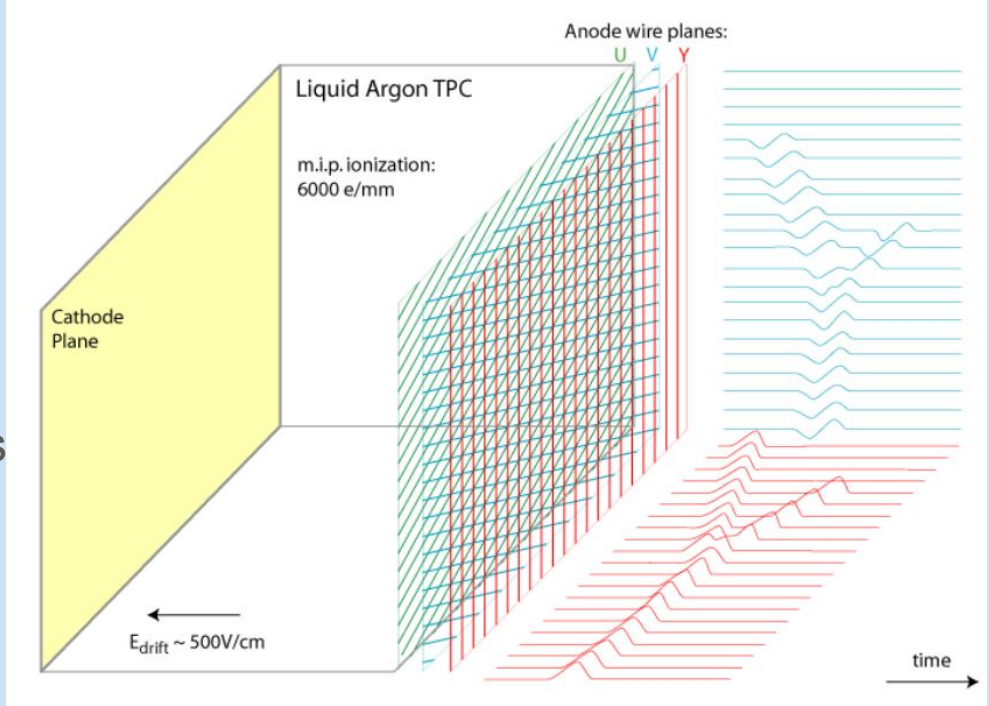
- ICARUS (**I**maging **C**osmics **A**nd **R**are **U**nderground **S**ignals) is a liquid argon Time Projection Chamber (LAr TPC) detector on-axis in the Fermilab Booster Neutrino Beam (BNB) beamline, and off-axis for the Neutrinos at the Main Injector (NuMI) beamline
- 760 tons total/476 tons active liquid argon
- ICARUS operated at Gran Sasso in Italy from 2010-2013, was refurbished at CERN from 2014-2017 and was shipped to Fermilab in the summer of 2017
- Commissioning of the detector is now just completed, with physics data being recorded this month!



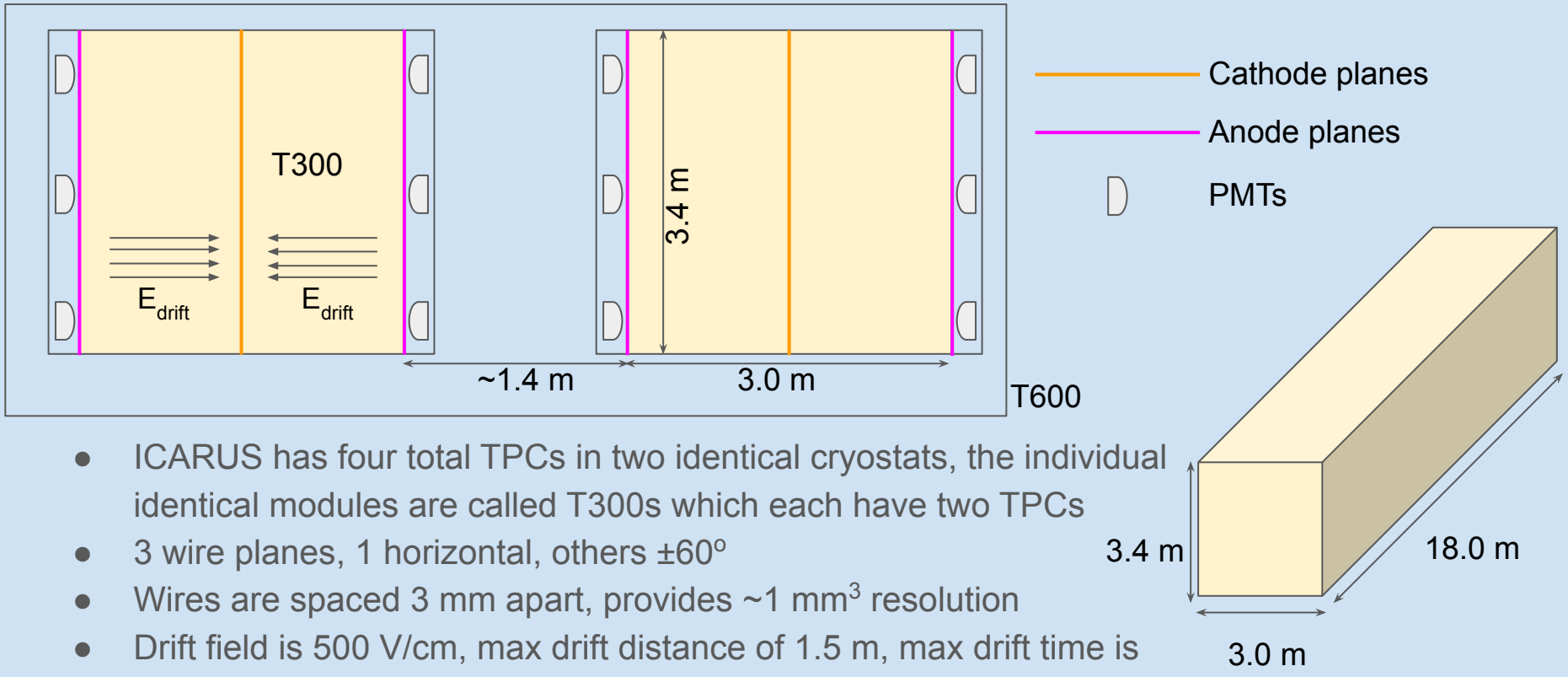


How liquid argon TPCs (LAr TPCs) work

- Have a cathode plane opposite three wire anode planes
- Strong drift electric field between planes pulls ionized electrons to anode wire planes for readout
- Flash from initial ionization is used for timing the signal, read by PMTs situated behind the anode planes
- Drift time is typically on the order of ms



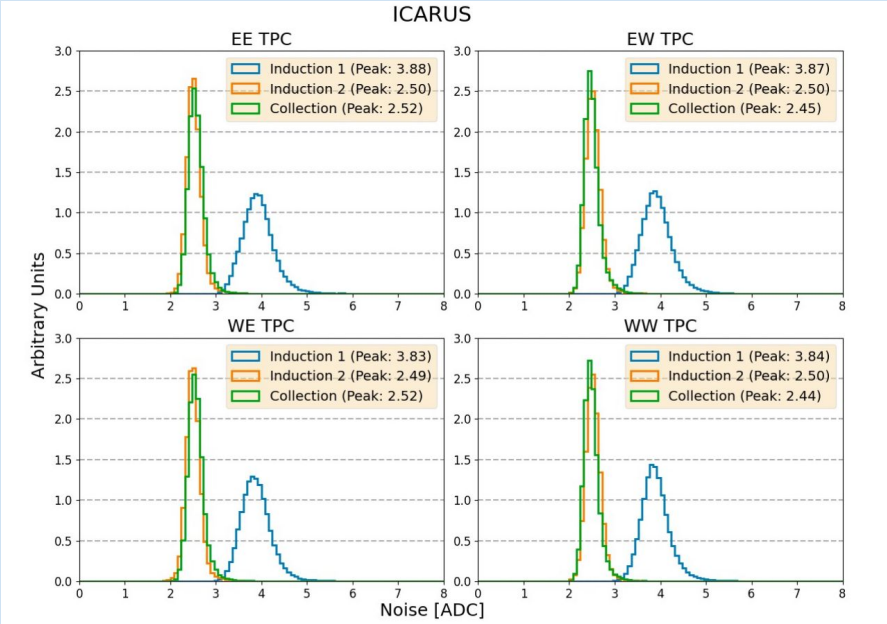
The ICARUS TPCs

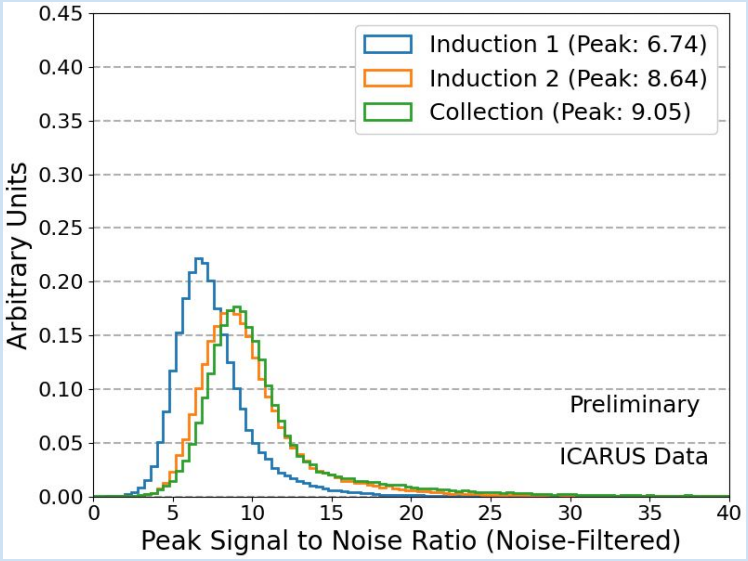


- ICARUS has four total TPCs in two identical cryostats, the individual identical modules are called T300s which each have two TPCs
- 3 wire planes, 1 horizontal, others ±60^o
- Wires are spaced 3 mm apart, provides ~1 mm^3 resolution
- Drift field is 500 V/cm, max drift distance of 1.5 m, max drift time is ~0.96 ms

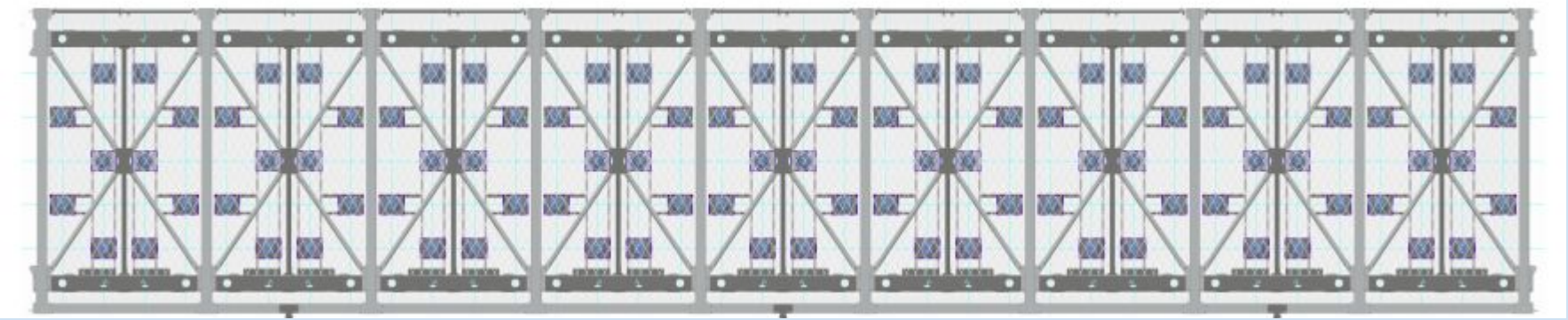
ICARUS TPC Status

- There was some anomalous noise in the TPC upon first activation
- Studies at Padova and hardware interventions at Fermilab allowed for rectification of this issue

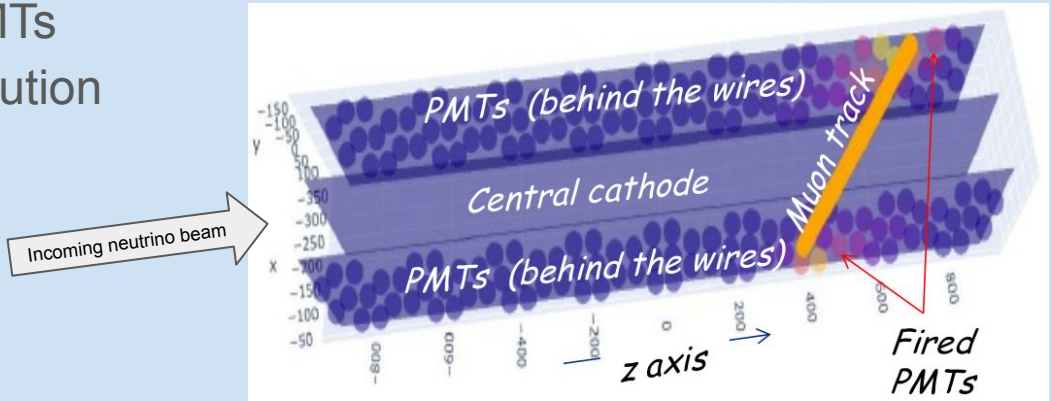




ICARUS PMTs

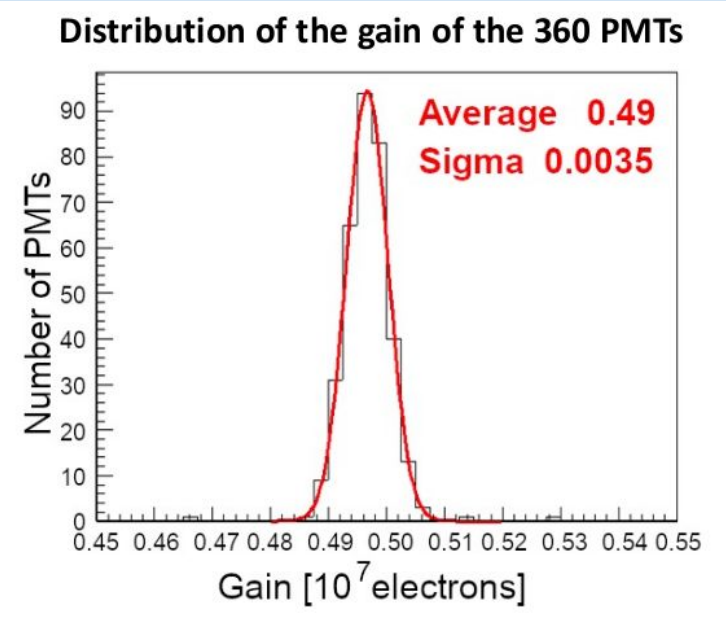


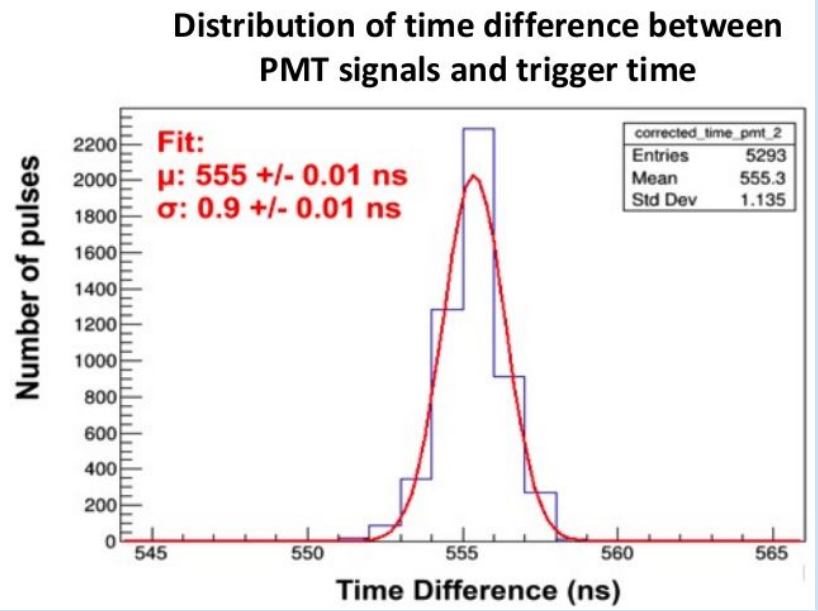
- 90 PMTs/TPC (360 total)
- TPB-coated Hamamatsu PMTs
- Provide ns-level timing resolution
- 5% photocathode coverage



ICARUS PMT Status

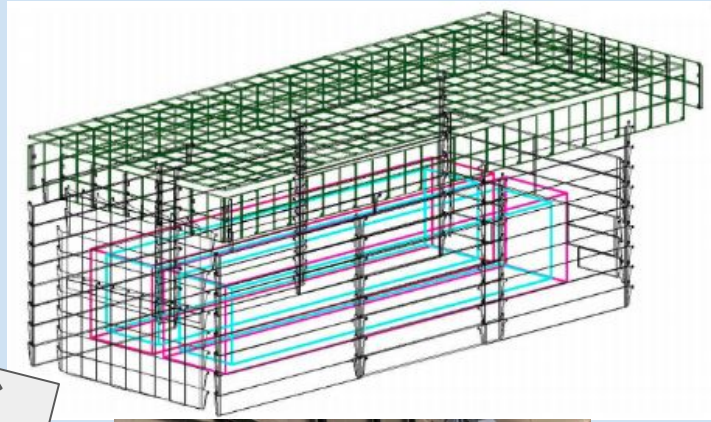
- PMT is in stable running condition, with gains equalized to within 1% spread
- The PMT transit and signal timing can be measured with ~1 ns precision



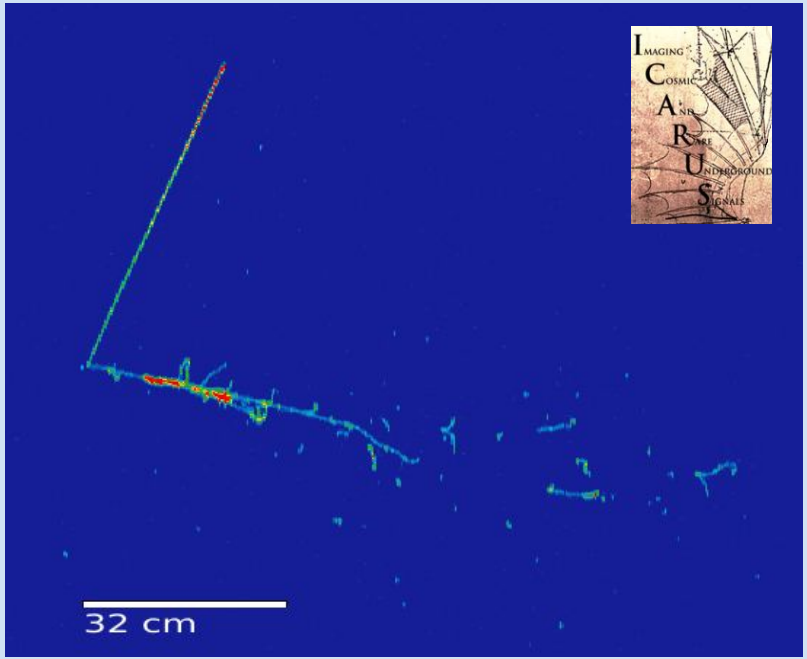


The Cosmic Ray Tagger (CRT)

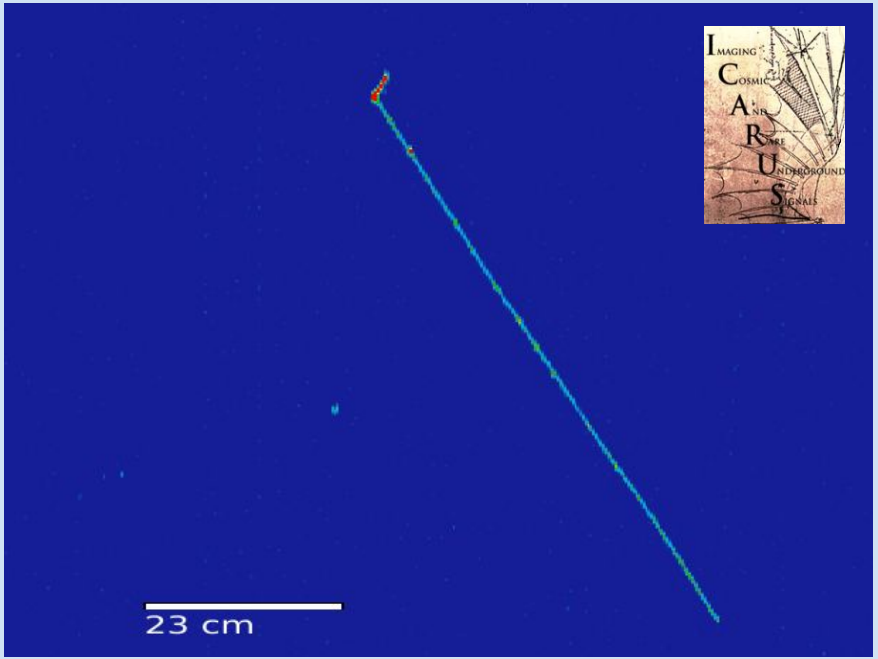
- We expect ~11 muons/drift window in the TPCs while operating at Fermilab
- The Cosmic Ray Tagger wraps around the warm vessel, providing 97% geometrical coverage with ~1000 m^2 total area
- The Top CRT modules were newly constructed at CERN by INFN collaborators
- Side portion was made from repurposed MINOS modules with new readout modules constructed at CSU
- Bottom panels under the warm vessel from Double Chooz



Neutrino candidate events in ICARUS at Fermilab!



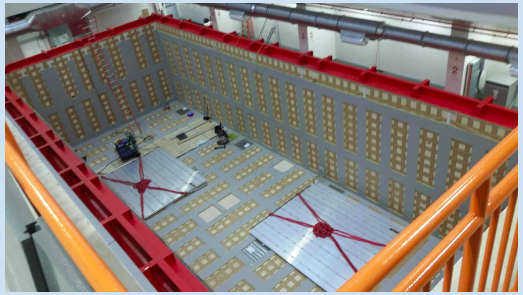
NuMI ν_e charged current candidate

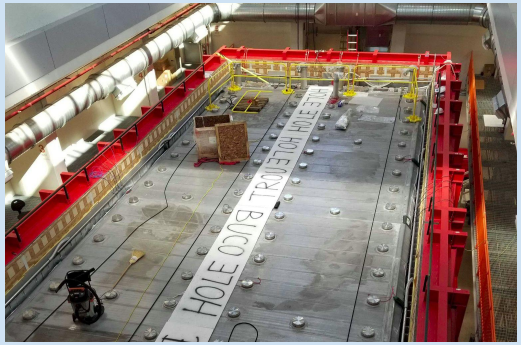


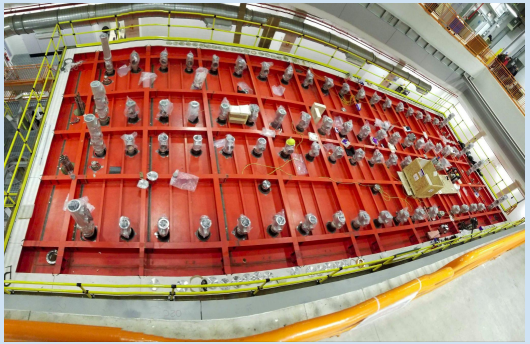
BNB ν_μ charged current candidate

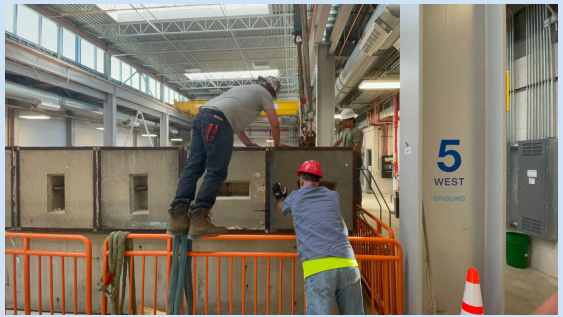
Summary

- The ICARUS detector is now fully operational and taking physics data
- In the 2022/2023 data runs ICARUS will seek to test the claim of the Neutrino-4 experiment's evidence for a ~7 eV^2 sterile neutrino
- SBND will be coming online in 2023, will run jointly with ICARUS until a "long shutdown" for LBNF in 2027

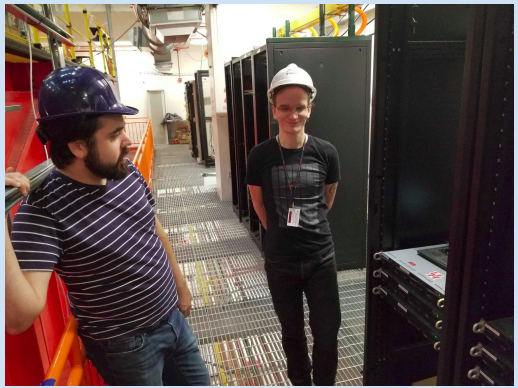








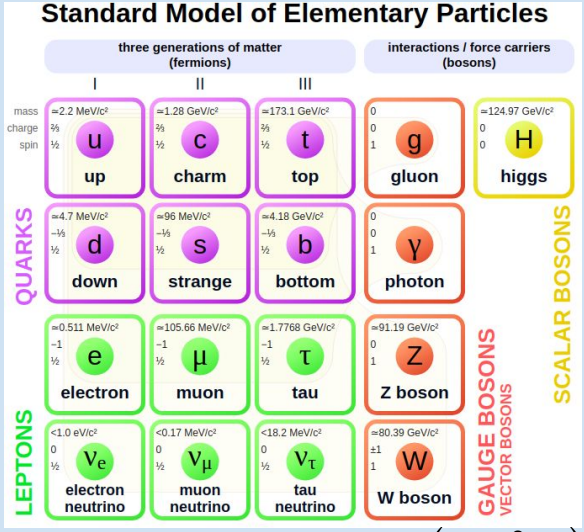
Thanks for listening!



Backups

Neutrinos (a quick summary)

- Neutrinos are charge 0 leptons that interact through the weak and gravitational forces
- We can infer the “flavor” of a neutrino by observing the charged lepton that emerges from interactions
- We can express the relationship between the neutrino “flavor” states and the mass states with a mixing matrix
- The probability of a neutrino oscillating is proportional to L/E, where L is the distance the neutrino travels after being created, and E is the energy of that neutrino



$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = \left| \delta_{\alpha\beta} - \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)\right|$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Flavor states

Mixing (PMNS) matrix

Mass states

CRT conceptual design

- Charged particle passes through plastic scintillator with an optical fiber embedded along the length
- Scintillation light is collected by the fiber and transported to the light-detection devices (Top/Sides: Silicon Photomultipliers; Bottom: PMTs)
- All ICARUS CRT systems use two layers of scintillator, either with the strips in parallel (XX) or perpendicular (XY), require a coincidence between the layers to trigger a readout by the electronics