The Short Baseline Neutrino Program at Fermilab

Angela Fava - FNAL

for the SBND, MicroBooNE and ICARUS Collaborations

The puzzling picture of short baseline ν oscillations

Three independent classes of anomalous experimental results in the last 20 years, not fitting into the "standard" landscape of 3-flavour ν mixing:

- disappearance of anti-ν_e detected from near-by nuclear reactors;
- disappearance of ν_e from intense calibration sources in solar ν experiments;
- appearance of $\nu_e/\bar{\nu}_e$ in $\nu_\mu/\bar{\nu}_\mu$ beams at particle accelerators.

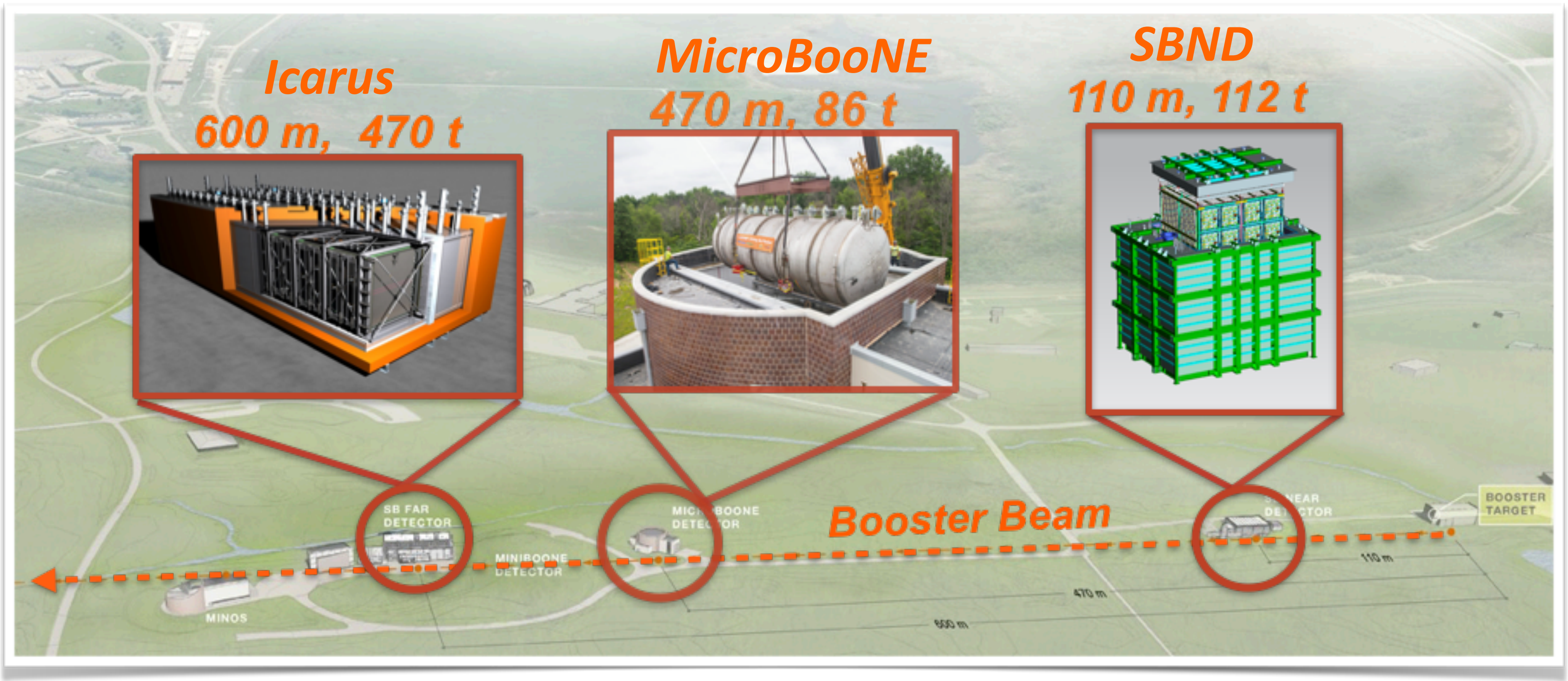
Experiment	Type	Channel	Significance
LSND	DAR accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8 σ
MiniBooNE	SBL accelerator	$\nu_\mu \rightarrow \nu_e$	4.5 σ
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8 σ
GALLEX/SAGE	Source – e capture	ν_e disappearance	2.8 σ
Reactors	β decay	$\bar{\nu}_e$ disappearance	3.0 σ

Each possibly explained by nonstandard "sterile" neutrino state(s) driving oscillations at $\Delta m^2_{new} \approx 1\ eV^2$ and relatively small $\sin^2(2\vartheta_{new})$, but no model so far successful in fitting all experimental results at once.

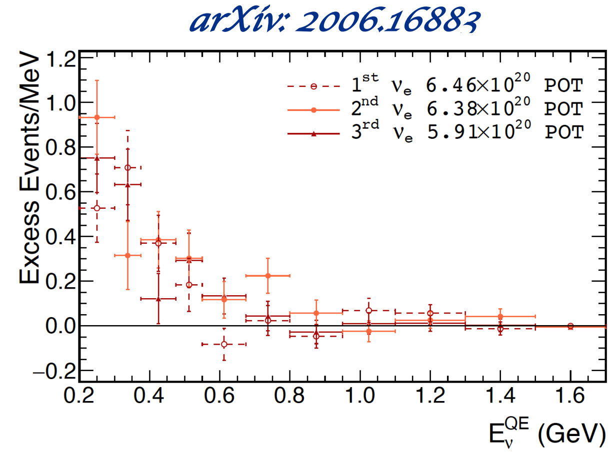
Short Baseline Neutrino Program at Fermilab

Program aimed at definitely solving the "sterile neutrino puzzle" by exploiting:

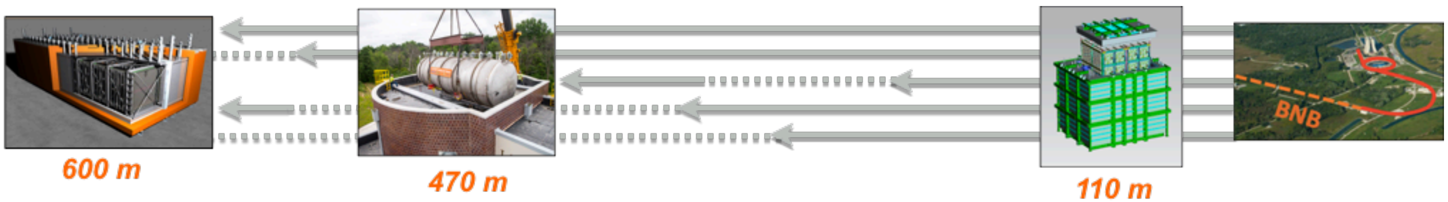
- the well characterized FNAL Booster ν beamline;
- three detectors based on the same liquid argon TPC technique.



SBN goals



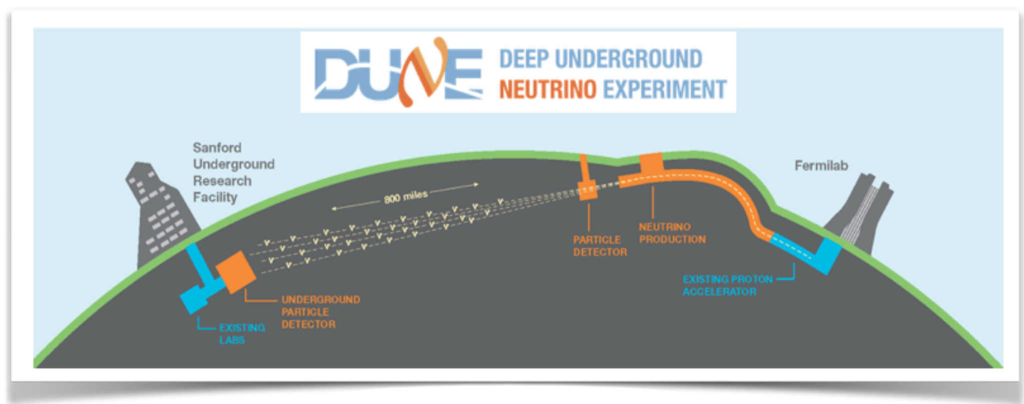
- **MicroBooNE**
  Understand the nature of the MiniBooNE “low energy” excess anomaly, using the same beam.
- **SBND + ICARUS**
  Search for short baseline oscillations both in appearance and disappearance channels.



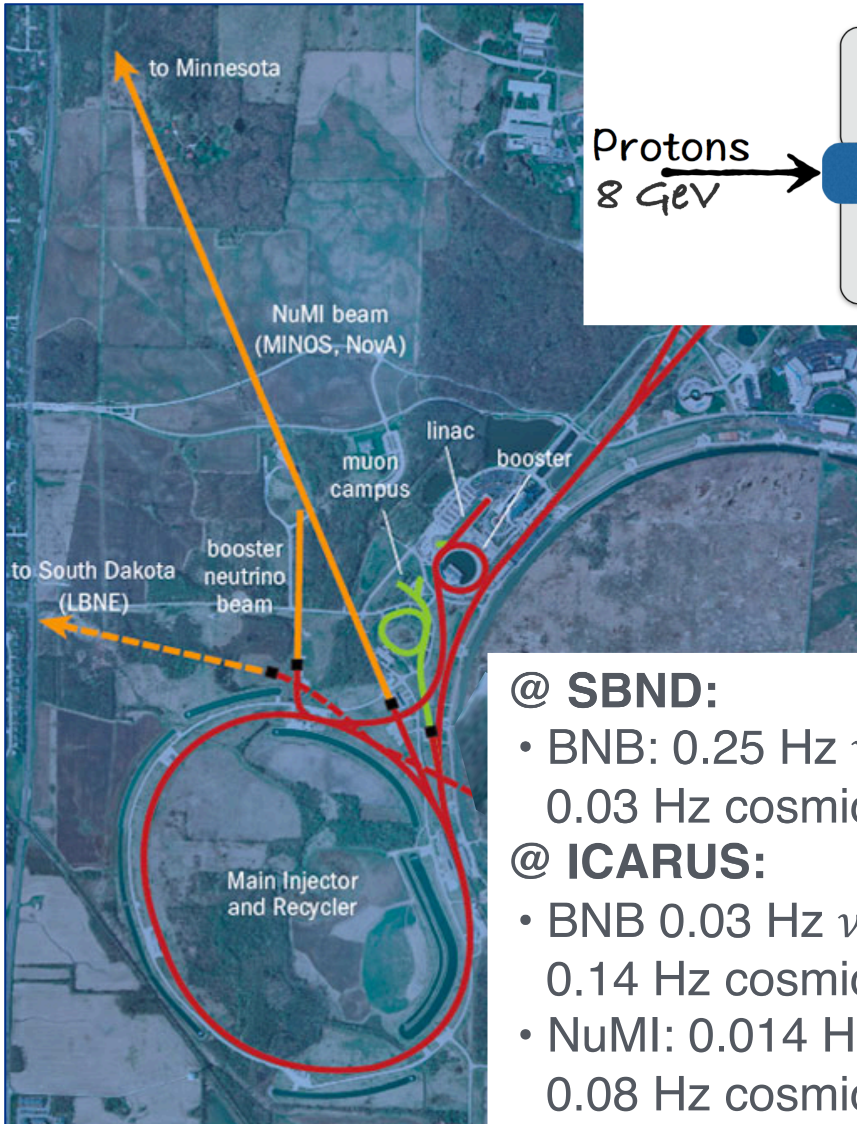
Appearance ν_e? ← ν_μ

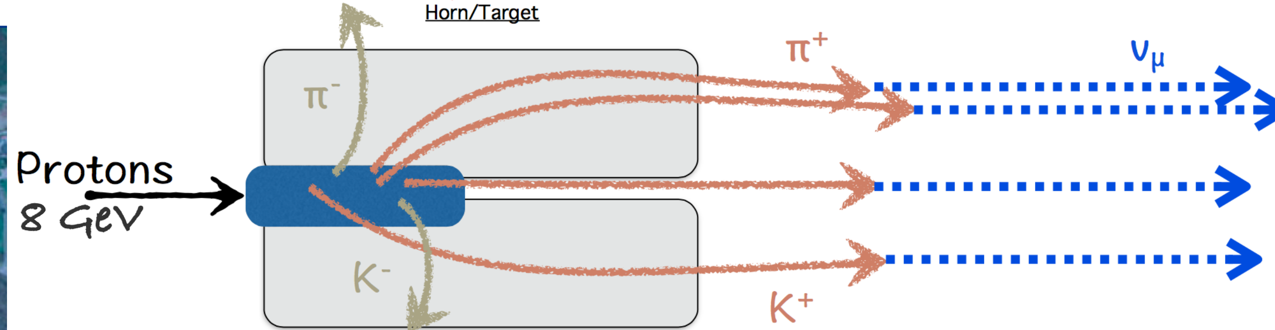
Disappearance ν_x? ← ν_μ

- Lay the ground for future long baseline program
  - Further develop LAr-TPC detector technology & software
  - Measure ν-Ar cross sections at energies relevant to DUNE



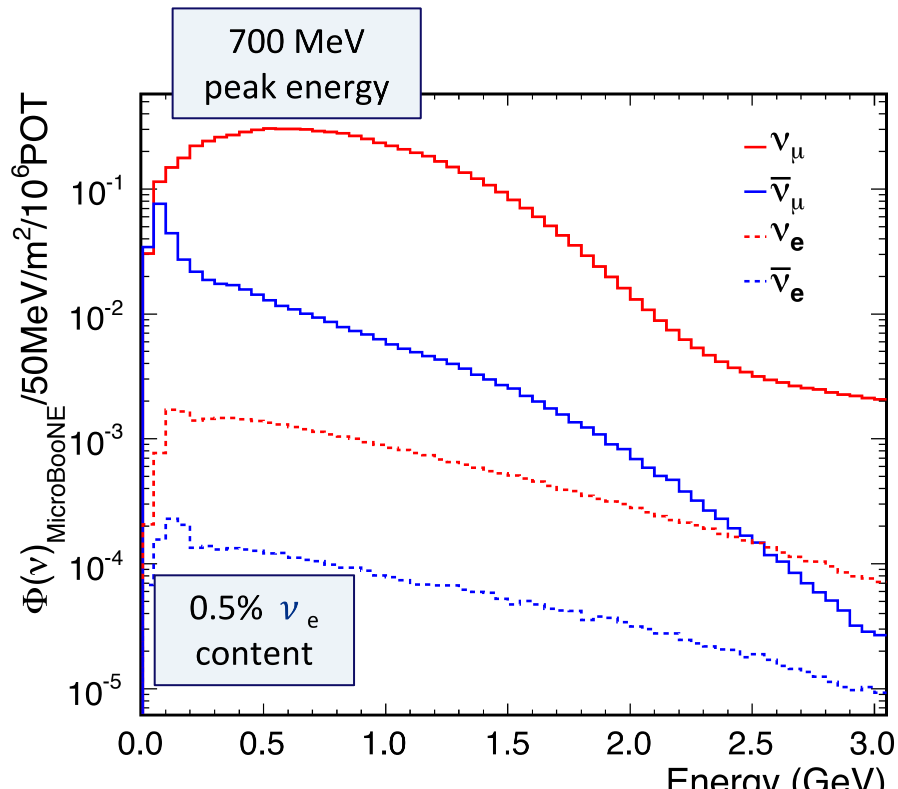
The Booster Neutrino Beam





@ SBND:
- BNB: 0.25 Hz ν, 0.03 Hz cosmic

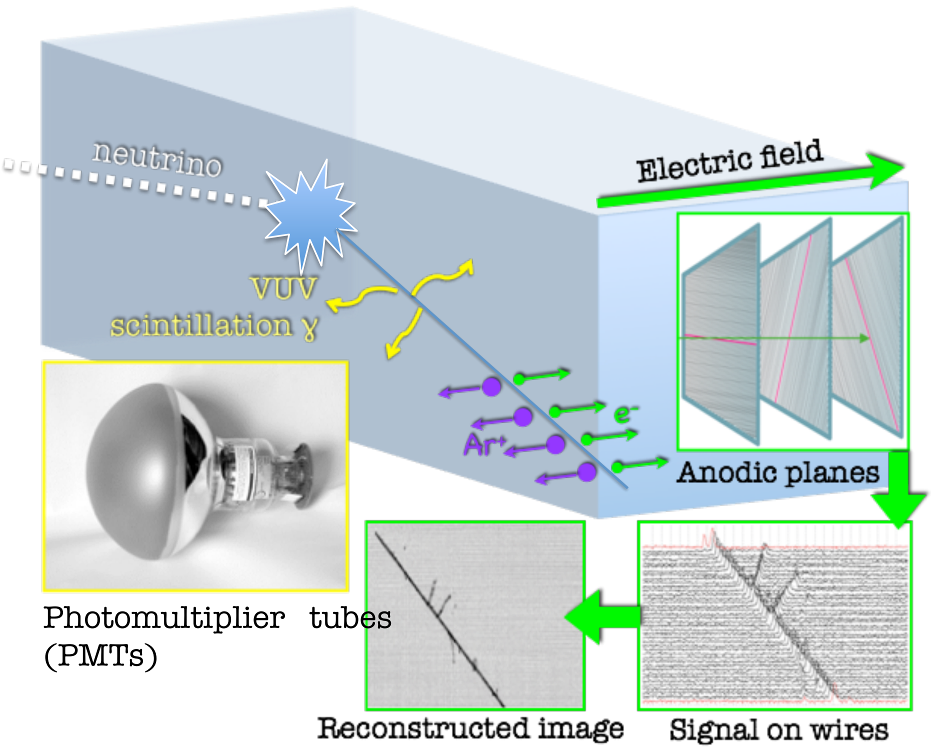
@ ICARUS:
- BNB 0.03 Hz ν, 0.14 Hz cosmic
- NuMI: 0.014 Hz ν, 0.08 Hz cosmic



Liquid Argon TPC detection technique

Very well suited for the experimental study of Neutrino Physics, pioneered by Icarus Collaboration.

Massive yet homogeneous target, excellent tracking & calorimetric capabilities.



<u>λ = 128 nm scintillation light</u>:

40000 γ/MeV wo electric field.

Response time ~ 6 ns ÷ 1.6 μs.

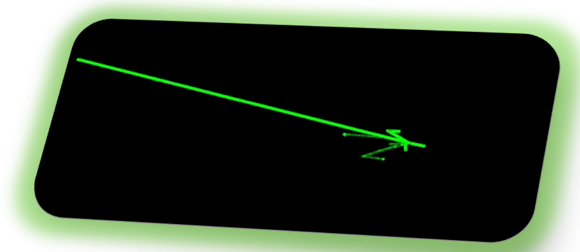
<u>Ionisation electrons</u>:

42000 e^-/MeV.

Drifted (E) toward planes of wires on which they induce a signal.

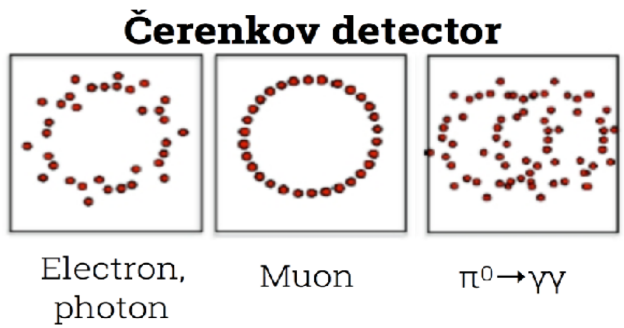
Response time = drift time (~ ms).

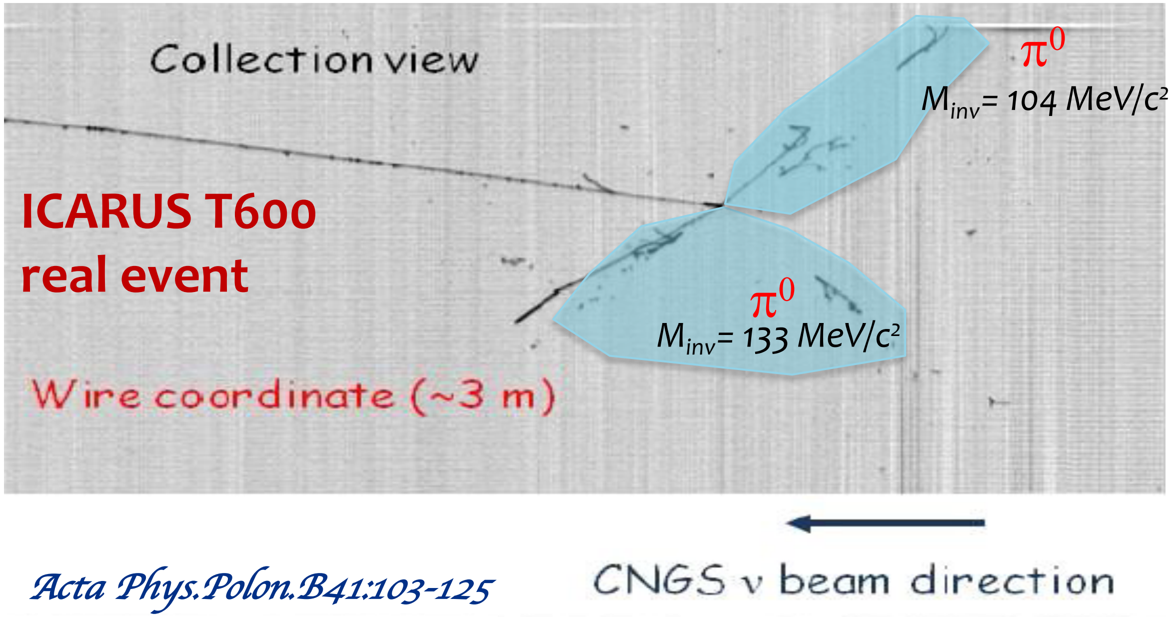
3D image reconstruction by combining coordinates on different wire planes at the same drift time.



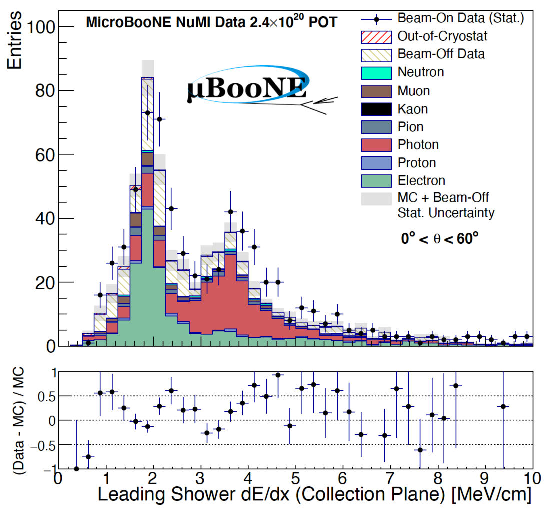
Electron neutrinos in LAr-TPC

Fine tracking & calorimetry essential for e/γ separation and π^0 reconstruction

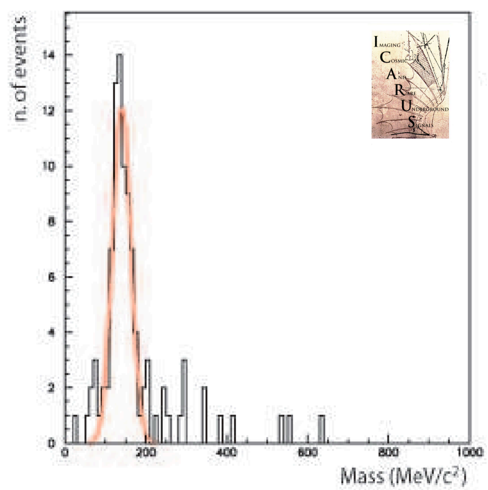




arXiv: 2101.04228



Acta Phys.Polon.B41:103-125

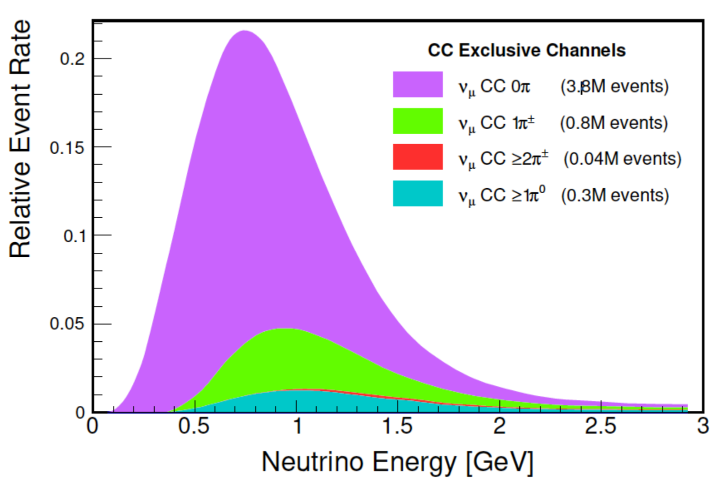


- Gap between vertex and shower.
- Ionization in the first segment of showers (1 mip or 2 mips).
- π^0 invariant mass.

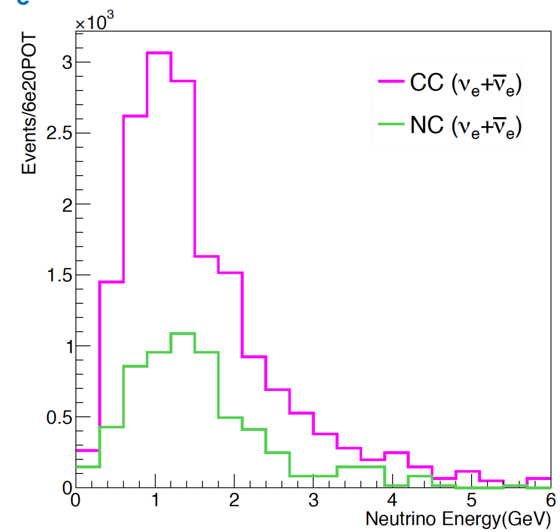
Neutrino interactions at SBN

- High statistics precision measurements of neutrino argon cross sections in the DUNE energy range.
  - SBND: word’s highest statistics cross section measurements on argon, ~ 7 million ν_μ and ~ 50,000 ν_e in 3 years
  - ICARUS: high statistics electron neutrino cross section measurement using the NuMI off axis, ~ 10^5 events/year
  - MicroBooNE is now delivering the first results on cross section measurements

ν_μ from the Booster at SBND



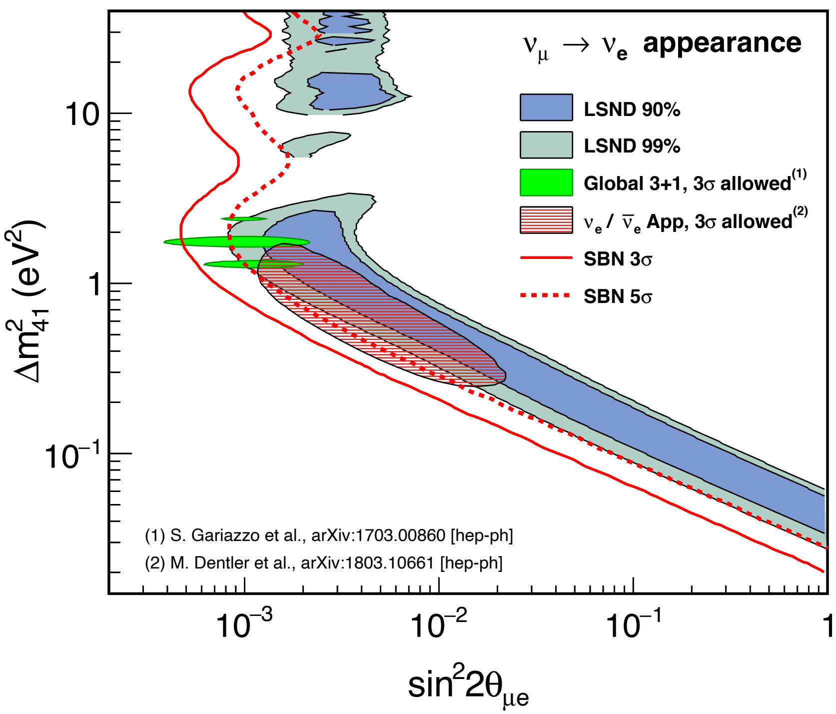
ν_e from the NuMI off axis at ICARUS

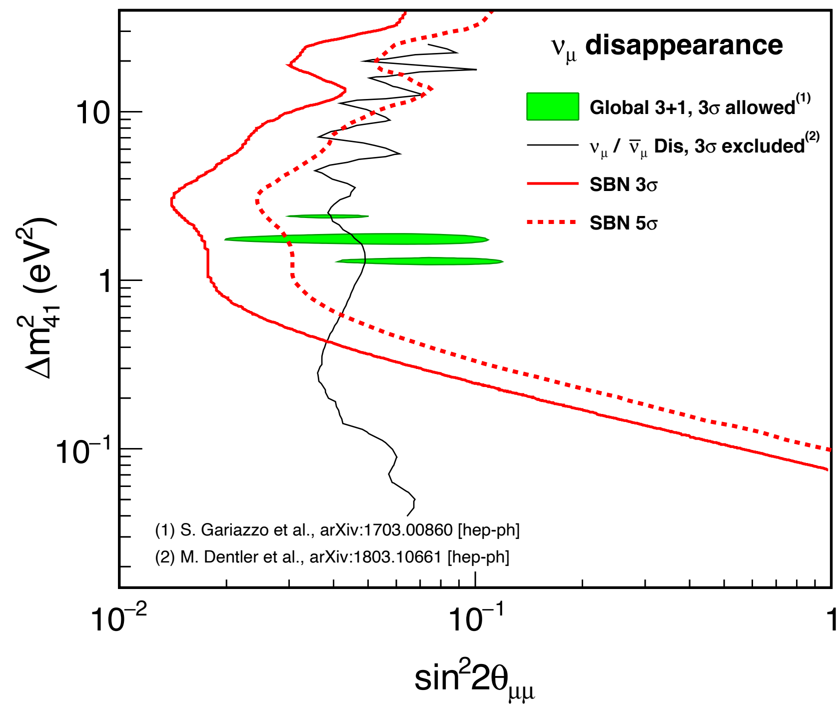


- Rich BSM searches: neutrino tridents, dark matter, millicharged particles… EX: MicroBooNE heavy neutral lepton search *Phys. Rev. D 101, 052001 (2020)*

Sterile neutrino sensitivity

Annual Rev. Nucl. Part. Sci. 2019.69:363-387



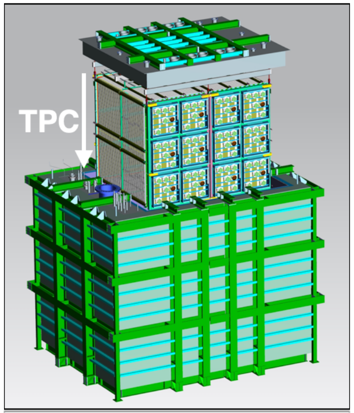


5σ coverage of the parameter area relevant to the LSND/MiniBooNE anomaly in 3 years (6.6 x 10^{20} pot).

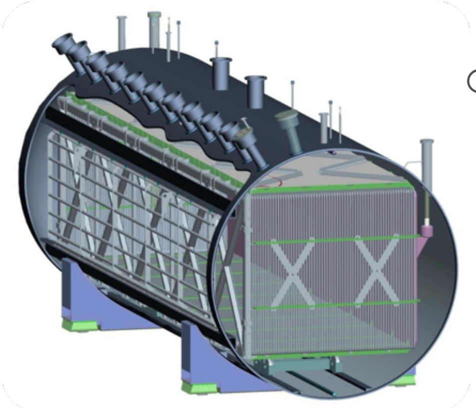
1 order of magnitude beyond SciBooNE + MiniBooNE limits in 3 years (6.6 x 10^{20} pot). Probing the parameter area relevant to reactor and gallium anomalies.

Unique capability to study appearance and disappearance channels simultaneously

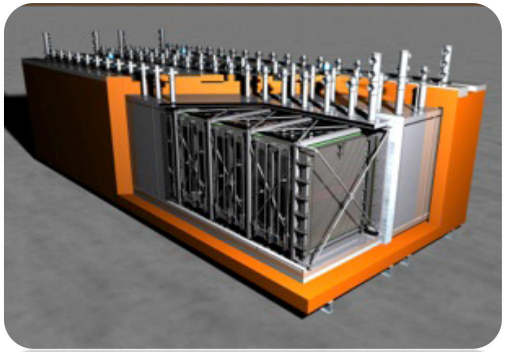
The SBN detectors



- **SBND _ construction/installation**
  - 260 t of LAr (112 t active), 110 m from target.
  - 2 TPCs with 2 m drift
  - 120 8" PMTs (96 coated with TPB), 192 X-ARAPUCA modules, TPB coated reflector foils on the cathode.
  - 4π CRT (cosmic ray tagger) coverage



- **MicroBooNE _ physics run completed**
  - 170 t of LAr (87 t active), 470 m from target.
  - 1 TPC with 2.5 m drift.
  - 32 8" PMTs on acrylic support coated with TPB.
  - Top and side CRT.



- **ICARUS _ commissioning**
  - 760 t of LAr (476 t active), 600 m from target.
  - 4 TPCs with 1.5 m drift.
  - 360 8" PMTs coated with TPB.
  - Almost full CRT coverage.

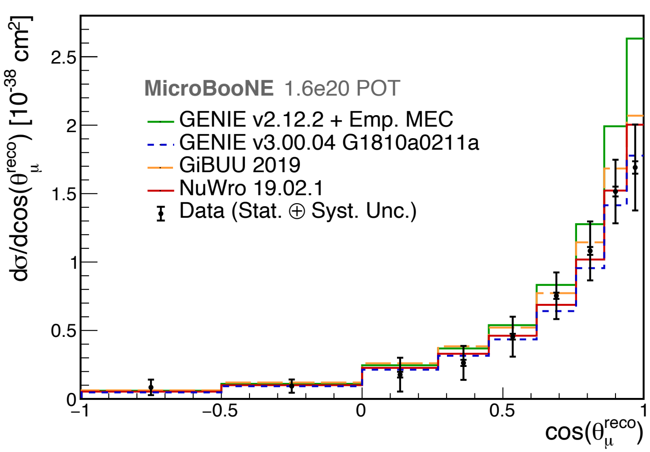
MicroBooNE is now producing the world's first high statistics measurements of ν-Ar interactions

- Enables in depth studies of both inclusive channels and exclusive final states

Phys. Rev. D 102, 112013 (2020)

Phys. Rev. Lett. 123, 131801 (2019)

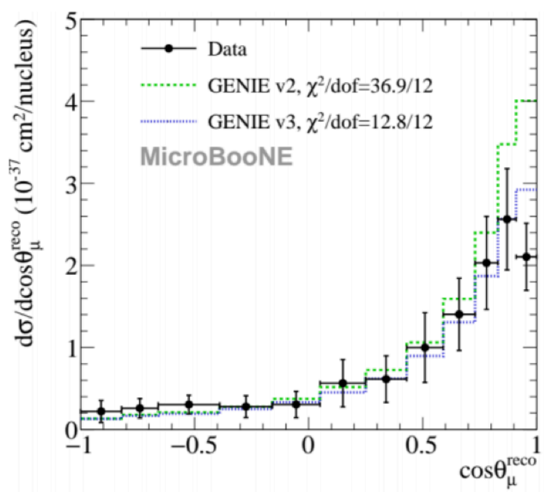
Eur. Phys. J. C 79 673 (2019) Phys. Rev. Lett. 125, 201803 (2020)



CC Inclusive

Inclusive

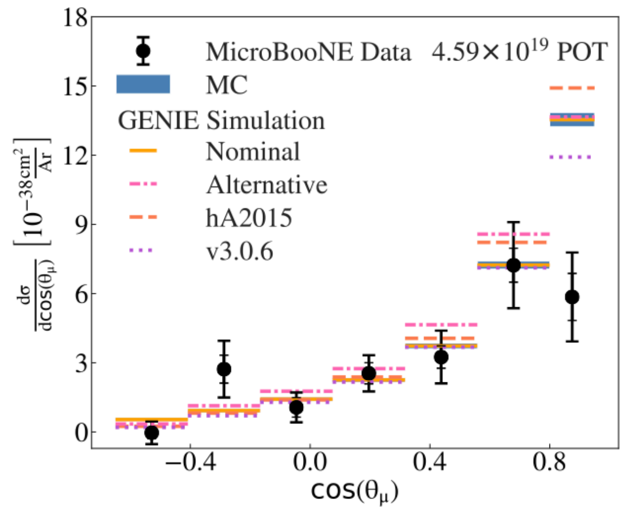
Some deficit



CC0πNp

More exclusive

Turnover in data



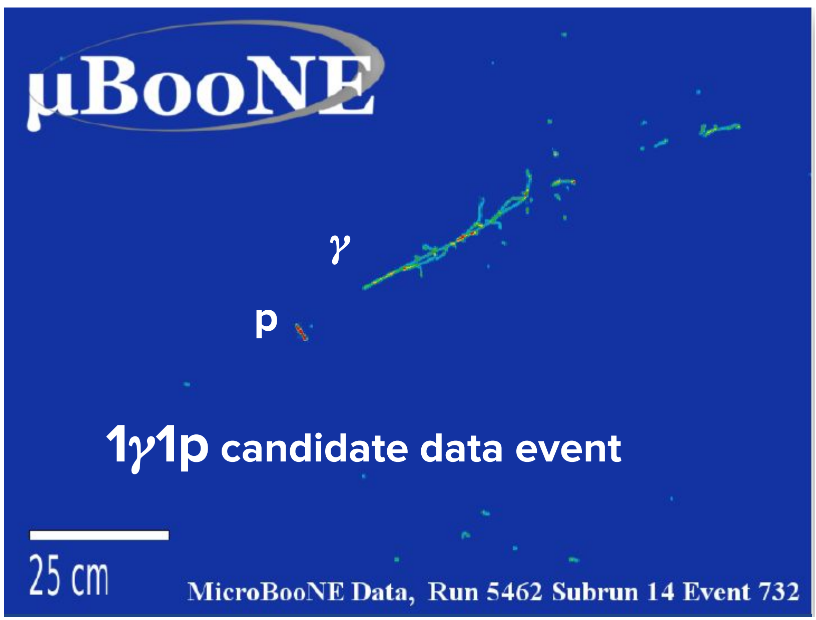
CCQE-like

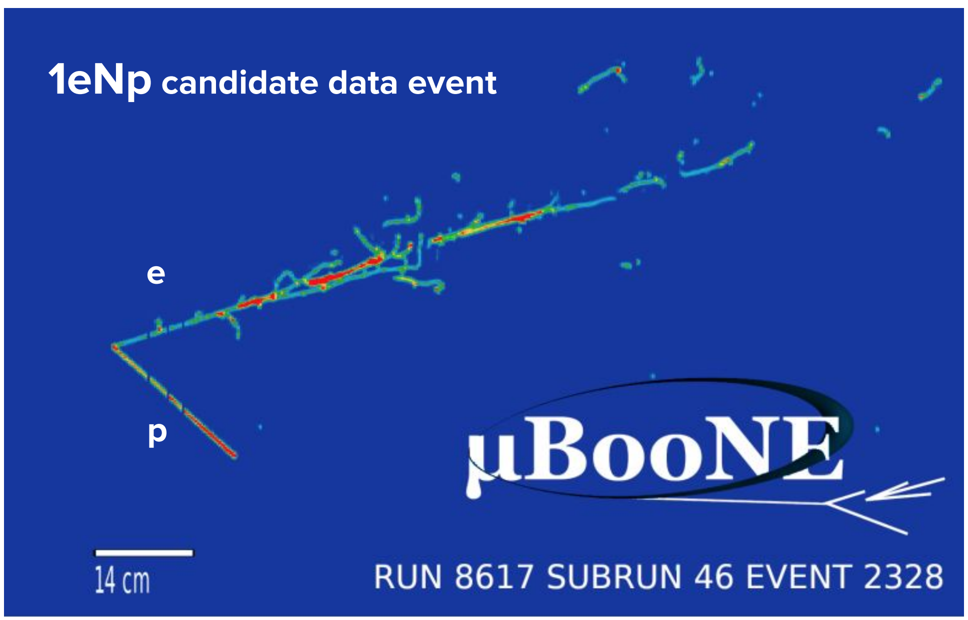
Even more exclusive

Even more deficit

MicroBooNE Anomalous Low-Energy Excess Search Strategy

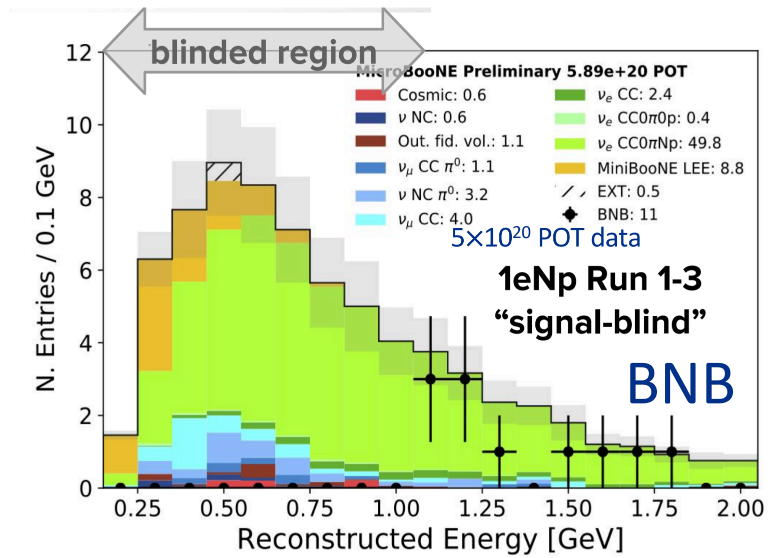
- Multiple analyses covering different final states
- Single photon analysis MICROBOONE-NOTE-1087-PUB
  - $1\gamma 0p+1\gamma 1p$ (targeting $NC\Delta \rightarrow N\gamma$ hypothesis)
- ν_e analyses
  - 1e1p (targeting CCQE hypothesis) MICROBOONE-NOTE-1086-PUB
  - 1e0p+1eNp (all MiniBooNE ν_e final states) MICROBOONE-NOTE-1085-PUB
  - 1e (inclusive search) MICROBOONE-NOTE-1095-PUB

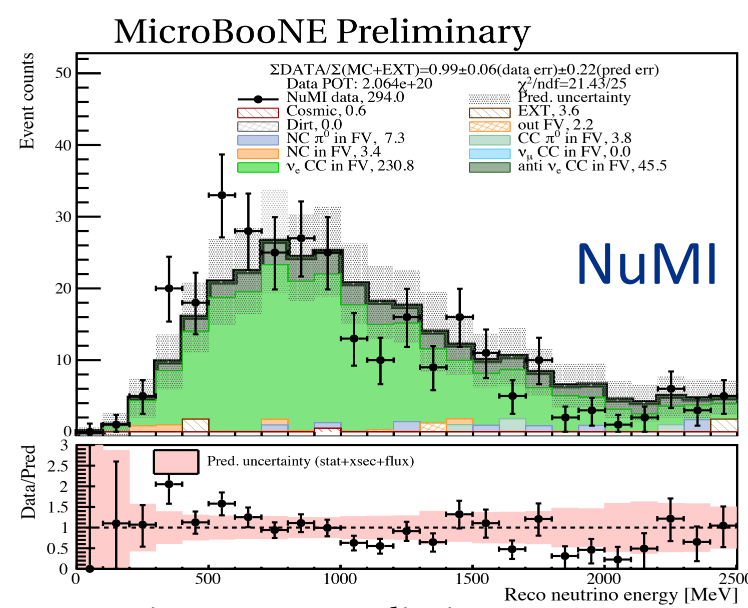




Prospects for MicroBooNE Low-Energy Excess Search

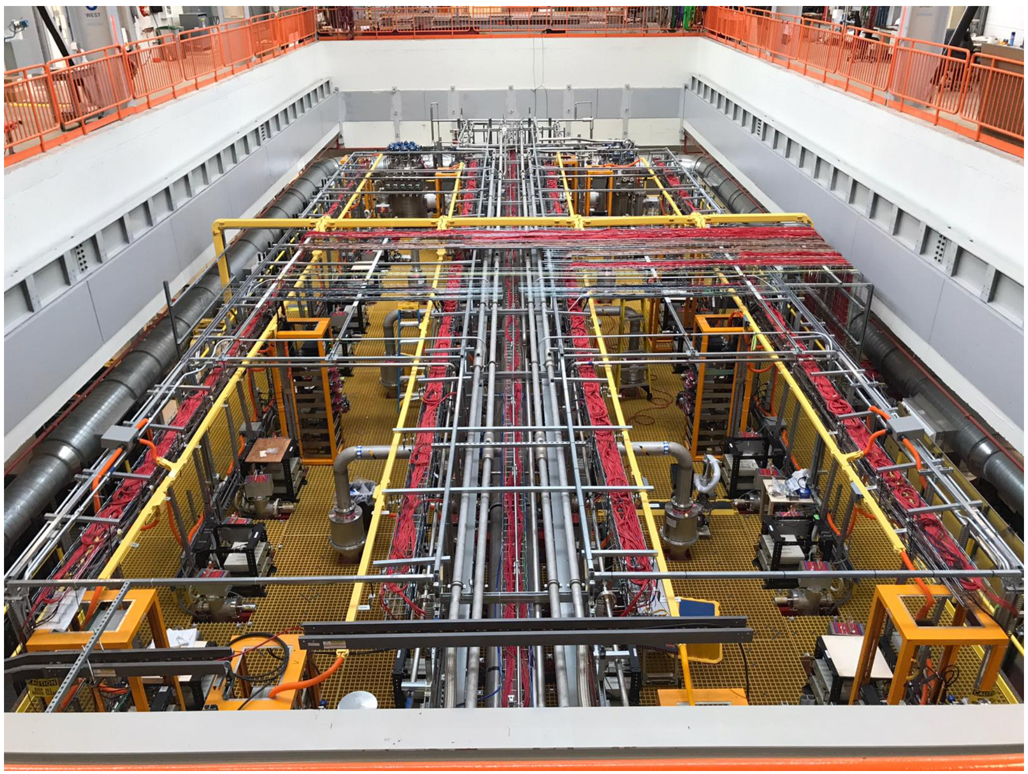
- The first LEE results based on 6×10^{20} POT data are imminent.
  - Results will be released in phases as we complete the various analyses
- Next-generation reconstruction tools show improvements in ν_e reconstruction allowing more sensitive tests of the SM and MiniBooNE anomalous event excess.
- Additional stats from the analysis of the full 13×10^{20} POT dataset will enable MicroBooNE to reach the ultimate sensitivity on the LEE search.



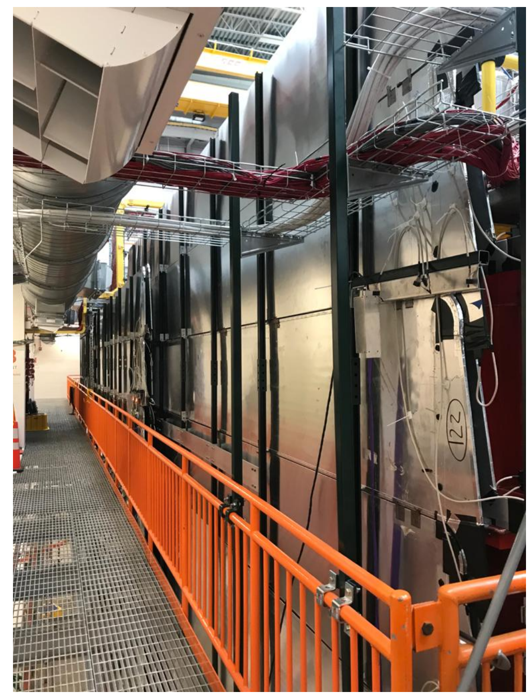


Status of Icarus detector

- TPC, PMT, trigger and DAQ installation activities complete, with latest achievements during Covid-19 restricted operations.
- Bottom CRT and 7 out of 8 walls of side CRT installation complete.
- 24/7 shifts since February 14th 2020. Remote only shifts since March 17th 2020.



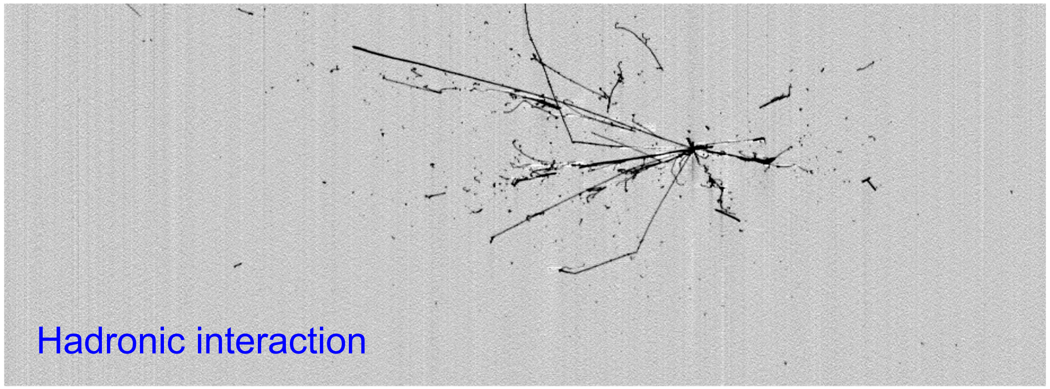
CRT East walls complete



Activation and commissioning of Icarus detector

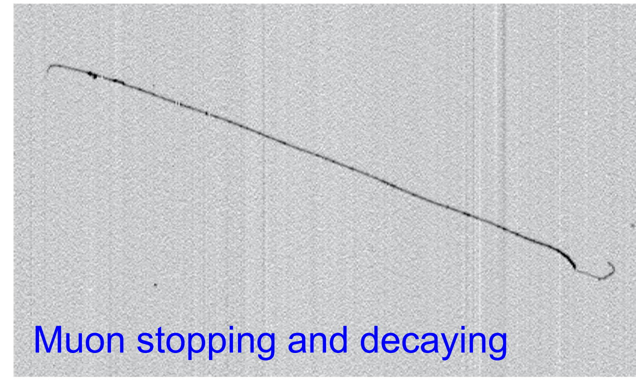
- TPC wire planes and cathode HV to nominal voltages on Aug 27th.
  - HV stable at -75 kV, without glitches or issues.
  - No significant currents on wire bias, except for 2 groups of Induction-2 wires of West module at 0 V (instead of -30 V).
- All PMTs switched on (3 out of 360 not working).
  - Calibration of gain with laser and fine tuning based on counting rates.
- 7 side CRT wall sections integrated into the readout.
- Cosmic-ray interaction events regularly collected with random 5 Hz trigger for calibration purposes. Dedicated runs for specific commissioning tasks (investigation of TPC noise, PMT calibration, DAQ upgrades/longevity tests, etc).
- Relatively short e^- lifetime $\tau \sim 2$ ms in both modules, to be compared with 1 ms maximum e^- drift time and required $\tau > 3$ ms (0.1 ppb O2 equiv.) goal.
  - Possibly related to insufficient gas recirculation.
  - Temporary mitigation with daily venting of gas argon.
  - Ongoing plan to regenerate gas filters and increase GAr flow.

Sample Icarus event displays



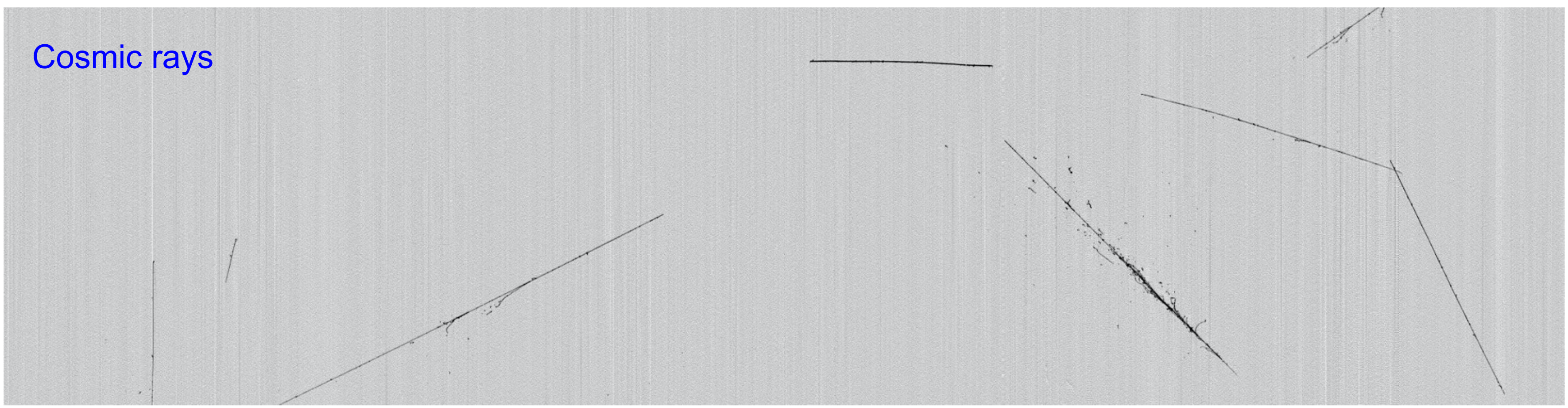
150 cm

280 cm



100 cm

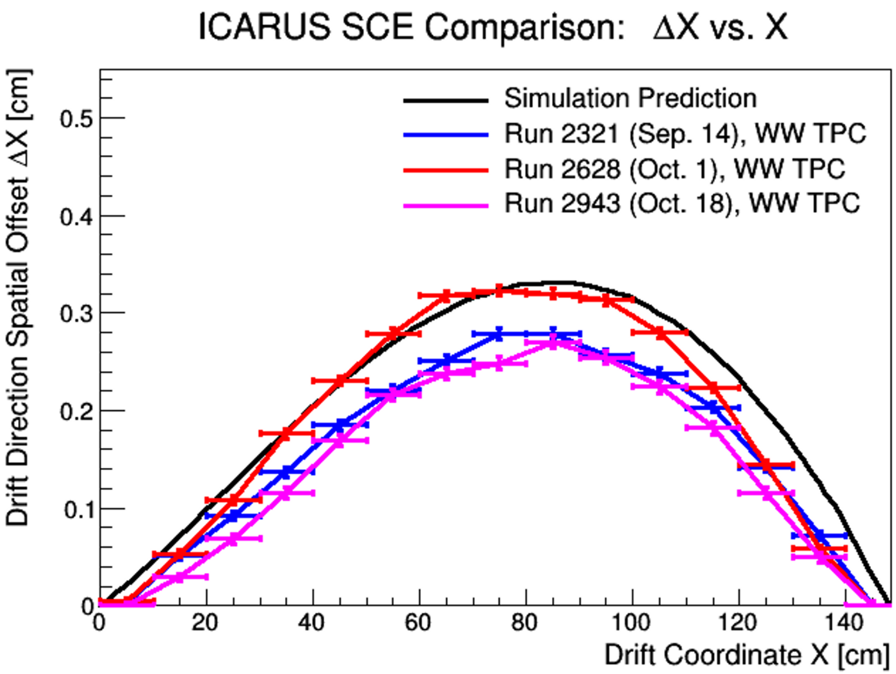
130 cm

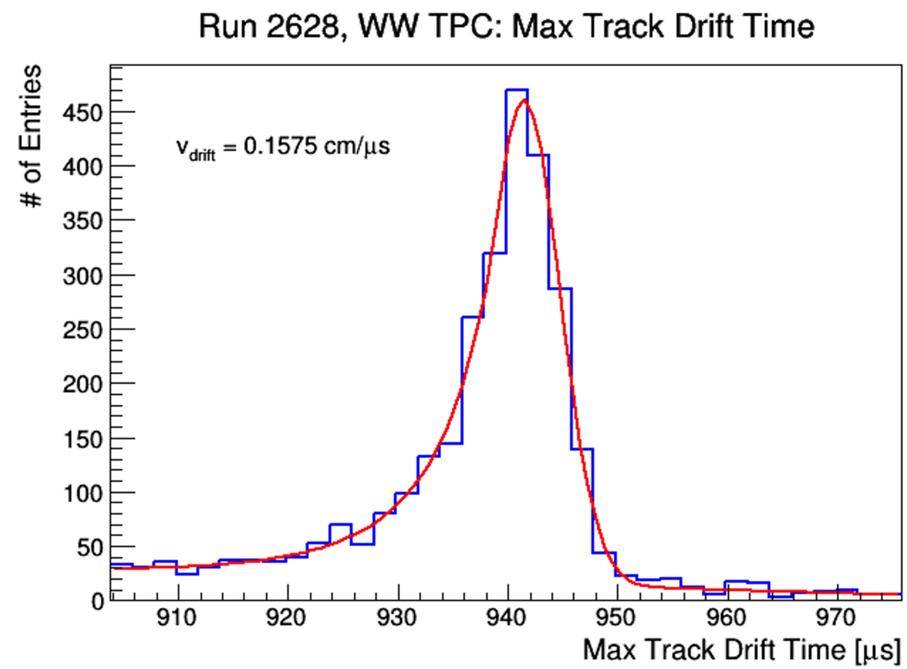


260 cm

720 cm

Early assessment of Icarus TPC performance





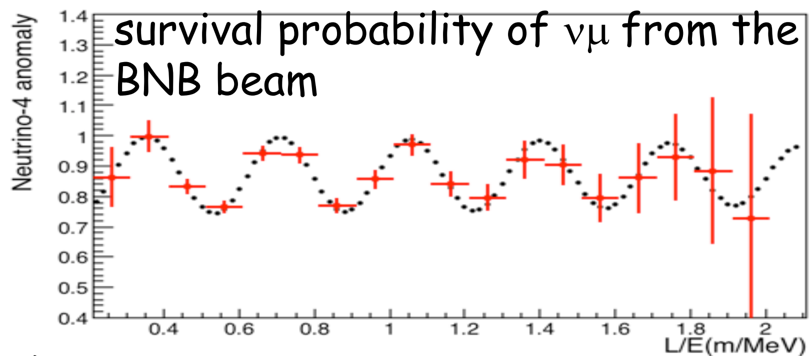
- Space charge effects (SCE) measured using anode-cathode-crossing cosmic muon tracks, looking at spatial distortions in drift direction. Rough agreement with previous measurement (ICARUS Coll., JINST 15 (2020) 07, P07001) and simulation aside from small time dependence.

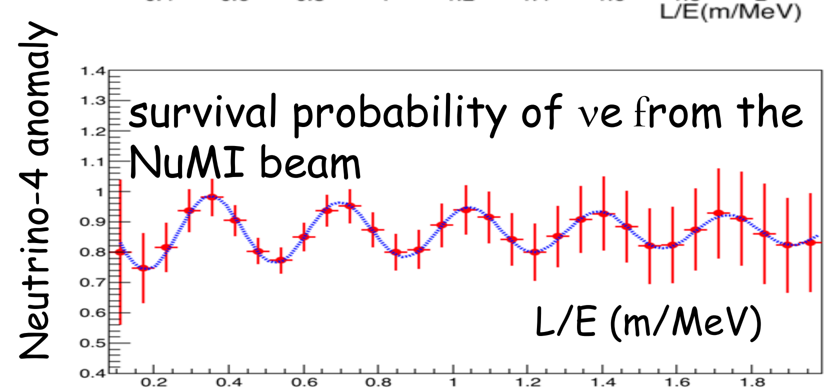
- Same track sample used to measure drift velocity by maximum drift time of charge associated with tracks - results in line with previous ICARUS measurements to 1-2%; small discrepancies being investigated.

Icarus data taking

See talk by C. Rubbia

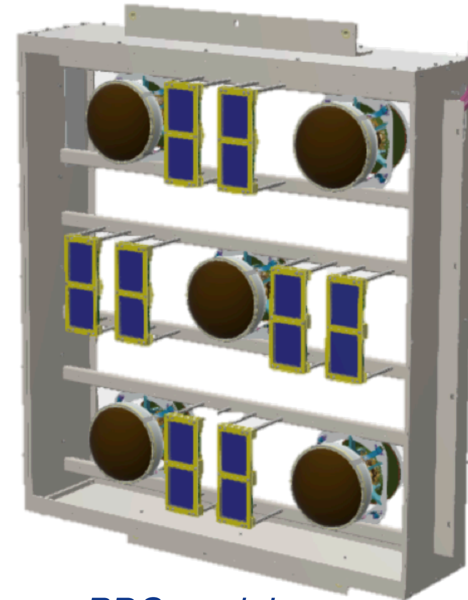
- ICARUS detector expected to initiate data taking early in the Fall with Booster and NUMI off-axis higher energy beam. After the first year, it will be operated jointly with SBND to address the sterile neutrino puzzle within the SBN program.
- Main goal of this initial one-year ICARUS data taking: definitive verification of the recent claim by NEUTRINO-4 reactor experiment both in the ν_μ channel with the BNB and in the ν_e with NUMI:
  - Survival ν_μ oscillation probability for Neutrino-4 anomaly (black) for the best fit (Δm^2_{N4}=7.25 eV^2, $\sin^2 2\theta_{N4}$=0.26), and expected corresponding ICARUS measurement for 3 months of BNB (red).
  - Survival ν_μ oscillation probability for Neutrino-4 anomaly (black) for the best fit (Δm^2_{N4}=7.25 eV^2, $\sin^2 2\theta_{N4}$=0.26), and expected corresponding ICARUS measurement for 1 year of NuMI (red).





SBND light detection system

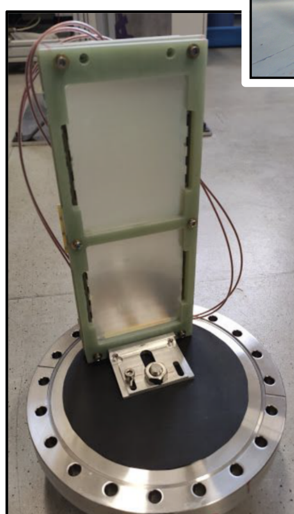
- PMTs:
  - tested at LANL in the Coherent Captain Mills experiment;
  - being packed for shipment to FNAL



PDS module

PMTs being tested at LANL

SiPM cold test



X-ARAPUCA

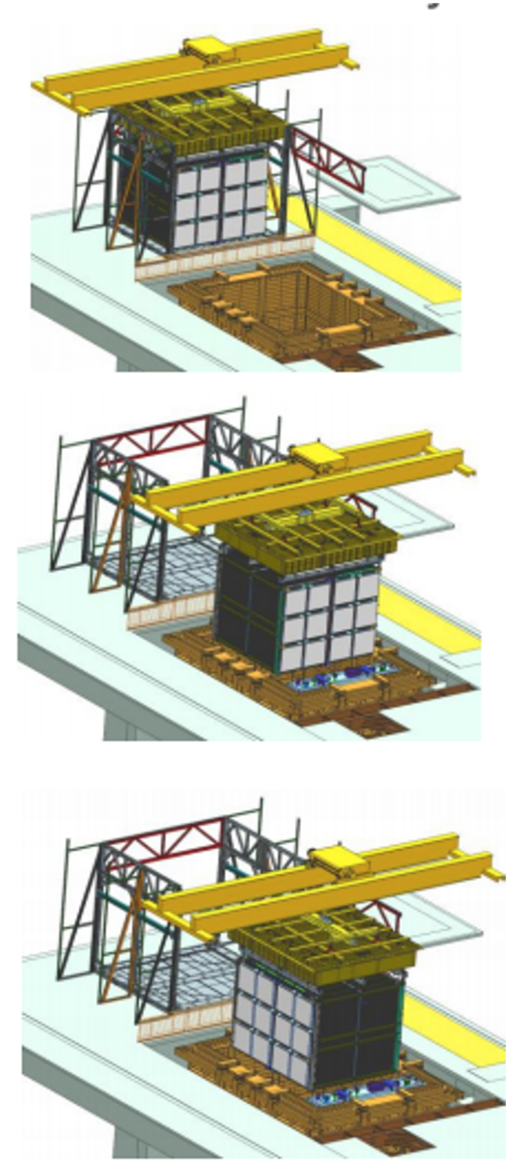
- X-ARAPUCAs:
  - assembly of the modules ongoing;
  - cold tests in Brazil with different light guides;
  - test stands at FNAL for mass testing of SiPMs and for readout development/test.
- TPB coated reflector foils on the cathode:
  - at FNAL, to be installed when CPA ready

SBND detector assembly

- All TPC components constructed.
- Assembly ongoing at Fermilab in clean room at Dzero.
- Readout electronics tested and ready for installation.

APA

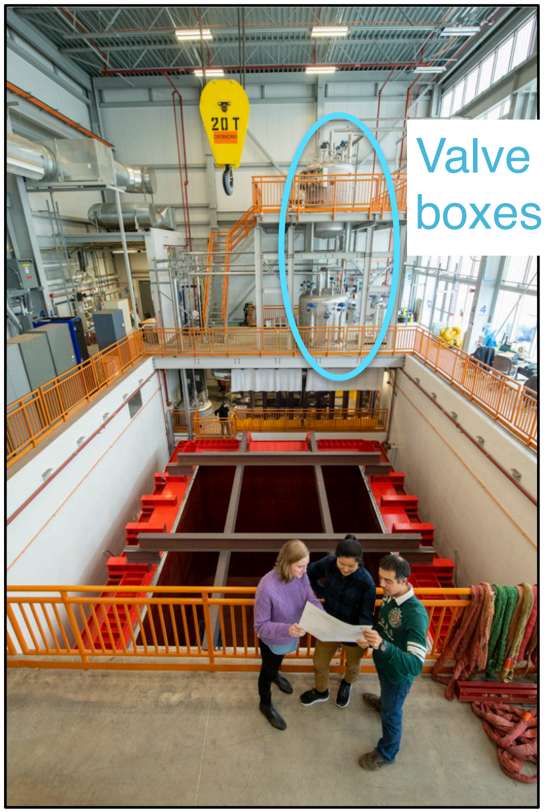
Test of mock APA hanging



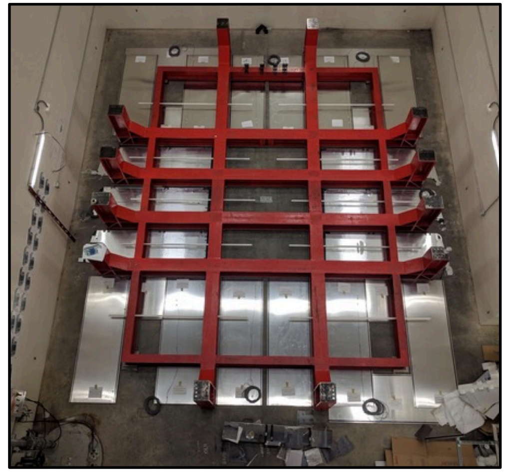
Assembly Transport Frame

SBND installation status

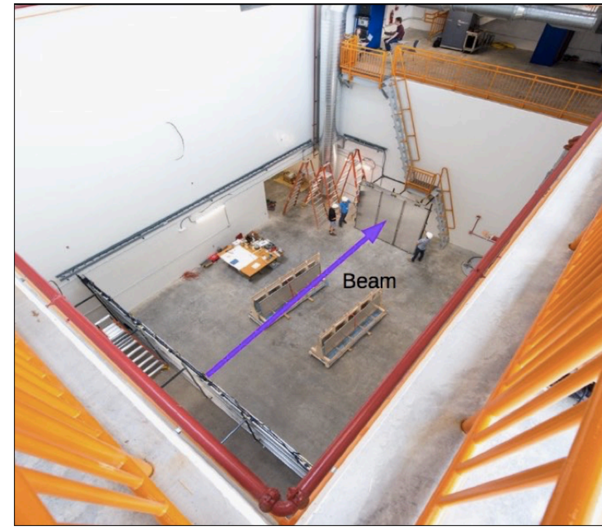
- CRT system:
  - Panels constructed
  - Bottom panels installed
  - Beam measurements in pit



Warm outer vessel in the pit



Bottom CRT



BNB measurement with CRT

Top cap _ part 1

- Cryostat/cryogenics:
  - Warm outer vessel installed.
  - Cryostat material at FNAL.
  - Top cap fabrication finalizing at CERN.
  - Cryogenics installation ongoing

Summary and outlook

- The SBN Program at Fermilab is well on its way to:
  - an exciting search for neutrino oscillations over short baseline addressing the sterile neutrino puzzle;
  - make high precision measurements of ν-Ar cross sections;
  - develop LAr-TPC technology & expertise in preparation for DUNE.
- **MicroBooNE** is now producing high statistics measurements of ν-Ar interactions and is getting closer to start releasing the first results on the low energy excess, based on 6×10^{20} POT.
- Despite the challenges posed by the Covid-19 pandemic:
  - the **Icarus** detector was activated in August 2020 and is now in commissioning phase, expected to be completed early in the Fall 2021;
  - assembly and installation of the **SBND** detector are progressing, with projected activation in 2022.

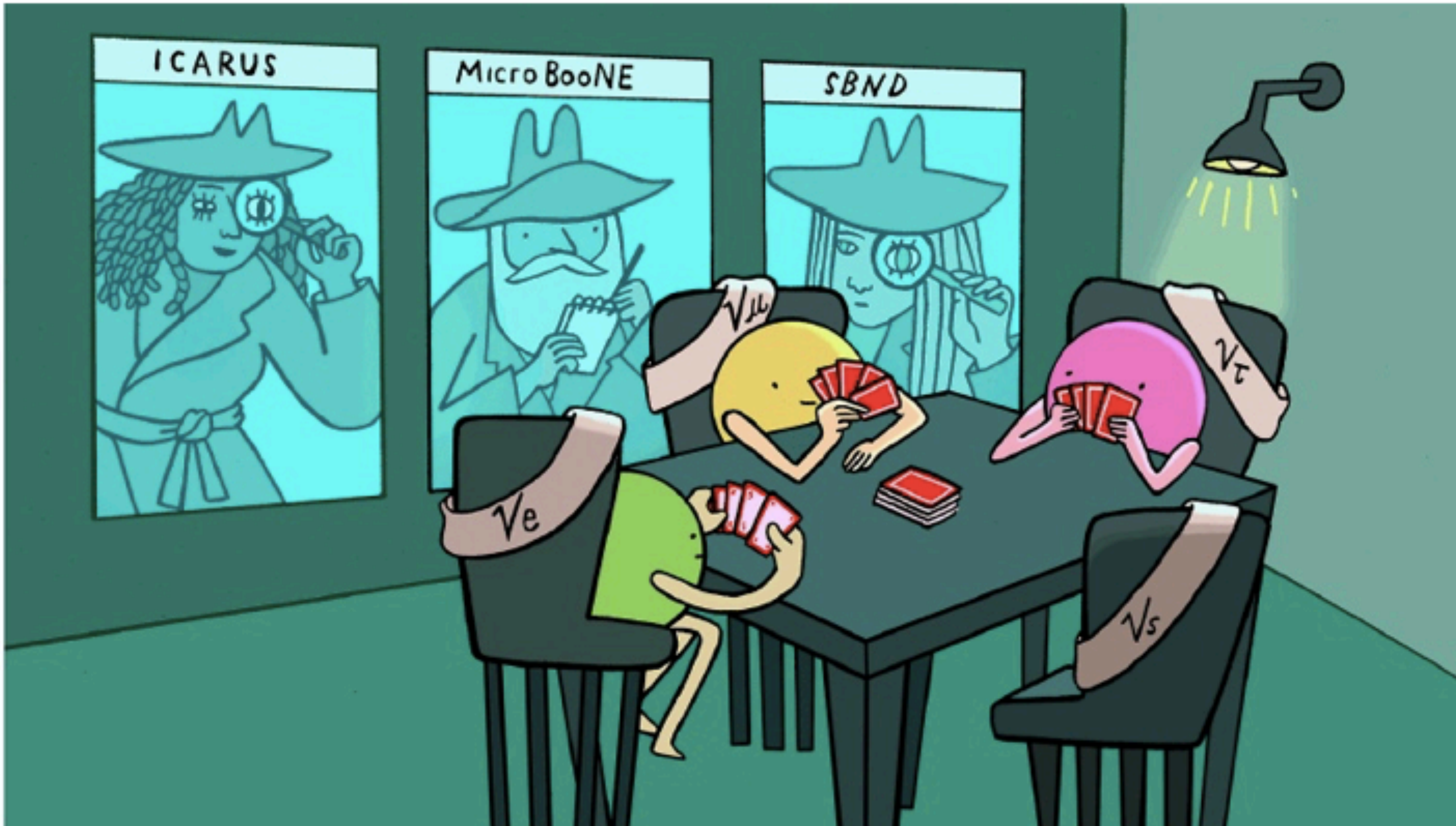
symmetry
dimensions of particle physics

Sterile neutrino sleuths

01/30/18

| By Tom Barratt and Leah Poffenberger

Meet the detectors of Fermilab's Short-Baseline Neutrino Program, hunting for signs of a possible fourth type of neutrino.



Artwork by Sandbox Studio, Chicago with Corinne Mucha

BACKUP

Oscillation signatures at SBN

SBN can exploit the complementarities between ν_e and ν_μ oscillation signatures.

- $\overset{(-)}{\nu}_e$ disappearance

$$P(\overset{(-)}{\nu}_e \nrightarrow \overset{(-)}{\nu}_e) = 1 - sin^2(2\theta_{ee})\cdot sin^2(\frac{\Delta m^2_{41}}{4E_\nu}),\ sin^2(2\theta_{ee}) = 4|U_{e4}|^2 \cdot (1 - |U_{e4}|^2)$$

- $\overset{(-)}{\nu}_\mu$ disappearance

$$P(\overset{(-)}{\nu}_\mu \nrightarrow \overset{(-)}{\nu}_\mu) = 1 - sin^2(2\theta_{\mu\mu})\cdot sin^2(\frac{\Delta m^2_{41}}{4E_\nu}),\ sin^2(2\theta_{\mu\mu}) = 4|U_{\mu 4}|^2 \cdot (1 - |U_{\mu 4}|^2)$$

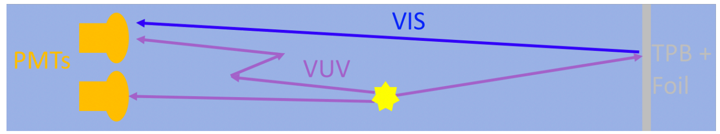
- $\overset{(-)}{\nu}_e$ appearance in $\overset{(-)}{\nu}_\mu$ beam

$$P(\overset{(-)}{\nu}_\mu \nrightarrow \overset{(-)}{\nu}_e) = 1 - sin^2(2\theta_{\mu e})\cdot sin^2(\frac{\Delta m^2_{41}}{4E_\nu}),\ sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 \cdot |U_{\mu 4}|^2$$

Relation between appearance and disappearance channels:
$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ appearance requires $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ disappearance.

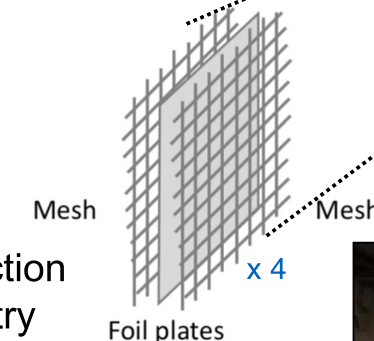
Boosting light collection

- Wavelength-shifting reflector foils (TPB coated) mounted at the cathode
  - 4 (50x60 cm) double-sided coated panels per cathode window (16)
  - Total surface area ~38 m^2



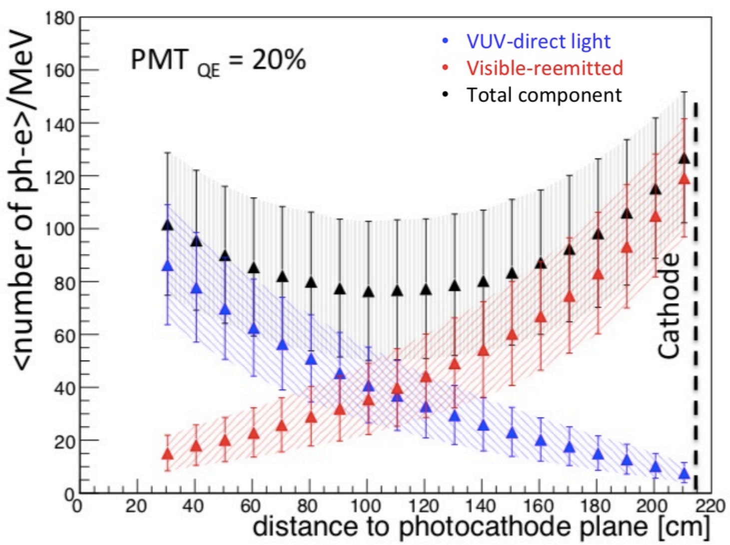
Cathode Plane Assembly

- Combination of direct and reflected light
  - Improved total light yield
  - Uniform light collection
  - Lower threshold



- SBND LDS enables new application of light collection in argon: timing, position reconstruction, calorimetry

<u>PMT only</u>
100 photoelectrons per MeV
when combining direct and reflect light!



Mesh frames with foils assembled

Initial activation of the Icarus trigger system

- Data collected by triggering on the BNB extraction signal in one cryostat used to check the timing/read-out of both TPC and PMTs signals and the timing of the beam gate, a prerequisite for the trigger deployment.
- Anode-to-cathode cosmic μ tracks with unambiguously measured crossing time in the TPC image t_{TPC} found to match the corresponding time of PMT light signal t_{PMT}. Clear ~2 μs peak in $t_{TPC} – t_{PMT}$ confirming the correct relative TPC - PMT timing.
- *Excess of PMT light signal in correspondence with the 1.6 μs BNB gate observed.*