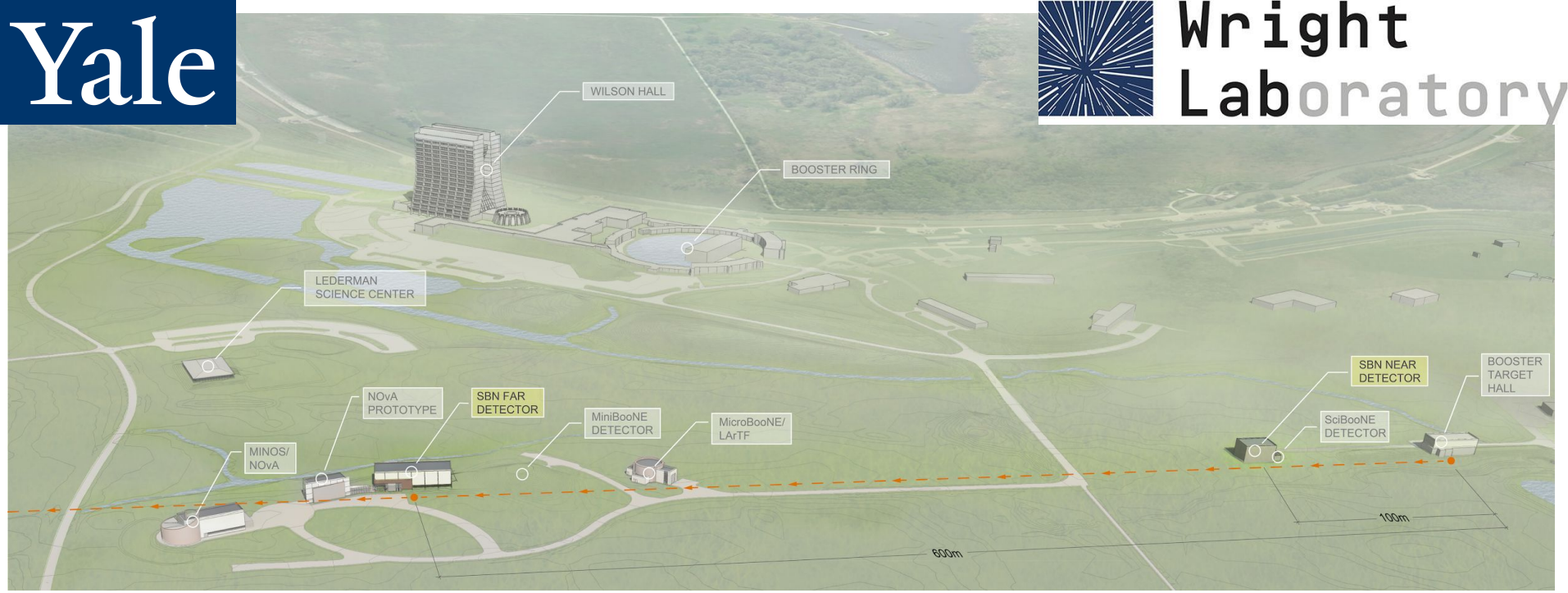


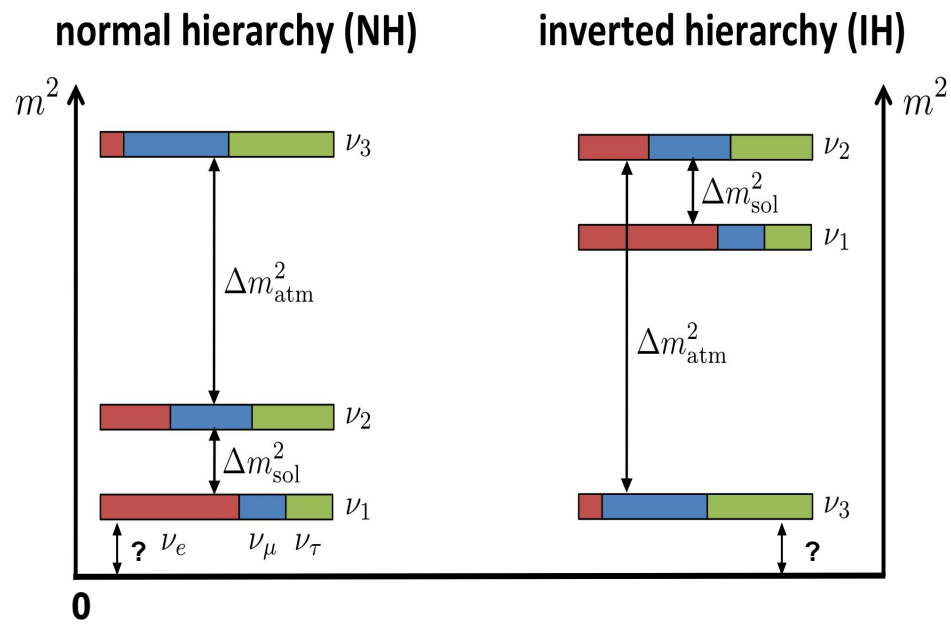
Sterile Oscillations and the Short-Baseline Neutrino Program at Fermilab

Serhan Tufanli
for the
SBN Program

Prospects in Neutrino Physics, 2018

Current state of the field

- Well established three neutrino mixing and oscillations with the data from solar, atmospheric and accelerator experiments
- "Large" mixing angle Θ_{13} opened the way to measure δ_{CP} and we have the first hints of non-zero δ_{CP}
- Mass hierarchy, absolute mass, δ_{CP} value, existence of sterile neutrinos are some of the remaining open questions



$\theta_{12} \approx 33°$

$\theta_{23} \approx 45°$

$\theta_{13} \approx 9°$

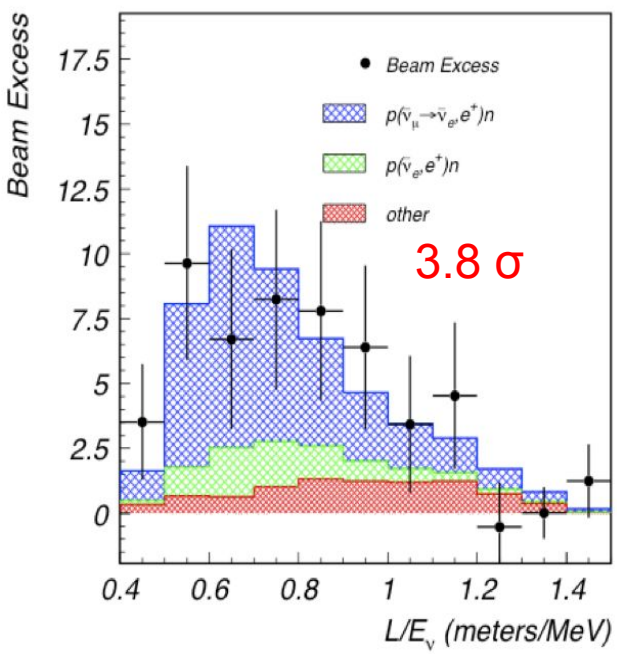
$\Delta m^2_{21} \approx 7.5 \times 10^{-5}\ \mathrm{eV}^2$

$|\Delta m^2_{32}| \approx 2.5 \times 10^{-3}\ \mathrm{eV}^2$

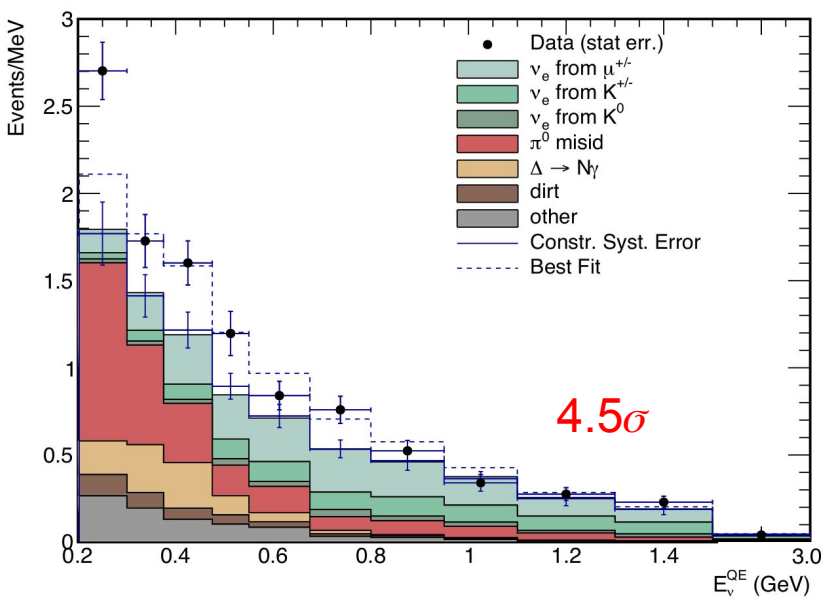
Neutrino short baseline anomalies

- Evidence for an low energy electron-like excess from neutrinos from particle accelerators (the "LSND and Mini-BooNE anomalies")
  - LSND observed a (3.8 sigma) excess of $\bar{\nu}_e$ events in a very pure $\bar{\nu}_\mu$ anti-numu beam
  - MiniBooNe observed a (4.5 sigma) excess of low energy electromagnetic events in neutrino and antineutrino mode in a ν_μ/ $\bar{\nu}_\mu$ beam

Phys. Rev. D 64, 112007

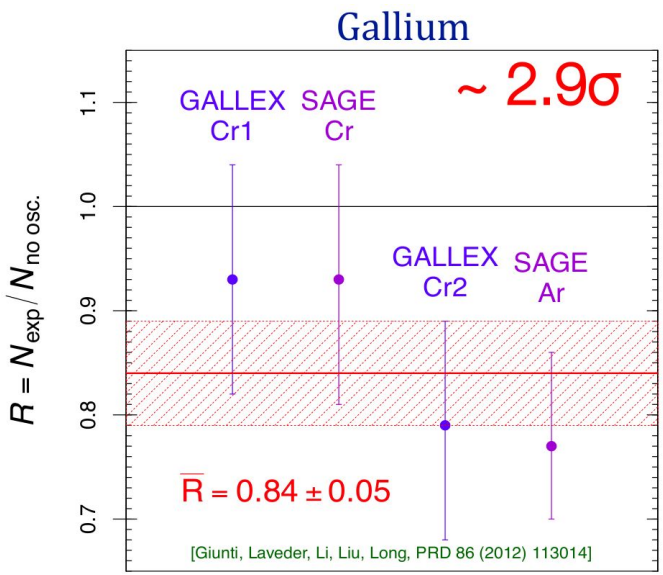


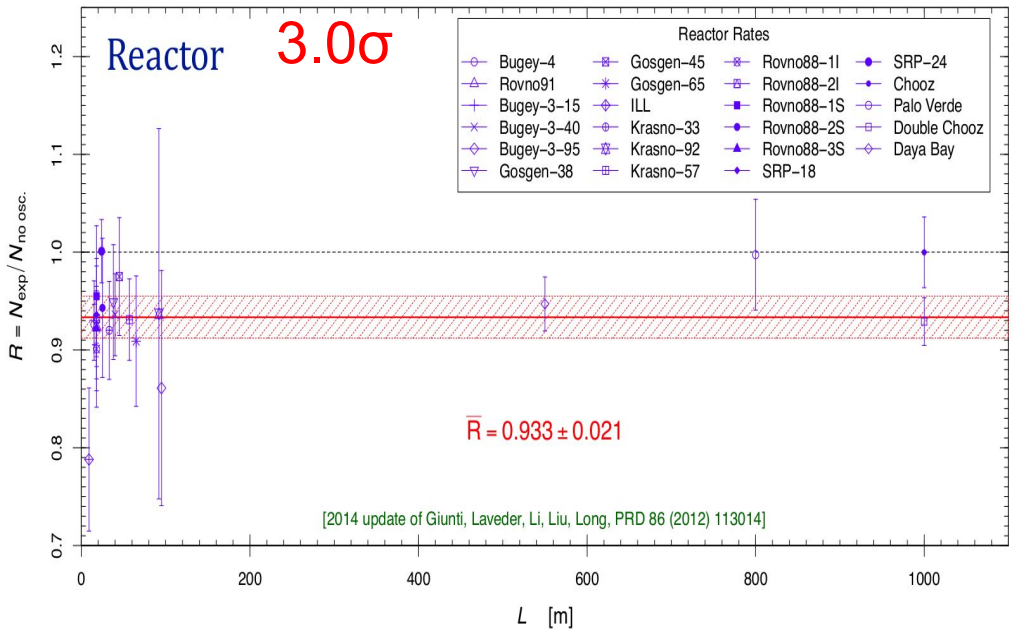
arXiv:1805.12028



Neutrino anomalies

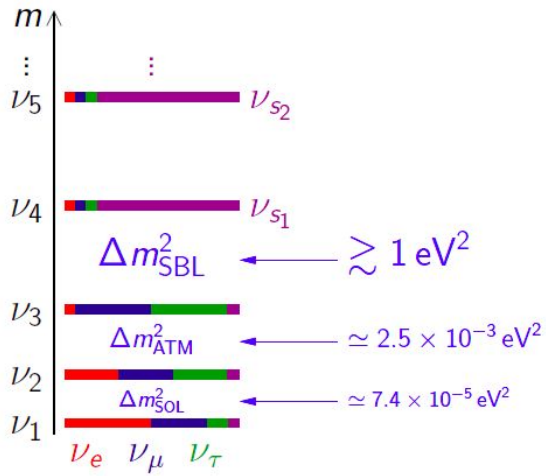
- ν_e disappearance signal in the low energy anti-neutrinos from nuclear reactors ("reactor anomaly") and from radioactive neutrino sources in the Gallium experiments ("Gallium anomaly")



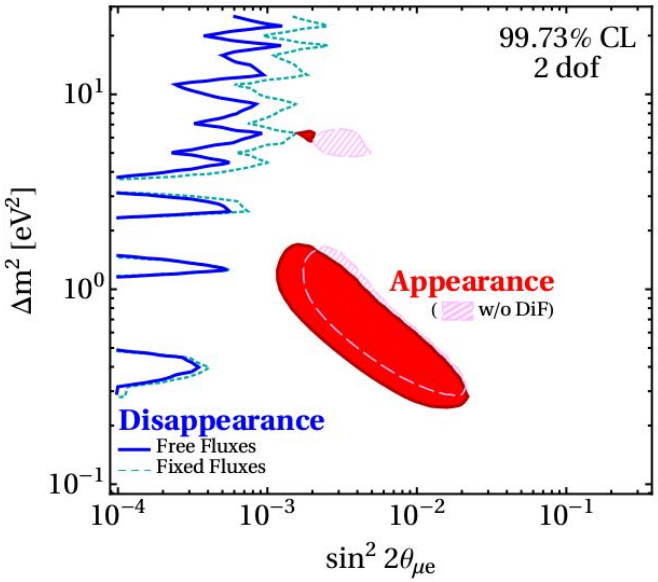


Global fits (3+1 model)

- Short-baseline neutrino anomalies are often interpreted as oscillations involving sterile neutrinos with $\Delta m^2 \sim 1 eV^2$ and an L/E ~ 1km/GeV
- However, there is a strong tension with experiments that observe no signal
  - Significant constraints from disappearance measurements, especially recent measurements by IceCube and MINOS+
- To conclude the short-baseline anomalies, new experimental efforts are needed
  - Repeating similar measurements
  - New ways addressing oscillation hypothesis
    - Appearance and disappearance data from the same experiment

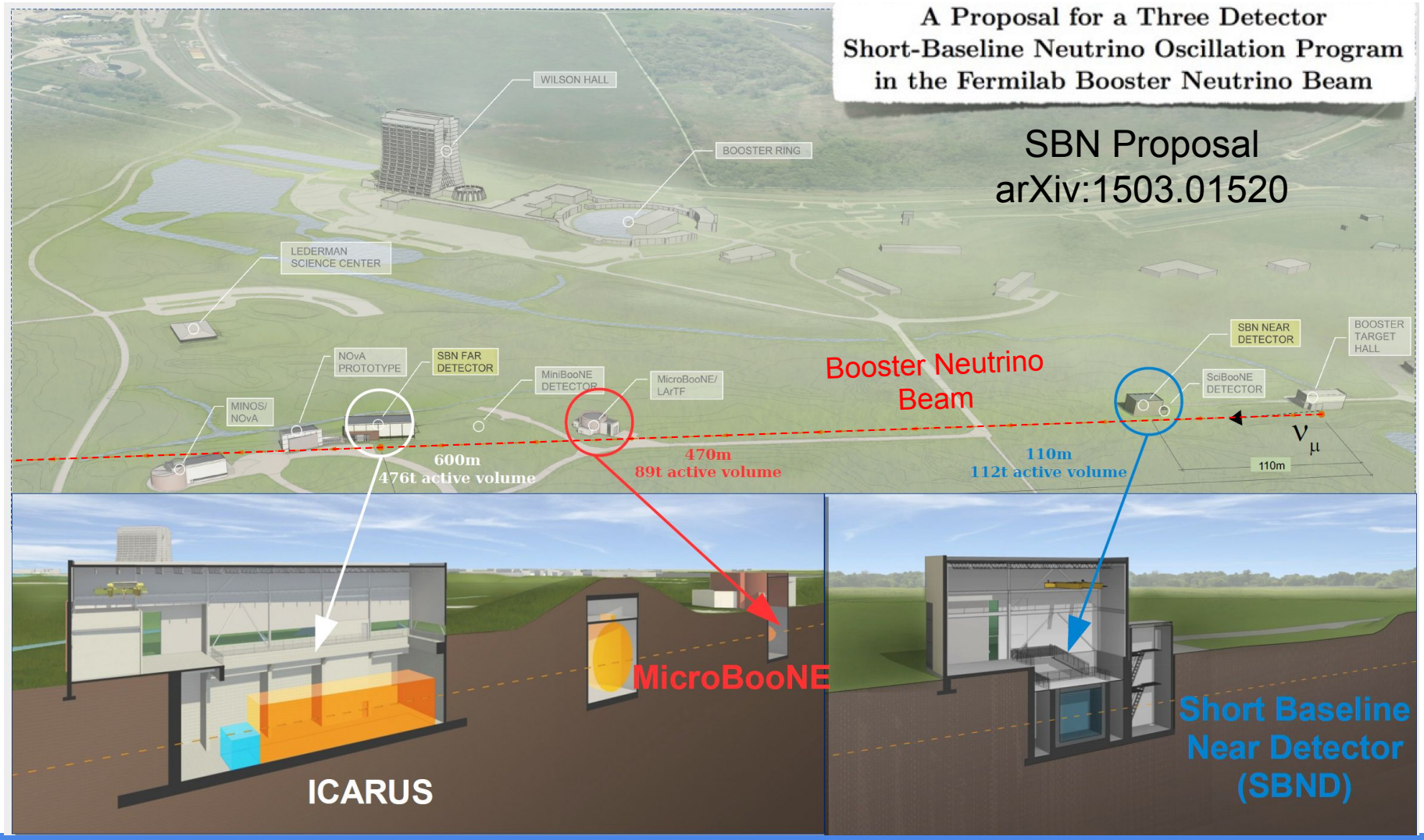


M. Dentler et al., arXiv:1803.10661

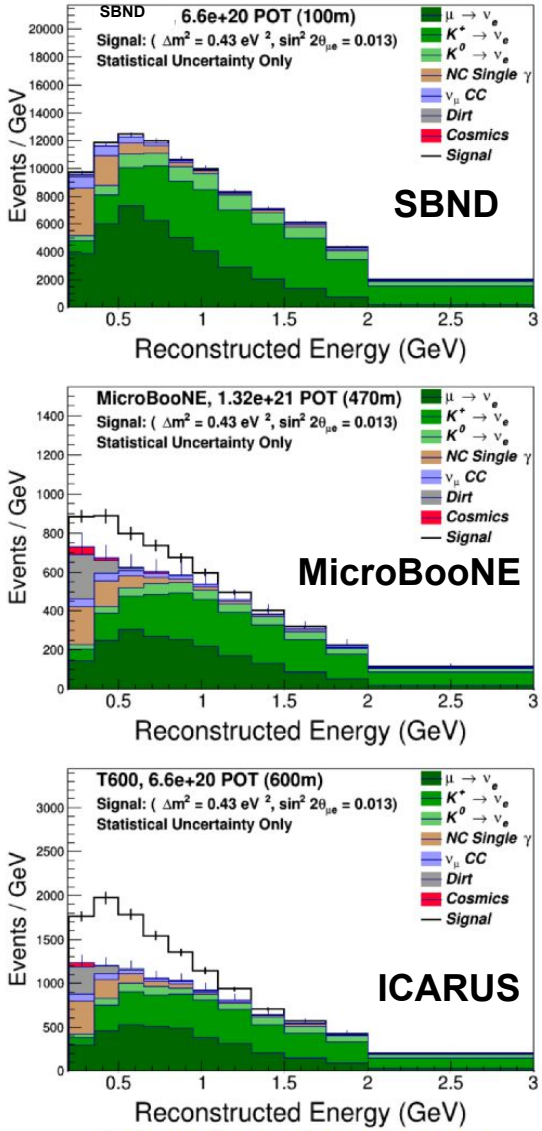


Short-Baseline Neutrino (SBN) program at Fermilab

- Three liquid argon time projection chamber (LArTPC) detectors in the Booster Neutrino Beam (BNB) at Fermilab.

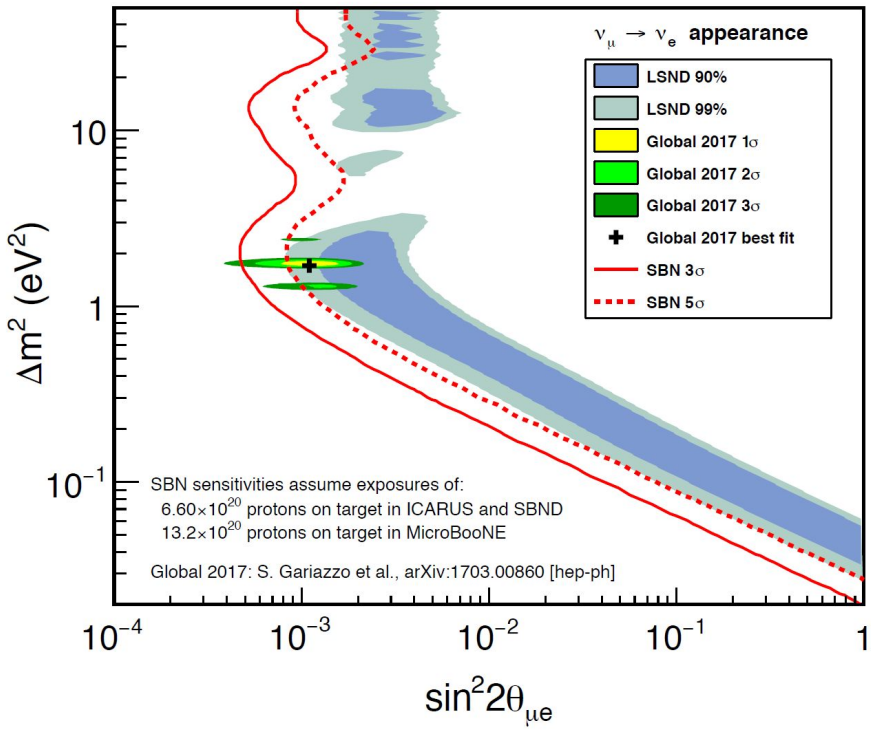


Search for sterile neutrinos: $\nu_\mu \rightarrow \nu_e$ appearance

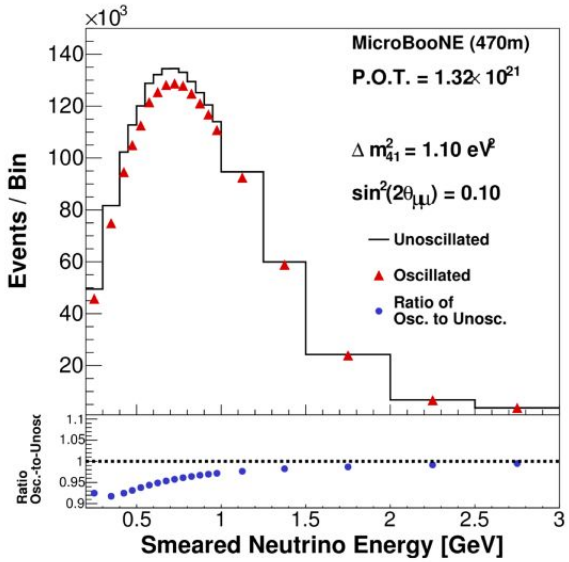


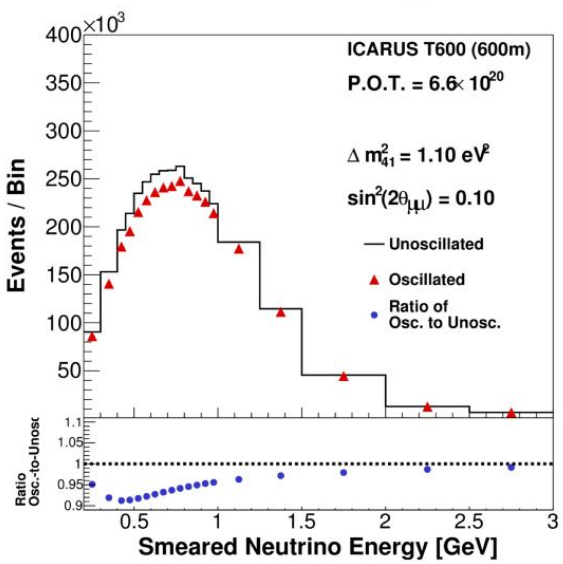
http://arxiv.org/abs/1503.01520

- A large mass far detector and a near detector of the same technology reduces both statistical and systematic uncertainties
- SBN detectors enable 5σ coverage the 99% C.L. allowed region of the LSND signal and global best fit values



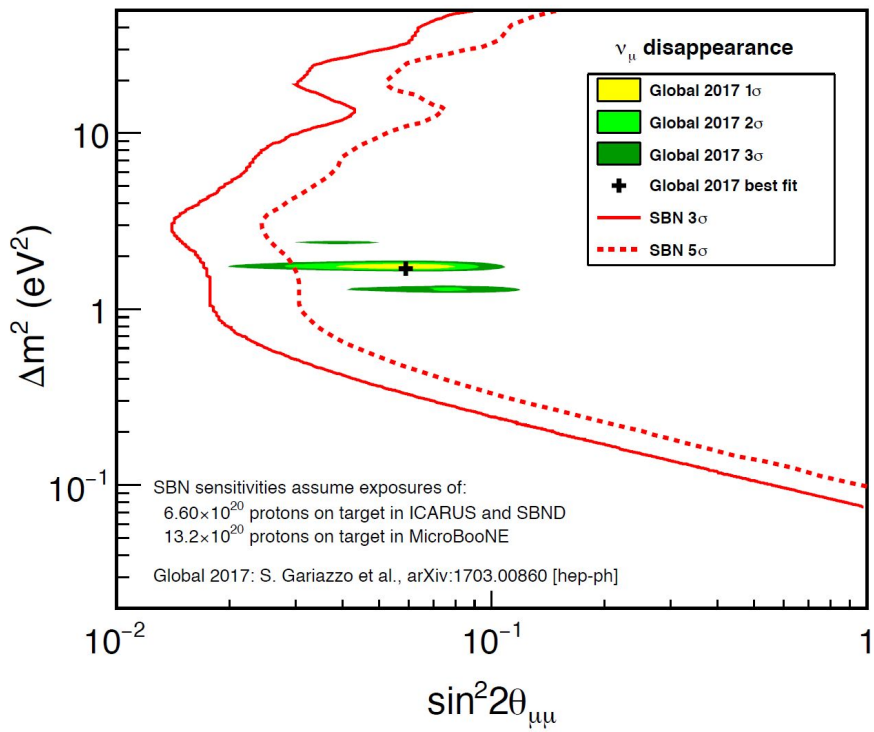
Search for sterile neutrinos: ν_μ disappearance





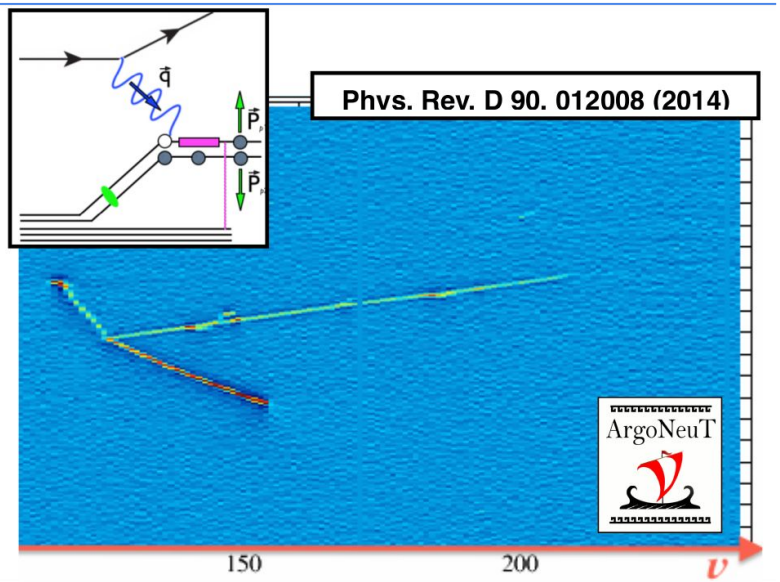
http://arxiv.org/abs/1503.01520

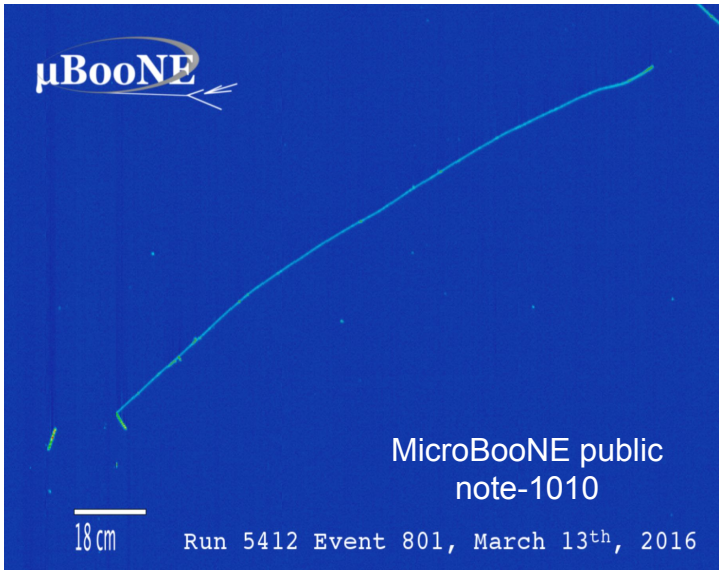
- SBN can extend the search for muon neutrino disappearance an order of magnitude beyond the combined analysis of SciBooNE and MiniBooNE
- Critical aspect to verify an oscillation hypothesis



ν–Ar cross section studies

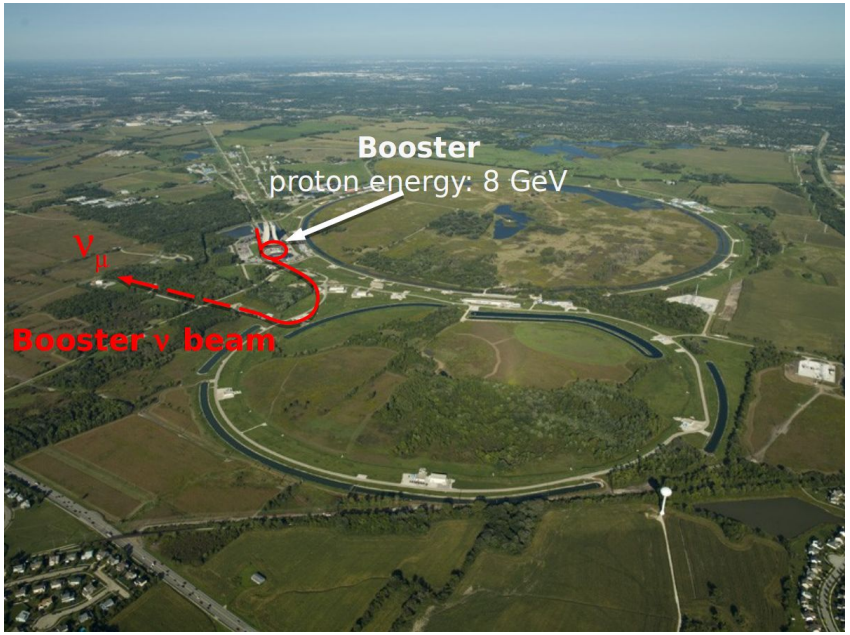
- ν oscillation experiments require precise understanding of ν-Ar interaction cross section for a correct interpretation of the experimental outcome
- SBN will provide huge data sets of ν – Ar interactions from BNB and off-axis NuMI
  - Large samples in MicroBooNE are already under analysis and first results have recently been published
  - SBND will record **1.5 million ν_μ CC** and **~12k ν_e CC** interactions per year
  - ~100k NuMI off-axis events in T600 per year

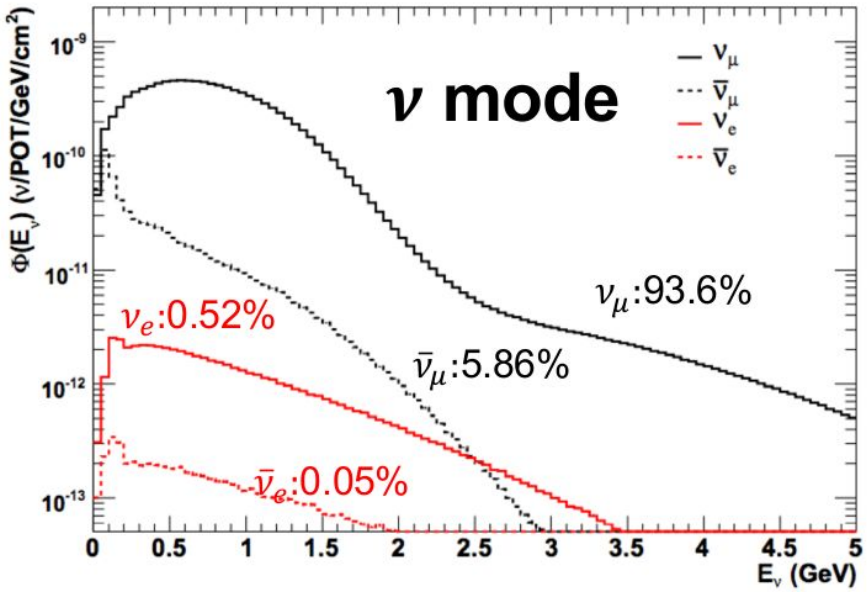




Fermilab Booster Neutrino Beam

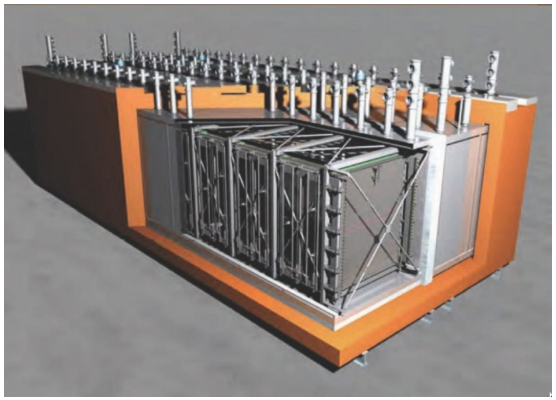
- Fermilab's low-energy Booster Neutrino Beam (BNB)
  - 8 GeV protons hit on Be target create neutrino flux with 700 MeV peak energy
  - Neutrino and antineutrino modes
  - ~0.5% electron neutrino contamination in neutrino mode
  - Stably running for a decade





SBN experimental setup

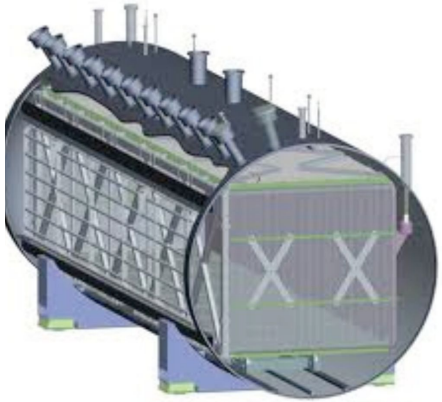
ICARUS



- LArTPC
- 600 m from ν production
- 476 ton active volume
- 4x1.5 m drift length
- 75kV high voltage
- 3 wire planes: horizontal, ∓30 deg, 3mm wire pitch, 53246 wires
- Warm analog and digital electronics
- 360 8” PMTs

INSTALLATION

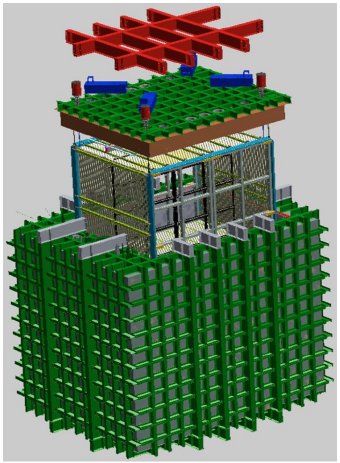
MicroBooNE



- LArTPC
- 470 m from ν production
- 85 ton active volume
- 2.56 m drift length
- 128 kV high voltage
- 3 wire planes: 0, ∓60 deg, 3mm wire pitch, 8256 wires
- Cold analog/warm digital electronics
- 32 8” PMTs

RUNNING

SBND

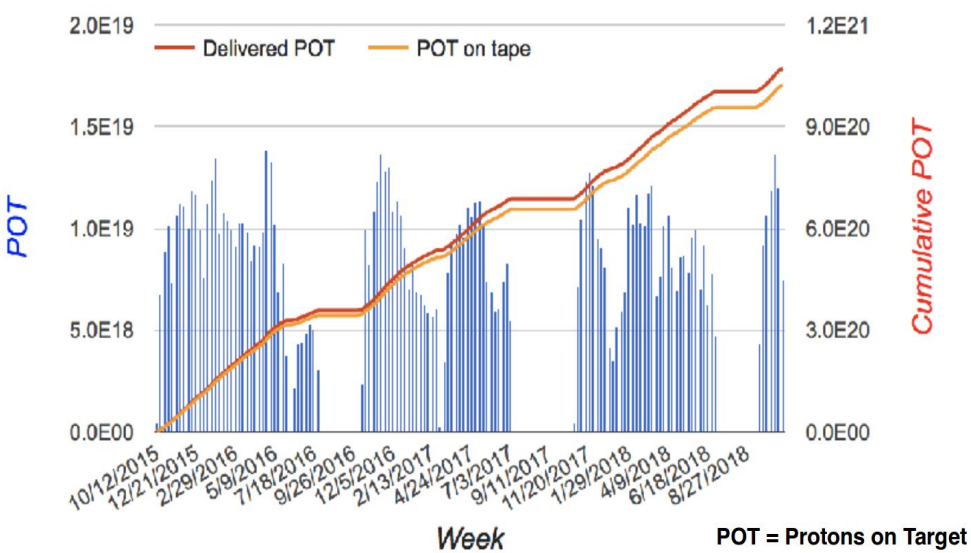


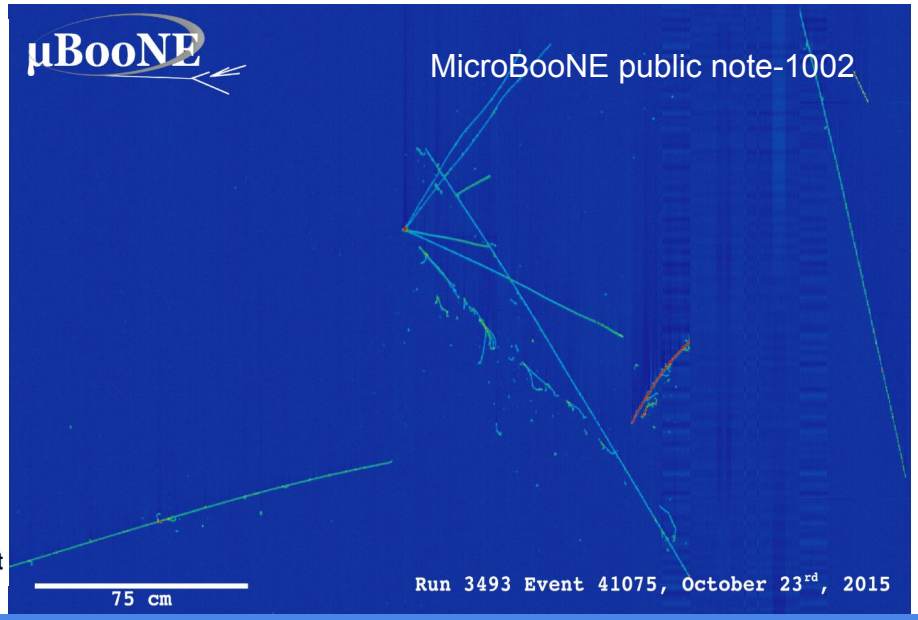
- LArTPC
- 110 m from ν production
- 112 ton active volume
- 2x2.0 m drift length
- 100 kV high voltage
- 3 wire planes: 0, ∓60 deg, 3mm wire pitch, 11264 wires
- Cold analog and digital electronics
- 120 8” PMTs && scin. bars

UNDER CONSTRUCTION

Phase-1: MicroBooNE

- Installation completed in 2015
- Collection date since October 2015 at BNB line at Fermilab with main goals of
  - Addressing the MiniBooNE low energy access
  - Performing Neutrino -- Argon cross section measurements
  - Performing R&D for future LArTPCs
- >96% uptime during stable operations and so far collected ~10^{21} POT

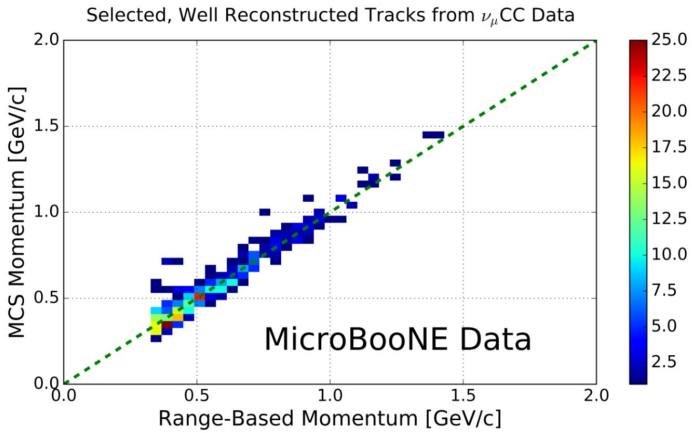




Ongoing efforts and publications

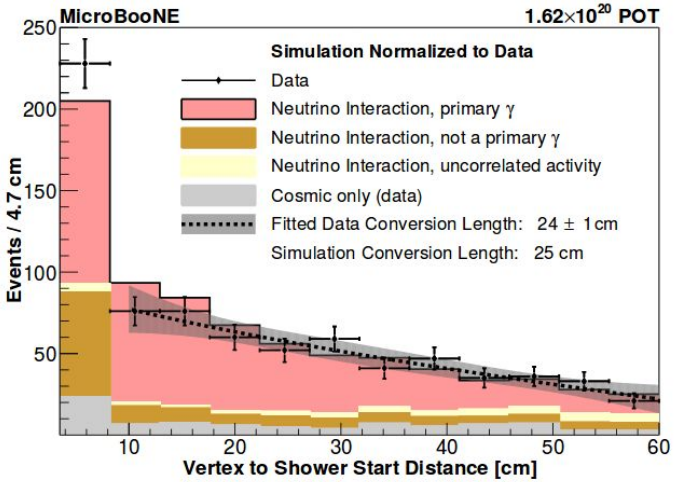
- MicroBooNE is doing an excellent job on LArTPC calibration, simulation, reconstruction and developing analysis tools for future detectors
  - Understanding the detector technology
  - Develop automated LArTPC reconstructions using 2D, 3D and machine learning techniques
  - Constrain ν-Ar interaction models with data
  - Develop multiple independent low energy excess searches

arXiv:1703.06187



- Public notes:
  - 30 analysis documented in details
  - http://microboone.fnal.gov/public-notes/

arXiv:1811.02700

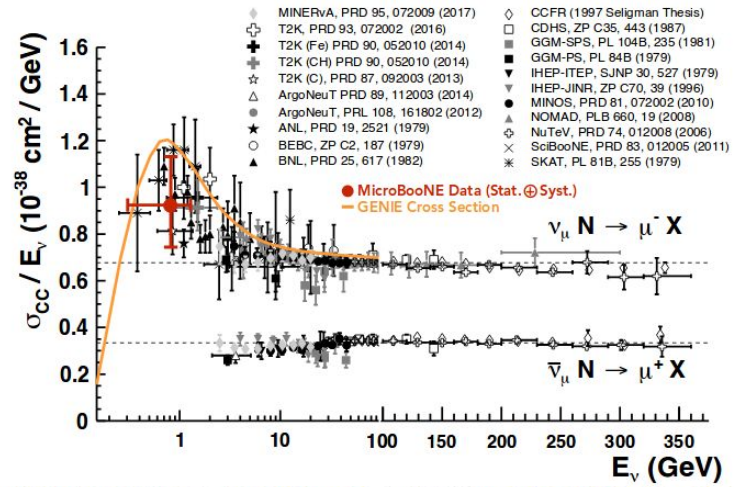


- Posters in this conference
  - Thomas Mettler, *"The Cosmic Ray Tagger of MicroBooNE"*
  - Andy Smith, *"The Pandora consolidated multi-algorithm approach to pattern recognition in MicroBooNE"*
  - Andrew Furmanski, *"MicroBooNE Cross Section Measurements"*

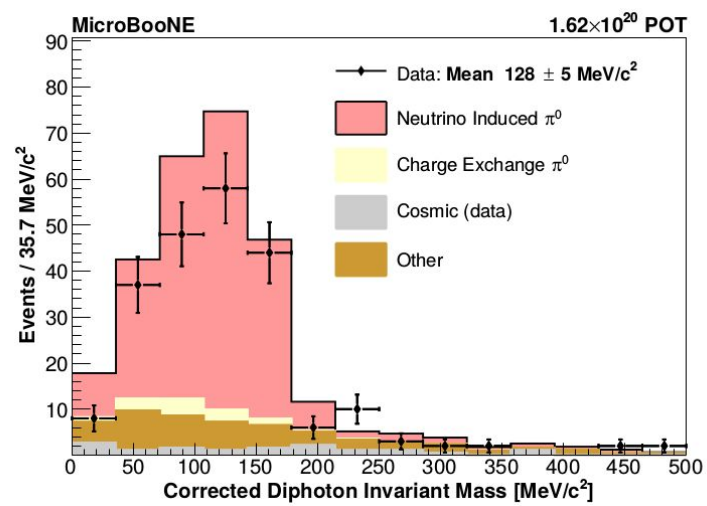
Understanding ν–Ar interactions and developing excess searches

- MicroBooNE's first physics results this year
- Understanding ν-Ar interactions:
  - ν_μ CC inclusive cross section
    - Starting point for more exclusive channels
    - First measurement on Ar at low energy
  - ν_μ CC pi0 production
    - First such measurement on Argon
    - Enables studies of shower energy reconstruction and resolution in data
  - For more details, see the poster *"MicroBooNE Cross Section Measurements"* by Andy Furmanski
- Low energy excess searches
  - Blind search strategy (small subset of open data)
  - Independent e-like and γ-like analysis
    - Complementary analysis targeting different final states
  - Completed first iteration of fully-automated ν_e and single photon selection

MICROBOONE-NOTE-1045



$$\sigma = 0.756 \pm 0.011\,(\text{stat}) \pm 0.027\,(\text{genie}) \pm 0.114\,(\text{flux}) \pm 0.141\,(\text{det}) \times 10^{-38}\,\text{cm}^2$$



arXiv:1811.02700

Phase-2: MicroBoNE + ICARUS and SBND

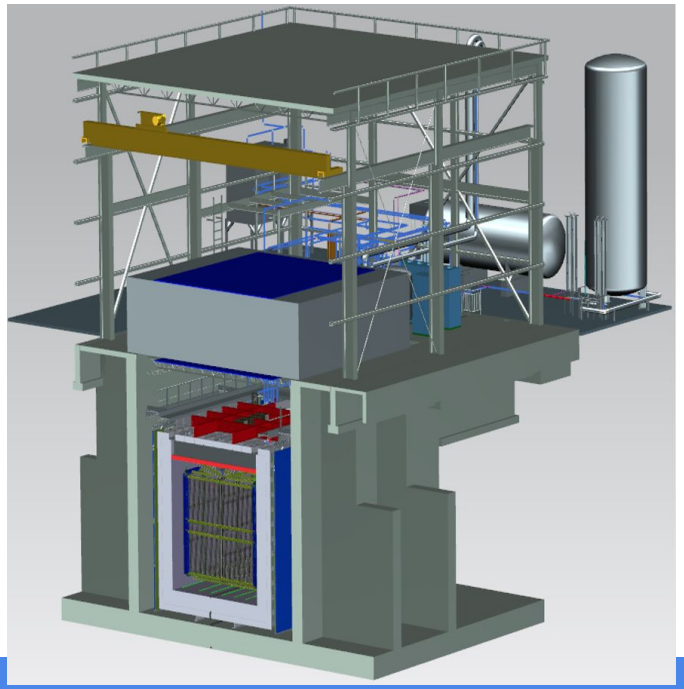
The ICARUS detector

- ICARUS is going to be the far detector in the SBN program
- It was operational at LNGS from 2010-2013
- In 2015, sent to CERN for refurbishment
- Shipped to Fermilab in June 2017

Status of ICARUS

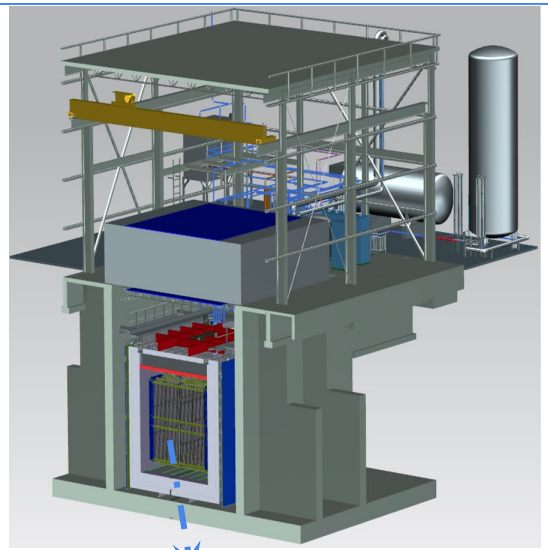
- Rigging and placement of the two modules into vessel was completed in August 2018
- Cold shielding and closing of the warm vessel has been finalized
- Process will continue with cryogenics, purification, vacuum and cabling activities
- Commissioning and data taking in 2019

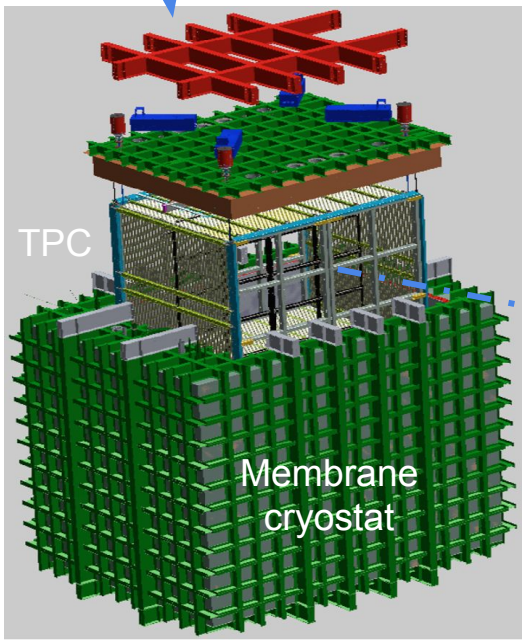
Short-Baseline Near Detector - SBND



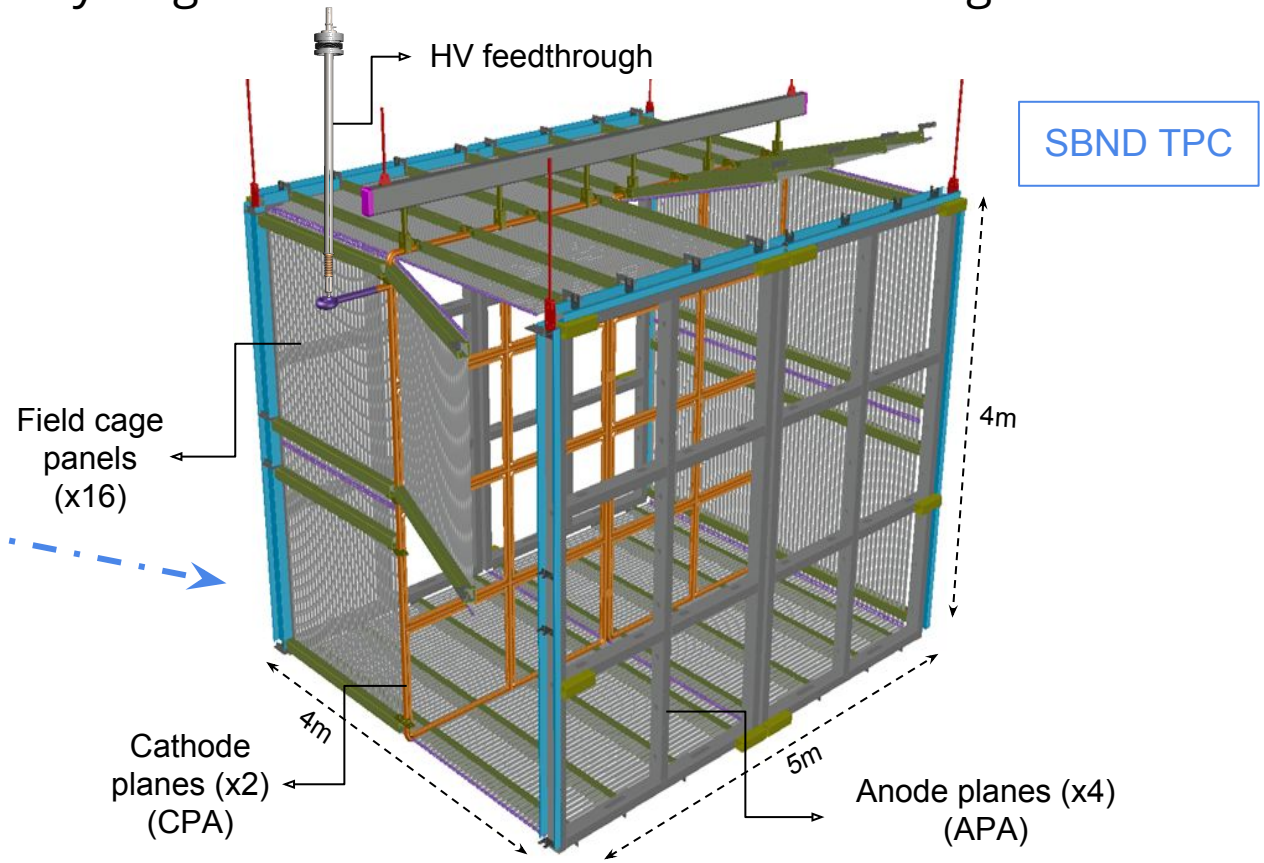
- Near detector at SBN with main goals
  - Detailed characterization of beam before oscillation
  - Reduction of the dominant systematics
  - Cross section studies with **1.5 million ν_μCC** and **12k ν_eCC** interactions per year
    - see poster from Rhiannon Jones for ν_μCC 0π Selection in SBND
  - Detector R&D for DUNE far detector
- Detector design has been finalized. Components are under construction
- Detector building is ready at Fermilab

SBND detector

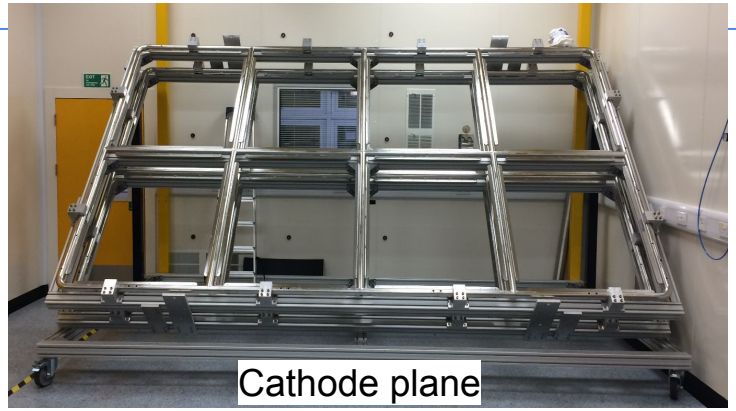




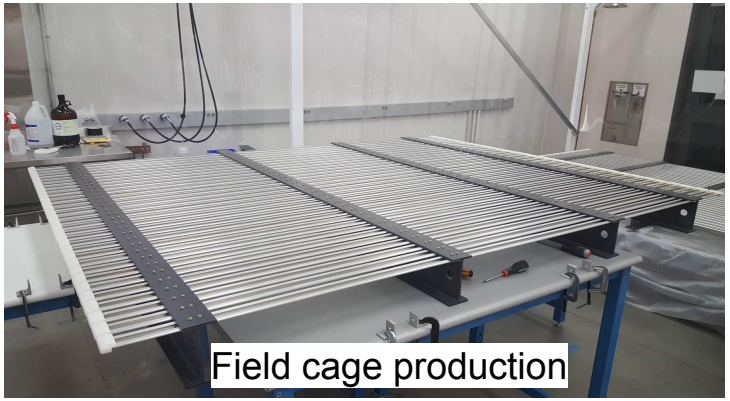
- Completely new detector incorporated experience from ICARUS, MicroBooNE
- LArTPC with 112 ton active volume
- Synergies with PrototDUNE for future large LArTPCs

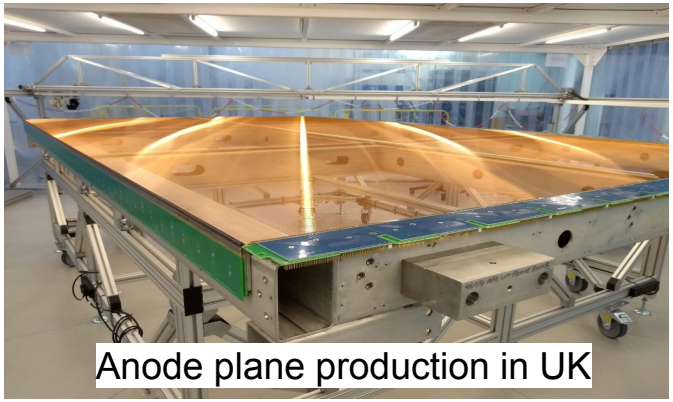


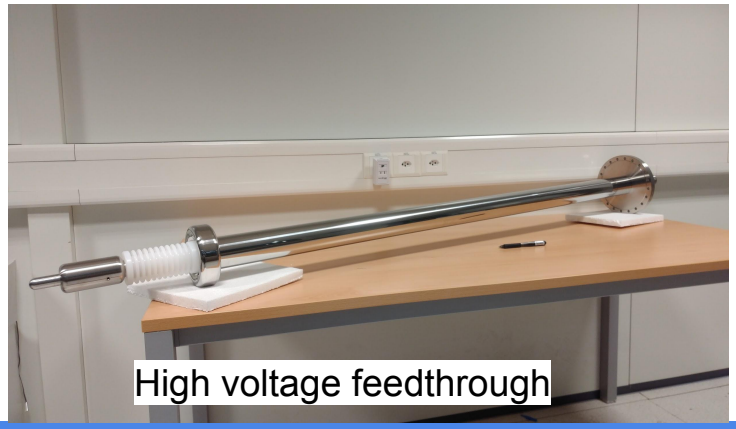
SBND detector construction

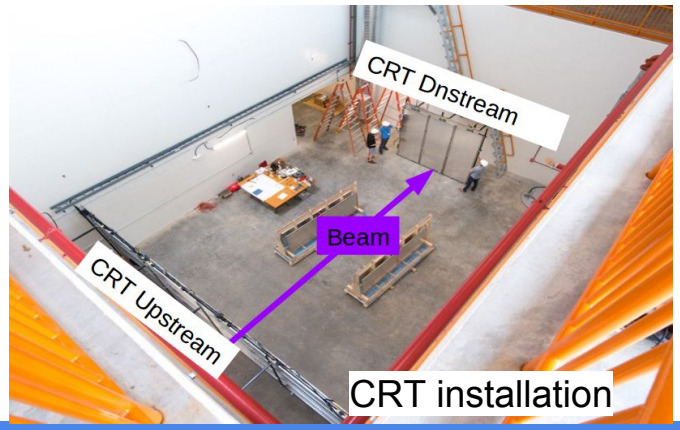

Cathode plane

Anode plane production in US


Field cage production


Anode plane production in UK


High voltage feedthrough

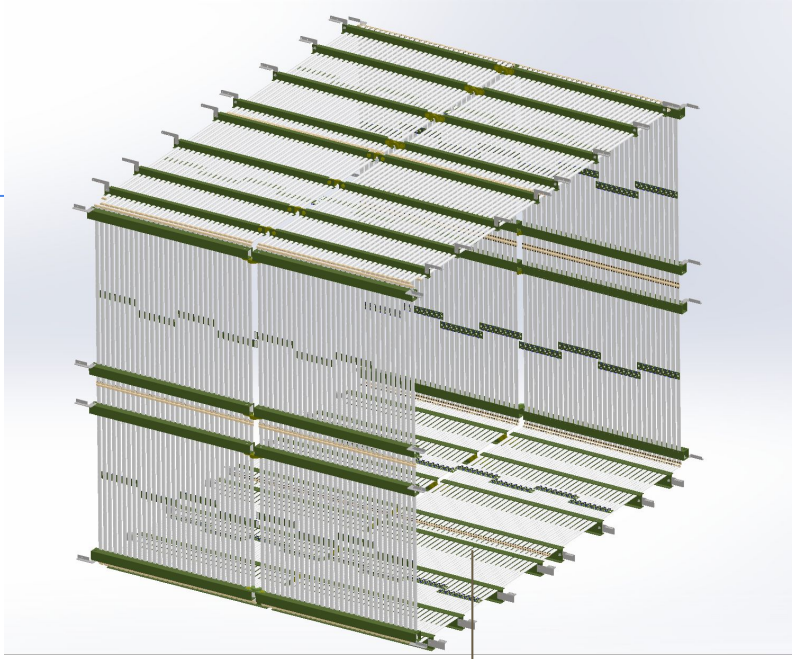


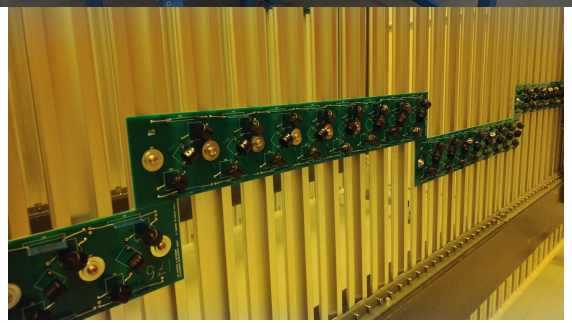
CRT installation

For more details, please see the poster *"Cosmic background removal with the cosmic ray tagger system in the Short-Baseline Near Detector"* by Tom Brooks

SBND field cage

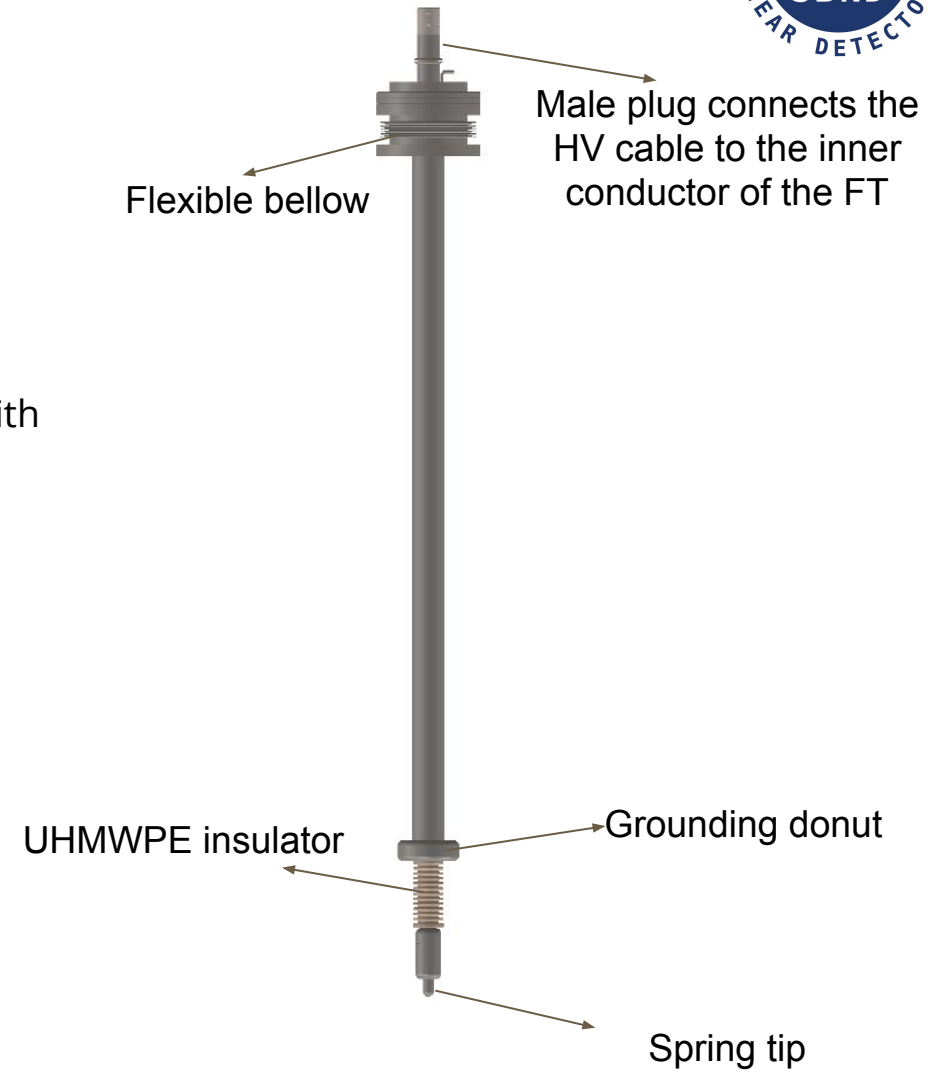
- Provides uniform electric field inside the active volume and surcharge protection
  - Receives bias voltage from cathode planes, terminates to ground at anode planes
- Mechanically connects anode and cathode planes, maintains the drift distance
- Accommodates laser beam from the laser calibration system to enter into the active volume
- 16 independent modules
  - Aluminium field shaping profiles
  - Reinforced fiberglass mechanical supports
  - Divider and surcharge protection circuits





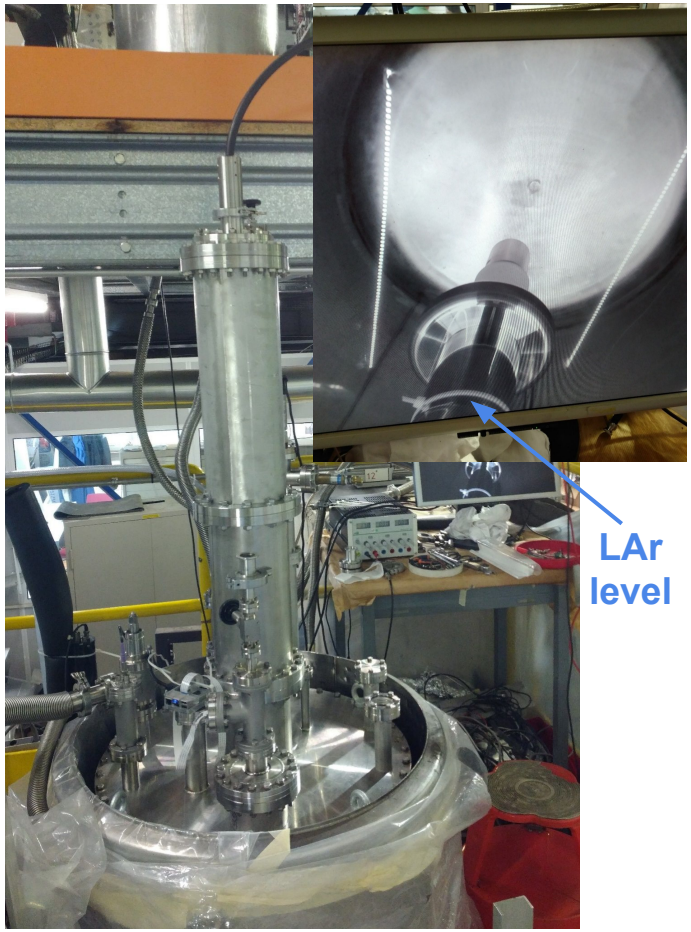
SBND high voltage feedthrough

- -100 kV nominal SBND high voltage, generated by an external power supply, is delivered to cathode via high voltage feedthrough
- Design basics:
  - Coaxial design: UHMWPE is interleaved with the stainless steel inner and outer conductors
  - Cryo-fit for leak tight seal
- Main components
  - High voltage cable plug
  - Top flanges
  - Inner and outer conductors
  - UHMWPE insulator
  - Bottom spring tip



SBND high voltage feedthrough

- Tested at CERN, in a set up reflecting more extreme boundary conditions than we'll have in SBND
- Worked perfectly at 150 kV (50% higher than the nominal SBND high voltage)



Conclusions

- SBN program consists of three LArTPCs that will sit in the Fermilab BNB beam and will
  - study the baseline dependence of the appearance and disappearance channels and cover the full LSND allowed parameter space with 5σ
  - make a high precision measurement on ν-Ar cross sections
  - develop LArTPC technology for future large neutrino experiments like DUNE

- A lot of progress has been achieved in the program
  - MicroBooNE is a big success - has already collected ~10^{21} pot from BNB, has recently published first physics results and working on it's signature analysis
  - SBND is making excellent technical progress on construction the detector pieces and improving the LArTPCs for future experiments
  - ICARUS detector has been installed and getting ready for commissioning

- Stay tuned for three detector run and physics results