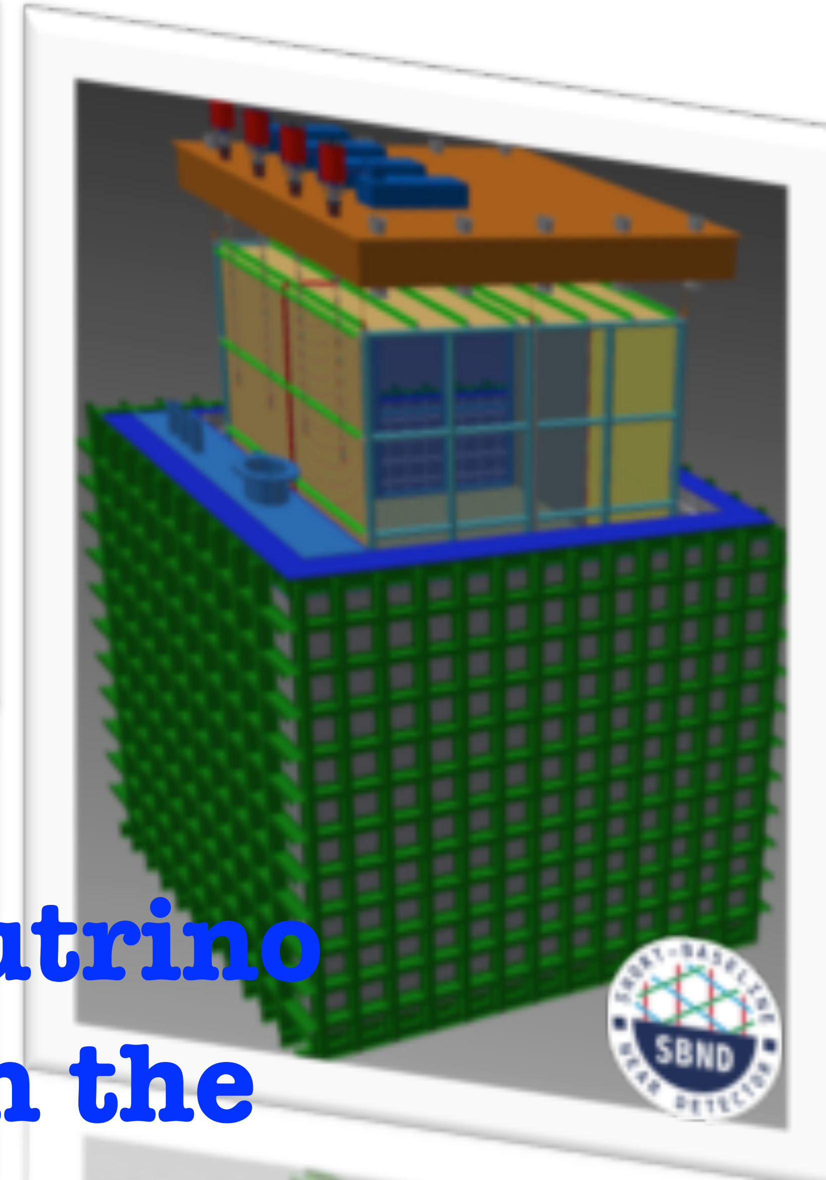


The Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

8th Infieri Workshop - Fermilab

October 20, 2016

Ornella Palamara

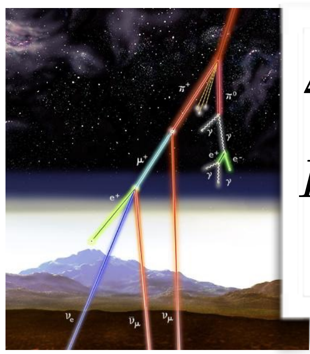
Fermilab & Yale University

Outline

- Why a Short-Baseline Accelerator Neutrino program?
- The Fermilab SBN Program
    - SBN physics reach
    - SBN program Status

Neutrino Oscillation - 3 neutrino mixing

- Three neutrino mixing is well established *(data from solar, atmospheric, reactor and accelerator neutrino experiments)*!
  - Picture consistent with the mixing of **3 neutrino flavors with 3 mass eigenstates** - with relatively small mass differences.

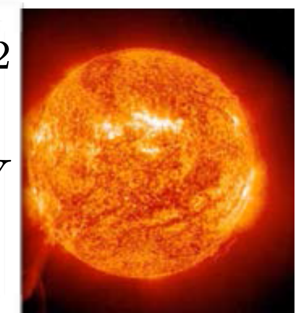


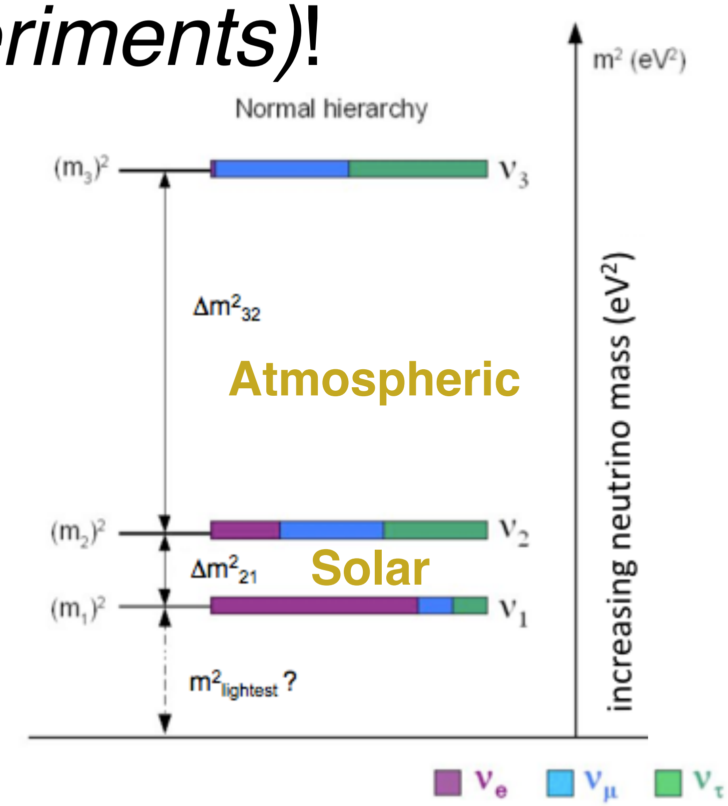
$$\Delta m^2_{32} \simeq 2.4 \cdot 10^{-3} eV^2$$
$$L/E = 500 Km/GeV$$

Atmospheric

$$\Delta m^2_{21} \simeq 7.5 \cdot 10^{-5} eV^2$$
$$L/E = 15,000 Km/GeV$$

Solar





- Forthcoming experiments will address many questions related to neutrino properties:
  - What are the masses of the neutrinos?
  - Are neutrinos their own antiparticles?
  - How are the masses ordered (referred as mass hierarchy)?
  - Do neutrinos and antineutrino oscillate differently?
  - Are there additional neutrino types or interactions?

β and ββ decay experiments

Neutrino Oscillation - 3 neutrino mixing

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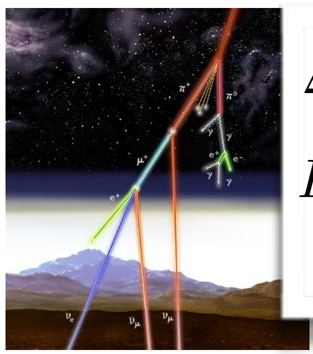

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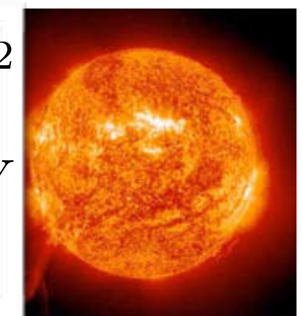

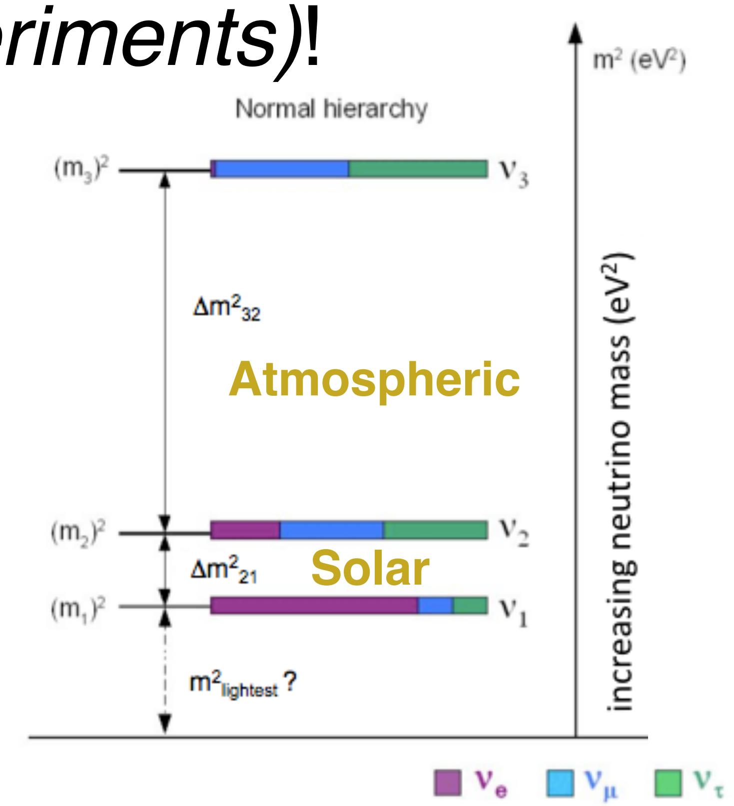

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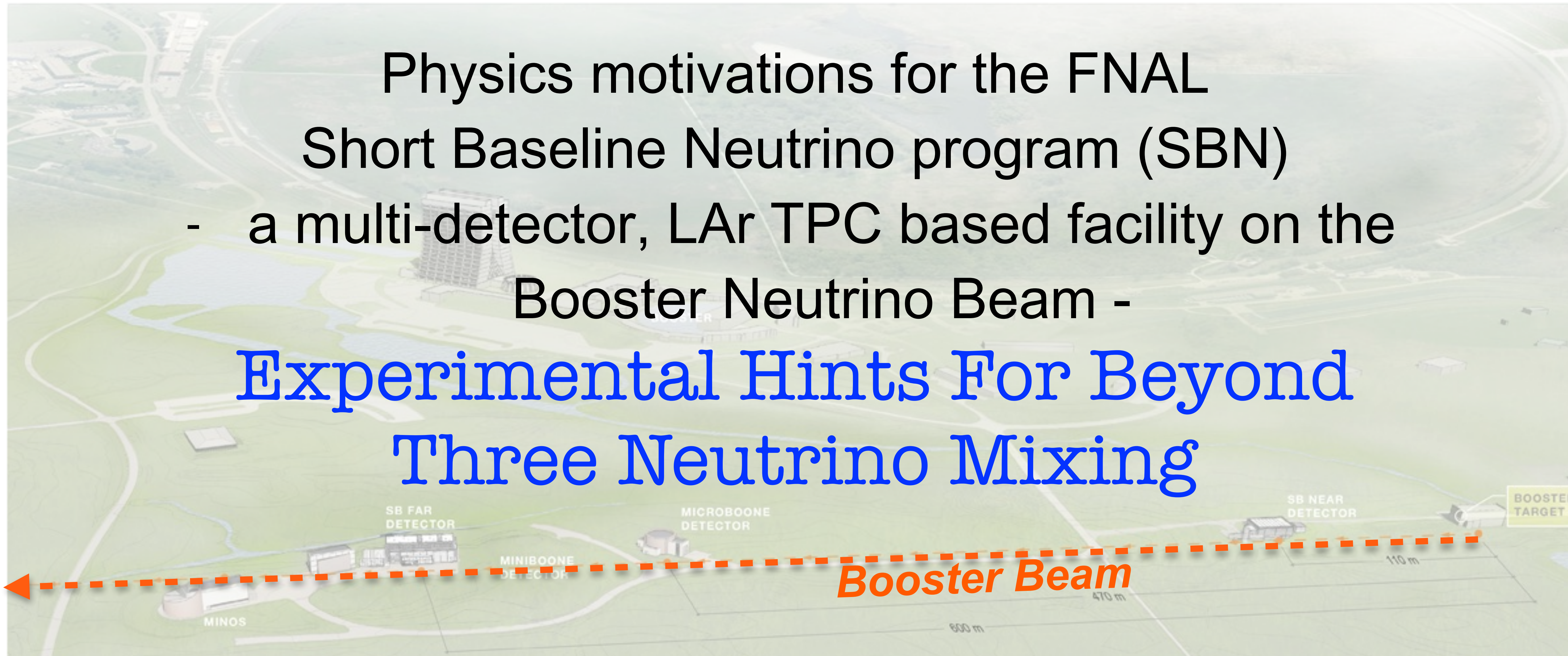
Accelerator Neutrino Oscillation (Short- and Long-Baseline)

Why a Short-baseline accelerator neutrino program?

Physics motivations for the FNAL
Short Baseline Neutrino program (SBN)
- a multi-detector, LAr TPC based facility on the Booster Neutrino Beam -

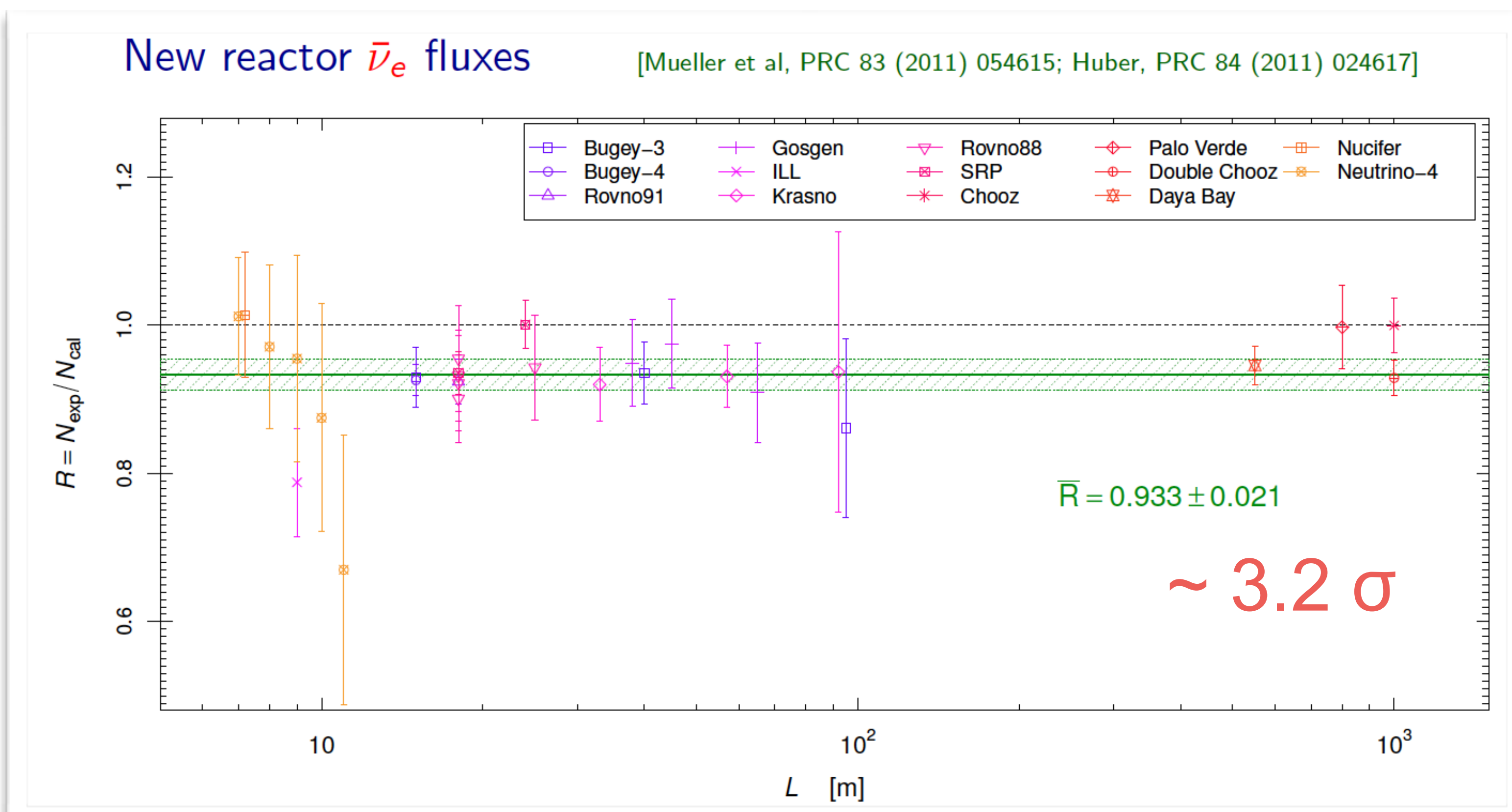
Experimental Hints For Beyond Three Neutrino Mixing

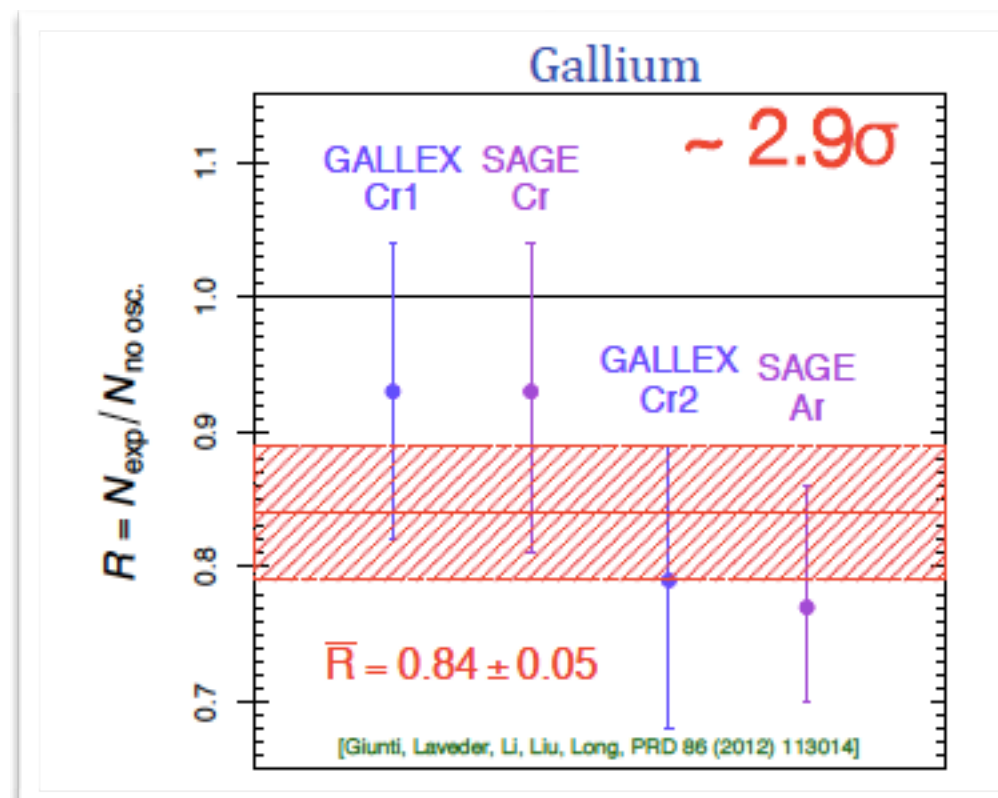


Short-Baseline Neutrino Anomalies (I)

In recent years, two classes of experimental "neutrino anomalies" have been reported from measurement at short-baseline:

(I) An apparent 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")

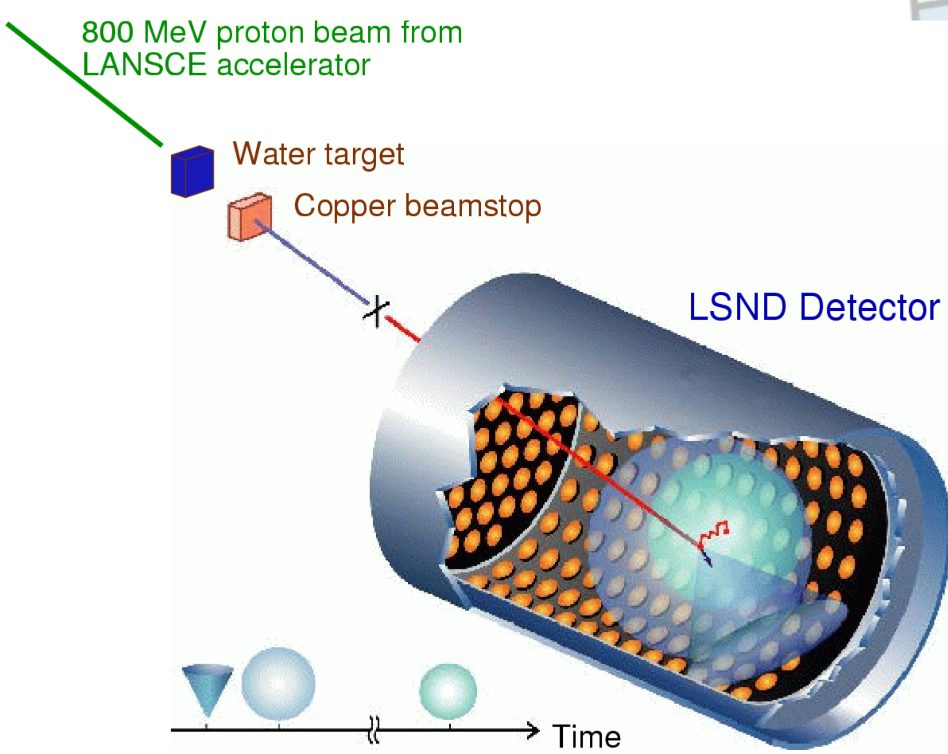




Short-Baseline Neutrino Anomalies (II)

(II) Evidence for an electron-like excess from neutrinos from particle accelerators (the “LSND and Mini-BooNE anomalies”)

LSND



MiniBooNE

Short-Baseline Accelerator Anomalies

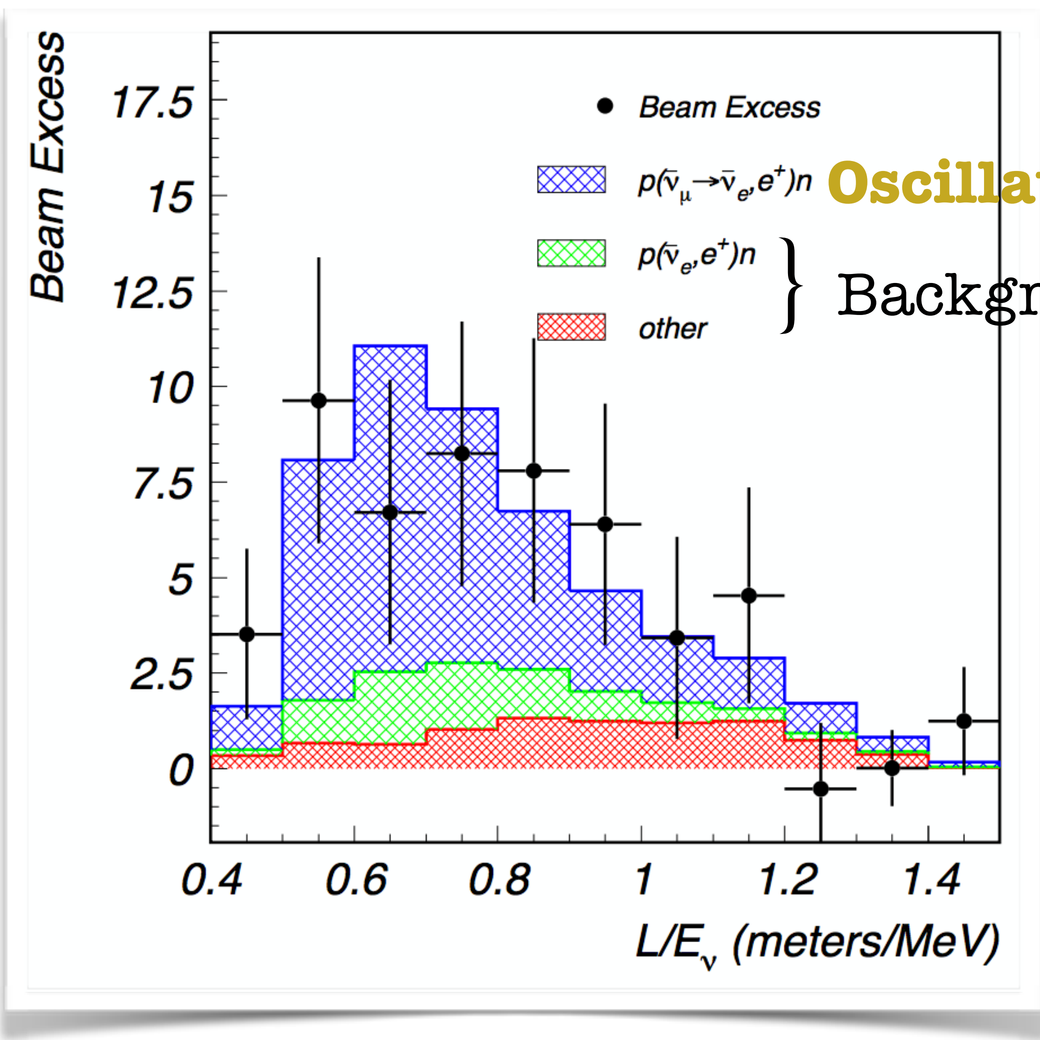
LSND

Baseline 30 m
E= [20 – 50] MeV
L/E ≈ 1 m/MeV

Low energy $\overline{\nu}_\mu$ beam from a decay-at-rest pion beam (Los Alamos)

167 tons liquid scintillator

PRD 64 (2001) 112007



Oscillation signal?

Backgrounds

Detected an excess in the appearance of $\overline{\nu}_e$, corresponding to a <u>3.8 σ</u> evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation occurring at $\Delta m^2 \simeq 1\ eV^2$

Short-Baseline Accelerator Anomalies

MiniBooNE

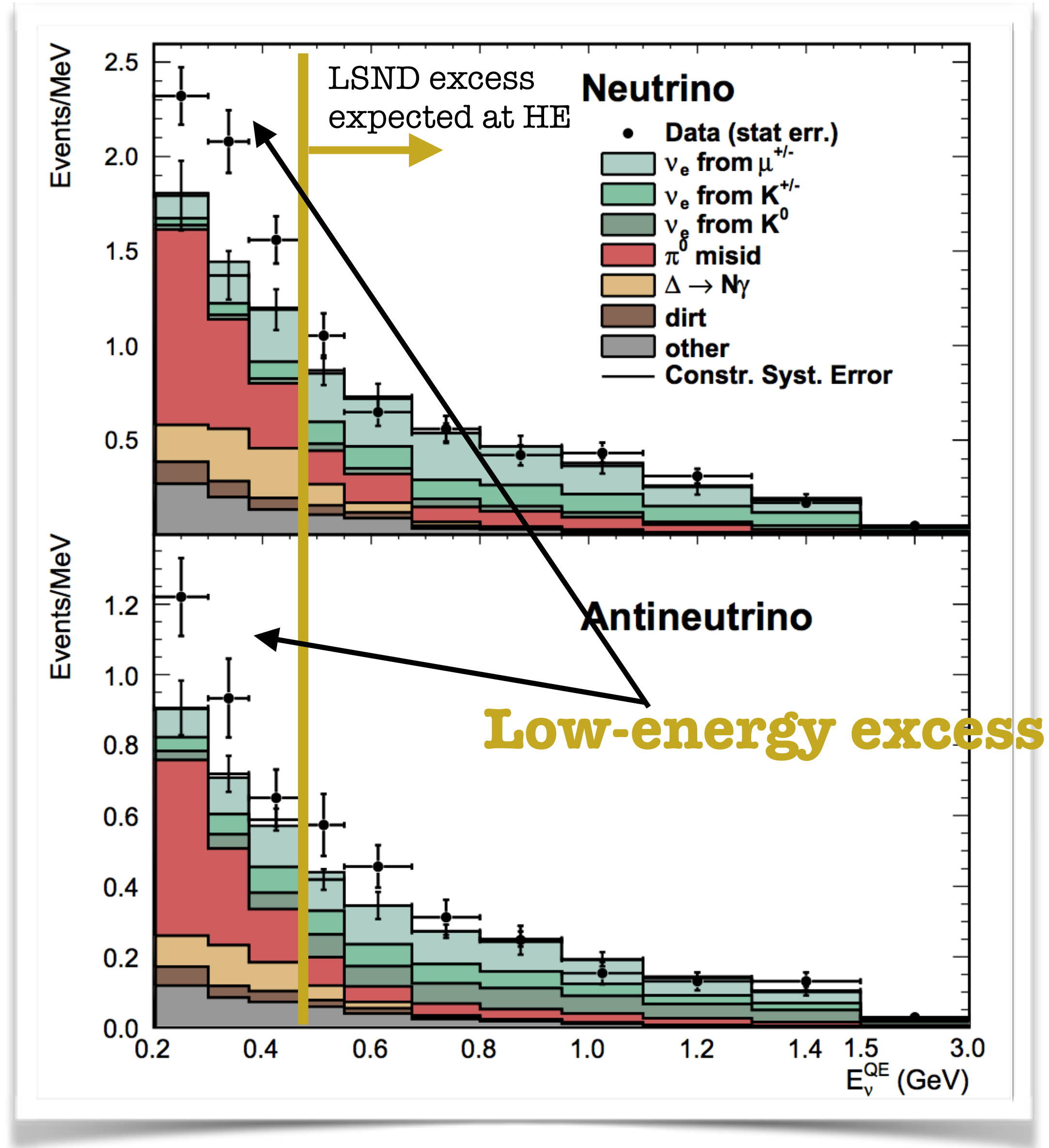
Baseline 540 m

E=[0 - 2] GeV

L/E ≈ 1 m/MeV

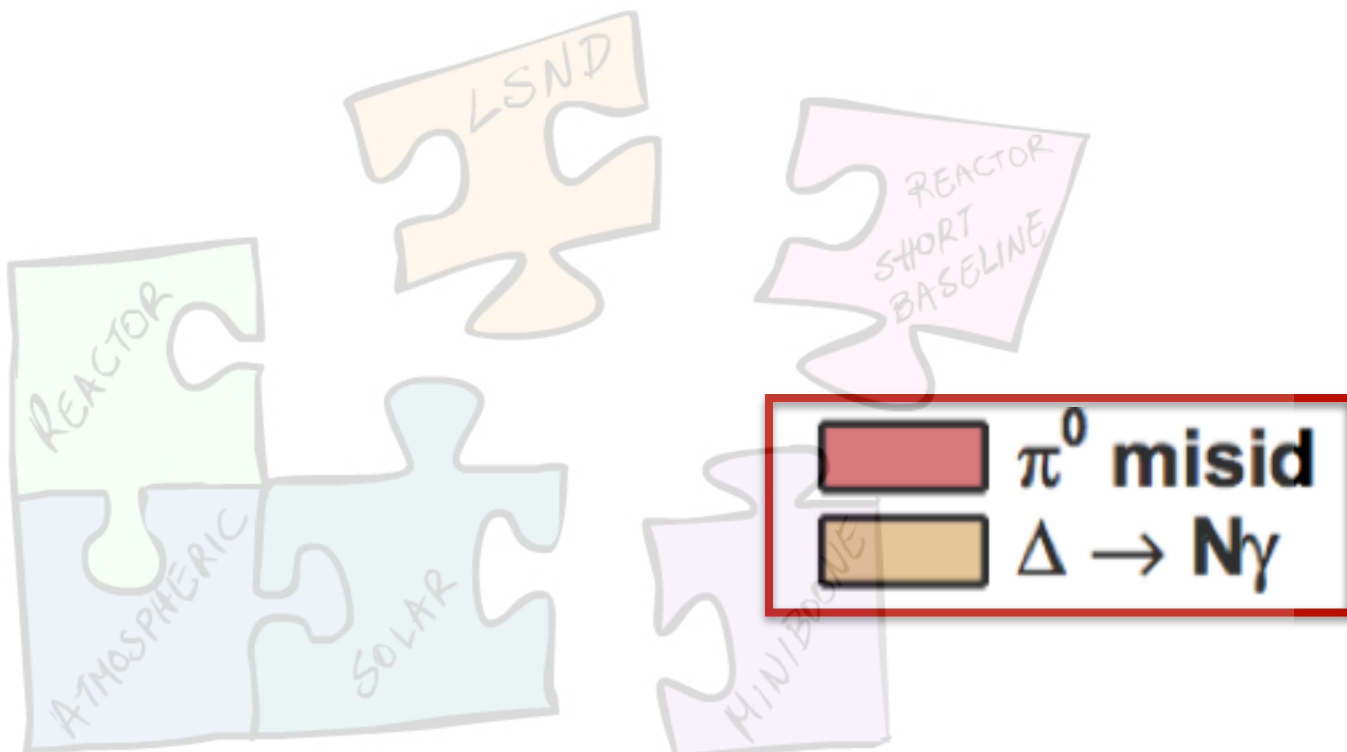
800 tons mineral oil

PRL 110 (2013) 161801



- Decay in flight neutrino source (Booster Neutrino Beam - Fermilab)
- L/E similar to LSND
- LSND anomaly not evident in MiniBooNE where ~~expected,~~ but a clear excess in $\nu_\mu \rightarrow \nu_e$ (3.4 σ) and $\nu_\mu \rightarrow \nu_e$ (2.8 σ) appearance is observed in a lower energy range

Short-Baseline Accelerator Anomalies



MiniBooNE

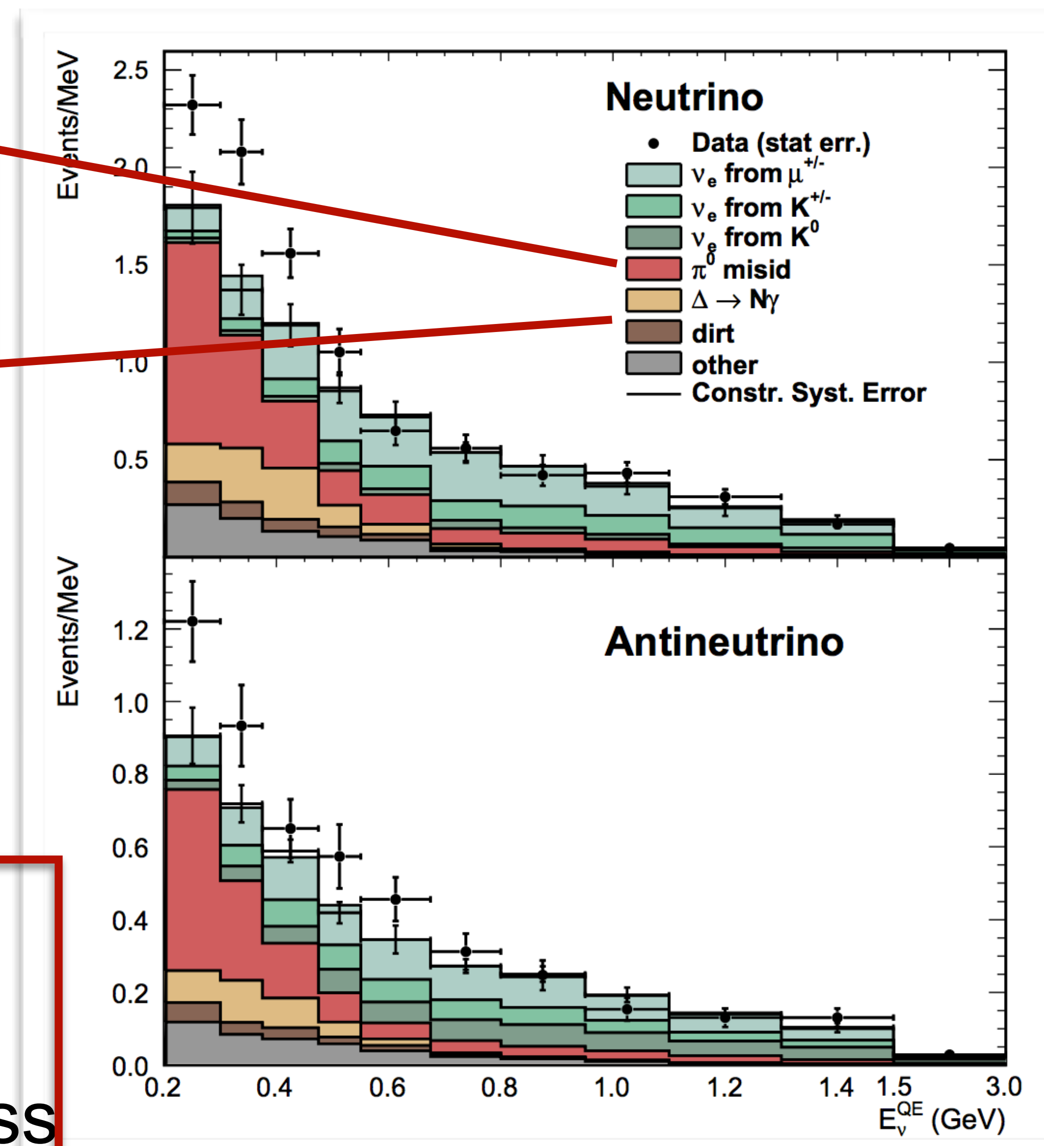
Baseline 540 m

E=[0 - 2] GeV

L/E ≈ 1 m/MeV

800 tons mineral oil

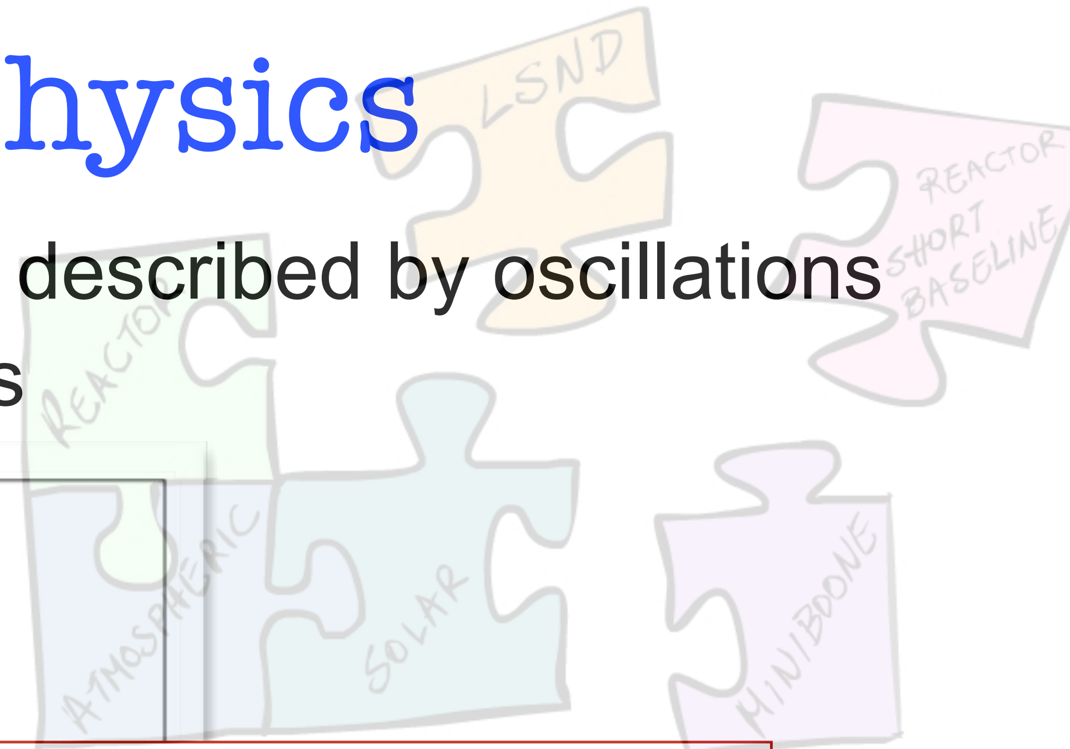
PRL 110 (2013) 161801



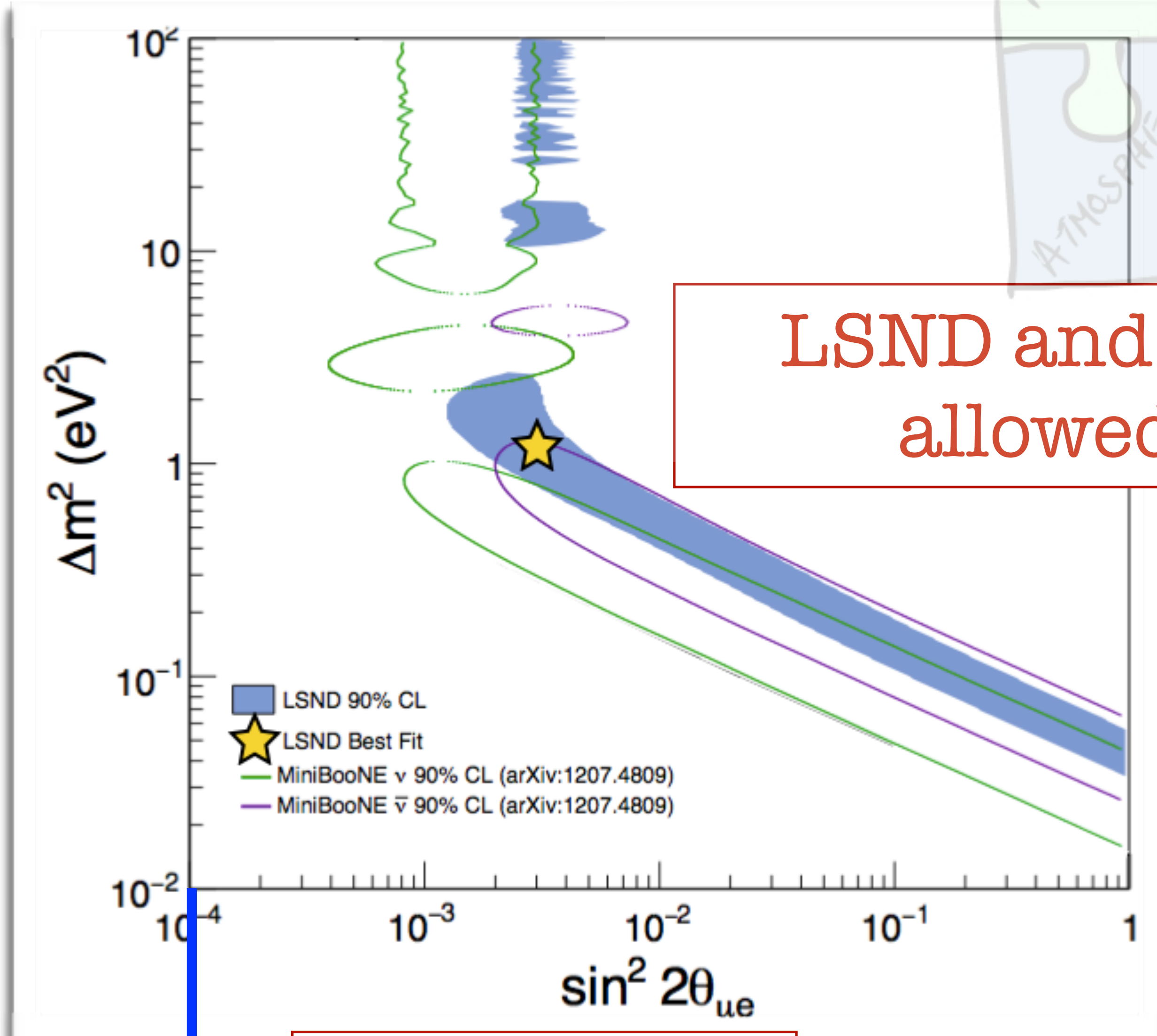
MiniBooNE (Cherenkov detector) <u>cannot distinguish electron from single gamma</u> and cannot determine the composition of the excess

– Electrons or photons?

Hints at new physics



None of the SBL neutrino anomalies can be described by oscillations between the three Standard Model neutrinos

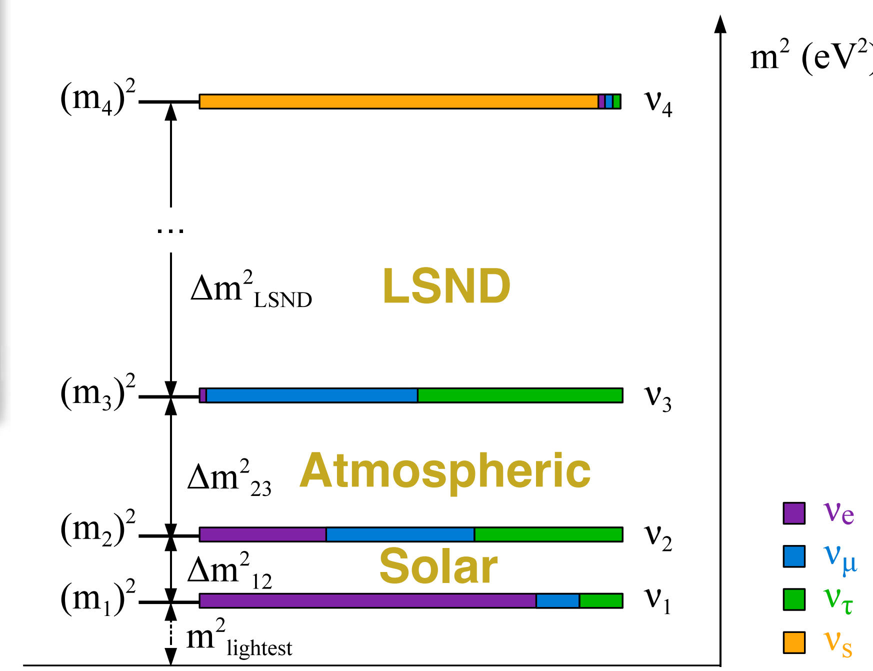


LSND and MiniBooNE allowed regions

The standard active neutrino mass splittings are way down here at 10^{-3} and 10^{-5} eV^2

10^{-3} Atmospheric

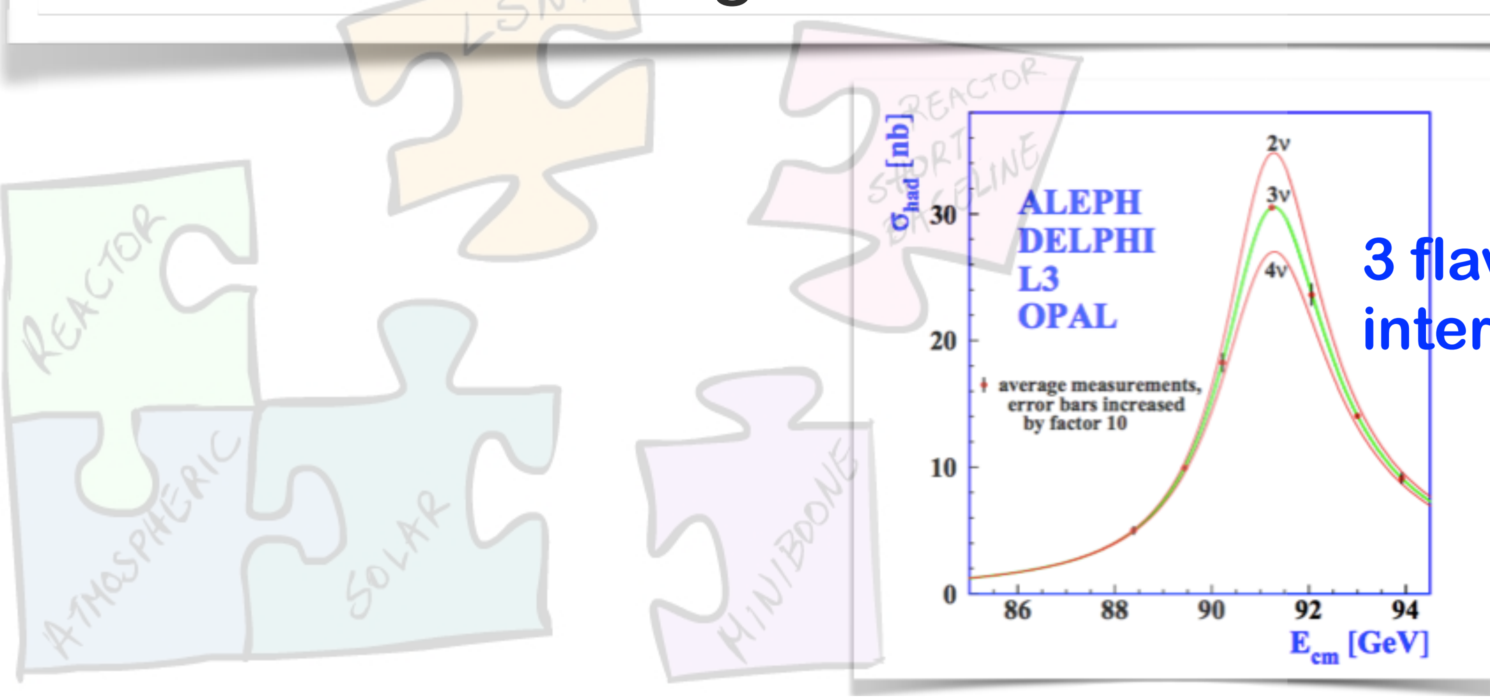
10^{-5} Solar



Hints at new physics

None of the SBL neutrino anomalies can be described by oscillations between the three Standard Model neutrinos **and …**

Could be pointing at **additional physics beyond the Standard Model** in the neutrino sector:
additional neutrino states with larger mass-squared differences
driving neutrino oscillation at small distances



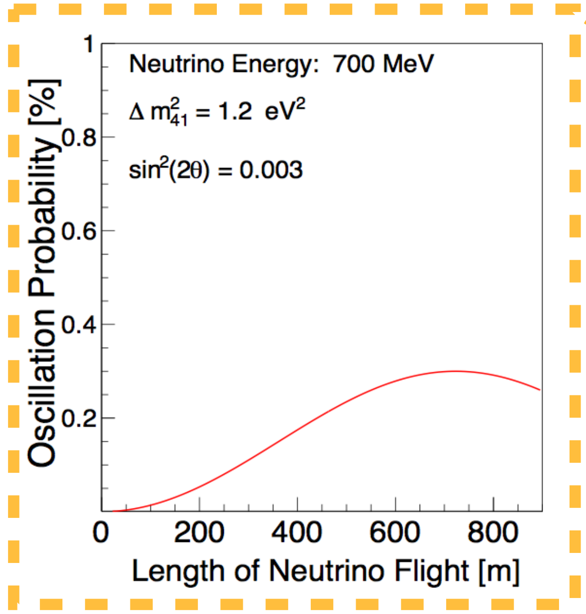
3 flavor states, 3 "active" (weakly interacting) neutrinos!

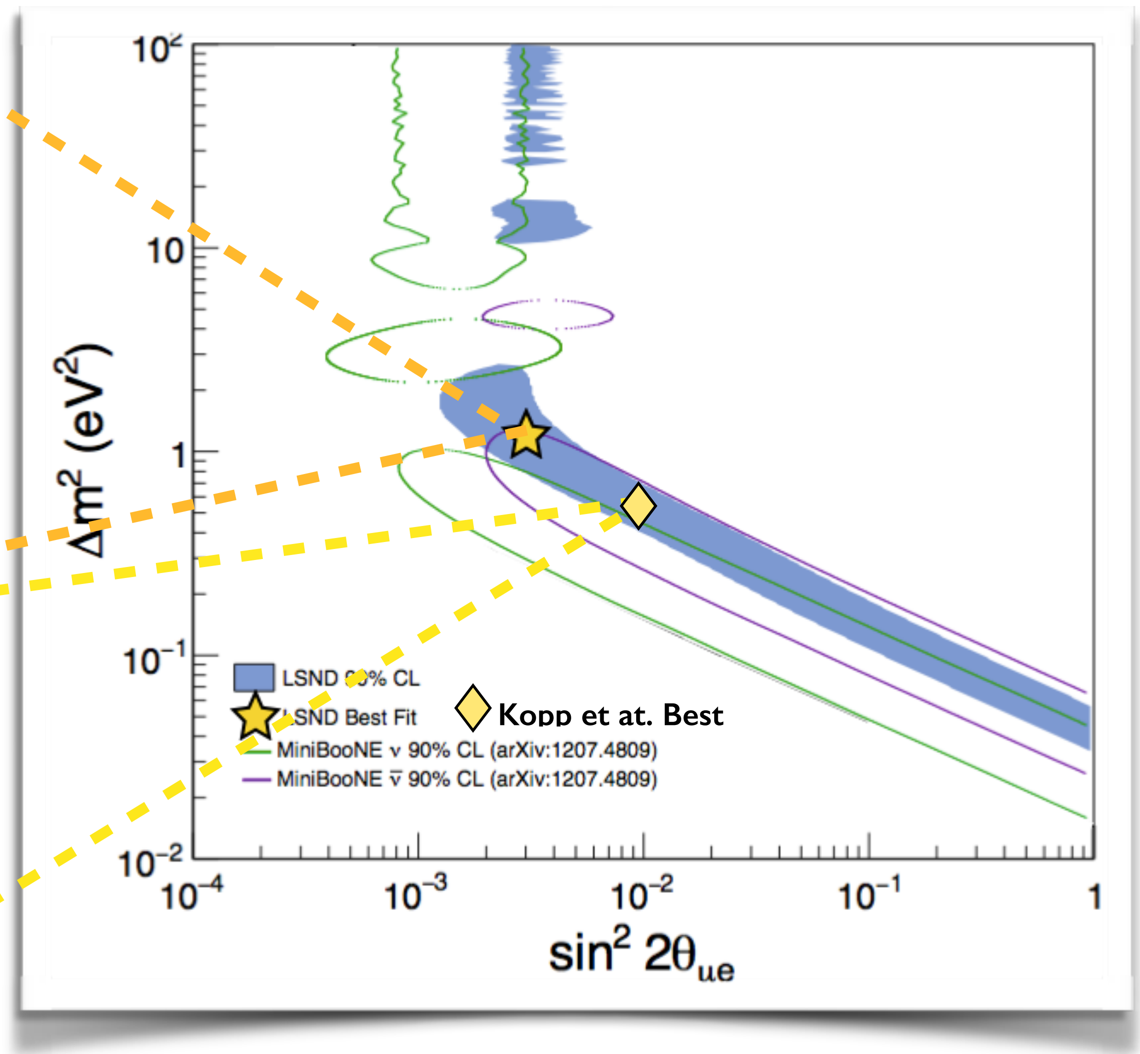
Any additional neutrino doesn't participate in weak interactions ⇒ **"sterile neutrino"** *

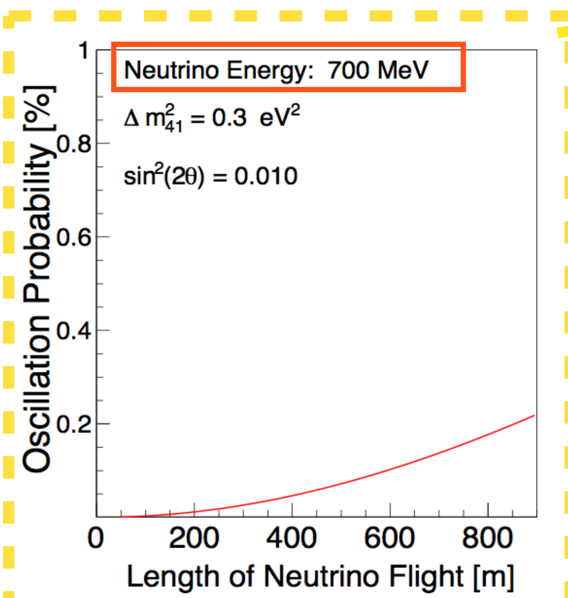
* Sterile neutrinos were introduced by Pontecorvo in 1968 as neutrinos with no standard model interaction

Sterile Neutrino Search at FNAL

- The accelerator neutrino anomalies at short-baseline hint at oscillation with very small amplitude
- Resolving small oscillation effects requires good control of **systematic uncertainties**

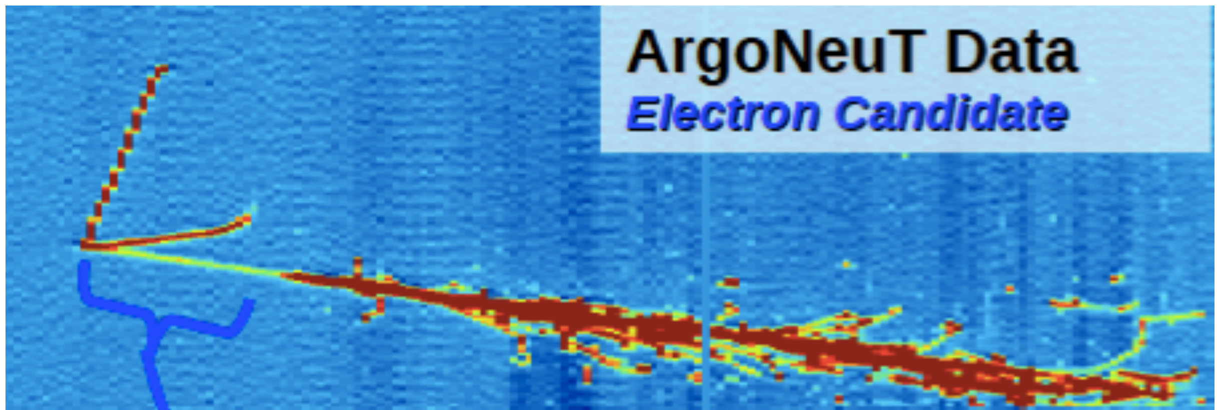


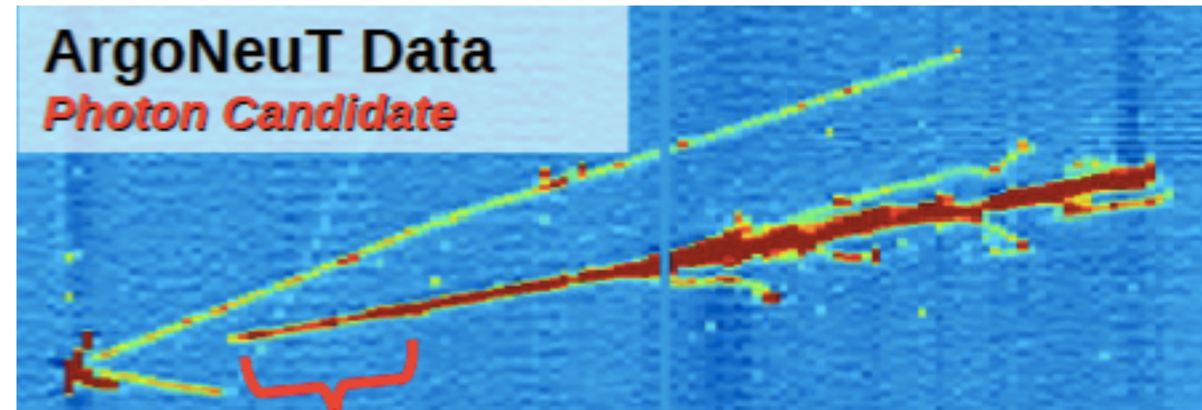


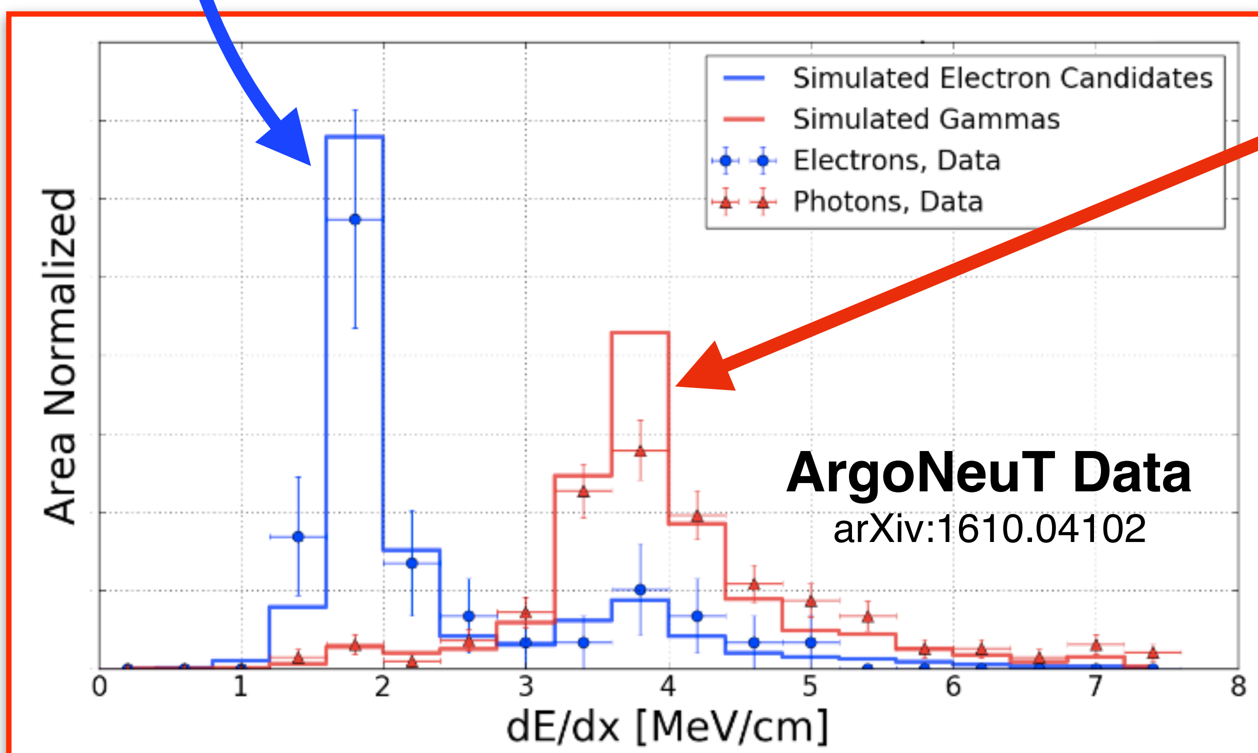


FNAL SBN: LAr TPC - multi-detector approach - in a well characterized beam

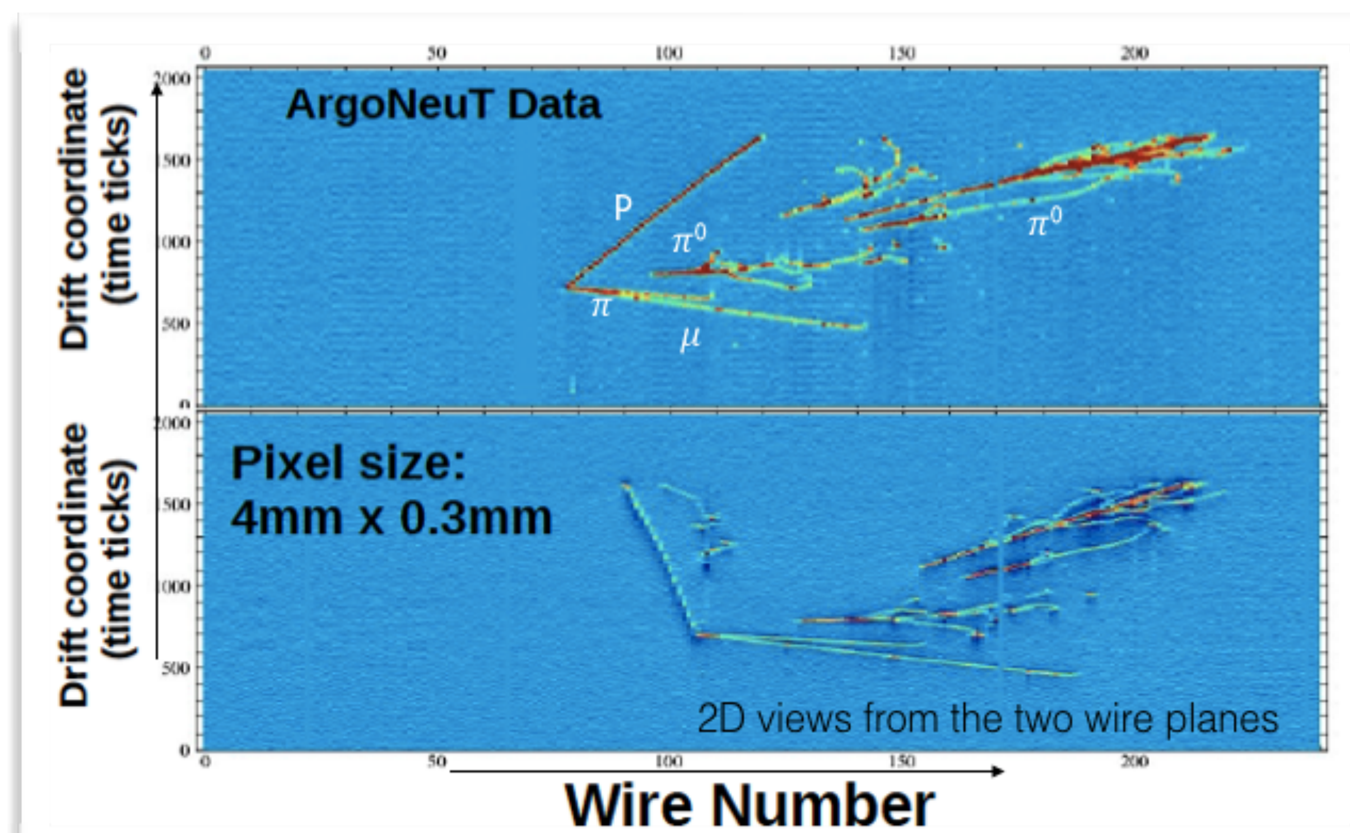
Electron-γ separation in LAr







Analyzing topology and dE/dx



LAr TPC offers incredible fine tracking along with electron/photon separation

Fermilab – aerial view

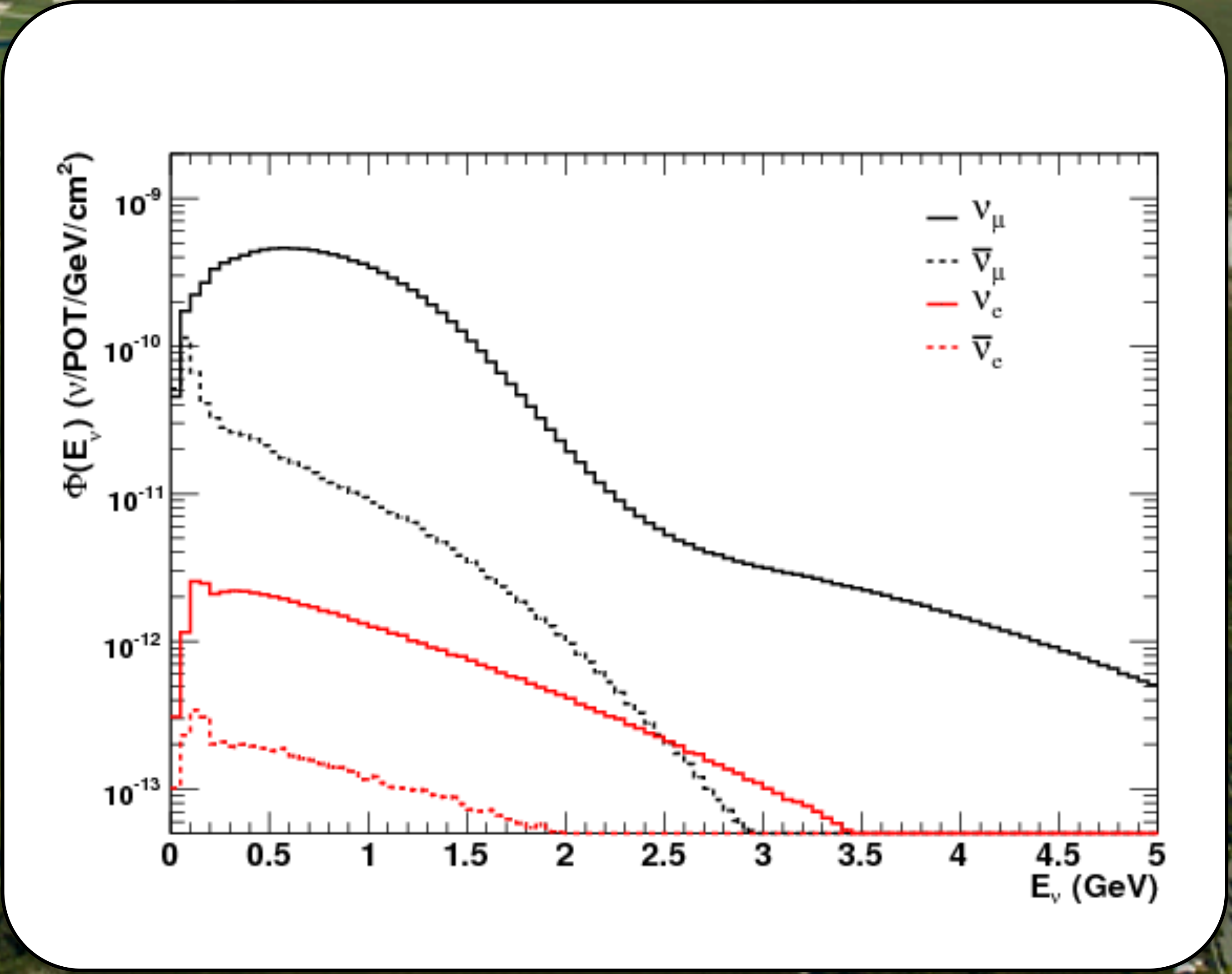
Fermilab – Neutrino beams

Booster Neutrino Beam (BNB)

Fermilab's **low-energy** neutrino beam:

$\langle E_\nu \rangle \approx 700$ MeV

Booster - 8 GeV protons



Fermilab – Neutrino beams

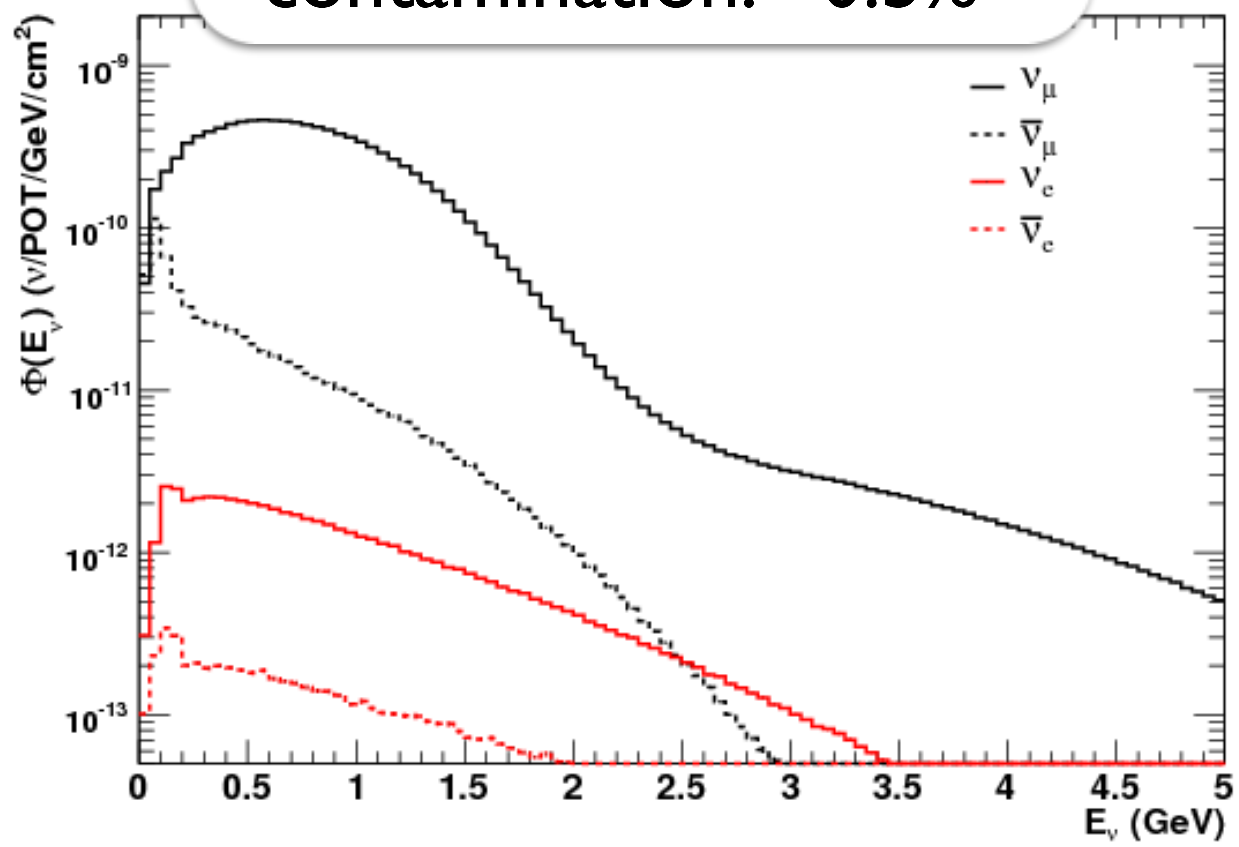
Booster Neutrino Beam (BNB)

Fermilab's **low-energy** neutrino beam:

$\langle E_\nu \rangle \approx 700$ MeV

Booster - 8 GeV protons

Small electron neutrino contamination: <0.5%



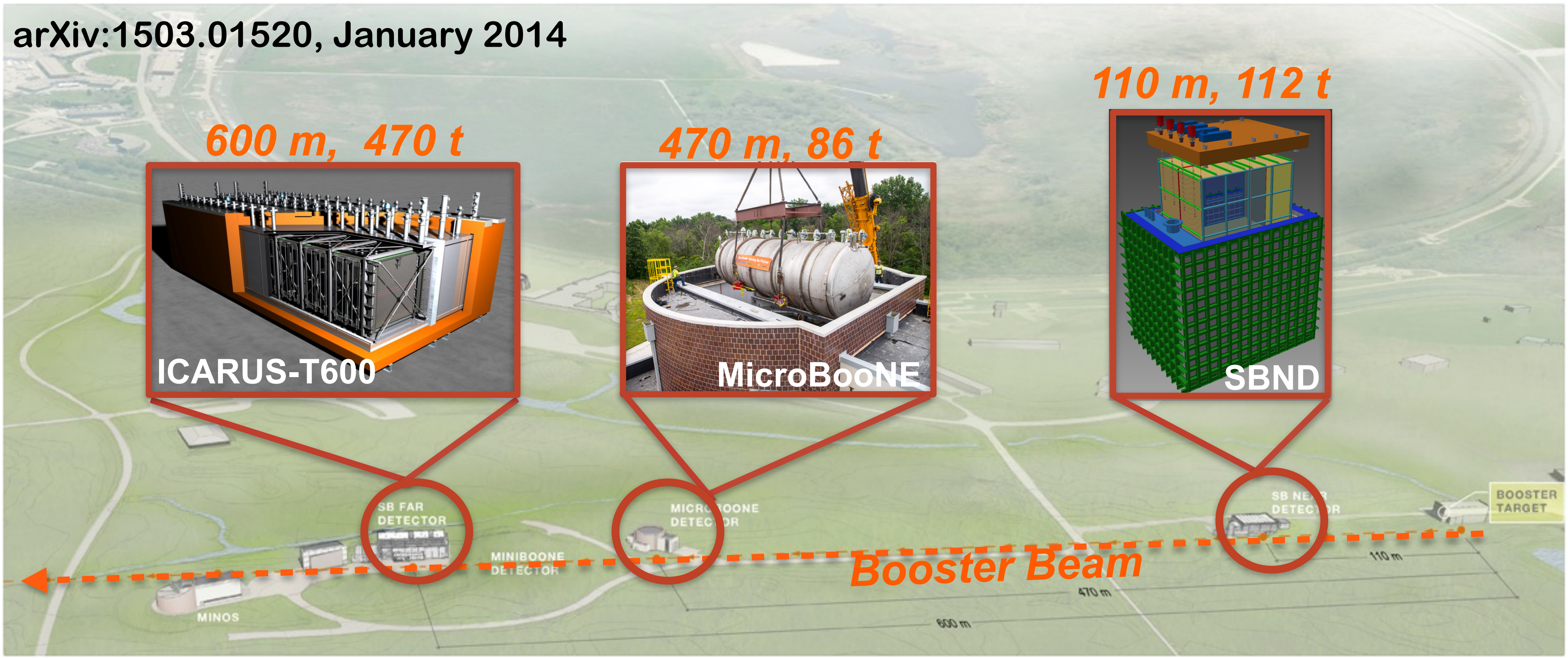
- Beam - mostly muon neutrinos
- BNB stably running for a decade (well characterized)
- Anomalies exist here (MiniBooNE)

MicroBooNE: testing an anomaly

SBN program - Phase 1 - The MicroBooNE detector is **taking neutrino data**

- Apply the **LArTPC technology** to test the **unexplained excess** in the **MiniBooNE** data (on the same beam)
- Determine its composition as **electrons** (from ν_e appearance) or **photons** (from unaccounted background).

FNAL Short Baseline Neutrino program

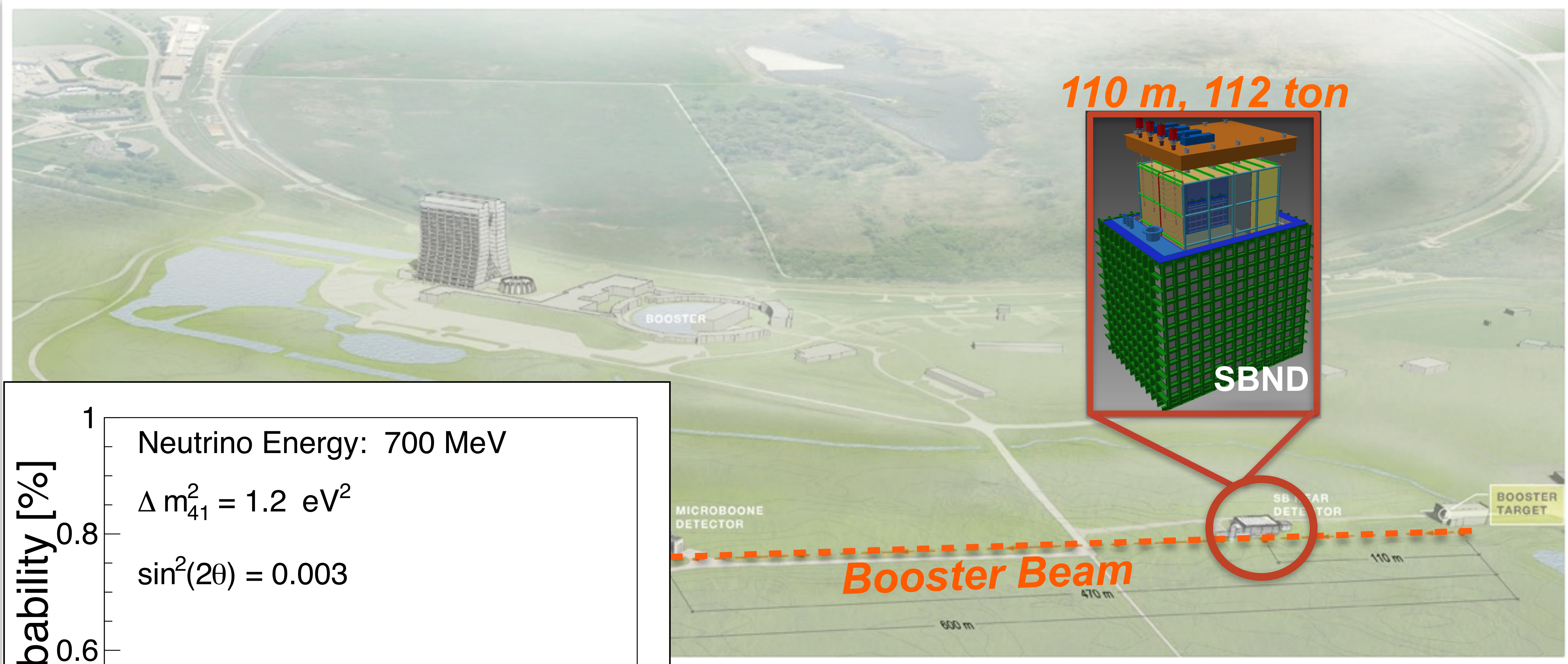


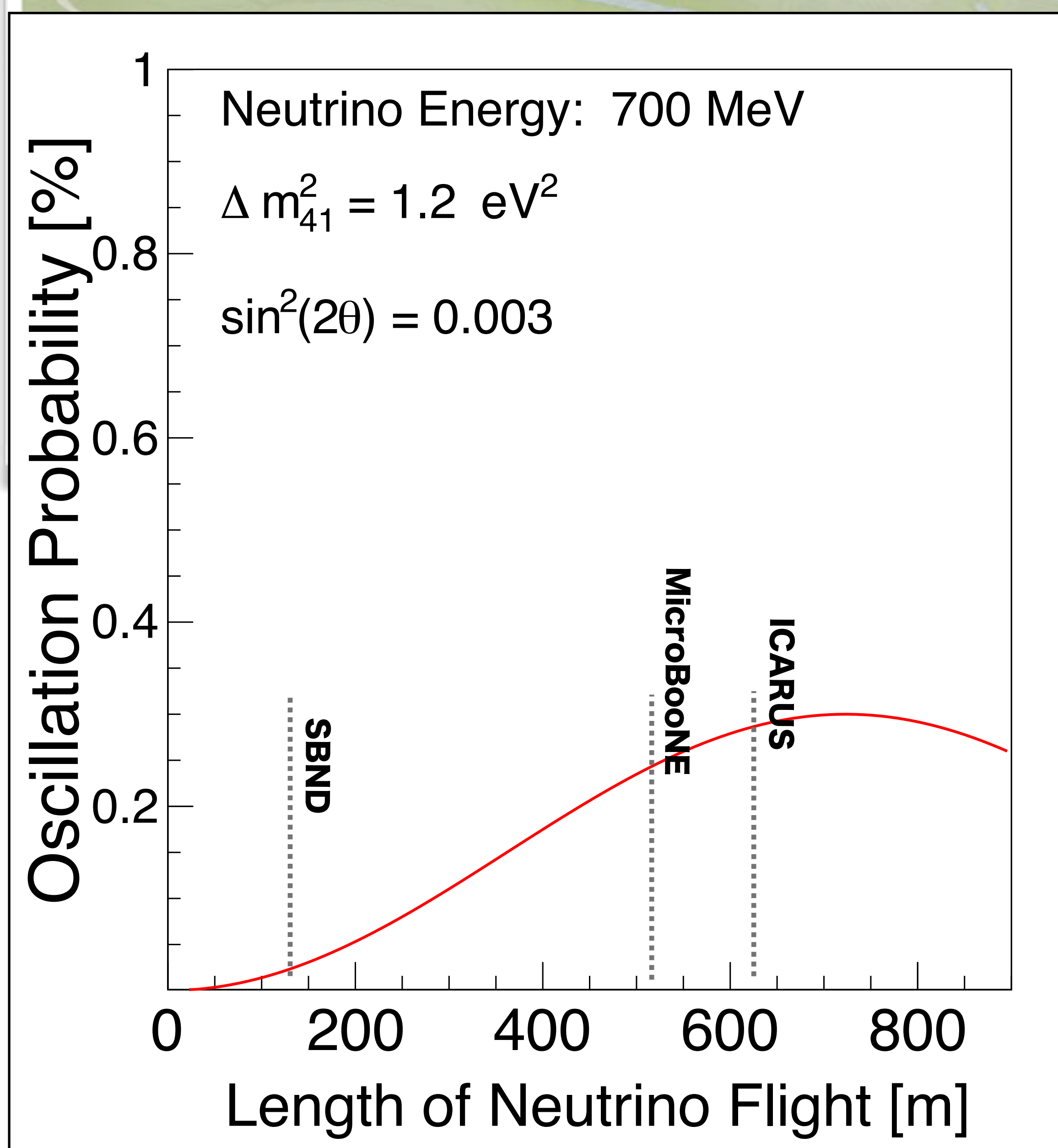
SBN program - Phase 2 - By 2018, the MicroBooNE detector will be joined by two additional LAr-TPC detectors at different baselines

- the **SBND** detector and
- the **ICARUS-T600** detector

forming a **LAr TPC trio** *(to sample the neutrino spectrum as a function distance)* for the SBN **neutrino oscillation** program

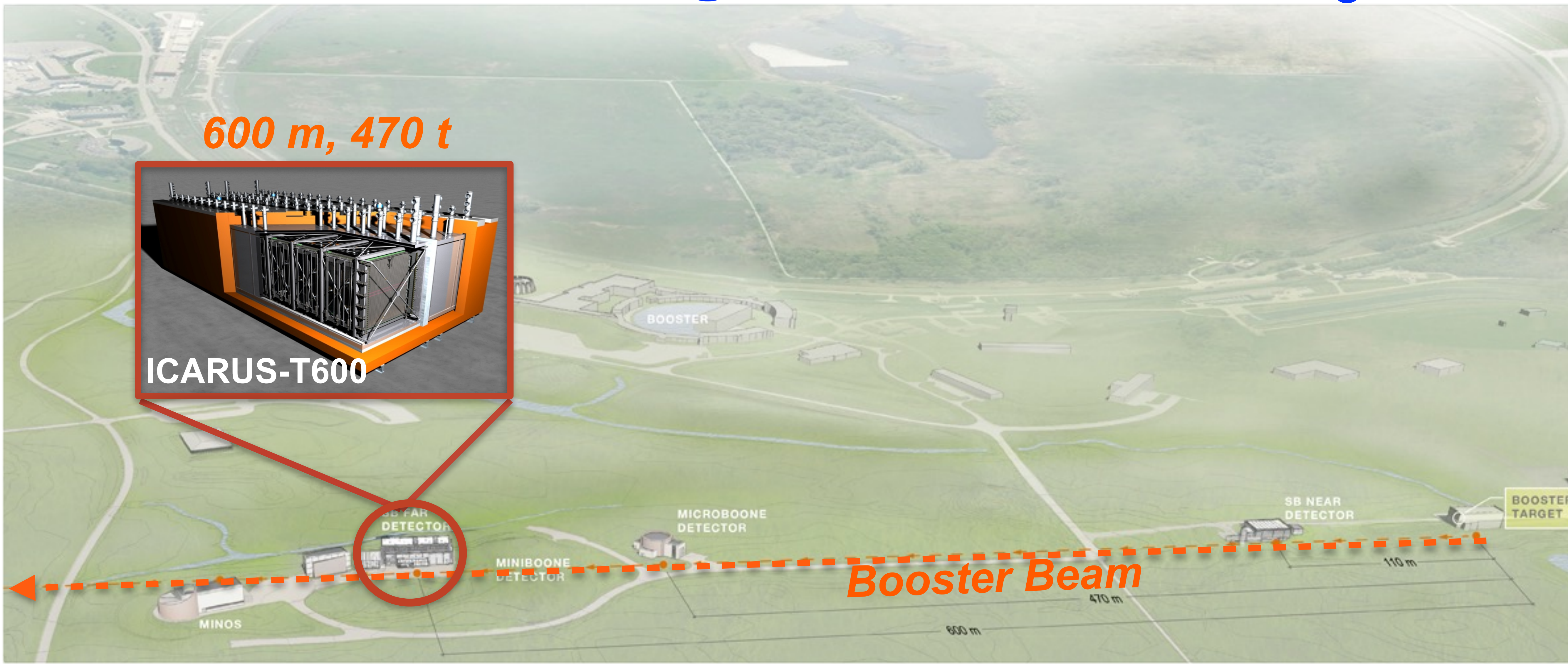
SBND - closest to the source





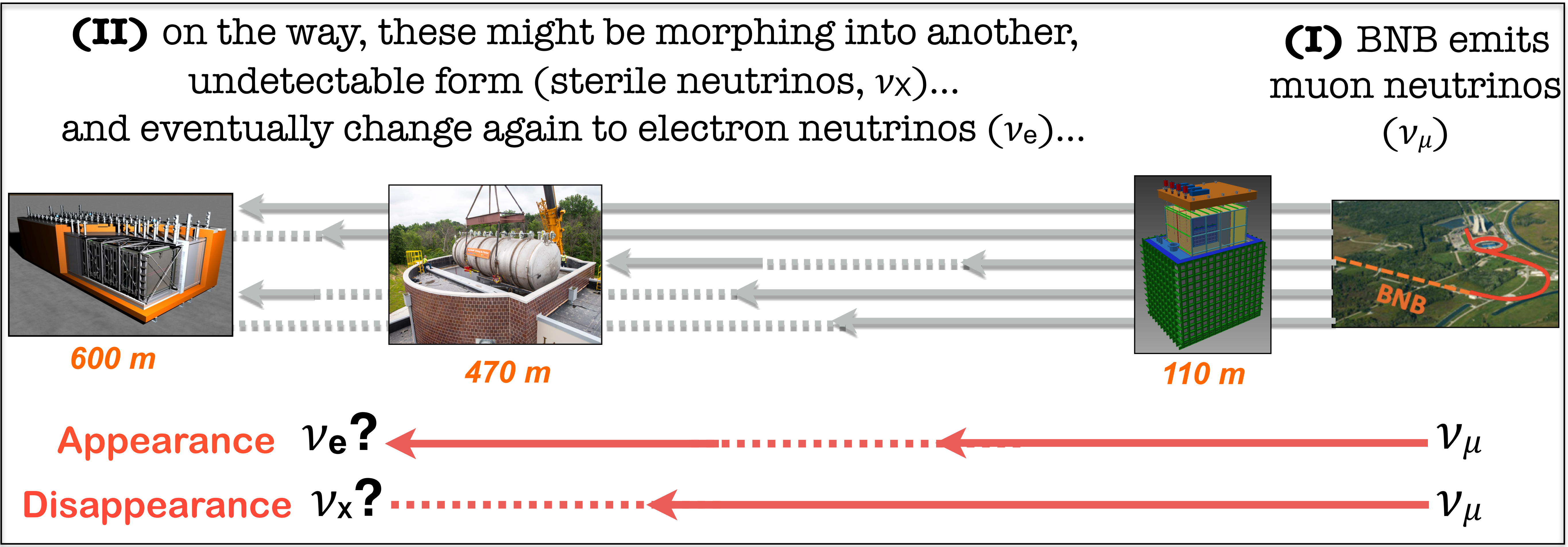
The Short-Baseline Near Detector (SBND), which will sit close to the source, plays a **unique role** in the chain of detectors, measuring the purity of the muon neutrino beam (it will **characterize the beam before oscillations occur** and address one of the dominant systematic uncertainties)

ICARUS - high-tech from Italy



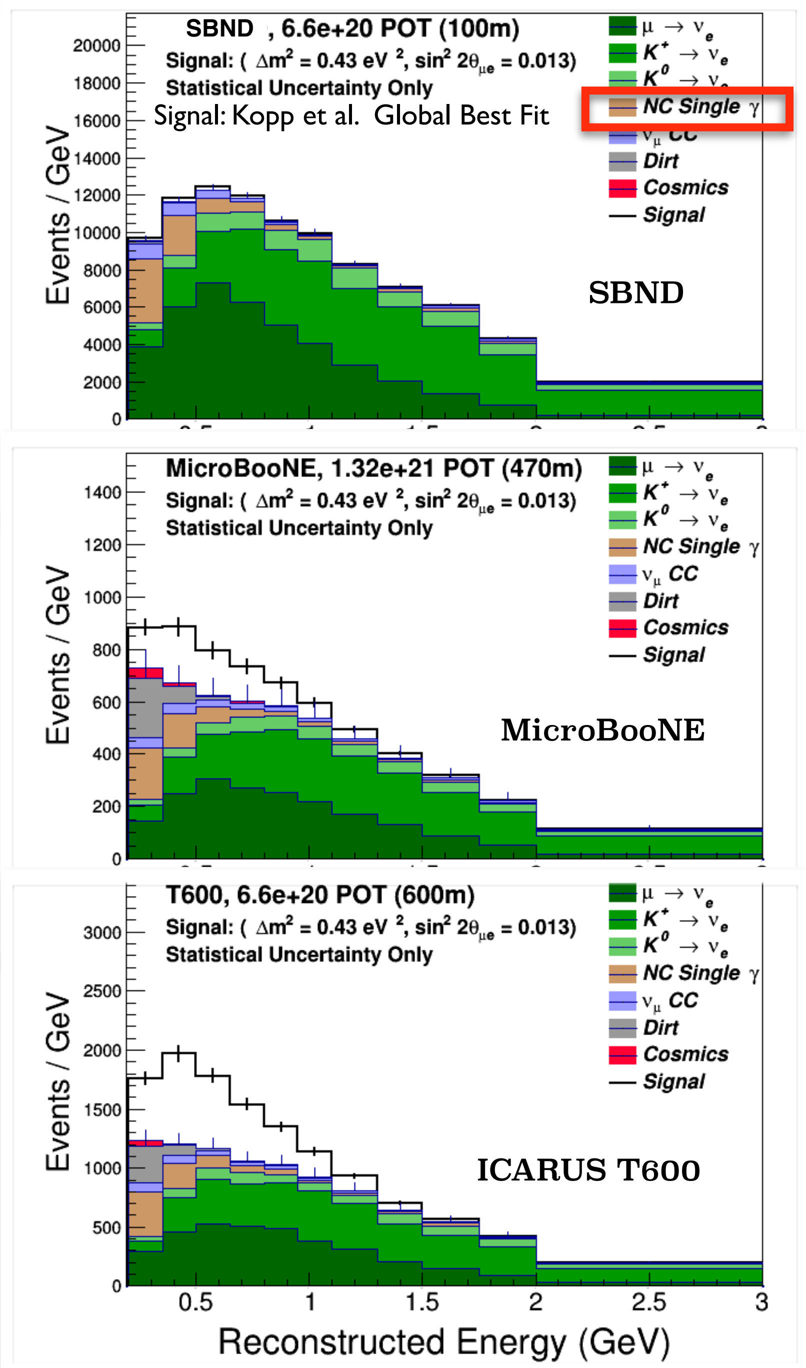
- The ICARUS T600 neutrino detector —the world's largest liquid-argon neutrino experiment — operated at Gran Sasso National Laboratory in Italy for four years on the CNGS beam, will make its way across the ocean for a new research at Fermilab.
- Given its **large mass and far location** ICARUS-T600 will provide high sensitivity to oscillated neutrinos allowing for a precision search.

The search for the forth neutrino in SBN

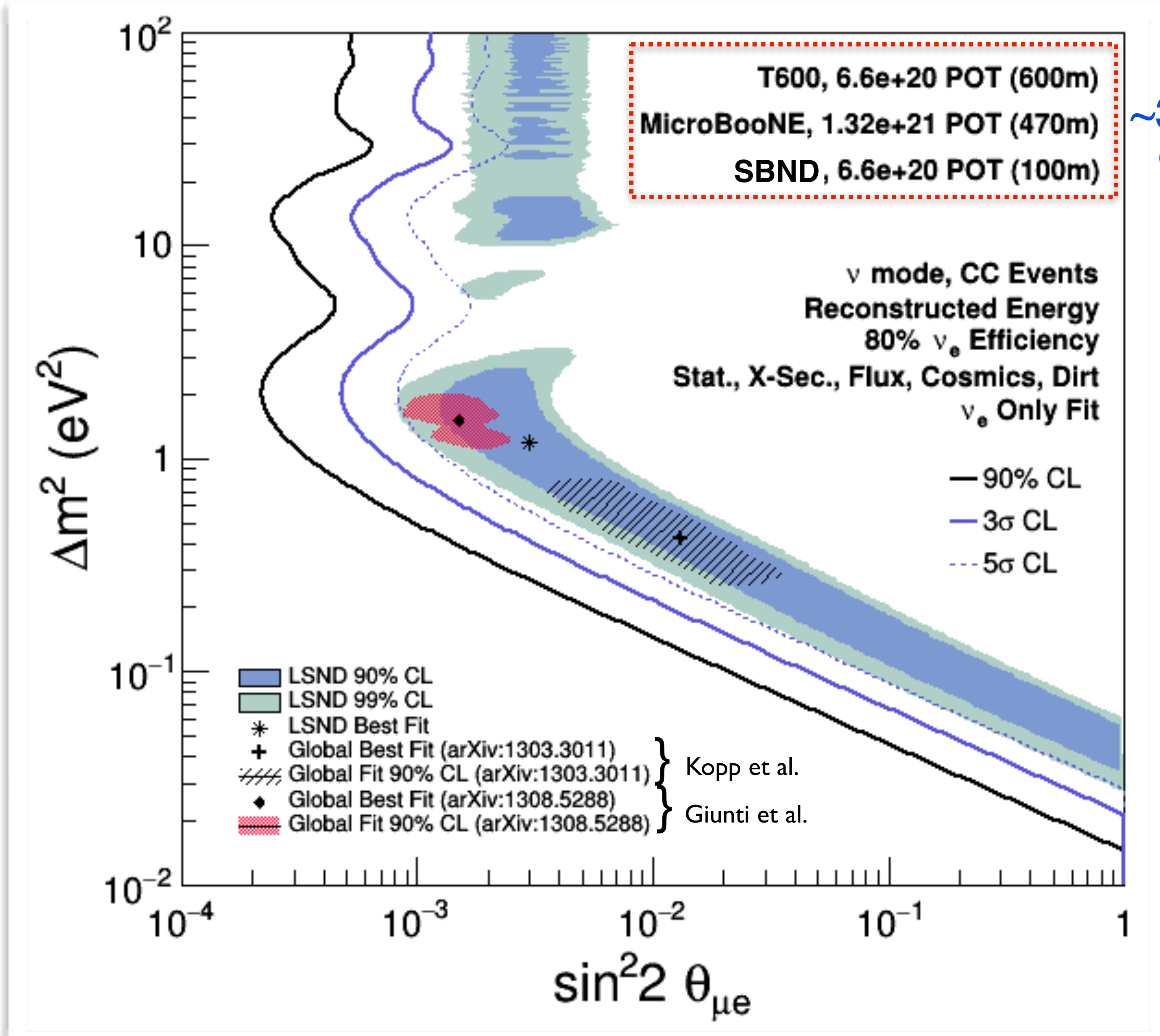


Having multiple detectors allows simultaneous searches for oscillations in **appearance <u>and</u> disappearance** channels, a very important constraint for interpreting the experimental observations.

Physics reach of the SBN Program



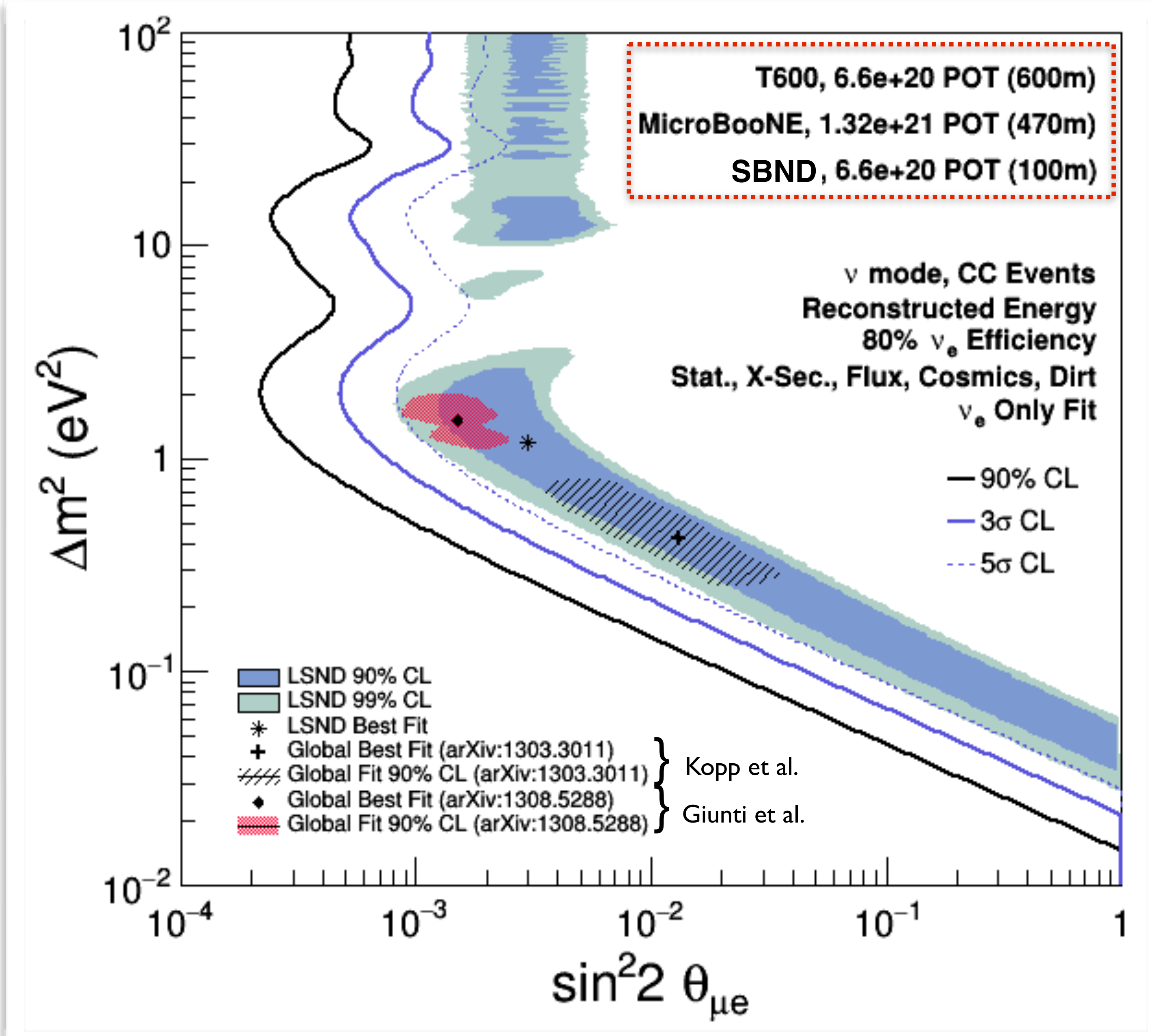
$\nu_\mu \rightarrow \nu_e$ Appearance sensitivity



A **large mass far detectors** and **a near detector of the same technology** is the key to large reductions of both statistical and systematic uncertainties (reduced to % level) in SBN oscillation searches,
allowing to address region of interest at 5σ

Physics reach of the SBN Program

$\nu_\mu \rightarrow \nu_e$ Appearance sensitivity



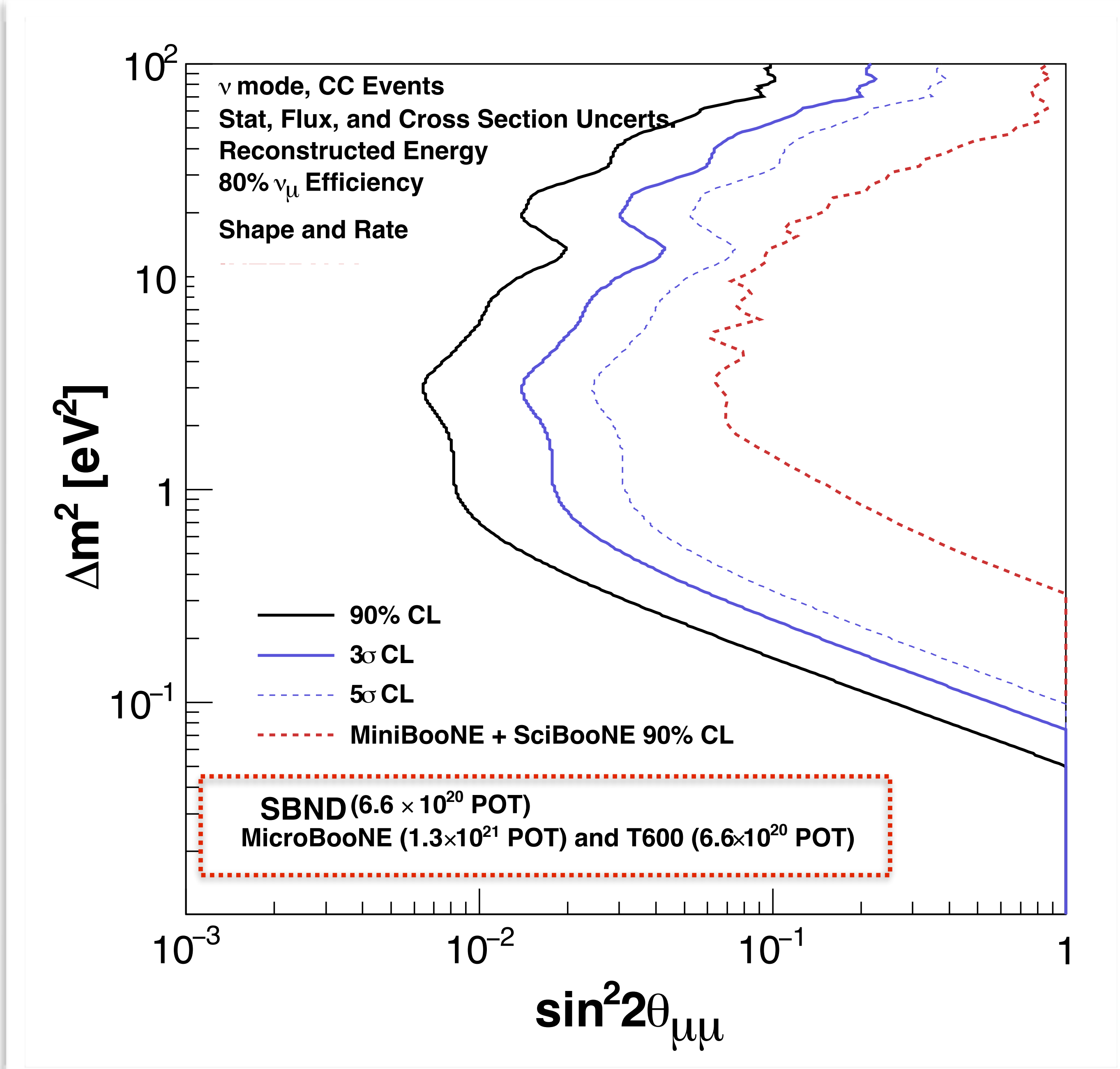
SBN will cover the LSND 99% C.L. allowed region with

≥ 5σ significance

(conclusive experiment w.r.t. LSND anomaly)

Physics reach of the SBN Program

$\nu_\mu \rightarrow \nu_x$ Disappearance sensitivity



SBN can extend the search for muon neutrino disappearance **an order of magnitude beyond** the combined analysis of SciBooNE and MiniBooNE

Not only oscillation physics: Cross Sections at the SBN

- A correct interpretation of the outcome of ν oscillation experiments requires precise understanding of ν interaction cross sections
- SBN detectors will provide **huge data sets of ν-Ar interactions** from the BNB on-axis and the NuMI off-axis fluxes
  - Large samples in MicroBooNE are coming!
  - SBND will record **~1.5 million ν_μ CC** and **~12,000 ν_e CC interactions** per year
  - ~100k NuMI off-axis events in T600 per year

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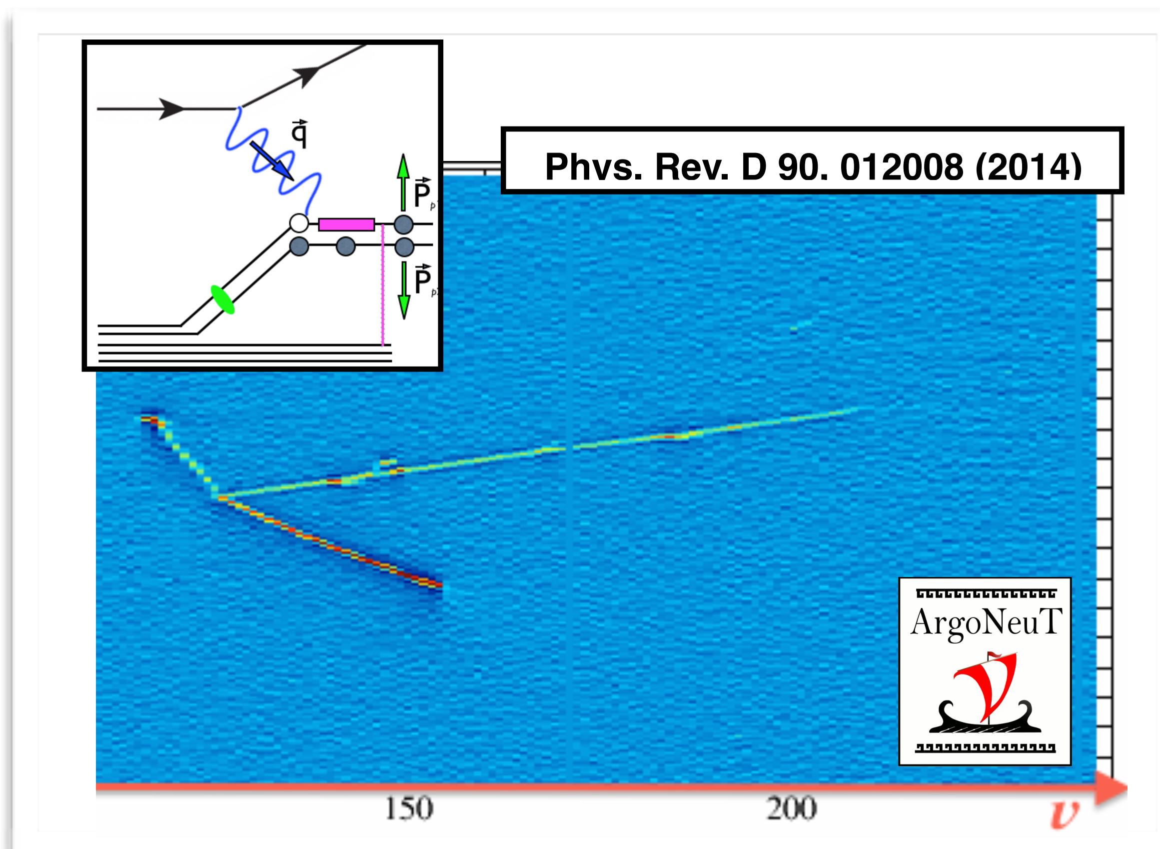
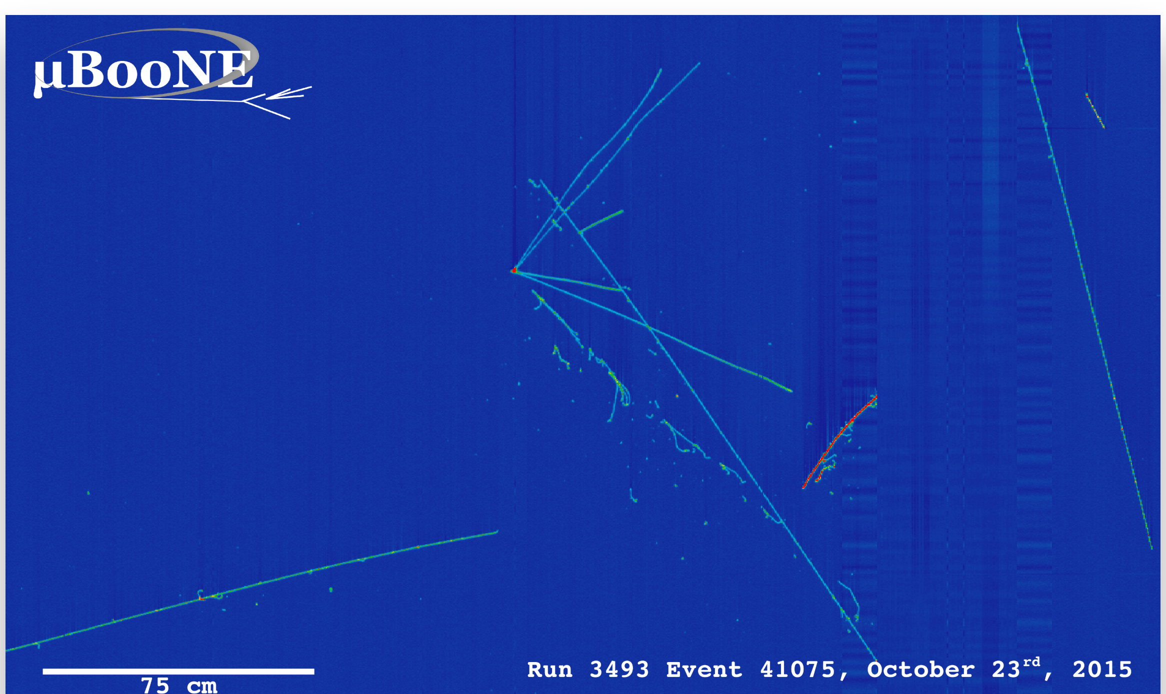
  - ~100k NuMI off-axis events in T600 per year

The only existing GeV neutrino-Ar scattering data are ~6000 events from ArgoNeuT (NuMI beam, 3 GeV peak energy)



MicroBooNE experiment

TPC Active volume:
86 t of LAr



MicroBooNE is taking neutrino data since Oct. 2015

(3.2×10^{20} POT collected in RUN I - 7 months)

μBooNE

Near and Far Detector Buildings

Ready for detector installation
Dec. 2016/early 2017

ICARUS: From Gran Sasso to Fermilab via CERN

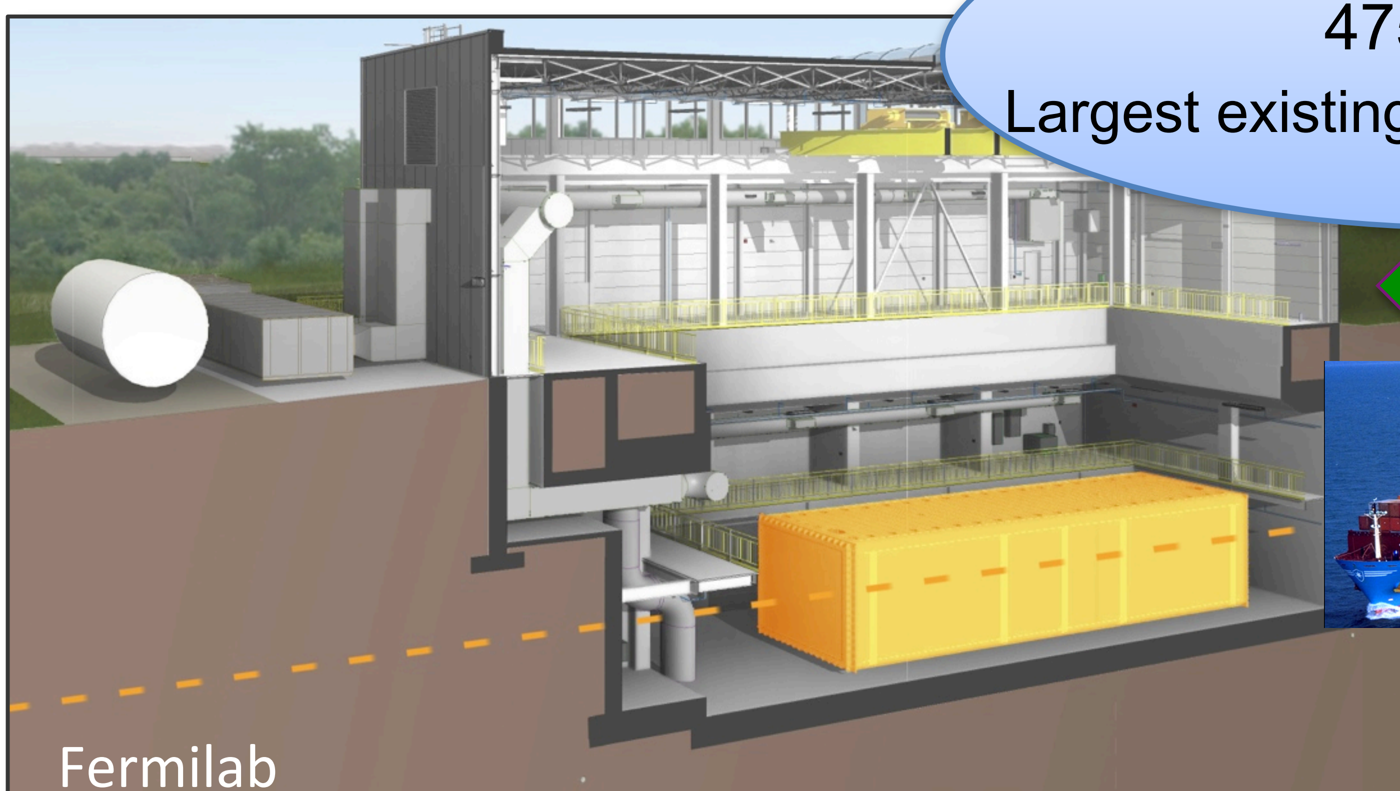
Moving from Gran Sasso

On the road to CERN

TPC Active volume:
475 t of LAr
Largest existing LAr TPC in the world

In Cleanroom @ CERN

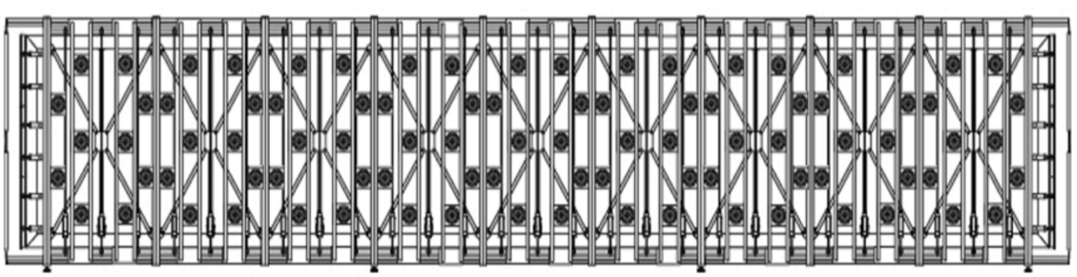
Early 2017



New building complete late 2016

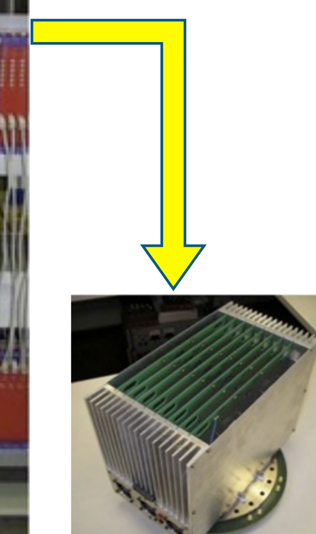
ICARUS T600 Refurbishment

- New thermal insulation and cold vessel
- Partial replacement of cryogenic and purification systems
- Improved planarity of TPC cathode
- Enlarged PMT system with improved electronics for surface operation
- Updated TPC electronics

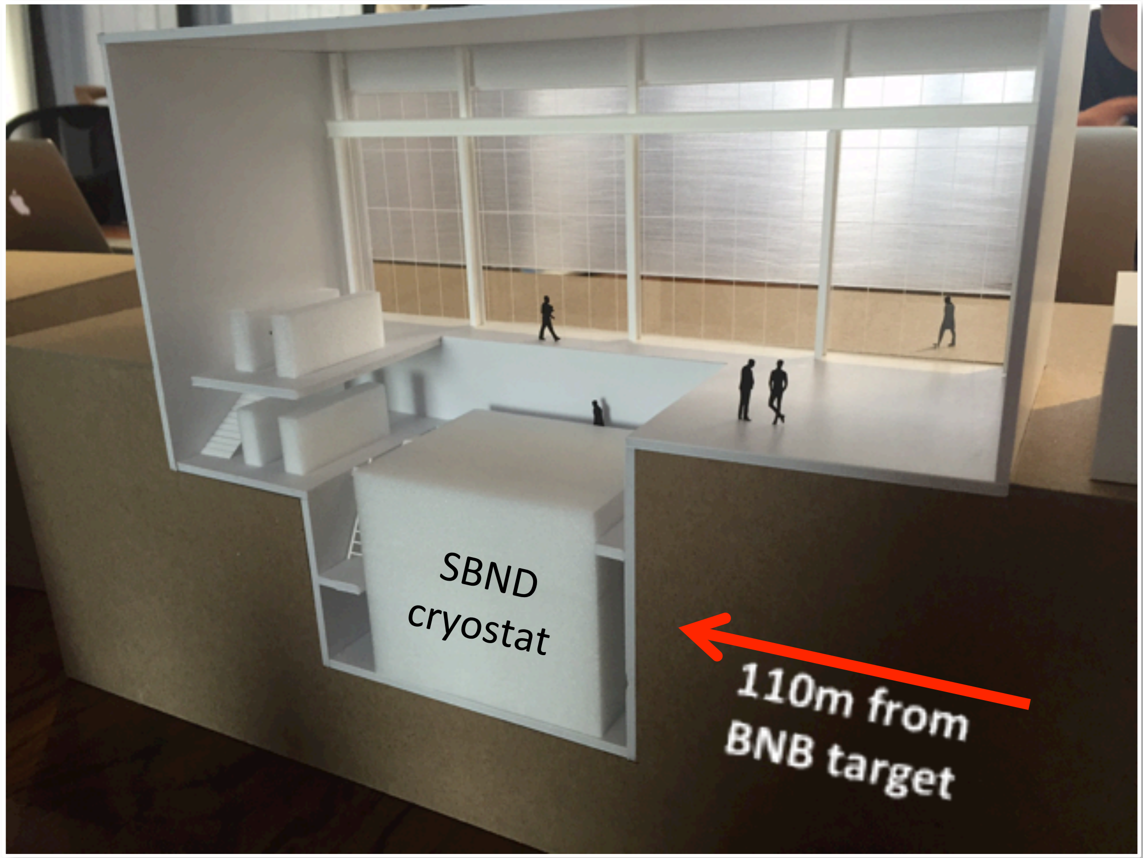


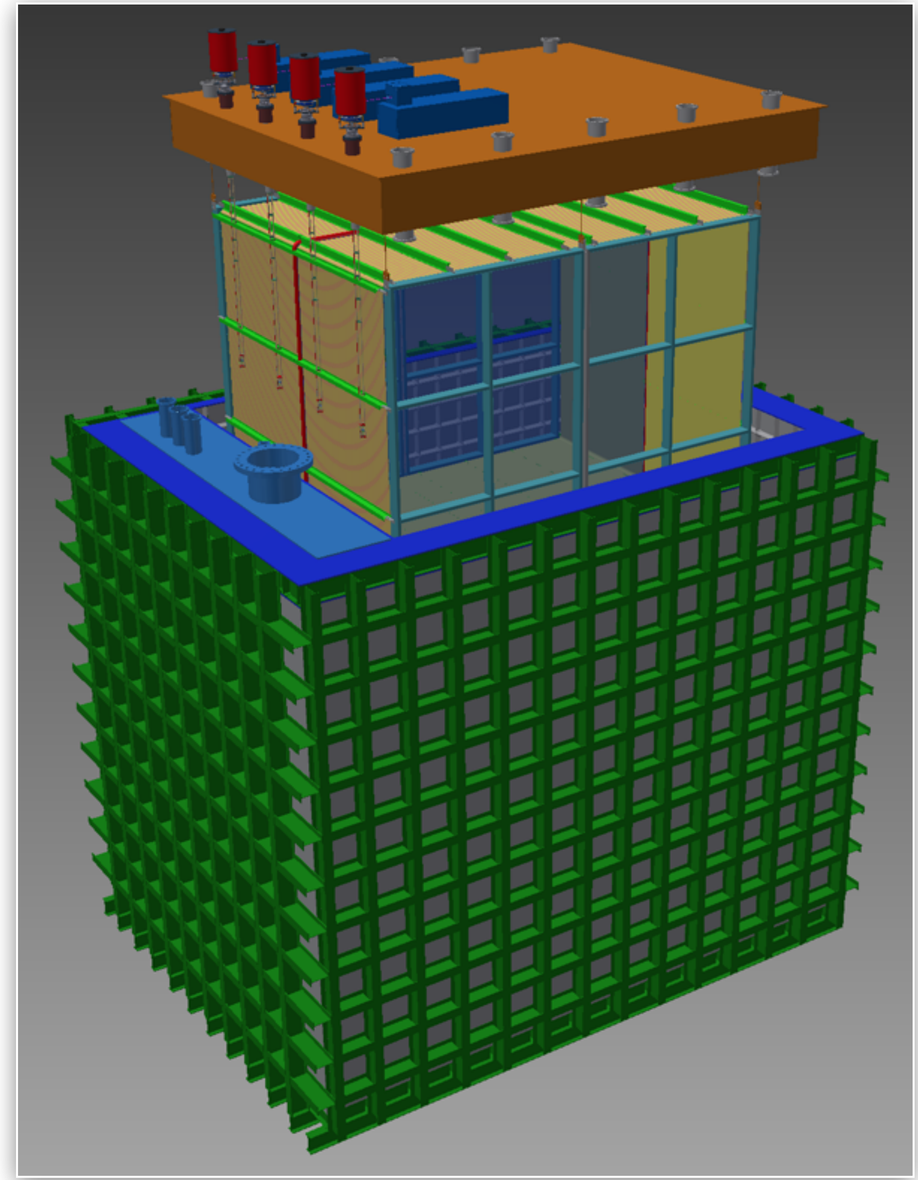
Z axis (beam direction)

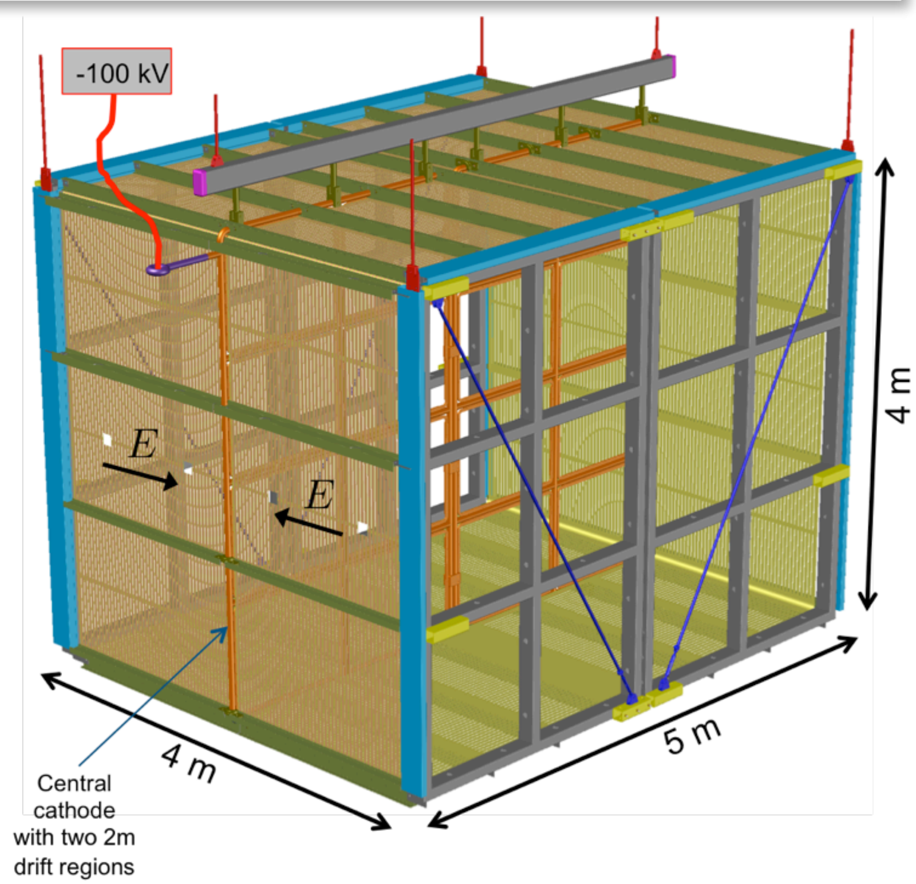
360 8" PMTs (90 per chamber)
coated with TPB wave-length shifter
~9 p.e./MeV at cathode



Short-Baseline Near Detector: SBND

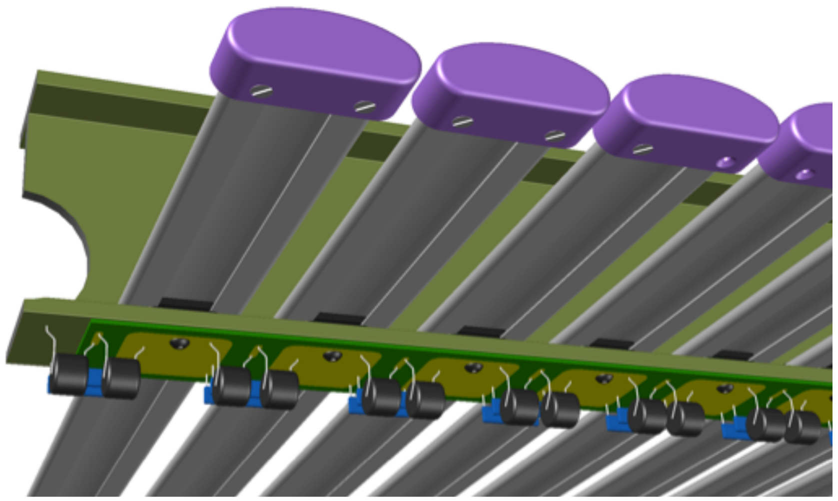




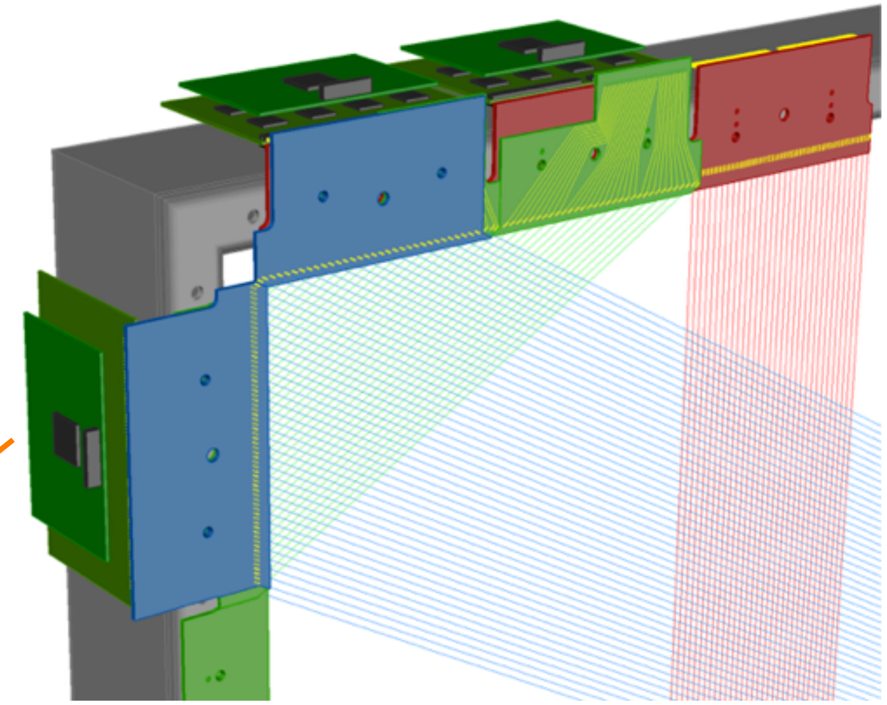


TPC Active volume:
112 t of LAr

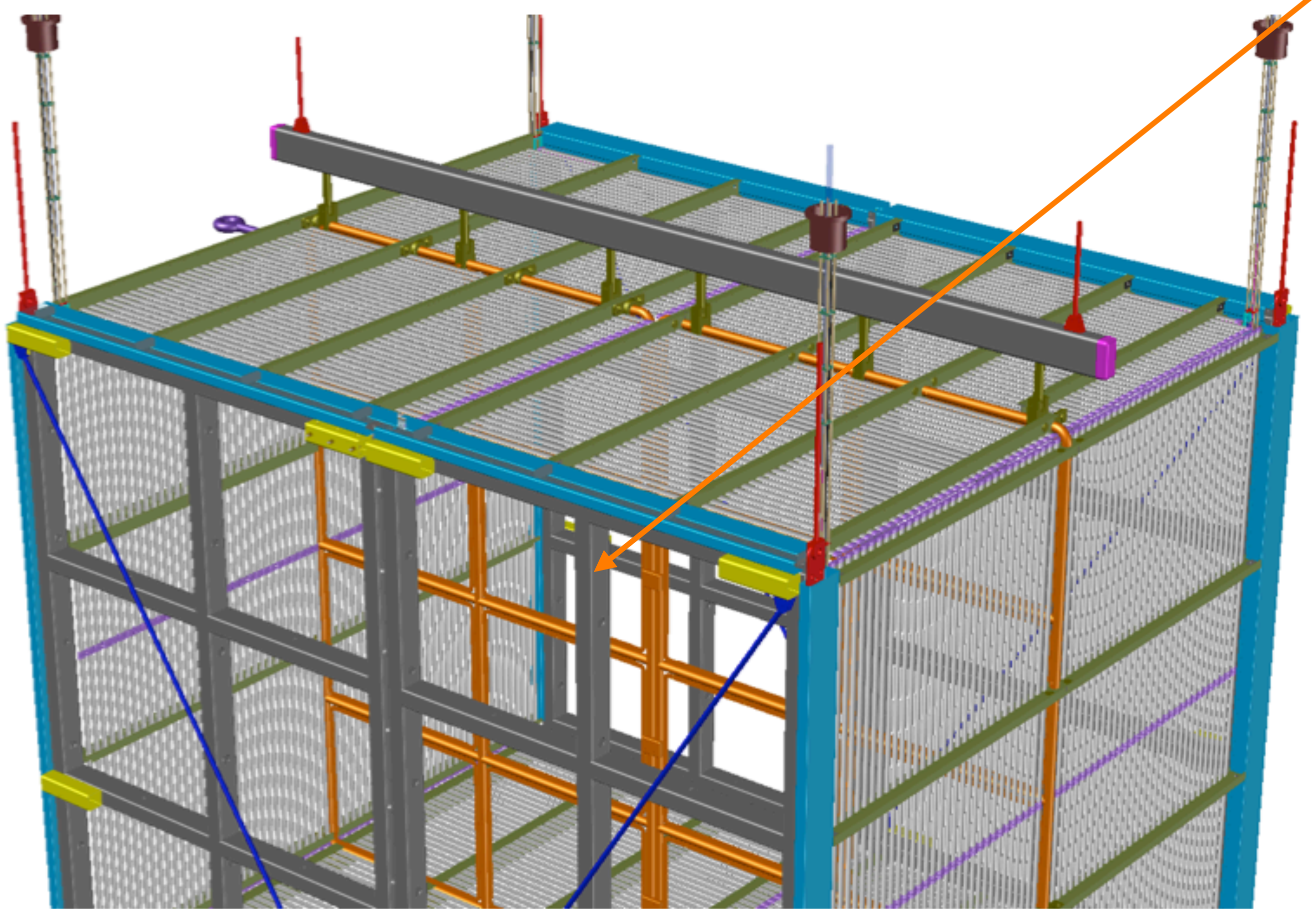
SBND: Detector Elements (I)

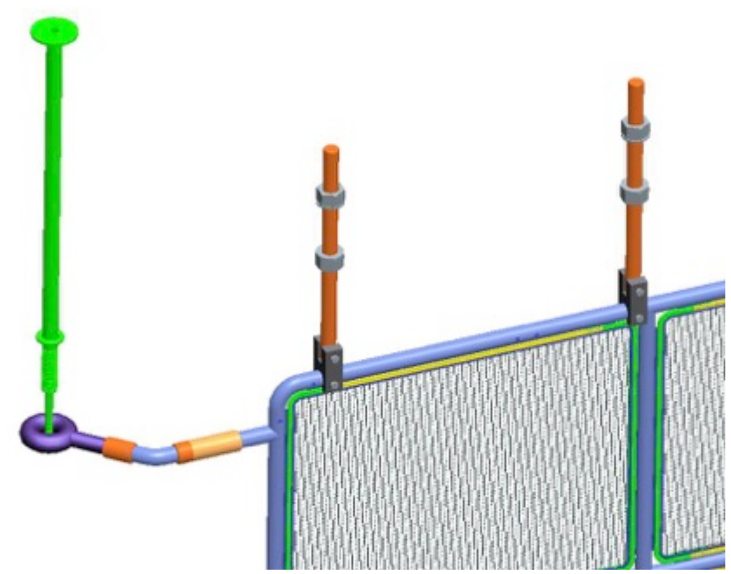


Field Cage: *roll-formed metal profiles installed in panels (16). Some are removable for detector access. Similar to protoDUNE-SP design.*



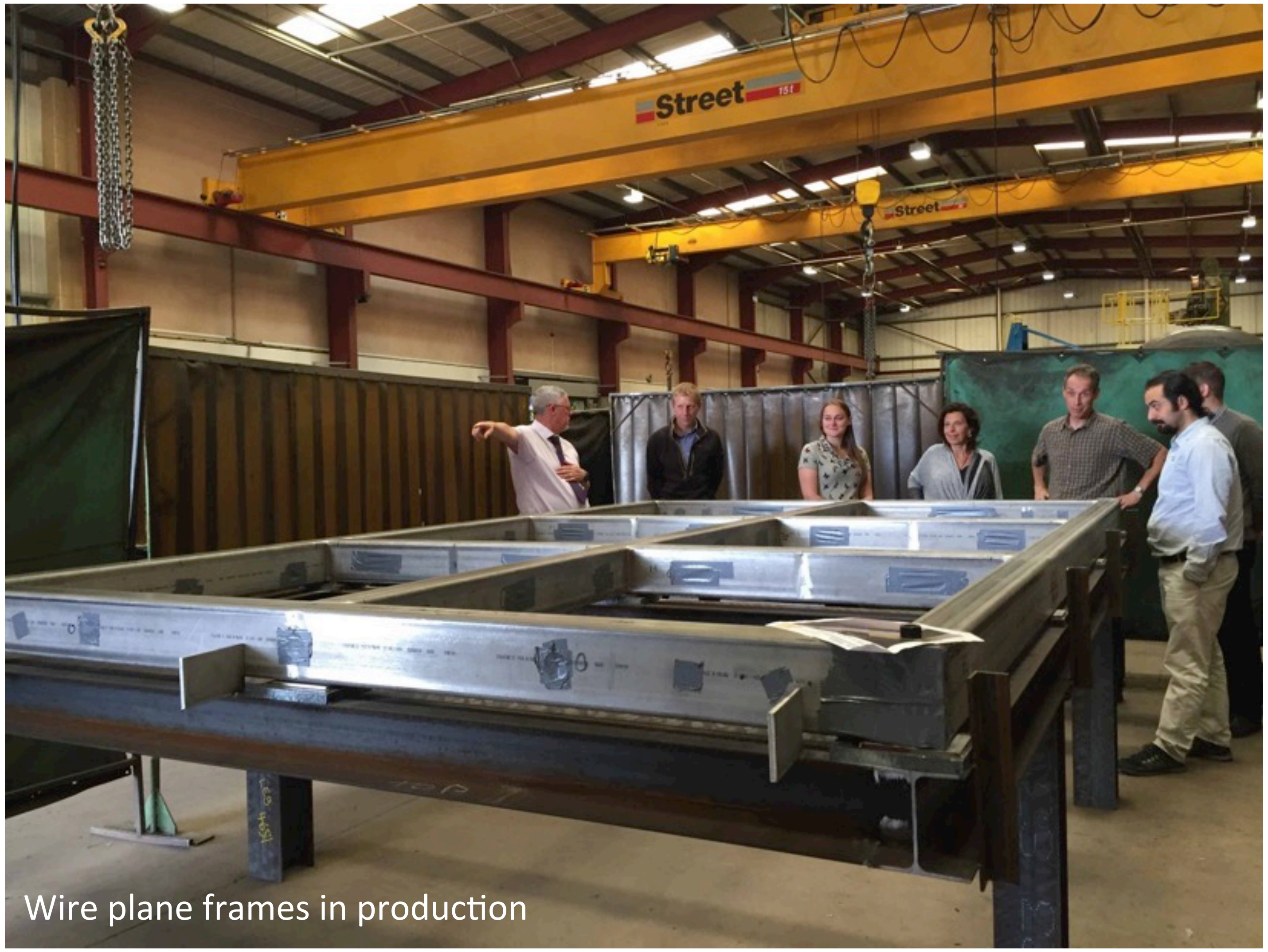
Anode Plane Assemblies: *4.1 x 2.5 m wire plane frames (4) tiled to create two drift regions*



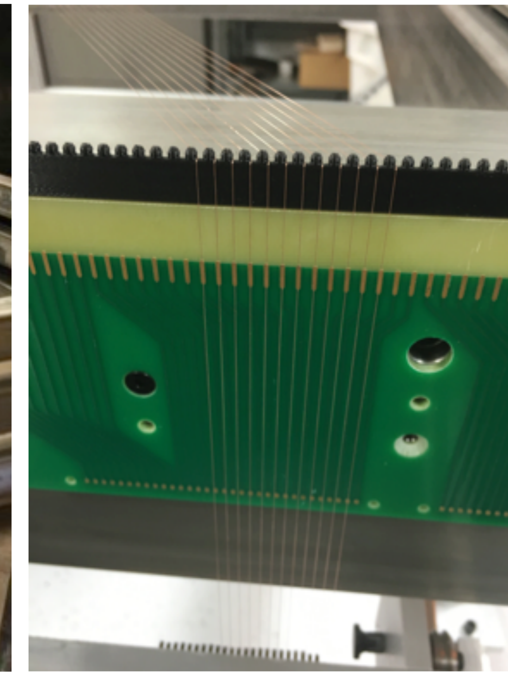


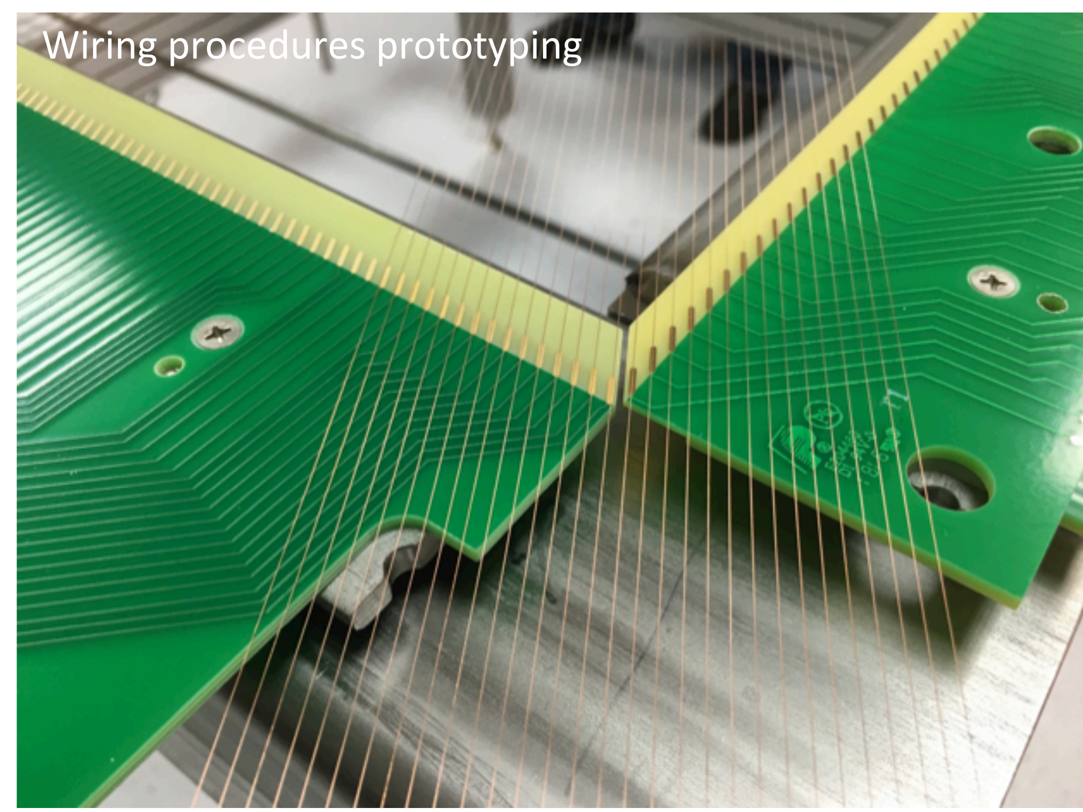
HV & Cathode: *SS tubing frames with mesh panels*

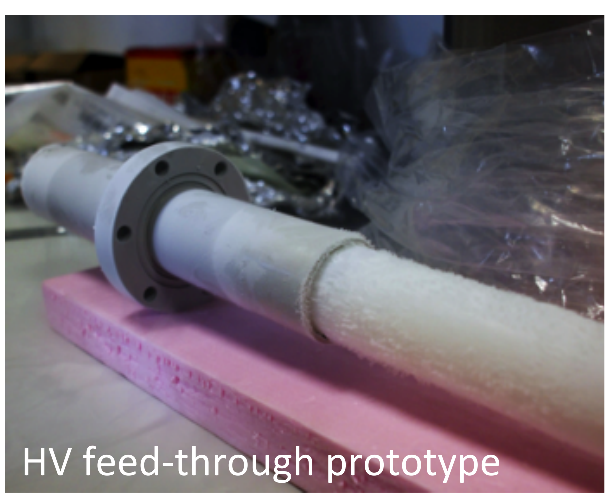
SBND: TPC Construction Has Begun

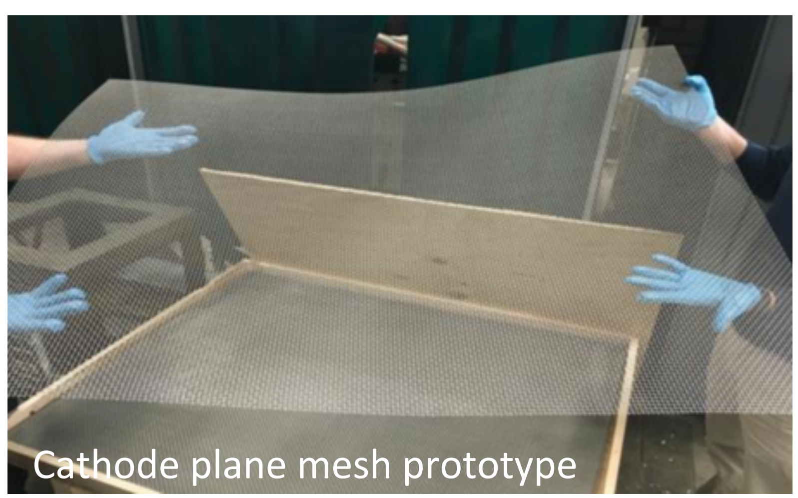


Wire plane frames in production

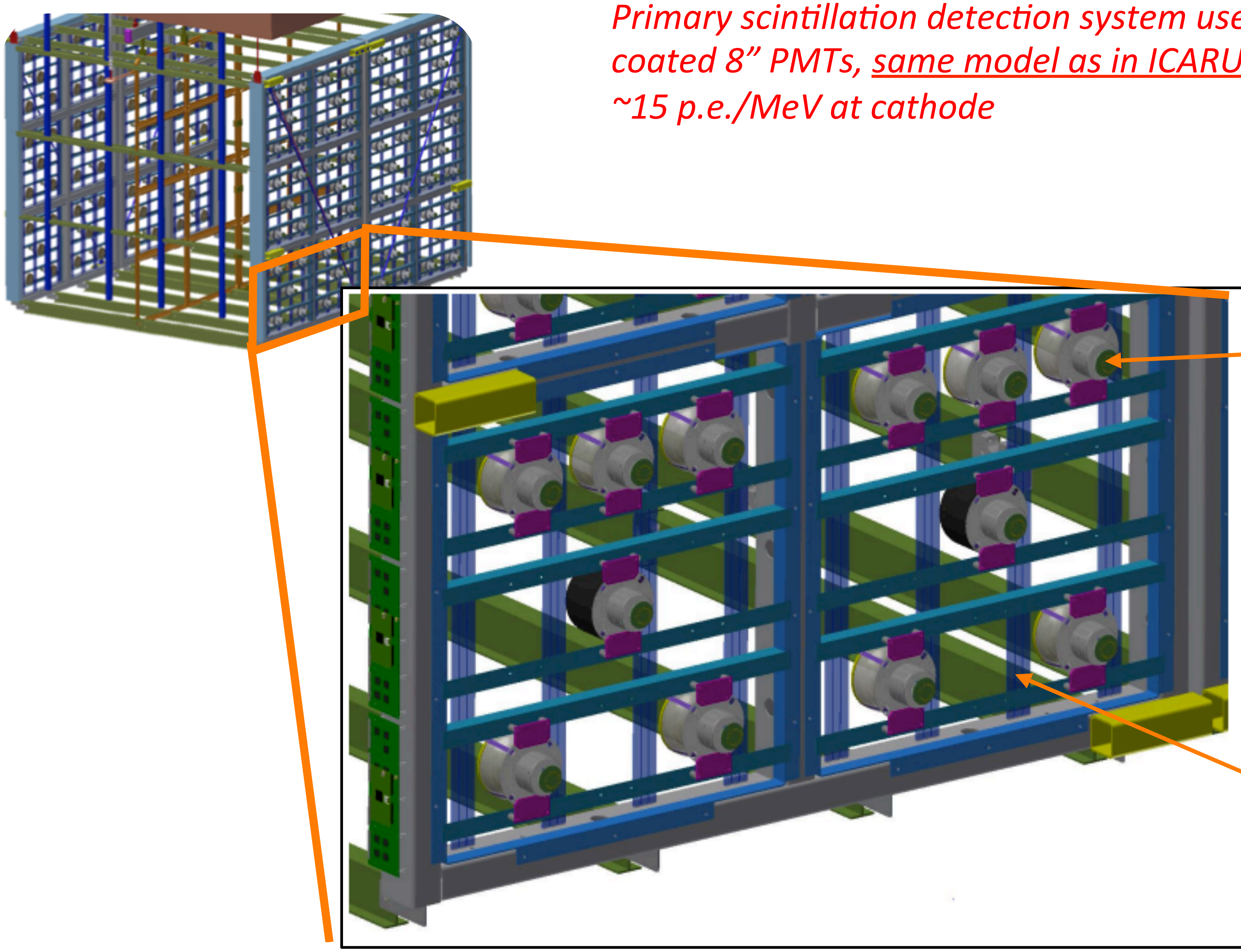



Wiring procedures prototyping

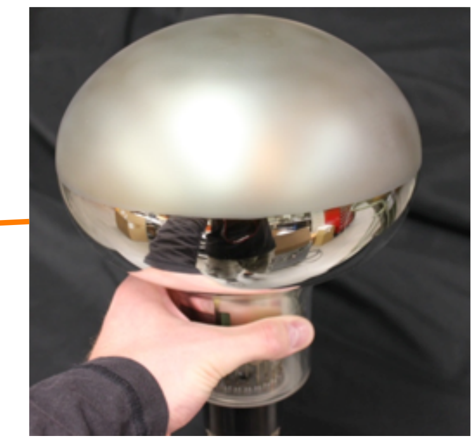

HV feed-through prototype


Cathode plane mesh prototype

SBND: Detector Elements (II)



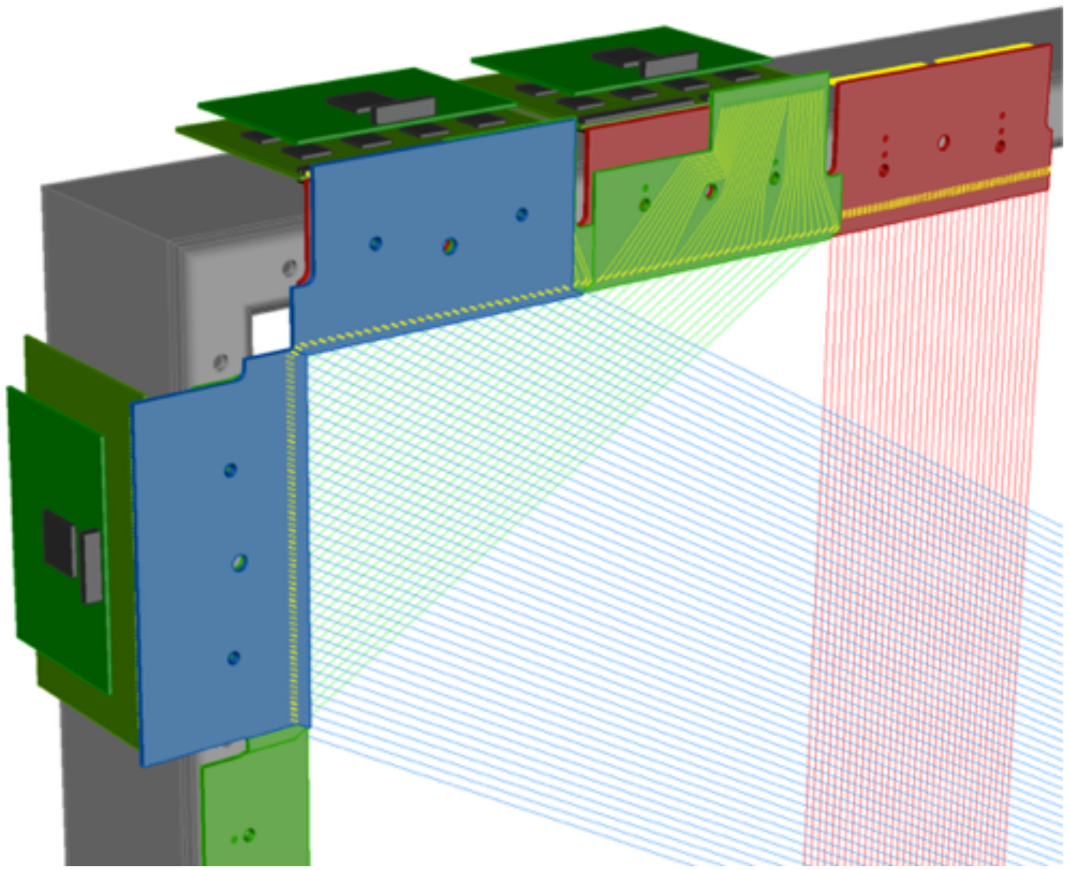
Primary scintillation detection system uses 144 TPB coated 8” PMTs, <u>same model as in ICARUS</u>
~15 p.e./MeV at cathode



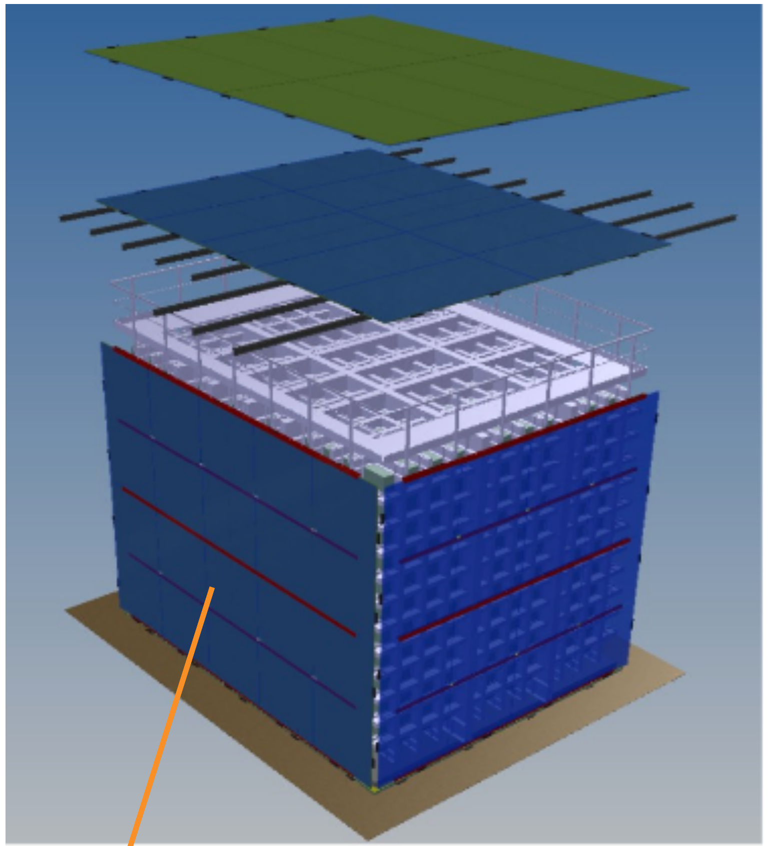
Scintillation detection R&D being pursued with <u>acrylic light-guides</u> & SiPM based readout system (DUNE)

Investigating possible further enhancement with <u>reflective foils</u> coated in wave-length shifter installed on the cathode plane. ***Simulations indicate much improved uniformity of collection efficiency across the drift volume.***

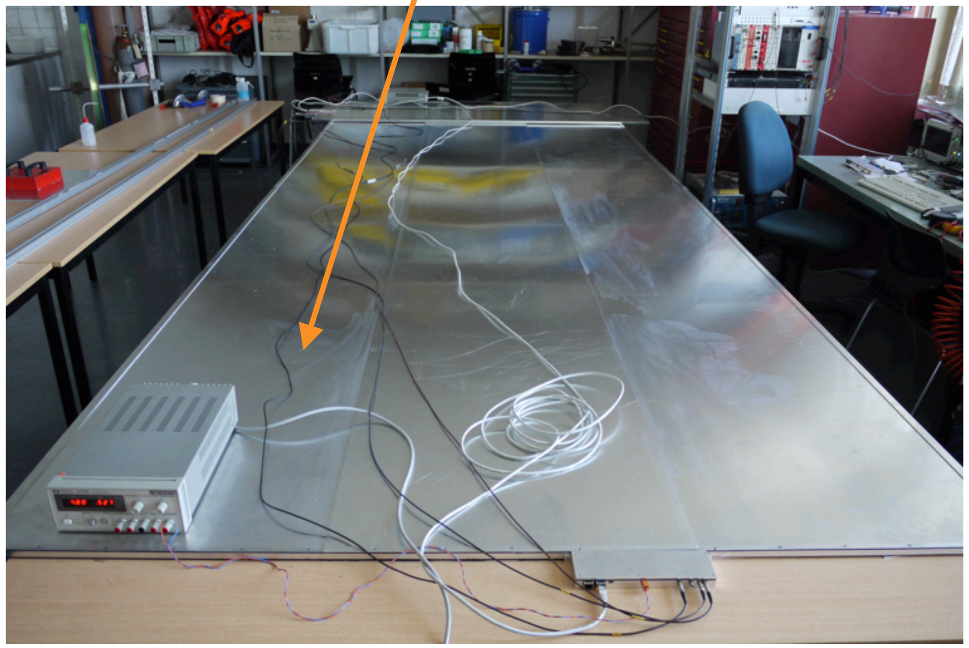
SBND: Detector Elements (III)



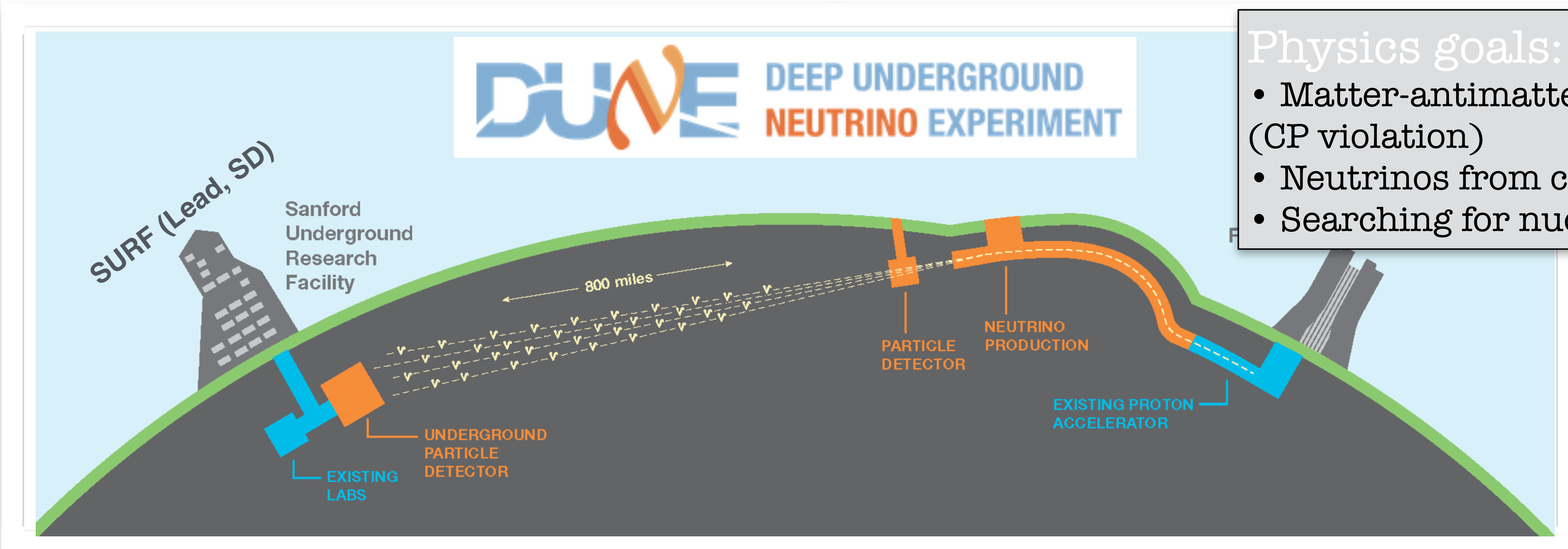
Front-end electronics with cold ADC
and multiplexing
11k channels → 4 feed-throughs
(MicroBooNE, 8.2k→ 11 feed-throughs)



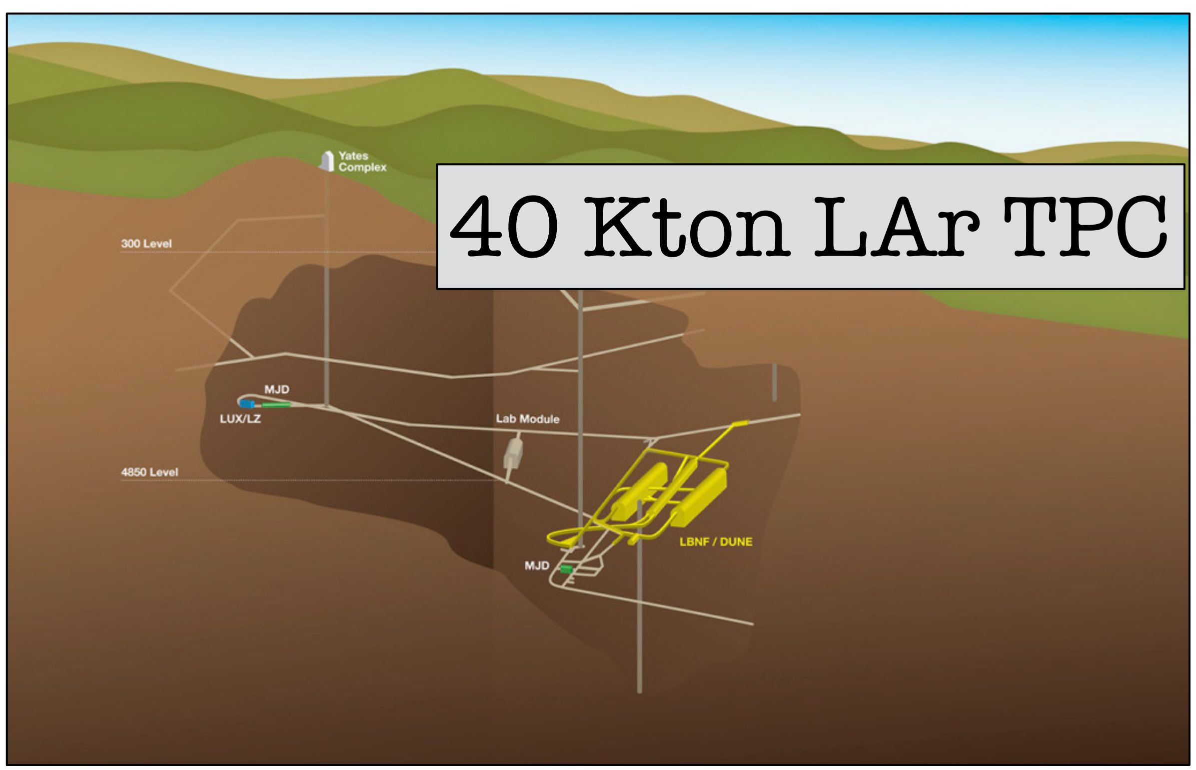
Nearly 4π coverage bi-layered
external cosmic ray tracker system



SBN ties to the Long-Baseline Program

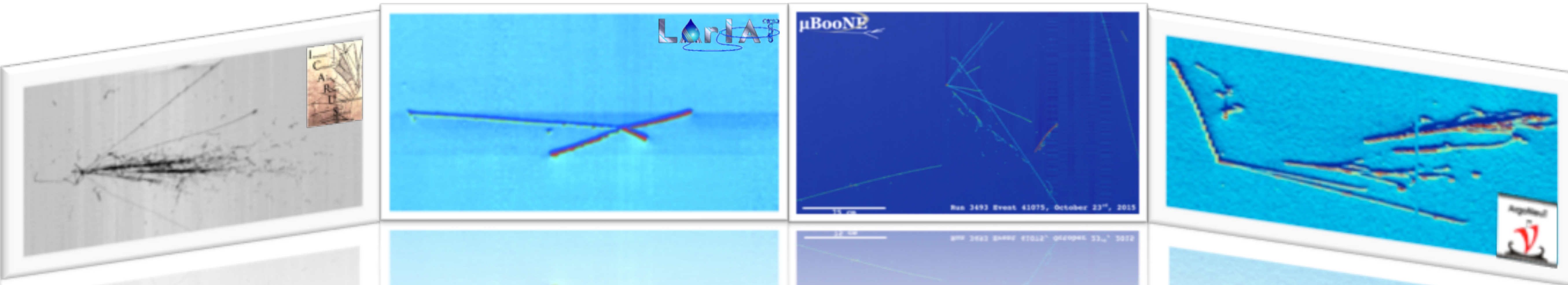


Physics goals:
- Matter-antimatter (a)symmetry? (CP violation)
- Neutrinos from core-collapse supernovae
- Searching for nucleon decay



40 Kton LAr TPC

- SBN provides an excellent opportunity for the continued **development of the liquid argon TPC technology** toward the **DUNE long-baseline program**
- SBN data also presents **important physics opportunities valuable to the future LBL program**
  - Measurements of **neutrino-argon interactions**
  - Execution of precision oscillation searches will drive the development of sophisticated **reconstruction and data analysis techniques** using TPC data



SBN: The search for a fourth type of neutrino

The three SBN detectors will all use state-of-the-art **liquid-argon time projection technology** to track neutrino interactions.

The SBN research program at Fermilab will probe one enduring mystery: Are there only three types of neutrinos, or is a **fourth type** waiting to be discovered?

In the coming years we will know if the neutrinos have still more surprises for us!

Finding Sterile Neutrinos Would be Revolutionary!