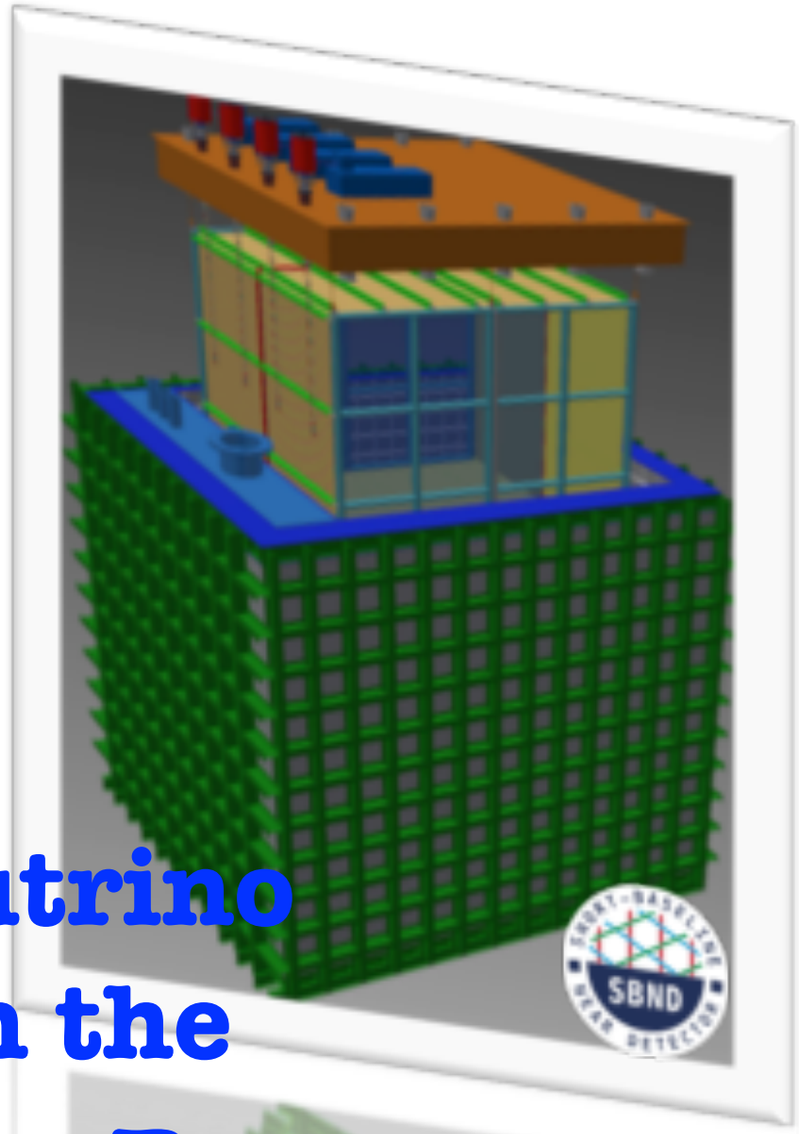


The Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

Neutrino Latin America Workshop - Fermilab

April 27th, 2016

Ornella Palamara

Fermilab & Yale University*

*on leave of absence from INFN, Laboratori Nazionali del Gran Sasso, Italy

U.S. future Accelerator Neutrino Physics: **LAr TPC Technology**

- The future U.S. accelerator neutrino program is based on the **Liquid Argon Time Projection Chamber (LAr TPC)** technology.

- LArTPC offers the ability to measure interactions of neutrinos and other particles in real time with sub-millimeter position resolution, allowing for
  - **track reconstruction**
  - **particle identification and**
  - **electron/gamma separation**

far beyond that offered by any other neutrino detection method.

The US LAr TPC Program: a path toward DUNE

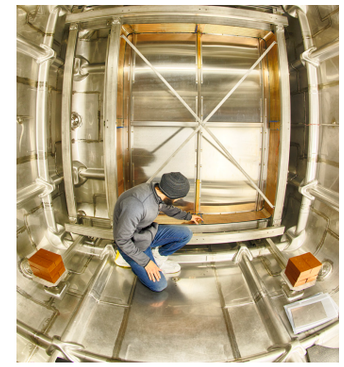
A rich R&D and physics program

R&D

Yale TPC and Bo
(2008-2009)
Proof of Concept

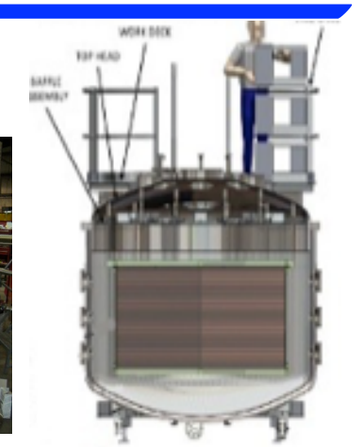
LUKE
(2008)
Material Teststand

LAPD
(2011)
LAr Purity



35Ton
(2013)
Cryostat Purity

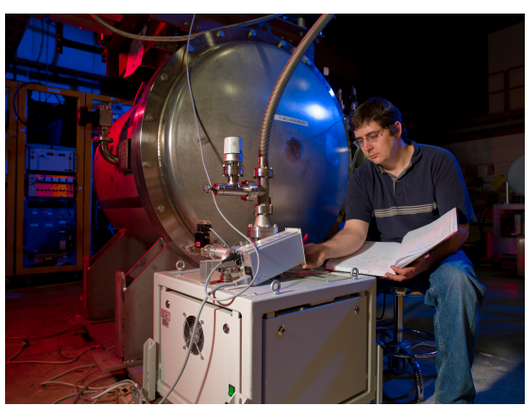
LArIAT
(2015)
LArTPC
Calibration



CAPTAIN

LArTPC
Calibration

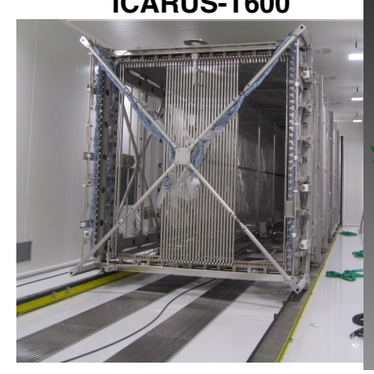
Physics

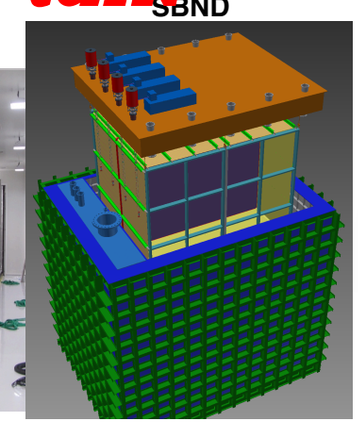


ArgoNeuT
(2009 - 2010)
ν-Ar Cross Sections

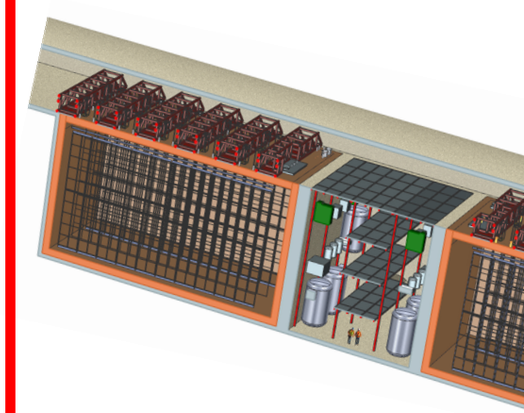
SBN program, this talk

MicroBooNE
(2015 - 2018)
MiniBooNE
Low Energy Excess





SBN (SBND, MicroBooNE, ICARUS-T600)
(2018 - 2021)
Searches for
Sterile Neutrino Oscillations



DUNE
(2023+)
CP Violation

Why a Short-baseline accelerator neutrino program?

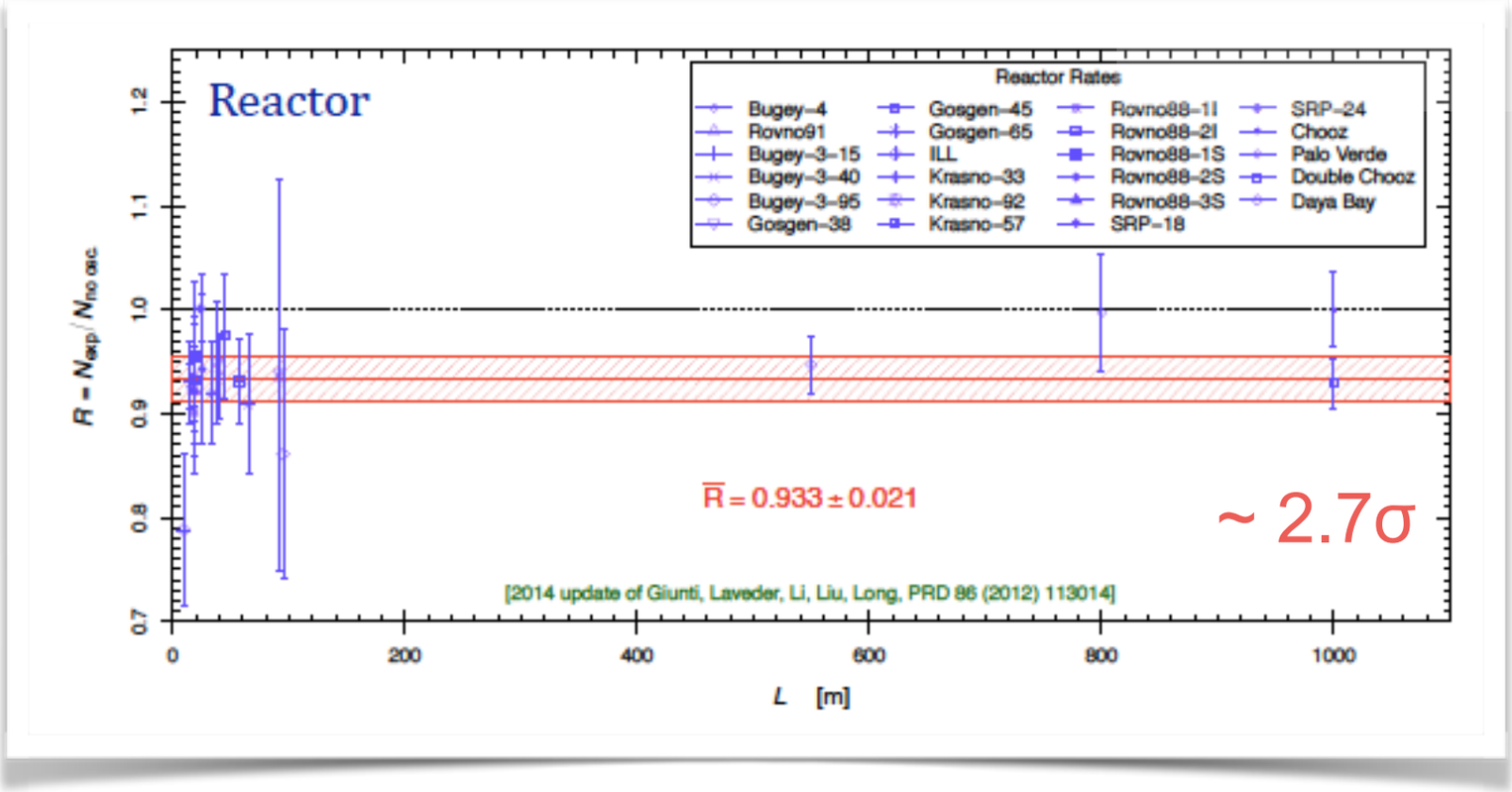
Physics motivations for the FNAL
Short Baseline Neutrino program (SBN)
- a multi-detector, LAr TPC based facility on the Booster Neutrino Beam -

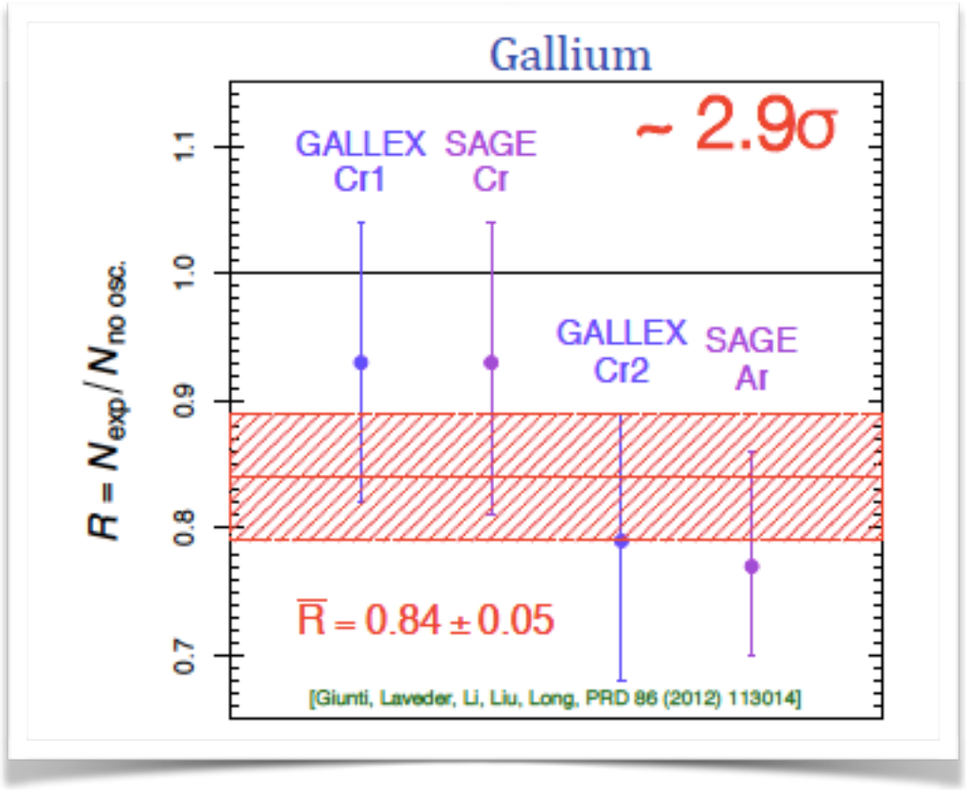
Experimental Hints For Beyond Three Neutrino Mixing

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")

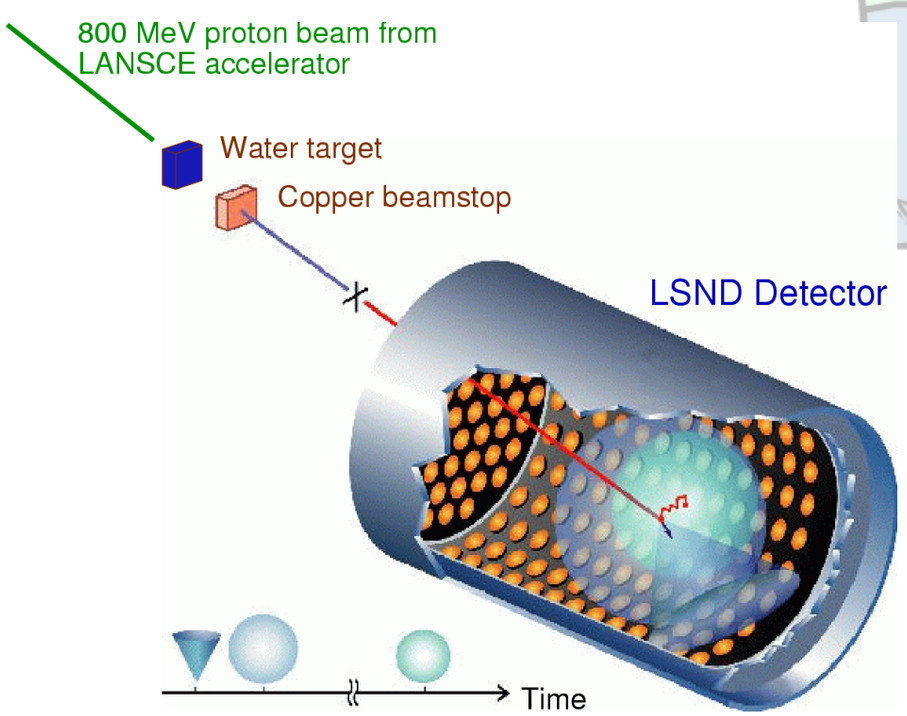




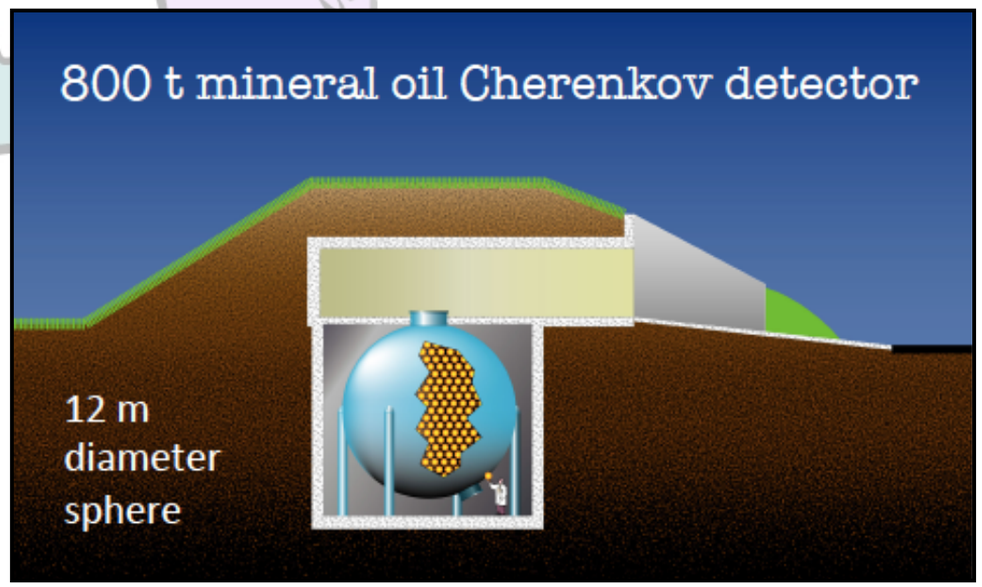
Short-Baseline Neutrino Anomalies (II)

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

LSND



MiniBooNE



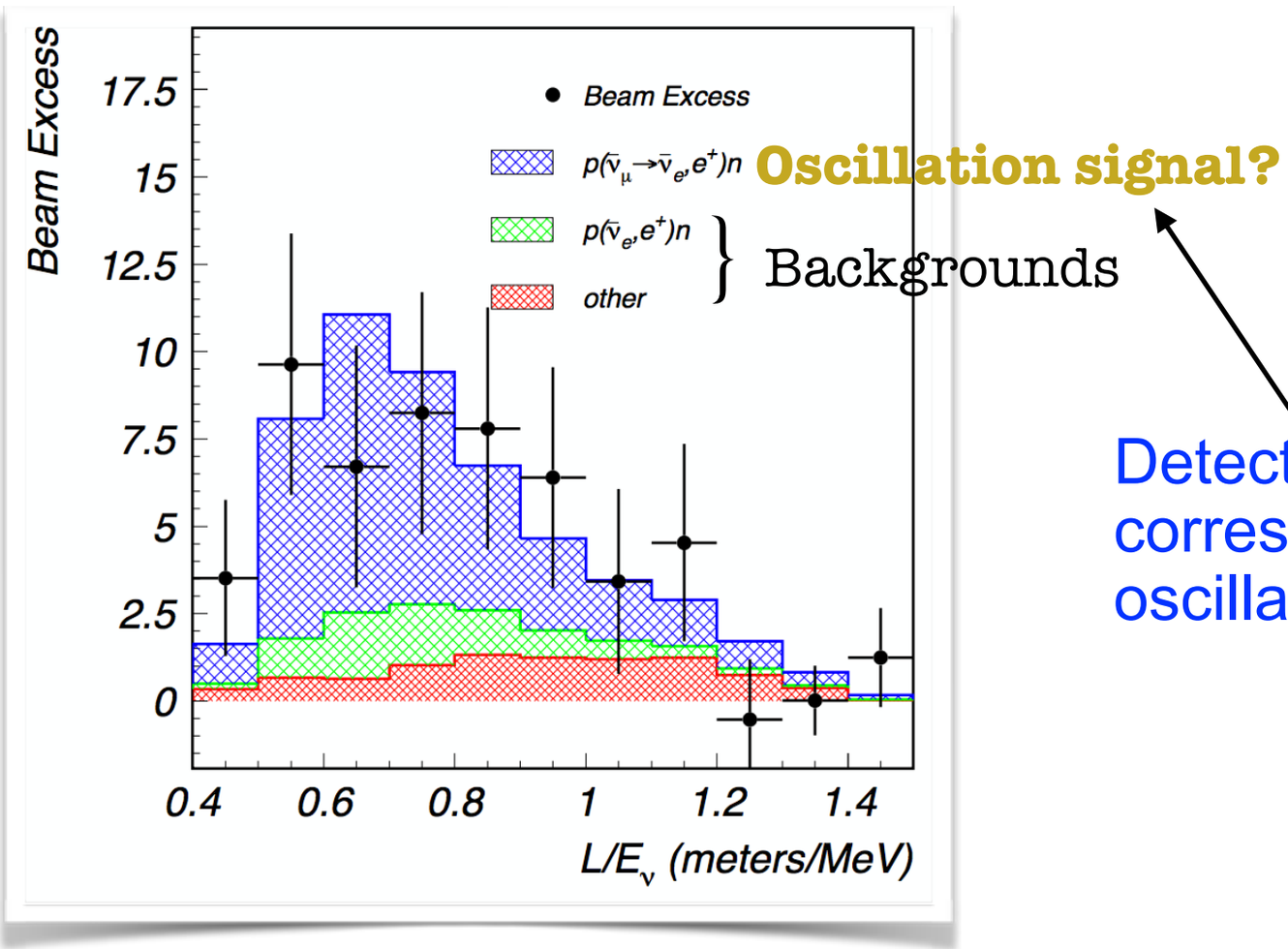
Short-Baseline Accelerator Anomalies

LSND

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

Low energy $\bar{\nu}_\mu$ beam from a decay-at-rest pion beam

167 tons liquid scintillator



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

This signal cannot be accommodated with the 3 SM neutrinos!

Short-Baseline Accelerator Anomalies

MiniBooNE

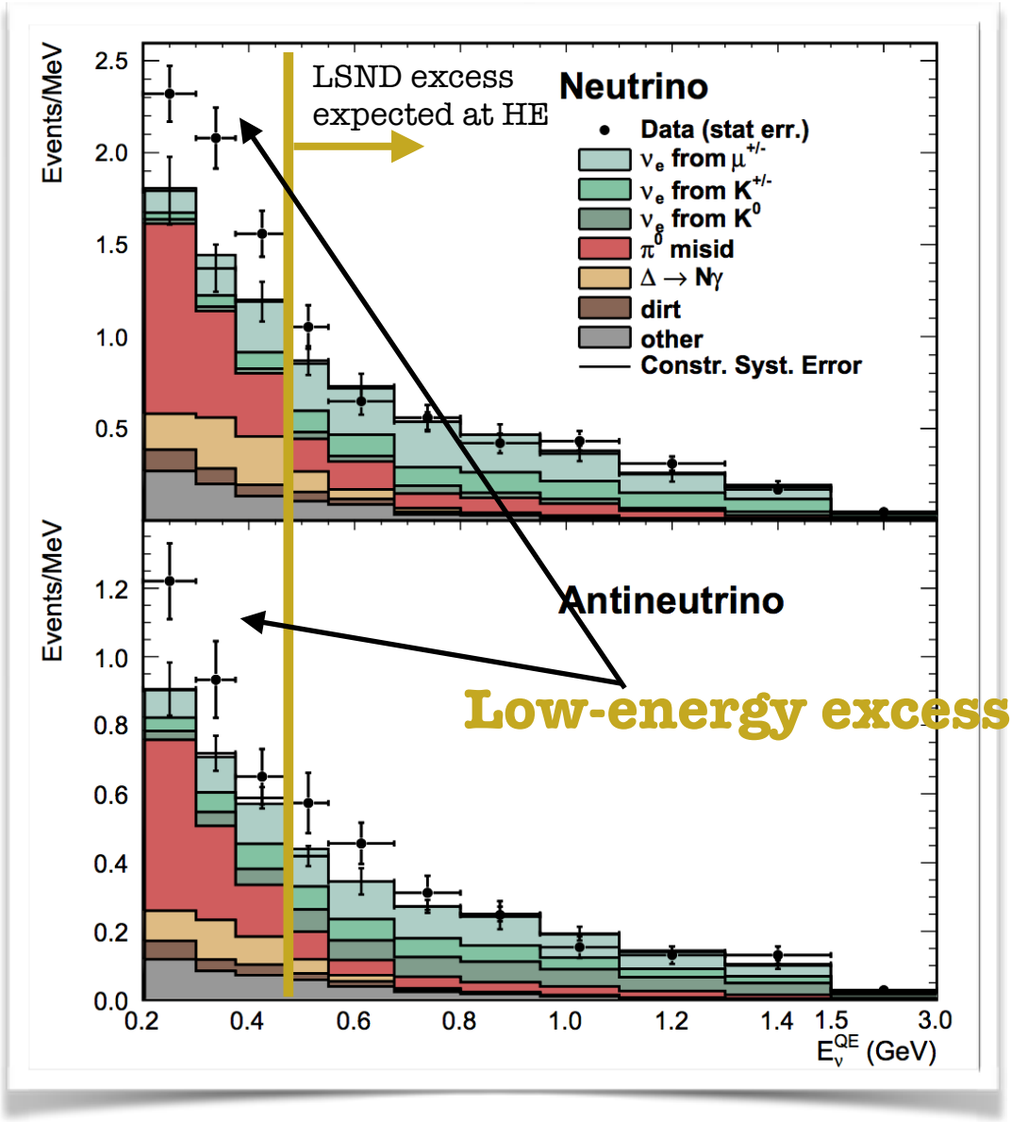
540 m from the target
E=[0 - 2] GeV

L/E ≈ 1 m/MeV

800 tons mineral oil

PRL 110 (2013) 161801

- Decay in flight neutrino source
- 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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (2.8 σ) appearance is observed in a lower energy range



Short-Baseline Accelerator Anomalies

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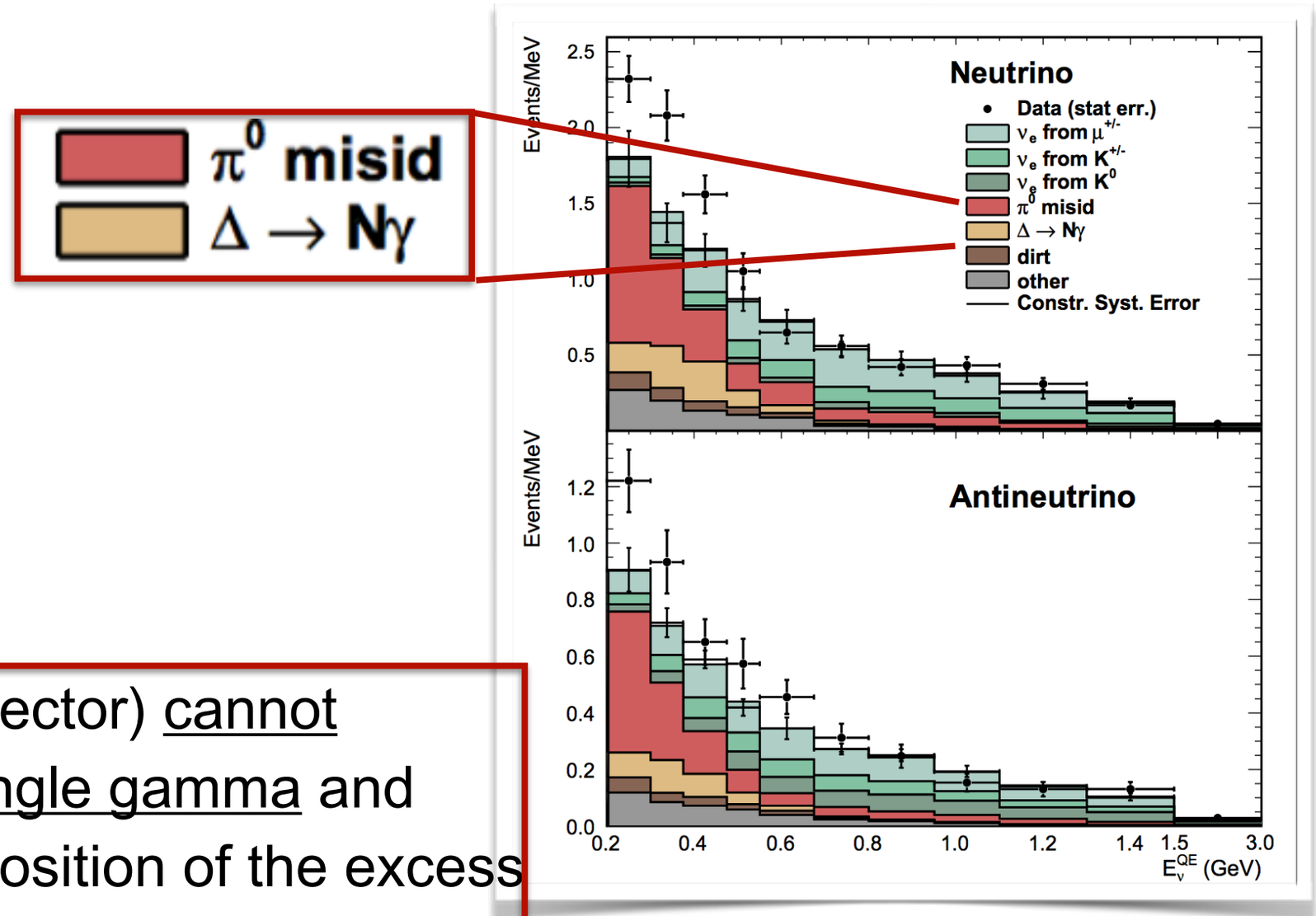
PRL 110 (2013) 161801

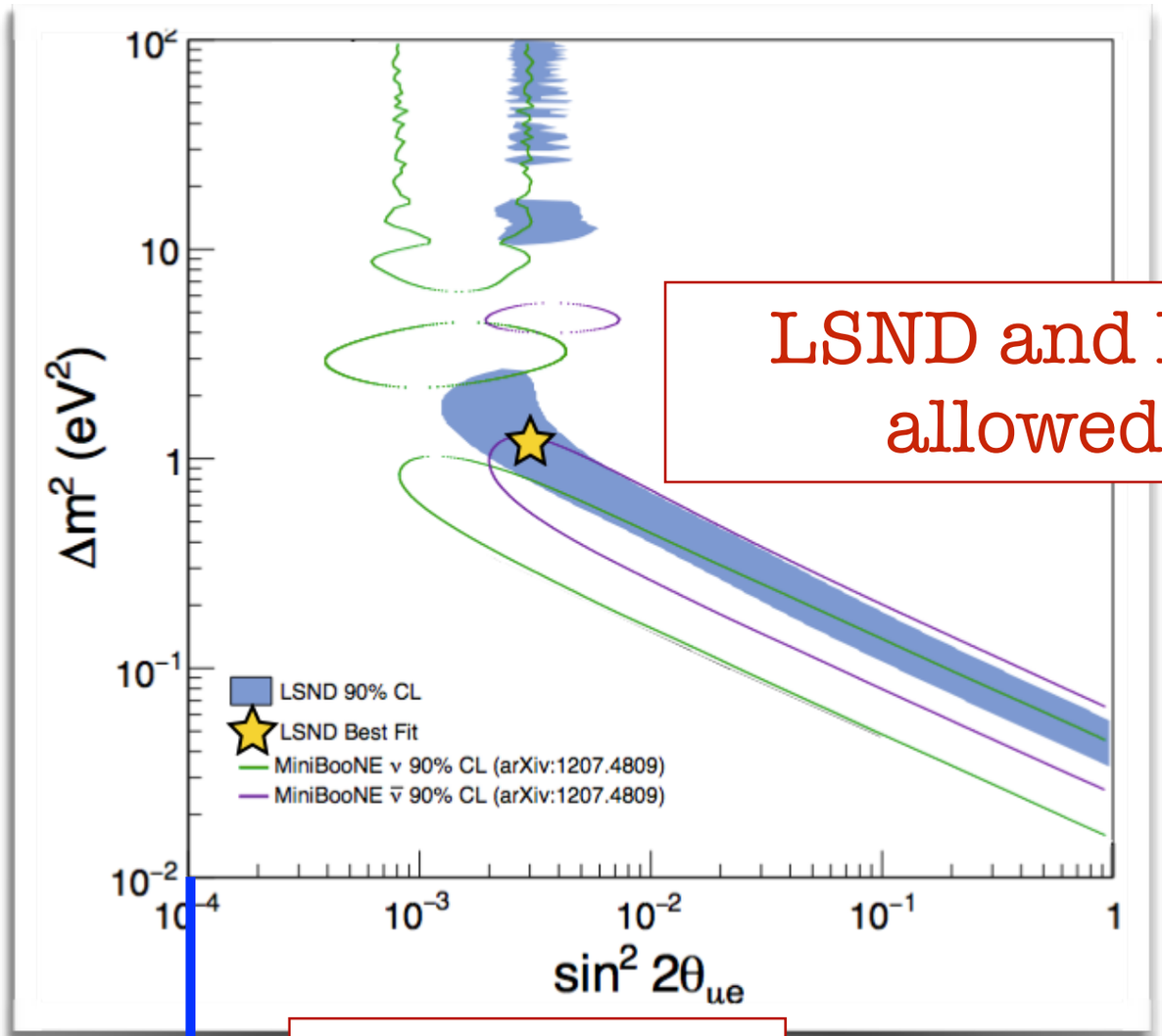


MiniBooNE (Cherenkov detector) cannot distinguish electron from single gamma and cannot determine the composition of the excess

– 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

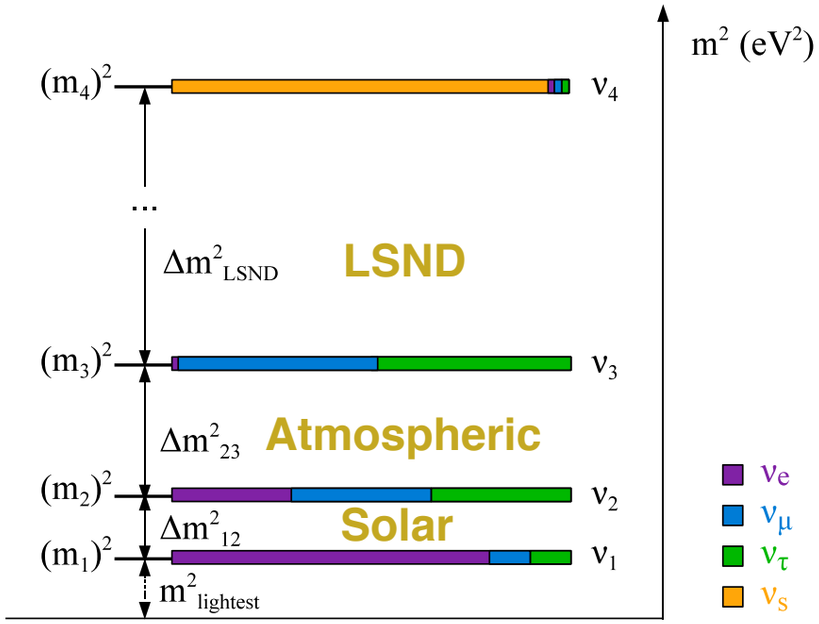
Atmospheric

Solar

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

10^{-3}

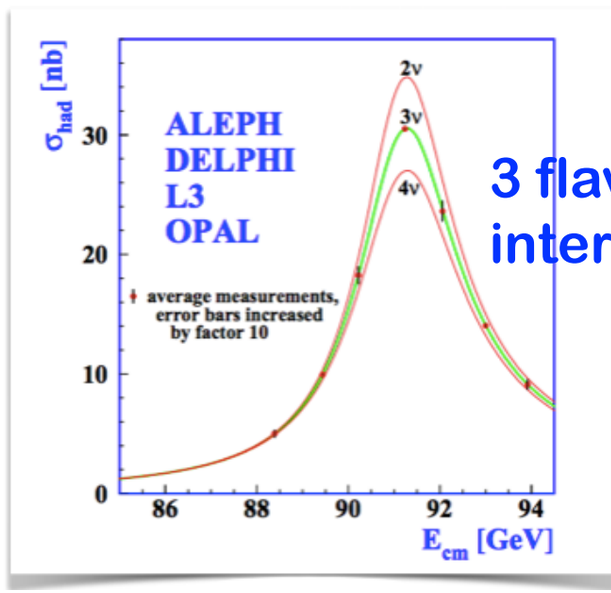
10^{-5}



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



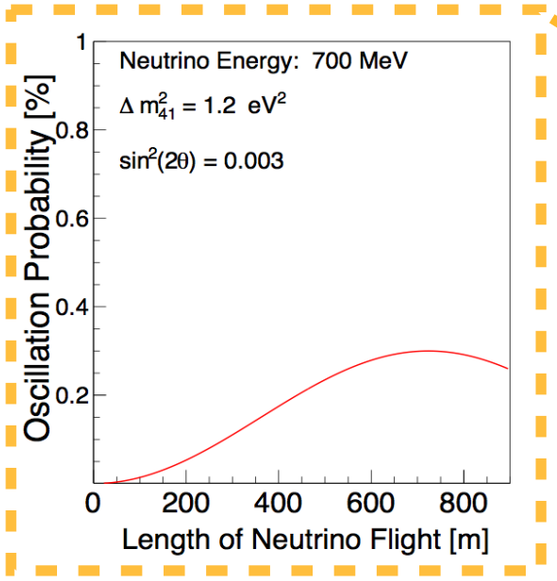
3 flavor states, 3 "active" (weakly interacting) neutrinos!

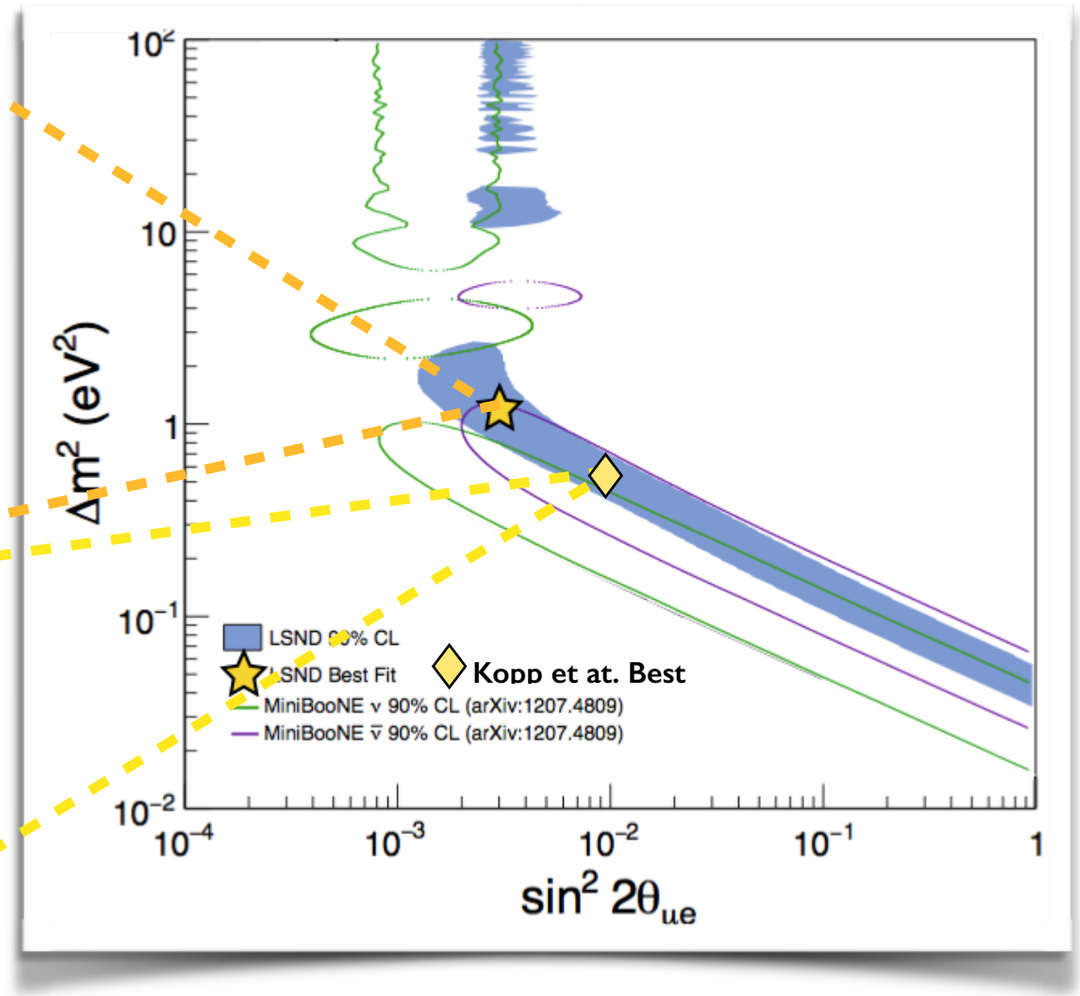
Any additional neutrino doesn't participate in weak interactions ⇒ **"sterile neutrino"***

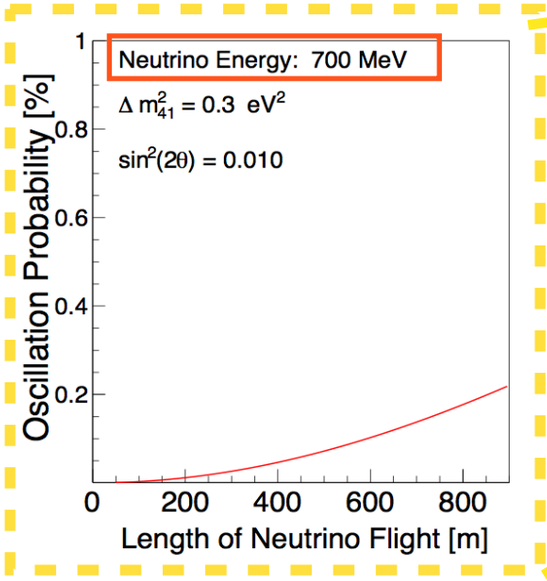
* Sterile neutrinos were introduced by Pontecorvo in 1968 as neutrinos with no standard model interaction

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: Multi-detector approach in a well characterized beam

Fermilab – aerial view

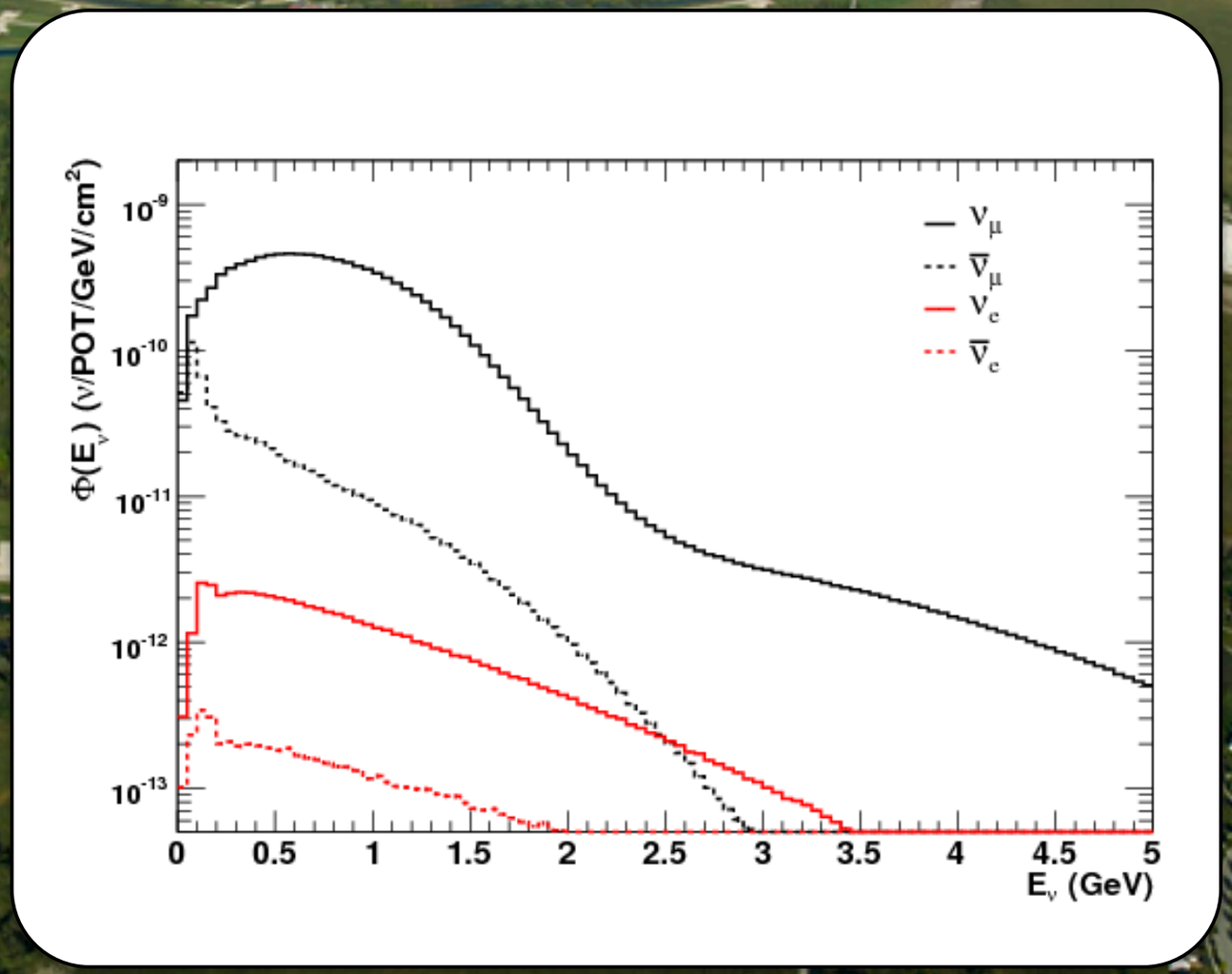
Fermilab – Neutrino beams

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)

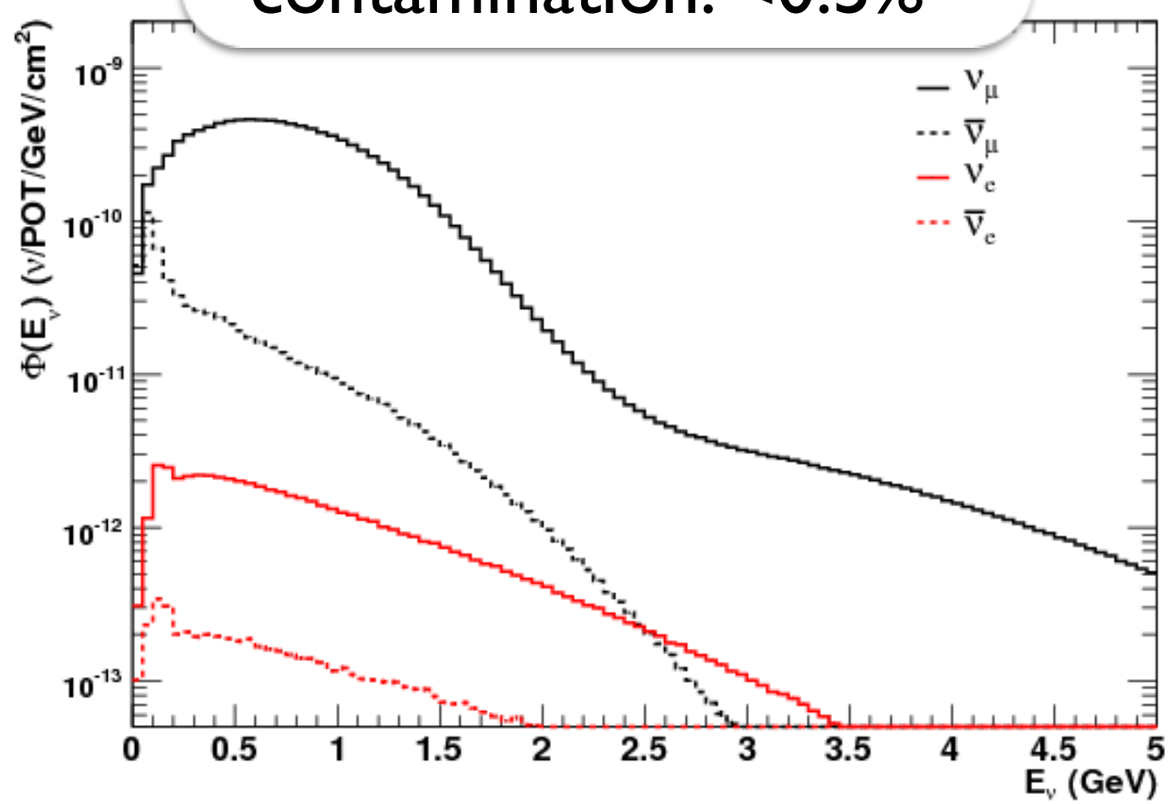
Fermilab's **low-energy** neutrino beam:

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

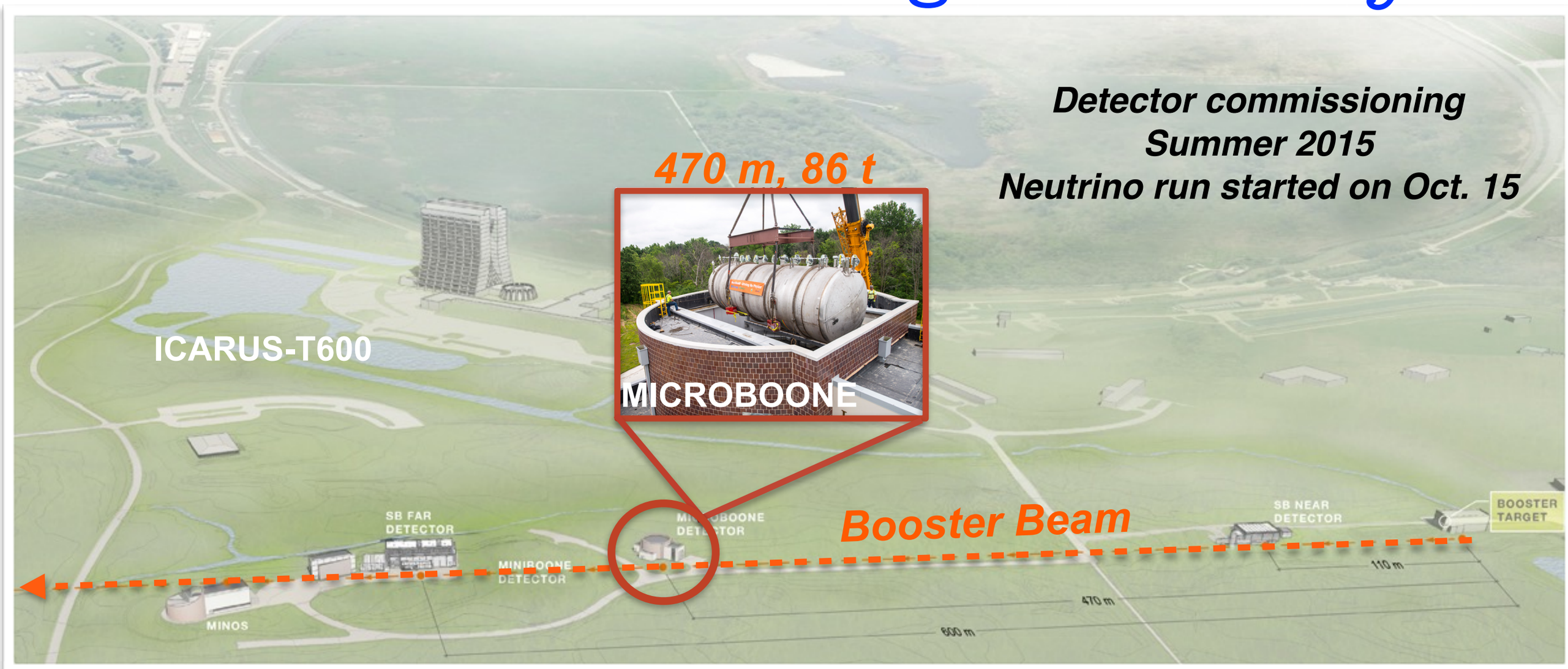
Booster - 8 GeV protons

- Beam of mostly muon neutrinos
- Search for flavor ν_μ disappearance and ν_e appearance
- BNB stably running for a decade (well characterized)
- Anomalies exist here (MiniBooNE)

Small electron neutrino contamination: <0.5%



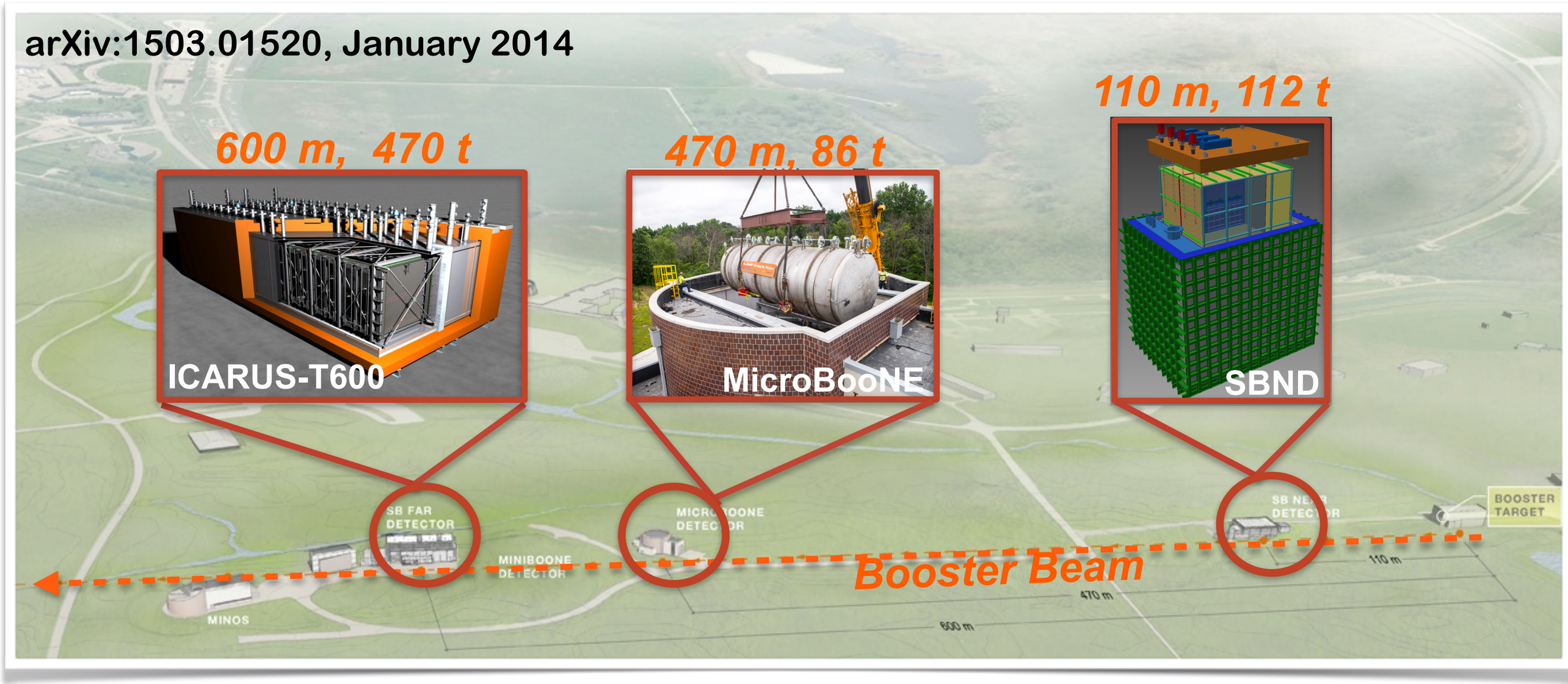
MicroBooNE: testing an anomaly



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

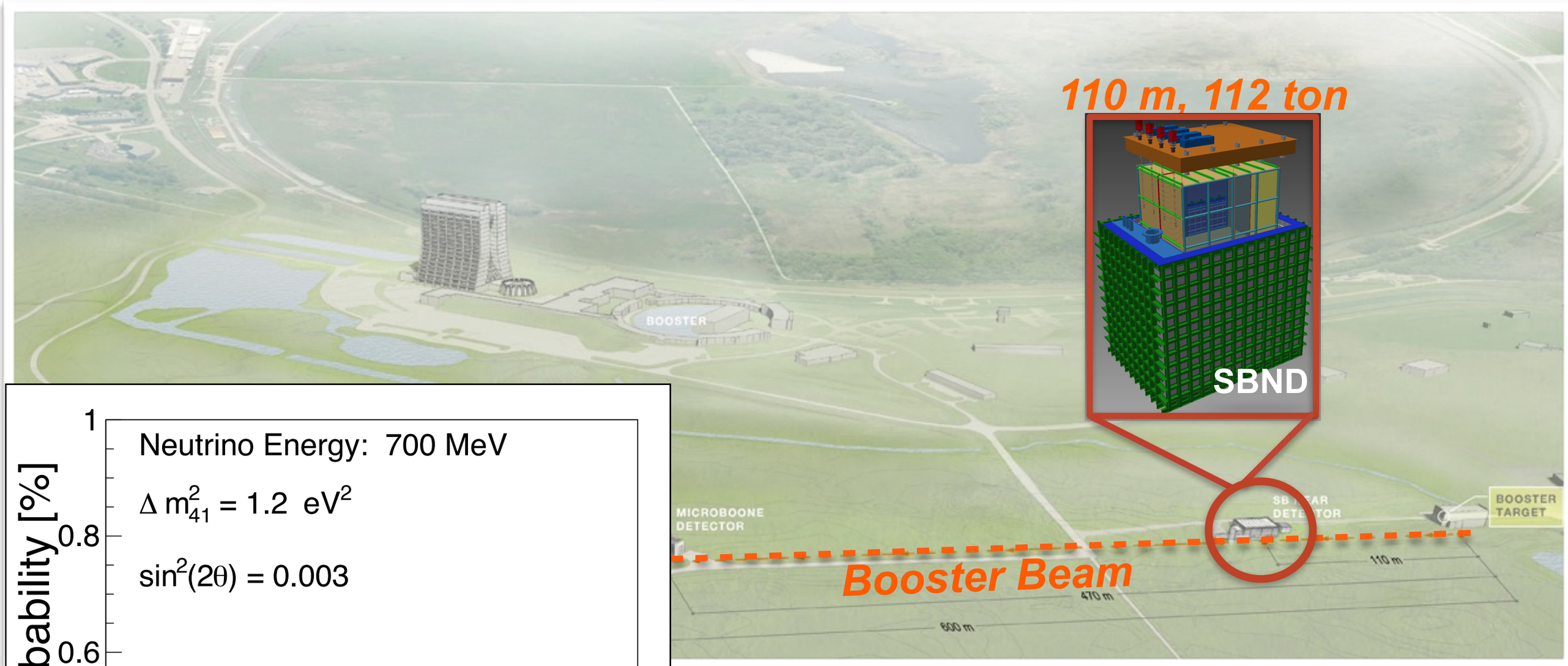


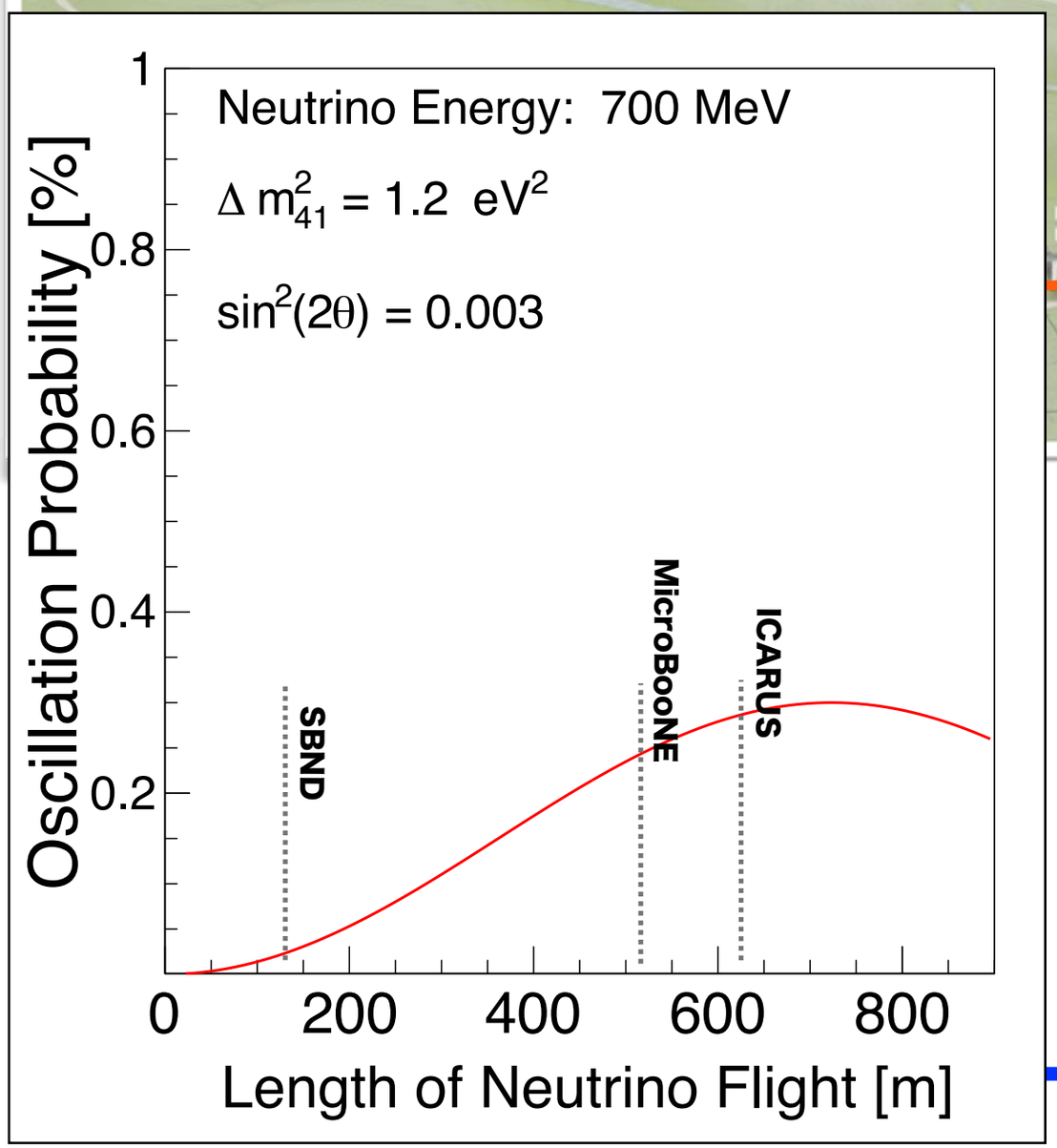
SBN program - Phase 2 - By 2018, the MicroBooNE detector will be joined by two additional LAr-TPC detectors at different baselines

- 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



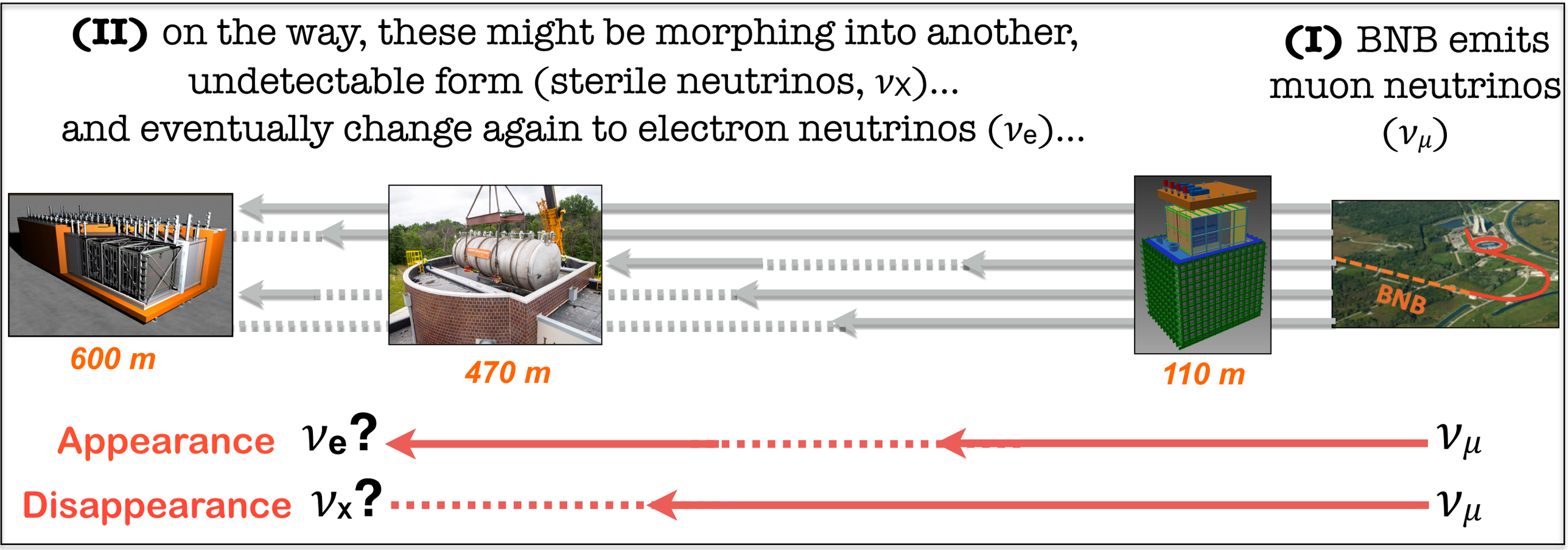


The Short-Baseline Near Detector (SBND), which will sit close to the source, plays a **unique role** in the chain of detectors, measuring the purity of the muon neutrino beam (it will **characterize the beam before oscillations occur** and address one of the dominant systematic uncertainties)

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.

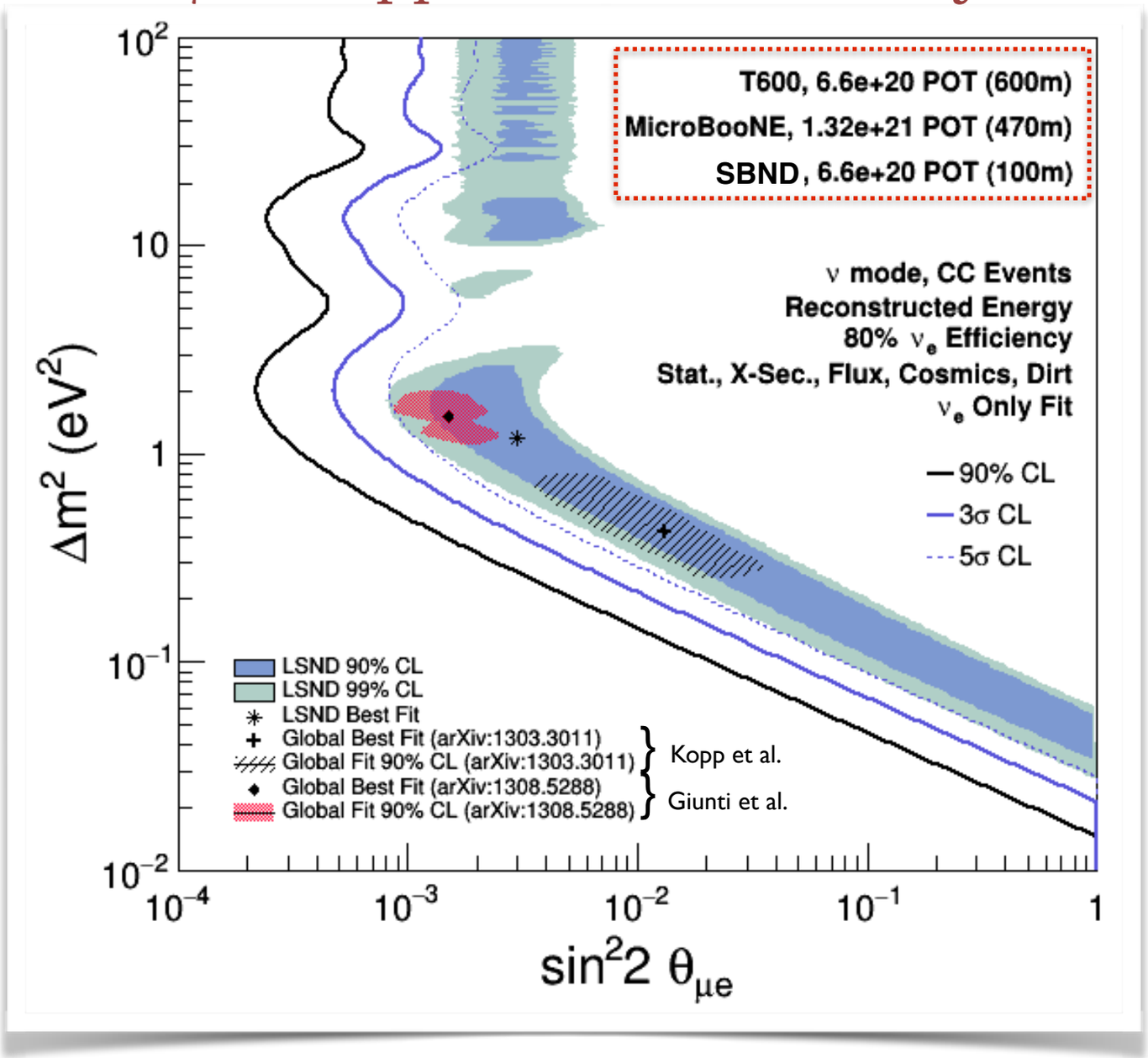
The search for the forth neutrino in SBN



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

Physics reach of the SBN Program

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

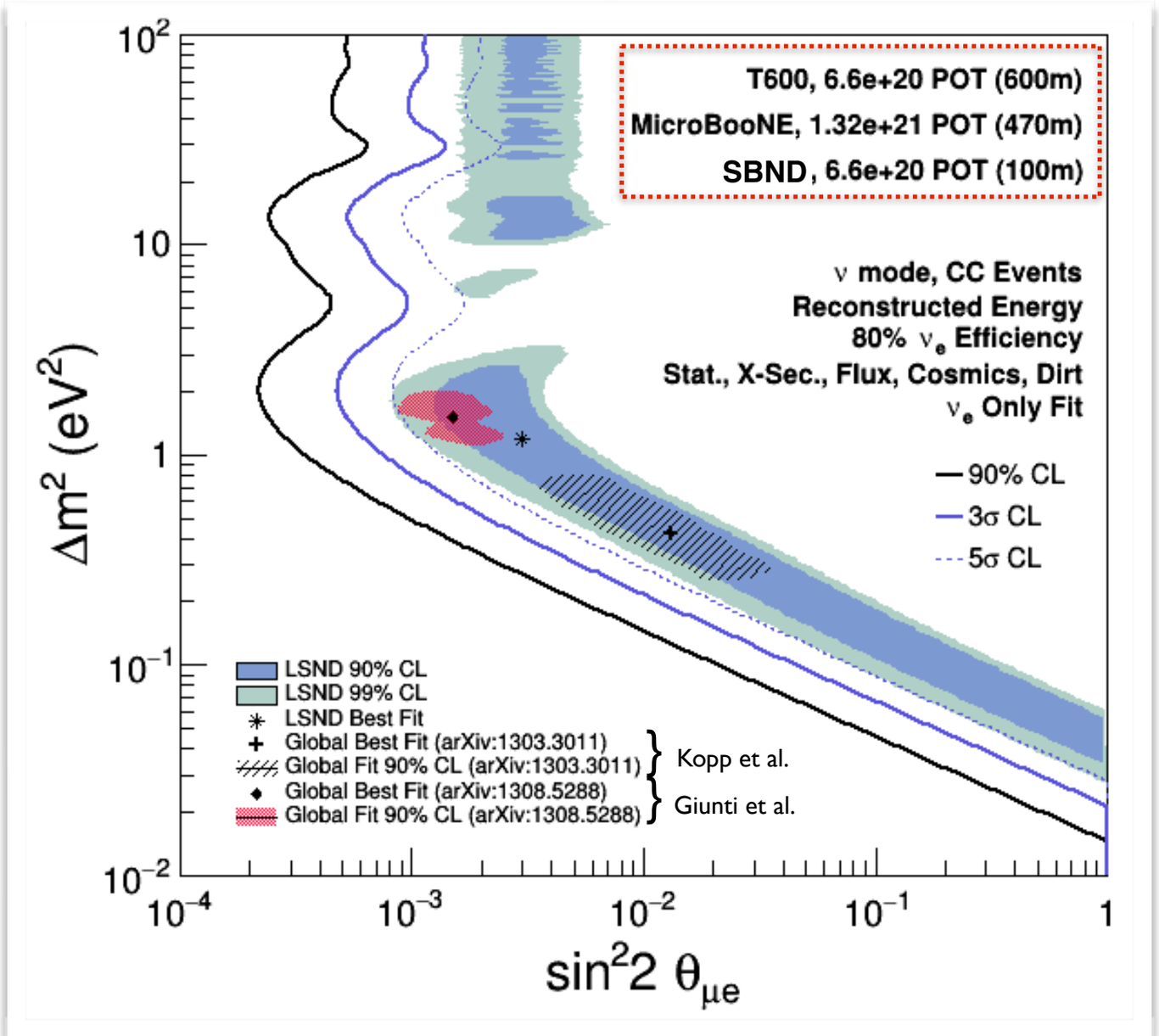


~3 years of run

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



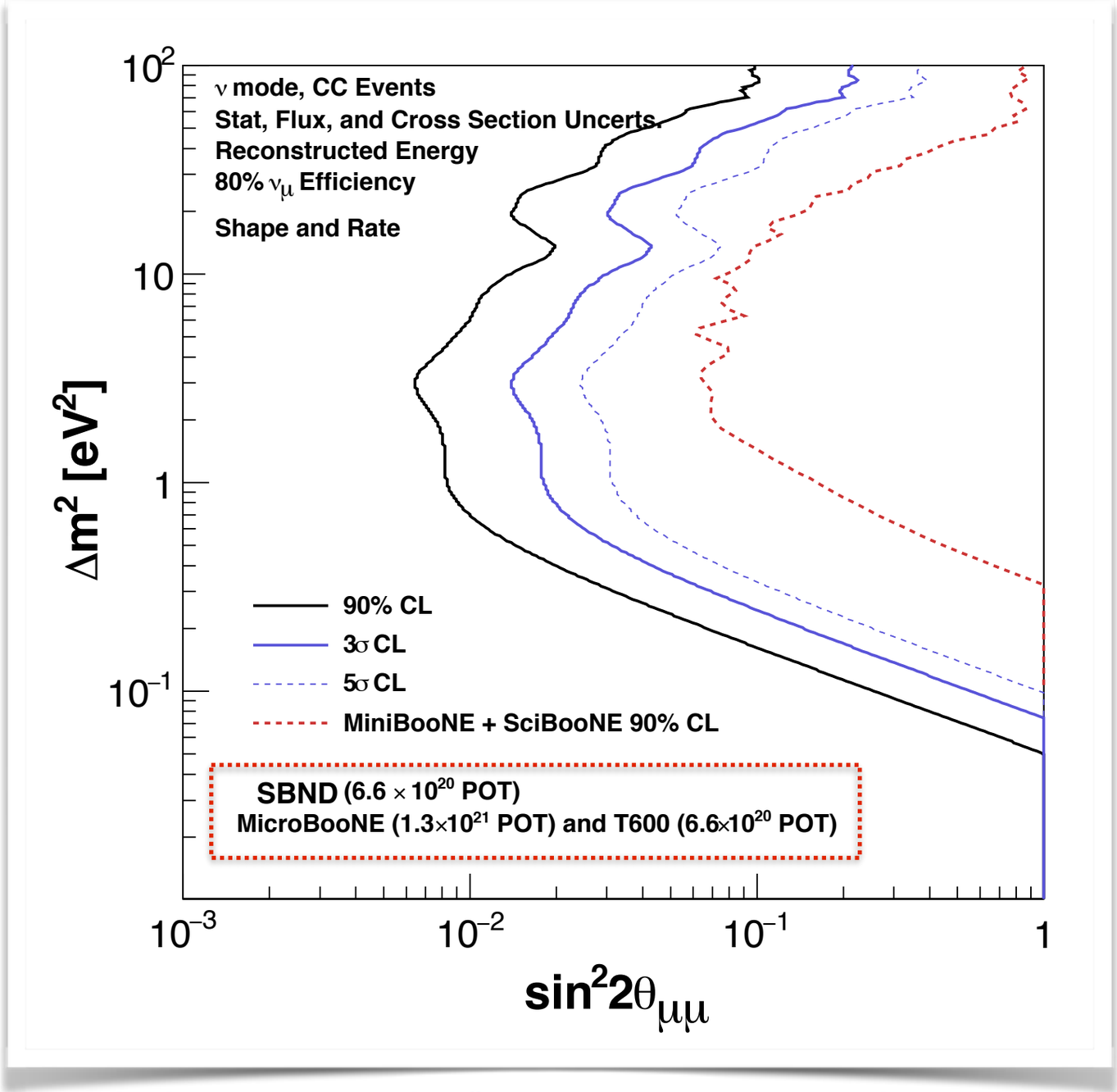
SBN will cover the LSND 99% C.L. allowed region with

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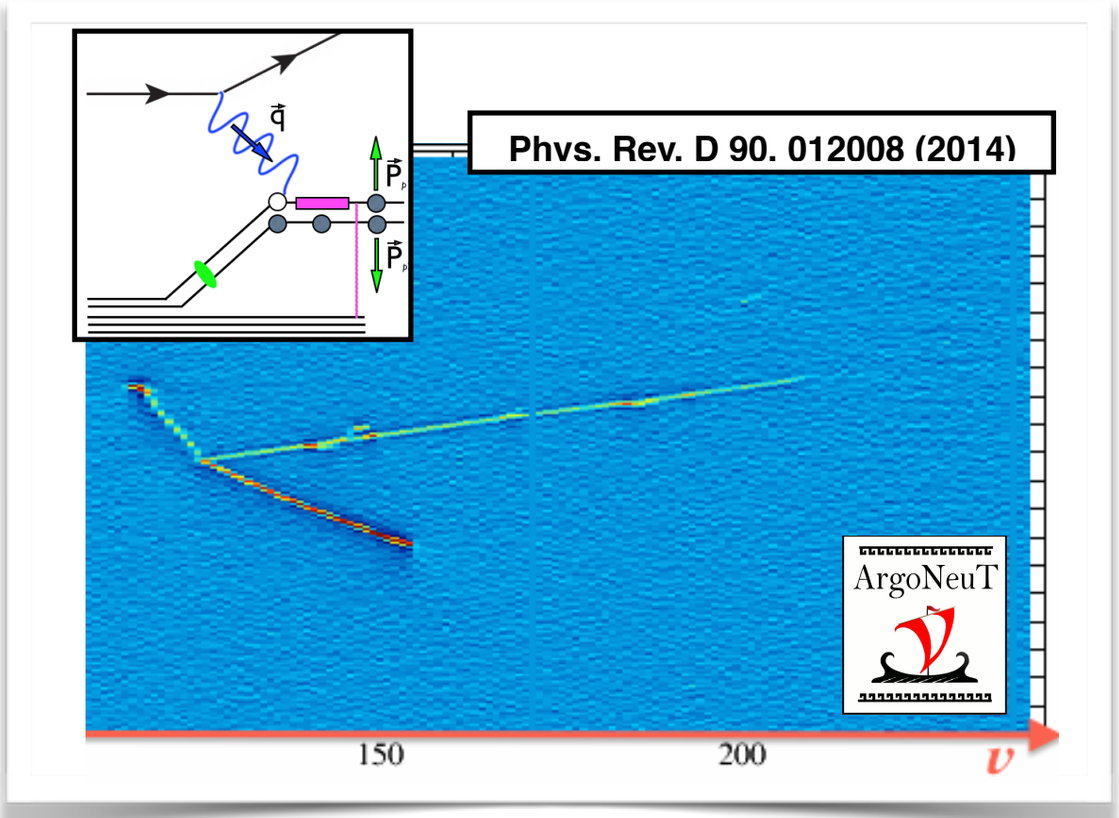
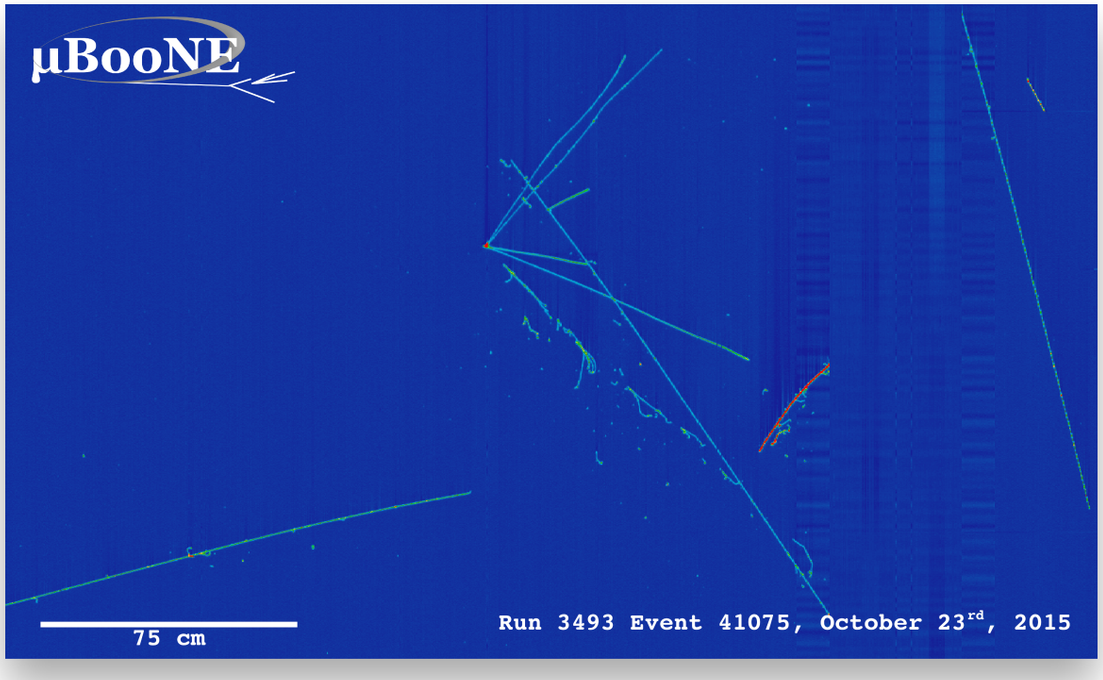
  - ~100k NuMI off-axis events in T600 per year

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

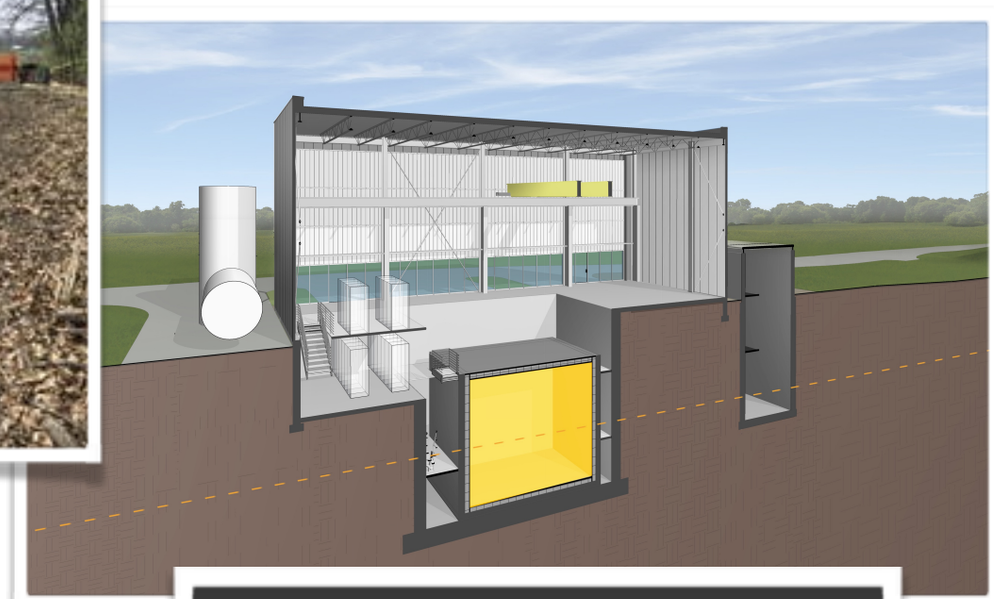


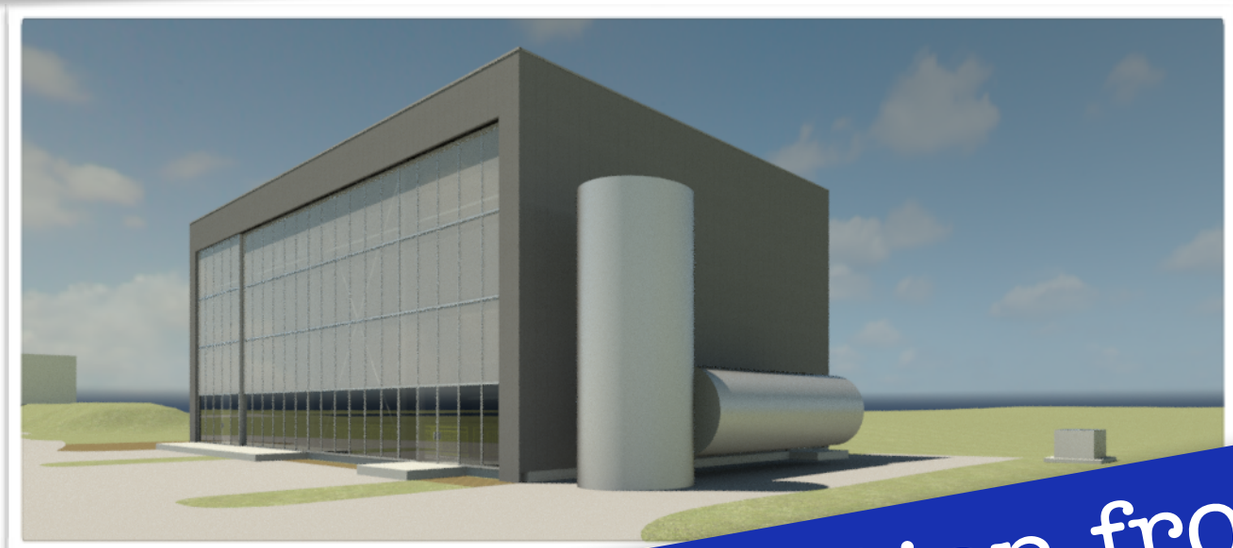
MicroBooNE experiment

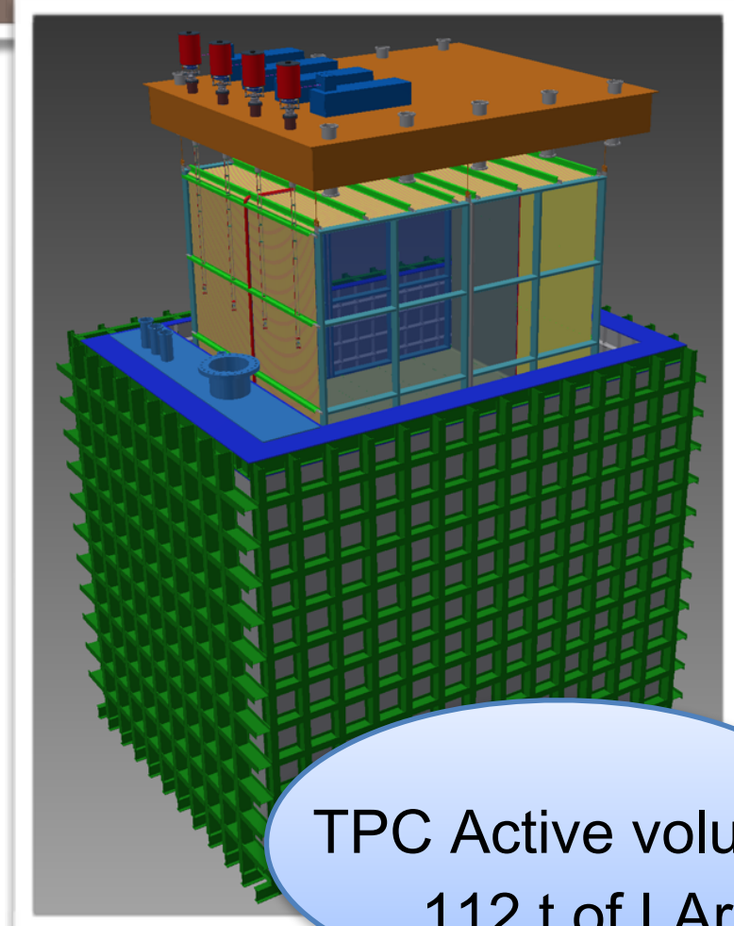


MicroBooNE is taking neutrino data since Oct. 2015

Near Detector: SBND







See presentation from T. Miao

TPC Active volume: 112 t of LAr

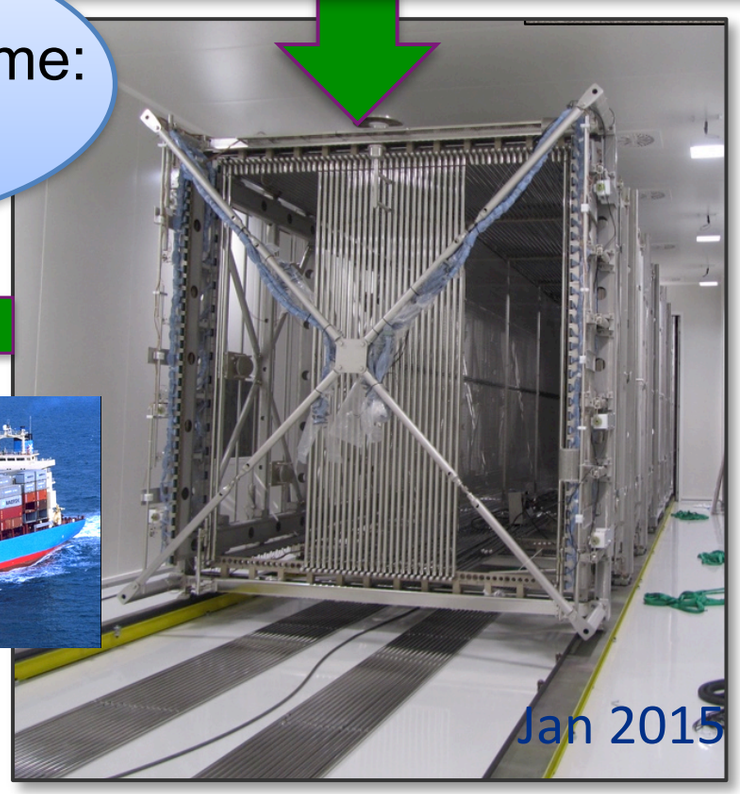
SBND design is in final stages and starting construction

ICARUS: From Gran Sasso to Fermilab via CERN

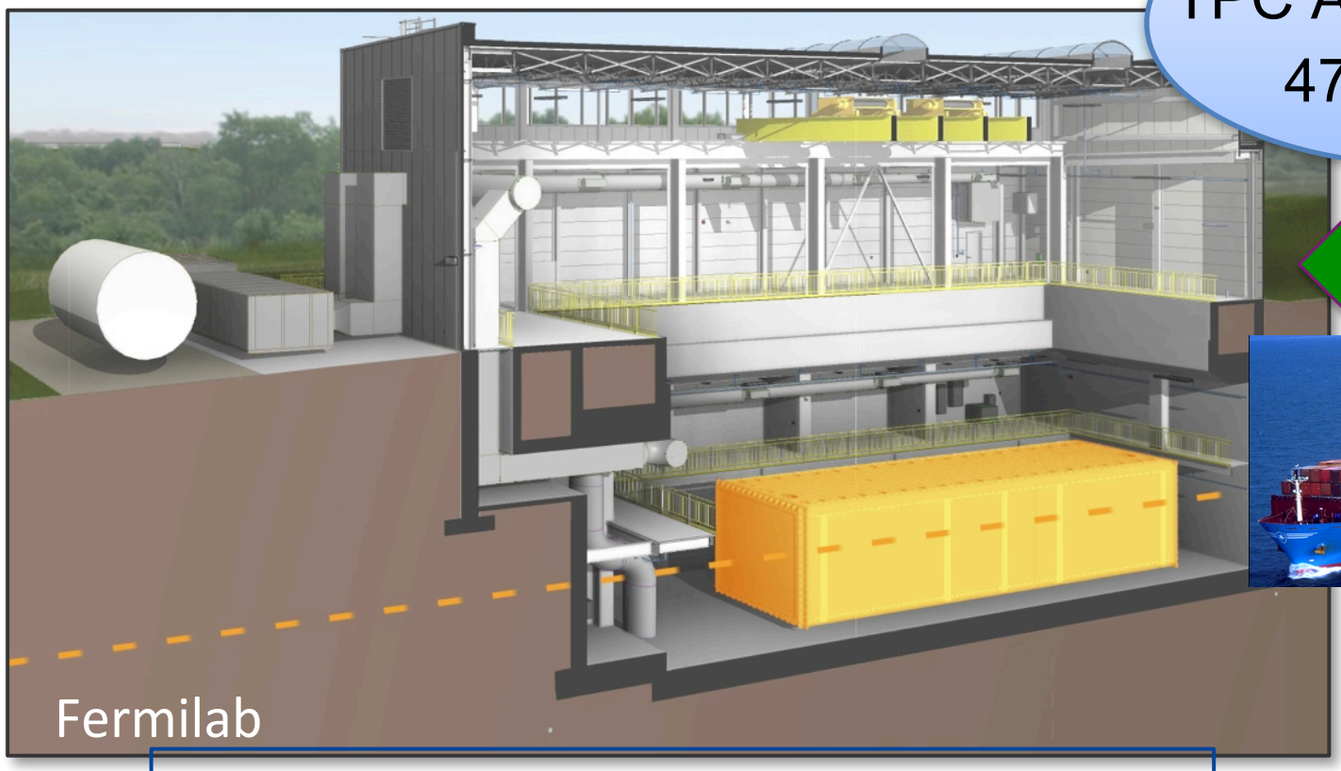
Removing from Gran Sasso

On the road to CERN

TPC Active volume:
475 t of LAr



Early 2017



New building complete late 2016

In Cleanroom @ CERN

SBN: International collaboration

SBN Institutions

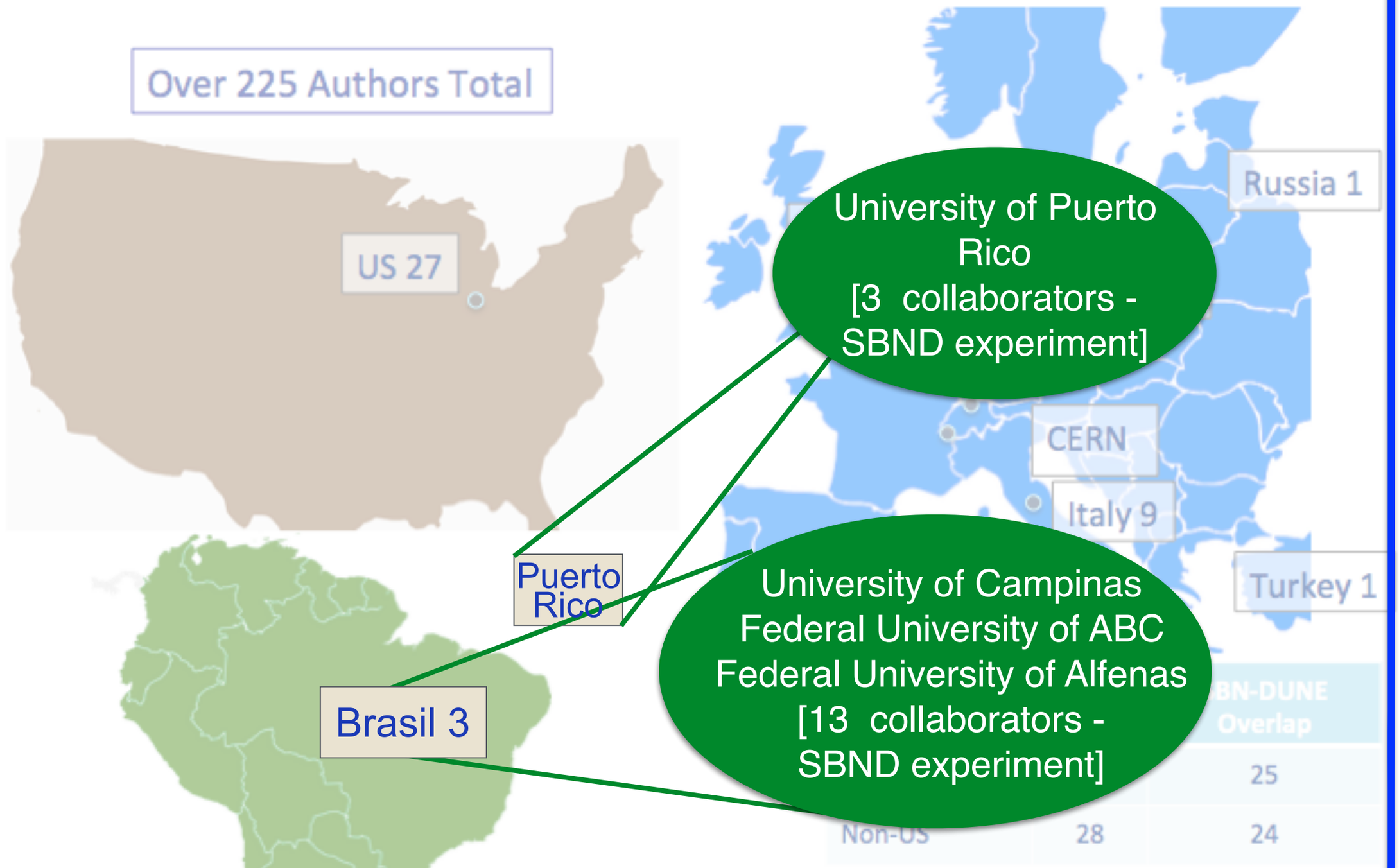
55 institutions, 8 countries
Five U.S. national laboratories plus CERN

Over 225 Authors Total

Institutions	SBN	SBN-DUNE Overlap
US	27	25
Non-US	28	24

SBN: International collaboration

Latin America institutions



SBN: International collaboration

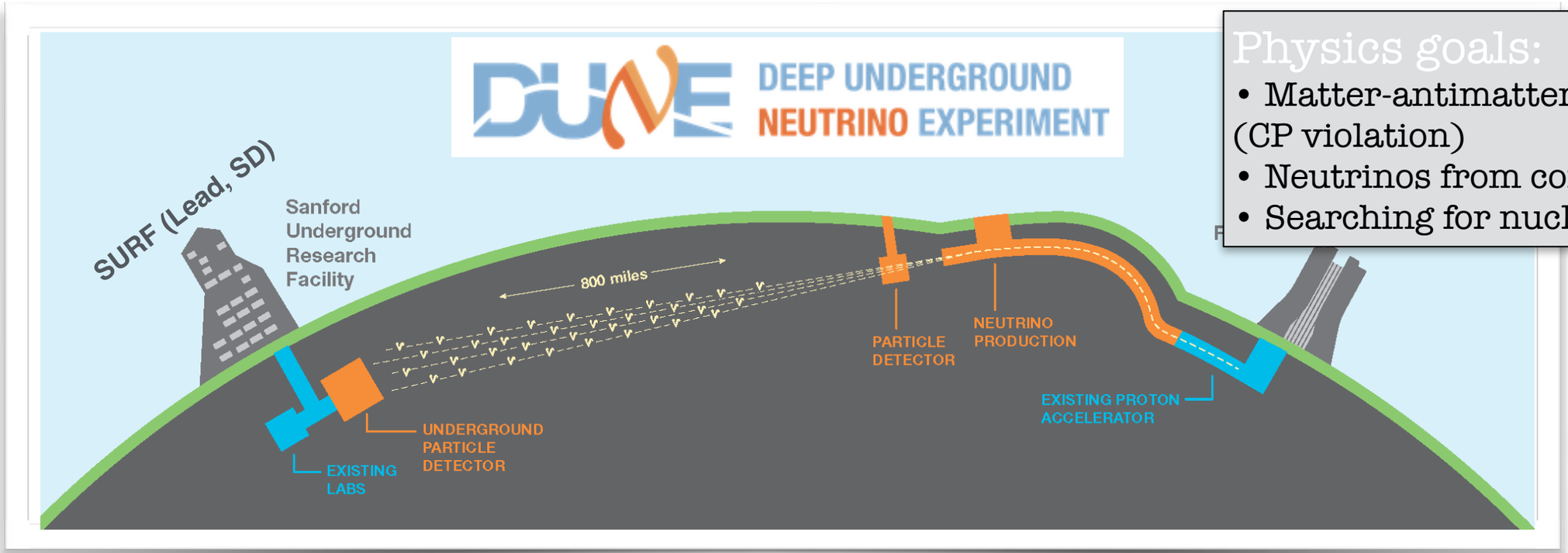
Latin America institutions

Over 225 Authors Total

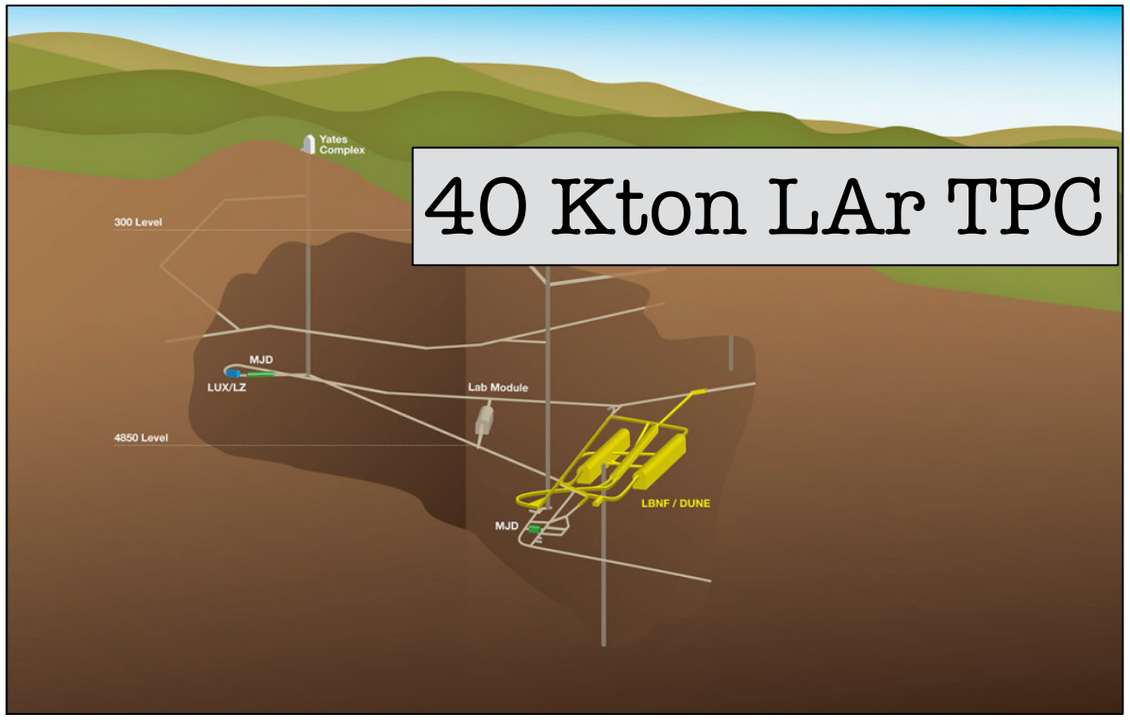
Greater participation by Latin American groups is welcome!

Institutions	SBN	SBN-DUNE Overlap
US	27	25
Non-US	28	24

SBN ties to the Long-Baseline Program



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



- 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 international SBN research program at Fermilab will probe one enduring mystery: Are there only three types of ghostly 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!