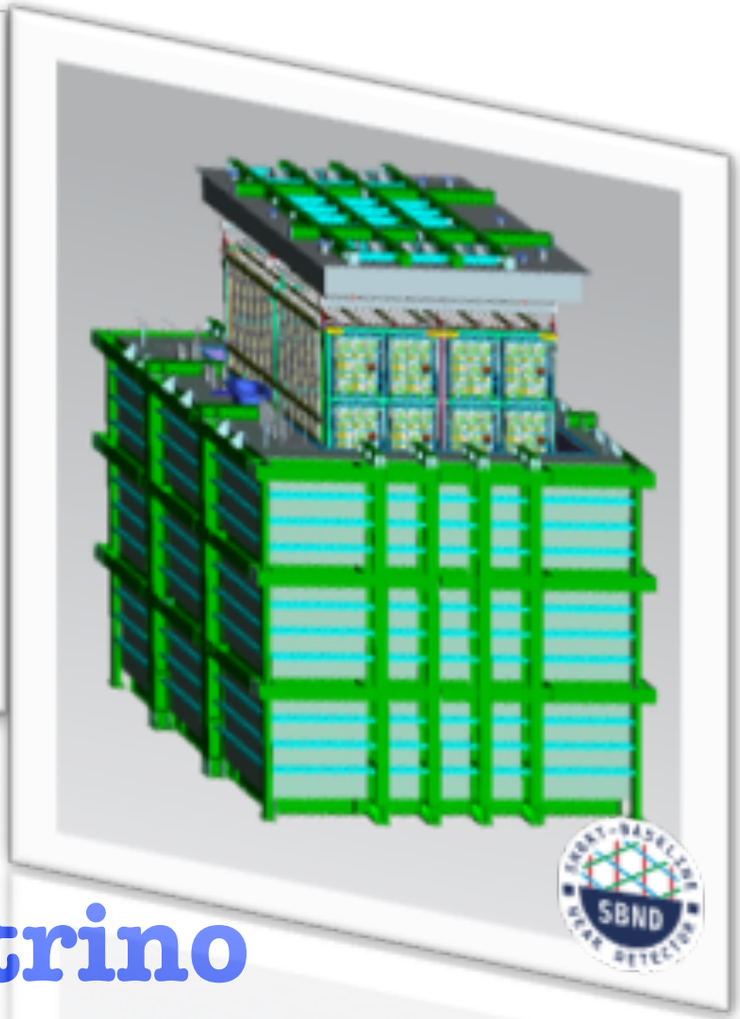


The Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

Erice Workshop on Nuclear Physics
Erice (Italy)
September 18, 2017

Ornella Palamara
Fermilab & Yale University (USA)*

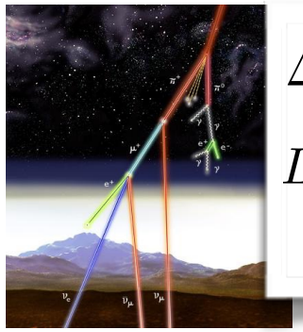
*on leave of absence from INFN, Laboratori Nazionali del Gran Sasso, Italy

Outline

- Why a Short-baseline Accelerator Neutrino program?
  - Oscillation Beyond Three-Neutrino Mixing - Status of Light Sterile Neutrinos
- The Fermilab Short-Baseline Neutrino (SBN) Program
  - Physics reach
  - 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.



$$\Delta m^2_{32} \simeq 2.4 \cdot 10^{-3} eV^2$$

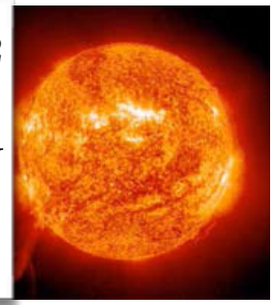
$$L/E = 500 Km/GeV$$

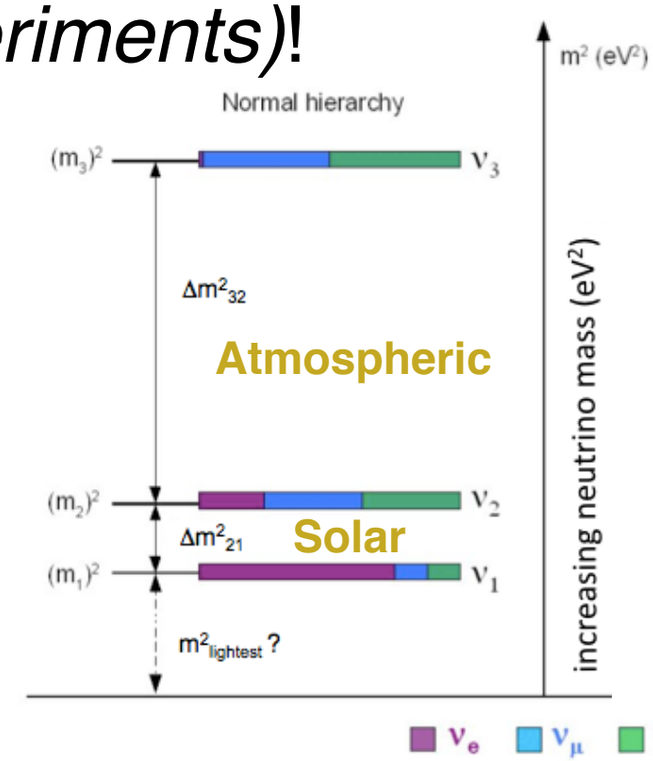
Atmospheric

$$\Delta m^2_{21} \simeq 7.5 \cdot 10^{-5} eV^2$$

$$L/E = 15,000 Km/GeV$$

Solar





- Forthcoming experiments will address many questions related to neutrino properties:
  - What are the masses of the neutrinos?
  - Are neutrinos their own antiparticles?

  } **β and ββ decay experiments**

  - How are the masses ordered (referred as mass hierarchy)?
  - Do neutrinos and antineutrino oscillate differently?
  - Are there additional neutrino types or interactions?

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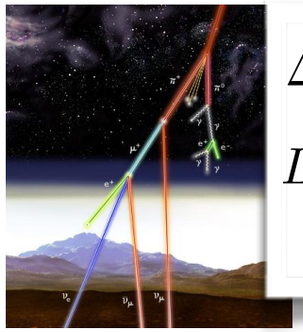

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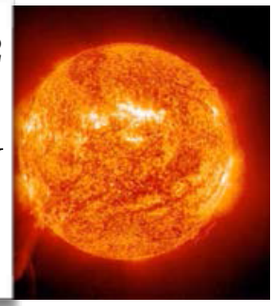

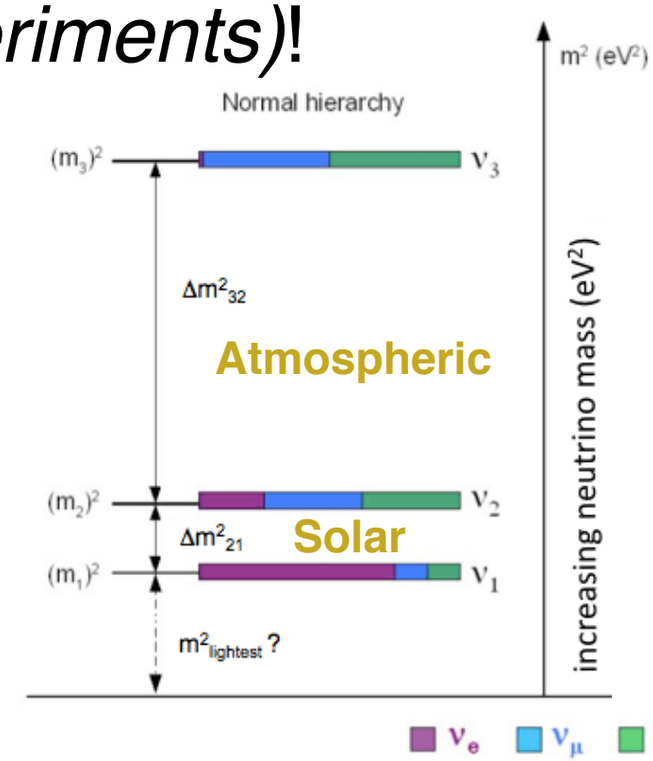

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Accelerator Neutrino Oscillation (Short- and Long-Baseline)

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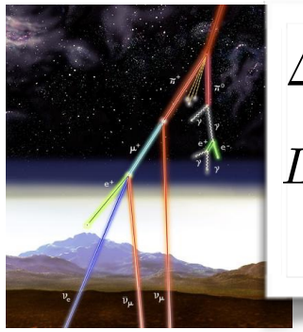

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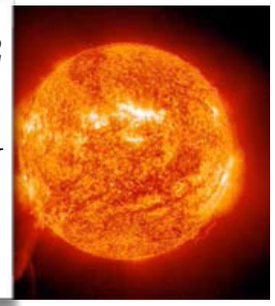

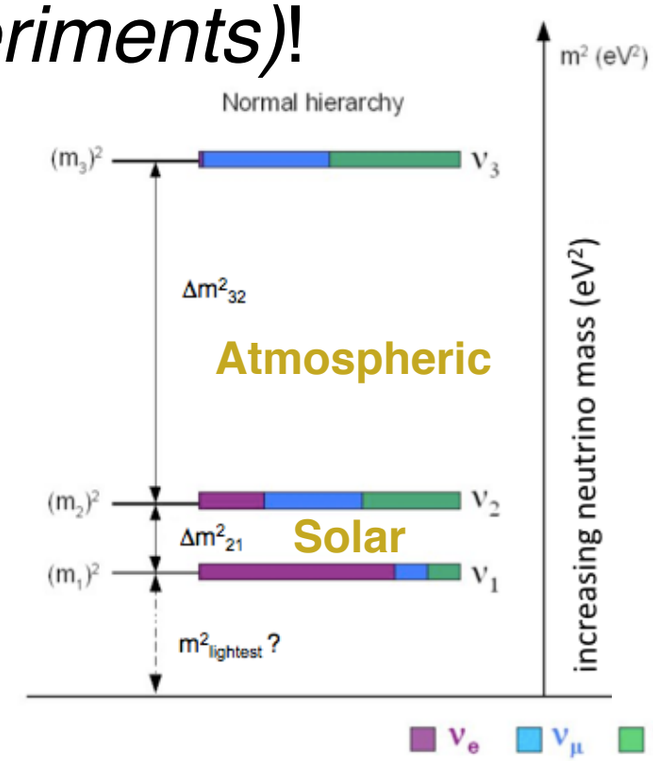

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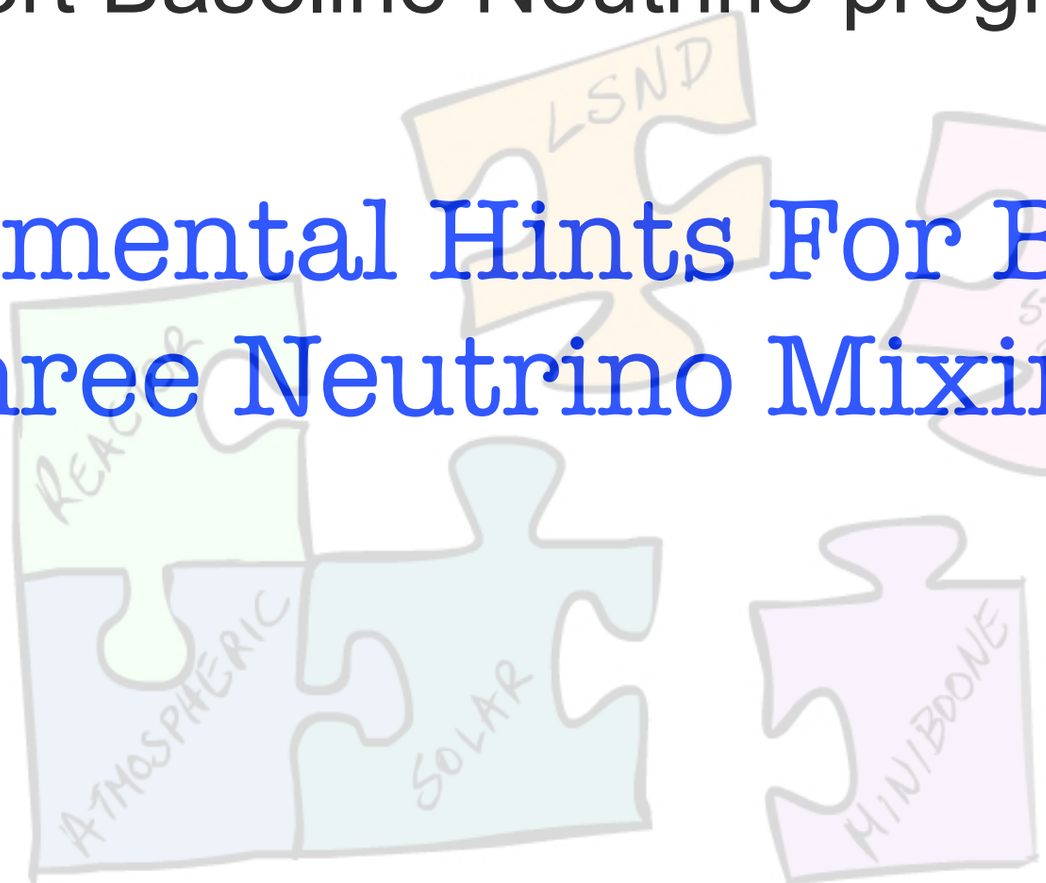
Accelerator Neutrino Oscillation (Short- and Long-Baseline)

Why a Short-baseline accelerator neutrino program?

Physics motivations for a
Short Baseline Neutrino program

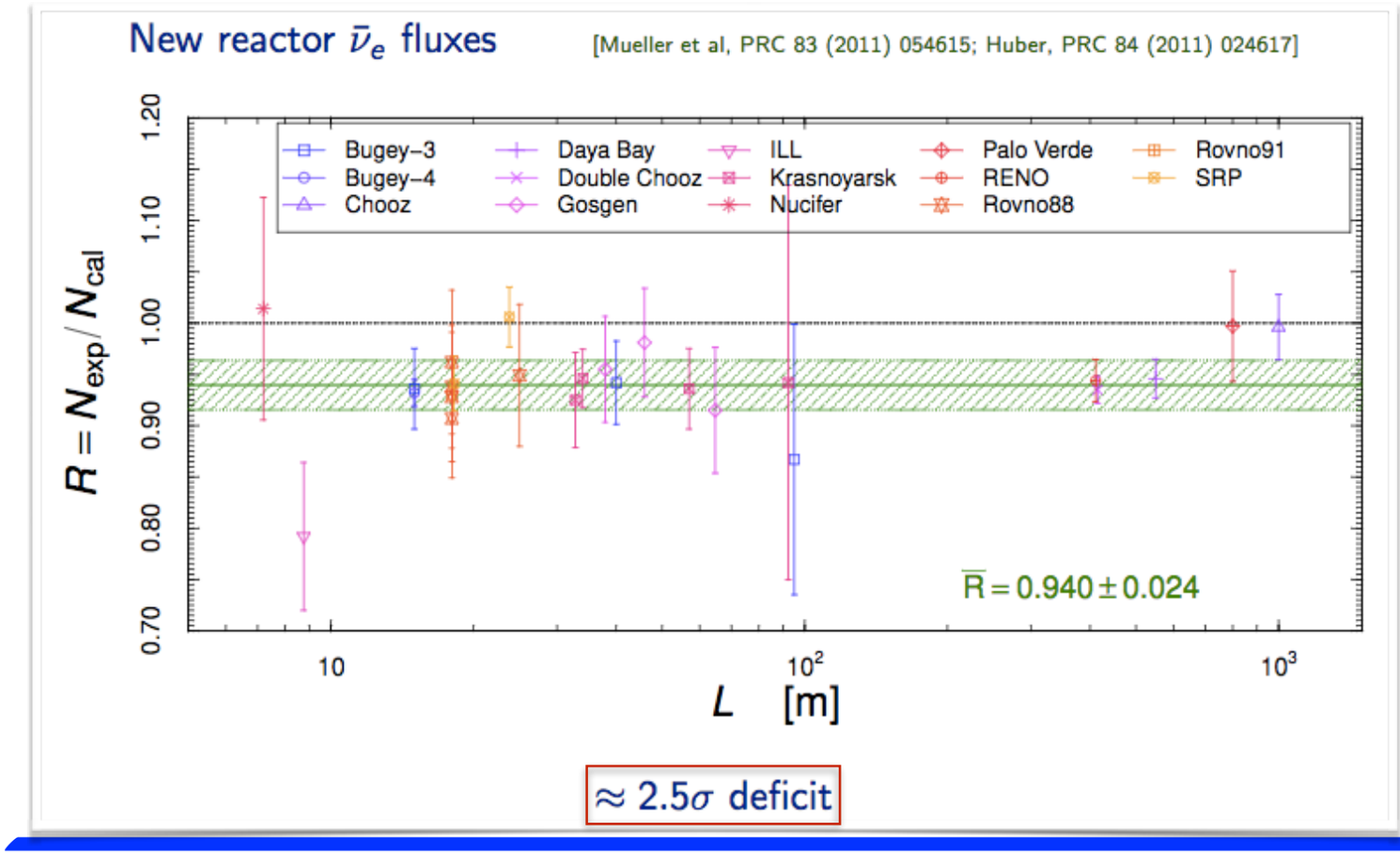
Experimental Hints For Beyond Three Neutrino Mixing

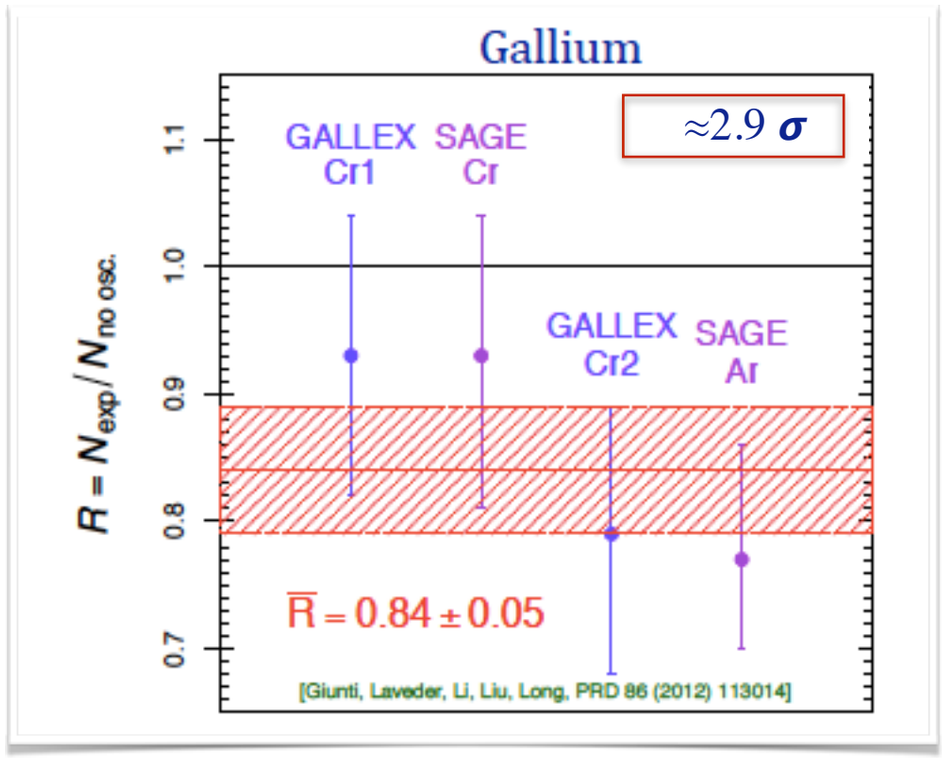


Short-Baseline Neutrino Anomalies (I)

Two classes of experimental "neutrino anomalies" have been reported from measurement at short-baseline:

(I) An apparent $\overline{\nu}_e$ disappearance signal in the low energy neutrinos from nuclear reactors ("reactor anomaly") and from radioactive neutrino sources in the Gallium experiments ("Gallium anomaly")

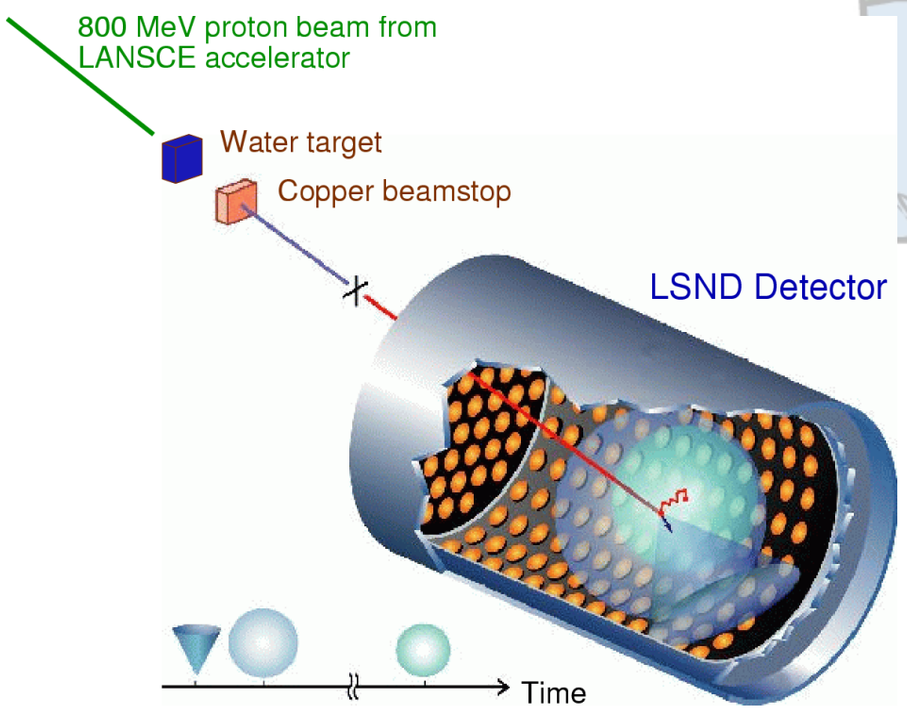




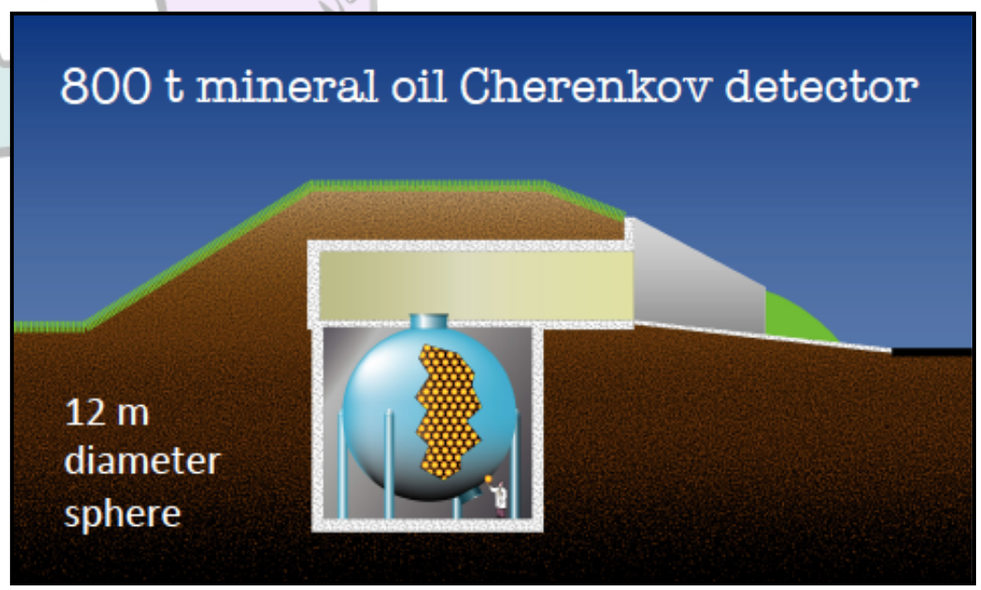
Short-Baseline Neutrino Anomalies (II)

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

LSND



MiniBooNE



Short-Baseline Accelerator Anomalies

LSND

Baseline 30 m

E= [20 – 50] MeV

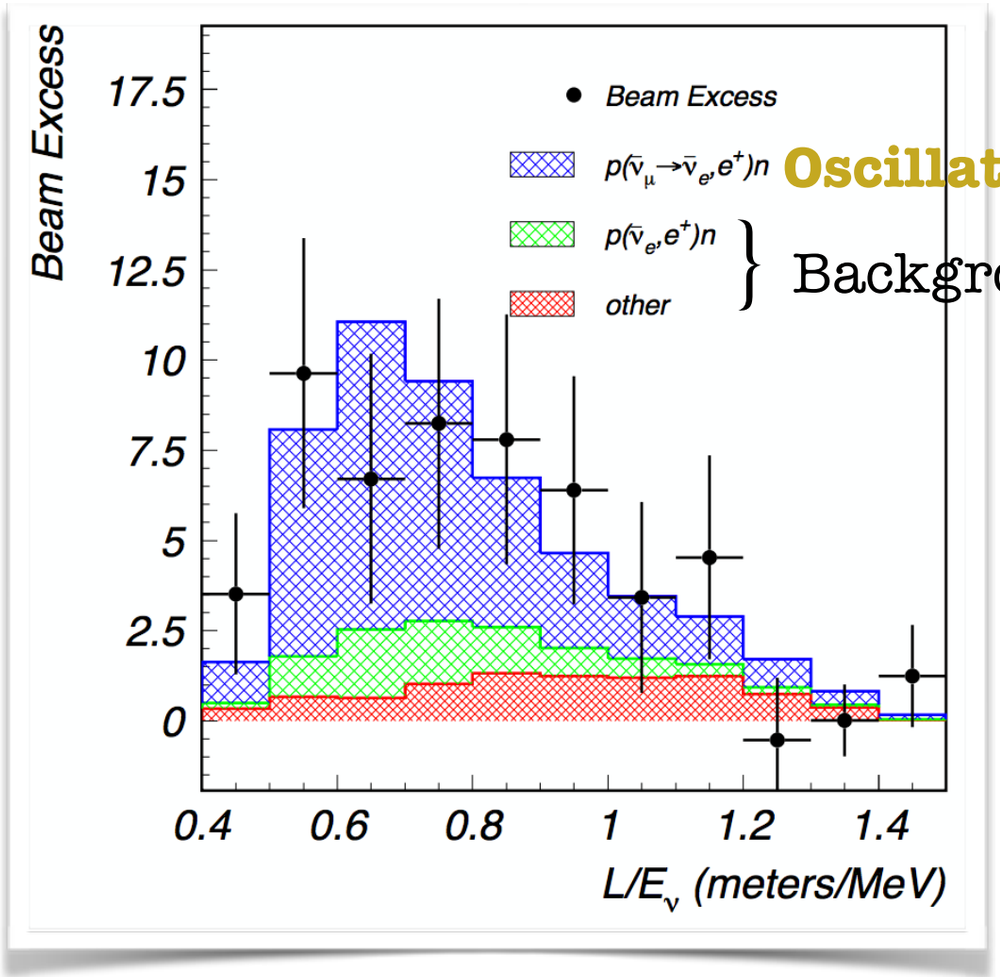
L/E ≈ 1 m/MeV

Most significant experimental hint of new physics comes from LSND

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?

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

Short-Baseline Accelerator Anomalies

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

MiniBooNE

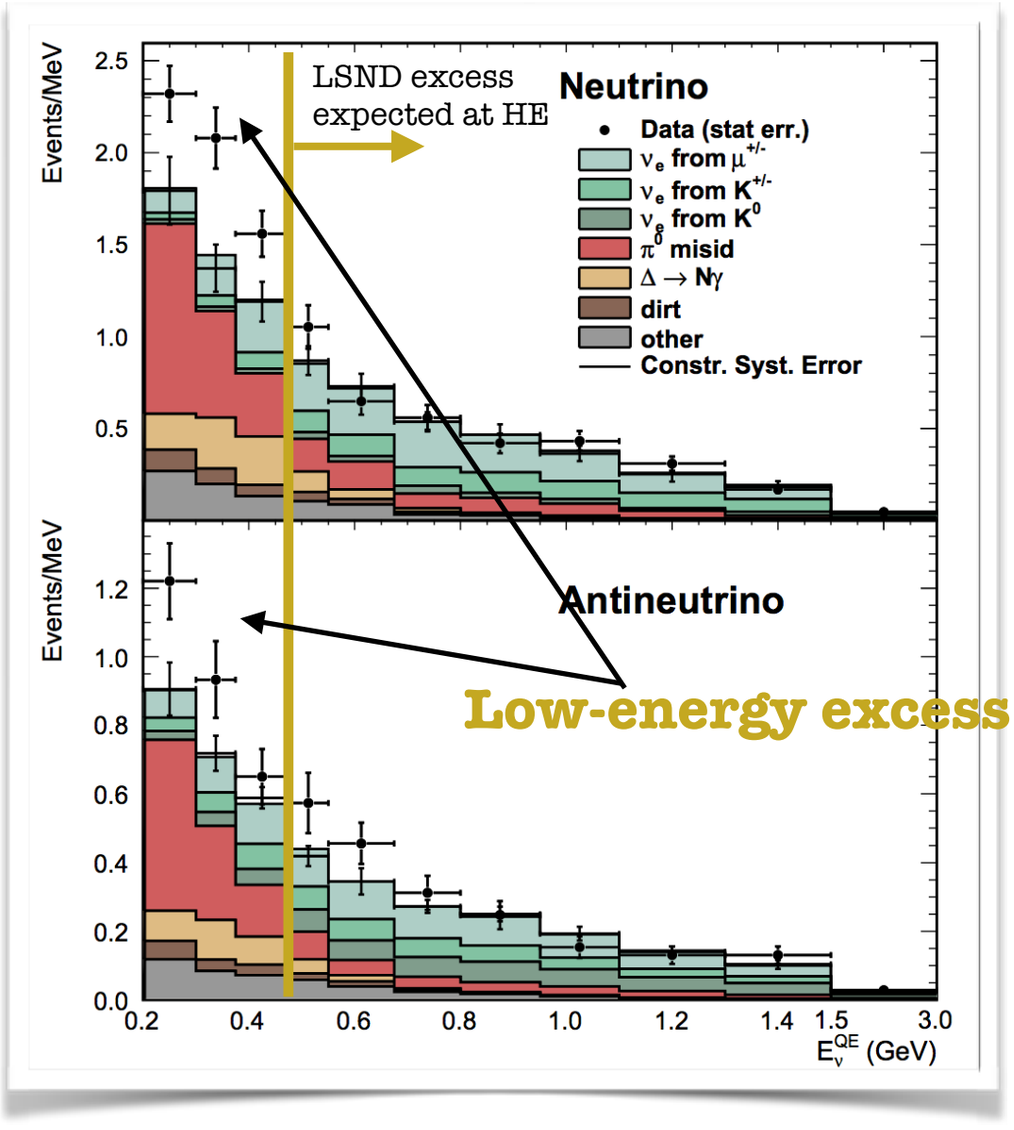
Baseline 540 m

E=[0 - 2] GeV

L/E ≈ 1 m/MeV

800 tons mineral oil

PRL 110 (2013) 161801



Short-Baseline Accelerator Anomalies

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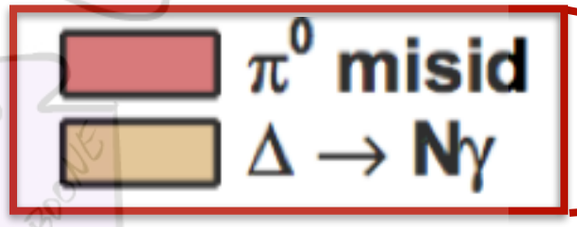
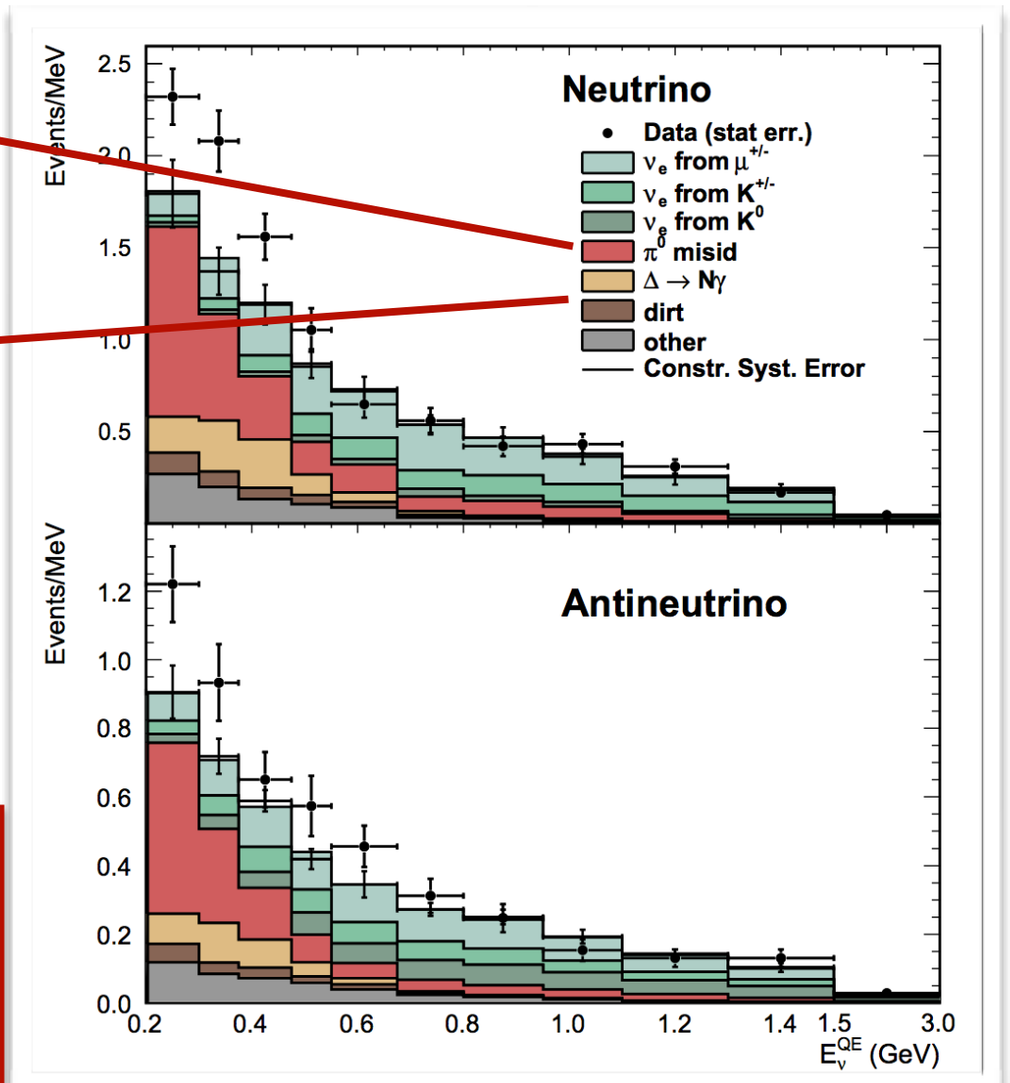
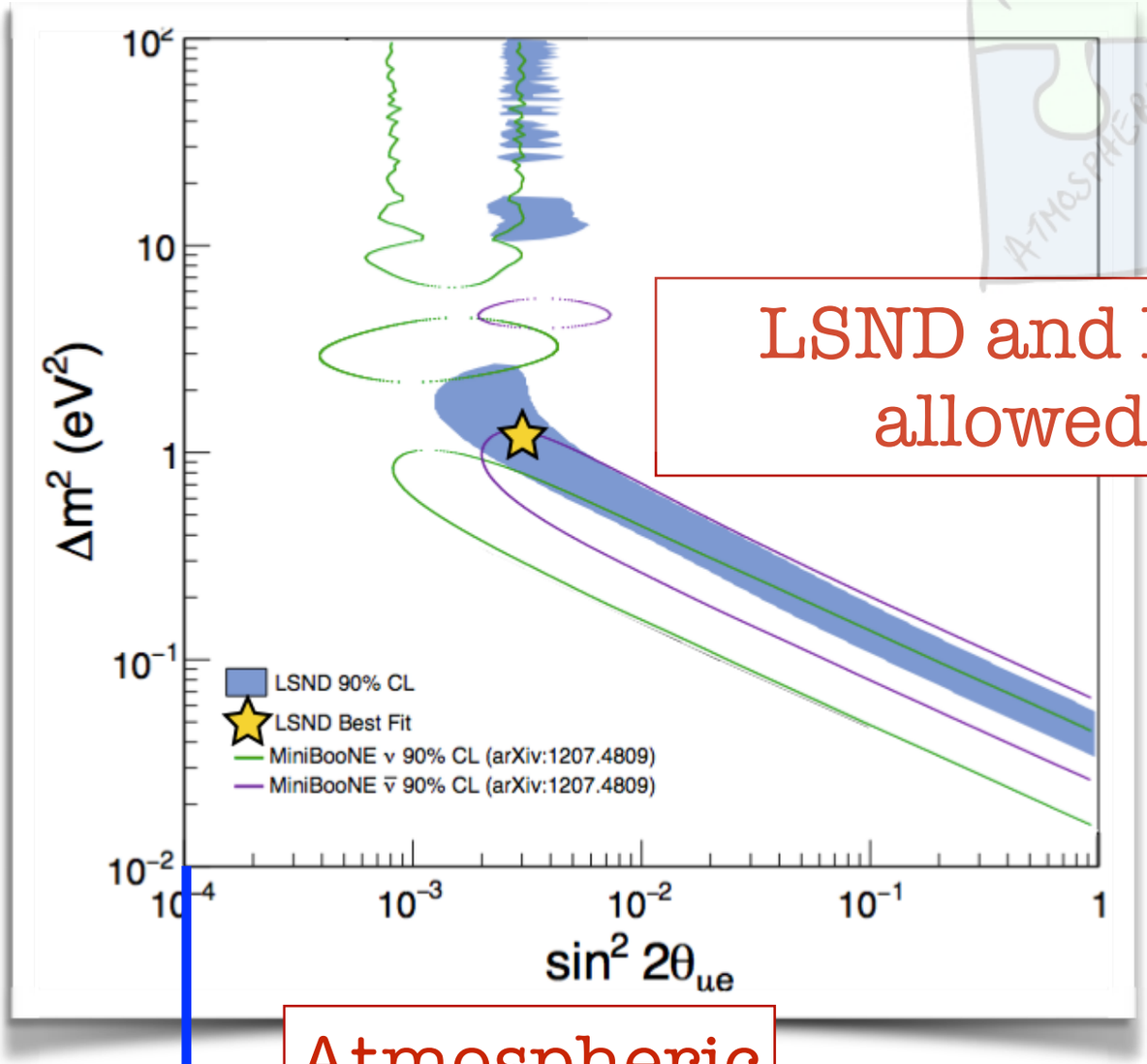




MiniBooNE (Cherenkov detector) cannot distinguish electron from single gamma and cannot determine the composition of the excess

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

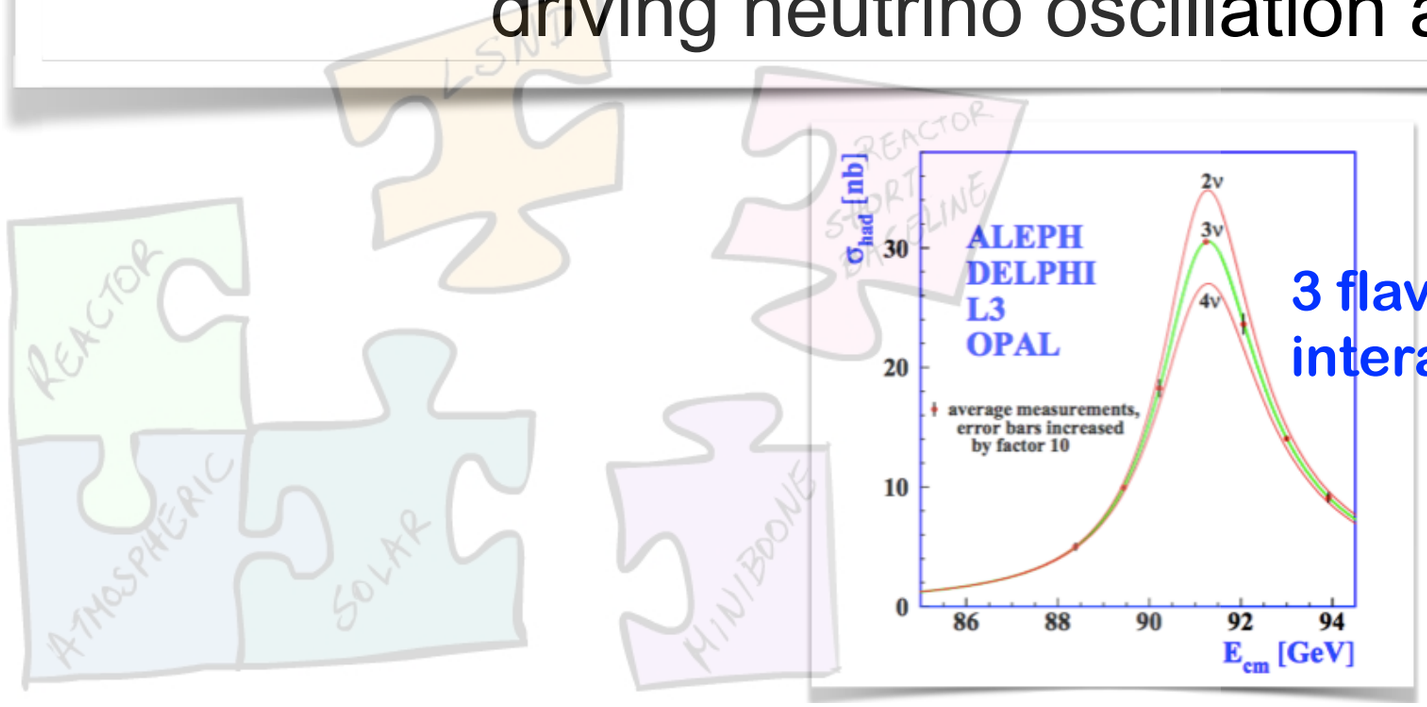
10^{-3} Atmospheric

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"**

Hints at new physics

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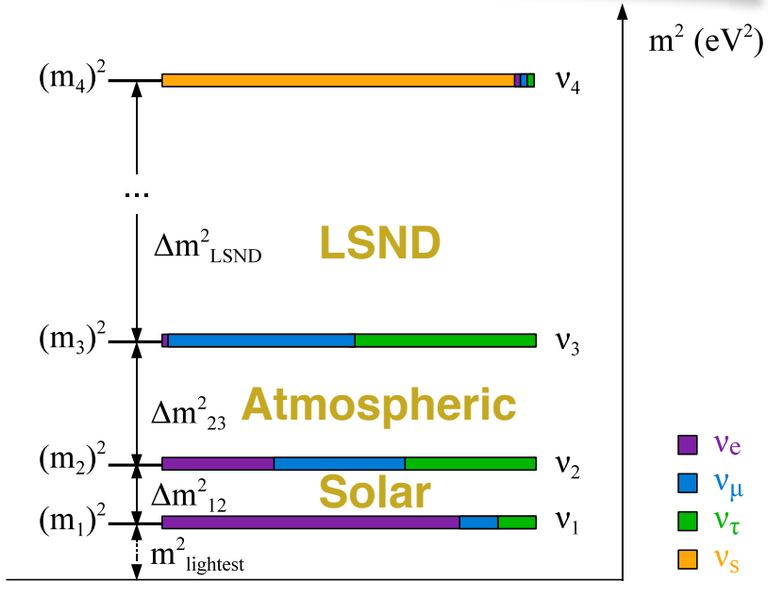
Minimal model

- a "3+1" neutrino mixing (minimal modification of the standard three-neutrino scheme)
- the new sterile neutrino would be mainly composed by a heavy neutrino ν_4 such that the new $\Delta m^2 = \Delta m^2_{41} \simeq [0.1 - 10] eV^2$ and $m_1, m_2, m_3 \ll m_4$



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Constraints on sterile neutrino mixing from ν_μ **disappearance** data (no hints of ν_μ disappearance in the $\Delta m^2 \sim 1$ eV^2 region):

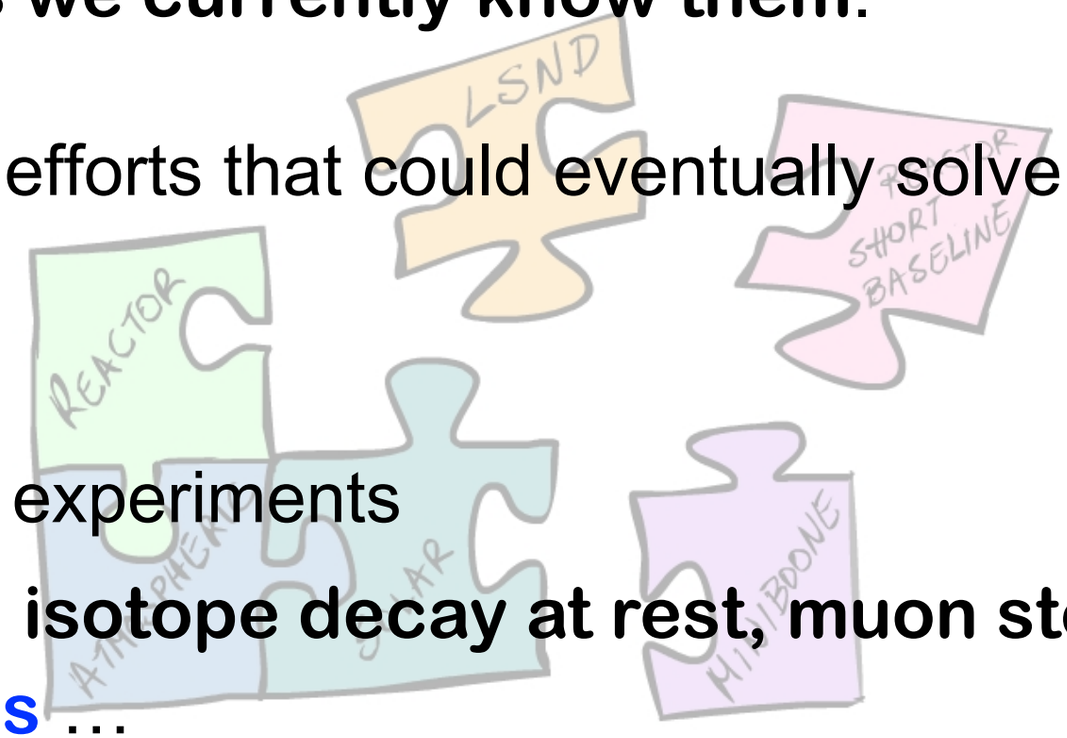
- Tension when combined with appearance data
- Some global analyses are performed including **more than one active sterile neutrino**.

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

Probing hints at new physics

- Data from previous experiments suggest that there might be a **fourth kind** of neutrino that **may not follow the rules of neutrino oscillations** and **interactions with matter as we currently know them**.

- Ongoing and future experimental efforts that could eventually solve this **puzzle** use different approaches:
  - **Reactor** experiments
  - **Intense radioactive sources** experiments
  - **Pion and kaon decay at rest, isotope decay at rest, muon storage ring, decay in flight neutrinos …**

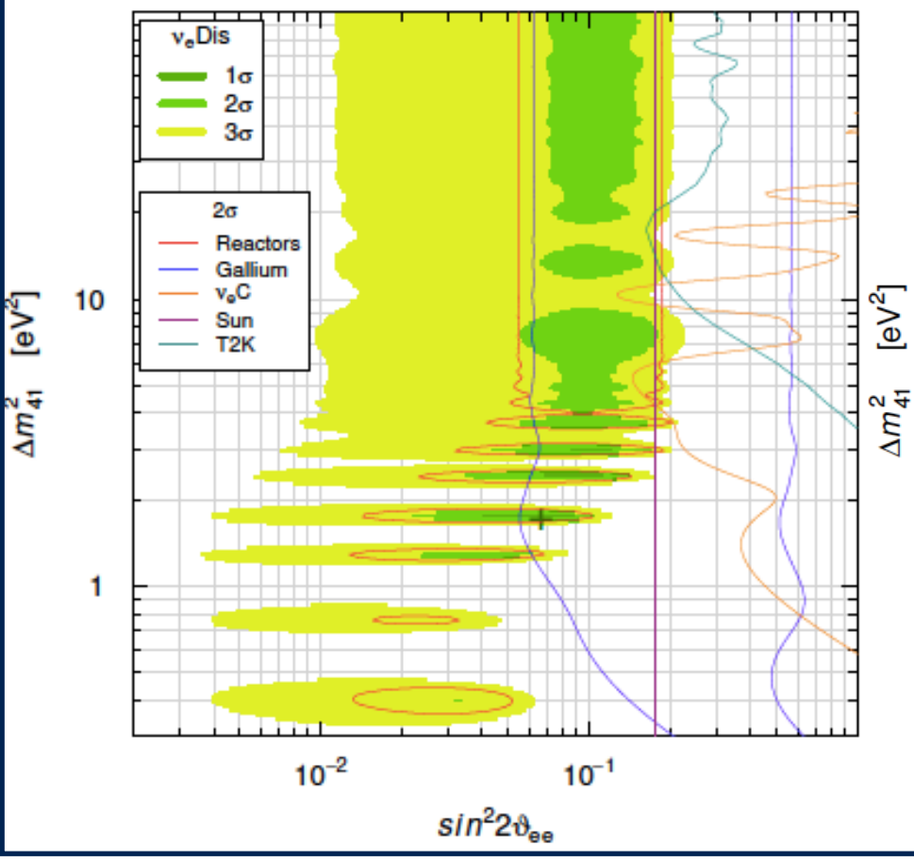


"Given the potential implications [and challenges] of sterile neutrinos, it is important to confirm their existence in multiple (preferably orthogonal) approaches."
Light Sterile Neutrinos: A White Paper (arXiv:1204.5379)

Global Analysis of Short-baseline Neutrino Current Exclusion Limits

S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, arXiv:1703.00860
"Updated Global 3+1 Analysis of Short-BaseLine Neutrino Oscillations"

$\nu_e \to \nu_e$ and $\bar{\nu}_e \to \bar{\nu}_e$
(ν_e disappearance)



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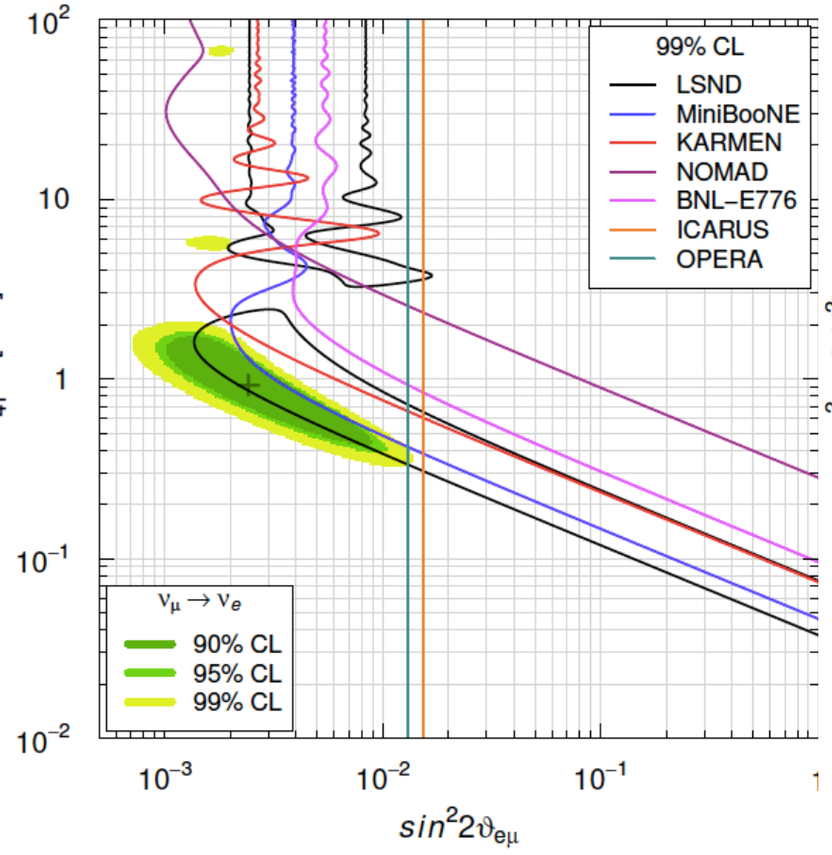

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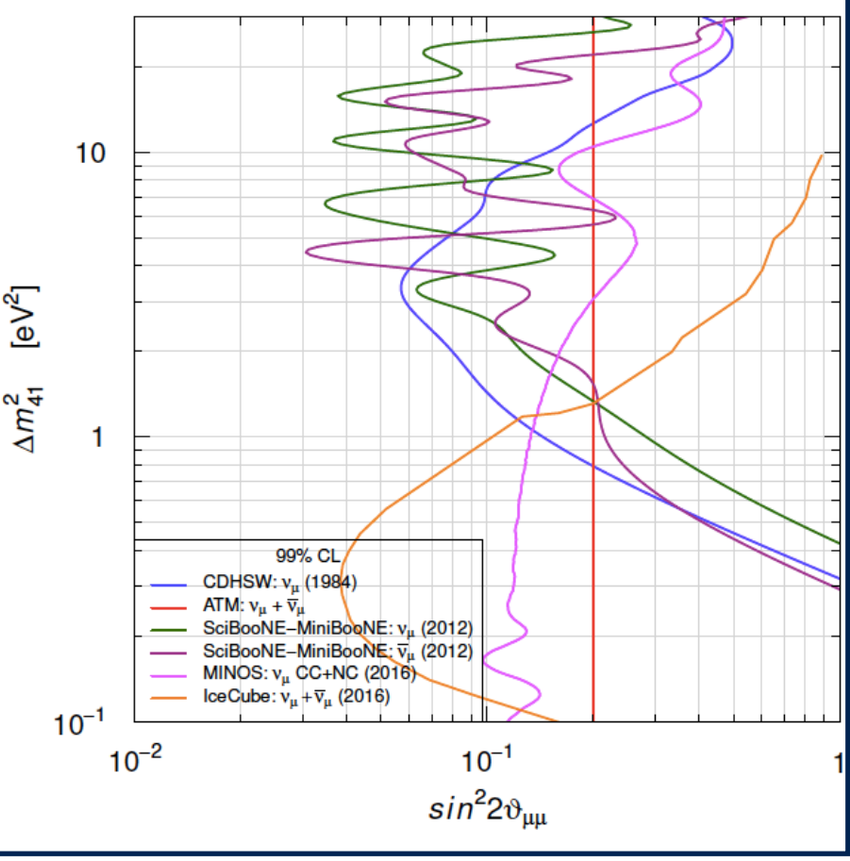

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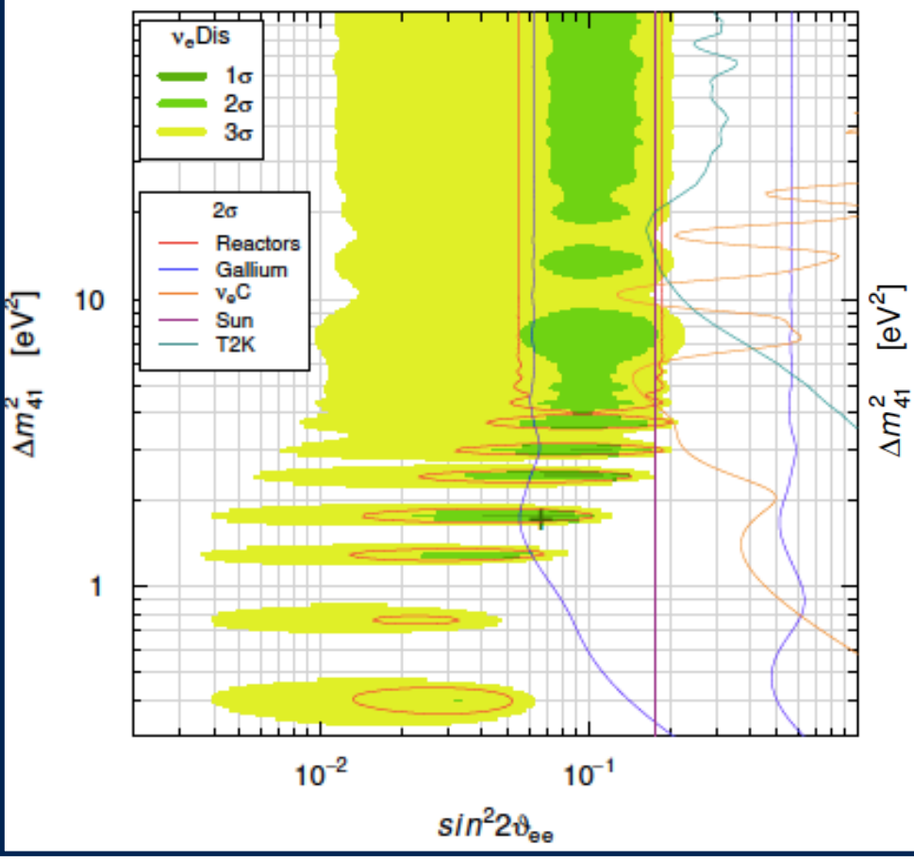

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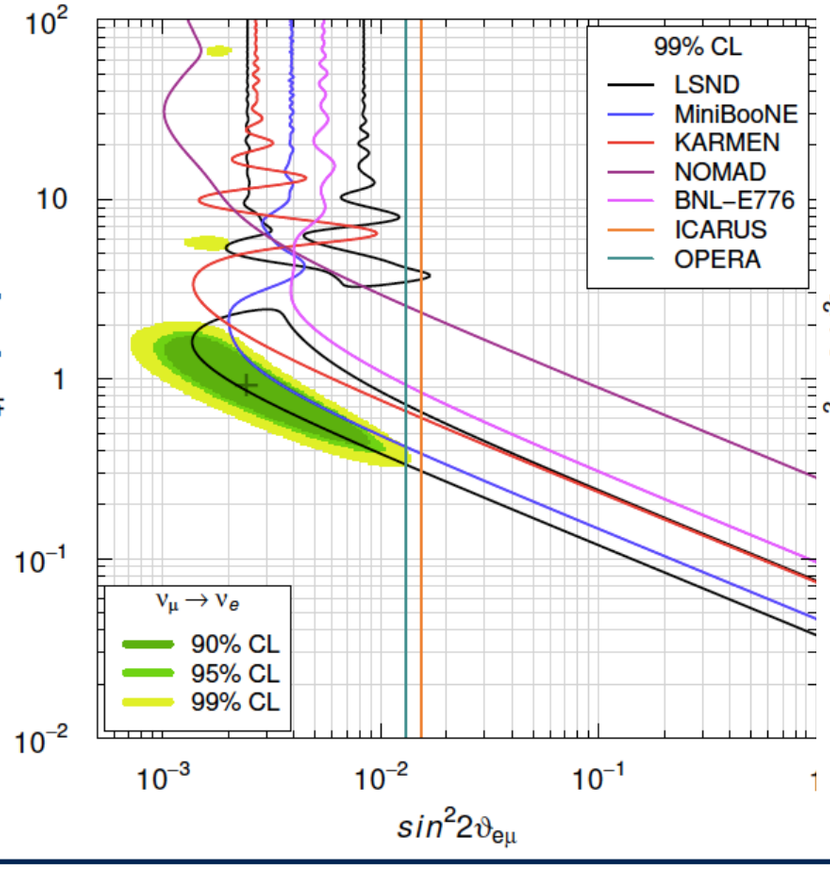

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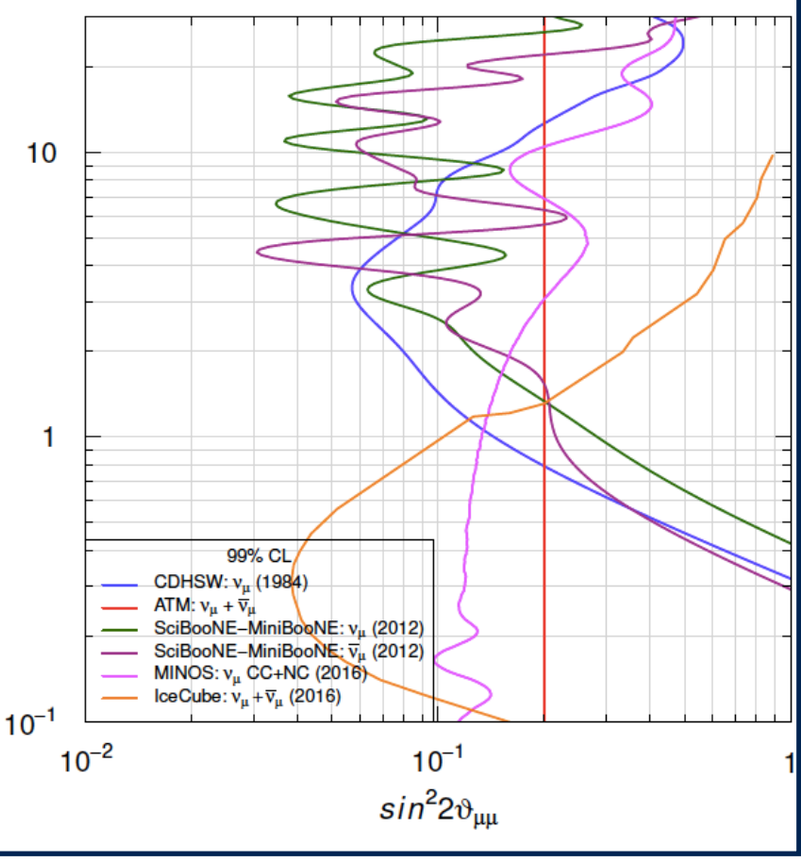
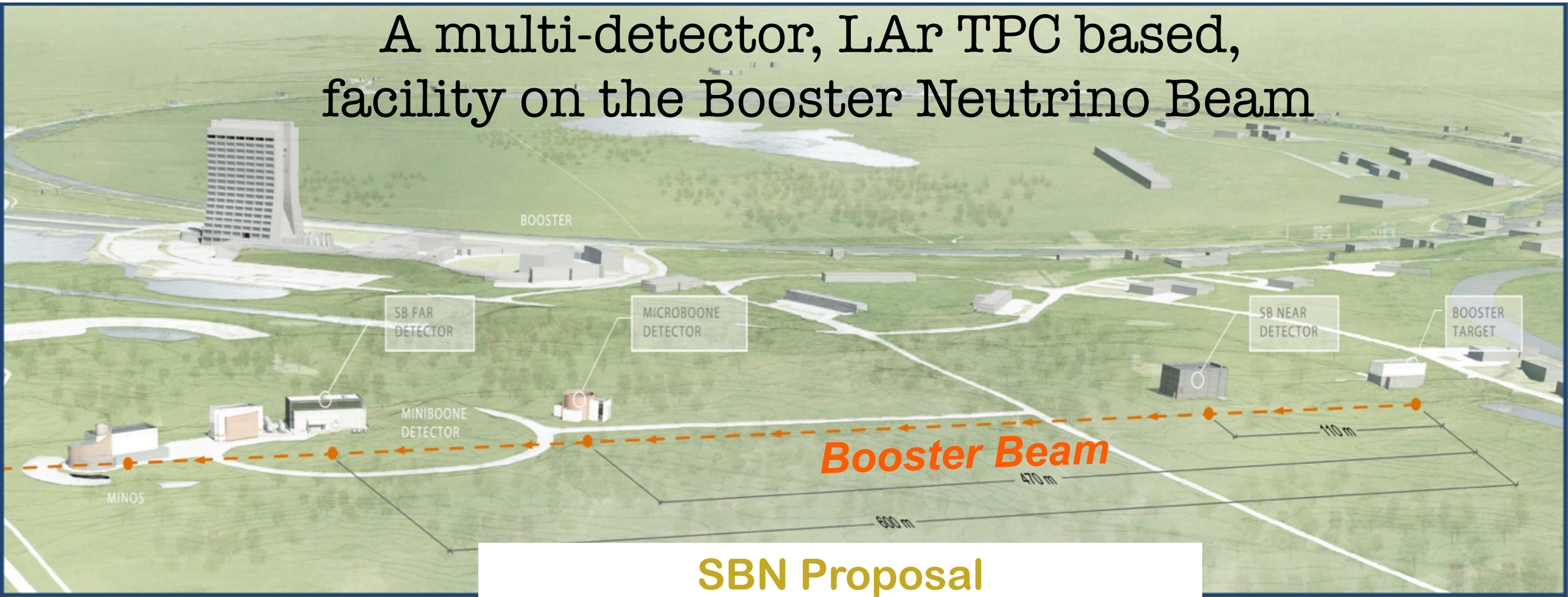


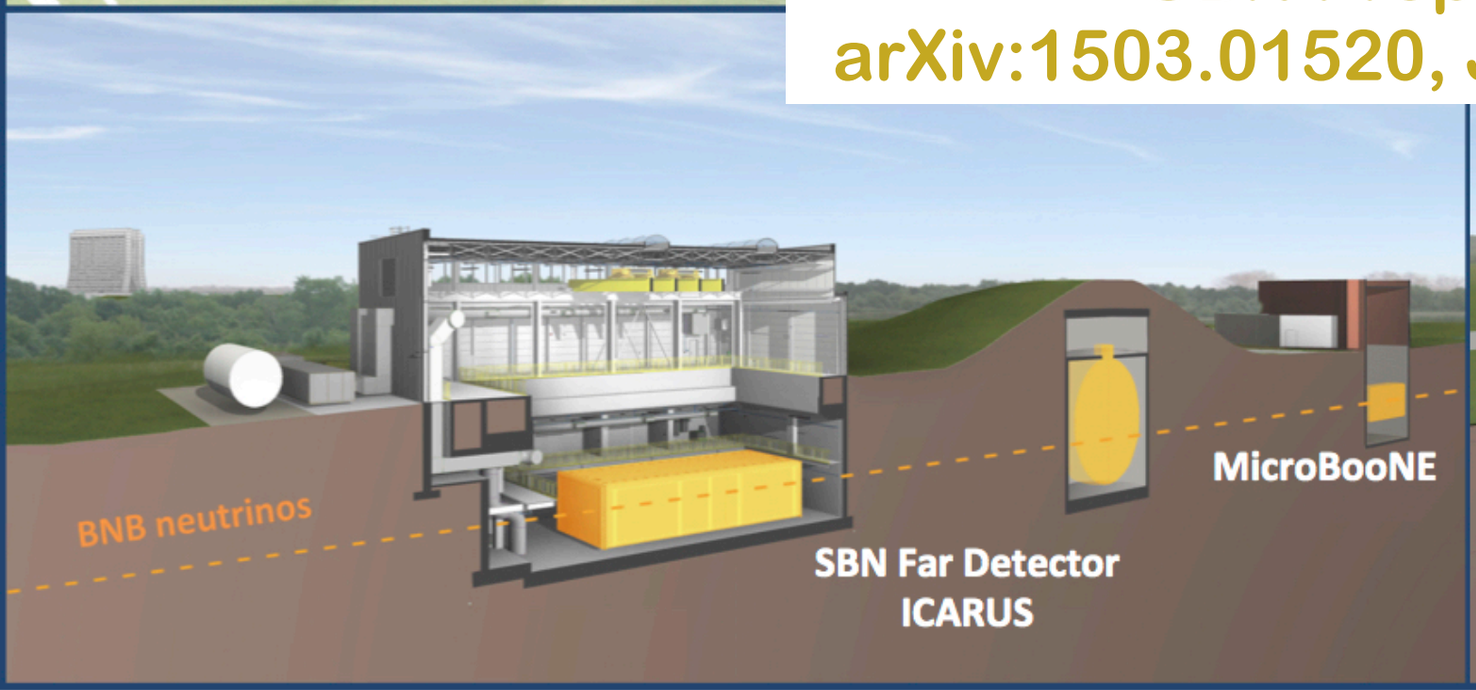
- Recent measurements, especially from **NEOS, IceCube and MINOS** experiments, have constrained the possible sterile neutrino parameters significantly (see later)
- Only a small region of mass-squared values remains compatible with all of the available data

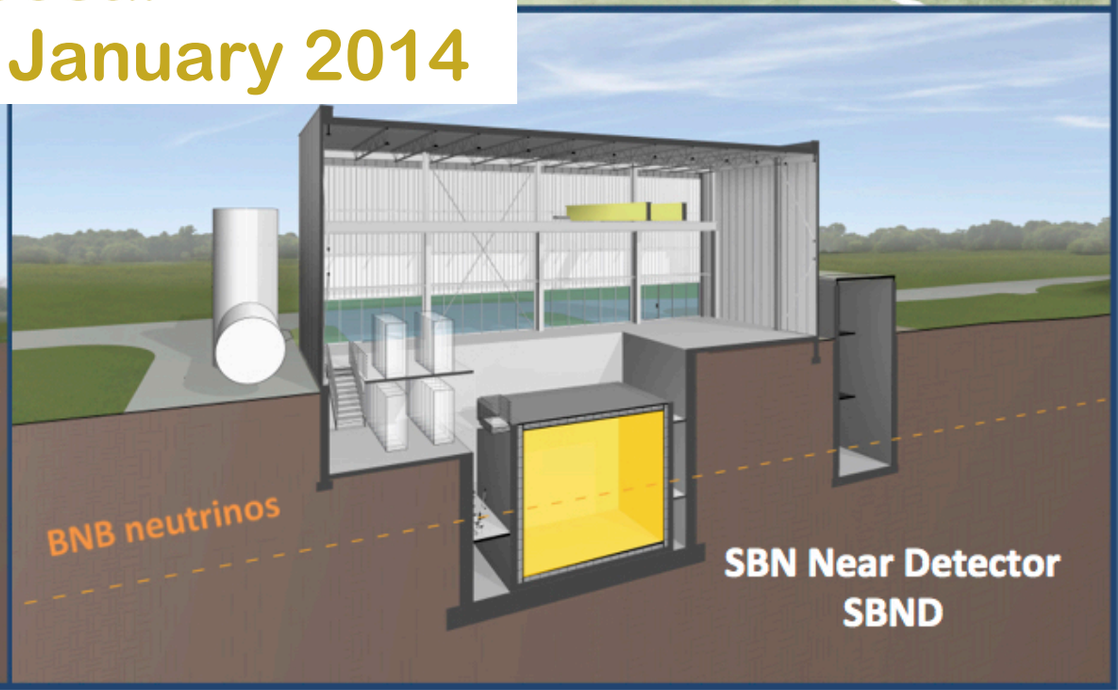
FNAL Short Baseline Neutrino program

A multi-detector, LAr TPC based, facility on the Booster Neutrino Beam



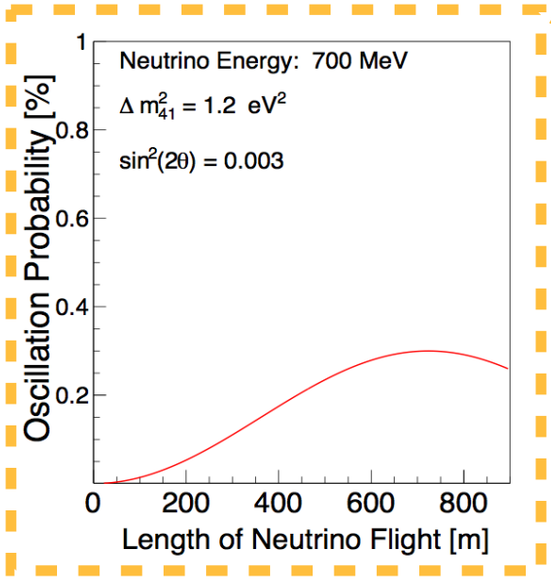
SBN Proposal
arXiv:1503.01520, January 2014

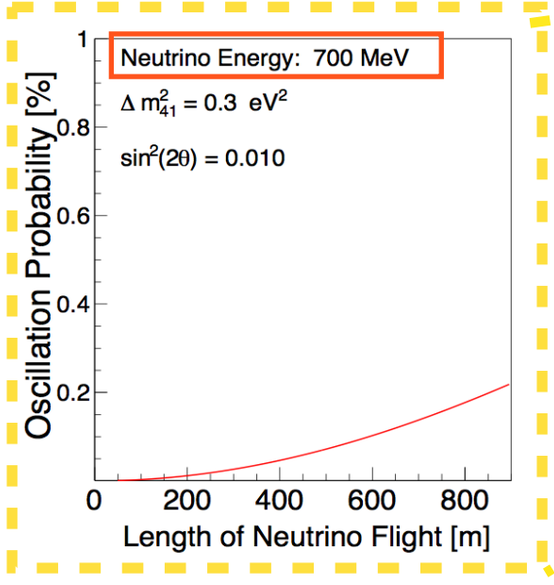


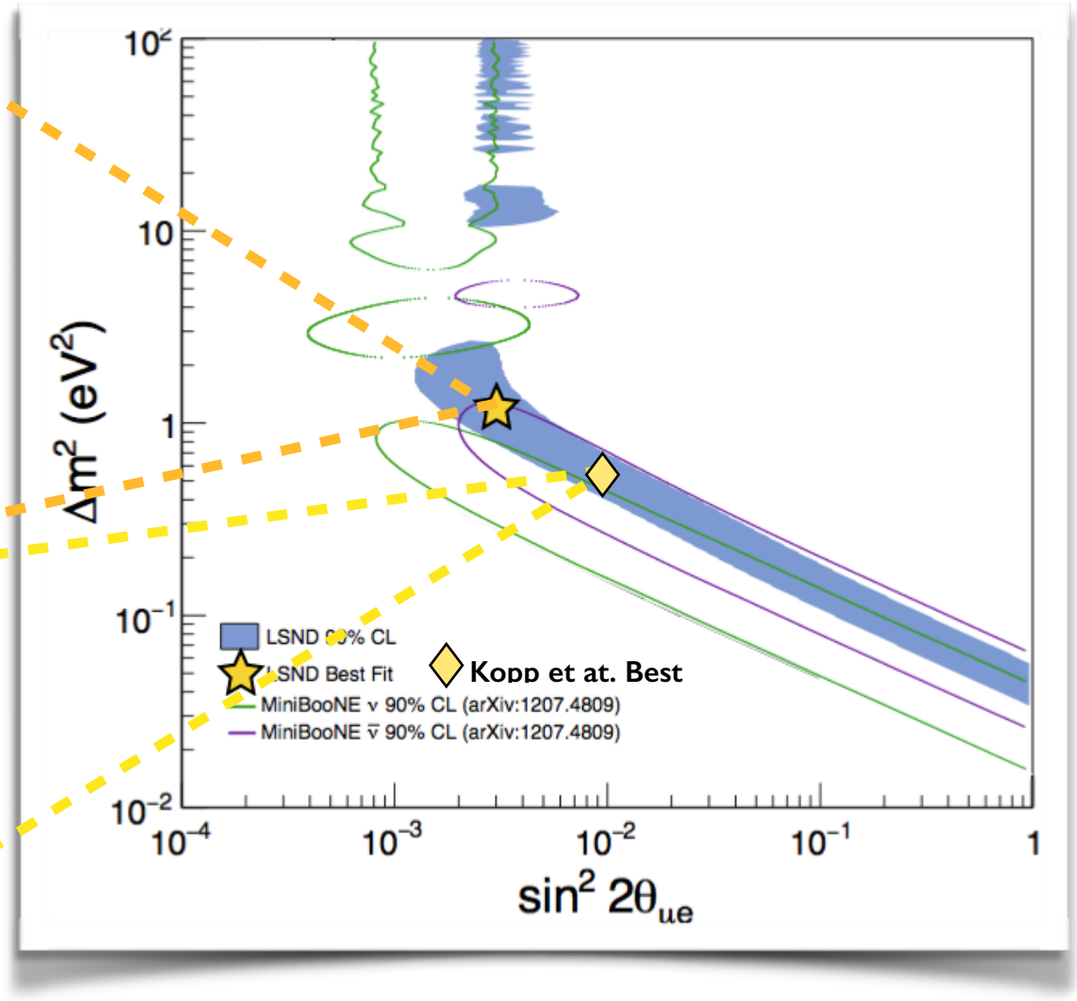


Sterile Neutrino Search at FNAL

- 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

Fermilab – aerial view

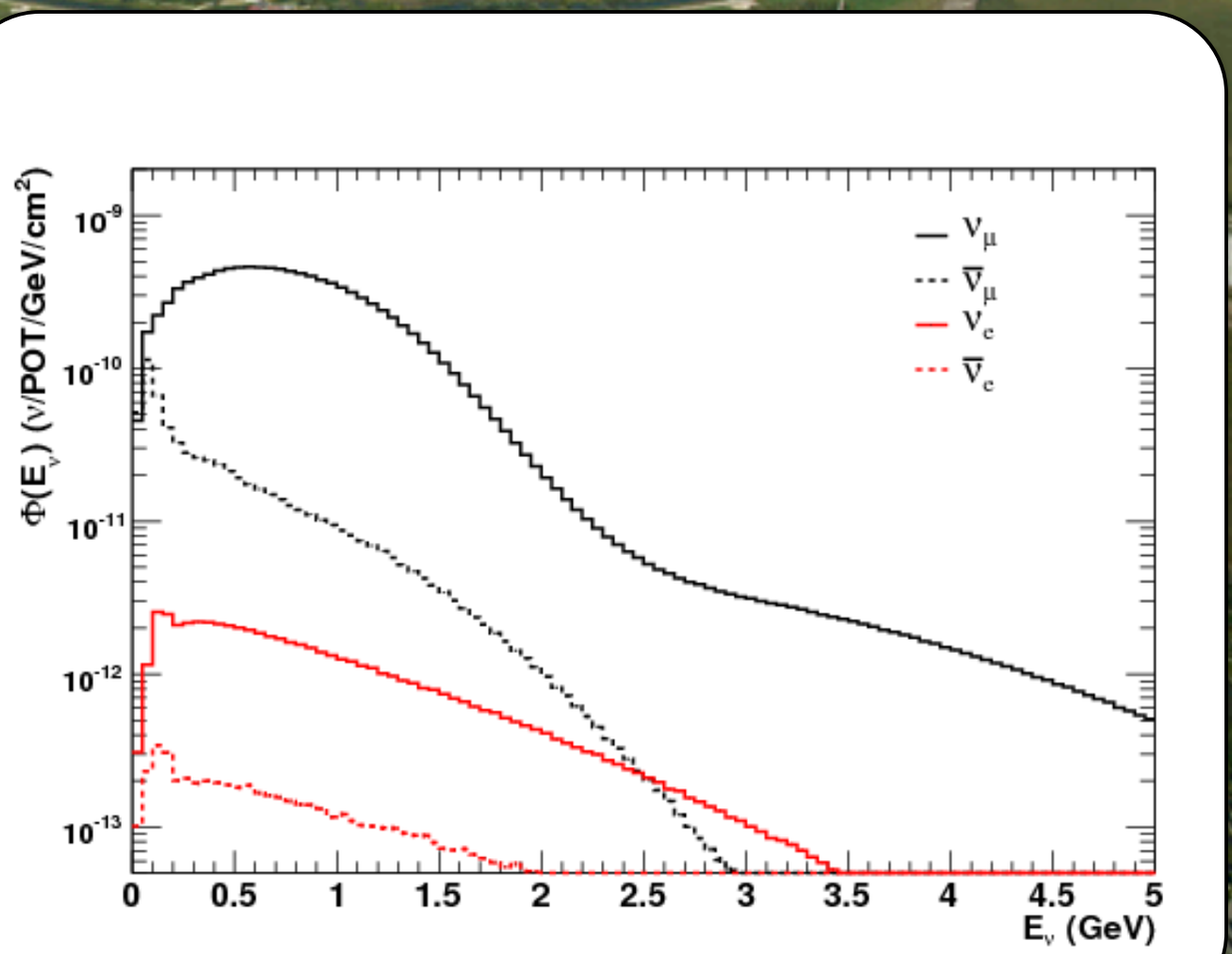
Fermilab – Neutrino beams

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)

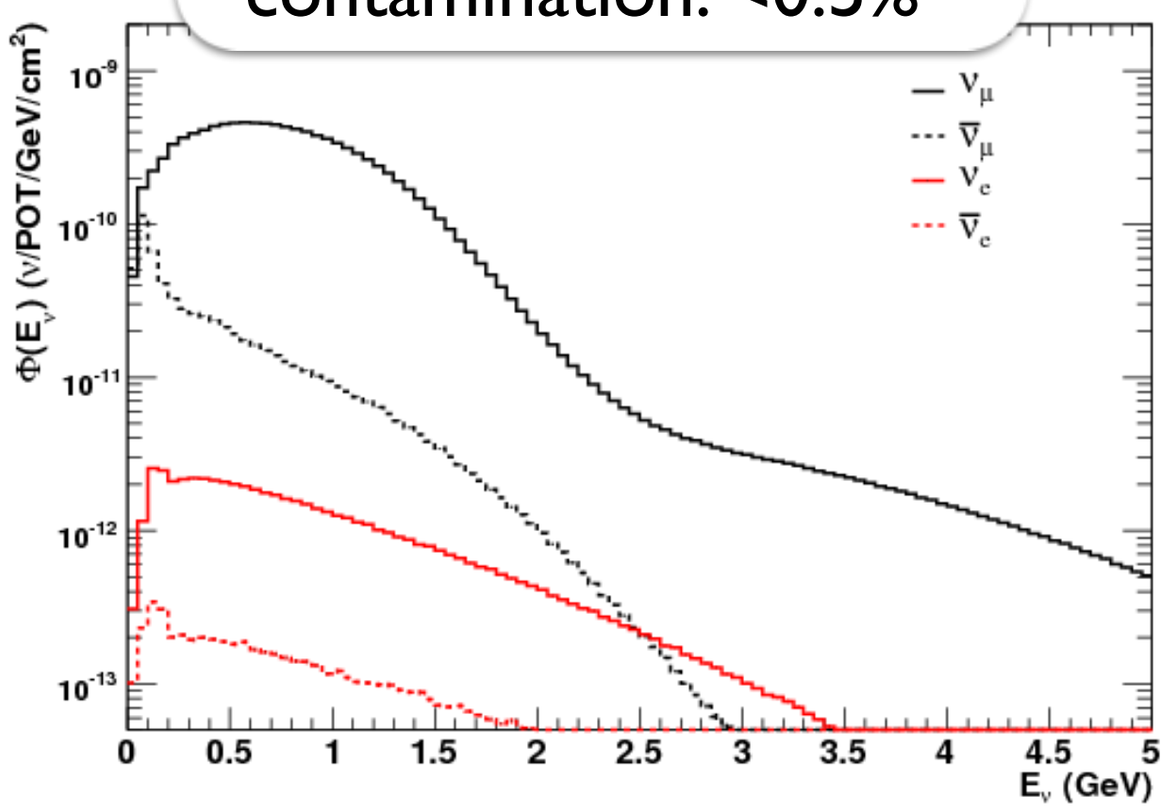
Fermilab's **low-energy** neutrino beam:

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

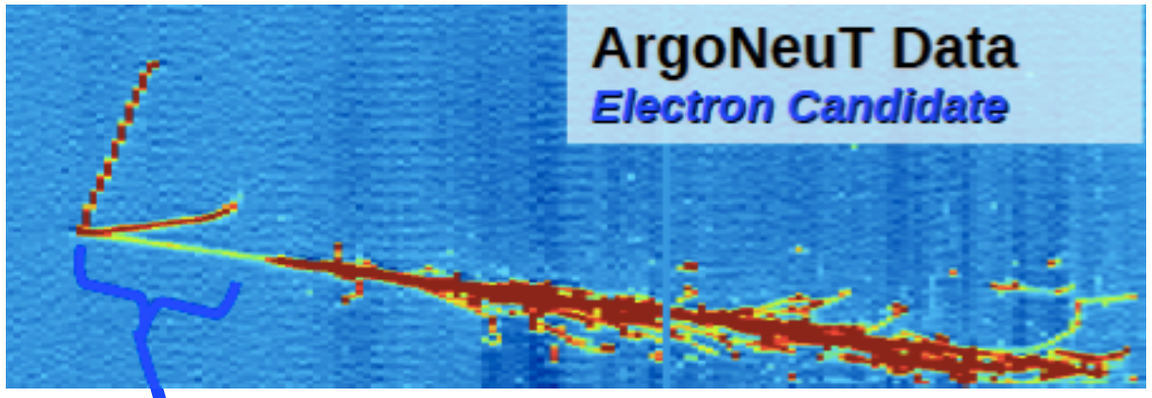
Booster - 8 GeV protons

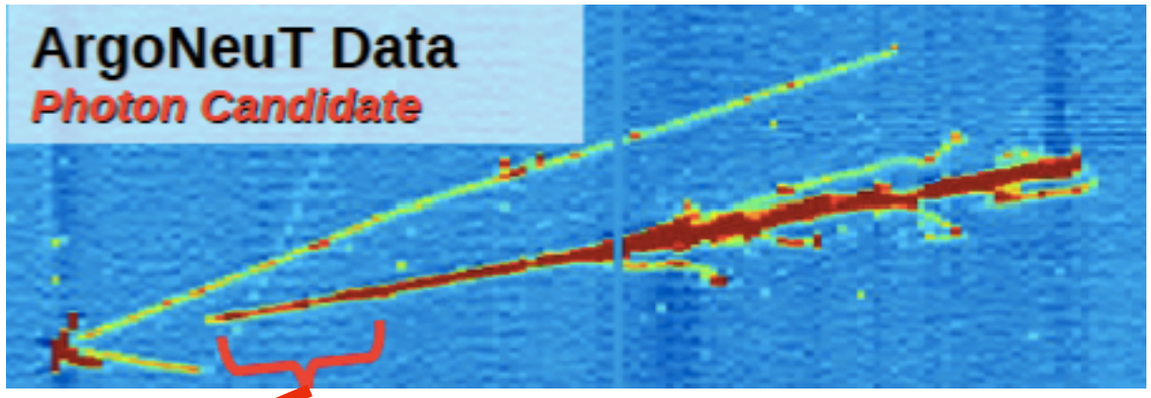
- Beam - mostly muon neutrinos
- BNB stably running for a decade (well characterized)
- Anomalies exist here (MiniBooNE)

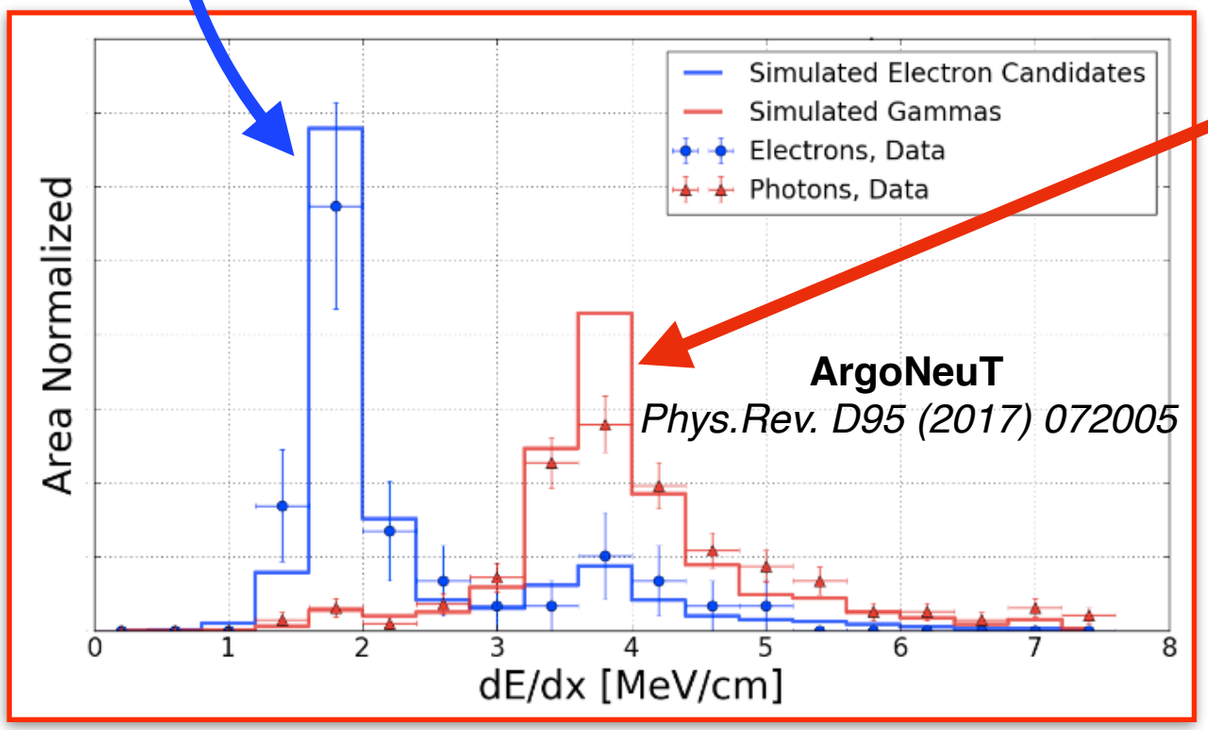
Small electron neutrino contamination: <0.5%



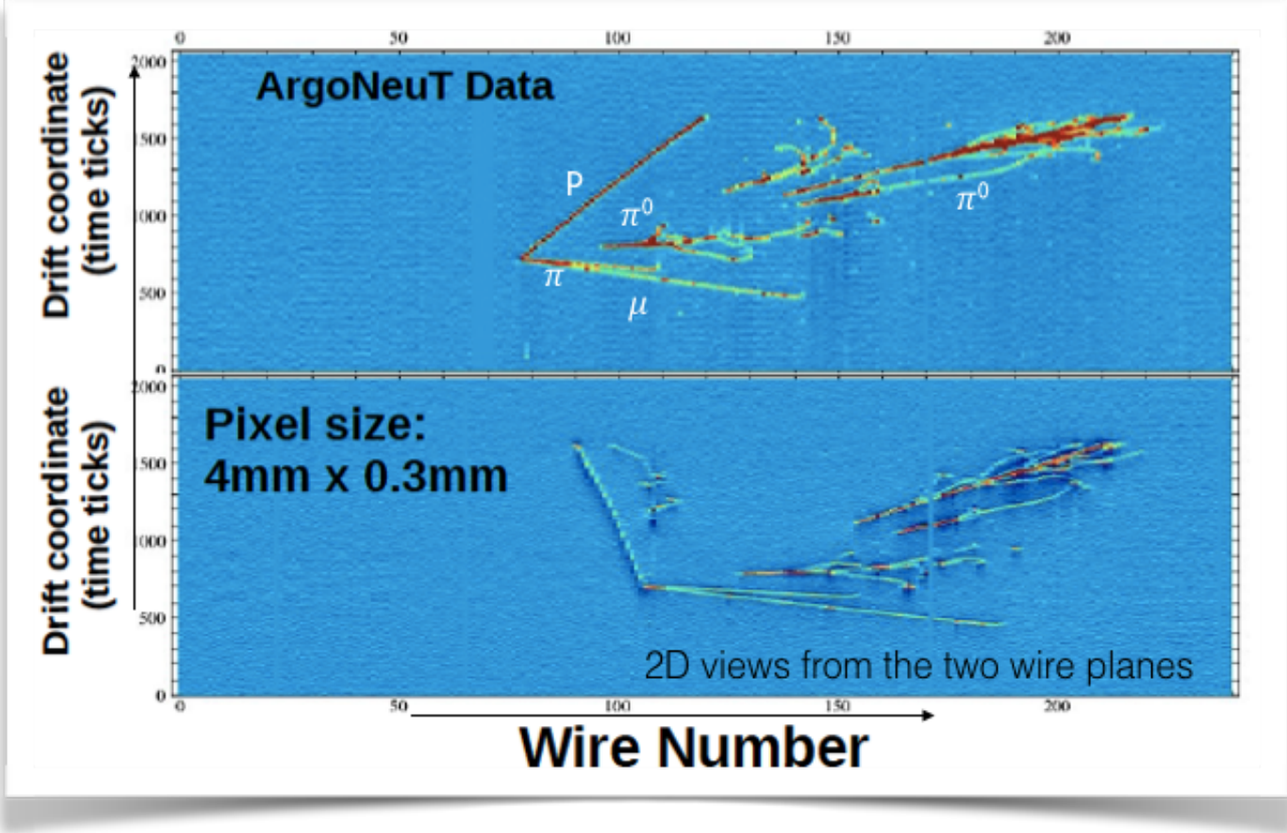
Electron-γ separation in LAr







Analyzing topology and dE/dx



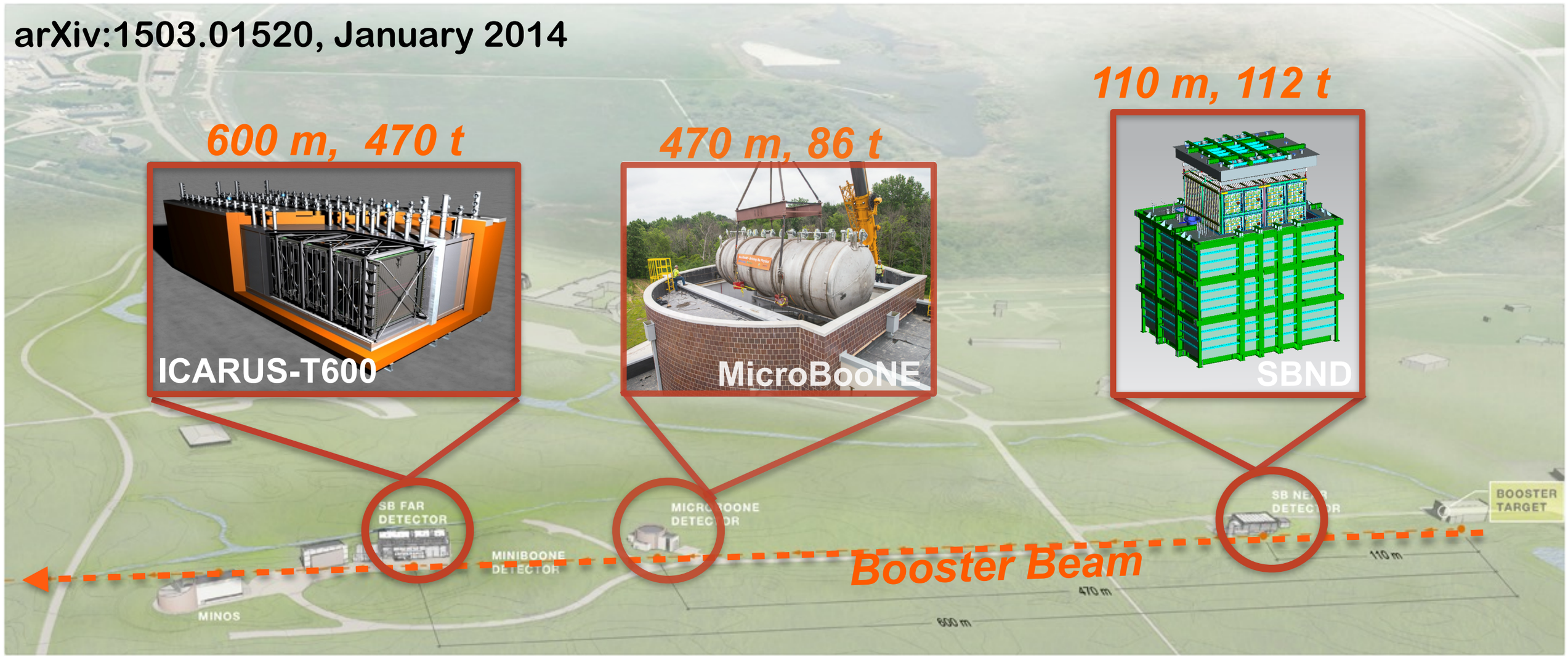
LAr TPC offers incredible fine tracking and calorimetry, along with electron/photon separation

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

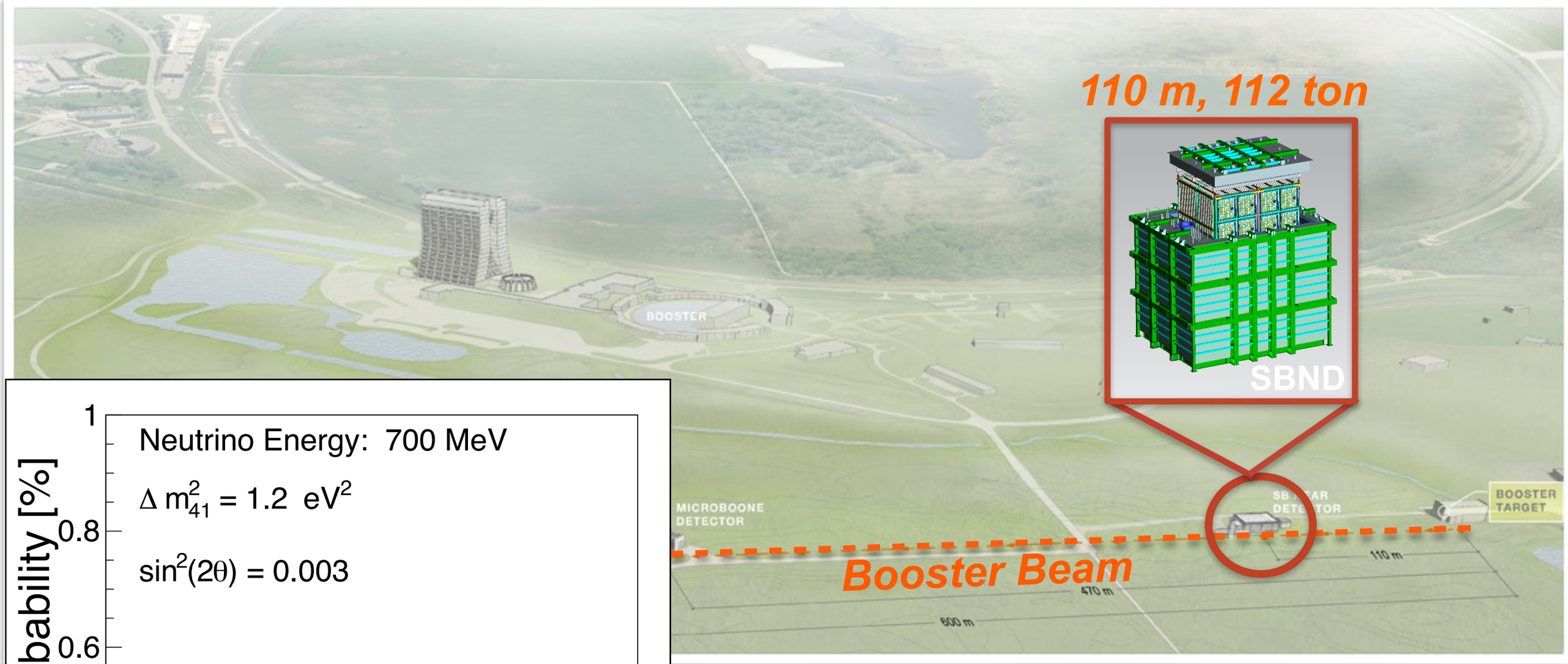


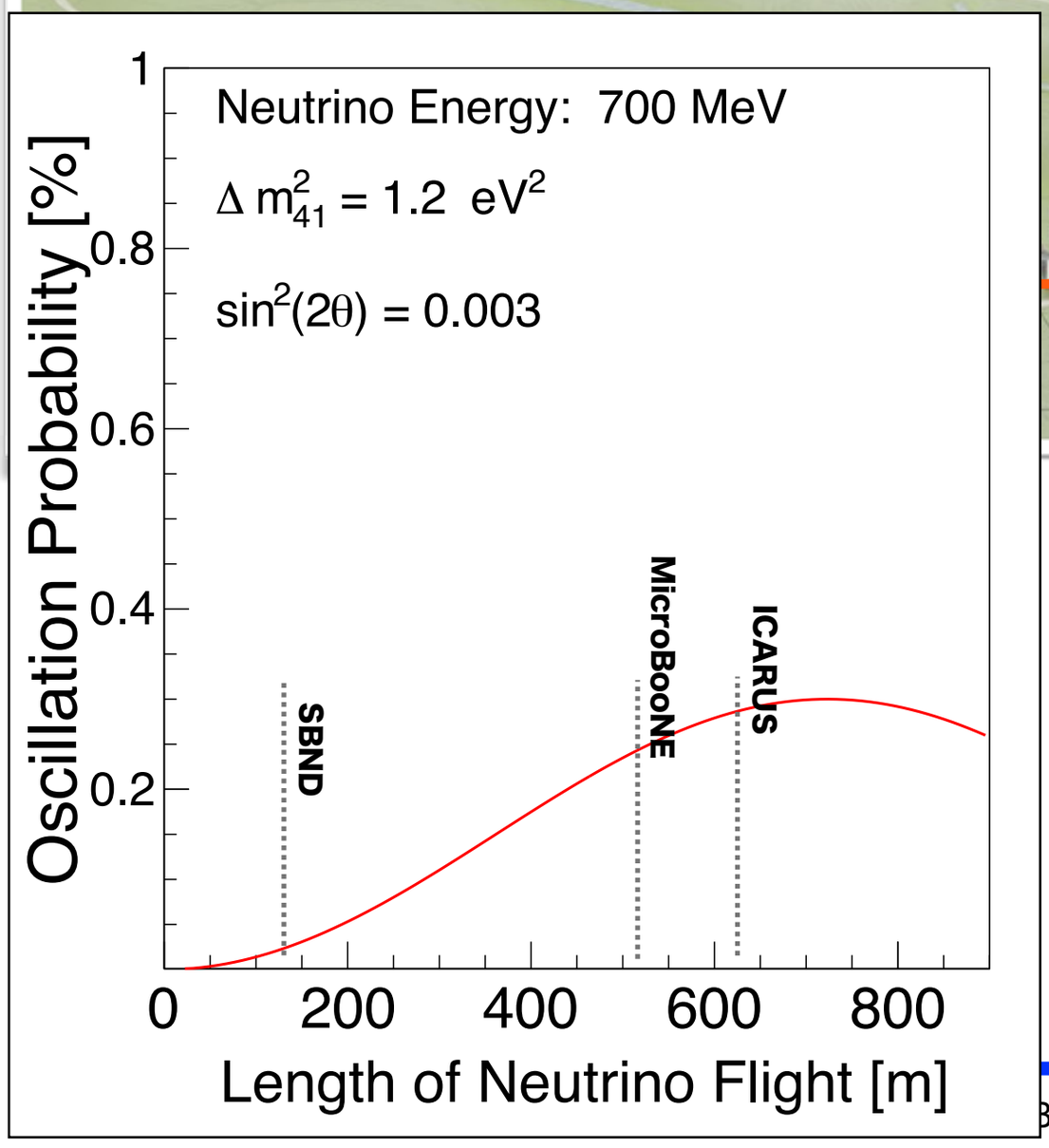
SBN program - Phase 2 - By 2018/19, the MicroBooNE detector will be joined by two additional LAr-TPC detectors at different baselines

- 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)

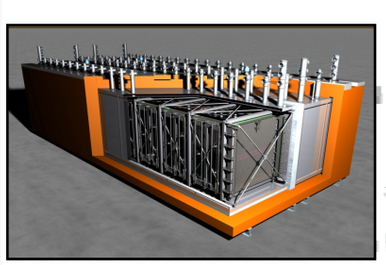
ICARUS - high-tech from Italy

- 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, has made 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

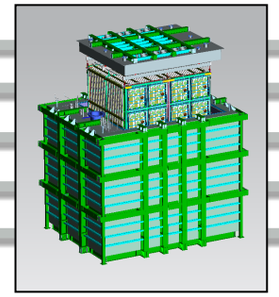
(II) on the way, these might be morphing into another, undetectable form (sterile neutrinos, ν_x)... and eventually change again to electron neutrinos (ν_e)...

(I) BNB emits muon neutrinos (ν_μ)



600 m

470 m



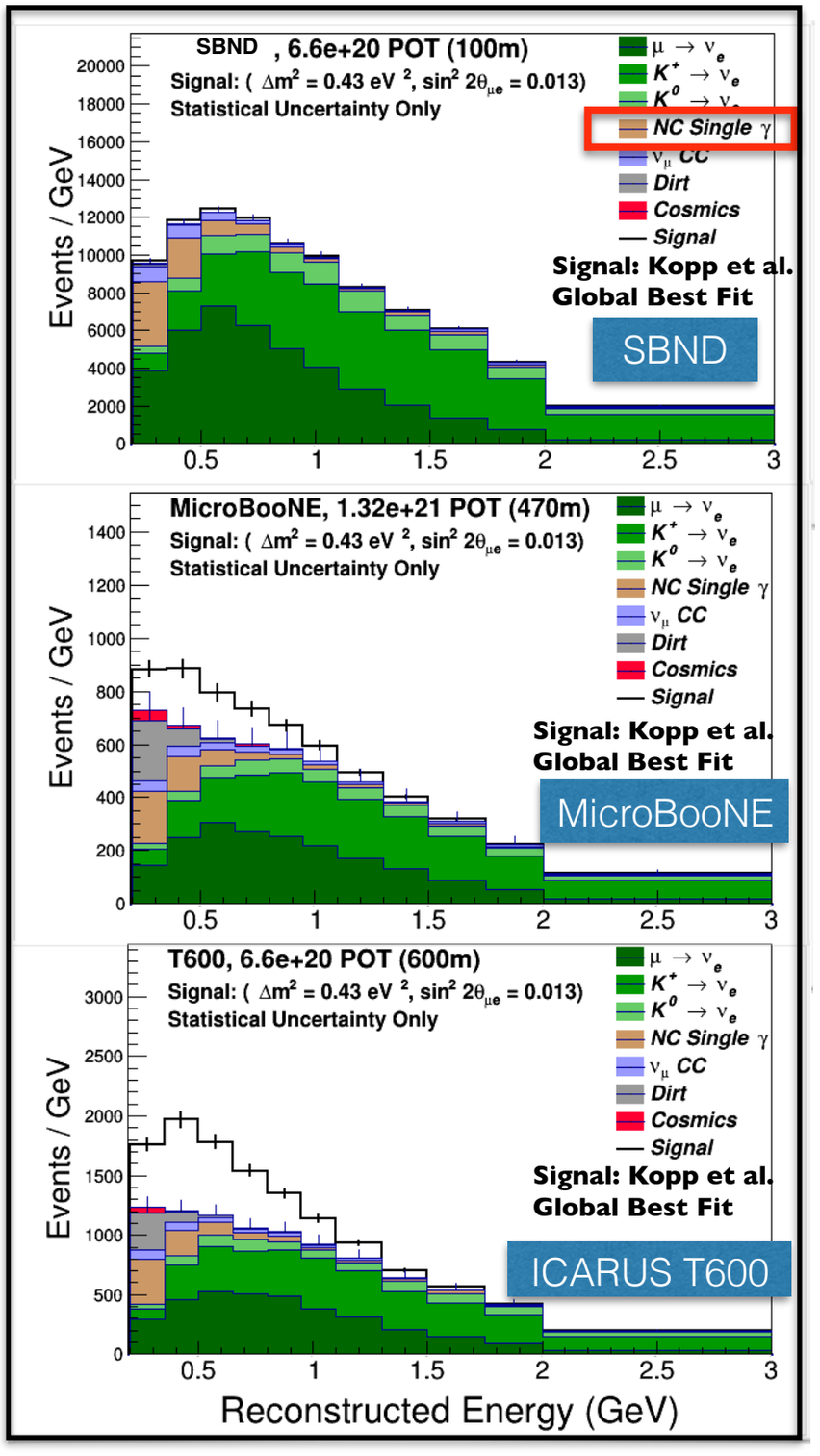
110 m

Appearance ν_e? ← ν_μ

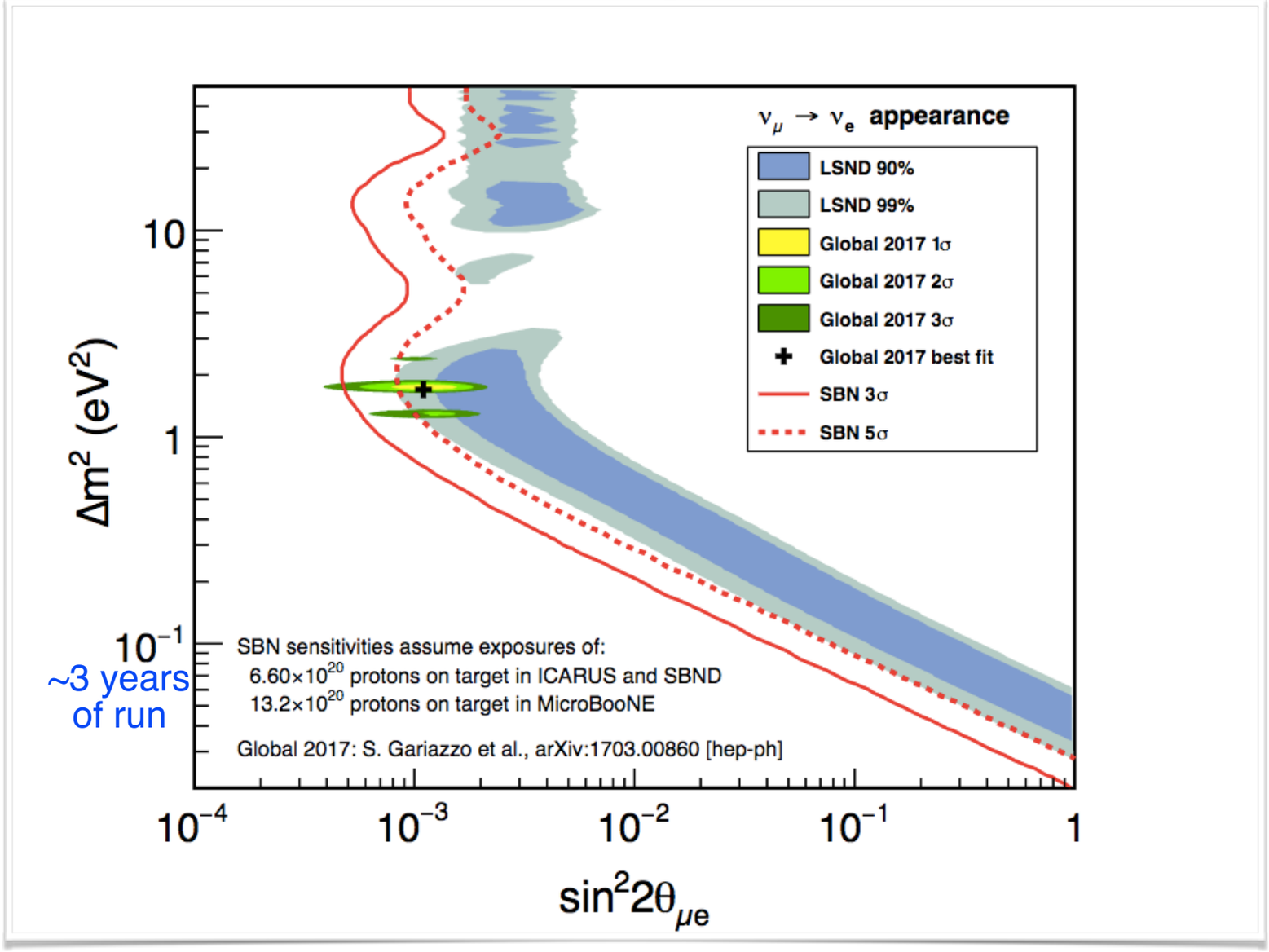
Disappearance ν_x? ← ν_μ

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



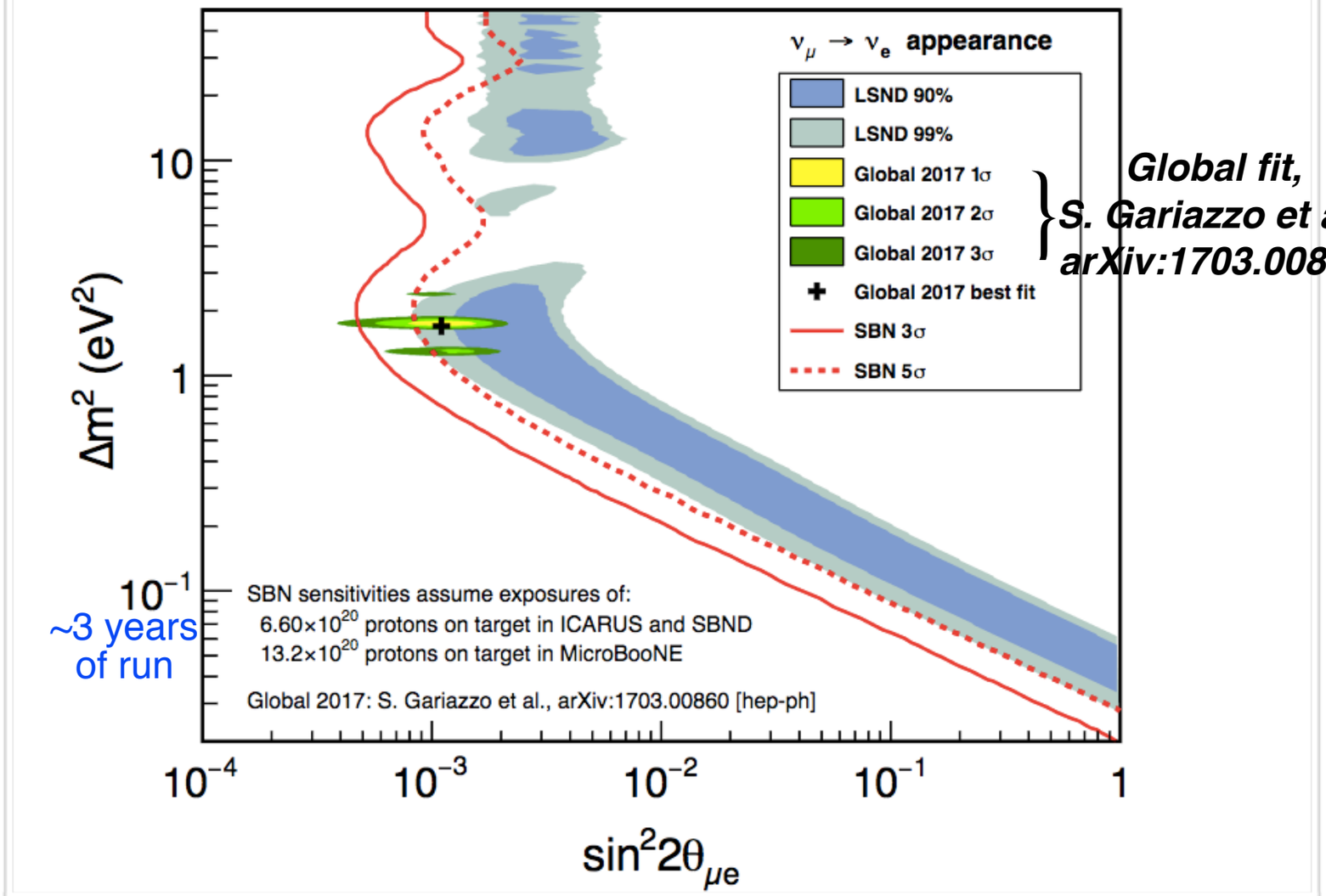
$\nu_\mu \rightarrow \nu_e$ Appearance sensitivity



Physics reach of the SBN Program

- ***3+1" Analysis***
- *Multi-channel approaches,* ***with possible improvements in sensitivity from*** *exclusive topology measurements* ***are under study***

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

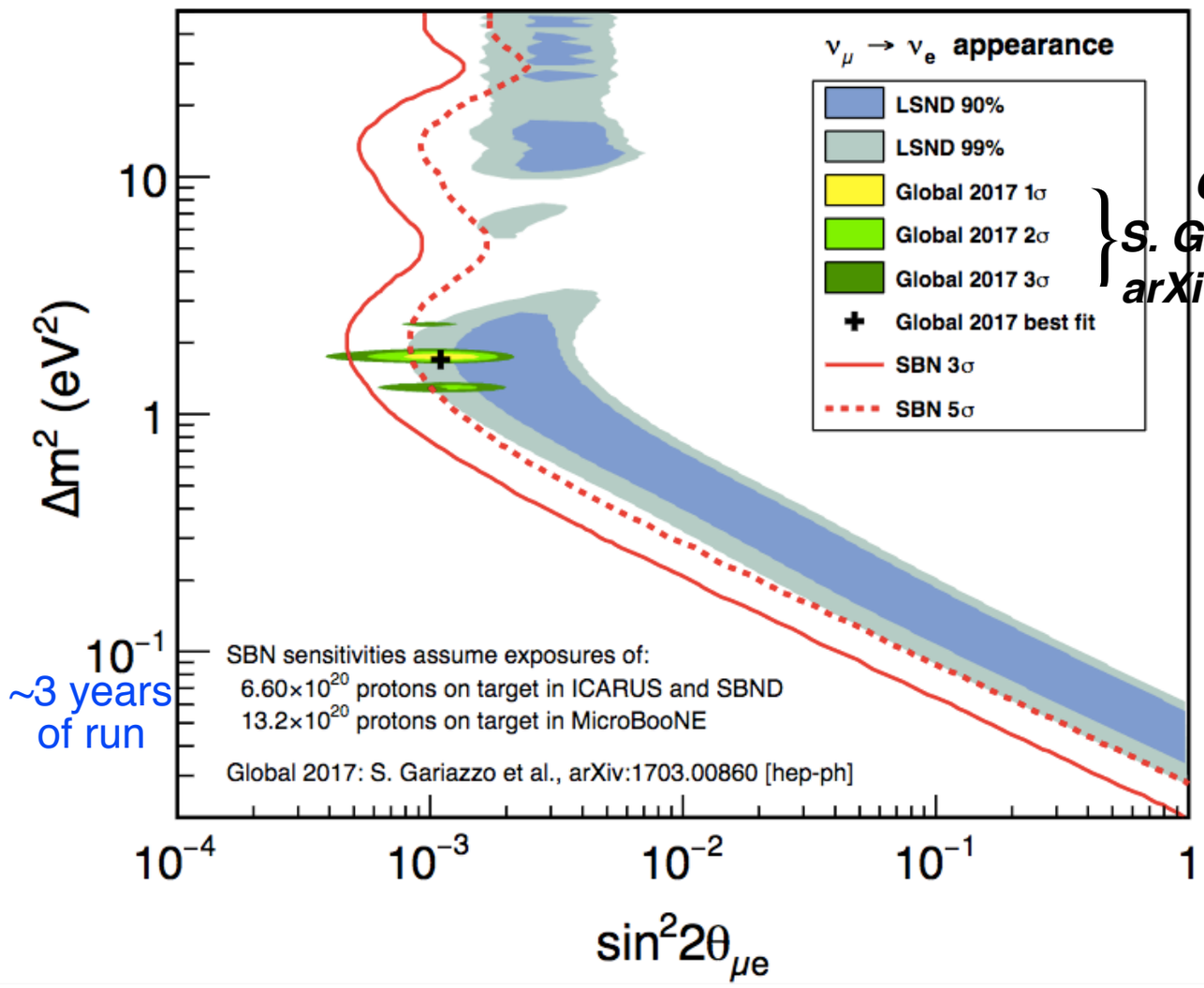


A **large mass far detectors** and **a near detector of the same technology** is the key to large reductions of both statistical and systematic uncertainties (reduced to % level) in SBN oscillation searches,
allowing to address region of interest at 5σ

Physics reach of the SBN Program

- ***3+1" Analysis***
- *Multi-channel approaches,* ***with possible improvements in sensitivity from*** *exclusive topology measurements* ***are under study***

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

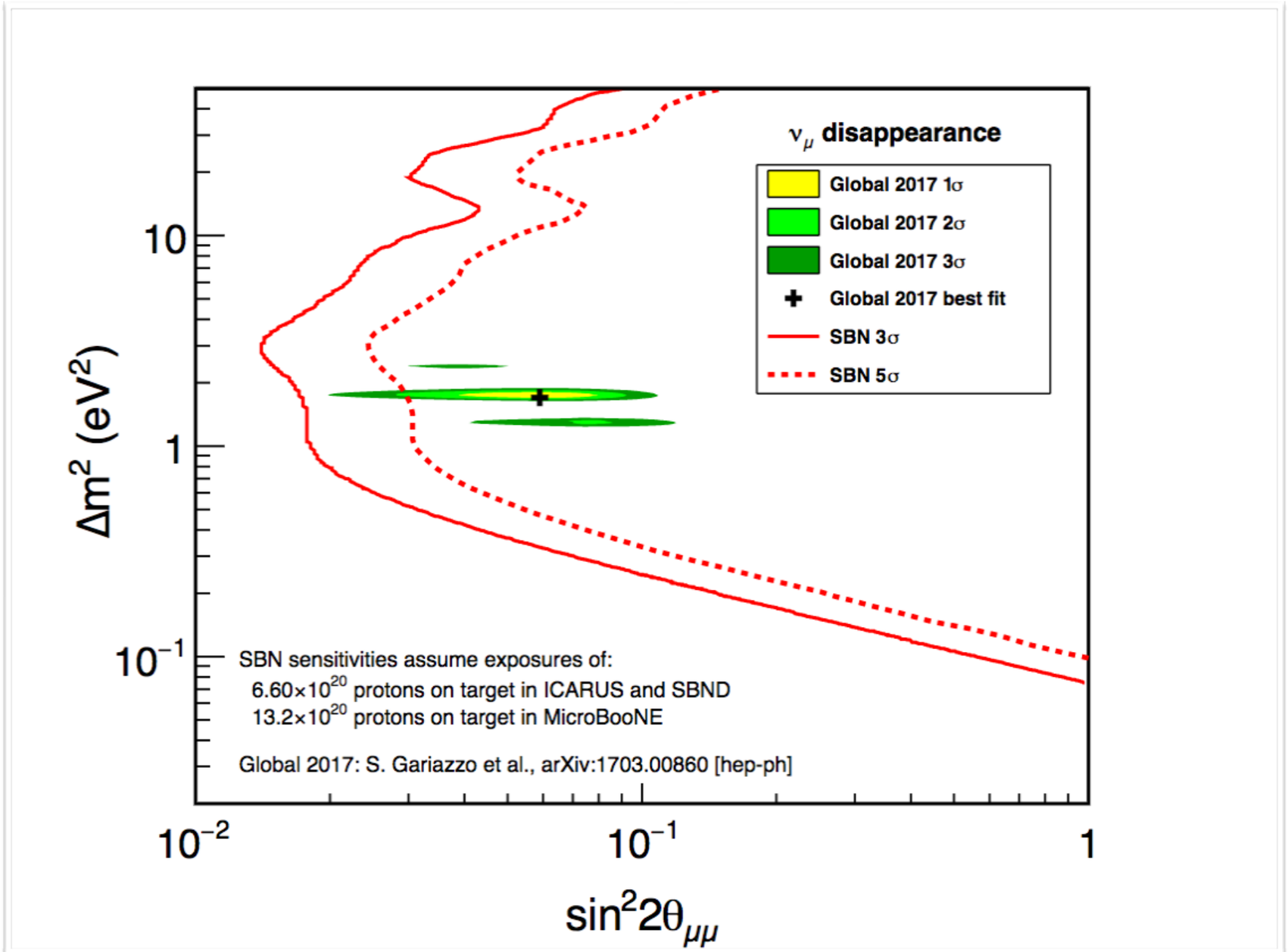


Global fit, S. Gariazzo et al., arXiv:1703.00860

- The sensitivity of the SBN program is highest near the most favored values of Δm^2
- 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



In addition to ν_e appearance, SBN also has sensitivity to ν_μ disappearance

- Needed to confirm an oscillation interpretation of any observed appearance signal
- Providing a more robust result on sterile-neutrino-induced oscillations

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 have by far the largest data set of neutrino-argon interactions in the world for the foreseeable future. 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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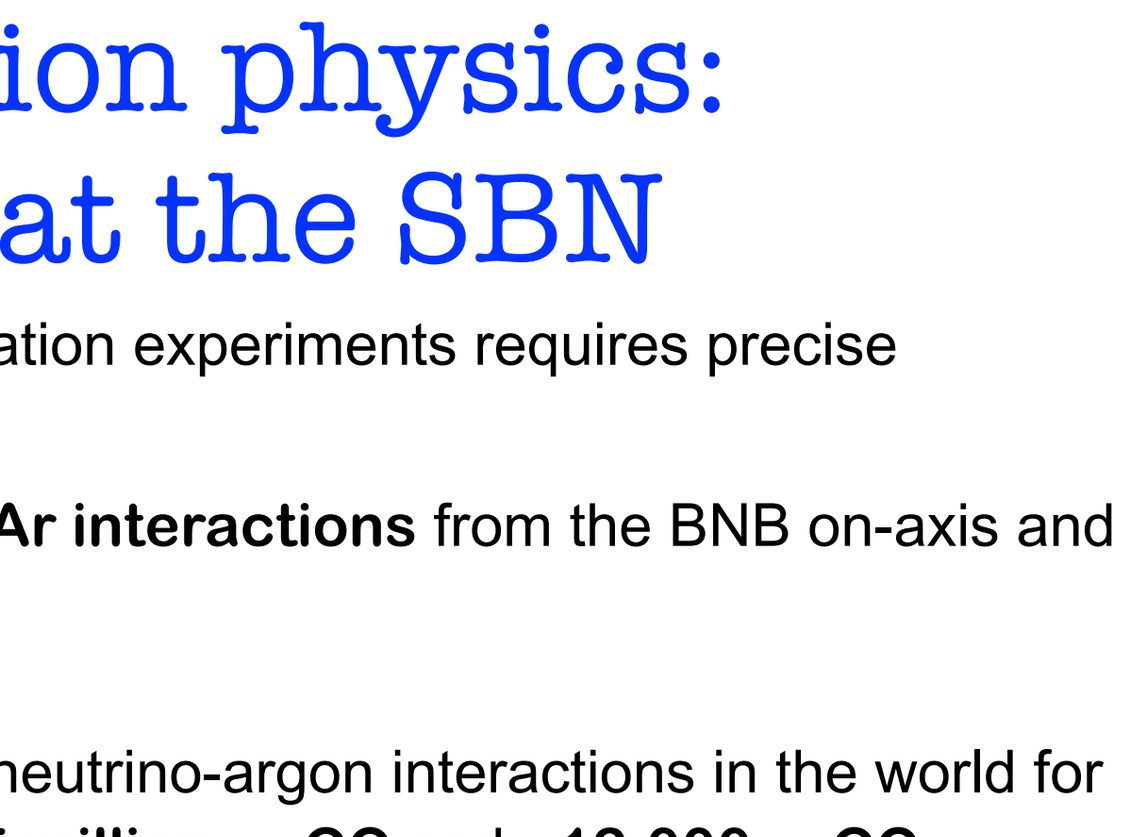
The only published GeV neutrino-Ar scattering data are ~6000 events from ArgoNeuT (NuMI beam, 3 GeV peak energy)



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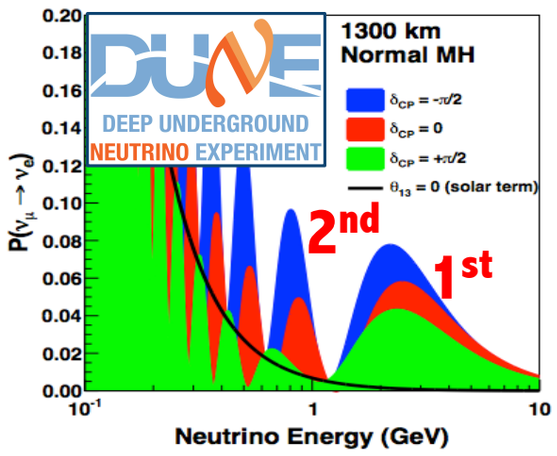
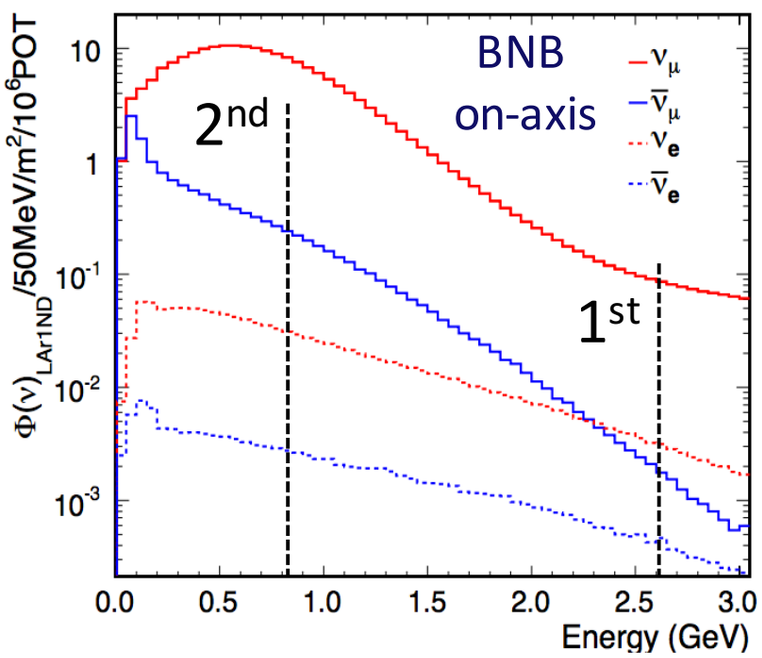
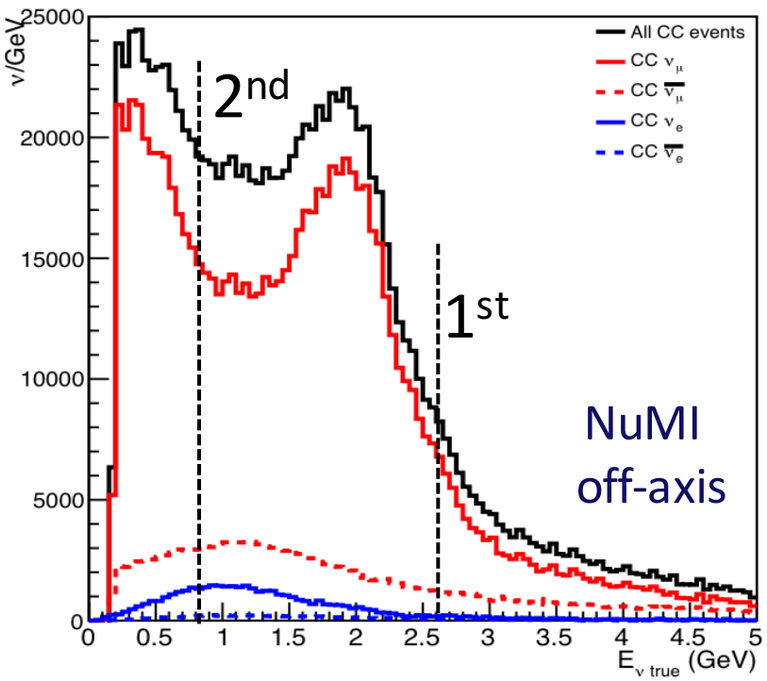
  - ~100k NuMI off-axis events in T600 per year
  - Large statistics at both the 1st and 2nd DUNE oscillation peaks

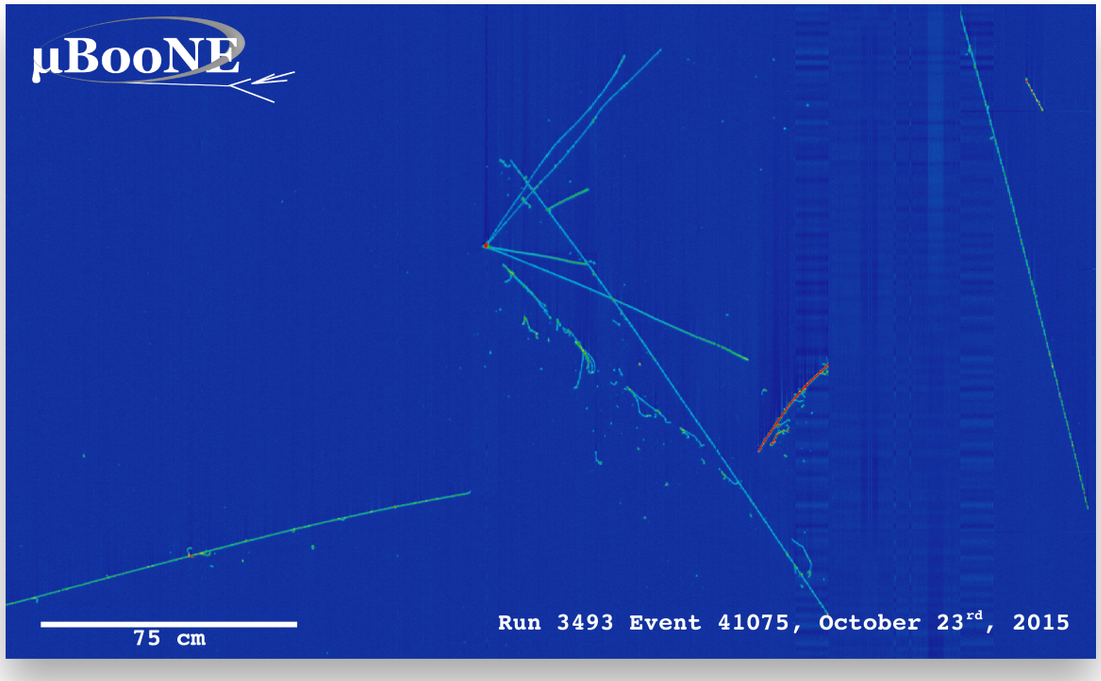






MicroBooNE experiment

TPC Active volume:
86 t of LAr



MicroBooNE is taking neutrino data since Oct. 2015
(~5×10^{20} POT collected)

See G. Karagiorgi's talk on Friday

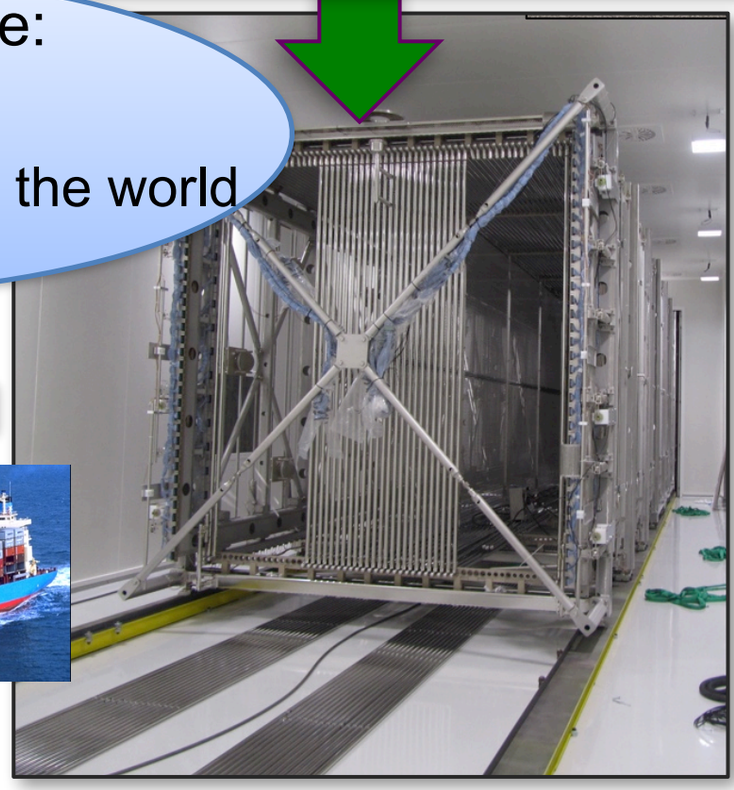
μBooNE

ICARUS: From Gran Sasso to Fermilab via CERN

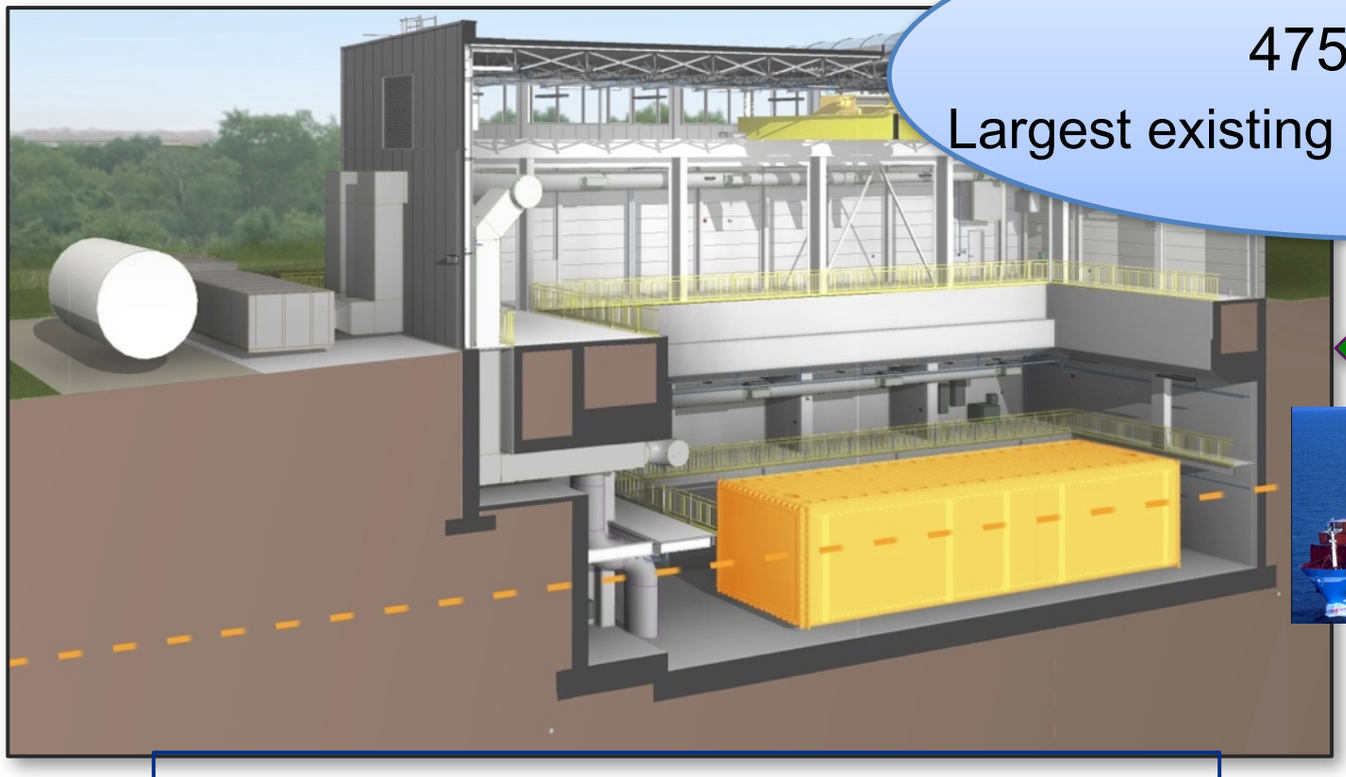
Removing from Gran Sasso

On the road to CERN

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



2017



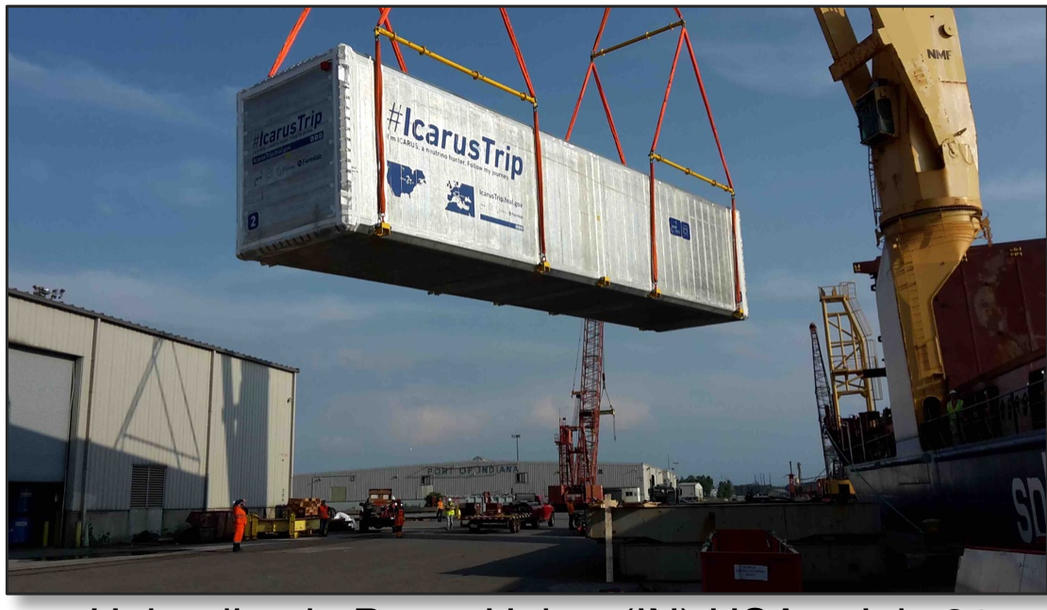
New Building at Fermilab

In Cleanroom @ CERN

ICARUS: Transport from CERN to Fermilab (2017)

Ready to leave from CERN - June 12

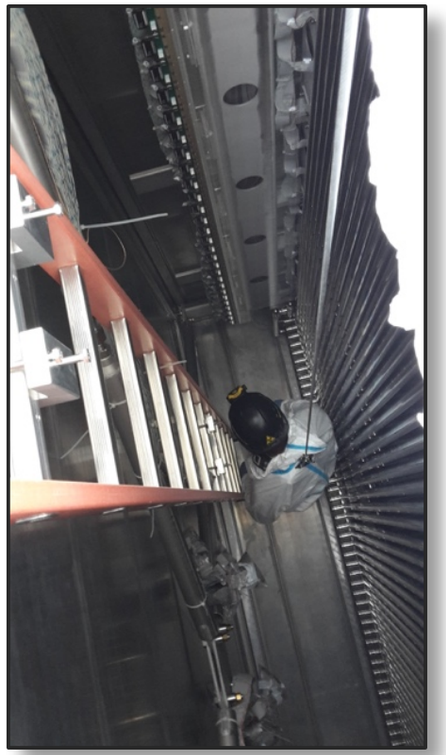
Loading in Antwerp (Belgium) – June 21



Unloading in Burns Habor (IN) USA – July 21

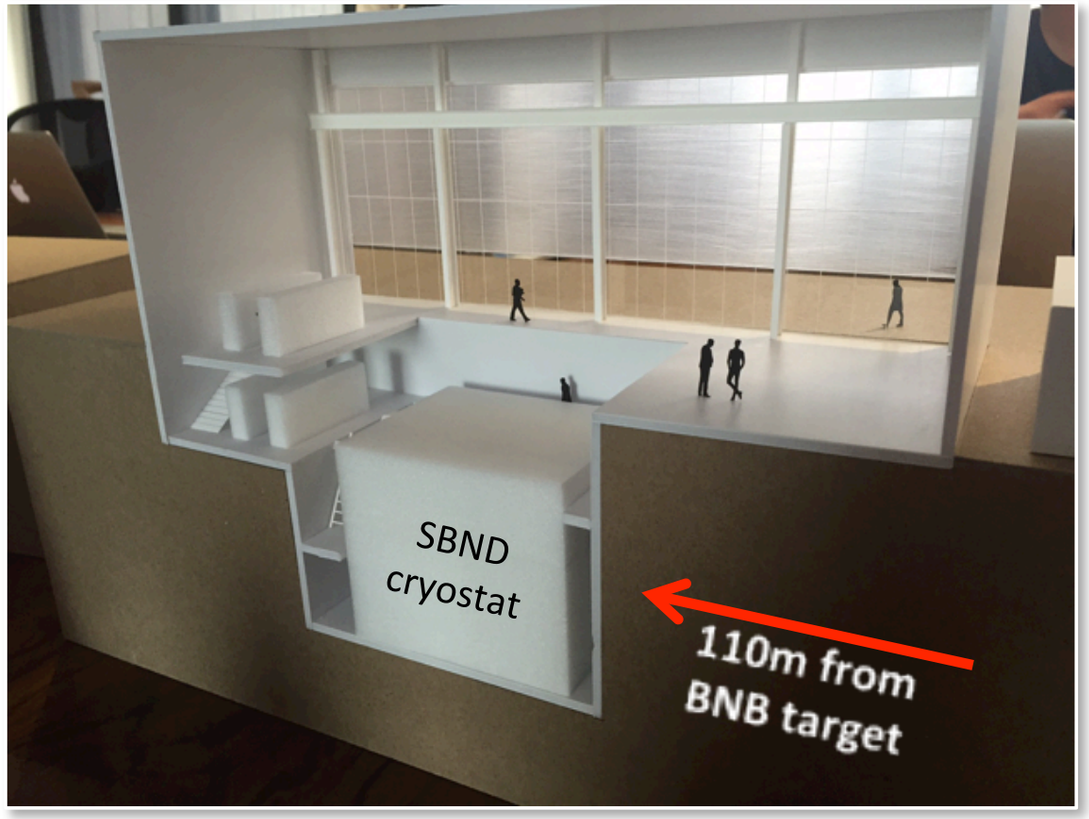
On the Road in IN – July 25

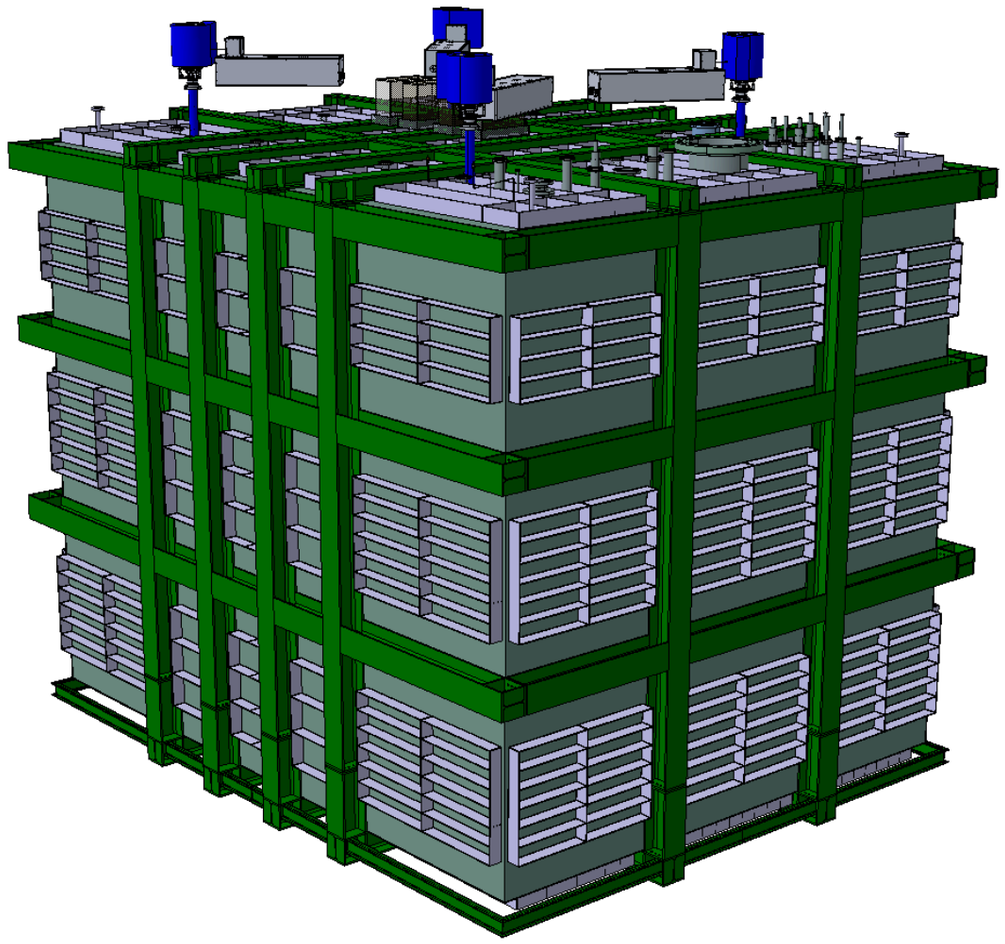
Behind the ICARUS building – July 26

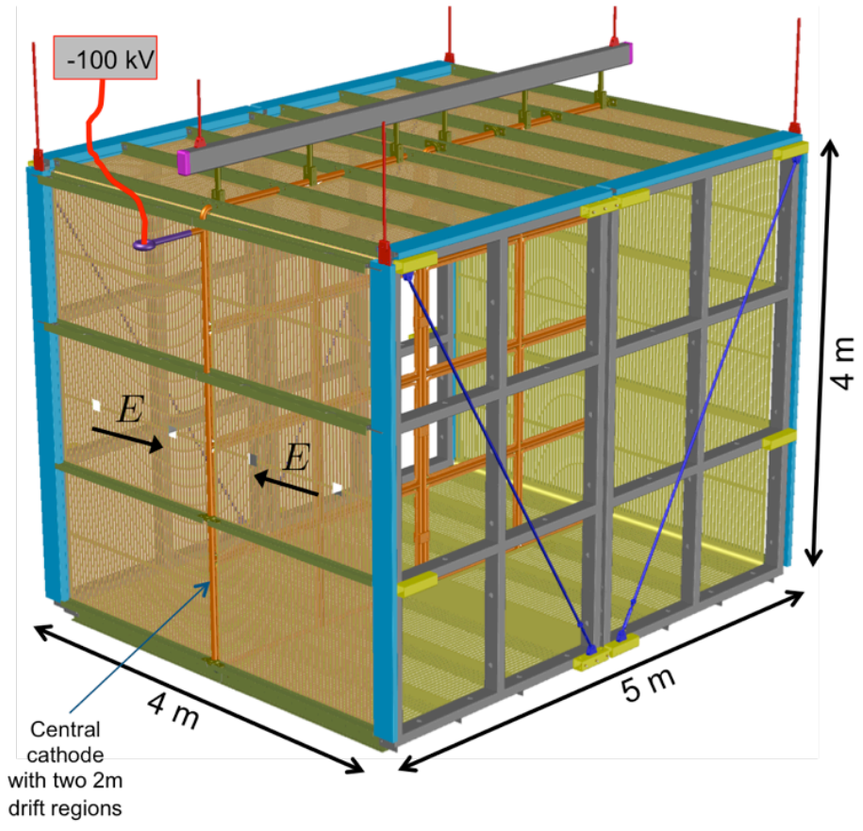


Entering the vessel

Short-Baseline Near Detector: SBND

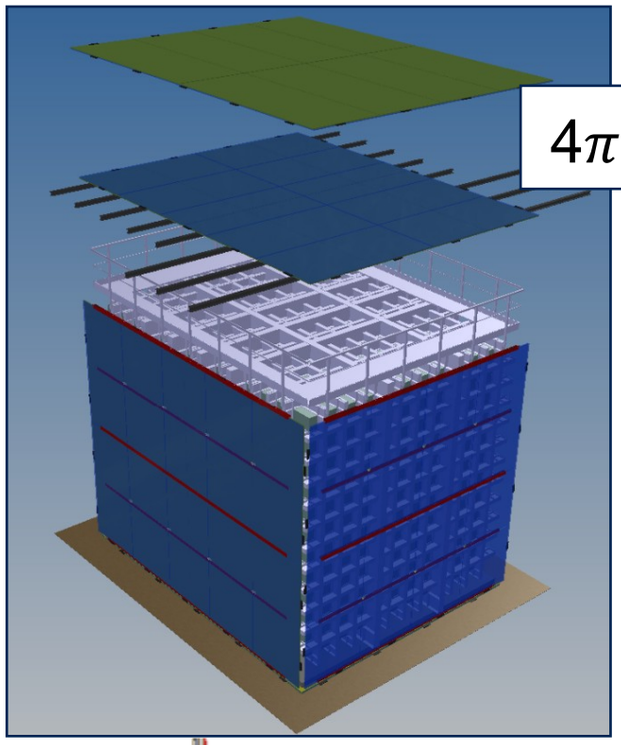




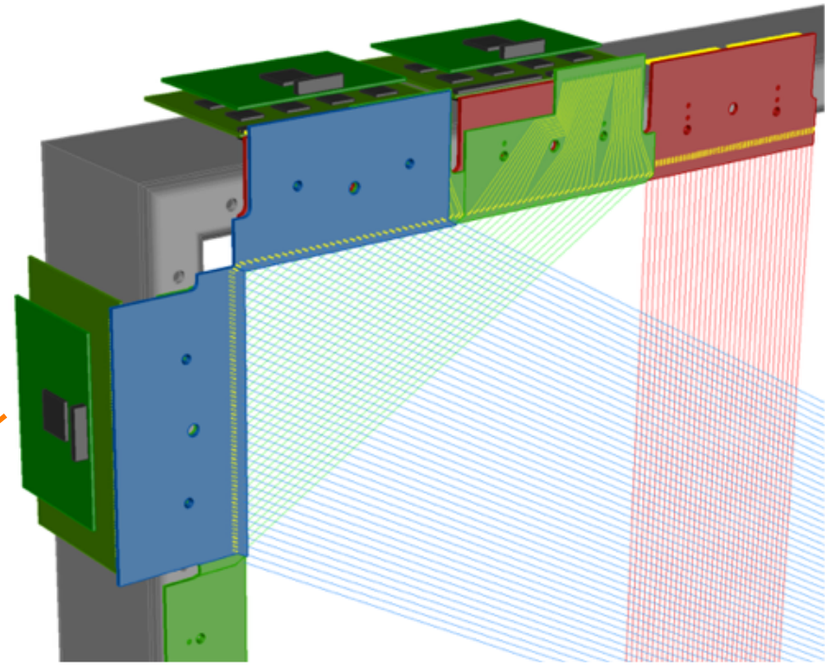


TPC Active volume:
112 t of LAr

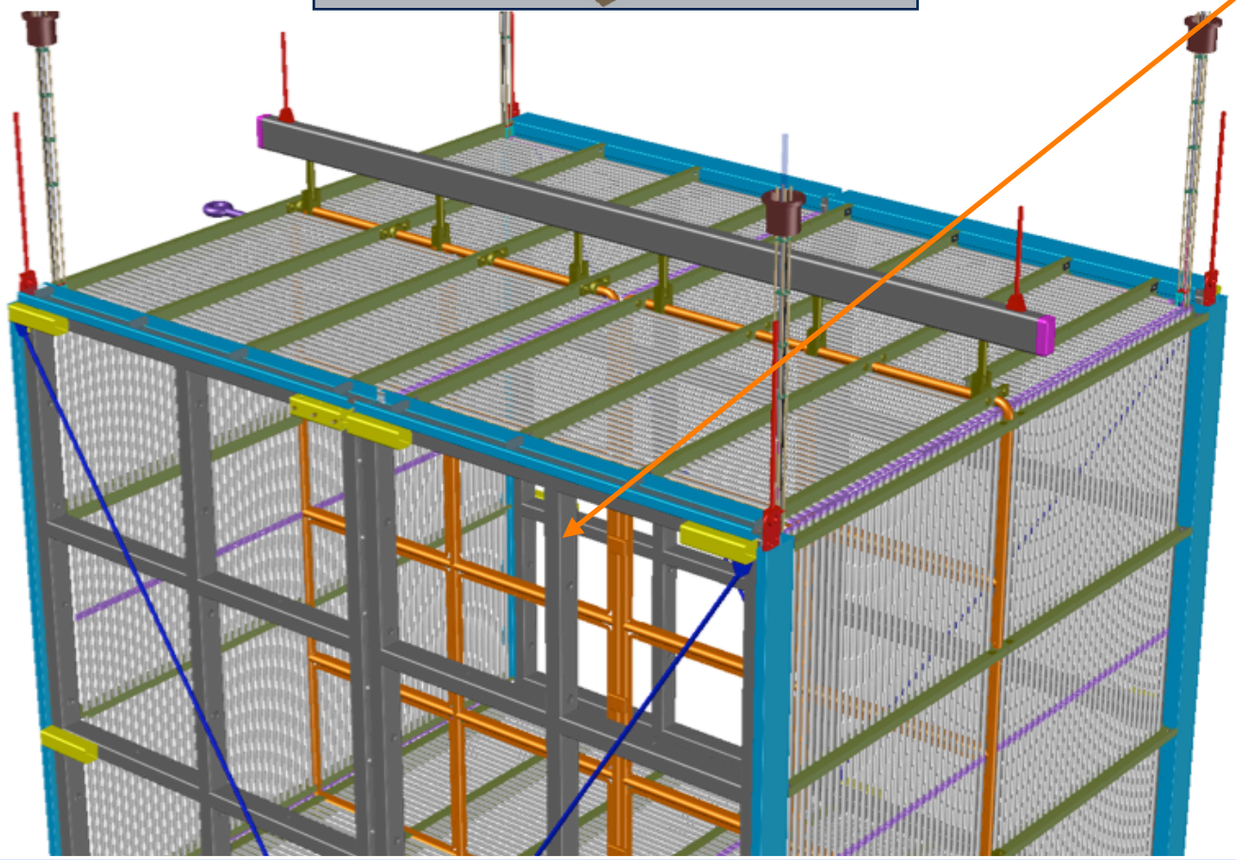
SBND: Detector Elements

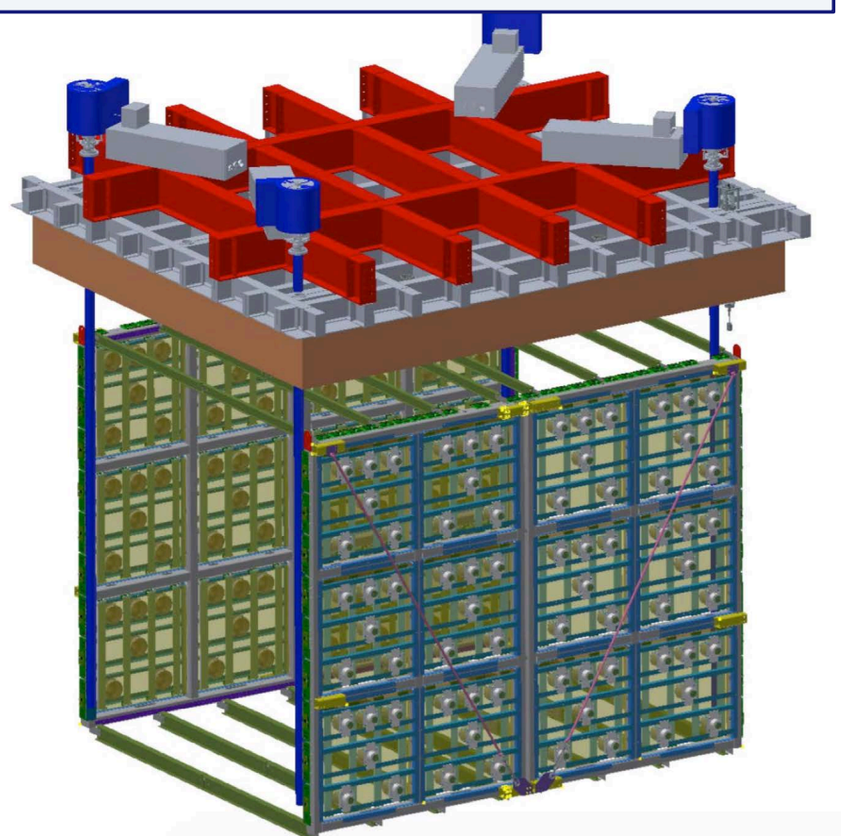


4π CRT coverage

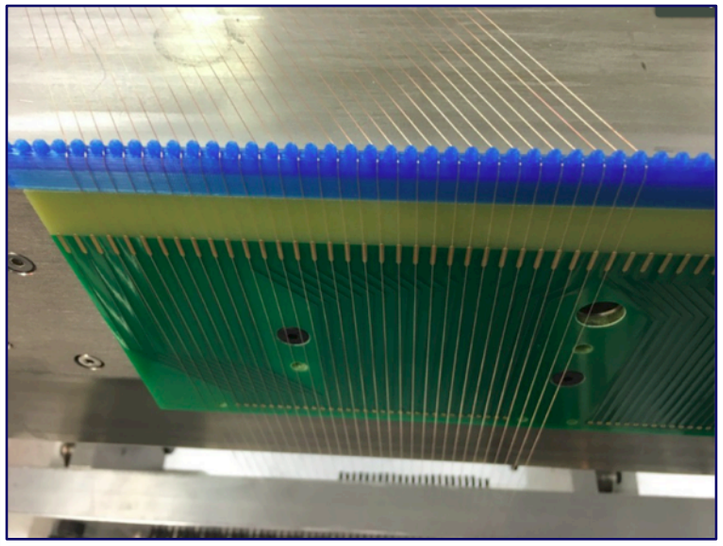


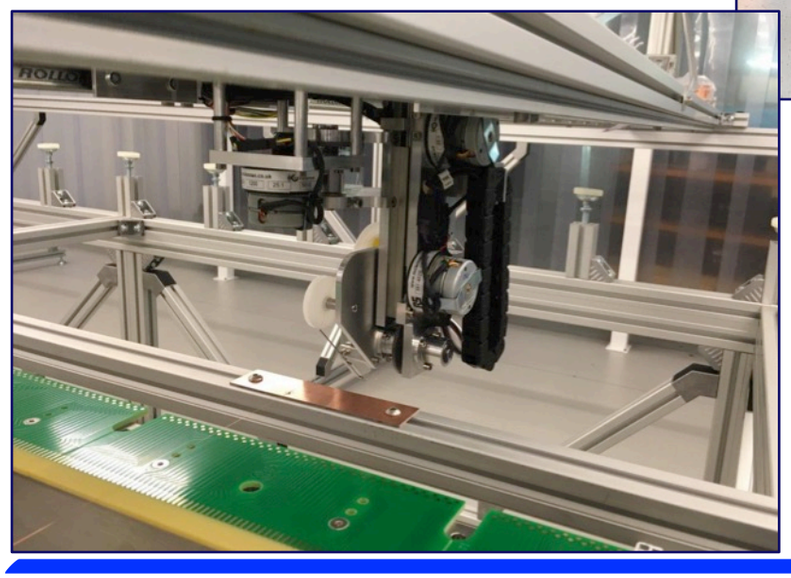
Anode Plane Assemblies: *4.1 x 2.5 m wire plane frames (4) tiled to create two drift regions*

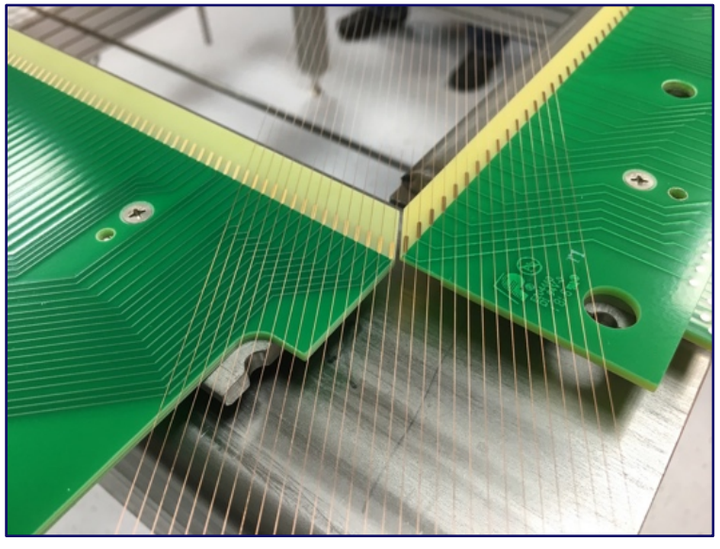




SBND: TPC Construction







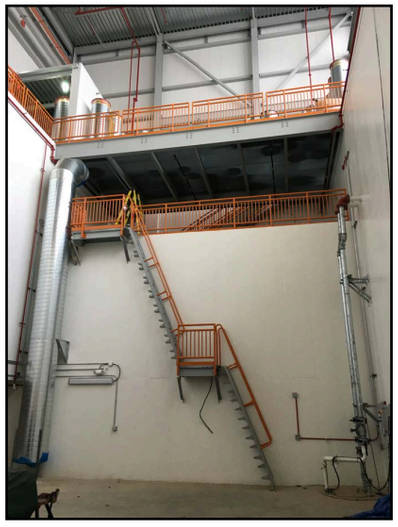
Near and Far Detector Buildings

© Steinkamp Photography 05.23.17 76

8850-22_DSC7952.tif

Holabird Root Fermilab 1st Edit

Near Detector building



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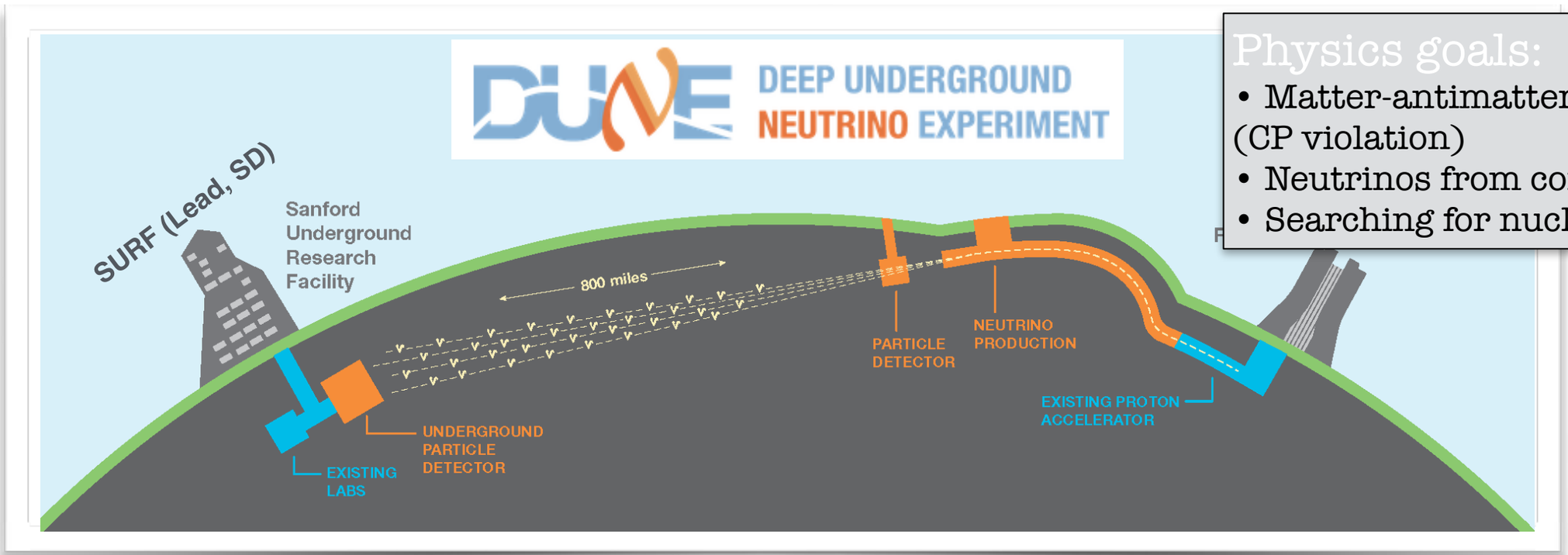
Holabird Root Fermilab 1st Edit

Far Detector building

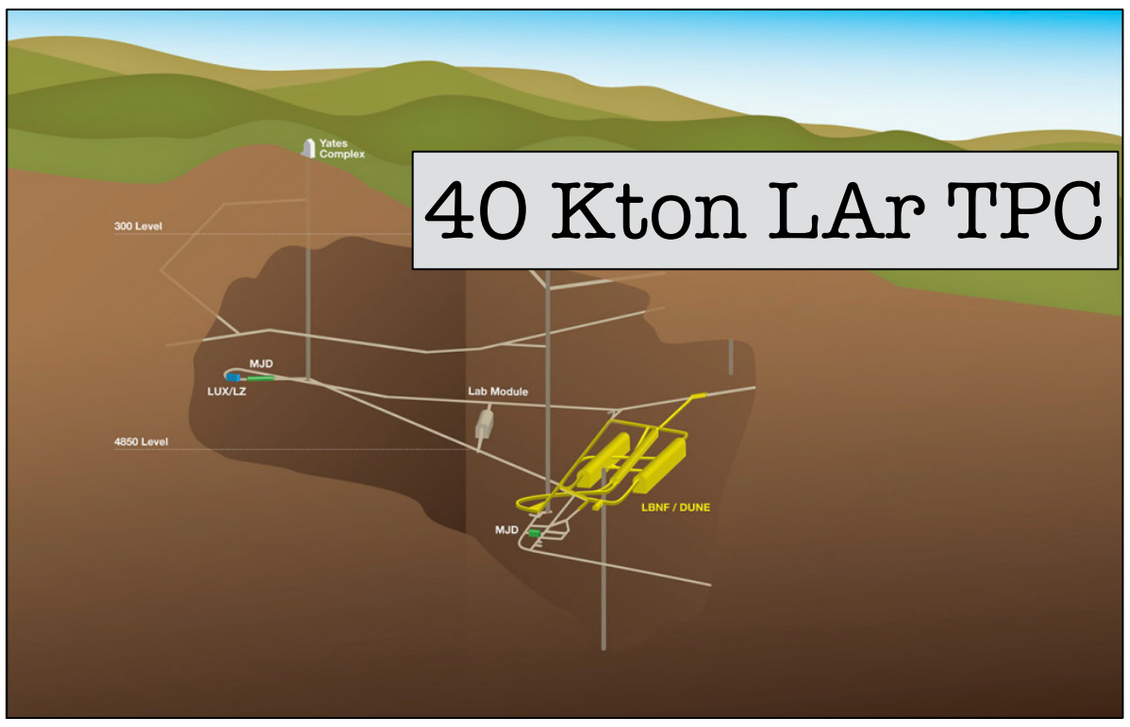
43 O. Palamara | The SBN Oscillation Program in the Fermilab BNB Erice | Sept. 18 2017

SBN ties to the Long-Baseline Program

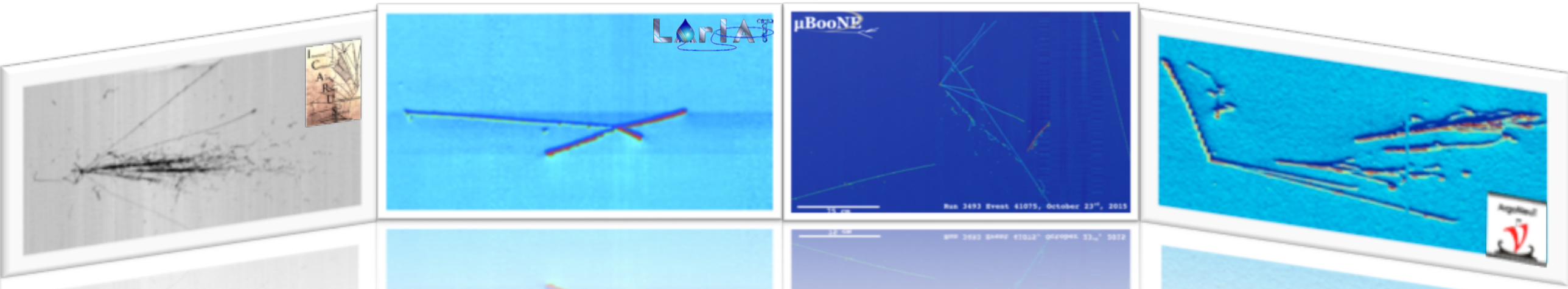


Physics goals:

- 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 sit on the Booster Neutrino Beamline at Fermilab and will all use the state-of-the-art **liquid-argon time projection technology** to perform the most sensitive search to date for eV-scale sterile neutrino. The SBN program will

- Follow up on hints of new physics, in particular the LNSD allowed region will be covered at >5σ
- Make high precision measurements of ν-Ar cross sections
- Develop LAr TPC technology & expertise in preparation for DUNE

Well on our way to an exciting Short-Baseline Accelerator Neutrino Oscillation Program!!