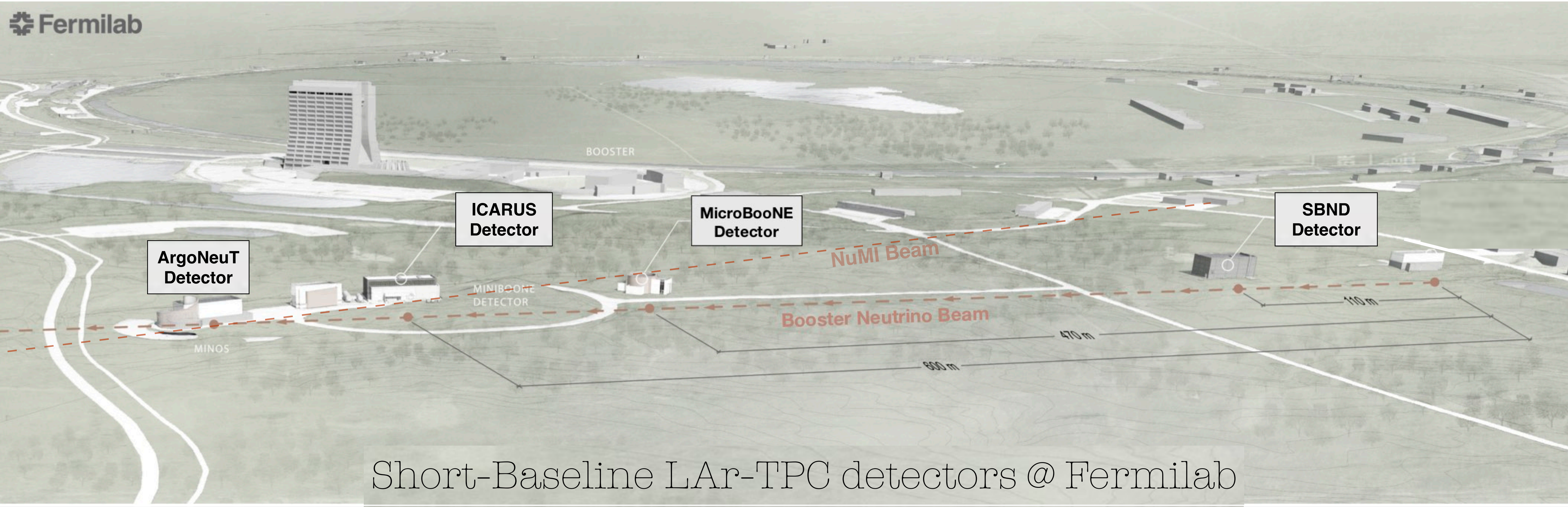


Signatures for New Physics in Short-Baseline Liquid Argon Neutrino Experiments

Twentieth Lomonosov Conference on Elementary Particle Physics
August 25th 2021

Ornella Palamara
Fermilab

Outline

- Why BSM in Short-Baseline* (SBL) Liquid Argon Time Projection Chamber (LAr TPC) Neutrino Experiments?

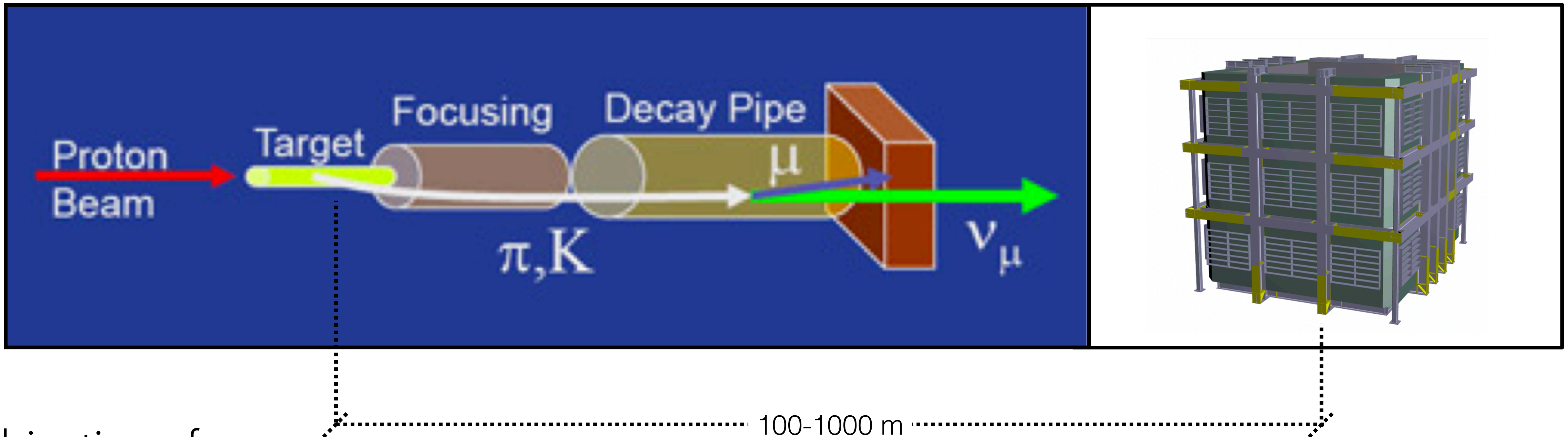
- Four LAr TPC experiments sitting on two neutrino beams (NuMI and BNB) at Fermilab

  - Short-Baseline Neutrino Program: sterile neutrinos & other BSM explorations

  - ArgoNeuT: improved limits on millicharged particles and heavy Neutral Leptons

* Short-Baseline: L~100-1000 m, L/E~1eV^2, to be compared with Long-Baseline: L~100-1000 Km, L/E~$10^{-3}eV^2$

Why BSM in SBL LAr TPC Neutrino Experiments?



- The combination of:
  - **High-intensity proton beams (high intensity neutrino beams)** for neutrino precision measurements coupled with
  - **(Large mass) LAr TPC detectors** close to the beam target, with
    - Extraordinary event imaging
    - Fine granularity calorimetry and excellent particle identification
    - Excellent timing resolution and
    - Low energy threshold

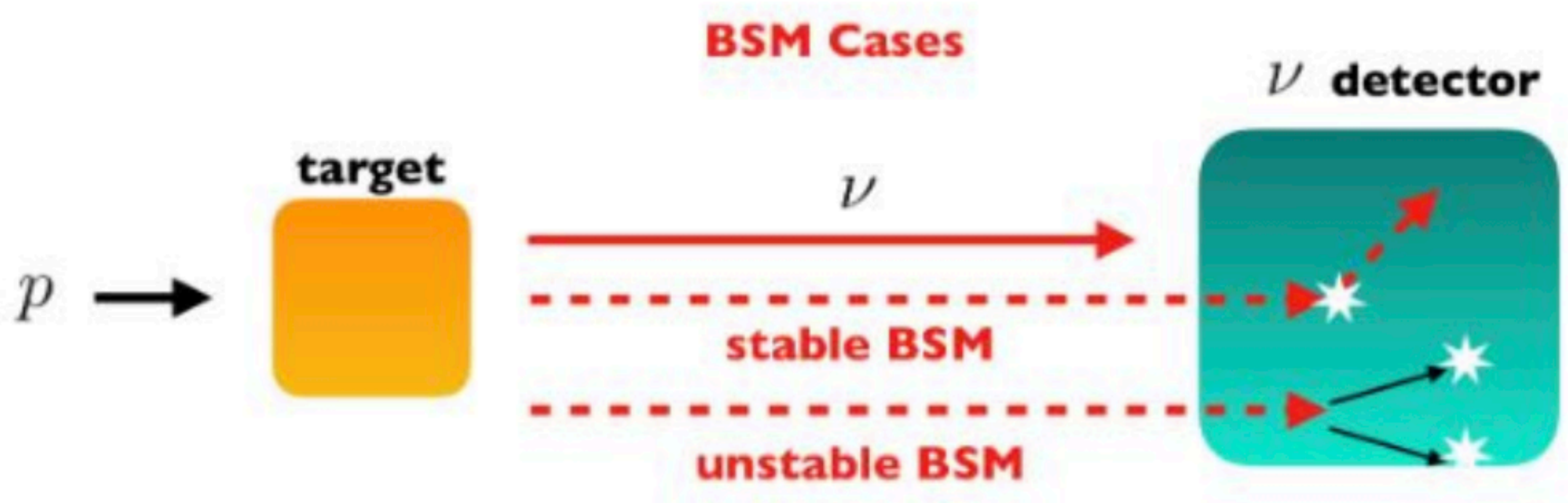
opens unprecedented opportunities to probe signatures for New Physics scenarios/BSM phenomena in the neutrino sector and beyond

New Physics Opportunities

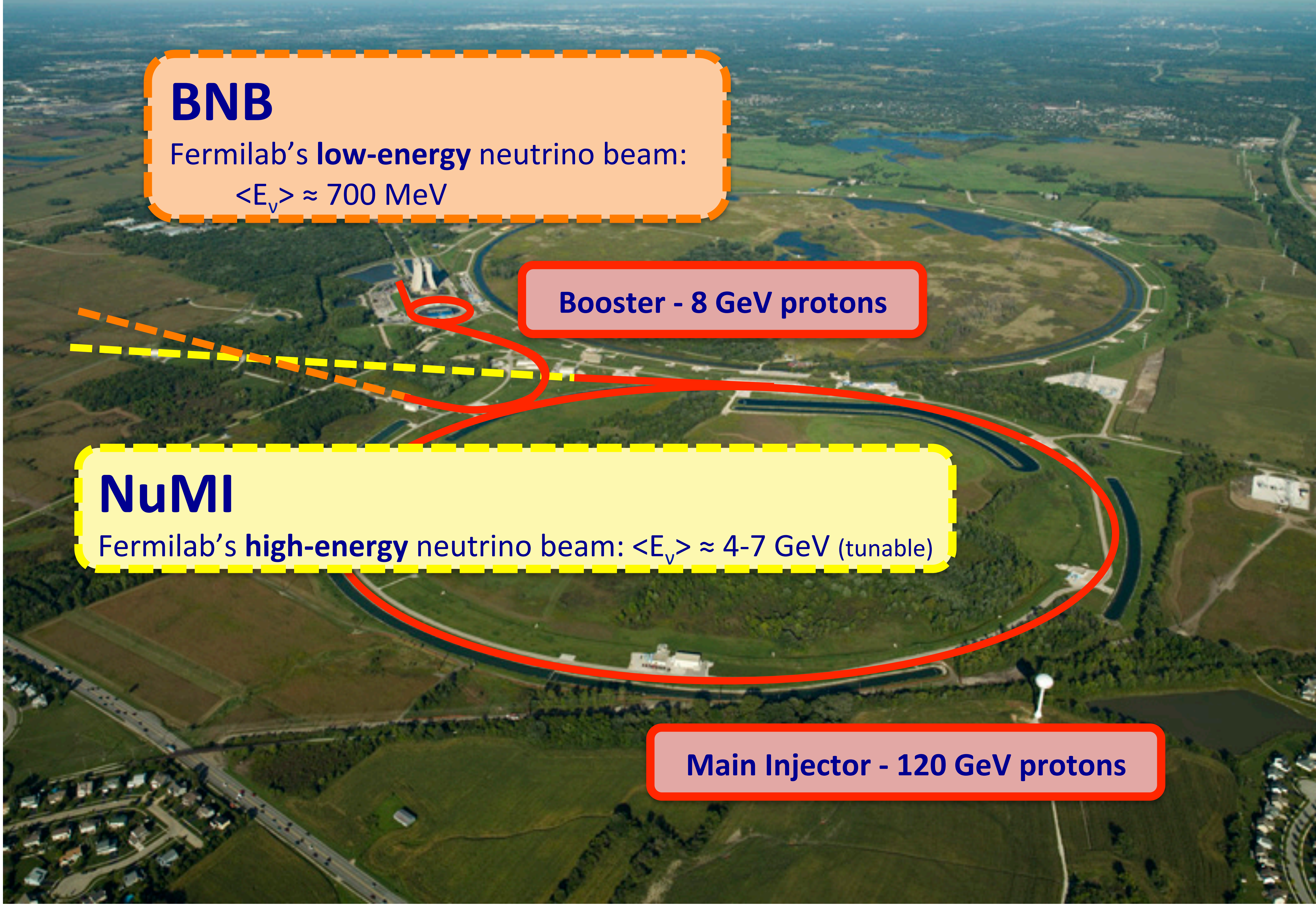
New Physics observables can be placed into two categories:
Modifications to the neutrino oscillation paradigm
(effects of BSM physics on neutrino oscillation)

Novel experimental signatures
(dark matter, heavy neutrinos, millicharged particles…)
produced in the beam target

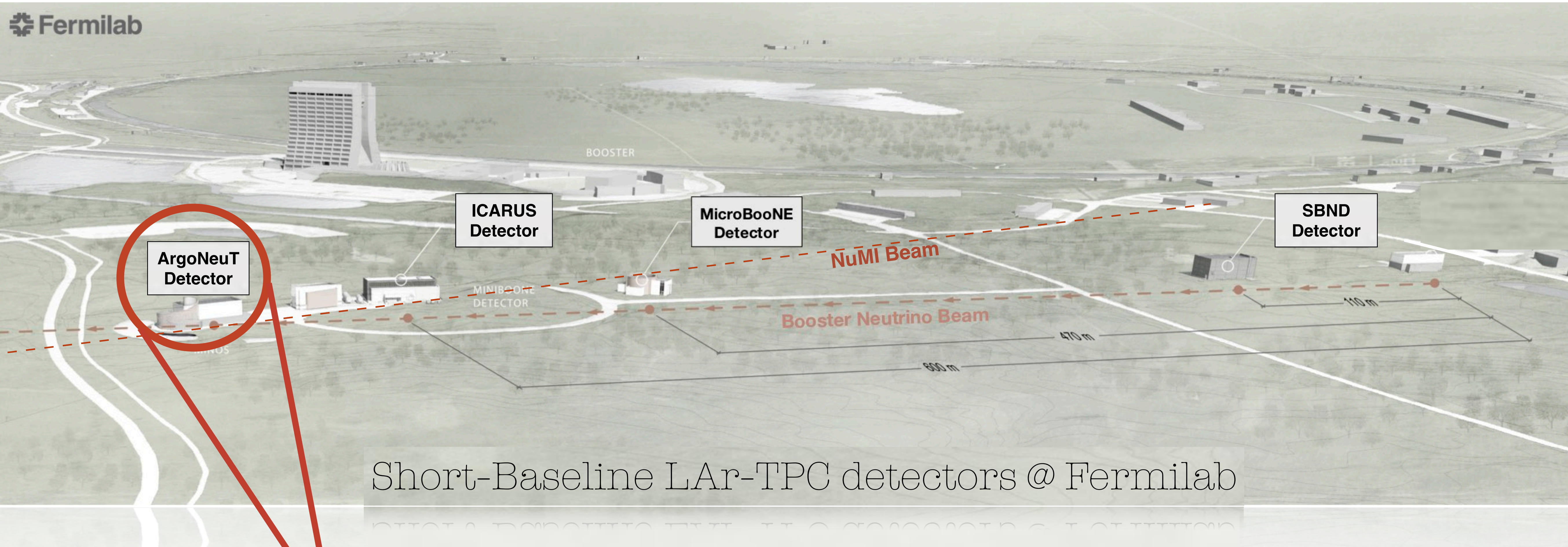
Sterile neutrinos
Neutrino tridents
Light Dark Matter
Heavy Neutral Leptons
Millicharged particles
…



Fermilab – Neutrino beams



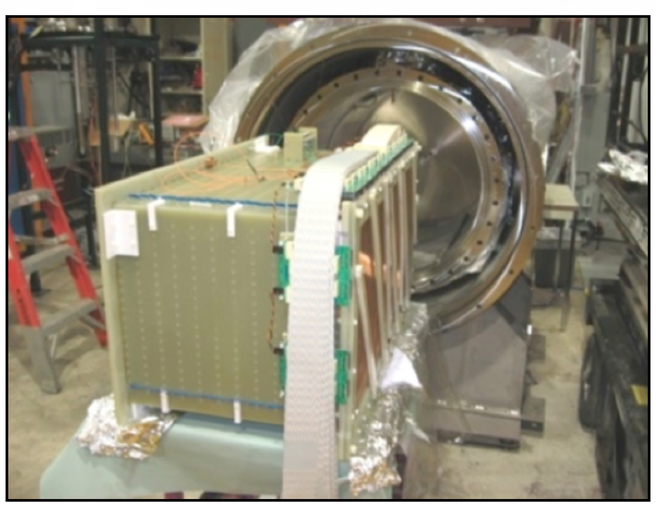
Short-Baseline LAr TPC detectors at Fermilab: ArgoNeuT



First LAr TPC detector at FNAL

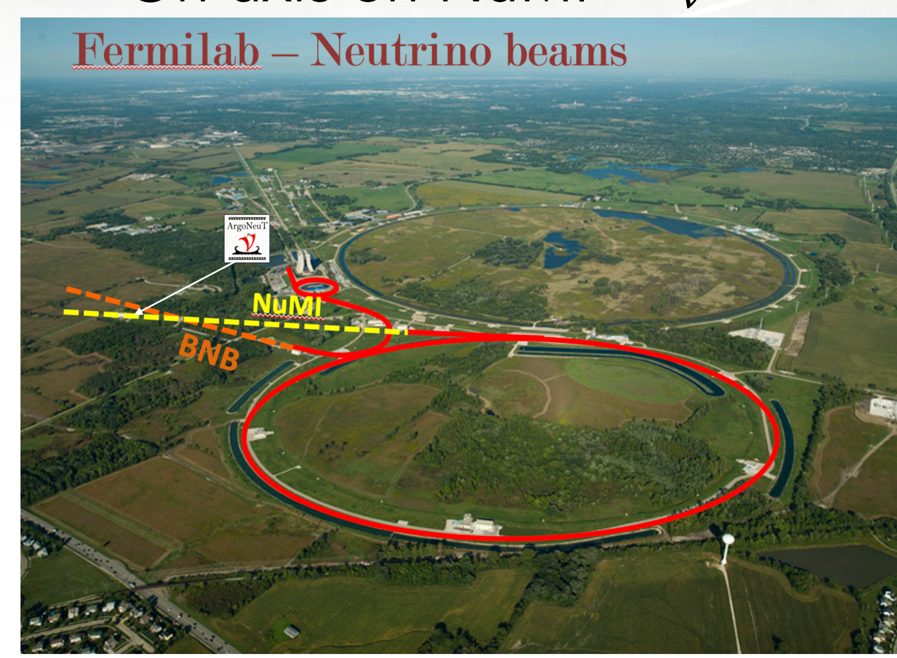
5 months data taking in 2009-2010

On-axis on NuMI $<E_\nu> \simeq 4$ GeV

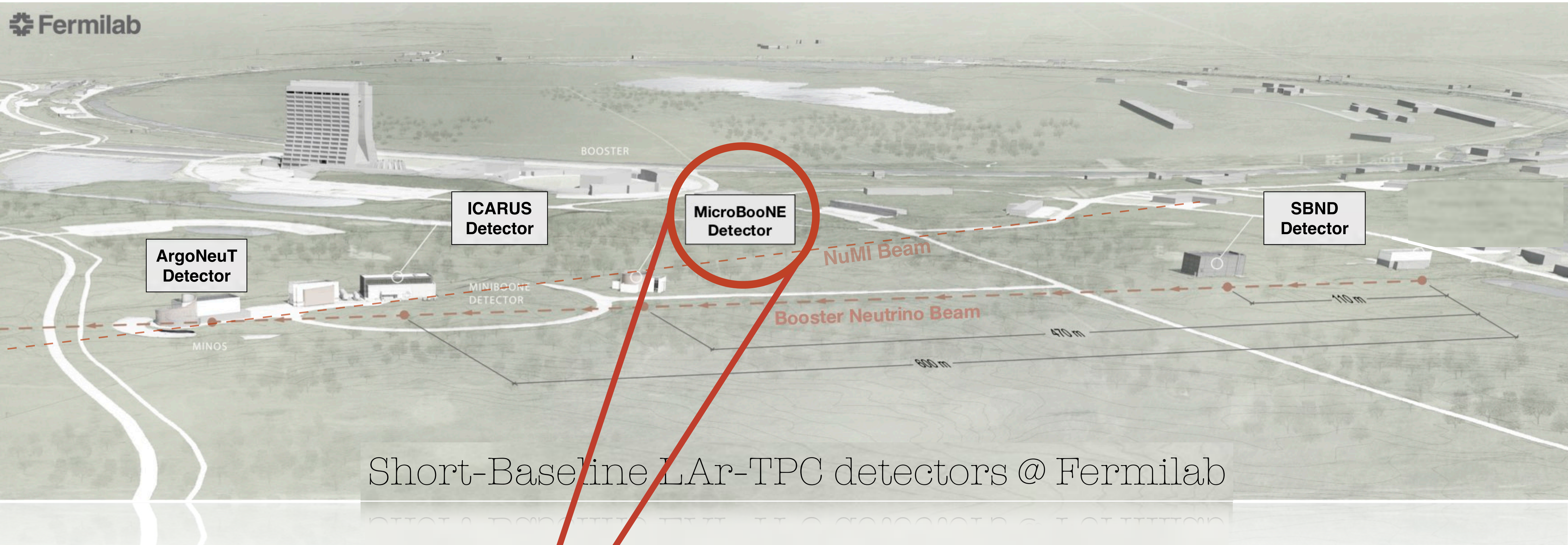


0.24 tons active volume LAr TPC

100 m underground, in front of the MINOS ND, ~ 1km from target

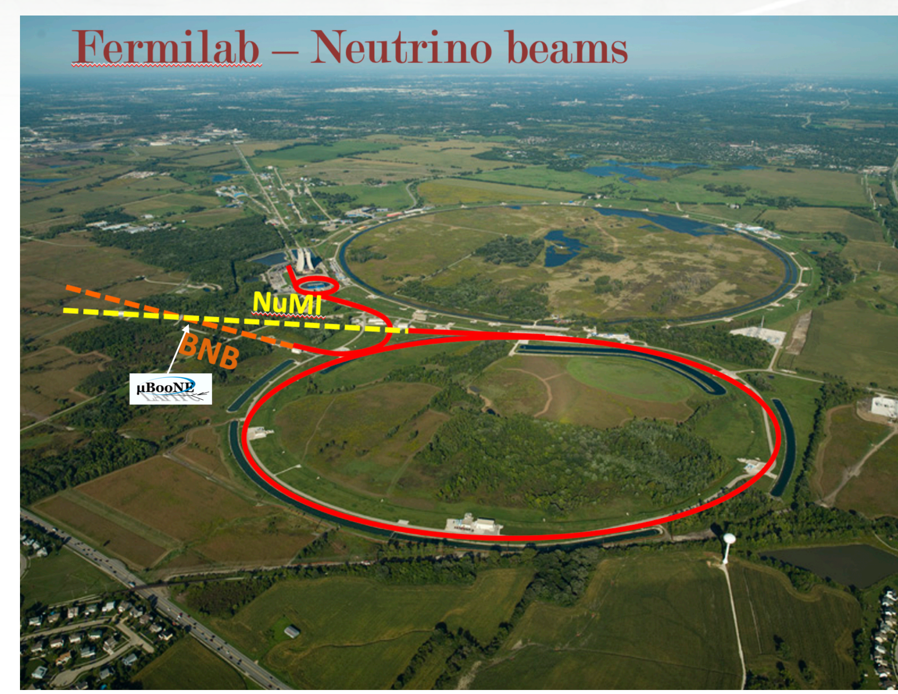


Short-Baseline LAr TPC detectors at Fermilab: MicroBooNE



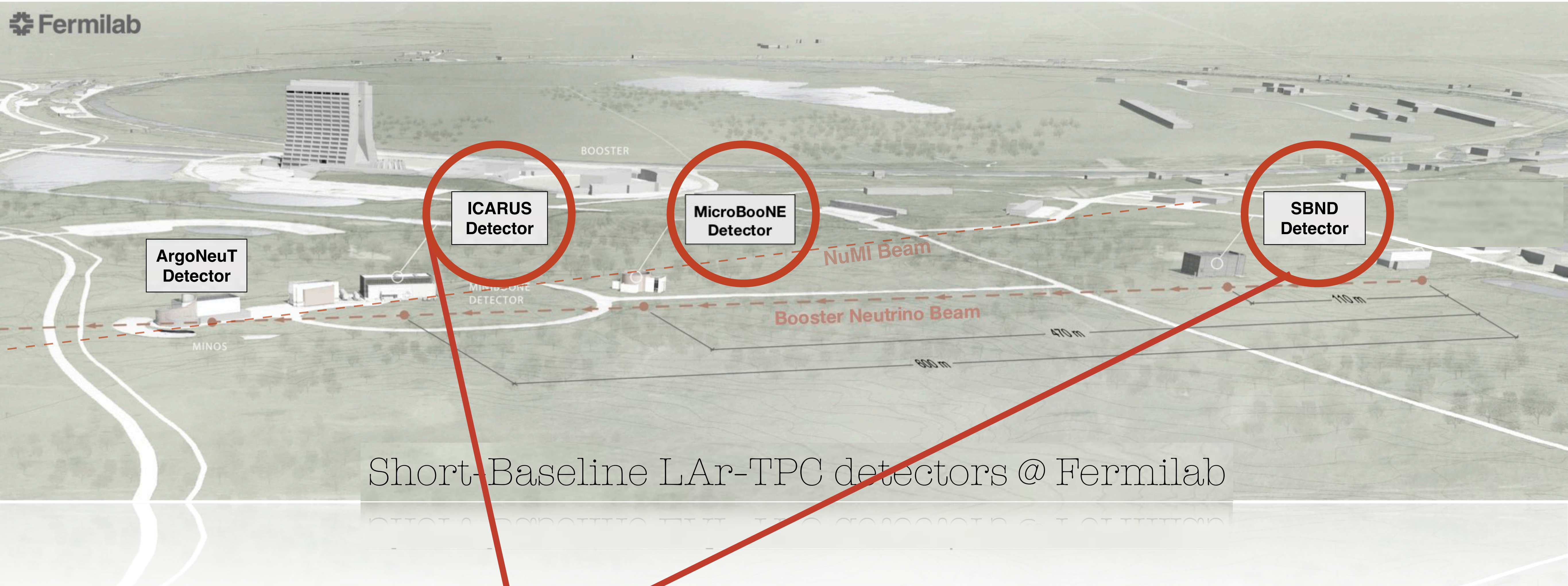
Currently the world's longest running LAr TPC (2015-present)

On-axis on BNB and off-axis on NuMI



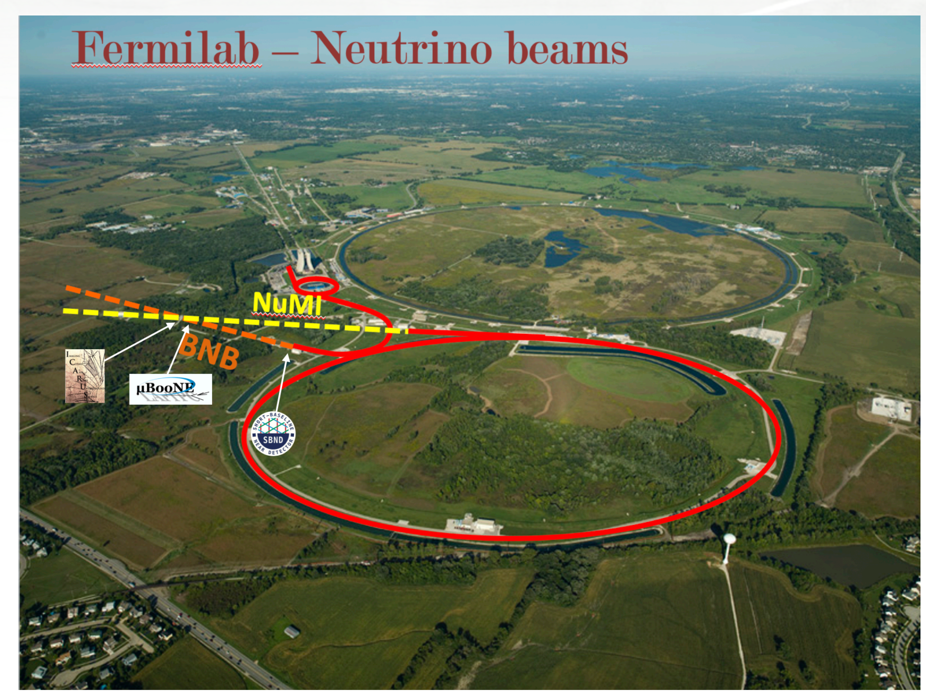
[see presentation by J.H. Jo on Aug. 19th]

Short-Baseline LAr TPC detectors at Fermilab: SBN detectors



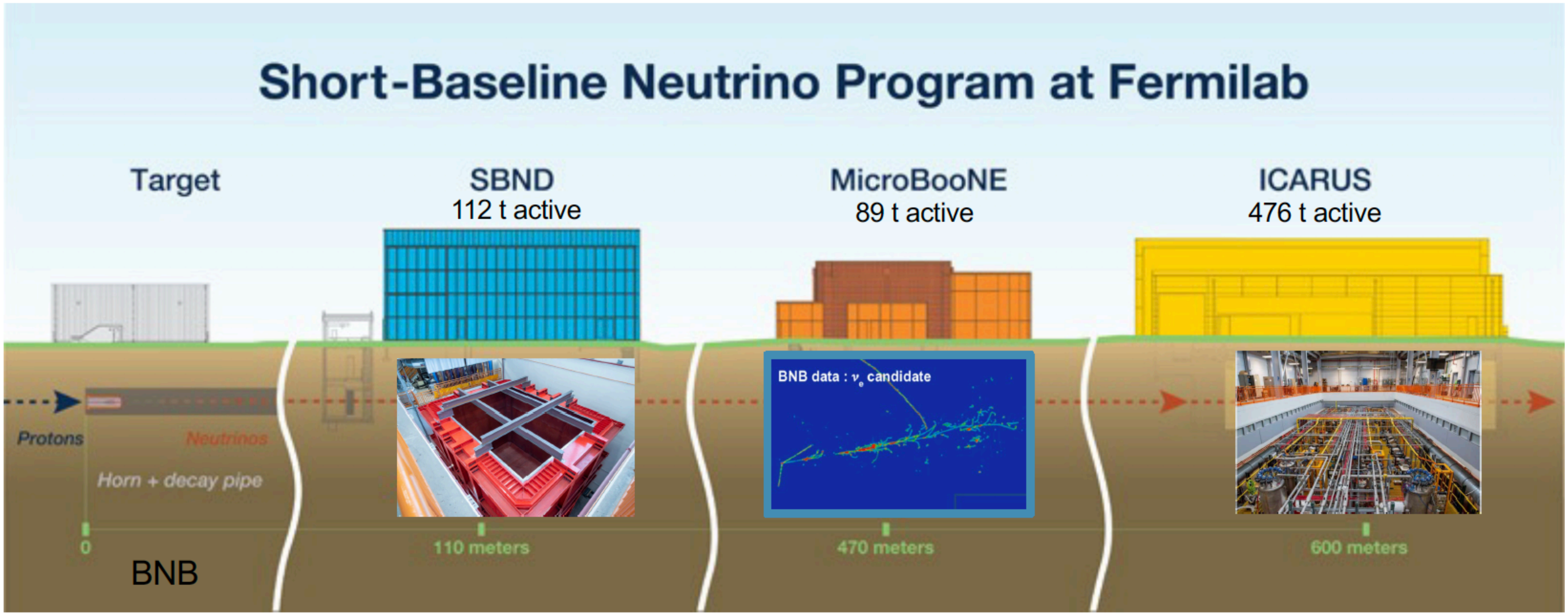
Two other detectors to form the Short-Baseline (SBN) program

On-axis on BNB (SBND, MicroBooNE, ICARUS) and off-axis on NuMI (MicroBooNE, ICARUS)



Short Baseline Neutrino program

arXiv:1503.01520, January 2014
P.Machado, O.P., D. Schmitz, Annu. Rev. Nucl. Part. Sci. 2019 DOI 10.1146



Installation in progress | Taking data since 2015 | Commissioning in progress

Designed for Sterile Neutrino searches

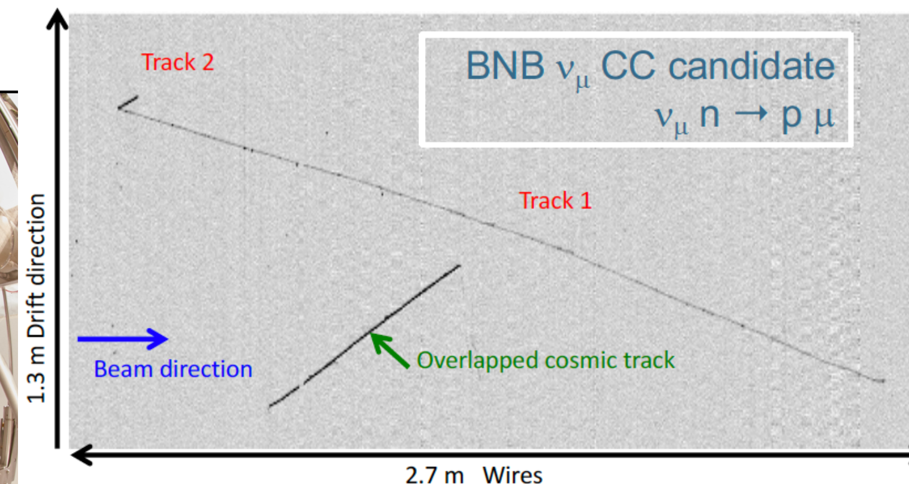
Same neutrino beam, nuclear target, detector technology:
reducing systematic uncertainties to the % level

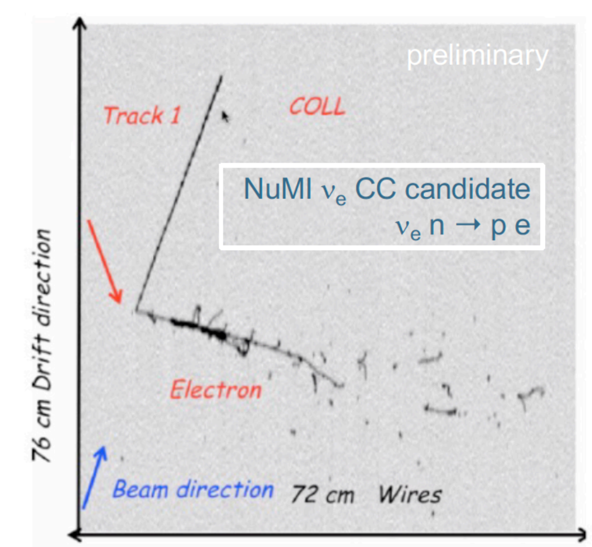
SBN Far detector: ICARUS

ICARUS has been commissioning since Summer 2020 and collecting neutrino data from the BNB and NuMI beams since March 2021

Improvements in progress during Summer 2021 shutdown

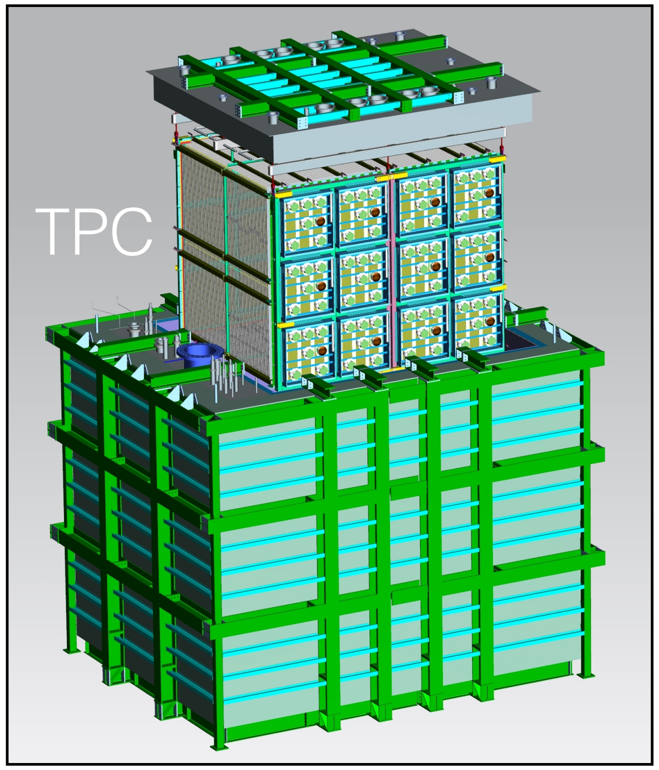
Physics data collection will begin in October 2021!

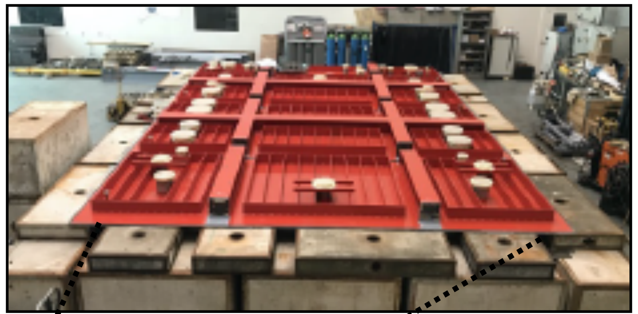




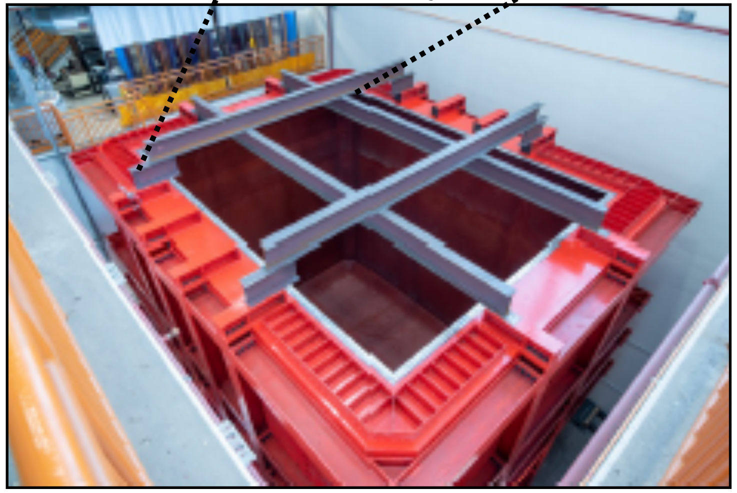
SBN Near detector: SBND

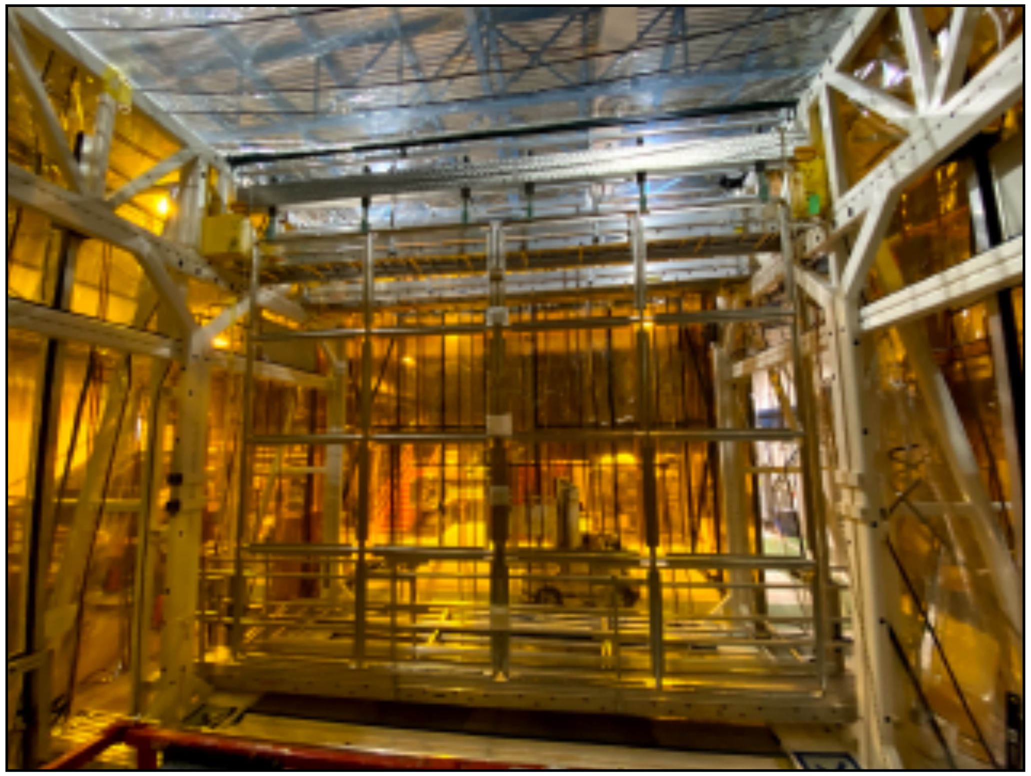
TPC components all at Fermilab
TPC assembly in progress at Fermilab
Warm outer vessel installed in the building
Cryogenics/cryostat installation in progress
Ready for cold commissioning by end of 2022



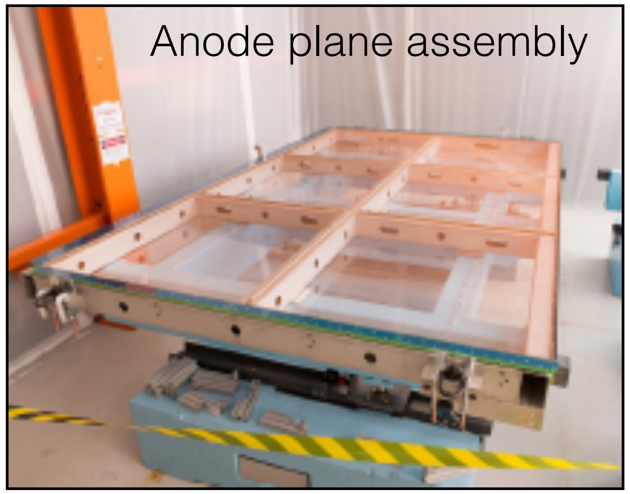


Warm cryostat



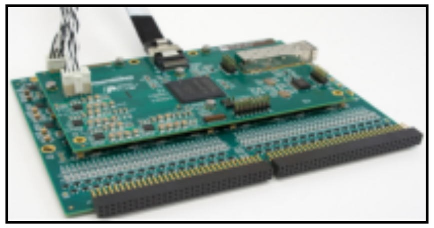


CPA plane installed



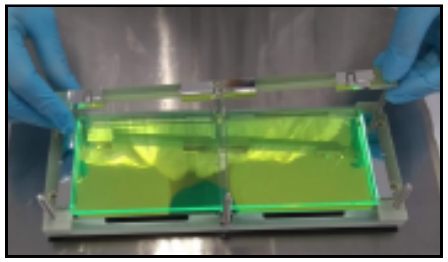
Anode plane assembly

CE front-end motherboard

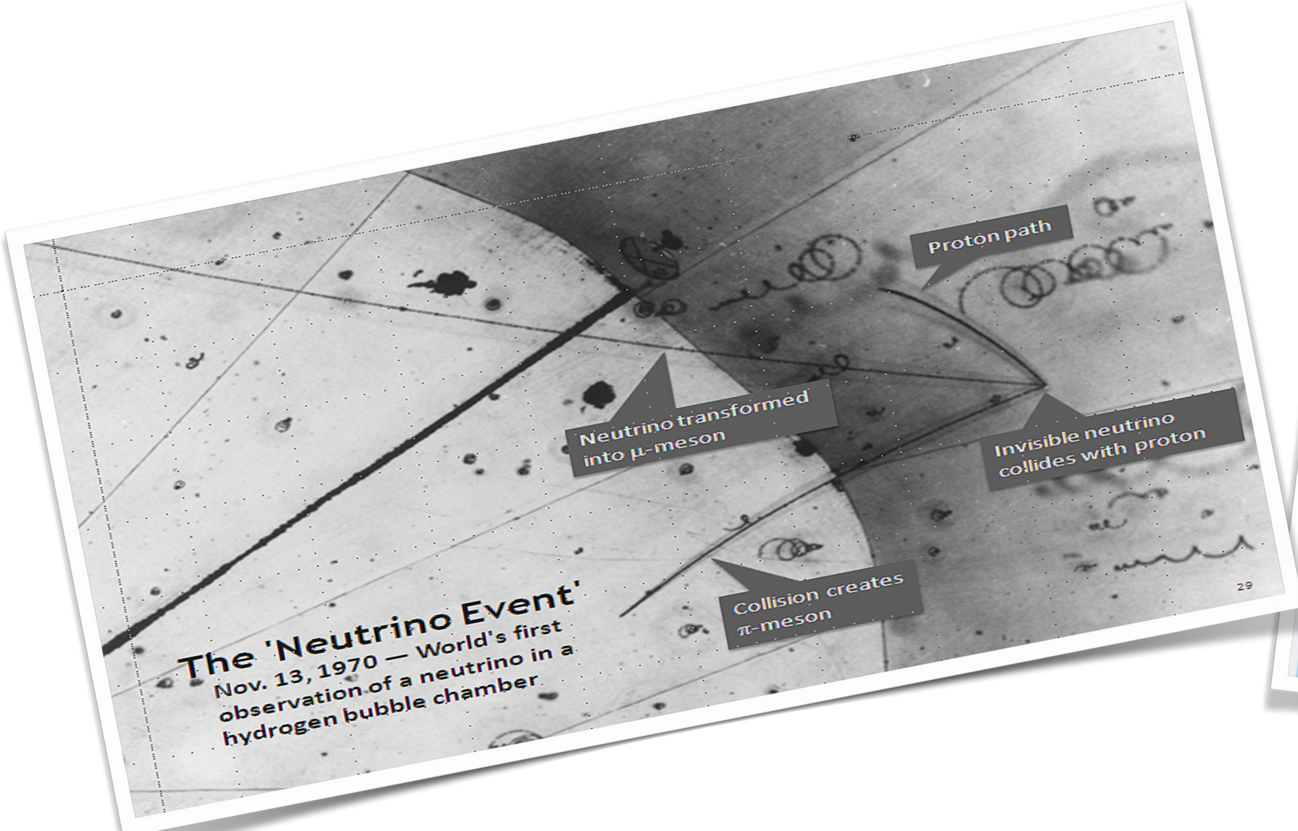


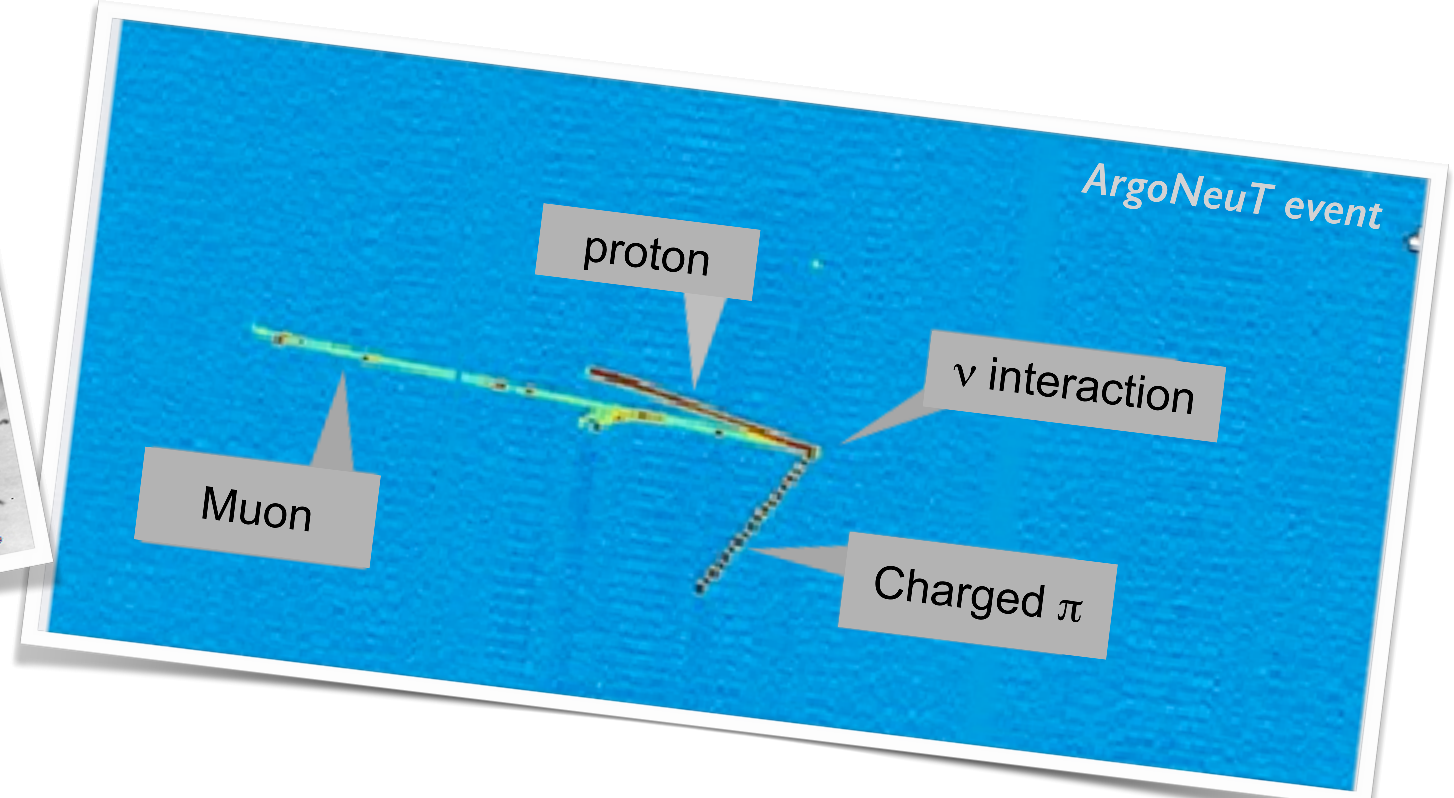
PDS module

X-ARAPUCA production



Why **Liquid Argon Time Projection Chamber**?



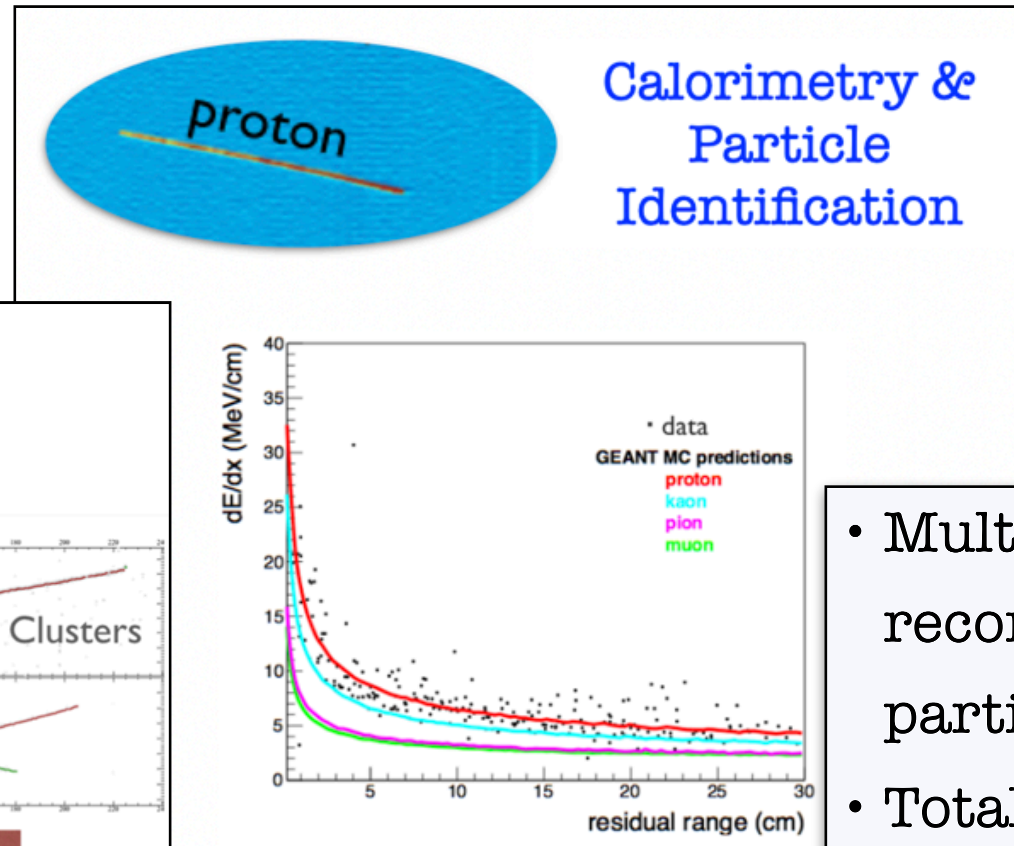


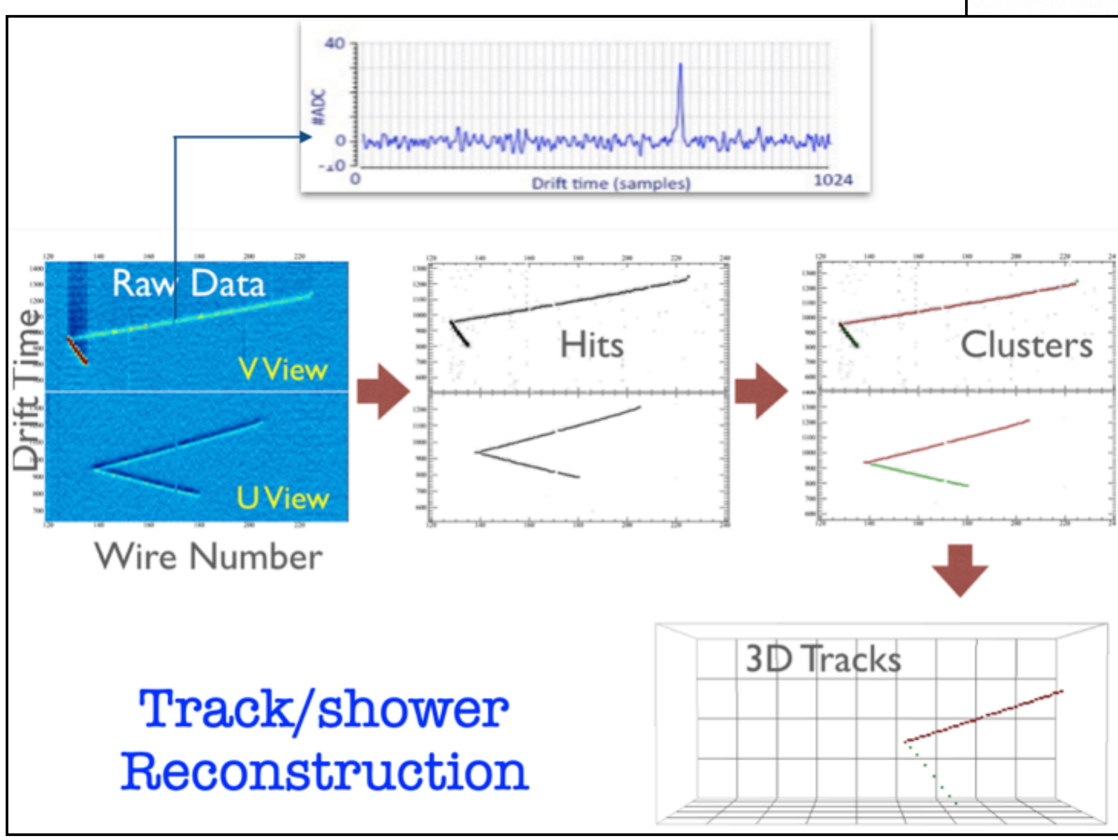
LAr TPC: Bubble chamber quality of data with added calorimetry

The LAr TPC Technology

LAr TPC technology offers the ability to measure neutrino interactions **in real time with (sub)-millimeter position resolution**, and has excellent sensitivity for energy depositions **from sub-MeV to few GeV**, far beyond that offered by any other neutrino detector

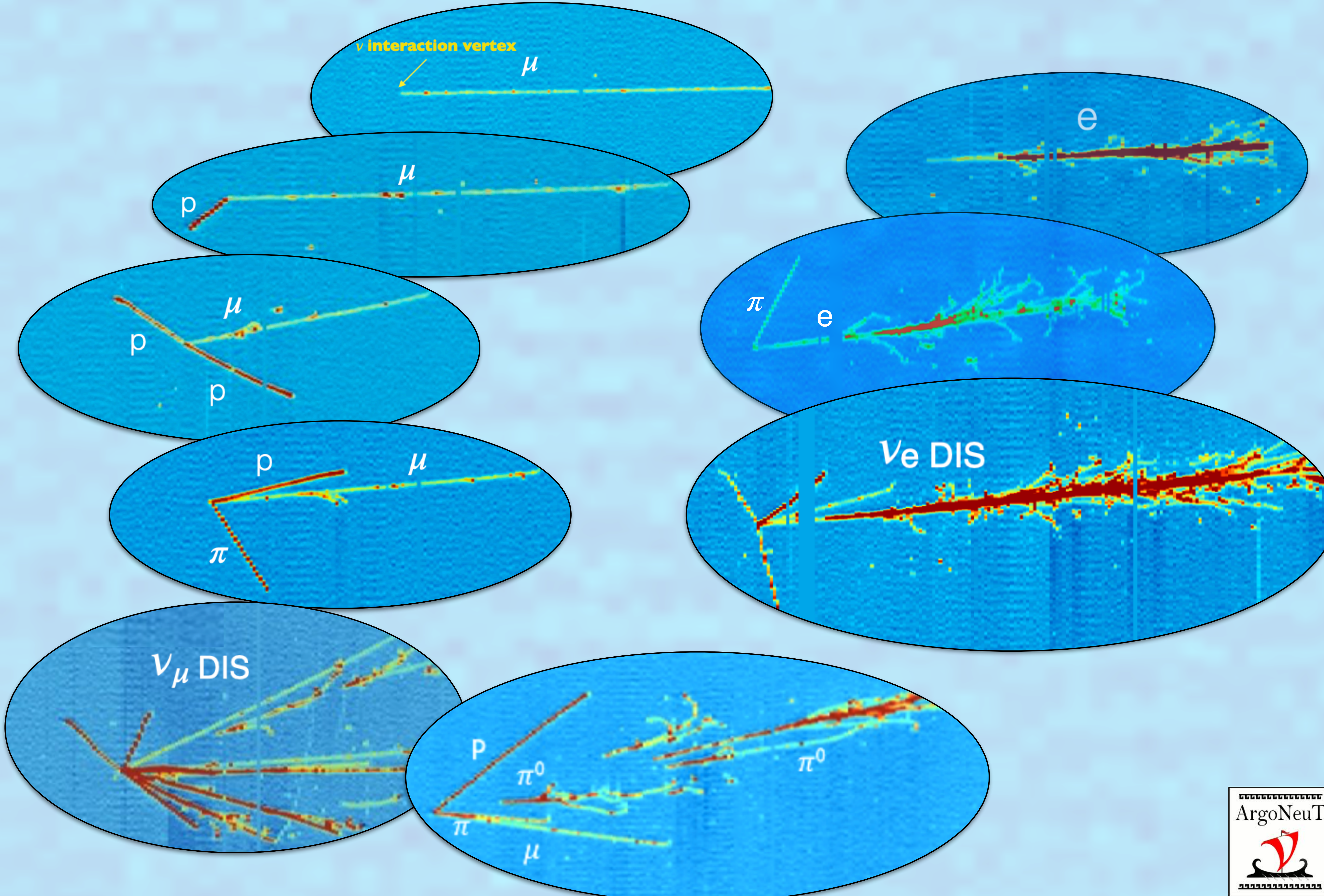
LArTPC at work: imagining and energy





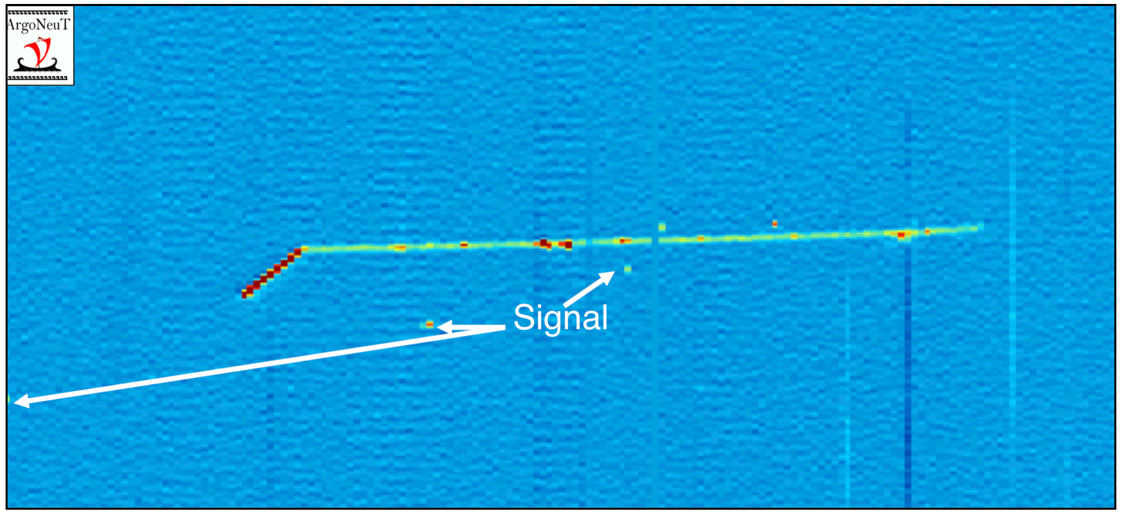
- Multiple 2D and the 3D reconstruction of charged particles ⇒ **Imaging**
- Total charge proportional to the deposited energy ⇒ **Calorimetry**
- dE/dx along the track ⇒ **Particle Identification**

From “easy” to progressively more complicated topologies…

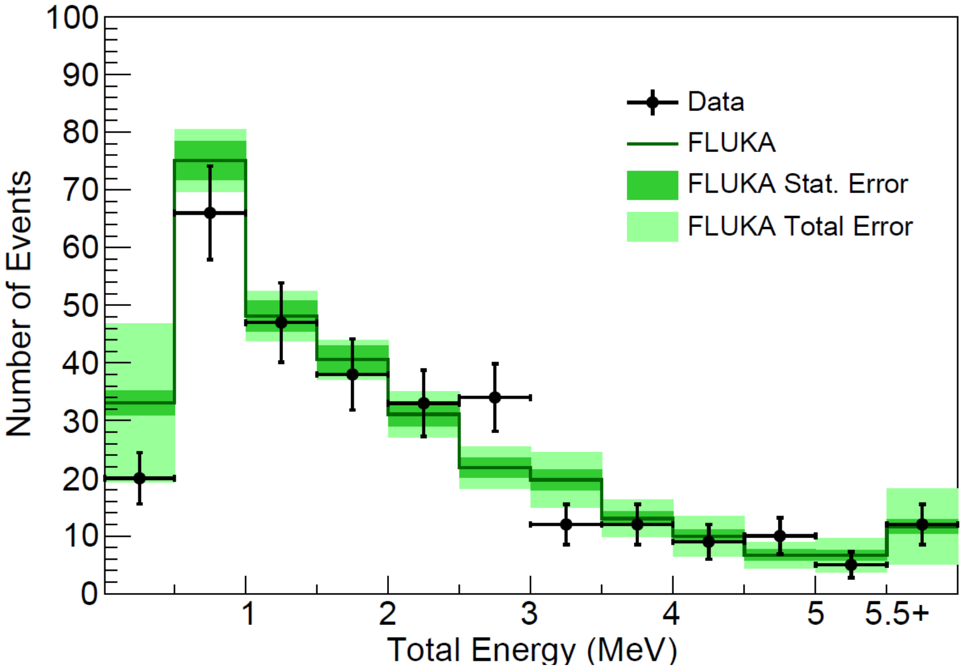


The Low Energy Frontier

LAr TPC's have demonstrated to be able to detect and reconstruct (sub-)MeV energy depositions!



R. Acciarri et al., Phys. Rev. D 99, 012002 (2019)



300 KeV threshold!

- Topologically separated low-energy depositions are identified as electrons produced by Compton scattering of
  - de-excitation photons from the target nucleus and
  - photon produced by neutron inelastic interactions
- The capability to resolve the individual collisions down to < MeV threshold is crucial for
  - detection and reconstruction of supernova neutrino interactions in large LArTPCs (ex. DUNE)
  - studies of new physics scenarios that could benefit invaluably from such low-energy reconstruction

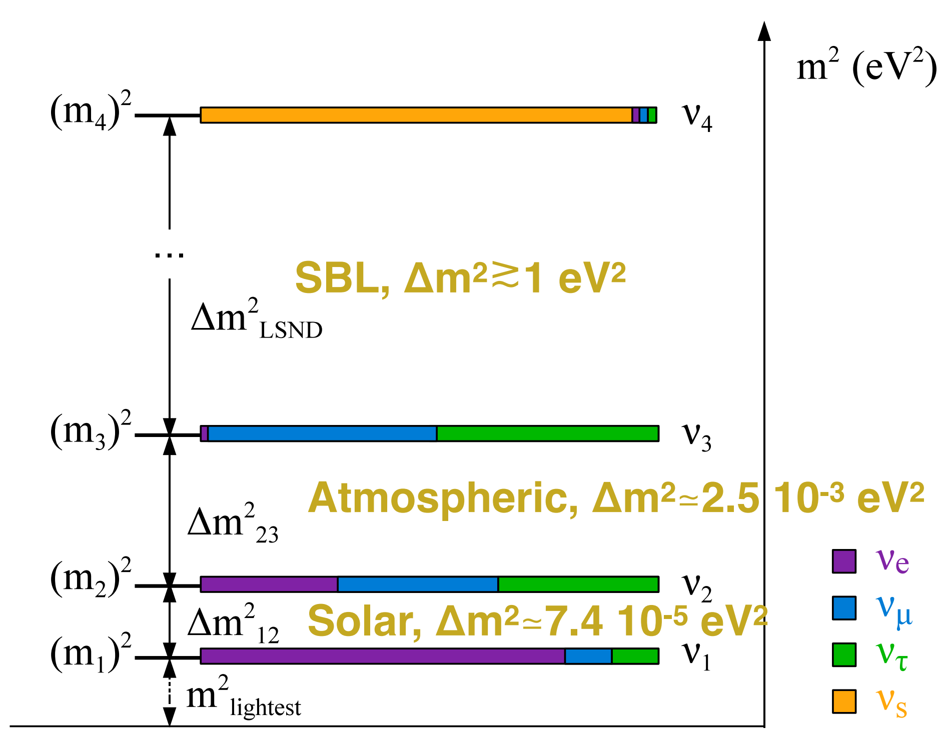
Experimental Hints For Beyond Three Neutrino Mixing

Short-Baseline Neutrino Anomalies

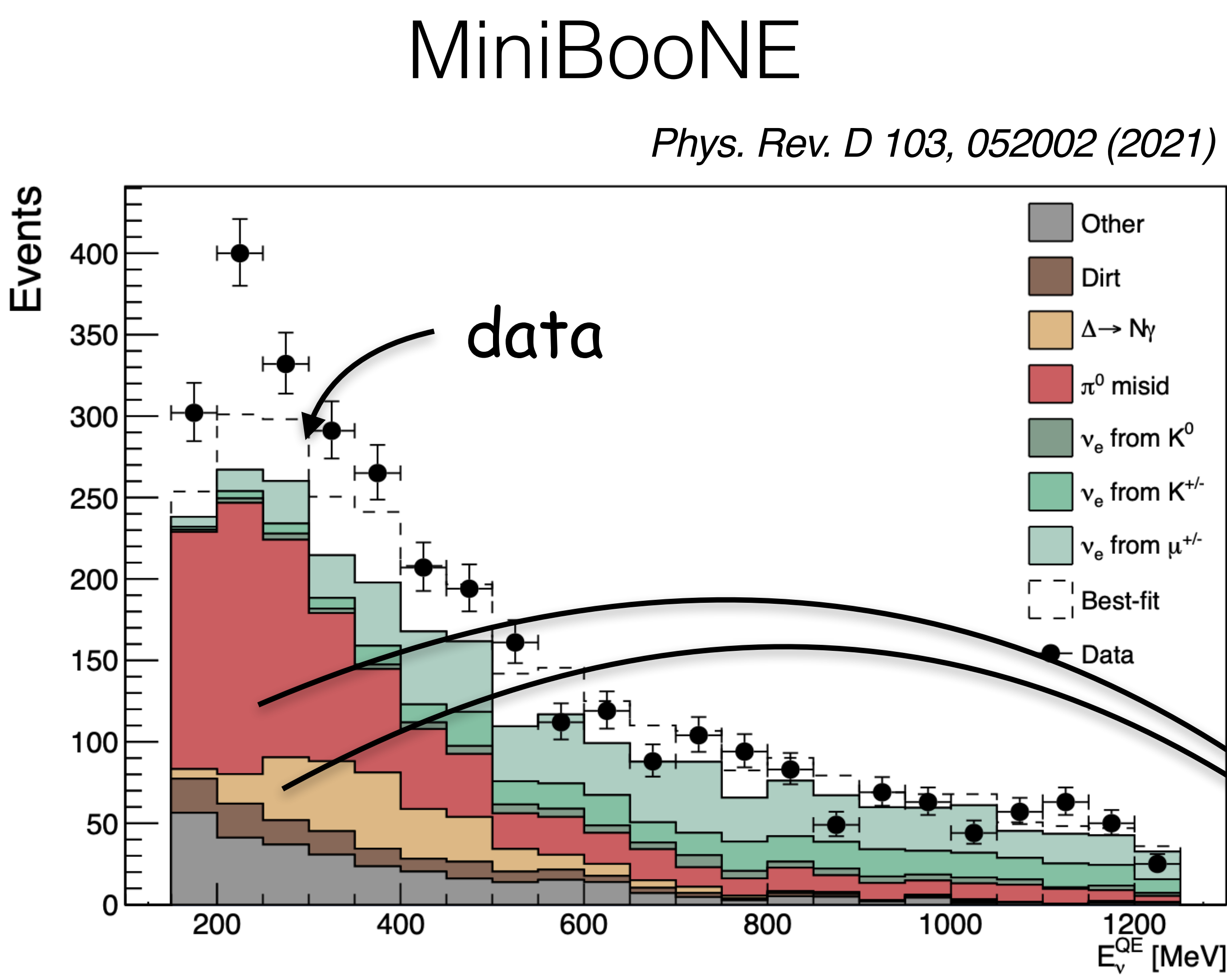
Accelerator "anomalies" (LNSD and MiniBooNE experiments) +
Reactor and gallium "anomalies"

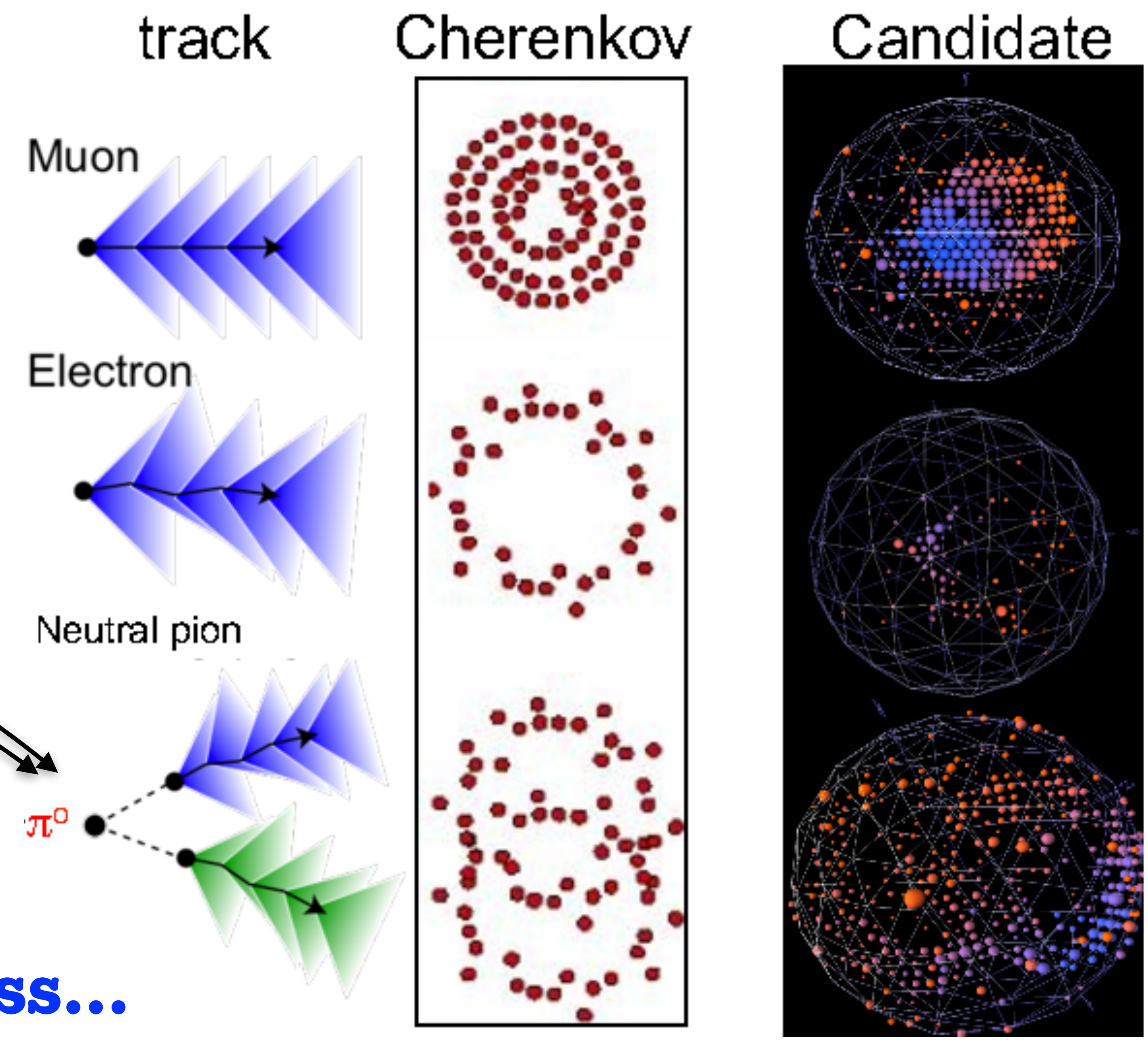
[see presentations by A. Minotti and S.H. See on Aug. 20th]

could be pointing at BSM physics in the neutrino sector:
additional "sterile" neutrino state(s) with
large mass-squared differences,
driving neutrino oscillation at small distances



Electrons or photons?



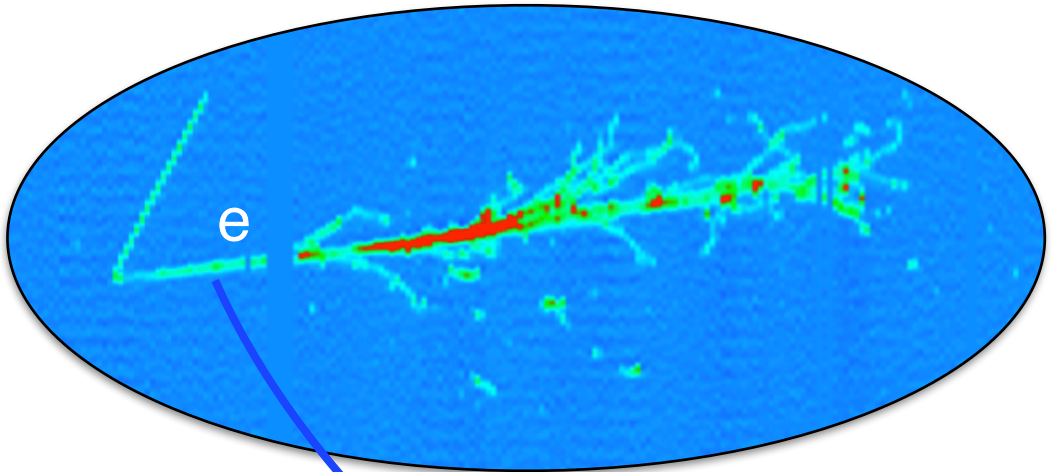


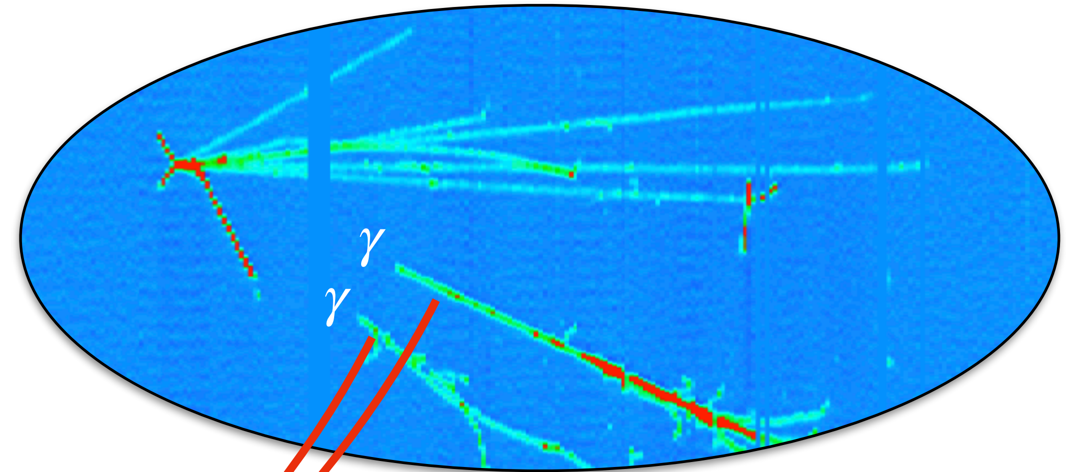
MiniBooNE Low Energy excess…

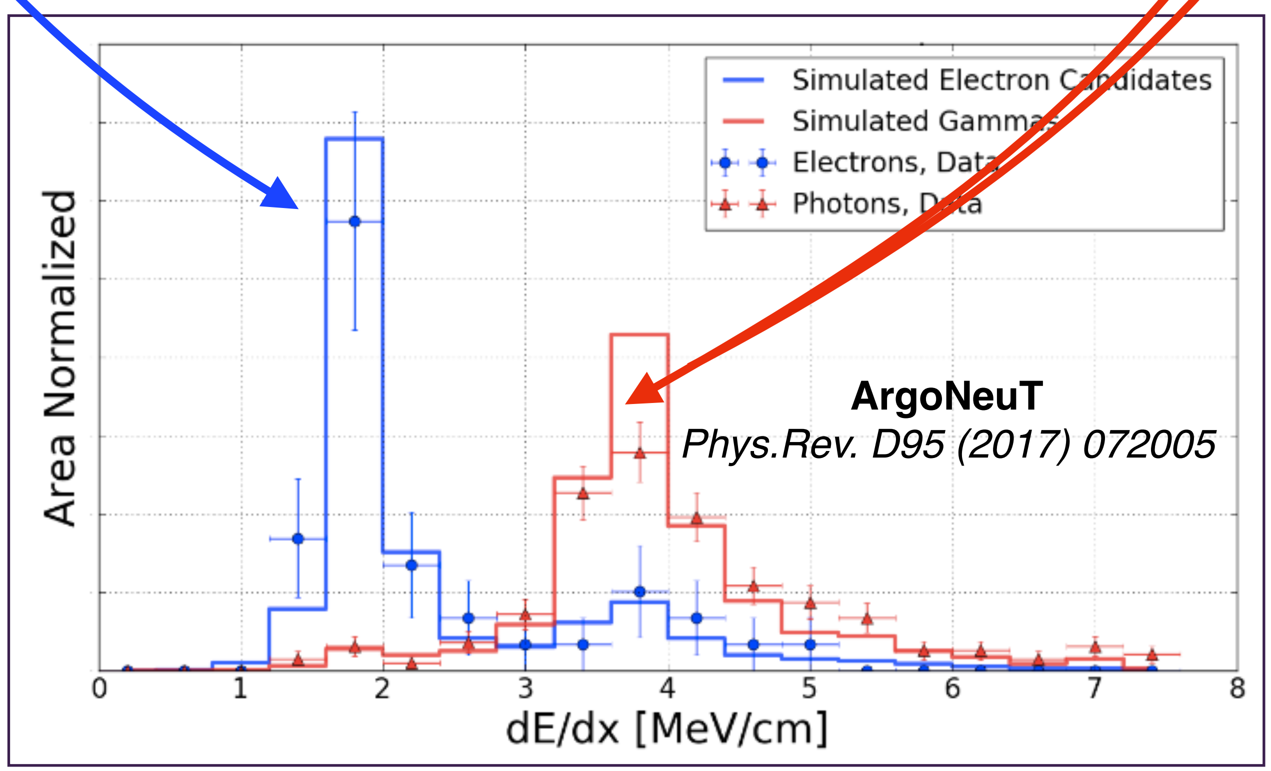
Photons? Electrons?

LAr TPC !

Electron-γ discrimination in LAr TPC





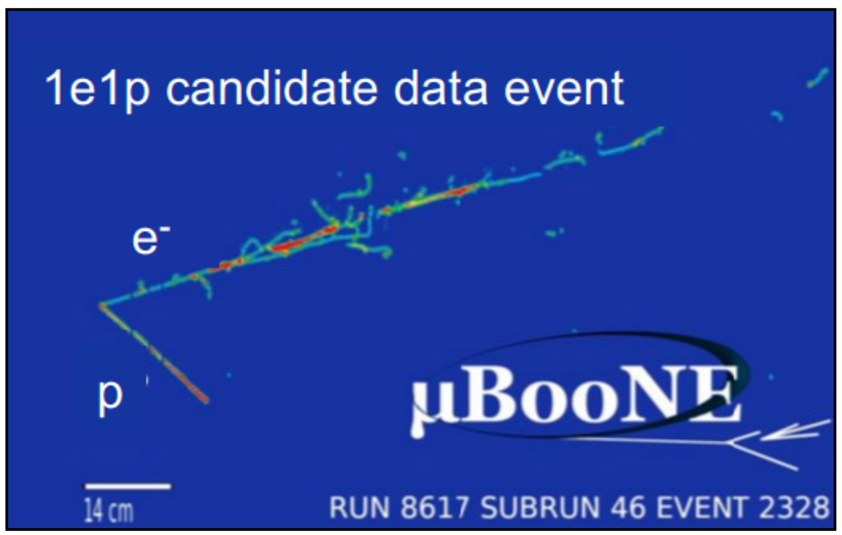


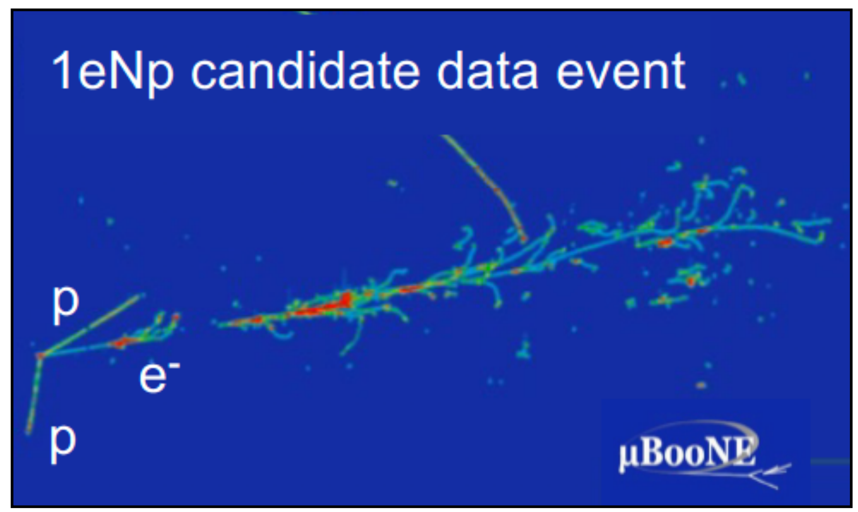
Analyzing topology (gap from the vertex) and dE/dx

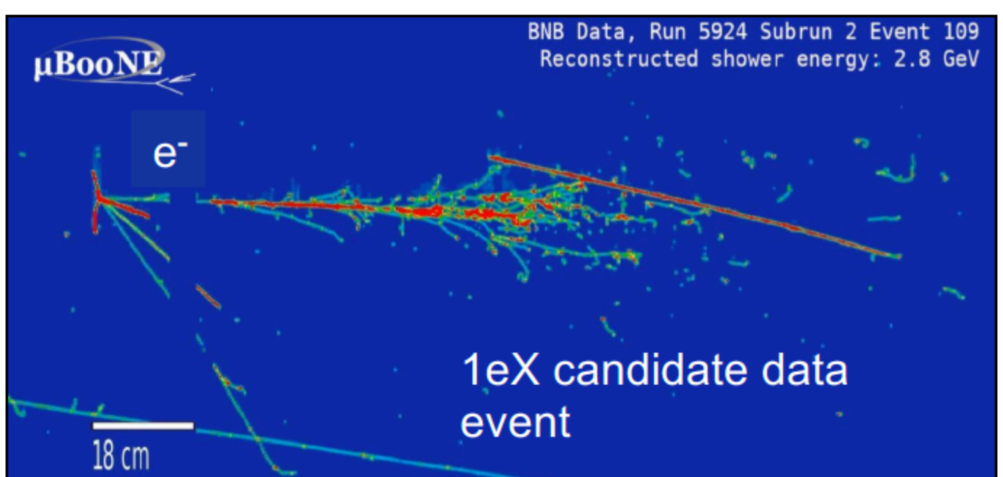
e-γ discrimination capability of LAr is crucial to understand the signal/background nature of the ν_e-like excess observed by MiniBooNE

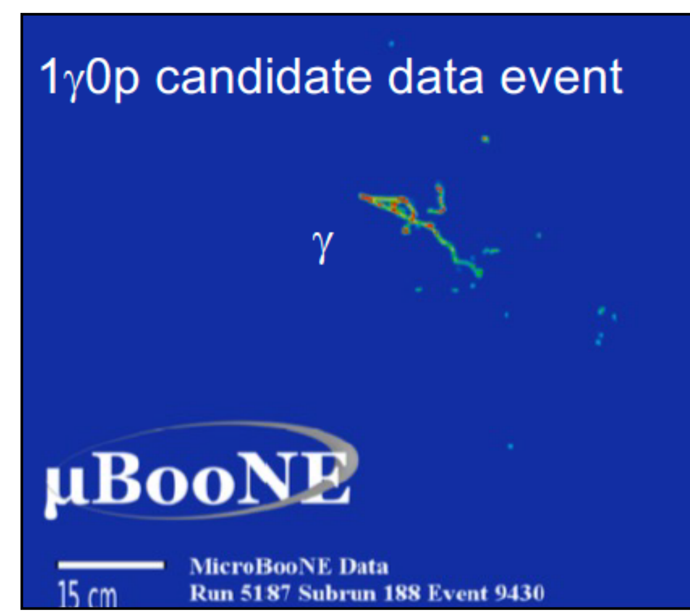
MicroBooNE experiment

- Designed to investigate the low energy excess events observed by the MiniBooNE experiment
- Physics run completed, R&D program now underway
- A series of first results on the "low energy excess" are around the corner (different final states)



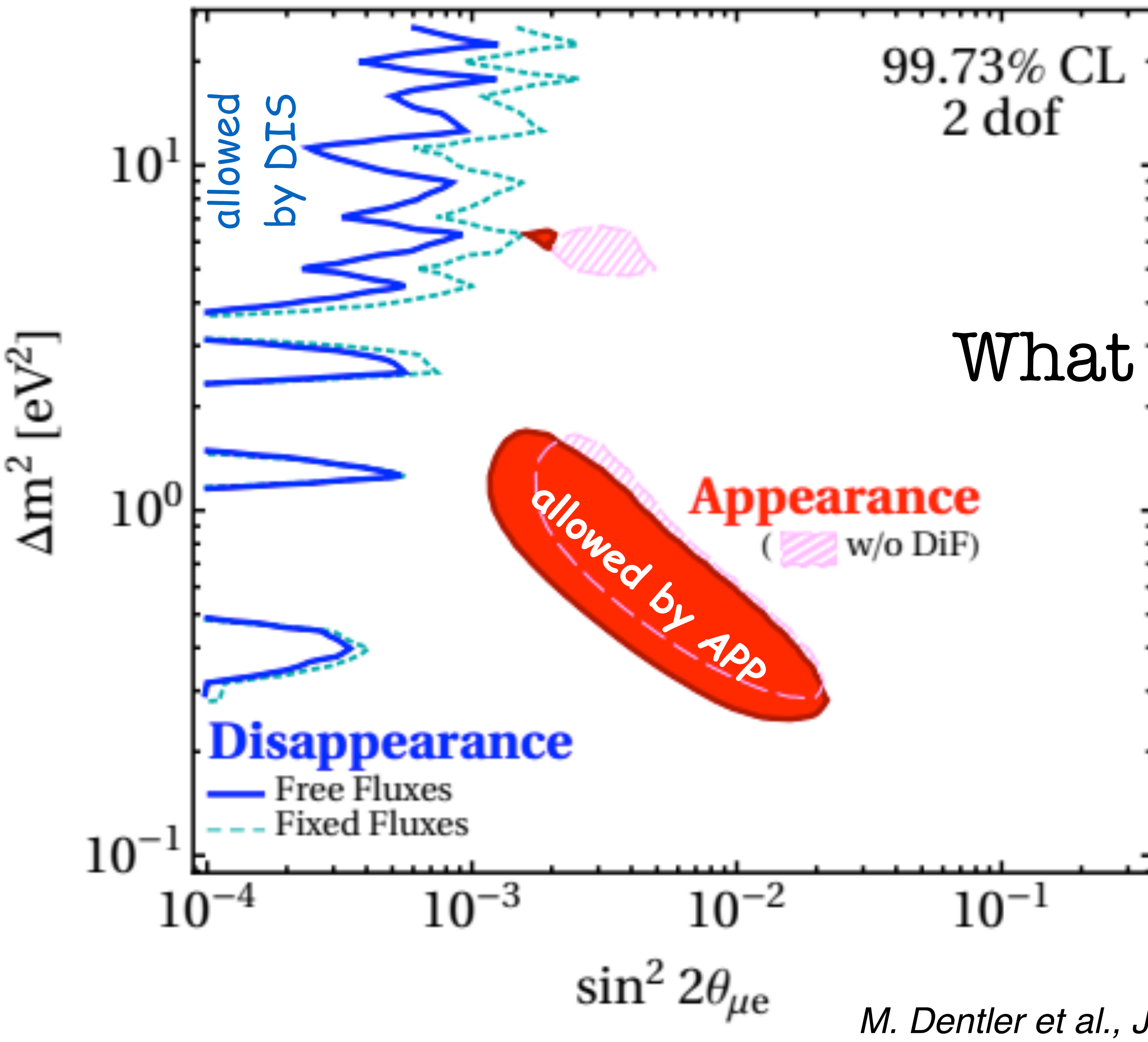






The Light Sterile Neutrino Experimental Landscape

The test of the sterile hypothesis



What is going on?

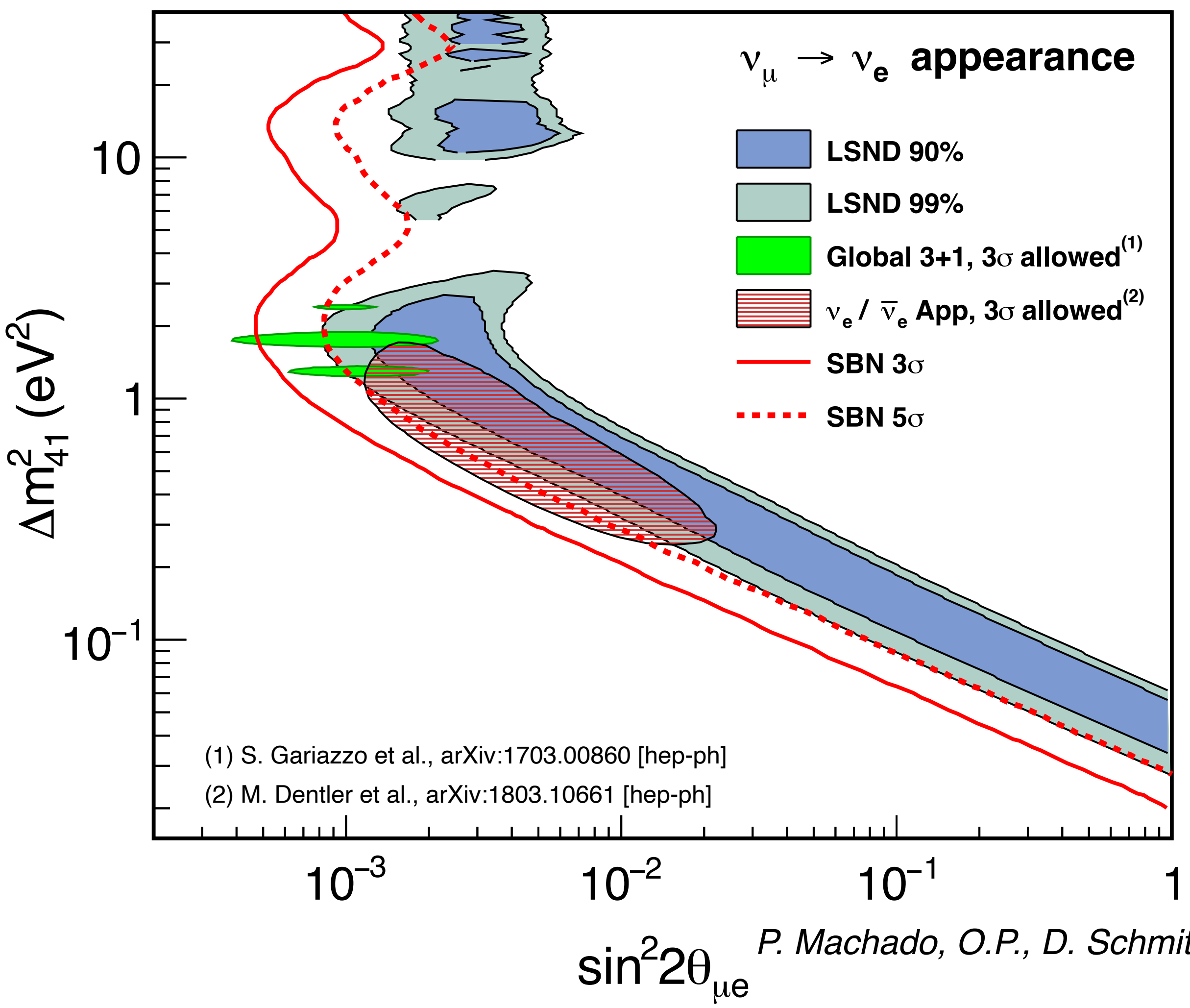
M. Dentler et al., JHEP 08:010 (2018)

4.7 σ tension arises when combining

ν_e appearance and ν_μ disappearance data sets

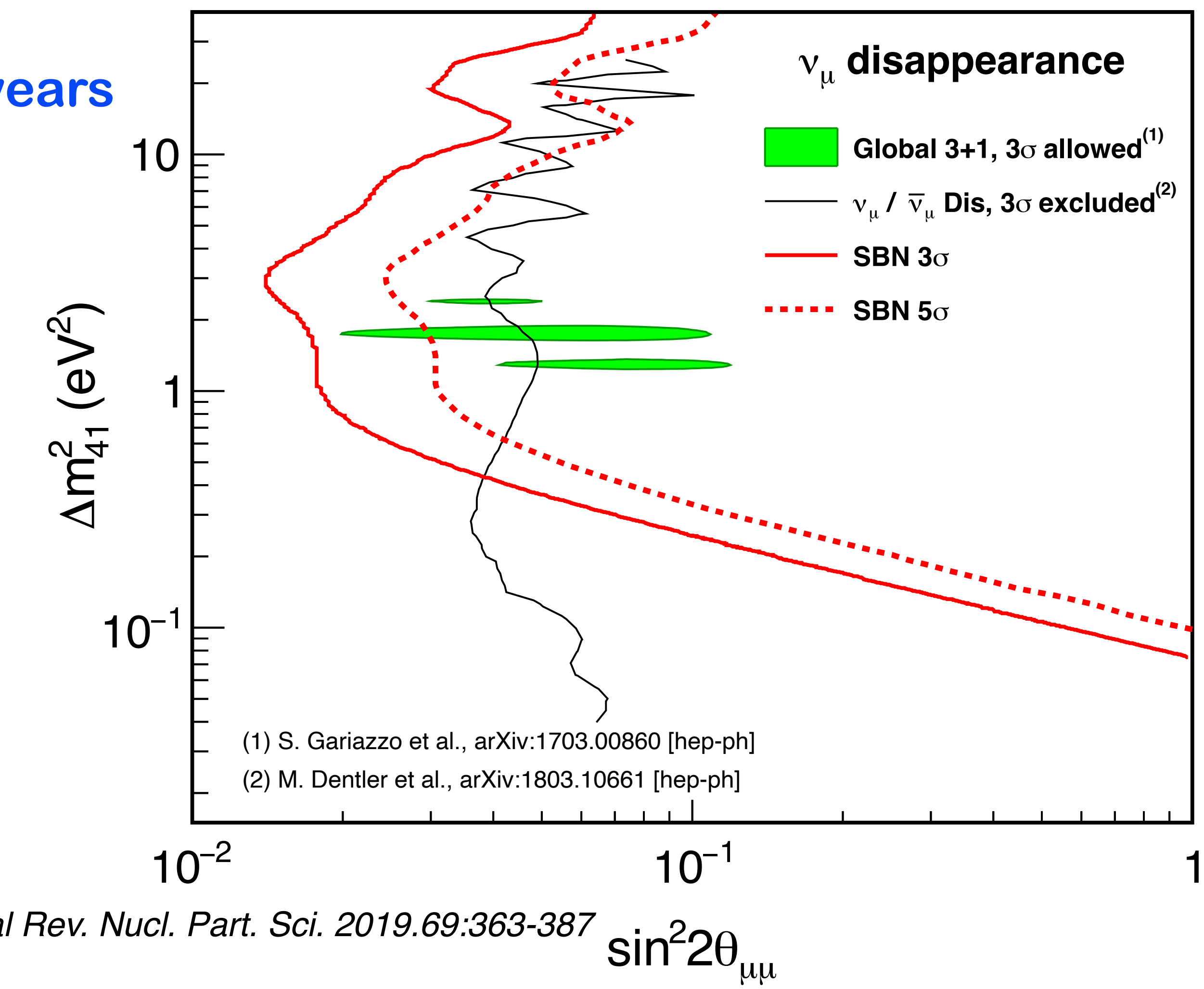
SBN Sterile Neutrino Sensitivity

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



~3 years

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



P. Machado, O.P., D. Schmitz: Annual Rev. Nucl. Part. Sci. 2019.69:363-387

SBN can cover the parameters allowed by past anomalies at 5σ significance

SBN also has sensitivity to ν_μ disappearance

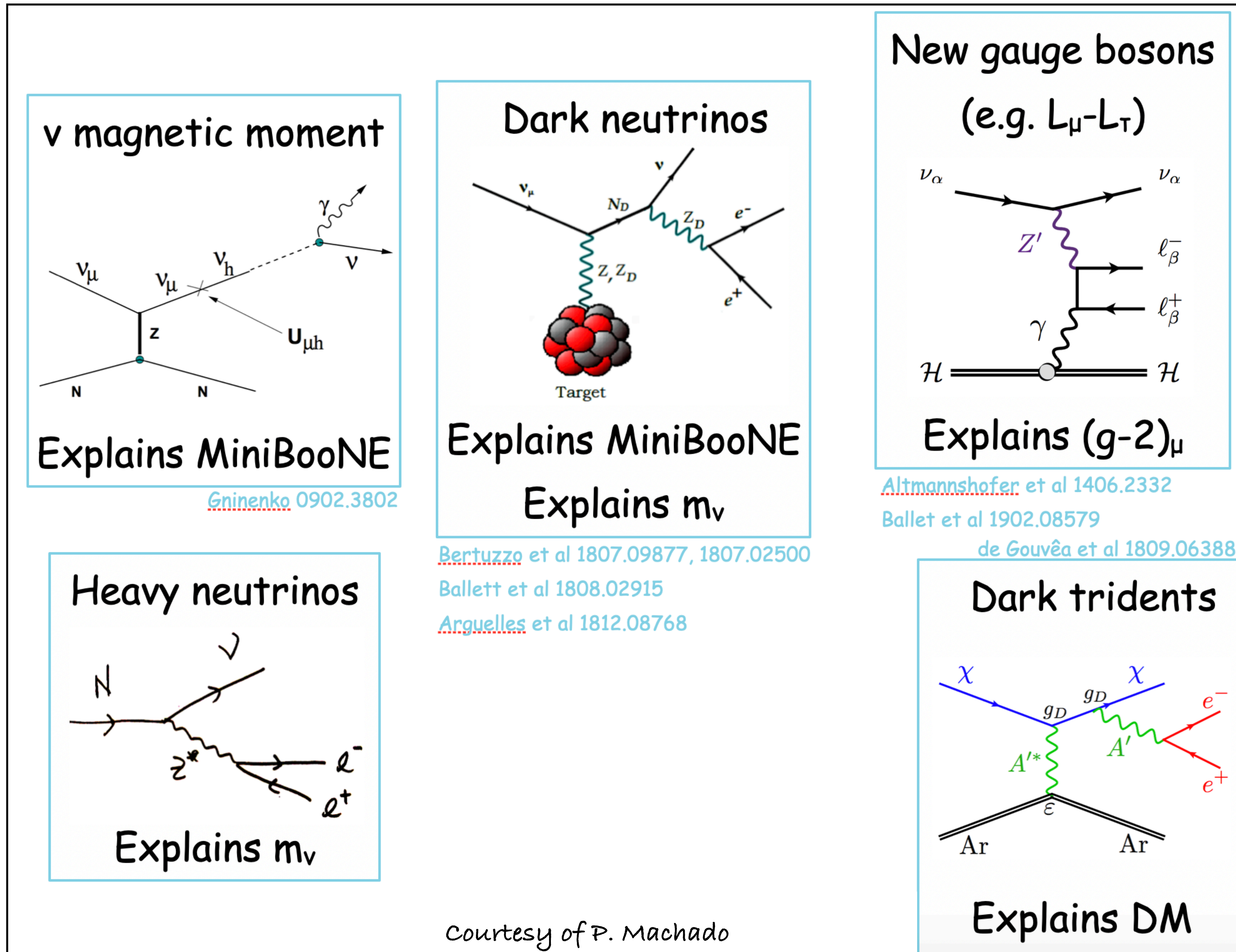
The observation of ν_μ disappearance would be essential to the interpretation of any electron neutrino excess as being due to the existence of sterile neutrinos

Evolving Landscape…

Several alternative BSM models to explain **SBL anomalies** (ex. ν_e appearance but not ν_μ disappearance) have been proposed

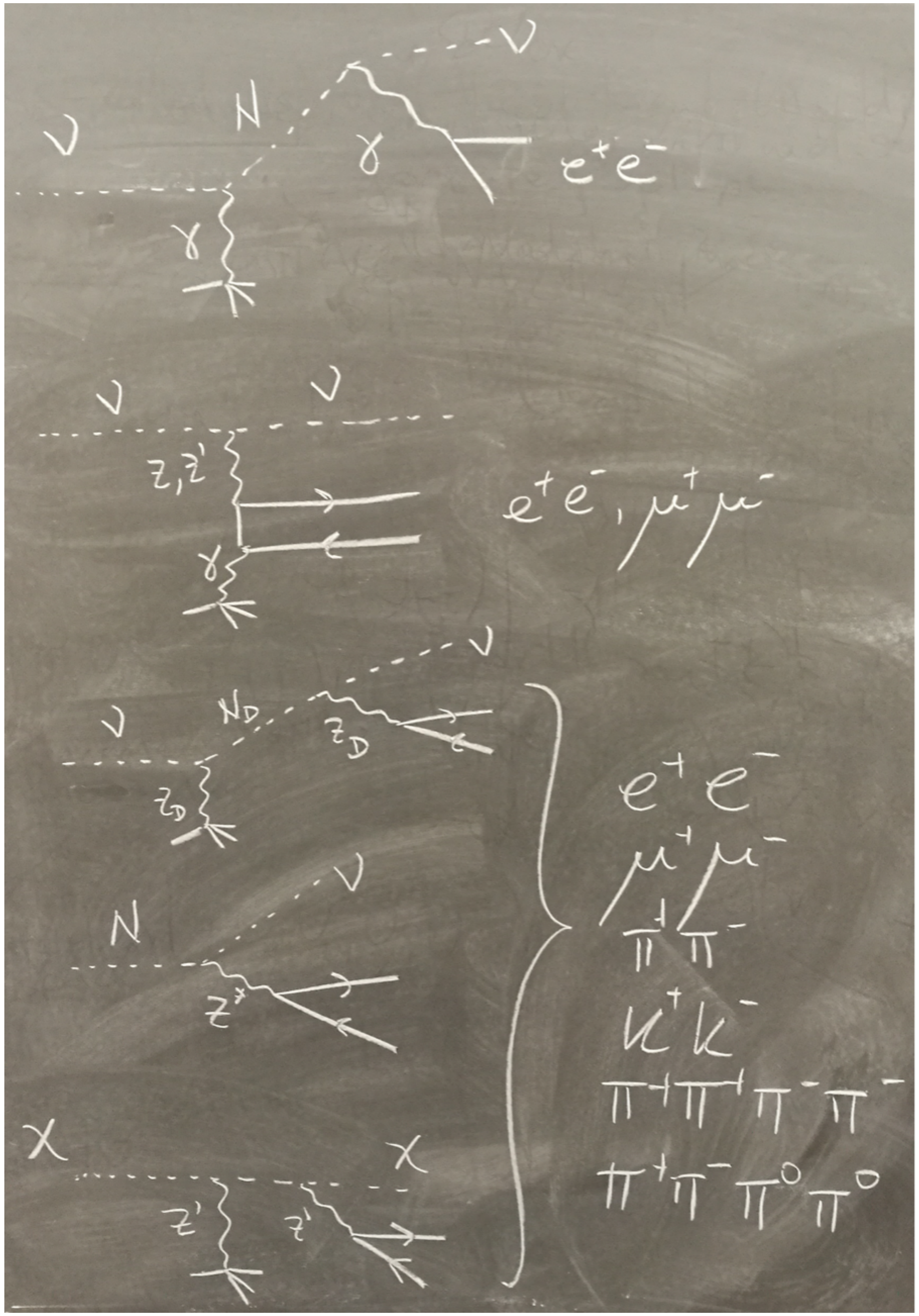
- Many of these models predict complex final states and differing levels of hadronic activity

Several cases:
"trident" **lepton⁺lepton⁻** final state



Note: not an exhaustive list!

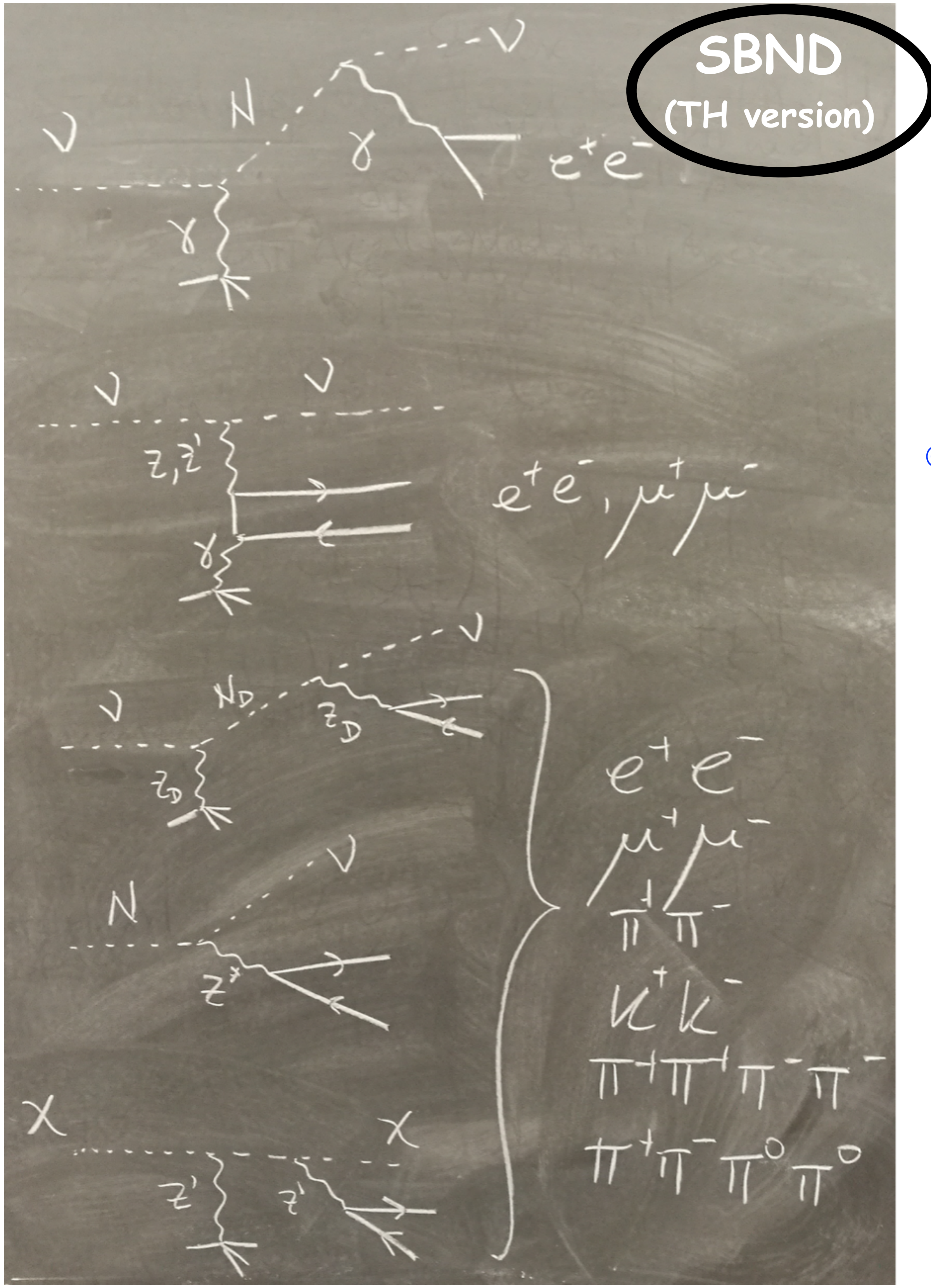
Evolving Landscape…



Courtesy of P. Machado

- Some of these signatures are *"clearer"*, like the $\mu^+\mu^-$ trident
- Others are more challenging, especially due to backgrounds
- In several detectors
  - photons, electrons and e^+e^- are indistinguishable

Evolving Landscape...



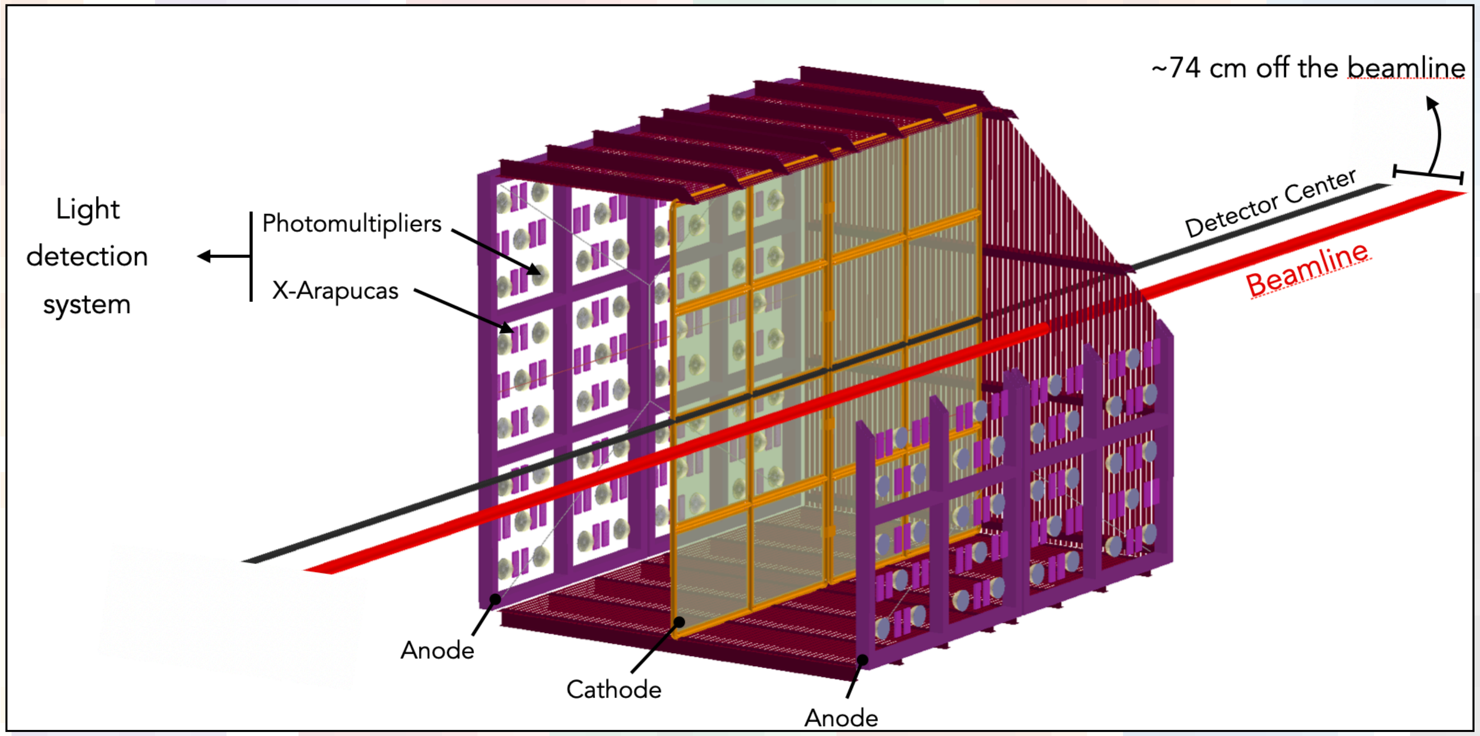
Courtesy of P. Machado

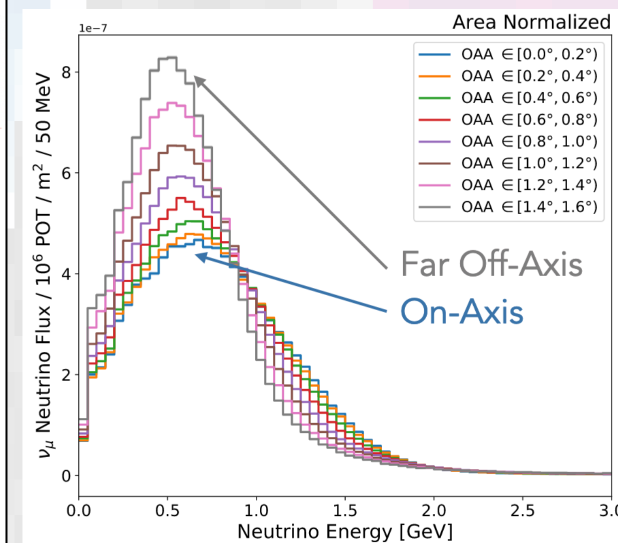
- SBN(D) experiment(s) exploring the landscape and **testing not only the sterile neutrino hypothesis**, but also other **new physics models**
  - Leveraging on the unique capabilities of the LAr TPC technology which open up more information than available in a Cerenkov detector such as MiniBooNE
  - Characterize in term of particle content and kinematics
  - Recognize the presence hadronic activity is critical to distinguish these possibilities!

P. Machado, O.P., D. Schmitz: Annu. Rev. Nucl. Part. Sci. 2019.69:363-387

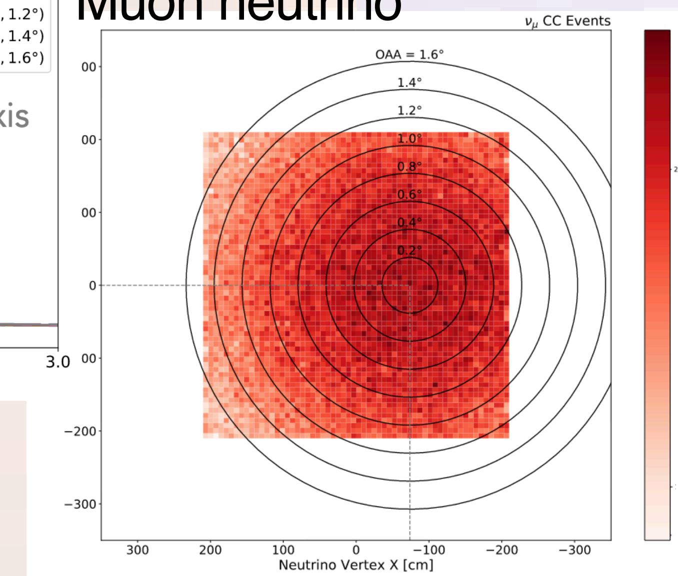
SBND-PRISM: Sampling Multiple Off-Axis Fluxes with the Same Detector

Unique feature: a Slightly Off-Axis Detector

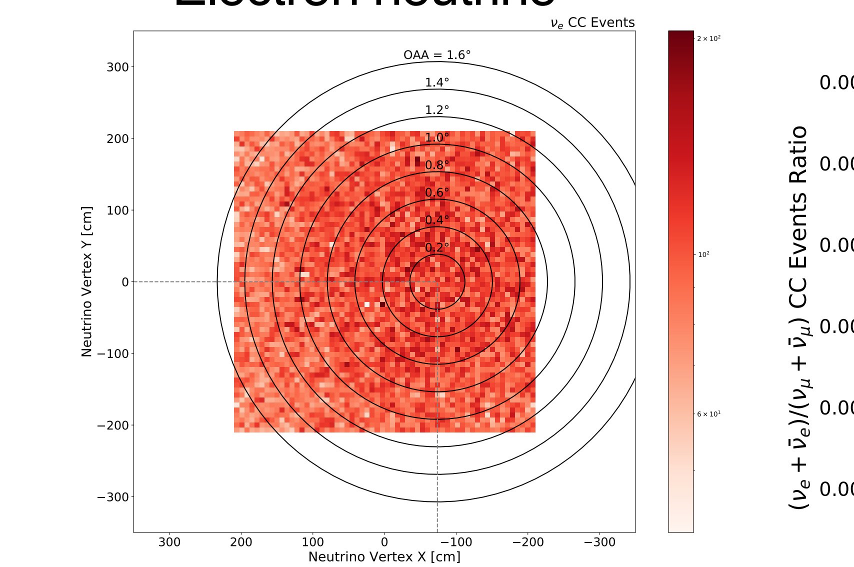


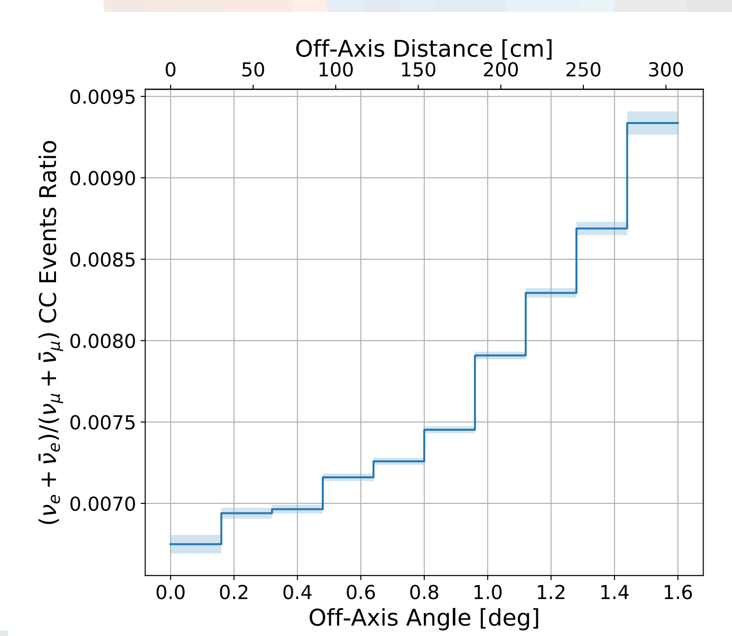


Muon neutrino



Electron neutrino





ν_e to ν_μ ratio changes moving off-axis

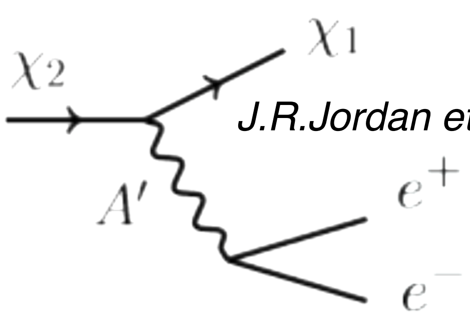
Exploring physics potential of SBND-PRISM

- Interaction Model Constraint
- SBN Sterile Neutrino Oscillations
- SBND-Only Sterile Neutrino Oscillations
- Dark Matter Searches
- ….

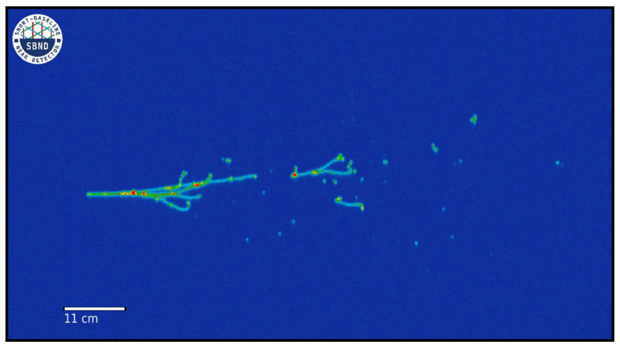
Searches for new physics in LAr TPC: signatures in SBND

Monte Carlo simulations

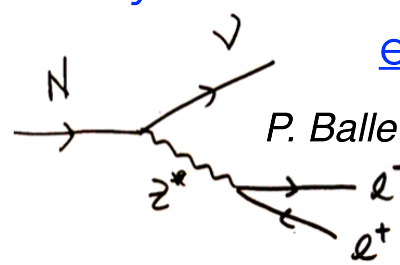
Dark Matter - electron-positron pair



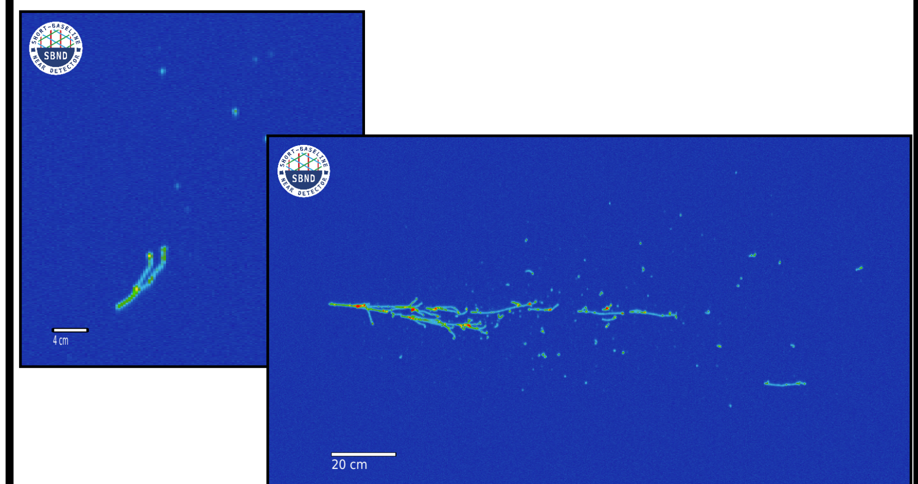
J.R.Jordan et al., arXiv:1806.05185



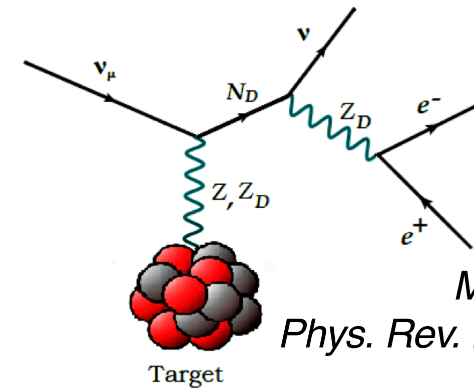
Heavy Sterile Neutrino - electron-positron pair



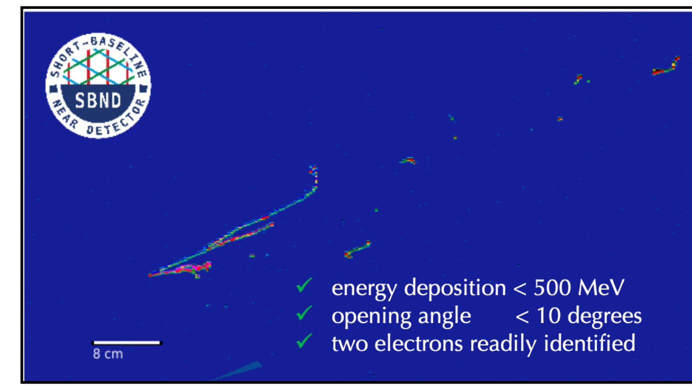
P. Ballet et al., JHEP 04 (2017) 102



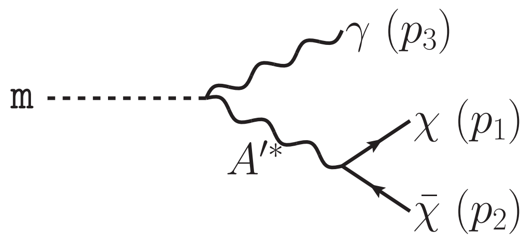
Dark Neutrino - electron-positron pair



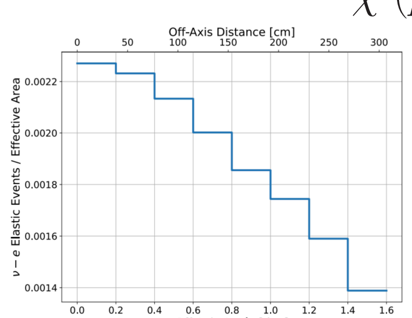
Machado et al., Phys. Rev. Lett. 121, 241801 (2018)



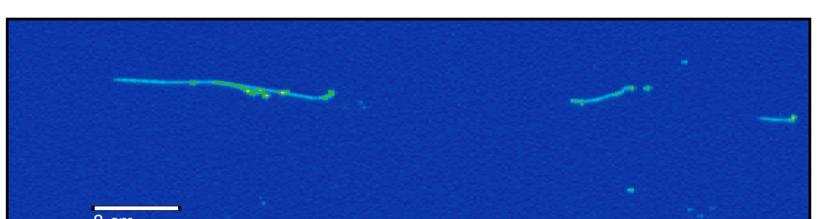
Dark Matter - forward electron



V. De Romeri et al., arXiv:1903.10505 [hep-ph]



SBND-PRISM: Signal is unfocused while background (ν-e elastic events) decrease with the off-axis angle

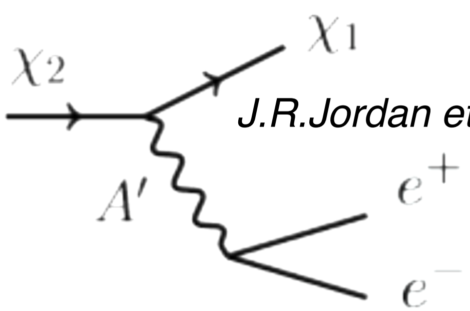


…several other SBND studies are ongoing

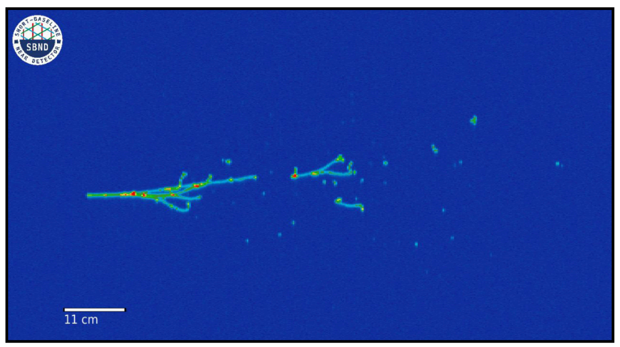
Searches for new physics in LAr TPC: signatures in SBND

Monte Carlo simulations

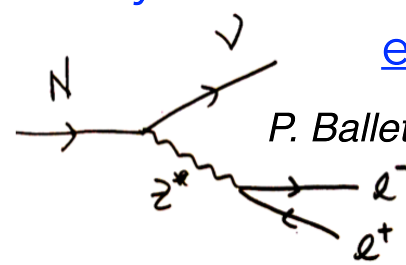
Dark Matter - electron-positron pair



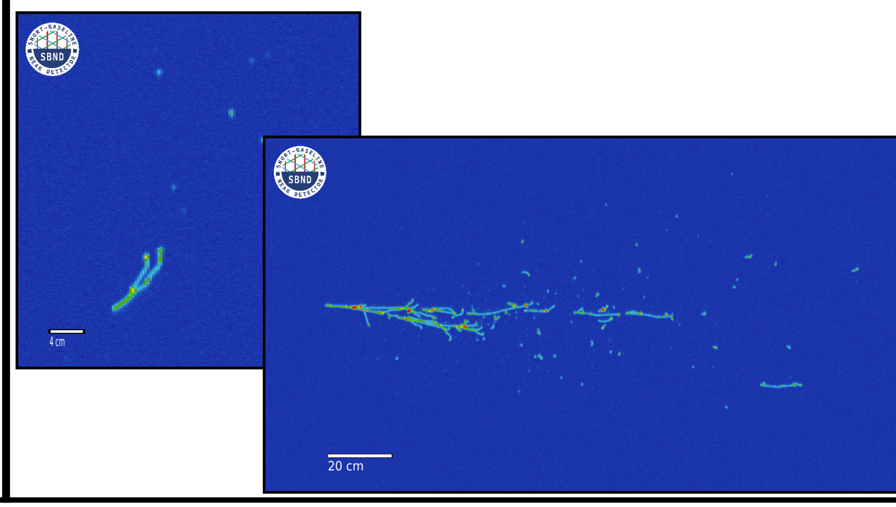
J.R.Jordan et al., arXiv:1806.05185



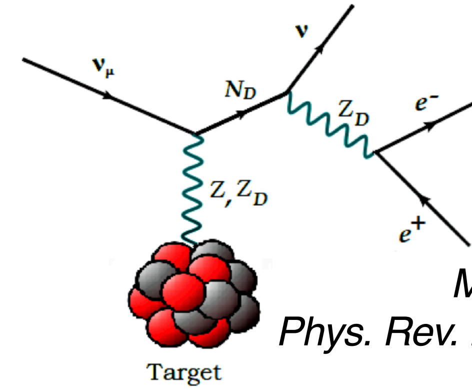
Heavy Sterile Neutrino - electron-positron pair



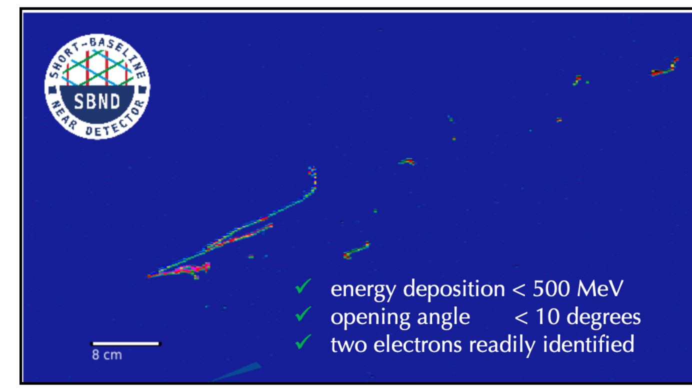
P. Ballet et al., JHEP 04 (2017) 102



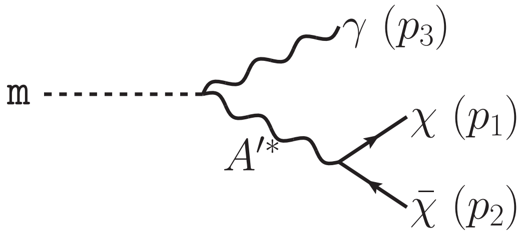
Dark Neutrino - electron-positron pair



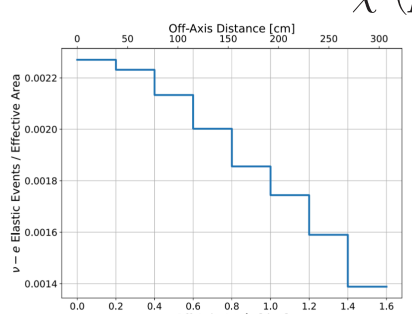
Machado et al., Phys. Rev. Lett. 121, 241801 (2018)



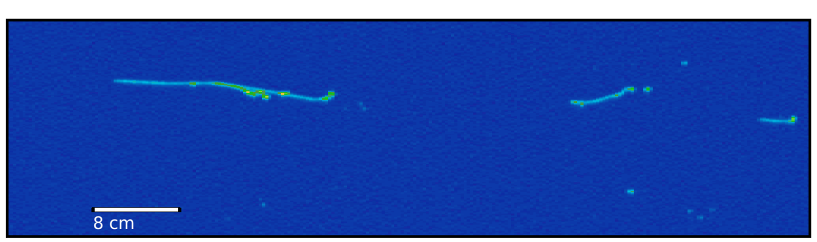
Dark Matter - forward electron



V. De Romeri et al., arXiv:1903.10505 [hep-ph]



SBND-PRISM: Signal is unfocused while background (ν-e elastic events) decrease with the off-axis angle



- **MicroBooNE** searched for
  - Heavy Neutral leptons ($N \rightarrow \mu^{\pm}\pi^{\mp}$ decay channel in a delayed time window)

    P. Abratenko et al., Phys. Rev. D 101, 052001
  - Higgs scalar portal (e^+e^- final state from NuMi off-axis events)

    P. Abratenko et al., arxiv:2106.00568
- **DUNE(-ND)** will also probe several BSM scenarios

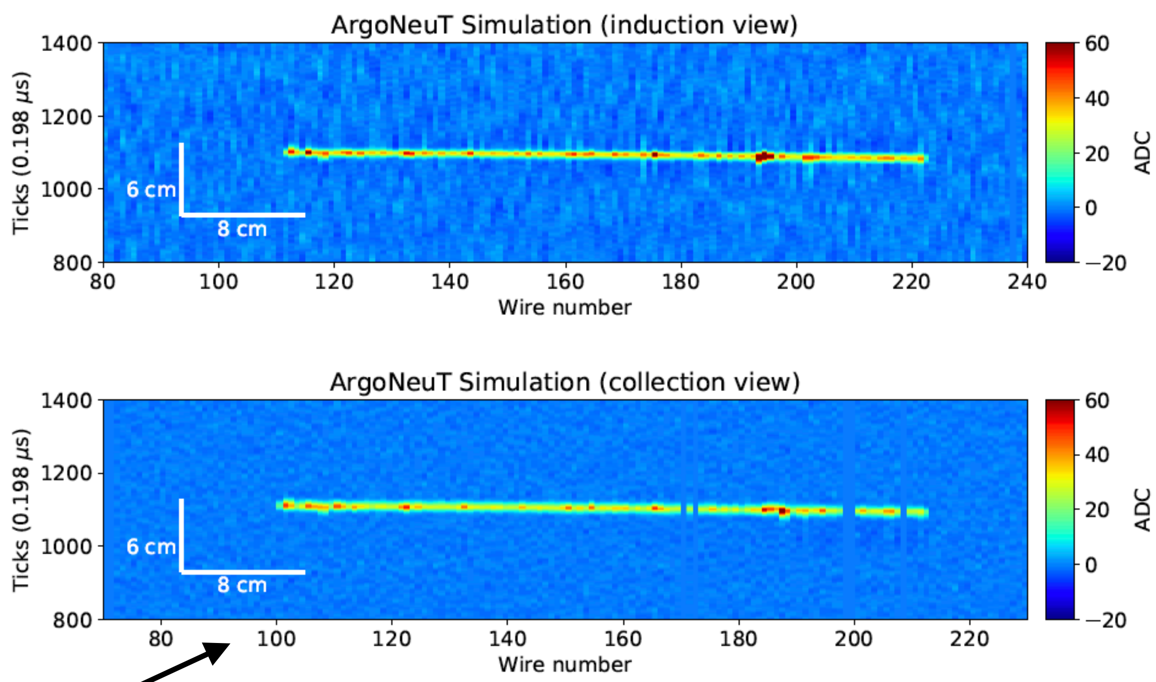
  B. Abi et al, Eur. Phys. J. C (2021) 81

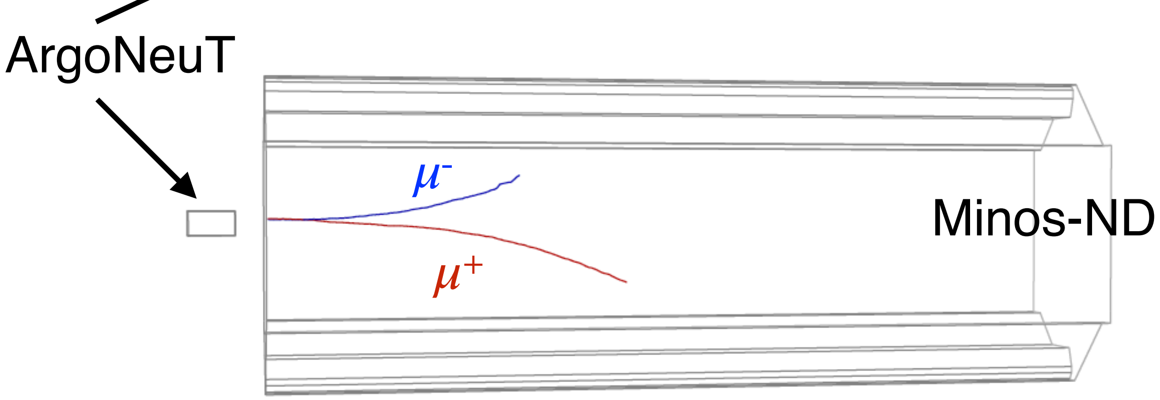
Searches for new physics in LAr TPC: ArgoNeuT

First search for Heavy Neutral Leptons $N \rightarrow \nu\mu^{+}\mu^{-}$ in LAr TPC

Assuming HNL production predominately from $\tau^{\pm}$ decay:
D/D_s decay to τ, that subsequently decay to HNLs
$\tau^{\pm} \rightarrow N X^{\pm}$ ($X^{\pm}$ is a SM particle e.g. $\pi^{\pm}$)

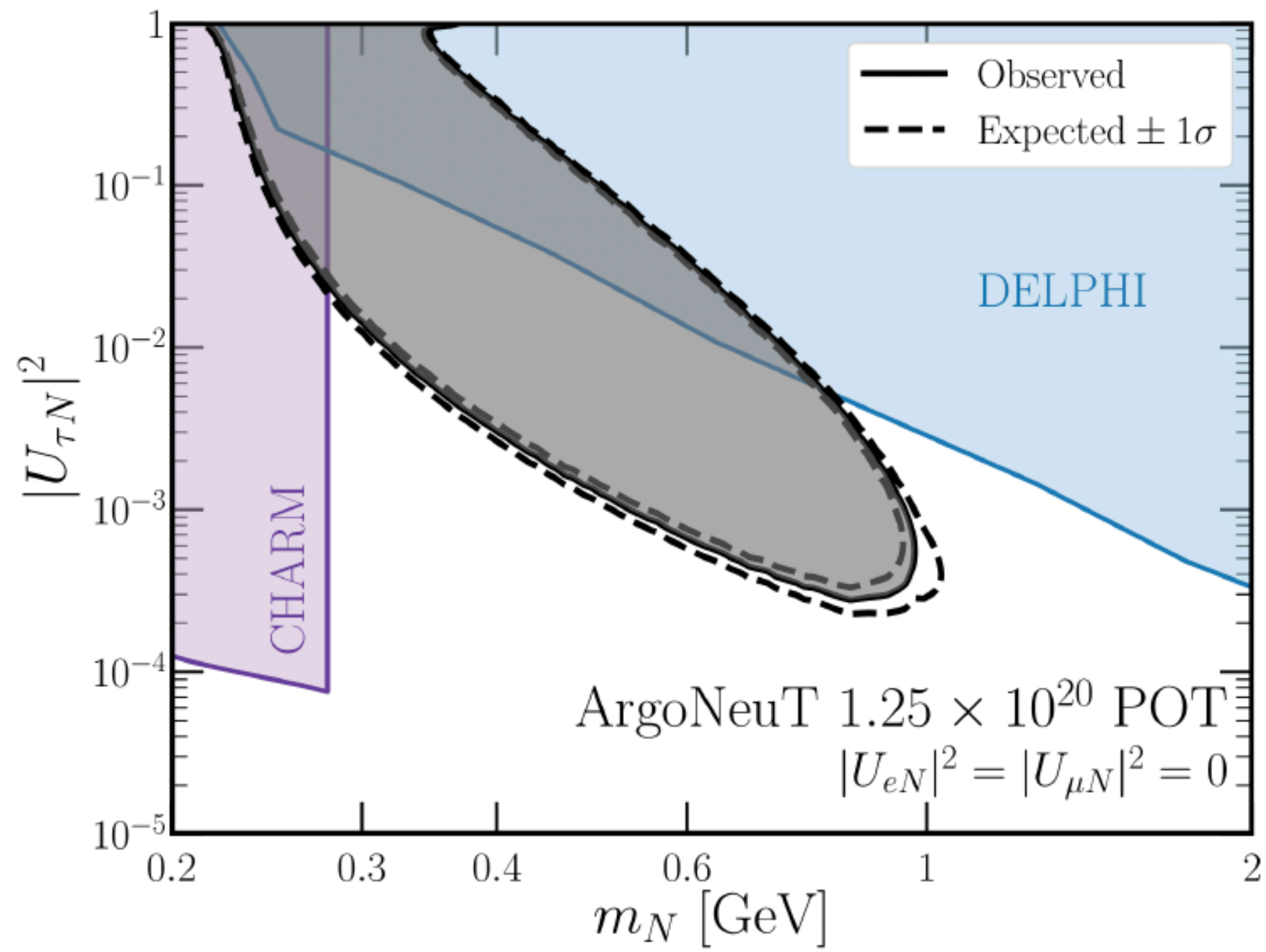
HNL decay (MC)
$N \rightarrow \nu\mu^{+}\mu^{-}$





0 events observed in the data

R. Acciarri et al., accepted by Phys. Rev. Lett.

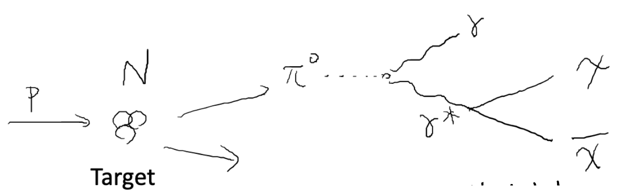


Significant increase in the parameter space exclusion region!

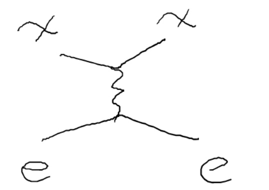
Searches for new physics in LAr TPC: ArgoNeuT

First search for Millicharged Particles in LAr TPC

mCP have an electric charge Q=ϵ·e (ϵ≪1)

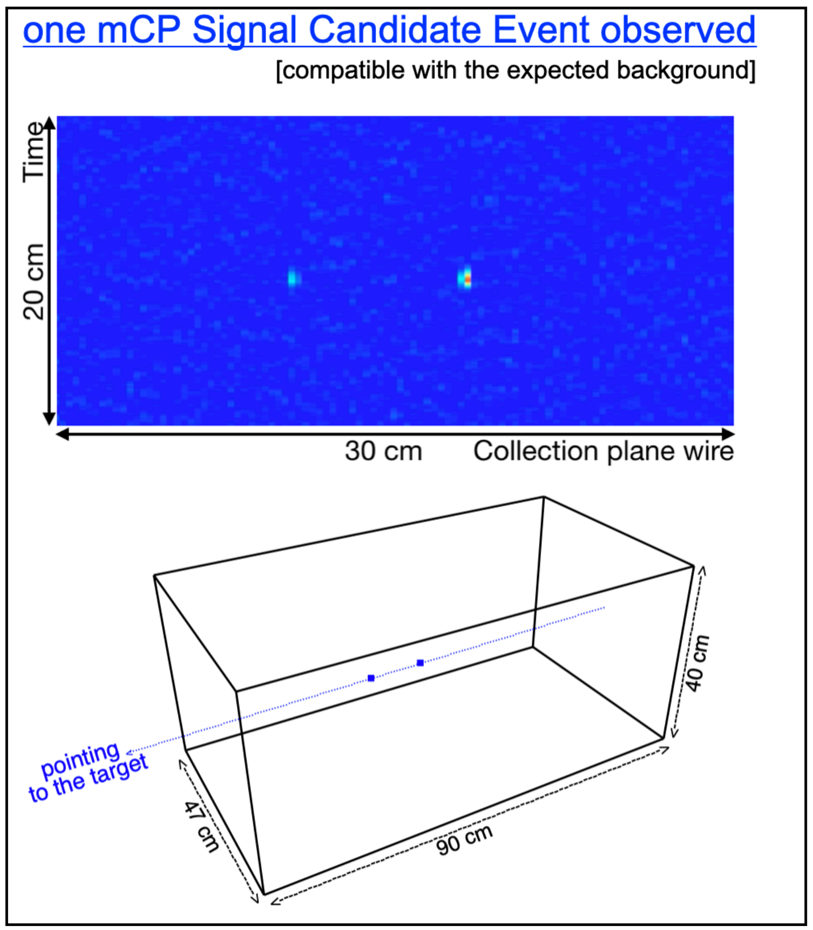


❑ production: meson decays



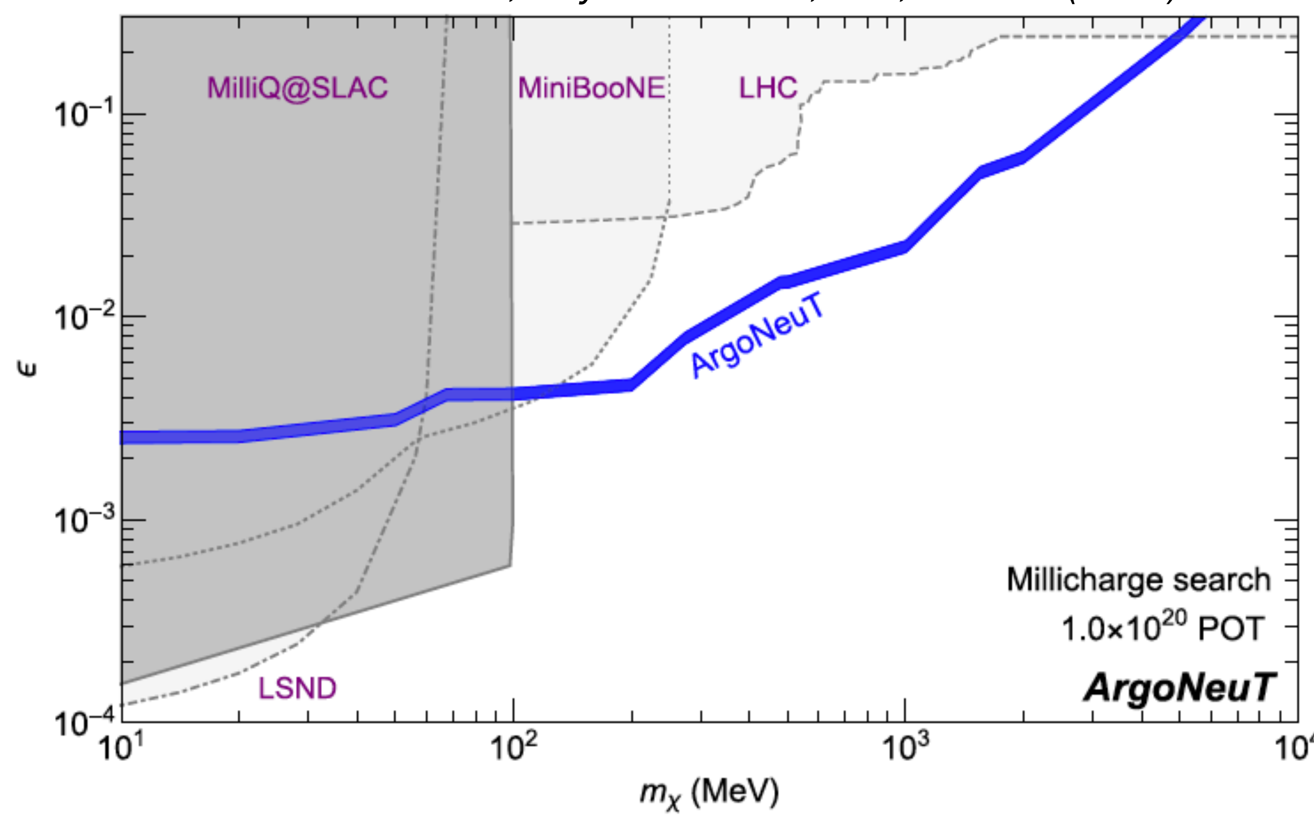
❑ detection: scattering electron

Low energy threshold (300 KeV) is the key!



[see presentation by Z. Liu on Aug. 20th]

R. Acciarri et al., Phys. Rev. Lett., 124, 131801 (2020)



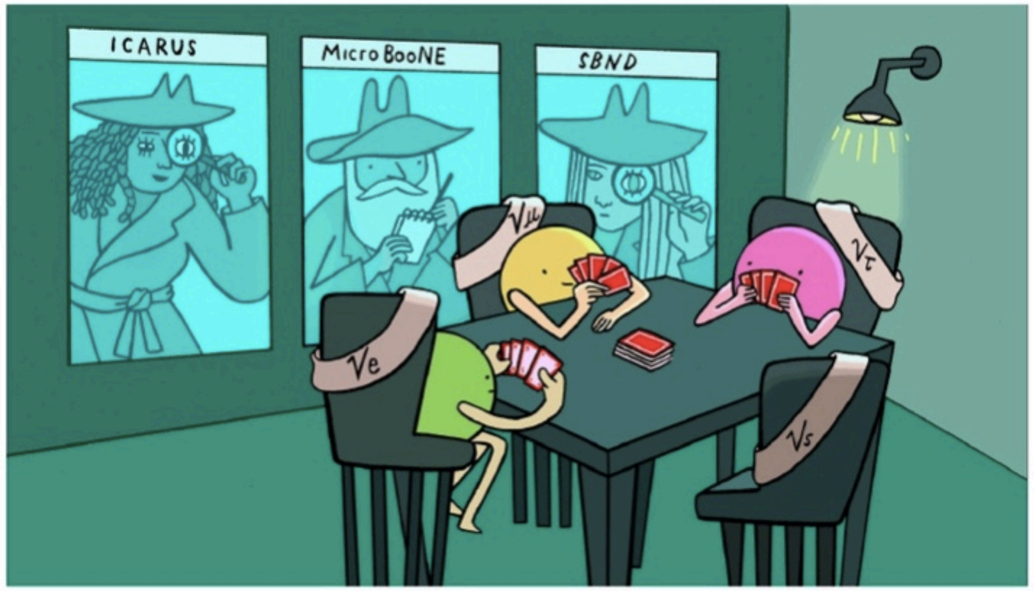
Leading constraints in unexplored parameter regions!

Summary

LAr TPC neutrino detectors at Short-Baseline are fantastic tools to look for new physics in the neutrino sector and beyond!

ArgoNeuT, a small LAr-TPC exposed to the NuMI beam at Fermilab provided leading constraints on millicharged particles and heavy neutral leptons in unexplored parameter space regions!

The three SBN detectors sitting on the BNB at Fermilab will perform a world-leading search for eV-scale sterile neutrinos

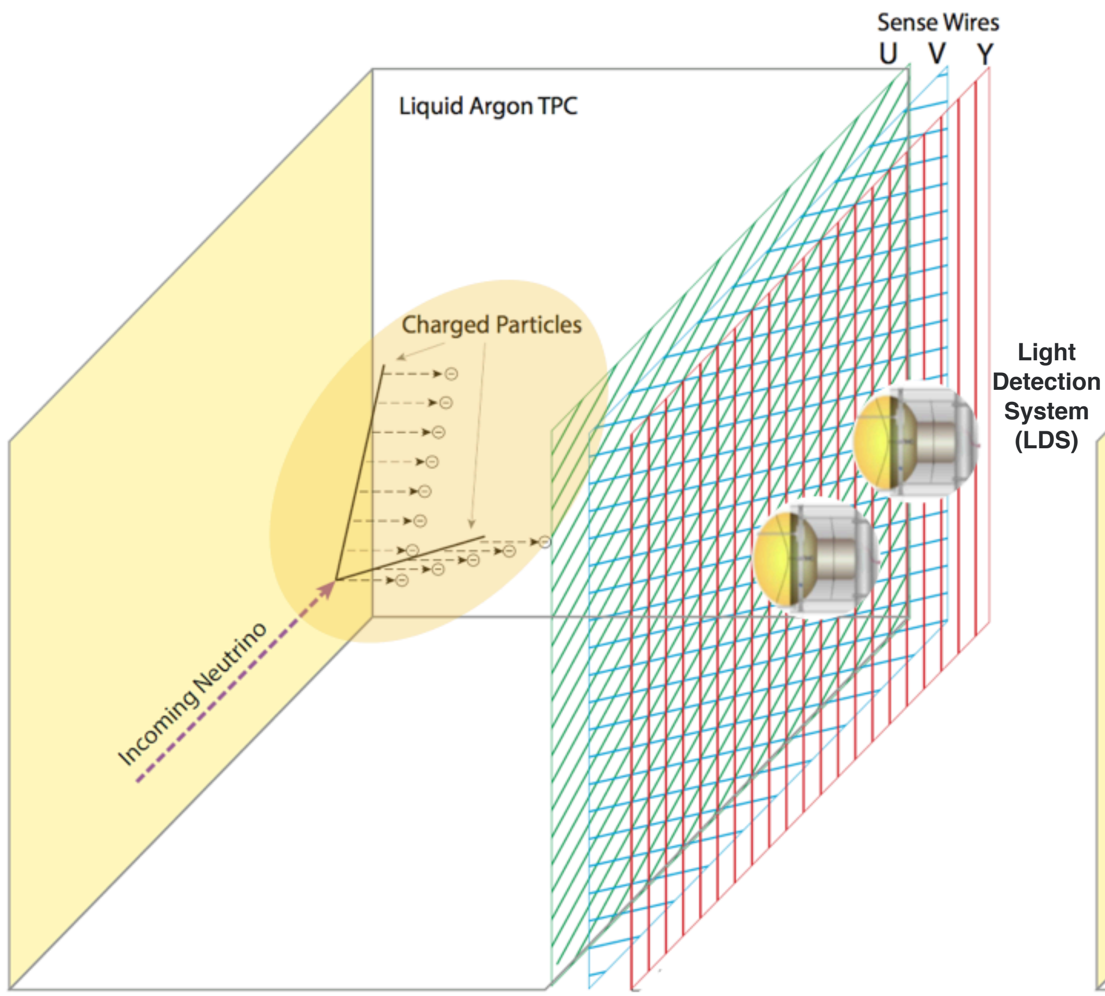


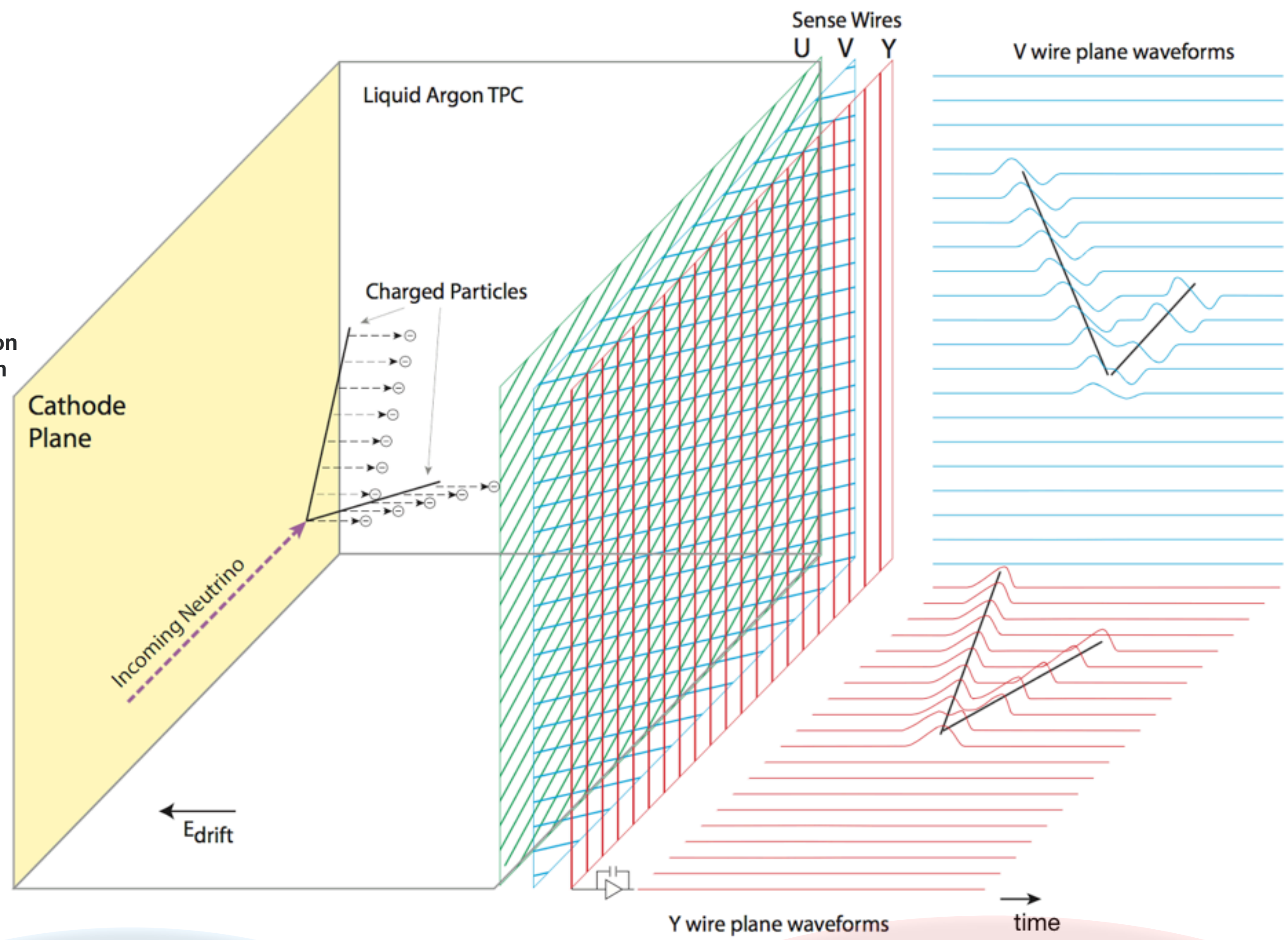
Artwork by Sandbox Studio, Chicago with Corinne Mucha

Beyond the flagship oscillation searches, the SBN program has a broad science goal, which addresses alternative explanations of the SBL anomalies and includes other BSM explorations

OVERFLOW

LArTPC at work





Charged particles in LAr produce free ionization electrons and scintillation light

Ionization charge drifts in a uniform electric field towards the readout wire-planes

Digitized signals from the wires are collected [*time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge*]

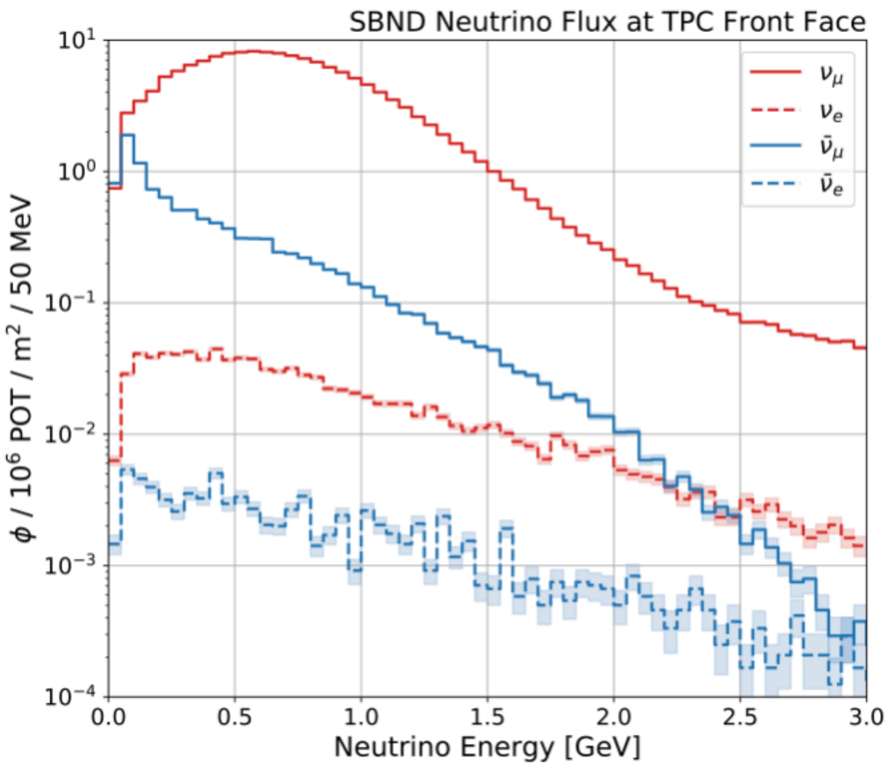
m.i.p. at 500 V/cm: ~ 60,000 e/cm
~ 50,000 photons/cm

Electron drift time ~ ms

VUV photons propagate and are shifted into VIS photons

Scintillation light fast signals from LDSs give event timing

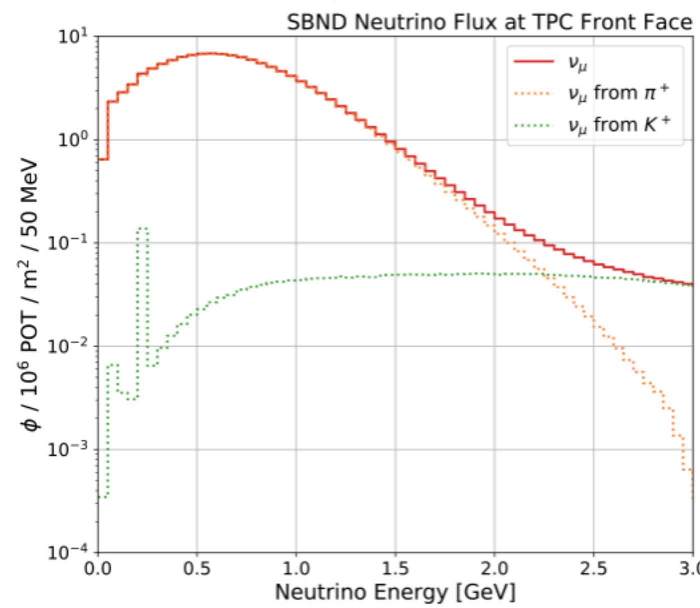
Neutrino Flux



Neutrino flux at the SBND front face.

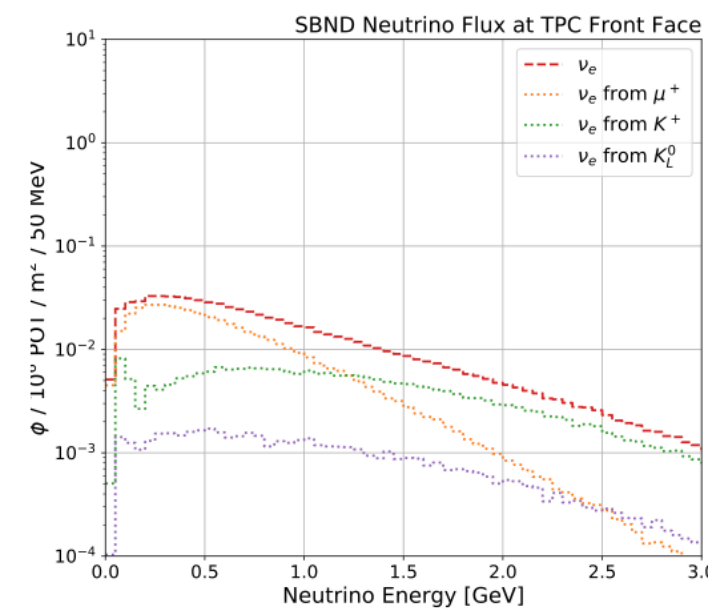
ν_μ (93.6%), $\bar{\nu}_\mu$ (5.9%), ν_e+$\bar{\nu}_e$ (0.5%)

ν_μ Flux



$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$K^+ \rightarrow \nu_\mu + \mu^+$$

ν_e Flux



$$\mu^+ \rightarrow \nu_e + \bar{\nu}_\mu + e^+$$
$$K^+ \rightarrow \nu_e + e^+ + \pi^0$$
$$K_L^0 \rightarrow \nu_e + \pi^- + e^+$$

The ν_μ come predominantly from two-body decays while the ν_e come from three-body decays: the flux of ν_e has a larger angular spread than that of ν_μ (at the same parent energy): the ν_e to ν_μ flux ratio changes as we move off-axis.