# New Opportunities in Neutrino Physics and Beyond

## Beyond the SM from Collider to early Universe

*Symposium in honor of Marcela carena and Carlos Wagner 60th birthday*

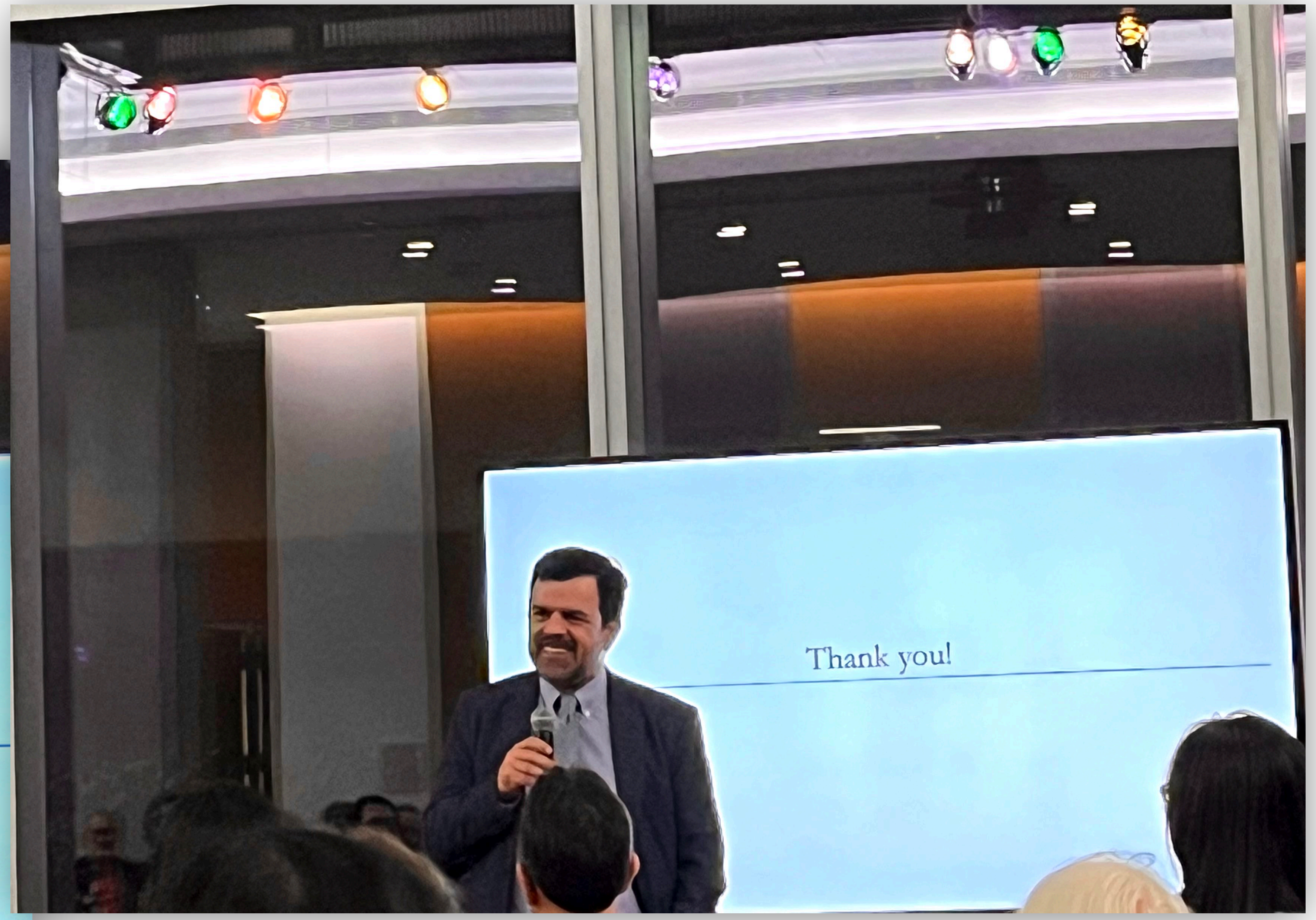
University of Chicago, May 29th, 2023

Ornella Palamara
Fermilab

# To Begin

We're delighted to celebrate our friends Marcela and Carlos and congratulate them for their brilliant and impactful scientific careers.

We appreciate that they have, directly and indirectly, fostered so much influential work and have helped cultivate the careers of so many people in our field.


As a neutrino experimentalist, I want to thank you for exposing to and trapping me into a variety of **New Physics ideas**!

# OUTLINE

Beyond the Standard Model with Neutrinos

A successful history of experiment-theory joint projects*

Some examples, including physics from "empty" events…

**ArgoNeuT**: constraints on **New Physics** in unexplored parameter space regions

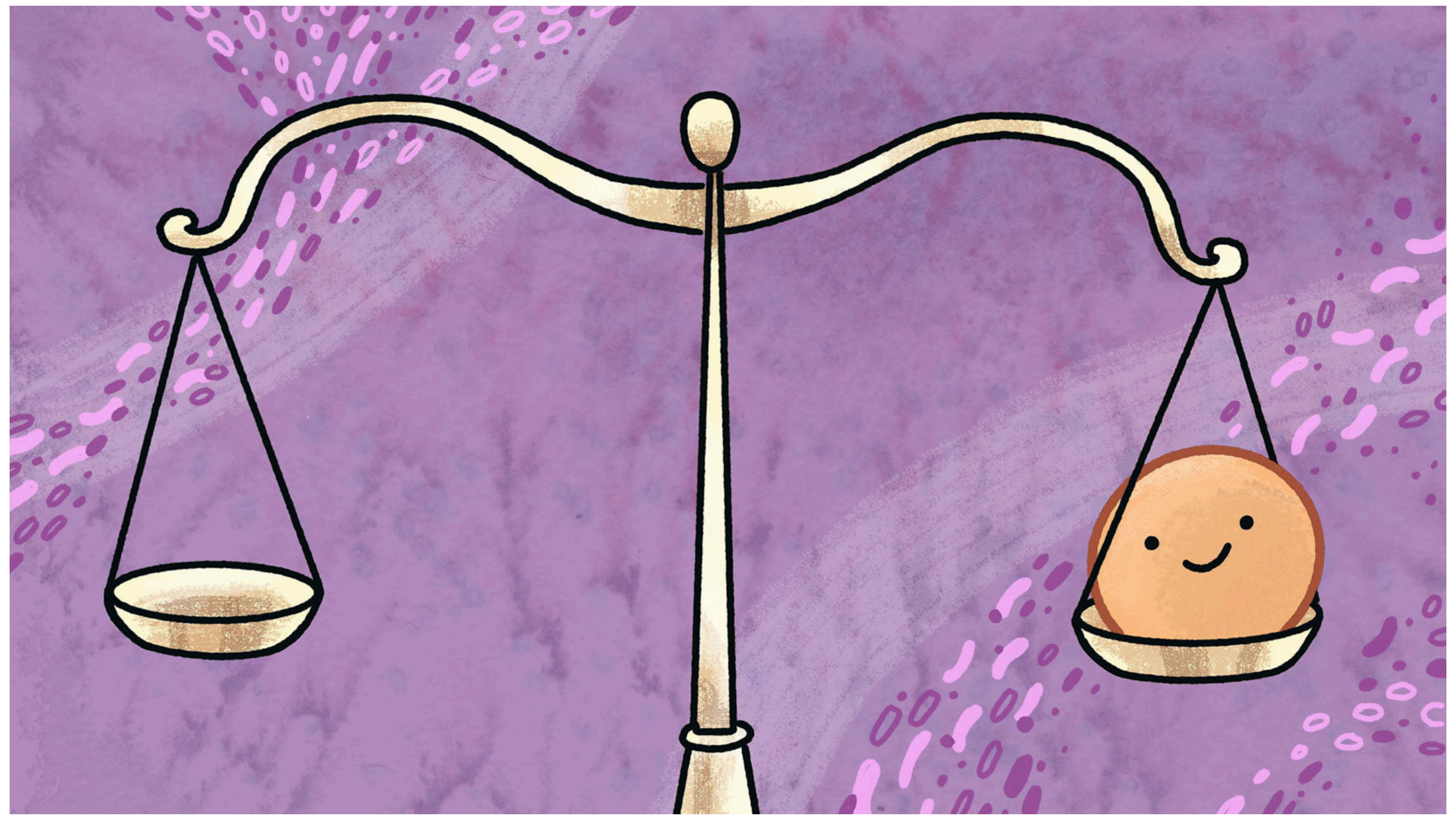
**Short-Baseline Neutrino** program: **eV-scale sterile neutrinos** & other **BSM explorations**.

*Examples are from personal experience! Focus on **Short-Baseline Liquid Argon Time Projection Chamber neutrino detectors**.

# BEYOND THE STANDARD MODEL WITH NEUTRINOS

The existence of non-zero neutrino masses, inferred from neutrino oscillation measurements, is the only laboratory-based evidence of physics beyond the standard model!

**How do neutrino get their masses?**



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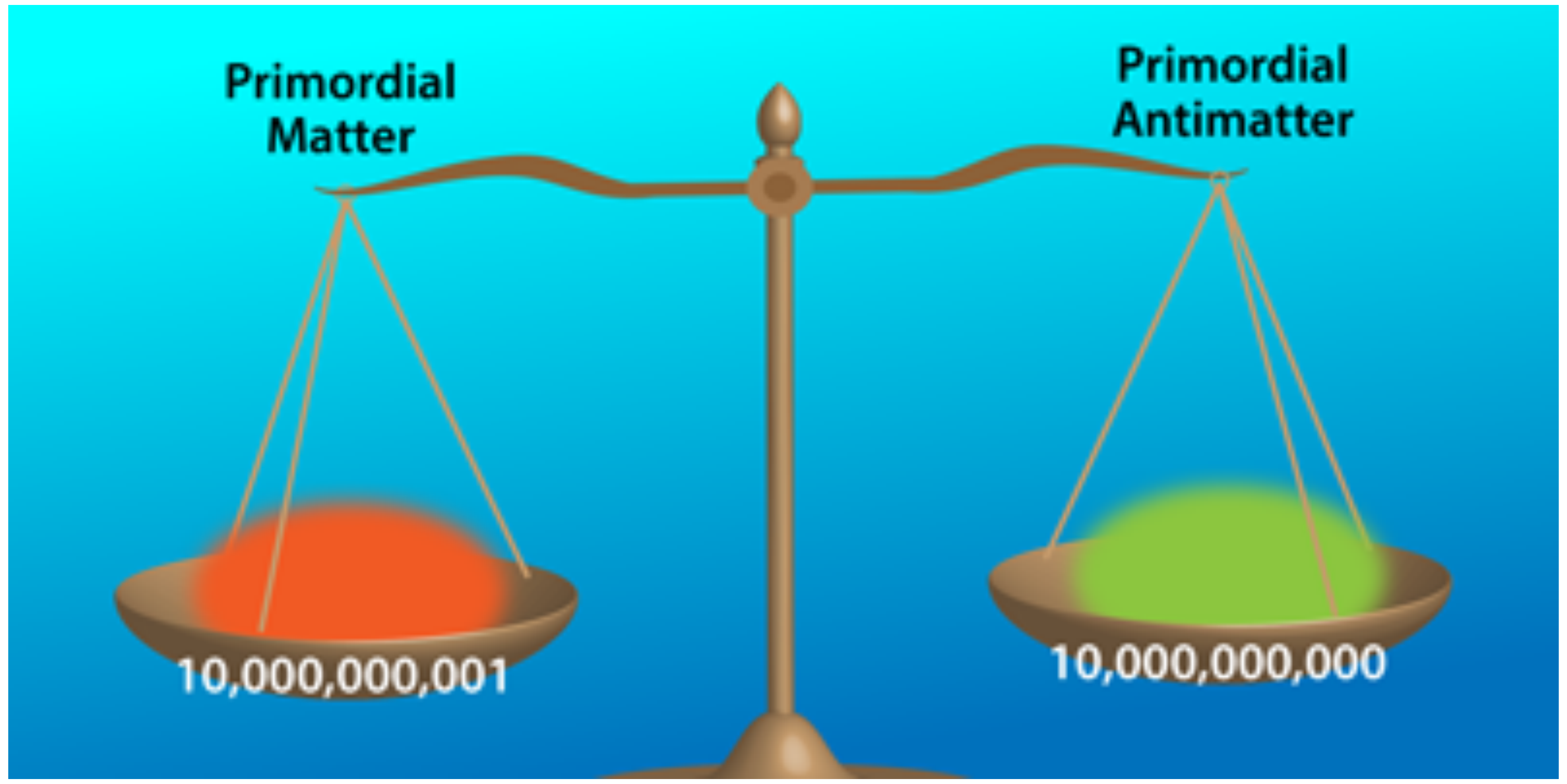
**Are neutrinos the key to the matter-antimatter asymmetry?**



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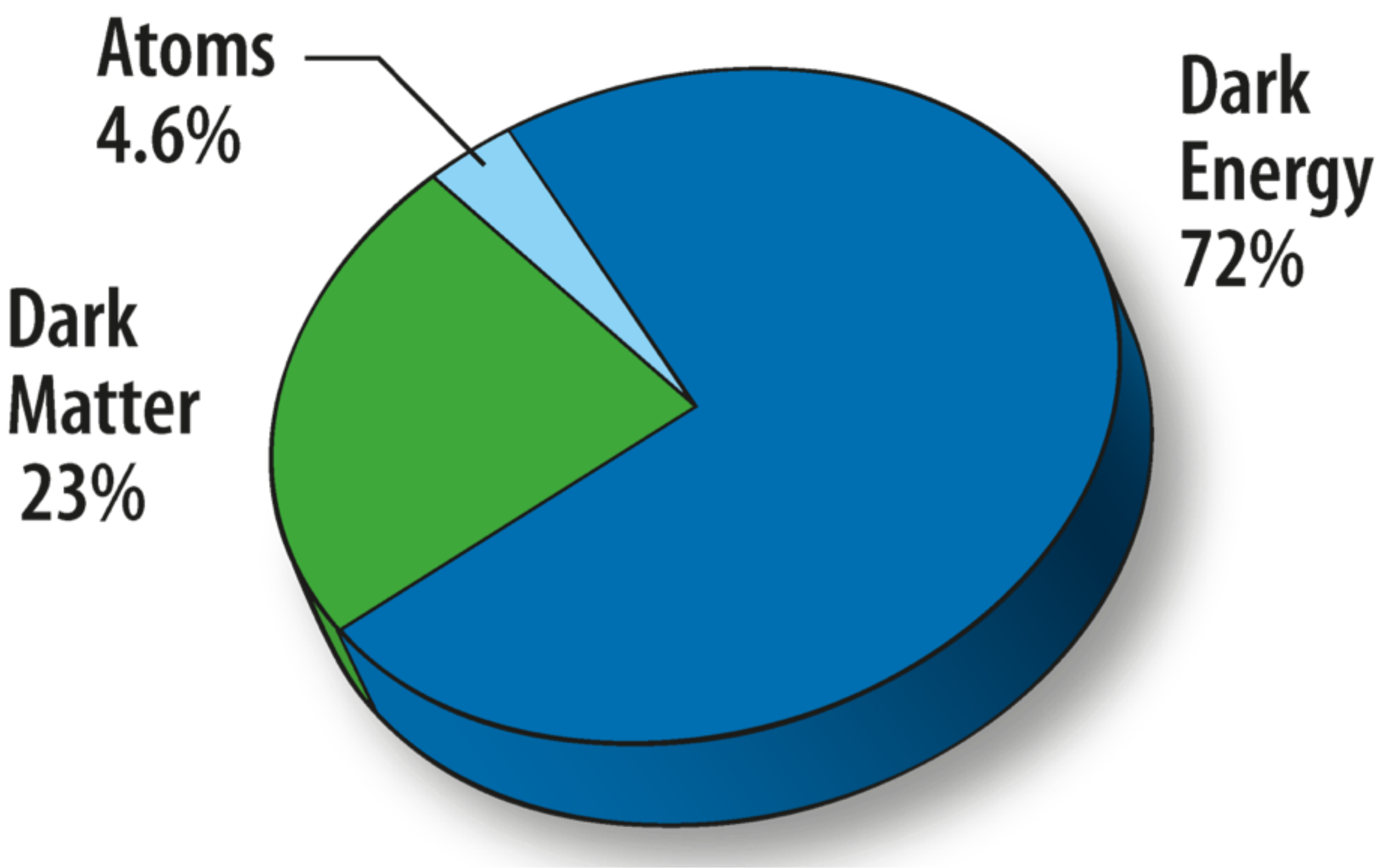

# BEYOND THE STANDARD MODEL WITH NEUTRINOS

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**How do neutrino get their masses?**

**Are neutrinos the key to the matter-antimatter asymmetry?**

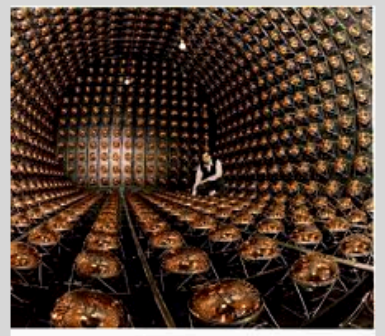
**Do neutrinos communicate with DM?**

**Are neutrinos their own antiparticle?**

**Are there more than three neutrinos?**

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

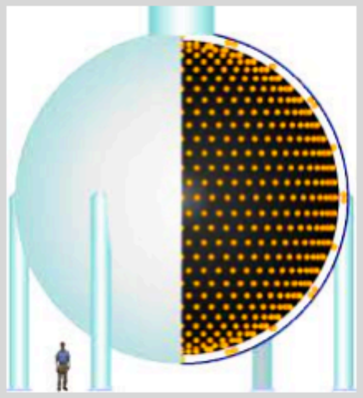
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?
$\nu_\mu \rightarrow \nu_e$?
LSND, MiniBooNE anomalies



**LSND**
Liquid Scintillator Neutrino Detector

anti-$\nu_e$ **appearance**
in anti-$\nu_\mu$ beam

**3.8 σ excess**



**MiniBooNE**
an independent check of LSND

$\nu_e$ (anti-$\nu_e$) **appearance**
in $\nu_\mu$ (anti-$\nu_\mu$) beam

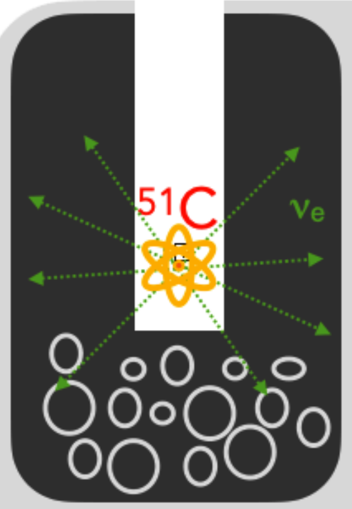
**4.5 (2.8) σ excess**

$\bar{\nu}_e \rightarrow \bar{\nu}_e$?
Reactor, Gallium anomaly

**Reactor Anomaly**
reactor
flux calculations

anti-$\nu_e$ **disappearance**
in anti-$\nu_e$ beam

**3 σ deficit**

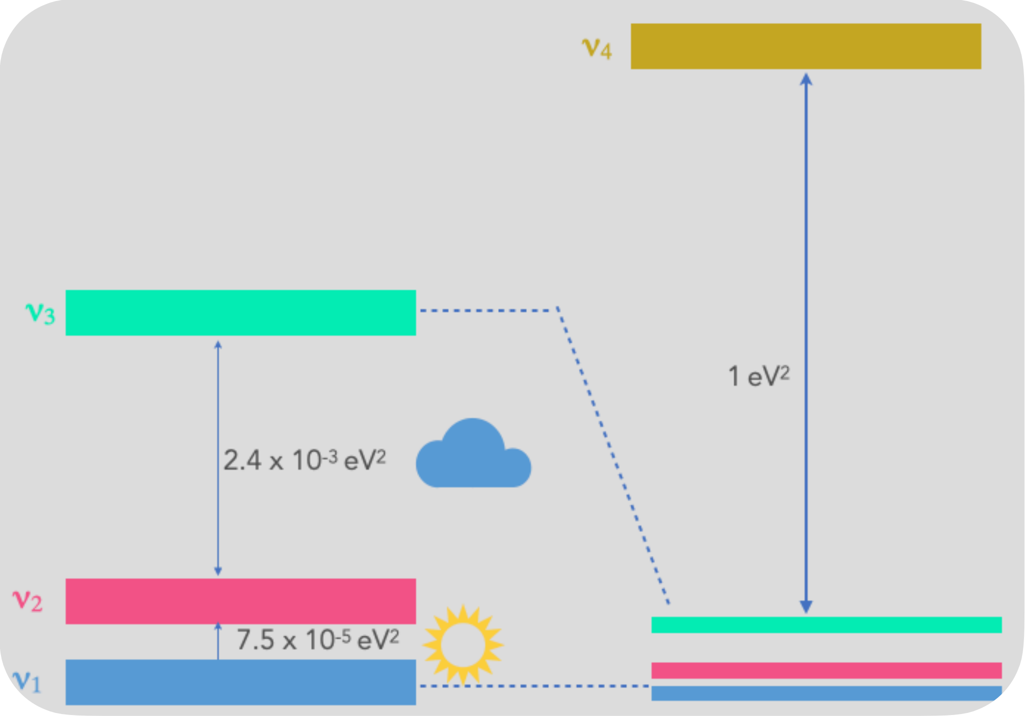



**Gallium Anomaly**
Solar neutrino
expt. calibrations

anti-$\nu_e$ **disappearance**
anti-$\nu_e$ source

**3 σ deficit**

It is a long (more than 30 years!) standing mystery if other types of neutrinos might exist.




Could point at new physics in the neutrino sector: additional neutrino state(s) with **large mass differences** ($eV^2$ scale), driving *neutrino oscillation at **short distances****

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

But…
$\nu_\mu \rightarrow \nu_\mu$
not Observed
Strong appearance-disappearance tension!

* Short-Baseline: L~100-1000 m, $\Delta m^2$~1eV²
cfr.: Long-Baseline: L~100-1000 km, $\Delta m^2$~$10^{-3}$eV²

# WHERE TO STUDY NEW PHYSICS?

We know there needs to be **physics beyond the standard model**. We have **no idea** of what and where that is.

A reach science program to explore the unknown!

For a given experiment, search in many diverse signal regions for new models.

New physics searches have been the domain of high-energy colliders for decades.


Increasing interest for similar/complementary opportunities to be explored in **neutrino experiments**!

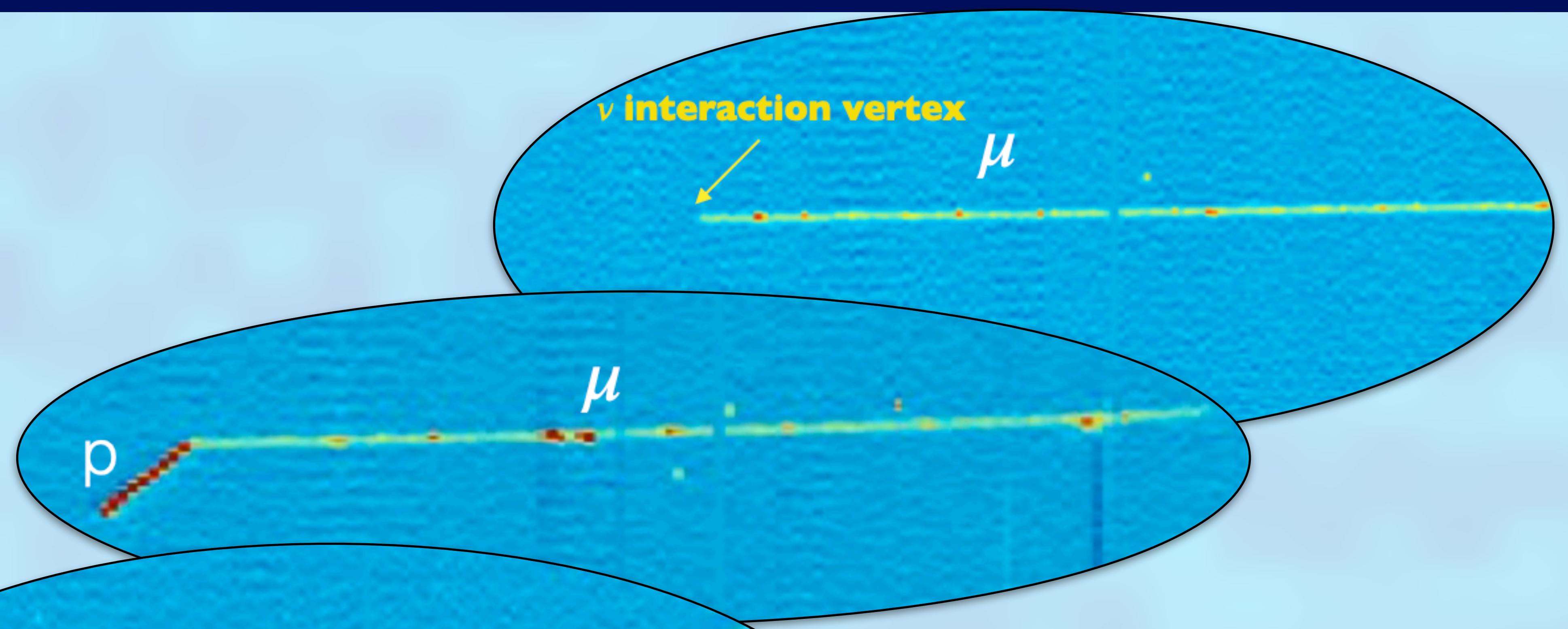
The BSM models accessible are specific to the neutrino source used.

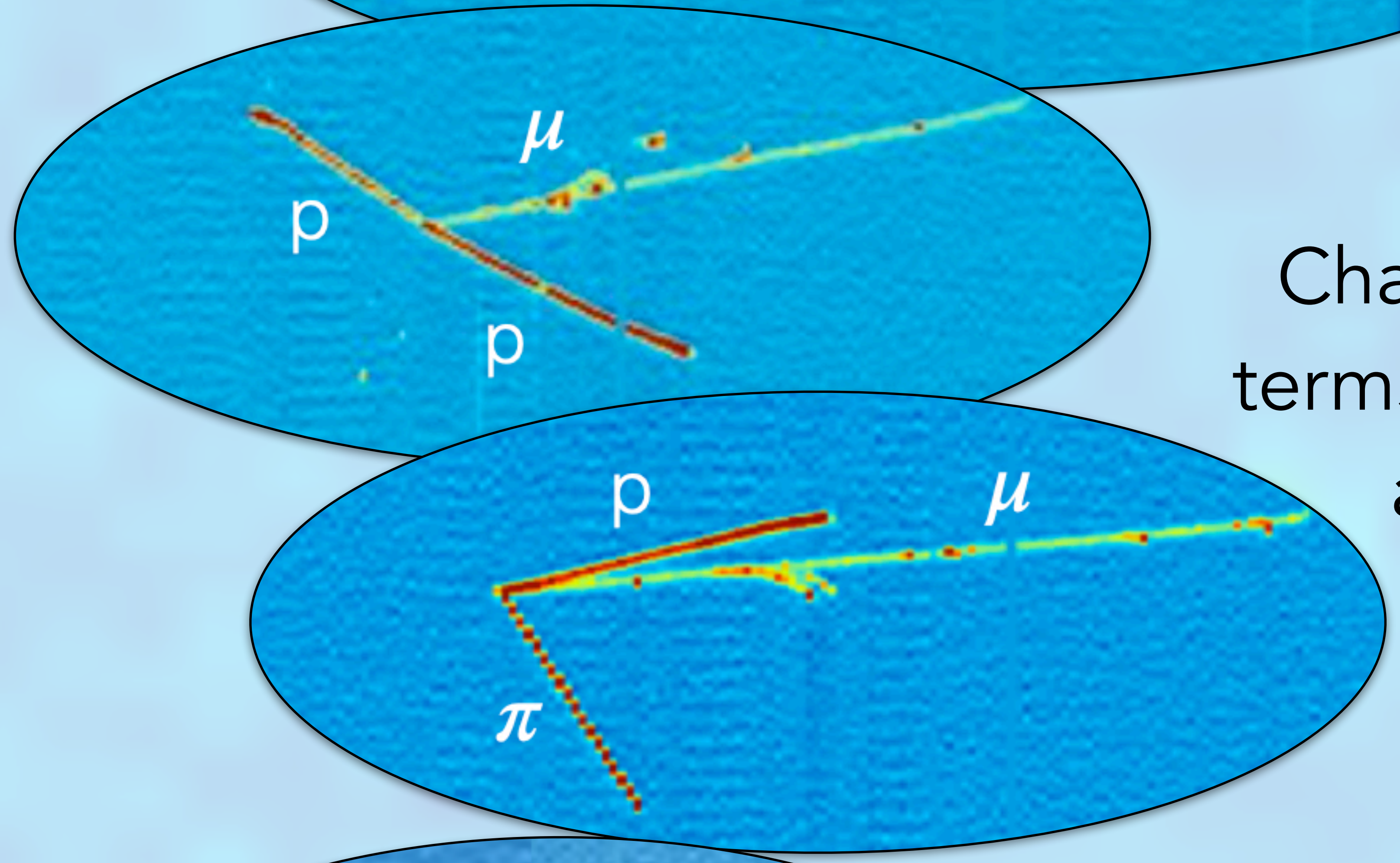
Here we will focus on Short-Baseline **Liquid Argon** detectors on **accelerator neutrino beams** at Fermilab

ArgoNeuT SBND µBooNE ICARUS @ Fermilab

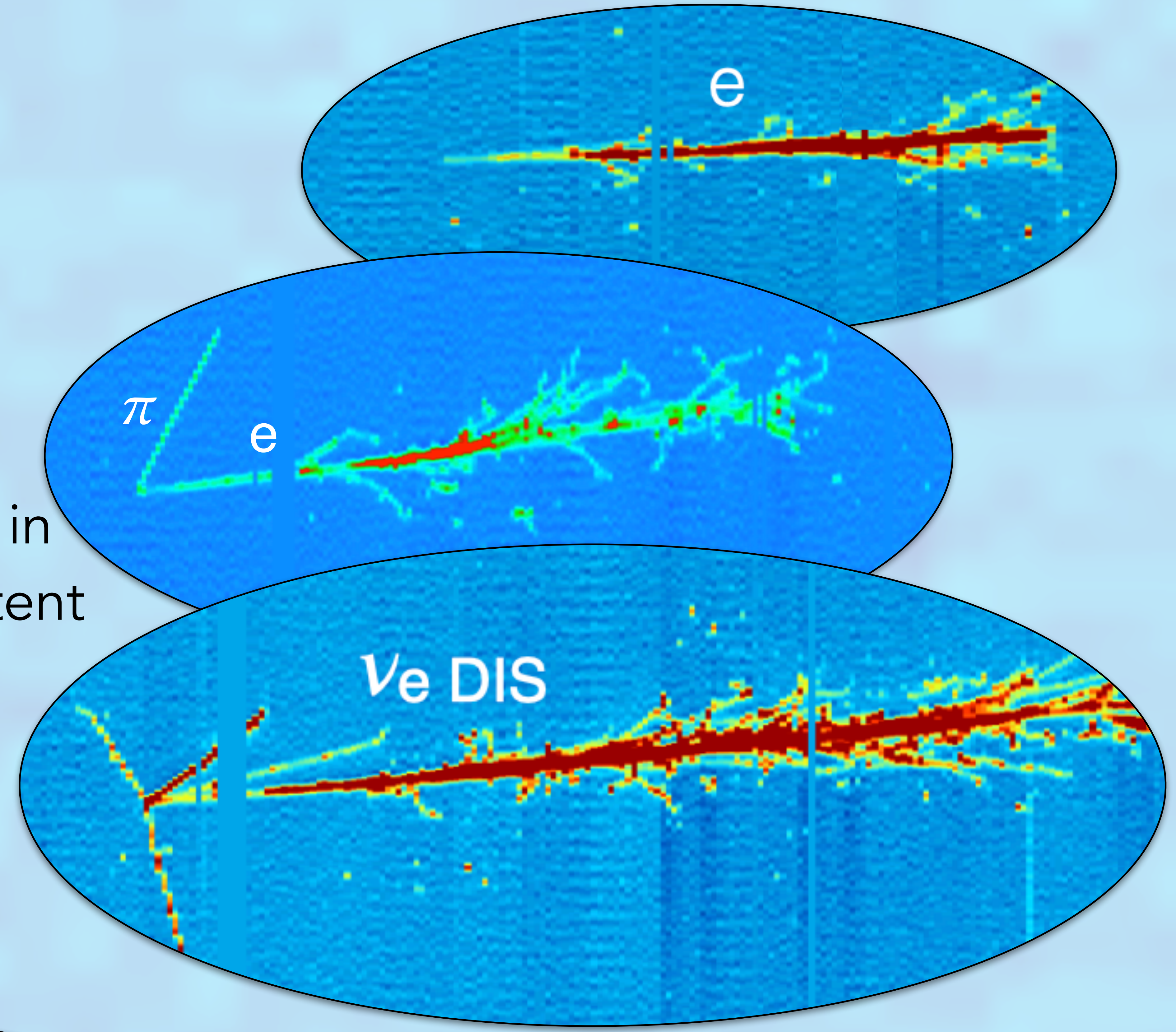
# WHY LIQUID ARGON NEUTRINO DETECTORS?

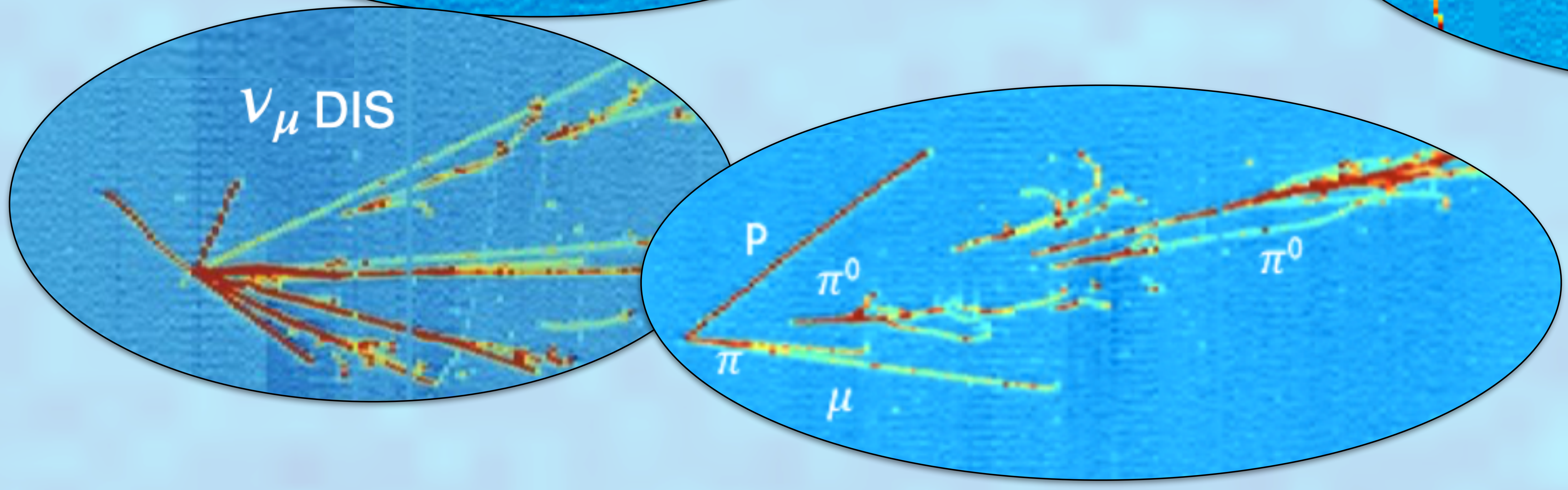
ArgoNeuT



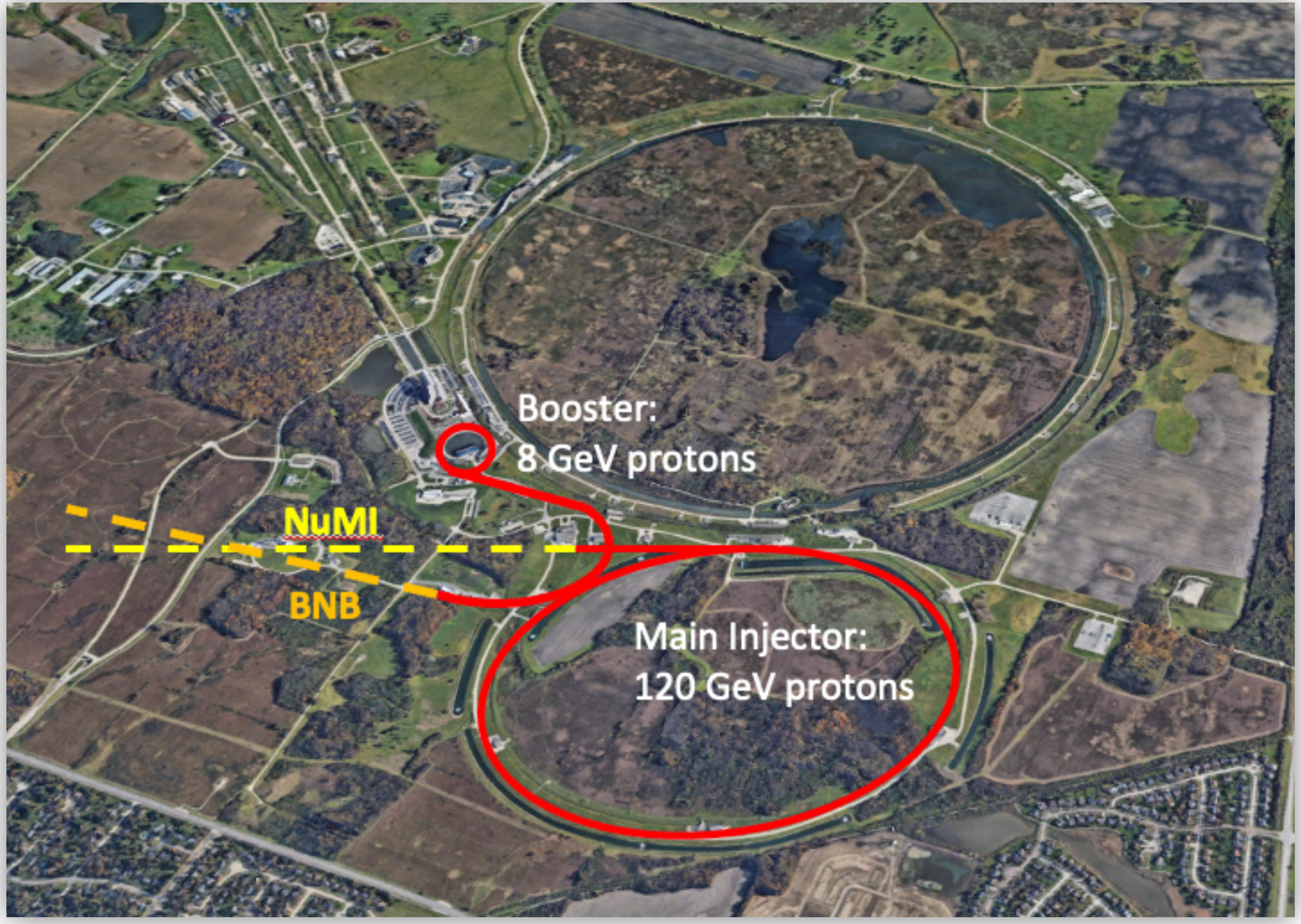

Characterize events in terms of particle content and kinematics.




Event imaging
Fine granularity calorimetry and particle identification
Electron-$\gamma$ separation
Good timing resolution
Low energy threshold

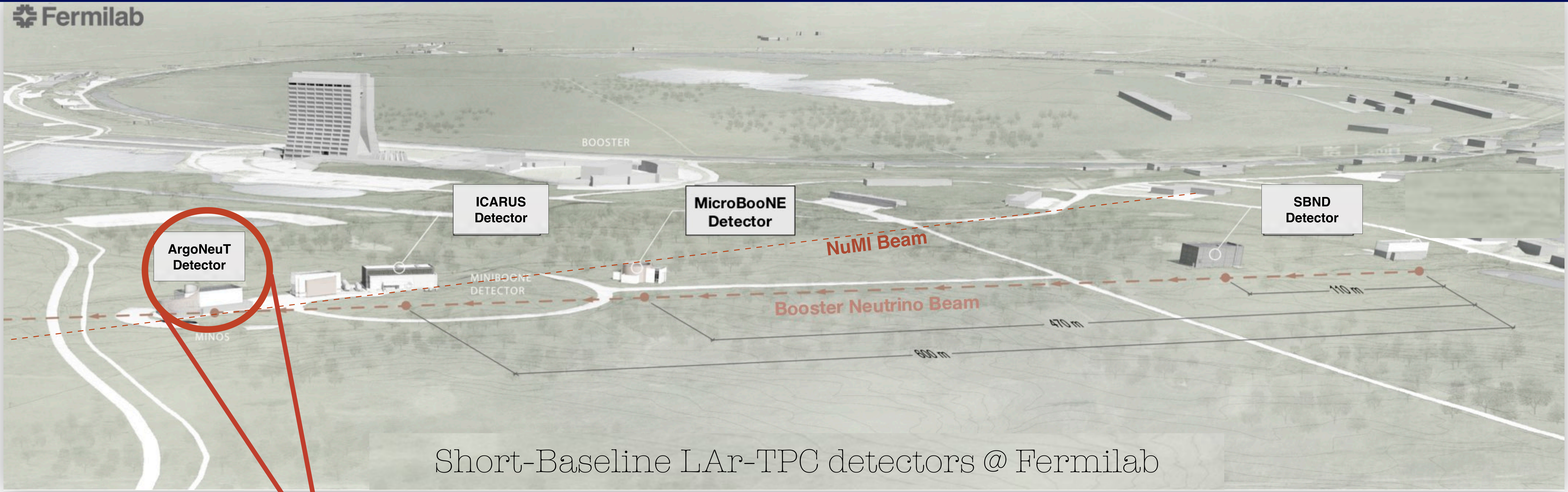
# Fermilab - Neutrino beams




Two neutrino beams:

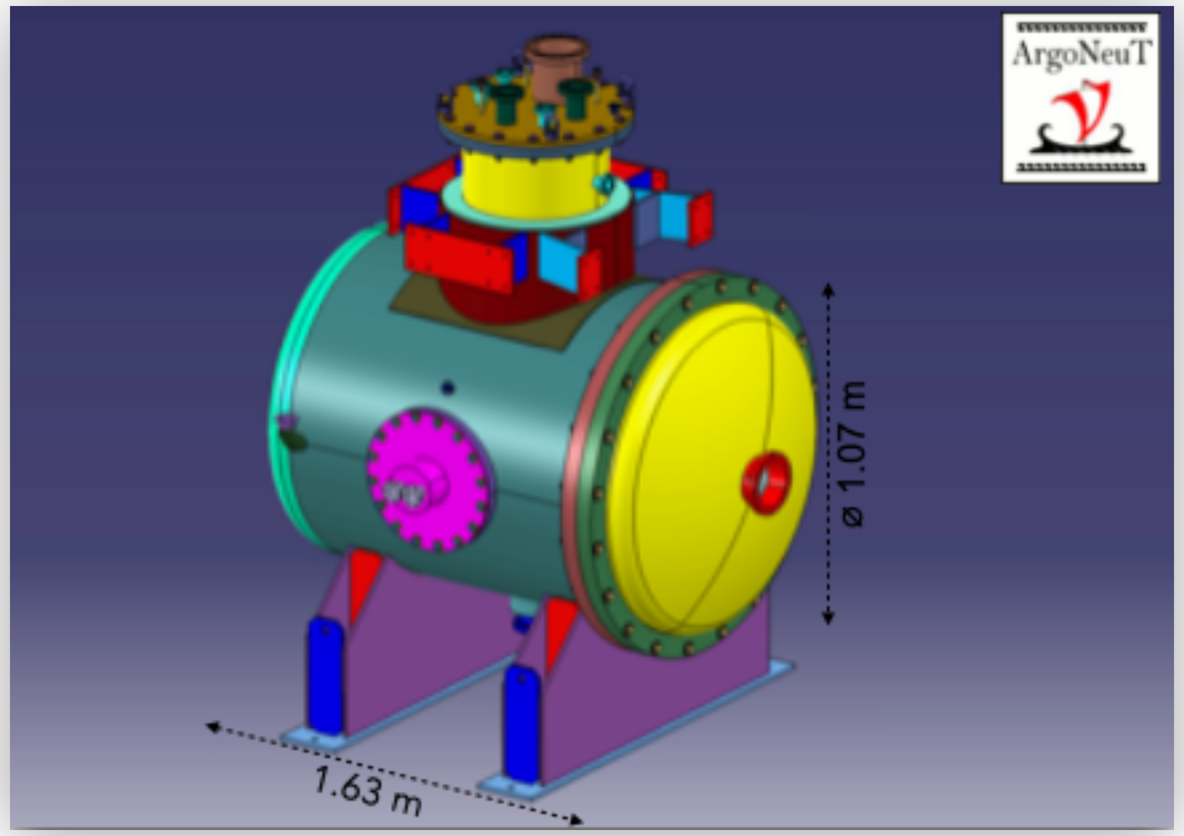
- Neutrinos at the Main Injector (NuMI)
- Booster Neutrino Beam (BNB)

# SHORT-BASELINE LAR DETECTORS AT FERMILAB: ARGONEUT

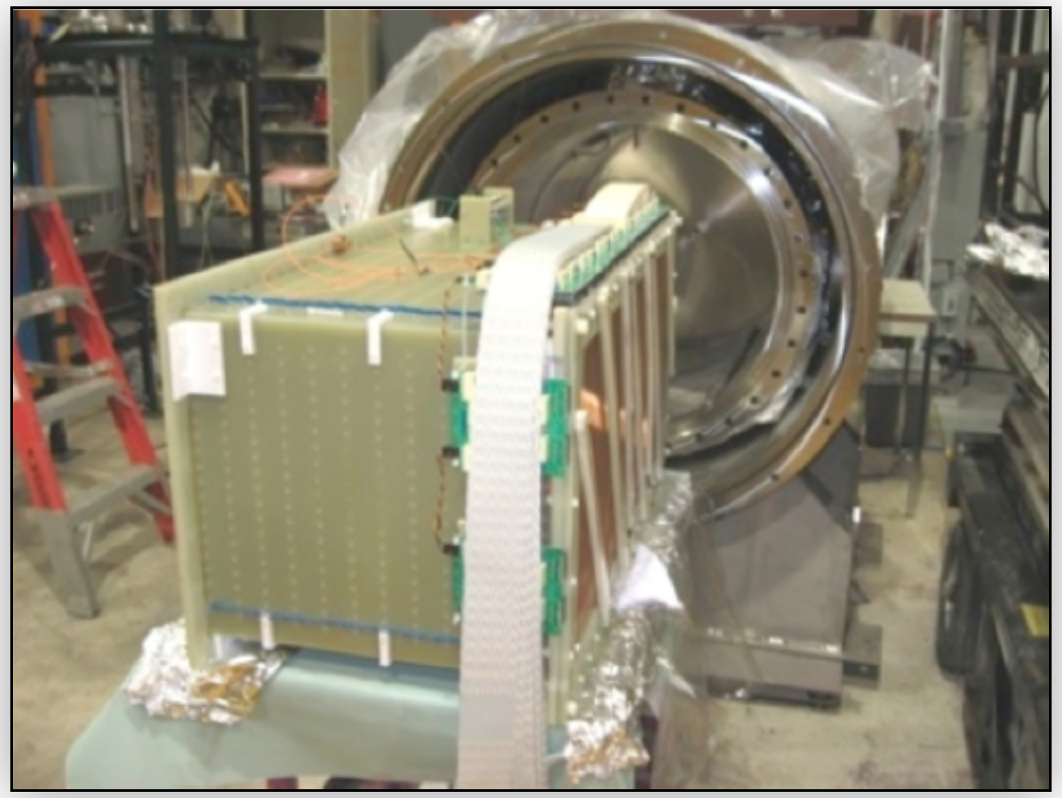



First LAr TPC detector at Fermilab. 5 months neutrino data collected in 2009-2010

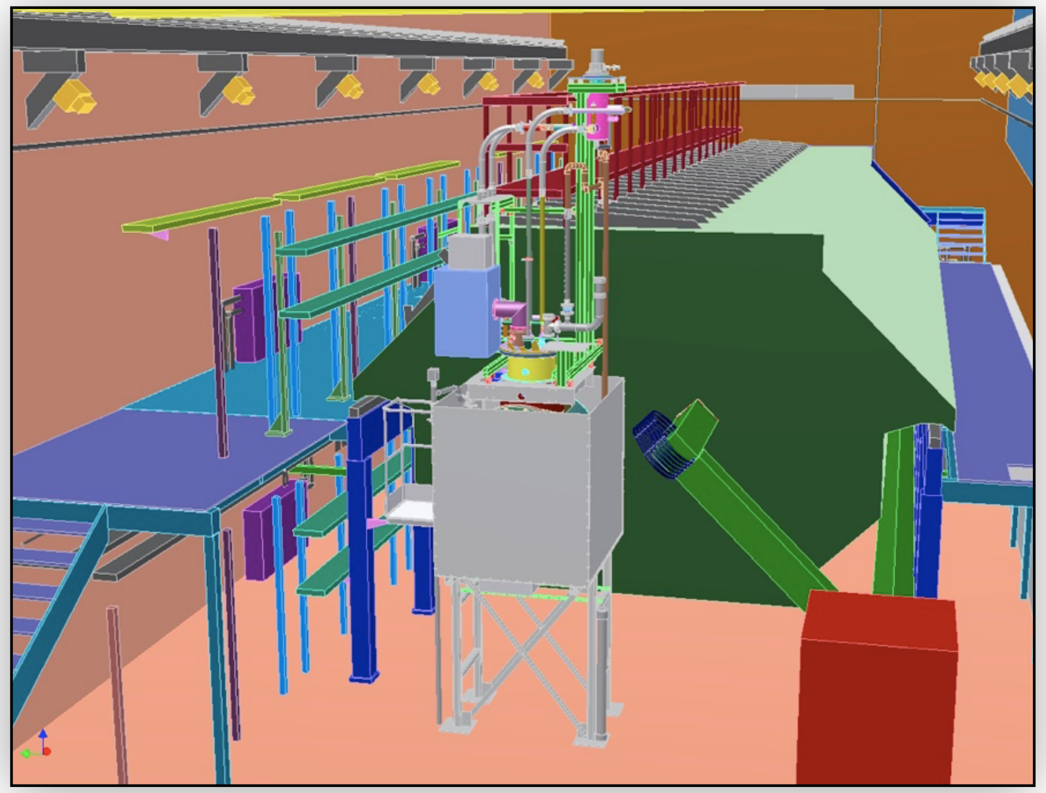
On-axis on NuMI
<$E_\nu$>≃4 GeV




*ArgoNeuT Collaboration, JINST 7 (2012) P10019*



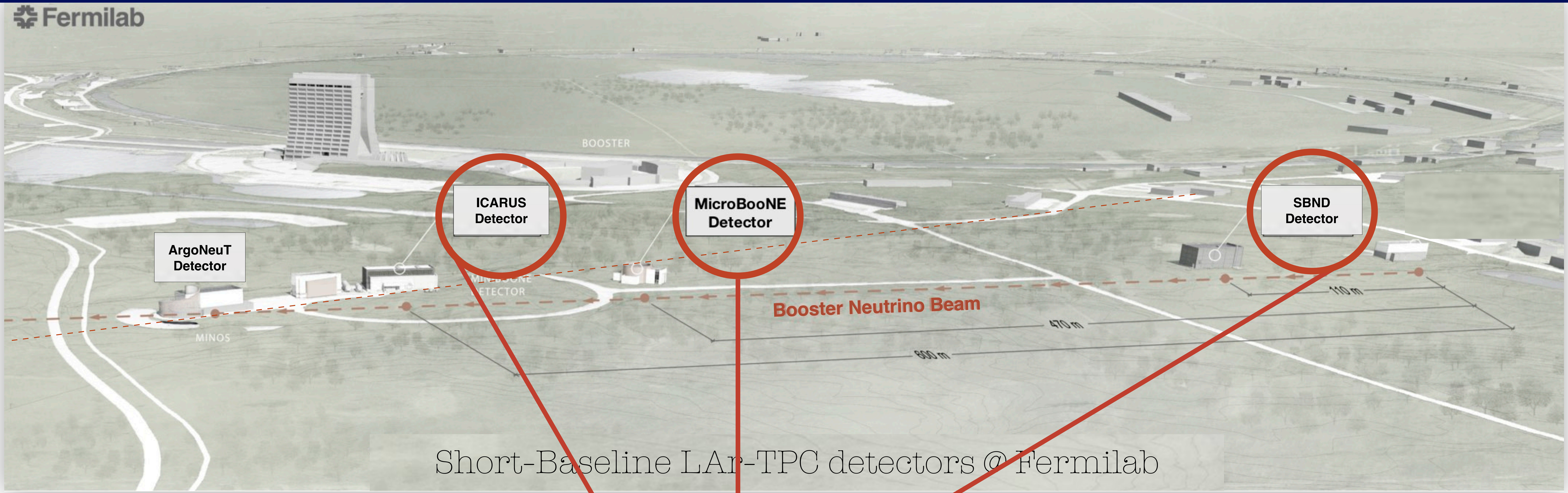
**0.24 tons** active volume LAr TPC



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

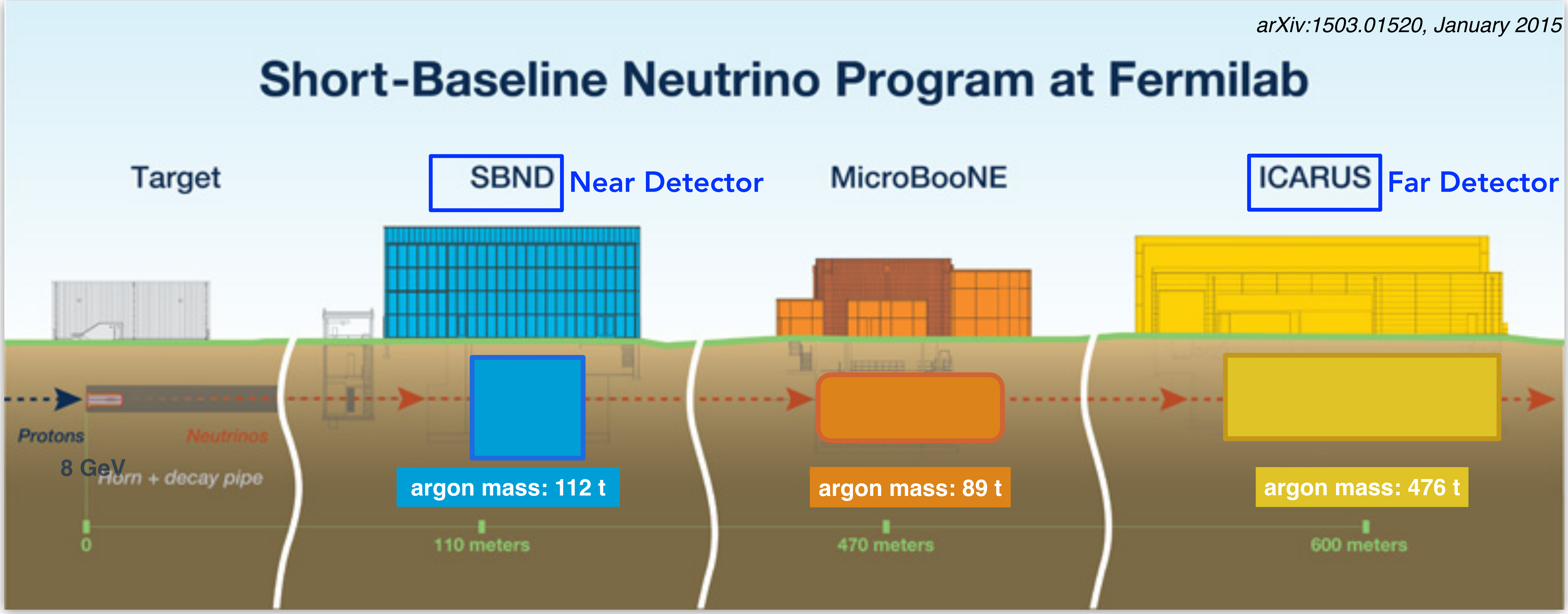
**Table-top size, built as a test experiment… but still producing physics results!**

# SHORT-BASELINE LAR DETECTORS AT FERMILAB: SBN DETECTORS




Multiple LAr detectors on-axis on the Booster Neutrino Beam

# SHORT BASELINE NEUTRINO PROGRAM




**Booster Neutrino Beam**

**Mean $\nu_\mu$ energy: ~0.8 GeV**

Beam composition:
$\nu_\mu$ (93.6%)
$\bar{\nu}_\mu$ (5.9%)
$\nu_e+\bar{\nu}_e$ (0.5%)

**2015-2021**
Large production of scientific results

A program designed for **Sterile Neutrino** searches: same neutrino beam, nuclear target and detector technology to reduce systematic uncertainties to the % level.

But large mass LAr detectors and proximity to intense beams enables a **broad physics program**.

*See later…*

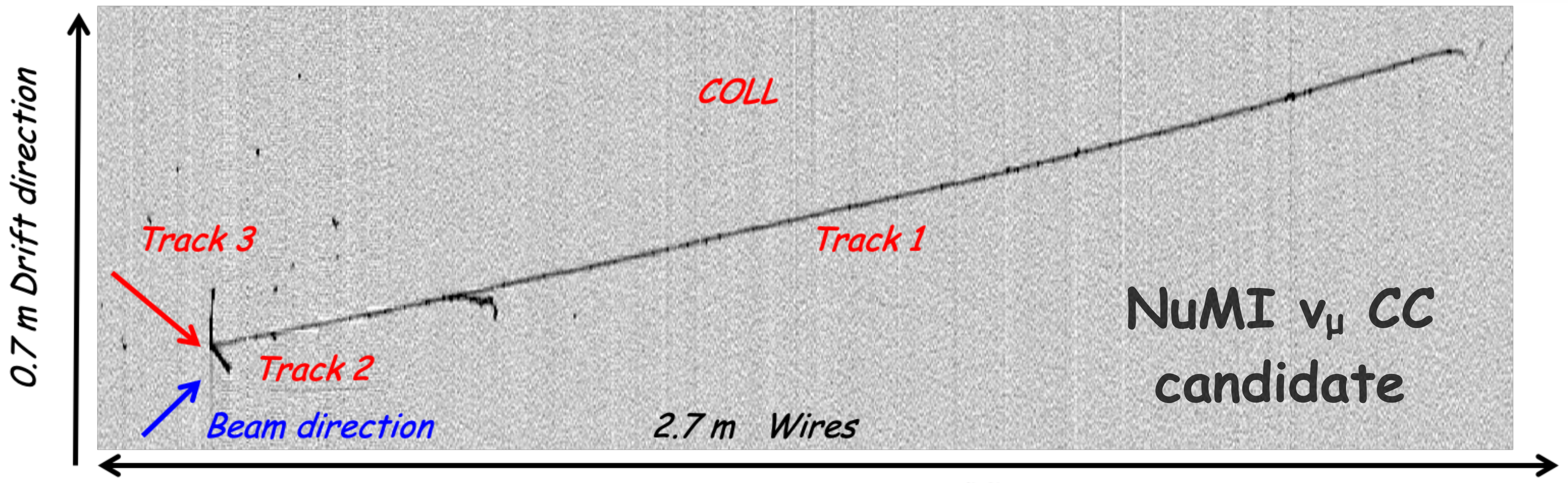
# SBN Far detector: ICARUS

From **Gran Sasso Laboratory** to **Fermilab** via **CERN**

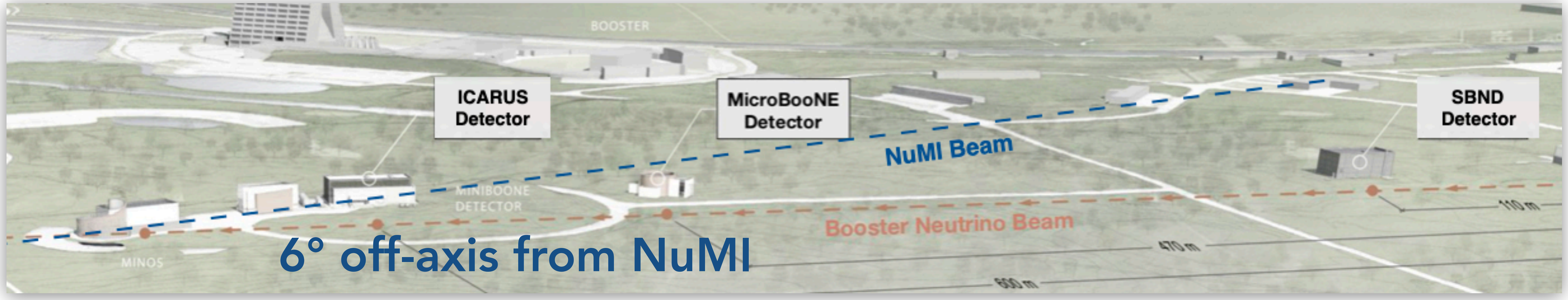

Four Time Projection Chambers in two modules
**Each module dimension**:
3m x 4m x 18m

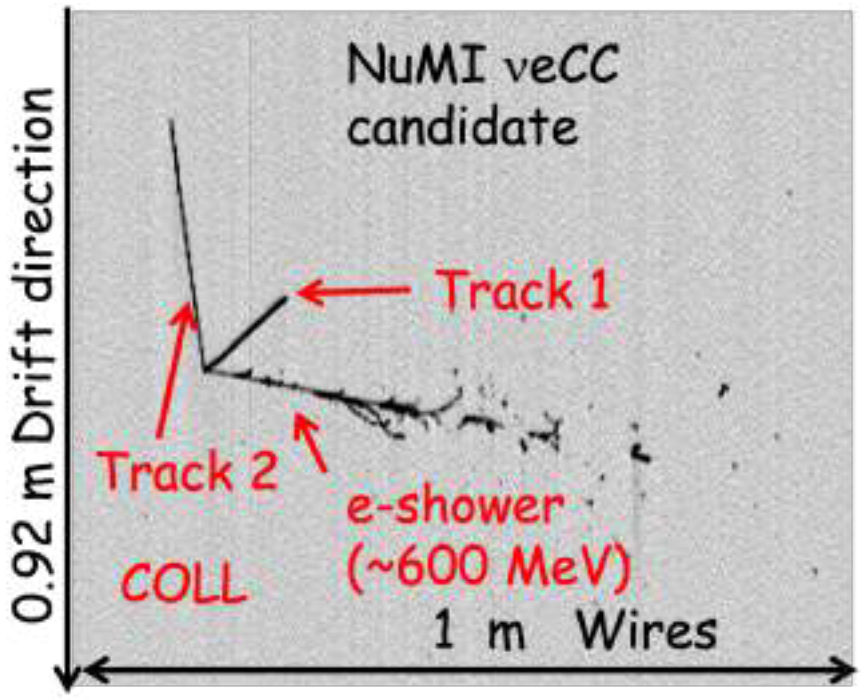
Installation of ICARUS cryostats

Collecting data in final configuration since **June 2022**

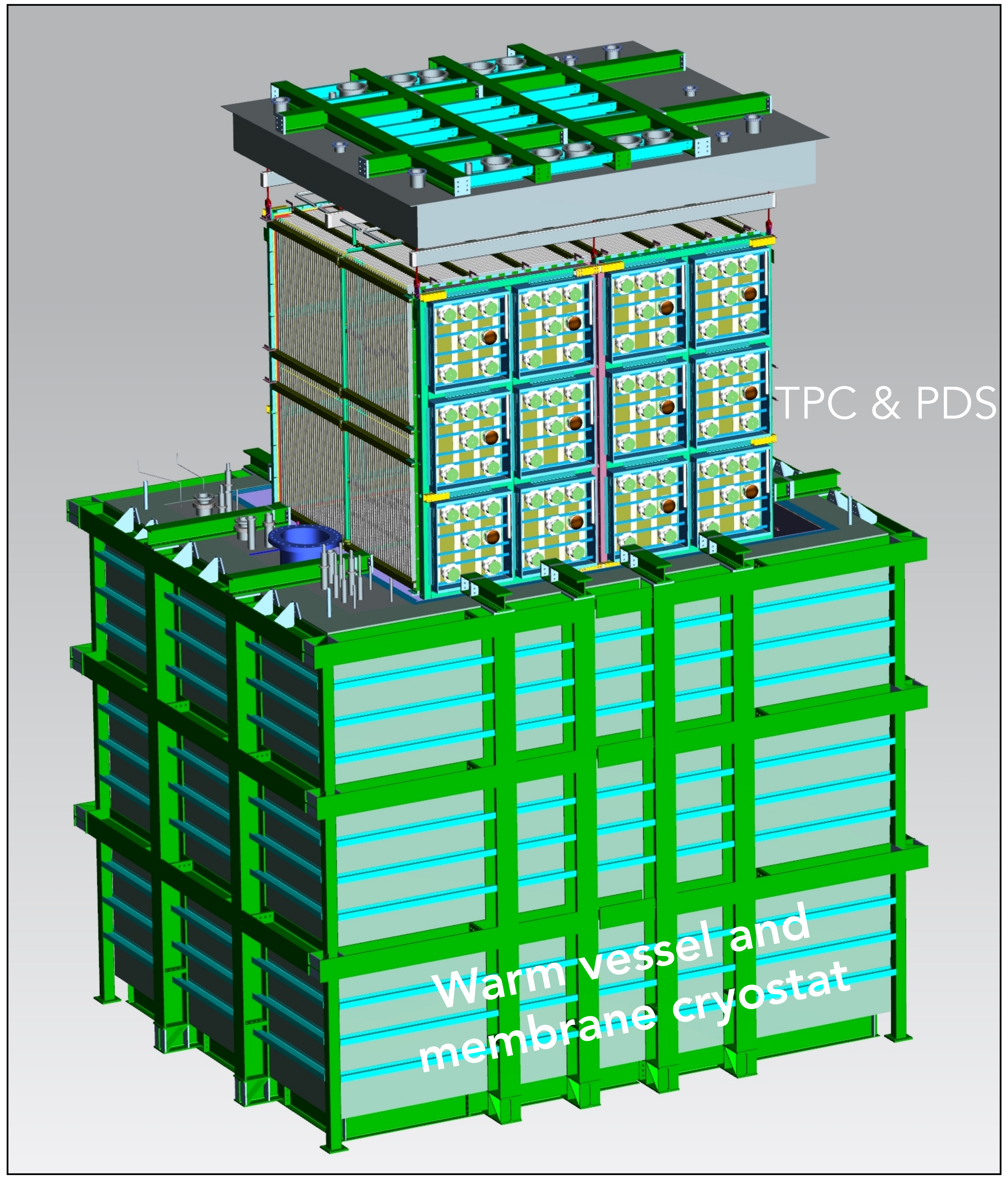


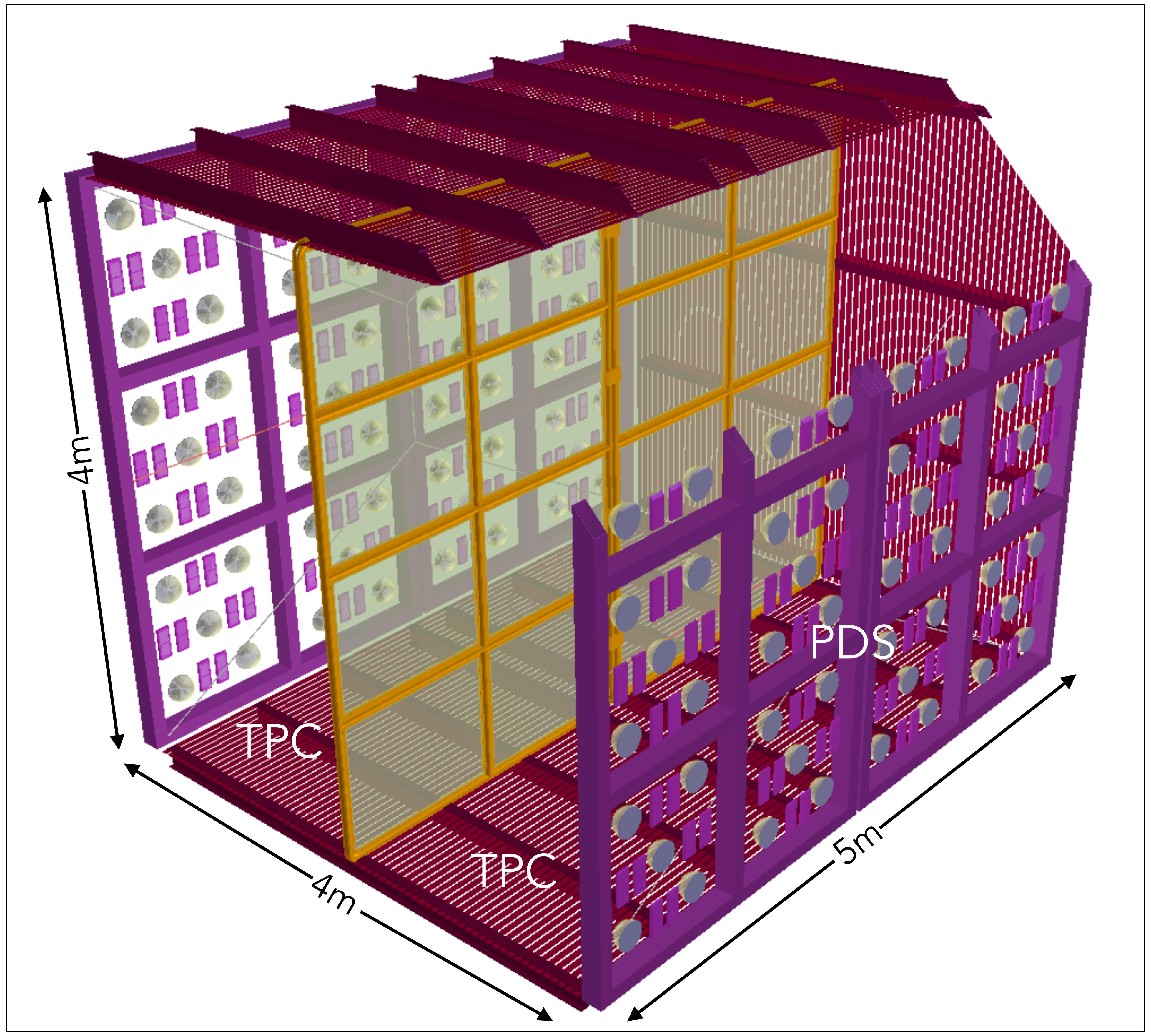

ICARUS receives two neutrino beams: it also sits 6° off-axis from the NuMI beam



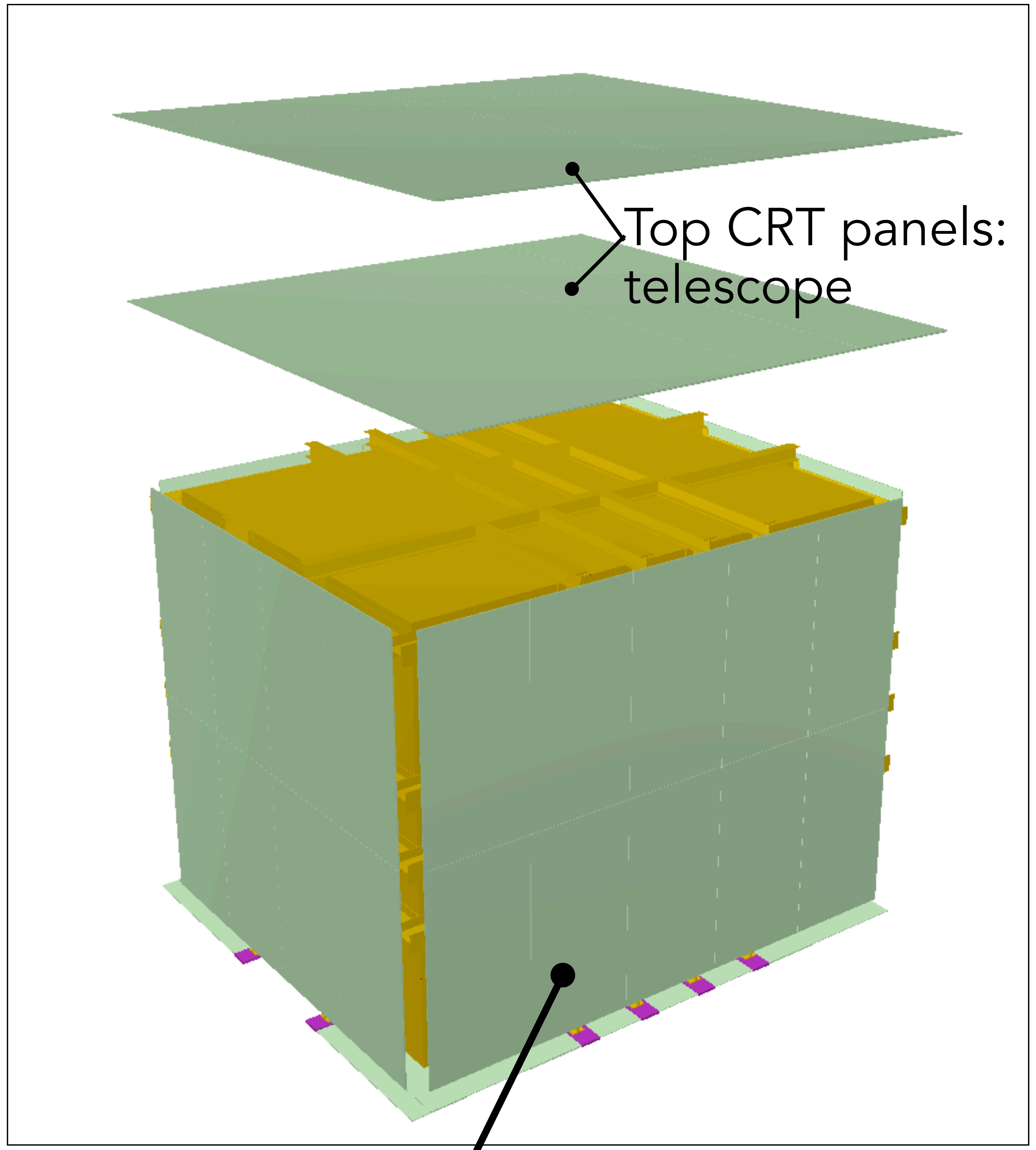
# SBN Near detector: SBND




Two Time Projection Chambers
and Photon Detection systems

Cryostat surrounded by a
Cosmic Ray Tagger system
for cosmic ray rejection

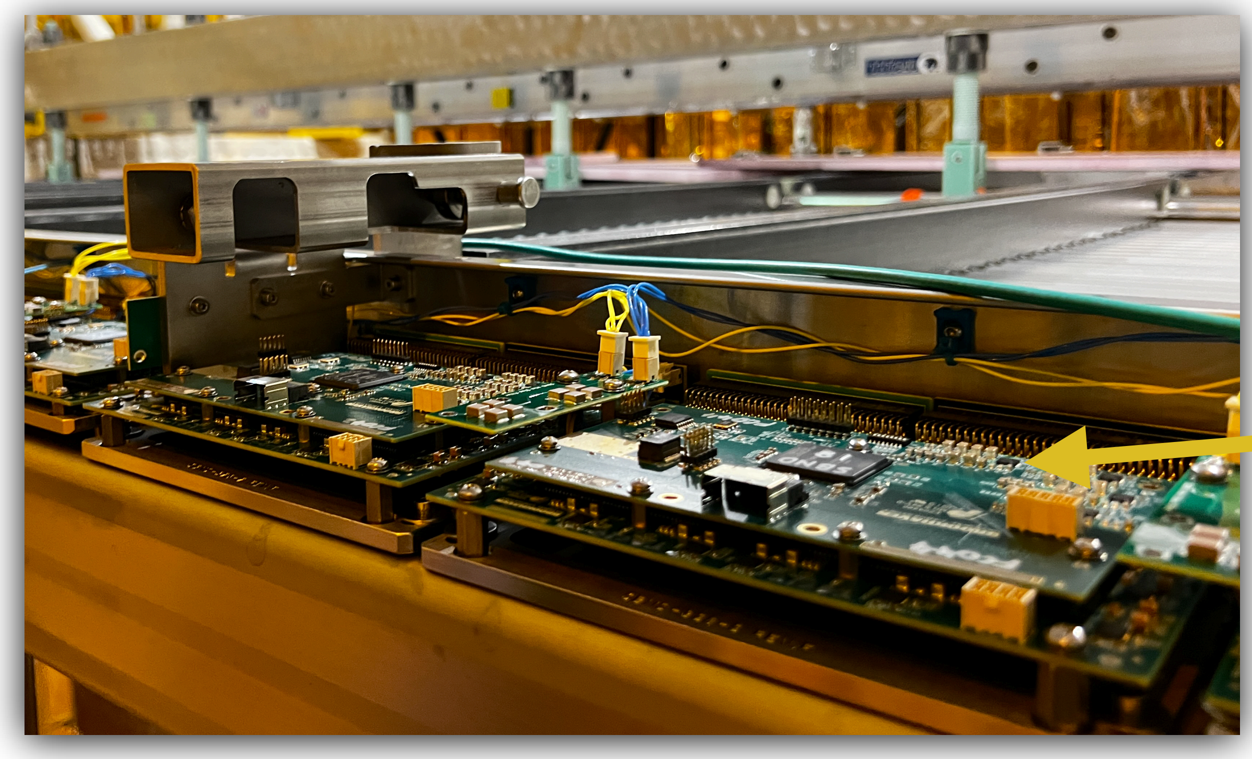


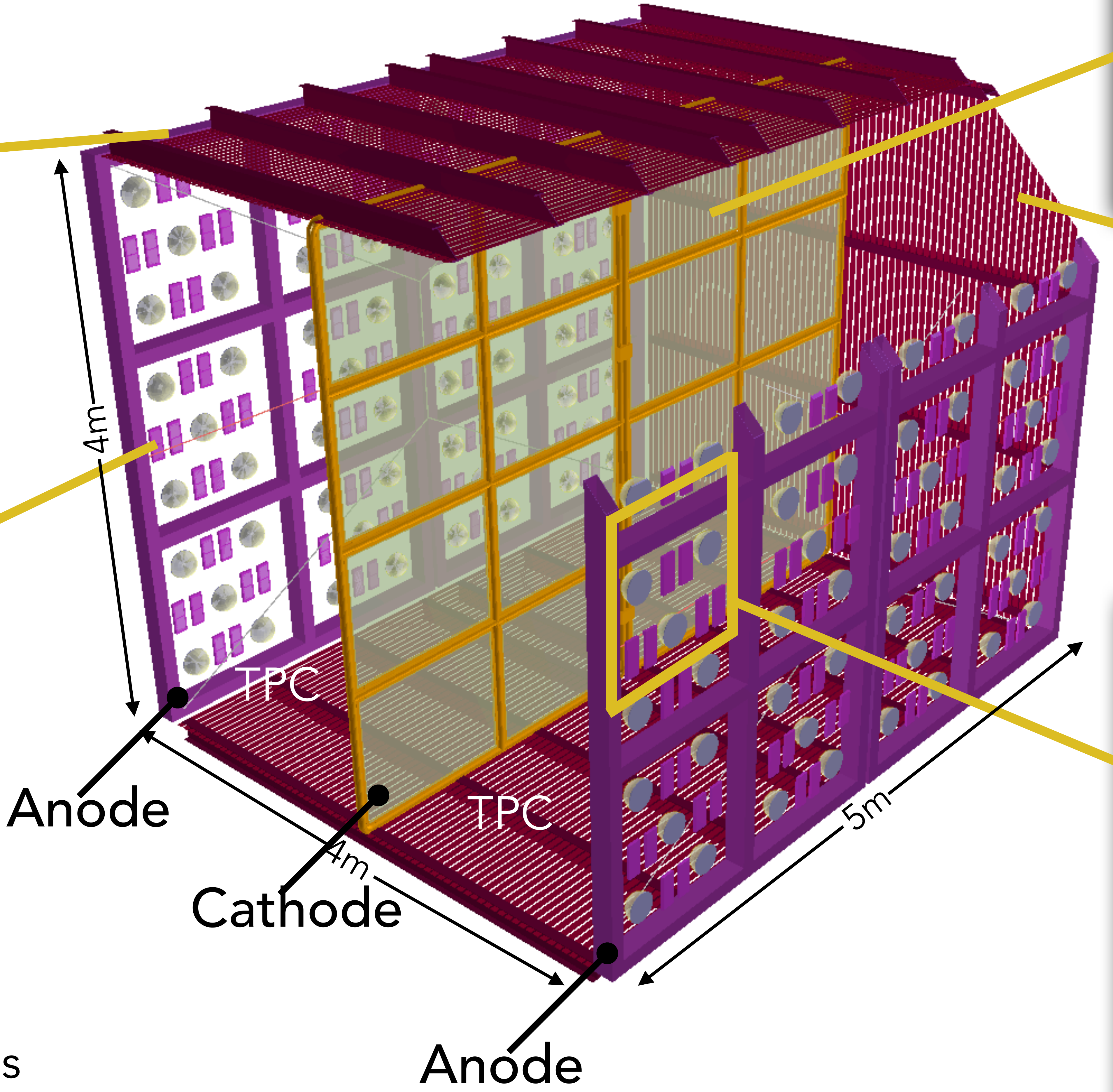

Panels made of scintillator strips

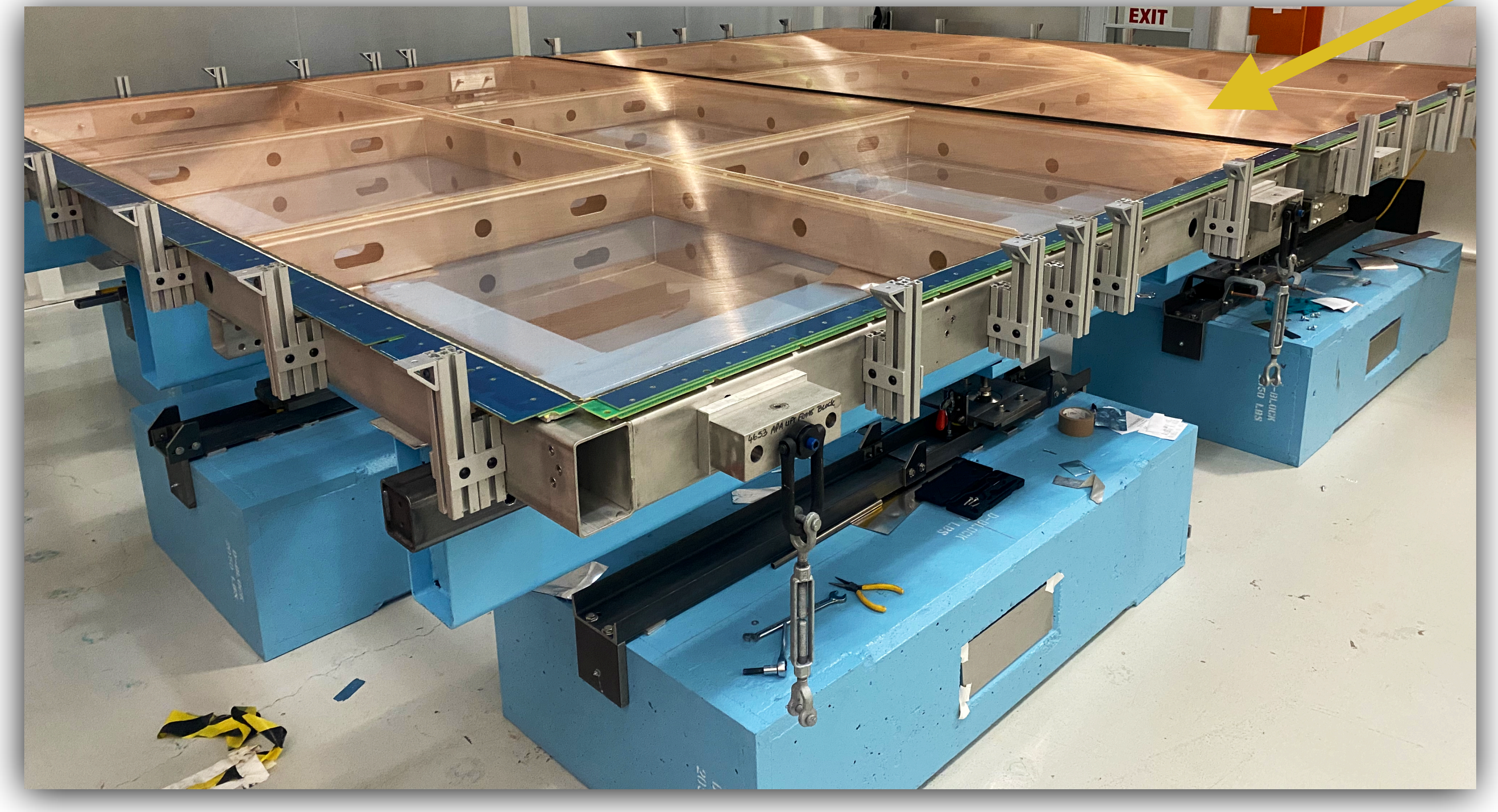
# SBND DETECTOR: TPC AND PDS

Two Time Projection Chambers
**Total dimension**: 4m x 4m x 5m

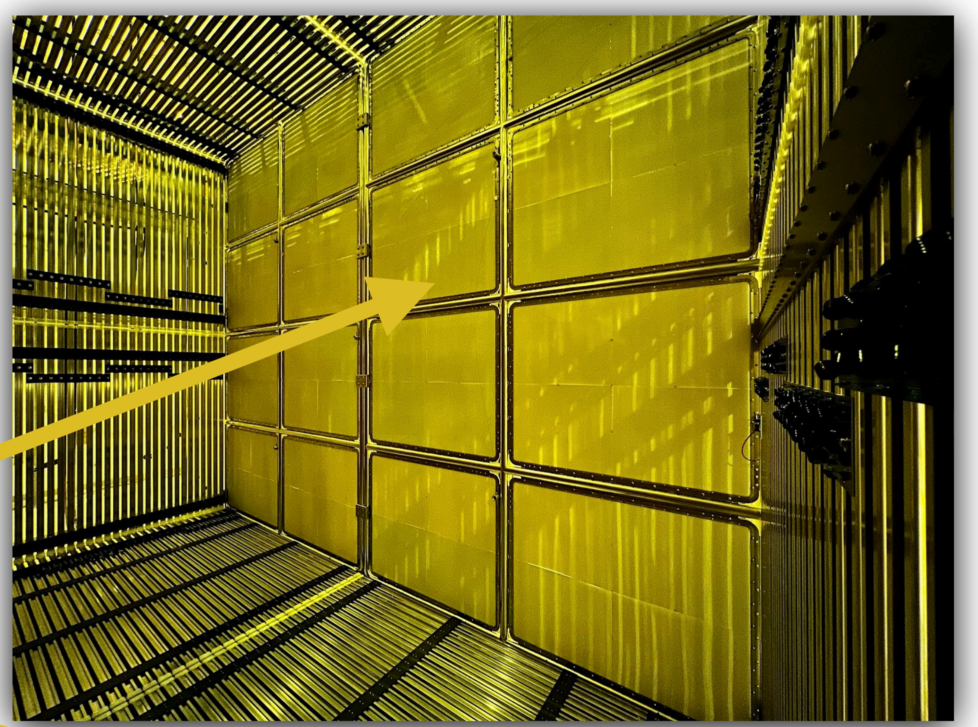
TPC Cold electronics





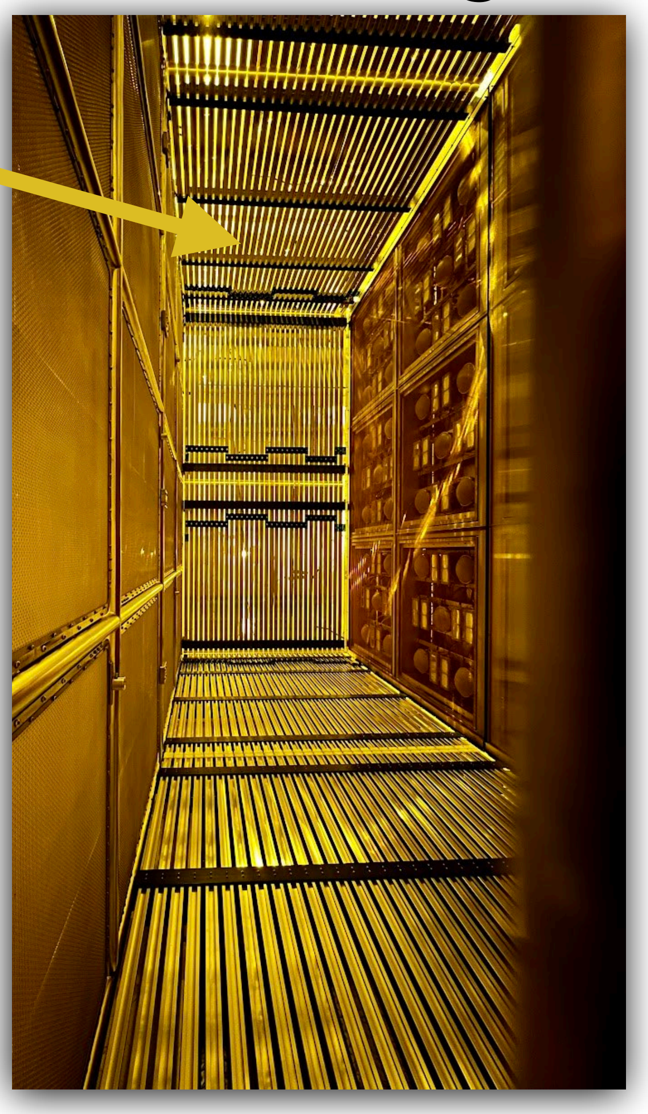



APA-Wire Planes- 3 planes, ~11000 wires



**CPA-Cathode** covered with TPB coated reflectors

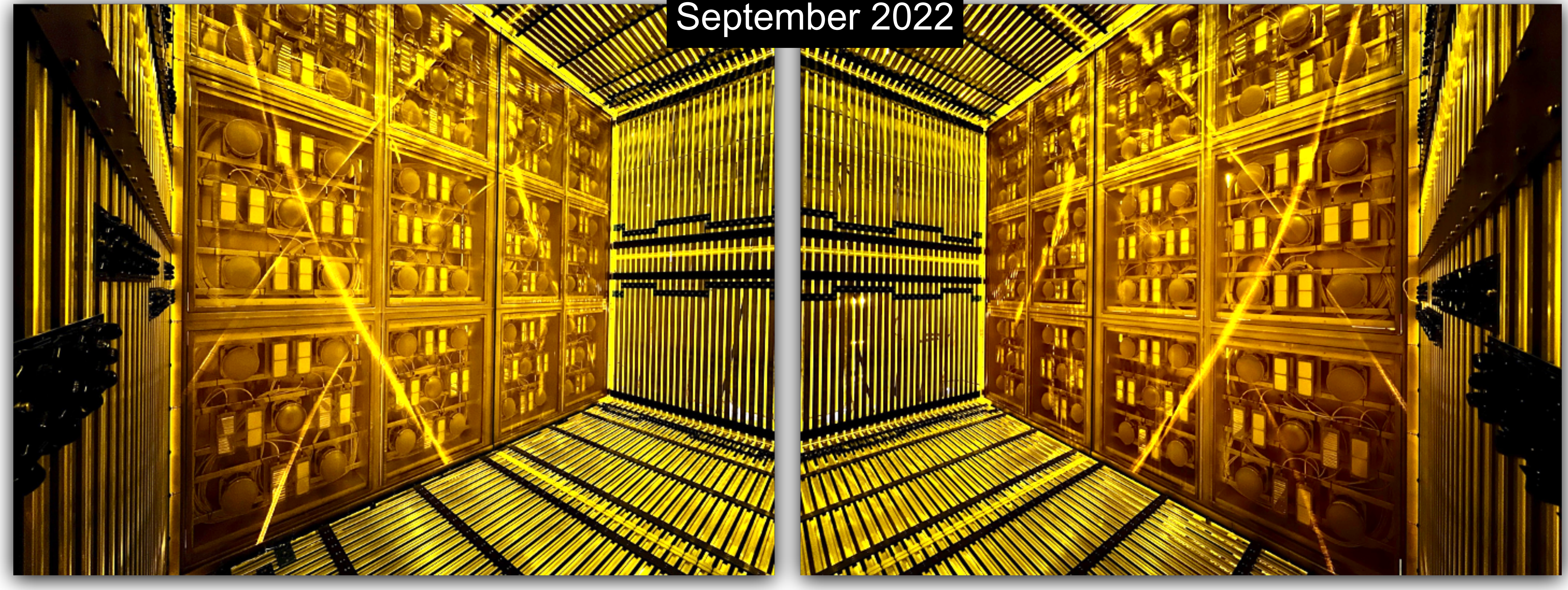
Field Cage



**Photon Detection Systems**: 120 PMTs, 192 X-Arapucas

# SBND Status

September 2022

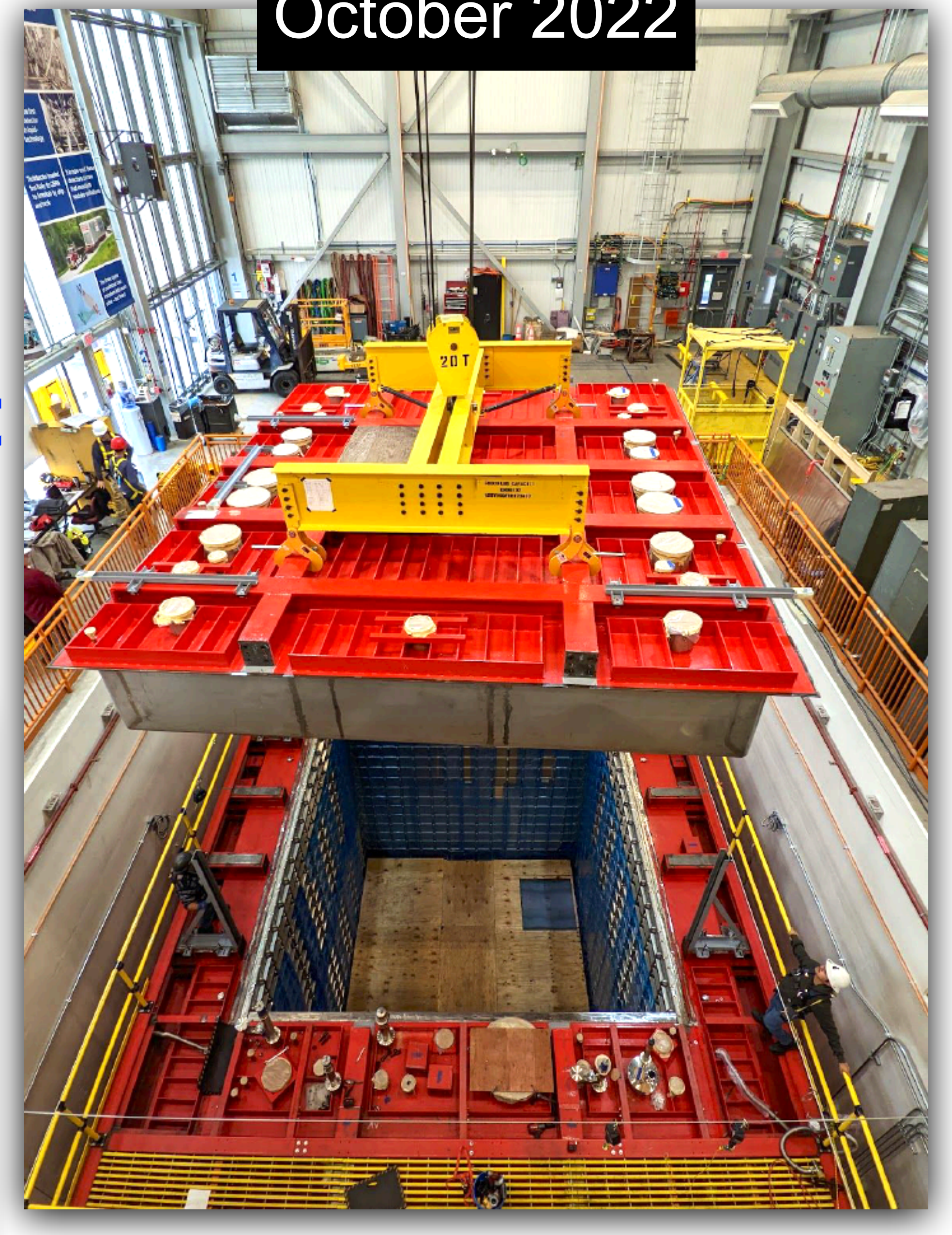


SBND detector completed

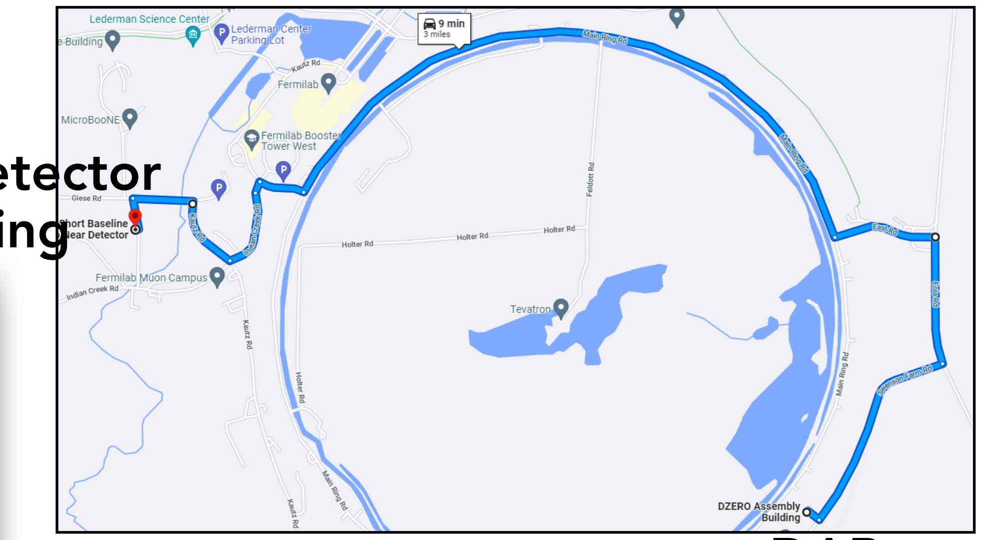
Membrane cryostat

SBND cryostat completed

October 2022

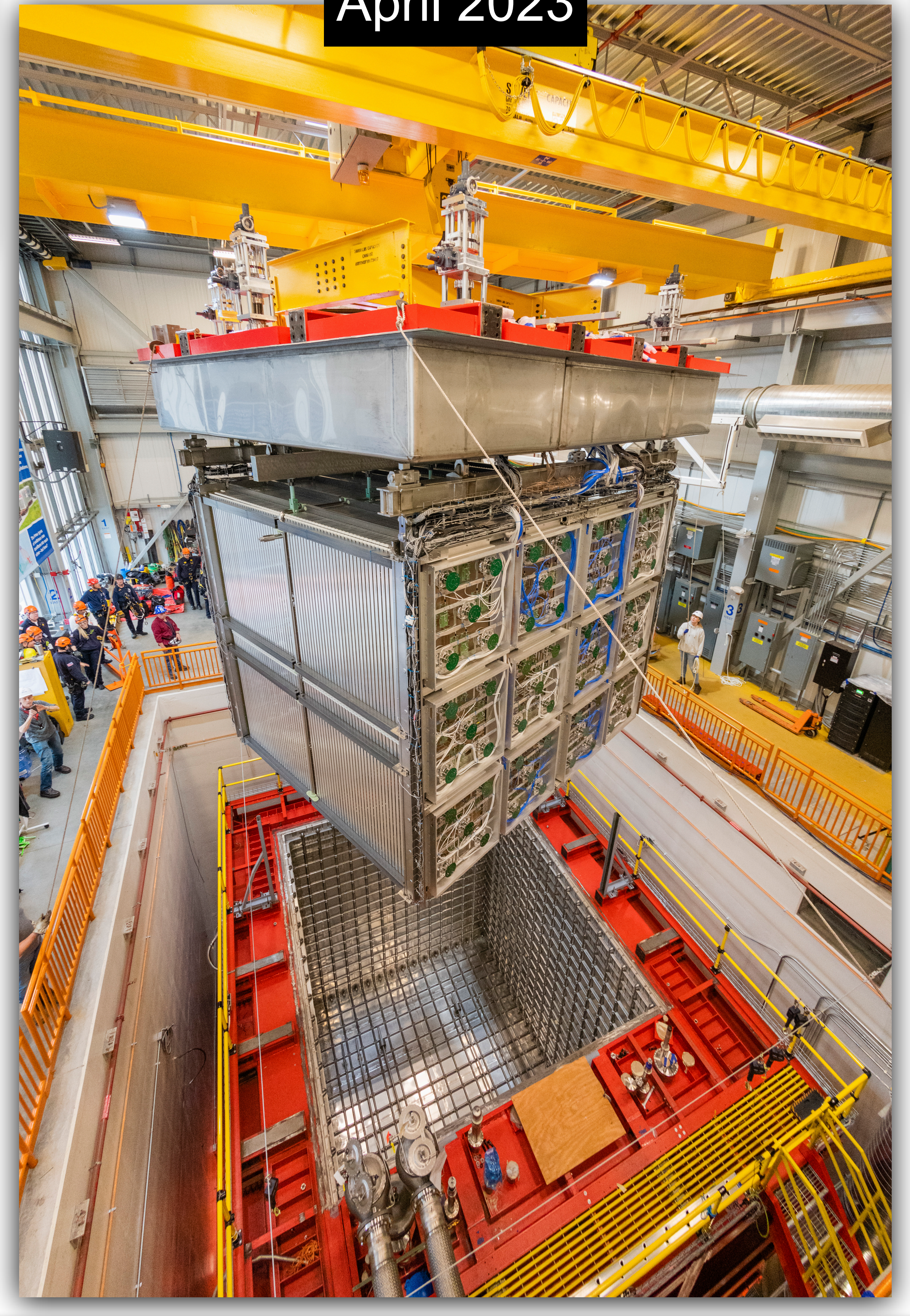


SBND detector move




December 2022

April 2023

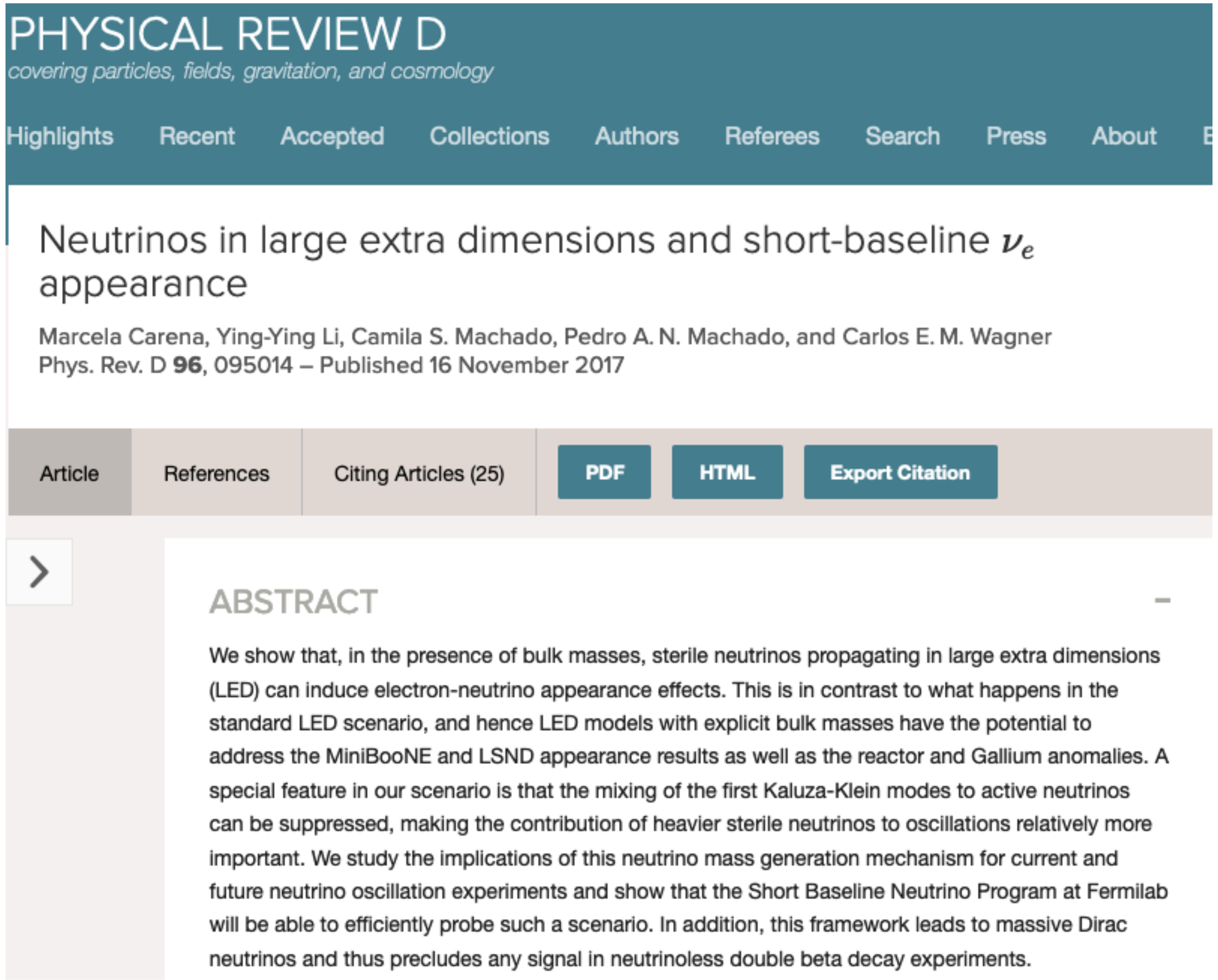


SBND detector into the cryostat

Expected to begin operations in **Fall 2023**

Soon after I moved to Fermilab in 2014, I was invited to be part of a couple of theory search committees and this gave me the opportunity to start interacting with the Fermilab Theory Division, lead by Marcela.

In **2017**, **Marcela** contacted me to discuss about a neutrino model that, with **Carlos** and Collaborators, they wanted to test against possible Short-Baseline Neutrino (SBN) program sensitivity.


PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

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Neutrinos in large extra dimensions and short-baseline $\nu_e$ appearance

Marcela Carena, Ying-Ying Li, Camila S. Machado, Pedro A. N. Machado, and Carlos E. M. Wagner
Phys. Rev. D **96**, 095014 – Published 16 November 2017

Article References Citing Articles (25) PDF HTML Export Citation

ABSTRACT

We show that, in the presence of bulk masses, sterile neutrinos propagating in large extra dimensions (LED) can induce electron-neutrino appearance effects. This is in contrast to what happens in the standard LED scenario, and hence LED models with explicit bulk masses have the potential to address the MiniBooNE and LSND appearance results as well as the reactor and Gallium anomalies. A special feature in our scenario is that the mixing of the first Kaluza-Klein modes to active neutrinos can be suppressed, making the contribution of heavier sterile neutrinos to oscillations relatively more important. We study the implications of this neutrino mass generation mechanism for current and future neutrino oscillation experiments and show that the Short Baseline Neutrino Program at Fermilab will be able to efficiently probe such a scenario. In addition, this framework leads to massive Dirac neutrinos and thus precludes any signal in neutrinoless double beta decay experiments.

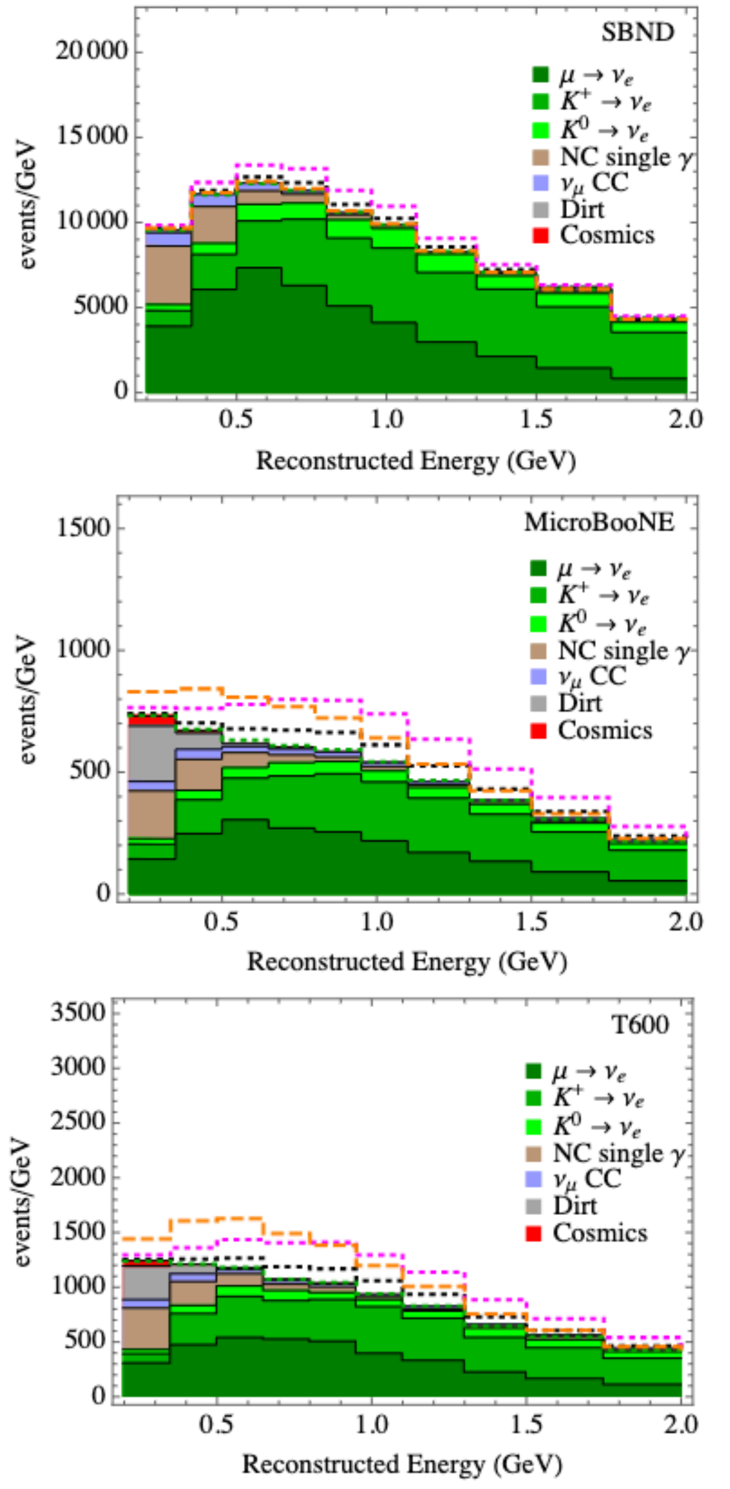
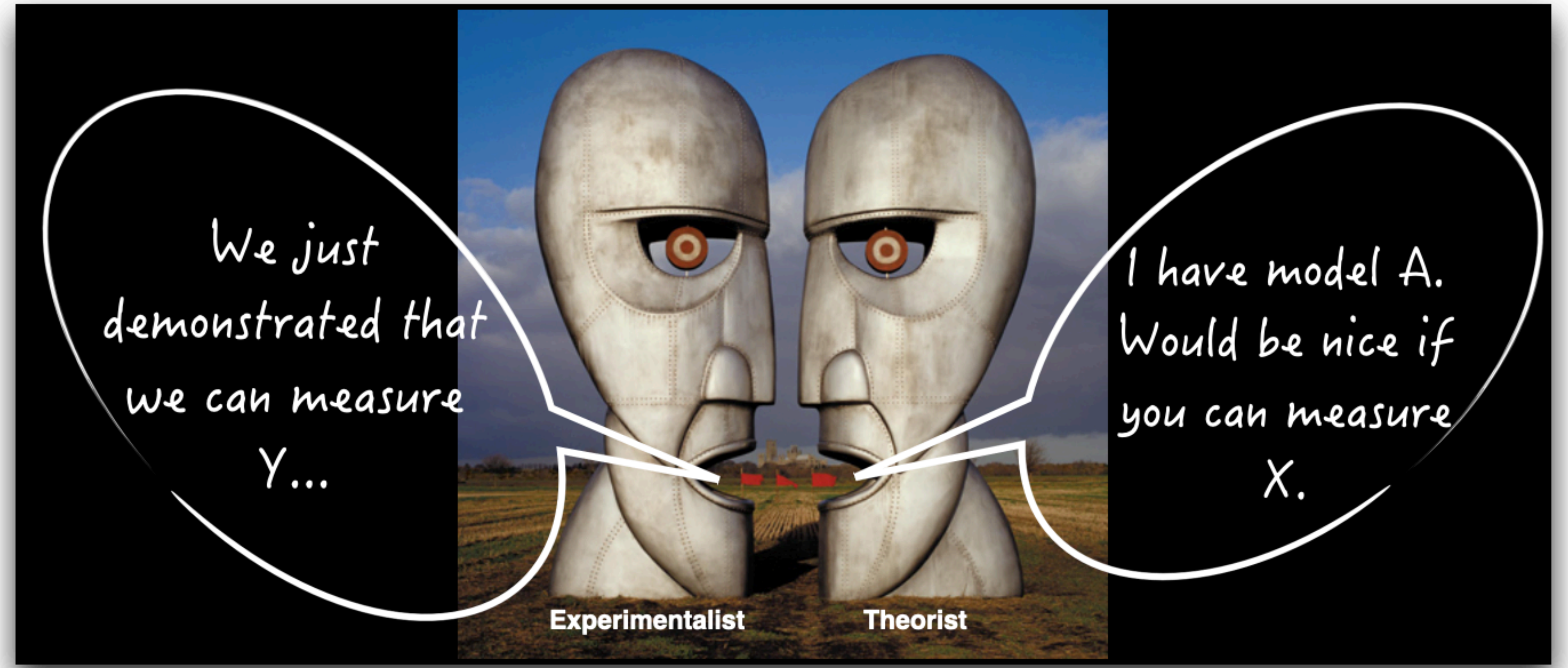



FIG. 10: $\nu_e$ appearance spectrum at SBN detectors: (top) LAr1-ND, (middle) MicroBooNE, and (bottom) ICARUS-T600. Full data set at these three detectors are assumed (see text). The shaded histograms are the different background components as indicated in the legend (taken from Ref. [32]). Black, green, magenta and orange lines are for points 1, 2, 3 in Table I and the best-fit 3+1 sterile neutrino model, respectively.

Appearance spectrum at SBN detectors

# A BRIDGE BETWEEN THEORY AND NEUTRINO EXPERIMENTAL PROGRAM




## Fermilab is an ideal place to develop this program

Some informal discussion between neutrino experimentalists and theorists turned into the **SBN-Theory working group** (started in 2018 - a joint experiment+theory effort).

Goal: to exploit possibilities to enrich the physics program of LAr TPC neutrino experiments with **New Physics scenarios**.

Direct, regular and continued collaboration turned in several **successful projects** [a few examples in the following]

# SBN-Theory Working Group meetings

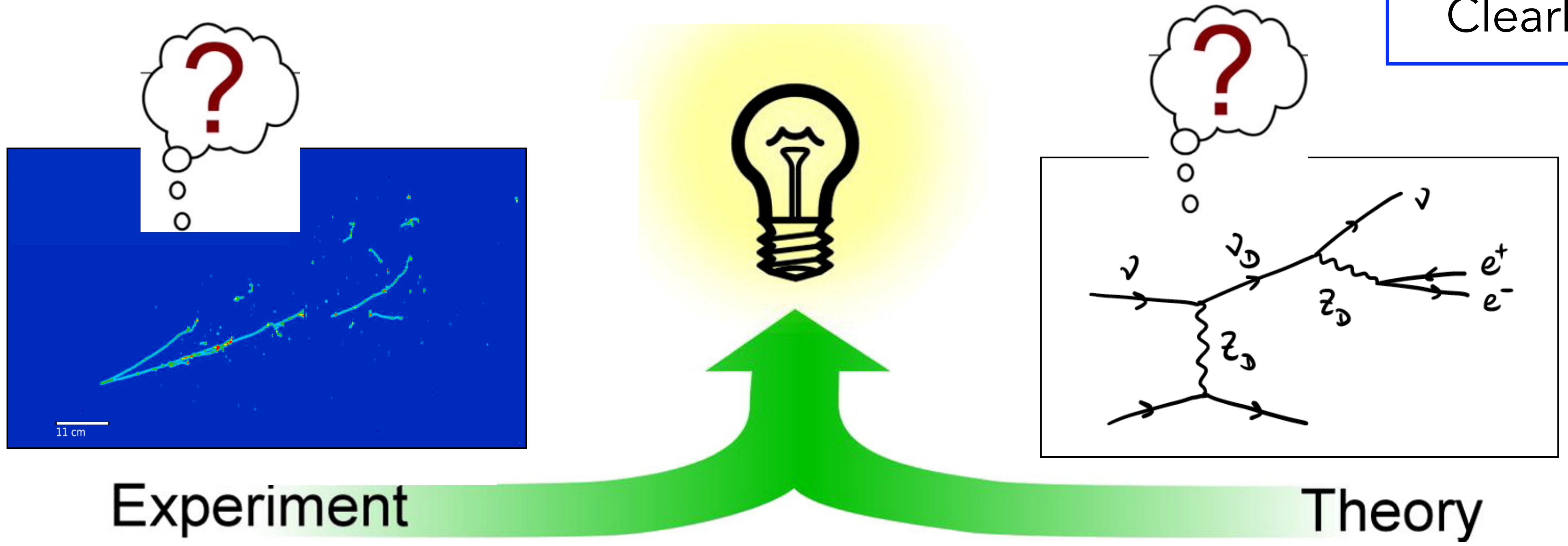
Informal meetings (slides+backboard!!) *Organizer: Pedro Machado*

- Discuss experimental capabilities of LAr TPC neutrino detectors, current status of event reconstruction, thresholds and resolution.
- Discuss **New Physics** models.
- Theorists to better know how the LAr TPC technology works and experimentalists to know what to look for.
- Work **side-by-side** on various projects, understanding signal and background.

~90 people in the SBN-TH mailing list

30+ participants in each meeting.

Clearly a lot of interest in the community!

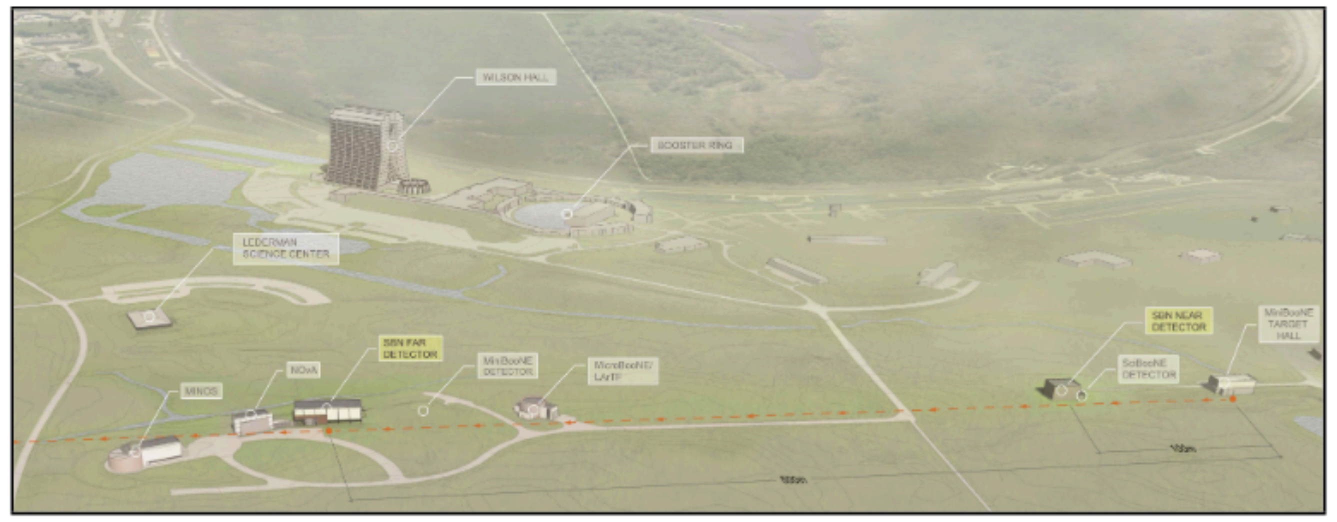



Marcela's and Carlos' influential impact on a new way to make physics today!

# SBN PROGRAM: NOT ONLY OSCILLATION PHYSICS!

The Short-Baseline Neutrino program proposal (**2014**) only mentioned about another possible search for “New Physics”:
*“SBN will also be able to search for* sub-GeV dark matter *(mass less than a few hundred MeV) by* running in beam-dump mode, *where the 8 GeV proton beam is steered above the beryllium target and into the 50 m (or 25 m) downstream absorber.*

**A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam**



*The ICARUS, SBND and MicroBooNE collaborations*
*arXiv:1503.01520, January 2014*

Designed for **Sterile Neutrino** searches
Same neutrino beam, nuclear target and detector technology: reducing systematic uncertainties to the % level

---

It is an evolving landscape!

Alternative potential explanations to the SBL neutrino anomalies from more recently emerging new physics scenarios from theory.

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Joint experiment+theory effort evolved into a review paper (**2019**), where a range of ideas [now under active development] for using the SBN detectors and beam to search for signatures of **New Physics** are discussed!

ANNUAL REVIEWS

*Annual Review of Nuclear and Particle Science*

The Short-Baseline Neutrino Program at Fermilab

Pedro A.N. Machado,[1] Ornella Palamara,[1] and David W. Schmitz[2]

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[2]Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637, USA; email: dwschmitz@uchicago.edu

*Annu. Rev. Nucl. Part. Sci. 69 363-387 (2019)*

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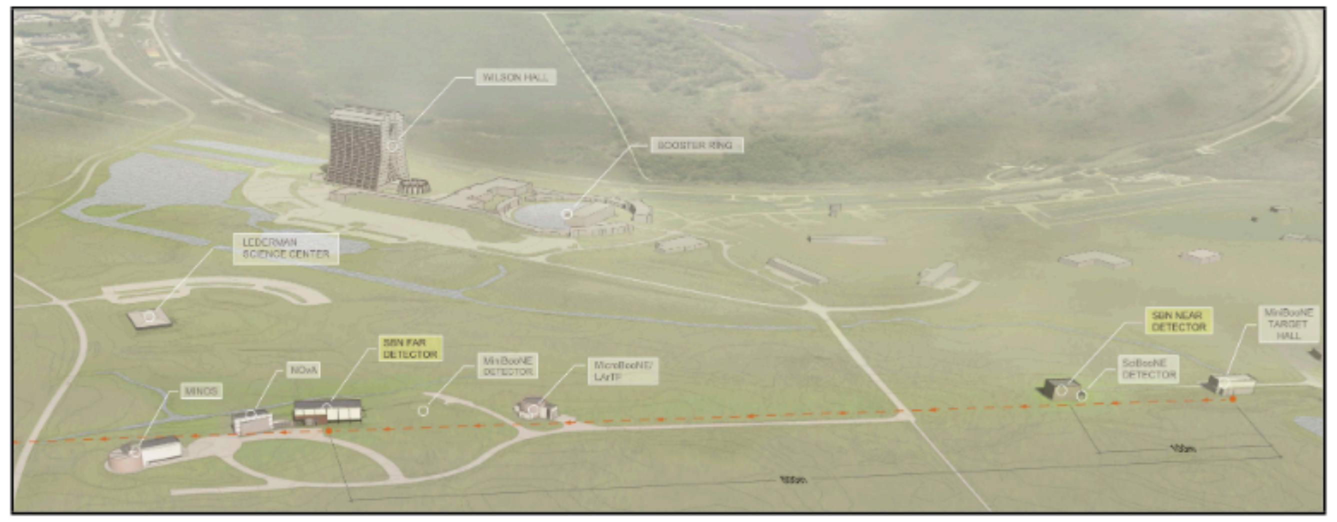

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*Pedro Machado & OP - Neutrino University (2019)*


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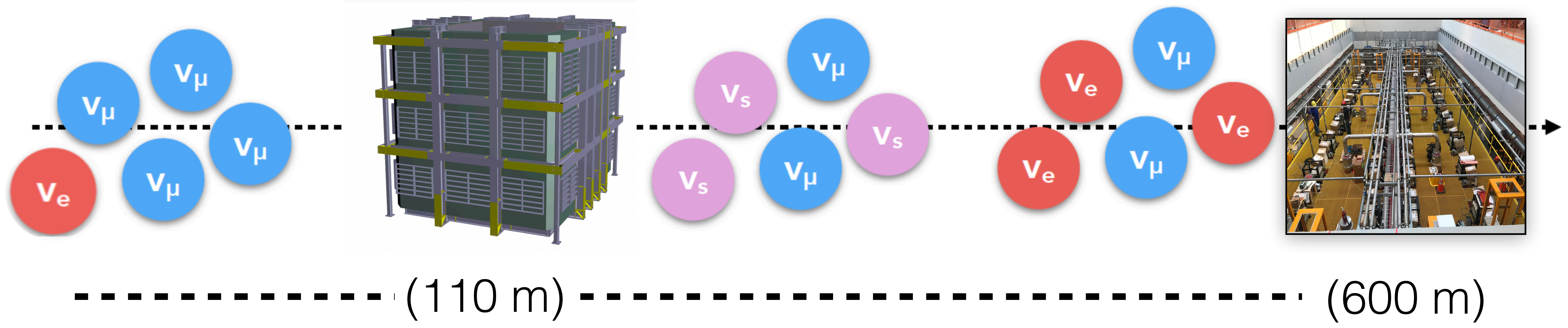
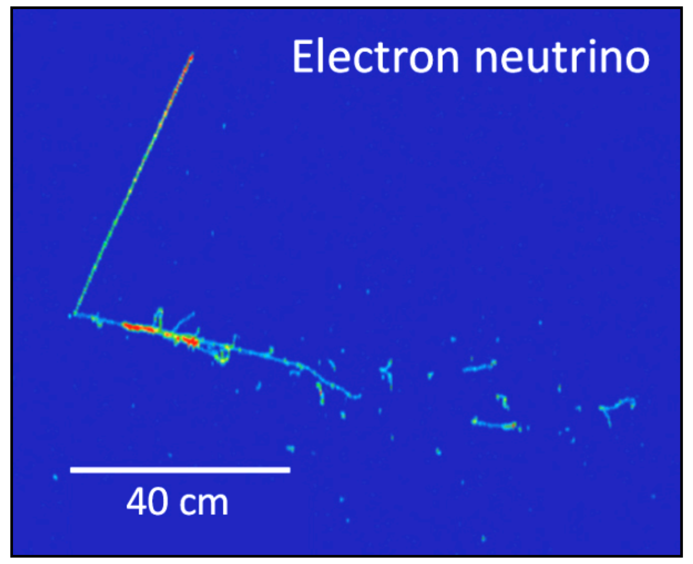
# SBN - A Broad Physics Program

**eV-scale sterile neutrinos:** searches for physics beyond the three-neutrino mixing with **multiple-detectors at different baselines.**




**Neutrino-argon interactions:** with **an order of magnitude more data** than is currently available.

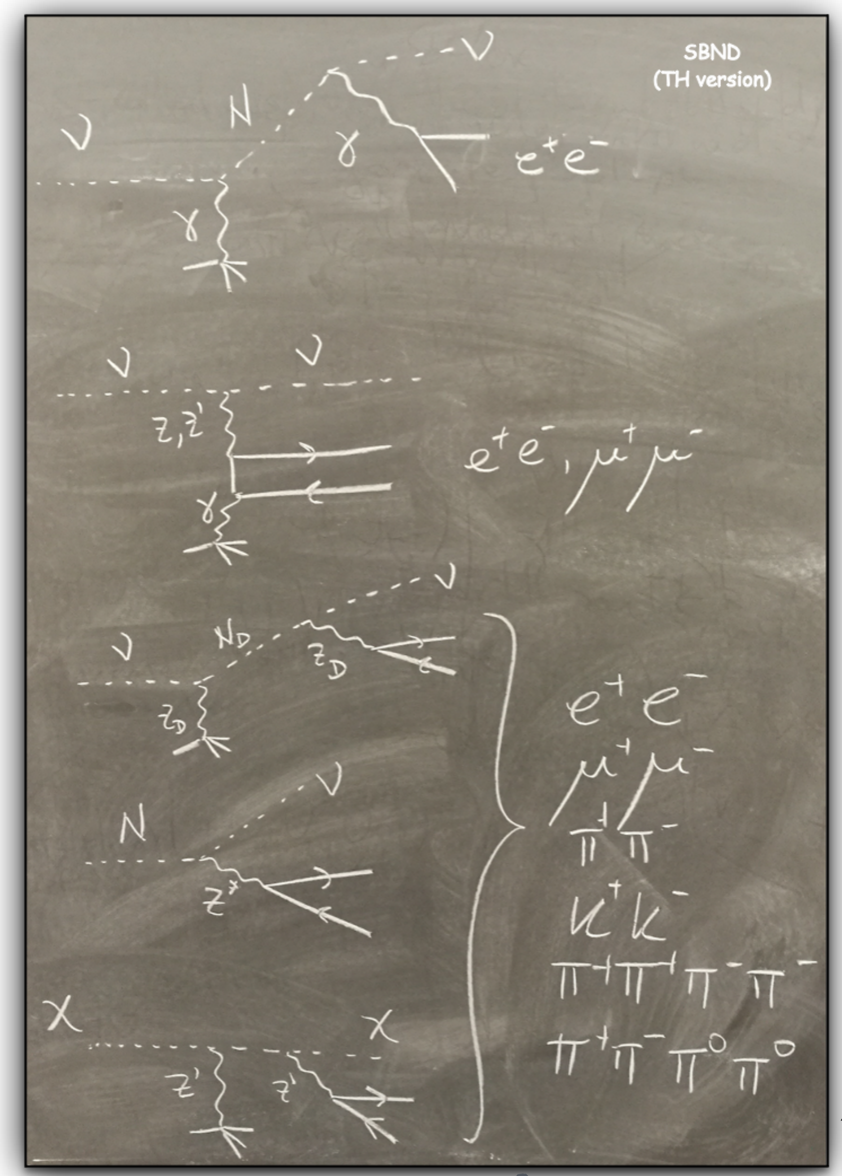



**Up to 7000 $\nu$ events/per day in SBND!**

**We have expanded the physics program!**

**New physics scenarios:** study alternative explanations of the short-baseline anomalies and other Beyond Standard Model scenarios.

**Many ideas for new searches** emerging from collaboration with theory colleagues.



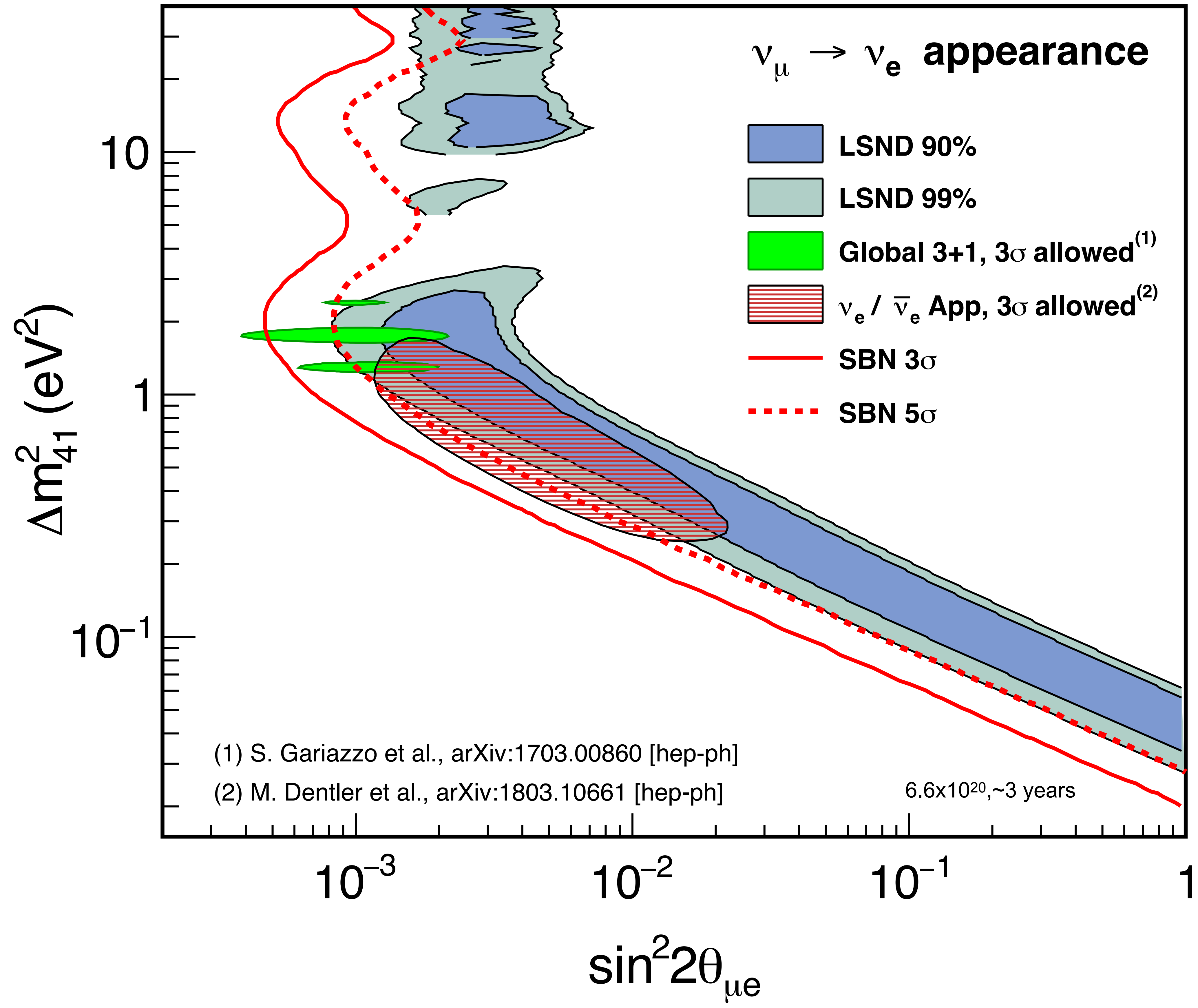

*Courtesy of P. Machado*

*P.Machado, O.P., D. Schmitz,*
*Annu. Rev. Nucl. Part. Sci. 69 363-387 (2019)*

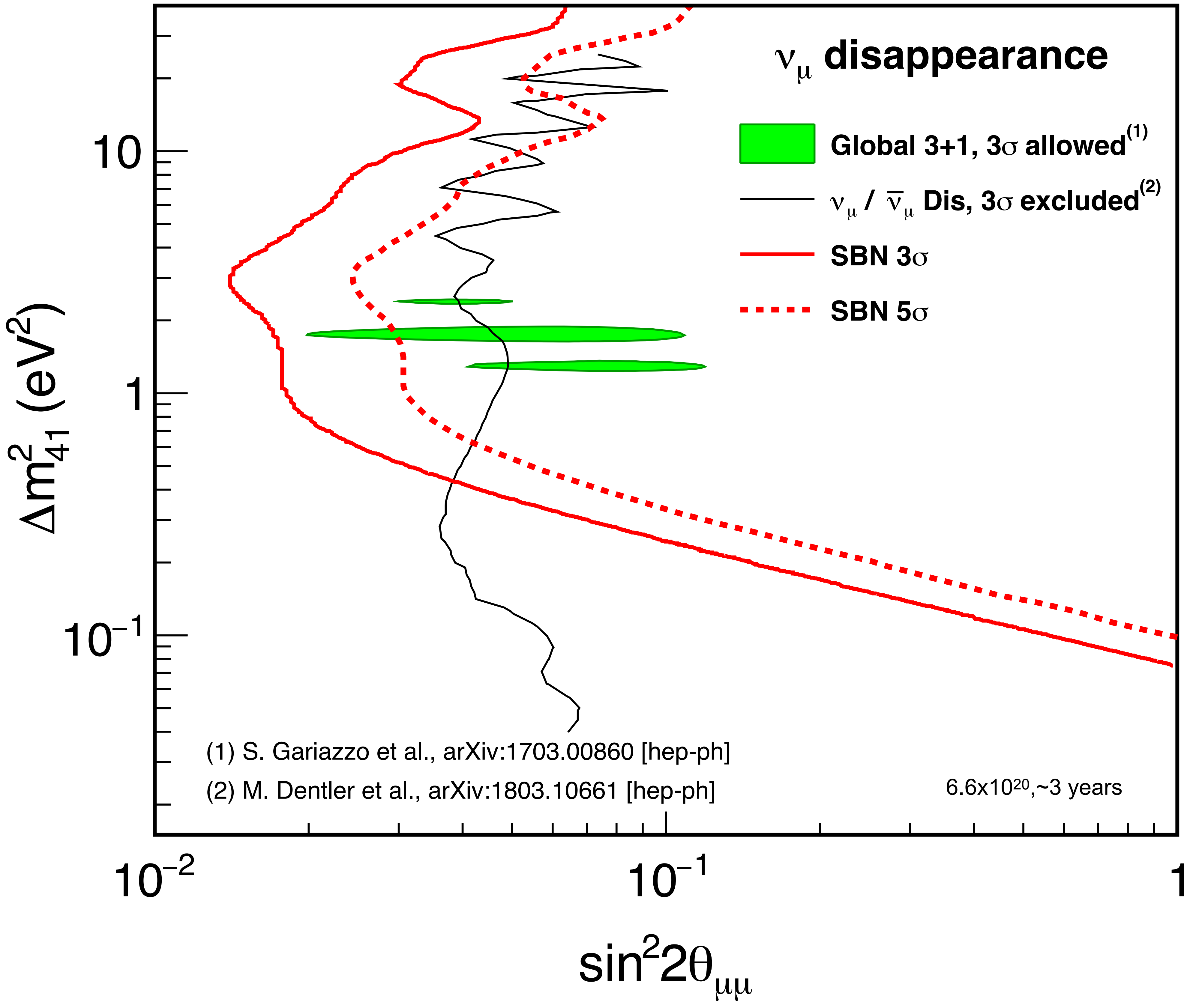
# SBN STERILE NEUTRINO SENSITIVITIES

*P. Machado, O.P., D. Schmitz: Annual Rev. Nucl. Part. Sci. 69 363-387 (2019)*

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



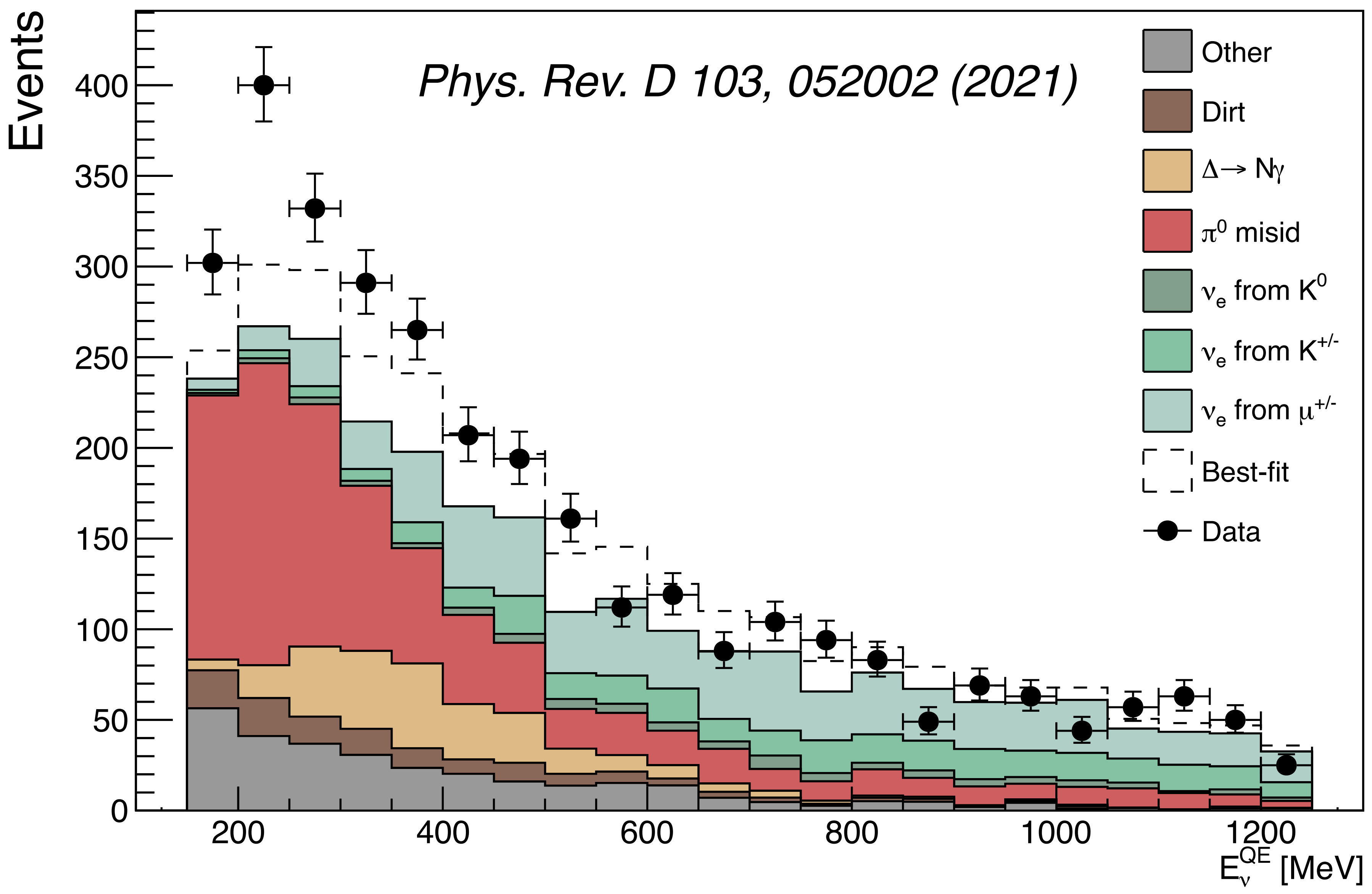

## $\nu_\mu \rightarrow \nu_x$ Disappearance sensitivity



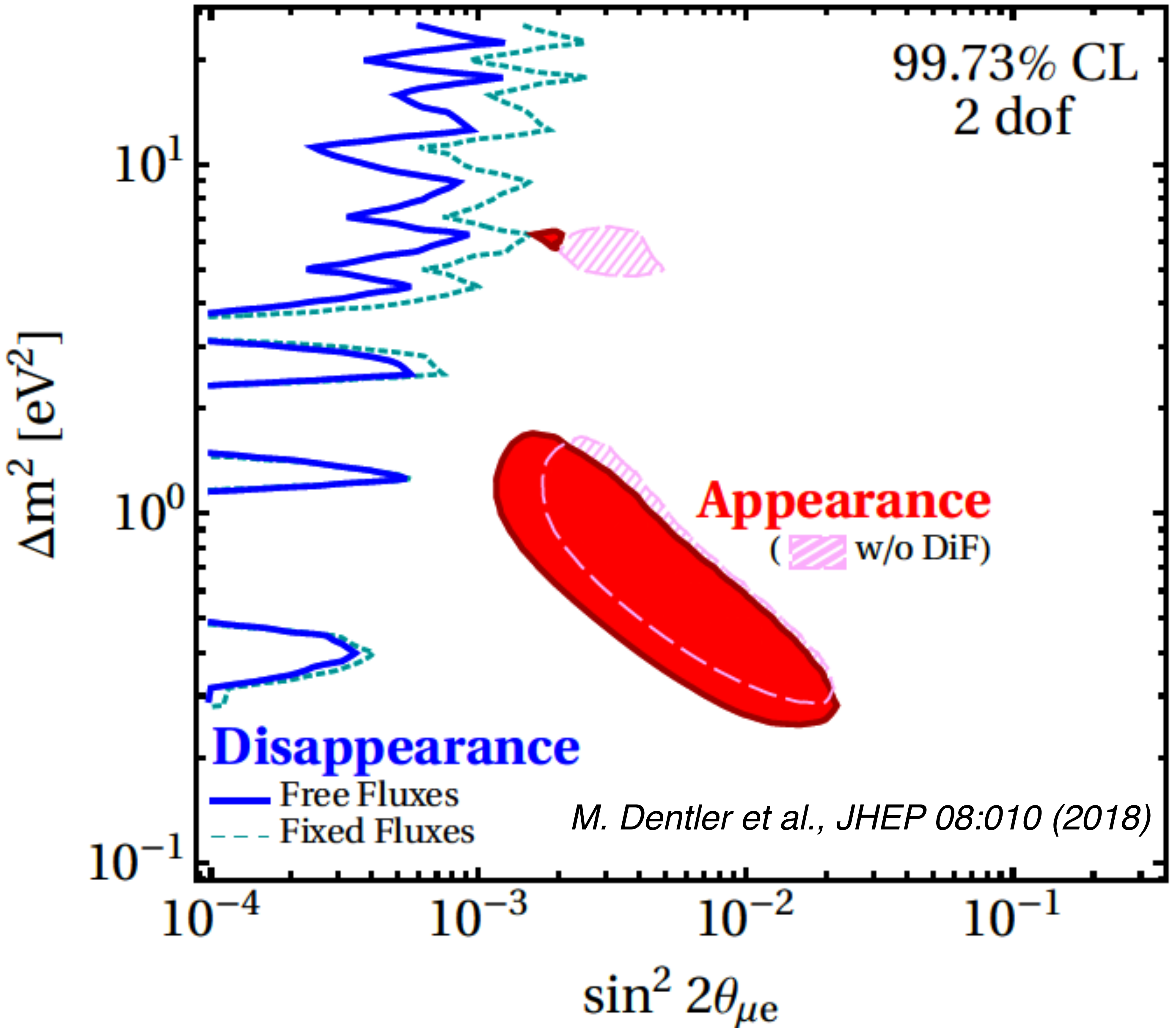

SBN can cover the parameters allowed by past anomalies at 5σ significance

A 4.7 $\sigma$ tension arises when combining $\nu_e$ appearance and $\nu_\mu$ disappearance data sets.

MiniBooNE electron-like excess

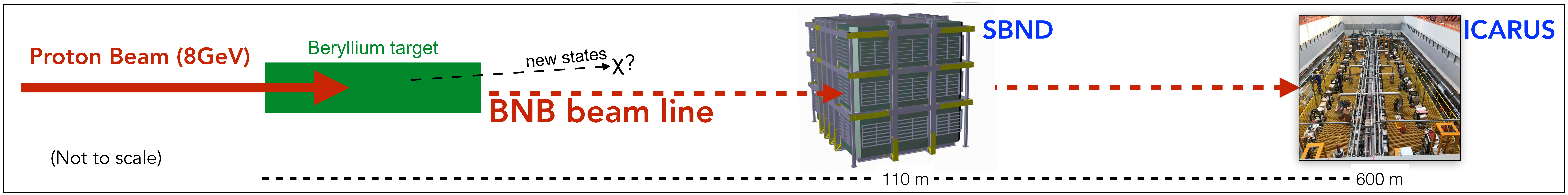


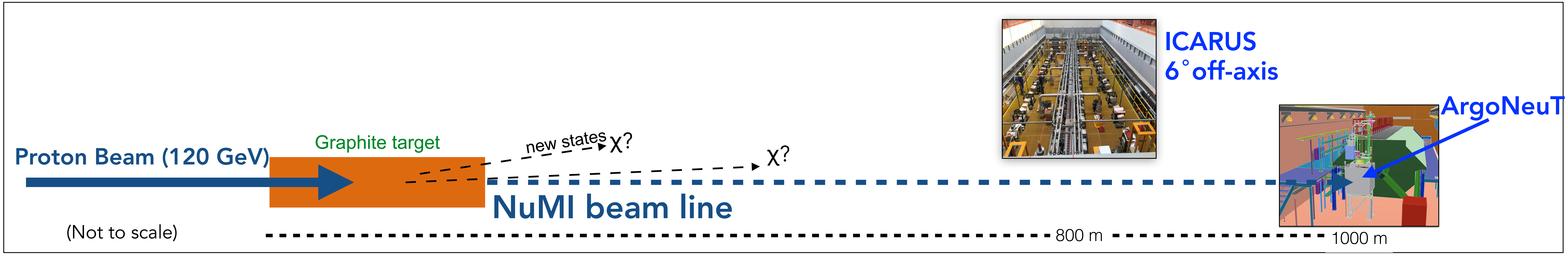

Limits from disappearance and appearance allowed region




Alternative (Beyond Standard Model) explanations exist that could explain the MiniBooNE anomaly

# SIGNATURES FOR NEW PHYSICS IN SBN AND ARGONEUT



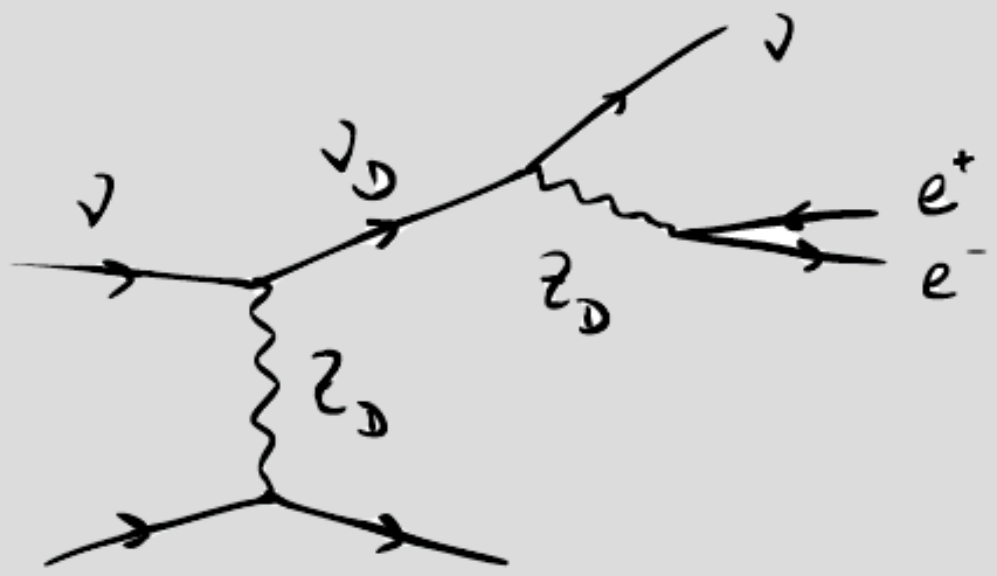

High-intensity proton beams (high-intensity neutrino beams)

(Large mass) LAr detectors close to the beam target

Opportunities to **probe signatures** for **new physics scenarios** in the **neutrino sector** (modifications to the neutrino oscillation paradigm) and **beyond** (novel experimental signatures produced in the beam target )

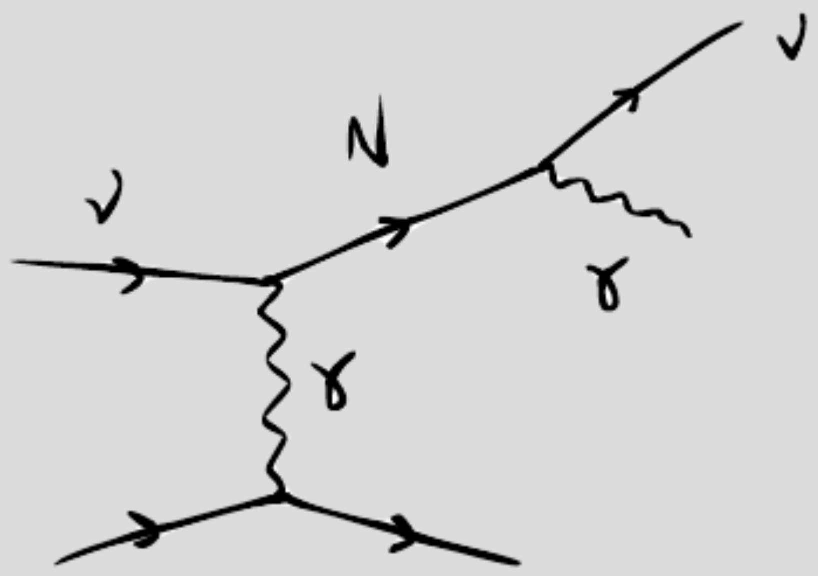
Alternative explanations of the MiniBooNE excess and other Beyond Standard Model scenarios

## Dark Neutrinos



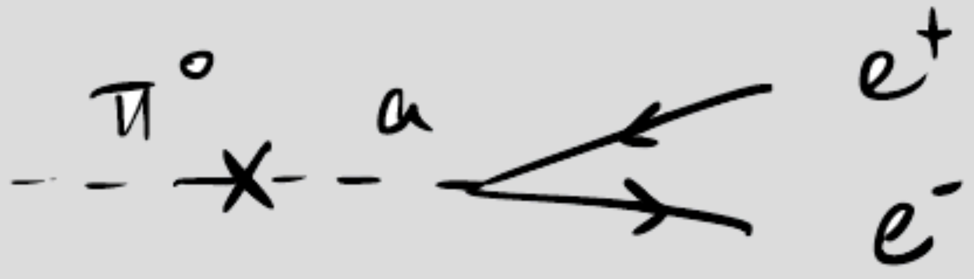

Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

## Transition Magnetic Moment



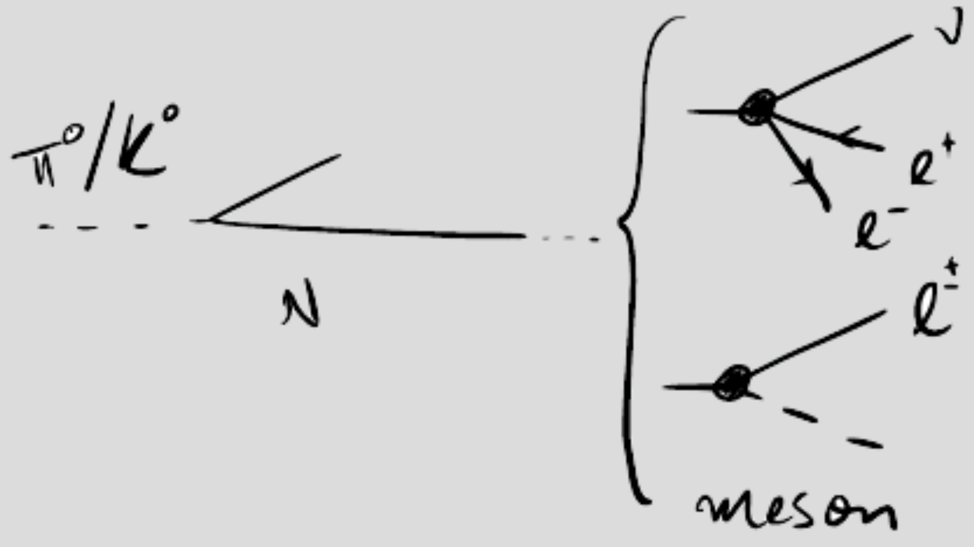

Gninenko PRL 2009
Coloma Machado Soler Shoemaker PRL 2017
Atkinson et al 2021 Vergani et al 2021

## Axion-like Particles




Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

## Heavy Neutral Leptons

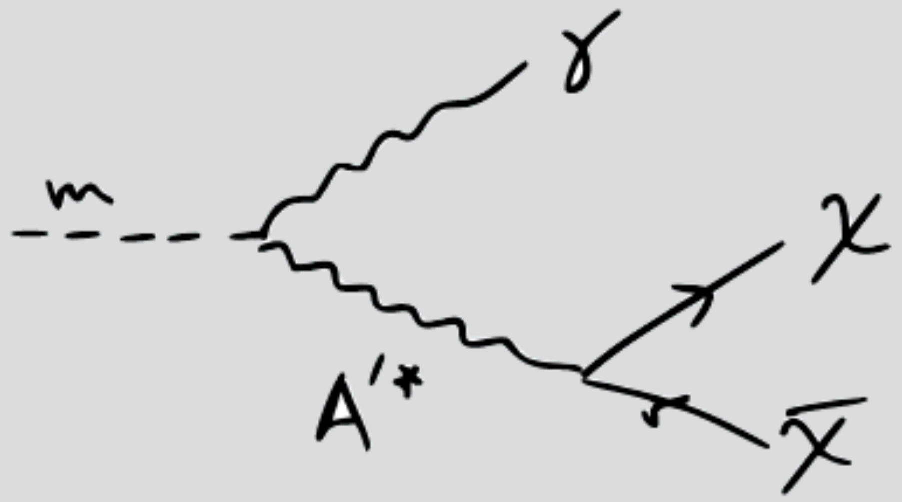



Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

## Higgs Portal Scalar


Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

## Light Dark Matter




Romeri Kelley Machado PRD 2019

## Millicharged Particles

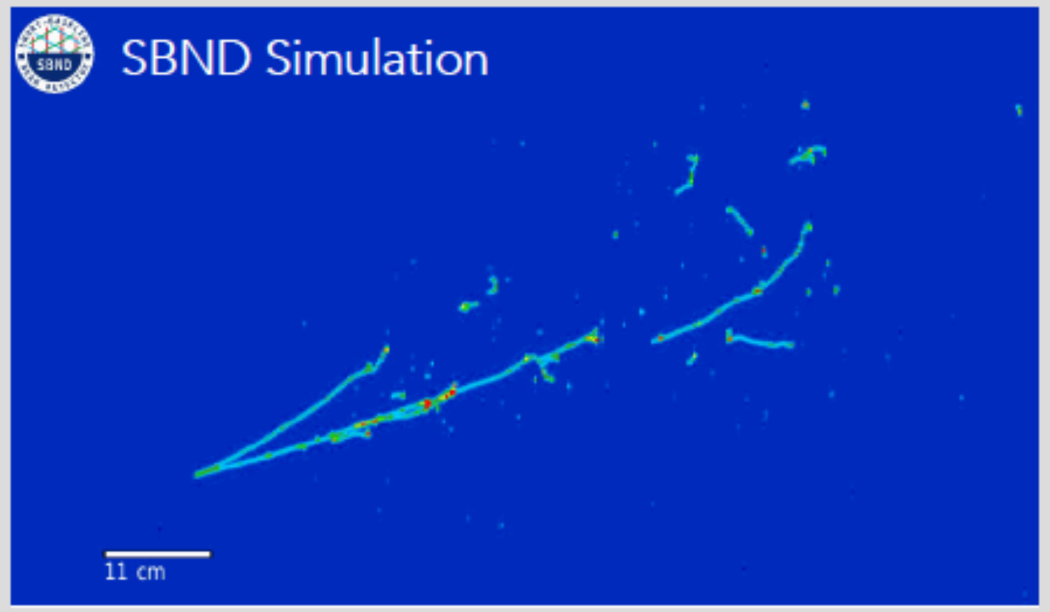

Magill, Plestid, Pospelov, Tsai, PRL 2019
Harnik Liu Palamara, JHEP 2019

*Note: not an exhaustive list!*

# Joint Experiment-Theory projects - New Physics searches in SBND

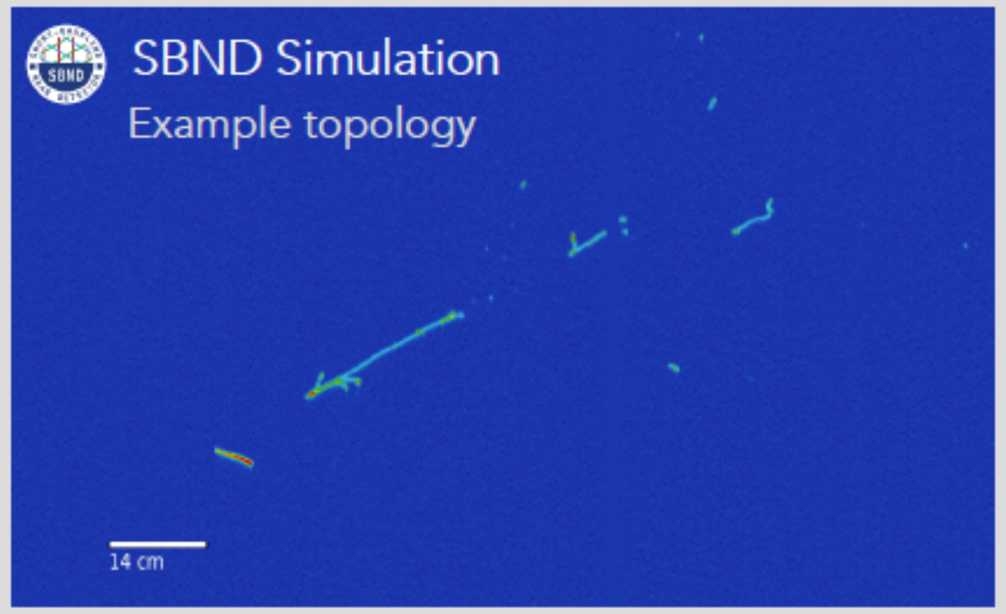
SBN(D) experiment(s) will explore the landscape and test **not only the sterile neutrino hypothesis**, but also other **New Physics models**

## Dark Neutrinos



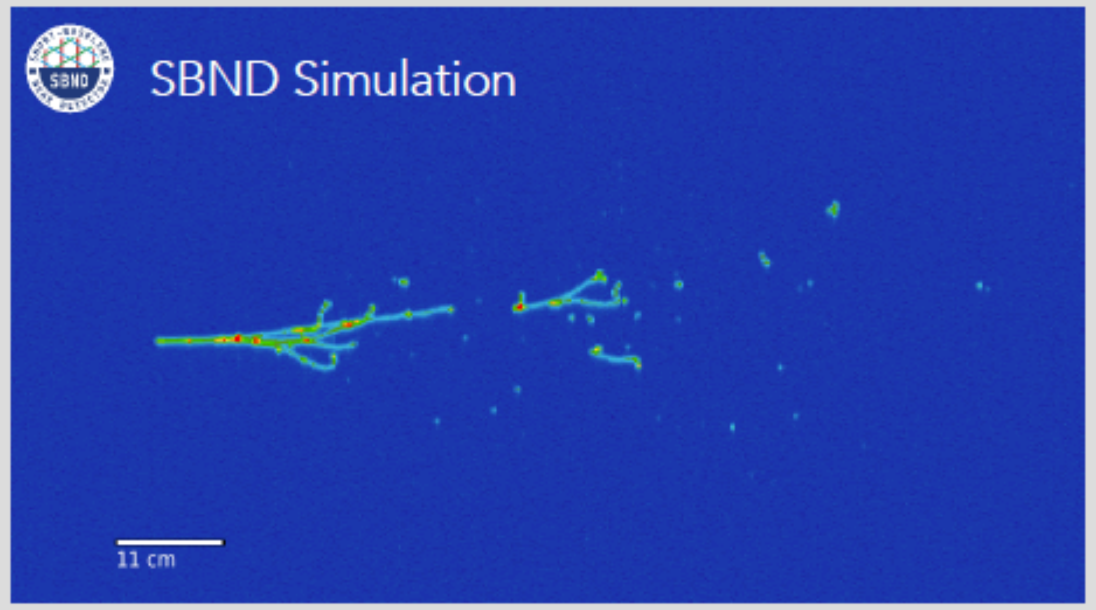

e+e- pair w/ or w/o hadronic activity

## Transition Magnetic Moment



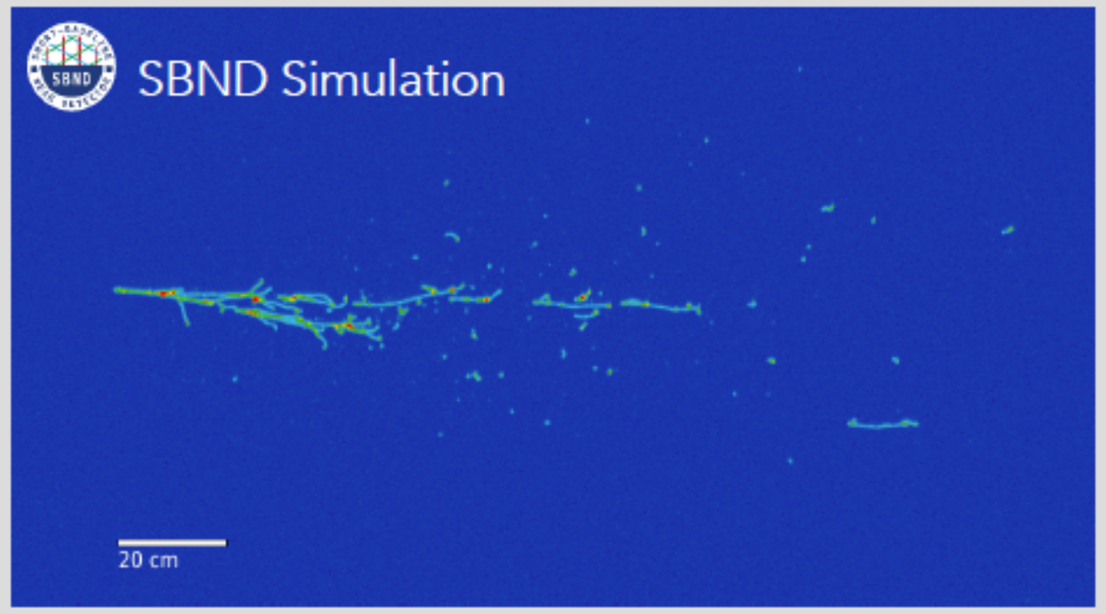

photon shower and hadronic activity

## Axion-like Particles



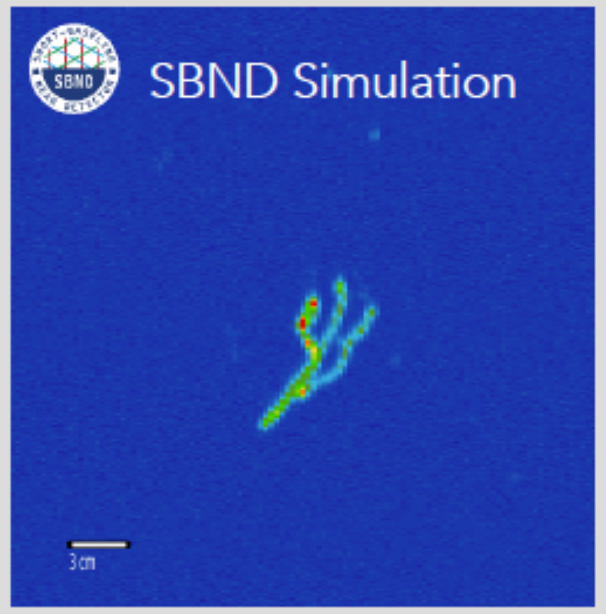

high-energy $e^+e^-$, $\mu^+\mu^-$

## Heavy Neutral Leptons



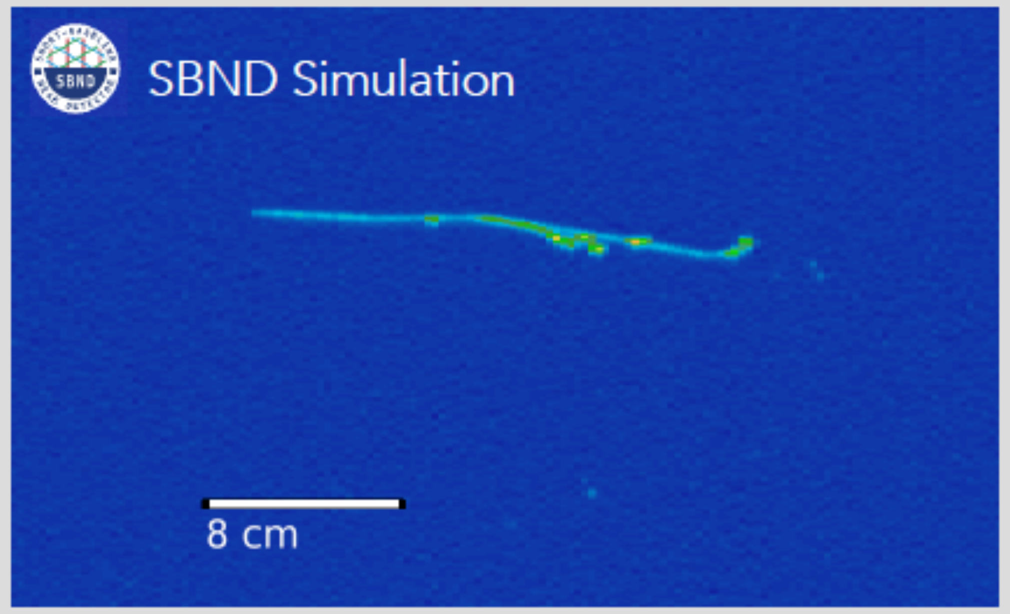

$e^+e^-$, $\mu^+\mu^-$, $\mu\pi$

## Higgs Portal Scalar



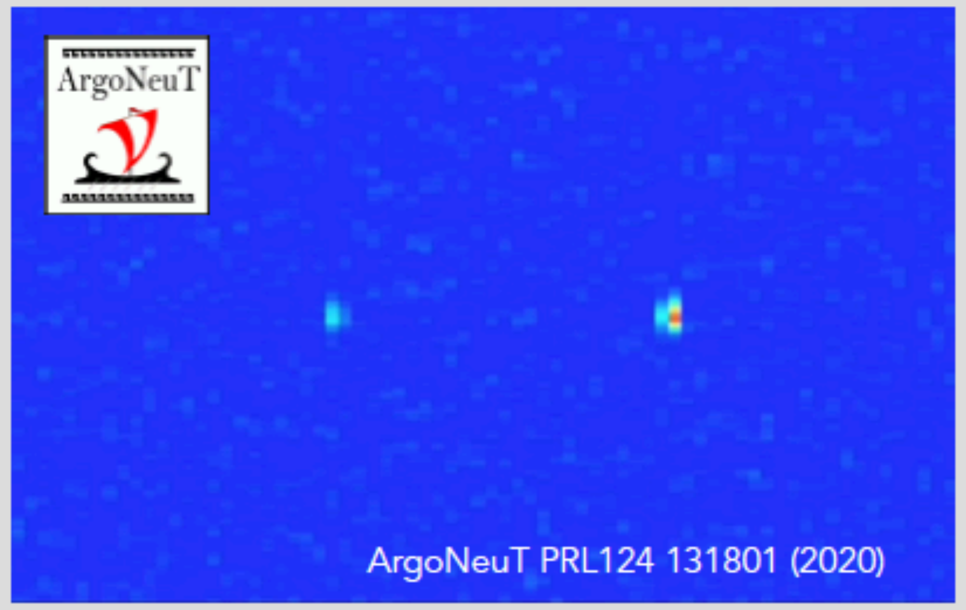

$e^+e^-$, $\mu^+\mu^-$, no hadronic activity

## Light Dark Matter




electron scattering

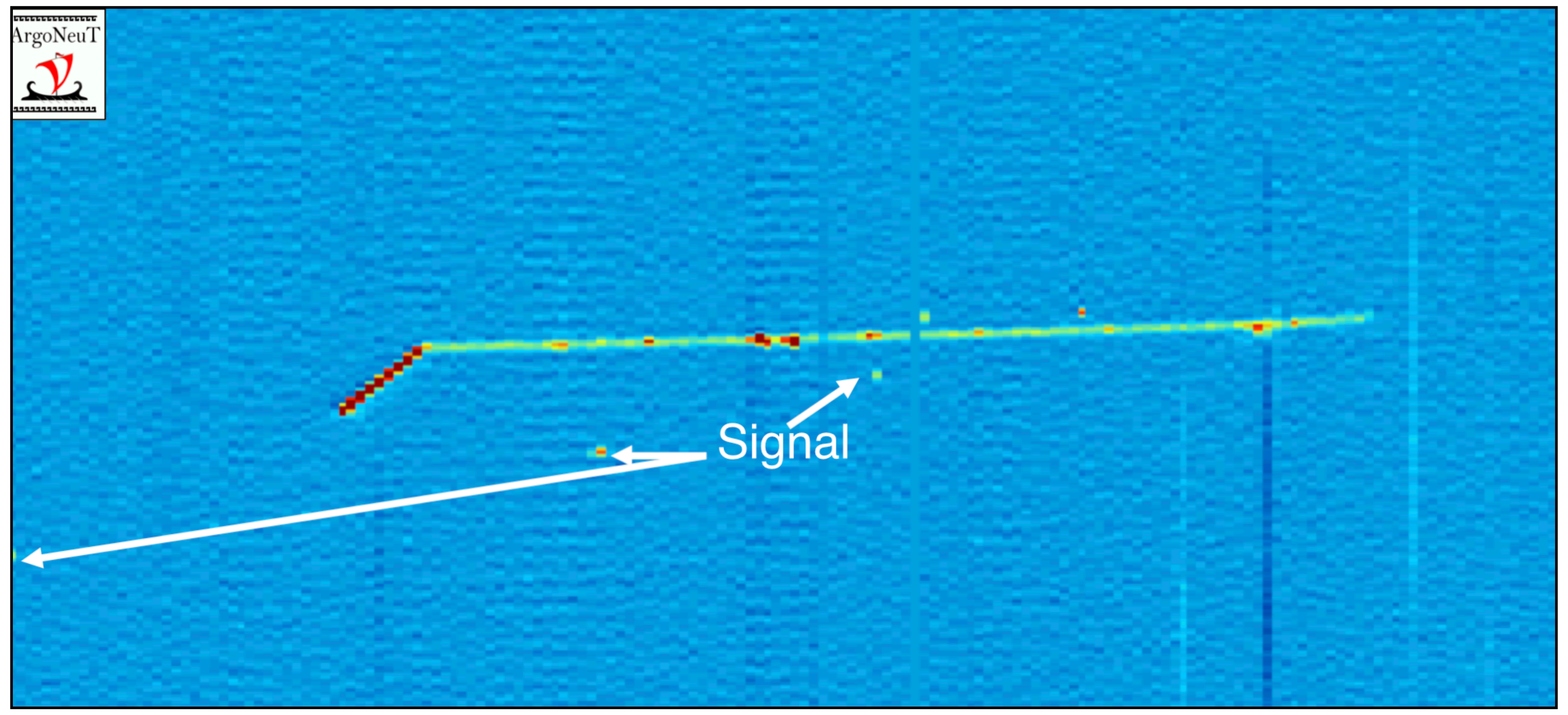
## Millicharged Particles



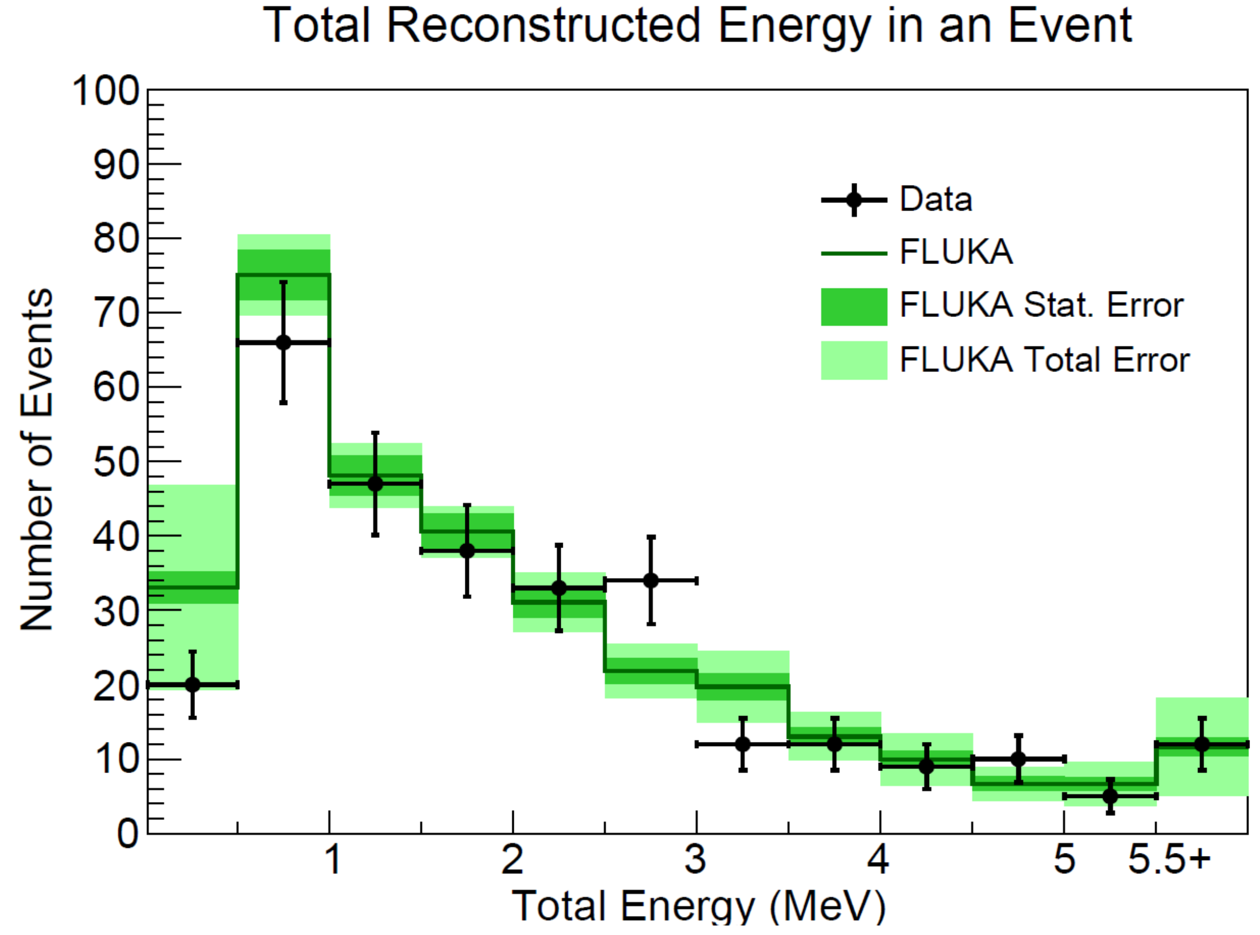

blips/faint tracks

*Note: not an exhaustive list!*

Motivated by the fact that LAr TPC's have demonstrated to be able to detect and reconstruct (sub-)MeV energy depositions




**300 KeV threshold**
In ArgoNeuT




*R. Acciarri et al., PRD 99, 012002 (2019)*

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

We started a common project, which evolved into two papers:

Theory paper

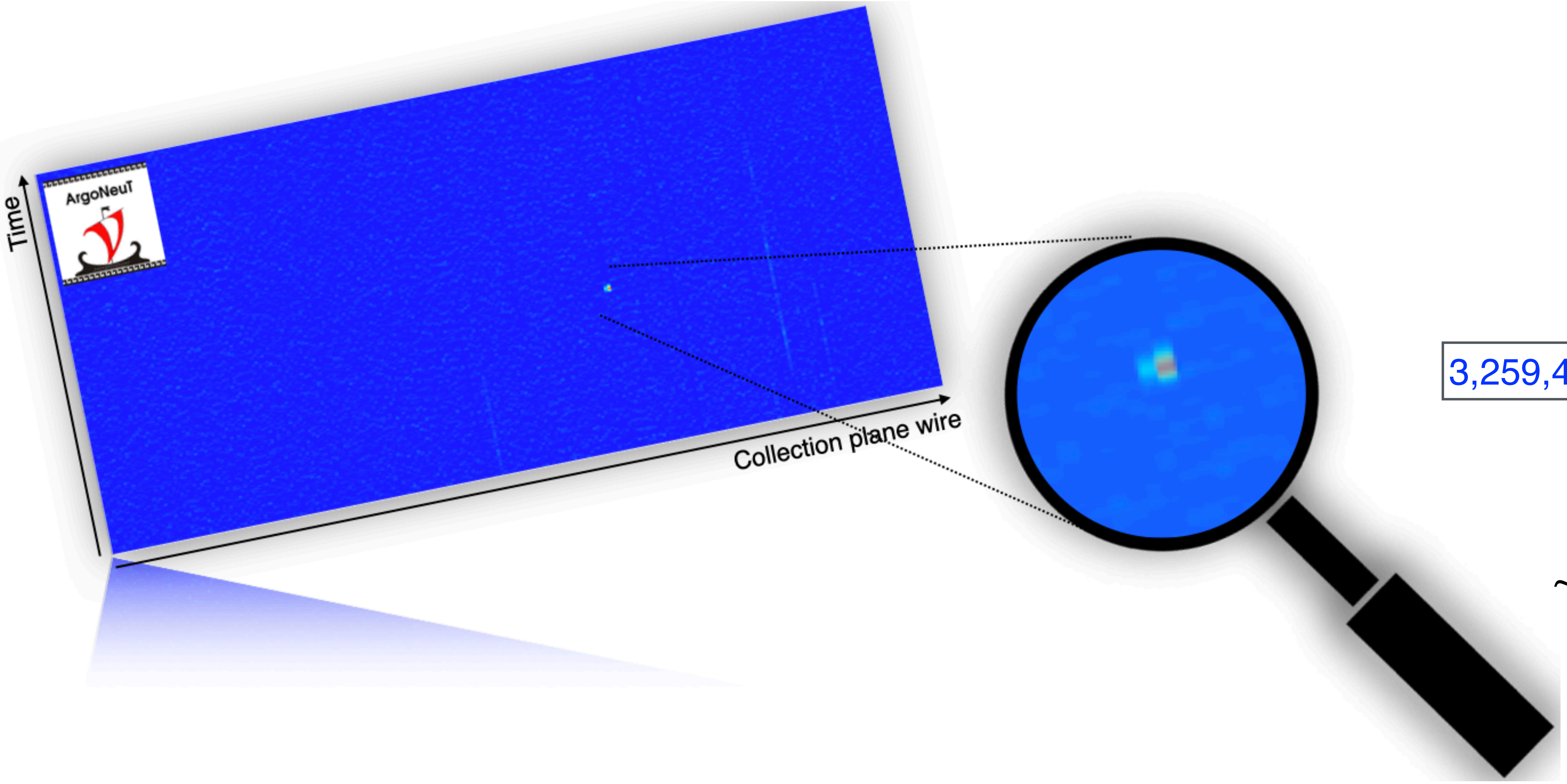
*Roni Harnik, Zhen Liu, and O. P., "**Millicharged particles** in liquid argon neutrino experiments", JHEP 07, 170 (2019)*

*ArgoNeuT Collaboration + 2 theorists (R. Harnik and Z. Liu)*
*R. Acciarri et al., PRL124 131801 (2020)*

Experimental paper

# JOINT EXPERIMENT+THEORY PROJECT: USE OF "EMPTY" EVENTS!

The vast majority of NuMI beam spills delivered did not produce a neutrino interaction within the ArgoNeuT TPC (due to the limited size of the detector)




5 months of ArgoNeuT data

3,259,427 events in $1.0 \cdot 10^{20}$ protons on target (POT)

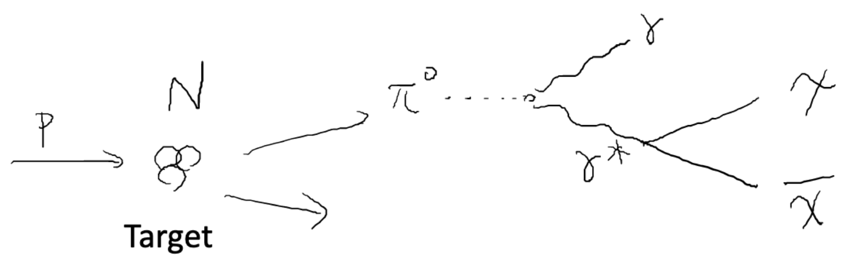
~88% have 0 clusters, ~2% have 2 clusters

We searched for the possible presence of mCPs in these empty events.

# JOINT EXPERIMENT-THEORY PROJECT

## First search for Millicharged Particles in LAr TPC

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

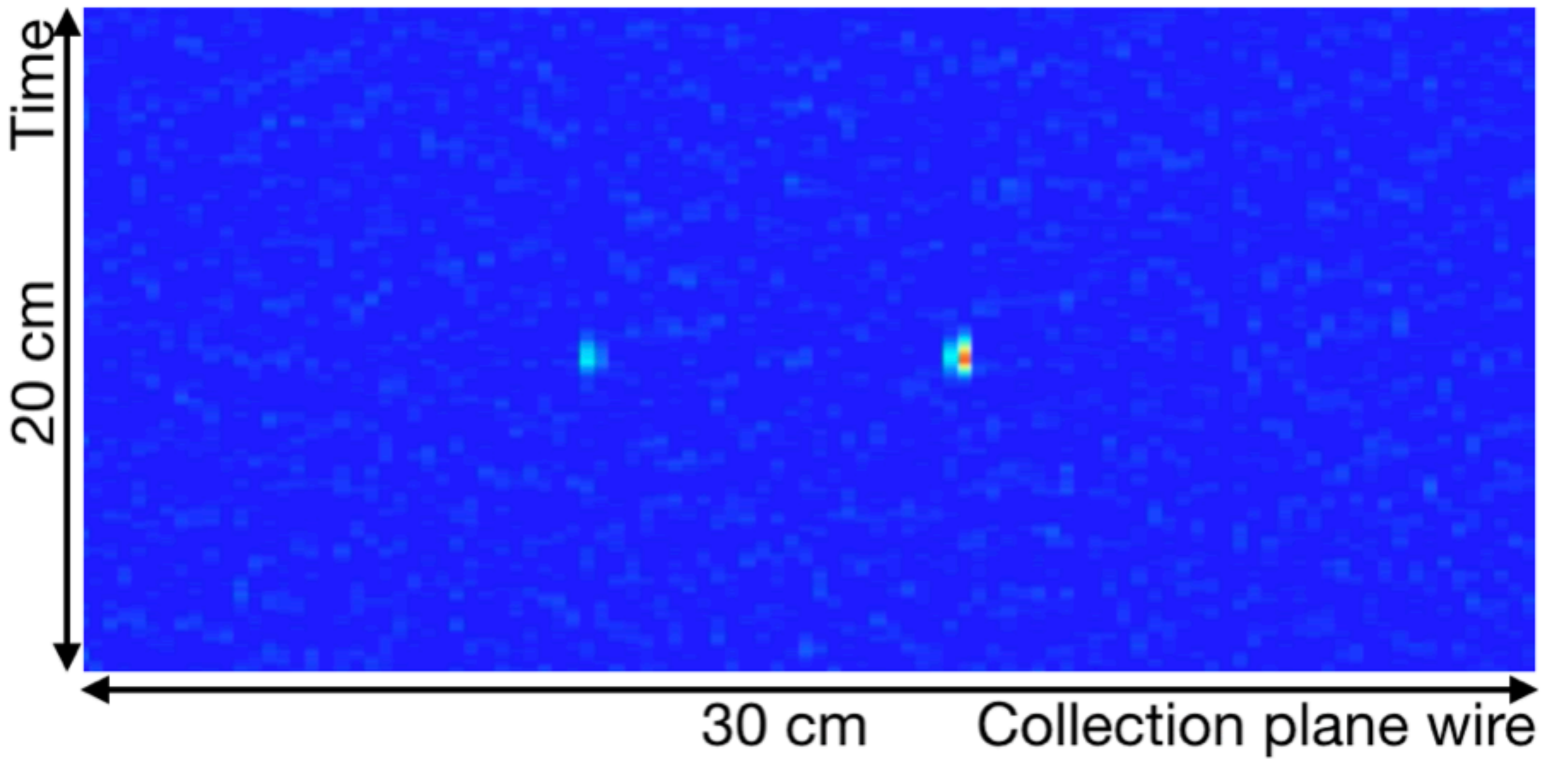


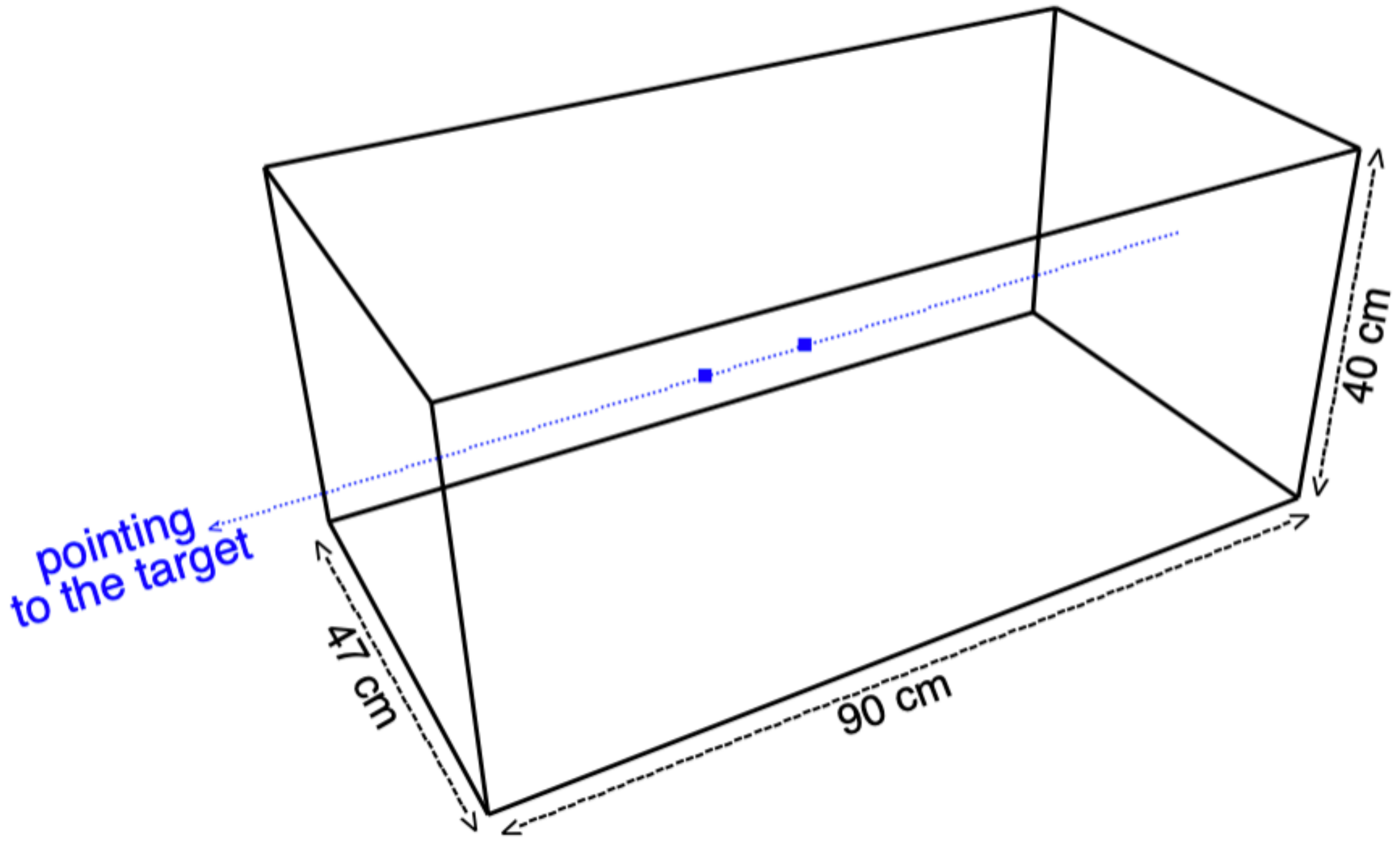

- production: meson decays

one mCP Signal Candidate Event observed

[compatible with the expected background]

1.46 background events which point back to the target expected

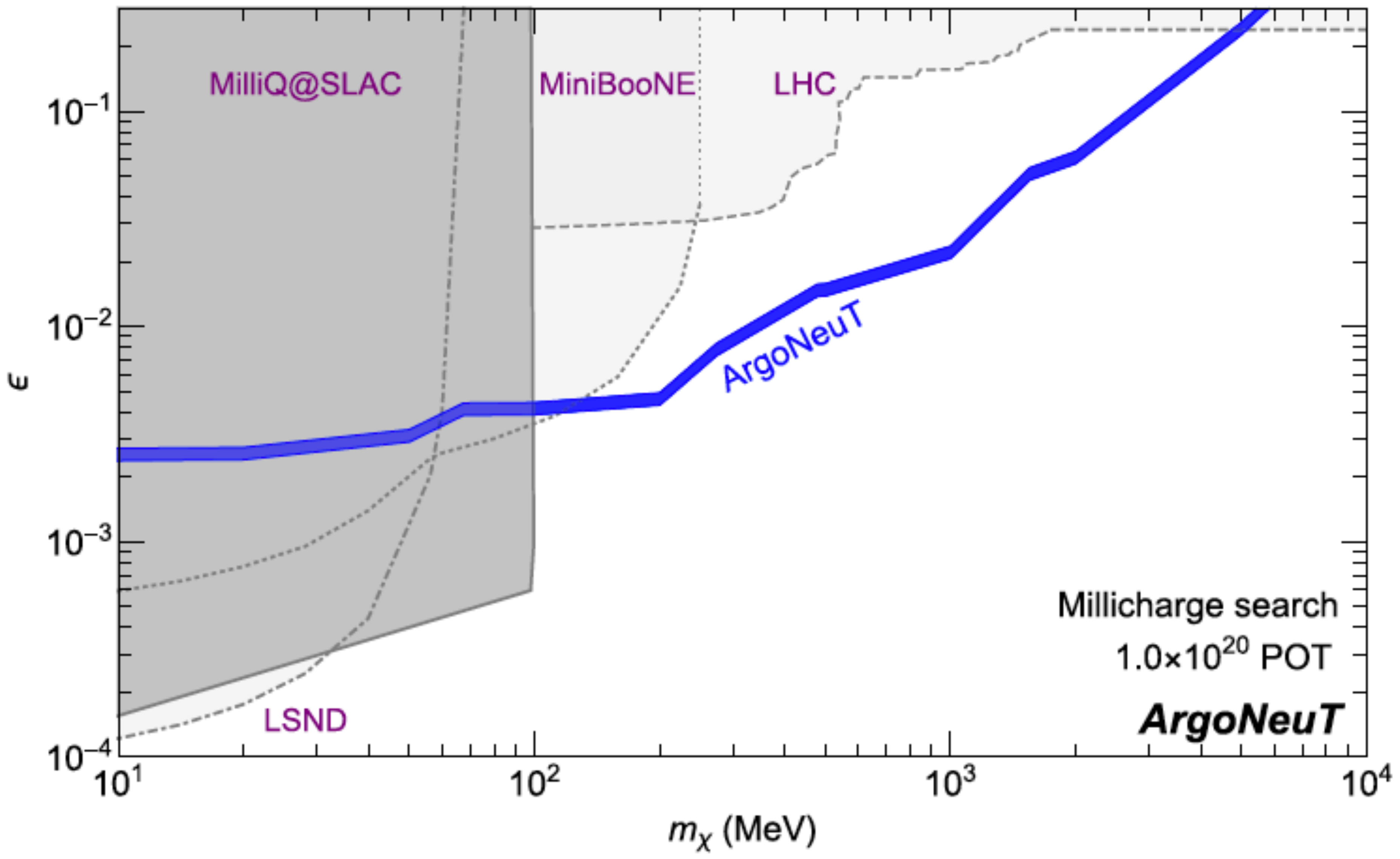



**Low energy threshold (300 KeV) is the key!**

*Roni Harnik, Zhen Liu, and O. P., "Millicharged particles in liquid argon neutrino experiments", JHEP 07, 170 (2019)*

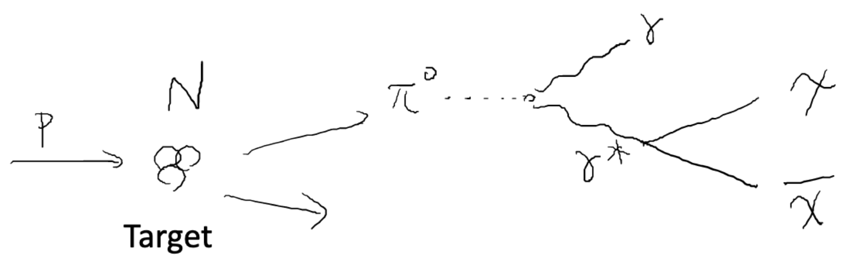
*ArgoNeuT Collaboration + 2 theorists (R. Harnik and Z. Liu)*
*R. Acciarri et al., PRL124 131801 (2020)*




**Leading constraints in unexplored parameter region!**

# First search for Millicharged Particles in LAr TPC

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

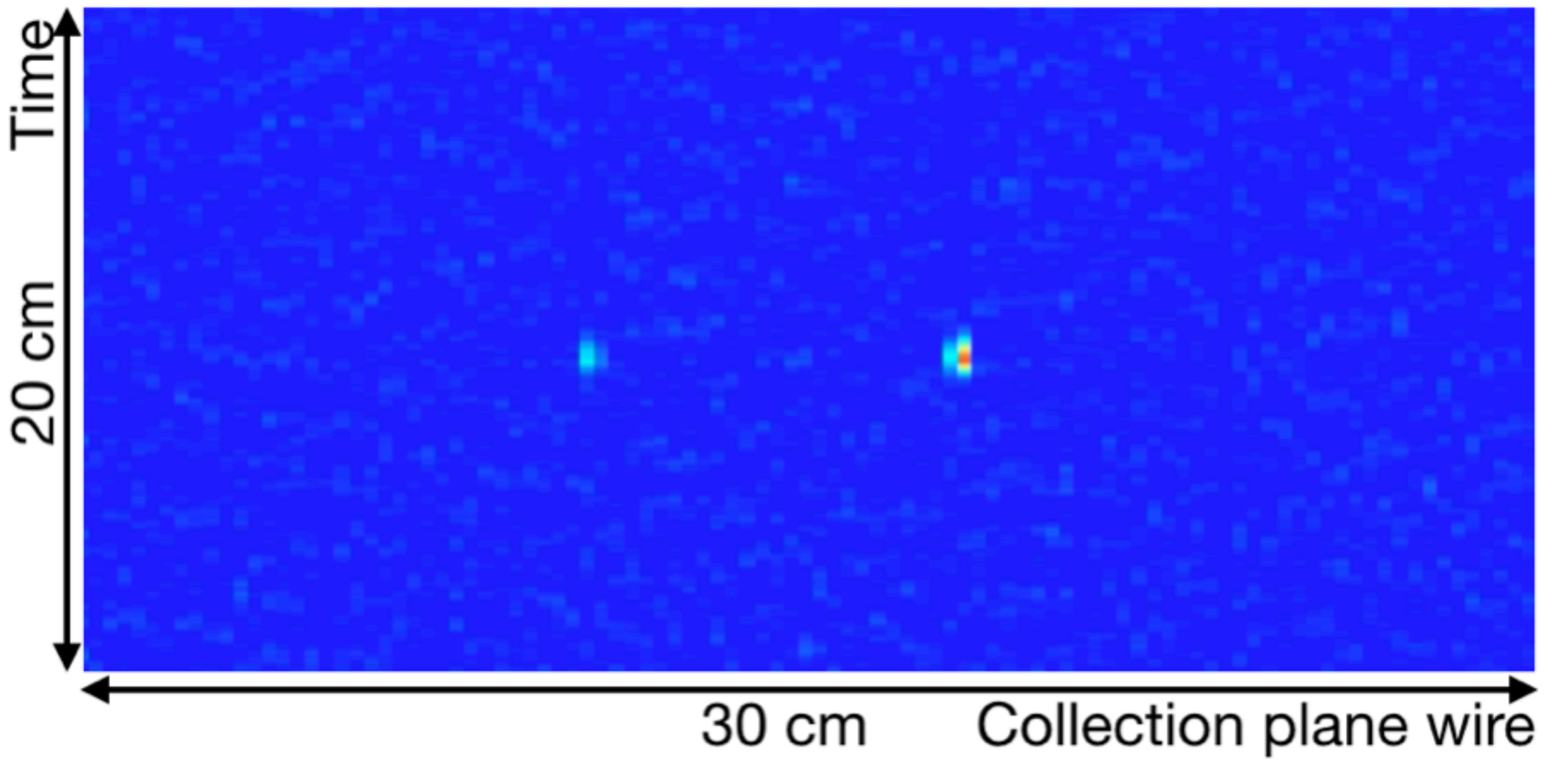


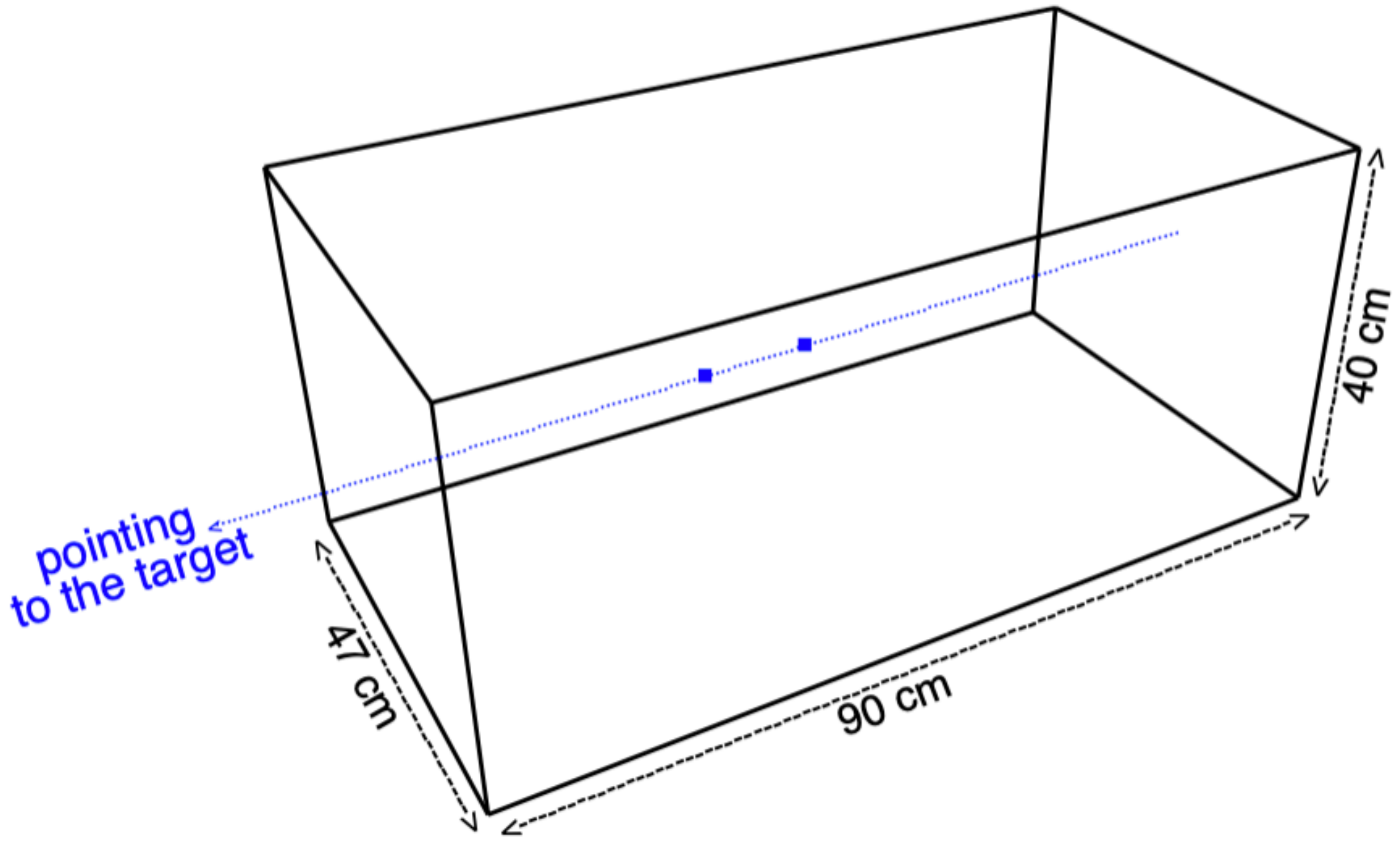

- production: meson decays

**one mCP Signal Candidate Event observed**

[compatible with the expected background]

1.46 background events which point back to the target expected




**Low energy threshold (300 KeV) is the key!**

*Roni Harnik & OP - Wine and Cheese seminar (2020)*

# Search for Millicharged Particles in SBND

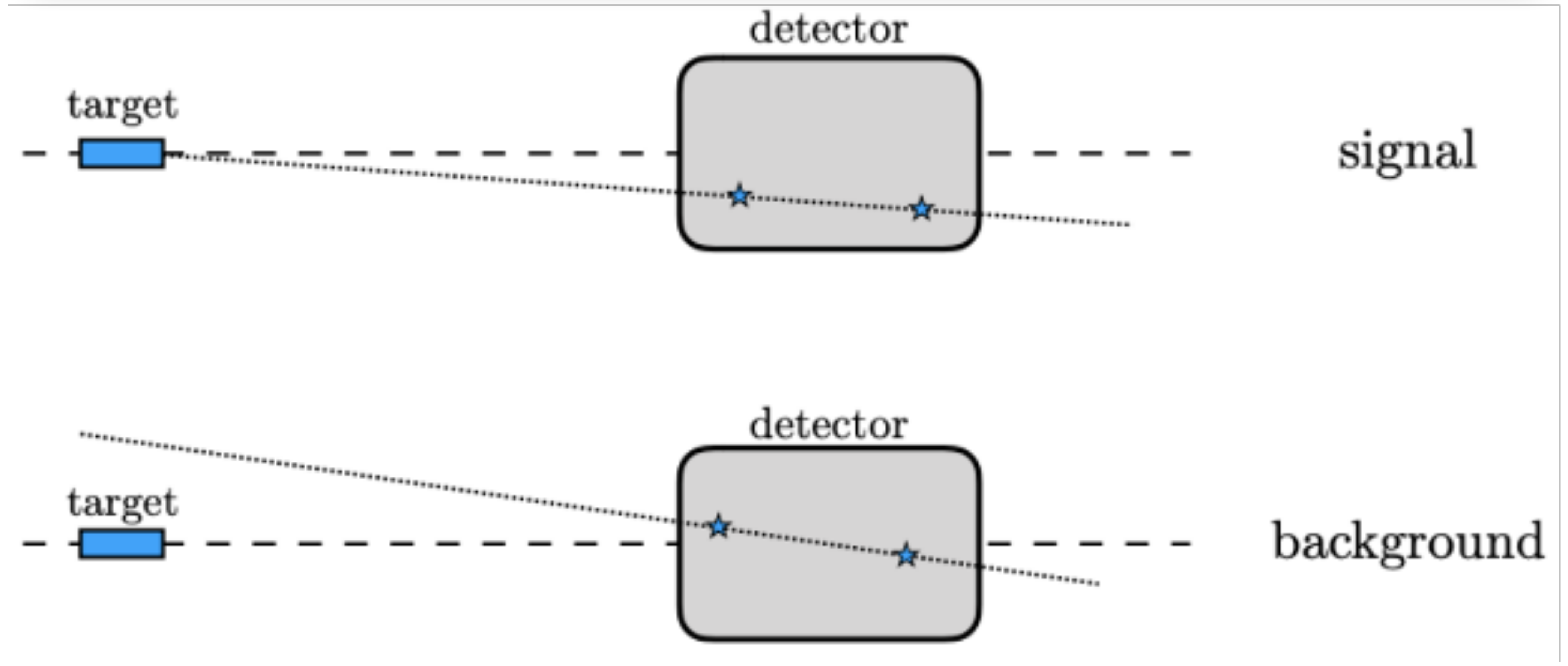
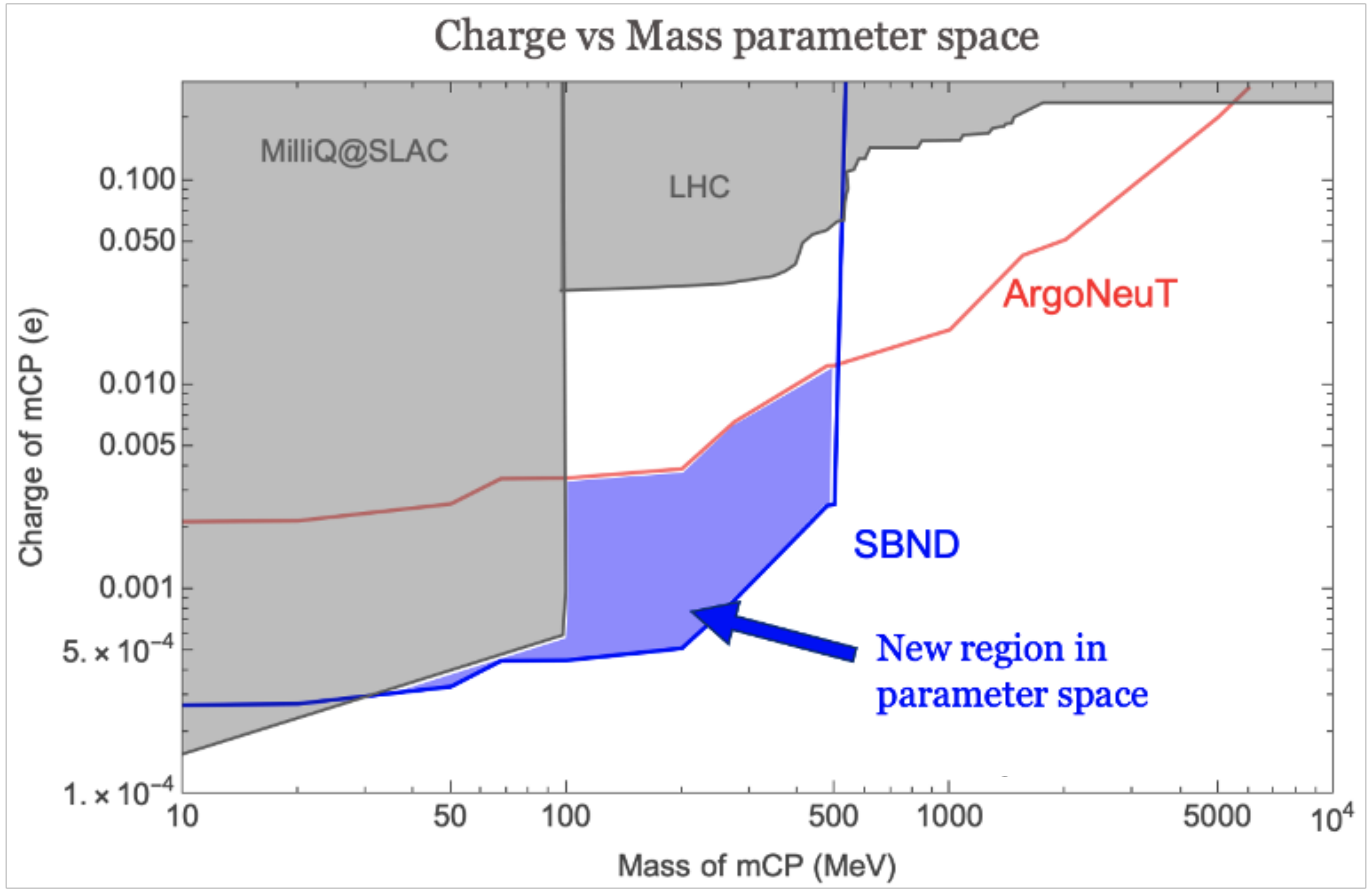




Image credit: ArgoNeuT, PRL124 131801 (2020)

To reduce background:
search for double hits events aligned with the target

Millicharged particles would appear in SBND as **blips** or **faint tracks** pointing back to the target.




Projected SBND threshold: 50 keV

# JOINT EXPERIMENT-THEORY PROJECT

## First search for Heavy neutral Leptons $N\to\nu\mu^+\mu^-$ in LAr TPC

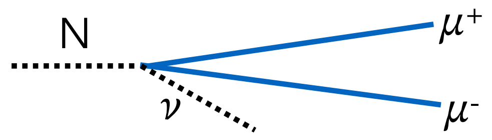
Consider **tau-coupled scenario**, i.e. $|U_{\tau N}|^2 \neq 0$ and $|U_{eN}|^2 = |U_{\mu N}|^2 = 0$

Assuming HNL production predominately from $\tau^\pm$ decay*:

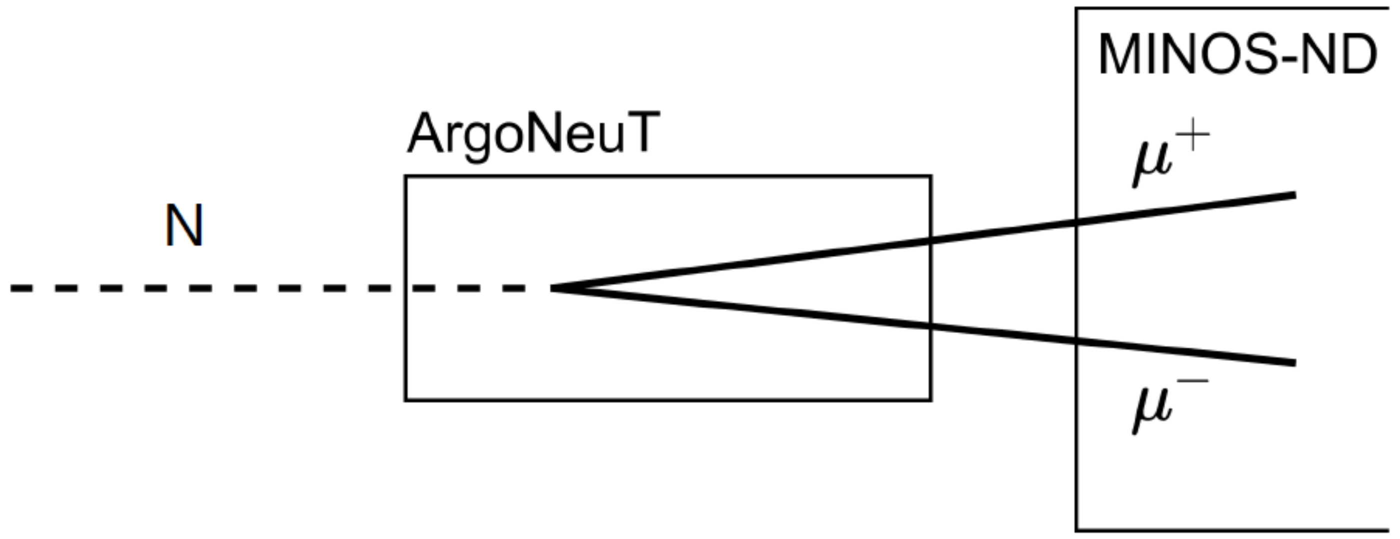
$D/D_s$ decay to $\tau$, that subsequently decay to HNLs

$\tau^\pm \to N X^\pm$ ($X^\pm$ is a SM particle e.g. $\pi^\pm$)

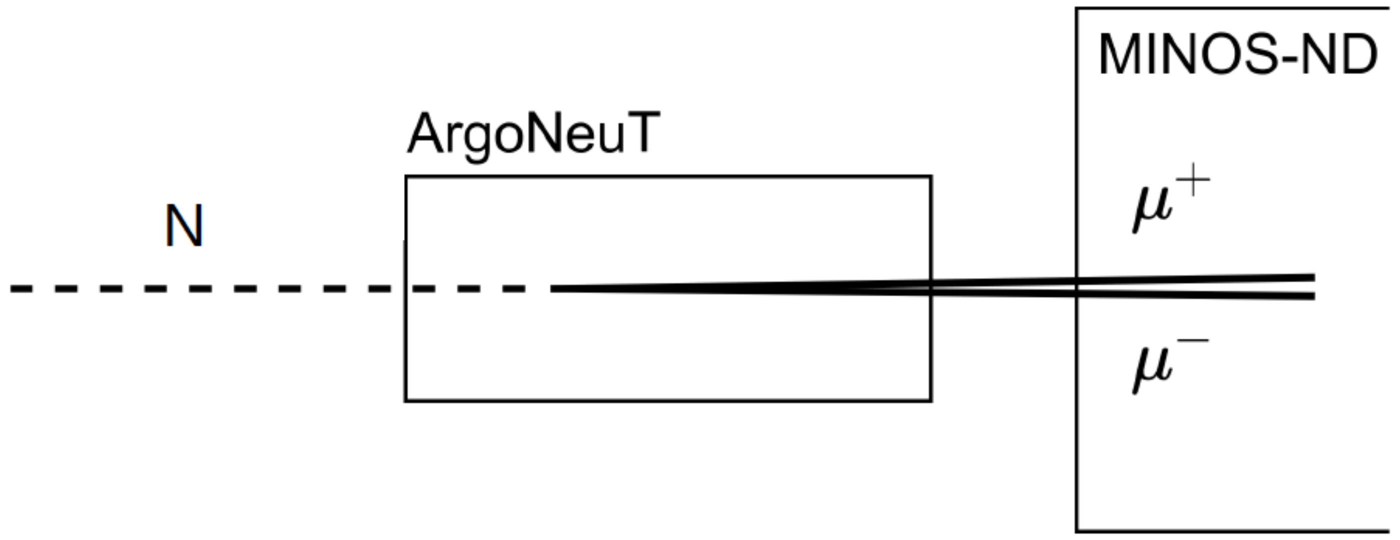
HNL decay
$N\to\nu\mu^+\mu^-$

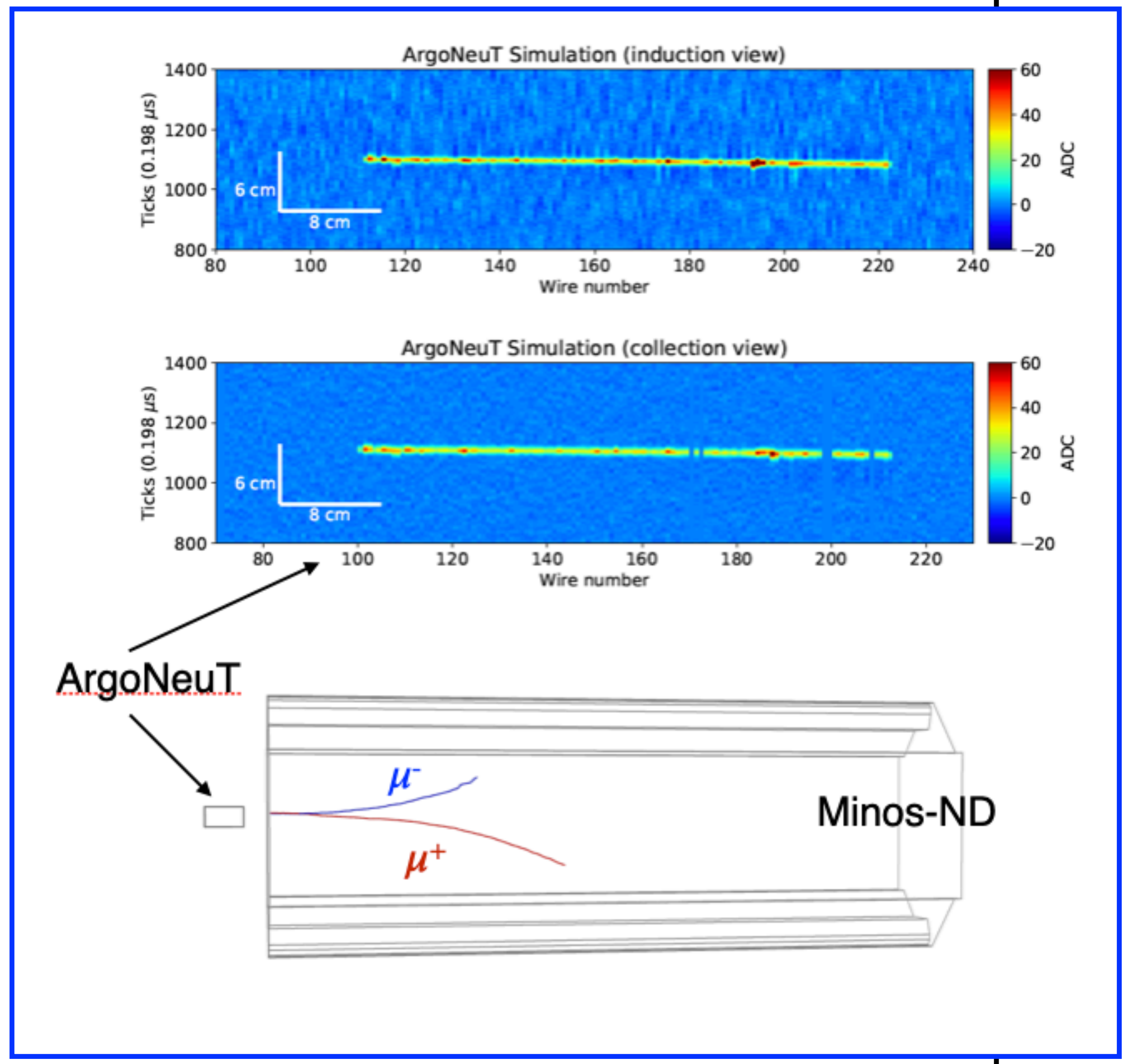



*Two-track* Event




*Double-MIP* Event

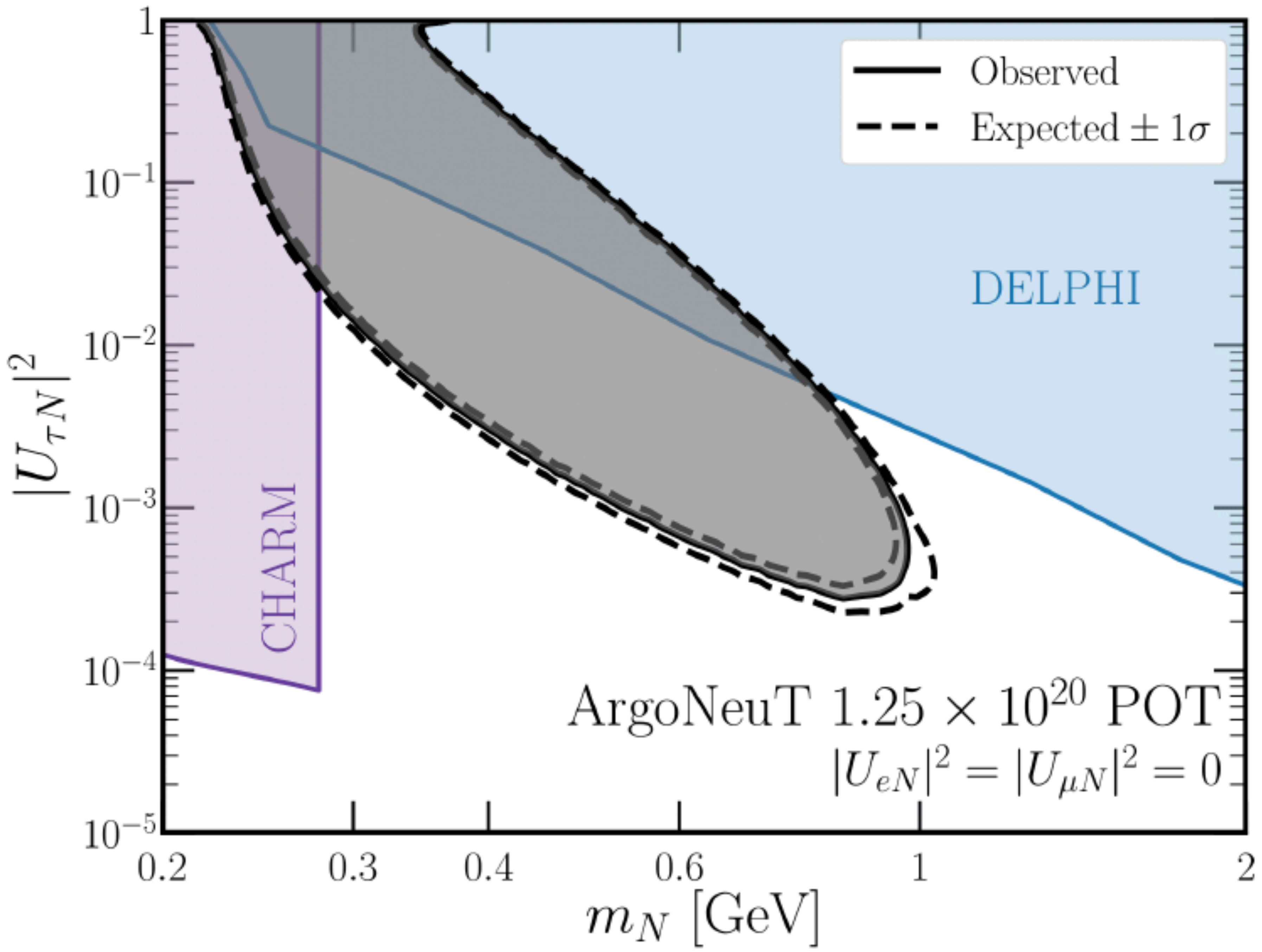



*For details see: P. Coloma et al. Eur. Phys. J. C, 81(1):78, 2021*

**0 events observed in the data,** consistent with background expectation of 0.4±0.2 event

*ArgoNeuT Collaboration + 2 theorists (K. Kelly and A. de Gouvêa)*
*R. Acciarri et al., PRL 127 121801 (2021)*



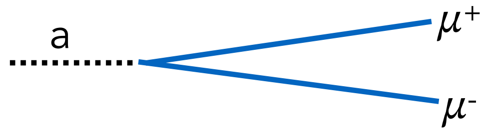

**Significant increase in the parameter space exclusion region!**
**New exclusion limits for tau-coupled HNLs with $m_N$=280–970 MeV.**

# JOINT EXPERIMENT-THEORY PROJECT

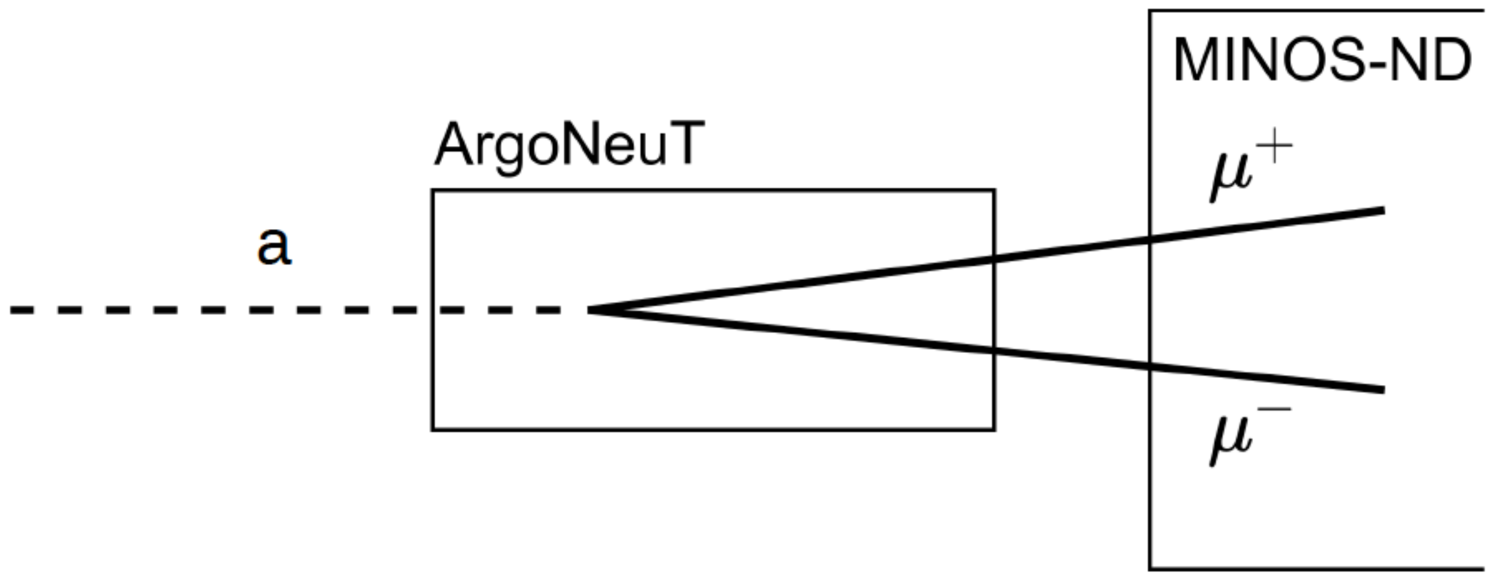
## First search for Heavy QCD Axions in LAr TPC

Heavy QCD axions production from $\pi^0$, $\eta$ and $\eta'$ mesons*
and decay to ee, μμ, ɣɣ + hadronic modes.
Contributions depend on axion-lepton coupling, cl: two benchmark scenarios cl = 1/36 and cl = 1/100.

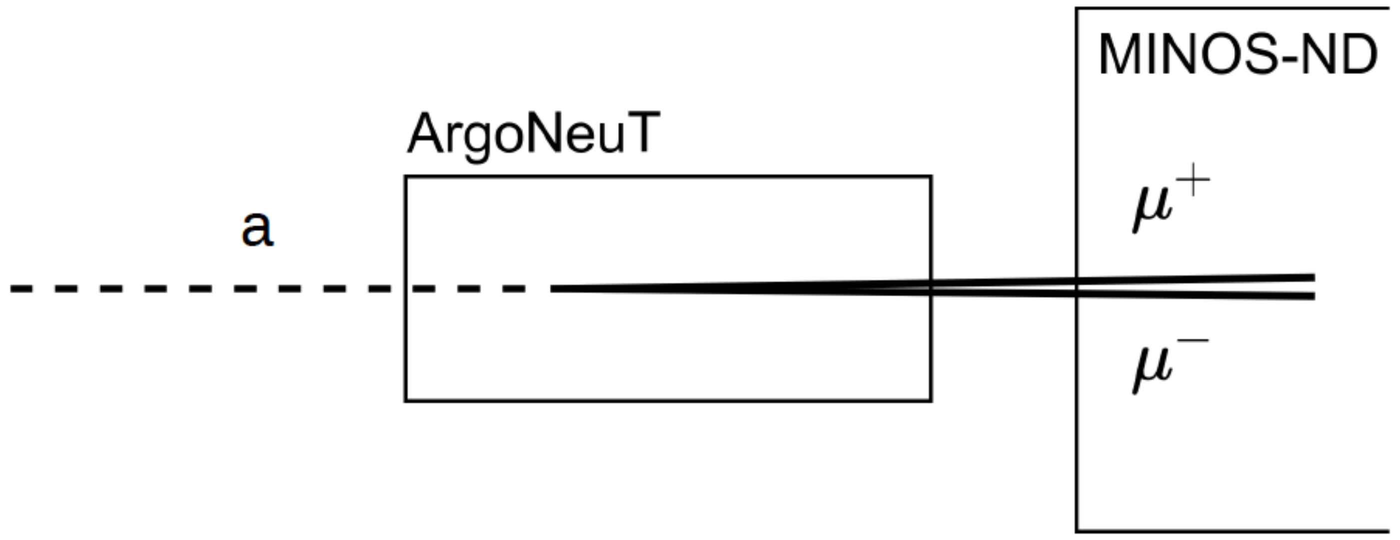
Axion decay
$a \to \mu^+\mu^-$




*Two-track* Event



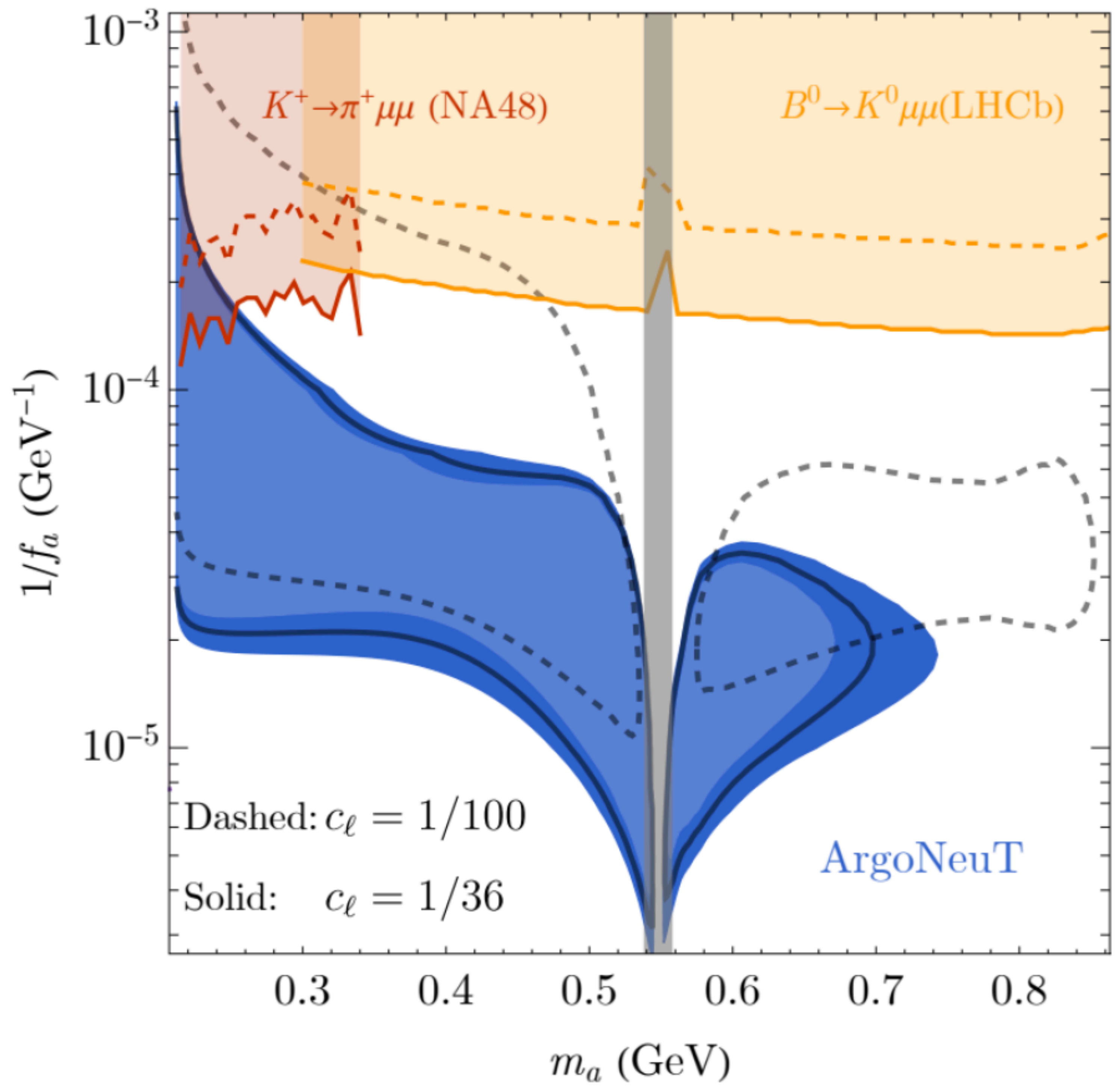

*Double-MIP* Event




*For details see: K. Kelly, S. Kumar and Z. Liu Phys. Rev. D 103 (2021) 9, 095002

**0 events observed in the data,** consistent with background expectation of 0.1±0.1 event

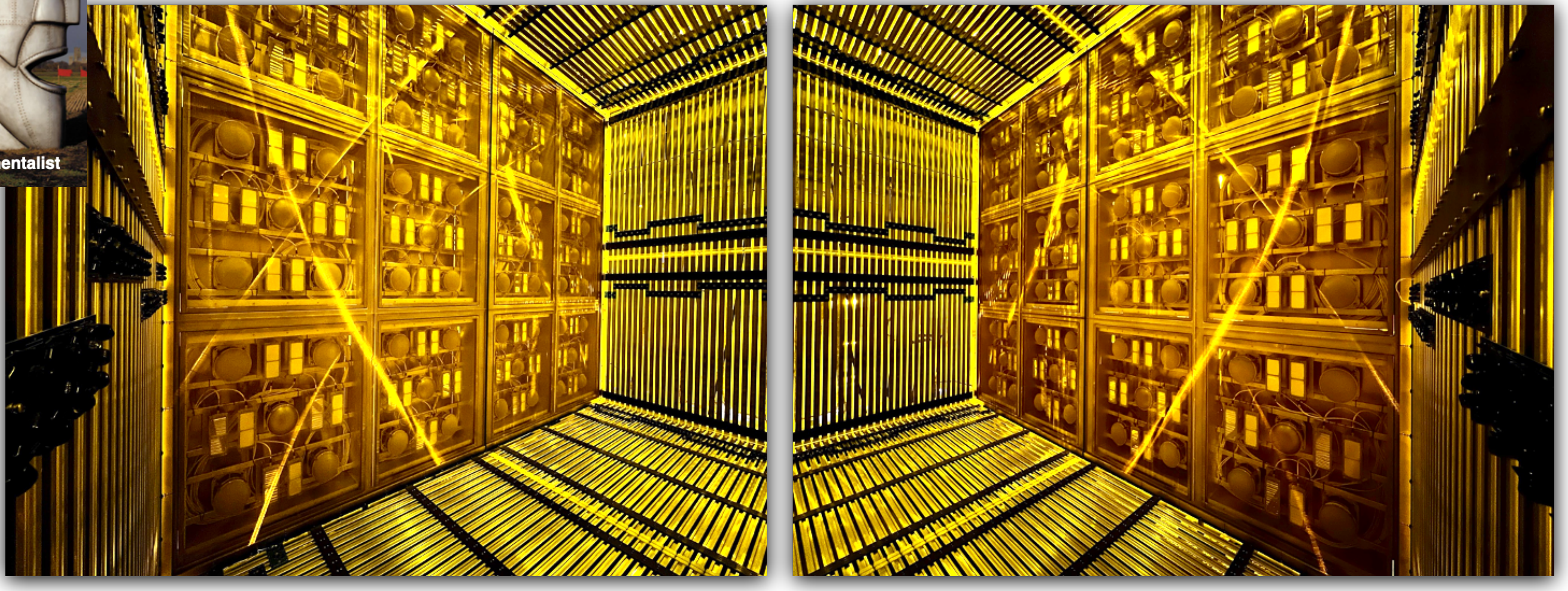
*ArgoNeuT Collaboration + 6 theorists (R. Co, R. Harnik, K. Kelly, S. Kumar, Z. Liu. K Lyu)*
*R. Acciarri et al., accepted by Phys. Rev. Lett., and selected as PRL Editors' Suggestion*



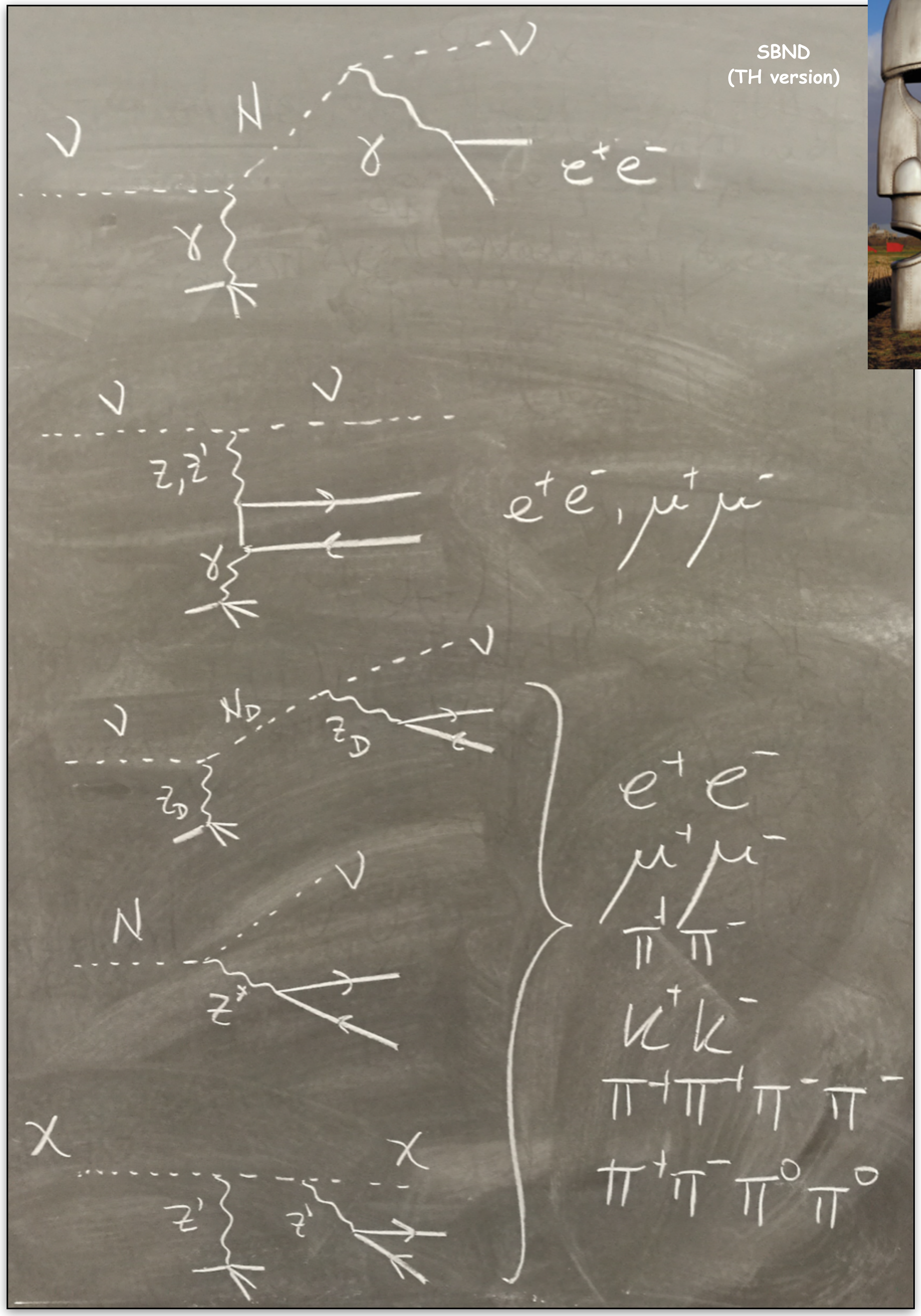

**New exclusion constraints for heavy QCD axions with $m_a$~0.2–0.9 GeV and axion decay constant $f_a$~10 TeV.**

# SAME PERSPECTIVE FROM TWO DIFFERENT ANGLES


*SBND Detector*



*SBND Theory version*




# SAME PERSPECTIVE FROM TWO DIFFERENT ANGLES


*SBND Detector*

…but… I've heard theorists explain better
than an experimentalist could do
how the LAr TPC technology works!

SBND 2nd APA installation

Pedro Machado


SBND detector move

Roni Harnik, Pedro Machado, Olivia Vizcarra

…and theorists support experimentalist…

Theorists are now members of the SBND Collaboration!
…and I'm invited to attend phenomenology conferences…

# SUMMARY

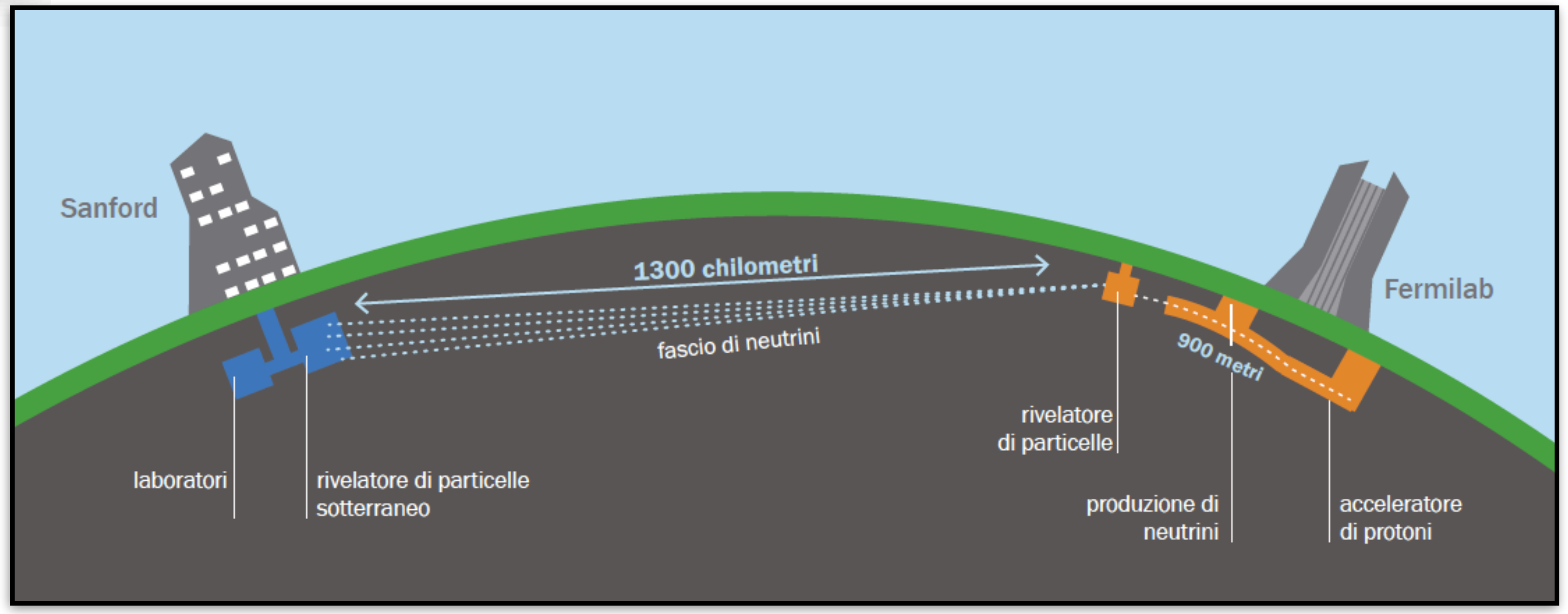
ArgoNeuT, a small LAr TPC running for 5 months on the NuMI beam produced world leading BSM searches.

Current and next- generation LAr neutrino experiments are fantastic tools to look for **New Physics in the neutrino sector and beyond**.


Short-Baseline Neutrino Program

coming online soon…

in the next decade




DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Collaborations between experimentalists and theorists are of great relevance to the neutrino physics community, that needs the theory support to strengthen the neutrino experimental measurements, particularly when searching for New Physics.

# …Now…on a personal level…

Marcela and Carlos are amazing friends!
I have so many memories of beautiful moments spent with them.
Here are some examples…

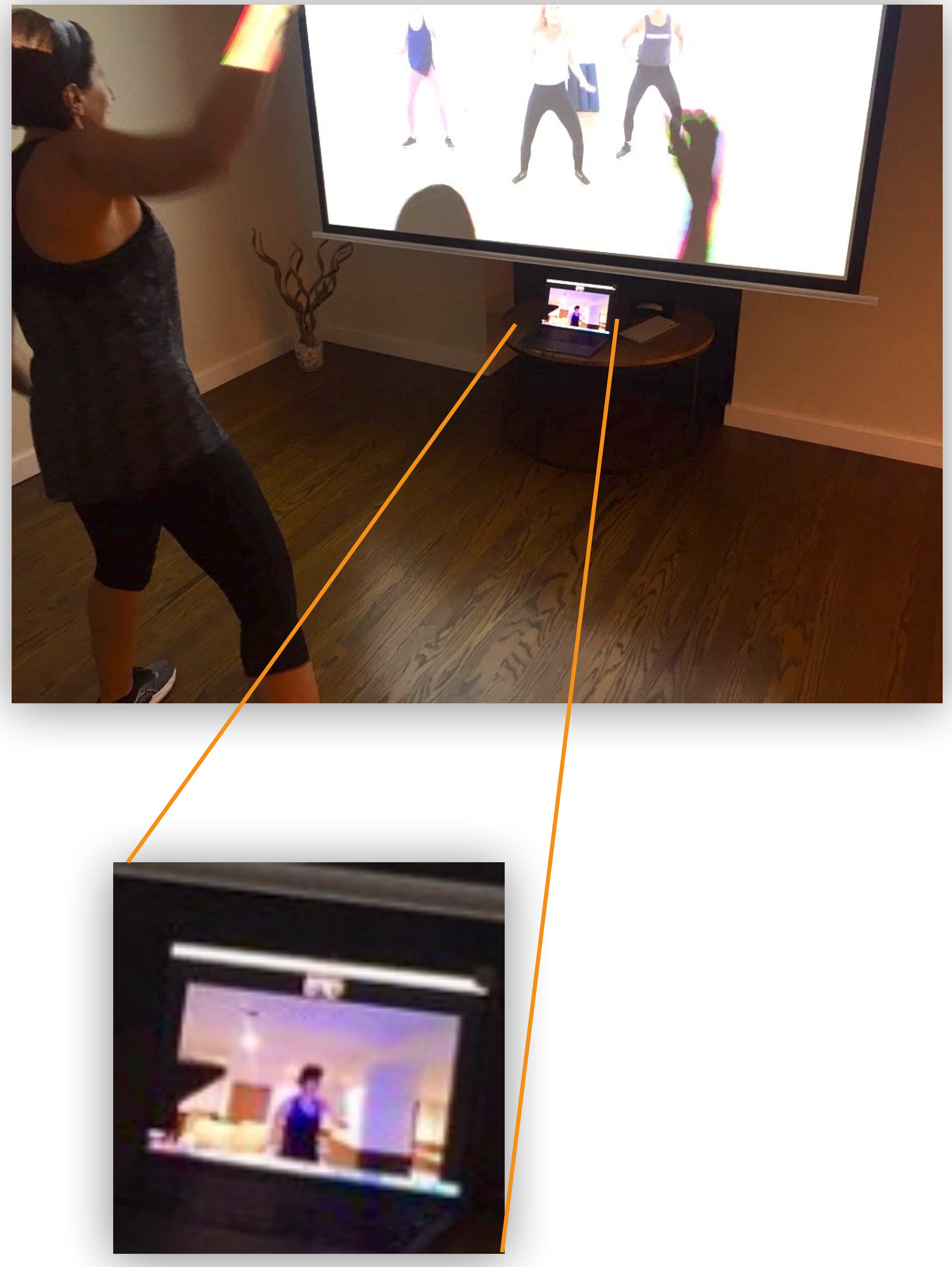
Staying 3 feet apart but **together during the pandemic!**





at Marcela & Carlos house

Marcela and Ornella Zoom workout during the pandemic!



# …Now…on a personal level…

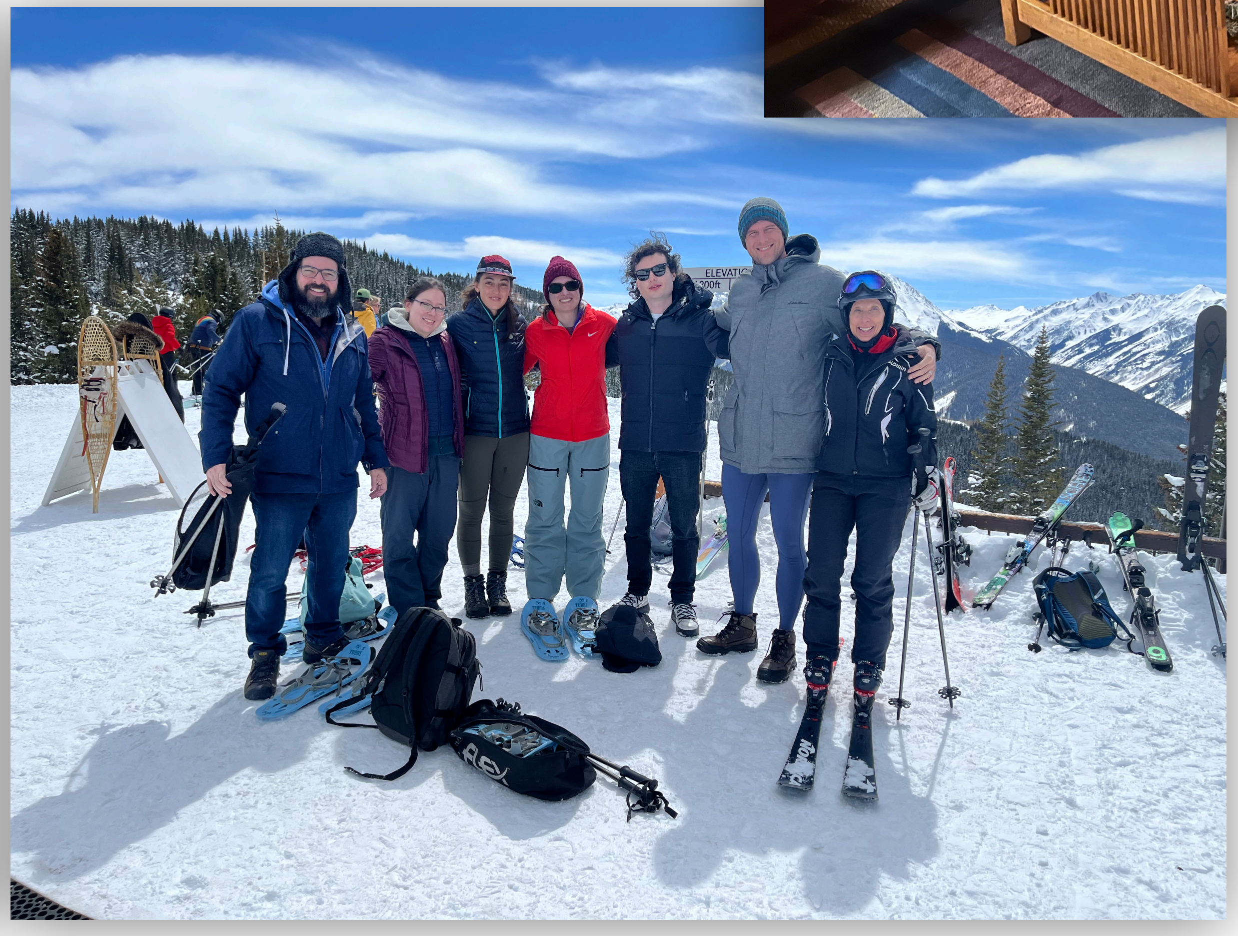
Sailing - Lake Geneva (WI) - Sept. 11 2021
Carlo's birthday!

Thanksgiving 2021

One of the many handmade pizzas at our house - June 2022

# …Now…on a personal level…

Aspen - March 2023



Chicago - April 2022

Marcela and Ornella workout now!

orangetheory FITNESS

Marcela's influential impact on a new way to workout today!

# To Conclude

Marcela & Carlos, we feel extremely fortunate to have you as friends and honored to be here!

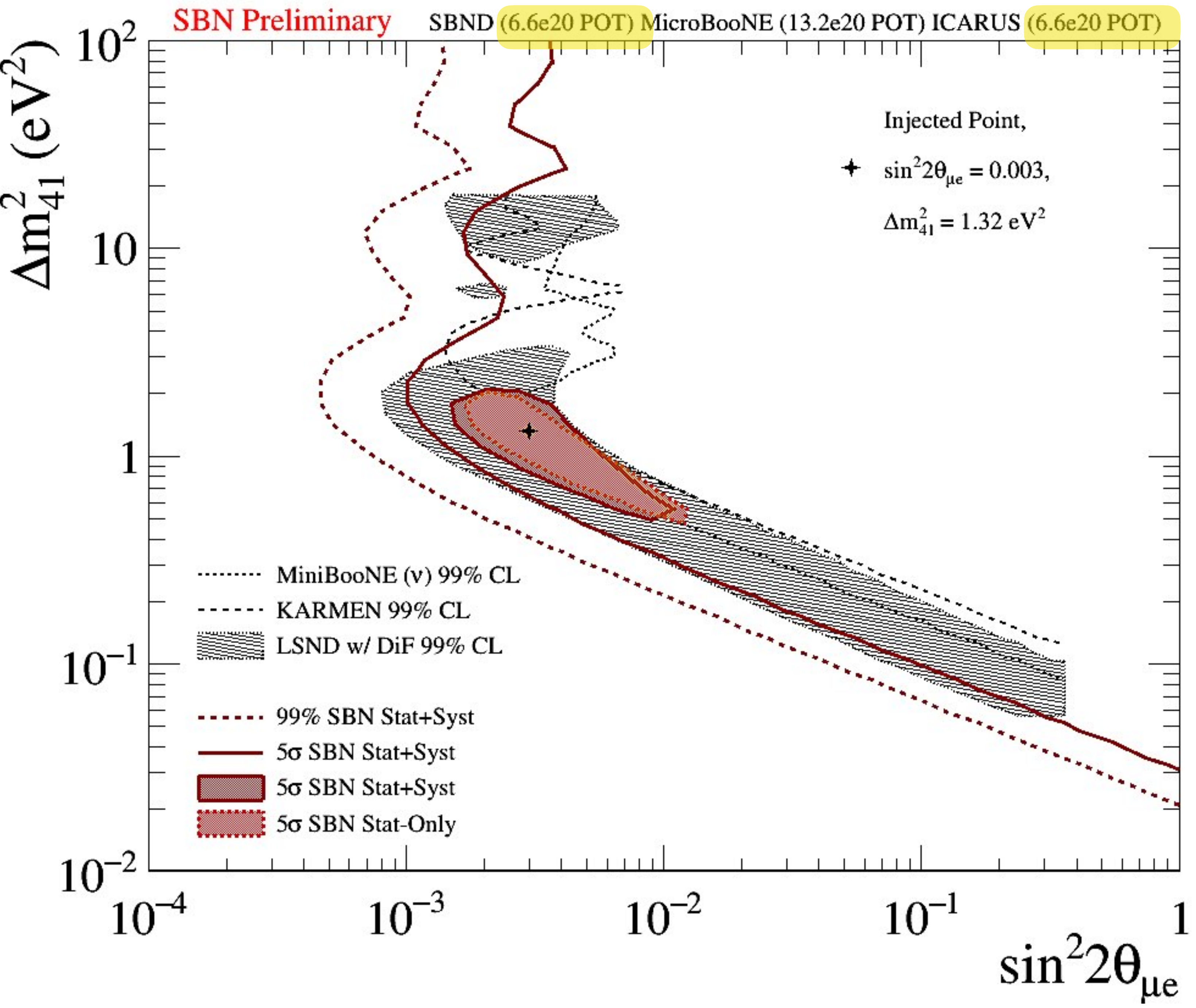
Congratulations on your 60th birthday!

To many more years filled with New Physics questions and lovely friendship to come!

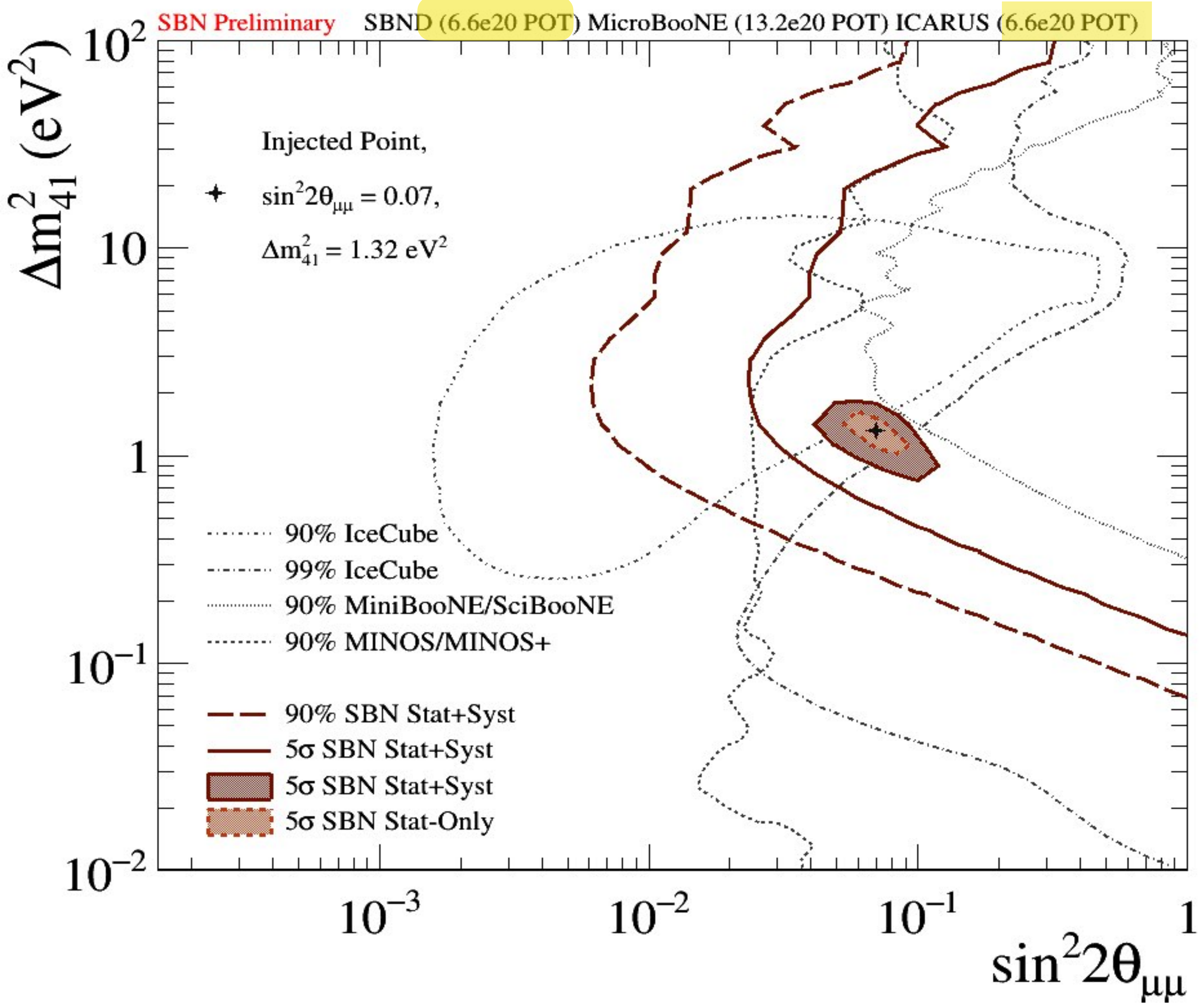
# EXTRAS

# SBN STERILE NEUTRINO SENSITIVITIES

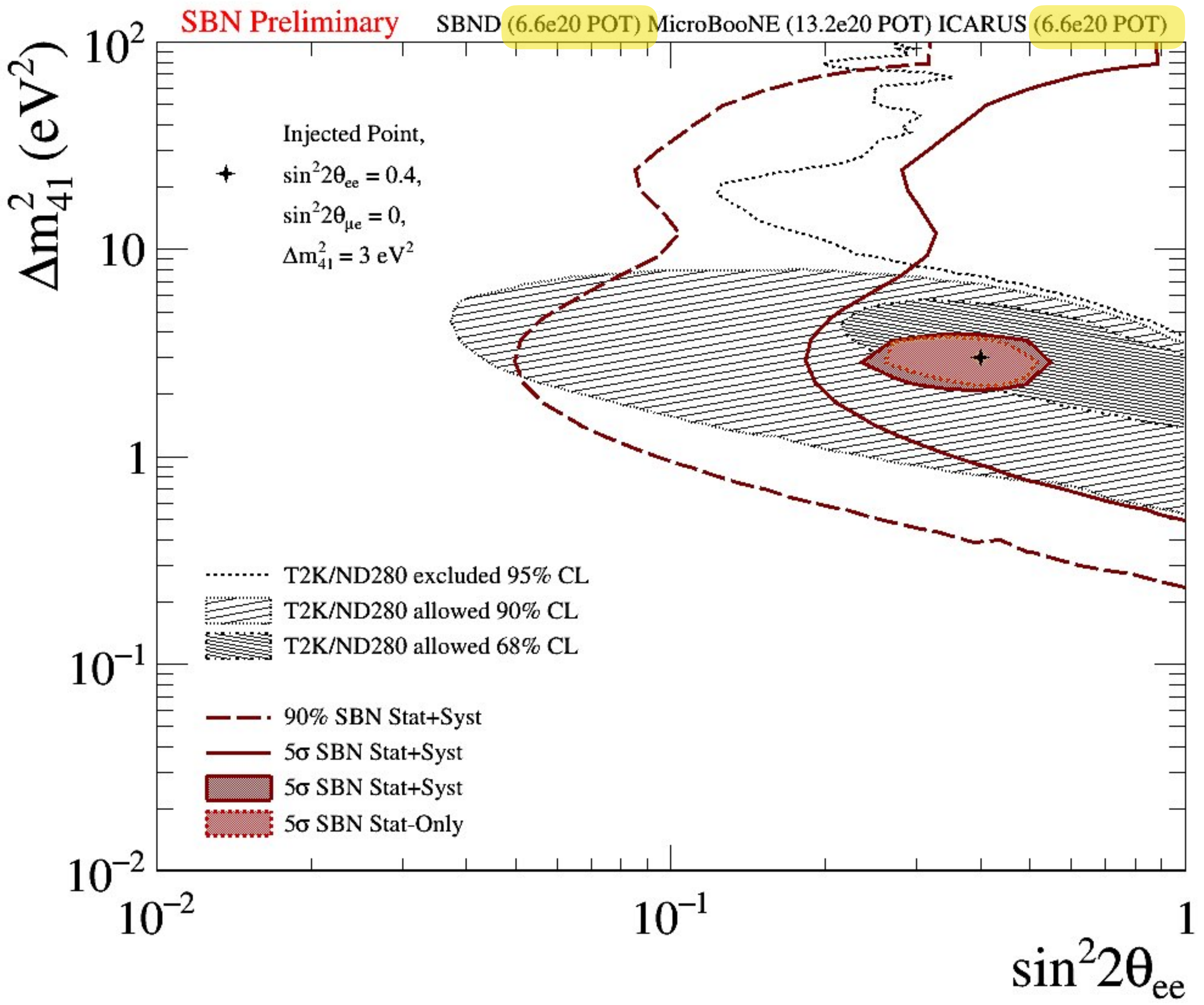
### $\nu_e$ Appearance




### $\nu_\mu$ Disappearance




### $\nu_e$ Disappearance




The SBN program tests the sterile neutrino hypothesis by covering the parameter regions allowed by past anomalies at **$5\sigma$ significance**.

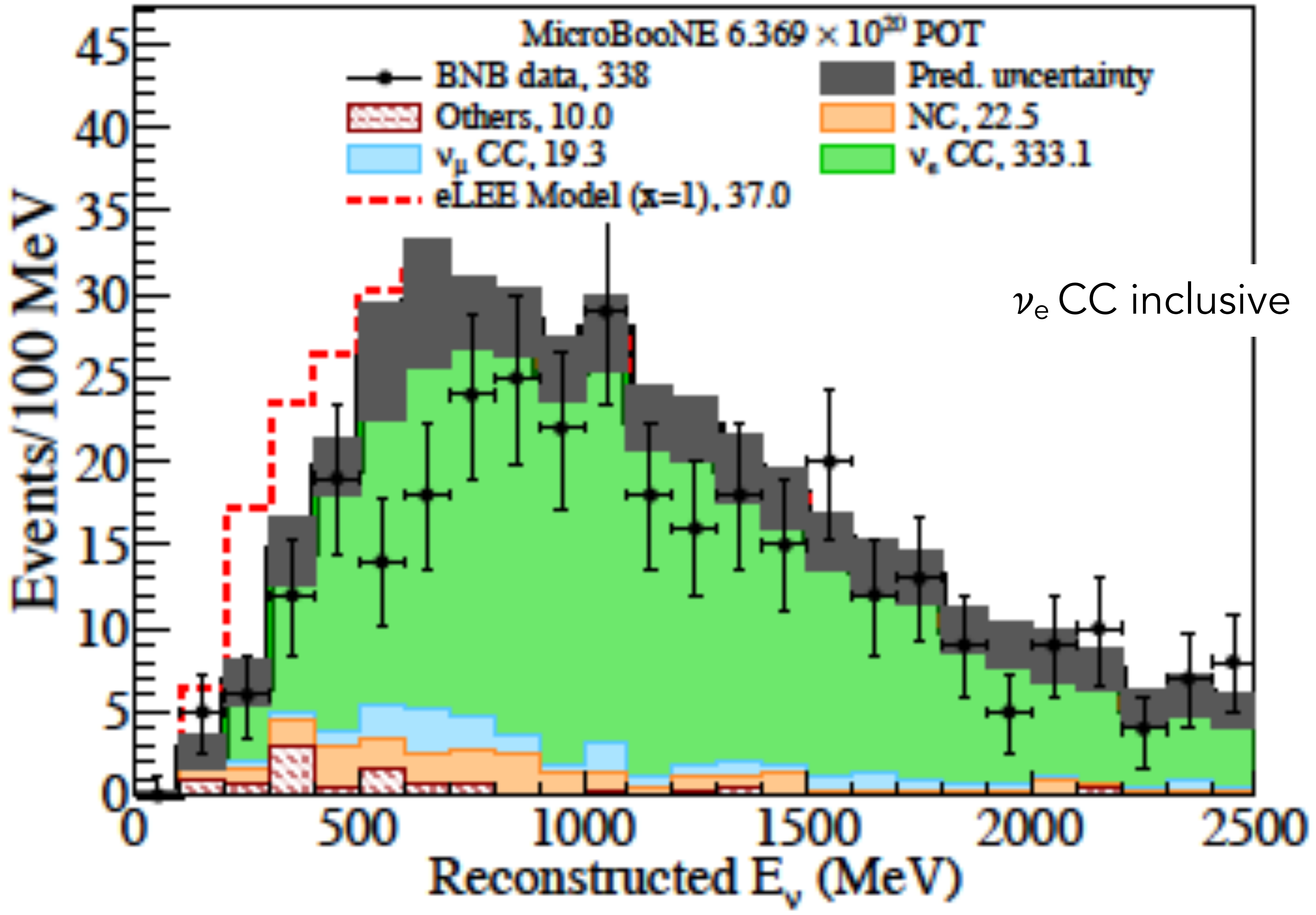
Complementary measurements in different modes:
important for interpretation in terms of **sterile neutrino oscillation**.

# Sterile Neutrino Searches Beyond MicroBooNE

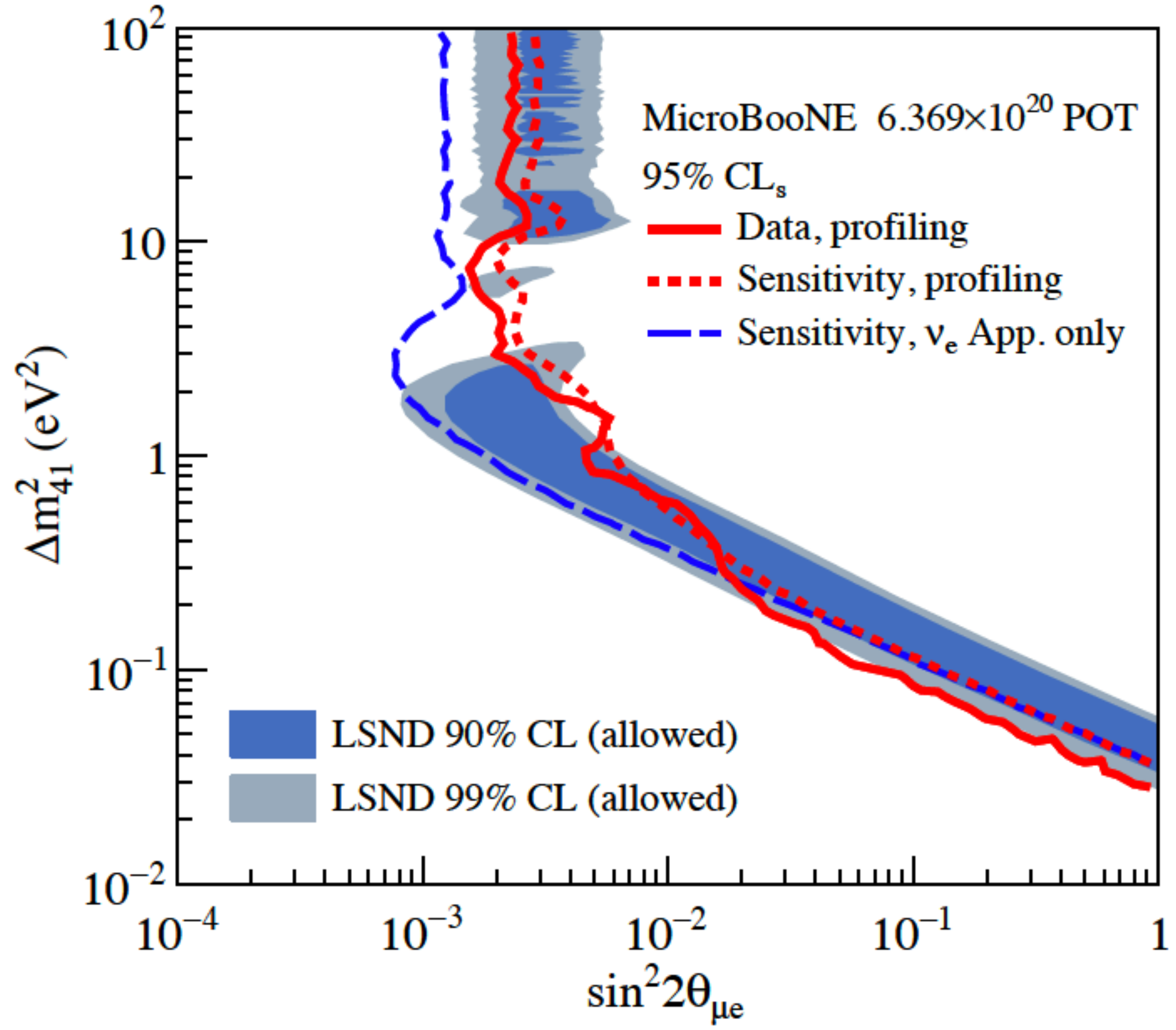
The MicroBooNE experiment presented very interesting results of first analyses searching for an excess of low-energy electromagnetic events:

**no hints of an electromagnetic event excess**, but results **do not rule out existence of sterile neutrinos**.

*P. Abratenko et al., Phys. Rev. Lett. 128, 241801*




*P. Abratenko et al., https://arxiv.org/abs/2210.10216*

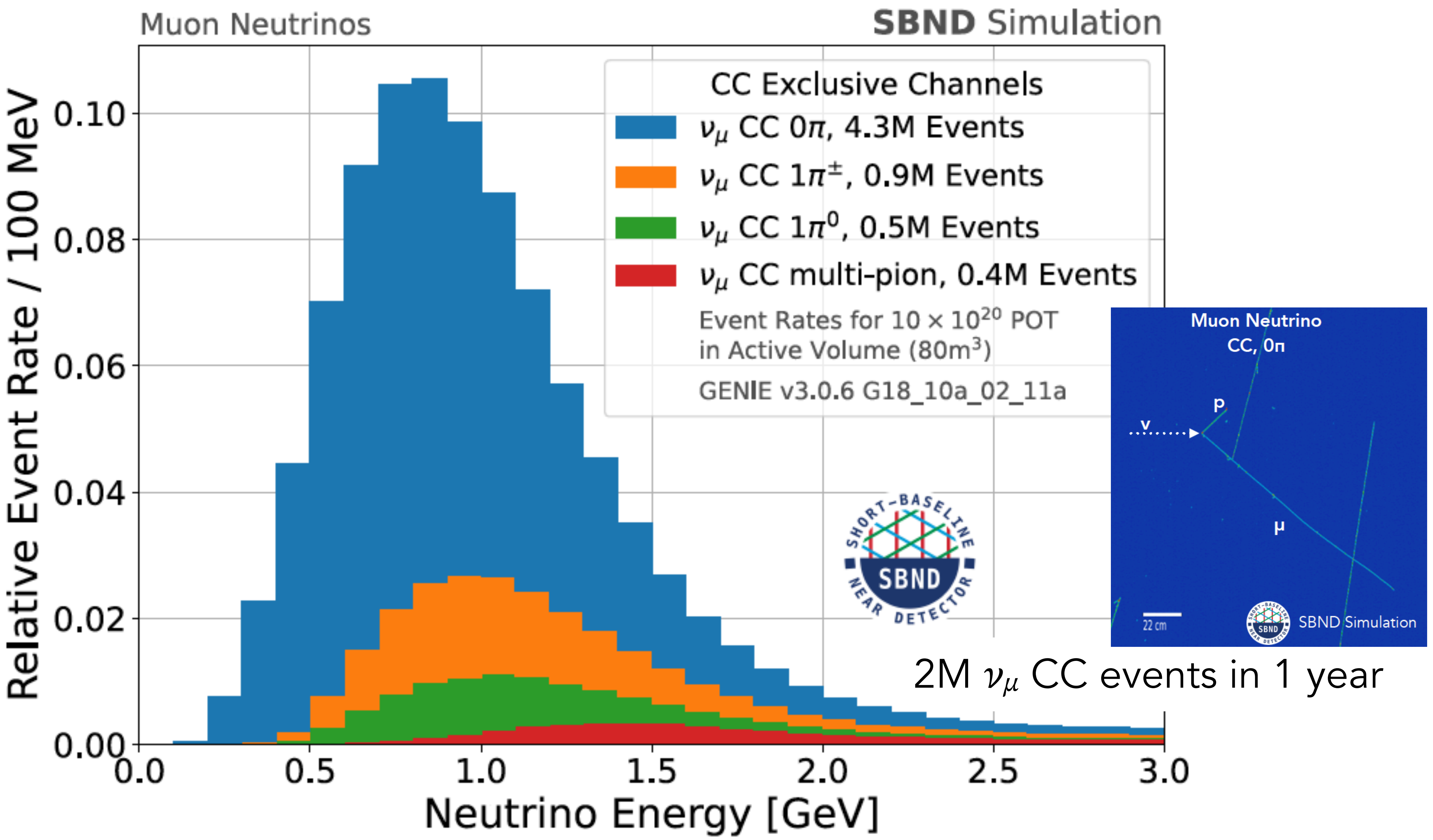



Entering the **next phase** now, with a **Near detector** and a **larger Far detector**.

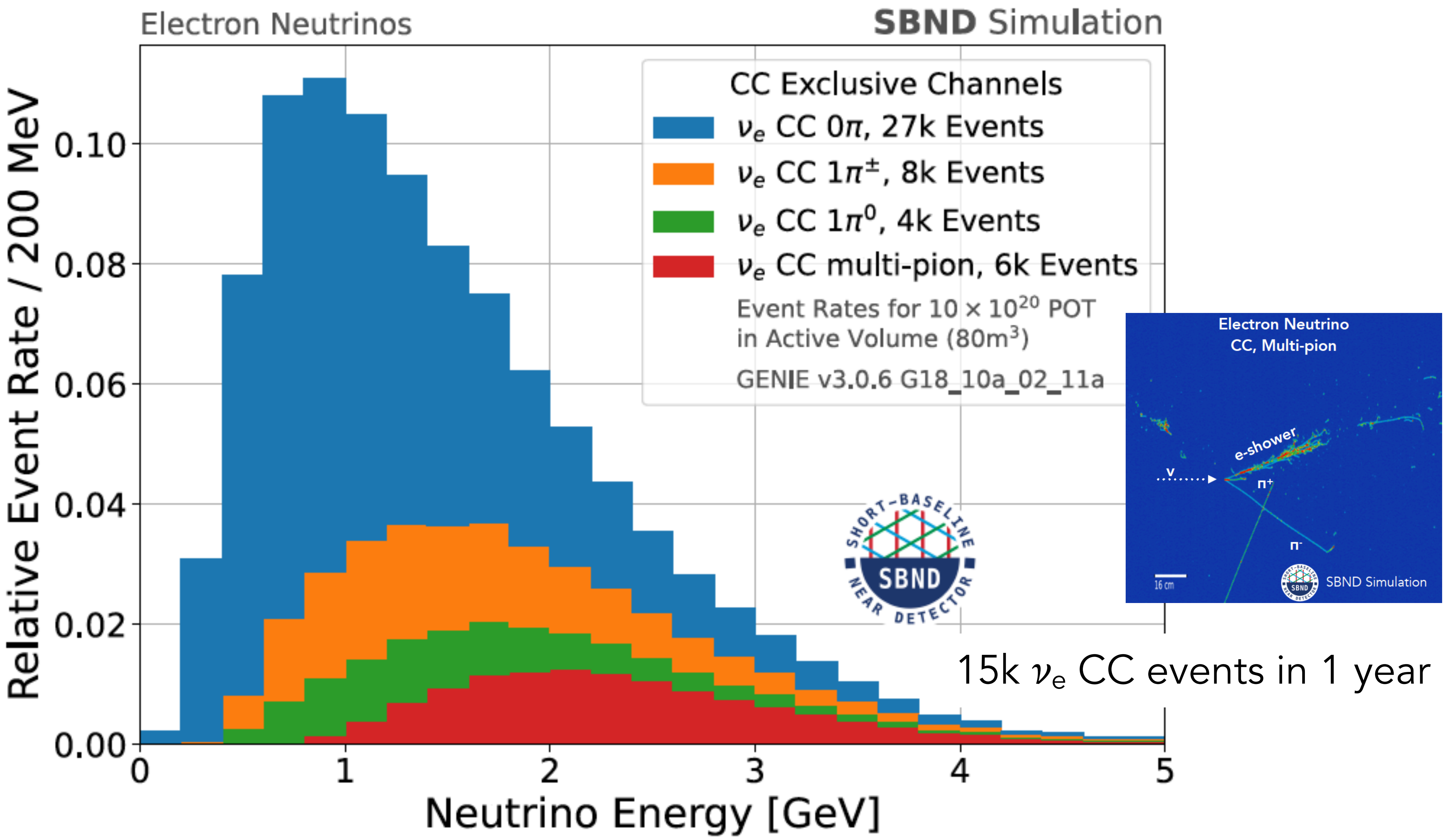
# Precision Studies of Neutrino-Argon Interactions in SBND

With its proximity to the neutrino source, **SBND** will compile neutrino data with unprecedented high event rate and will enable a generational advance in the study of neutrino-argon interactions in the GeV energy range.

**Up to 7000 $\nu$ events/per day in SBND!**




2M $\nu_\mu$ CC events in 1 year

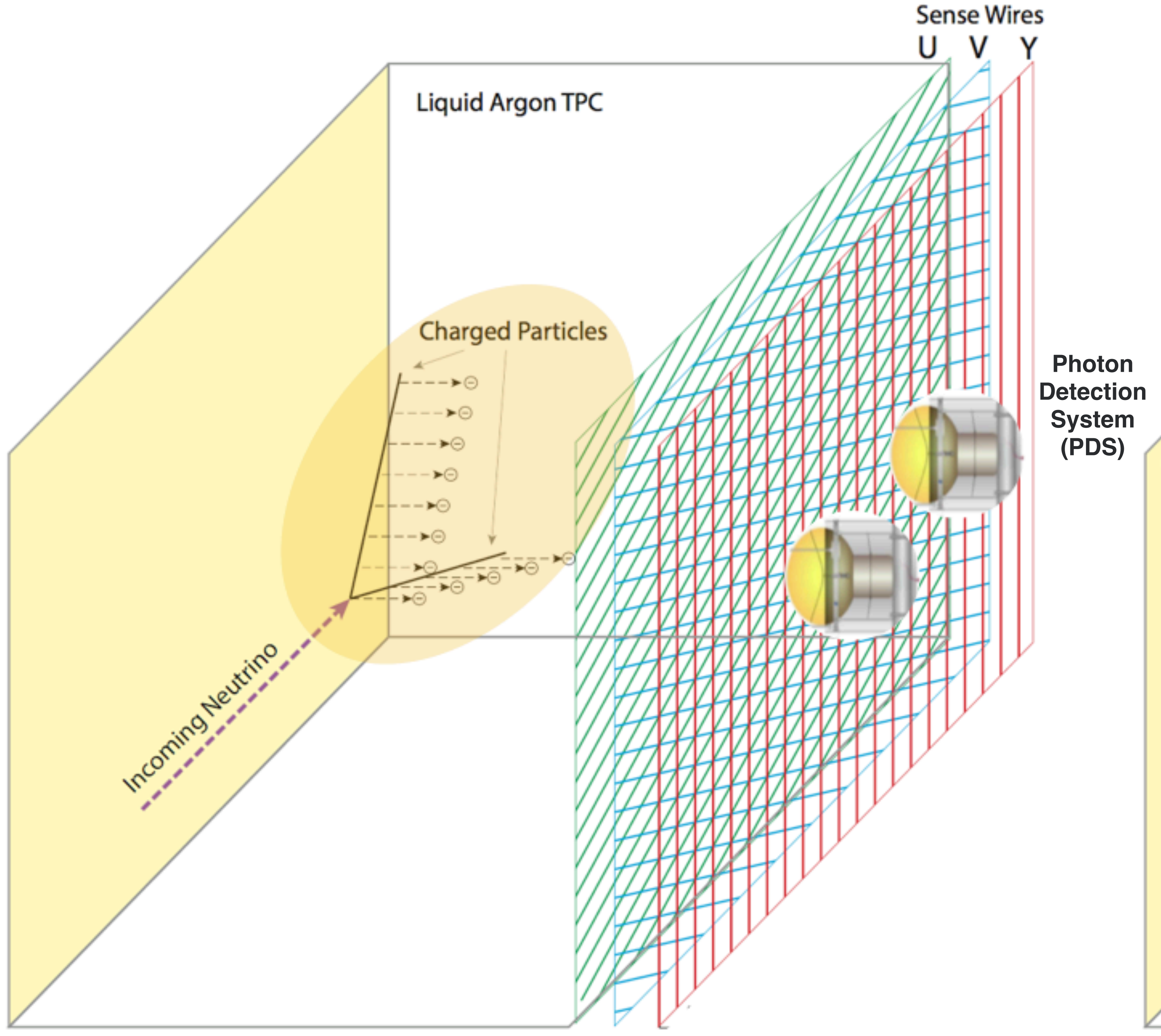


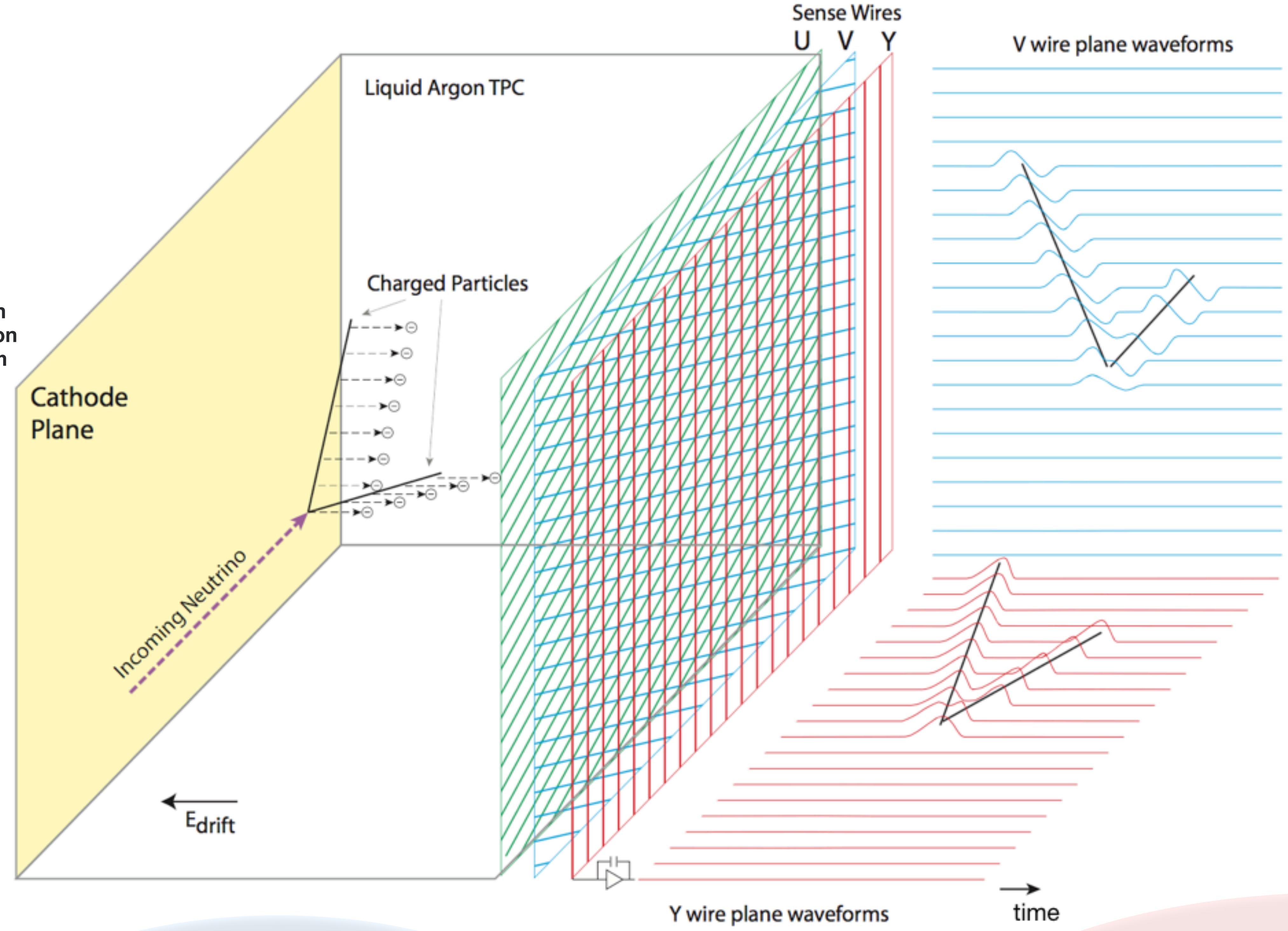

15k $\nu_e$ CC events in 1 year

SBND will record **20-30x more neutrino-argon interactions** than is currently available

(10 million total events (CC+NC), including around 50,000 $\nu_\mu$ CC events above 2 GeV, and 50,000 $\nu_e$ CC events).

# LAr TPC AT WORK




Charged particles in LAr produce free ionization electrons and scintillation light

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

VUV photons propagate and are shifted into VIS photons

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

*Electron drift time ~ ms*

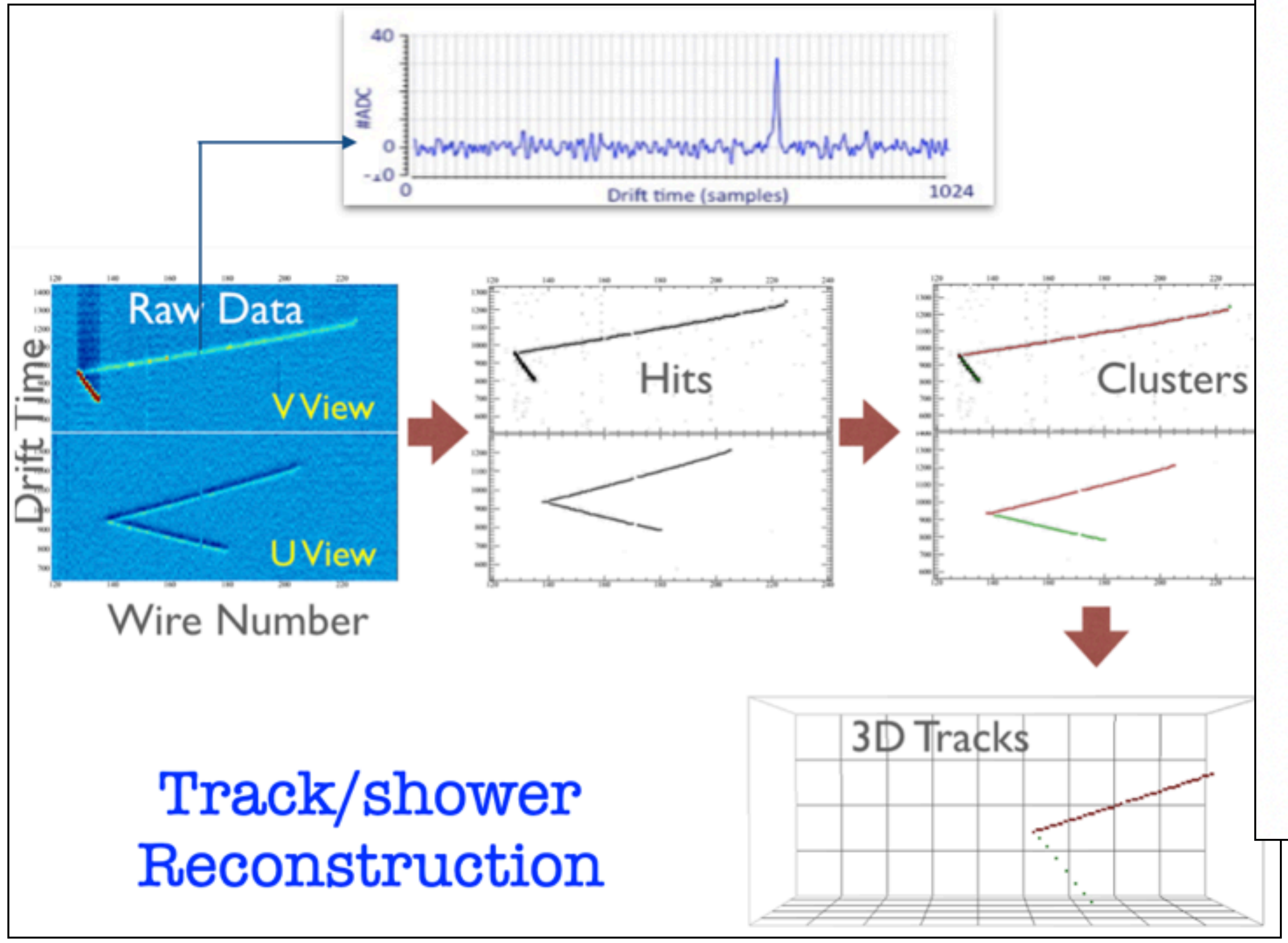
Digitized signals from the wires are collected [*time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge*]

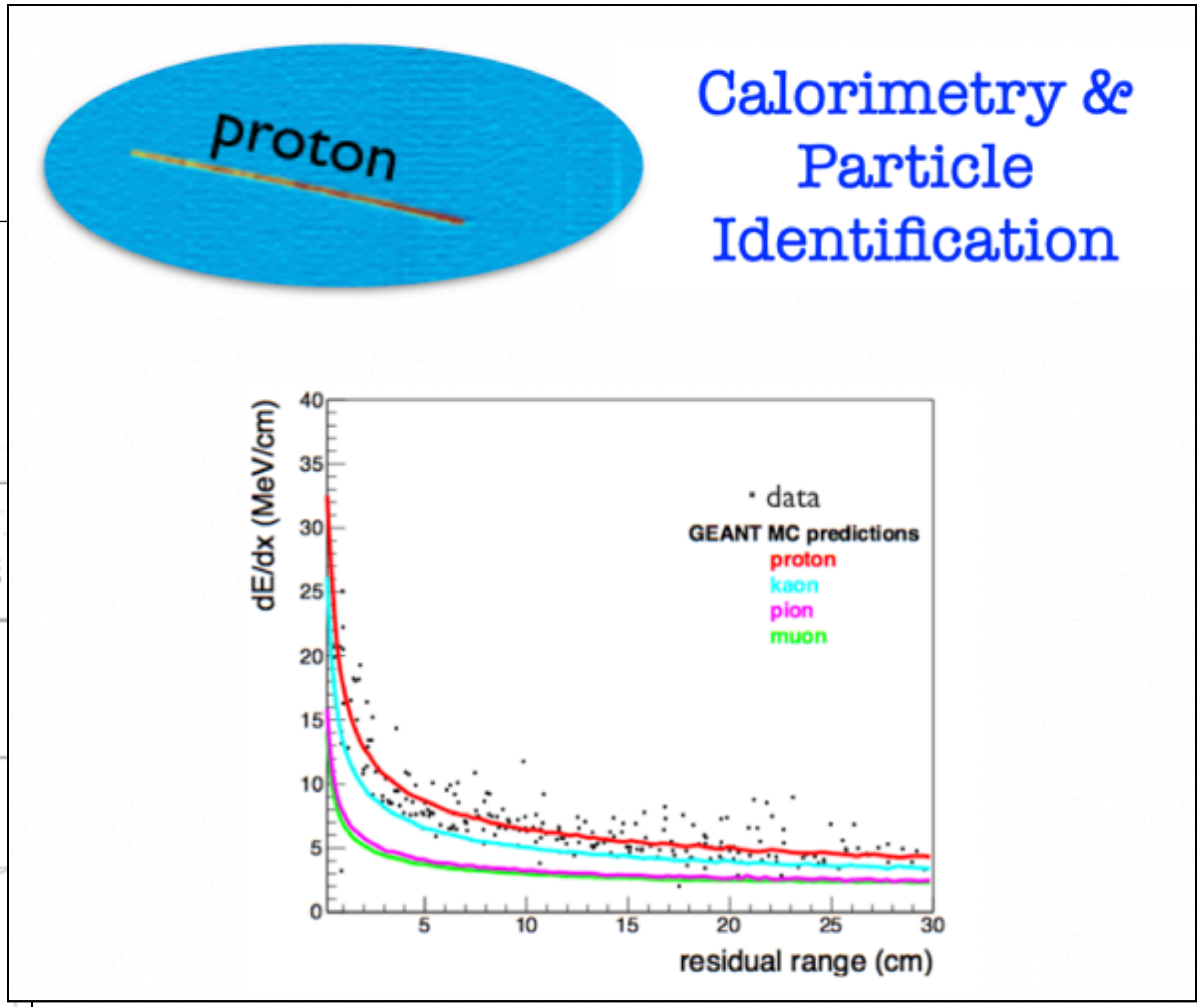
Scintillation light fast signals from PDSs give event timing

# The LAr Technology

Measure neutrino interactions **with millimeter position resolution.**
Excellent capability for energy depositions **from sub-MeV to few GeV**,
far beyond that offered by any other neutrino detector.

LArTPC at work: imagining, energy and timing



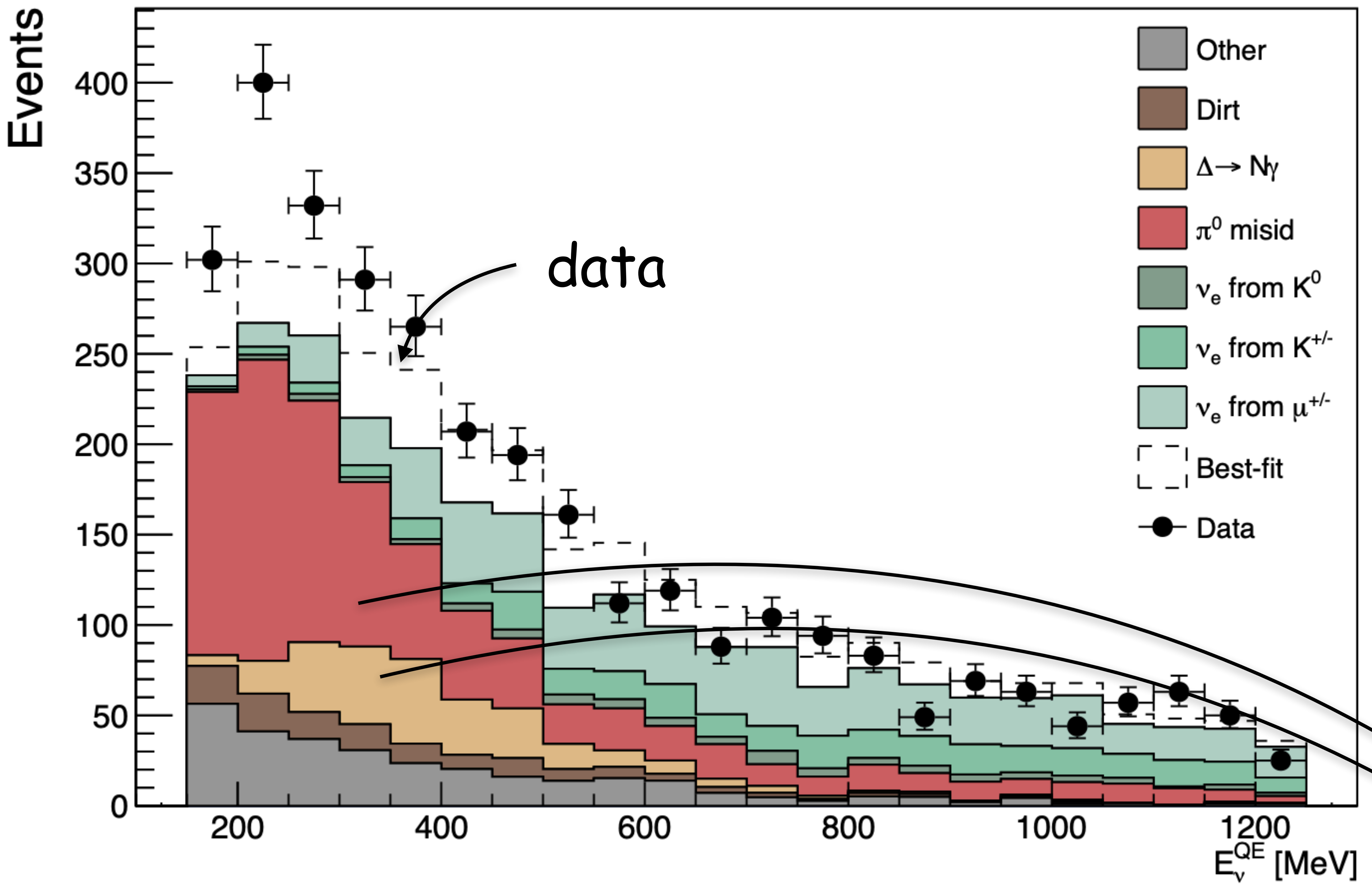

- Multiple 2D and the 3D reconstruction of charged particles ⇒ **Imaging**
- Total charge proportional to the deposited energy ⇒ **Calorimetry**
- dE/dx along the track ⇒ **Particle Identification**

and few ns **timing** resolution from photon detection system(s).

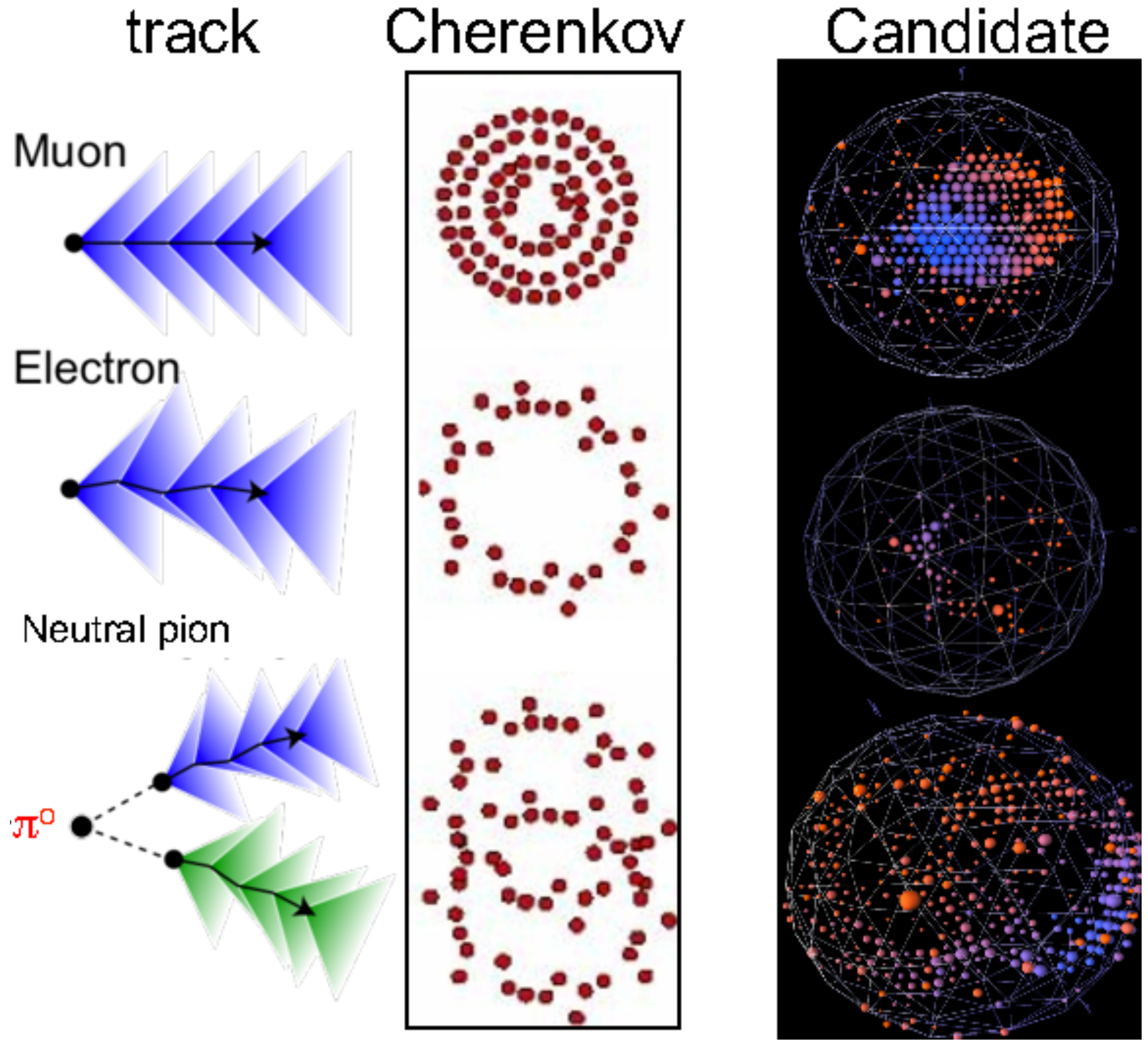
# ELECTRONS OR PHOTONS?

MiniBooNE

*Phys. Rev. D 103, 052002 (2021)*

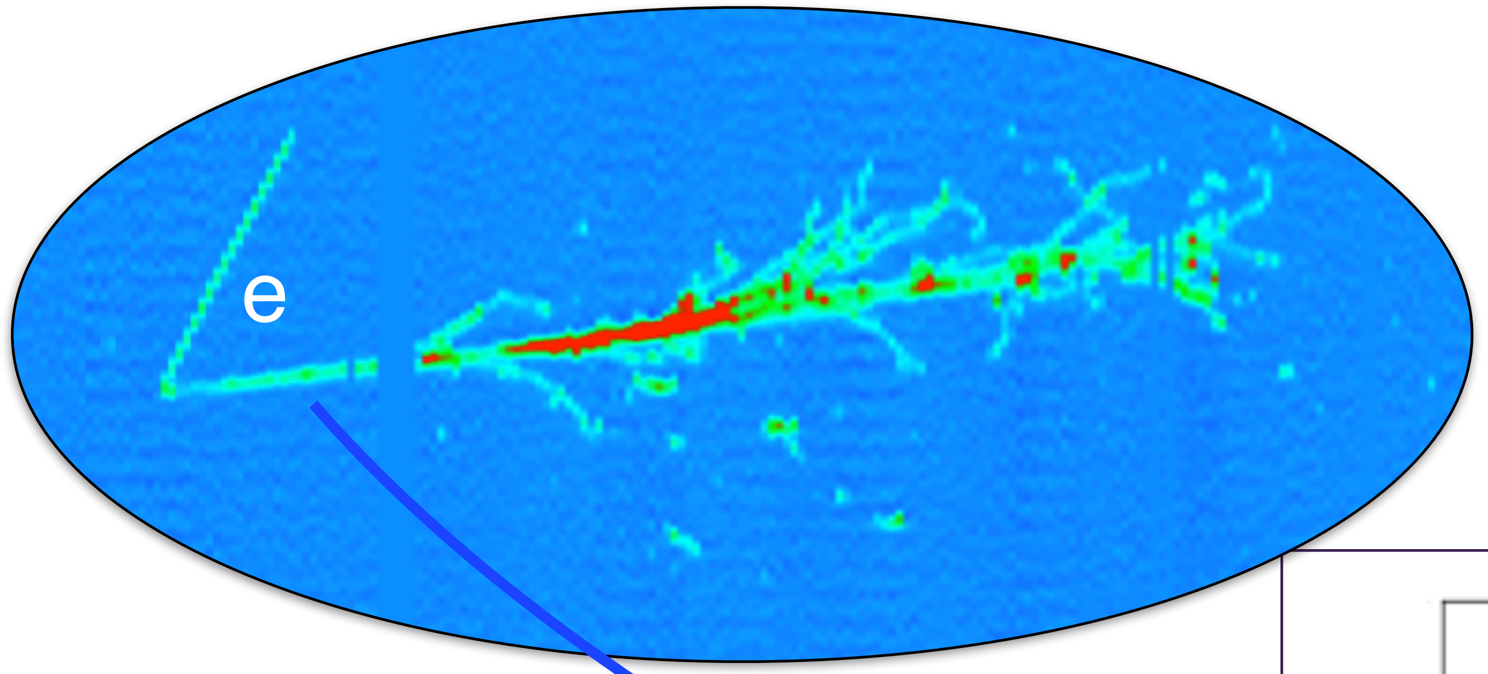


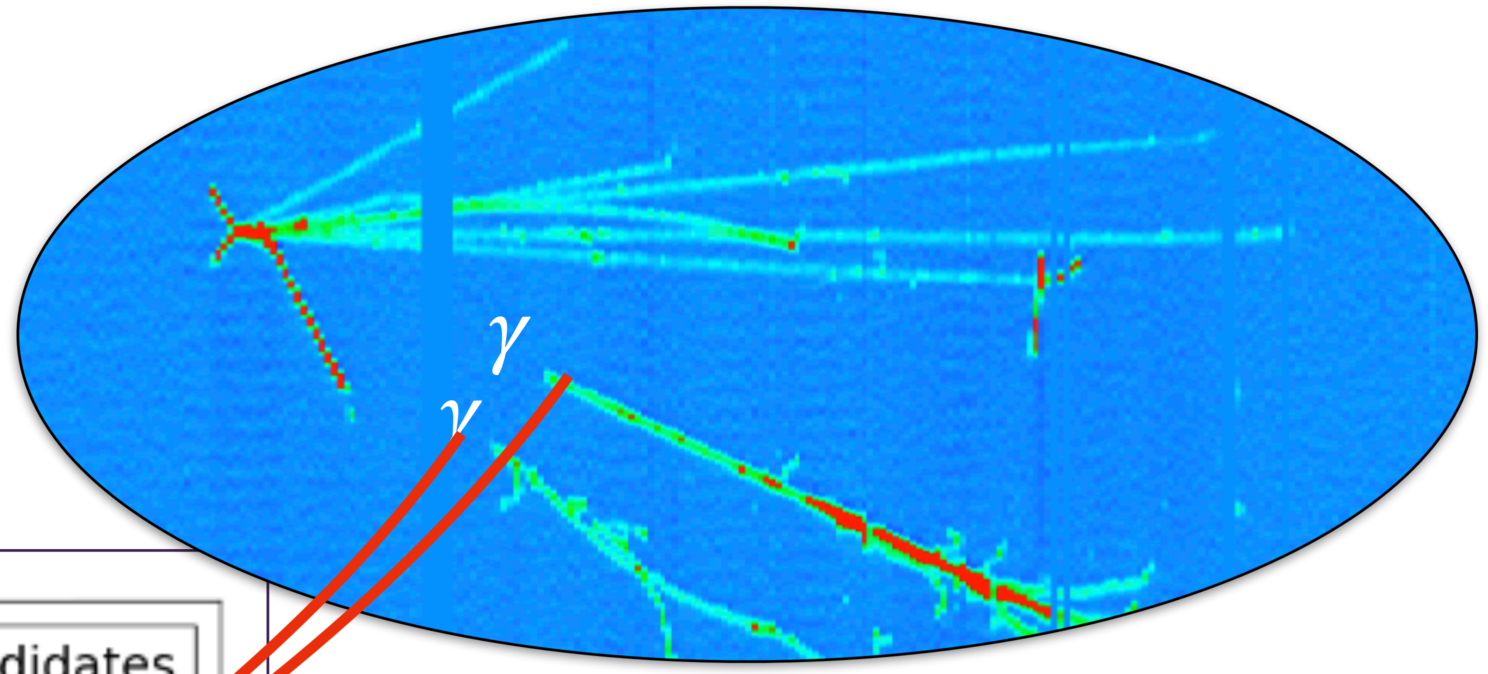

**MiniBooNE electron-like "Low Energy excess"… Photons? Electrons?**

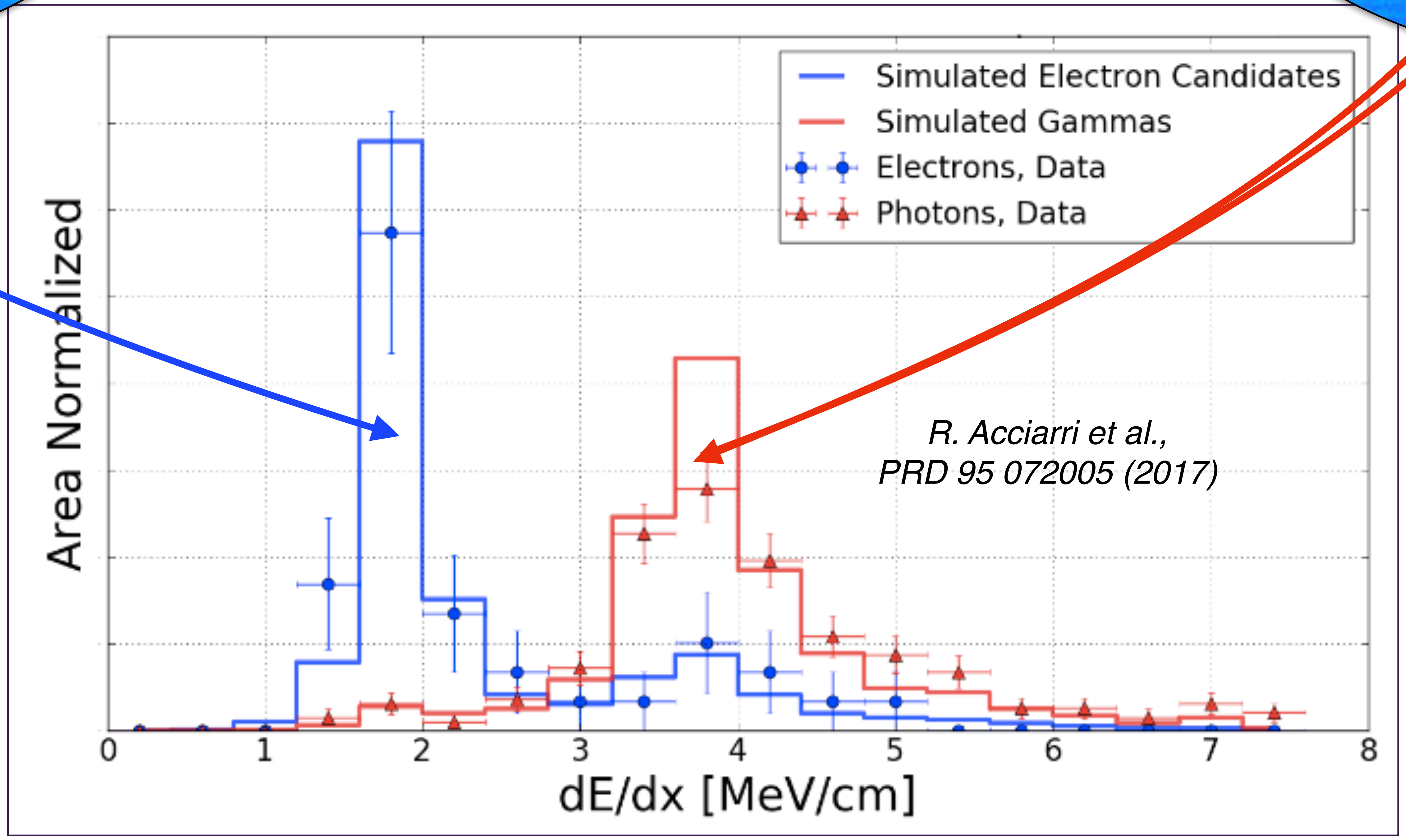



**LAr TPC!**

# ELECTRON-$\gamma$ DISCRIMINATION IN LAR TPC



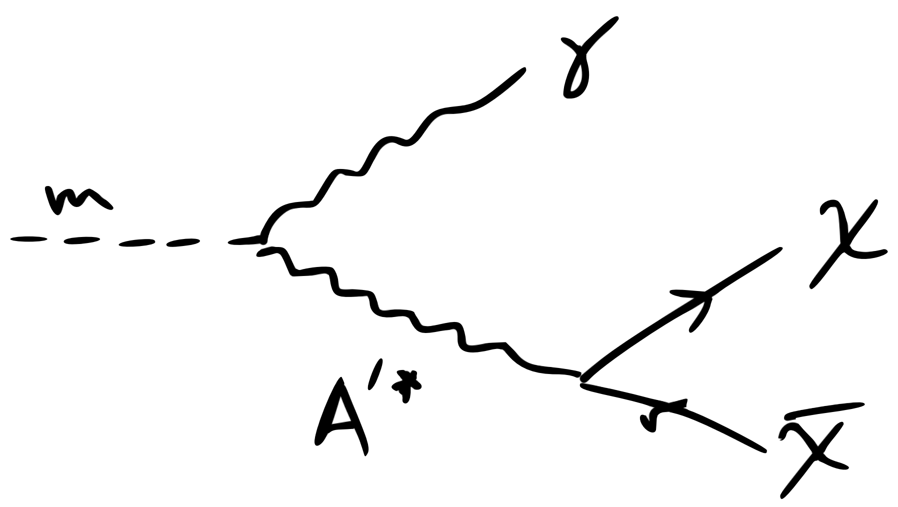




Analyzing topology (gap from the vertex) and dE/dx

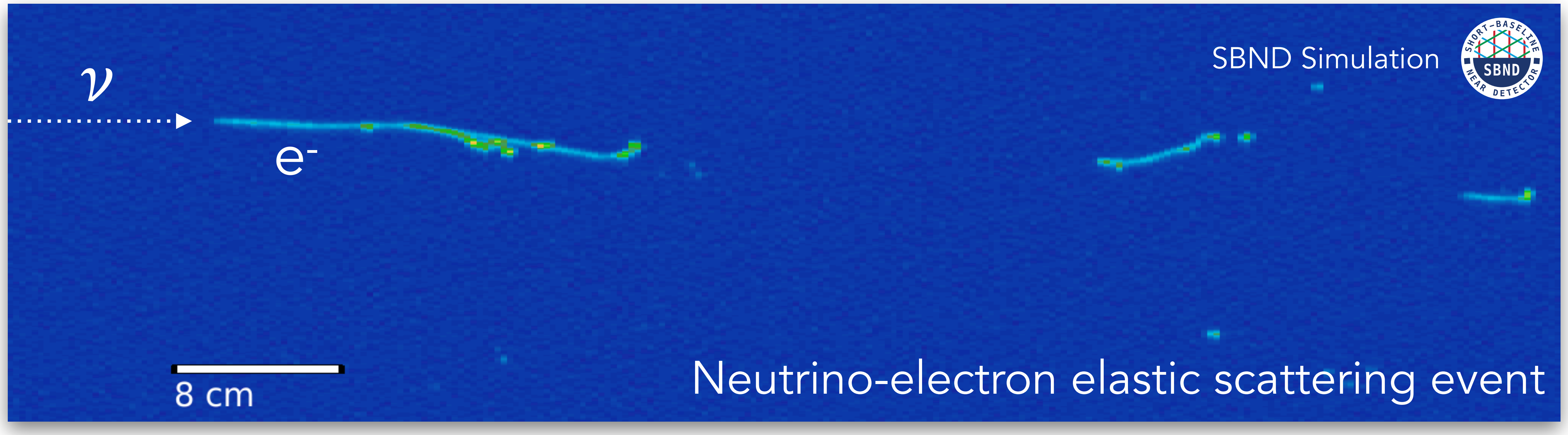
e-$\gamma$ discrimination capability of LAr is crucial to disentangle the signal/background nature of the electron-like excess observed by MiniBooNE

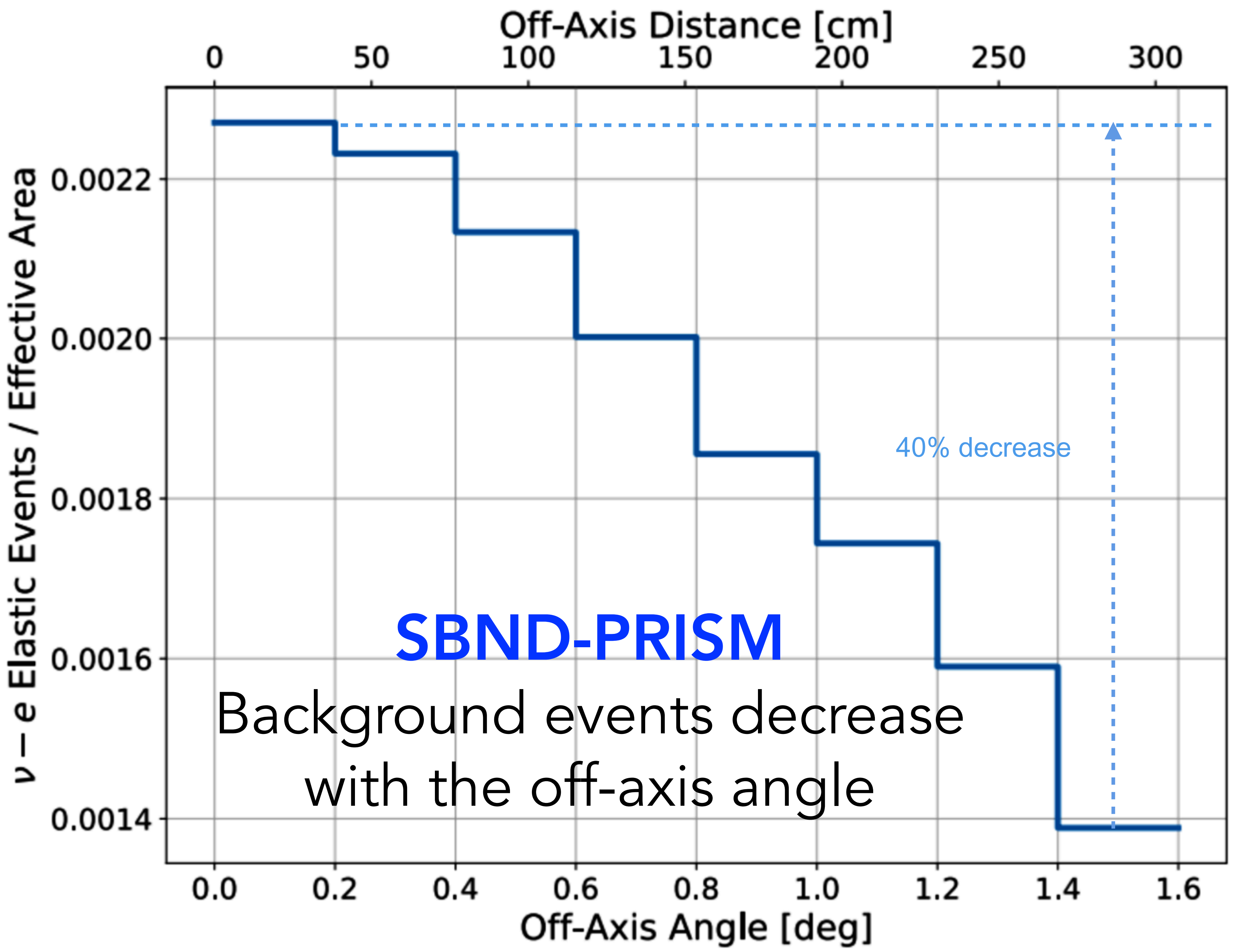
# Searches for Light Dark Matter in SBND




An example: **light** (sub-GeV) **dark matter**, coupled to the Standard Model via a dark photon. Dark photons can be produced by the decay of neutral meson (pions, etas) in the target, and decay into dark matter.

The dark matter, through the dark photon, **scatter off electrons** in the detector.




**SBND-PRISM**

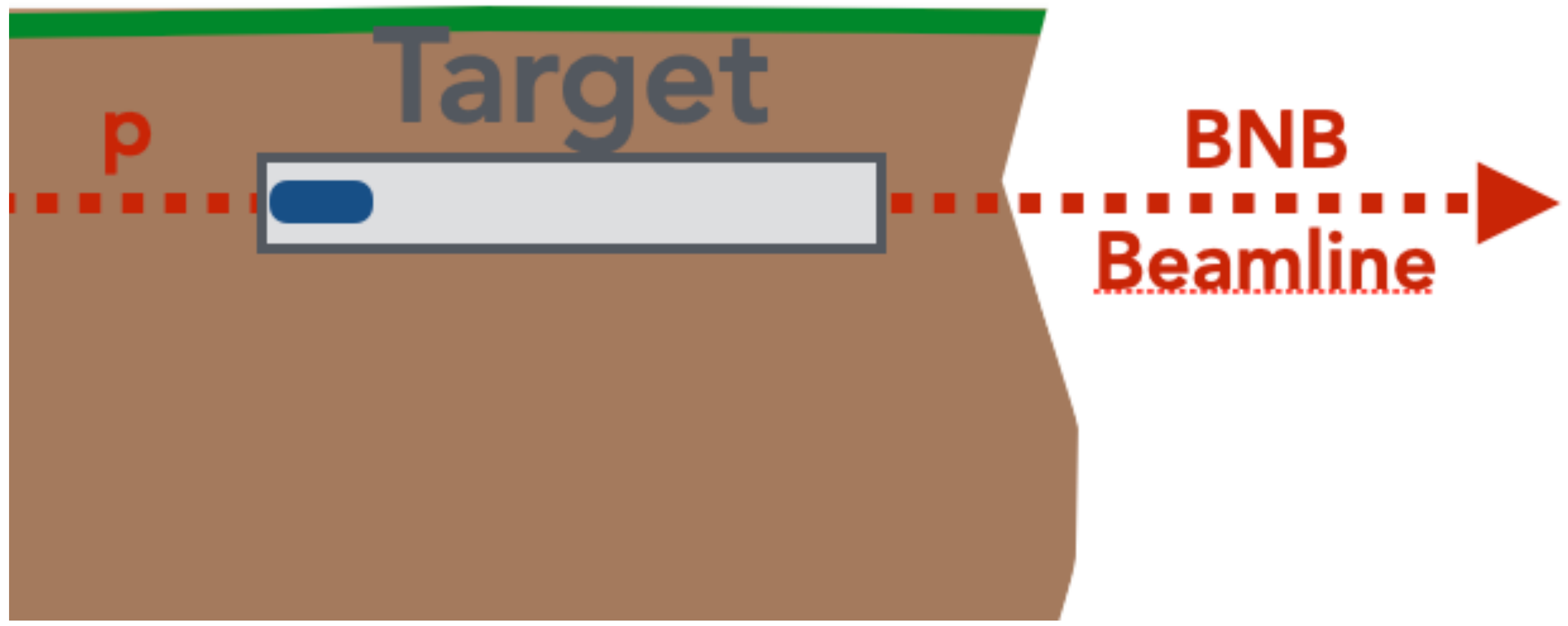
Background events decrease with the off-axis angle

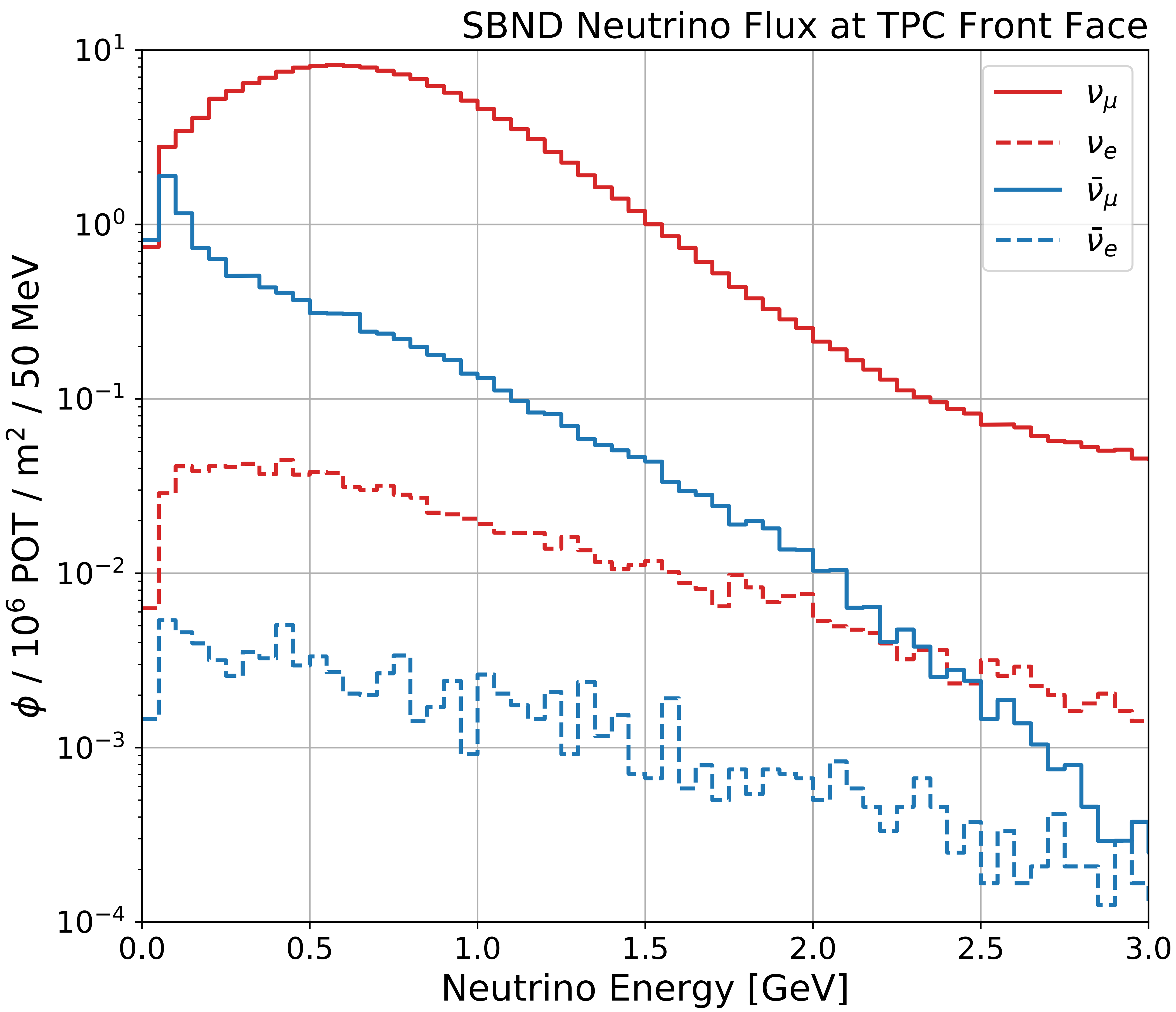
- **Signal**: DM elastic scattering electron events. DM comes from neutral (unfocused) mesons.
- **Background**: neutrino-electron elastic scattering. Neutrinos come from charged (focused) mesons.

‣ **Neutrino flux drops off more sharply as a function of radius!**

# Booster Neutrino Beam

**High-intensity neutrino beam** from 8 GeV proton beam.




Neutrino flux at the SBND front face.

Mean muon-neutrino energy: ~0.8 GeV

Beam composition:

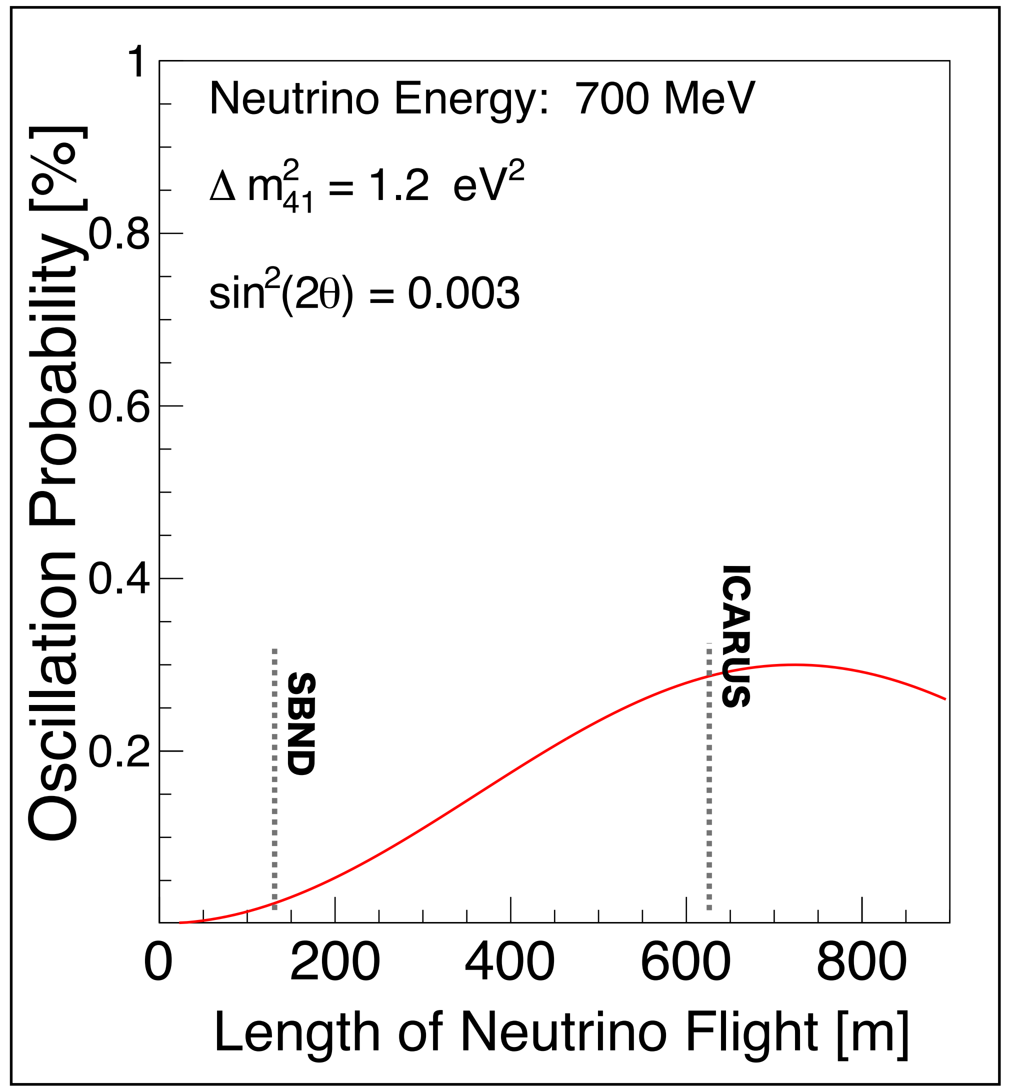
$\nu_\mu$ (93.6%)

$\bar{\nu}_\mu$ (5.9%)

$\nu_e+\bar{\nu}_e$ (0.5%)

# WHAT MAKES THE SBN PROGRAM UNIQUE?

## LAr Technology




## Near detector SBND

Crucial for oscillation searches.

Sitting close to the neutrino source, SBND plays a **unique role.**

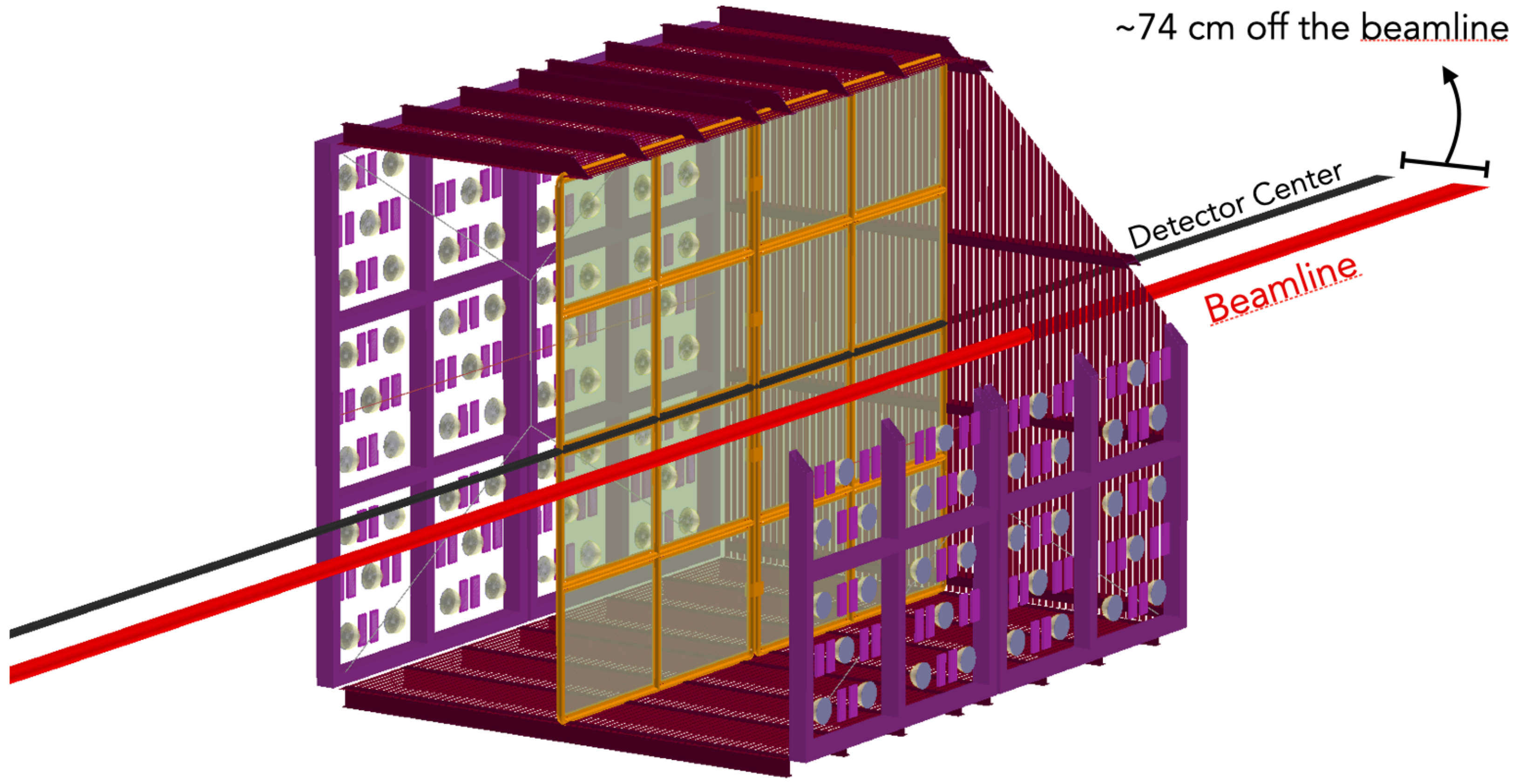
It sits before oscillations turn on @eV-scale → it characterizes the beam and **addresses the dominant systematic uncertainties**

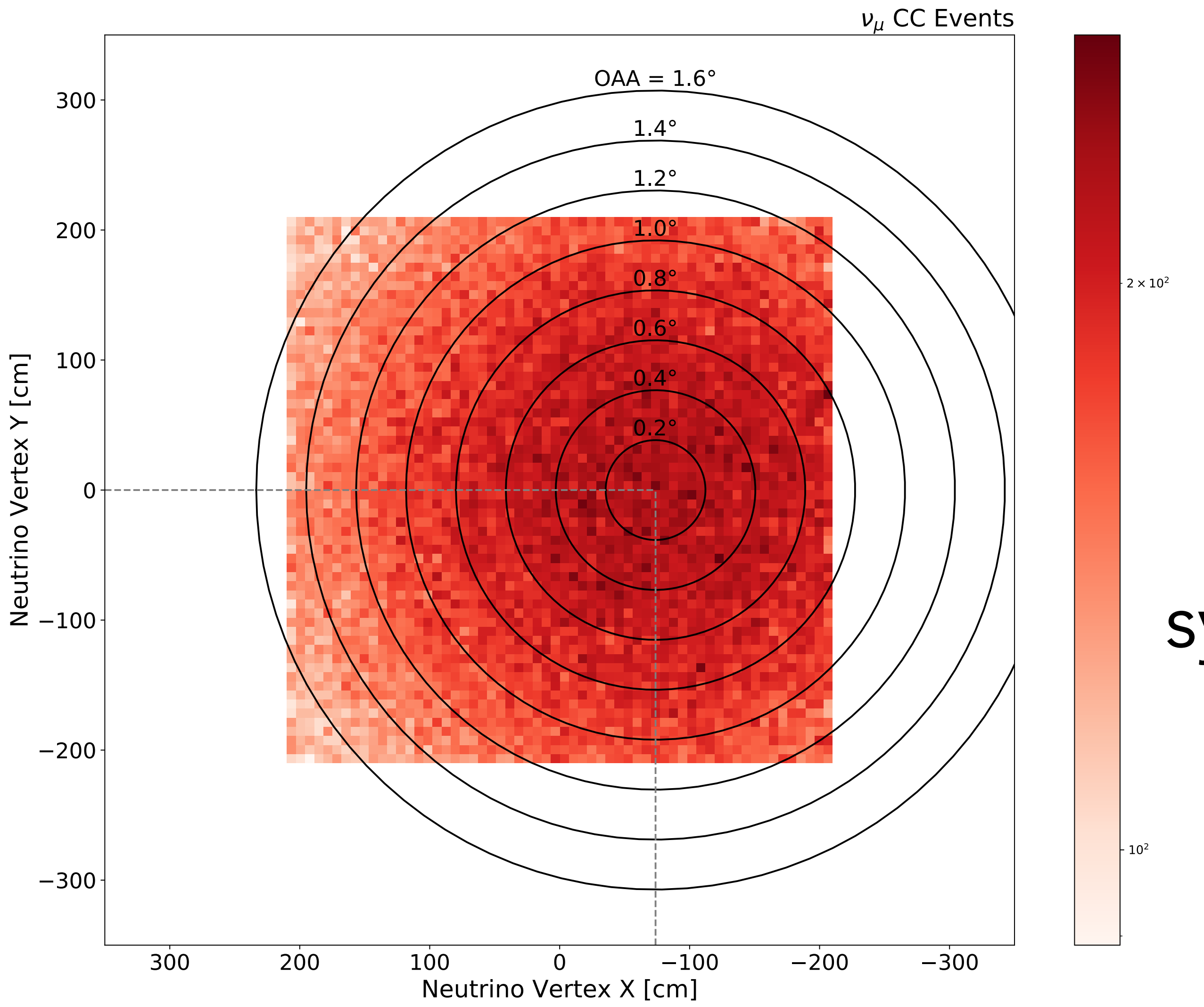
## Far detector ICARUS

Given its far location and large mass provides big exposure to oscillated neutrinos, allowing for a **high sensitivity oscillation search**

## SBND-PRISM

SBND is close (110 m) to the neutrino source and intentionally positioned offset relative to the beam center.



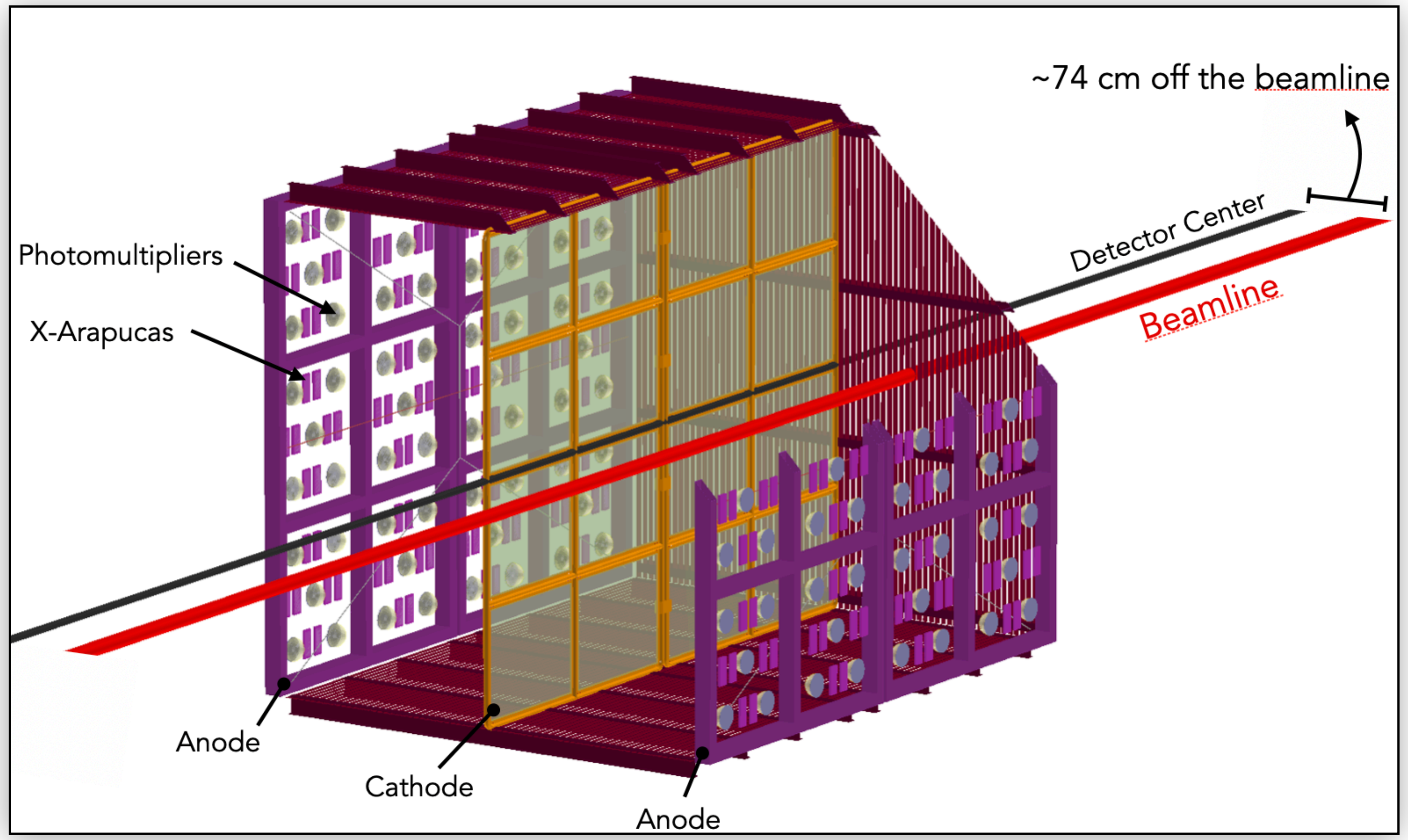



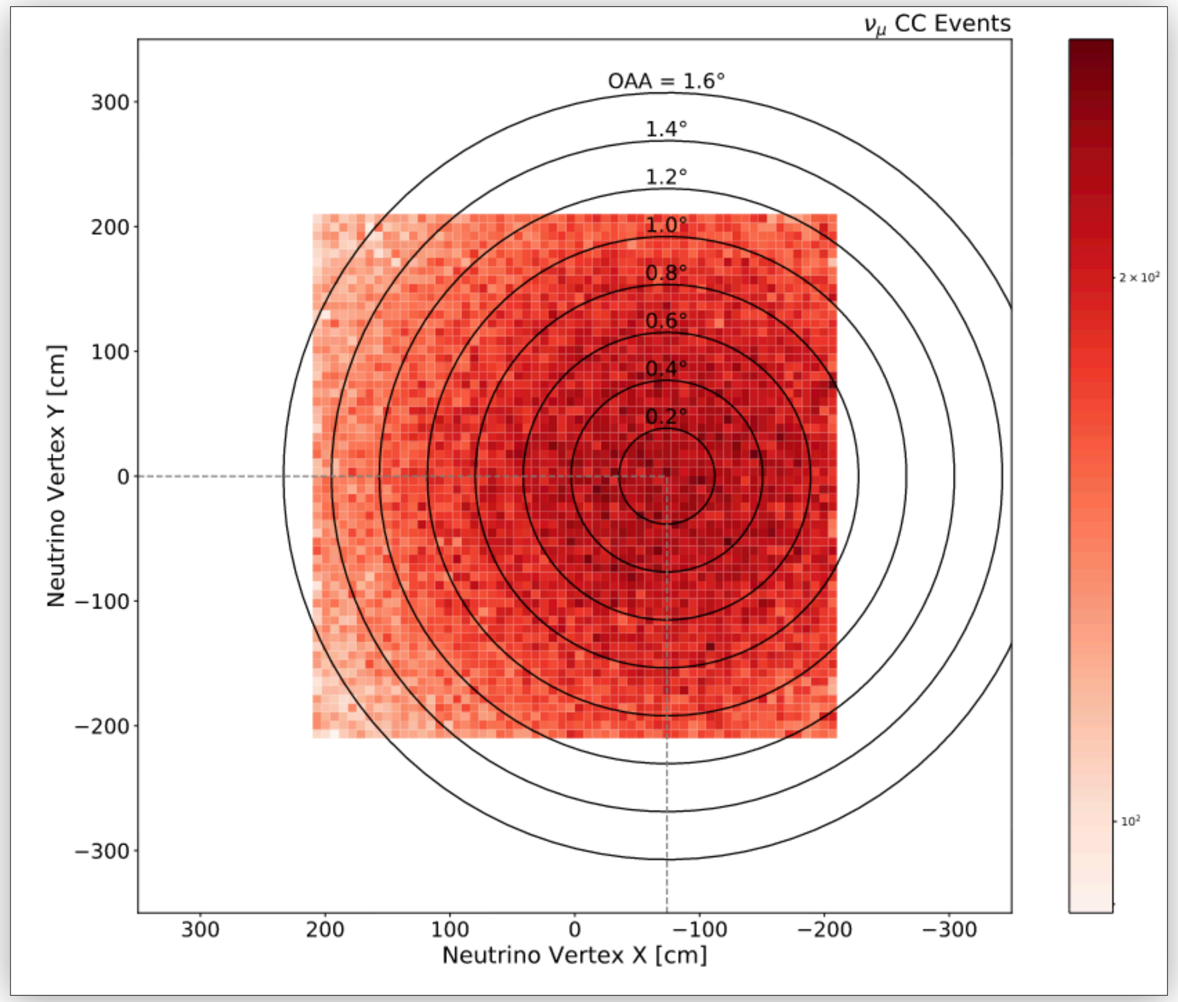

This "PRISM"* feature of SBND allows **sampling multiple neutrino fluxes in the detector**

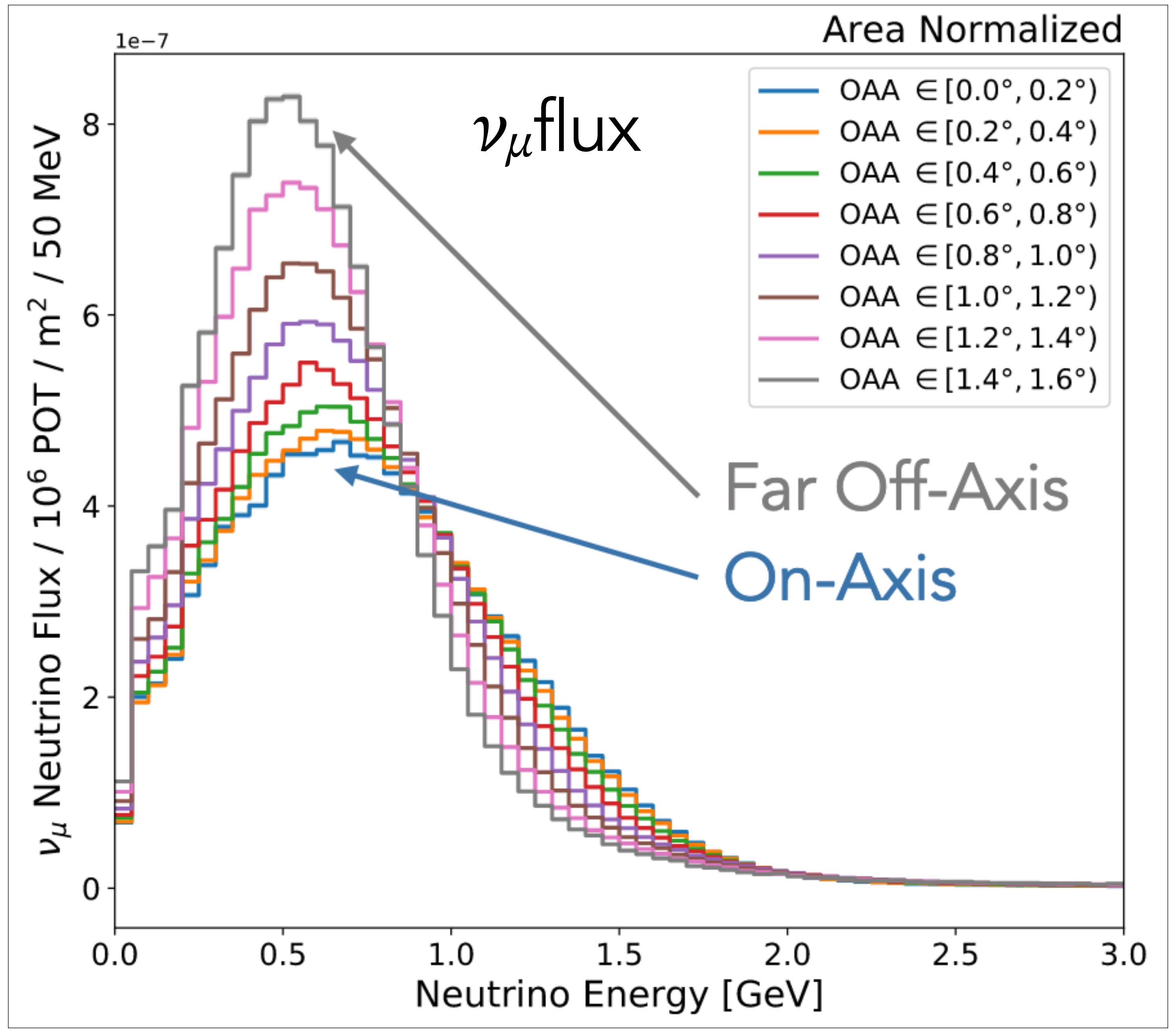
**SBND-PRISM** provides unique constraints of systematic uncertainties, helps mitigate backgrounds, and expands the SBN(D) physics potentials

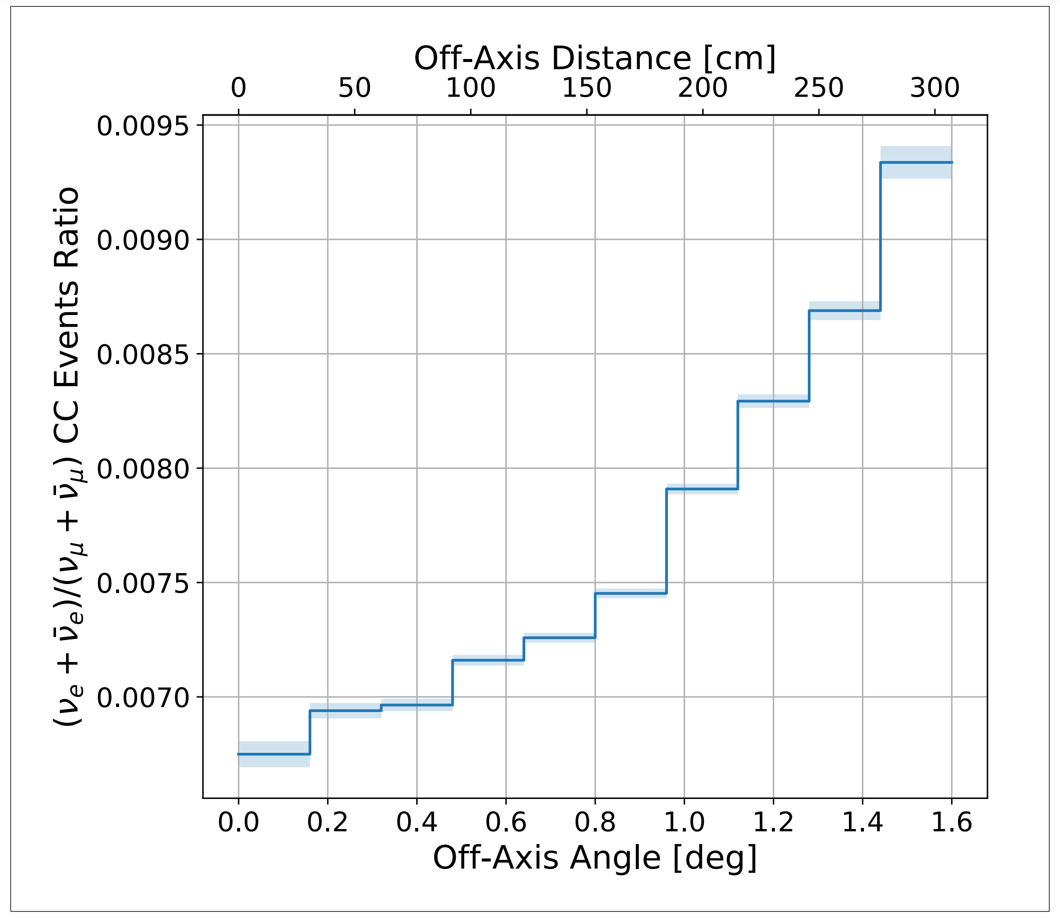
*Similar to the nu-PRISM and DUNE-PRISM concepts, but with a fixed detector.

## A Slightly Off-Axis Detector close to the neutrino source

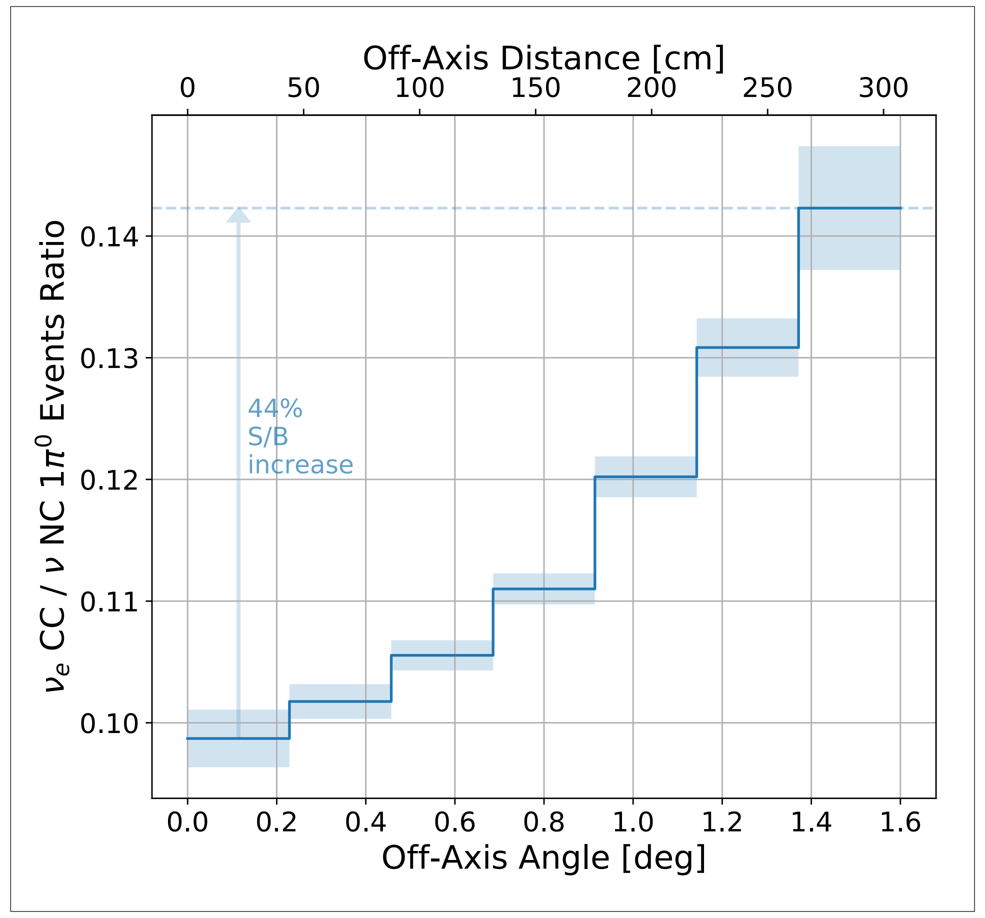



$\nu_e$ to $\nu_\mu$ ratio changes moving off-axis




NC $\pi^0$ decreases moving off-axis

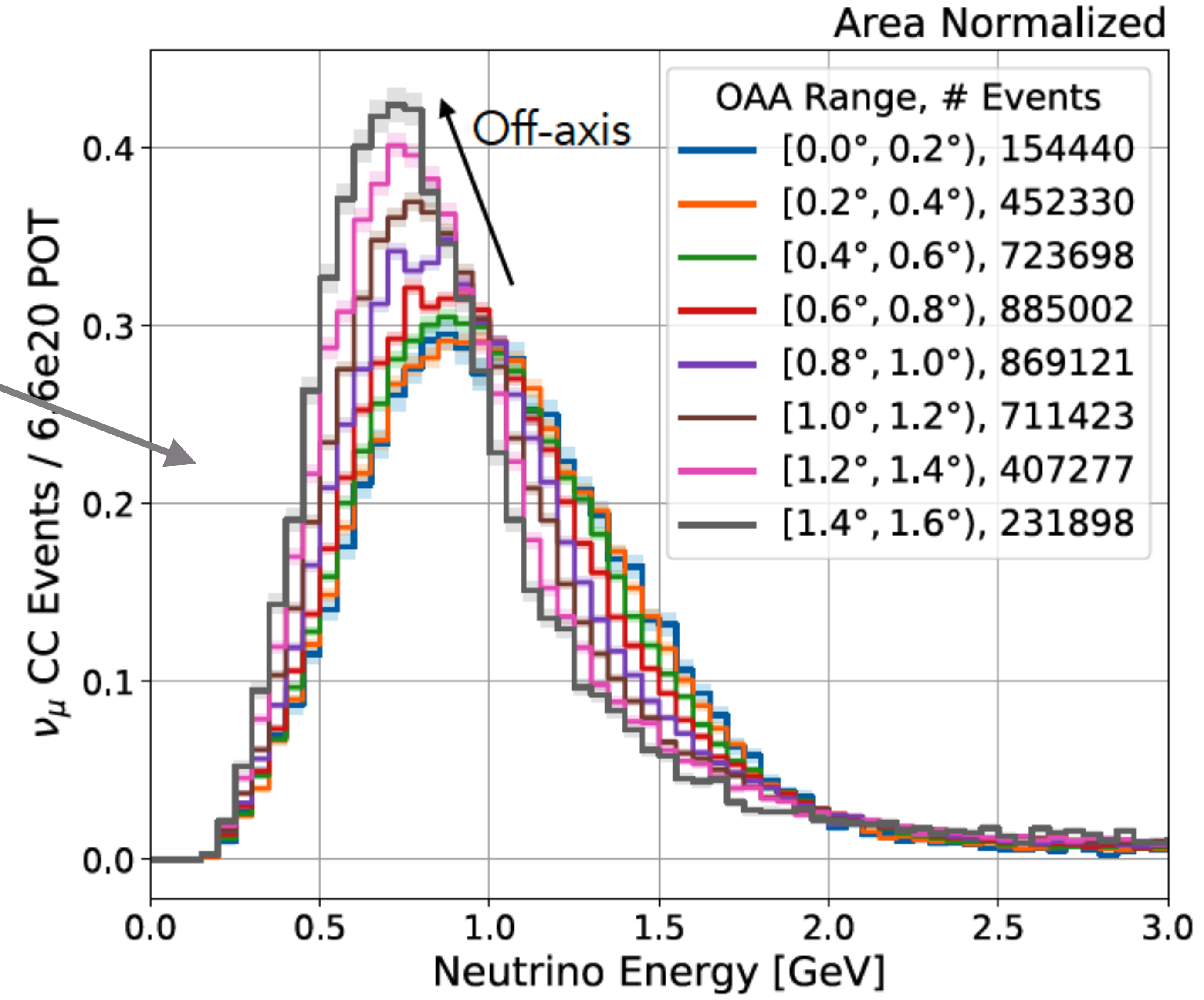
Additional physics potentials from SBND-PRISM

- Further constrain neutrino interactions in oscillation physics.
- Perform targeted neutrino interaction measurements and disentangle nuclear effects.
- Background reduction moving off-axis.

# SBND-PRISM - Neutrino Fluxes

The **Muon** neutrino energy distributions are affected by the off-axis position [$\nu_\mu$ come predominantly from two-body decay]. Larger off-axis angle → lower mean energy.

Neutrino Fluxes in Off-Axis Angle (OAA) regions

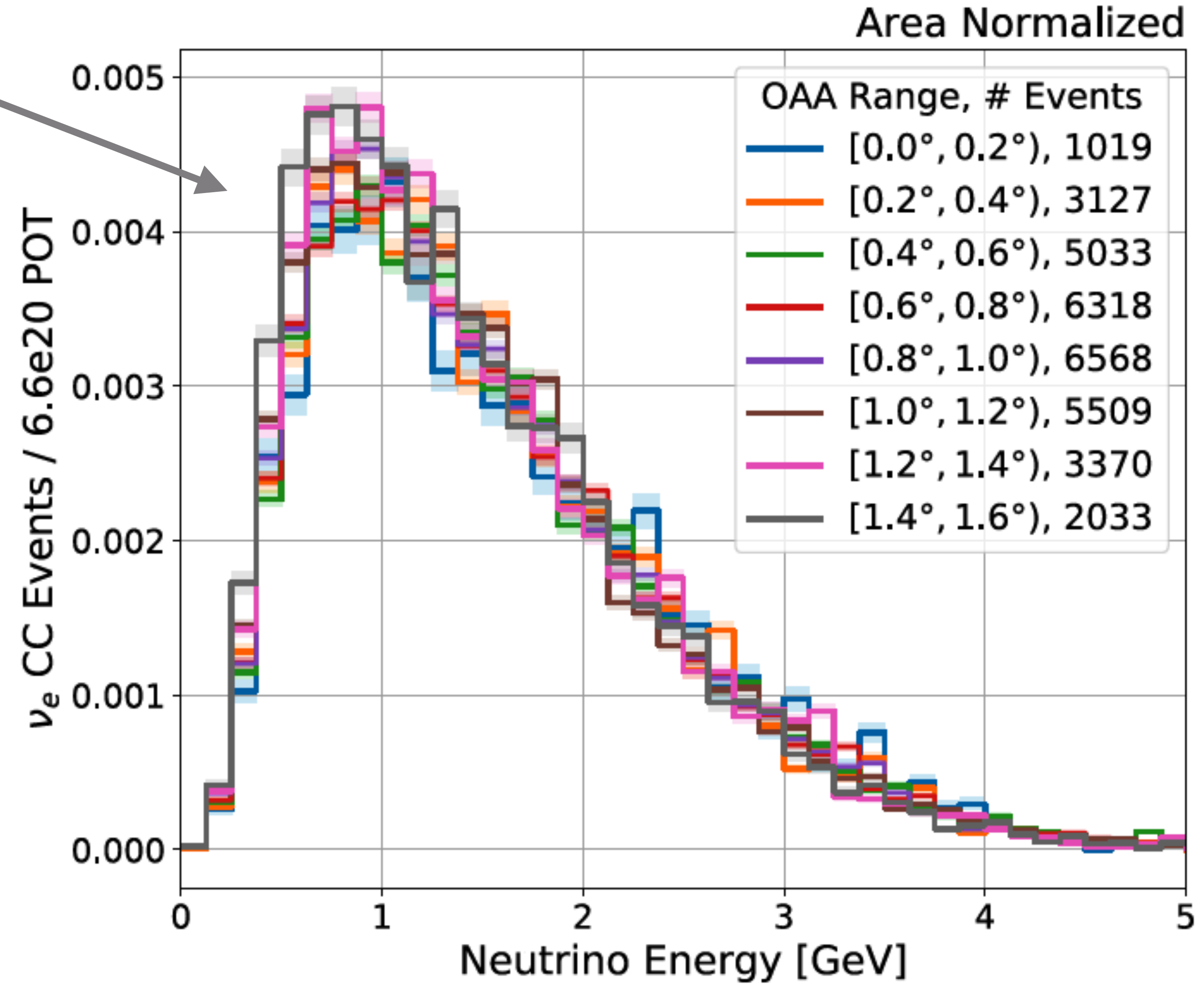



**Muon** neutrino

High event statistics in all off-axis regions.

The **Electron** neutrino energy distributions also change, but they are less affected by off-axis position [$\nu_e$ come from three-body decay].

**Muon and electron neutrino spectra change in a different way!**



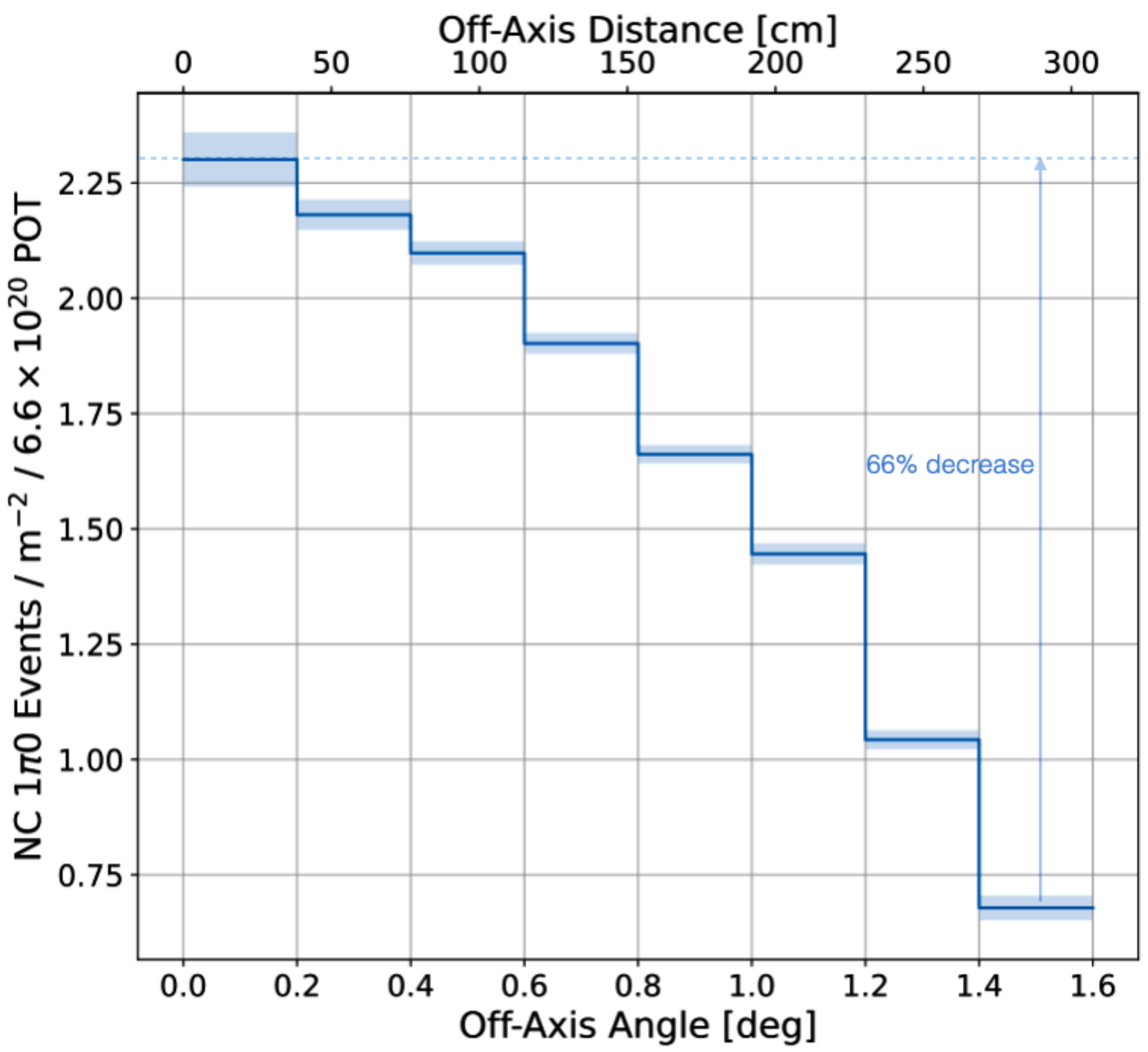

**Electron** neutrino

Leveraging the different behavior of muon and electron neutrinos in the OAA regions, we can improve sensitivity for sterile neutrino searches.

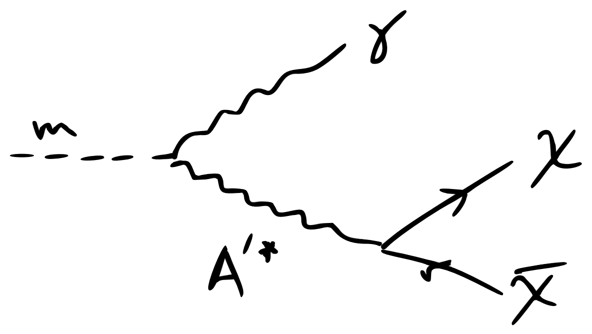
# SBND-PRISM TO MITIGATE BACKGROUNDS

**An example: electron neutrino measurements**

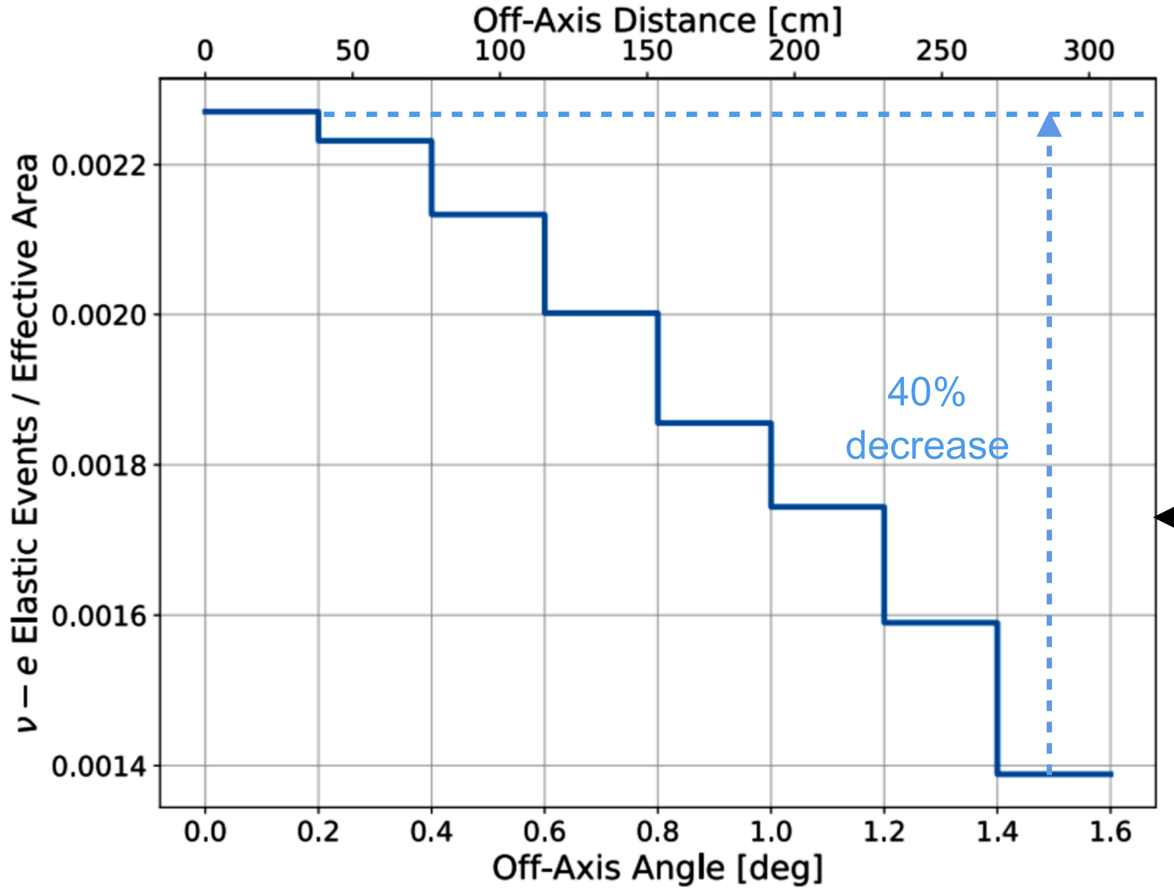
Main background for electron neutrino: NC 1 $\pi^0$ events.



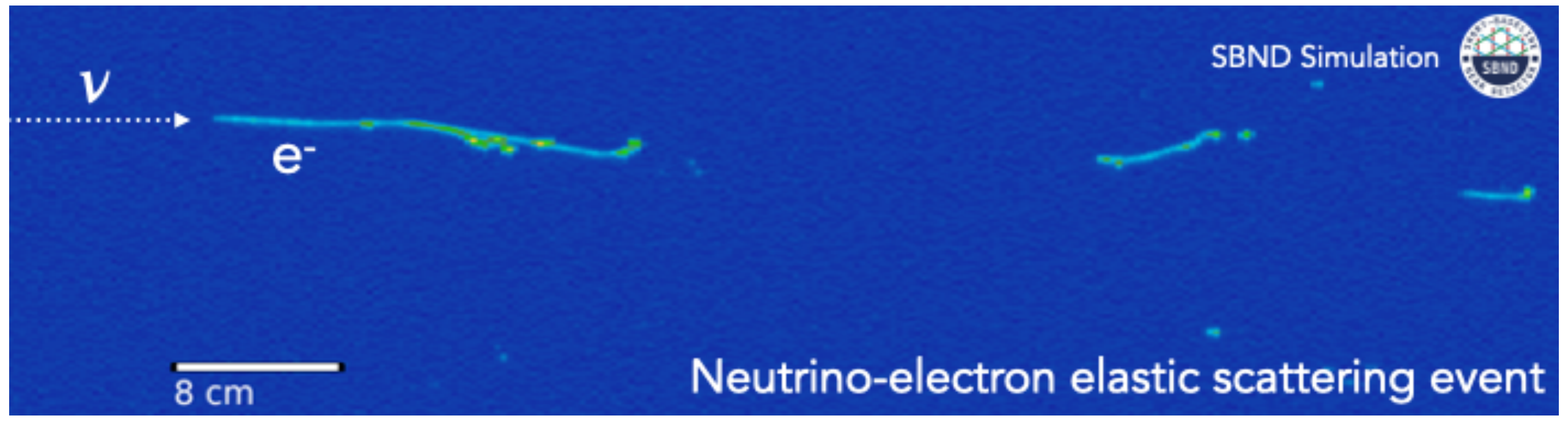

**Another example: search for Light** (sub-GeV) **Dark Matter**




Dark photons, produced by the decay of neutral meson (pions, etas) in the target and decay into dark matter.
The dark matter, through the dark photon, **scatter off electrons in the detector**.




- **Signal**: DM elastic scattering electron events. DM comes from neutral (unfocused) mesons.
- **Background**: neutrino-electron elastic scattering. Neutrinos come from two-body decays of charged (focused) mesons.

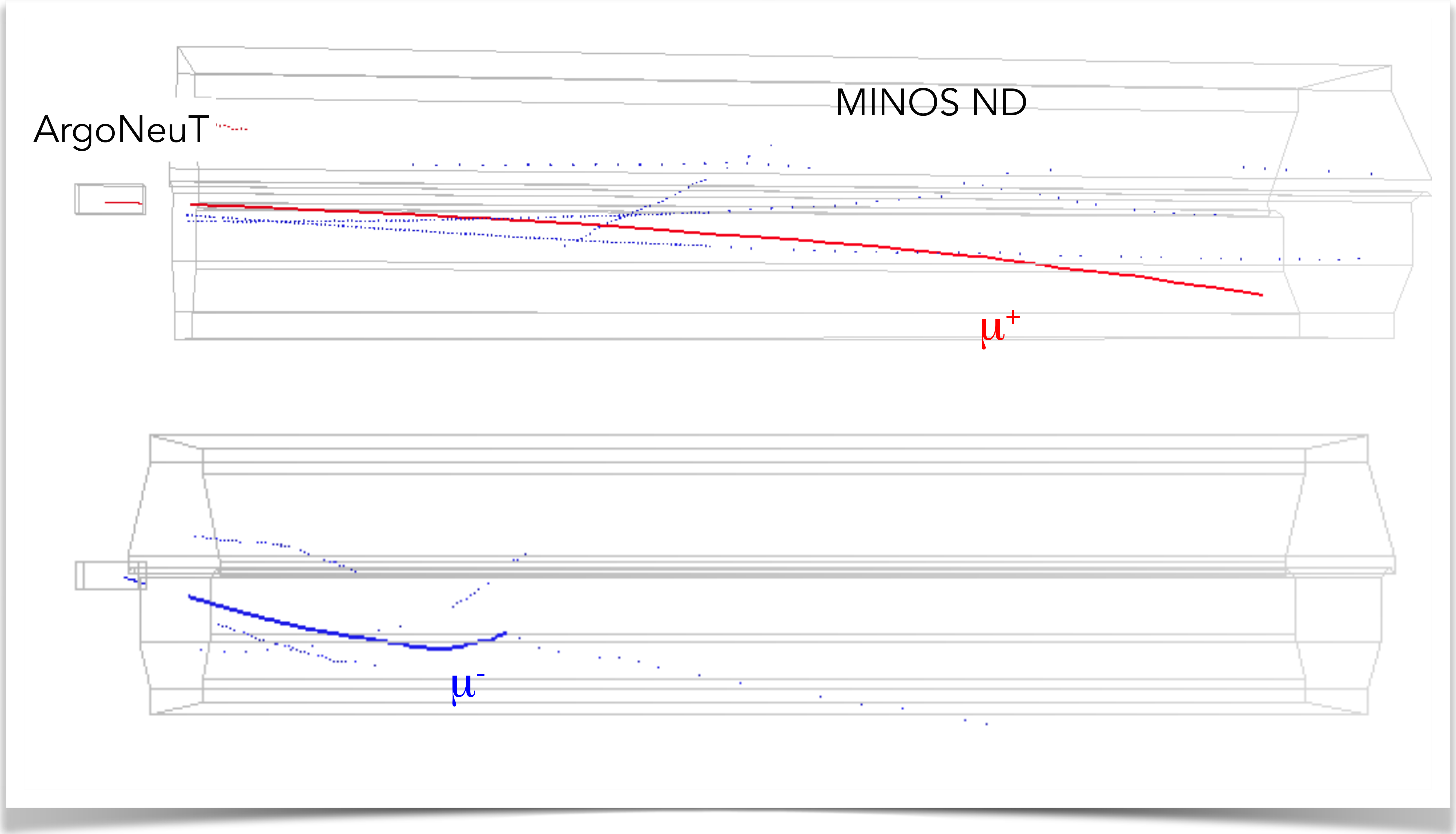



**SBND-PRISM** provides a natural way to **reduce backgrounds by looking off-axis**.

# ADVANTAGES OF ARGONEUT

Despite being a small LAr TPC and taking data for a short time, Argoneut has some advantages:

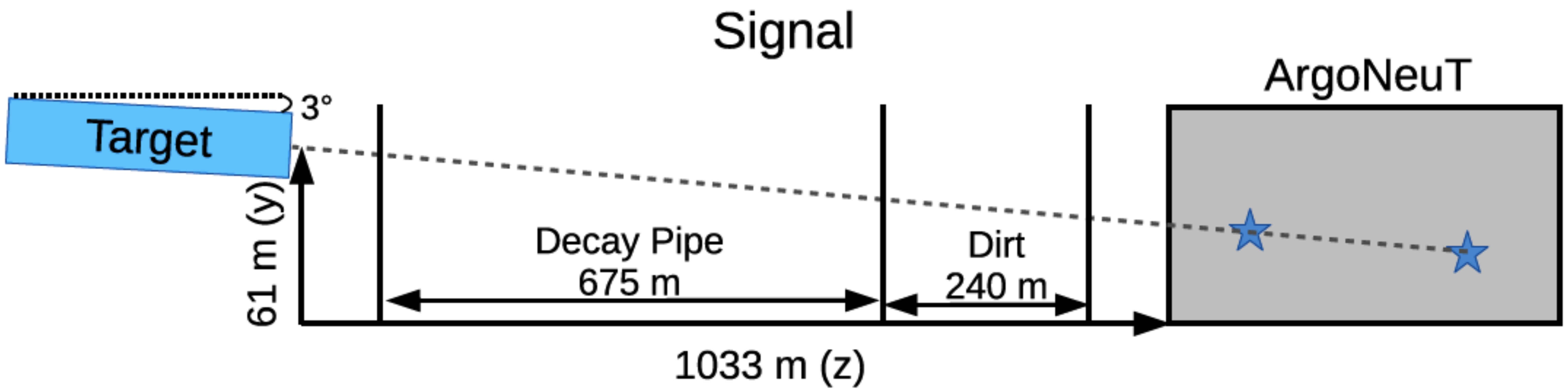
- 100 m underground → no cosmics
- Well understood/calibrated data set
- MINOS ND as spectrometer
  - Magnetic field allows muon momentum measurement and charge recognition
  - Allows to distinguish pion from muon, typically difficult in LAr TPCs



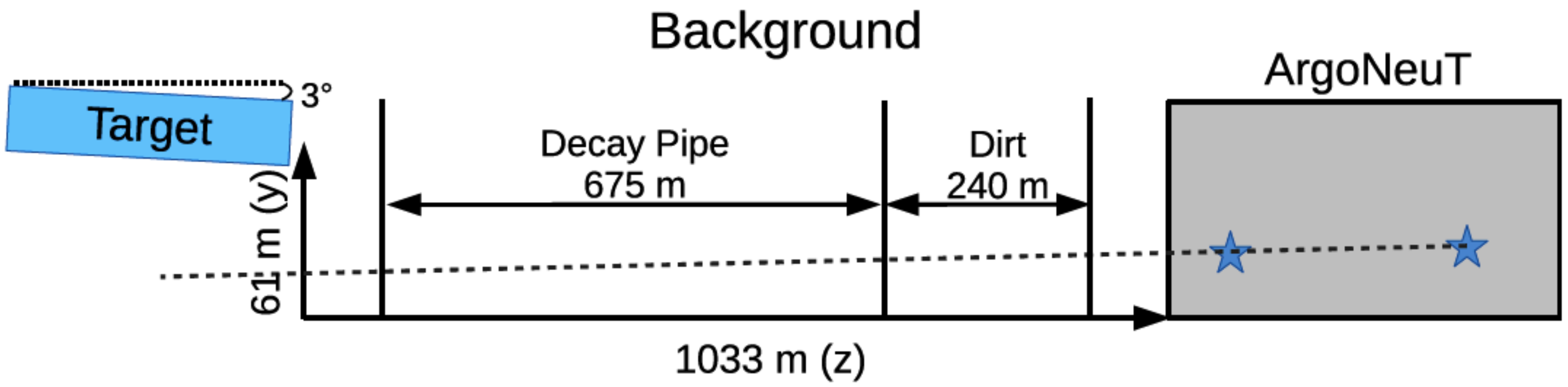

MINOS ND used to identify muons - tracks exiting ArgoNeuT are reconstructed in MINOS ND

# MCP Search - ArgoNeuT Analysis Technique

En route to the detector, mCPs travel through hundreds of meters of dirt, energy loss is negligible and angular deflections are small → **mCPs point back to the target.**




Signal is a double-hit event with a line defined by the two hits pointing to the target




A background double-hit event doesn't point to the target

**To reduce background:**
**search for double hits events aligned with the target**

# Highly Forward-going di-muon Signatures

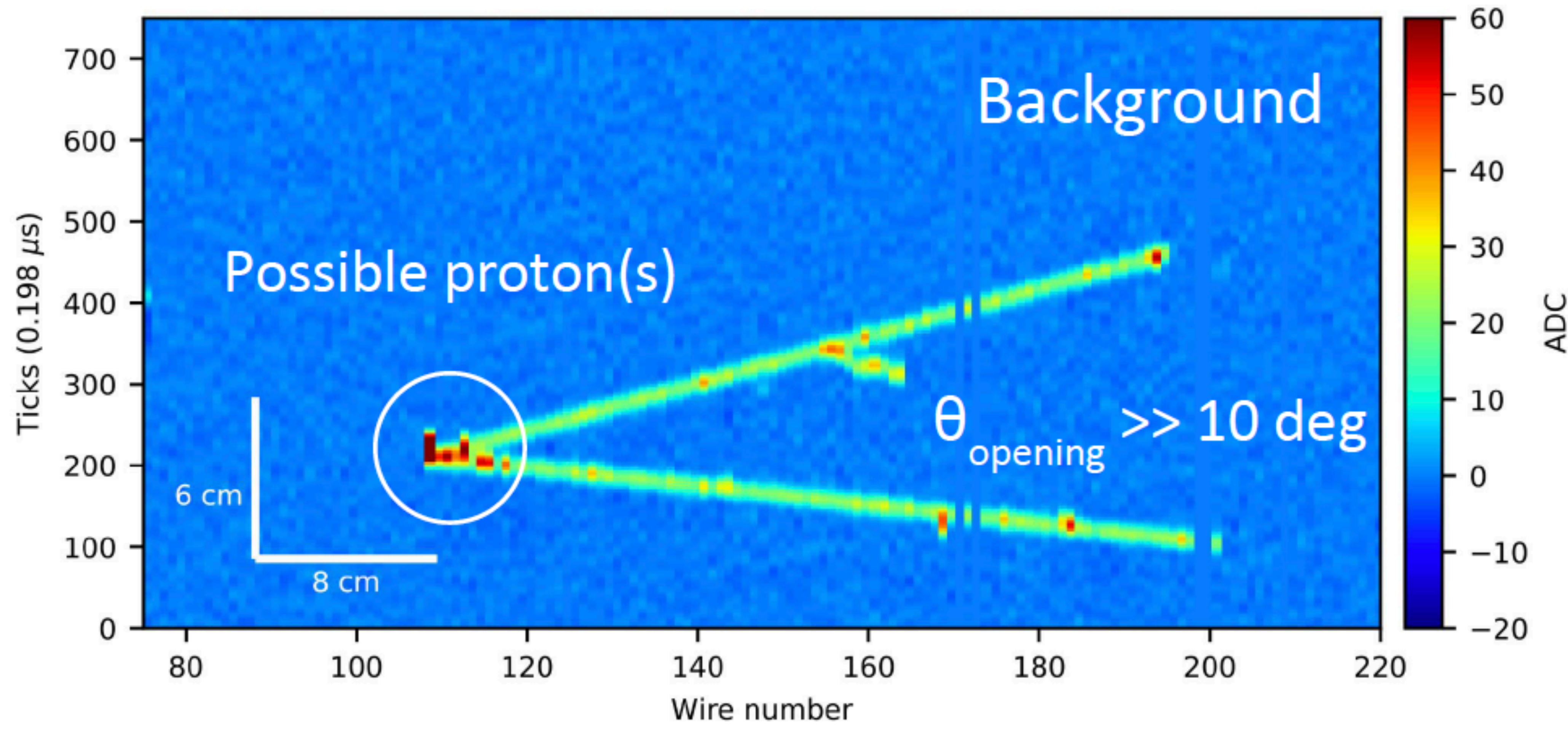
HNL and Heavy QCD axions are very different models… but can produce similar decay signatures in ArgoNeuT

**HNLs** decaying to muon pair N → ν μ+ μ-
Muons highly boosted:
- average energy ~ 7 GeV
- average angle with respect to beam direction ~ 1.5 deg
- average opening angle ~ 3 deg

**Axions** decaying to muon pair a → μ+ μ-
Muons highly boosted:
- average energy ~ 20 GeV
- average angle with respect to beam direction ~ 1.5 deg
- average opening angle ~ 2.5 deg

ArgoNeuT + MINOS ND, ideal to search for $\mu^+\mu^-$ **signatures**

- ArgoNeuT LArTPC: vertex identification and reconstruction of low energy particles - allows identification of background
- MINOS ND: muon charge reconstruction and pion rejection




Identify the presence of hadronic activity at the vertex

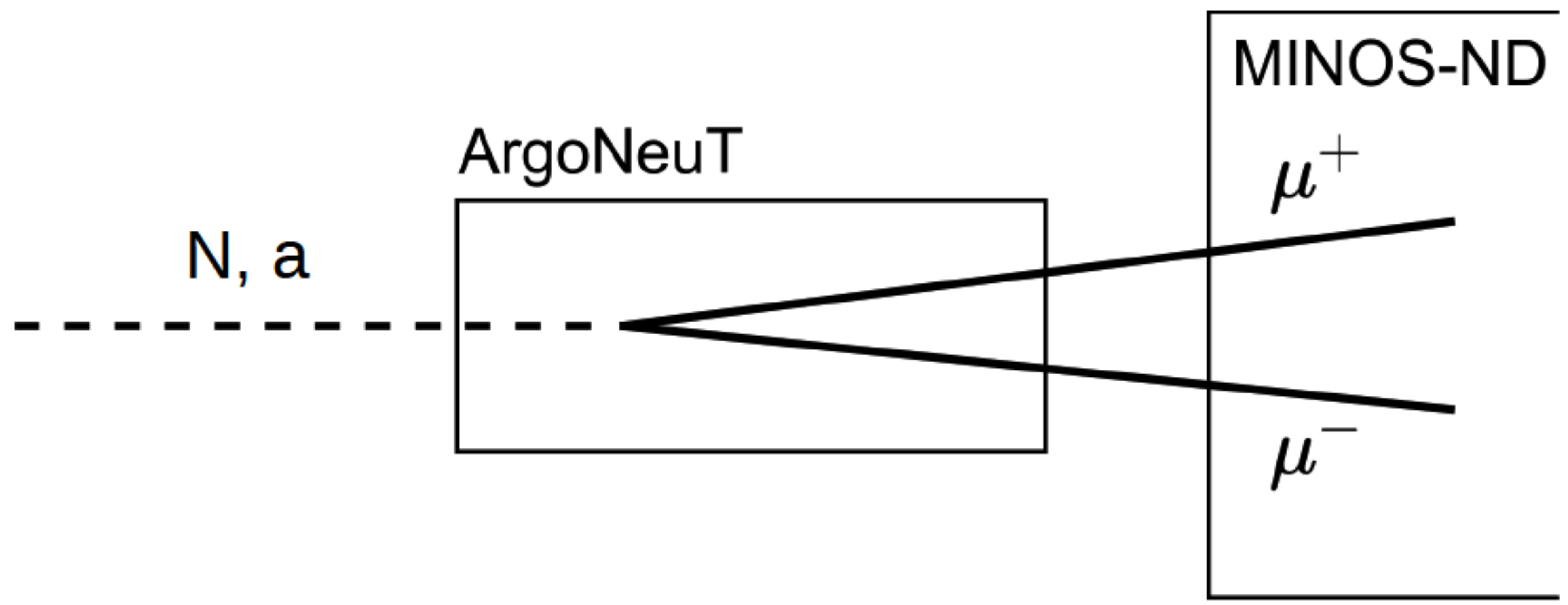
# DI-MUON SIGNATURES IN ARGONEUT

Two different signatures, depending on how forward going the muons are:

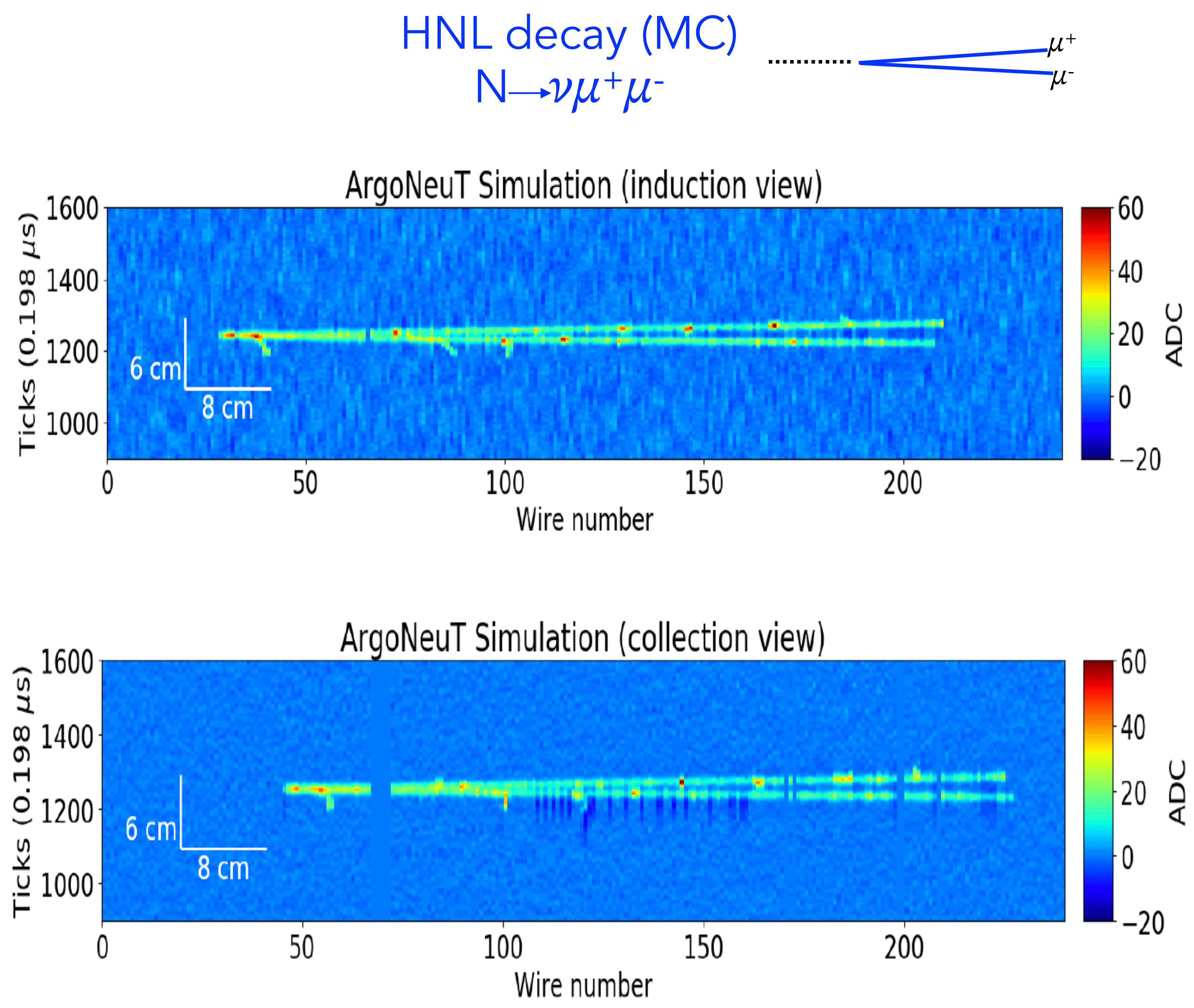
Signature 1: **two MIP tracks** in ArgoNeuT, match to **two tracks** in MINOS-ND

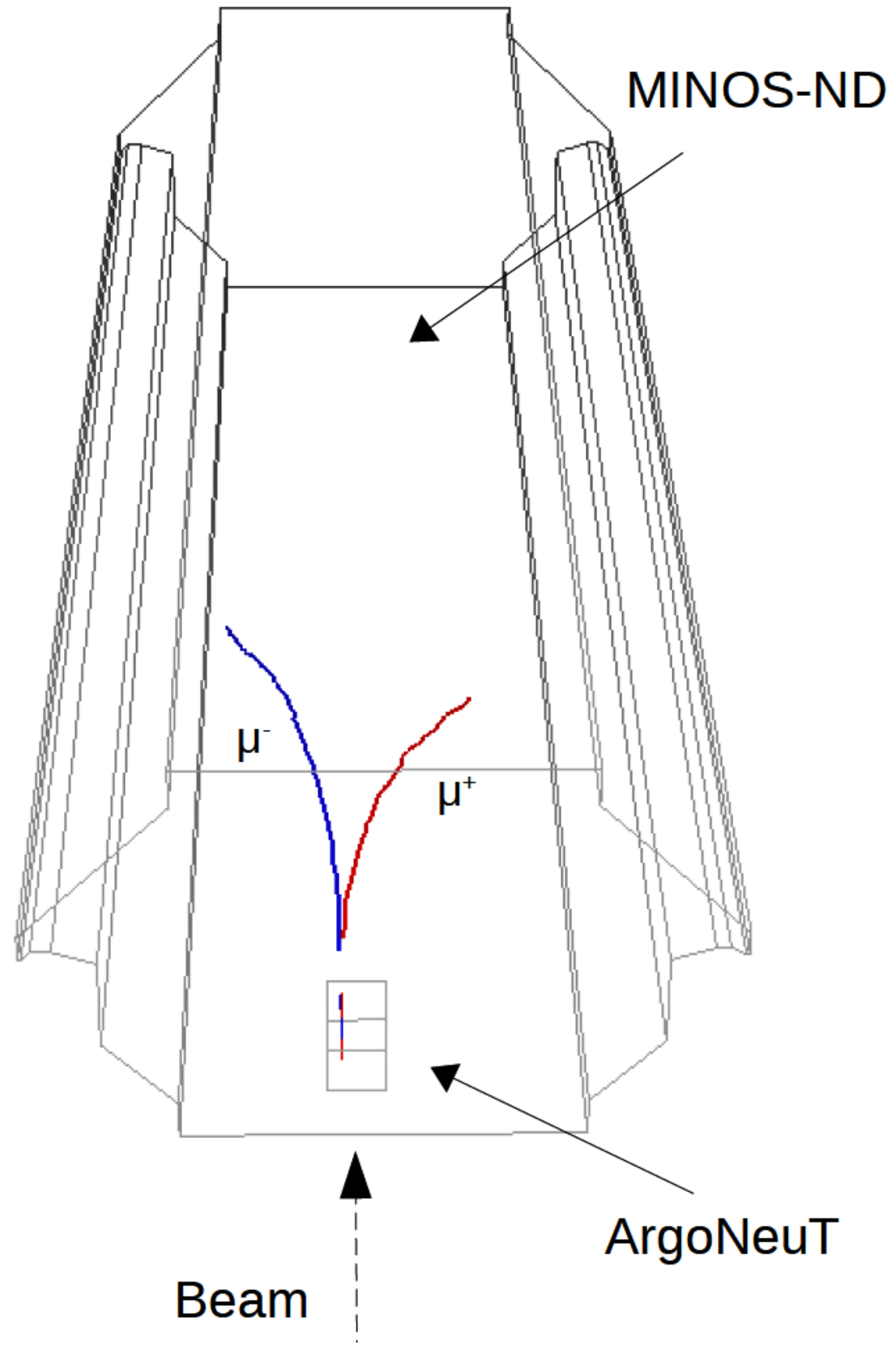
Signature 2: single **double-MIP dE/dx** track in ArgoNeuT, matches to **two tracks** in MINOS-ND

*Two-track* Event




Signature 1



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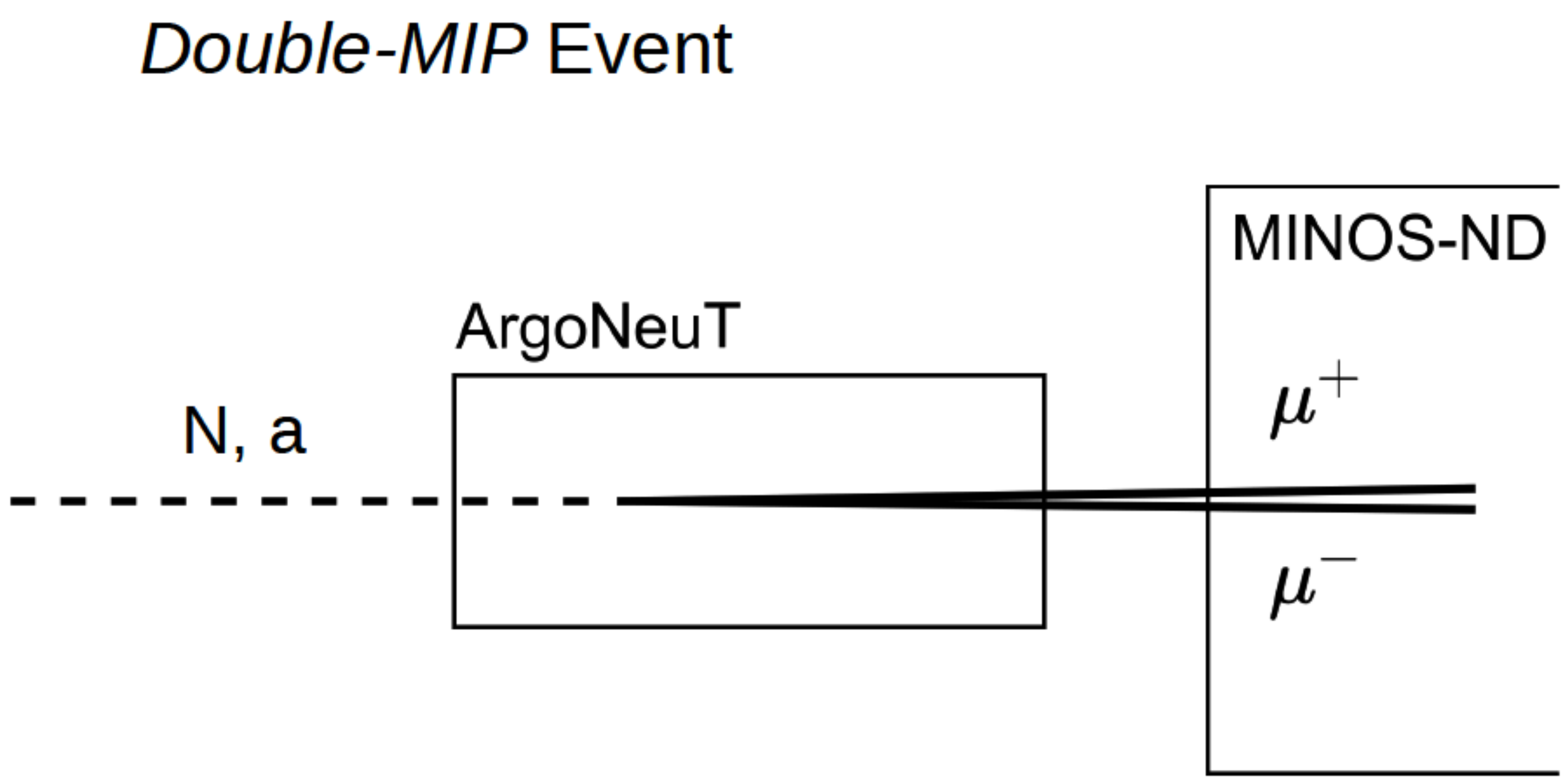
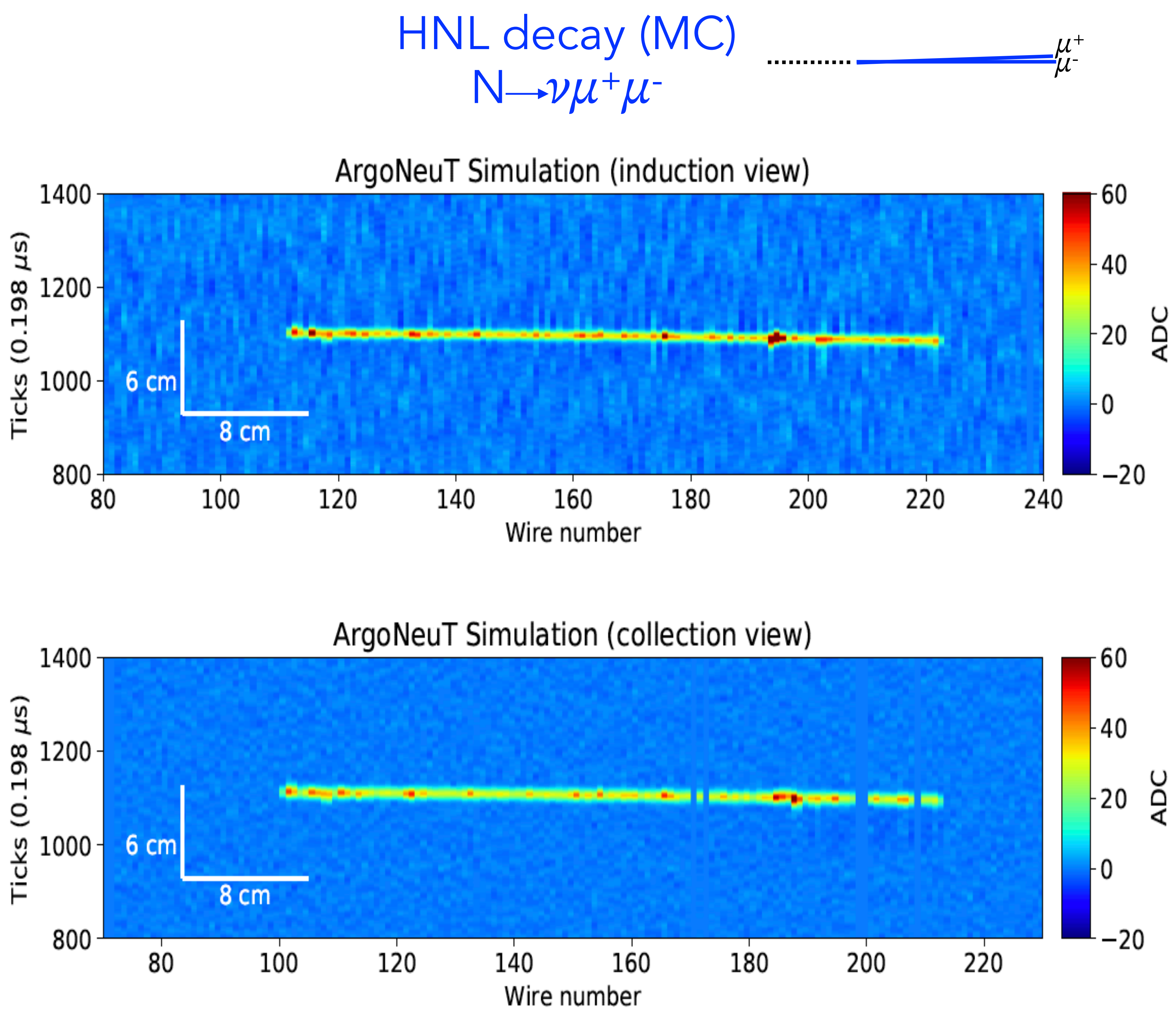
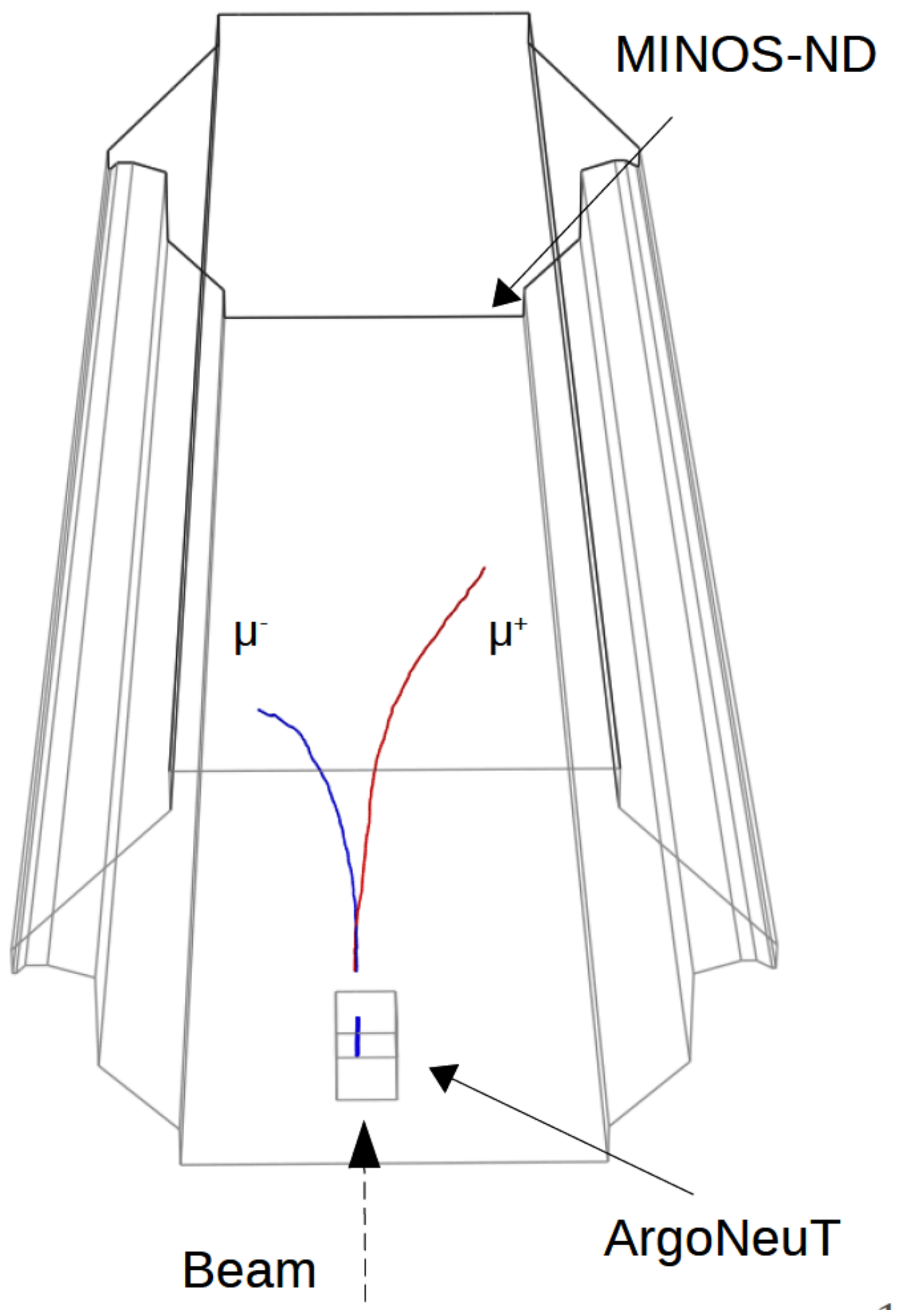



Signature 2




In most forward-going cases, muon pair may be reconstructed as overlapping in ArgoNeuT.

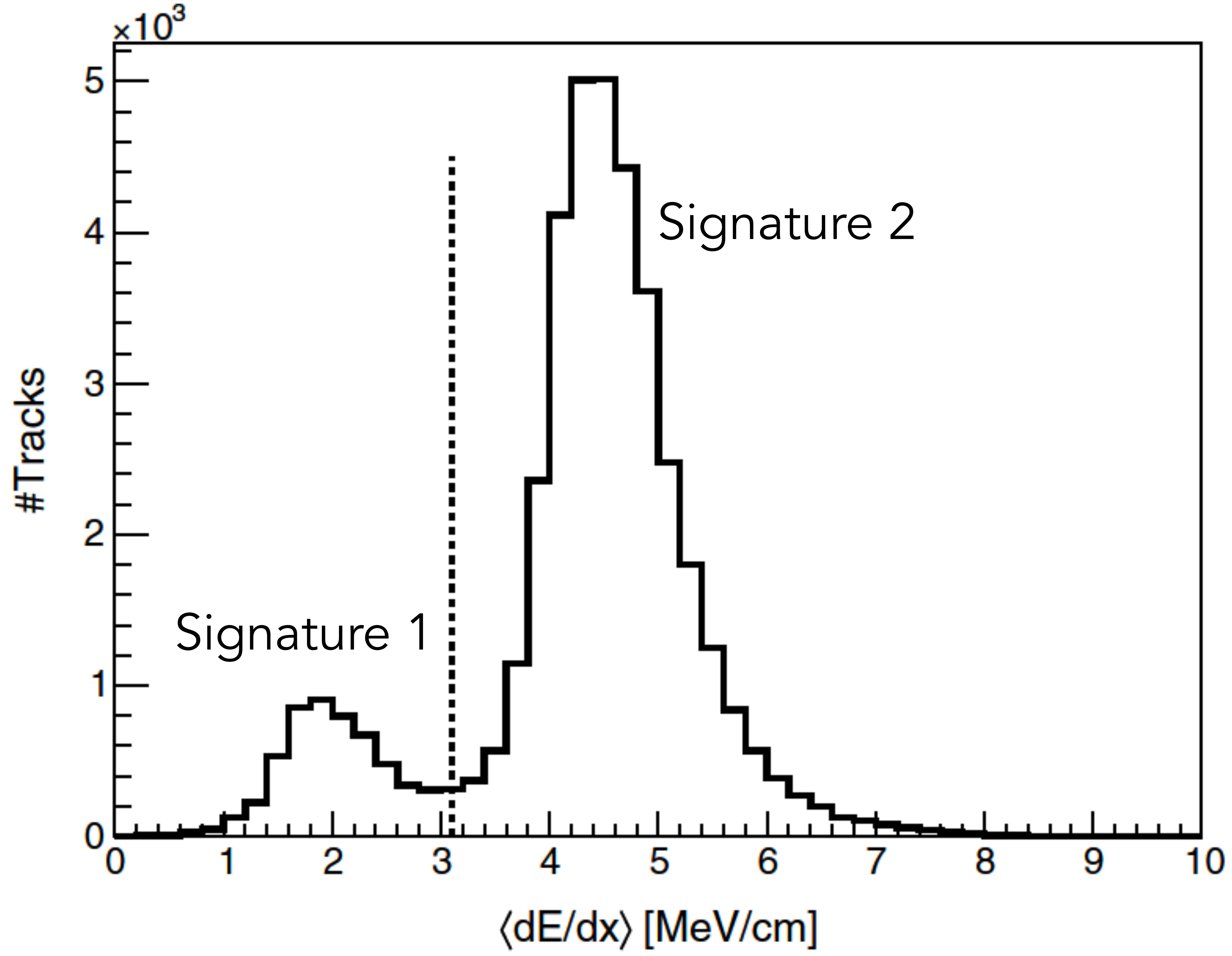
# DI-MUON SIGNATURES IN ARGONEUT

Two different signatures, depending on how forward going the muons are:

Signature 1: **two MIP tracks** in ArgoNeuT, match to **two tracks** in MINOS-ND

Signature 2: single **double-MIP dE/dx** track in ArgoNeuT, matches to **two tracks** in MINOS-ND

Developed new techniques to identify highly-forward-going muon pairs, applicable to future searches in LArTPC detectors, e.g. the DUNE near detector.

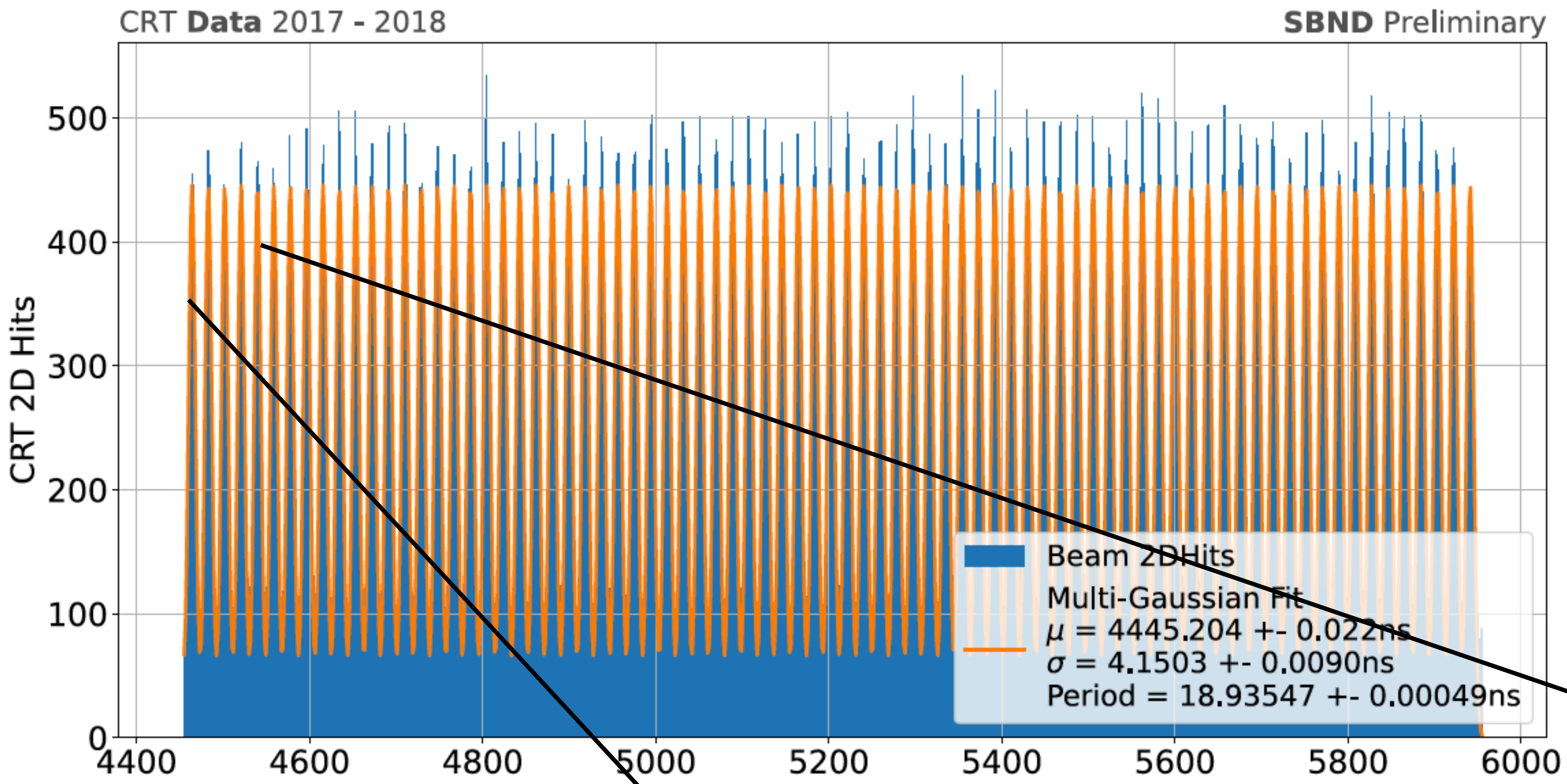



Identifying overlapping muon pairs:

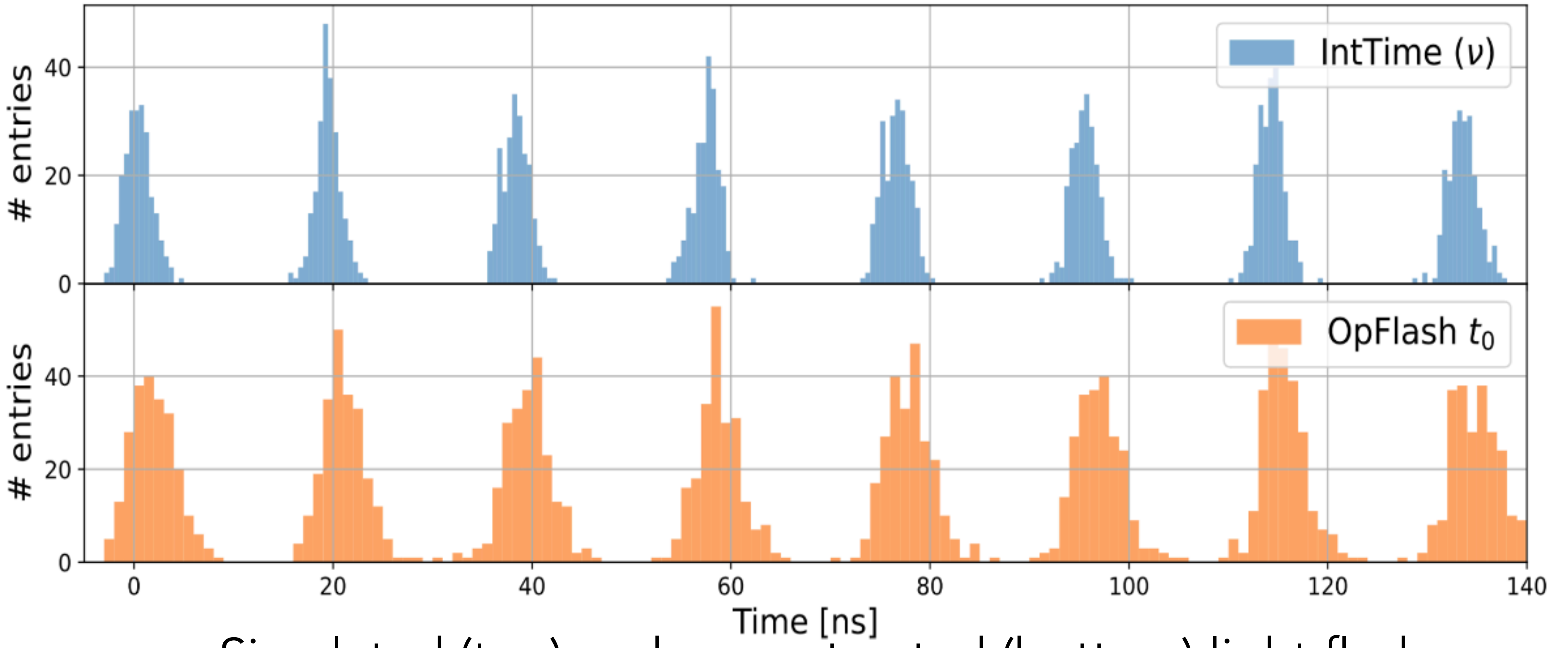
Average reconstructed dE/dx over the first 5 cm of tracks resulting from simulated HNL decays.

# BNB Time Structure

## CRT Beam Telescope Run 2017-2018




Plot credit: Marco Del Tutto




Simulated (top) and reconstructed (bottom) light flashes showing the neutrino beam structure.

Muons from neutrino interactions in the dirt up of the pit are detected by the telescope.
The beam spill substructure can be seen

- 81 bunches with 19 ns spacing
- spill duration of 1.6 μs