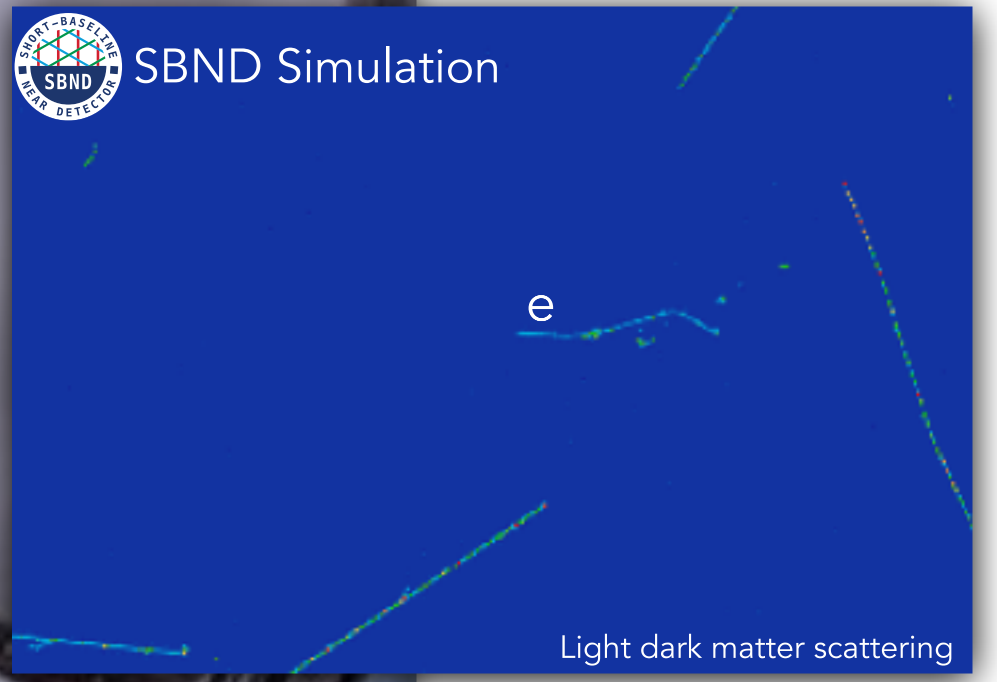
Signatures for New Physics in the Short-Baseline Near Detector Experiment

International Conference on Neutrinos and Dark Matter
Sharm El-Sheik
September 25th 2022

Ornella Palamara
Fermilab & Yale University



Sterile neutrino search beyond MicroBooNE

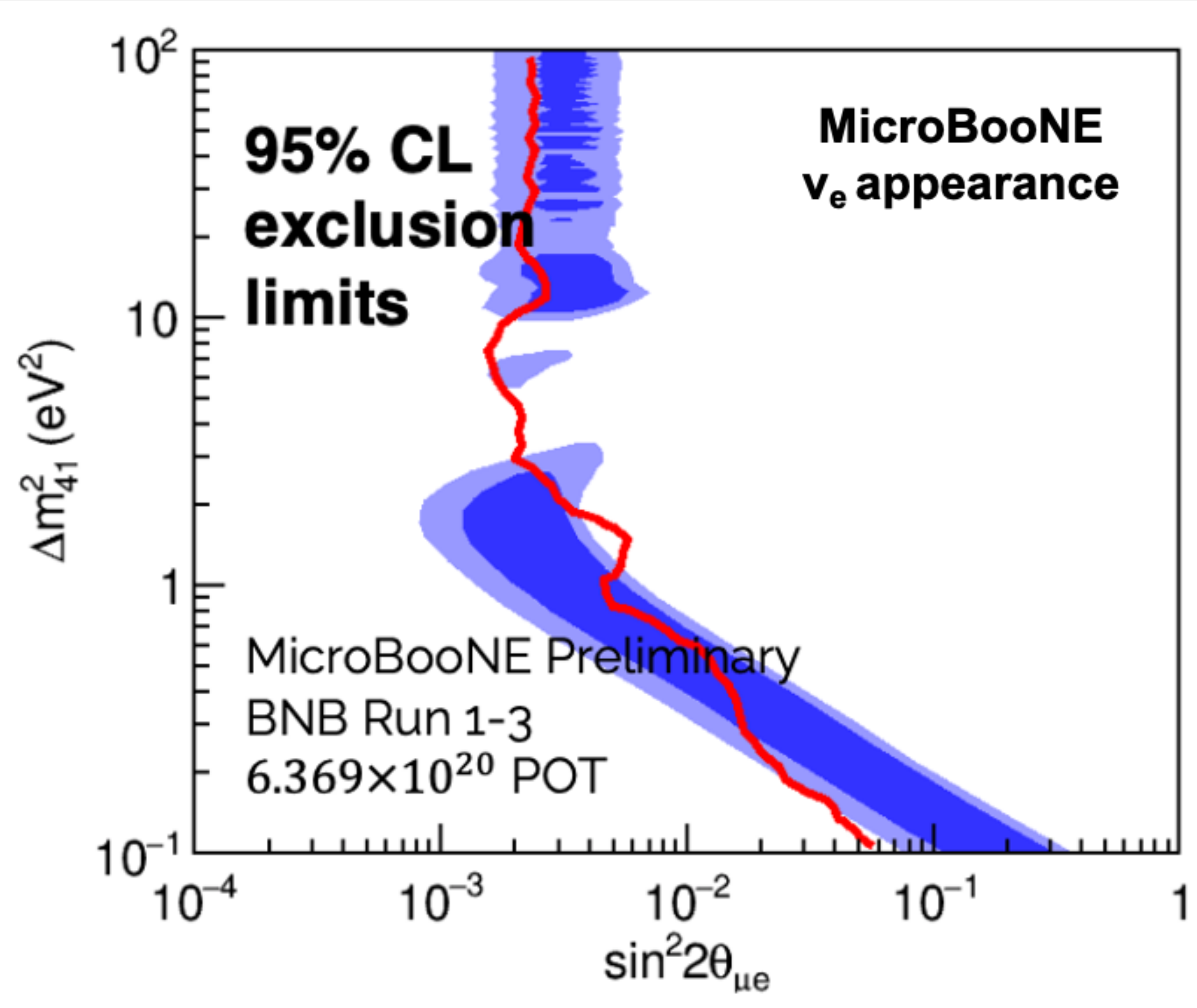
Various hints of anomalous electron-flavour appearance and disappearance may be indicative of new neutrinos participating in oscillations (eV-scale sterile neutrinos).

The parameter space of new oscillations continues to be explored with accelerator-based and reactor-based Short-Baseline (SBL) experiments.

—> see previous presentation by A. Minotti for a review of sterile neutrino searches at SBL.

The MicroBooNE experiment recently presented the 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.**

—> see next presentation by M. Bishai for latest oscillation results from MicroBooNE



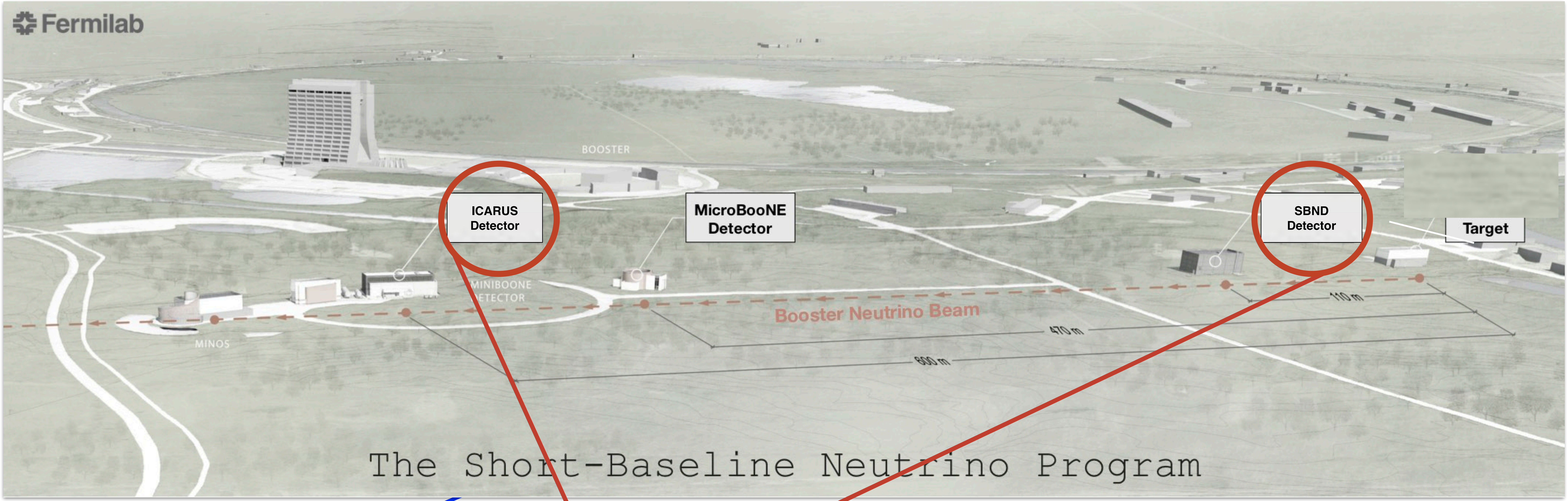
Entering the **next phase** of accelerator-based short baseline oscillation searches requires:

increased exposure through a larger **far detector** and

a **near detector** for systematics constraints.

Short-Baseline Neutrino Program

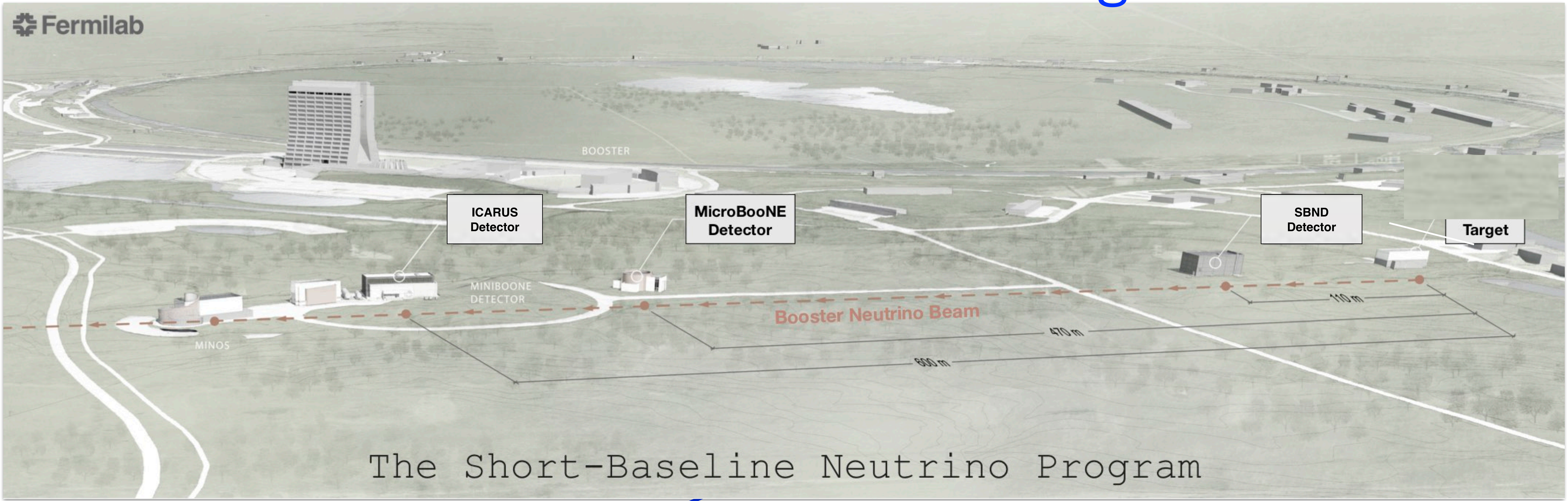
Two other detectors to form the **Short-Baseline Neutrino (SBN)** program:
multiple LAr TPC detectors on the Booster Neutrino Beam at Fermilab



Far Detector: **ICARUS**

Near Detector: **SBND**

Short-Baseline Neutrino Program



arXiv:1503.01520, January 2014
P.Machado, O.P., D. Schmitz, Annu. Rev. Nucl. Part. Sci. 69 363-387 (2019)

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

But large detector masses and proximity to intense beams enables
a **broad physics program**.

Short-Baseline Neutrino Program

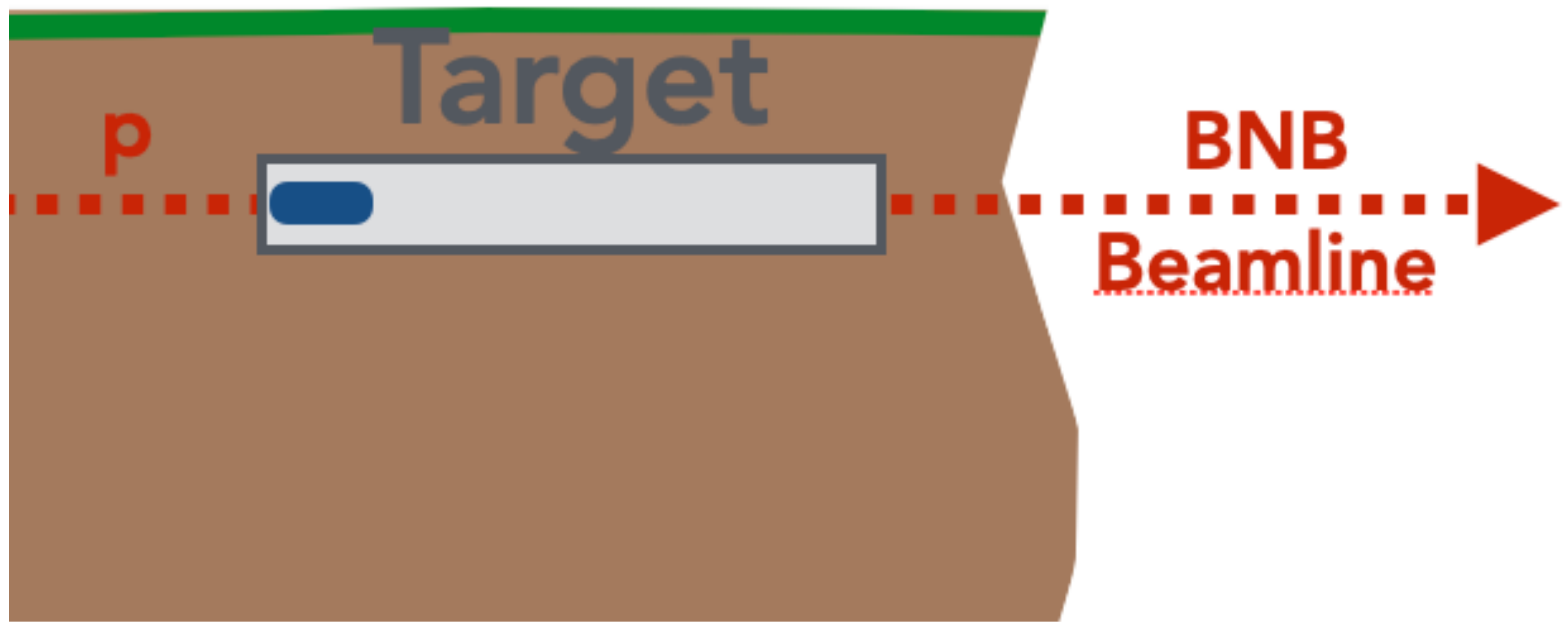
Under construction
Expected begin operation: 2023

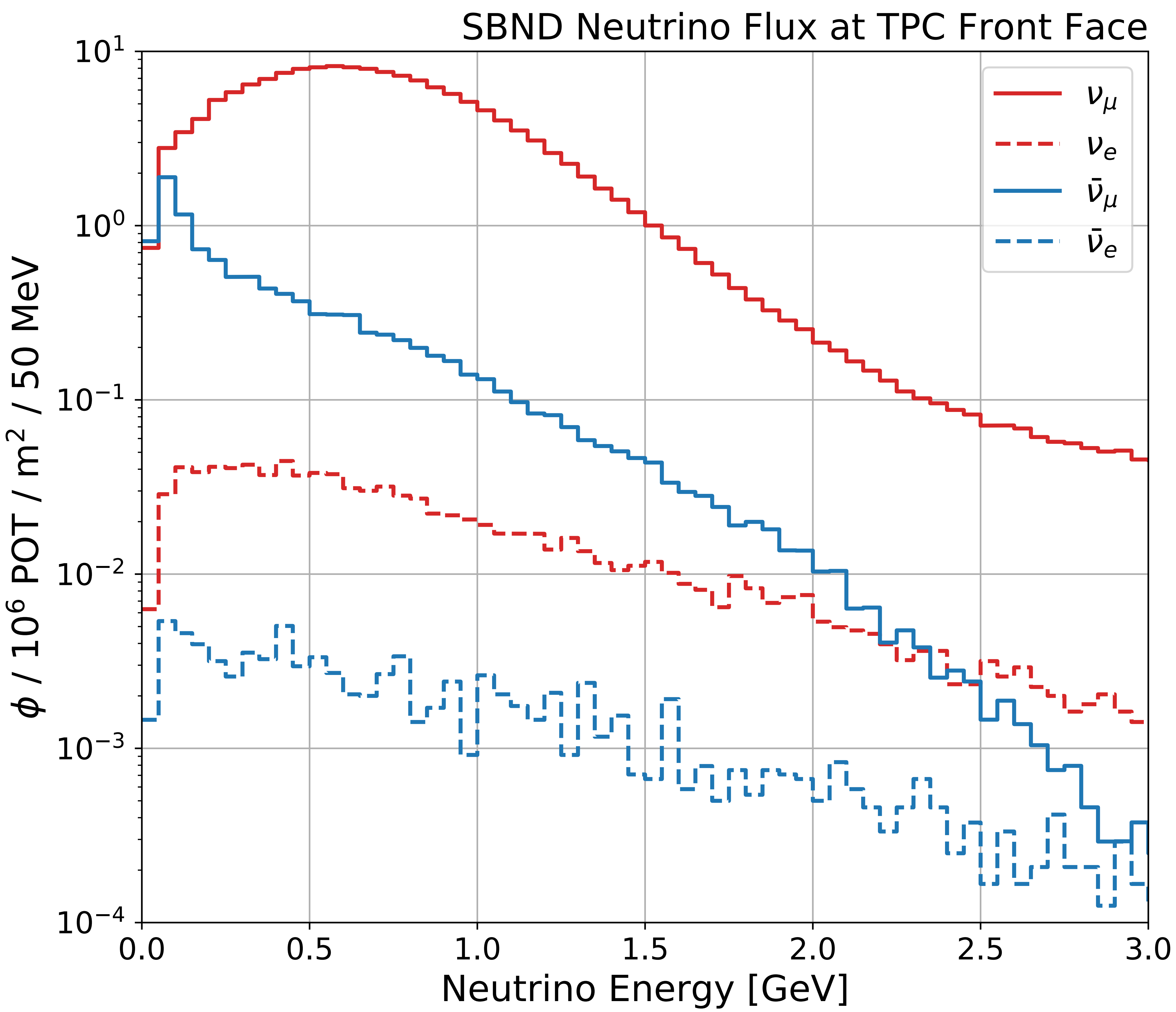
2015-2021

Collecting data since Oct. 2021

Booster Neutrino Beam Neutrino Flux

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:

ν_μ (93.6%)

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

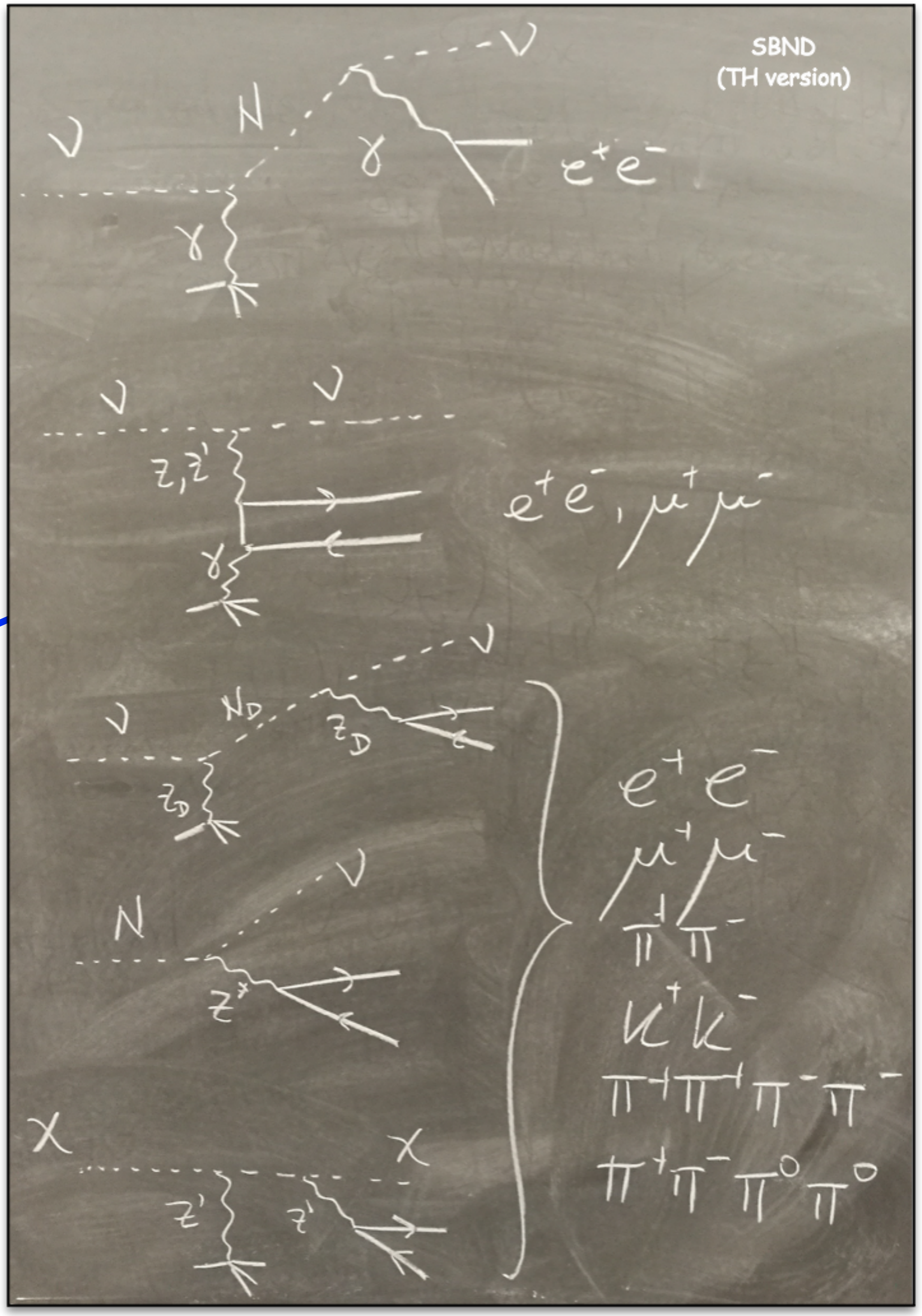
ν_e+$\bar{\nu}_e$ (0.5%)

SBND Physics Program

eV-scale sterile neutrinos: searches with **multiple-detectors at different baselines.**

New physics scenarios: BSM physics program is an evolving landscape, with **many new search ideas** emerging from collaboration with theory colleagues.

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



Courtesy of P. Machado

New Physics Scenarios in SBND

The combination of

- a **high-intensity proton beam** coupled with
- a **large mass LAr TPC detector** close to the beam target, with
- event imaging, fine granularity calorimetry and particle identification, good timing resolution and low energy threshold

opens up unprecedented opportunities to probe signatures for

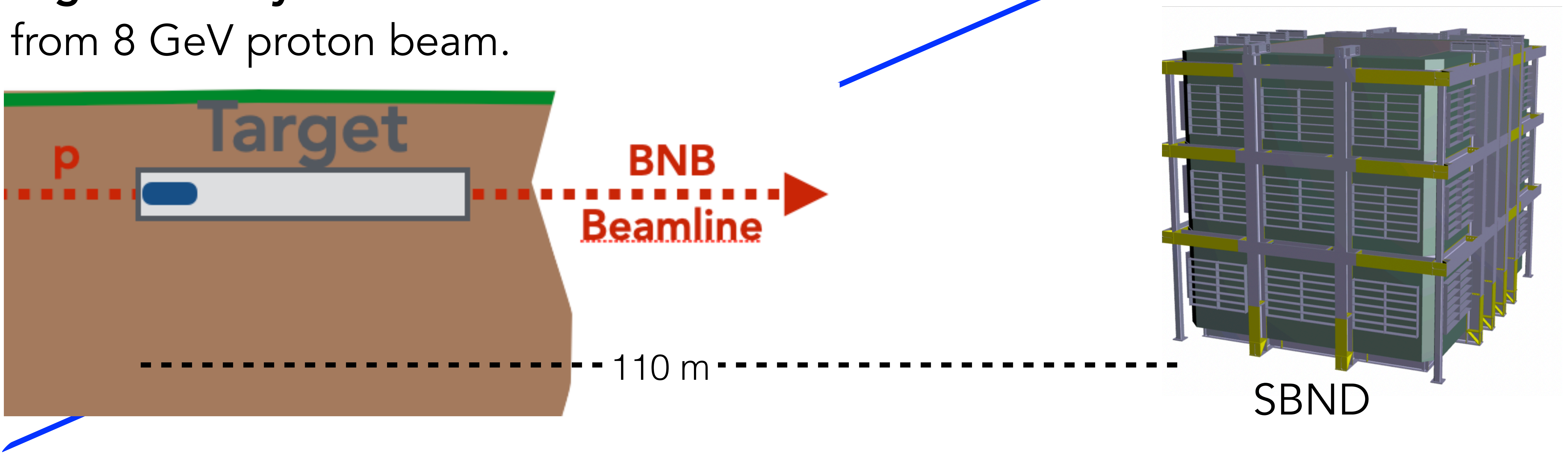
new physics scenarios in the neutrino sector and beyond

Modifications to the neutrino oscillation paradigm

(effects of BSM physics on neutrino oscillation)

High-intensity neutrino beam

from 8 GeV proton beam.



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Novel experimental signatures
produced in the beam target

High-intensity neutrino beam
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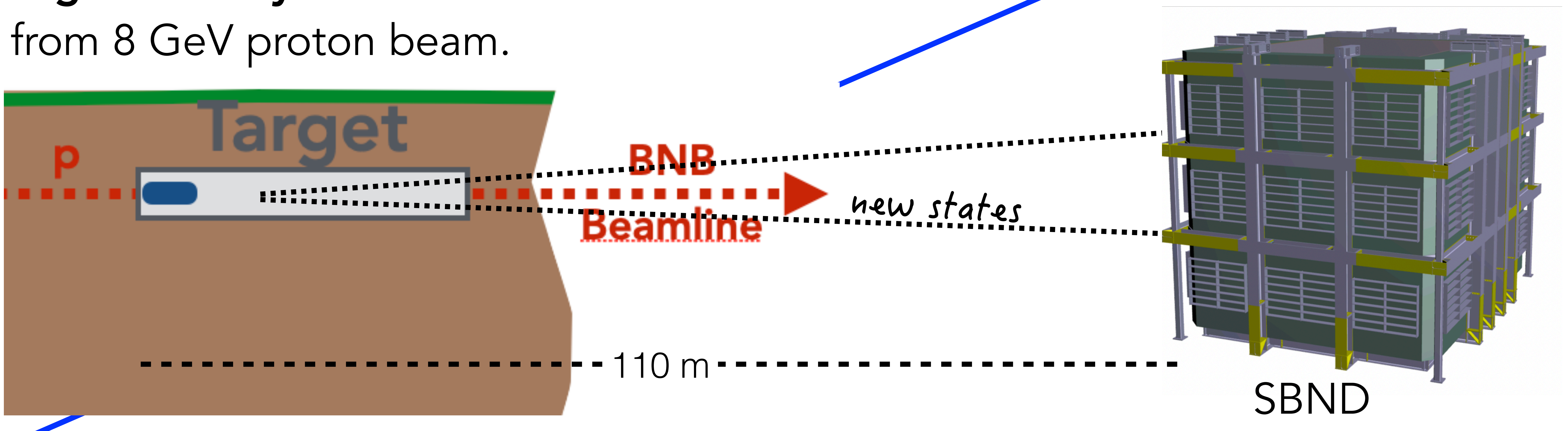

New Physics Scenarios in SBND

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Novel experimental signatures
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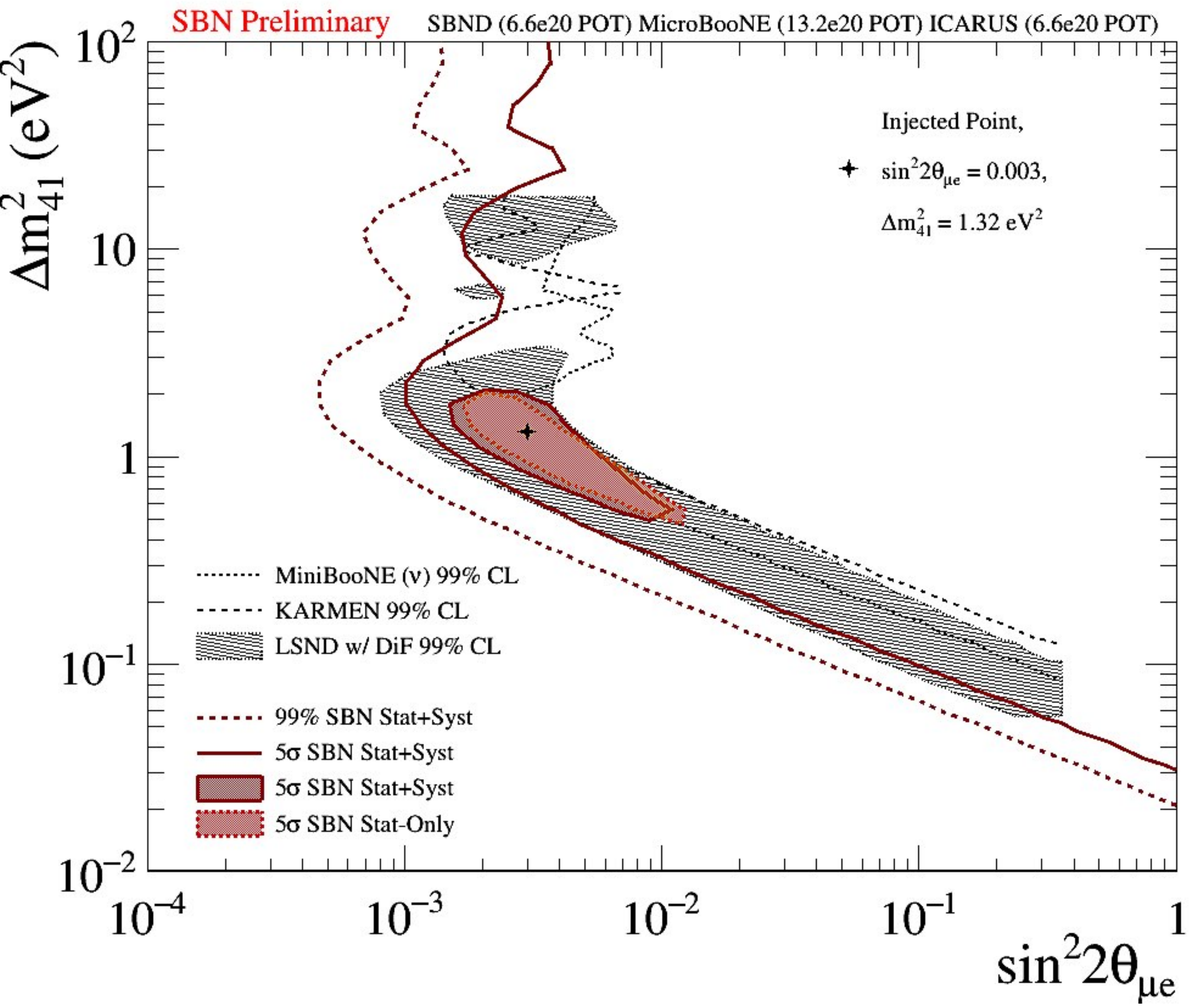
NOTE: Ability of SBL LAr TPC experiments to perform BSM searches have been demonstrated by recent measurements from MicroBooNE and ArgoNeuT (small LAr TPC - 0.24 t - exposed to the NuMI beam at Fermilab put leading constraints on millicharged particles, heavy neutral leptons and axions in unexplored parameter space regions*).

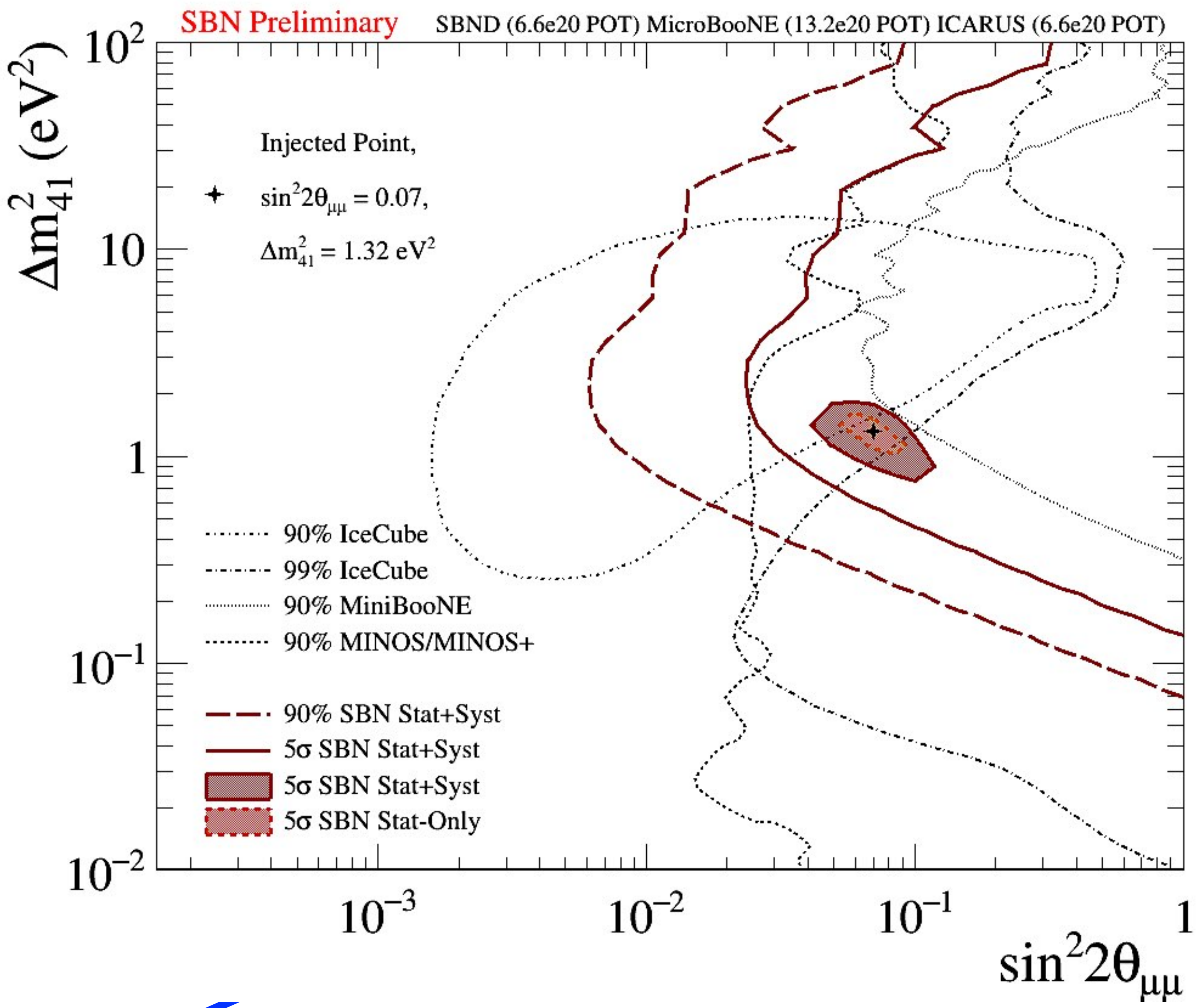
*PRL124 131801 (2020), PRL 127 121801 (2021), https://arxiv.org/abs/2207.08448

SBN Sterile Neutrino Sensitivities

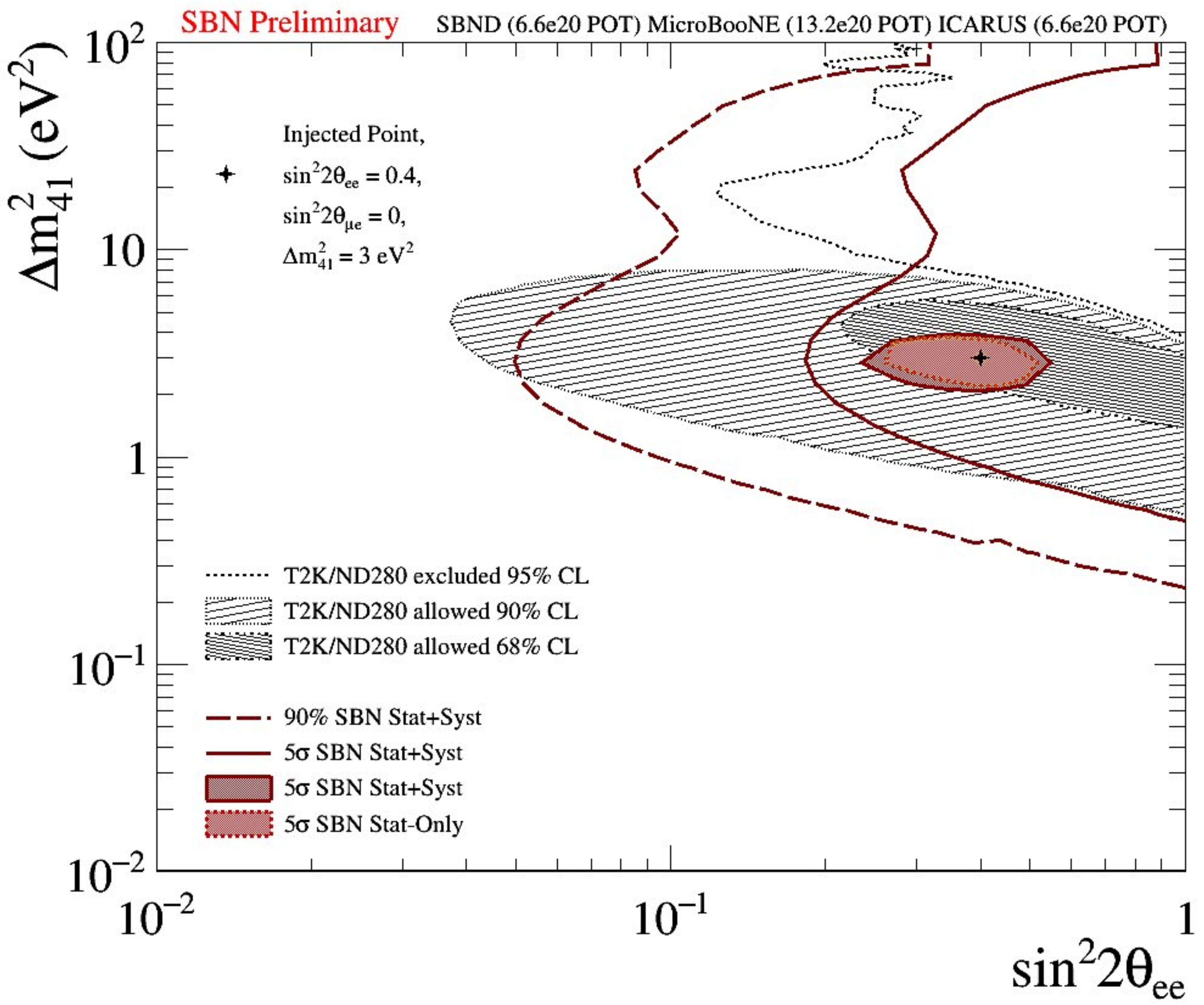
ν_e Appearance



ν_μ Disappearance



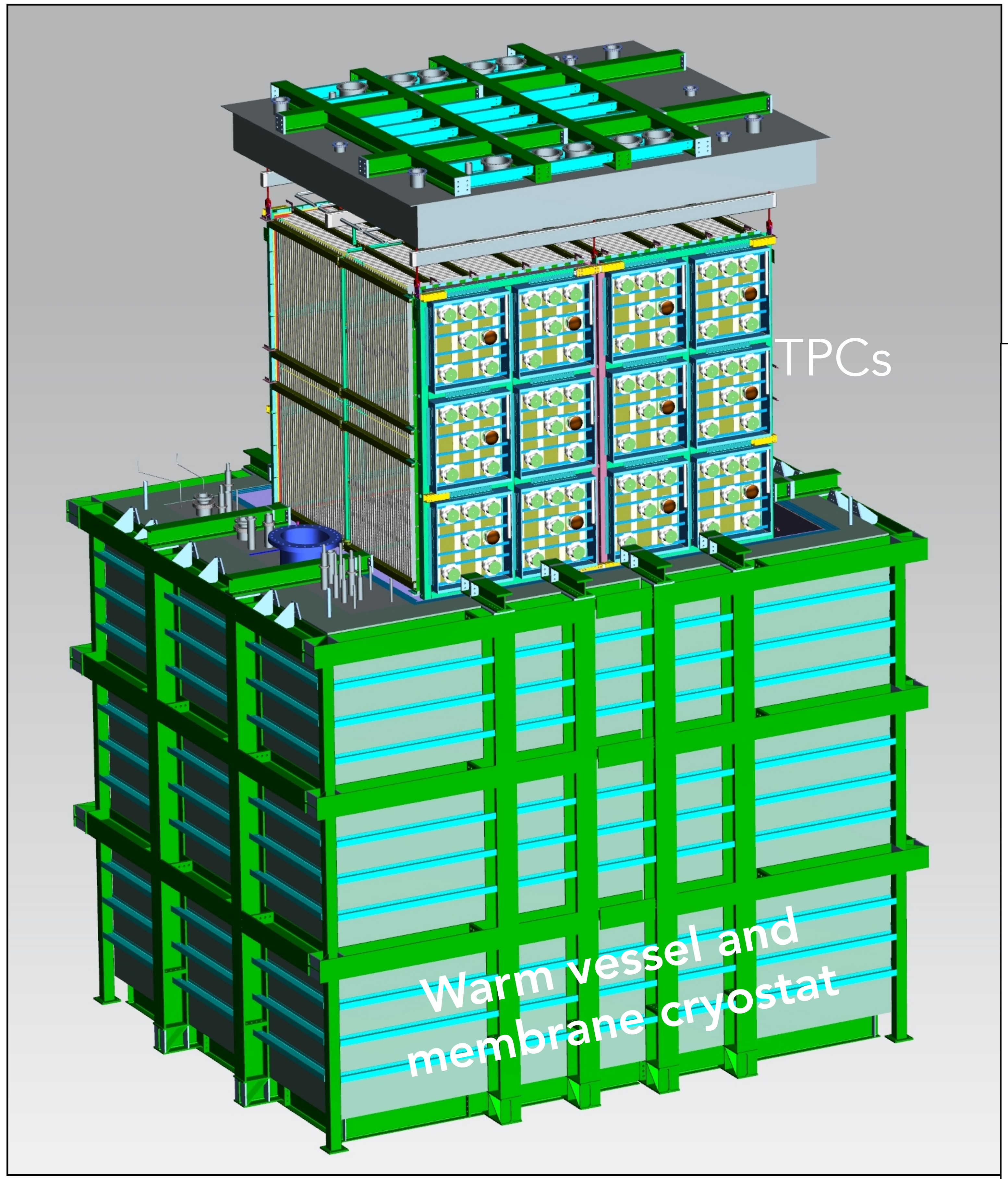
ν_e Disappearance

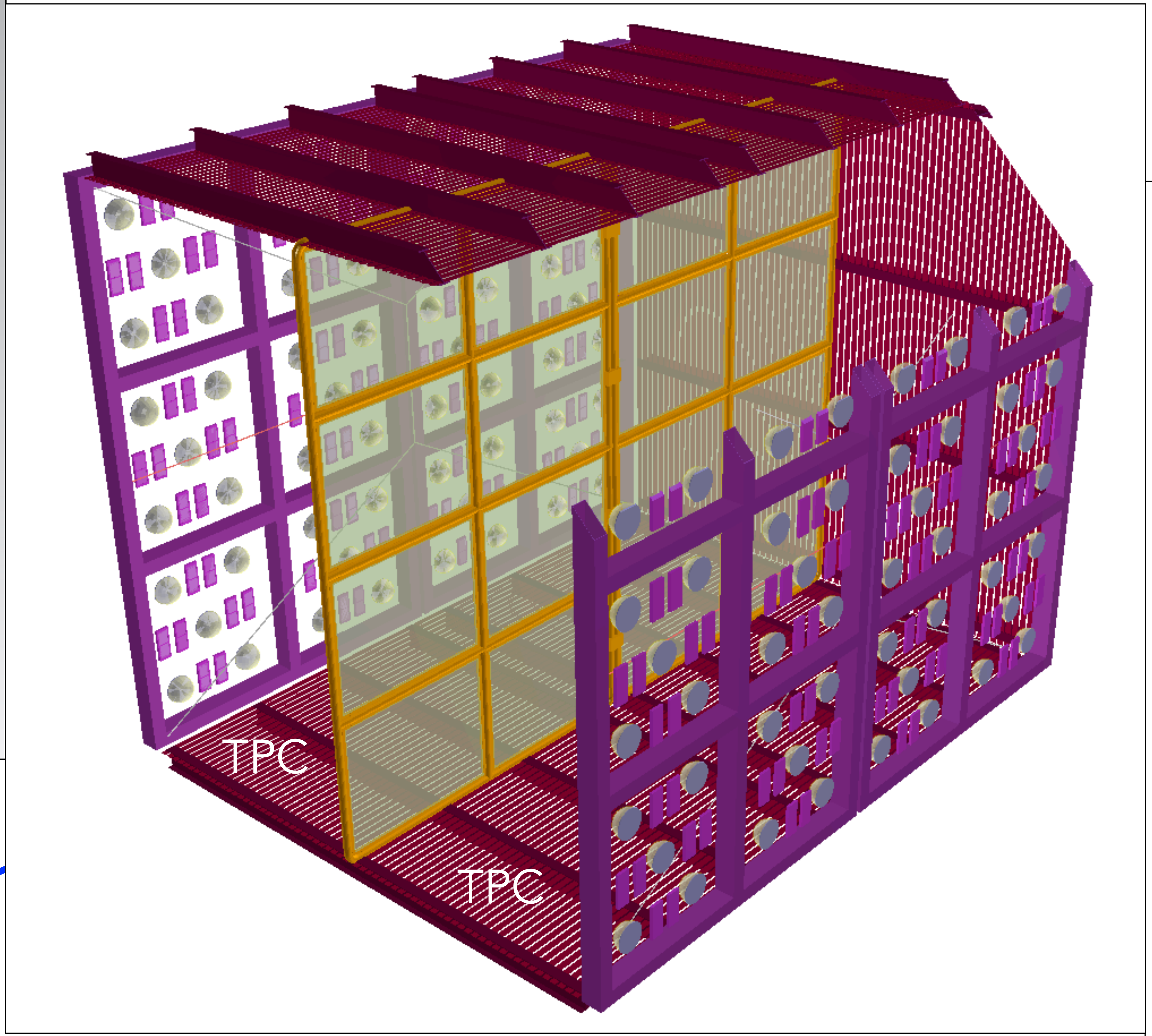


SBN program will test the sterile neutrino hypothesis by covering the parameter regions allowed by past anomalies at 5σ significance.

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

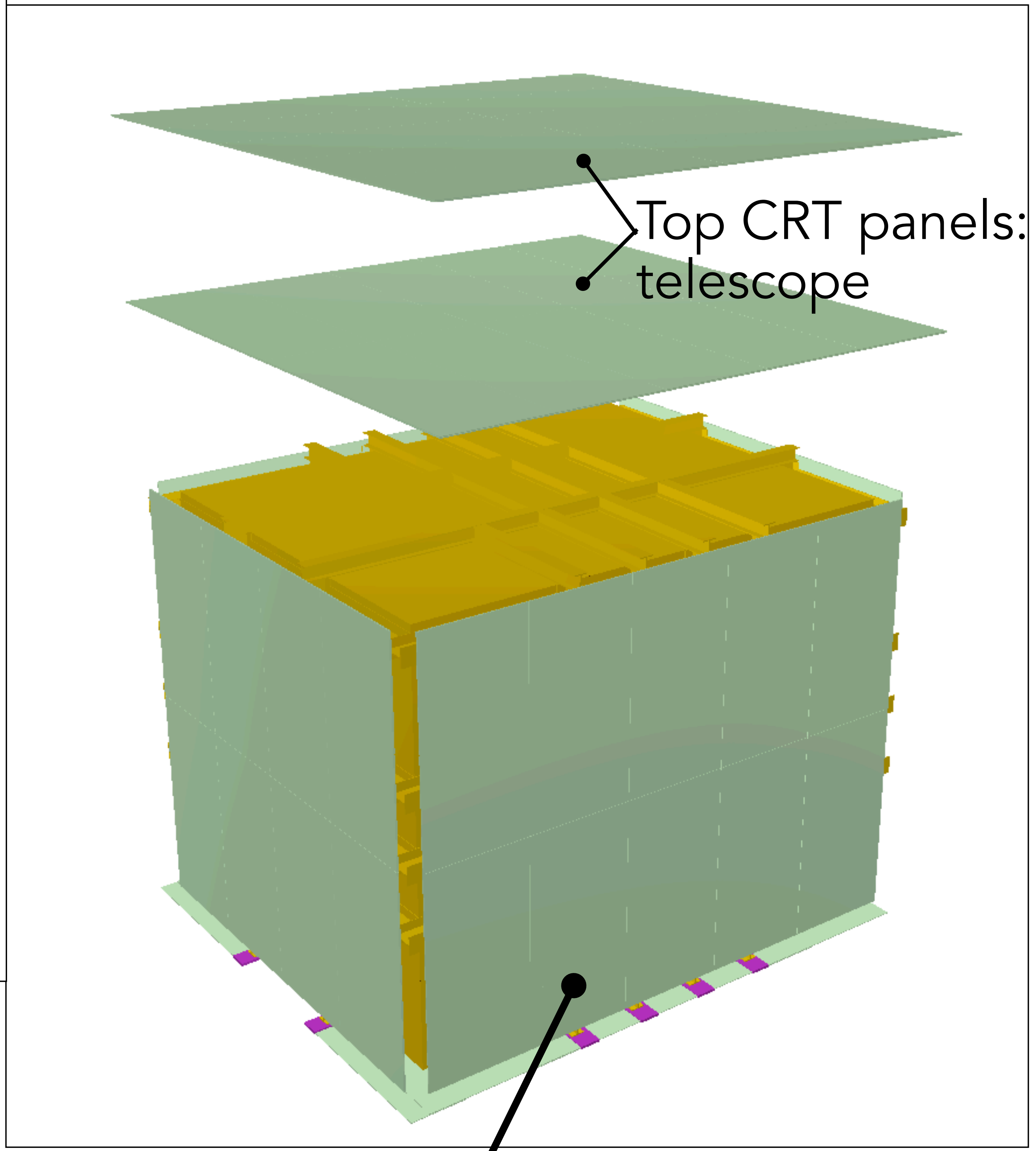
SBND Detector





Two Time Projection Chambers

Cryostat surrounded by a Cosmic Ray Tagger system

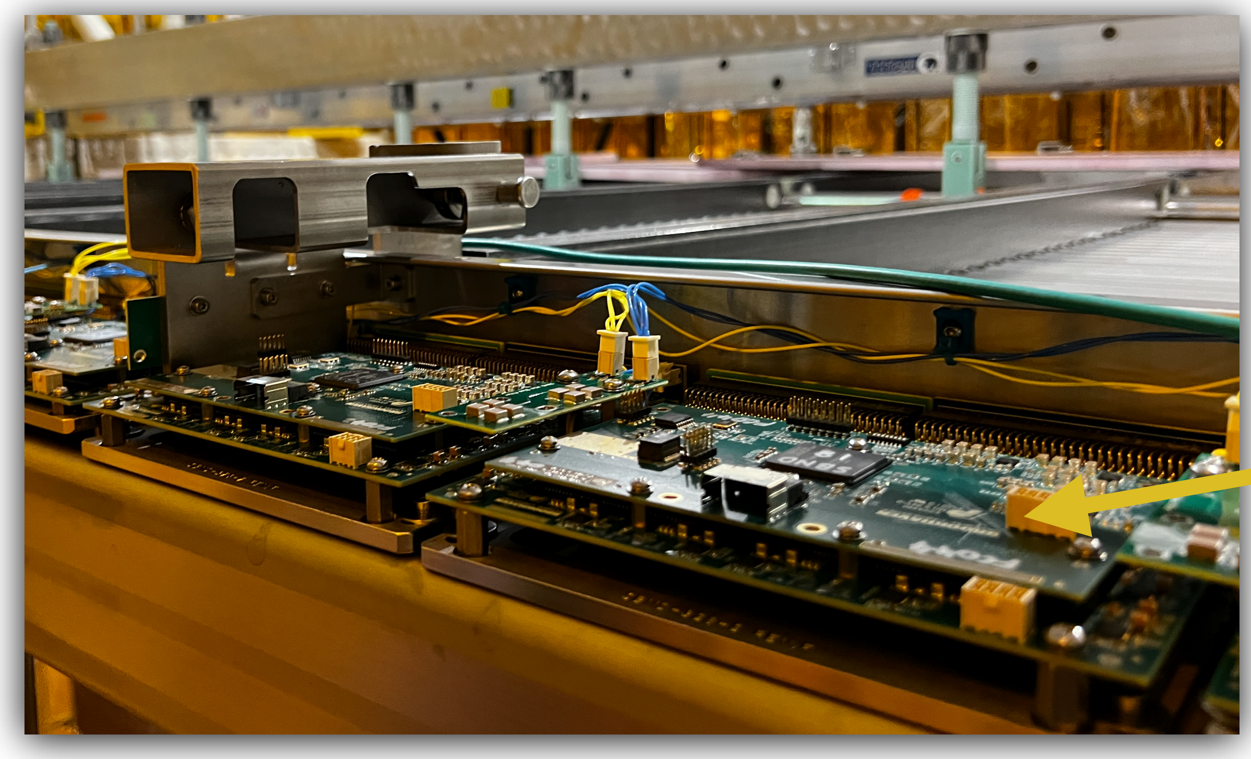


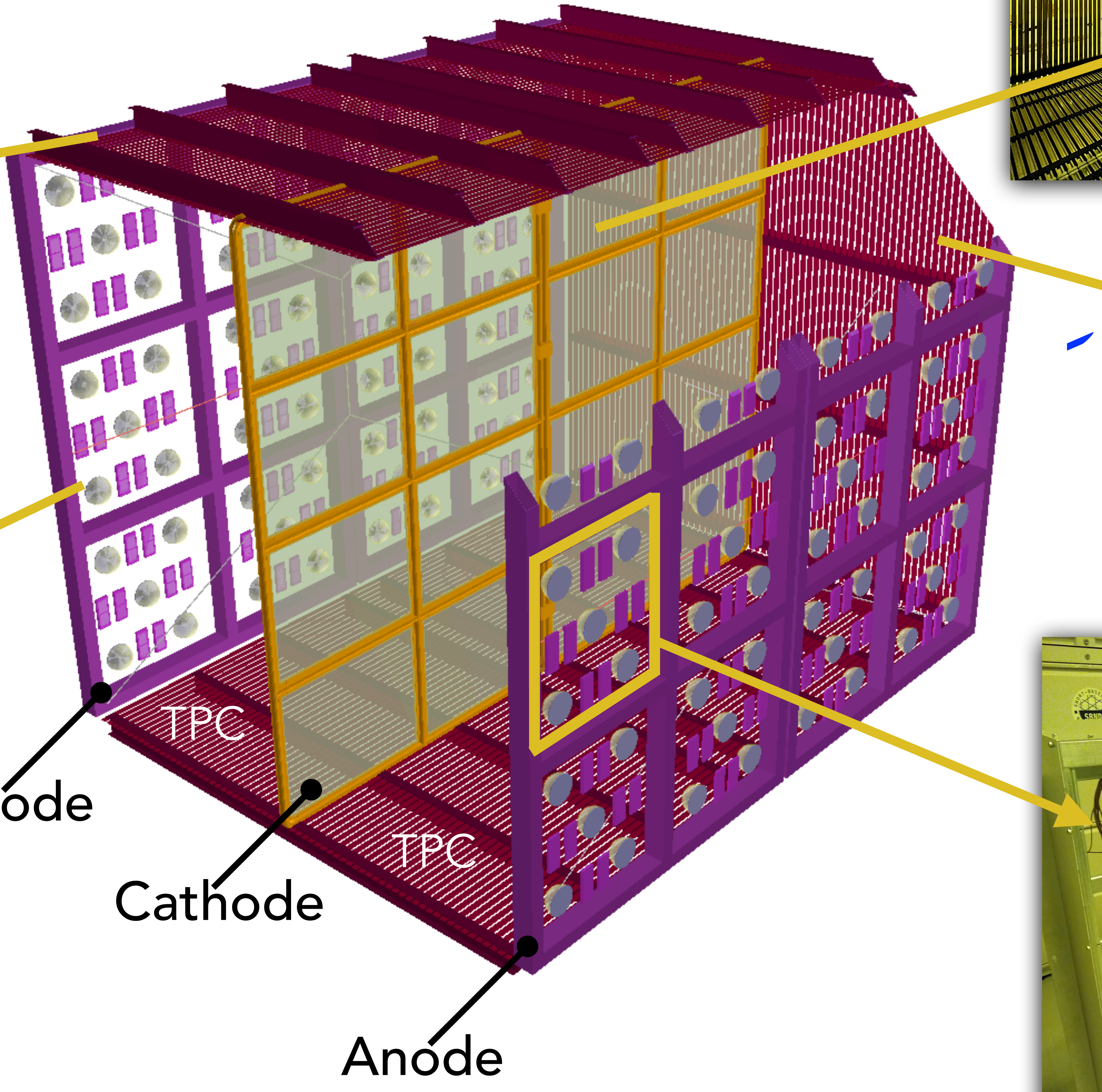
CRT panels made of scintillator strips

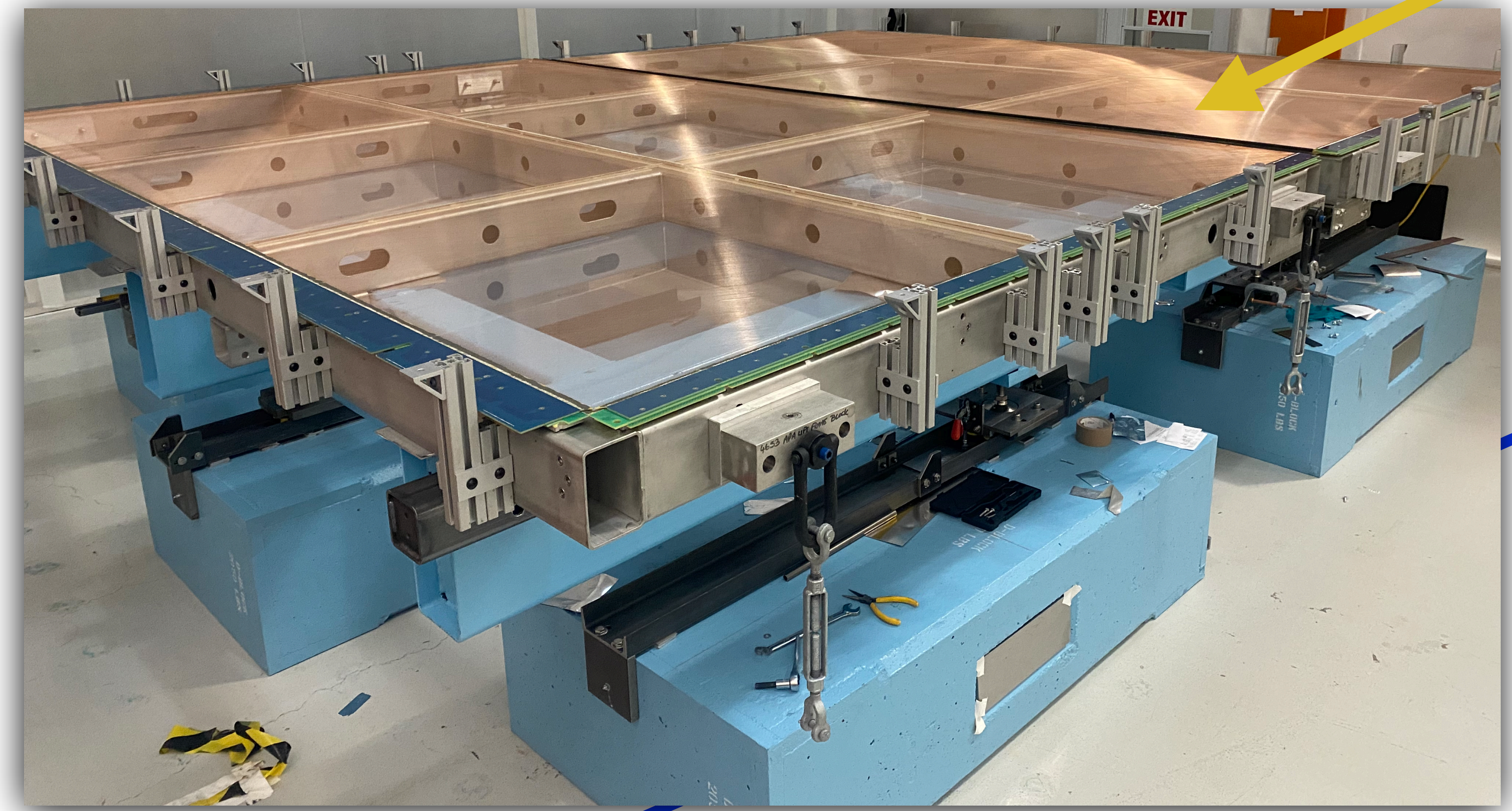
SBND detector: TPC and PDS

2 Time Projection Chambers
total dimension: 4m x 4m x 5m

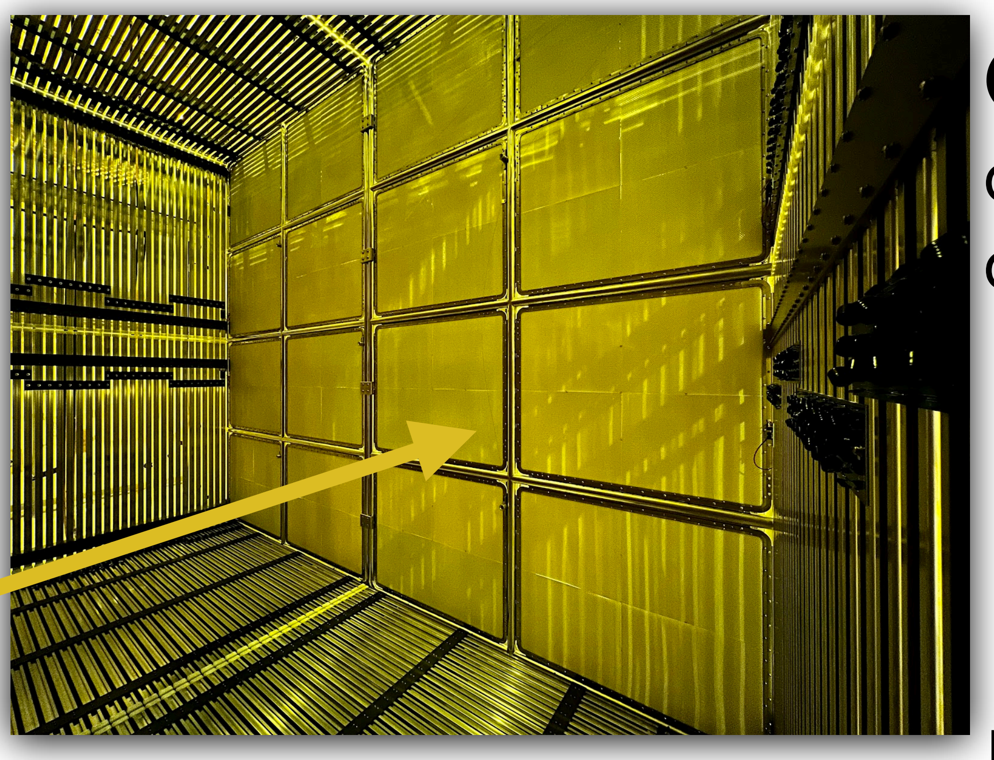
TPC Cold electronics







Wire Plane - 3 readout planes, ~11000 wires

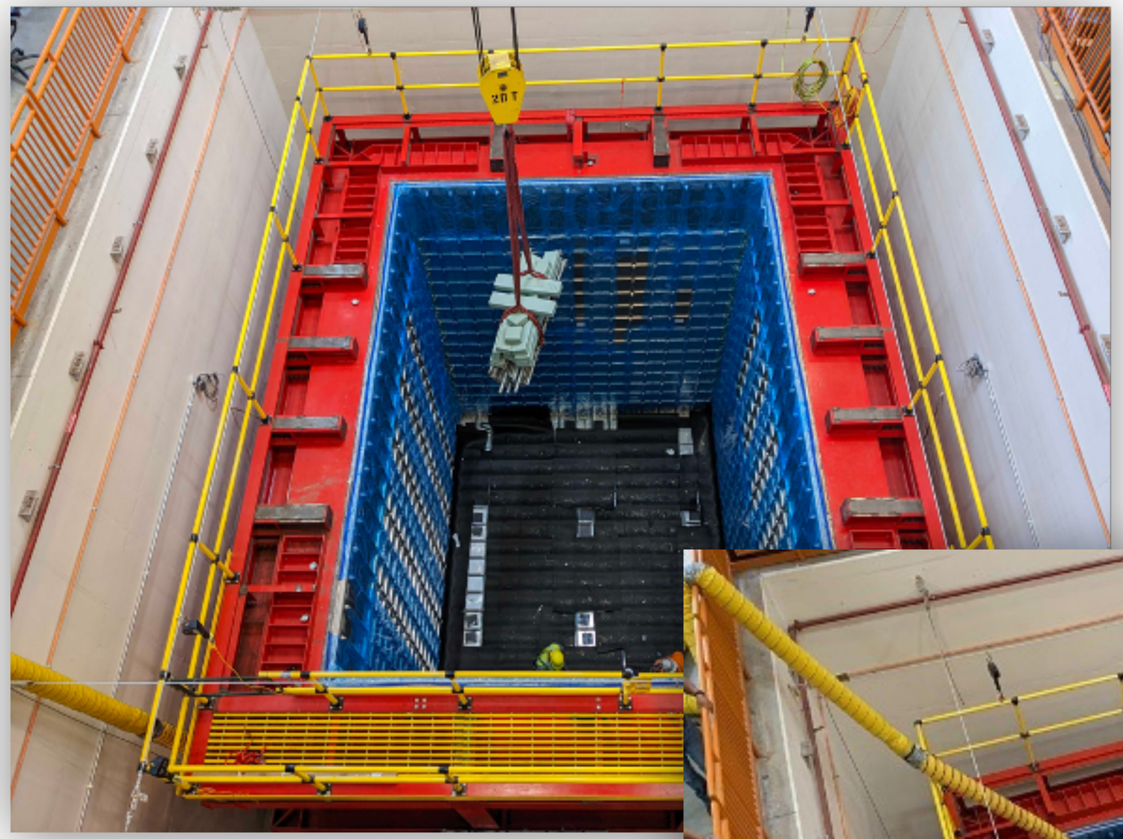
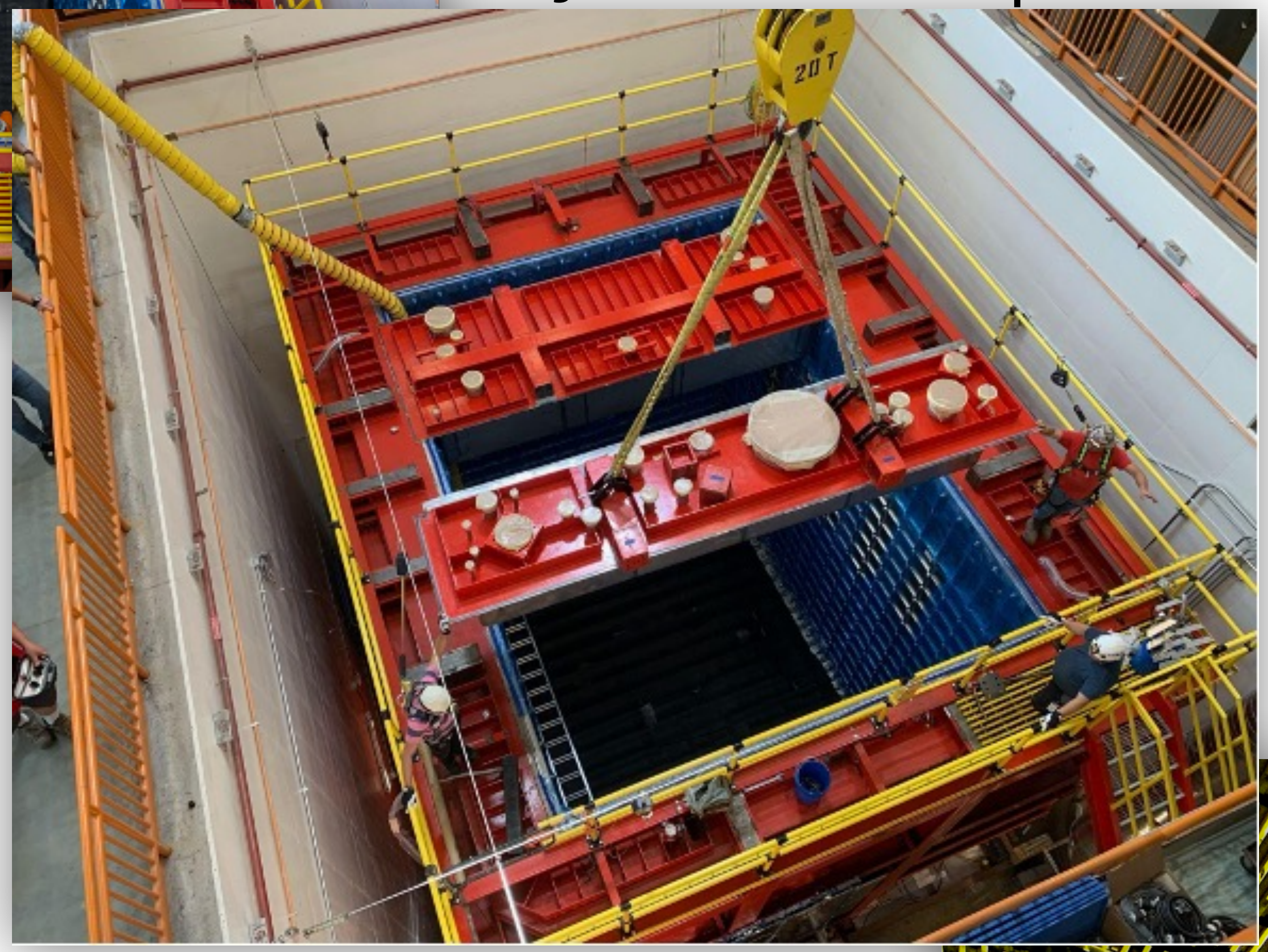


Cathode
covered with TPB coated reflectors

Field Cage

Photo Detection System: 120 PMTs, 192 X-Arapucas

SBND Construction

Warm vessel and membrane cryostat completed

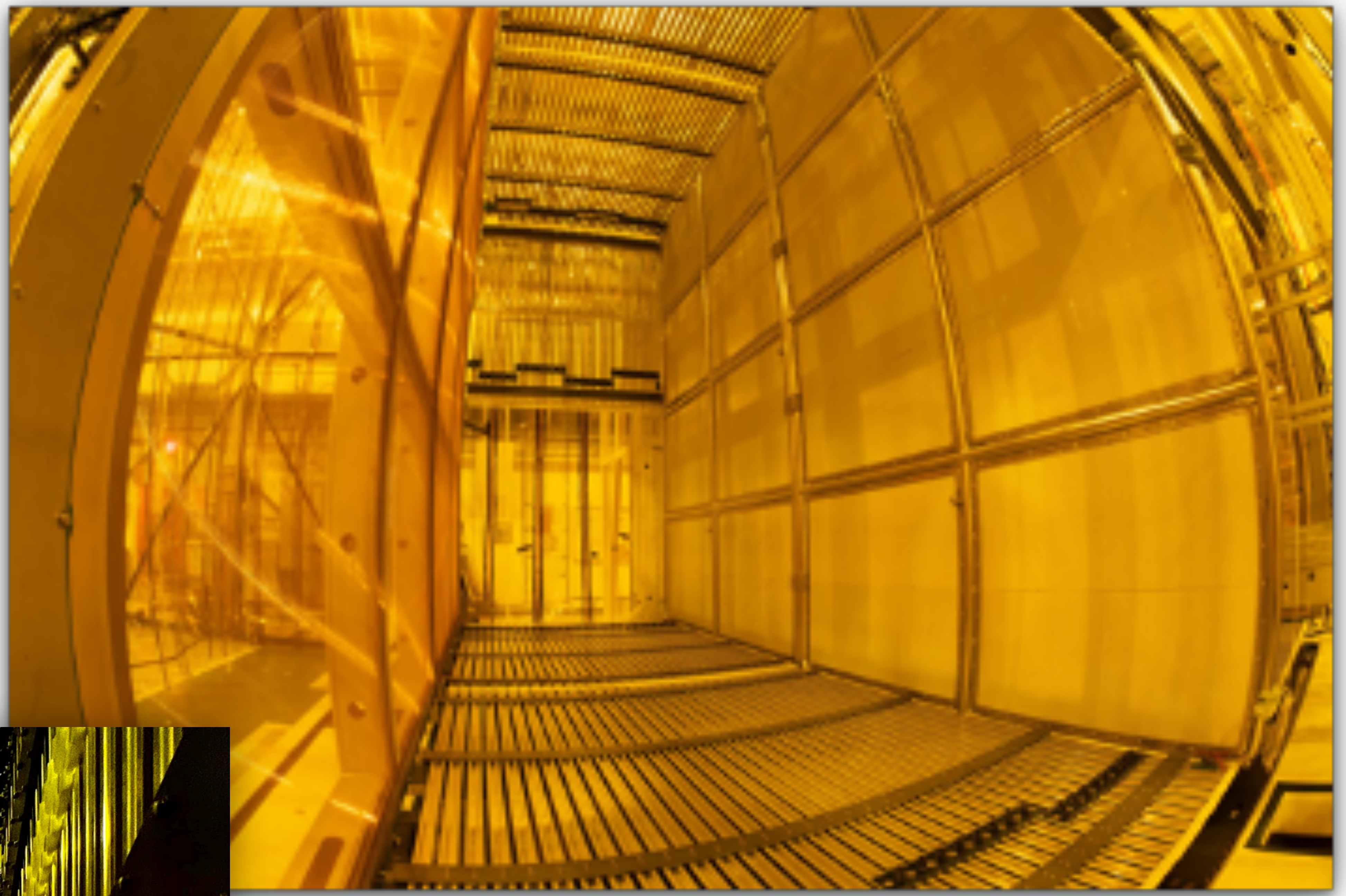
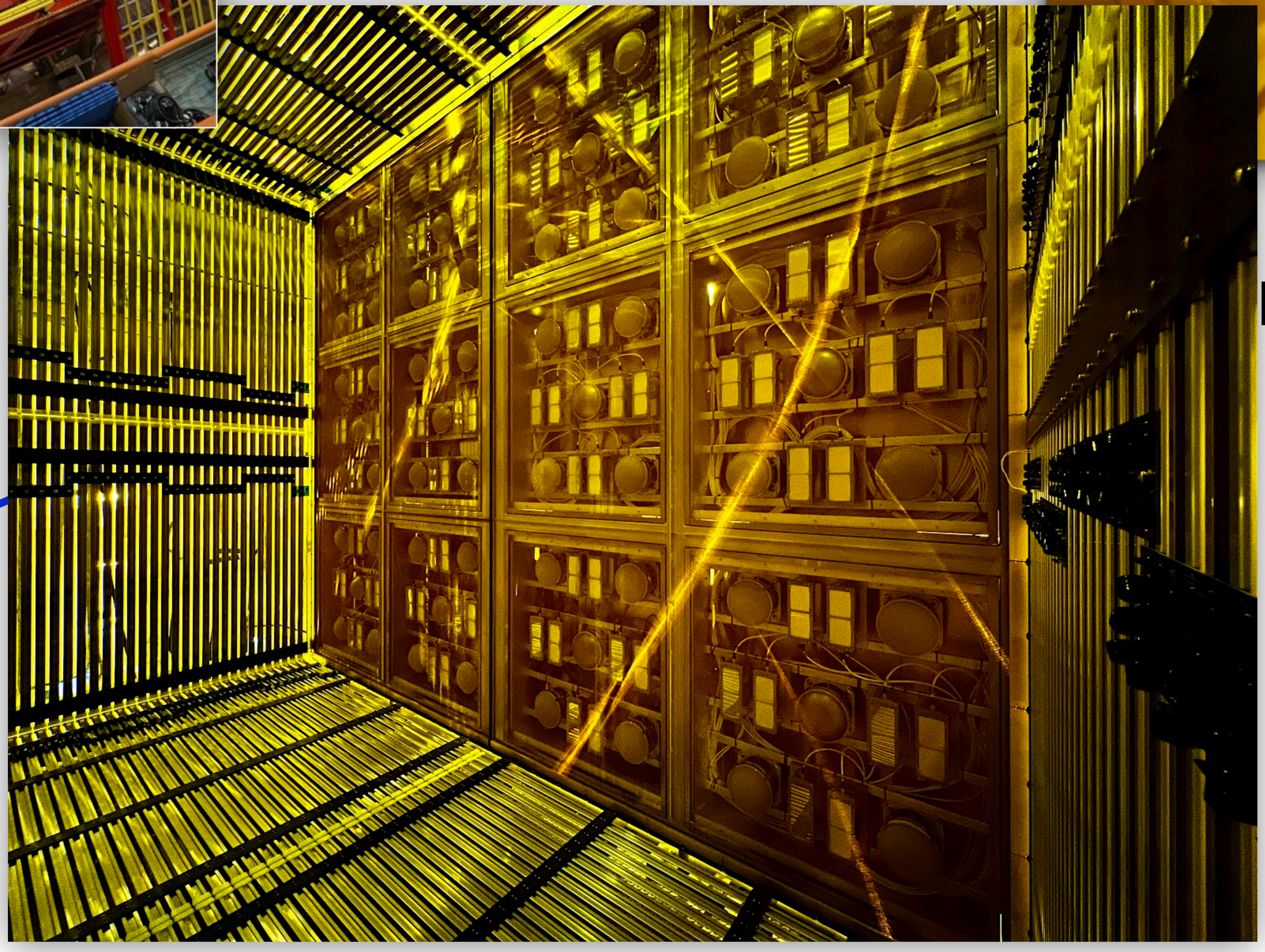


Photo credit: Ryan Postel

Detector assembly completed.



Cryogenics installation in progress

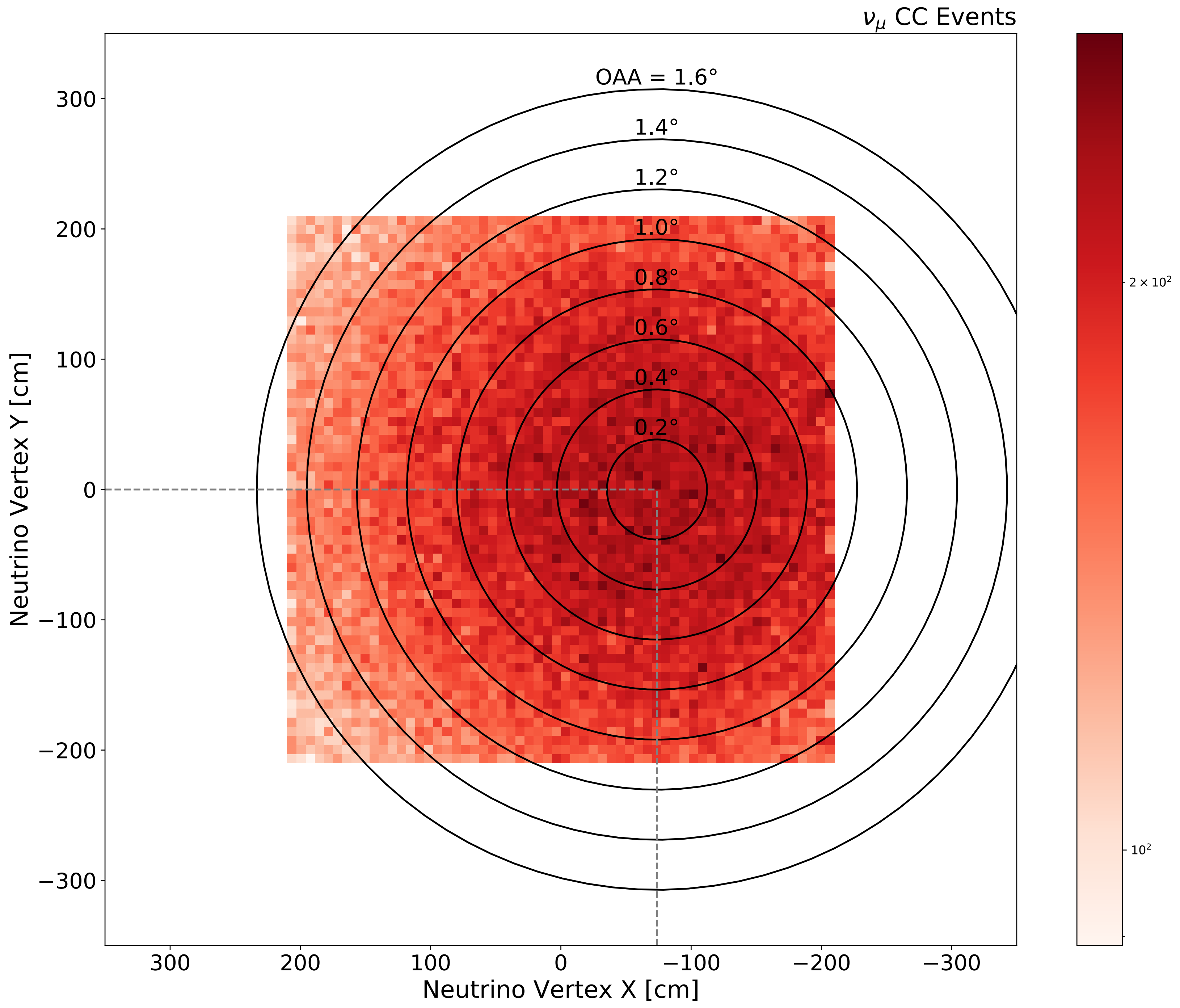
Cold commissioning - Summer 2023

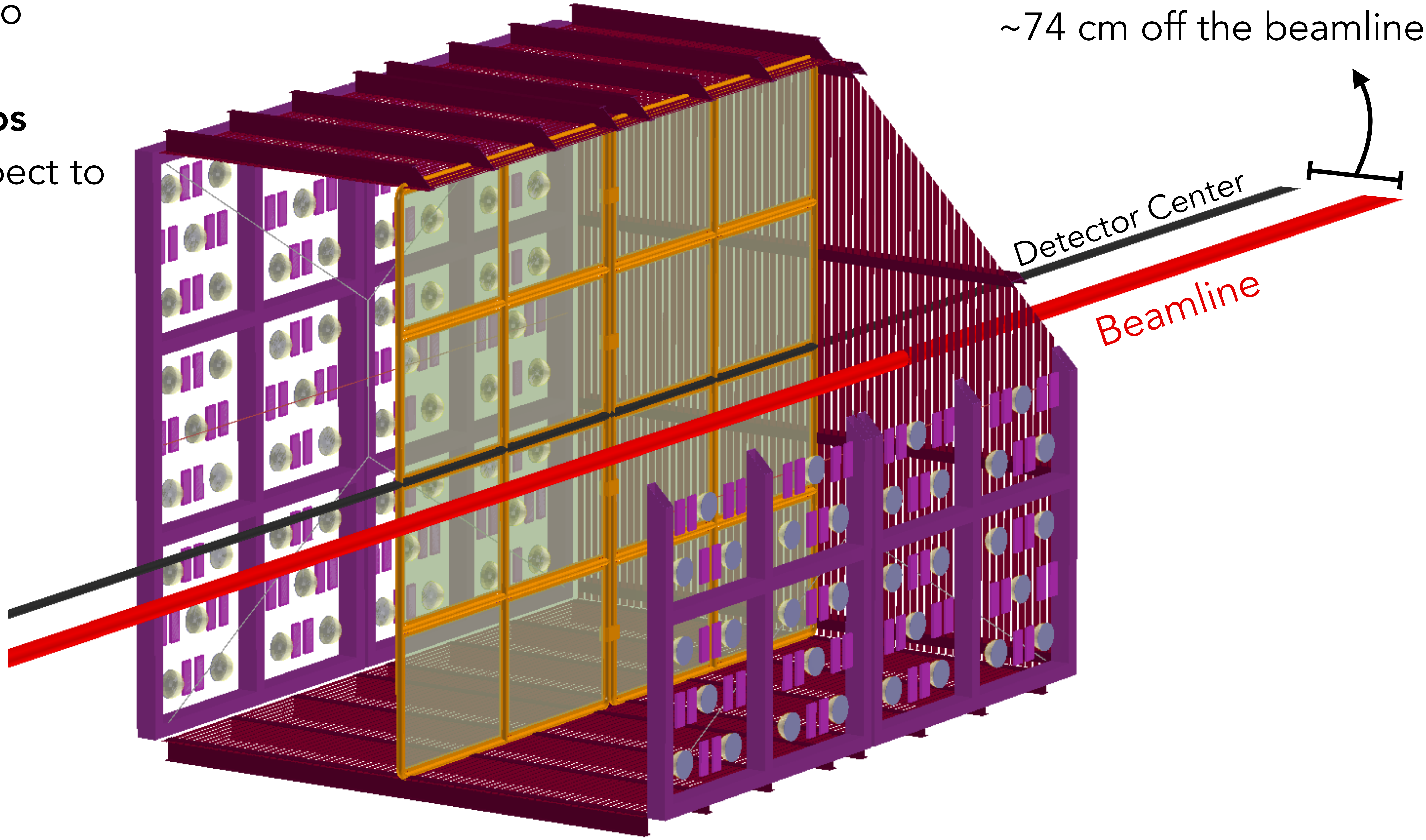
A Slightly Off-axis Detector — SBND-PRISM

Being

- close (110 m) to the neutrino source
- not perfectly aligned with the neutrino beamline

SBND detector is traversed by **neutrinos** coming from **different angles** with respect to the beam axis.





SBND-PRISM - Neutrino Fluxes

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

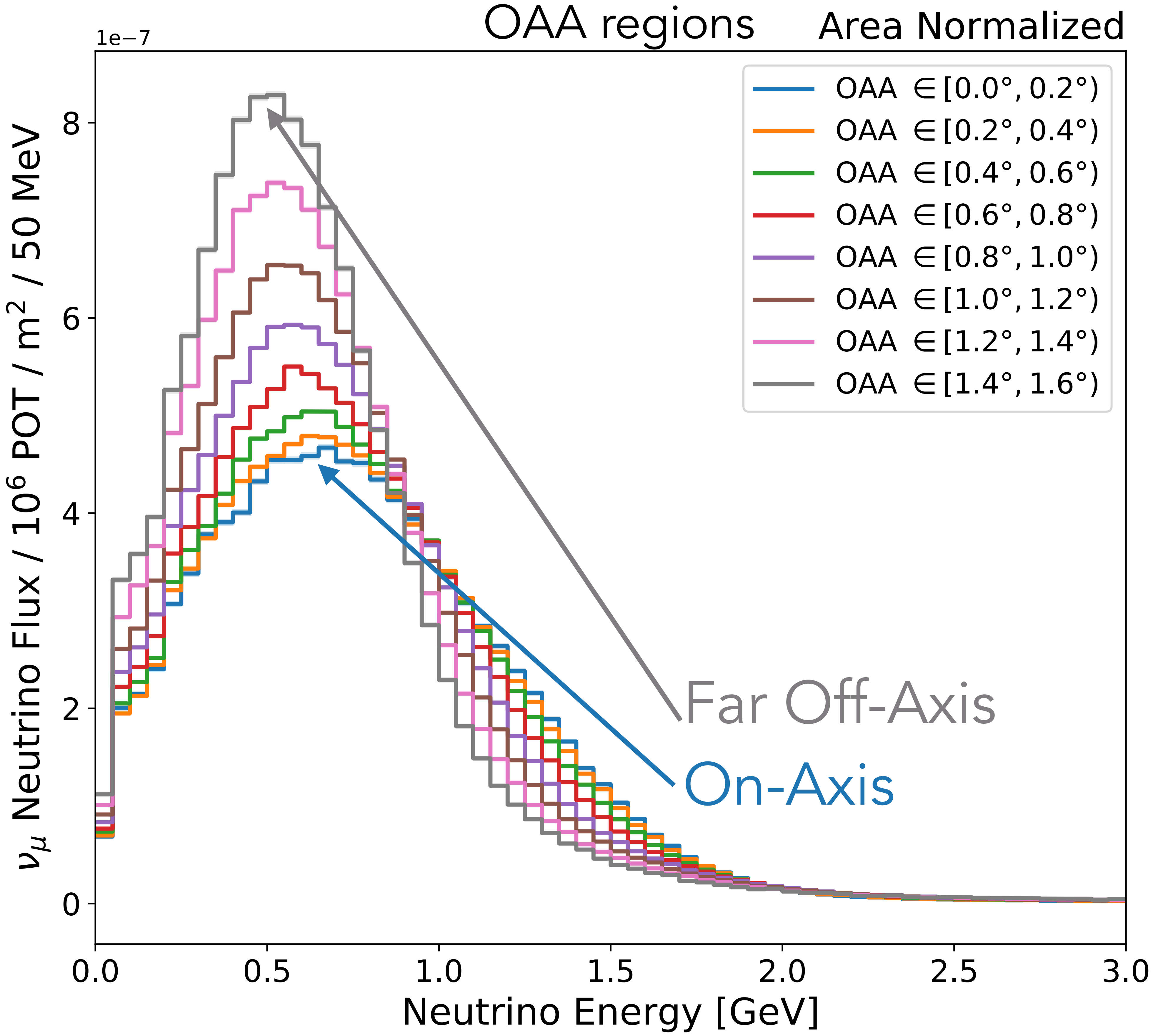
Similar to the nu-PRISM and DUNE-PRISM concepts*, but with a fixed detector.

The **Muon** neutrino energy distributions are affected by the off-axis position.

Larger off-axis angle → lower mean energy.

The **Electron** neutrino energy distributions also change, but they are less affected by off-axis position. **Muon and electron neutrino spectra change in a different way!**

Muon neutrino flux in OAA regions



High event statistics in all off-axis regions.

SBND-PRISM expands the SBND physics potentials.

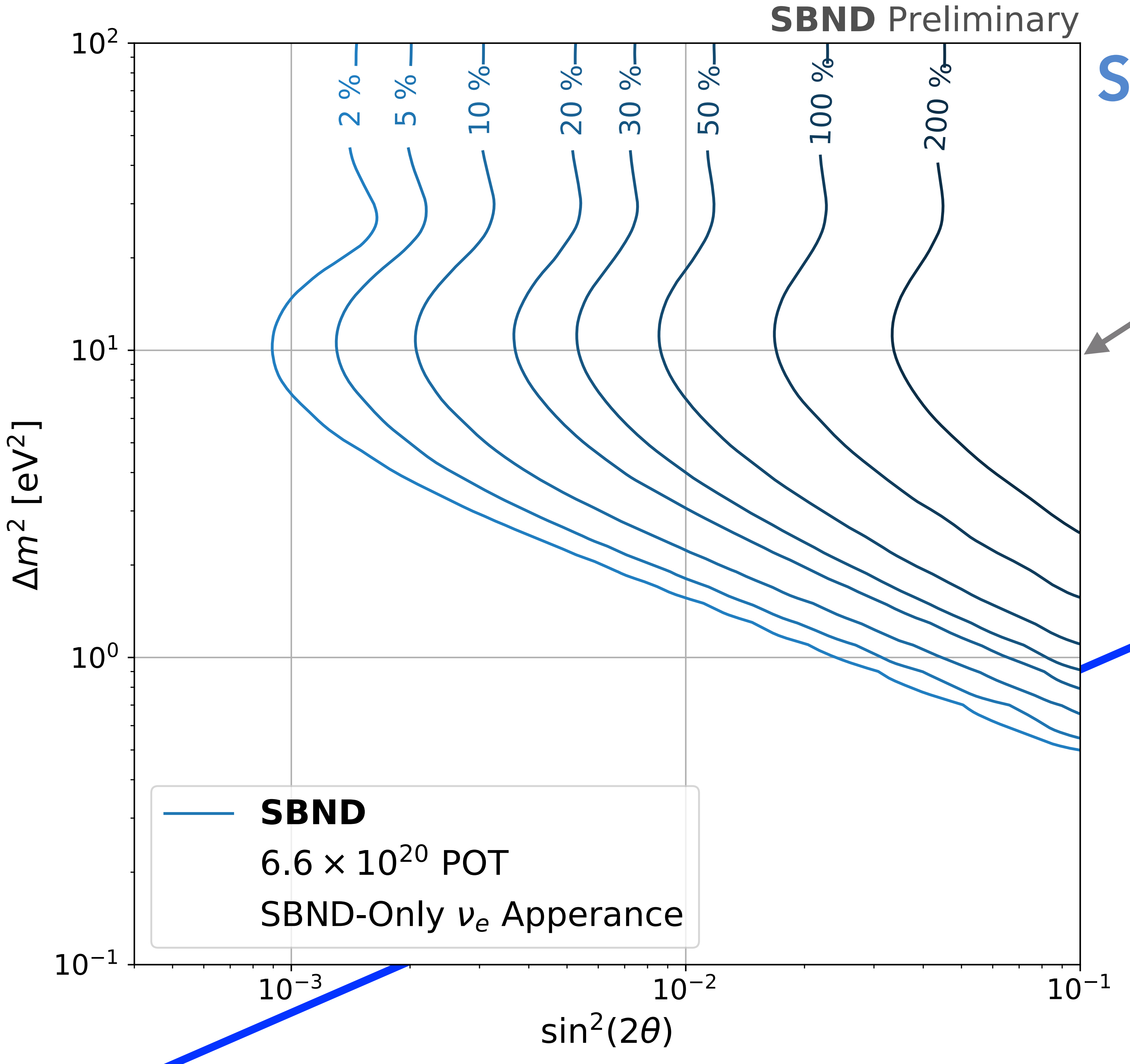
*perform measurements at different off-axis angles by moving the detector transverse to the neutrino beam

Sterile Neutrino Sensitivities with SBND-PRISM

SBND-only ν_e Appearance Sensitivity

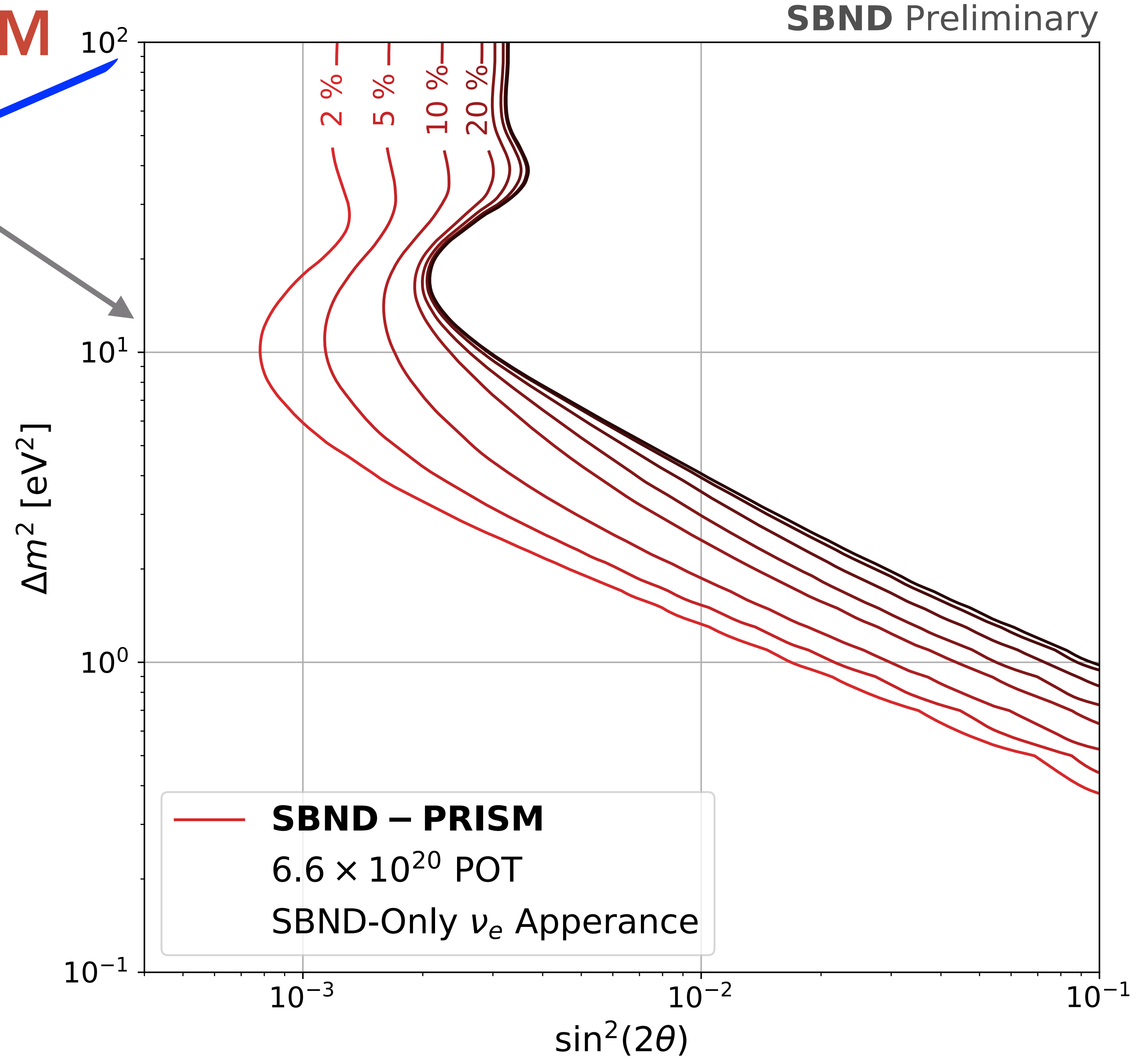
Leveraging on the different behavior of muon and electron neutrinos in the OAA regions, we can improve sensitivity for sterile neutrino searches.

Treat SBND as eight "sub-detectors" at different off-axis positions and include those in the SBN oscillation fit.



SBND as a single detector vs SBND-PRISM

Curves include flux plus 2-to-200% systematics on total cross section.



Sterile Neutrino Sensitivities with SBND-PRISM

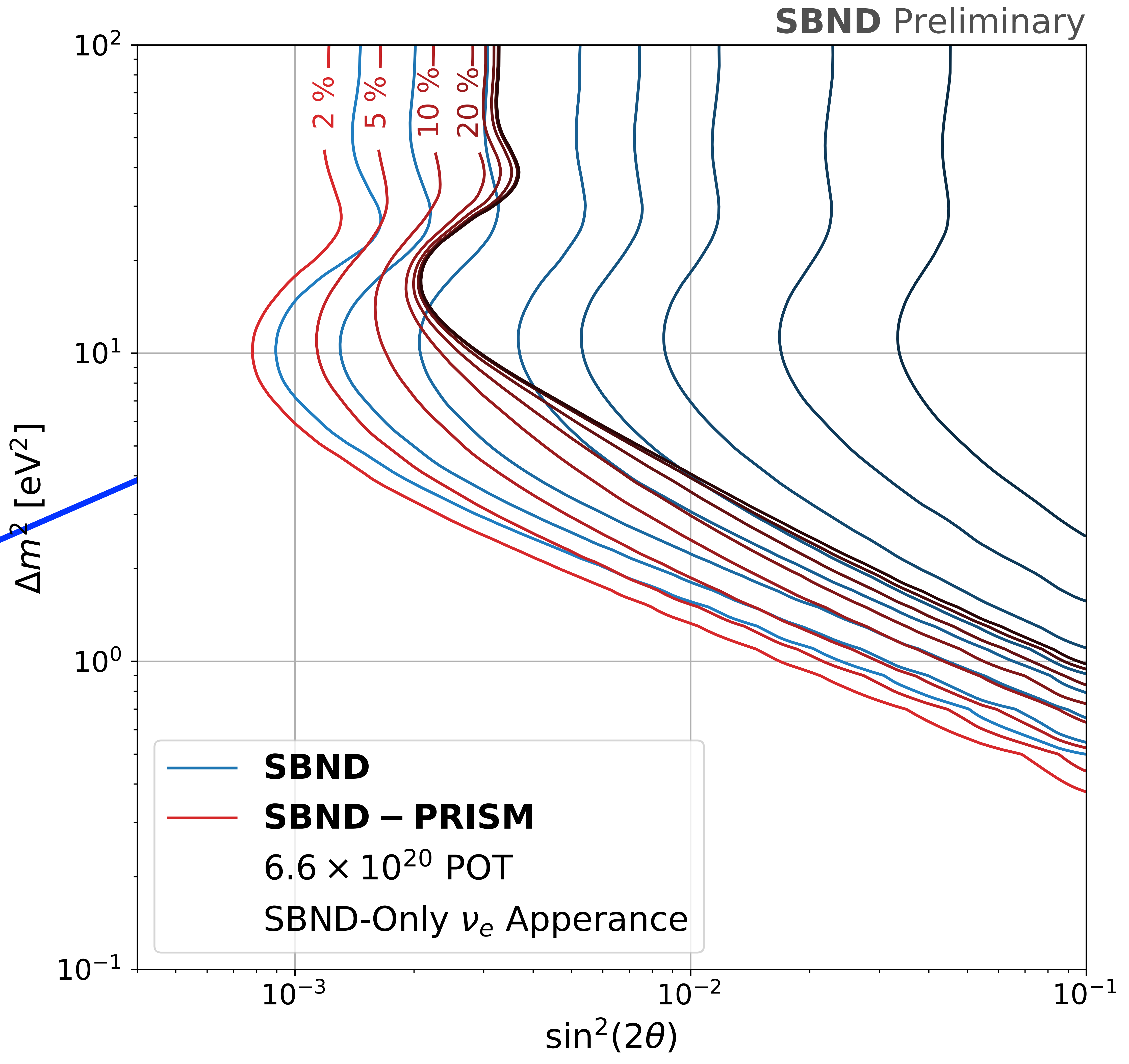
SBND-only ν_e Appearance Sensitivity

Improvement in sensitivity by exploiting SBND-PRISM.

Exploiting SBND-PRISM, the neutrino interaction model is over constrained, becoming ~ insensitive to cross section model uncertainties above 20%.

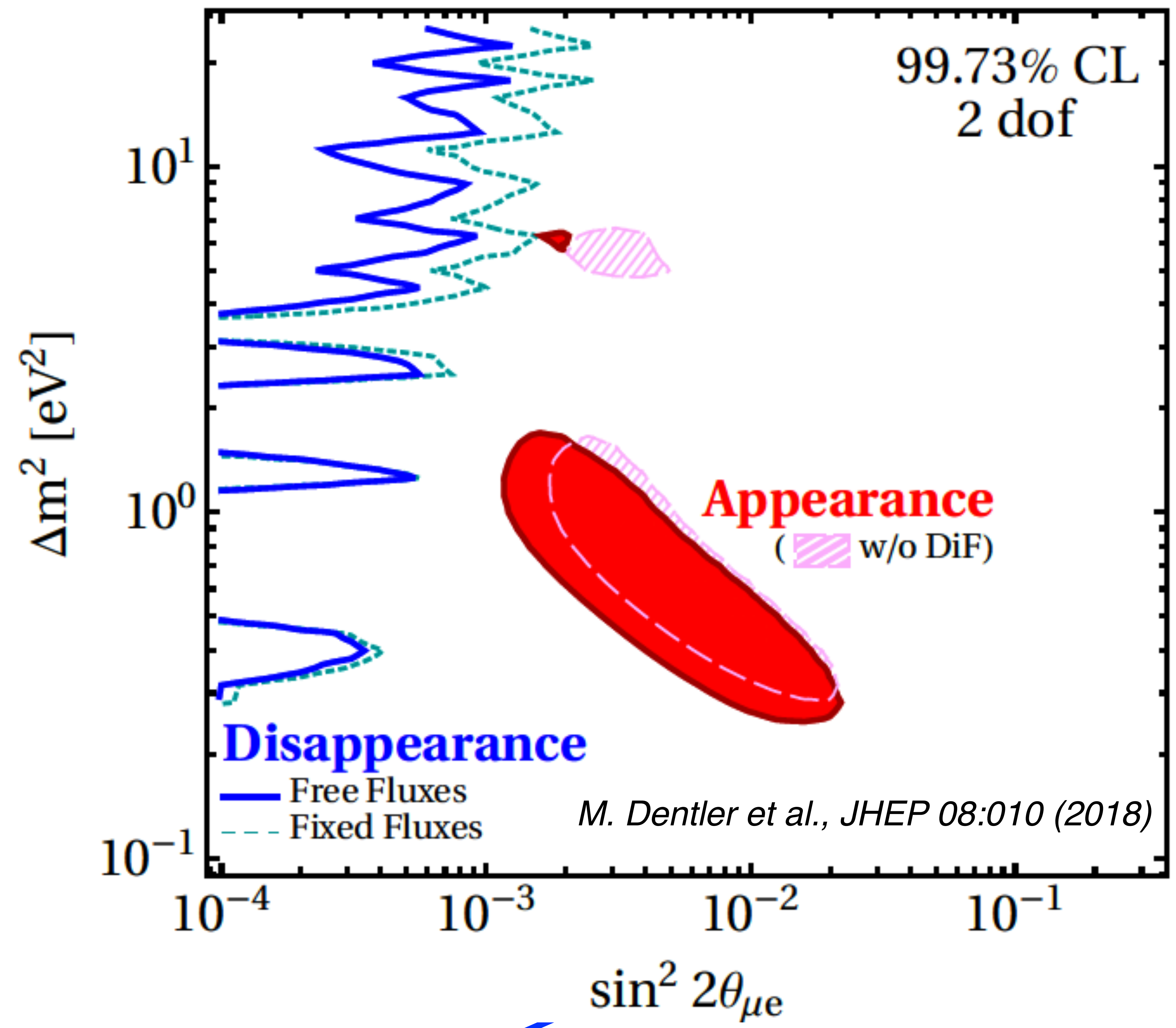
Study of the effect of SBND-PRISM on SBN Sterile neutrino oscillation sensitivities is ongoing.

SBND as a single detector vs SBND-PRISM



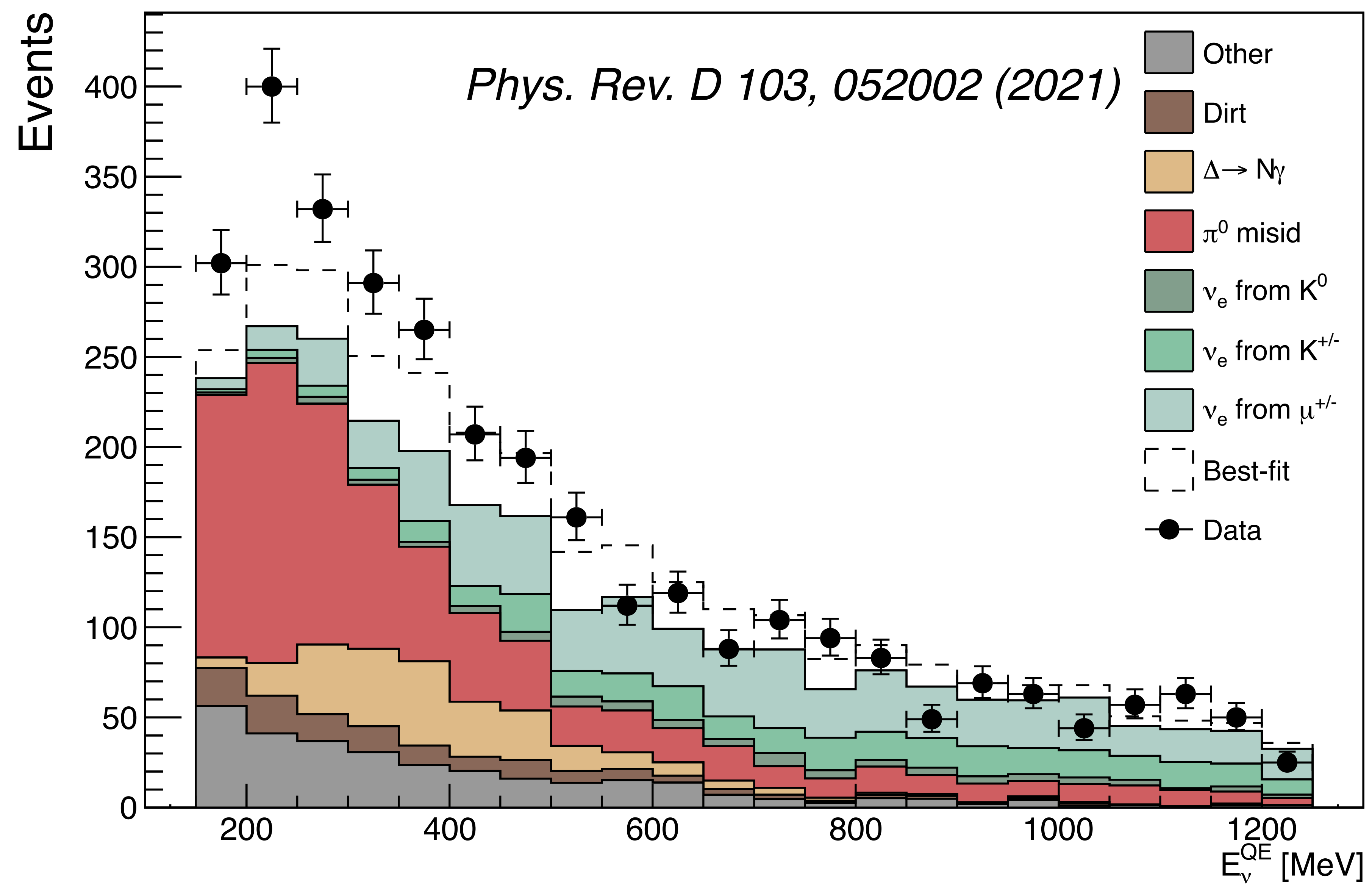
Light Sterile Neutrino - Experimental Landscape

A 4.7 σ tension arises when combining ν_e appearance and ν_μ disappearance data sets.



Limits from disappearance and appearance allowed region

MiniBooNE electron-like excess

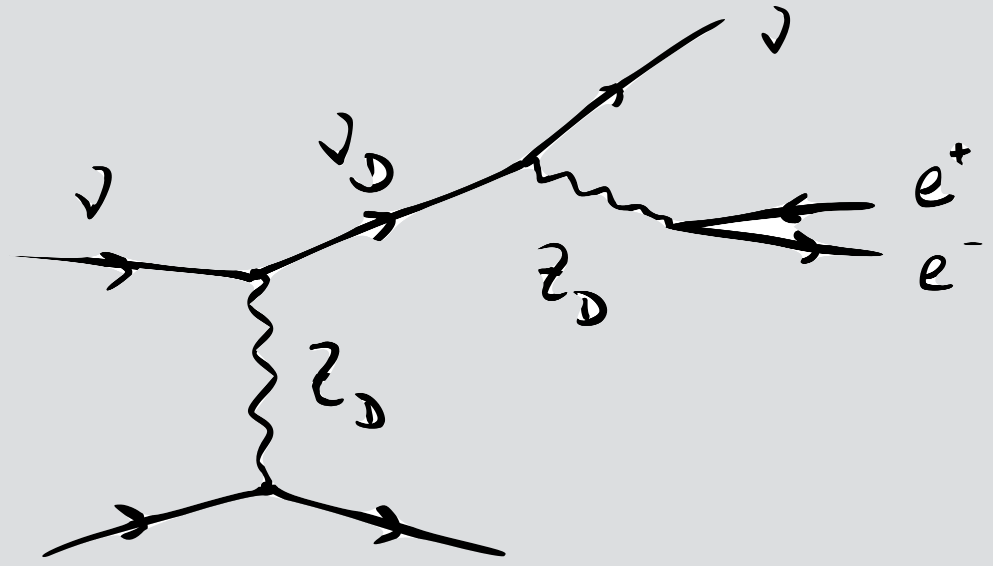


Alternative explanations exist that could explain the MiniBooNE (and LSND) anomalies.

Evolving Landscape...

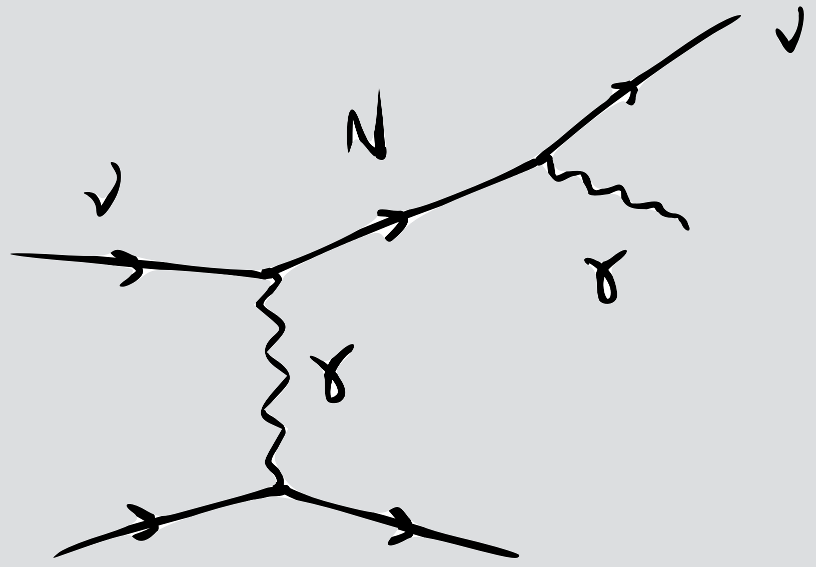
Alternative explanations of the MiniBooNE excess and other BSM scenarios.

Dark Neutrinos



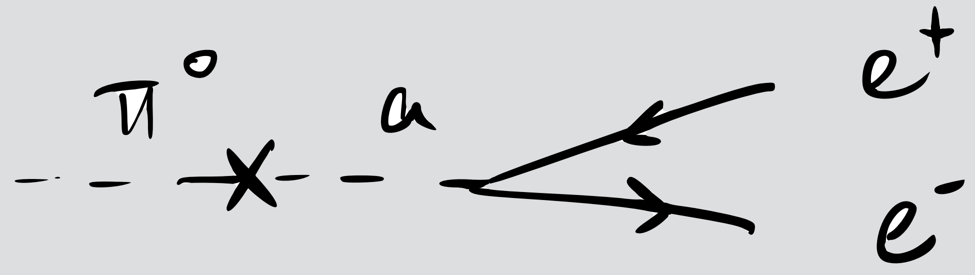
Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

Transition Magnetic Moment



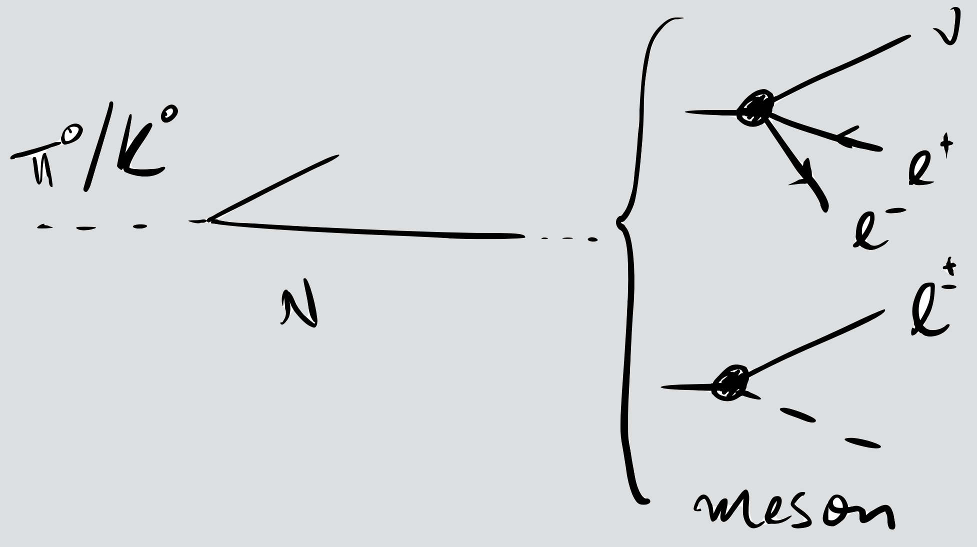
Gninenko PRL 2009
Coloma Machado Soler Shoemaker PRL 2017
Atkinson et al 2021 Vergani et al 2021

Axion-like Particles



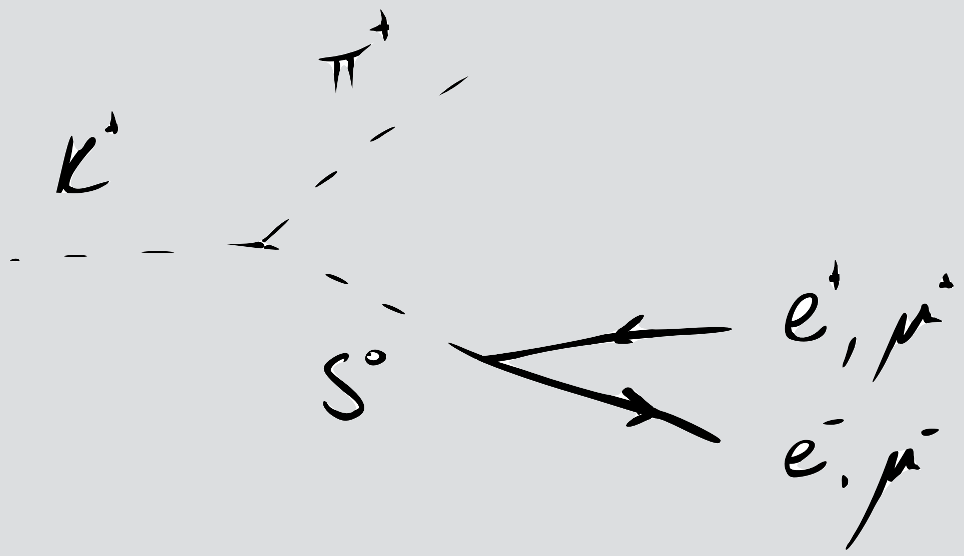
Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

Heavy Neutral Leptons



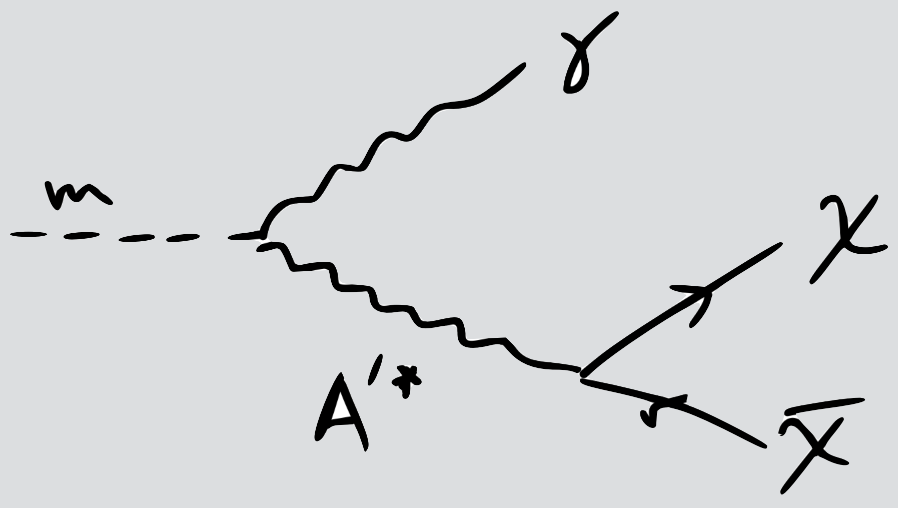
Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Higgs Portal Scalar



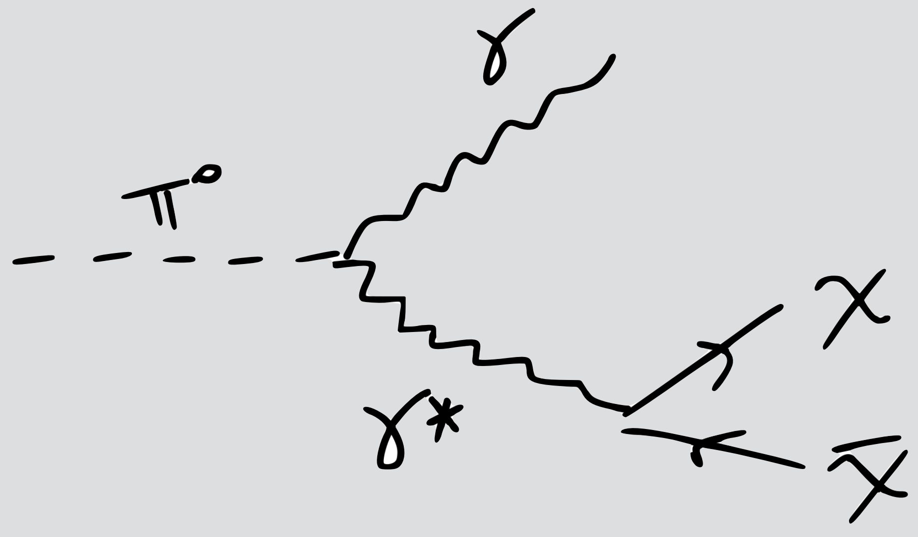
Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

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!

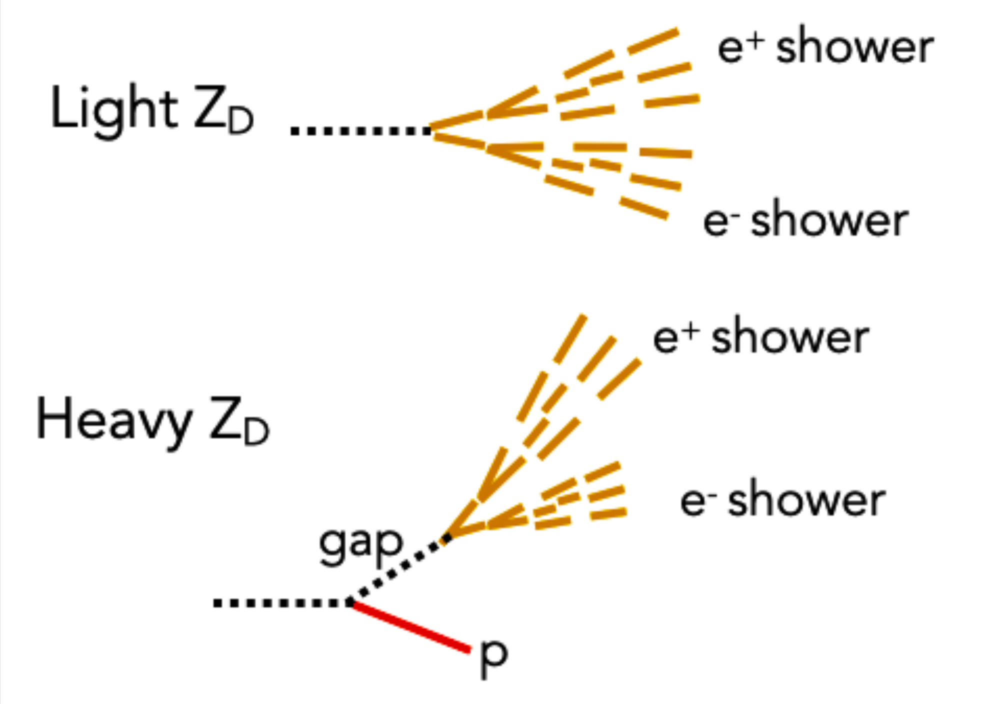
Image credit P. Machado and M. Del Tutto

Evolving Landscape…

Final state experimental signature: single photon, single electron, “trident” with di-leptons - overlapping and/or highly asymmetric,

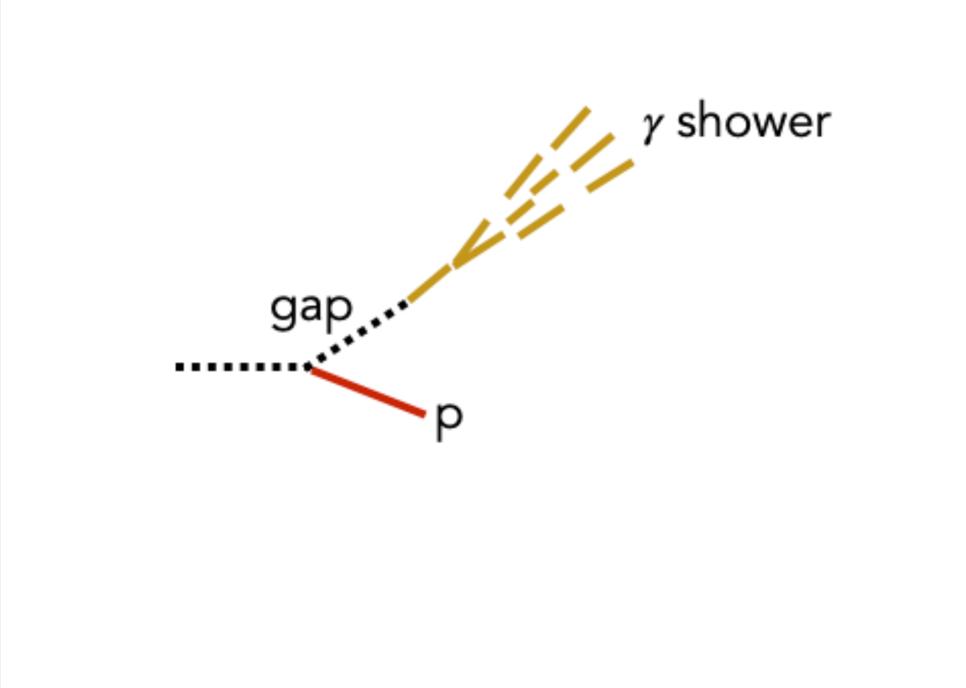
with different levels of hadronic activity.

Dark Neutrinos



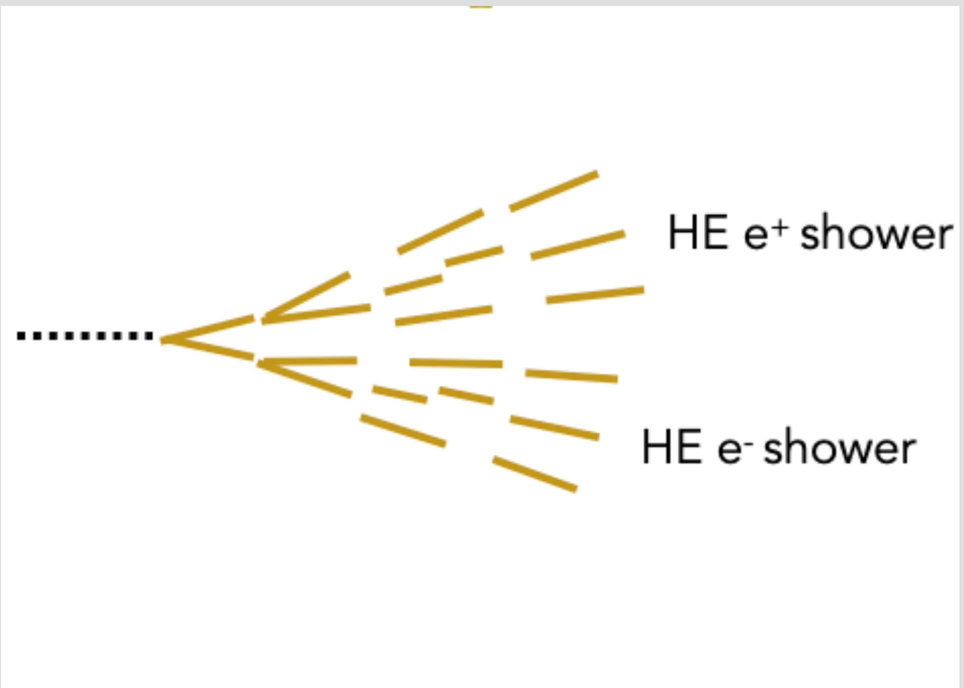
e^+e^- pair with or without hadronic activity

Transition Magnetic Moment



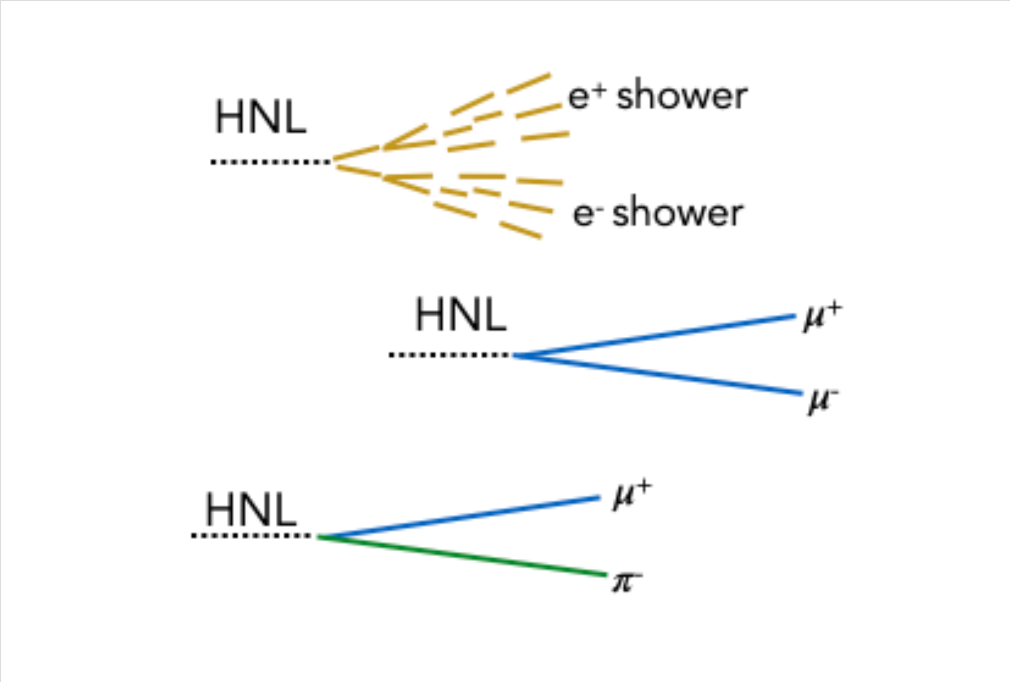
Photon and hadronic activity

Axion-like Particles



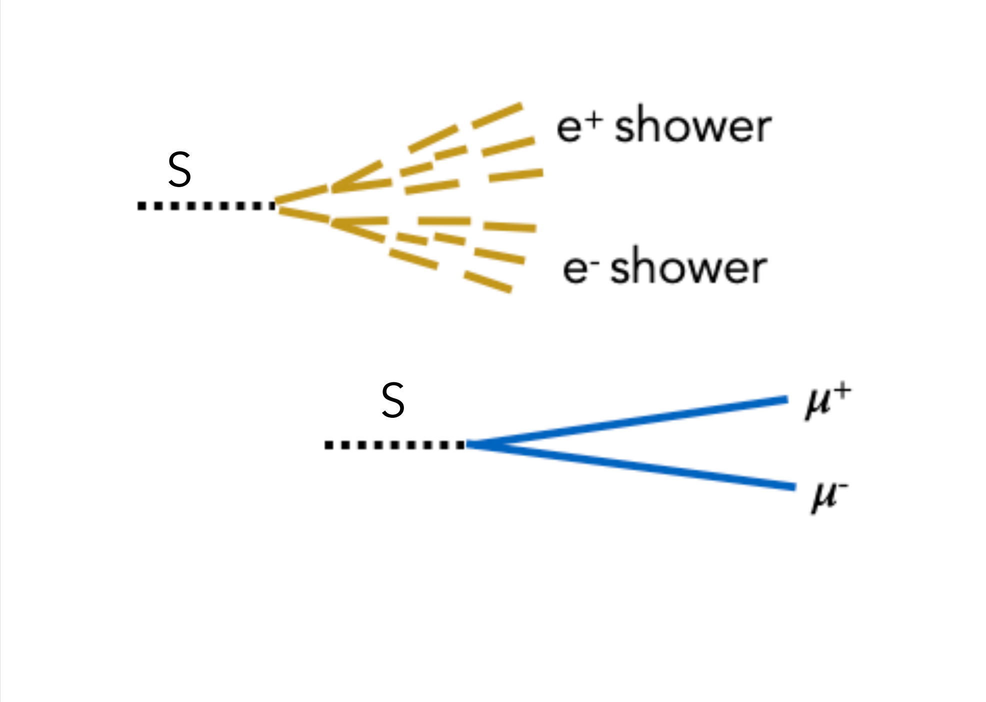
high-energy e^+e^- pair

Heavy Neutral Leptons



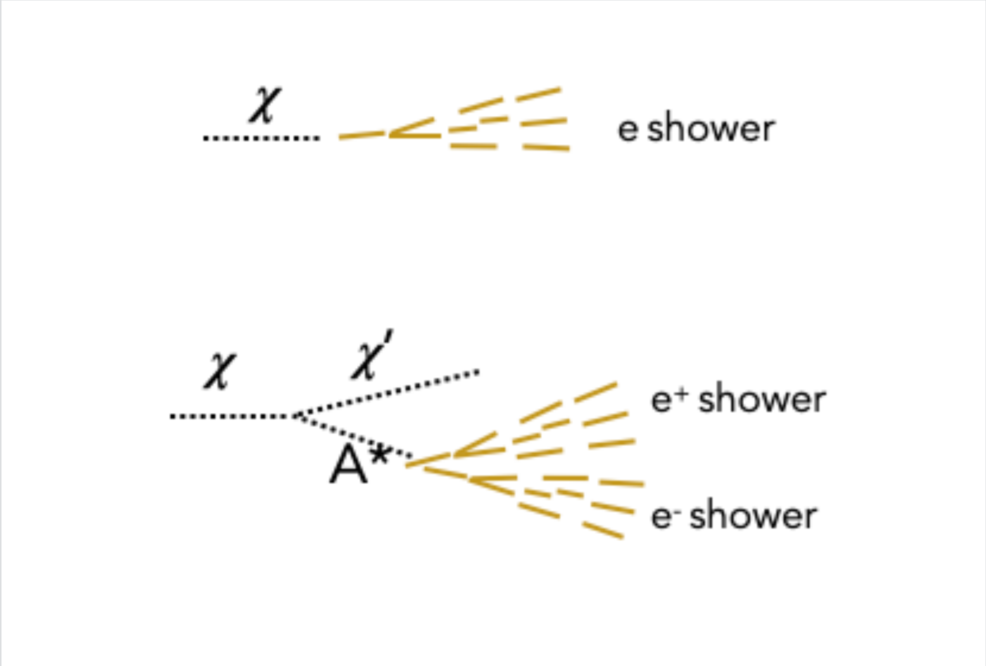
e^+e^-, $\mu^+\mu^-$, or $\mu^\pm\pi^\mp$ pair with no hadronic activity

Higgs Portal Scalar



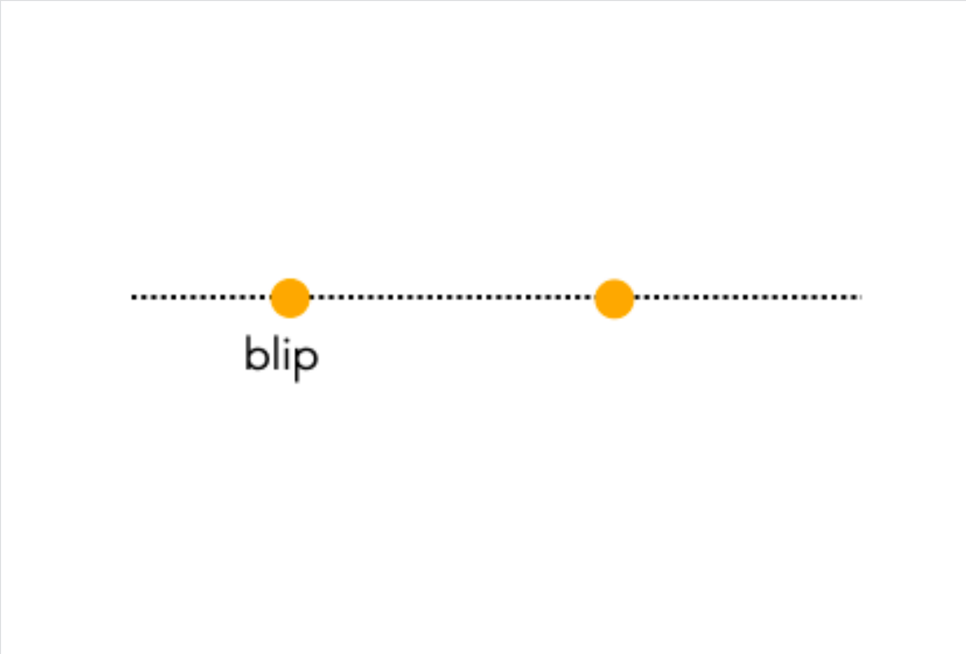
e^+e^- or $\mu^+\mu^-$ pair with no hadronic activity

Light Dark Matter



single e^- scattering or e^+e^- pair with no hadronic activity

Millicharged Particles



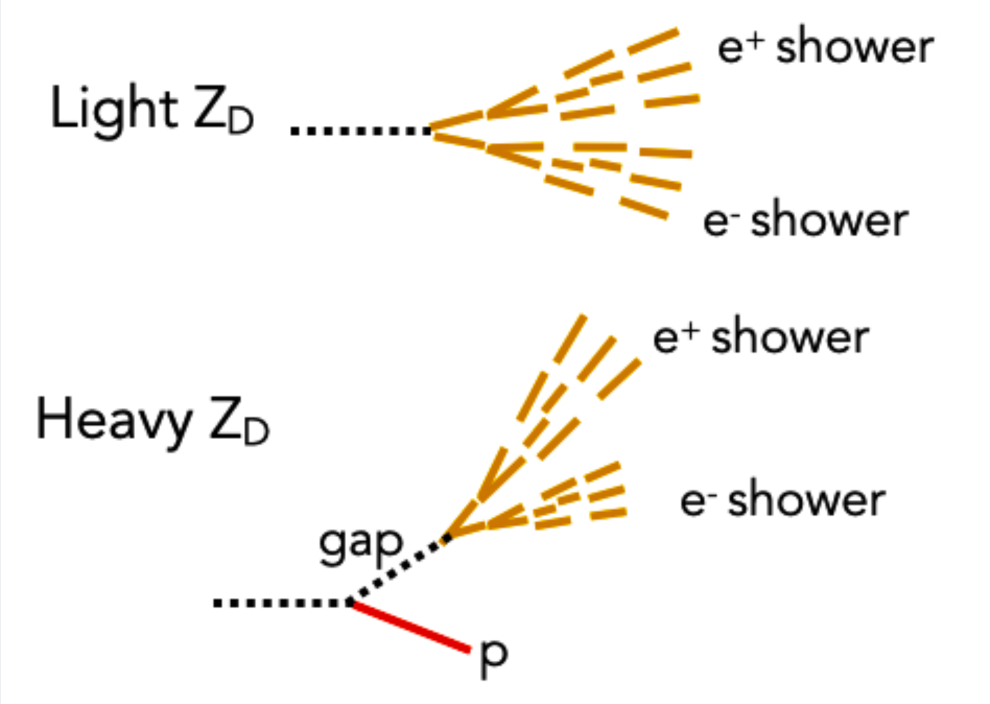
blips or faint tracks

Evolving Landscape…

The unique capabilities of the LAr TPC technology open up more information than available in a Cherenkov detector (such as MiniBooNE)

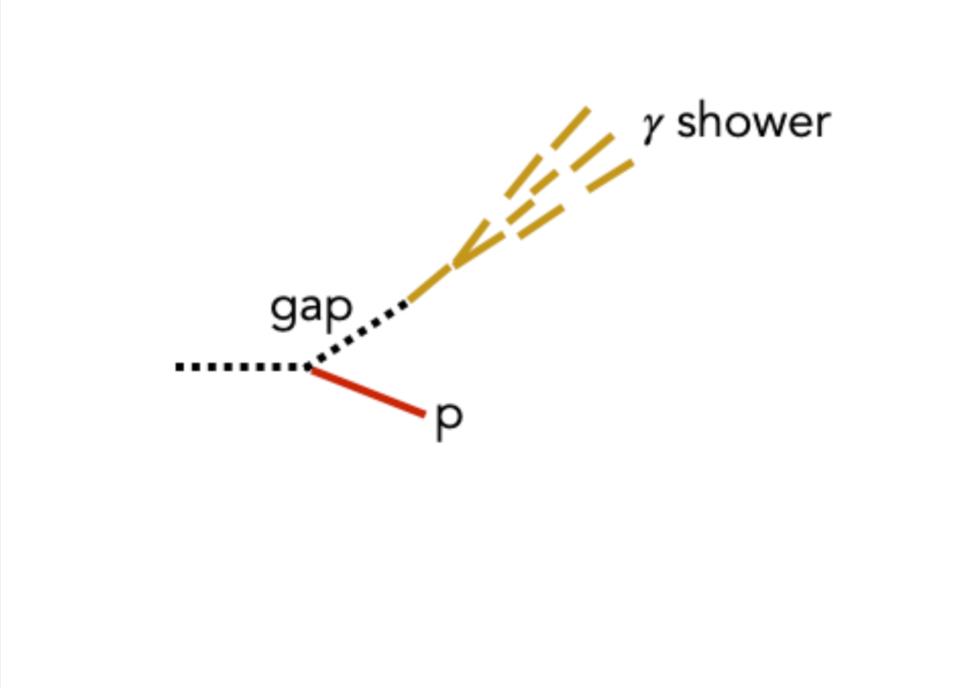
- Characterize events in term of final state particle content and kinematics.
- Recognize the presence hadronic activity.

Dark Neutrinos



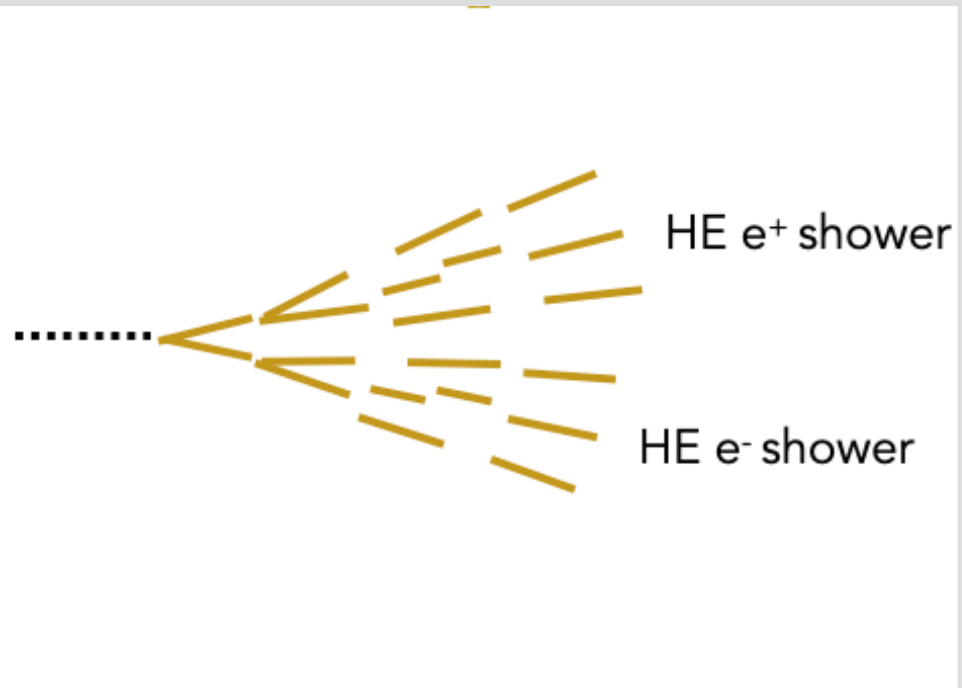
e^+e^- pair with or without hadronic activity

Transition Magnetic Moment



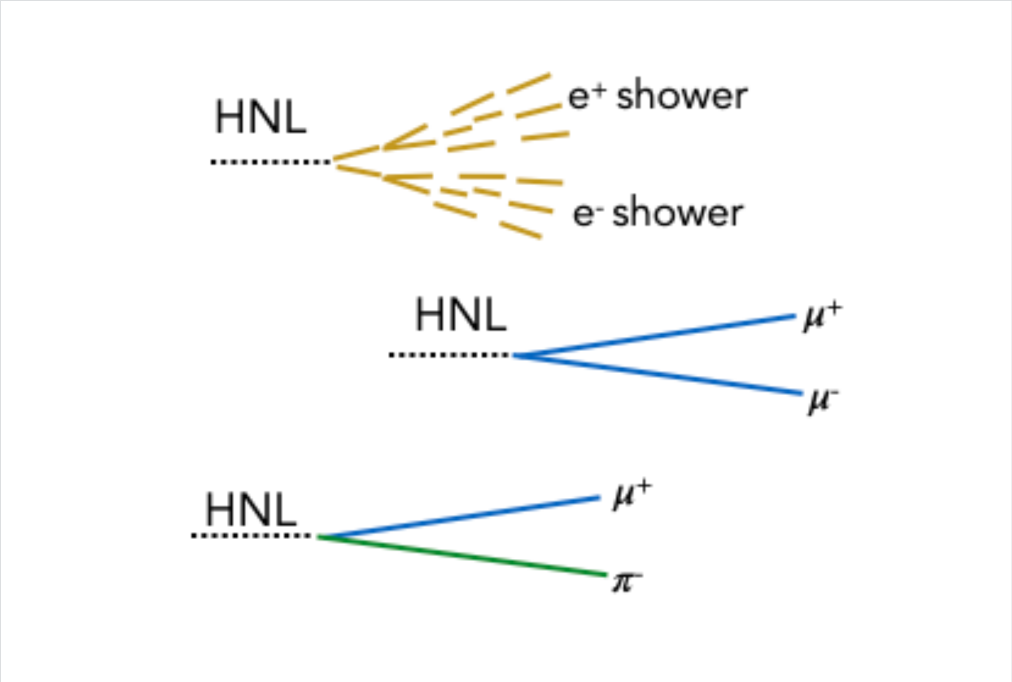
Photon and hadronic activity

Axion-like Particles



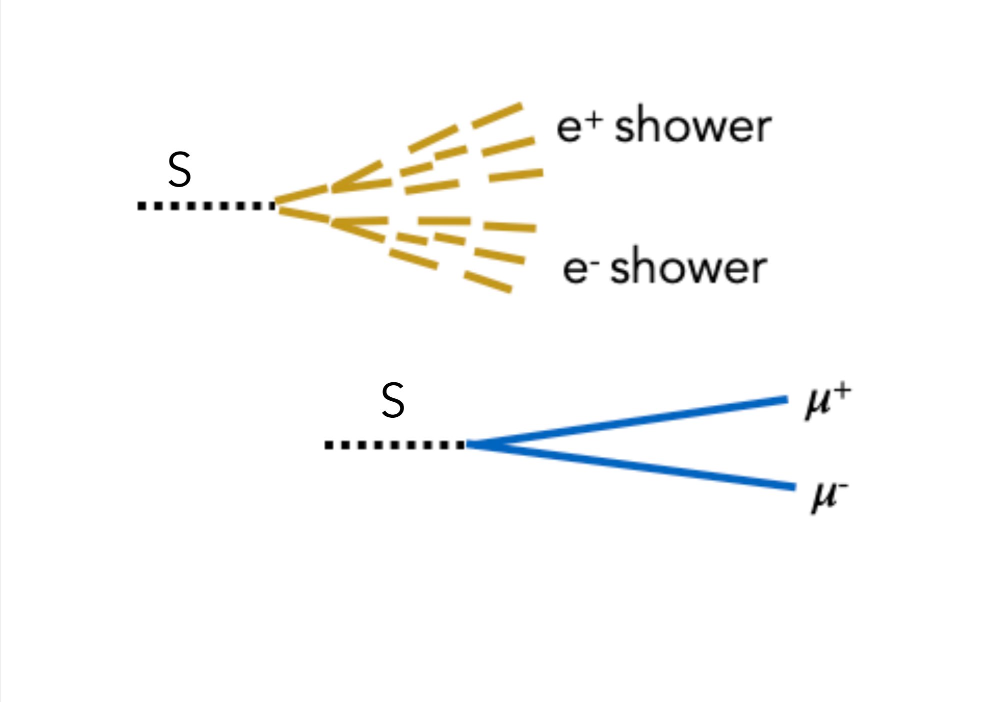
high-energy e^+e^- pair

Heavy Neutral Leptons



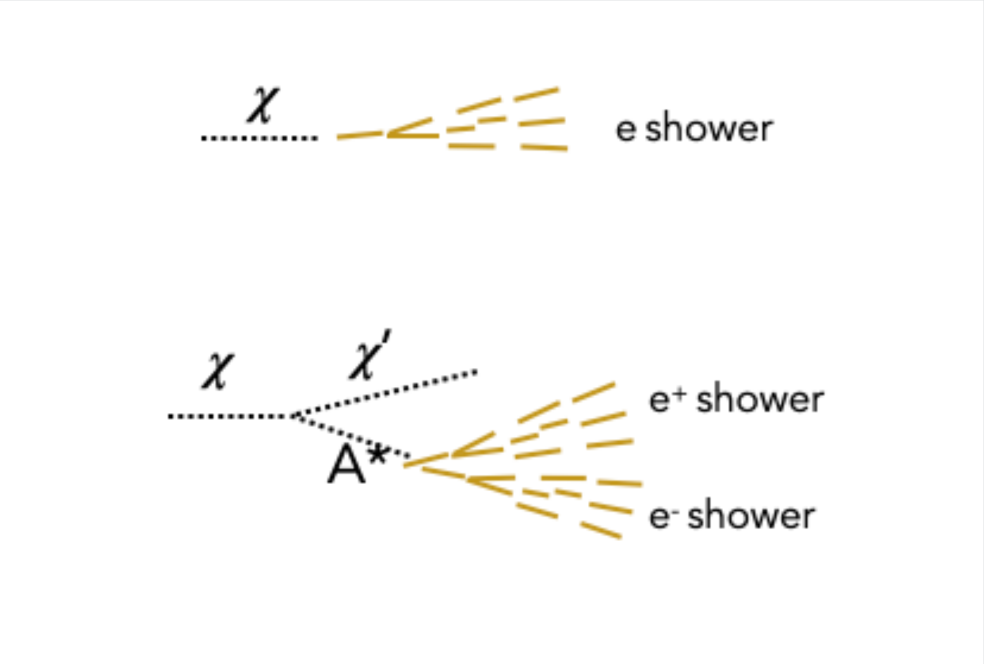
e^+e^-, $\mu^+\mu^-$, or $\mu^\pm\pi^\mp$ pair with no hadronic activity

Higgs Portal Scalar



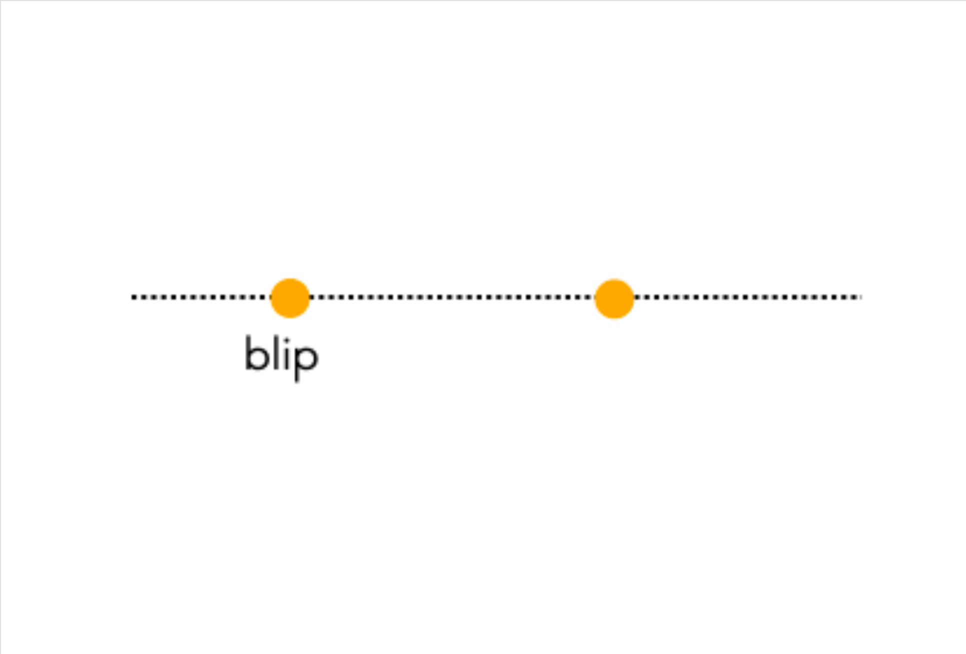
e^+e^- or $\mu^+\mu^-$ pair with no hadronic activity

Light Dark Matter



single e^- scattering or e^+e^- pair with no hadronic activity

Millicharged Particles

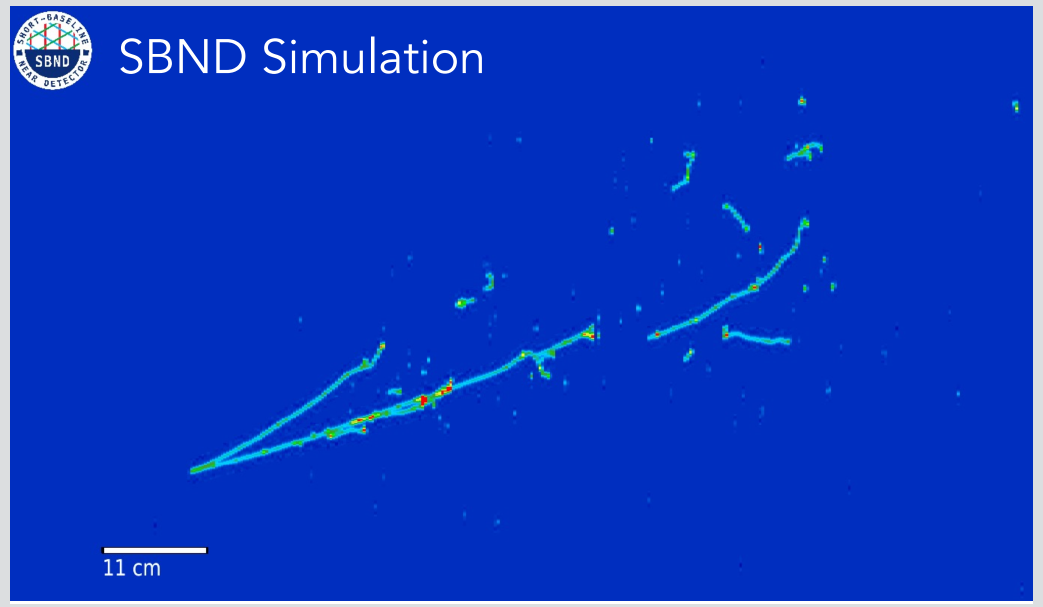


blips or faint tracks

Signatures for New Physics in SBND

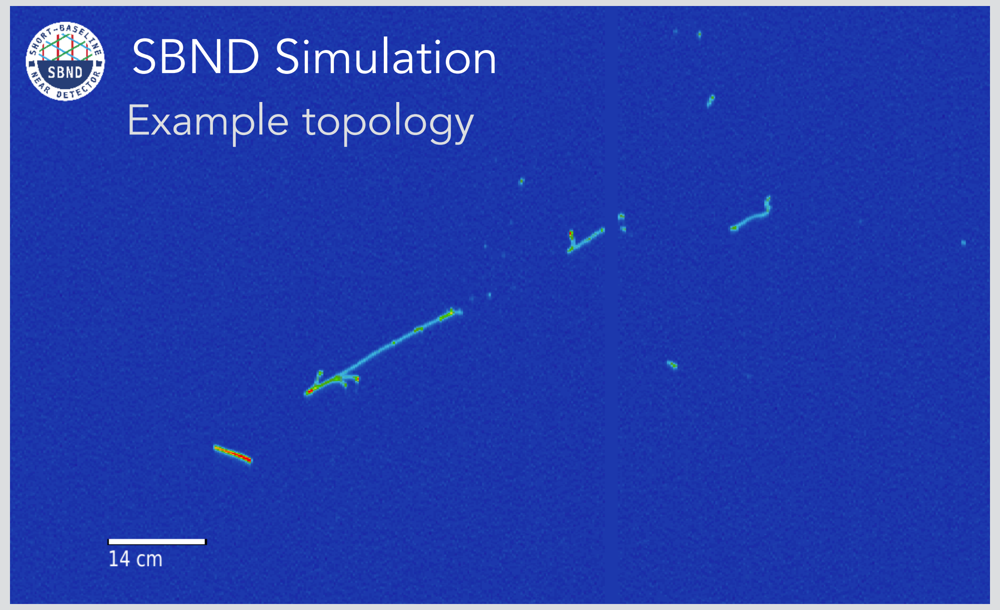
Collaboration between experimentalists and theorists is crucial for these searches.

Dark Neutrinos*



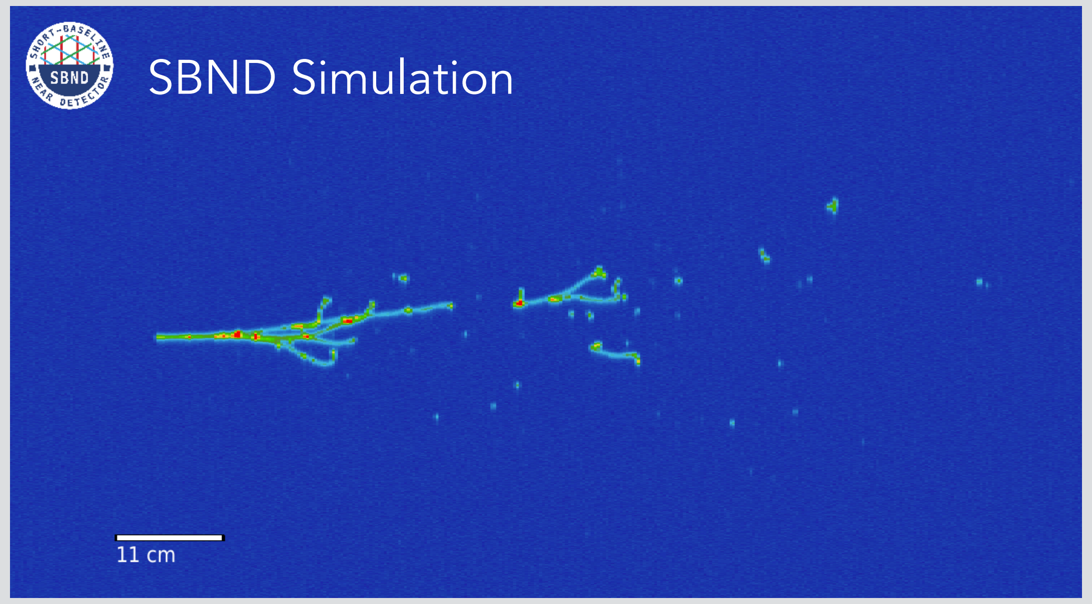
$e+e-$ pair w/ or w/o hadronic activity

Transition Magnetic Moment



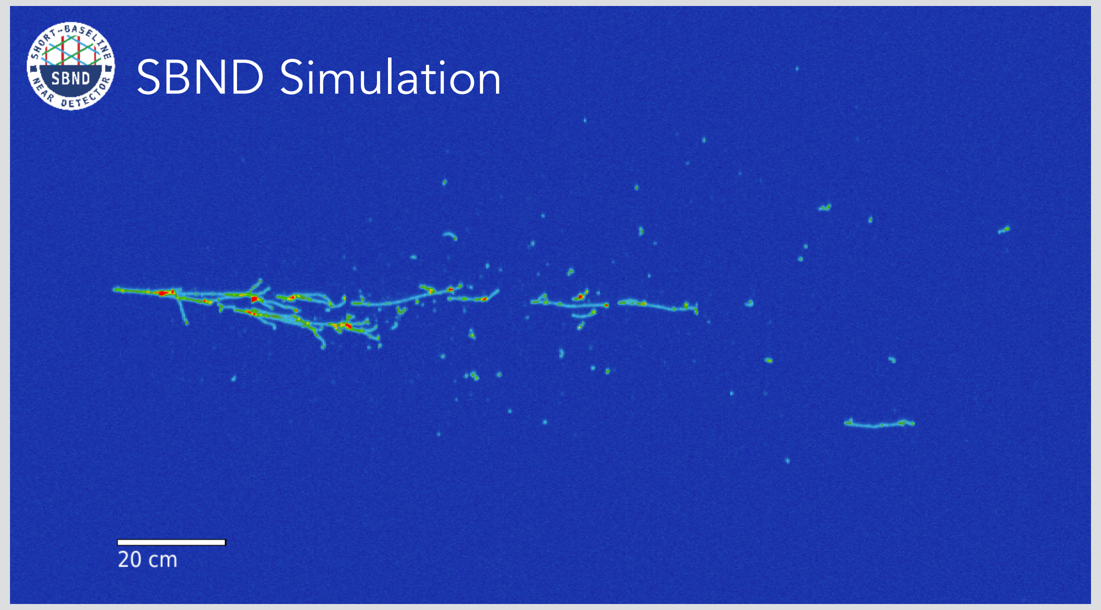
photon shower and hadronic activity

Axion-like Particles



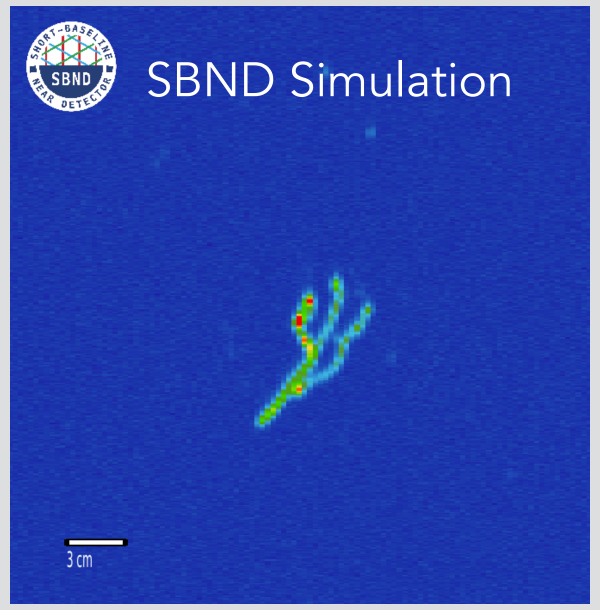
high-energy e^+e^-, $\mu^+\mu^-$

Heavy Neutral Leptons



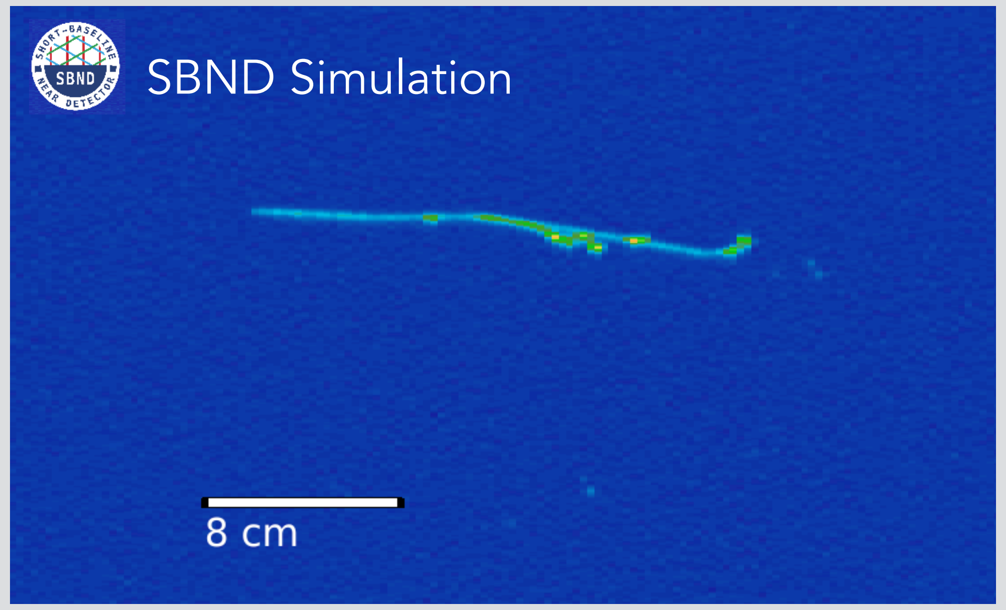
e^+e^-, $\mu^+\mu^-$, $\mu\pi$

Higgs Portal Scalar



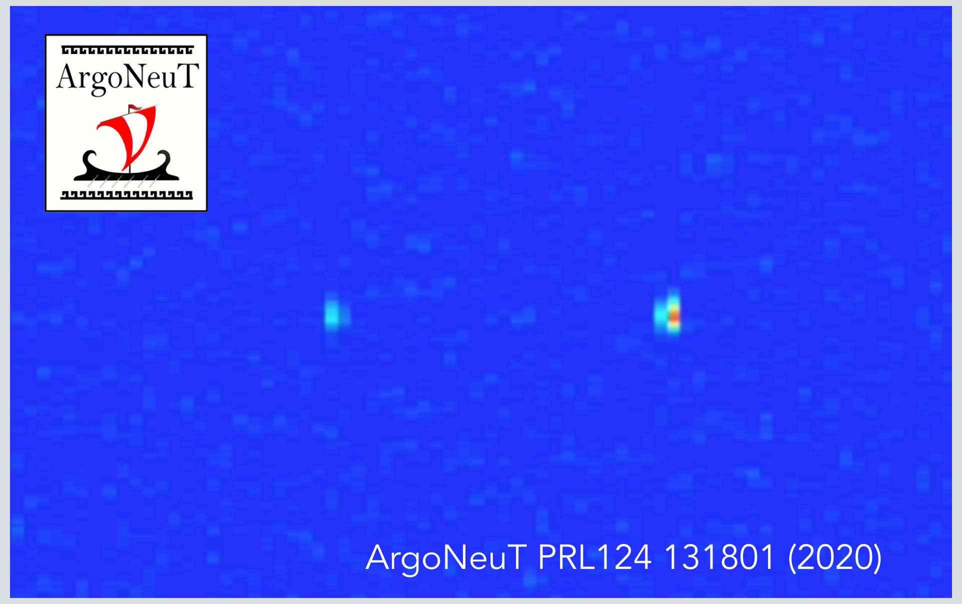
e^+e^-, $\mu^+\mu^-$, no hadronic activity

Light Dark Matter



electron scattering

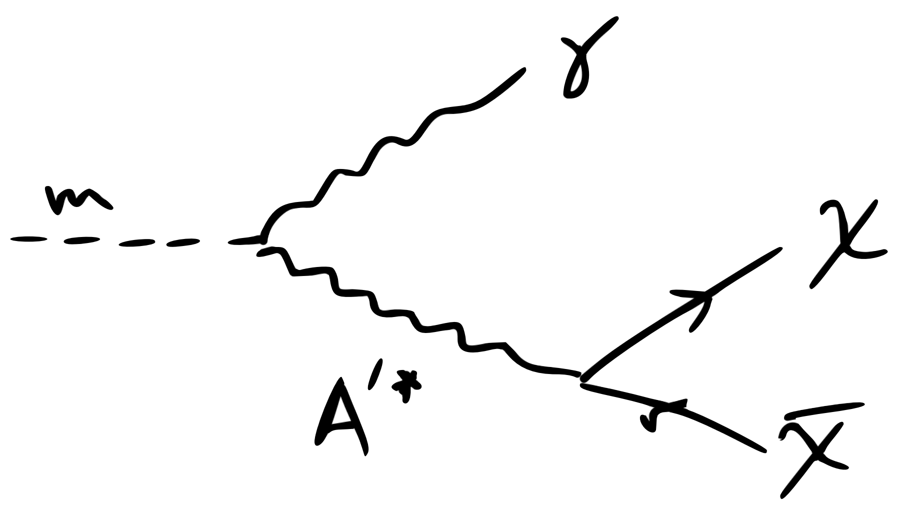
Millicharged Particles



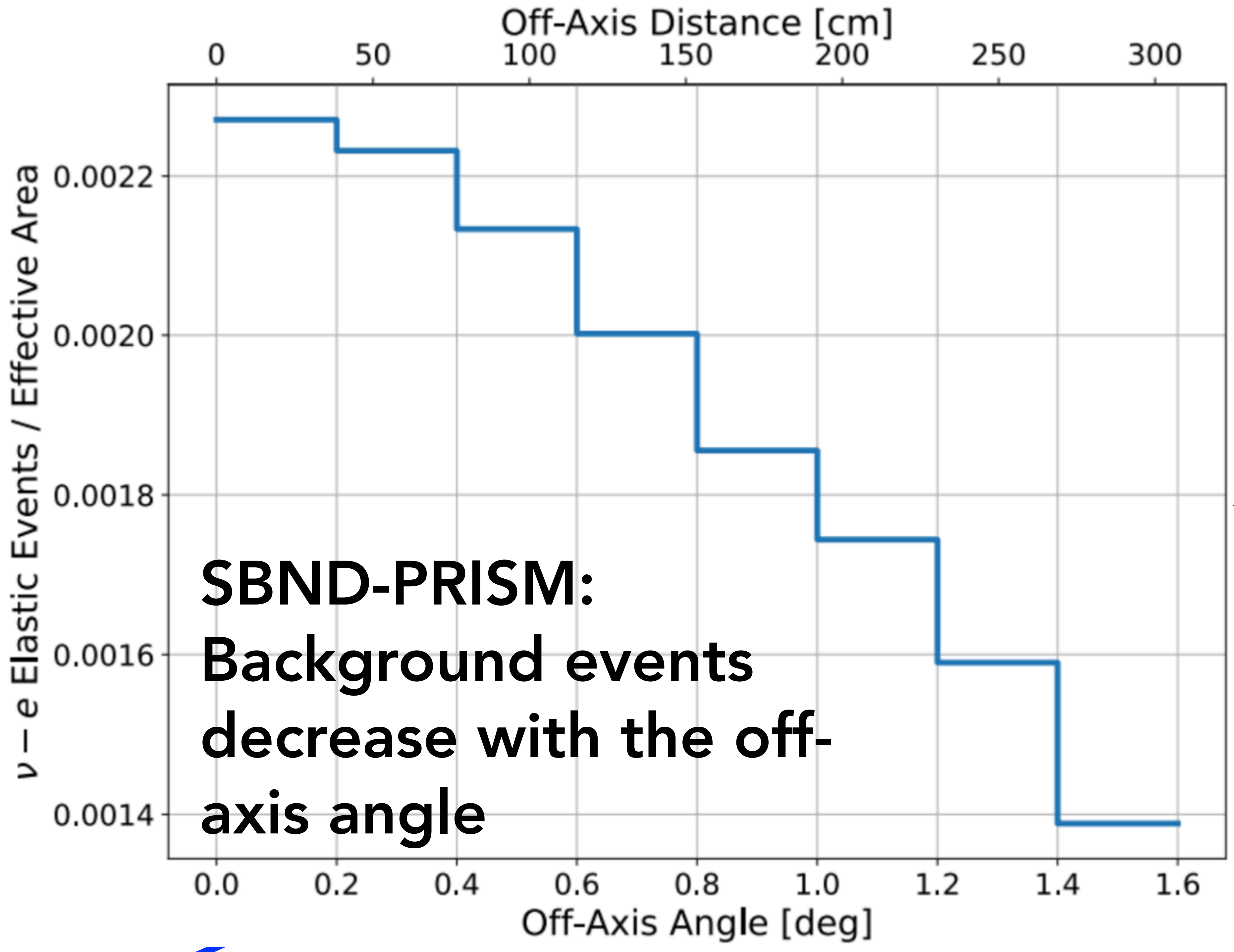
blips/faint tracks

*see presentation by I. de Icaza Astiz in the Neutrino parallel session on Wednesday.

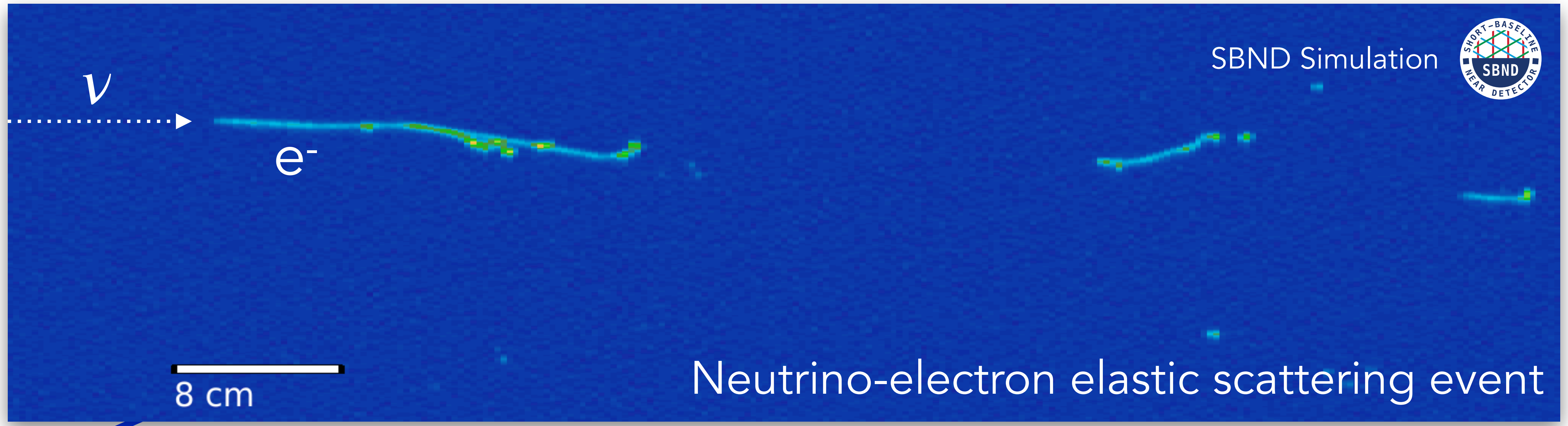
Search for Light Dark Matter in SBND



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



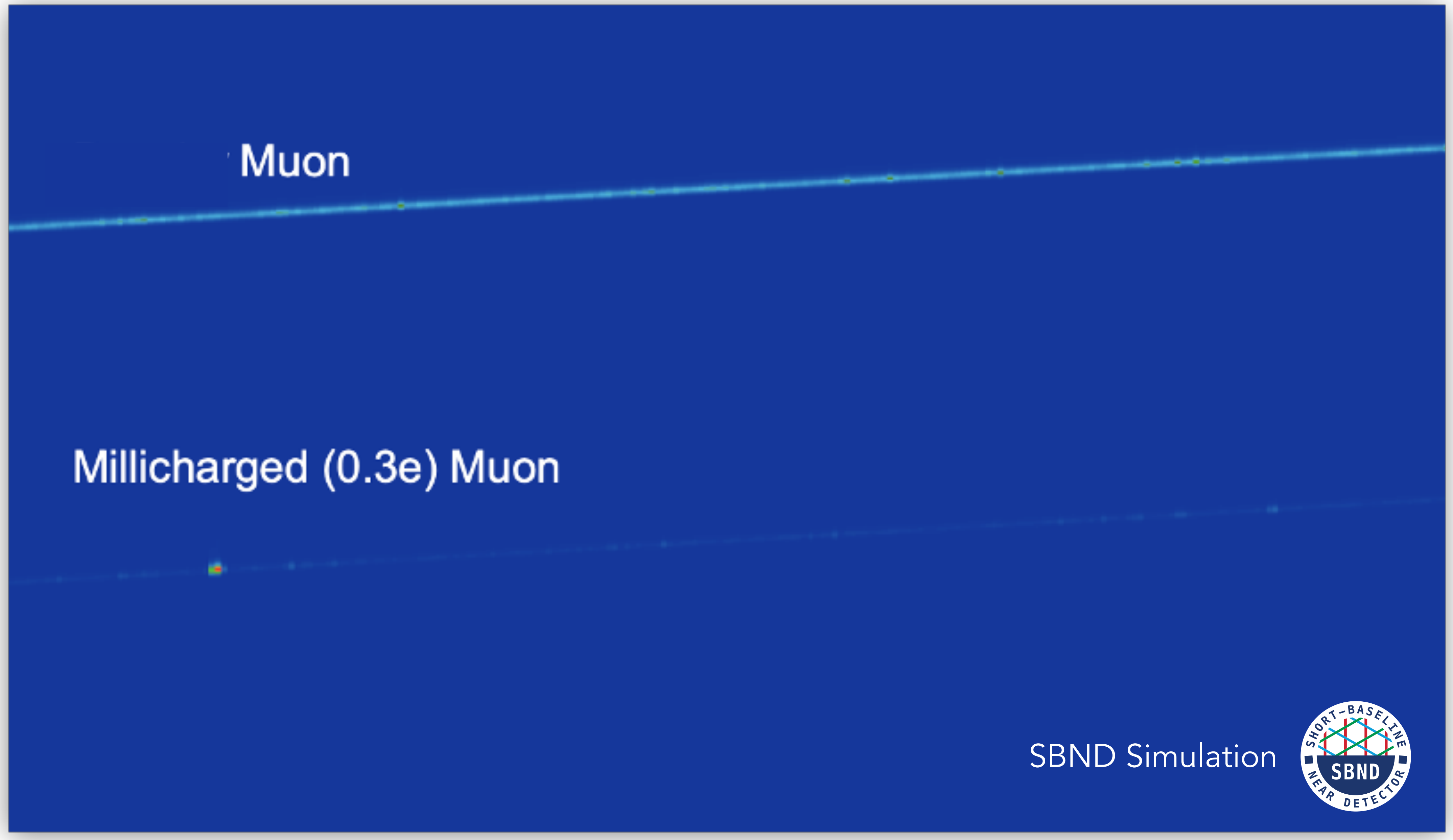
SBND-PRISM: Background events decrease with the off-axis angle



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

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

Search for Millicharged Particles in SBND



Millicharged particles would appear in SBND as **blips** or **faint tracks** pointing back to the target.
Projected SBND threshold: 50 keV

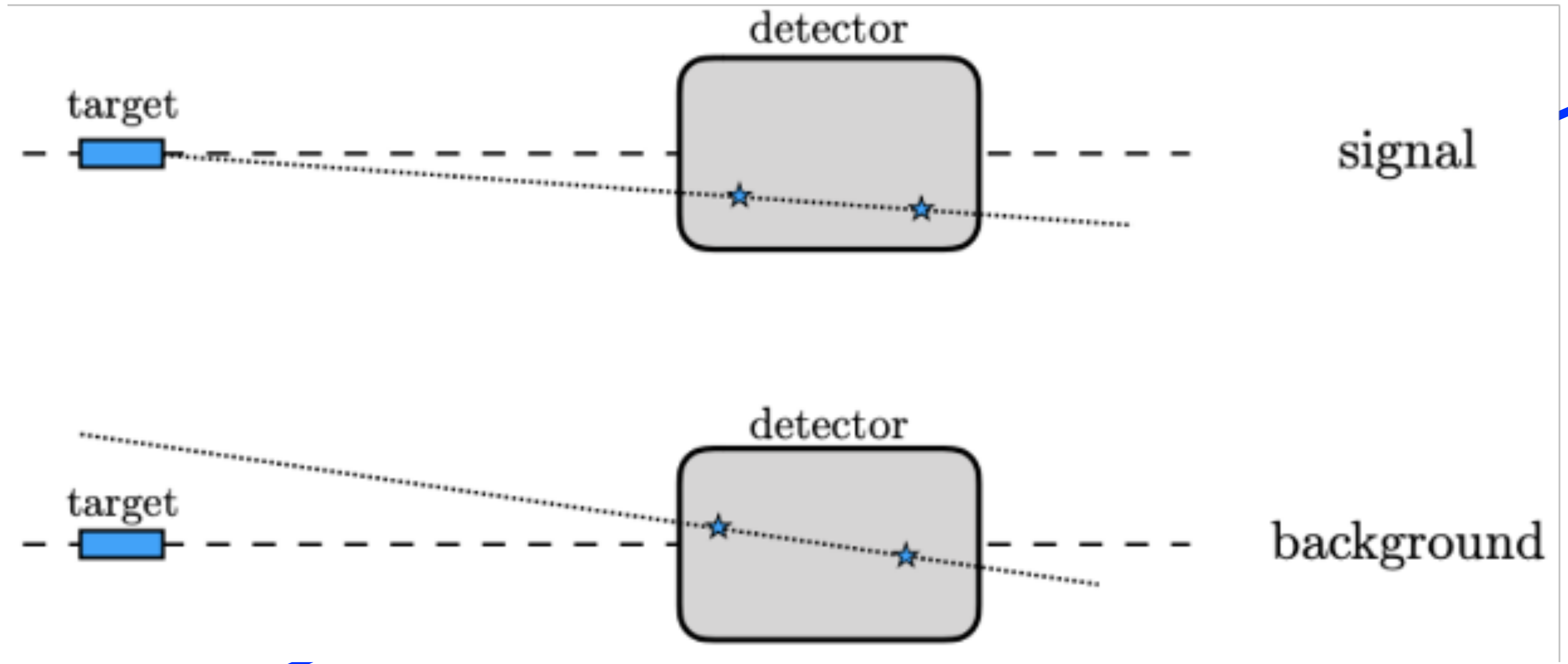
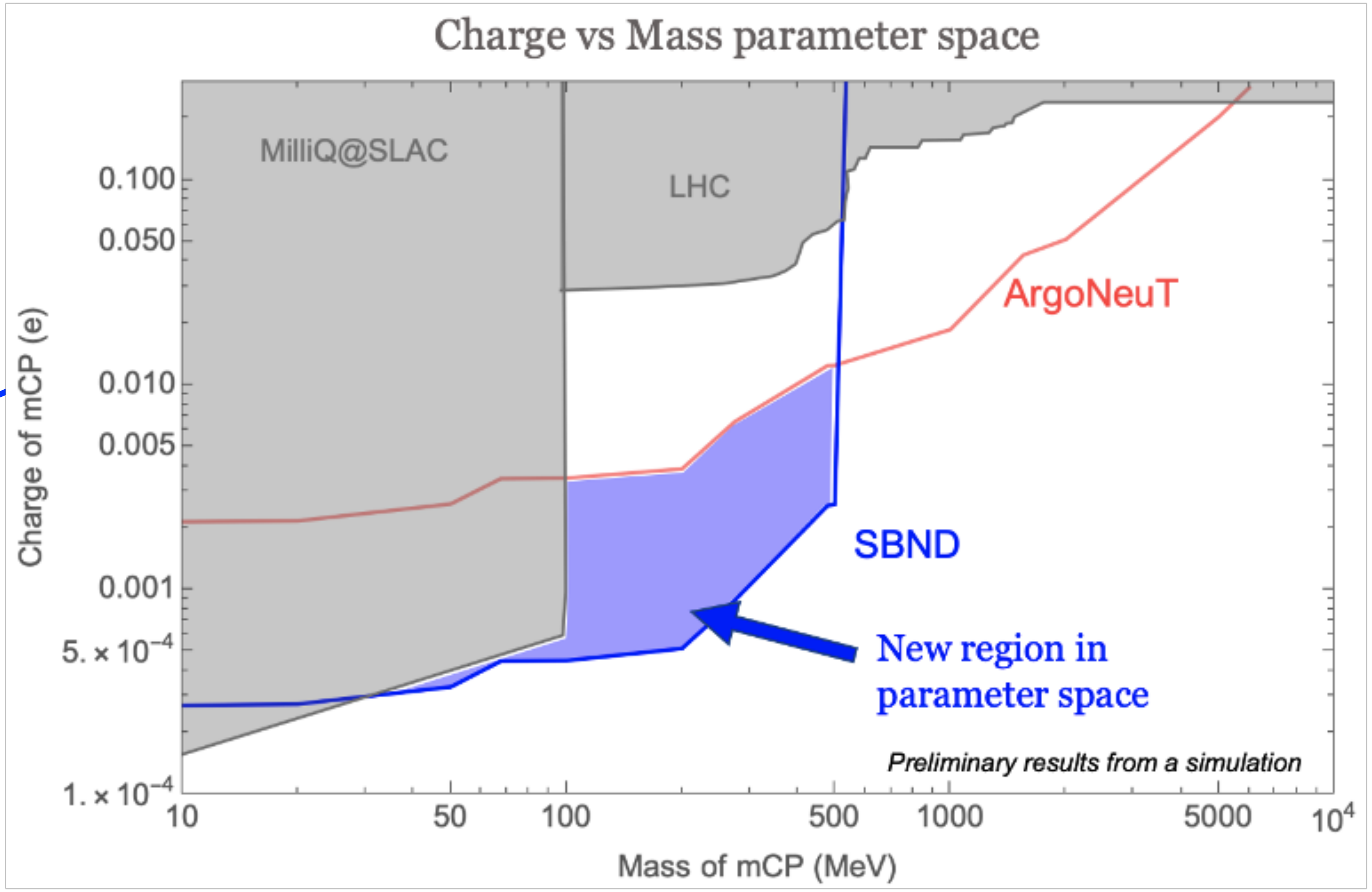


Image credit: ArgoNeuT, PRL124 131801 (2020)



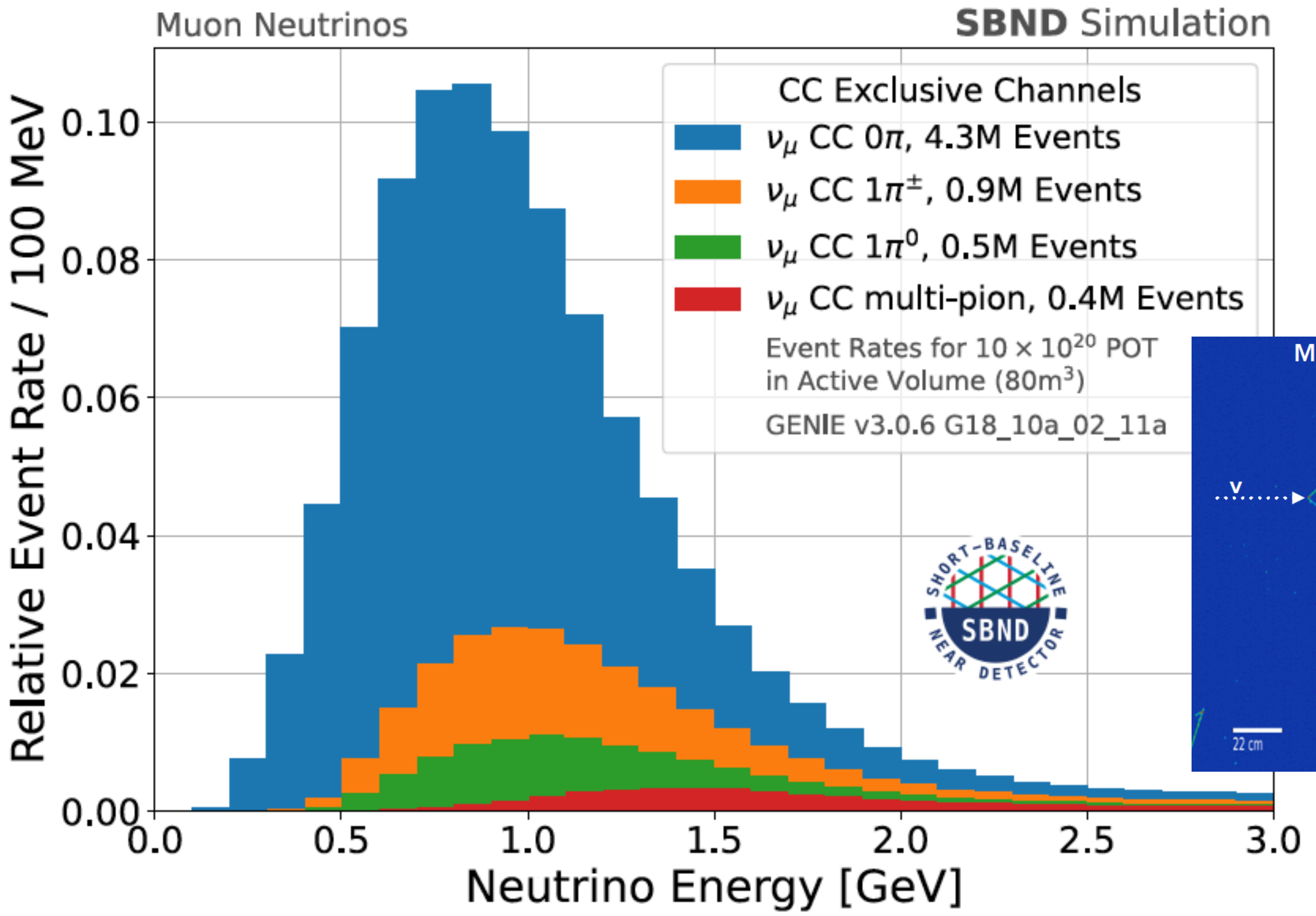
Precision Studies of Neutrino-argon Interactions in SBND

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.

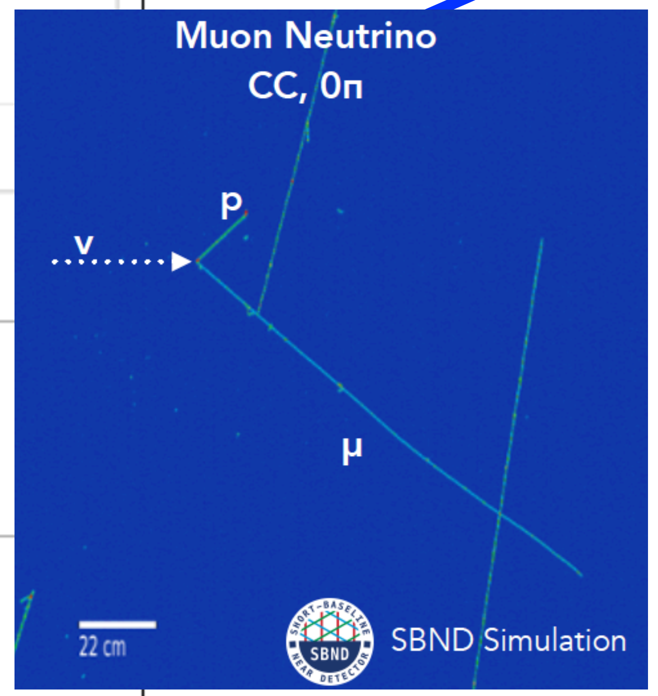
—> see presentation by V. Pandey in this session for an overview of neutrino-nucleus interactions

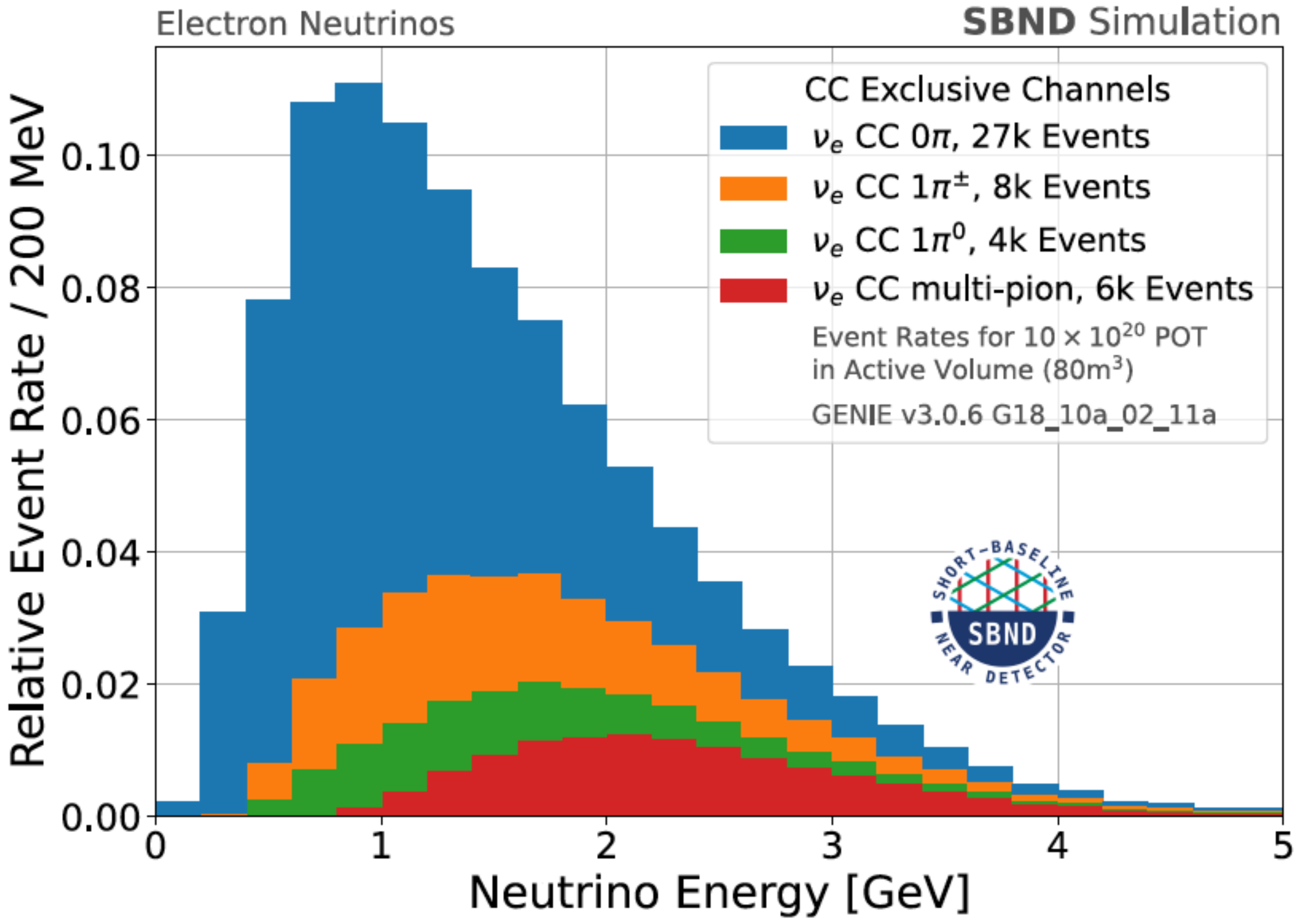
5000 ν events/per day in SBND!

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



1.5M ν_μ CC events in 1 year





12k ν_e CC events in 1 year

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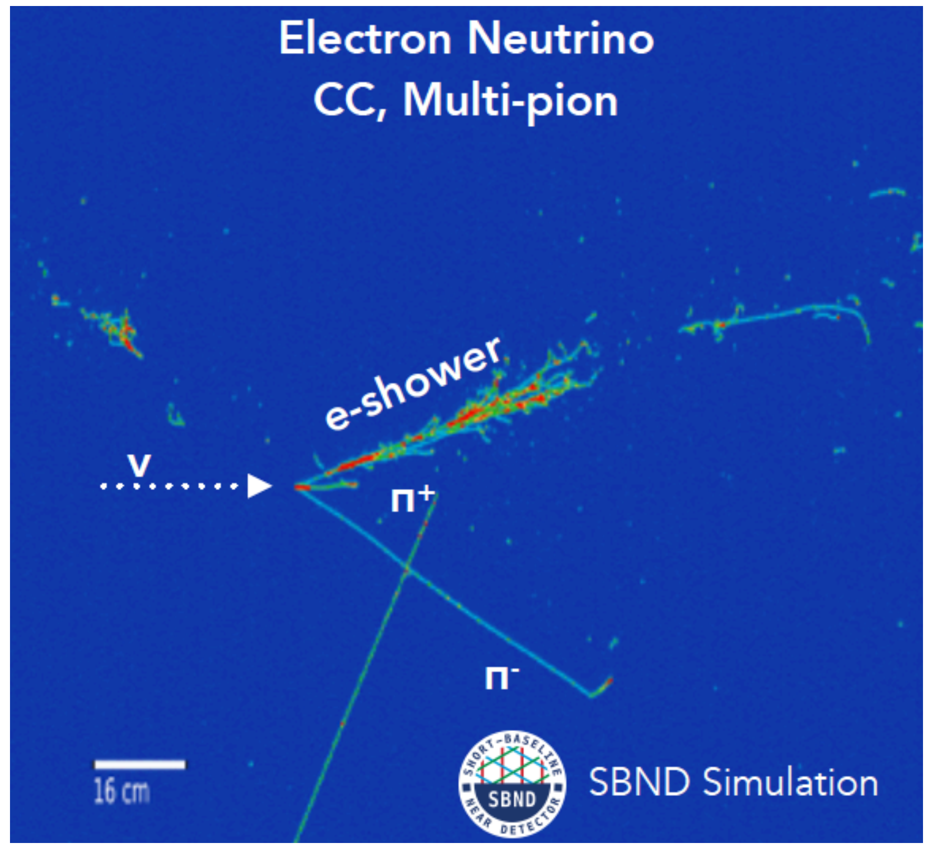
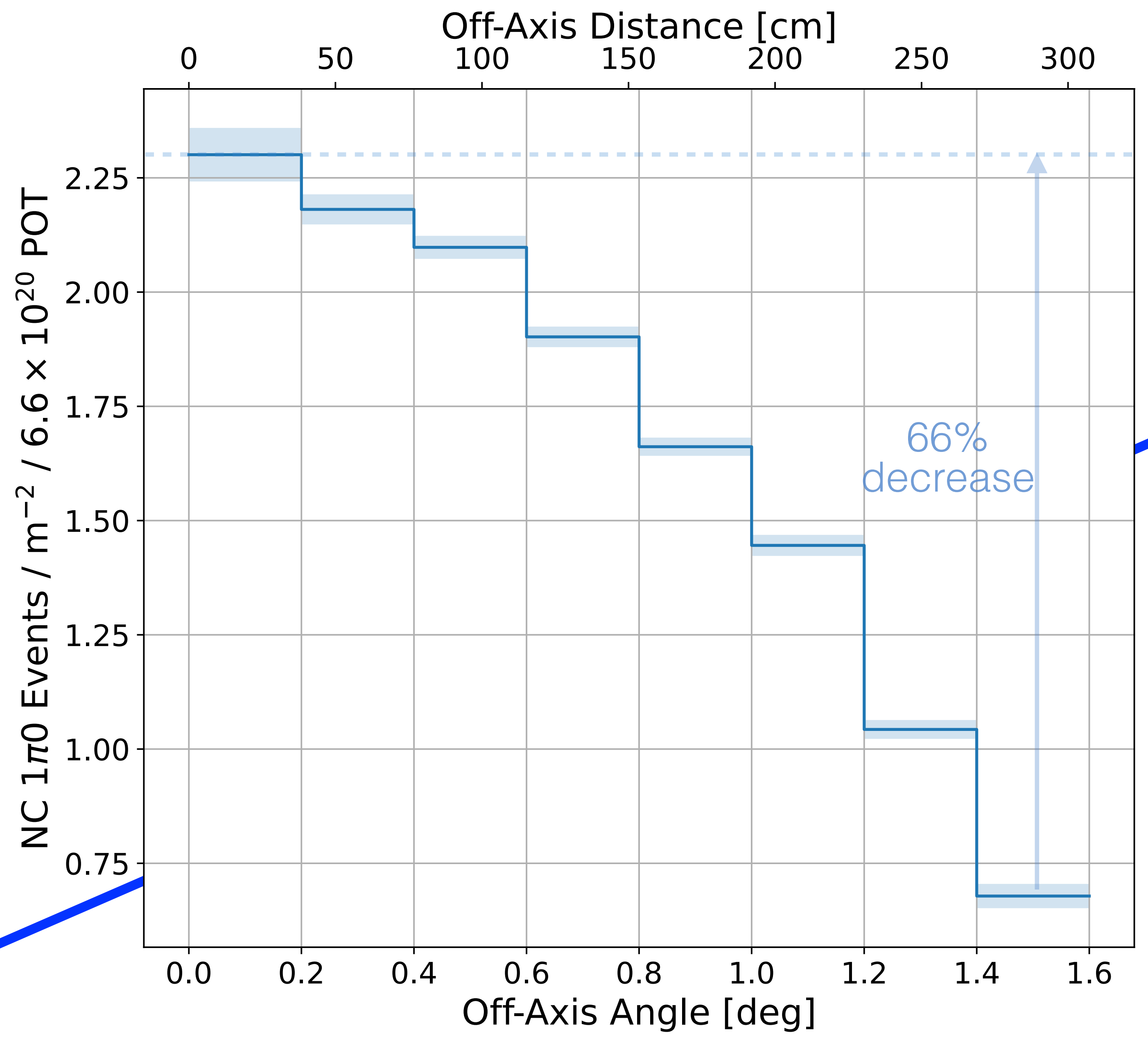
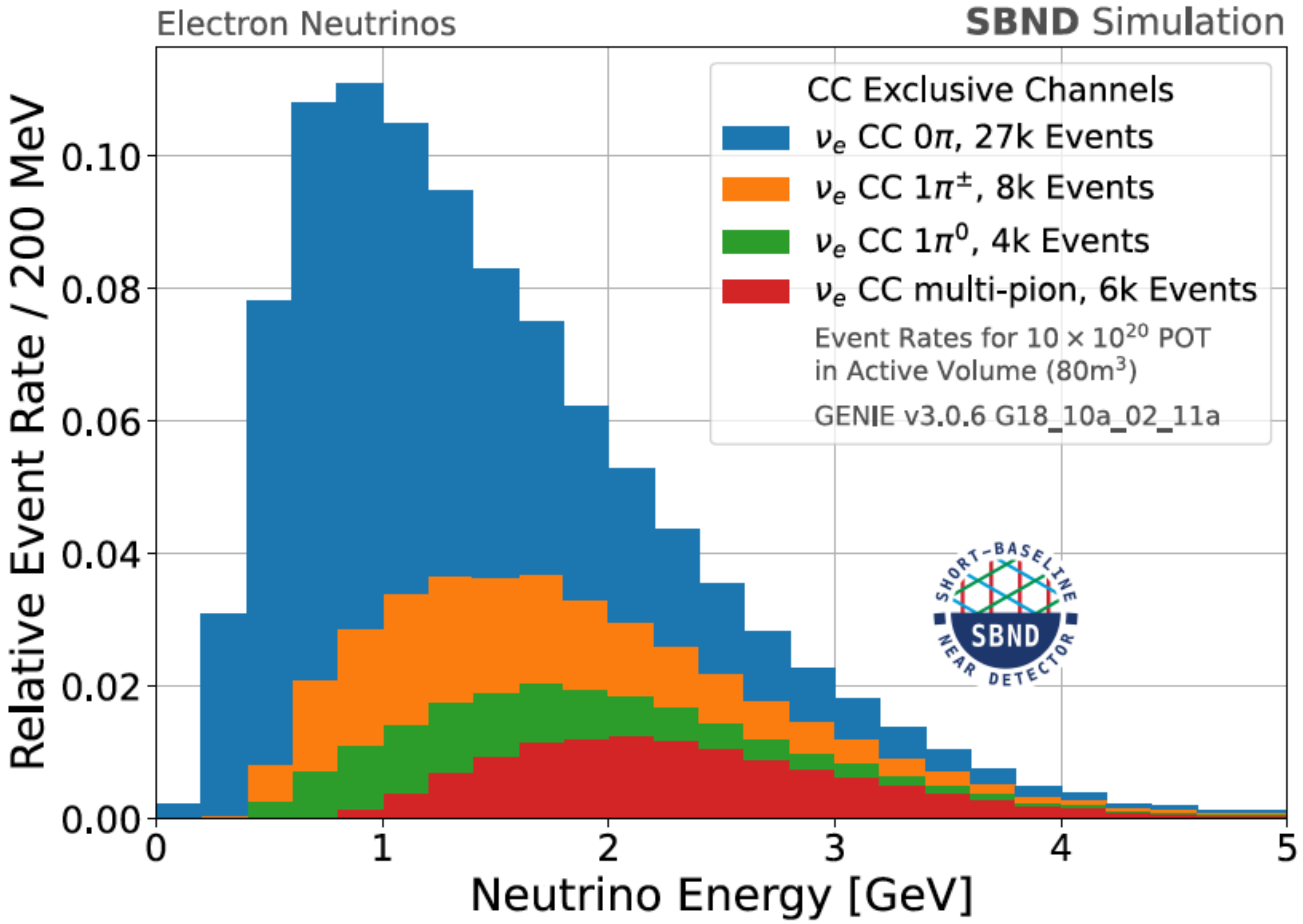




Main background: NC 1 π^0 events.
SBND-PRISM provides a natural way to **reduce background by moving off-axis**.

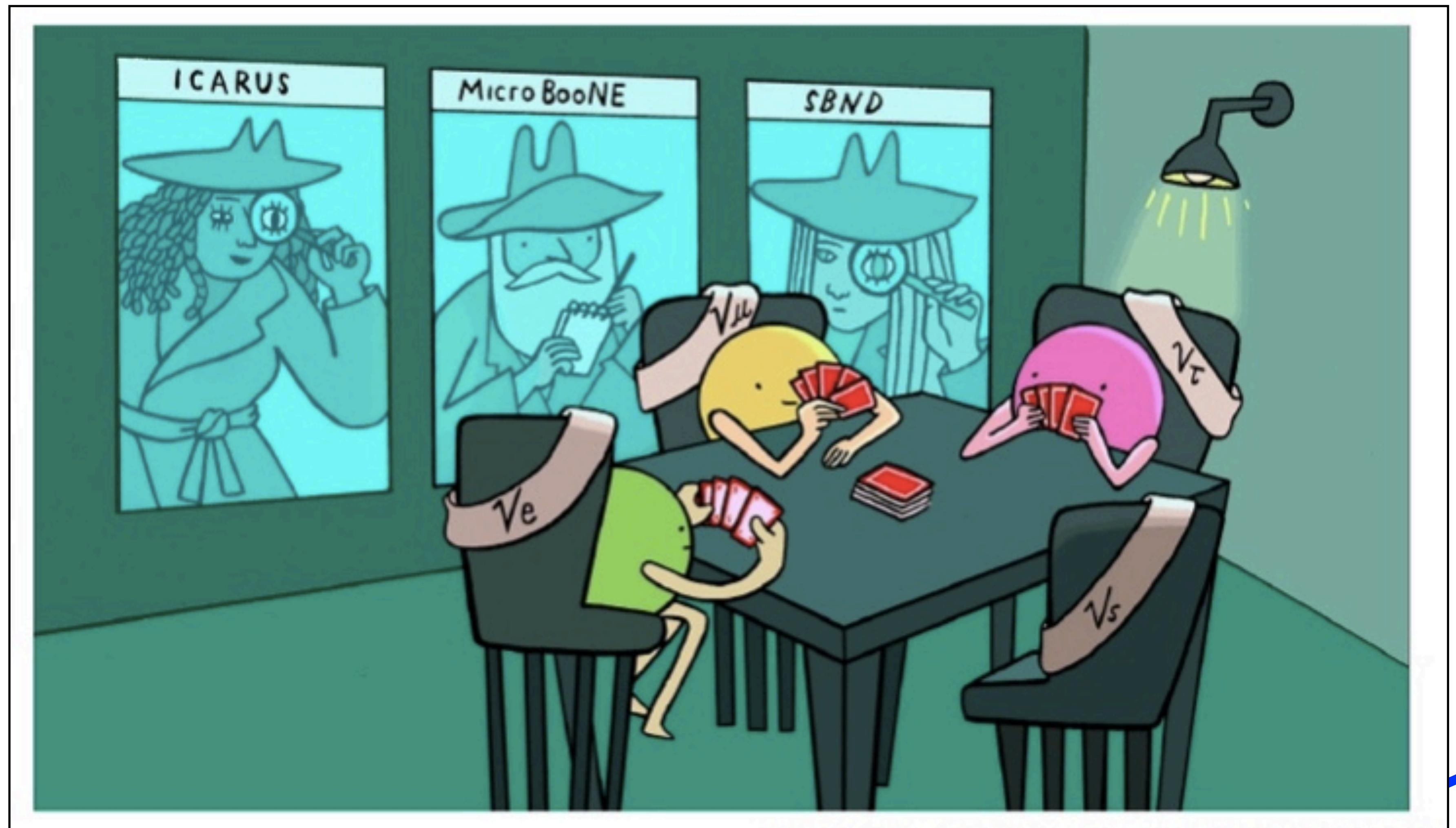


12k ν_e CC events in 1 year

Summary

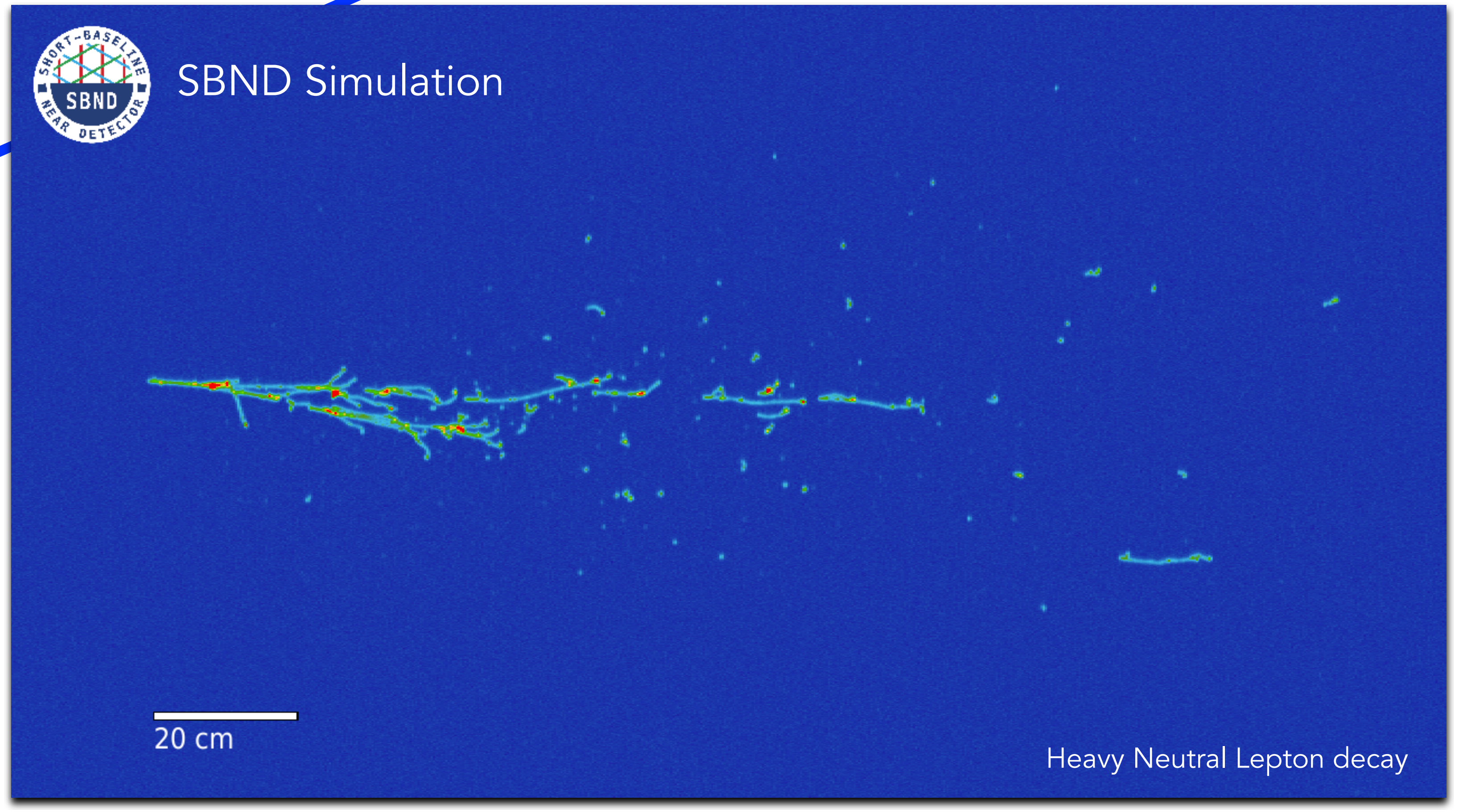
LAr TPC neutrino detectors at Short-Baseline are fantastic tools to look for new physics in the neutrino sector and beyond!

The SBN detectors will perform a world-leading search for eV-scale sterile neutrinos.



Artwork by Sandbox Studio, Chicago with Corinne Mucha

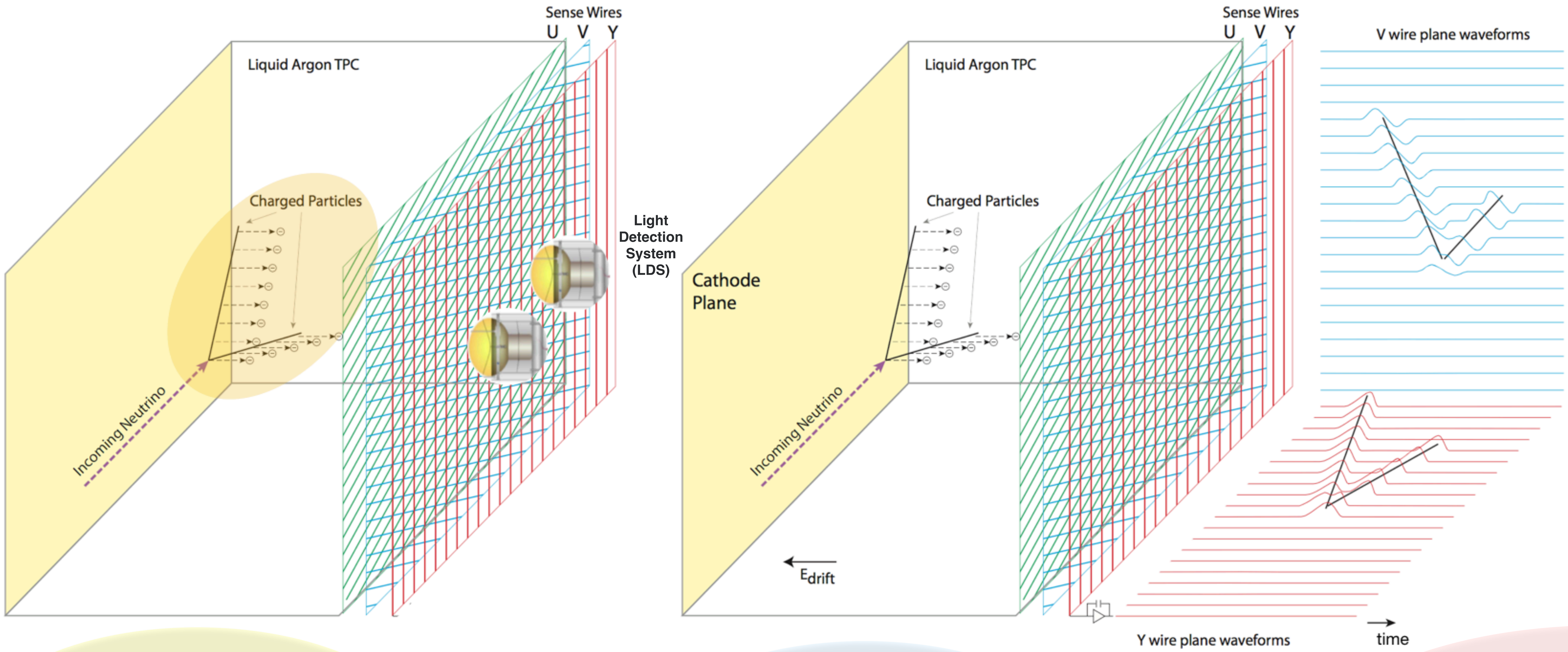
Beyond oscillation searches, the SBND has a broad science goal, which addresses alternative explanations of the Short-Baseline anomalies, includes other BSM explorations and precision studies of neutrino-argon interactions.



Exciting times are ahead for the Short-Baseline Neutrino Program. ICARUS is collecting data. SBND completed the construction of the and will begin operations next year.

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

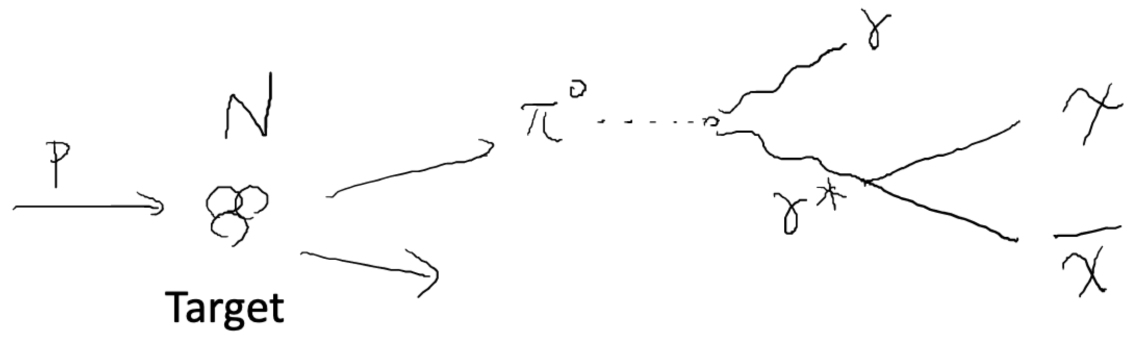
VUV photons propagate and are shifted into VIS photons

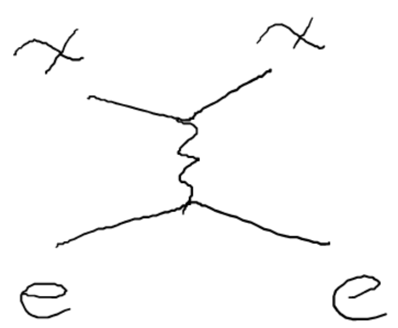
Scintillation light fast signals from LDSs give event timing

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)



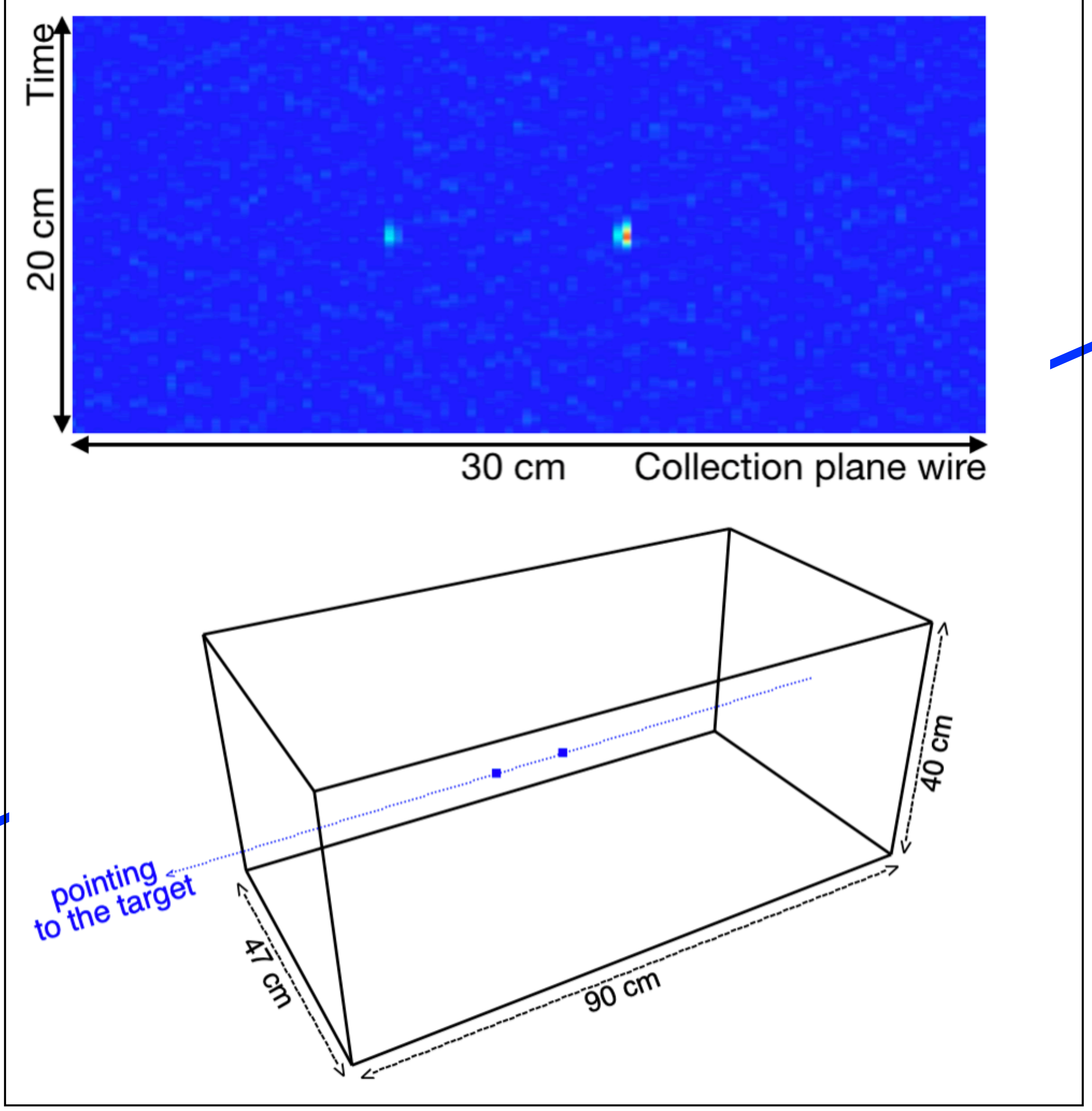


- production: meson decays
- detection: scattering electron

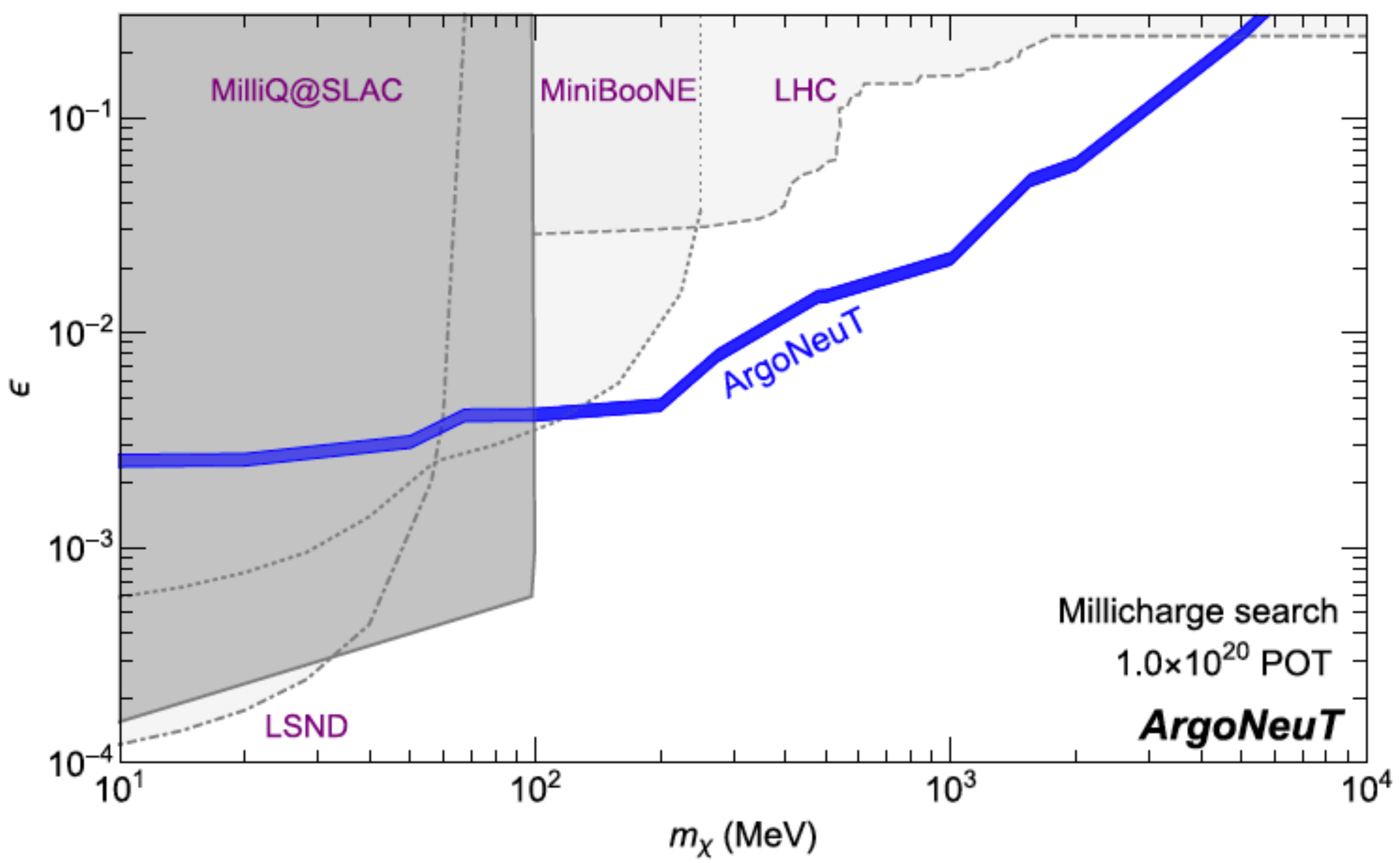
Low energy threshold (300 KeV) is the key!

one mCP Signal Candidate Event observed

[compatible with the expected background]



R. Acciarri et al., PRL124 131801 (2020)



Leading constraints in unexplored parameter region!

Searches for new physics in LAr TPC: ArgoNeuT

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

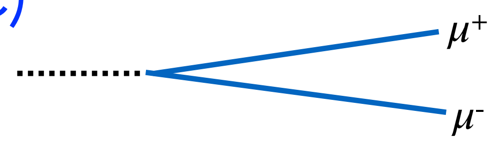
Assuming HNL production predominately from $\tau^\pm$ decay*:

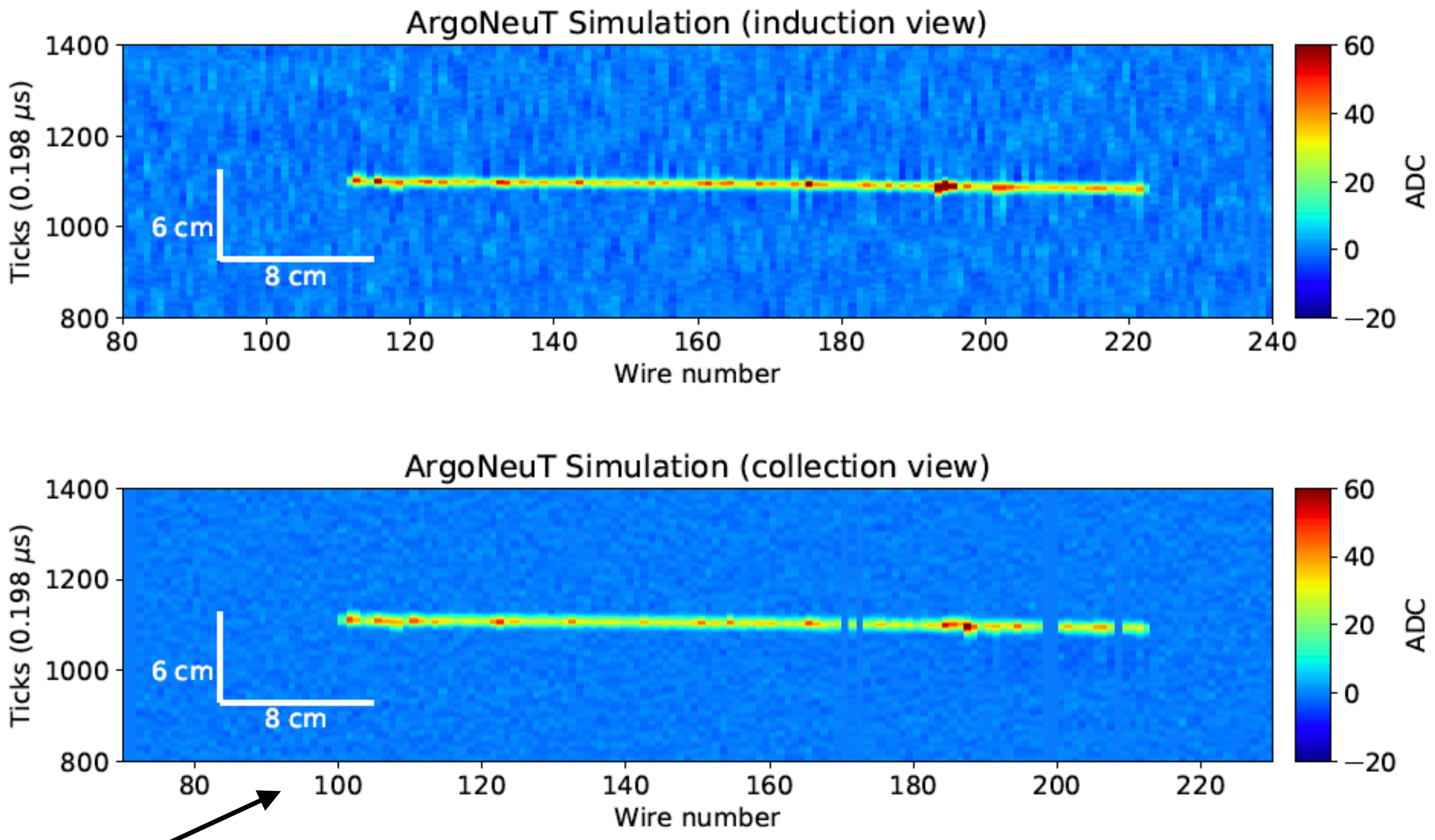
D/D_s decay to τ, that subsequently decay to HNLs

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

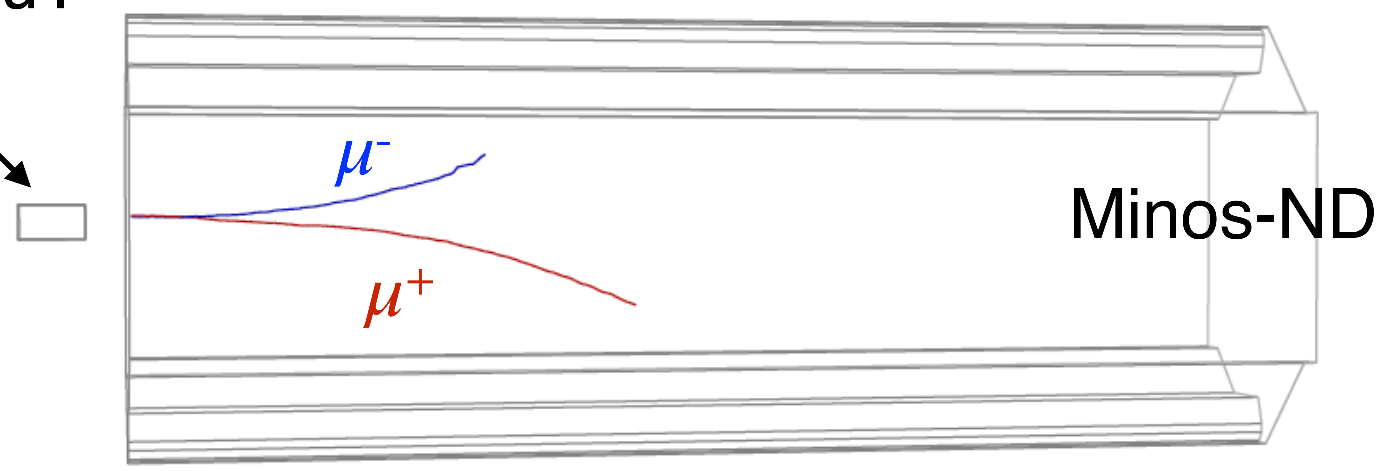
HNL decay (MC)

$N \rightarrow \nu\mu^+\mu^-$





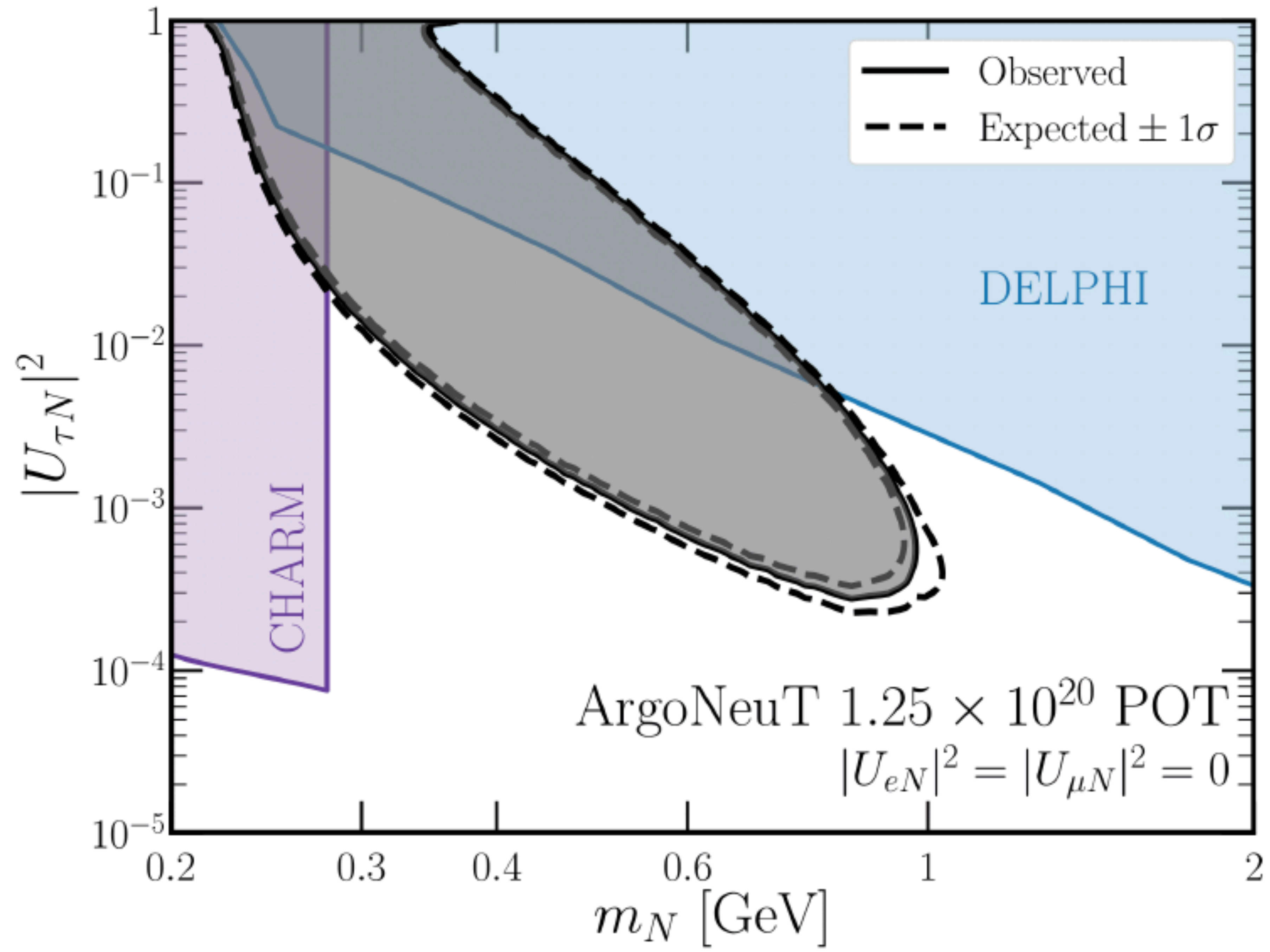
ArgoNeuT



*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

R. Acciarri et al., PRL 127 121801 (2021)



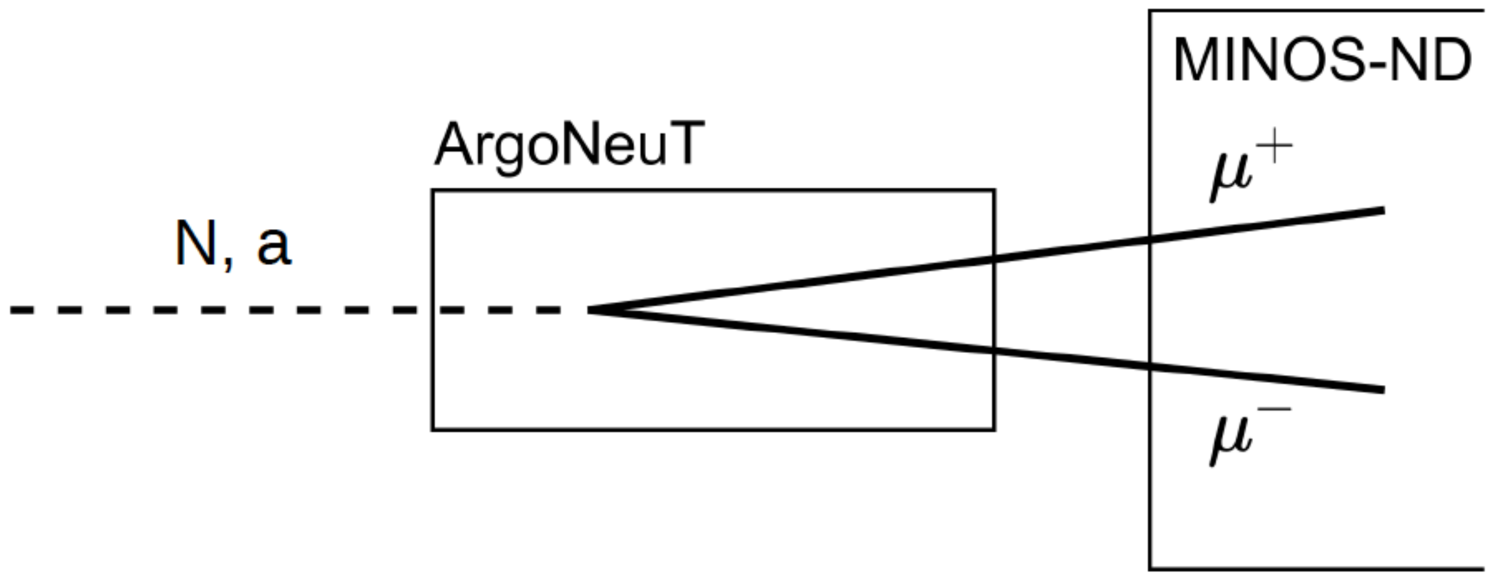
Significant increase in the parameter space exclusion region!

Searches for new physics in LAr TPC: ArgoNeuT

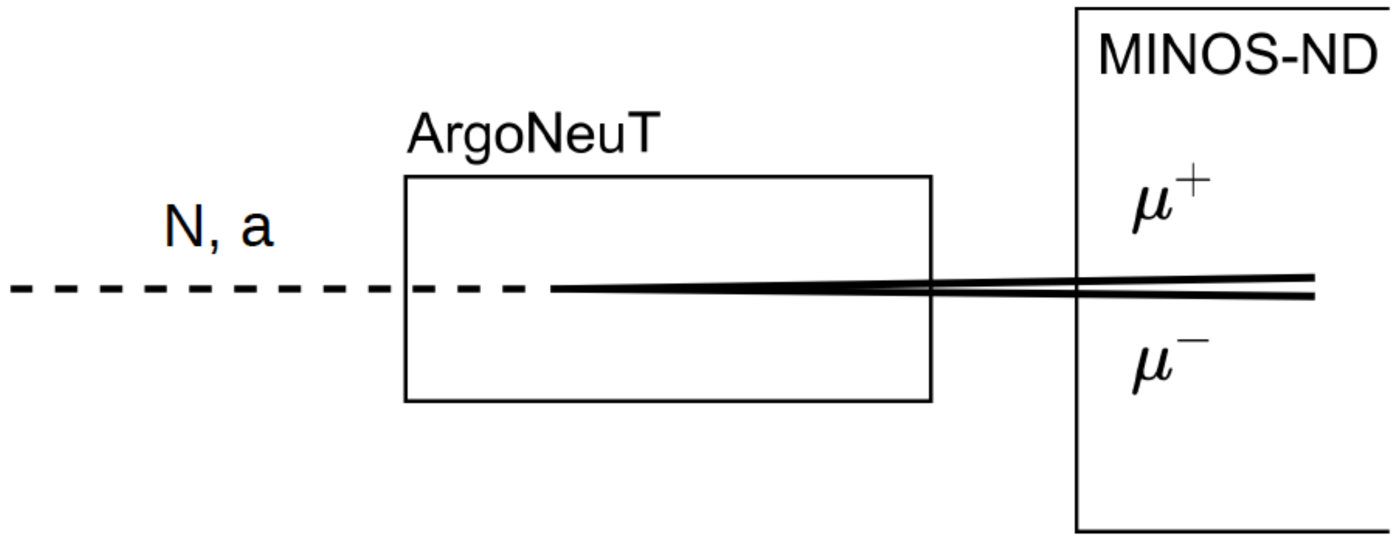
First search for Heavy QCD Axions in LAr TPC

Heavy QCD axions production from π^0, η and η' mesons.*
Heavy QCD axions decay to ee, μμ, γγ + hadronic modes..
Contributions depend on axion-lepton coupling, c_l: two benchmark scenarios $c_l = 1/36$ and $c_l = 1/100$.
In ArgoNeuT search for: $a \rightarrow \mu^+ + \mu^-$

Two-track Event



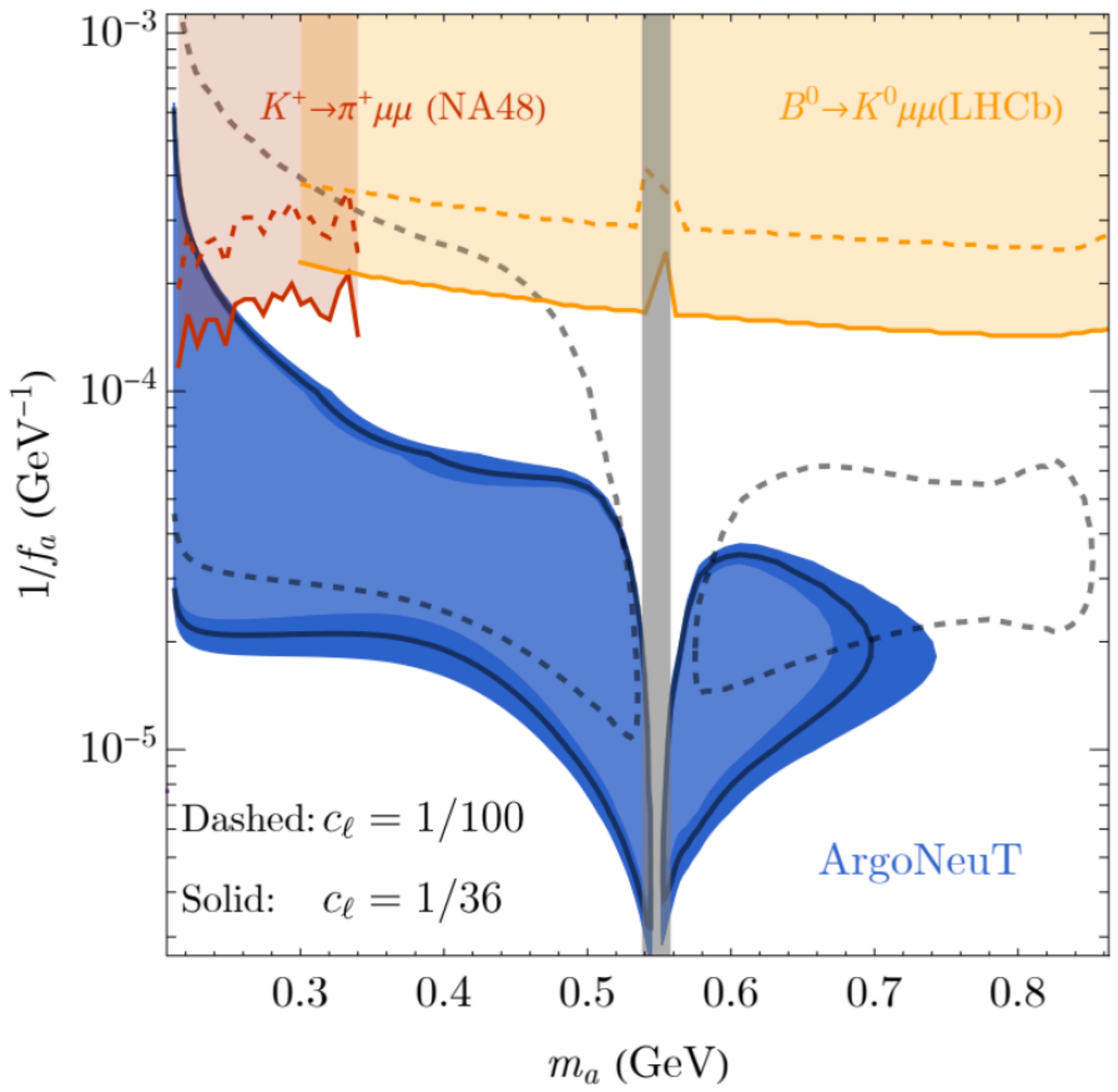
Double-MIP Event



*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

R. Acciarri et al., *https://arxiv.org/abs/2207.08448*



New exclusion constraints for heavy QCD axions with $m_a \sim 0.2 - 0.9$ GeV andaxion decay constant $f_a \sim 10$ TeV