Sterile Neutrino and Short Baseline Neutrino (SBN) Program

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NuSteam/NuPumas @BNL 2024

Brookhaven National Laboratory

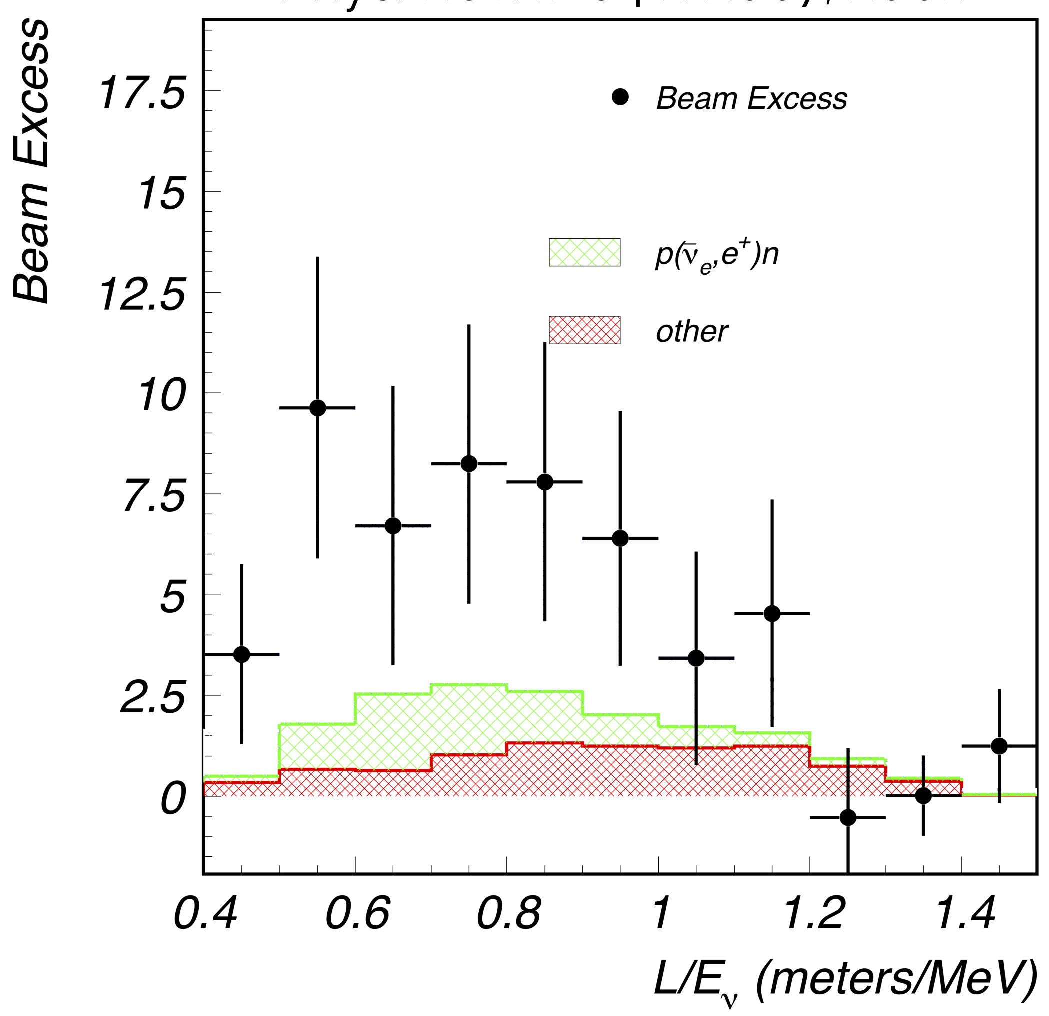
Outline

- **recap: remaining questions in neutrino physics**
- sterile neutrino: what is it, why is it, and how do we detect it
- Short Baseline Neutrino (SBN) Program @ Fermilab

Why do we want to detect neutrinos?

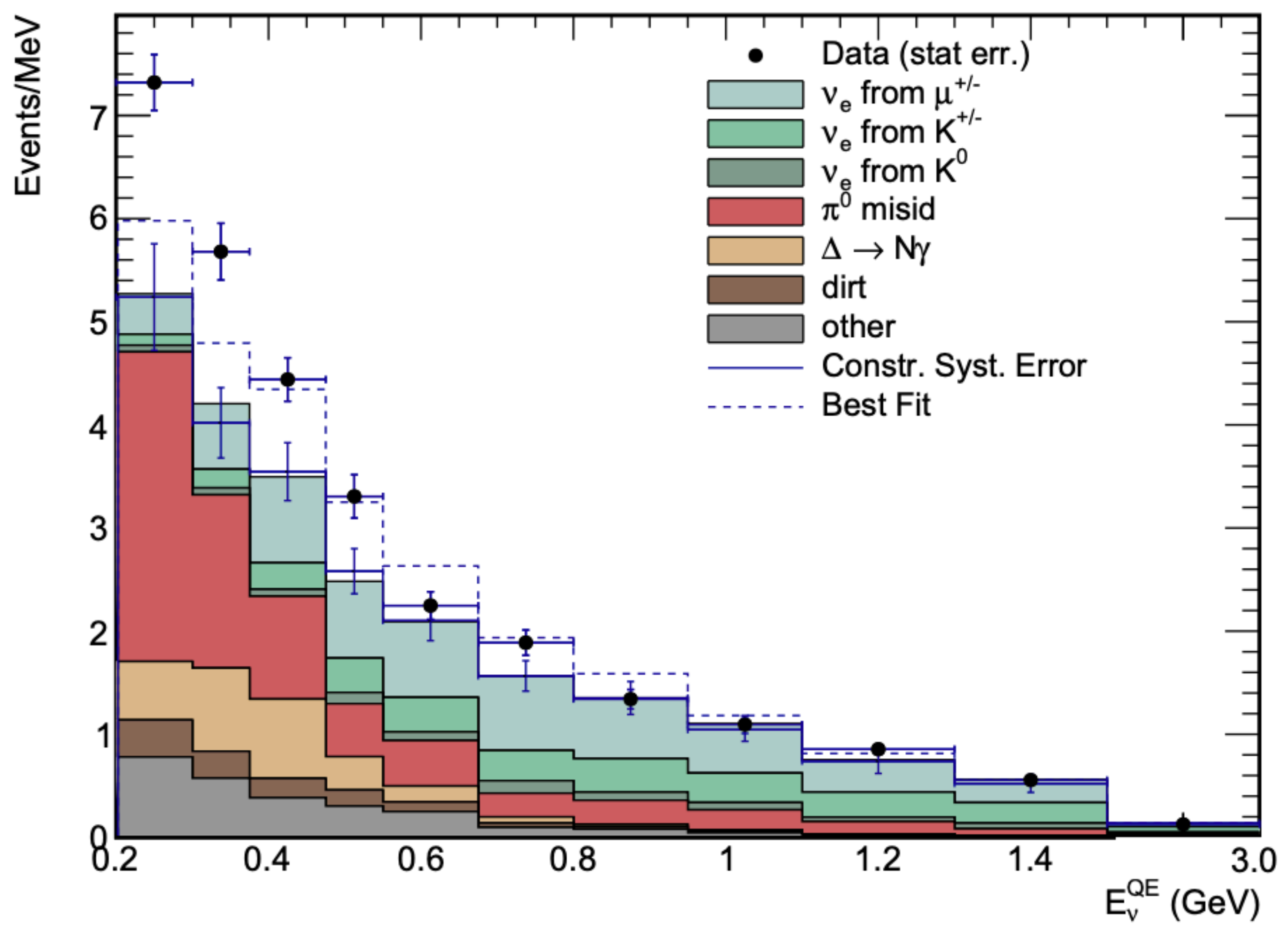
- we are already starting to see few "anomalies" in the neutrino physics
  - seeing results where the measurements and our best prediction of neutrinos start to disagree
  - remember the Solar neutrino problem?
  - will these lead to a discovery of new physics?

Phys. Rev. D 64 112007, 2001

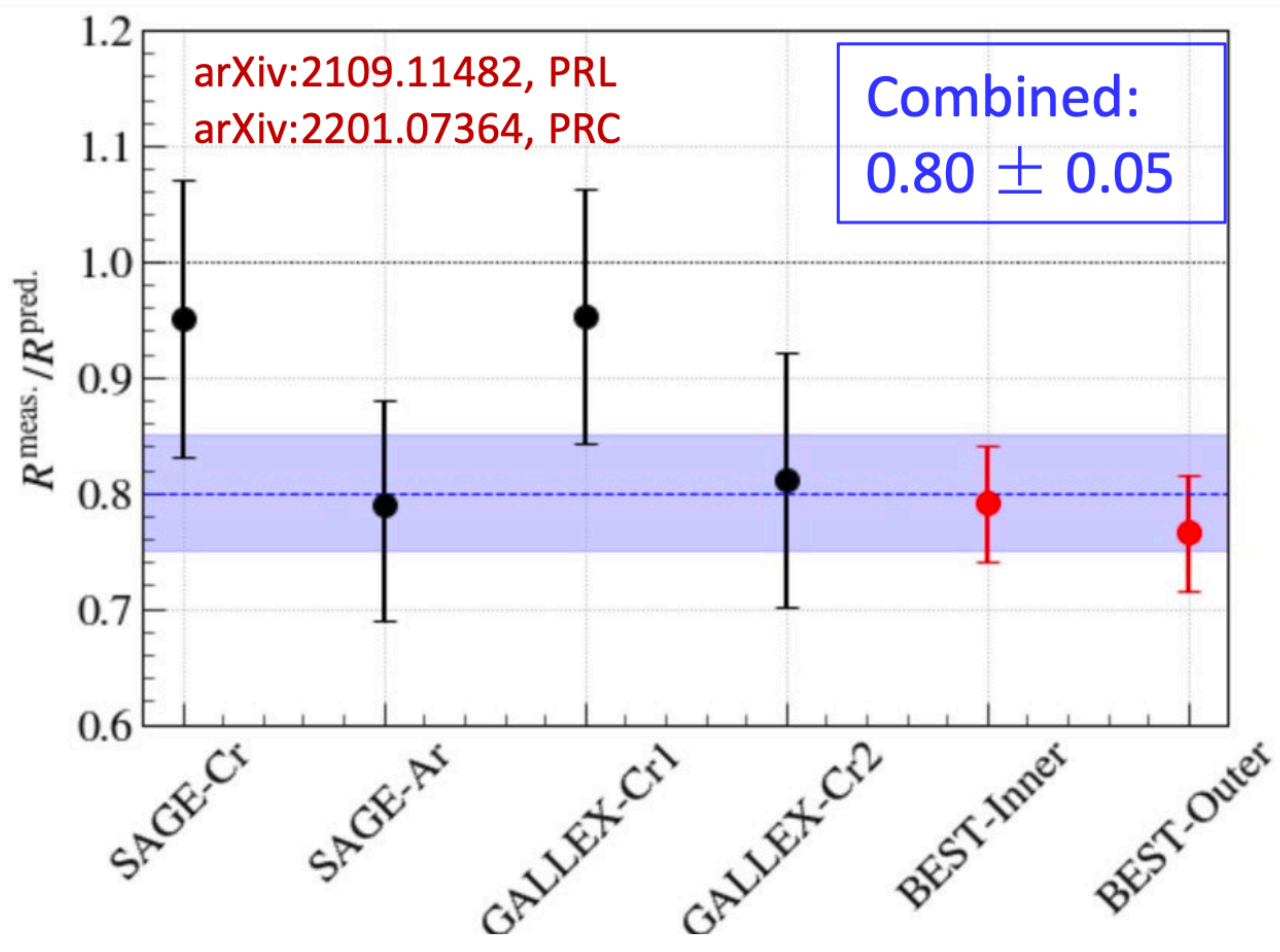


LSND anomaly

Phys. Rev. D 103, 052002 (2021)



MiniBooNE anomaly



Gallium anomaly

remaining questions in ν-physics

standard model

could **CP violation** in neutrino interactions explain the matter/antimatter asymmetry?

what is the **ordering of the neutrino mass**?

beyond the standard model

are there **new interactions** we could discover via neutrino?

are there **additional neutrinos** beyond known three types?

what is neutrino mass?

is the neutrino its own anti particle?

remaining questions in ν-physics

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Outline

- recap: remaining questions in neutrino physics
- **sterile neutrino: what is it, why is it, and how do we detect it**
- Short Baseline Neutrino (SBN) Program @ Fermilab

Why add extra neutrino?

- since the detection of neutrino and oscillation, many experiments start to collect & analyze neutrino data

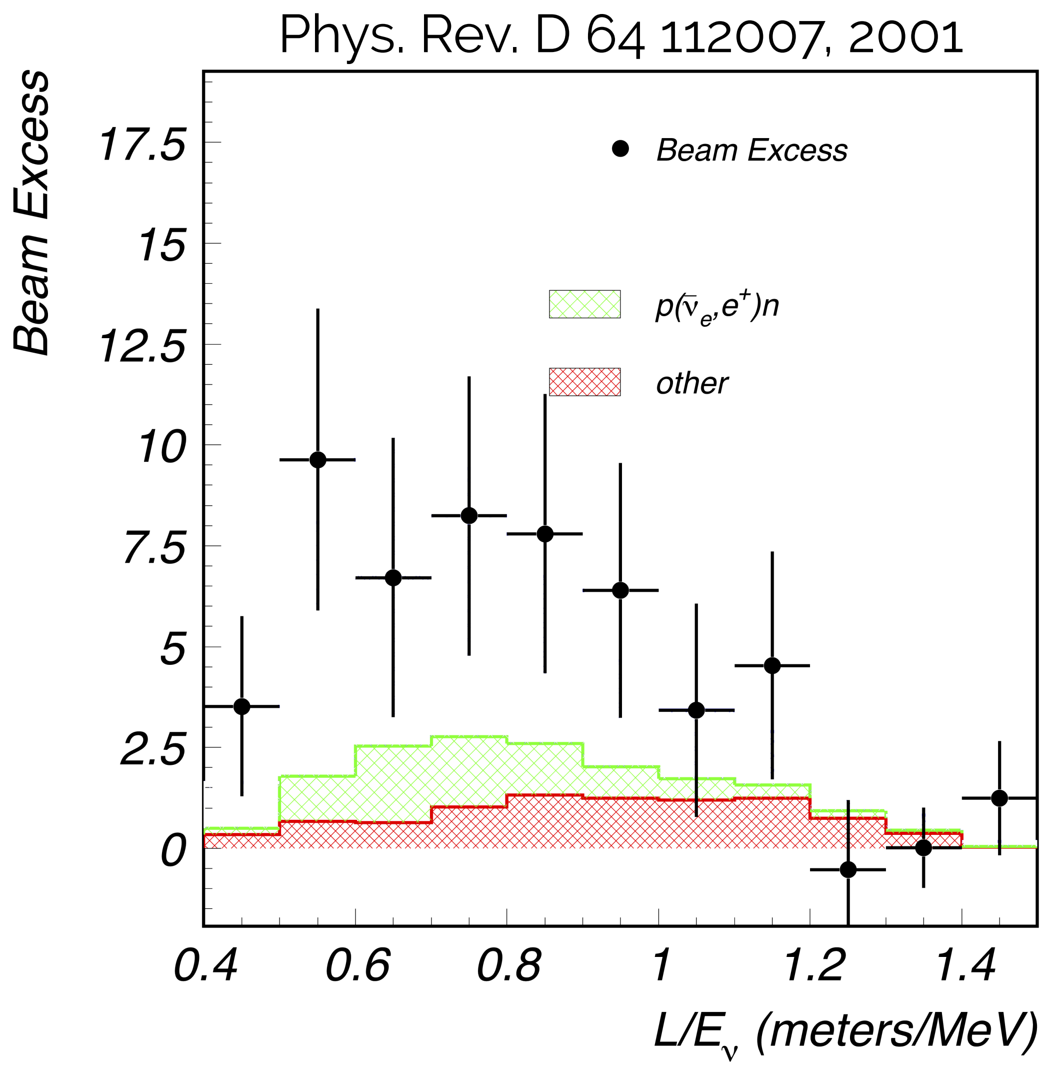
- several experiments have found series of anomalous results

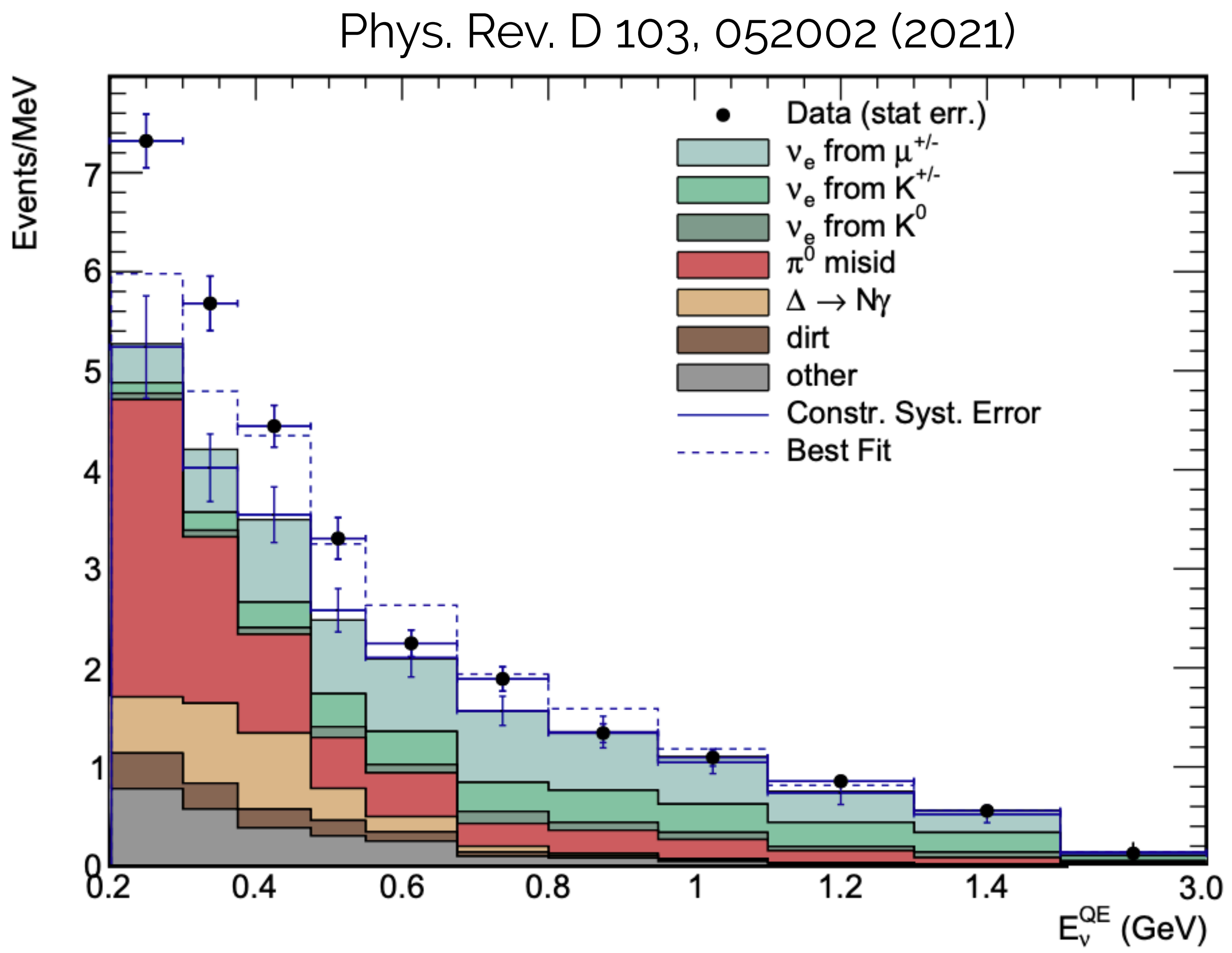
  - anomalous in a way that "observation" (detected/measured data) does not agree with "prediction" (simulation/model generated with the current best of our knowledge)

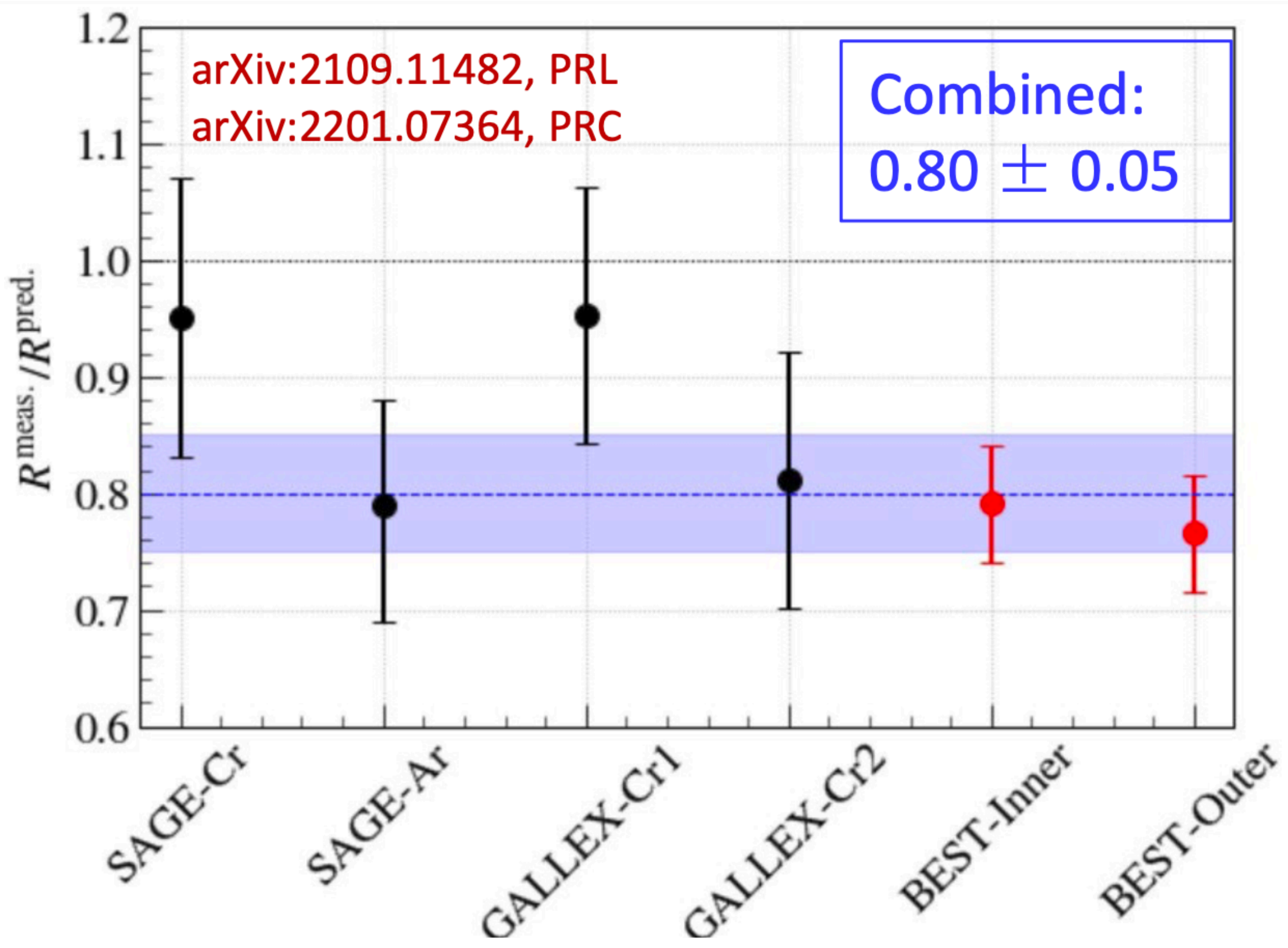
  - LSND: measured more ν_e than predicted

  - MiniBooNE: measured more ν_e than predicted

  - GALLEX/SAGE/BEST: measured less ν_e than predicted







Why add extra neutrino?

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

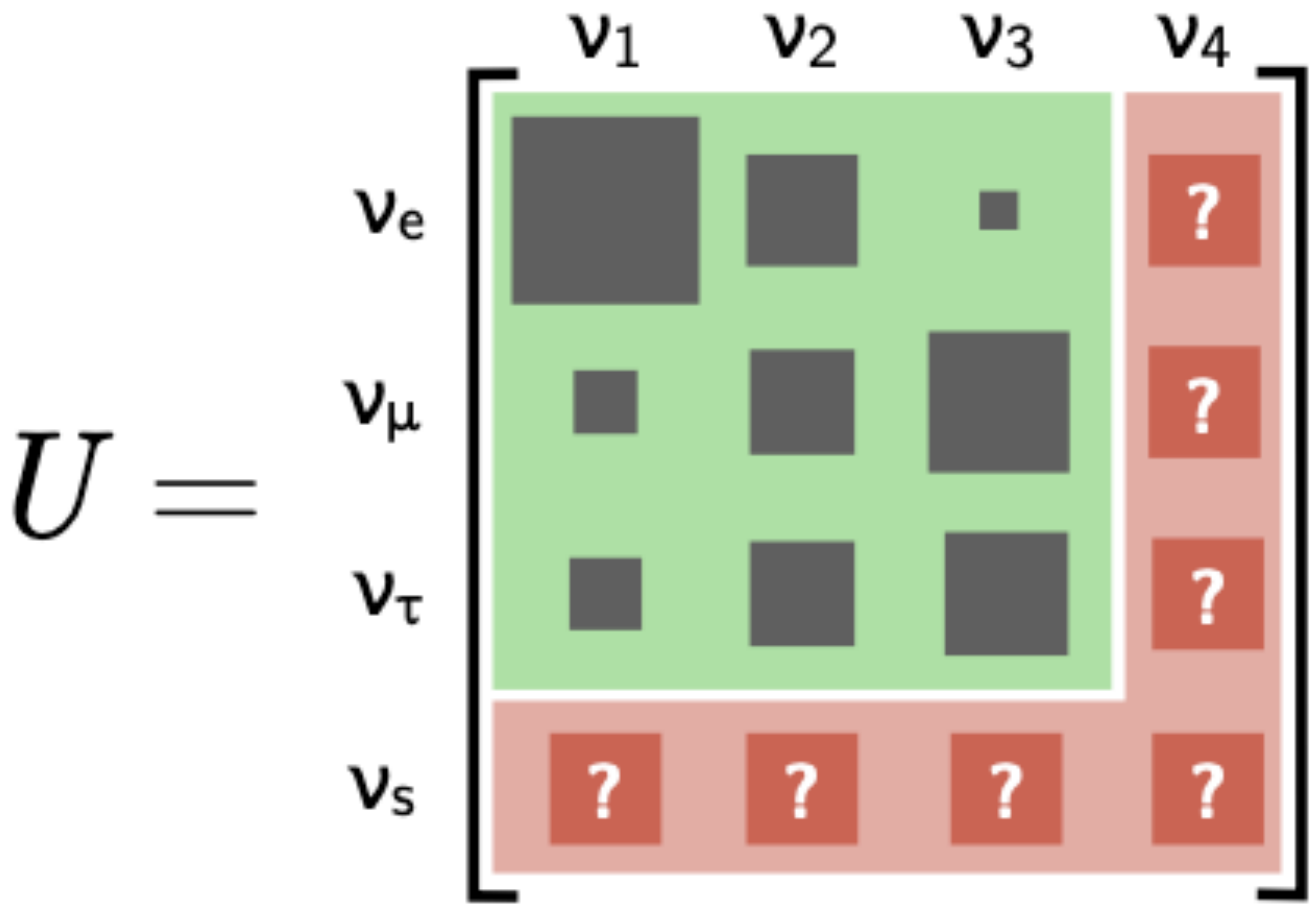
K. N. Abazajian et al. “Light Sterile Neutrinos: A Whitepaper”
arxiv:1204.5379

- taken individually, each anomaly is not significant enough to be convincing: but they all are pointing toward the similar thing

- most commonly interpreted as hint for one or more new “sterile” neutrino (oscillates but does not interact weakly)

Why add extra neutrino?

- the number of *weakly interacting* "**active**" neutrino flavors is fixed to three, by the Z width measurements (LEP)
- but additional, *non-interacting* "**sterile**" neutrino states could still exist
- potentially detectable through impact on neutrino oscillations

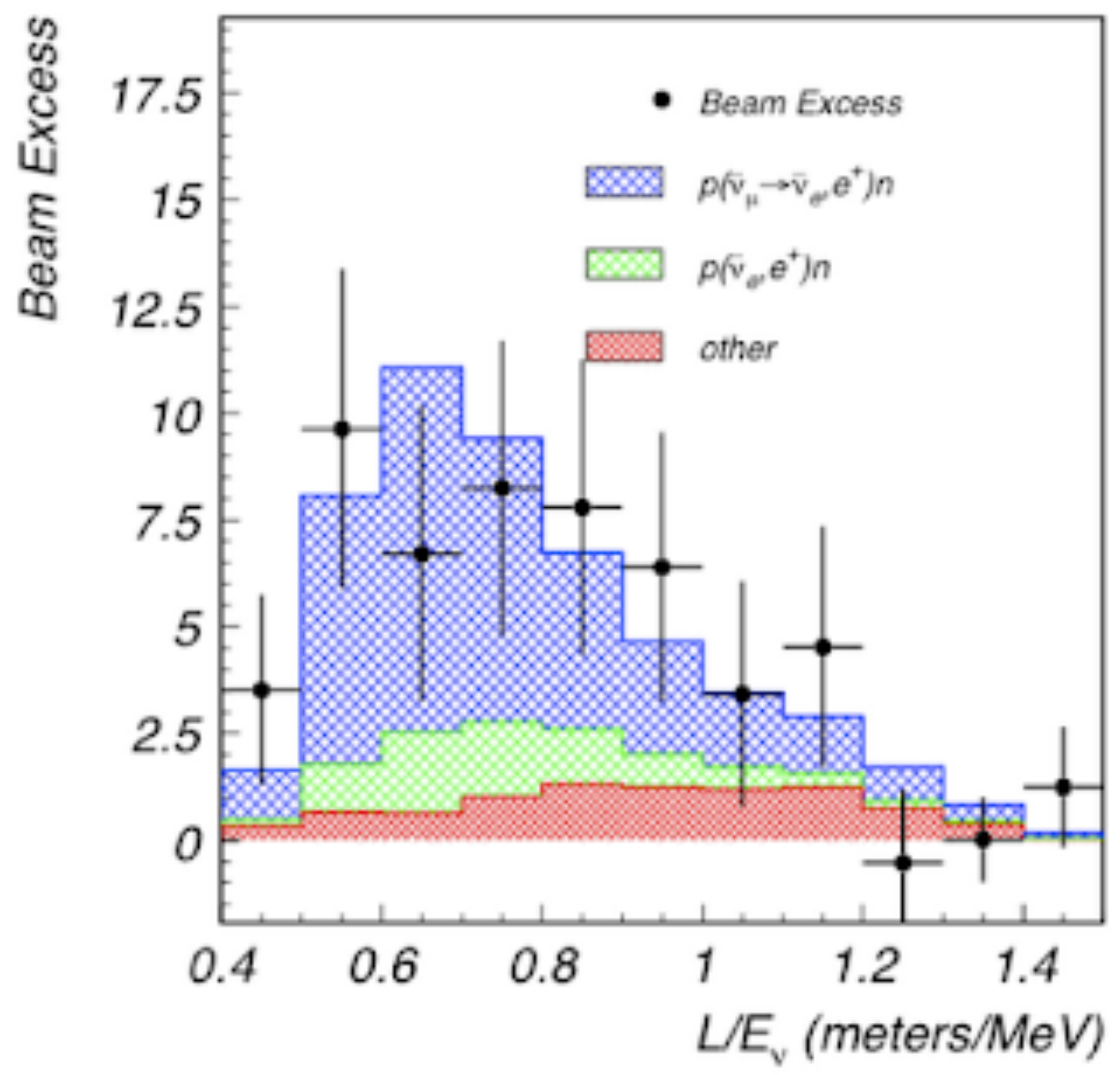


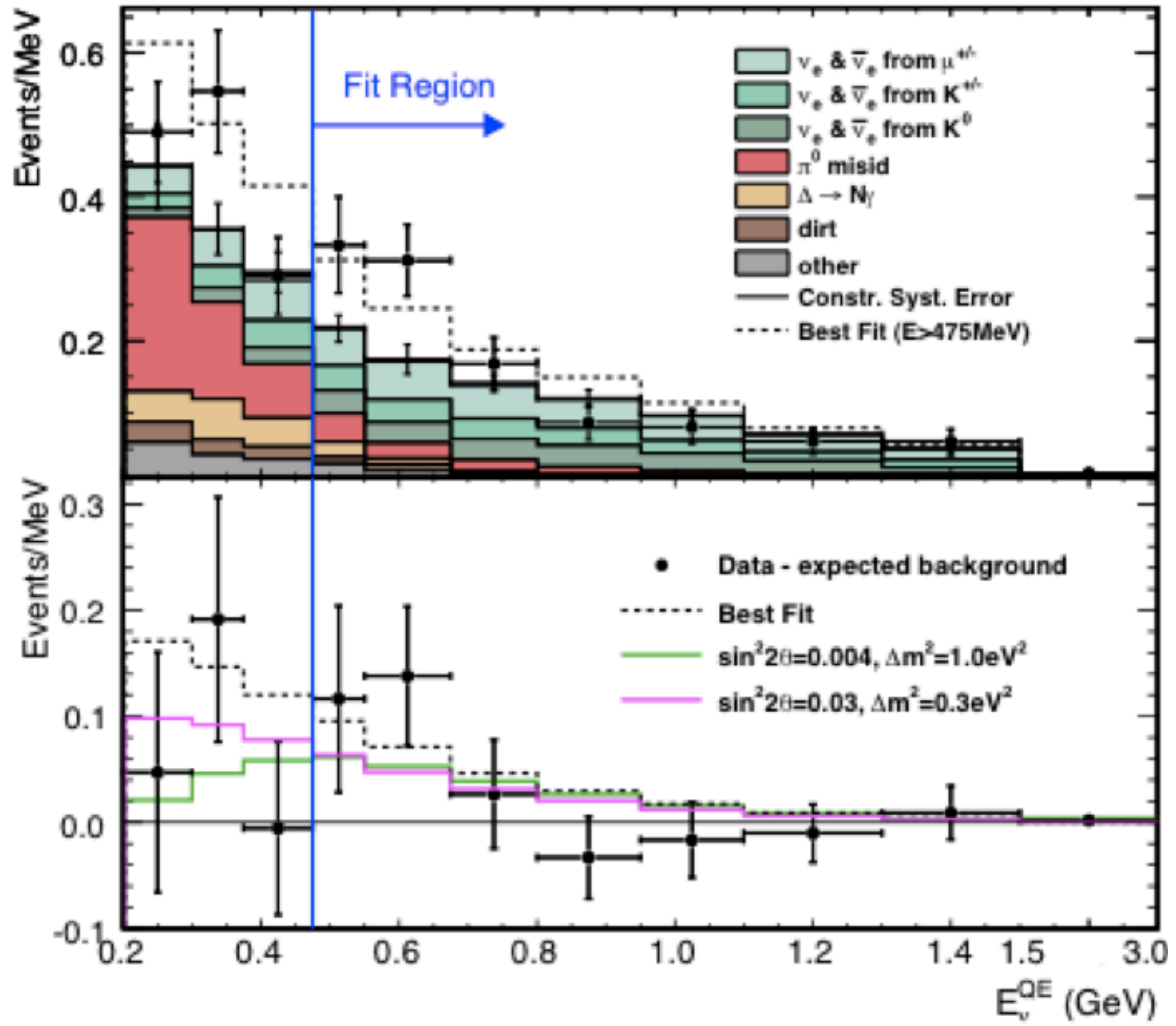
Flavor transitions via this new mixing:

$$P_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2\left(1.27\frac{\Delta m^2_{41} L}{E}\right)$$

Why add extra neutrino?

- maybe adding an extra, “**sterile**” neutrino help resolving these anomalies
- *Q: can this new type of neutrino be solution to these anomalies?*
- *A: unfortunately, it’s not so simple… there are severe tension between different measurements & channels*

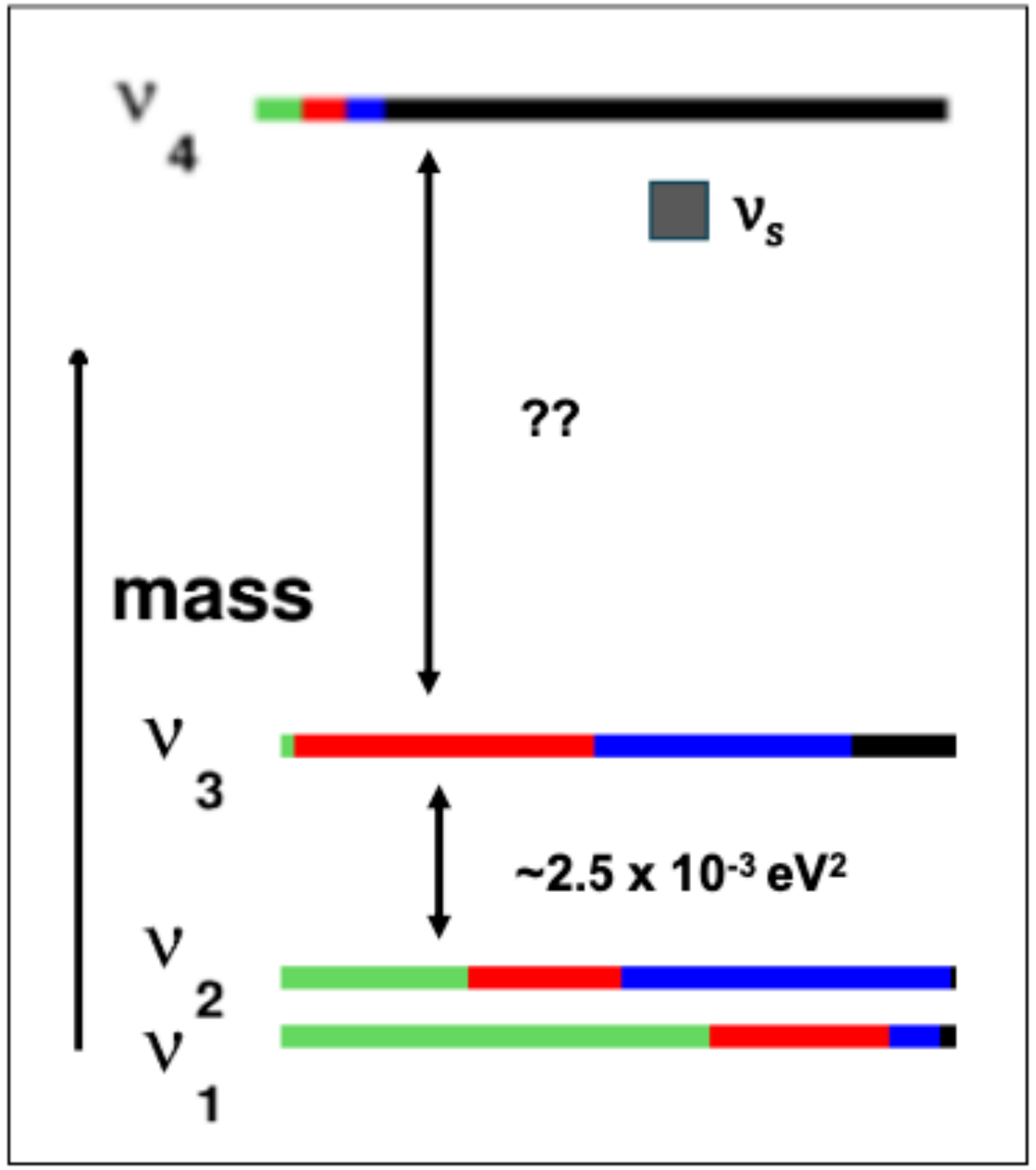




How can we detect sterile neutrino?

- **sterile neutrino does not interact weakly**, only experience gravity: no way to *directly* detect it
- **but it still oscillates** like other neutrino species, hence affecting neutrino oscillation pattern
  - oscillation probability of how one neutrino state morphs into the other state will be different if extra neutrino exists (i.e. PMNS matrix changes)
  - ν_e disappearance channel: $\nu_e \rightarrow \nu_e$
    - how many ν_e has been oscillated into other (including ν_s) neutrino types?
  - ν_e appearance channel: $\nu_u \rightarrow \nu_e$
    - how many ν_e has been oscillated from ν_u?

3+1 mixing model



The MiniBooNE Anomaly: Low Energy Excess (LEE)

- MiniBooNE observed low-energy excess (LEE) of electron-neutrino-like events
  - LEE: more events measured/detected than predicted, in the low energy region
- eV-scale sterile neutrino could explain this excess
  - the excess is due to sterile neutrino oscillated into electron neutrino
  - prediction is lower than observed because the prediction is made based on 3-neutrino paradigm

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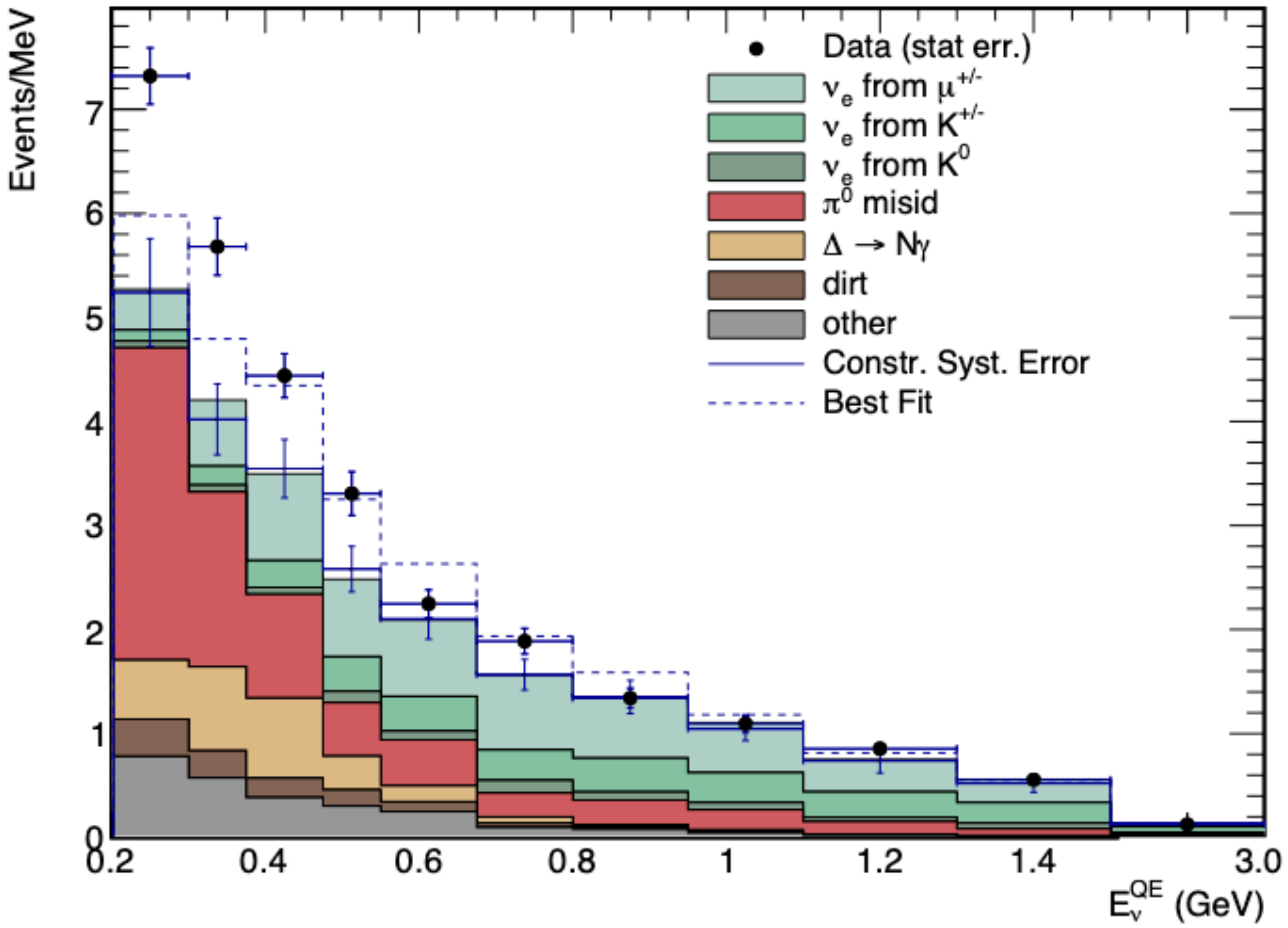
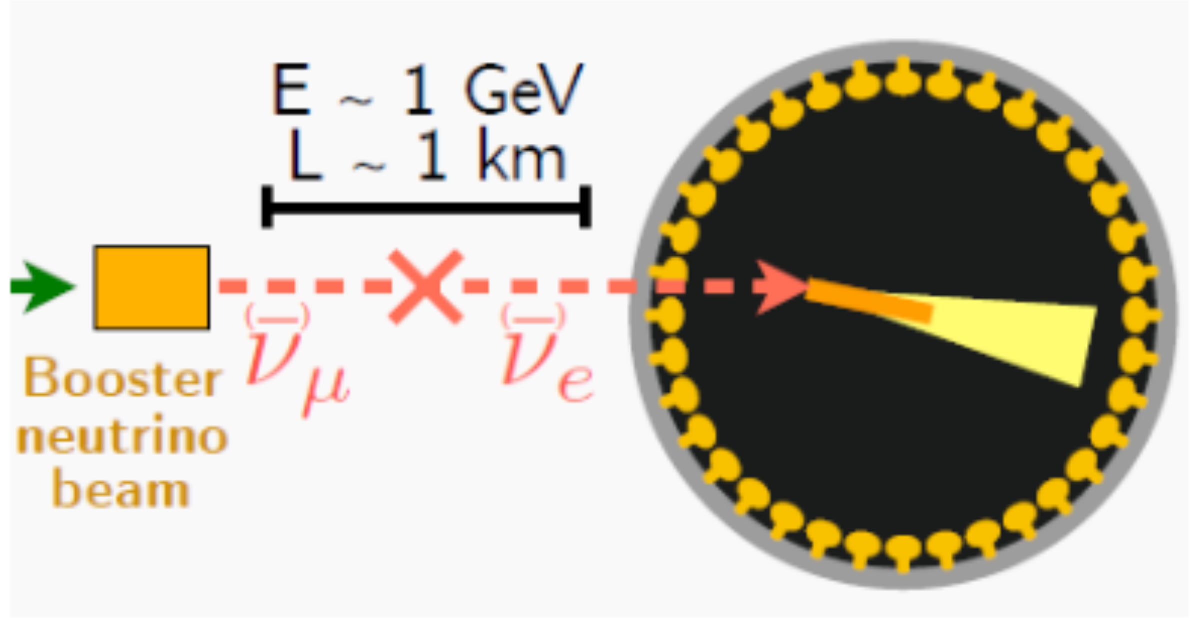
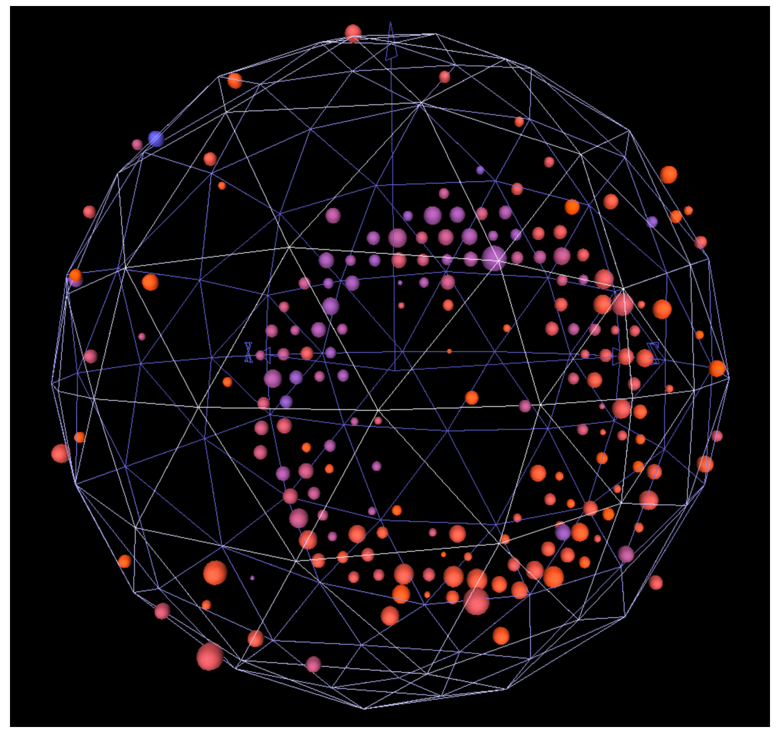
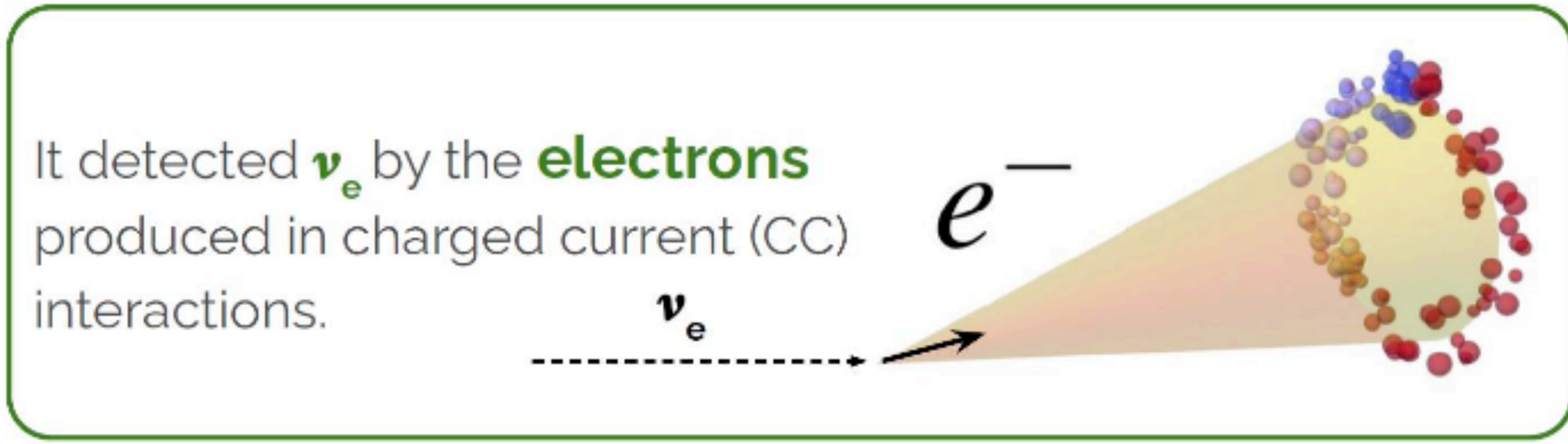


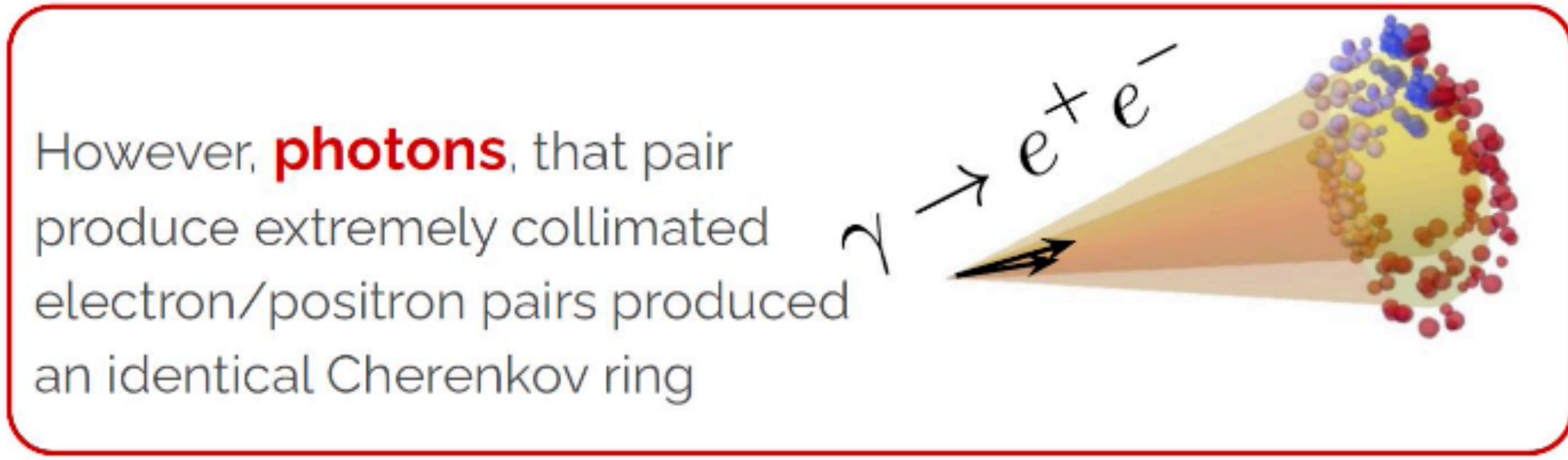
The MiniBooNE Anomaly: Low Energy Excess (LEE)

- MiniBooNE is a Cherenkov detector
  - mostly detecting outgoing leptons (electrons, muons, etc)
  - cannot distinguish between electrons and photons
- this limitation makes it hard to interpret the origin of LEE
  - if electrons, this can be explained by sterile neutrino oscillated into electron neutrinos
  - if photons, this can be explained by underestimated prediction of single-photon-producing SM process









LArTPC: Liquid Argon Time Projection Chamber

- Liquid argon (LAr) as total absorption calorimeter
  - dense, abundant, cheap
  - ionization and scintillation signals
- Time Projection Chamber (TPC) as 4π charged particle detector
  - 3D reconstruction with a fully active volume
- LAr+TPC: fine-grained 3D tracking with local dE/dx information and fully active target medium

NUCLEAR INSTRUMENTS AND METHODS 120 (1974) 221–236; © NORTH-HOLLAND PUBLISHING CO.

LIQUID-ARGON IONIZATION CHAMBERS AS TOTAL-ABSORPTION DETECTORS*

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Received 14 May 1974

1974

The Time-Projection Chamber
- A new 4π detector for charged particles

David R. Nygren

Lawrence Berkeley Laboratory
Berkeley, California 97420

1976

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

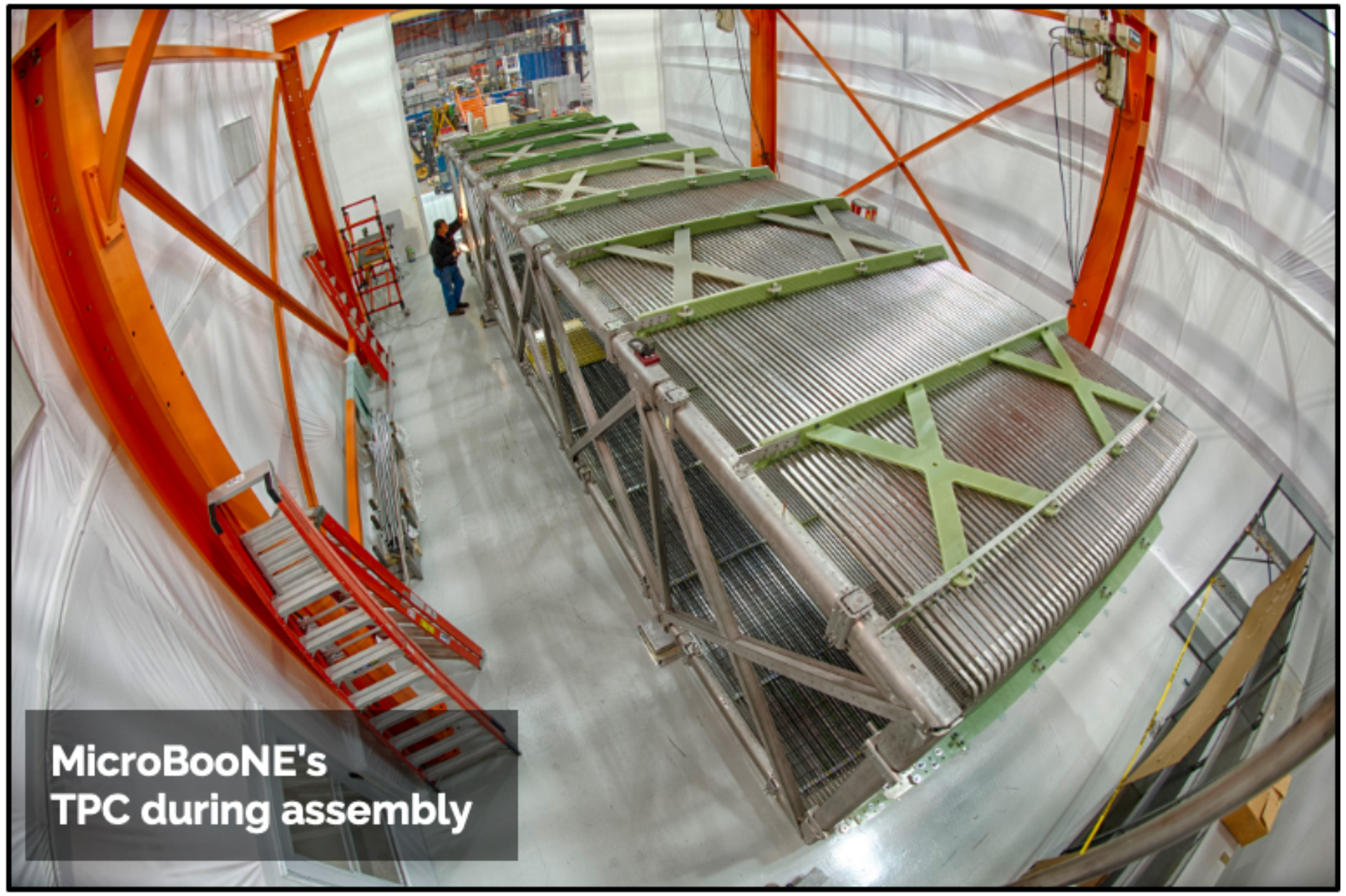
A NEW CONCEPT FOR NEUTRINO DETECTORS

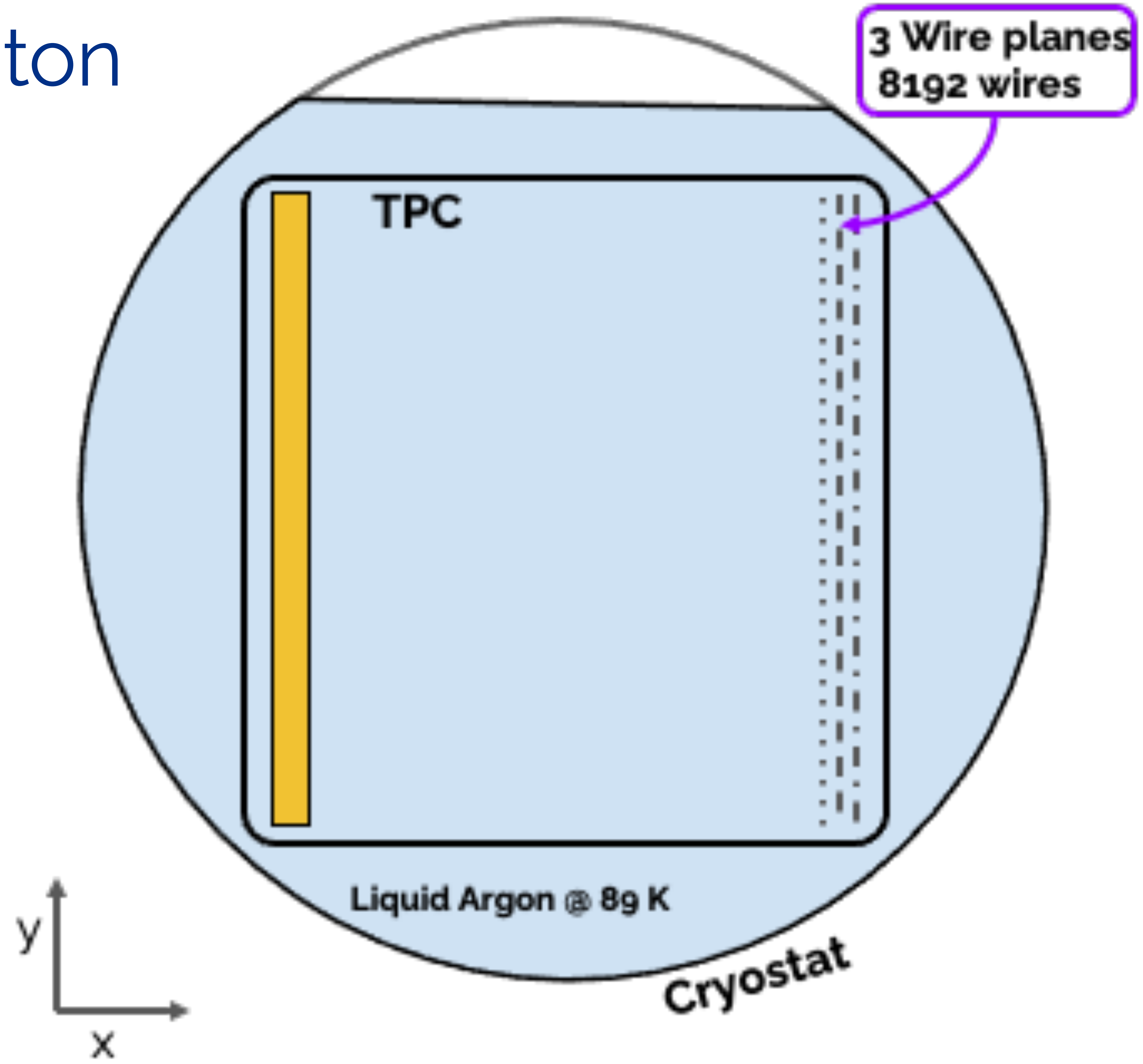
C. Rubbia

1977

the MicroBooNE detector

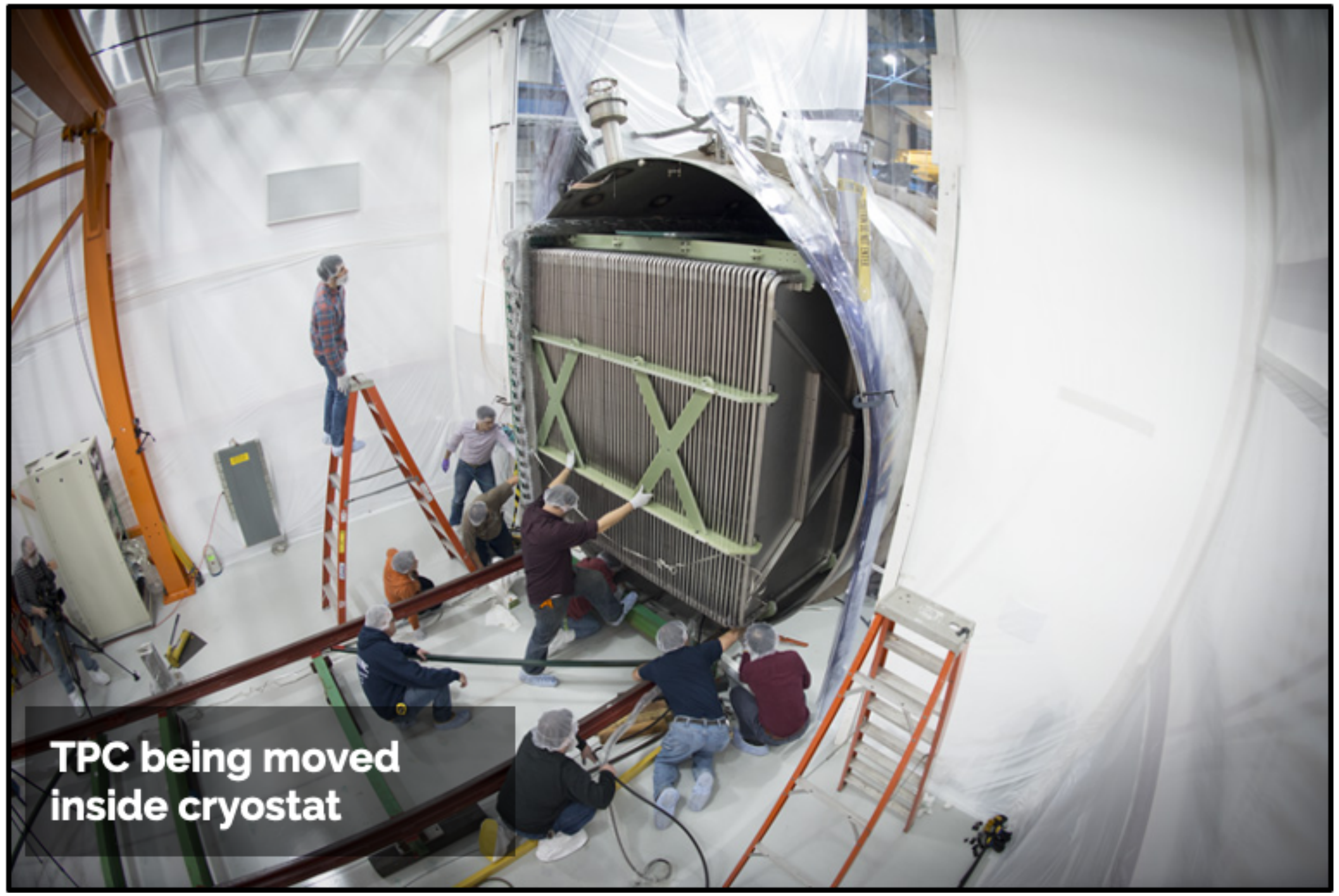
at MicroBooNE's core is an 85 ton LArTPC

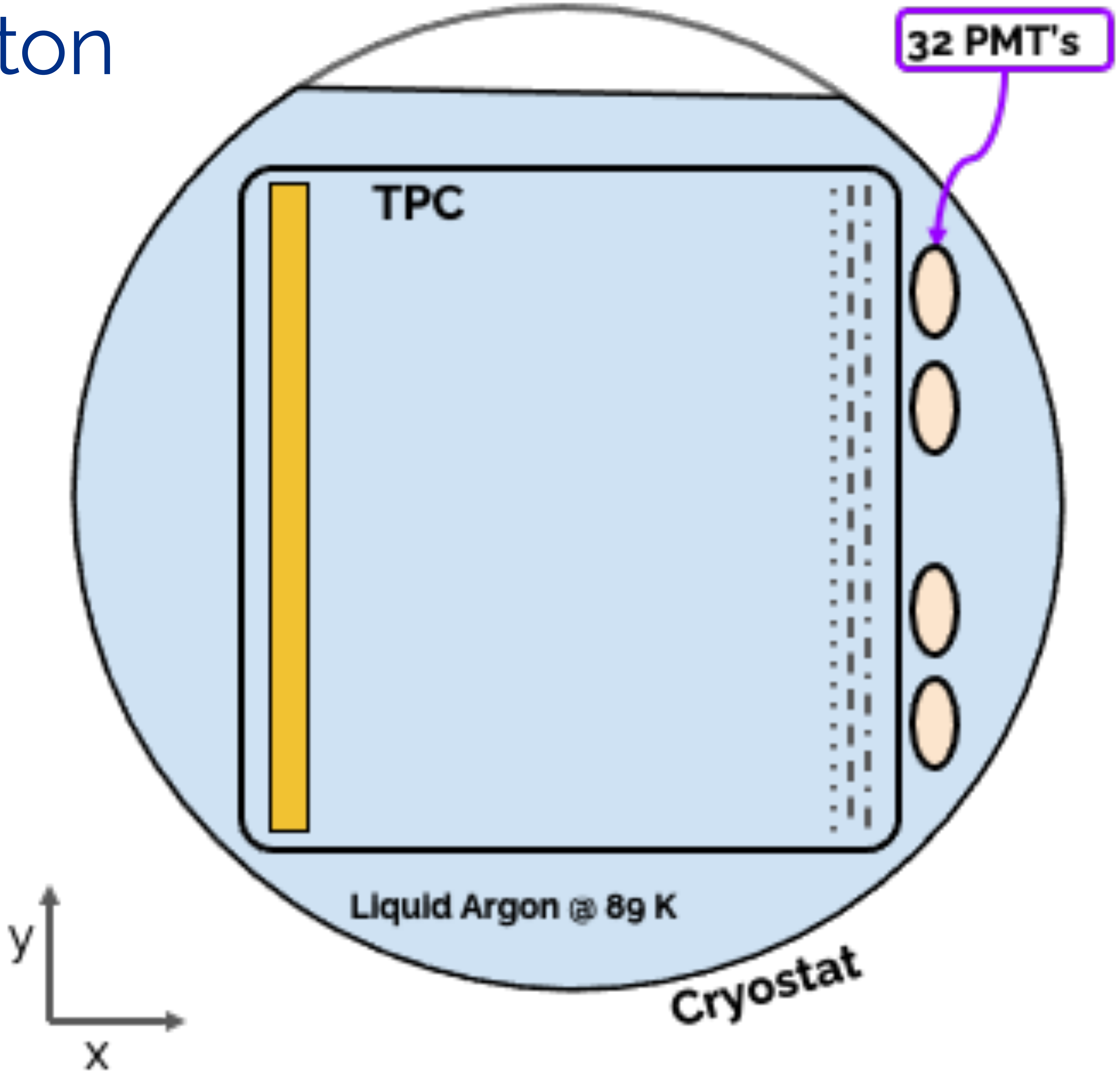




the MicroBooNE detector

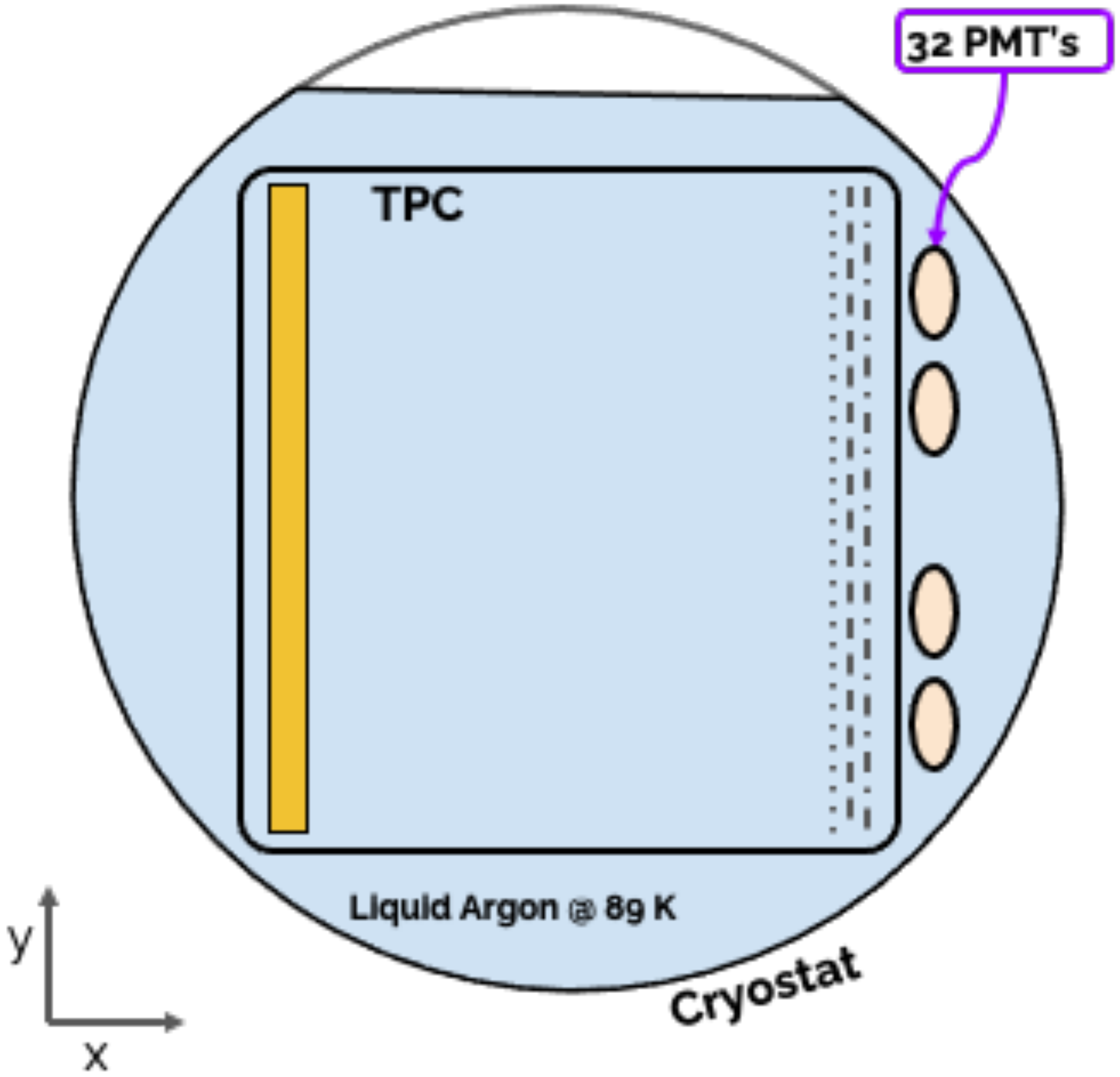
at MicroBooNE's core is an 85 ton LArTPC

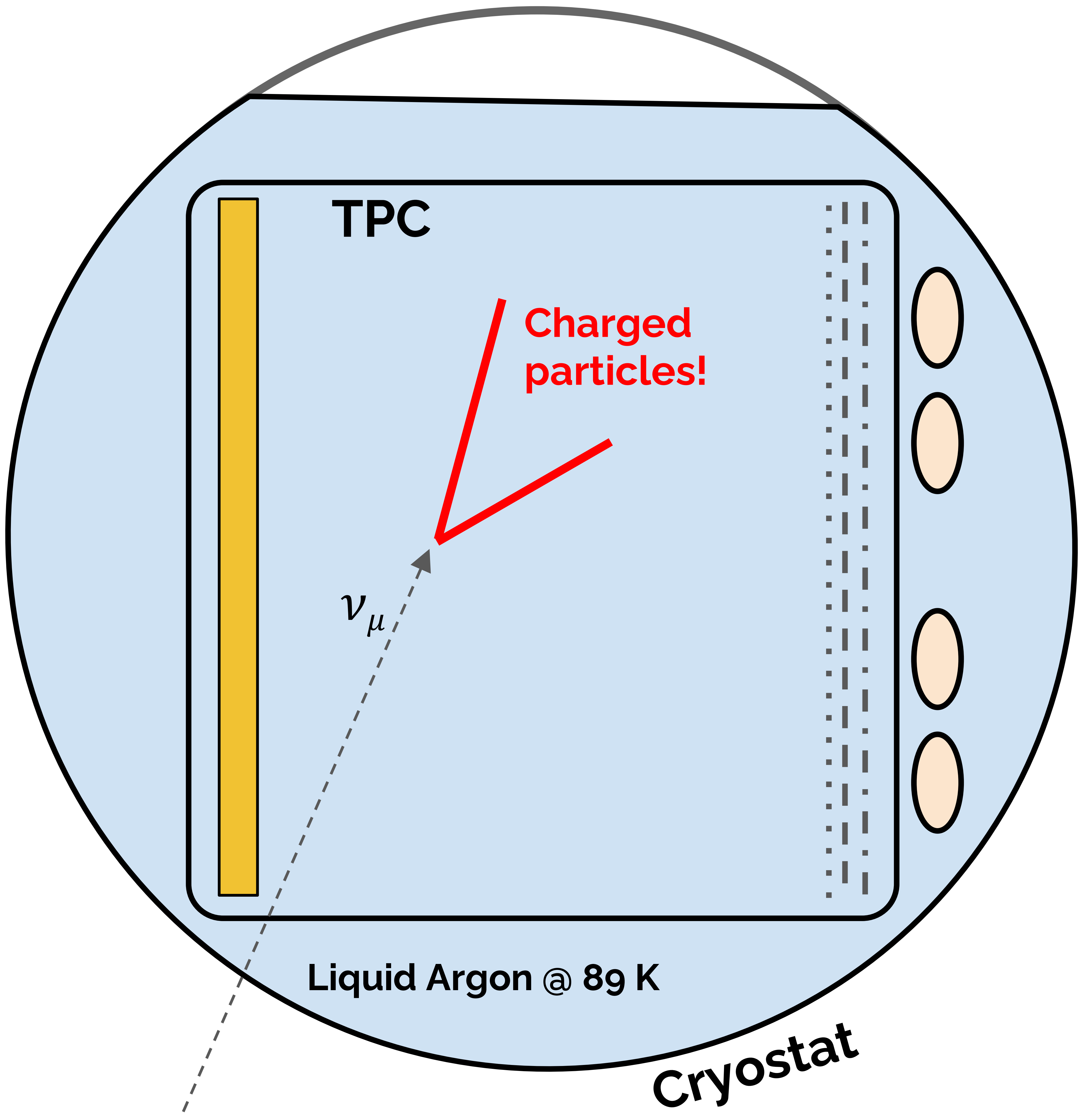




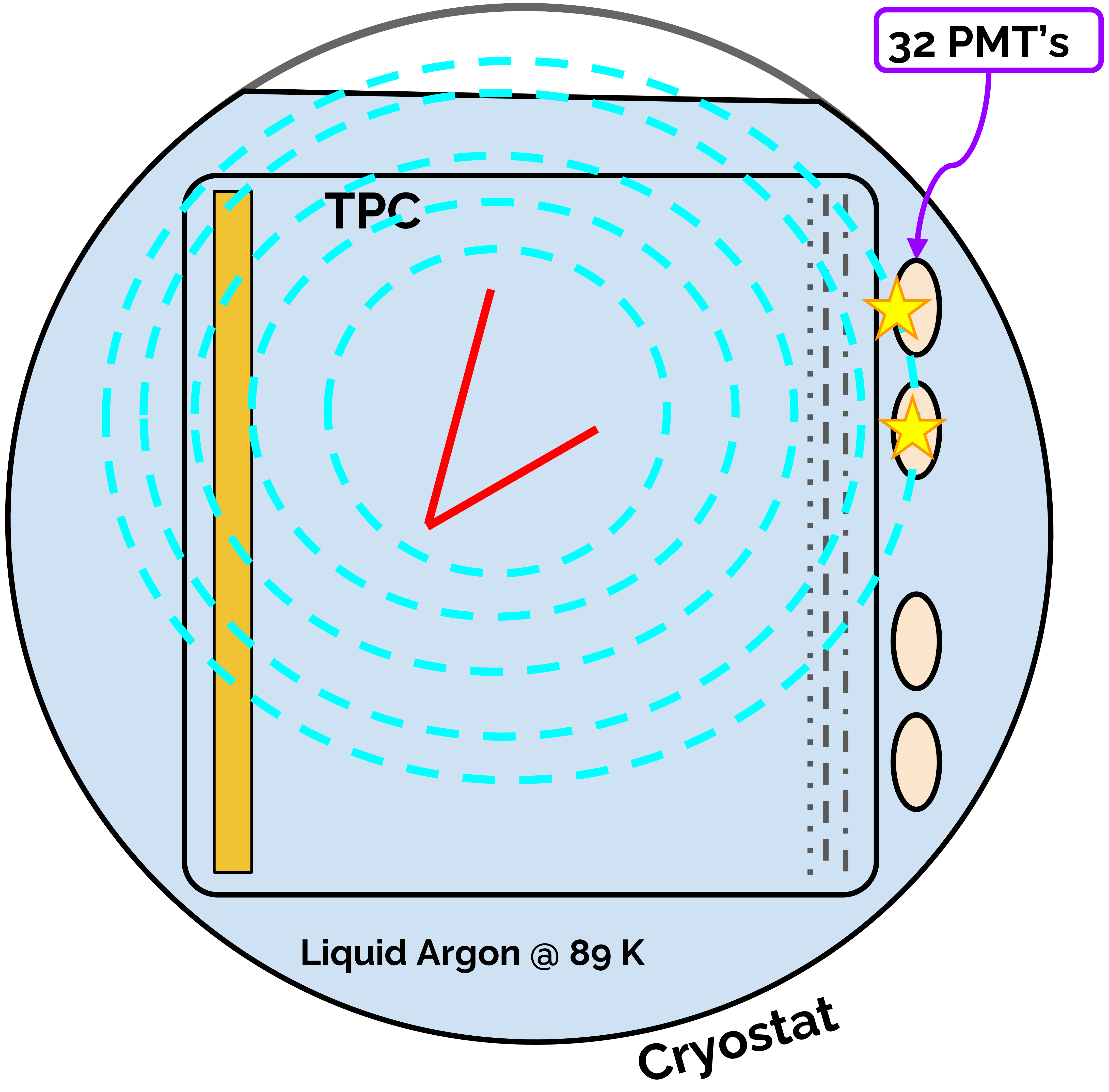
the MicroBooNE detector

in addition there is a **light detection system** consisting of 32 8-inch PMTs

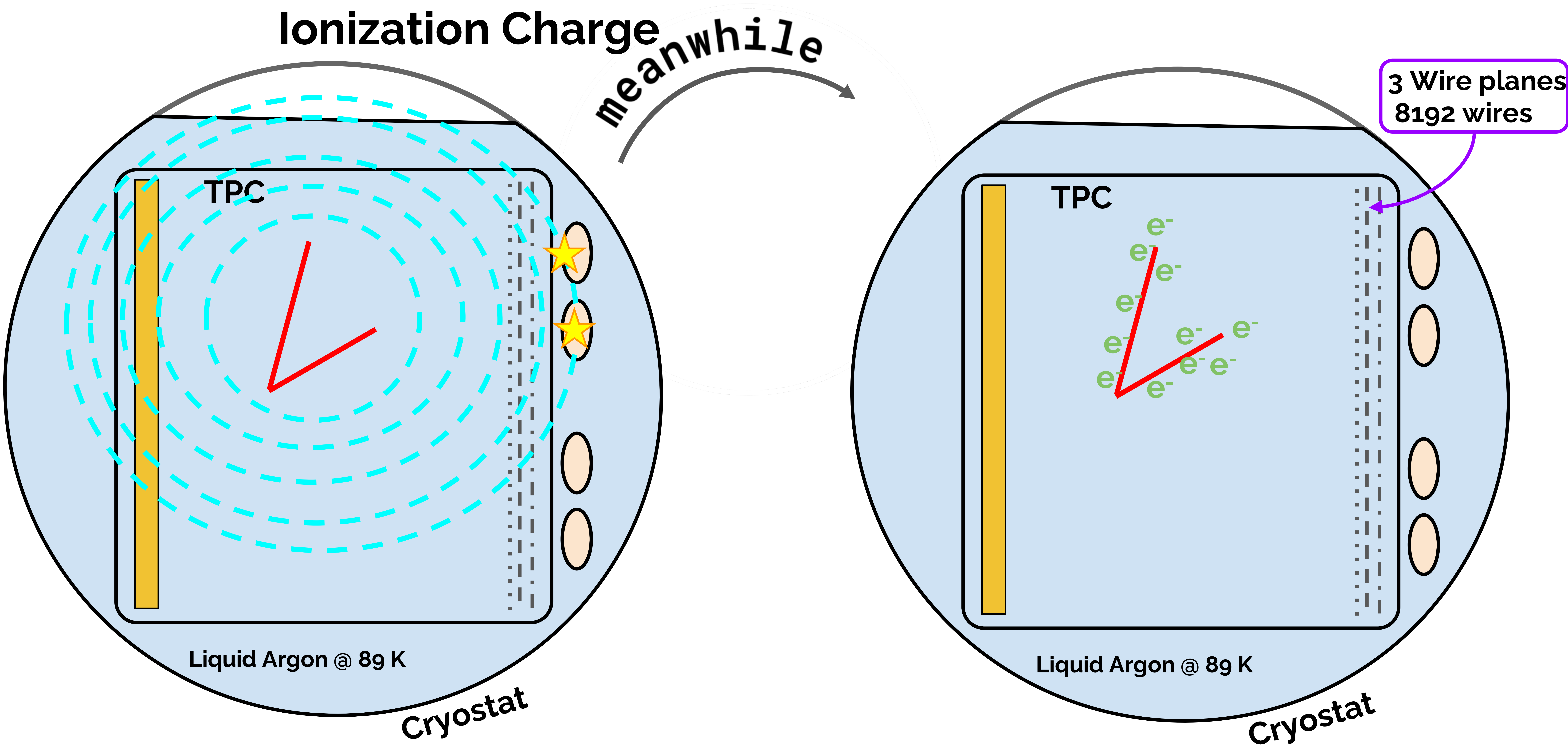



TPC
Charged particles!
ν_μ
Liquid Argon @ 89 K
Cryostat

Scintillation light



Scintillation light
Ionization Charge



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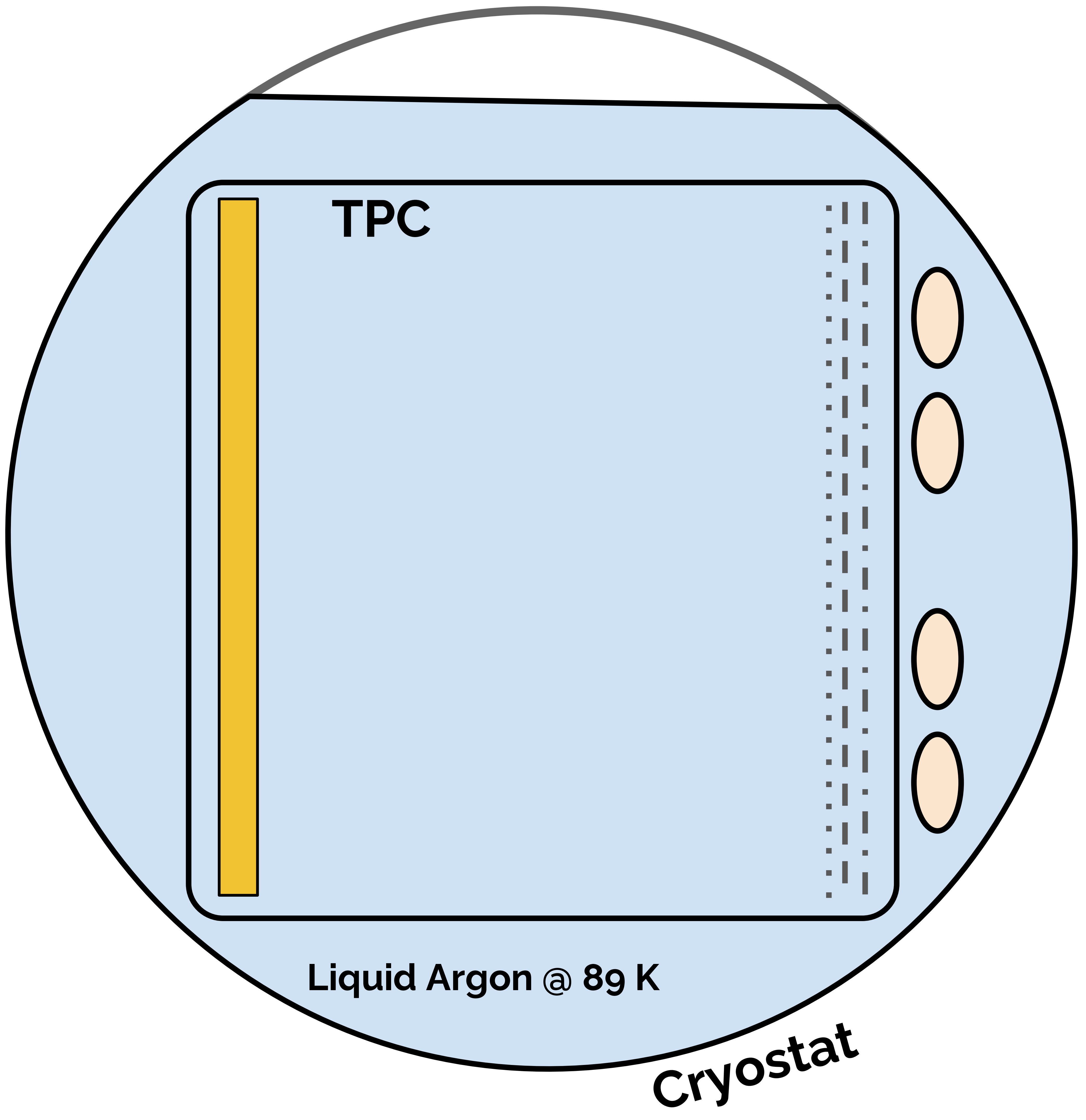

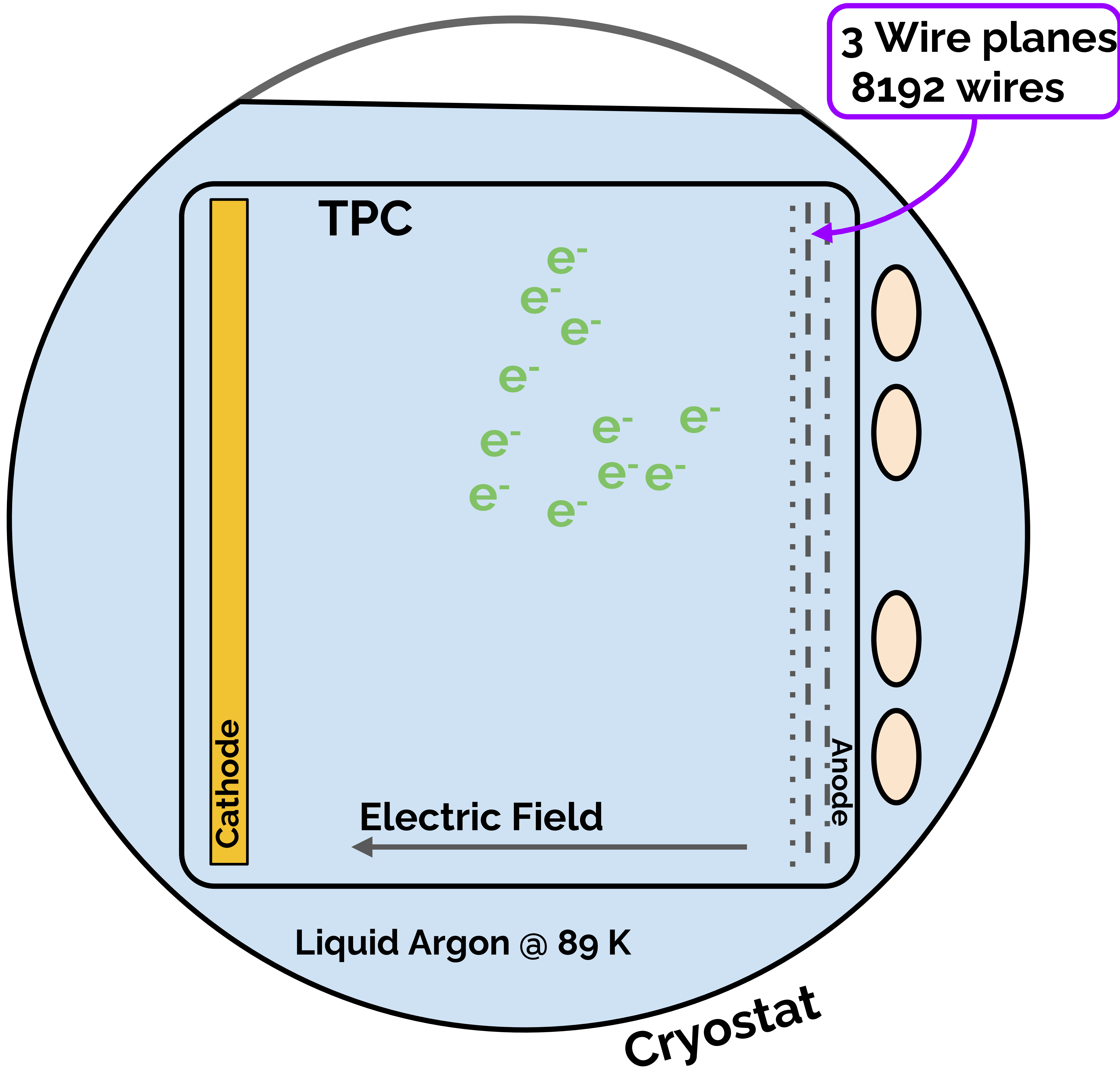

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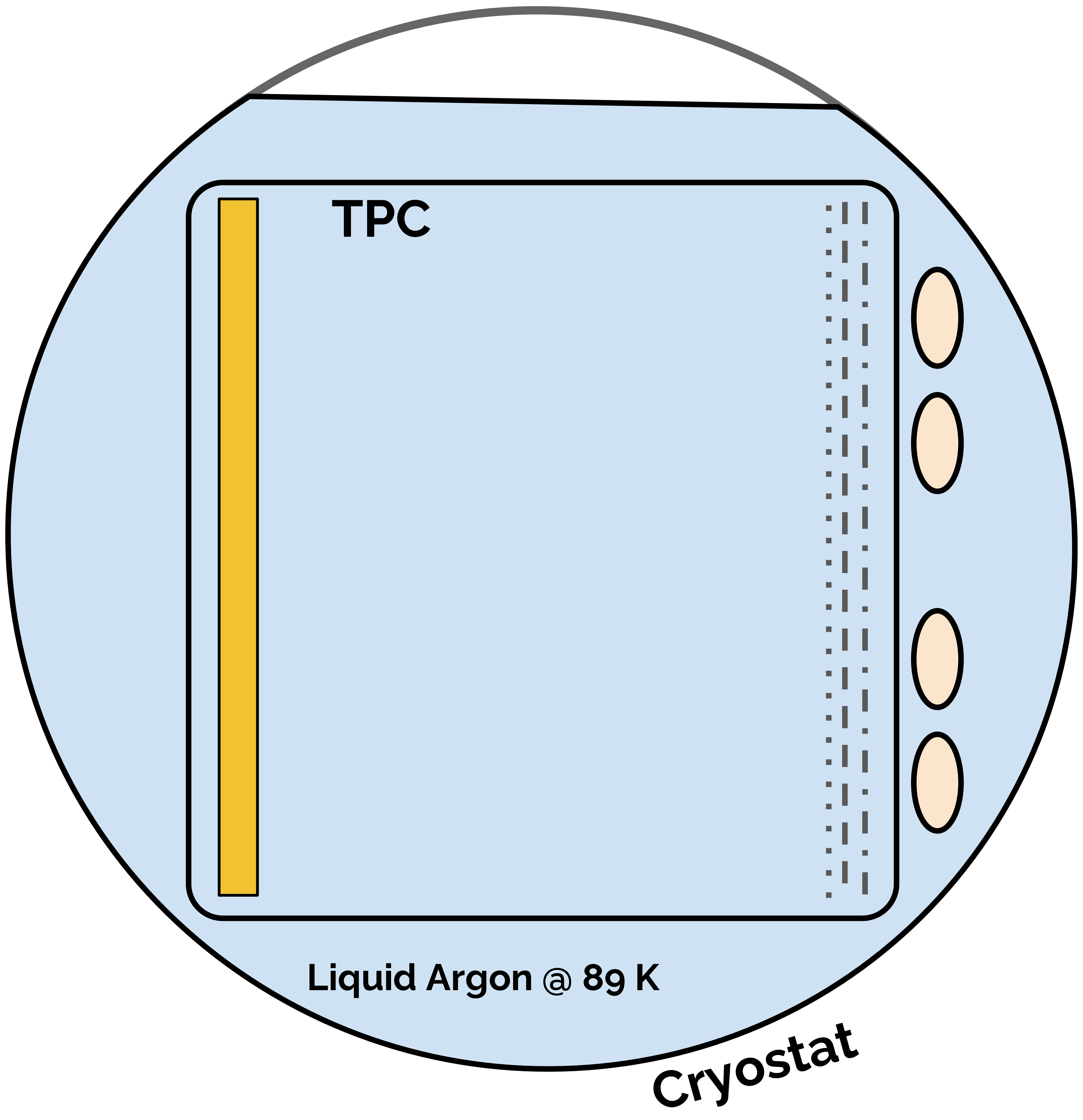
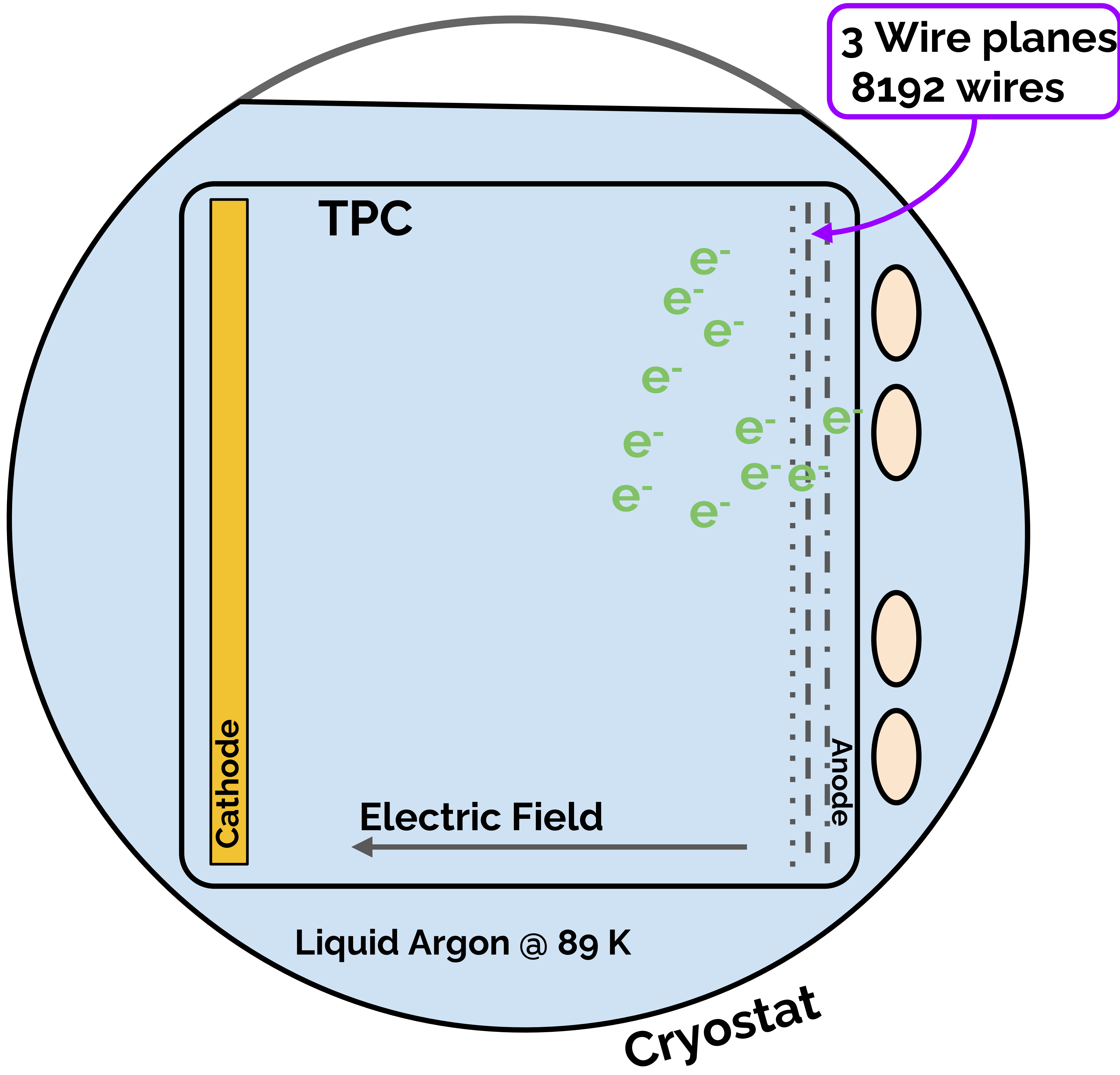
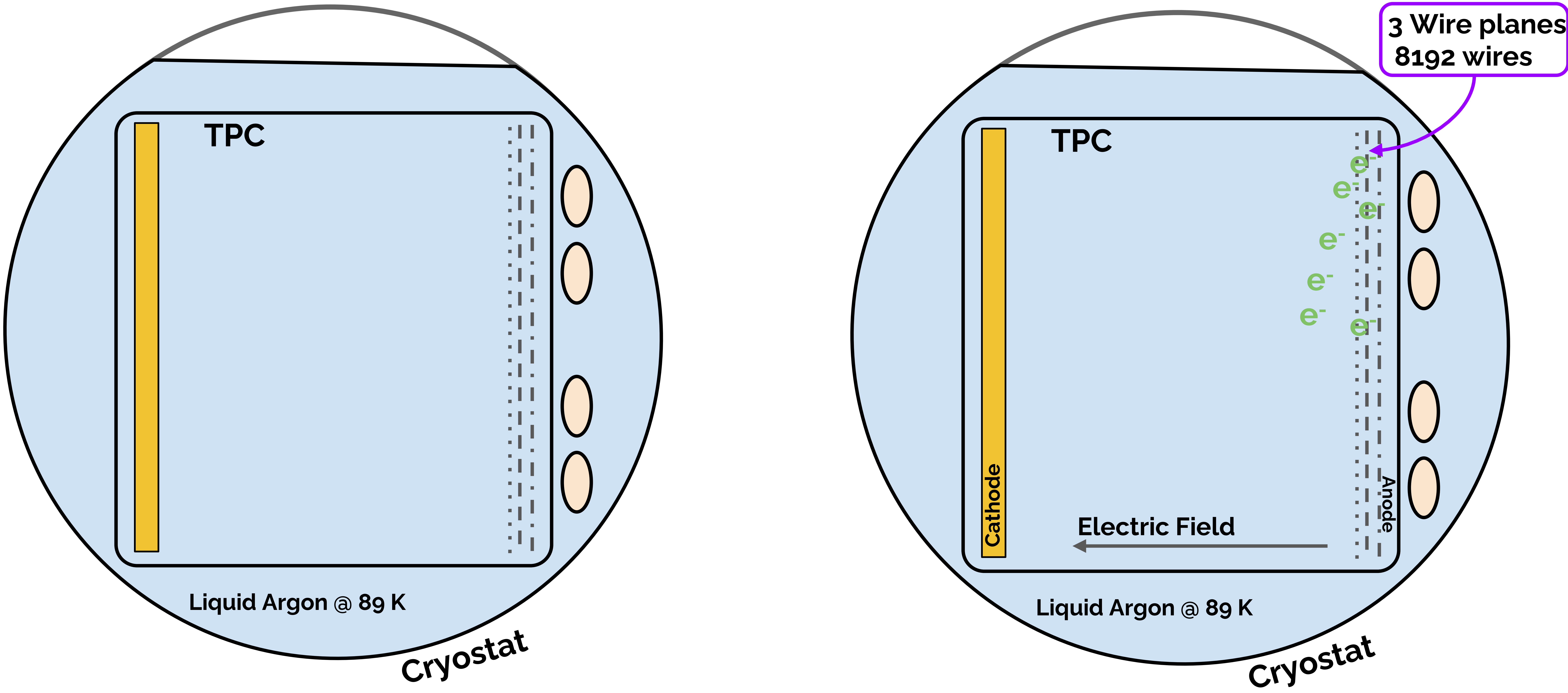


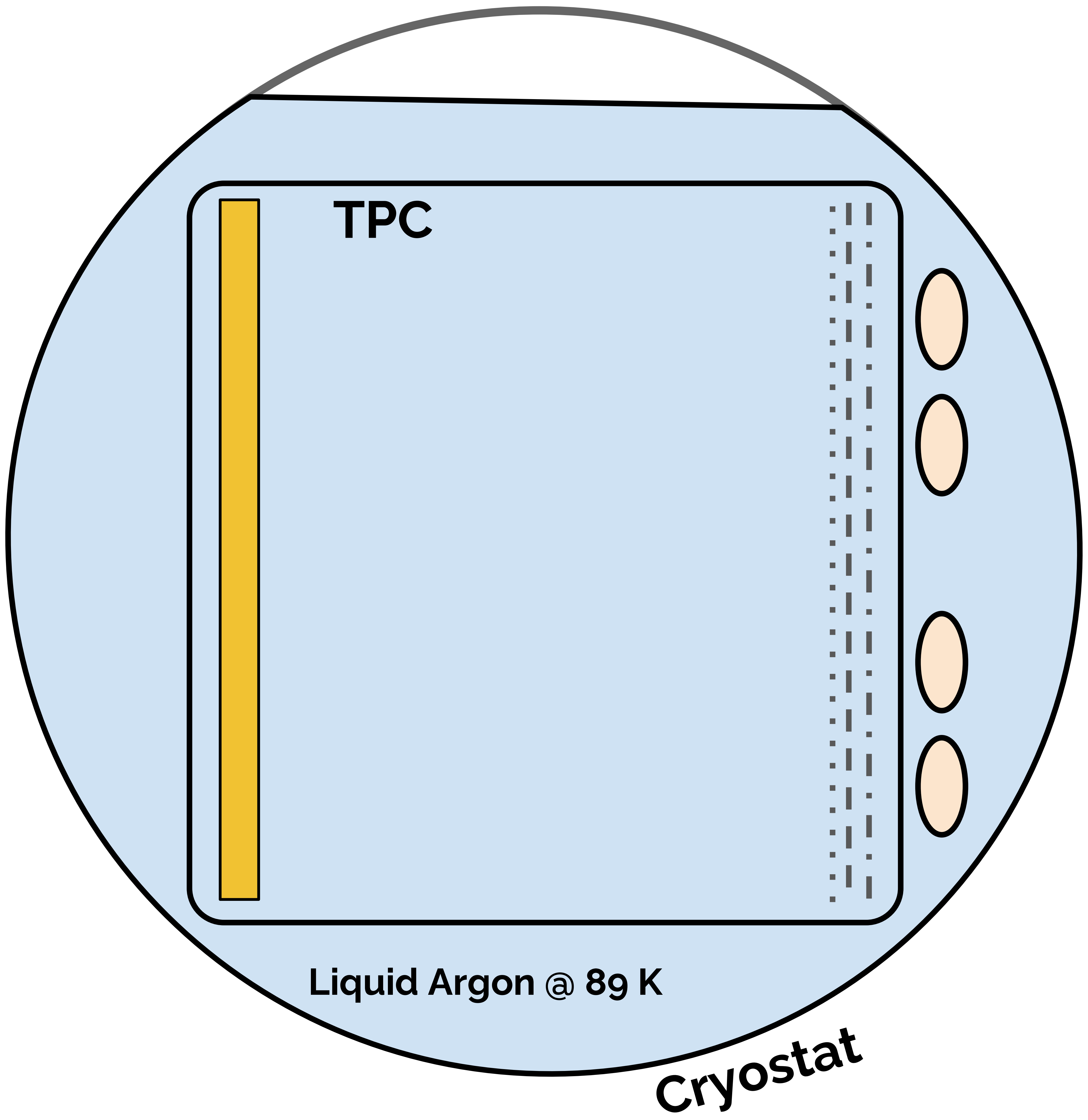


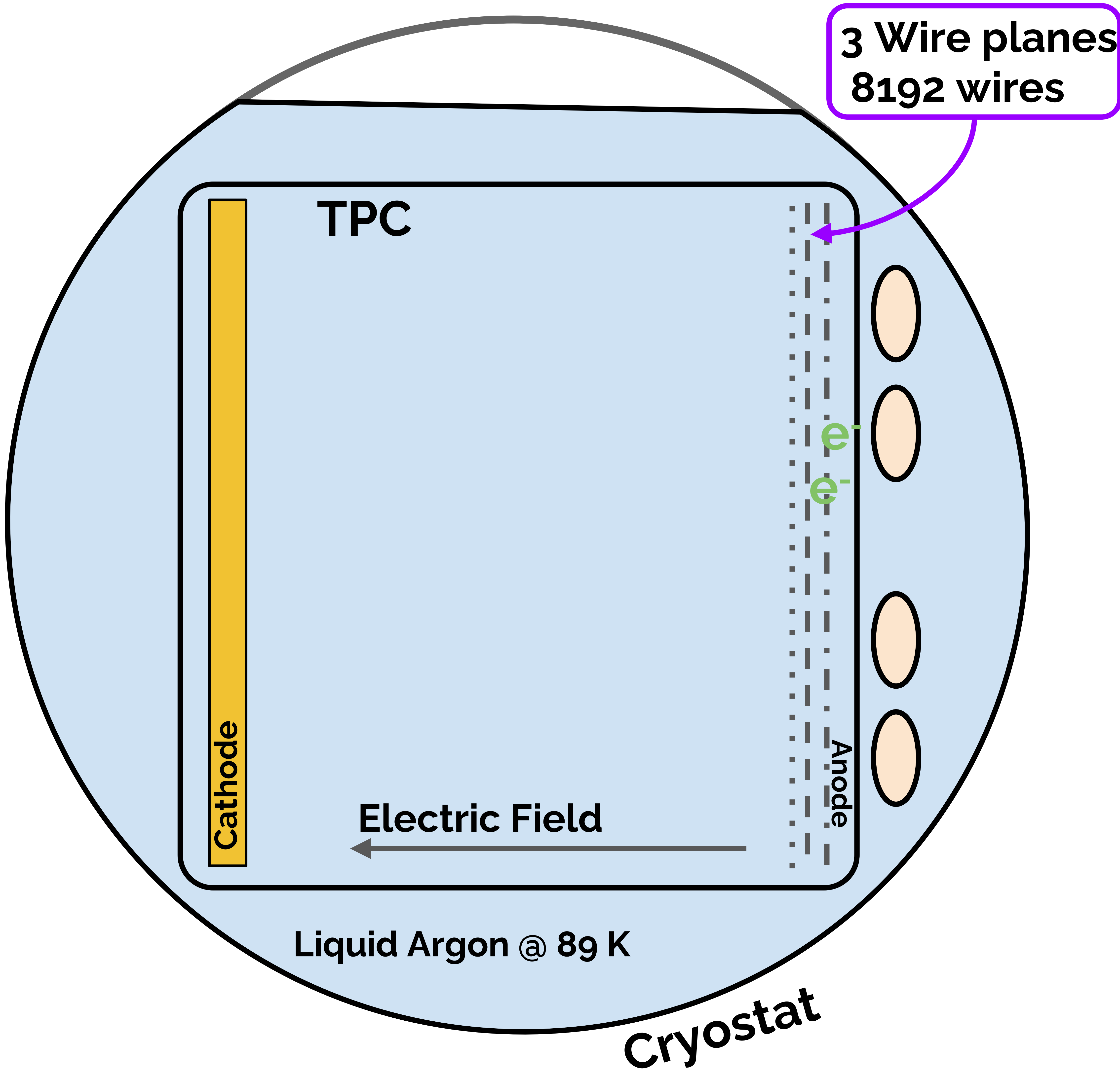
Scintillation light

Ionization Charge

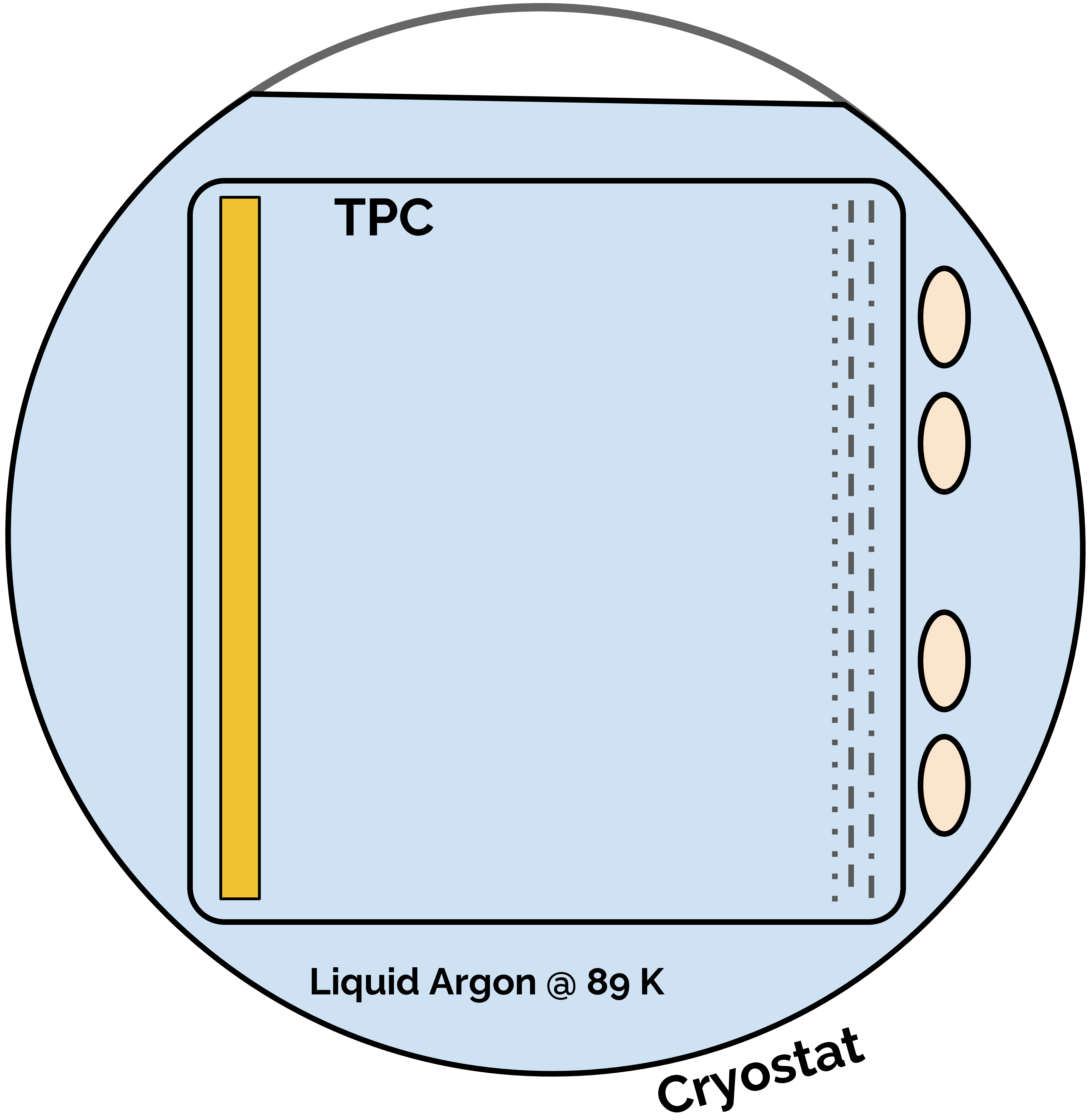


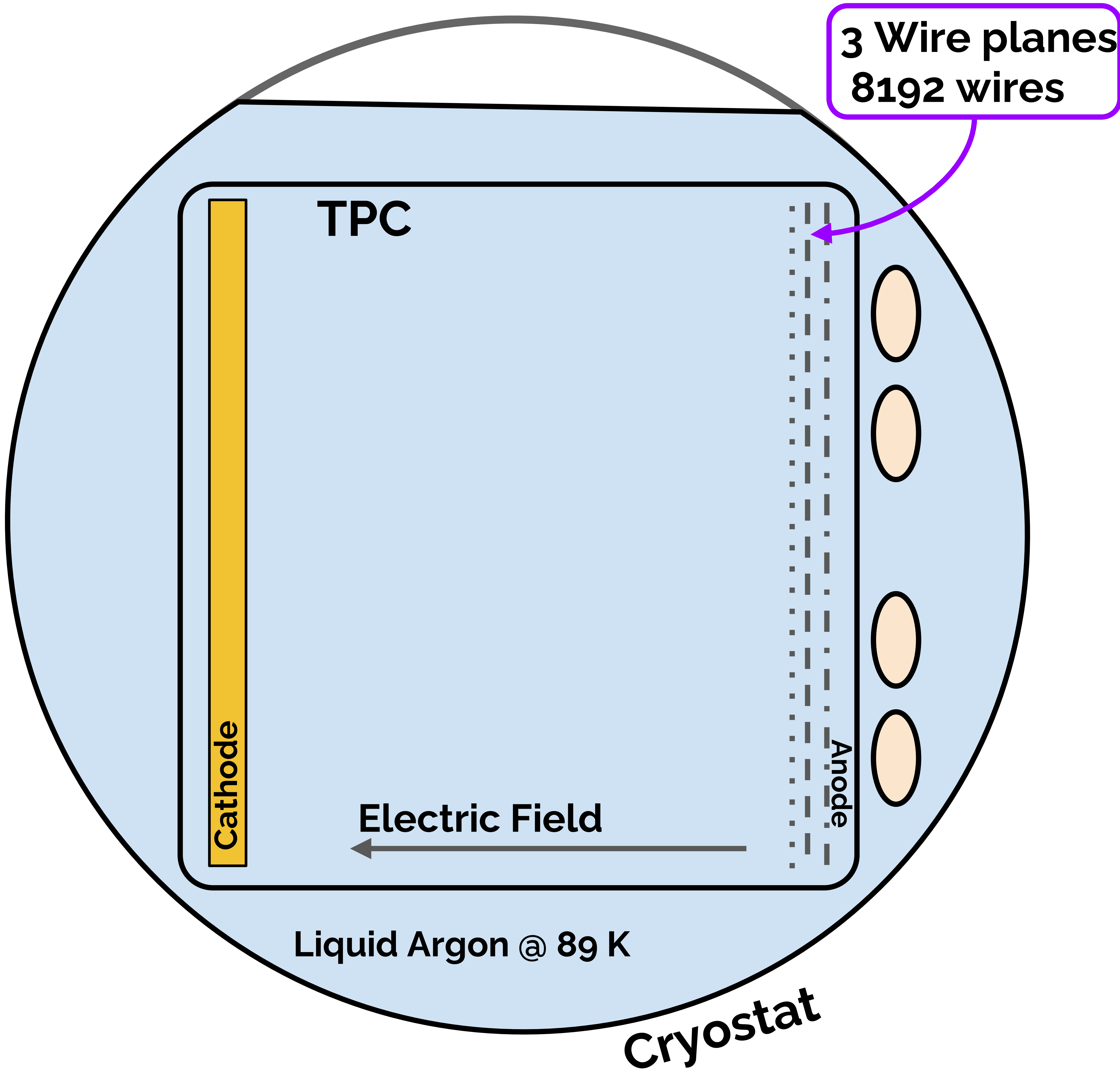
Scintillation light
Ionization Charge



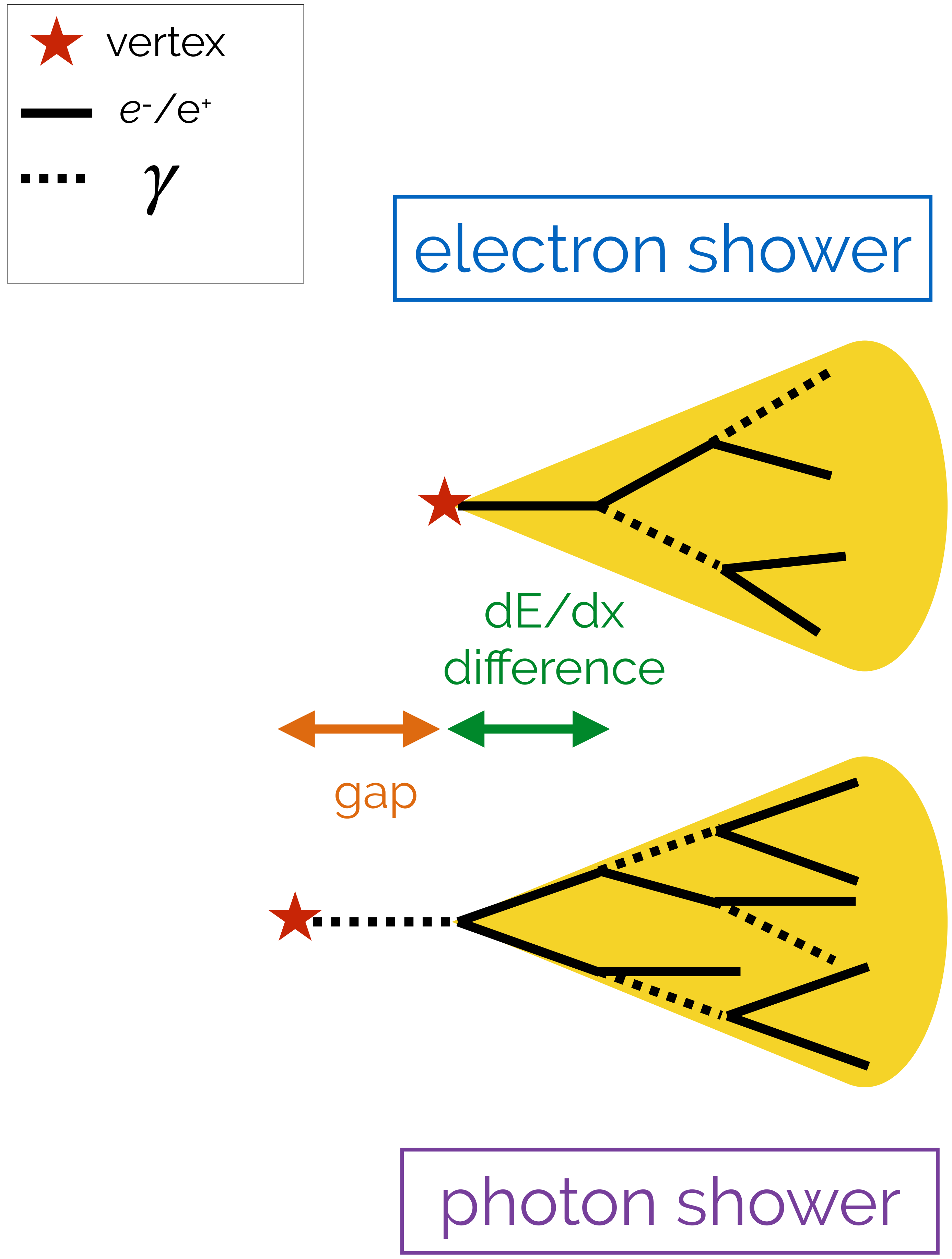


Scintillation light
Ionization Charge

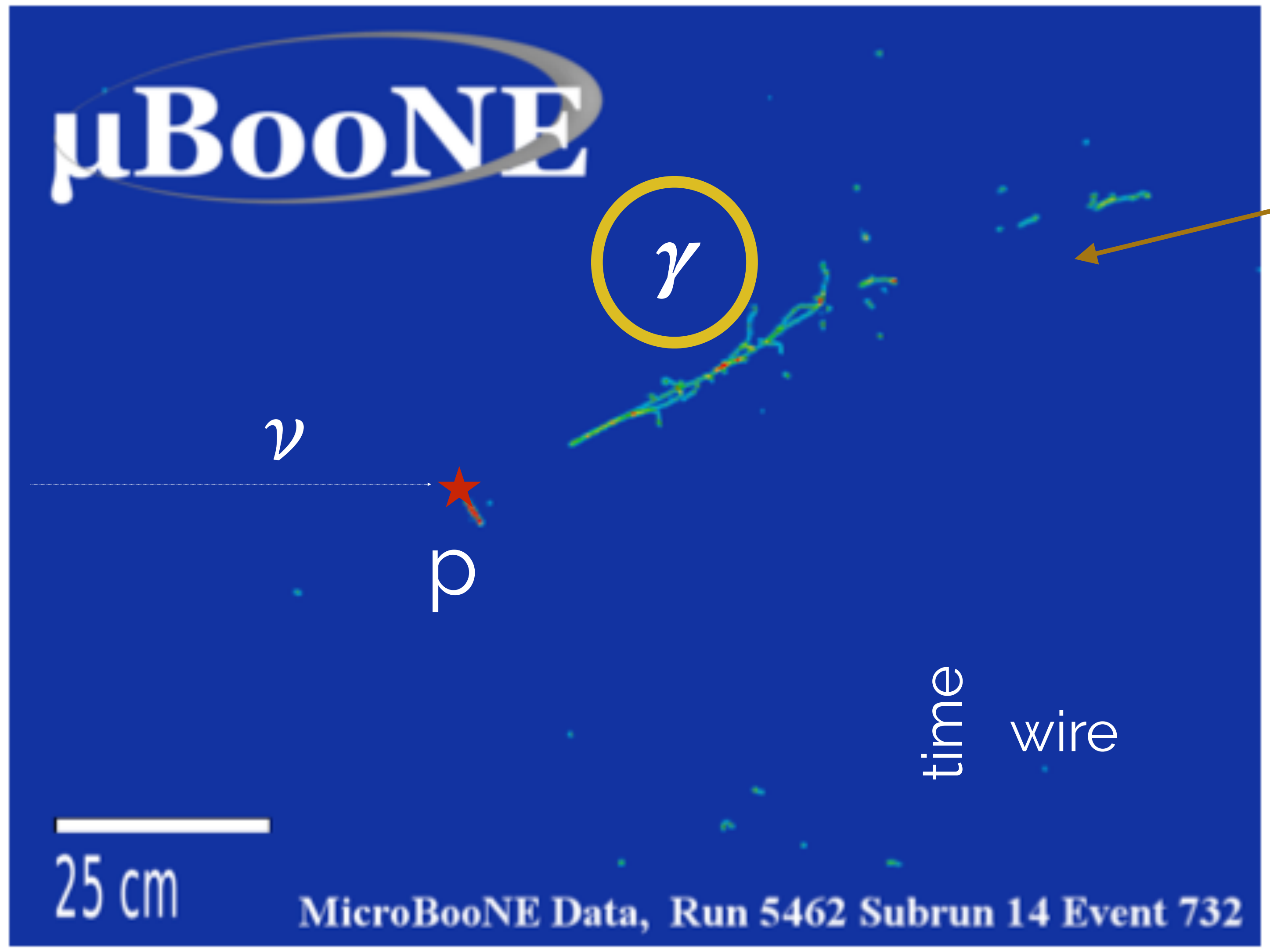


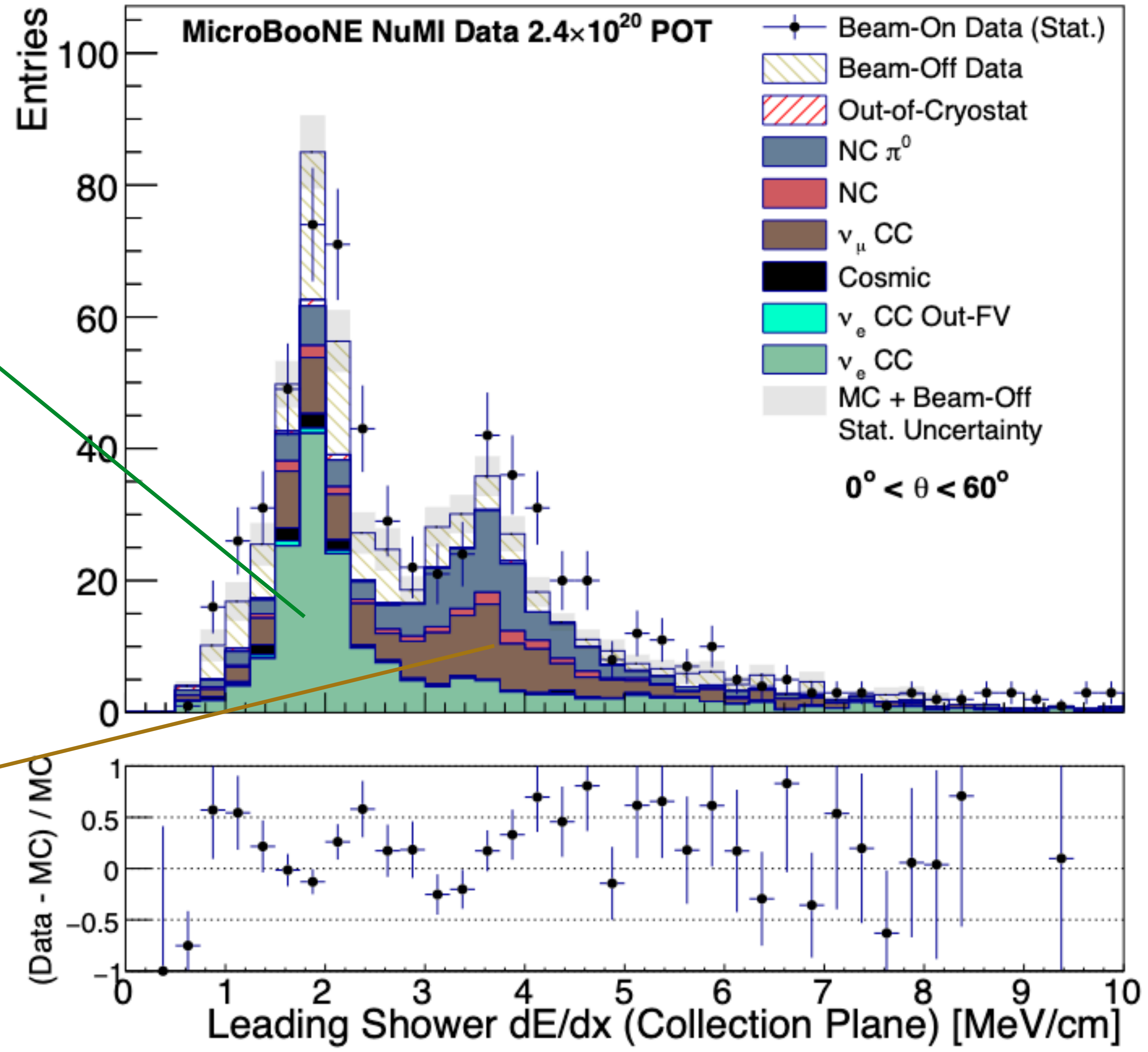


LArTPC to rescue



topology information

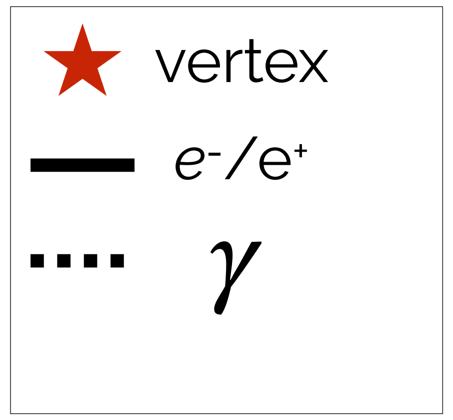




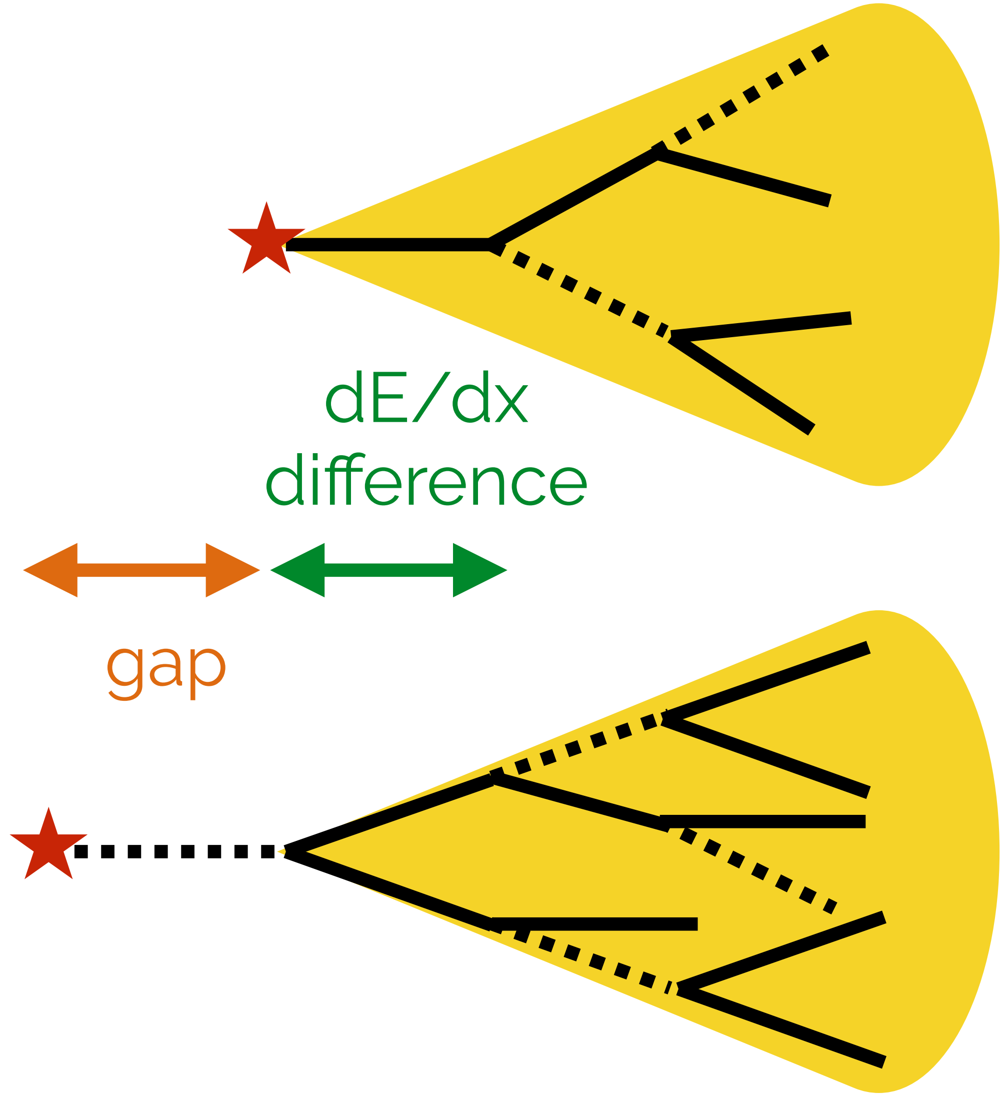
ionization dE/dx

MicroBooNE uses the excellent properties and resolution of its LArTPC to select both eLEE and γLEE signals with high purity

LArTPC to rescue

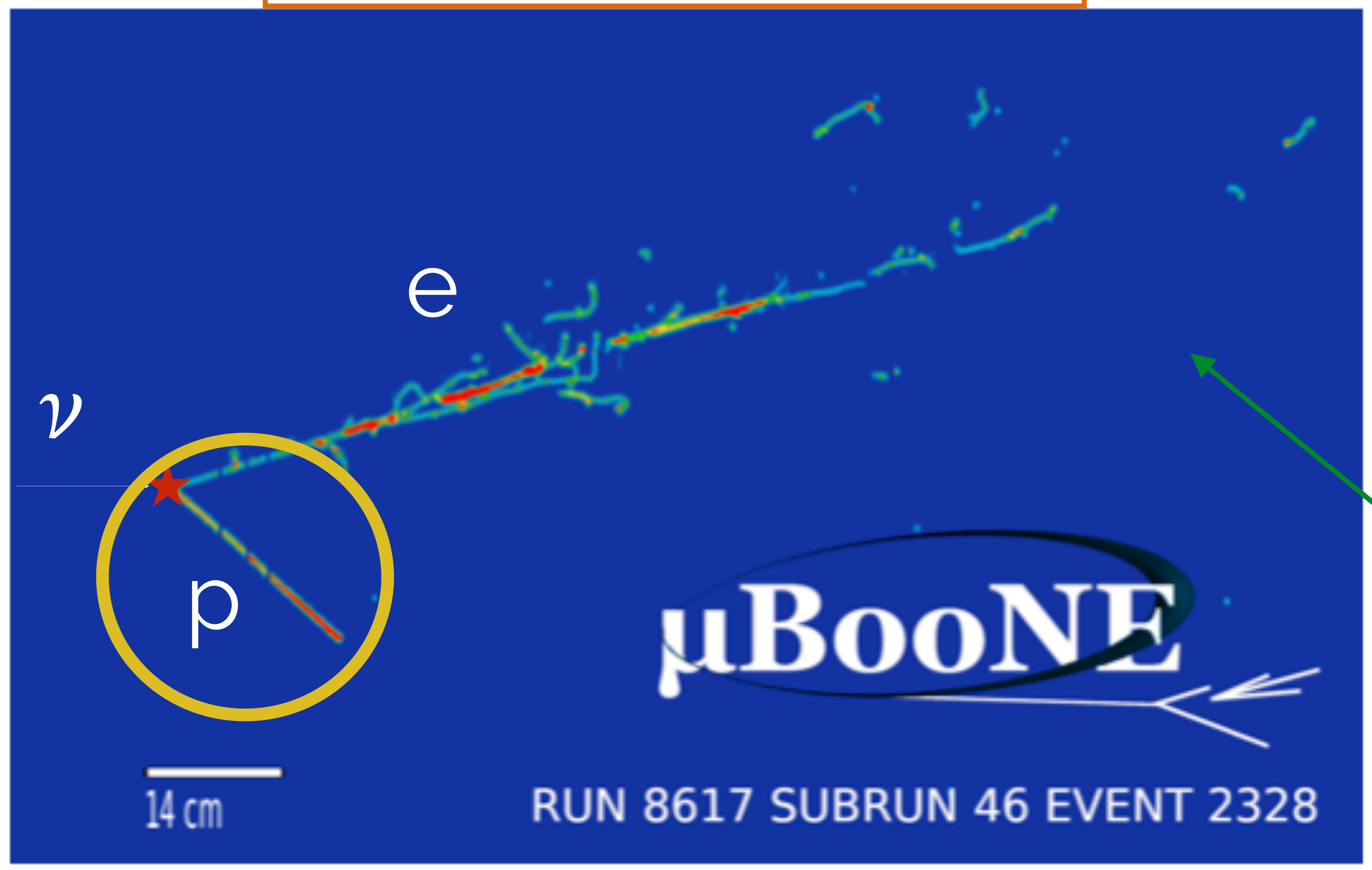


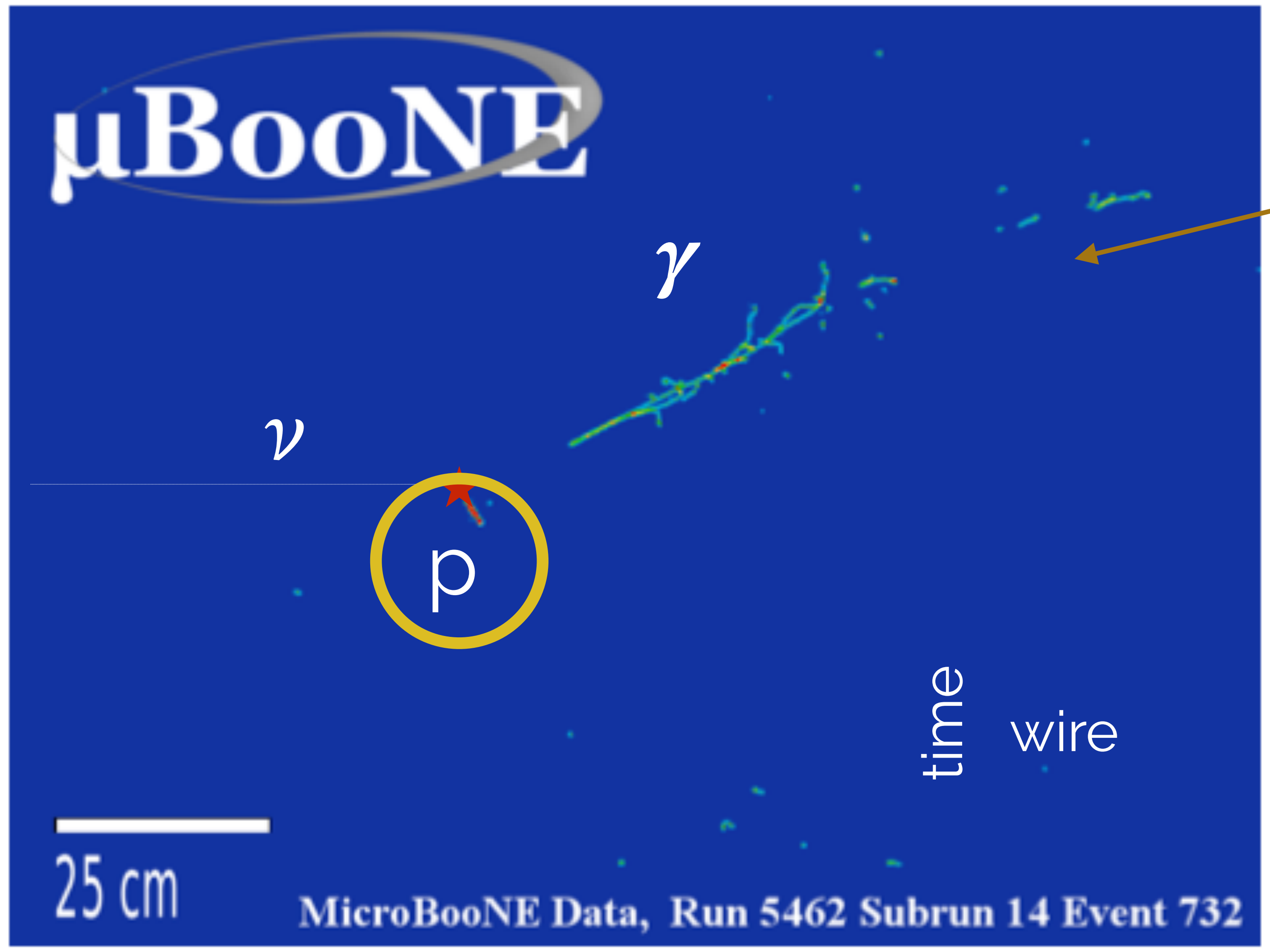
electron shower

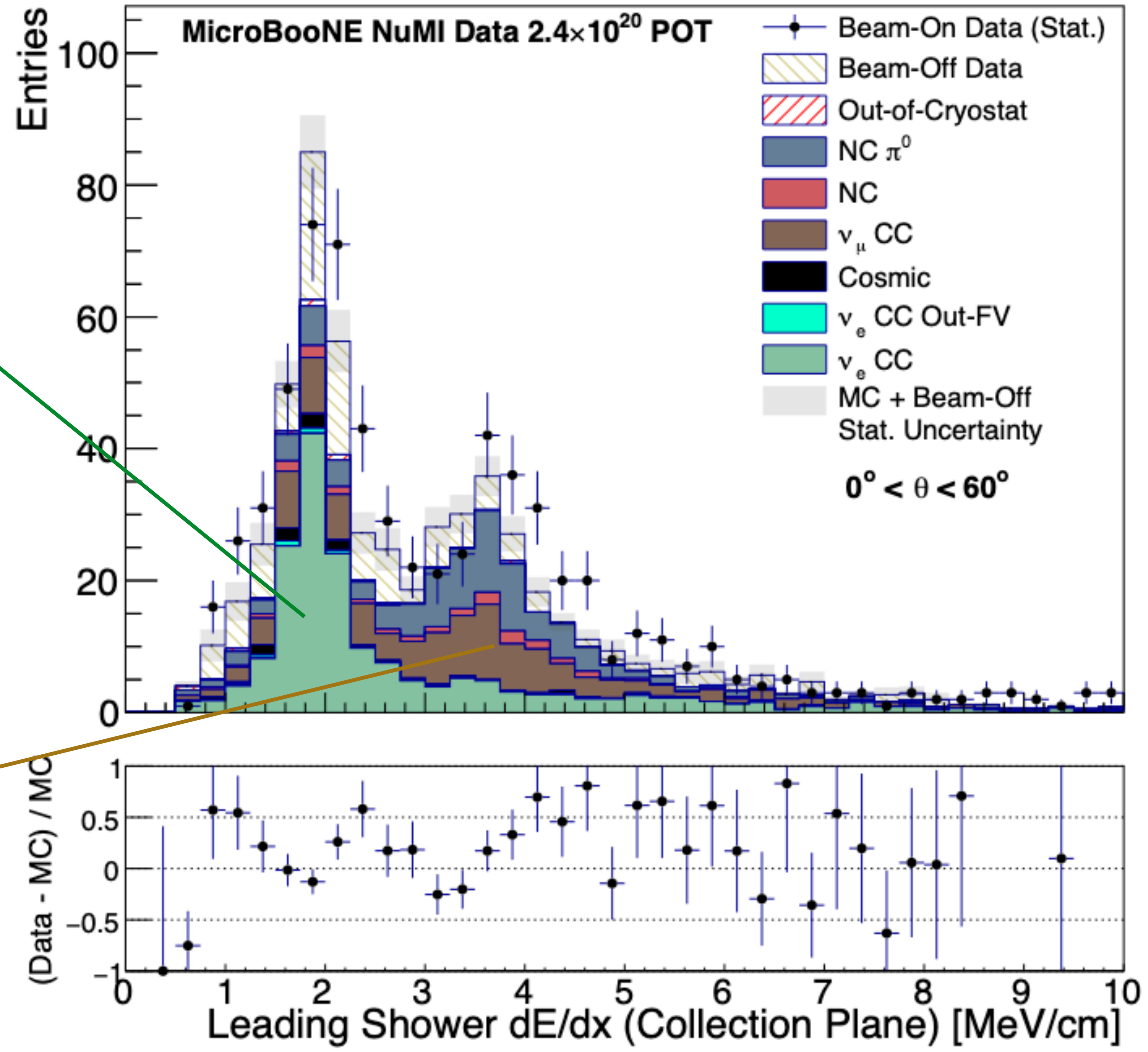


photon shower

topology information



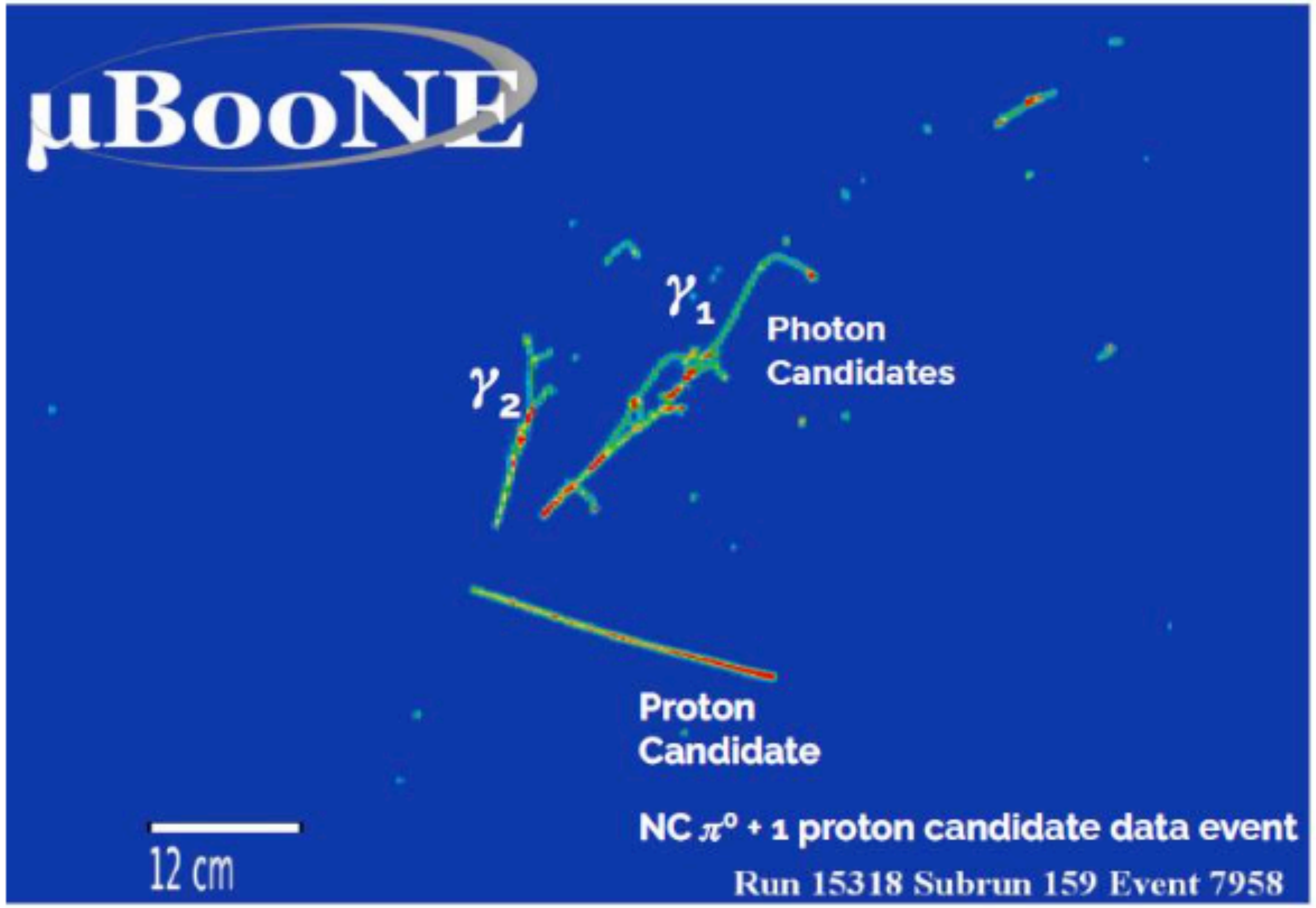


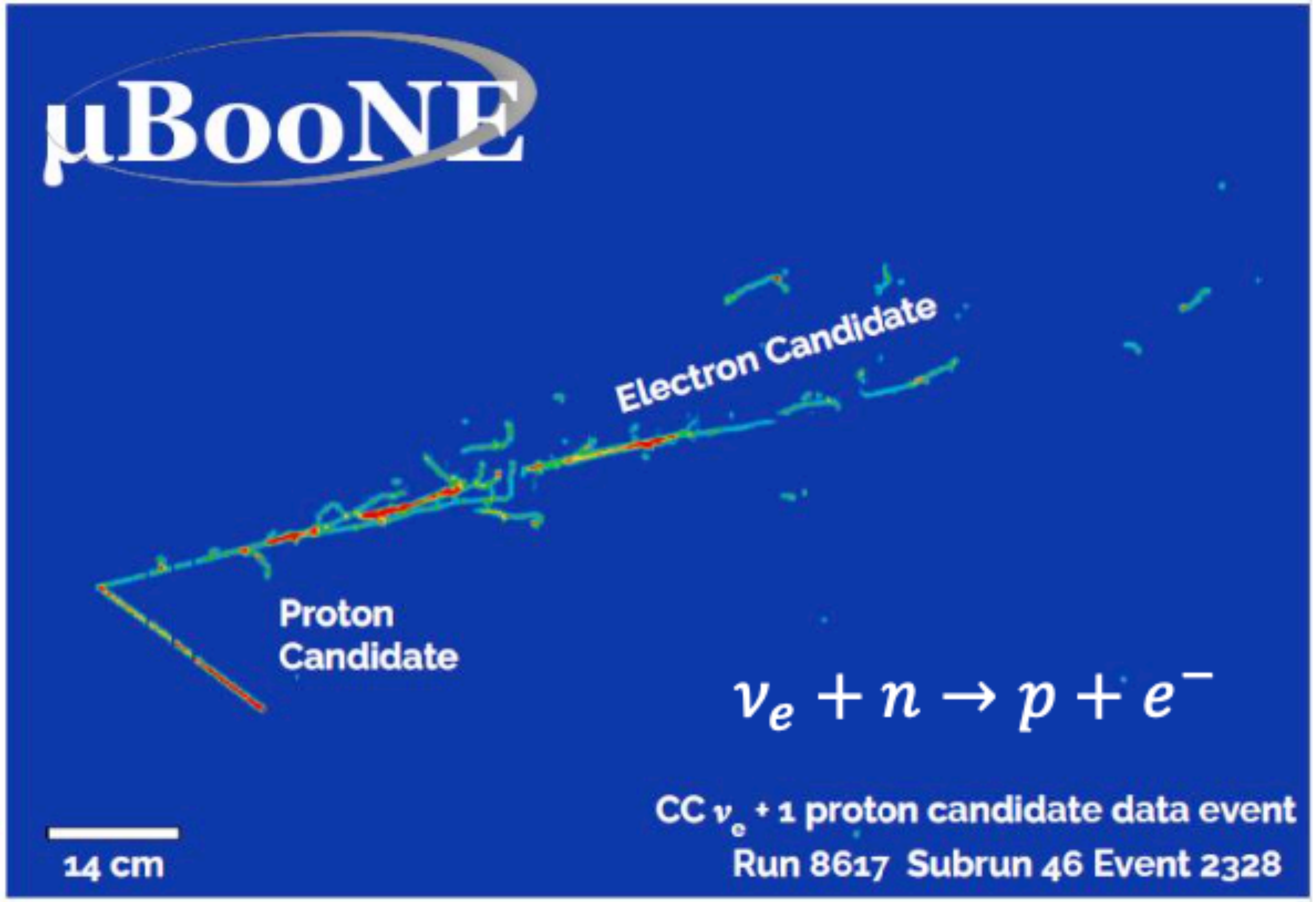


ionization dE/dx

...also to identify hadronic final states to provide more information of different interactions

LArTPC to rescue



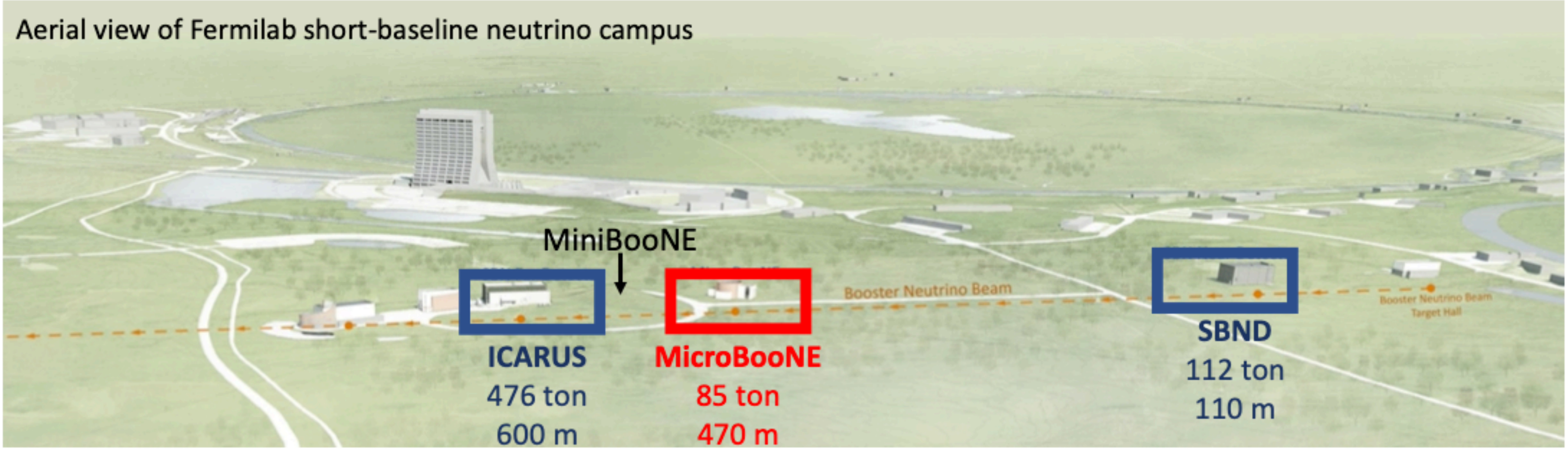


- capable of separating electrons from photons, with gap and calorimetry information

Outline

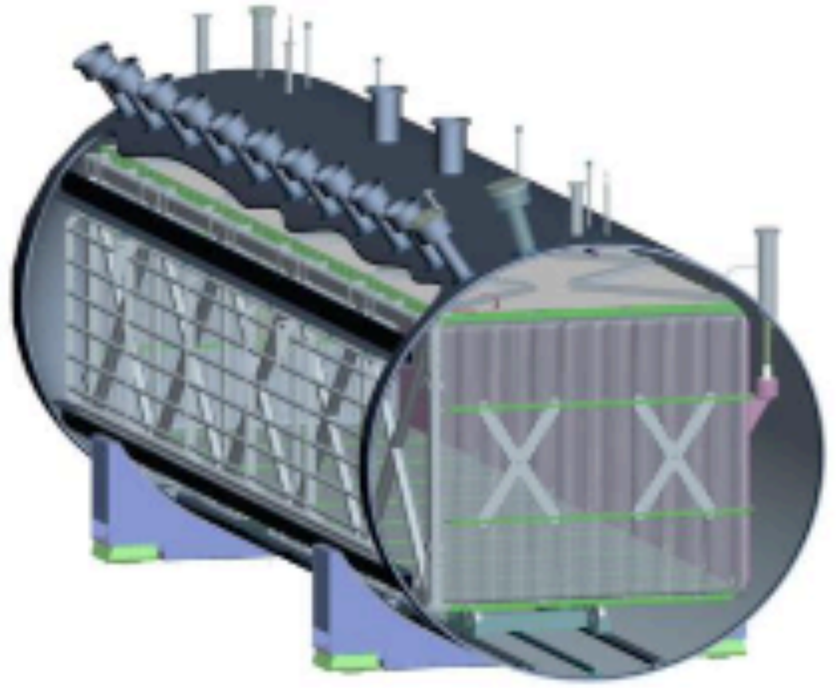
- recap: remaining questions in neutrino physics
- sterile neutrino: what is it, why is it, and how do we detect it
- **Short Baseline Neutrino (SBN) Program @ Fermilab**

Fermilab SBN program

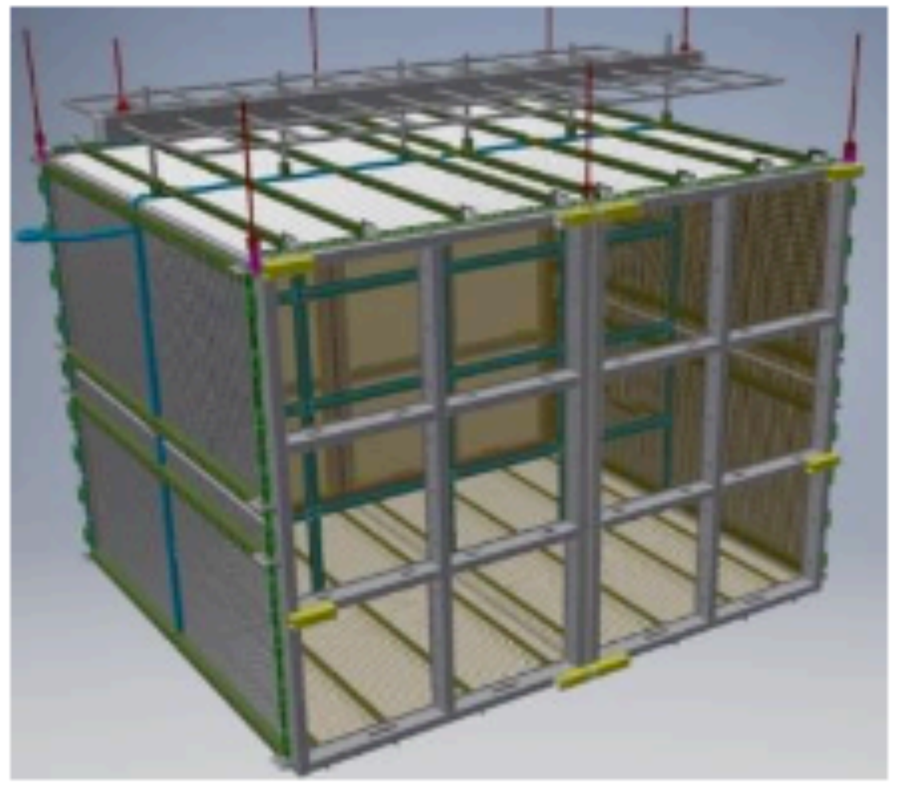


- three LArTPC detectors, with same neutrino beamline and different baseline
- reduce statistical uncertainties with large mass far detector (ICARUS)
- reduce systematic uncertainties with same LArTPC detector technology

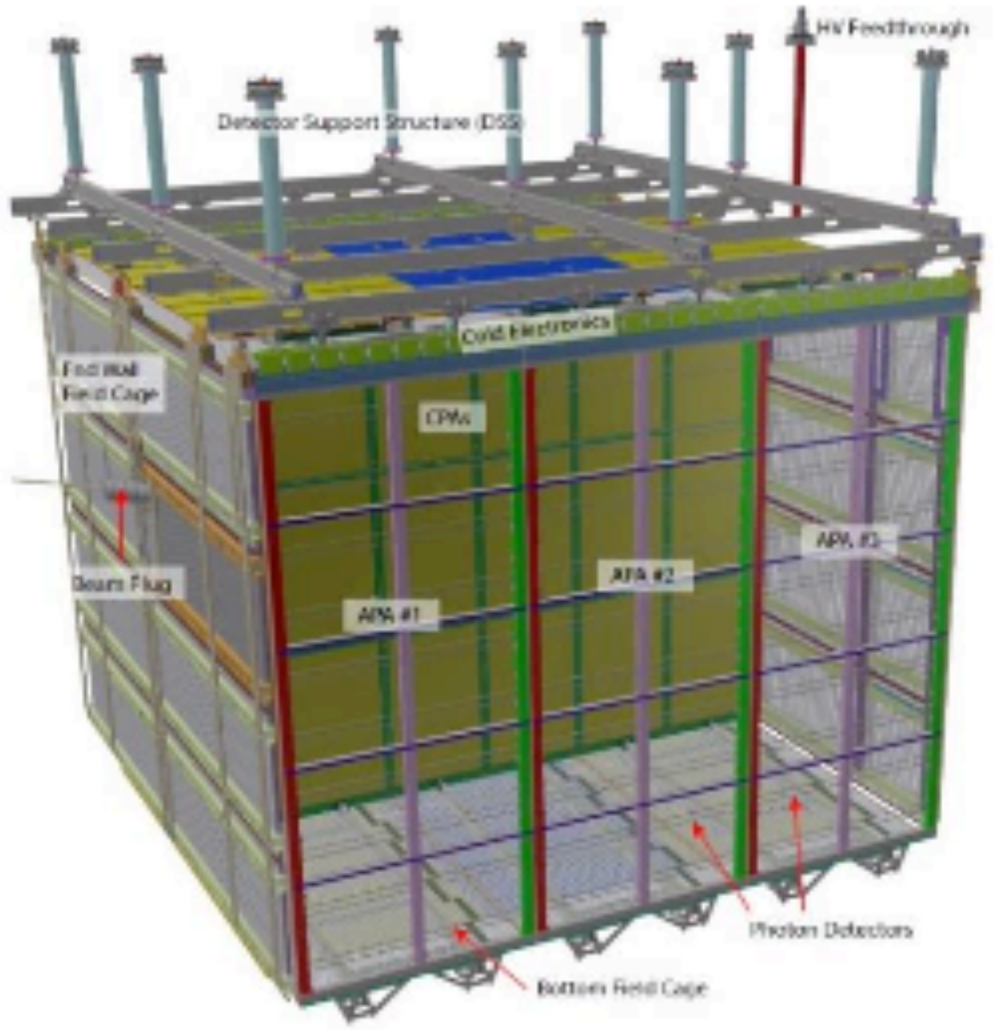
Fermilab SBN program



MicroBooNE, 87 ton
2.3m x 2.5m x 10.4m



SBND, 112 ton
4m x 4m x 5m



ICARUS, 476 ton
1.5m x 2.2m x 18m x 4

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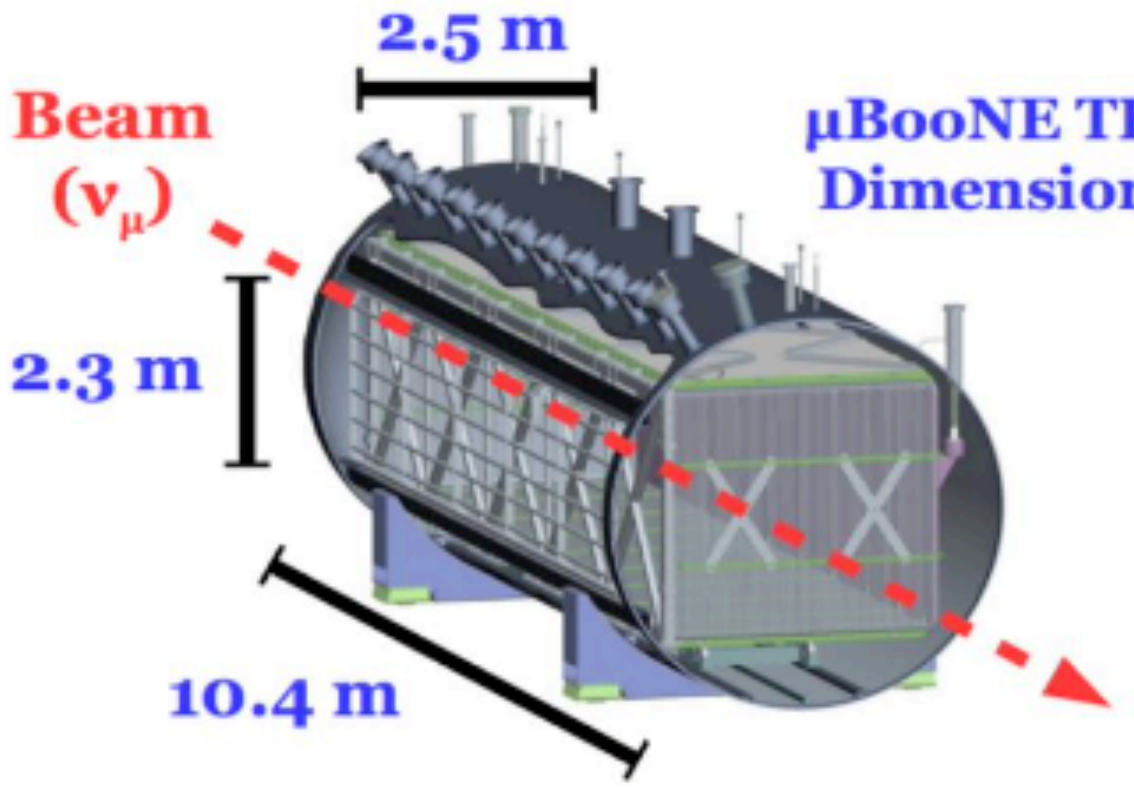
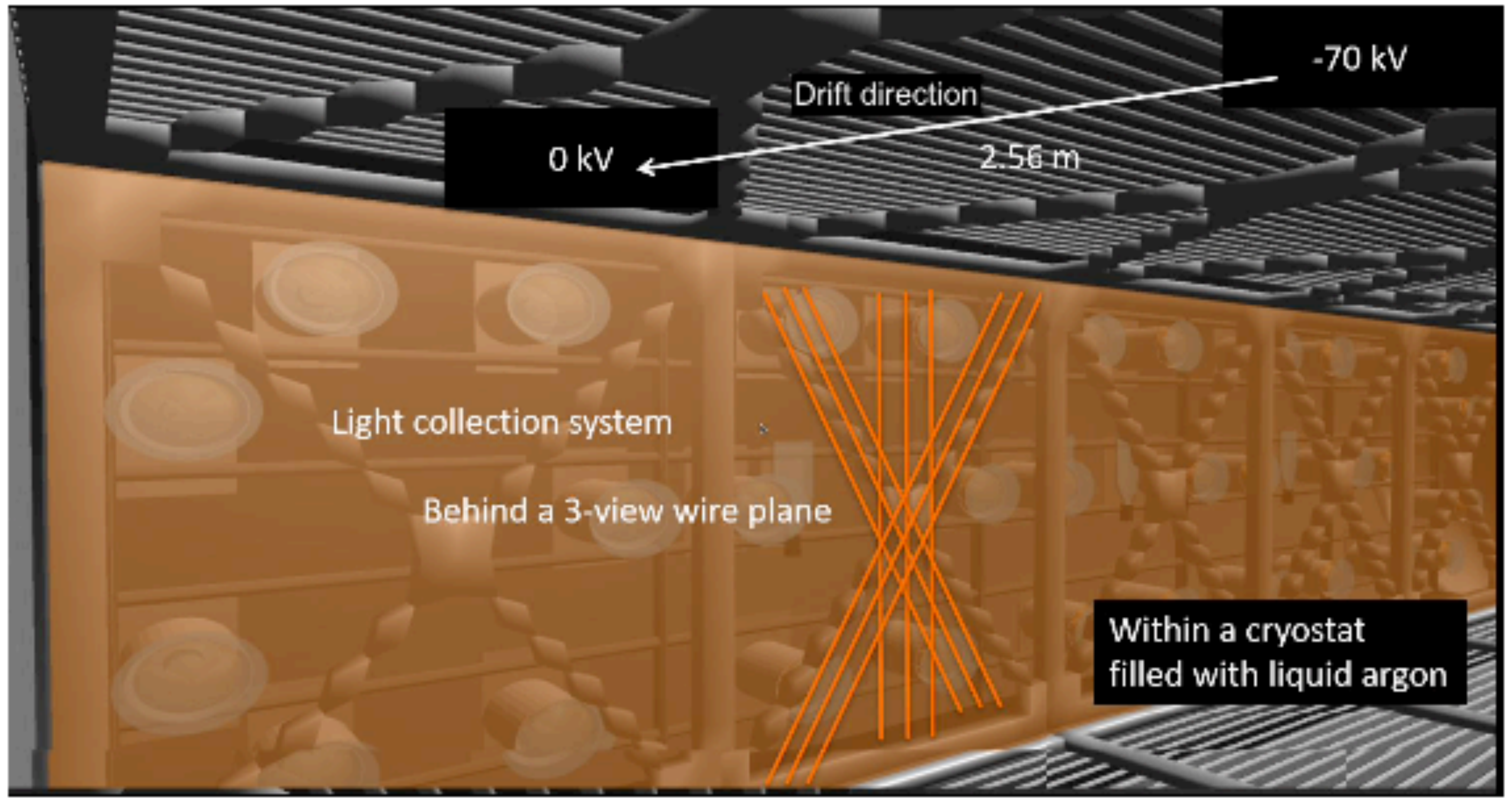
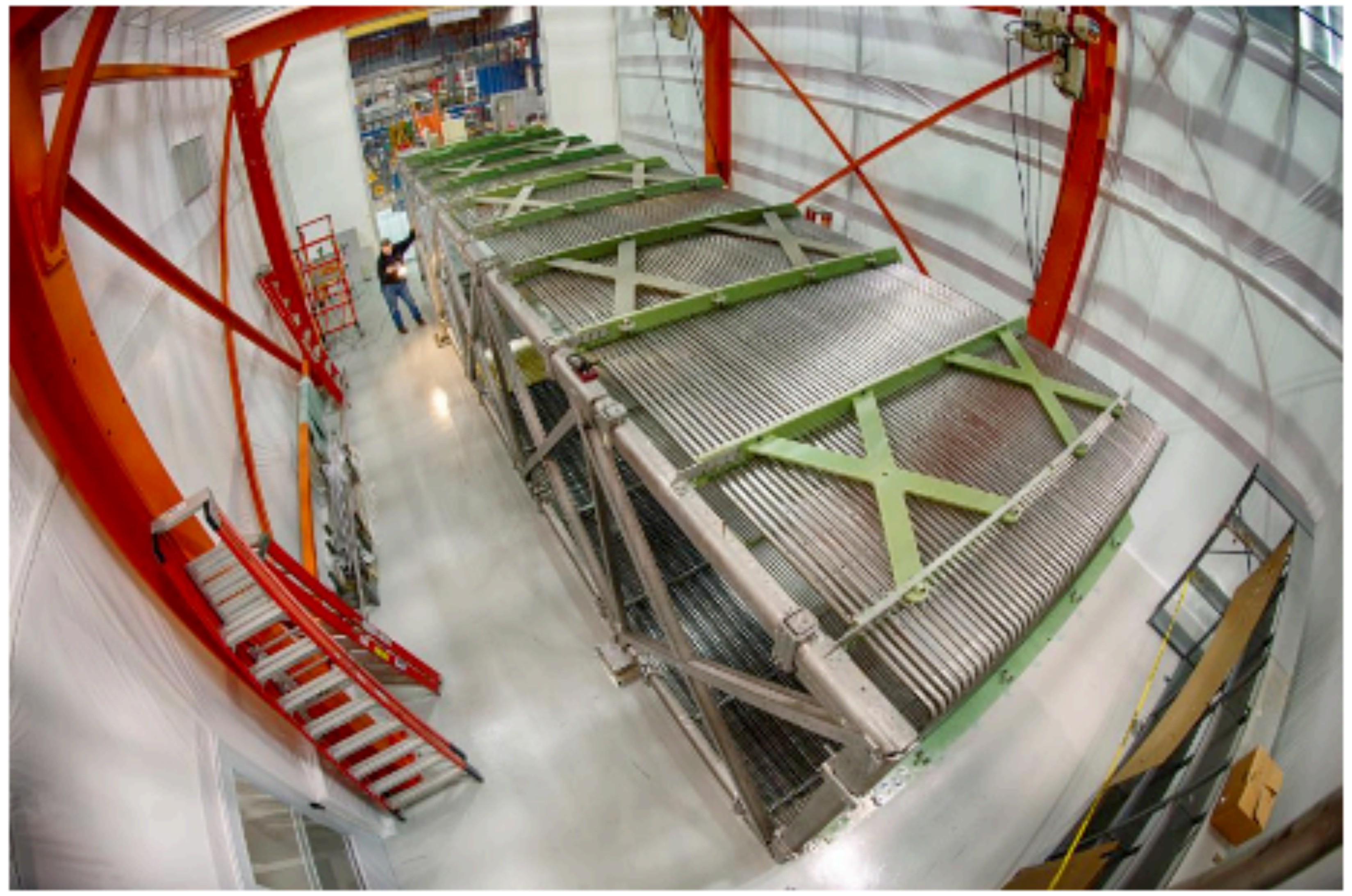
MicroBooNE

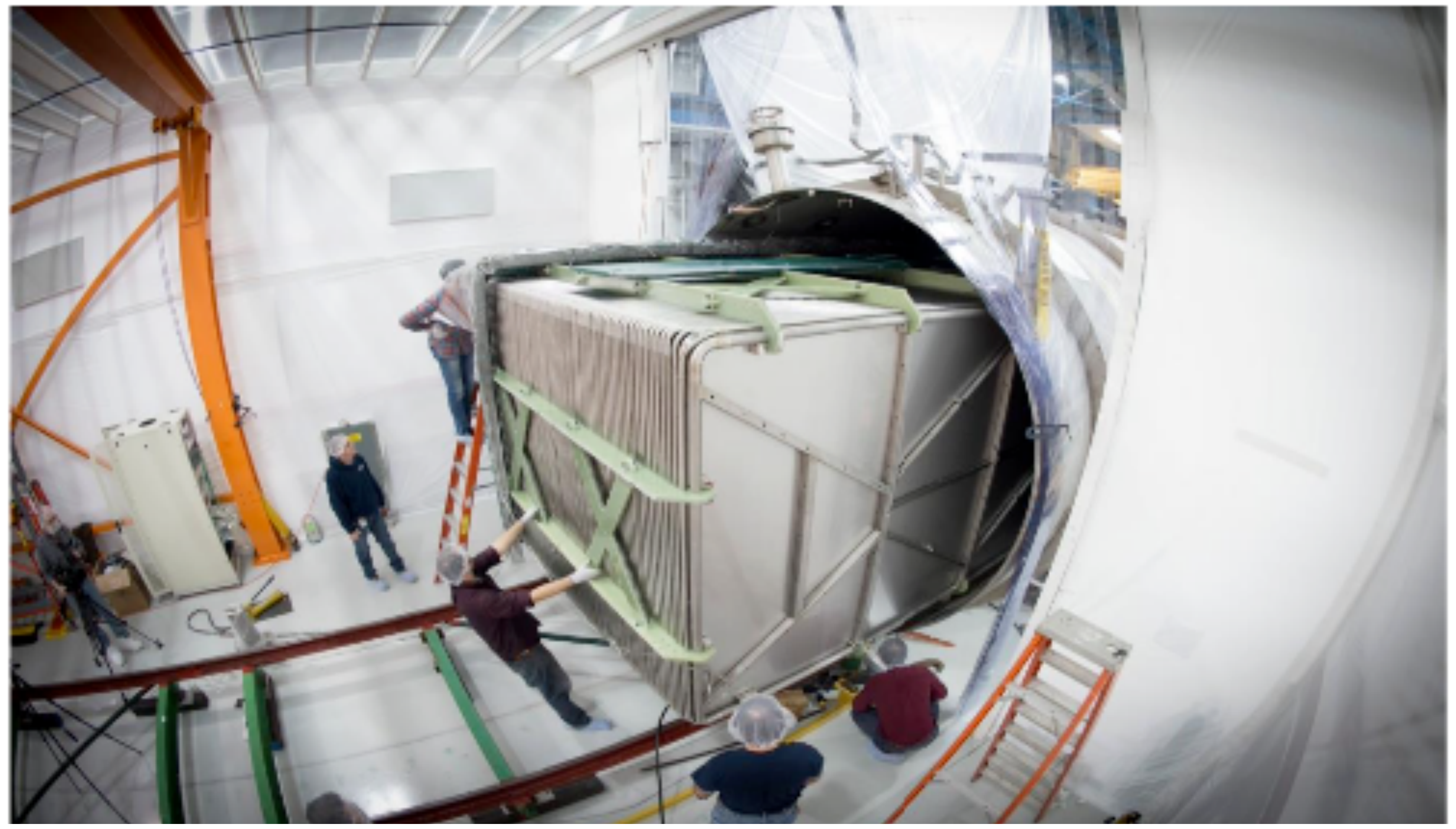

2.5 m
Beam
(ν_μ)
µBooNE TPC
Dimensions
2.3 m
10.4 m

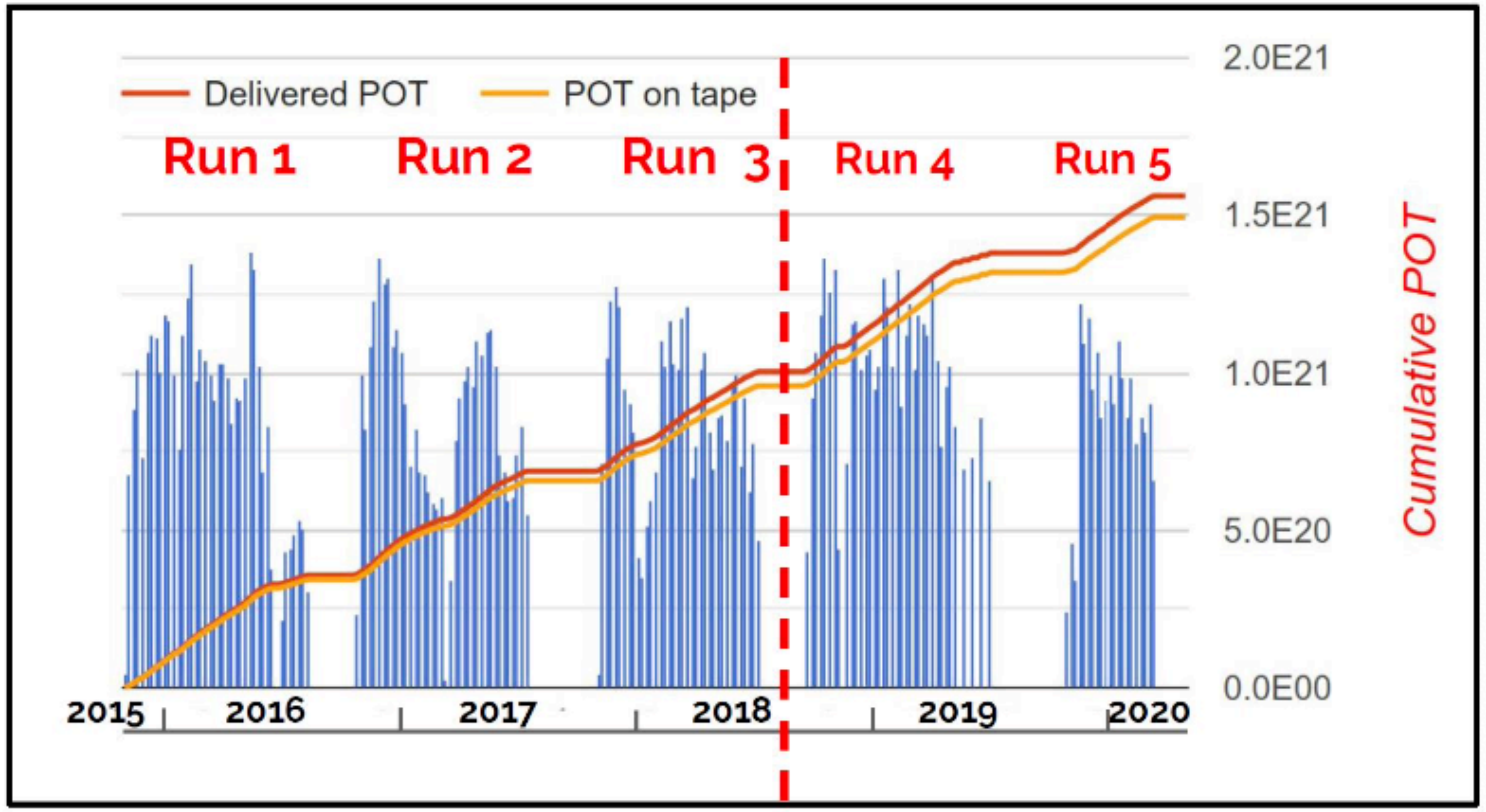

-70 kV
Drift direction
0 kV
2.56 m
Light collection system
Behind a 3-view wire plane
Within a cryostat
filled with liquid argon



MicroBooNE

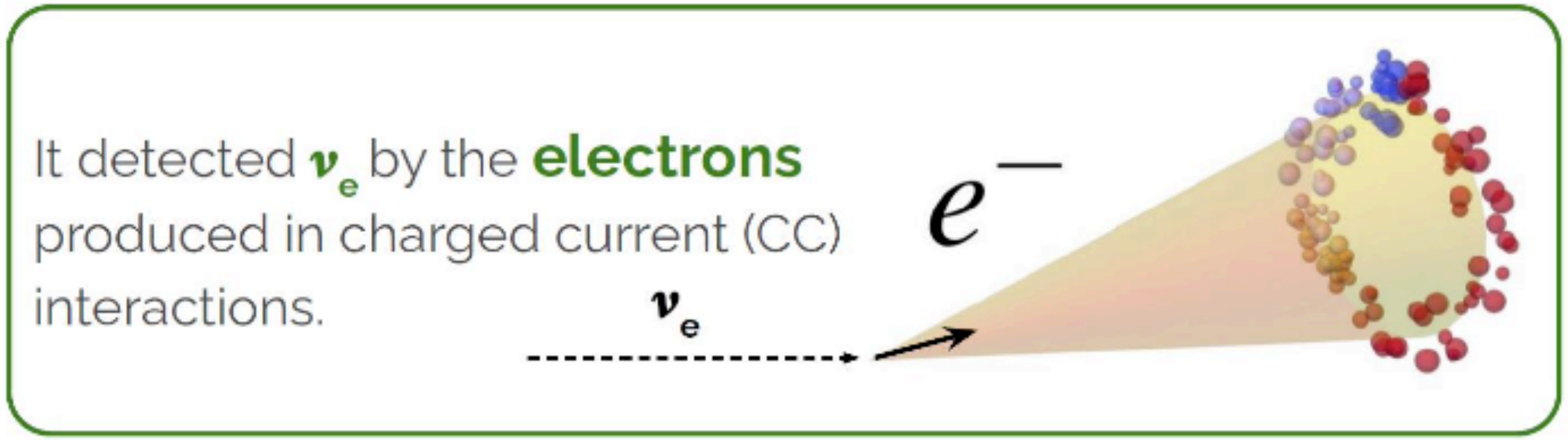
- started taking data since 2015
- finished operation in 2021
- accumulated the world's largest sample of neutrino interaction on argon
- one of the first LArTPC detectors with many new features
  - cold, low noise electronics *(see Shanshan's talk at 3pm)*
  - excellent LAr purity
  - pioneered LArTPC detector physics
  - stable & long-term running

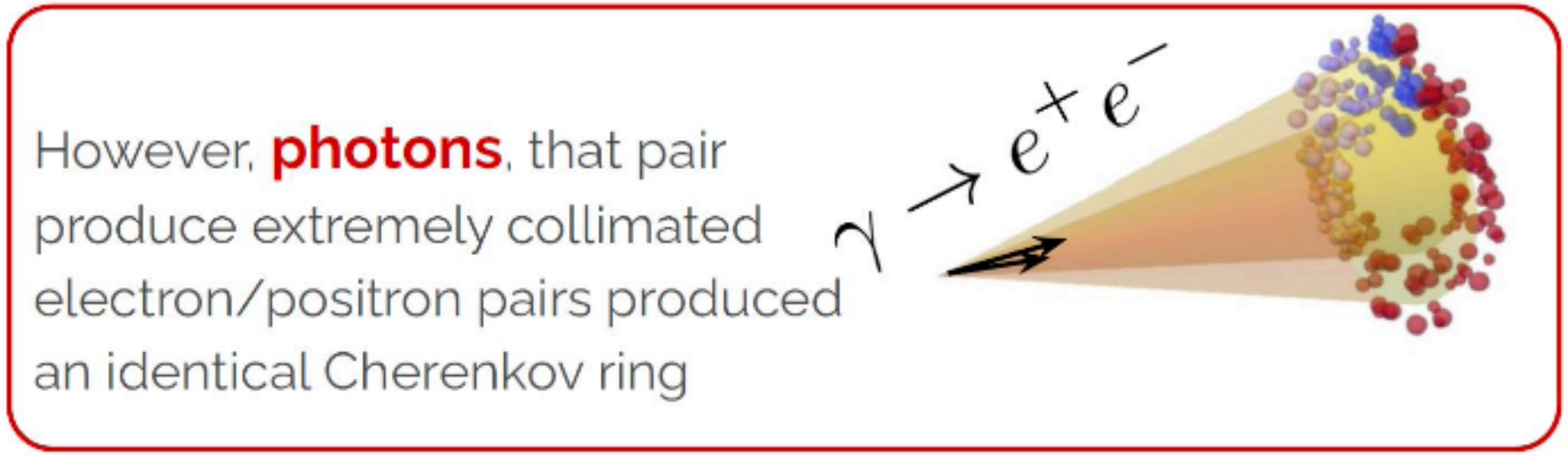




The MiniBooNE Anomaly: recap

- this limitation makes it hard to interpret the LEE
  - if electrons, this can be explained by sterile neutrino oscillated into electron neutrinos
  - if photons, this can be explained by underestimated prediction of single-photon-producing SM process

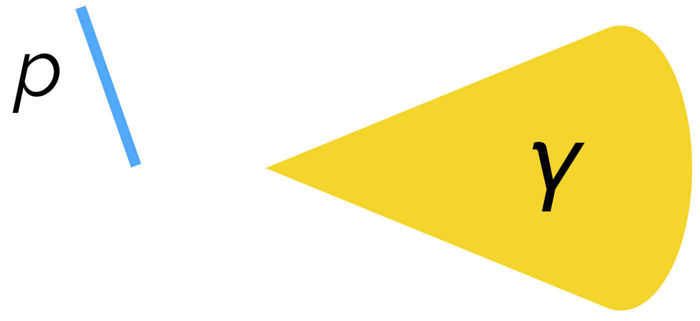


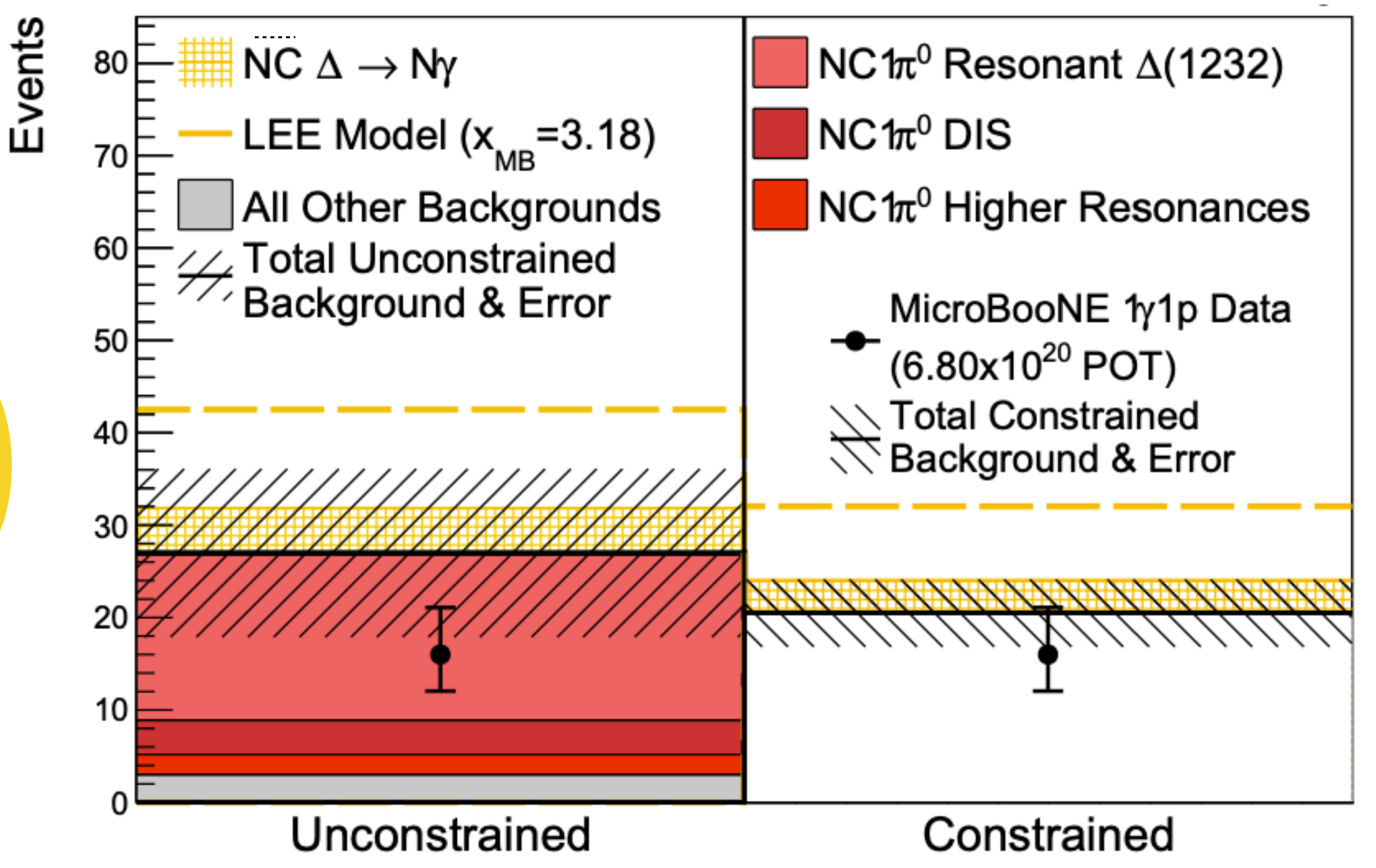


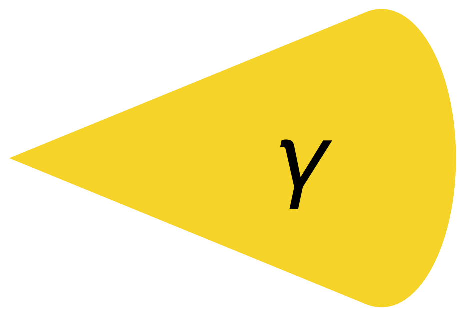
MicroBooNE LEE result

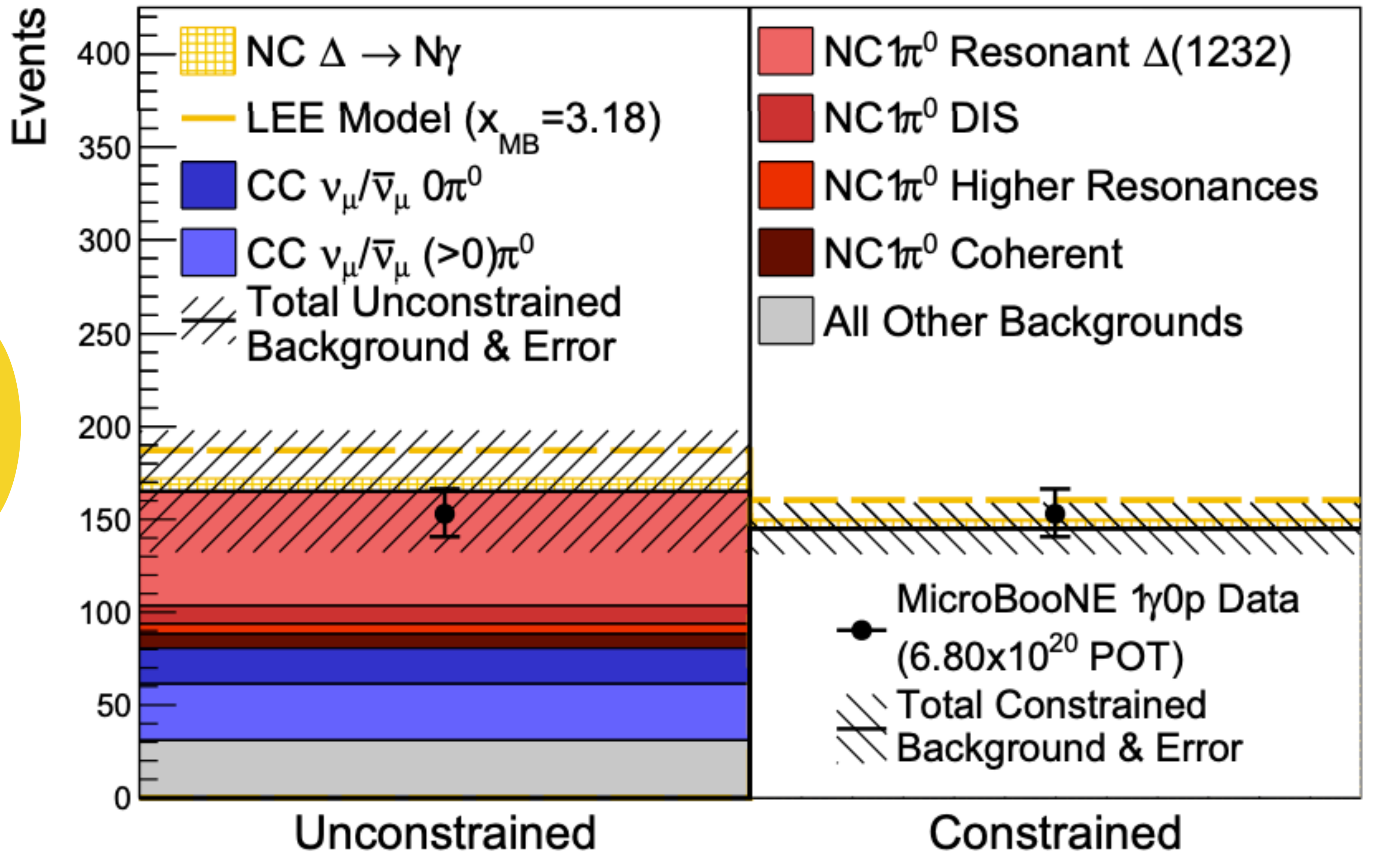
- first MicroBooNE result probed both electron-like and photon-like signals, with LArTPC's ability of e/γ separation

- photon analysis targets NC Δ—>Nγ channel
  - test if this channel is underestimated in the standard model
  - result shows no evidence for enhanced rate of single photons from NCΔ decay





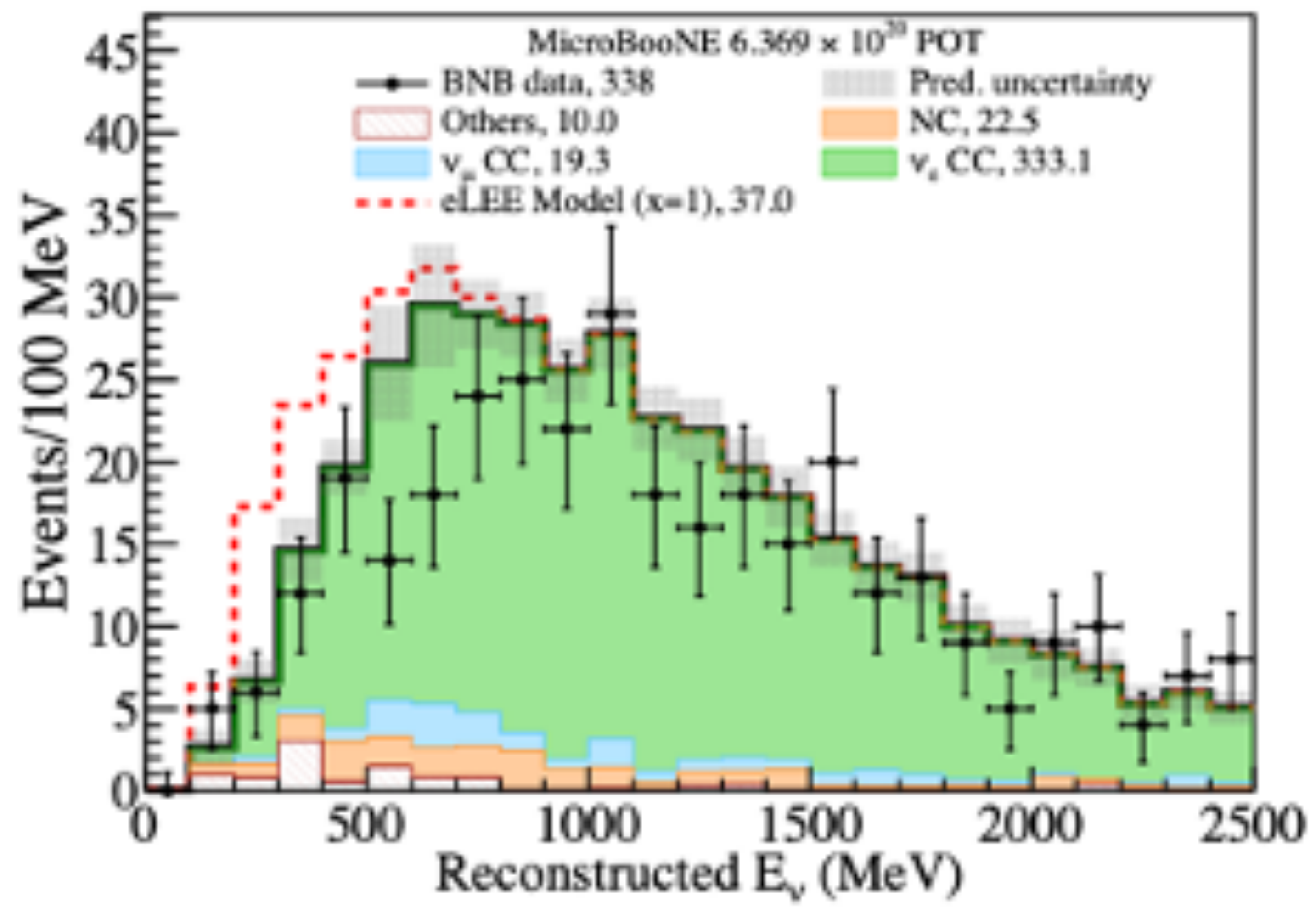




MicroBooNE LEE result

- first MicroBooNE result probed both electron-like and photon-like signals, with LArTPC's ability of e/γ separation
- electron analysis selects electron neutrino events
- test if the MiniBooNE low energy excess can be seen
  - probes 4 different topologies
  - result shows the observation is in agreement with prediction, no sign of MiniBooNE LEE

Phys. Rev. Lett. 128, 241801 (2022)



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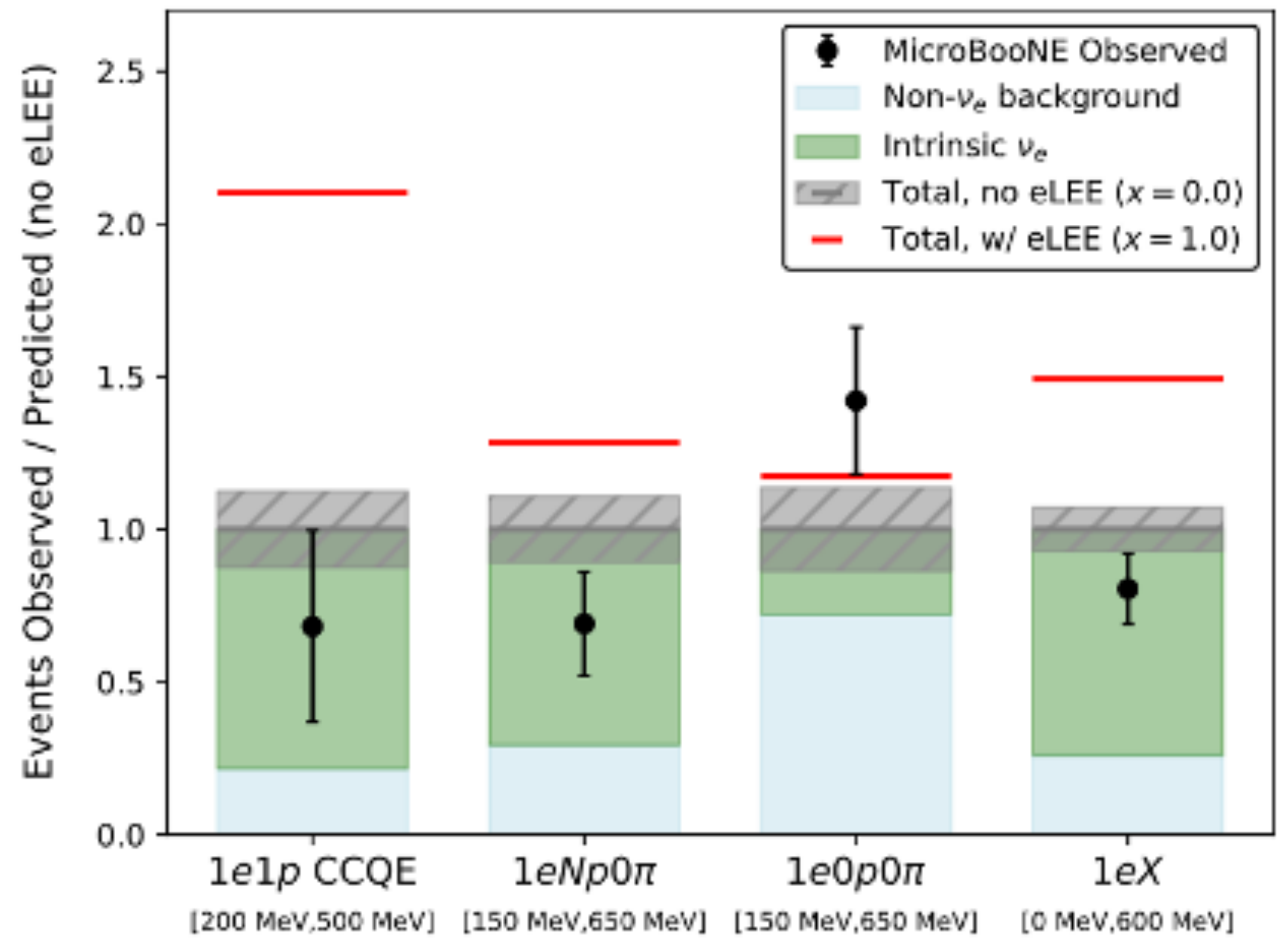
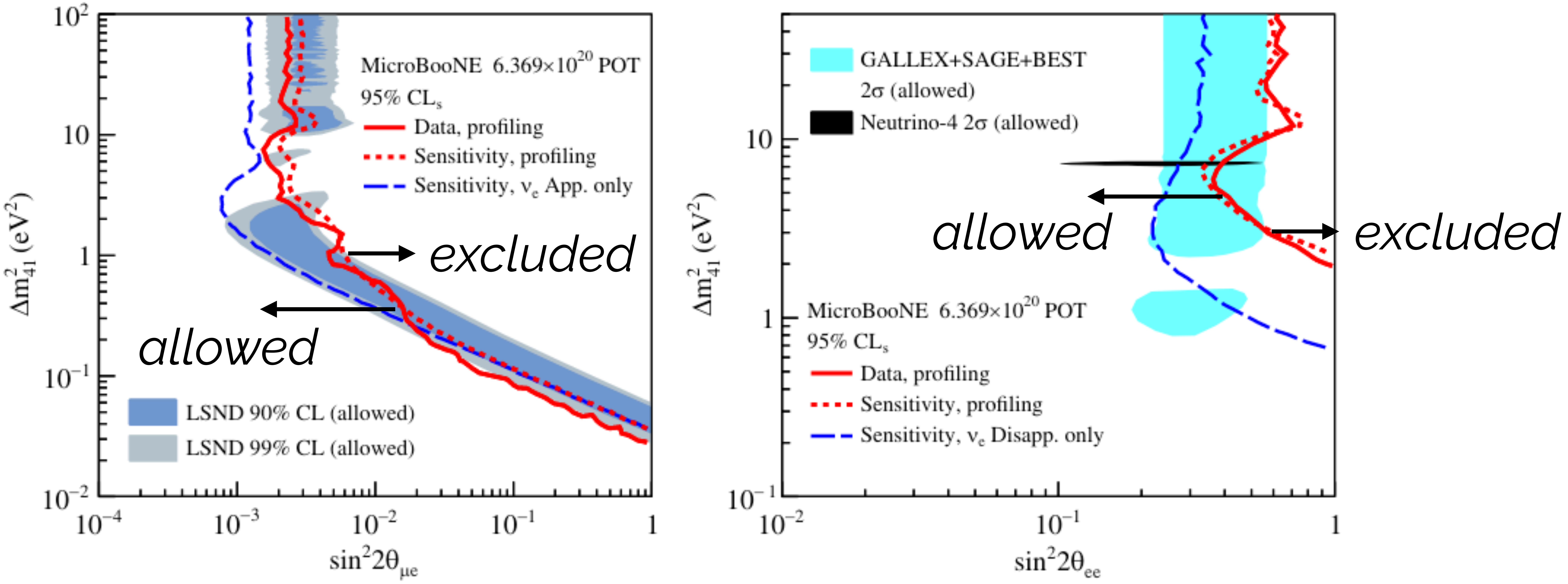


MicroBooNE sterile neutrino search

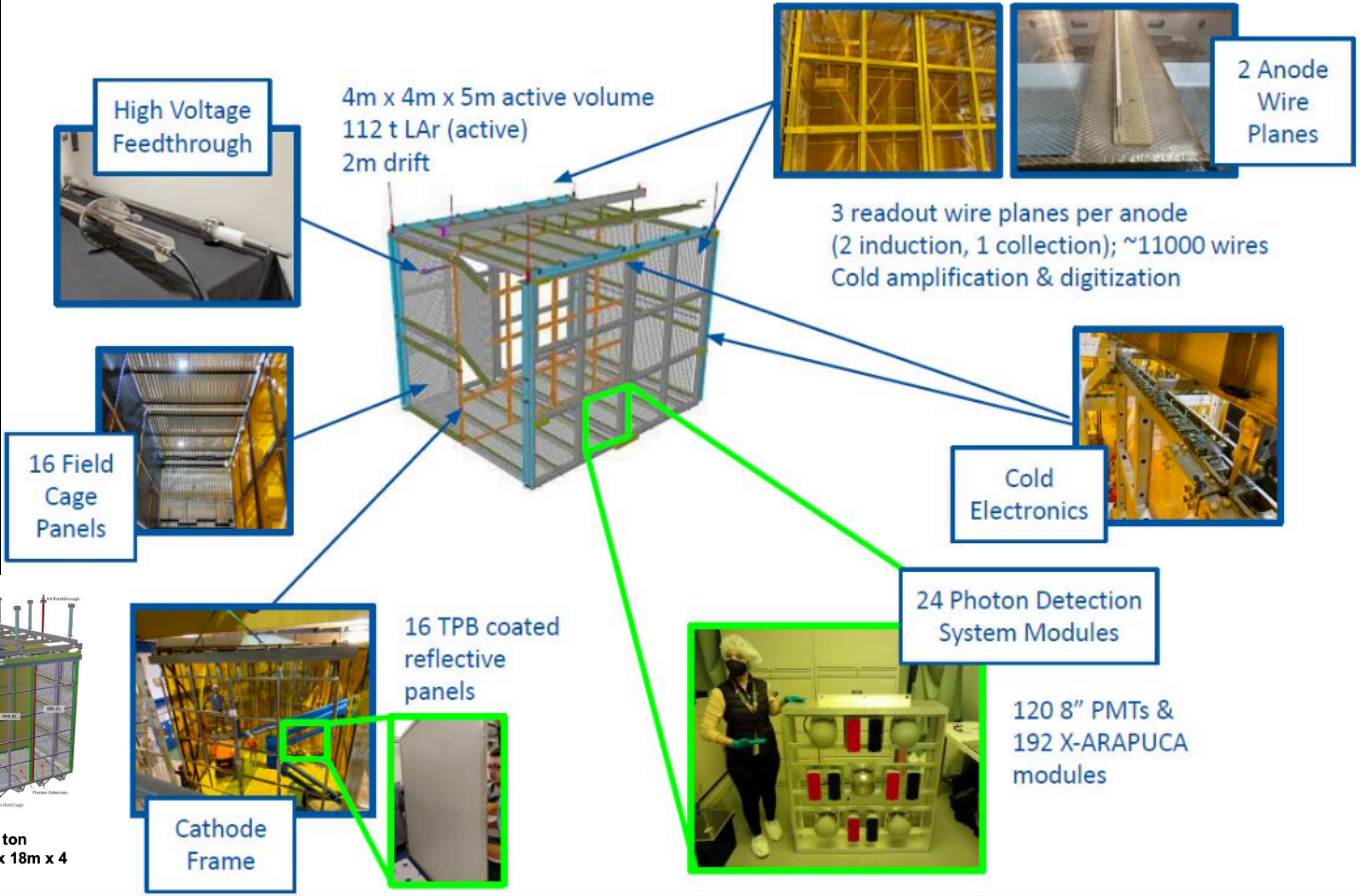
Phy. Rev. Lett. 130 011801 (2023)

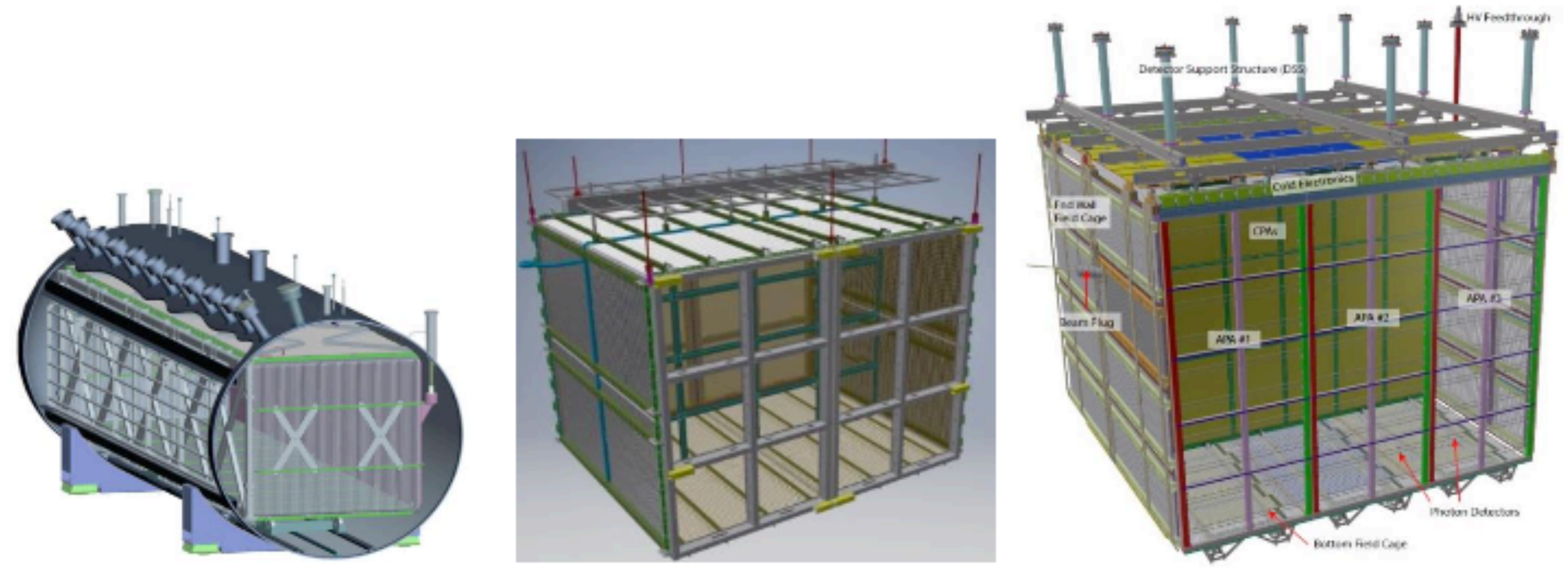


- LEE results are re-interpreted under a sterile neutrino oscillation hypothesis
- MicroBooNE could reject some portion of LSND and GALLEX/SAGE/BEST allowed region
- updated result is aiming to exclude most of the allowed region

Short Baseline Neutrino Detector: SBND

- same LArTPC technology with some upgrade
- closer to the target: much more neutrinos detected
- will start taking data very soon





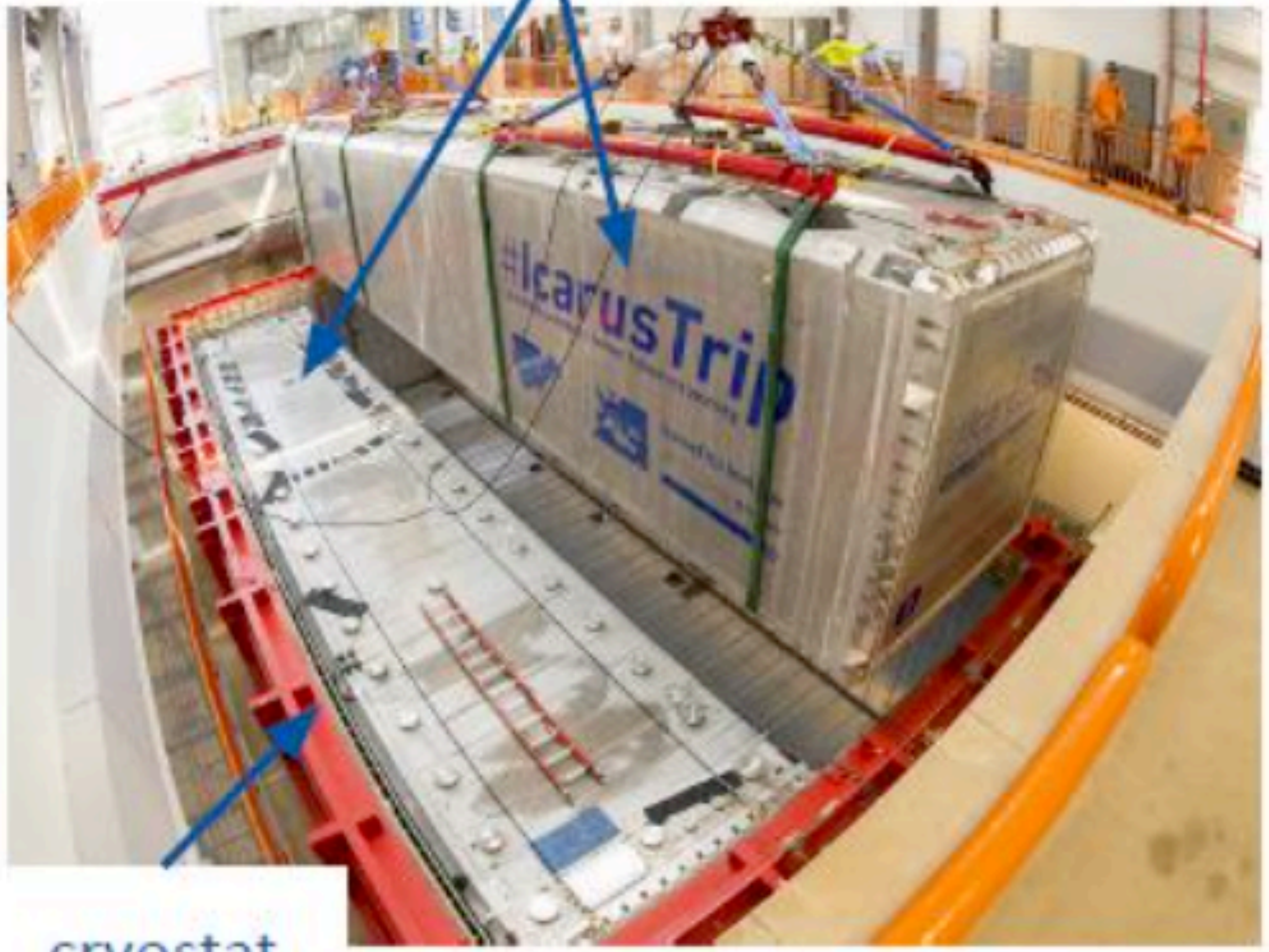
MicroBooNE, 87 ton
2.3m x 2.5m x 10.4m

SBND, 112 ton
4m x 4m x 5m

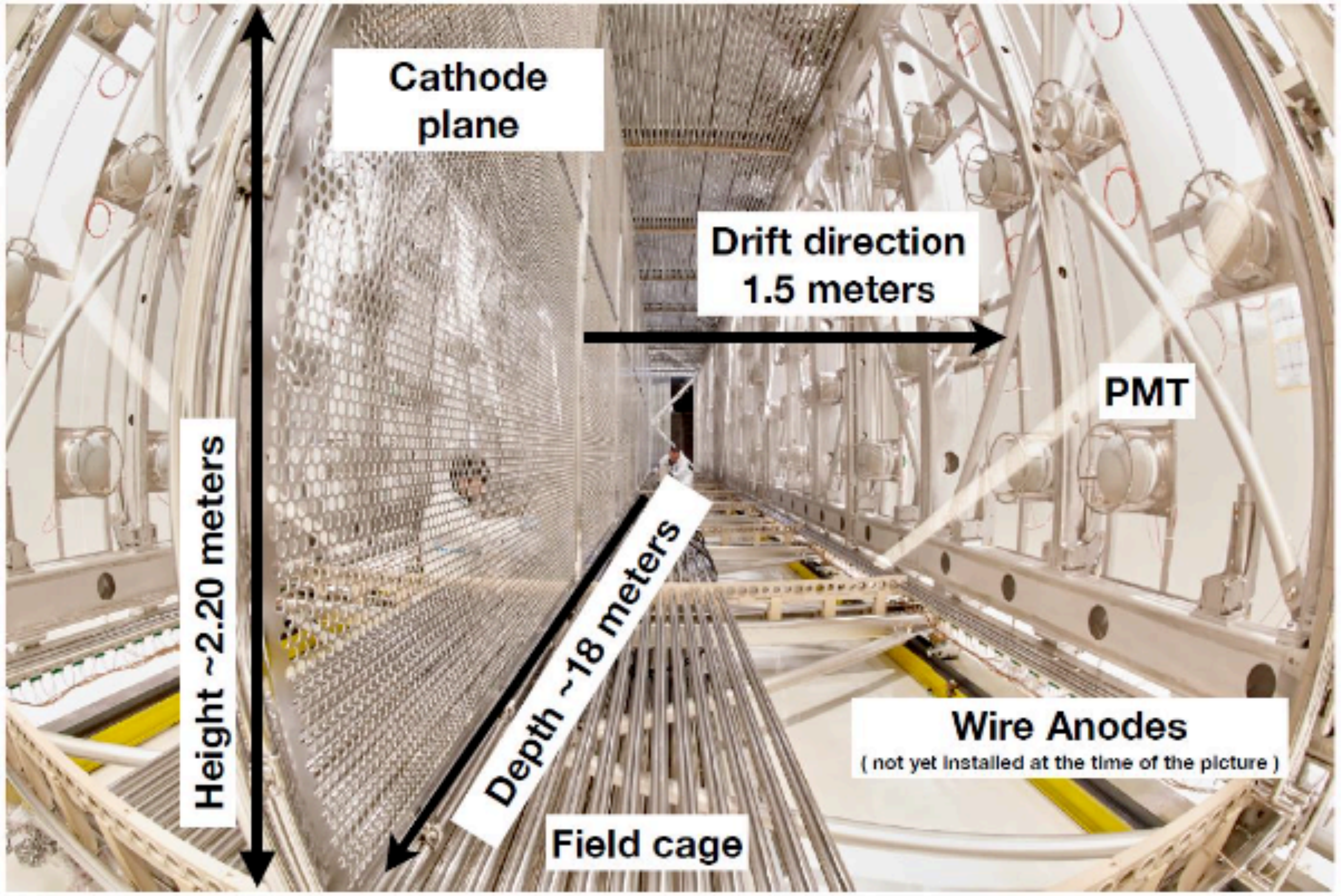
ICARUS, 476 ton
1.5m x 2.2m x 18m x 4

ICARUS

2 LArTPC modules
Total of 760t LAr (467t active)

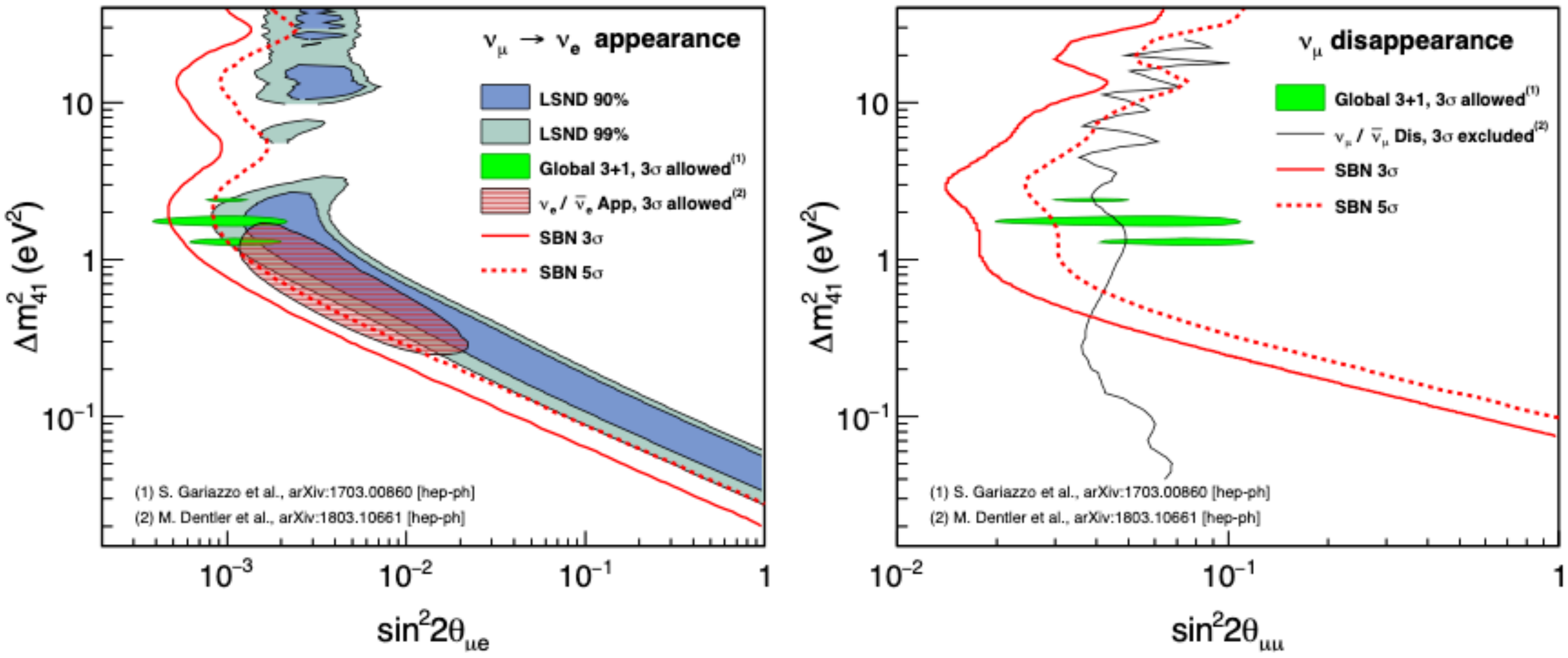


cryostat



- shipped from Europe (LSNG), refurbished & upgraded
- farther away from the target, but much larger volume
- started taking neutrino data since 2021

SBN program



- main goal is to definitively test sterile neutrino hypothesis
  - confirm or dispute anomalies that can be explained by sterile neutrino hypothesis
- also will measure & study how neutrino interacts with argon: important input to future DUNE experiment

Summary

- neutrinos oscillate, and three-neutrino oscillation is well understood
- however several neutrino experiments showed anomalies, which could be explained by postulating an additional neutrino: **sterile neutrino**
- Fermilab SBN program consists of three LArTPC neutrino detectors, MicroBooNE, SBND, ICRAUS, with a goal to tackle this topic
  - MicroBooNE result showed that MiniBooNE anomaly is not from electron neutrinos & excluded some sterile neutrino-allowed region
  - ICARUS started taking data in 2021 and SBND will be taking data in 2023
  - together, SBN program will search for eV-scale sterile neutrino

Backup slides

Homework (advanced)

- Can you calculated nue rate, that takes into account both numu—>nue appearance and nue—>nue disappearance, in 3+1 scenario?

  - predominant numu beam, with small fraction of nue within: let's assume number of "initial" numu is Tnumu, "initial" nue is Tnue

  - hint 1: mixing matrix is now

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

  - hint 2: we can replace matrix elements term with "effective mixing angles"

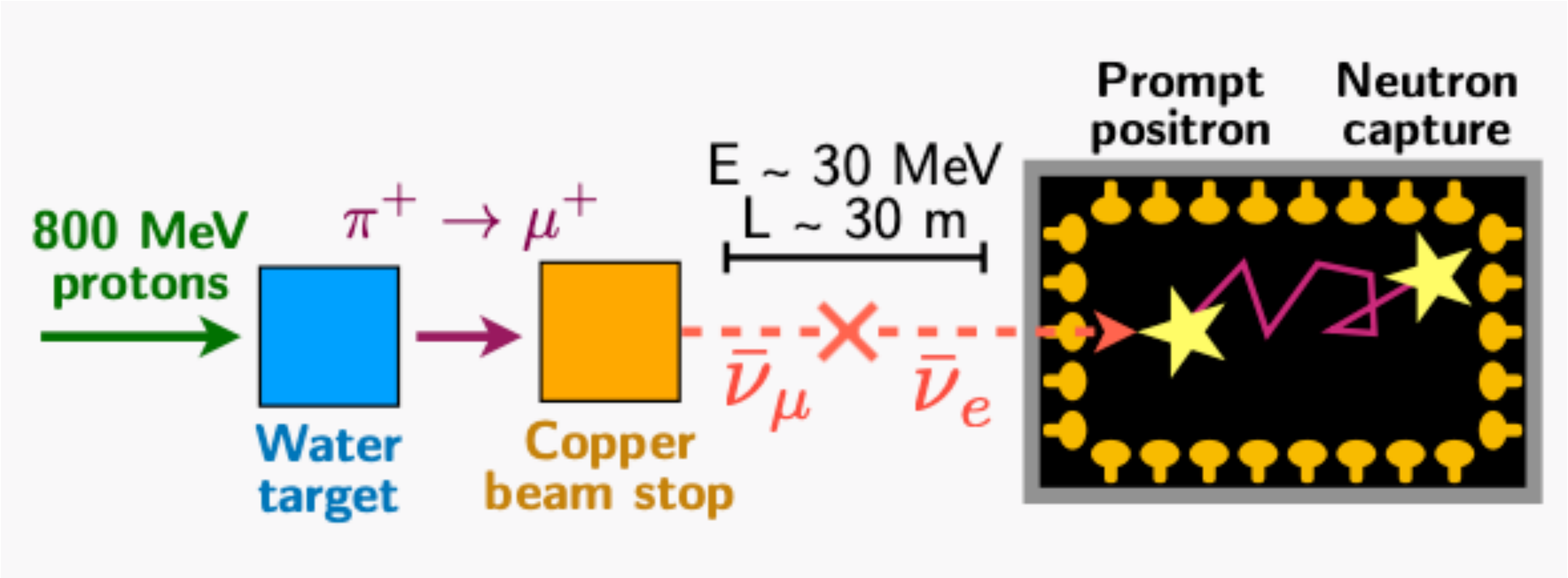
$$\sin^2 2\theta_{ee} = 4(1-|U_{e4}|^2)|U_{e4}|^2,$$
$$\sin^2 2\theta_{\mu\mu} = 4(1-|U_{\mu 4}|^2)|U_{\mu 4}|^2,$$
$$\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2.$$

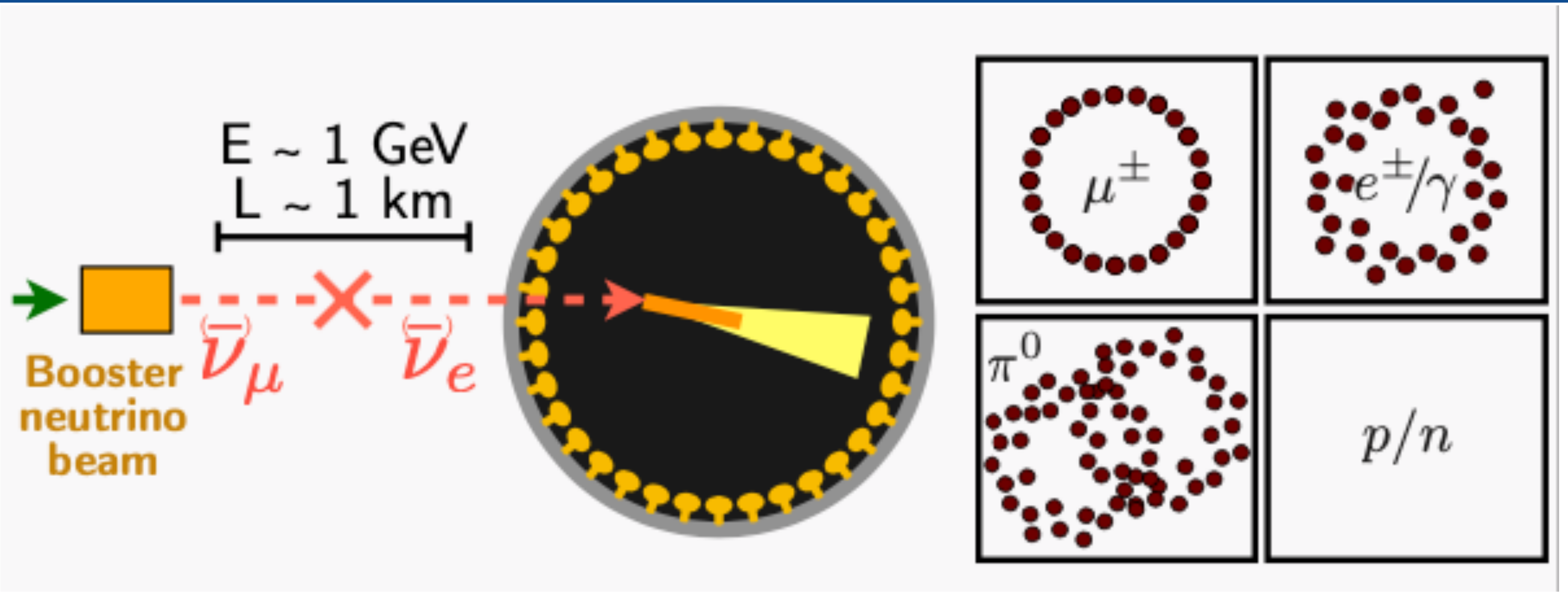
  - step1: calculate oscillation probability for numu—>nue and nue—>nue each

  - step2: now you multiply this probability to "original" numu and nue to get "oscillated" nue

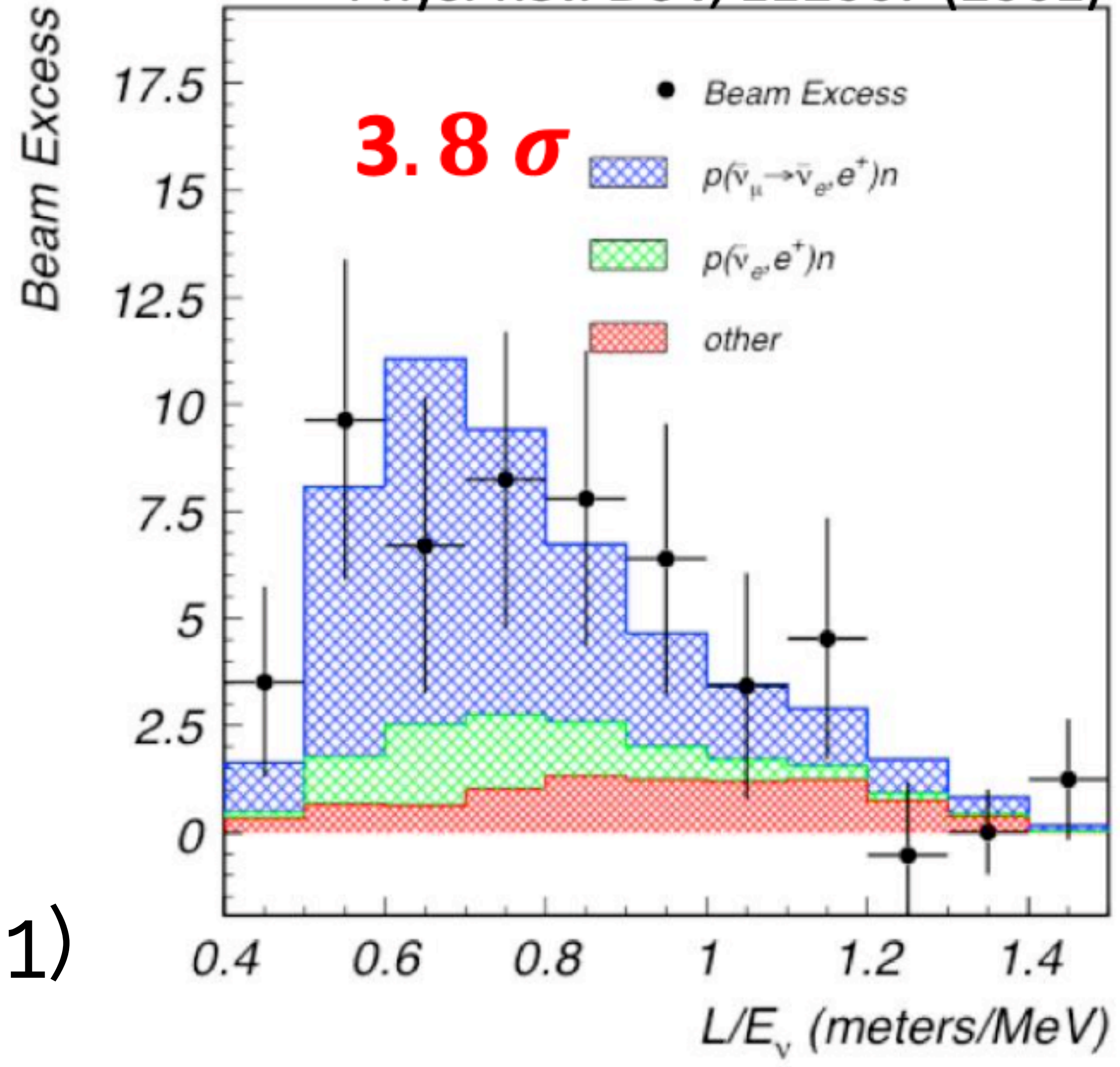
  - step3: combine both numbers together

LSND & MiniBooNE anomaly

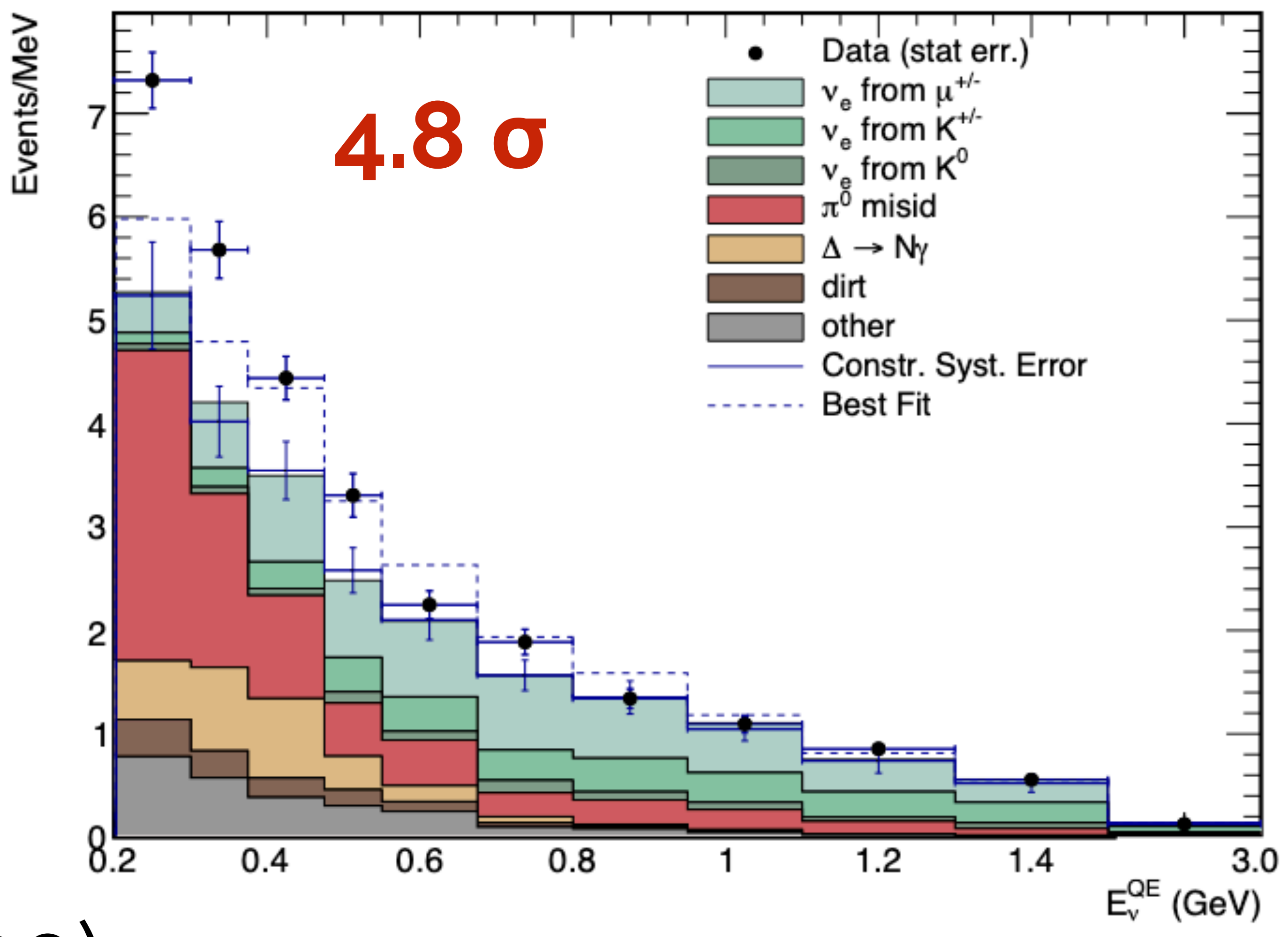




Phys. Rev. **D64**, 112007 (2001)



arxiv:2006.16883



- **LSND** (1990-2001)
- $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ excess over background suggests evidence for oscillation at $\Delta m^2 \sim 1 eV^2$

- **MiniBooNE** (1998-2020)
- measured ν_μ-> ν_e and $\bar{\nu}_\mu$-> $\bar{\nu}_e$ appearance
- the excess of events at low energy

LArTPC: Liquid Argon Time Projection Chamber

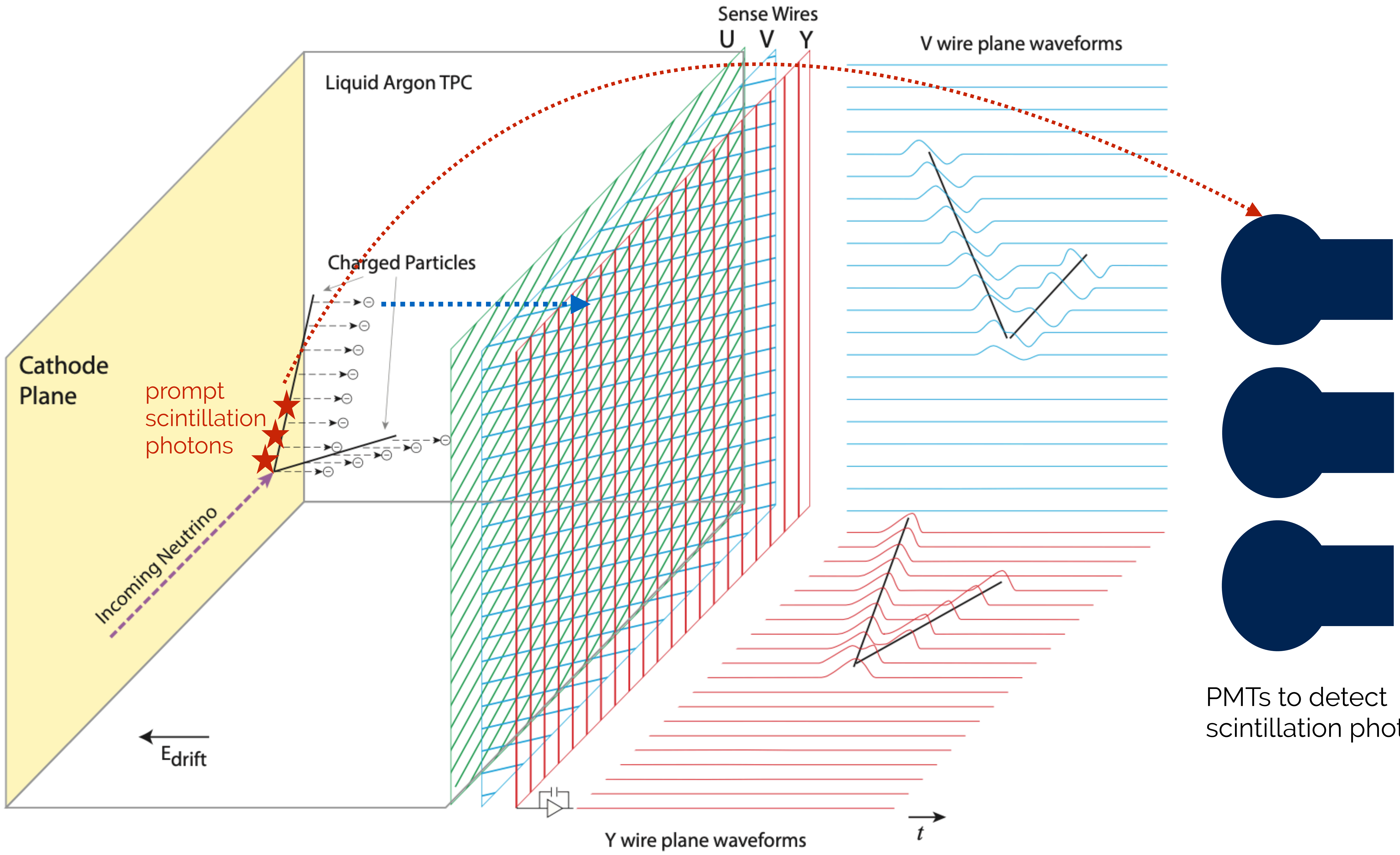
charged particle enters detector

⬇

scintillation light emitted by excited Ar, detected by PMTs

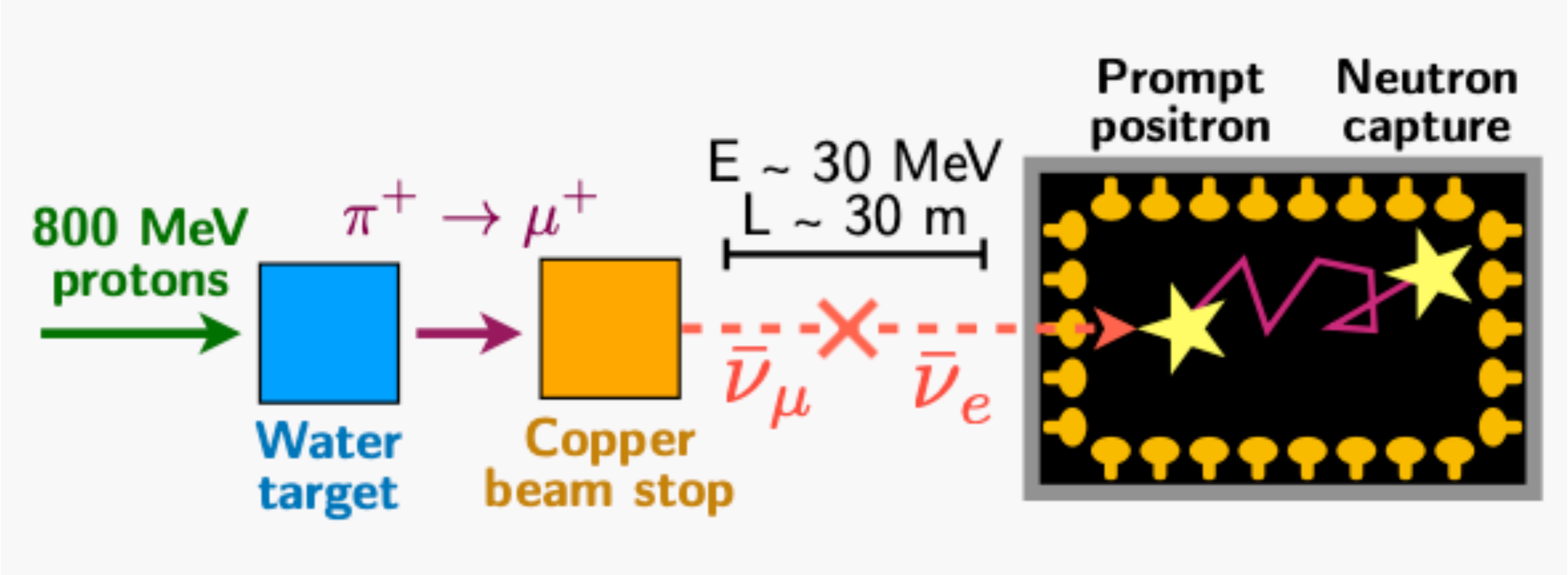
⬇

ionization electrons drift to anode plane, detected by sense wires



PMTs to detect scintillation photons

LSND & MiniBooNE anomaly



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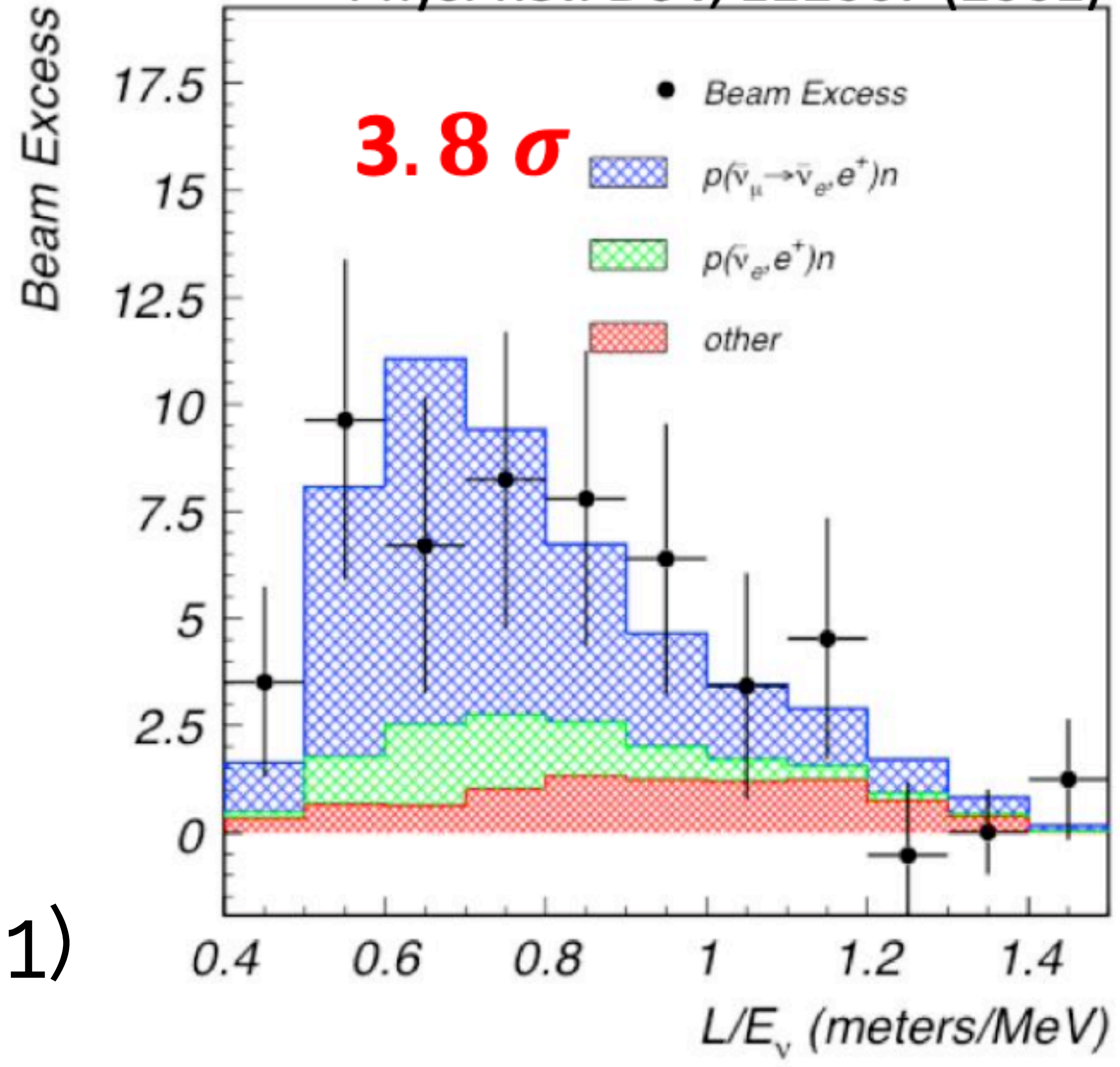

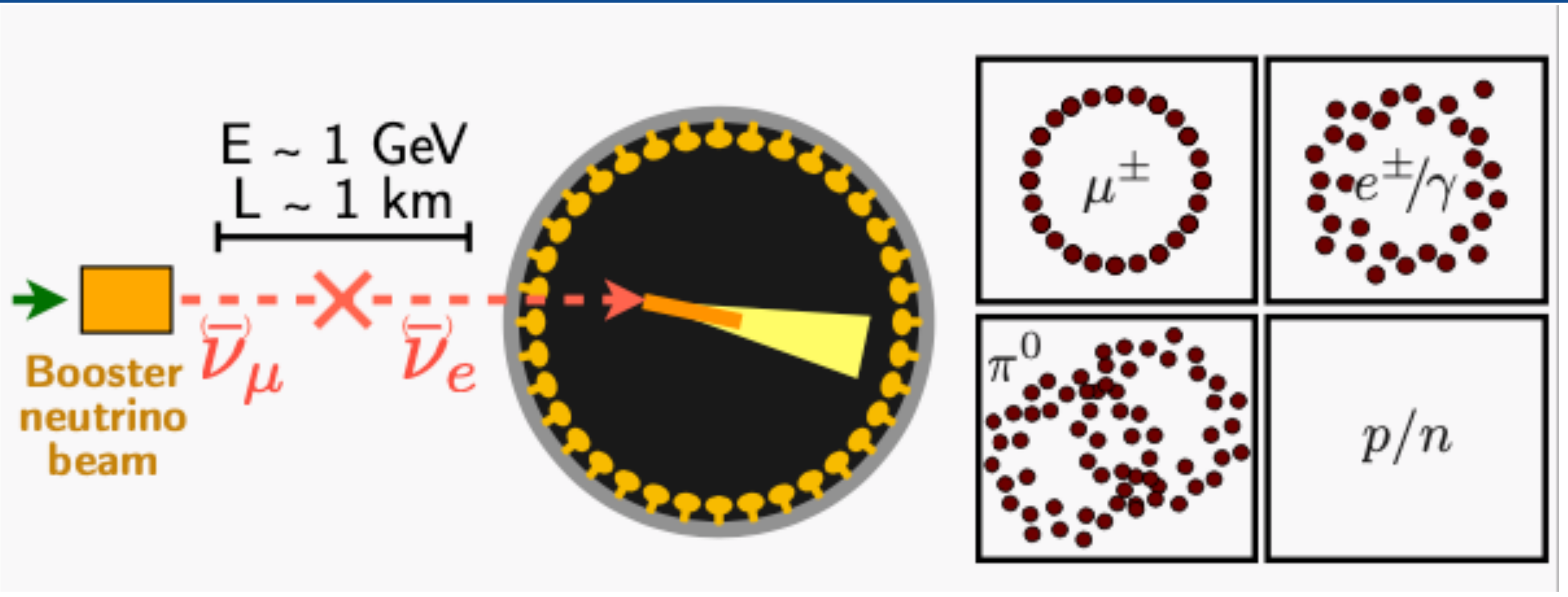

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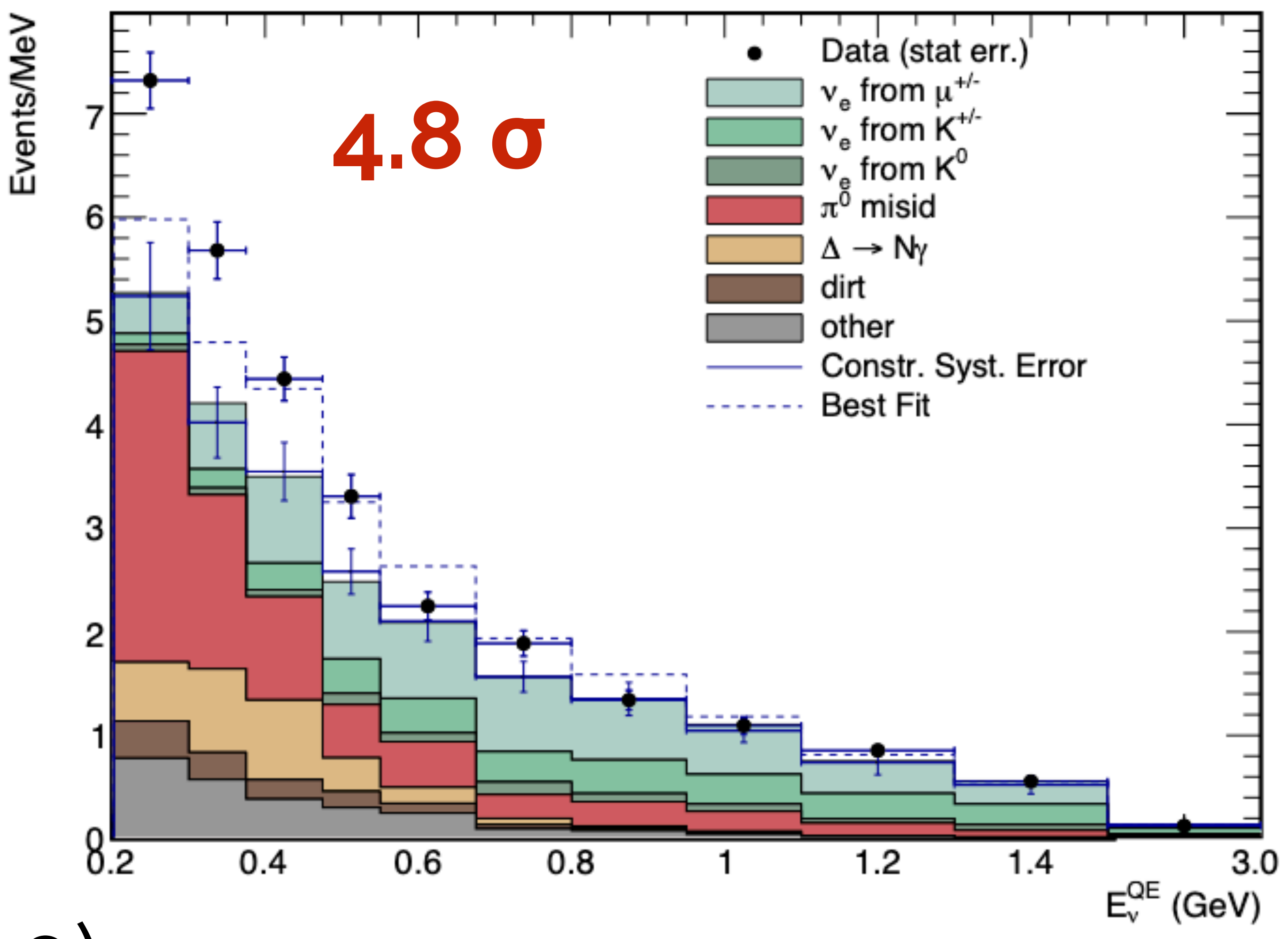

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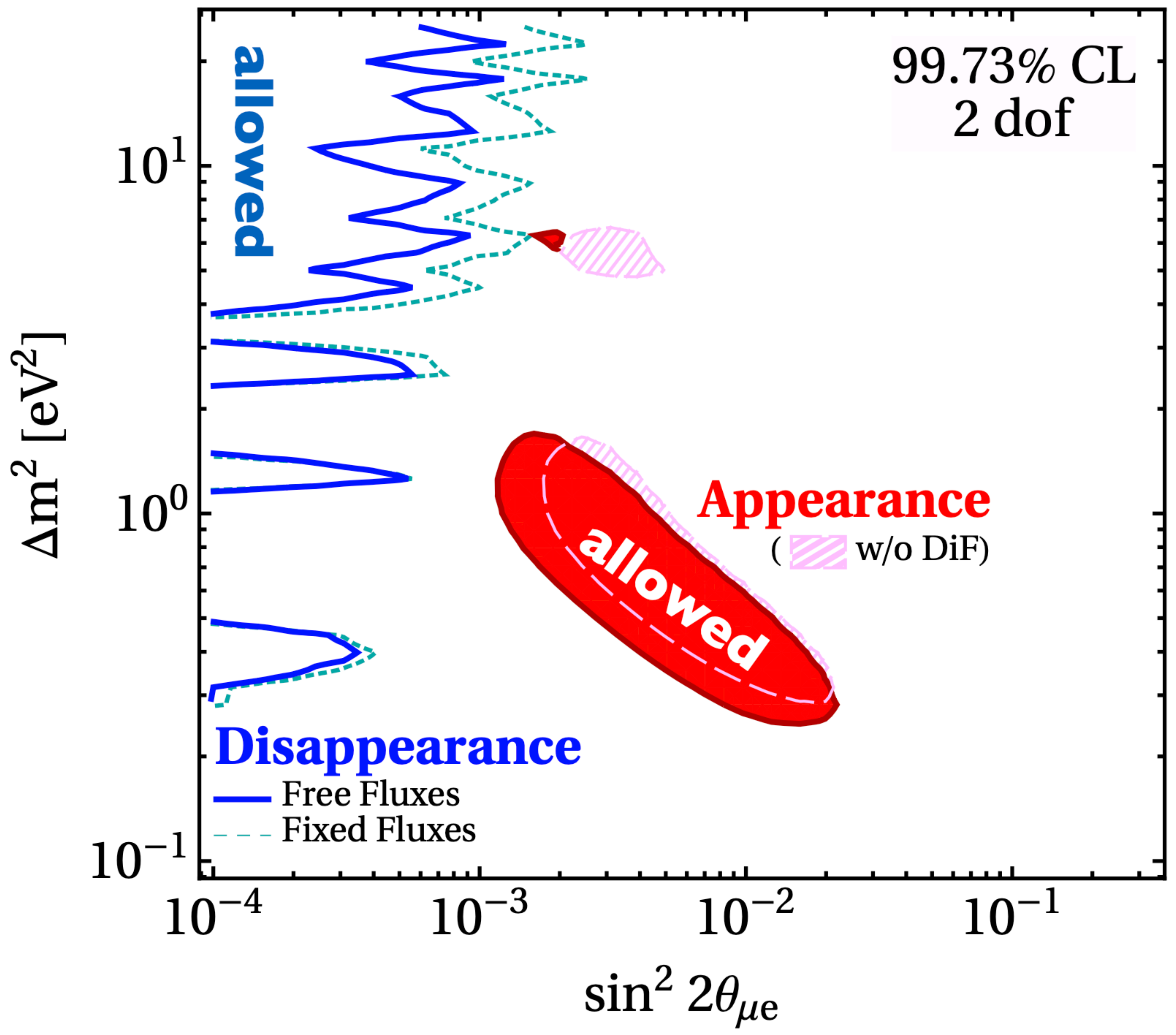
- measured ν_μ-> ν_e and $\bar{\nu}_\mu$-> ν_e appearance
- the excess of events at low energy

tension in global picture



From Pedro Machado's Neutrino 2020 talk: Sterile Neutrino Global Picture

- *unfortunately, it's more complicated than that…*
- significant tension between ν_e appearance and ν_e and ν_μ disappearance
- lots of different independent observations currently unexplained
- *we need to understand the anomalies better!*

short-baseline anomalies

PMNS mixing matrix

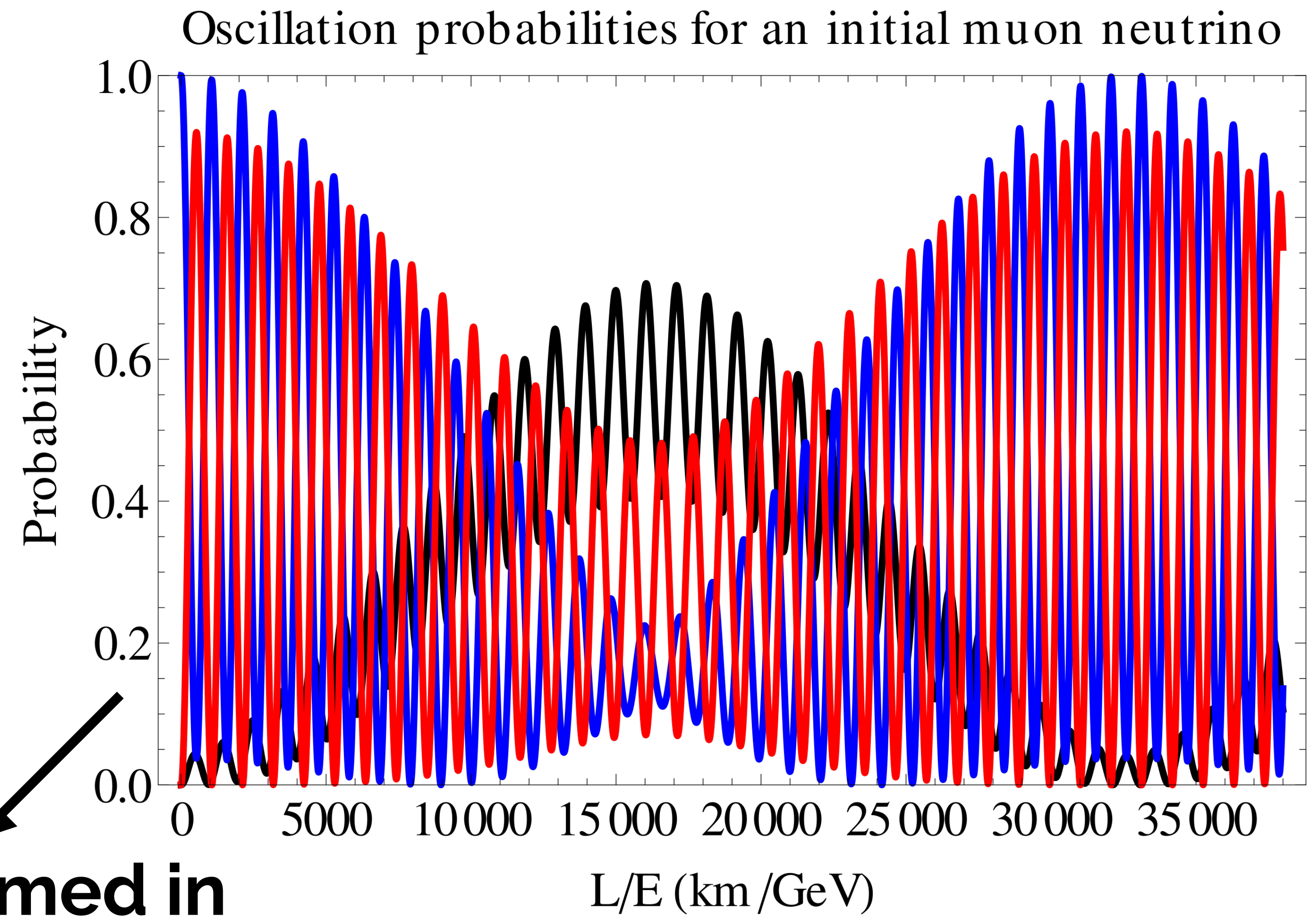
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates | Atmospheric | Reactor/Accelerator | Solar | mass eigenstates

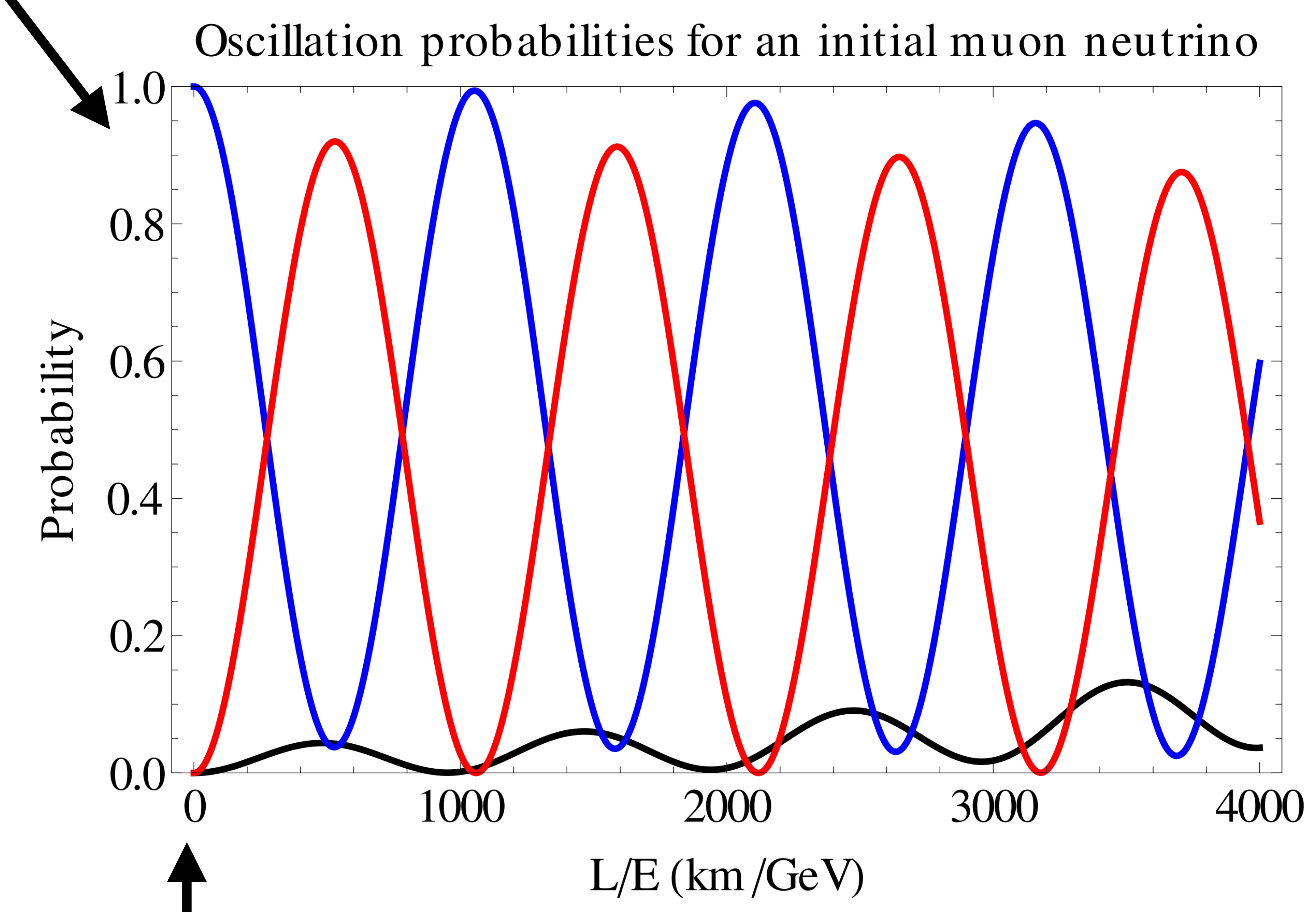
$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

- three flavor neutrino states is well established by neutrino oscillation physics in solar, atmospheric, reactor, and accelerator domains
- puzzling collection of short-baseline anomalies: reactor anomaly, gallium anomaly, LSND & MiniBooNE anomaly
  - possible portal for new physics: the holy grail of the particle physics community
  - correctly estimating backgrounds/oscillation is important for the future neutrino program such as DUNE
  - need to resolve the anomalies -> MicroBooNE & SBN program

Neutrino Oscillations



zoomed in



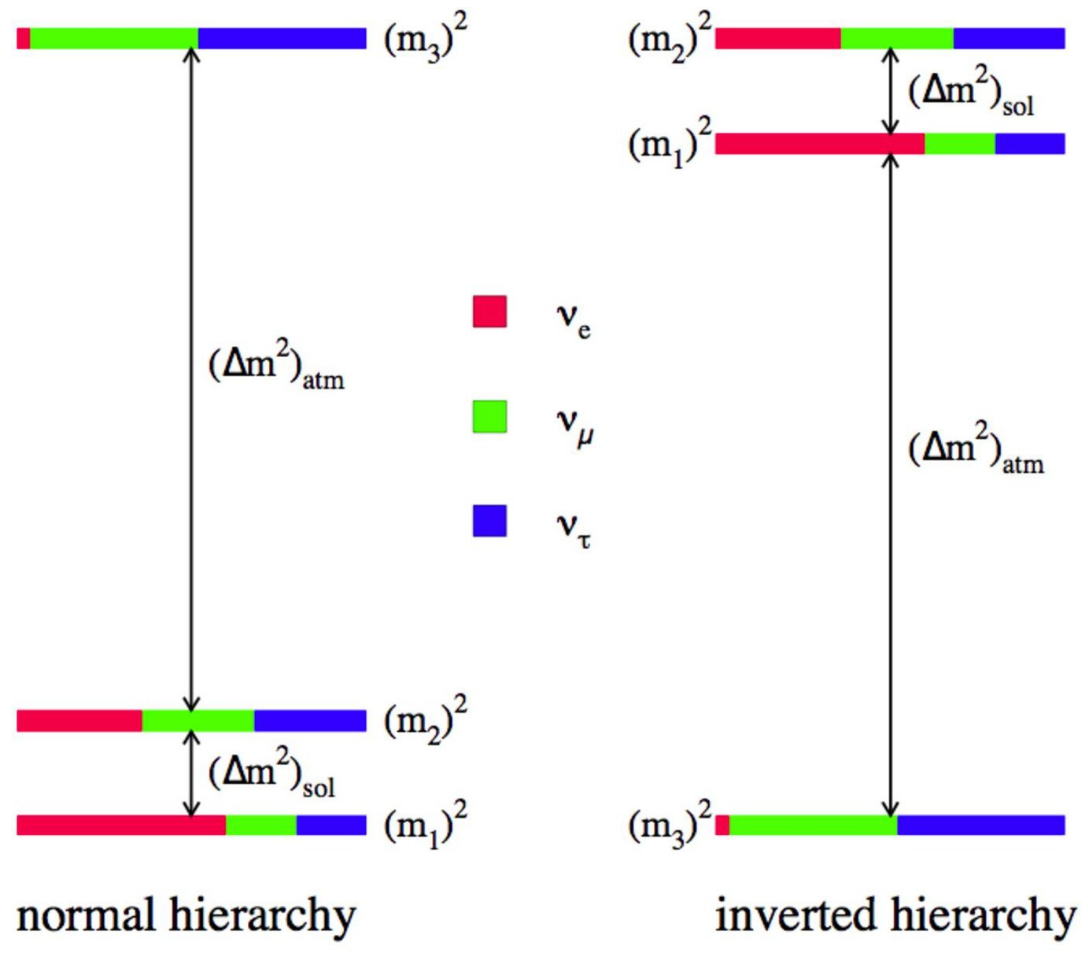
ν_μ

ν_e

ν_τ

MicroBooNE: ~0.5 km / ~1GeV, negligible neutrino oscillation expected

from https://en.wikipedia.org/wiki/Neutrino_oscillation



- Neutrino flavor eigenstates are not the same as the mass eigenstates
- Neutrinos generally are produced in a flavor eigenstate, which is a superposition of three mass eigenstates
- These mass eigenstates have different energies, and therefore change phase over time at different rates according to Schrodinger's equation
- This leads to neutrino oscillations when viewed in the flavor basis
- The existence of sterile neutrinos (additional mass eigenstates) would change the details of this picture