Sterile Neutrino and Short Baseline Neutrino (SBN) Program

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NuSteam/NuPumas @BNL 2025

Brookhaven National Laboratory

A brief bio…

- as a kid, I always was fascinated with the stars and galaxies (who isn't?), wanted to become an **astrophysicist** like Hawking

- in college, I started to become more interested in **theoretical particle physics**, with inspirations from Einstein, Feynman, Gell-Mann (who doesn't?)

- in graduate school, I started working on **experimental particle physics** (neutrino) as we started to have breakthroughs in experimental particle physics during the time (Higgs boson discovery, neutrino oscillation, gravitational wave…)

- as a postdoc, I also worked on dark matter search for few years, then came back to **experimental neutrino physics** as a faculty here at BNL

- now I work on experimental neutrino physics: how to detect, measure, and understand neutrinos and their nature

  - feel free to stop by 3-181 anytime to say hello or to ask/talk about anything

  - you can also email me with any questions: jjo@bnl.gov

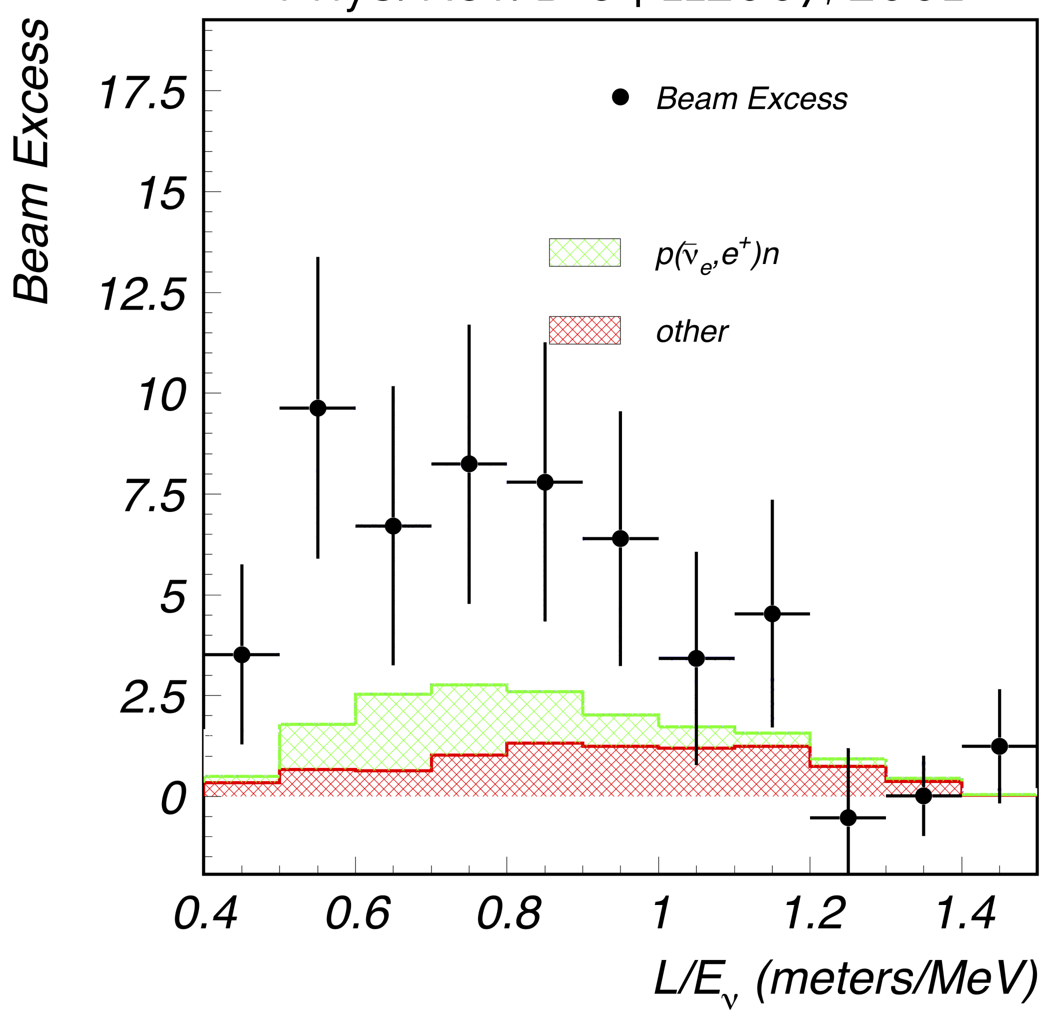
Outline

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

Why do we want to detect neutrinos?

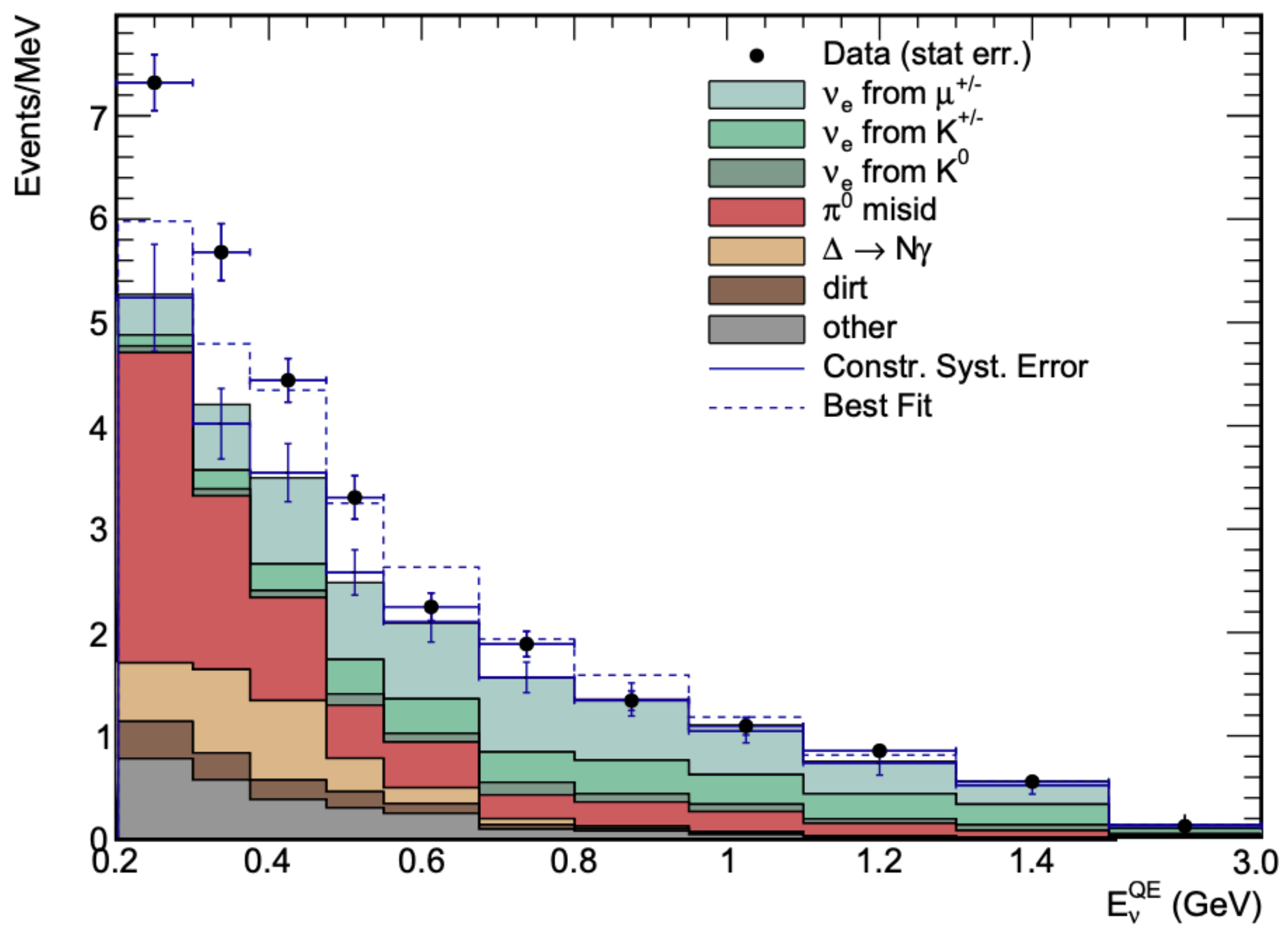
- we are already starting to see few "anomalies" in the neutrino physics
  - seeing results where the measurements and our best prediction of neutrinos start to disagree
  - remember the Solar neutrino problem? see Chao's slides earlier today (link)
  - will these lead to a discovery of new physics?

Phys. Rev. D 64 112007, 2001

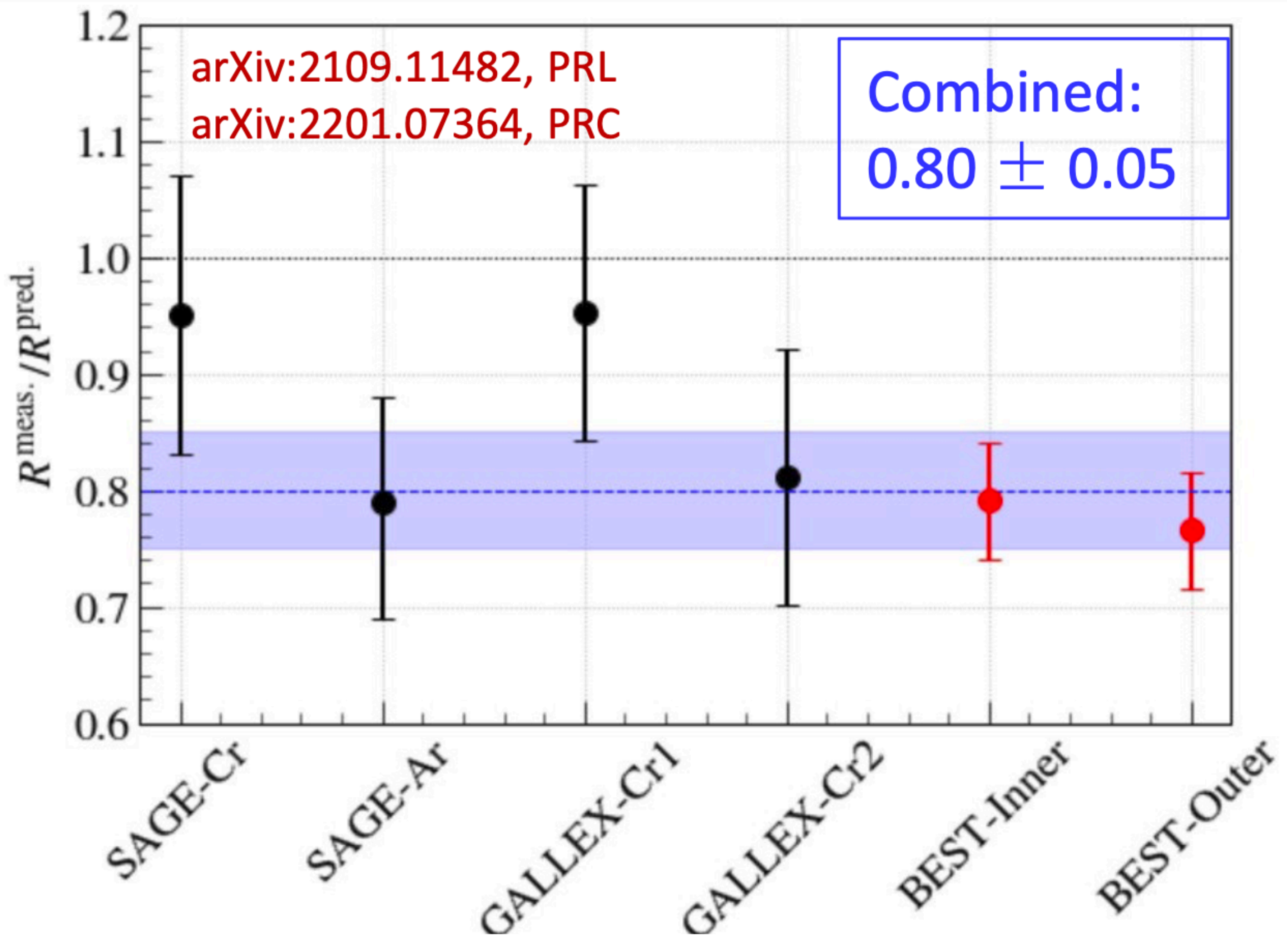


LSND anomaly

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

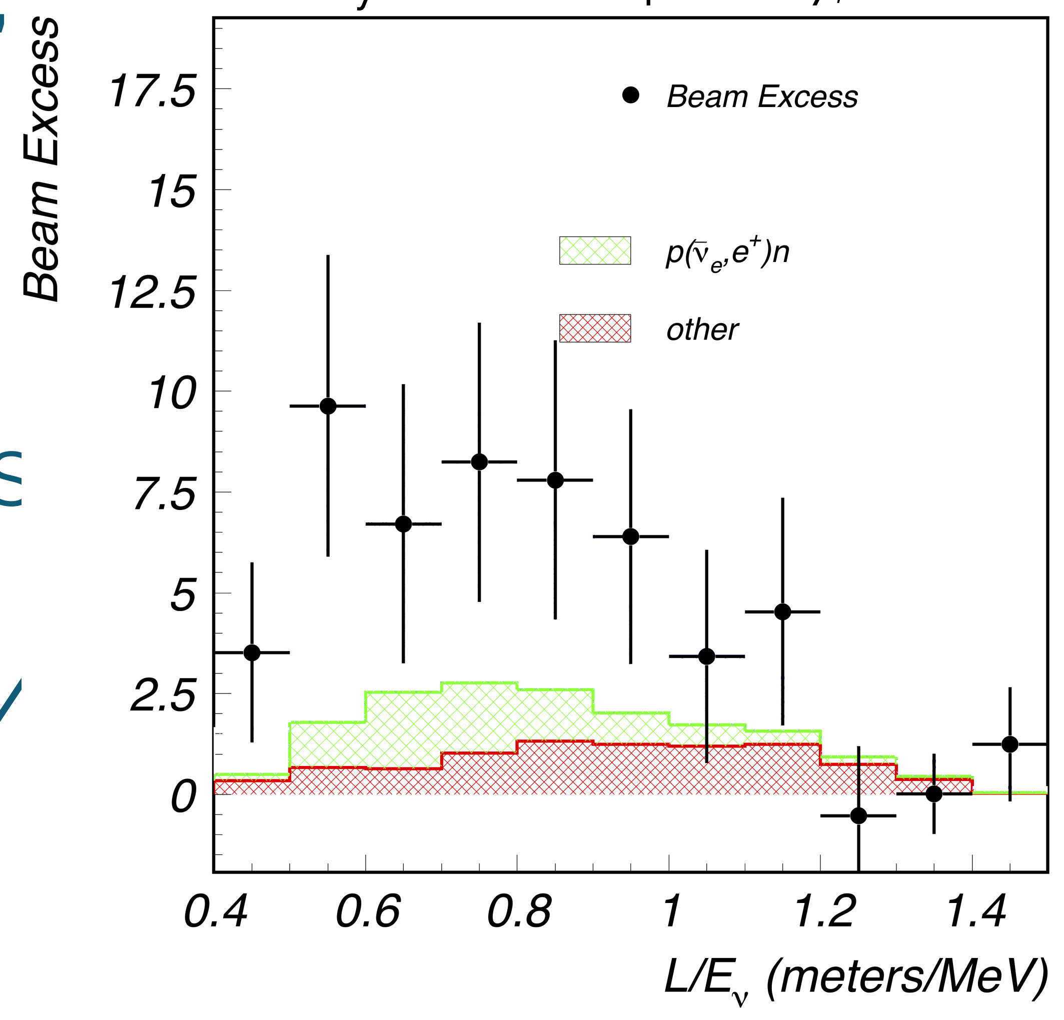
- remaining questions in neutrino physics
- **sterile neutrino: what is it, why is it, and how do we detect it**
- Short Baseline Neutrino (SBN) Program

Why add extra neutrino?

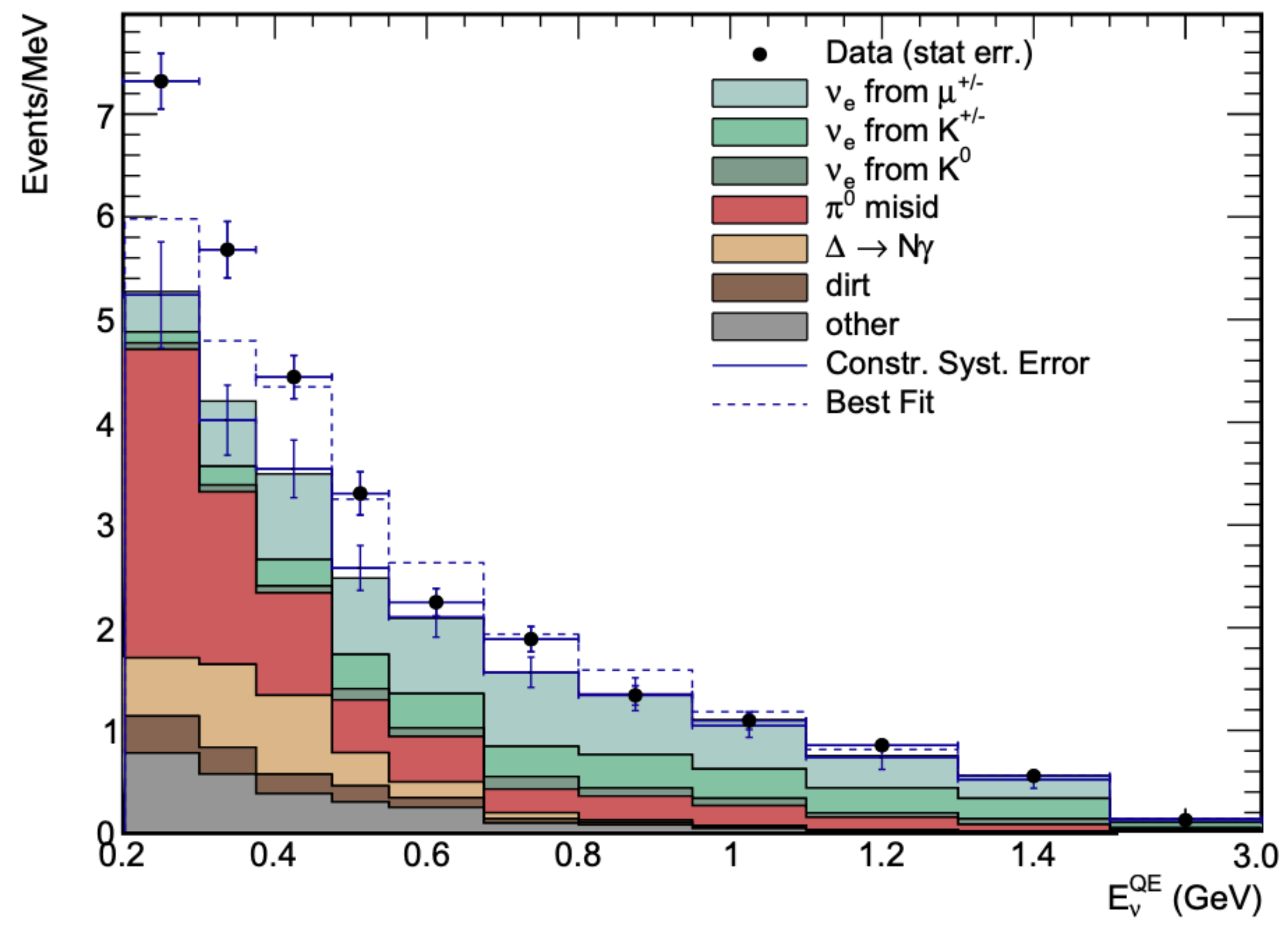
- since the first detection of neutrino and oscillation, many experiments start to collect & analyze neutrino data

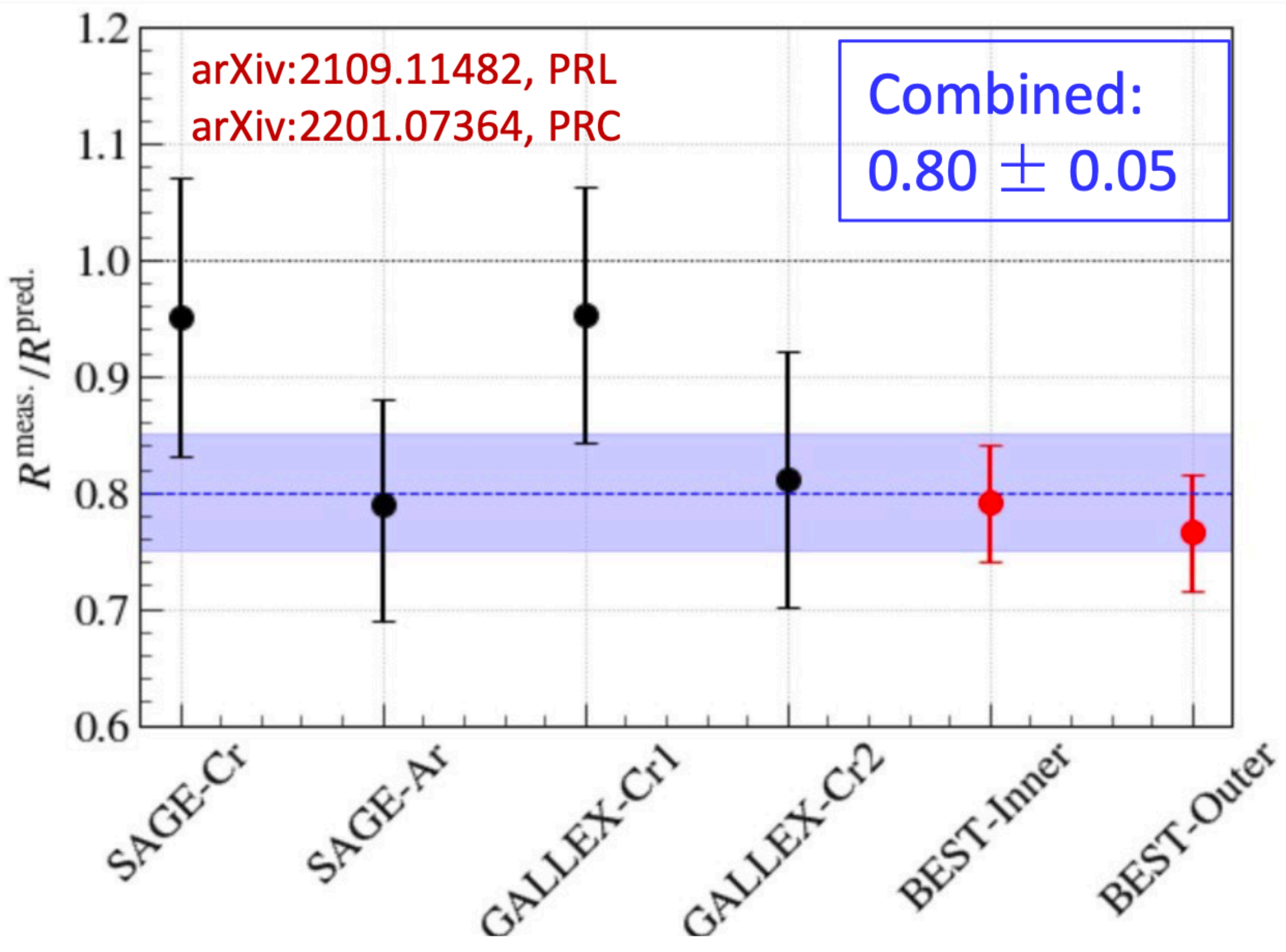
- several experiments have found *anomalous* results
  - *anomalous* in a way that "observation" (detected/measured data) does not agree with "prediction" (simulation/model generated with the current best of our knowledge)
  - LSND: measured more ν_e than predicted (from ν_μ source)
  - MiniBooNE: measured more ν_e than predicted (from ν_μ source)
  - GALLEX/SAGE/BEST: measured less ν_e than predicted (from ν_e source)

Phys. Rev. D 64 112007, 2001



Phys. Rev. D 103, 052002 (2021)





Why add extra neutrino?

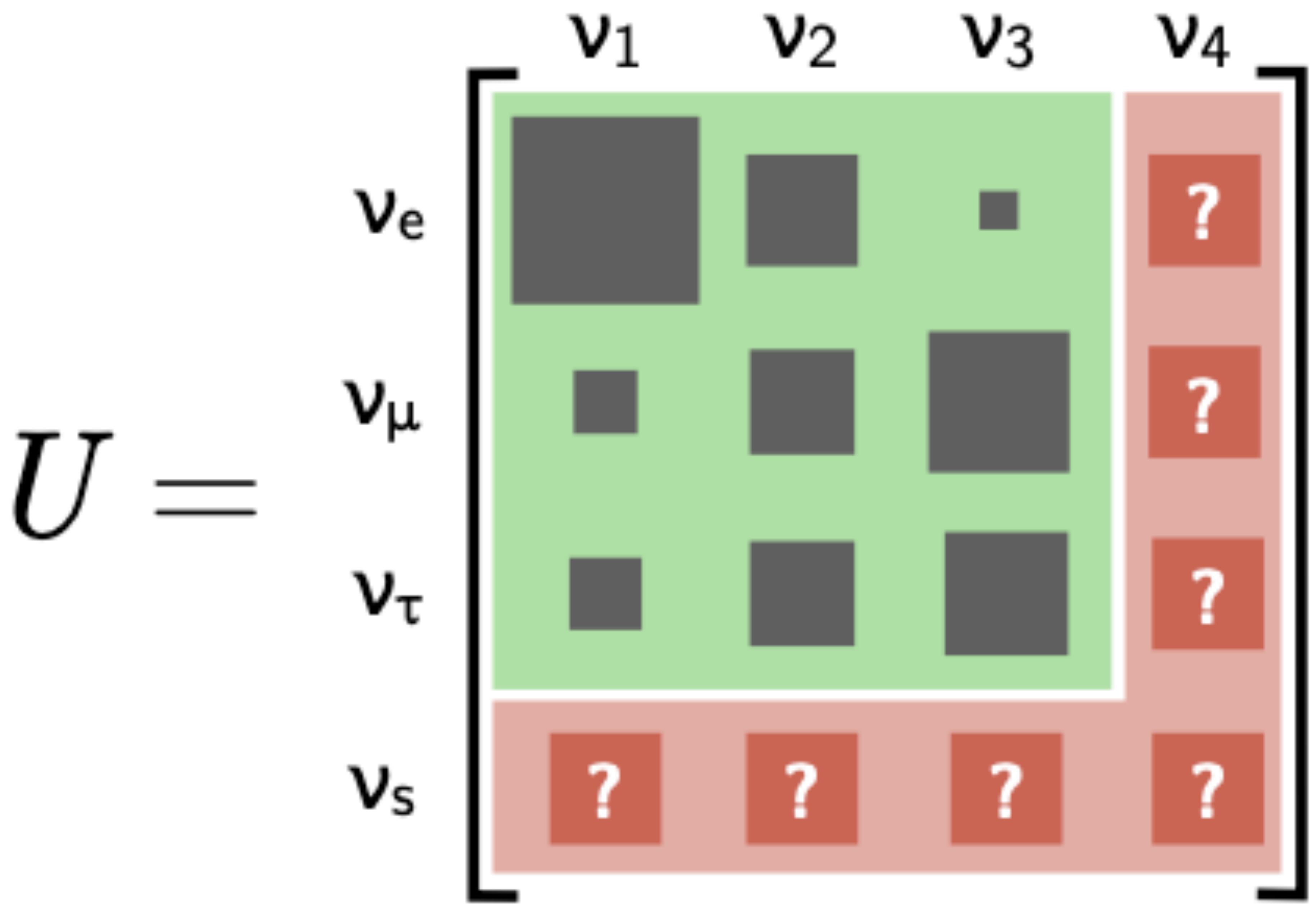
Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance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

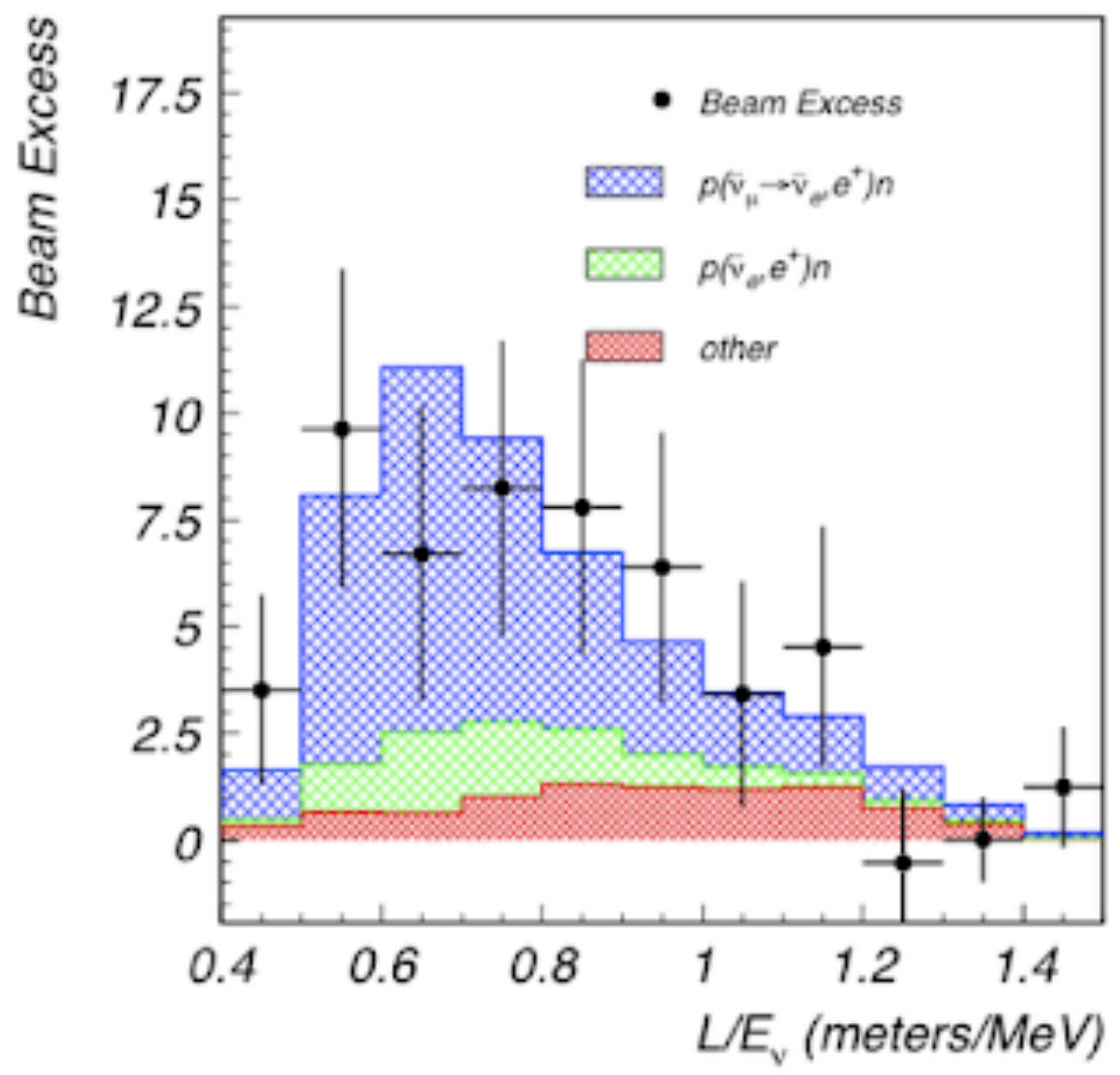


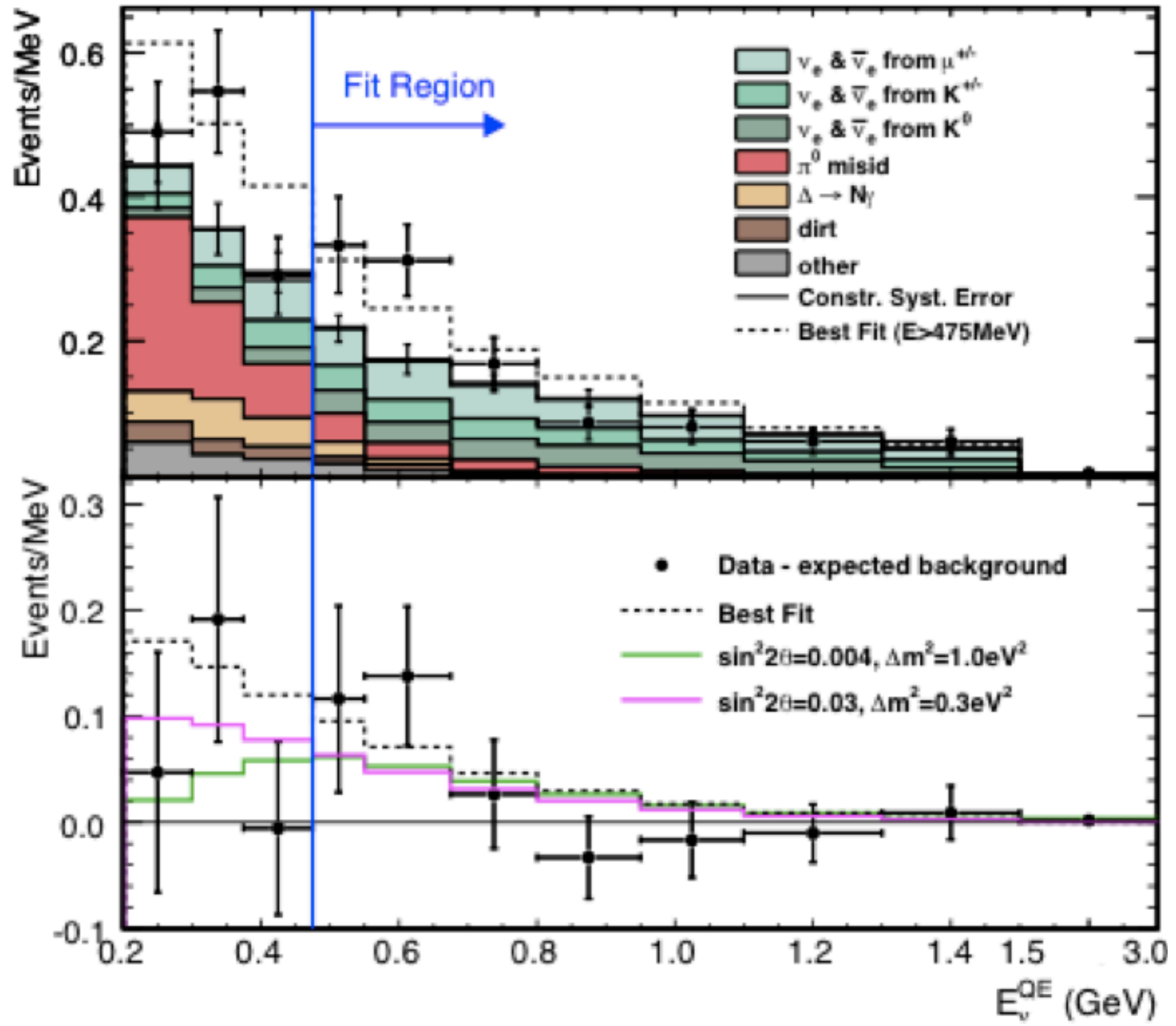
Flavor transitions via this new mixing:

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

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*
- out best guess at the moment is, if sterile neutrino actually does exist, it's not a simple/single type of neutrino but in a rather more complex system
  - but we should check if such simple sterile neutrino hypothesis is indeed ruled out!
  - and what about the "anomalies"?





How can we detect sterile neutrino?

- **sterile neutrino does not interact weakly**, only experiences 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)

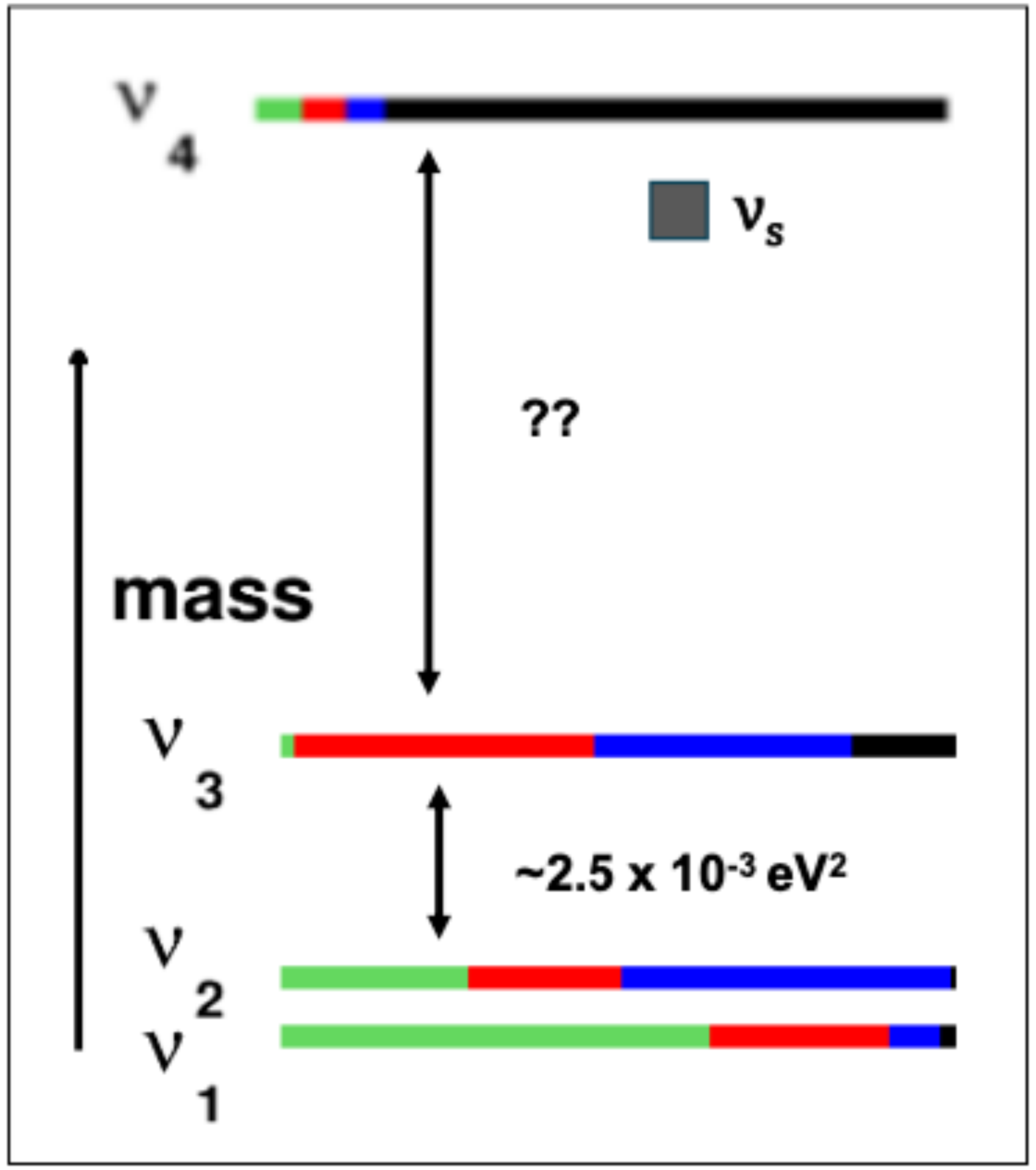
  - ν_e disappearance channel: $\nu_e \longrightarrow \nu_e$

    - how many ν_e has been oscillated into other (including ν_s) neutrino types?

  - ν_e appearance channel: $\nu_u \longrightarrow \nu_e$

    - how many ν_e has been oscillated from ν_u?

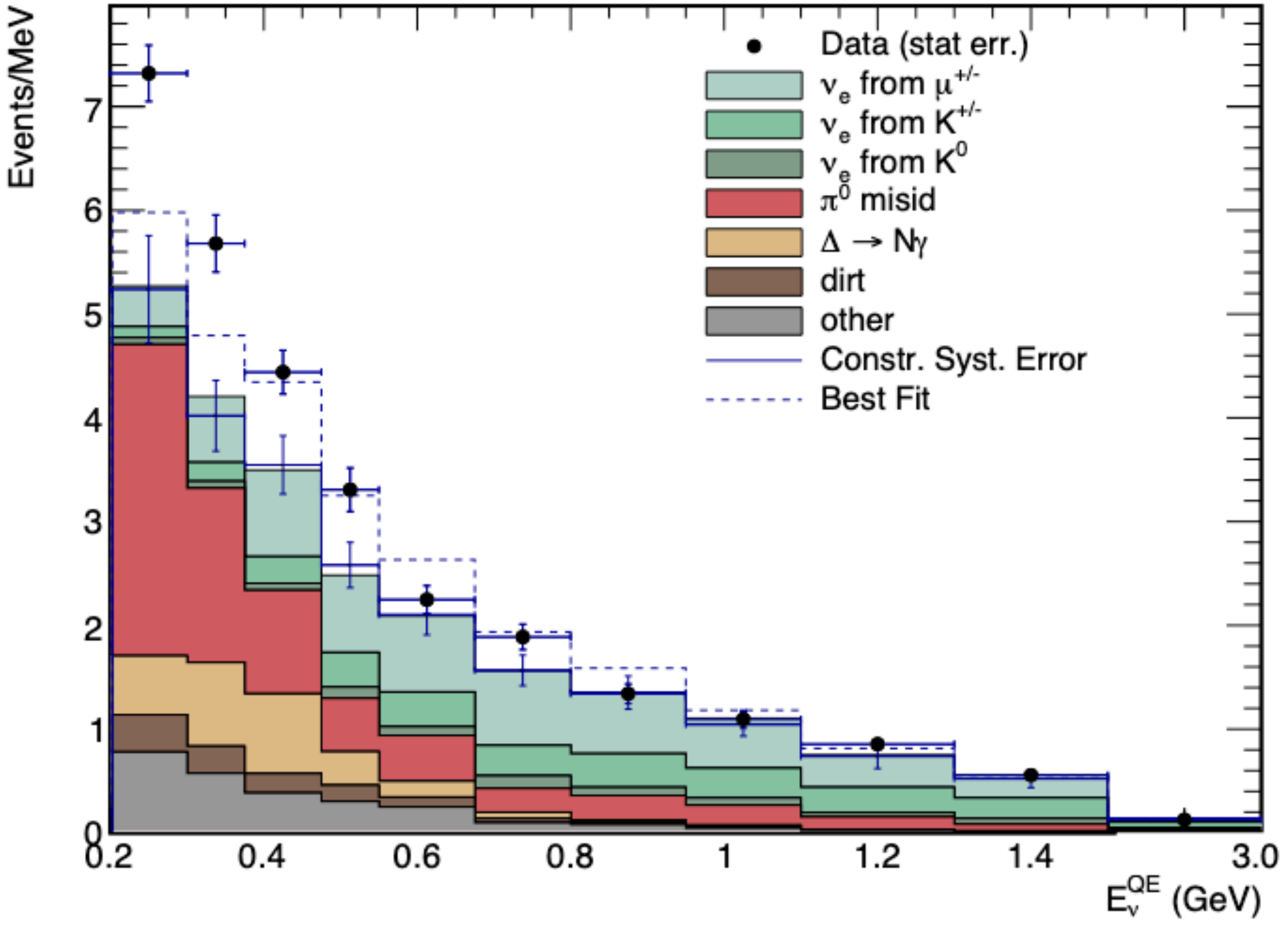
3+1 mixing model



The MiniBooNE Anomaly: Low Energy Excess (LEE)

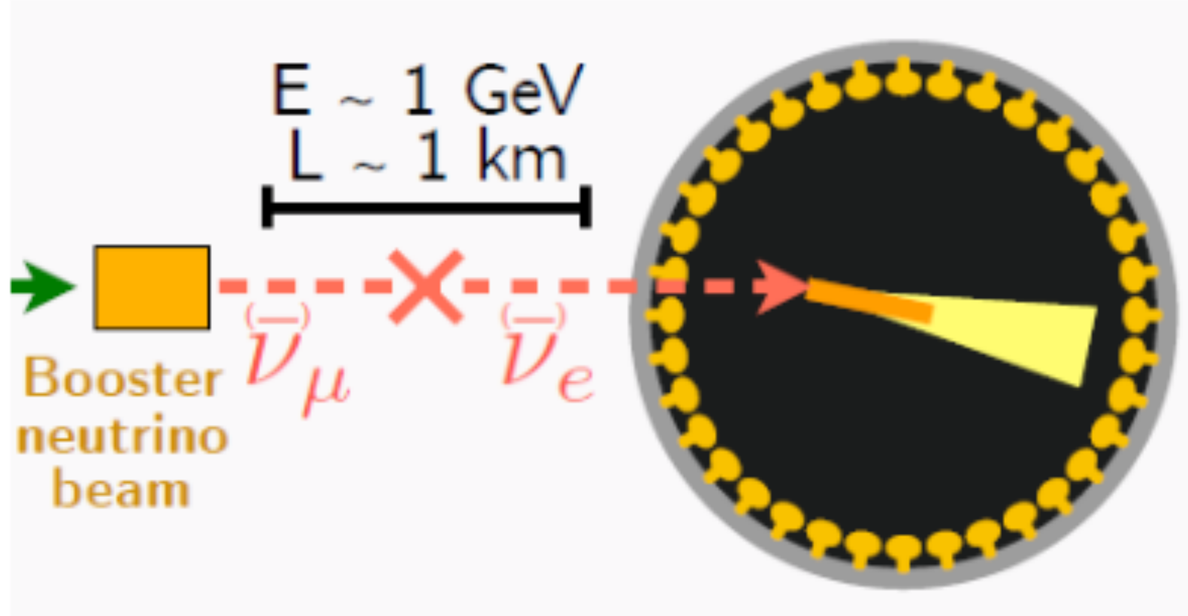
- MiniBooNE observed low-energy excess (LEE) of electron-neutrino-like events
  - LEE: more events measured/detected than predicted, in the low energy region
- eV-scale sterile neutrino could explain this excess
  - the excess may be due to sterile neutrino oscillated into electron neutrino
  - if so,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

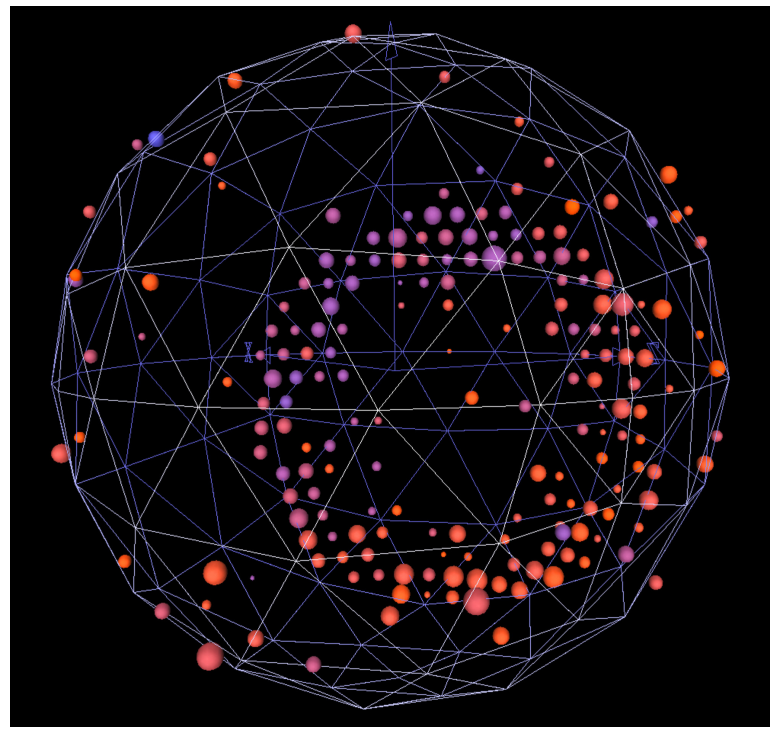
Phys. Rev. D 103, 052002 (2021)



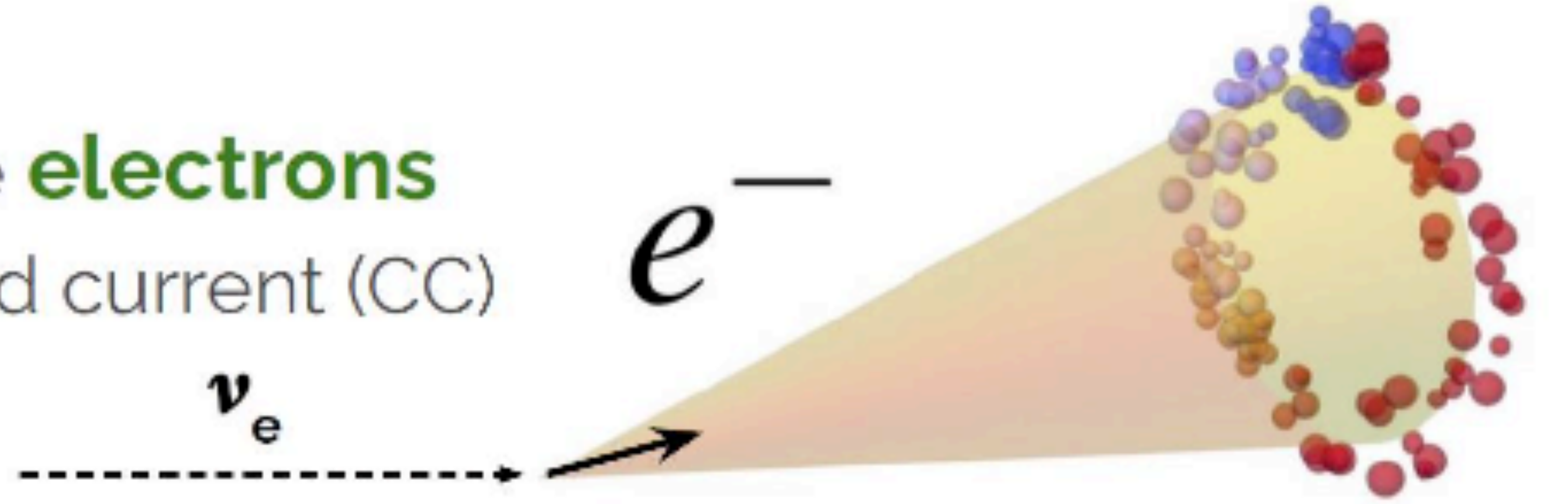
The MiniBooNE Anomaly: Low Energy Excess (LEE)

- 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

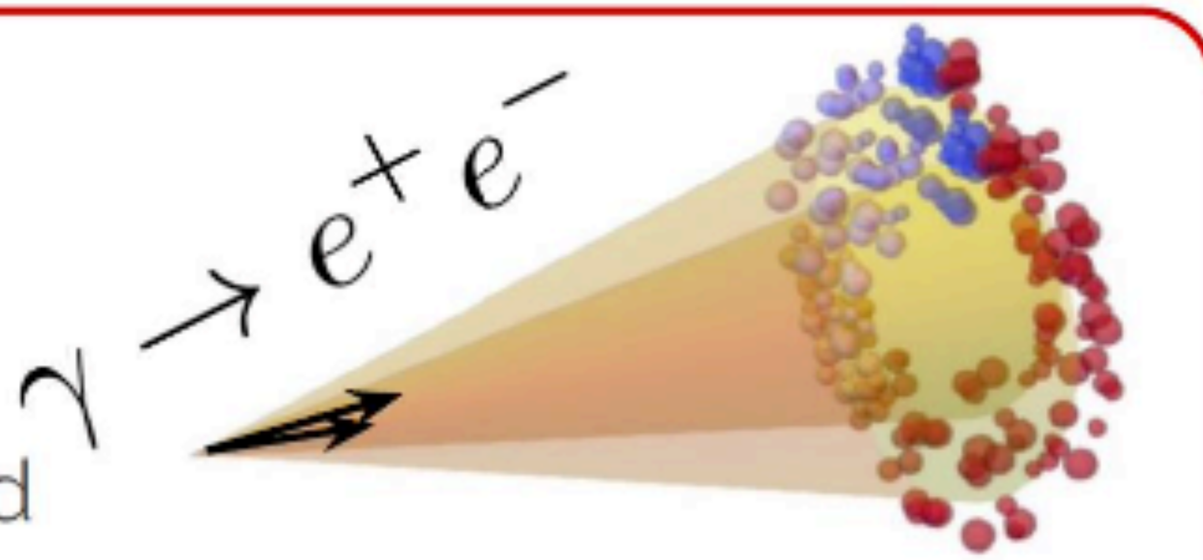




It detected ν_e by the **electrons** produced in charged current (CC) interactions.



However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring



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
  - see more details on LArTPC signal & electronics this afternoon from Shanshan (link)

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

LIQUID-ARGON IONIZATION CHAMBERS AS TOTAL-ABSORPTION DETECTORS*

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Department of Physics, Yale University, New Haven, Connecticut 06520, U.S.A.

and

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Instrumentation Division, Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

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

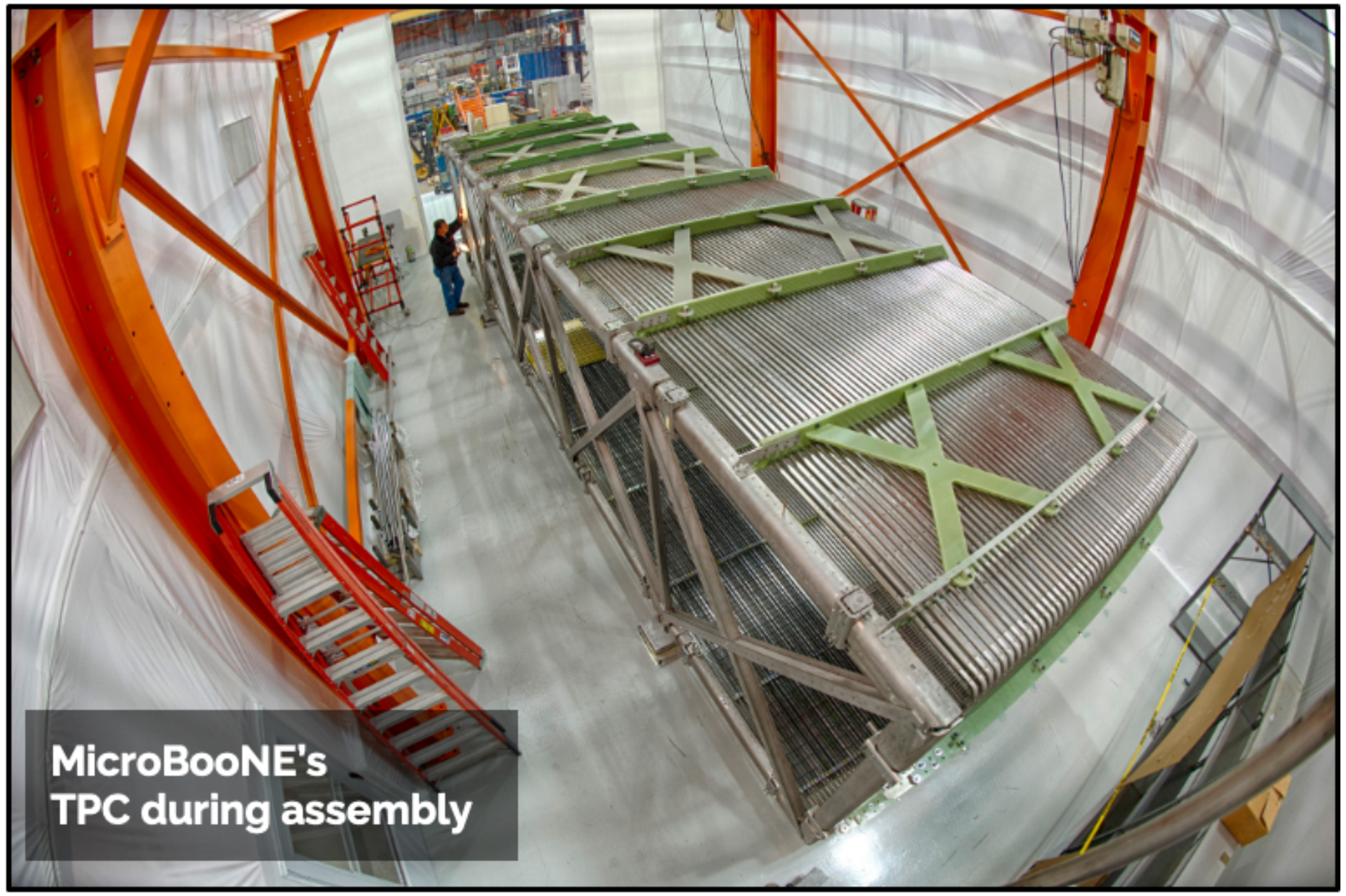
THE LIQUID-ARGON TIME PROJECTION CHAMBER:

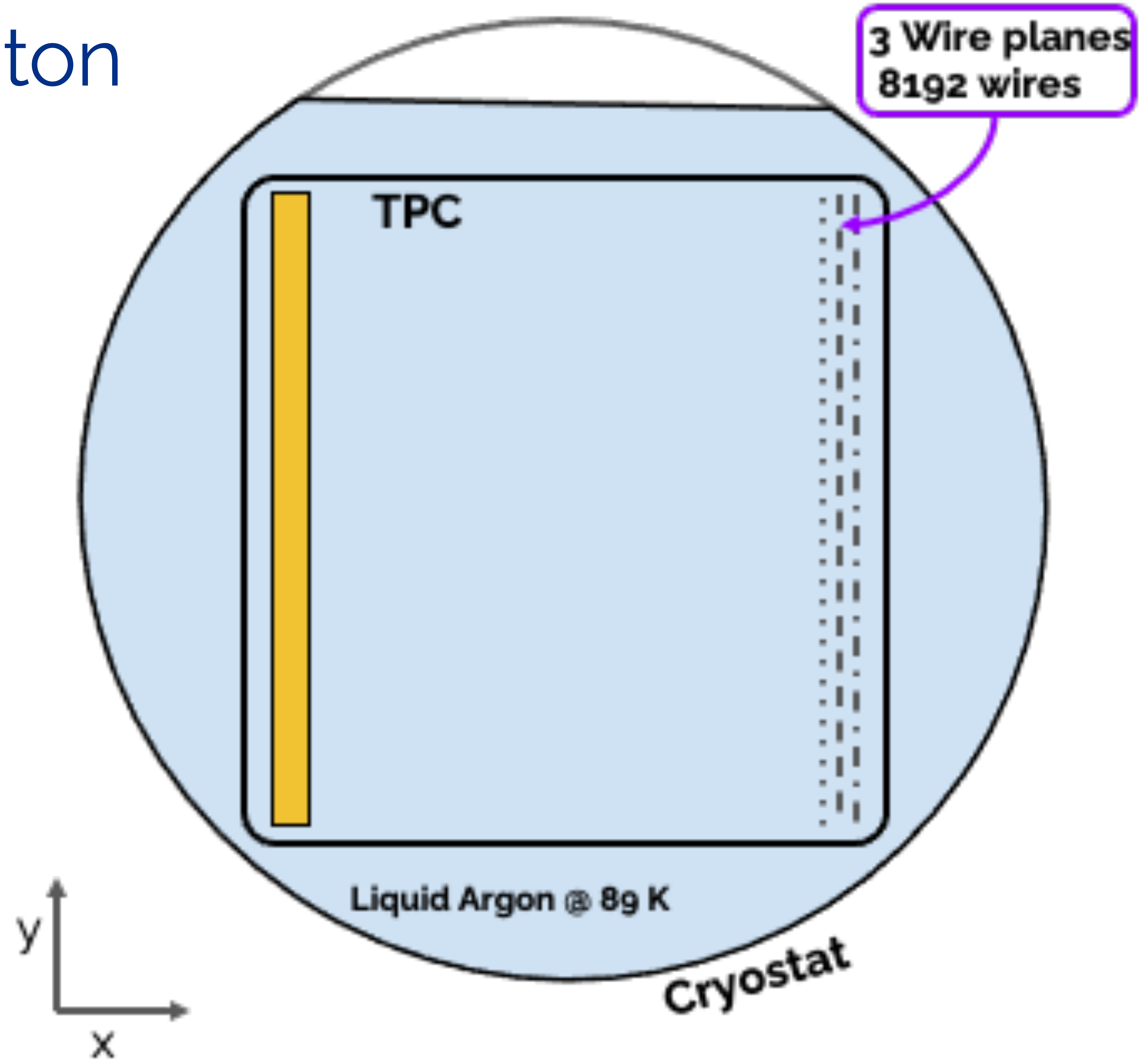
A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

1977

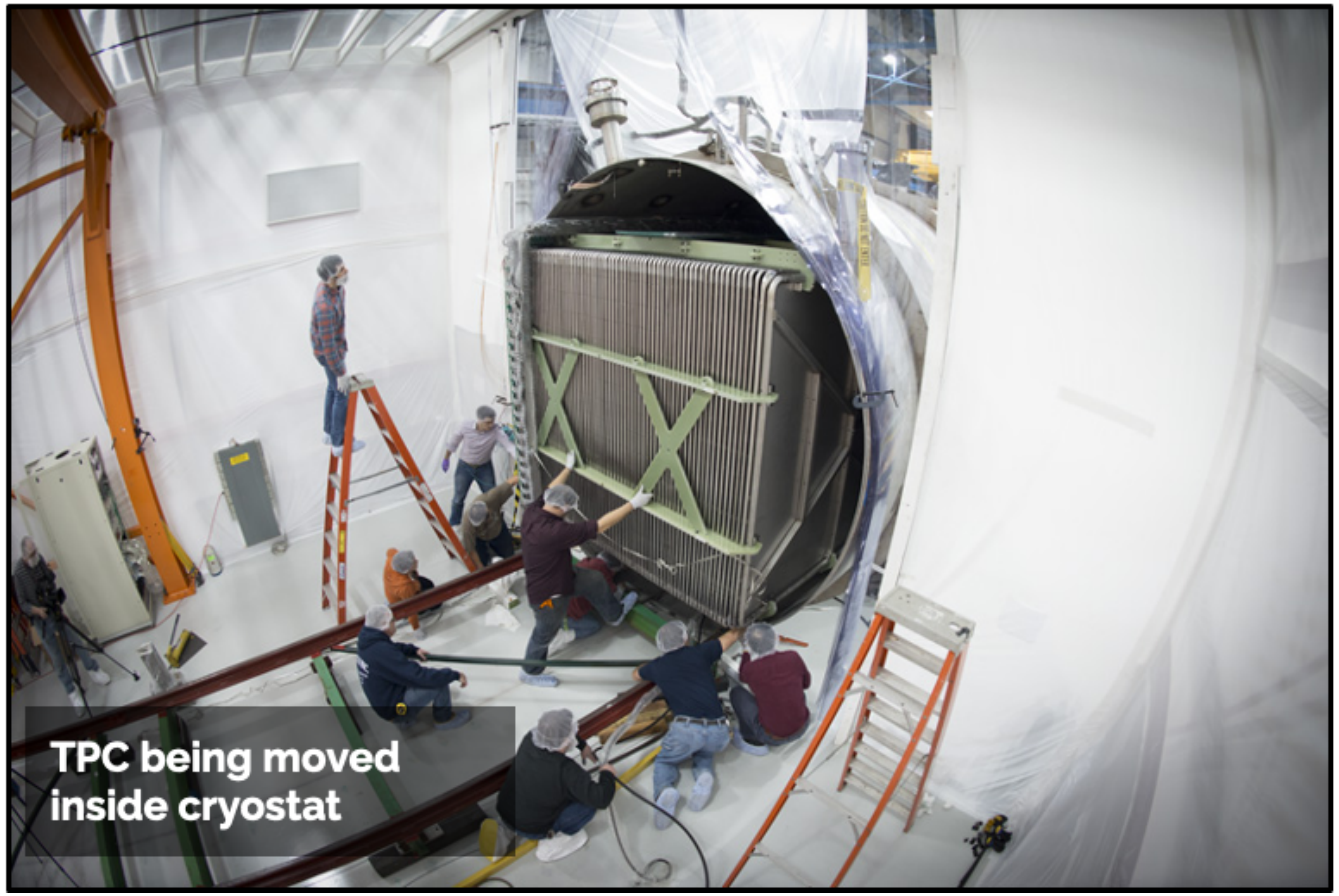
at MicroBooNE's core is an 85 ton LArTPC

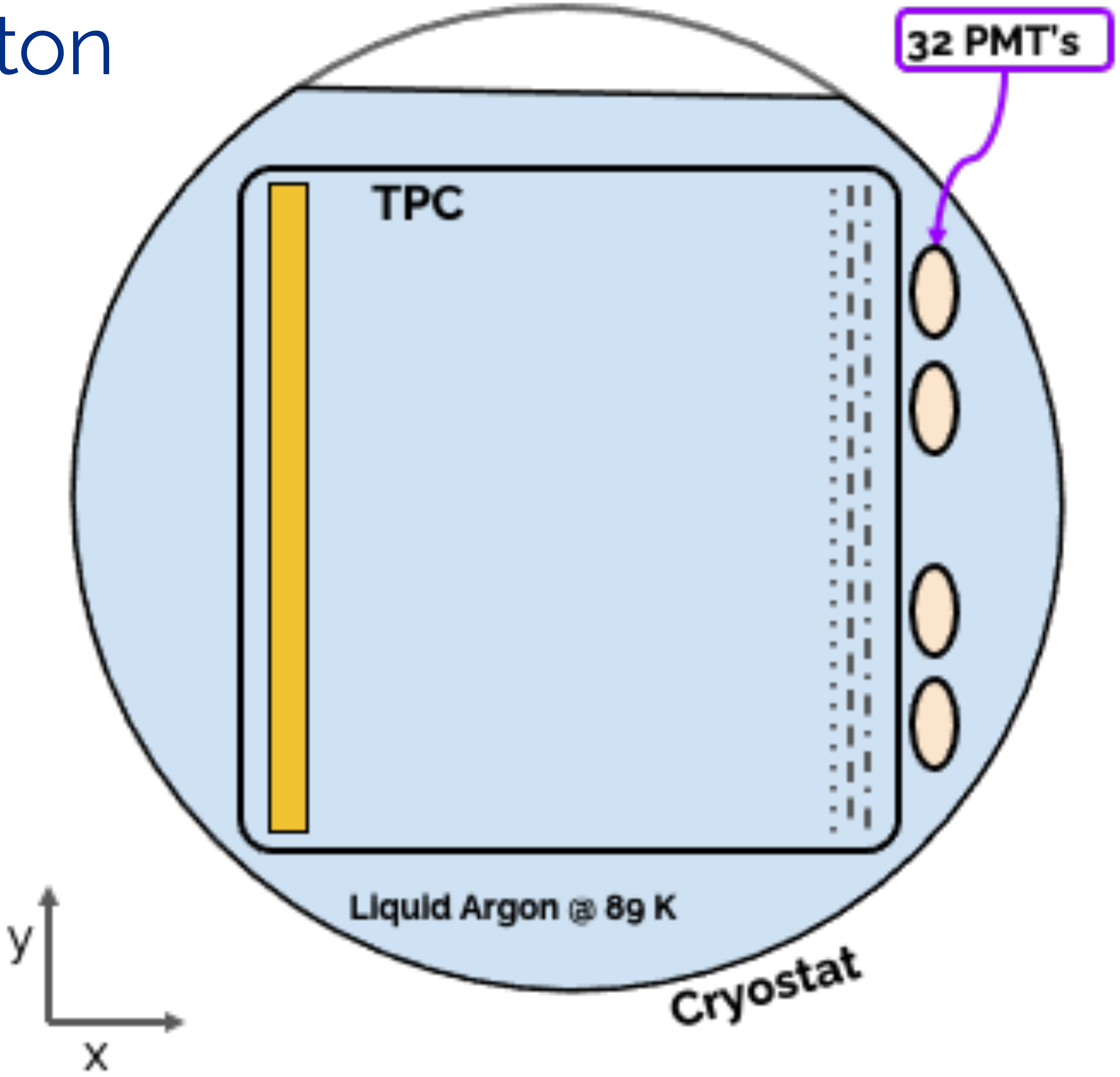




the MicroBooNE detector

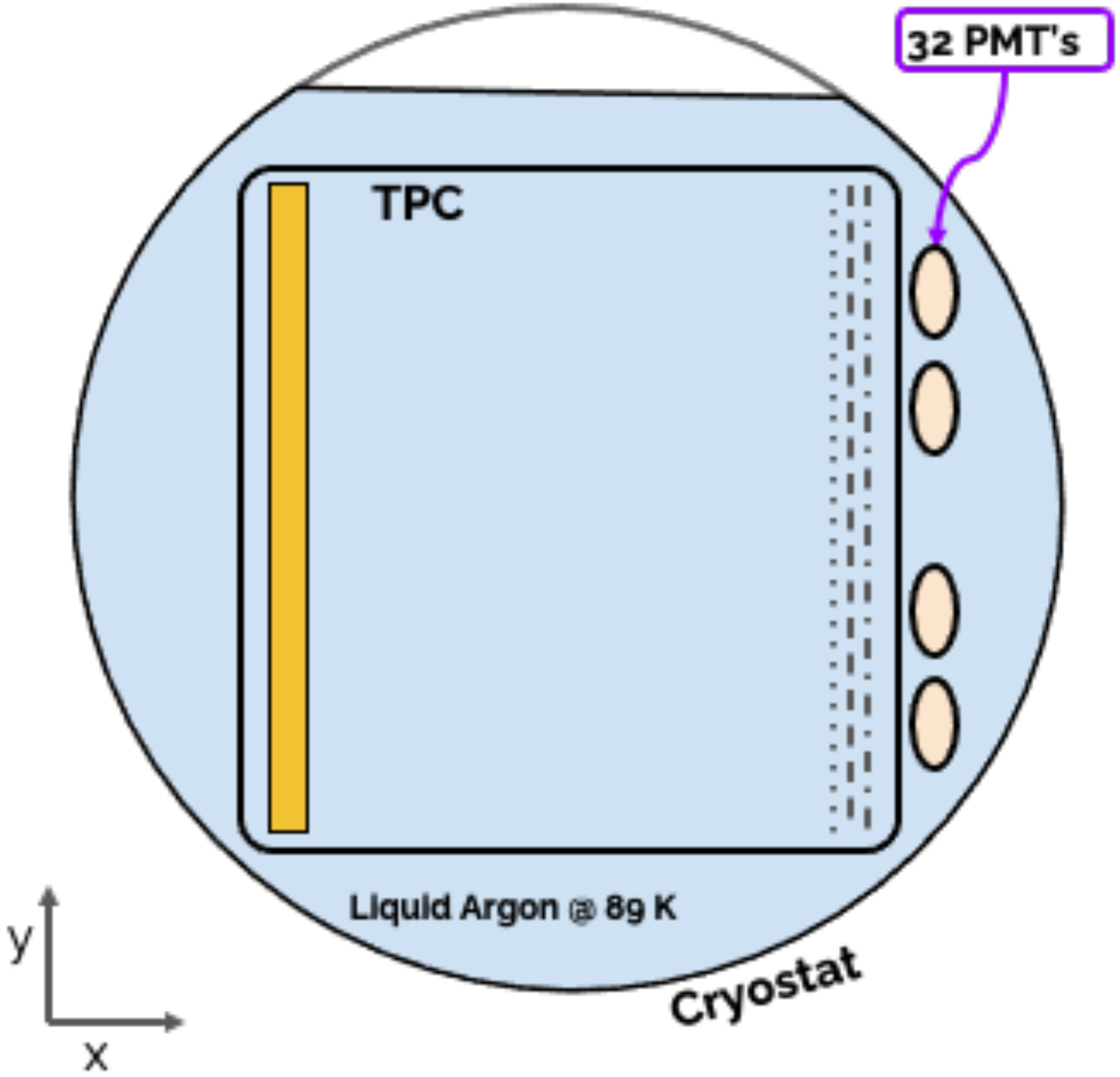
at MicroBooNE's core is an 85 ton LArTPC

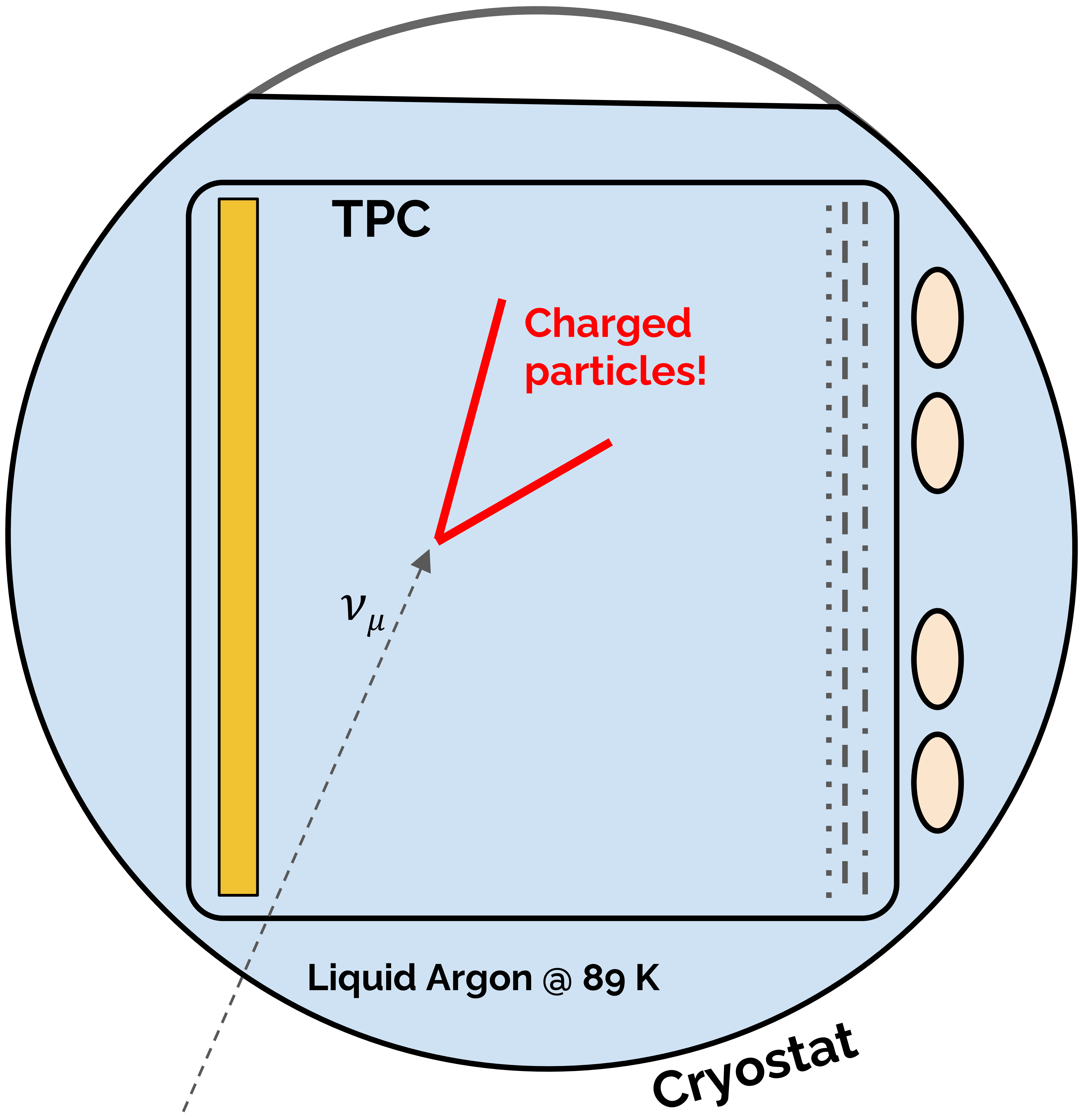




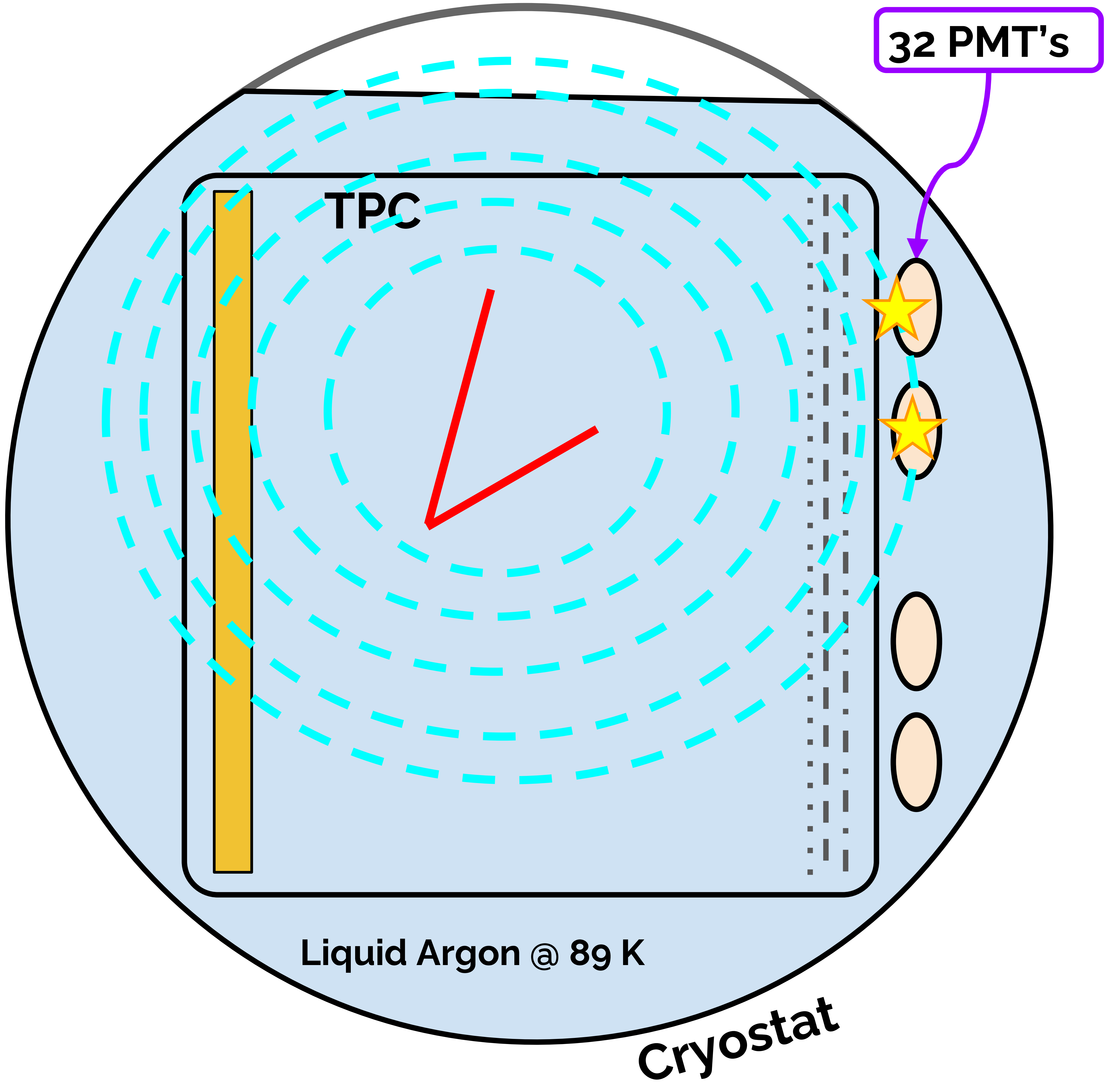
the MicroBooNE detector

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

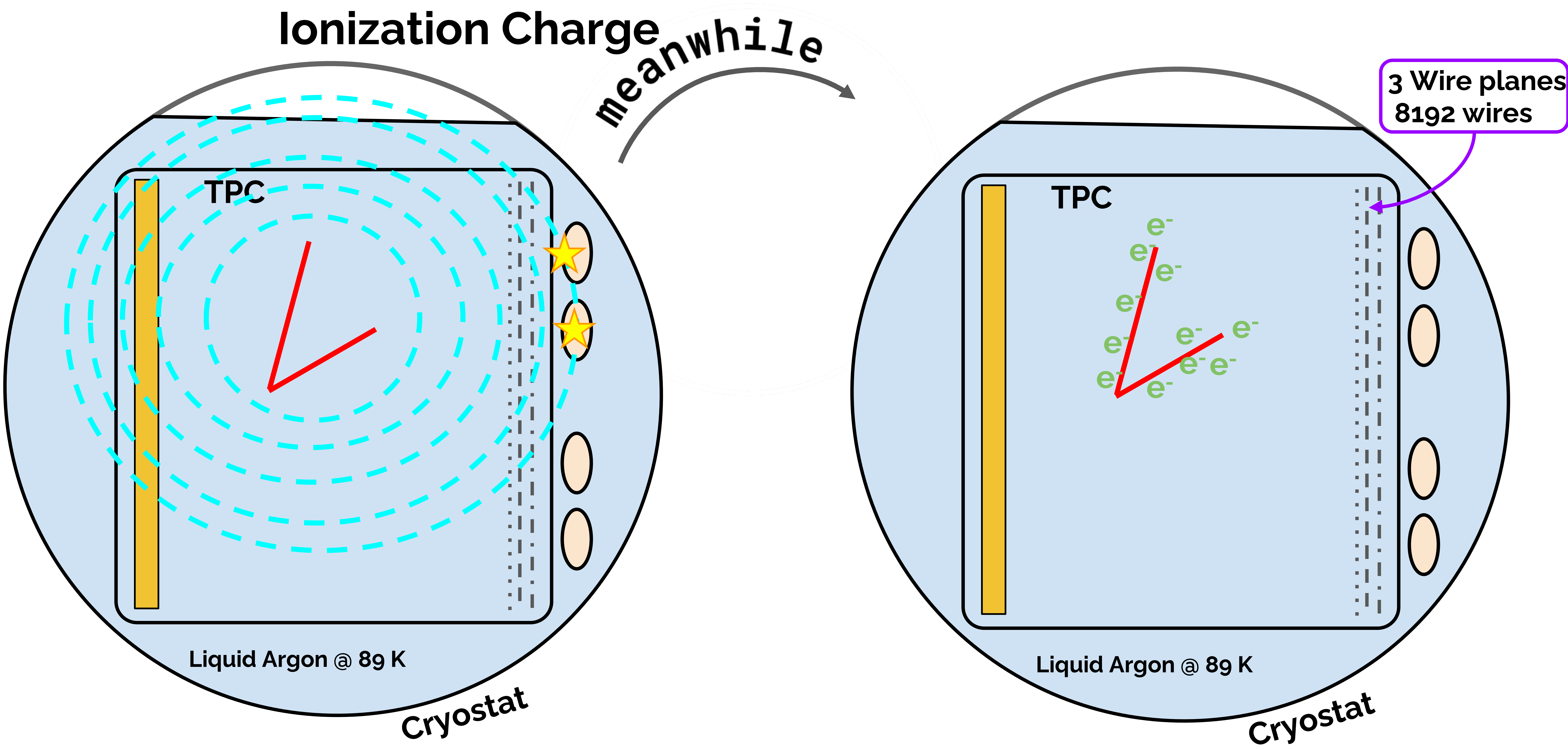



TPC
Charged particles!
ν_μ
Liquid Argon @ 89 K
Cryostat

Scintillation light



Scintillation light
Ionization Charge



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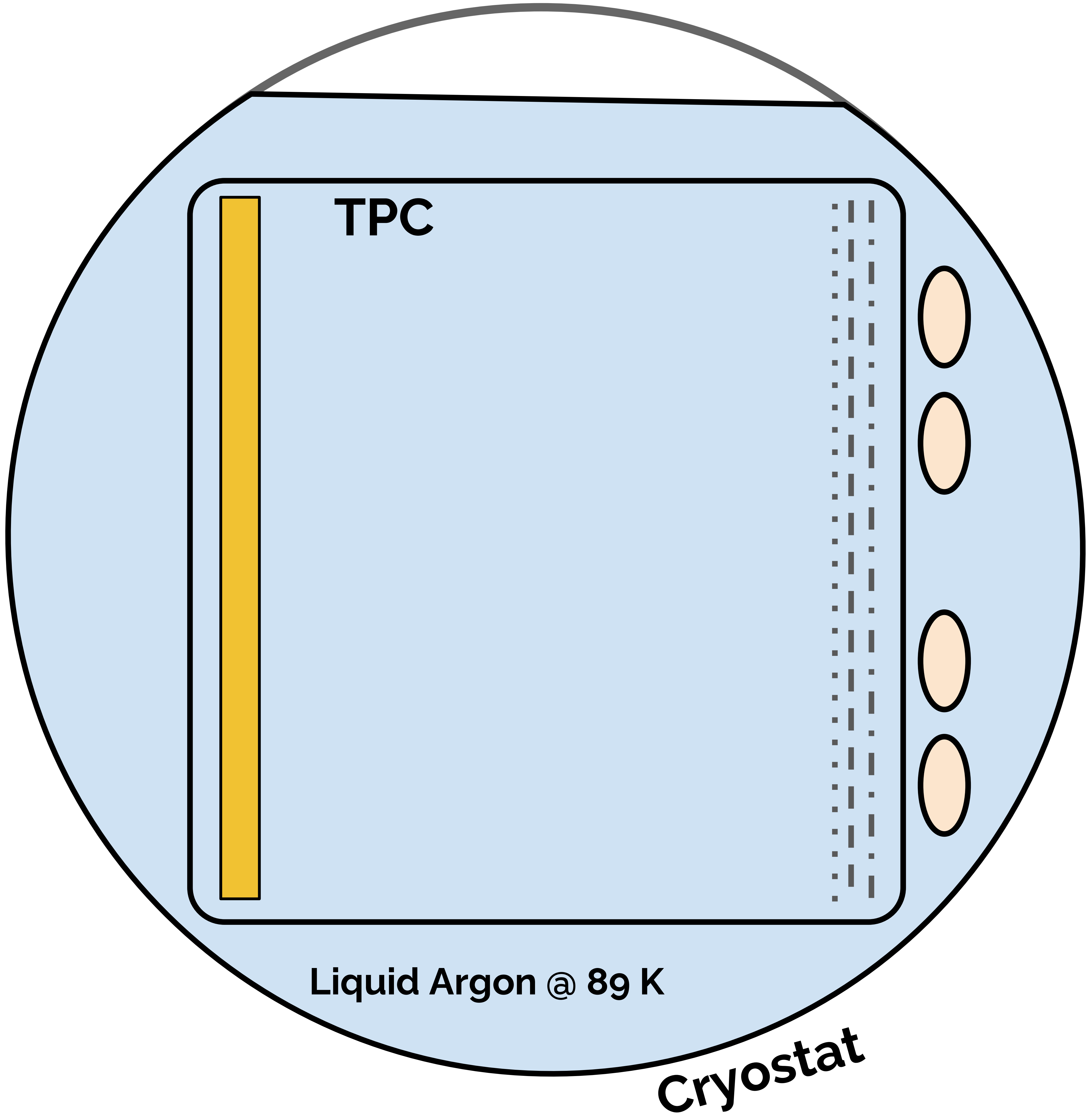

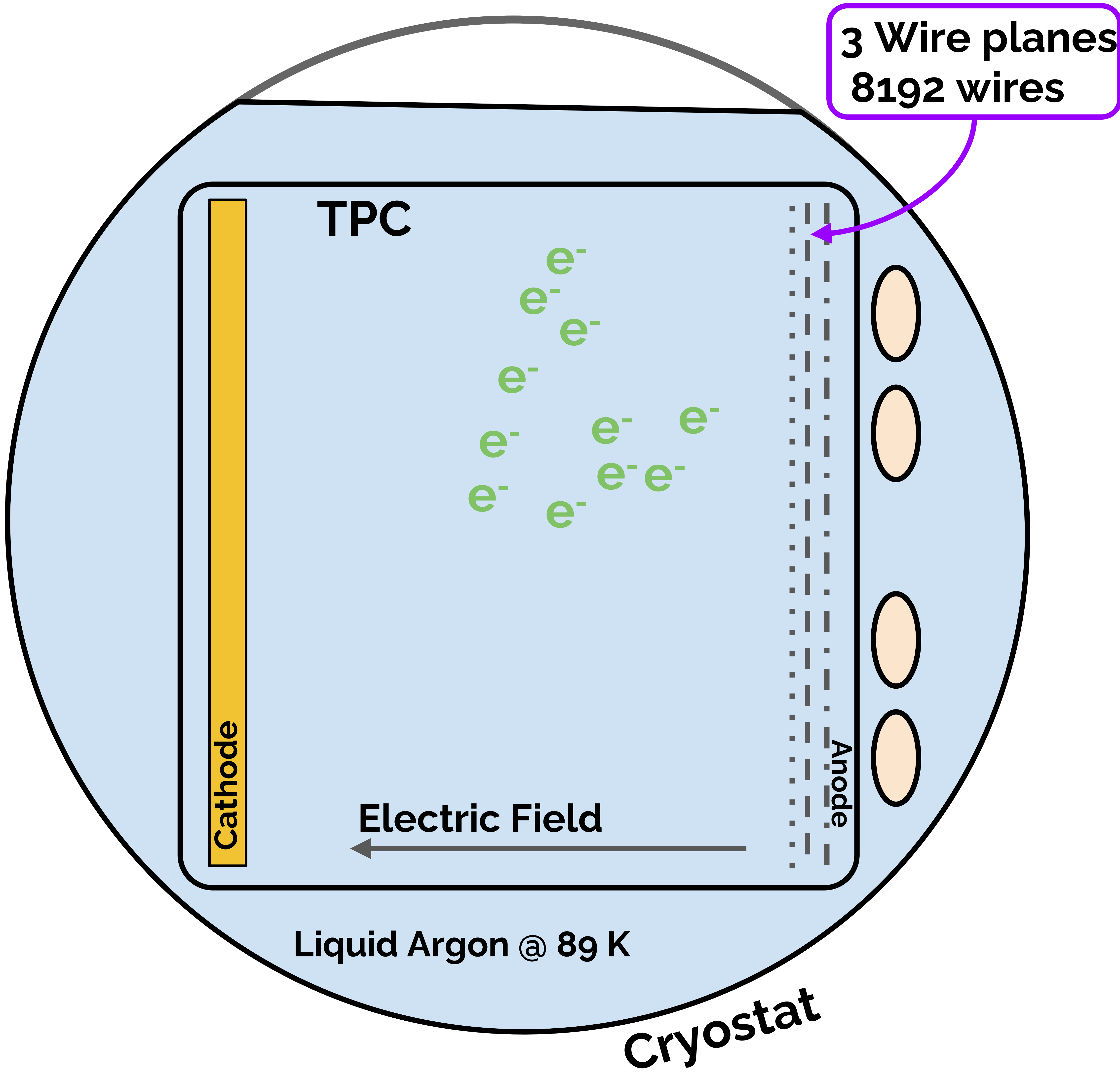

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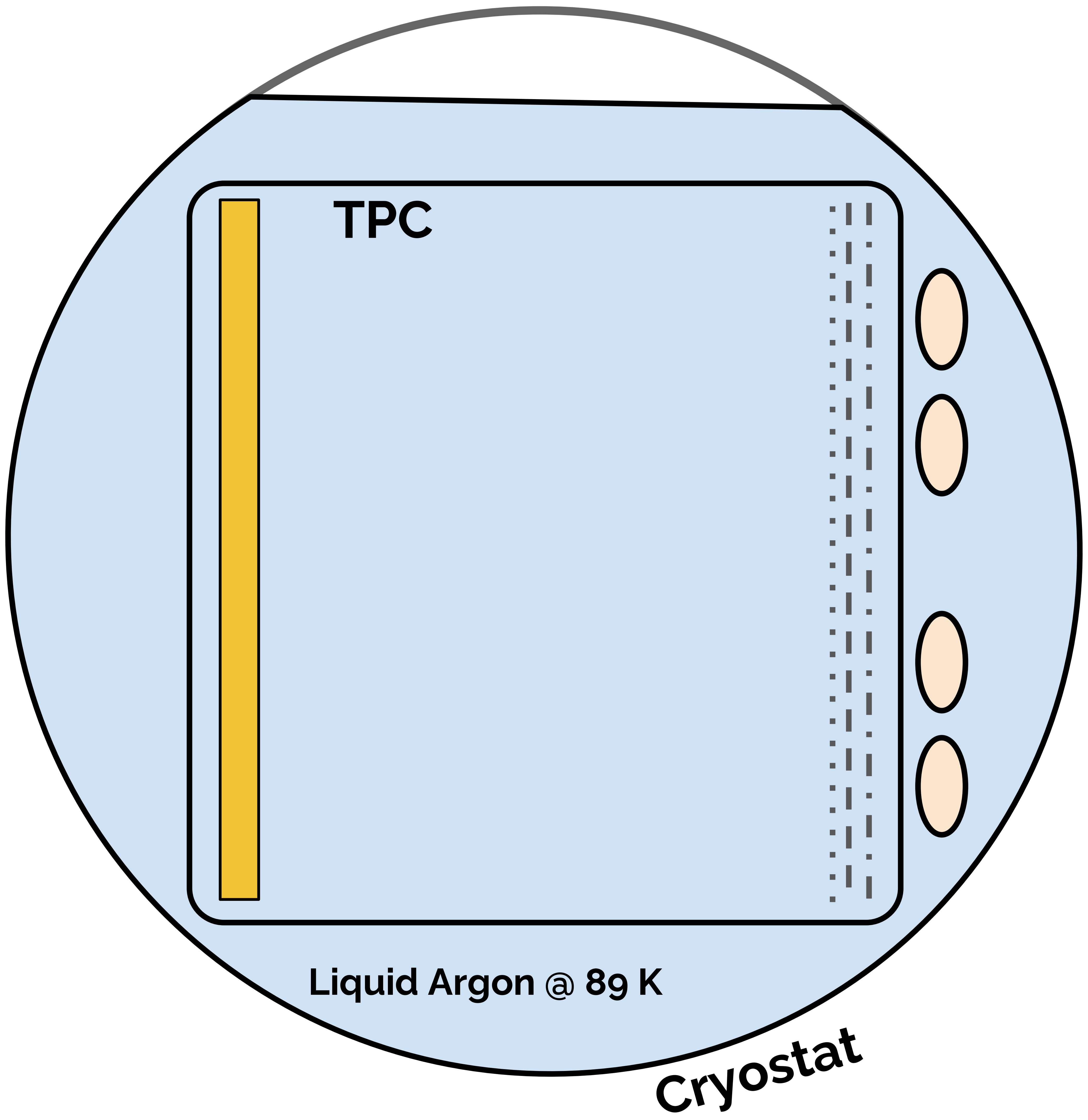
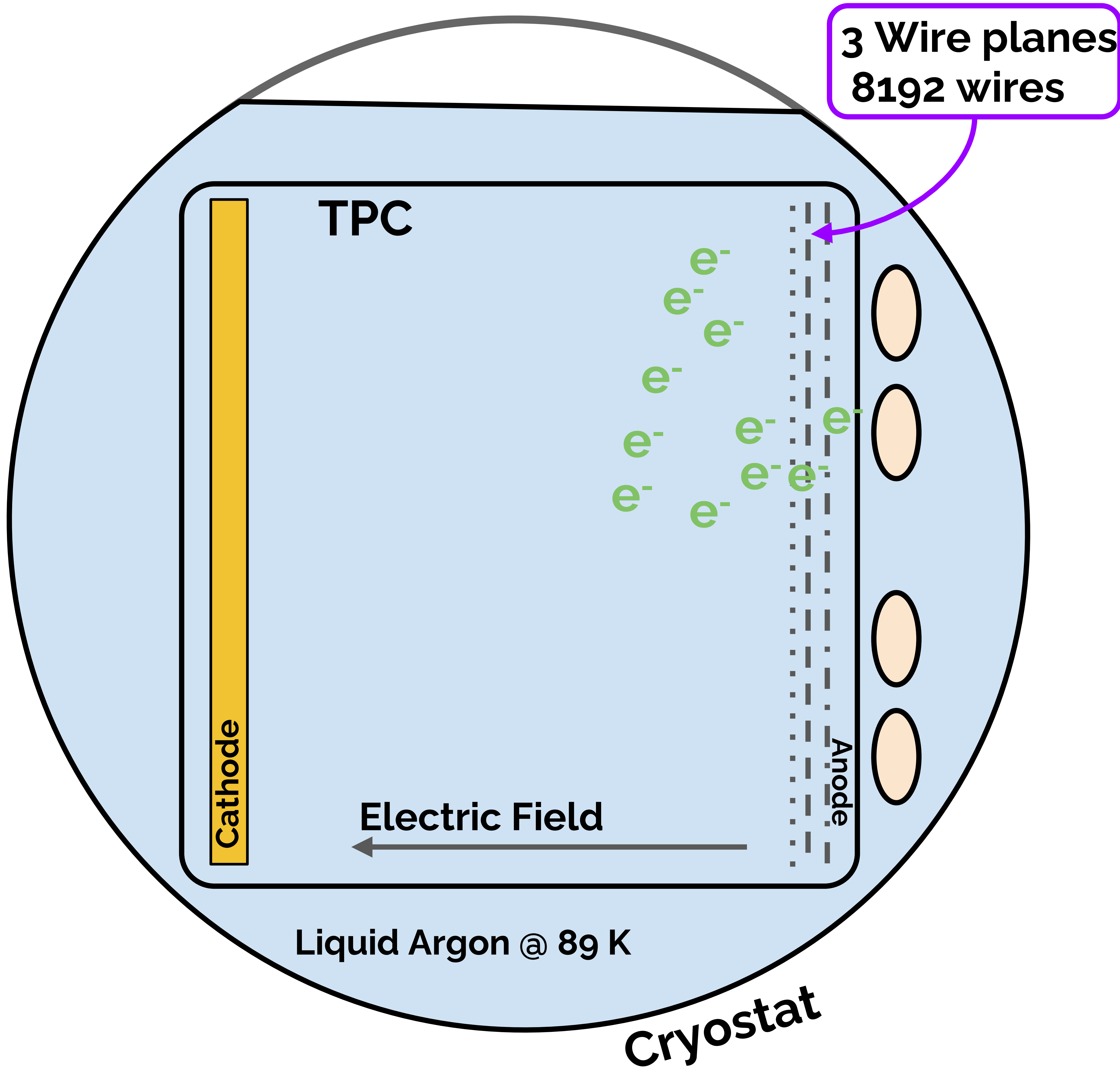
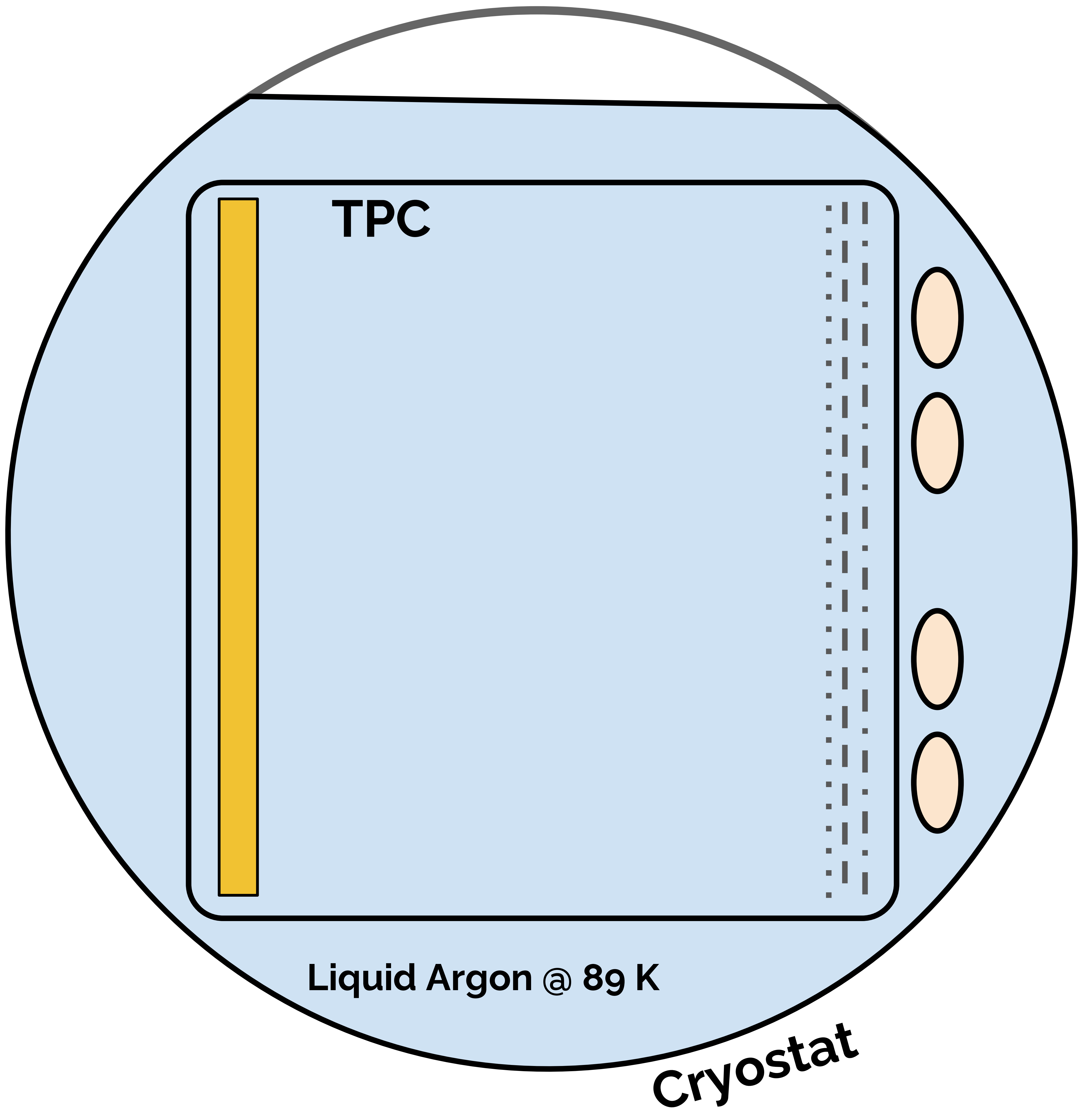
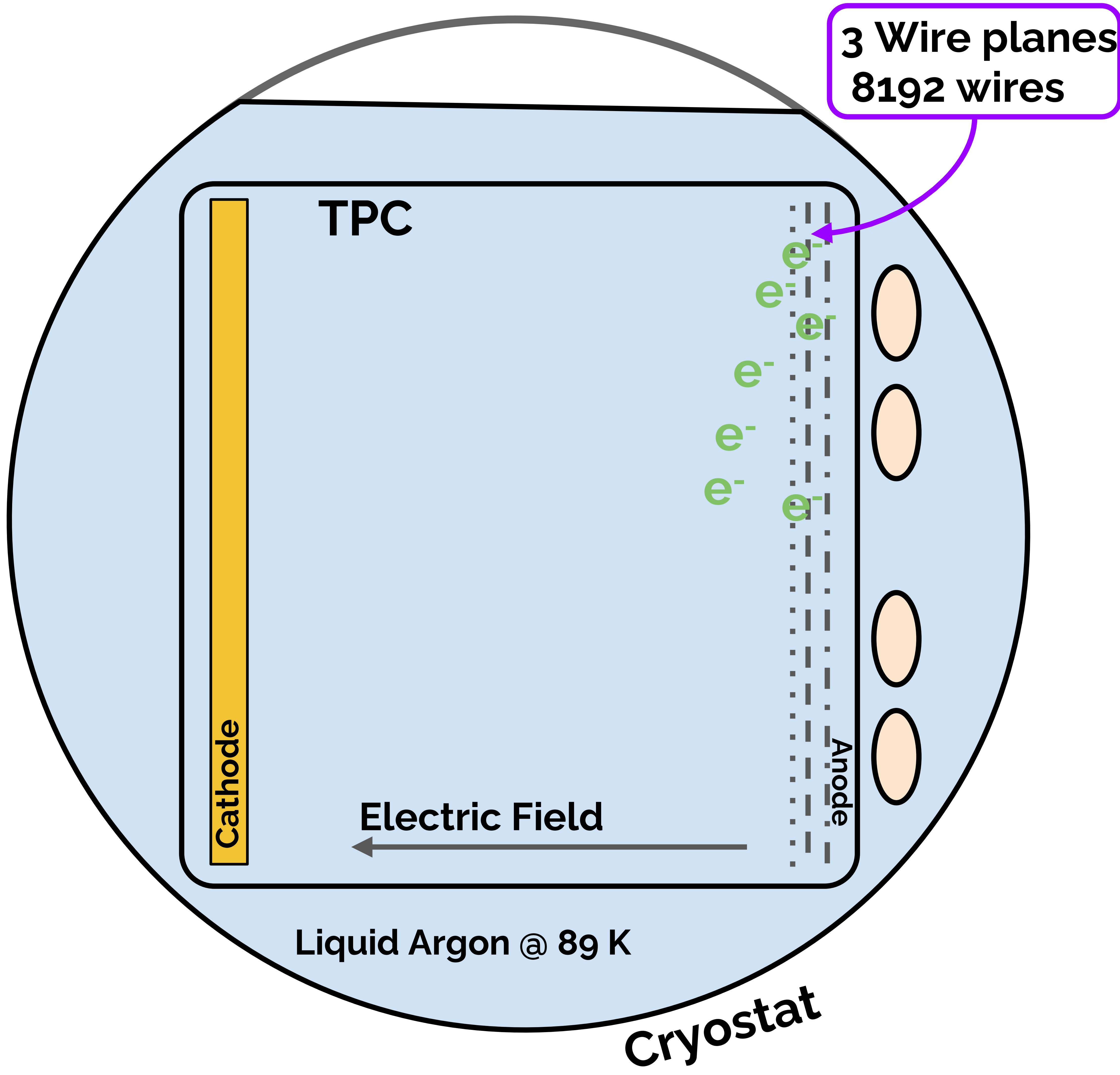


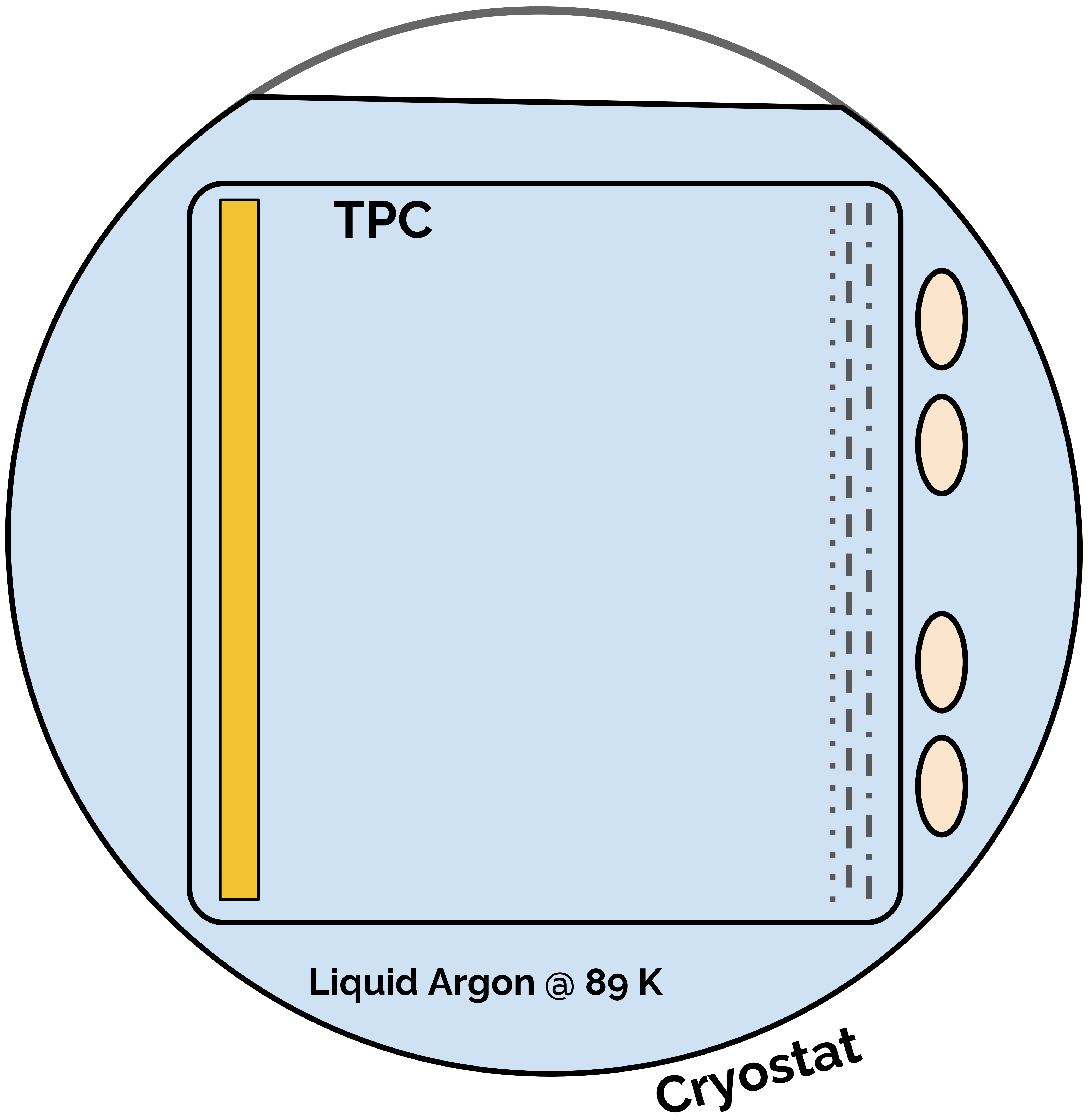


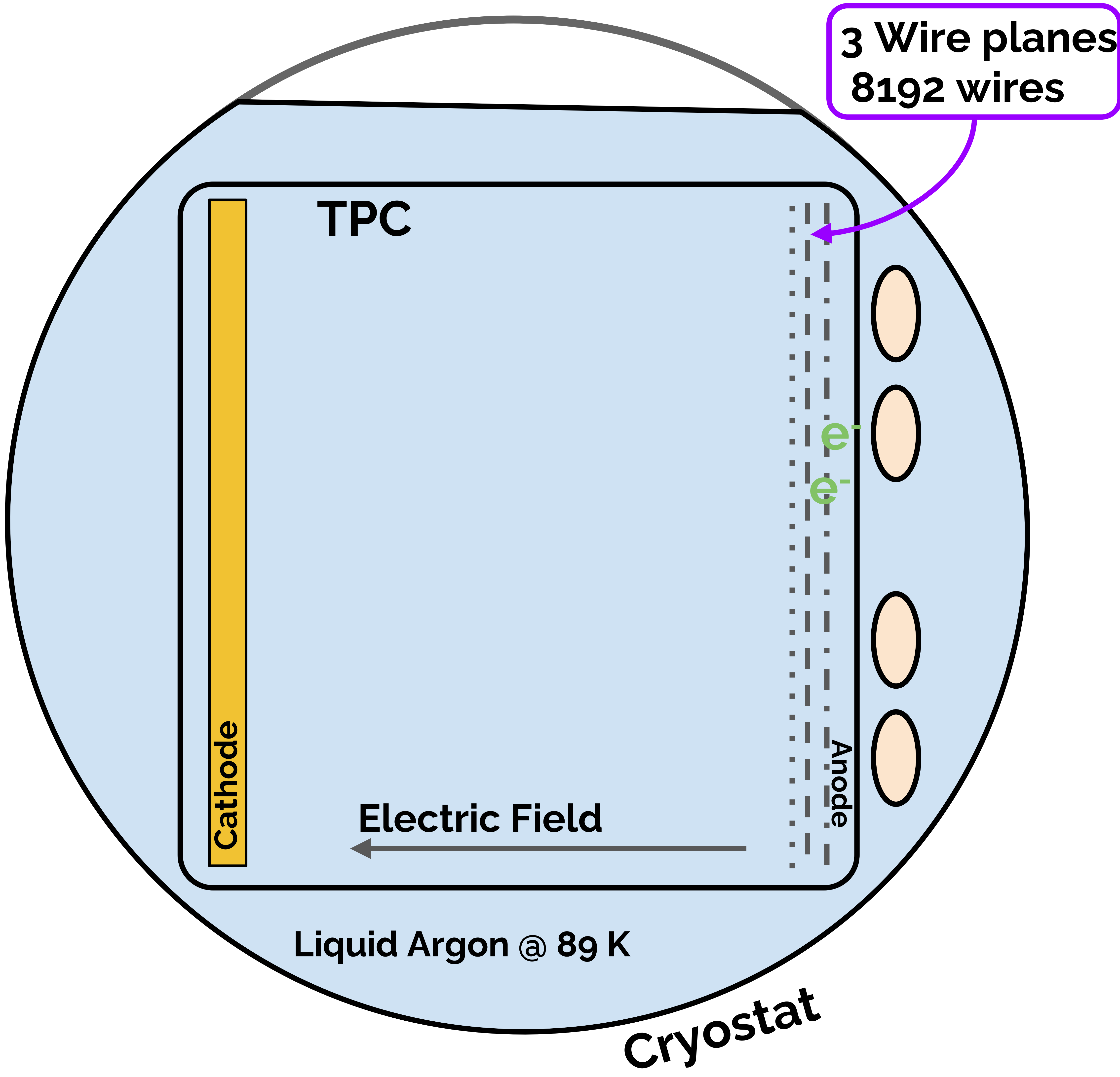
Scintillation light
Ionization Charge





Scintillation light
Ionization Charge





Scintillation light
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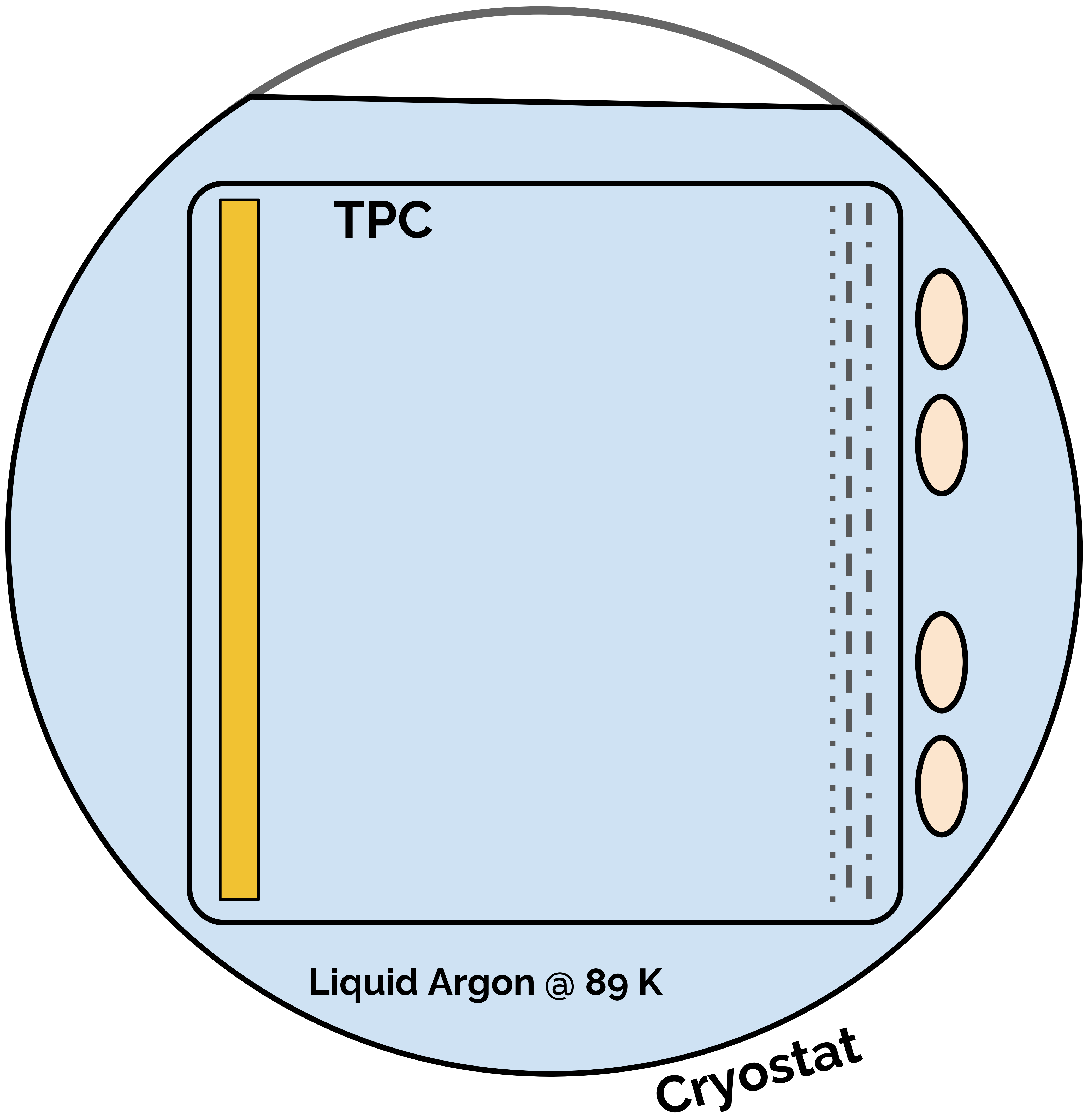
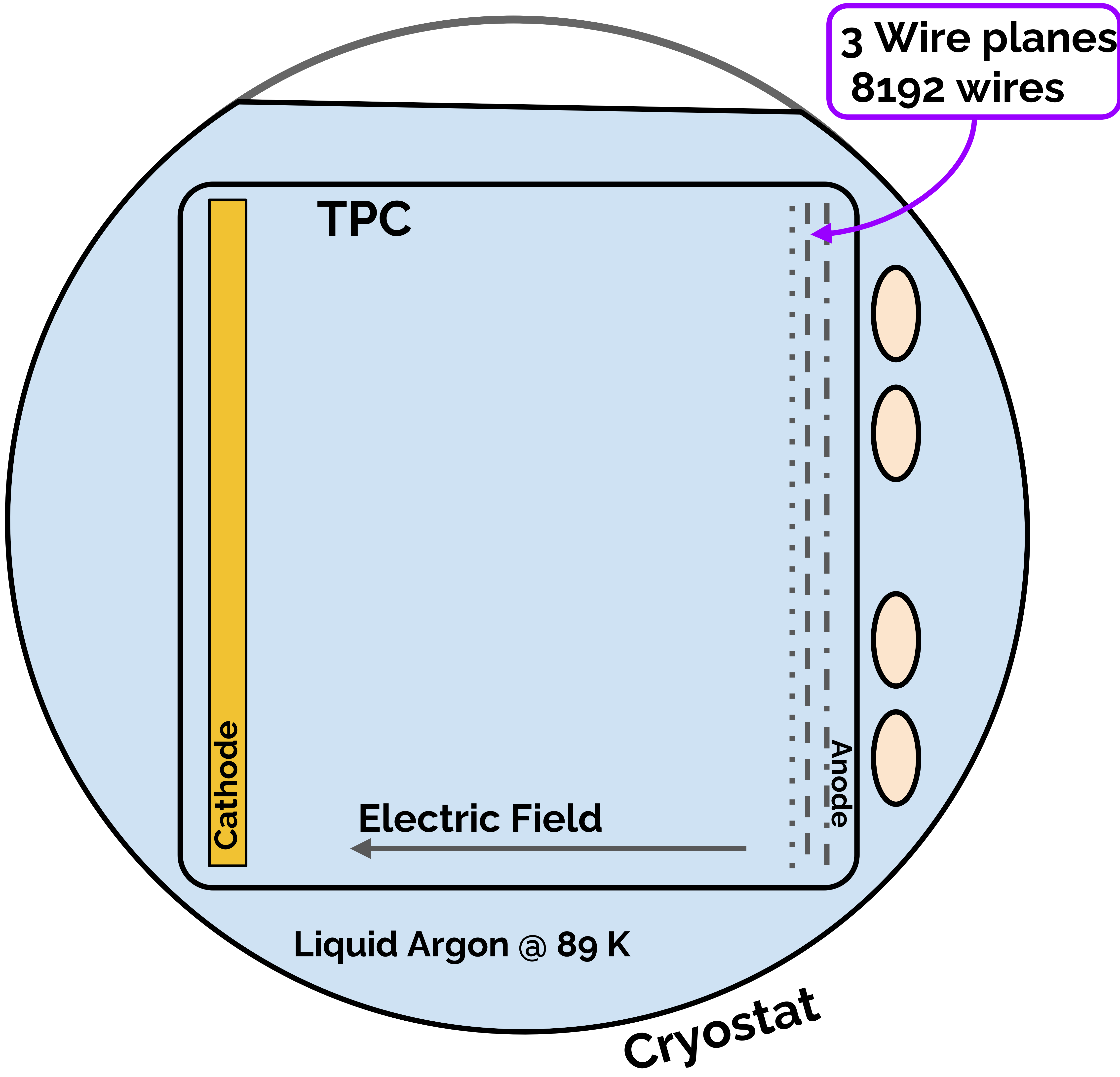
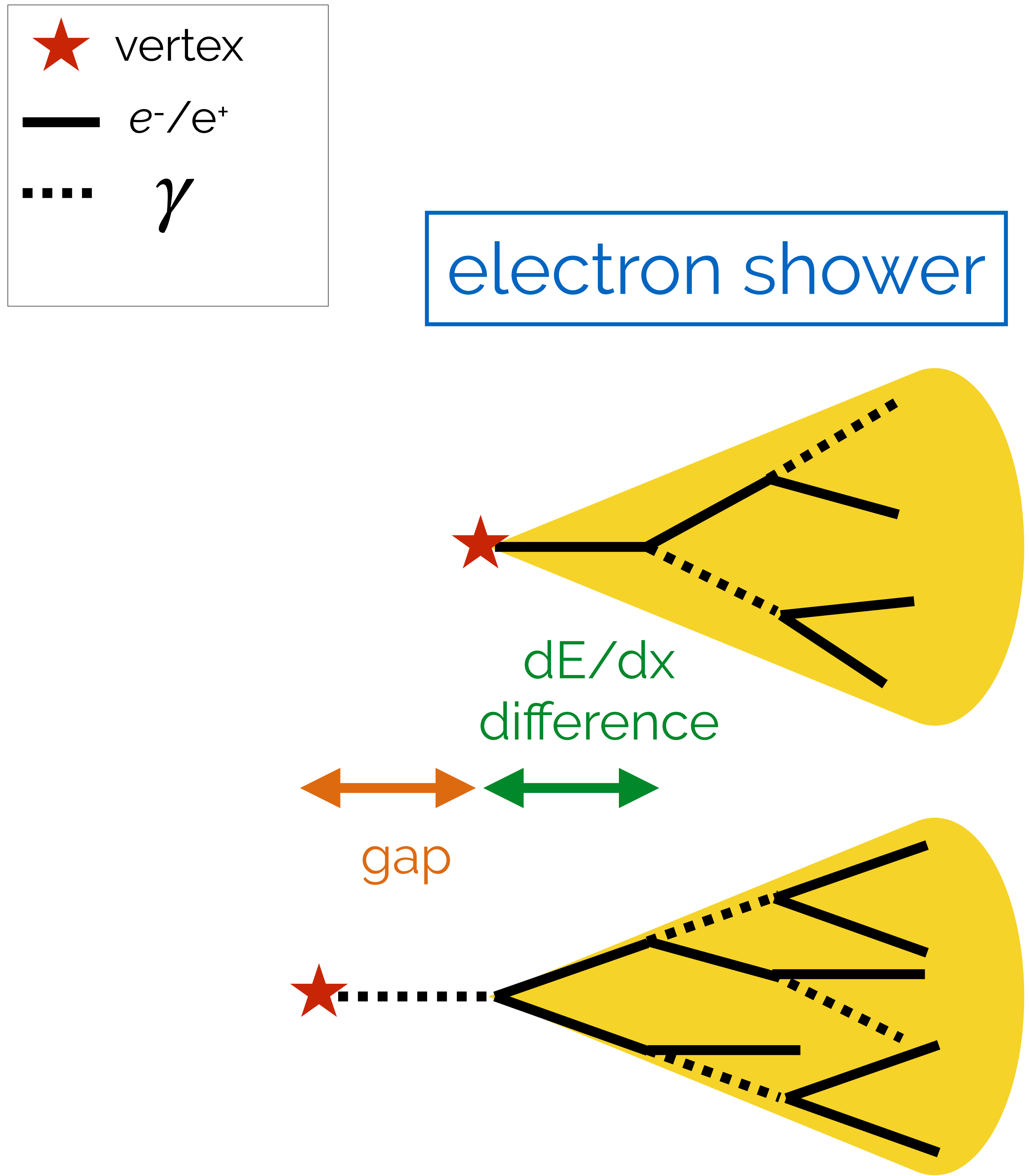


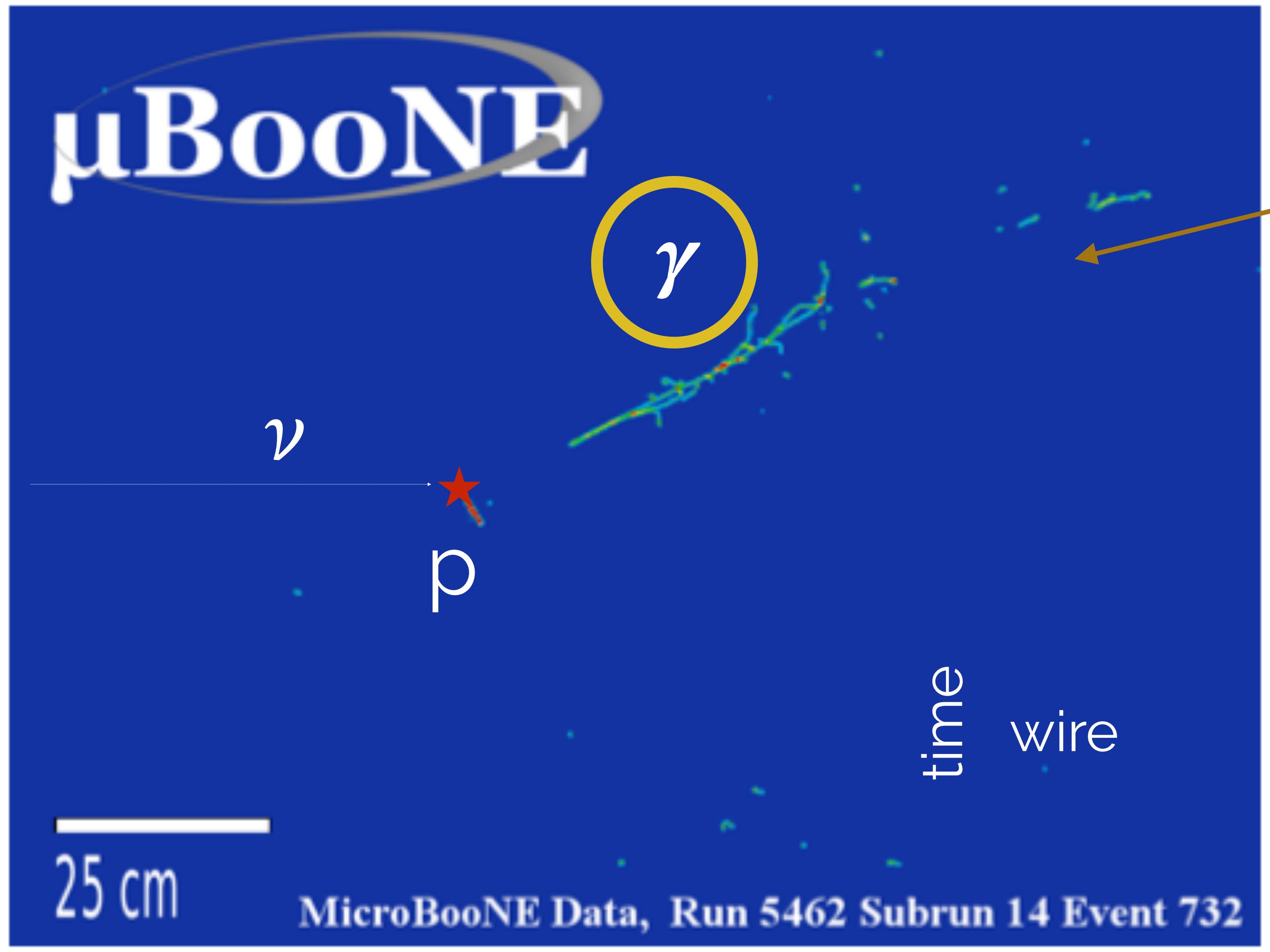


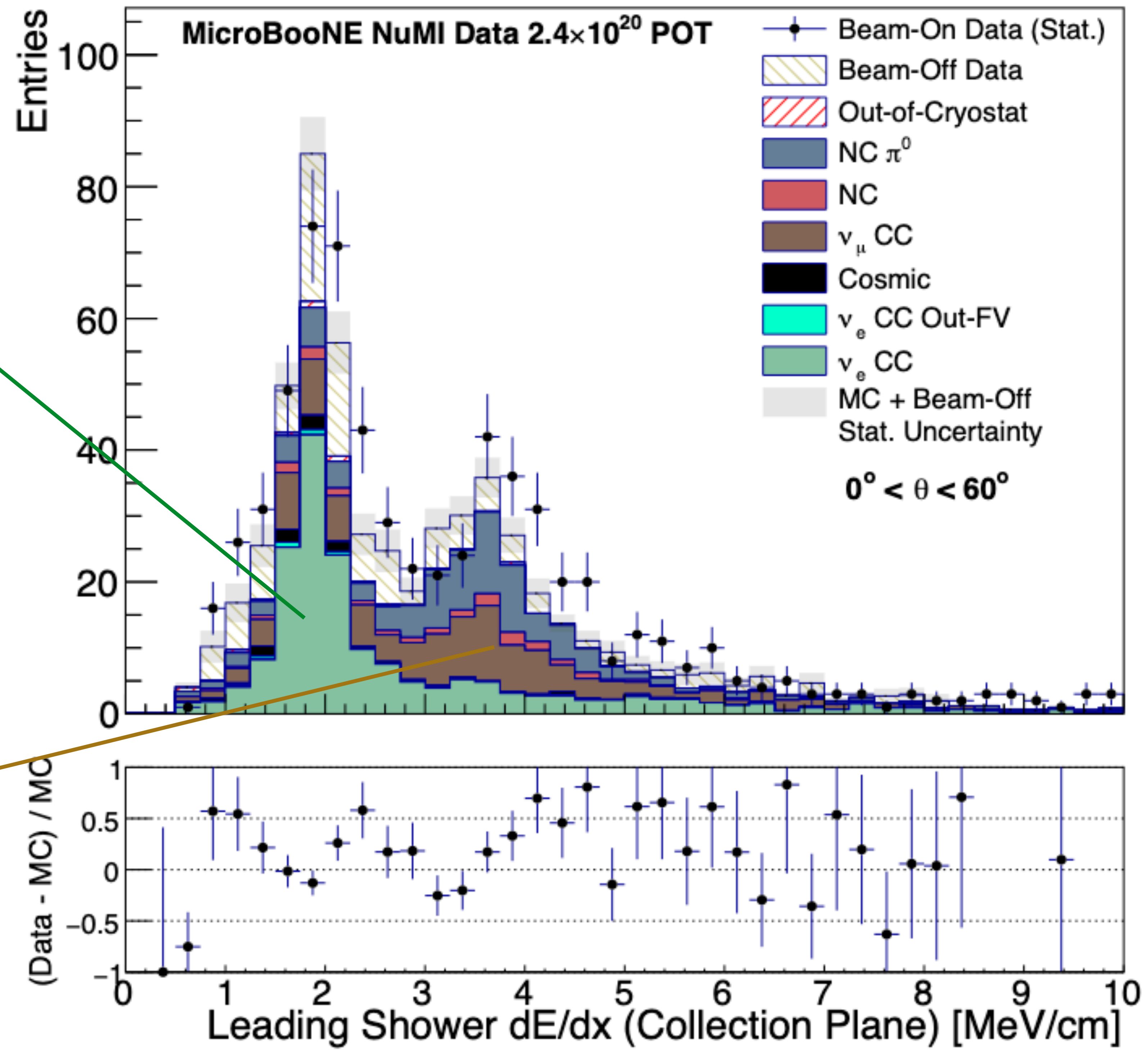
LArTPC to rescue



photon shower

topology information

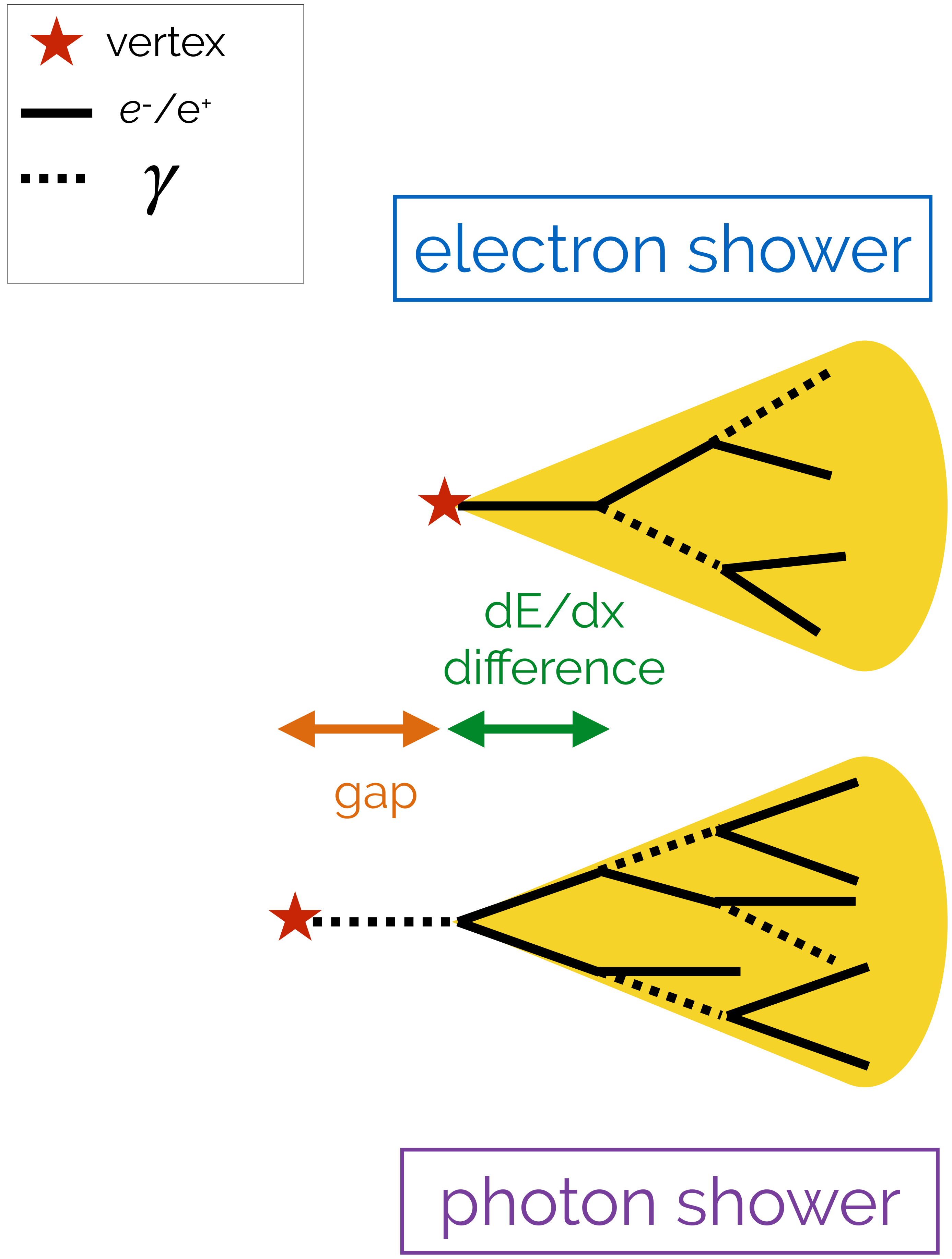




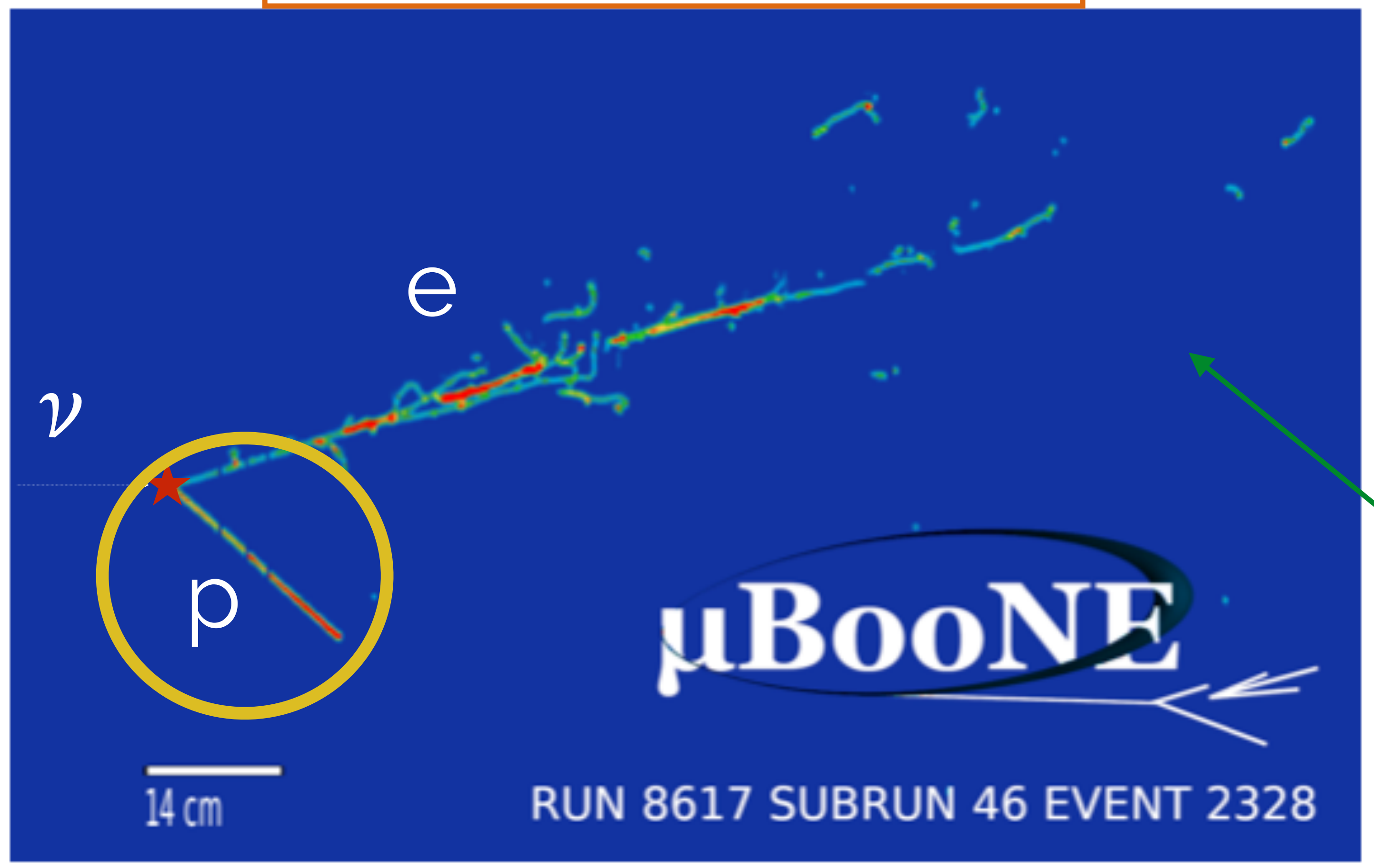
ionization dE/dx

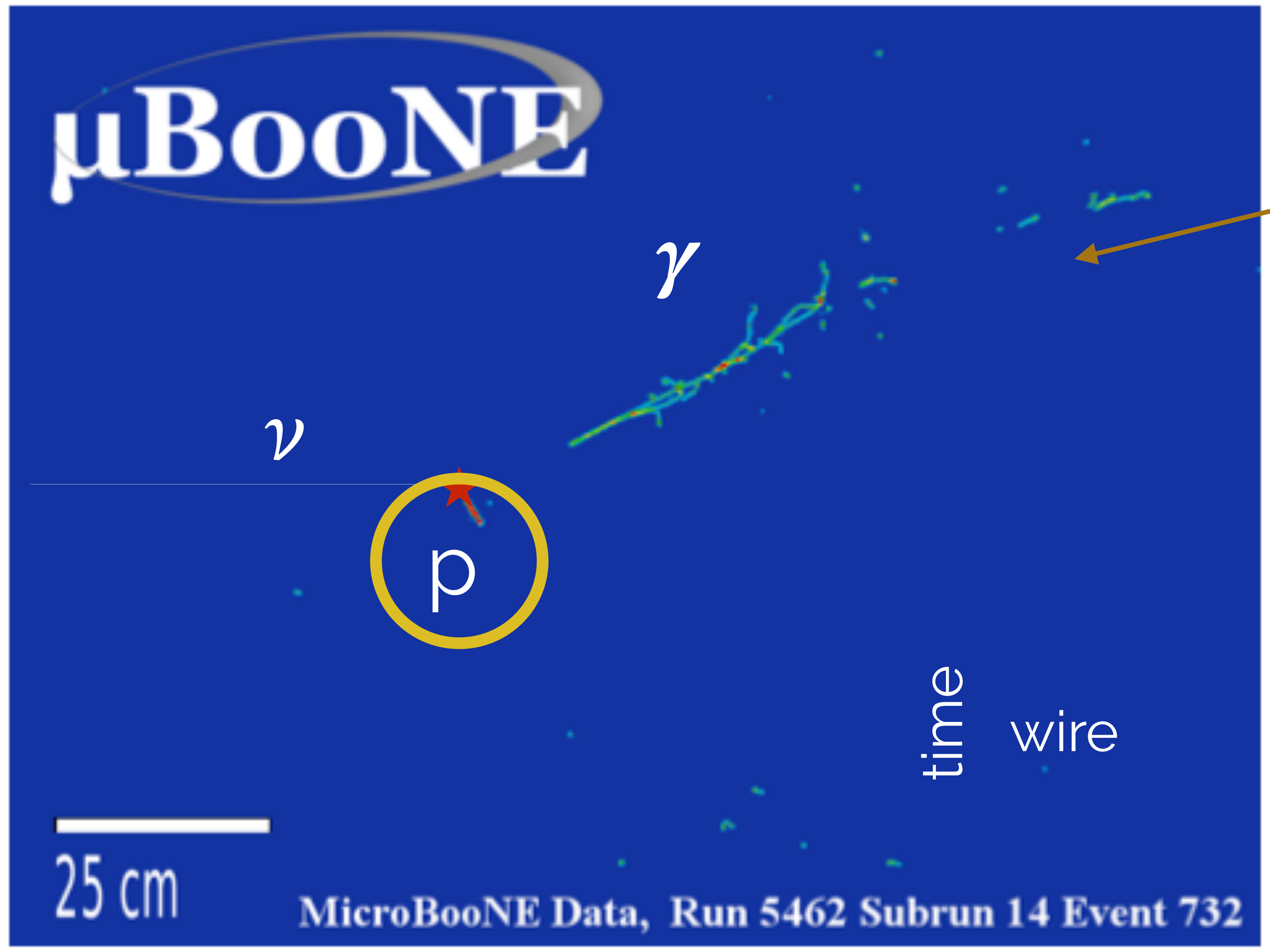
MicroBooNE uses the excellent properties and resolution of its LArTPC to select both eLEE and γLEE signals with high purity

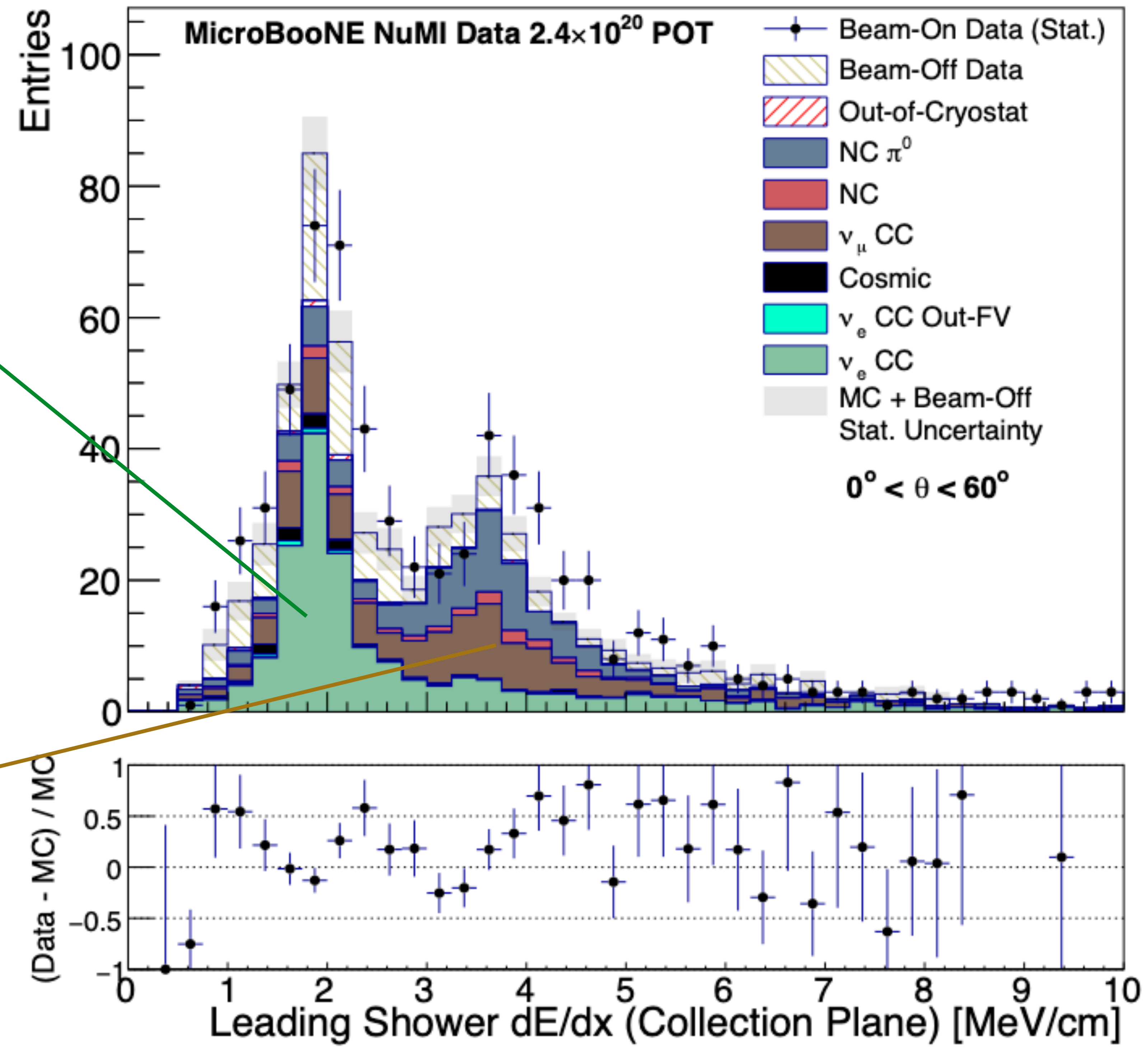
LArTPC to rescue



topology information



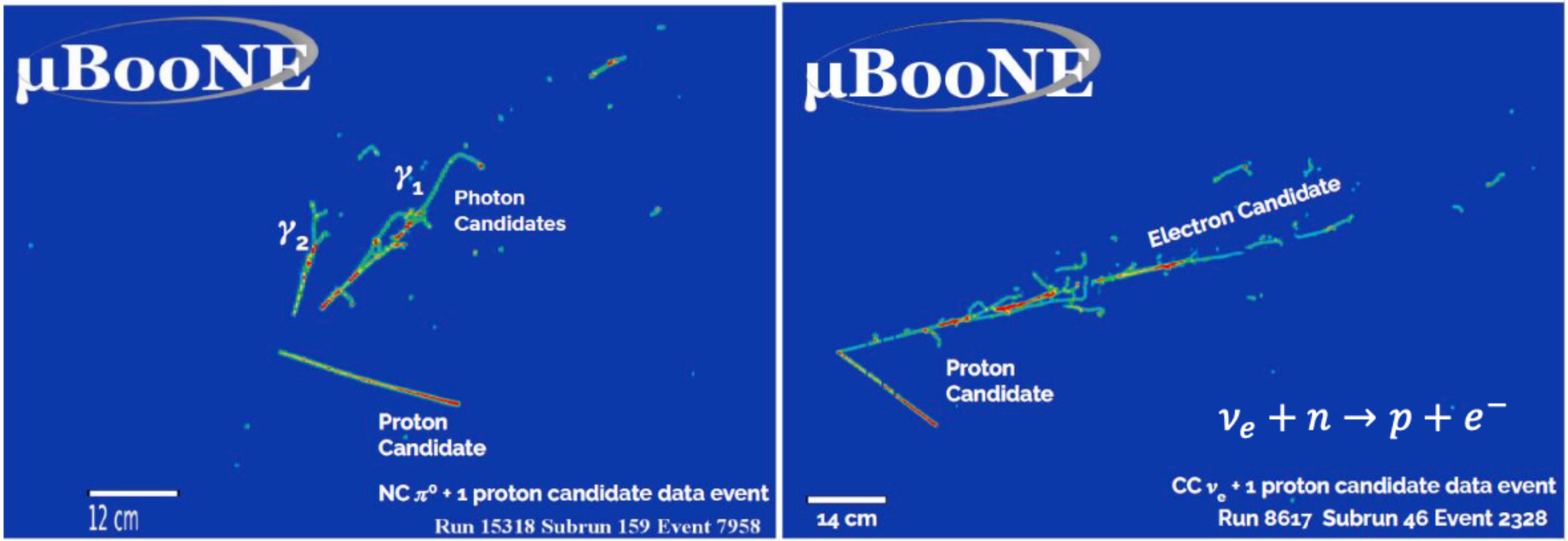




ionization dE/dx

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

LArTPC to rescue

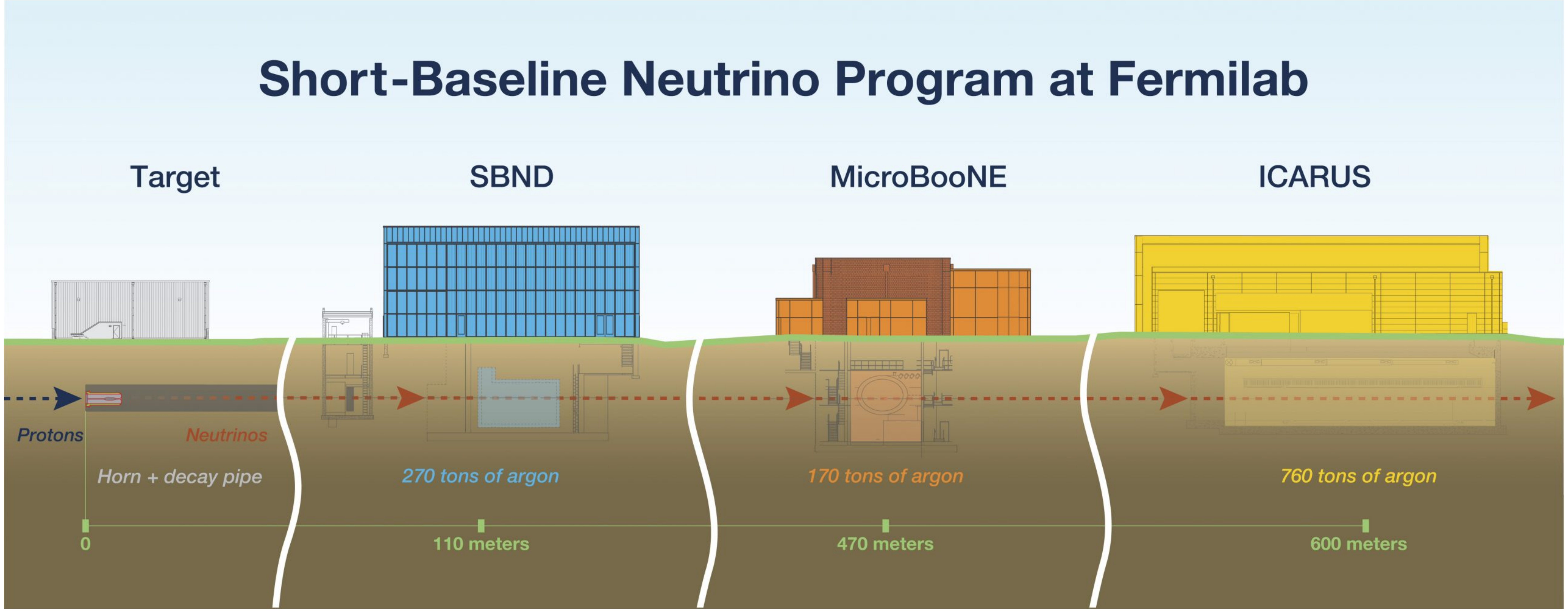


- capable of separating electrons from photons, with gap and calorimetry information
- hear more about LArTPC event reconstruction on Thursday from Haiwang

Outline

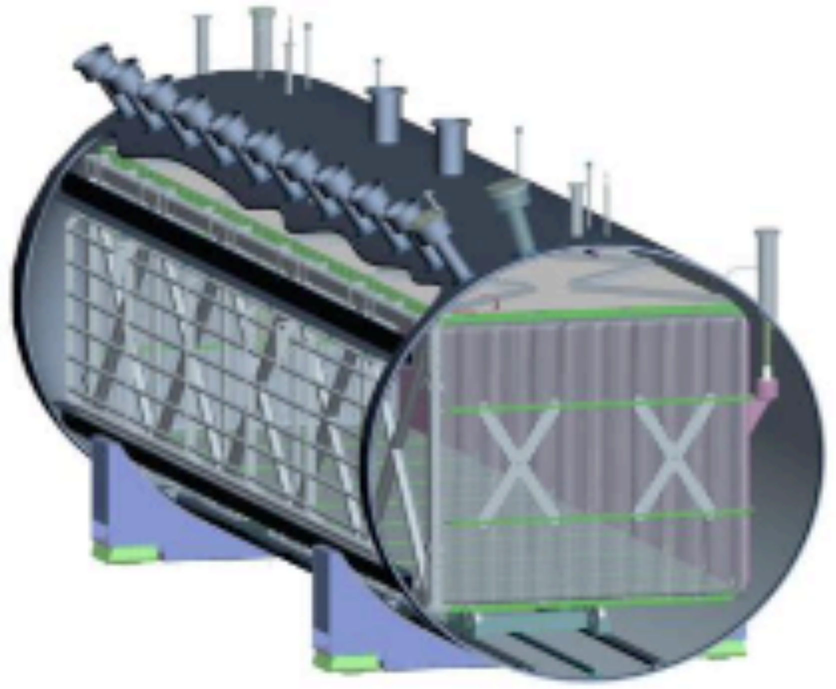
- remaining questions in neutrino physics
- sterile neutrino: what is it, why is it, and how do we detect it
- **Short Baseline Neutrino (SBN) Program**

SBN Program

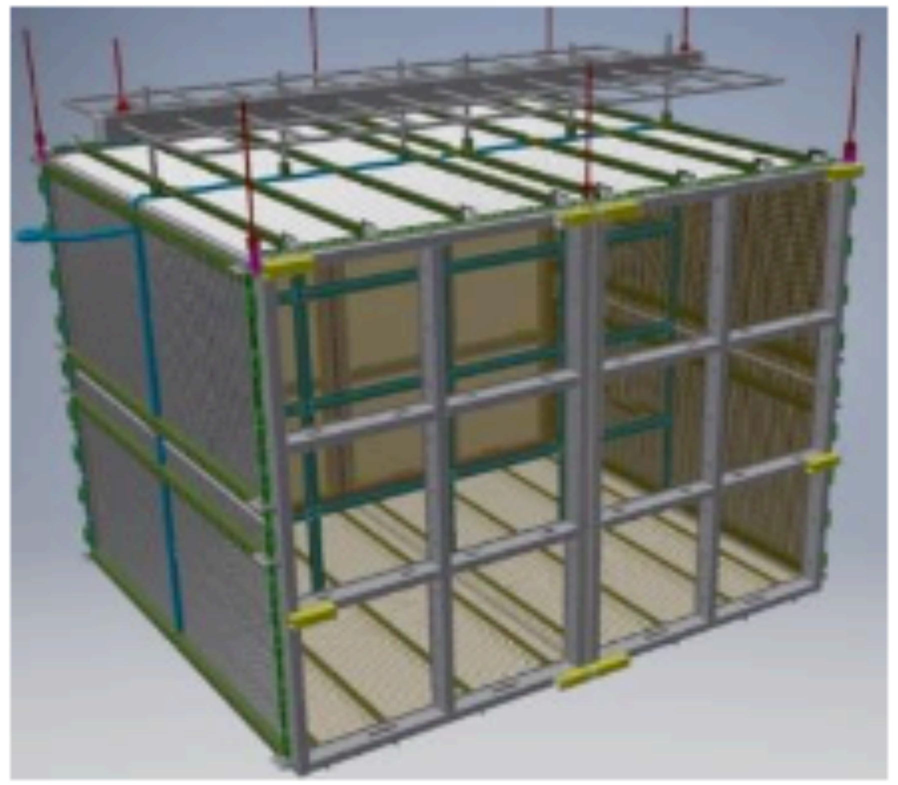


- three LArTPC detectors, with same neutrino beamline and different baseline
- reduce statistical uncertainties with large mass far detector (ICARUS) and higher neutrino flux (SBND)
- reduce systematic uncertainties with same LArTPC detector technology

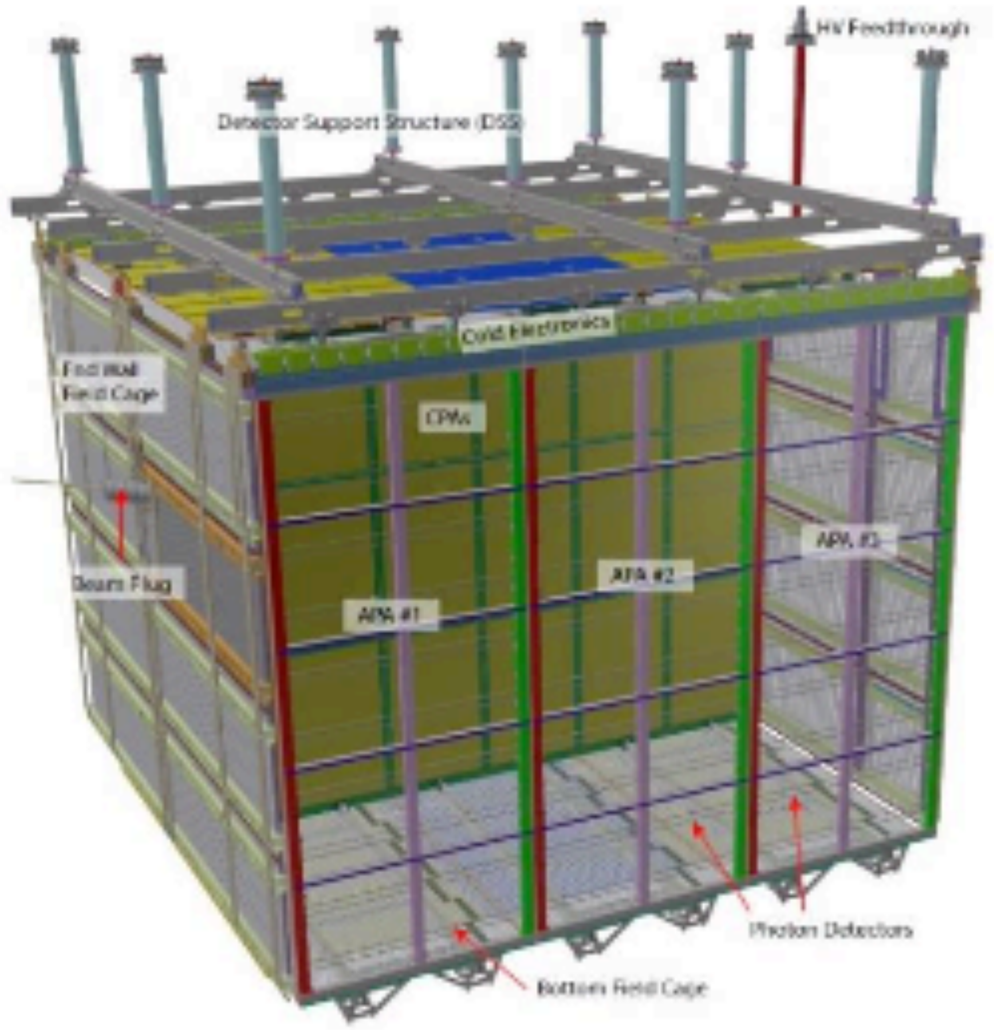
Fermilab SBN program



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



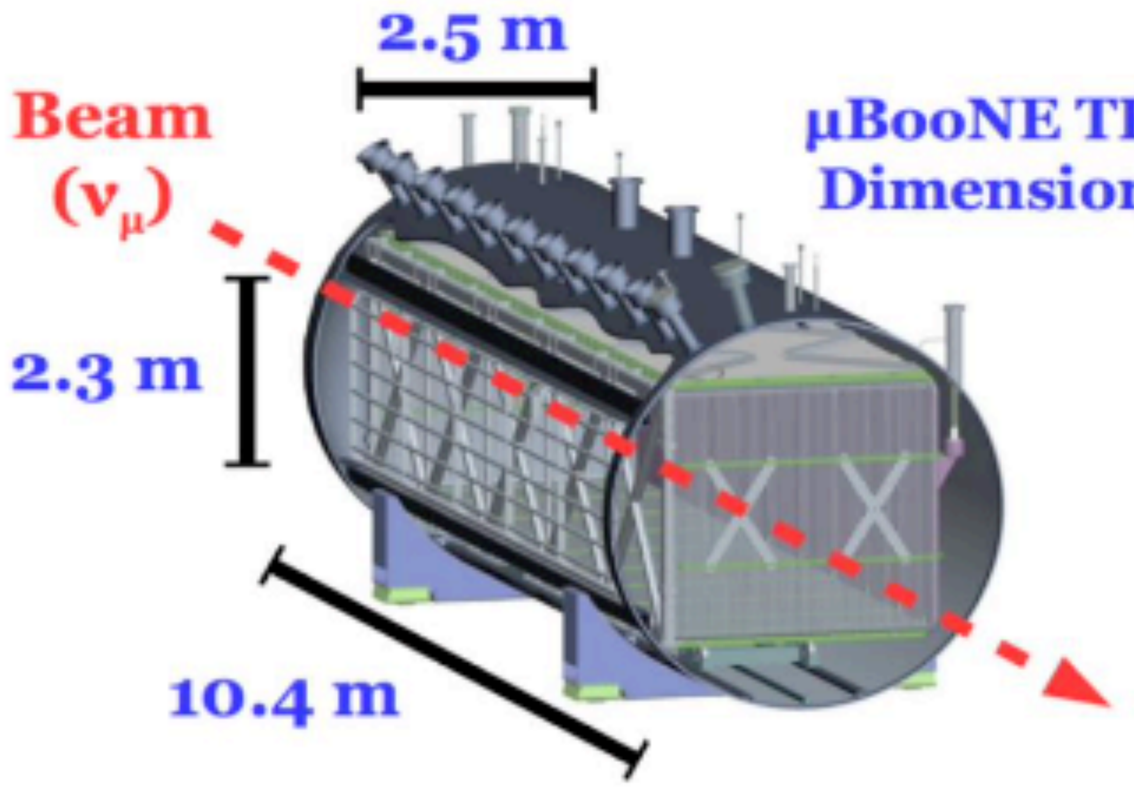
SBND, 112 ton
4m x 4m x 5m

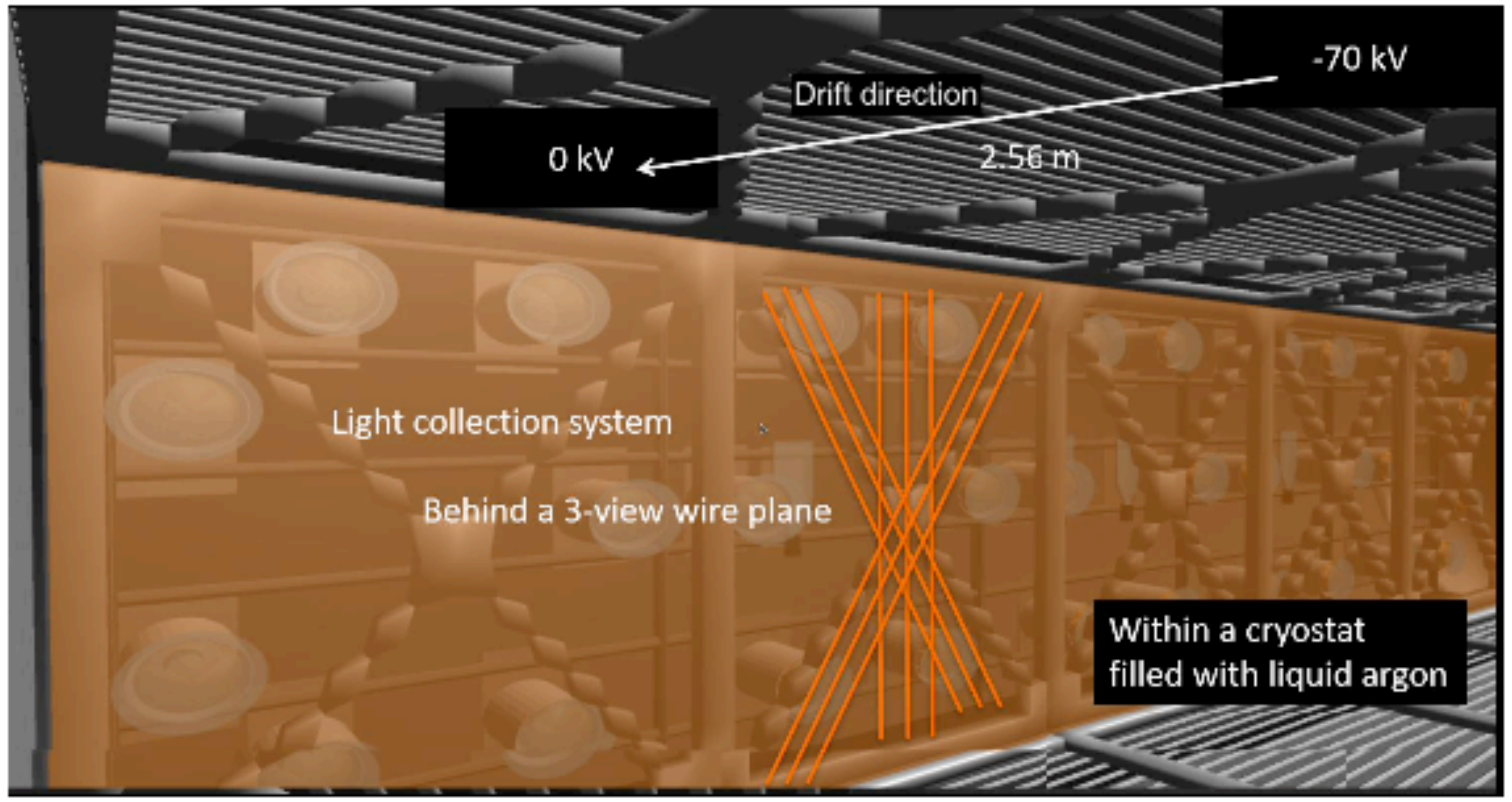


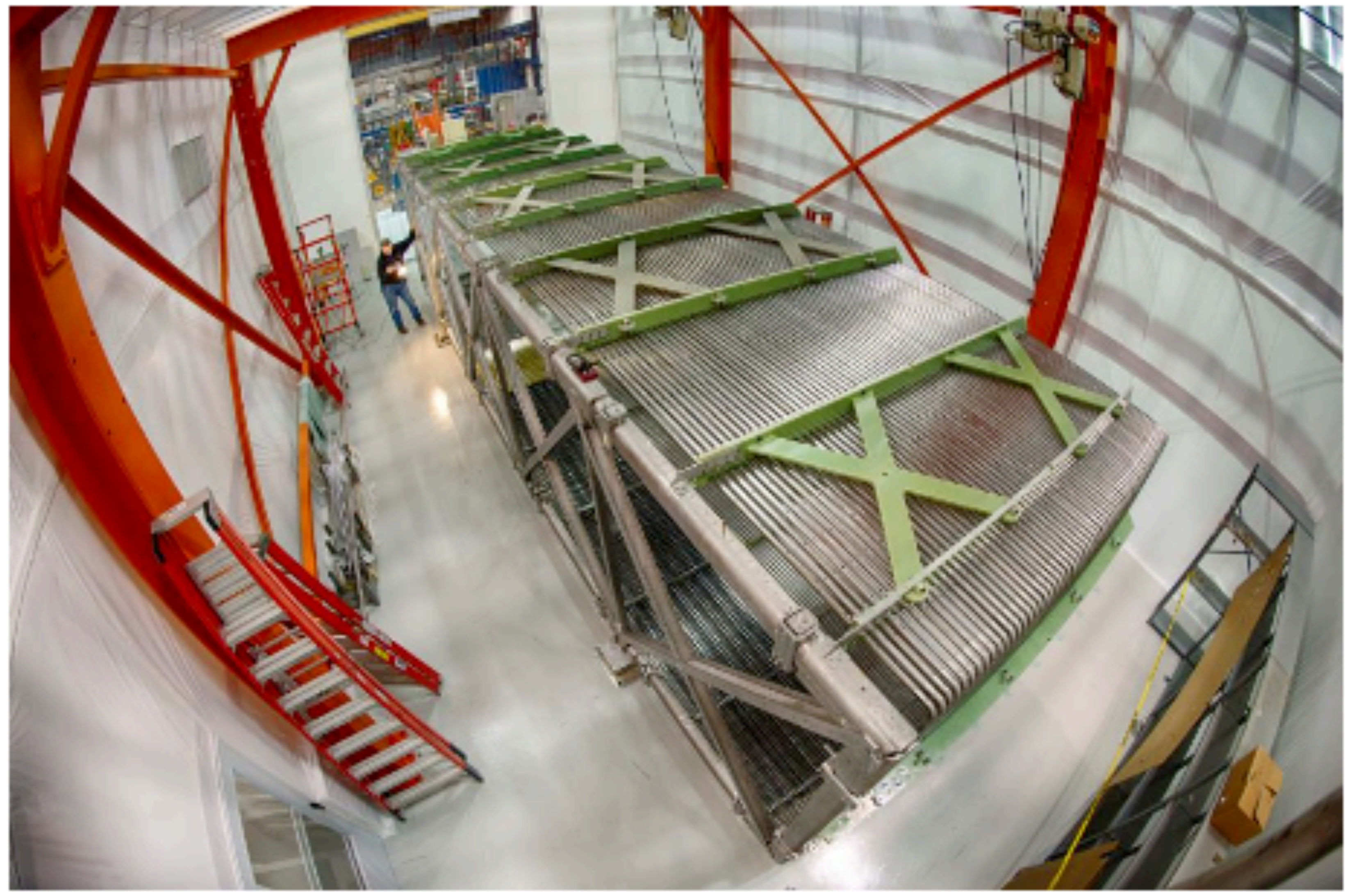
ICARUS, 476 ton
1.5m x 2.2m x 18m x 4

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

MicroBooNE

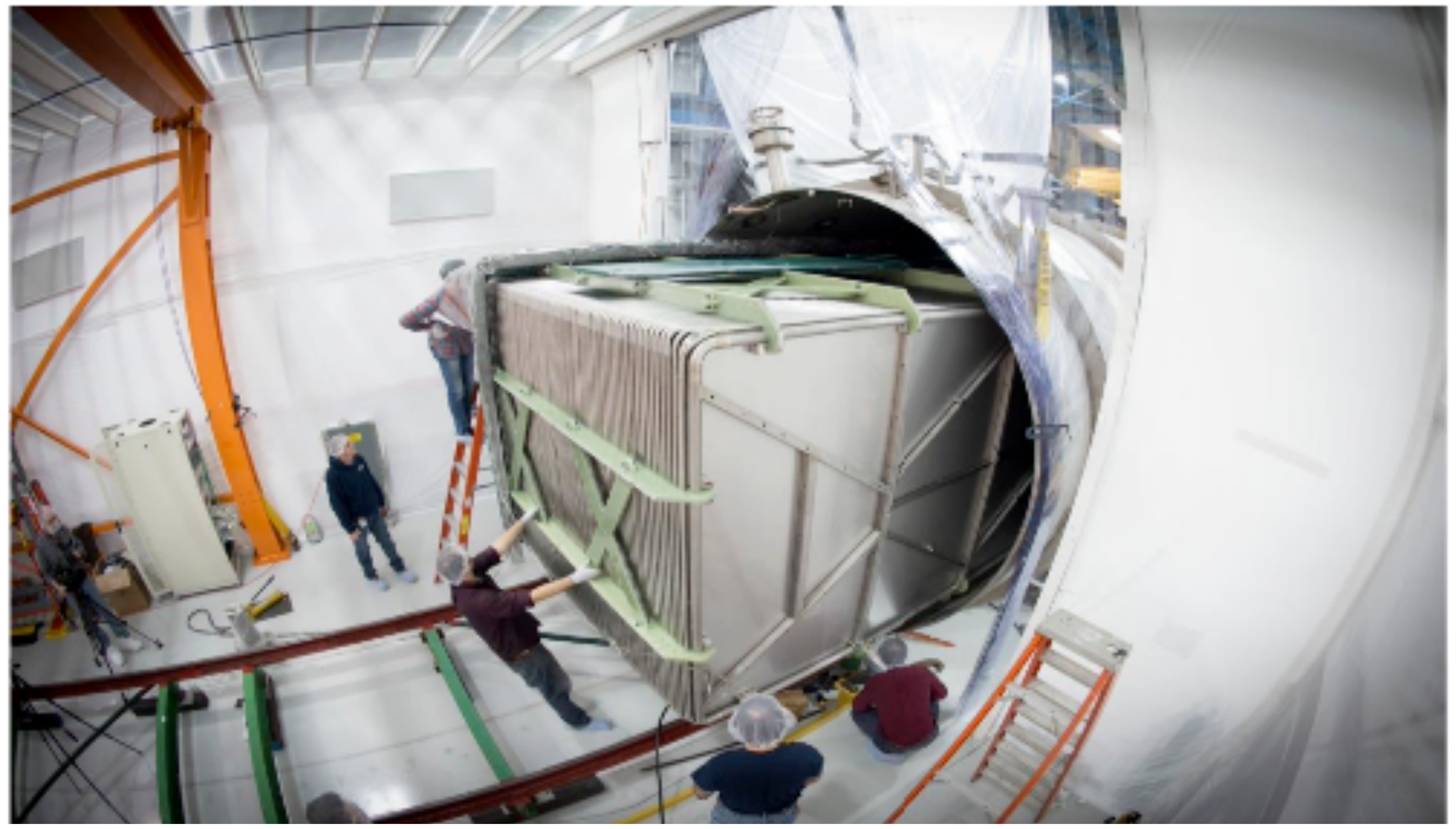

2.5 m
Beam
(ν_μ)
µBooNE TPC
Dimensions
2.3 m
10.4 m

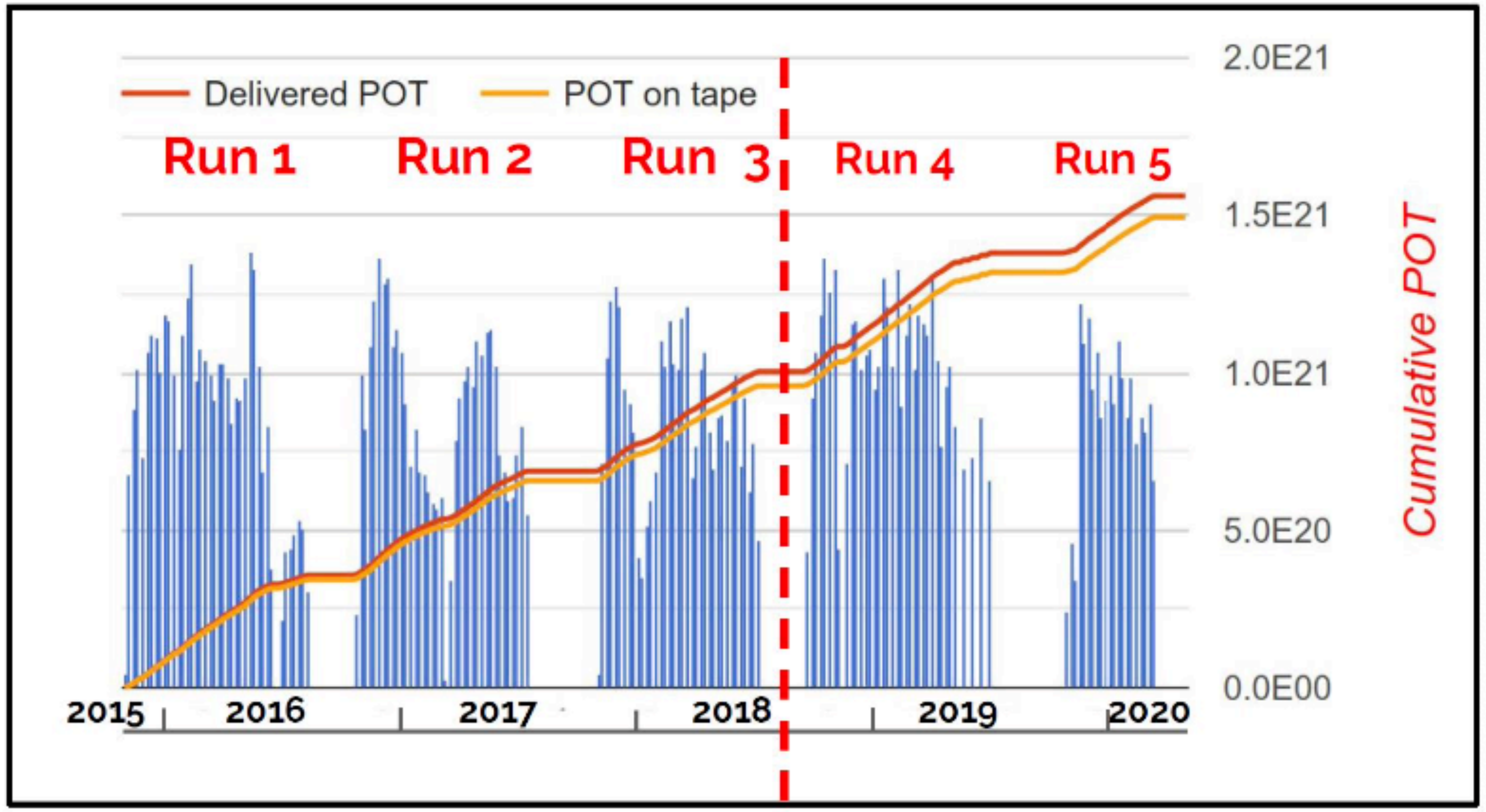

-70 kV
Drift direction
0 kV
2.56 m
Light collection system
Behind a 3-view wire plane
Within a cryostat
filled with liquid argon



MicroBooNE

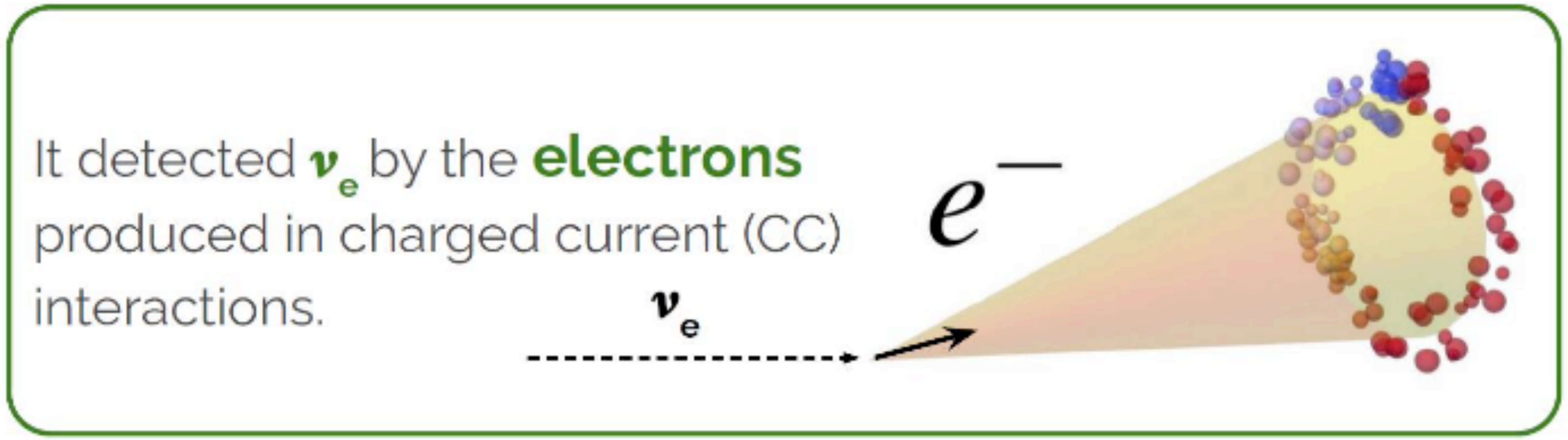
- started taking data since 2015
- finished operation in 2021
- accumulated the world's largest sample of neutrino interaction on argon
- one of the first LArTPC detectors with many new features
  - cold, low noise electronics *(see Shanshan's talk at 3pm)*
  - excellent LAr purity
  - pioneered LArTPC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

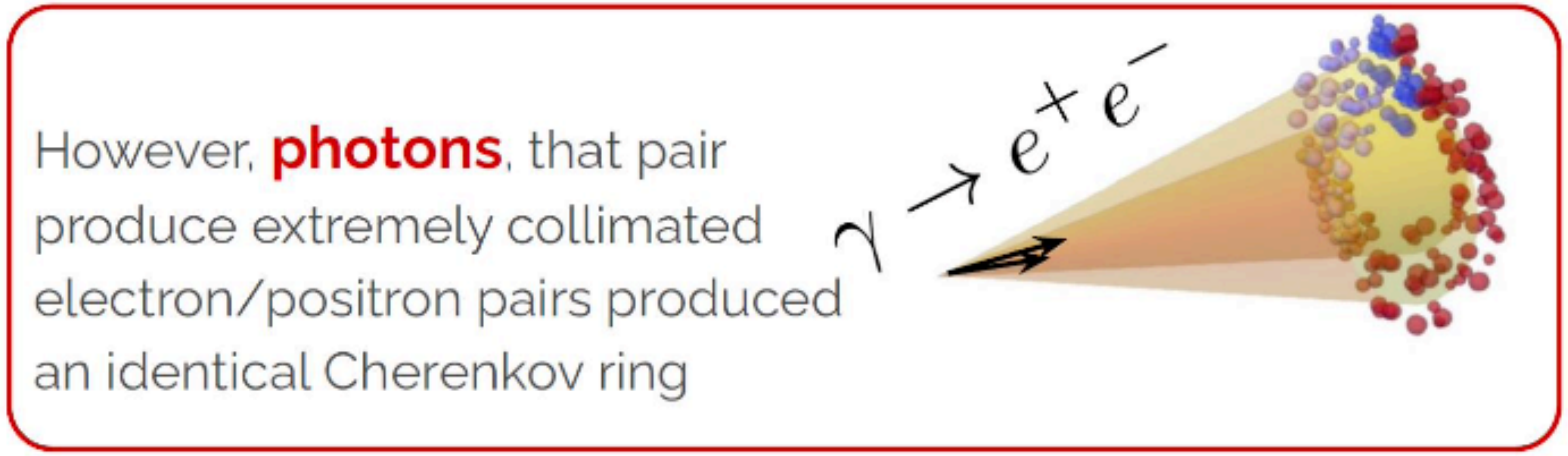




The MiniBooNE Anomaly: recap

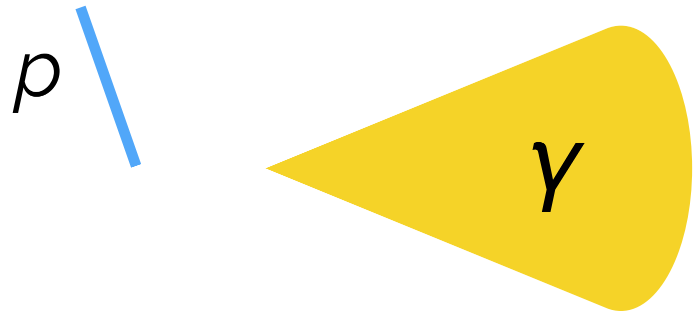
- this limitation makes it hard to interpret the LEE
  - if electrons, this can be explained by sterile neutrino oscillated into electron neutrinos
  - if photons, this can be explained by underestimated prediction of single-photon-producing SM process

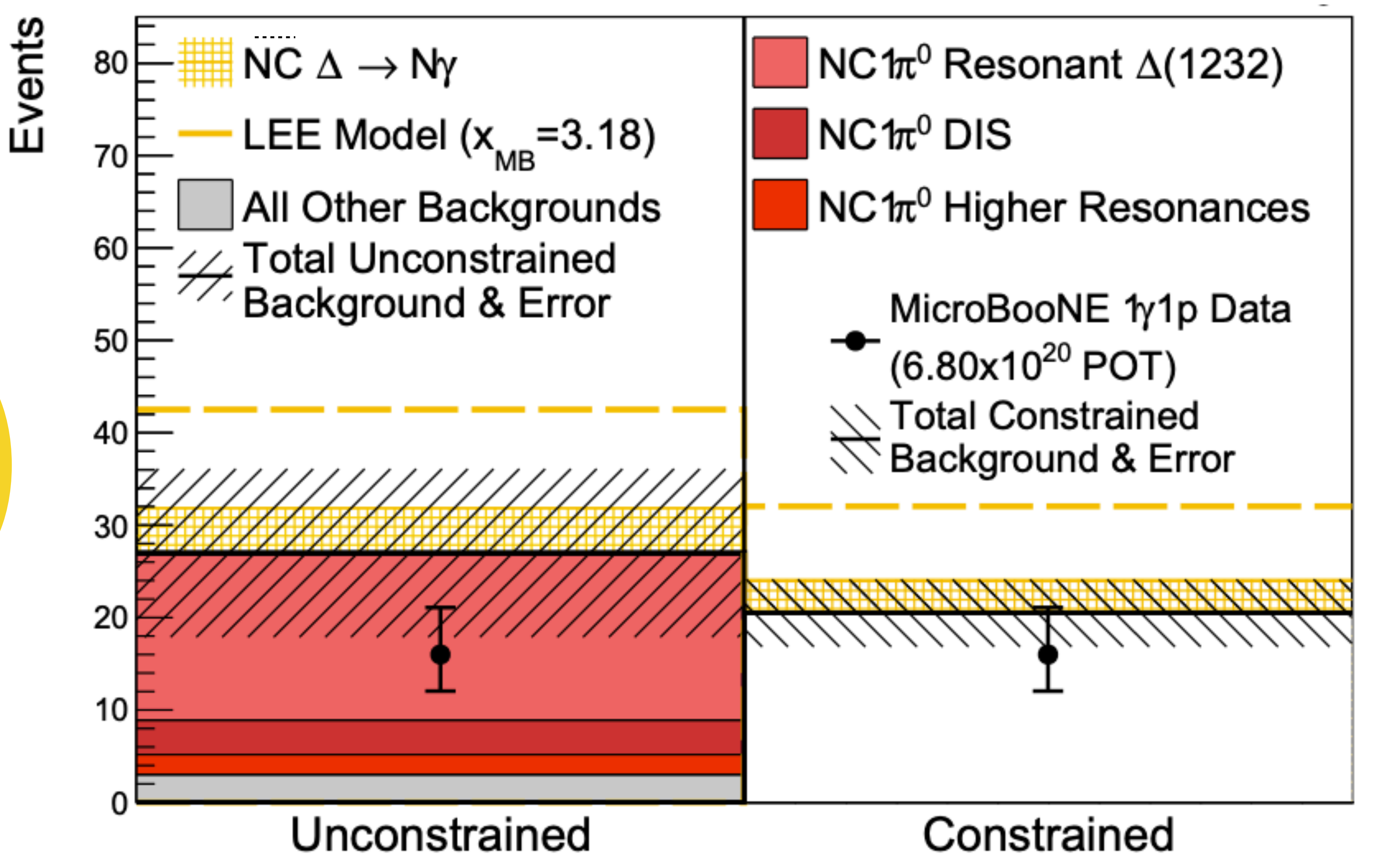




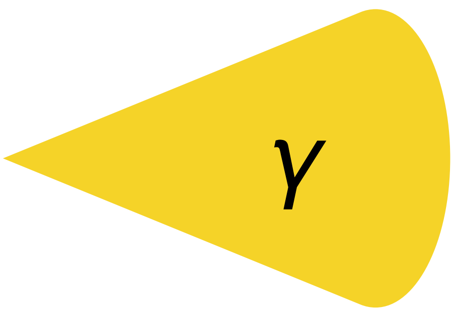
MicroBooNE LEE result

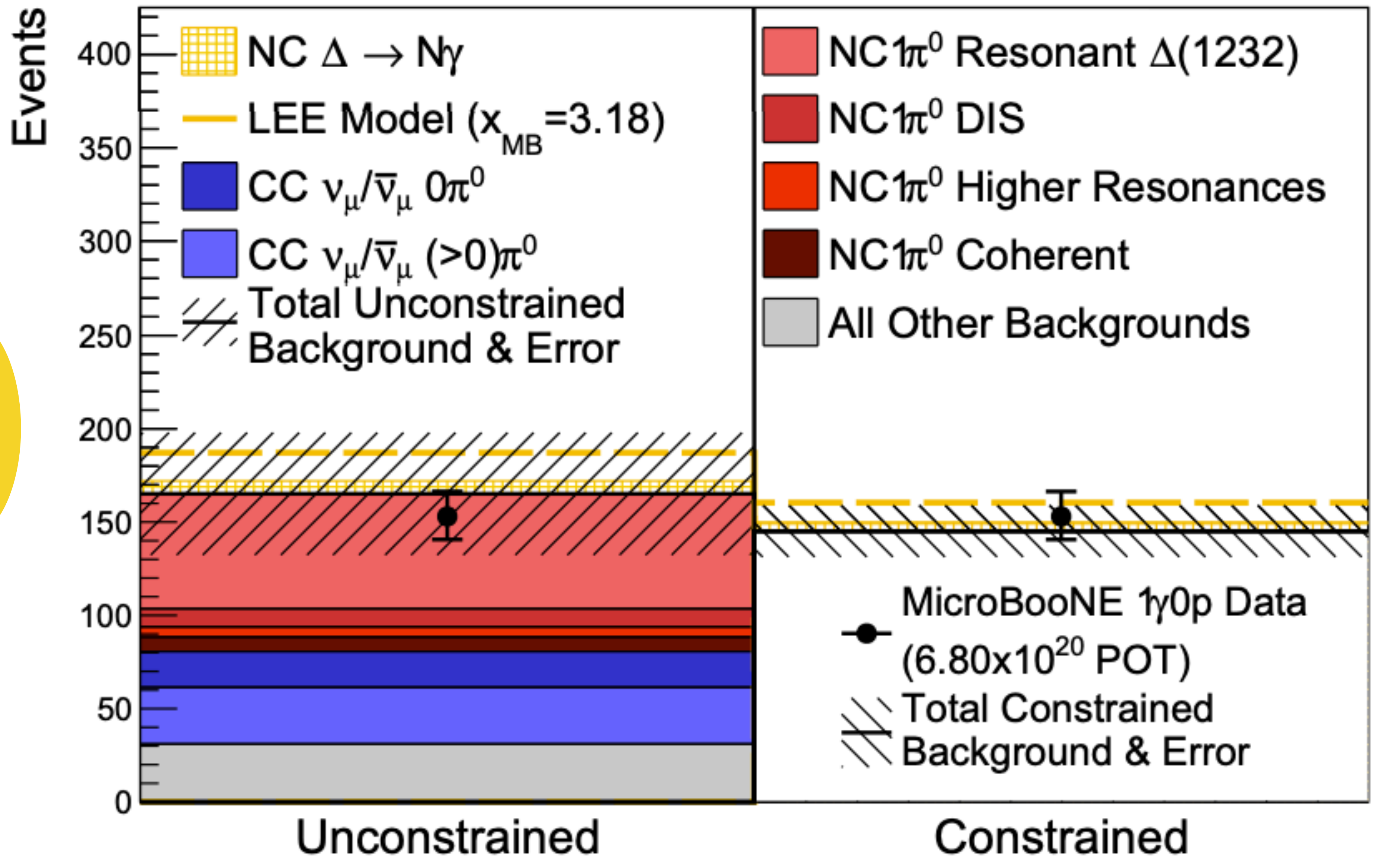
- first MicroBooNE result probed both electron-like and photon-like signals, with LArTPC's ability of e/γ separation





- photon analysis targets NC $\Delta \rightarrow N\gamma$ channel
  - test if this channel is underestimated in the standard model
  - result shows no evidence for enhanced rate of single photons from NCΔ decay





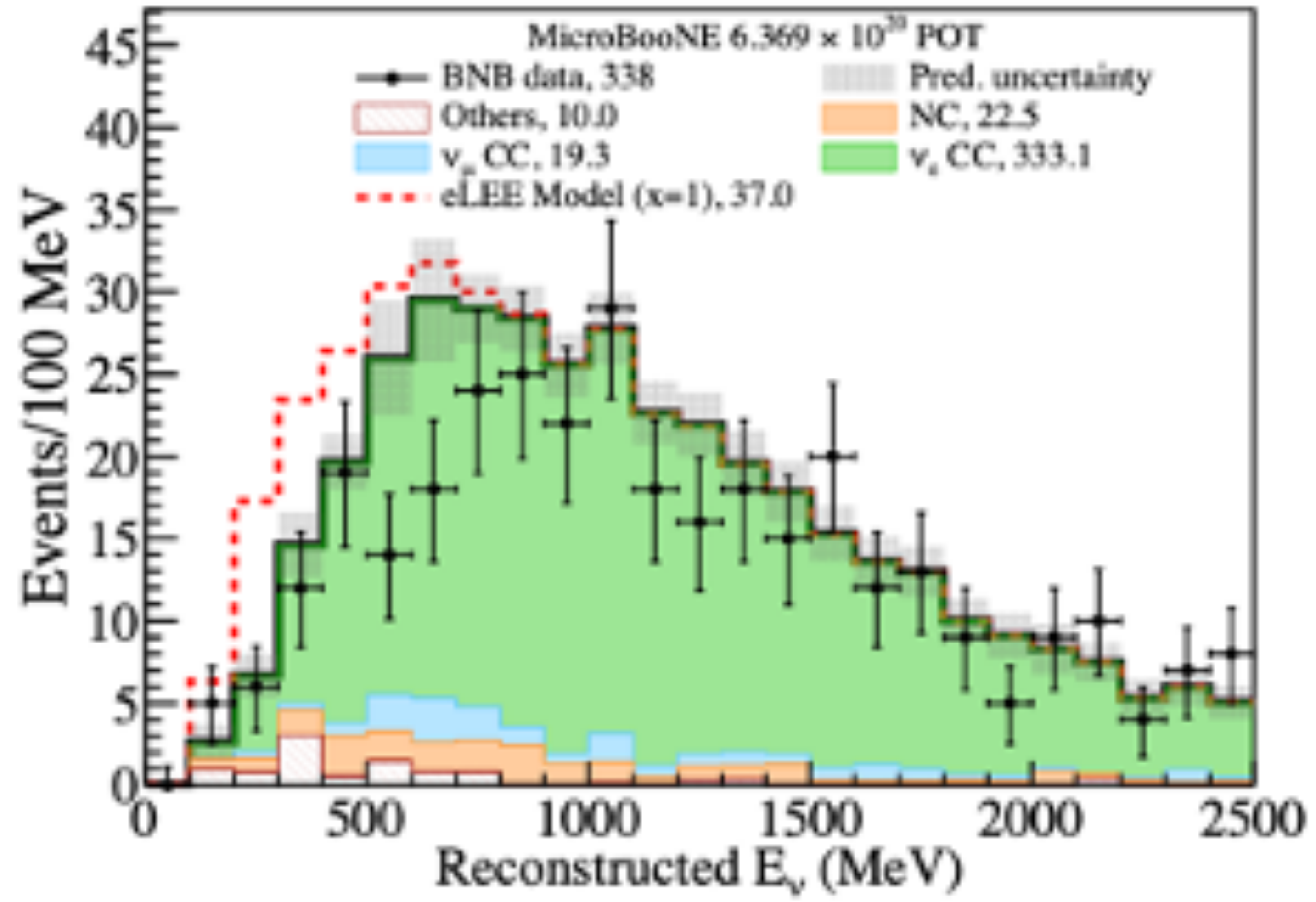
MicroBooNE LEE result

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

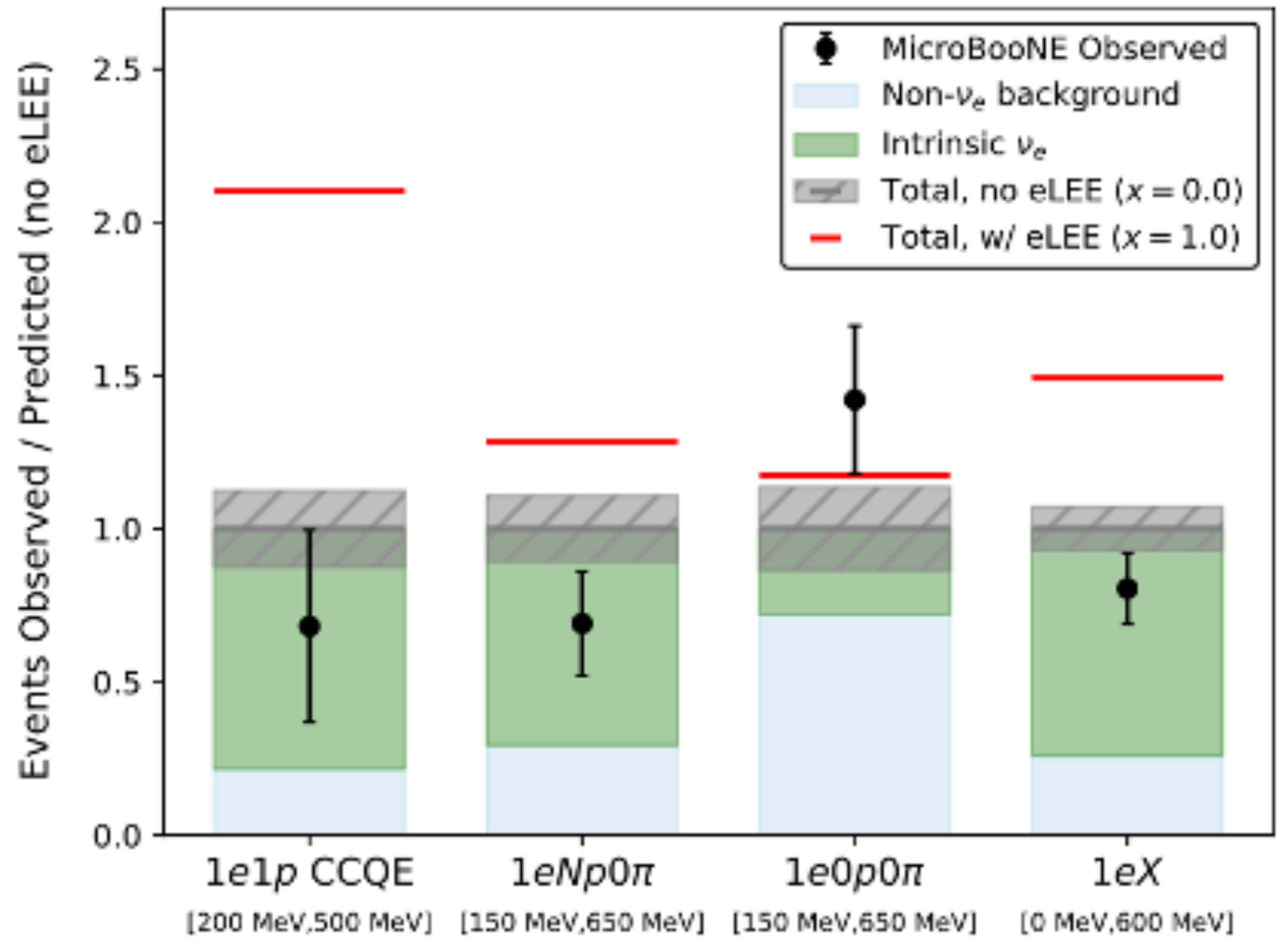
- electron analysis selects electron neutrino events

- 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)

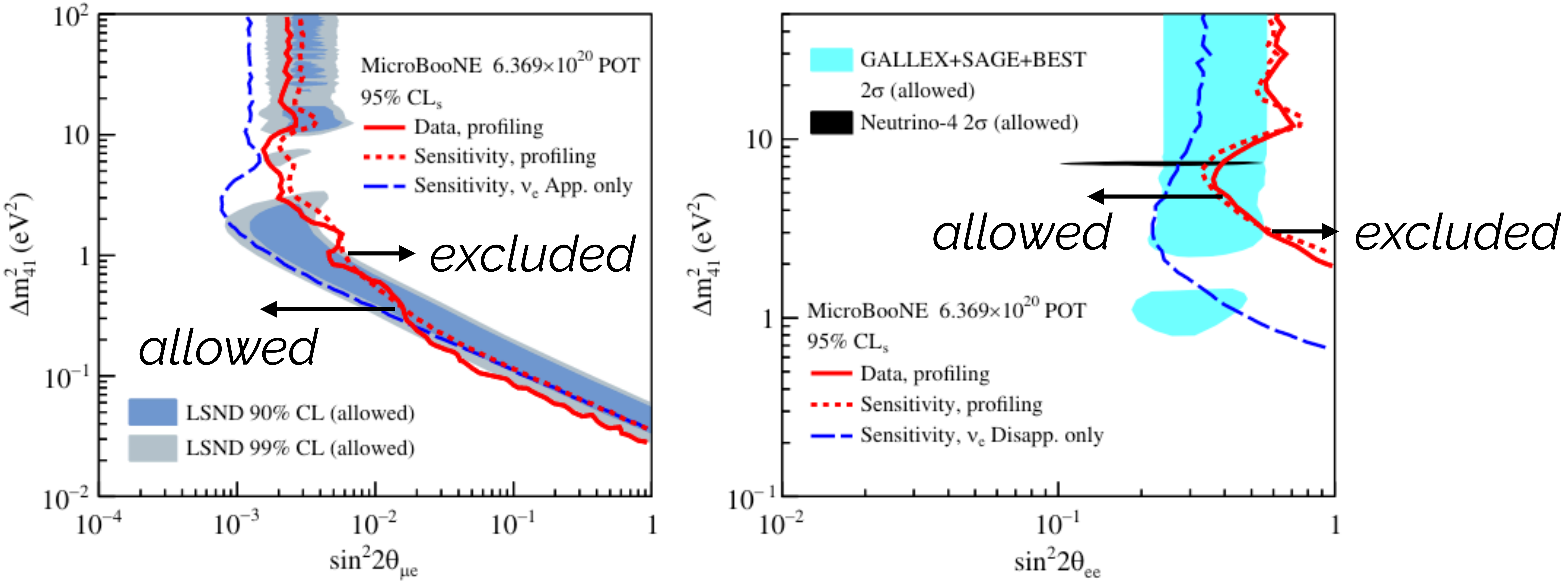


Phys. Rev. Lett. 128, 241801 (2022)



MicroBooNE sterile neutrino search

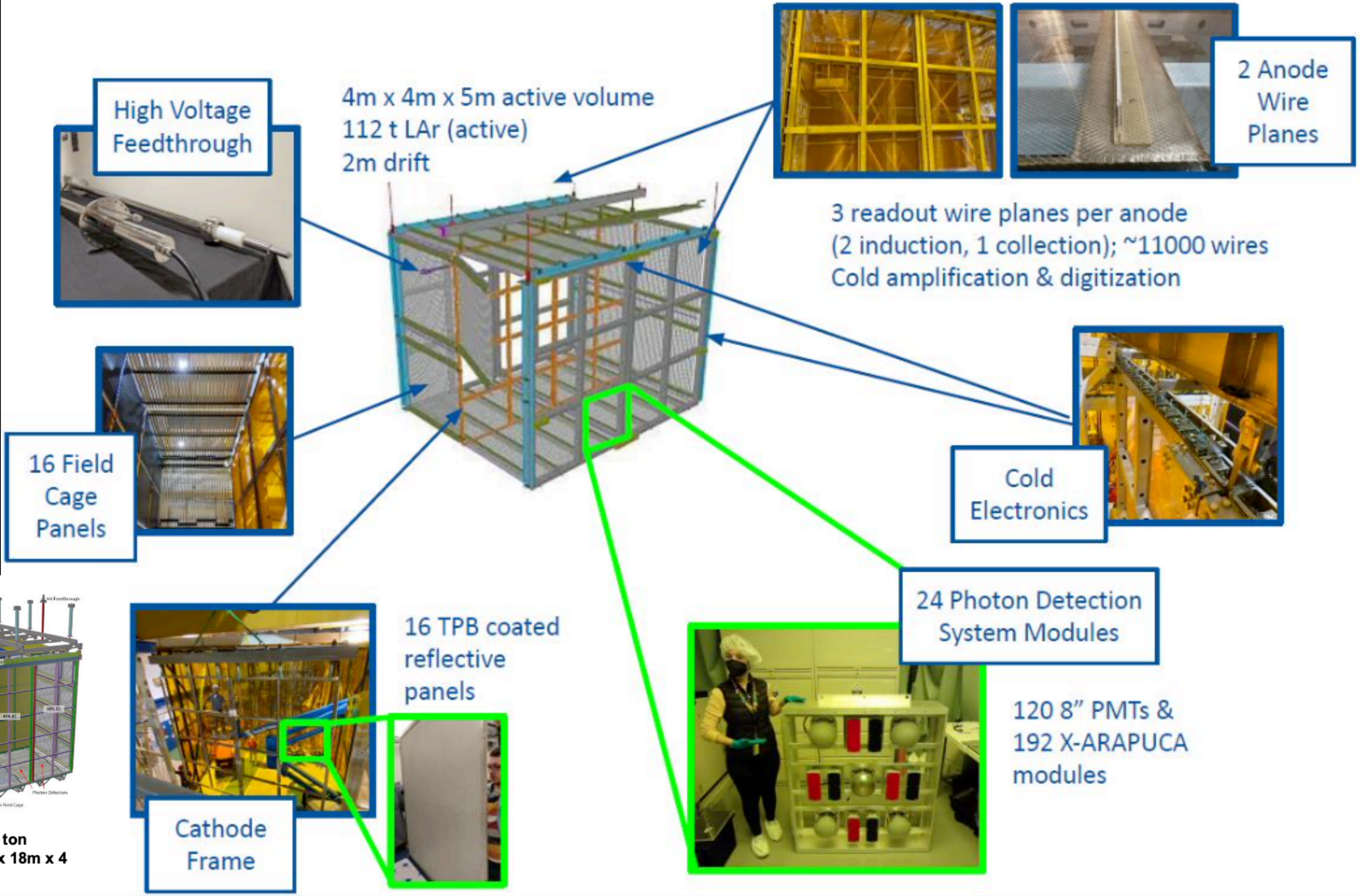
Phy. Rev. Lett. 130 011801 (2023)

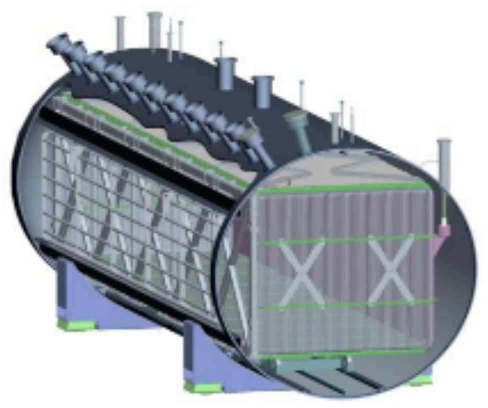


- LEE results are re-interpreted under a sterile neutrino oscillation hypothesis
- MicroBooNE could reject some portion of LSND and GALLEX/SAGE/BEST allowed region
- updated result is aiming to exclude most of the allowed region

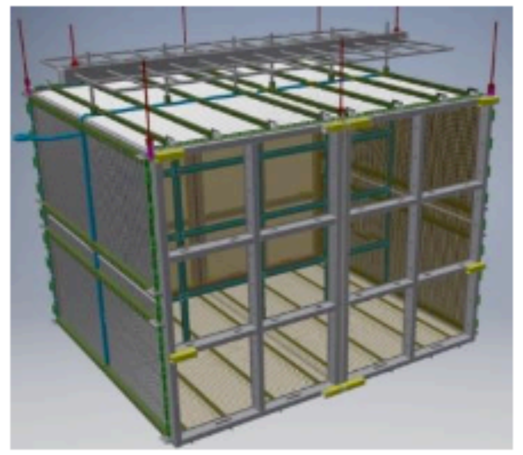
Short Baseline Neutrino Detector: SBND

- same LArTPC technology with various upgrades
- closer to the target: much more neutrinos detected
- started taking data 2024

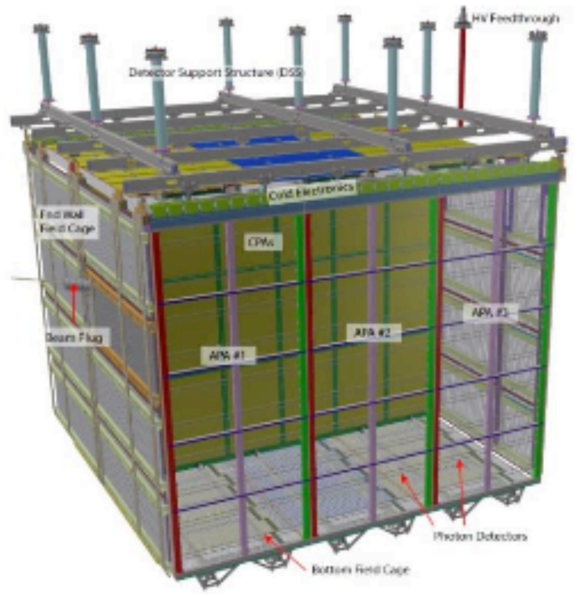




MicroBooNE, 87 ton
2.3m x 2.5m x 10.4m

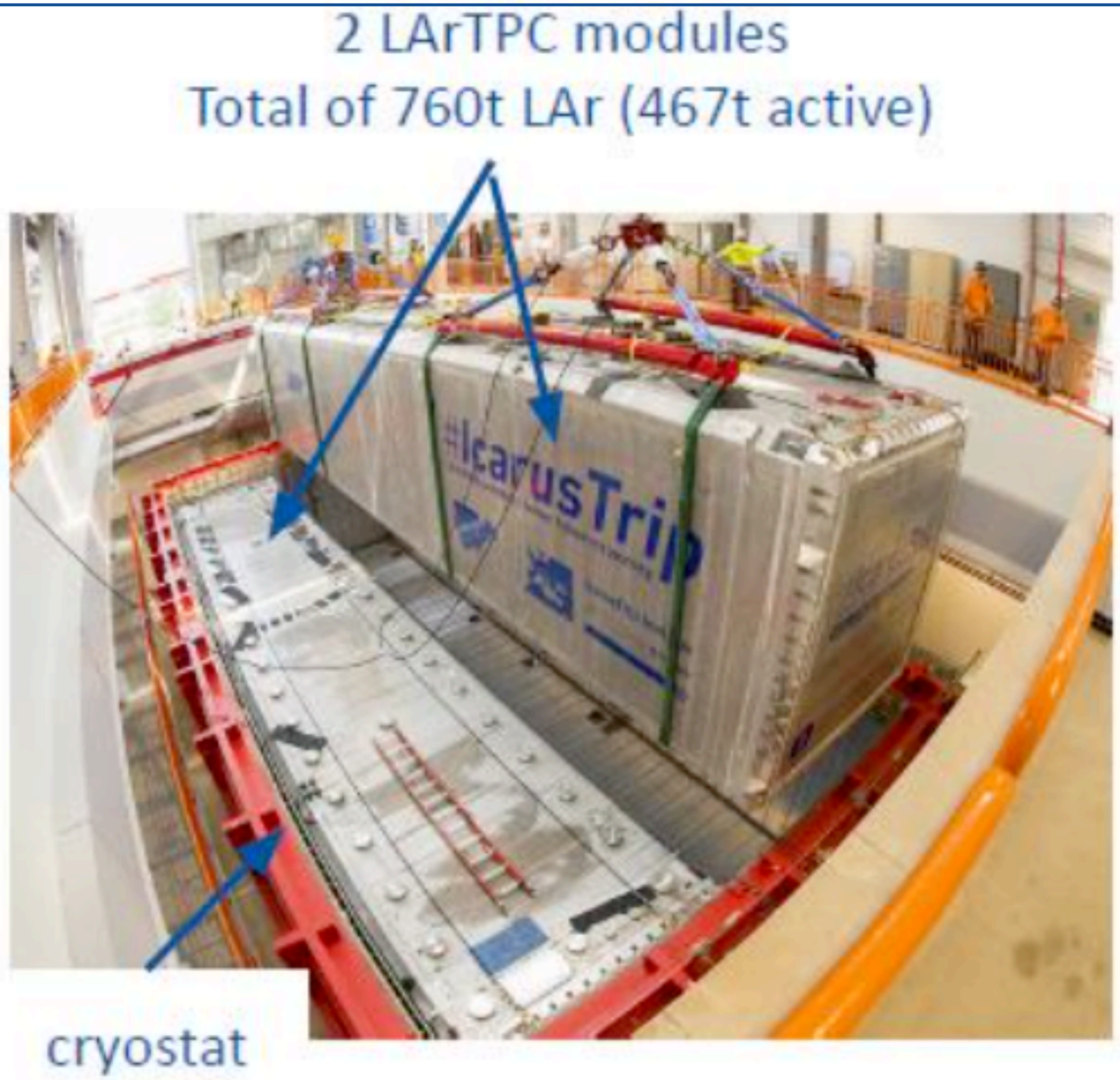


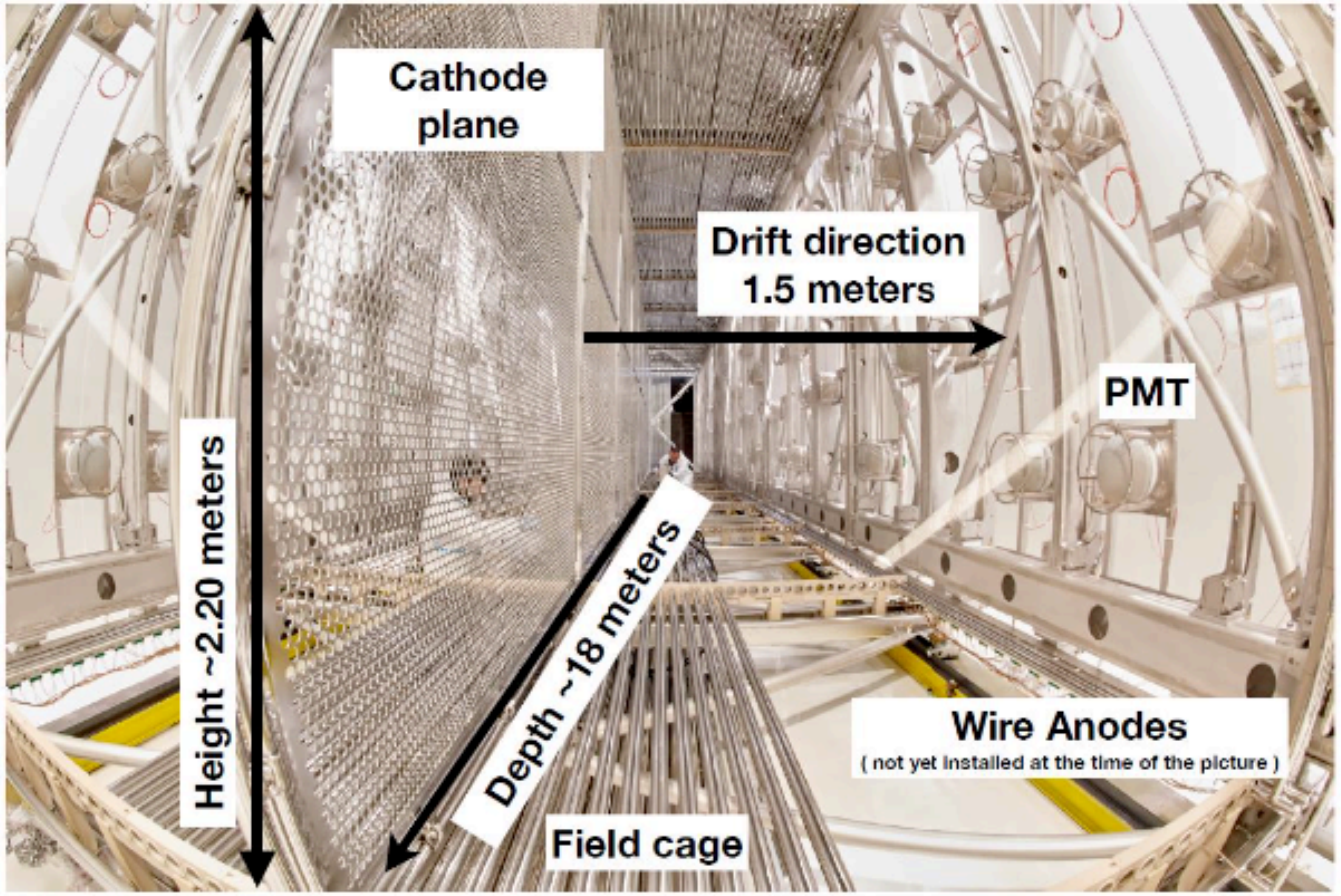
SBND, 112 ton
4m x 4m x 5m



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

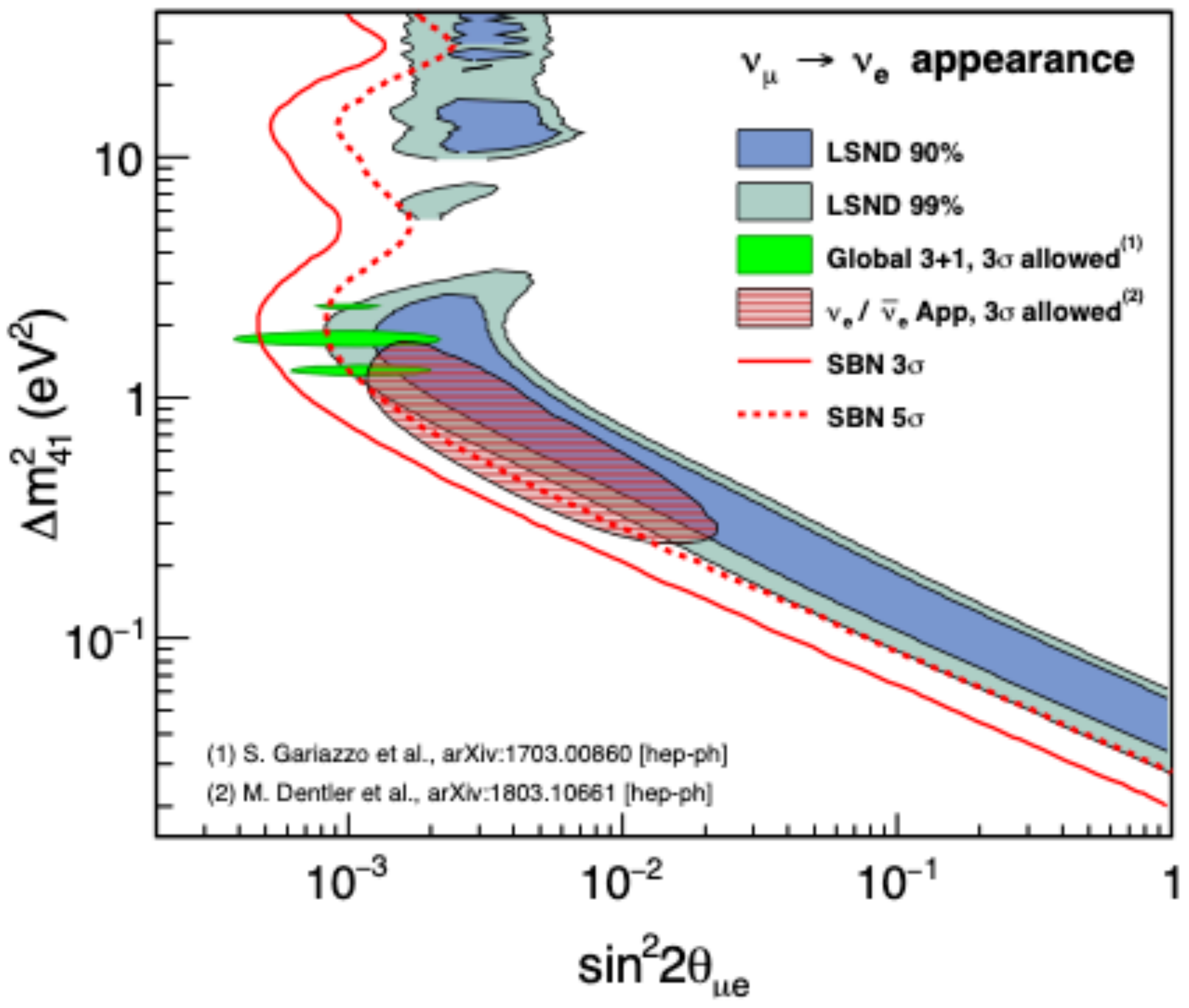
ICARUS

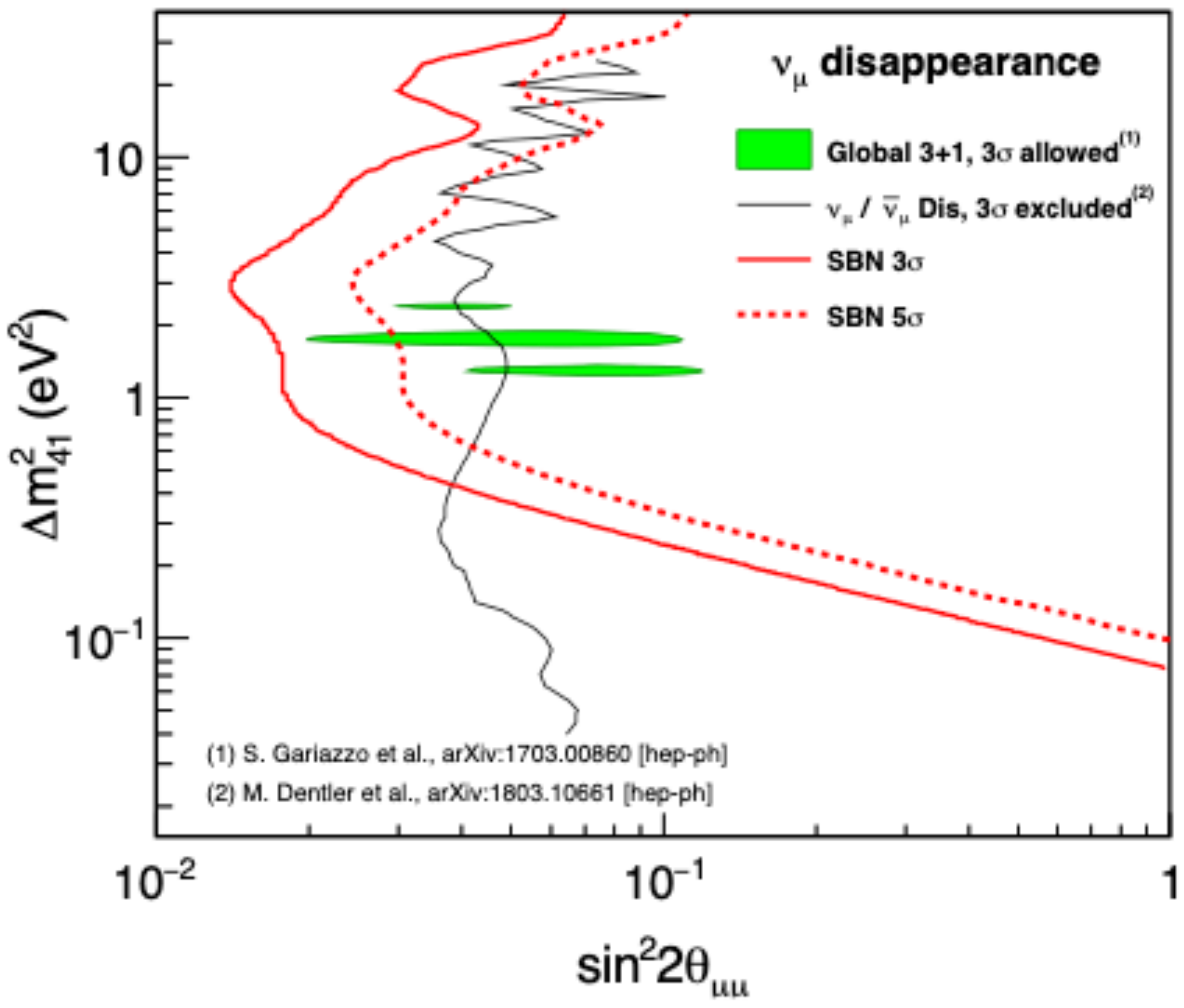




- shipped from Europe (LSNG), refurbished & upgraded
- farther away from the target, but much larger volume
- started taking neutrino data since 2021

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

- Let's assume there's only two flavors of neutrinos, ν_α and ν_β. Can you derive probability of ν_α oscillate to ν_β?
  - *hint*: flavor-mass eigenstate relation is now: $\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$
  - **step1**: how does mass eigenstates ν_1/ν_2 propagates over time *t* with E_1 and E_2?
  - **step2**: what would be an initial state of ν_α/ν_β at time *t*?
  - **step3**: with mixing matrix above, what would be the evolved state of ν_α in terms of flavor eigenstates?
  - **step4**: what would be the probability of detecting ν_β at time *t*?
  - **step5**: simplify the expression
  - *answer*: $P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

Homework (advanced)

- Can you calculated ν_e rate, that takes into account both $\nu_u \rightarrow \nu_e$ appearance and $\nu_e \rightarrow \nu_e$ disappearance, in 3+1 scenario?

  - predominant ν_u beam, with small fraction of ν_e within: let's assume number of "initial" ν_u is $T\nu_u$, "initial" ν_e is $T\nu_e$

  - *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"

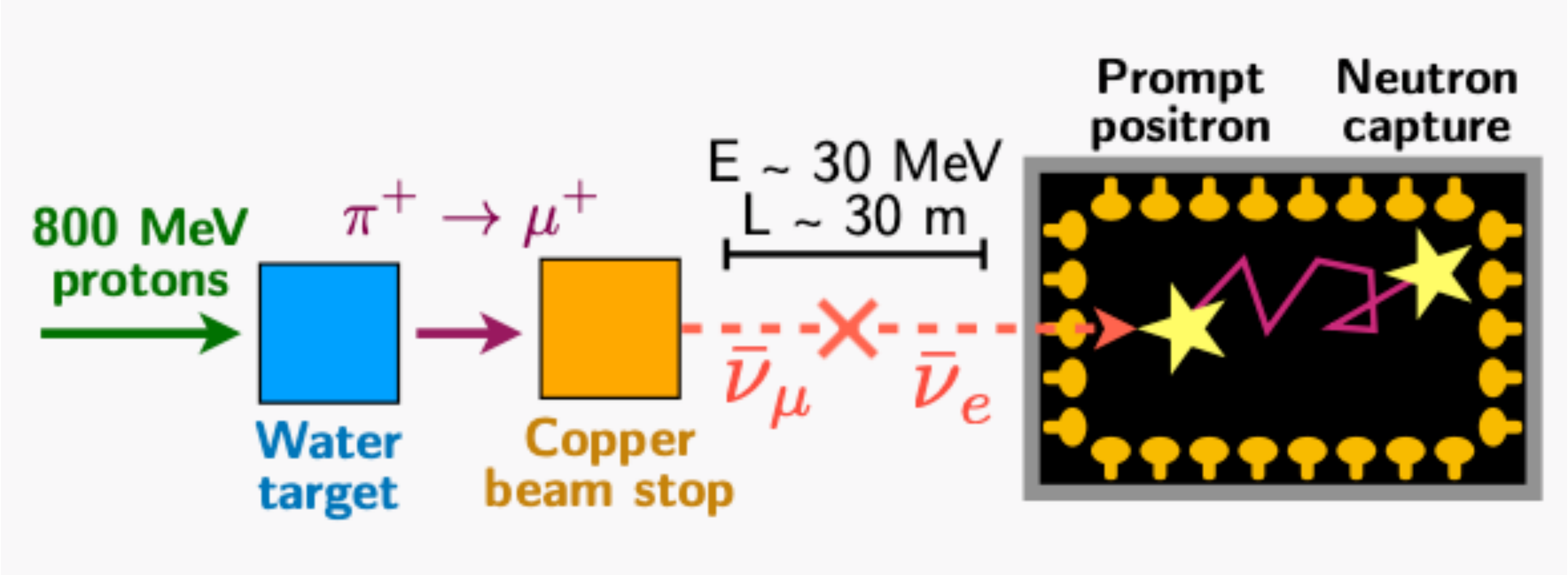
$$\sin^2 2\theta_{ee} = 4(1 - |U_{e4}|^2)|U_{e4}|^2,$$
$$\sin^2 2\theta_{\mu\mu} = 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2,$$
$$\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2.$$

  - **step1**: calculate oscillation probability for $\nu_u \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_e$ each

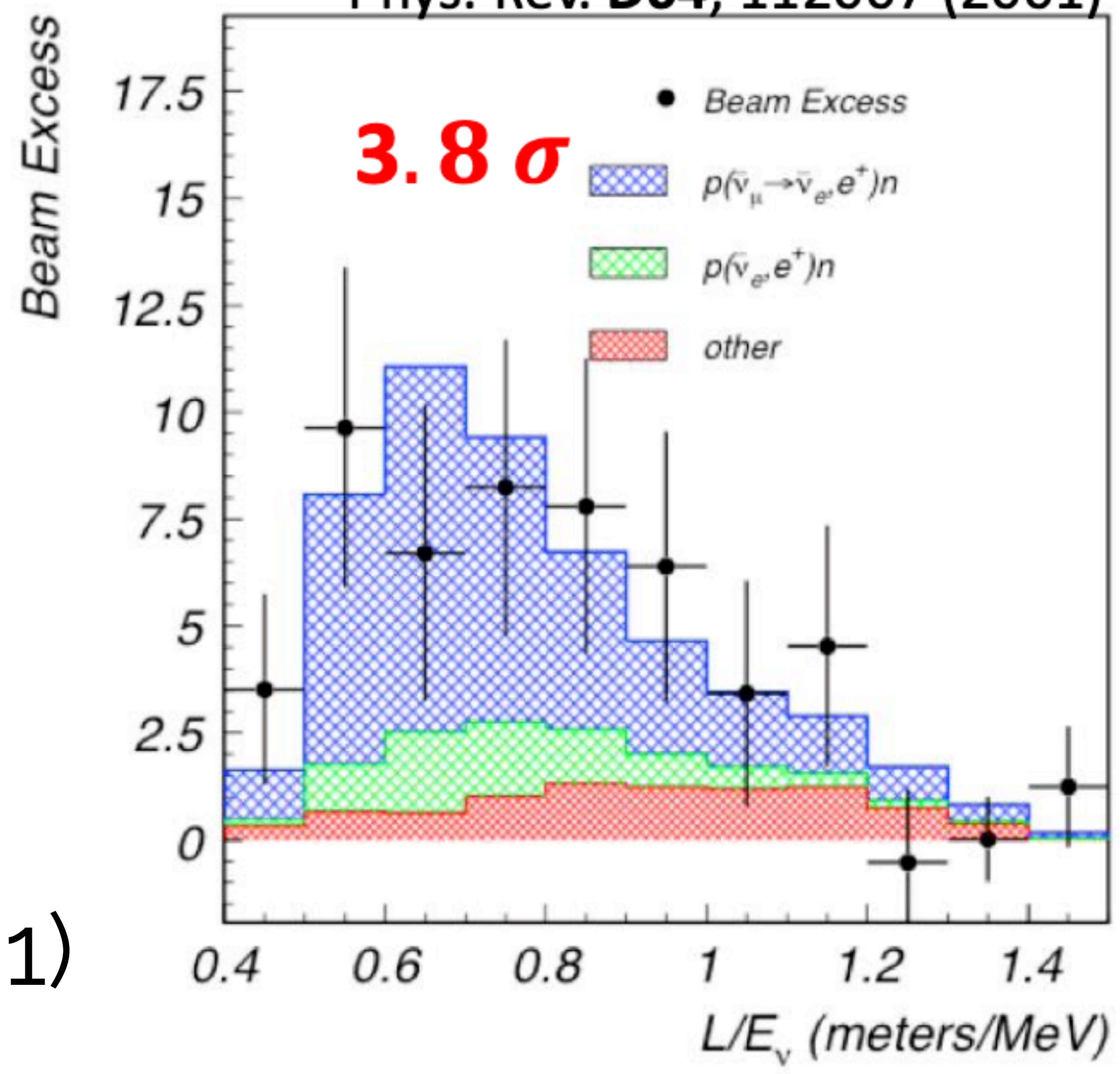
  - **step2**: now you multiply this probability to "original" ν_u and ν_e to get "oscillated" ν_e

  - **step3**: combine both numbers together

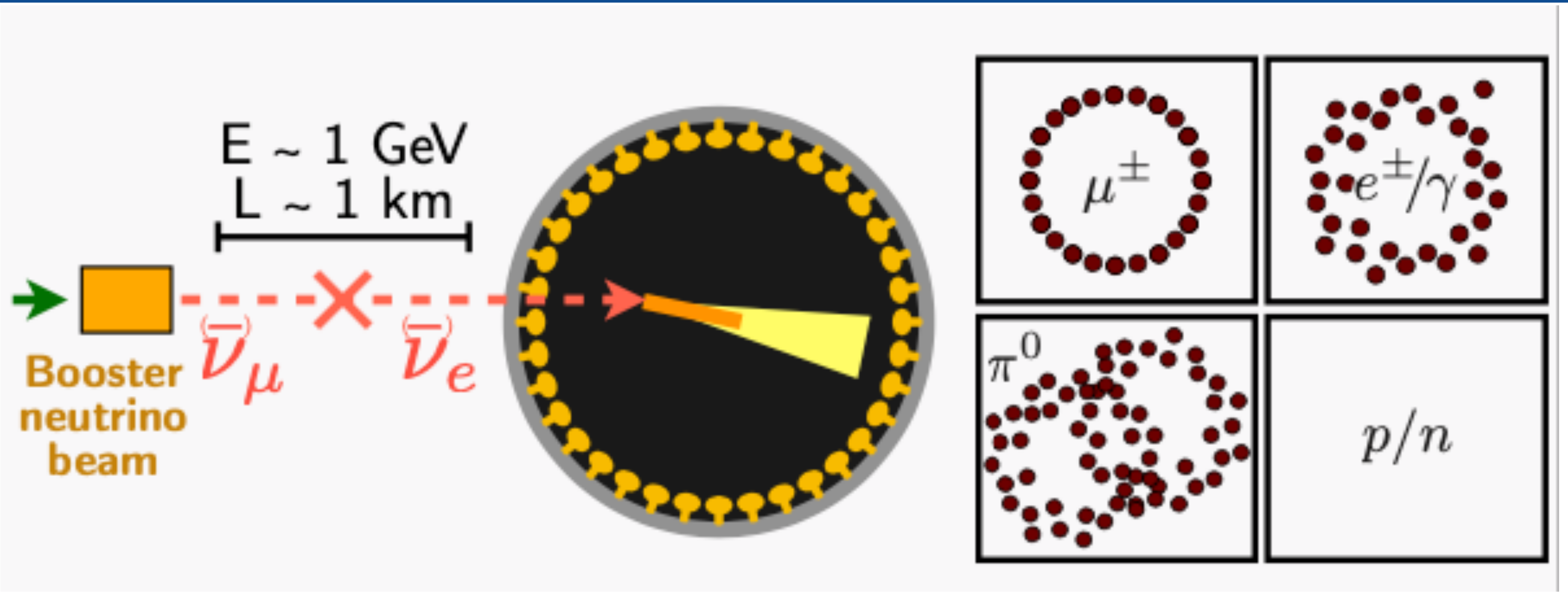
LSND & MiniBooNE anomaly



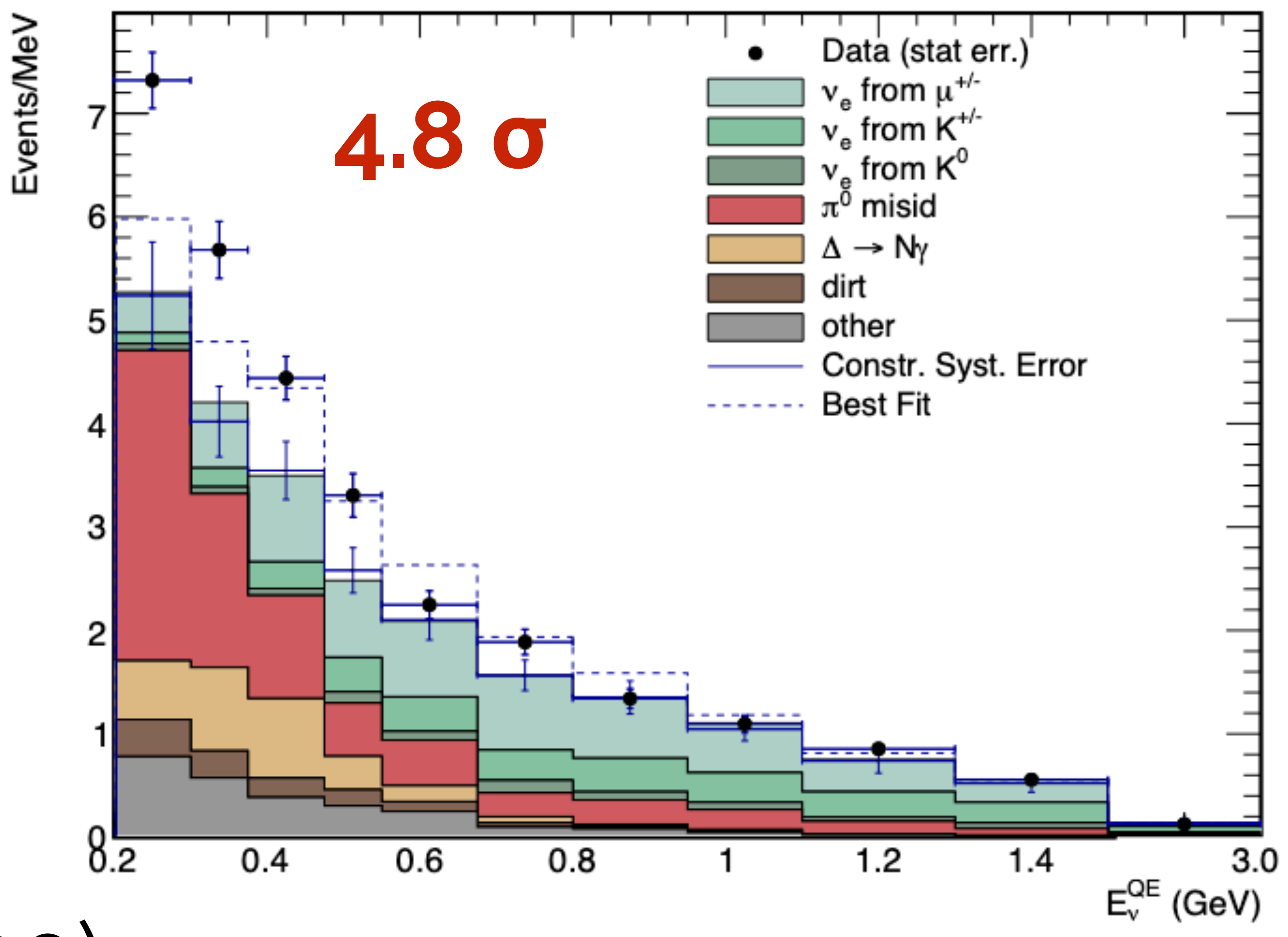
Phys. Rev. **D64**, 112007 (2001)



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



arxiv:2006.16883



- **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

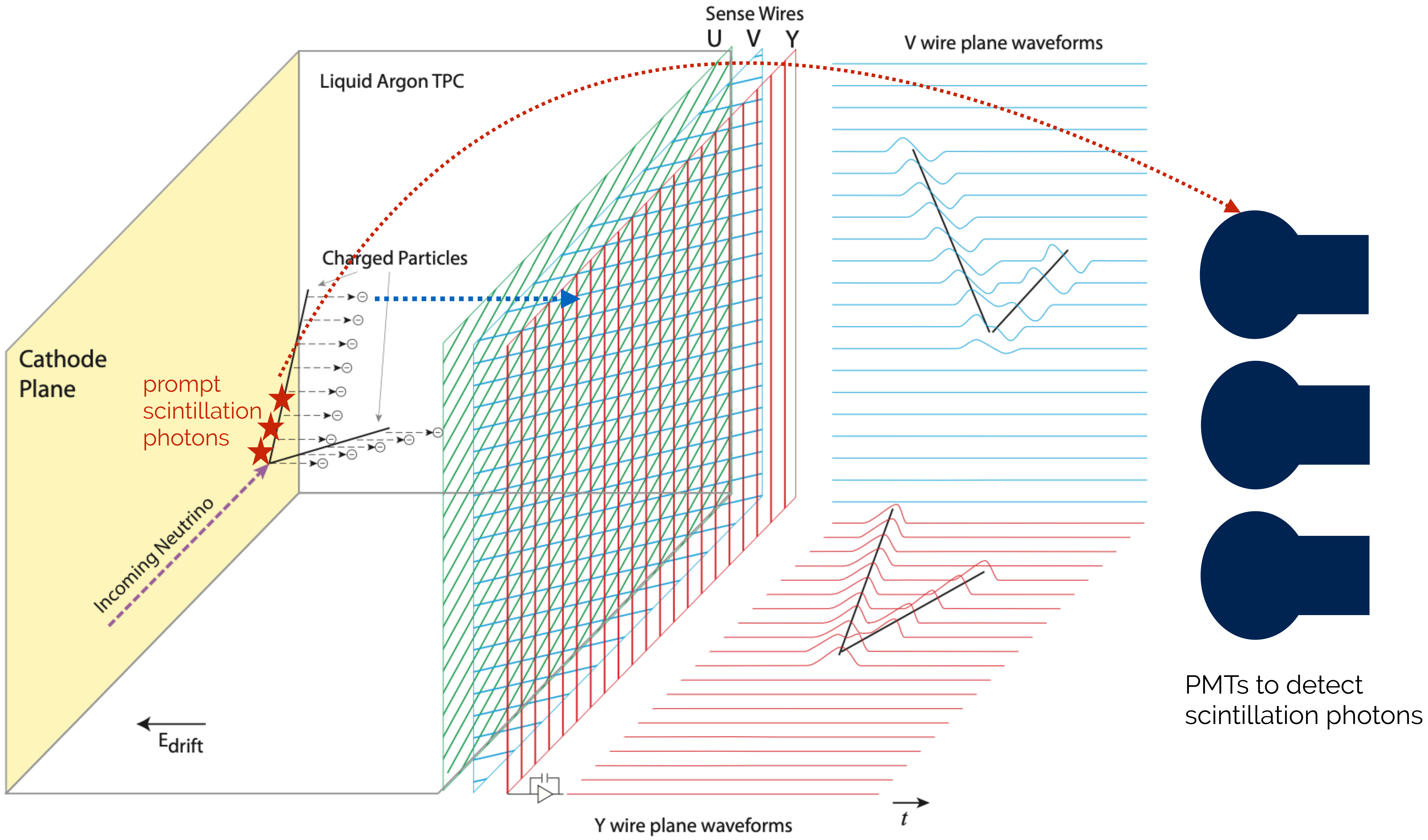
charged particle enters detector

⬇

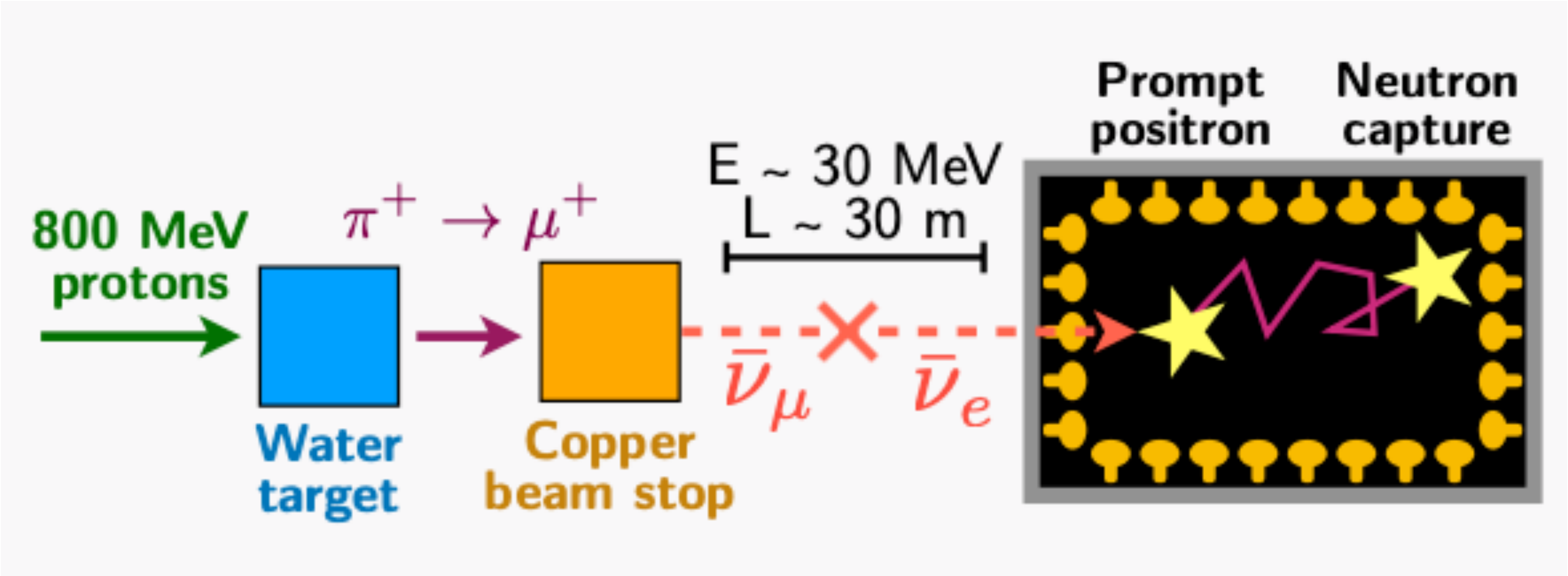
scintillation light emitted by excited Ar, detected by PMTs

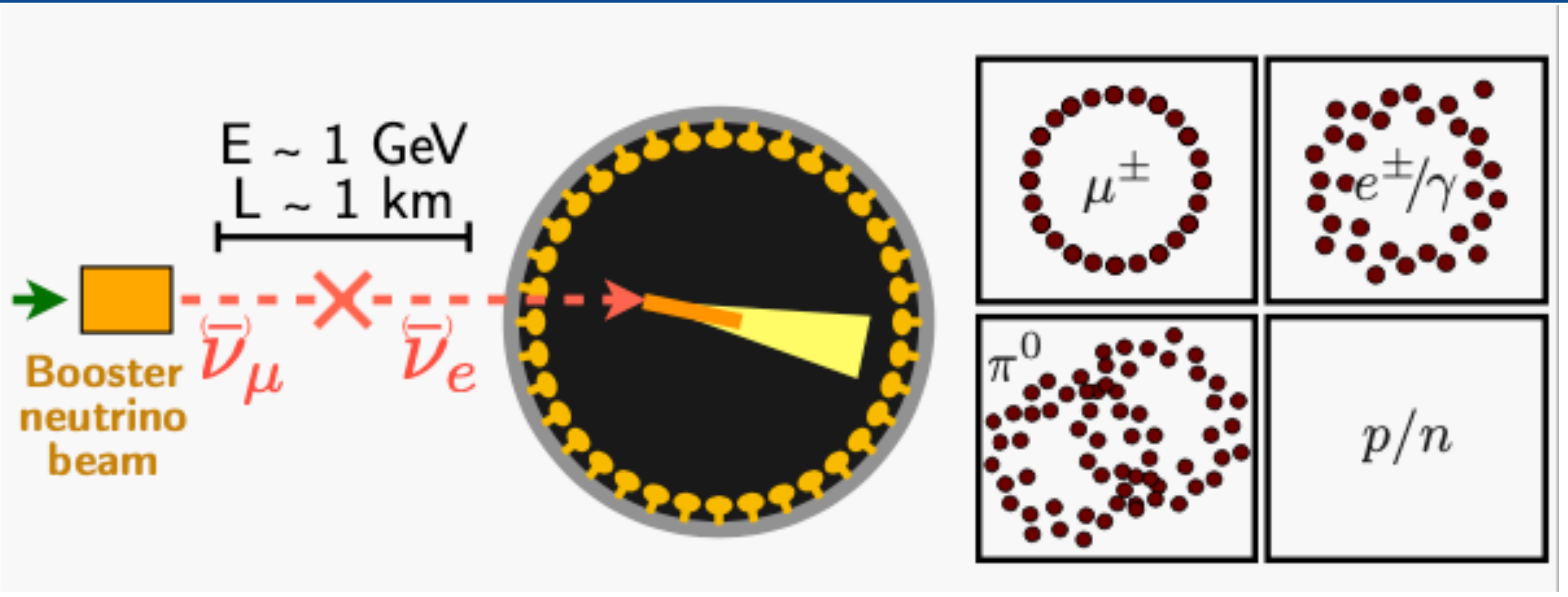
⬇

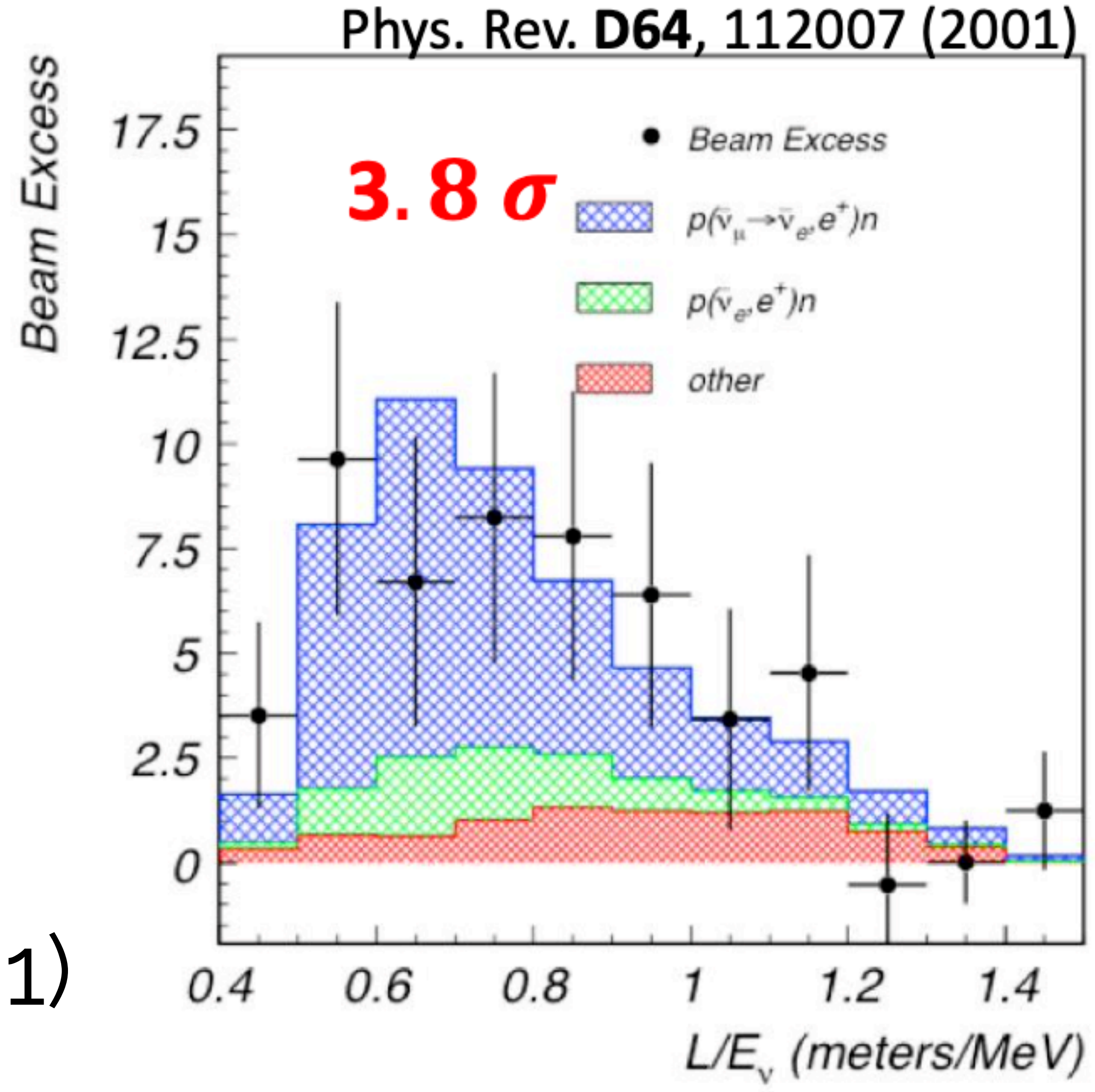
ionization electrons drift to anode plane, detected by sense wires



LSND & MiniBooNE anomaly







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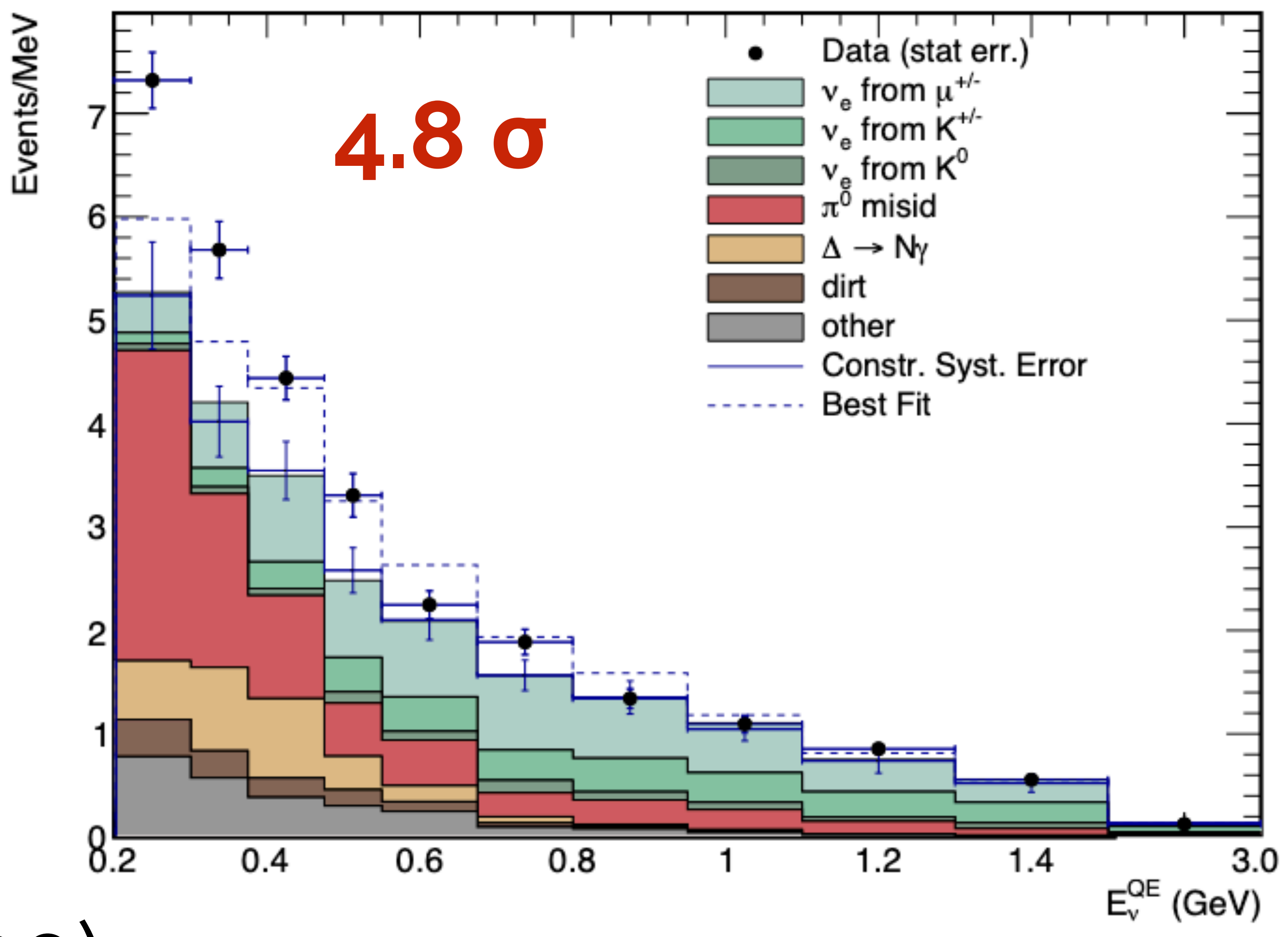

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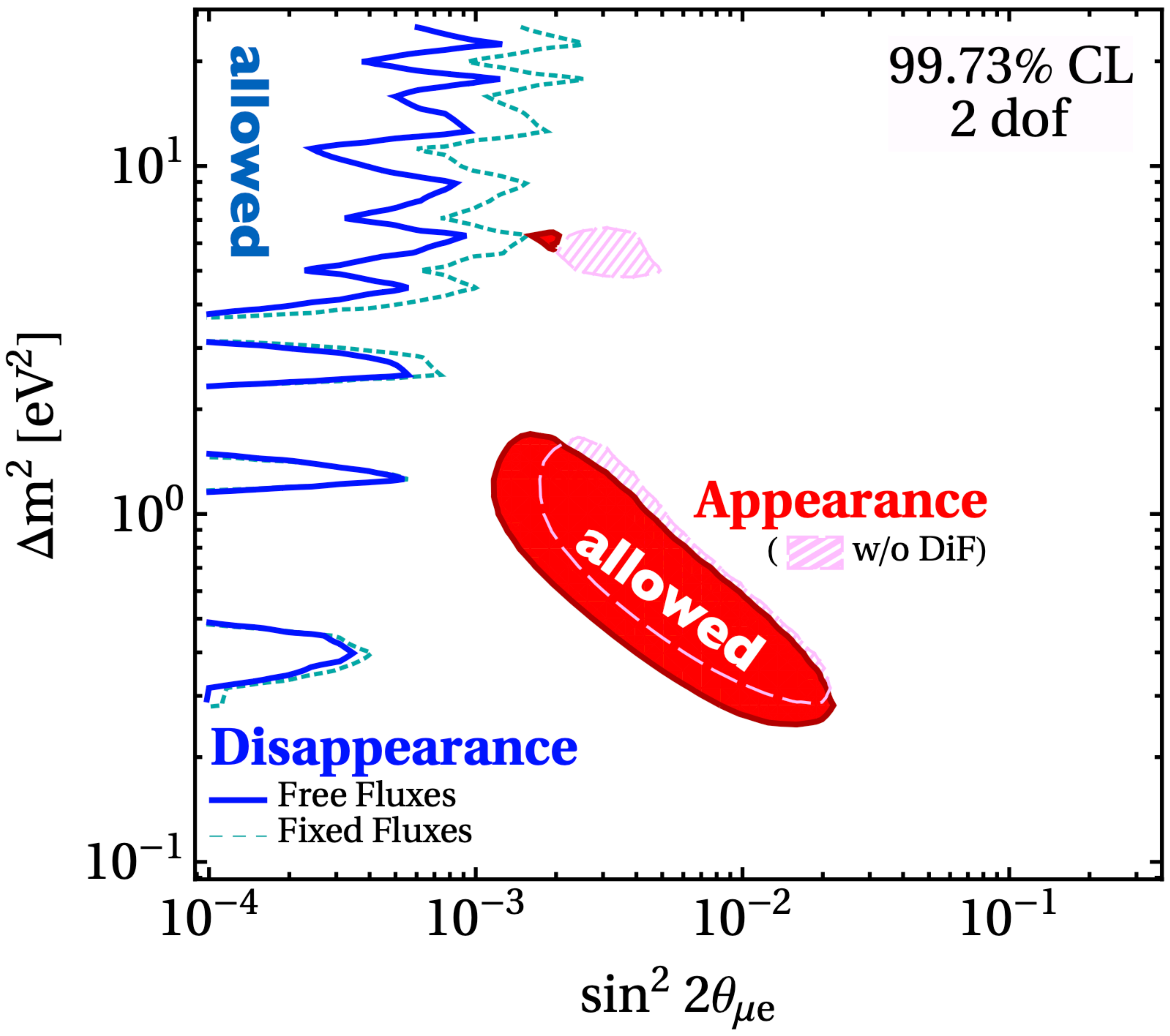
tension in global picture



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

- *unfortunately, vanilla sterile neutrino cannot be an answer to everything…*
- 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

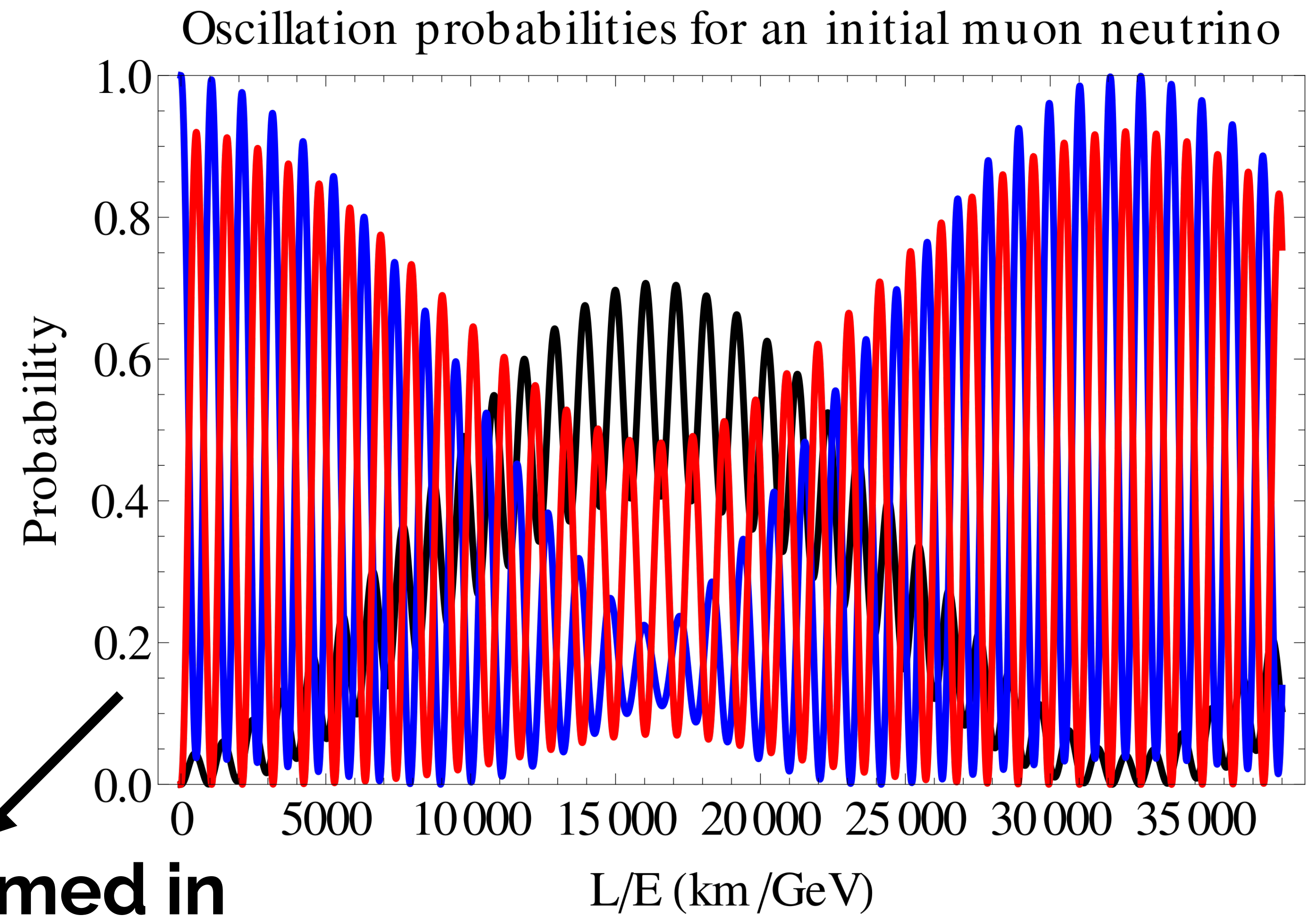
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} &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

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

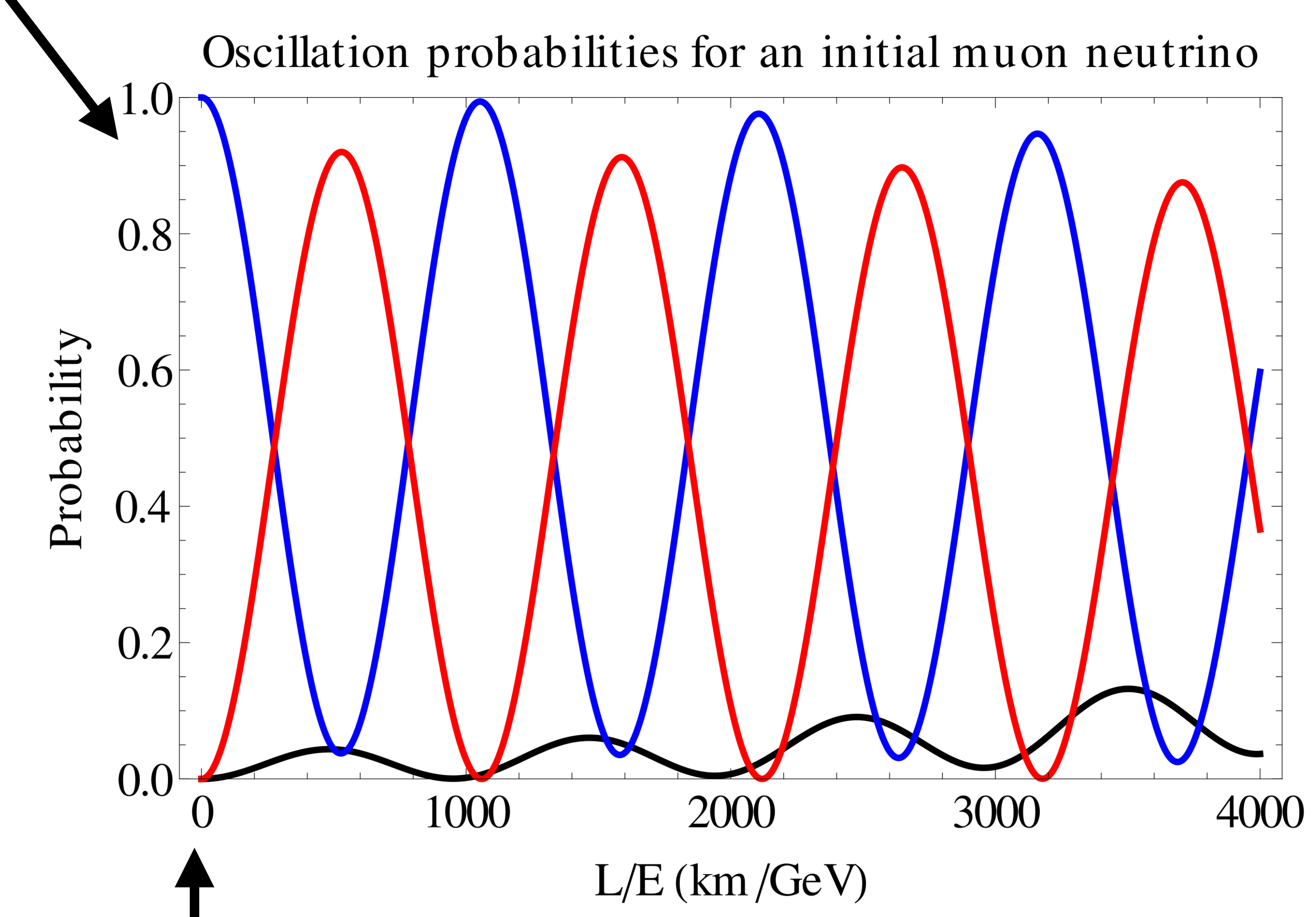
$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

- 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



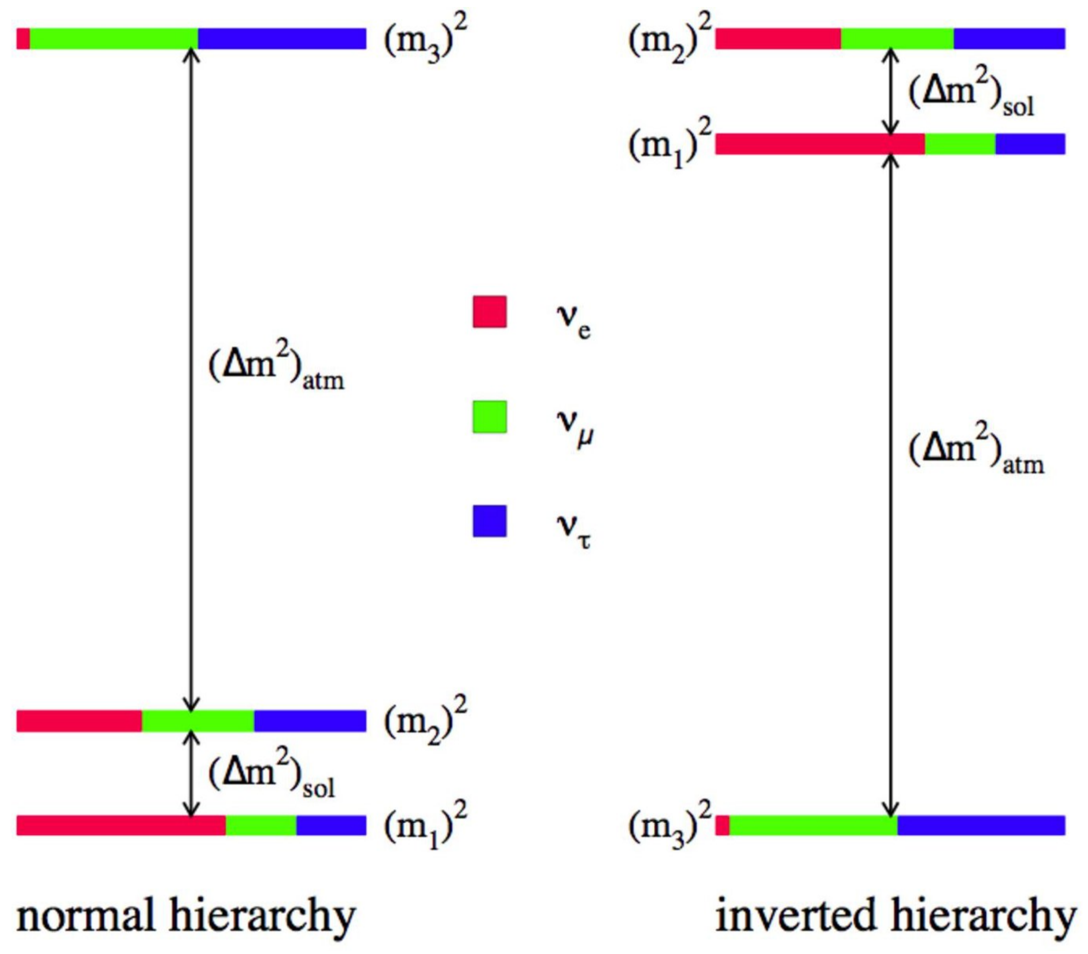
ν_μ

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