Sterile Neutrino and Short Baseline Neutrino (SBN) Program

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NuSteam/NuPumas @ BNL 2023

Brookhaven National Laboratory

Outline

- recap: standard model, neutrino, and neutrino oscillation
- sterile neutrino: what is it, why is it, and how do we detect it
- Short Baseline Neutrino (SBN) Program @ Fermilab

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- **recap: standard model, neutrino, and neutrino oscillation**
- sterile neutrino: what is it, why is it, and how do we detect it
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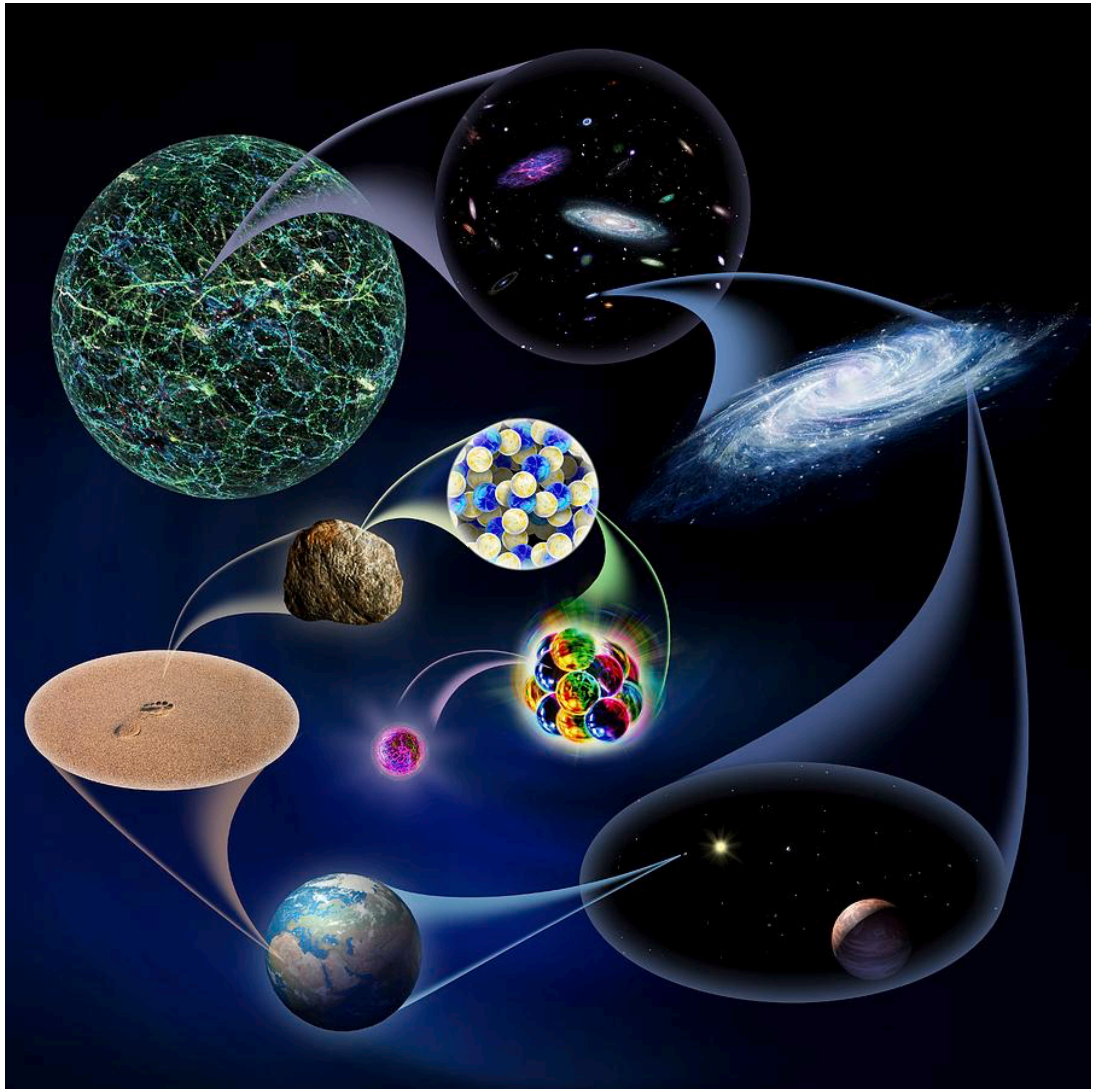
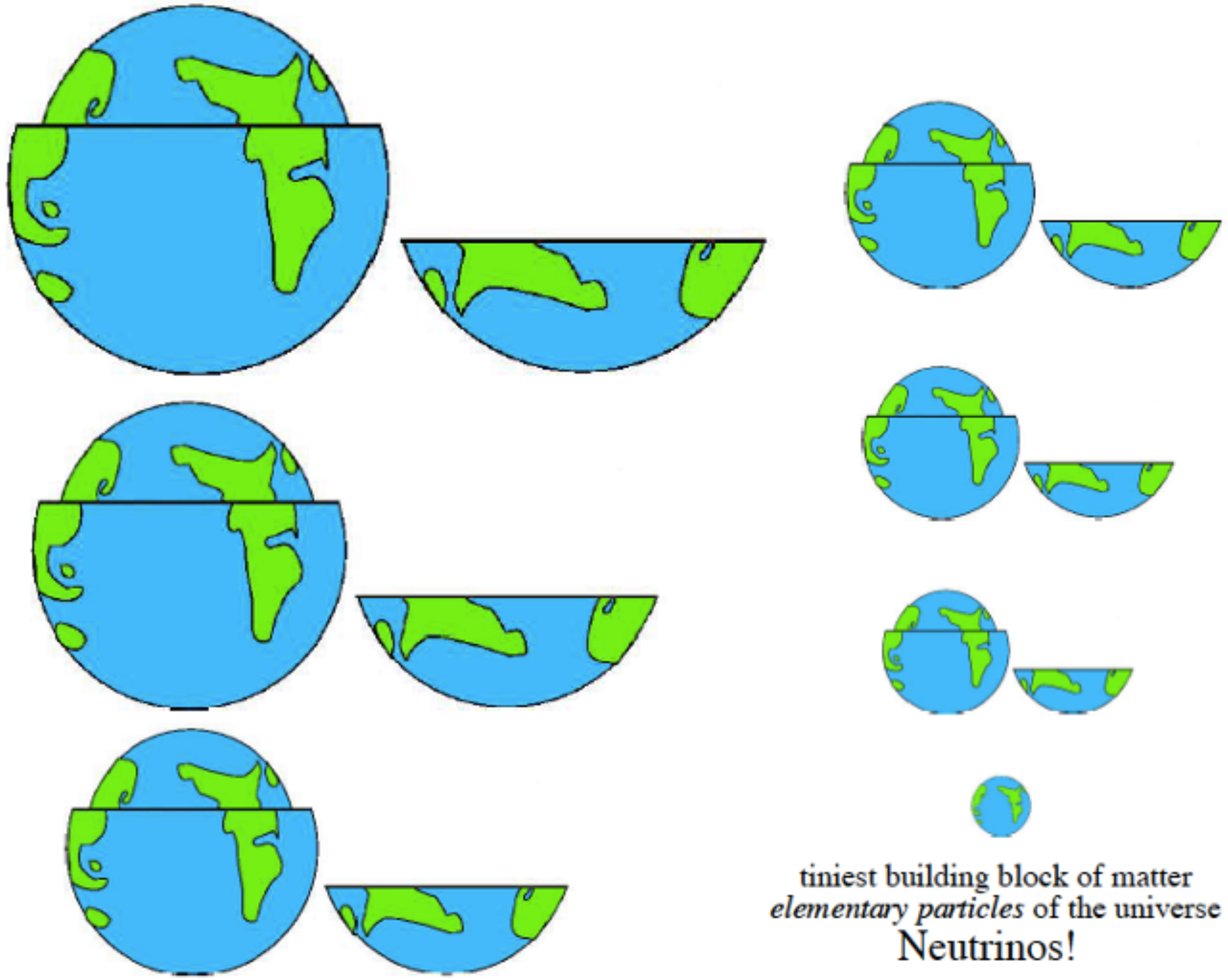
Particle physicist trying to understand ordinary matter…





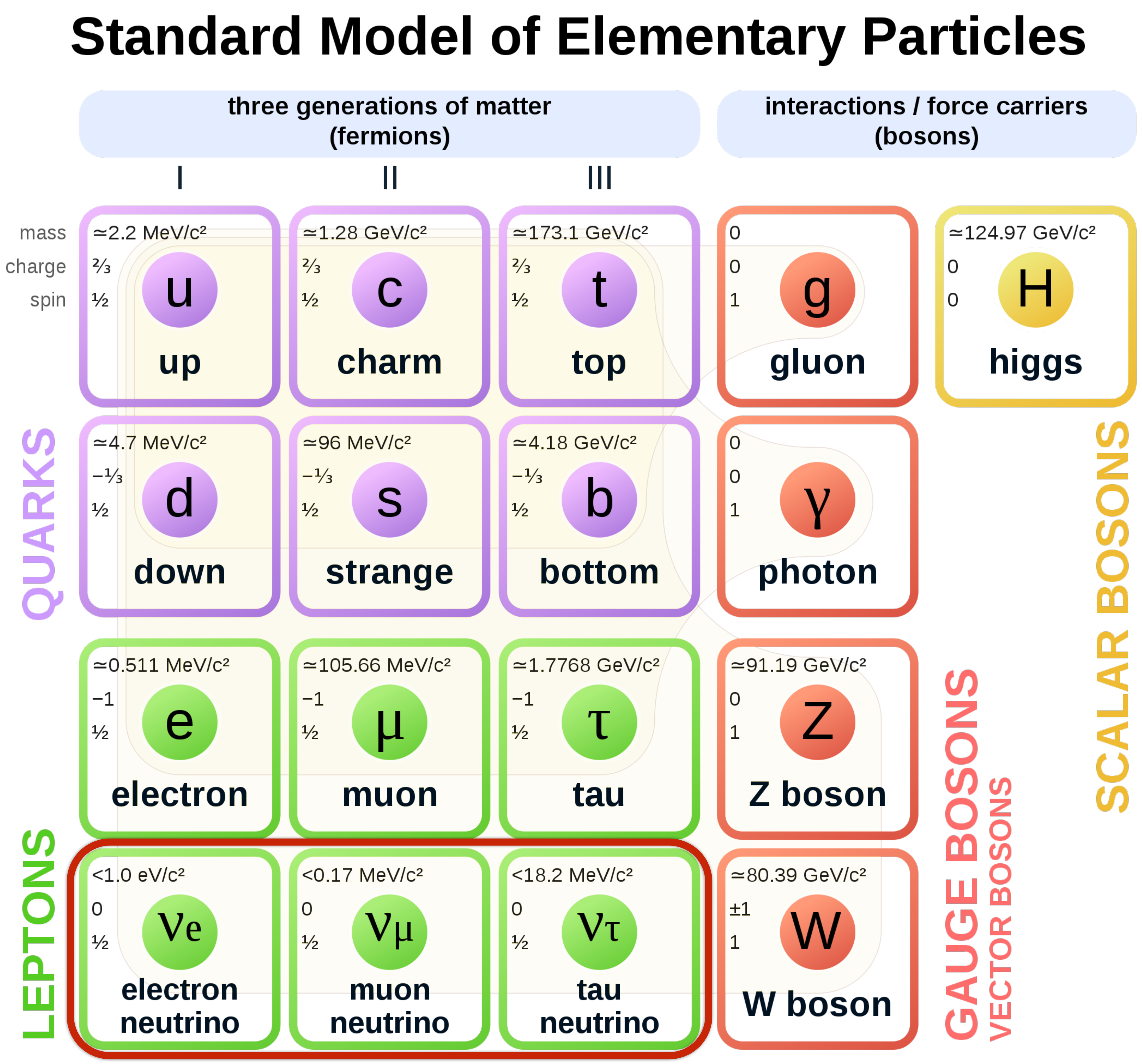
tiniest building block of matter:

elementary particles of the universe

standard model of particle physics

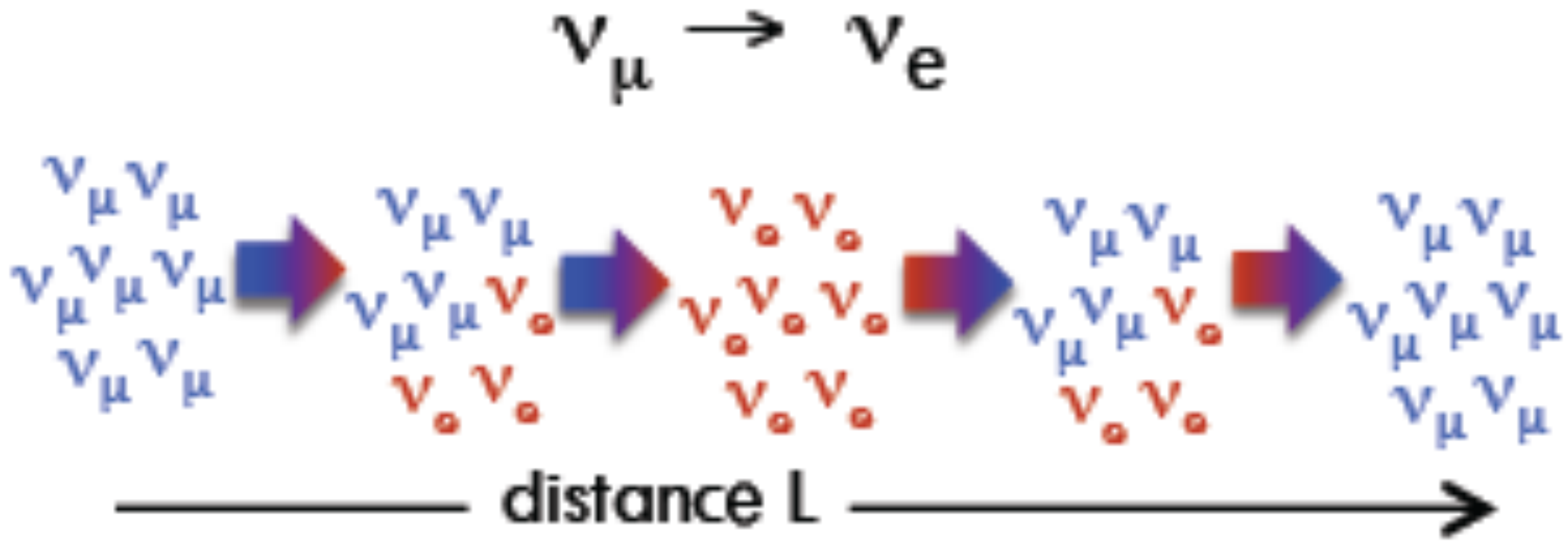
- ordinary matter is well described by **12 building blocks of matter** and the force carriers through which they interact

- **neutrinos** make up three of the 12 building blocks, with special characteristics of:
  - neutral charge
  - tiny mass
  - weakly interacting only



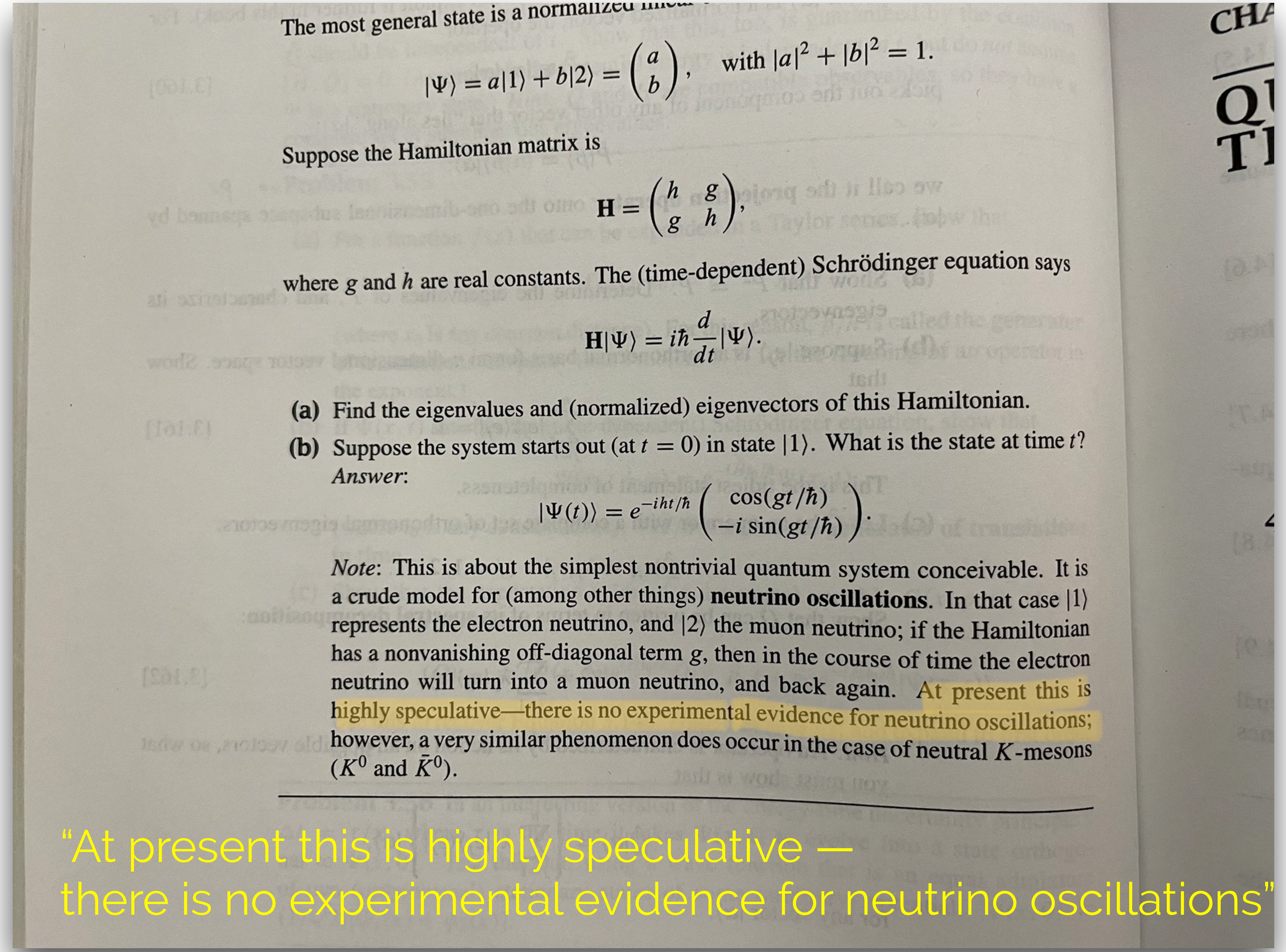
Crack in the Standard Model: Massive neutrinos

- the Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald “for the discovery of neutrino oscillations, which showed that **neutrinos have mass**”



- neutrino morph into another kind & back again: quantum mechanical effect
  - **if neutrinos oscillate, they must have mass**
  - depend on neutrino flavor and neutrino energy

Crack in the Standard Model: Massive neutrinos


The most general state is a normalized linear ...

$$|\Psi\rangle = a|1\rangle + b|2\rangle = \begin{pmatrix} a \\ b \end{pmatrix}, \quad \text{with } |a|^2 + |b|^2 = 1.$$

Suppose the Hamiltonian matrix is

$$\mathbf{H} = \begin{pmatrix} h & g \\ g & h \end{pmatrix},$$

where g and h are real constants. The (time-dependent) Schrödinger equation says

$$\mathbf{H}|\Psi\rangle = i\hbar \frac{d}{dt}|\Psi\rangle.$$

(a) Find the eigenvalues and (normalized) eigenvectors of this Hamiltonian.

(b) Suppose the system starts out (at $t = 0$) in state $|1\rangle$. What is the state at time t?

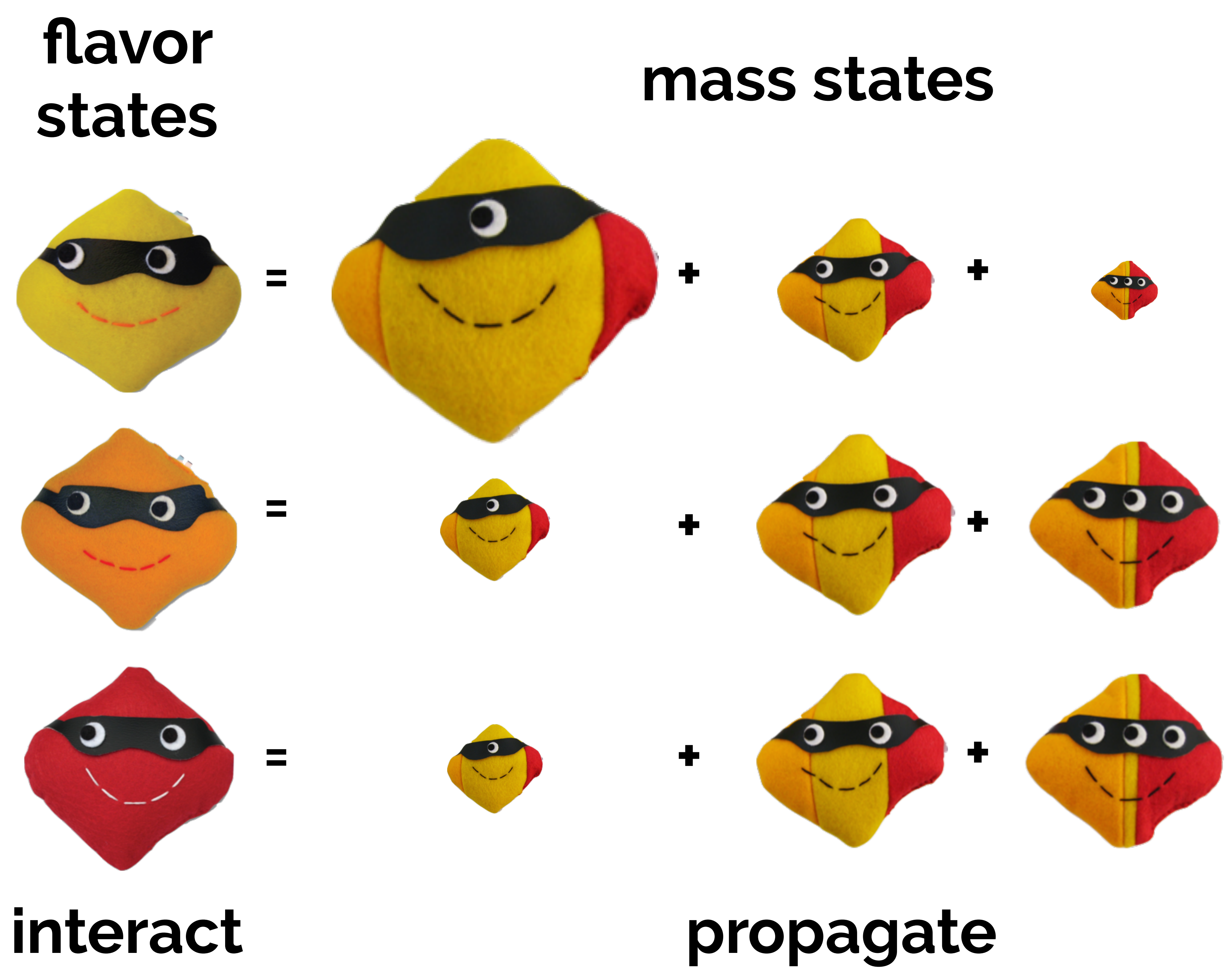
Answer:

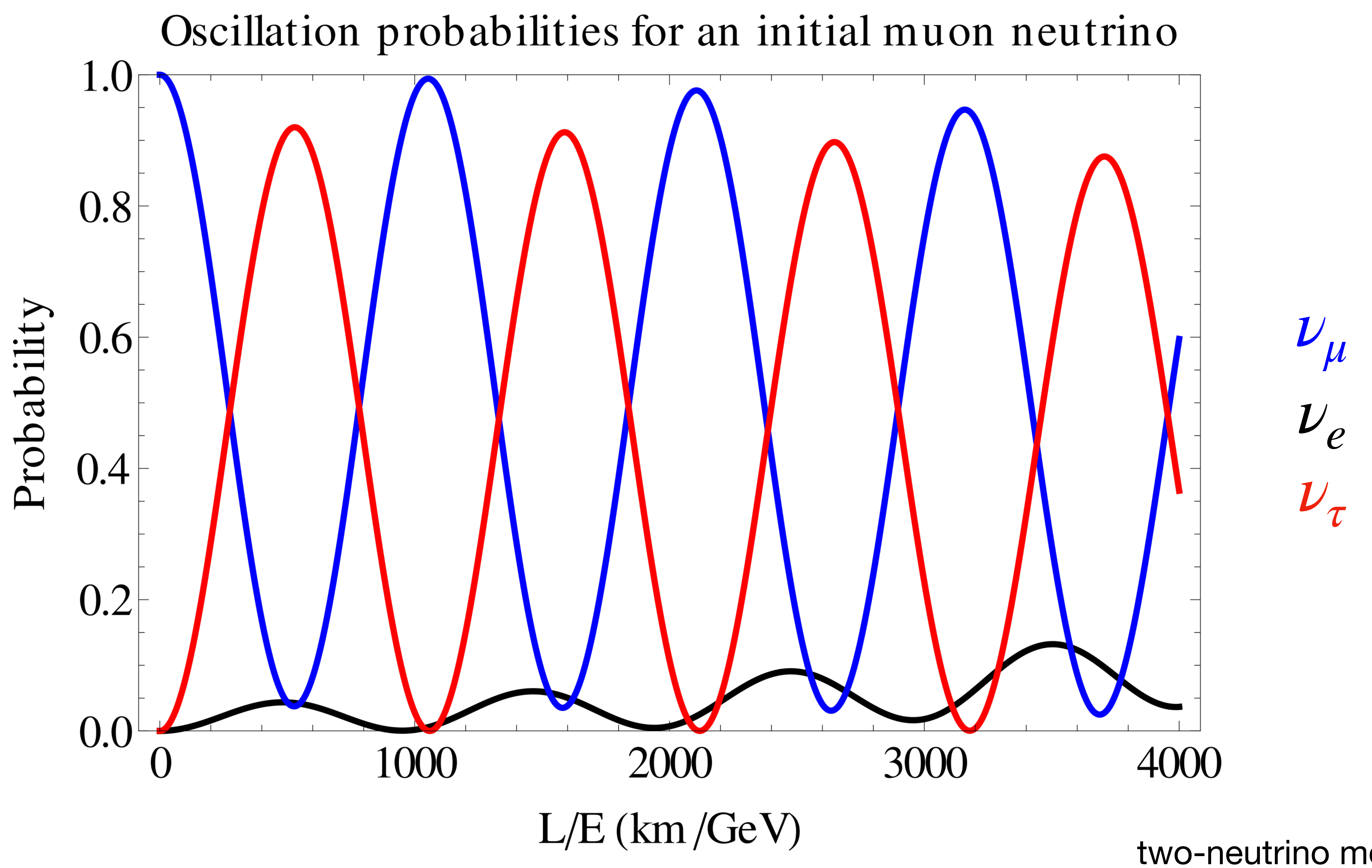
$$|\Psi(t)\rangle = e^{-iht/\hbar}\begin{pmatrix} \cos(gt/\hbar) \\ -i\sin(gt/\hbar) \end{pmatrix}.$$

Note: This is about the simplest nontrivial quantum system conceivable. It is a crude model for (among other things) **neutrino oscillations**. In that case $|1\rangle$ represents the electron neutrino, and $|2\rangle$ the muon neutrino; if the Hamiltonian has a nonvanishing off-diagonal term g, then in the course of time the electron neutrino will turn into a muon neutrino, and back again. At present this is highly speculative—there is no experimental evidence for neutrino oscillations; however, a very similar phenomenon does occur in the case of neutral K-mesons (K^0 and $\bar{K}^0$).

D. J. Griffith, *Introduction to Quantum Mechanics* (p.120, 1995)

Neutrino oscillation





two-neutrino model

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2\ [\mathrm{eV}]^2 \cdot L\ [\mathrm{km}]}{E_\nu\ [\mathrm{GeV}]}\right)$$

- neutrino *flavor* states are not the same as the *mass* states
- neutrinos generally are produced in a *flavor* state, which is a superposition of three *mass* states
- these *mass* states change phase over the time at different rates, leads to neutrino oscillation when viewed in the *flavor* basis
- this critical phenomenon is now very well known for 3-neutrino oscillation, described by PMNS matrix: and the physics parameters precisely measured with experiments in the last two decades

Recap: neutrino & neutrino oscillation

- neutrinos make up three of the 12 building blocks of the ordinary matter in the Universe
- we have found out that neutrinos oscillate; they change their states as they propagate over time
  - this quantum mechanical behavior can only happen if neutrinos have mass
  - this was not predicted in the “standard model”, cracking the otherwise almost-perfect model that describes the ordinary matter
- three-neutrino oscillation is well understood with PMNS matrix

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?

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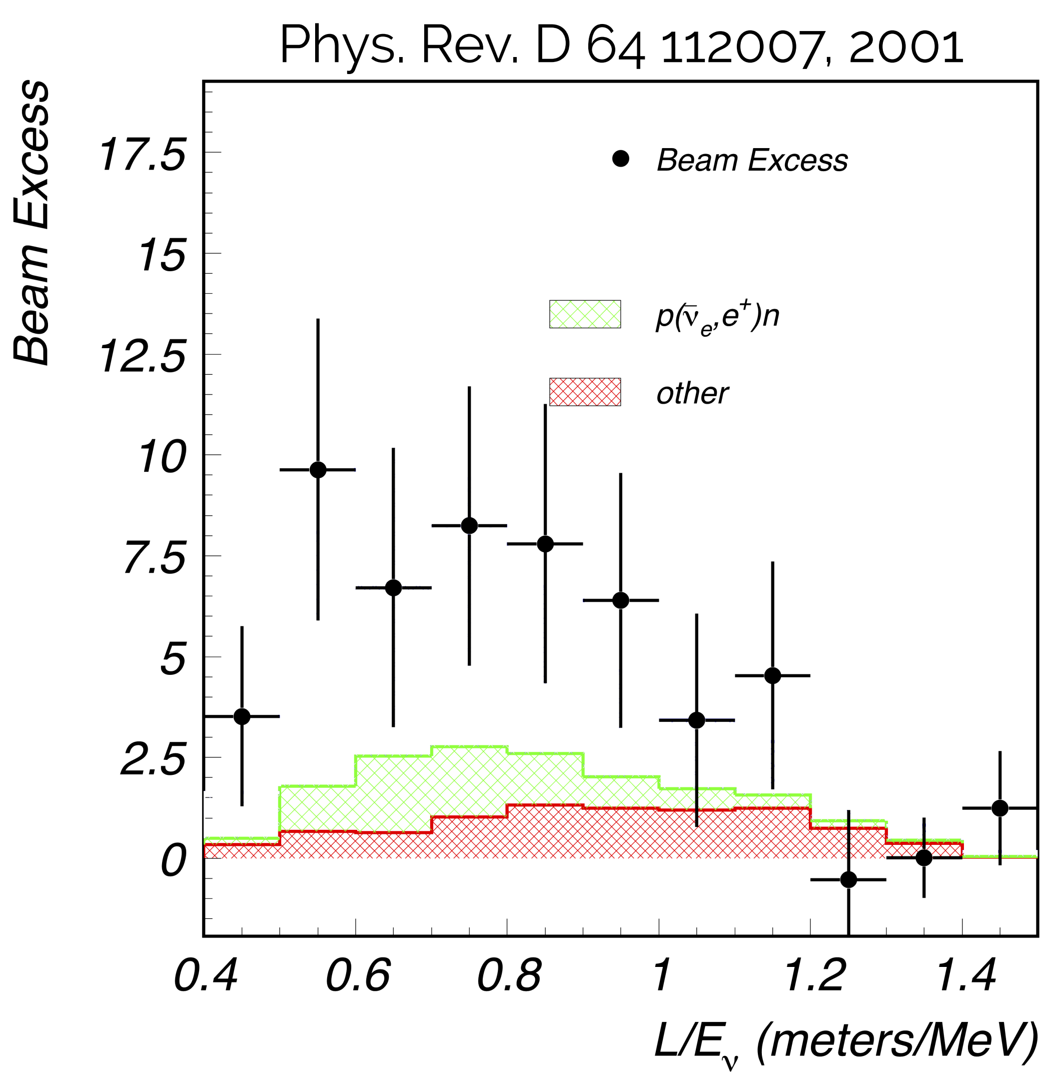
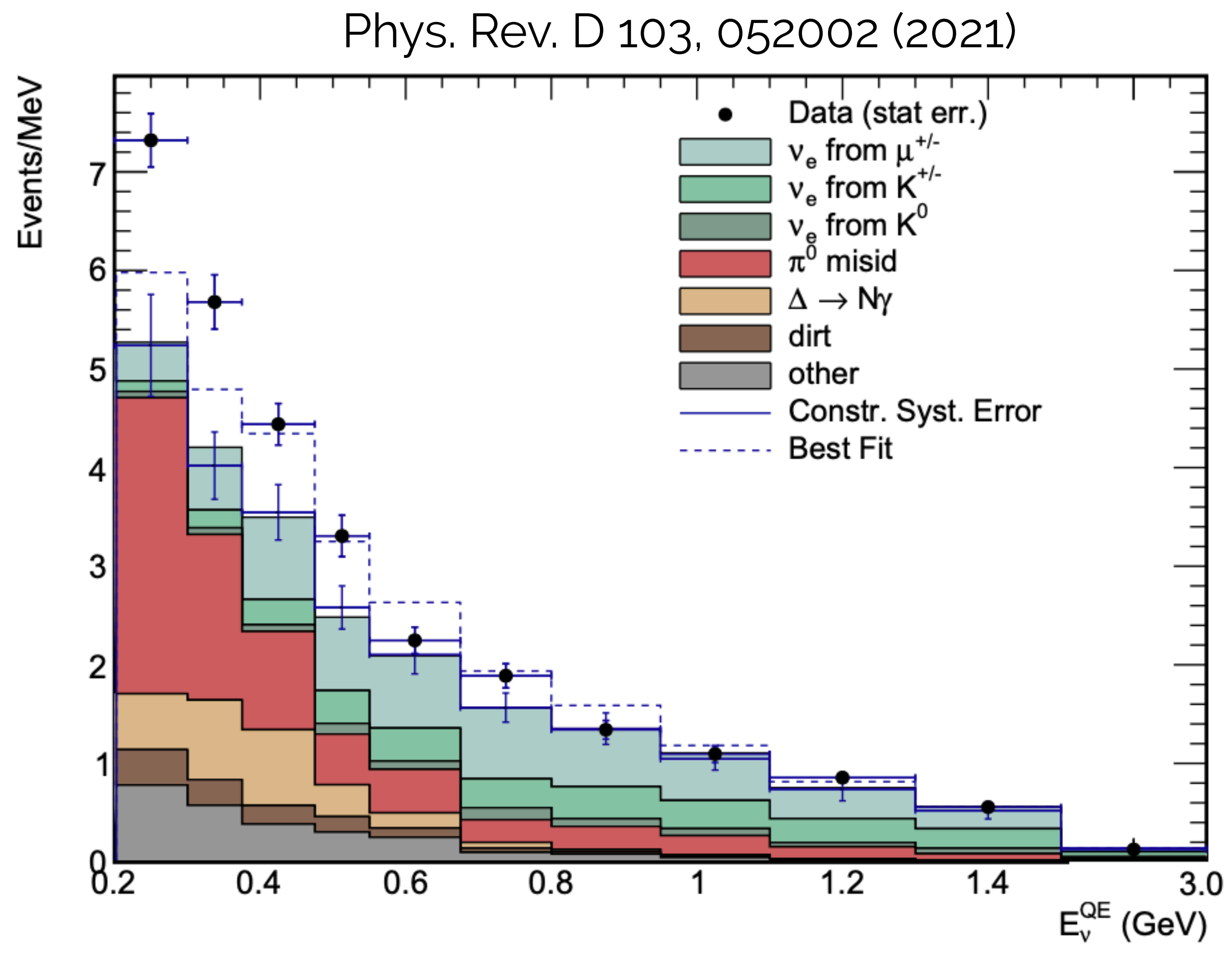
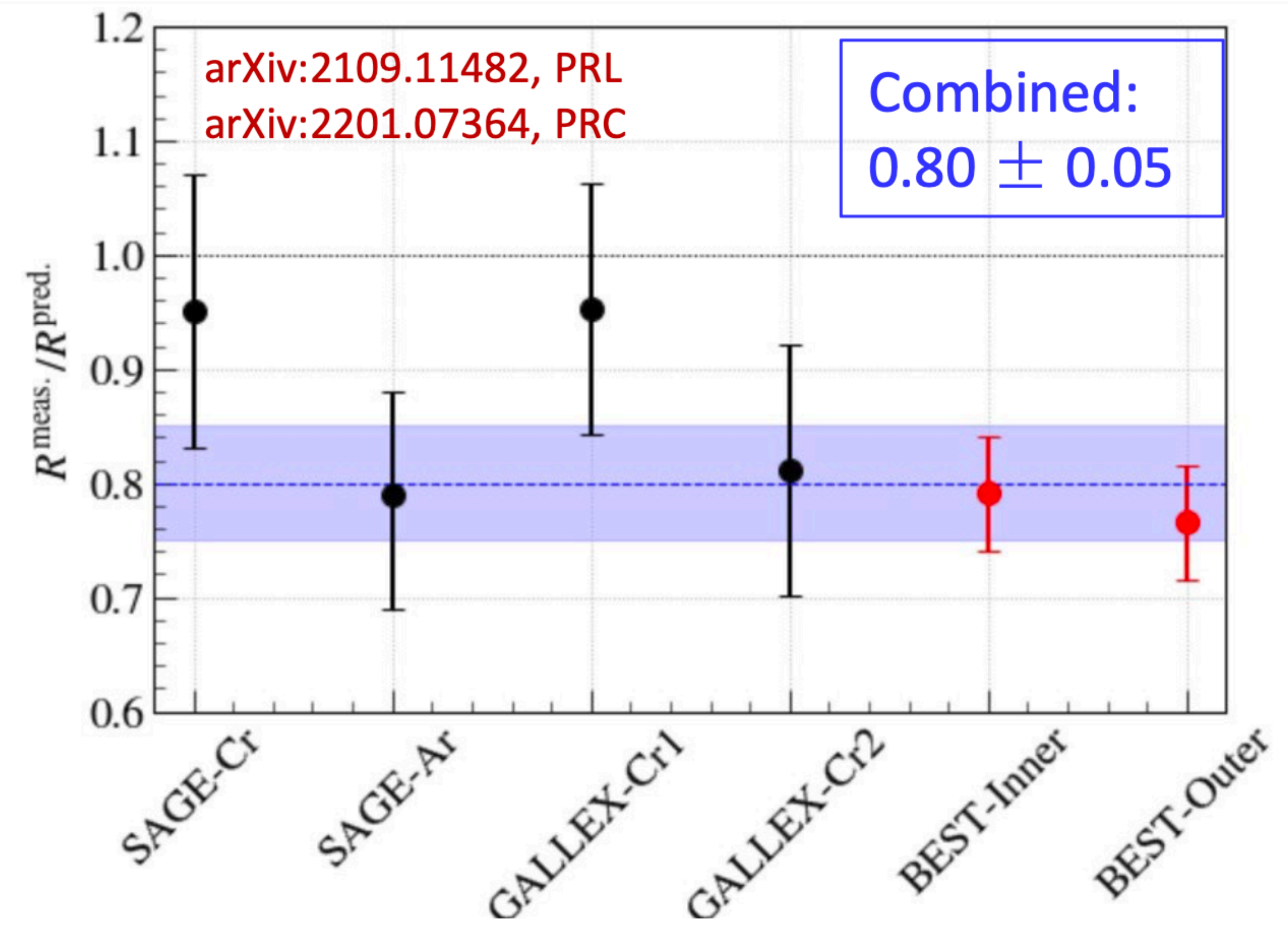
Why add extra neutrino?

- 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?

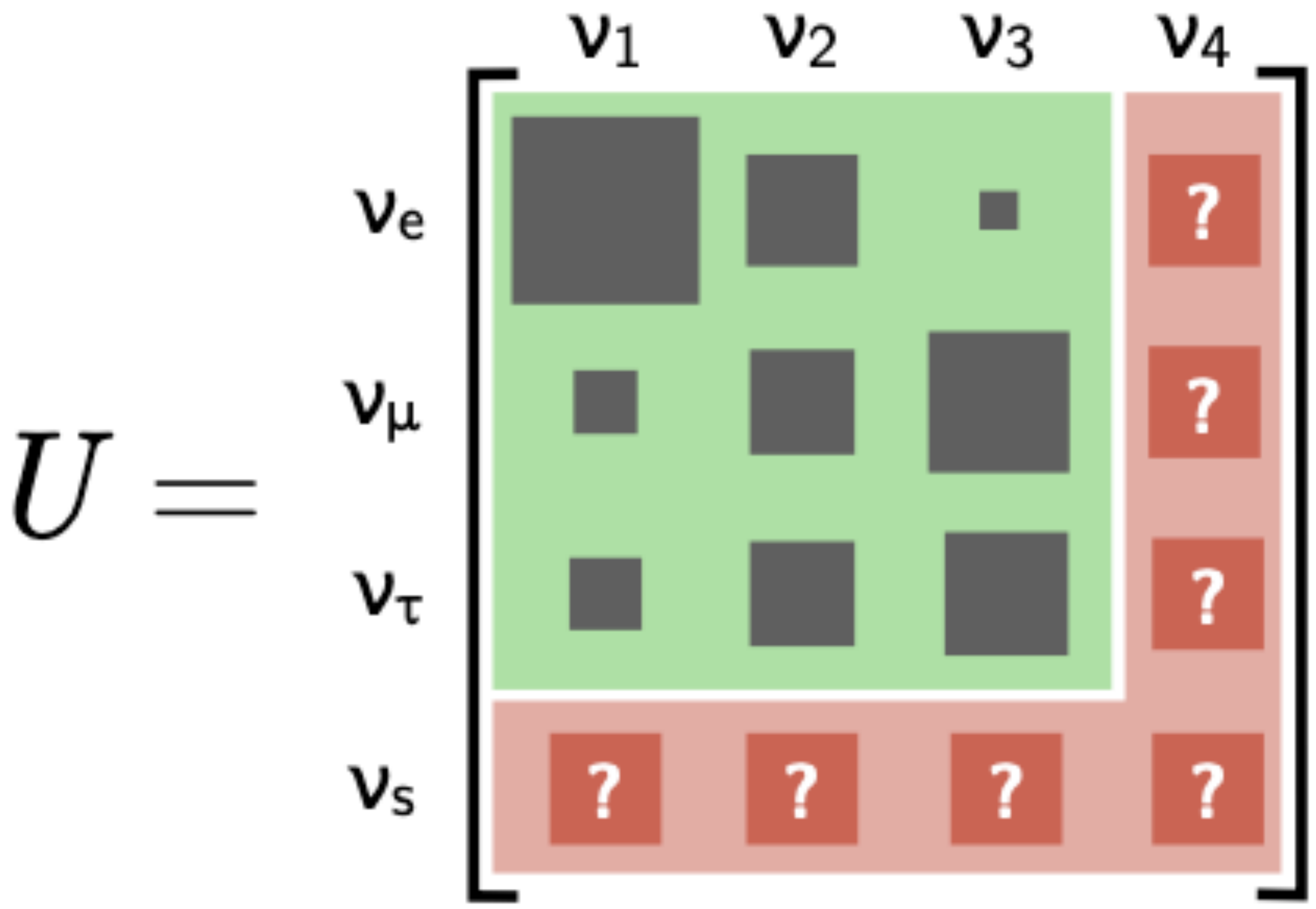
Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance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



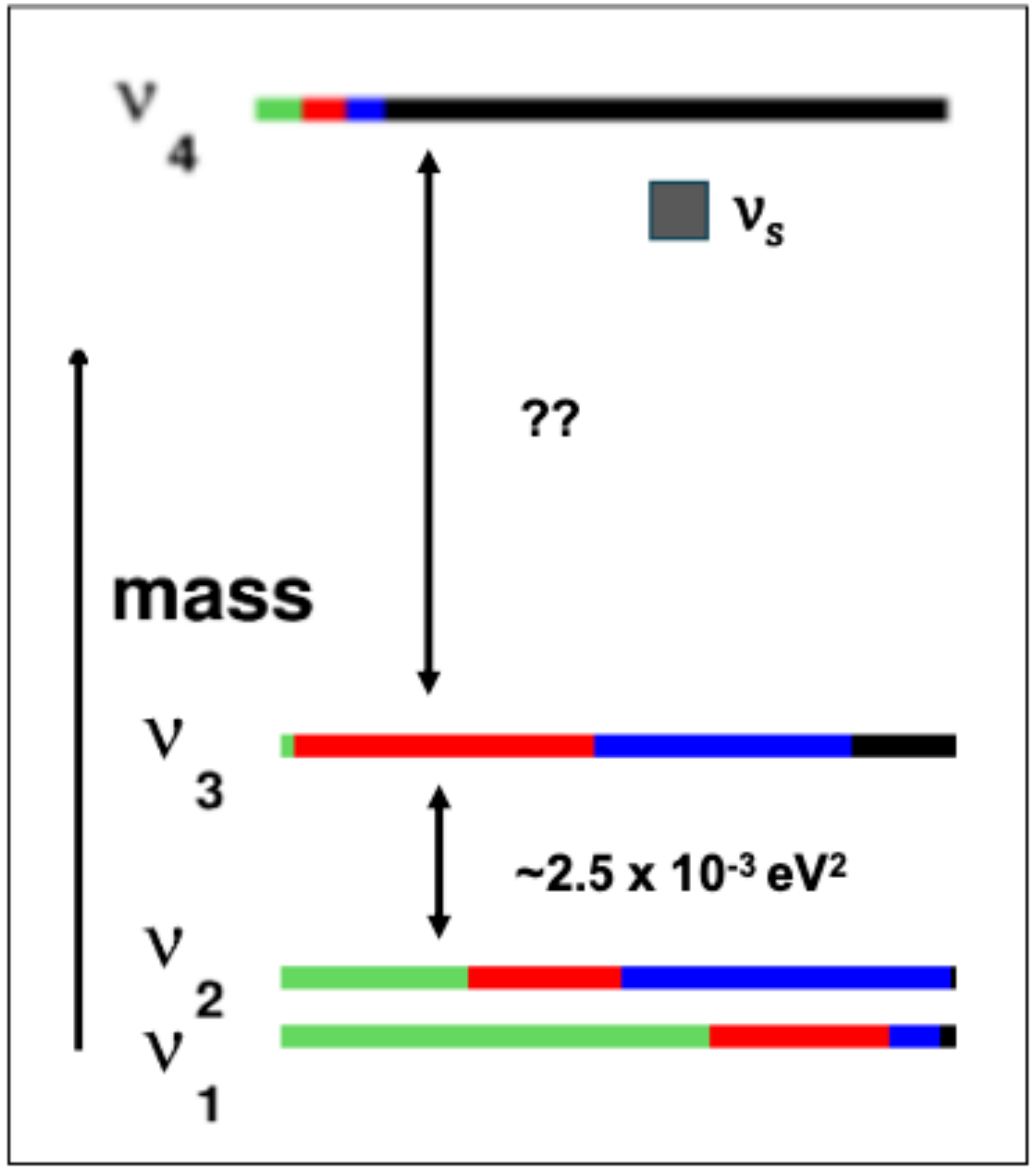
Flavor transitions via this new mixing:

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

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: $\nu_e \longrightarrow \nu_e$
    - 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?

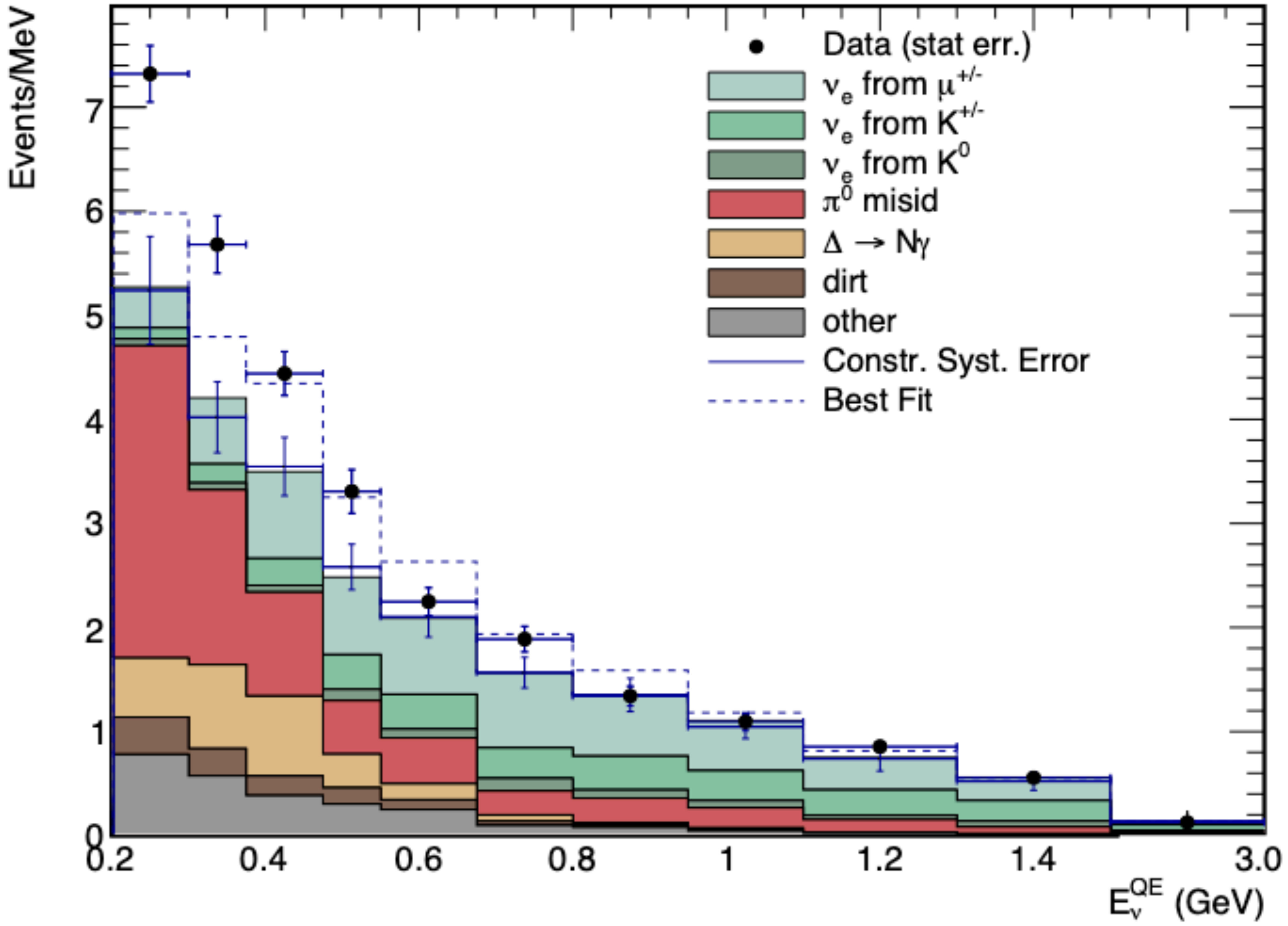
3+1 mixing model



The MiniBooNE Anomaly: Low Energy Excess (LEE)

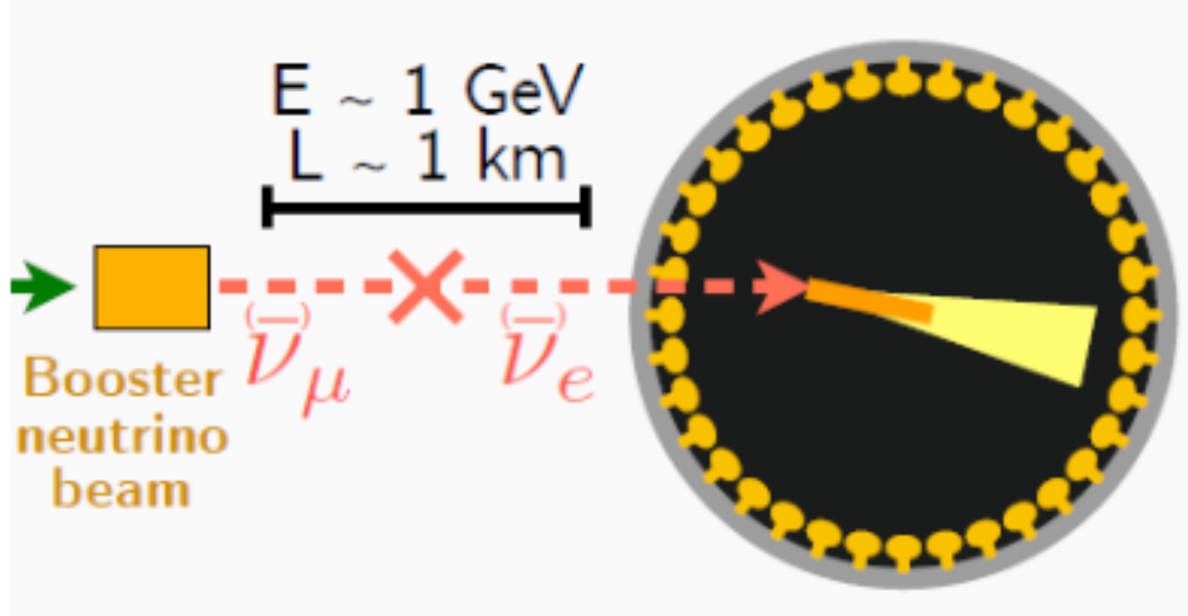
- MiniBooNE observed low-energy excess (LEE) of electron-neutrino-like events
  - LEE: more events measured/detected than predicted, in the low energy region
- eV-scale sterile neutrino could explain this excess
  - the excess is due to sterile neutrino oscillated into electron neutrino
  - prediction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

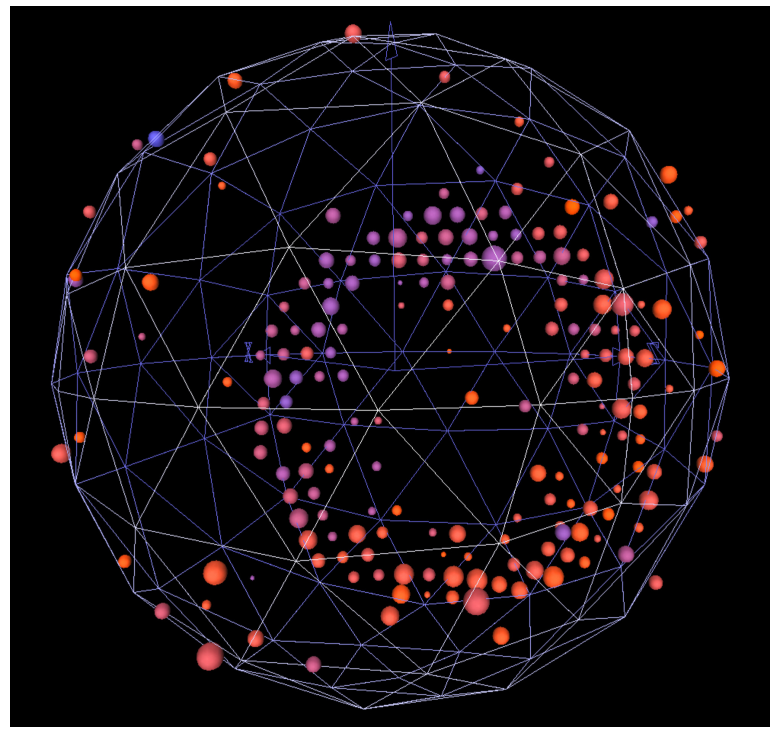
Phys. Rev. D 103, 052002 (2021)



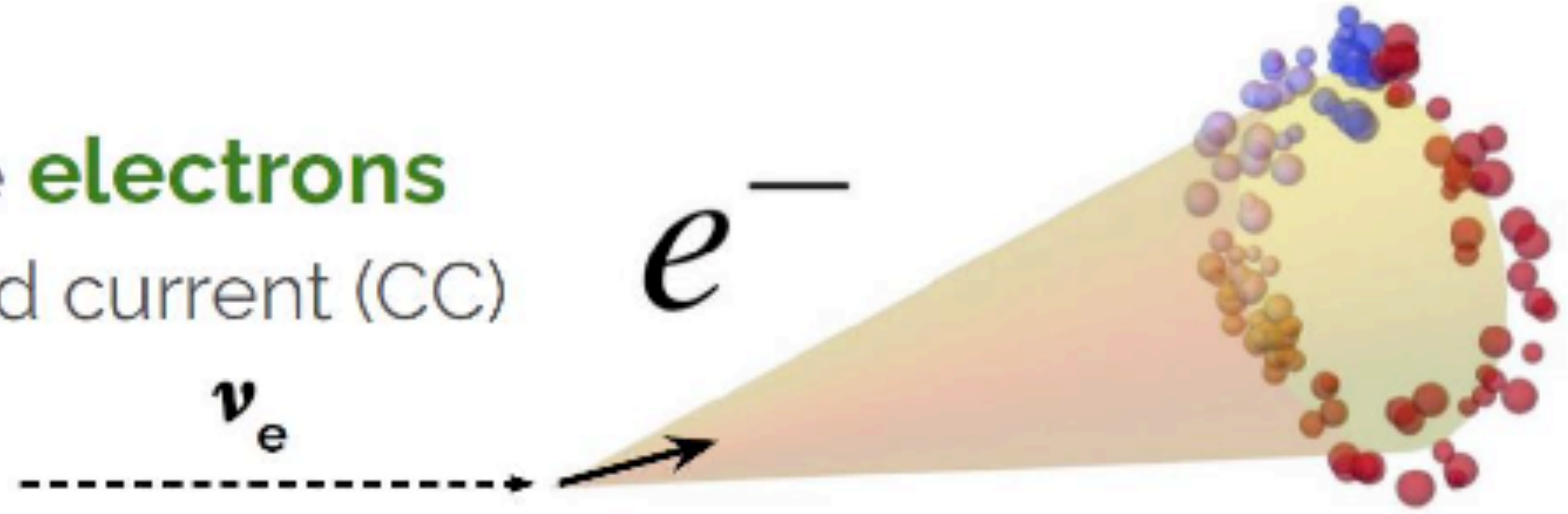
The MiniBooNE Anomaly: Low Energy Excess (LEE)

- 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

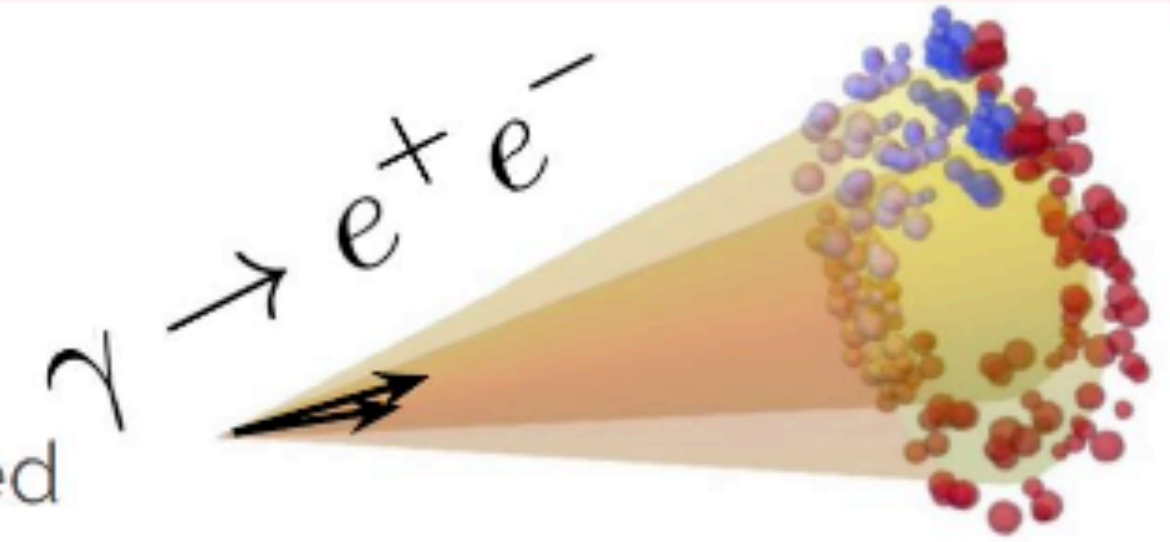




It detected ν_e by the **electrons** produced in charged current (CC) interactions.



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

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:

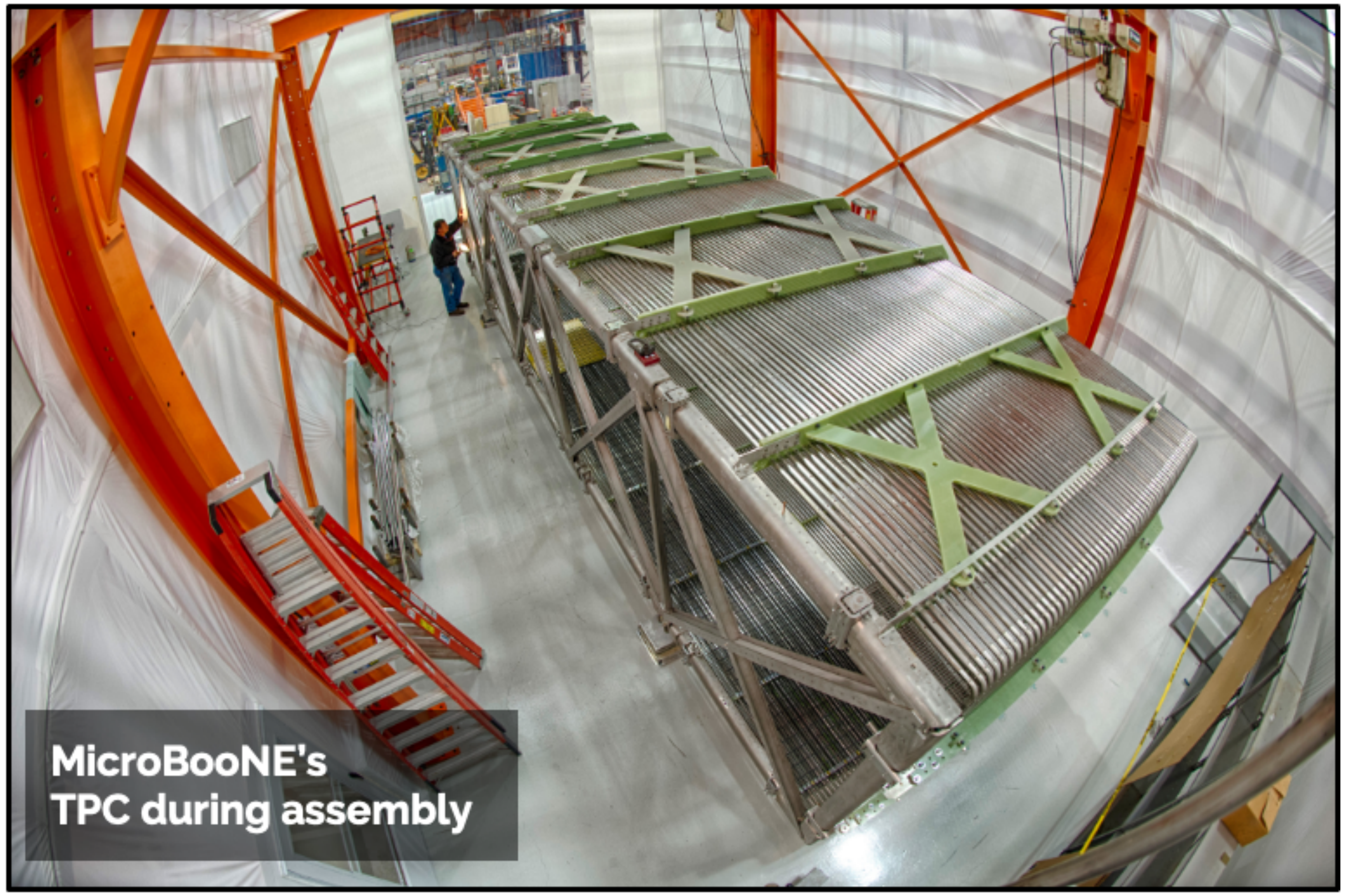
A NEW CONCEPT FOR NEUTRINO DETECTORS

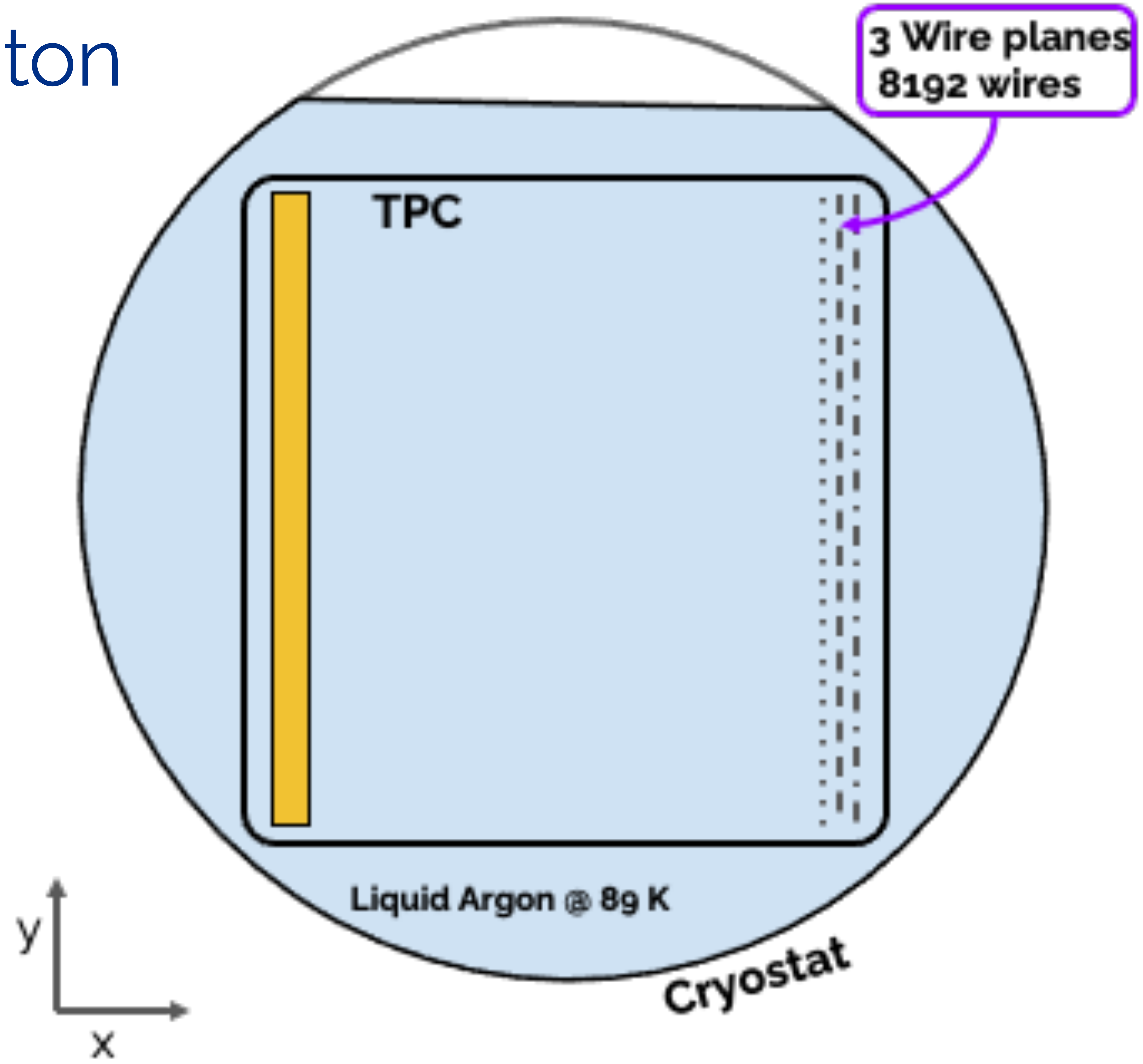
C. Rubbia

1977

the MicroBooNE detector

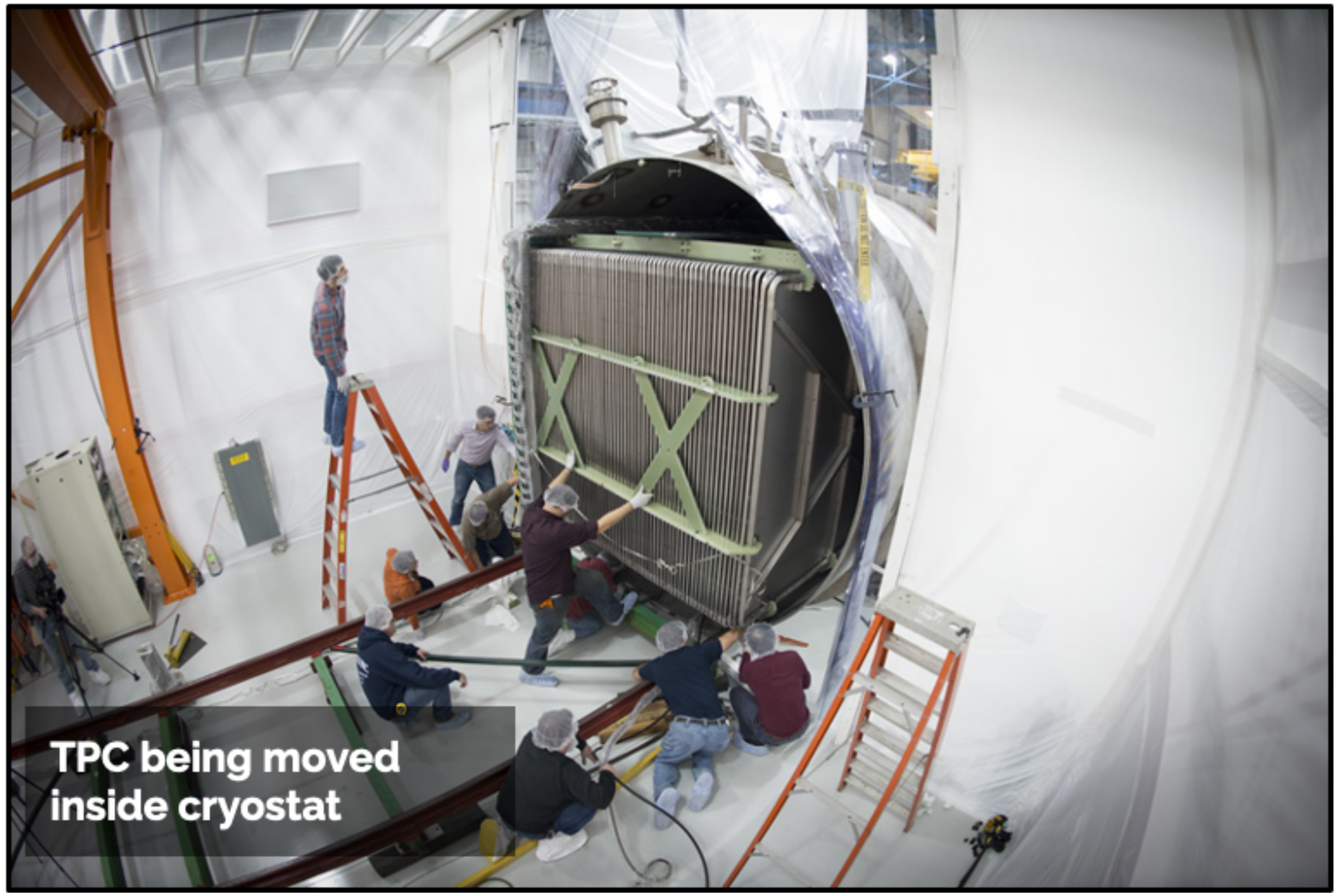
at MicroBooNE's core is an 85 ton LArTPC

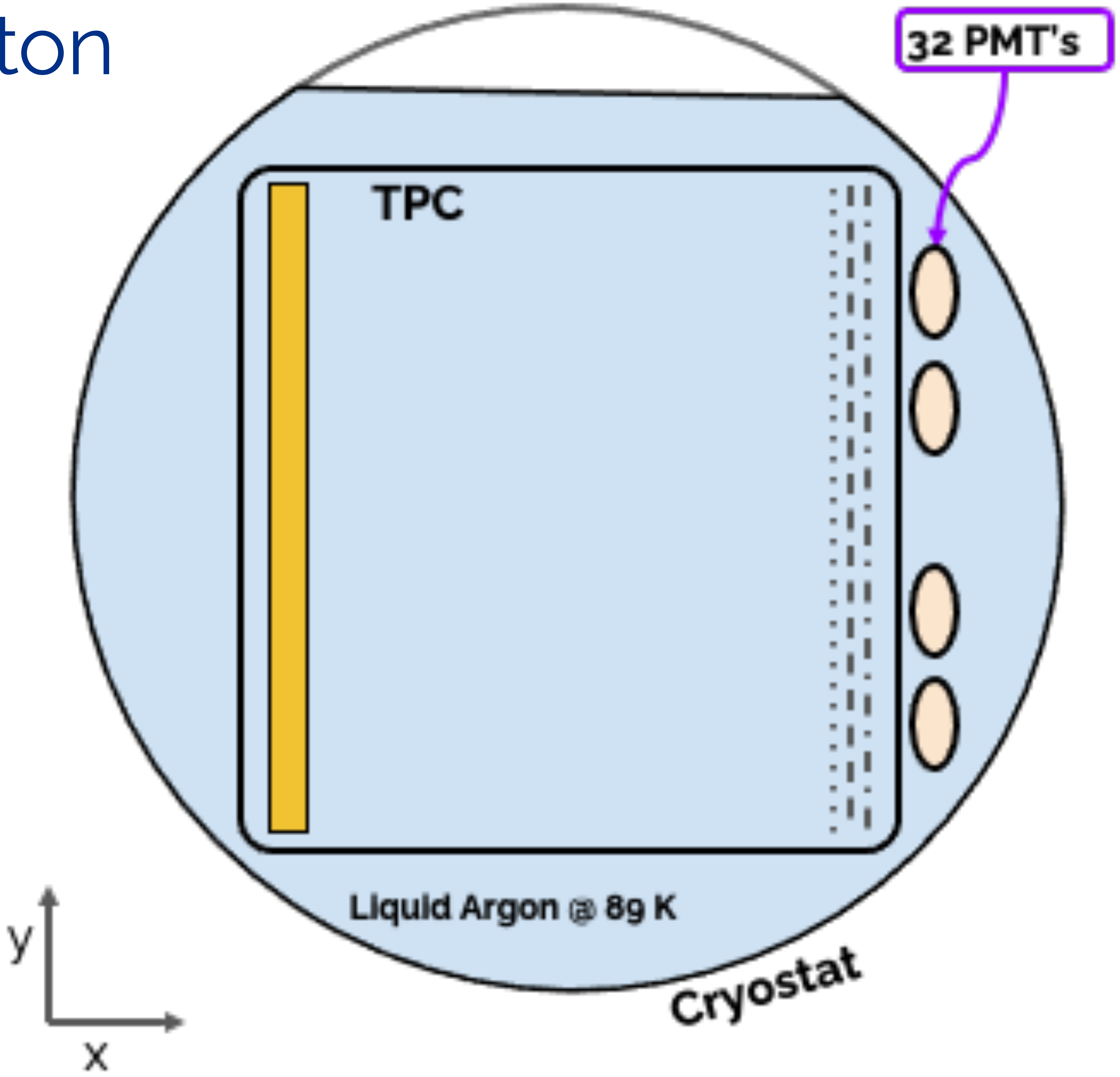




the MicroBooNE detector

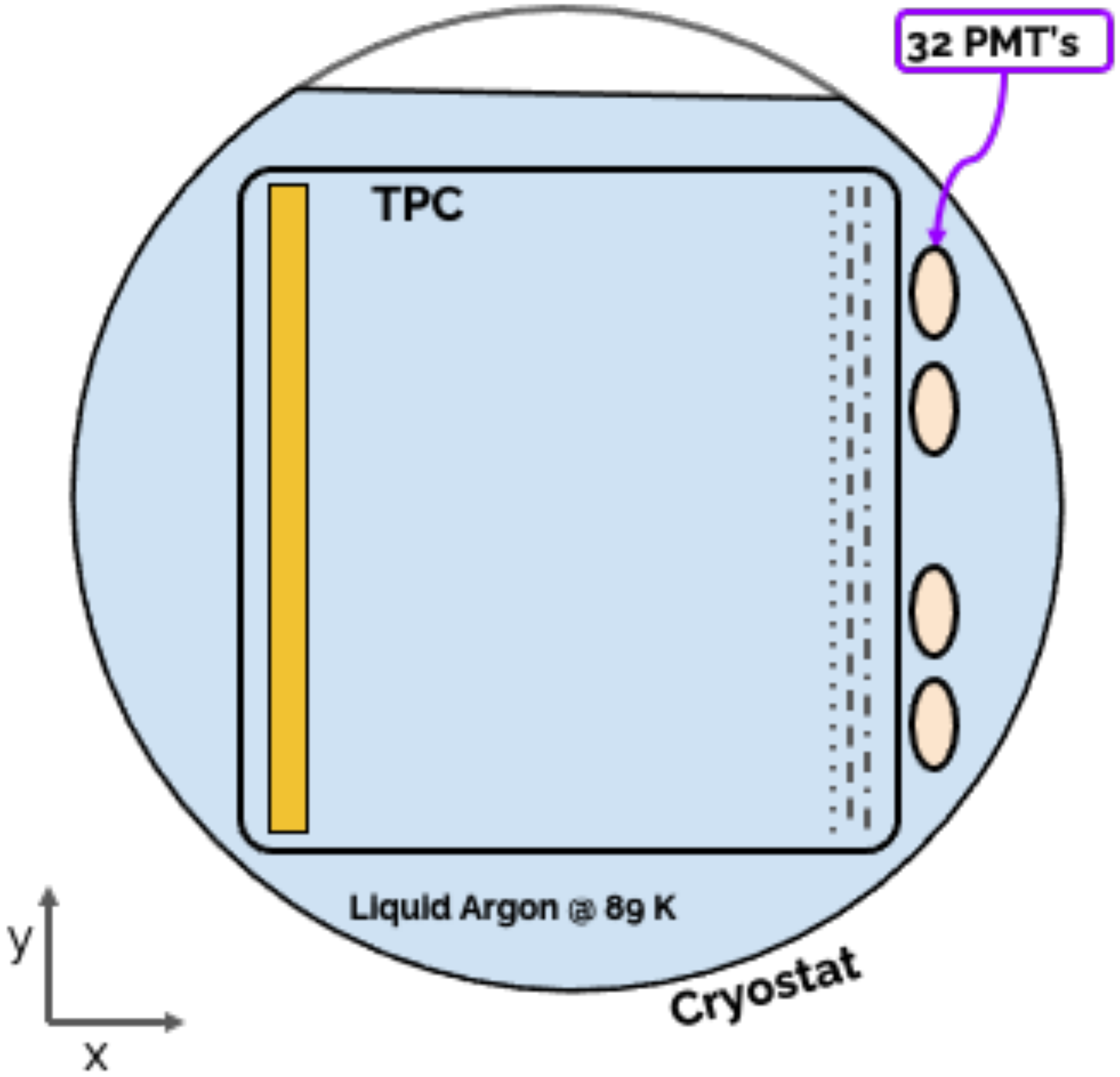
at MicroBooNE's core is an 85 ton LArTPC

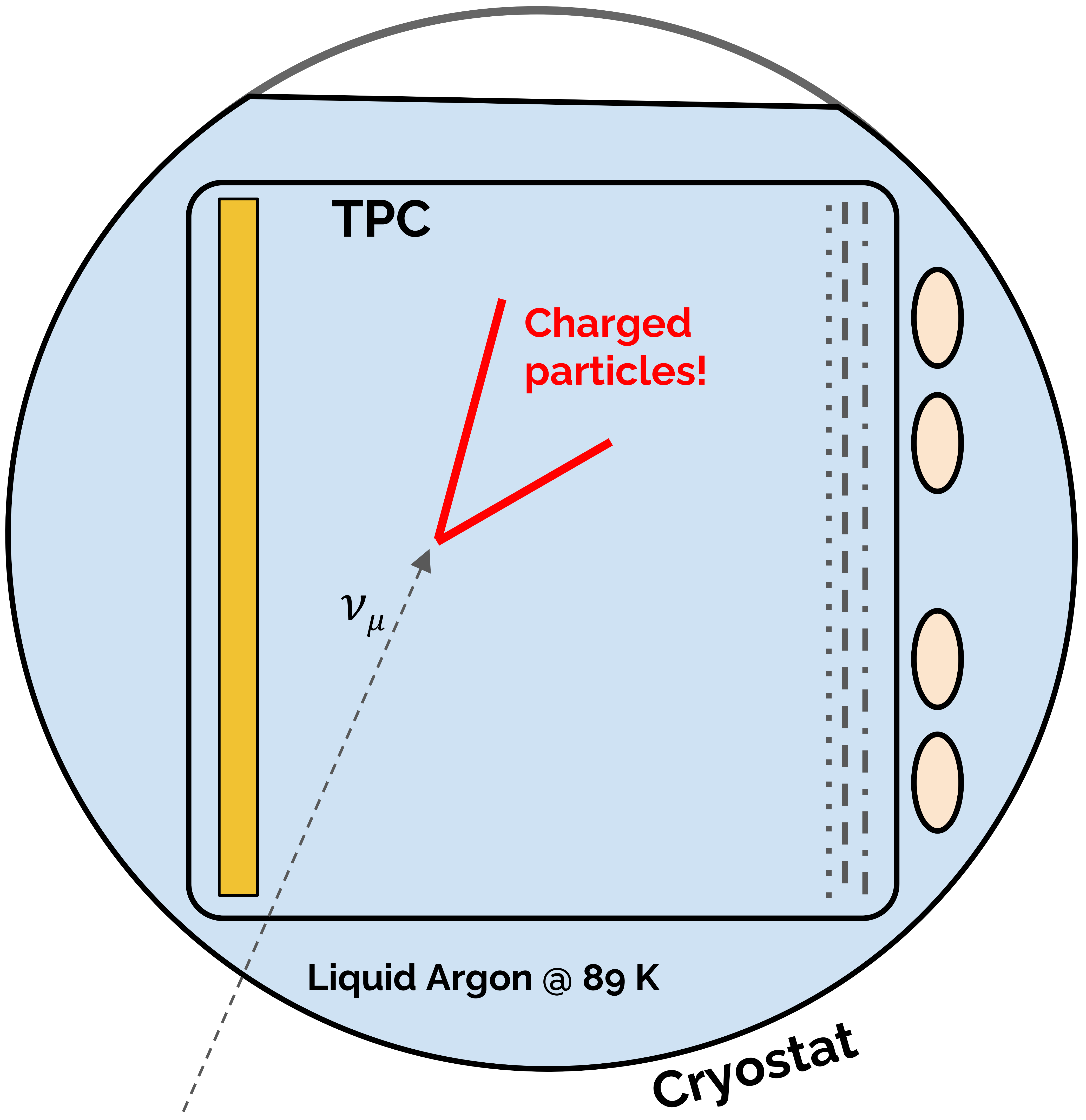




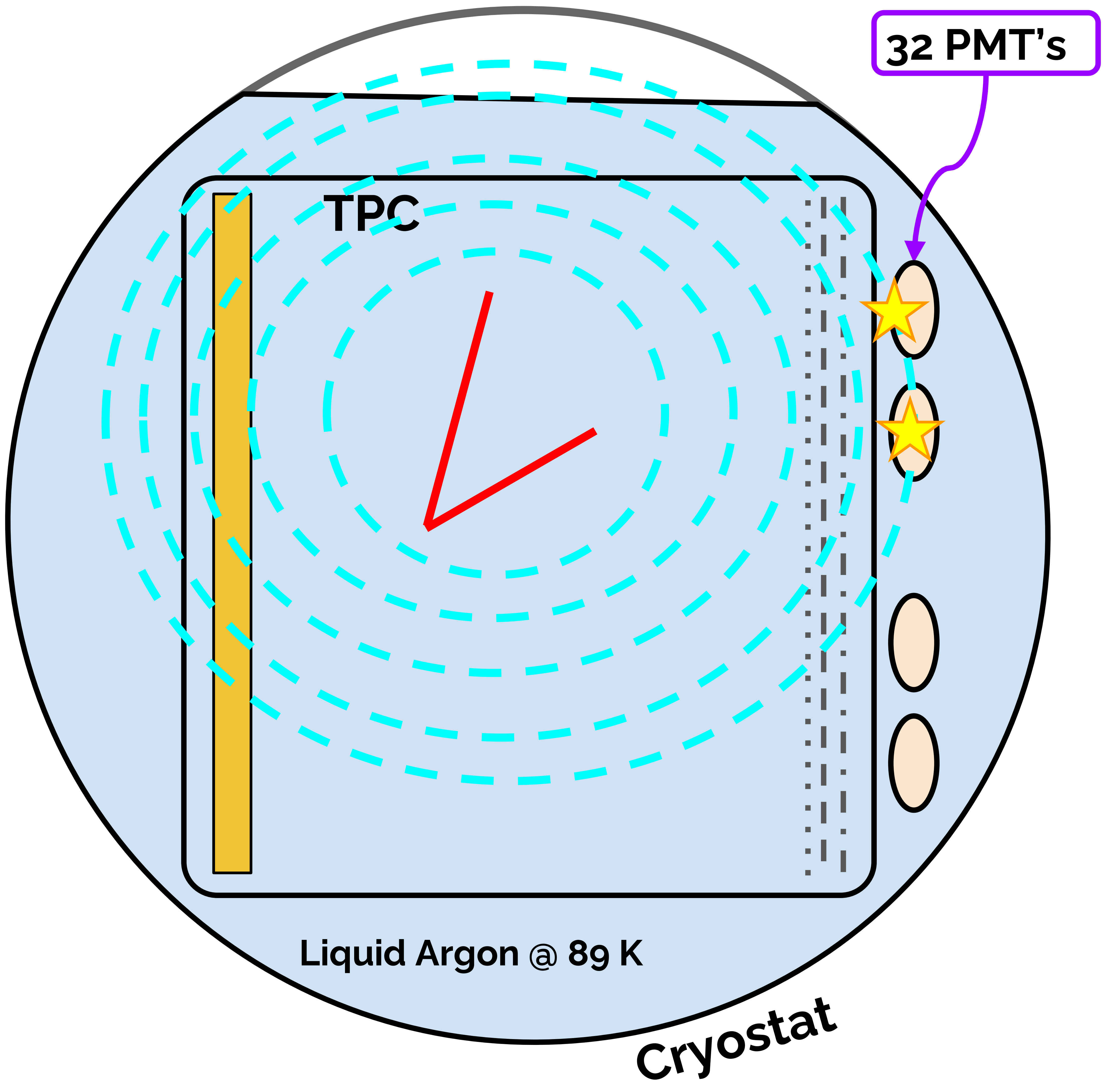
the MicroBooNE detector

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

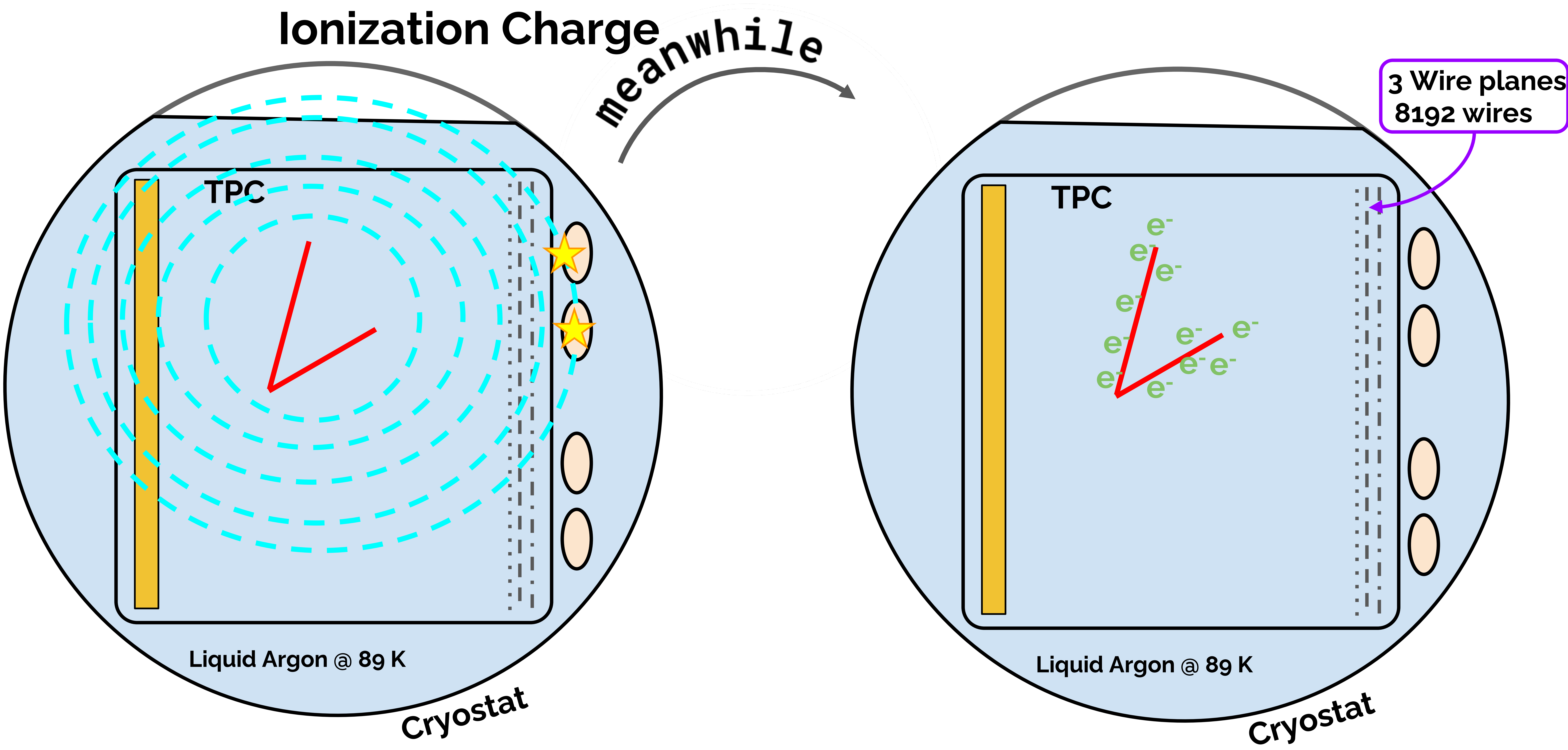



TPC
Charged
particles!
ν_μ
Liquid Argon @ 89 K
Cryostat

Scintillation light



Scintillation light
Ionization Charge



Scillation light

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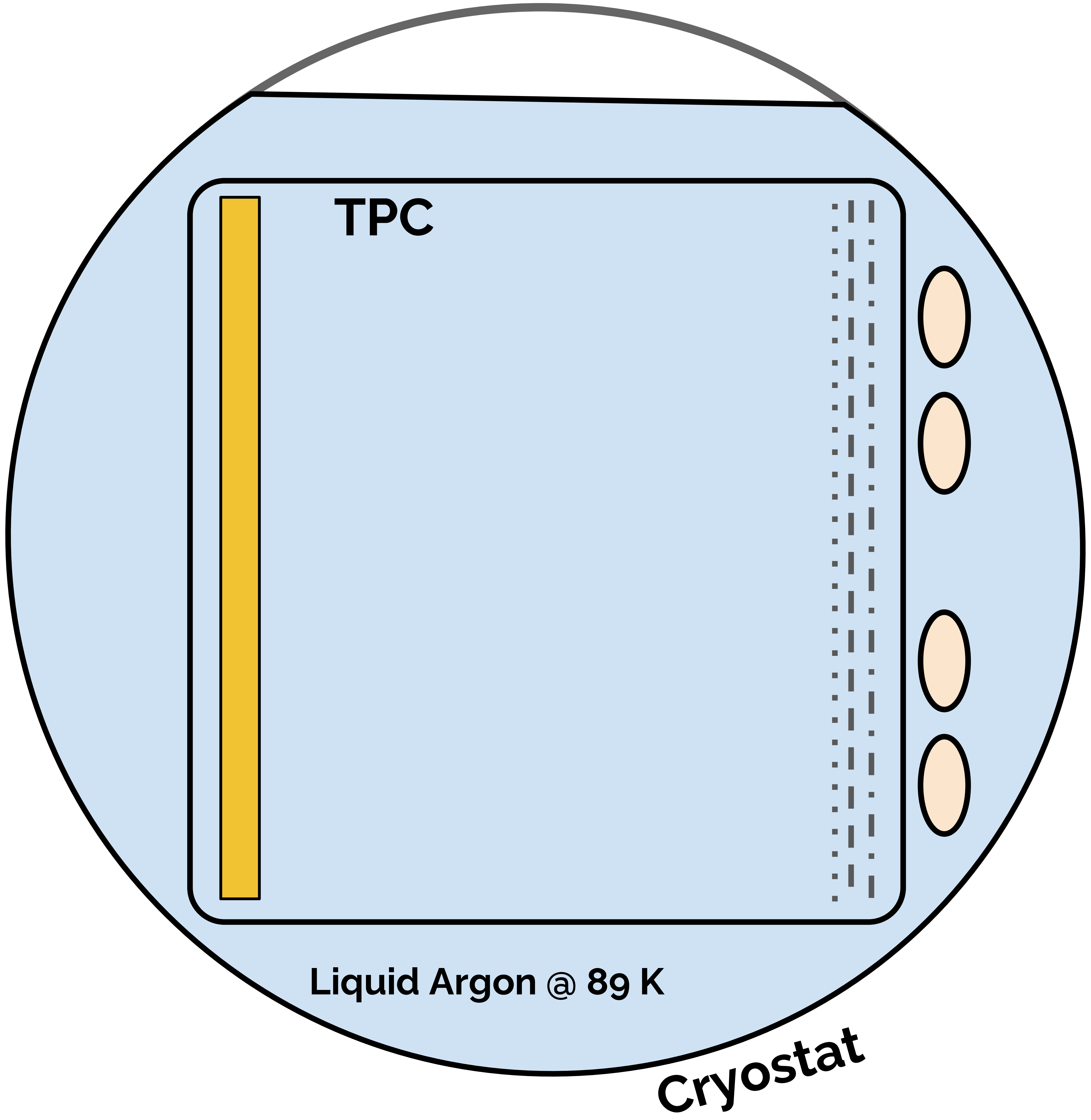

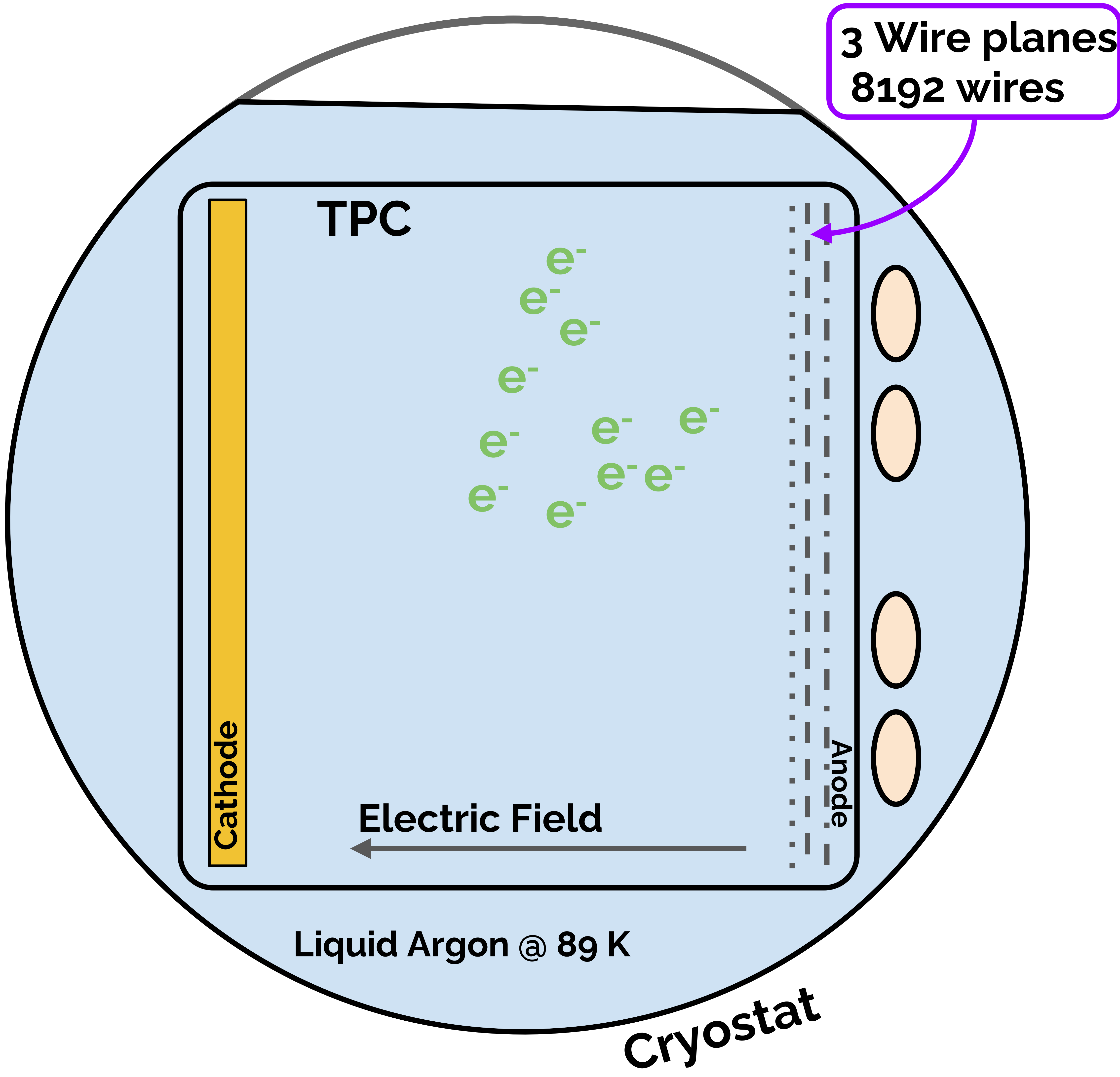

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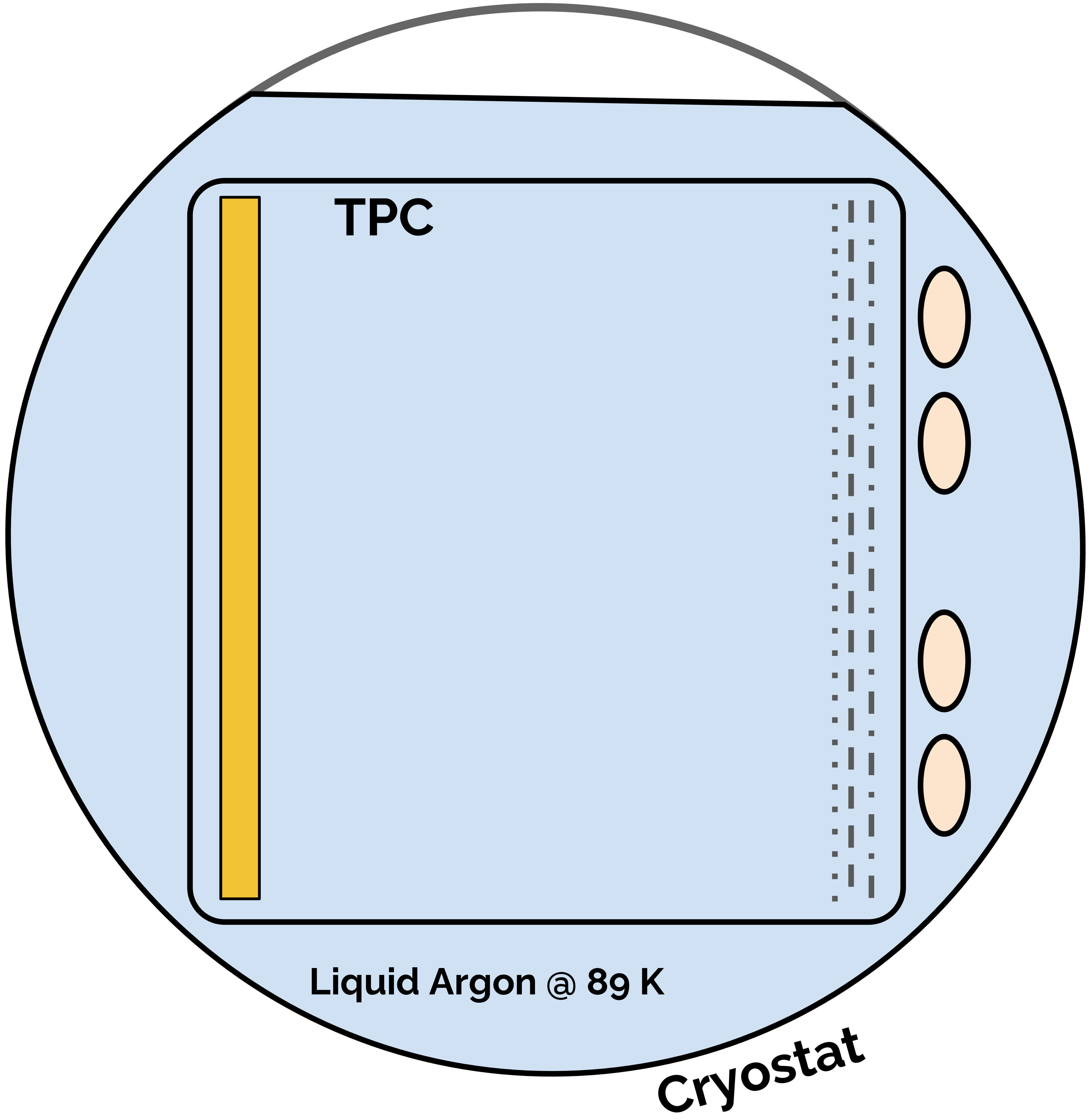
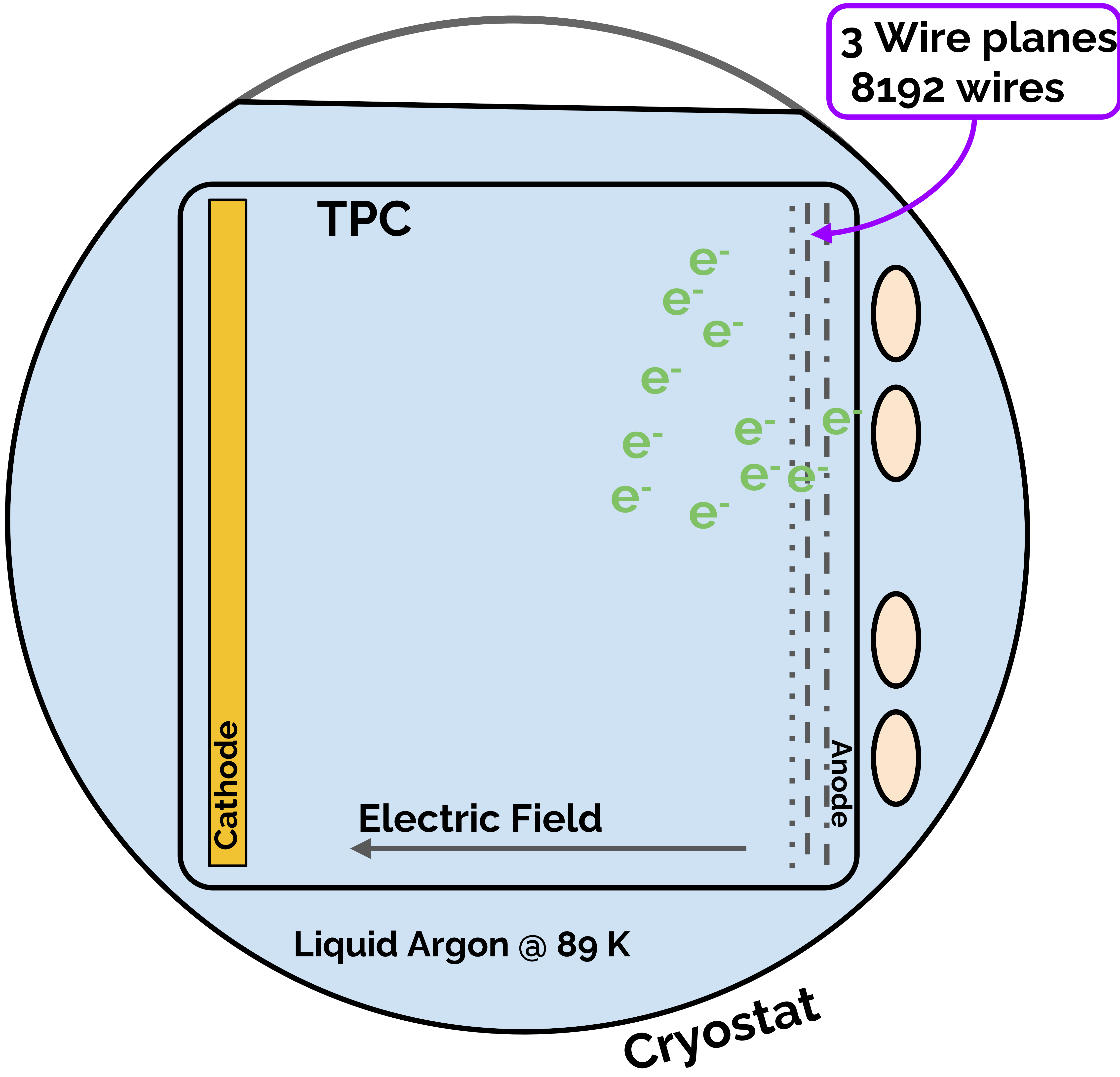
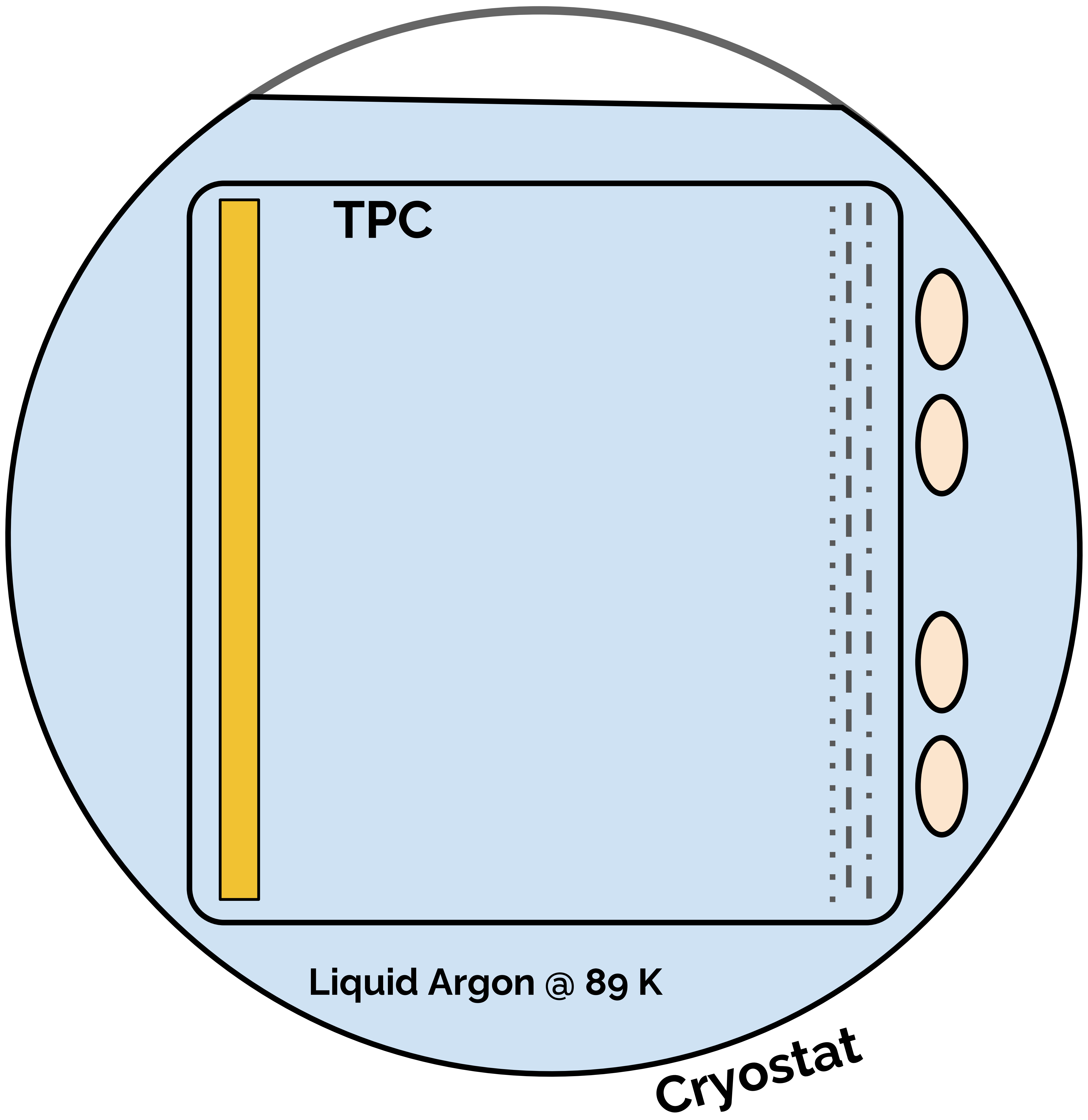
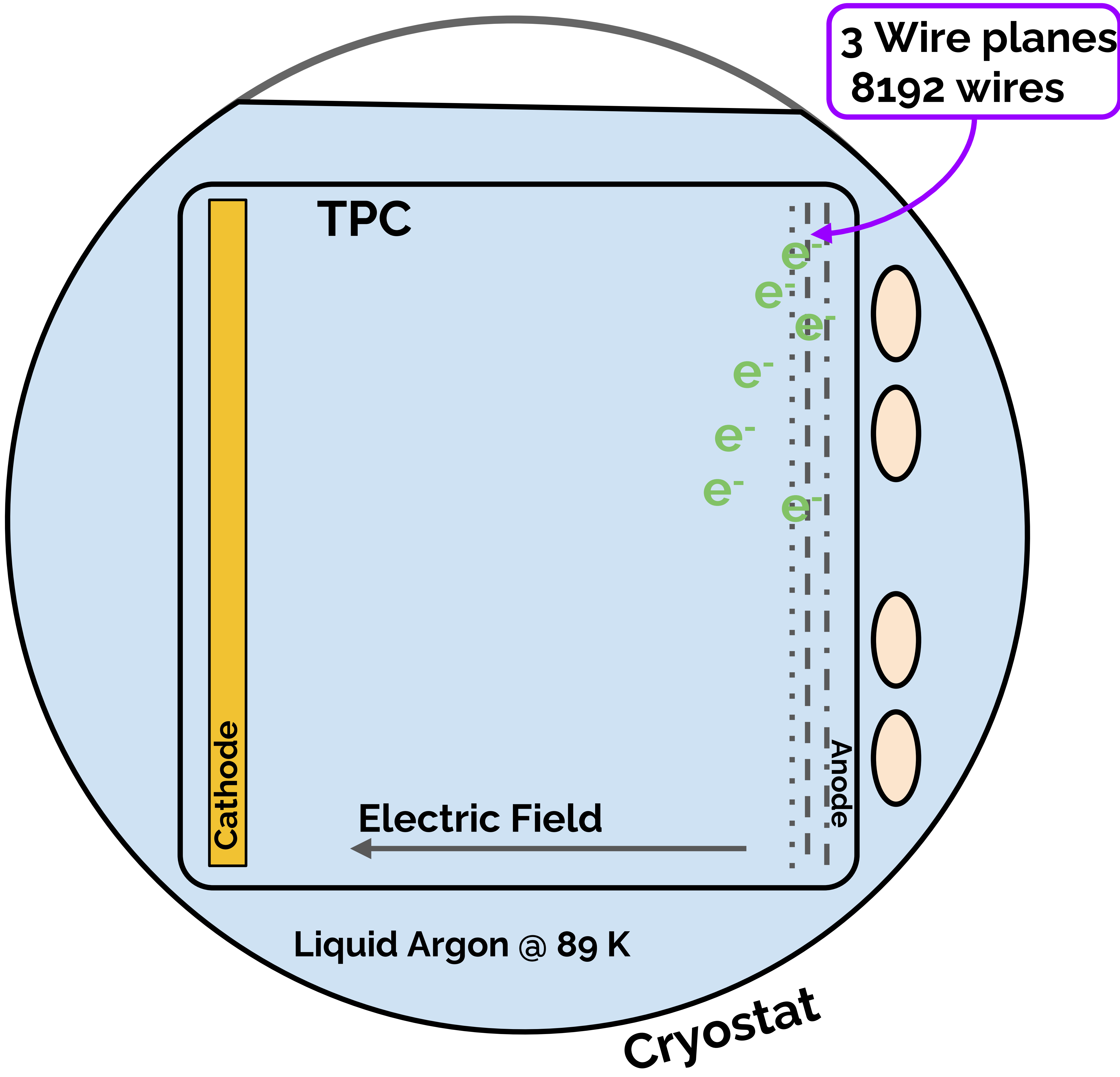


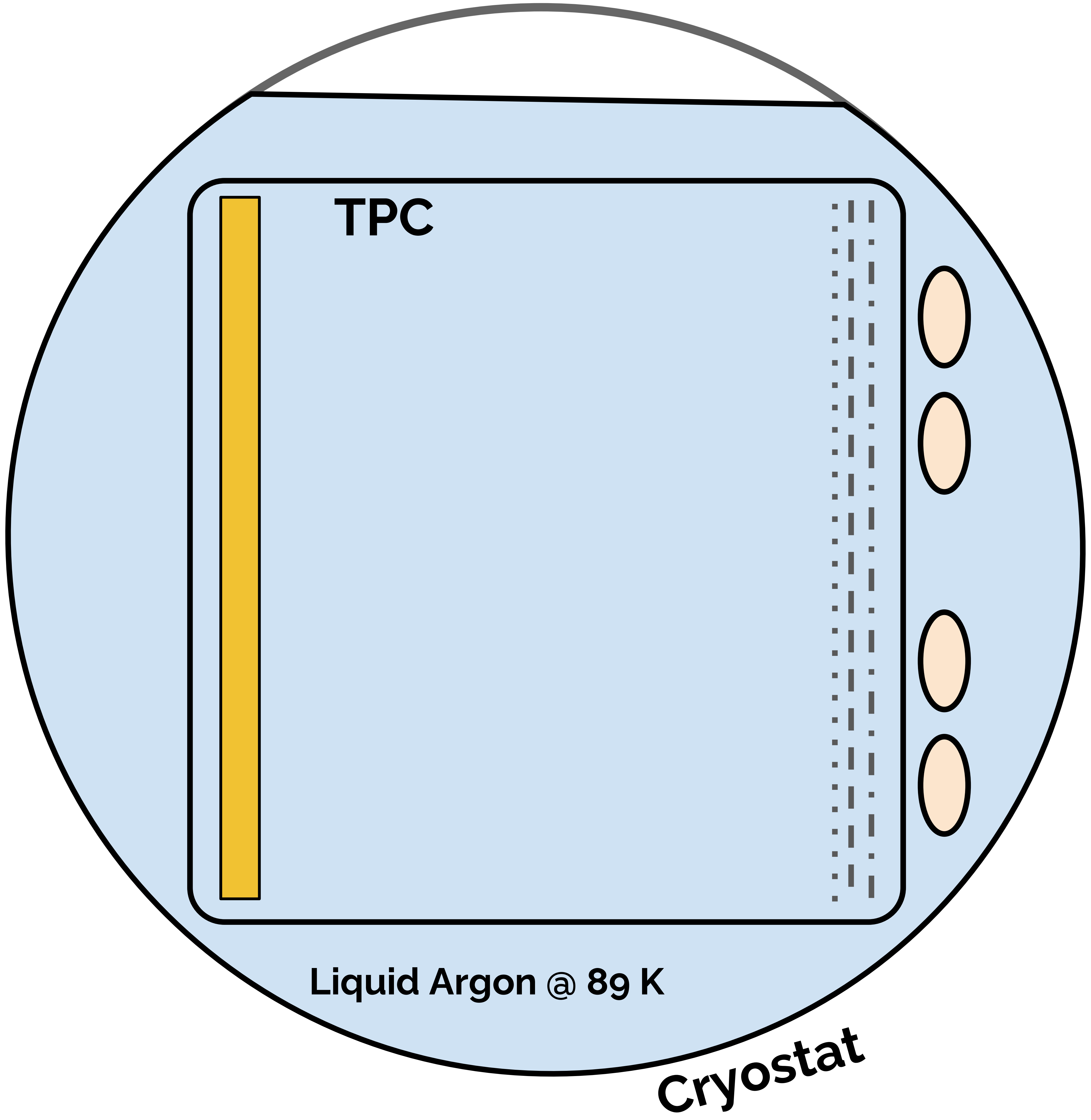


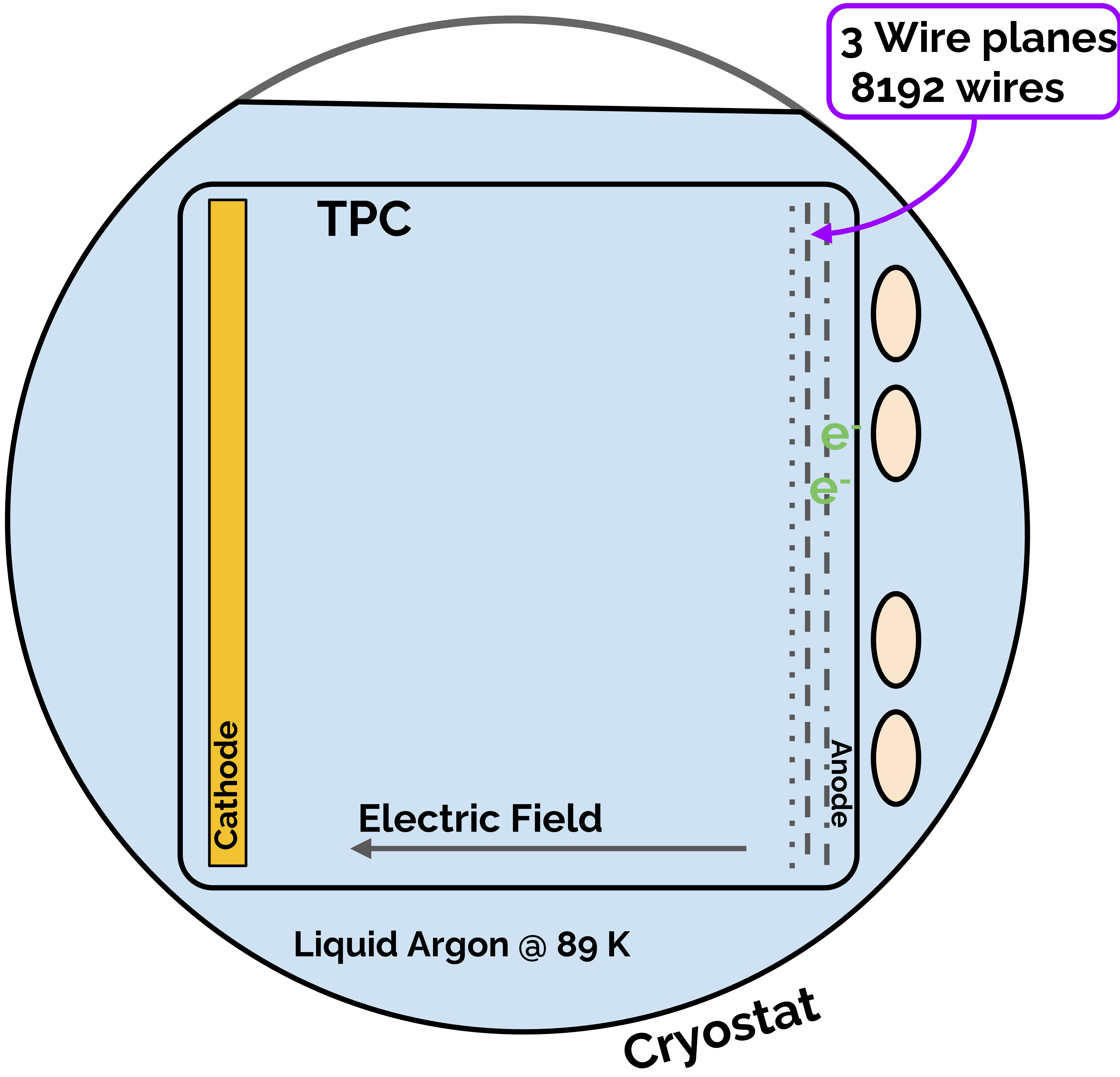
Scintillation light
Ionization Charge



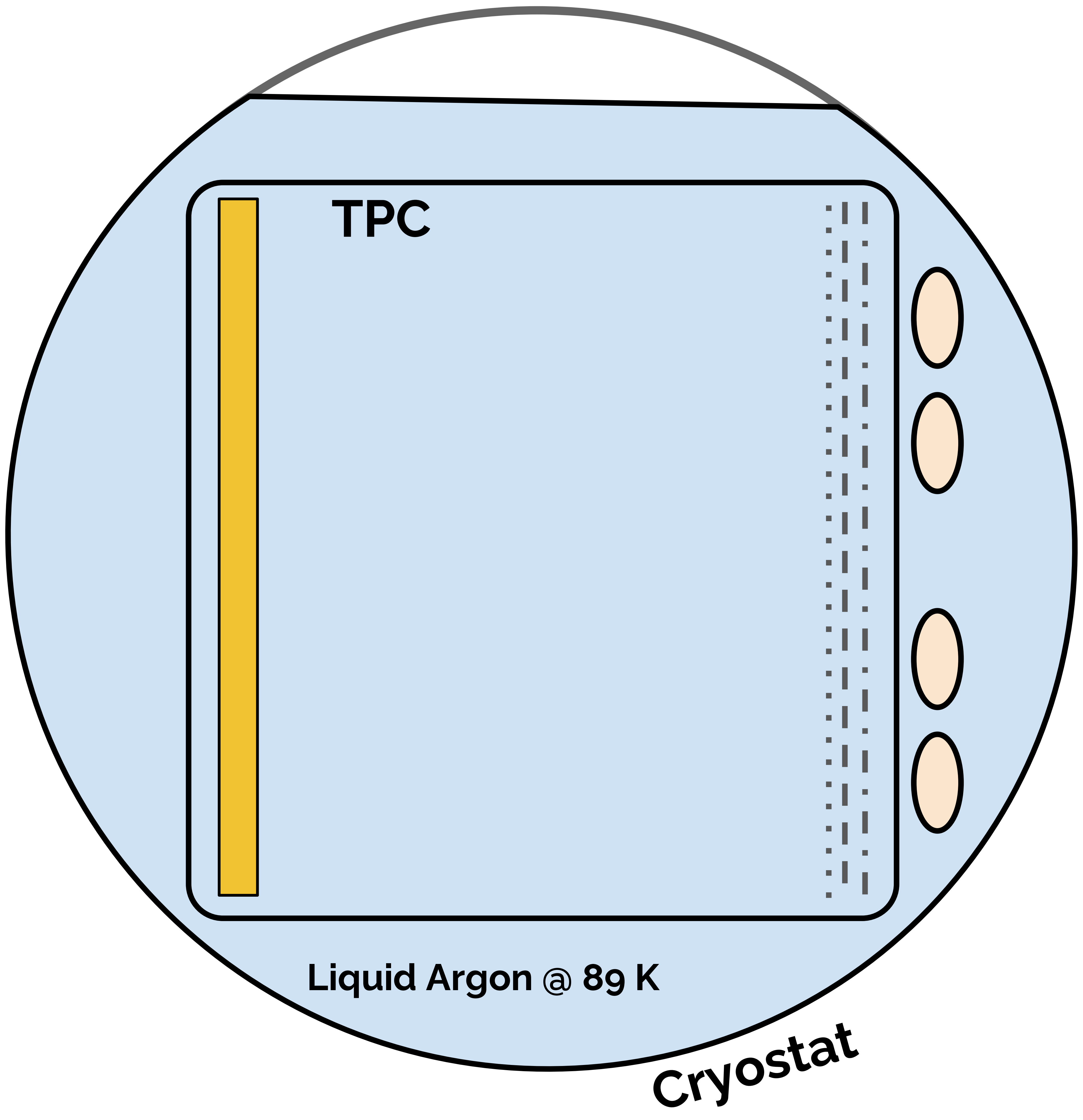


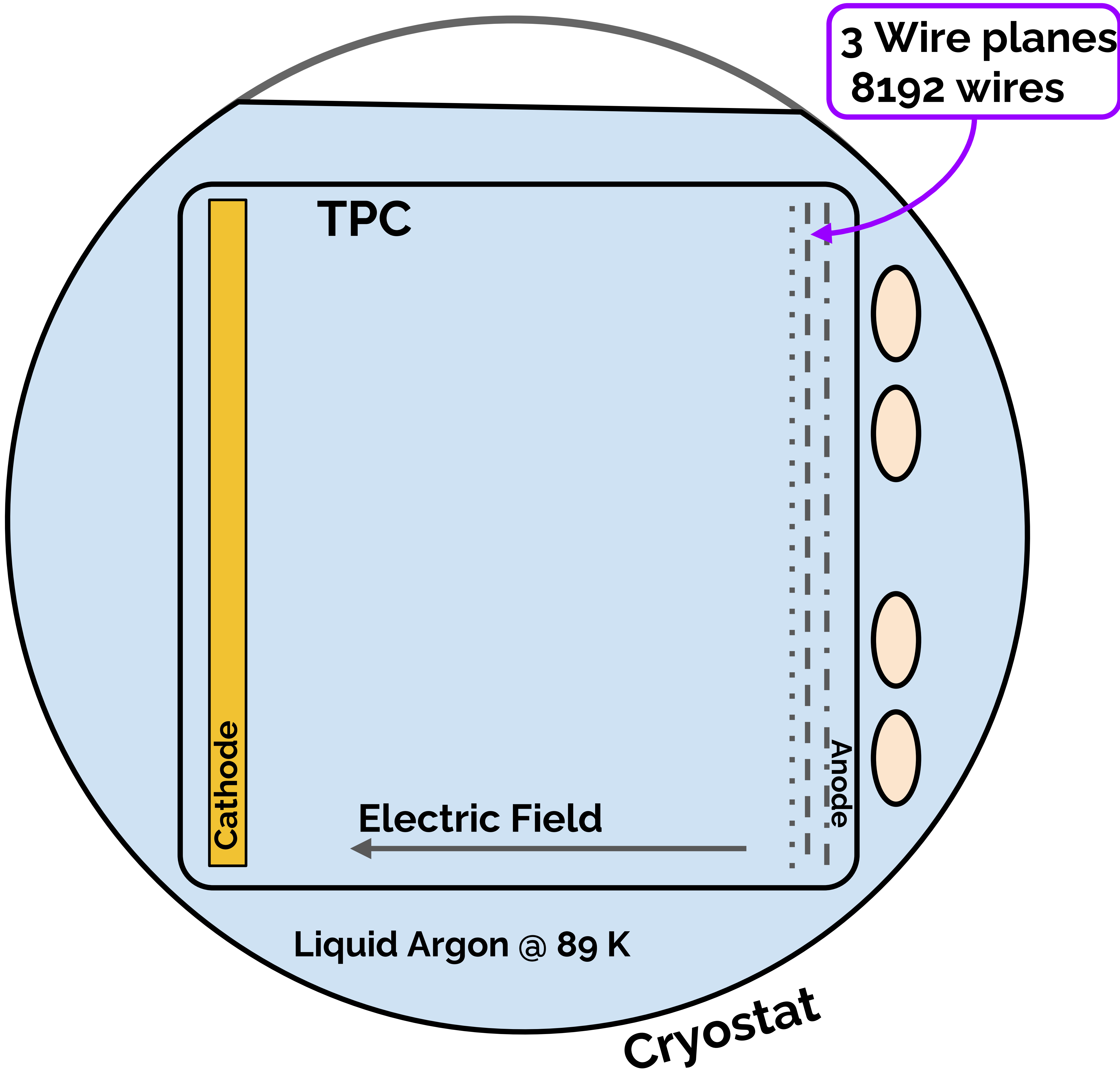
Scintillation light
Ionization Charge



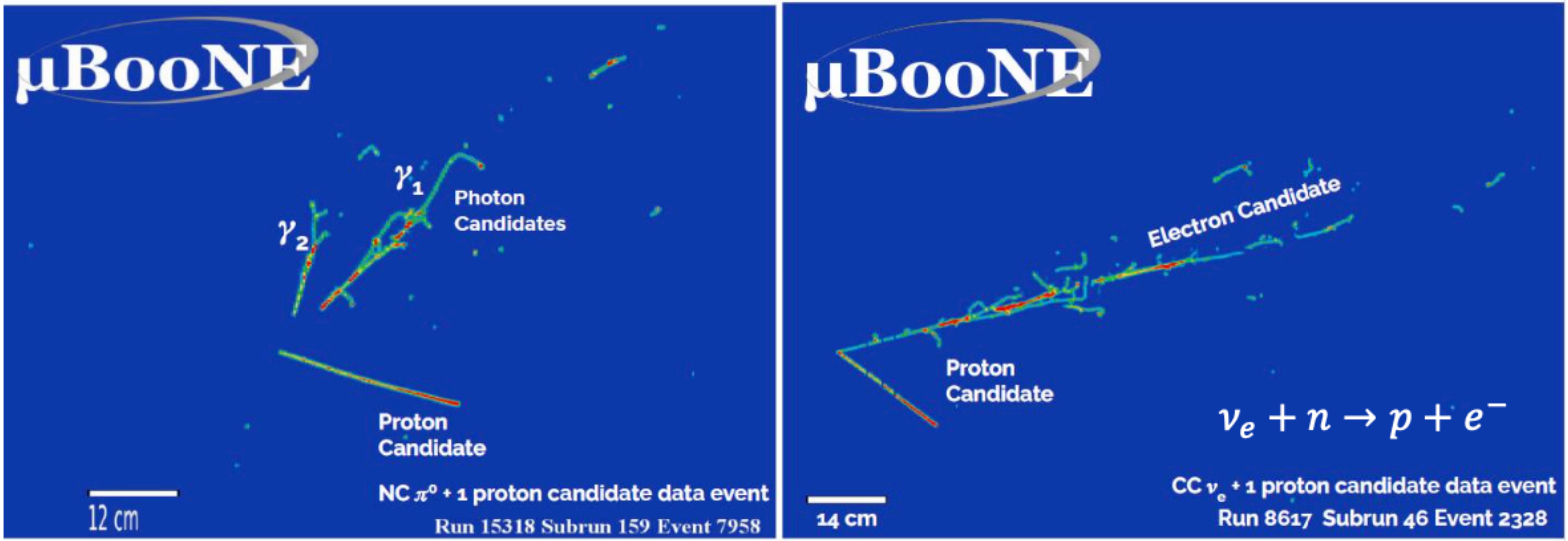


Scintillation light
Ionization Charge





LArTPC: Liquid Argon Time Projection Chamber



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

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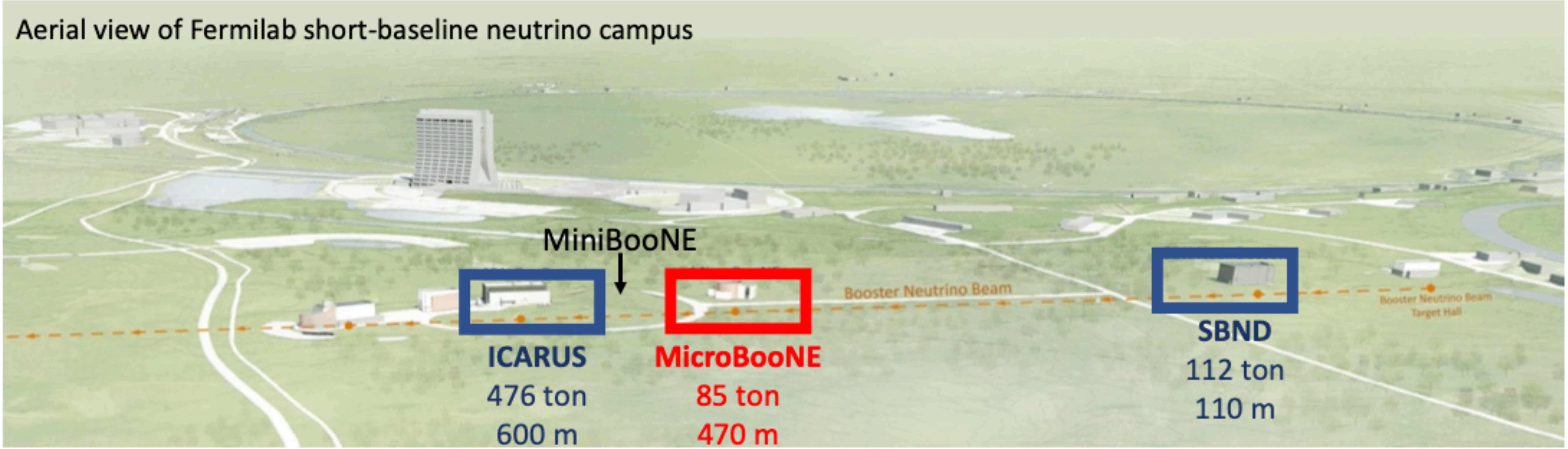
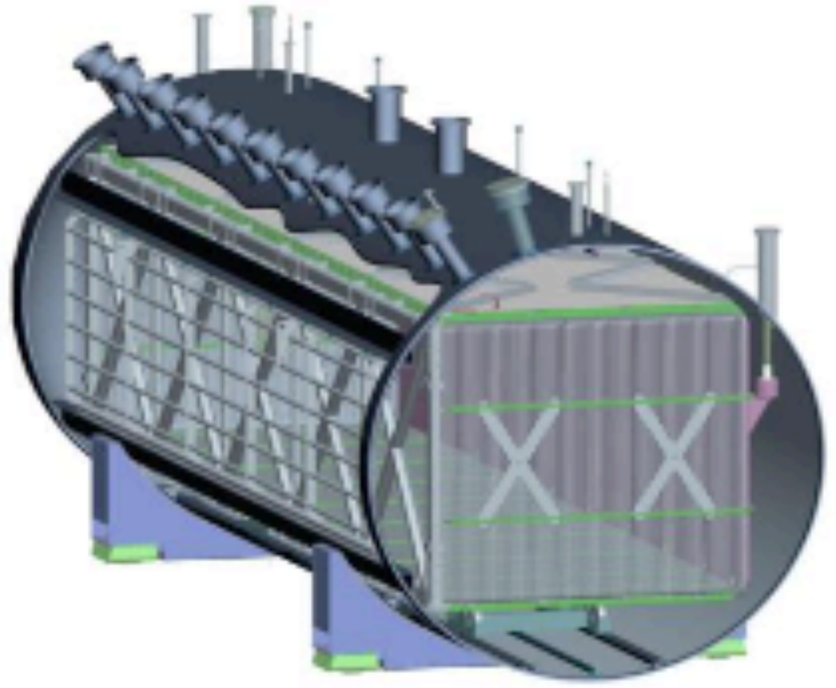
- **Short Baseline Neutrino (SBN) Program @ Fermilab**

Fermilab SBN program

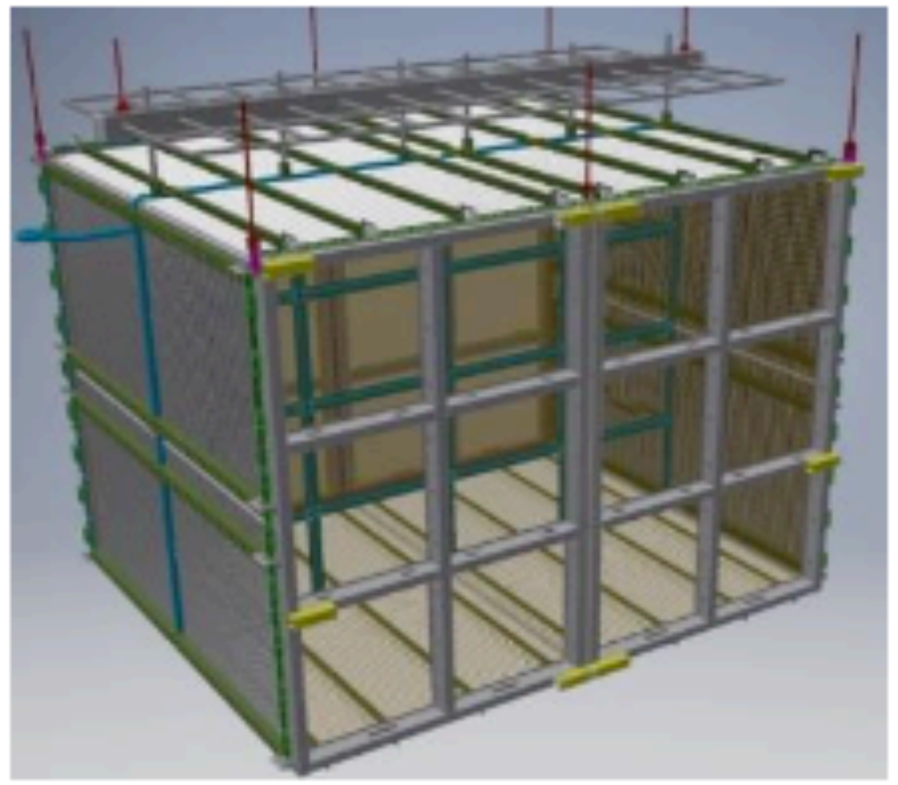


- three LArTPC detectors, with same neutrino beamline and different baseline
- reduce statistical uncertainties with large mass far detector (ICARUS)
- reduce systematic uncertainties with same LArTPC detector technology

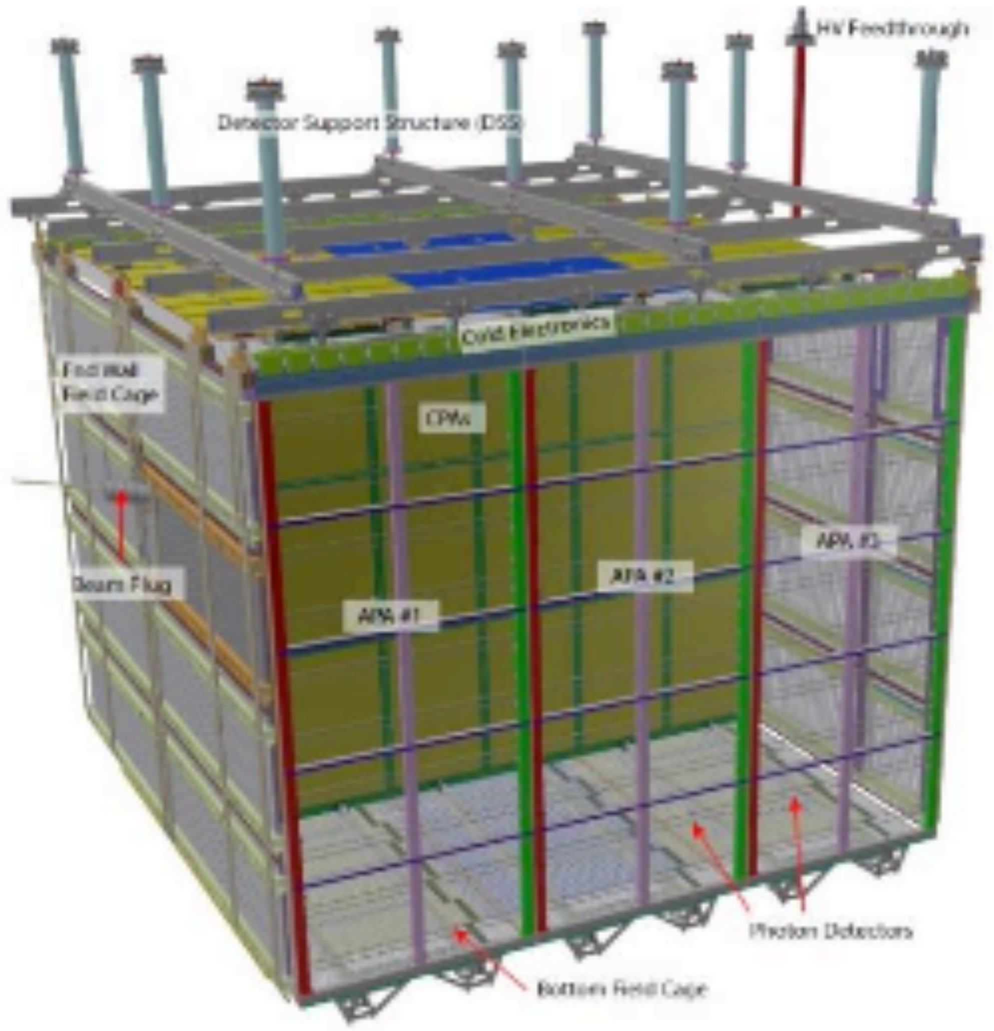
Fermilab SBN program



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



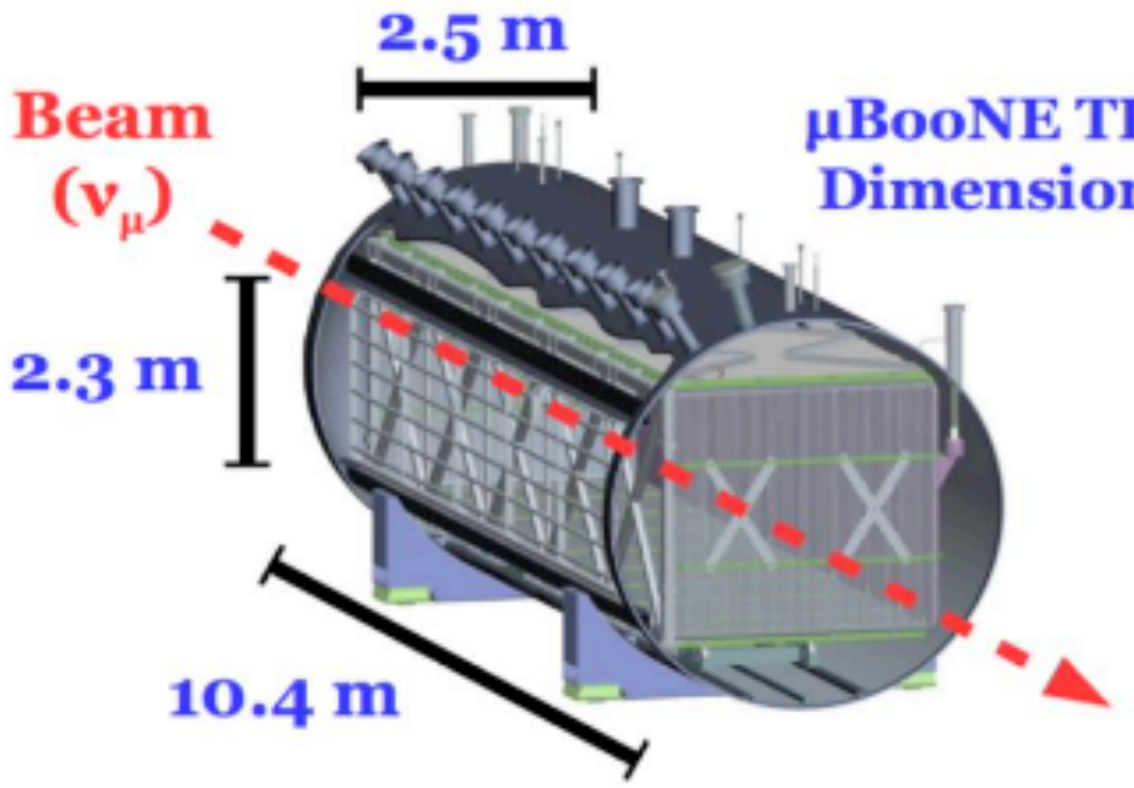
SBND, 112 ton
4m x 4m x 5m



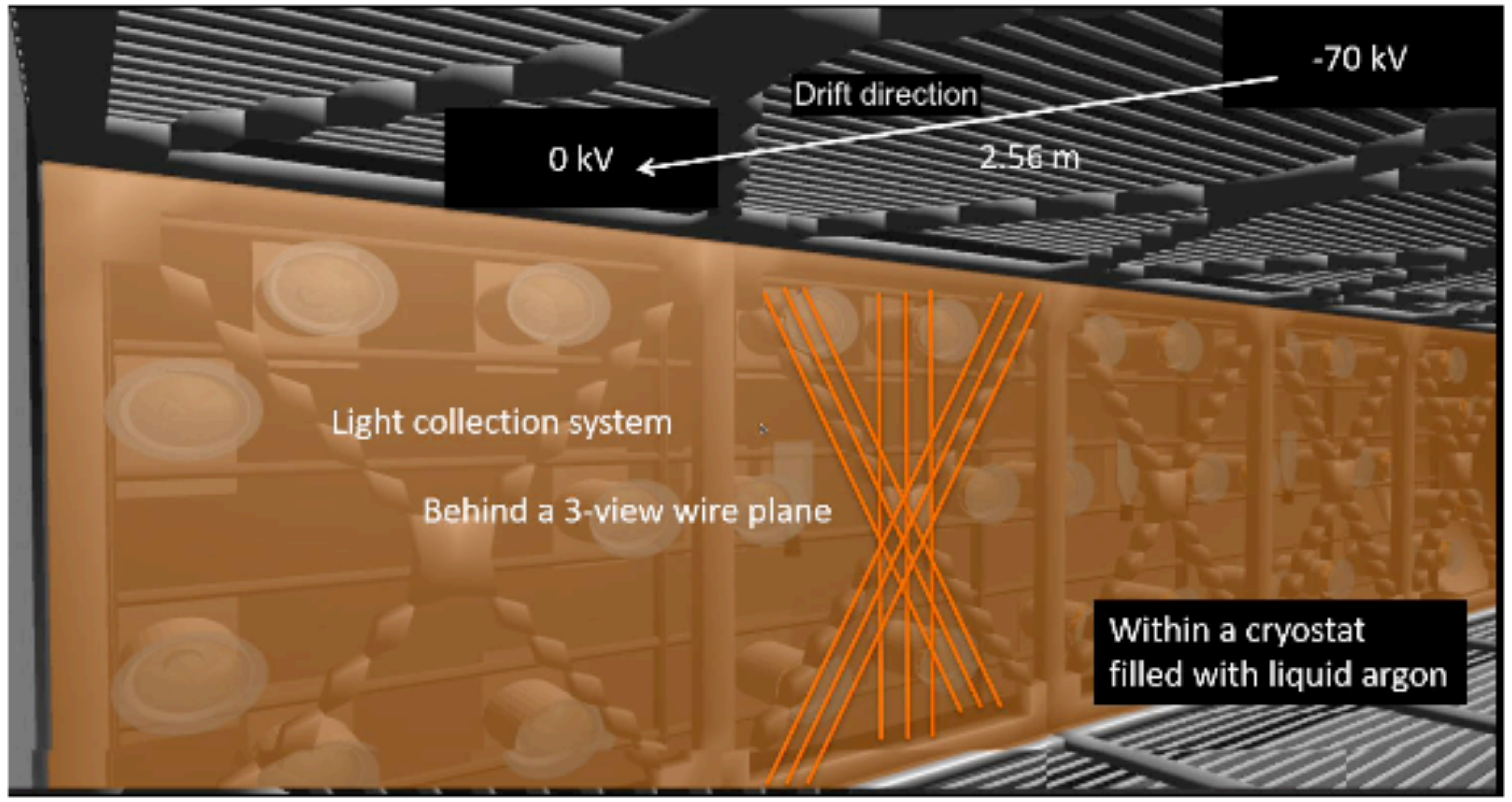
ICARUS, 476 ton
1.5m x 2.2m x 18m x 4

- 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

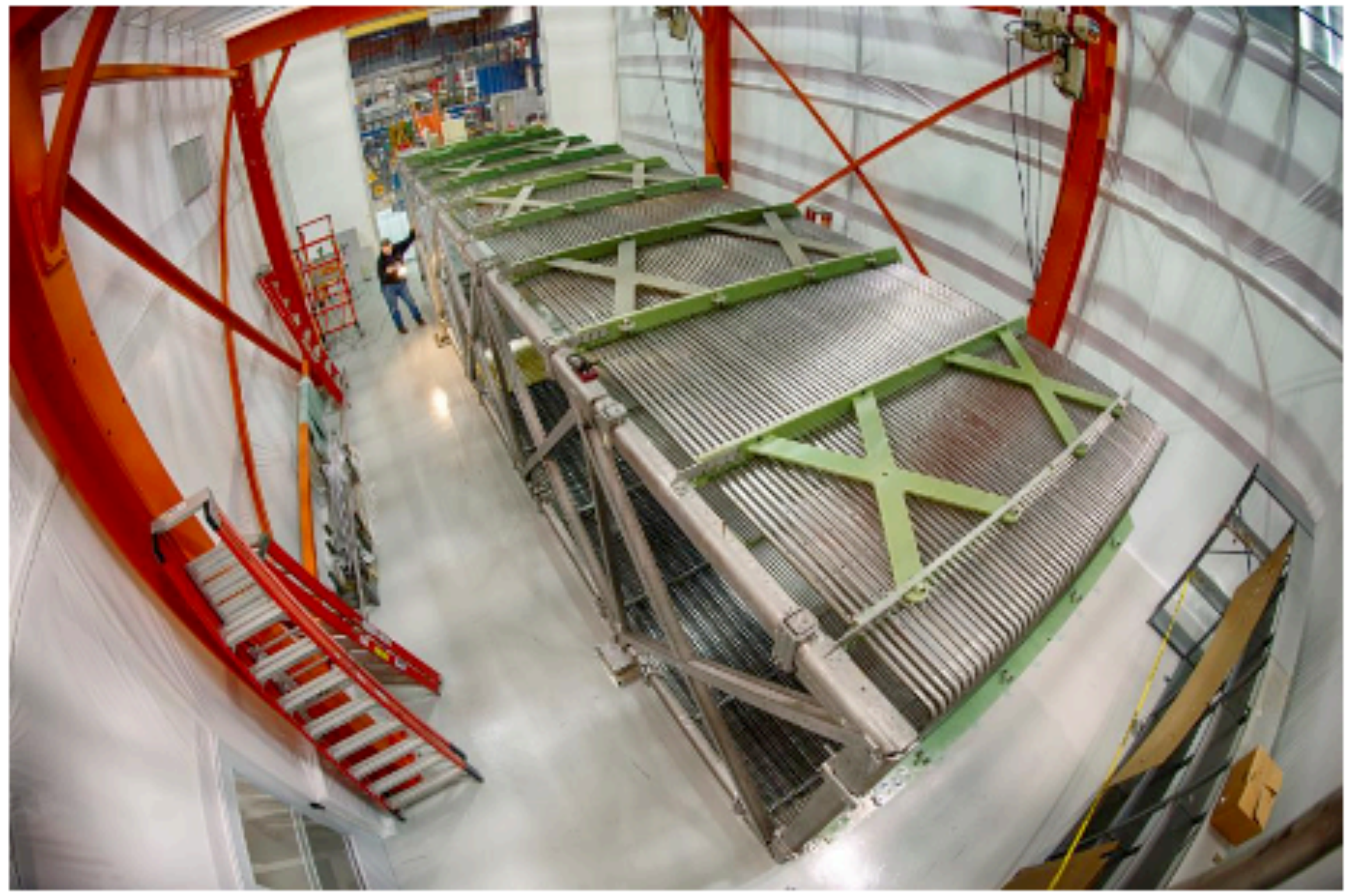
MicroBooNE



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

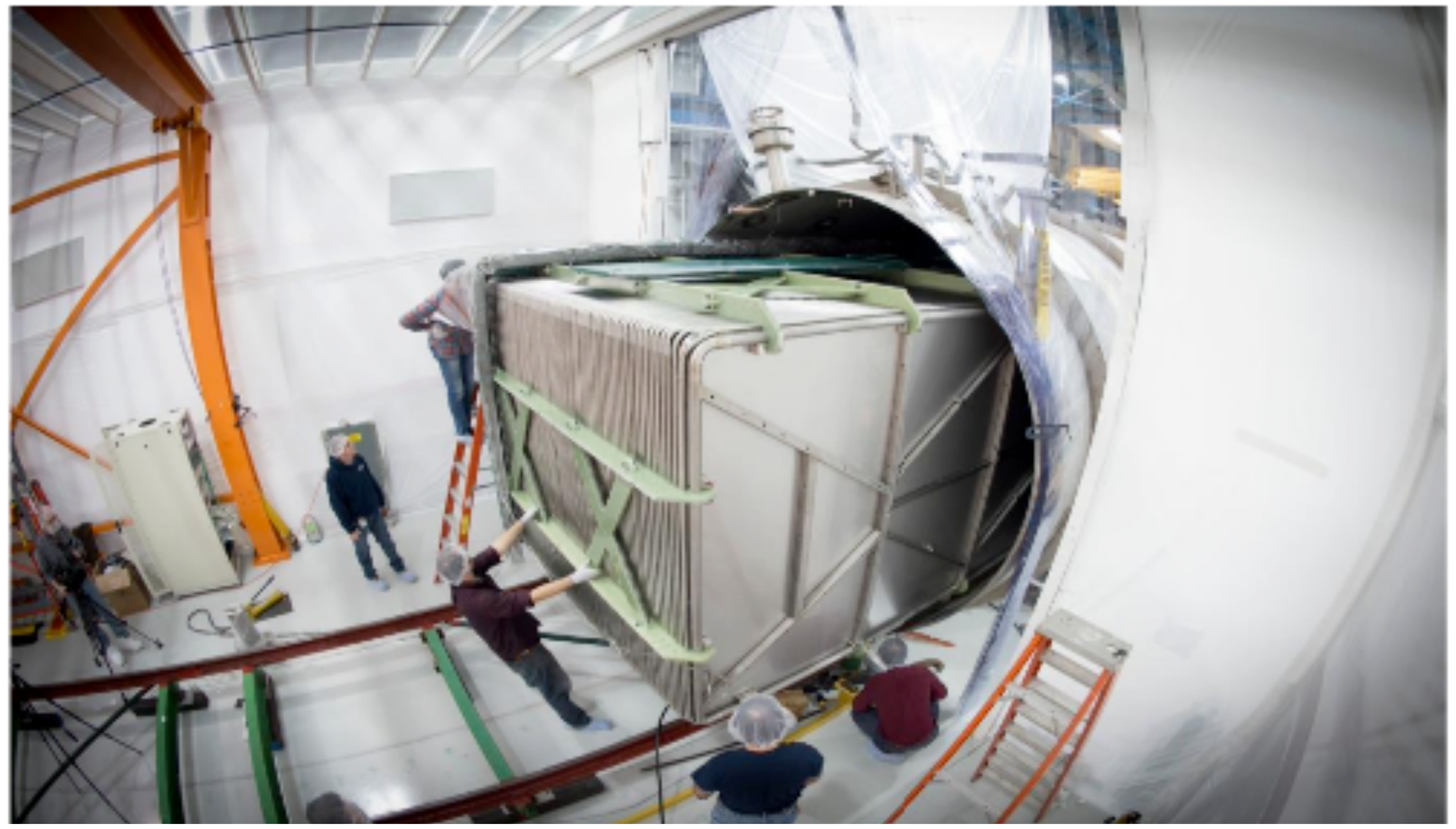


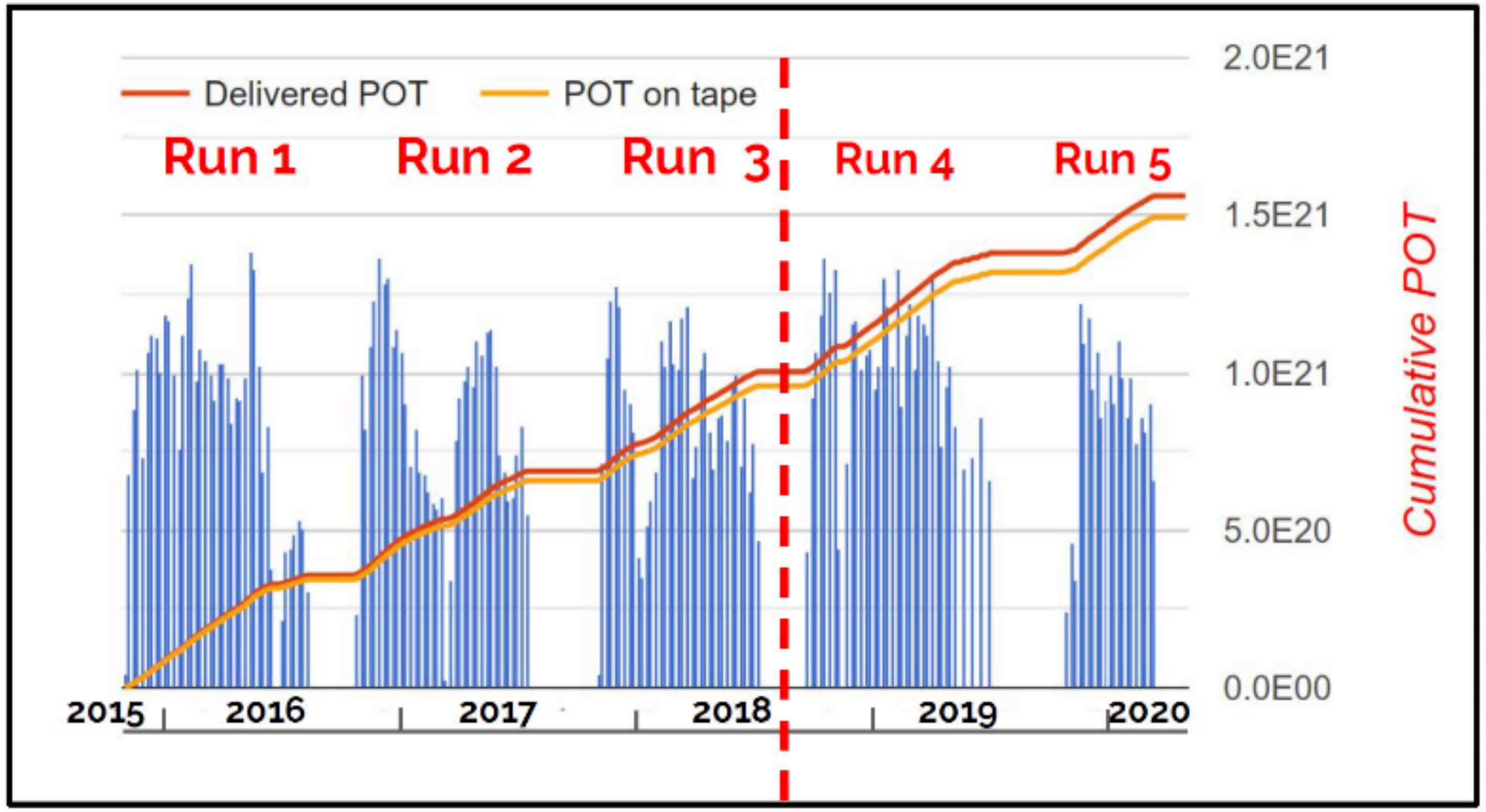
-70 kV
Drift direction
0 kV
2.56 m
Light collection system
Behind a 3-view wire plane
Within a cryostat
filled with liquid argon



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
  - excellent LAr purity
  - pioneered LArTPC detector physics
  - stable & long-term running

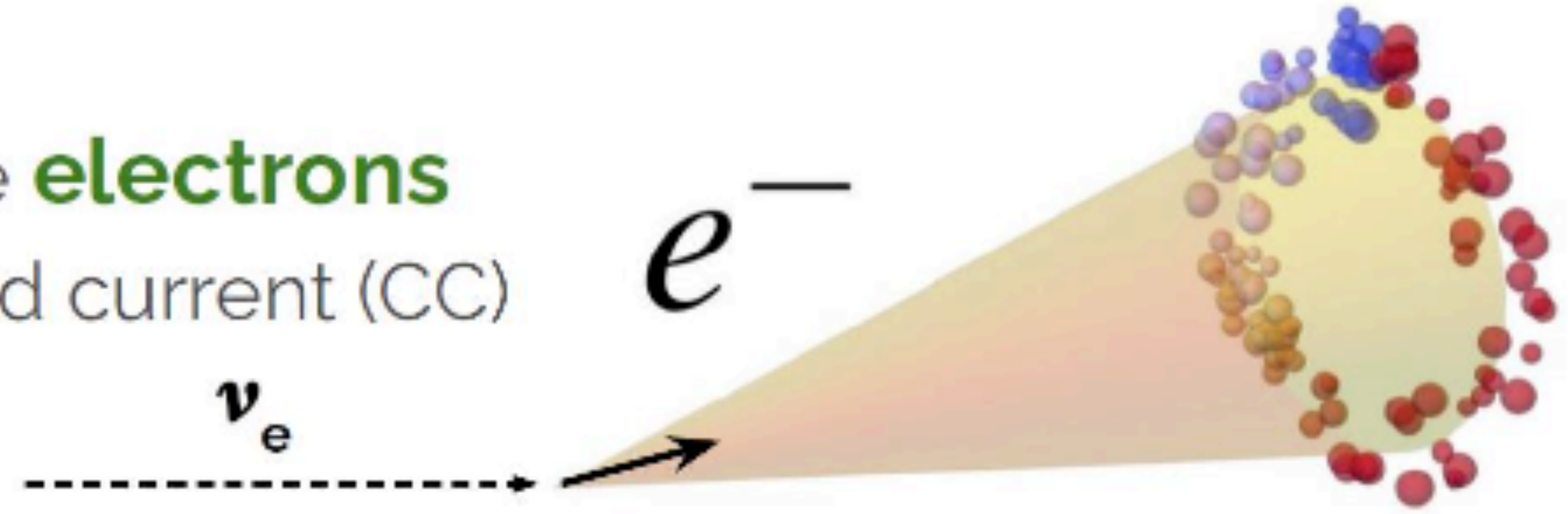




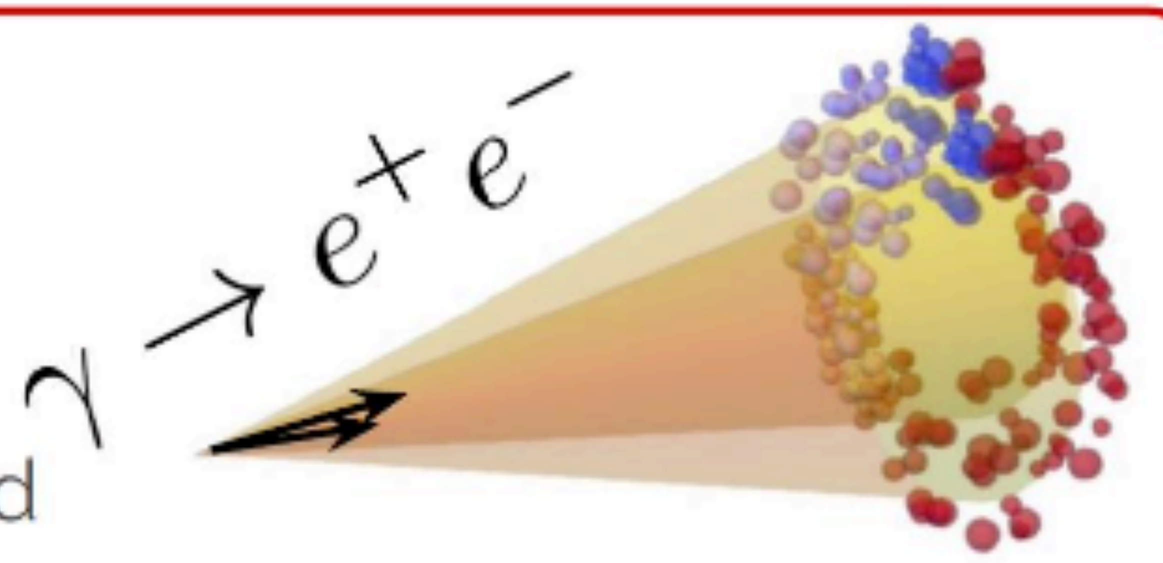
The MiniBooNE Anomaly: recap

- 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

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



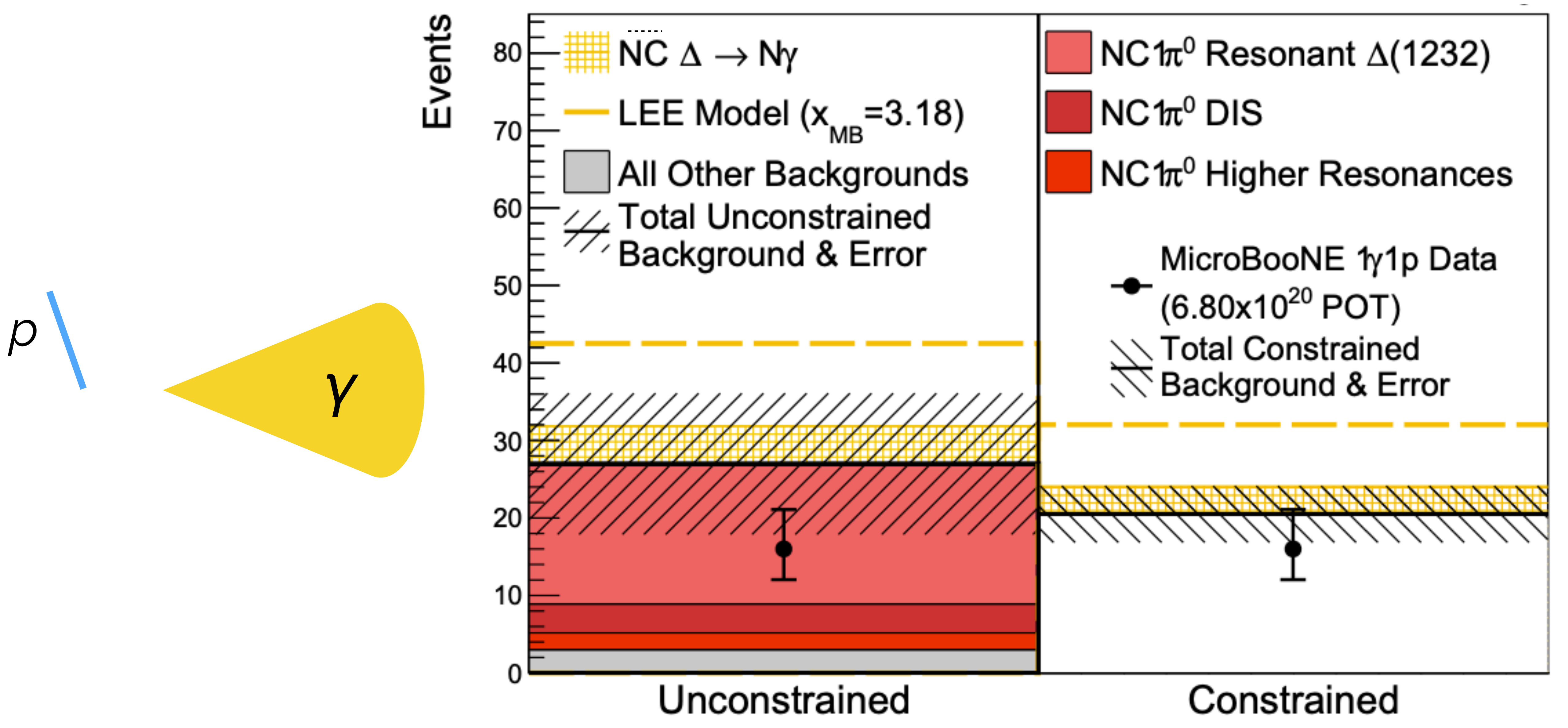
However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring

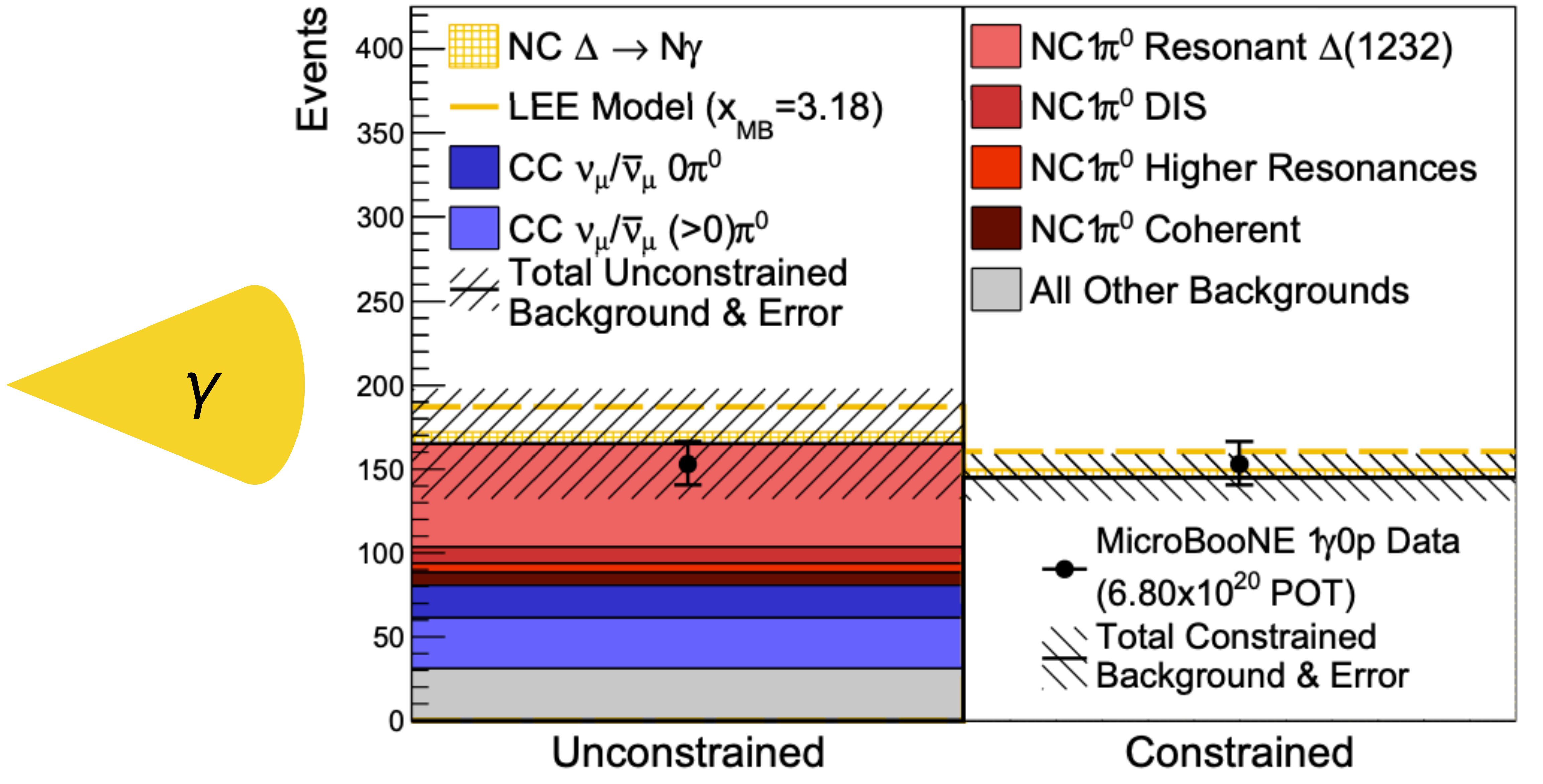


MicroBooNE LEE result

- 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

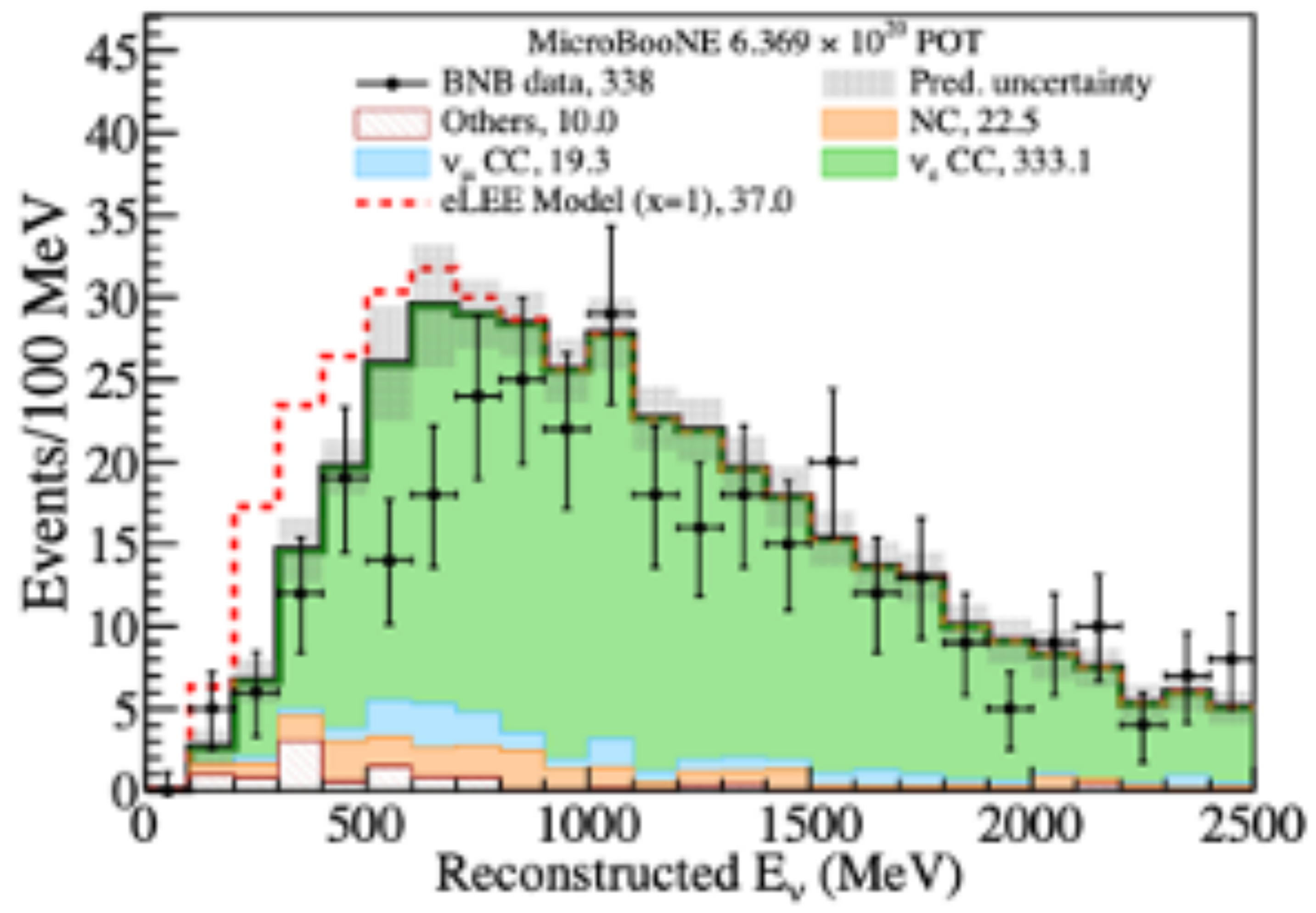




MicroBooNE LEE result

- 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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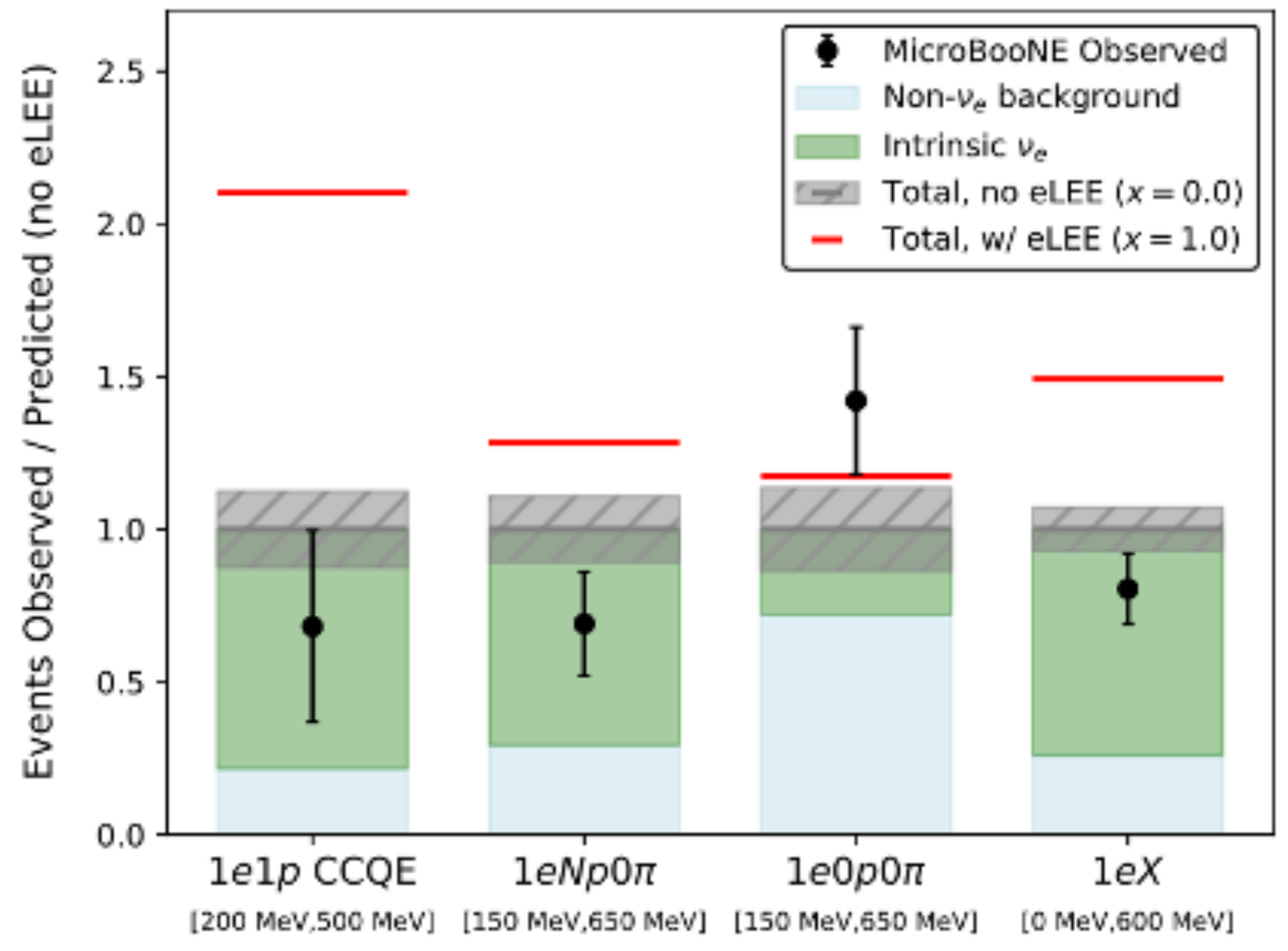
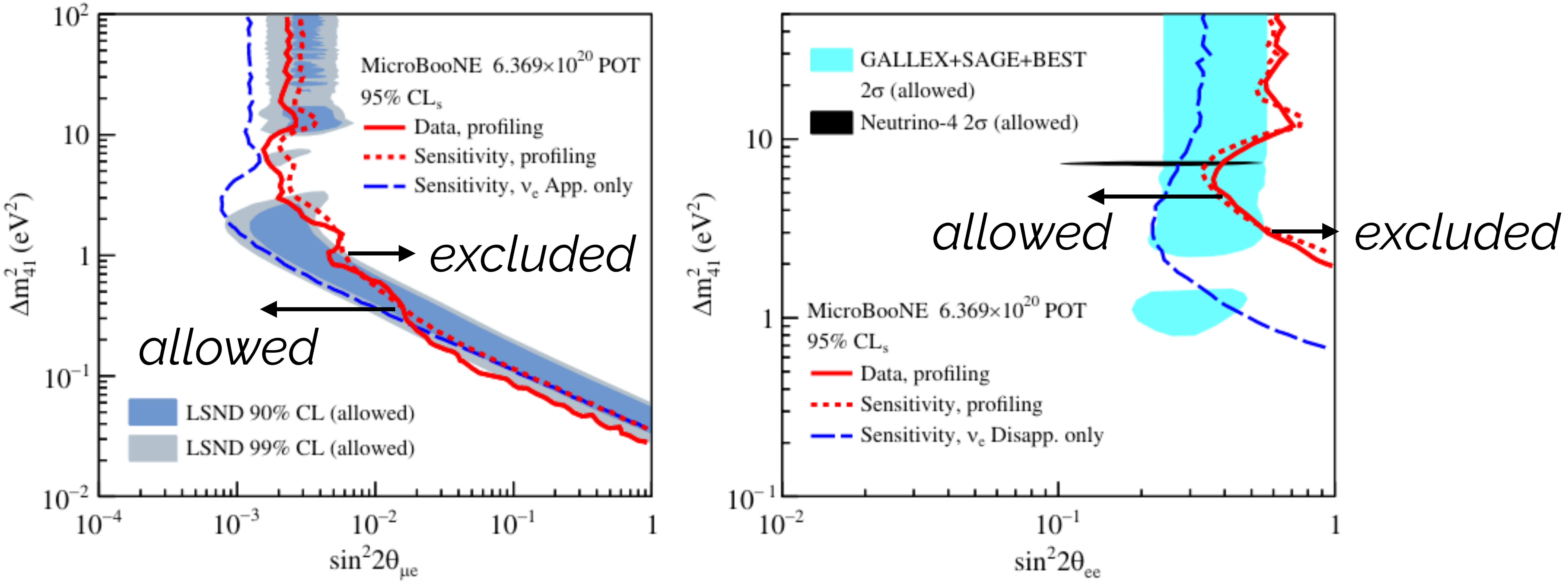


MicroBooNE sterile neutrino search

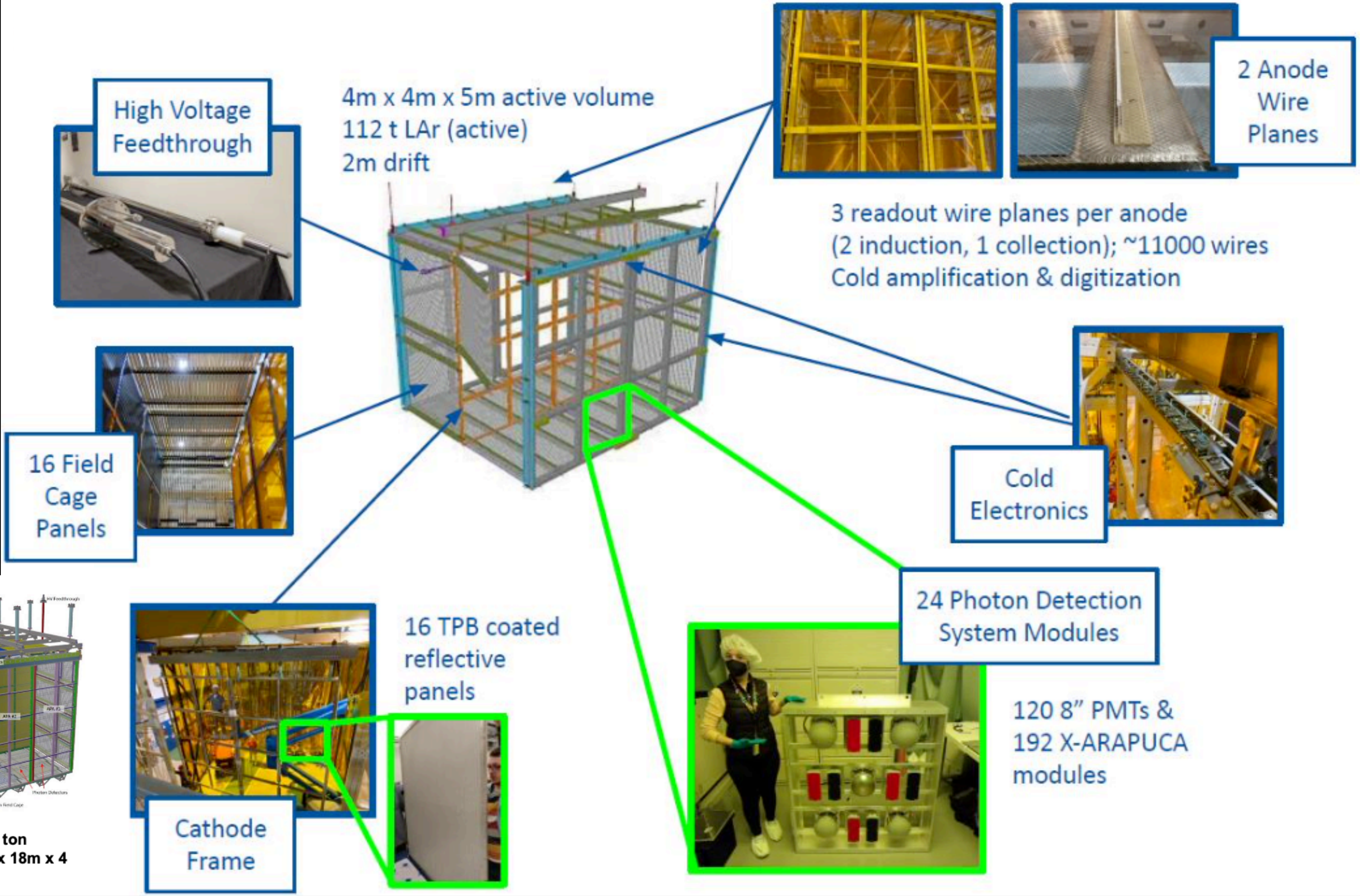
Phy. Rev. Lett. 130 011801 (2023)

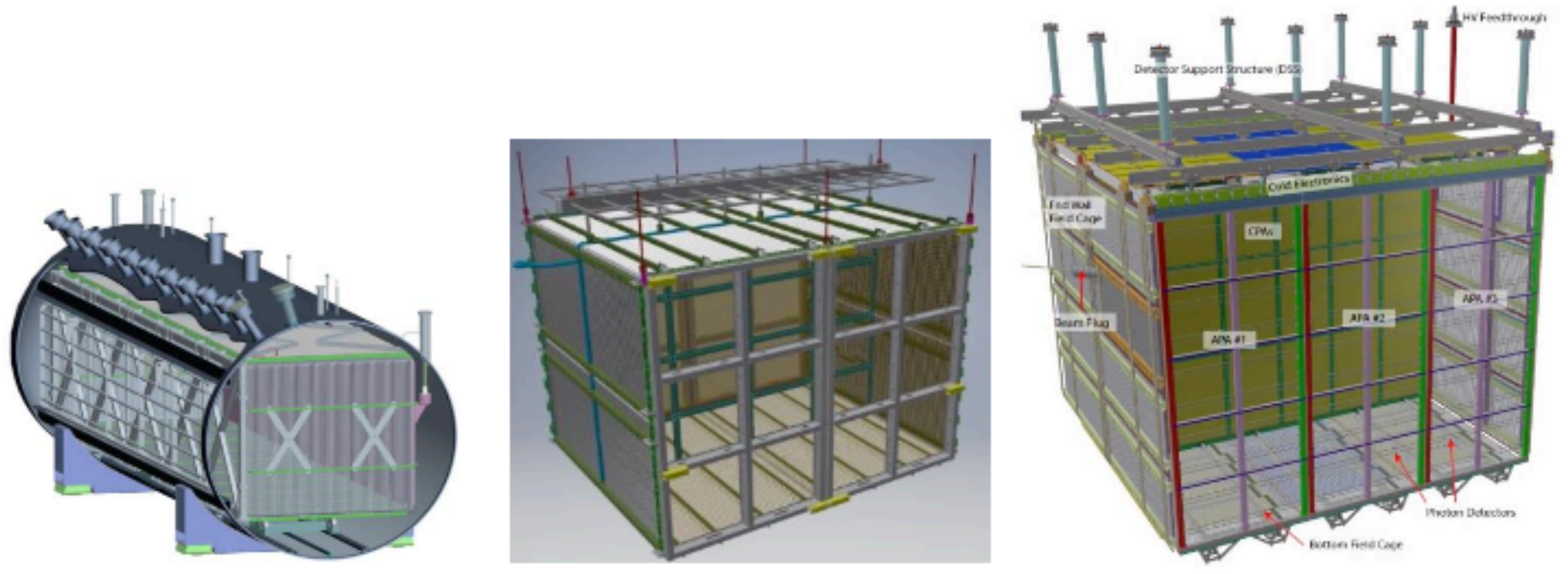


- LEE results are re-interpreted under a sterile neutrino oscillation hypothesis
- MicroBooNE could reject some portion of LSND and GALLEX/SAGE/BEST allowed region
- updated result is aiming to exclude most of the allowed region

Short Baseline Neutrino Detector: SBND

- same LArTPC technology with some upgrade
- closer to the target: much more neutrinos detected
- will start taking data in late 2023



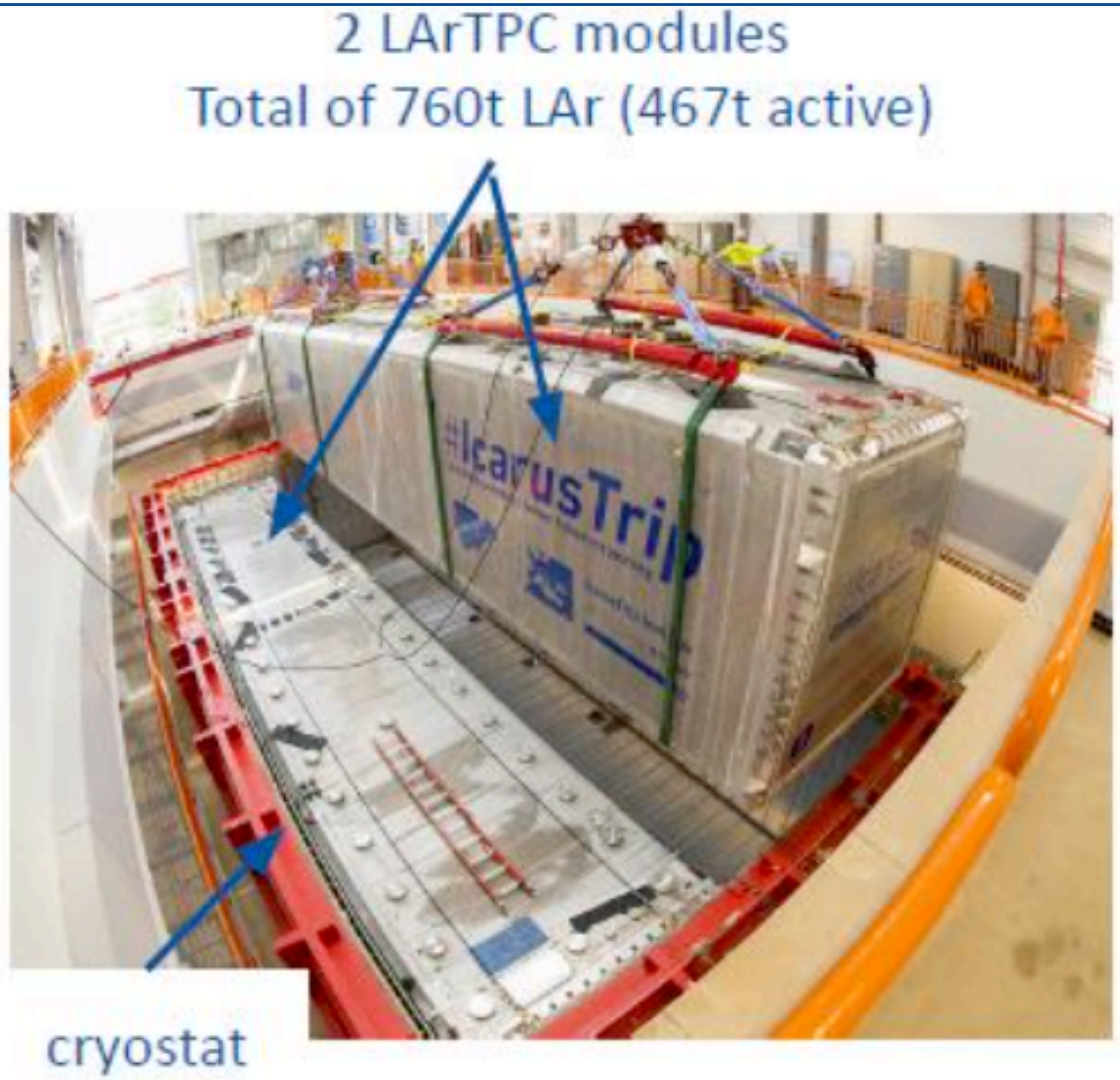


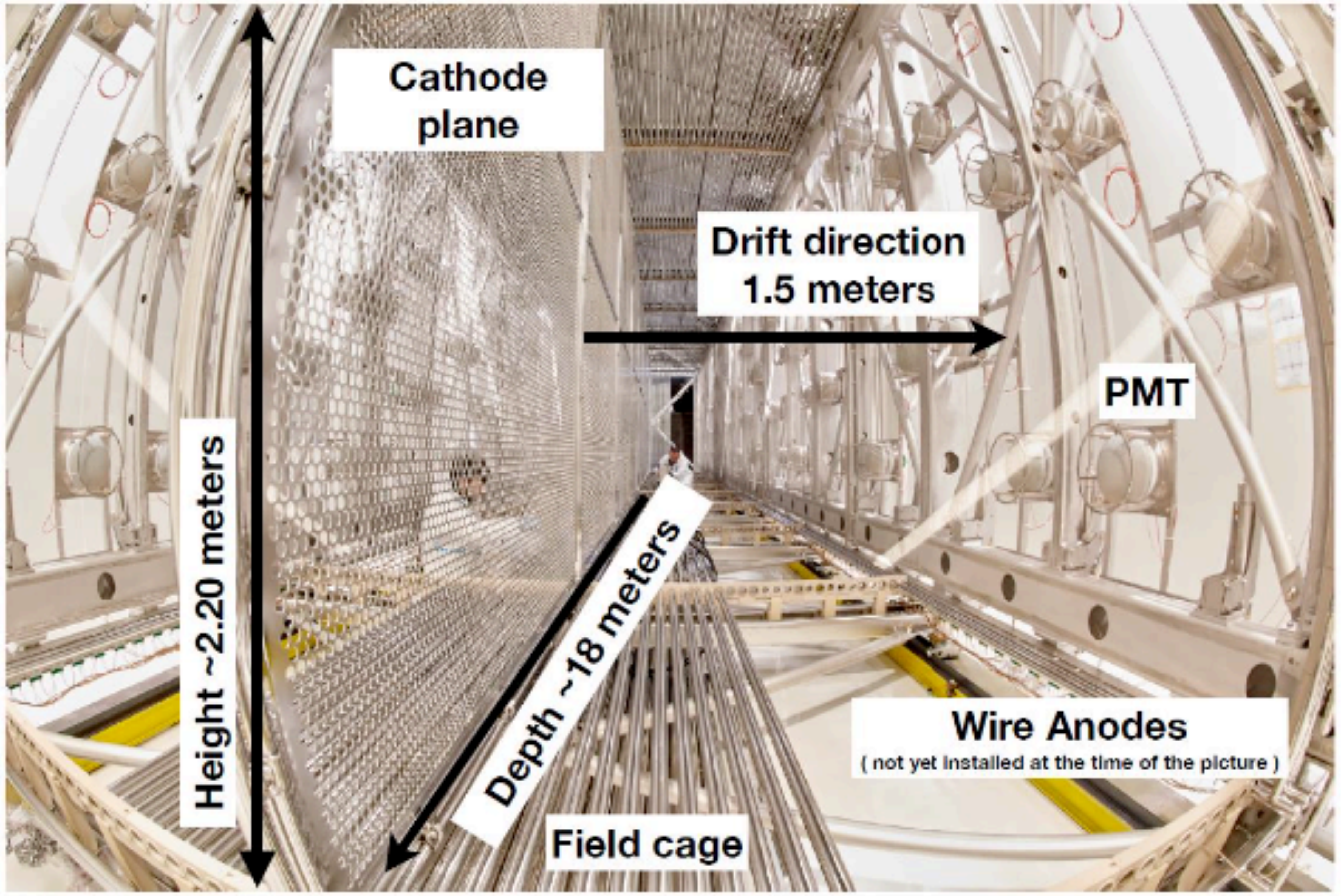
MicroBooNE, 87 ton
2.3m x 2.5m x 10.4m

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

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

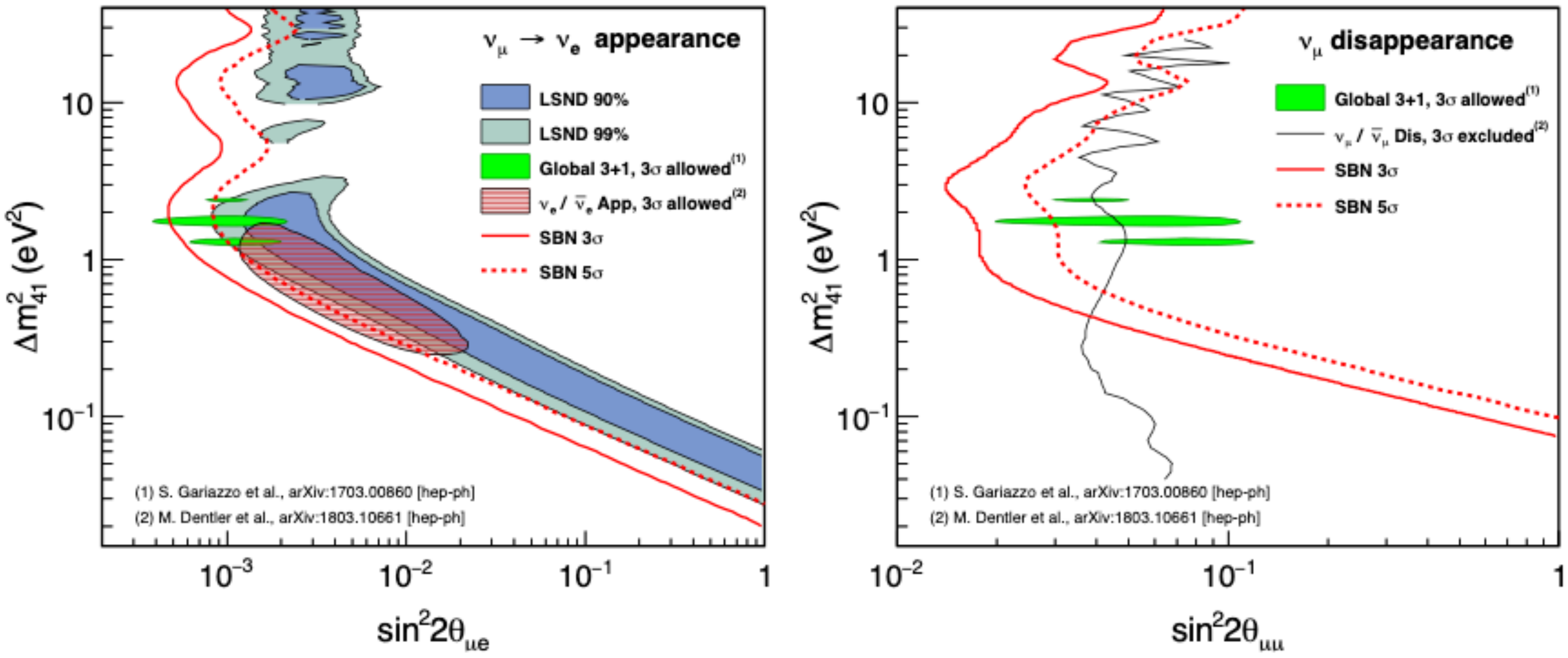
ICARUS





- 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

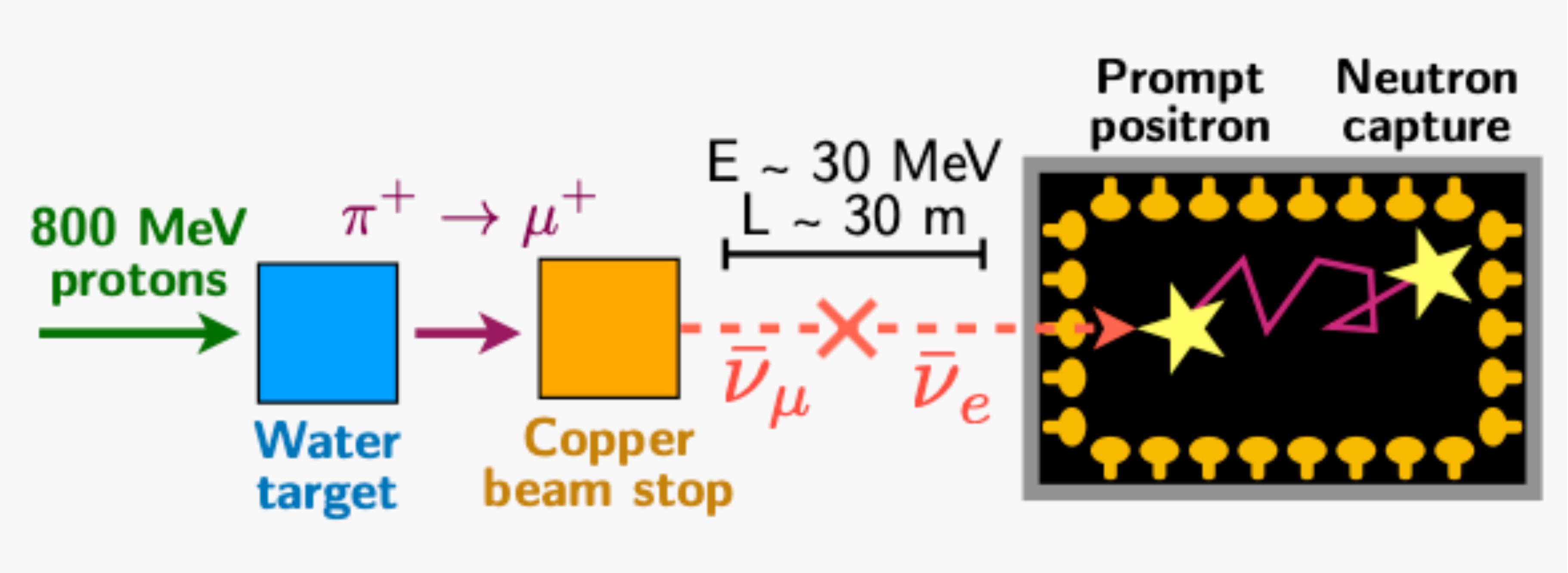
Summary

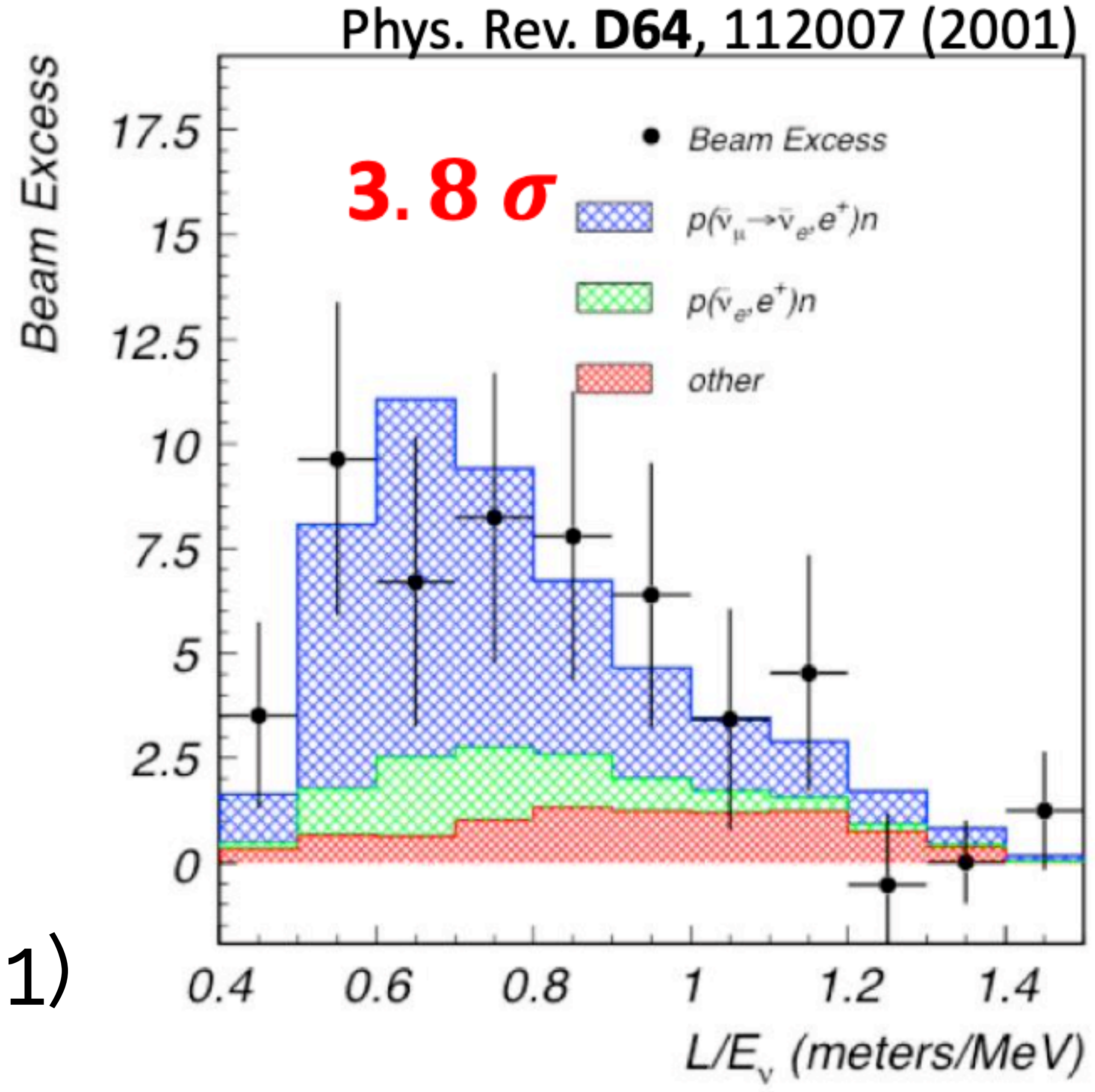
- neutrinos oscillate, and three-neutrino oscillation is well understood
- however several neutrino experiments showed anomalies, which could be explained by postulating an additional neutrino: **sterile neutrino**
- Fermilab SBN program consists of three LArTPC neutrino detectors, MicroBooNE, SBND, 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

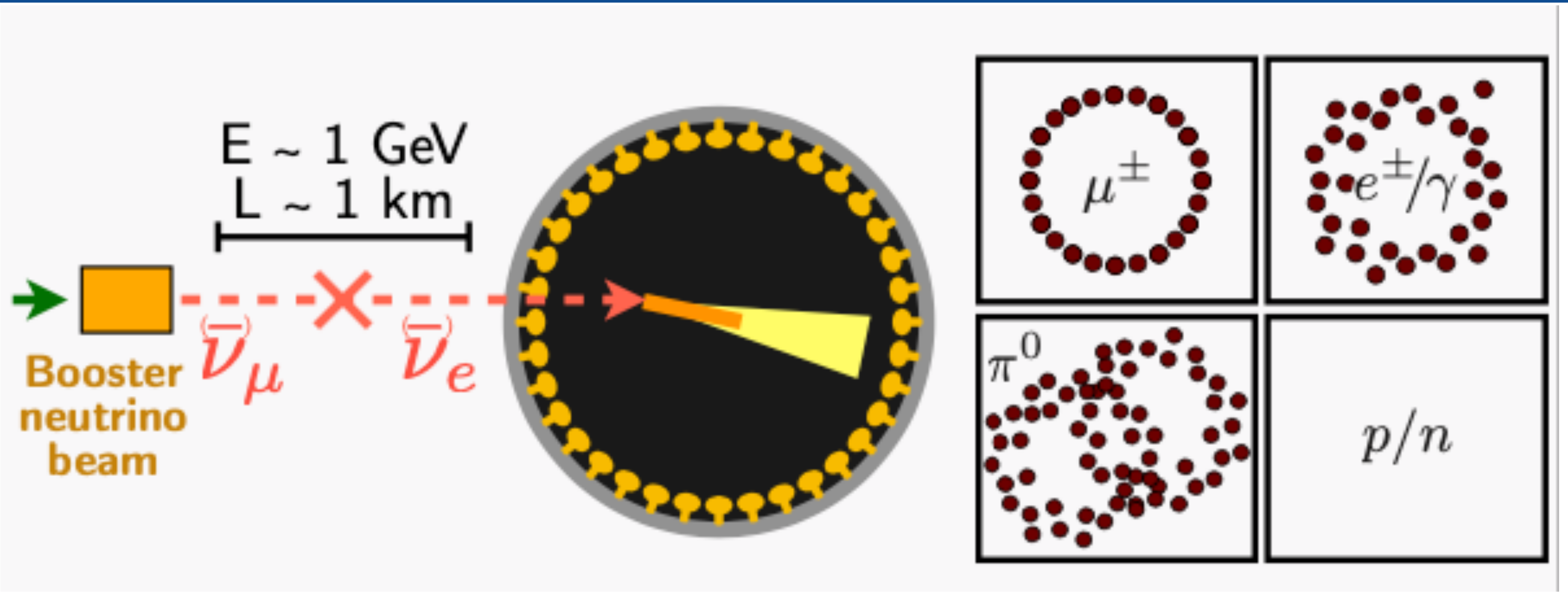
Backup slides

LSND & MiniBooNE anomaly

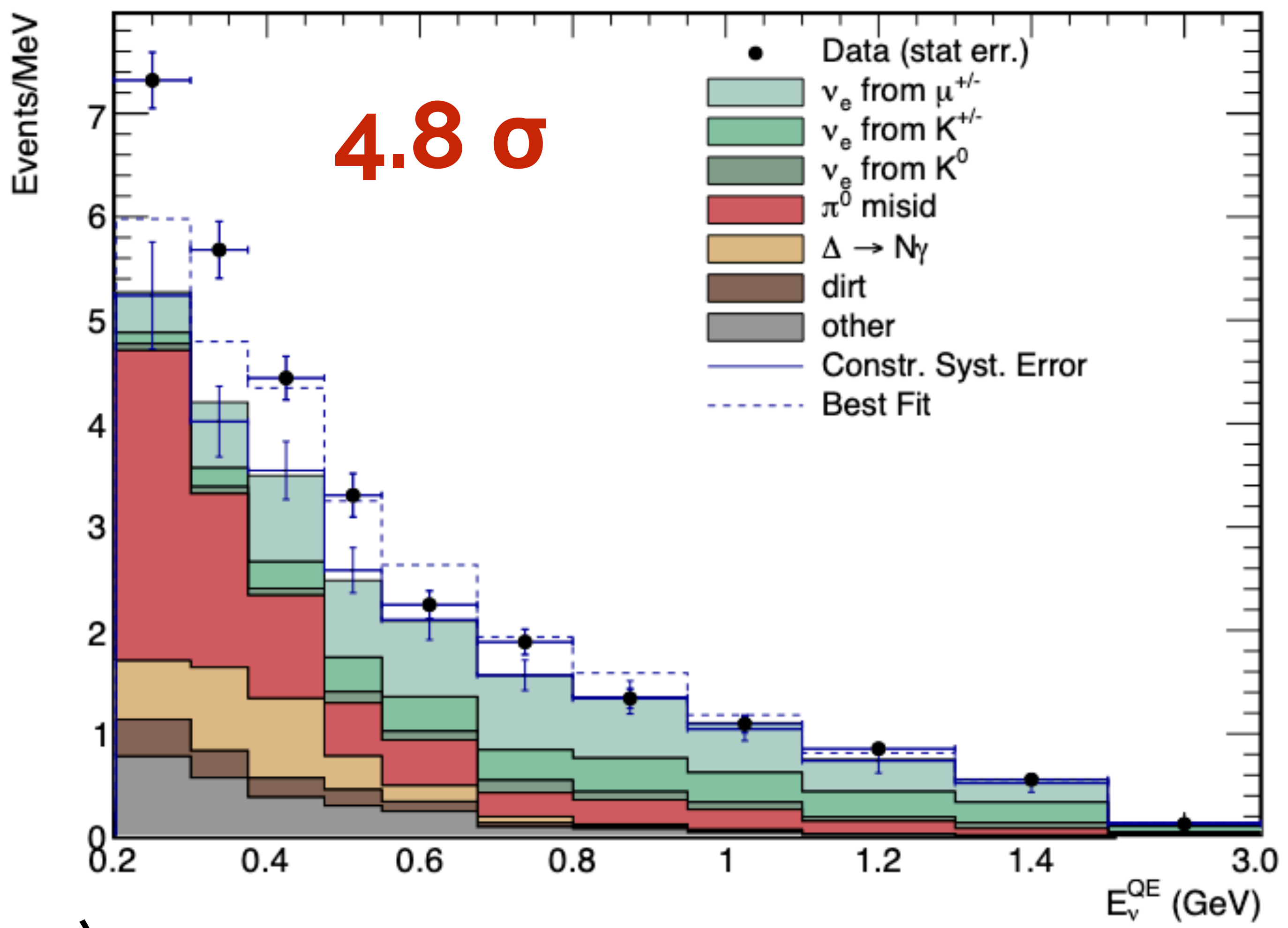




- **LSND** (1990-2001)
- $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ excess over background suggests evidence for oscillation at Δm^2 ~ 1eV^2



arxiv:2006.16883



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

LArTPC: Liquid Argon Time Projection Chamber

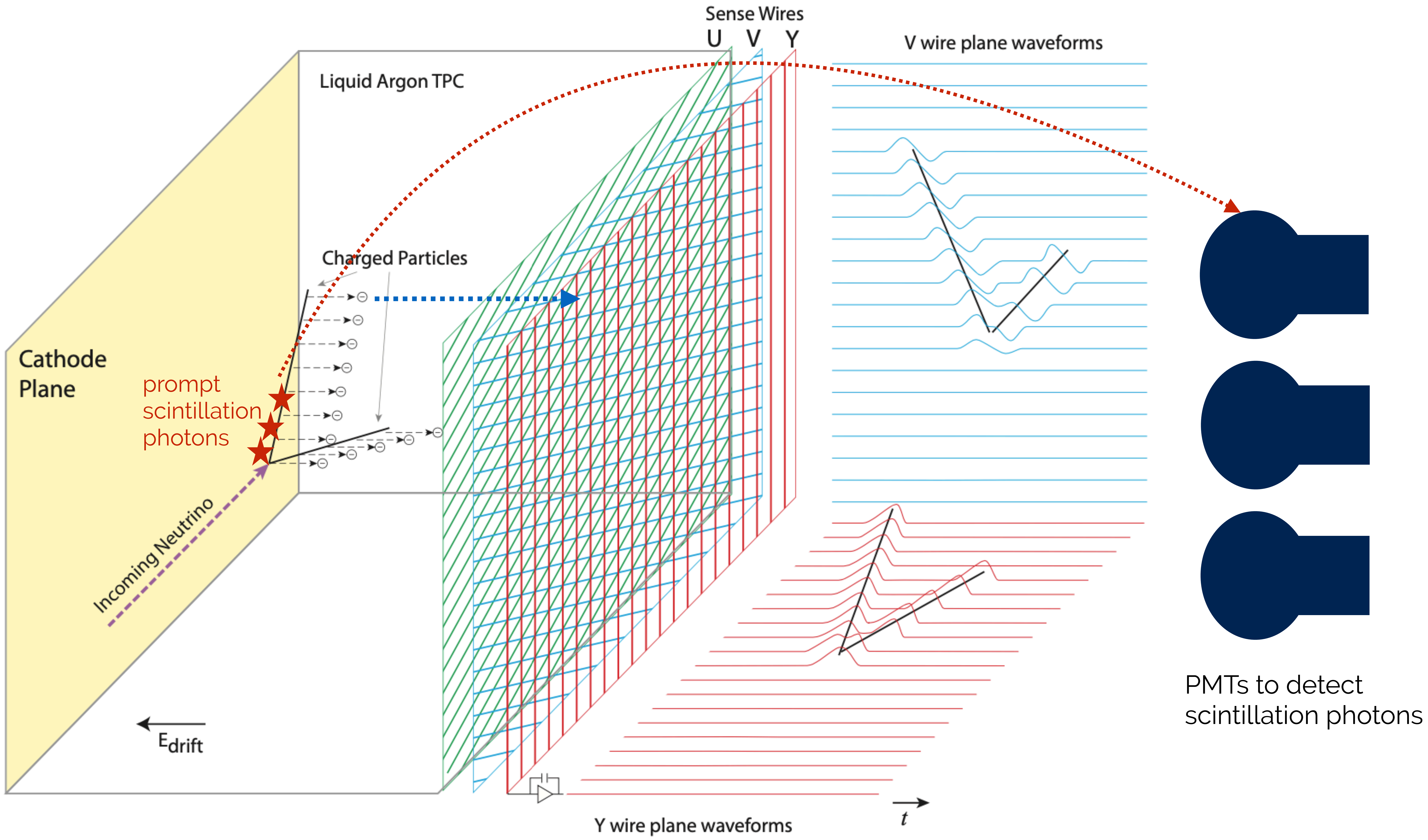
charged particle enters detector

⬇

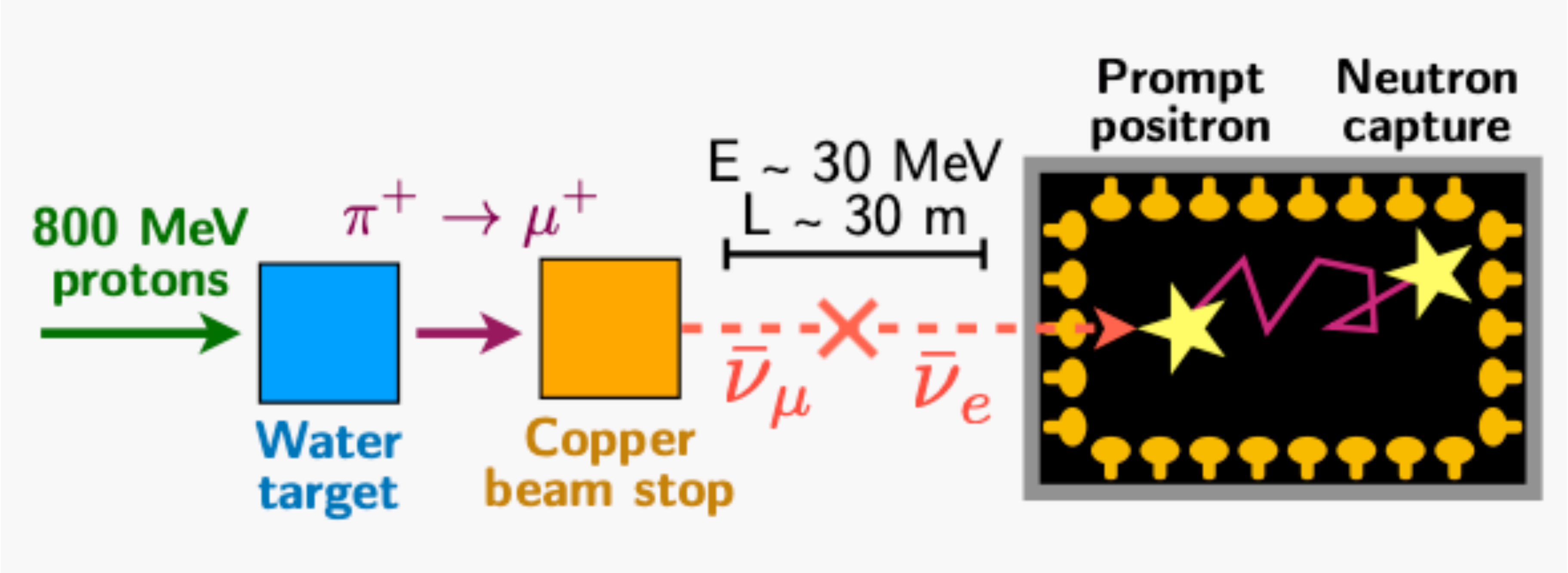
scintillation light emitted by excited Ar, detected by PMTs

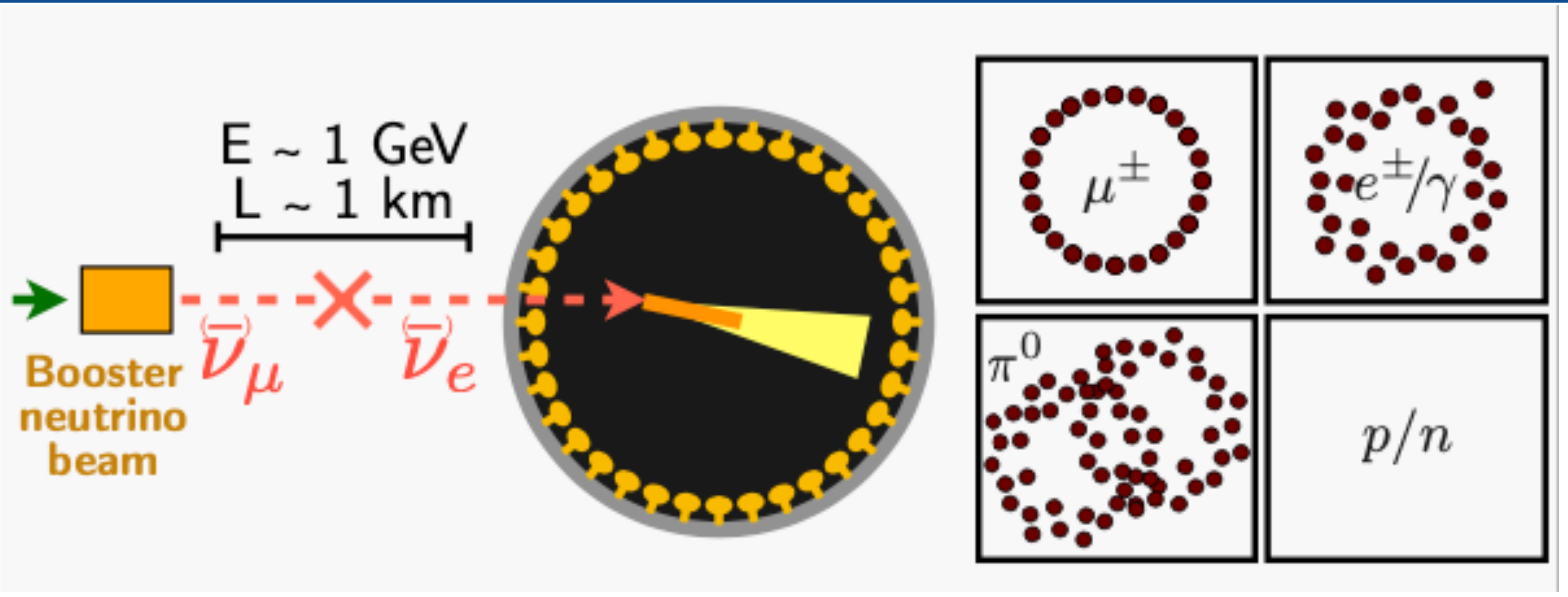
⬇

ionization electrons drift to anode plane, detected by sense wires

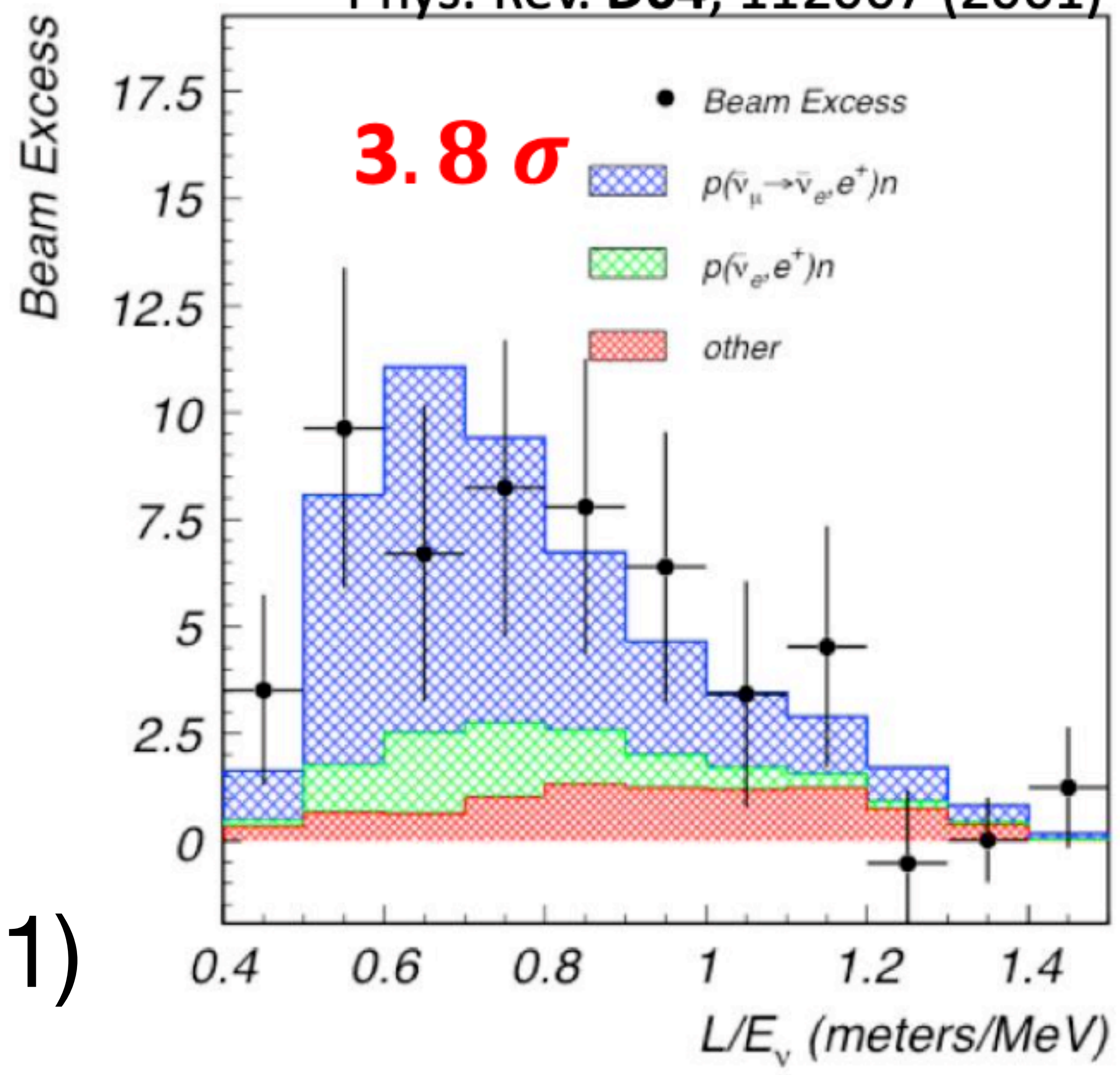


LSND & MiniBooNE anomaly

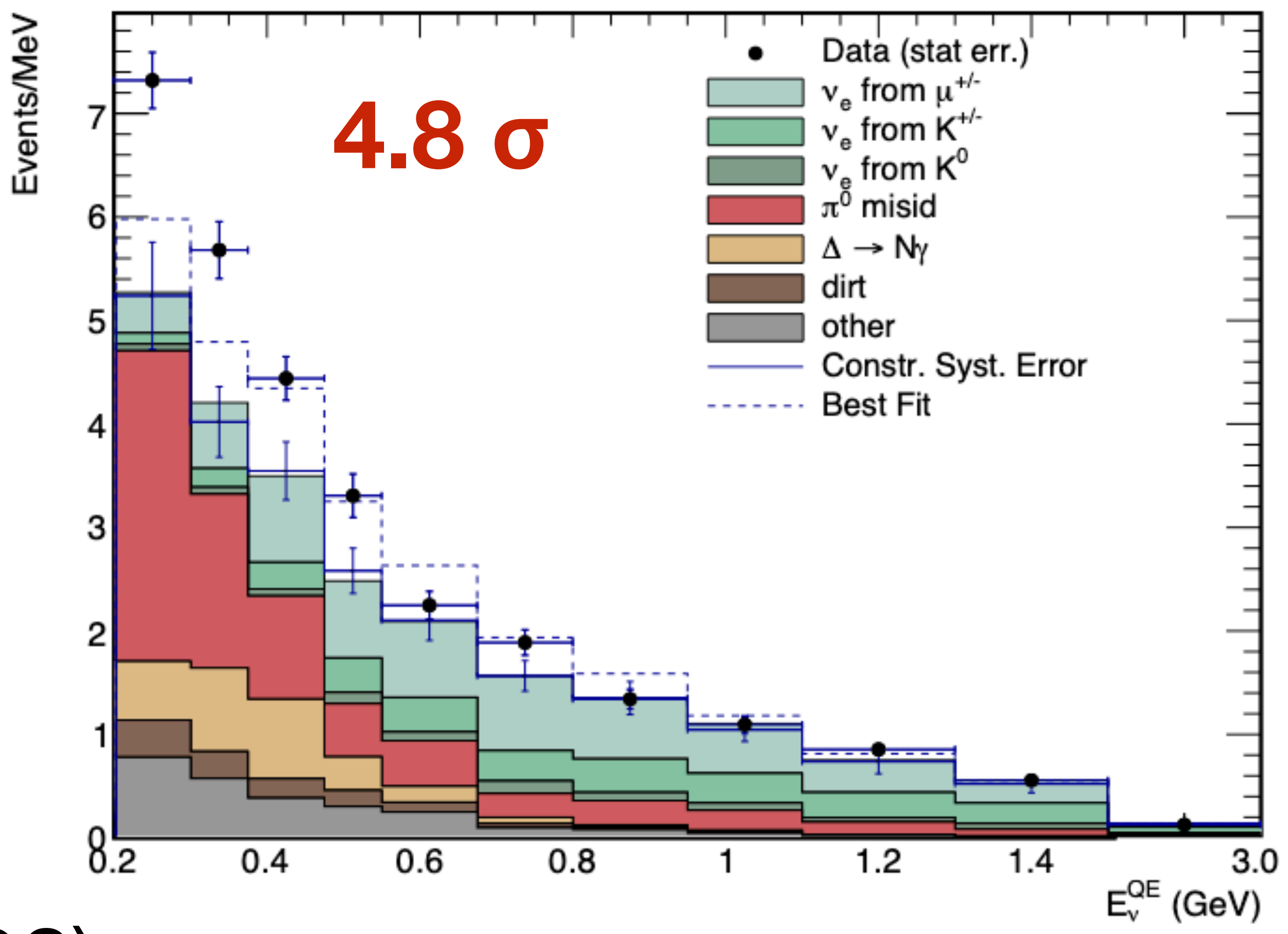




Phys. Rev. **D64**, 112007 (2001)



arxiv:2006.16883



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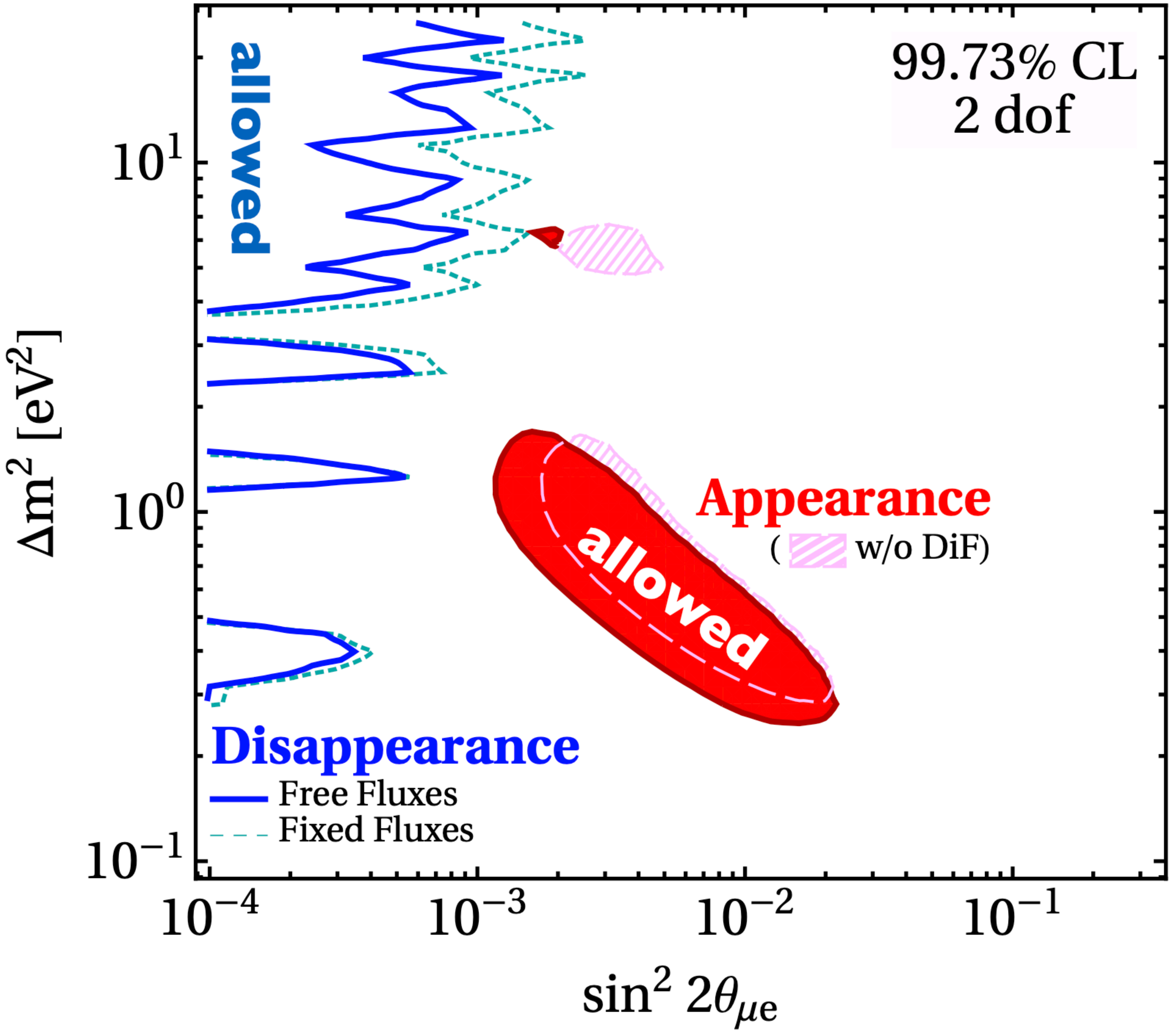
- measured ν_μ-> ν_e and $\bar{\nu}_\mu$-> $\bar{\nu}_e$ appearance
- the excess of events at low energy

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

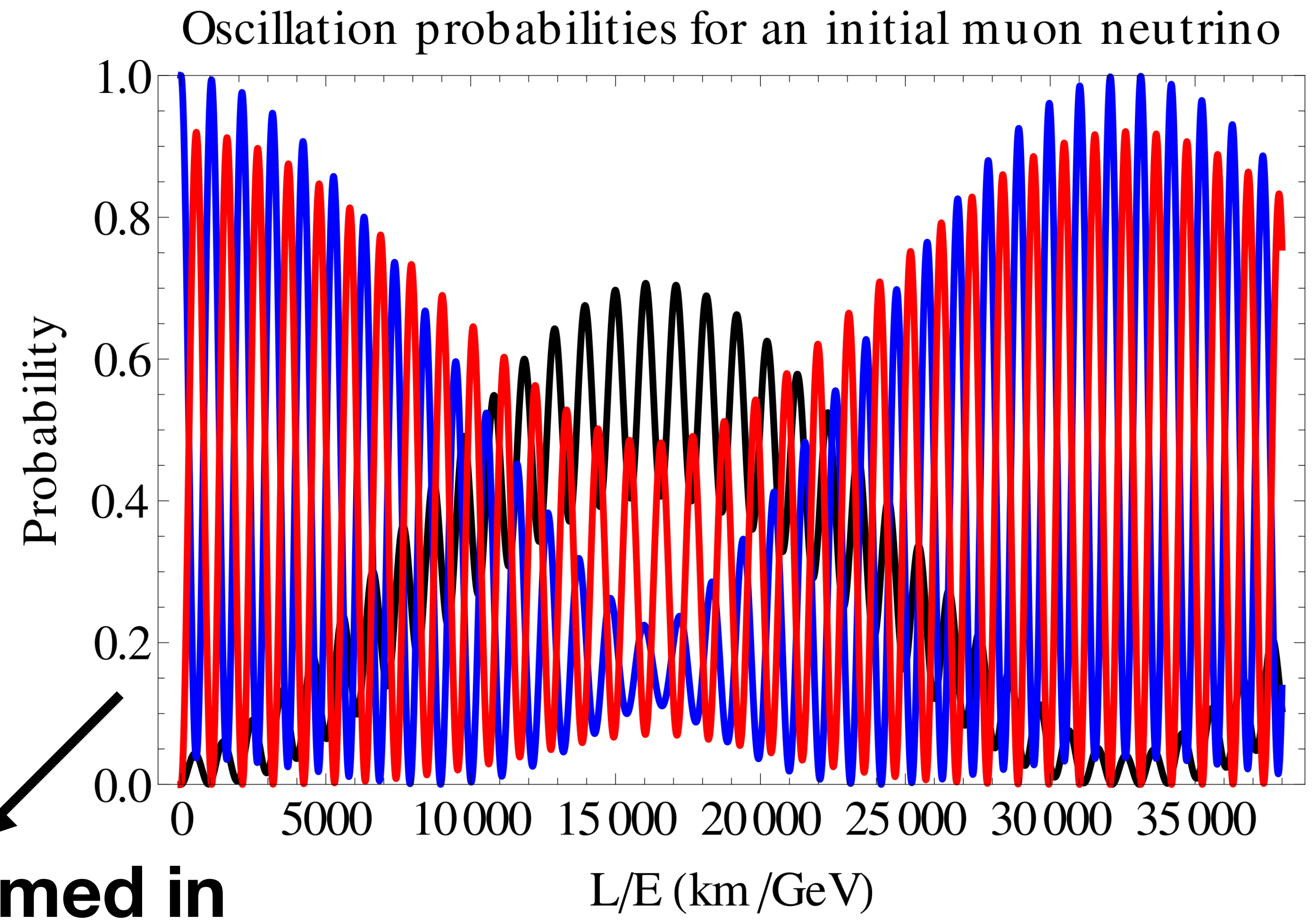
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} &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

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

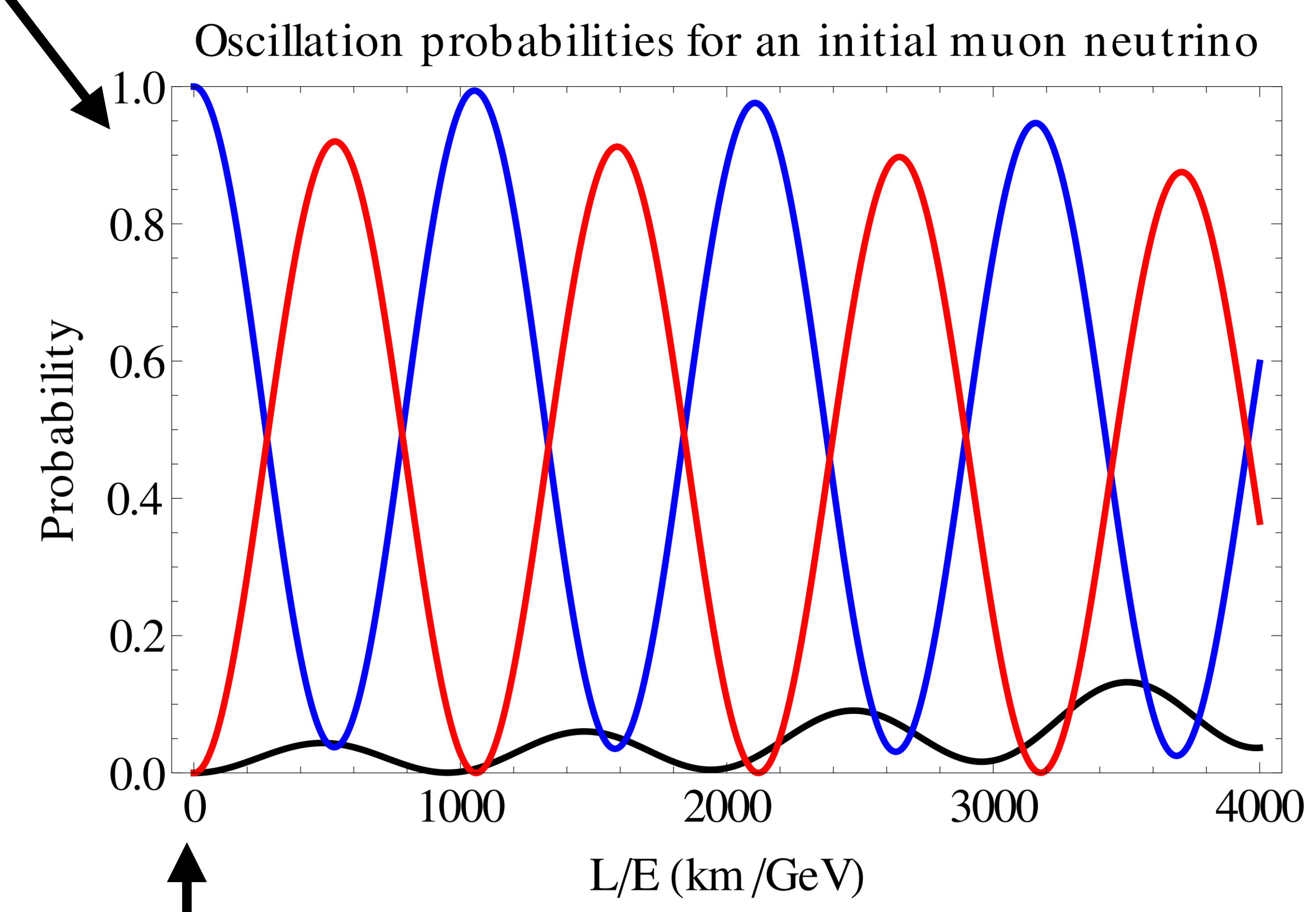
$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

- 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



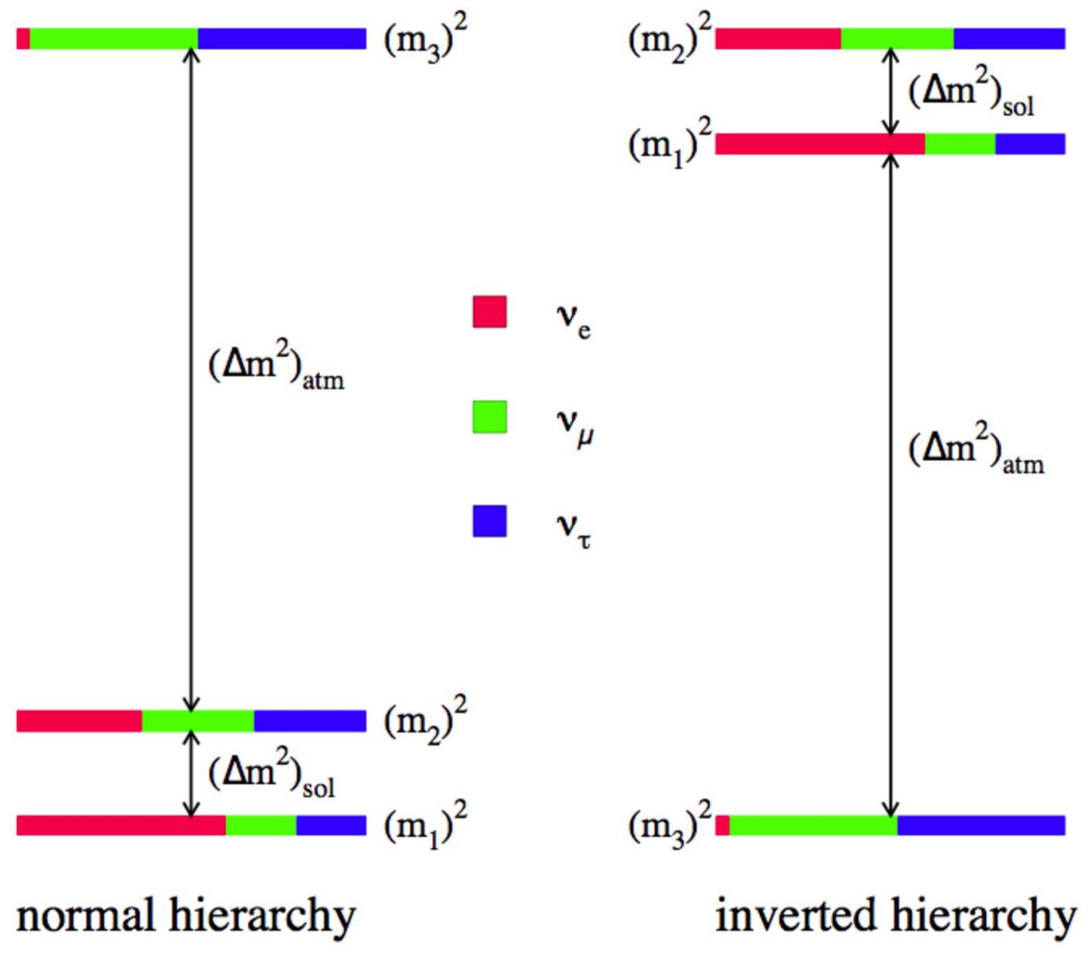
zoomed in



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