(A quick) Introduction to Neutrino Physics

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July 1, 2024
Physics Summer Lecture

Brookhaven
National Laboratory

A brief bio…

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

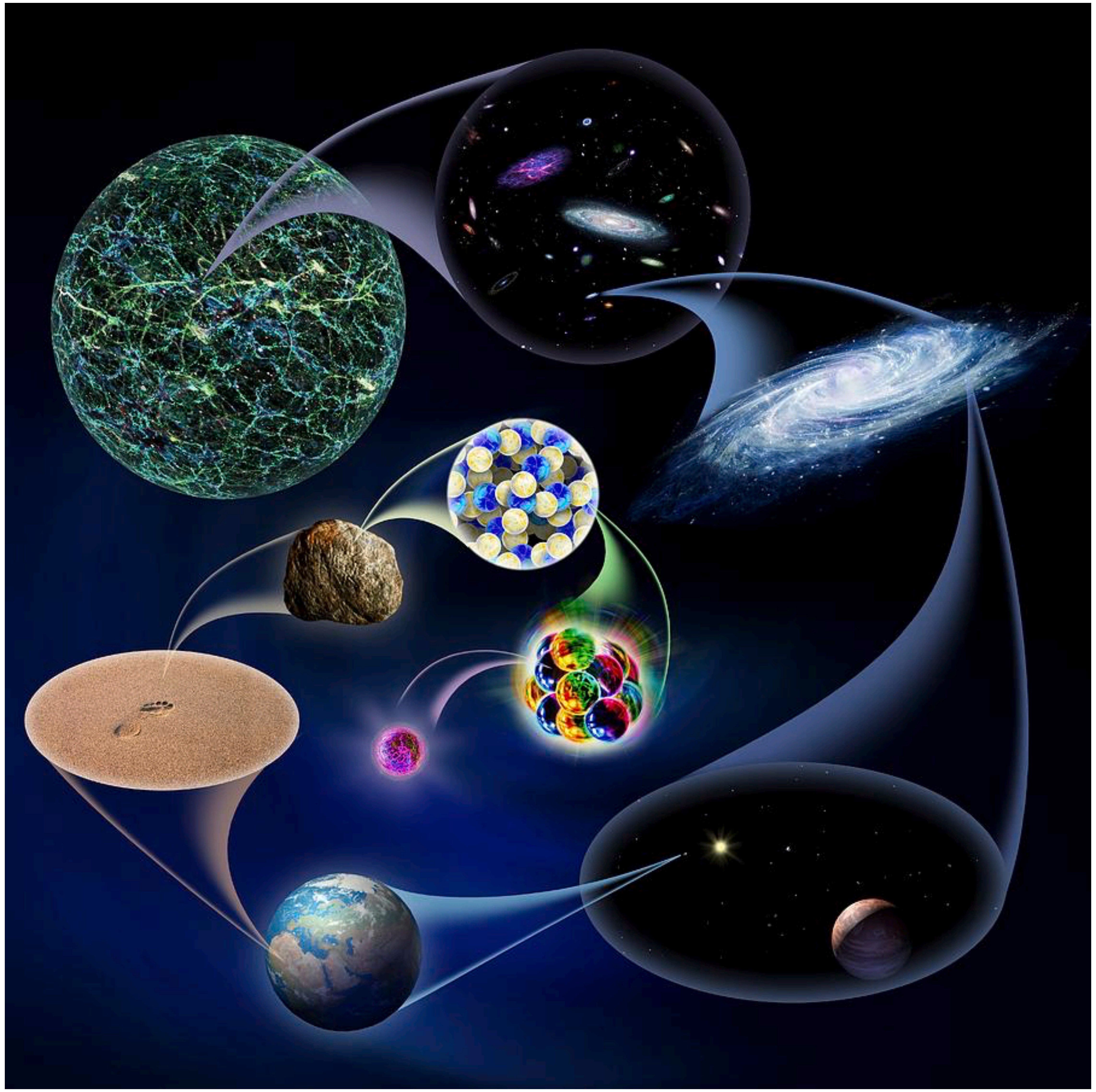
- in college, I started to become more interested in **theoretical particle physic**, with inspirations from Einstein, Feynman, Gell-Mann (who doesn't?)

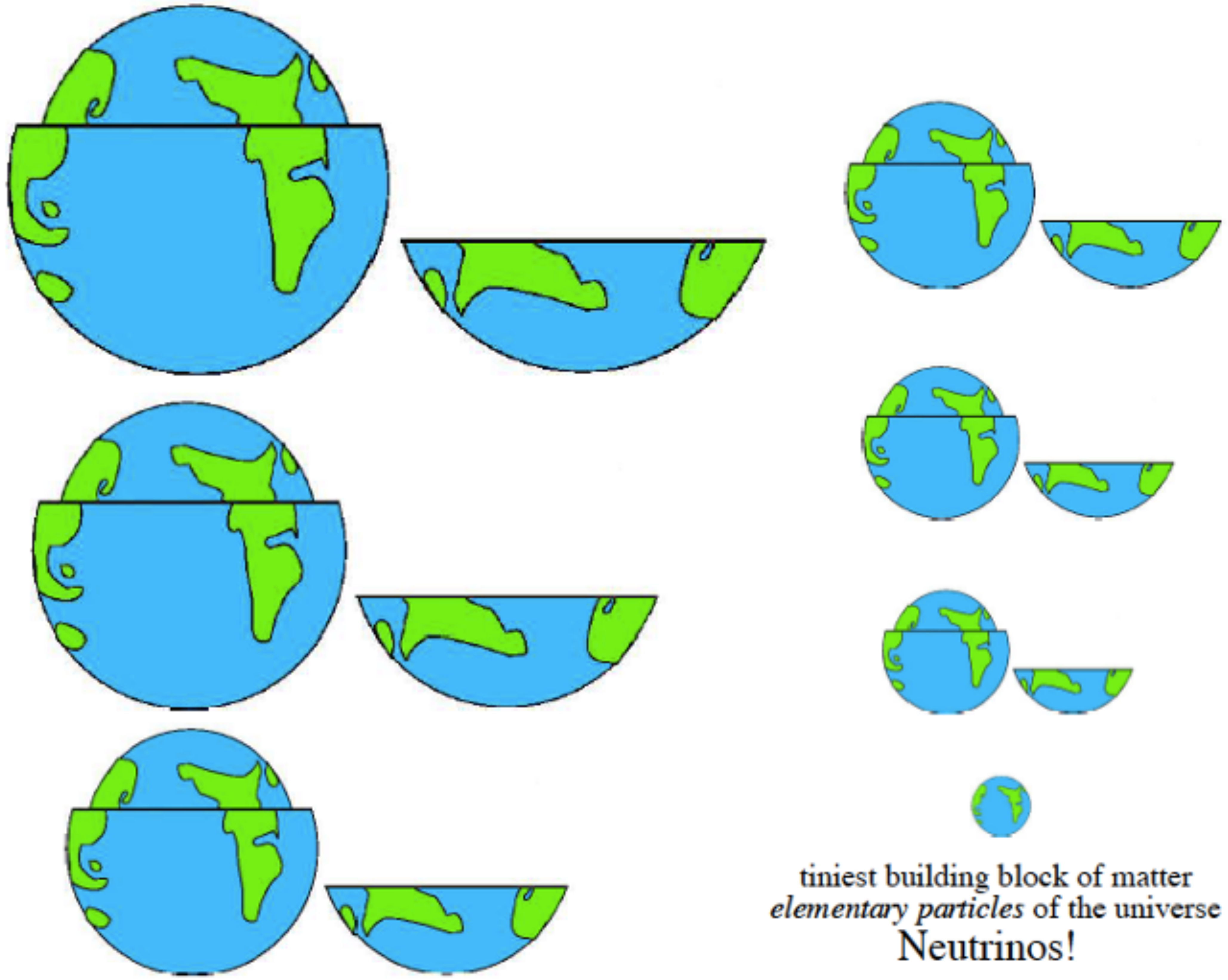
- in graduate school, I started working on **experimental particle physics** (neutrino) as we started to have breakthroughs in experimental particle physics during the time (Higgs boson, neutrino oscillation, gravitational wave…)

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

  - stop by 3-181 anytime to say hello or to talk about anything!

Particle physicist trying to understand ordinary matter…





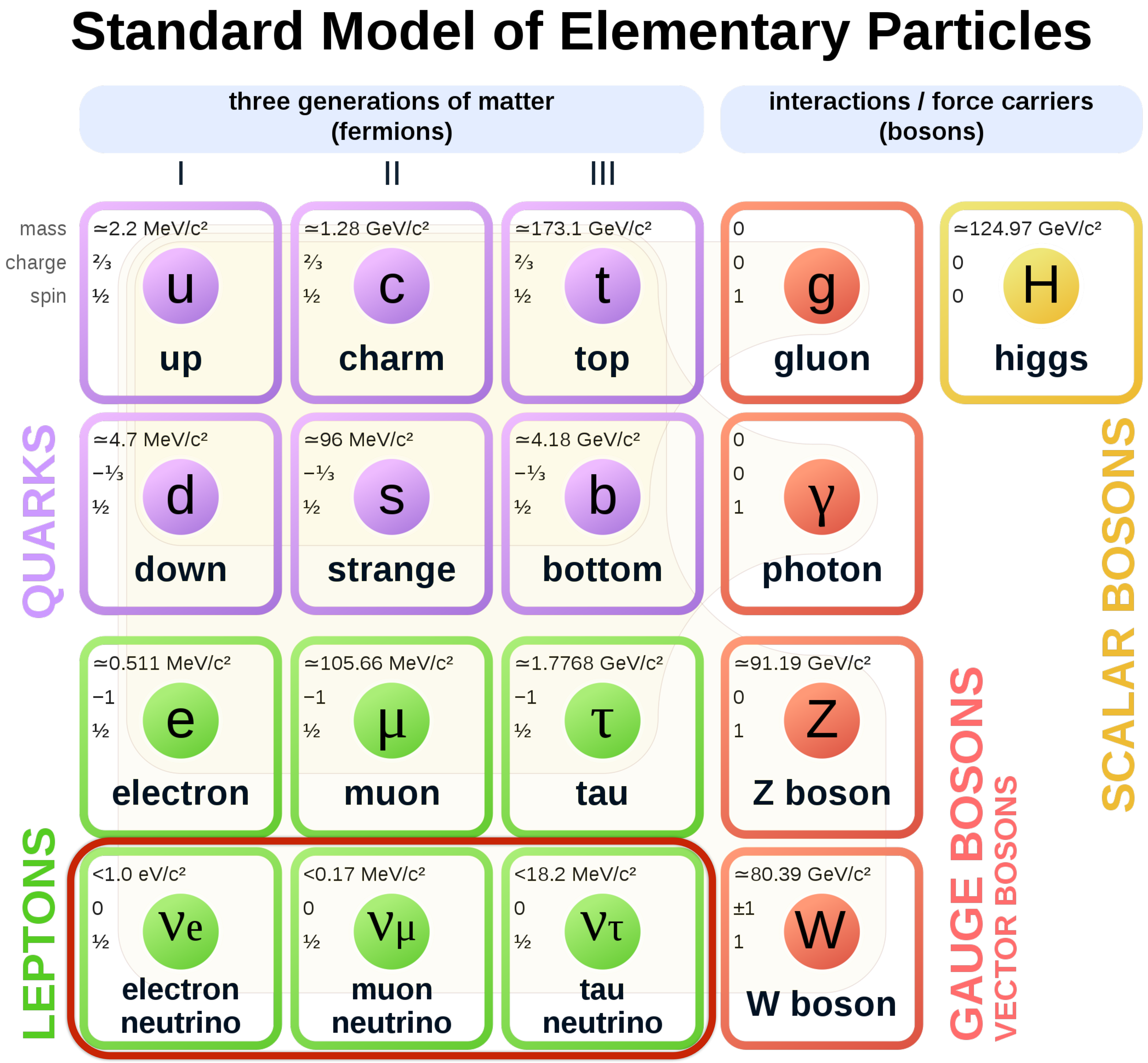
tiniest building block of matter:

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



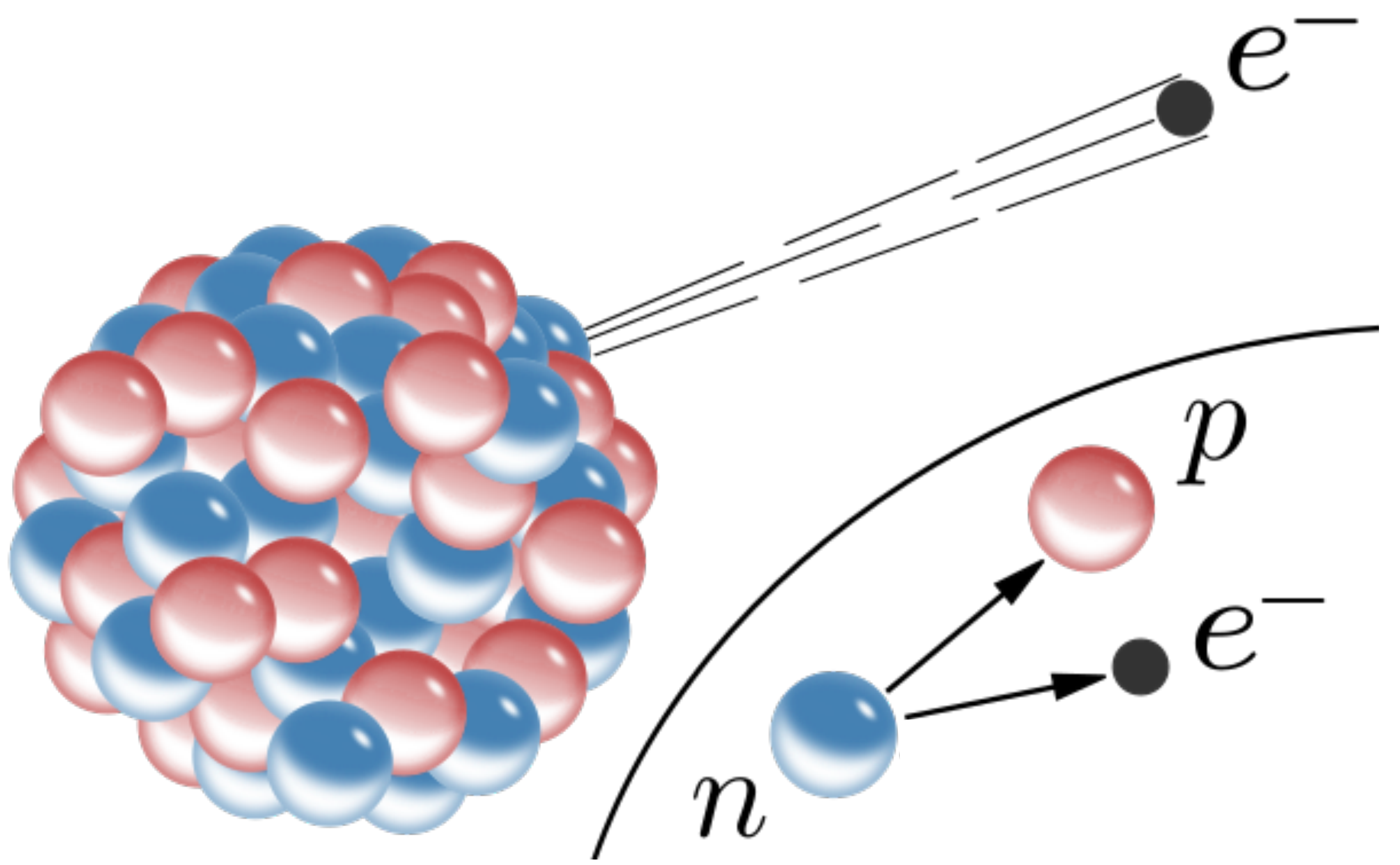
Contents

- **beta decay**: how the neutrinos found
- **missing neutrinos**: how the neutrinos change their flavors
- **detecting invisible particles**: what and how we detect neutrinos

Beta decay: how the neutrinos were found

Beta decay: Theoretical prediction

- the beta decay is a radioactive decay in which **a proton in a nucleus is converted into a neutron** (or vice-versa)
- in the process, the nucleus **emits a beta particle** (electron or positron); hence *beta decay*



number of protons and neutrons

$$^{210}_{83}\mathrm{Bi} \rightarrow\ ^{210}_{84}\mathrm{Po} + e^-$$

number of protons

$$n \rightarrow p^+ + e^-$$

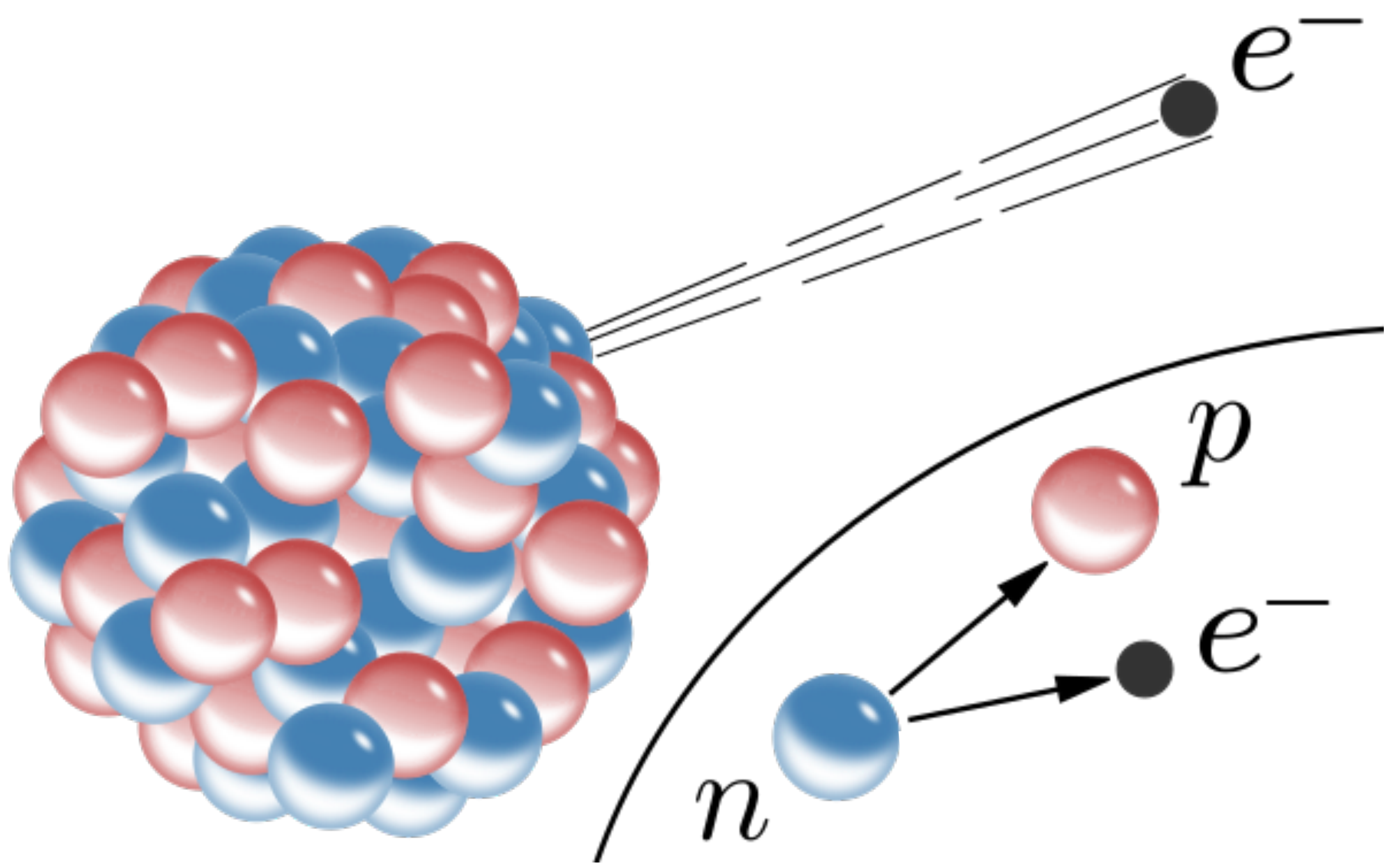
1899 – 1927

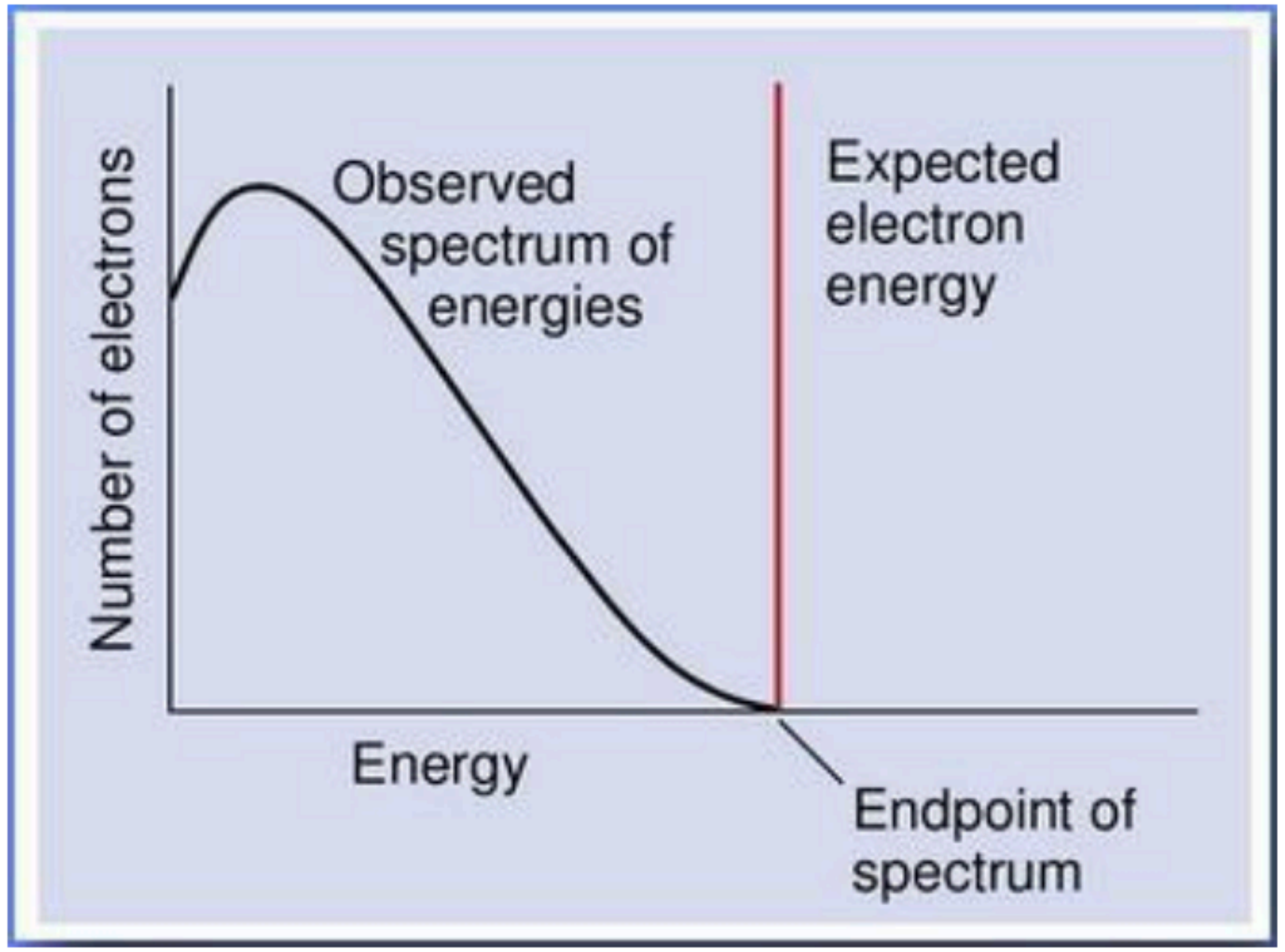
Rutherford, Meitner, Hahn, Chadwick, Ellis, Mott, *et. al*

Beta decay: Theoretical prediction

- if the decay happens with the atom nucleus at rest, the energy of the electron is **expected to be always the same** considering energy conservation

- but instead **"spectrum" of energies was observed**, always less energy than expected
  - maybe there's an invisible particle that takes away the energy?



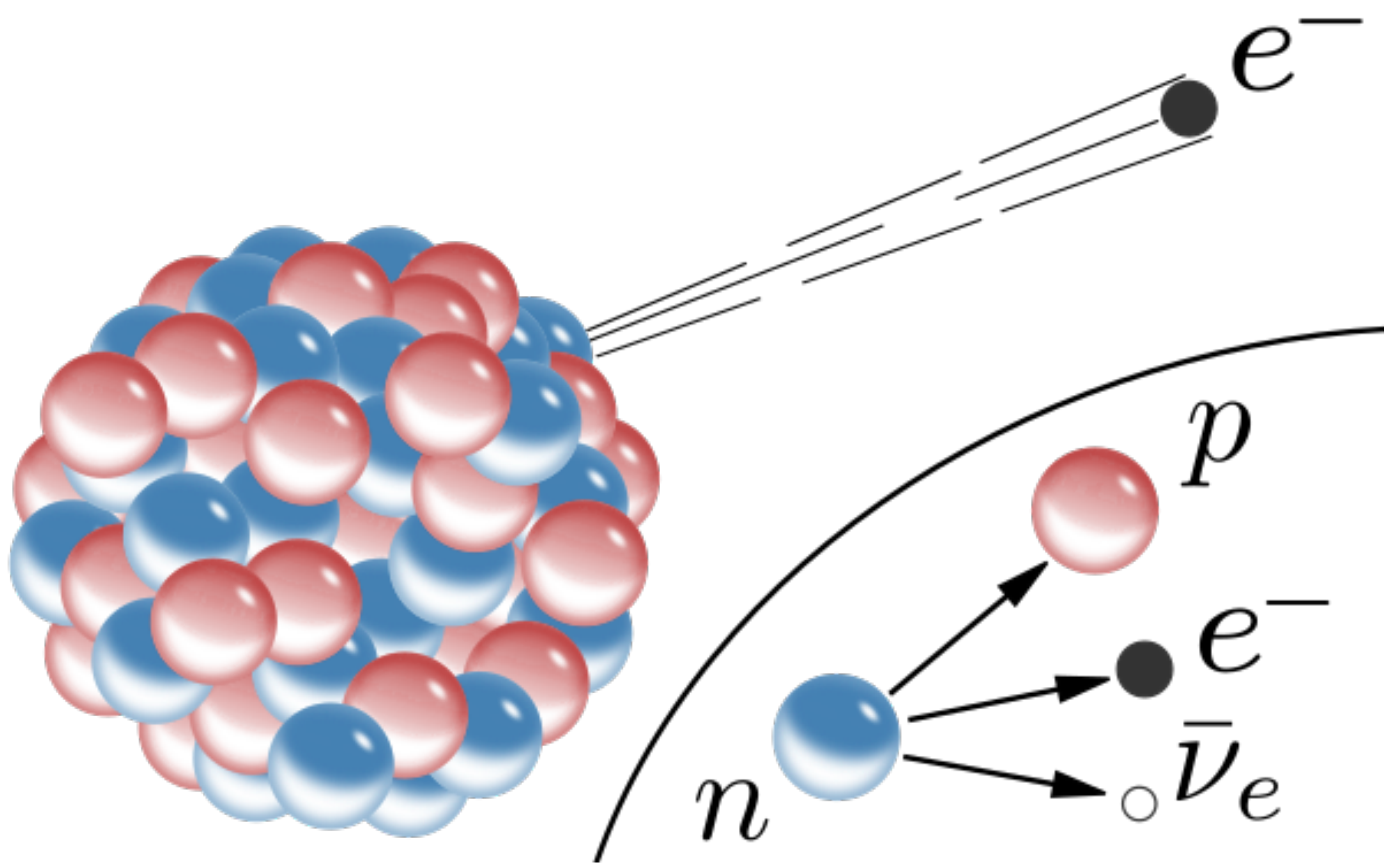


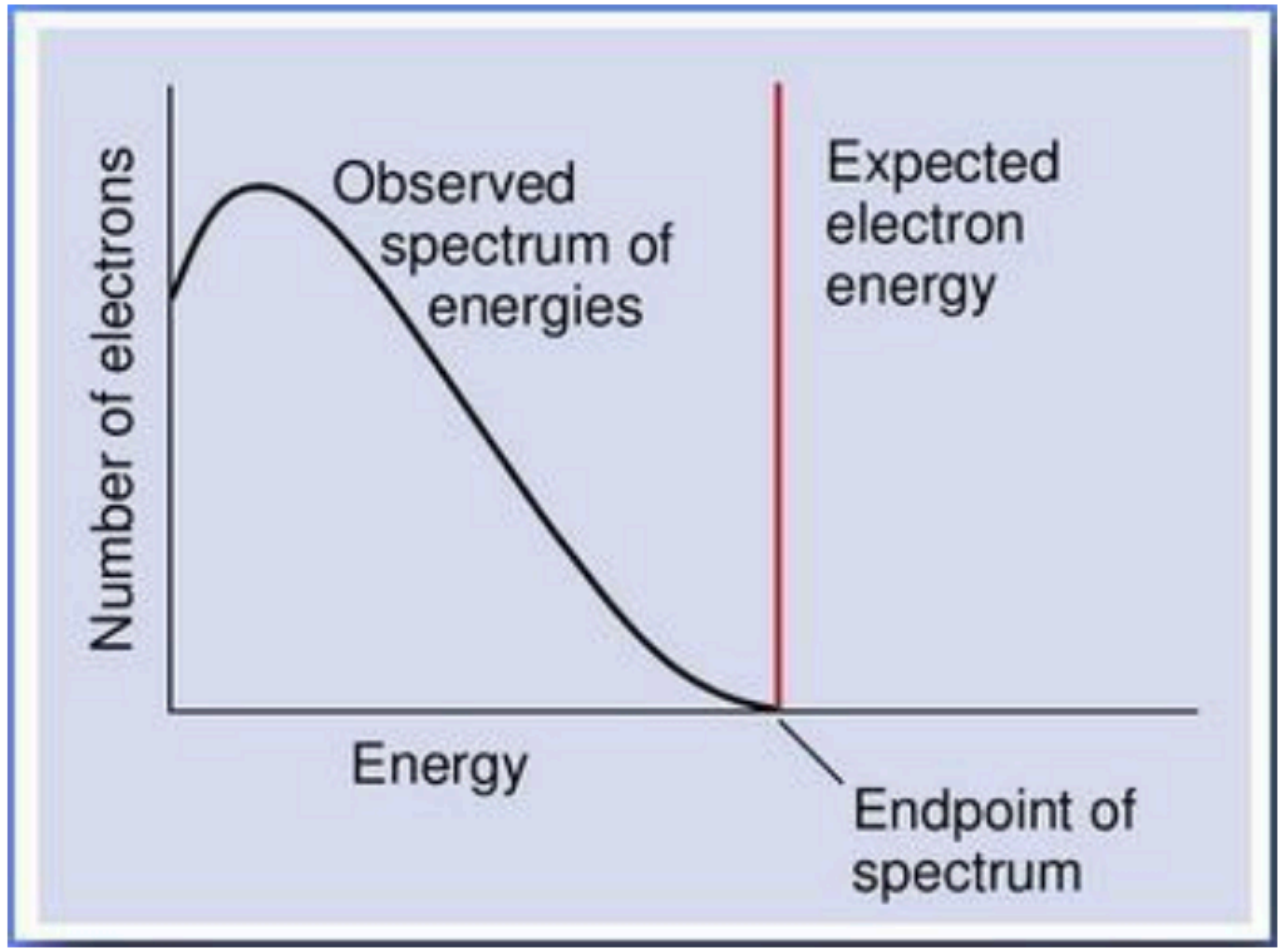
Beta decay: Theoretical prediction

- Wolfgang Pauli in 1930 postulated exactly that:
  an undetectable particle emitted during the decay, sharing the energy with the electron

- given the observation, this particle had to be electrically *neutral* and very *light*
  → ***neutrino***

$$^{210}_{83}\mathrm{Bi} \rightarrow {}^{210}_{84}\mathrm{Po} + e^- + \bar{\nu}_e$$





Beta decay: Theoretical prediction

Translation of the open letter sent by Wolfgang Pauli to Lise Meitner and Hans Geiger and a group of radioactive people at the Gauverein meeting in Tübingen.

Zürich, Dec. 4, 1930

Physics Institute of the ETH
Gloriastrasse

Zürich

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than e • (10 -13cm).

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I amindispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

W. Pauli

Wolfgang Ernst Pauli

Pauli in 1945

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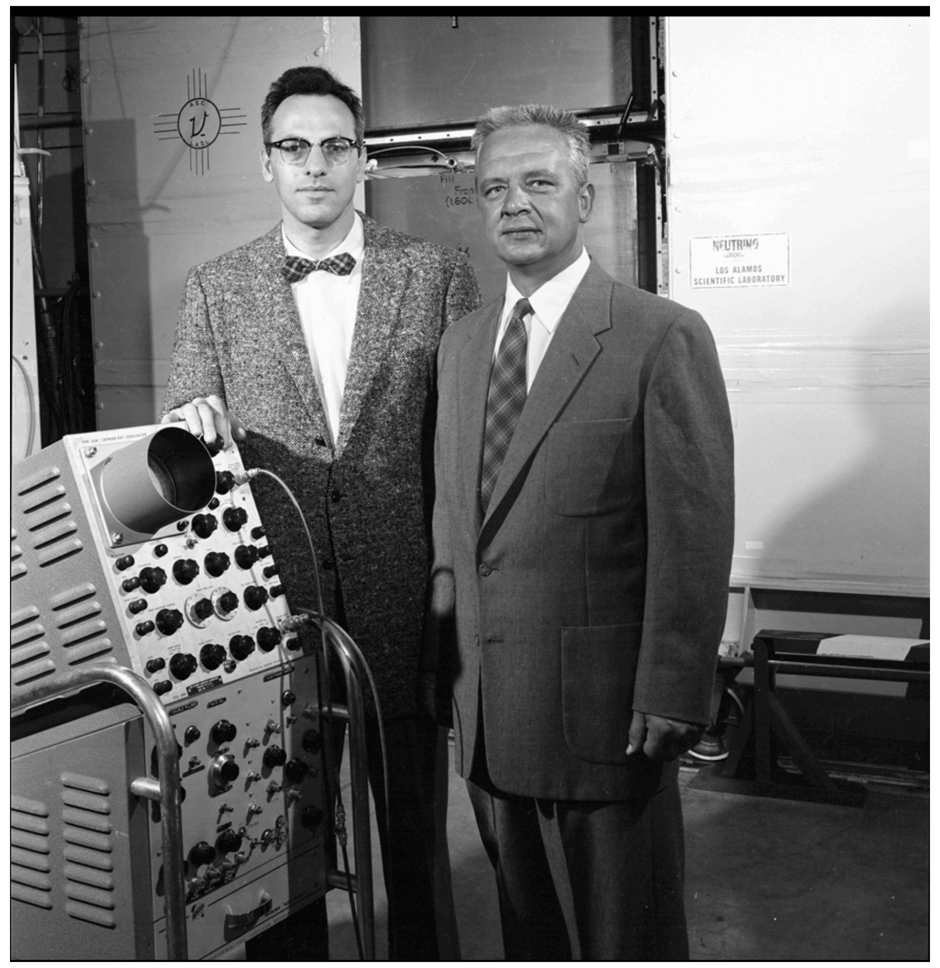
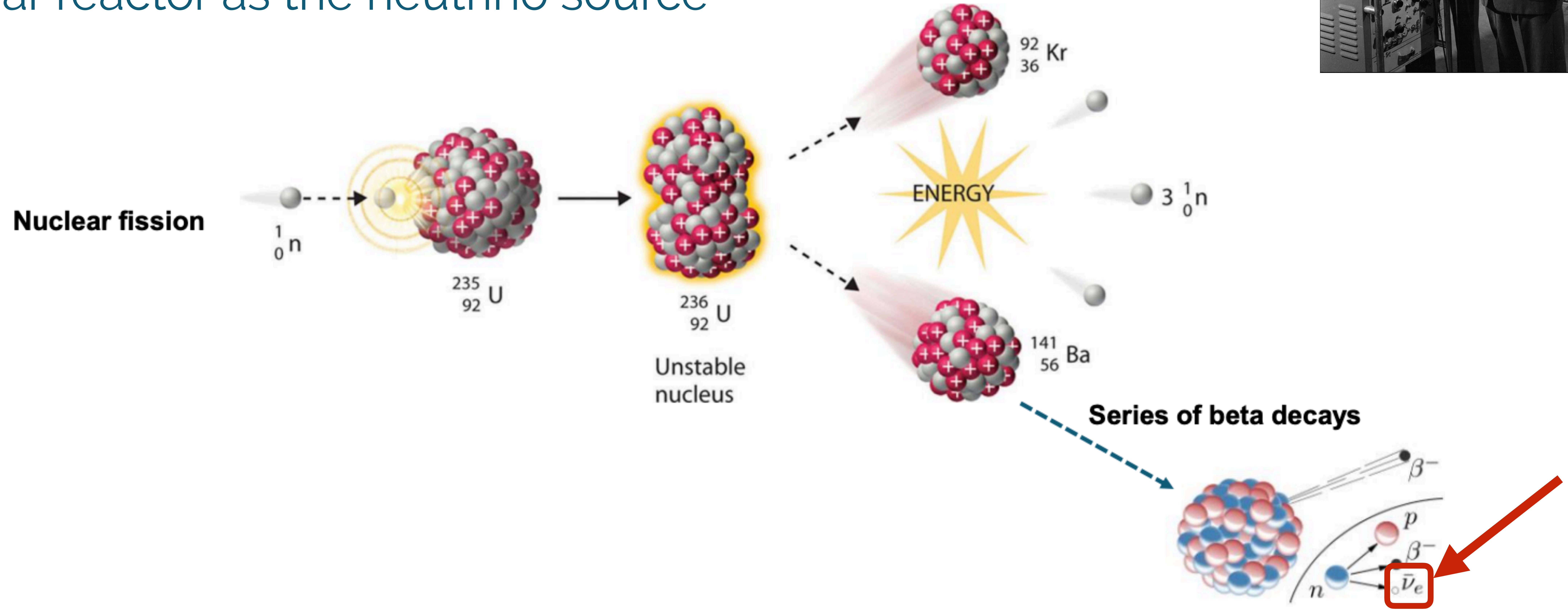
Detection of neutrinos

Nobel Prize 1995

- neutrinos were first detected experimentally in 1956 by Clyde Cowan and Frederick Reines
- the experiment took place in the Savannah River Plant using a nuclear reactor as the neutrino source





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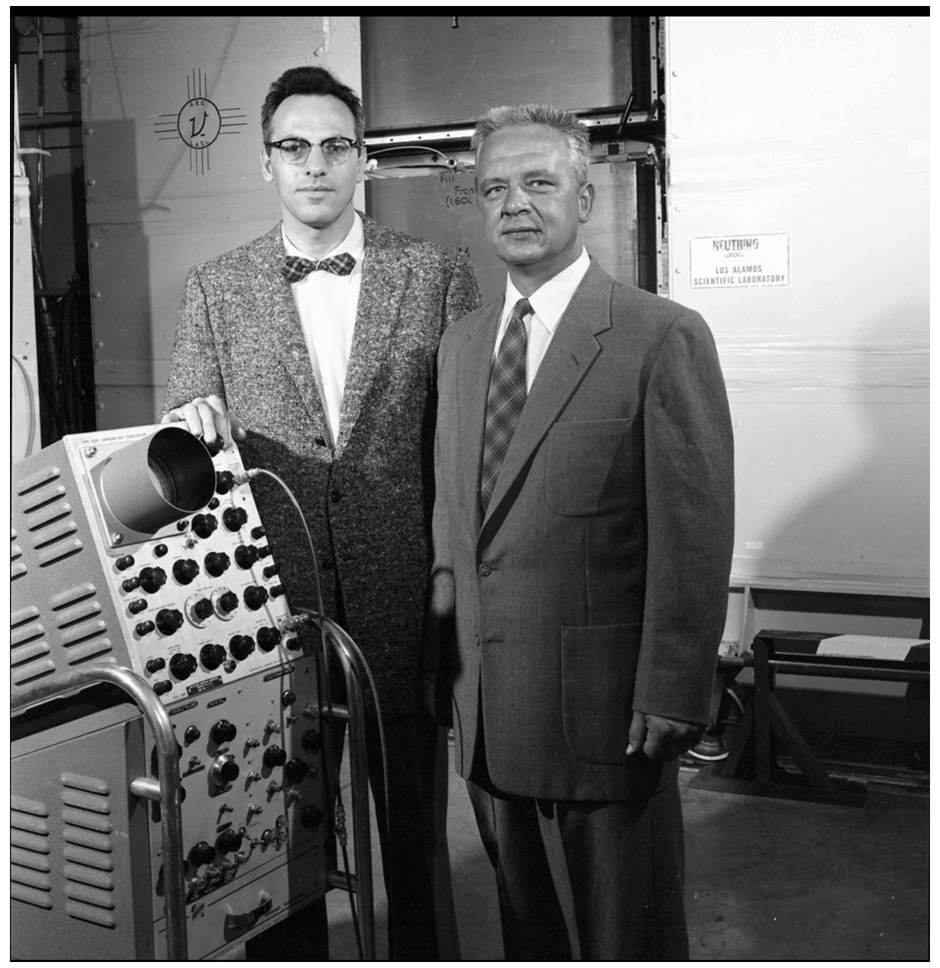

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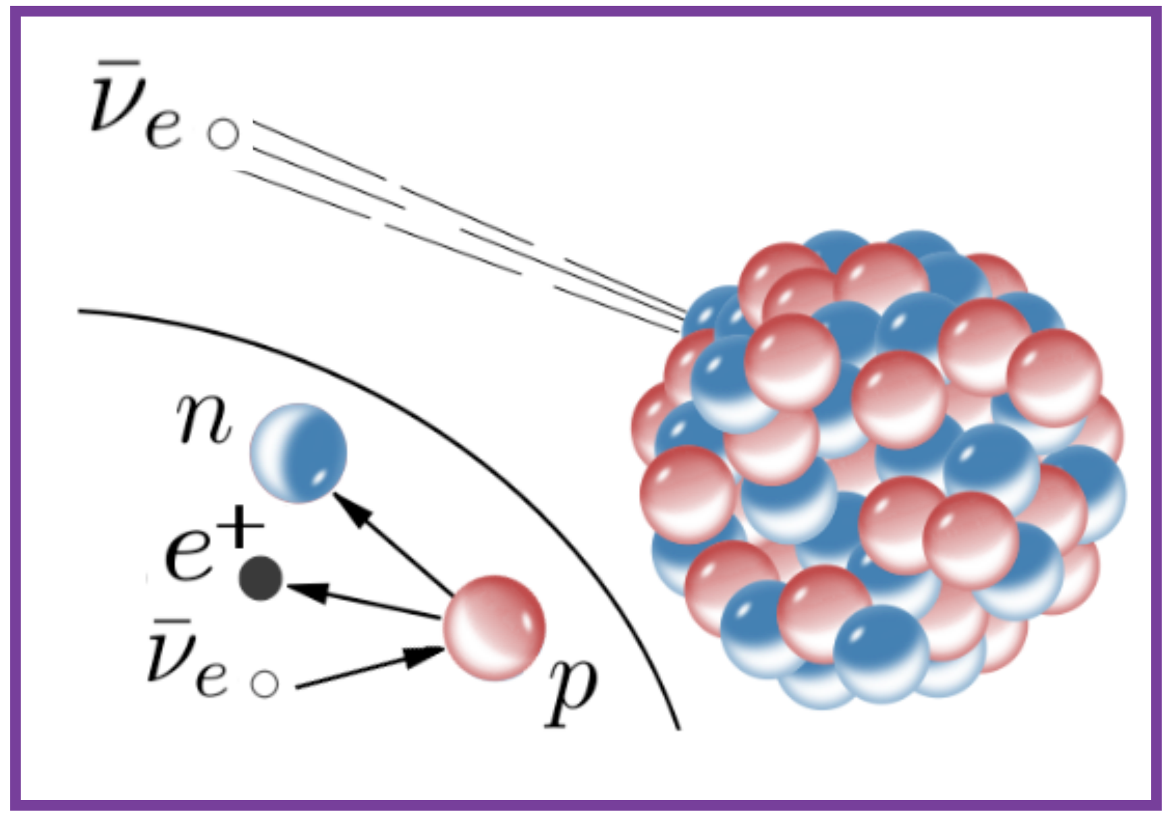
- the detection was made with the ***inverse beta decay*** process:
  neutrino interact with **proton**, turning it into **neutron** and emitting **positron**

  - using water (with large number of **protons**) with cadmium chloride

  - signal 1: **positron** interact immediately with electrons, create gamma rays

  - signal 2: **neutron** captured by cadmium, gives off a gamma ray



- *note: notice “beta” particles (electrons) are always associated here?*

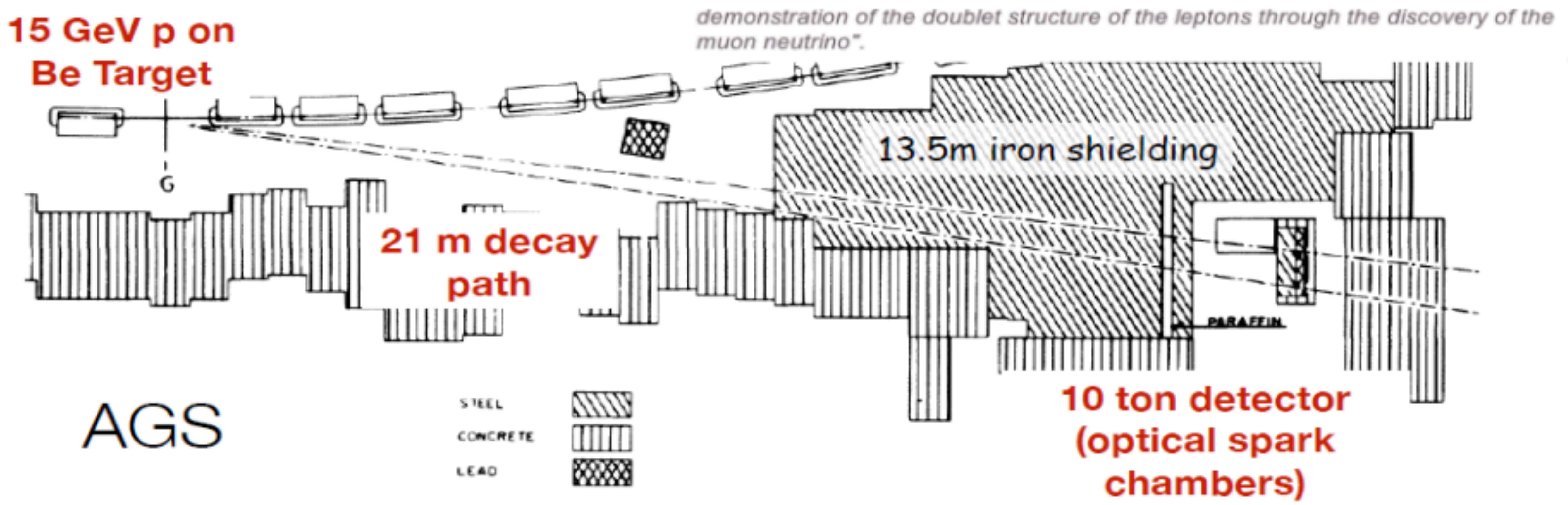
$$\bar{\nu}_e + p \to e^+ + n$$

Detection of neutrinos: more flavors

Nobel Prize 1988 

- with following theories, different types of neutrinos were hypothesized
  - muon was discovered in cosmic rays in 1936; very similar to electrons, but heavier
  - muon neutrinos, **associated with muons instead of electrons**, then may exist
    - remember how beta decay always involves electrons?
  - at BNL in 1962, using proton beam on Be target, Lederman/Schwartz/Steinberger discovered neutrinos producing muons
- similarly, followed by tau lepton discovery, tau neutrino was discovered by DONUT experiment at Fermilab (2000)

World's first accelerator neutrino experiment



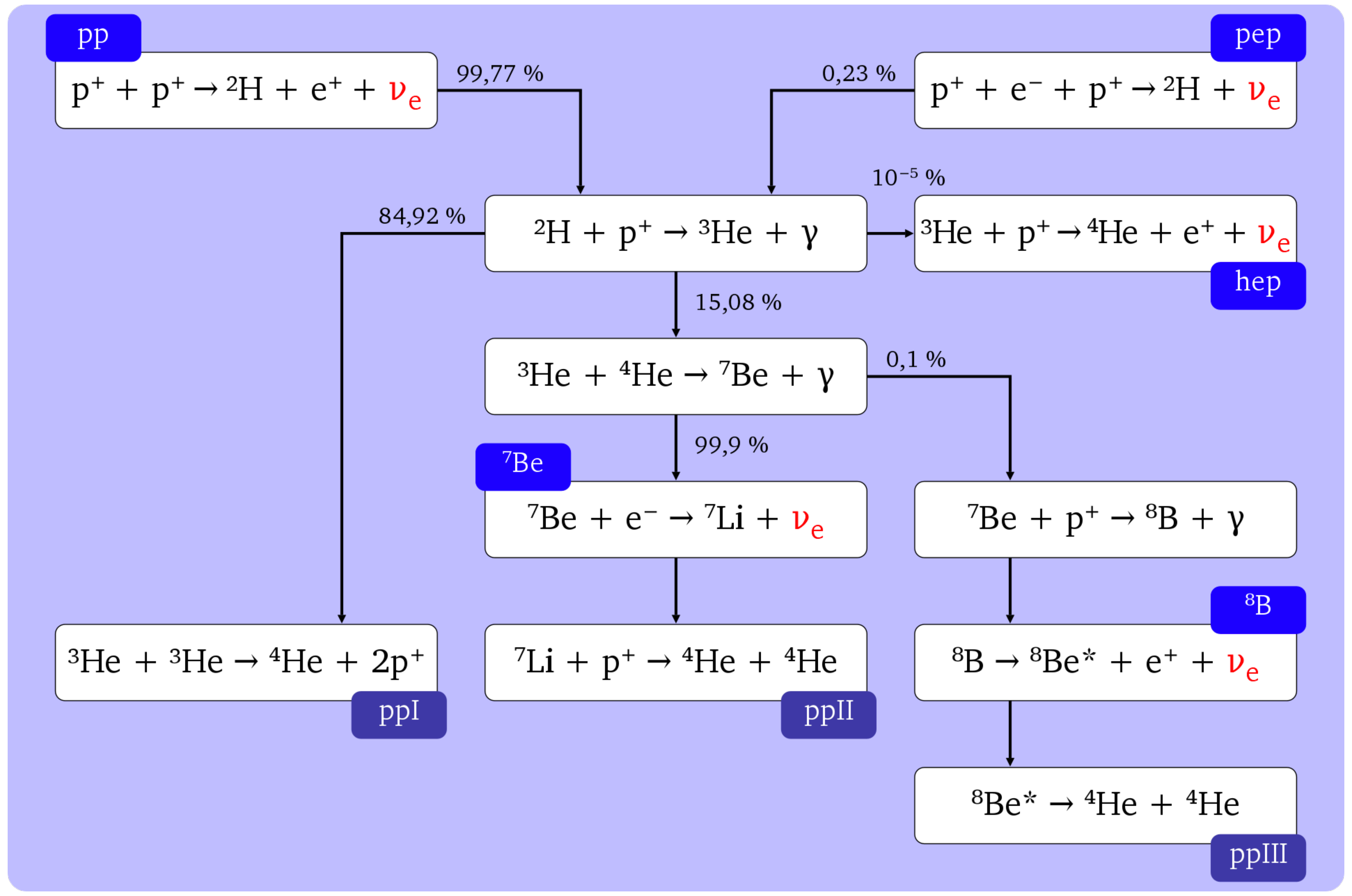
$$\nu_\mu + n \rightarrow \mu^- + p$$

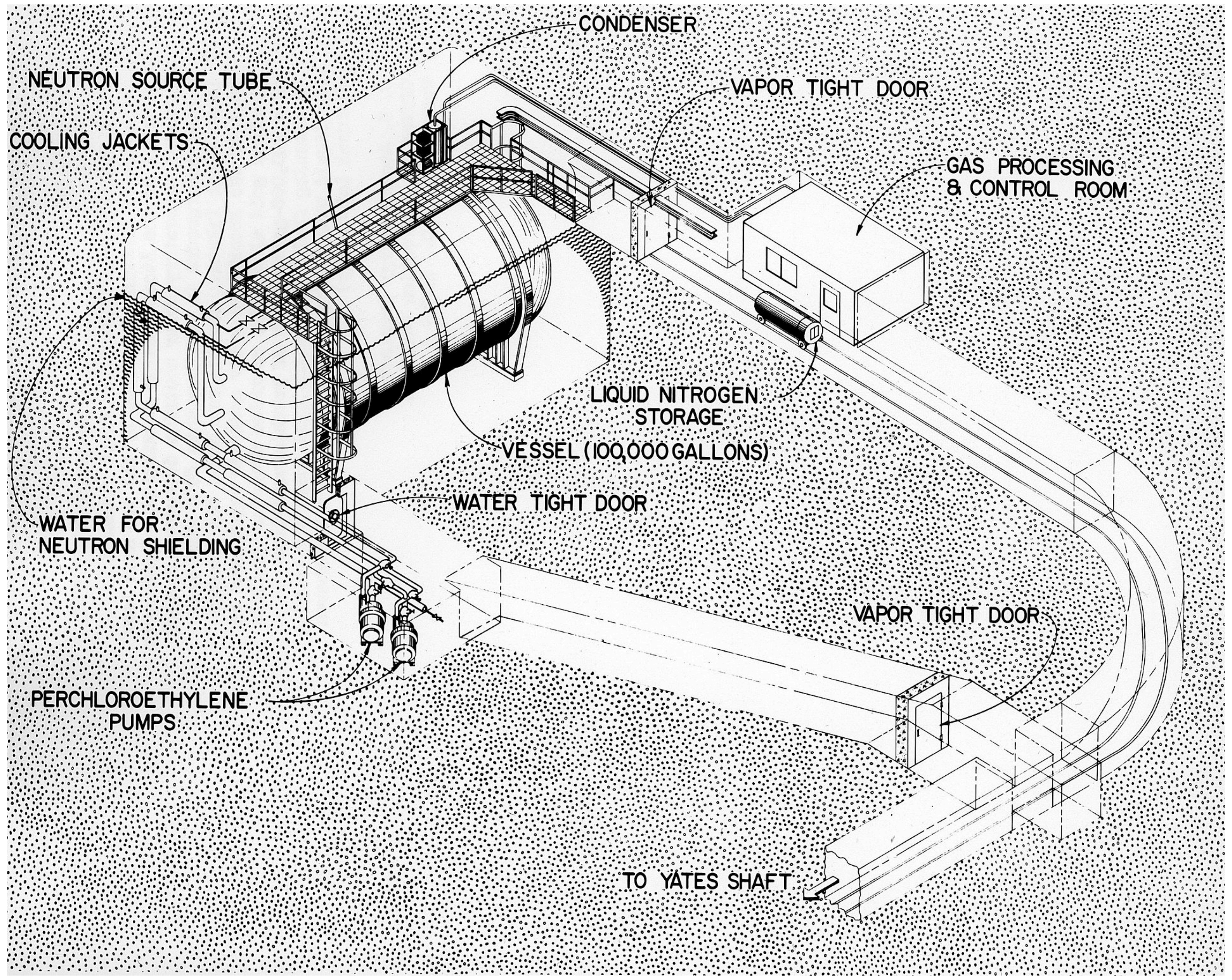
Missing neutrinos: how neutrinos change their flavors

The solar neutrino problem

Nobel Prize 2002

- the Sun is a huge source of neutrinos from nuclear fusion
  - ~100 billion neutrinos from the Sun pass through your thumbnail every second!
- J. Bahcall calculated expected number of solar neutrinos expected to arrive at Earth
  - all the neutrinos generated in the Sun was to be electron neutrinos
- R. Davis used the Homestake experiment to detect these neutrinos in 1968
  - buried deep underground (1500m) to avoid cosmic ray background
  - one needs to detect chlorine-to-argon conversion, from an interaction from the electron neutrinos



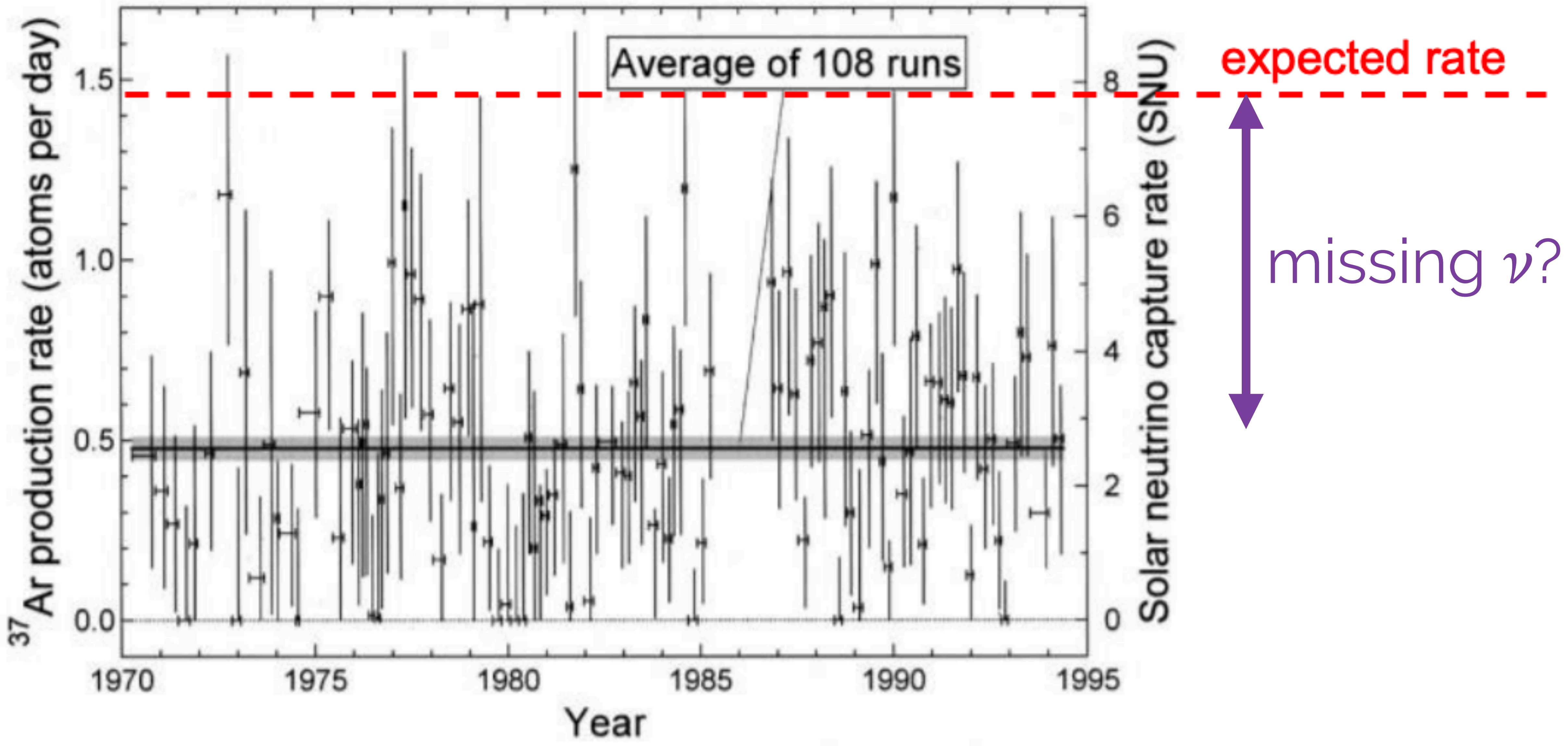


$$\nu_e + {}^{37}_{17}Cl \rightarrow {}^{37}_{18}Ar + e^-$$

The solar neutrino problem

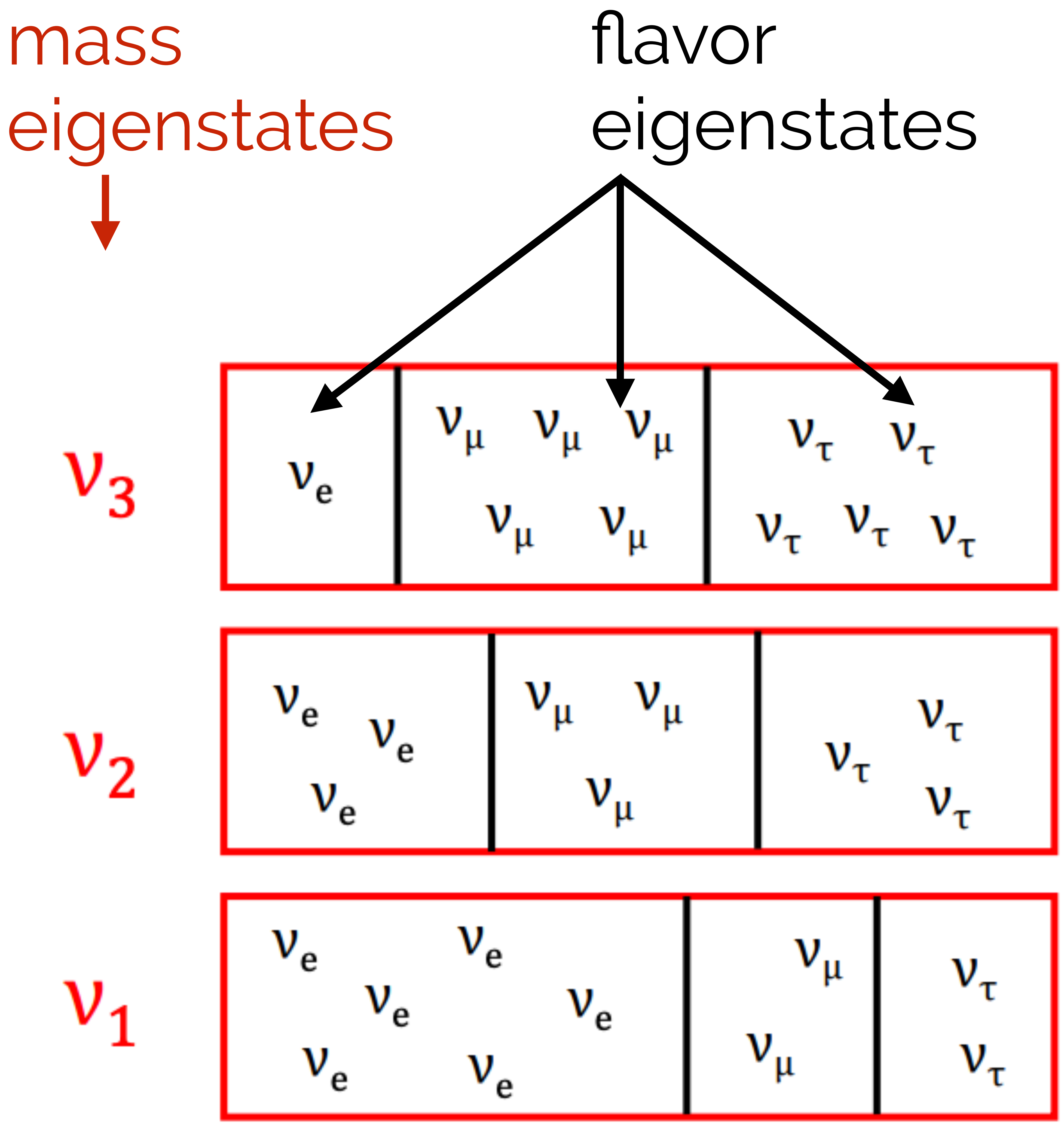
$$\nu_e + {}^{37}_{17}Cl \rightarrow {}^{37}_{18}Ar + e^-$$

- but detected number of (electron) neutrinos seem to be too small: **2/3 of them were missing!**
  - was the solar neutrino calculation off?
  - was it an error with the experiment?
- B. Pontecorvo suggested in 1969, that **neutrinos could change in some way while traveling** from Sun to Earth



Neutrino oscillation: model

- **flavor mixing**: neutrinos are special, as they have two different eigenstates with weak/flavor & mass
  - **weak/flavor eigenstates**: states associated with the weak interaction, in which neutrinos are produced & detected; “interaction basis”
  - **mass eigenstates**: states of definite mass, which propagate through space-time; “propagation basis”
  - *note: in order to have this “oscillation”, neutrinos need to have mass!*



- PMNS matrix can describe the mixing between these two eigenstates

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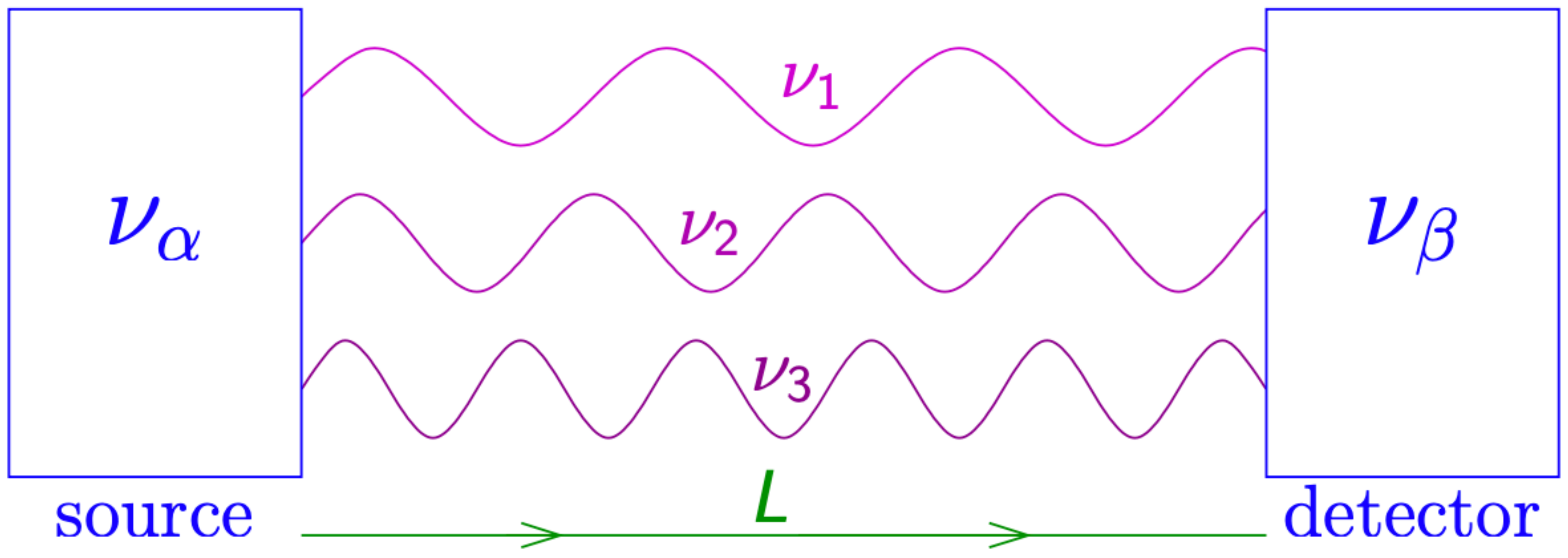

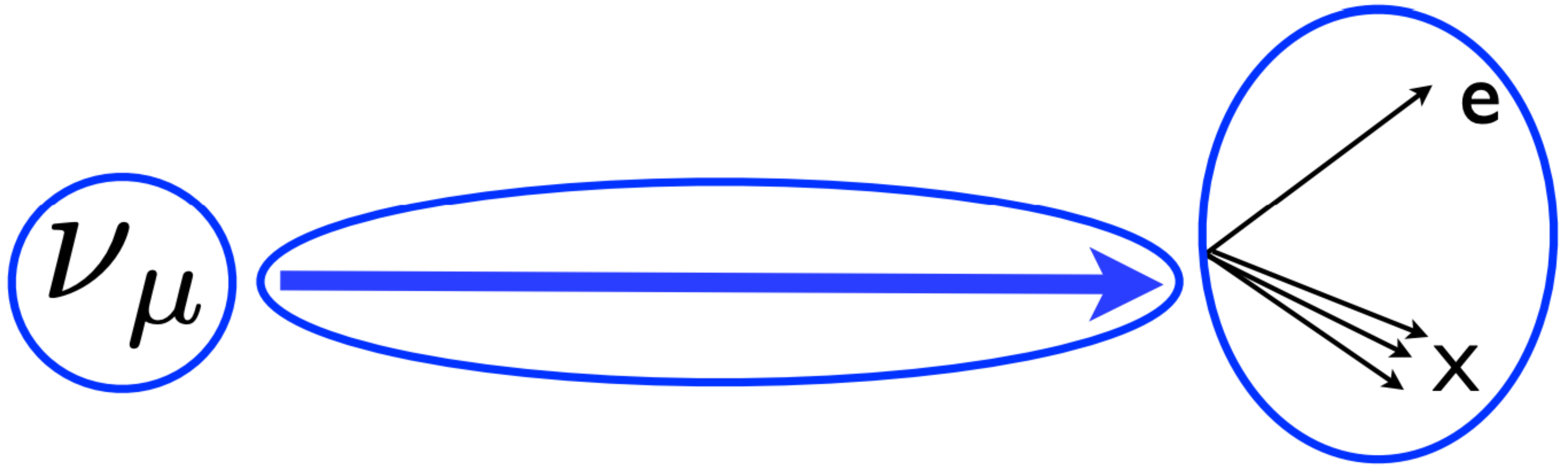

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flavor (α = e, μ, τ) ⇔ linear combinations ⇔ mass (i = 1, 2, 3)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \qquad\qquad |\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

- PMNS matrix can describe the mixing between these two eigenstates

Neutrino oscillation: model

- PMNS matrix contains different parameters, such as mixing angles and δ_{c}
  - mixing angles represent the oscillation probabilities between two flavors of neutrinos
- δ_{cp} represents the difference in oscillation between neutrinos and antineutrinos
  - if $\delta_{cp}=0$, neutrinos and antineutrinos will behave/oscillate in same fashion
  - if not, CP violation exist in the neutrino sector: which is a necessary condition for explaining matter-antimatter asymmetry in our Universe

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \underbrace{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}}_{\text{Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix}} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

Mixing angles = $(\theta_{12}, \theta_{23}, \theta_{13})$, δ_{CP} is the CP-violation phase

$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\substack{\text{I} \\ \text{atmospheric}}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\substack{\text{II} \\ \text{reactor}}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{III} \\ \text{solar}}}$$

where: $c_{\alpha\beta} = \cos\theta_{\alpha\beta}$; $s_{\alpha\beta} = \sin\theta_{\alpha\beta}$

Nonzero δ_{CP} ⟹ neutrinos and antineutrinos oscillate different

Neutrino oscillation: confirmation

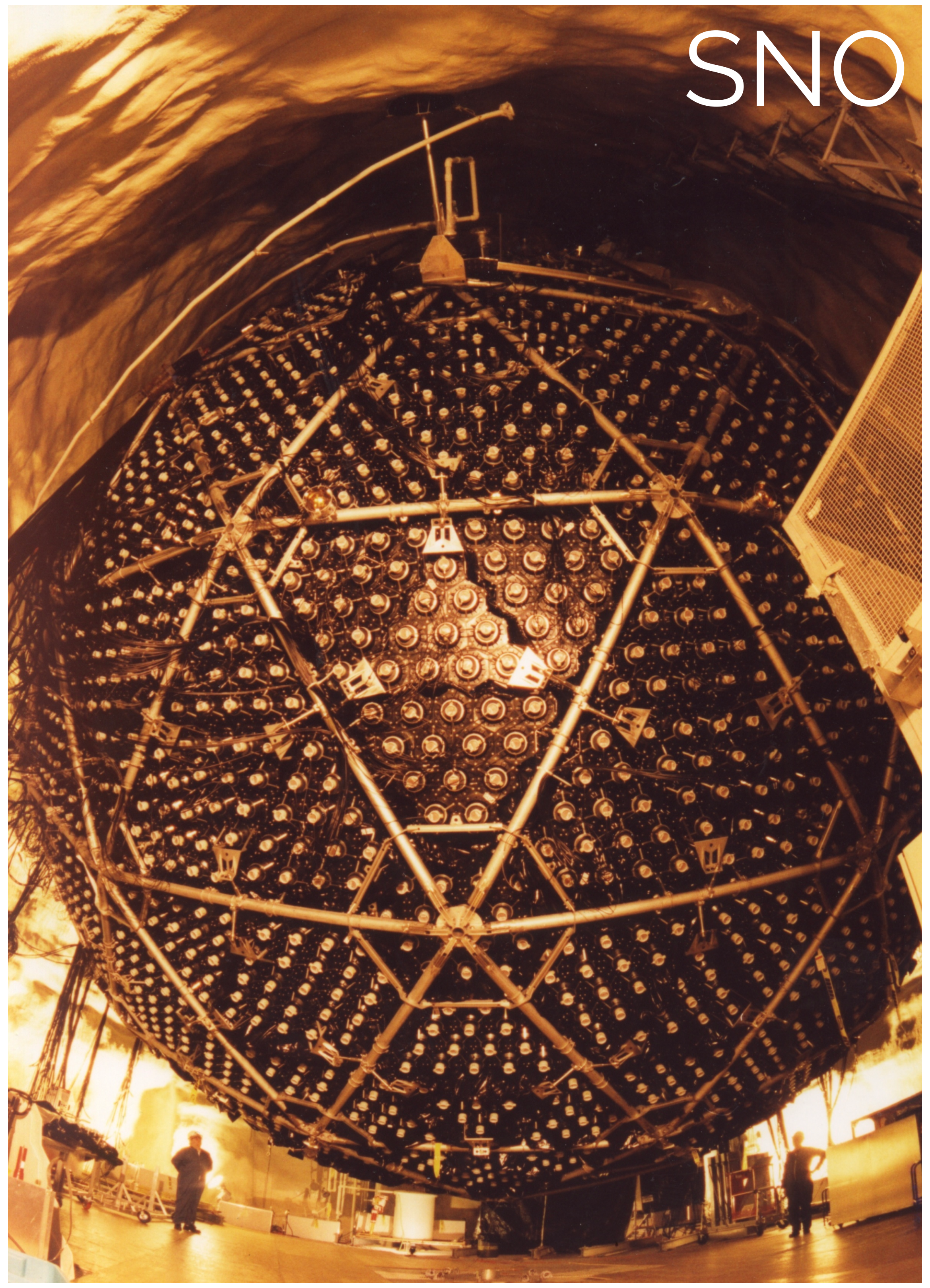
Nobel Prize 2015

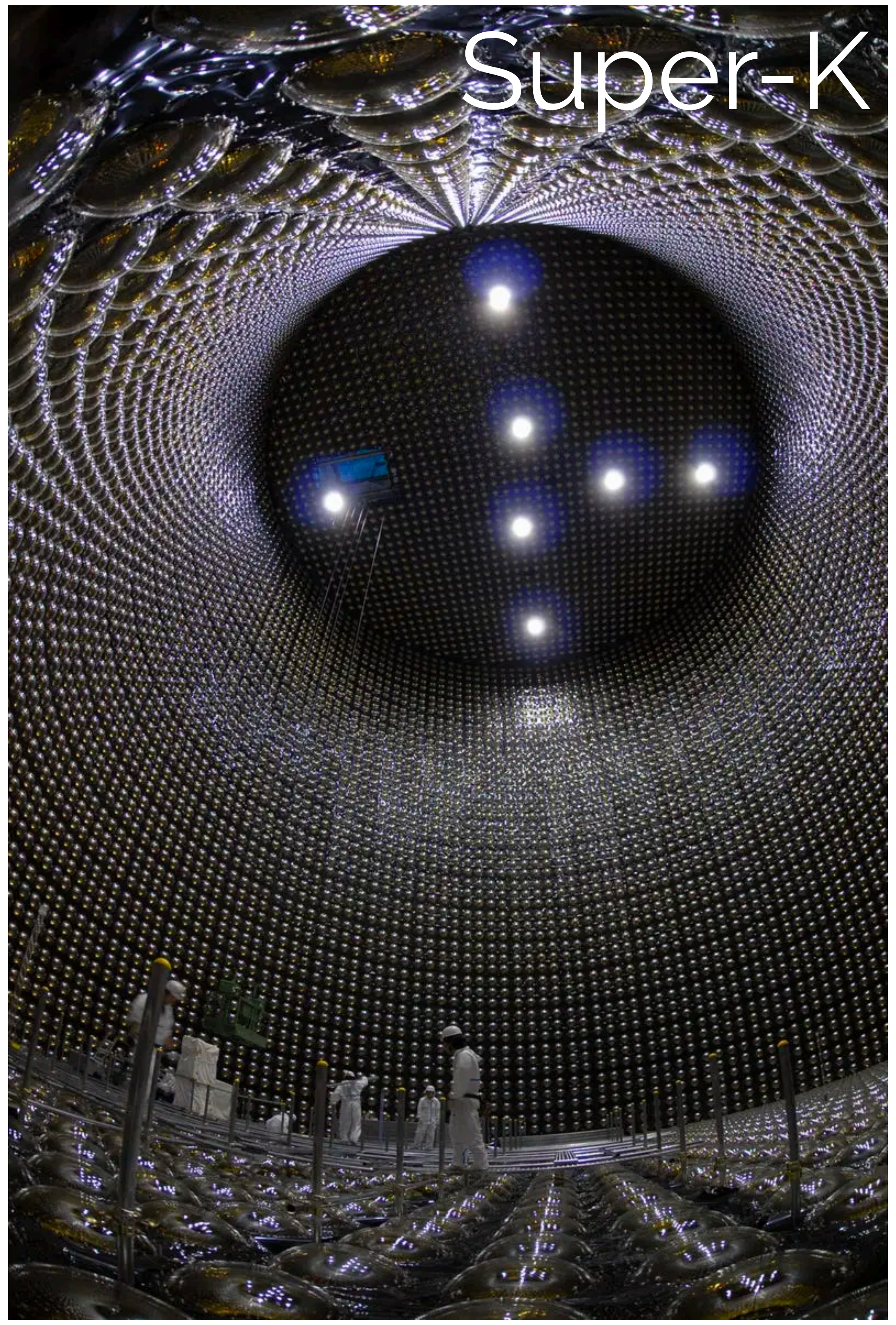
- neutrino changing its flavor during travel (neutrino oscillation) can explain why we detect only 1/3 of expected electron neutrinos; but can this neutrino oscillation be experimentally confirmed?

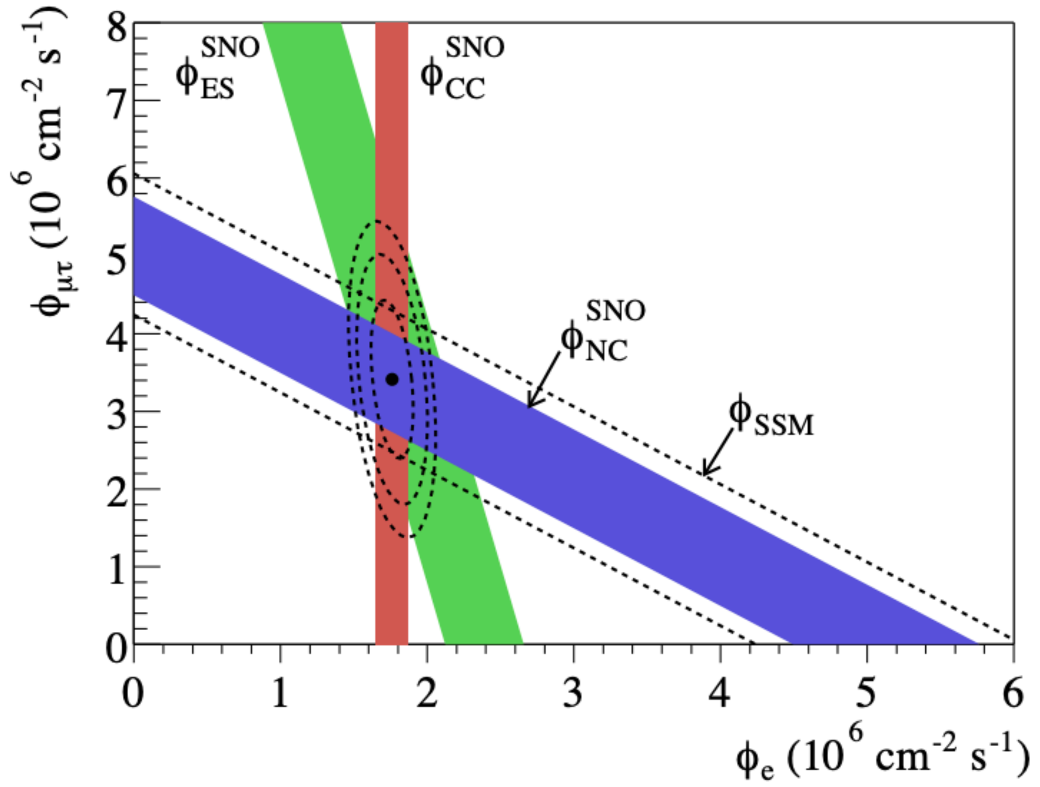
- two separate experiments, Super-Kamiokande and SNO, confirmed this:

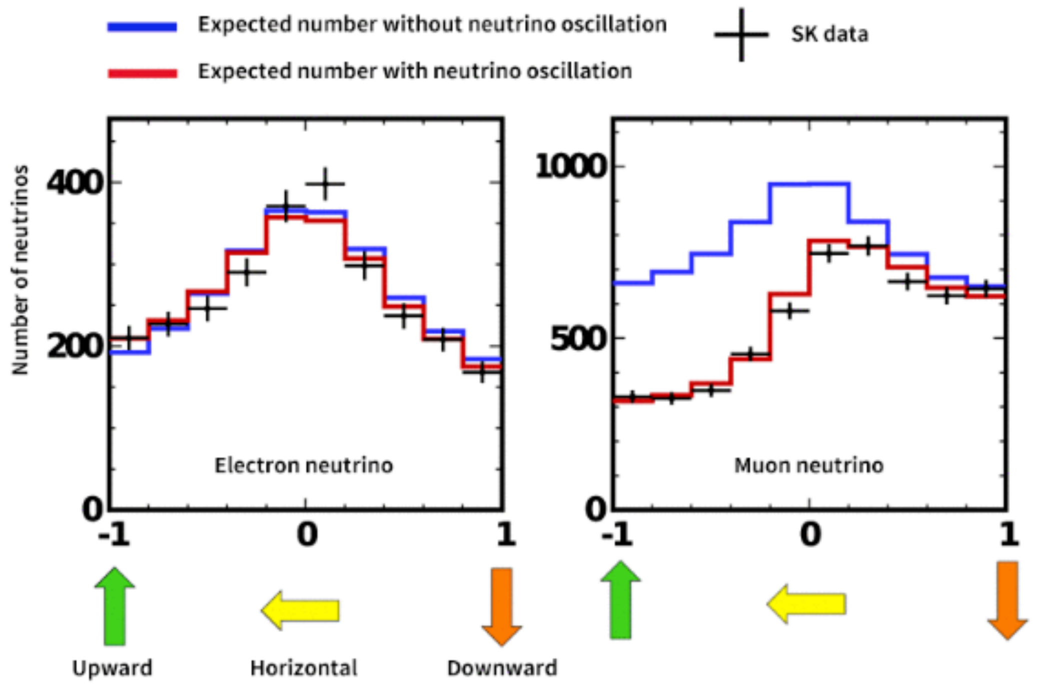
  - **SNO** detected different interactions from solar neutrinos, sensitive to different neutrino flavors: confirming **electron neutrino indeed changed into muon/tau neutrinos**

  - **SK** observed a deficit of muon neutrinos coming from the opposite side of the Earth (longer travel distance), compared to those coming from right above (shorter travel distance): **confirming muon neutrinos oscillating into tau neutrinos**





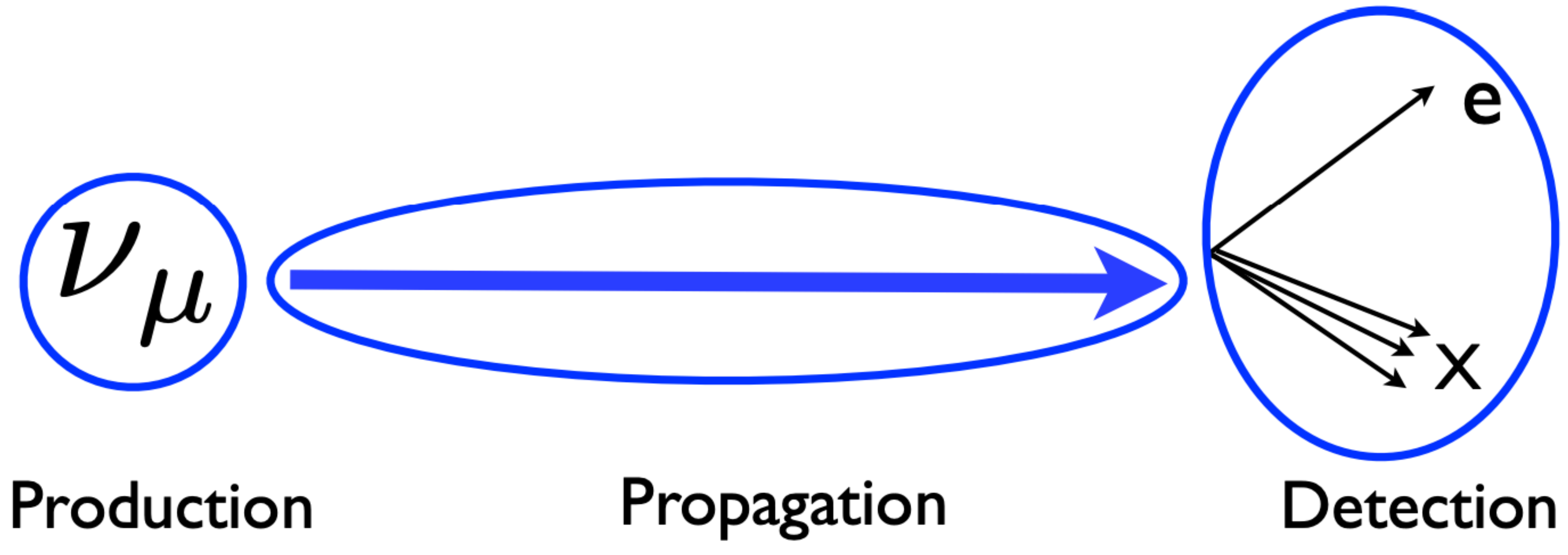


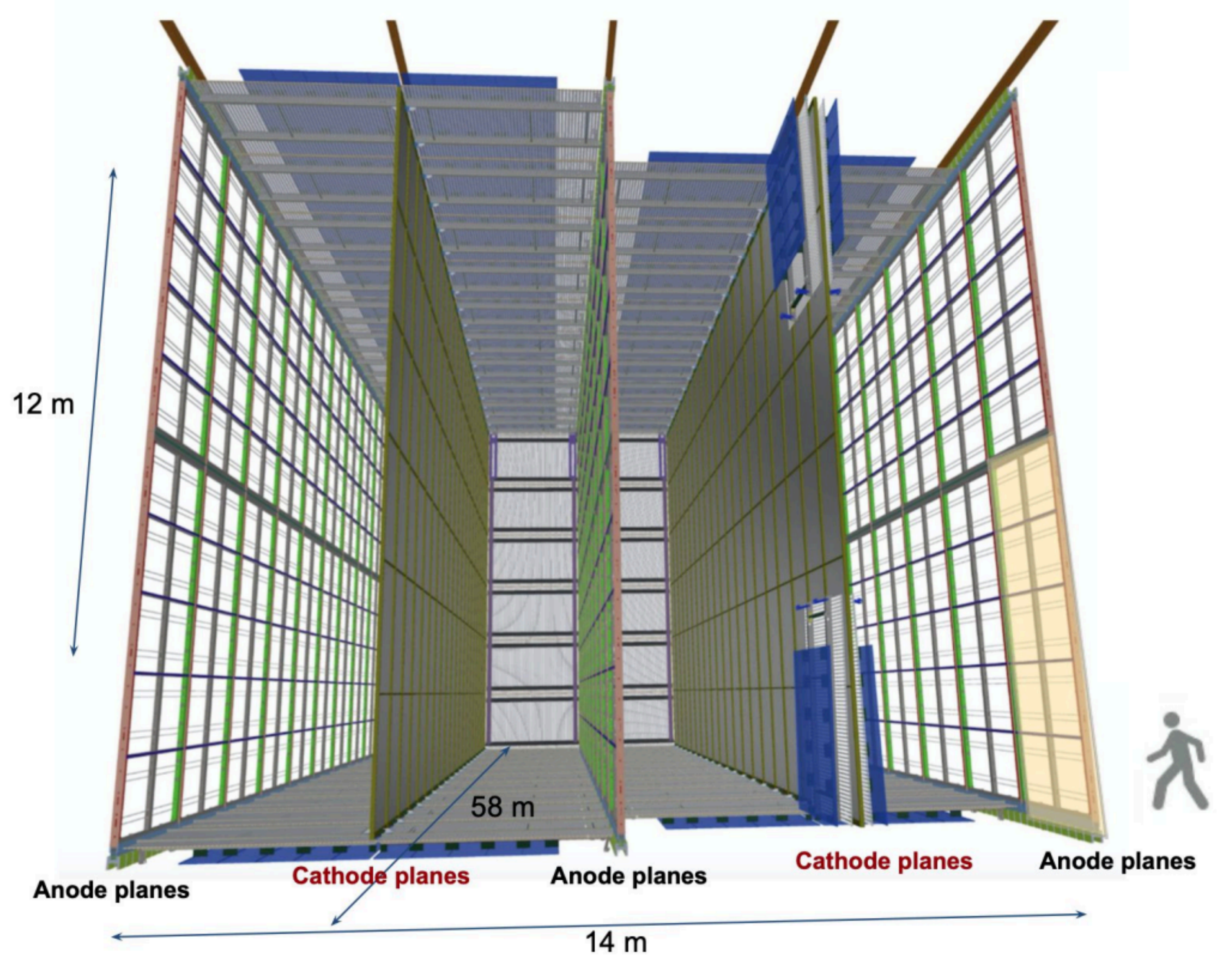


Detecting invisible particles: what, how, & why we detect neutrinos

What do we detect

- neutrinos are really hard to detect: they carry no charge, interact very rarely, and only through the Weak force
- but **we can detect what comes out** of the interaction of the neutrinos
  - electrons, muons, hadrons, photons, …
- what do we need?
  - need a **source** of neutrinos: either natural or artificial
  - need a **big detector**, to increase probability of the neutrino interaction
  - need to detect the **outgoing particles** precisely
  - need good **theoretical predictions/models** of neutrino production, propagation, and interaction





How do we detect

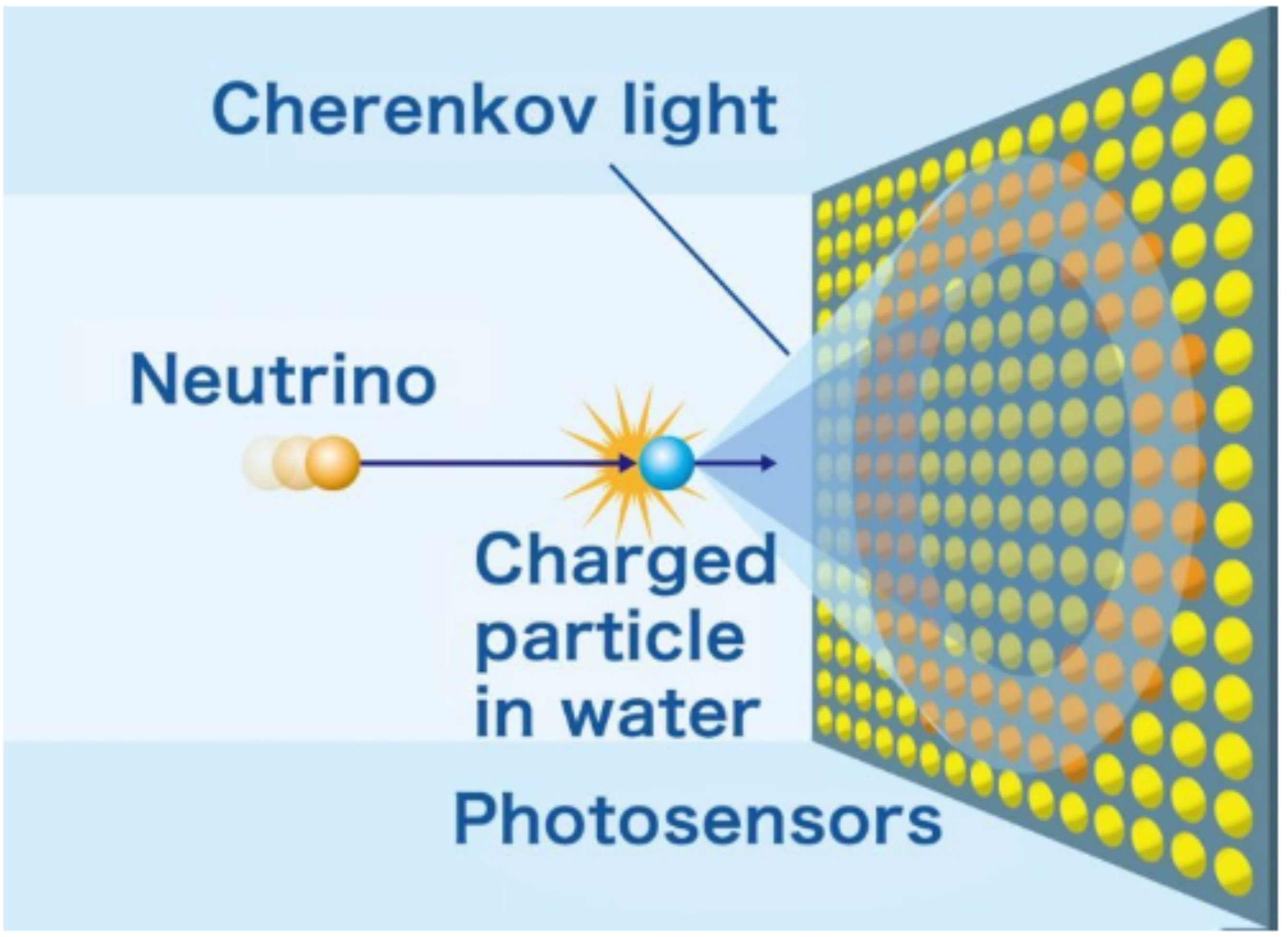
physicsopenlab.org

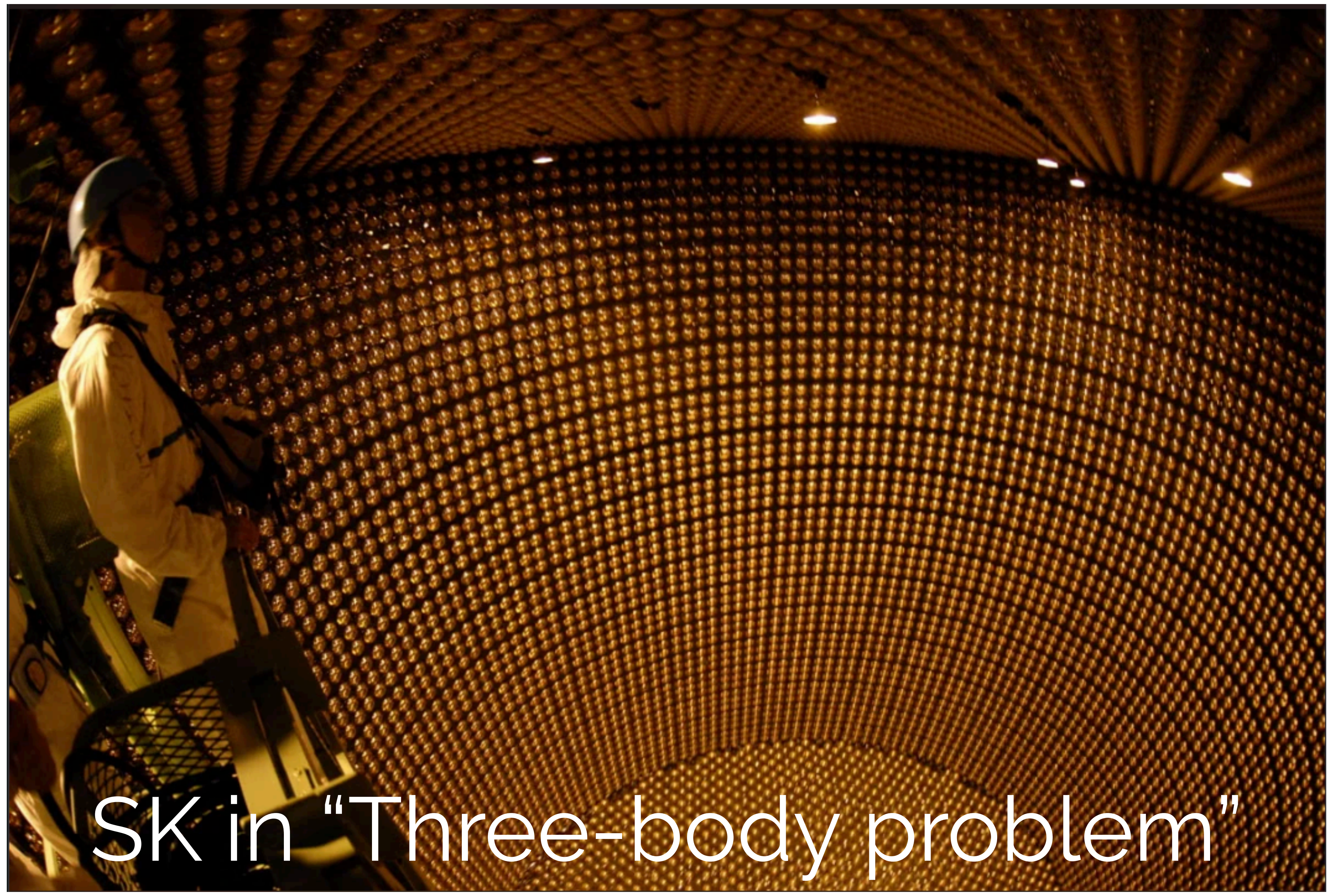
- at the end of the day, we want to (precisely) detect outgoing particles:
  their type, direction, energy, …

- as technology develops, we began to gather more and more information of these particles

- an example: **water Cherenkov detector** of Super-Kamiokande, where charged particle generating a "light shock wave" as it travels through water

- here we take a look at state-of-the-art neutrino detection technology:
  Liquid Argon Time Projection Chamber (LArTPC)





How do we detect: 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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and

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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:

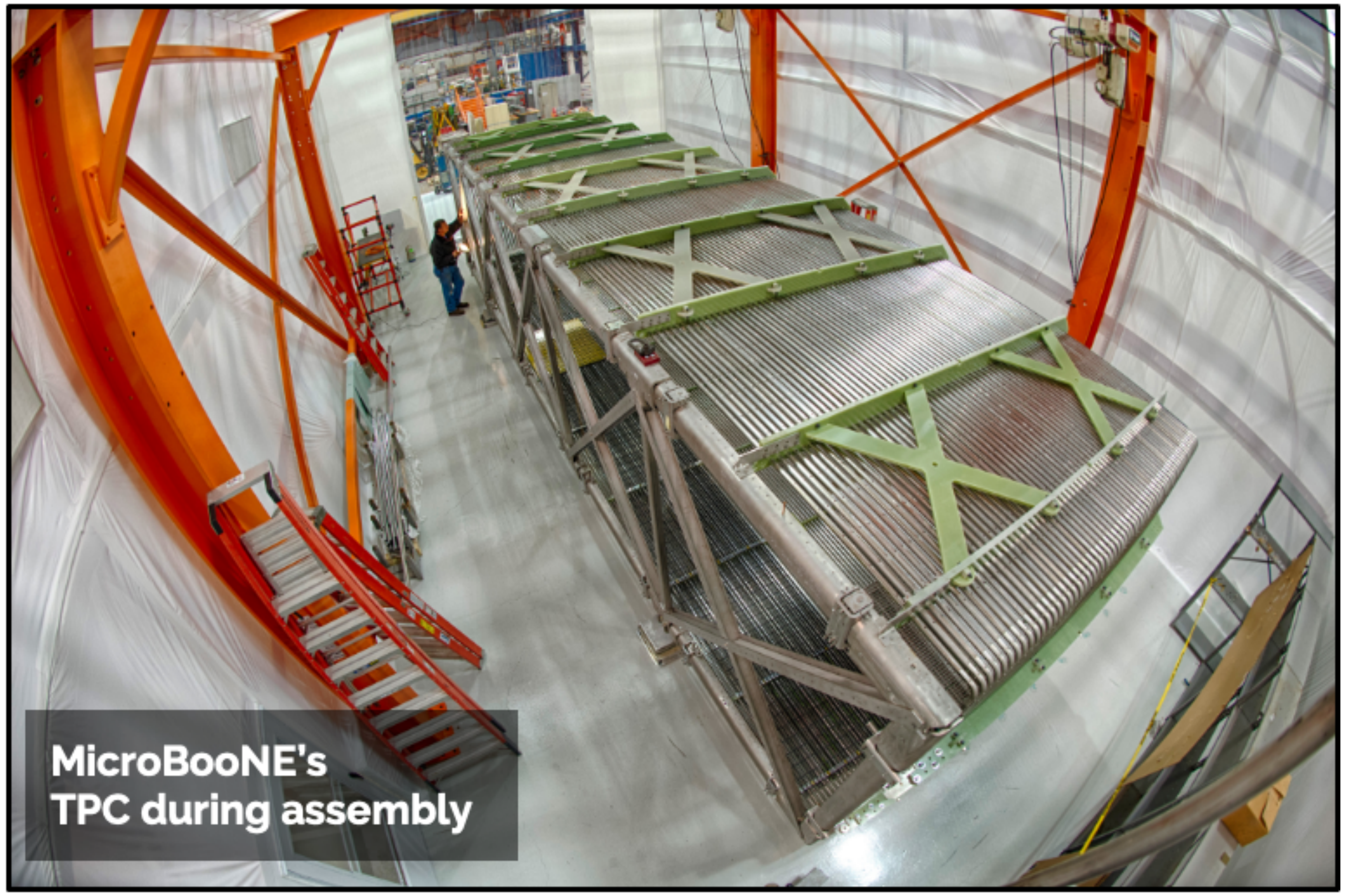
A NEW CONCEPT FOR NEUTRINO DETECTORS

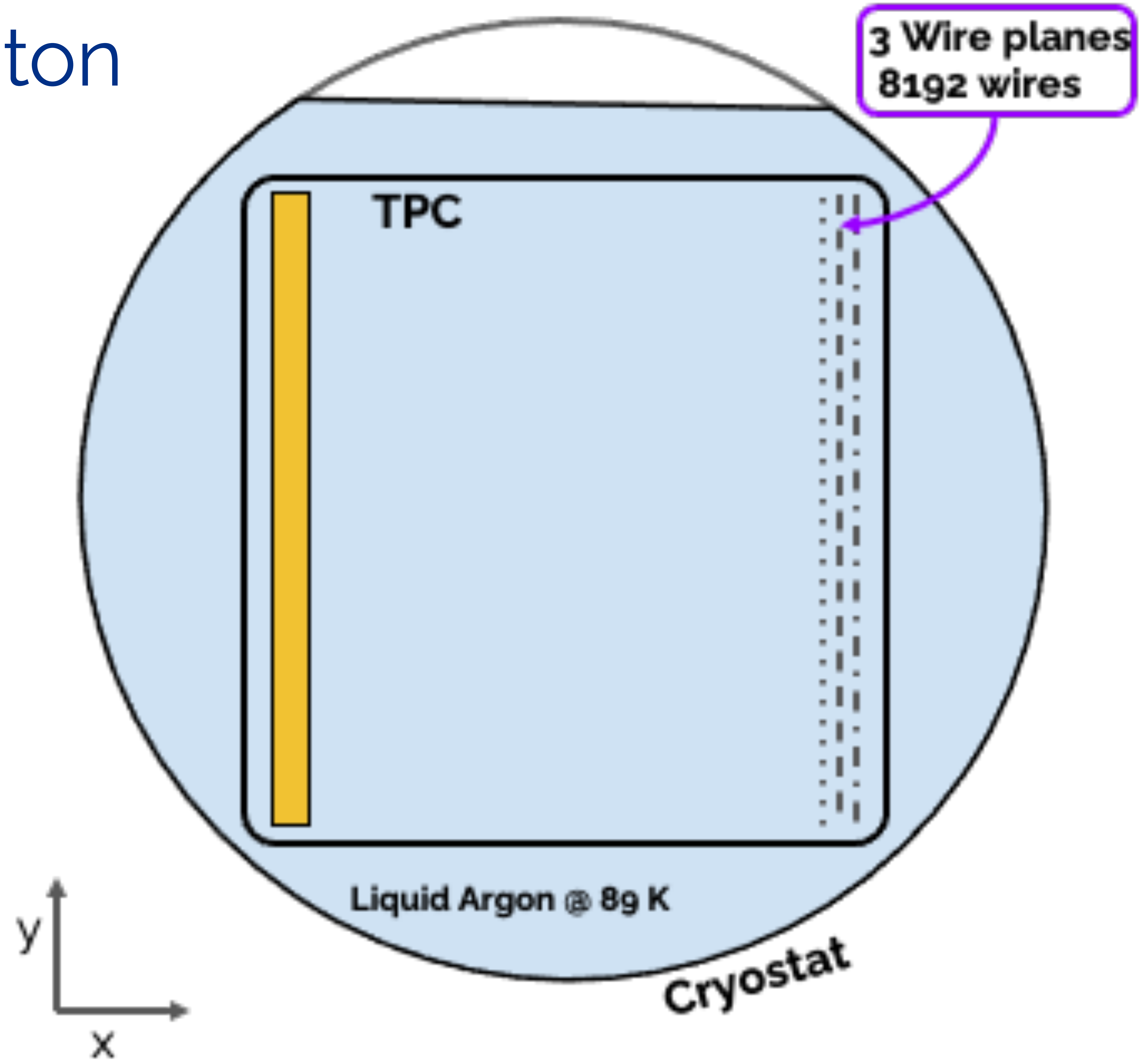
C. Rubbia

1977

LArTPC principle: the MicroBooNE detector

at MicroBooNE's core is an 85 ton LArTPC





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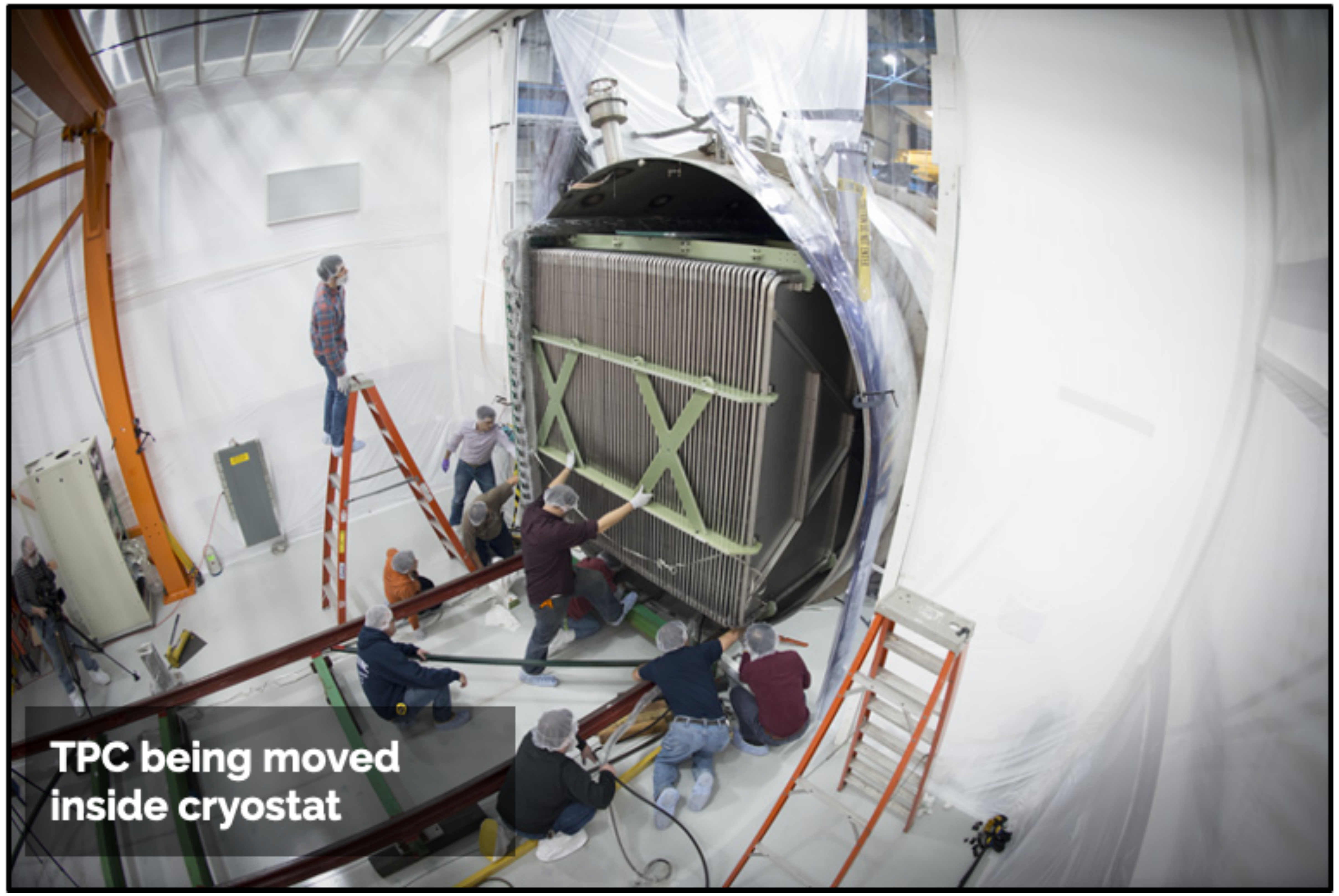
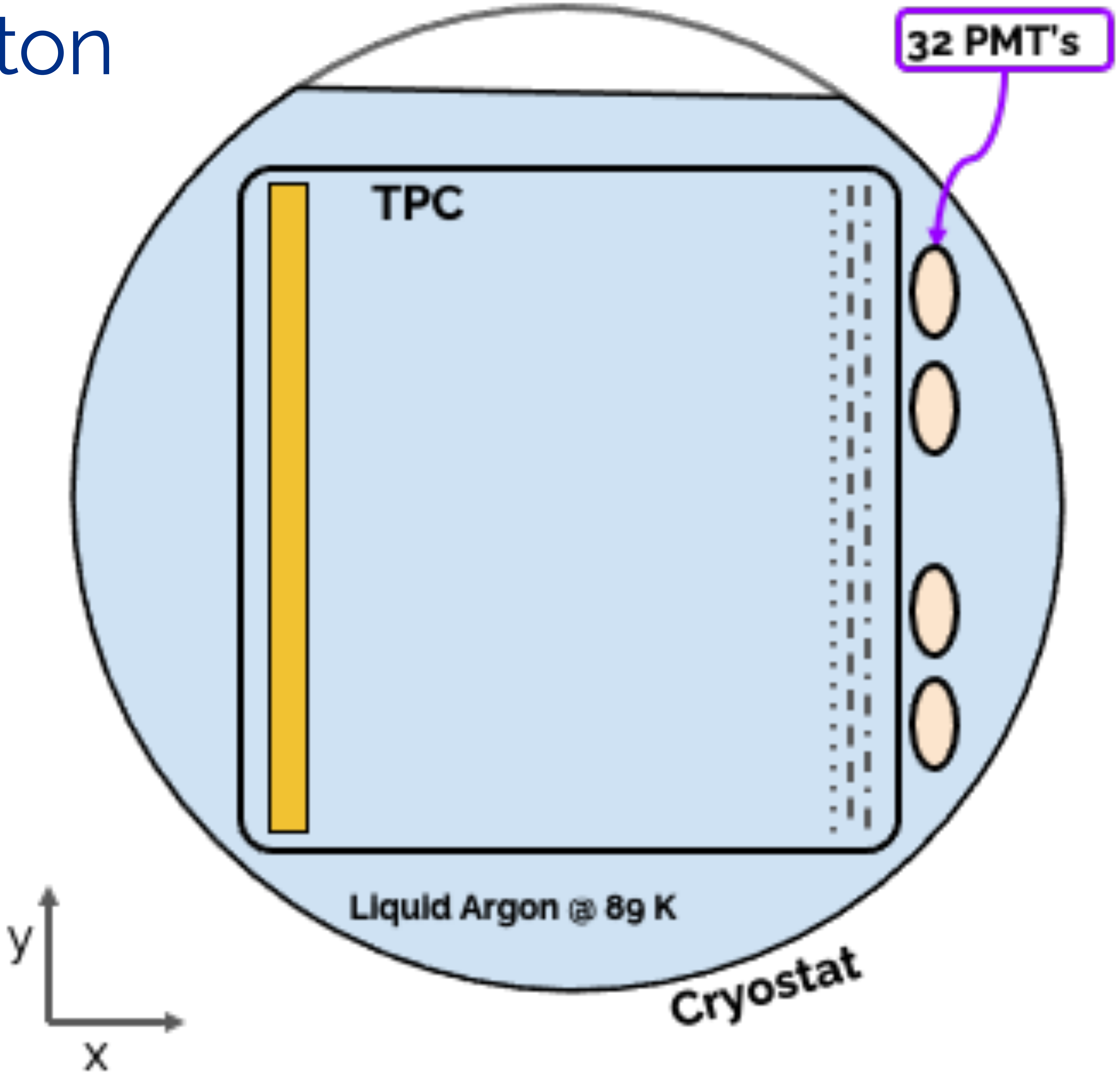
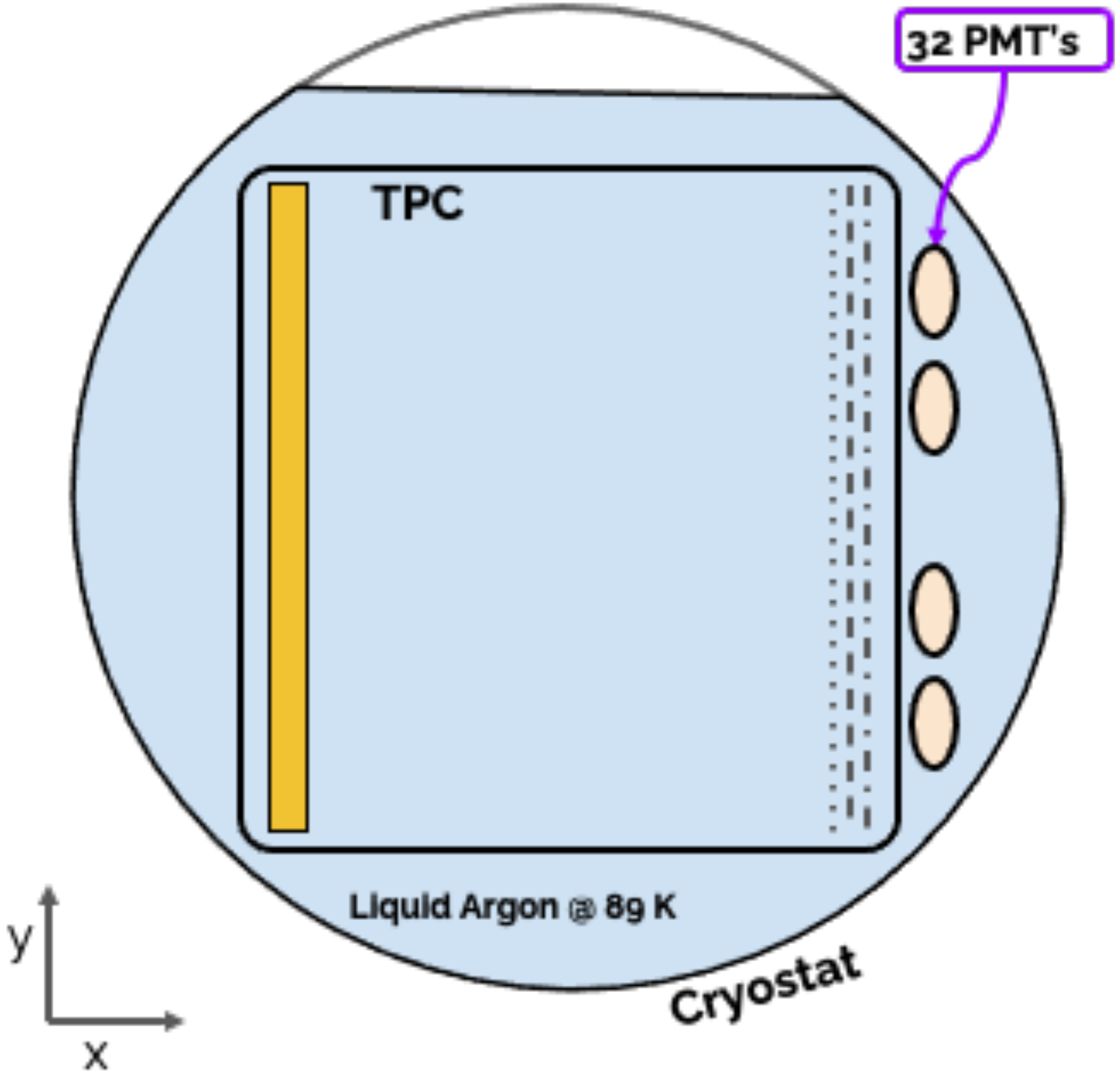
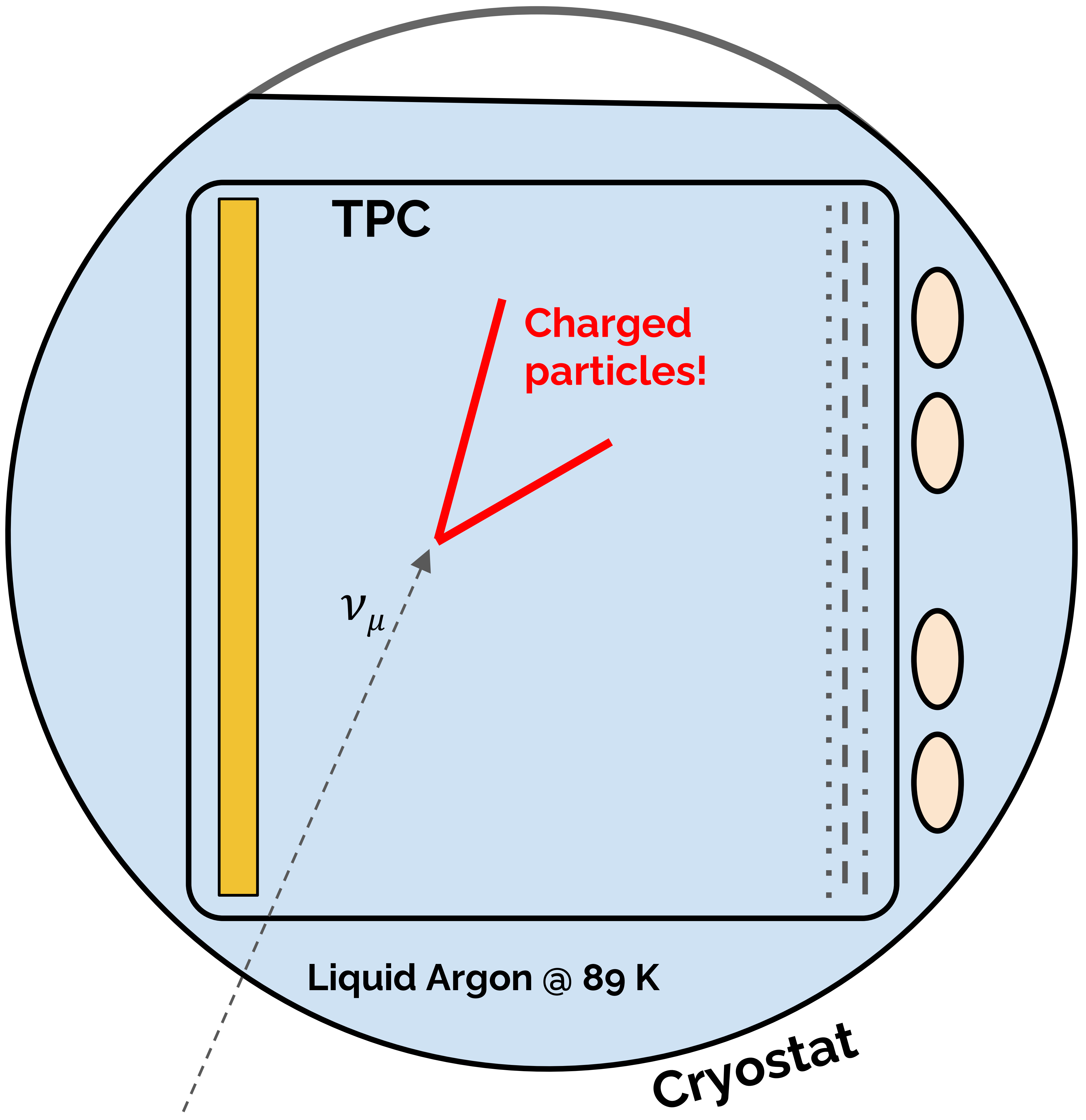




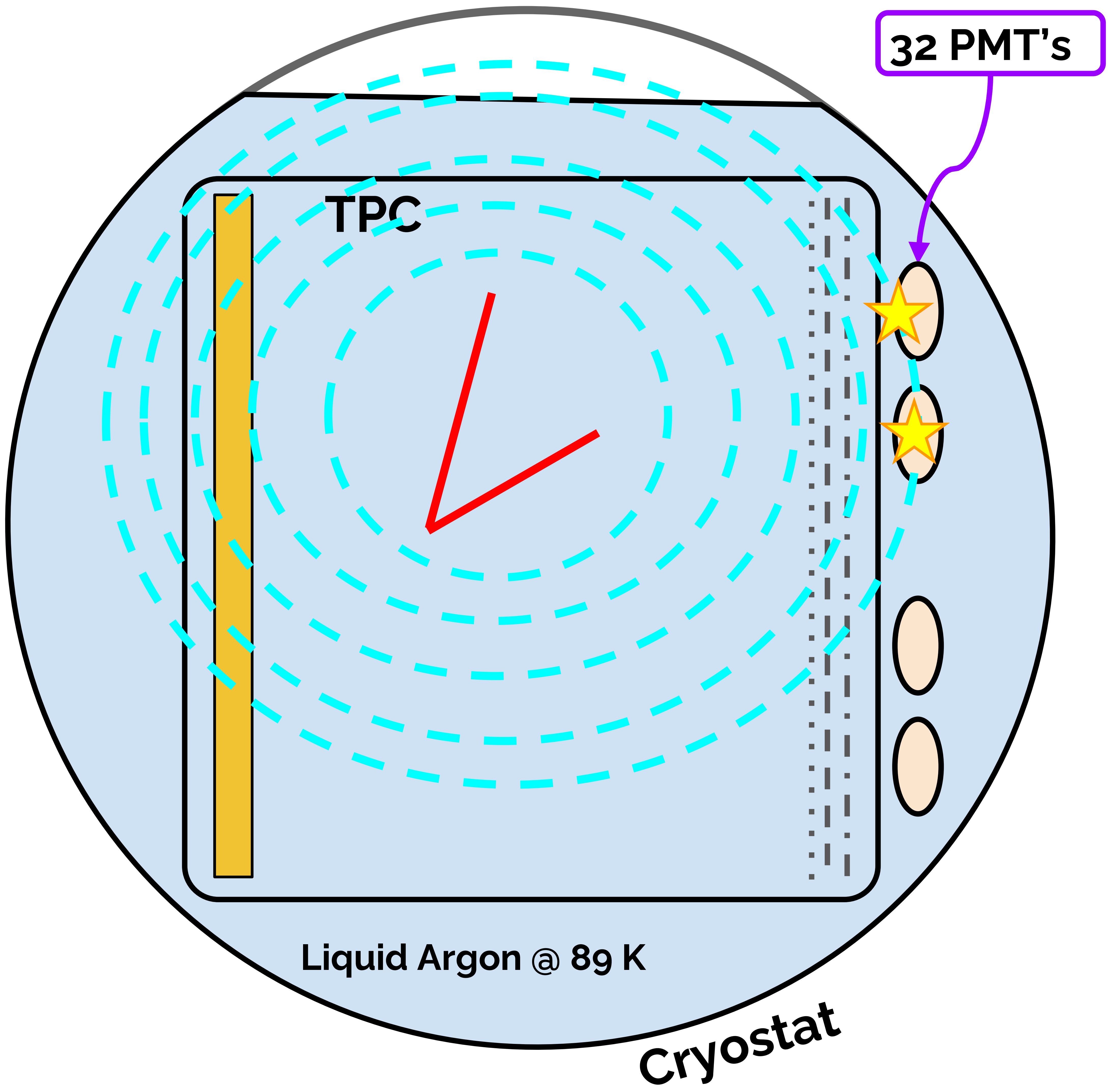
LArTPC principle: the MicroBooNE detector

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

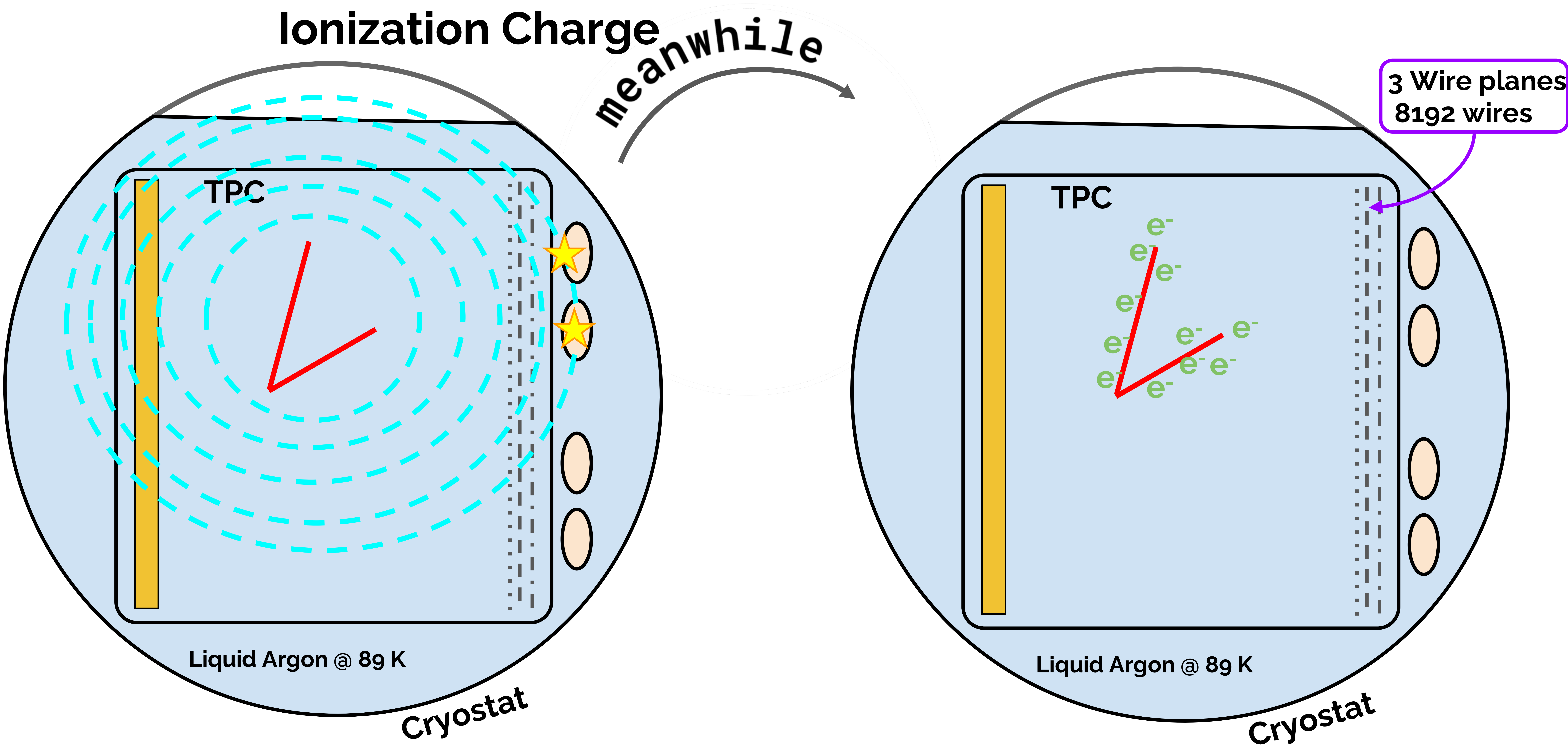



TPC
Charged
particles!
ν_μ
Liquid Argon @ 89 K
Cryostat

Scintillation light



Scintillation light
Ionization Charge



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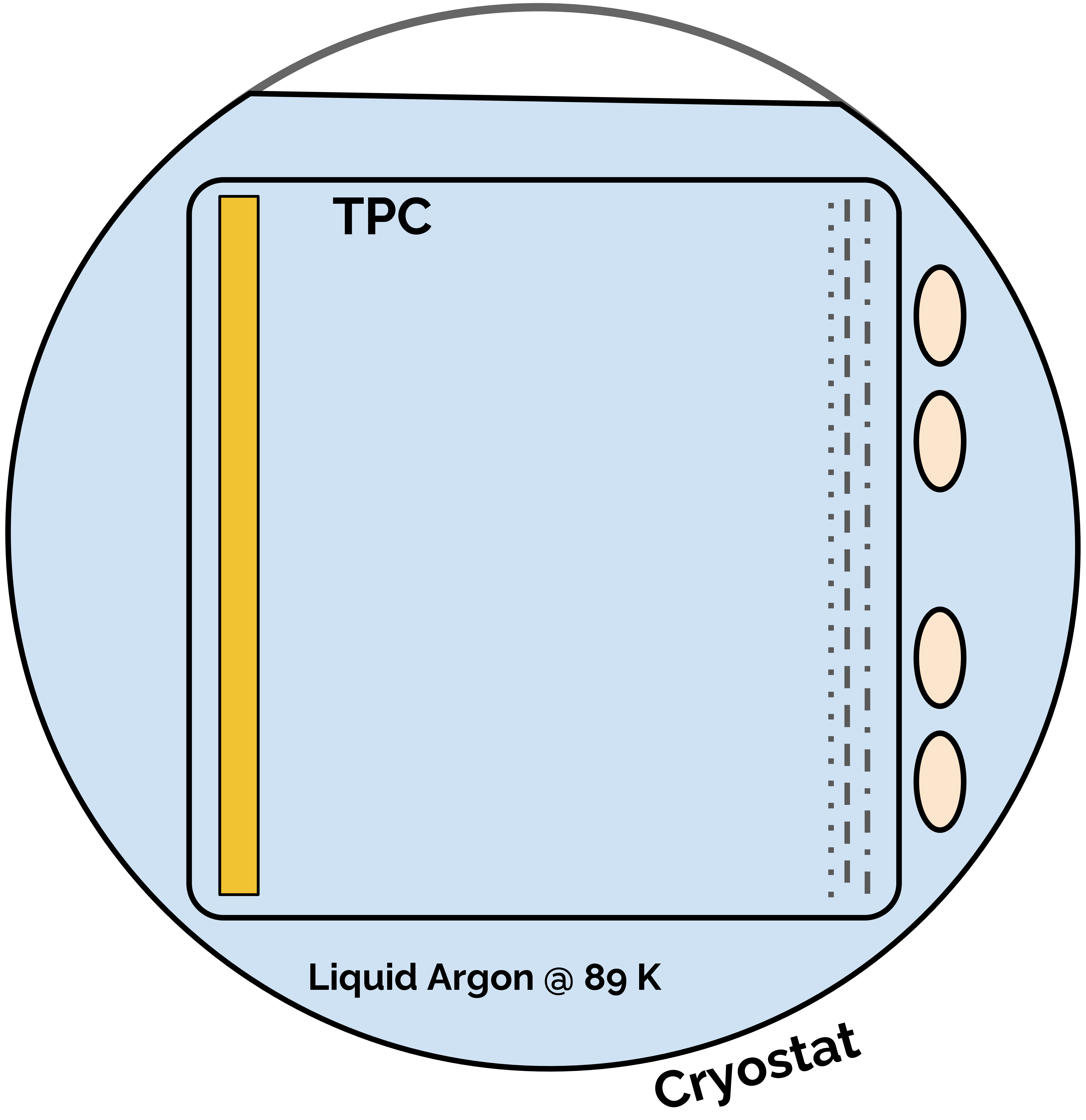
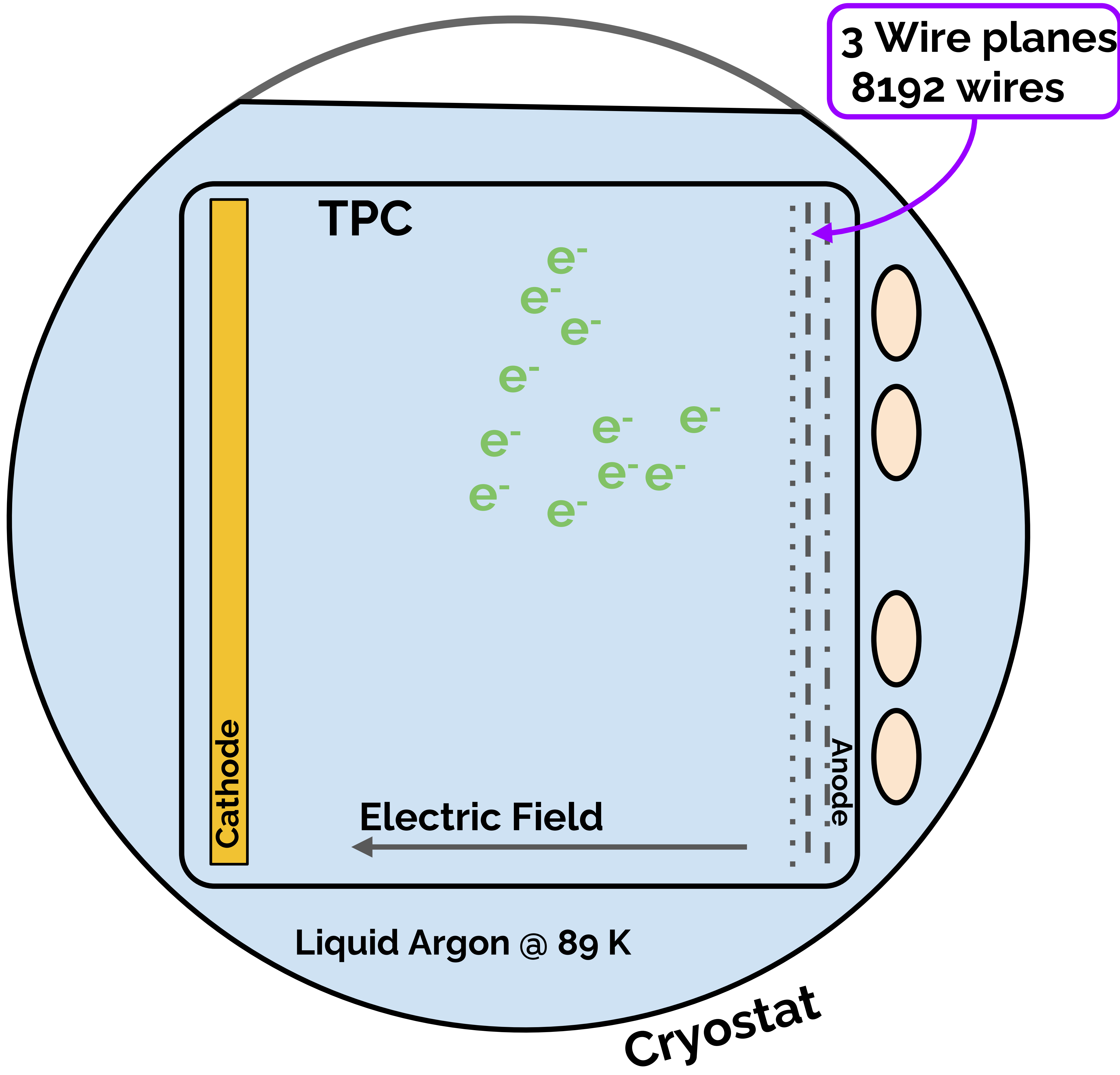
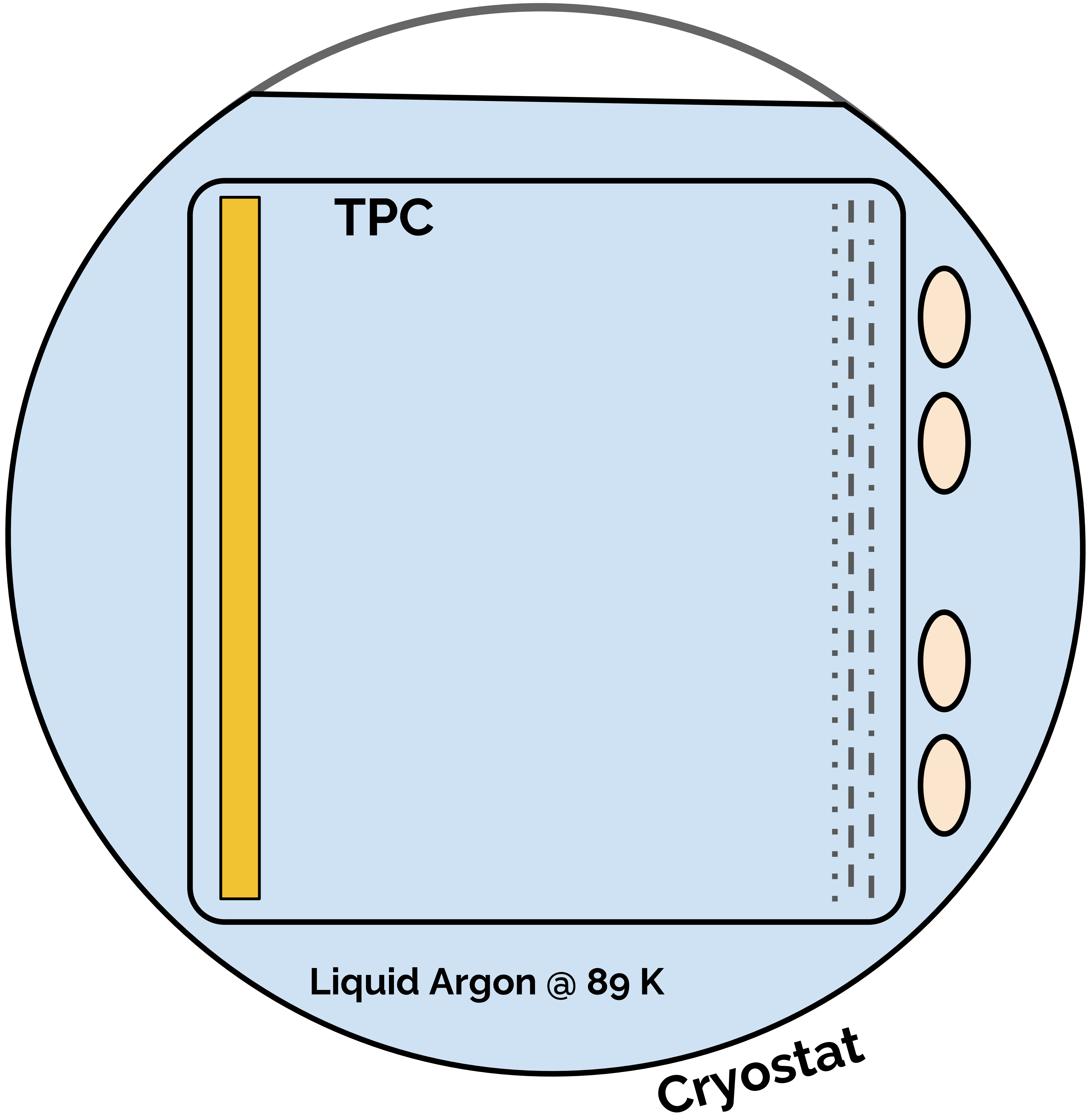
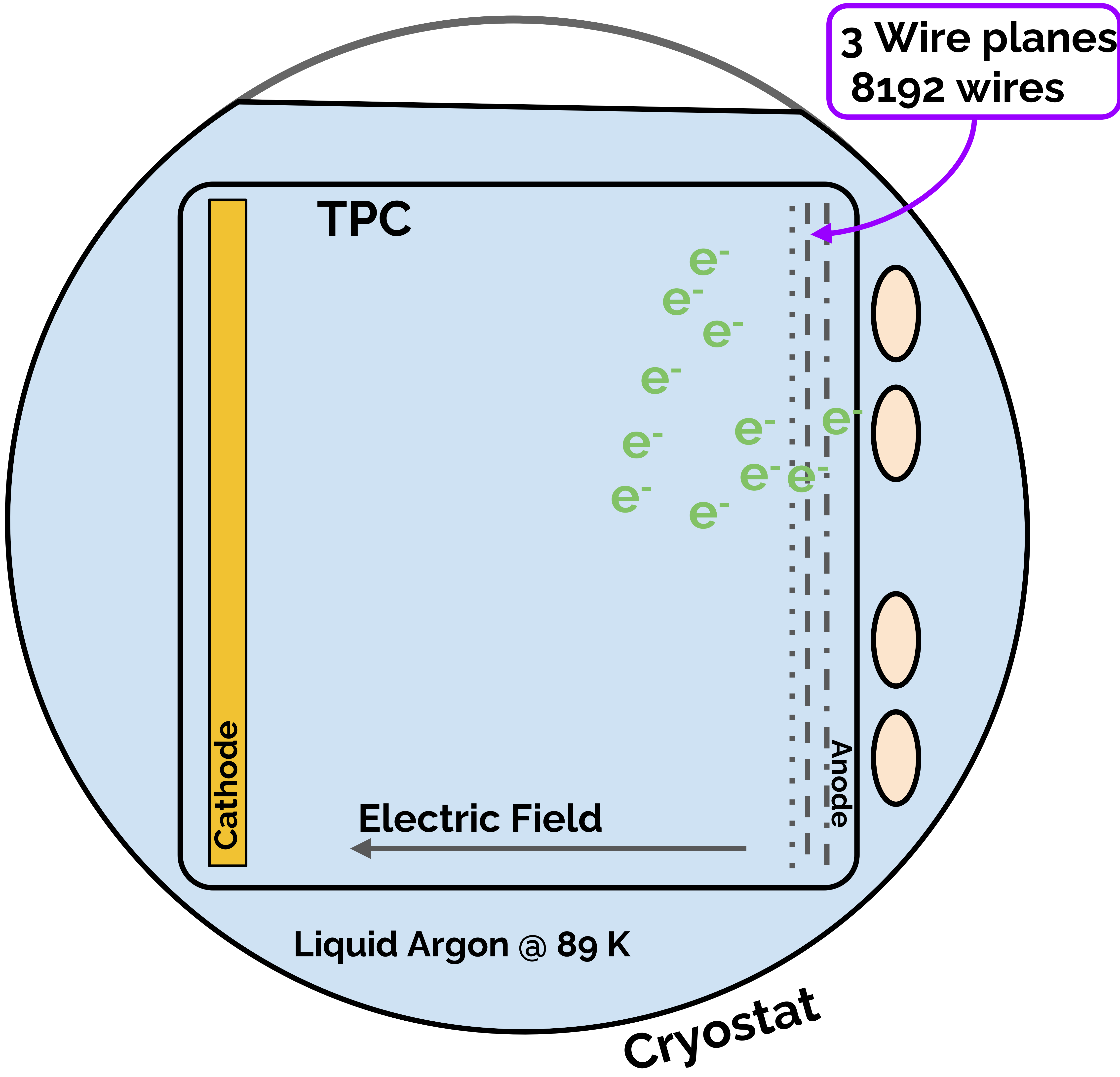




Scintillation light
Ionization Charge





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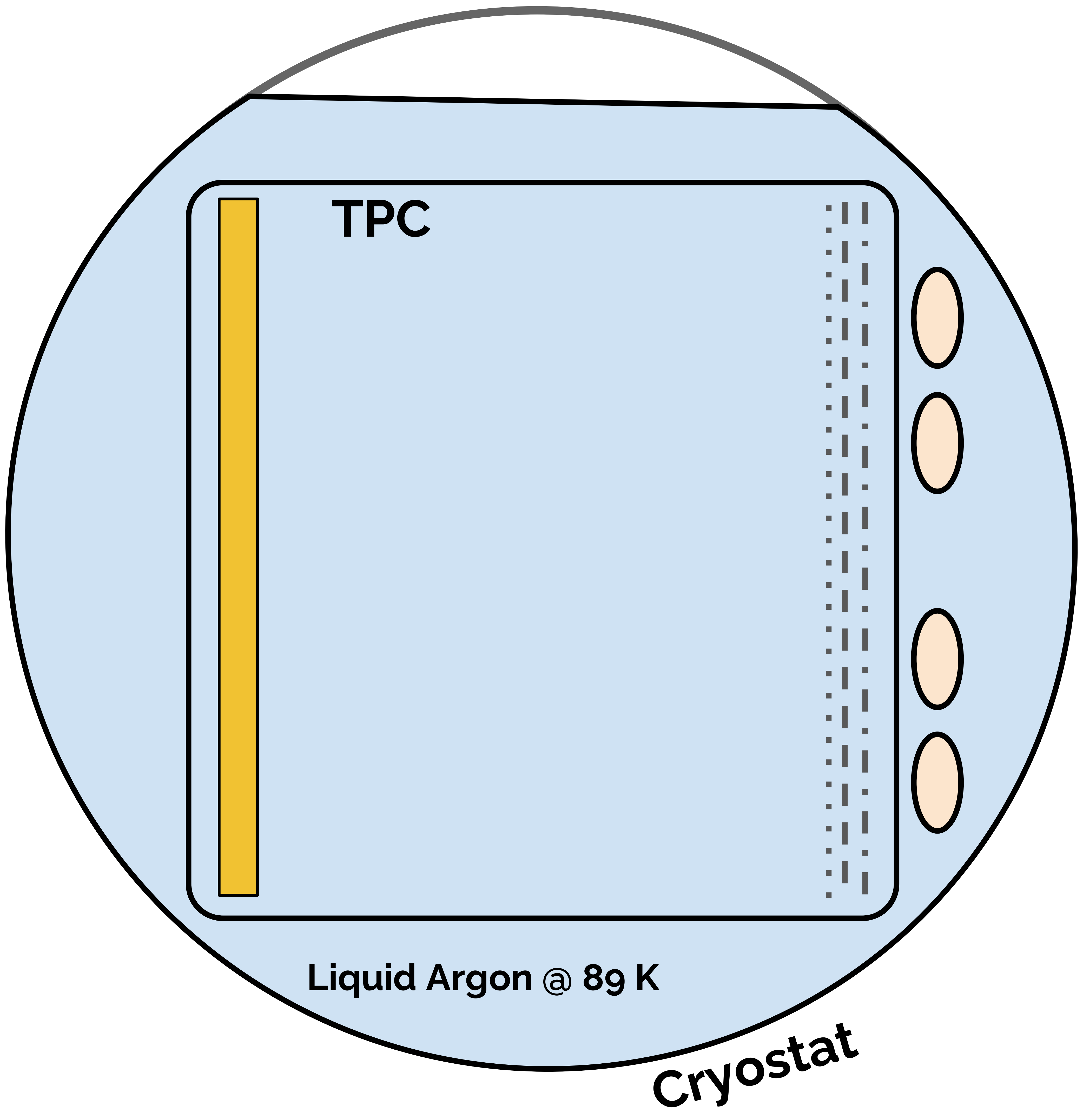

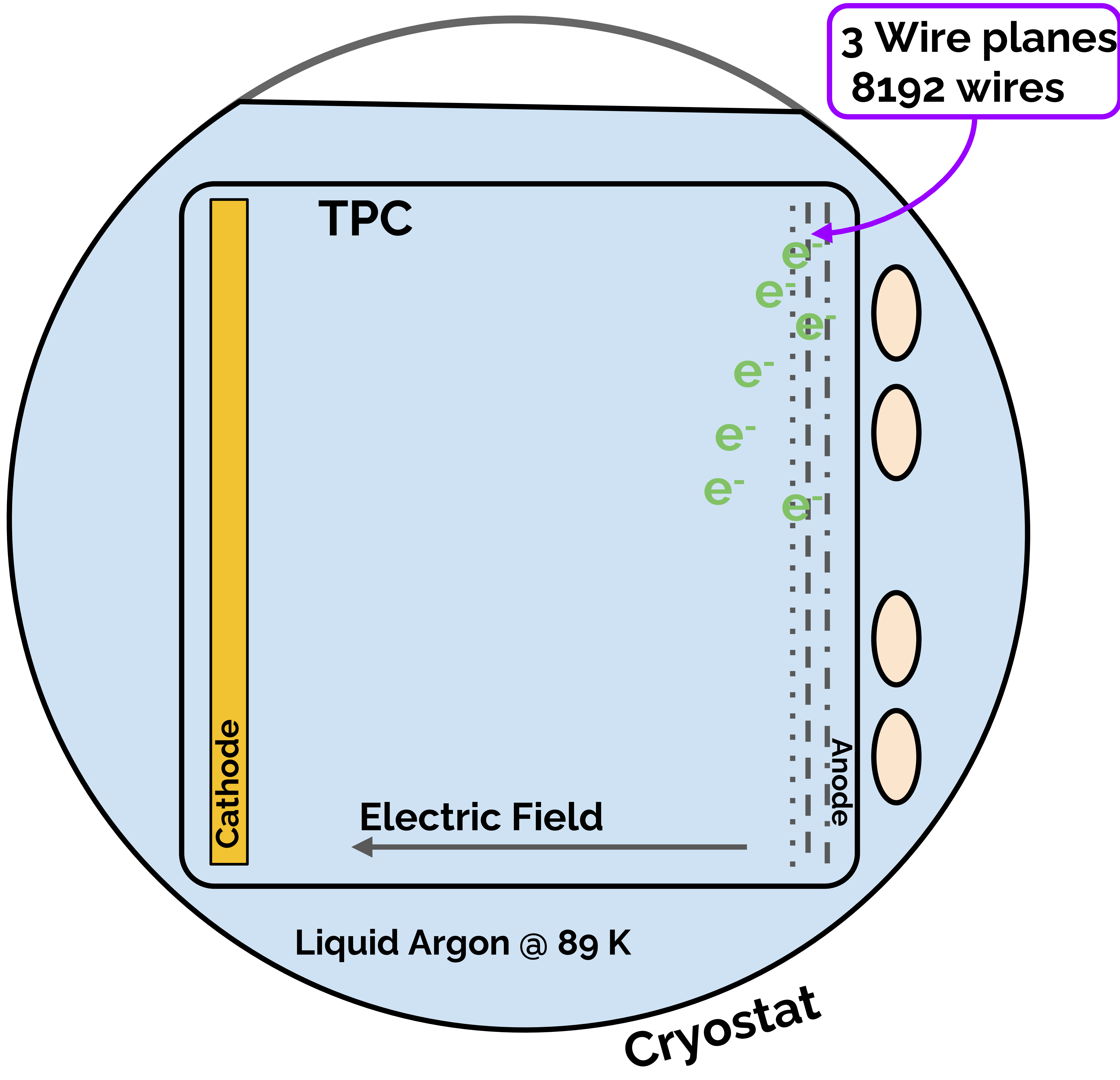

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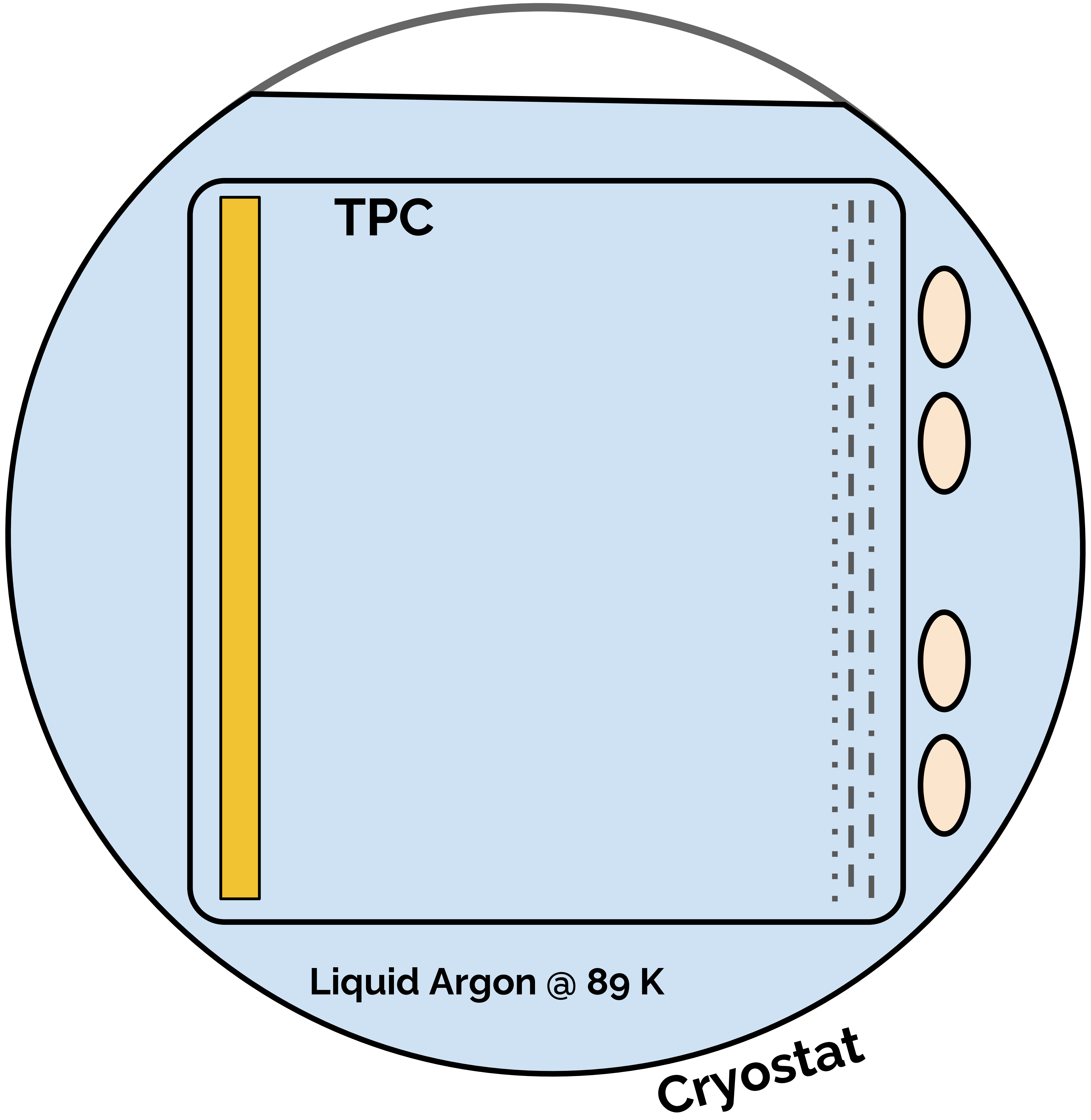

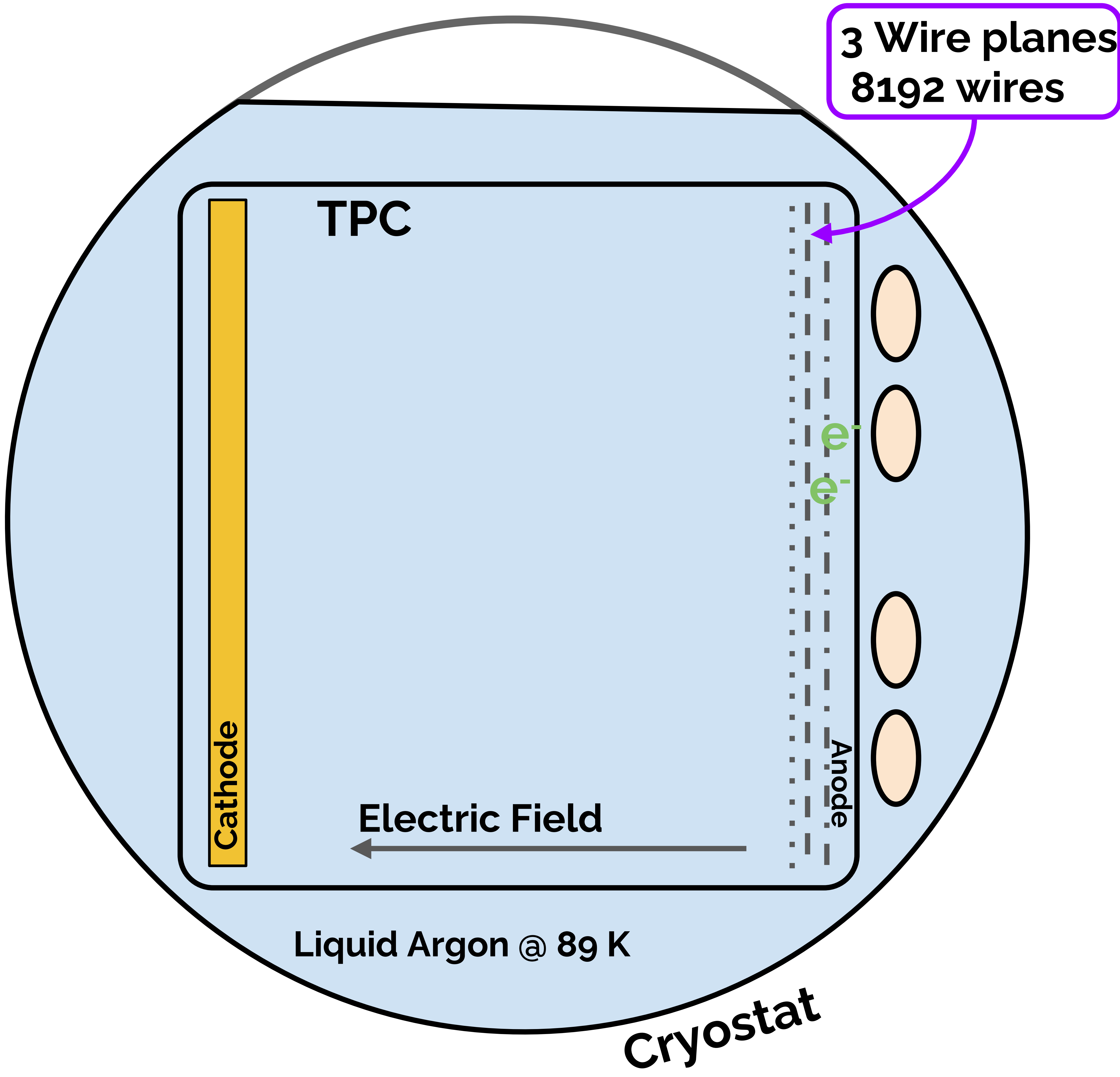

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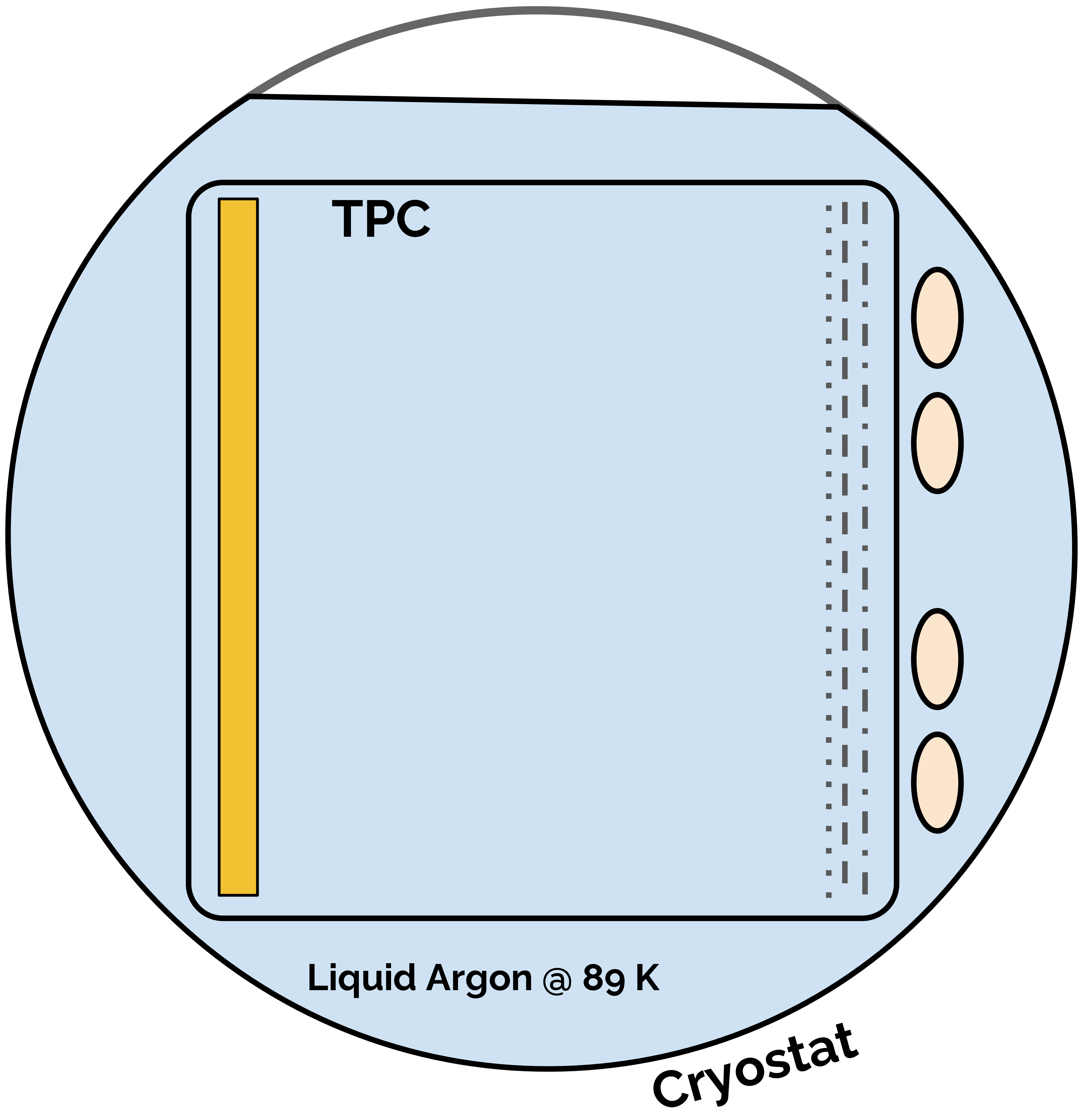
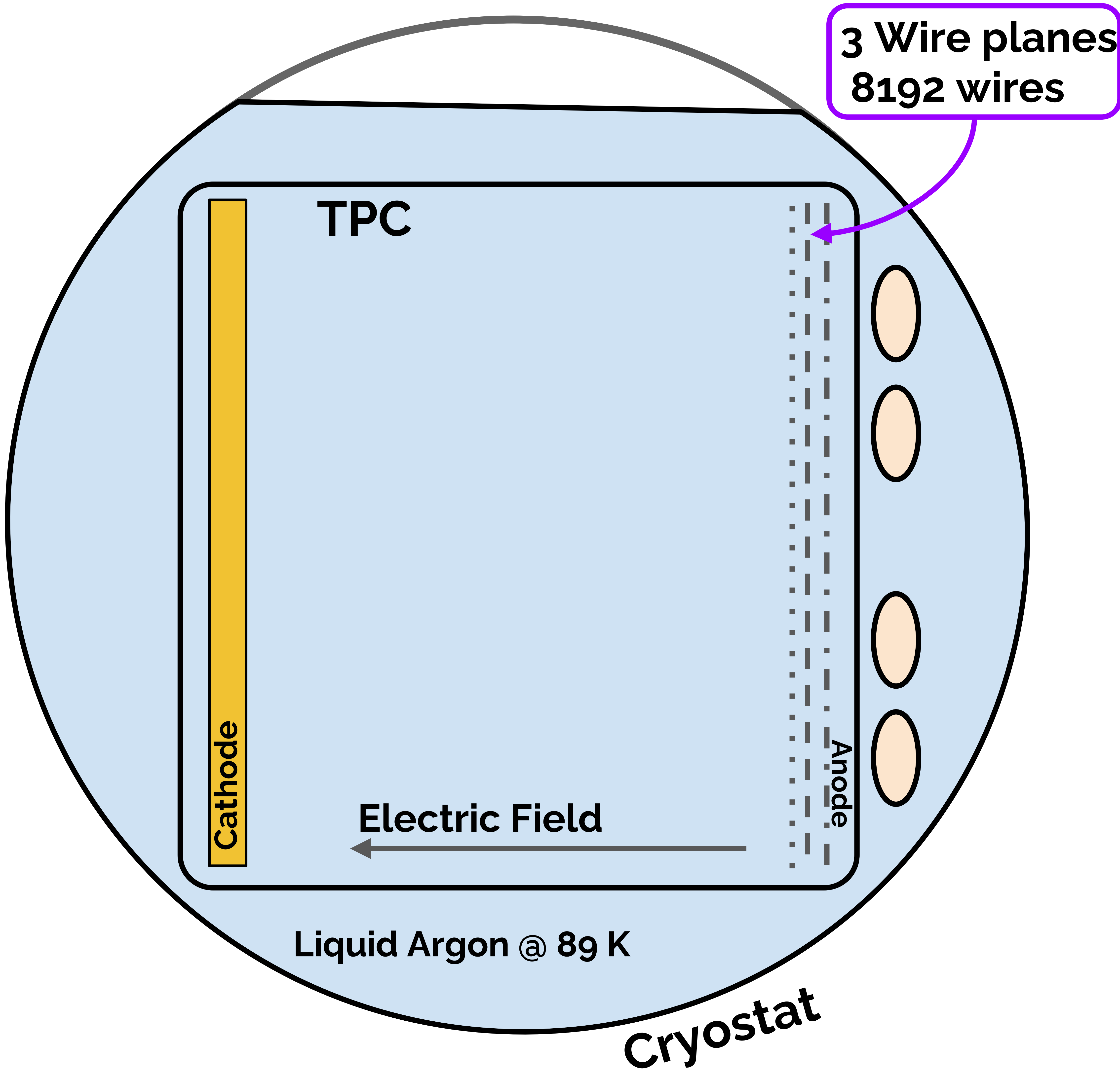
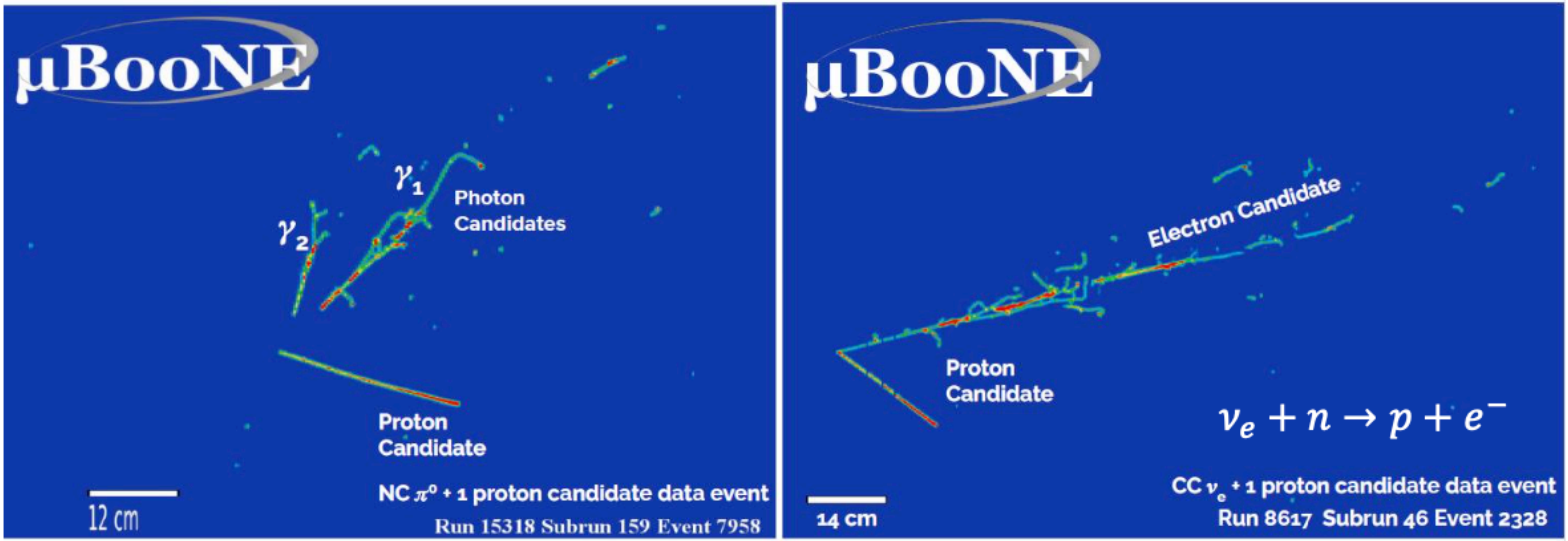




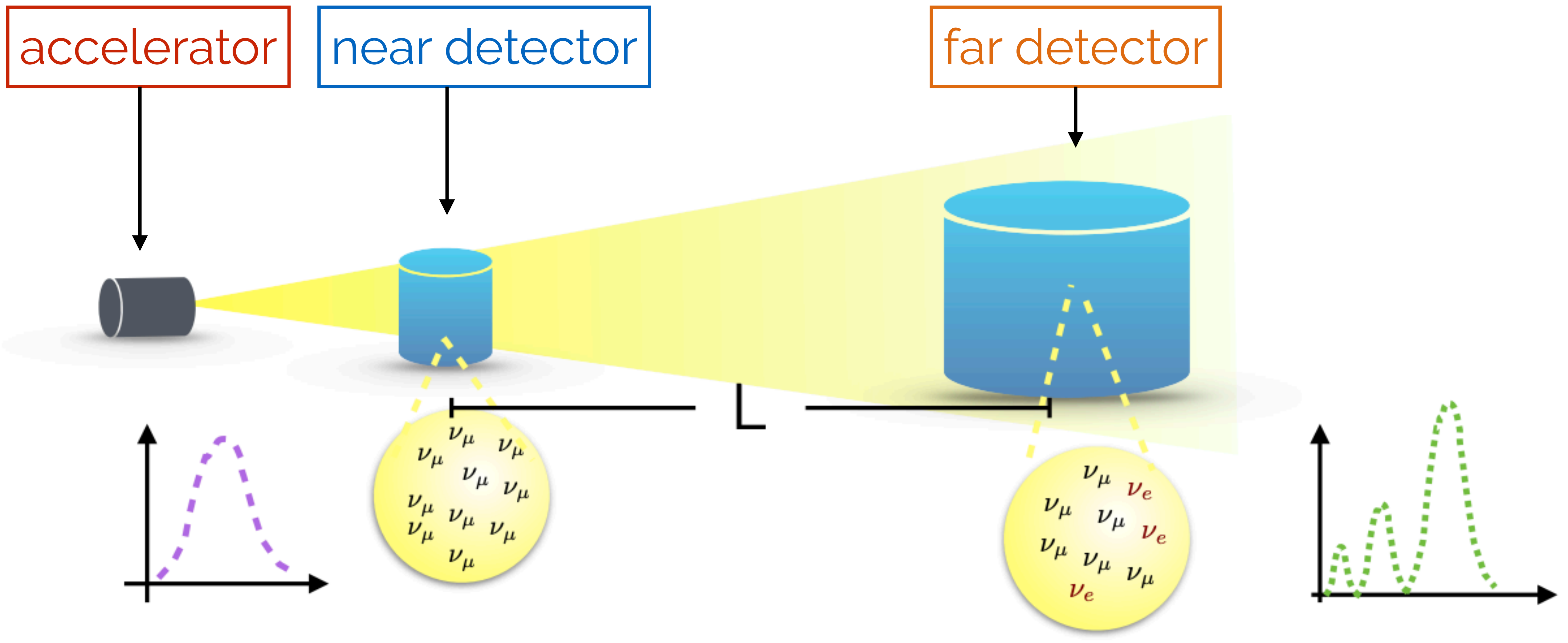
LArTPC principle: the MicroBooNE detector



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

Long-baseline neutrino experiment principles

- artificial neutrino beam generated at an **accelerator**
- measure rate of neutrino events ir the **near detector**
  - use the measurement to predict the neutrino flux at far detector
- measure rate of (un/oscillated) neutrino events in the **far detector**



$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

Detector effects

$$N_\mu(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

$$N_e(E_\nu) = P(\nu_\mu \to \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Oscillation probability

$$P(\nu_\mu \to \nu_x) \sim \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{true}}\right)$$

DUNE: next-generation long-baseline neutrino experiment

Far Site

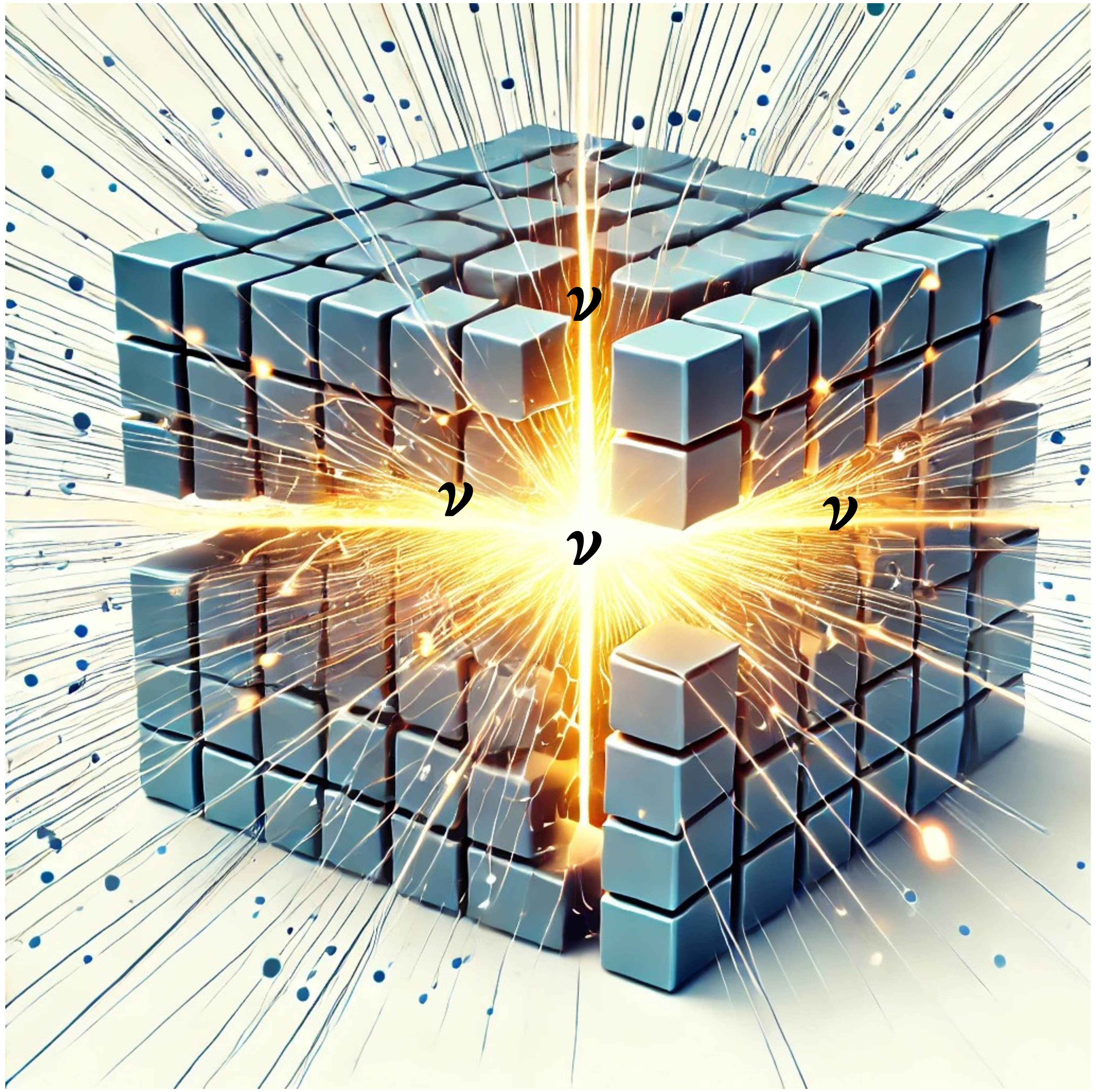
- *1300km from the proton source*
- *very large LAr TPCs (each 17 ktons)*
- *underground in South Dakota*

Near Site

- *550m from proton source*
- *on-site at Fermilab*
- *both stationary & moveable detectors*

Why do we want to detect neutrinos?

- remember neutrinos need to have ***mass*** to oscillate?
  - the Standard Model, which predicts hundreds of properties of all the particles we can measure precisely, assumes the neutrinos to be massless
  - discovery of neutrino oscillation, starts to make a crack in this incredibly successful model of particle physics



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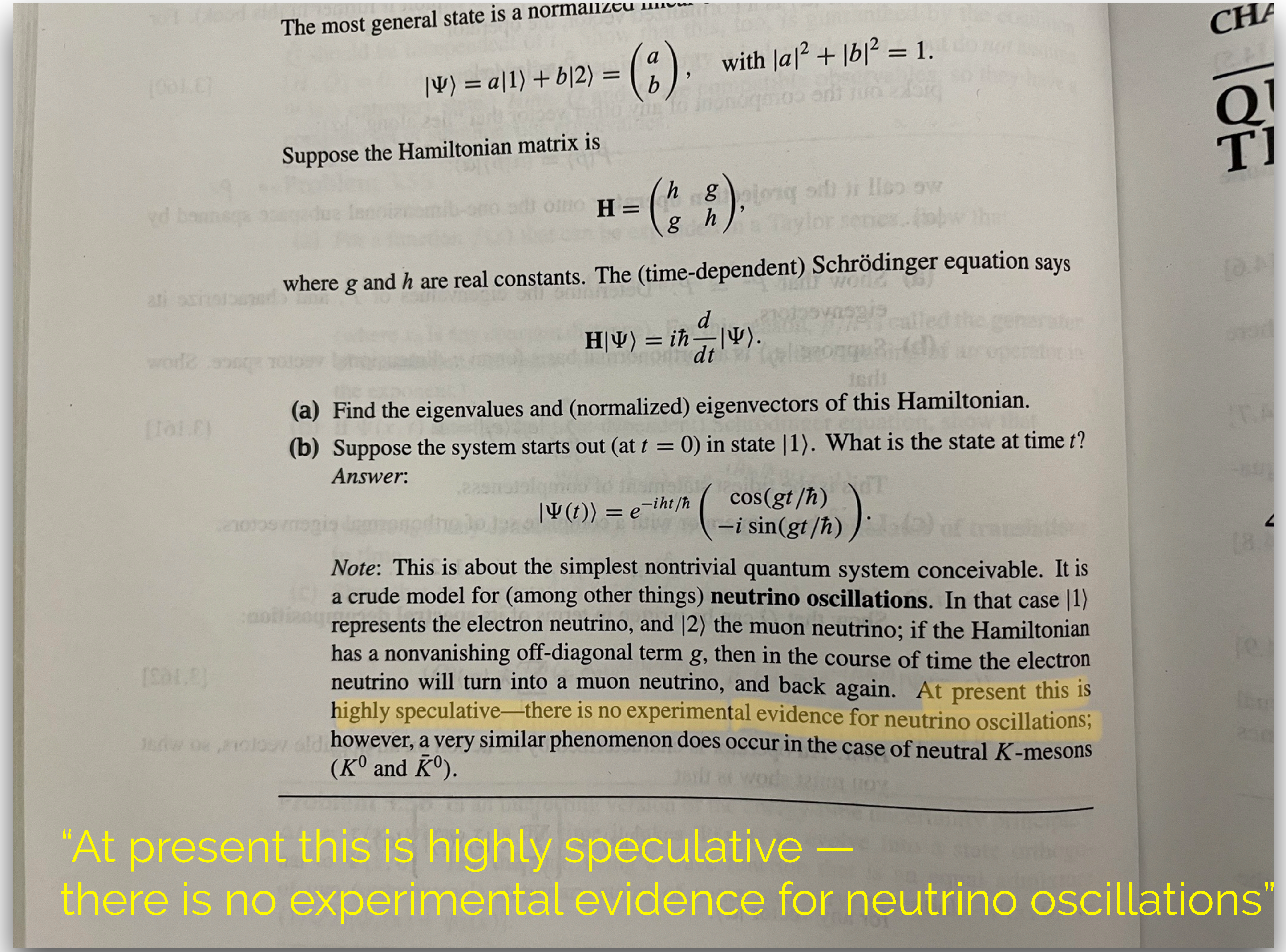

The most general state is a normalized linear ...

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

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 $\bar{K}^0$).

"At present this is highly speculative —
there is no experimental evidence for neutrino oscillations"

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

Why do we want to detect neutrinos?

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?

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?

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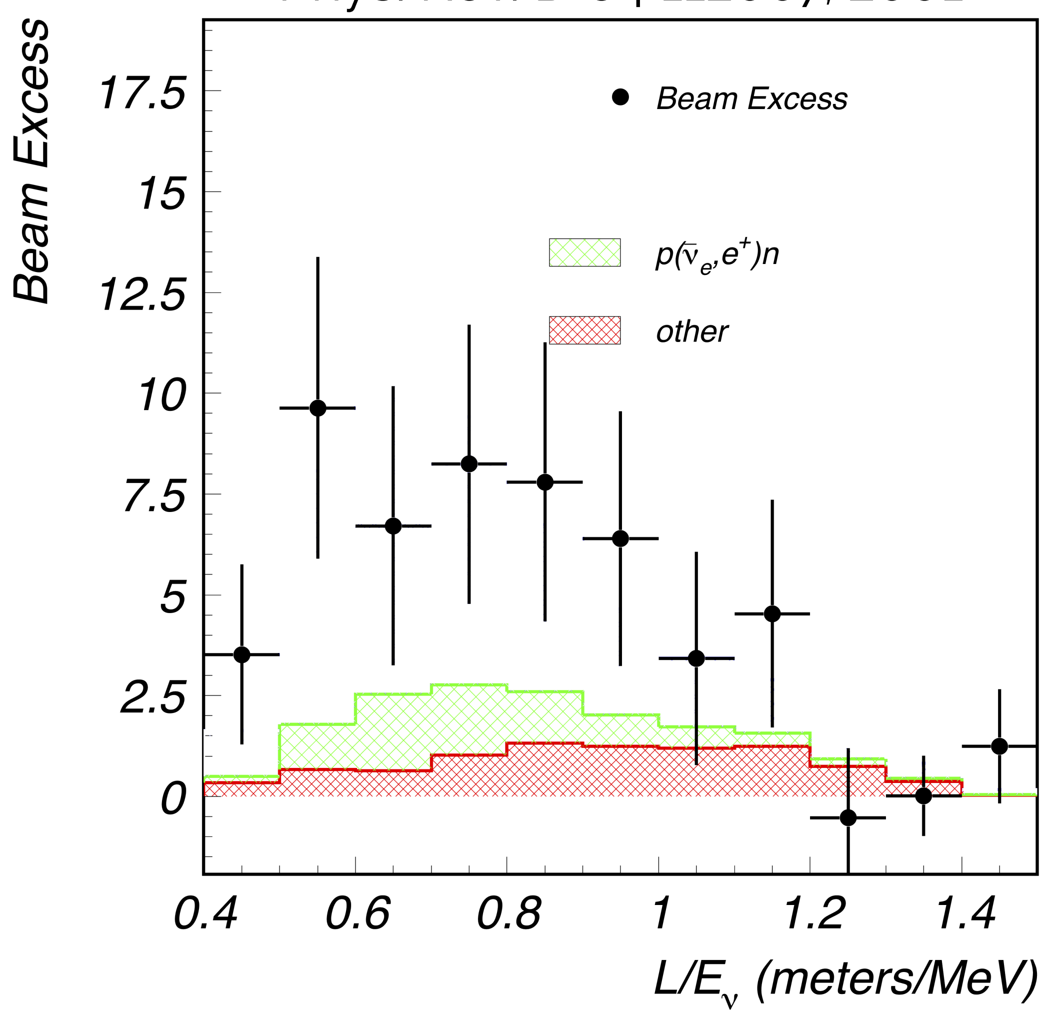
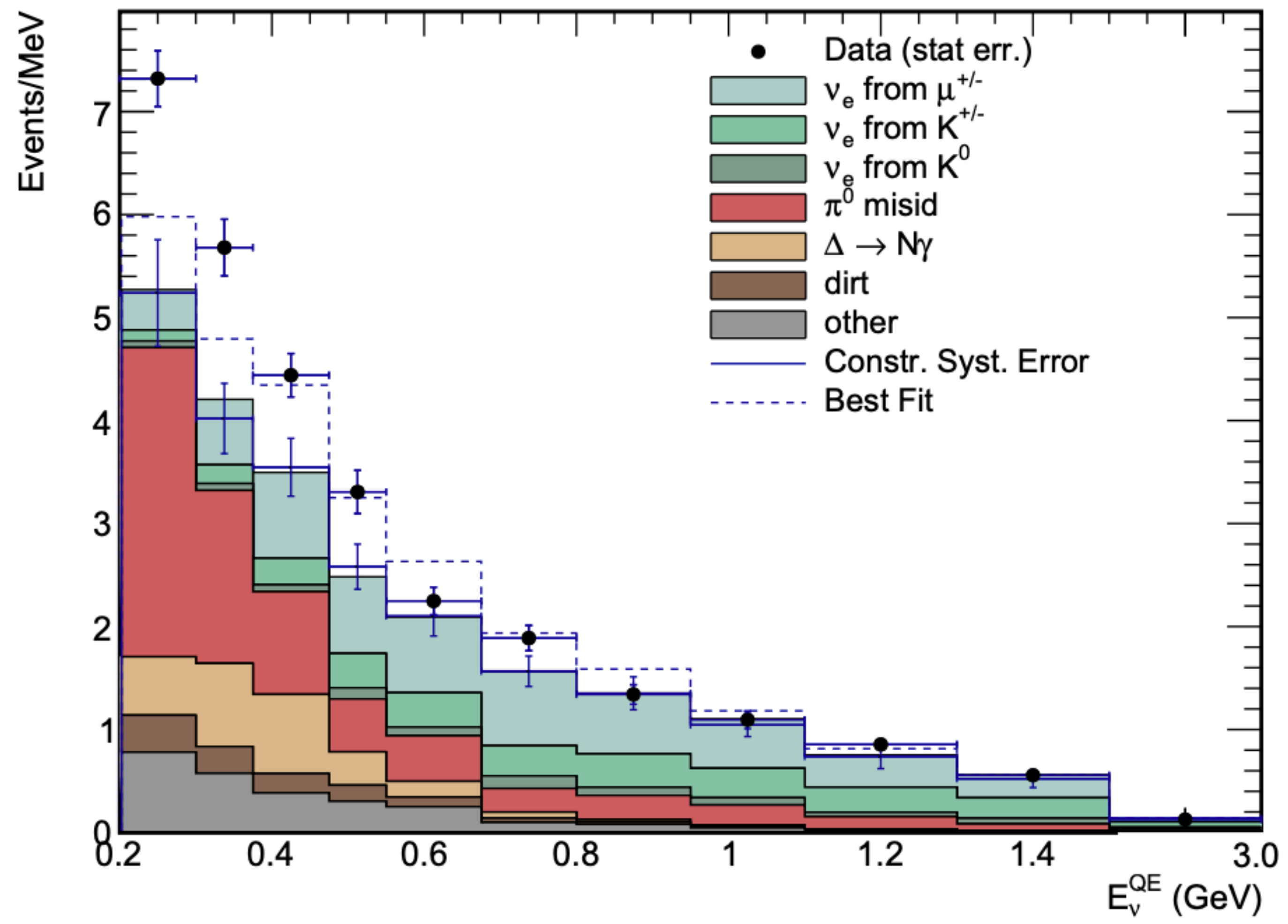
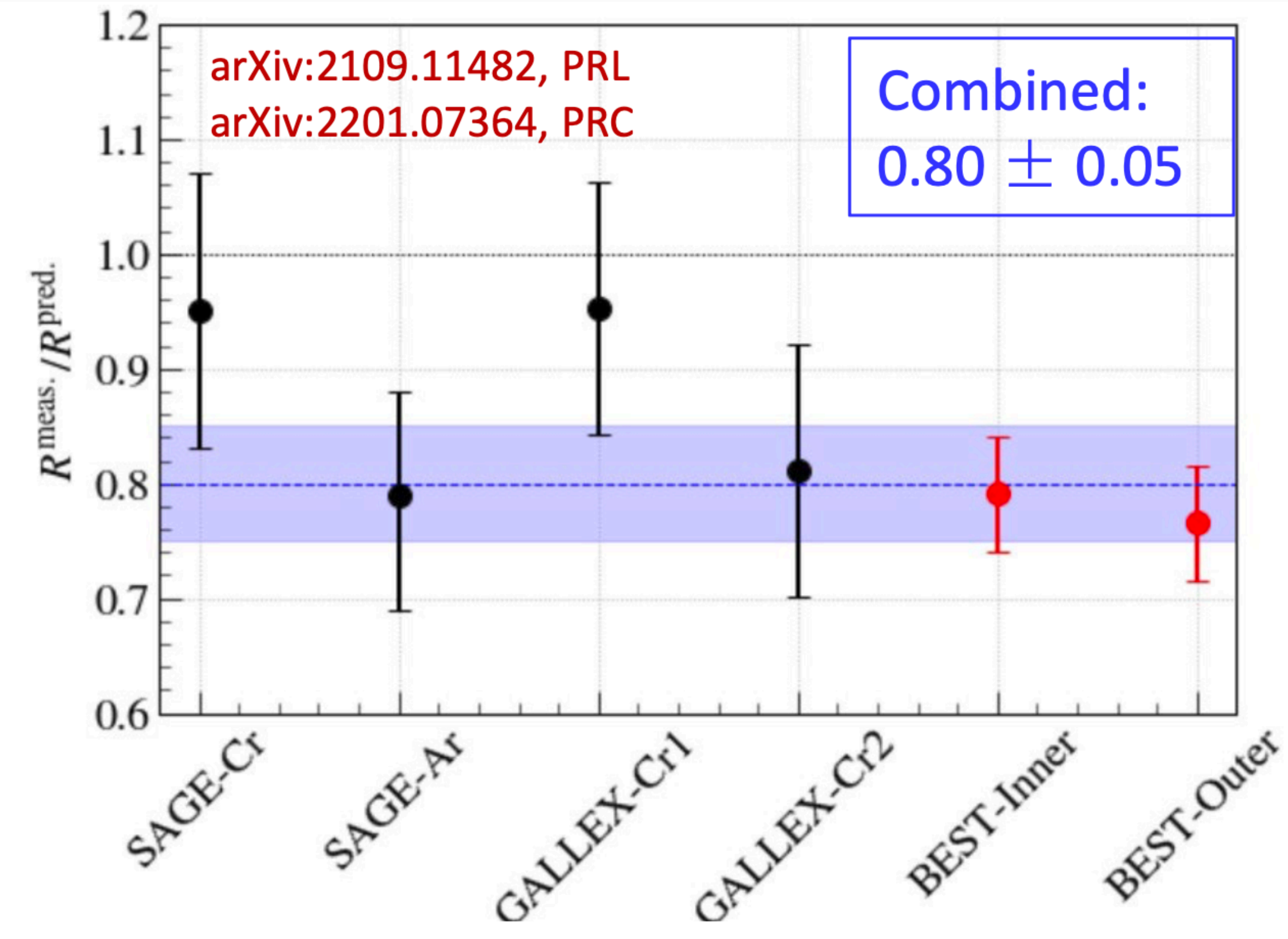


LSND anomaly

Phys. Rev. D 103, 052002 (2021)



MiniBooNE anomaly



Gallium anomaly

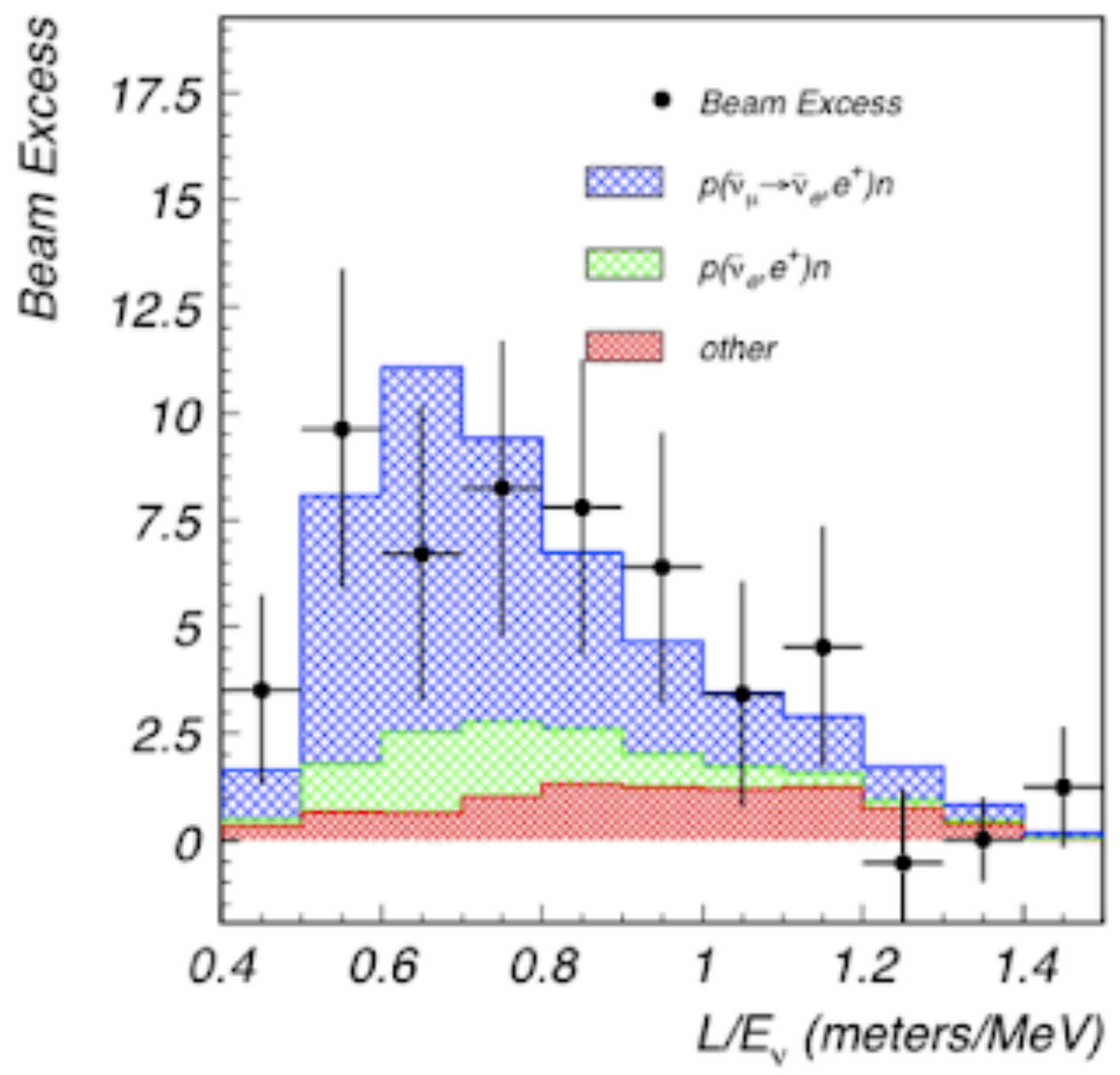
Why do we want to detect neutrinos? Example of “sterile” neutrino

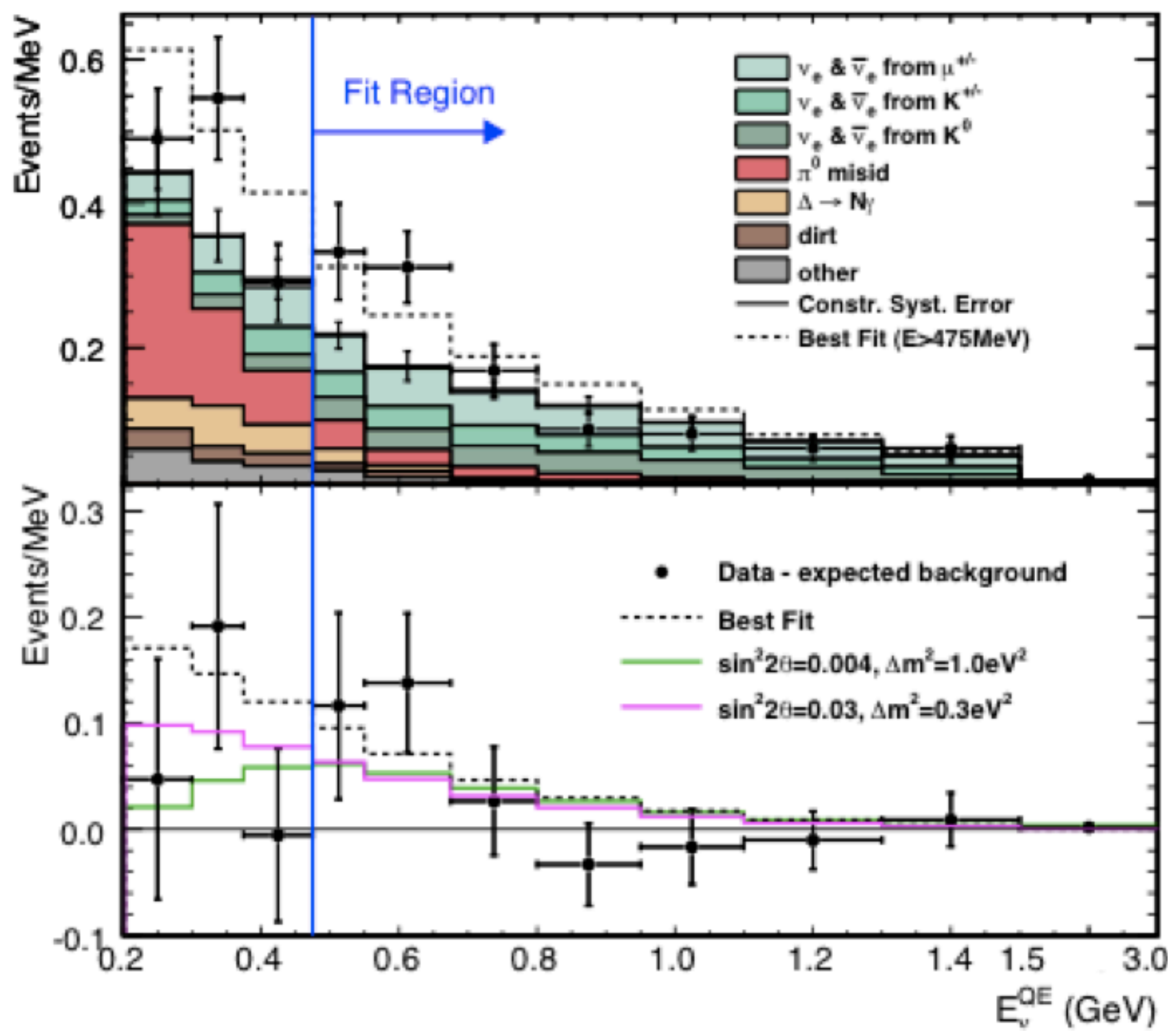
- maybe adding an extra, “**sterile**” neutrino help resolving these anomalies

- 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*





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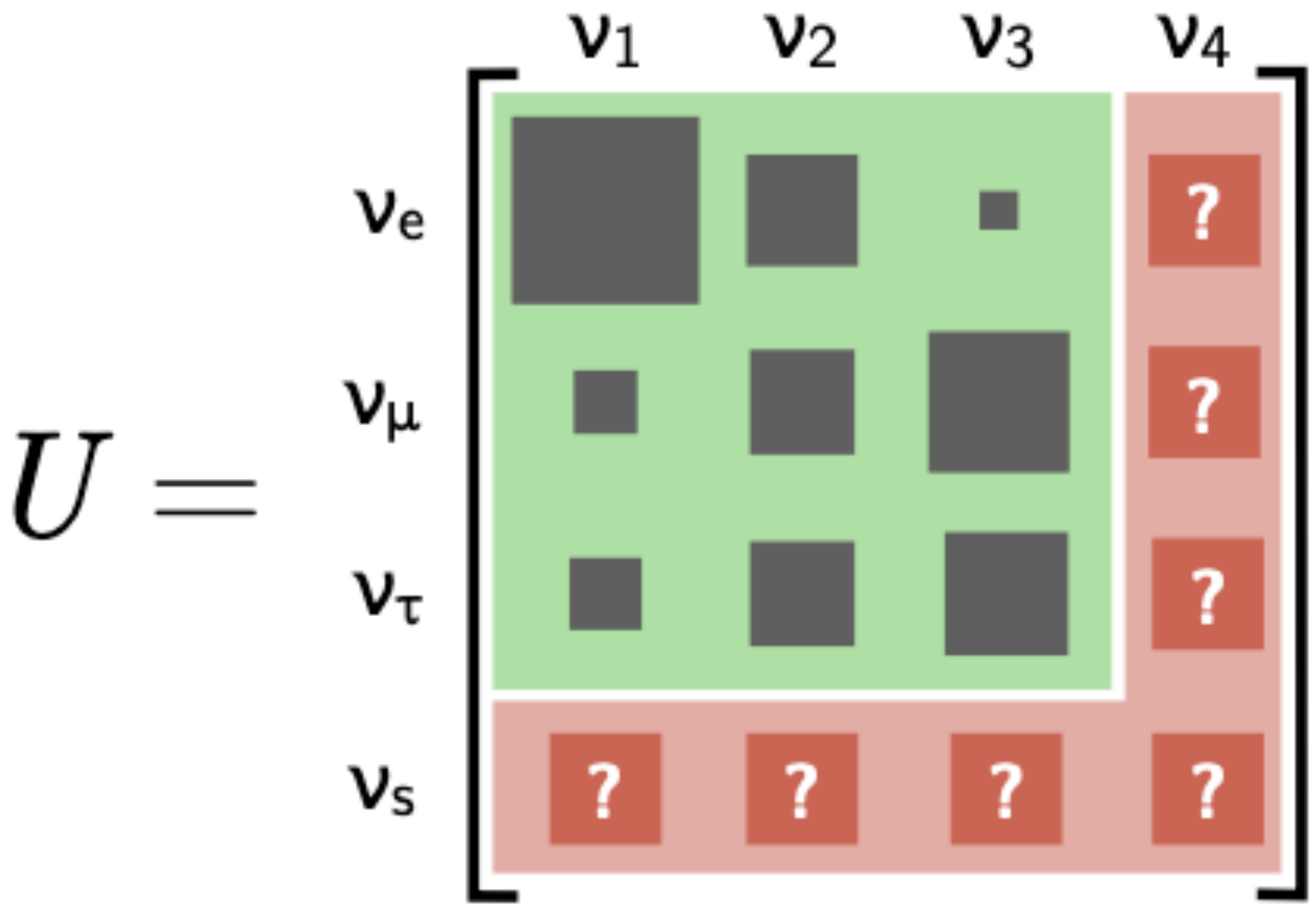

Flavor transitions via this new mixing:

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

Summary

- neutrino physics is relatively young, but started to have a big impact in our understanding of the Universe
- at the heart of neutrino physics, there is massive neutrino & neutrino oscillation
- detecting neutrino is challenging, yet we can do it… and pretty well!
- precise measurements of neutrino's behavior will open a new era of particle physics