

Neutrinos: How to Catch a Ghost Particle

(A brief) Introduction to Neutrino Physics

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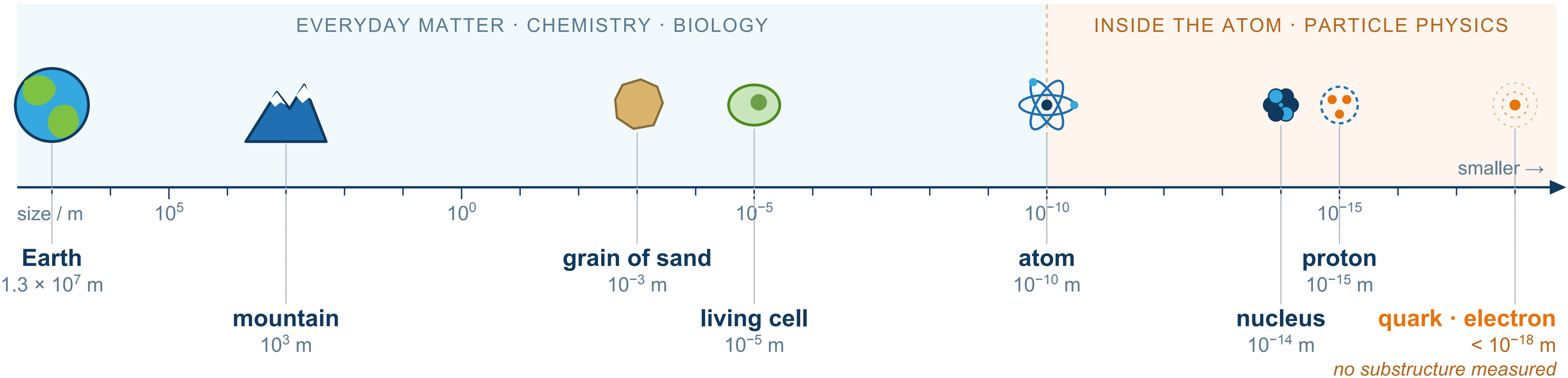
July 20, 2026

BNL Physics Department Summer Lecture

A brief bio...

- As a kid, I always was fascinated with the stars and galaxies (who wasn'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 didn't?).
- In graduate school, I started working on **experimental particle physics** (neutrinos) as we started to have breakthroughs in experimental particle physics during the time (Higgs boson discovery, neutrino oscillation, gravitational waves...).
- As a postdoc, I also worked on **dark matter search** for a few years, then came back to **neutrino physics** as a faculty here at BNL.
- 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

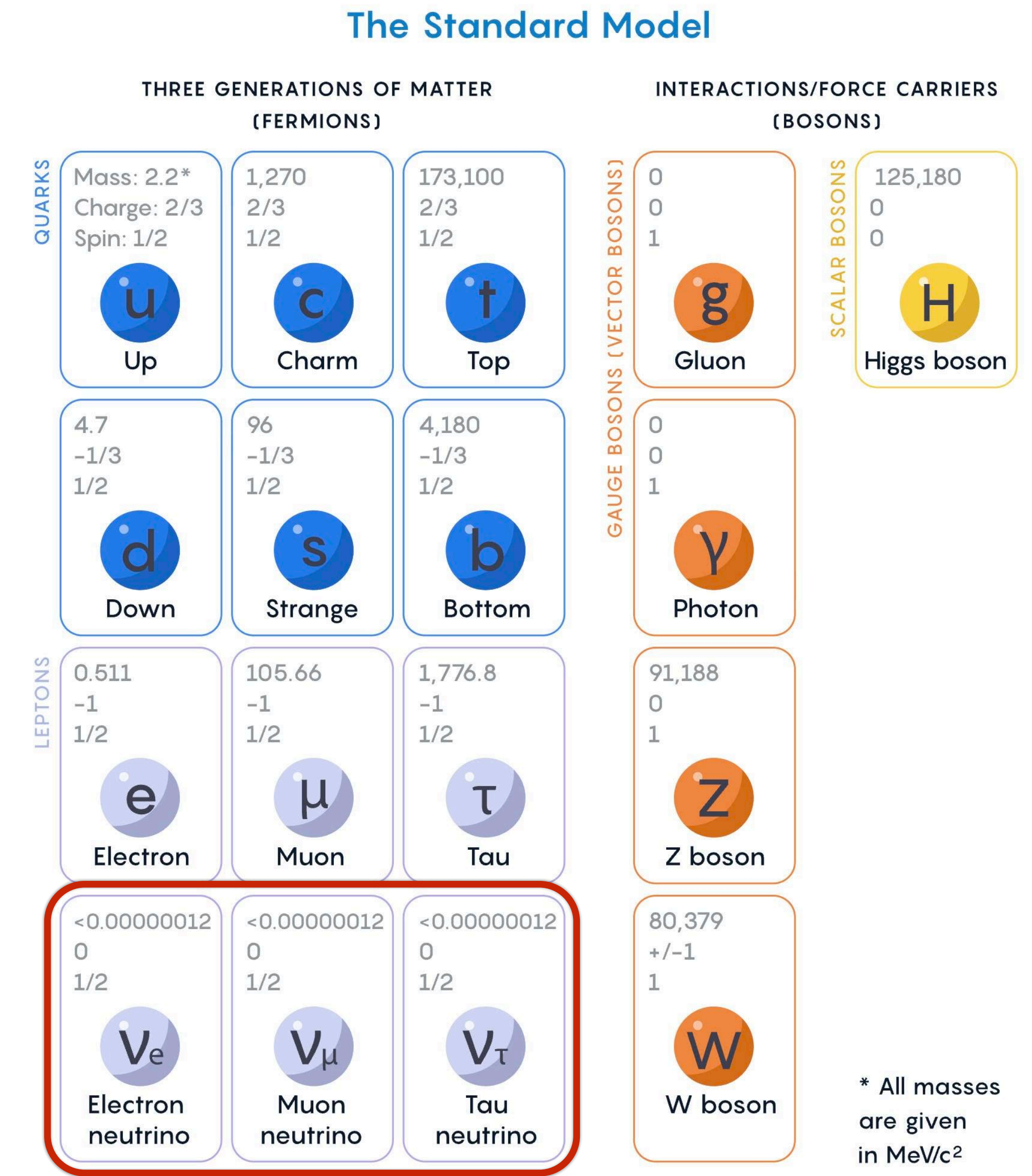
Particle physicist trying to understand ordinary matter...



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
- all these characteristics make neutrinos almost “invisible”
- today, we will be talking about these neutrinos



Standard model of particle physics

Table 10.5: Principal Z pole observables and their SM predictions (*cf.* Table 10.4). The first M_Z is from LEP 1 [288] and the second from CDF [289]. The first $\bar{s}_\ell^2$ is the effective weak mixing angle extracted from the hadronic charge asymmetry at LEP 1 [288], the second is the combined value from the Tevatron [309], and the third is from the LHC [310–314]. The values of A_e are (i) from A_{LR} for hadronic final states [315]; (ii) from A_{LR} for leptonic final states and from polarized Bhabha scattering [316]; and (iii) from the angular distribution of the τ polarization at LEP 1 [288]. The A_τ values are from SLD [316], the total τ polarization from LEP [288], and from CMS [317], respectively. Note that the SM errors in Γ_Z , the R_ℓ , and σ_{had} are largely dominated by the uncertainty in α_s .

Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1884 ± 0.0019	-0.4
	91.192 ± 0.007		0.6
Γ_Z [GeV]	2.4955 ± 0.0023	2.4940 ± 0.0009	0.7
σ_{had} [nb]	41.481 ± 0.033	41.481 ± 0.009	0.0
R_e	20.804 ± 0.050	20.736 ± 0.010	1.4
R_μ	20.784 ± 0.034	20.736 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.781 ± 0.010	-0.4
R_b	0.21629 ± 0.00066	0.21583 ± 0.00002	0.7
R_c	0.1721 ± 0.0030	0.17221 ± 0.00003	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01606 ± 0.00006	-0.6
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.6
$A_{FB}^{(0,b)}$	0.0996 ± 0.0016	0.1026 ± 0.0002	-1.8
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0732 ± 0.0002	-0.7
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1027 ± 0.0002	-0.4
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23161 ± 0.00004	0.7
	0.23148 ± 0.00033		-0.4
	0.23145 ± 0.00028		-0.6
A_e	0.15138 ± 0.00216	0.1463 ± 0.0003	2.3
	0.1544 ± 0.0060		1.3
	0.1498 ± 0.0049		0.7
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.6
	0.144 ± 0.015		-0.2
A_b	0.923 ± 0.020	0.9347	-0.6
A_c	0.670 ± 0.027	0.6674 ± 0.0001	0.1
A_s	0.895 ± 0.091	0.9356	-0.4

Table 10.6: Results derived from Table 10.5 and the corresponding covariance matrices [288,332], and the SM predictions for the partial and total Z decay widths [in MeV]. In the (second) third column lepton universality is (not) assumed.

Quantity	Value	Value (universal)	Standard Model
Γ_{e+e-}	83.87 ± 0.12	83.942 ± 0.085	83.955 ± 0.009
$\Gamma_{\mu+\mu-}$	83.95 ± 0.18	83.941 ± 0.085	83.955 ± 0.009
$\Gamma_{\tau+\tau-}$	84.03 ± 0.21	83.759 ± 0.085	83.772 ± 0.009
Γ_{inv}	498.9 ± 2.5	500.5 ± 1.5	501.435 ± 0.045
$\Gamma_{u\bar{u}}$	—	—	299.87 ± 0.20
$\Gamma_{c\bar{c}}$	300.3 ± 5.3	300.0 ± 5.2	299.81 ± 0.20
$\Gamma_{d\bar{d}}, \Gamma_{s\bar{s}}$	—	—	382.75 ± 0.14
$\Gamma_{b\bar{b}}$	377.4 ± 1.3	377.0 ± 1.2	375.73 ∓ 0.18
Γ_{had}	1744.8 ± 2.6	1743.2 ± 1.9	1740.88 ± 0.86
Γ_Z	2495.5 ± 2.3	2495.5 ± 2.3	2494.00 ± 0.87

Table 10.7: Principal electroweak SM fit result including mutual correlations.

M_Z [GeV]	91.1884 ± 0.0019	1.00	-0.08	0.00	0.00	0.02	0.02
$\hat{m}_t(\hat{m}_t)$ [GeV]	163.18 ± 0.54	-0.08	1.00	0.00	-0.12	-0.23	0.04
$\hat{m}_b(\hat{m}_b)$ [GeV]	4.180 ± 0.008	0.00	0.00	1.00	0.19	-0.02	0.01
$\hat{m}_c(\hat{m}_c)$ [GeV]	1.274 ± 0.009	0.00	-0.12	0.19	1.00	0.48	0.01
$\alpha_s(M_Z)$	0.1187 ± 0.0017	0.02	-0.23	-0.02	0.48	1.00	-0.04
$\Delta\alpha_{\text{had}}^{(3)}(2 \text{ GeV})$	0.00608 ± 0.00004	0.02	0.04	0.01	0.01	-0.04	1.00

S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

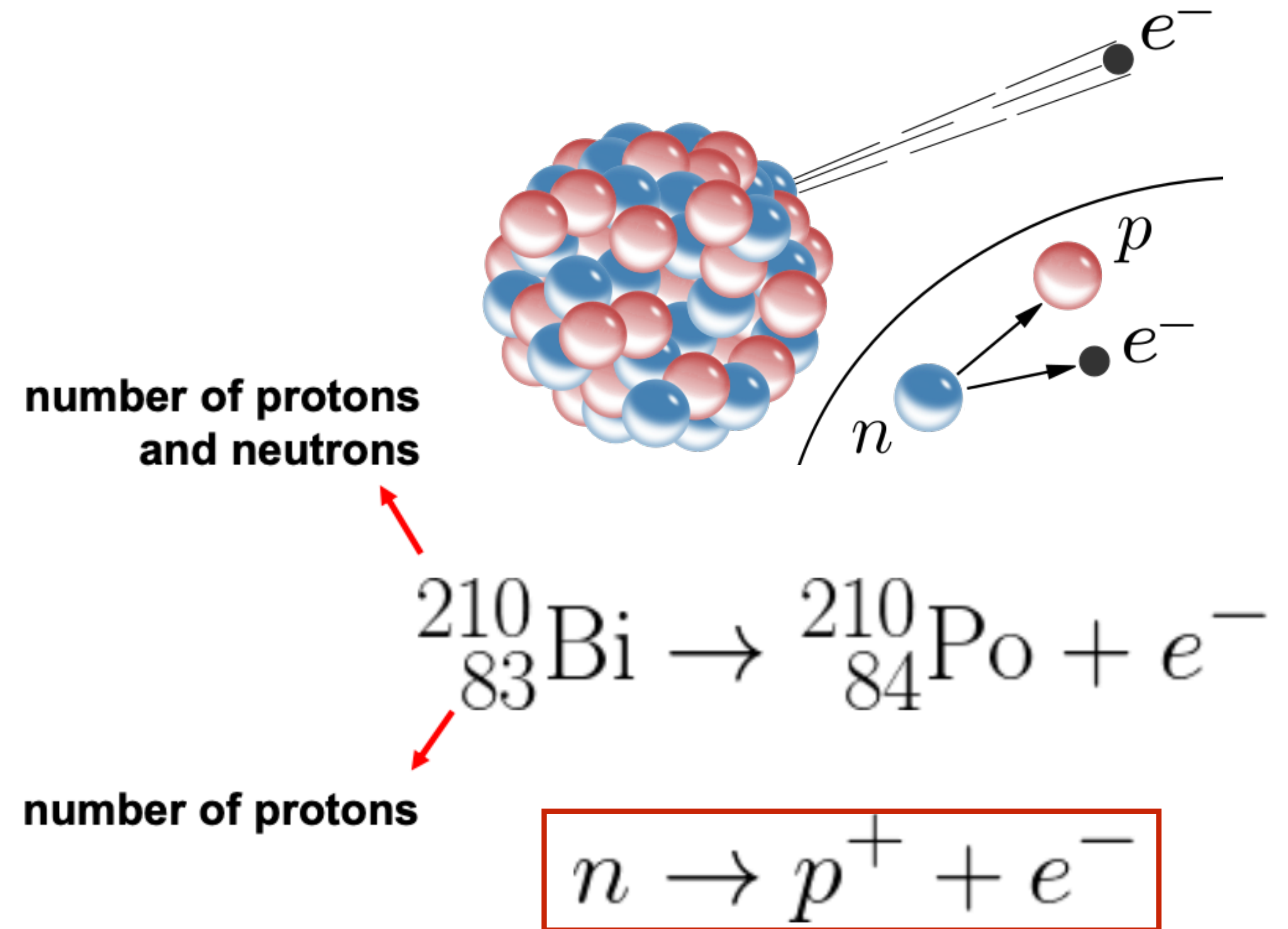
Contents

- **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*

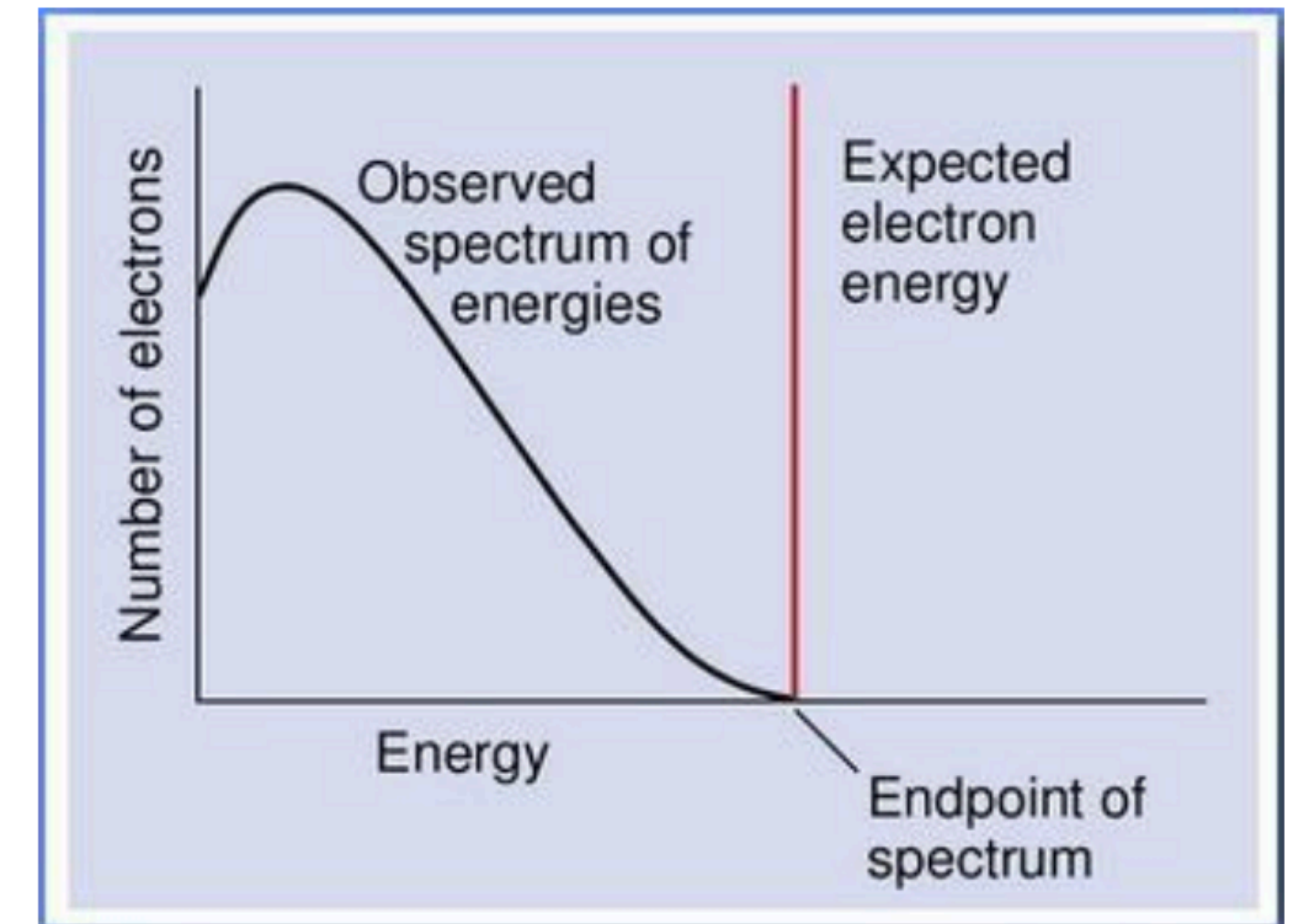
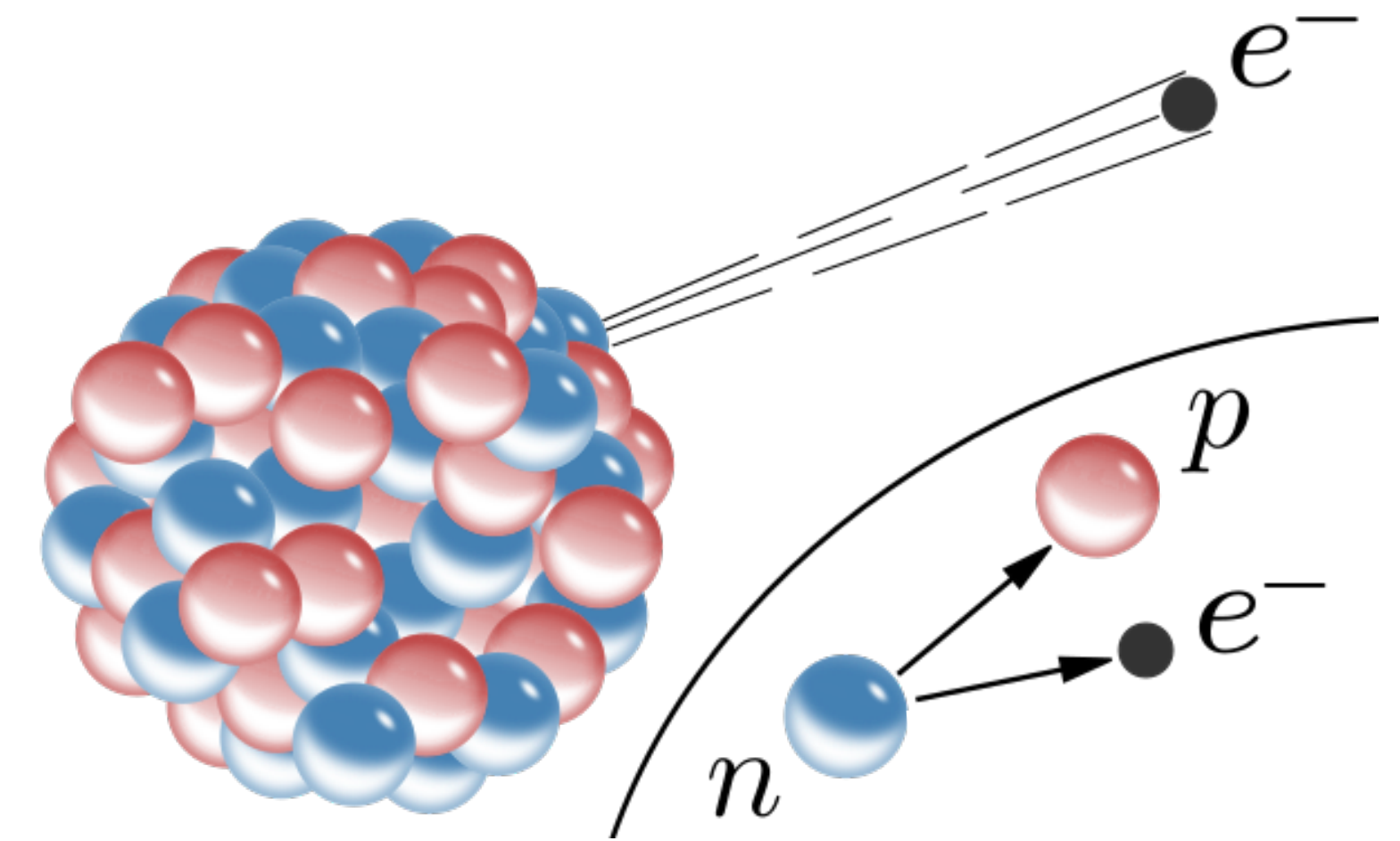


1899 – 1927

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

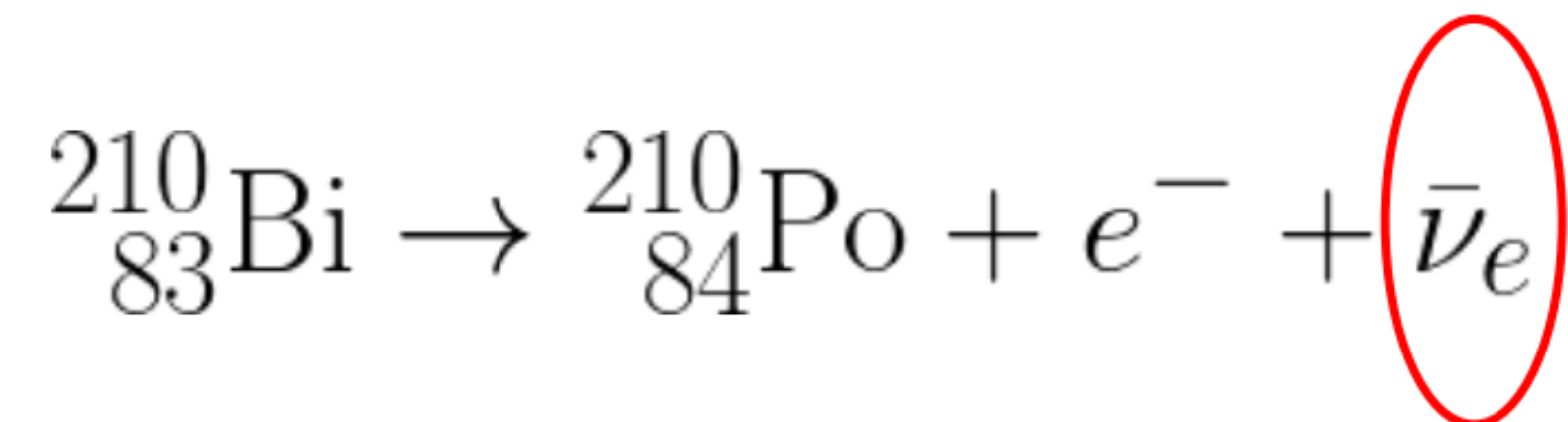
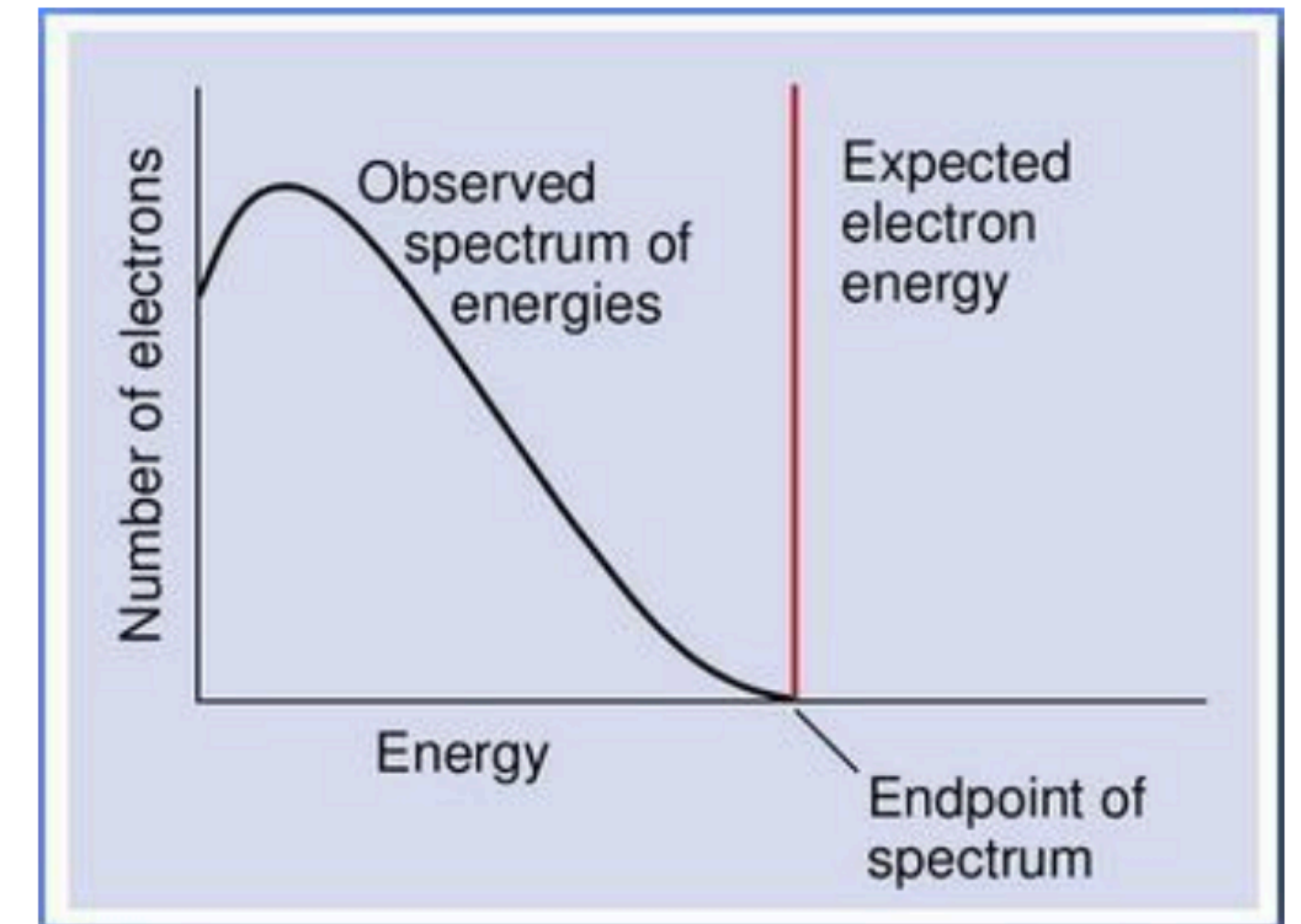
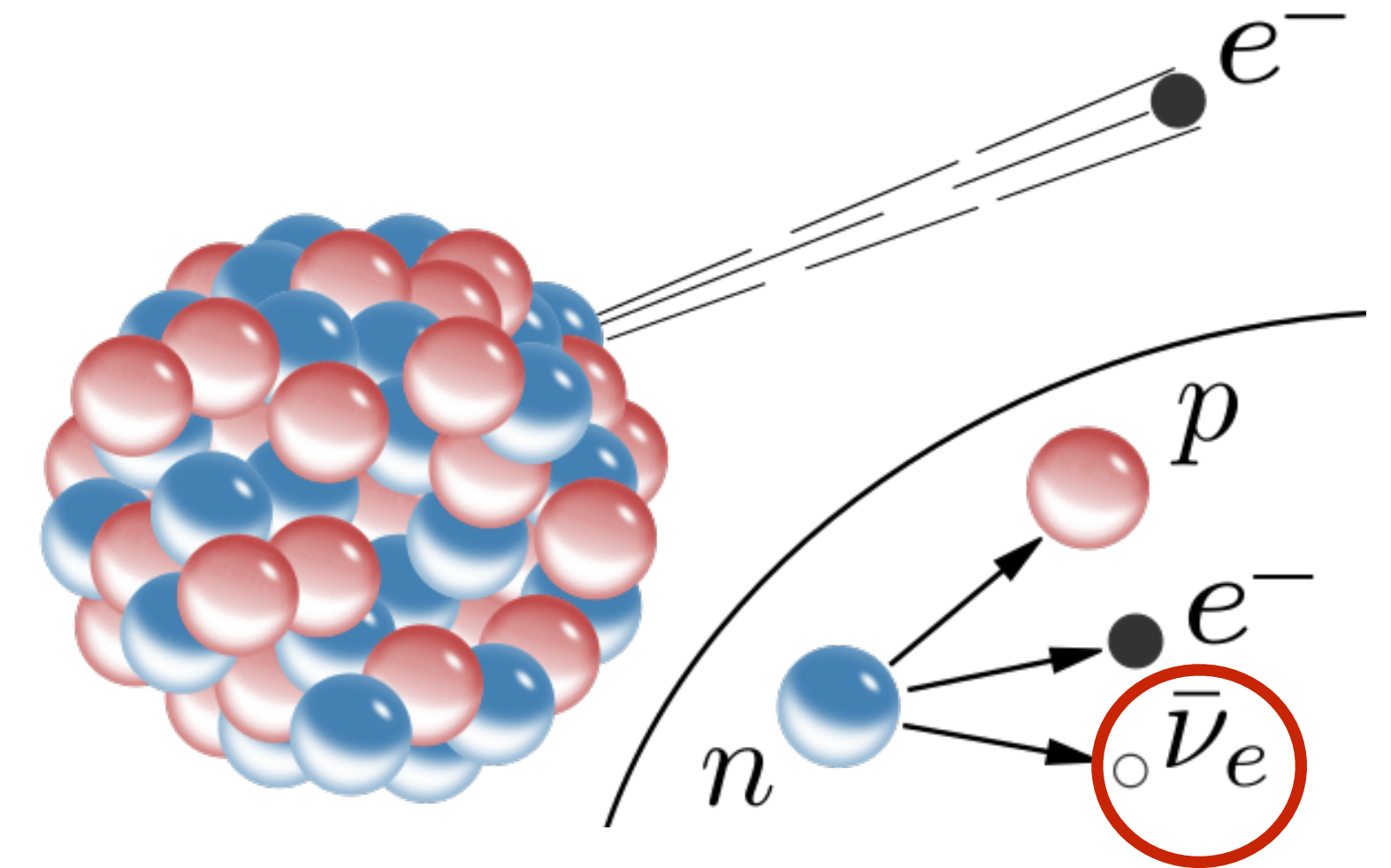
Beta decay: Theoretical prediction

- 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?



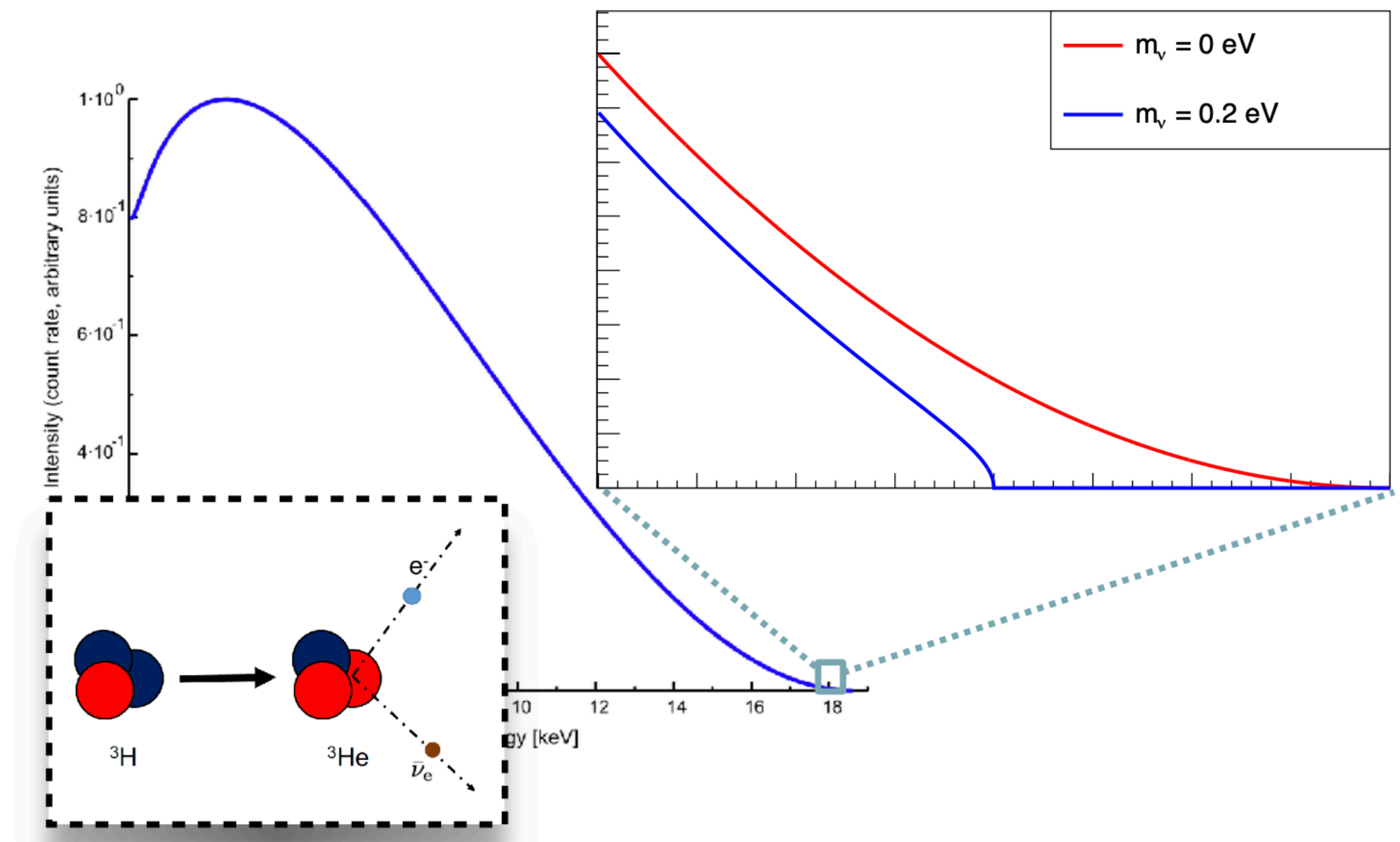
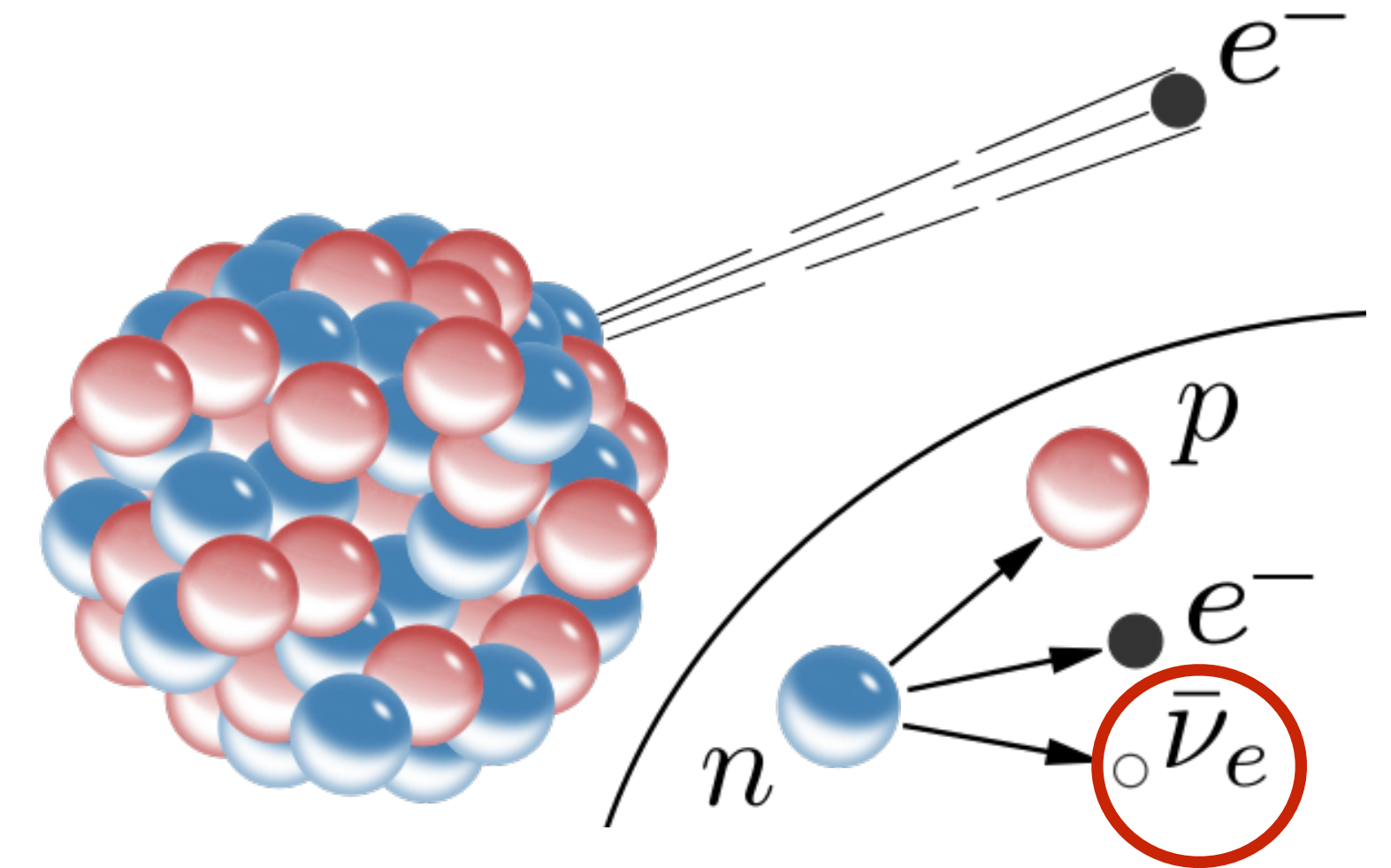
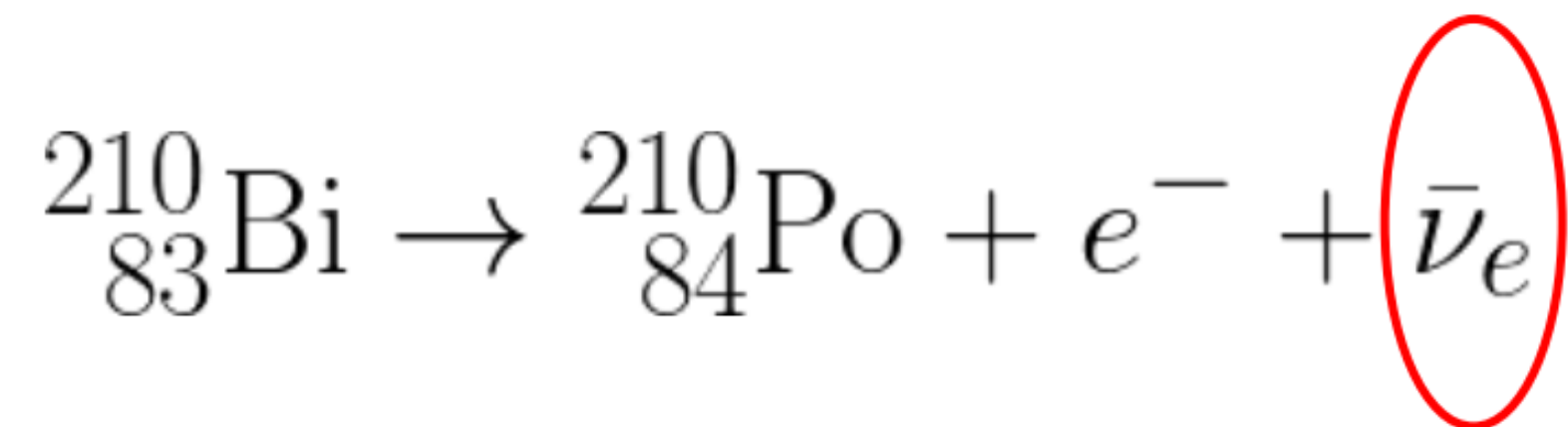
Beta decay: Theoretical prediction

- 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***



Beta decay: Theoretical prediction

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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**



Beta decay: Theoretical prediction (1930)

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 $e \cdot (10^{-13}\text{cm})$.

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 am indispensable 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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Letter | Published: 07 April 1934

The “Neutrino”

H. BETHE & R. PEIERLS

Nature 133, 532 (1934) | Cite this article

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5346 Accesses | 97 Citations | 8 Altmetric | Metrics

Abstract

THE view has recently been put forward¹ that a neutral particle of about electronic mass, and spin $\frac{1}{2}\hbar$ (where $\hbar = h/2\pi$) exists, and that this neutrino is emitted together with an electron in decay. This assumption allows the conservation laws for energy and angular momentum to hold in nuclear physics², Both the emitted electron and neutrino could be described either (*a*) as having existed before in the nucleus or (*b*) as being created at the time of emission. In a recent paper³ Fermi has proposed a model of disintegration using (*b*) which seems to be confirmed by experiment.

532

NATURE

APRIL 7, 1934

The following comparison of the structure given by Badami and by me for the line $\lambda 5639\cdot7$ ($6s\ ^3P_{\frac{3}{2}} - 6p\ ^3S_{\frac{1}{2}}$) shows to what extent the hollow cathode patterns are more clearly resolved:

Badami	0 (6)	205 (5)		450 (4)	584 (4)	780 (1)	$\text{cm.}^{-1} \times 10^{-3}$		
Tolansky	0 (10)	71 (8)	217 (9)	319 (3)	399 (3½)	477 (6)	605 (5)	728 (1½)	$\text{cm.}^{-1} \times 10^{-3}$

It is seen that Badami's values are those which would arise from the blending of components due to excessive line width.

Full details with analysis will be communicated elsewhere shortly.

S. TOLANSKY.

Astrophysics Department,
Imperial College of Science,
London, S.W.7.
March 3.

¹ J. S. Badami, *Z. Phys.*, **79**, 206; 1932.

The “Neutrino”

THE view has recently been put forward¹ that a neutral particle of about electronic mass, and spin $\frac{1}{2}\hbar$ (where $\hbar = h/2\pi$) exists, and that this ‘neutrino’ is emitted together with an electron in β -decay. This assumption allows the conservation laws for energy and angular momentum to hold in nuclear physics². Both the emitted electron and neutrino could be described either (*a*) as having existed before in the nucleus or (*b*) as being created at the time of emission. In a recent paper³ Fermi has proposed a model of β -disintegration using (*b*) which seems to be confirmed by experiment.

According to (*a*), one should picture the neutron as being built up of a proton, an electron and a neutrino, while if one accepts (*b*), the rôles of neutron and proton would be symmetrical⁴ and one would expect that positive electrons could also sometimes be created together with a neutrino in nuclear transformations. Therefore the experiments of Curie and Joliot⁵ on an artificial positive β -decay give strong support to method (*b*), as one can scarcely assume the existence of positive electrons in the nucleus.

Why, then, have positive electrons never been found in the natural β -decay? This can be explained by the fact that radioactivity usually starts with α -emission and therefore leads to nuclei the charge of which is too small compared with their weight. The artificial β -emission was found for two unstable nuclei (most probably N^{13} and P^{32}) formed by capture of an α -particle and emission of a neutron, and therefore having too high a charge for their mass.

A consequence of assumption (*b*) is that two isobares differing by 1 in atomic number can only be stable if the difference of their masses is less than the mass of electron and neutrino together. For otherwise the heavier of the two elements would disintegrate with emission of a neutrino and either a positive or negative electron. There will be only a limited region on the mass defect curve, probably at medium atomic weight, where such small differences are possible. In fact, neighbouring isobares have only been found with the mass numbers 87, 115, 121, 123, (187), (203), while isobares with atomic numbers differing by 2 are very frequent. In the

first case, one of the two nuclei (Rb) is known to emit β -rays. In each of the last two cases one of the two isobares is stated to be exceedingly rare and its identification might be due to experimental error. The other three cases actually lie close together and have medium weight. A particular case of isobares are proton and neutron. Since all experimentally deduced values of the neutron mass lie between 1·0068 and 1·0078, they are certainly both stable even if the mass of the neutrino should be zero.

The possibility of creating neutrinos necessarily implies the existence of annihilation processes. The most interesting amongst them would be the following: a neutrino hits a nucleus and a positive or negative electron is created while the neutrino disappears and the charge of the nucleus changes by 1.

The cross section σ for such processes for a neutrino of given energy may be estimated from the lifetime t of β -radiating nuclei giving neutrinos of the same energy. (This estimate is in accord with Fermi's model but is more general.) Dimensionally, the connexion will be

$$\sigma = A/t$$

where A has the dimension $\text{cm.}^2 \text{ sec.}$ The longest length and time which can possibly be involved are $\hbar/mc$ and $\hbar/mc^2$. Therefore

$$\sigma < \frac{\hbar^2}{m^2 c^4 t}$$

For an energy of $2\cdot3 \times 10^6$ volts, t is 3 minutes and therefore $\sigma < 10^{-44} \text{ cm.}^2$ (corresponding to a penetrating power of 10^{16} km. in solid matter). It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations.

With increasing energy, σ increases (in Fermi's model³ for large energies as $(E/mc^2)^2$) but even if one assumes a very steep increase, it seems highly improbable that, even for cosmic ray energies, σ becomes large enough to allow the process to be observed.

If, therefore, the neutrino has no interaction with other particles besides the processes of creation and annihilation mentioned—and it is not necessary to assume interaction in order to explain the function of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino.

H. BETHE.
R. PEIERLS.

Physical Laboratory,
University,
Manchester.
Feb. 20.

¹ W. Pauli, quoted repeatedly since 1931, to be published shortly in “Rapports du Septième Conseil Solvay, Brussels”, 1933.

² C. D. Ellis and N. F. Mott, *Proc. Roy. Soc. A*, **141**, 502; 1933.

³ E. Fermi, *La Ricerca Scientifica*, **2**, No. 12; 1933.

⁴ This point of view was first put forward by I. Curie and F. Joliot at the Conseil Solvay, 1933.

⁵ I. Curie and F. Joliot, *NATURE*, **133**, 201, Feb. 10, 1934.

Changes in the Lipolytic Activity of Different Organs during Tuberculosis

IN continuation of our earlier work on lipases¹, we have followed the changes in the lipase content of different organs of guinea pigs infected with bovine tuberculosis. Lipase determinations were made from liver, pancreas, lungs and blood serum, using tributyrine as substrate. It appeared that, coincident

Detection of neutrinos

Nobel Prize 1995



- neutrinos were first detected experimentally in 1956 by Clyde Cowan and Frederick Reines
- but before in 1951, they proposed to use nuclear bomb as a source of neutrinos (and approved! 🤯)

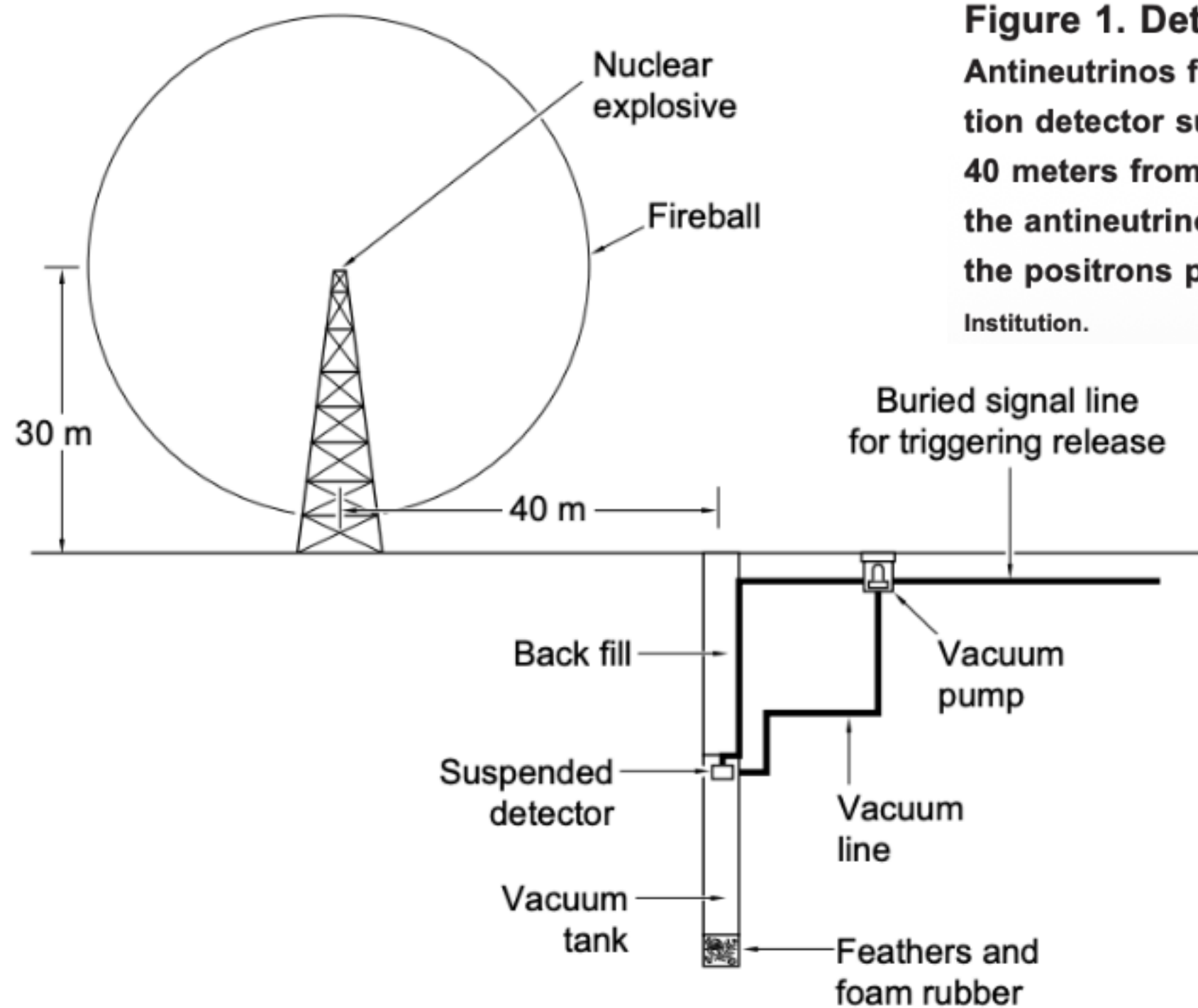


Figure 1. Detecting Neutrinos from a Nuclear Explosion

Antineutrinos from the fireball of a nuclear device would impinge on a liquid scintillation detector suspended in the hole dug below ground at a distance of about 40 meters from the 30-meter-high tower. In the original scheme of Reines and Cowan, the antineutrinos would induce inverse beta decay, and the detector would record the positrons produced in that process. This figure was redrawn courtesy of Smithsonian Institution.



“Our crude knowledge of the expected energy spectrum of neutrinos from a fission bomb suggested that the inverse beta decay reaction would occur several times in a several-ton detector located about 50 meters from the tower-based explosion of a 20-kiloton bomb.

(Anyone untutored in the effects of nuclear explosions would be deterred by the challenge of conducting an experiment so close to the bomb, but we knew otherwise from experience and pressed on). The detector we dreamed up was a giant liquid scintillation device, which we dubbed ‘El Monstro.’ This was a daring extrap-

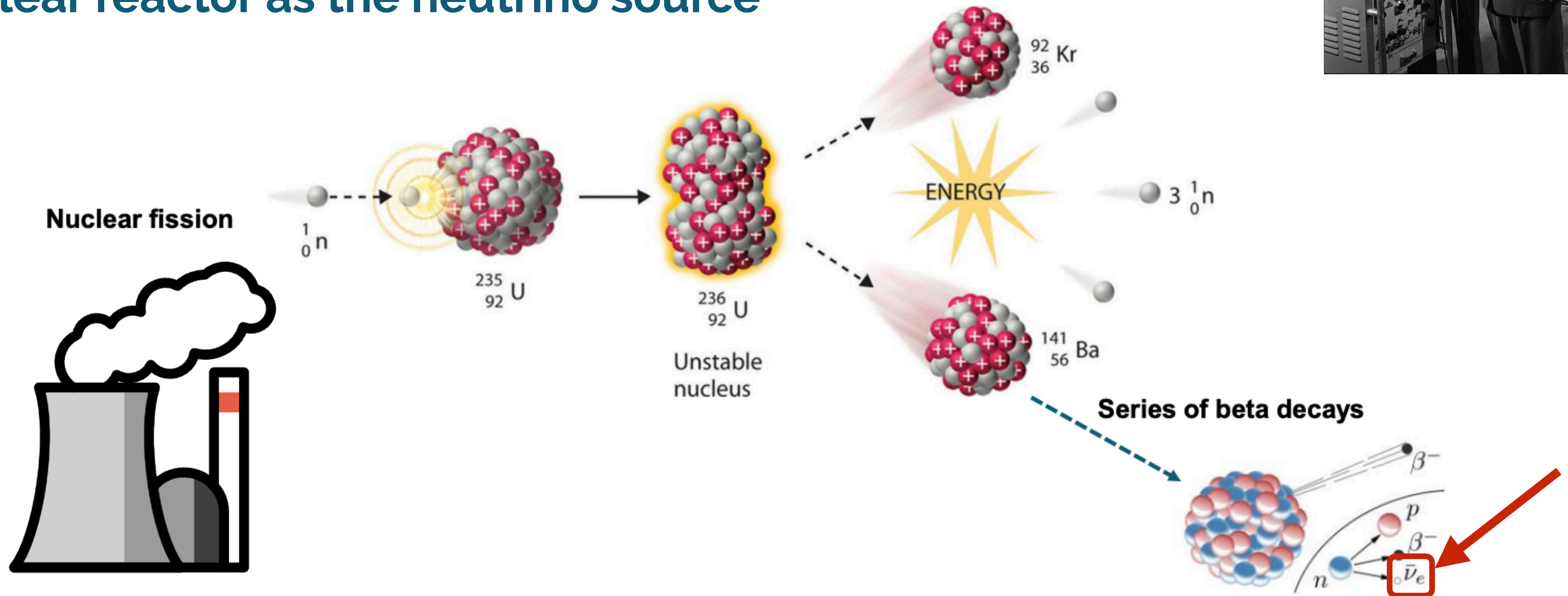
(Reines, 1997)

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**

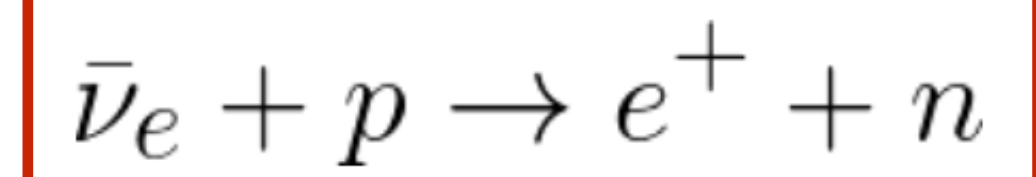
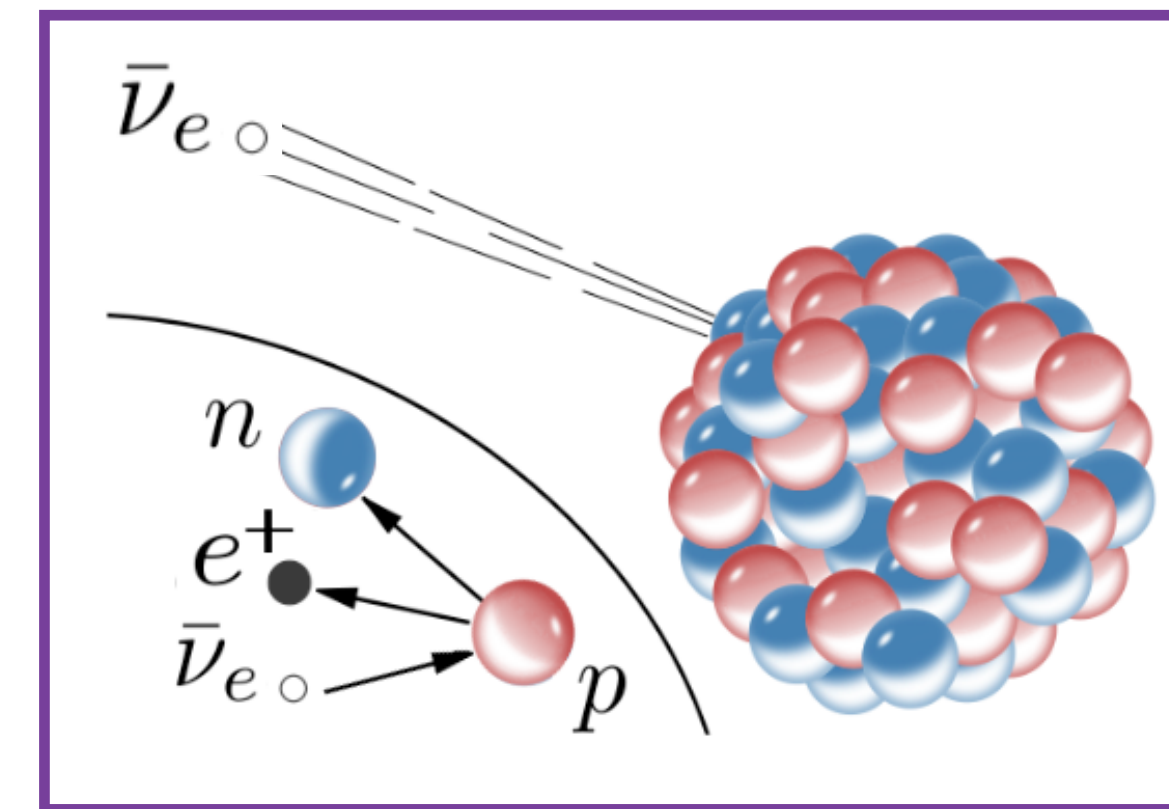


Detection of neutrinos

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
- 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?*

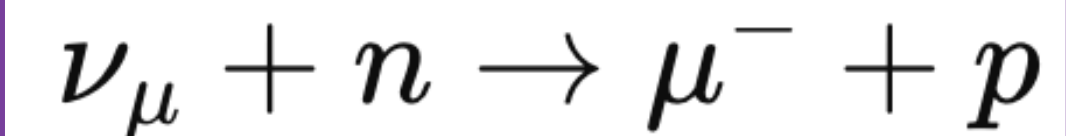
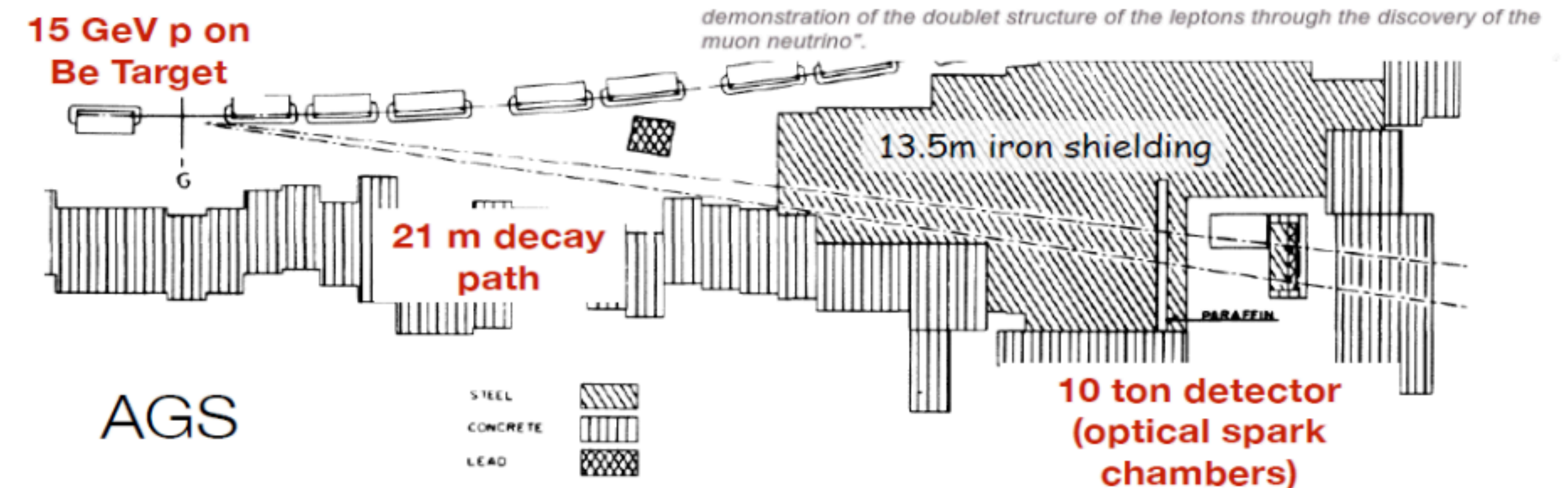




- with following theories, different types of neutrinos were hypothesized
 - **muons** were discovered in cosmic rays in 1936; very similar to electrons, but heavier
 - muon neutrinos, **associated with muons instead of electrons**, then may exist
 - remember how beta decay always involves electrons?
 - 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



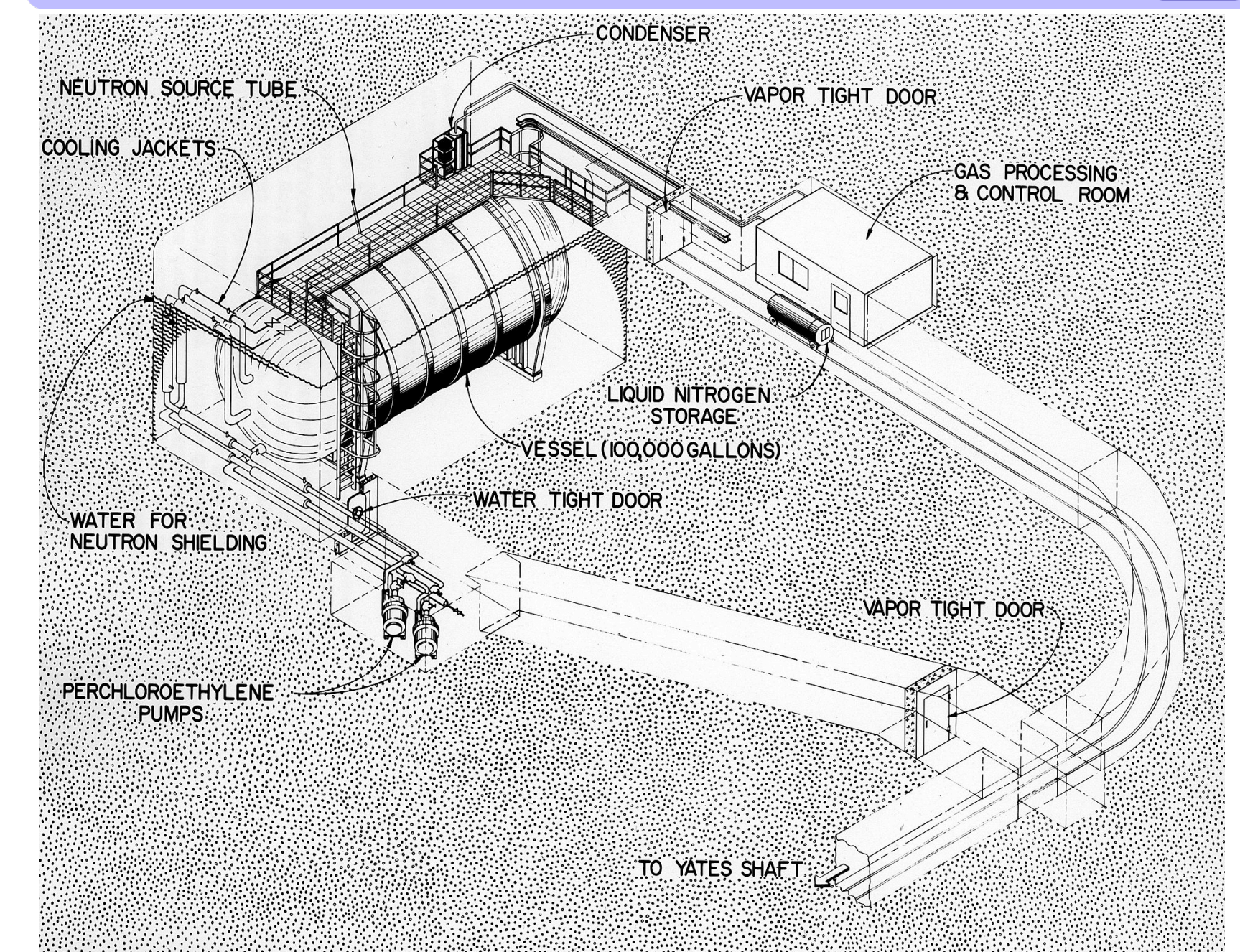
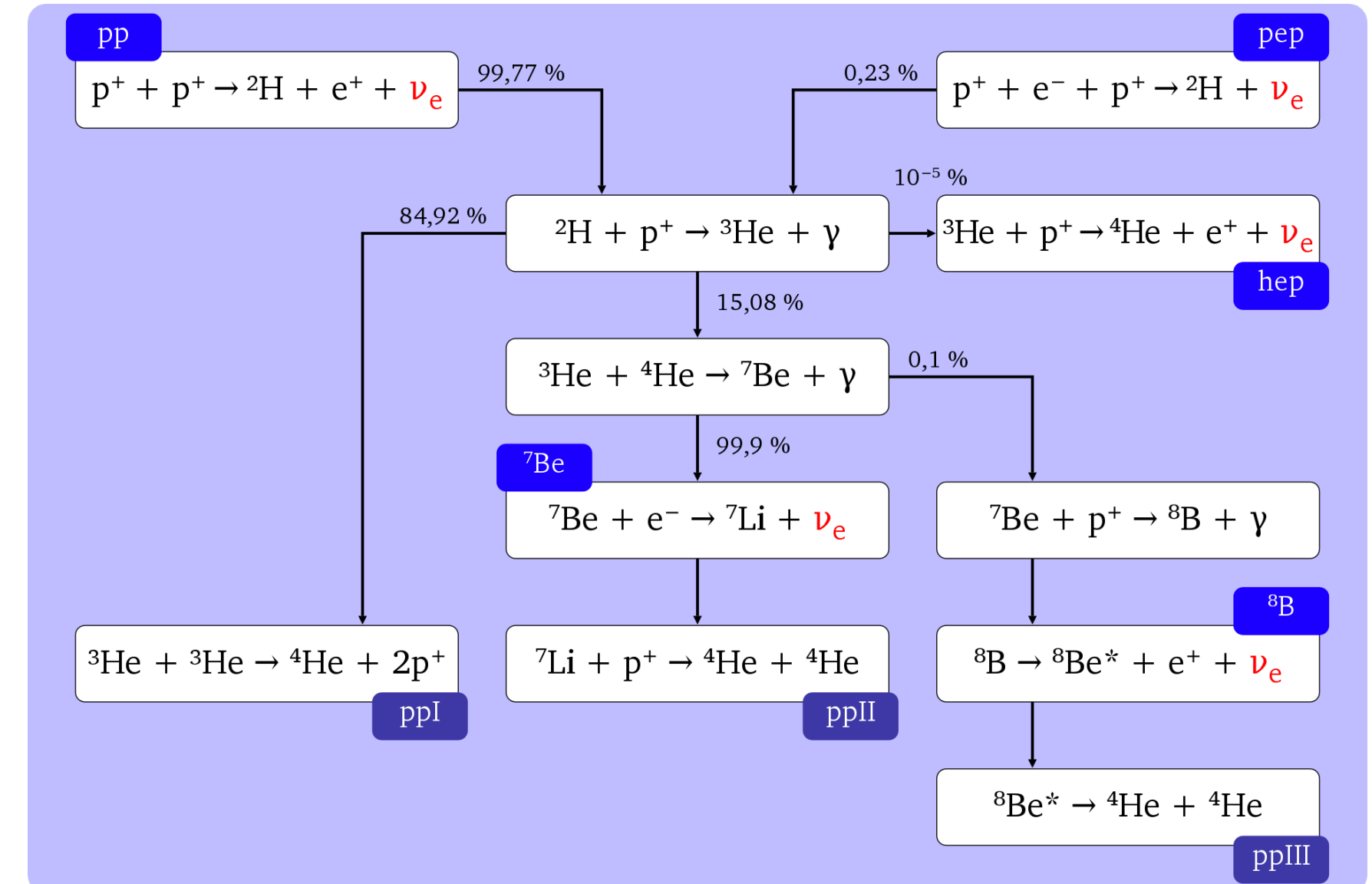
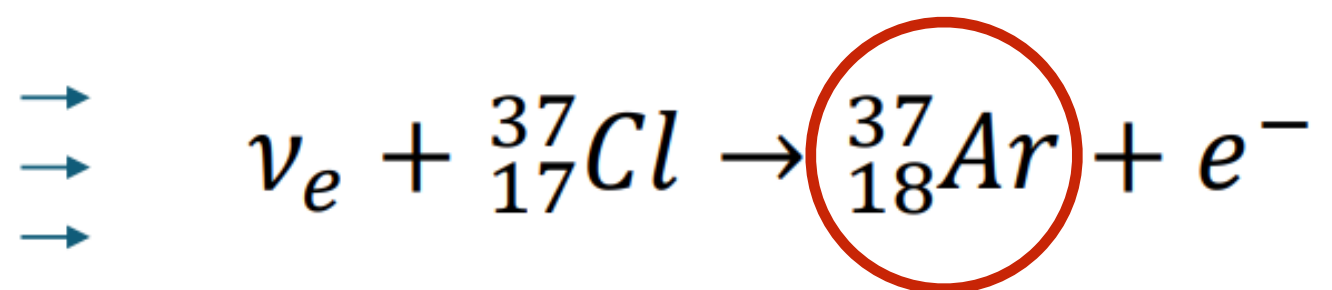
Missing neutrinos: how neutrinos change their flavors

The solar neutrino problem

Nobel Prize 2002

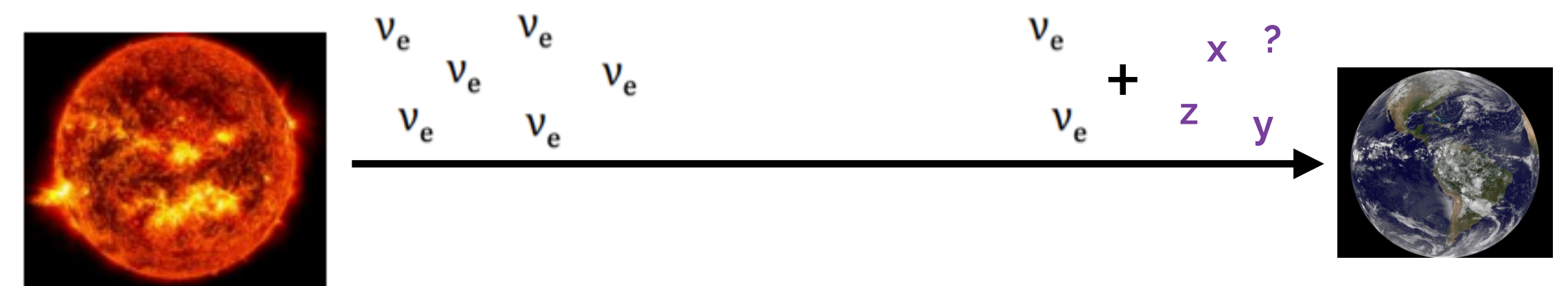
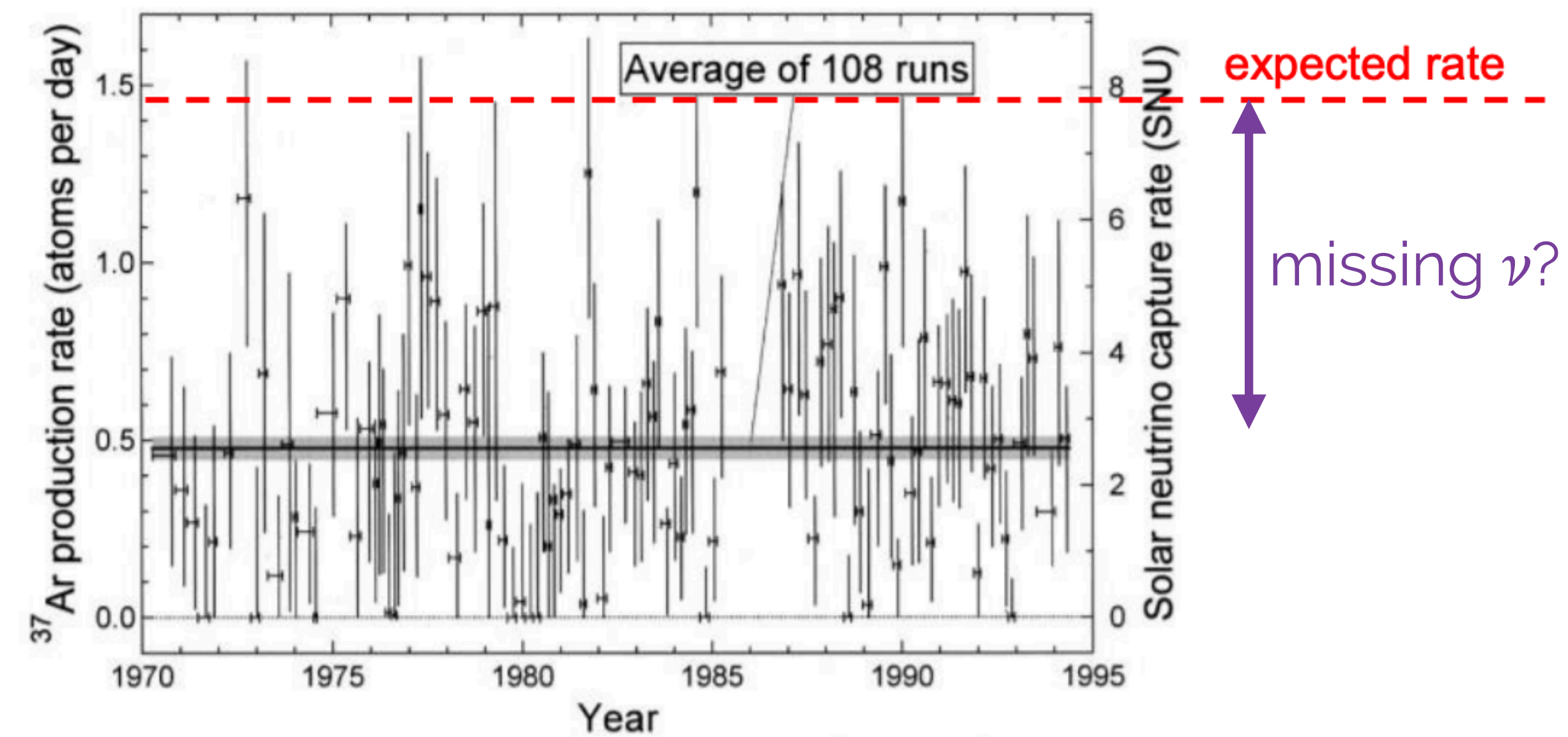
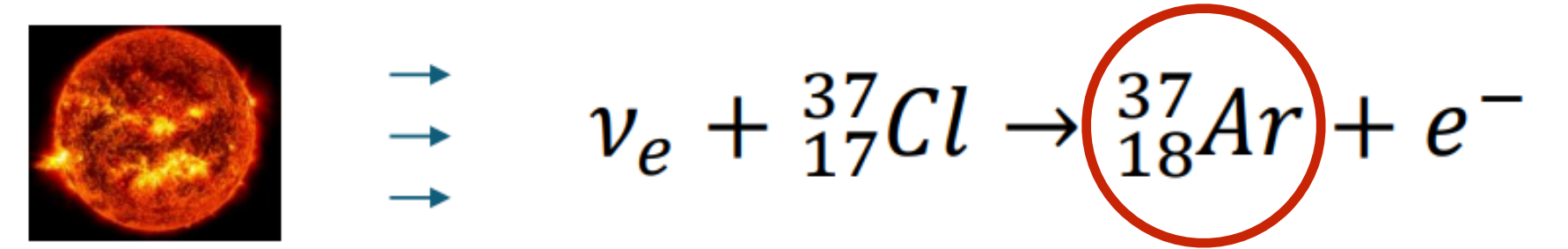


- the Sun is a huge source of neutrinos from nuclear fusion
 - ~100 billion neutrinos from the Sun pass through your thumbnail every second!
- J. Bahcall calculated expected number of solar neutrinos expected to arrive at Earth
 - all the neutrinos generated in the Sun was to be electron neutrinos
- 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



The solar neutrino problem

- 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



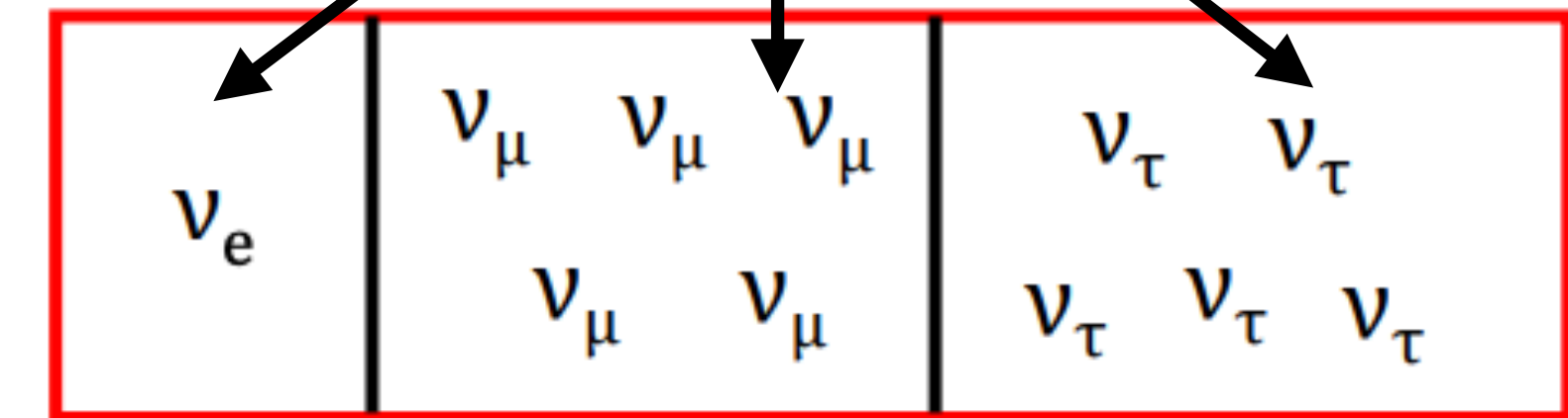
Neutrino oscillation: model

- **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

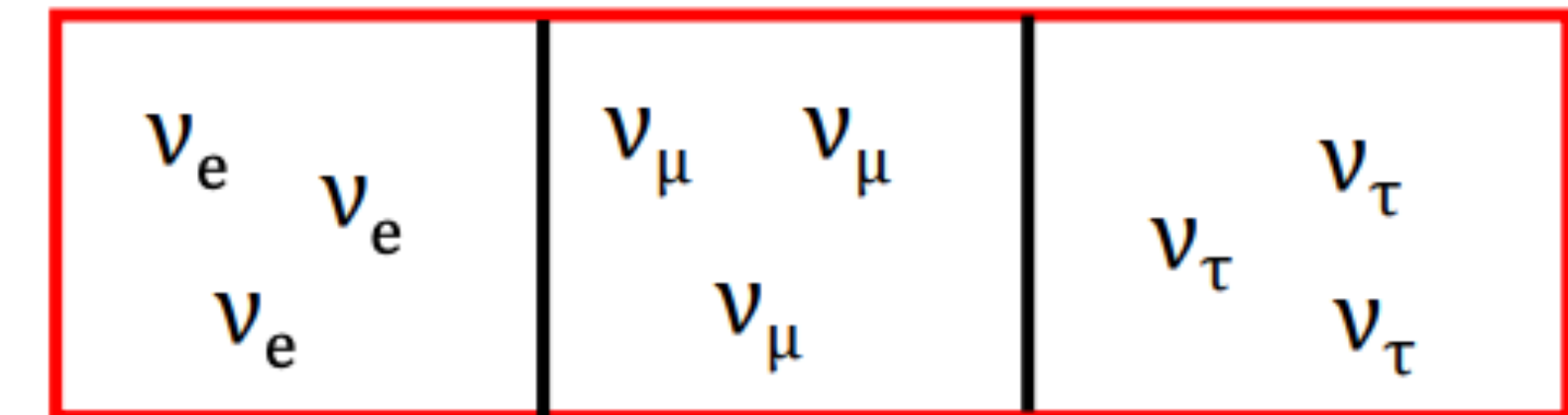
mass
eigenstates



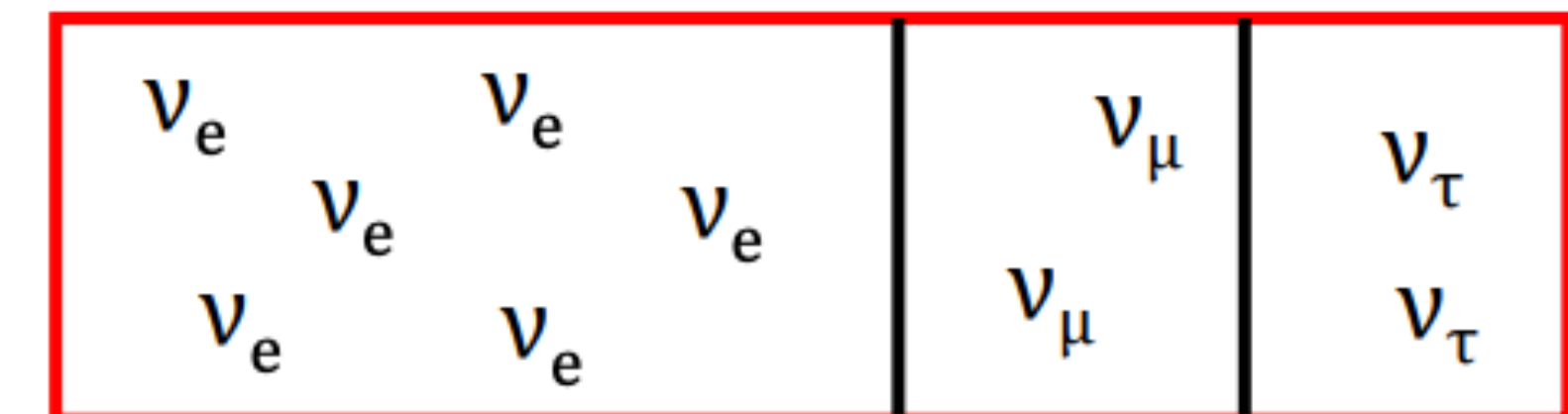
ν_3



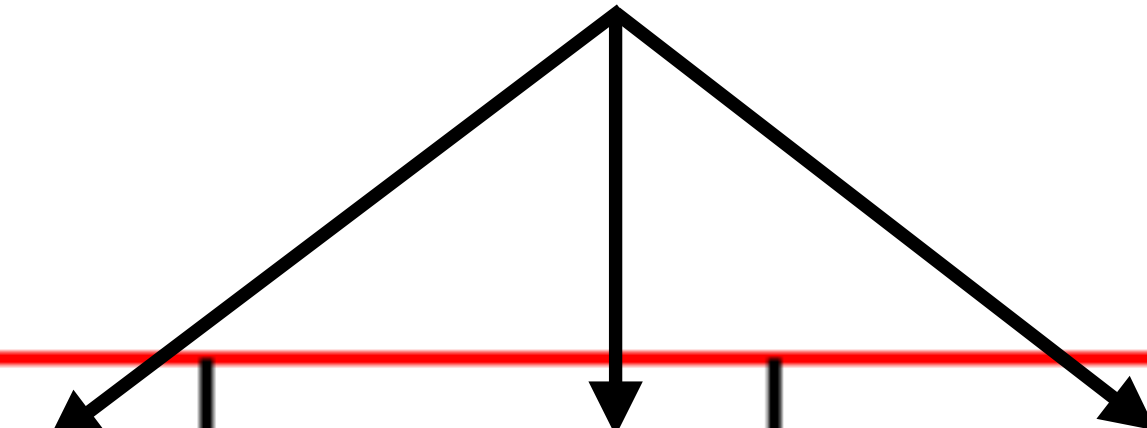
ν_2



ν_1

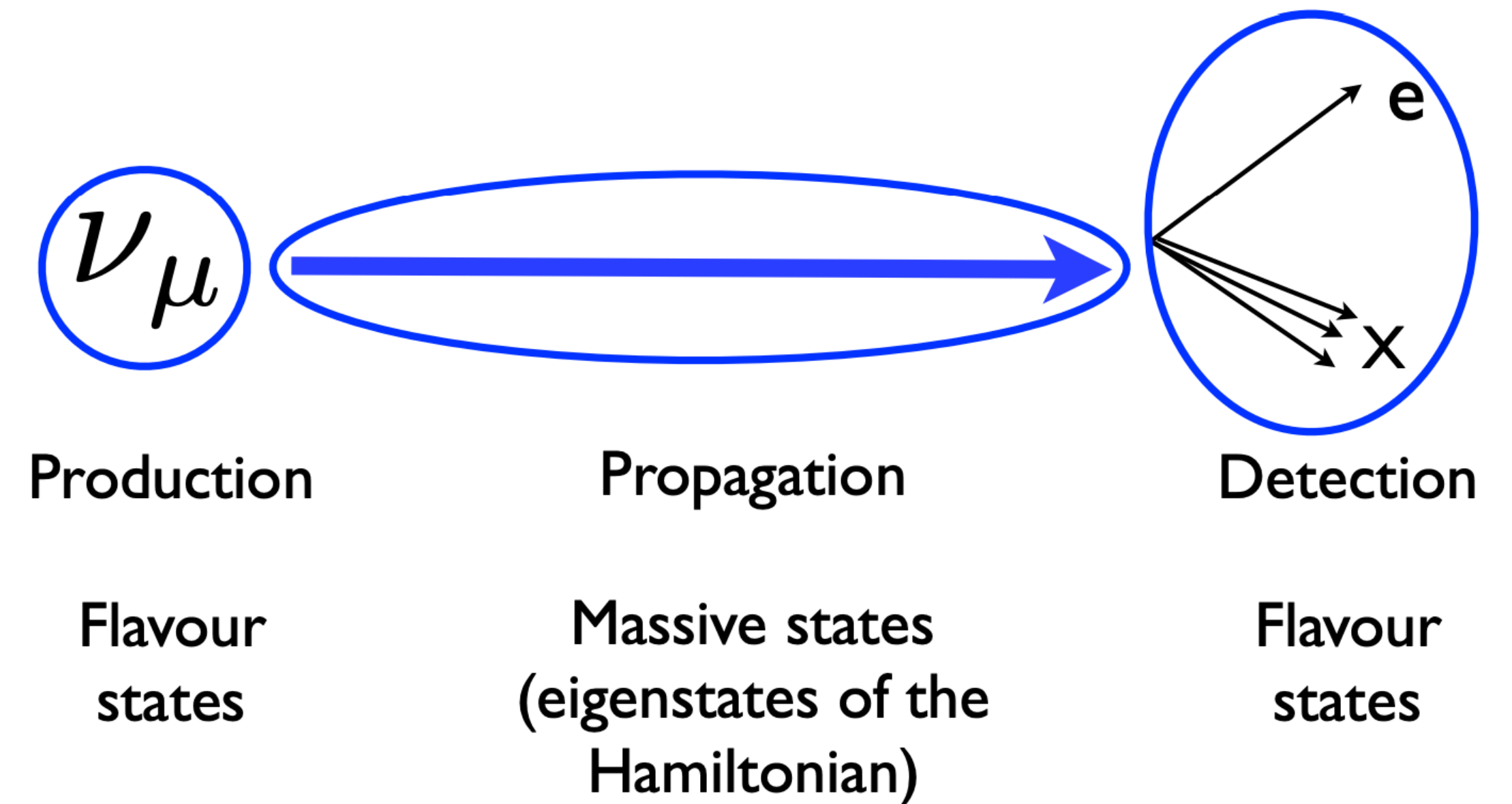
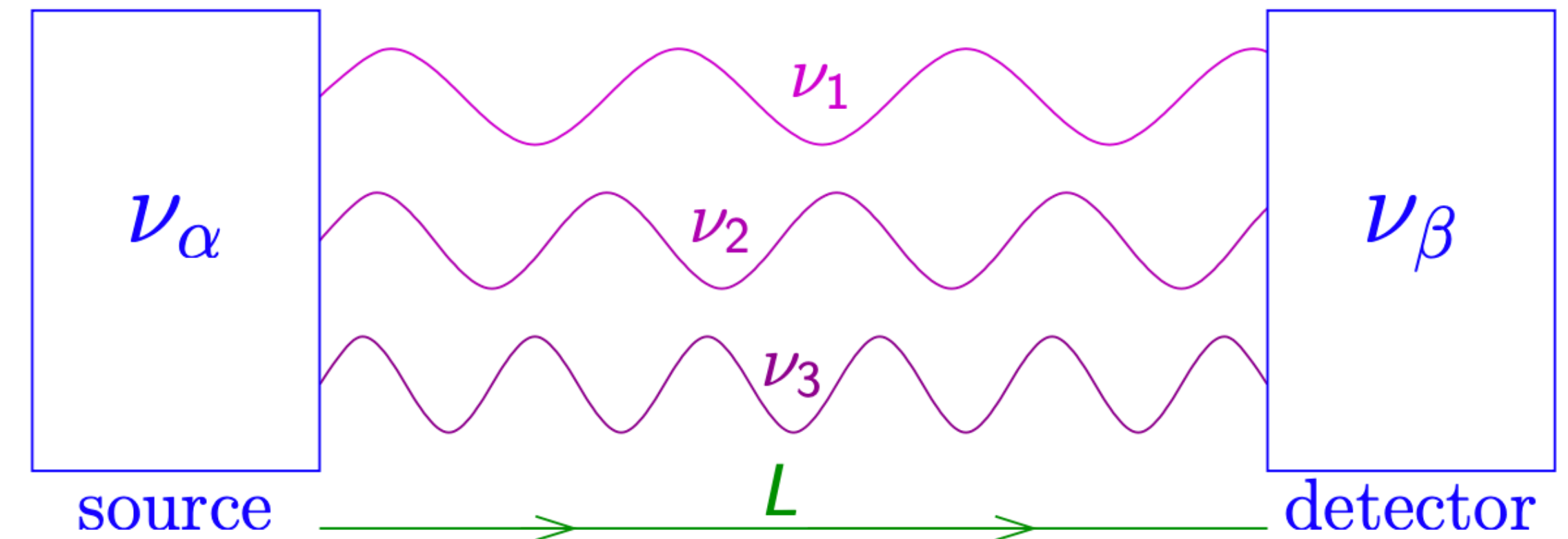


flavor
eigenstates



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



Neutrino oscillation: model

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flavor ($\alpha = e, \mu, \tau$) $\Leftrightarrow$ linear combinations $\Leftrightarrow$ mass ($i = 1, 2, 3$)

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \quad \longleftrightarrow \quad |\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

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

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

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

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

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

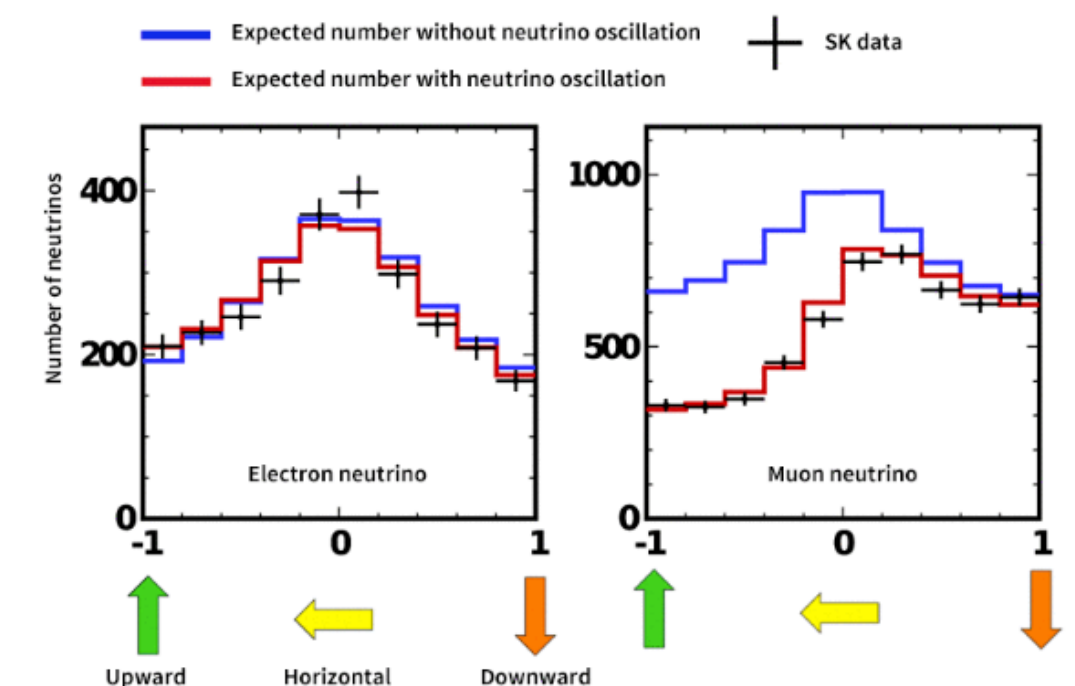
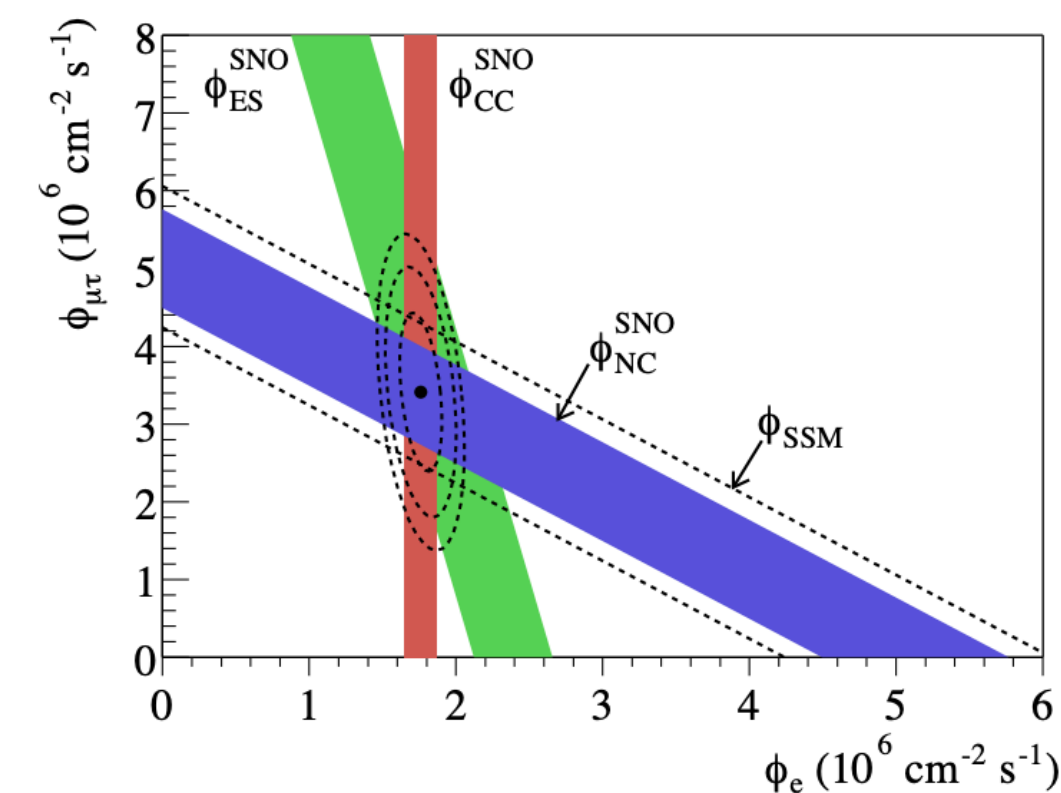
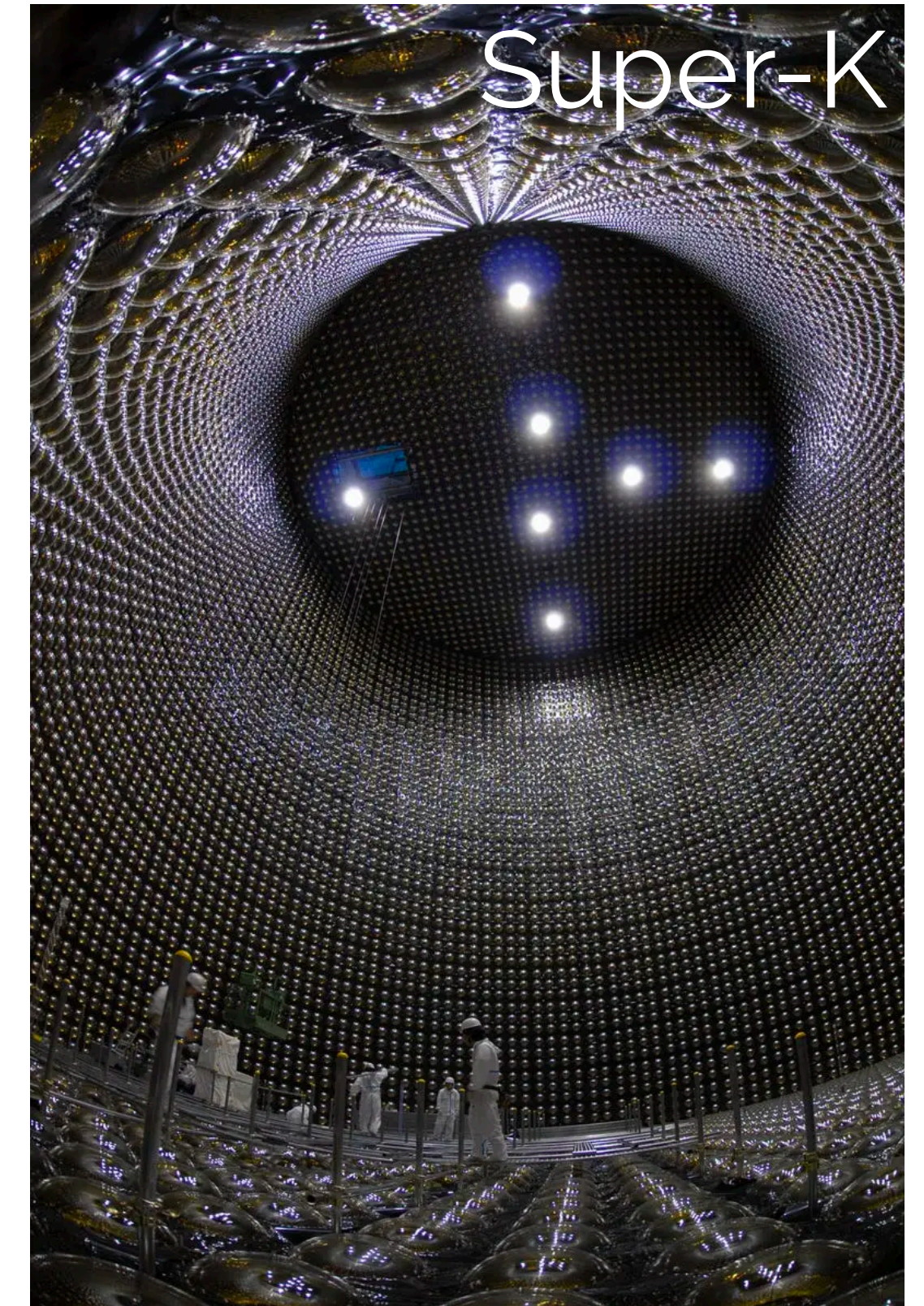
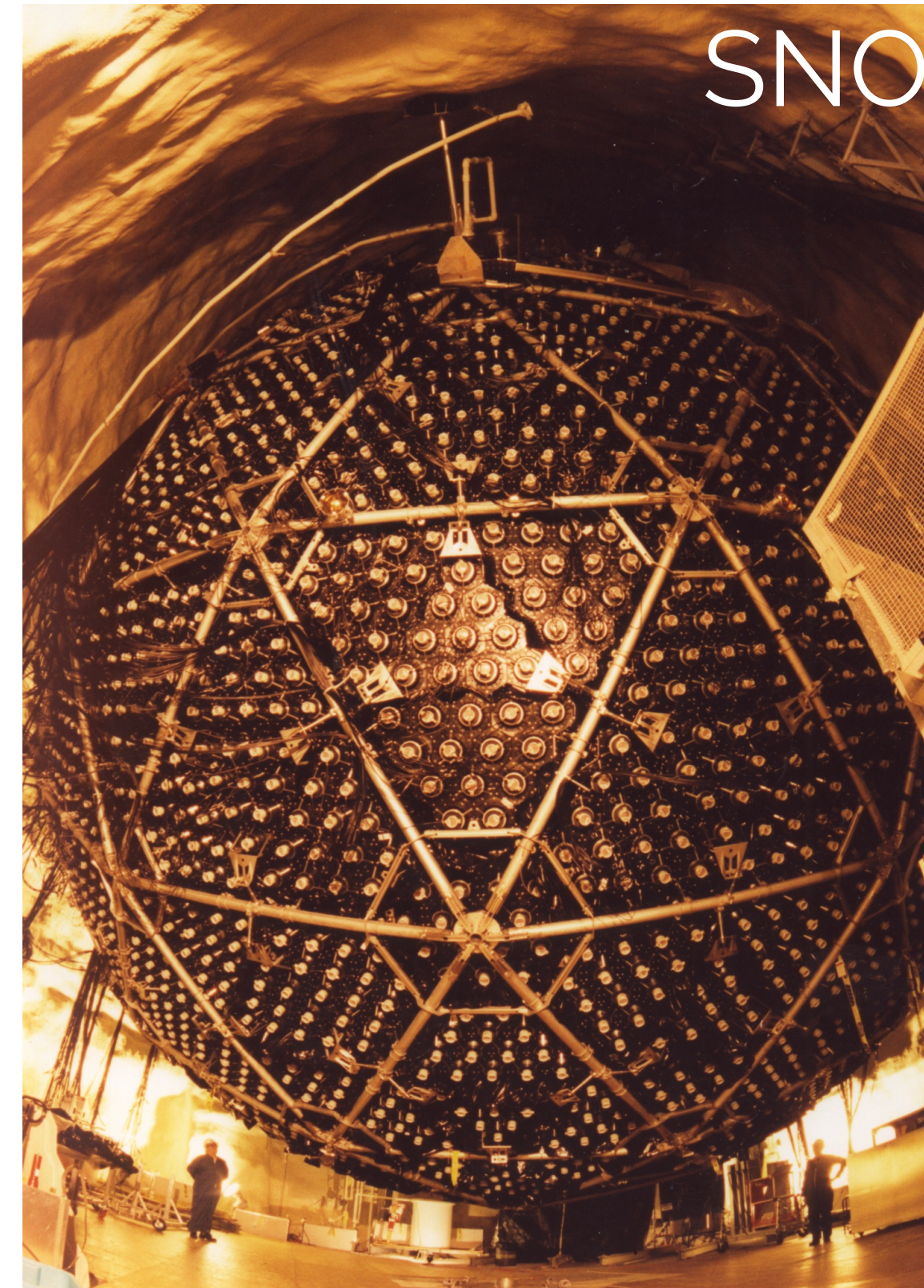
Nonzero δ_{CP} $\implies$ neutrinos and antineutrinos oscillate different

Neutrino oscillation: confirmation

Nobel Prize 2015



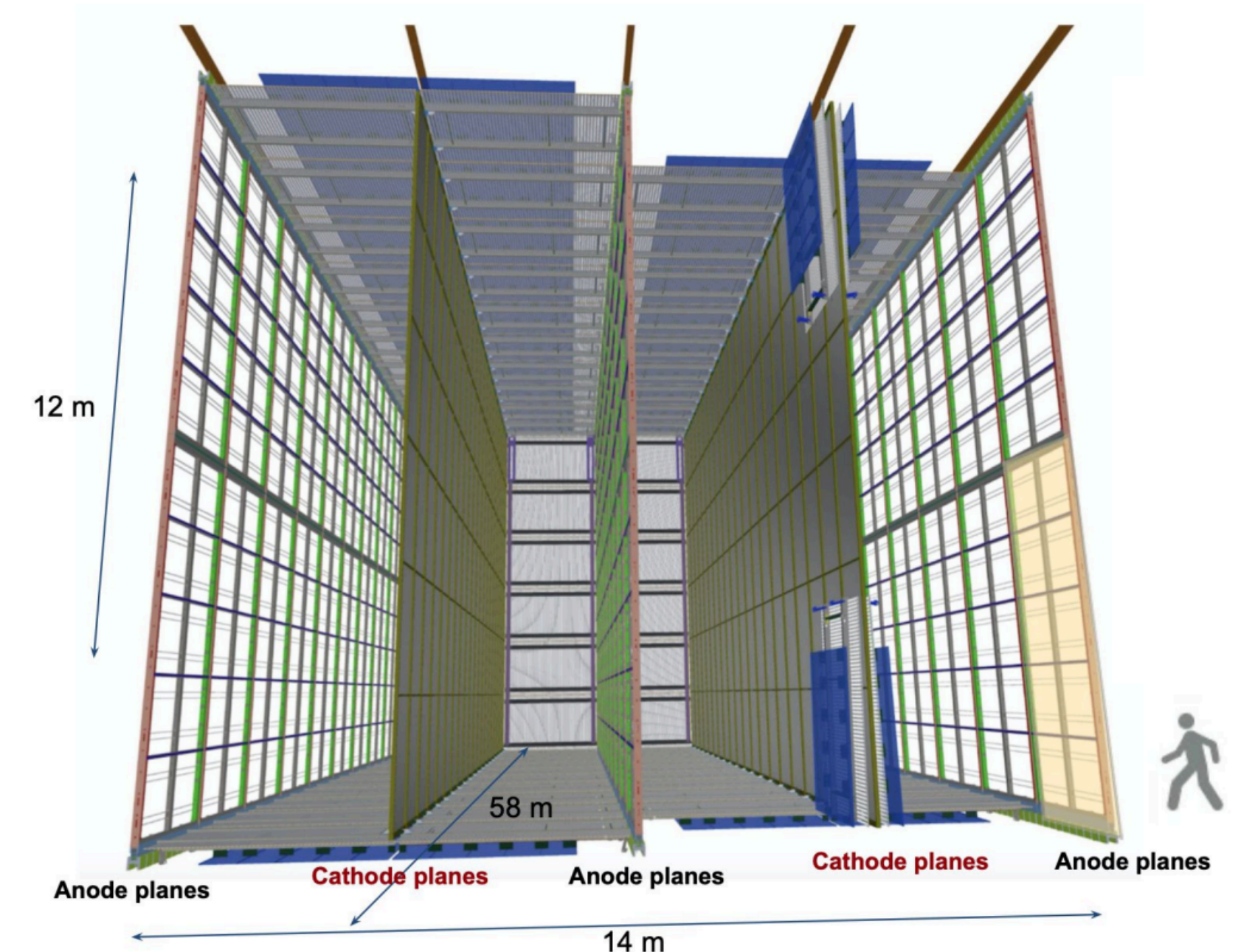
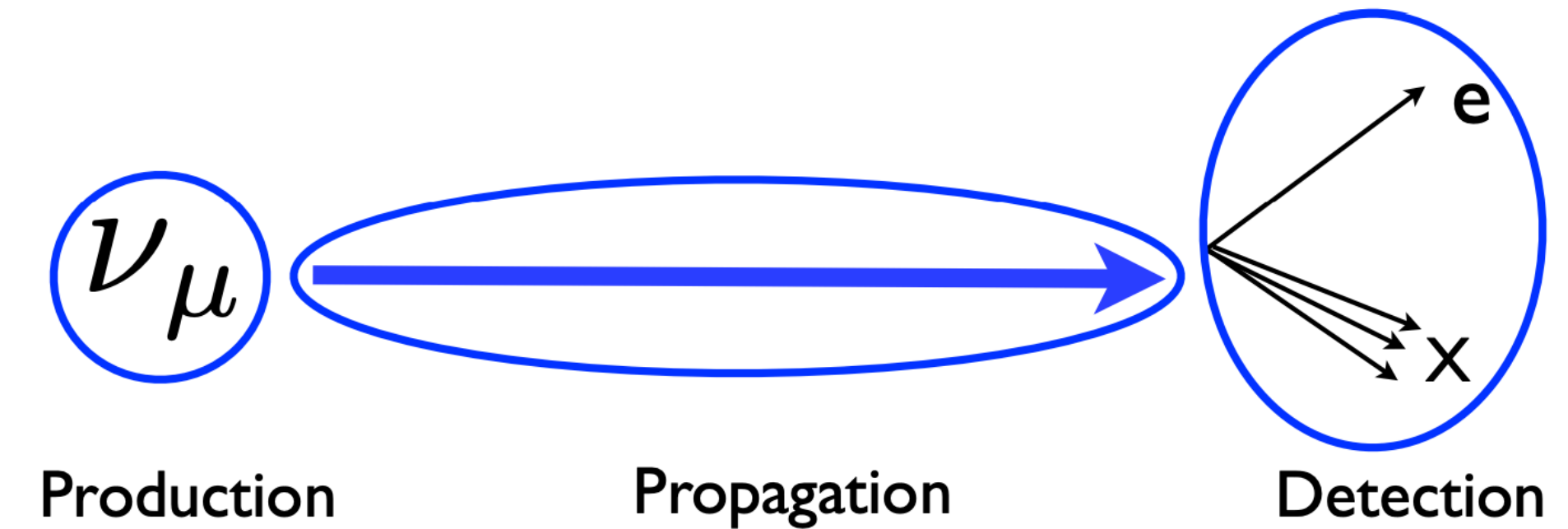
- neutrino changing its flavor during travel (neutrino oscillation) can explain why we detect only 1/3 of expected electron neutrinos; but can this neutrino oscillation be experimentally confirmed?
- two separate experiments, Super-Kamiokande and SNO, confirmed this:
 - **SNO** detected different interactions 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

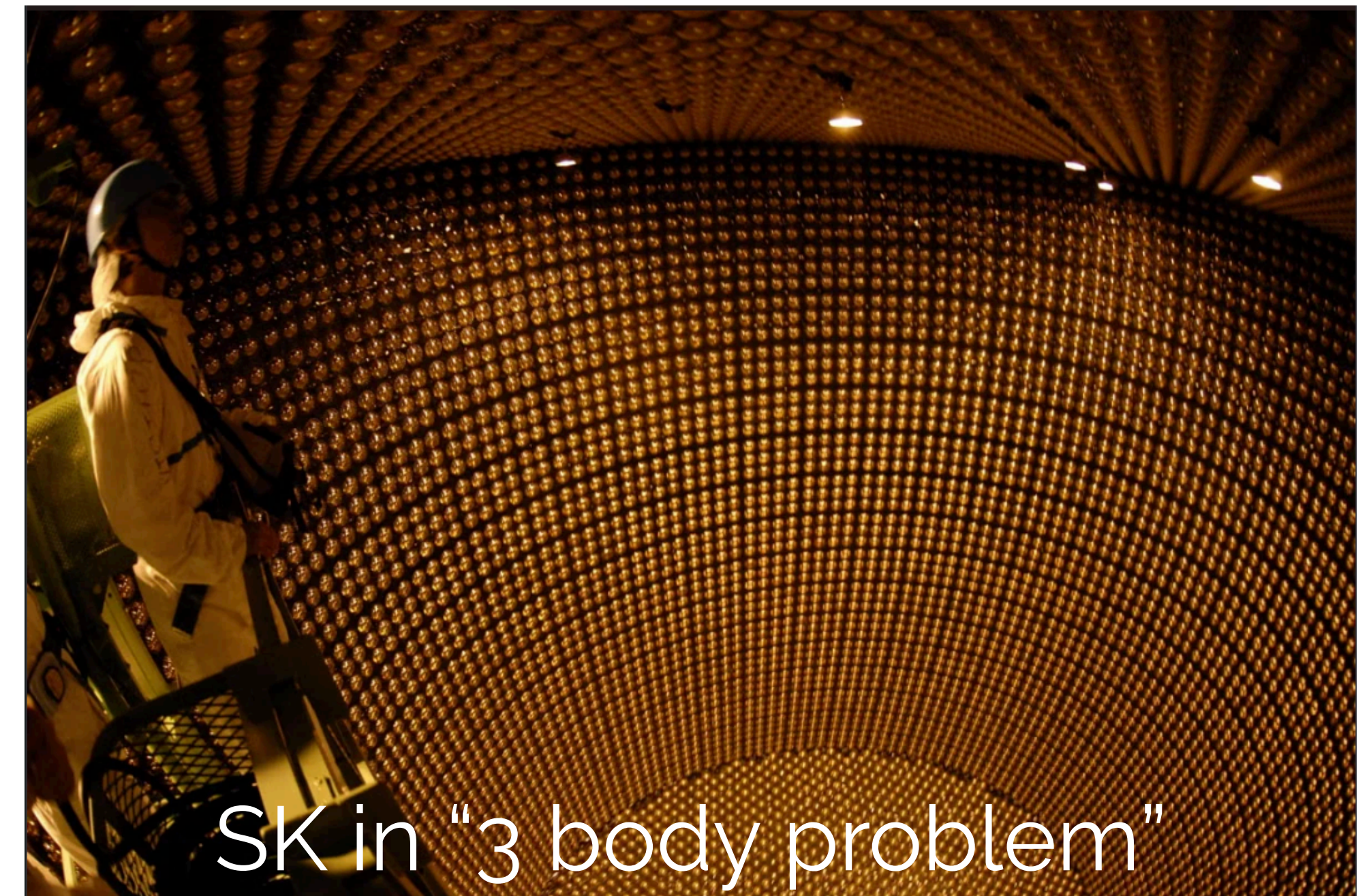
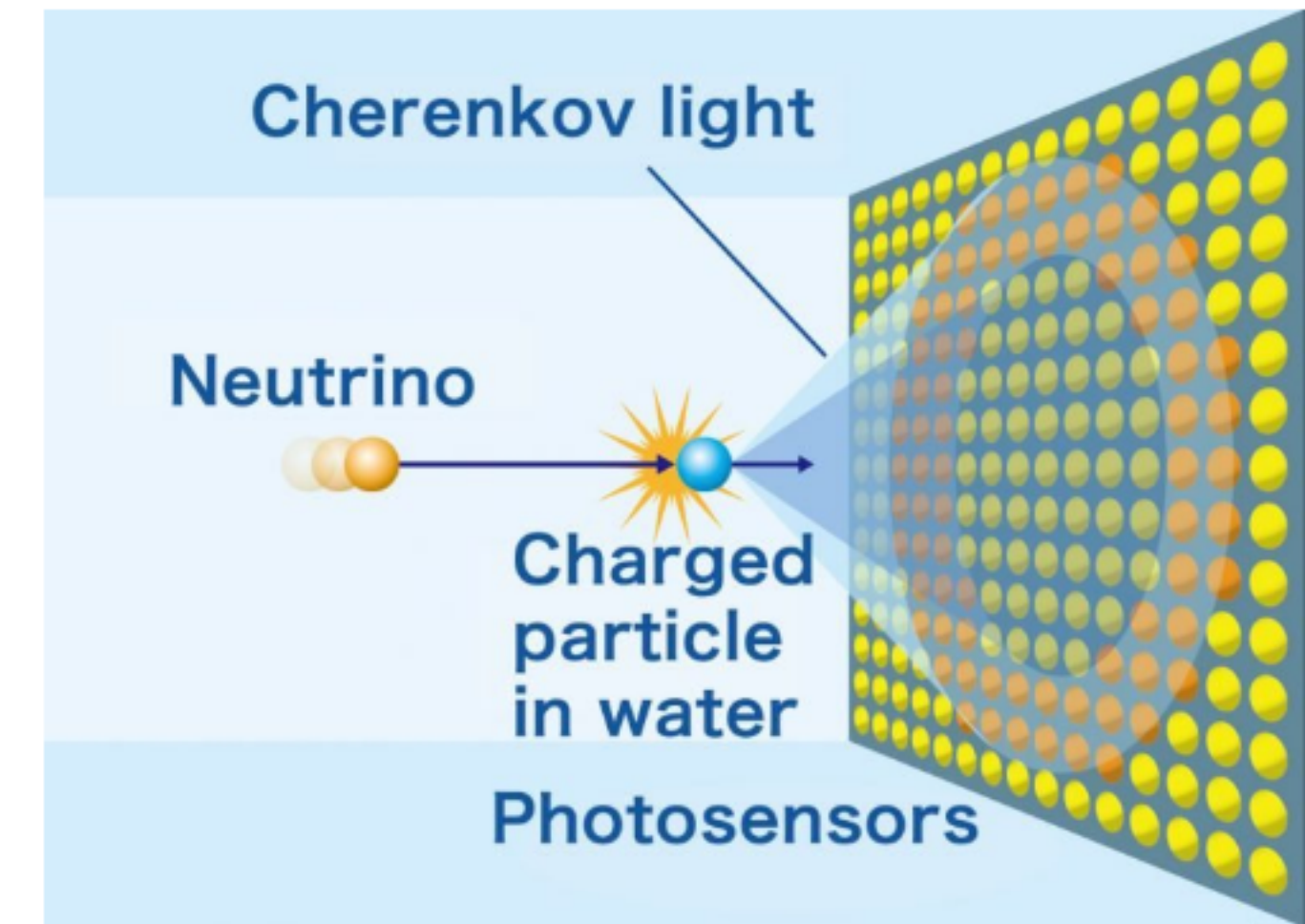
- neutrinos are really hard to detect: they carry no charge, interact very rarely, and only through the Weak force
- but **we can detect what comes out** of the interaction of the neutrinos
 - electrons, muons, hadrons, photons, ...
- what do we need?
 - need a **source** of neutrinos: either natural 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)



SK in “3 body problem”

DUNE far detector cavern



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*

W. J. WILLIS†

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 94720

1976

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

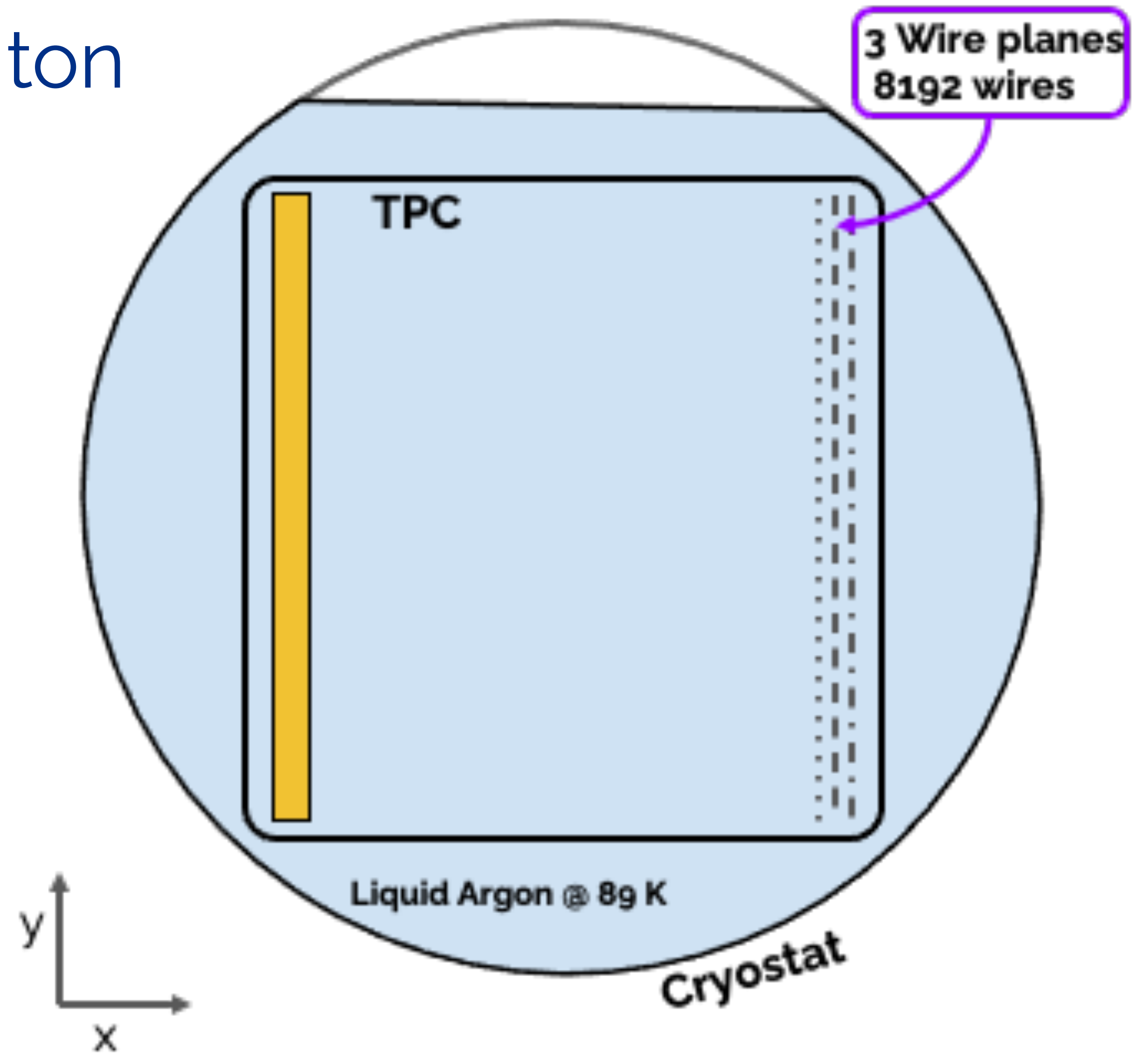
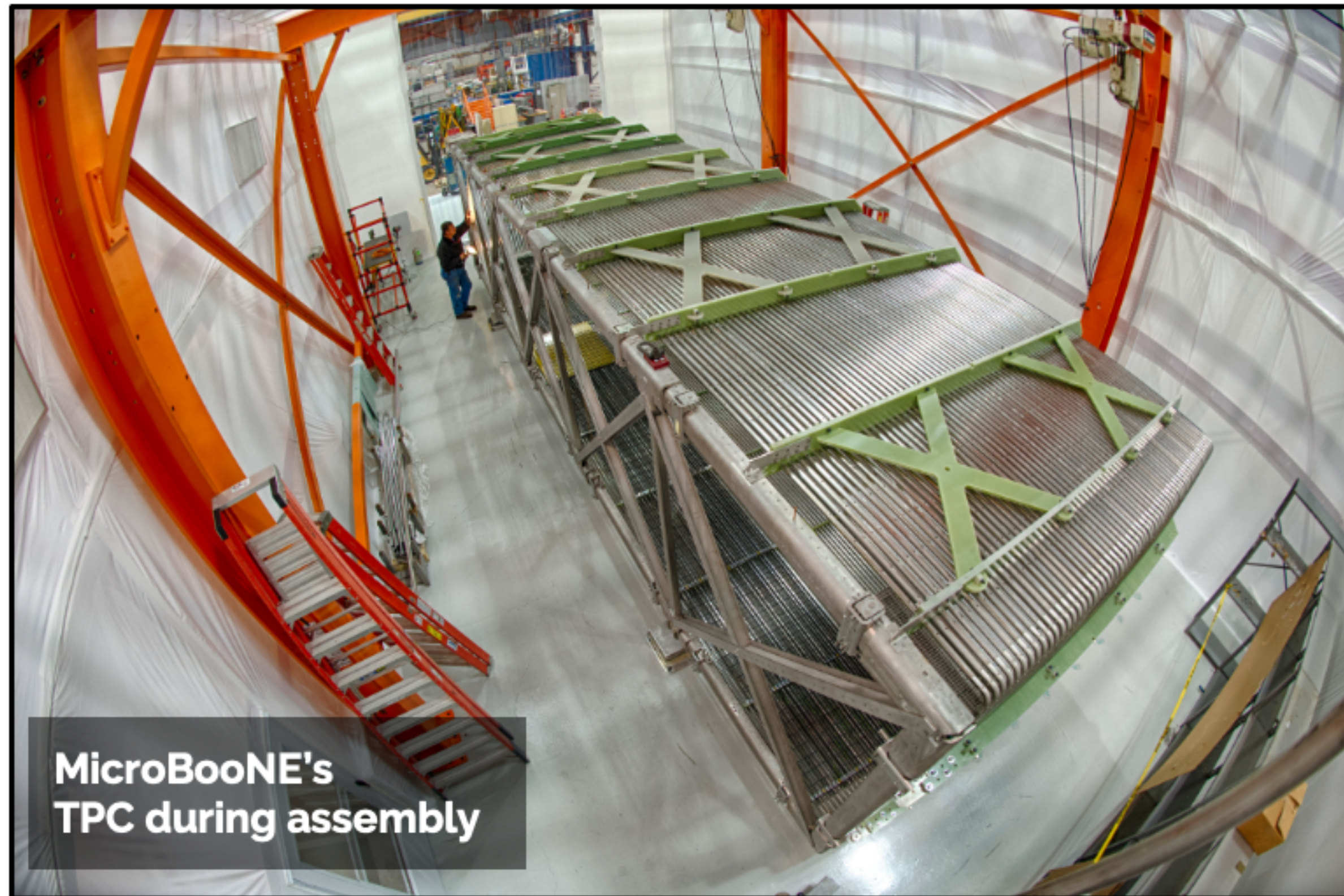
A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

1977

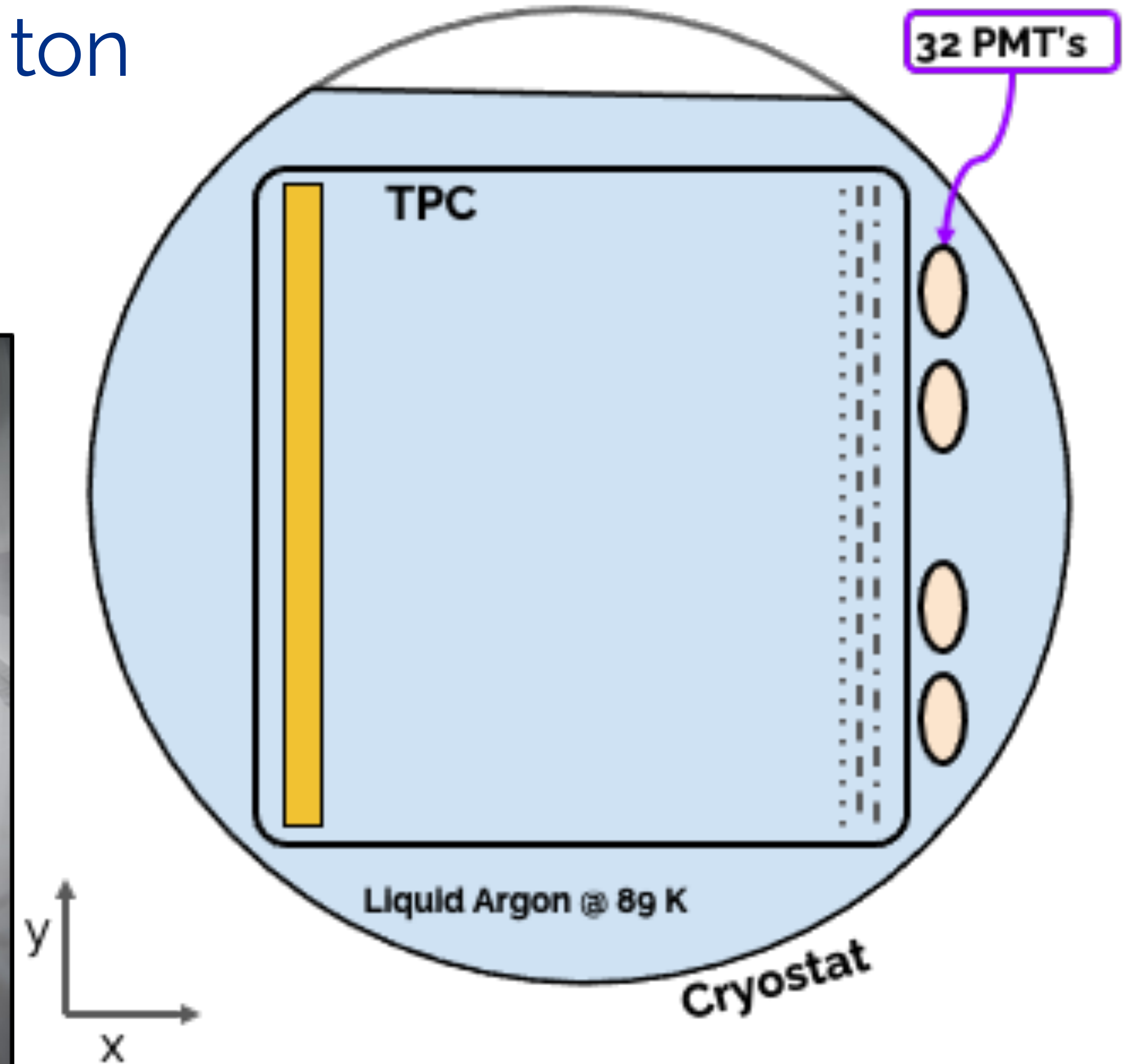
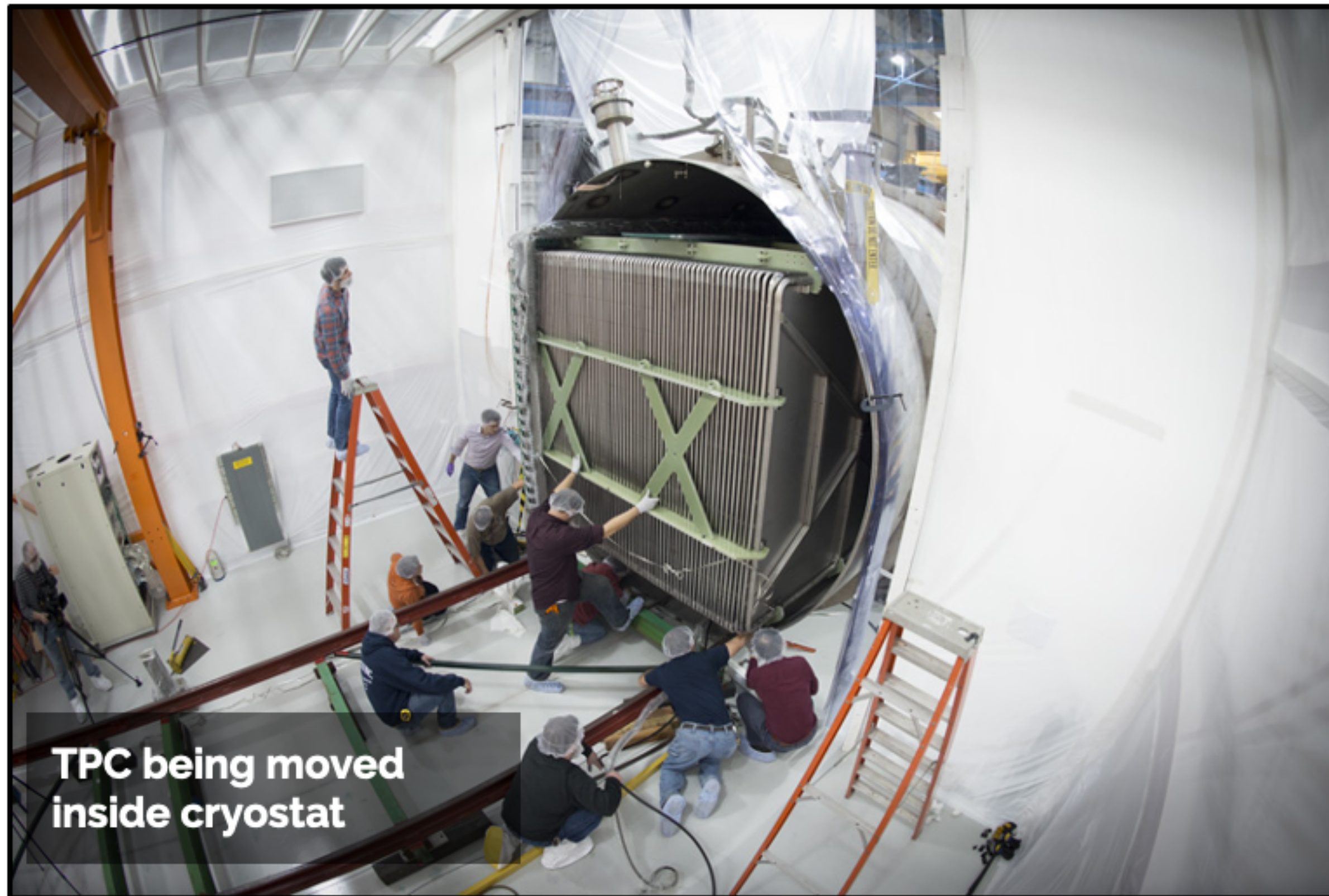
LArTPC principle: the MicroBooNE detector

at MicroBooNE's core is an 85 ton LArTPC



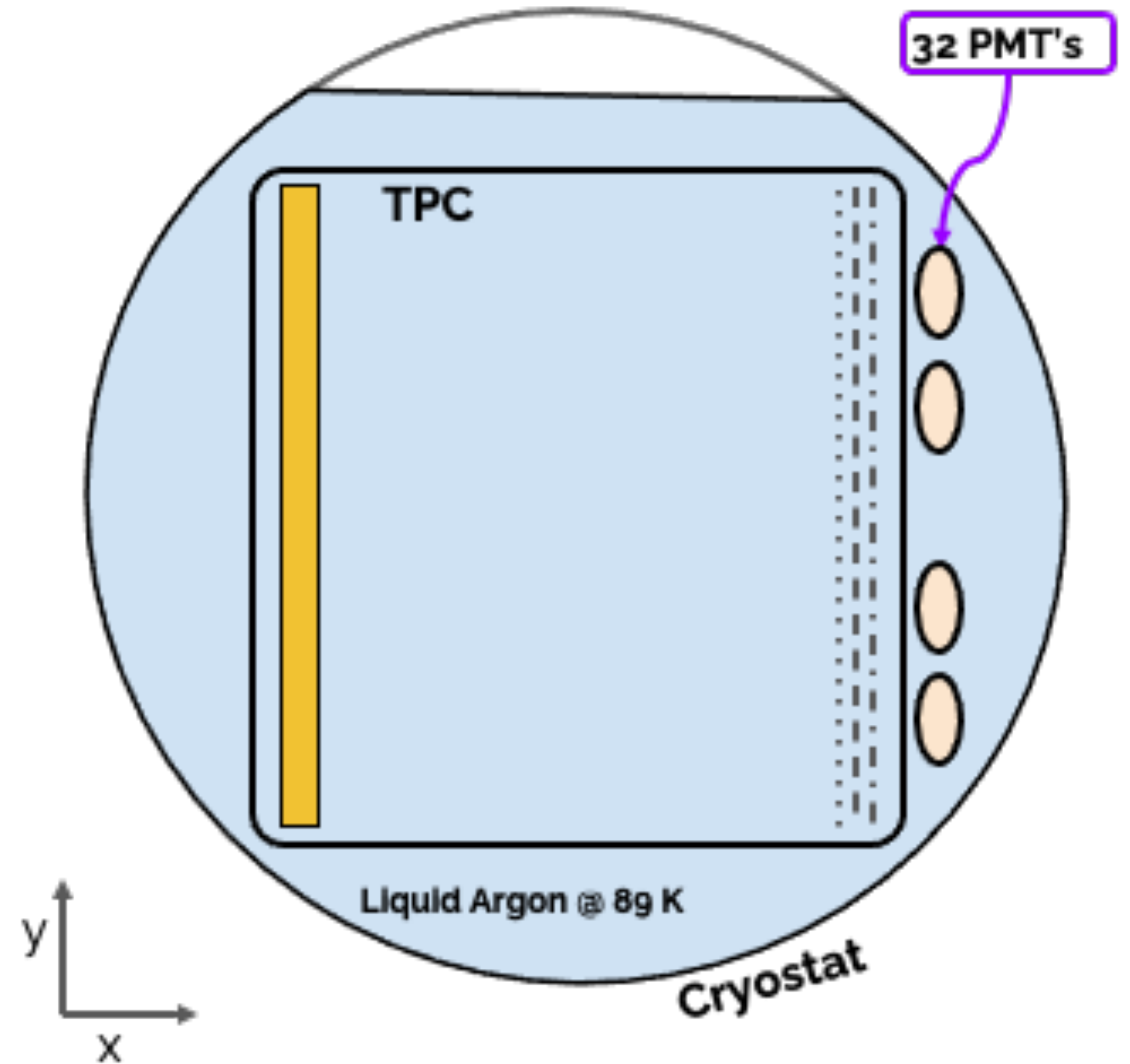
LArTPC principle: the MicroBooNE detector

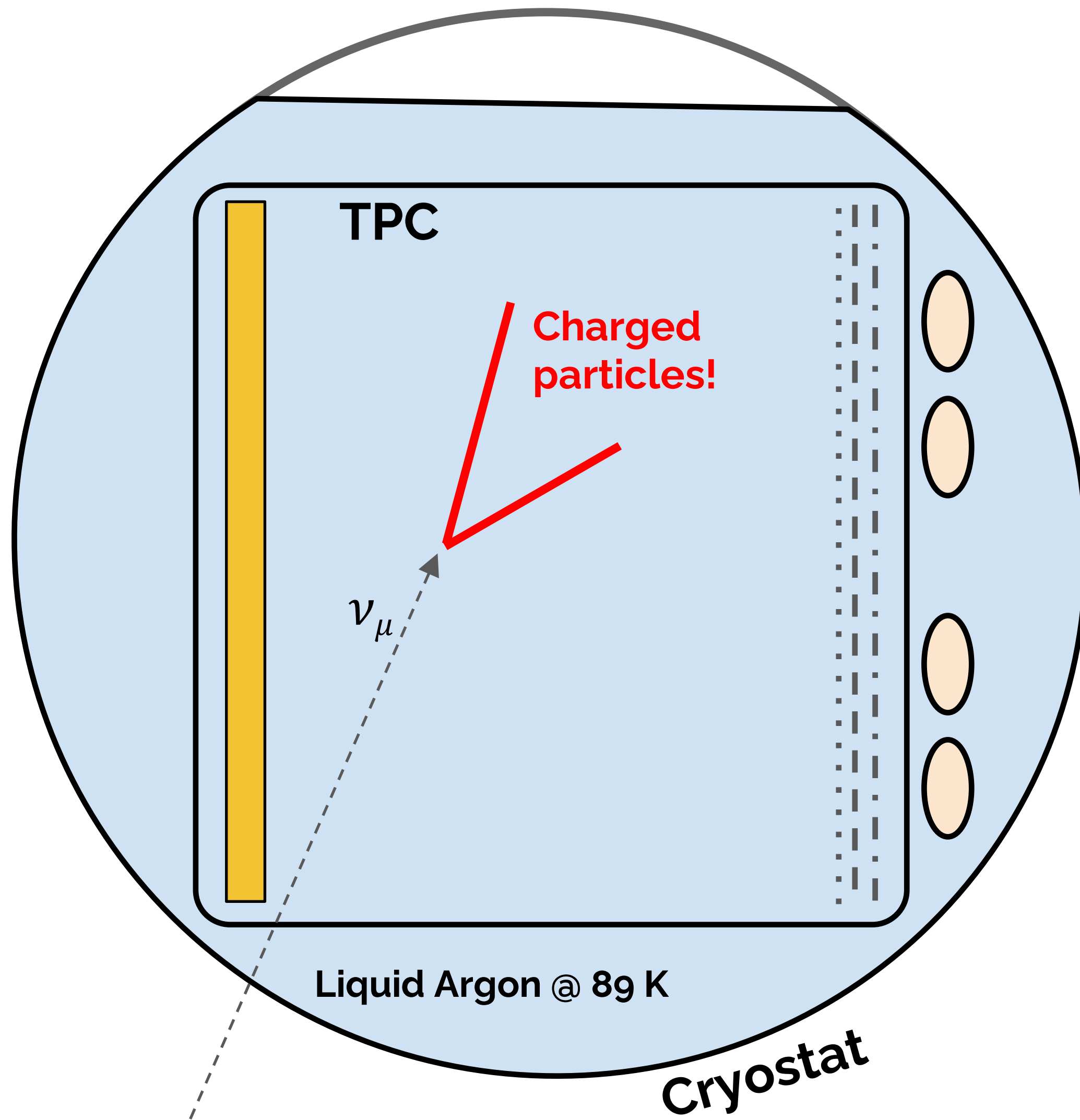
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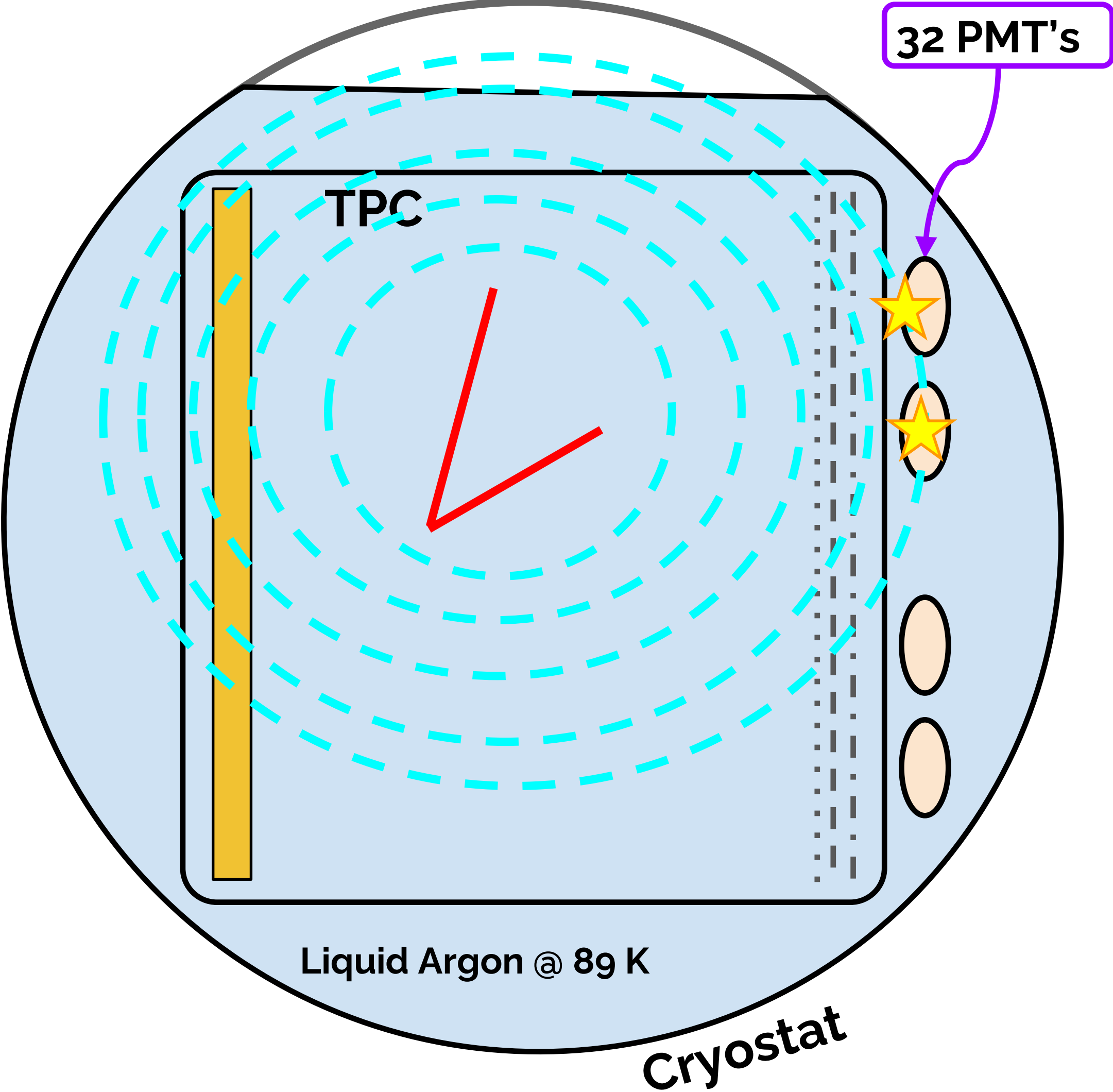
LArTPC principle: the MicroBooNE detector

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



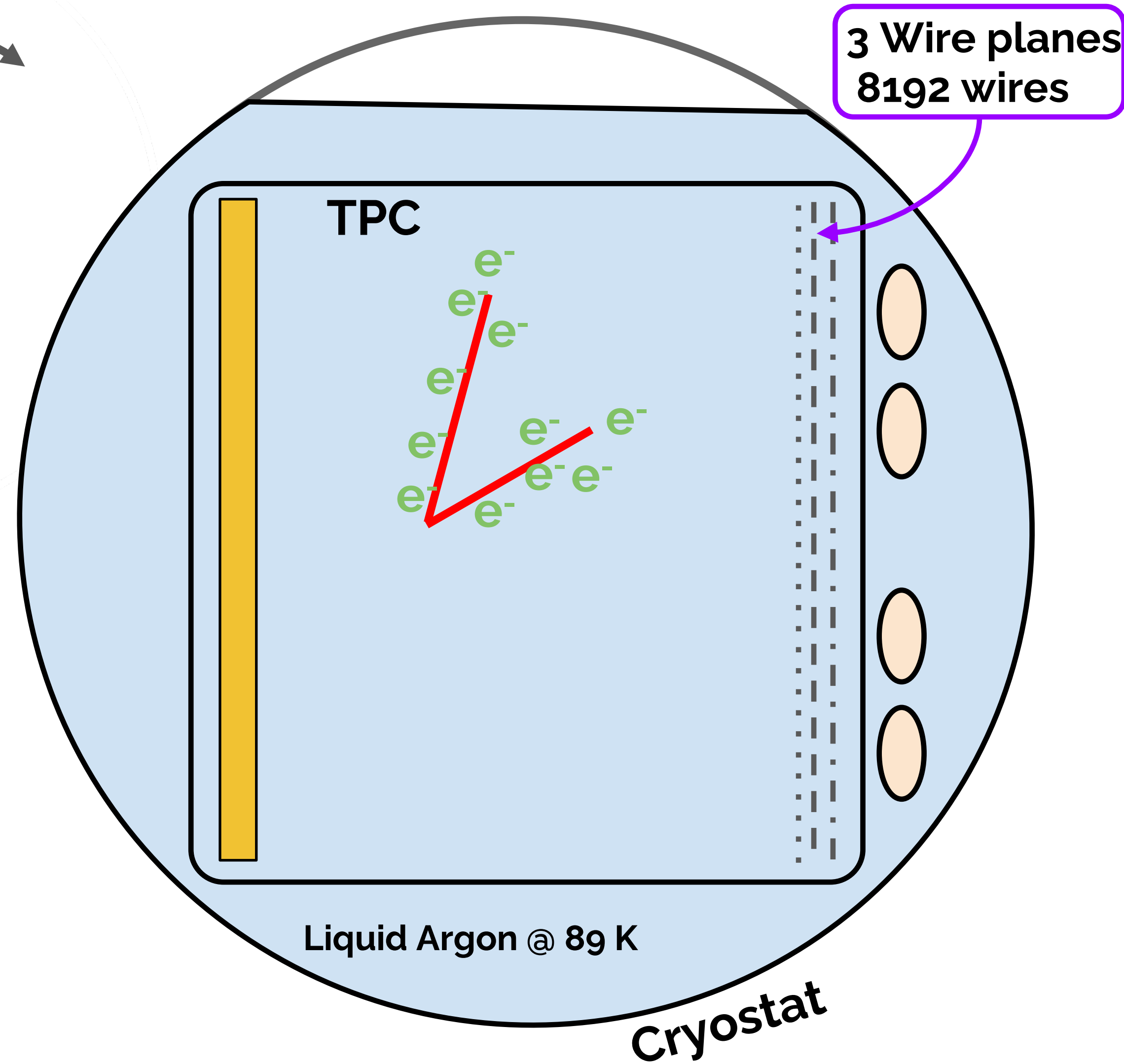
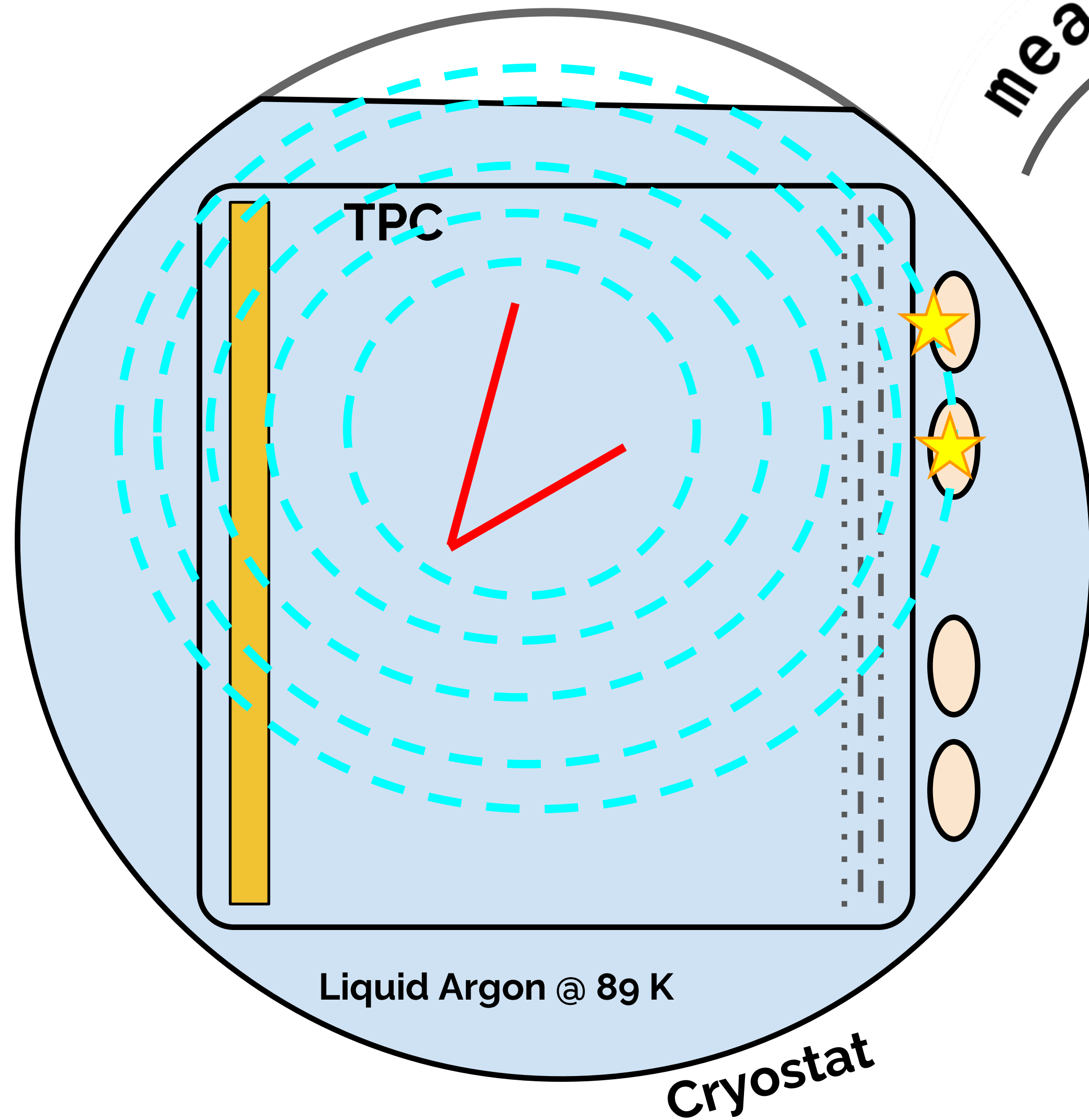


Scintillation light



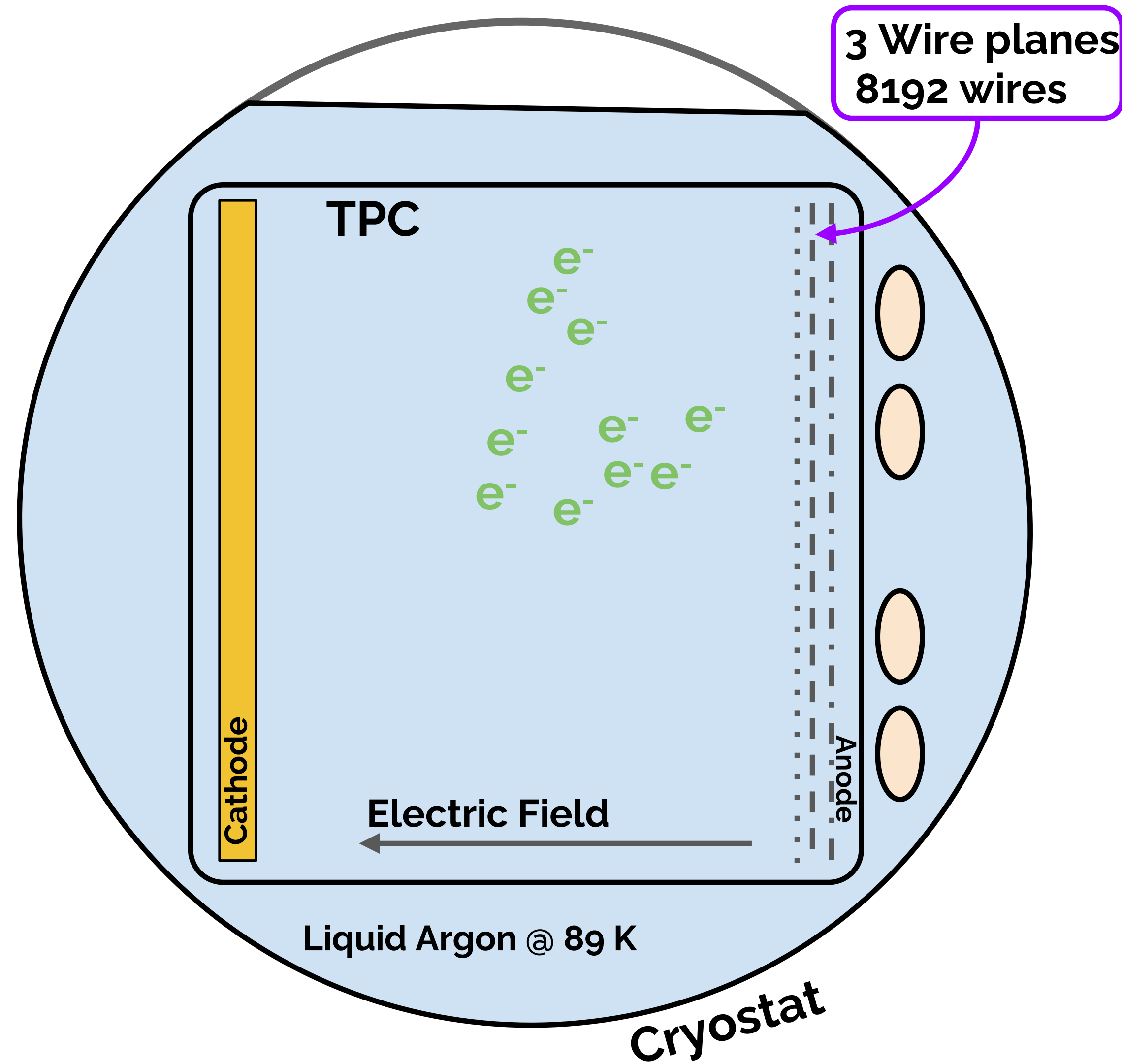
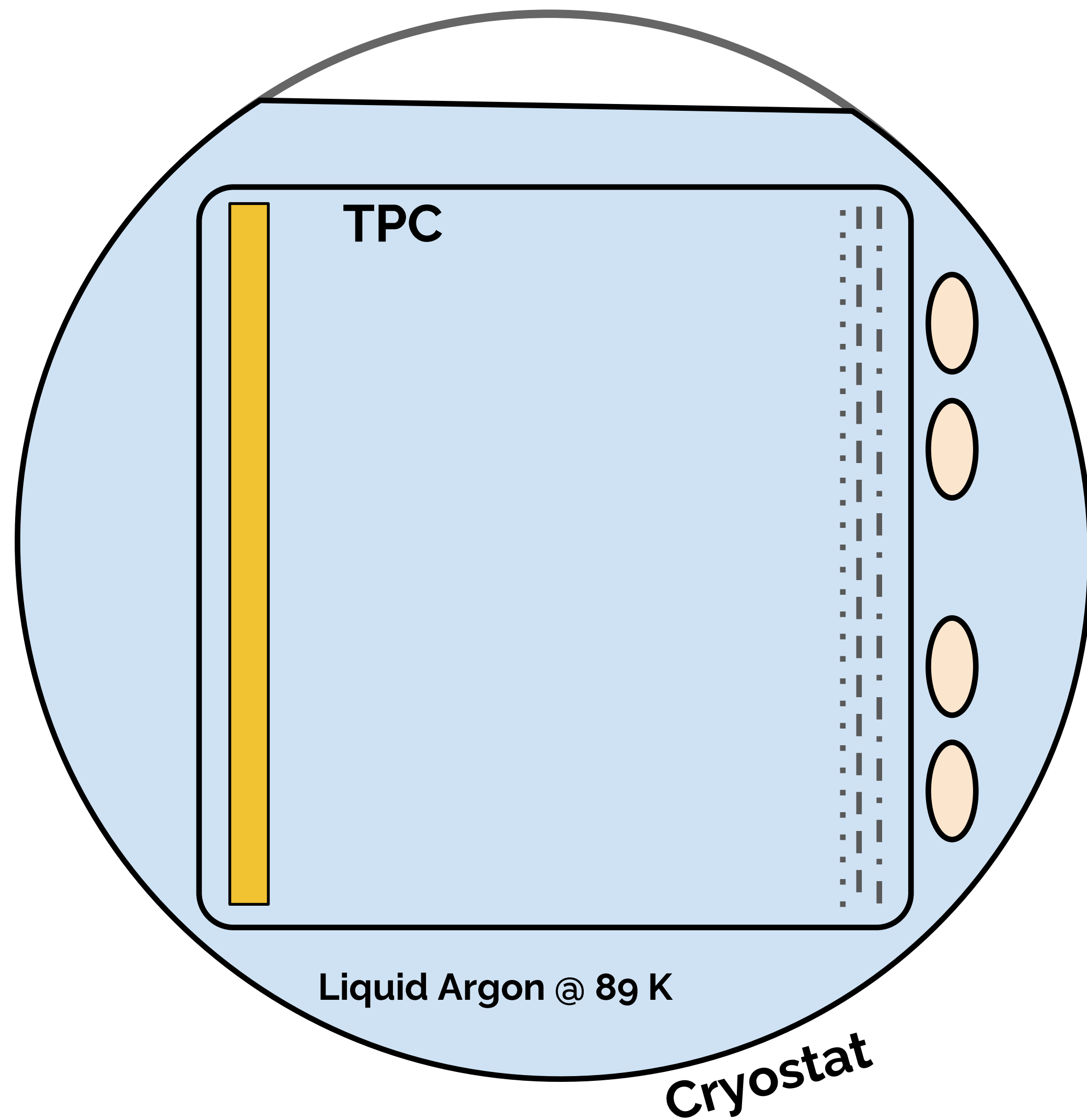
Scintillation light Ionization Charge

meanwhile



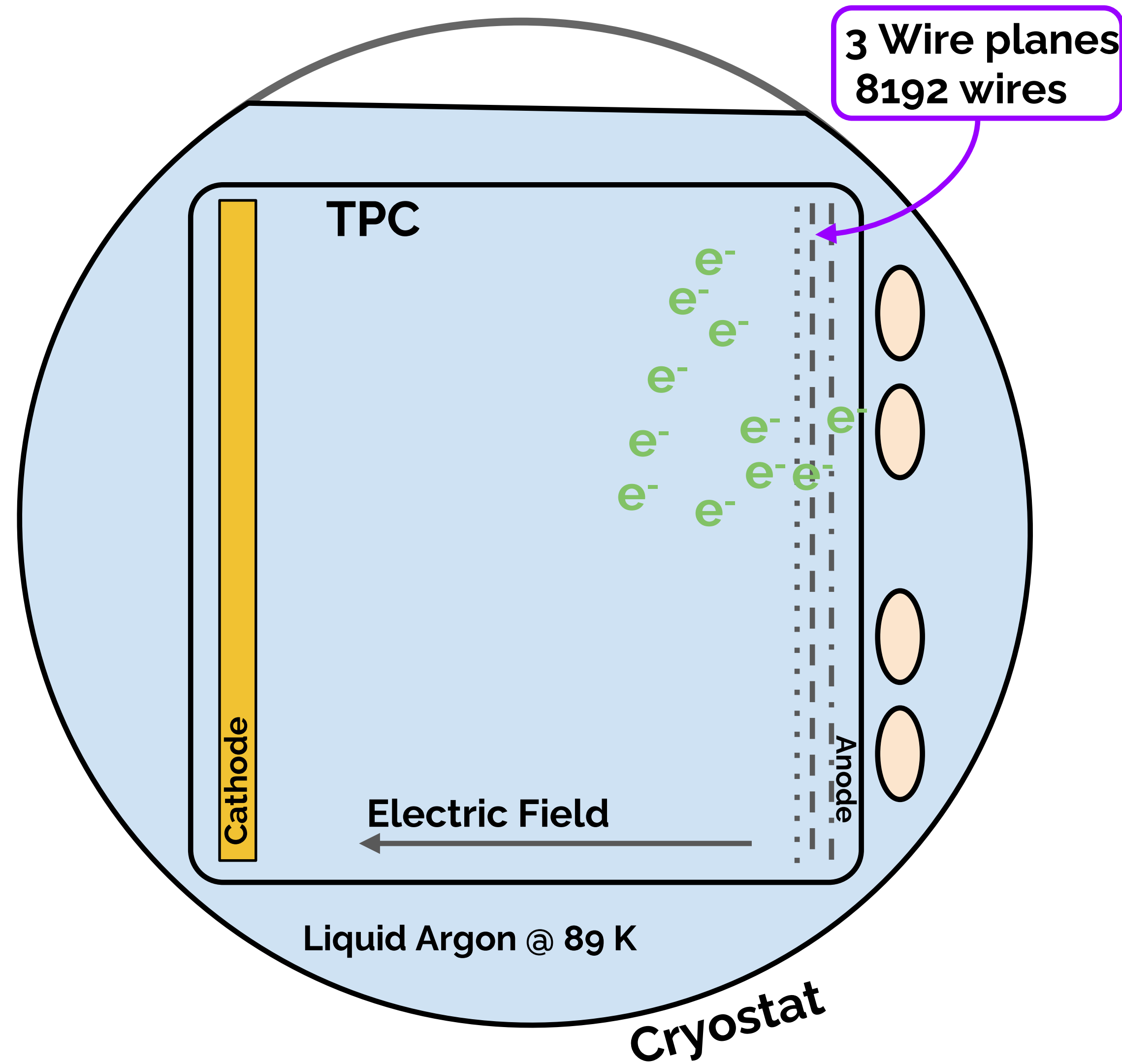
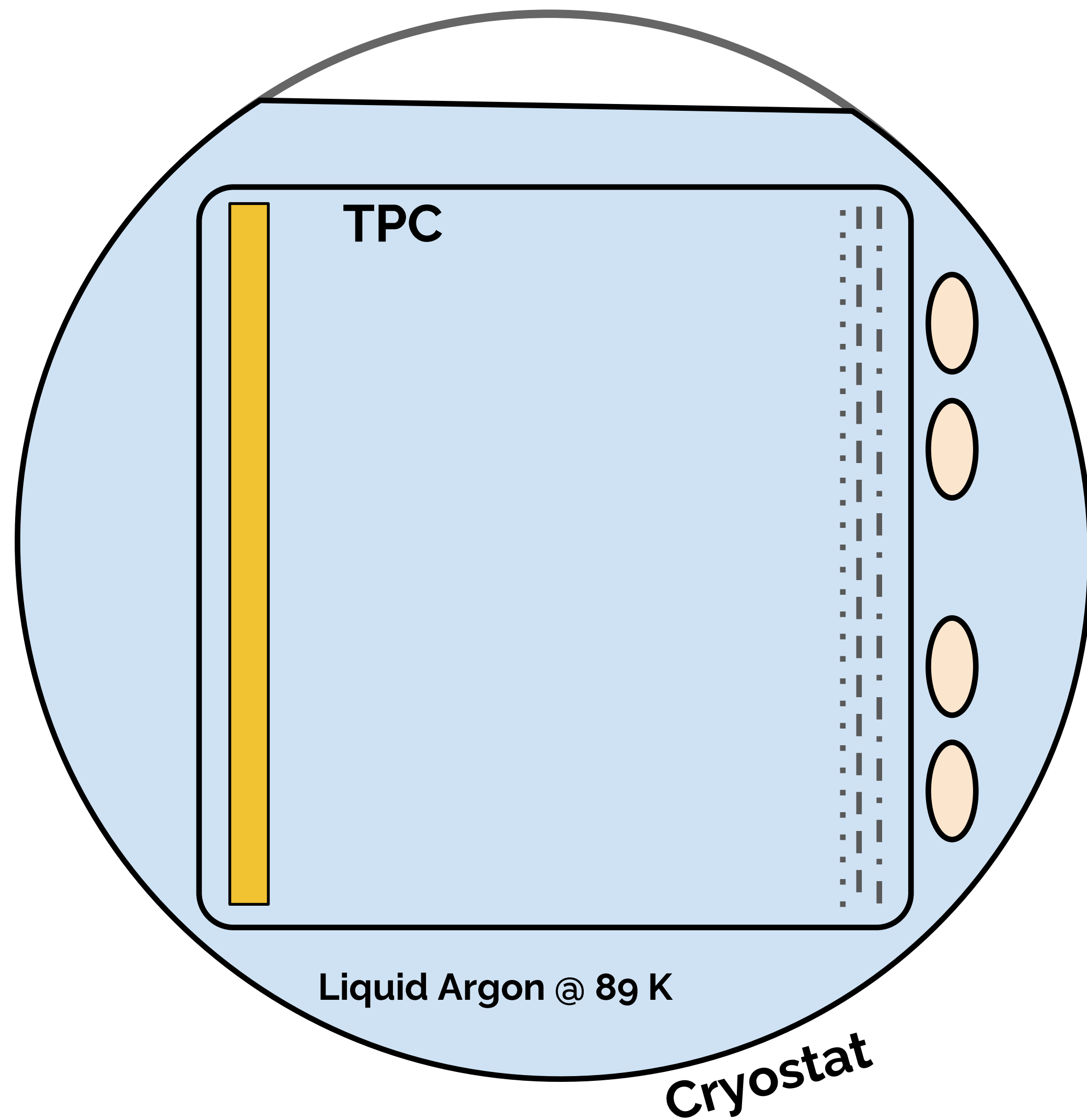
Scintillation light

Ionization Charge



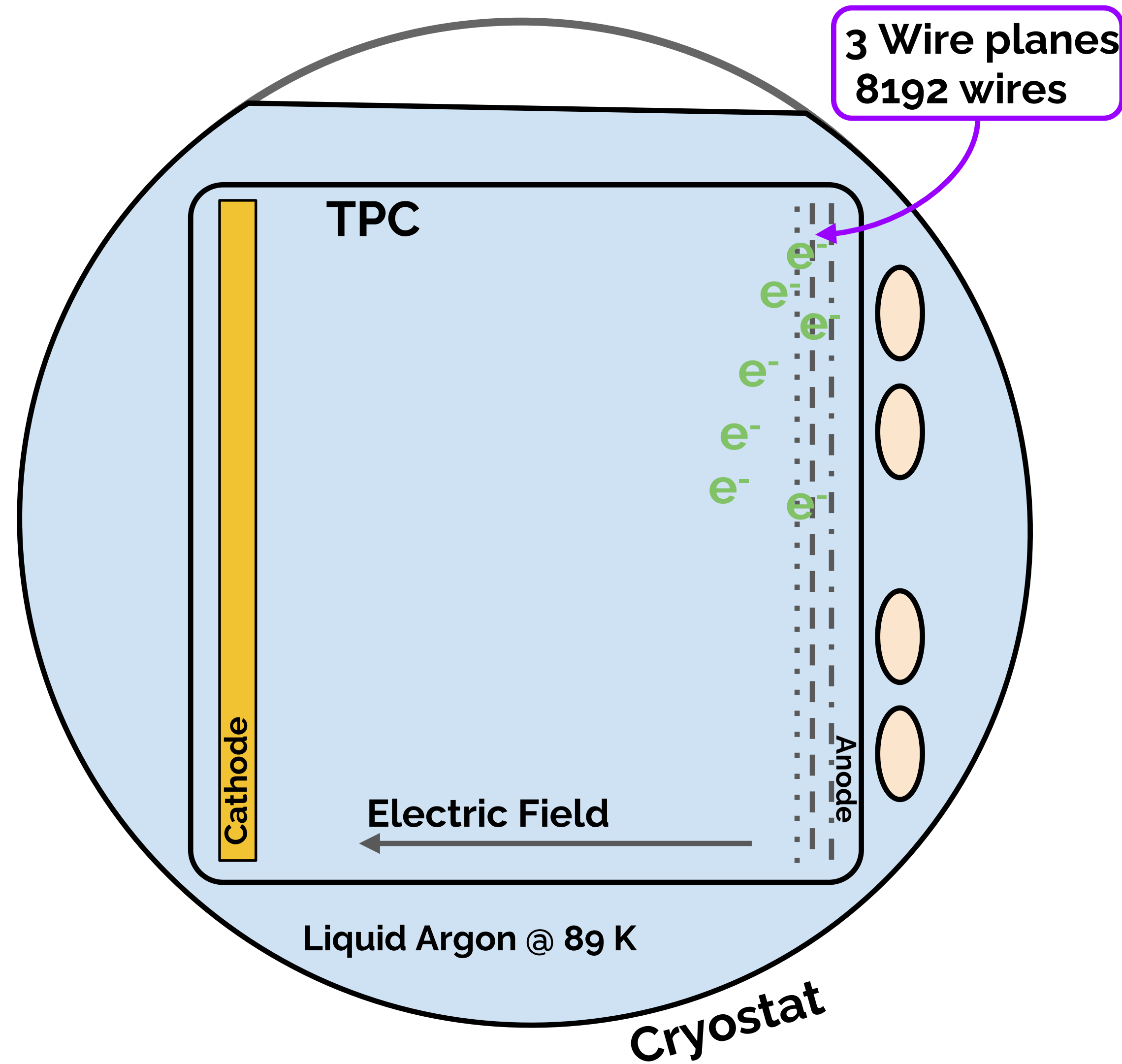
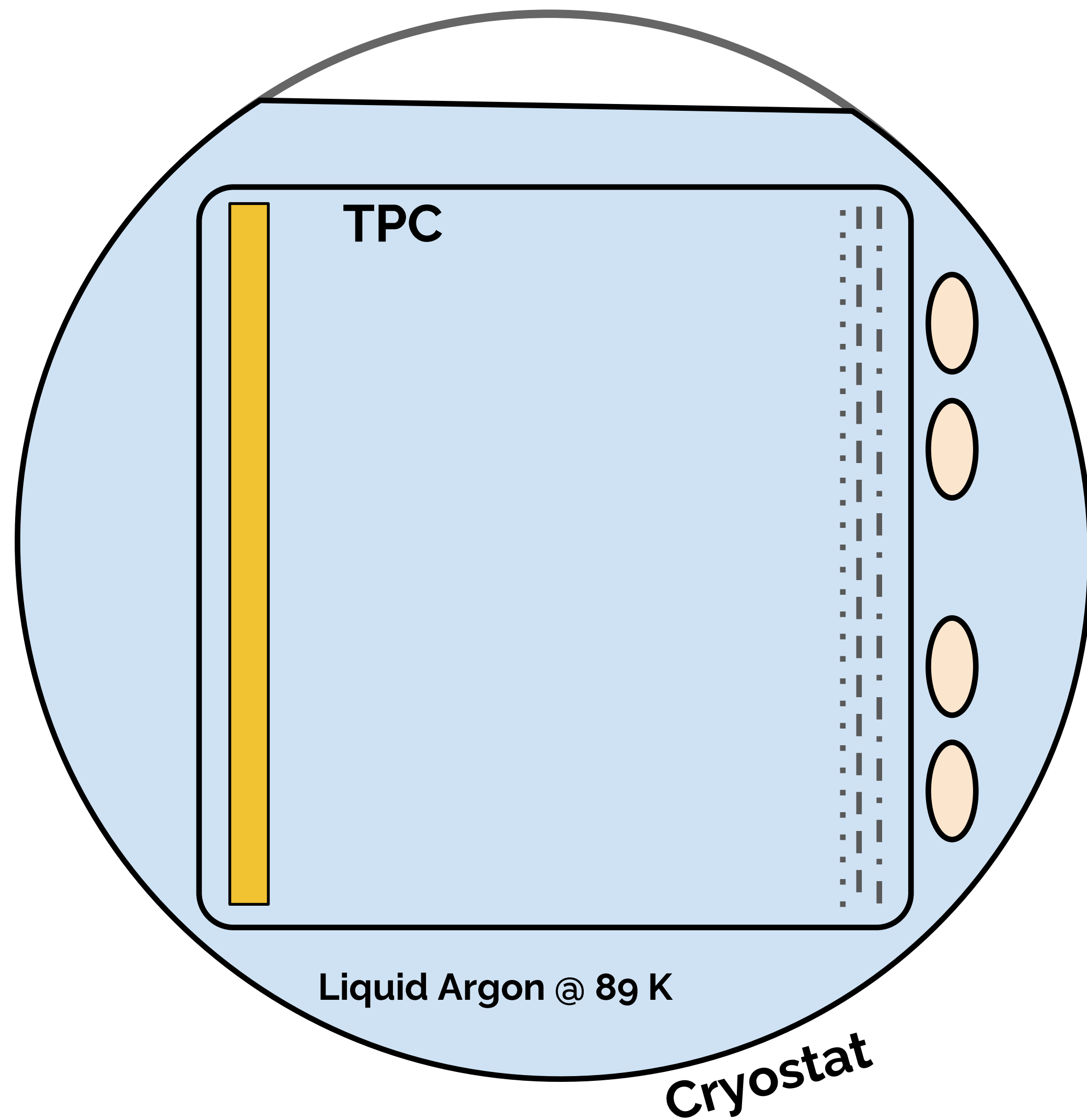
Scintillation light

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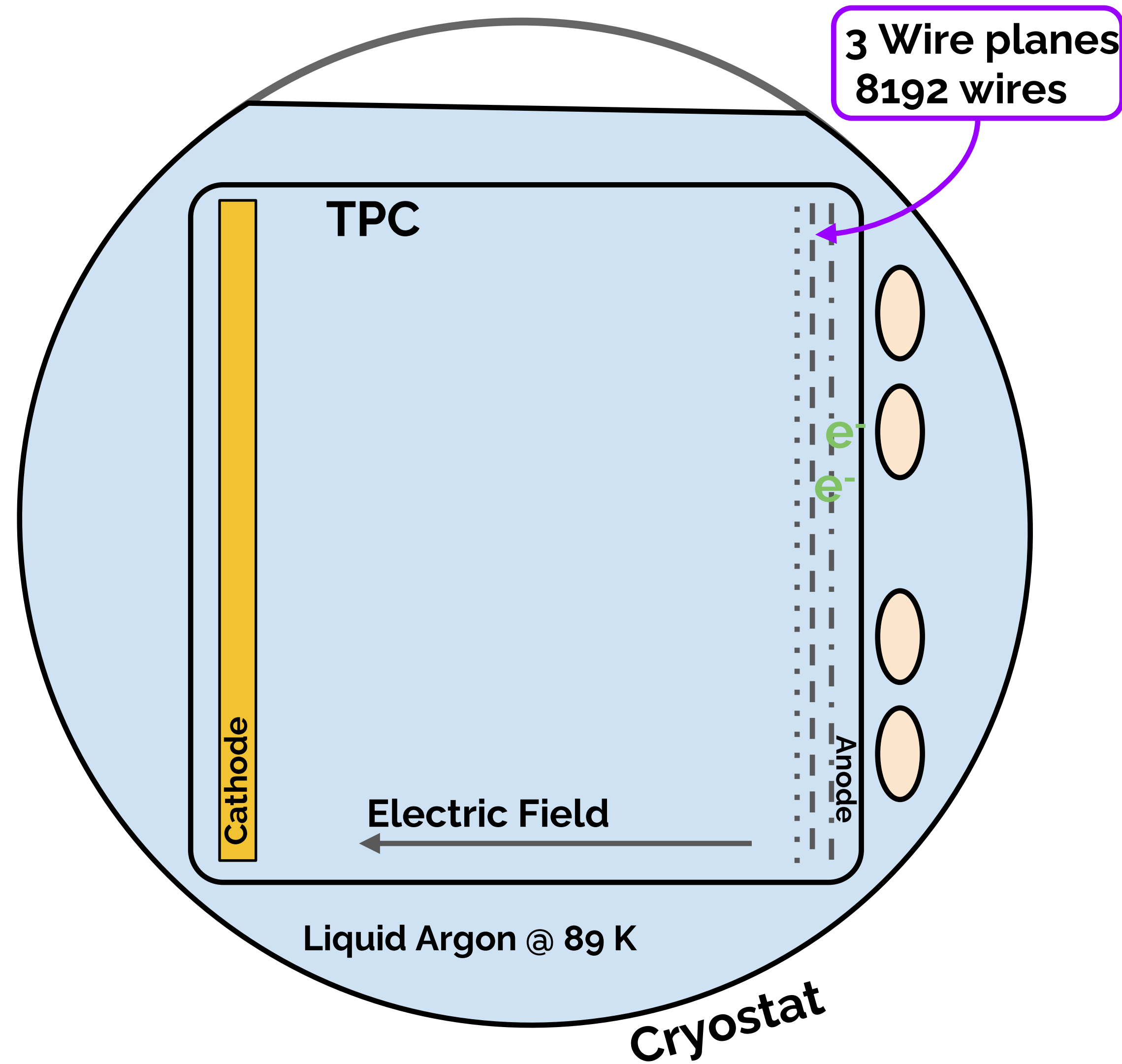
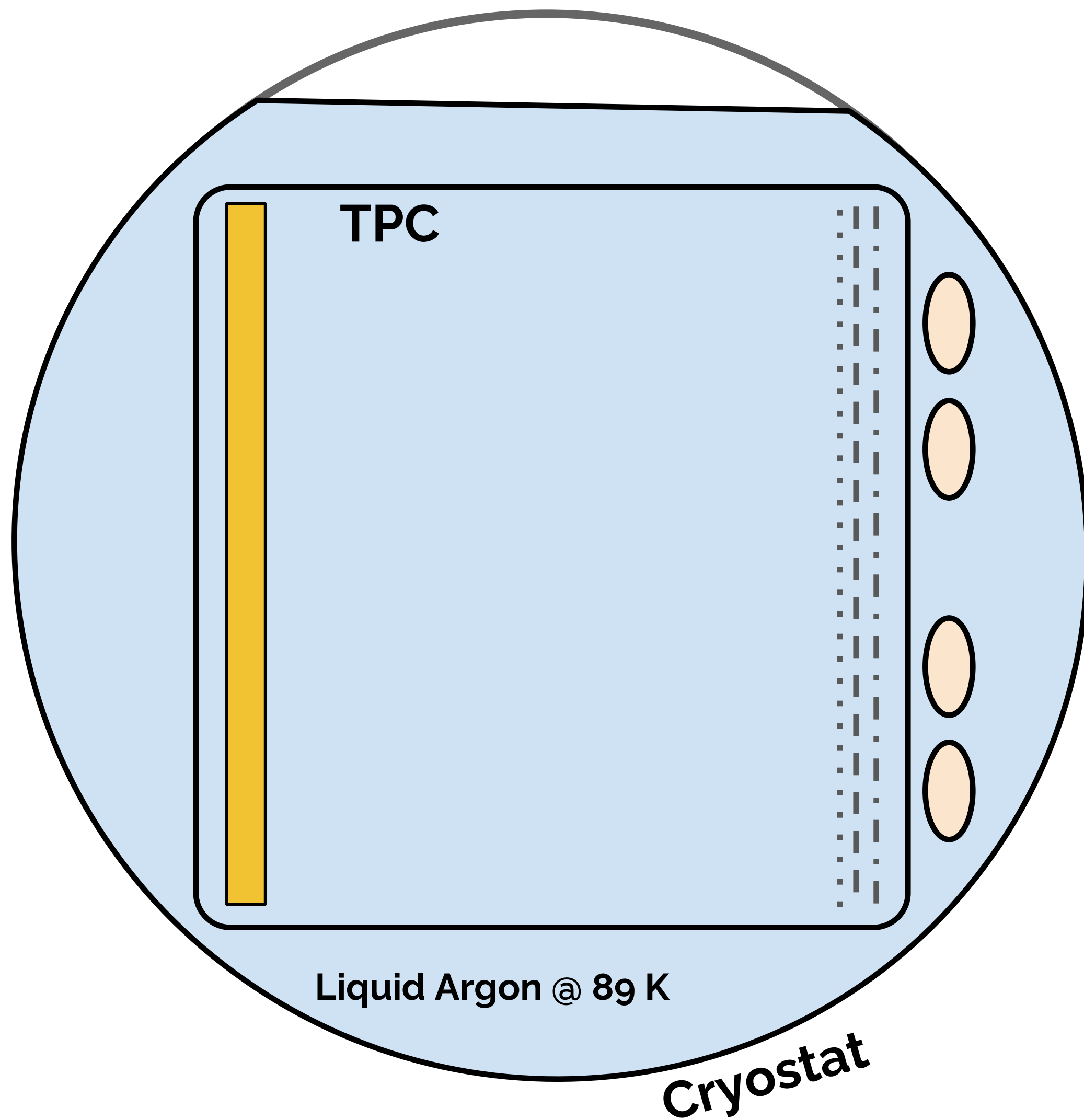
Scintillation light

Ionization Charge



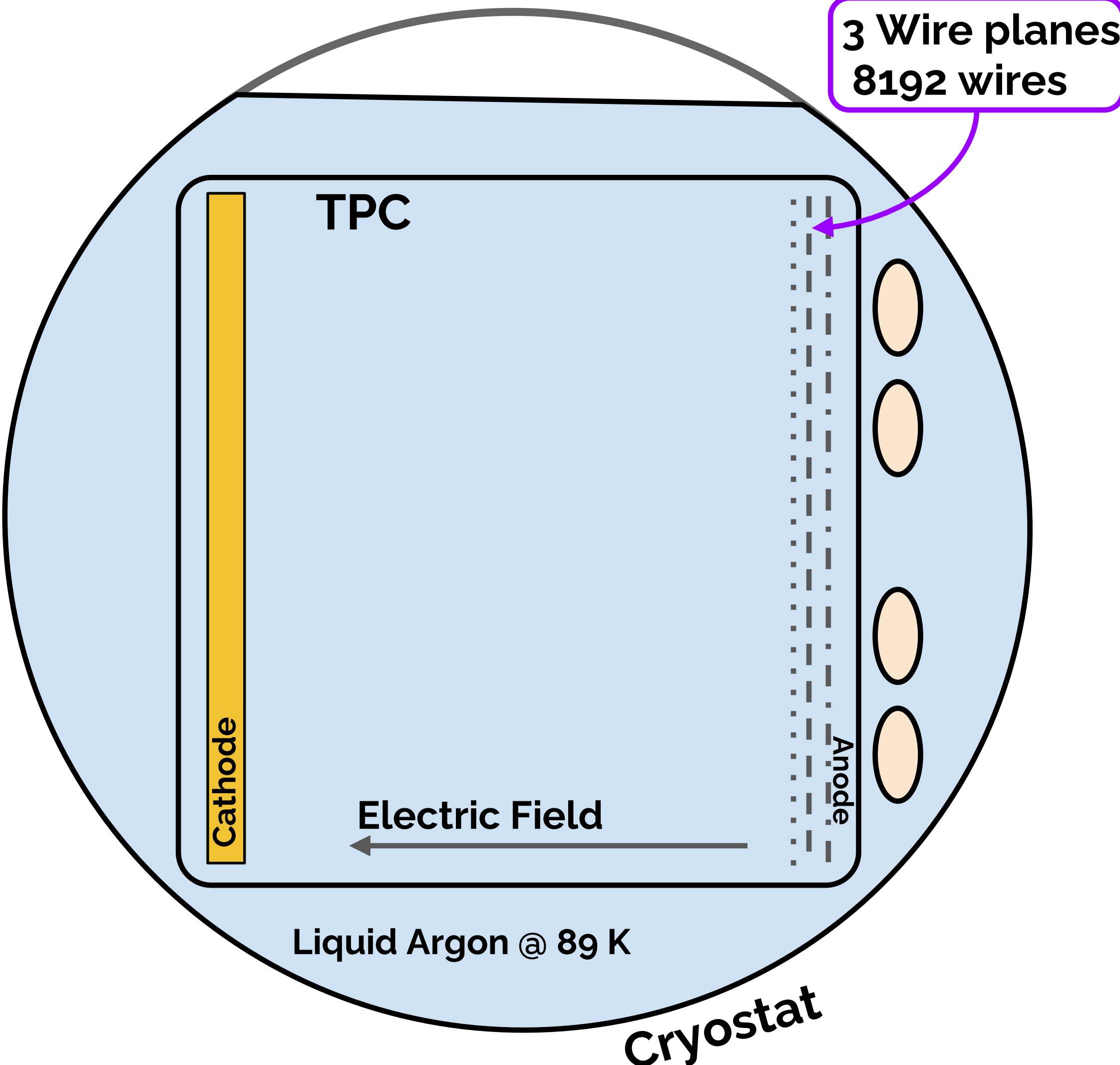
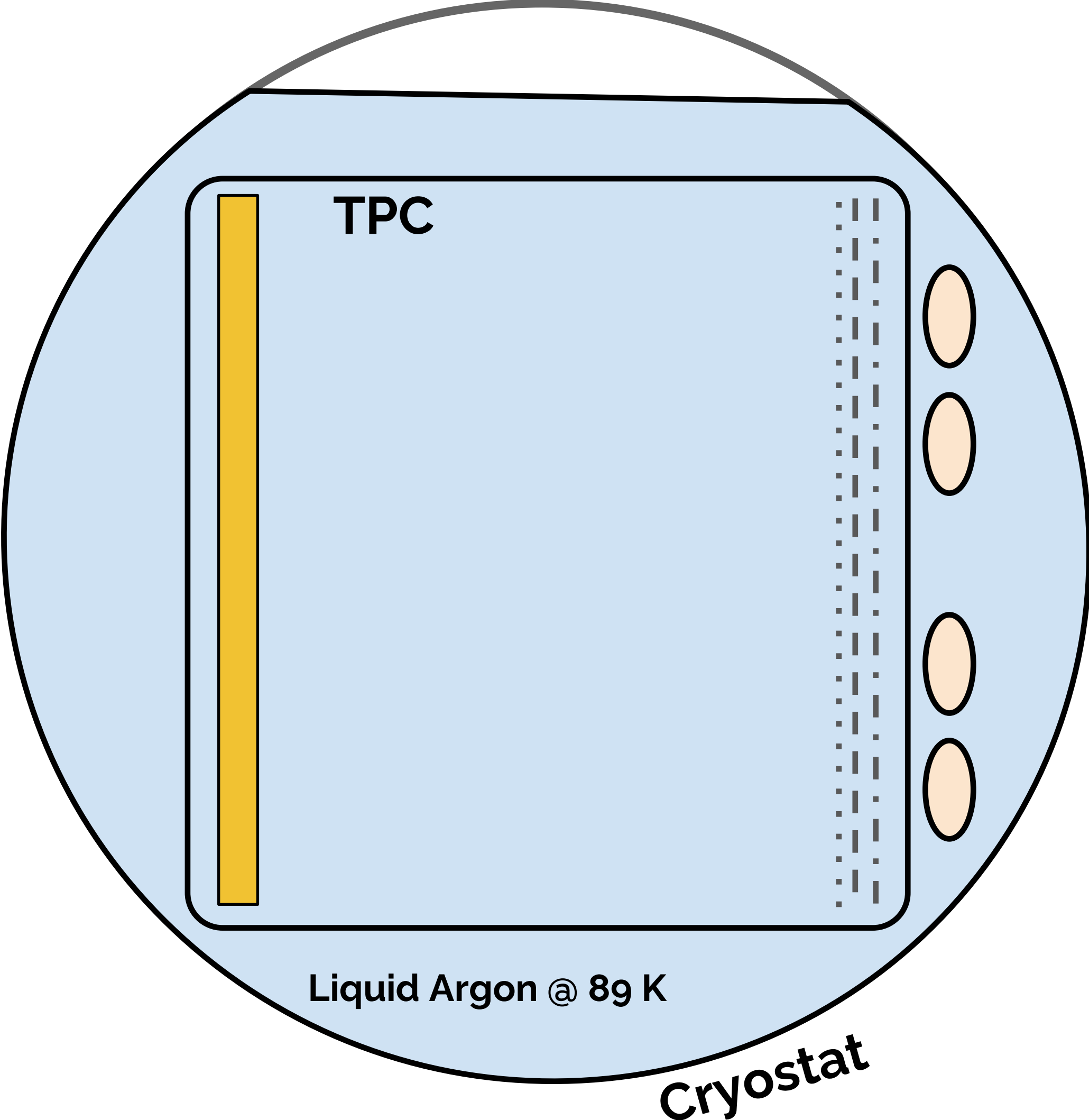
Scintillation light

Ionization Charge

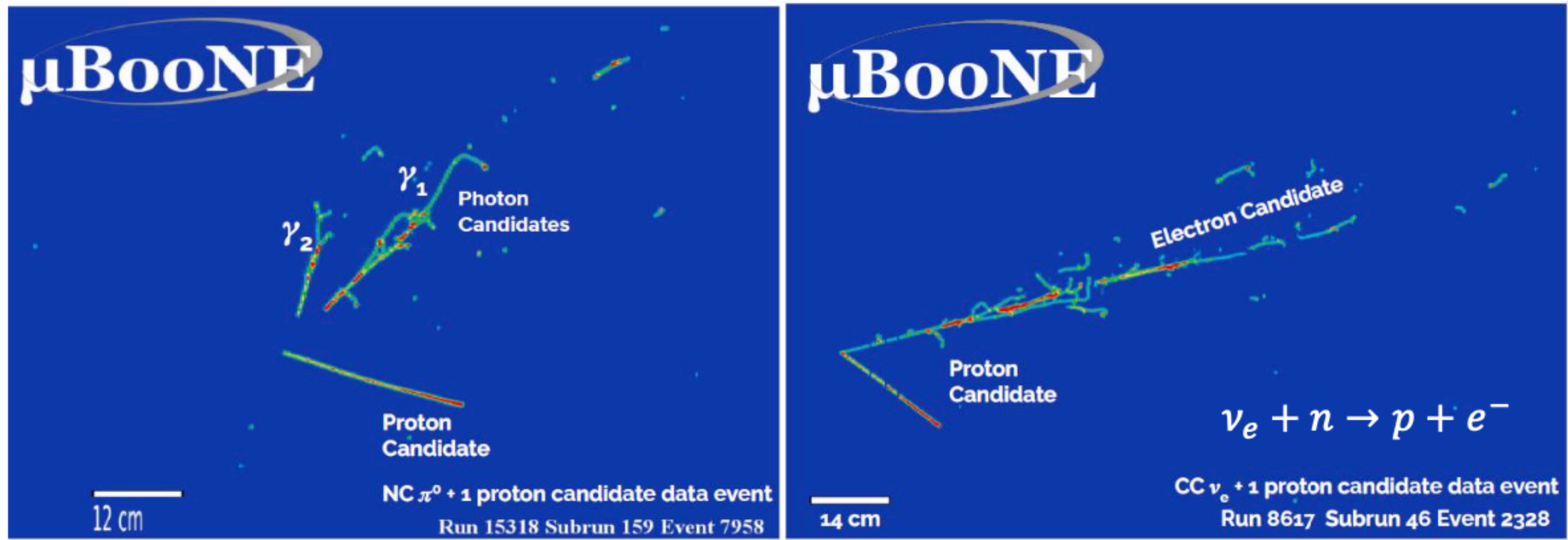


Scintillation light

Ionization Charge



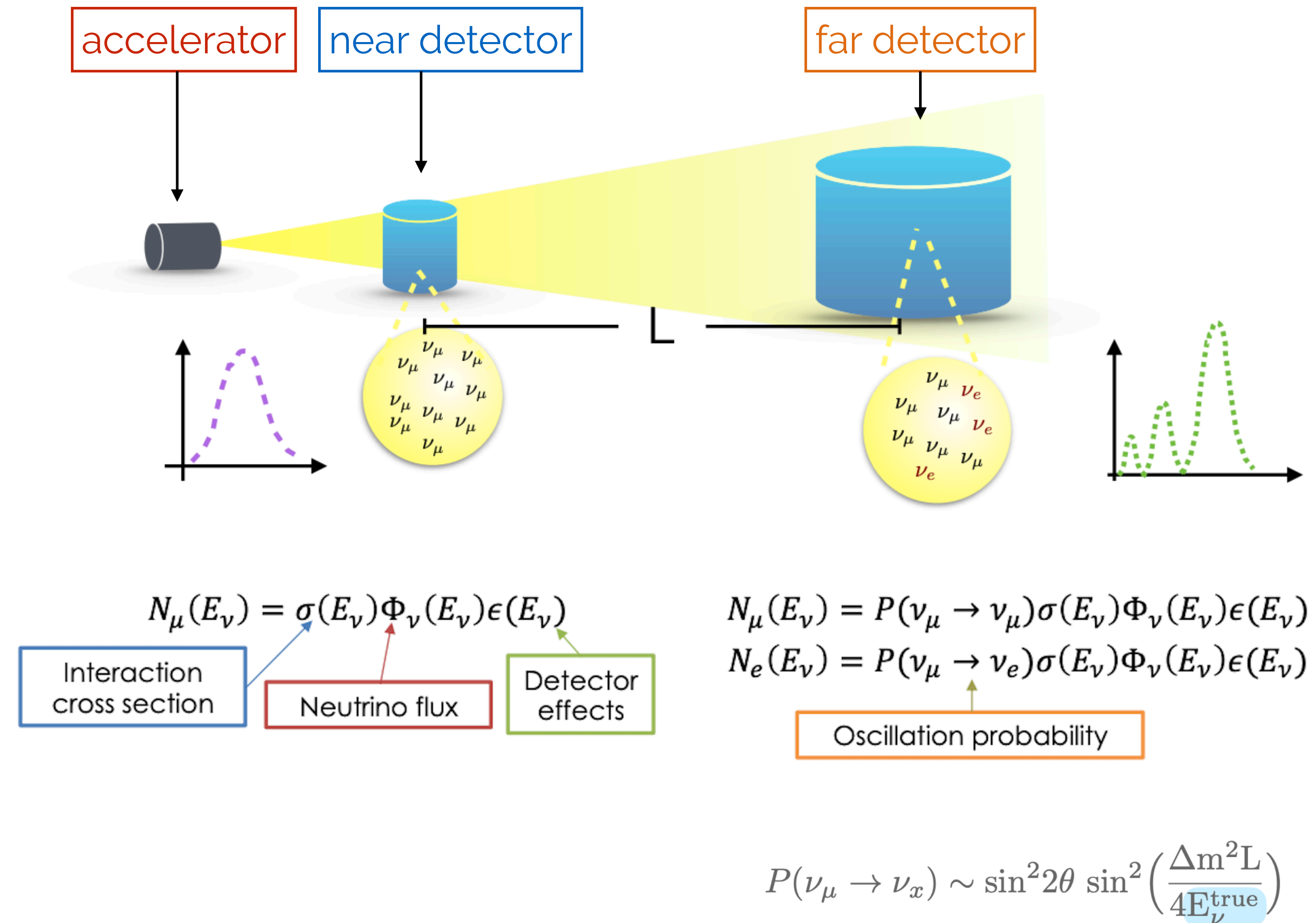
LArTPC principle: the MicroBooNE detector



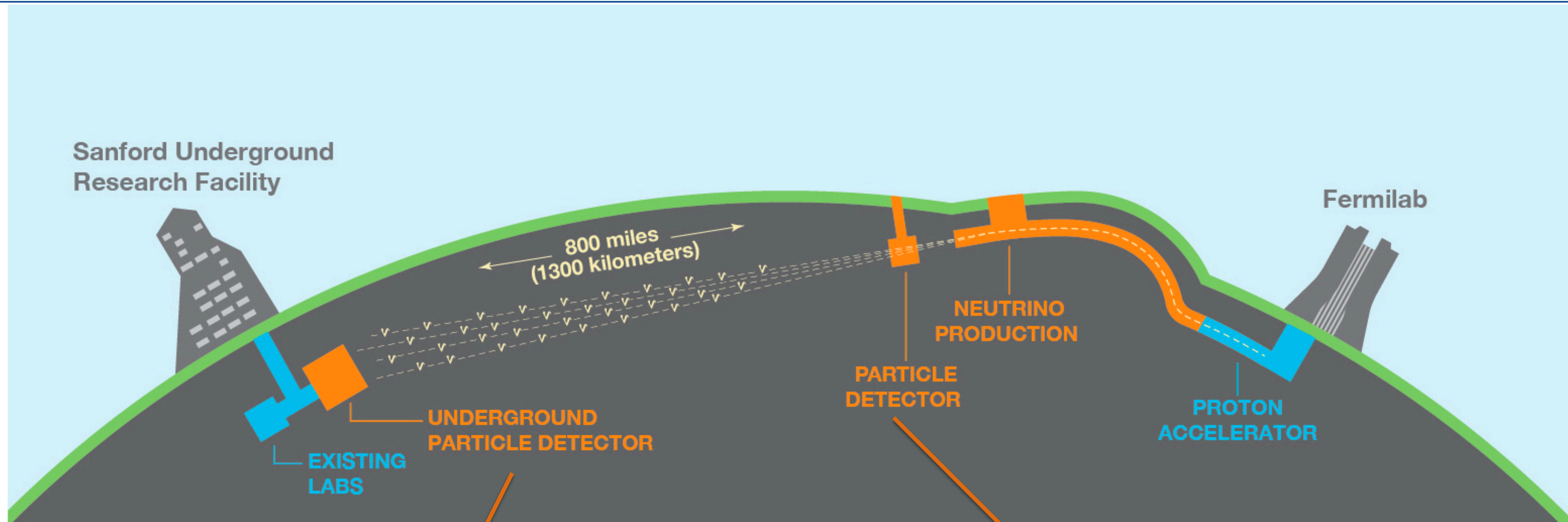
- capable of separating electrons from photons, with gap and calorimetry information

Long-baseline neutrino experiment principles

- artificial neutrino beam generated at an **accelerator**
- measure rate of neutrino events in 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**



DUNE: next-generation long-baseline neutrino experiment



Far Site

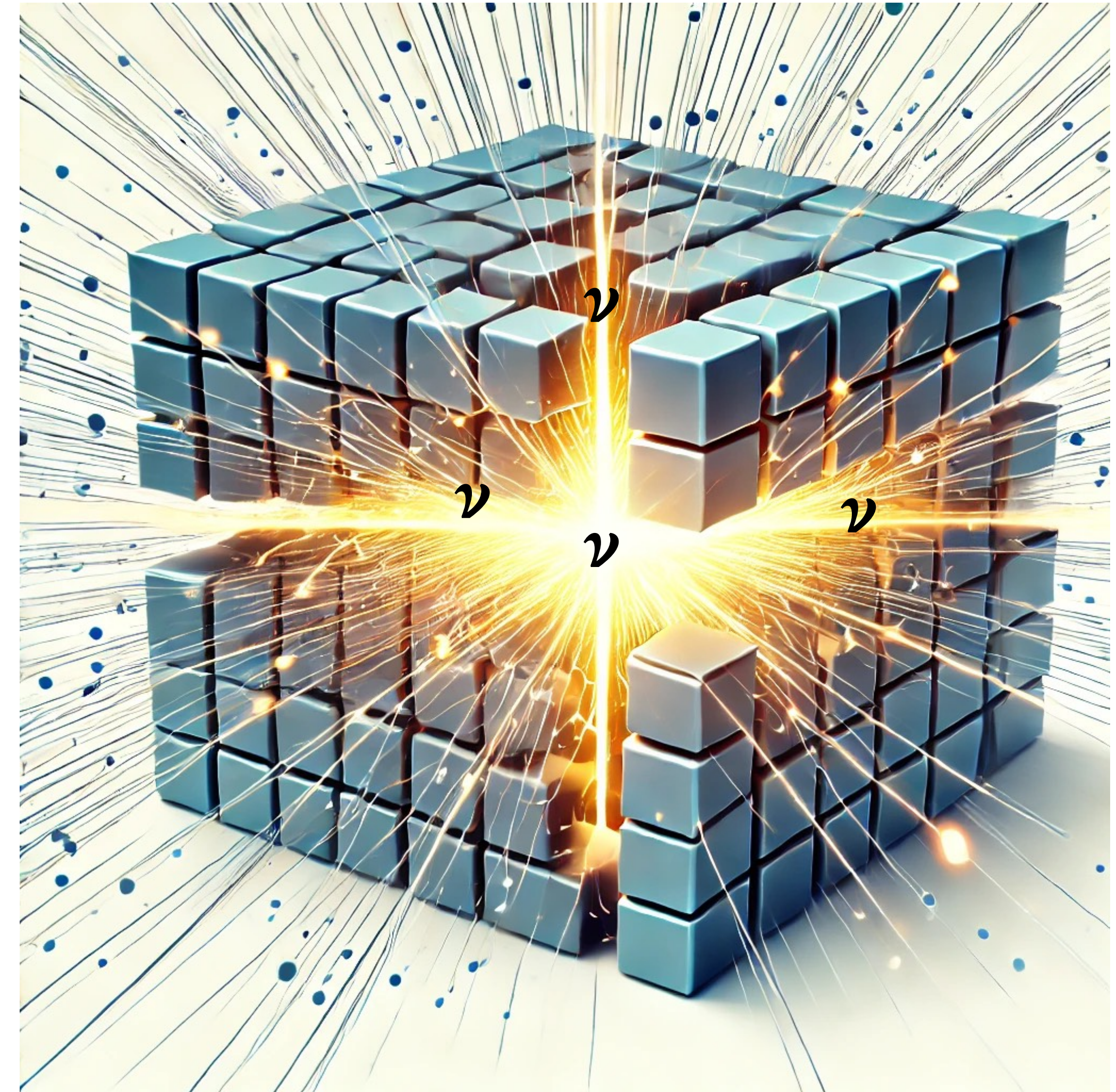
- 1300km from the proton source
- very large LAr TPCs (each 17 ktons)
- underground in South Dakota

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



Why do we want to detect neutrinos?

The most general state is a normalized linear combination of the two basis states

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

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?

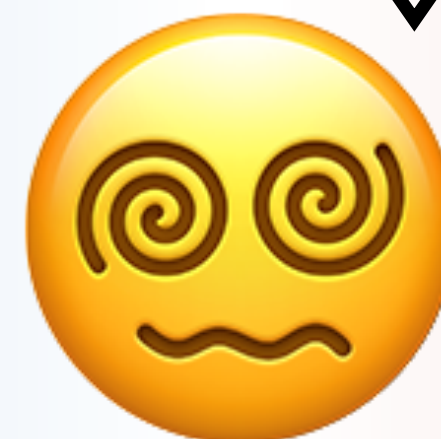
standard model

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

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



what is neutrino mass?
is the neutrino
its own anti particle?



beyond the standard model

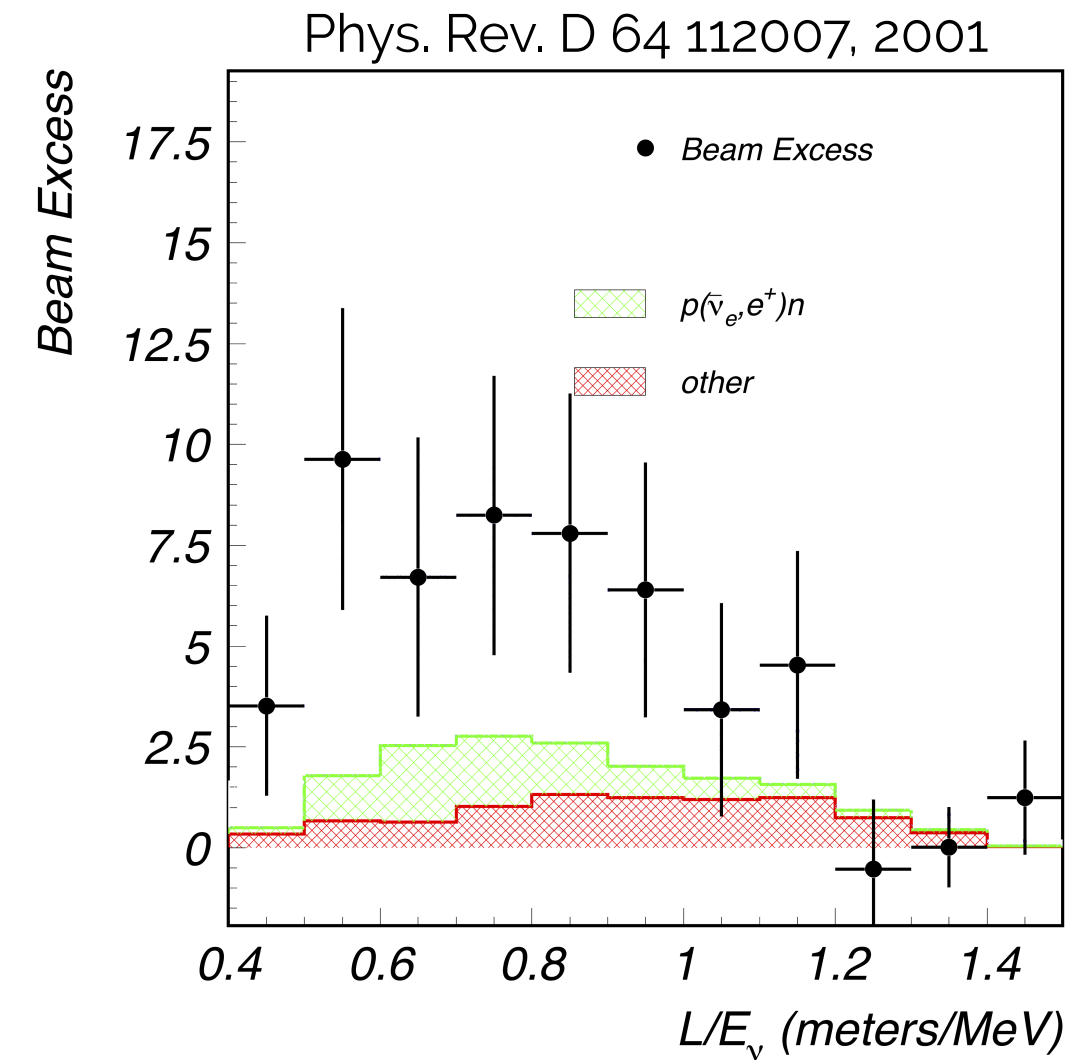
are there **new interactions** we could discover via neutrino?

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

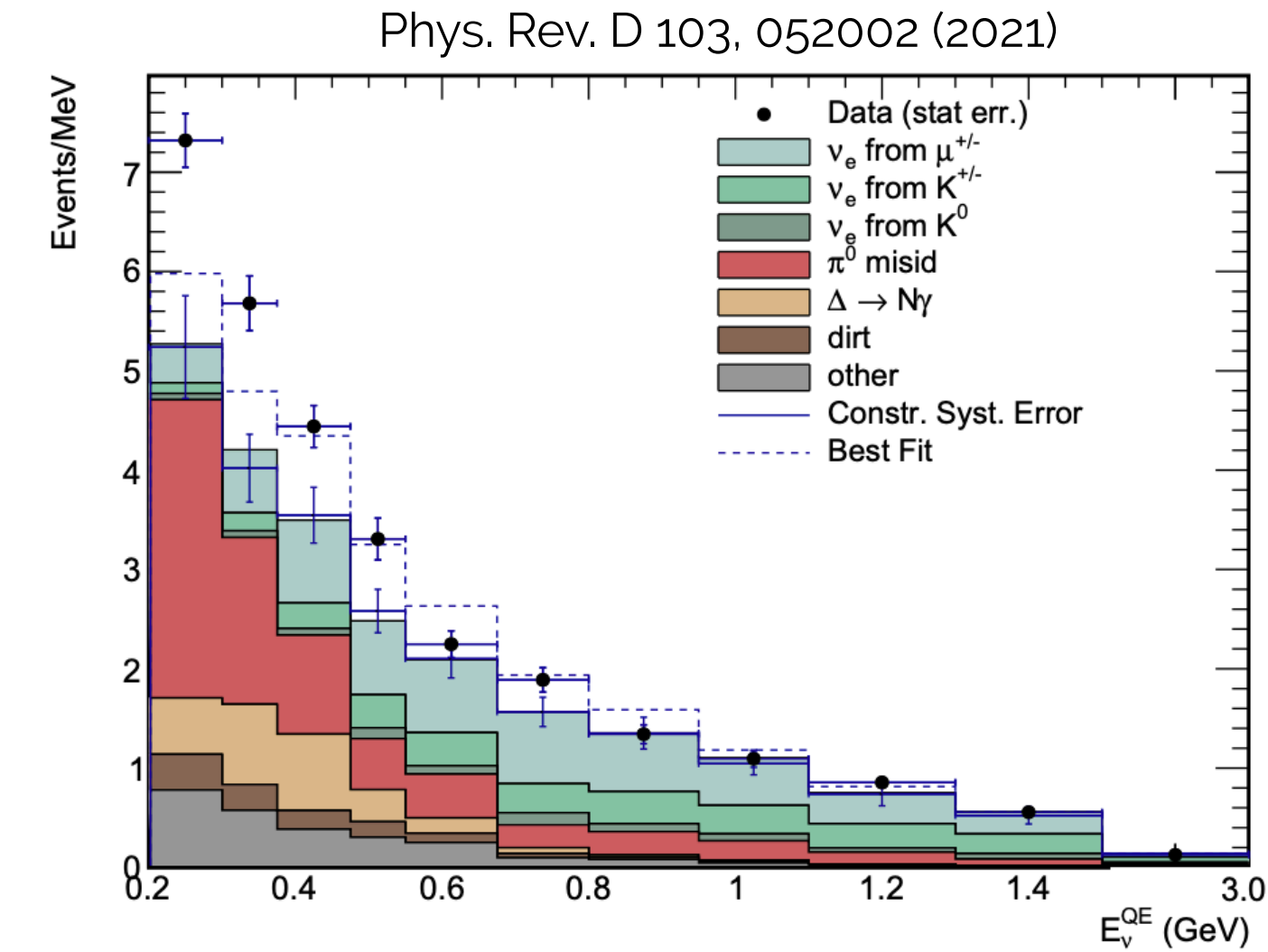


Why do we want to detect neutrinos?

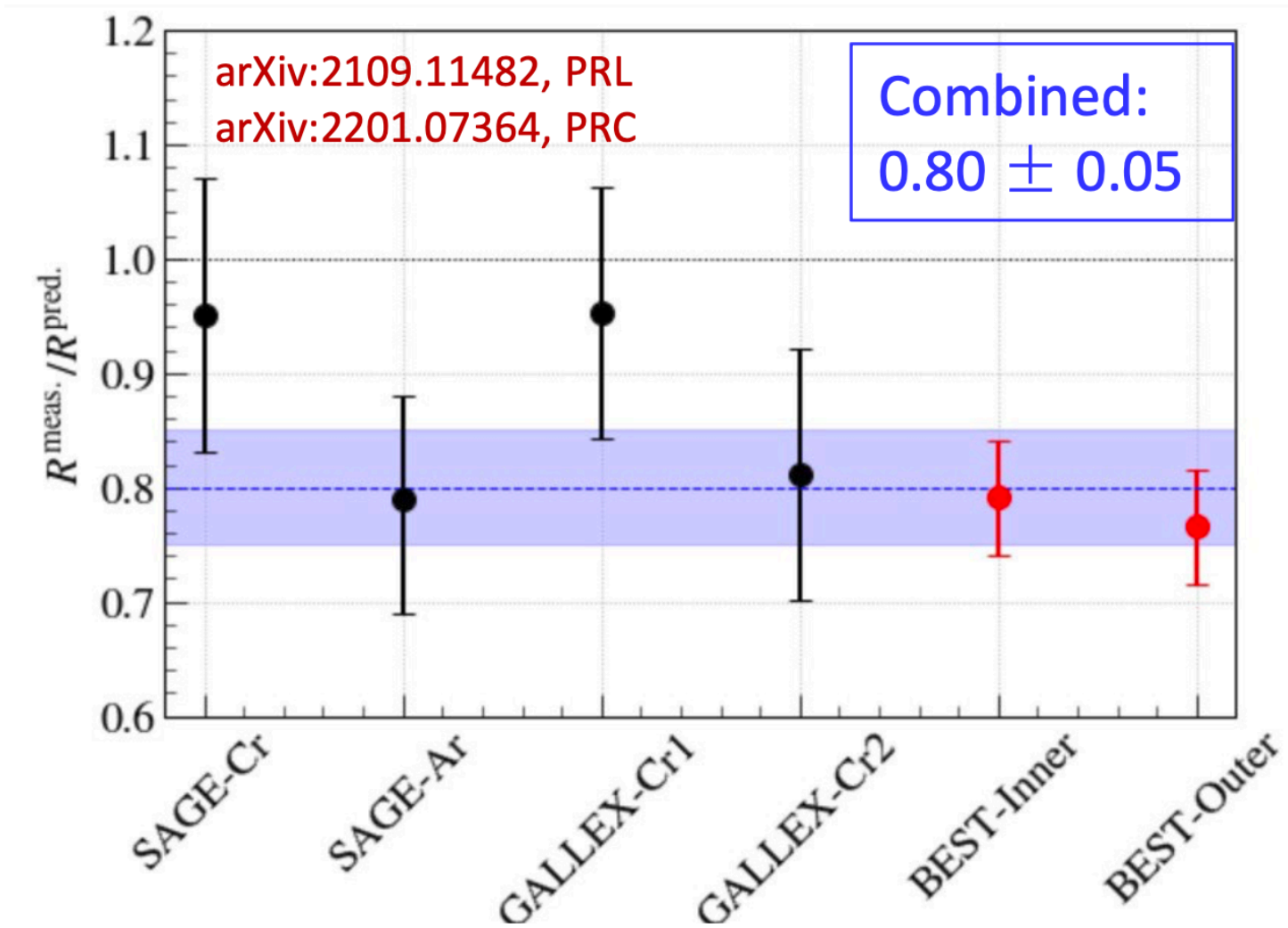
- we are already starting to see few “anomalies” in the neutrino physics
- seeing results where the measurements and our best prediction of neutrinos start to disagree
- remember the Solar neutrino problem?
- will these lead to a discovery of new physics?



LSND anomaly



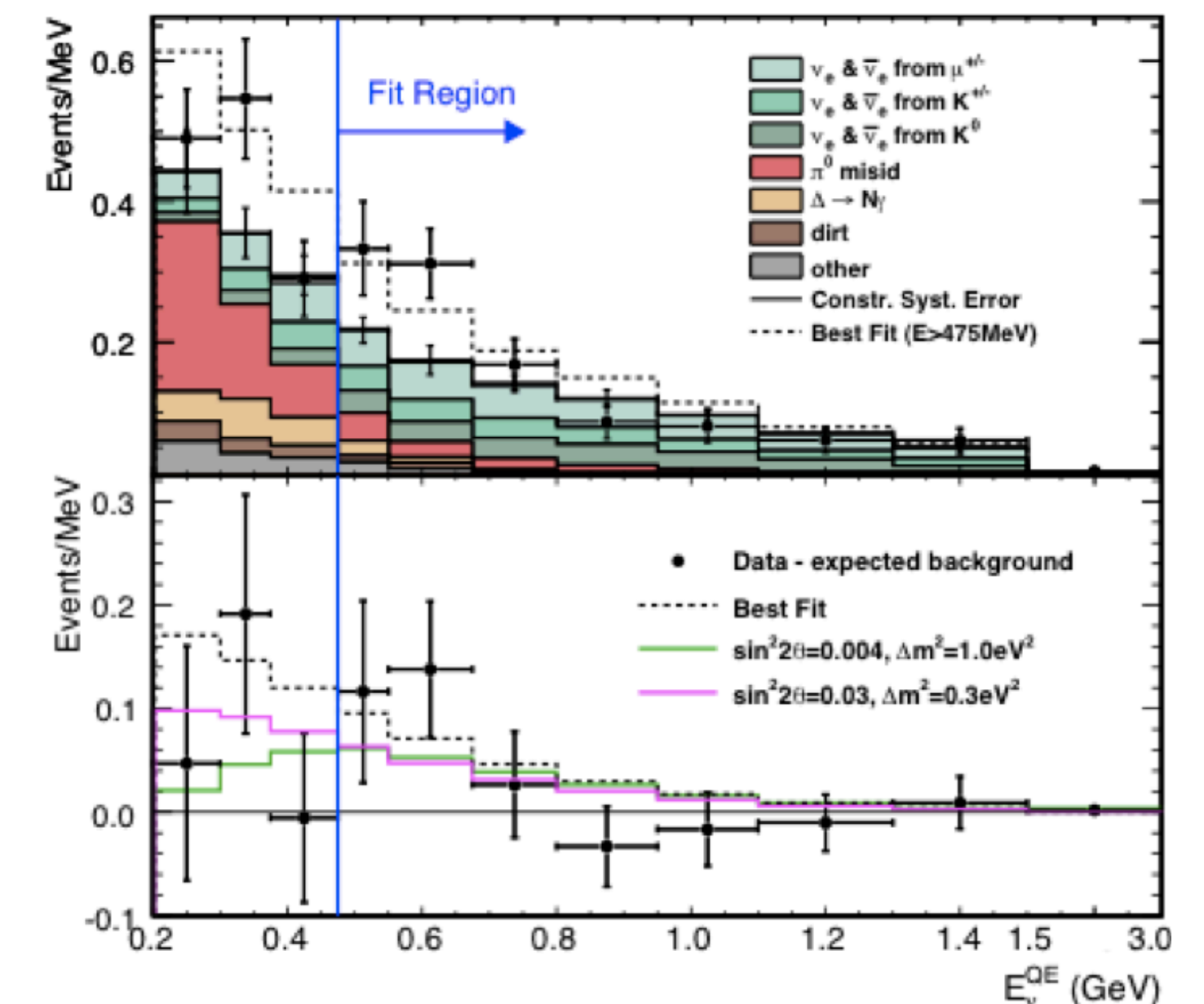
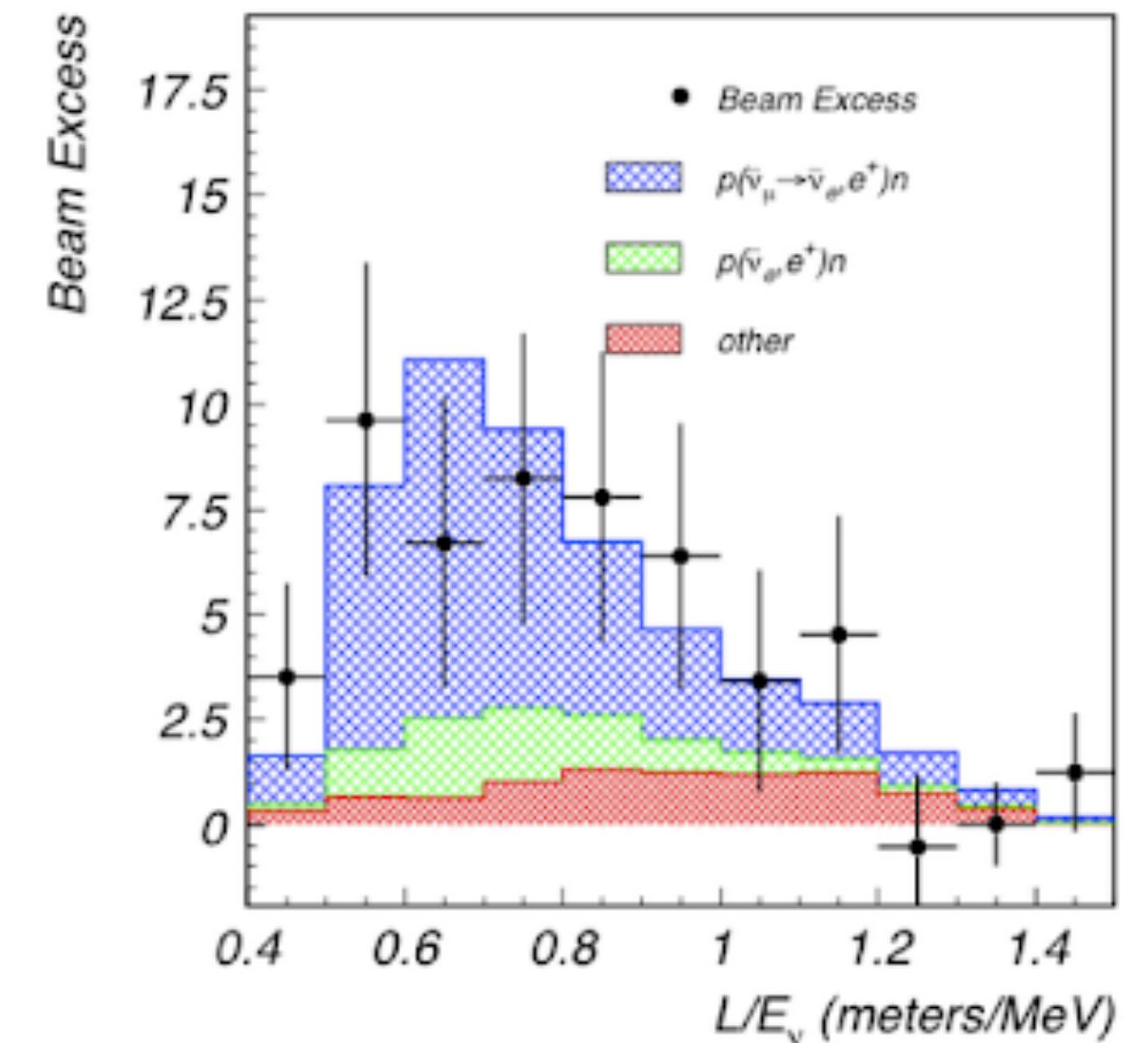
MiniBooNE anomaly



Gallium anomaly

Why do we want to detect neutrinos? Example of “extra” 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*



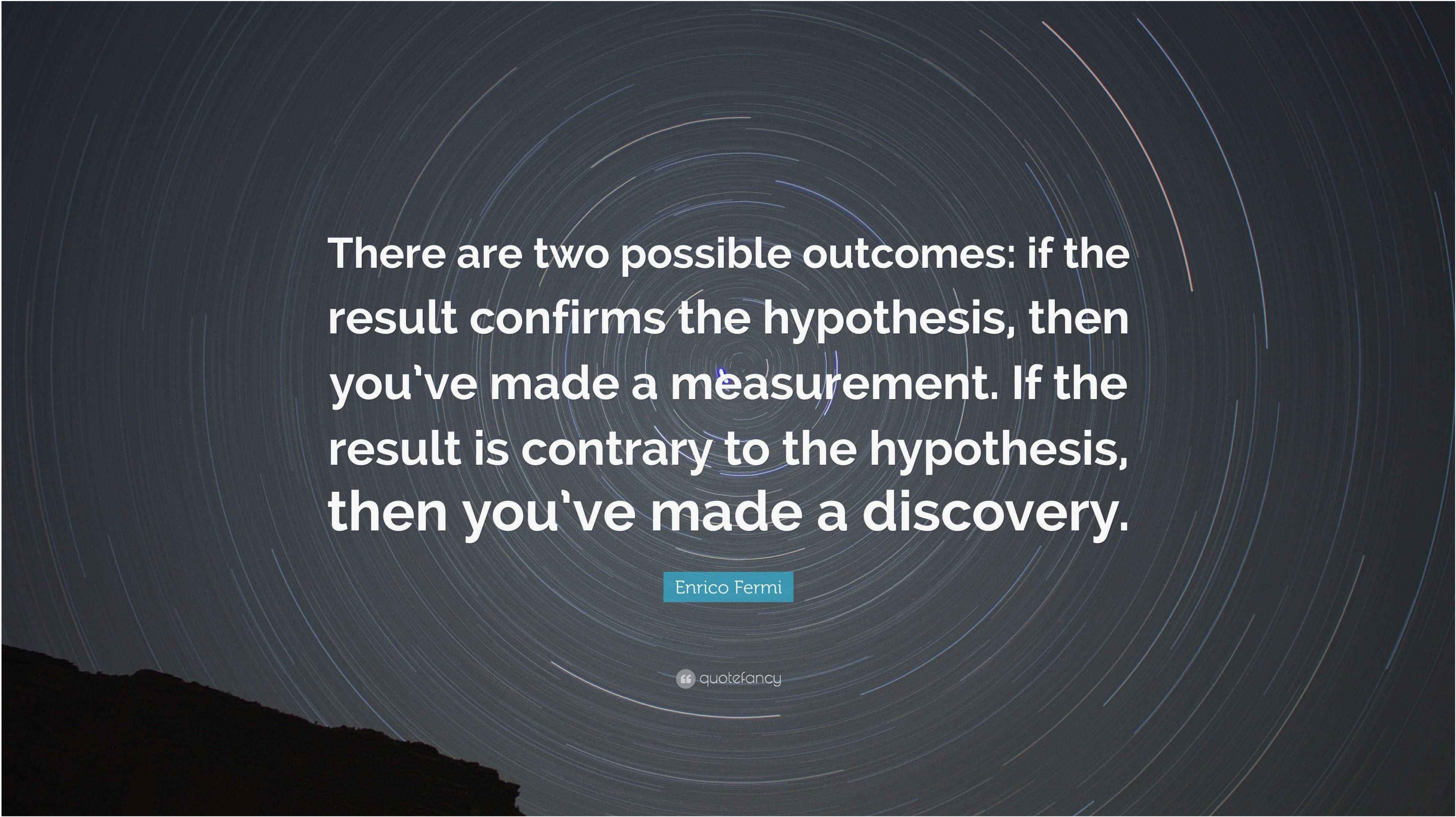
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- *A: unfortunately, it's not so simple... there are severe tension between different measurements & channels*

$$U = \begin{array}{c} \begin{array}{cc} & \begin{array}{cccc} \nu_1 & \nu_2 & \nu_3 & \nu_4 \end{array} \\ \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{array} & \begin{bmatrix} \text{large} & \text{medium} & \text{small} & ? \\ \text{small} & \text{medium} & \text{large} & ? \\ \text{small} & \text{medium} & \text{large} & ? \\ ? & ? & ? & ? \end{bmatrix} \end{array} \end{array}$$

Flavor transitions via this new mixing:

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

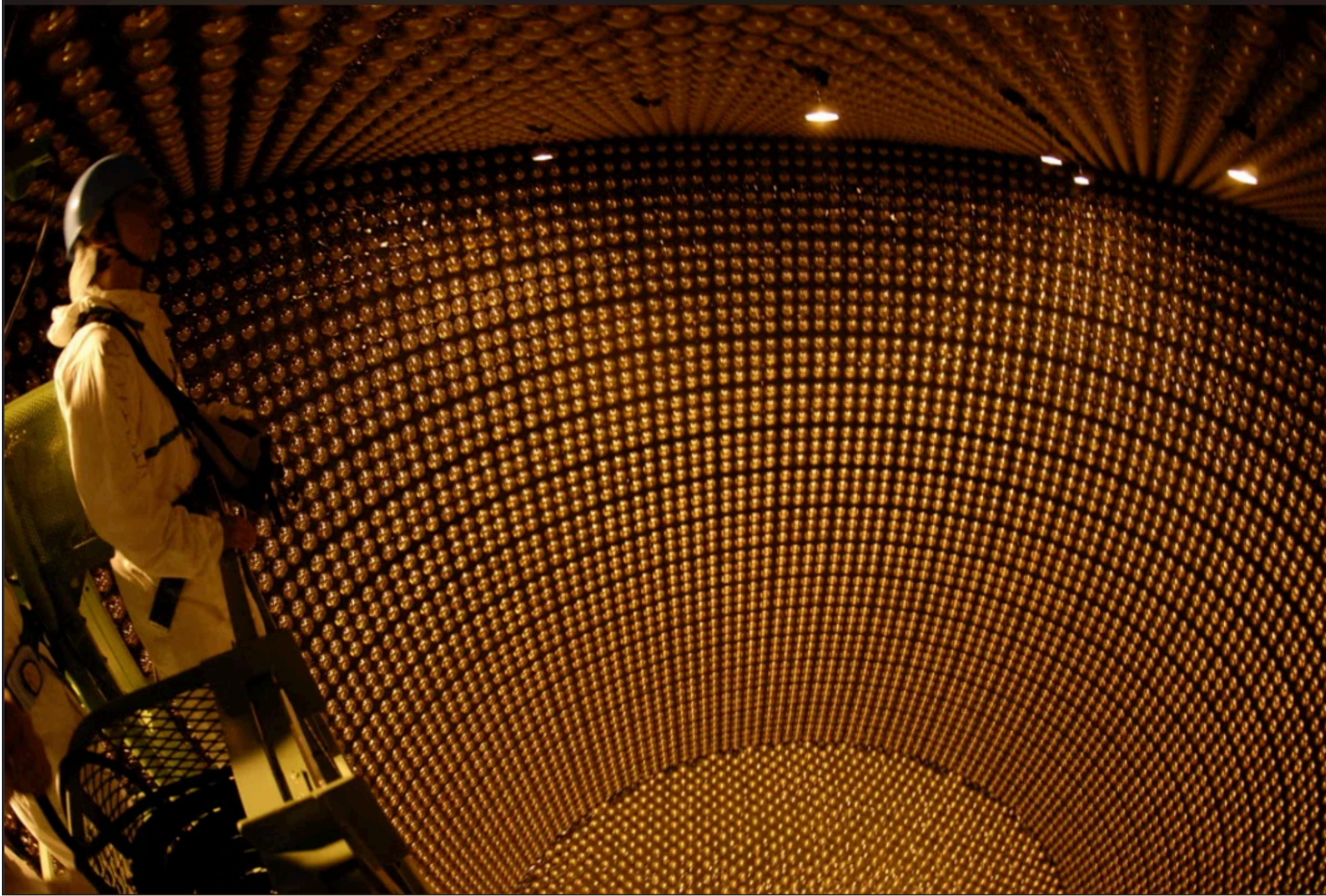
A long-exposure photograph of a starry night sky, showing numerous concentric circular light trails from stars. The trails are primarily blue and white, with a few streaks of orange and red. The bottom left corner shows a dark, silhouetted horizon line.

There are two possible outcomes: if the result confirms the hypothesis, then you've made a measurement. If the result is contrary to the hypothesis, then you've made a discovery.

Enrico Fermi

quotefancy

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

Backup

Properties of neutrinos

- extremely weakly interacting with matter
- can pass through most materials without being detected
- travel close to the speed of light
- important in various astrophysical processes and fundamental to our understanding of universe

The solar neutrino problem: neutrino oscillation

- **flavor mixing**: mismatch between weak/flavor eigenstates and mass eigenstates of fermions, due to coexistence of 2 types of interactions
 - **weak eigenstates**: members of weak isospin doublets transforming into each other through the interaction with the W boson
 - **mass eigenstates**: states of definite masses that are created by the interaction with the Higgs boson (Yukawa coupling)

flavor ($\alpha = e, \mu, \tau$) $\Leftrightarrow$ linear combinations $\Leftrightarrow$ mass ($i = 1, 2, 3$)

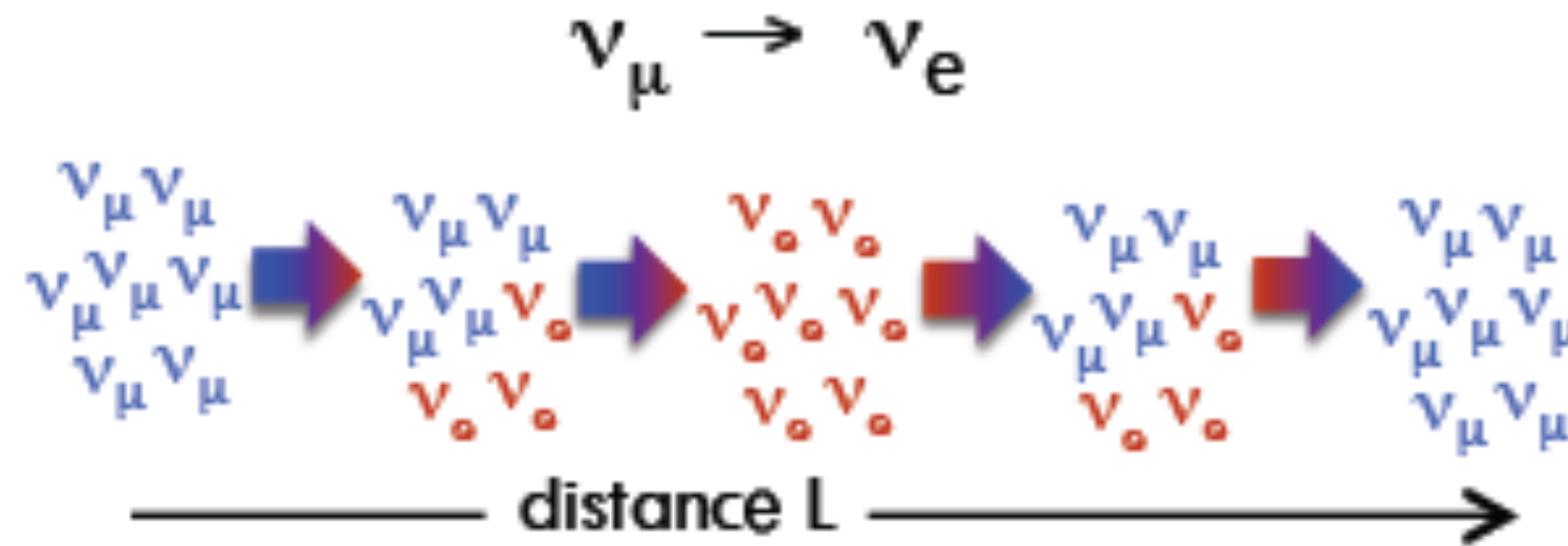
$$\boxed{|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle} \quad \longleftrightarrow \quad \boxed{|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle}$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \underbrace{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix}}_{\text{Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix}} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

Crack in the Standard Model: Massive neutrinos

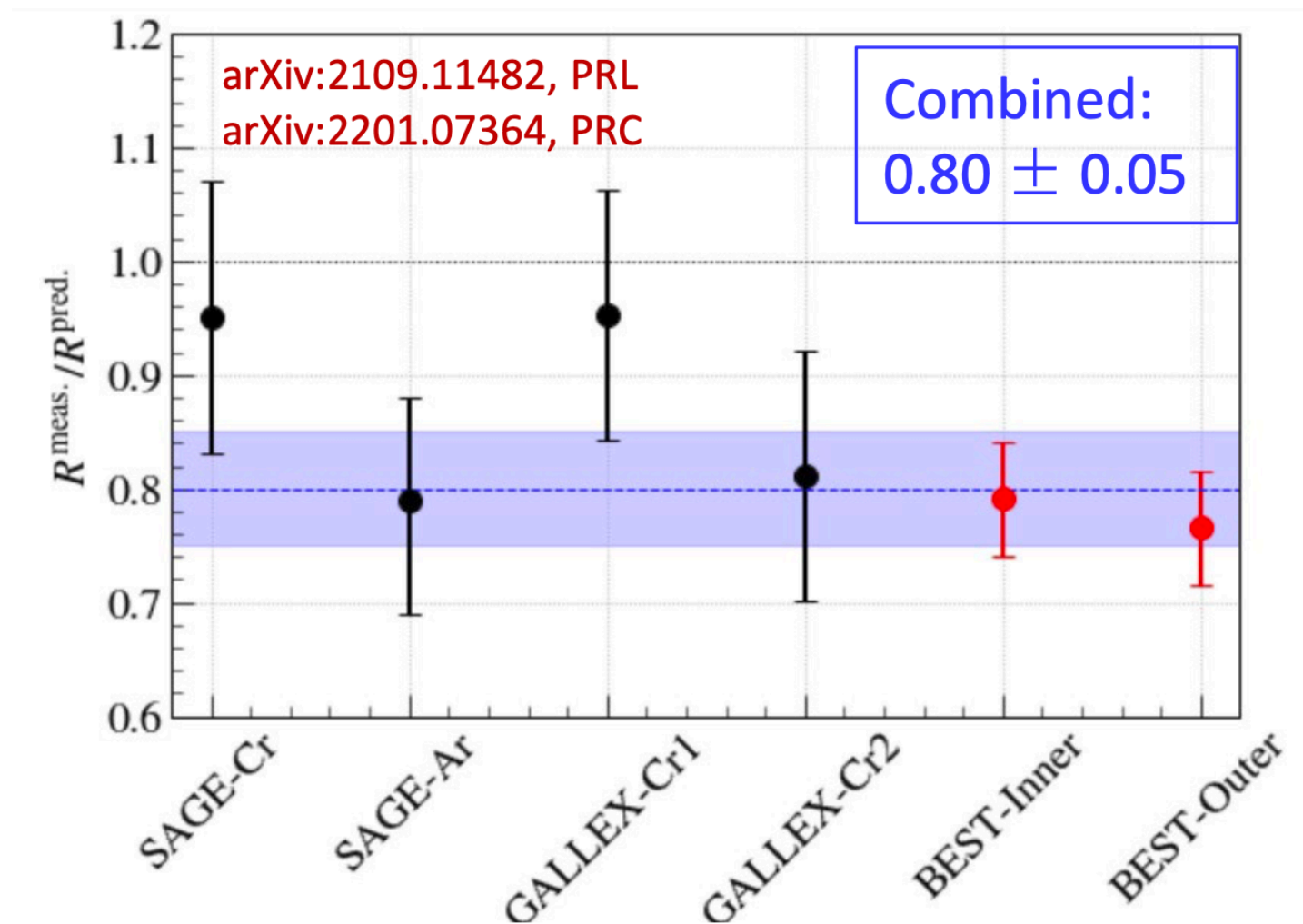
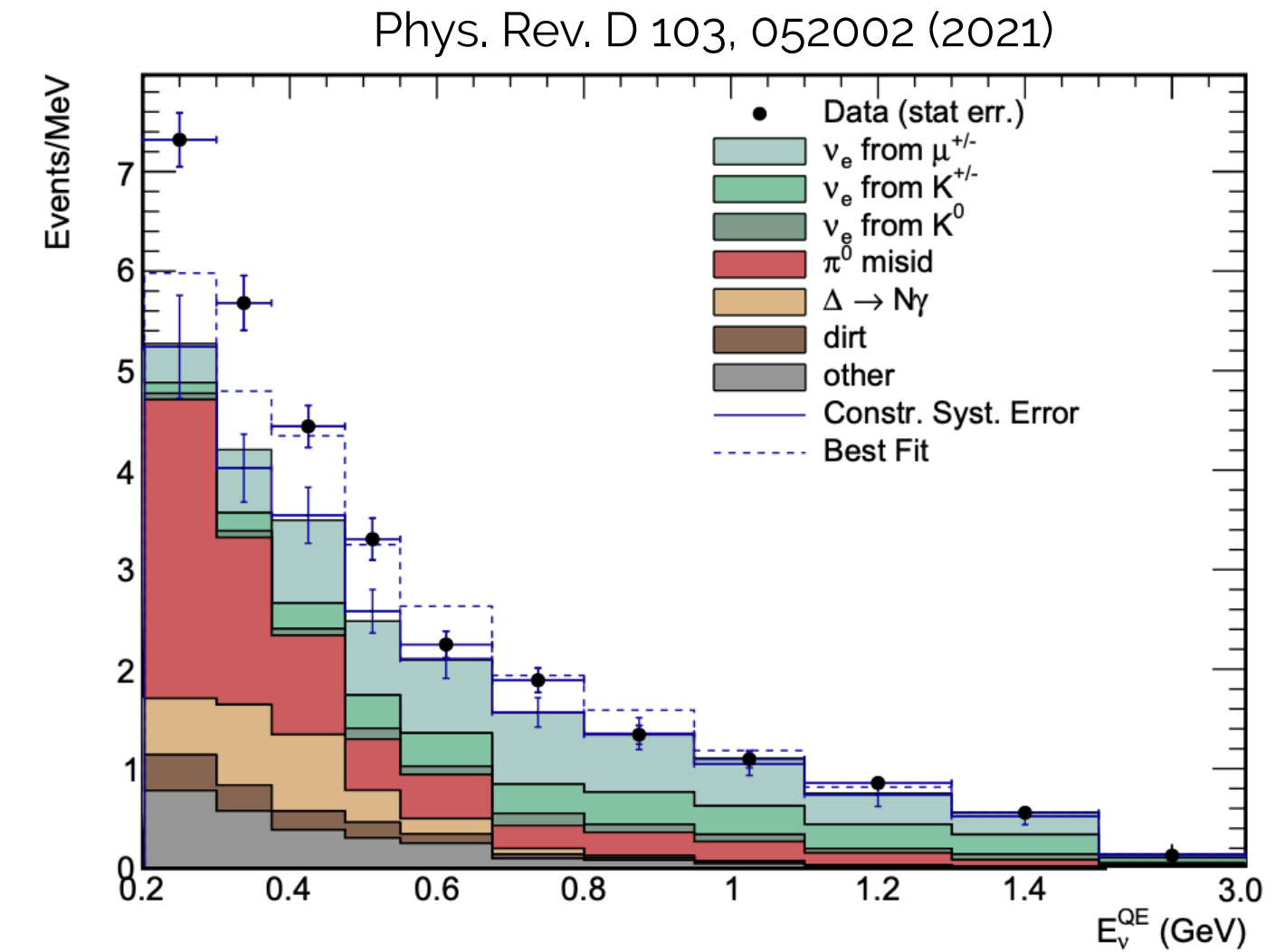
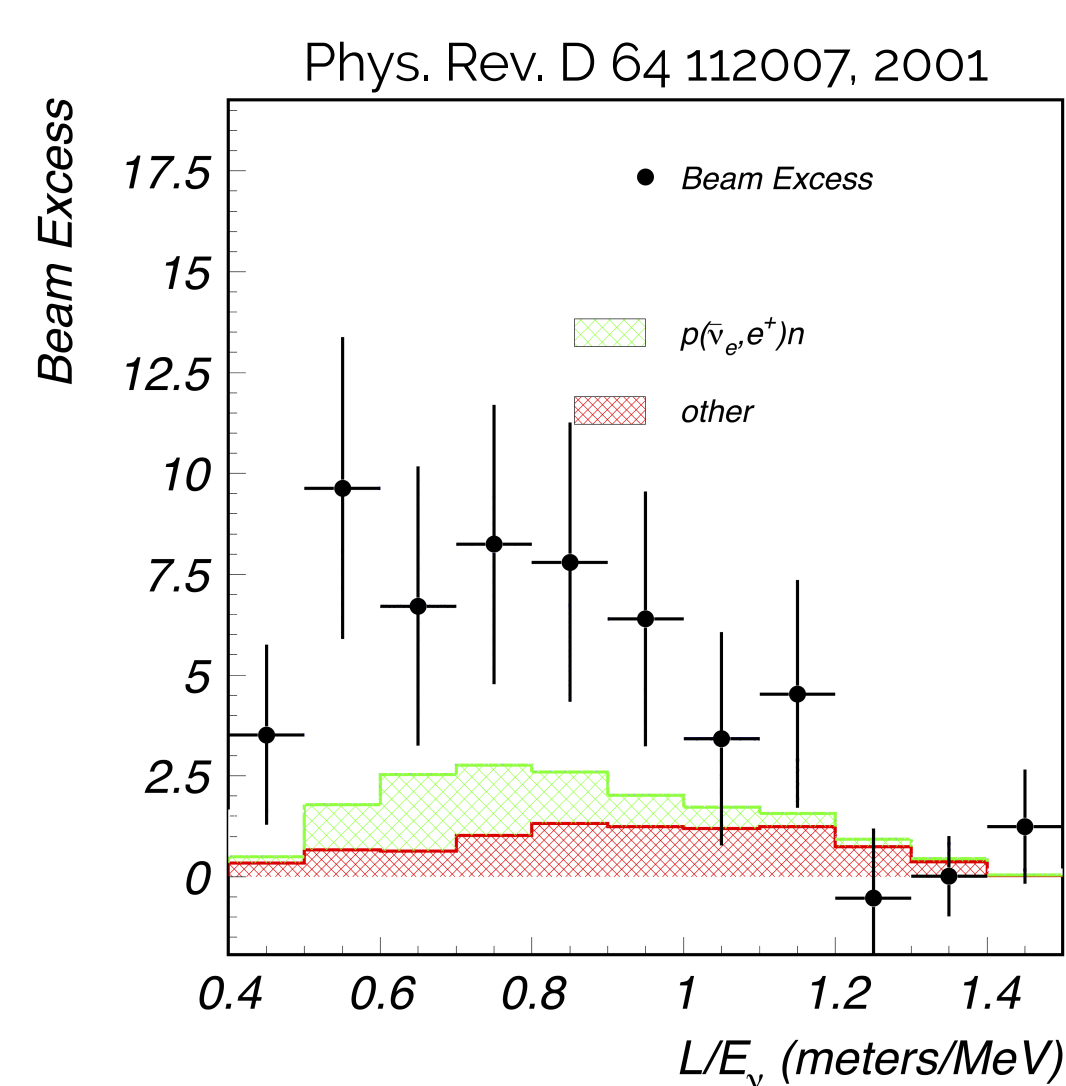
- the Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald “for the discovery of neutrino oscillations, which showed that **neutrinos have mass**”



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

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	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \rightarrow \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 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](https://arxiv.org/abs/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*

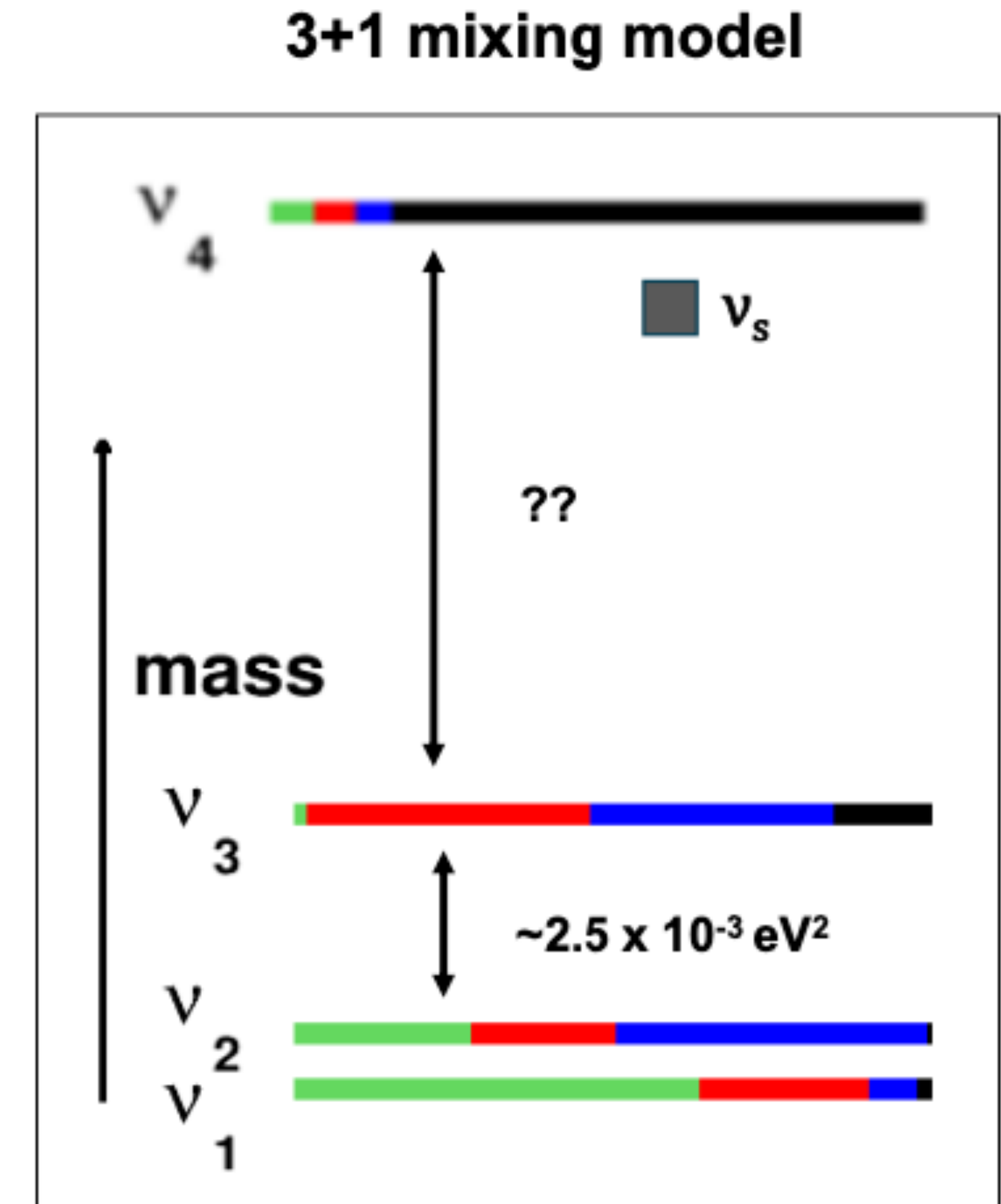
$$U = \begin{array}{c} \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{array} \begin{array}{c} \nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4 \end{array} \begin{bmatrix} \text{large} & \text{medium} & \text{small} & ? \\ \text{small} & \text{medium} & \text{large} & ? \\ \text{small} & \text{medium} & \text{large} & ? \\ ? & ? & ? & ? \end{bmatrix} \end{array}$$

Flavor transitions via this new mixing:

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

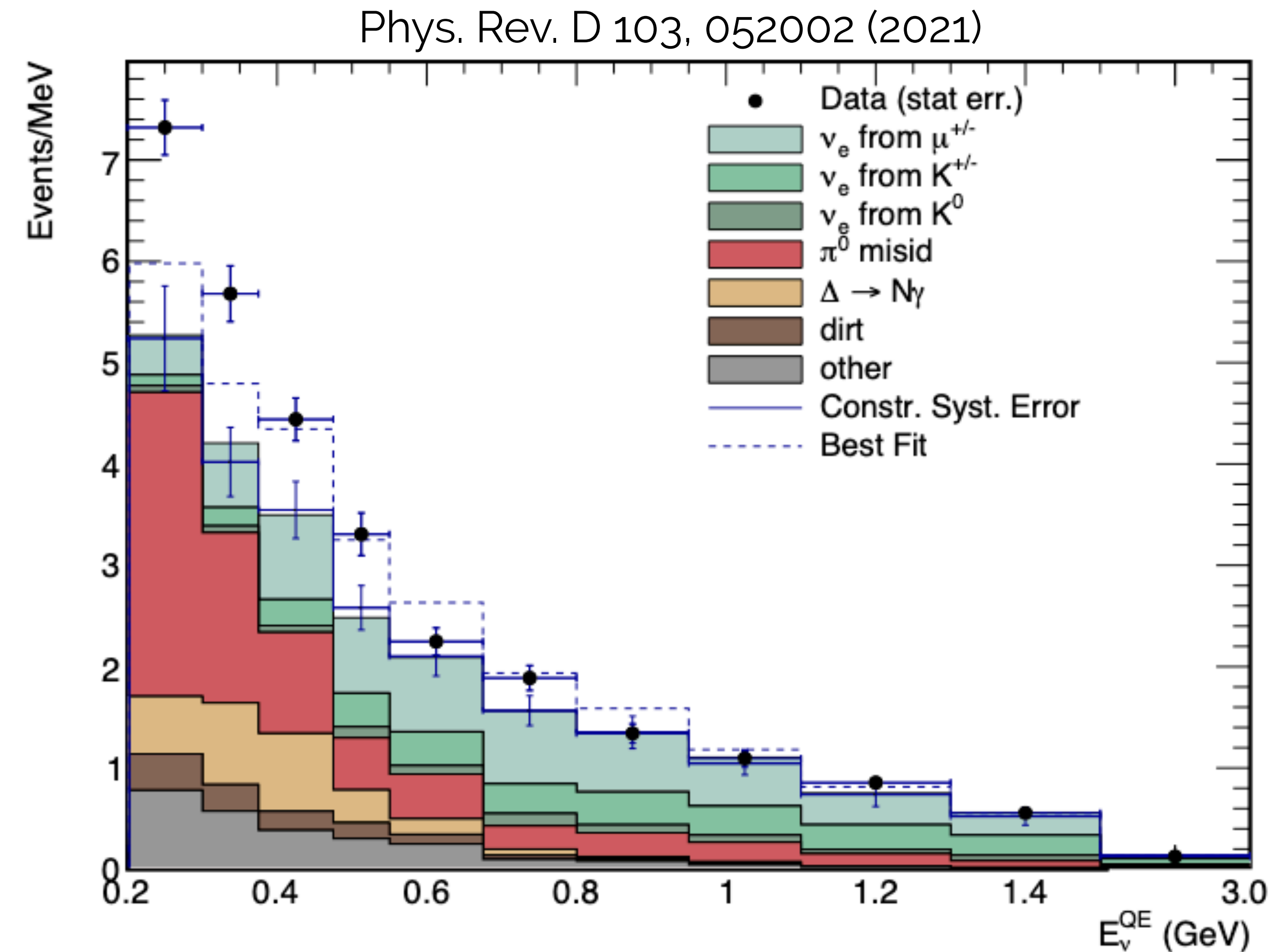
How can we detect sterile neutrino?

- 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: $\nu_e \rightarrow \nu_e$
 - how many ν_e has been oscillated into other (including ν_s) neutrino types?
 - ν_e appearance channel: $\nu_\mu \rightarrow \nu_e$
 - how many ν_e has been oscillated from ν_μ ?



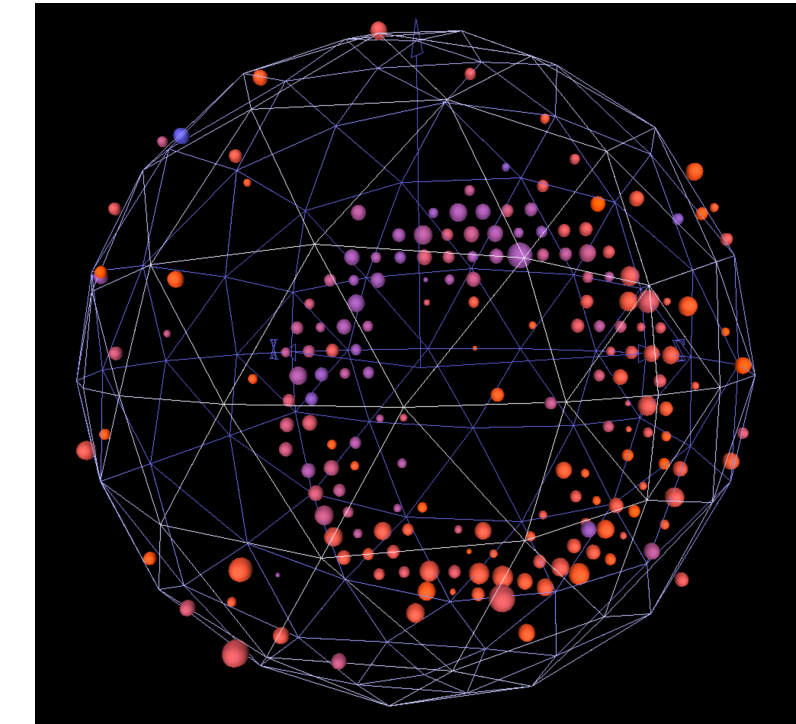
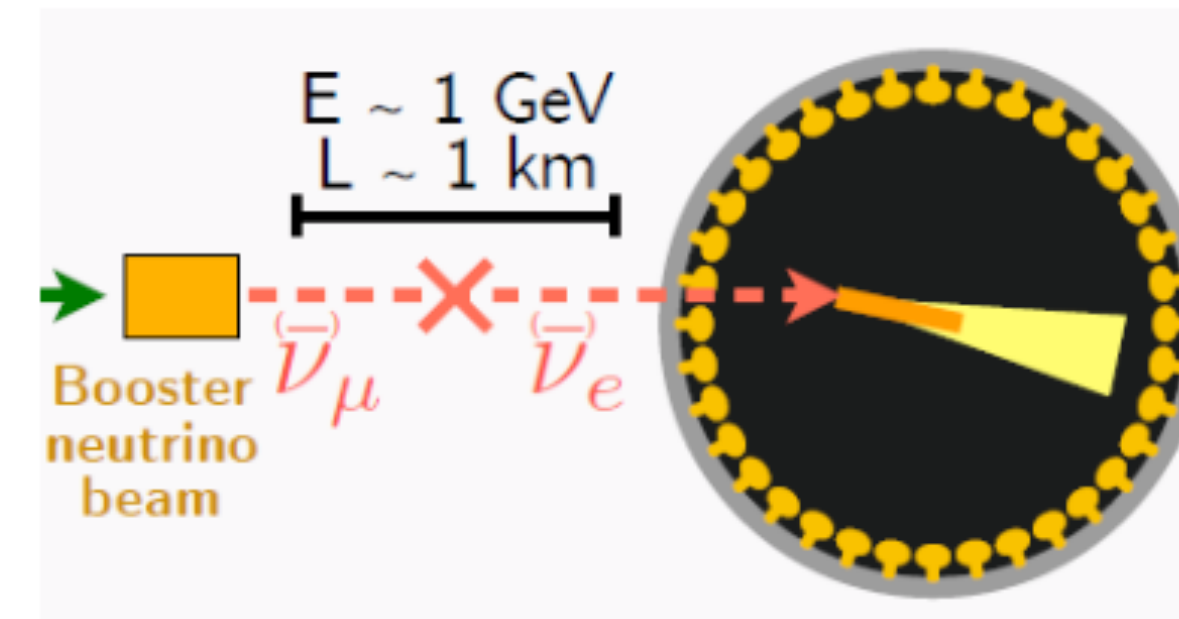
The MiniBooNE Anomaly: Low Energy Excess (LEE)

- 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

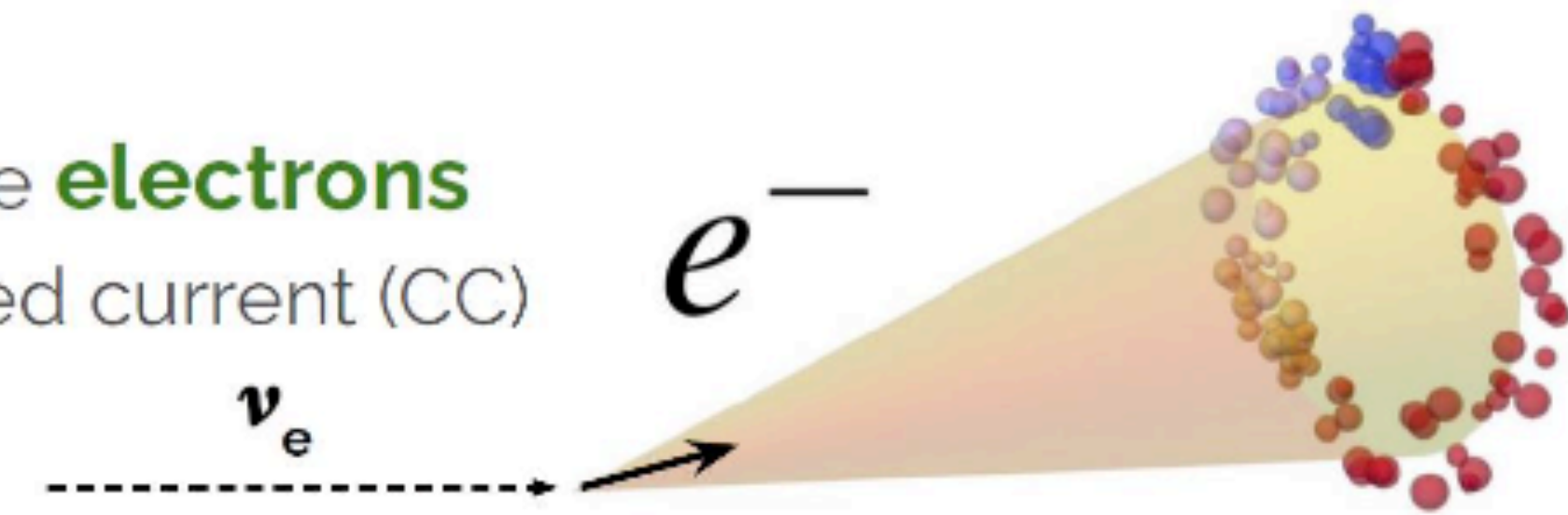


The MiniBooNE Anomaly: Low Energy Excess (LEE)

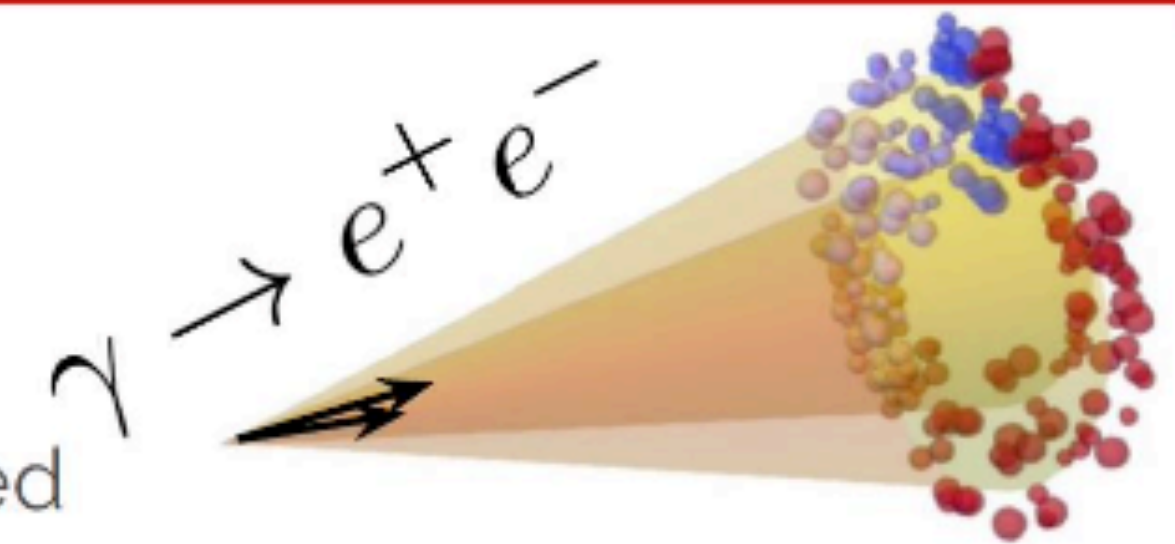
- MiniBooNE is a Cherenkov detector
 - mostly detecting outgoing leptons (electrons, muons, etc)
 - cannot distinguish between electrons and photons
- this limitation makes it hard to interpret the origin of LEE
 - if electrons, this can be explained by sterile neutrino oscillated into electron neutrinos
 - 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 94720

1976

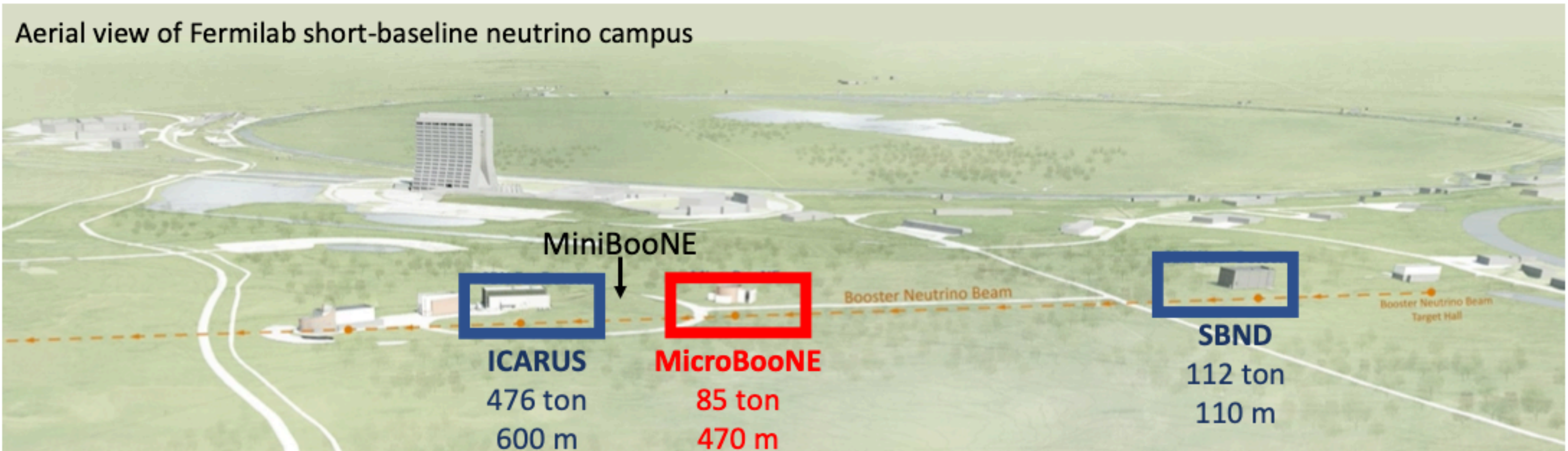
THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

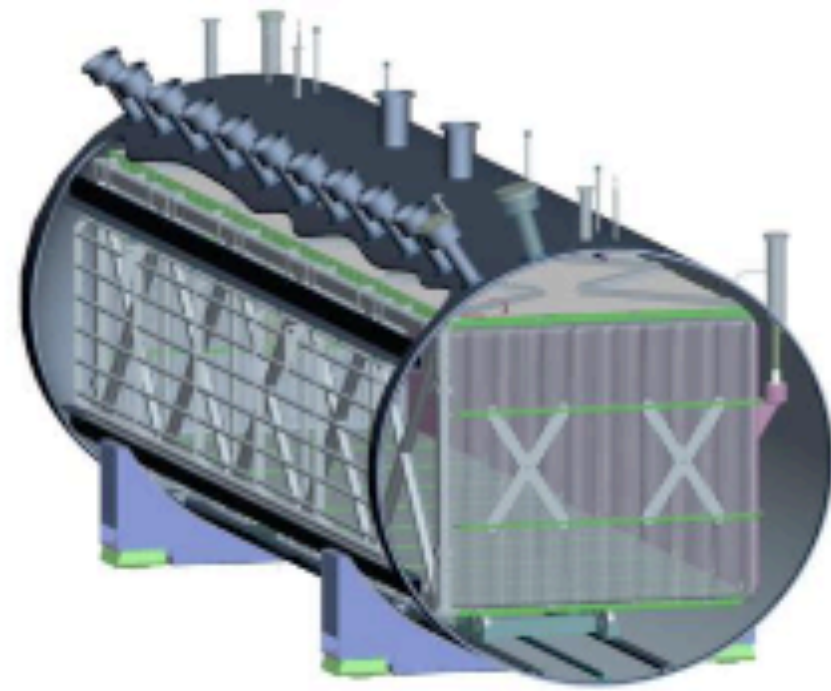
1977

Fermilab SBN program

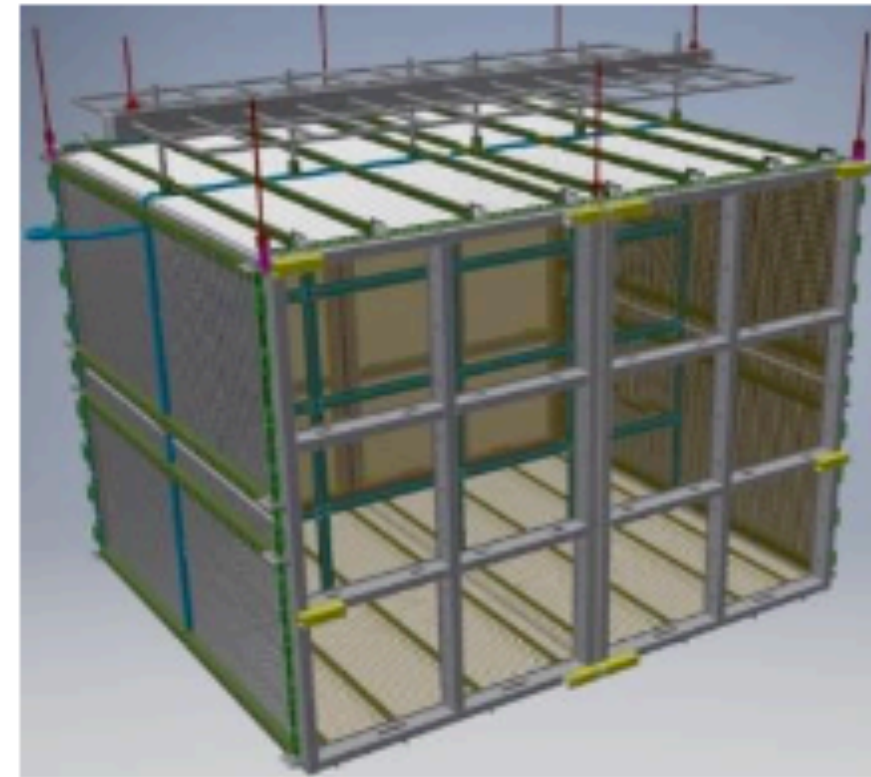


- three LArTPC detectors, with same neutrino beamline and different baseline
- reduce statistical uncertainties with large mass far detector (ICARUS)
- reduce systematic uncertainties with same LArTPC detector technology

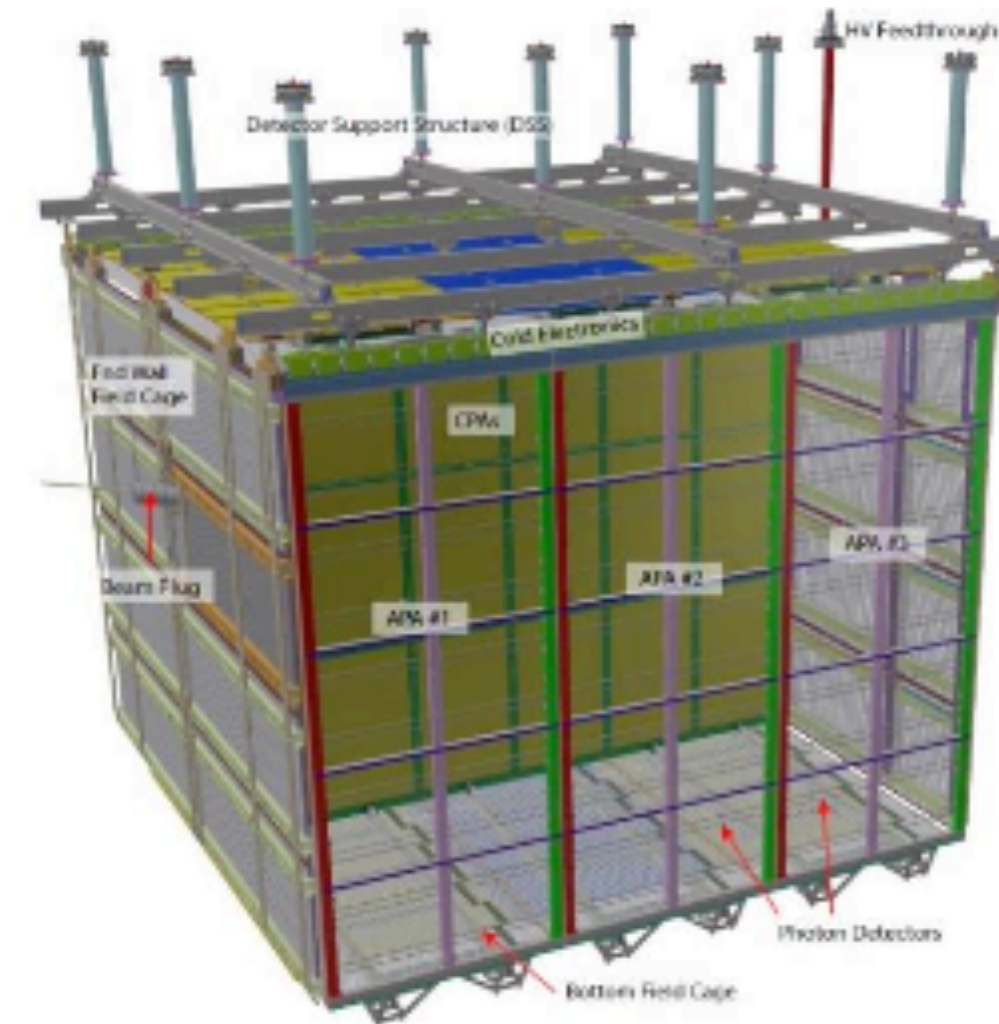
Fermilab SBN program



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



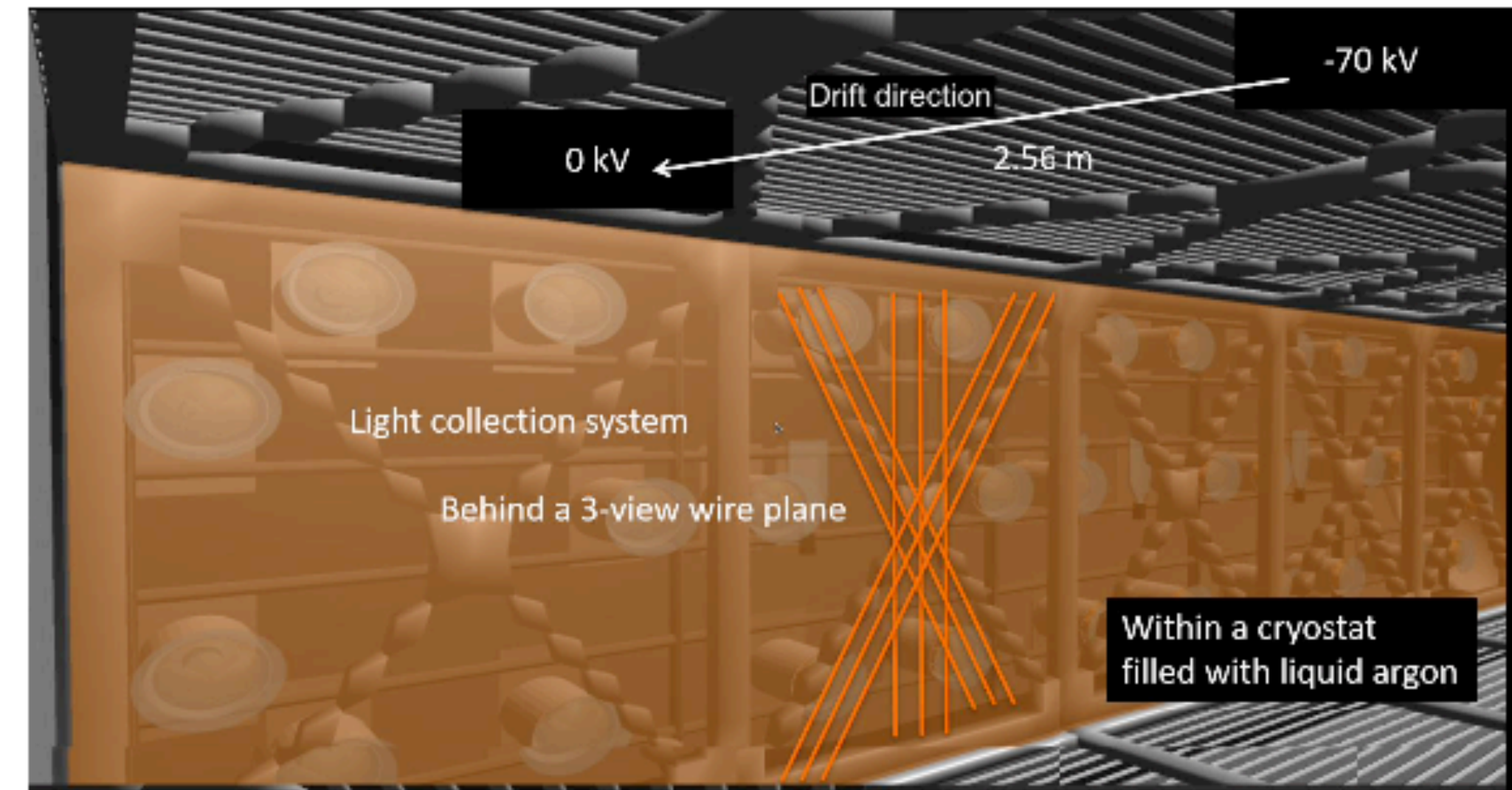
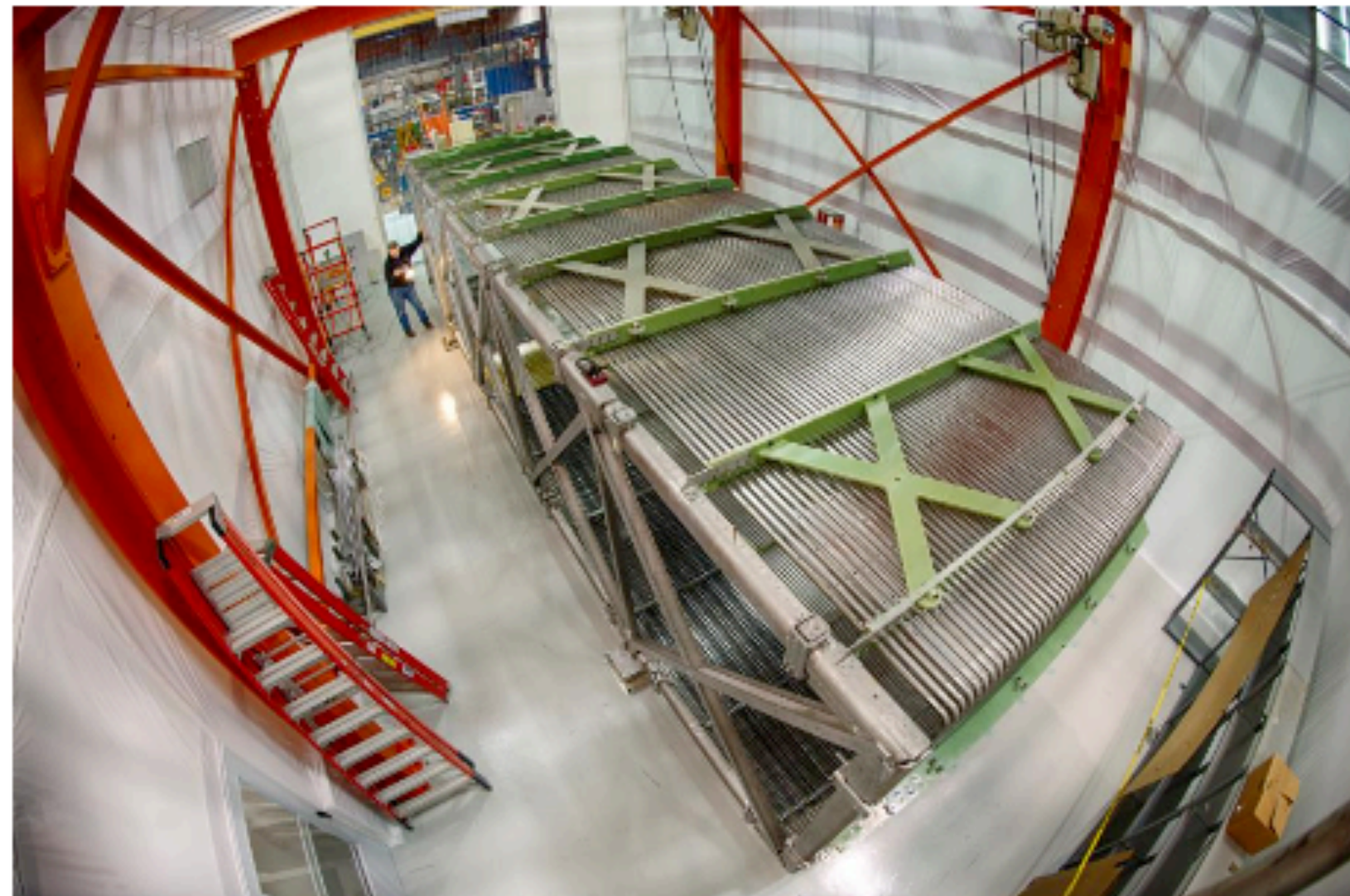
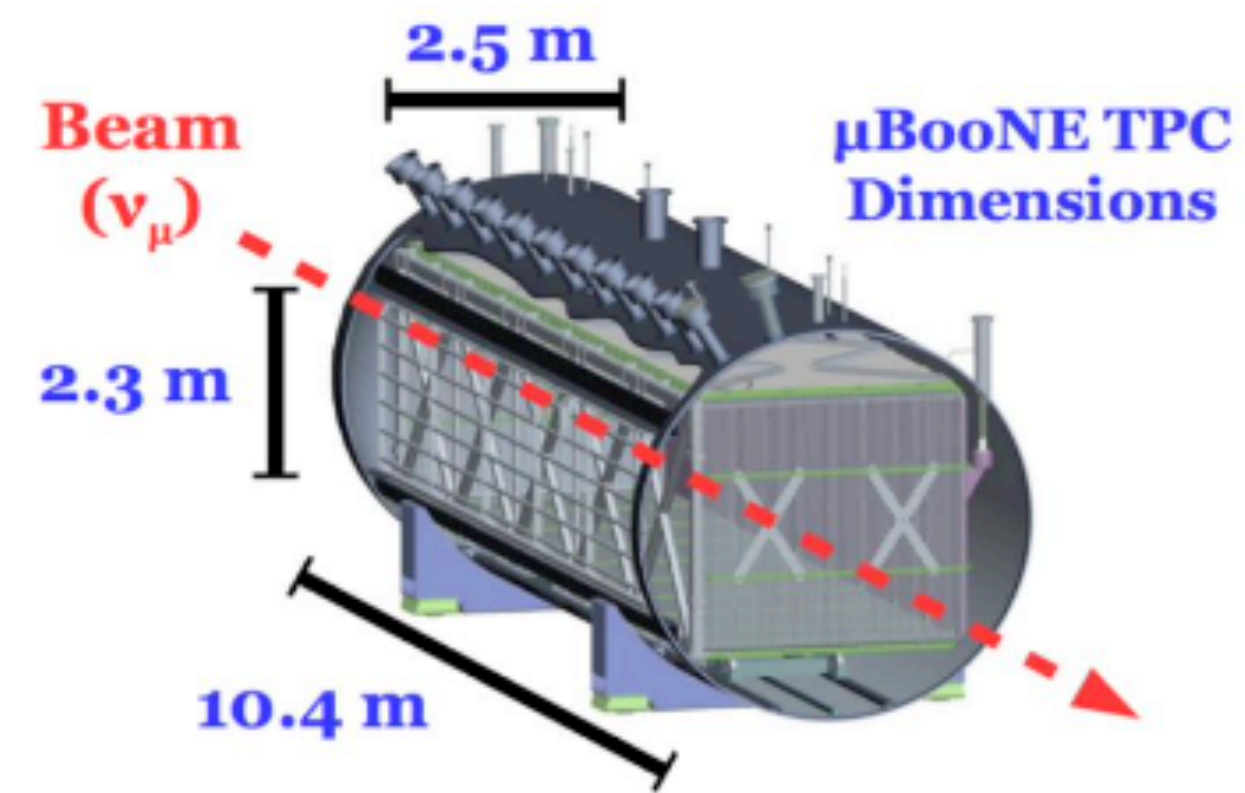
SBND, 112 ton
4m x 4m x 5m



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

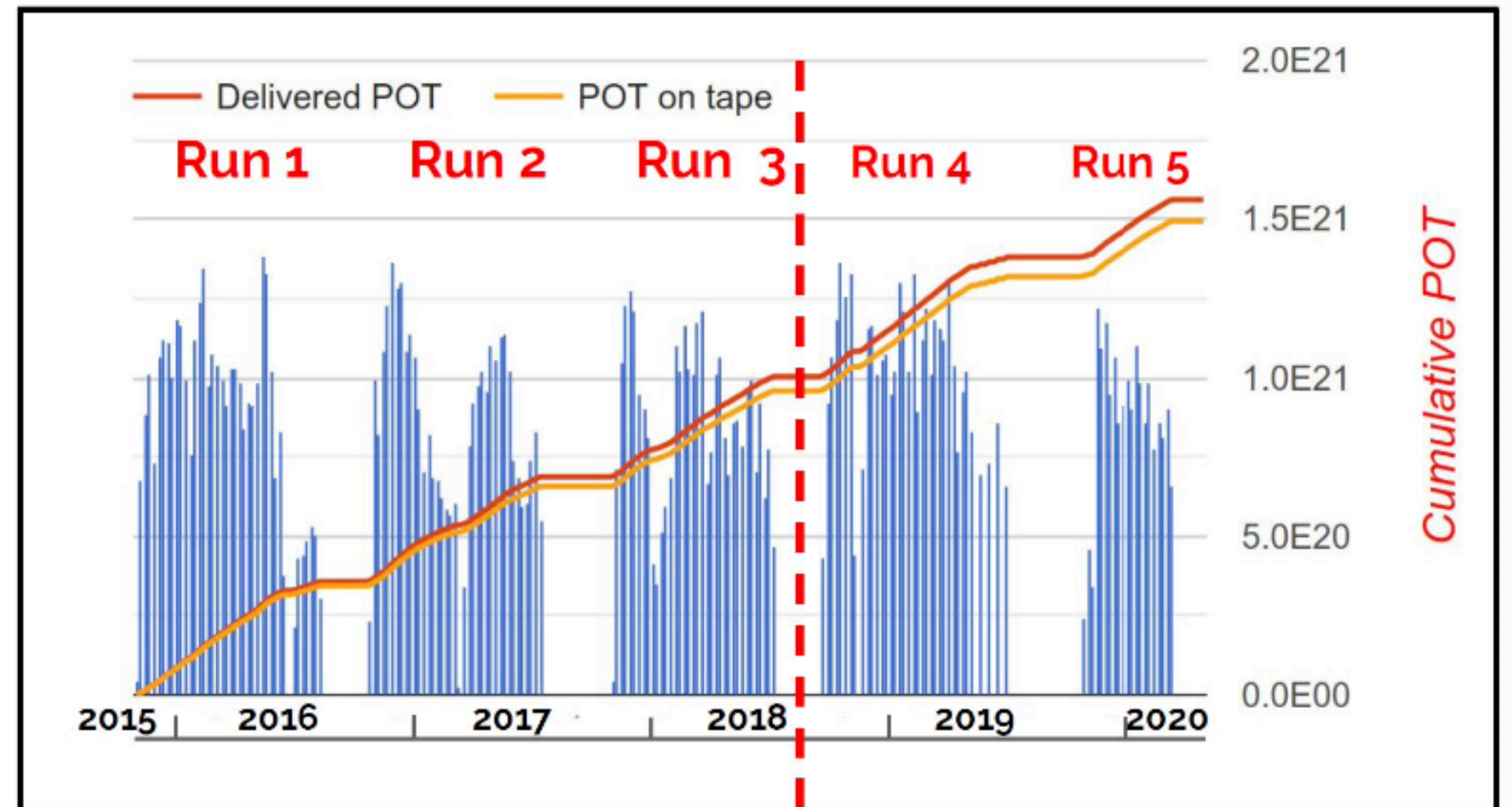
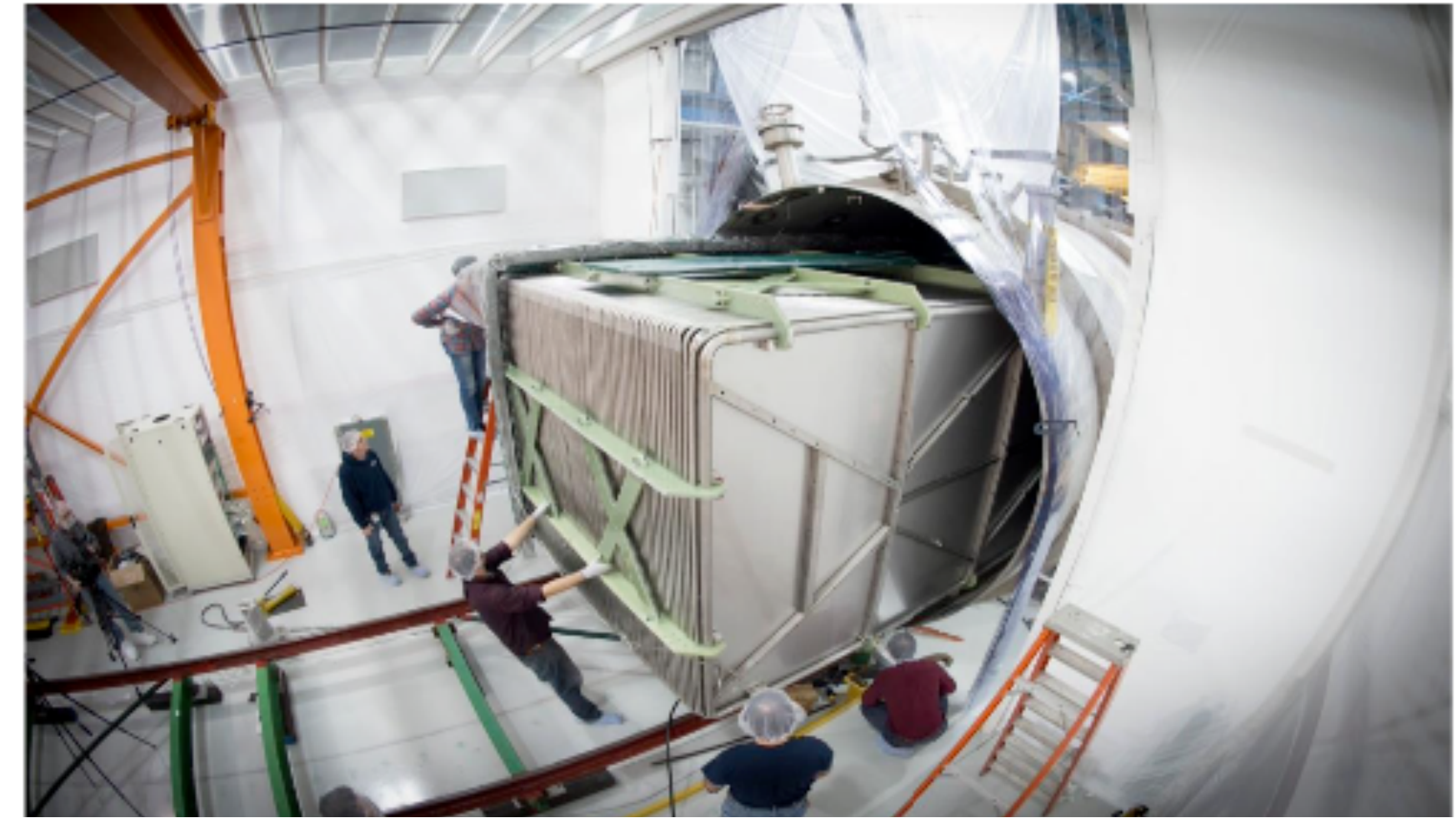
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MicroBooNE



MicroBooNE

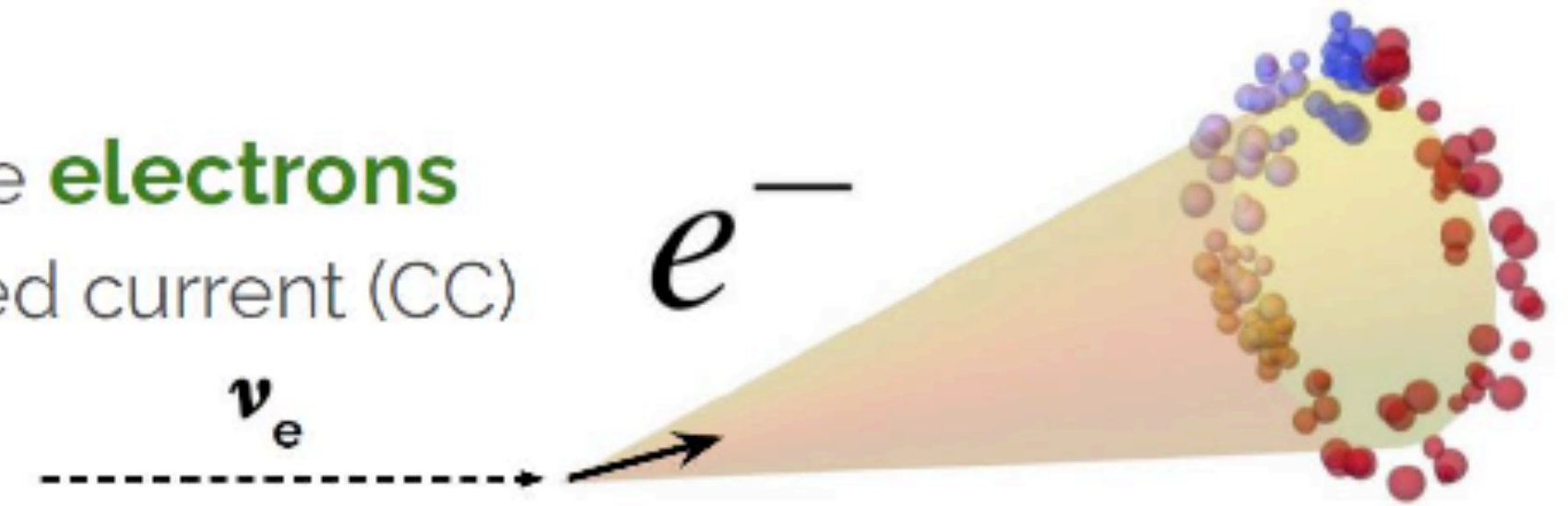
- started taking data since 2015
- finished operation in 2021
- accumulated the world's largest sample of neutrino interaction on argon
- one of the first LArTPC detectors with many new features
 - cold, low noise electronics
(see Shanshan's talk at 3pm)
 - excellent LAr purity
 - pioneered LArTPC detector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



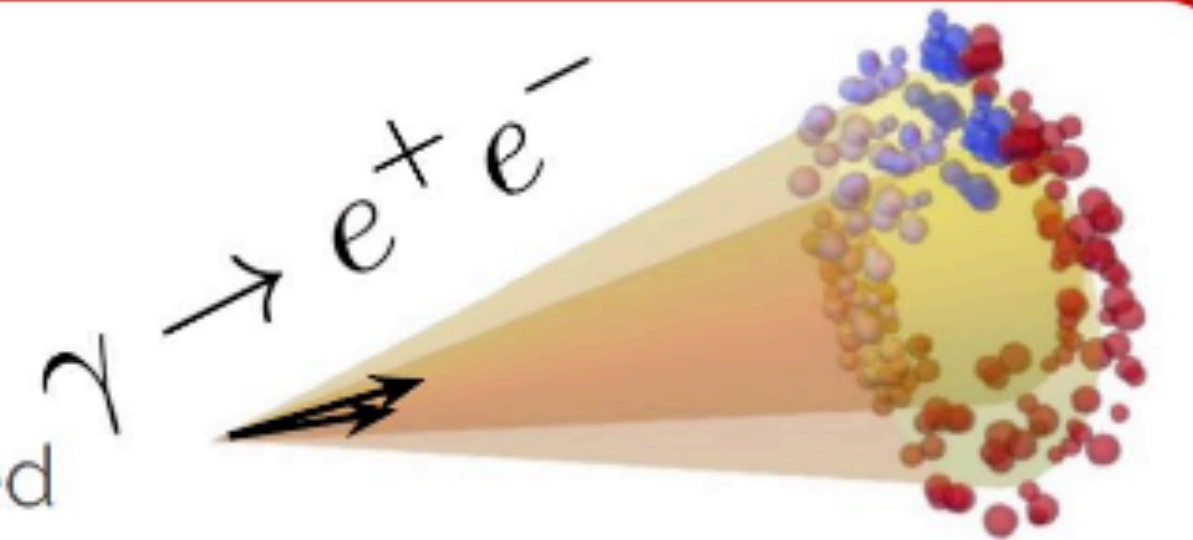
The MiniBooNE Anomaly: recap

- 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

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

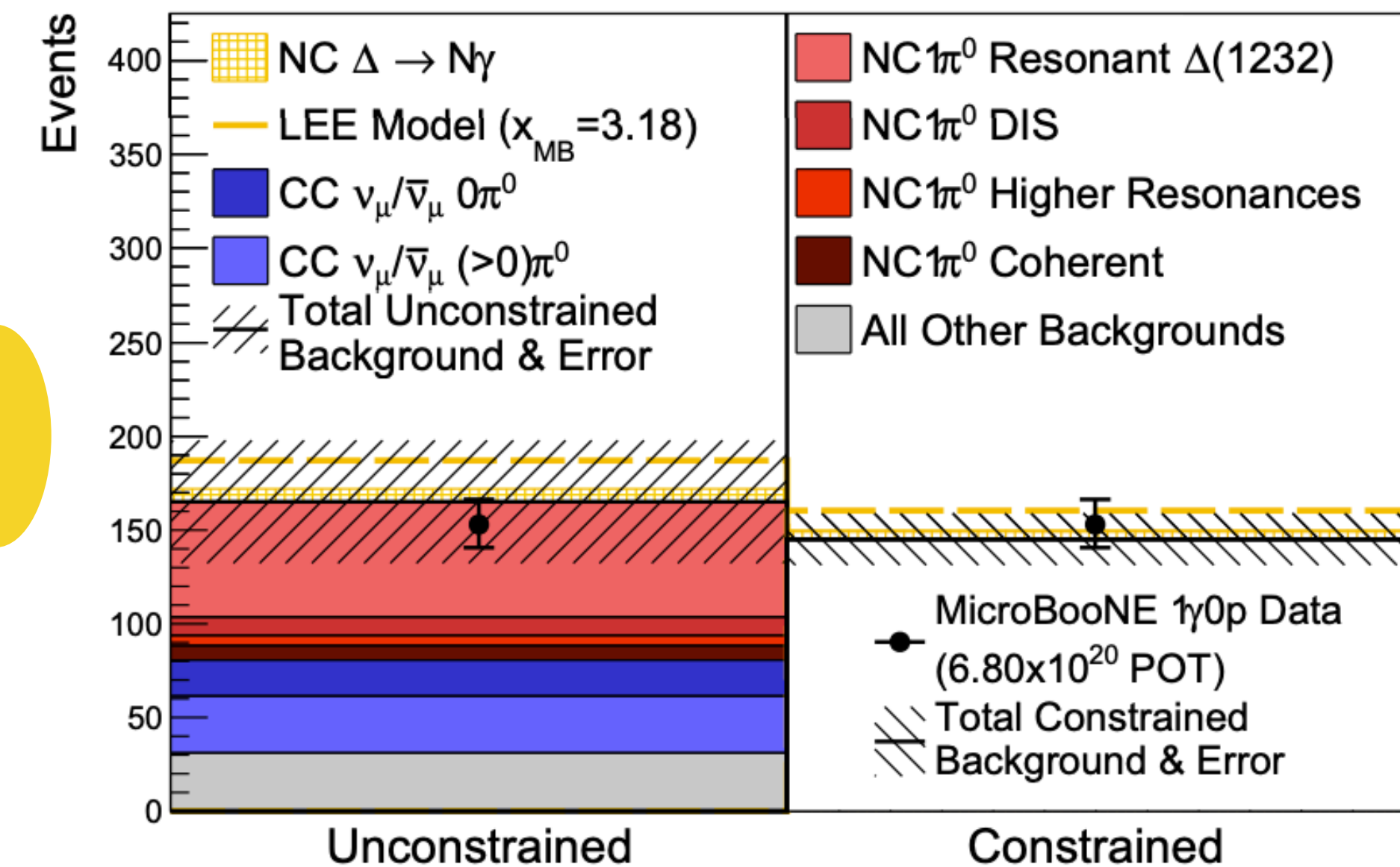
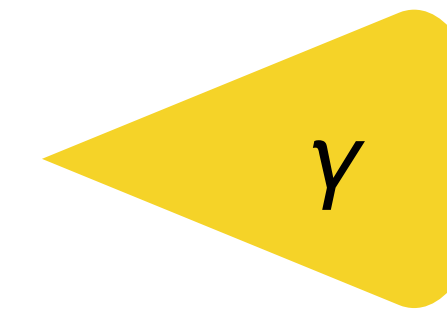
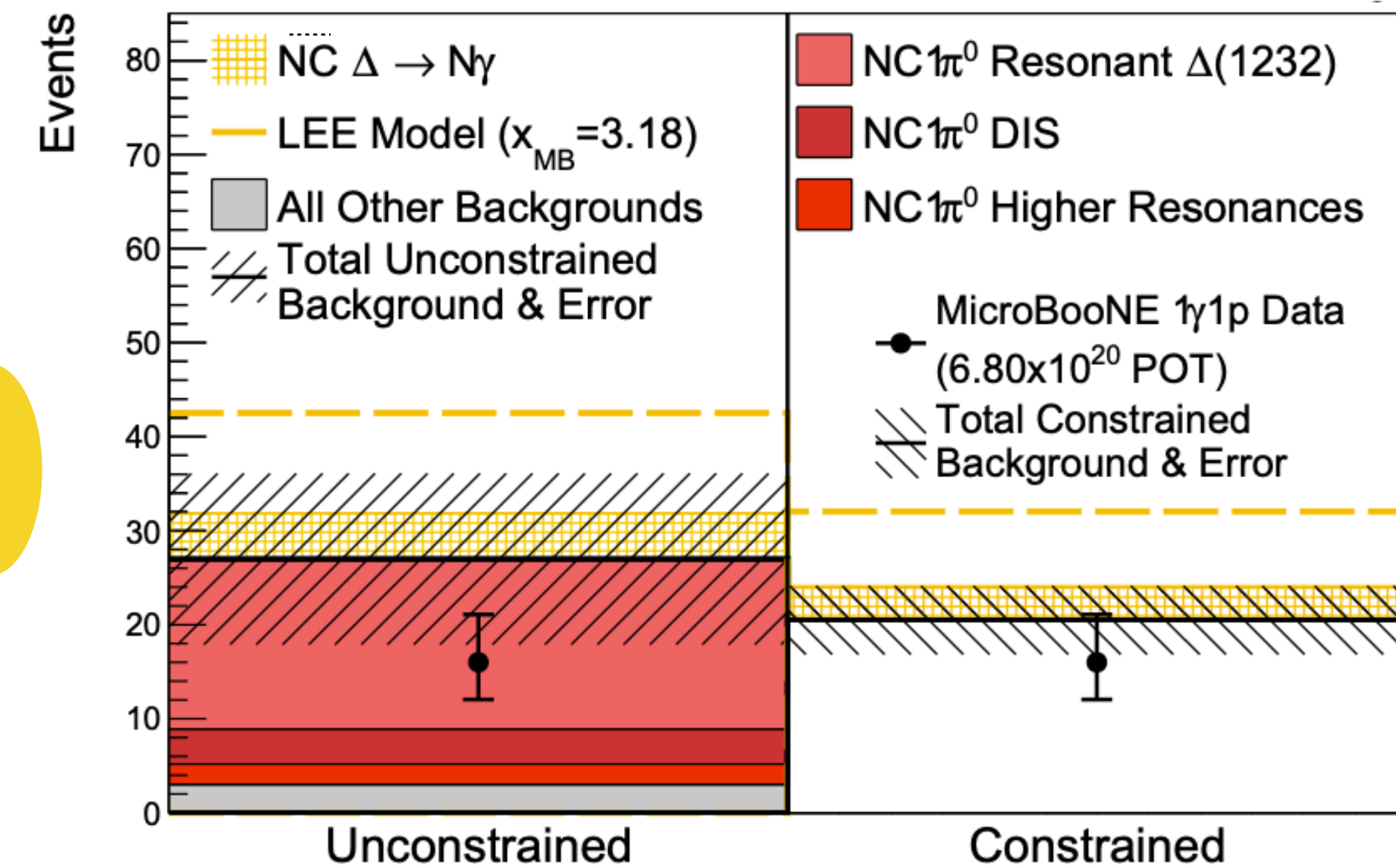
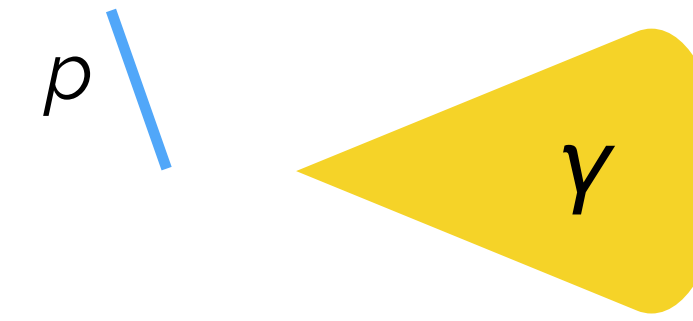


However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring



MicroBooNE LEE result

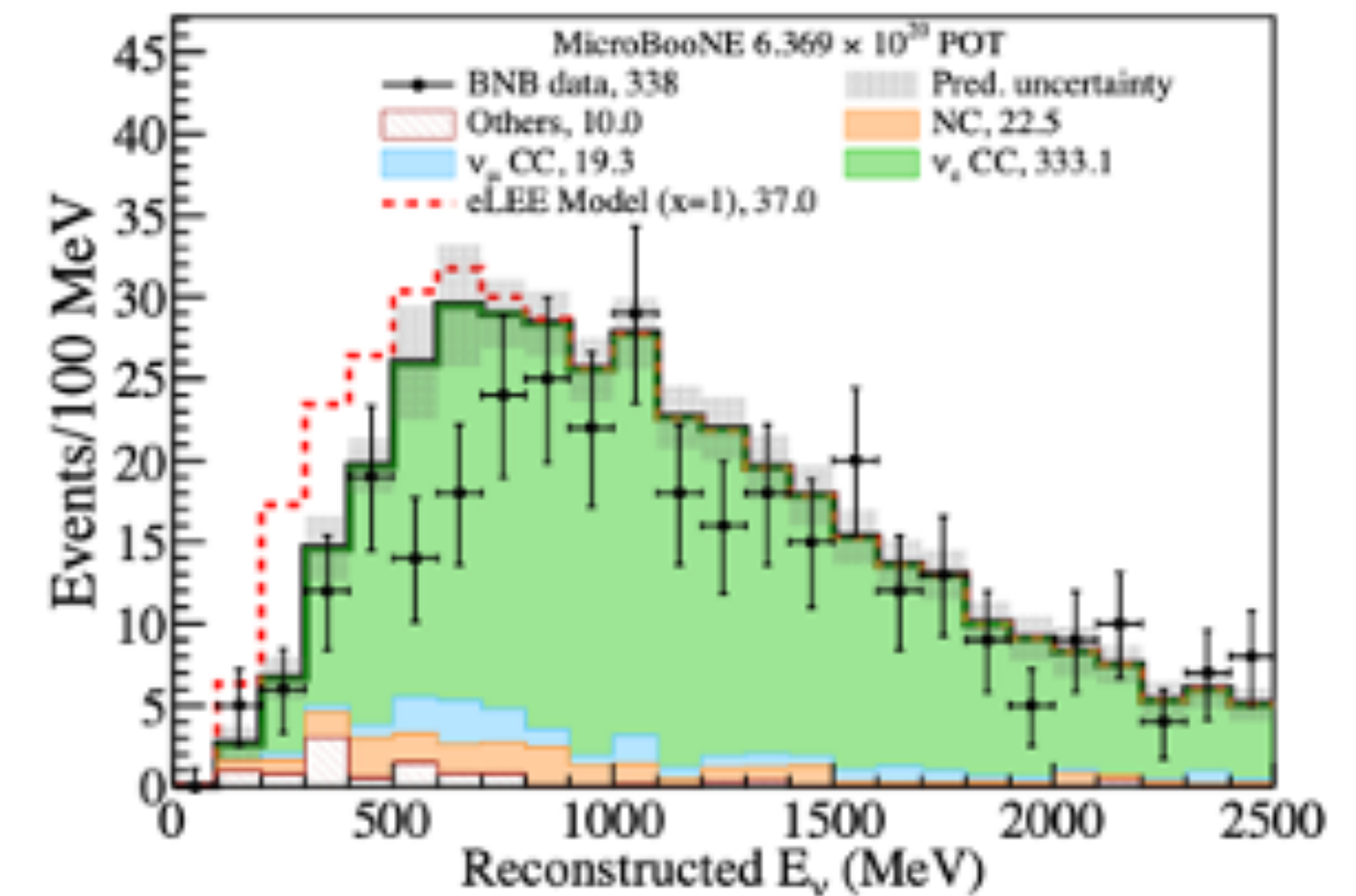
- first MicroBooNE result probed both electron-like and photon-like signals, with LArTPC's ability of e/γ separation
- photon analysis targets NC $\Delta \rightarrow N\gamma$ channel
 - test if this channel is underestimated in the standard model
 - result shows no evidence for enhanced rate of single photons from NC Δ decay



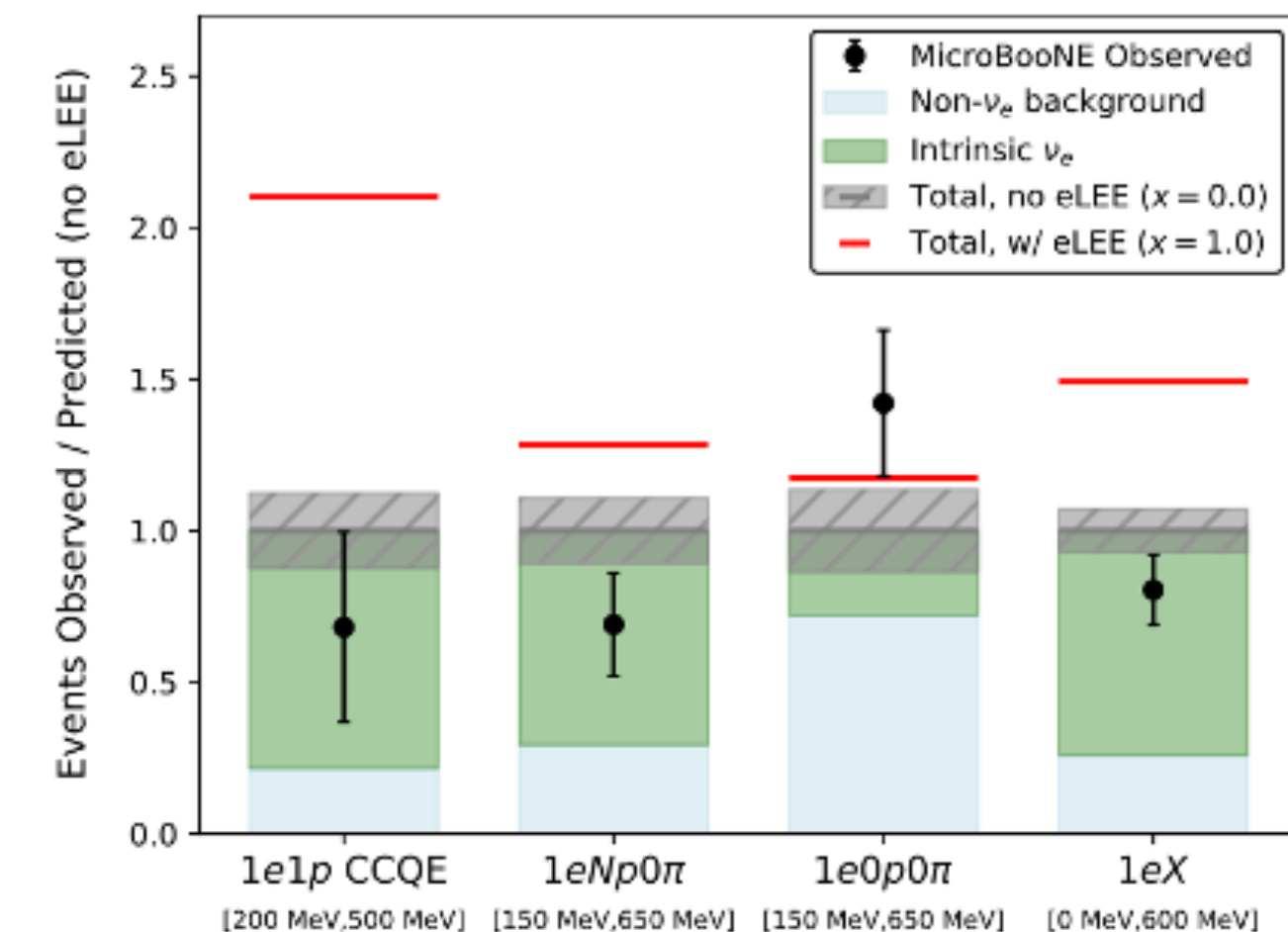
MicroBooNE LEE result

- 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)

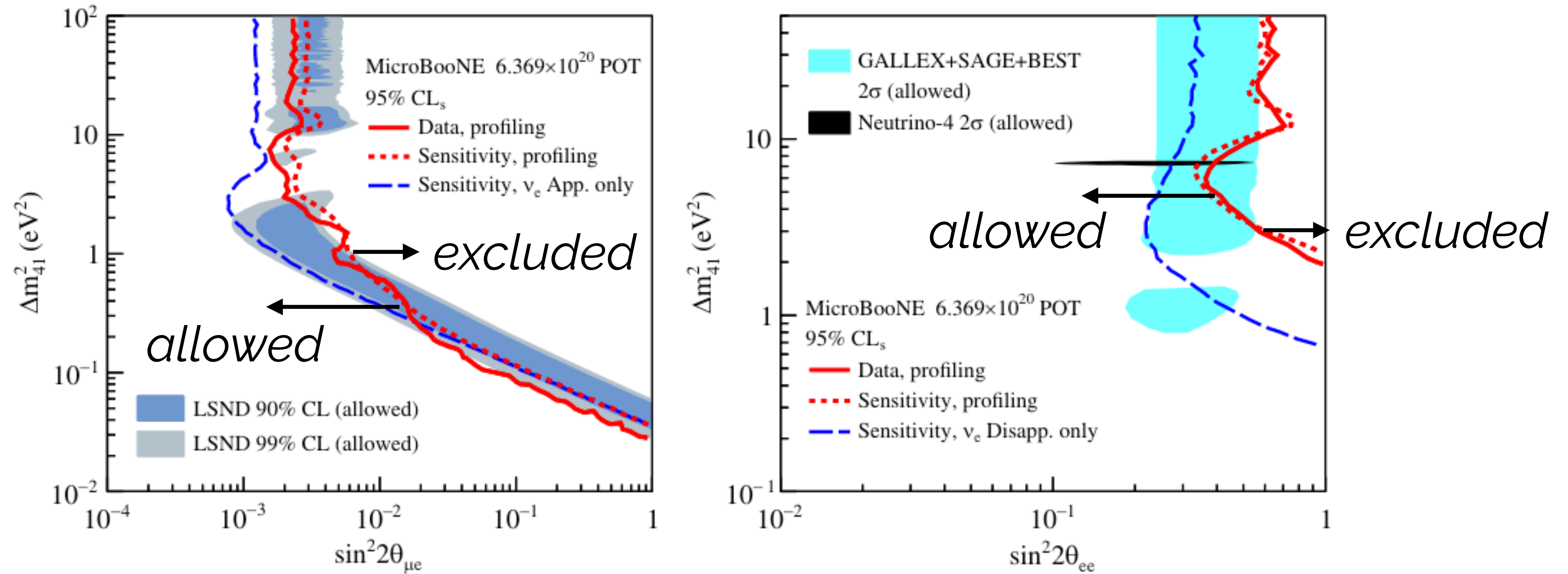


Phys. Rev. Lett. 128, 241801 (2022)



MicroBooNE sterile neutrino search

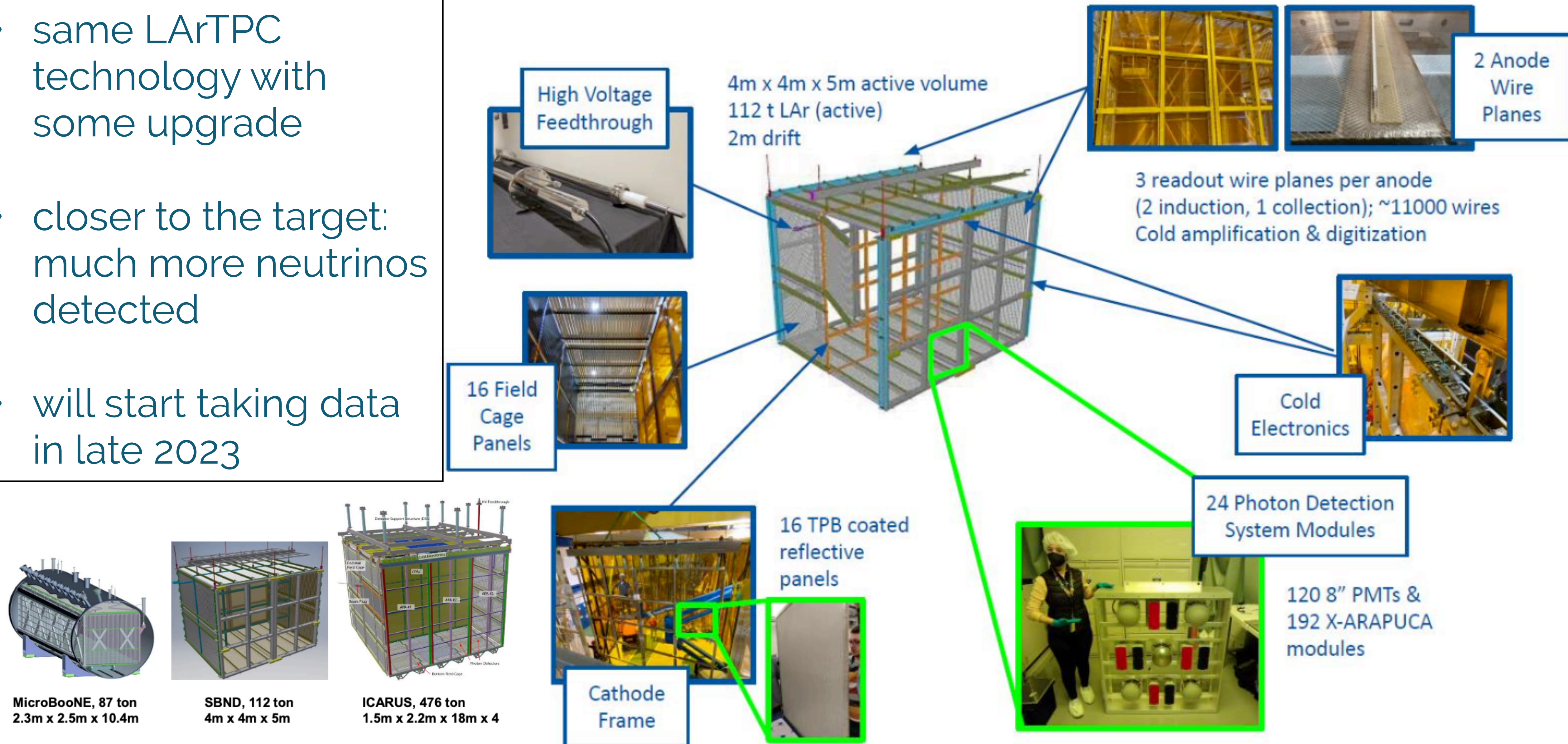
Phy. Rev. Lett. 130 011801 (2023)



- 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

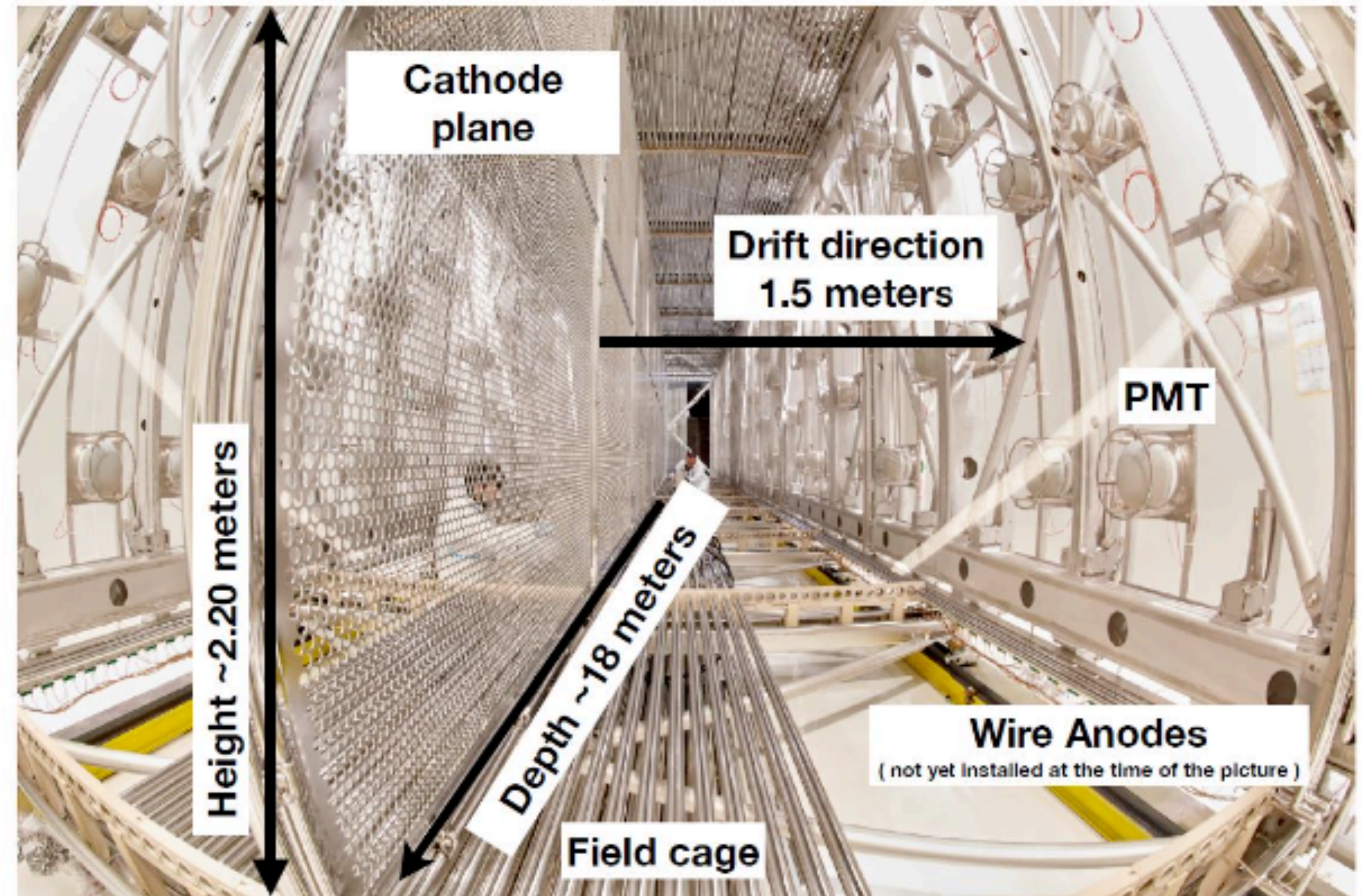
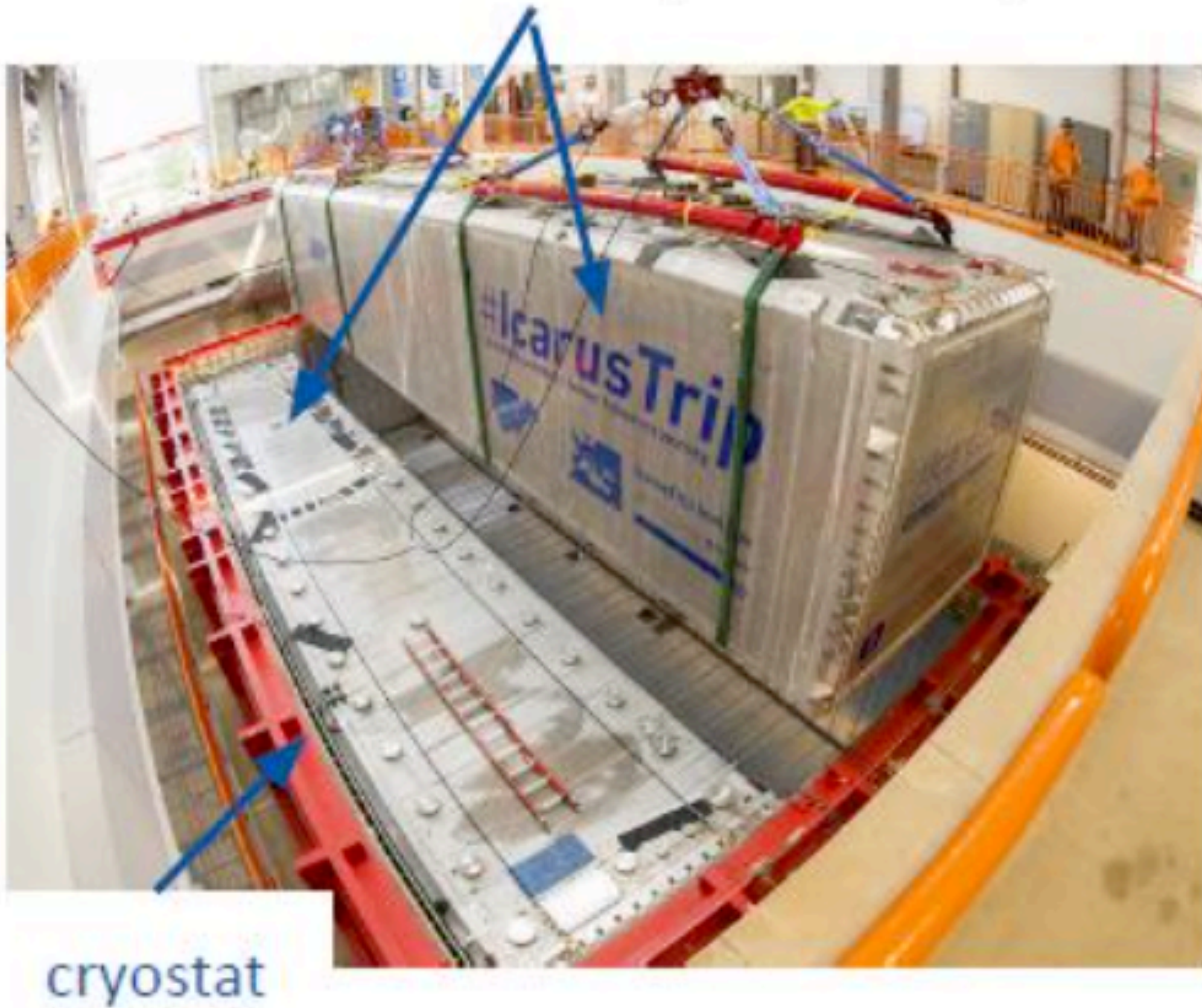
Short Baseline Neutrino Detector: SBND

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



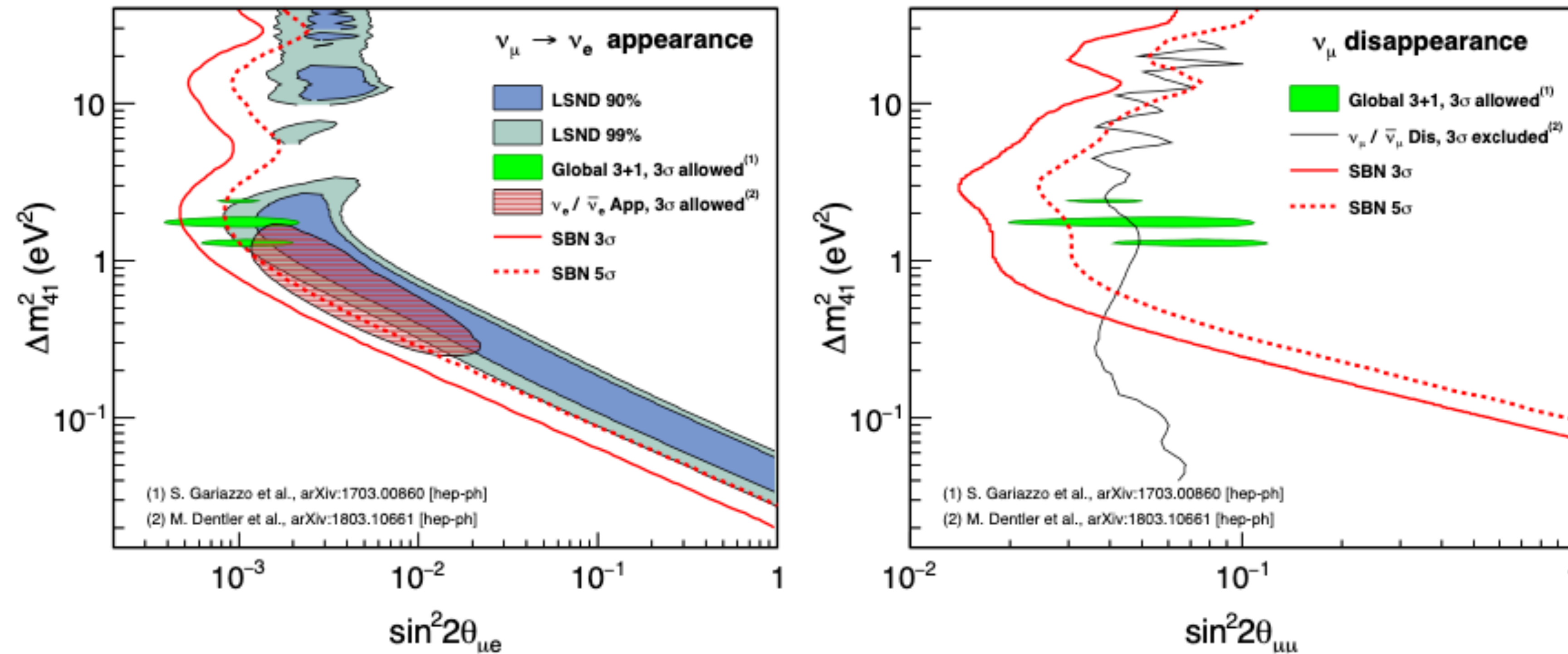
ICARUS

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



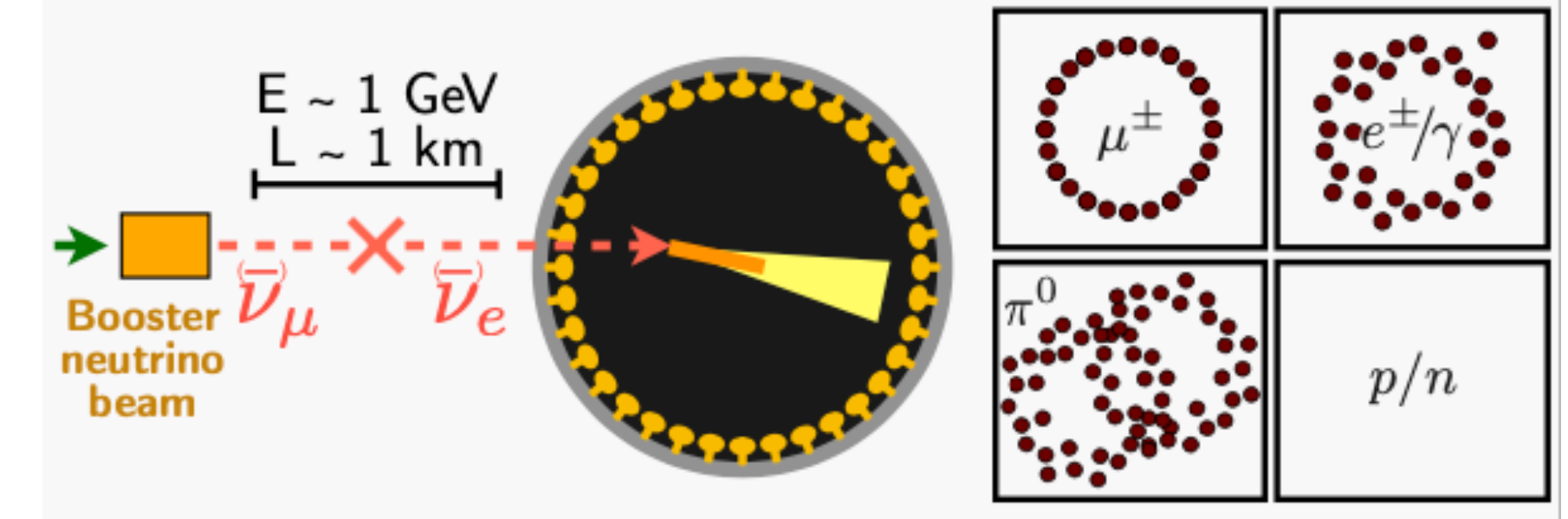
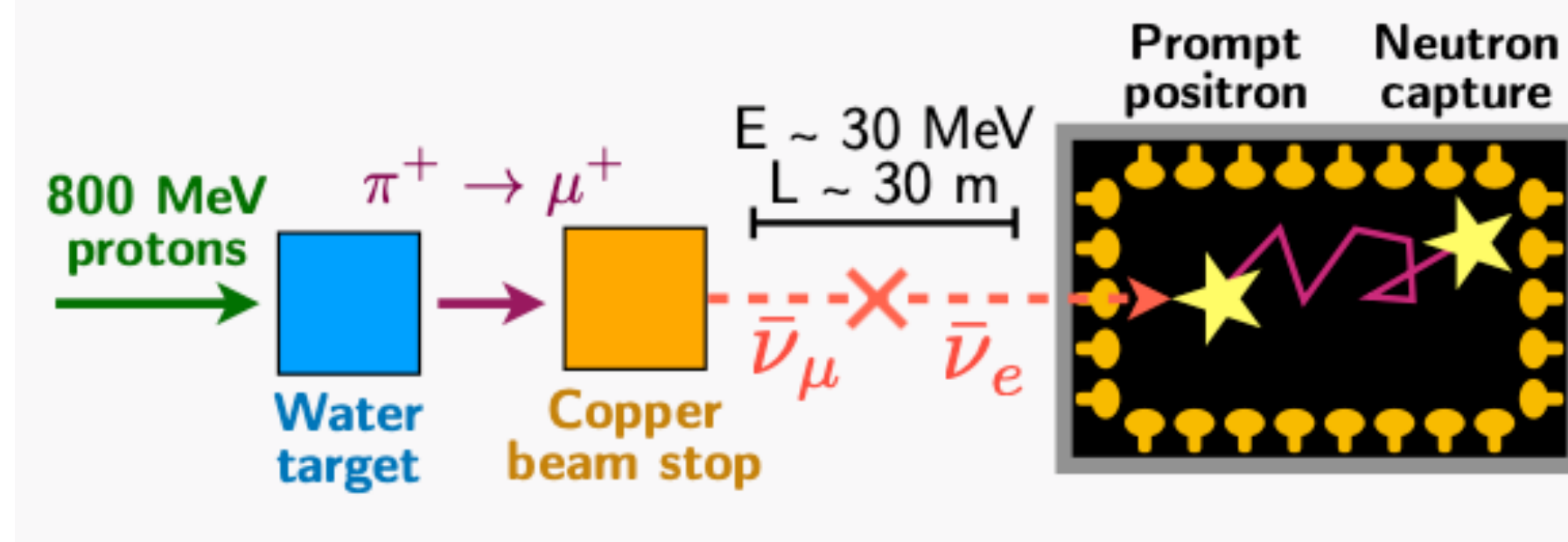
- shipped from Europe (LSNG), refurbished & upgraded
- farther away from the target, but much larger volume
- started taking neutrino data since 2021

SBN program

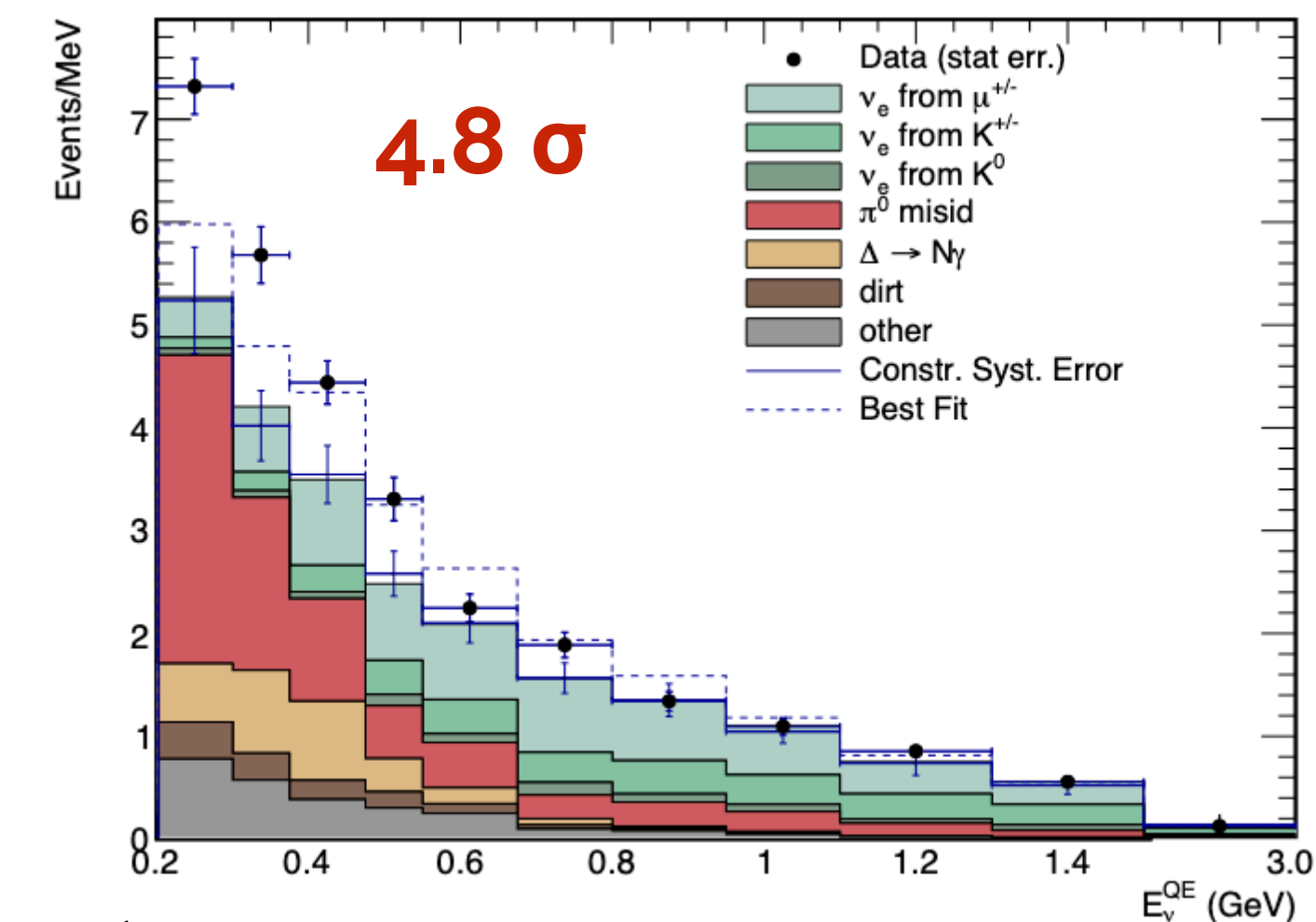
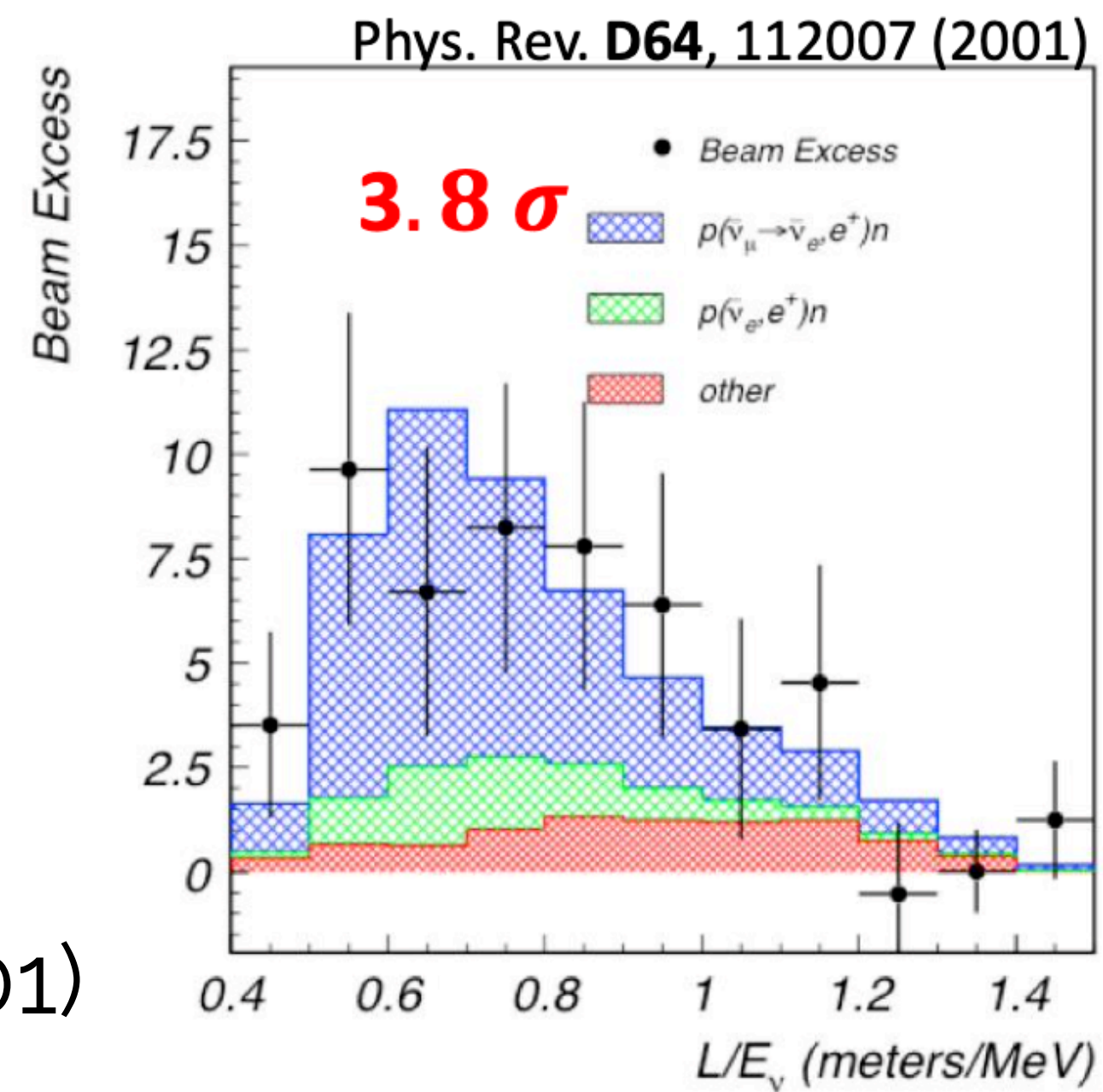


- main goal is to definitively test sterile neutrino hypothesis
 - confirm or dispute anomalies that can be explained by sterile neutrino hypothesis
- also will measure & study how neutrino interacts with argon: important input to future DUNE experiment

LSND & MiniBooNE anomaly



arxiv:2006.16883

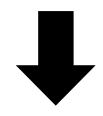


- **LSND** (1990-2001)
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess over background suggests evidence for oscillation at $\Delta m^2 \sim 1 \text{eV}^2$

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

LArTPC: Liquid Argon Time Projection Chamber

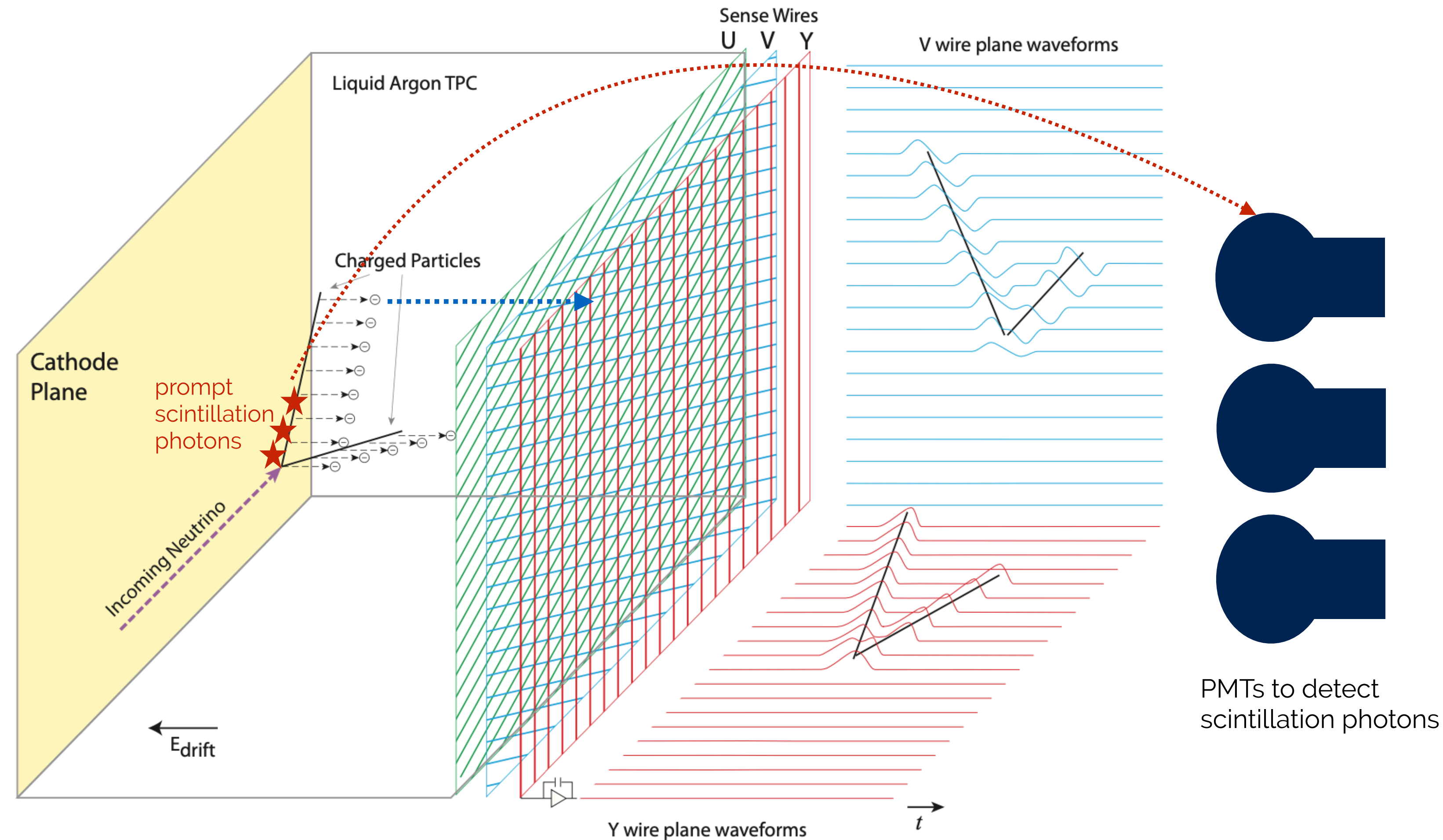
charged particle enters detector



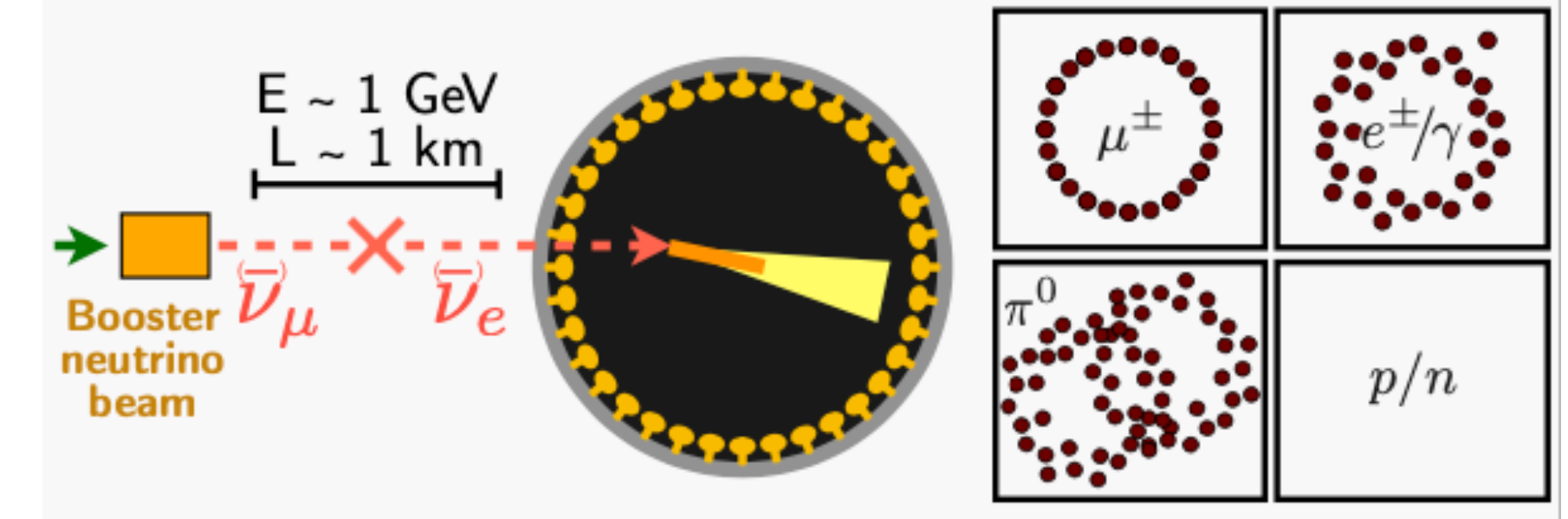
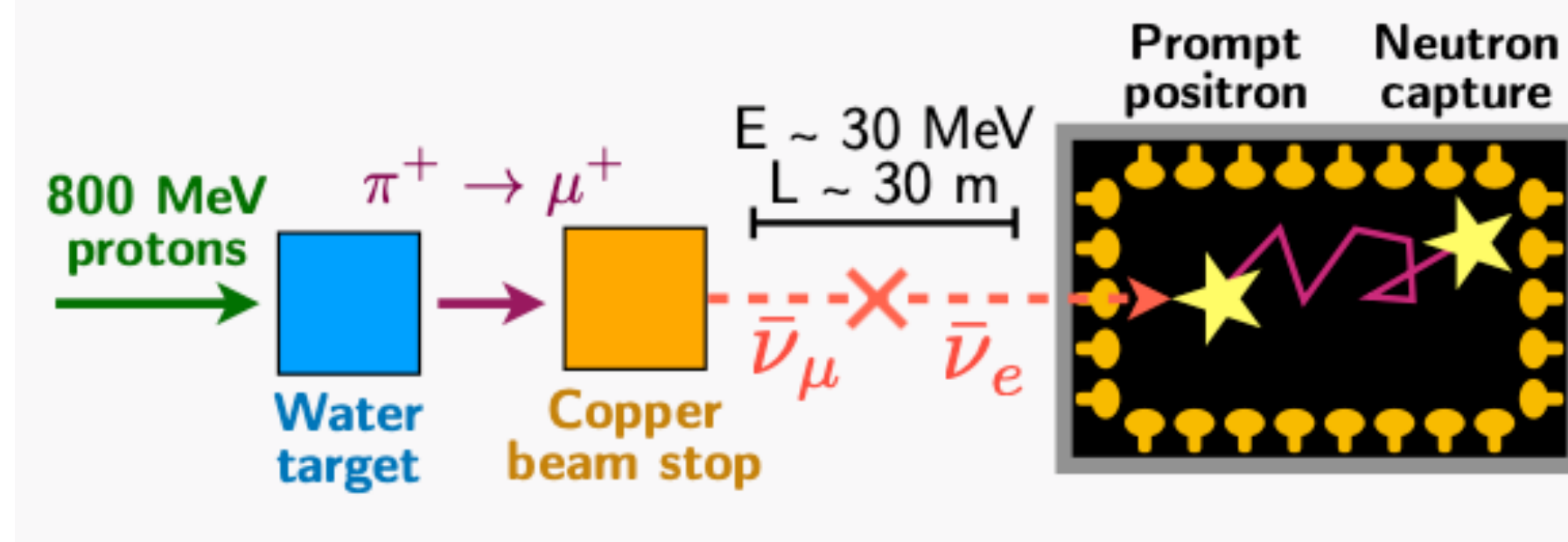
scintillation light emitted by excited Ar, detected by PMTs



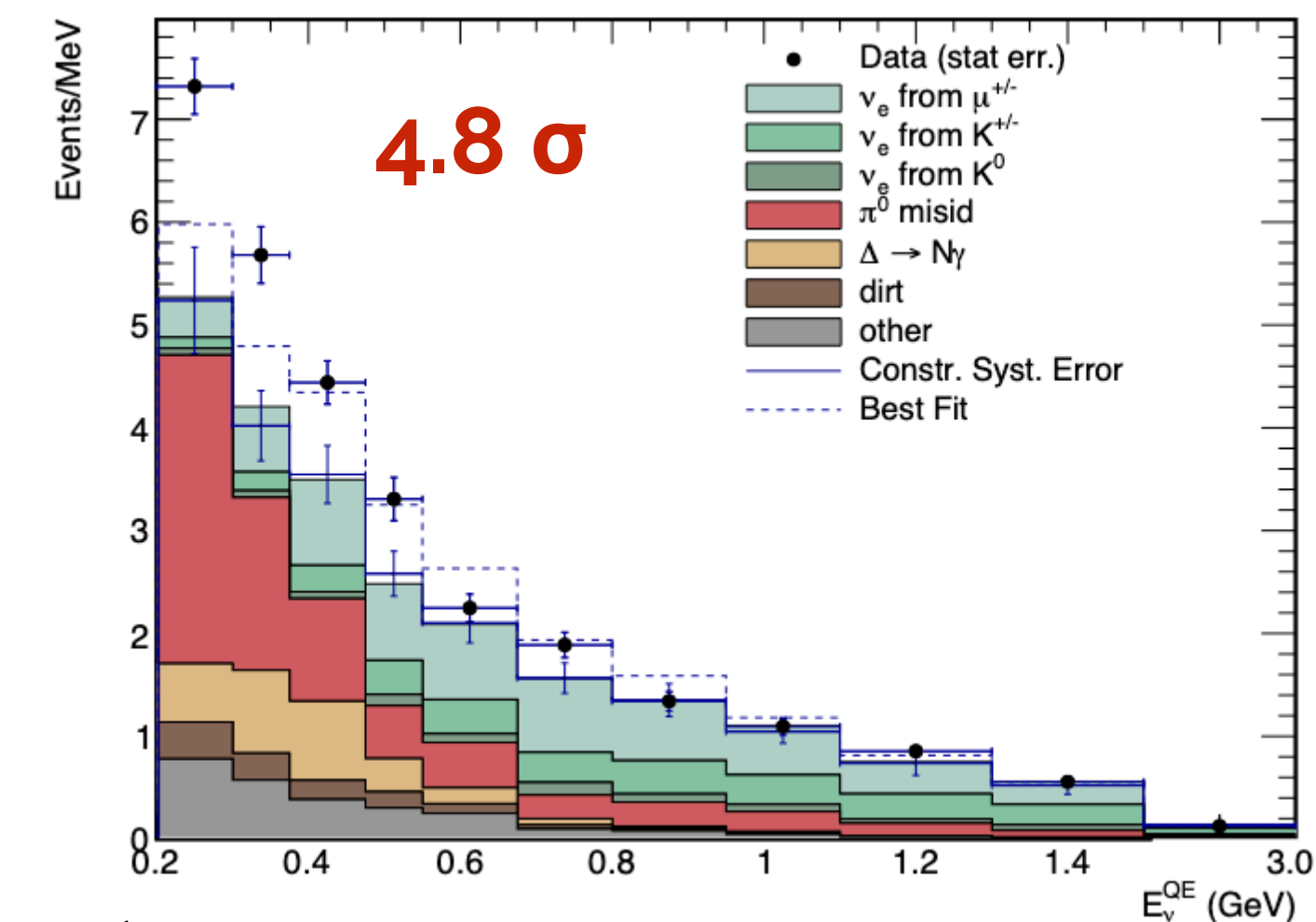
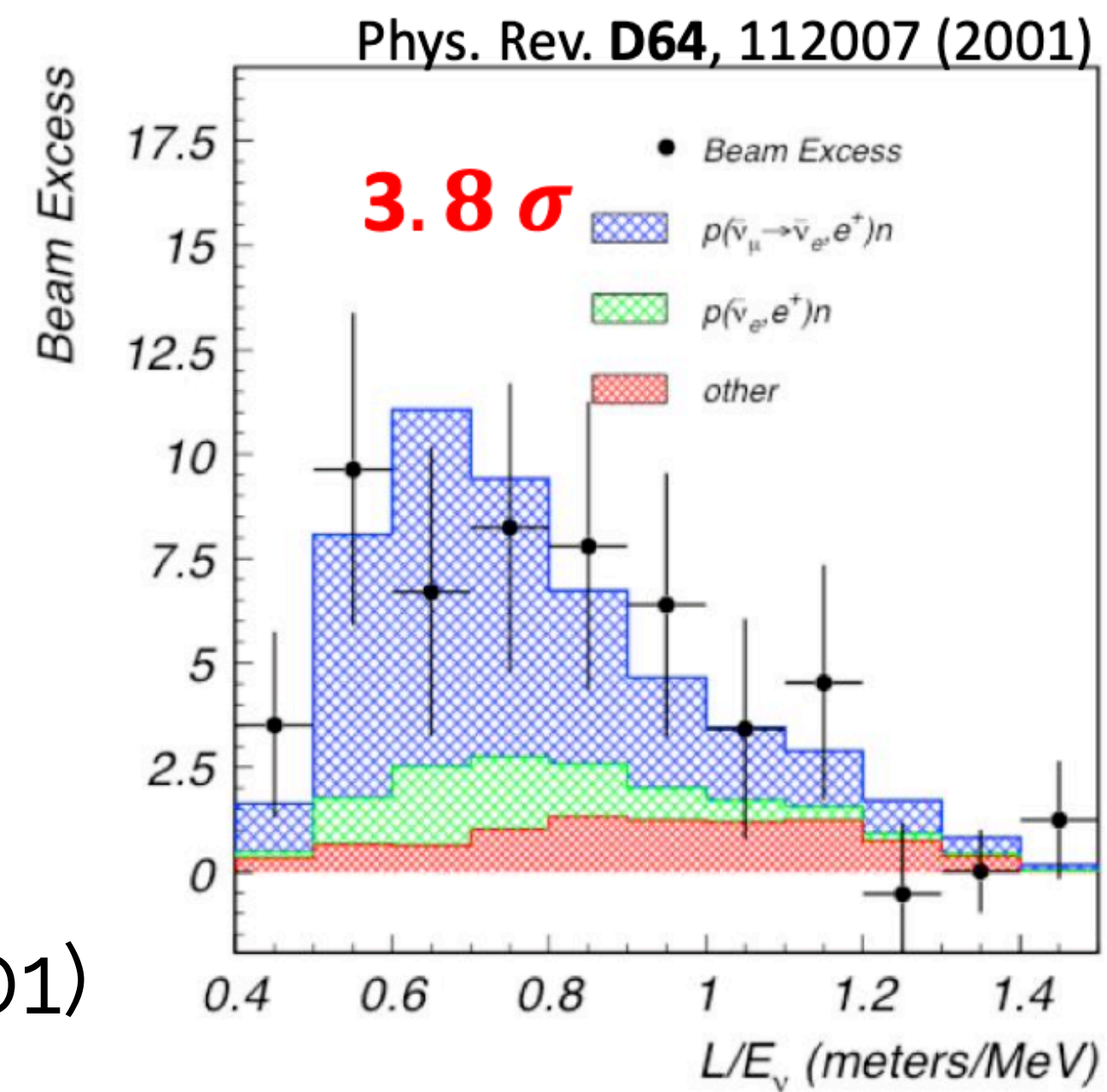
ionization electrons drift to anode plane, detected by sense wires



LSND & MiniBooNE anomaly



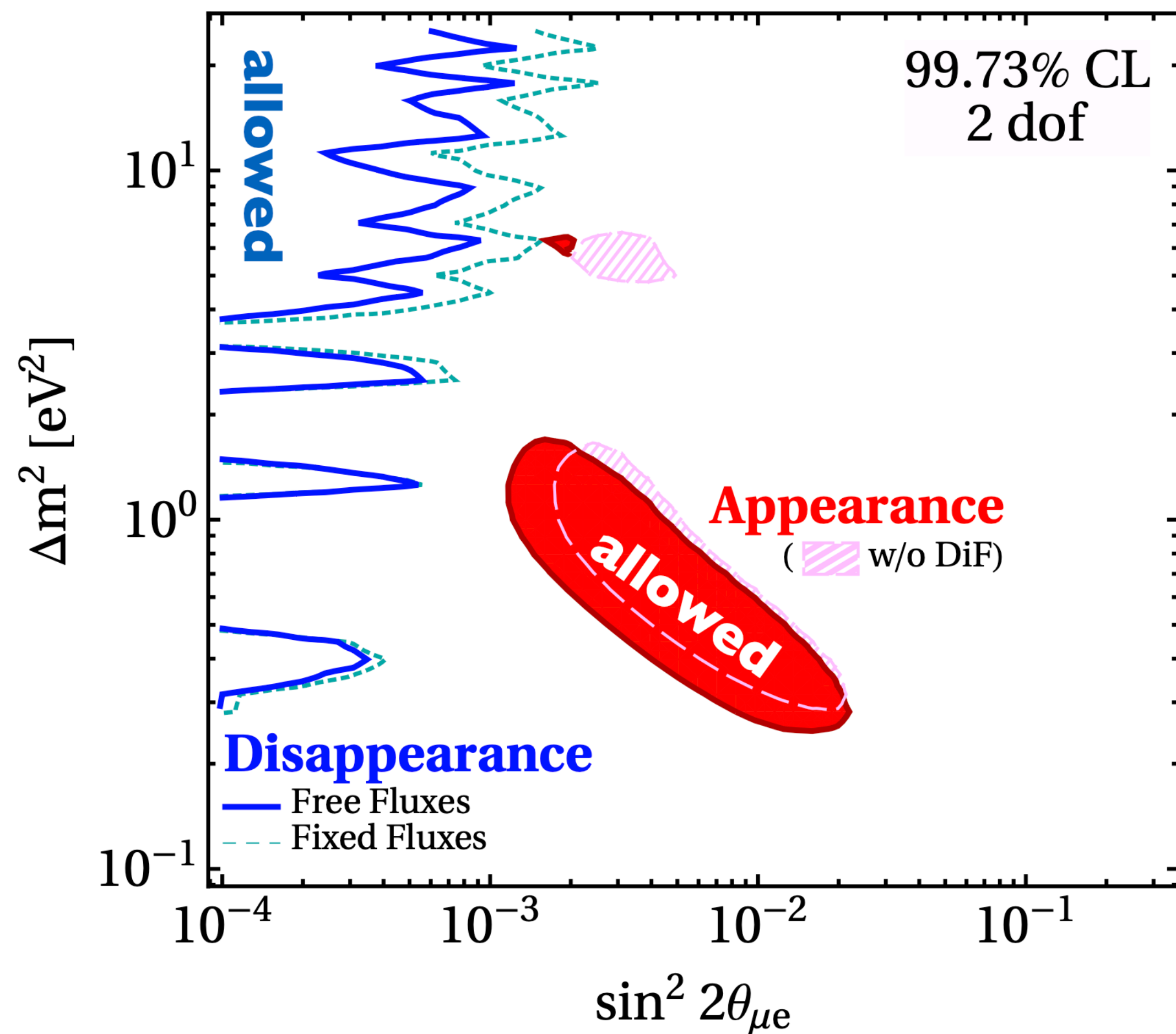
arxiv:2006.16883



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

tension in 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!*

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

short-baseline anomalies

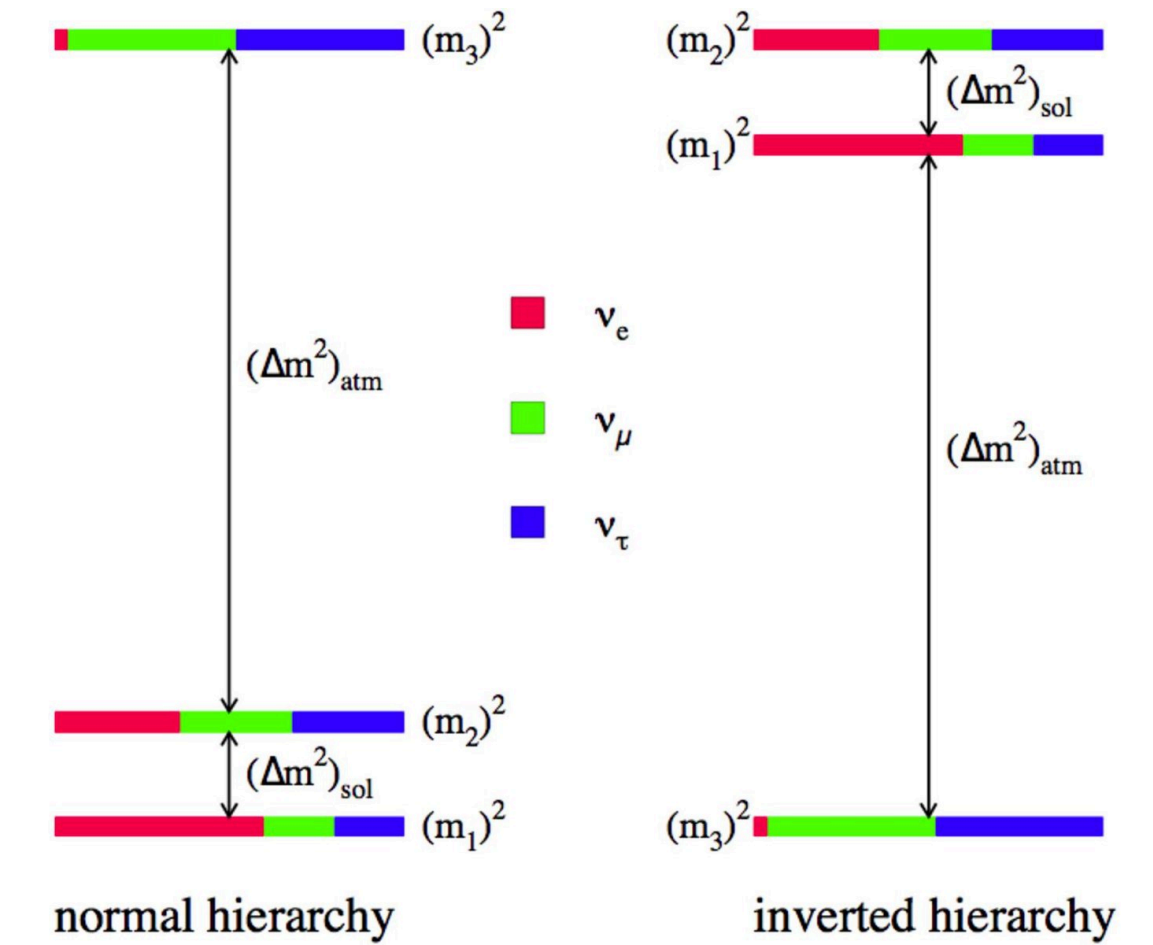
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix}}_{\text{Reactor/Accelerator}} \underbrace{\begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates
mass eigenstates

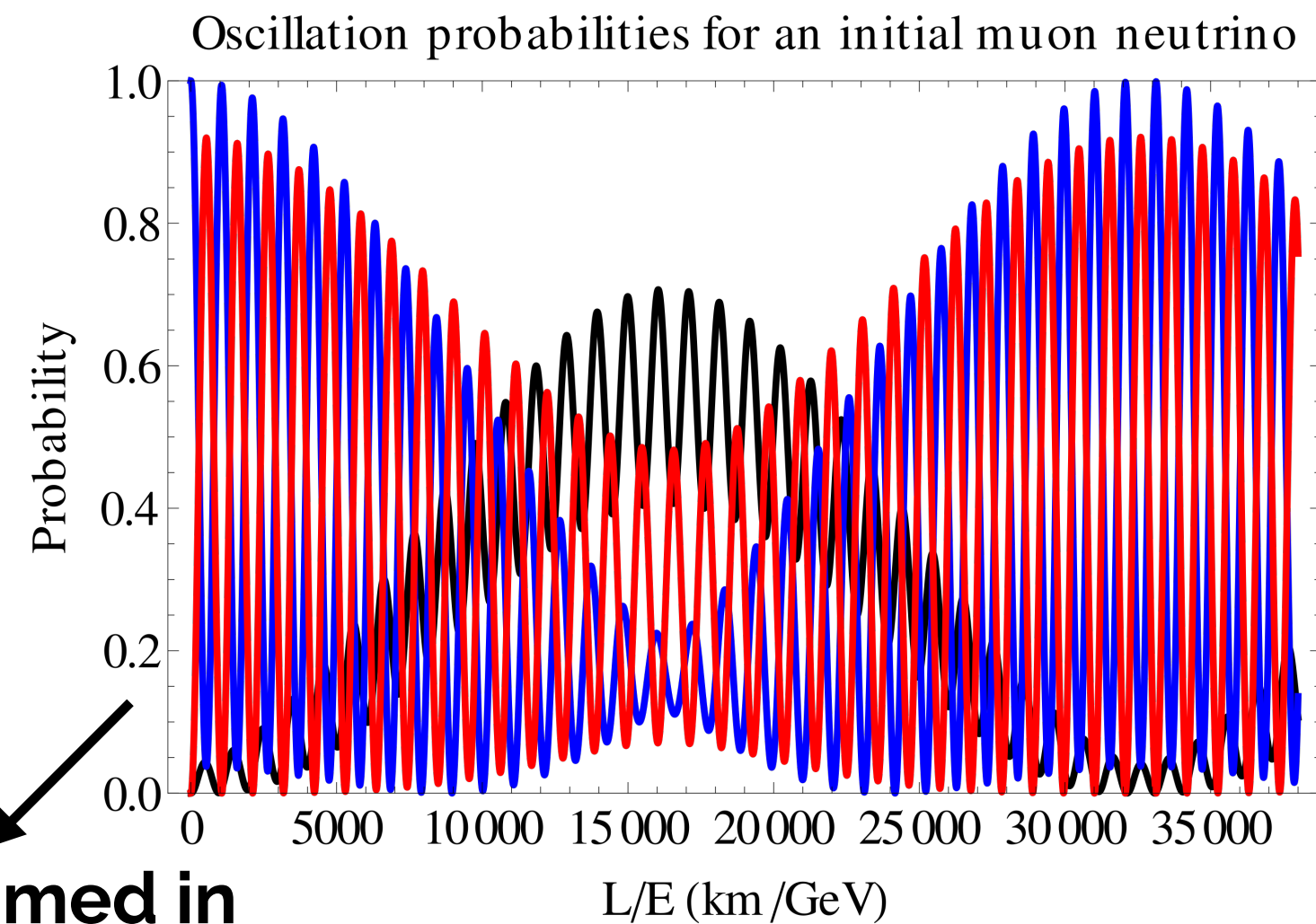
$$(c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij})$$

- 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

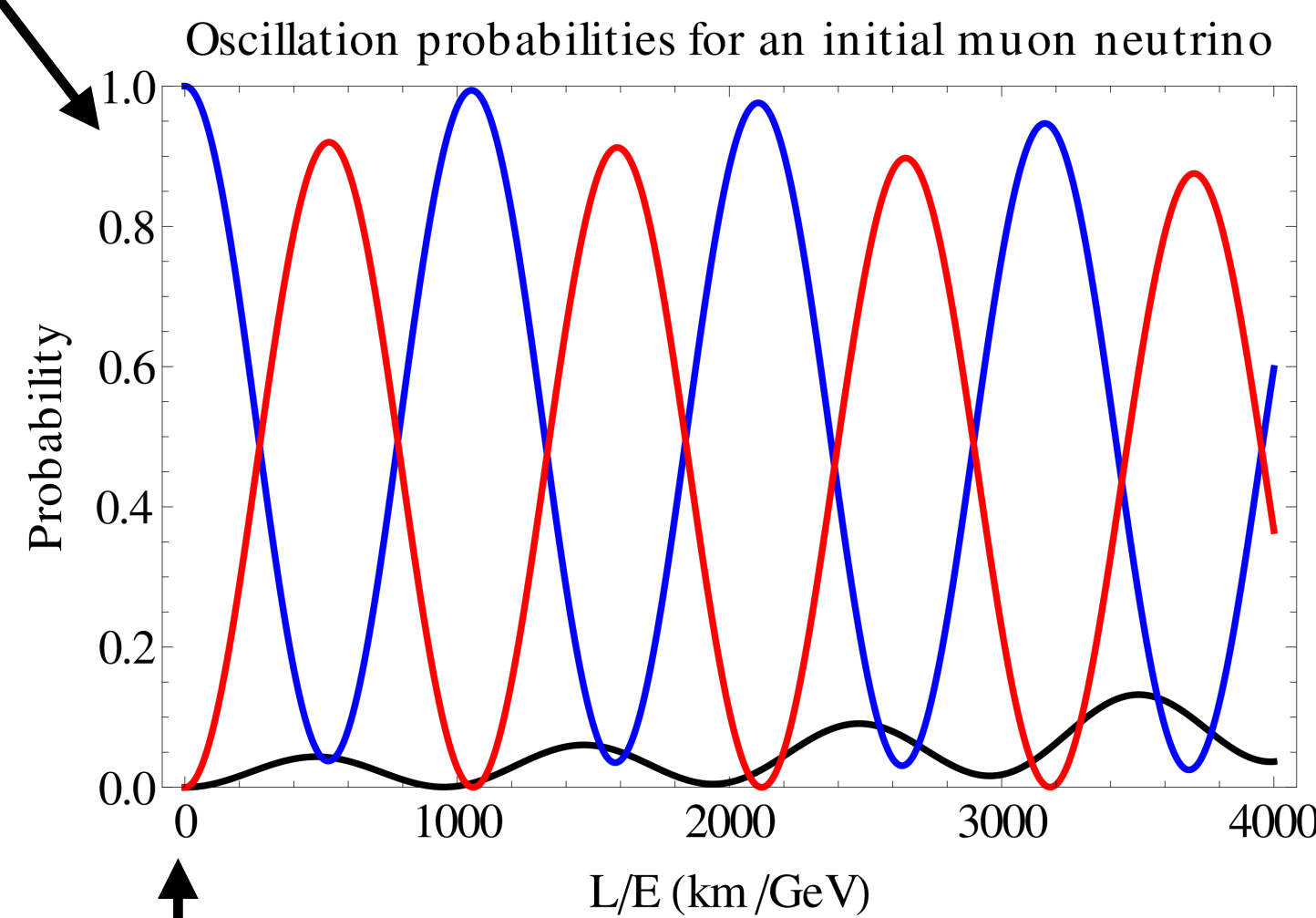


- Neutrino flavor eigenstates are not the same as the mass eigenstates
- Neutrinos generally are produced in a flavor eigenstate, which is a superposition of three mass eigenstates
- These mass eigenstates have different energies, and therefore change phase over time at different rates according to Schrodinger's 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



ν_μ
 ν_e
 ν_τ

zoomed in



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

Detector mass needed for 1000 events/yr?

- the first most important consideration for neutrino detection is the **mass of detector**
- O(1000) tons are needed for many experiments
- if flux is high, mass can be lowered
 - powerful neutrino beam
 - proximity to neutrino source
- both energy and flux need to be known

Atmospheric Neutrinos

$$\varphi = 5000 \text{ m}^{-2} \text{ sec}^{-1}$$

$$E \sim 1 \text{ GeV}$$

$$\sigma \sim 10^{-38} \text{ cm}^2$$

$$\text{Nucleons} = 6 \times 10^{29} \text{ ton}^{-1}$$

$$N = \varphi \cdot \sigma \cdot 6 \times 10^{29} \cdot 3 \times 10^7 \text{ ton}^{-1} \text{ yr}^{-1}$$

$$N = 0.1 \text{ events / ton / yr}$$