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U.S. DEPARTMENT OF ENERGY

Charge and Light Detection for Noble Liquid Time Projection Chambers

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Physics Department Summer Lecture

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About me

- I grew up in San Diego and have liked physics since high school…
- But I didn't commit in college and split my majors between physics and literature at UCSD
- I applied to half physics and half literature graduate programs and got into 2 physics and 0 literature so here I am…
- I stayed at home with my kids for 3 years
- After that I joined BNL in 2014 and have focused on developing detectors for particle physics since

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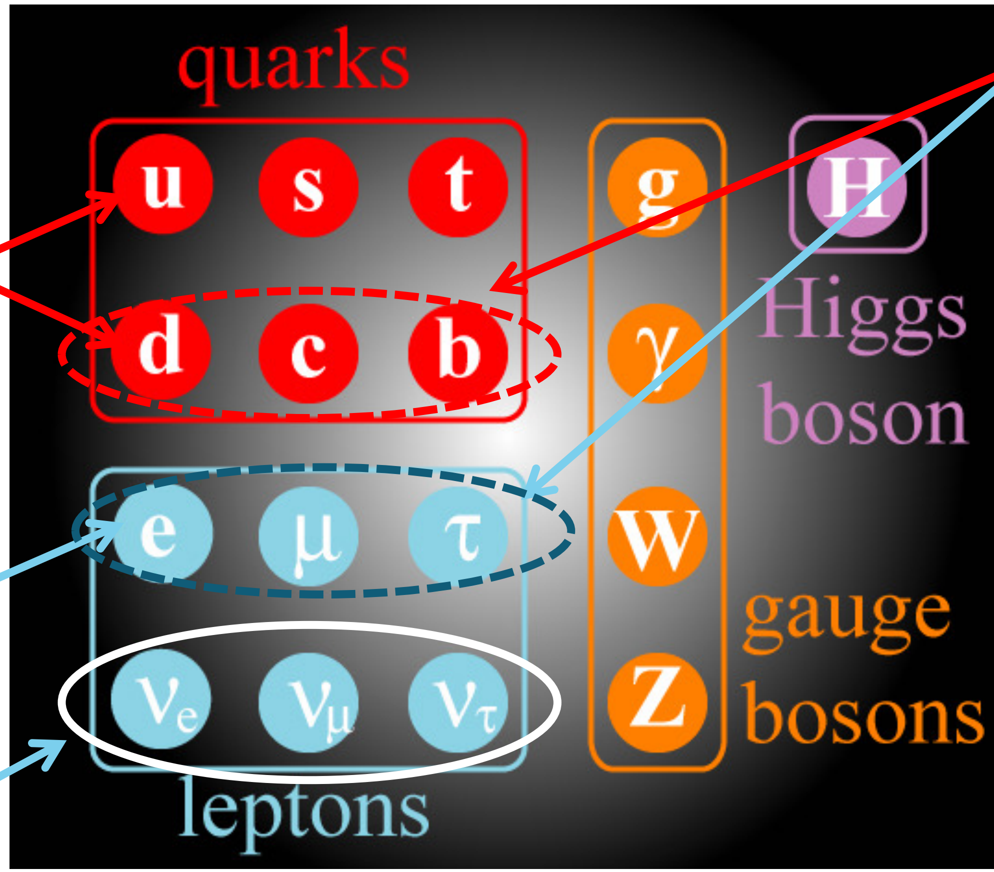
Outline

- Neutrino refresher
- Noble liquid time projection chambers
- DUNE and charge readout
- nEXO and photon detection

The elementary particles

3 “generations”

Make up protons and neutrons



Orbit nucleus in atoms

Neutrinos!

+ antiparticles!

Neutrinos are…

- Are very, very small
  - If a neutrino were the size of a grain of sand, a grain of sand would be the size of the known universe!

- Are very, very hard to see
  - The probability of neutrino interaction is so low that a typical neutrino could pass through a light year of lead before experiencing a single interaction.

  - Which means trillions of neutrinos pass through our bodies every second of every day on Earth, but we can't feel them and they have no impact on our health.

Neutrino oscillation

- Behavior of elementary particles is described by quantum mechanics, which has consequences that are not observed in everyday objects, like blocks or balls.
- One of these consequences is "superposition of states" which means that a given neutrino is really a mixture of all three flavors of neutrino:

$$\nu_1 = \alpha\nu_e + \beta\nu_\mu + \gamma\nu_\tau$$

  - The "coefficients" α, β, and γ tell us the probability that if we observe ν_1 we will find a ν_e, a ν_μ, or a ν_τ.
  - To make things even more complicated, the mixture changes as the neutrino moves through space, so the probability of observing a given type of neutrino depends on where you are relative to where the neutrino was created. This is called "neutrino oscillation."

Neutrino oscillation

- Each of the neutrino masses (1,2,3) are made of some probability of being a flavor (e, μ, τ) when observed by people!
- Physicists express this as a mixing matrix:

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

U_{PMNS}: relates flavor and mass states

MEASURE THESE!

parametrized by 4 parameters (3 angles, 1 phase)

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Antiparticles and beta decay

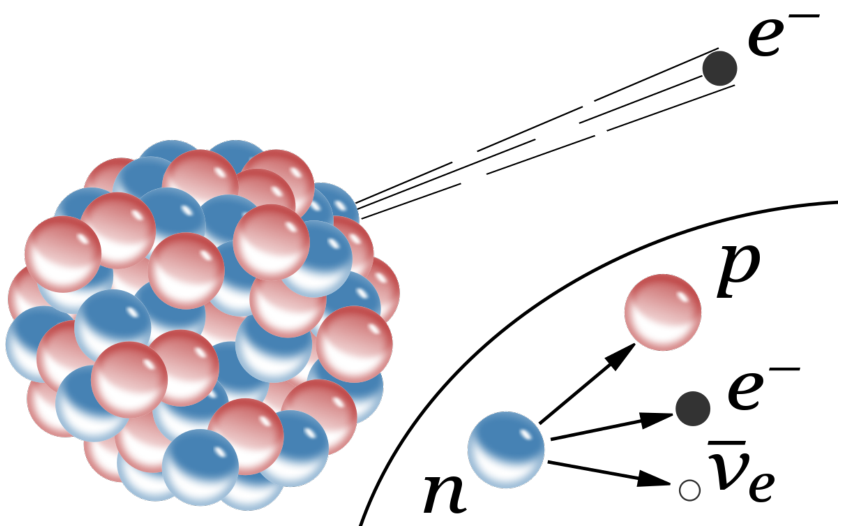
- Antiparticles have the same mass as their particles, but other physical properties are reversed
- A positron has the same mass as an electron except with a + electric charge

$e^- \Leftrightarrow e^+$ positron!

- Since neutrinos have 0 electric charge, we express the antineutrino:

$\nu_e \Leftrightarrow \overline{\nu}_e$

- The beta decay:



- Because of lepton number conservation, a lepton must always be created with its own flavor of antineutrino

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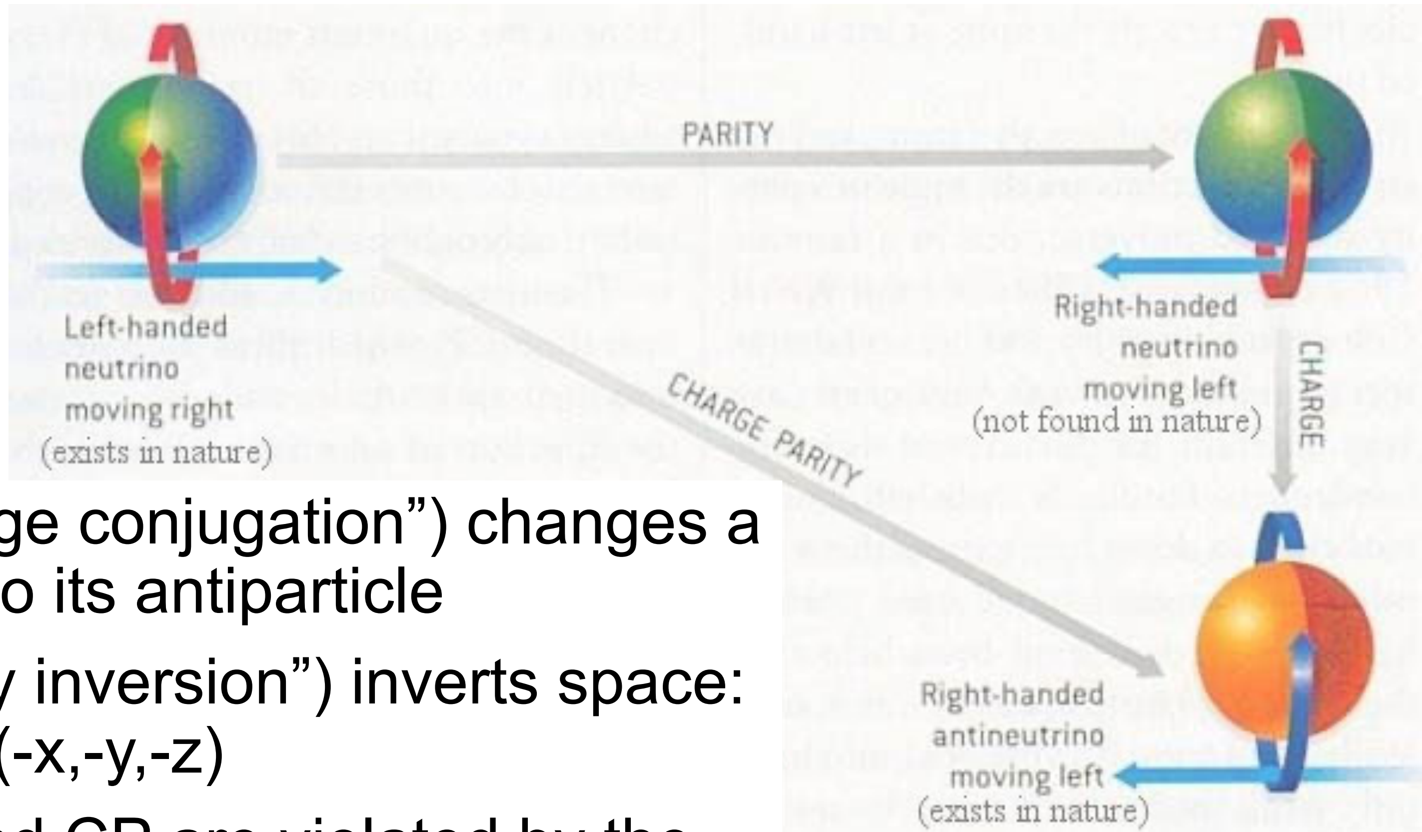
Charge parity violation in neutrinos



- C ("charge conjugation") changes a particle to its antiparticle
- P ("parity inversion") inverts space: (x,y,z)→(-x,-y,-z)
- Parity and CP are violated by the weak (W boson) interaction

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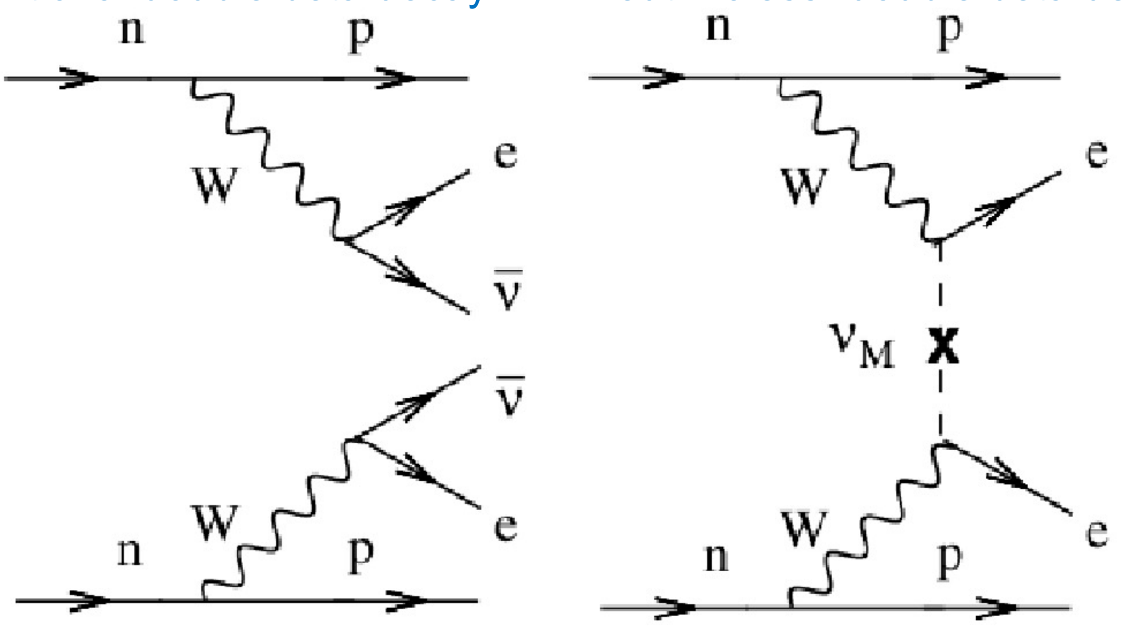
Are neutrinos their own antiparticle?

- Some materials (such as ^{136}Xe) double beta decay, with two pairs of e- and ν_e created

Conventional double beta decay

“Neutrinoless” double beta decay



https://en.wikipedia.org/wiki/Neutrinoless_double_beta_decay

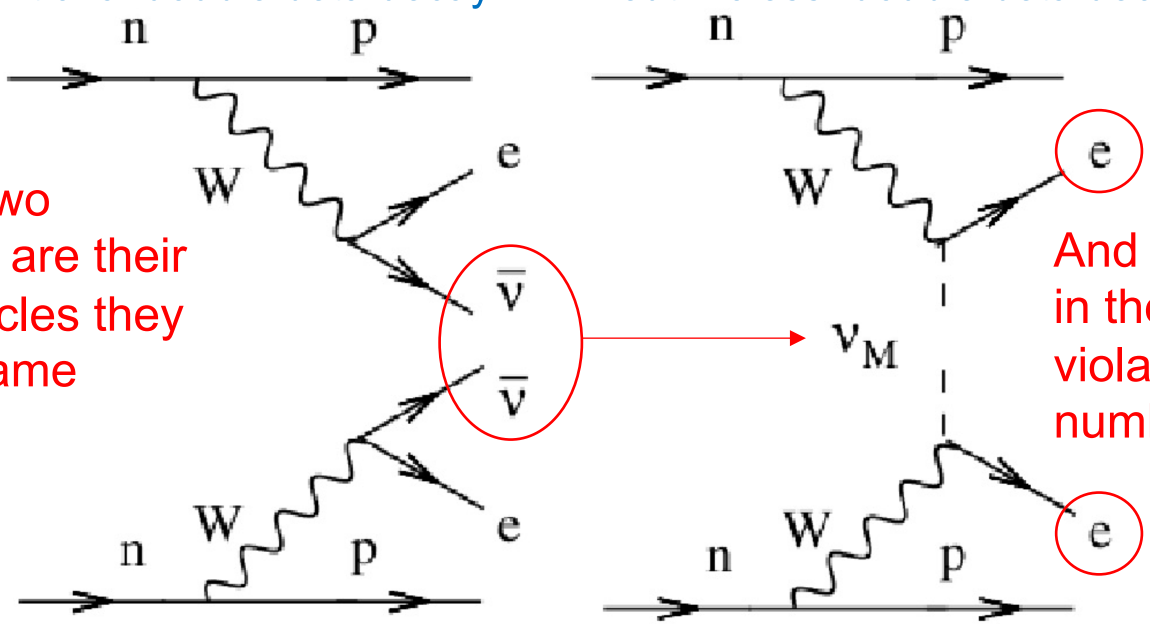
Are neutrinos their own antiparticle?

- Some materials (such as 136Xe) double beta decay, with two pairs of e- and ν_e created

Conventional double beta decay

“Neutrinoless” double beta decay

But if these two antineutrinos are their own antiparticles they can be the same particle!



And only 2 e^- are in the final state, violating lepton number conservation

Lepton number violation has NEVER been observed

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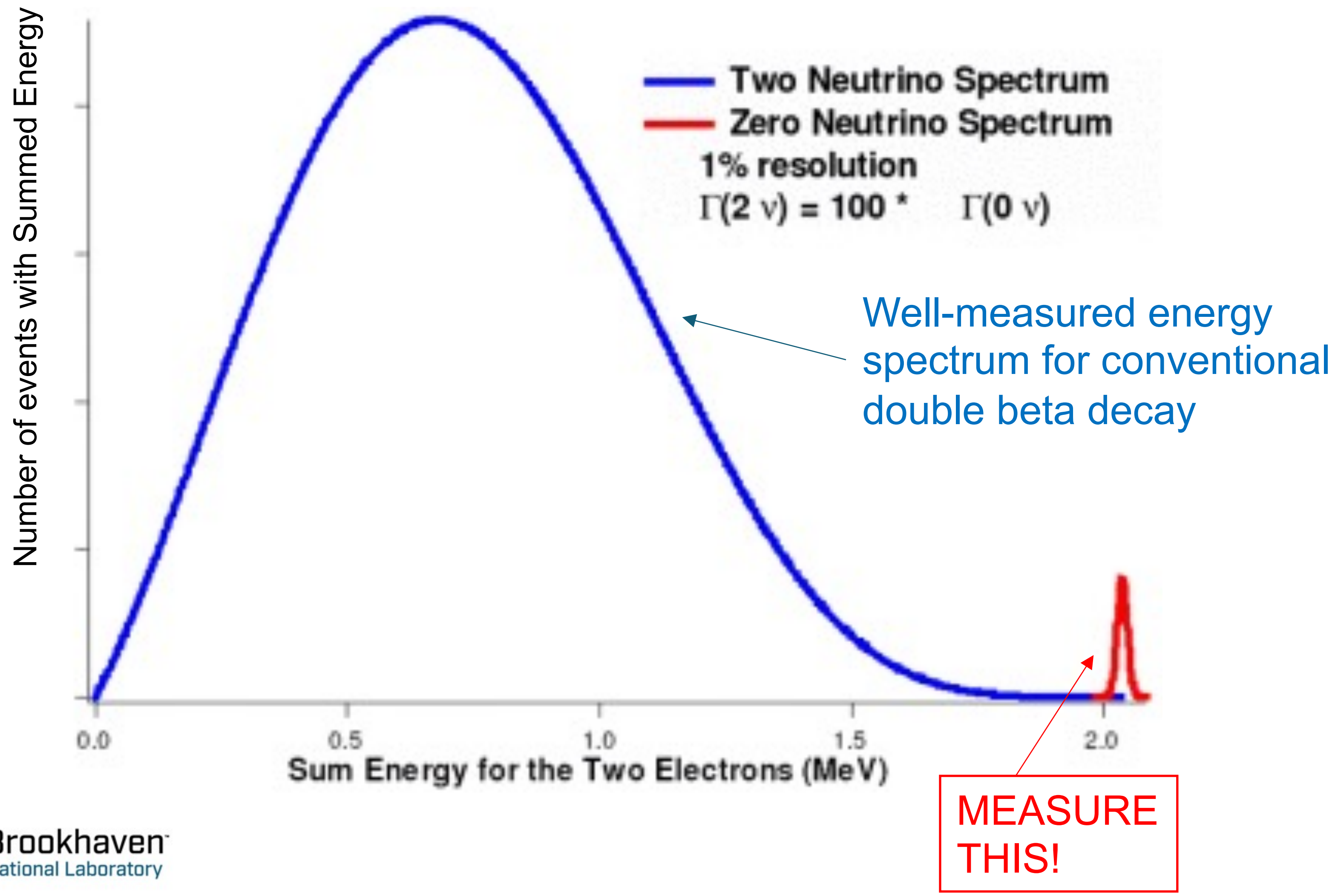
https://en.wikipedia.org/wiki/Neutrinoless_double_beta_decay

Double beta decay spectrum



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If we can barely see neutrinos, what can we do to make it possible to measure neutrino properties?

If we can barely see neutrinos, what can we do to make it possible to measure neutrino properties?

- Make LOTS of neutrinos
- Make VERY BIG detectors

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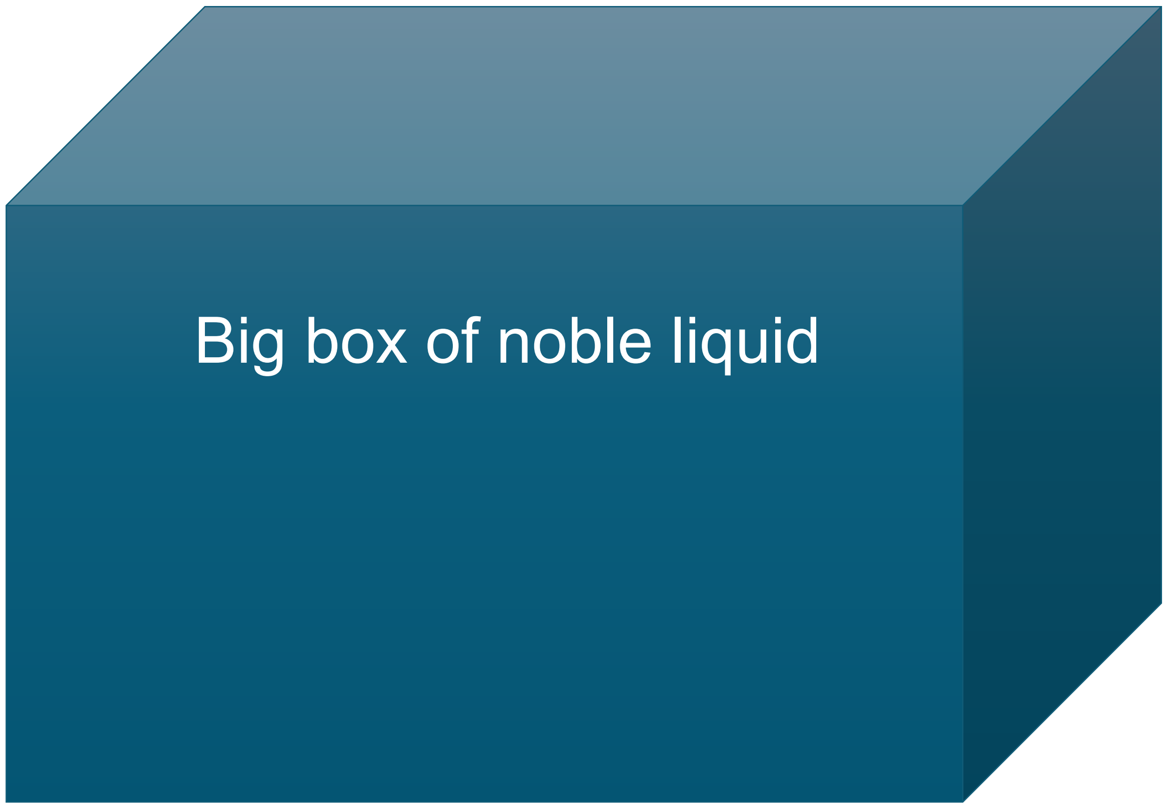
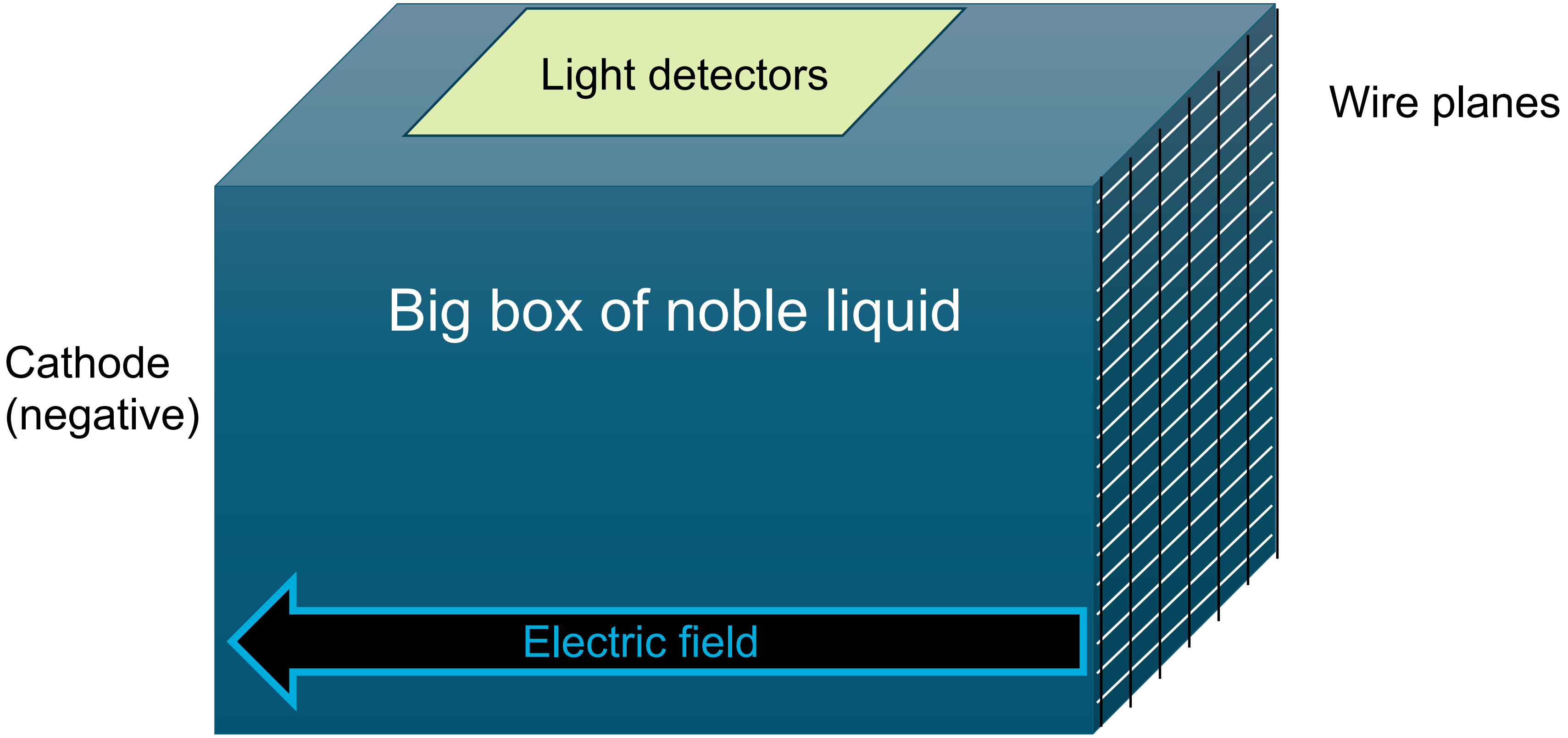
Noble liquid time projection chamber



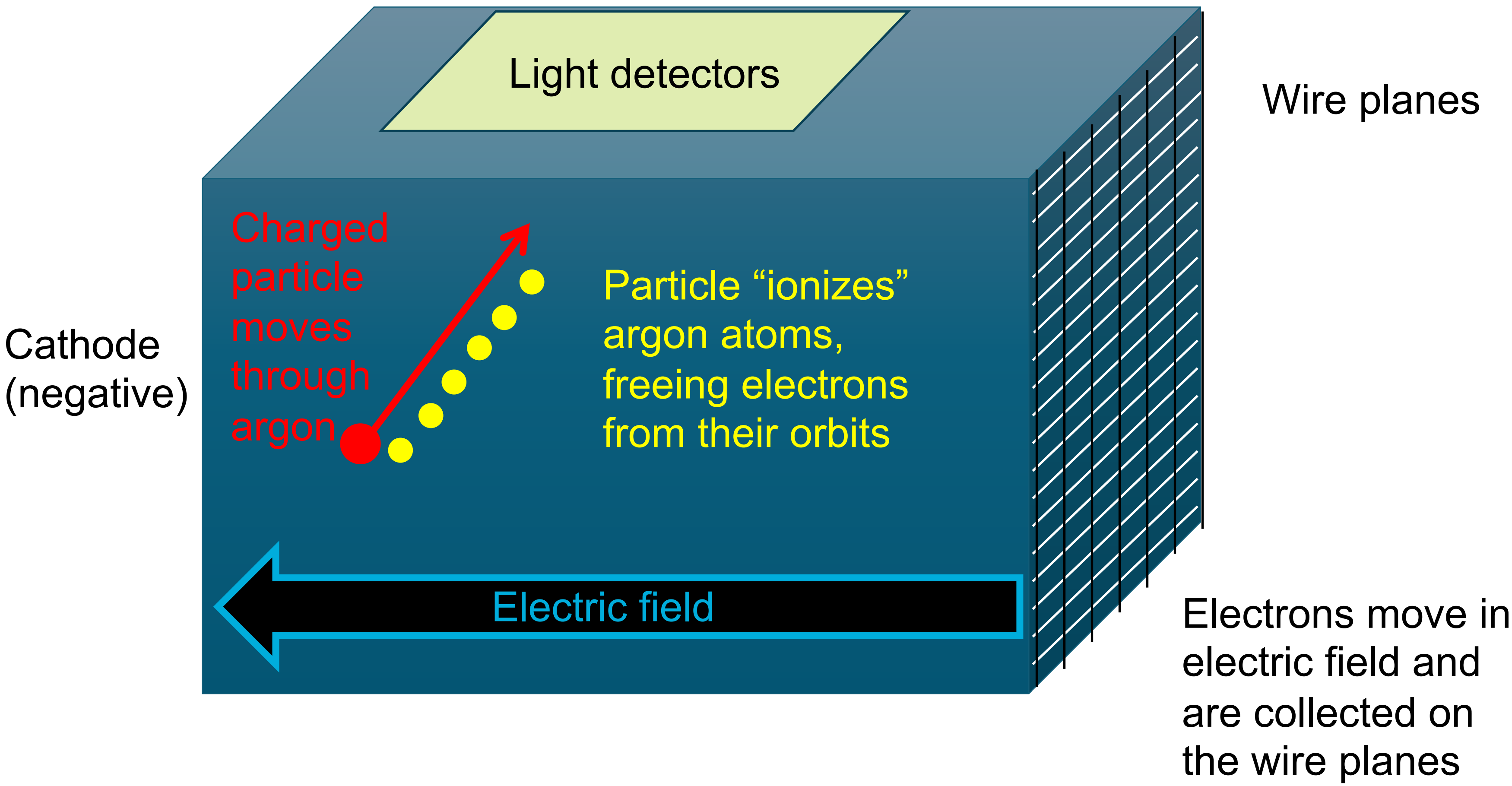
Noble liquids have to be very cold, for example argon is liquid at 87K (303^{o} F below zero) and xenon is liquid at 165K

Noble liquid time projection chamber

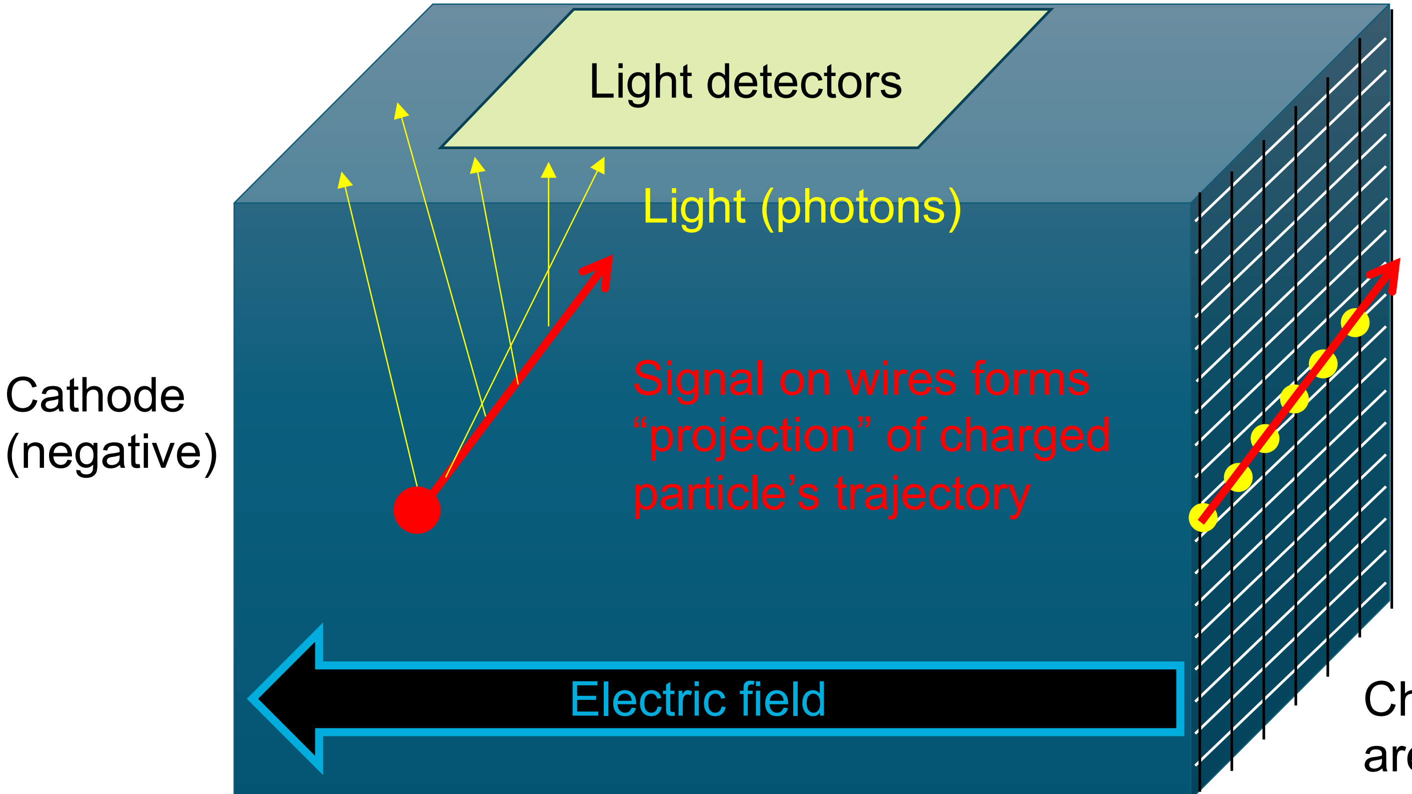


A negative charged cathode and positively charged anode wire planes create a powerful electric field in the liquid

Noble liquid time projection chamber



Noble liquid time projection chamber



Charge on wires are read out electronically and saved as digital data

Charged particles also produce photons, some of which are instantly detected by the light detectors

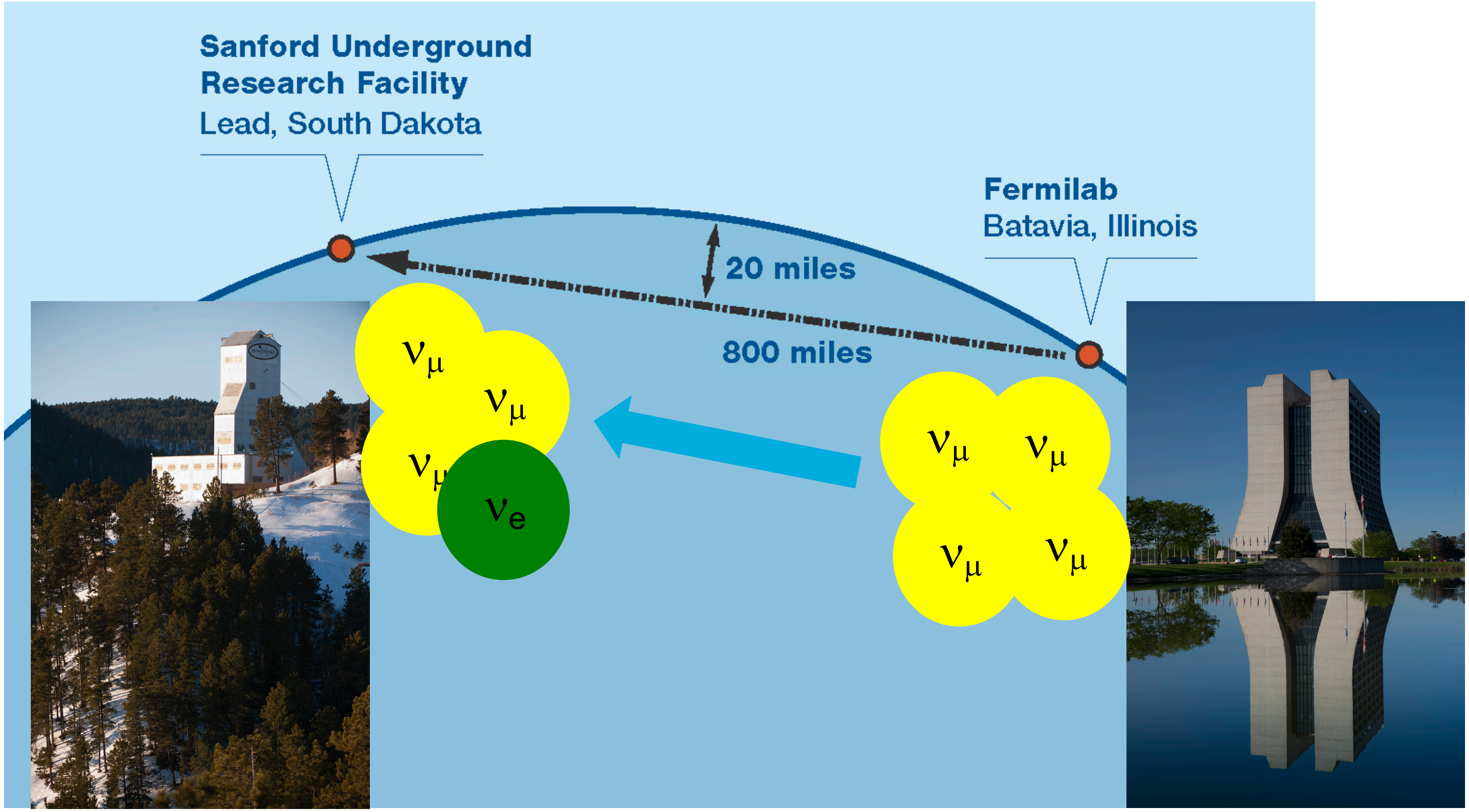
https://en.wikipedia.org/wiki/Time_projection_chamber

Why are we using noble liquids in these detectors?

Why are we using noble liquids in these detectors?

- Noble liquids don’t absorb the drifting electrons because all their valence shells are filled

Deep Underground Neutrino Experiment

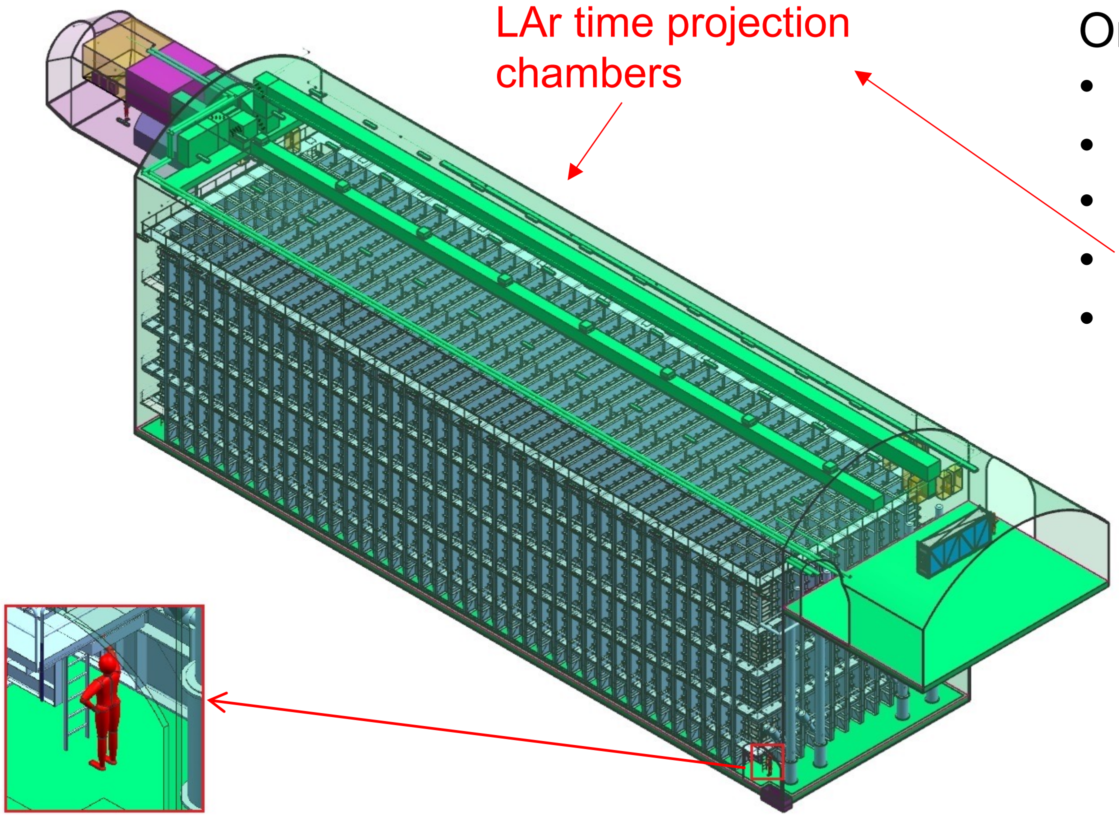


DUNE will use a muon neutrino beam from Fermilab to measure the parameters of neutrino oscillation

https://lbnf-dune.fnal.gov

DUNE far detector

Contains 150 separate
LAr time projection
chambers



One 10-kt module (fiducial):

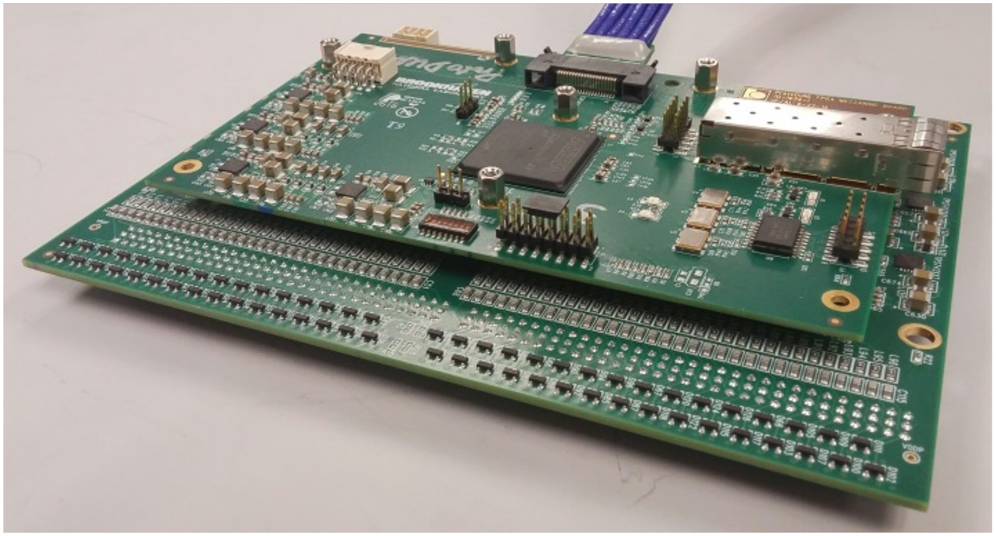
- 12 m high
- 15.5 m wide
- 58 m long
- 150 “APAs” (2.3 m x 6 m)
- 384,000 readout wires

All the parts of the DUNE detector have to operate at liquid argon temperature (87K) including the charge readout electronics and the light detectors!

DUNE cold electronics

- All the electron charge collected on the wires must be:
  - Amplified and filtered (electron charge is really small)
  - Digitized (converted from analog to digital so that computers can cope with it)
  - Transmitted outside of the cryostat (the big box of liquid argon)

This is done with the "cold electronics": custom microchips and circuit boards developed by DUNE that must work very reliably at 87K



Front-end motherboard (FEMB)

Testing the cold electronics

ProtoDUNE APA1 installed in the Cold Box

In 2017-18, DUNE tested and installed 6 APAs with 20 FEMBs each in ProtoDUNE

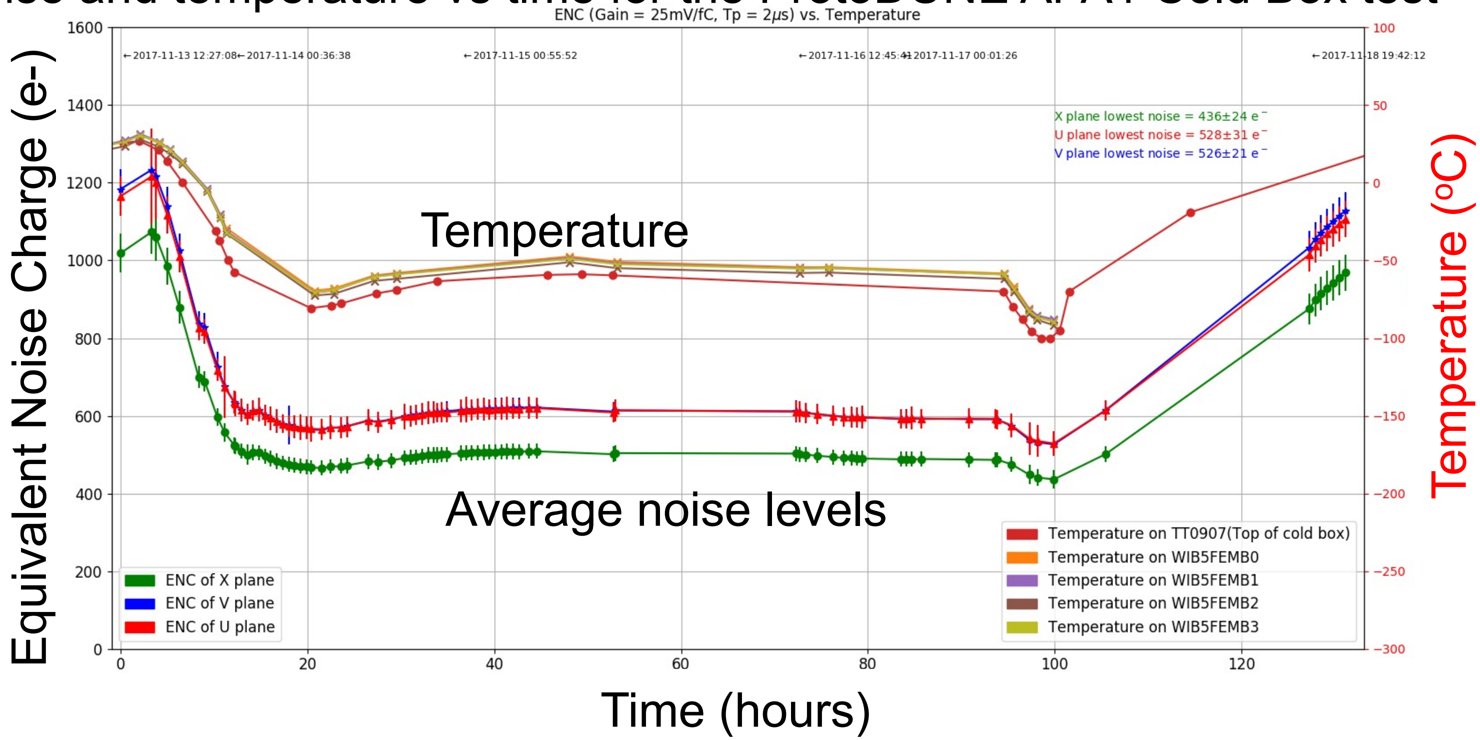
The Cold Box could test an entire APA + 20 FEMBs down to 160K using gas nitrogen

The critical tests were:
1. All electronics channels (2560 wires) responded to injected pulses
2. The noise is low enough to easily read out the electron charge picked up by the wires

Cold electronics and noise

A typical muon flying through the DUNE detector will deposit around 20,000 e^- on *each* wire. To achieve the DUNE physics goals, this means that the electronics must have the equivalent noise charge of < 1000 e^-

Noise and temperature vs time for the ProtoDUNE APA1 Cold Box test



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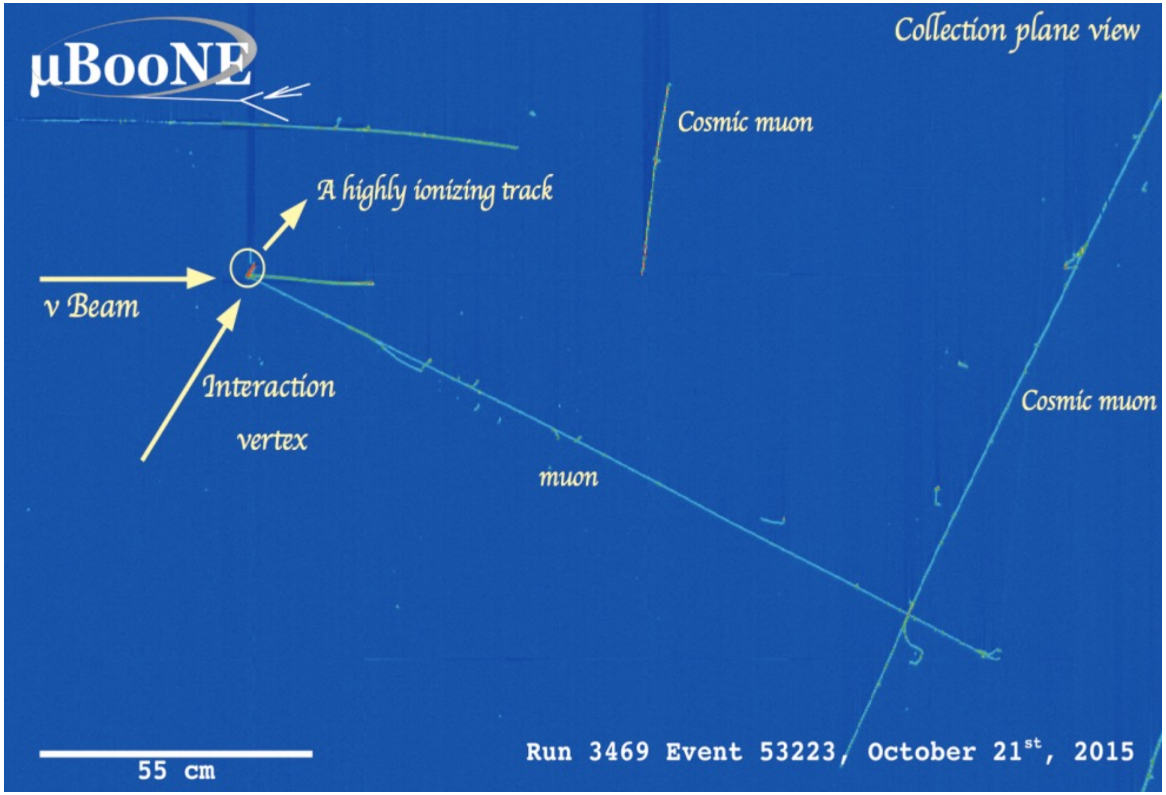
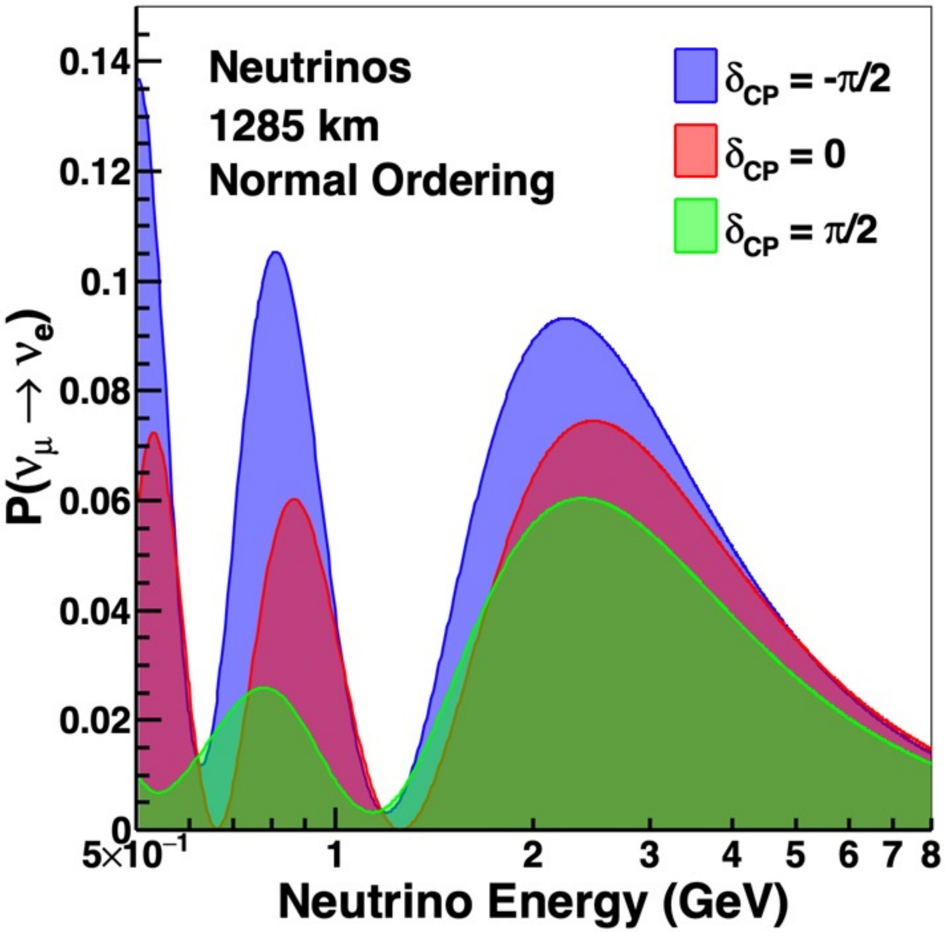
Neutrino event



Put it all together and we can make the incredibly clear pictures of neutrino interactions in the DUNE liquid argon time projection chambers that we need to distinguish the ν_e or ν_μ interactions and measure the neutrino properties

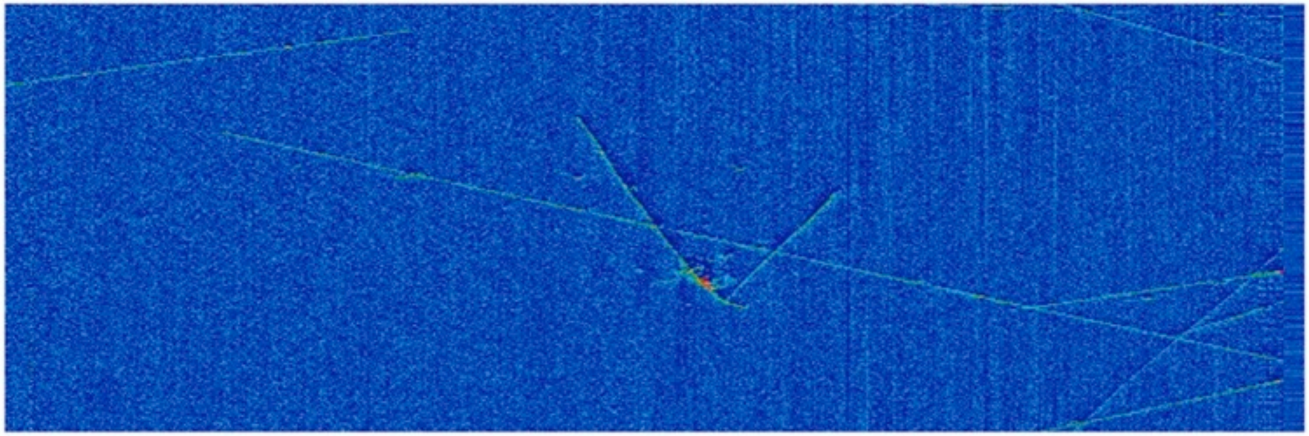
ν_e Appearance

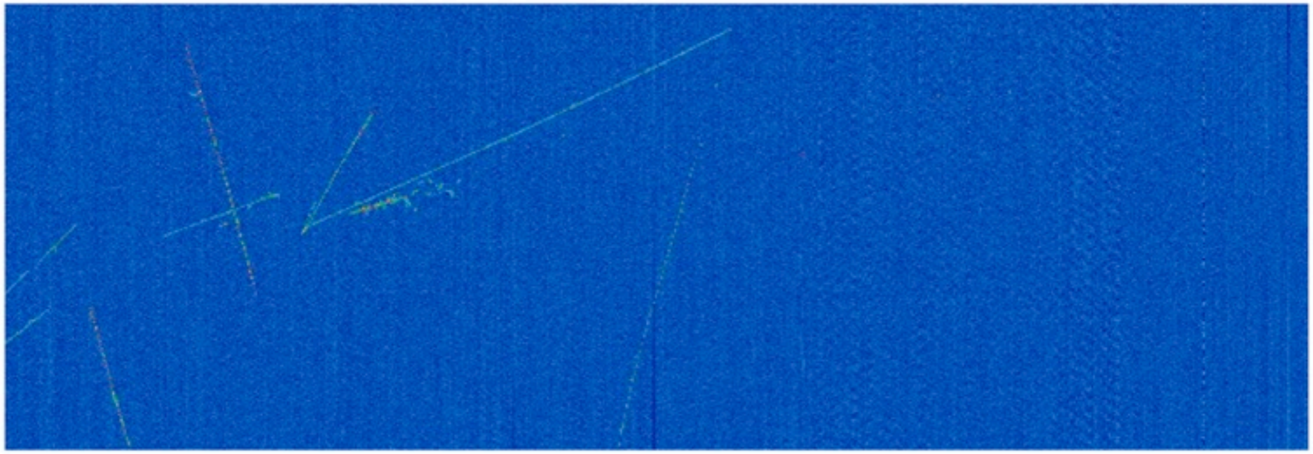
- We will count the number of ν_e at different neutrino energies that we measure in the DUNE far detector
- The shape of that distribution will measure the CP violating phase in the neutrino parameters!



Can you find the neutrino candidate?

These images are from the same event!



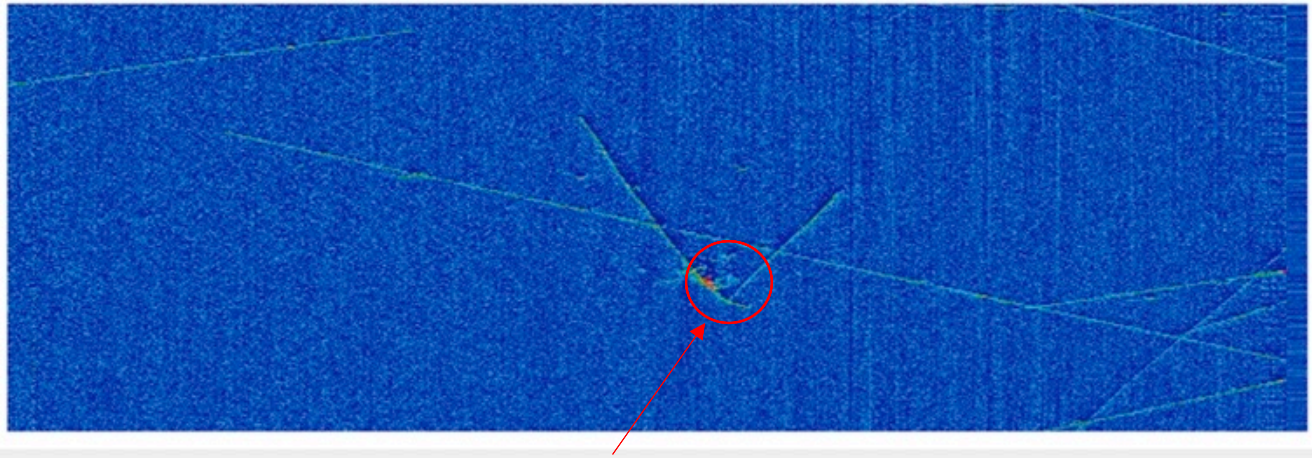


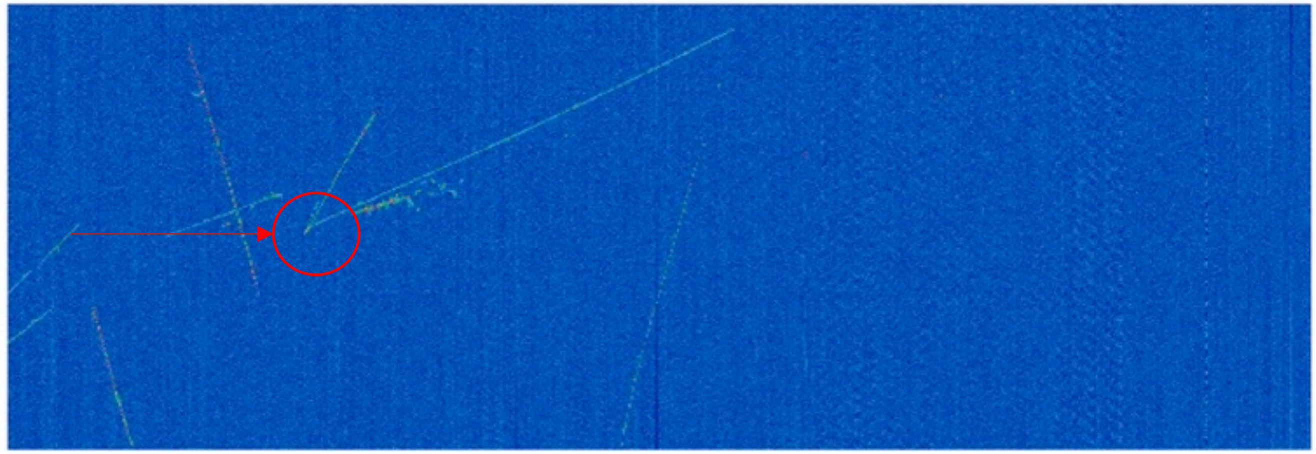
Side view

Can you find the neutrino candidate?

There it is!

These images are from the same event!

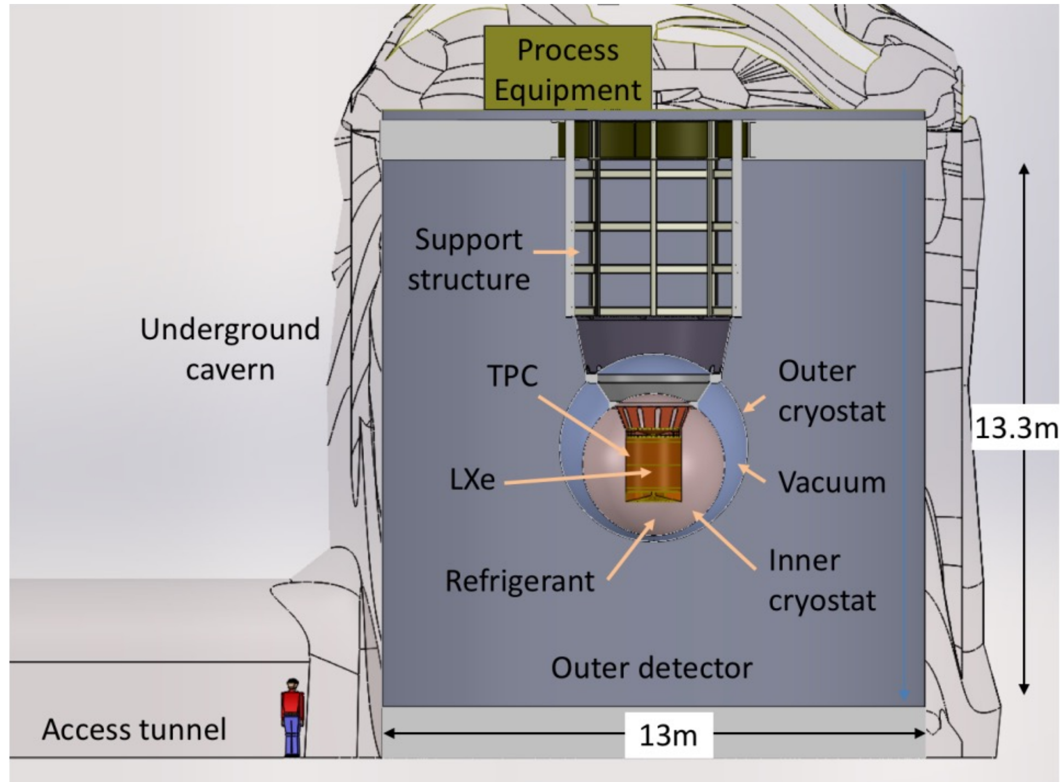




Side view

nEXO

- nEXO is a liquid xenon time projection chamber with about 4,000 kg fiducial volume of xenon enriched to 90% of ^{136}Xe
- Once the detector is running, we "sit and wait" for a neutrinoless double beta decay:



$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$$

Current experiments detect the emitted electrons

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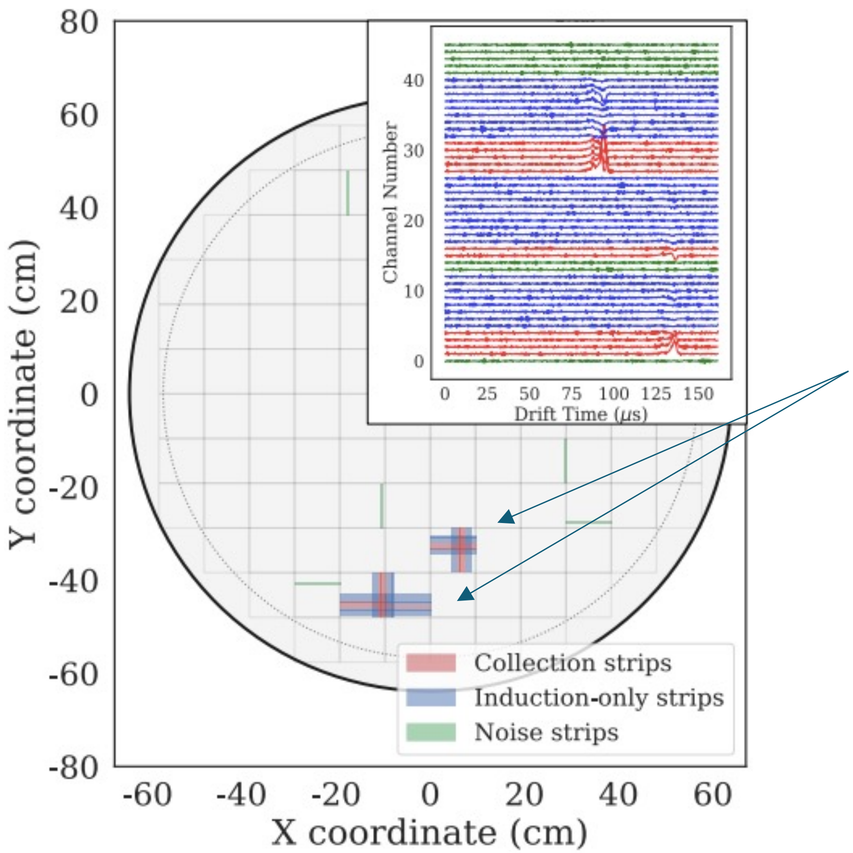
https://nexo.llnl.gov/

nEXO double beta decay signal



- The nEXO time projection chamber is looking "down" a cylinder filled with liquid xenon
- A double beta decay event looks like two electrons depositing charge on the readout planes a short distance apart
- The nEXO photon detector is needed to find the electron position vertically inside the cylinder and measure the total energy for each electron

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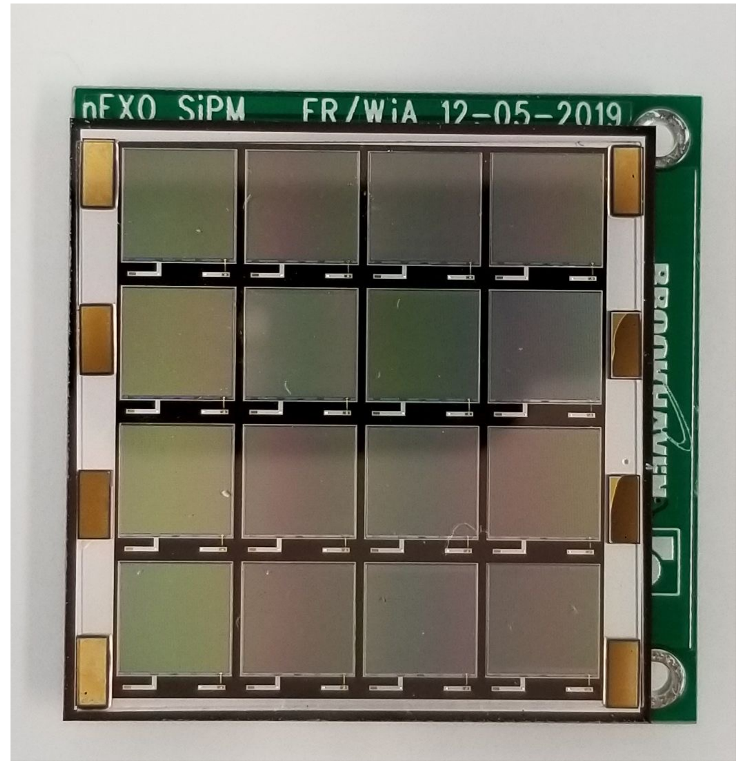
Silicon Photomultiplier (SiPM)

- SiPMs are small (up to 1x1 cm^2) active area
- SiPMs can detect down to single photons that arrive on their surface!
- Their gain is similar to a photomultiplier tube, generally around 10^6
- Importantly for nEXO, they are much smaller than photomultiplier tubes and can operate reliably at 165K



16 SiPMs fabricated by Hamamatsu Photonics in Japan, a candidate supplier for nEXO SiPMs

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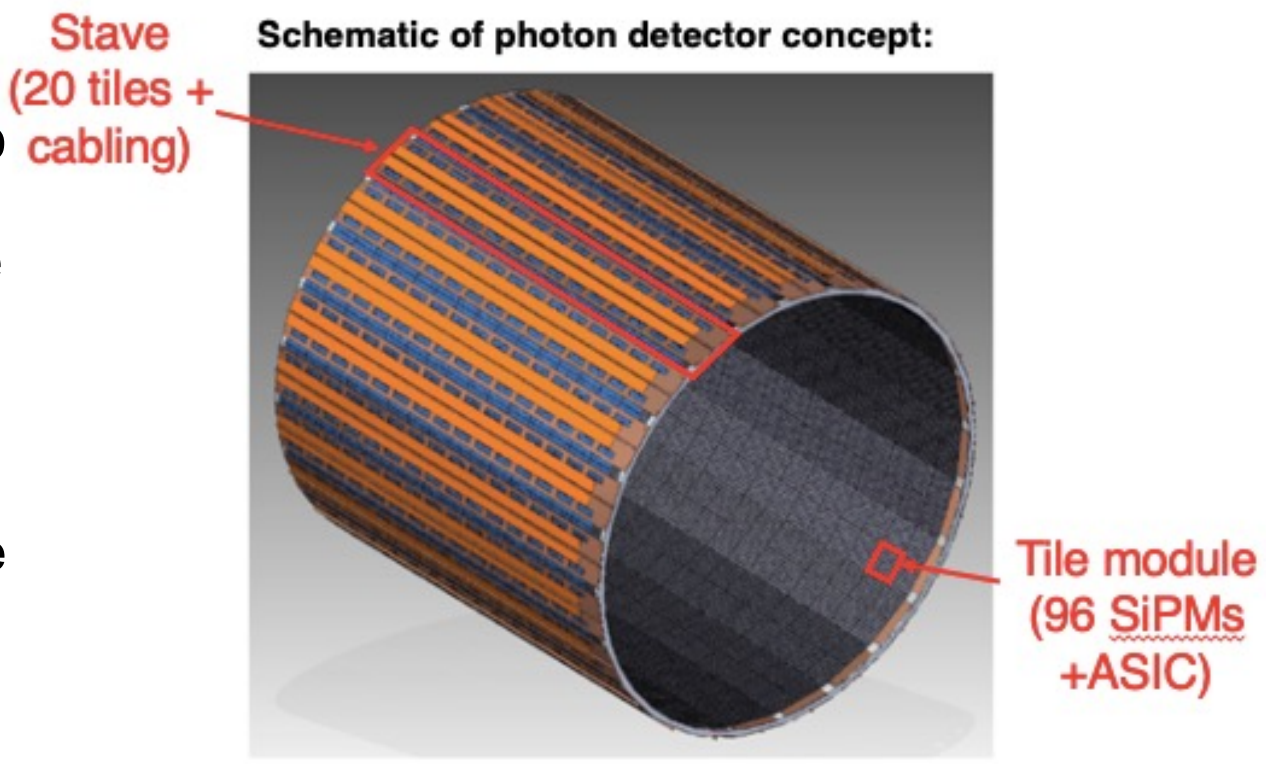
https://en.wikipedia.org/wiki/Silicon_photomultiplier

nEXO photon detector

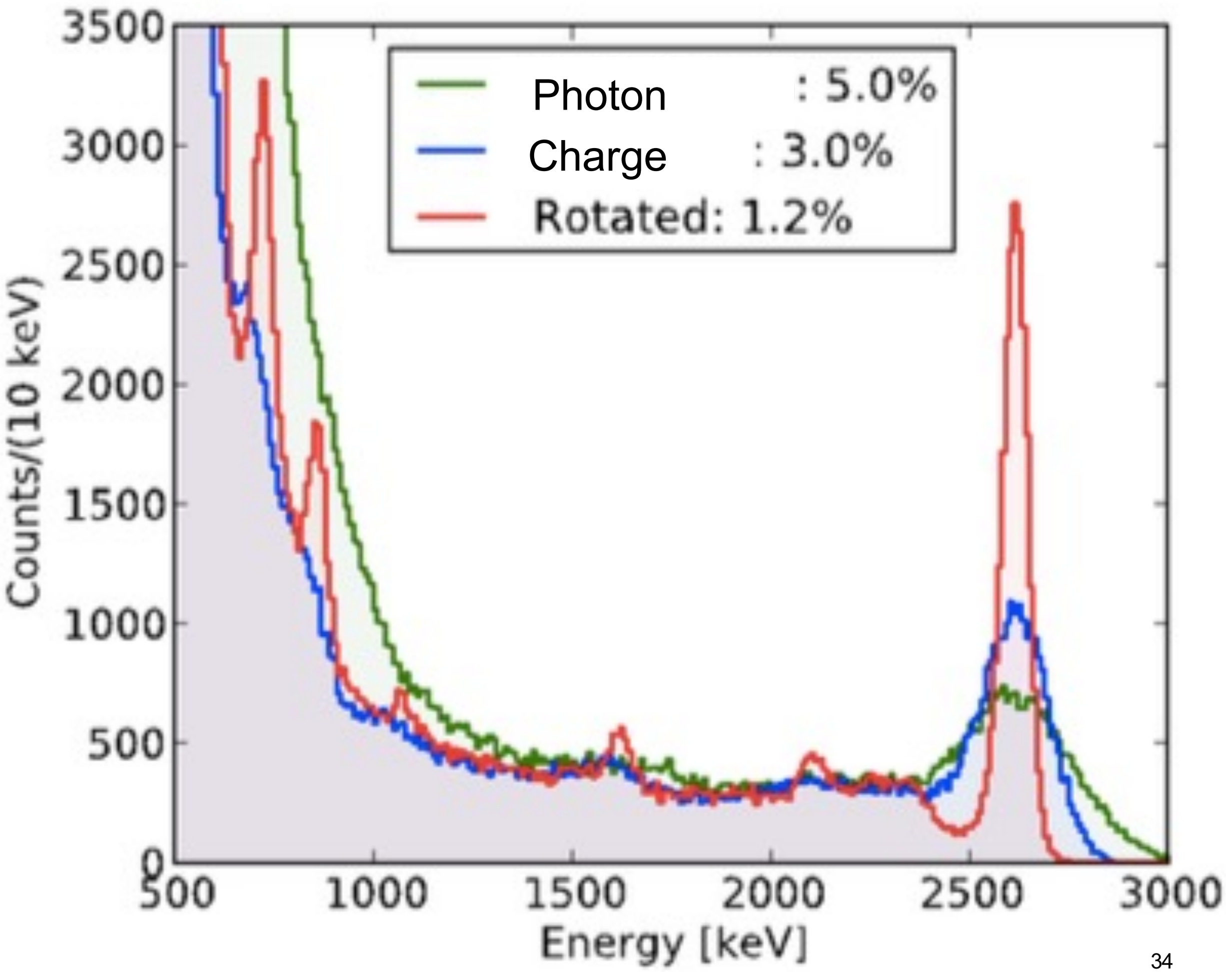
- The nEXO photon detector will use SiPMs to detect the light signal in the time projection chamber
  - nEXO will need about 46,000 SiPMs to achieve the level of light detection needed for the double beta decay measurement



Cold electronics using ASICs very similar to DUNE amplify, digitize, and transmit the signals

nEXO double beta decay spectrum

By combining the charge and photon energy into a combined measurement (aka ”rotated”) nEXO can clearly distinguish the neutrinoless double beta decay peak around 2.6 MeV if that process occurs at a high enough rate



Summary

- Neutrinos have some very compelling properties
  - Neutrino oscillation means they change flavor as they propagate
  - Neutrinos could be their own antiparticles
- We know how to build huge time projection chambers that can observe neutrino interactions
  - Both charge and light detection are necessary for these time projection chambers to make the measurements we need
  - Each method of detection has interesting technical challenges
- Studying these tiny particles helps to answer big questions about the origins of the universe and the origins of life

Thanks for your attention!

Questions?