# Neutrino Oscillations

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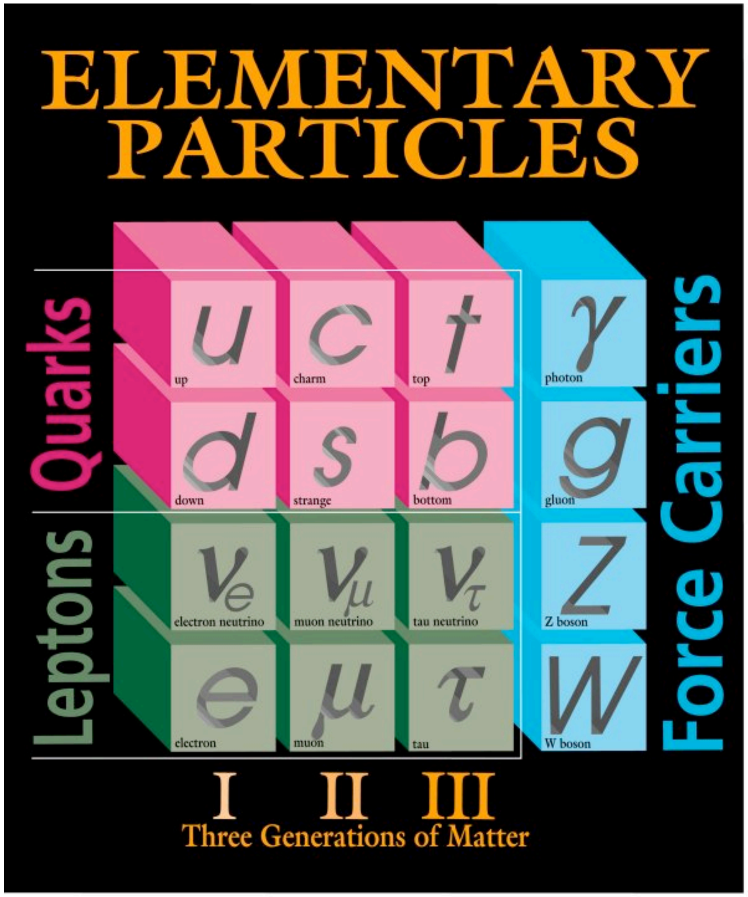
Neutrino oscillation experiments may be seeing signs of a new fundamental particle, the sterile neutrino!

# Outline

- Neutrinos
  - Properties
  - Sources
- Neutrino Oscillations
- Experiments
  - MiniBooNE
  - MicroBooNE

# Neutrinos are fundamental particles that interact via the weak force

- Neutrinos are neutral leptons
- Interact with other particles via the W+, W- and Z bosons
- Small probability of interaction
- Neutrinos were originally predicted to be mass-less
- Oscillations measurements over the last two decades are evidence that neutrinos have non-zero mass



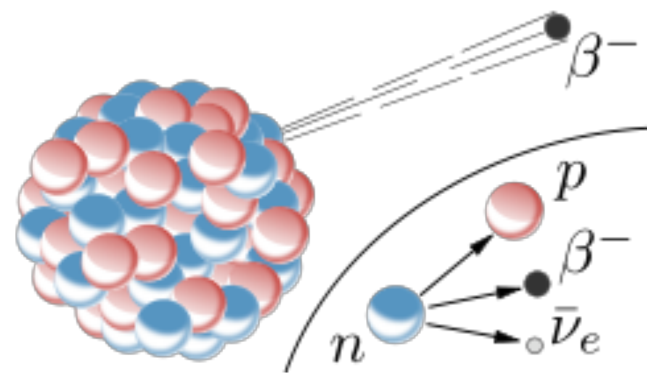

Fermilab 95-759

# Neutrinos are produced in nuclear reactions, such as beta decay

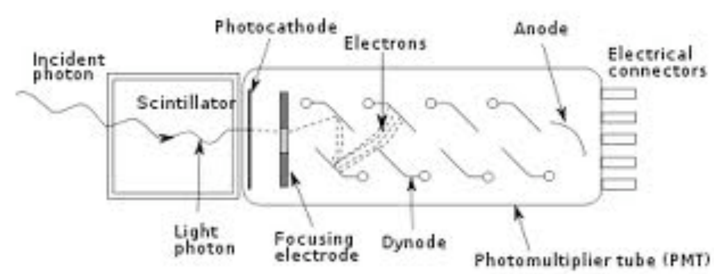
- Neutrinos were first hypothesized to explain the missing energy in beta decay
- The Reines-Cowan Experiment was the first detection of neutrinos via inverse beta decay

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

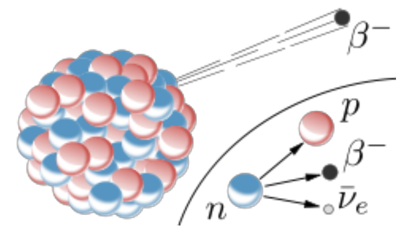
- Anti-neutrinos from a reactor interacted with protons in a tank and produced light
- Photomultiplier tubes detected the light



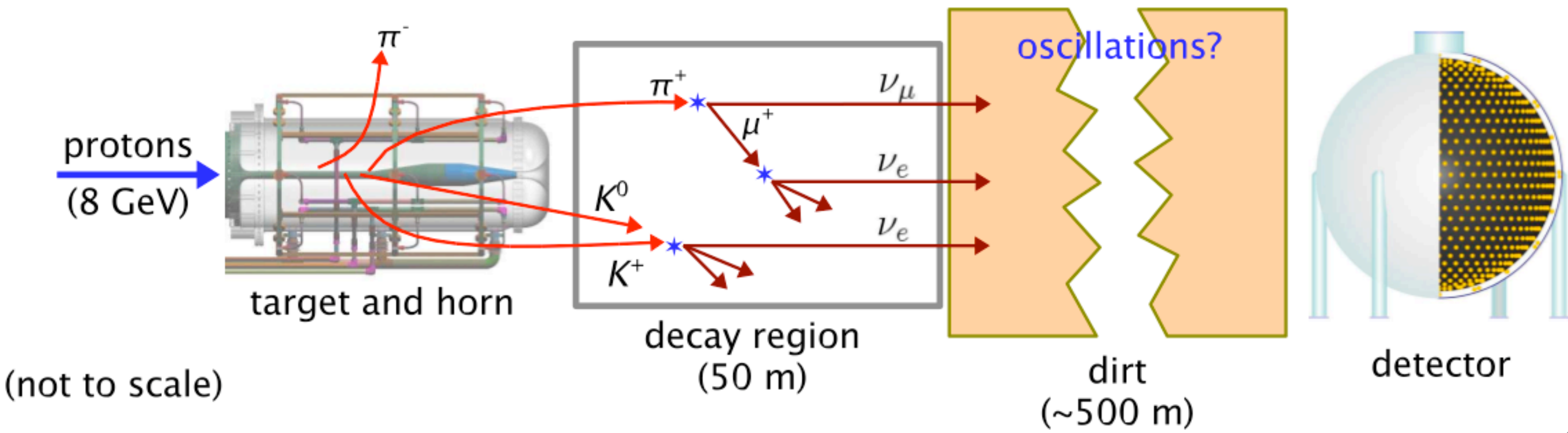

$$n \rightarrow p + e^- + \bar{\nu}_e.$$



# Neutrino Sources in Modern Experiments



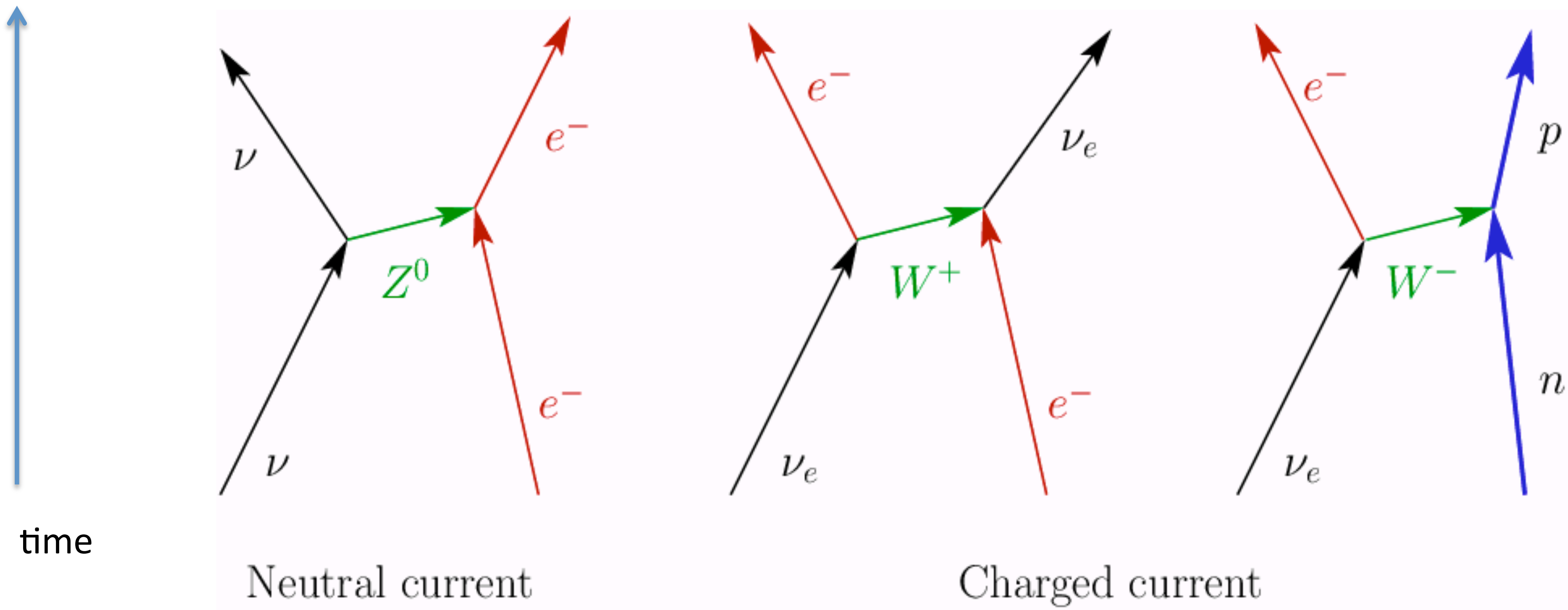

- Antineutrinos are produced by beta decay in nuclear reactors
- Particle accelerators produce intense neutrino beams
  - Accelerated protons are smashed into a target
  - Unstable charged pions and kaons are produced
  - Magnetic fields focus the pions and kaons in a beam, where they decay into neutrinos as they travel



# Neutrinos come in three flavors

- Electron, muon, and tau neutrinos
- Produced and detected in association with the corresponding charged lepton
- Neutrino interactions conserve lepton flavor number

# Neutrinos interact with matter in three different ways




- Anti-electron-neutrino interactions will produce positrons as final state particles
- Lepton Flavor Conservation
- Muon neutrinos produce muons, tau neutrinos produce taus

# Neutrino flavor eigenstates can be linear combinations of mass states and vice versa

- The mixing matrix:

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

- The matrix for the two-neutrino case:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

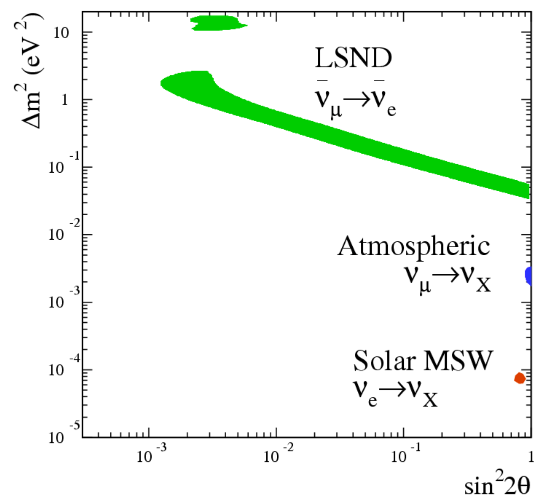
- Probability of Oscillation:

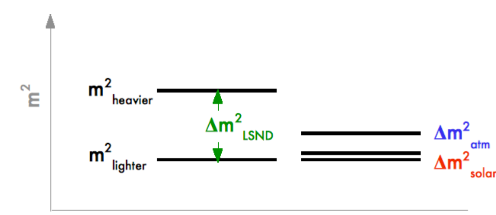
$\Delta m^2 = (m_2)^2 - (m_1)^2$

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\text{GeV}}{\text{eV}^2\,\text{km}}\right).$$

# Neutrinos oscillation experiments look for the disappearance or appearance of neutrinos

- Missing solar neutrinos and atmospheric neutrinos
- Reactor experiments look for disappearance of neutrinos to calculate mixing angles in the mixing matrix
- LSND experiment (Liquid Scintillator Neutrino Detector)
  - Used an accelerator source to confirm neutrino oscillation
  - Saw an excess of electron neutrino events in a muon neutrino beam
  - Results weren't compatible with the results of other experiments

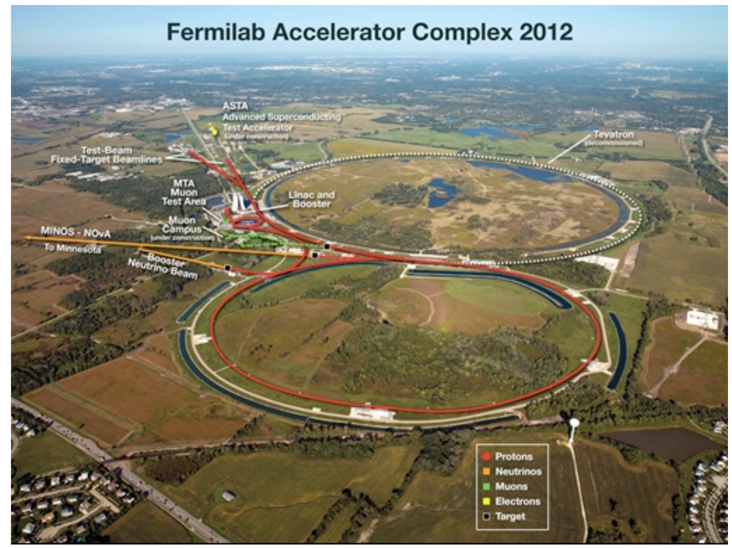


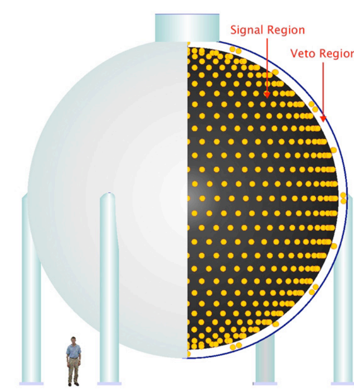

In conflict with well-understood, three-neutrino mixing model in the Standard Model (defined by only two independent oscillation signatures)

# MiniBooNE detected short baseline $\nu_\mu$ to $\nu_e$ oscillations at Fermilab

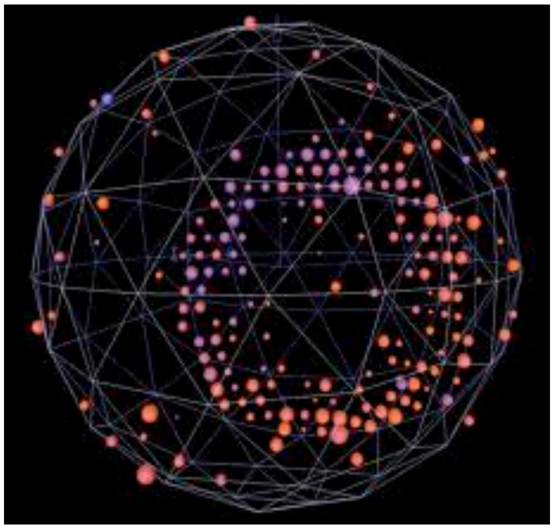
- Designed to investigate the LSND results
- Similar L/E as LSND, sensitive to same $\Delta m^2$
- Uses muon neutrinos from the Booster Neutrino Beam at Fermi National Accelerator Laboratory
- Tank of mineral oil and photomultiplier tubes to detect muon and electron neutrino signals




MiniBooNE Detector

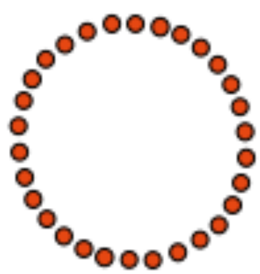


# MiniBooNE is a Cherenkov light detector

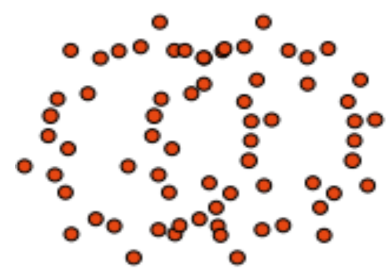


- Cherenkov radiation is emitted when charged particles pass through medium faster than the phase velocity of light in that medium
- Used Cherenkov light to detect electron and muon neutrino signals

Electron Neutrino



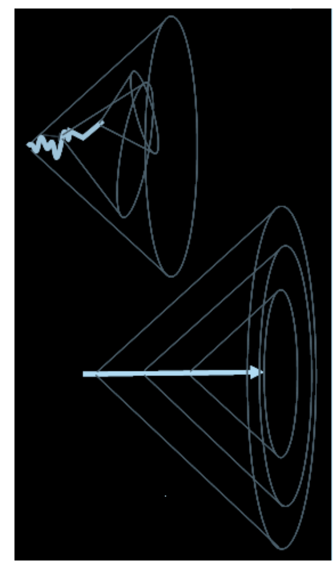
Muon Neutrino



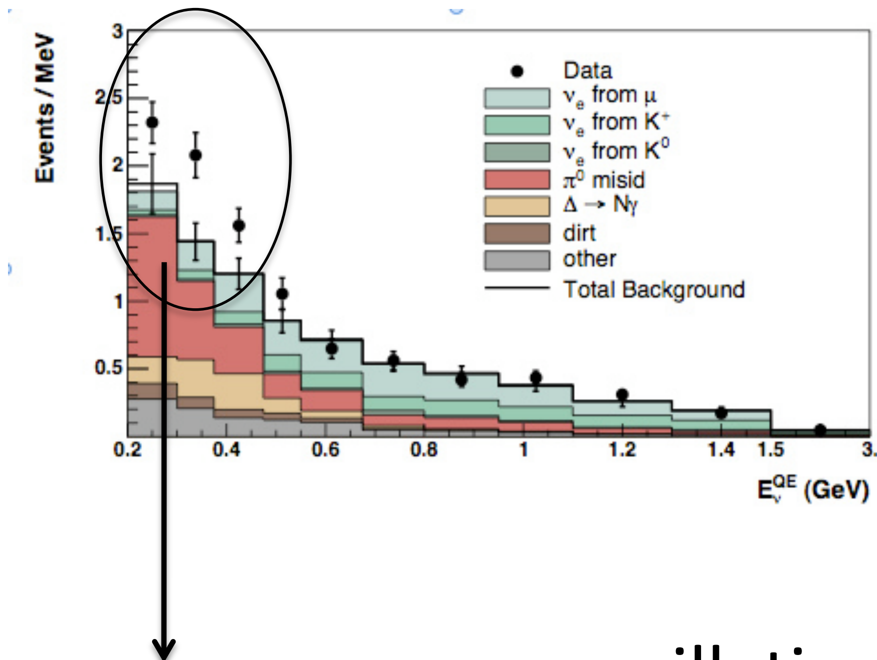
Pi0 (two photons)

e

μ



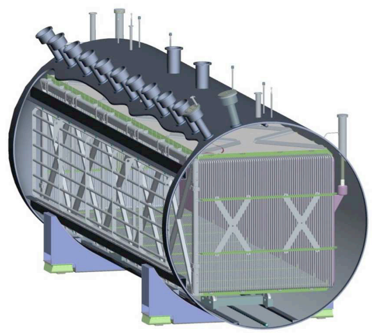
# MiniBooNE saw an unexpected excess of electron neutrino events



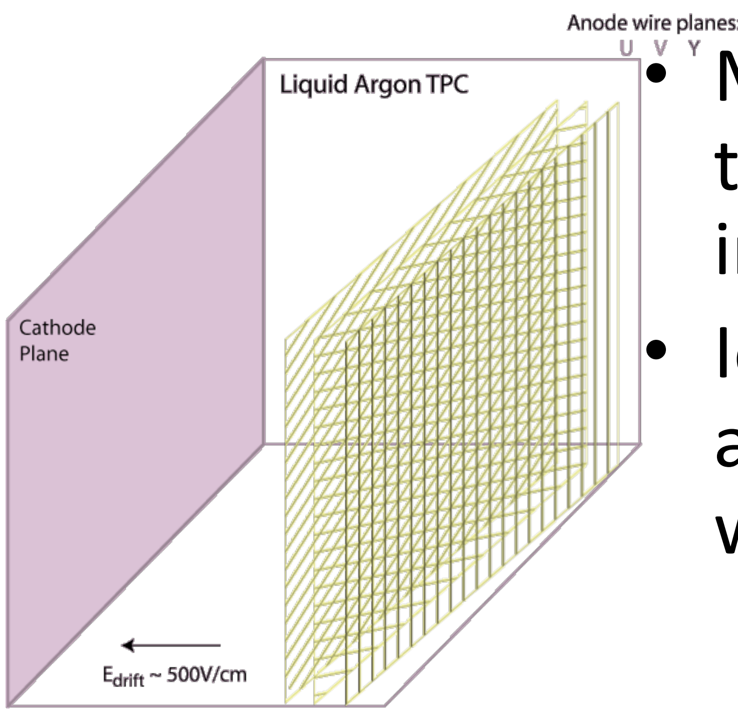

- Sign of the sterile neutrino?
- Muon neutrinos oscillate to a sterile neutrino, which oscillates back to an electron neutrino when detected

- $\nu_\mu \longrightarrow \nu_s \longrightarrow \nu_e$ oscillations??
- Are we sure the excess is really not background?
- MiniBooNE can't easily distinguish electron signals from photon signals

# MicroBooNE is designed to investigate the MiniBooNE excess

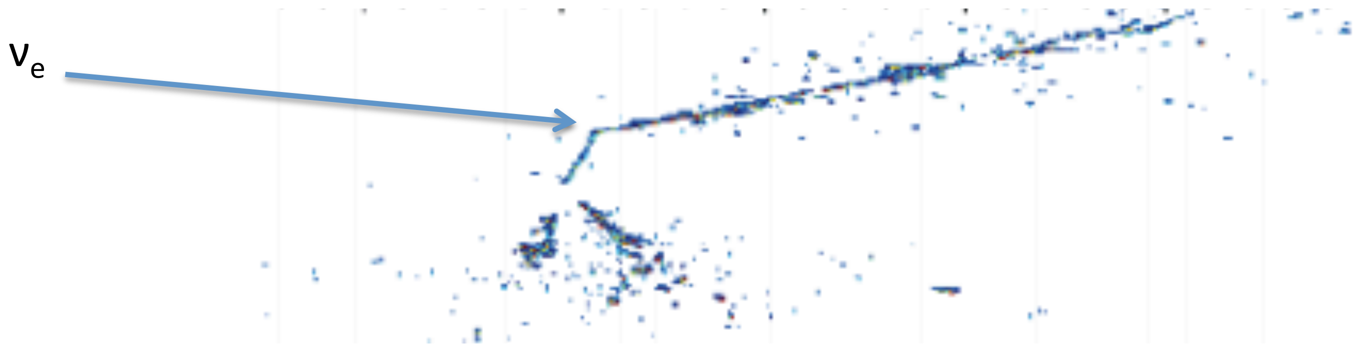


- MicroBooNE is a Liquid Argon Time Projection Chamber (LArTPC) neutrino detector being built a Fermilab




- Muon and electron neutrinos from the Booster Neutrino Beam weakly interact with the argon
- Ionization charges drift in an applied electric field toward three wire planes

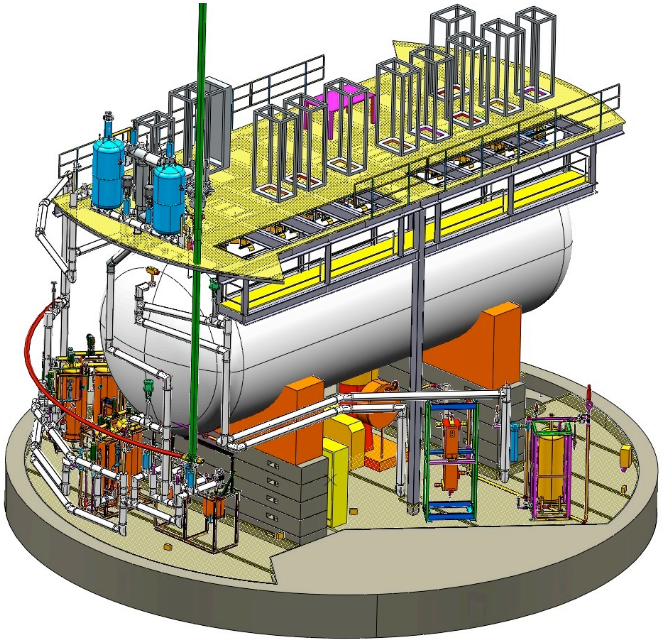
# The three wire planes allow us to produce 3-D images of the events




- Photon and electron signals still look similar, but we can now look at the energy deposition of the particles
- Electrons have a lower dE/dx that photons
- This will confirm whether or not electrons or photons are causing the MiniBooNE excess

# MicroBooNE will be the largest TPC detector built in the US

- TPC's are a relatively new technology
- Future experiments will use TPC's because of their good energy resolution

# Summary

- Intense neutrino beams and large scale detectors make it possible to study neutrinos

- Neutrino oscillations are a quantum mechanical effect

- Oscillation experiments may be showing the first signs of the sterile neutrino

- Neutrinos are tiny particles that are providing answers to important questions in fundamental physics

Thanks for listening!