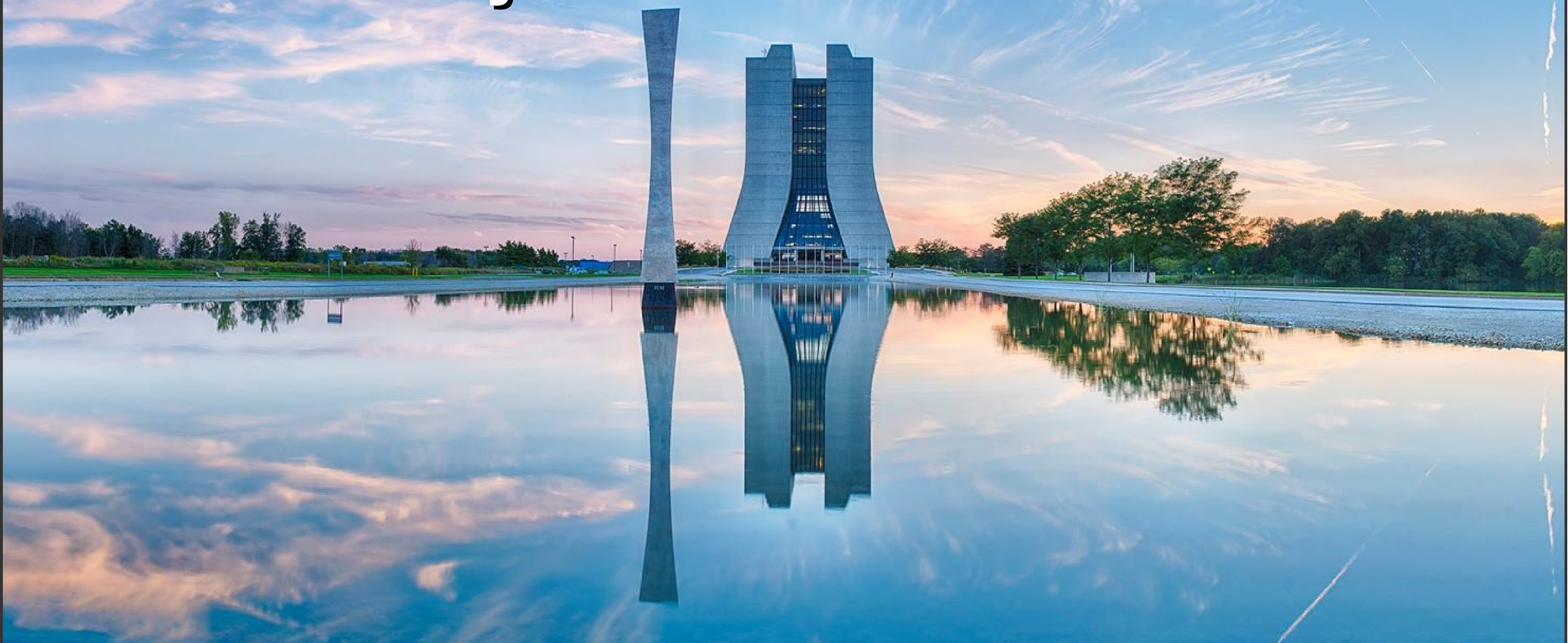
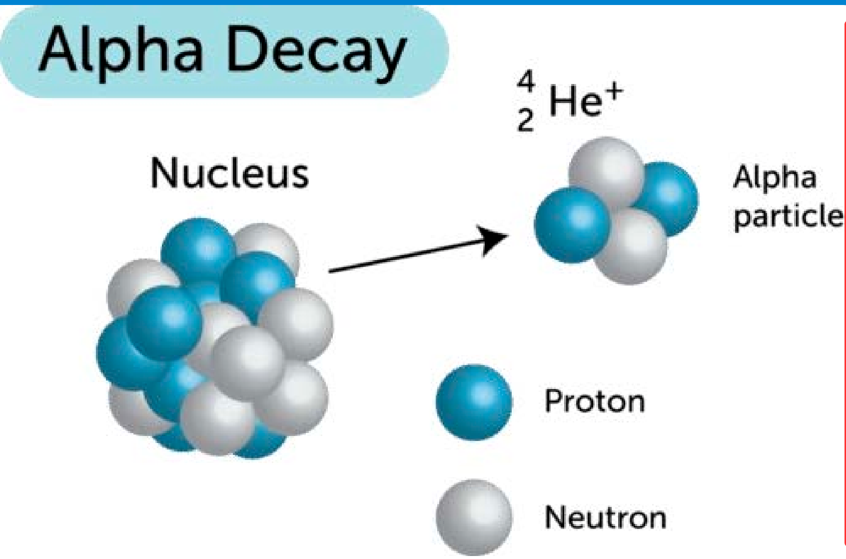
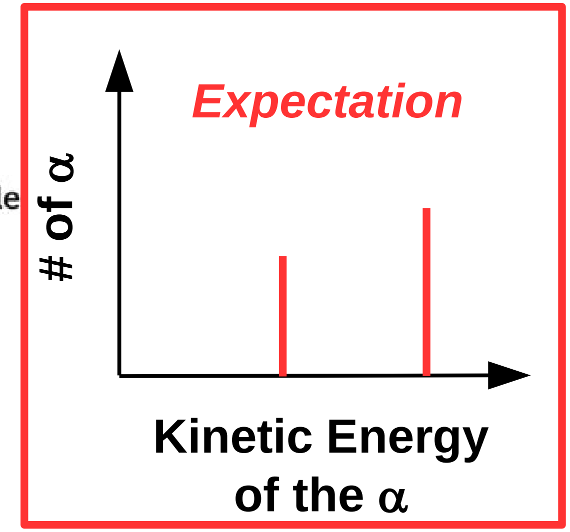
The Fermilab Neutrino Program & Liquid Argon Time Projection Chambers

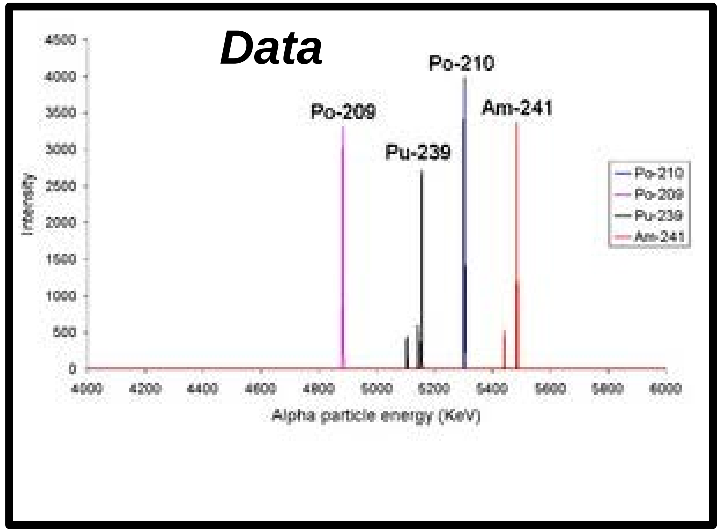


Jonathan Asaadi
University of Texas Arlington

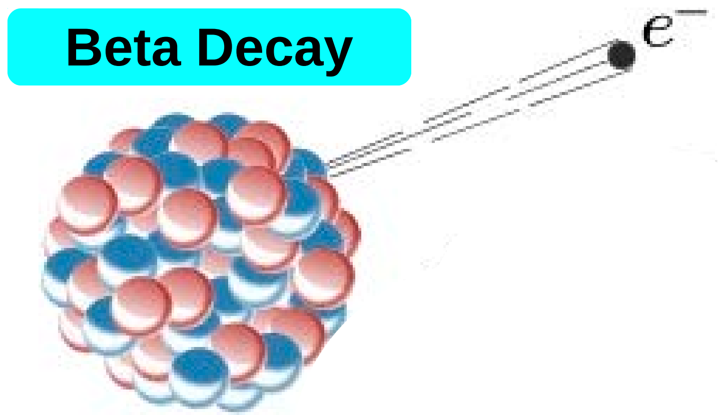
α-Decay

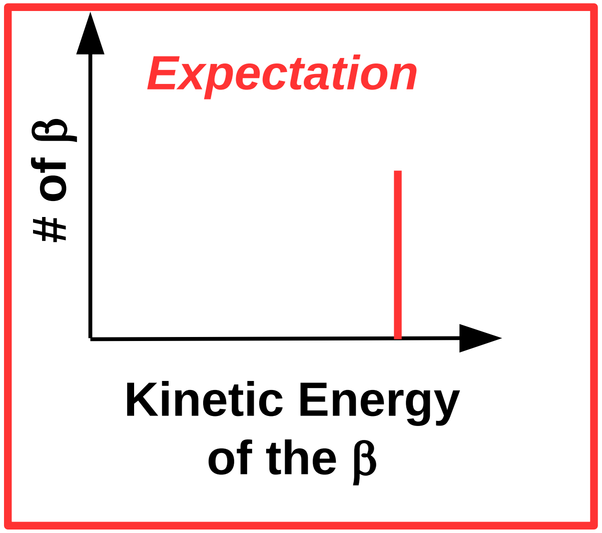






In the early 1900's there was a puzzle when looking at radioactive decay





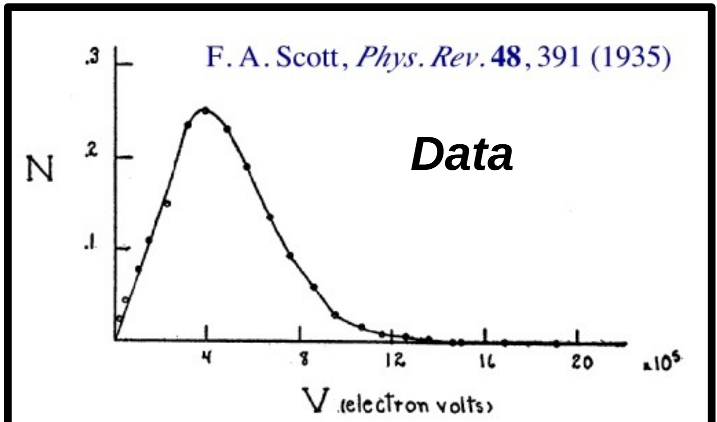
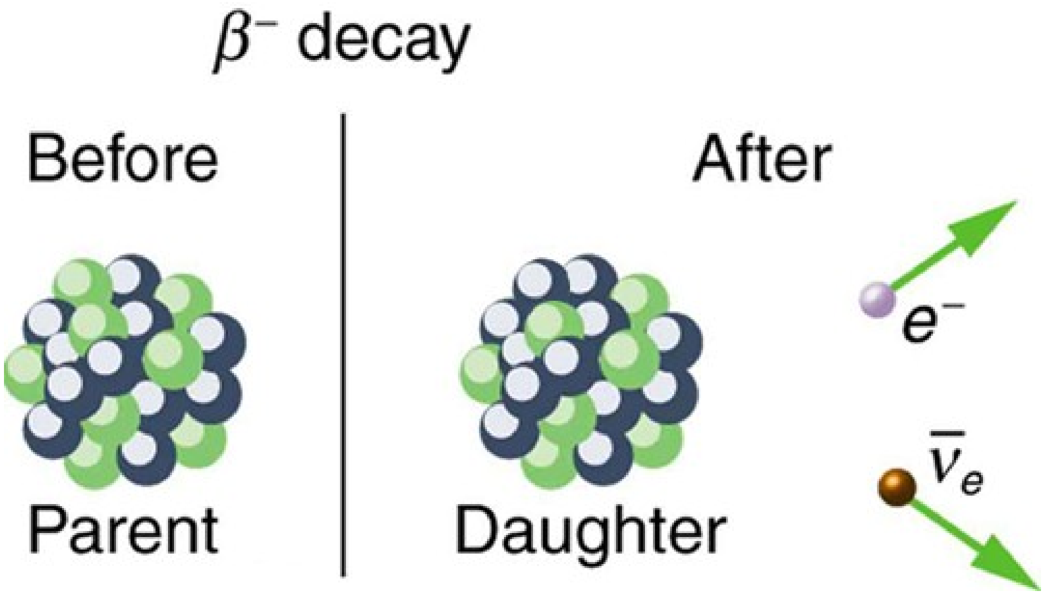
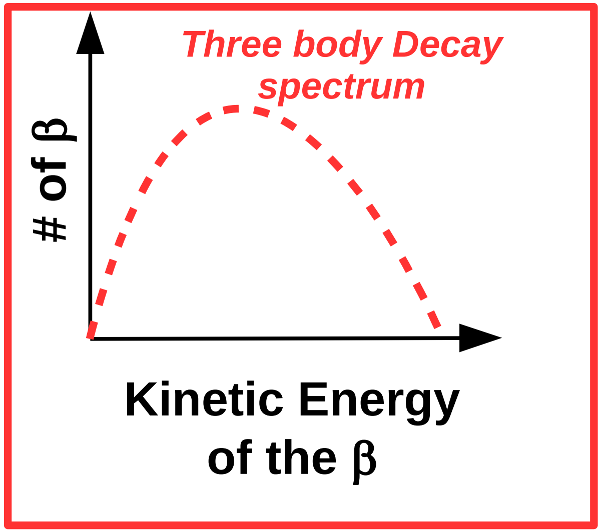


FIG. 5. Energy distribution curve of the beta-rays.

Desperate Remedy

- **1930 W. Pauli**
  Pauli's solution was to postulate there was a third particle in the decay who's mass is "not greater than 0.01 the proton mass" and who's ionizing power is "not greater than e x 10^{-13} cm"

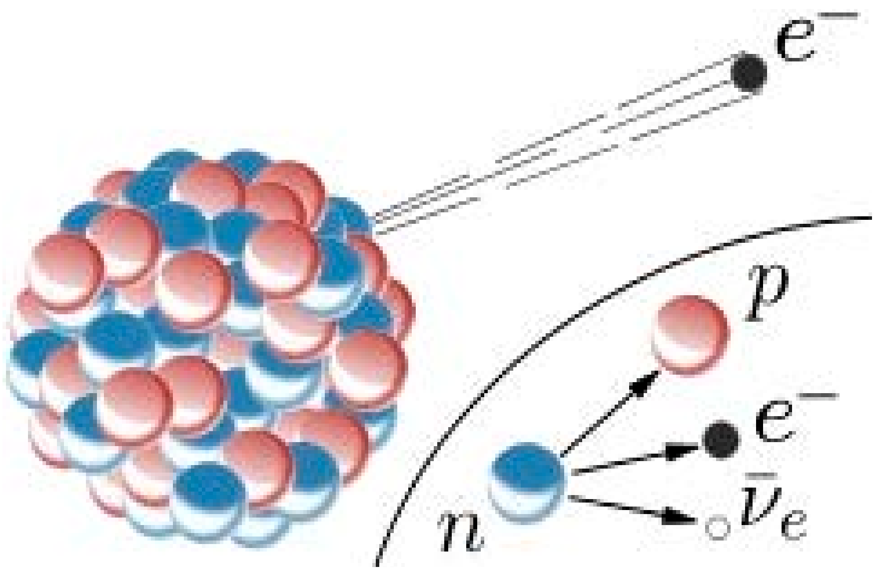




Desperate Remedy

- **<u>1930 W. Pauli</u>**
  "I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do"

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



The challenge to detect ν's

- **Hans Bethe concludes if you observe beta-decay**

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

- **Then the inverse should also happen**

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

- **With a cross-section, though, that was really small**

$$\sigma \approx 10^{-44}\,\mathrm{cm}^{2}$$

- **This give a neutrino a mean free path in water of**

$$\lambda = \frac{1}{n\sigma} \approx 1.5\,x\,10^{21}\,\mathrm{cm} \approx 1600\,\text{light years}$$

Not great news for experimentalist

You give me a problem and I'll give you an experiment

1951 Frederick Reines proposes to use organic scintillator (new'ish technology) to look for the inverse beta decay resulting from the flux of neutrinos released during the detention of a nuclear bomb

Project Poltergeist

(The real intensity frontier)

The experiment was never realized

(I have no idea why not!!!!)

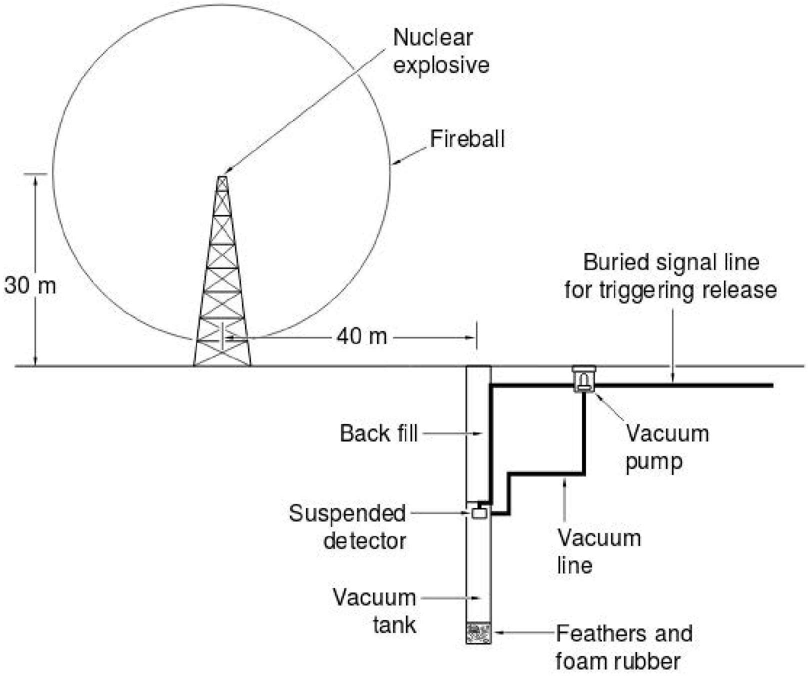
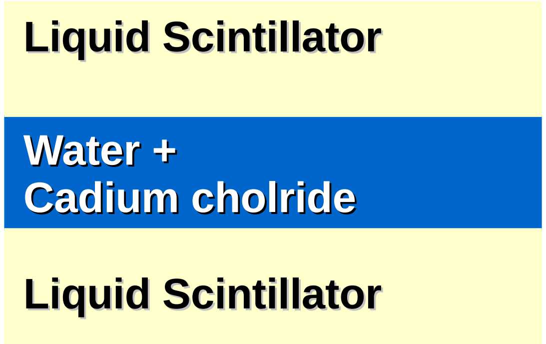
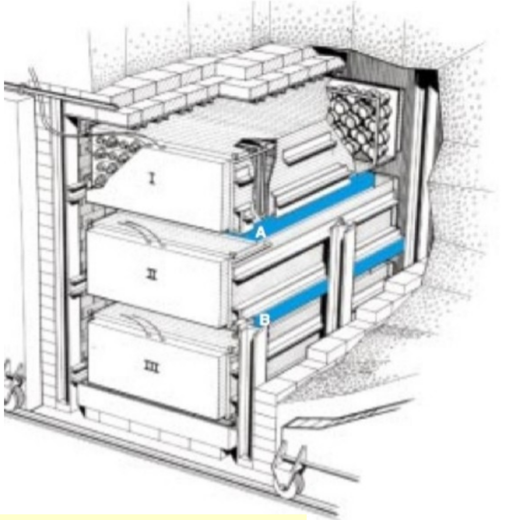


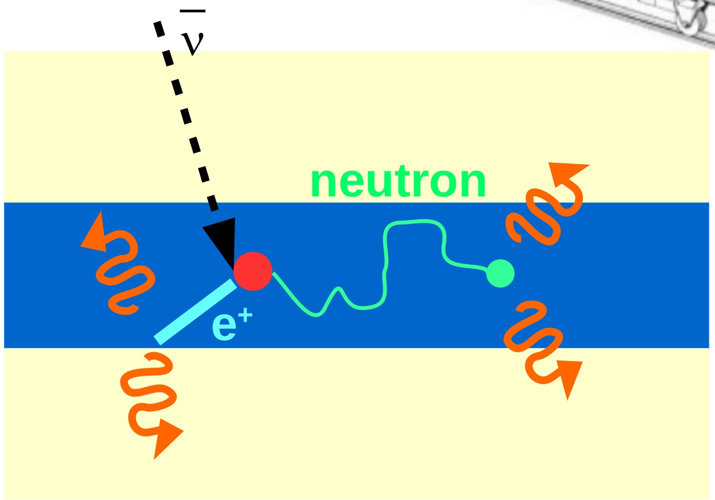
Figure 1. Detecting Neutrinos from a Nuclear Explosion
Antineutrinos from the fireball of a nuclear device would impinge on a liquid scintillation detector suspended in the hole dug below ground at a distance of about 40 meters from the 30-meter-high tower. In the original scheme of Reines and Cowan, 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.

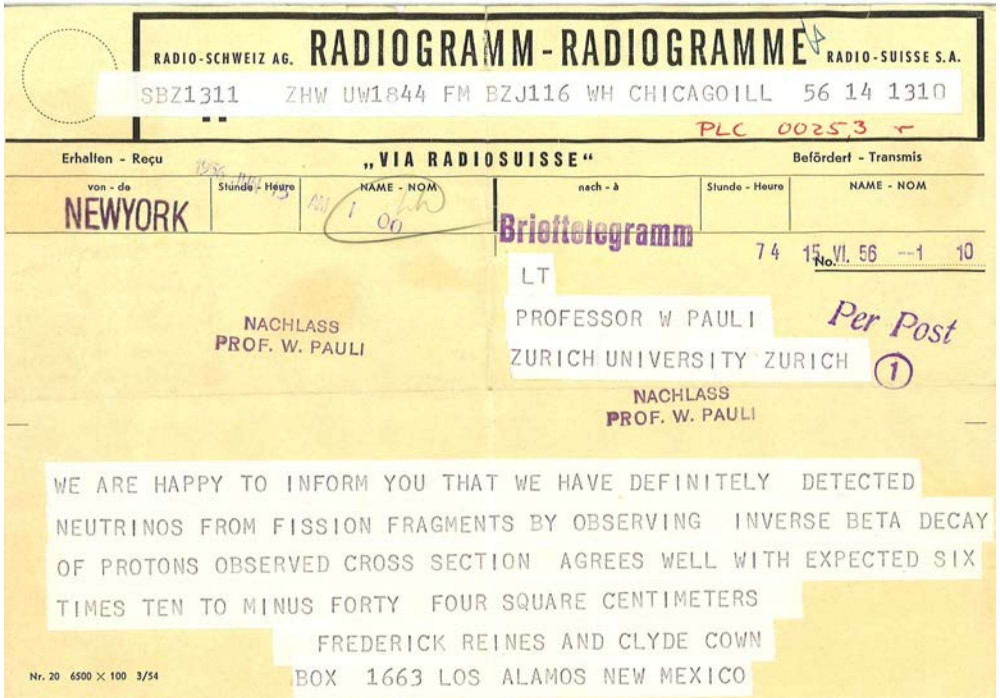
A more measured approach

- Instead, in 1956 a new detector is built near (11 meters away from) a nuclear reactor (strong source of ν's) and the neutrino is successfully observed









RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

PLC 00253

Erhalten - Reçu „VIA RADIOSUISSE" Befördert - Transmis

von - de: NEWYORK | Stunde - Heure | NAME - NOM | nach - à: Briefftelegramm | Stunde - Heure | NAME - NOM

74 15.VI.56 --1 10

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

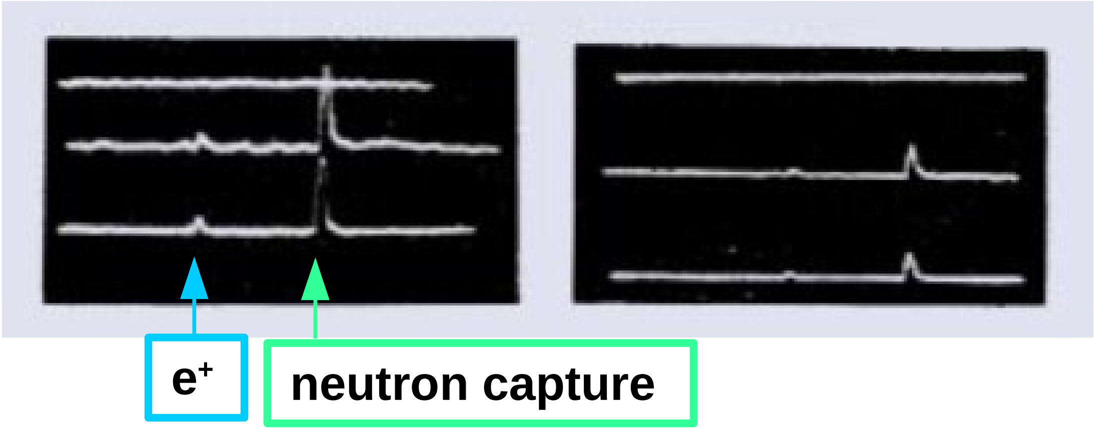
NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

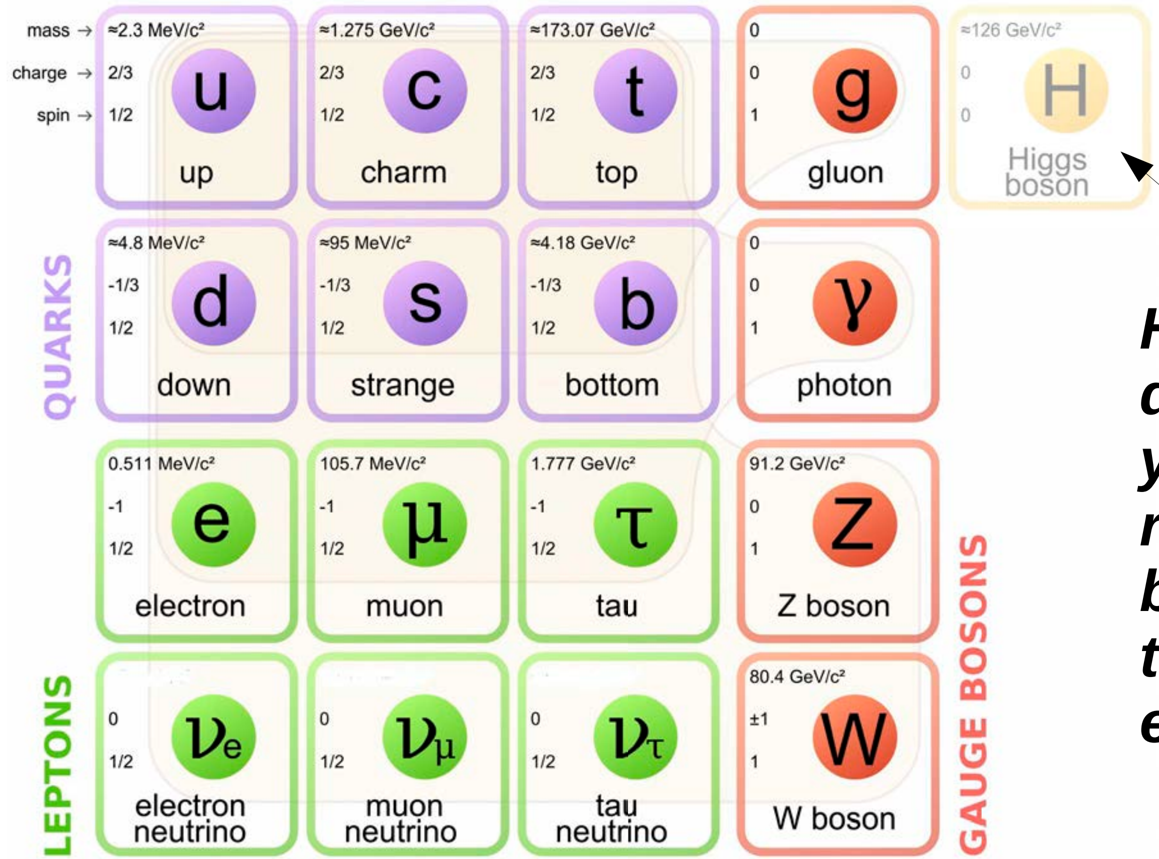
Nr. 20 6500 X 100 3/54



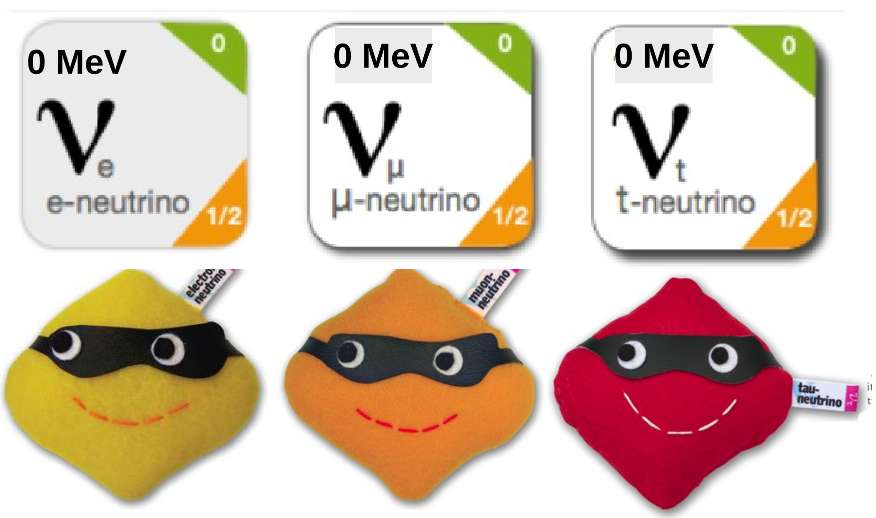
Fast forward 40 years

- **Skipping a lot of history here which establishes neutrinos as a piece of the standard model of particle physics**
- **Skipping over the some mysteries which pop up and remained a mystery for a number of years**
  - Solar neutrino puzzle

The picture of things



Hadn't been discovered yet….but good reason to believe it was the right explanation



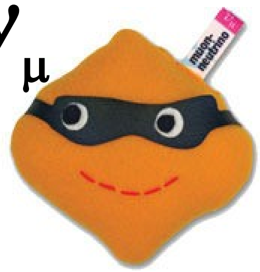
As recent as 1998 our view of neutrinos was simple:

1) 3 Flavors
2) Interact via Weak Force
3) Massless

Neutrinos only interact via the weak nuclear force

(They carry no charge)

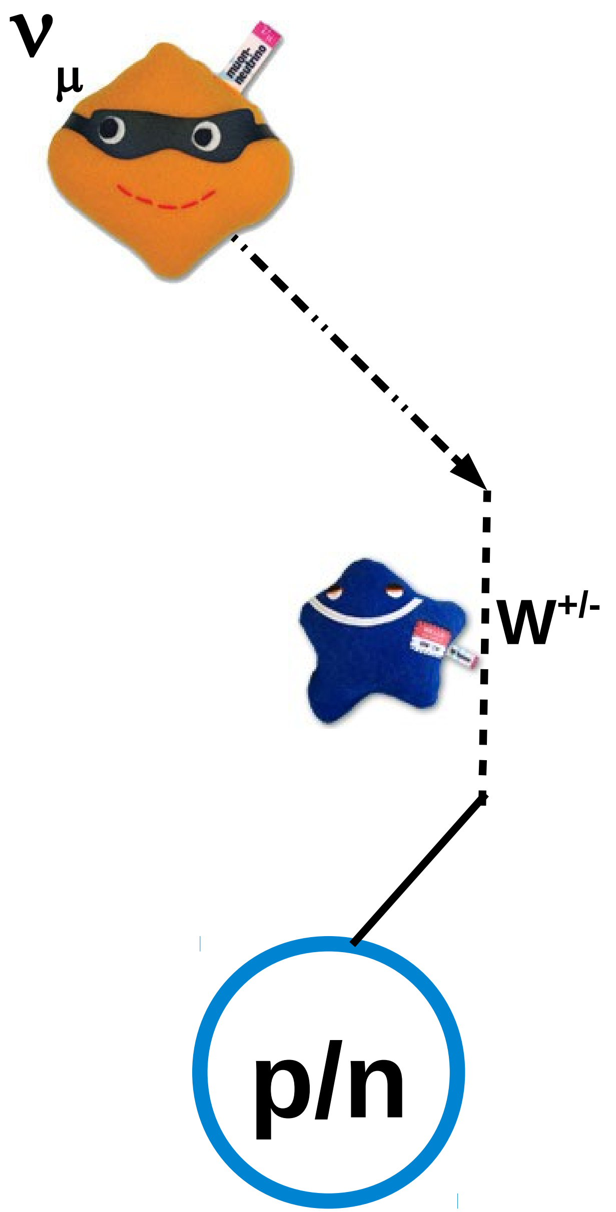
ν_μ



p/n

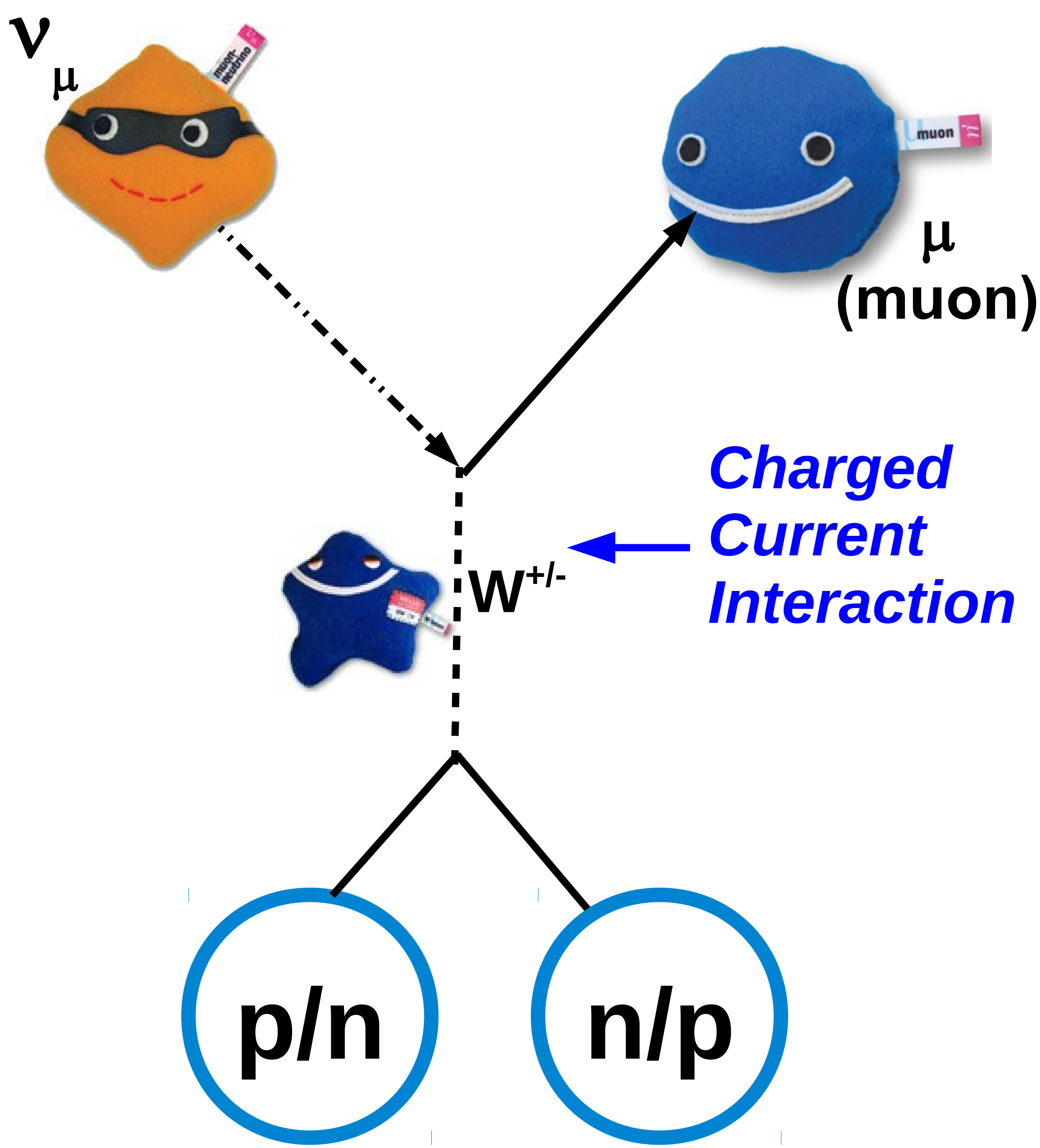
Neutrinos only interact via the weak nuclear force

(They carry no charge)



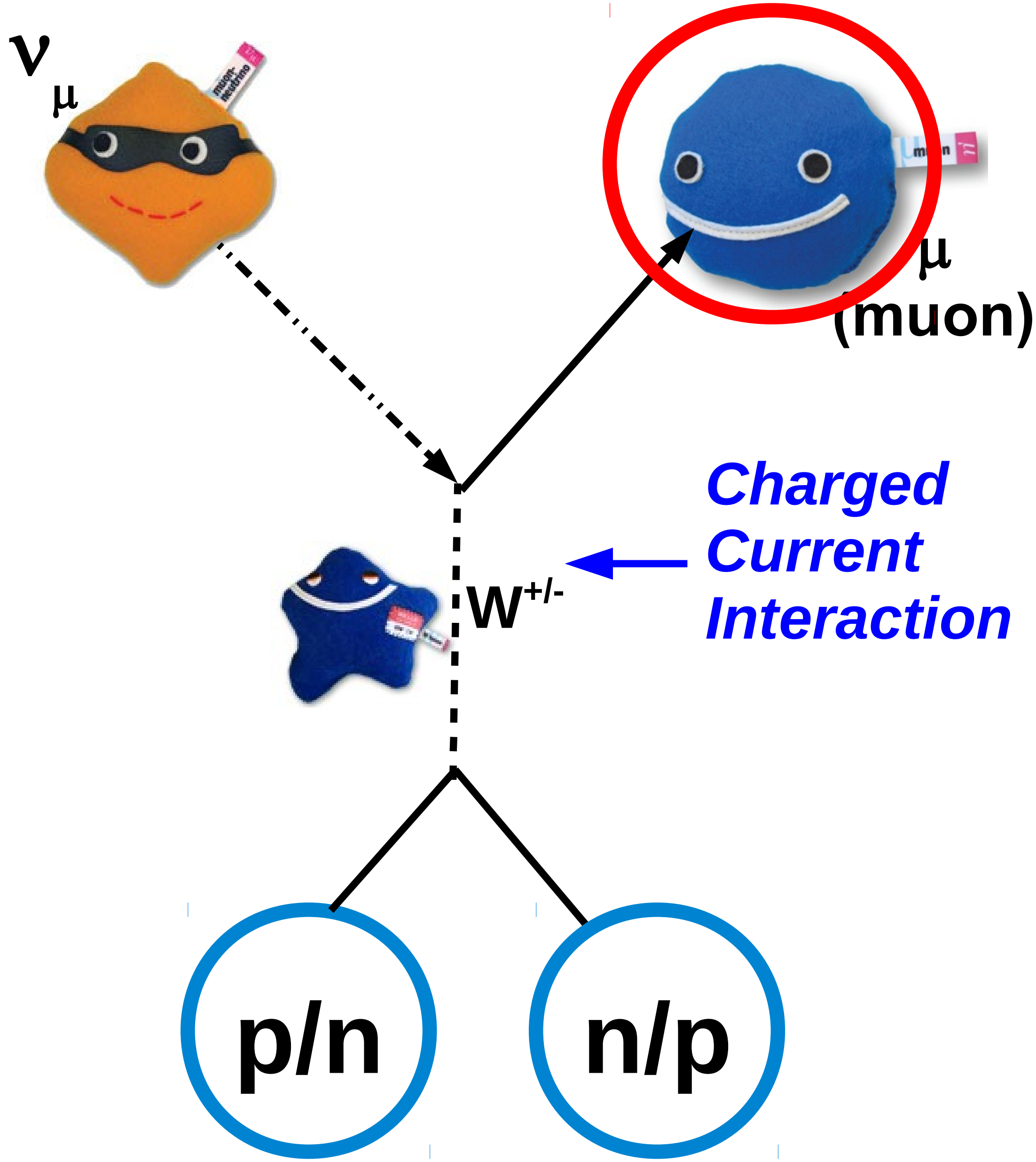
Neutrinos only interact via the weak nuclear force

(They carry no charge)



Neutrinos only interact via the weak nuclear force

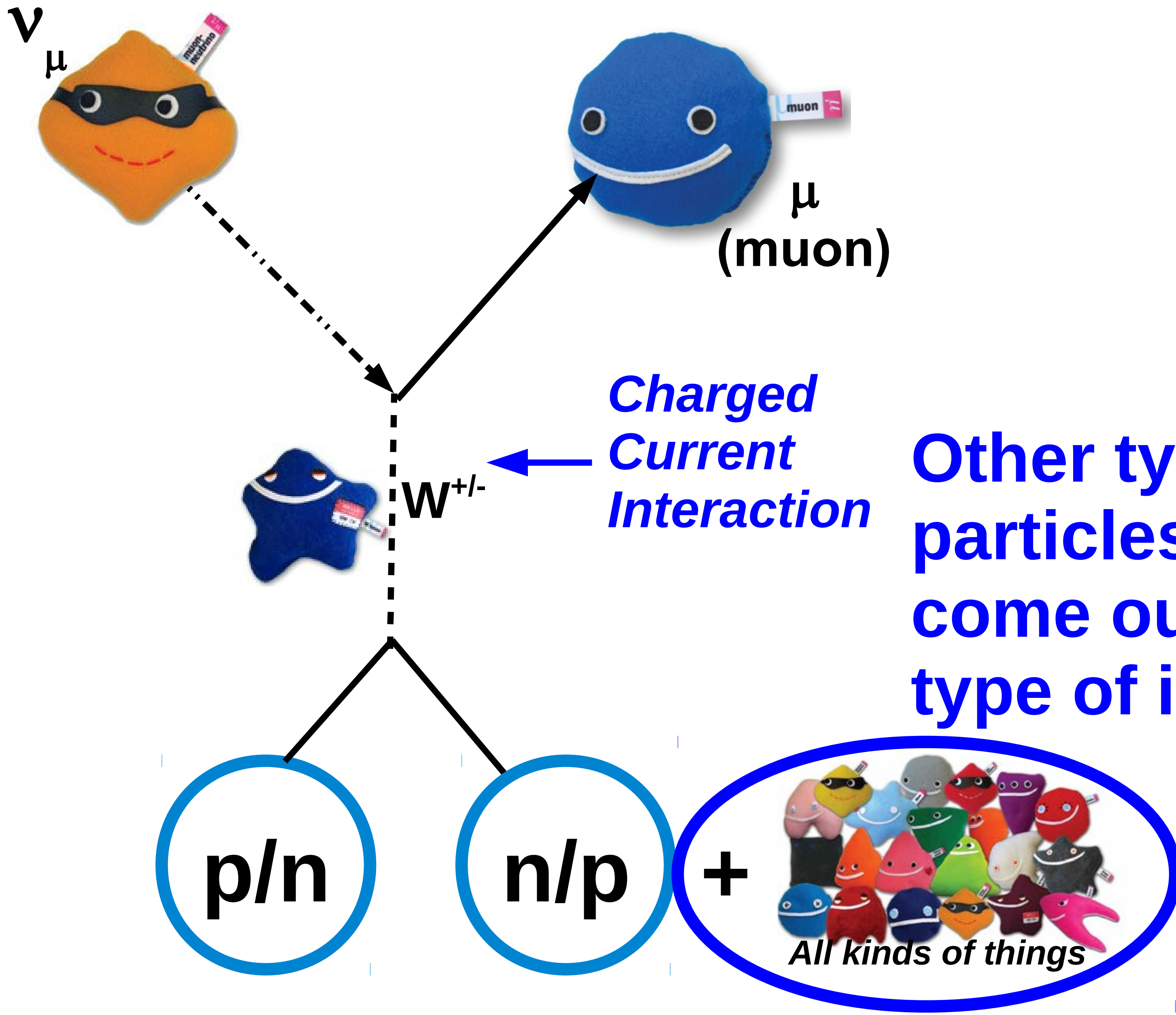
(They carry no charge)



The type of particle that comes out tells you information about the type of neutrino that interacted

Neutrinos only interact via the weak nuclear force

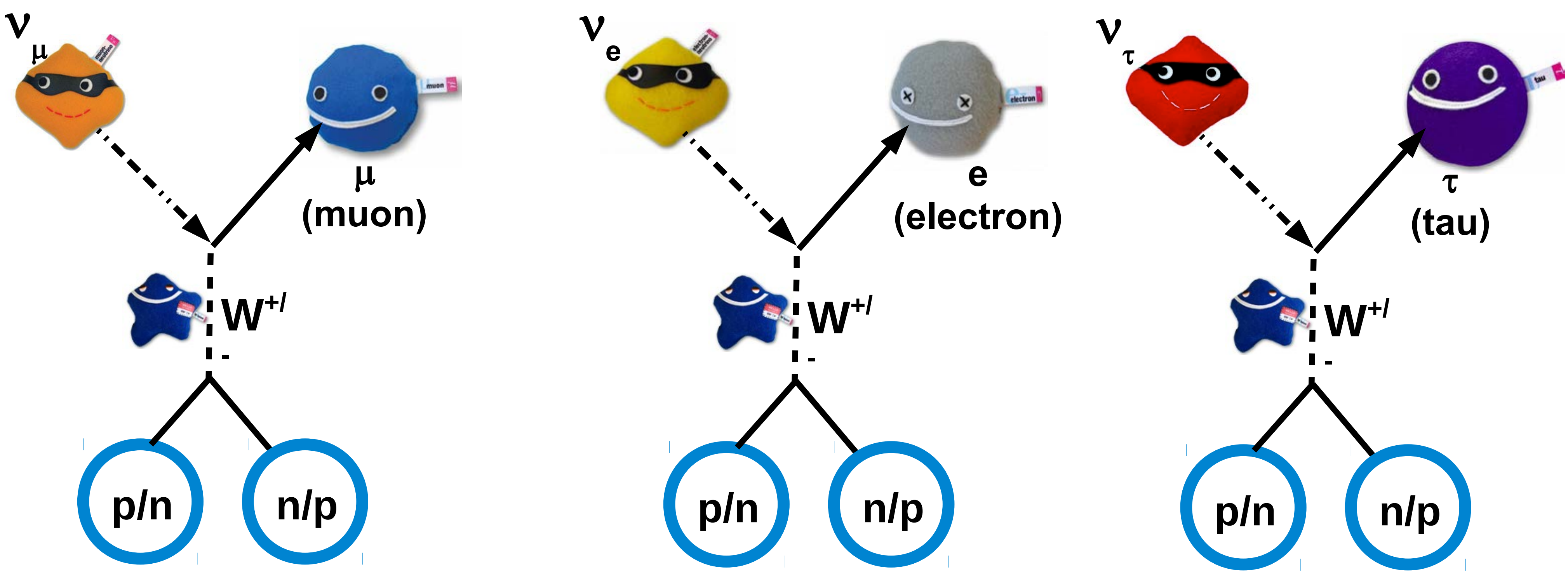
(They carry no charge)

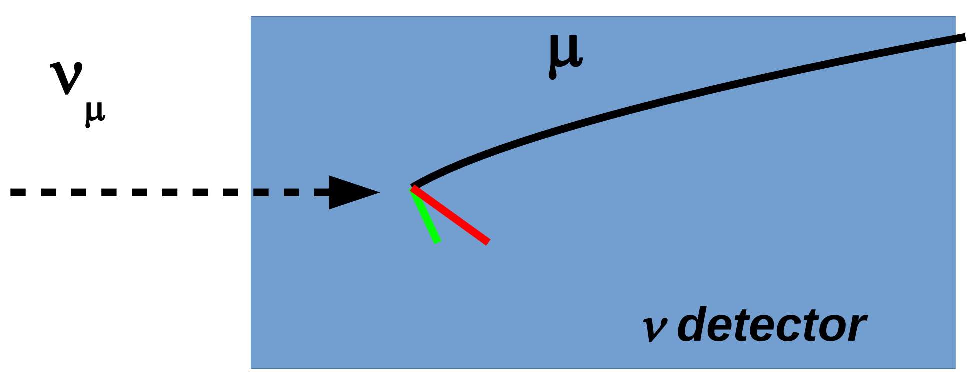


Other types of particles can also come out from this type of interaction

Neutrinos only interact via the weak nuclear force

(They carry no charge)

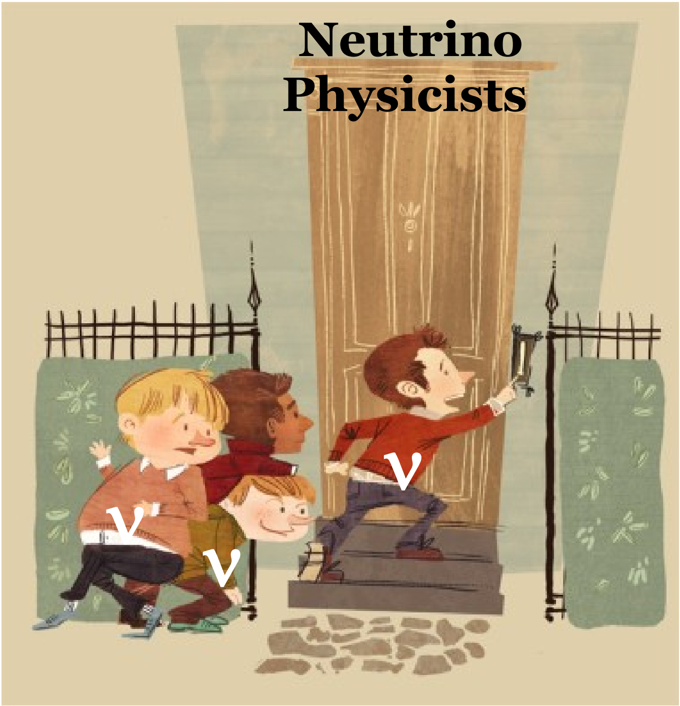




"Nothing" in....something out!

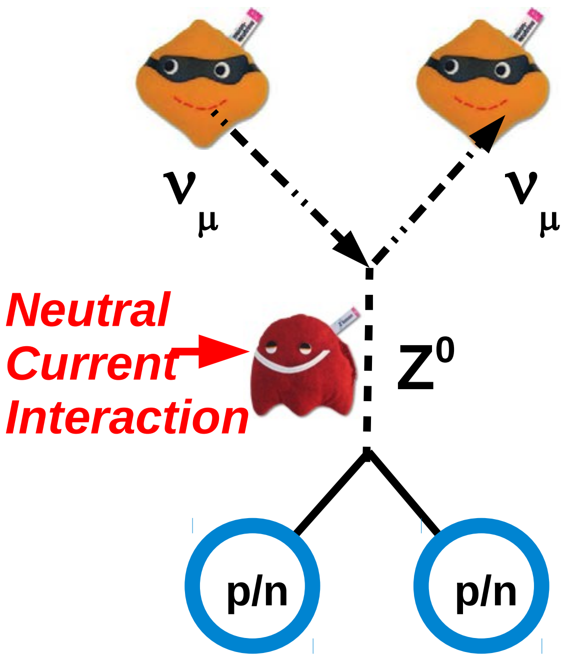
(One of those somethings is a lepton)

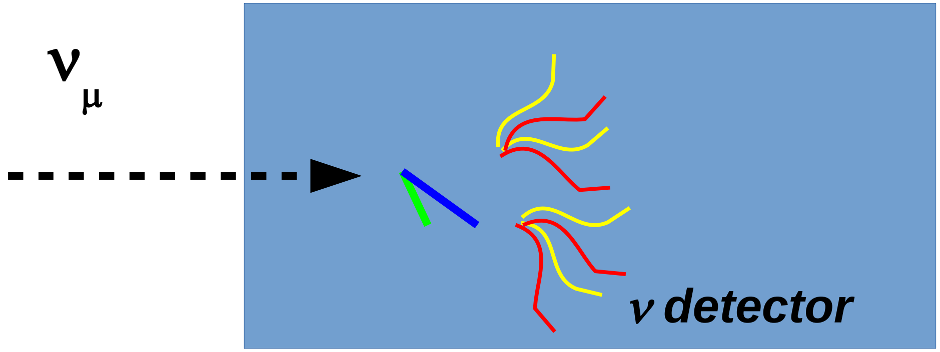
Neutral Current Interactions



"...sometimes, the neutrino opts to play ding-dong-ditch instead, depositing a fraction of its energy in the detector before speeding away. This is called a neutral current event, and, in many cases, it is the bane of the modern neutrino physicist's existence...."

– Symmetry Magazine, May 06th 2014

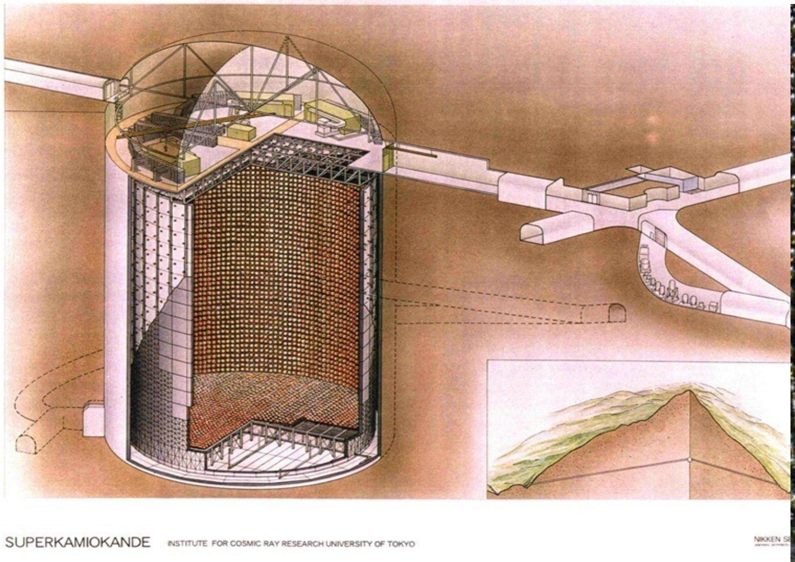


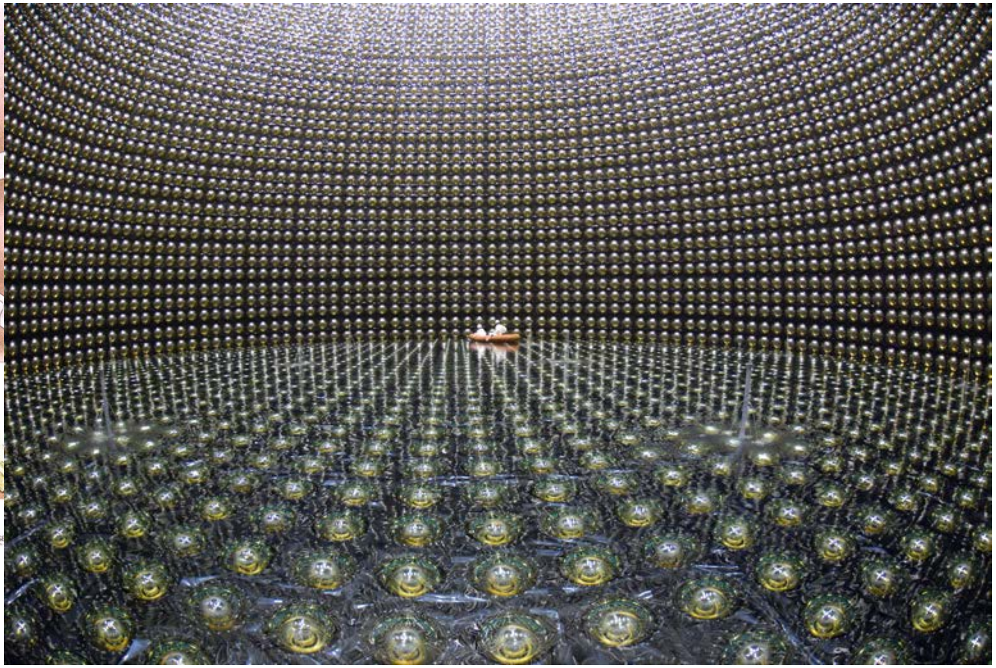


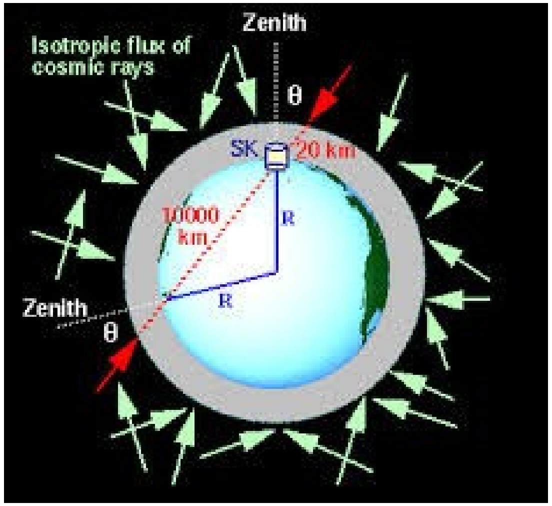
"Nothing" in....something out!

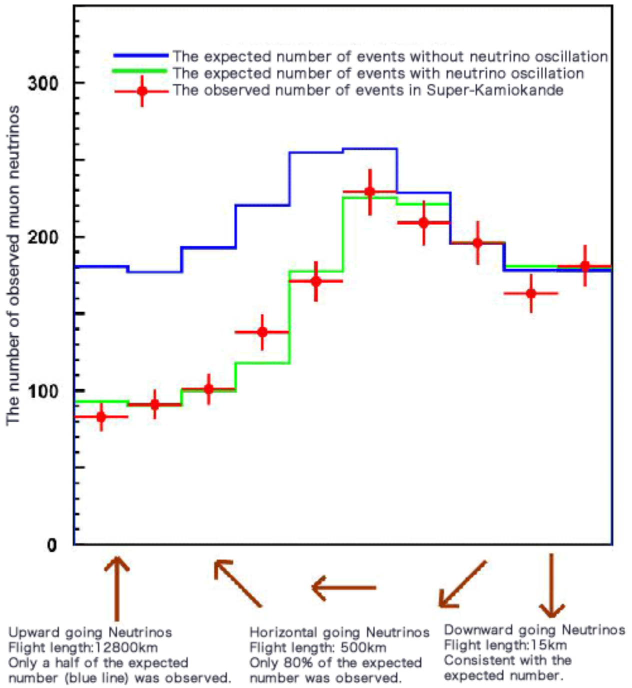
(Those somethings is NOT a lepton)

Mother nature had a surprise









- The Super-Kamiokande Experiment in Japan observed a deficit of muon neutrinos coming from the atmosphere

Neutrino Oscillation Physics

Neutrino Flavor States

Turns out that we observe neutrinos changing (oscillating) their type (flavor)

This means I can start with one type of neutrino

Let it travel some distance

And it will have changed its type

Neutrino Mass States

Headline Discovery

The New York Times
Copyright © 1998 The New York Times — NEW YORK, FRIDAY, JUNE 5, 1998 — $1 beyond the greater New York metropolitan

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

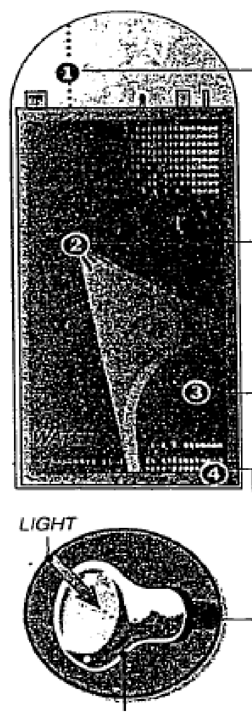
By MALCOLM W. BROWNE

TAKAYAMA, Japan, Friday, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that a significant part of the mass of the universe might be in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter, the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Detecting Neutrinos



1. Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .
2. . . . and collide with other particles . . .
3. . . . producing a cone-shaped flash of light.
4. The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

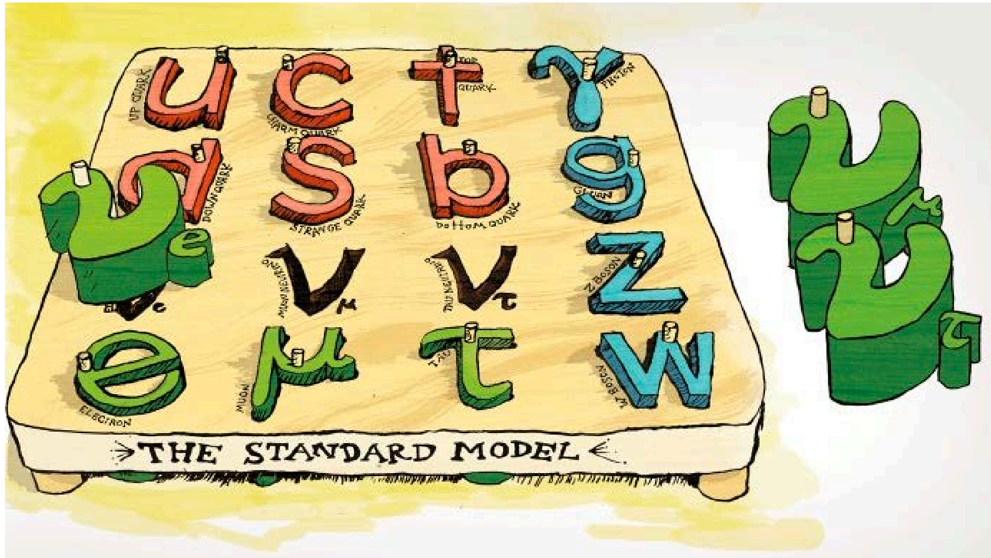
And Detecting Their Mass

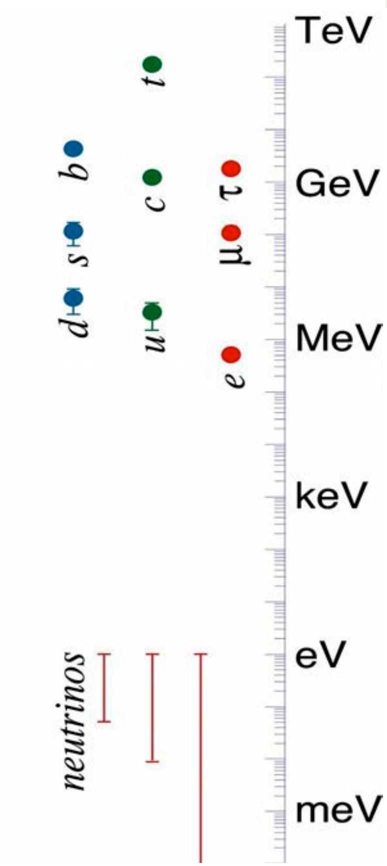
By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The Standard Model "Misfits"

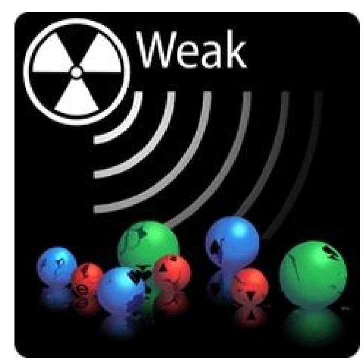
- Symmetry Magazine 2013





Neutrinos have EXTREMELY small masses

~10^{-6} times lighter than the electron



Neutrinos only interact (talk to the rest of the universe) via the weak nuclear force

Neutrino Oscillation Physics

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{\mu 1} & U^*_{\tau 1} \\ U^*_{e2} & U^*_{\mu 2} & U^*_{\tau 2} \\ U^*_{e1} & U^*_{\mu 3} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\boxed{|\nu_f> = \sum_{i=1}^{N} U^*_{fi} \, |\nu_i>}$$

- **The phenomenon of ν-oscillations can be understood by relating the flavor states to the mass states via a unitary mixing matrix**

Neutrino Oscillation Physics

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{\mu 1} & U^*_{\tau 1} \\ U^*_{e2} & U^*_{\mu 2} & U^*_{\tau 2} \\ U^*_{e1} & U^*_{\mu 3} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\nu_f> = \sum_{i=1}^{N} U^*_{fi} e^{-iE_i t} |\nu_i>$$

$$(E_i - E_j)t = \frac{m_i^2 - m_j^2 L}{2E} = \frac{\Delta m_{ij}^2 L}{2E}$$

- **The phenomenon of ν-oscillations can be understood by relating the flavor states to the mass states via a unitary mixing matrix**

Neutrino Oscillation Physics

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{\mu 1} & U^*_{\tau 1} \\ U^*_{e2} & U^*_{\mu 2} & U^*_{\tau 2} \\ U^*_{e1} & U^*_{\mu 3} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$(E_i - E_j)t = \frac{m_i^2 - m_j^2 L}{2E} = \frac{\Delta m_{ij}^2 L}{2E}$$

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} e^{-iE_i t} |\nu_i\rangle$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric & Accelerator Neutrinos

Use a combination to measure these

Solar & Reactor Neutrinos

$c_{ij} = \cos(\theta_{ij})$

$s_{ij} = \sin(\theta_{ij})$

$\delta = \text{CP phase}$

$\alpha_i = \text{Majorana Phase}$

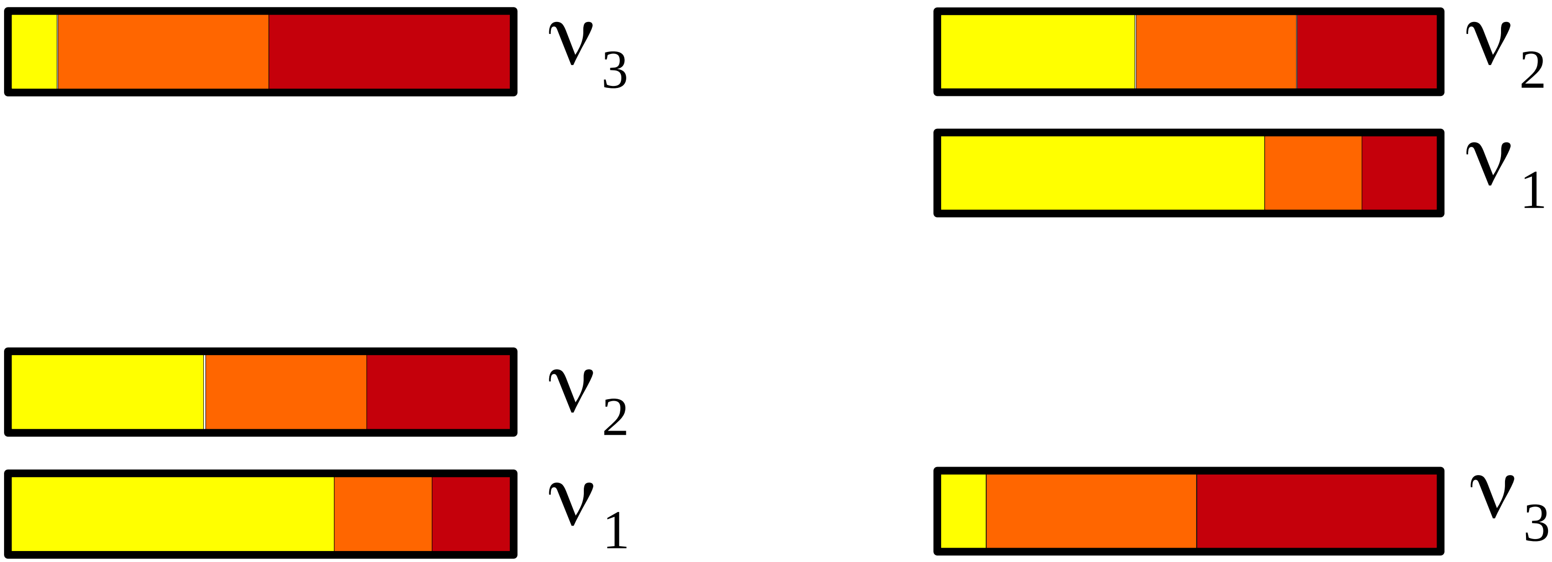
L/E ~ 500 km/GeV

L/E ~ 1500 km/GeV

- **We describe the mixing in terms of three masses (m_1, m_2, m_3), three mixing angles (θ_{23}, θ_{12}, θ_{13}), a CP-phase (δ), and two Majorana phases (α_1, α_2)**

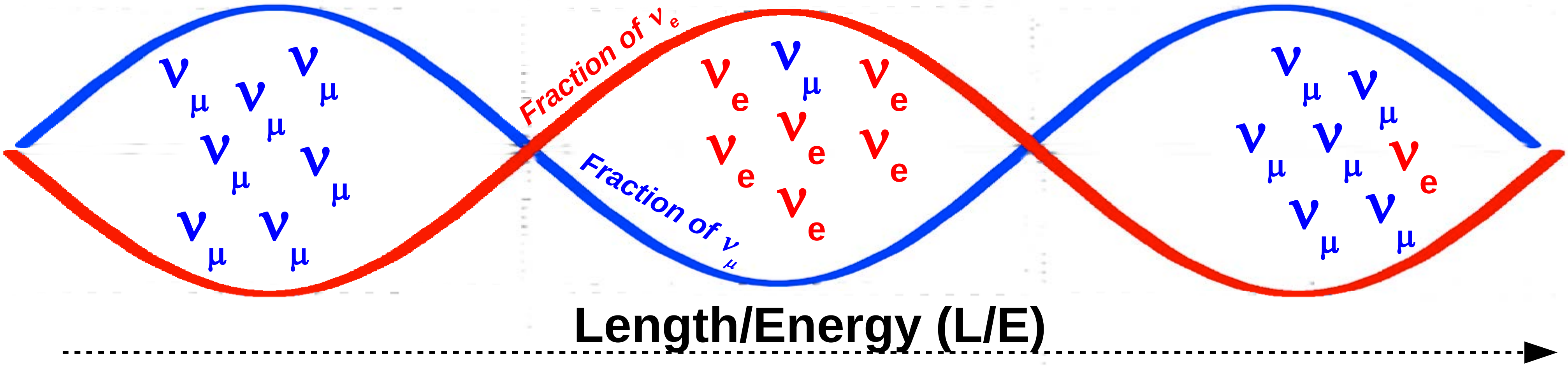
Neutrino Oscillation Physics

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{\mu 1} & U^*_{\tau 1} \\ U^*_{e2} & U^*_{\mu 2} & U^*_{\tau 2} \\ U^*_{e1} & U^*_{\mu 3} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- **Where we know $|\Delta m^2_{23}| >> |\Delta m^2_{12}|$, but we don't know the ordering of the mass states and we don't know the absolute scale**

Understanding Neutrino Oscillations



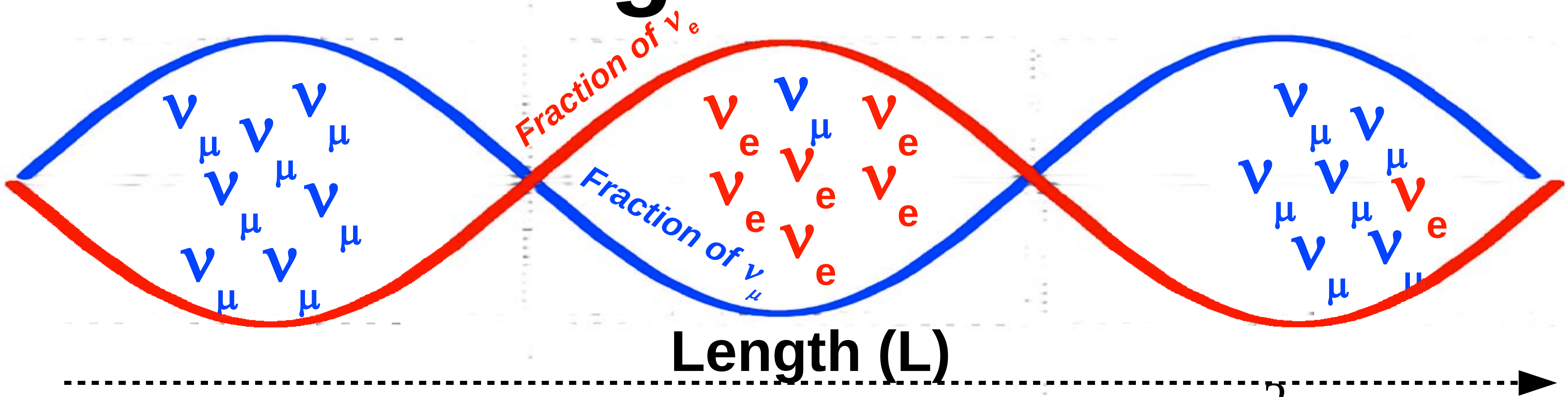
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

This oscillation between different flavors can be understood as a mixing which looks like a sine wave

Mother nature gives us Δm and θ

We use the length the neutrino has traveled (L), and the energy of the neutrino (E) to probe and understand the nature of the oscillation

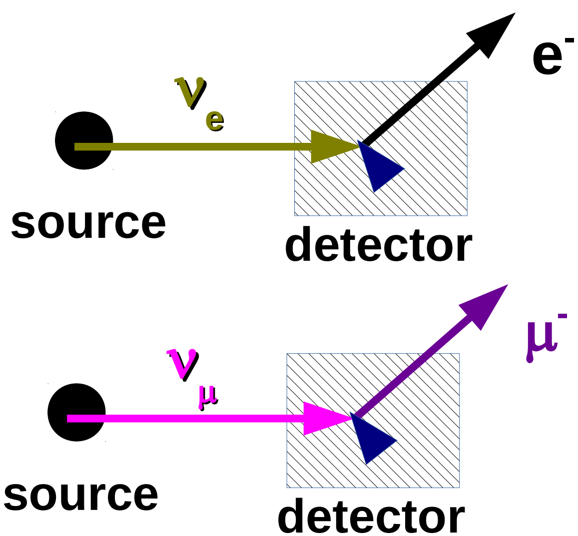
Understanding this weird behavior



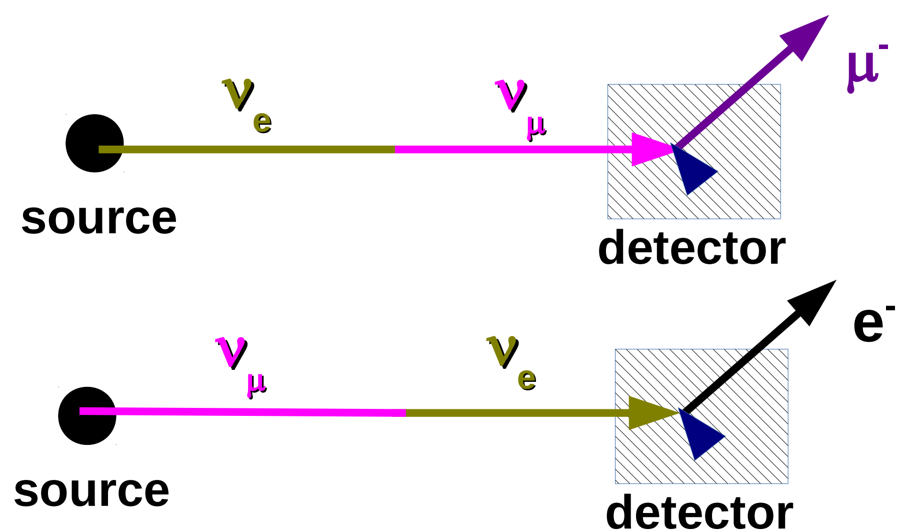
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

What this means for an experimentalist is if I have a source of neutrinos I can study their oscillation behavior

For very short distances



For longer distances

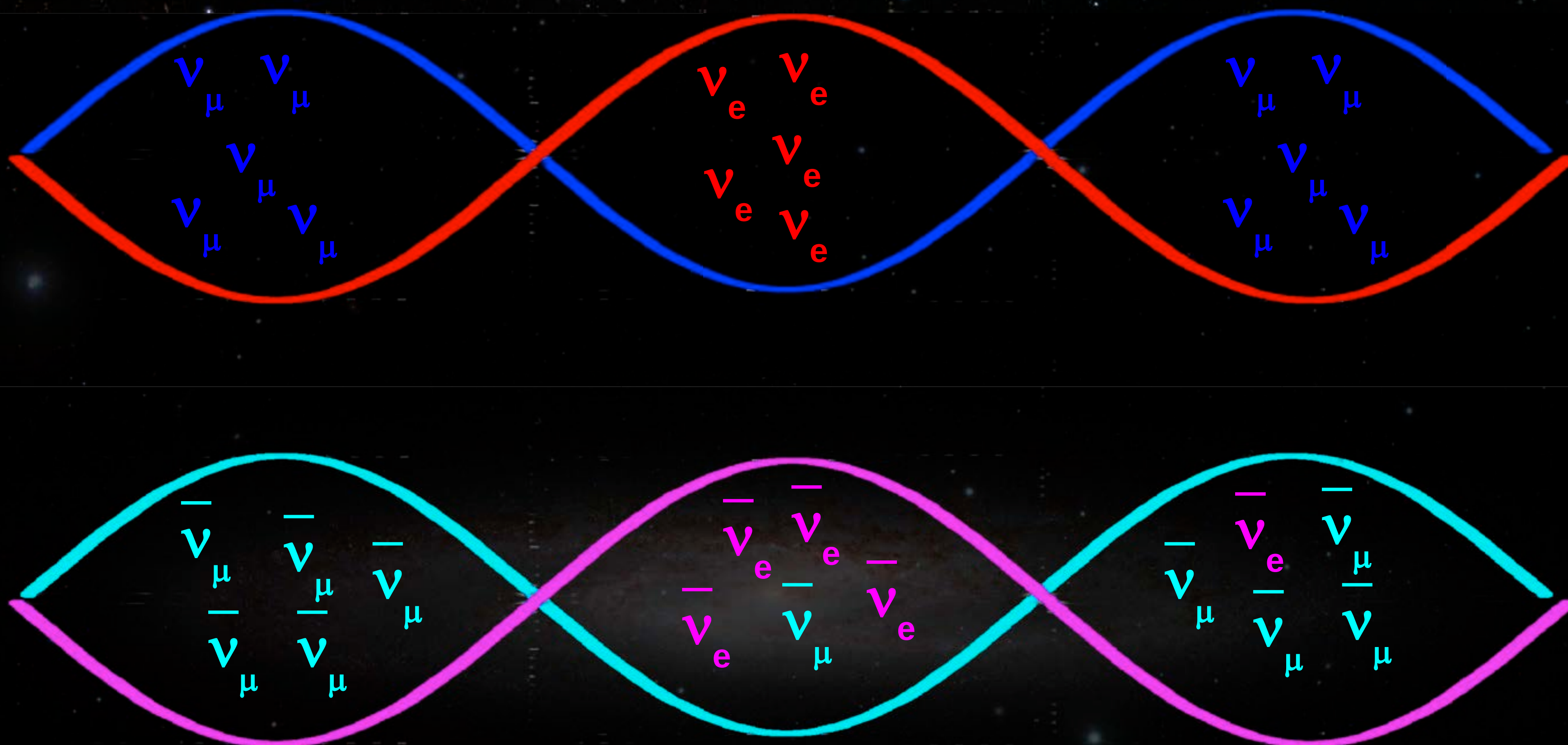


Puzzles in universe addressed with ν's

Puzzles in universe addressed with ν's

Where is all the anti-matter?

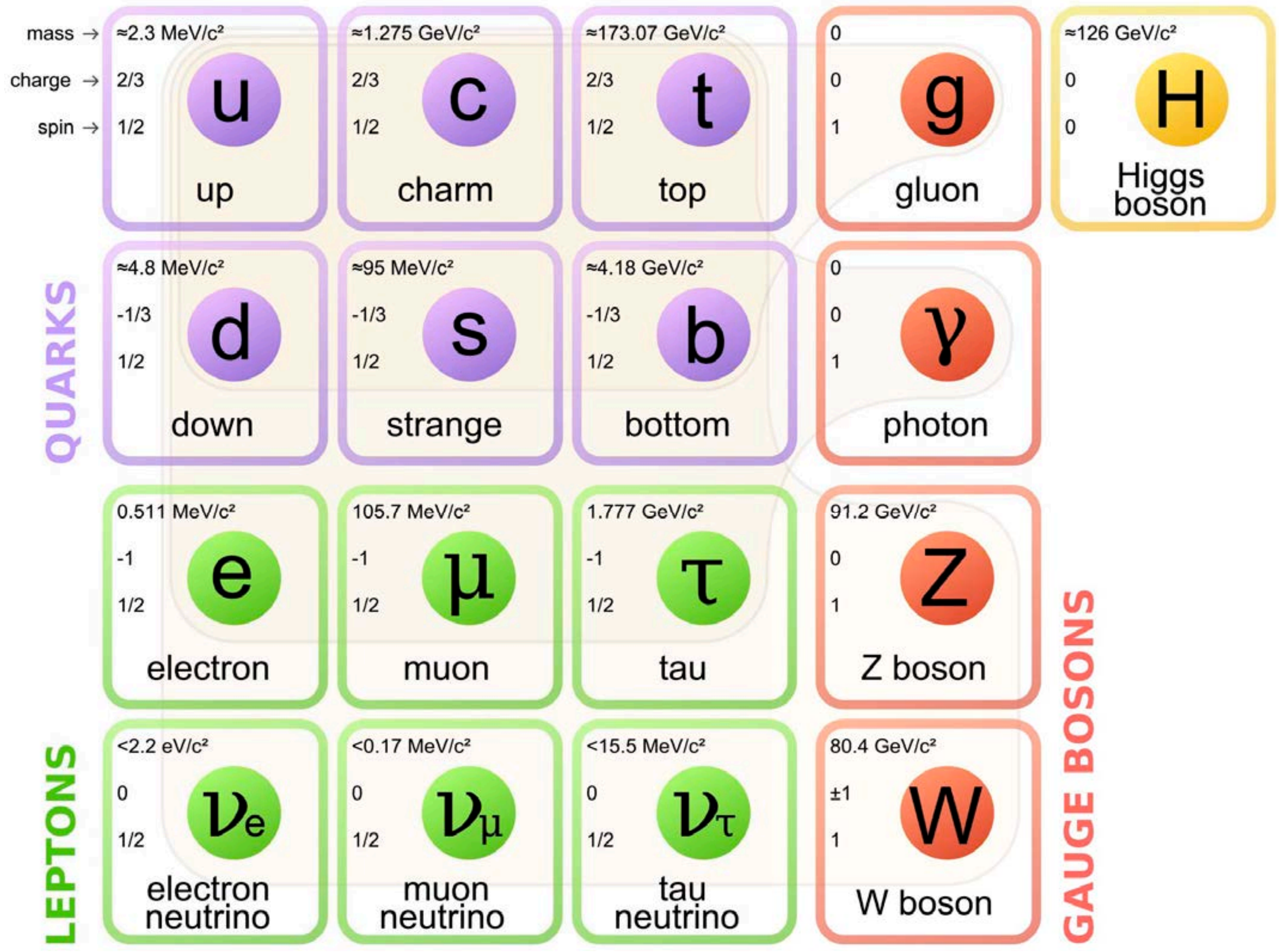
Puzzles in universe addressed with ν's



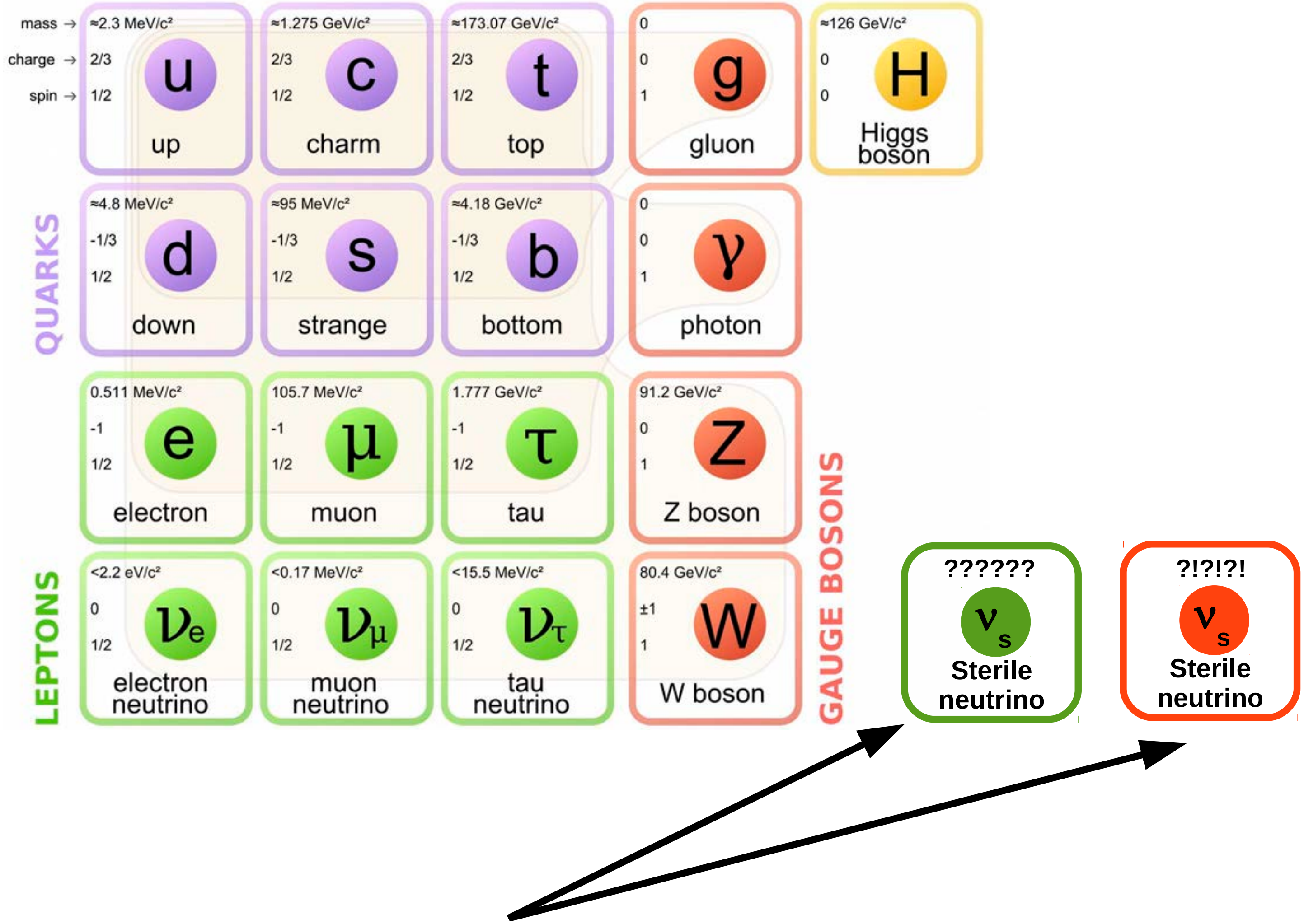
Neutrino oscillation could allow a preferential transition of matter to dominate in our early universe of anti-matter

Puzzles in universe addressed with ν's

Is this picture complete?

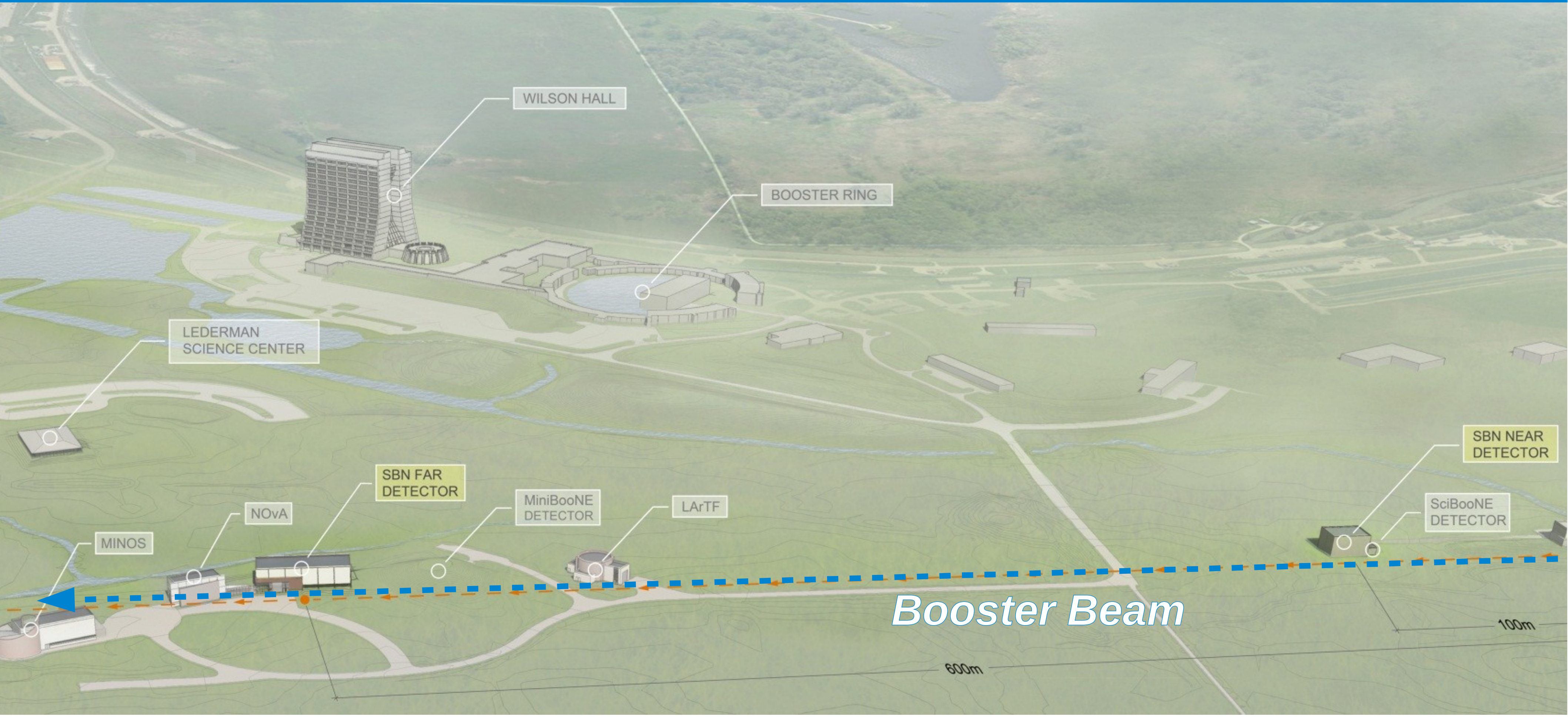


Puzzles in universe addressed with ν's



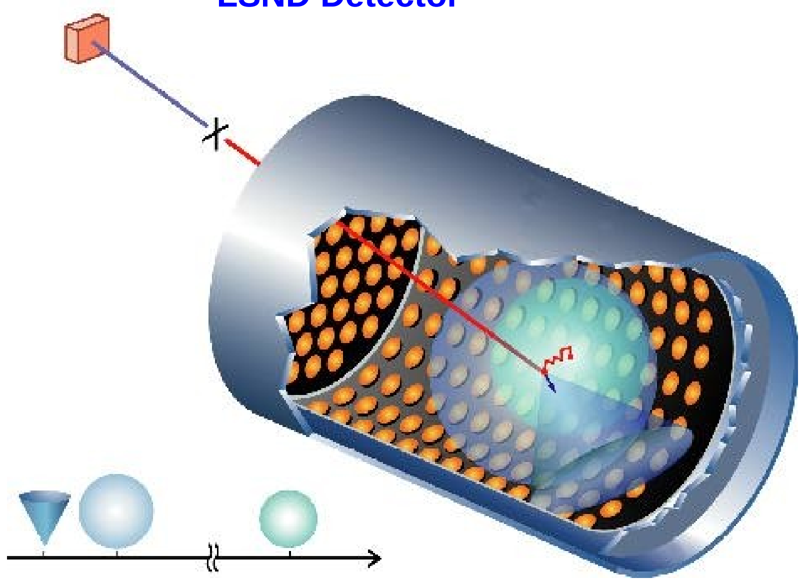
There is an ever growing body of work that suggests the possibility of more neutrinos than the three we know about in the Standard Model

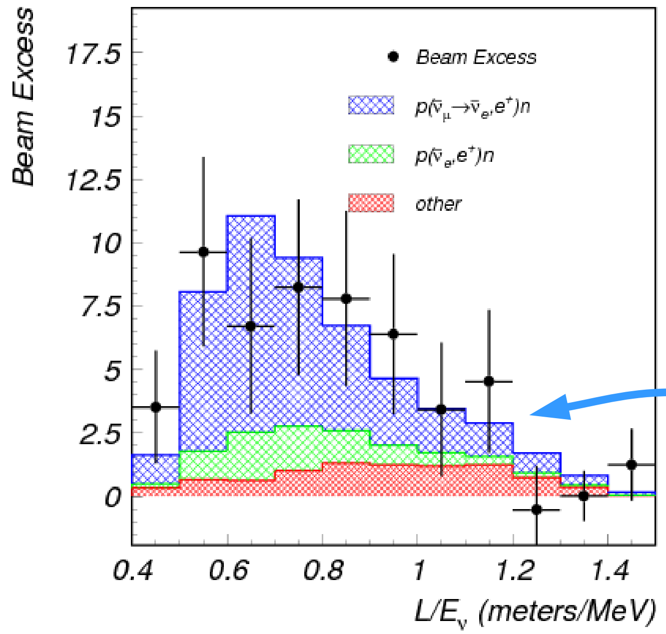
The Short-Baseline Neutrino Program



The story of the Short-Baseline Neutrino Program can best be understood through the history of the physics that we've been following

Liquid Scintillator Neutrino Detector





- **1993 – 1998 the LSND experiment took neutrino data from a stopped pion low energy $\bar{\nu}_\mu$ beam from a decay-at-rest source**
  - 30 meters from the beam stop with n-energies from 20 – 55 MeV
    - L/E ~ 1 m / MeV
- **Detected a 3.8σ excess in the appearance of $\bar{\nu}_e$**
  - The result was interpreted from within the neutrino oscillation model as an additional mixing

$$P(\nu_\beta \rightarrow \nu_\alpha) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

What if there are more types of ν's

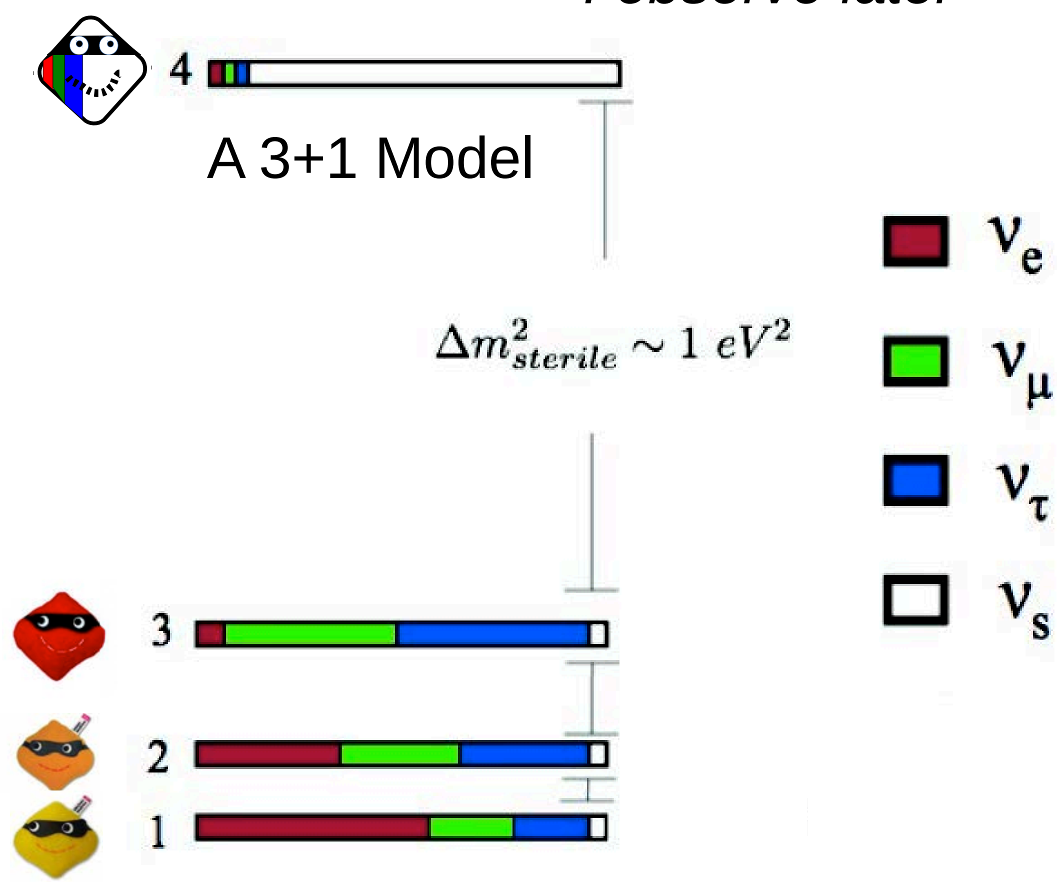
If I start with muon type neutrinos

There are 3+n ways it can oscillate

*And this will **enhance** the amount of electron neutrinos I observe later*

This would imply there are **new particles**

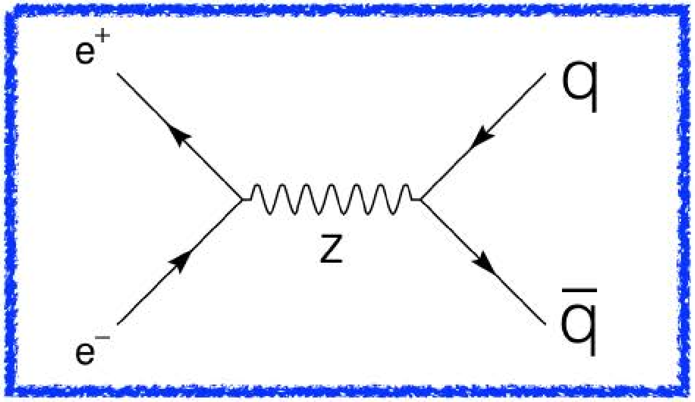
('sterile' neutrinos → neutrinos that don't participate via the weak force)

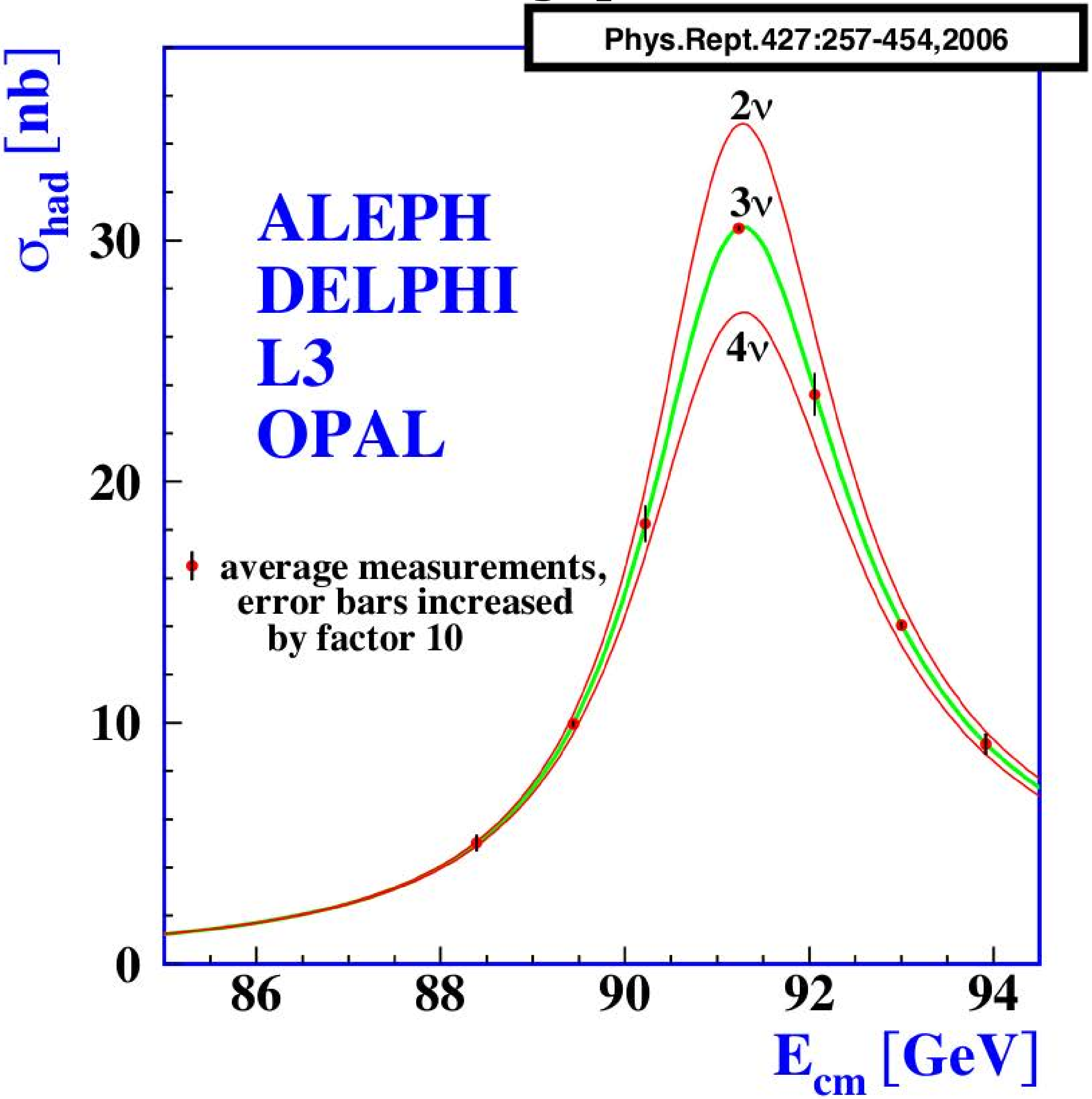


What if there are more types of ν's

- For the uninitiated one might wonder how we know that there are only 3 weakly interacting neutrinos

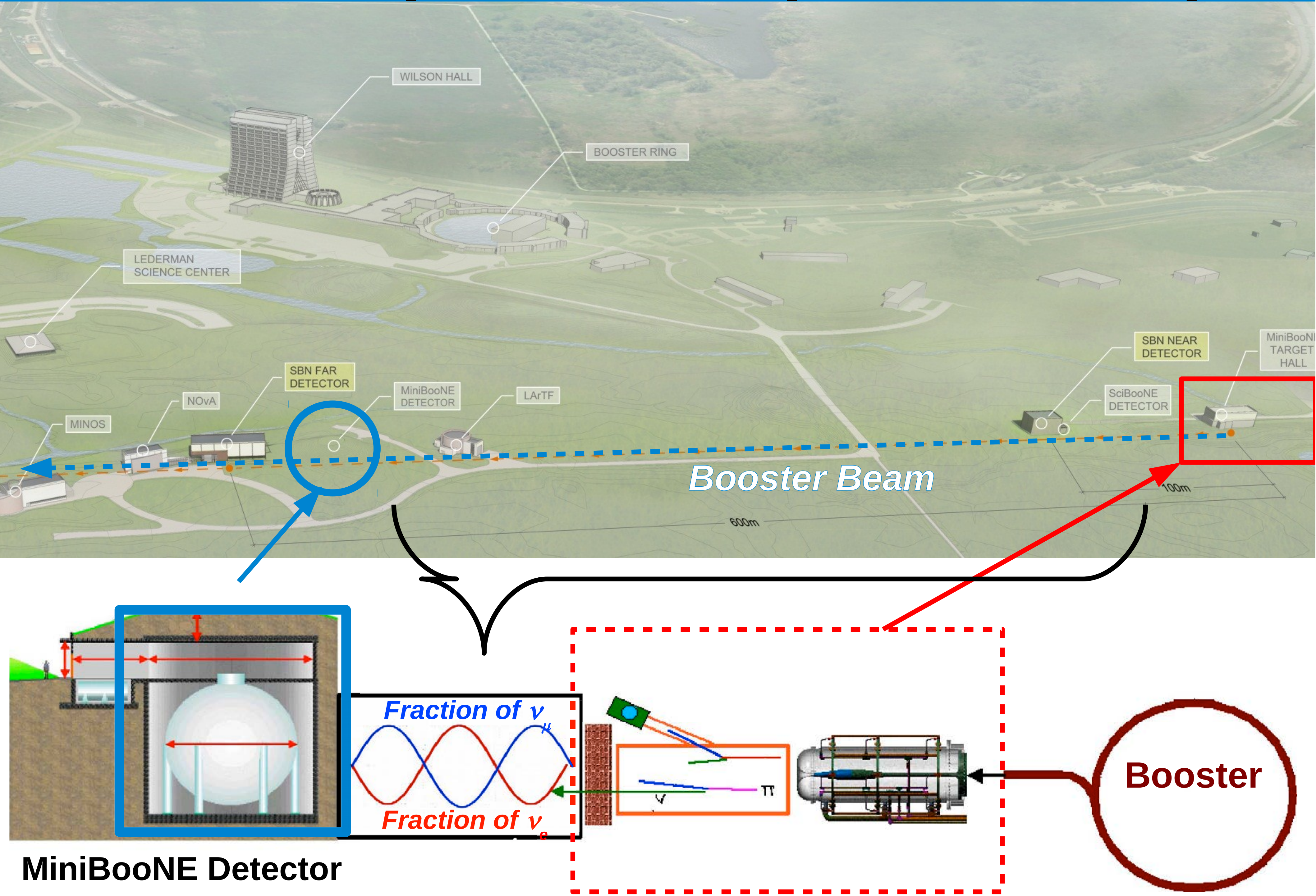
- LEP has conclusively shown that only 3 neutrinos couple to the Z boson



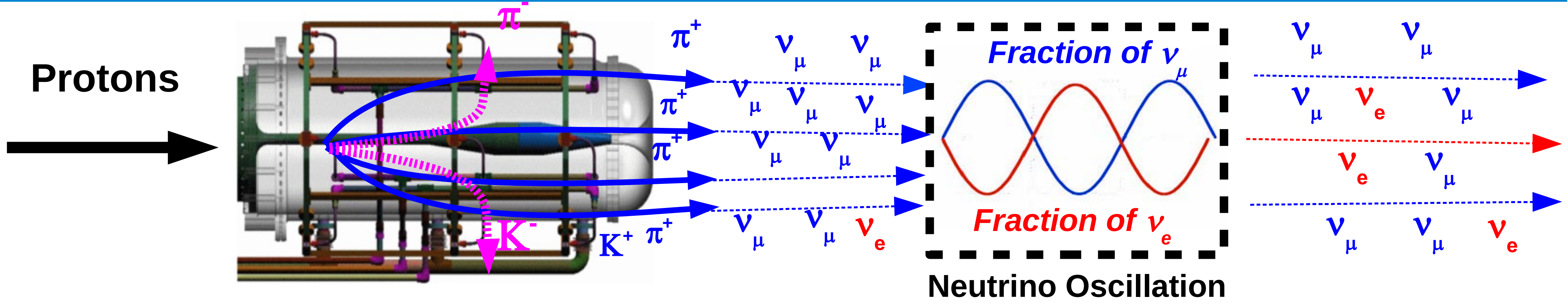


This means if the excess seen is due to $\nu_\mu \rightarrow \nu_e$ then the particle can't participate in the weak force

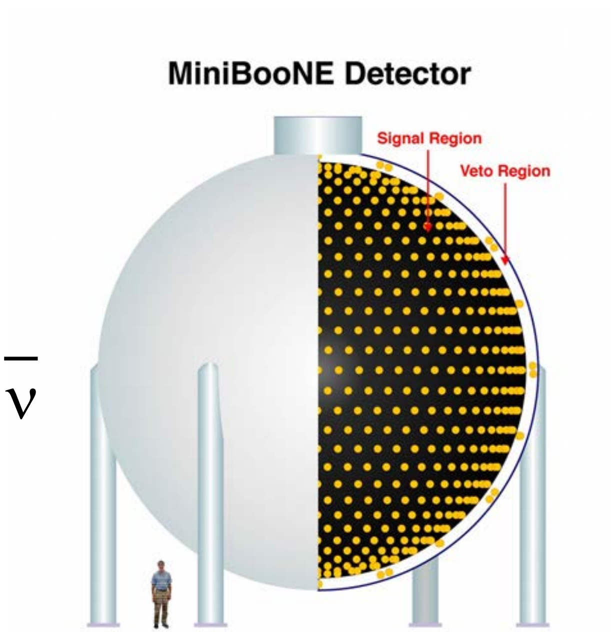
Follow-up to LSND (MiniBooNE)

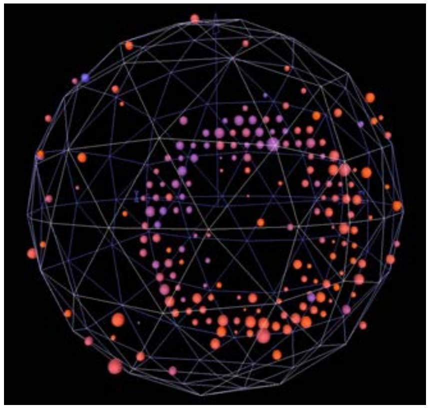


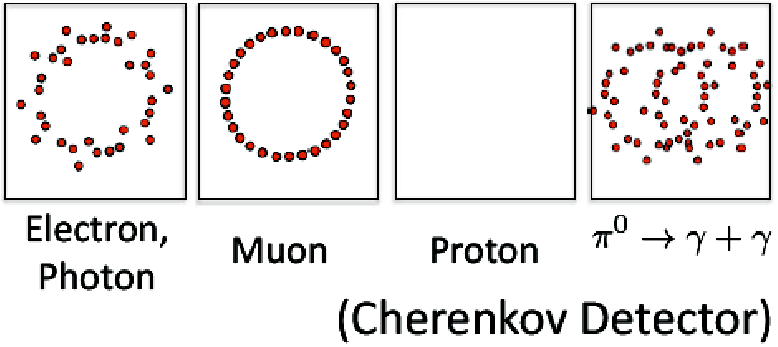
MiniBooNE



- **MiniBooNE used a decay-in-flight pion source from Fermilab's Booster Neutrino Beamline**
  - Allows you to sign select ν or $\bar{\nu}$
- **MiniBooNE ran at a different baseline and different neutrino energy, but the same L/E**
  - Should have the same oscillation probability

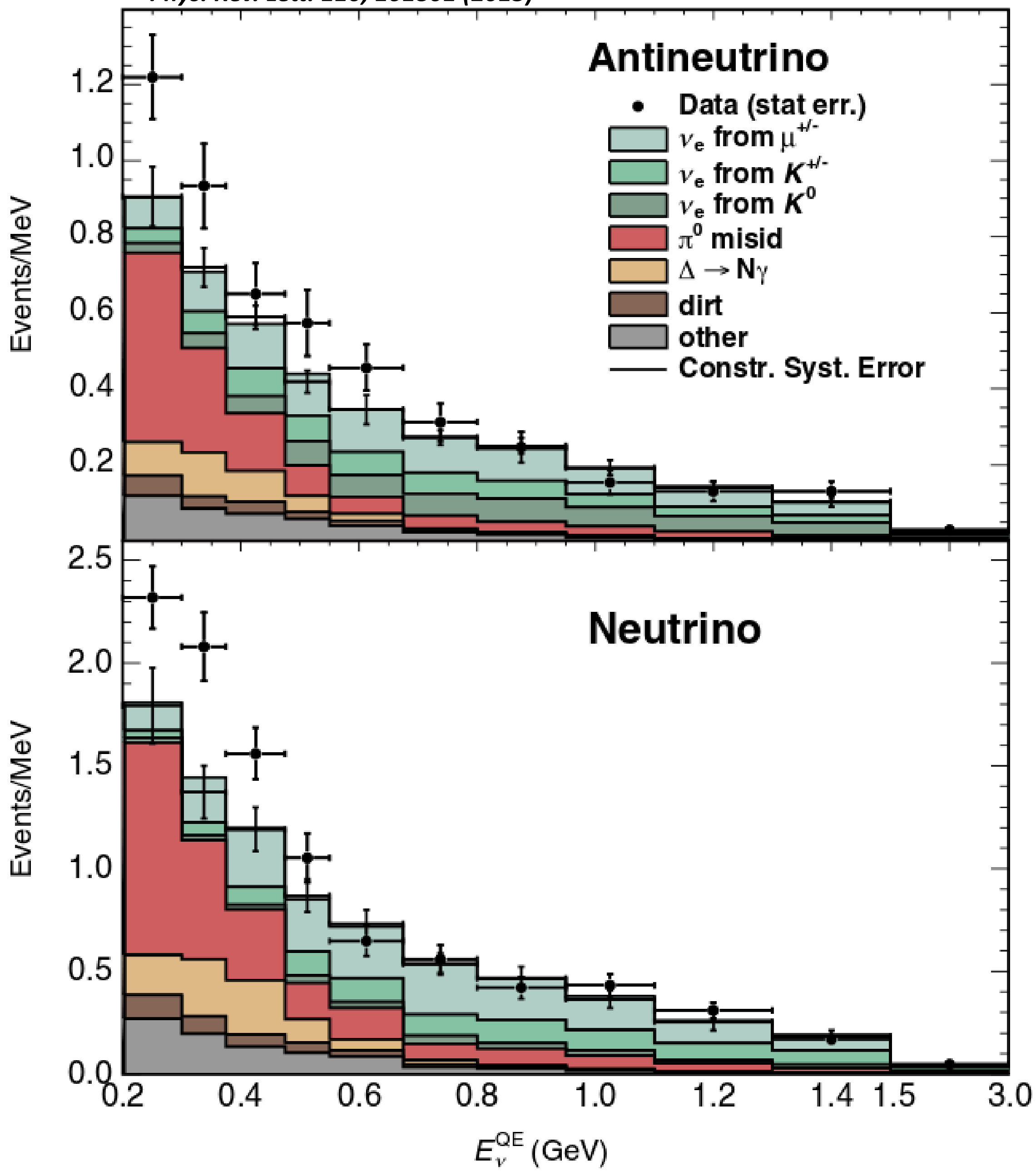






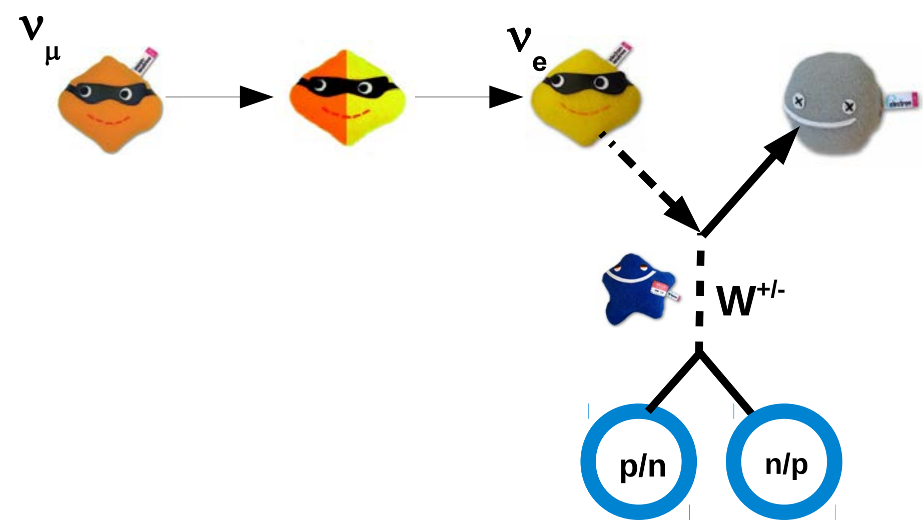
An accelerator based oscillation experiments sees an excess of ν_e events appearing

Phys. Rev. Lett. 110, 161801 (2013)



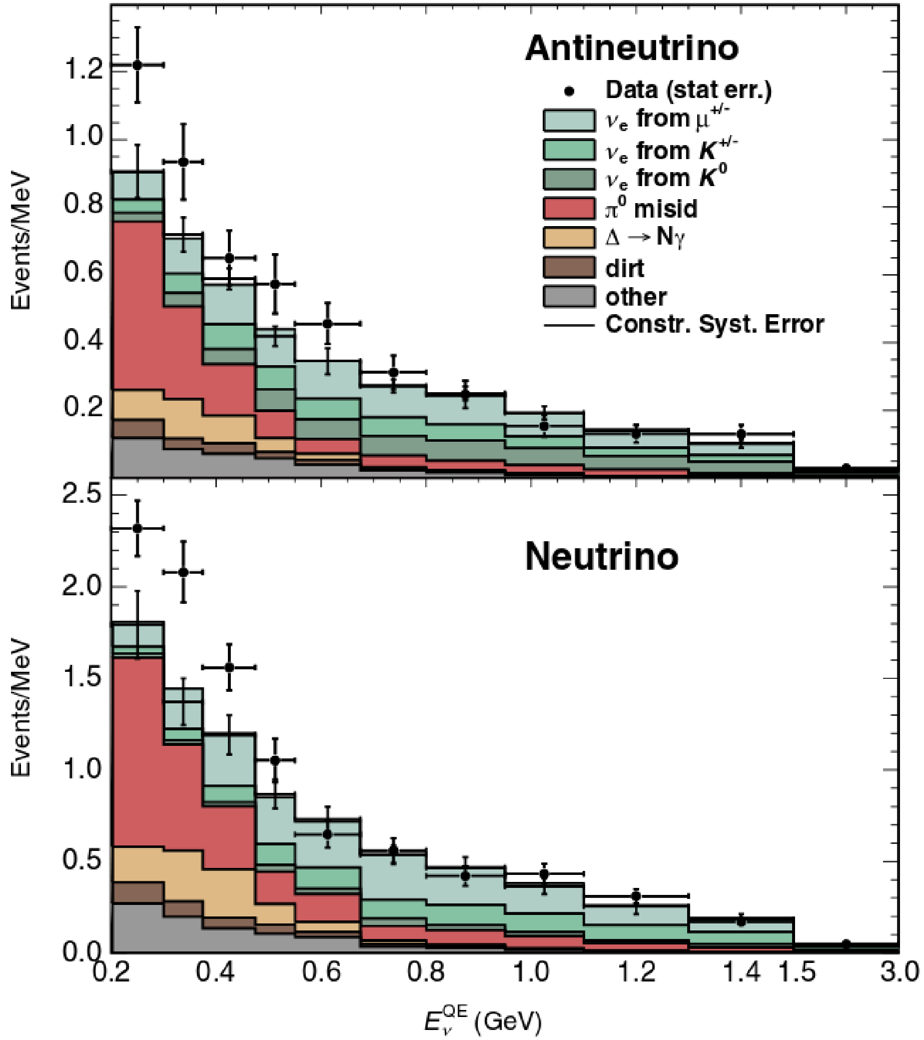
Mini-Booster Neutrino Experiment (MiniBooNE)

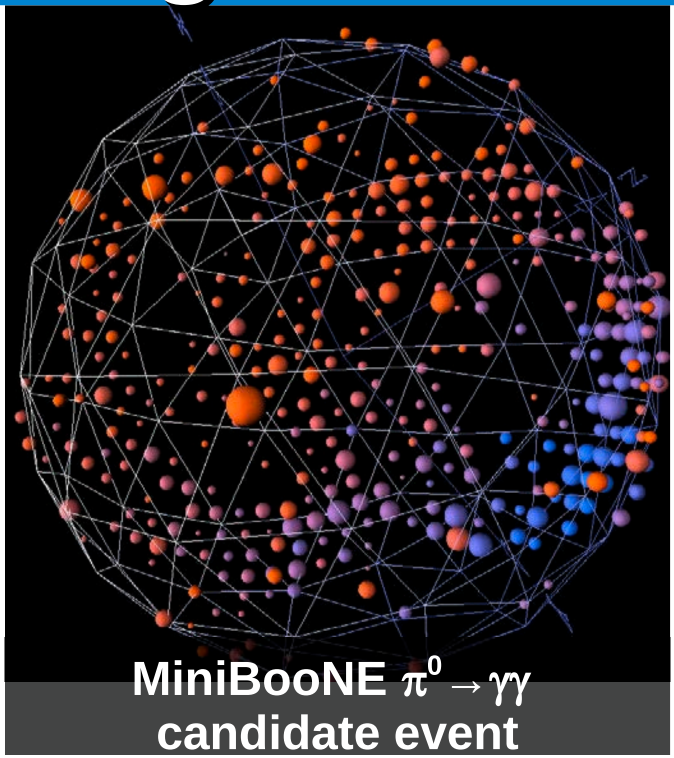
sees an excess of events in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ appearance

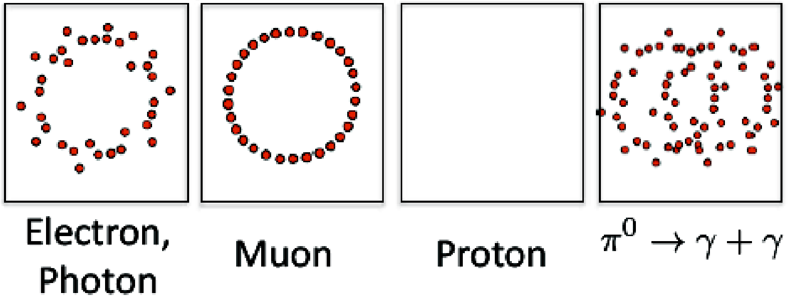


Could a different oscillation be causing this excess ???

MicroBooNE addressing MiniBooNE

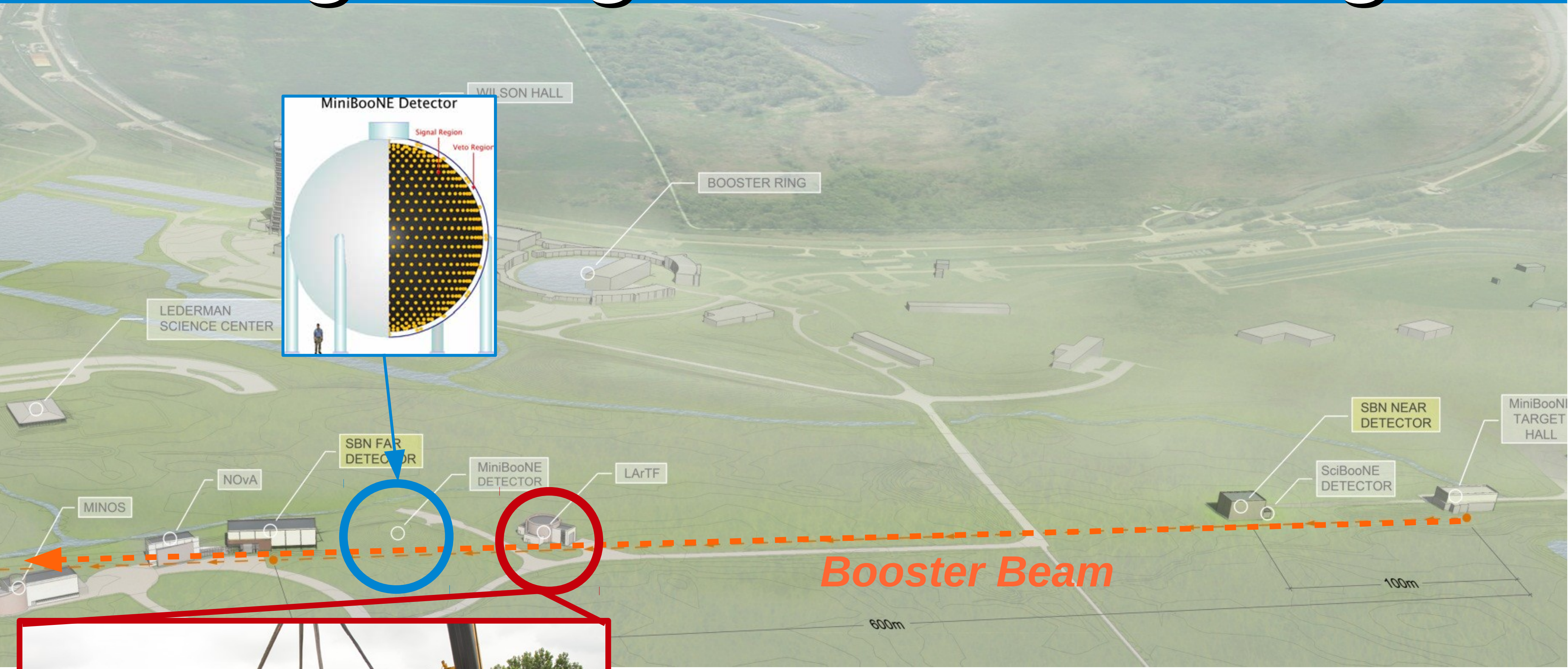






What you would like is an experiment that **sees the same beam** as MiniBooNE, at (nearly) the **same distance** as MiniBooNE but with **superior electron/photon separation ability**

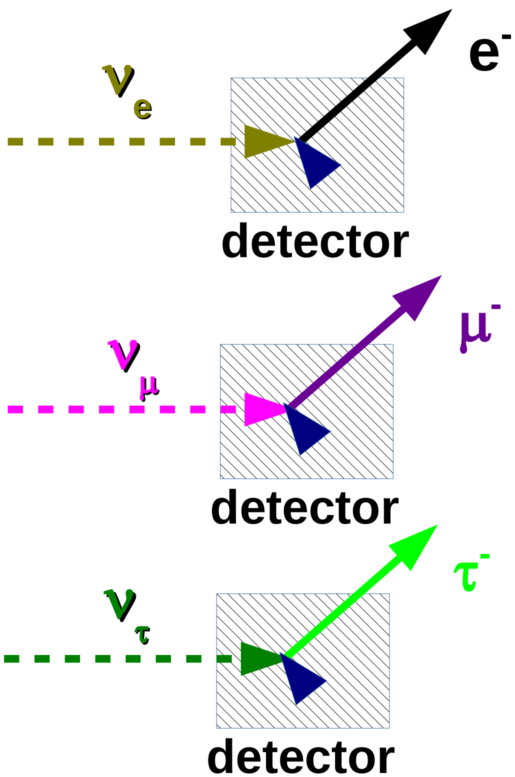
The beginning of the SBN Program



MicroBooNE is the first Liquid Argon Time Projection Chamber detector on the short-baseline and kicks off the SBN program

Neutrino Detectors

Since neutrinos only interact via the weak force a basic strategy for a neutrino detector is to be:



1) Big/Scalable

Put a large number of nuclei in the path of the neutrino, need to build big detectors

2) Sensitive Charge and Light

We want to collect information about the charged particles produced

3) High Resolution

We want to collect as much information about what took place during the neutrino interaction to understand the physics of the interaction

Liquid Nobel Detectors

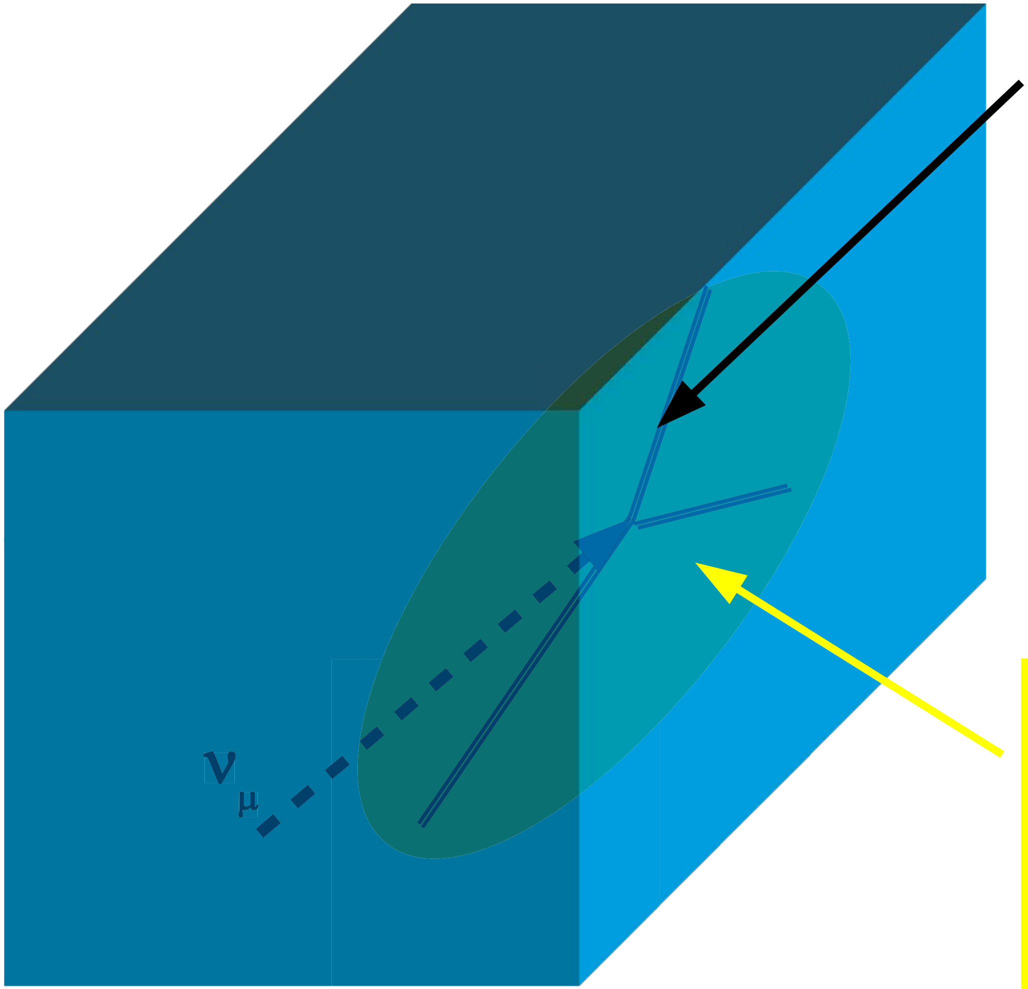
Nobel liquids are also considered for use in neutrino detectors because they have many attractive properties:

1) Ionization charge that won't recombine easily
2) Scintillation light
3) Good dielectric properties (doesn't breakdown easily at high voltage)

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

Note: This table was first produced by my former boss Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!

Liquid Argon Neutrino Detector

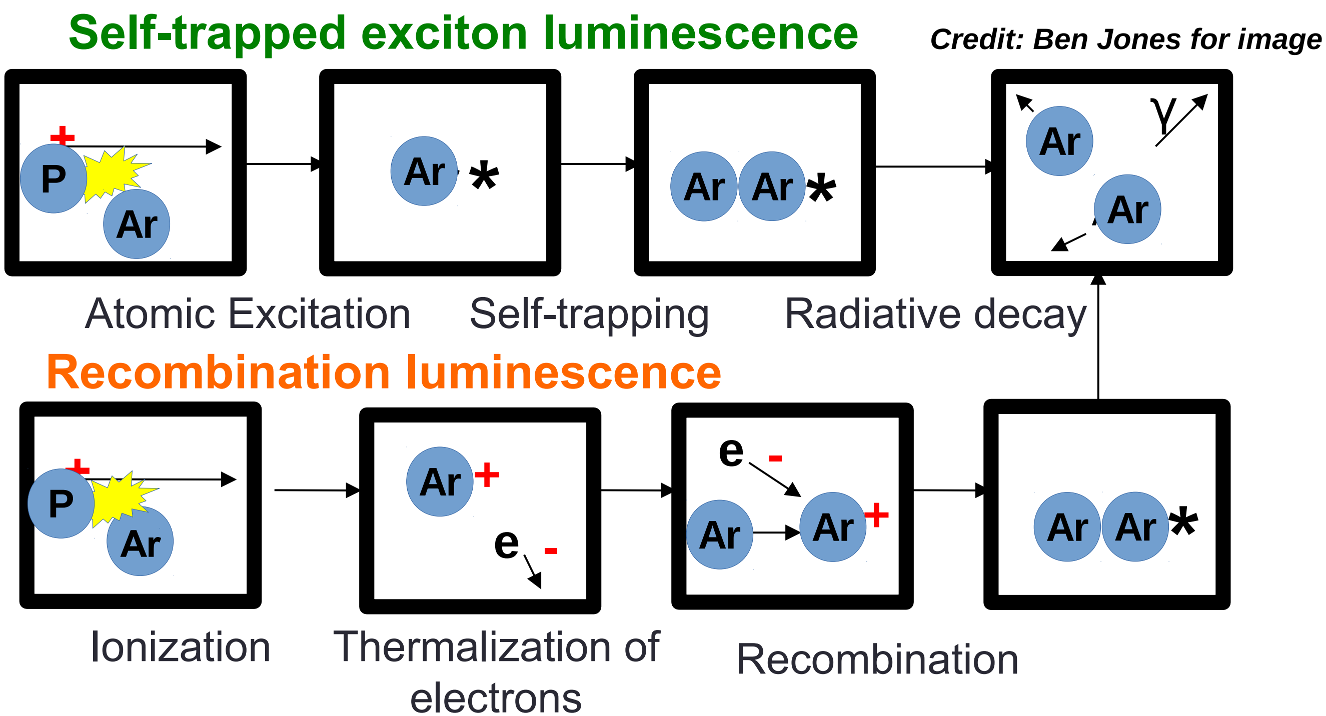


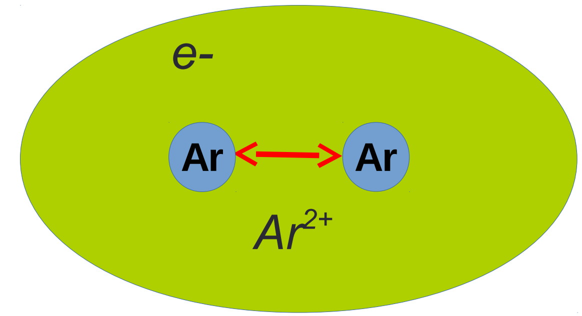
The charged particles produced in the ν-Ar interaction ionize the argon as they move through the volume

Additionally, the interaction causes scintillation light to be produced isotropically

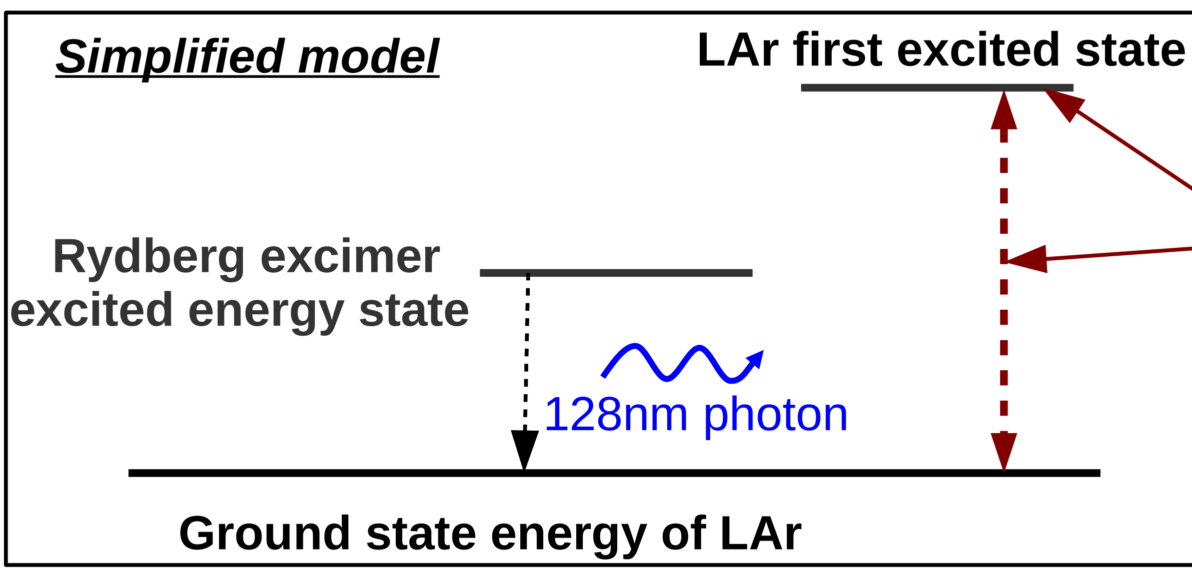
The light pulse provides an initial time (t_0) for the neutrino event

Interesting aside about scintiallation light



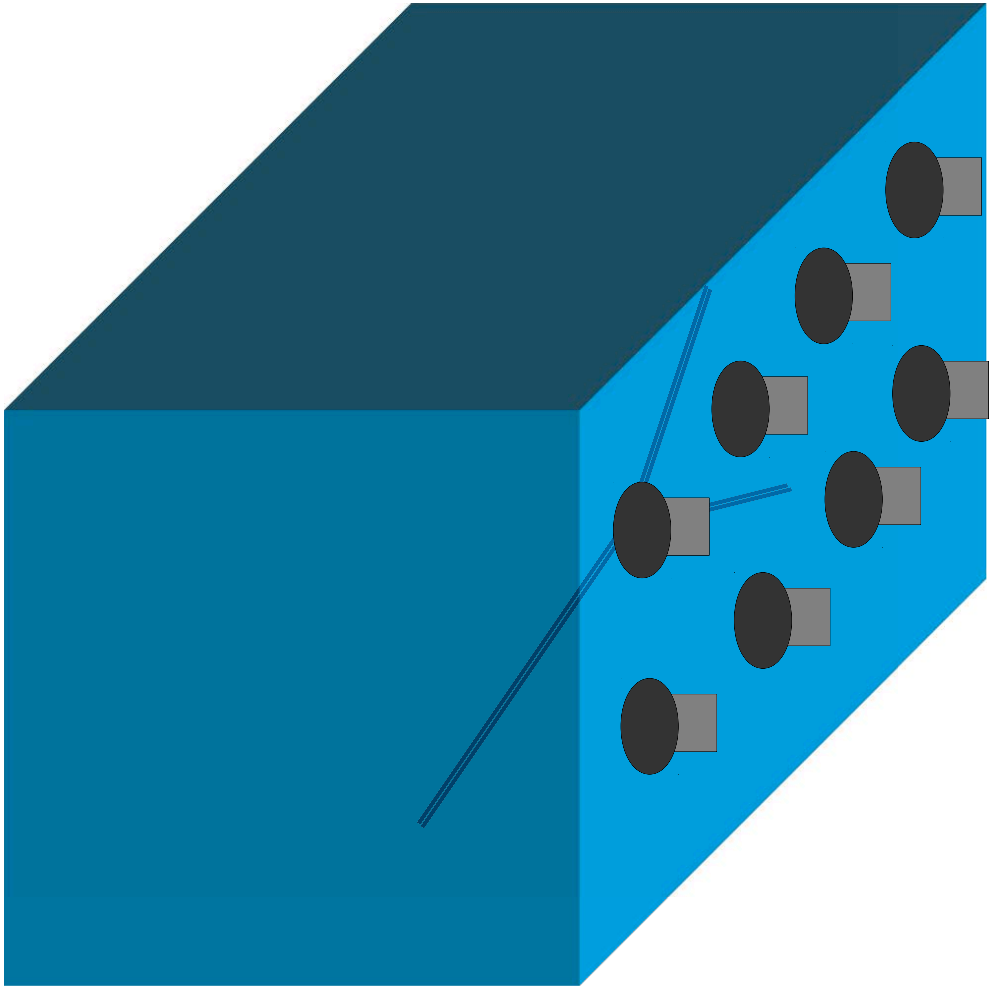


Excimer state formed during this process is a Rydberg state: Ar^{2+} with a bound electron



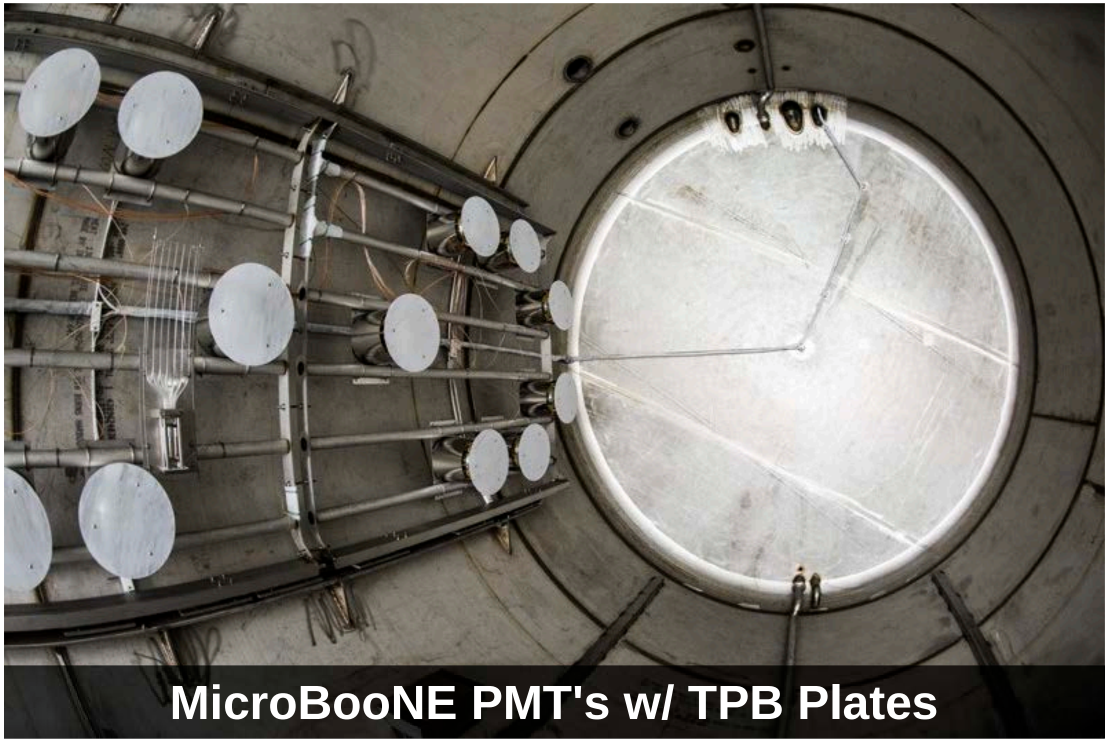
This difference between the energy levels is why LAr is transparent to the scintillation light it produces

Neutrino interactions in Liquid Argon

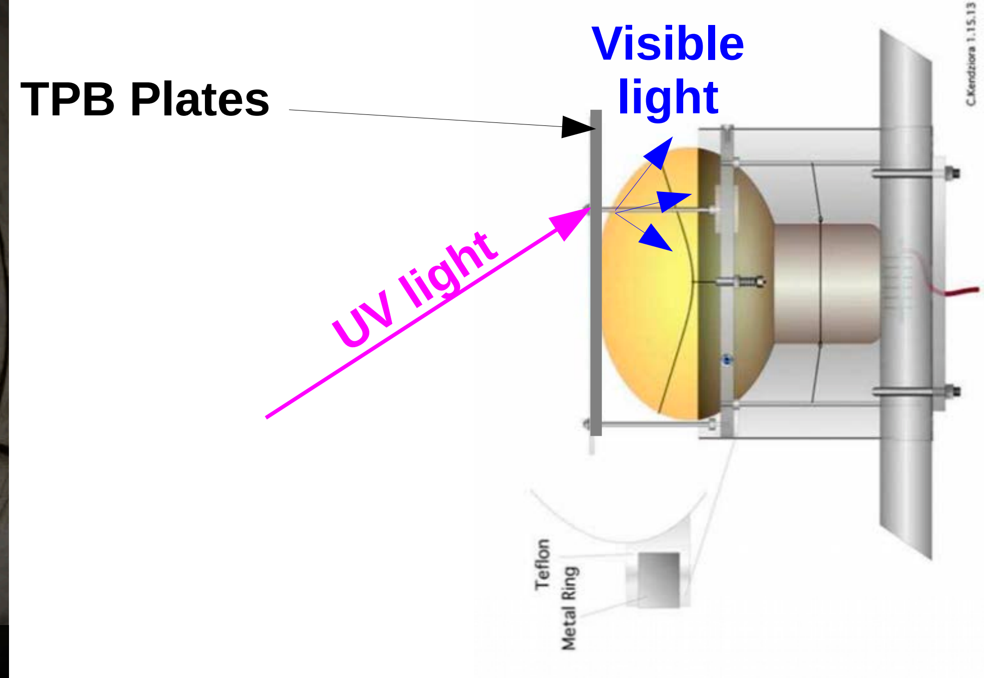


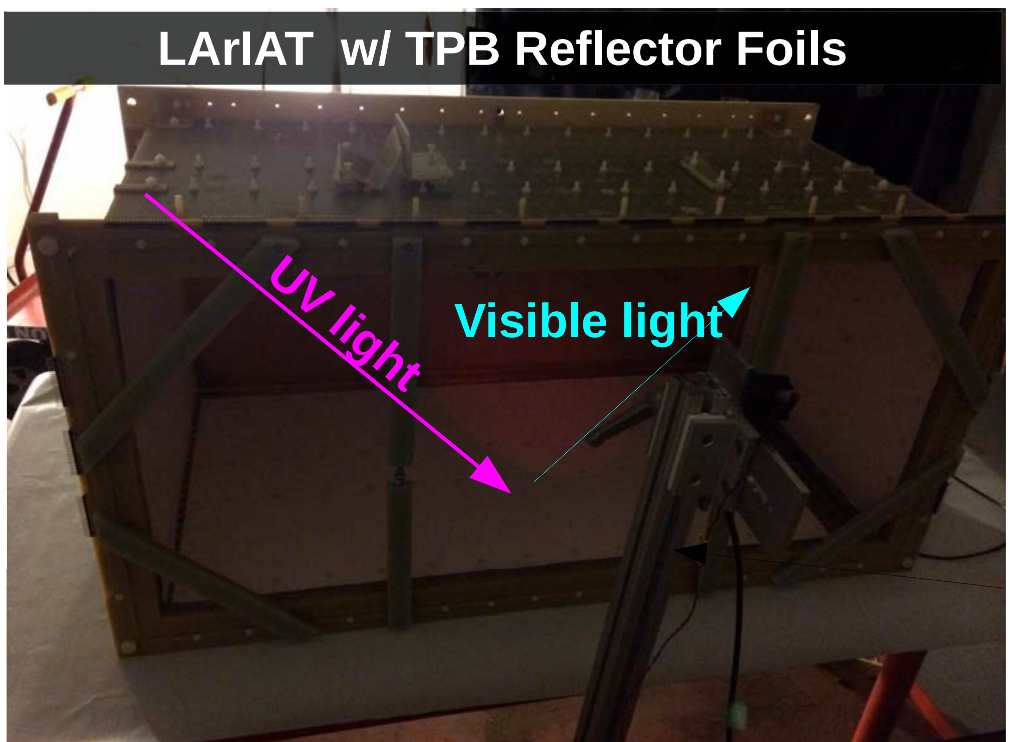
In order to detect the scintillation light using PMT's it is necessary to utilize wavelength shifting material

The light pulse provides an initial time (t_0) for the neutrino event

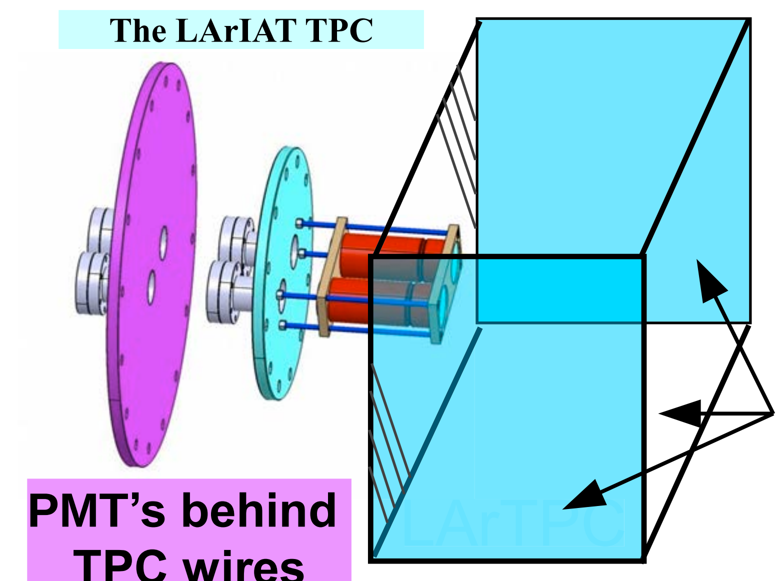


Credit: Ben Jones (MIT) for image



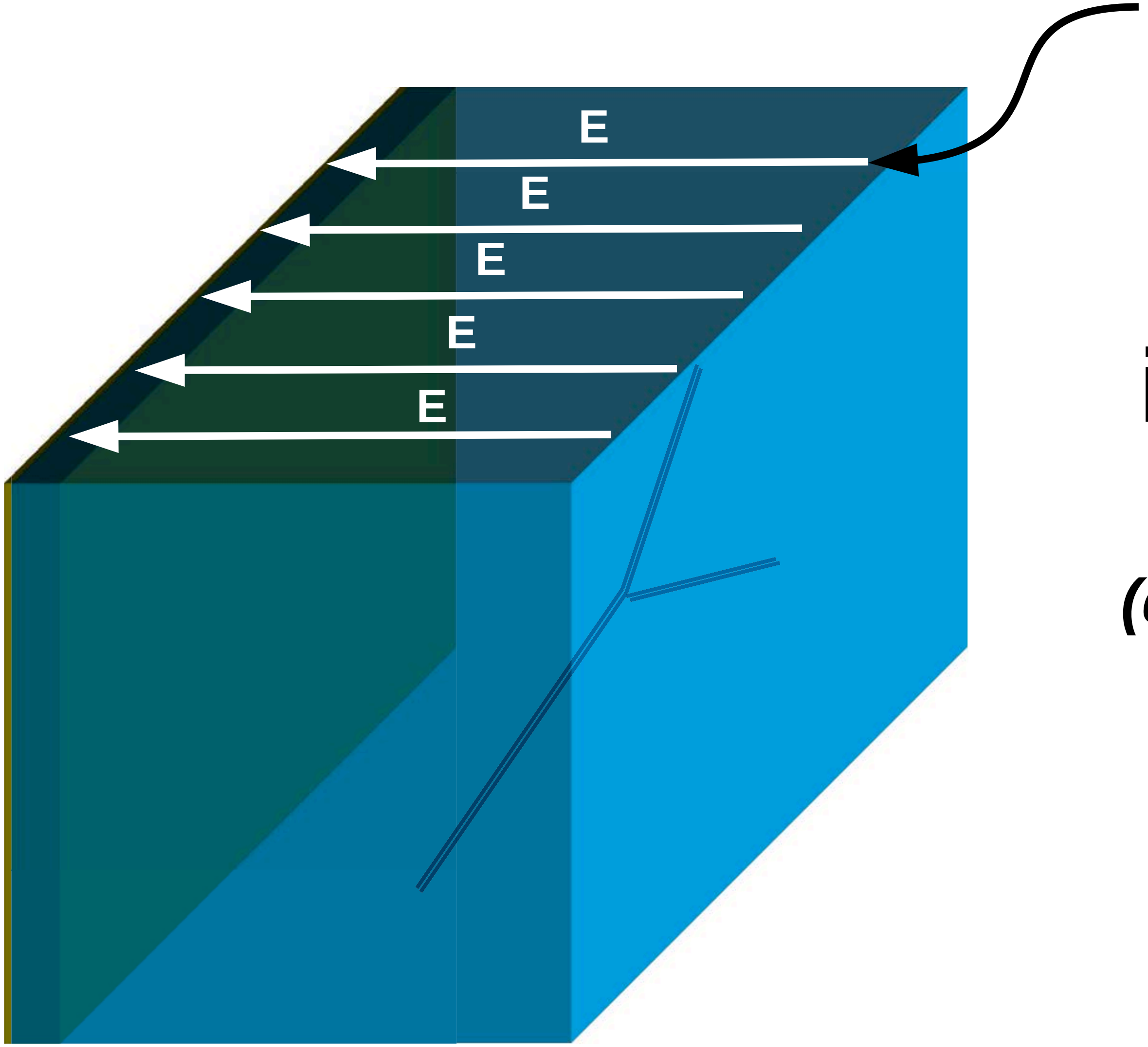


Wavelength shifting reflector foil lining the TPC to give uniform light yield



Credit: Flavio Cavanna (FNAL) for image

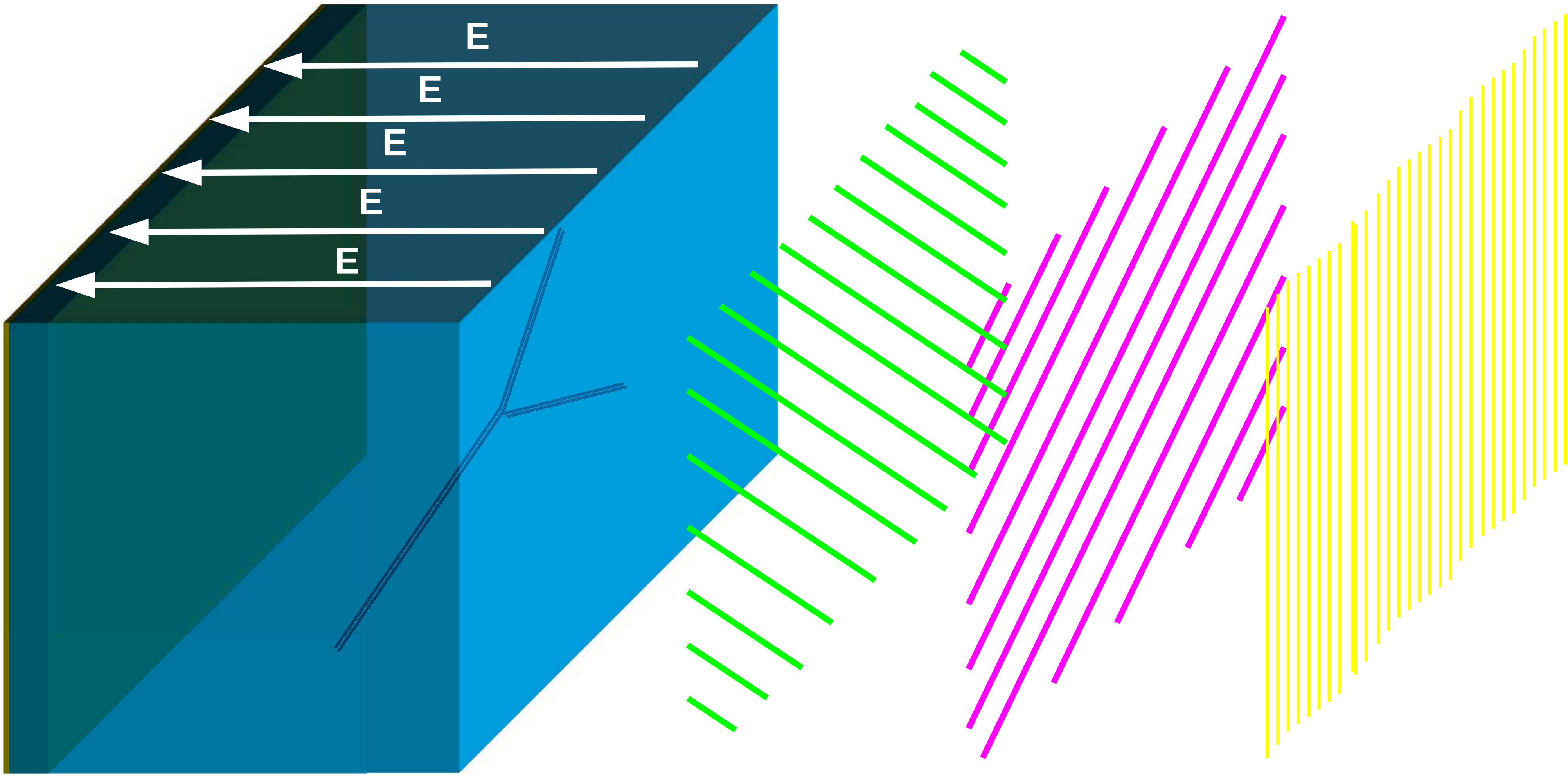
Liquid Argon Neutrino Detector



We apply a uniform electric field to drift the ionization charge

(drift times on the order of μs)

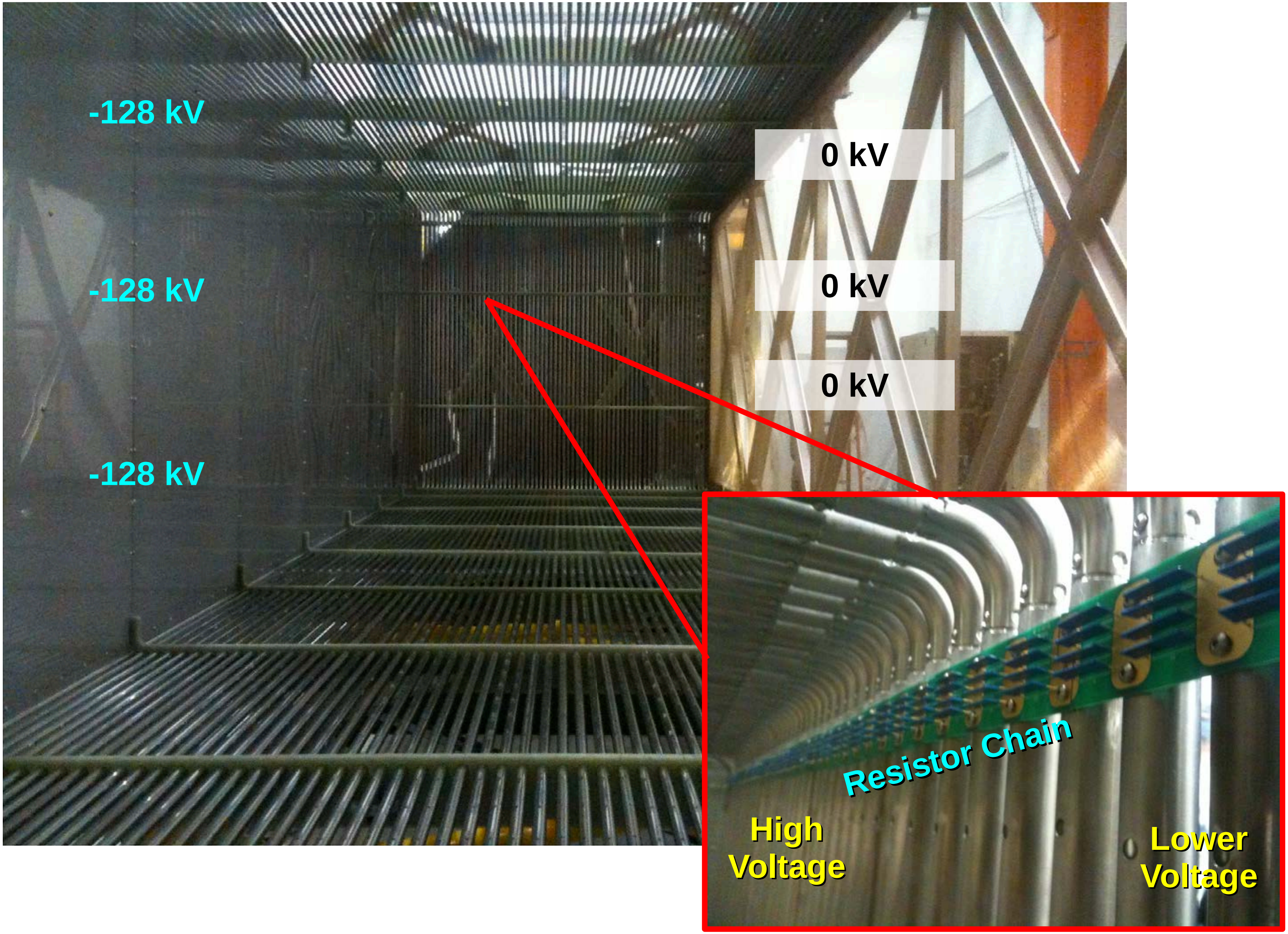
Liquid Argon Neutrino Detector



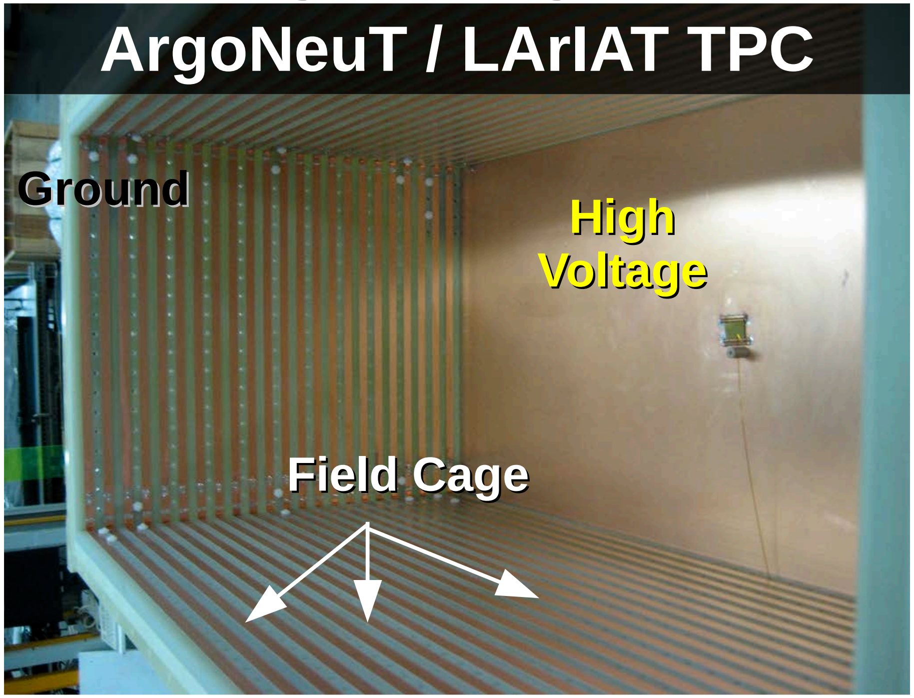
We collect this charge on a series of wires

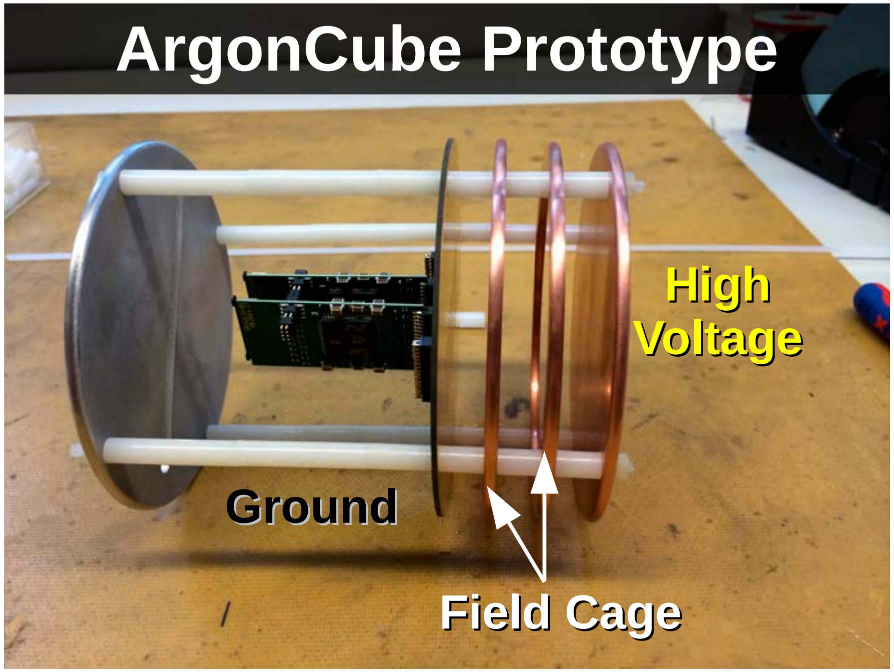
How to apply a uniform E-Field

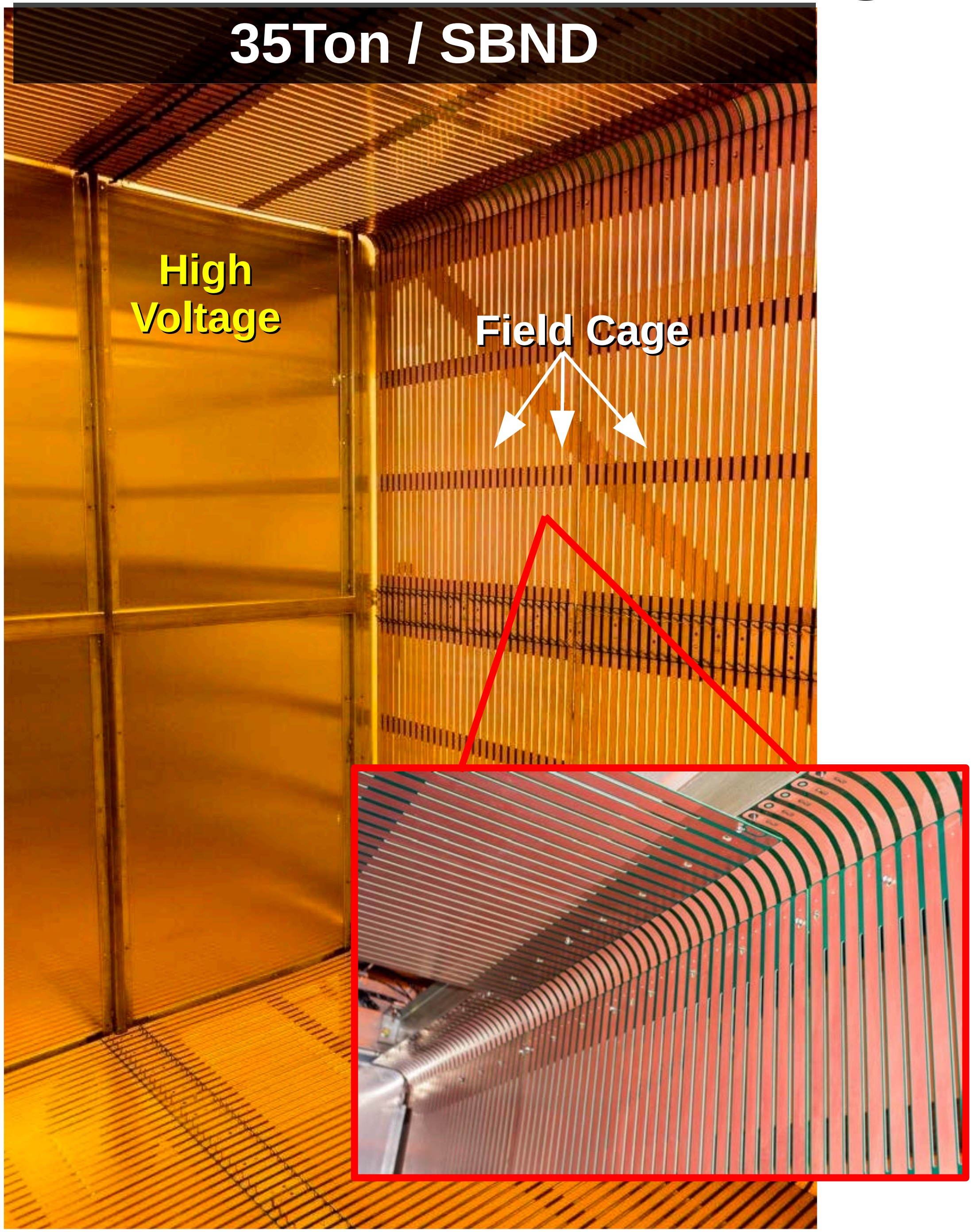
How to apply a uniform E-Field



Many ways to build the same thing

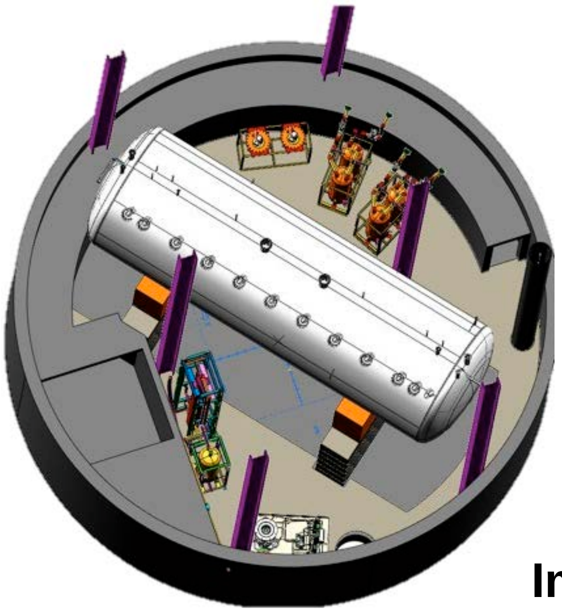






Uniformity matters

- Small variations in the electric field will distort the drift velocities of the electrons thus distorting the image of the neutrino interaction



Nonuniform drift velocities

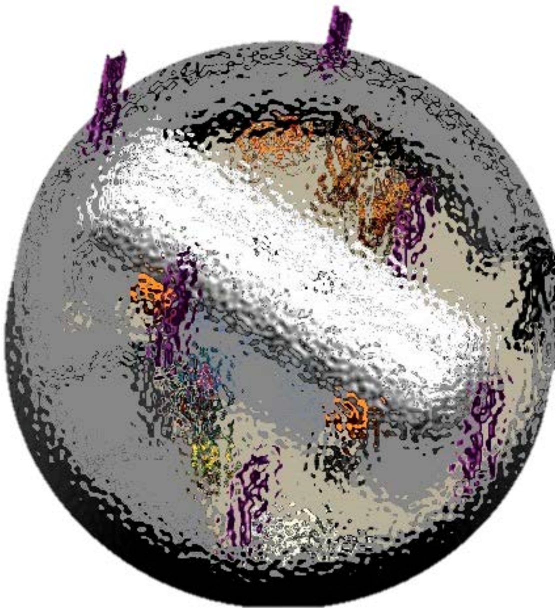
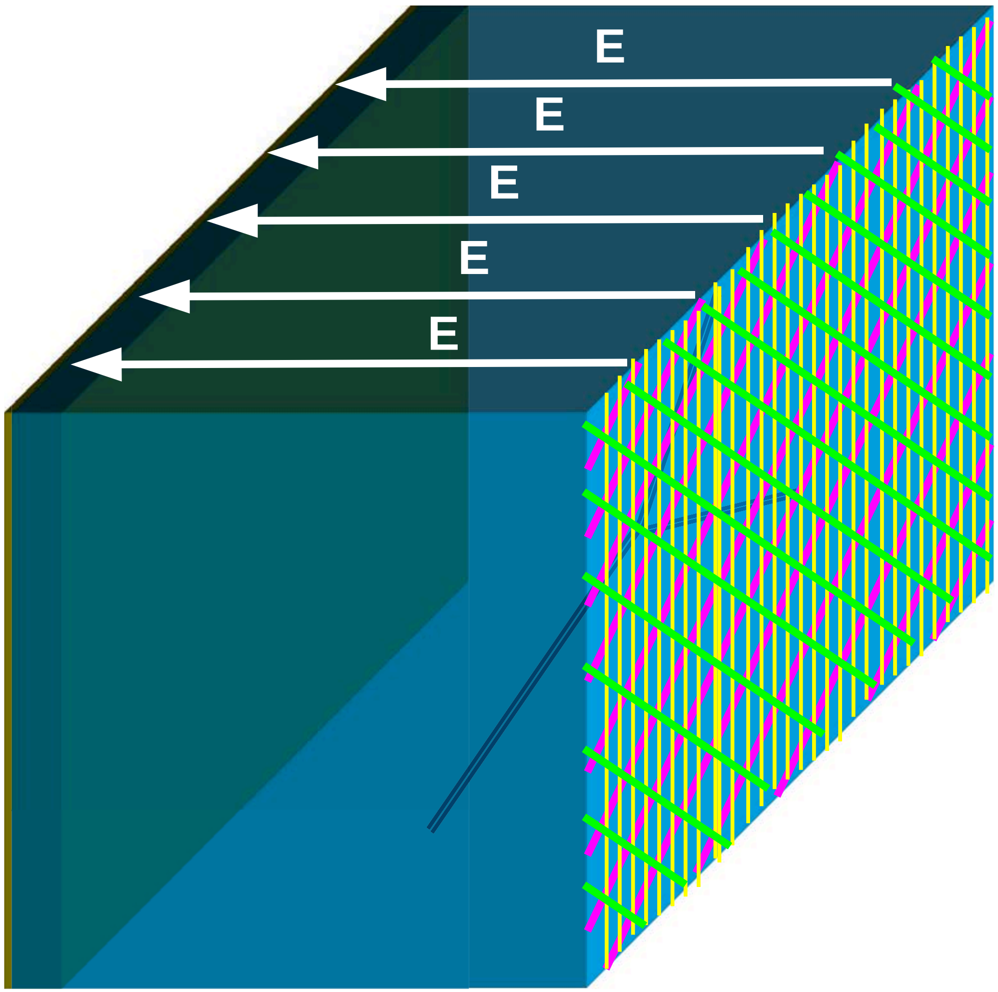


Image credit: B. Jones

Great care is taken during construction to ensure uniform fields
(other remediation strategies are also used to correct back for non-uniformities)

Liquid Argon Neutrino Detector



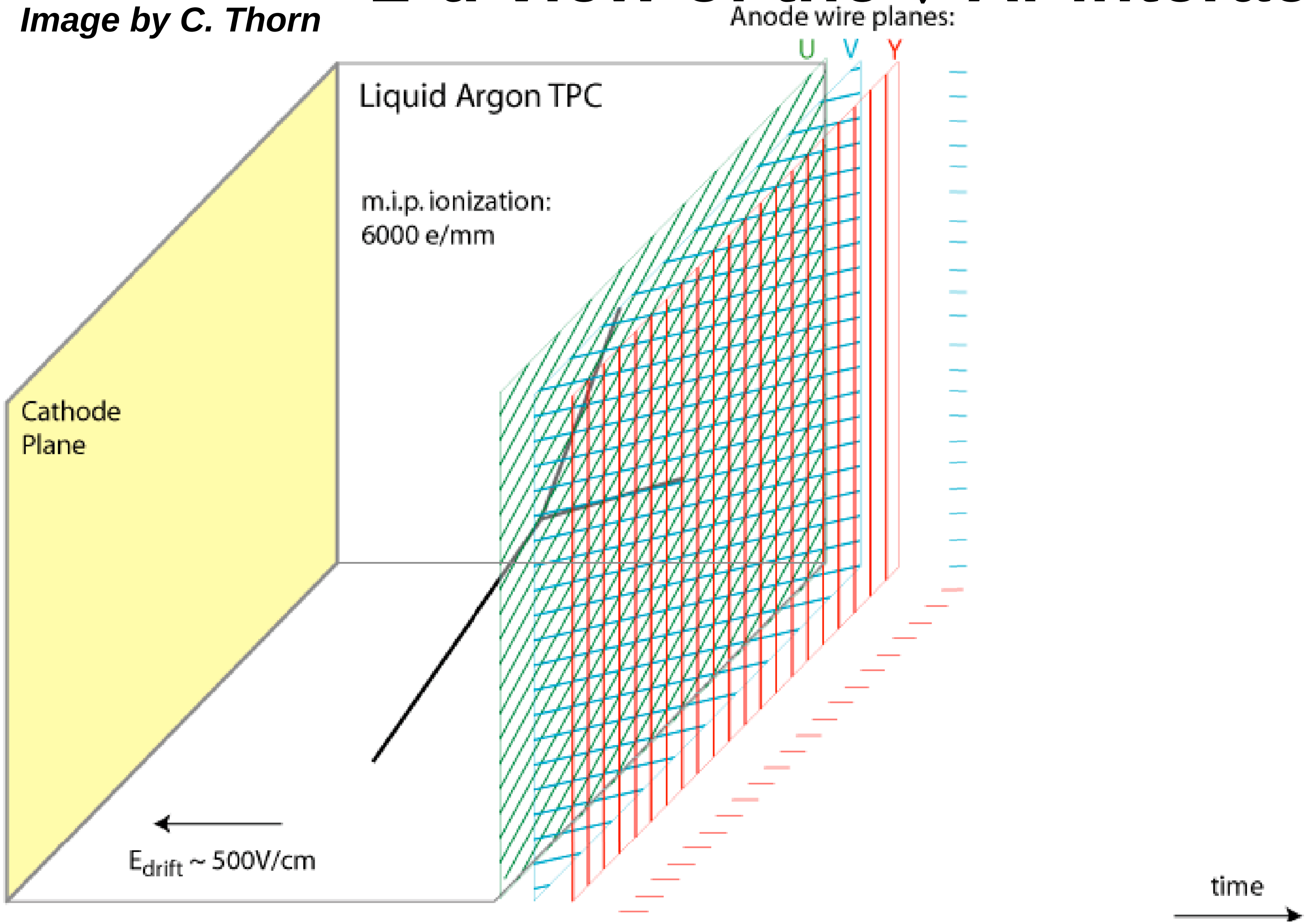
What you read off of your wires is the amount of charge and the drift time of the ionization "projected" back into the volume of liquid argon

Hence the name

Liquid Argon Time Projection Chamber

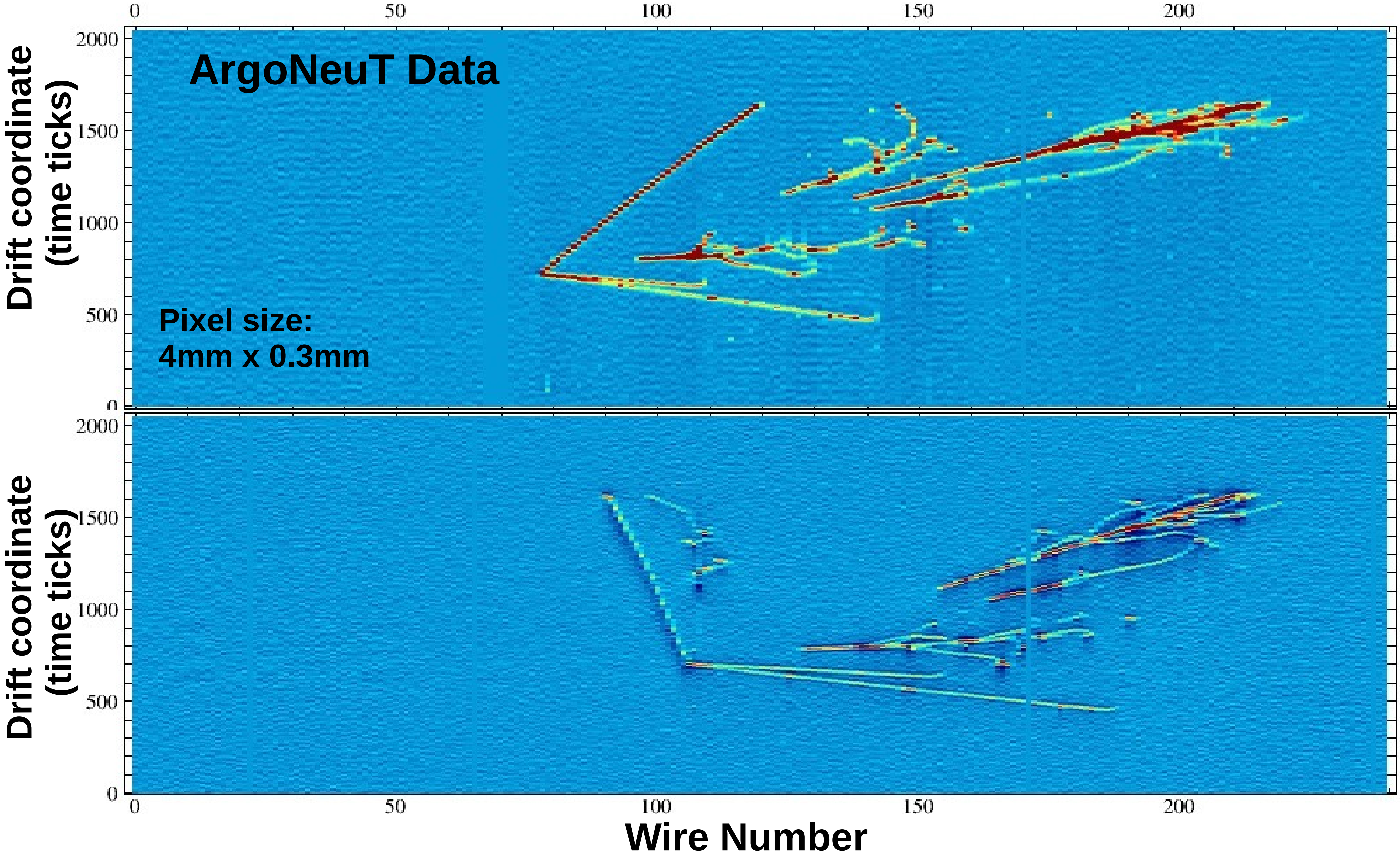
Wires placed at the end of the drift provide a 2-d view of the ν-Ar interaction

Image by C. Thorn

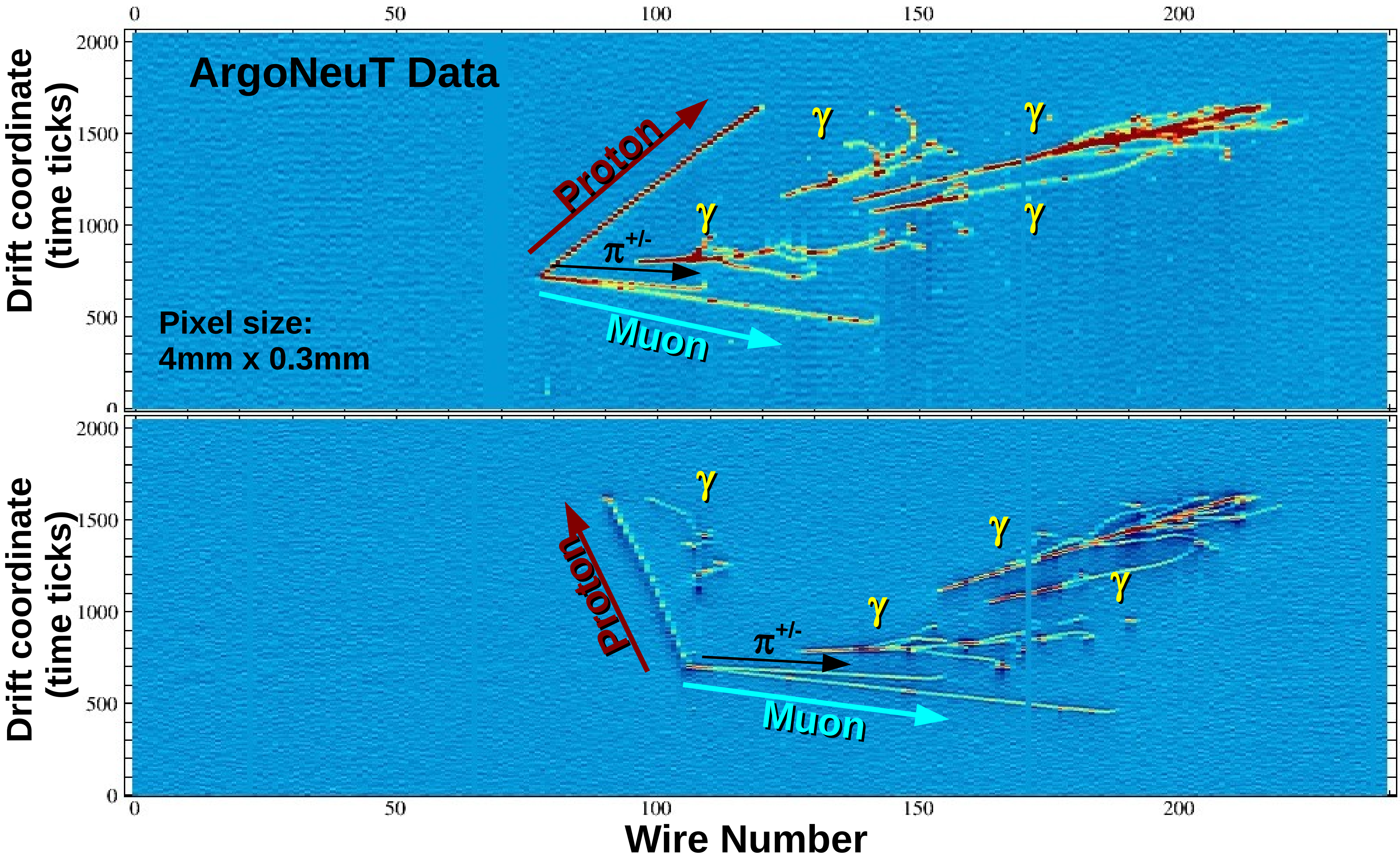


Using multiple wire planes with different angles allows us to perform 3-d event reconstruction!

Liquid Argon Time Projection Chamber

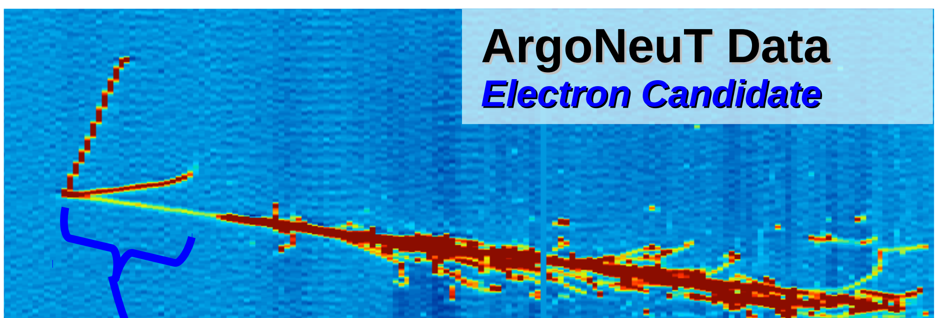


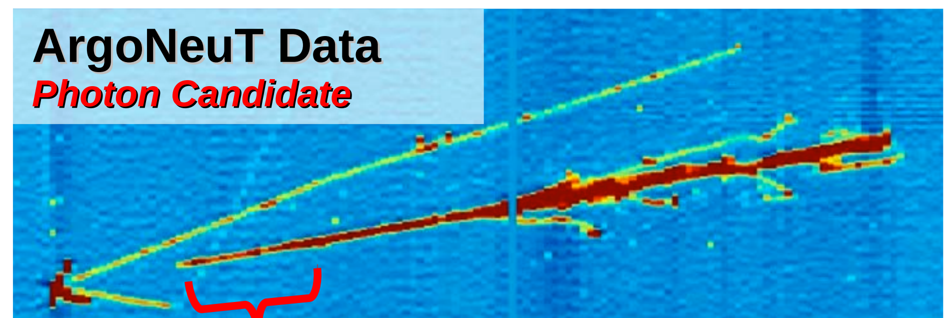
Liquid Argon Time Projection Chamber

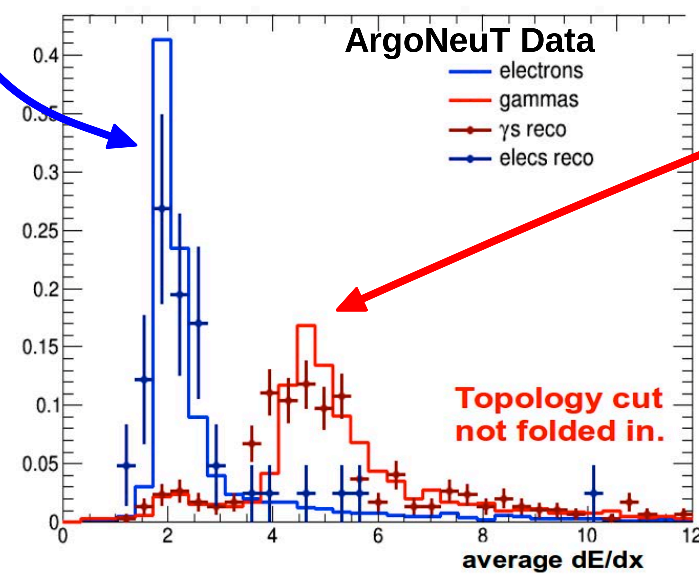


MicroBooNE

- **MicroBooNE will utilize the electron / photon discrimination power of LArTPC's to determine if the MiniBooNE excess is electron like** *(from ν_e appearance)* **or photon like** *(unaccounted for background)*



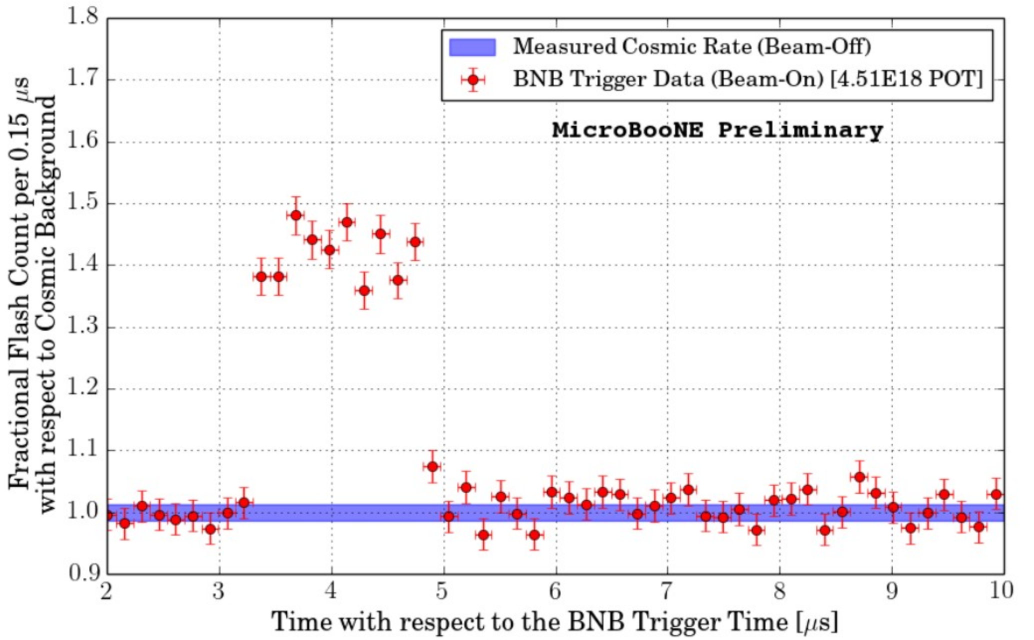


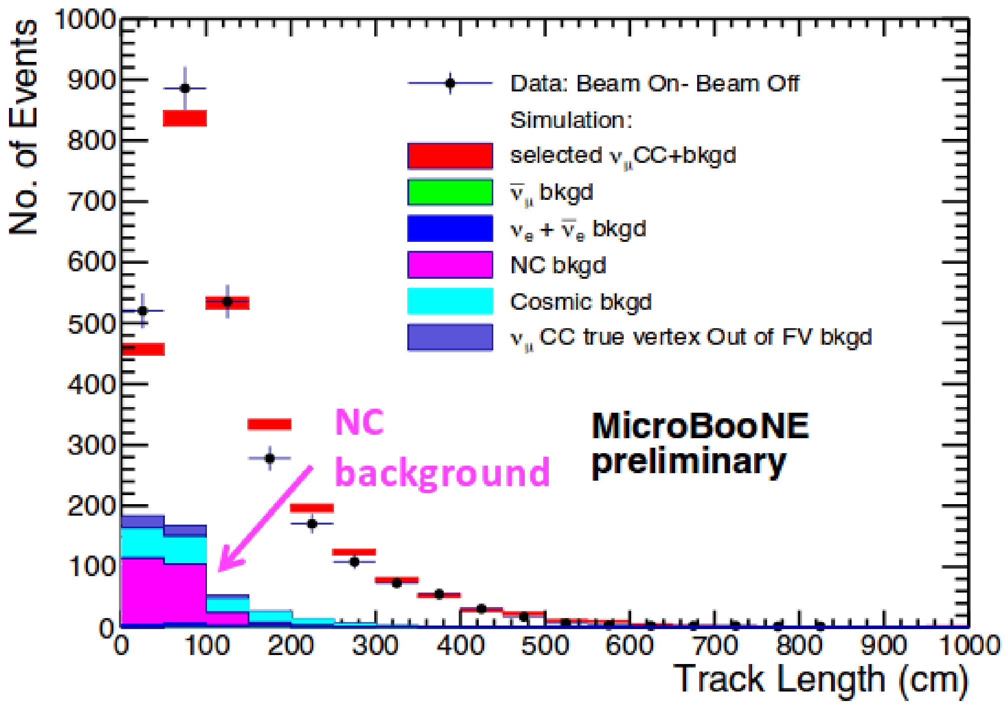


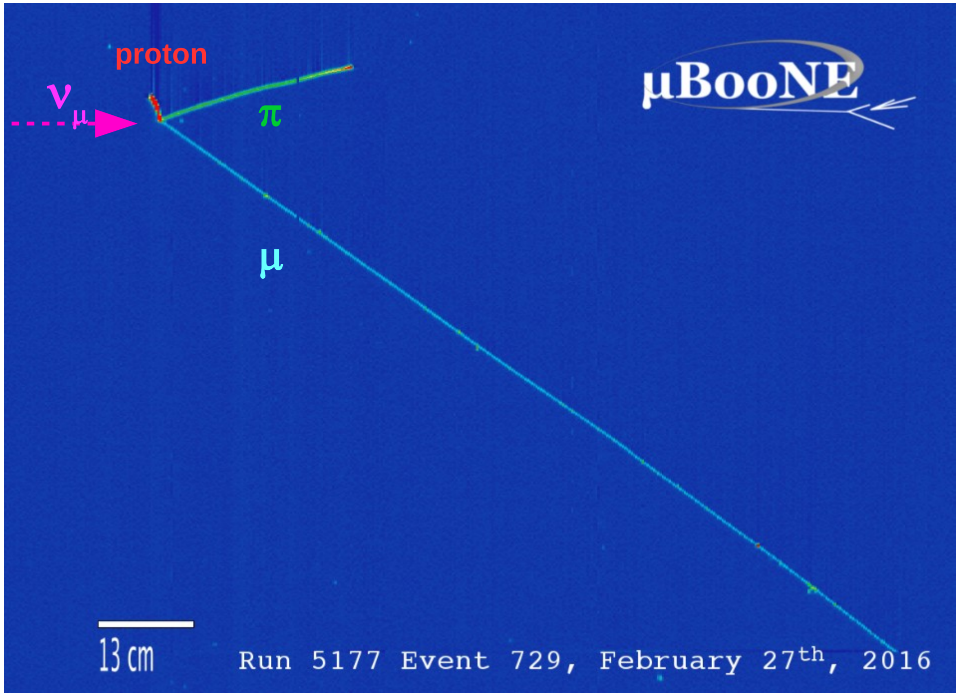
By analyzing the topology and the dE/dX of the electromagnetic shower, disentangling the MiniBooNE low energy excess becomes possible

MicroBooNE

- **MicroBooNE has been successfully recording neutrino interactions since late 2015**
  - First neutrino results were announced just this year!

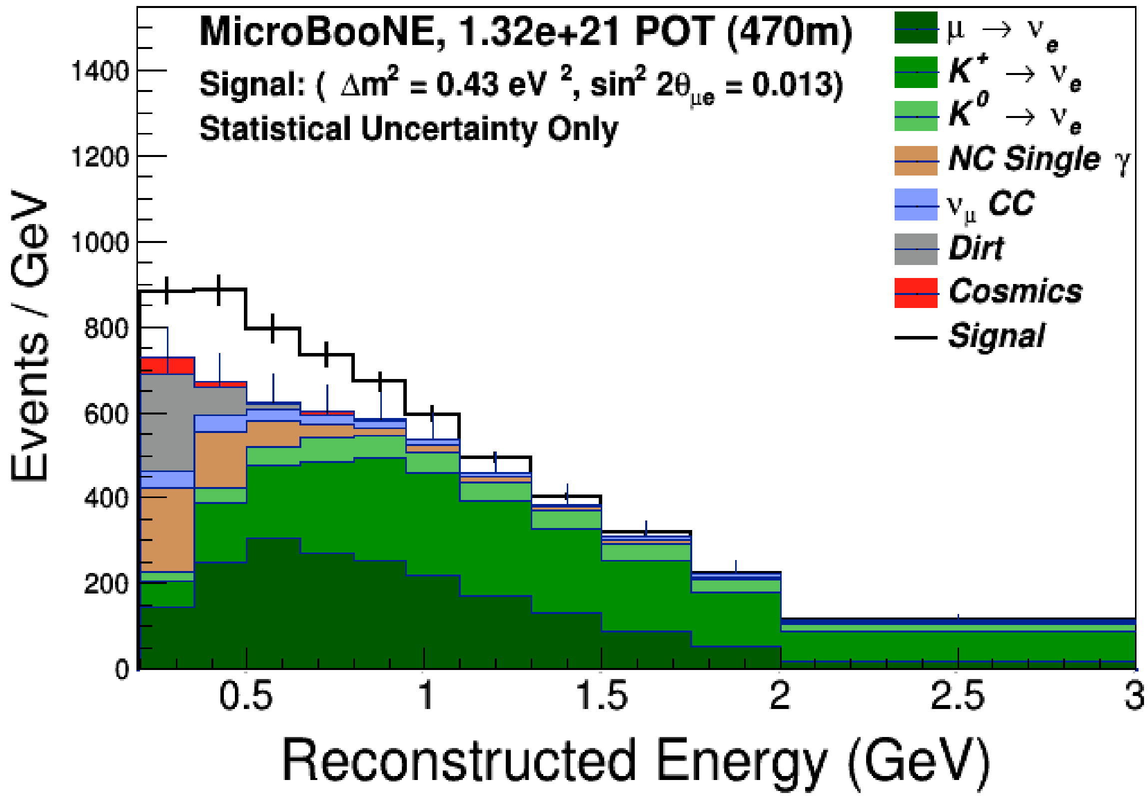






Addressing the low-energy excess of MiniBooNE

- **Oscillation Physics**
  - Utilize its e/γ separation to determine if the signal is photon-like or electron like
- **Regardless of if it is electron or photon like there is interesting physics to uncover!**
  - If it is electron-like than this is a compelling clue towards an oscillation signature
  - If it is photon like than there is a process that we are not including in our models

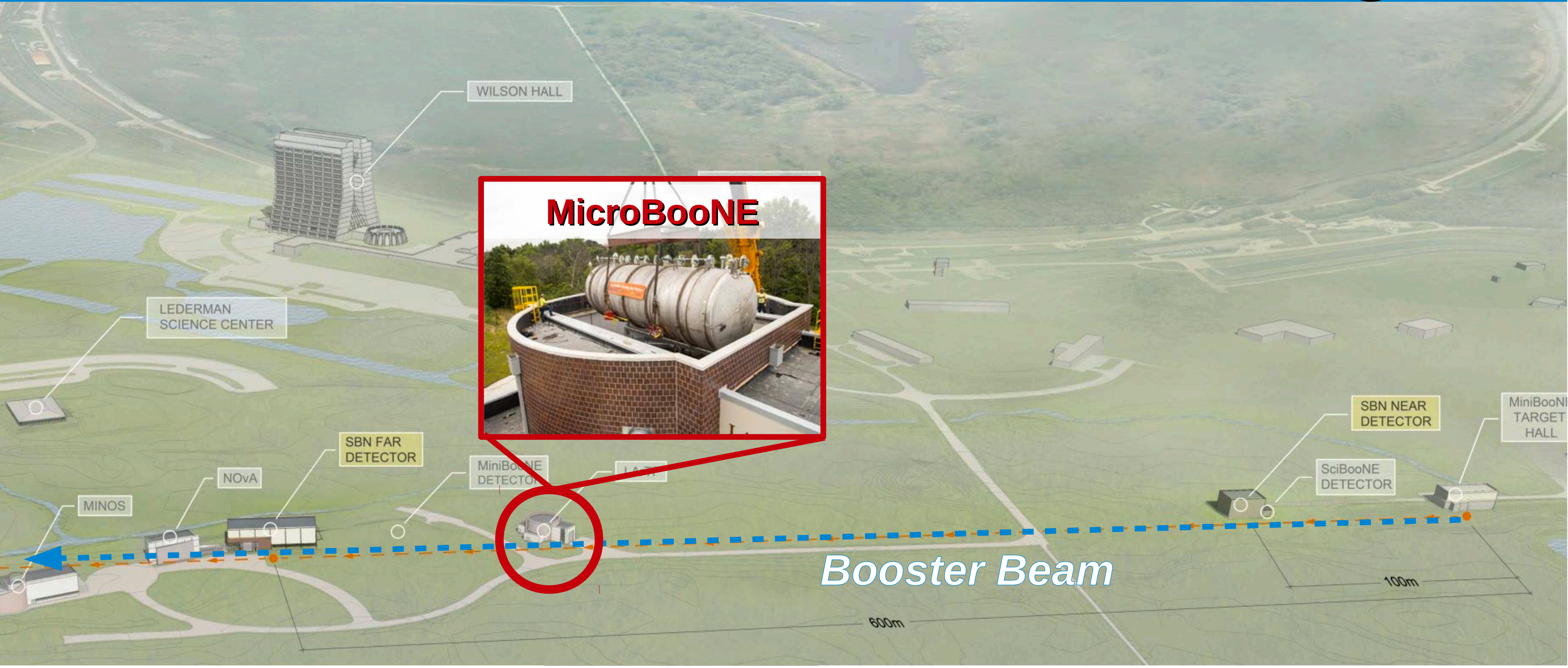


- **MicroBooNE is the largest LArTPC ever built in the U.S.**
  - 89 Tons of active mass

about this big

- **MicroBooNE also has a rich physics program planned**

The Short-Baseline Neutrino Program



What do I need to add to the existing program (top notch neutrino beam + world class neutrino detectors) to make a definitive search eV scale for sterile neutrinos?

→ Calibration of the detector technology **(LArTPC in a Testbeam)**

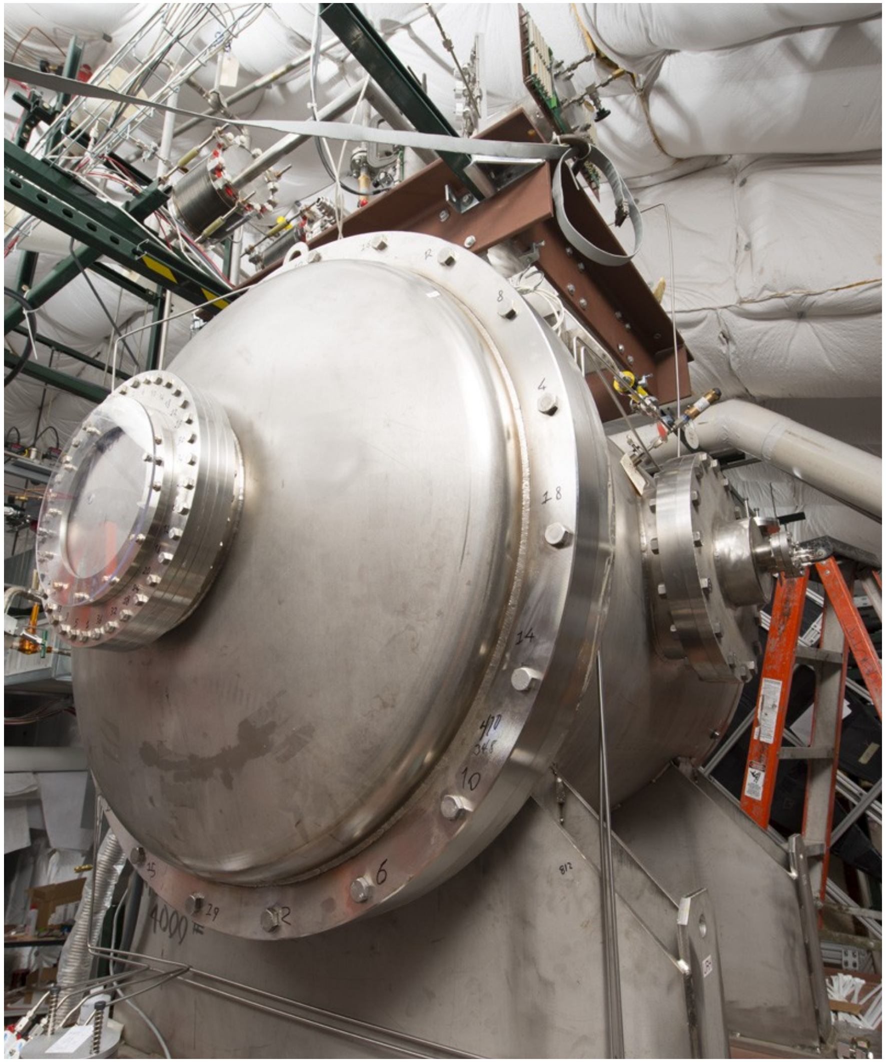
→ Normalization of the un-oscillated neutrino beam **(Near detector)**

→ High statistics in the appearance channel **(large mass far detector)**

→ Look for complimentary muon disappearance **(near/far comparison)**

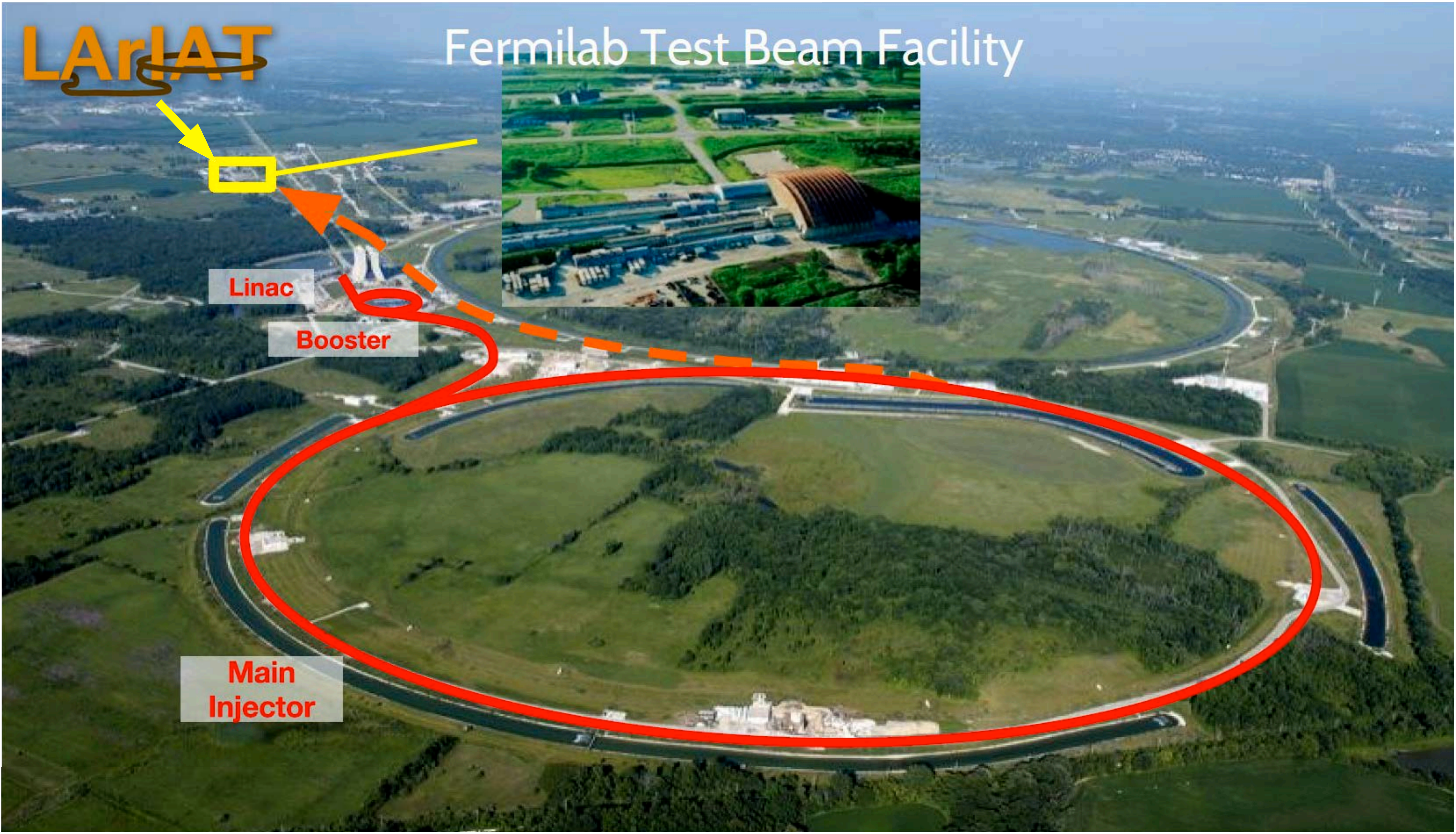
The LArIAT Mission

Executing a comprehensive program designed to characterize LArTPC performance and charged particles interaction in argon in the energy range relevant to the forthcoming neutrino experiments

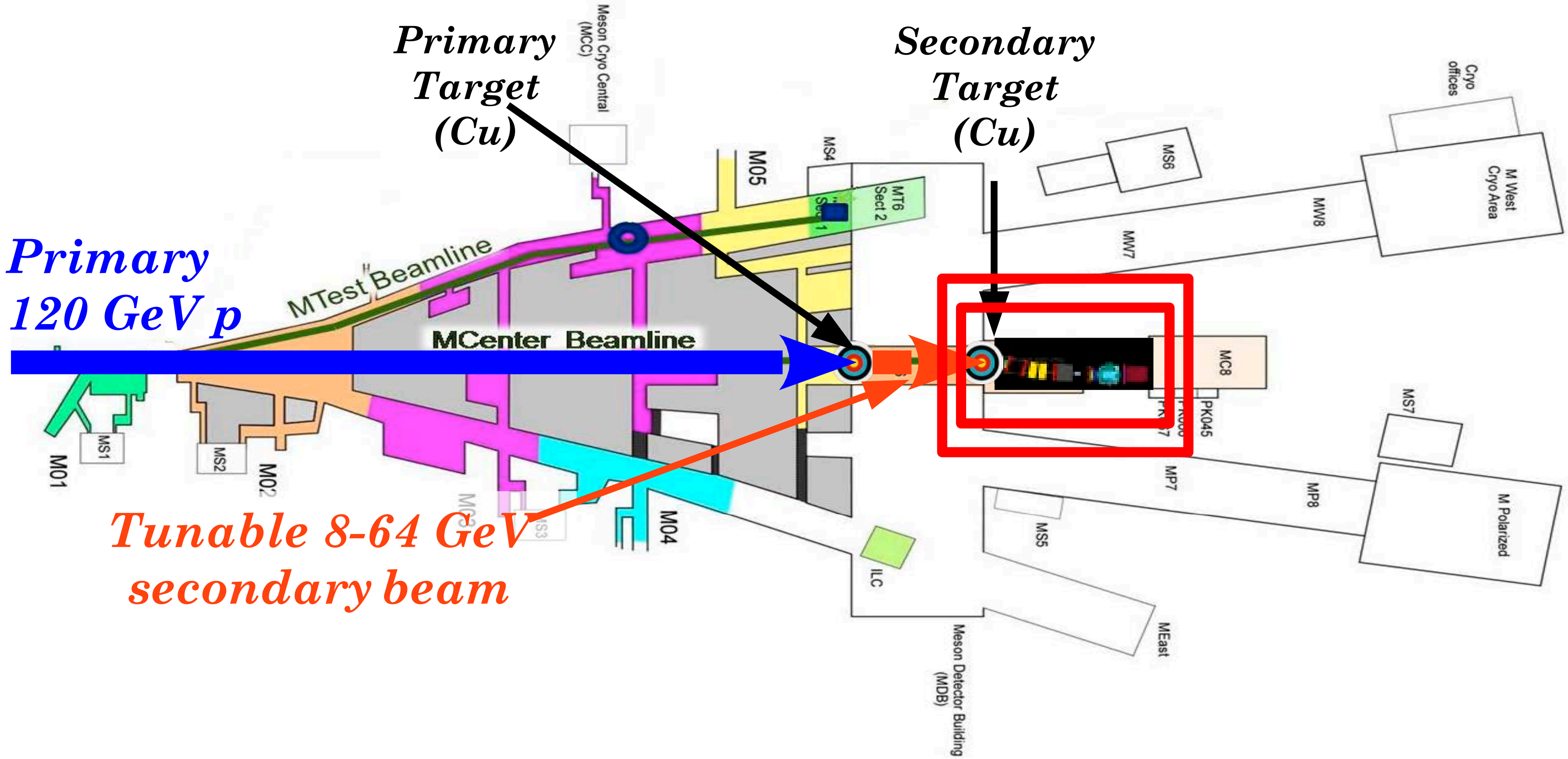


LArIAT: The experiment the LArTPC community needs

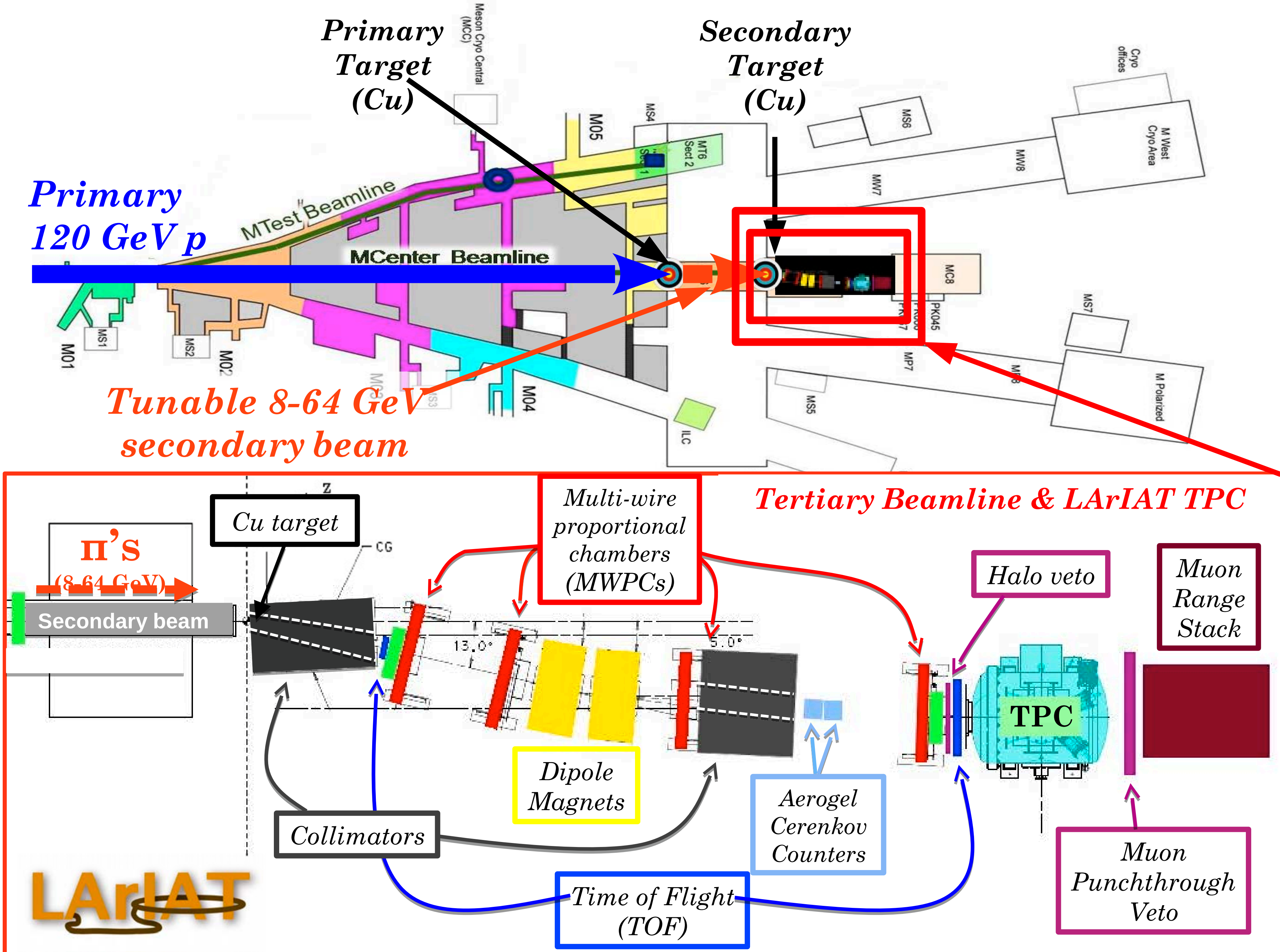
LArIAT's Home



Bird's eye view of LArIAT beamline



Bird's eye view of LArIAT beamline

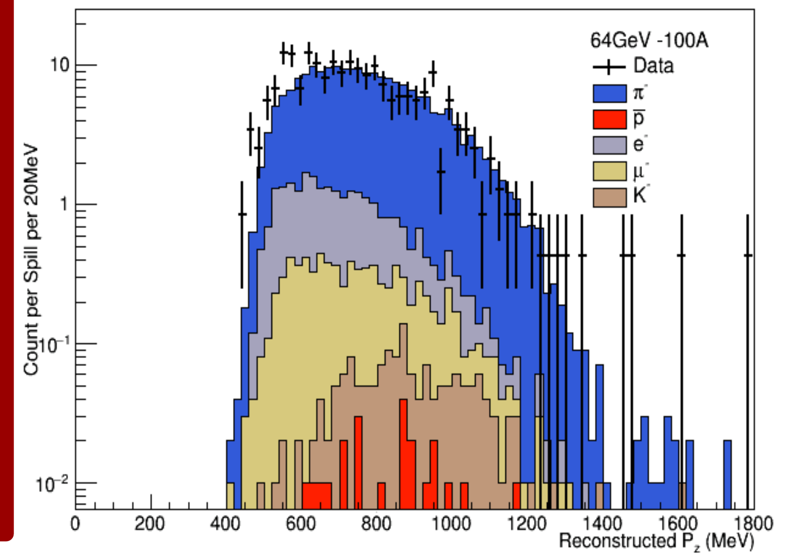


LArIAT Beamline Detectors

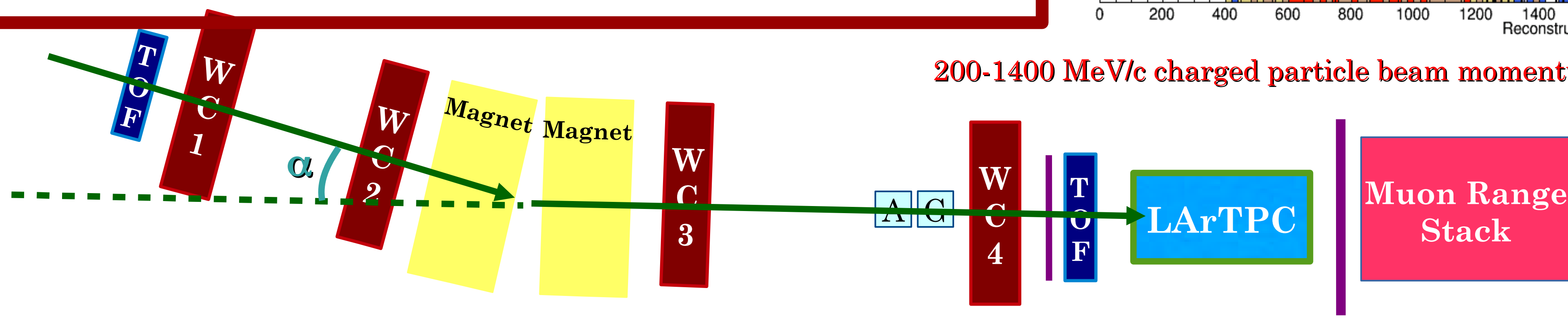
✔ WC pairs used to define particle tracks before and after the magnets

✔ The angle α between the two tracks determines the momentum reconstruction

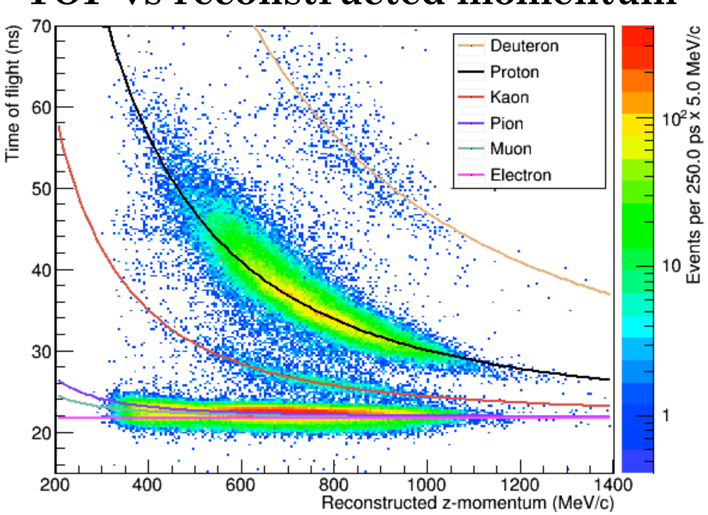
✔ Momentum reconstruction possible even if information from one of the two inner WC is missing



200-1400 MeV/c charged particle beam momentum range



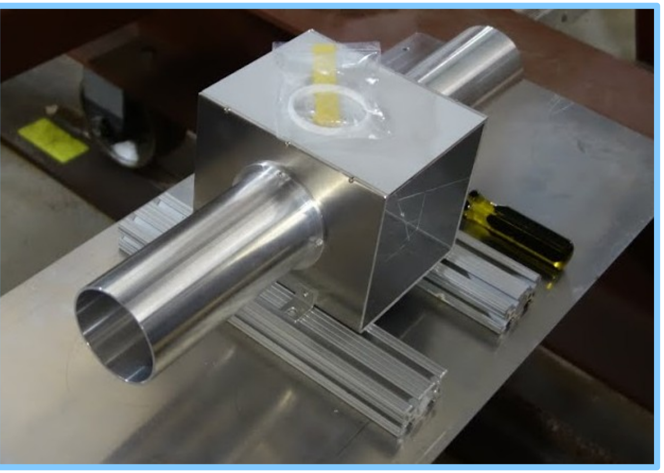
TOF vs reconstructed momentum

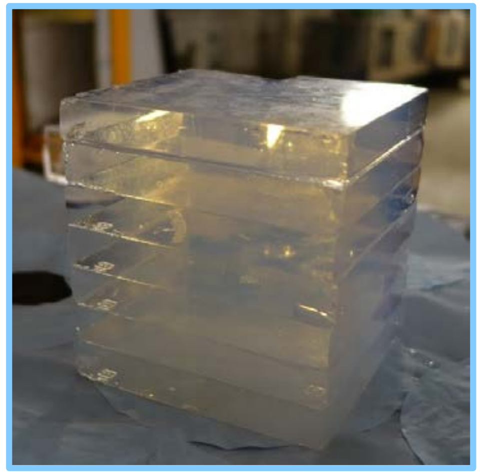


✔ 2 scintillator counters with 1 ns sampling provides TOF

✔ In conjunction with momentum derived by MWPCs, discrimination of π&μ&e/K/p is possible

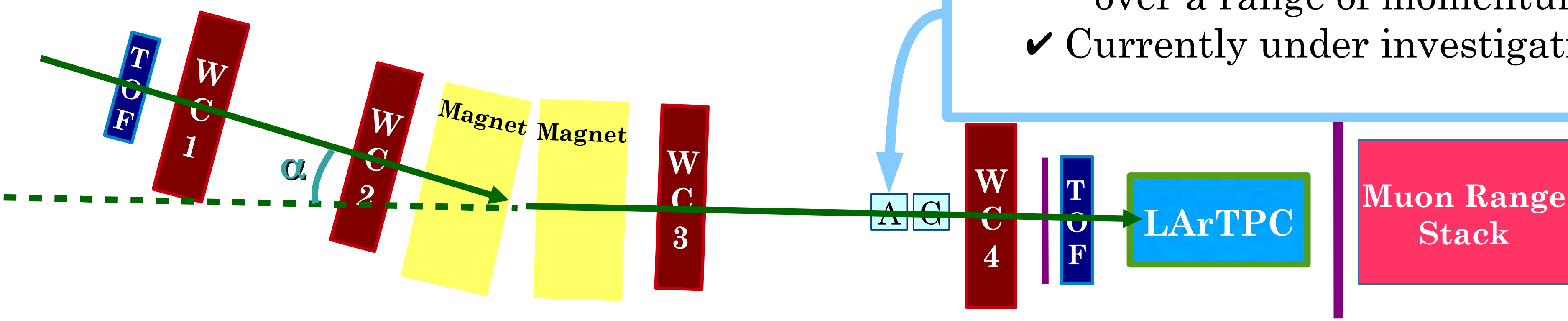
LArIAT Beamline Detectors



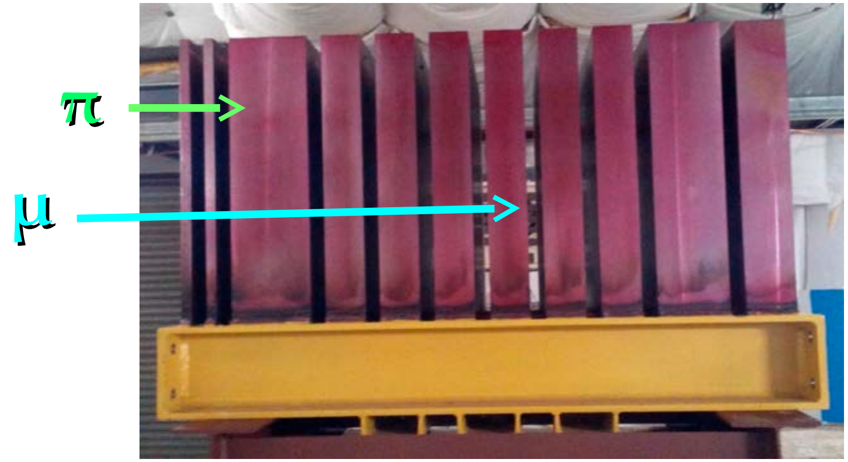


	n=1.11 Aerogel	n=1.057 Aerogel
200-300 MeV/c	μ π	μ π
300-400 MeV/c	μ π	μ π

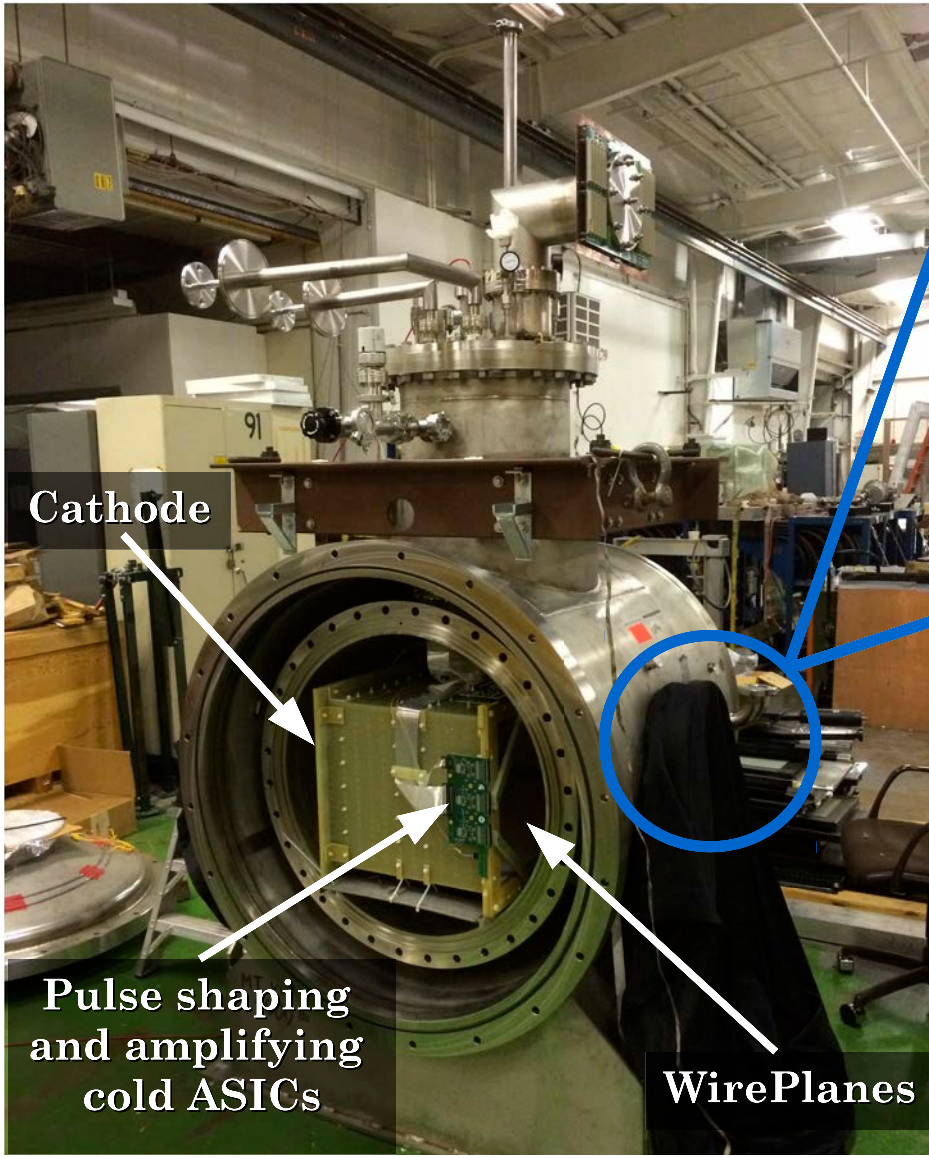
- ✔ Allows to perform π/μ separation over a range of momentum
- ✔ Currently under investigation

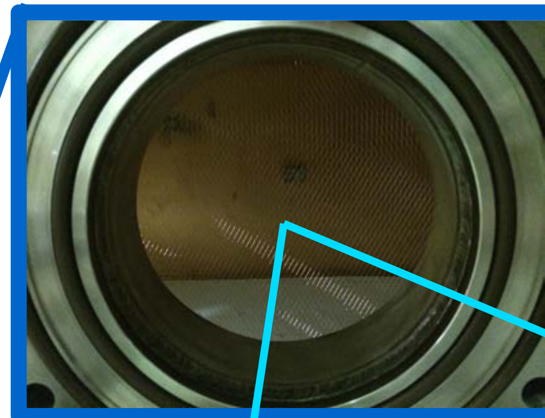


- ✔ Four layers of XY planes sandwiched between (pink) steel slabs
- ✔ Each plane is composed by 4 scintillating bars connected to a PMT
- ✔ Allows to discriminate π/μ exiting the cryostat
  - ✔ Currently under investigation

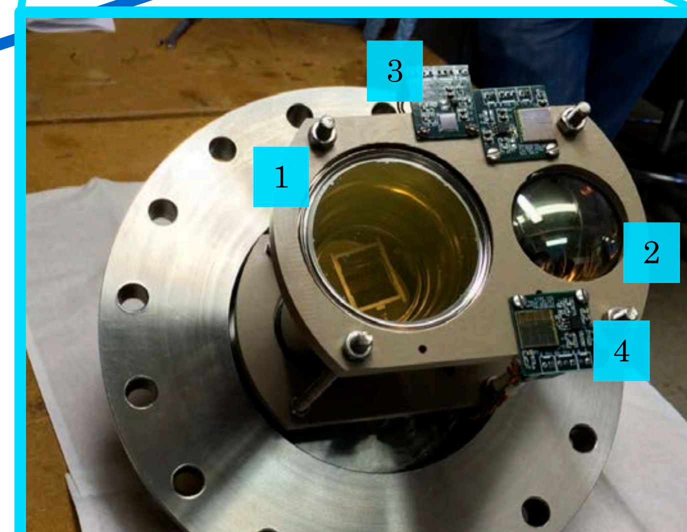


Inside the cryostat: TPC and light collection system



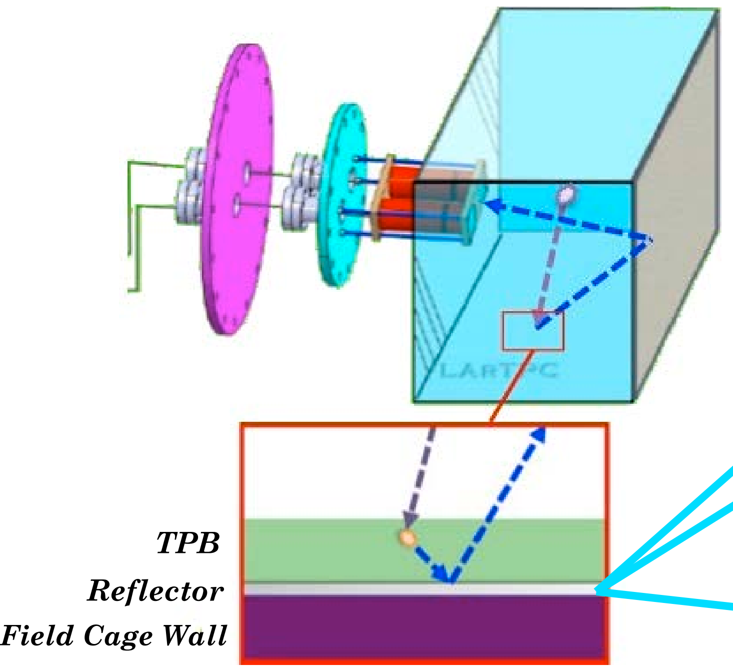


Light Collection System port

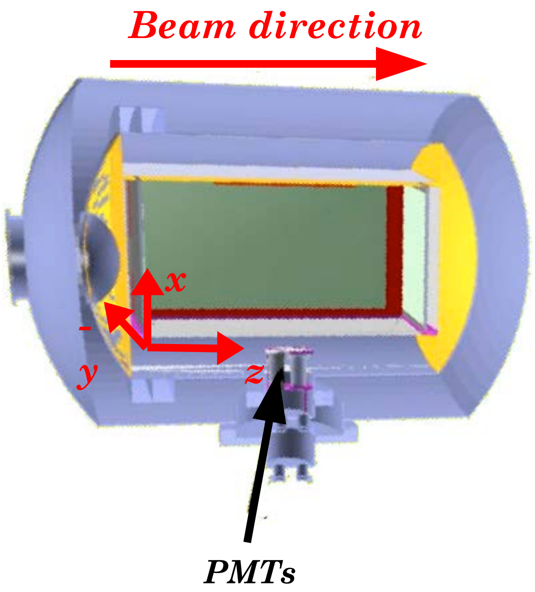


1. PMT: Hamamatsu R-11065 (3” diameter)
2. PMT: ETL D757KFL (2” diameter)
3. SiPM: SensL MicroFB-60035 w/preamp
4. SiPM: Hmm. S11828-3344M 4x4 array (Run I)
   SiPM: Hmm. VUV-sensitive (Run II)

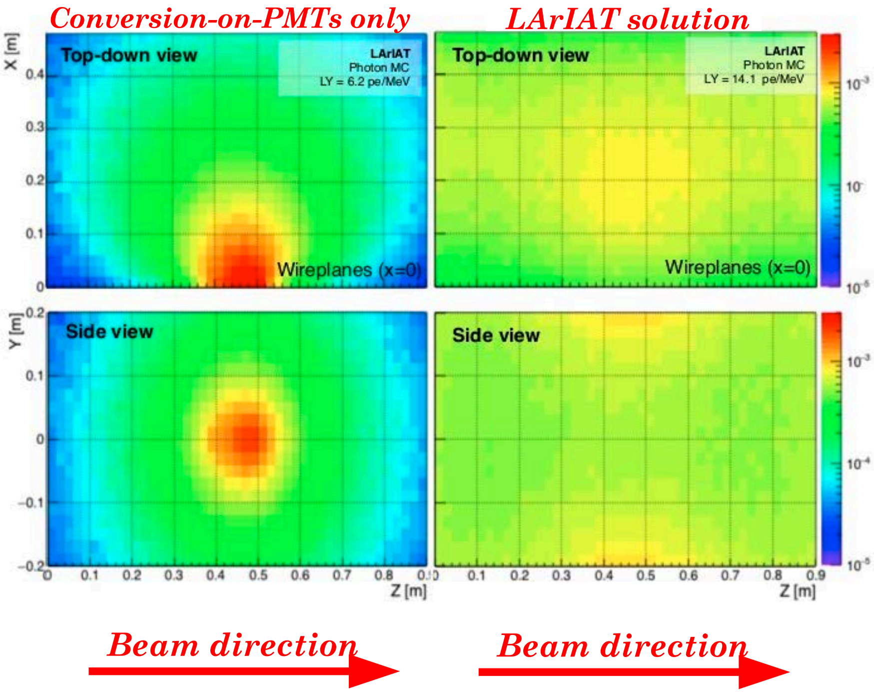
Light Collection System



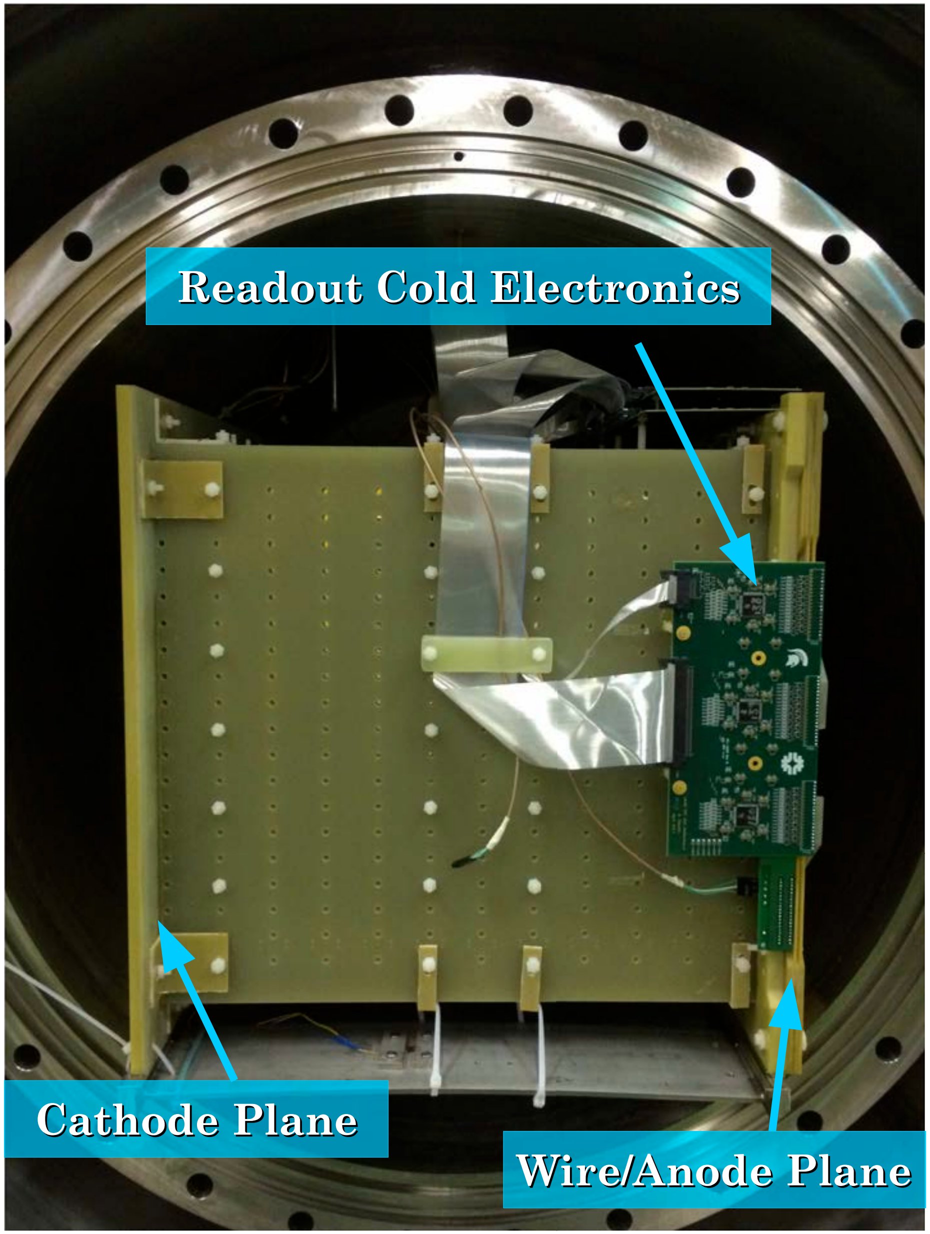
Credit: W. Foreman



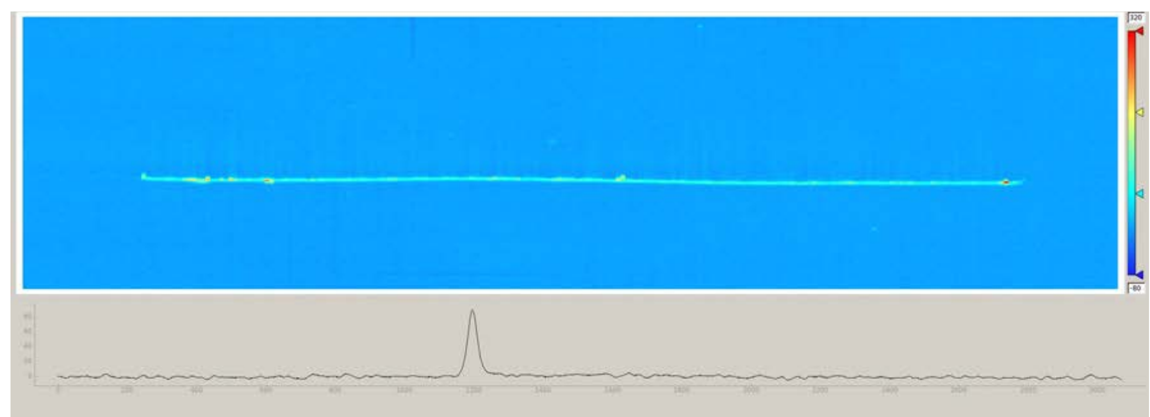
- ✔ **Wavelength shifting (evaporated) reflected foils on the four field cage walls**
  - ✔ *Technique borrowed from dark matter experiments*
- ✔ **Provides greater (~ 40 pe/MeV at zero field) and more uniform light yield respect to "conversion-on-PMTs-only" light systems**
- ✔ **R&D for future neutrino experiments as a way to improve calorimetry and triggering**



LArTPC



- **Refurbished ArgoNeuT TPC**
  - ✔ 2 Readout planes
  - ✔ 240 wires/plane, ±60° respect to beam, 4 mm pitch
  - ✔ 500 V/cm nominal drift field
- **Cold Electronics: MicroBooNE preamplifying ASICs on custom motherboards**
  - ✔ Signal to Noise ratio (MIP pulse height compared to pedestal RMS)
    - **Run 1** ~50:1 (ArgoNeuT warm electronics ~15:1)
    - **Run 2** ~70:1



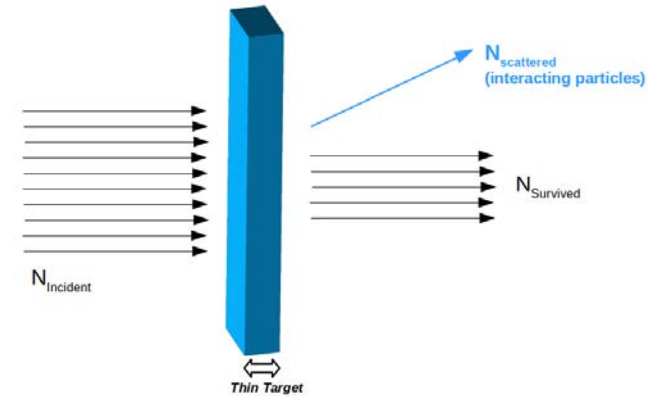
Example of putting it all together: LArIAT

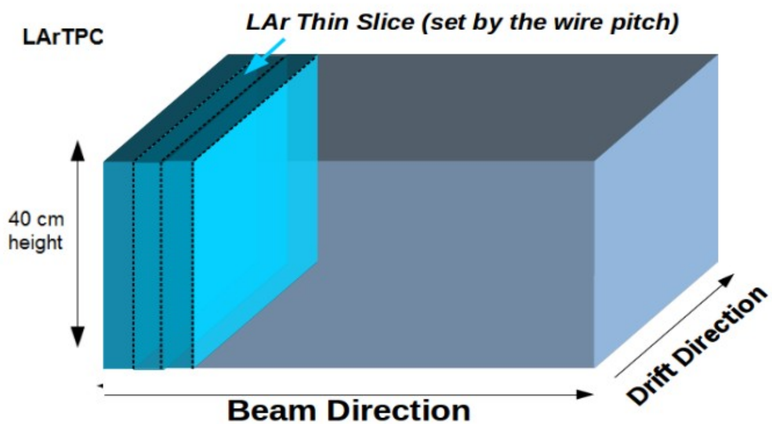
- You can calculate the probability of a particle interacting in a thin slab of argon as:

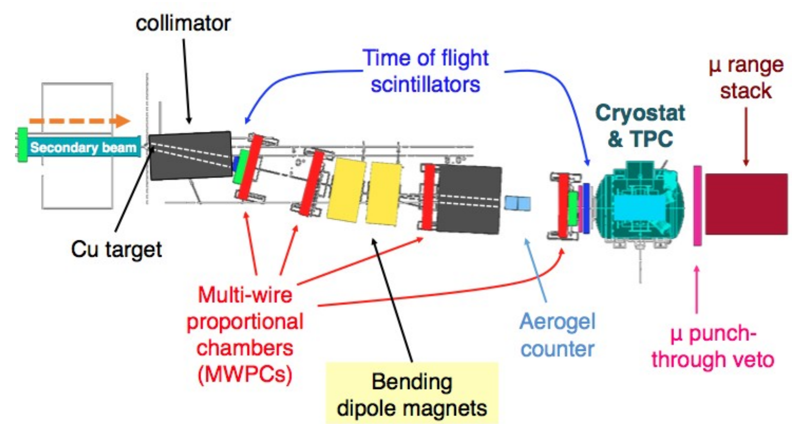
$$\frac{N_{\text{interacting}}}{N_{\text{Incident}}} = P_{\text{Interacting}} = 1 - e^{-\sigma n z}$$

- Using the granularity of the LArTPC, we can treat the wire-to-wire spacing as a series of “thin-slab” targets if we know the energy of the particle incident to that target

- LArIAT is a testbeam experiment where we measure the momentum of the particle prior to it entering the LArTPC





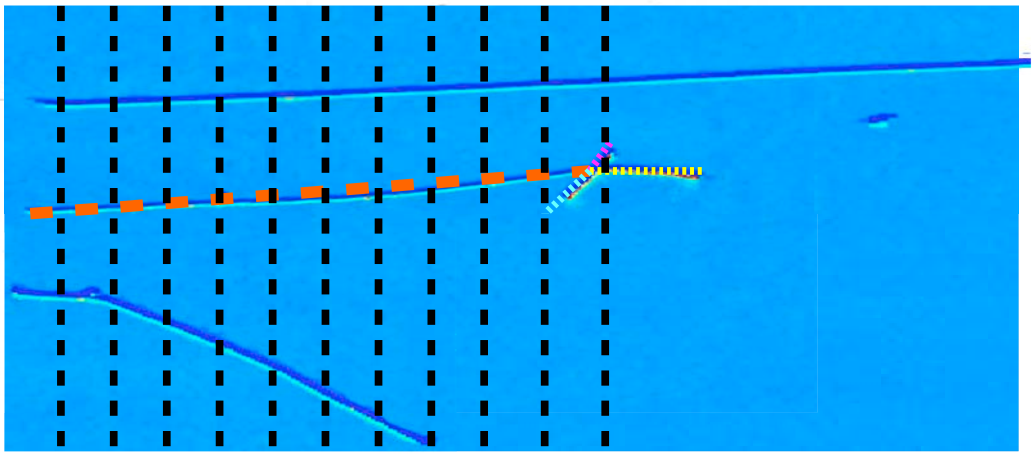


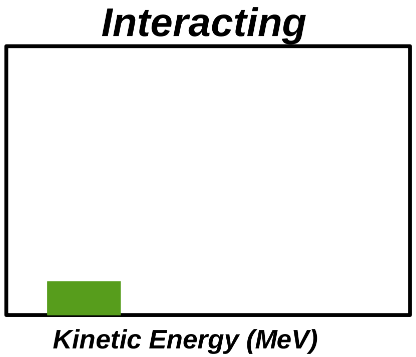
$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - E_{\text{Flat}}$$

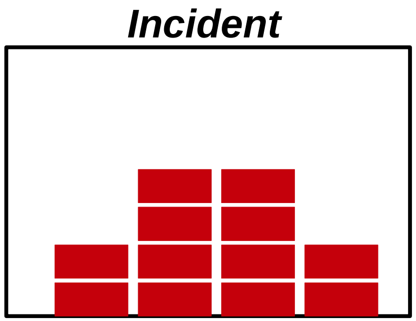
Example of putting it all together: LArIAT

- **Now that we have a wire chamber track (with an initial kinetic energy measured from the wire chambers) matched to a TPC track, we follow that TPC track in slices**
  - **The slice represents the distance between each 3D point in the track**
  - For each slice we ask: “Is this the end of the track?”
    - **NO:** Calculate the kinetic energy at this point and put that in our “non-interacting” histogram
    - **Yes:** Calculate the kinetic energy at this point and put that in both the **interacting** and **incident** histograms

$$KE_{Interaction} = KE_i - \sum_{i=0}^{nSpts} dE/dX_i \times Pitch_i$$

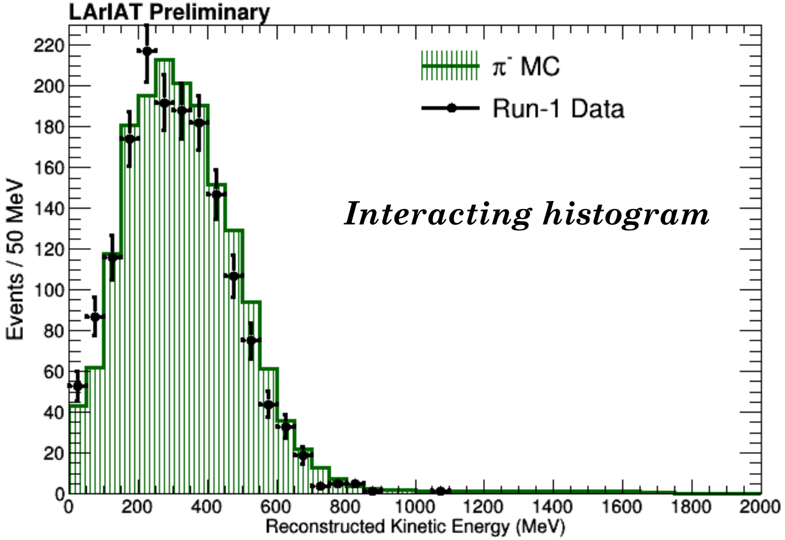






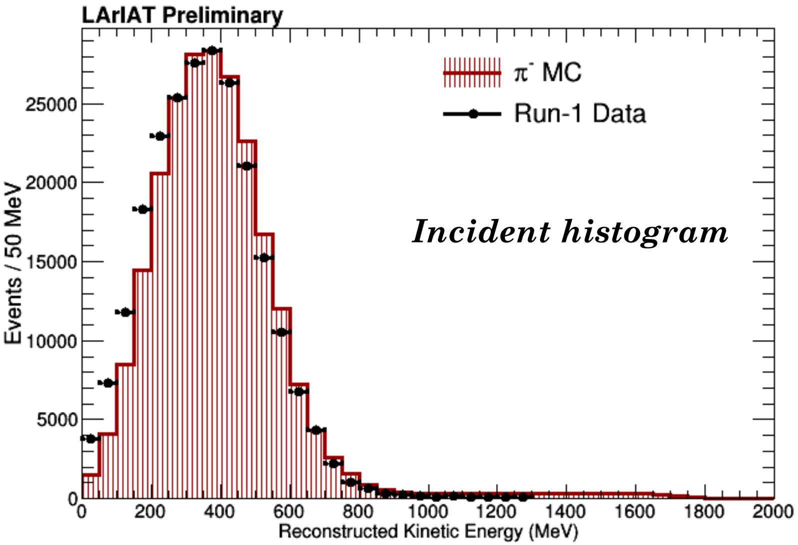
Example of putting it all together: LArIAT

- Repeat this process for your entire sample of π^-
- Use the thin slab approach and calculate the cross-section

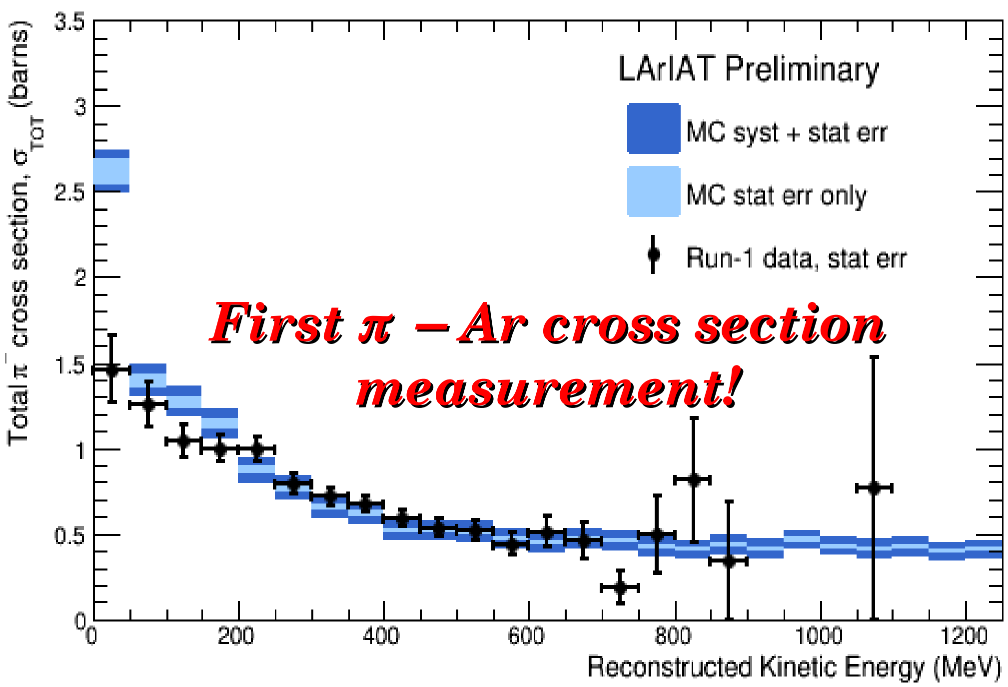


$$\sigma(E) \approx \frac{1}{nz} P_{\text{Interacting}} = \frac{1}{nz} \frac{N_{\text{interacting}}}{N_{\text{Incident}}}$$

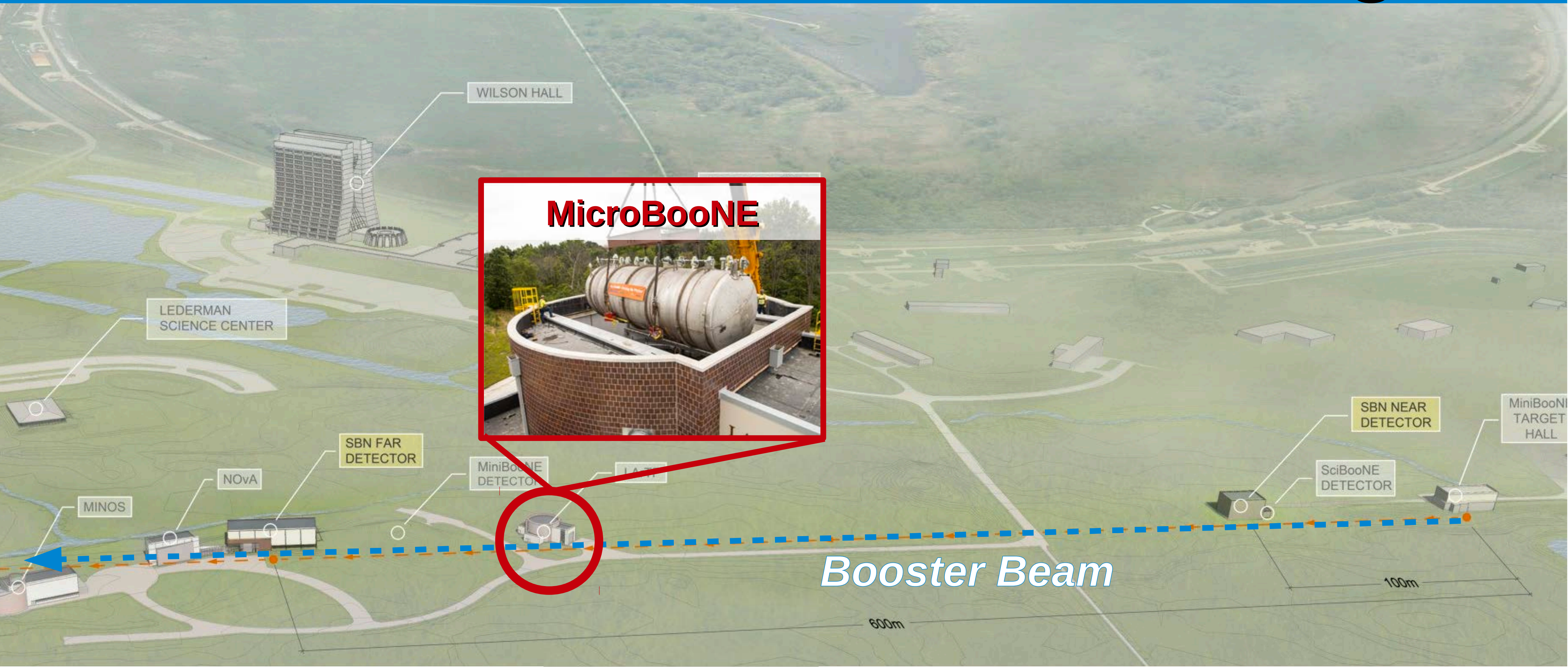
Where n = ρN_A / A
Z = slab depth



=



The Short-Baseline Neutrino Program



What do I need to add to the existing program (top notch neutrino beam + world class neutrino detectors) to make a definitive search eV scale for sterile neutrinos?

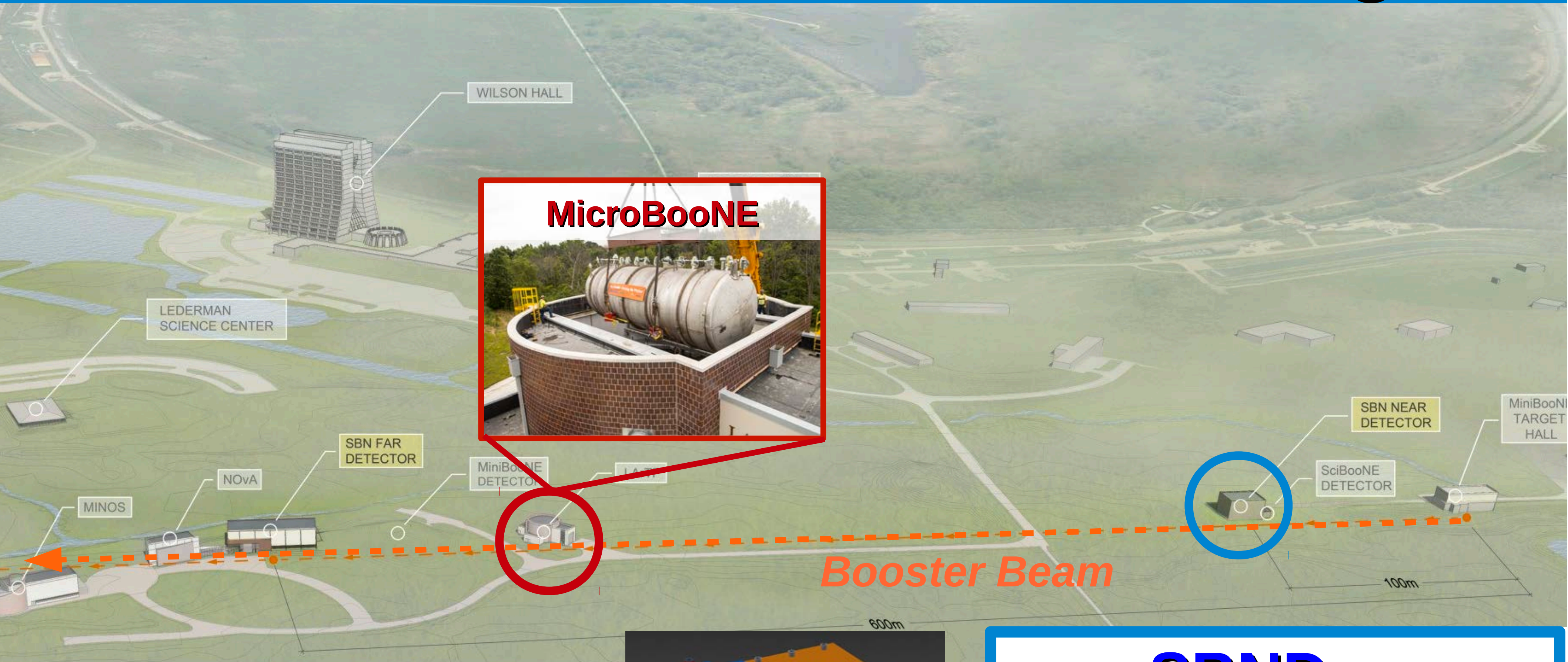
→ ~~Calibration of the detector technology **(LArTPC in a Testbeam)**~~

→ Normalization of the un-oscillated neutrino beam **(Near detector)**

→ High statistics in the appearance channel **(large mass far detector)**

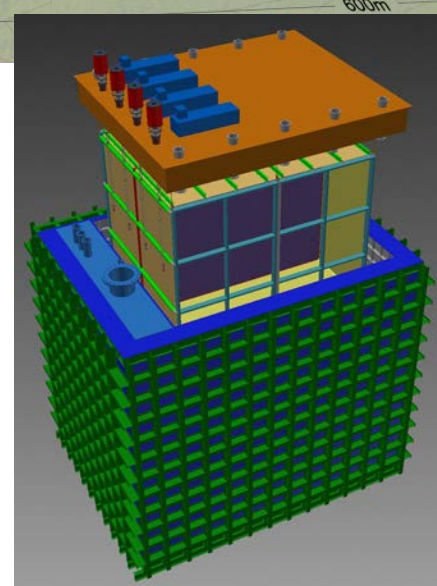
→ Look for complimentary muon disappearance **(near/far comparison)**

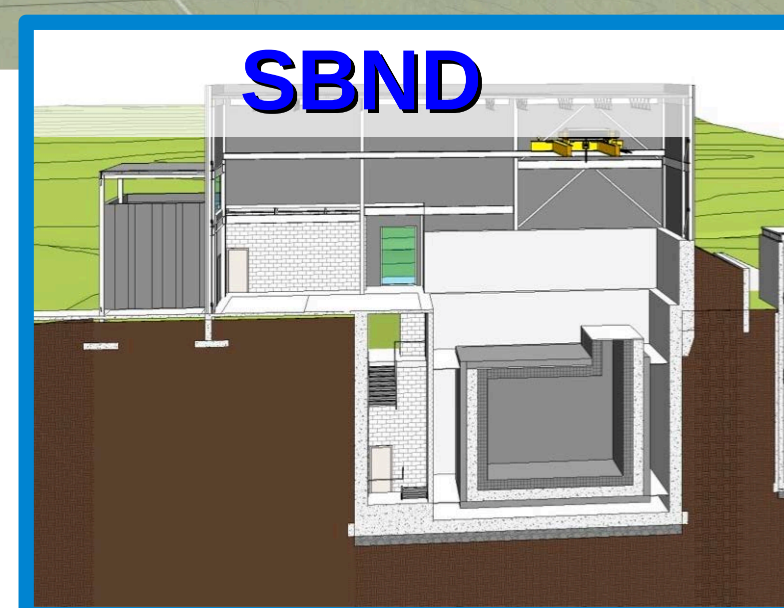
The Short-Baseline Neutrino Program



The Short-Baseline Near Detector (SBND) will be a 112 ton LArTPC located 110 meters from the target

- Characterize the beam before oscillation
- Cancel many dominant systematic



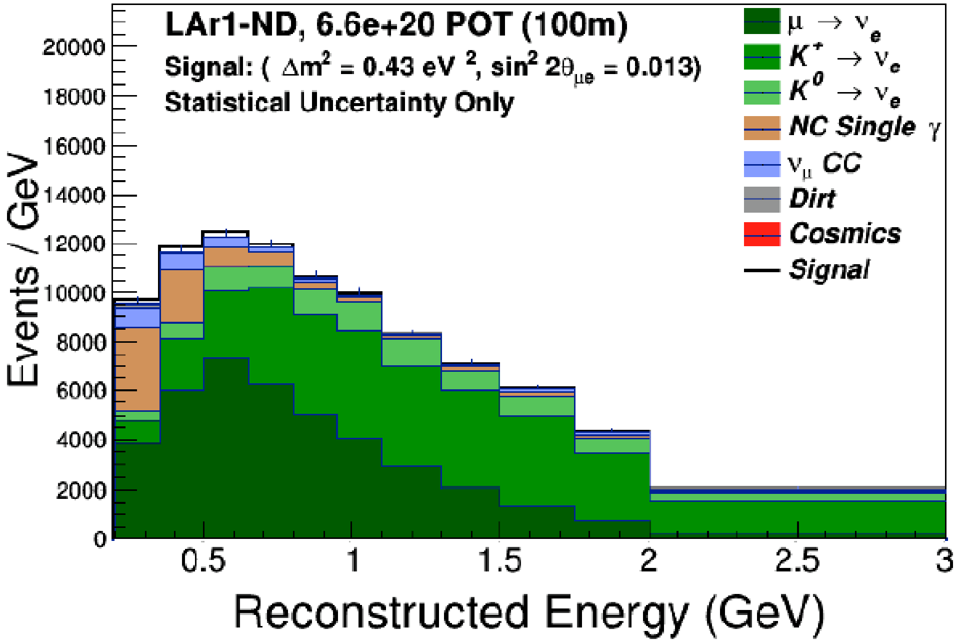


Short Baseline Near Detector (SBND)

Process		No. Events
	ν_μ *Events (By Final State Topology)*	
CC Inclusive		5,212,690
CC 0 π	$\nu_\mu N \to \mu + Np$	3,551,830
	$\cdot\ \nu_\mu N \to \mu + 0p$	793,153
	$\cdot\ \nu_\mu N \to \mu + 1p$	2,027,830
	$\cdot\ \nu_\mu N \to \mu + 2p$	359,496
	$\cdot\ \nu_\mu N \to \mu + \geq 3p$	371,347
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + 1\pi^\pm$	1,161,610
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + \geq 2\pi^\pm$	97,929
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu + \text{nucleons} + \geq 1\pi^0$	497,963
NC Inclusive		1,988,110
NC 0 π	$\nu_\mu N \to \text{nucleons}$	1,371,070
NC 1 $\pi^\pm$	$\nu_\mu N \to \text{nucleons} + 1\pi^\pm$	260,924
NC $\geq 2\pi^\pm$	$\nu_\mu N \to \text{nucleons} + \geq 2\pi^\pm$	31,940
NC $\geq 1\pi^0$	$\nu_\mu N \to \text{nucleons} + \geq 1\pi^0$	358,443
	ν_e *Events*	
CC Inclusive		36798
NC Inclusive		14351
Total ν_μ and ν_e Events		7,251,948

- **SBND will collect millions of neutrino interactions**
  - High statistics, precision neutrino cross-sections measurements

- **Provides an un-oscillated spectrum for the electron neutrino appearance search**



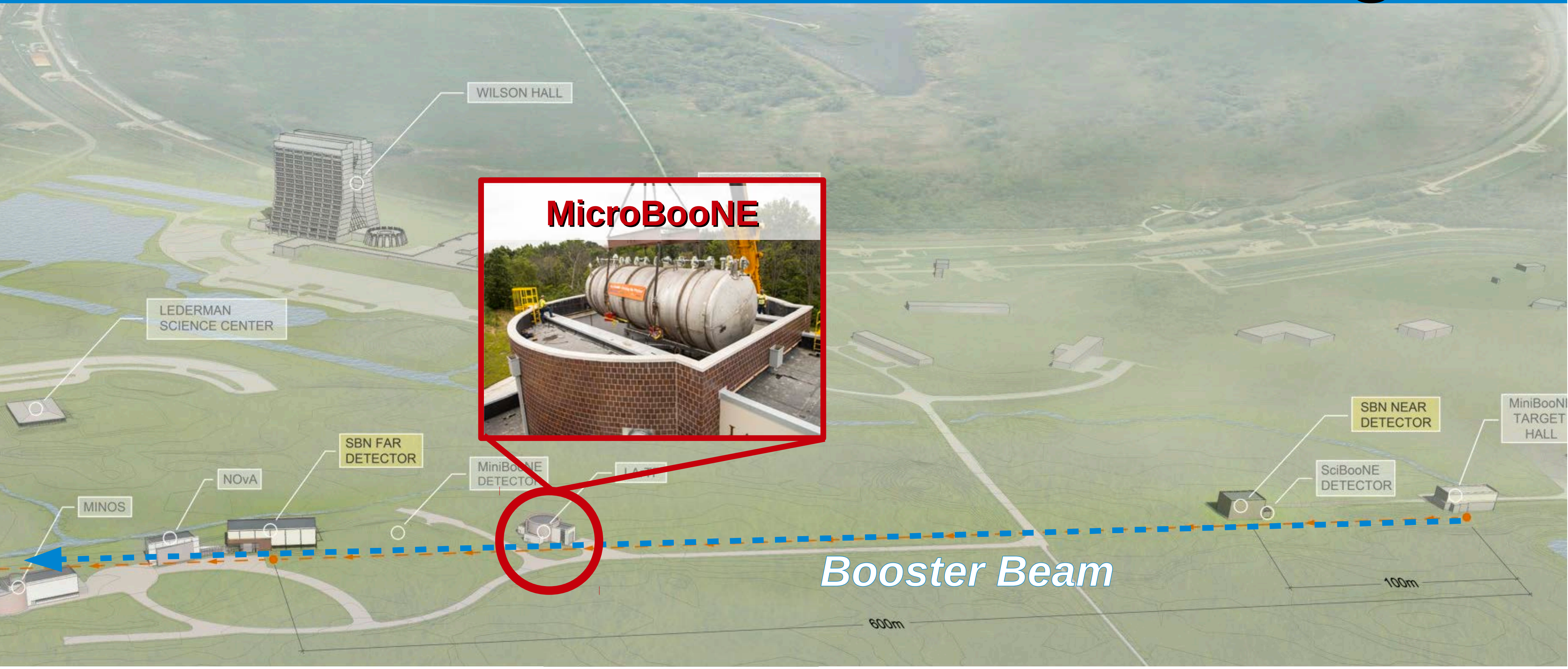
Short Baseline Near Detector (SBND)

- **Major components of the SBND detector are currently being fabricated in both the US and UK**
  - Wire frames being made by both US and UK collaborators
  - Civil construction of the building proceeding on schedule
- **Expect to start detector assembly and installation in late 2017/ early 2018**

Wire plane prototyping at University of Chicago

Detector building at Fermilab as of July 2016

The Short-Baseline Neutrino Program



What do I need to add to the existing program (top notch neutrino beam + world class neutrino detectors) to make a definitive search eV scale for sterile neutrinos?

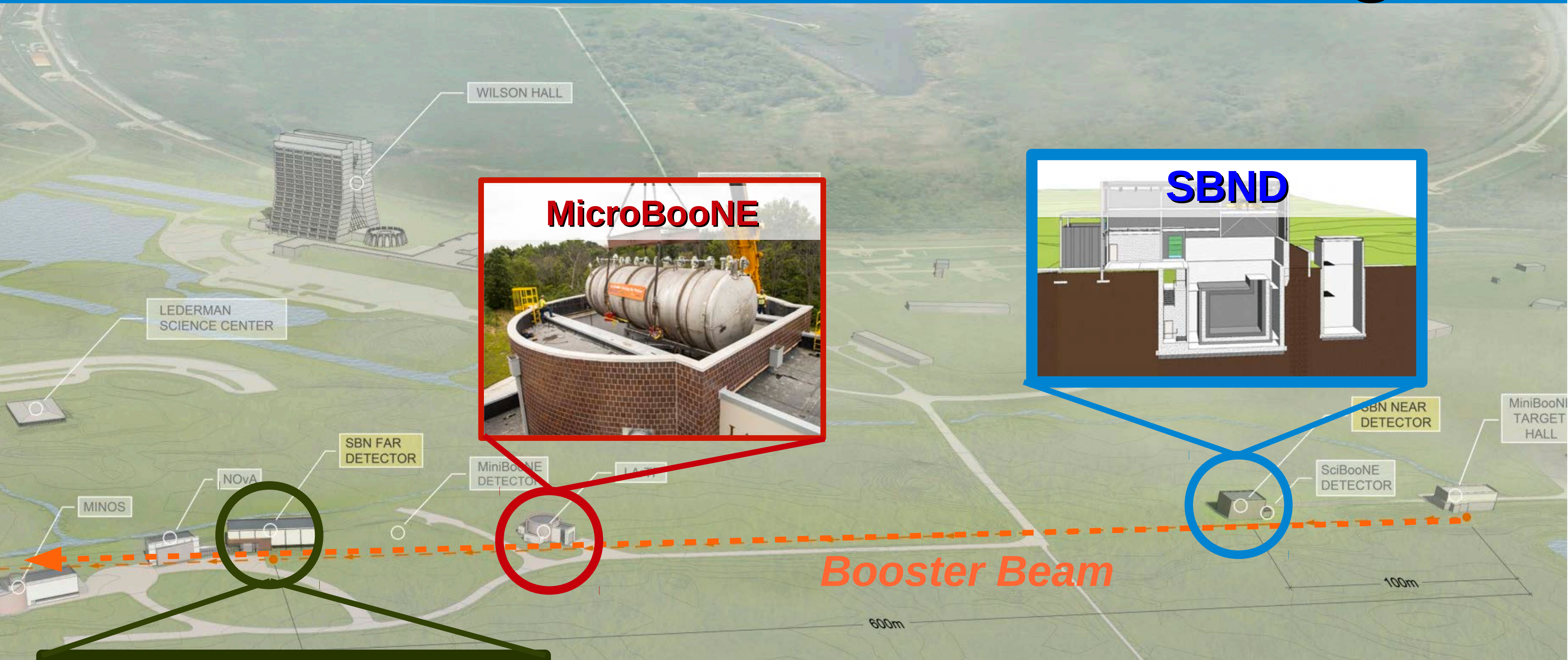
~~→ Calibration of the detector technology **(LArTPC in a Testbeam)**~~

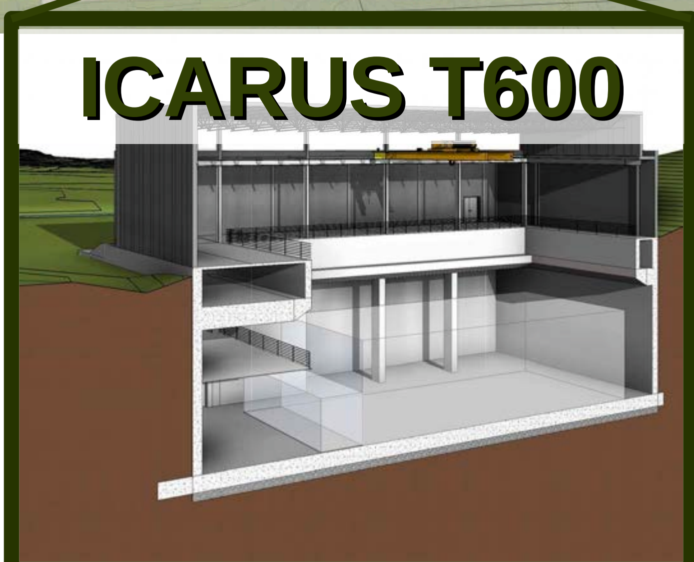
~~→ Normalization of the un-oscillated neutrino beam **(Near detector)**~~

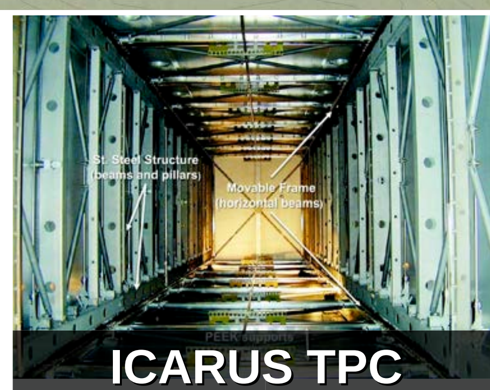
→ High statistics in the appearance channel **(large mass far detector)**

→ Look for complimentary muon disappearance **(near/far comparison)**

The Short-Baseline Neutrino Program



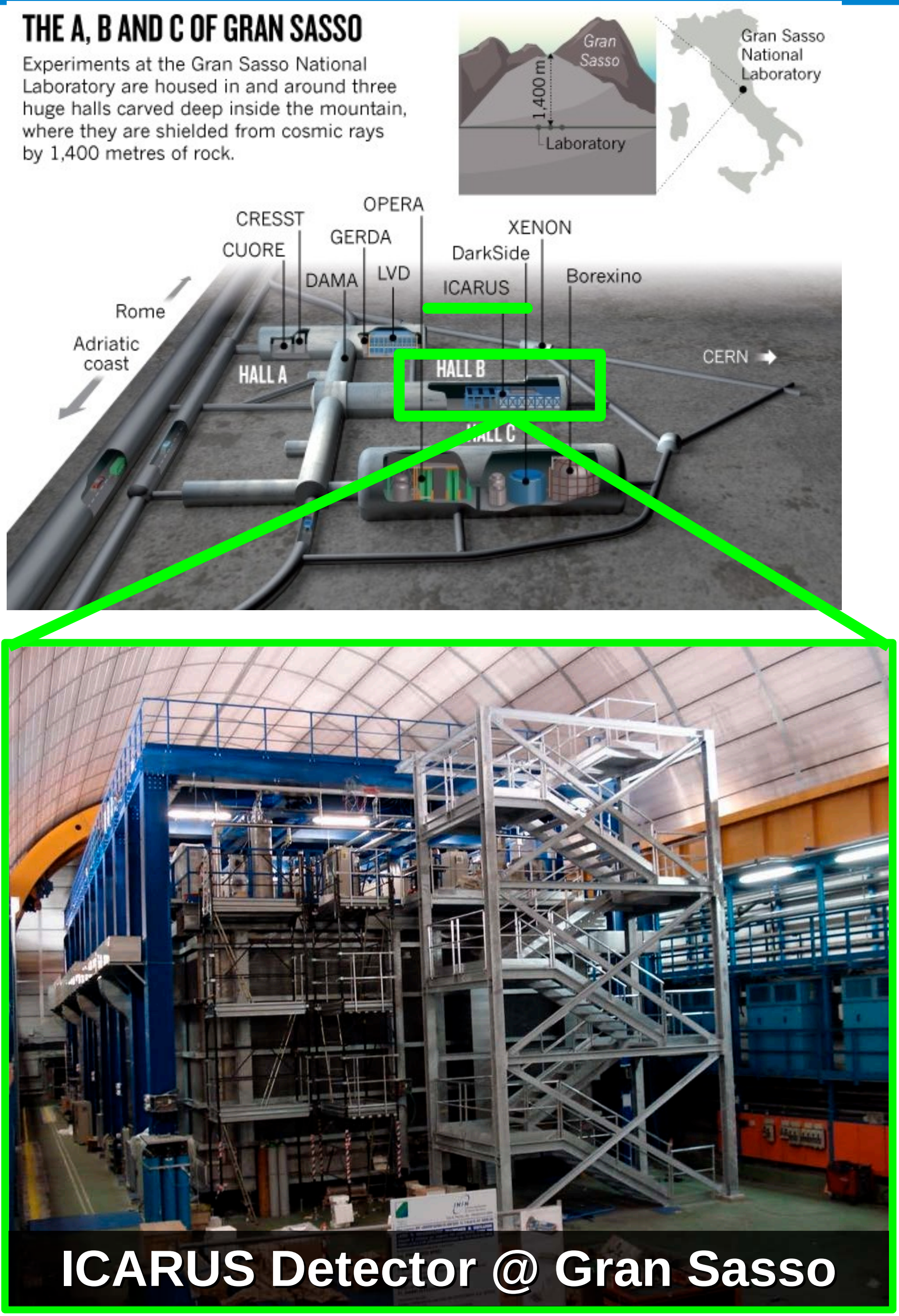




The ICARUS detector is the largest LArTPC ever built

- Adding the large mass allows for precision oscillation search

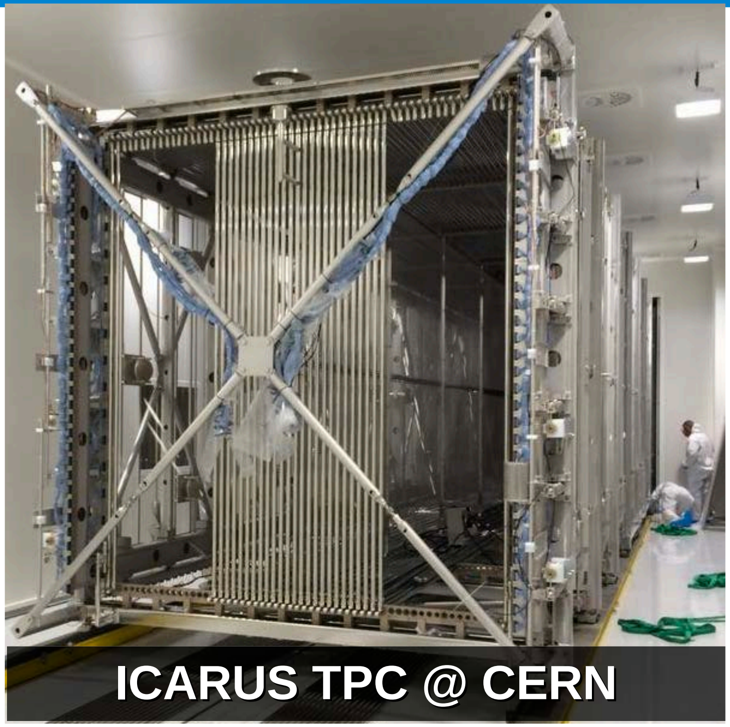
ICARUS T600



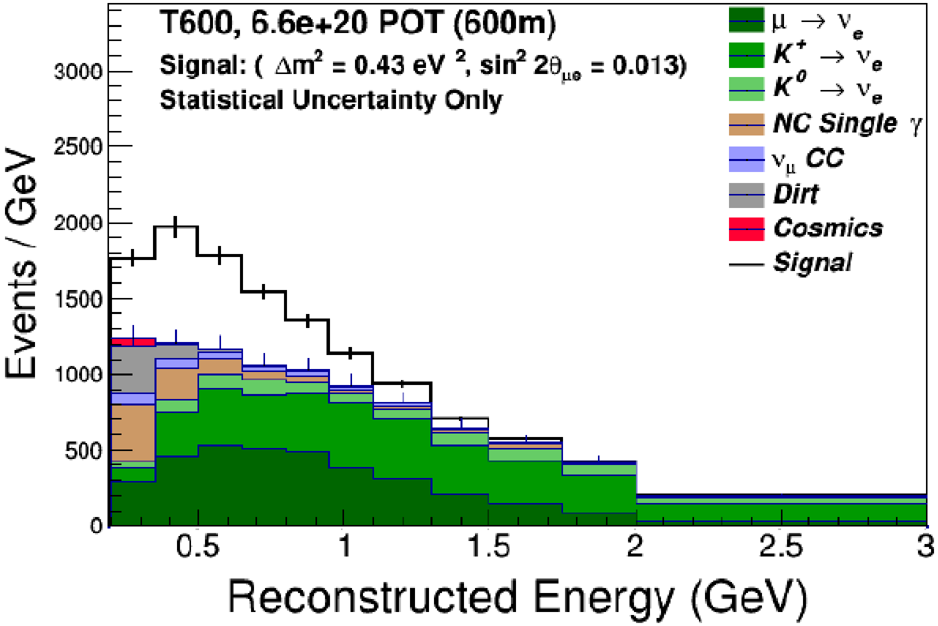
ICARUS Detector @ Gran Sasso

- **ICARUS was the first large scale LArTPC to run in a neutrino beam line**
  - Ran in the CNGS beam from CERN to Gran Sasso Labrotory from 2010 – 2013
- **After completing a successful neutrino run demonstrating the power of the LArTPC technology in an underground laboratory the detector has been moved from Gran Sasso to CERN**

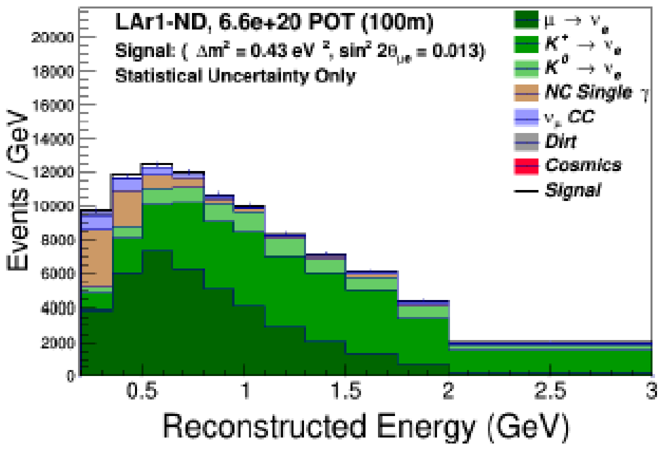
ICARUS T600

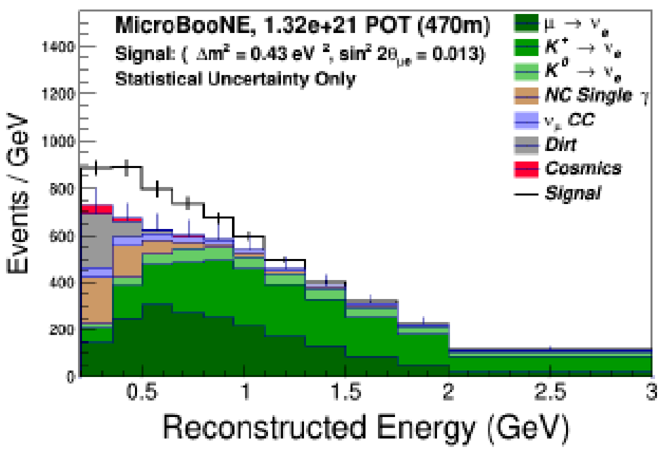


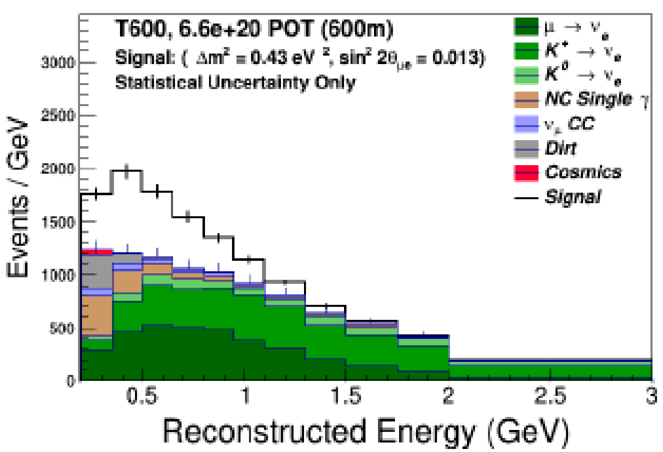
- **The ICARUS detector is at CERN for refurbishment before it is shipped to Fermilab**
  - The detector is expected to be finished in 2016 and move to FNAL in 2017
- **This large mass detector will provide increased sensitivity to the electron neutrino appearance search**



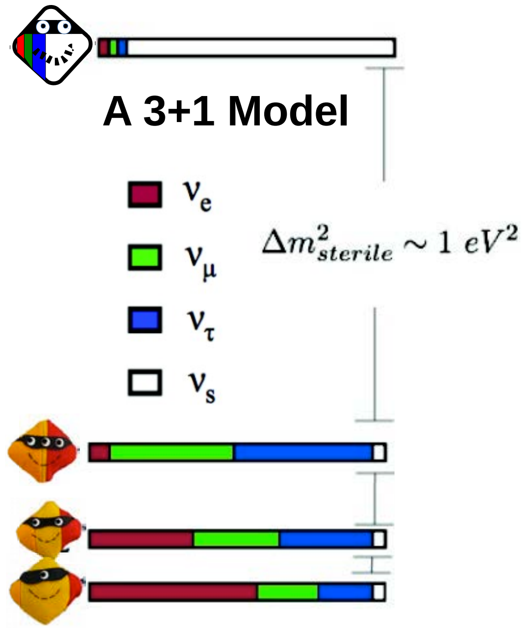
The SBN Program

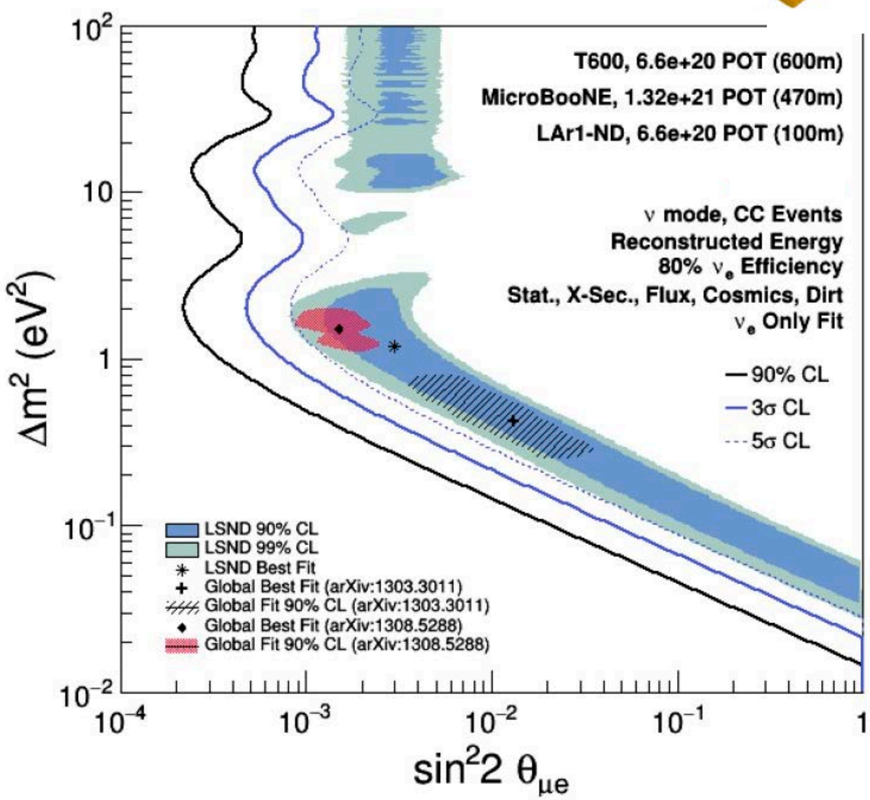




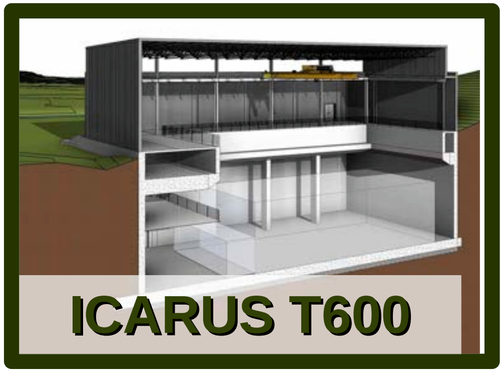


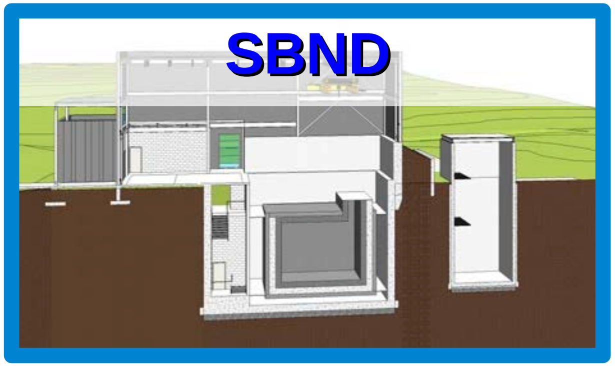
Utilizing three similar detectors at three different distances along the same neutrino beam allows for a **definitive measurement** of the allowed sterile neutrino parameter space

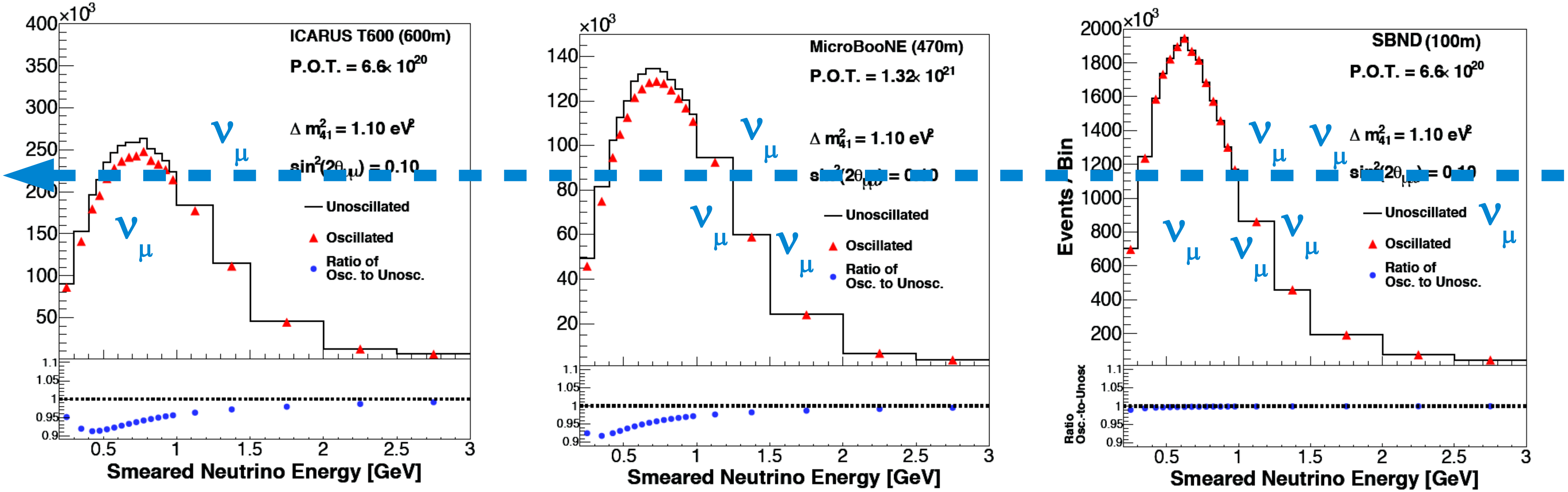




The SBN Program

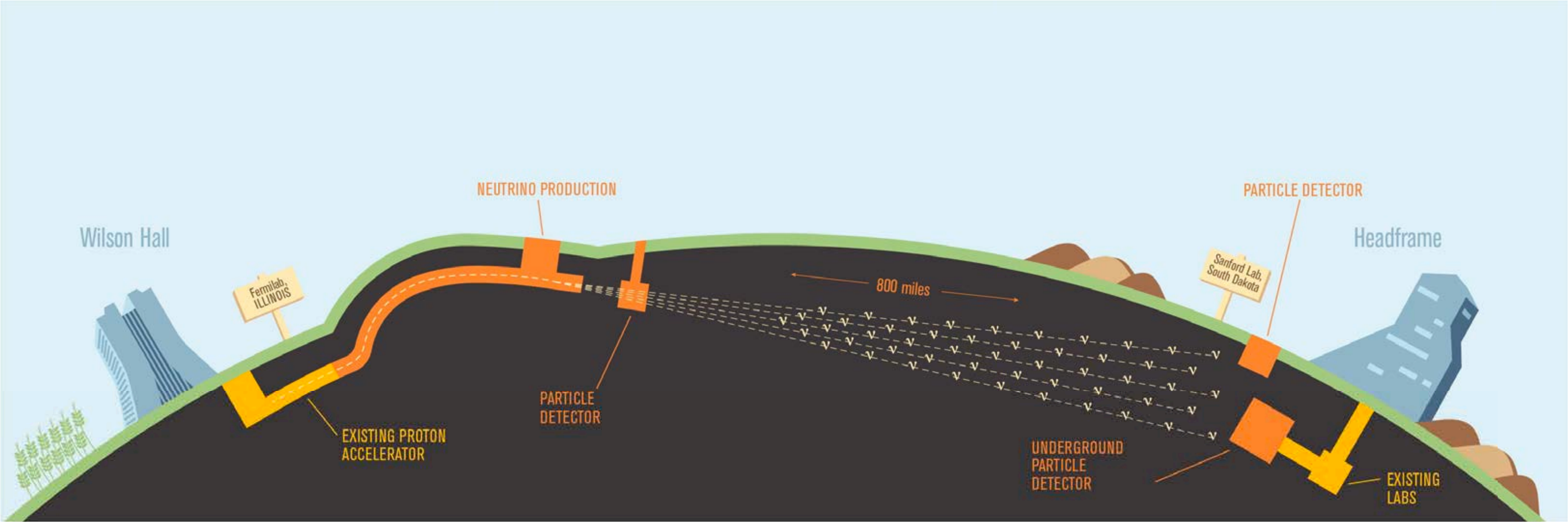


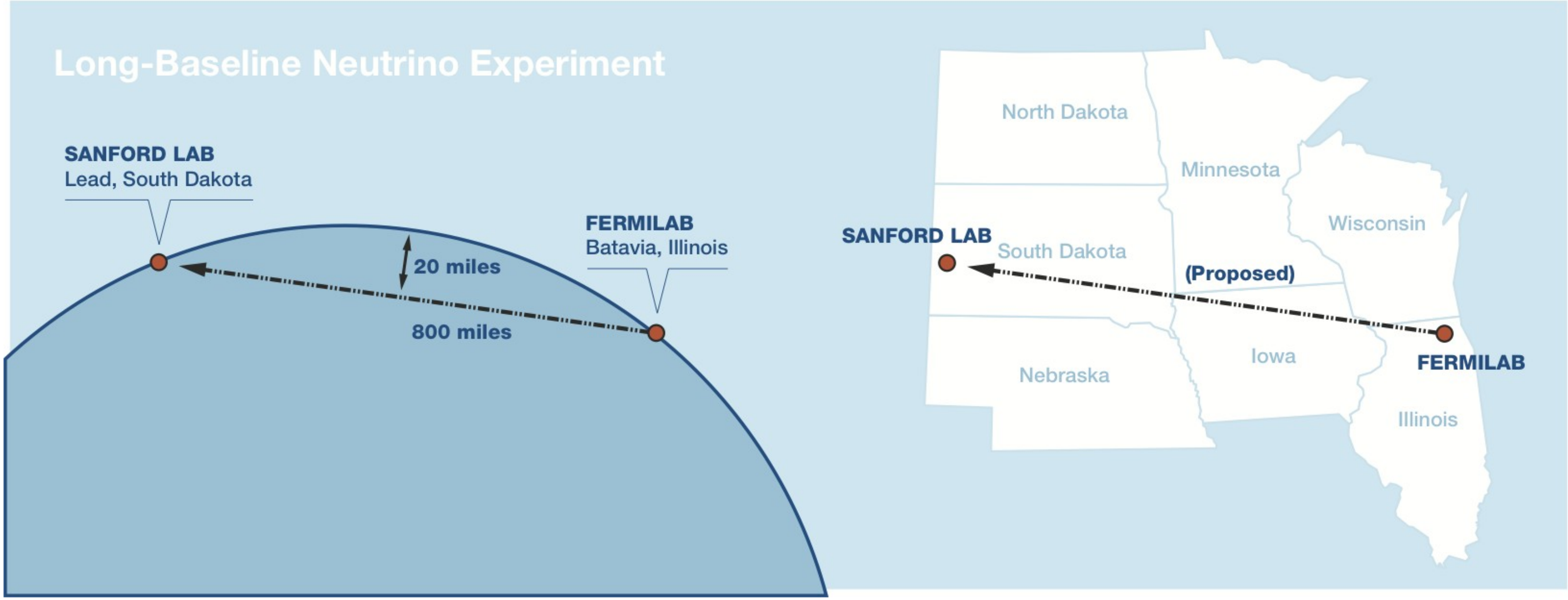




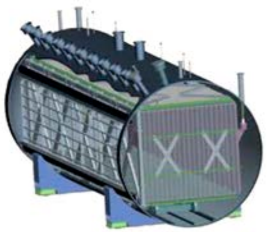
- **The three detector configuration also allows you to search for the muon neutrino disappearance channel as well**
  - Complimentary to the electron neutrino appearance search

The Long-Baseline Neutrino Program



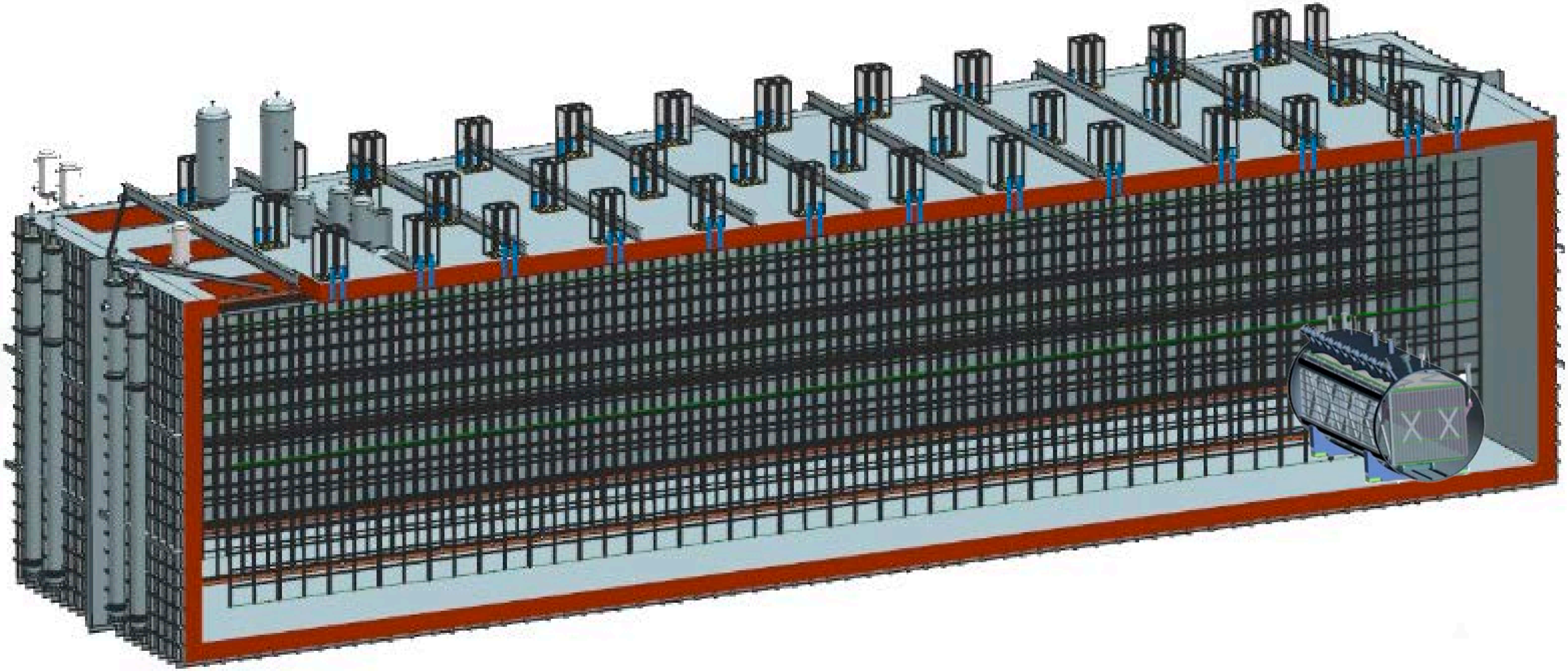


The Scale of Things....



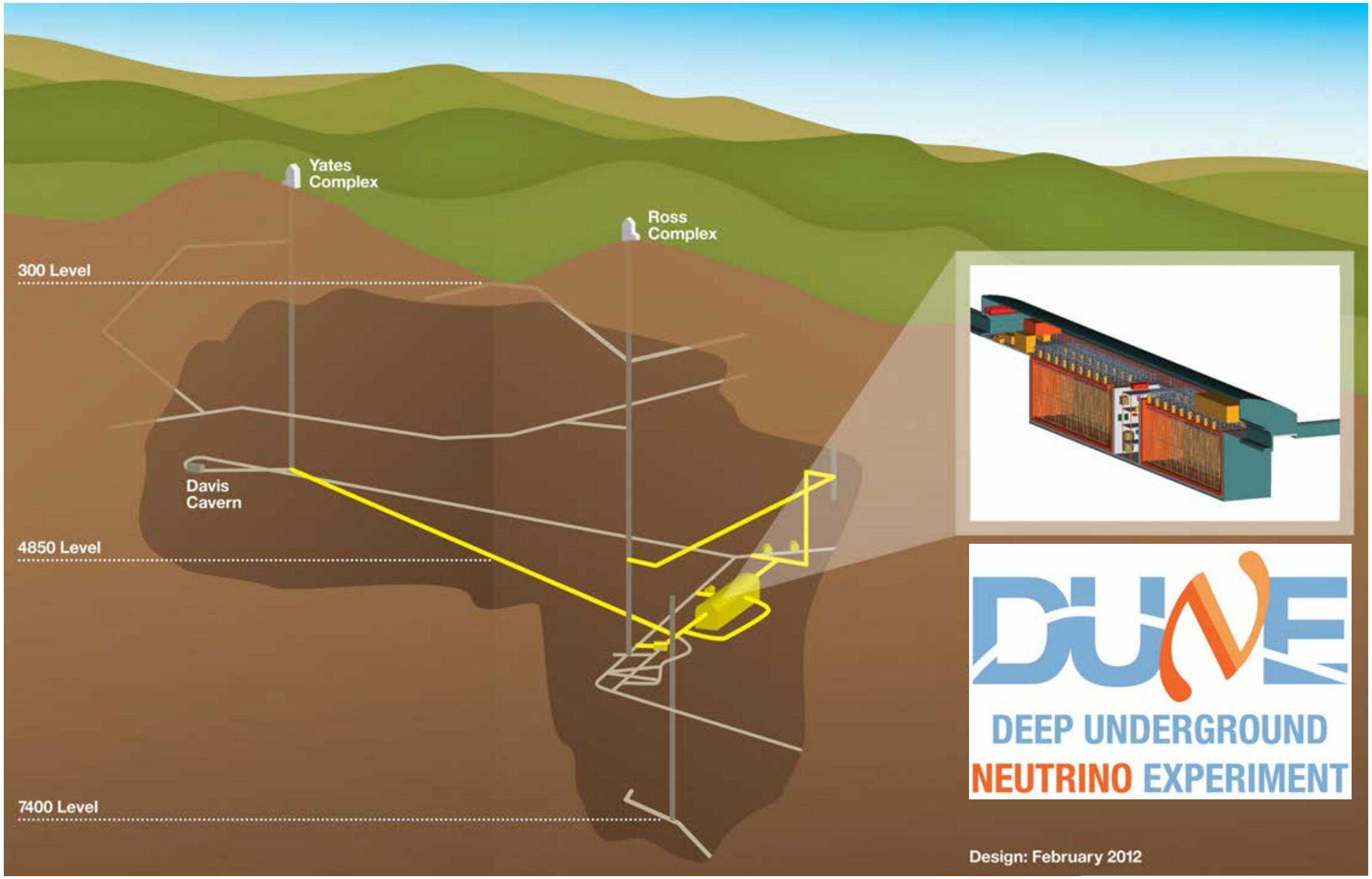
- **One MicroBooNE TPC (80 tons) (2.2 m x 2.5 m x 10 m)**
  - Largest operating LArTPC in the US

The Scale of Things....



- **One 10kT DUNE LArTPC Module (18 m x 19 m x 66 m)**
  - ¼ the total size of DUNE

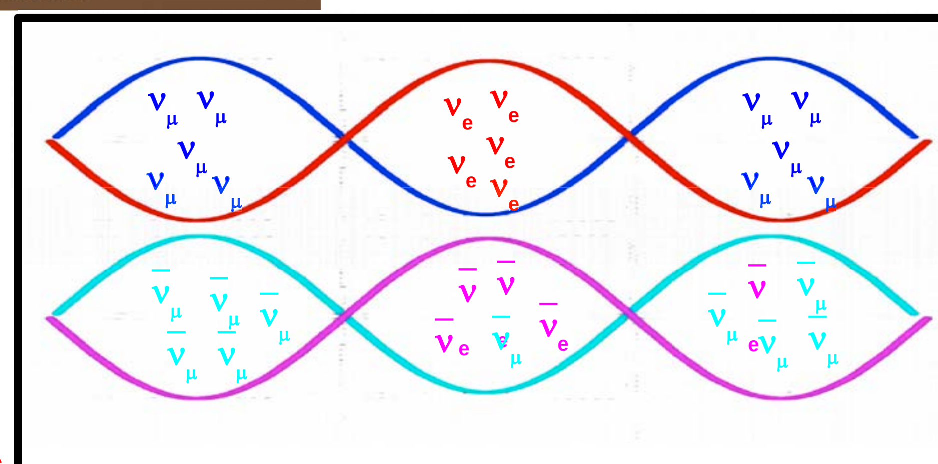
Long Baseline Neutrino Facility

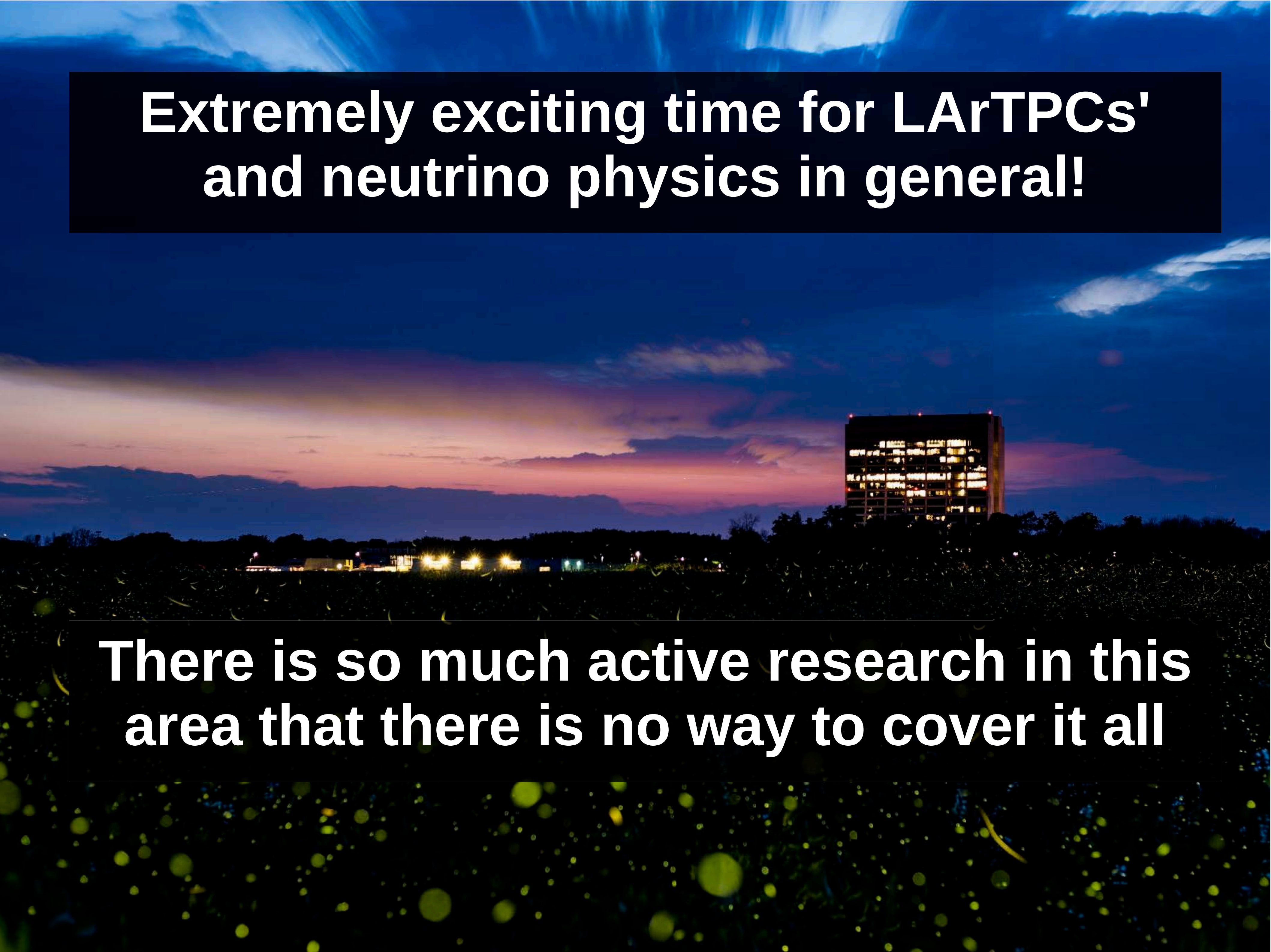


Build 40,000 ton LArTPC > 4000 feet underground and shoot a high power neutrino beam from Fermilab to South Dakota

Going deep underground allows you to open up a robust physics program and shields you from cosmic ray backgrounds

Going to a long baseline allows you to probe the nature of neutrino oscillations





Extremely exciting time for LArTPCs' and neutrino physics in general!

There is so much active research in this area that there is no way to cover it all

Thank you very much for your attention!

Things I omitted but you should feel free to ask me about

→ Single Phase vs Double Phase LArTPC's

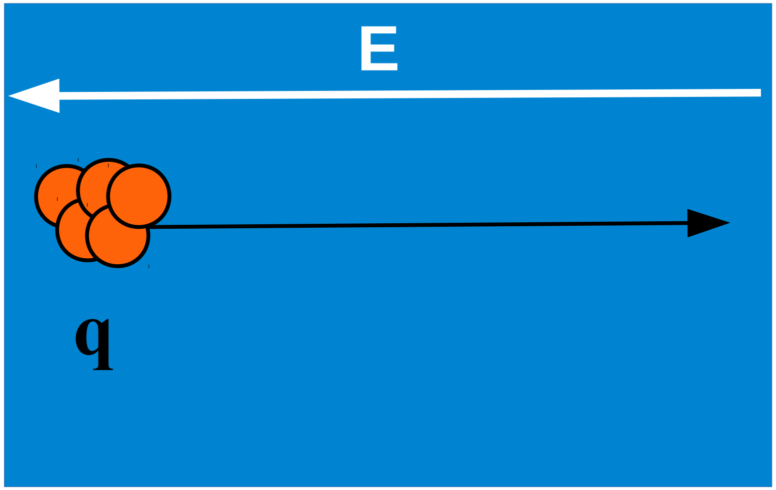
→ Cross-Section Measurements with LArTPC's

→ Deep Underground Neutrino Experiment (DUNE)

Backup Slides

Aside about ion drift

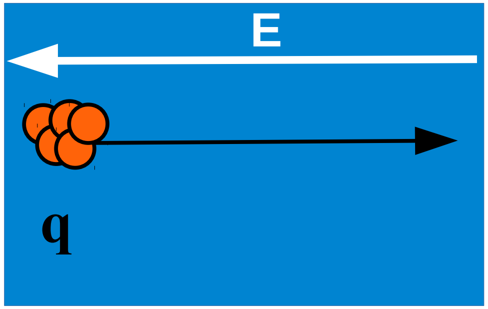
When drifting your electrons through the argon you encounter a lot of interesting physics that impacts your measurement



- **Ion Drift Velocity**
- **Ion Diffusion**
- **Ion Recombination**

Aside about ion drift

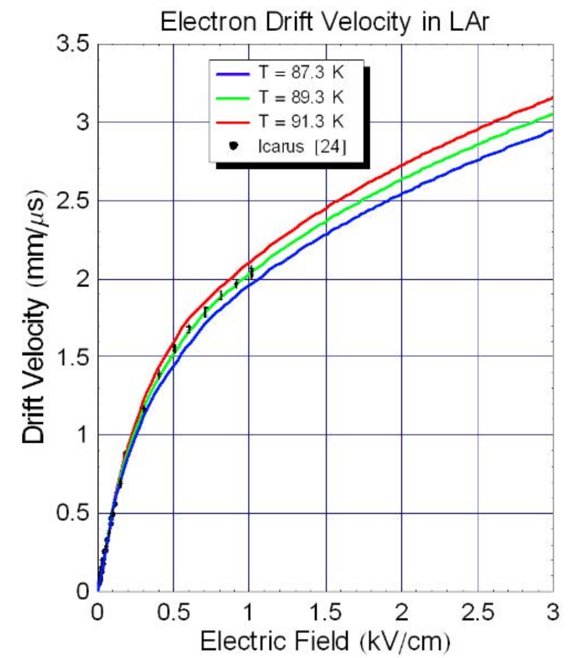
- **Ion Drift Velocity**



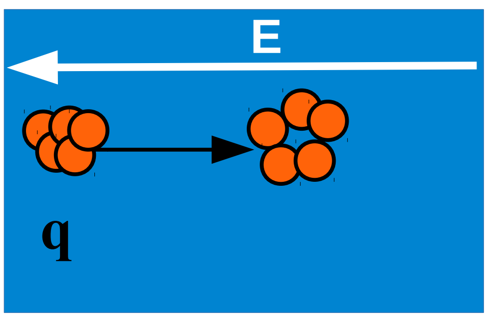
The drift velocity is an empirically modeled function depending on temperature (T) and electric field (E) in the argon

W. Walkowiak, NIM A 449

$$v_d(T,|E|) = (P_1(T-T_0)+1)(P_3|E|\ln(1+P_4/|E|)+P_5|E|^{P_6})+P_2(T-T_0)$$



- **Ion Diffusion**



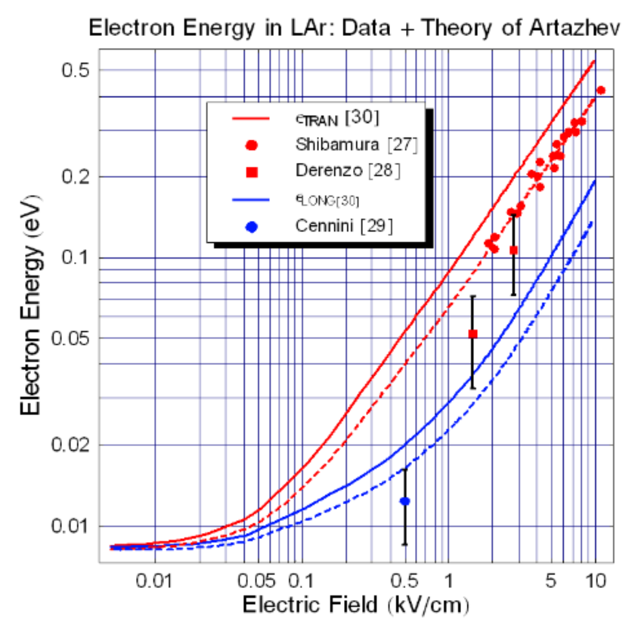
The ion diffusion (RMS spread) is related to the drift distance (Δz), the electric field (E), and the electron mobility in argon

S. Amoruso NIM **A516** (2004) 68

W. Walkowiak, NIM A449 (2000) 228

$$\sigma_{T(L)} = \sqrt{\frac{2\,\varepsilon_{T(L)}\,\Delta z}{E}}$$

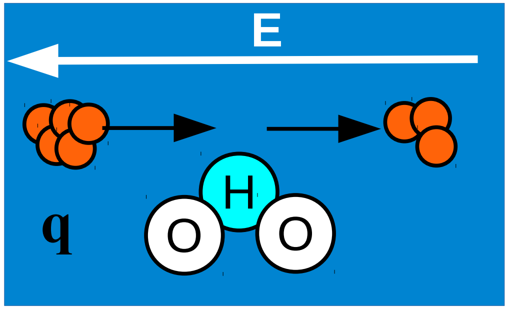
$$D = \mu\,\varepsilon$$

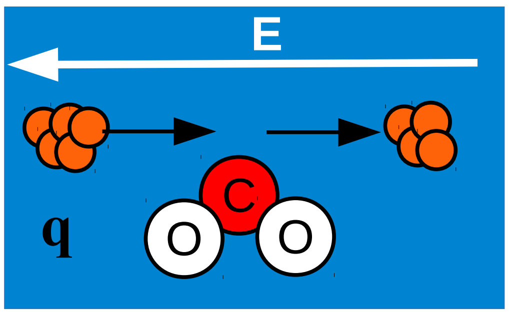


Note: What I measure is the electron energy (ε) and I get the diffusion constant using the relationship with the electron mobility

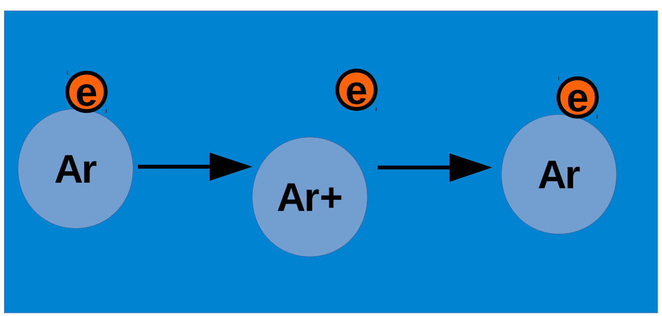
Aside about ion drift

- **Ion Recombination**

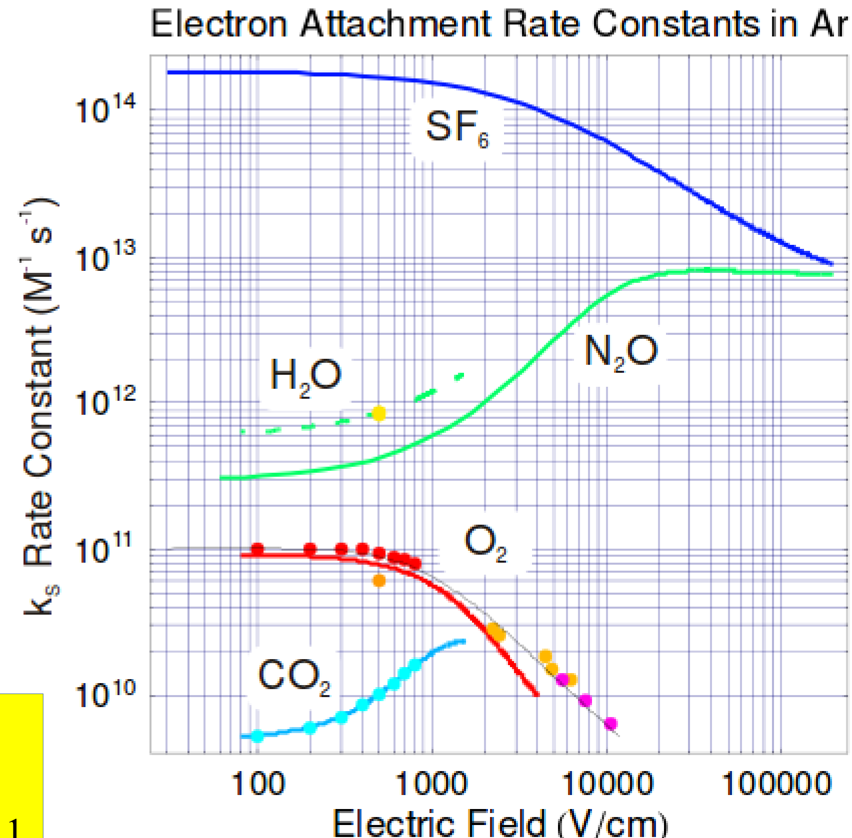




Ion recombination is also a complicated affair depending on various types of impurity, its concentration, and the electric field



$$Q(t)=Q_0 e^{t/\tau_a}$$
$$\text{where } \tau_a=(k_s n_s)^{-1}$$



Q(t) is the charge collected as a function of time

k_s is the electron attachment rate at a constant molar concentration (which itself has a dependence on the electric field)

n_s is the molar solute concentration in LAr

LAr Purity

(Electro-negative impurities diminish (eat) our signal; Nitrogen quenches scintillation light)

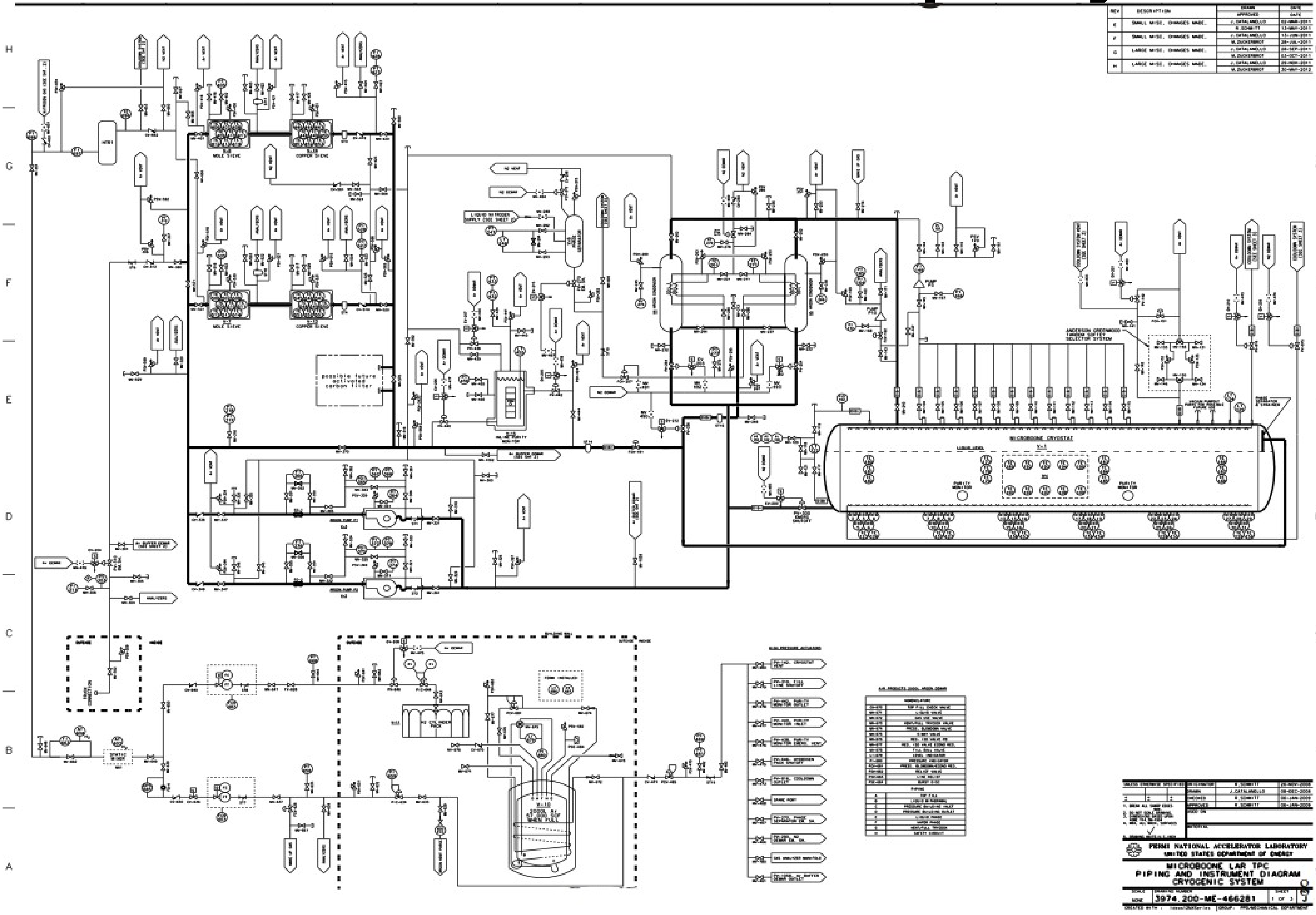
Image Credit: S. Lockwitz

How pure is pure?

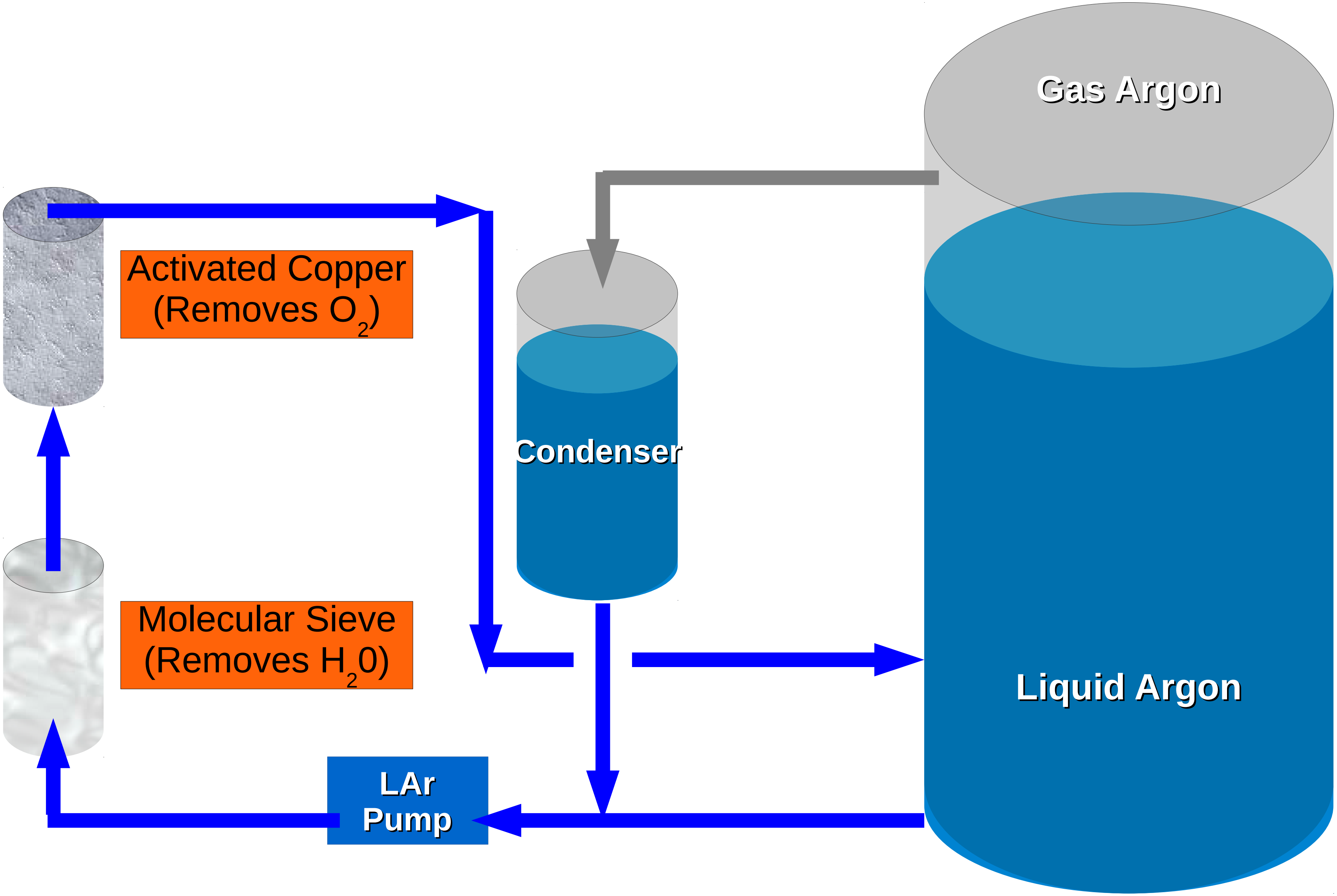
- **<100 parts per trillion (ppt) of O2 present**
  - This is so you can get the charge created by a minimum ionizing particle ~2.5 meters without the electrons being absorbed
- **< 1 part per million (ppm) of N2 present**
  - This is so the light from scintillation isn't quenched

A dogs nose is sensitive at the ppt level, but they tend not to like being employed as scientists and have an adversity to -303 degrees Fahrenheit

How to achieve this purity

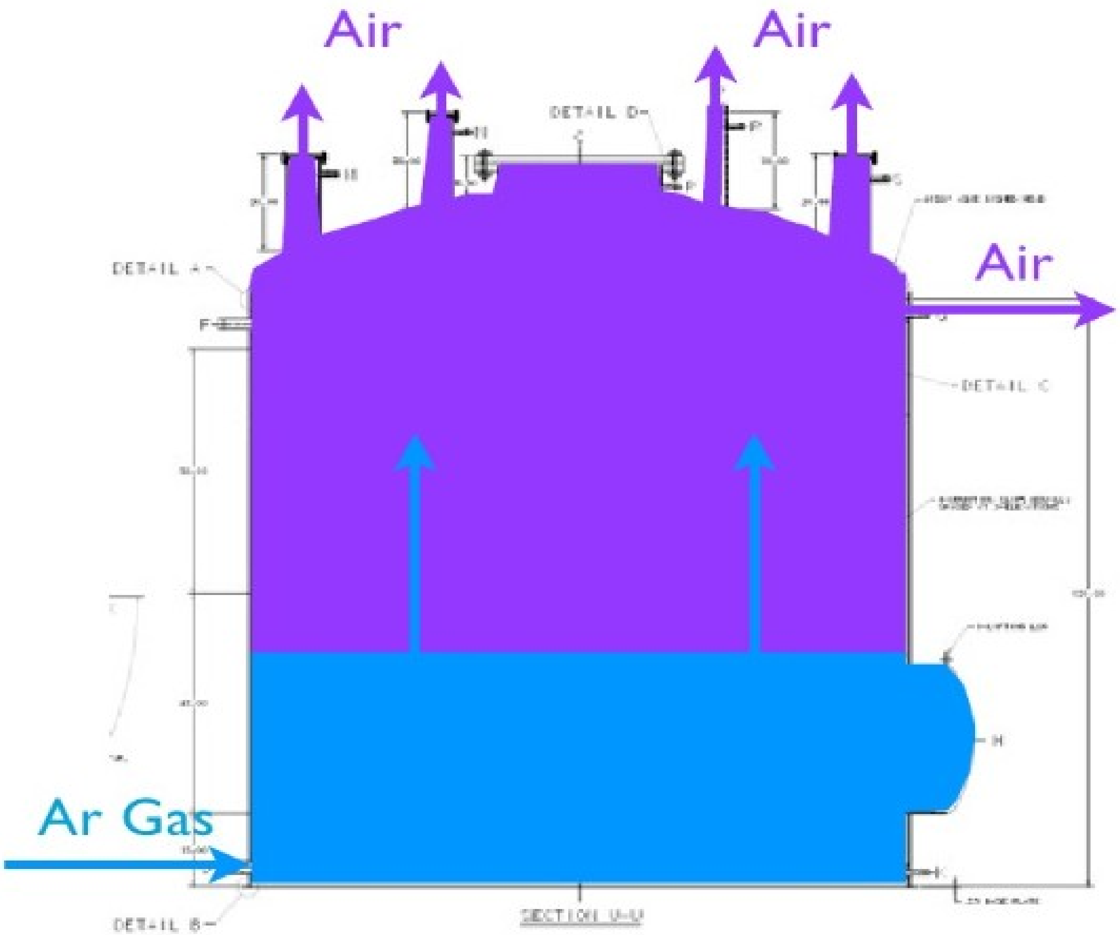


Purifying


Gas Argon
Activated Copper (Removes O_2)
Condenser
Molecular Sieve (Removes H_20)
Liquid Argon
LAr Pump

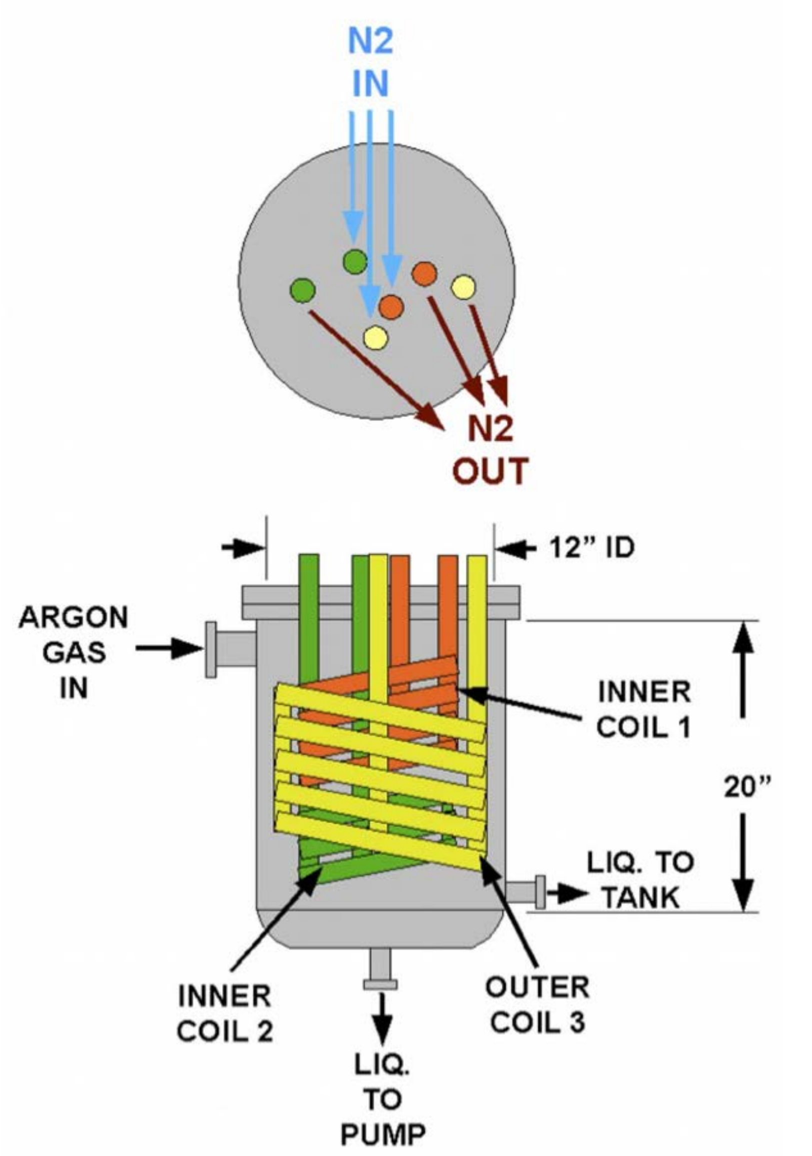
Vacuum Evacuation (small volume)
Argon Gas Purge (large volume)

LArIAT Cryostat



Cooling down

- **Cooling comes from LN_2 cooled condensers**
  - Argon passes over LN_2 coils to condense and cool the Argon before being pushed through the cryo-system
- **Some amount of heat in your cryostat is desirable because convection drives mixing**
  - Too much heat and you've just built a mini-pressure bomb



Cryostats

Argon has to be kept near 87 Kelvin in order to stay in the liquid phase (so you can't just put it in any old pot!)

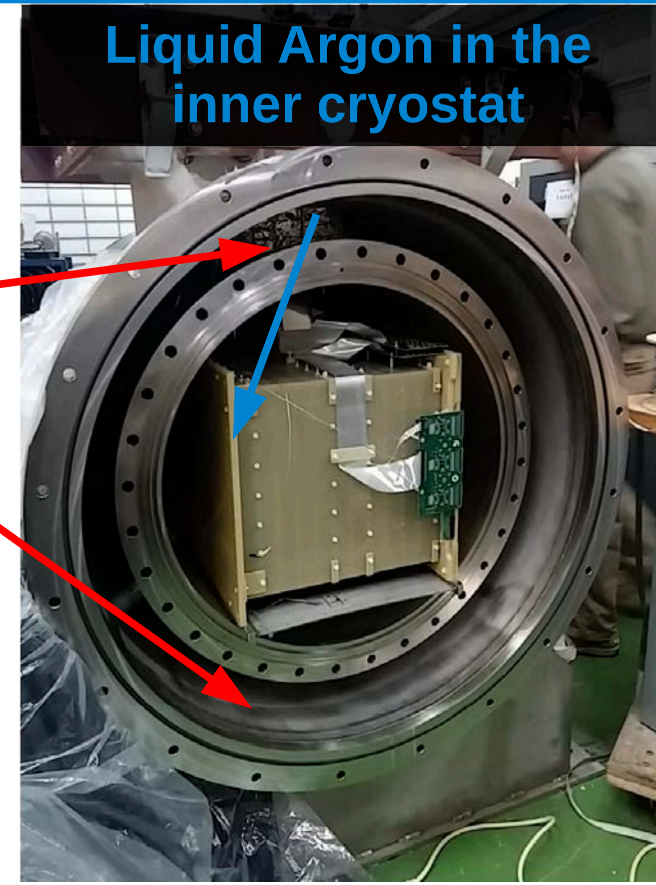
Although if you stick around in the LAr game long enough you may be surprised to see what we use for our High Voltage Filter Pot

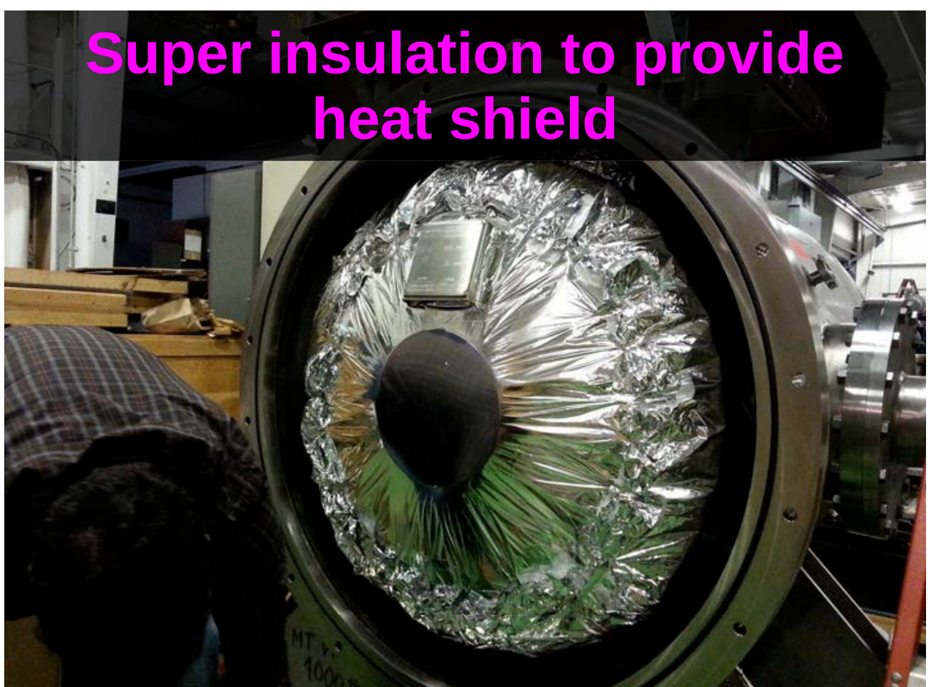
You need a vessel that is insulated to keep the Argon cold!

Cryostats

Vacuum-Jacketed Cryostat

Vacuum between the inner and outer cryostat acts like an insulator

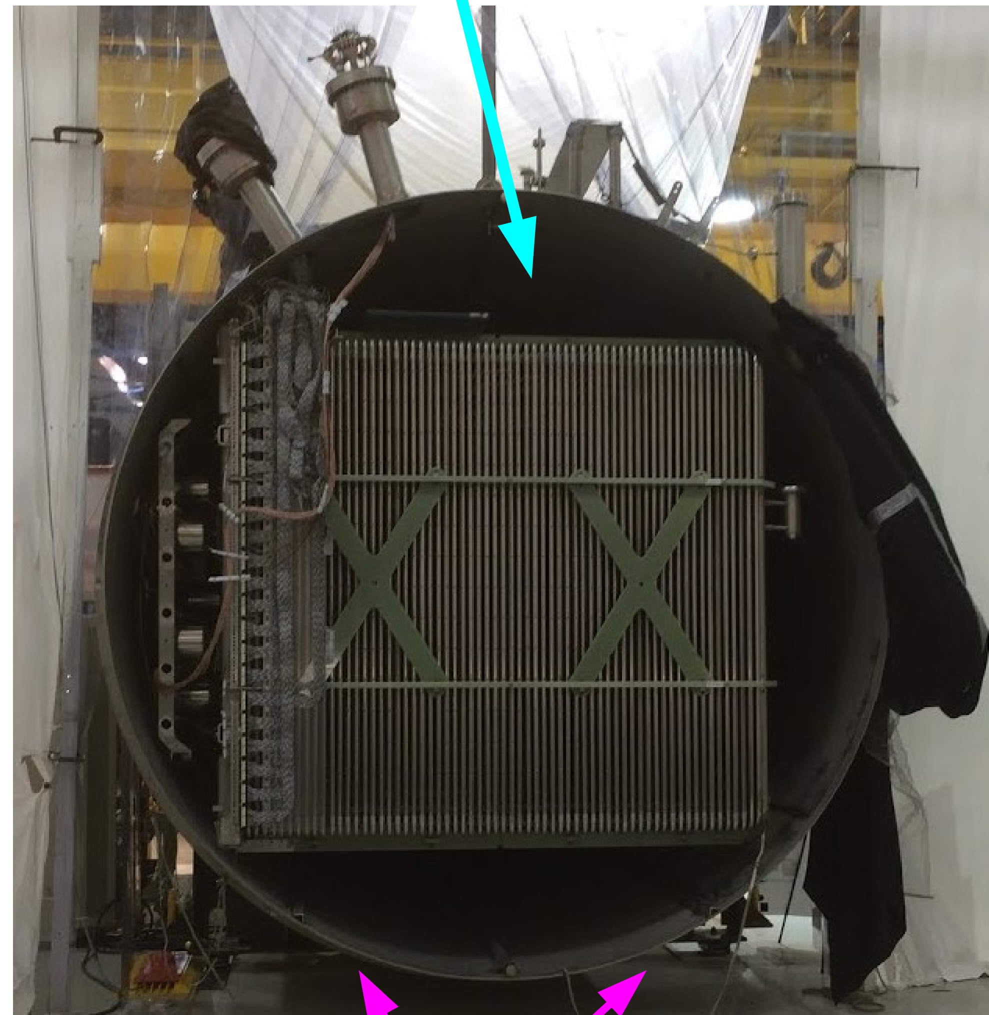




- You continuously pump on the external jacket and the vacuum provides your heat insulation

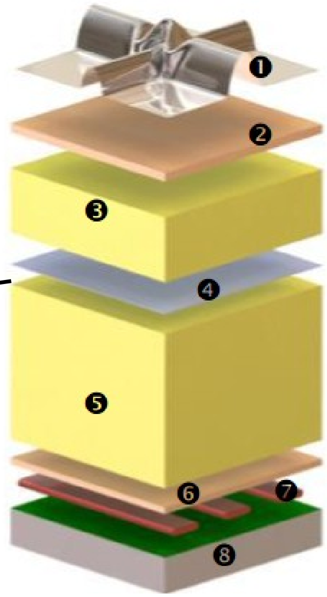
MicroBooNE Cryostat

Liquid Argon inside the cryostat



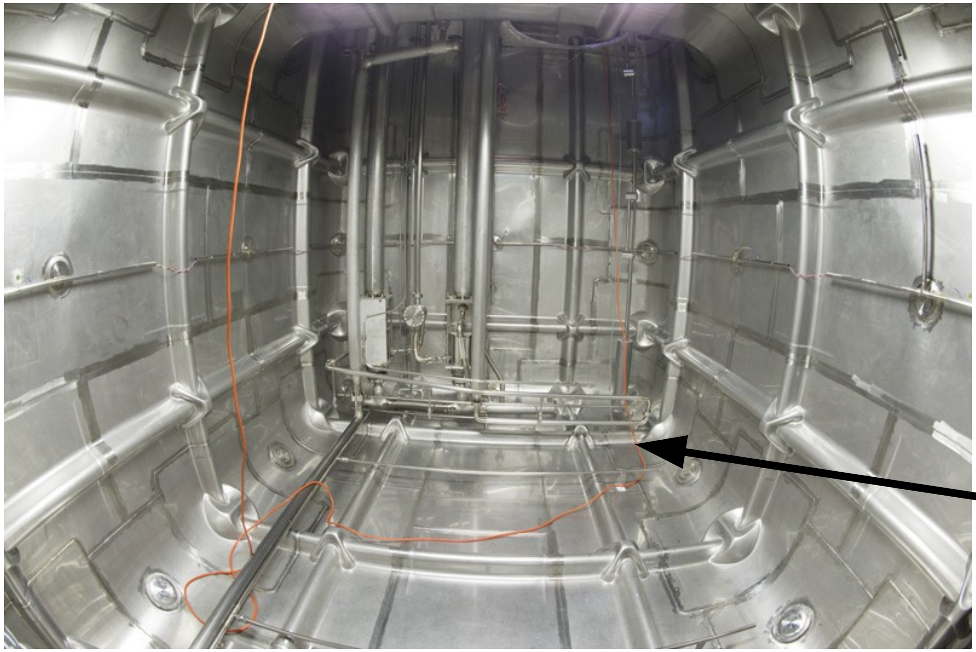
Then we spray the outside with insulating foam ~6” thick

Cryostats



1) Stainless steel primary membrane (LAr inside here)
2)Plywood board
3) Polyurethane foam
4)Secondary barrier
5) Polyurethane foam
6) Plywood board
7) Bearing mastic
8)Concrete

In order to go even bigger we will use a membrane cryostat borrowing experience from industry (used to ship liquid natural gas)



35 ton membrane cryostat constructed at Fermilab as a demonstrator

Neutrino Oscillation Physics

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = U \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

where

$$U = \begin{pmatrix} U_{e1} & U_{\mu 1} & U_{\tau 1} \\ U_{e2} & U_{\mu 2} & U_{\tau 2} \\ U_{e1} & U_{\mu 3} & U_{\tau 3} \end{pmatrix}$$

$c_{ij} = \cos(\theta_{ij})$
$s_{ij} = \sin(\theta_{ij})$
$\delta = \text{CP phase}$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Oscillations can be understood by writing the mass states() in terms of the flavor states () related through a mixing matrix