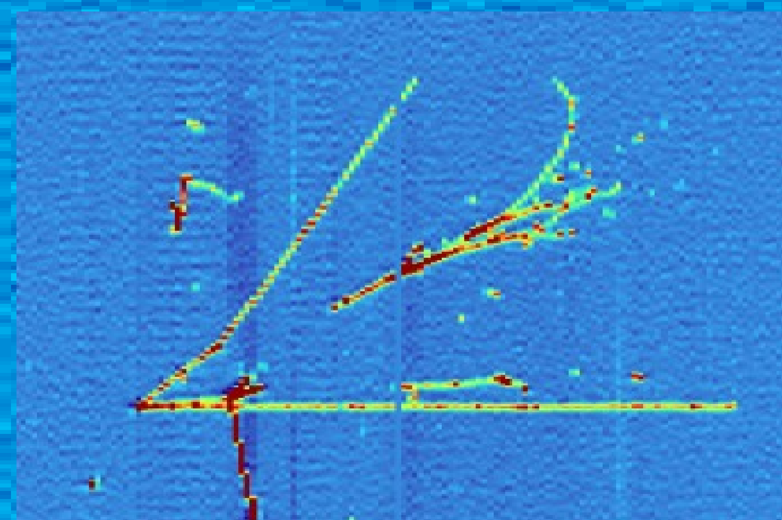
Liquid Argon Time Projection Chambers



Jonathan Asaadi

Syracuse University

What you already know

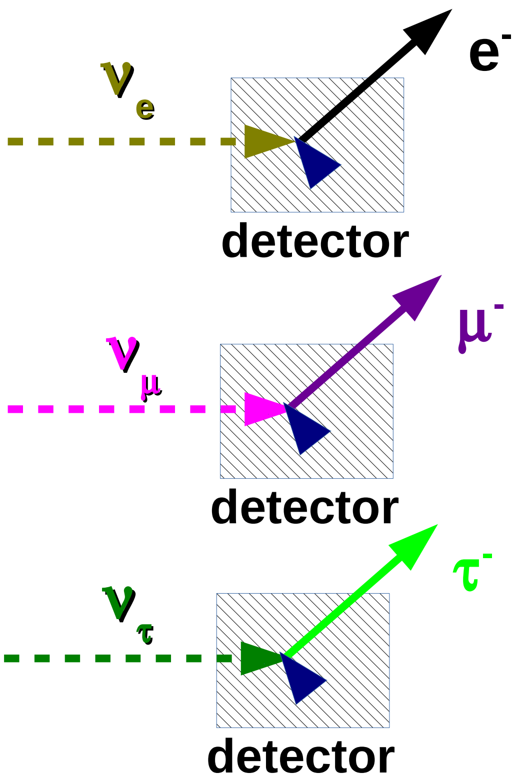
- **Tuesday, June 16**
  - Neutrino Physics: A General Overview (Jon Paley)
    - Why neutrinos are important?
    - What are the open questions?
    - What are the experiments that are addressing these questions?
- **Thursday, June 25**
  - Neutrino Beams (Alberto Marchionni)
    - How are neutrinos produced?
    - History of neutrino beams?
    - Different neutrino beams in operation

Do you have any questions left over that you want to ask a non-threatening (and handsome) post-doc?

What are some properties of a neutrino detector that you would list as important?

Neutrino Detectors

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



1) Big/Scalable

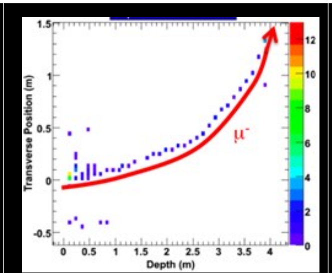
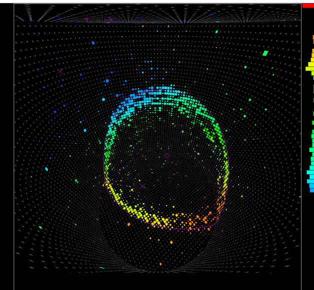
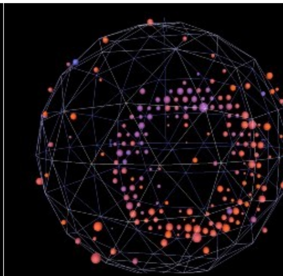
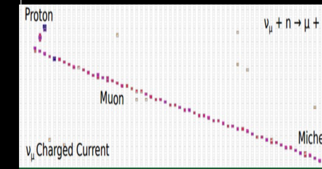
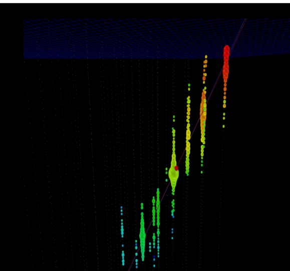
Put a large number of nuclei in the path of the neutrino, need to build big detectors

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

Example Event Display	 ν_μ candidate	 ν_μ candidate	 ν_μ candidate	 ν_μ candidate	 ν_μ candidate
Experiment	**MINOS**	**Super-Kamiokande**	**MiniBooNE**	**Nova**	**IceCube**
Detector Details	5400 tons of steel: scintillator	50,000 Tons of water: Cherenkov Detector	800 Tons of Mineral Oil: Cherenkov Detector	14,000 tons scintillator and PVC: Scintillator	1 km^3 of ice ~1 billion tons of ice: Cherenkov Detector
Big?	✓	✓	✓	✓	✓
Charge & Light?	✓	✓	✓	✓	✓
High Res?	✓	✓	✓	✓	✓

Your mileage may vary

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/cm^3]	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 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!

The other noble elements just don't measure up

	He	Ne	Ar	Kr	Xe	Water
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Helium isn't very dense, requires very cold temps to stay liquid, and doesn't ionize well

Neon has poor electron mobility and requires very cold temps to stay liquid

Krypton is not very abundant (1 ppm in the atmosphere) nor does it produce as much scintillation light

Xenon is even less abundant (87 ppb in the atmosphere)

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Liquid Argon

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Argon is more dense than water and can be kept in the liquid phase easily

Argon is relatively abundant (3.5 ppm in the atmosphere...or about 1% of the earth's atmosphere) more than CO_2

Argon ionizes easily (55,000 electrons / cm) and has a high electron mobility (it's greek name means slow)

Argon produces lots of scintillation light! (Added bonus...it is transparent to the light it produces)

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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!)

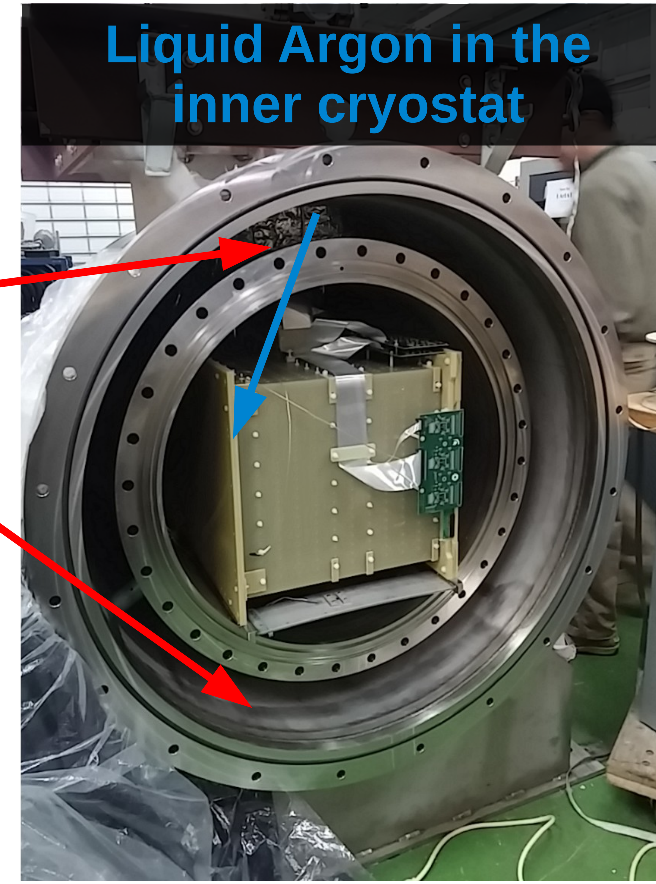
Although if you stick around in the LAr game long enough you may be surprised to see what we use for our High Voltage Filter Pot

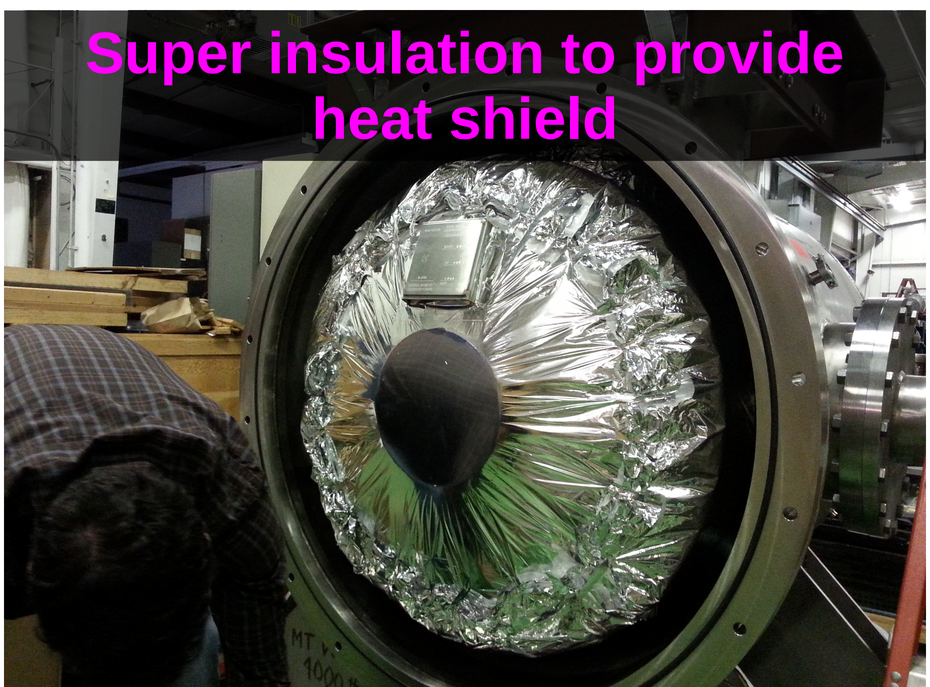
You need a vessel that is insulated to keep the Argon cold!

Cryostats

Vacuum-Jacketed Cryostat

Vacuum between the inner and outer cryostat acts like an insulator

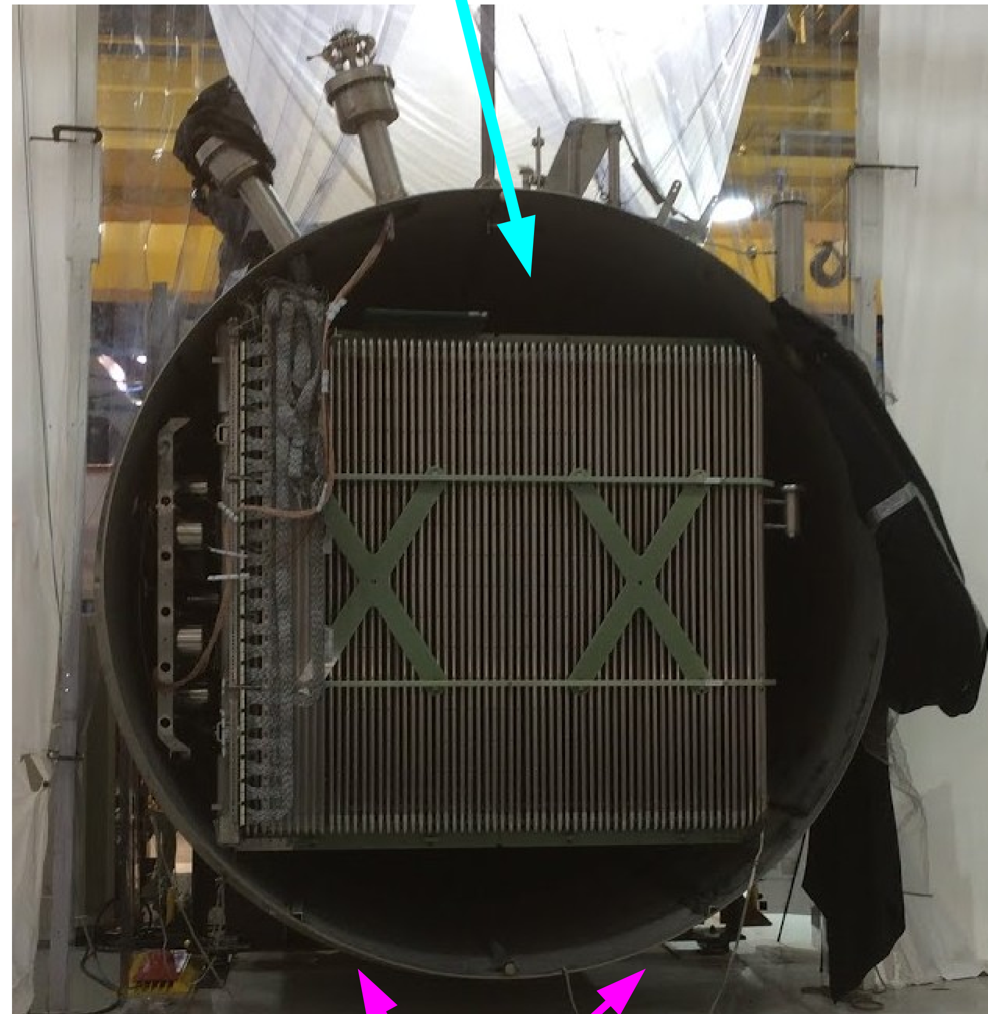




- You continuously pump on the external jacket and the vacuum provides your heat insulation

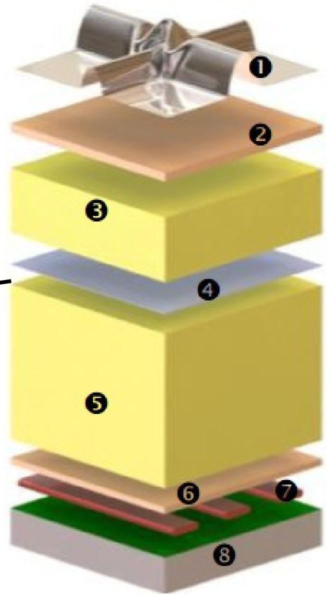
MicroBooNE Cryostat

Liquid Argon inside the cryostat

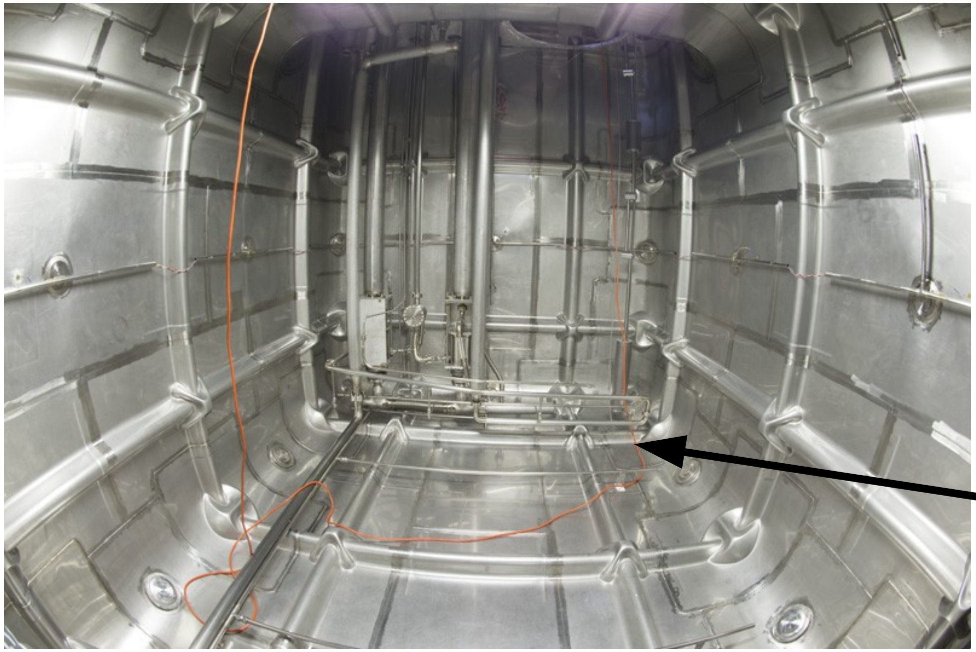


Then we spray the outside with insulating foam ~6” thick

Cryostats



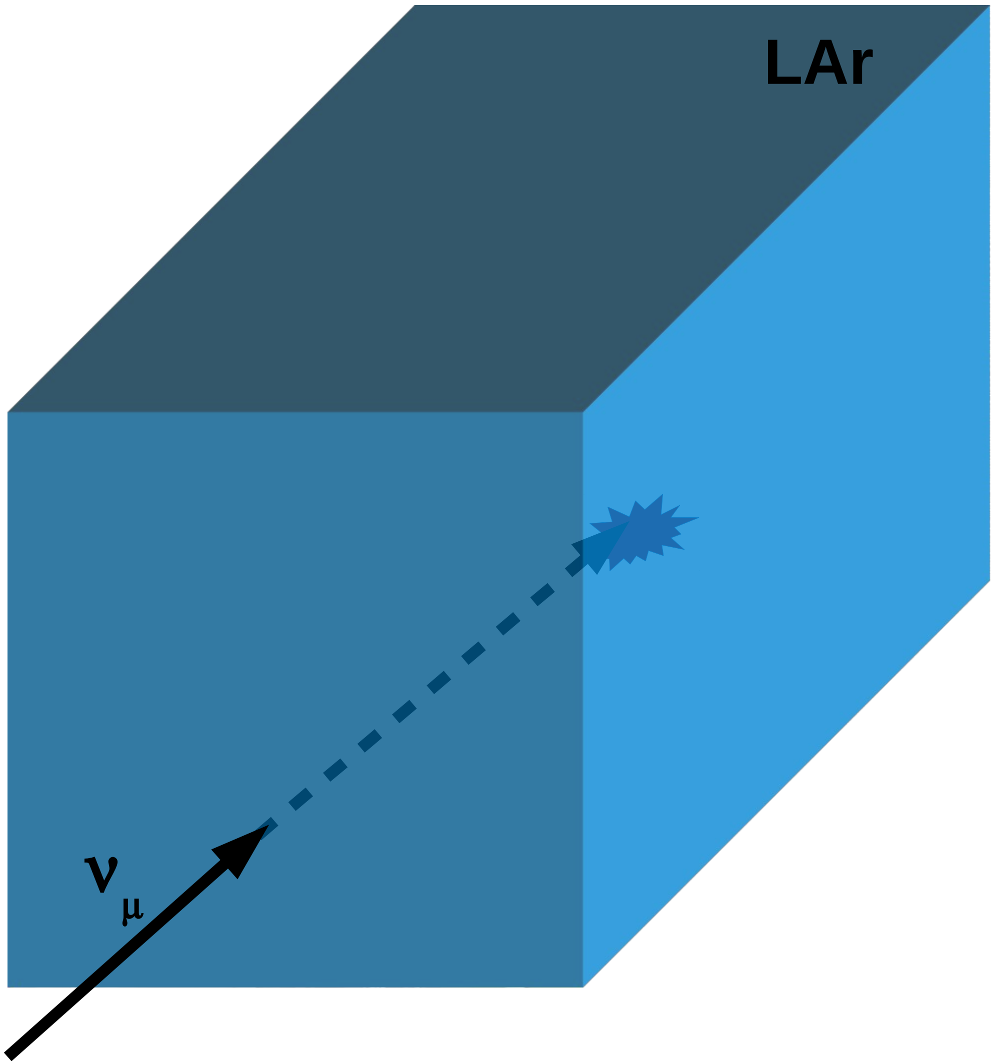
1) Stainless steel primary membrane (LAr inside here)
2)Plywood board
3) Polyurethane foam
4)Secondary barrier
5) Polyurethane foam
6) Plywood board
7) Bearing mastic
8)Concrete



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

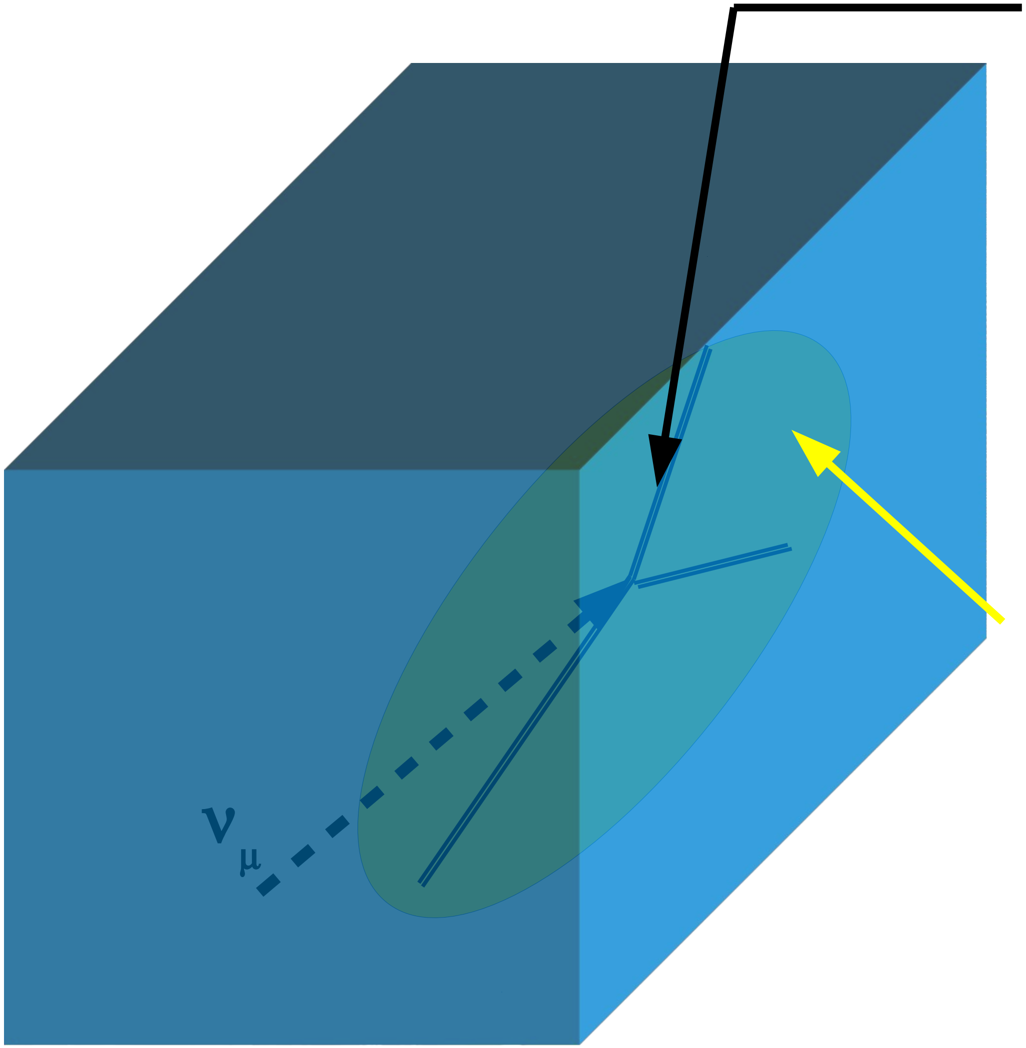
Neutrino interactions in Liquid Argon



To understand how a liquid argon (LAr) detector works we'll look at some of the details of what a neutrino-Argon (ν-Ar) nucleus interaction looks like

Imagine firing a beam of neutrinos into the volume of LAr and wait for an interaction

Neutrino interactions in Liquid Argon

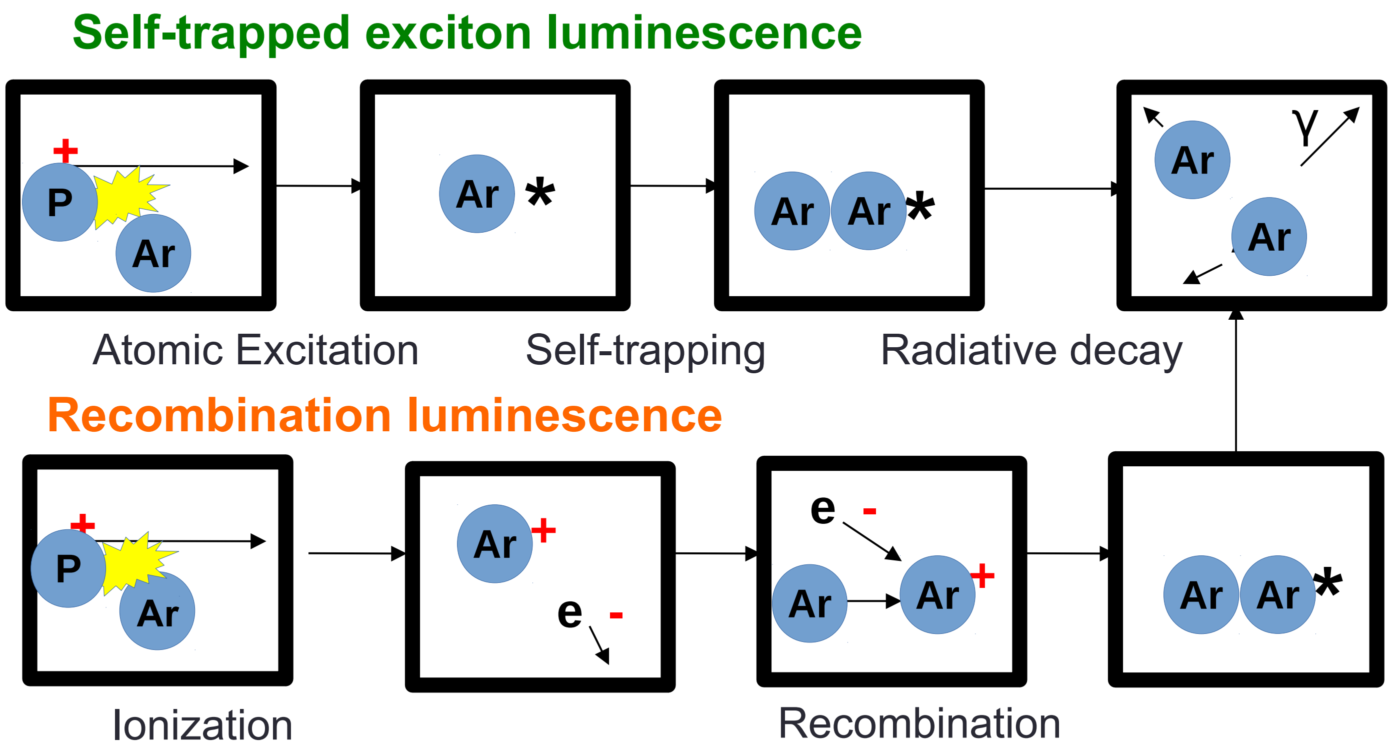


In the ν-Ar interaction the charged particles produced ionize the argon as they move through the volume

Additionally, the interaction causes scintillation light to be produced isotropically

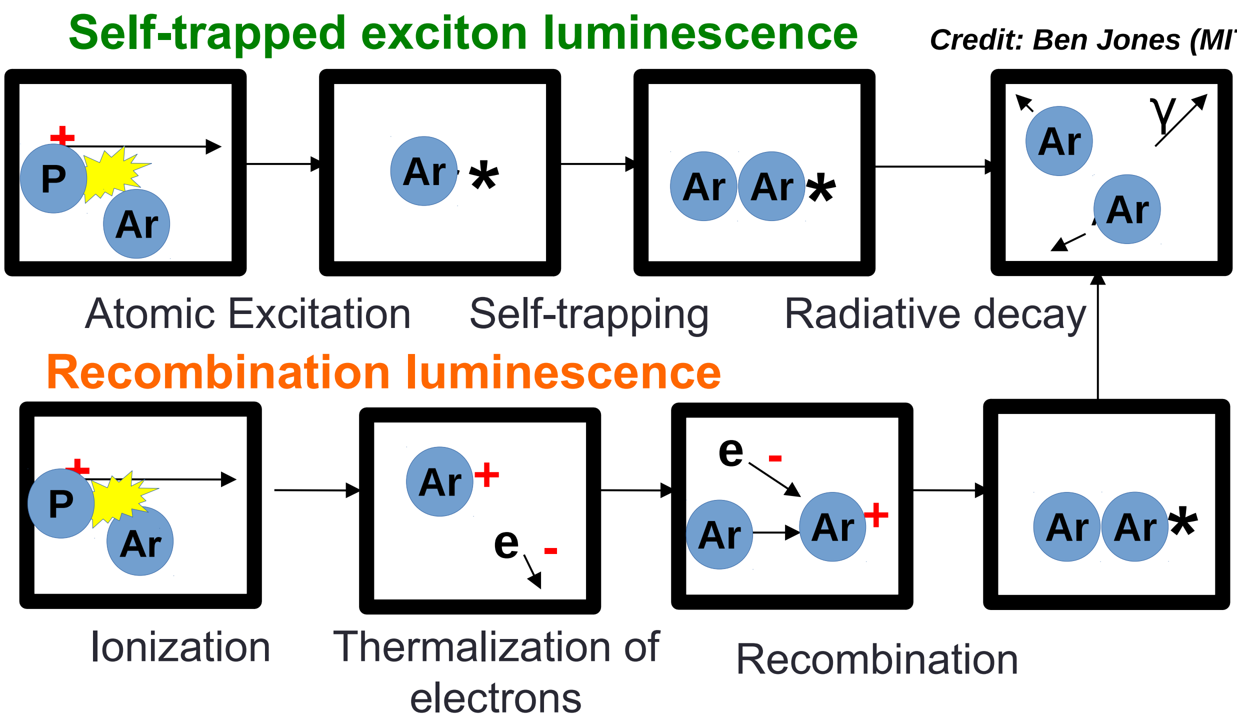
Interesting aside about scintiallation light

Image Credit: Ben Jones (MIT)

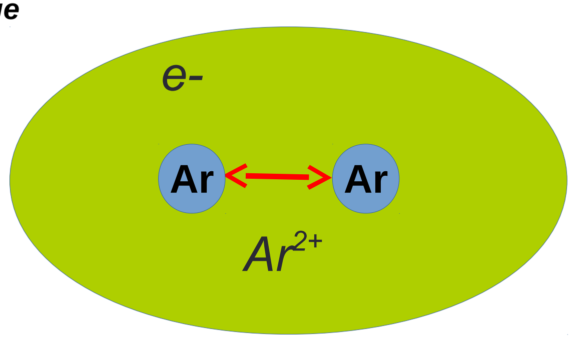


- **In liquid argon there are two important scintillation methods**
  - Self trapped exciton luminescence
  - Recombination luminescence

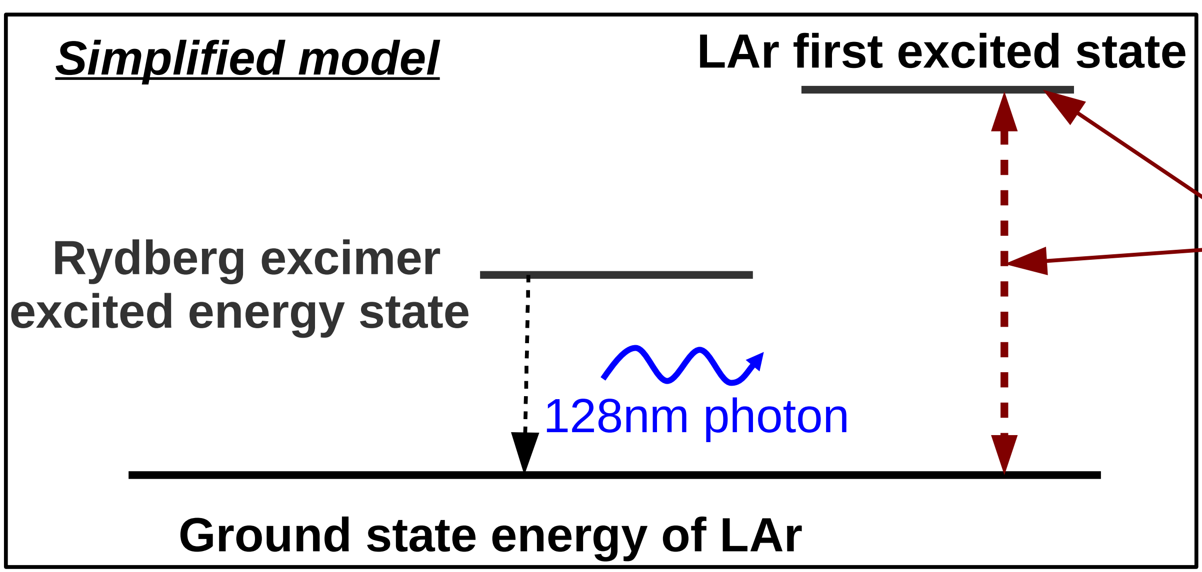
Interesting aside about scintiallation light



Credit: Ben Jones (MIT) for image

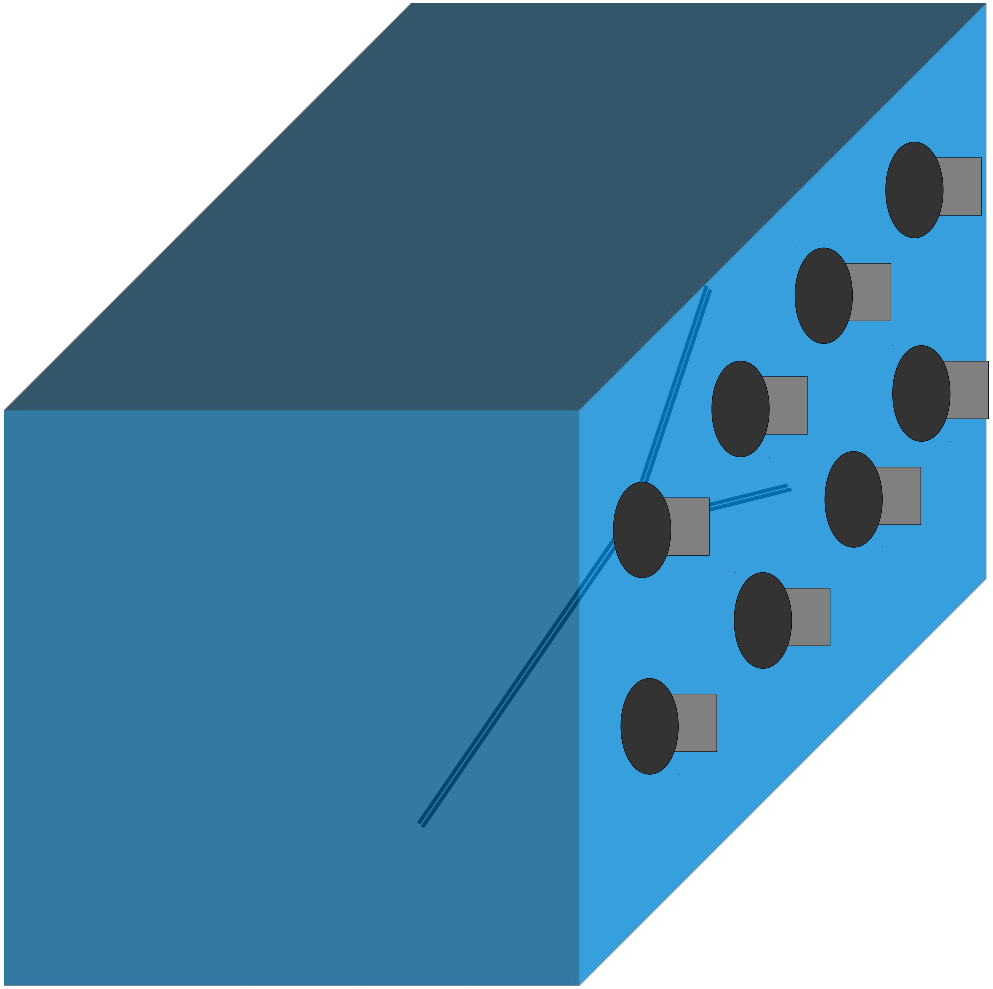


Excimer state formed during this process is a Rydberg state: Ar^{2+} with a bound electron



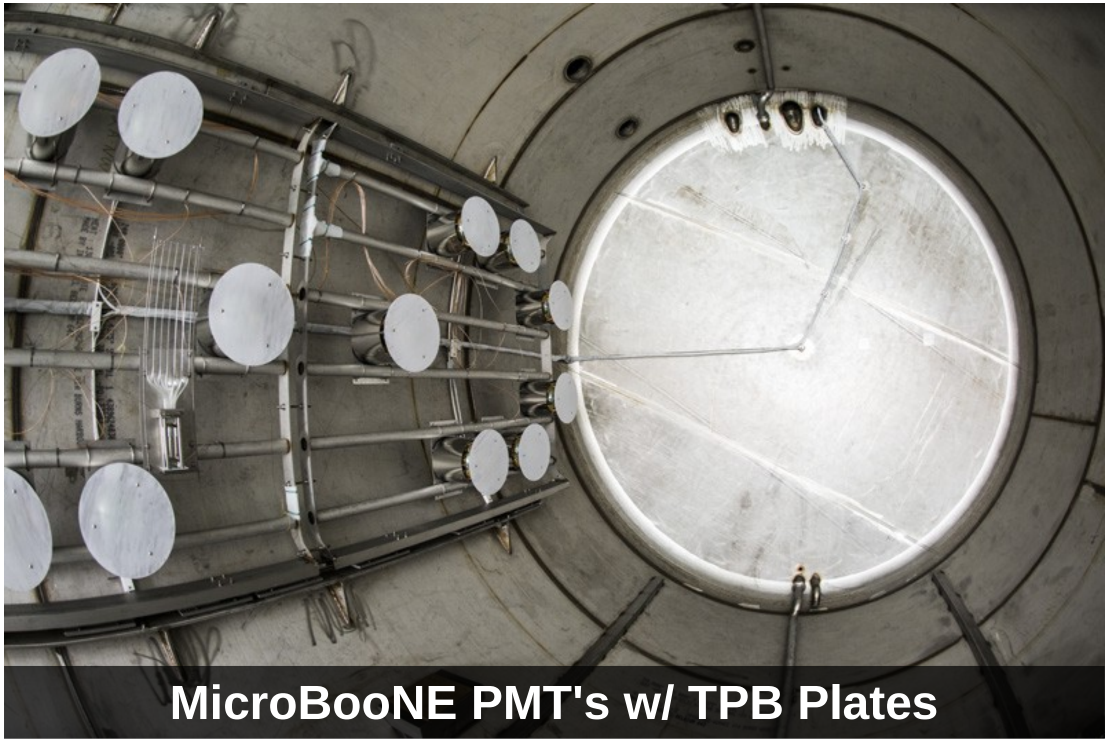
This difference between the energy levels is why LAr is transparent to the scintillation light it produces

Neutrino interactions in Liquid Argon

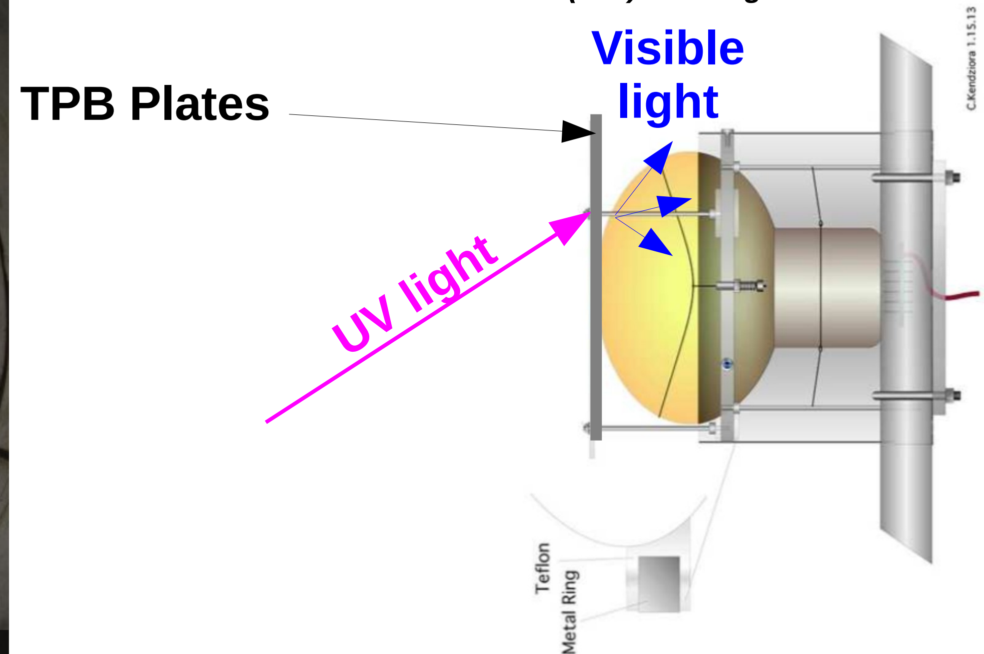


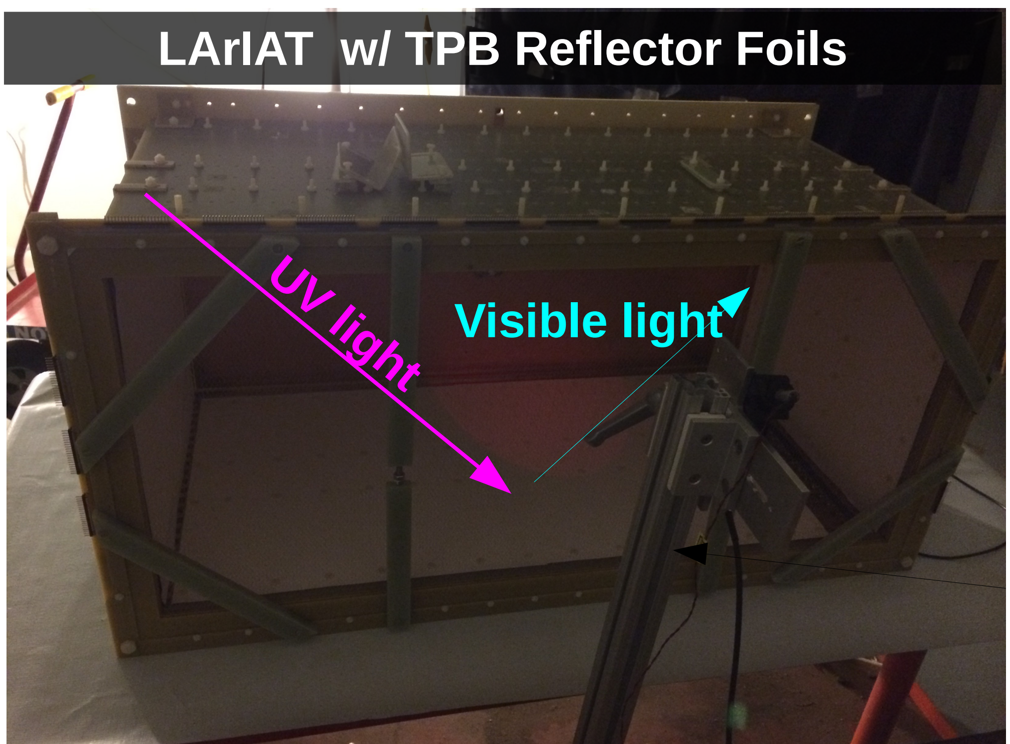
In order to detect the scintillation light using PMT's it is necessary to utilize wavelength shifting material

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

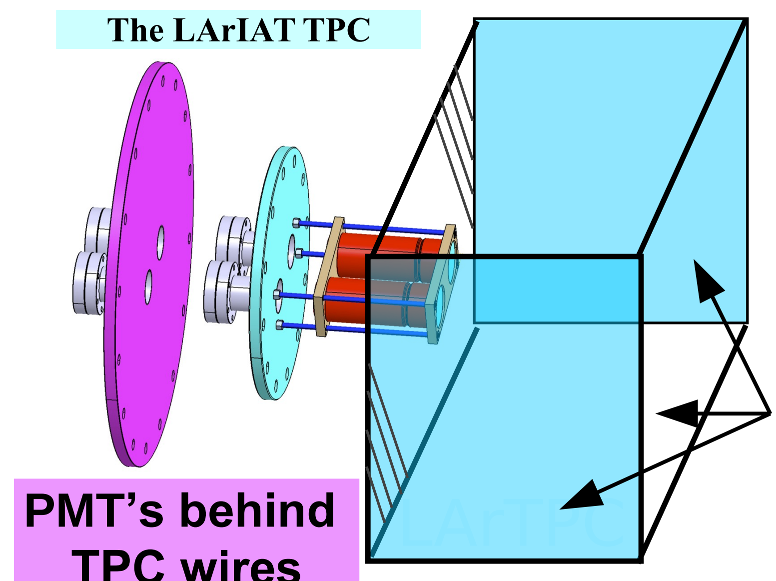


Credit: Ben Jones (MIT) for image



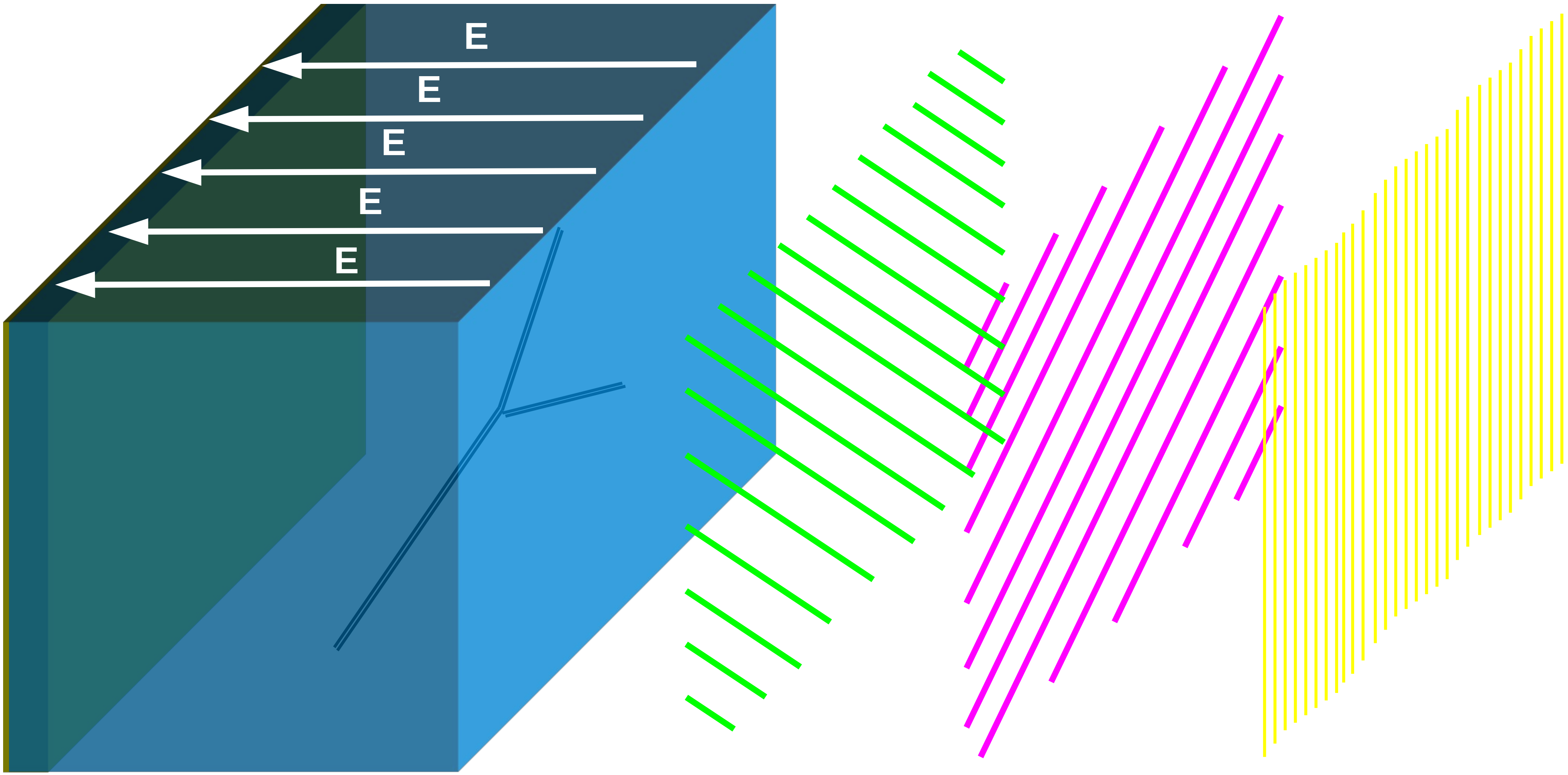


Wavelength shifting reflector foil lining the TPC to give uniform light yield



Credit: Flavio Cavanna (FNAL) for image

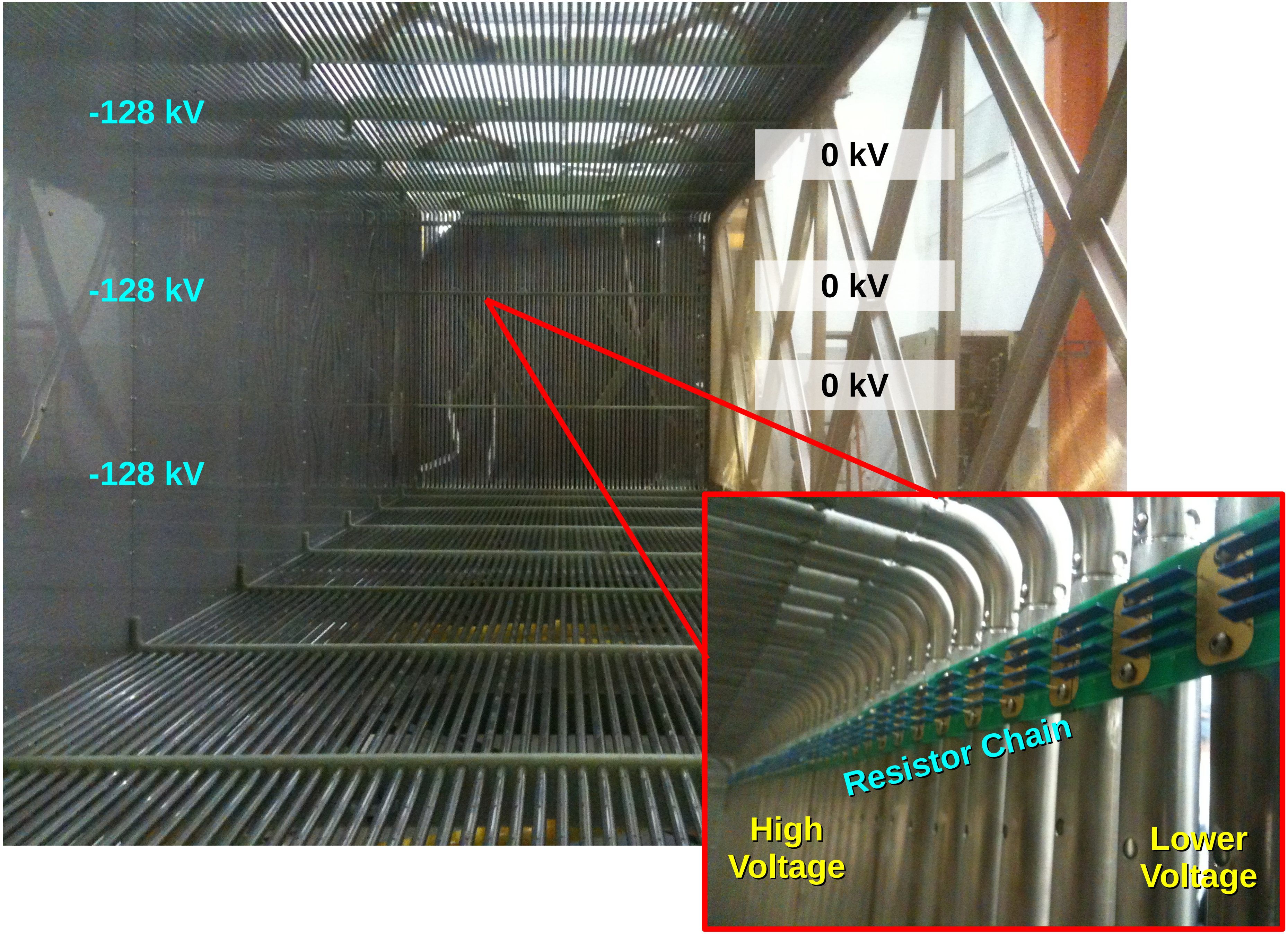
We apply a uniform electric field to drift the ionization charge



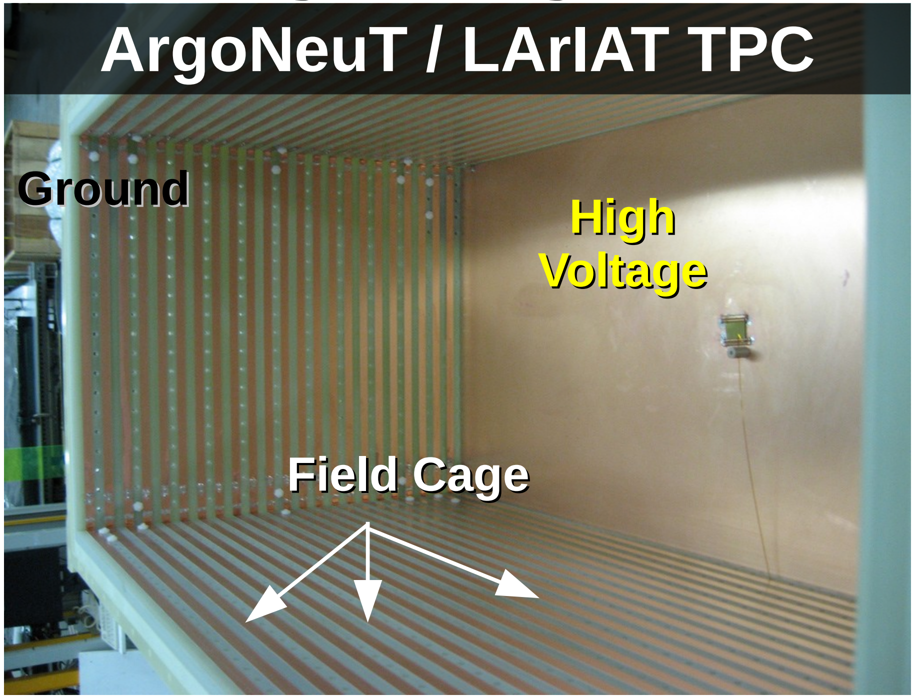
We collect this charge on a series of wires

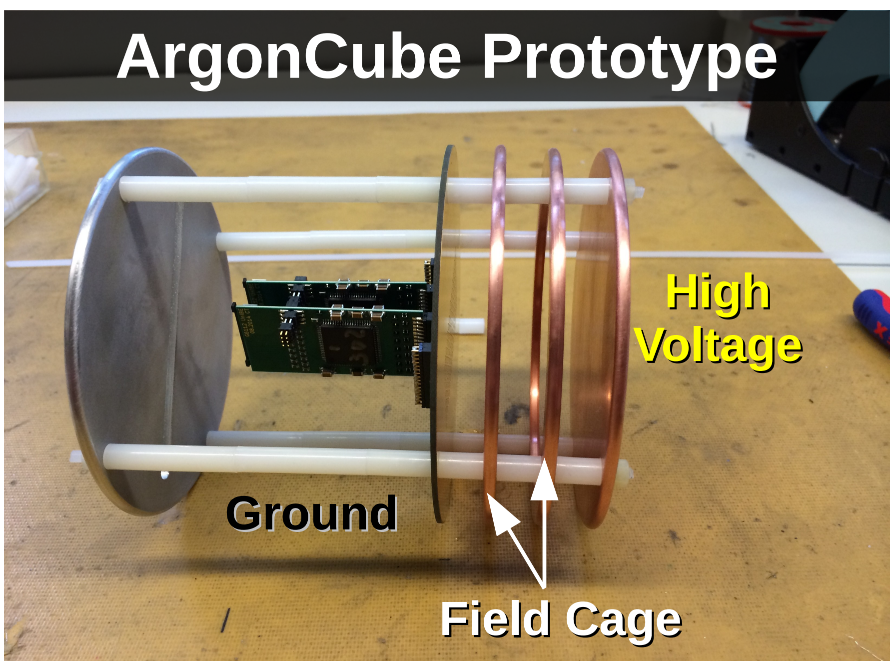
How to apply a uniform E-Field

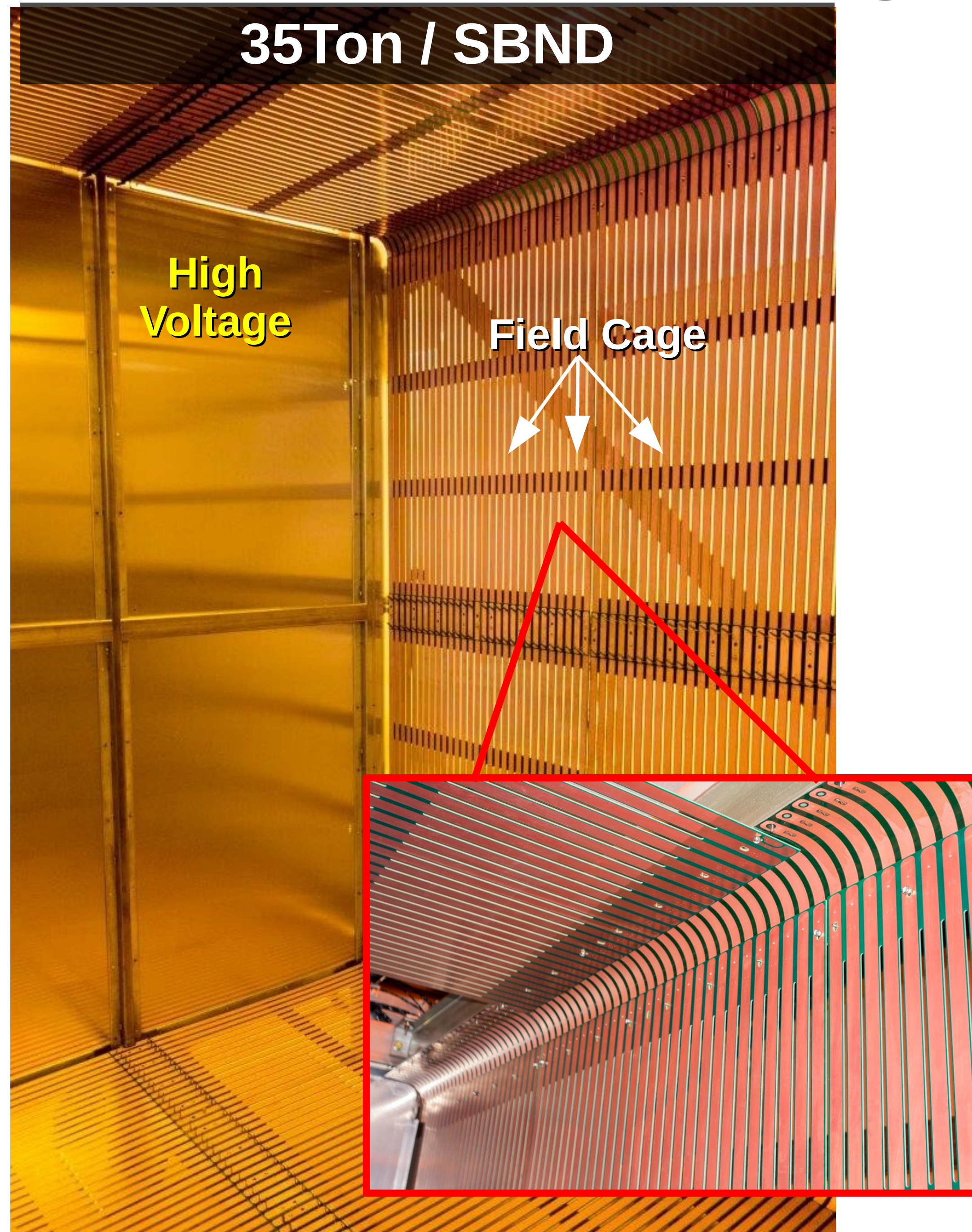
How to apply a uniform E-Field



Many ways to build the same thing

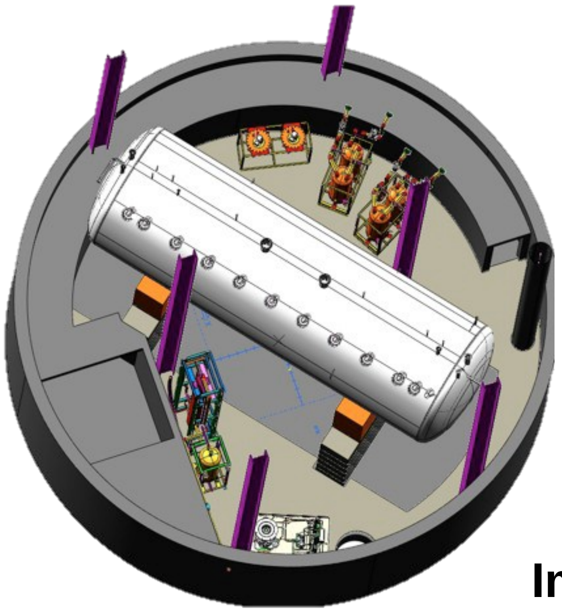






Uniformity matters

- 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 →

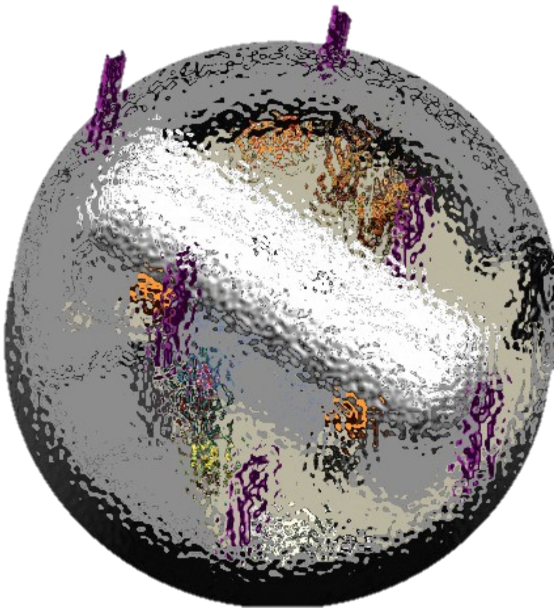
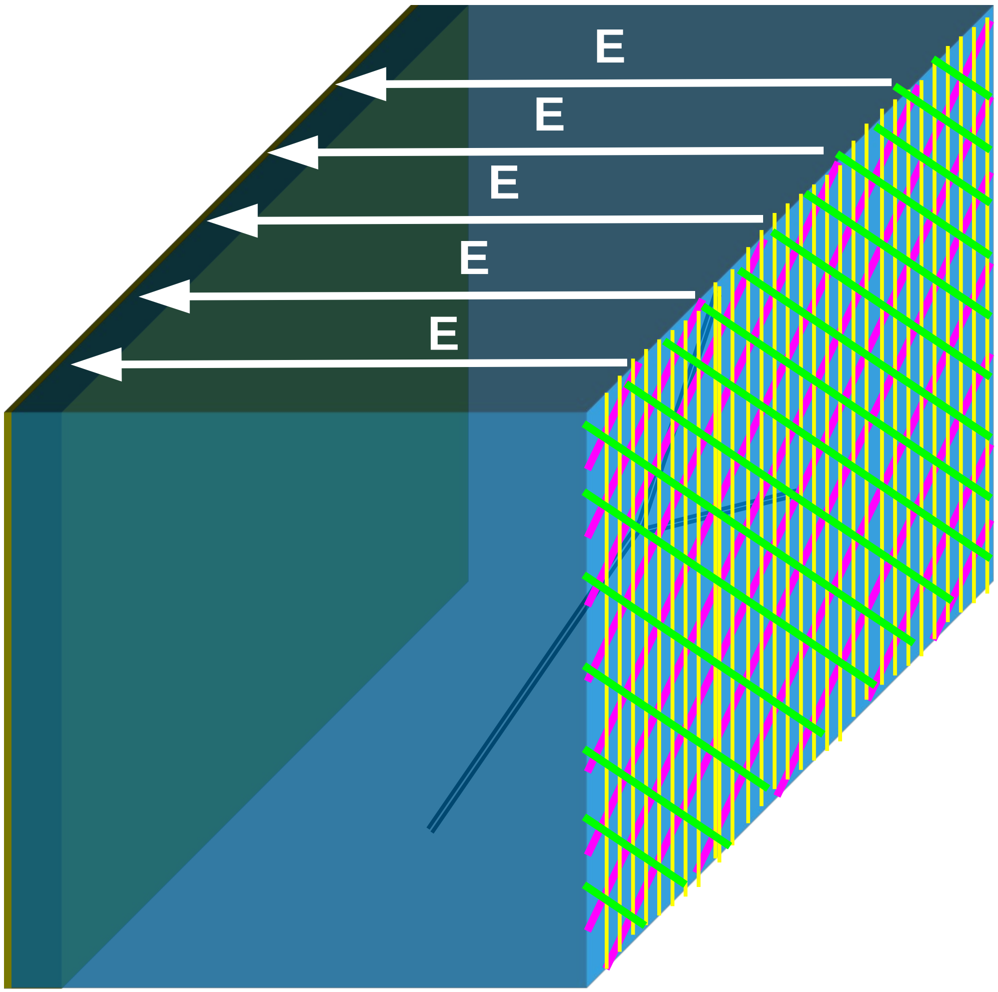


Image credit: B. Jones

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

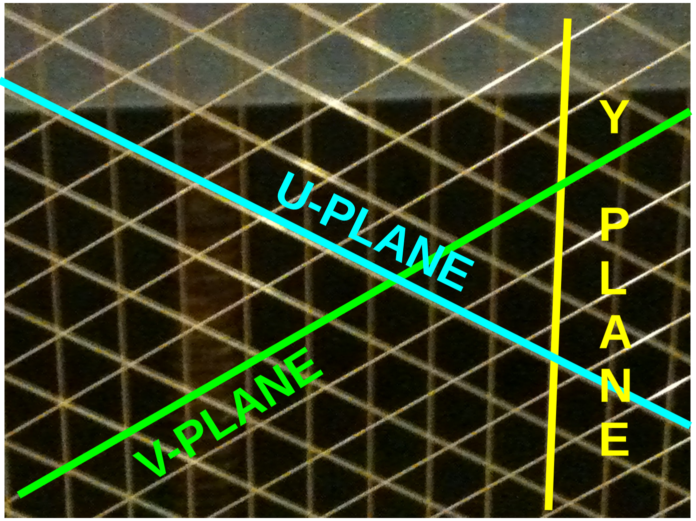


What you read off of your wires is the amount of charge and the drift time of the ionization "projected" back into the volume of liquid argon

Hence the name

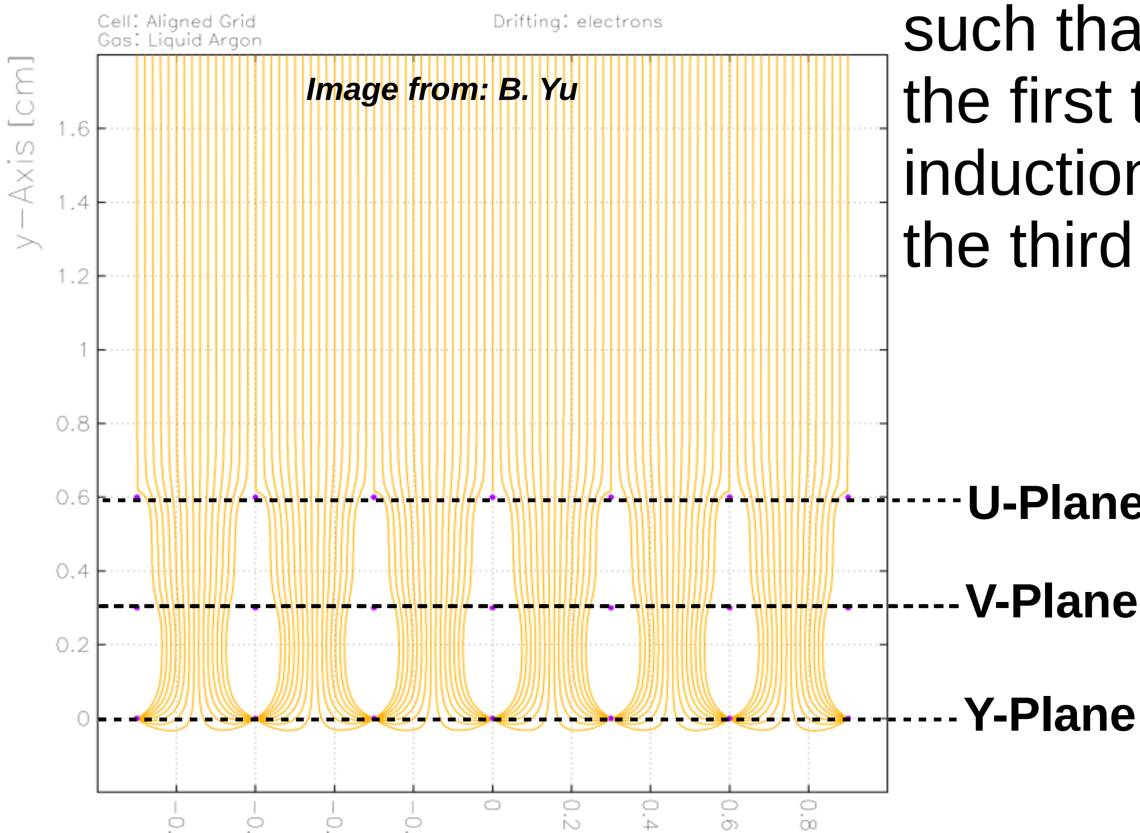
Liquid Argon Time Projection Chamber

A little more about wires



You will often hear people talk about the three planes of wires as being two induction planes and one collection plane

What we mean is that we've configured the electric field near the wire planes (meaning we've biased the wire planes) such that the drifting charge passes by the first two wire planes (creating an induction pulse) and then collects on the third wire plane



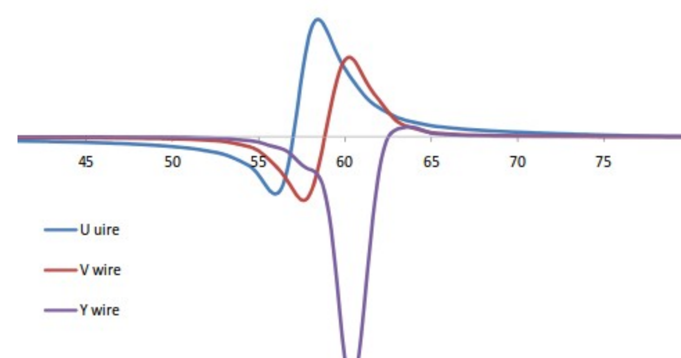
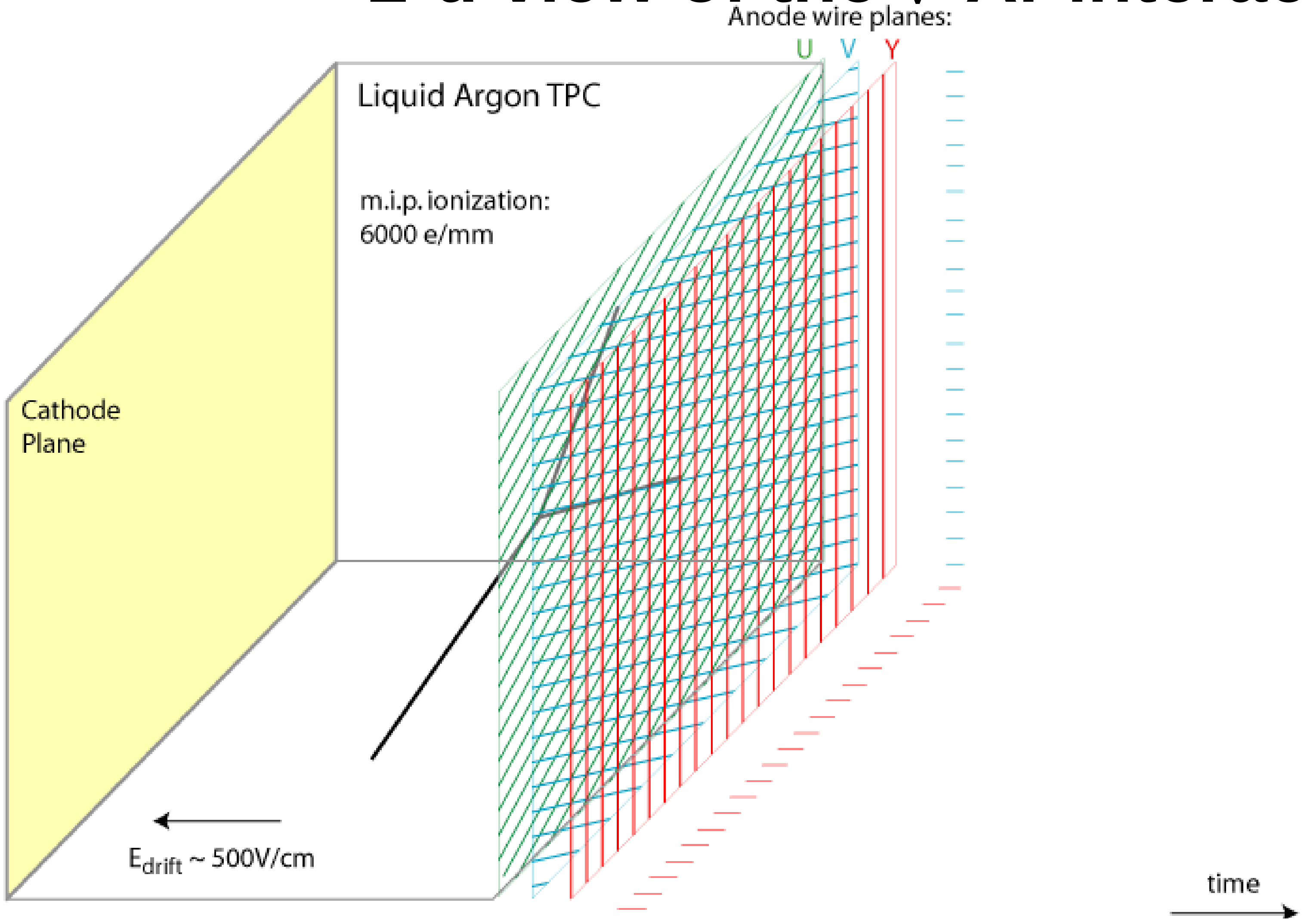


Image from: B. Yu

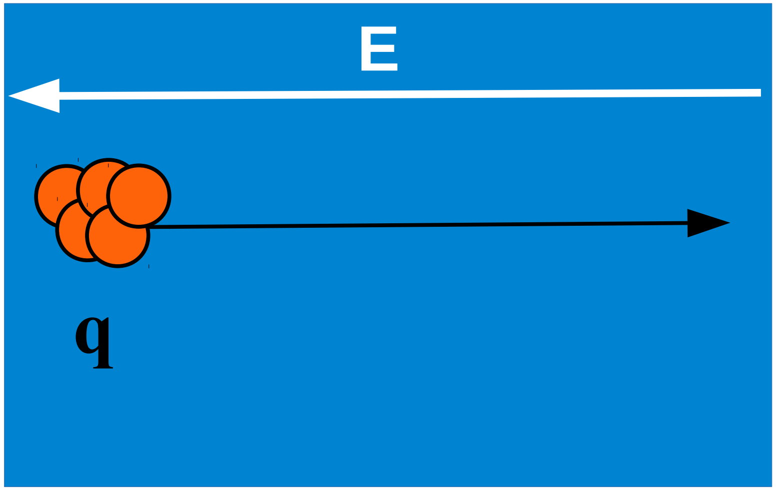
Wires placed at the end of the drift provide a 2-d view of the ν-Ar interaction



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

Aside about ion drift

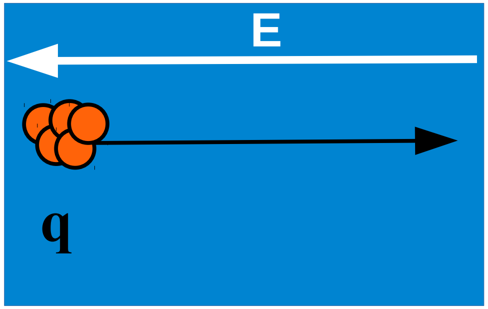
When drifting your electrons through the argon you encounter a lot of interesting physics that impacts your measurement



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

Aside about ion drift

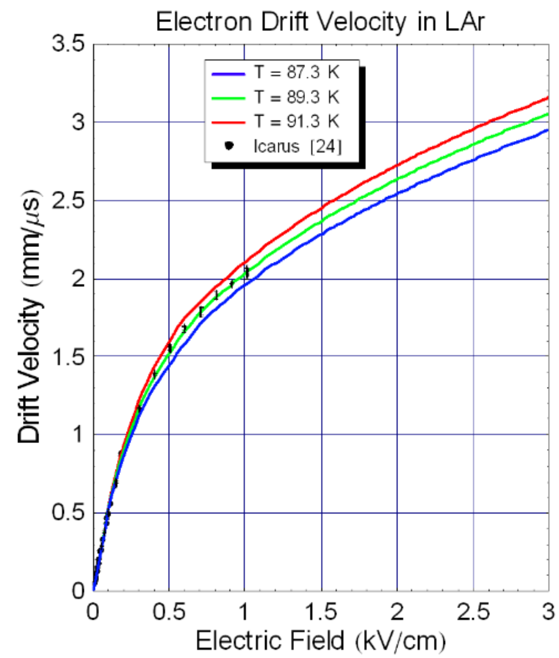
- **Ion Drift Velocity**



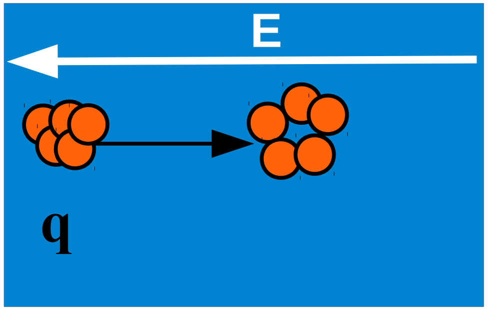
The drift velocity is an empirically modeled function depending on temperature (T) and electric field (E) in the argon

W. Walkowiak, NIM A 449 (20

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



- **Ion Diffusion**



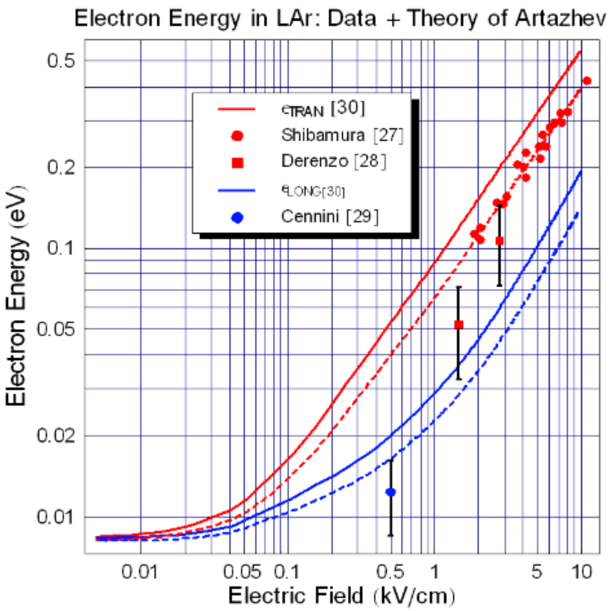
The ion diffusion (RMS spread) is related to the drift distance (Δz), the electric field (E), and the electron mobility in argon

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

W. Walkowiak, NIM A449 (2000) 228

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

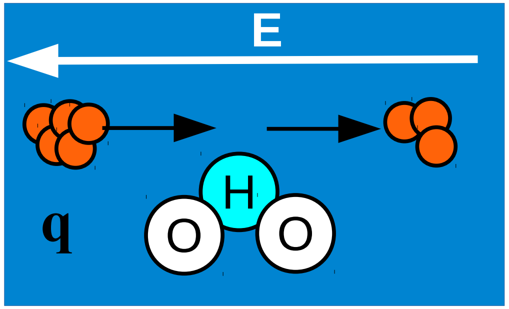
$$D = \mu\,\varepsilon$$

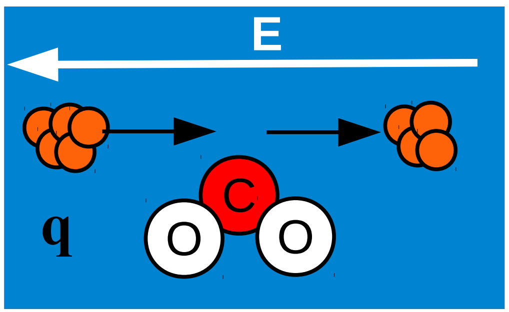


Note: What I measure is the electron energy (ε) and I get the diffusion constant using the relationship with the electron mobility

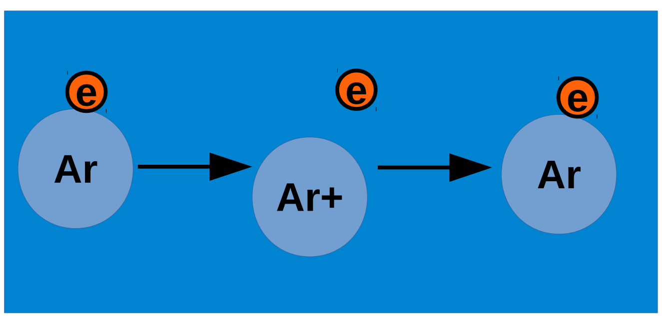
Aside about ion drift

- **Ion Recombination**

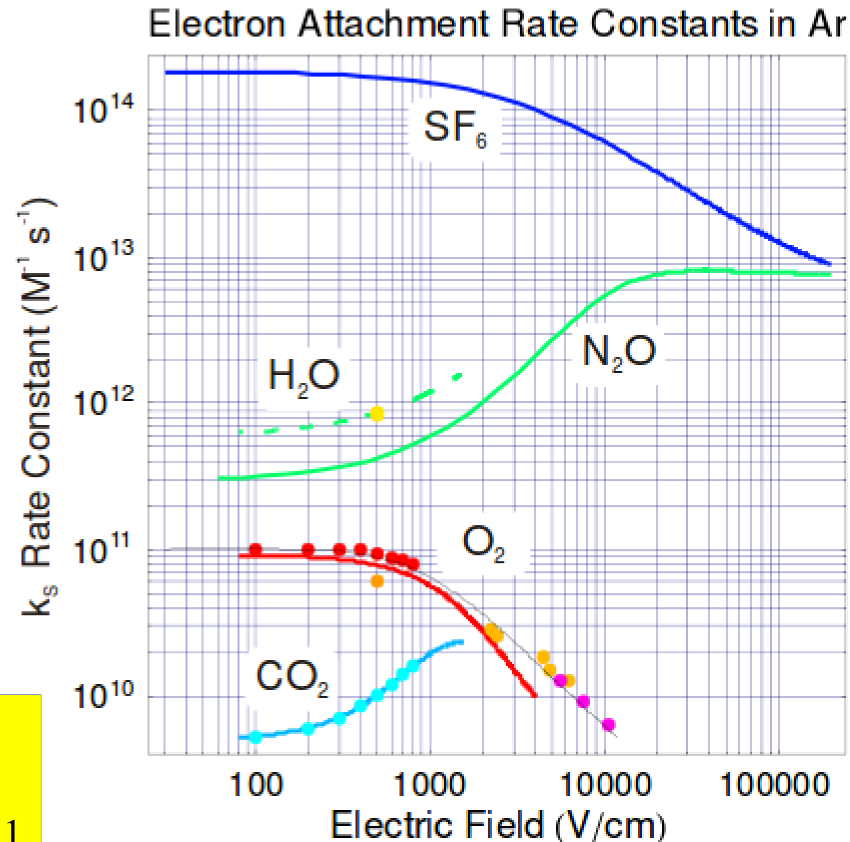




Ion recombination is also a complicated affair depending on various types of impurity, its concentration, and the electric field



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



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

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

$\mathbf{n_s}$ is the molar solute concentration in LAr

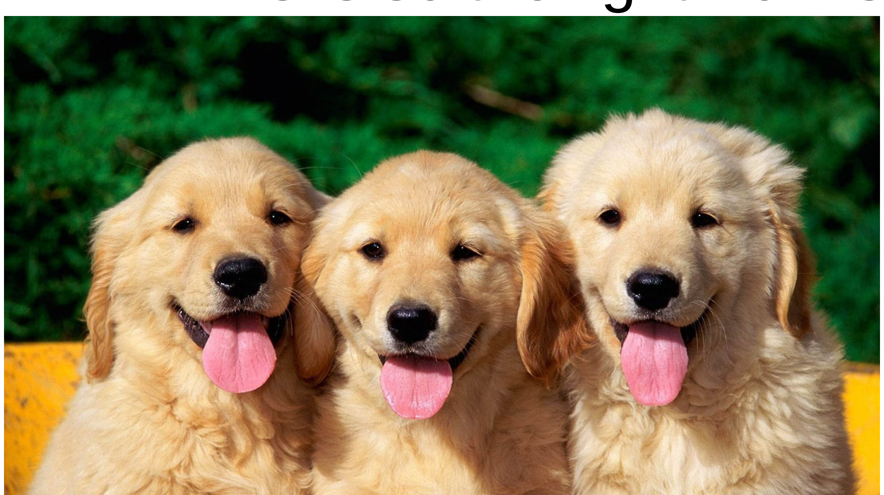
LAr Purity

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

Image Credit: S. Lockwitz

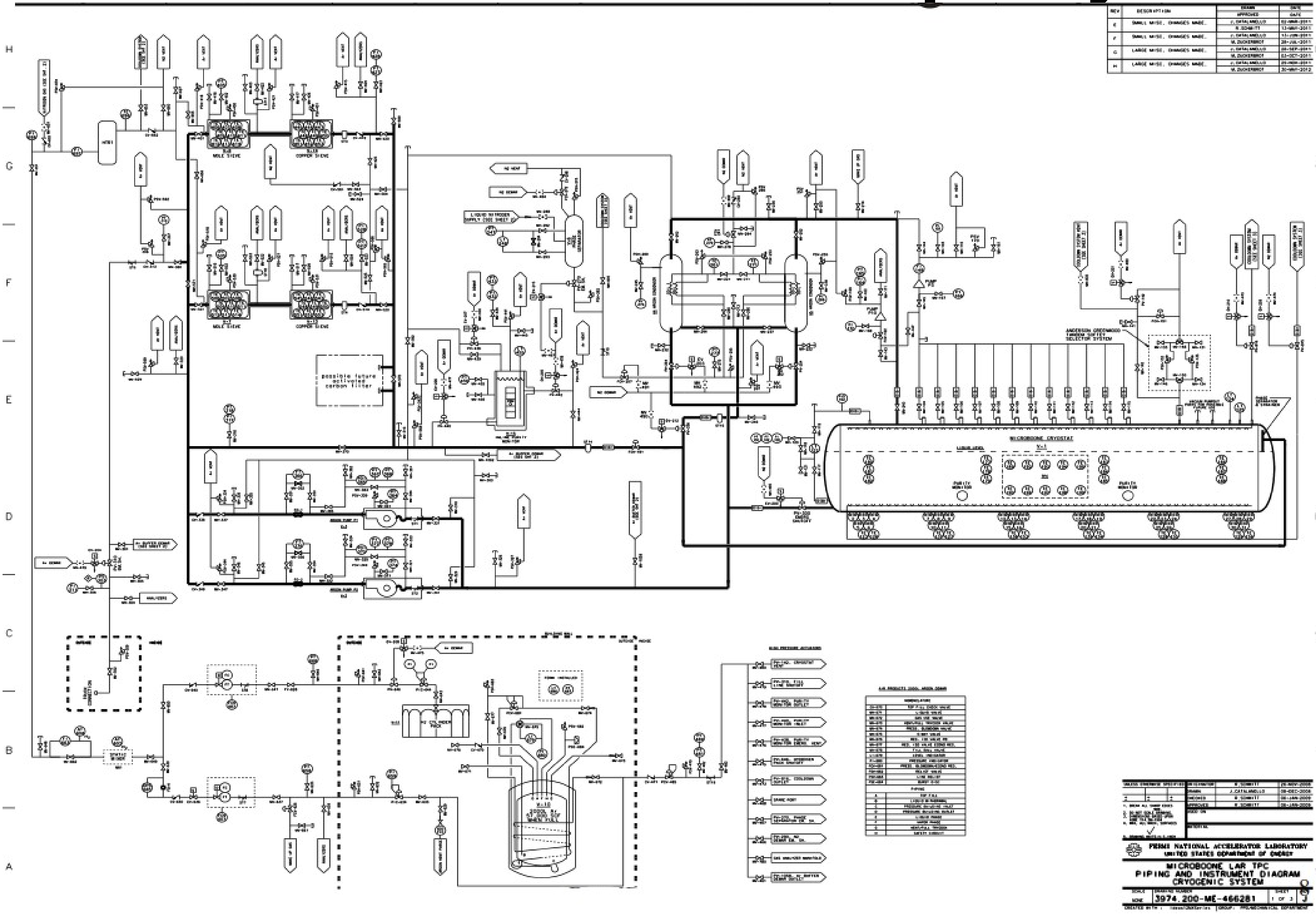
How pure is pure?

- **<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

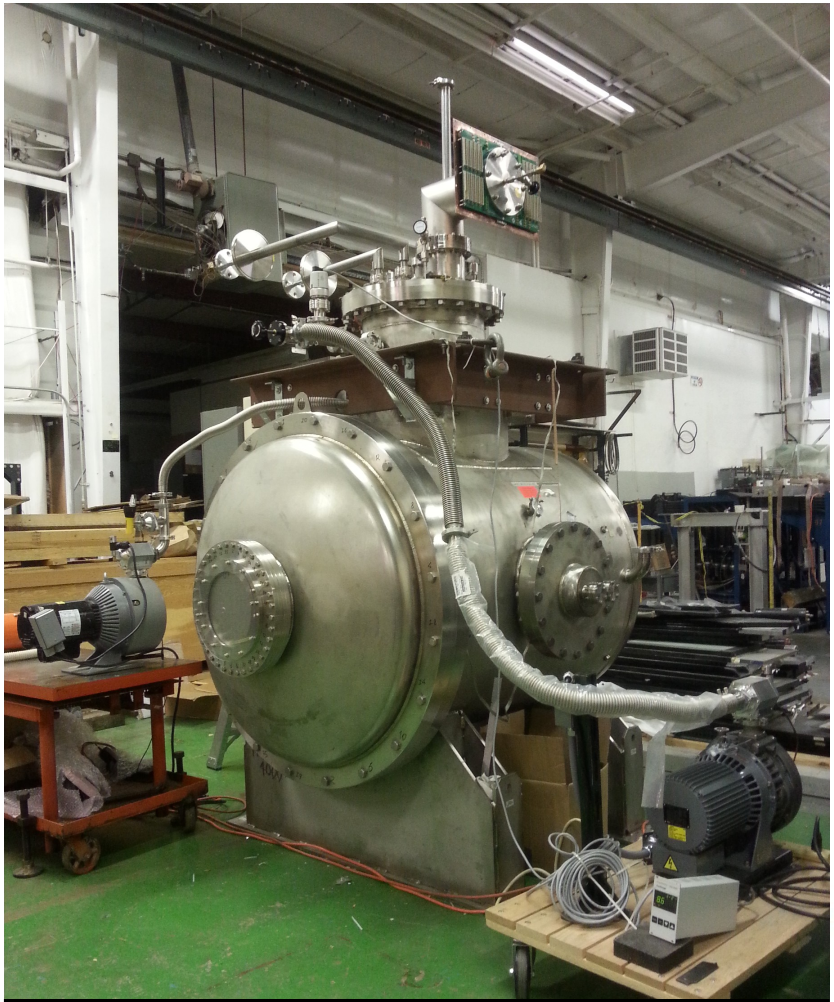


A dogs nose is sensitive at the ppt level, but they tend not to like being employed as scientists and have an adversity to -303 degrees Fahrenheit

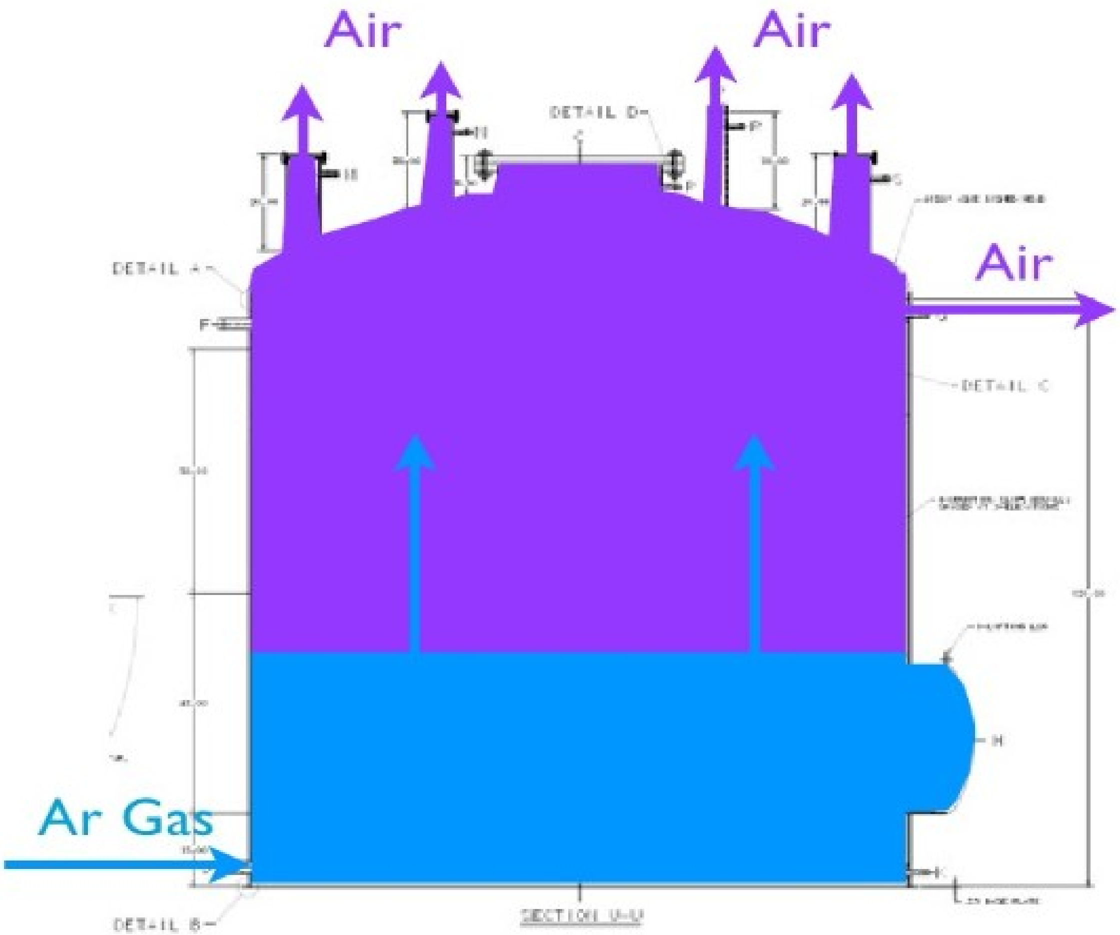
How to achieve this purity



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

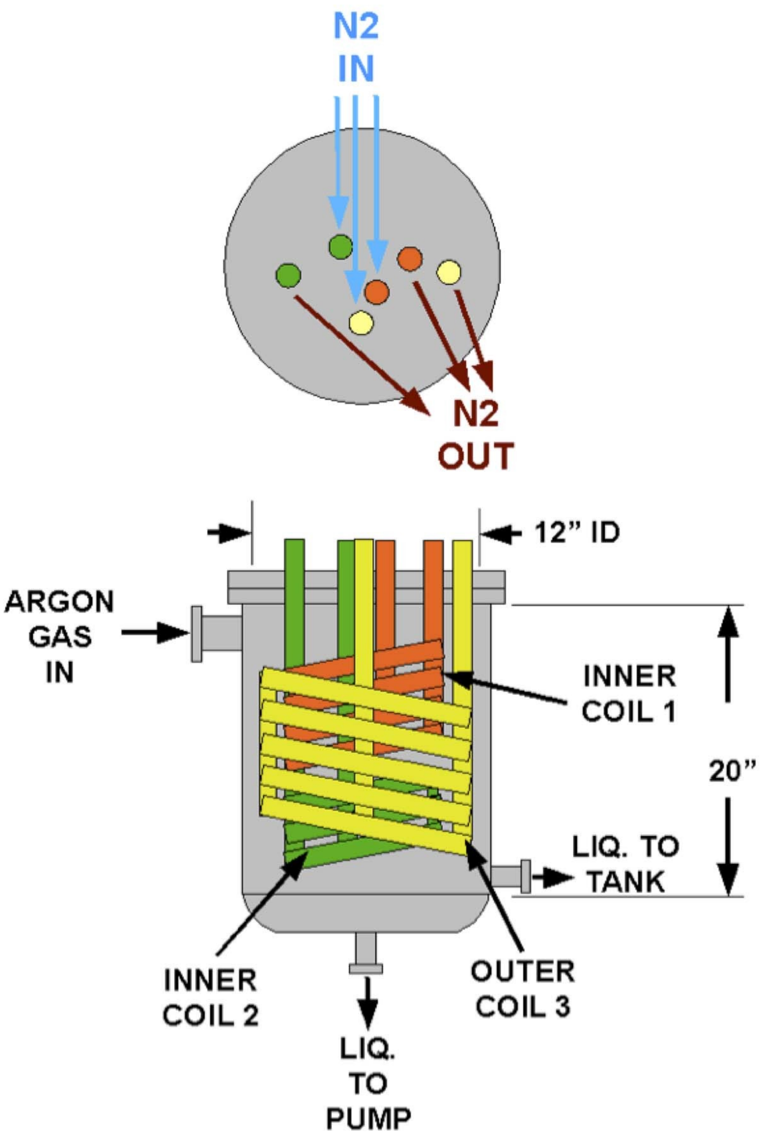


LArIAT Cryostat

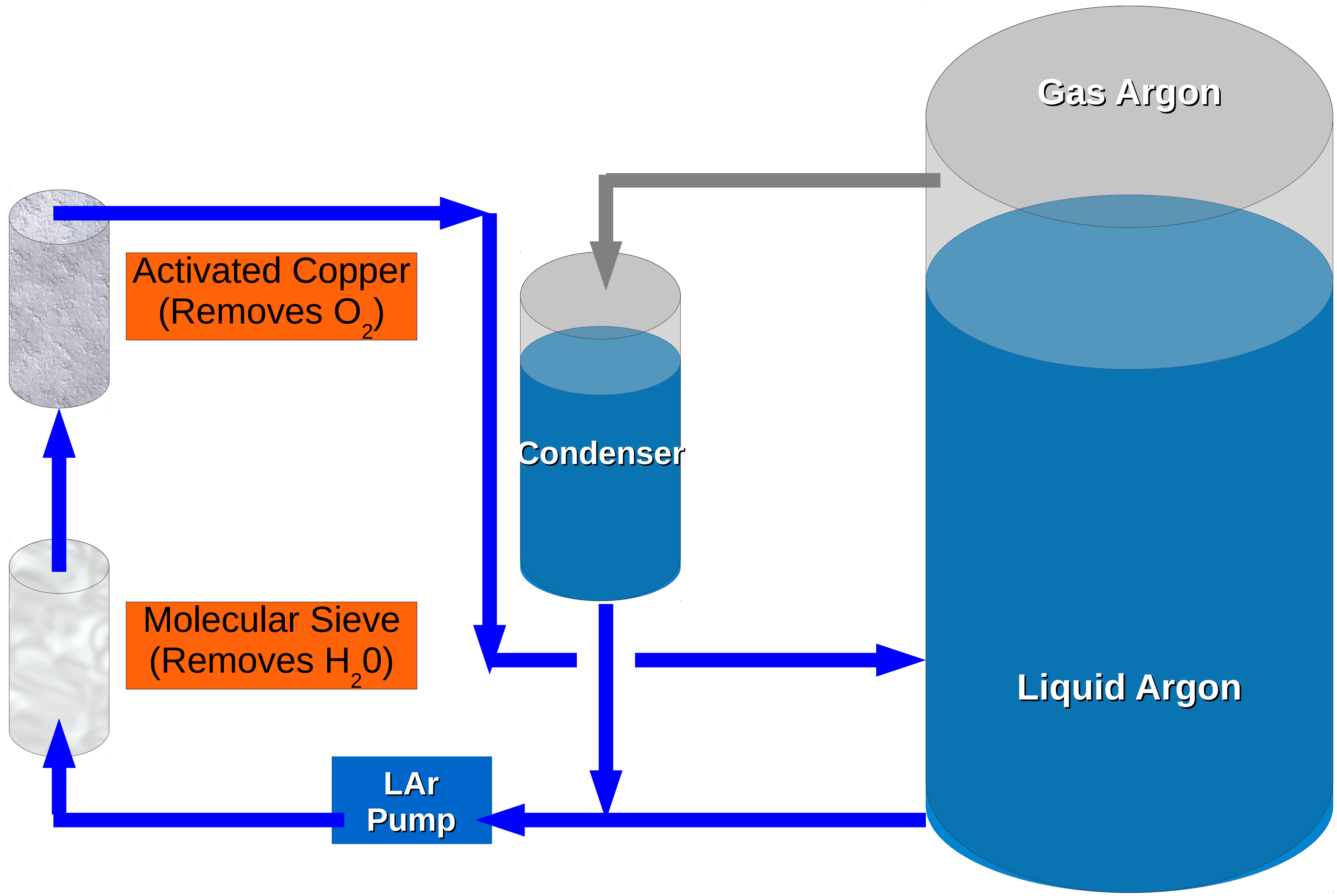


Cooling down

- **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

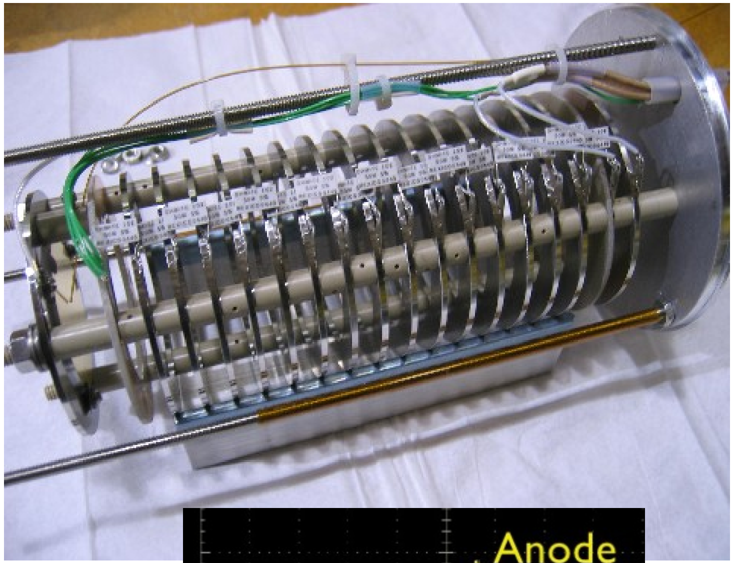


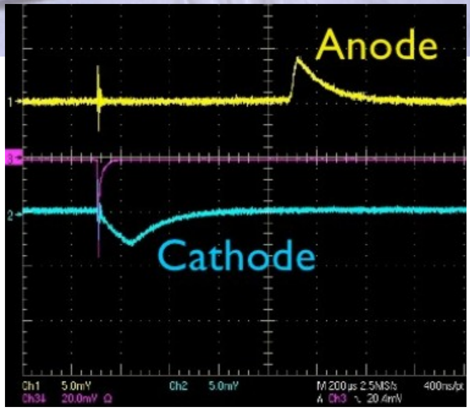
Purifying


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

Monitoring the Purity

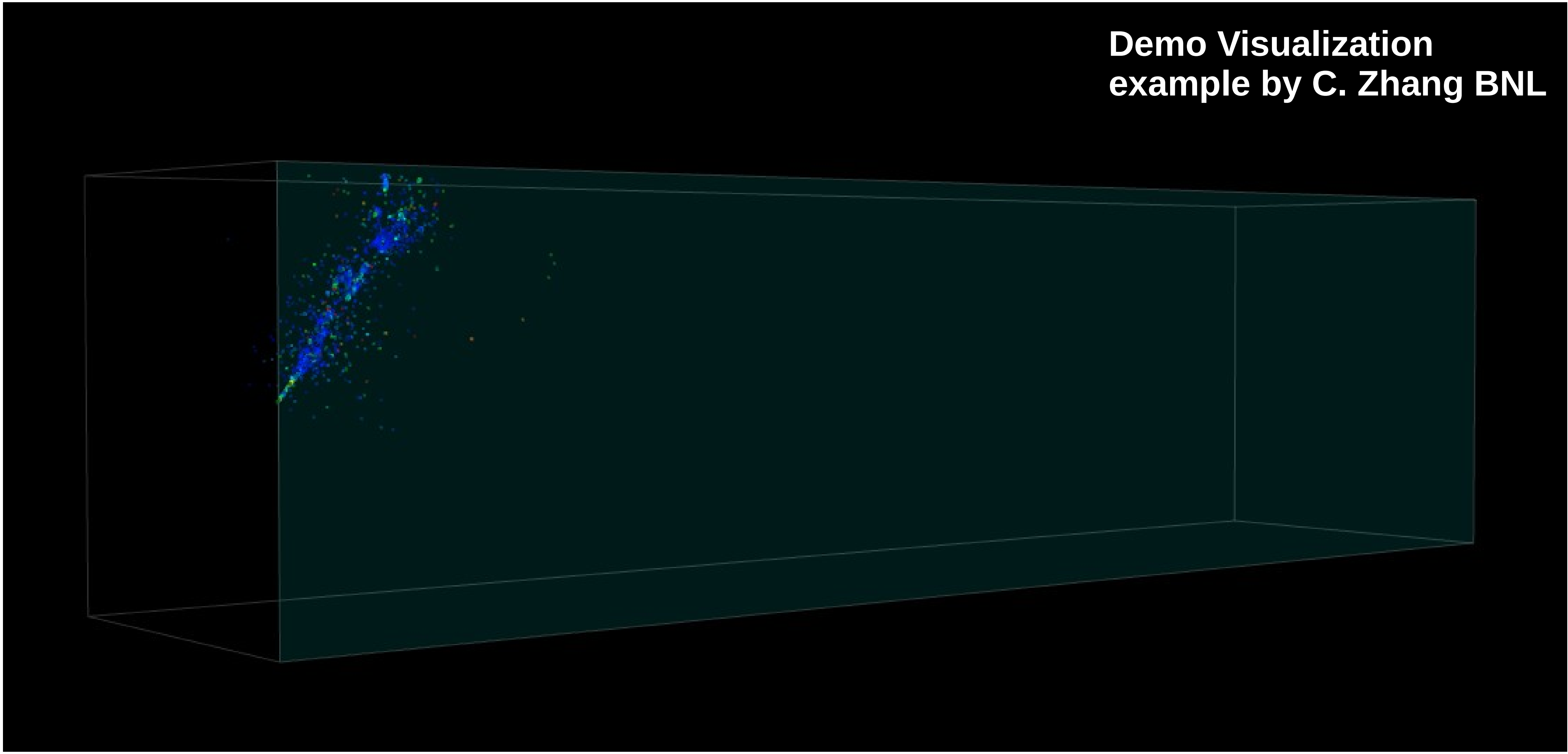
- **We use tiny little TPC's to monitor the purity**
  - Called purity monitors
- **Utilize a Xenon Flasher Lamp at the cathode**
  - Measure Qcathode
- **The electrons take some time to drift**
  - Measure tdrift
- **The electrons arrive at the anonde**
  - Measure Qanode





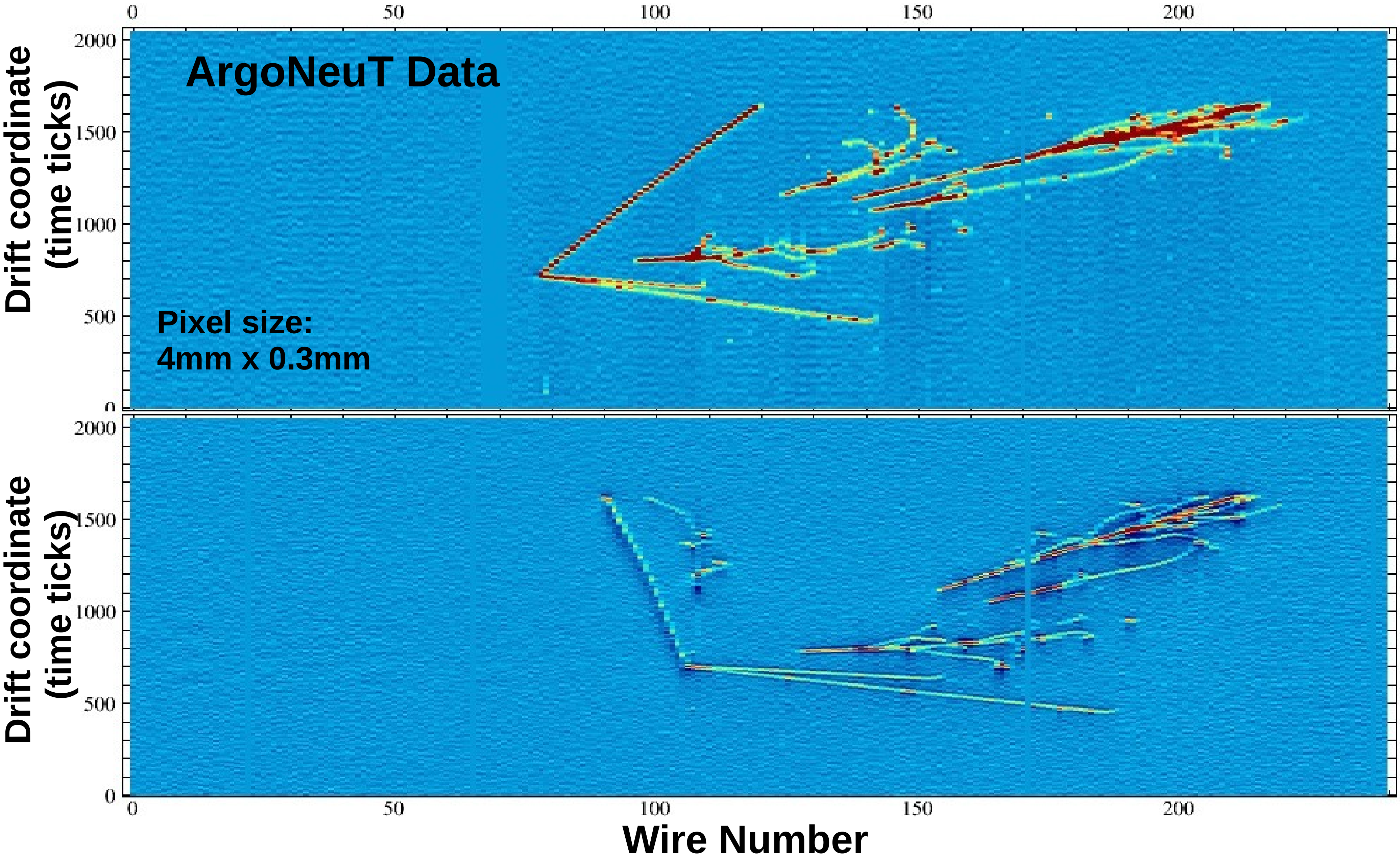
$$\frac{Q_{\text{anode}}}{Q_{\text{cathode}}} = e^{\frac{-t_{\text{drift}}}{\tau_e}}$$

What do you get when it all works

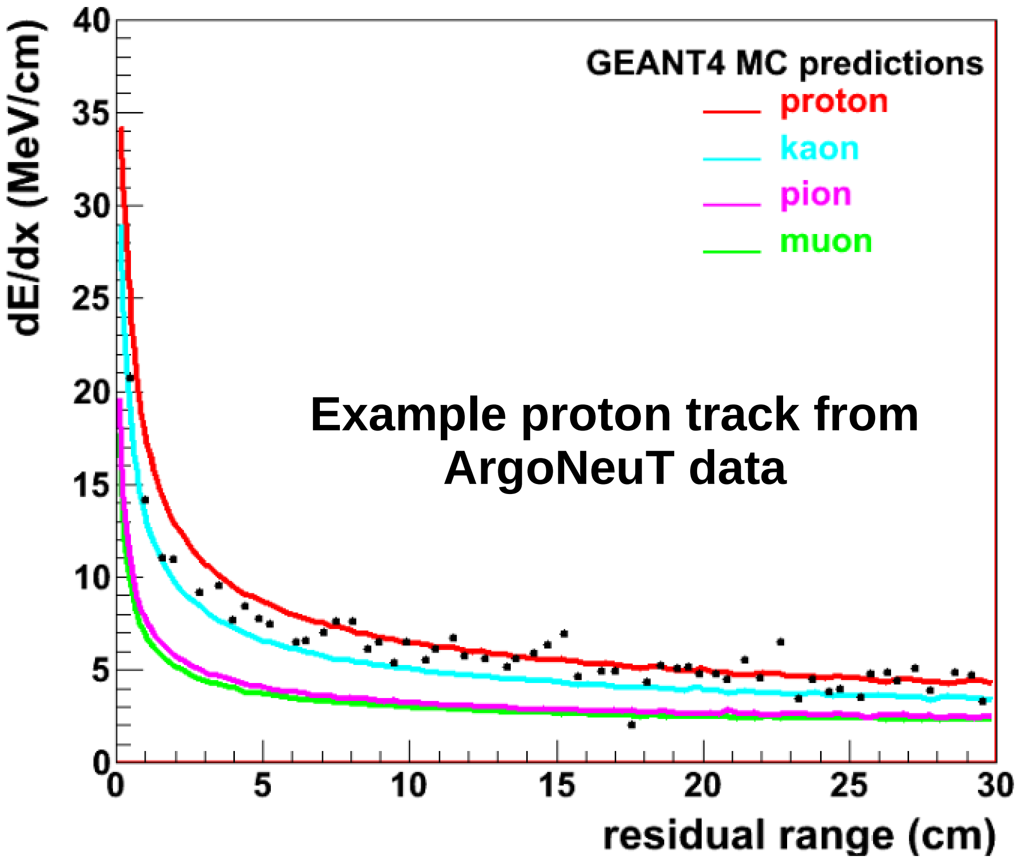


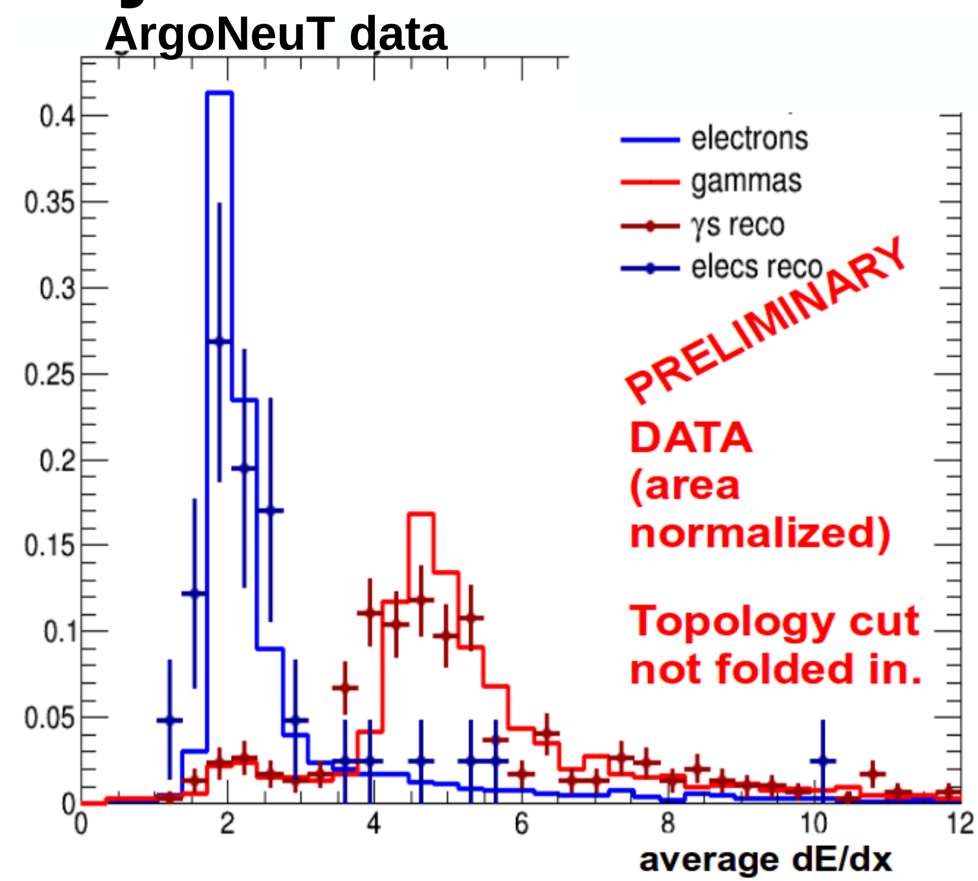
High Resolution 3-d event reconstruction

Liquid Argon Time Projection Chamber



Liquid Argon Time Projection Chamber

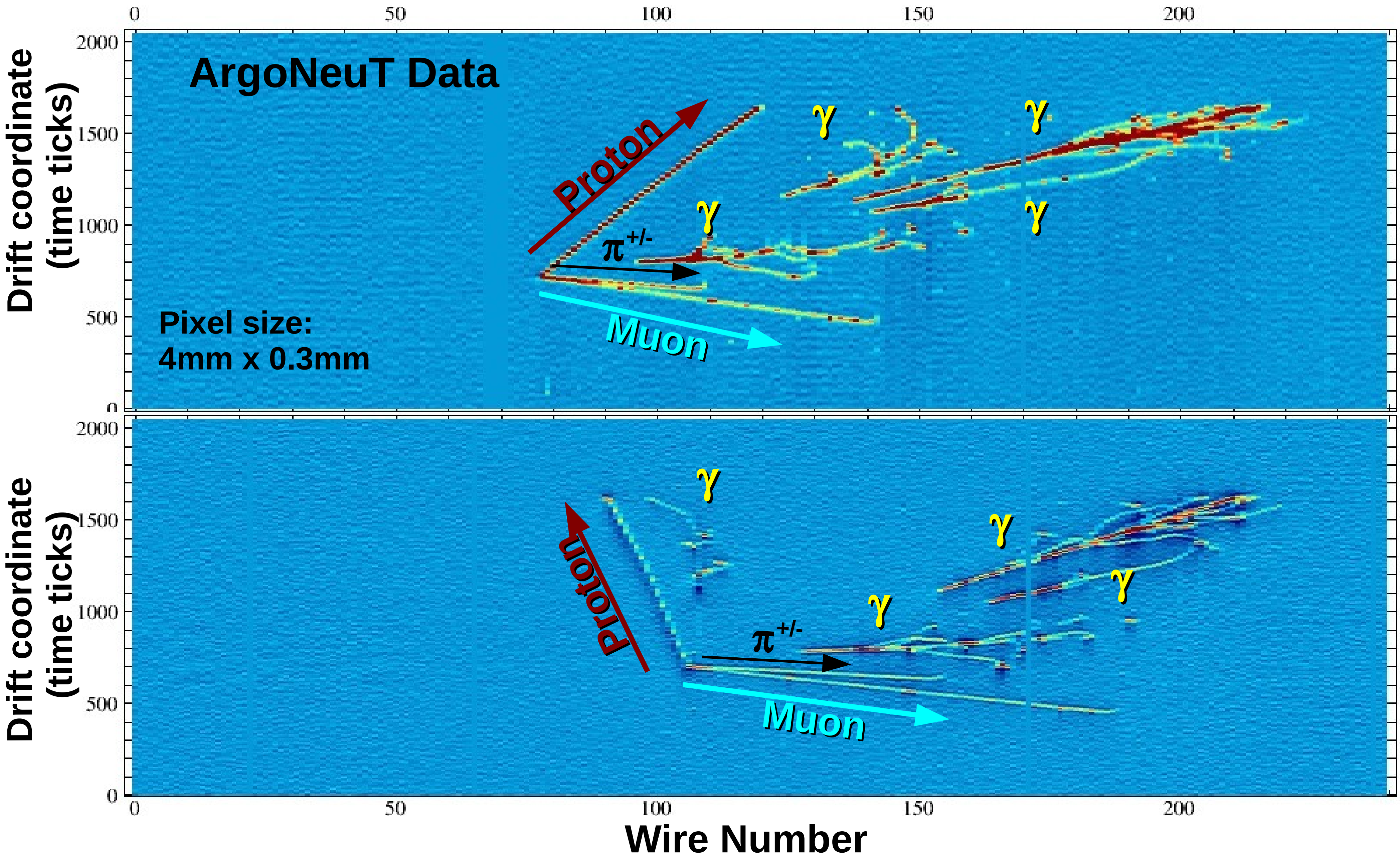


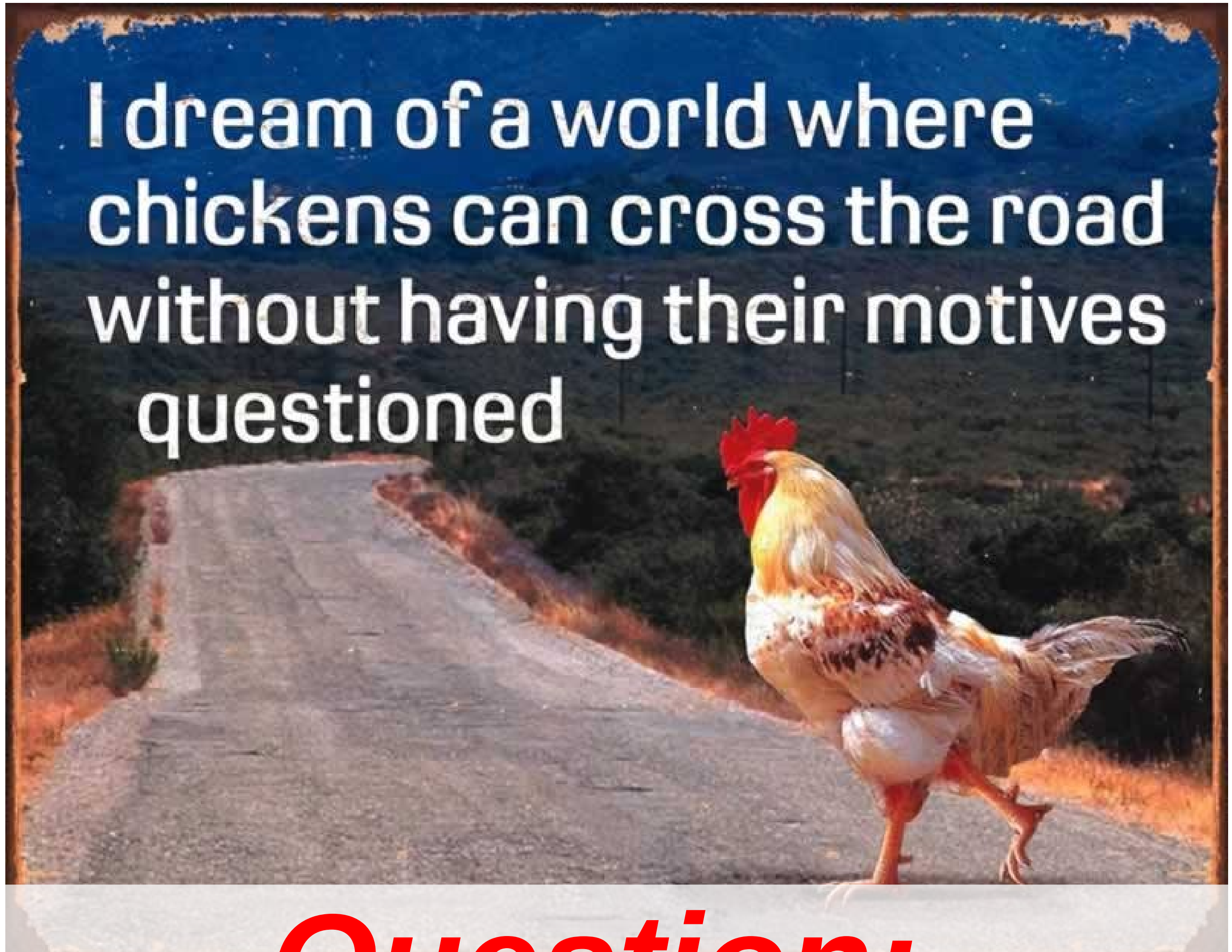


By analyzing the energy deposited along the track (dE/dX) as a function of distance along the track (range) you can perform particle identification (PID)

Analyzing the dE/dX for the start of an electromagnetic shower you can identify and separate photons from electrons

Liquid Argon Time Projection Chamber





Question:

Why do you want all this detail with a neutrino interaction?

Neutrino Oscillation Physics

ν_e ν_μ ν_τ

Neutrino Flavor States

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

ν_μ ν_e

This means I can start with one type of neutrino

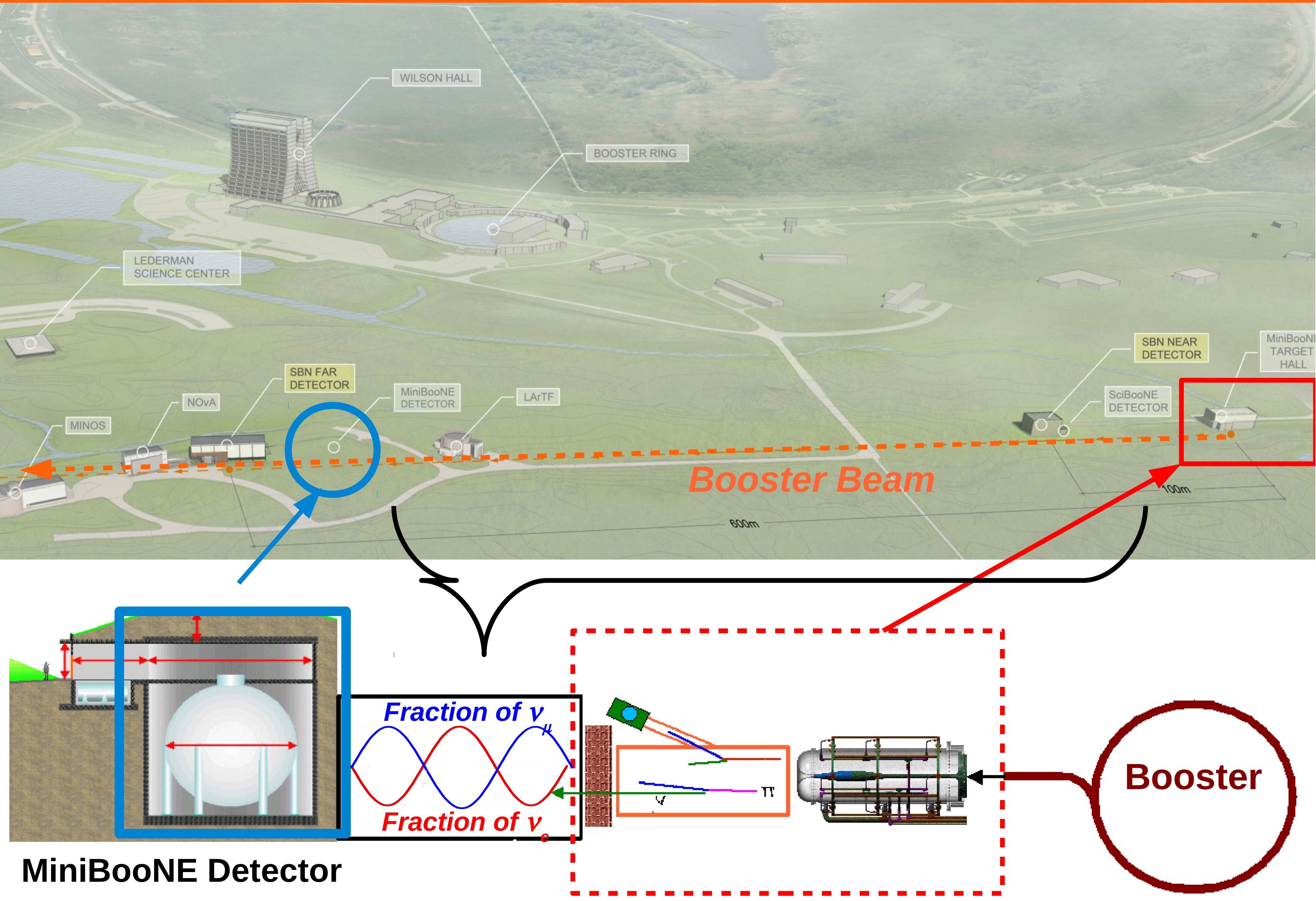
Let it travel some distance

And it will have changed its type

ν_1 ν_2 ν_3

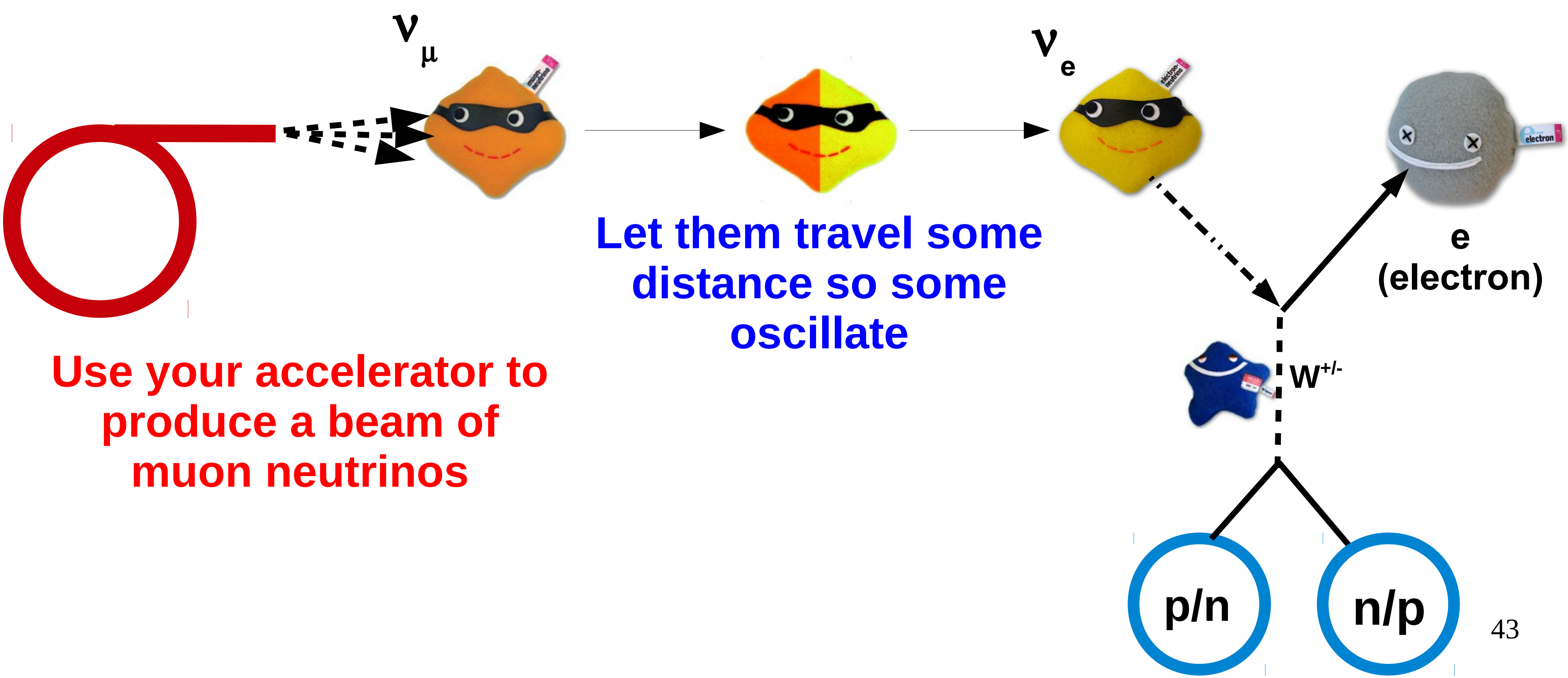
Neutrino Mass States

MiniBooNE


WILSON HALL
BOOSTER RING
LEDERMAN SCIENCE CENTER
SBN FAR DETECTOR
MiniBooNE DETECTOR
LArTF
NOvA
MINOS
SBN NEAR DETECTOR
SciBooNE DETECTOR
Booster Beam
100m
600m
Fraction of ν_μ
Fraction of ν_e
π
ν
Booster
MiniBooNE Detector

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

Look for the appearance of the other type of electron neutrinos

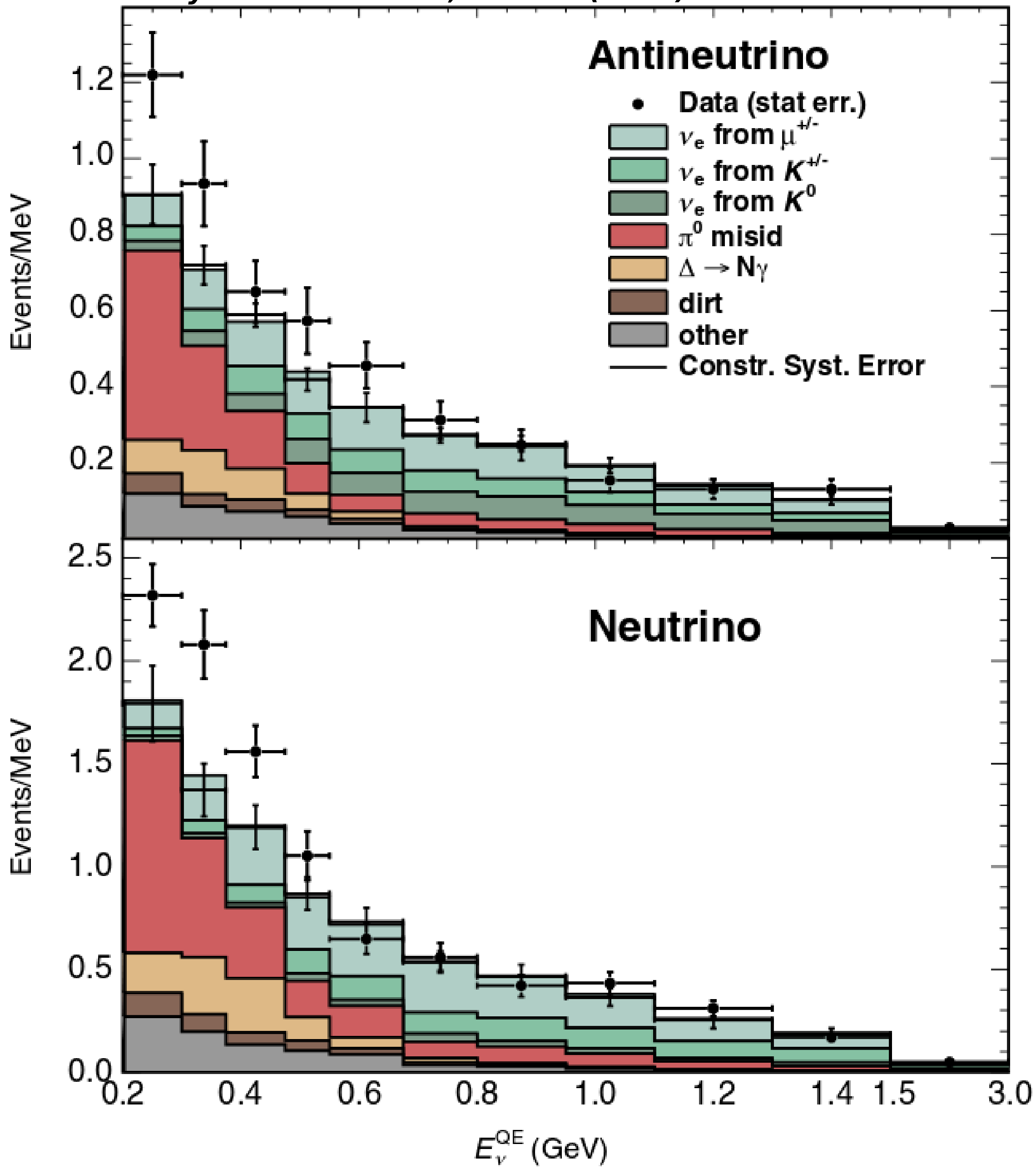


Let them travel some distance so some oscillate

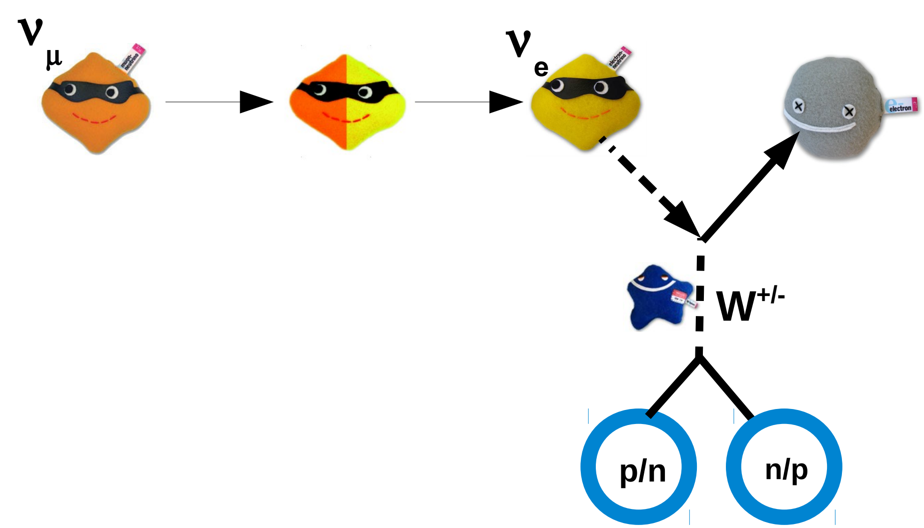
Use your accelerator to produce a beam of muon neutrinos

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 ???

What if there are more types of ν's

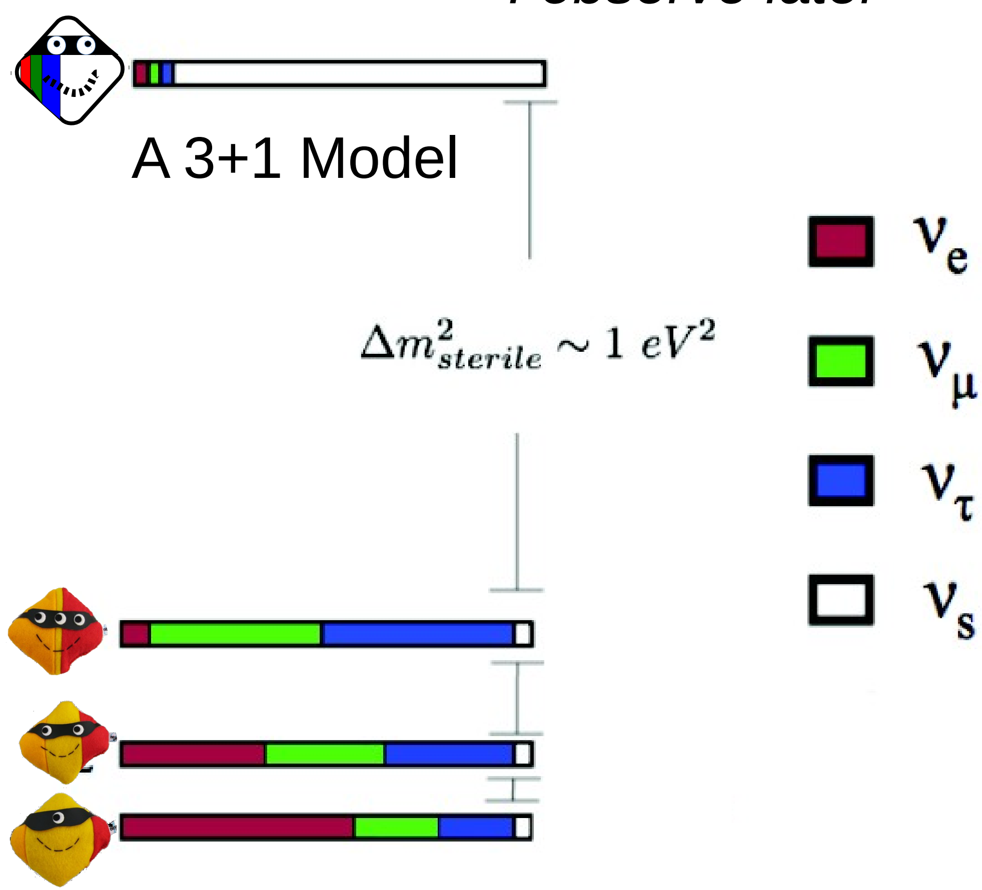
If I start with muon type neutrinos

There are 3+n ways it can oscillate

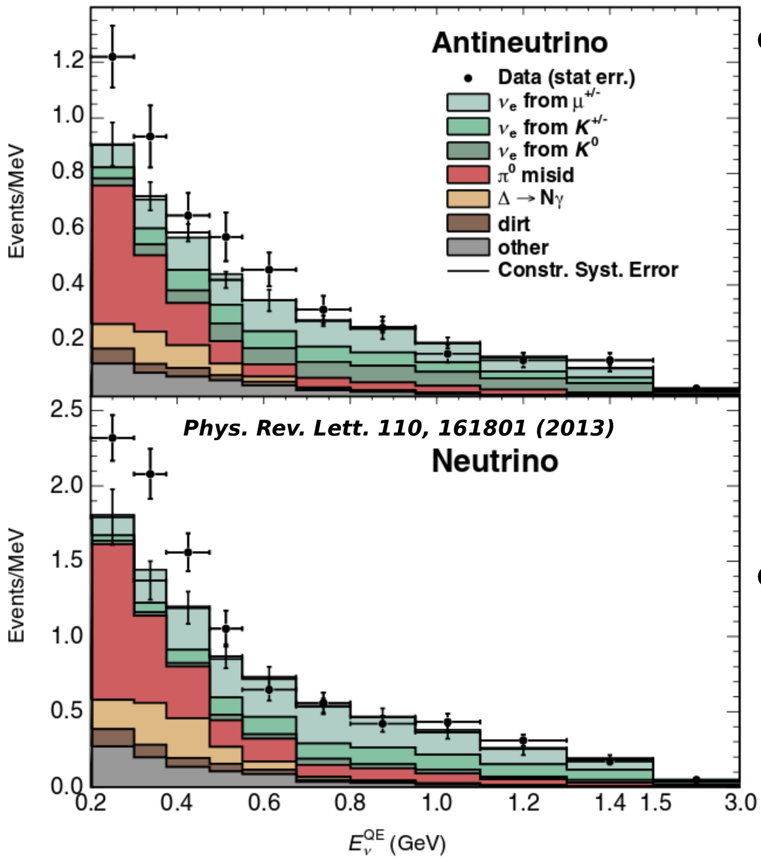
And this will __enhance__ the amount of electron neutrinos I observe later

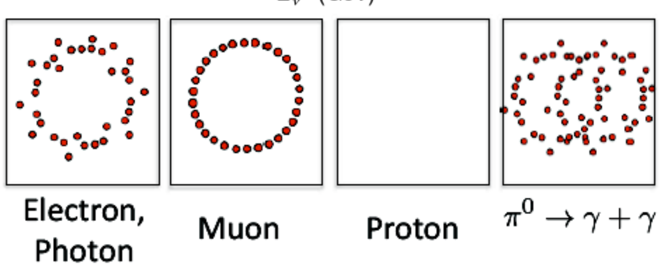
This would imply there are new particles

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



Hints of new physics?

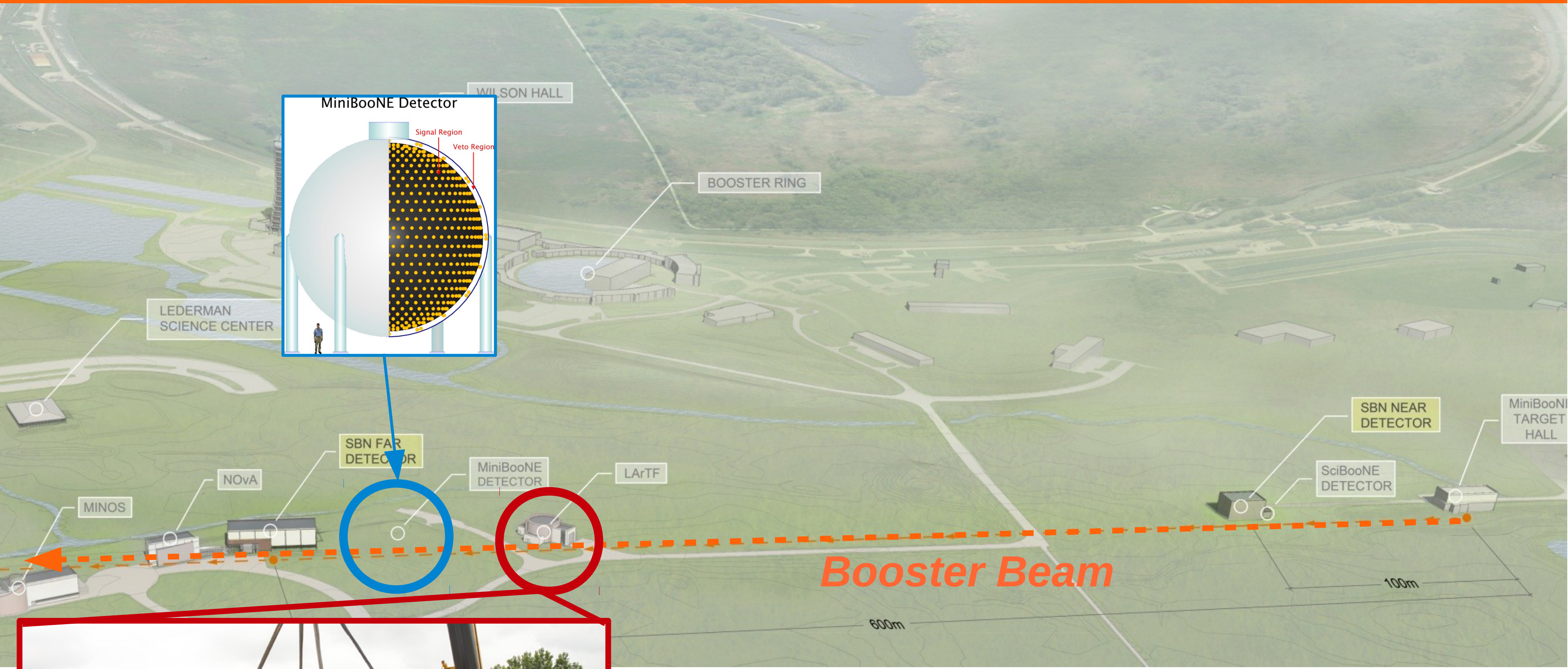




- **MiniBooNE sees a low energy excess in $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ appearance search**
  - Excess can also be interpreted as an additional mixing
- **However, MiniBooNE (Cherenkov detector) has a difficult time determining the composition of the excess**
  - **Electron like?**
  - **Photon like?**

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

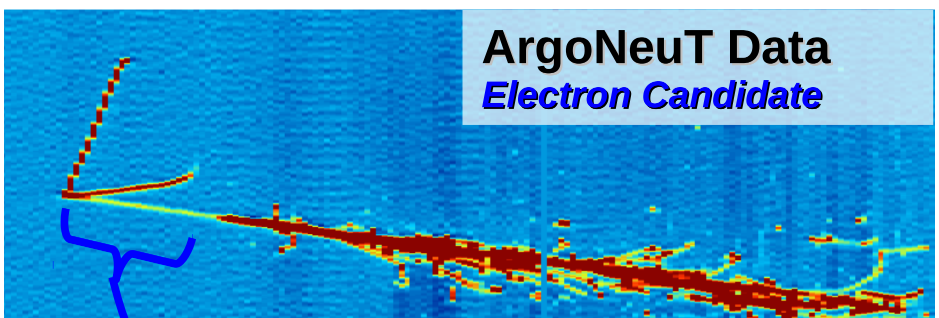
MicroBooNE

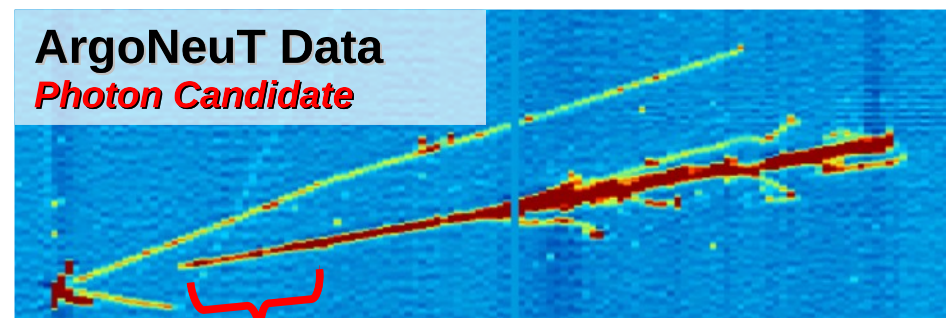


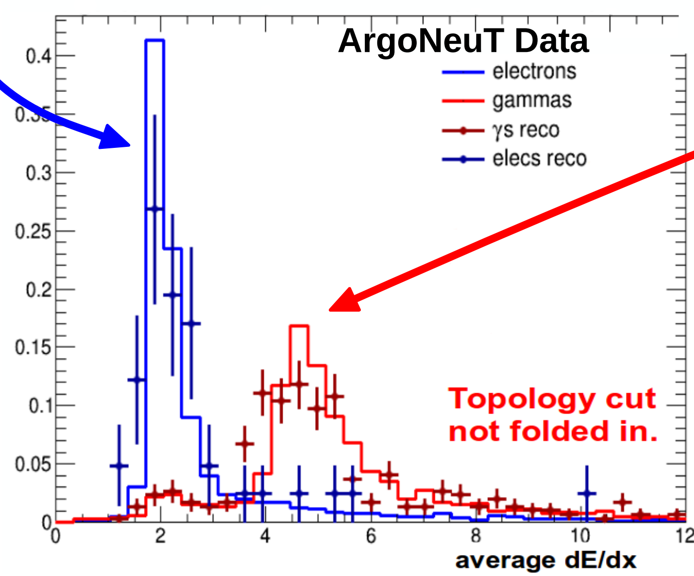
MicroBooNE is the first LArTPC detector on the short-baseline and kicks off the SBN program

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)*

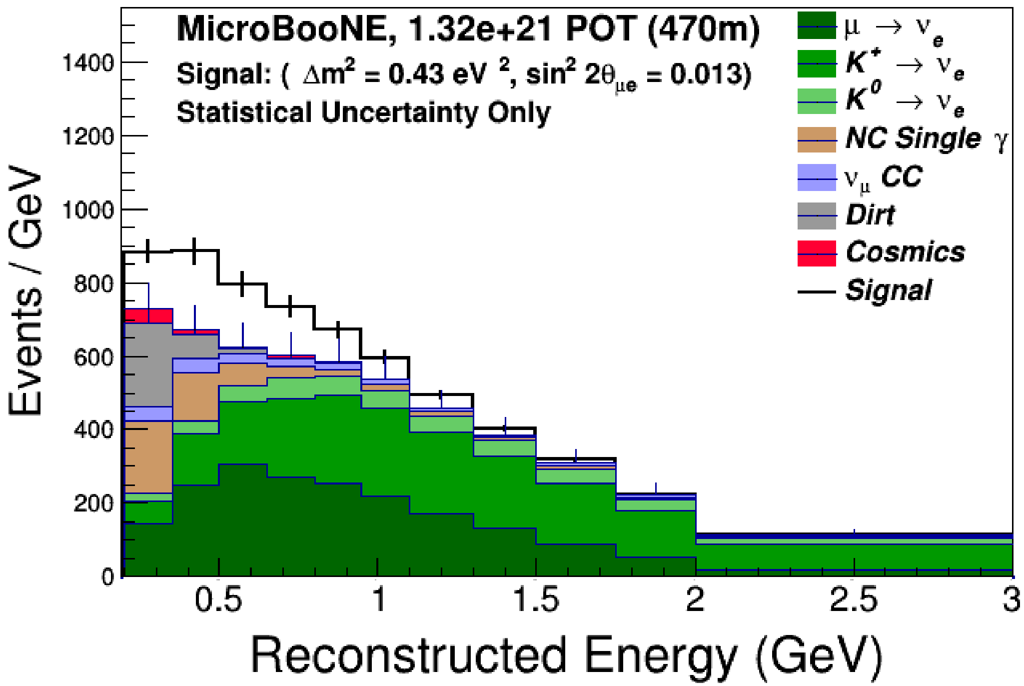






By analyzing the topology and the dE/dX of the electromagnetic shower, disentangling the MiniBooNE low energy excess becomes possible

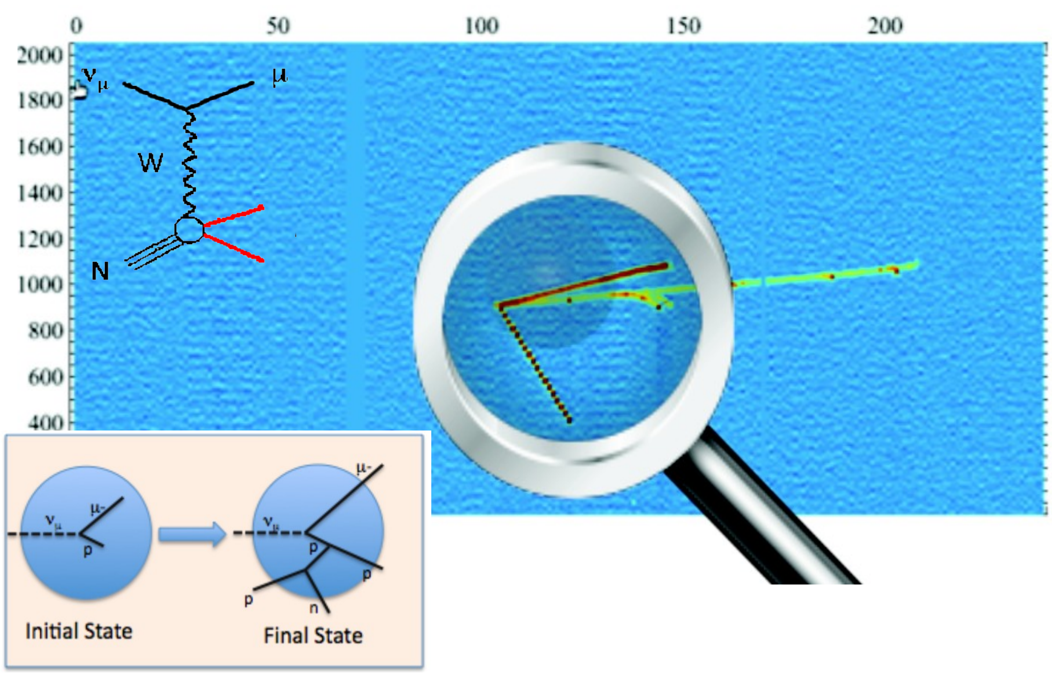
MicroBooNE



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

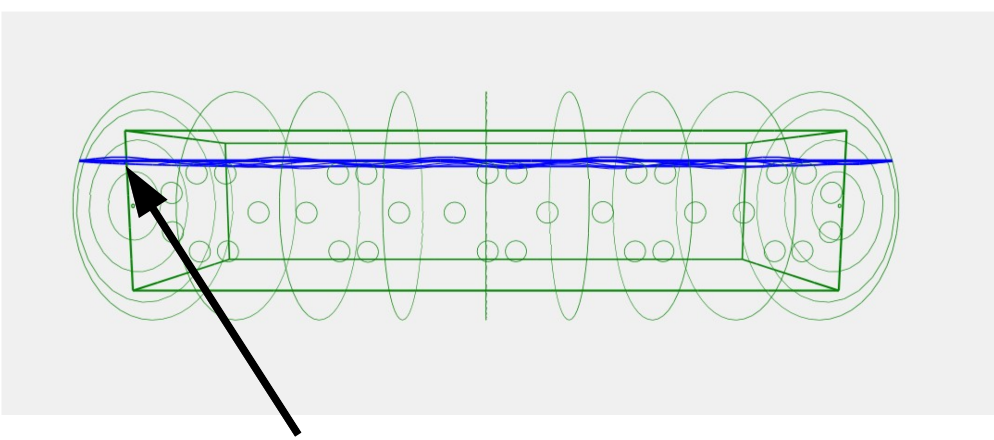
about this big

- **MicroBooNE also has a rich physics program planned**
  - Determining the nature of the MiniBooNE low energy excess
  - Neutrino cross-sections
  - Studying nuclear final state interactions
  - Exploring the capabilities for LArTPC to look at astroparticle and exotic phenomenon



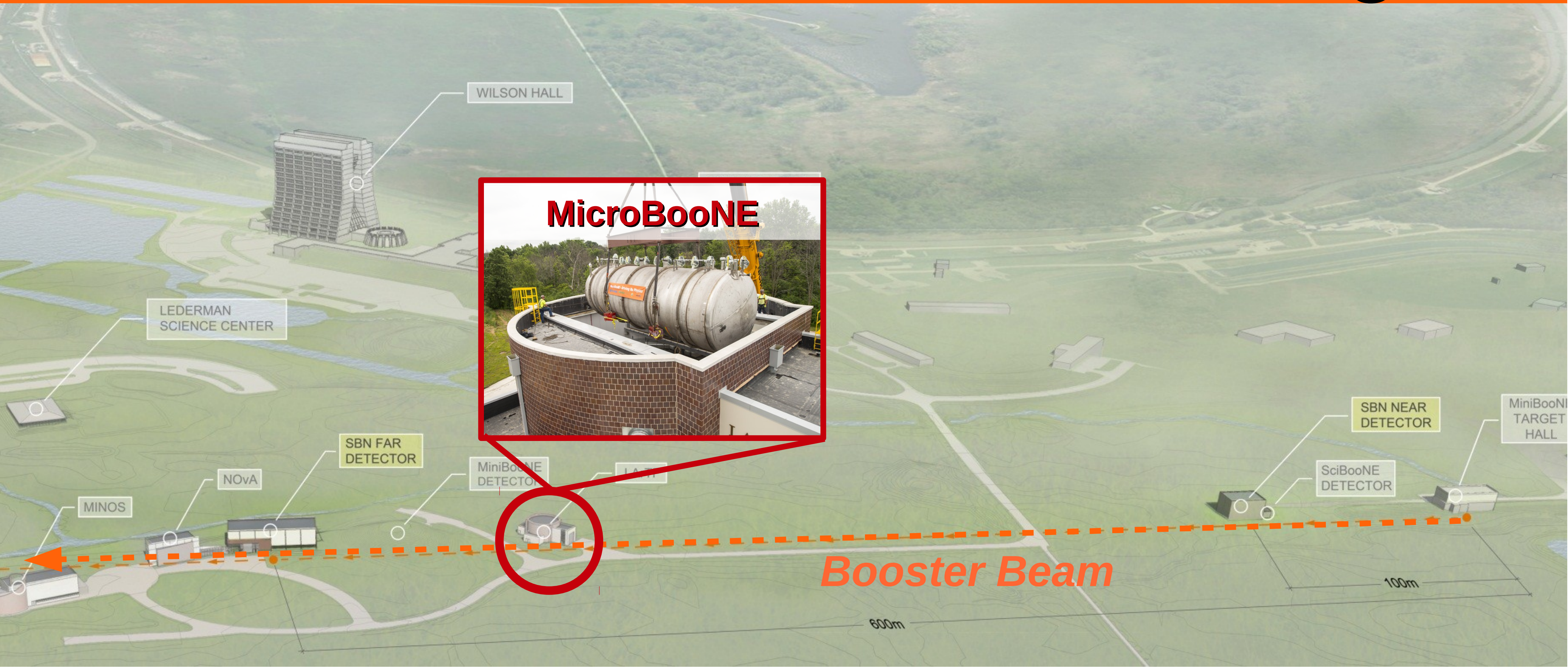
MicroBooNE is about to enter the era of being a world class neutrino experiment and start the era of the LArTPC short baseline neutrino program

We turn on for the first time this month!!!!!



Current LAr Level in the cryostat

The Short-Baseline Neutrino Program



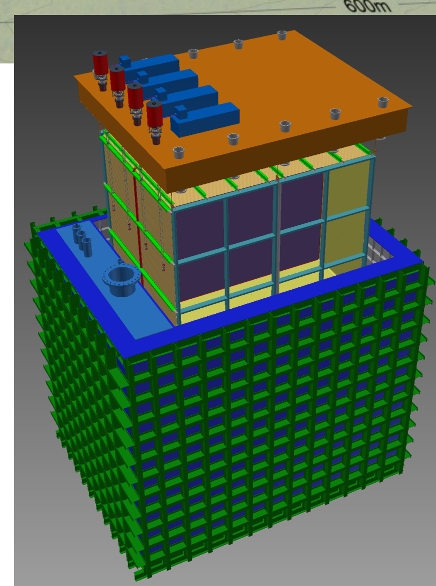
What do I need to add to the existing program (top notch neutrino beam + world class neutrino detectors) to make a definitive search eV scale for sterile neutrinos?

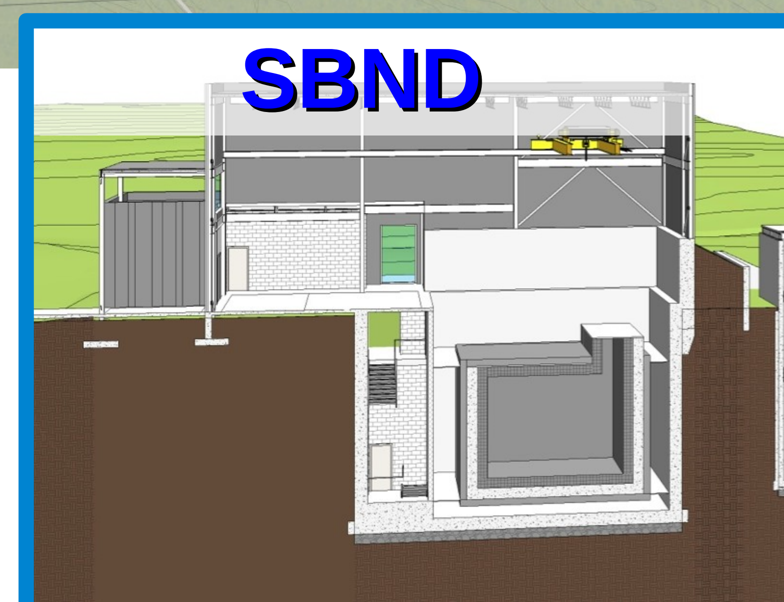
→ Normalization of the unoscillated neutrino beam **(Near detector)**
→ High statistics in the appearance channel **(large mass far detector)**
→ Look for complimentary muon disappearance **(near/far comparison)**

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

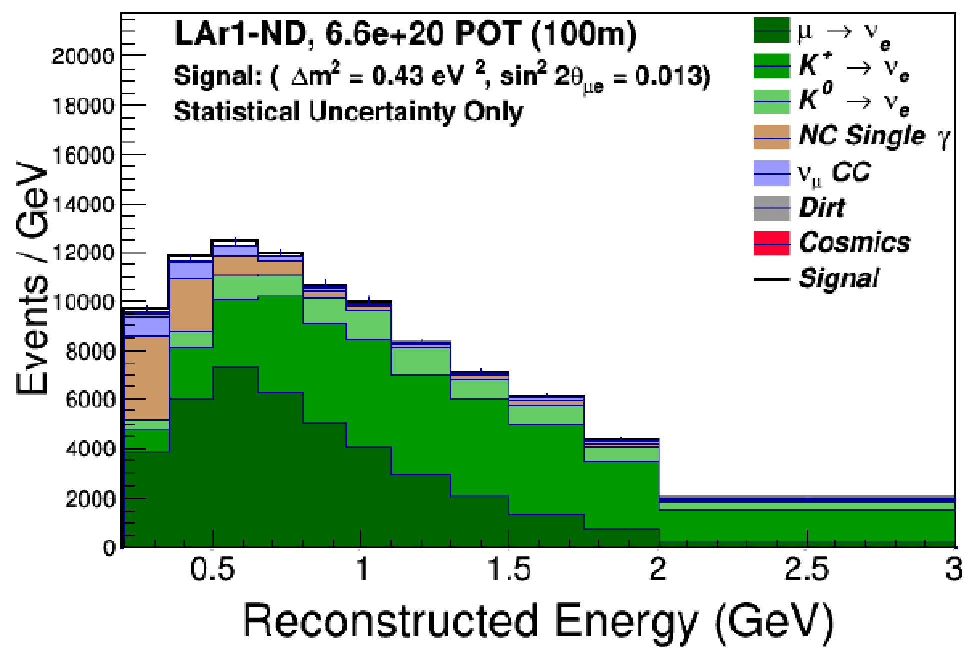




Short Baseline Near Detector (SBND)

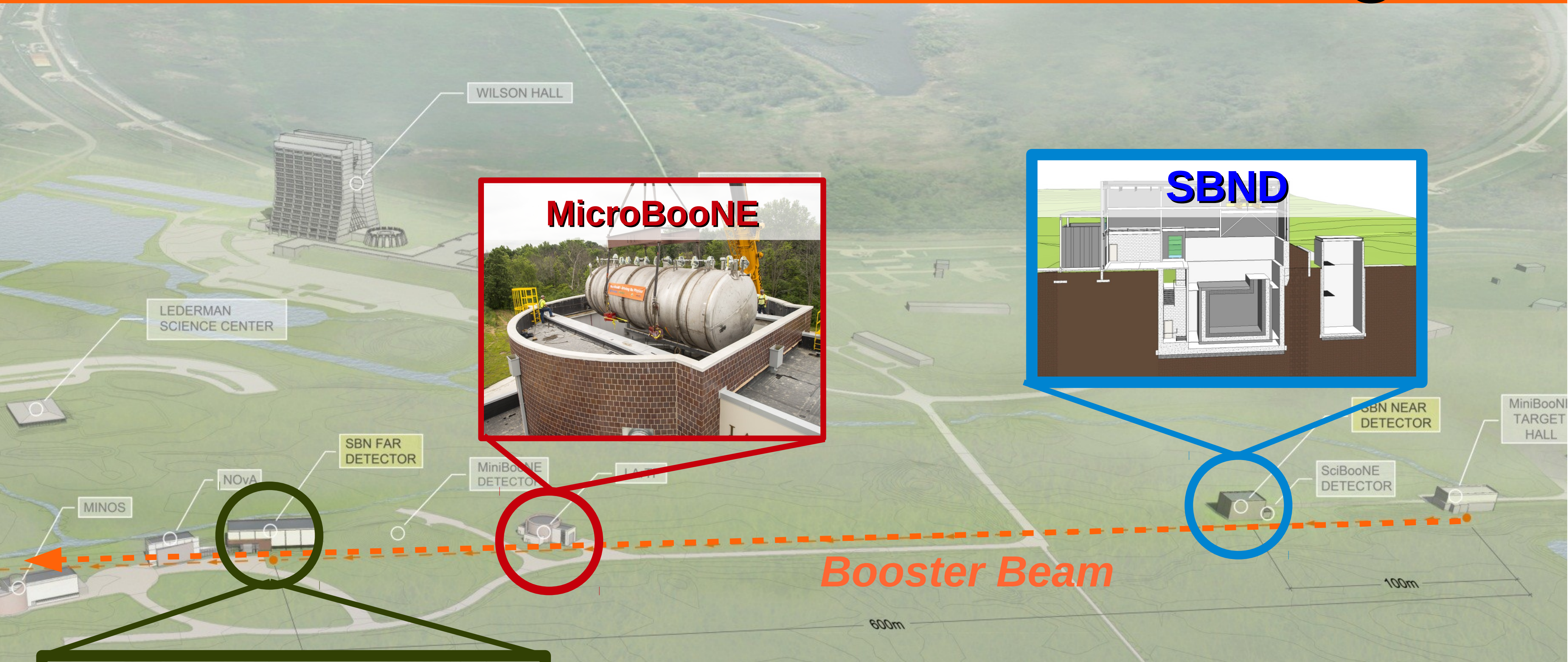
Process		No. Events
	ν_μ *Events (By Final State Topology)*	
CC Inclusive		5,212,690
CC 0 π	$\nu_\mu N \rightarrow \mu + Np$	3,551,830
	$\cdot\ \nu_\mu N \rightarrow \mu + 0p$	793,153
	$\cdot\ \nu_\mu N \rightarrow \mu + 1p$	2,027,830
	$\cdot\ \nu_\mu N \rightarrow \mu + 2p$	359,496
	$\cdot\ \nu_\mu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

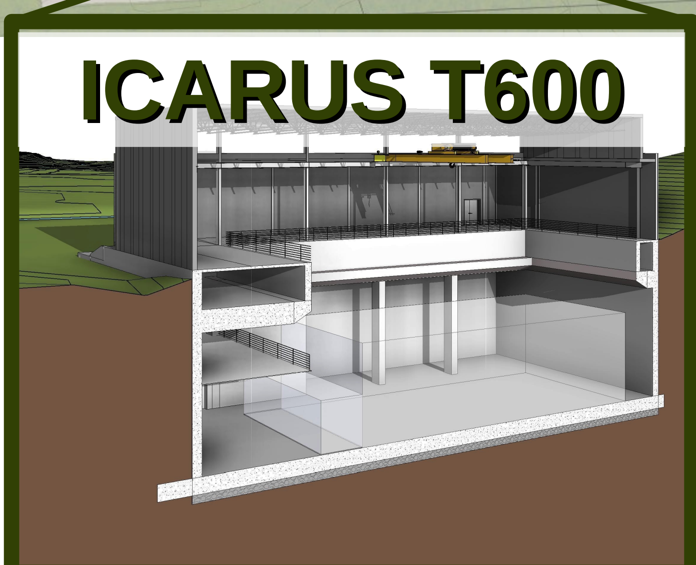
- **SBND will collect millions of neutrino interactions**
  - High statistics, precision neutrino cross-sections measurements



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

The Short-Baseline Neutrino Program

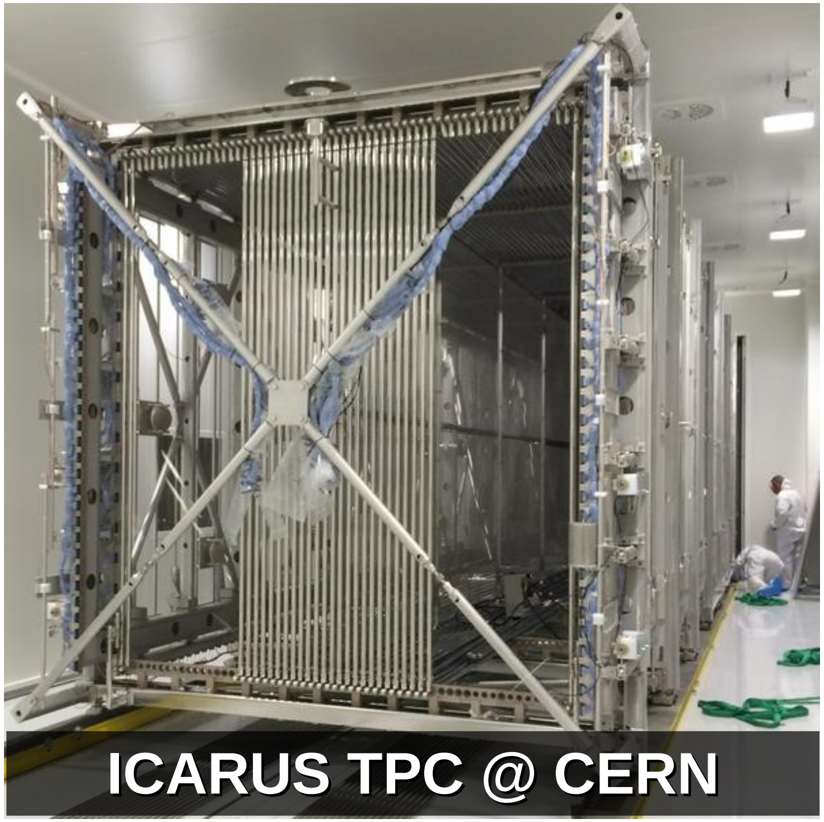




The ICARUS detector is the largest LArTPC ever built

- Adding the large mass allows for precision oscillation search

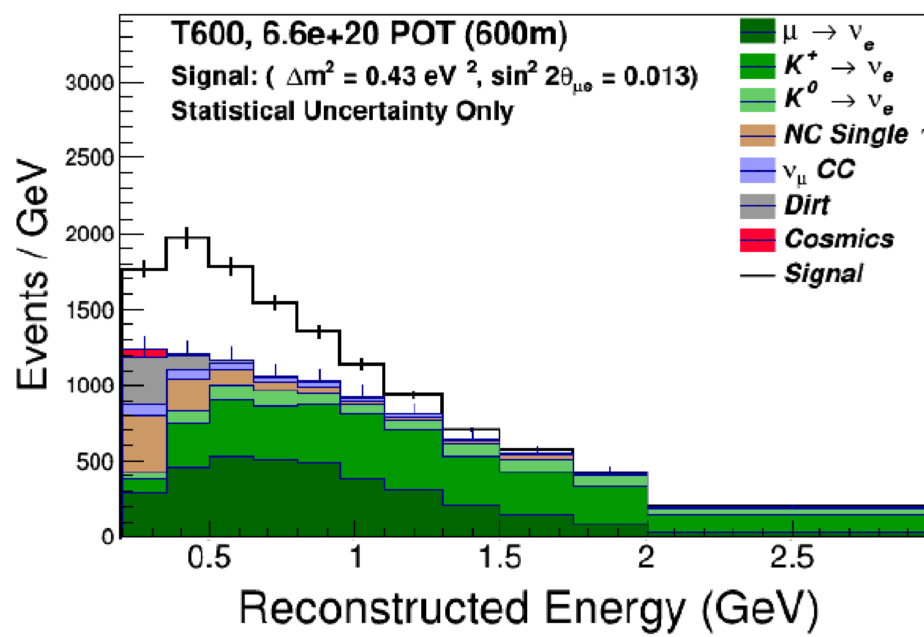
ICARUS T600



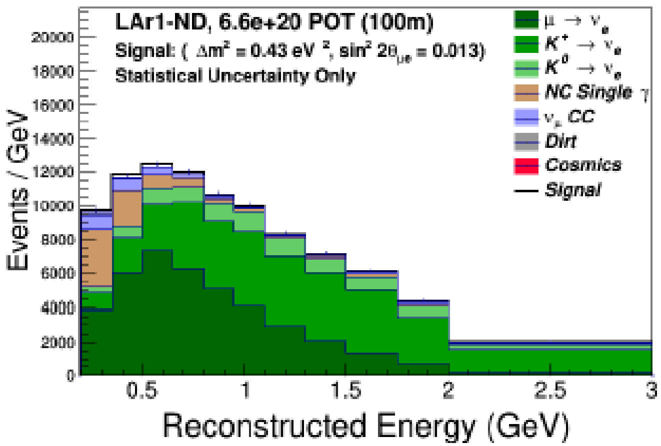
ICARUS TPC @ CERN

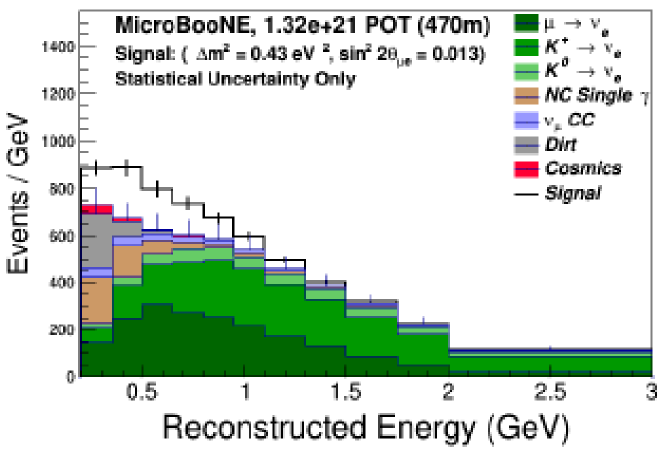
- **The ICARUS detector is at CERN for refurbishment before it is shipped to Fermilab**
  - The first module is expected to be finished in 2015
- **This large mass detector will provide increased sensitivity to the electron neutrino appearance search**

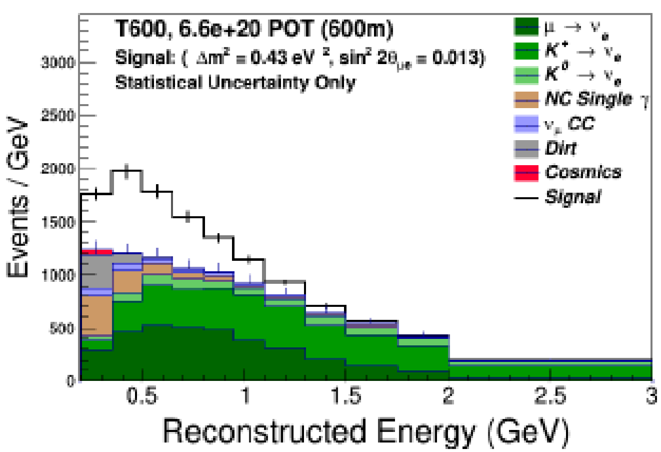
Far Detector Building Design



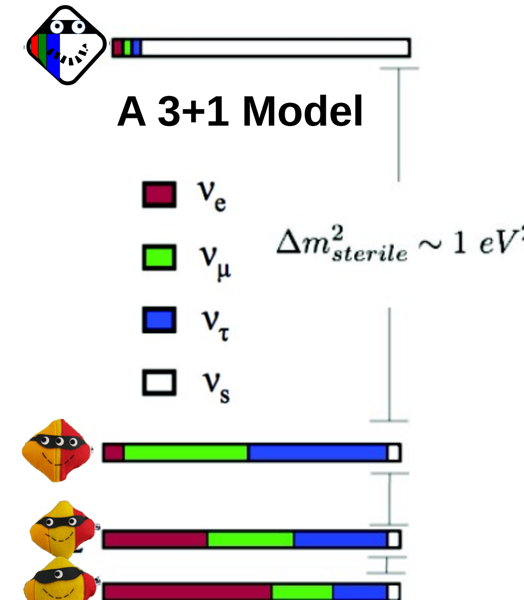
The SBN Program

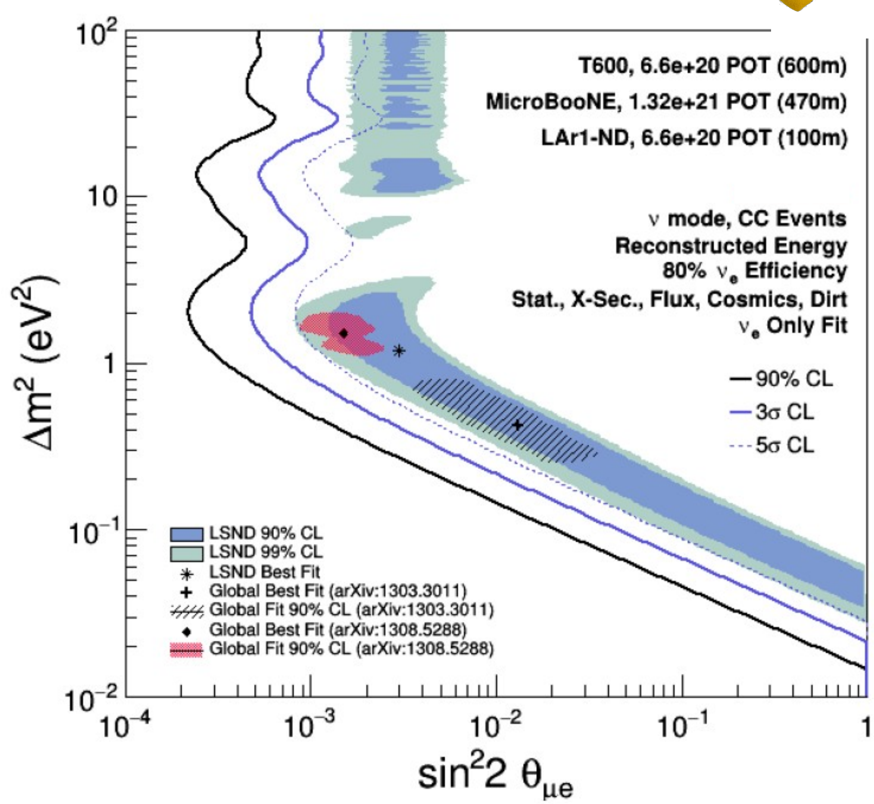




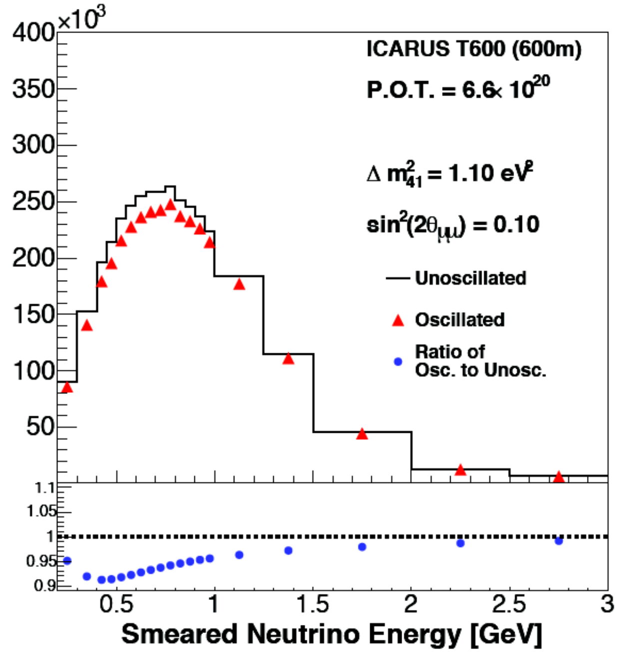


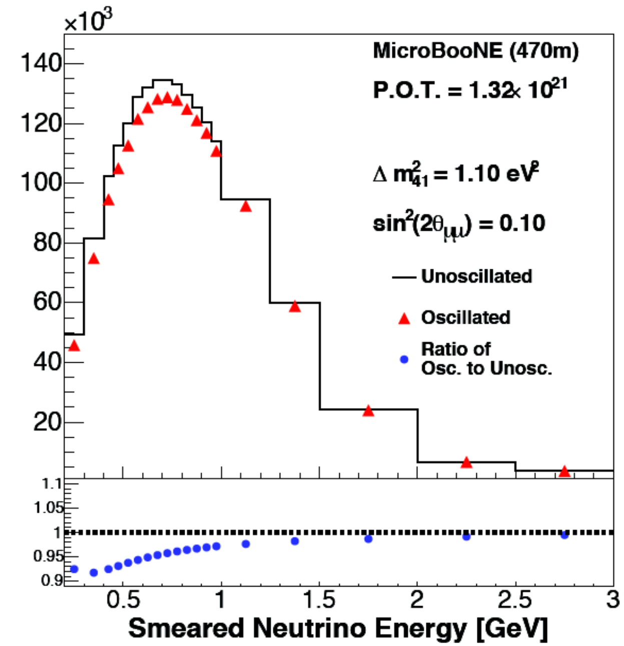
Utilizing three similar detectors at three different distances along the same neutrino beam allows for a test of the allowed sterile neutrino parameter space

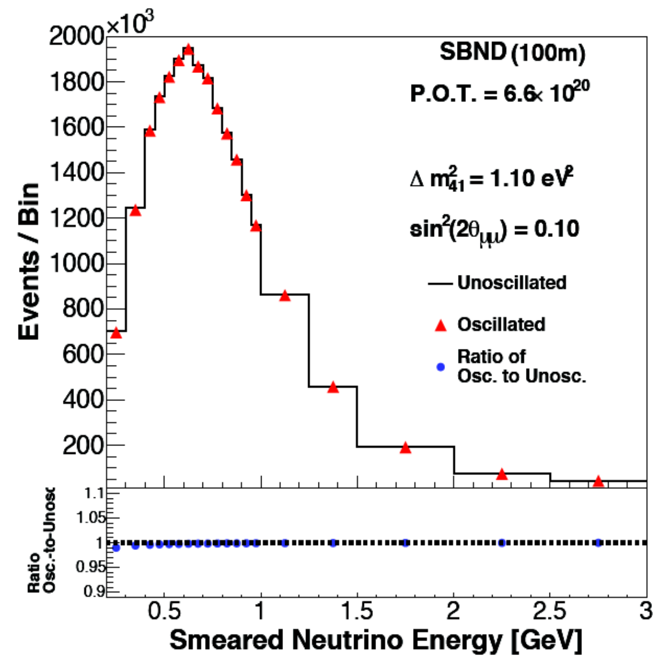




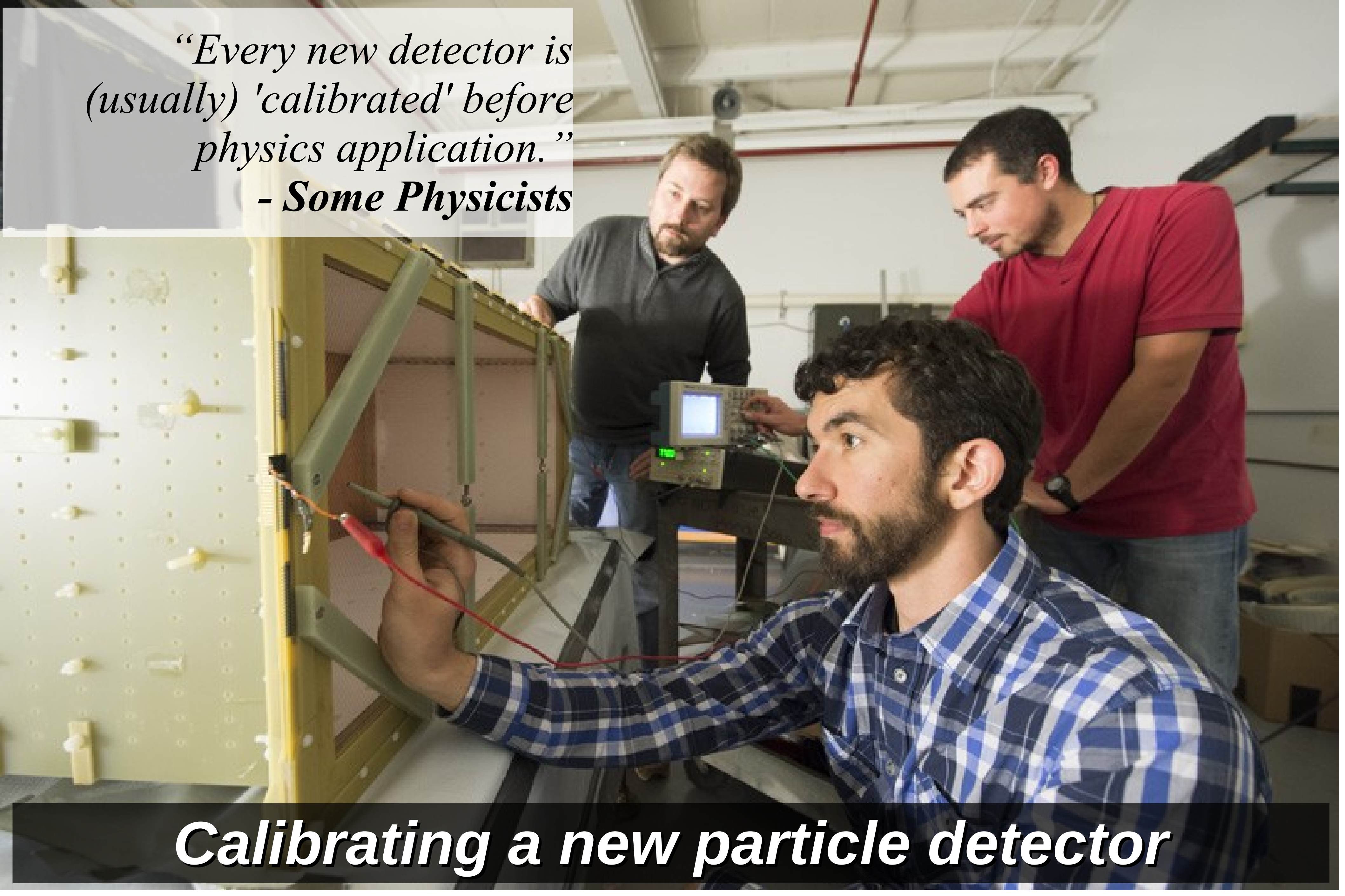
The SBN Program







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



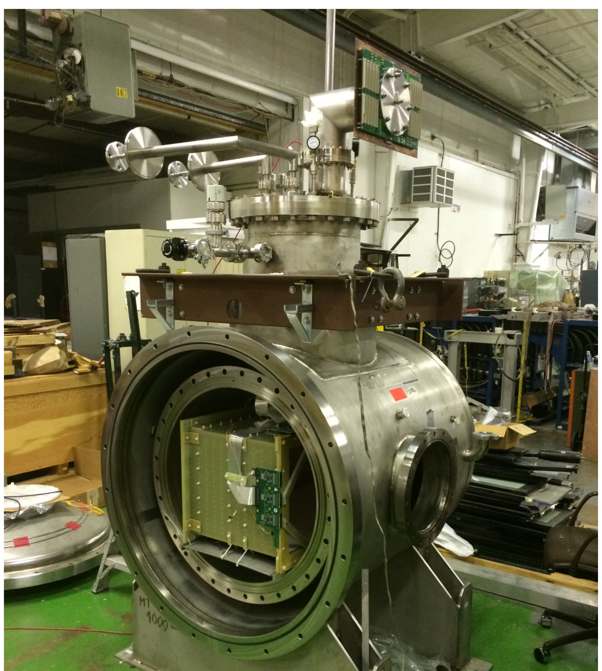
“Every new detector is (usually) 'calibrated' before physics application.”
- Some Physicists

Calibrating a new particle detector

LArIAT: Liquid Argon In A Testbeam

LArIAT:
Liquid Argon In A Testbeam

- ***The ArgoNeuT detector gets a second life!***
  - Better understanding the response of LArTPC's can be best accomplished by placing these detectors in front of a test beam



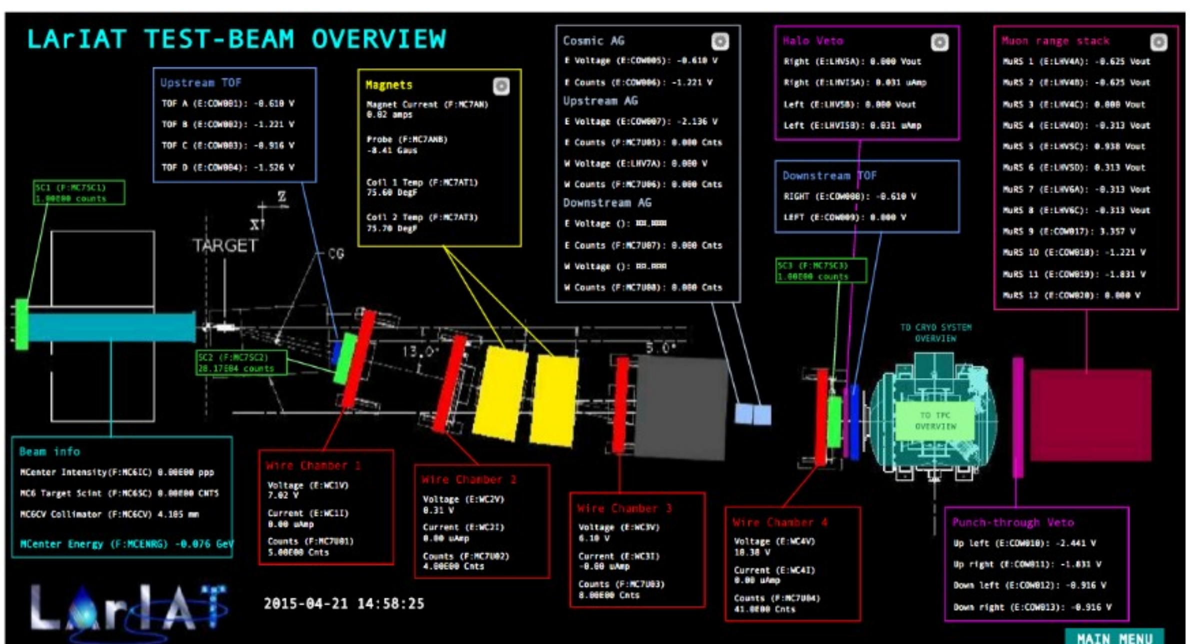
Refurbished TPC and Electronics

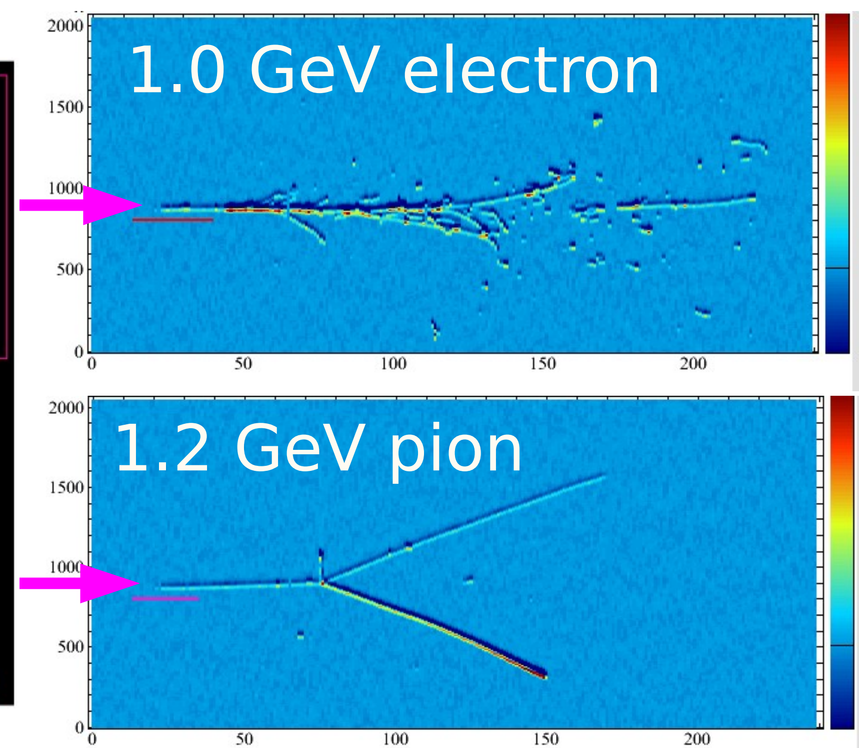
LArIAT TPC being put into the beam line

The LArIAT Testbeam

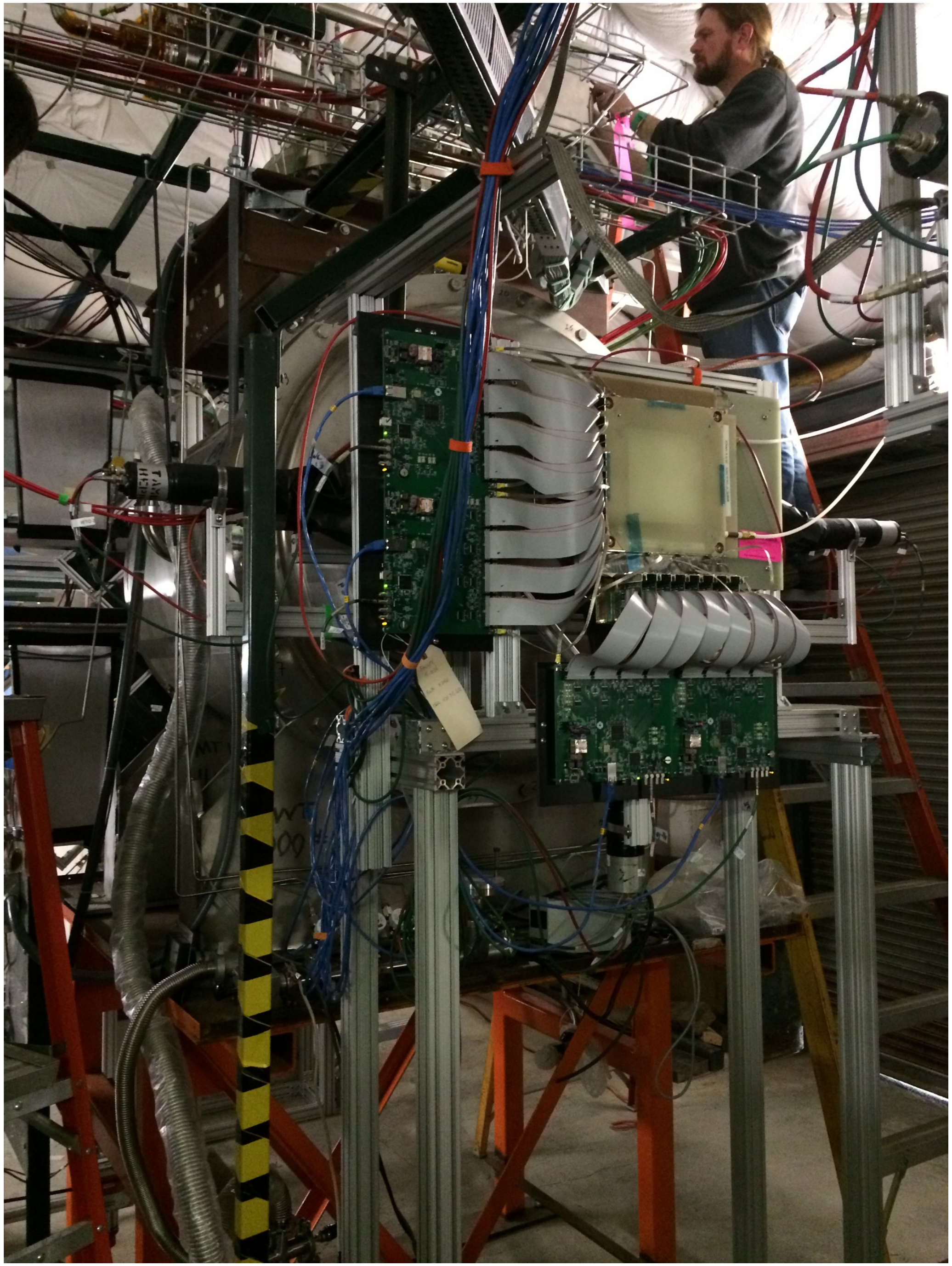
LArIAT

- **Neutrino events are <u>inherently</u> ambiguous**
  – Better to measure Liquid Argon properties in a controlled environment
- **Test beam allows control of initial conditions:**
  – Momentum measurement
  – Particle type identification

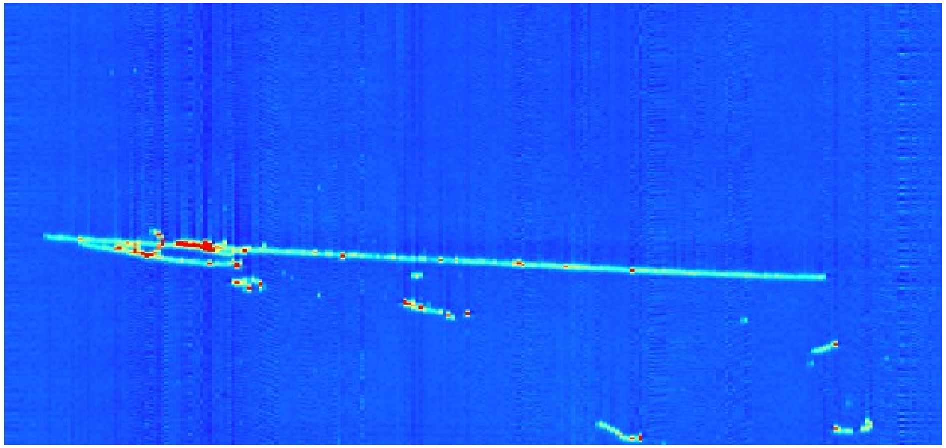




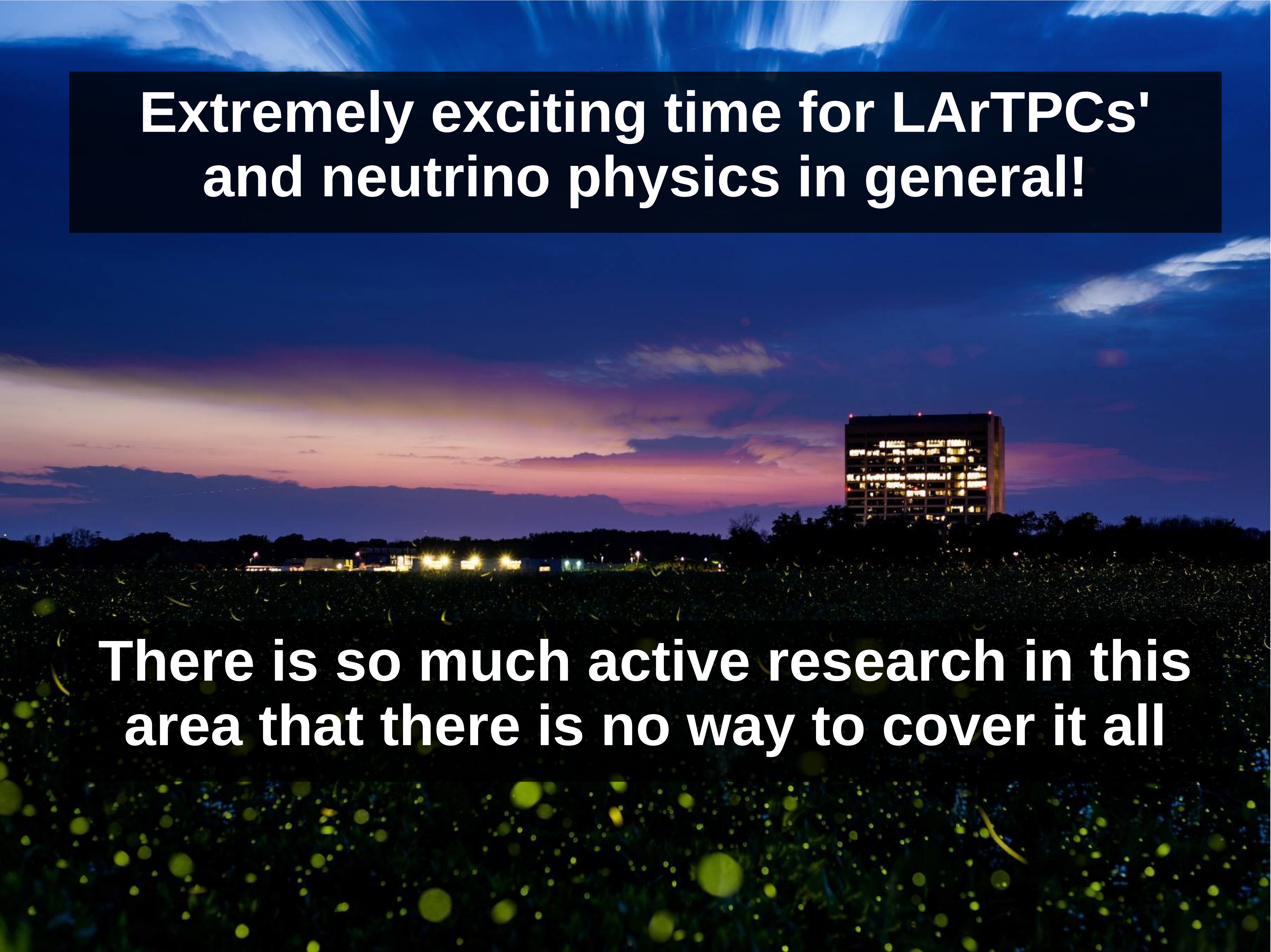
LArIAT



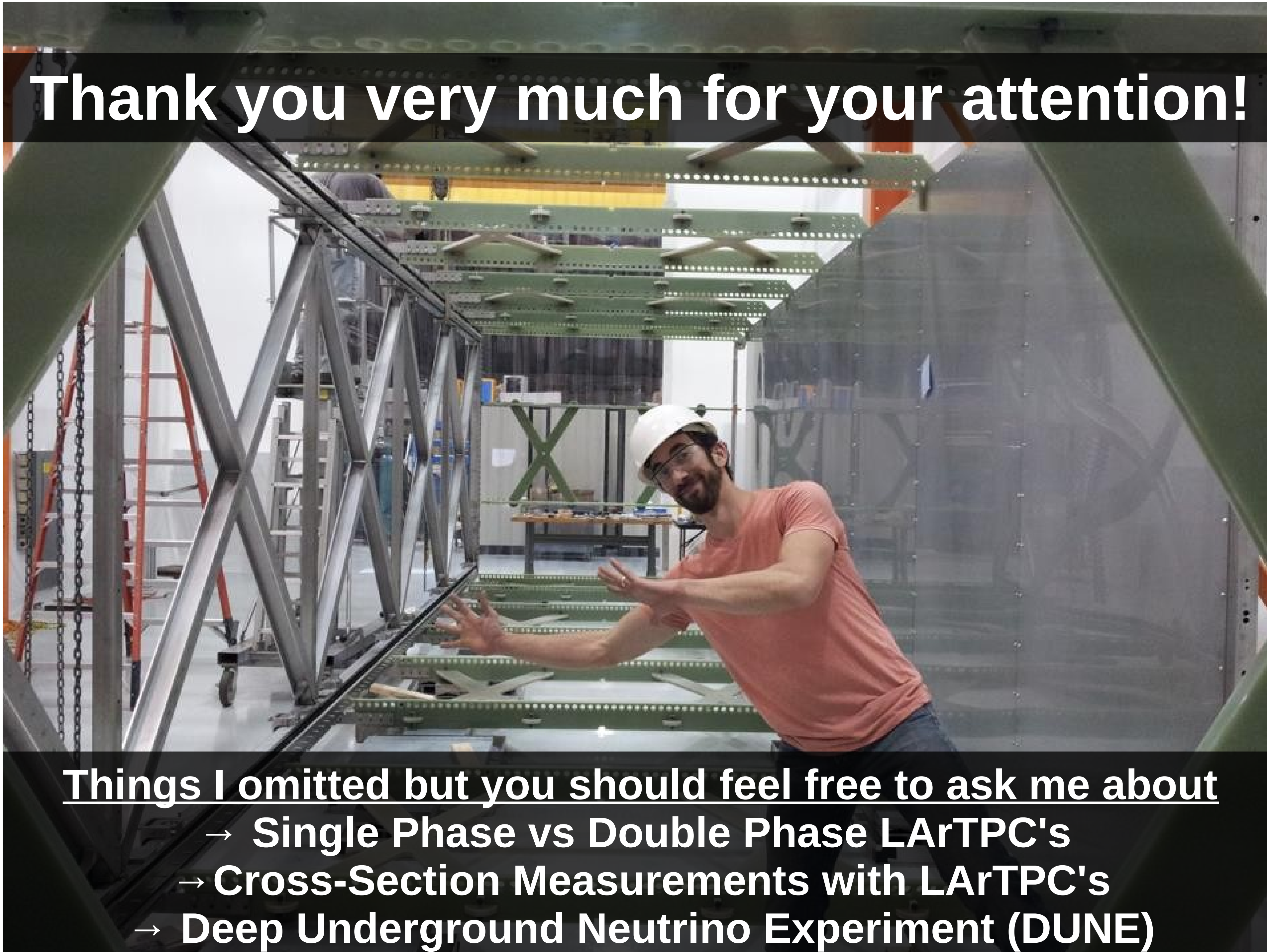
LArIAT is finishing its first physics run



We expect to new physics results from test-beam data very soon!


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!



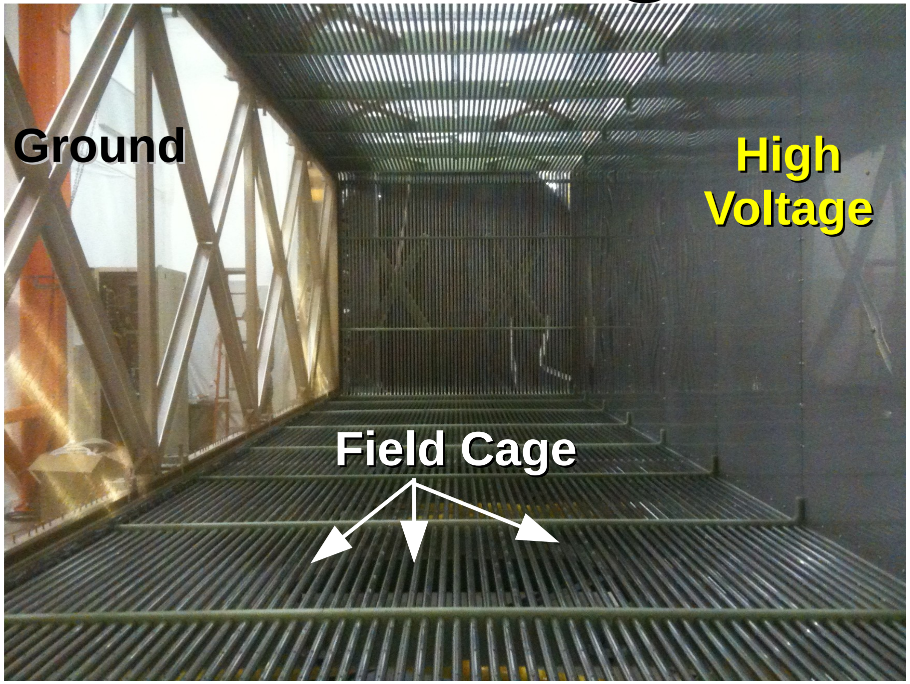
Things I omitted but you should feel free to ask me about

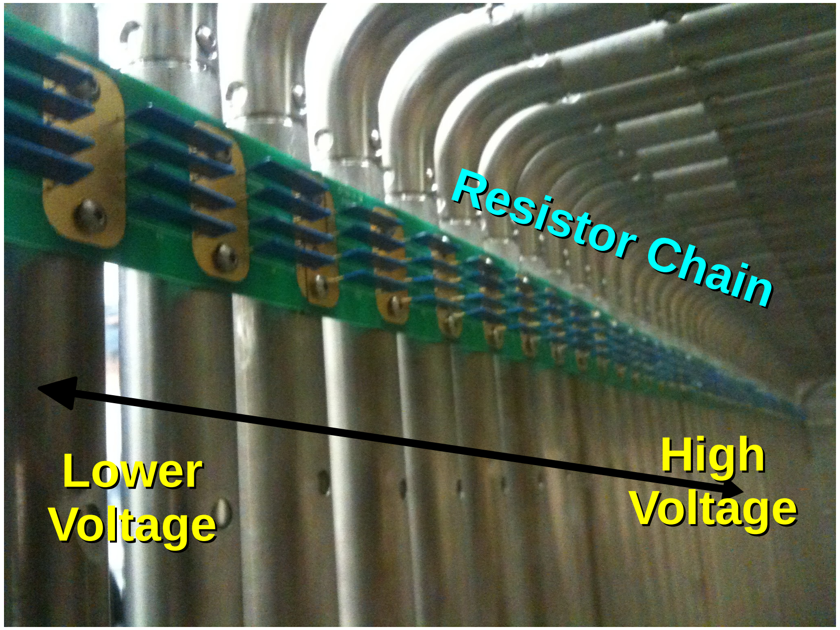
→ **Single Phase vs Double Phase LArTPC's**

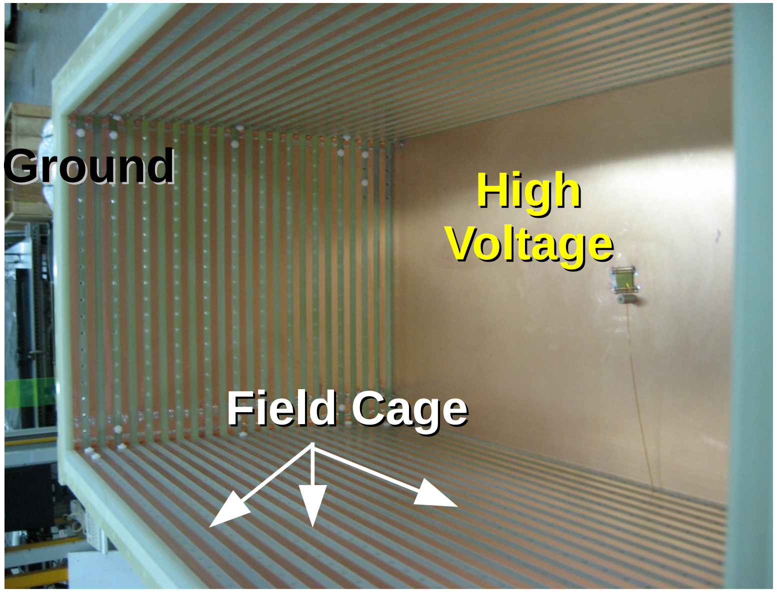
→ **Cross-Section Measurements with LArTPC's**

→ **Deep Underground Neutrino Experiment (DUNE)**

High Voltage in LAr







To achieve a very uniform electric field we construct field cages.

They start with very uniform cathode planes and evenly spaced conductors that “step down” the voltage and create a uniform electric field

One of the reasons Liquid Argon detectors are so attractive is that the argon has **very good dielectric properties for high voltages**

However, recent studies have began to uncover that the electric breakdown properties of LAr **aren't as well understood** as previously thought

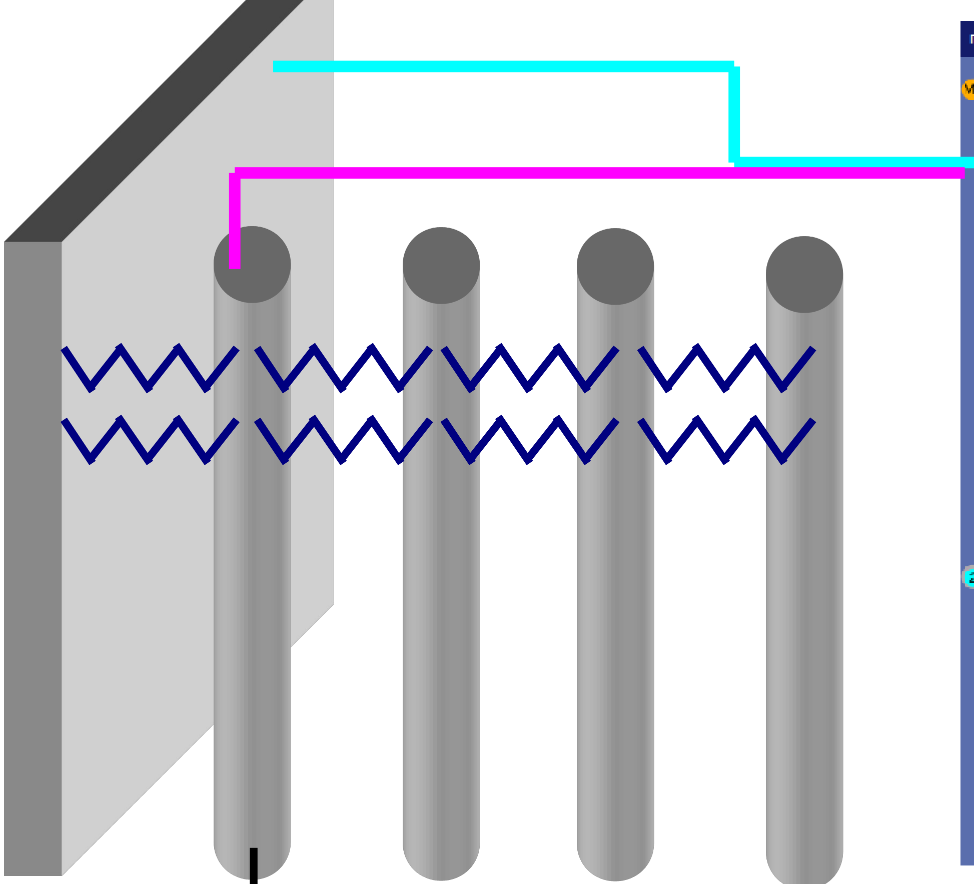
A. Rubbia / Nuclear Physics B Proceedings Supplement 00 (2013) 1–9 2

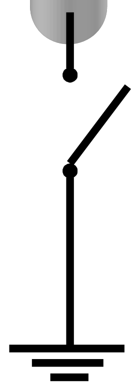
Atomic number	18
Molecular weight	39.948 g/mol
Natural concentration	0.934% of air
Melting point	83.4K at 1 atm
Boiling point	87.3K at 1 atm
Triple point	83.8K at 0.687 bar
Liquid density (at 83.7K)	1392.8 kg/m^3
Latent heat (1 atm)	160.81 kJ/kg
Dielectric constant	1.5
Electric breakdown	1.1–1.4 MV/cm
dE/dx for m.i.p.	2.12 MeV/cm
Ionisation energy W_e ($E = \infty$)	23.6 eV
Excitation energy W_γ ($E = 0$)	19.5 eV
Radiation length X_0	14 cm
γ pair production length $(9/7)X_0$	18 cm
Molière radius	9.28 cm
Nuclear interaction length λ_{int}	84 cm
Critical energy	30 MeV

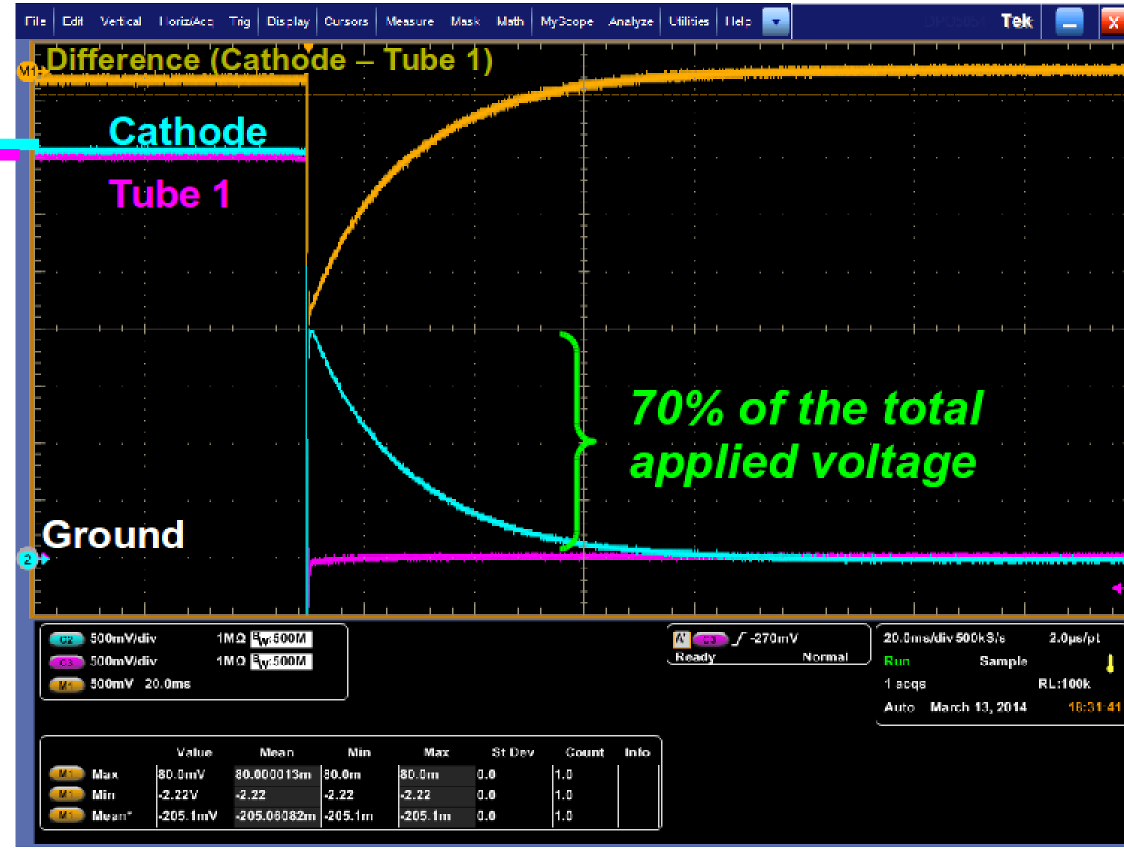
Table 1: Some physical parameters of argon.

In fact, the breakdown voltage of liquid argon may be strongly depend on the **geometry of your setup, the material of your conductor, the purity of your argon, and more....**

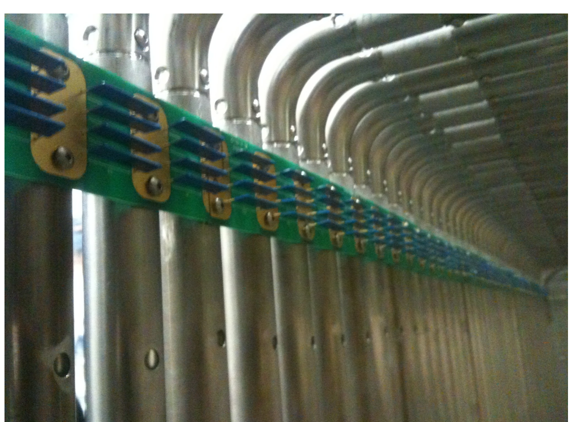
This creates the possibility for key components of your detector to see larger voltages than they are rated for during electric breakdown

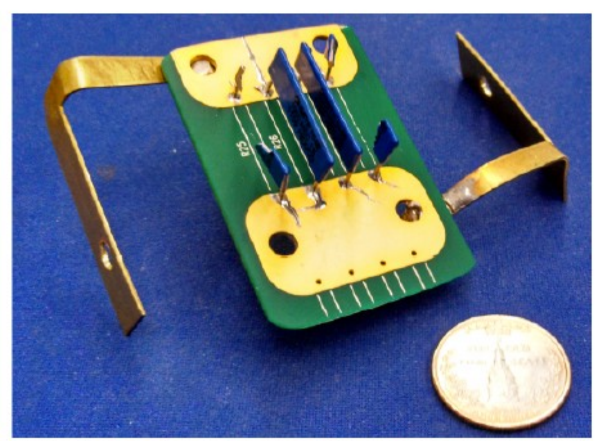






Studies done on a field cage confirm the risk during an unexpected discharge to ground





Solution: Surge Protection

Testing of high voltage surge protection devices for use in liquid argon TPC detectors

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Show affiliations

J Asaadi *et al* 2014 *JINST* **9** P09002. doi:10.1088/1748-0221/9/09/P09002
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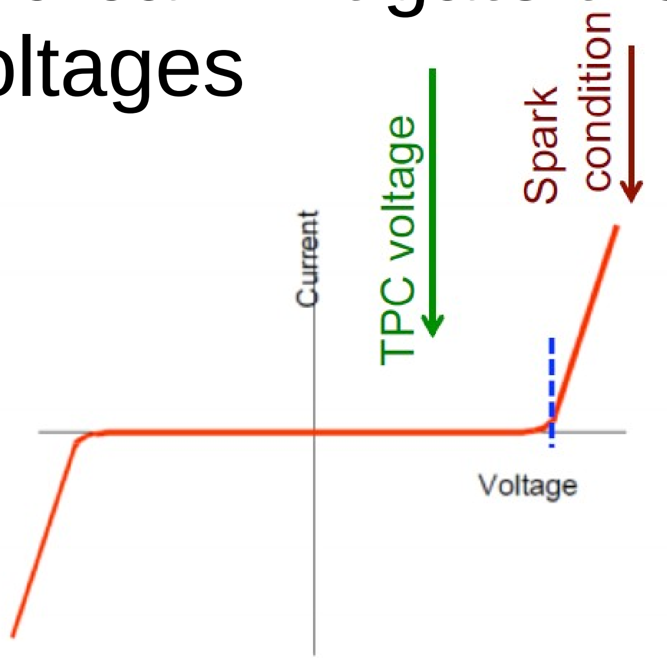
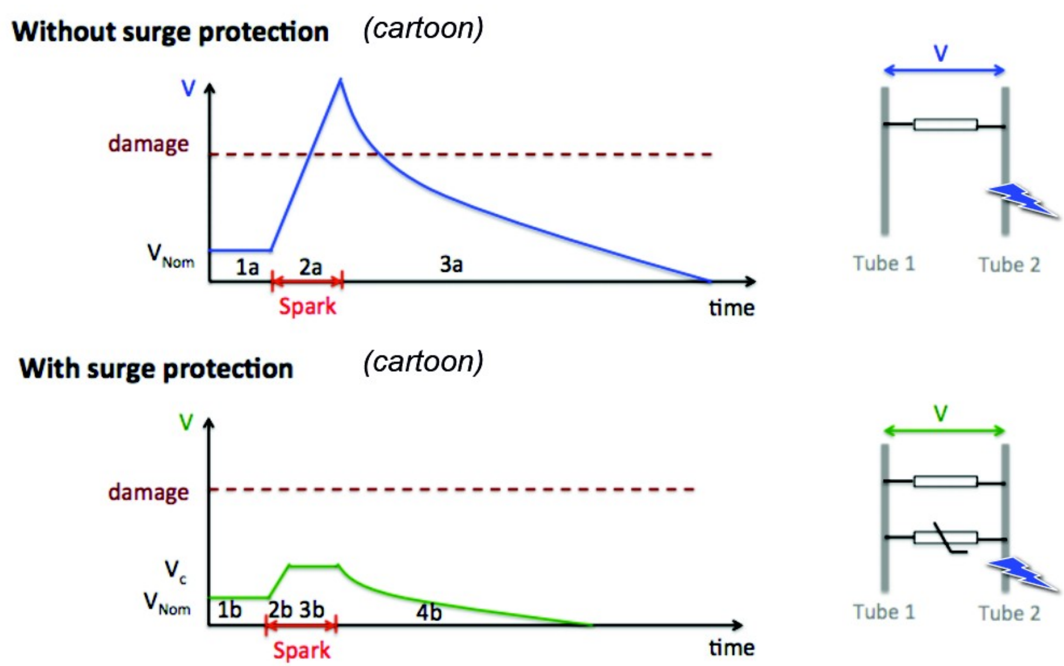
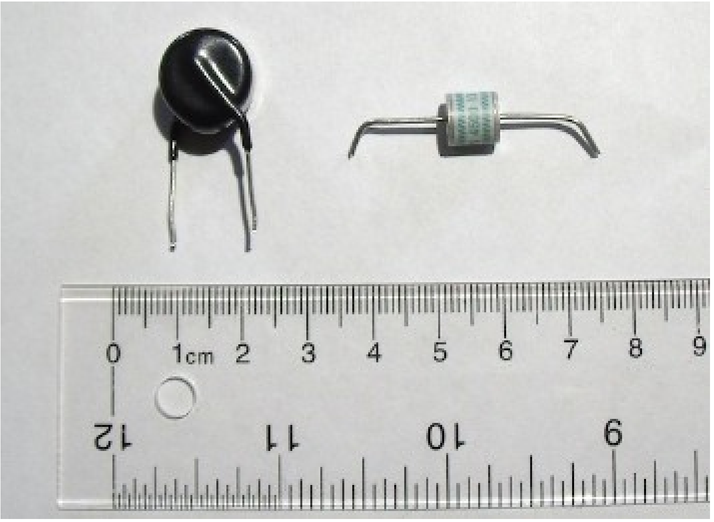
- By utilizing "off the shelf" surge protection devices you can mitigate the risk of dangerous over-voltages





- We had to prove that they would work in a liquid argon environment



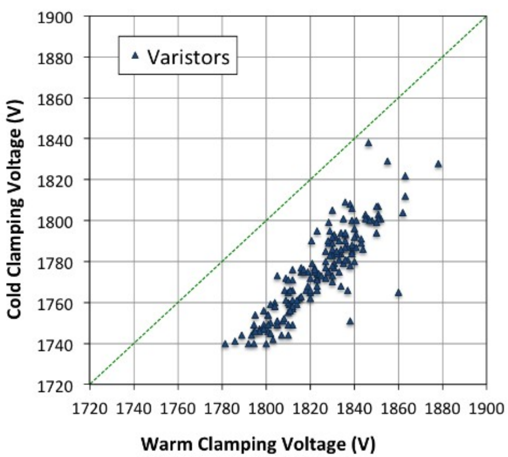
<u>We examined two possible solutions</u>

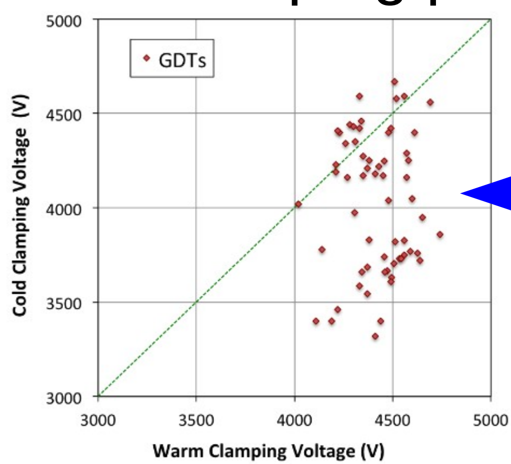
1) Metal Oxide Varistors:

Zinc Oxide ceramic grains act as a matrix of p-n junctions, giving a highly nonlinear I-V curve

2) Gas Discharge Tubes:

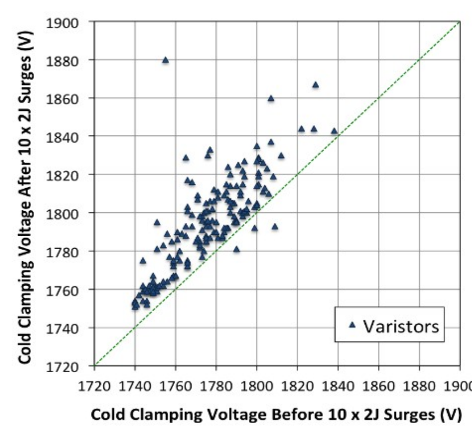
Two electrodes 1-2 mm apart in a gas, at the clamping point, spark develops within the gas

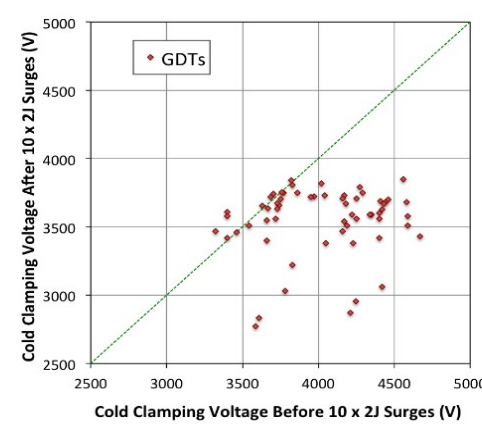




The clamping voltage is stable at both room temperatures and at Liquid Argon temperatures

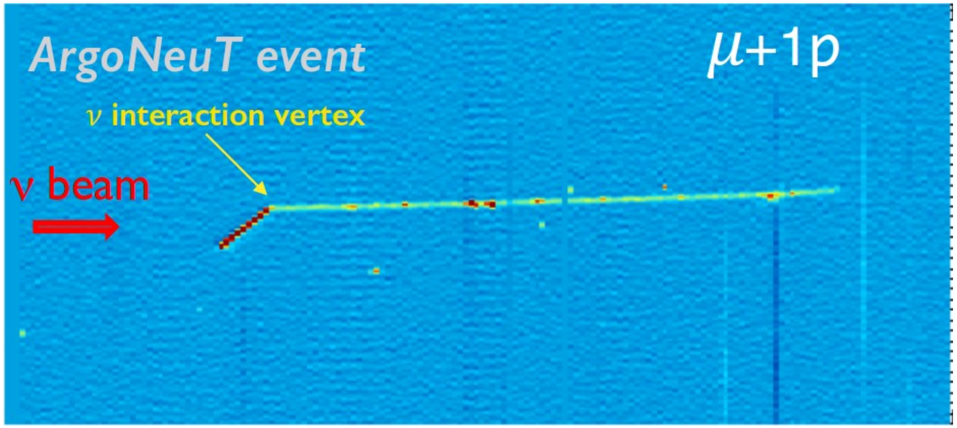
The clamping voltage remains stable even after repeated breakdowns in liquid argon

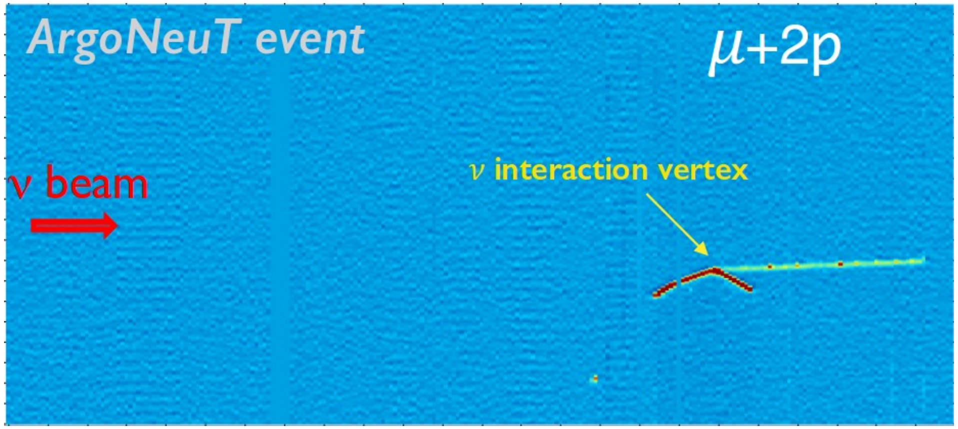




CC-Zero Pion

- Utilizing the 3-d imaging capabilities of LArTPC's as well as the calorimetric and particle ID allows for MC-independent measurements of both **exclusive topologies** (ν_μ-CC0π) as well as **exploring nuclear effects** (ν-nucleus scattering)

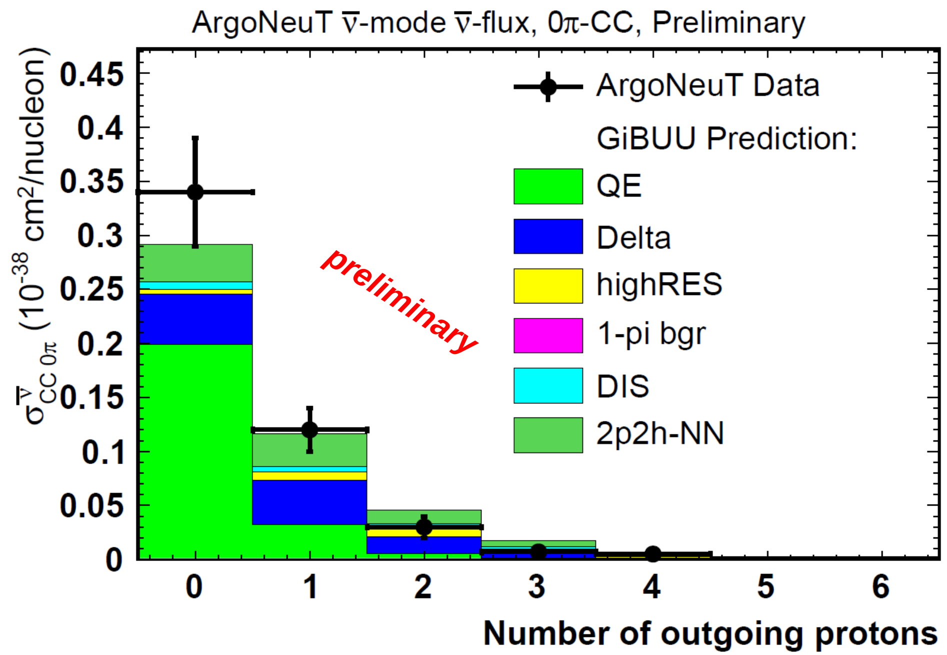


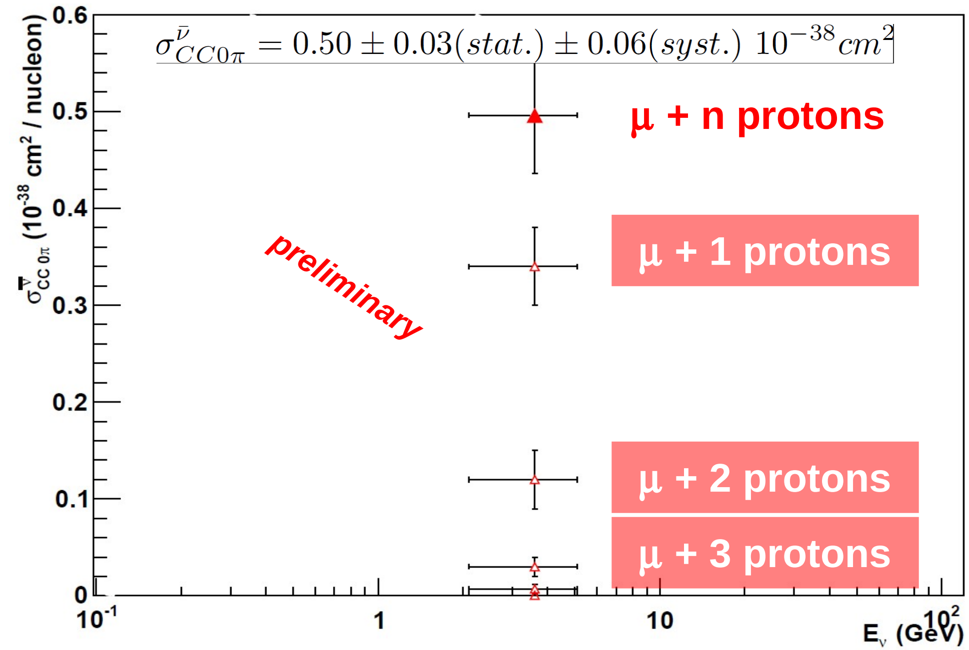


- **Event Topology:**
  - **Leading μ + N Protons**
    (neutrons present as well but not detected due to ArgoNeuT's small volume)
- **Proton Energy Threshold:**
  - **~21 MeV Kinetic Energy**

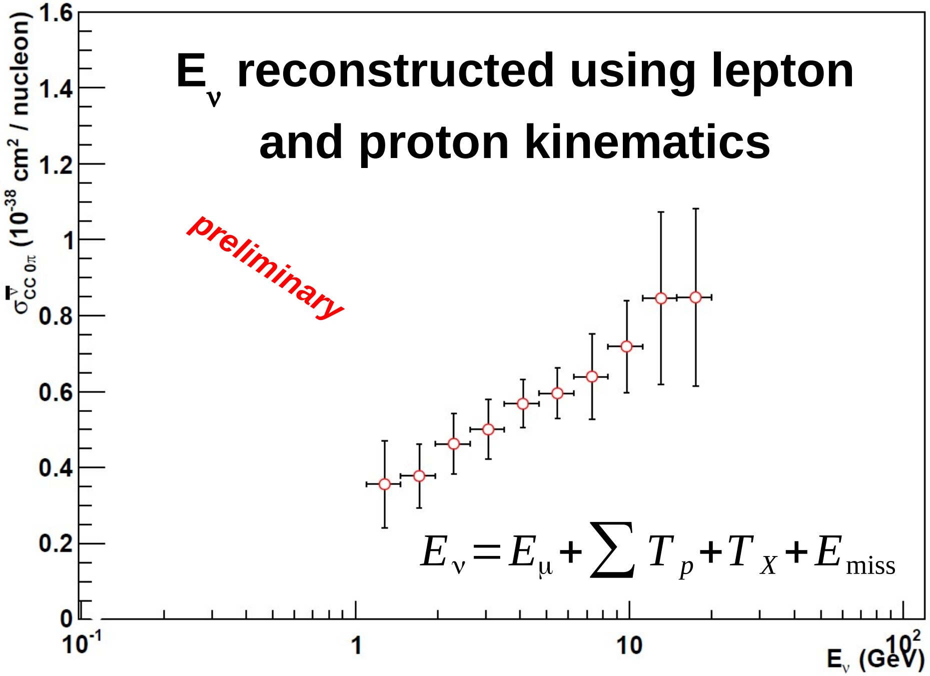
CC-Zero Pion

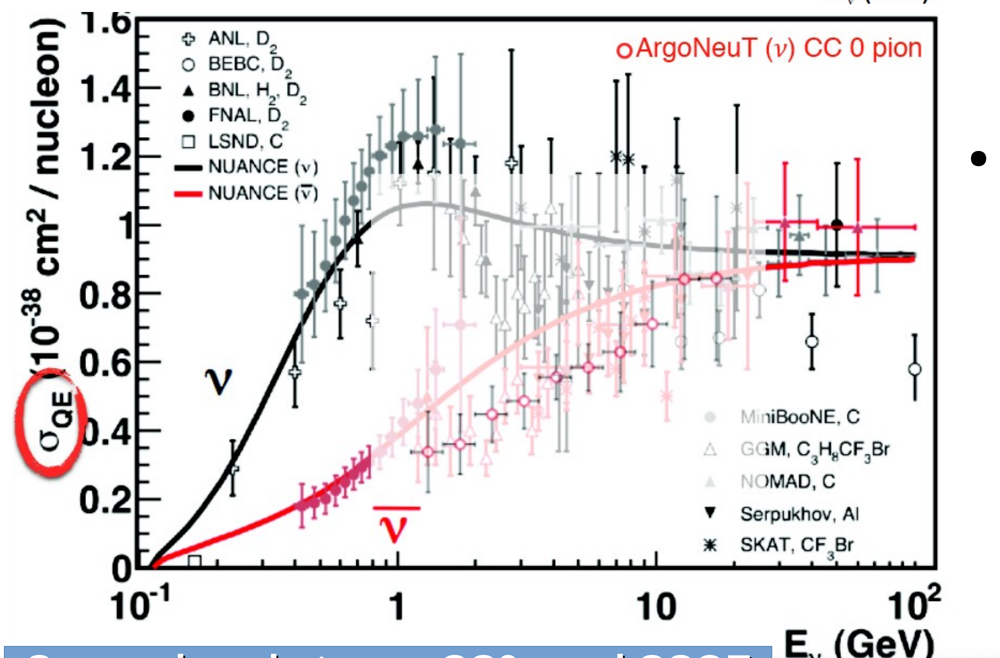
- LarTPC's enable you to examine the production cross-section as a function of the number of outgoing protons in the event
  - See good agreement between MC with final state interactions and data
- Inclusive cross-section for a <E$_\nu$> = 3.6 GeV +/- 1.5 GeV
  - **0.5 ± 0.03** *(stat)* **± 0.06** *(sys)* **x 10^{-38} cm^2**
  - Also shown as sum of its proton multiplicity components





CC-Zero Pion



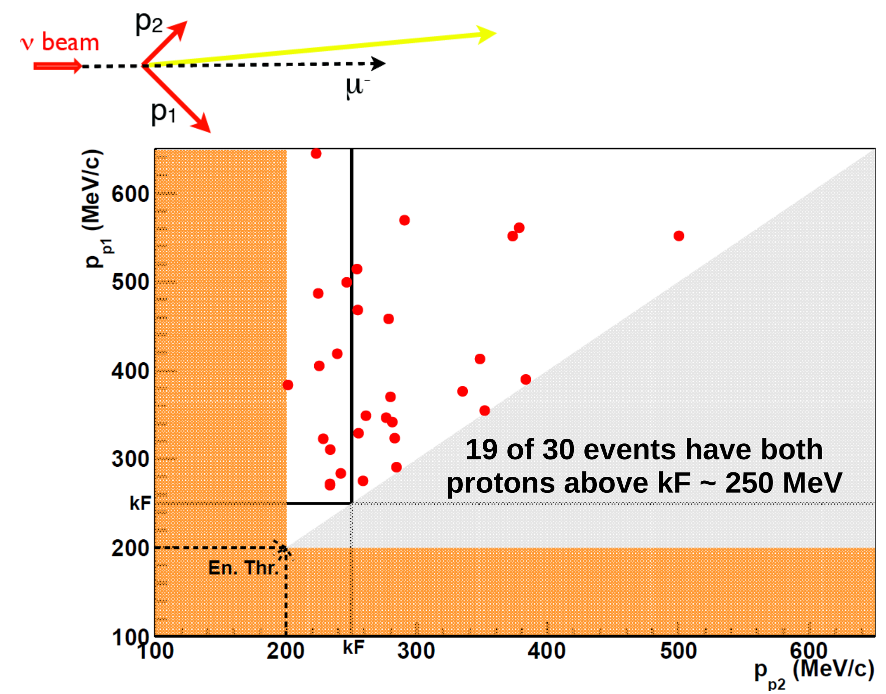


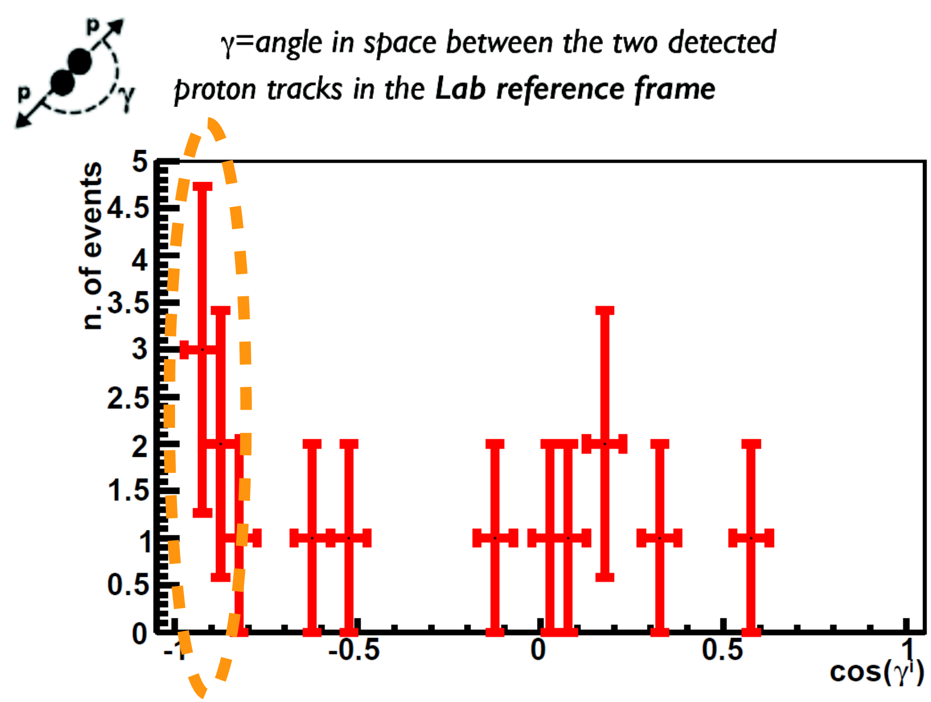
Comparison between CC0π and CCQE data and MC provided just "to guide the eye"

- **Interpret the data as a function of the reconstructed neutrino energy**
  - $\mathbf{T_p}$: kinetic energy of the protons
  - $\mathbf{T_x}$: Recoil energy of the residual nuclear system
    - Estimated from missing transverse momentum
  - $\mathbf{E_{miss}}$: Missing energy
    - Nucleon separation energy from the nucleus + excitation energy of the residual nucleus
      - Estimated from a fixed average value
- **Plotting this compared to the world data for Quasi-elastic processes is expected to give some discrepancy**
  - We are not making a quasi-elastic assumption for our interaction
  - Detailed MC comparison currently underway

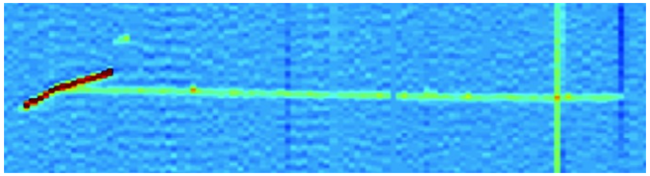
Studying Short Range Correlation

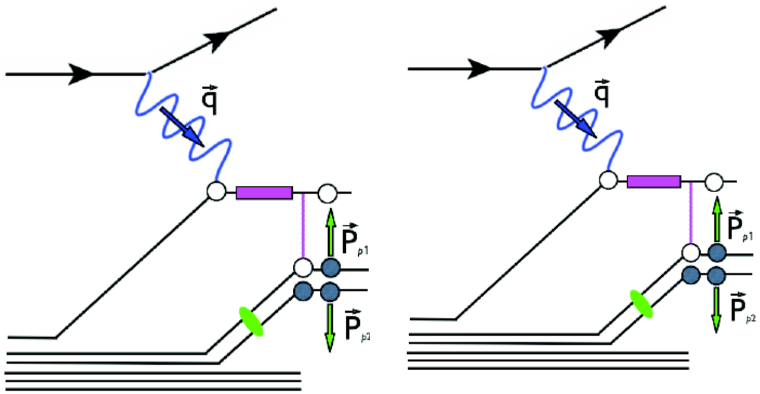
- Subsample from the CC0π sample is the μ+2p sample (30 events) which allows us to look for **hints for nucleon-nucleon short range correlation** (NN-SRC)
  - Look for pairs of protons with **high momentum** (above the Fermi momentum) and **strong angular correlation**
- Four events are found with two protons in a **back-to-back** configuration in the lab frame
  - cos(γ) < -0.95
  - All for have the momentum of the protons nearly perfectly balanced





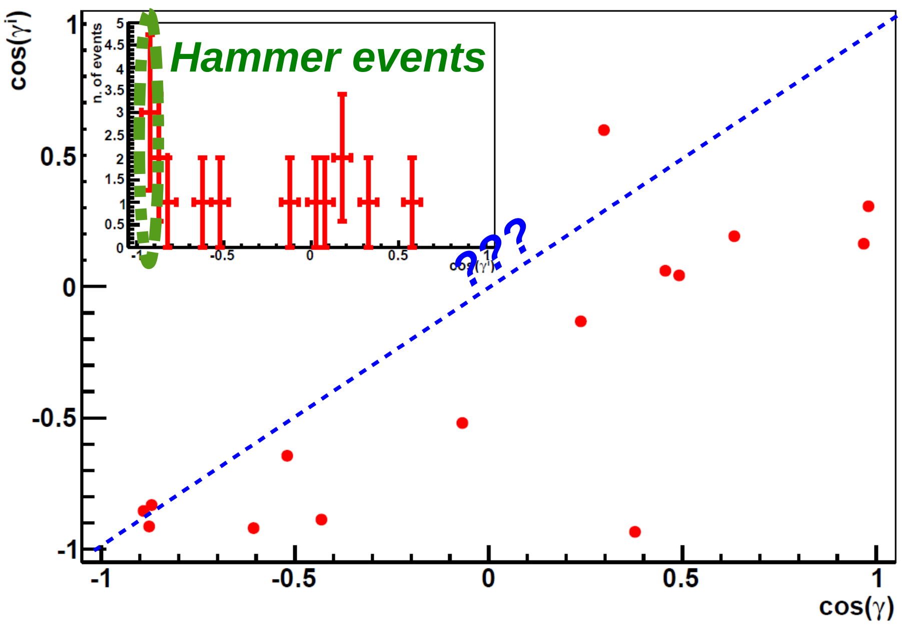
Studying Short Range Correlation





via nucleon RES excitation and subsequent two-body absorption of the decay π^+ by a SRC pair

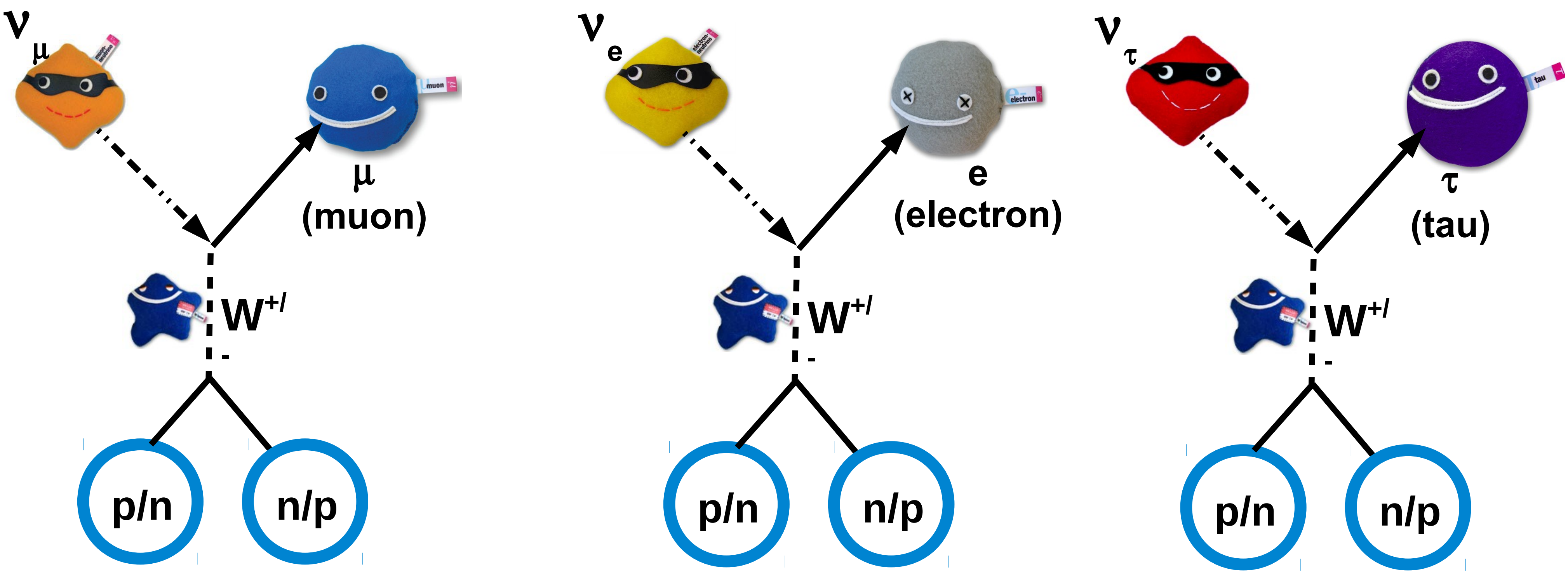
via nucleon RES excitation and subsequent two-body absorption of the decay π^+ by a SRC pair

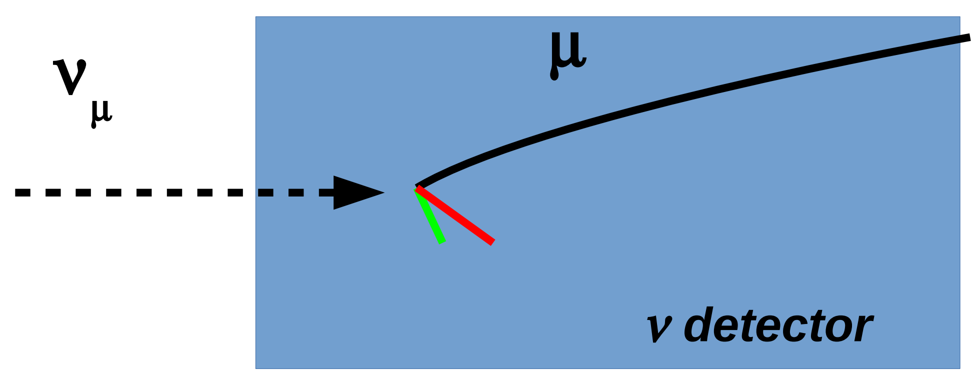


- The features of the four "hammer" events look compatible with the hypothesis of CC RES pionless reactions involving pre-existing SRC np pairs
  - γi: opening angle between the struck nucleon and the recoil proton
  - γ: angle between the two proton tracks in the lab frame
- No immediate interpretation of the remaining events which seem to have an ***apparent correlation(?)***
  - Final State interactions appear disfavored because these events are energetic and angularly correlated
- **Future larger LArTPC experiments will study these effect with higher statistics in the near future**

Neutrinos only interact via the weak nuclear force

(They carry no charge)





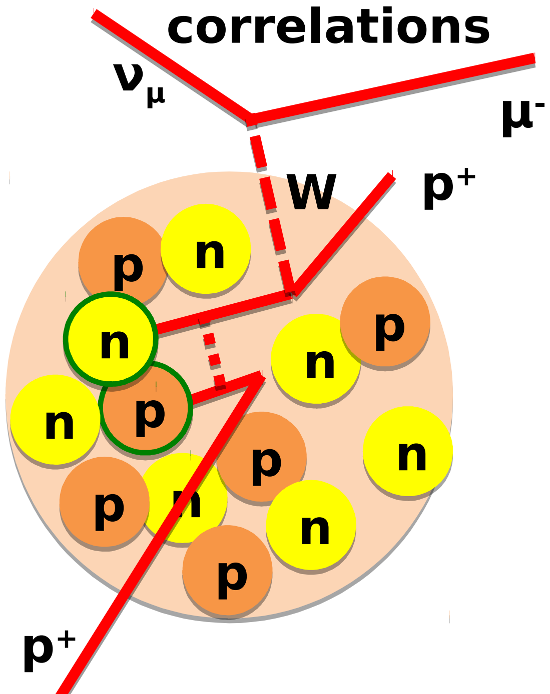
"Nothing" in....something out!

(One of those somethings is a lepton)

Of course this is an oversimplification

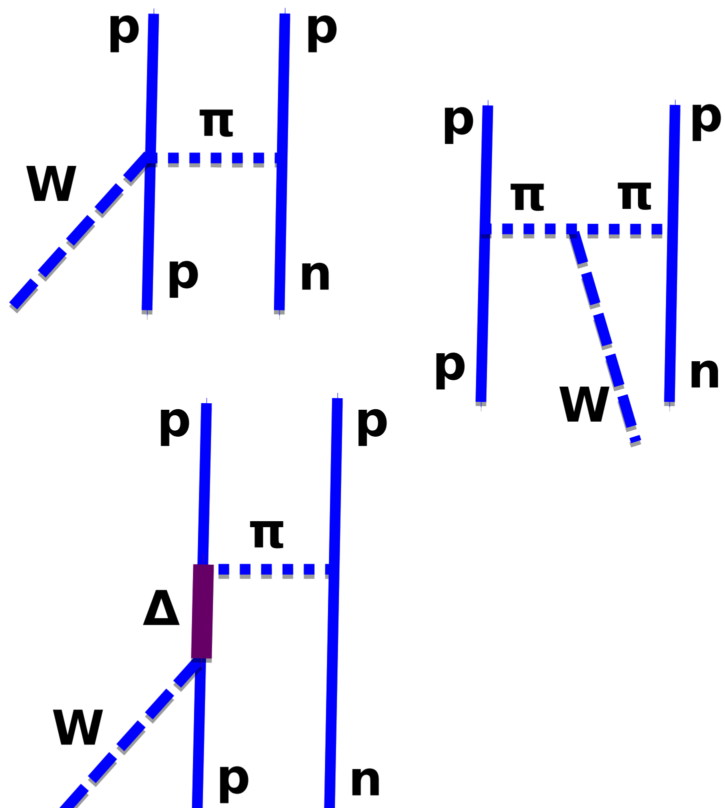
When scattering off nuclei instead of free nucleons the observed topology can be more complex:

Short-range nucleon-nucleon correlations



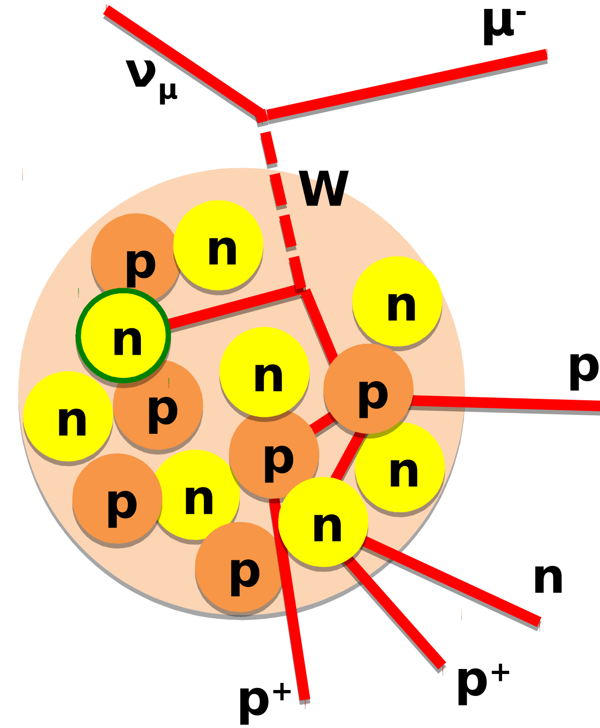
Two nucleons in correlation
Means for the experimentalist:
Multi-nucleon knockout!
The pair has:
large relative momentum,
small total momentum

Meson exchange currents



The observed state looks like QE but it was not!

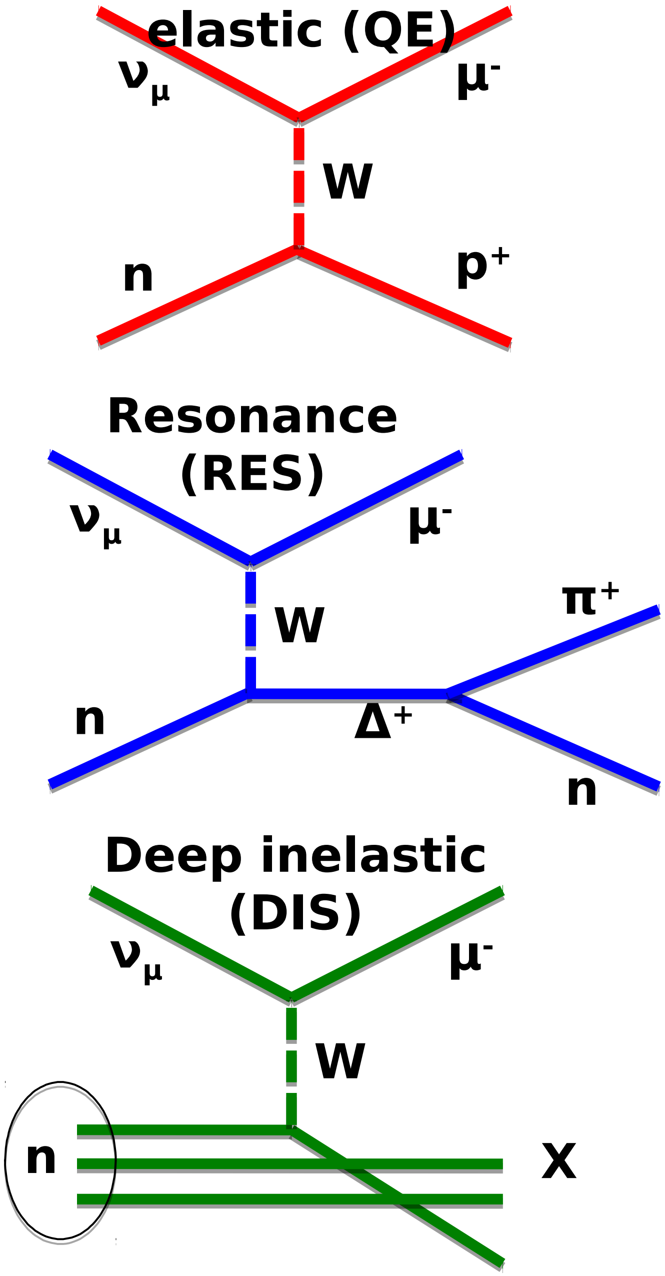
Final state interactions



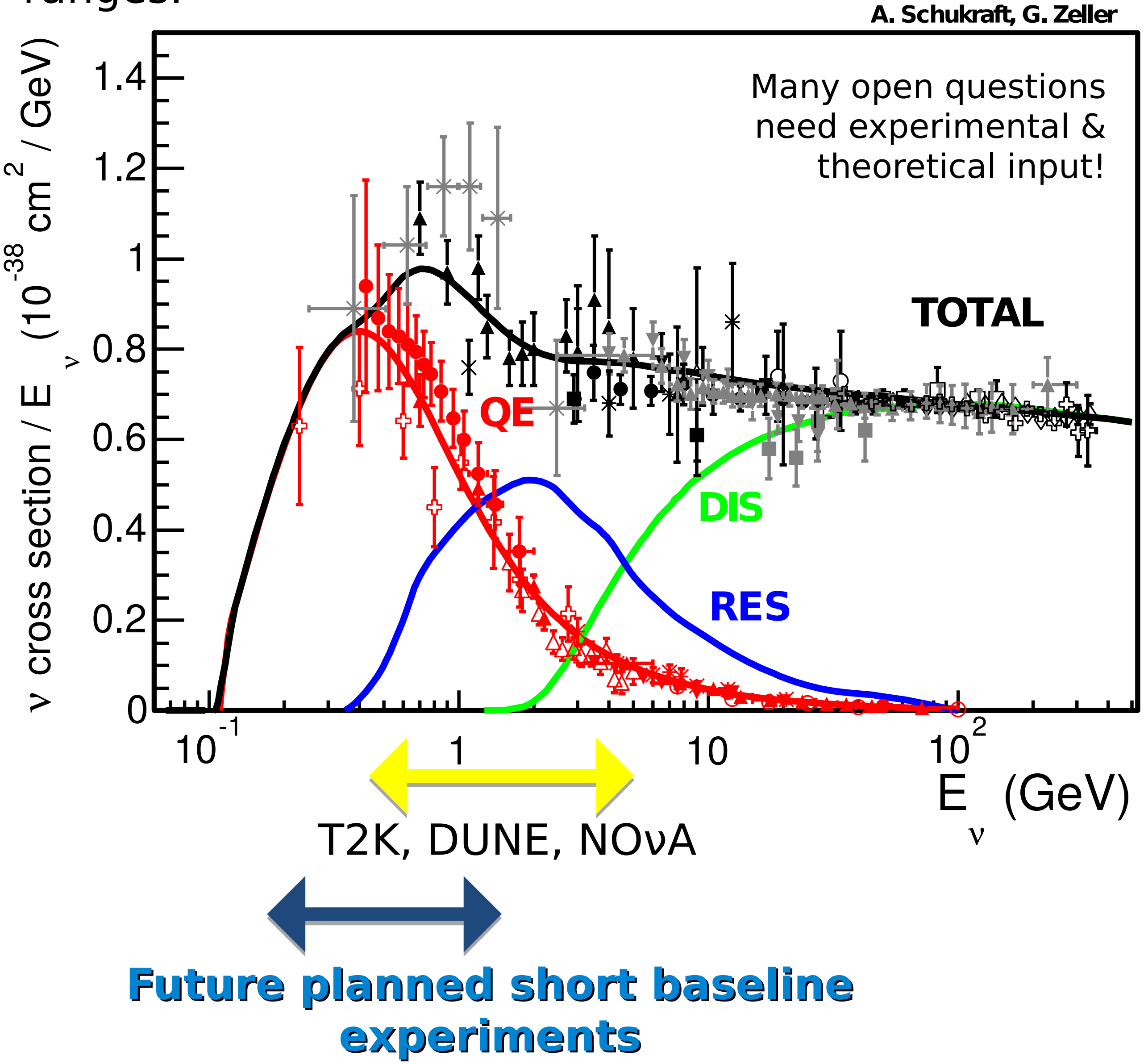
Multi-nucleon knockout through re-interaction of the outgoing nucleon

Veritable treasure trove of physics wrapped into ν-nucleus interactions

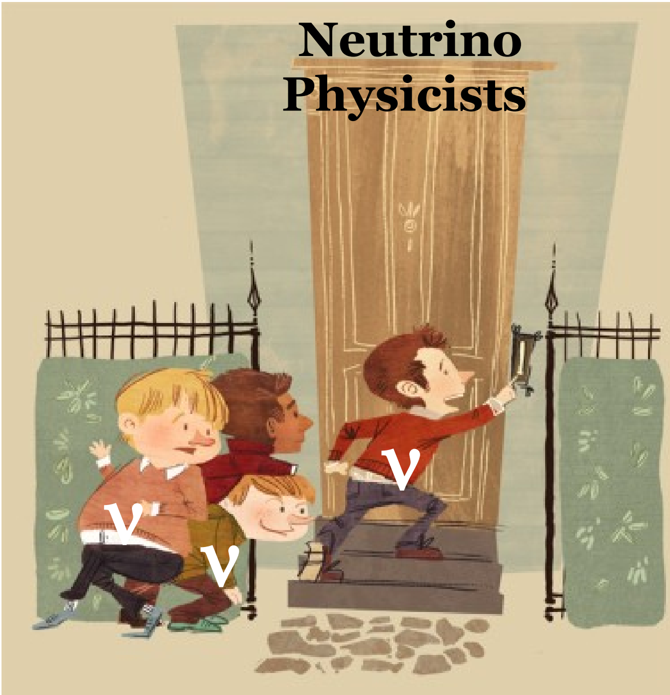
Neutrinos can interact with matter in many ways



Lots of interesting (nuclear) physics over all energy ranges.

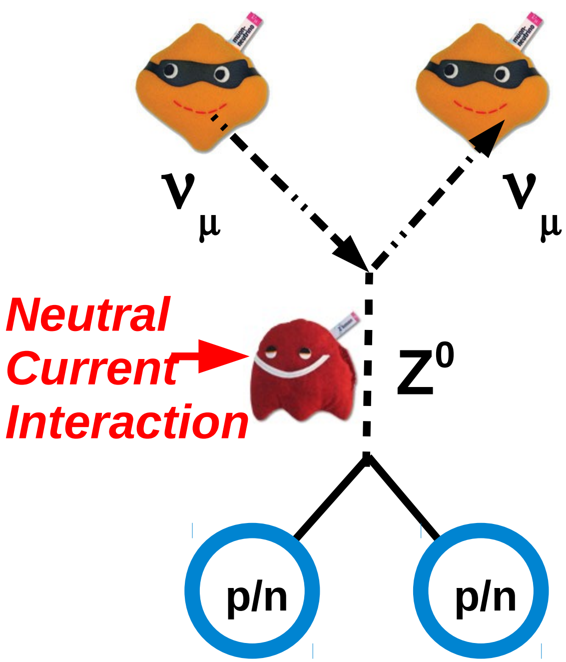


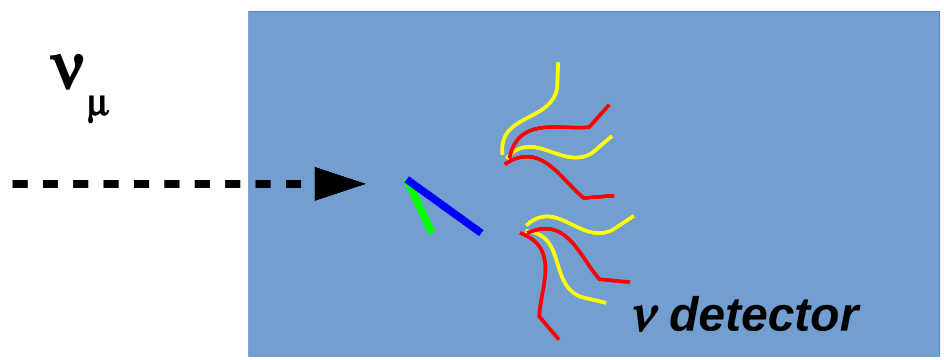
Neutral Current Interactions



"...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



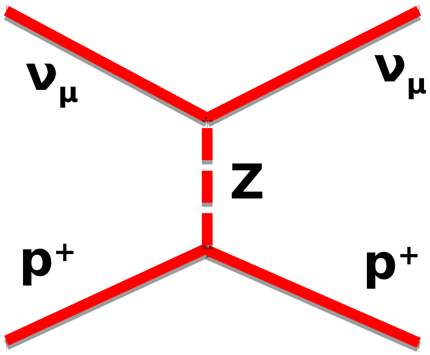


"Nothing" in....something out!

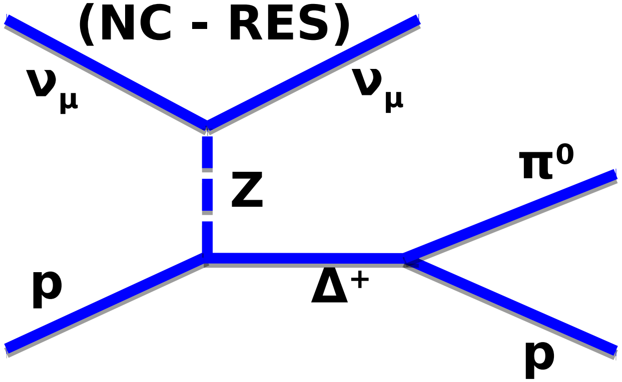
(Those somethings is NOT a lepton)

Neutrinos can interact with matter in many ways

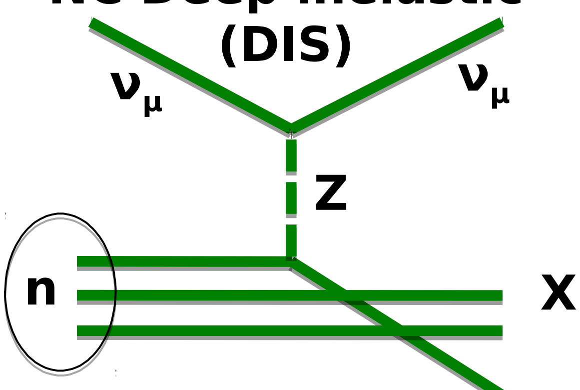
NC-elastic



NC Resonance (NC - RES)



NC Deep inelastic (DIS)



Neutral current interactions are particularly interesting and little data exists