Liquid Argon Time Projection Chambers for Neutrino Physics

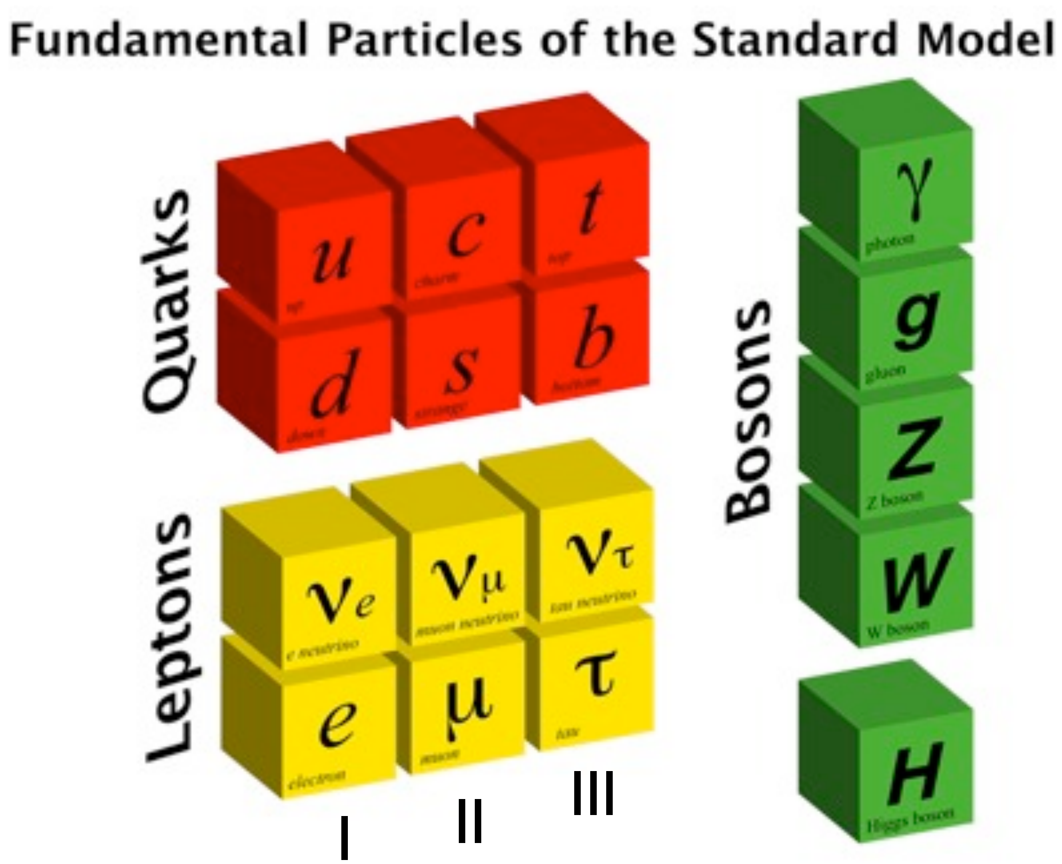
Mitch Soderberg
Syracuse University / Fermilab

Outline

- Brief Overview of Neutrinos
- Liquid Argon Detectors for Neutrino Physics
- The ArgoNeuT Project
- MicroBooNE, and beyond

Neutrino Physics

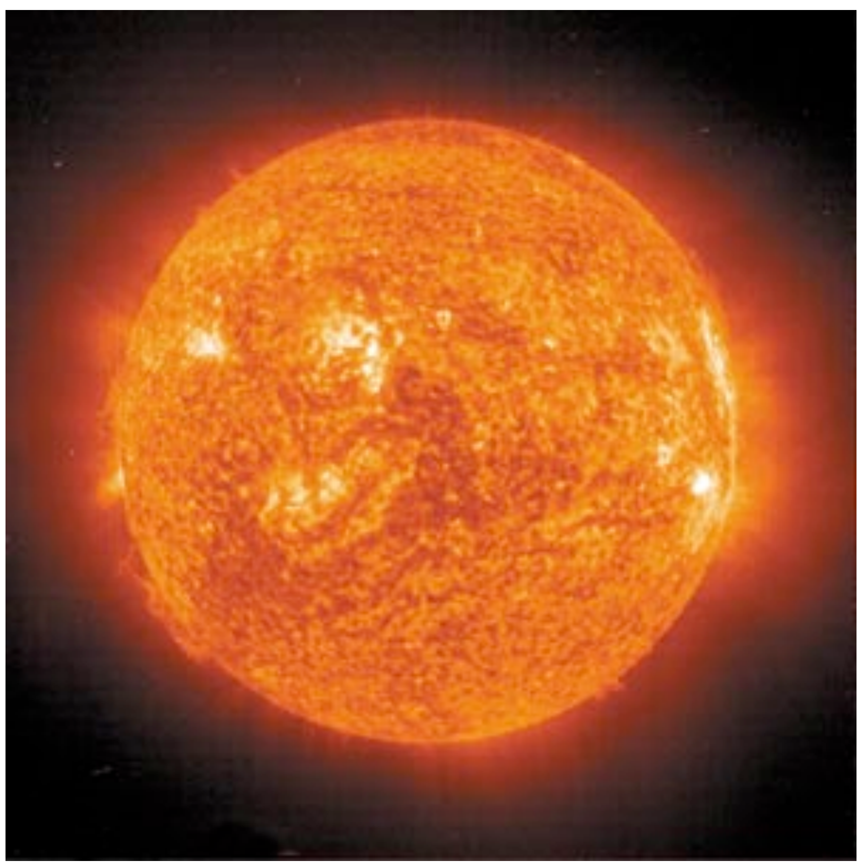
- In the Standard Model **neutrinos** are neutral massless leptons that only interact via the Weak force.
- Three generations (or flavors) of neutrinos with similar properties.
- All three flavors of neutrino have been observed.
- Neutrinos are very elusive, making experimental inquiry a tough job.



Neutrino Physics

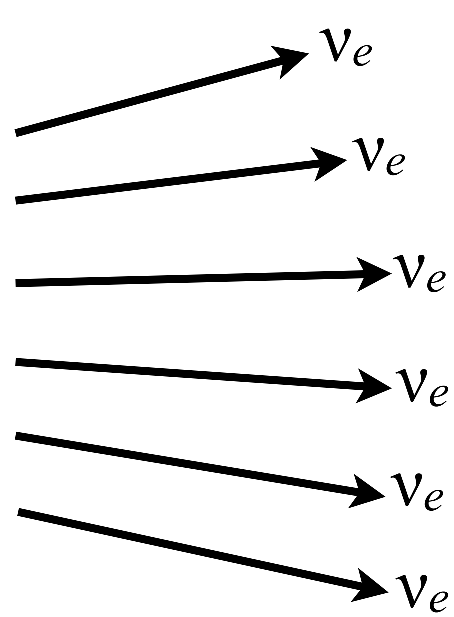
- In the late 1960s the number of neutrinos from the Sun was measured by Ray Davis and colleagues in the Homestake Mine to be ~2/3 lower than predicted.
  - This experiment was located deep underground so that only neutrinos could penetrate down through the rock
  - This deficit of neutrinos was referred to as the "Solar Neutrino Problem"
- This was one of the first hints of what we now know as neutrino oscillations.

~100,000,000,000 neutrinos from the Sun stream through every square centimeter on the Earth every second!



$$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$$

Solar Fusion



Half-life of 35 days.

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

From the Sun

~600 tons of C_2Cl_4

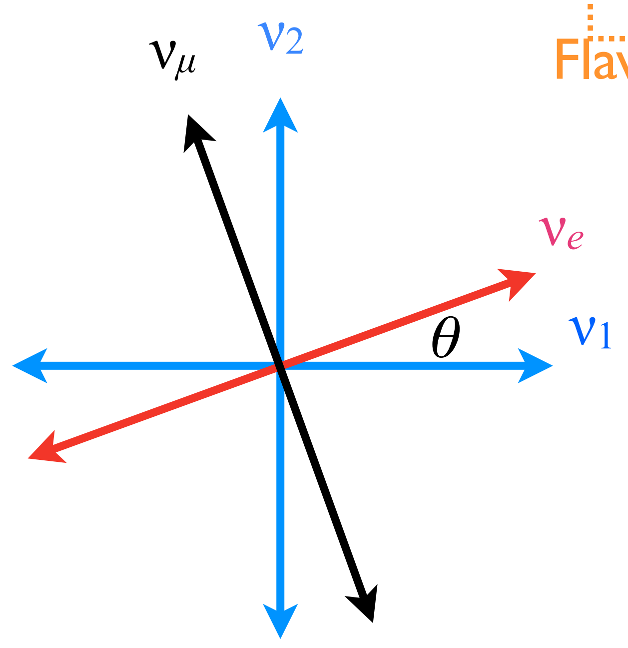
Neutrino Physics

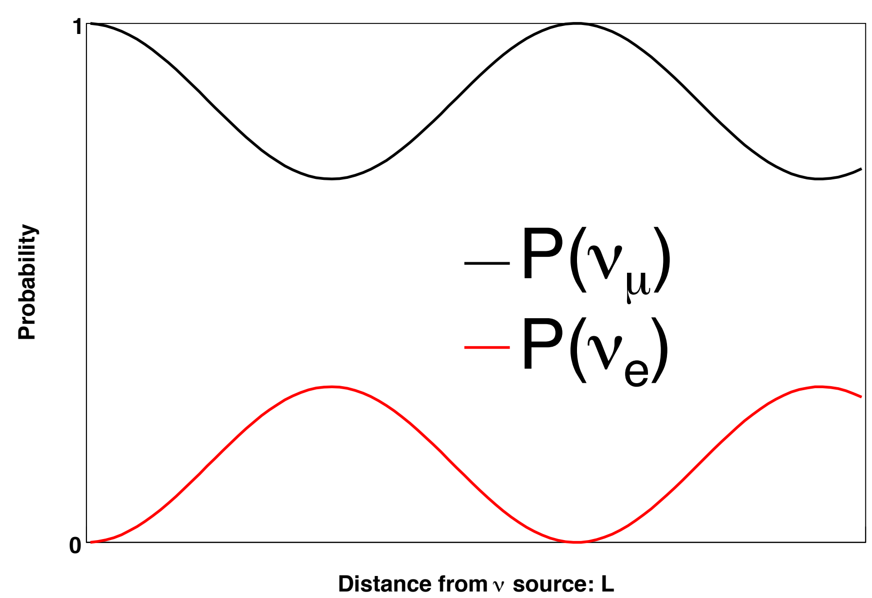
- The relation between neutrino flavor and mass states is parameterized by a mixing matrix, U.
- Probability for a neutrino to oscillate flavors is dependent on:
  - The length (L) over which the neutrino travels before detection.
  - The energy (E) of the neutrino
  - The square of the mass-splitting (Δm^2) between neutrino mass states.
  - A rotation angle from the mass to flavor states (θ)
- A neutrino that's initially 100% muon neutrino can evolve into an electron neutrino.

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

Flavor state — Mass state

Simplified 2-neutrino oscillations in vacuum



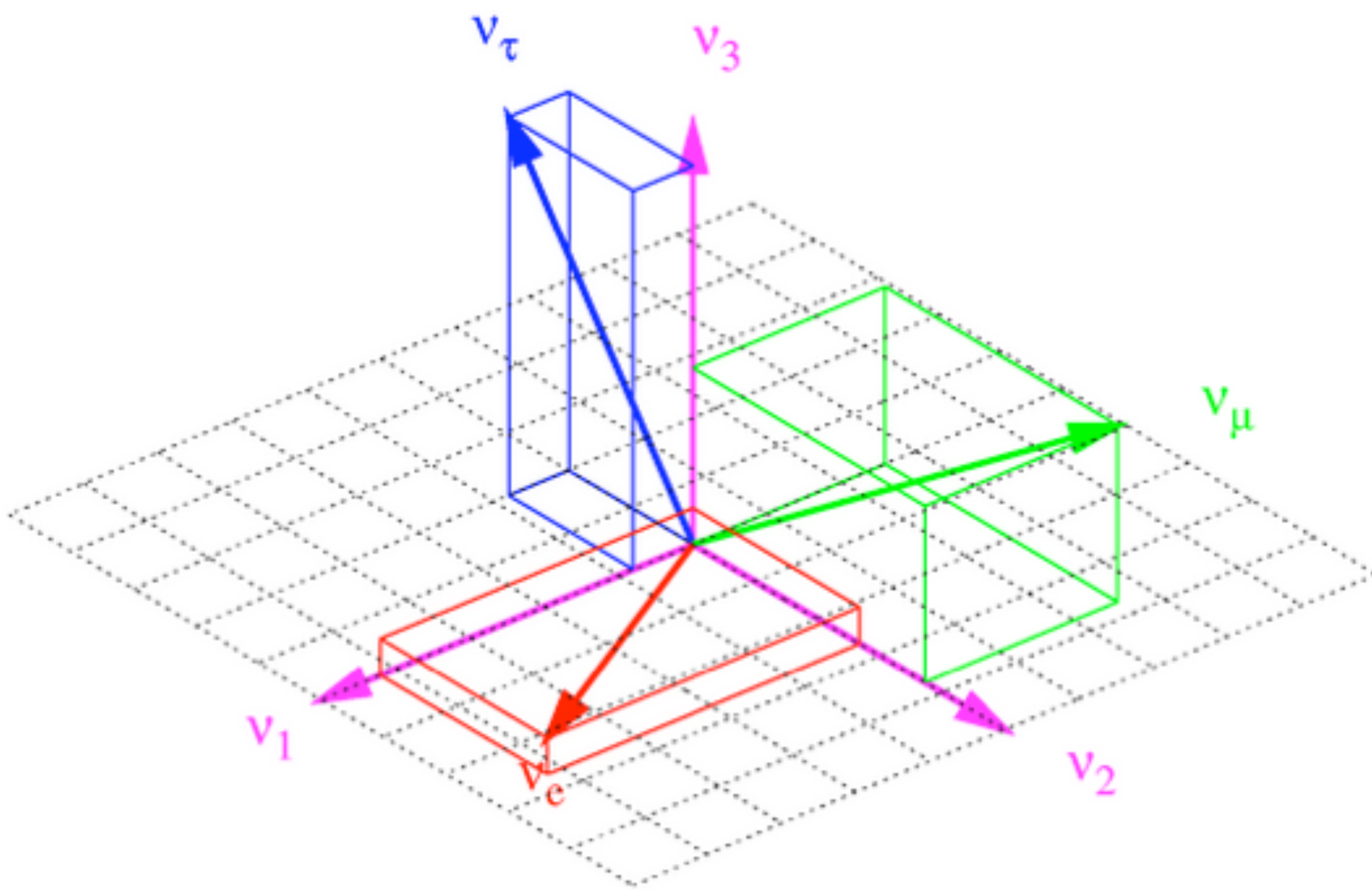


$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P_{osc} = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2 L}{E})$$

Neutrino Physics

- We know there are three active flavors of neutrinos, three corresponding mixing angles, two independent mass splittings, and one phase.
  - There is also a matrix that depends on Majorana nature of neutrino...doesn't impact oscillation probabilities.



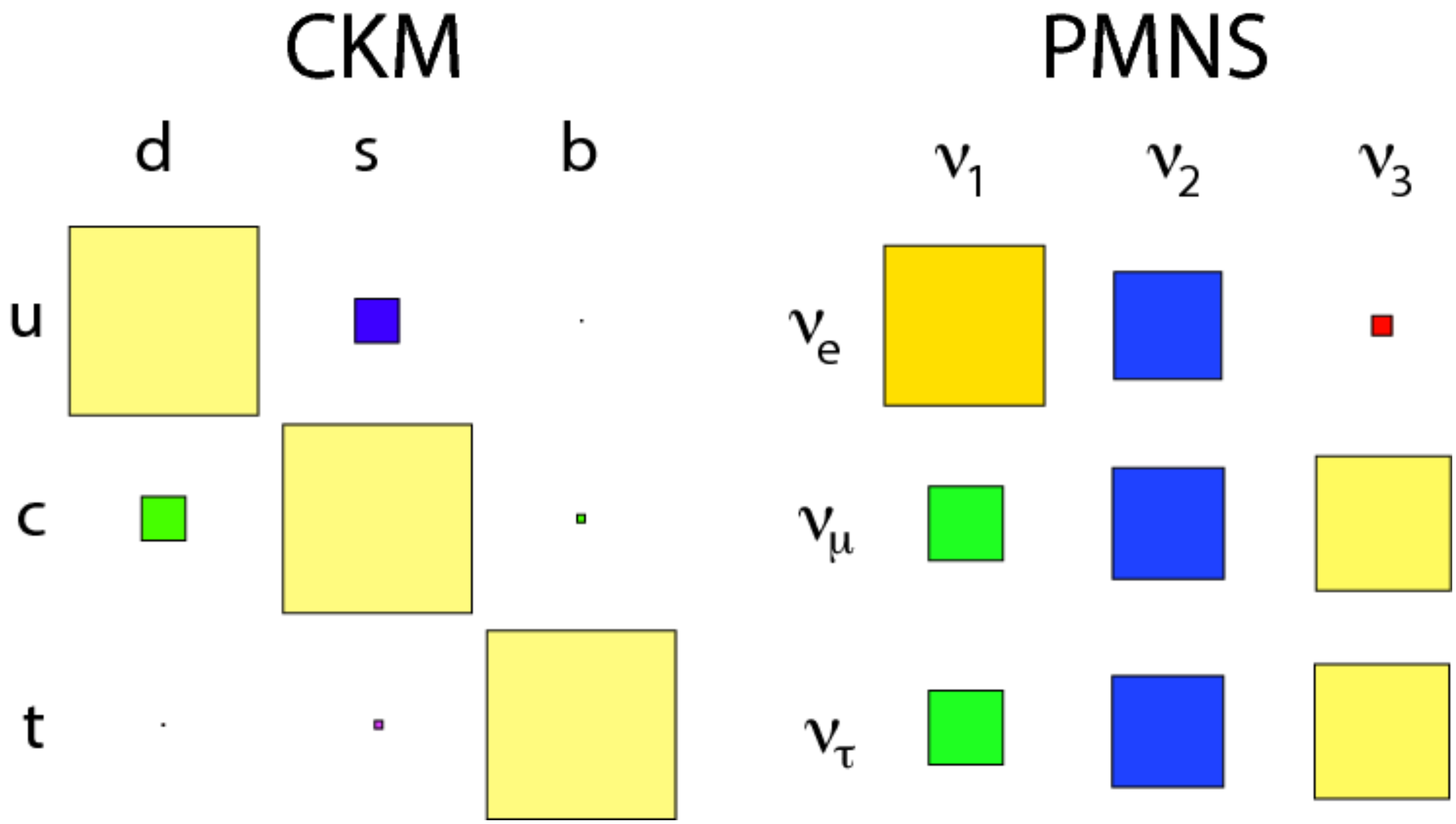
Three possible rotations when all neutrino flavors are included

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Mixing Matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{pmatrix} \times \begin{pmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13})e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13})e^{i\delta} & 0 & \cos(\theta_{13}) \end{pmatrix} \times \begin{pmatrix} \cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\ -\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrino Physics

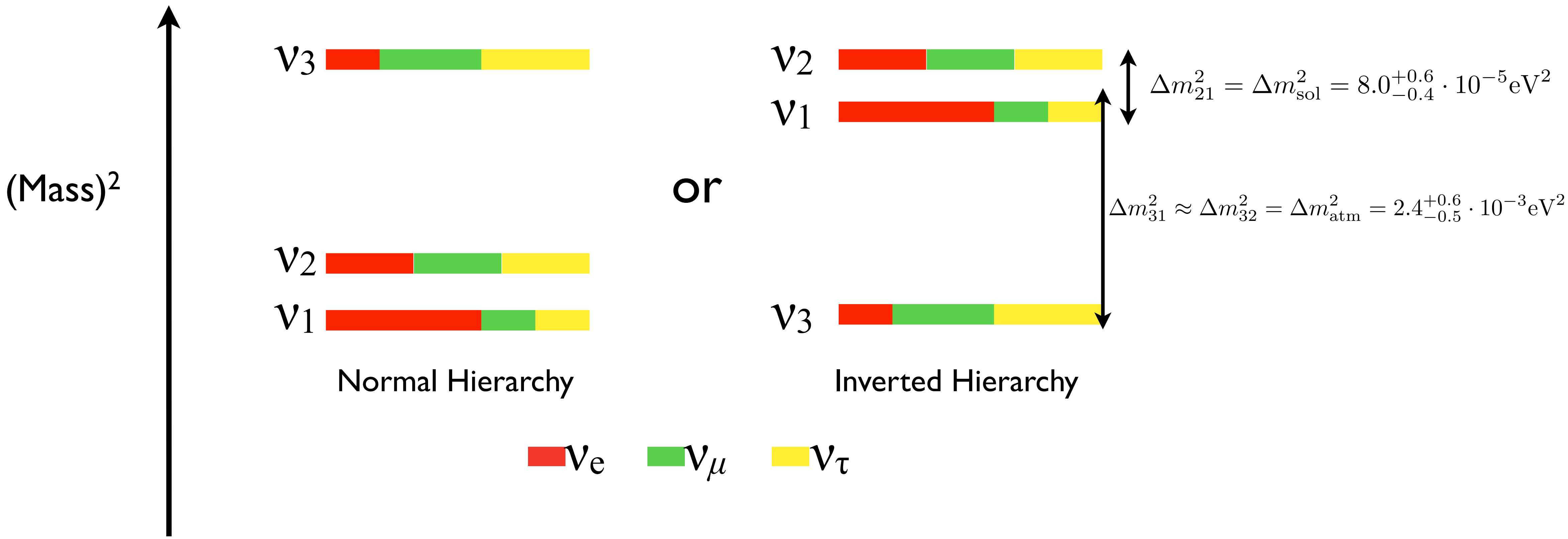
- Mixing angles and mass splittings have all been measured
- $\Sigma m < 0.3$ eV (total mass of the 3 generations of neutrino)
- Don't yet know the value of the CP phase, or the ordering of the mass states.



Refs:
1.) *New Physics from Flavor*, S. Stone, ICHEP 2012 Conference Proceedings

Some Neutrino Physics Goals

- Measure the CP-violating phase, δ_{CP} (Could this explain matter/antimatter asymmetry of universe?)
- Determine Mass Hierarchy:

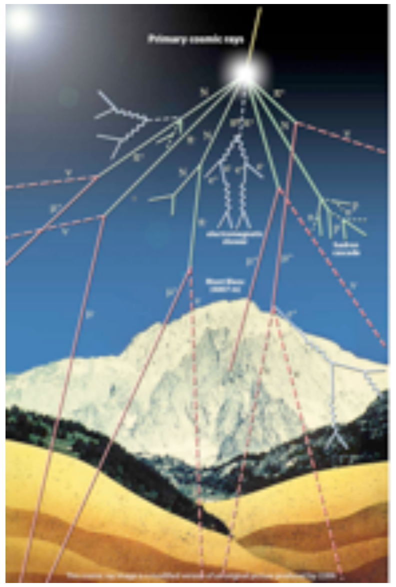


Intense neutrino beam and **<u>massive</u>** detector with good background rejection required for much of this physics....

Studying Neutrinos

- To study neutrino oscillations we need:
  - A source (many different types available...intensity is important)
  - Big Detectors (to accumulate sizeable statistics...interaction cross-sections are small)
  - Good understanding of signal vs. background

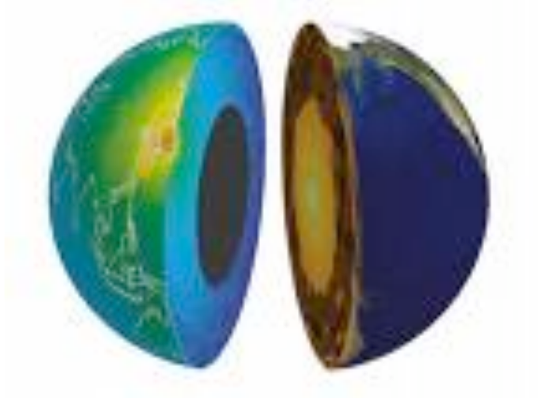
Nuclear Reactors



Cosmic Ray Showers

The Sun

Astrophysical (SuperNova/Big Bang)

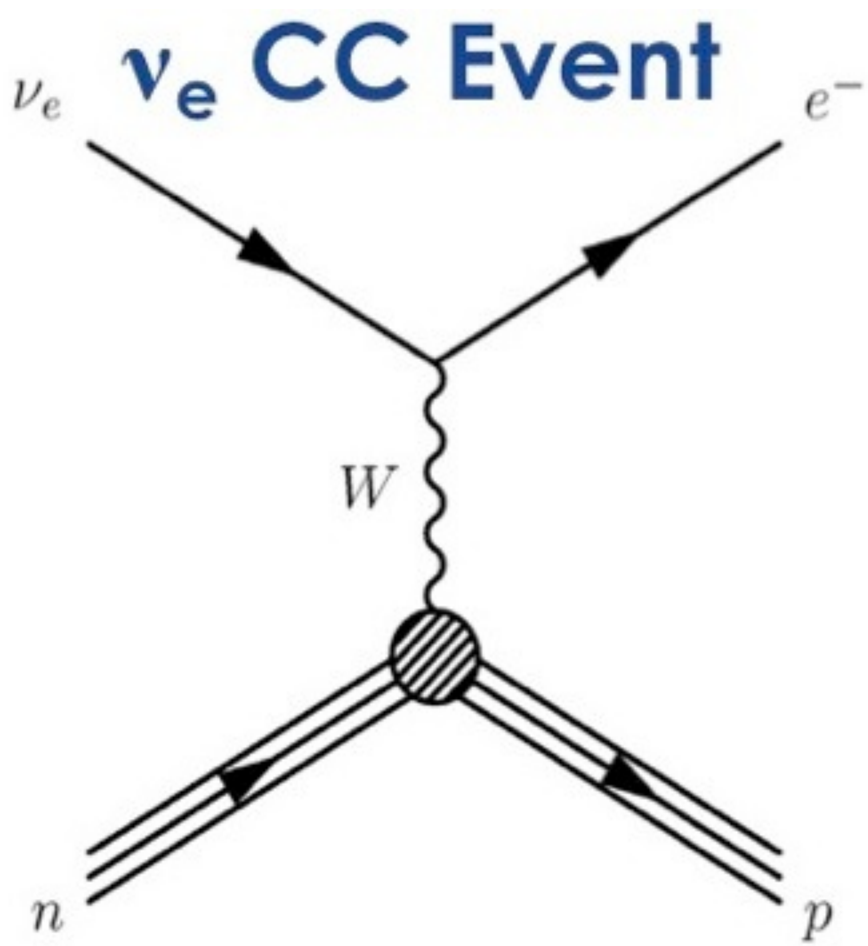


The Earth (Radioactive Elements)

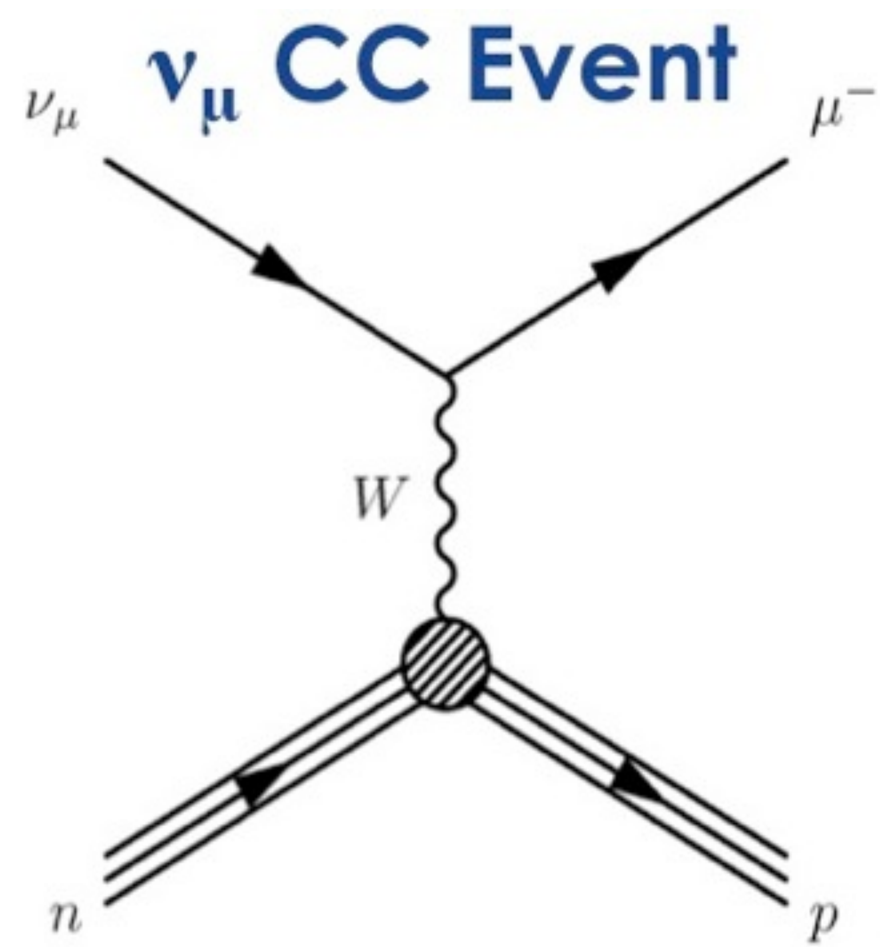
Accelerators

Studying Neutrinos

- Accelerator neutrino experiments look for oscillations by studying the data observed when a very pure beam of muon neutrinos is aimed at a far detector:
  - "appearance" - Do we see an excess of electron neutrino events?
  - "disappearance" - Do we see a deficit of muon neutrino events?
- Charged-Current interactions are the "signal" events that allow the neutrino flavor to be identified, via identification of the charged lepton flavor.



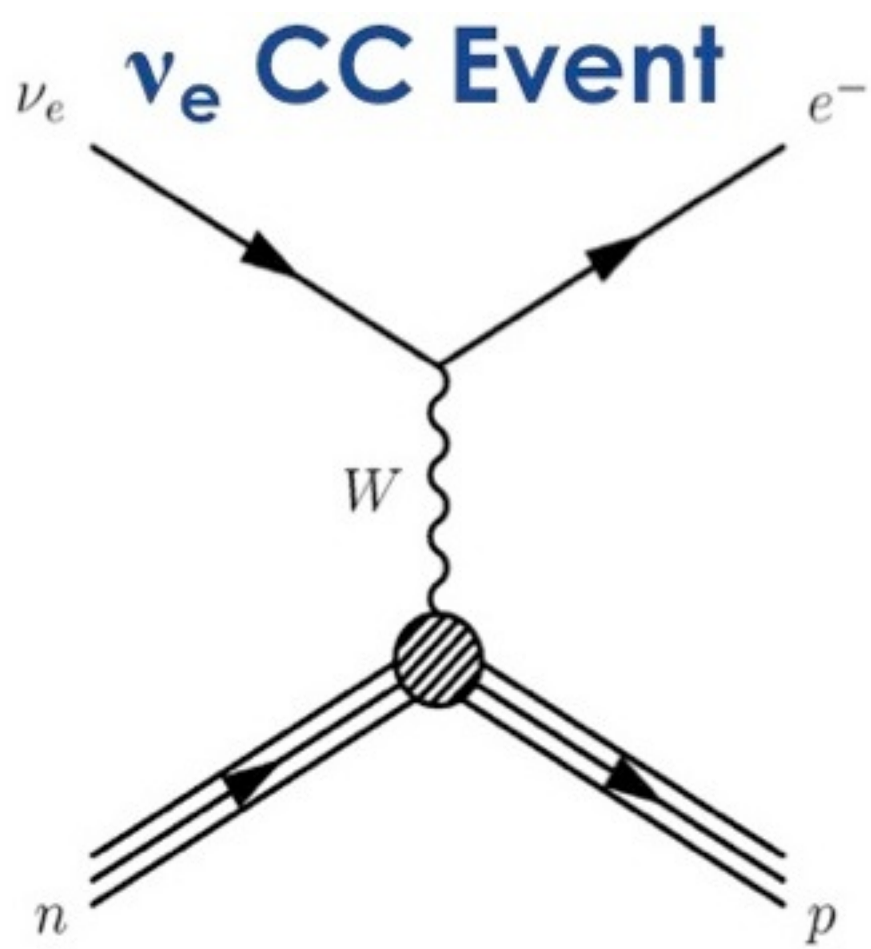
"appearance" signal



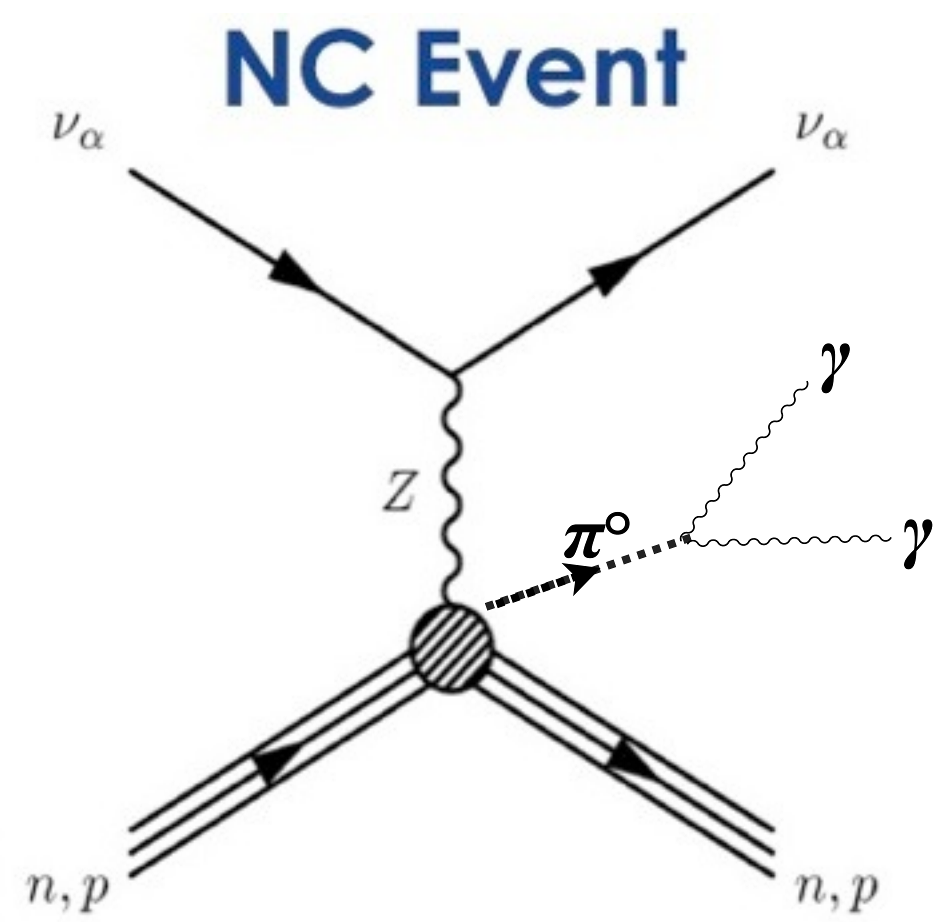
"disappearance" signal

Studying Neutrinos

- Background processes can confuse a measurement.
- There are background processes in appearance and disappearance analyses.
  - Example: Neutral Current (NC π^o) events where a π^o is produced can fake CC ν_e if one of the gammas from the π^o decay get misidentified as an electron.



"appearance" signal



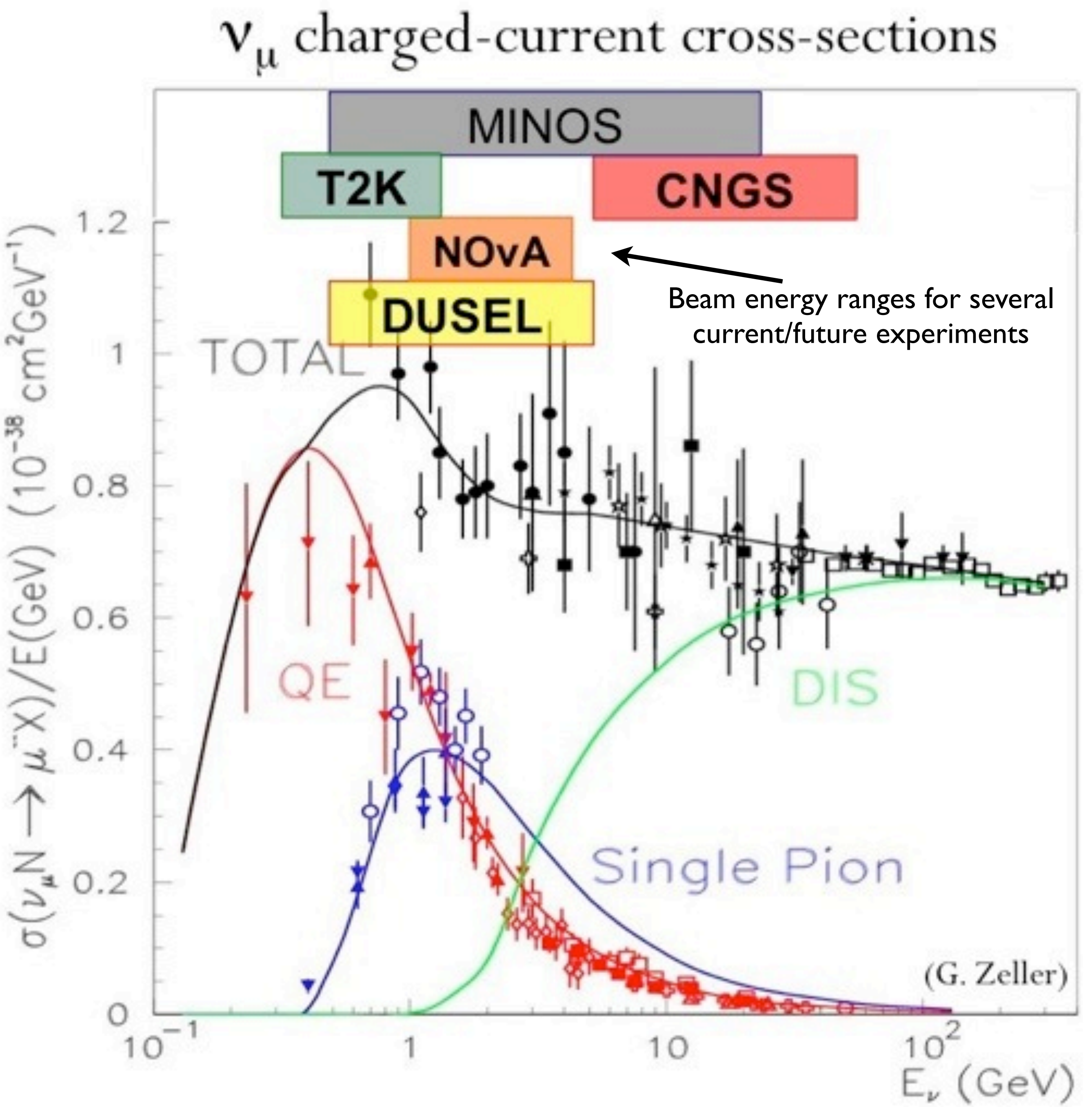
"appearance" background

Studying Neutrinos

- Energy range of current/future accelerator neutrino oscillation experiments is in the range where both signal and background processes are relevant.

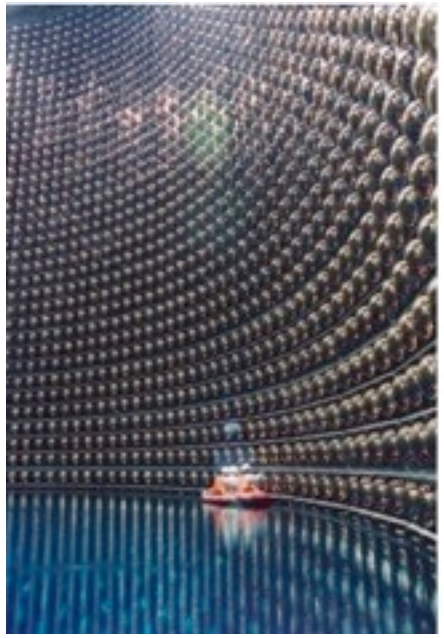
- Improved cross-section measurements, and increased background rejection would greatly benefit future oscillation experiments.

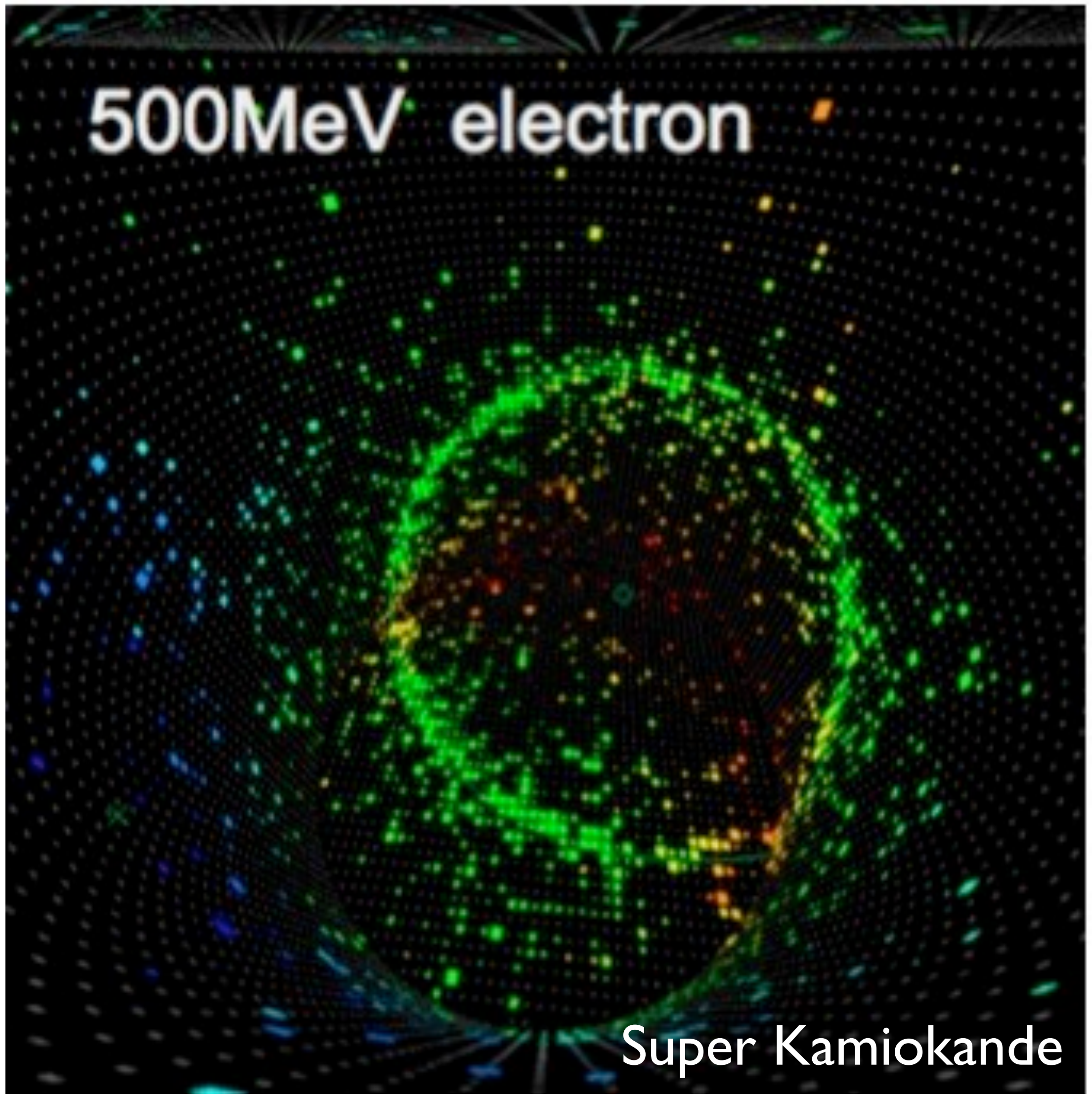
- Comparisons of theoretical predictions and experimental measurements of these processes is a topic of considerable interest.

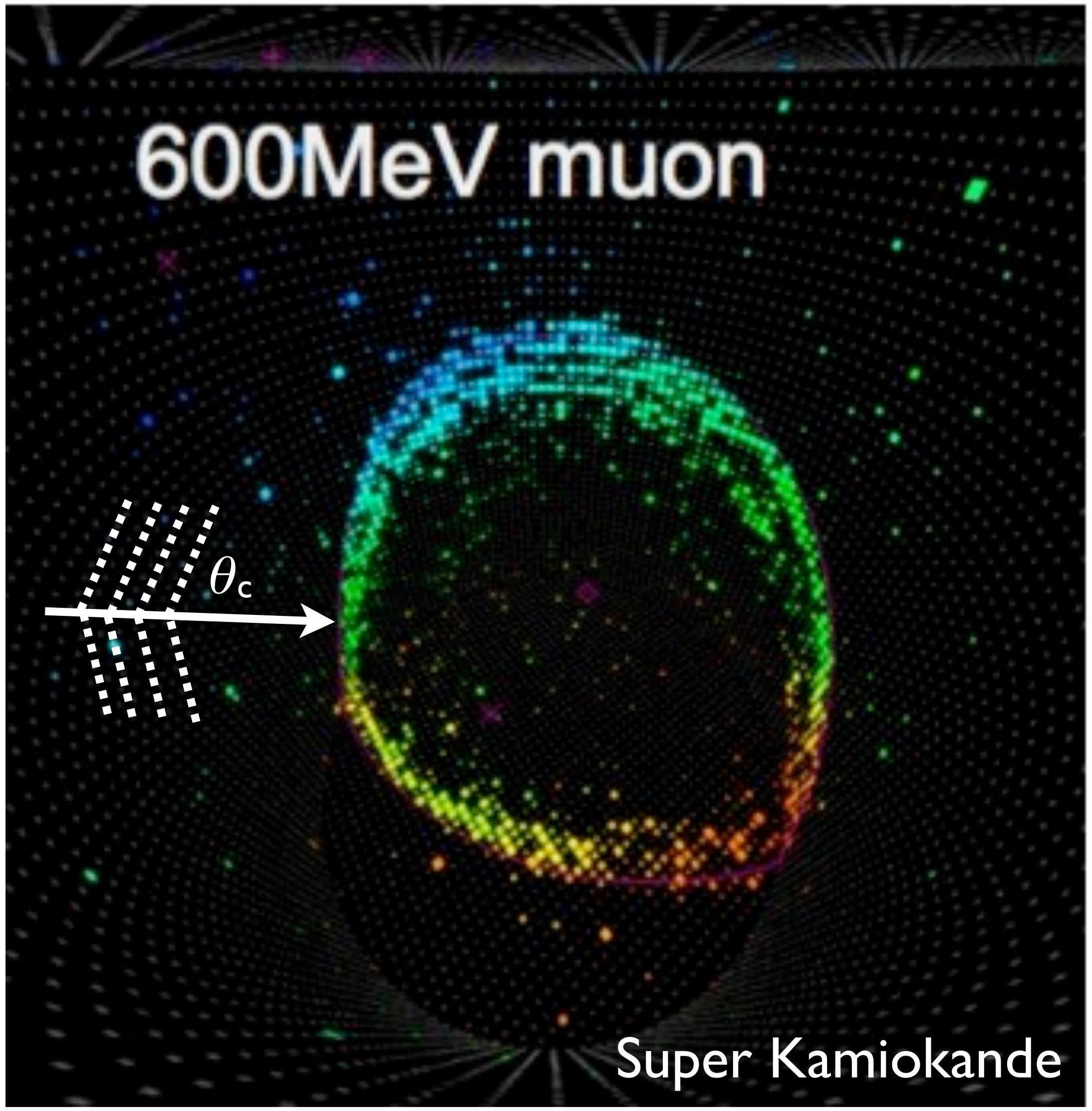


Cerenkov Detectors.

- Particles traversing medium faster than light emit Cerenkov light at a characteristic angle.
- Cerenkov light collected and produces signals on PhotoMultiplier Tubes (PMTs)
  - Muons: straight trajectories lead to crisp rings
  - Electrons: showering and multiple scattering produce fuzzy rings
  - π^{o}s: decay into two gammas, which each appear as electron-like rings





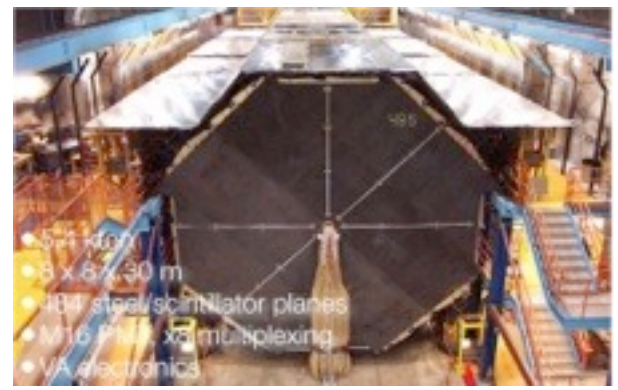


Neutrino Detectors

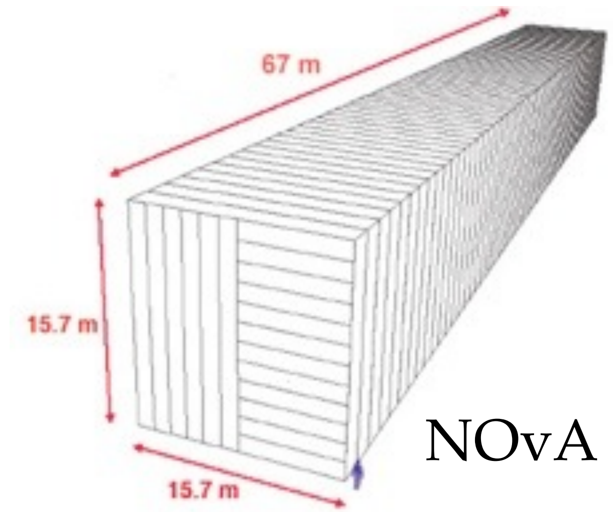
Scintillator Tracking detectors:

- Use scintillator distributed throughout detector that produces light when particles pass through.
- Collect scintillator light via fiber optic readout that connects to a PMT.
- Reconstruct event in 3D by merging information from alternate coordinate views.

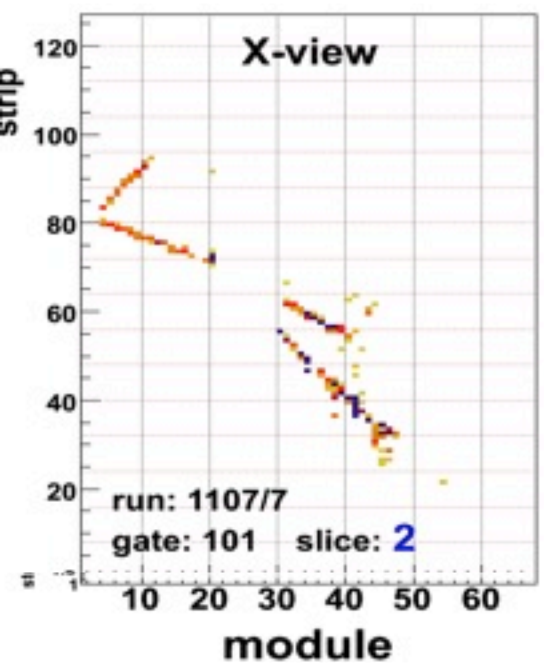
MINERvA

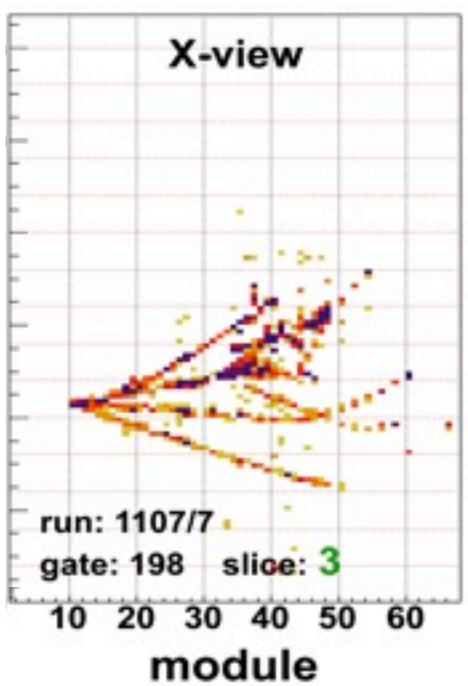


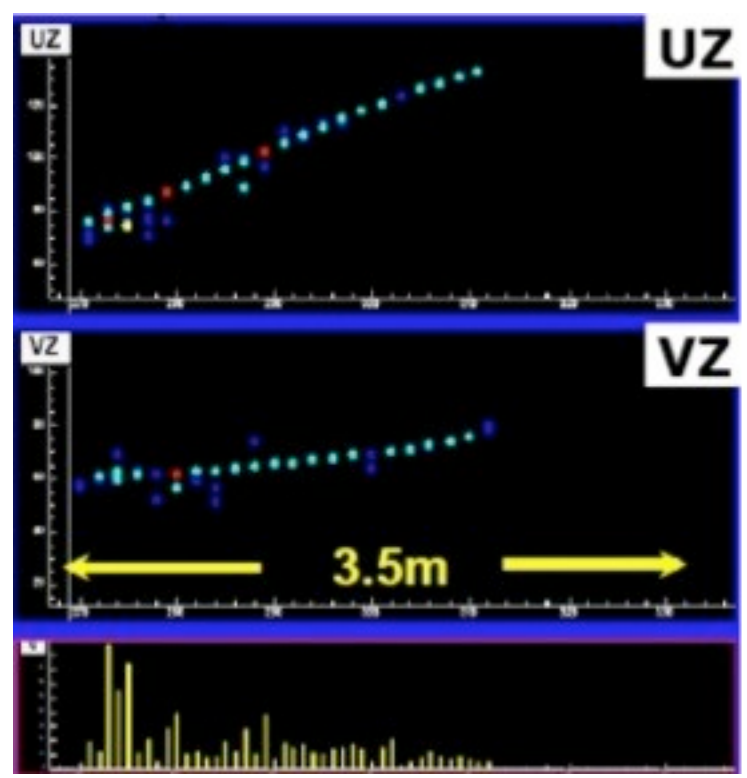
MINOS

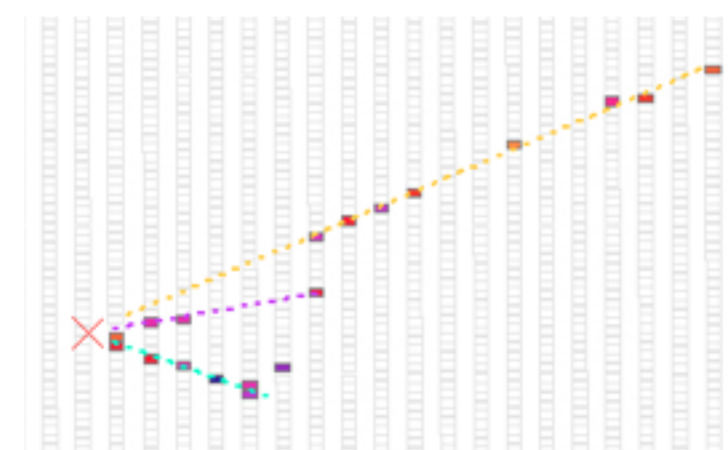


NOvA







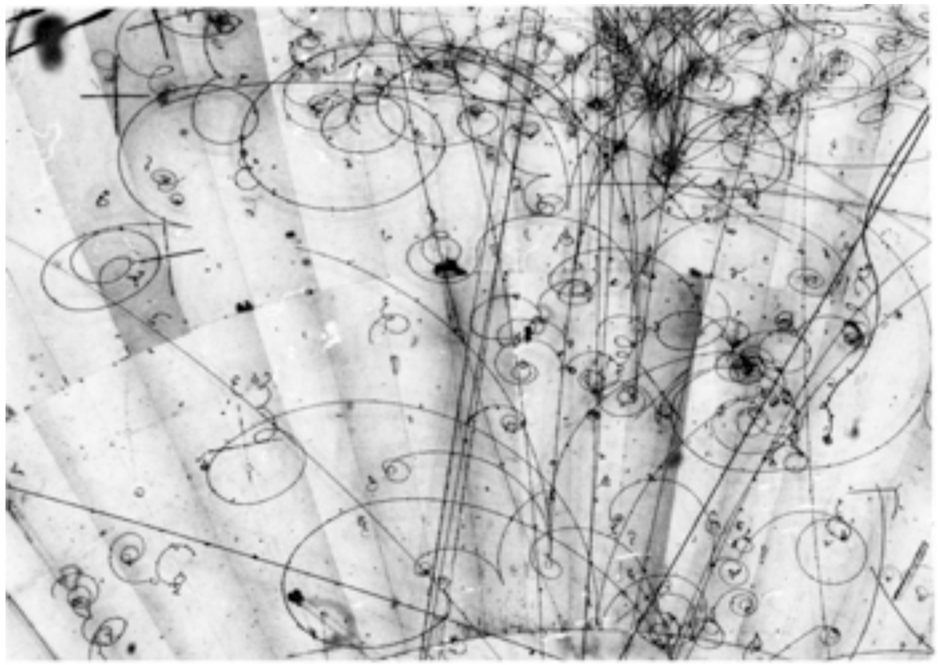


Neutrino Detectors

We already are thinking about the next generation of experiments...

In order to improve sensitivity by reducing backgrounds and improving resolution, would love to have a neutrino detector with the image quality of a bubble-chamber, and a few modern upgrades:

1.) Scalable
2.) Not infinitely expensive
3.) Fast electronic readout



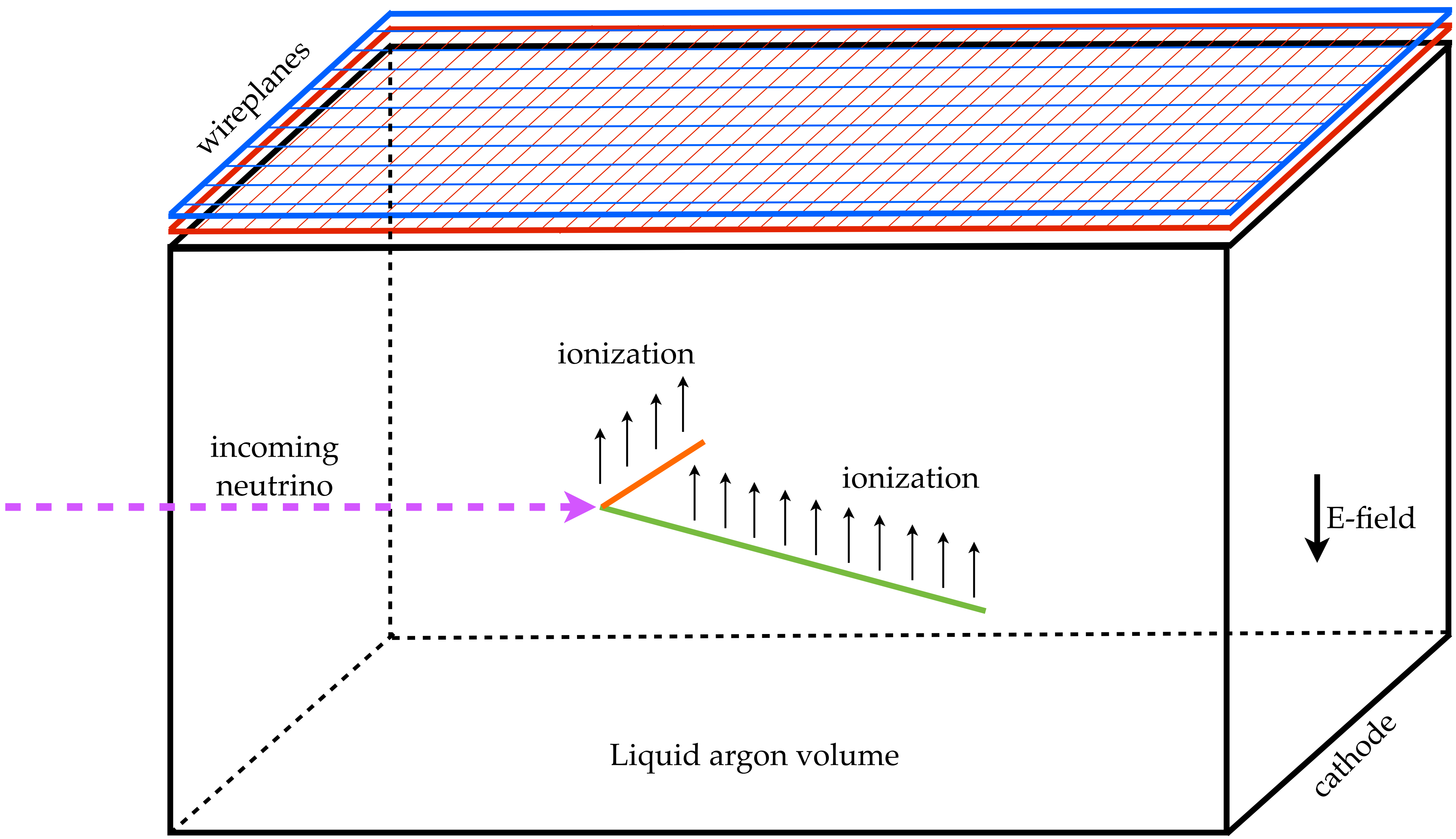
Fermilab 15-foot Bubble Chamber

Are there any modern bubble-chambers?

Yes! **Liquid-Argon Detectors**

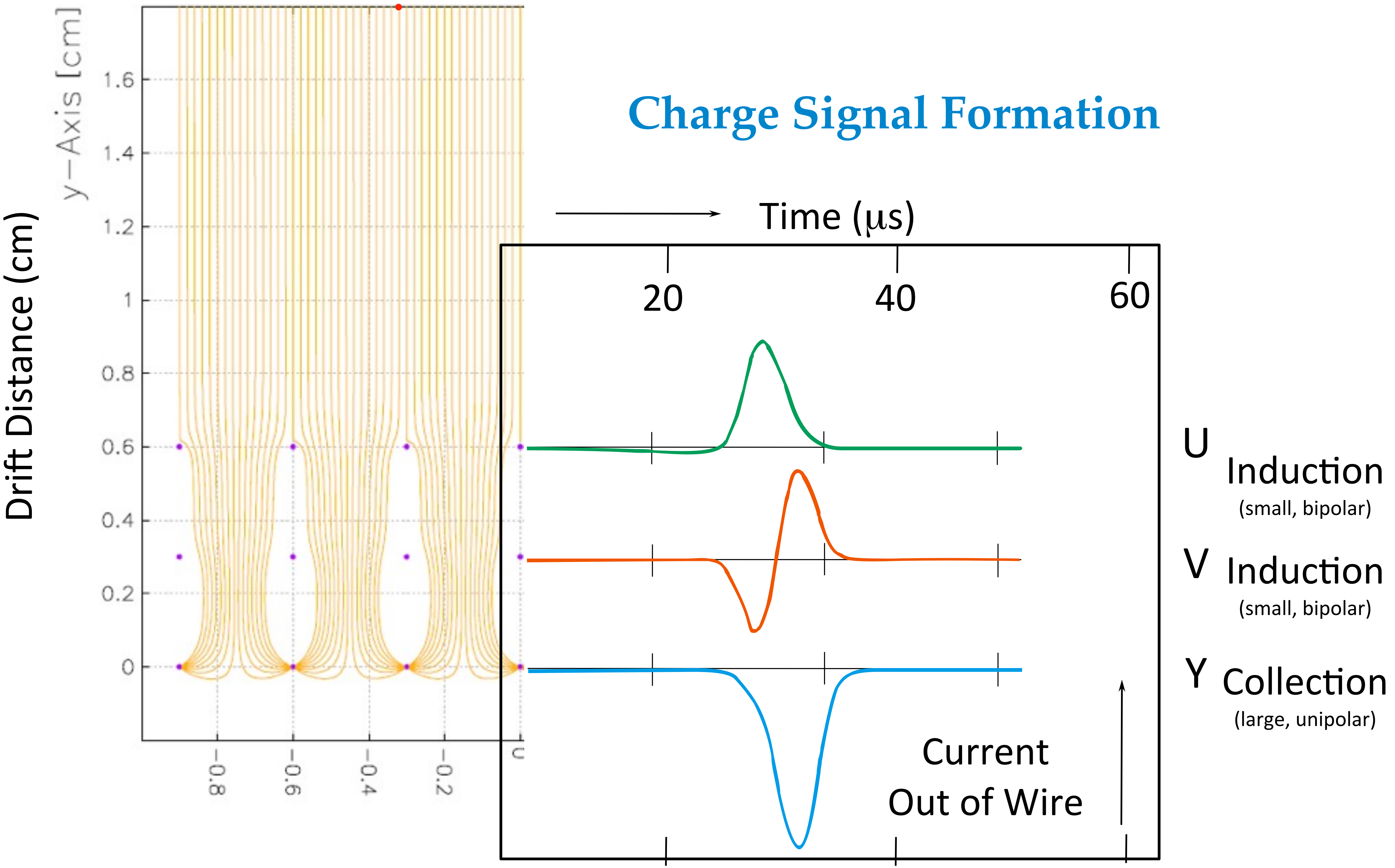
Liquid Argon Neutrino Detectors

- Ionization produced in neutrino interactions is drifted along E-field to finely segmented wireplanes.
- Timing of wire pulse information is combined with known drift speed to determine drift-direction coordinate.
- Calorimetry information is extracted from wire pulse characteristics.
- Abundant scintillation light, which LAr is transparent to, also available for collection and triggering.

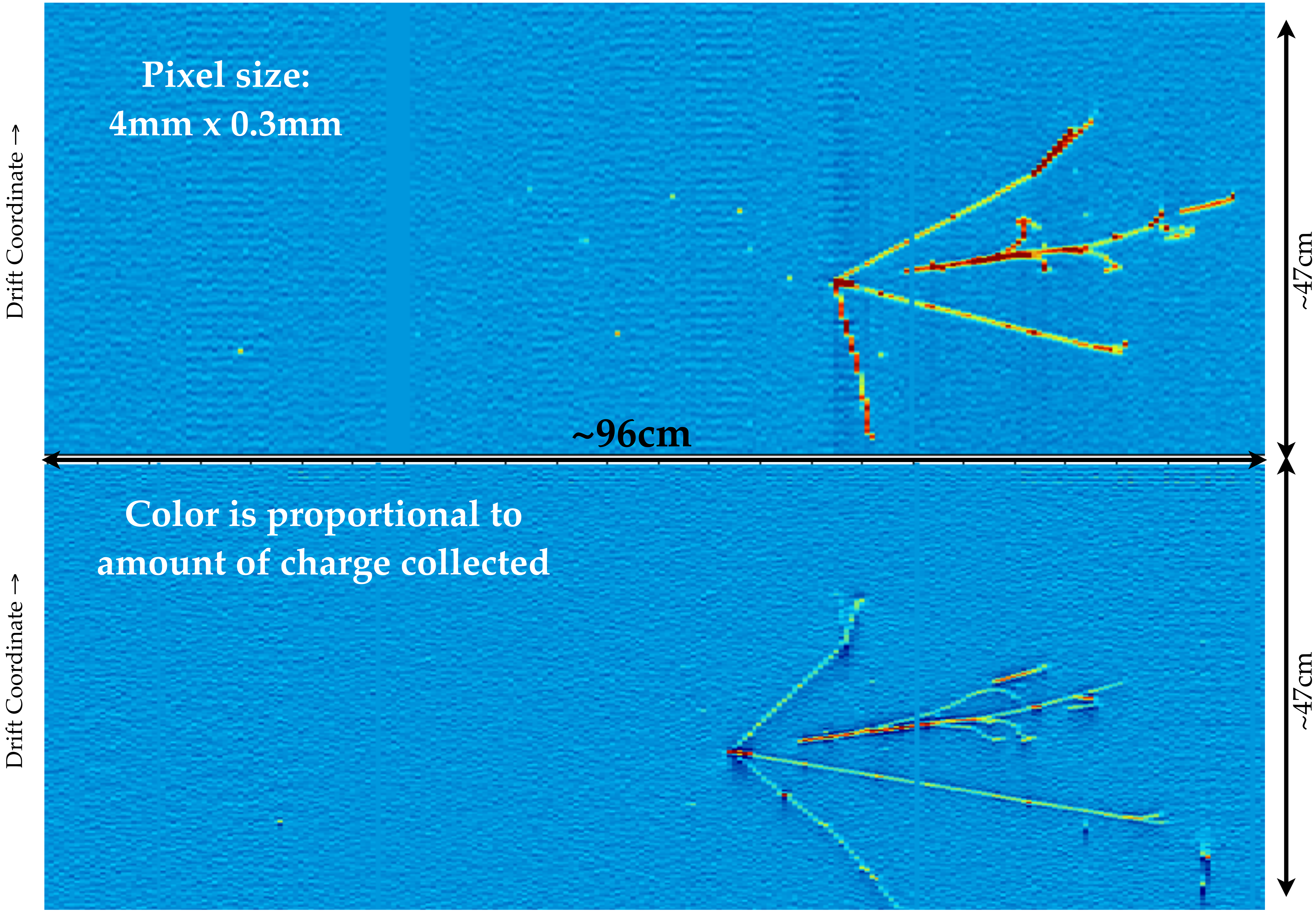


Refs:
1.) *Liquid-argon ionization chambers as total-absorption detectors*, W. Willis and V. Radeka, Nuclear Instruments and Methods 120 (1974), no. 2, 221-236.
2.) *The Liquid-argon time projection chamber: a new concept for Neutrino Detector*, C. Rubbia, CERN-EP/77-08 (1977)

Liquid Argon Neutrino Detectors



Neutrino Interaction in ArgoNeuT

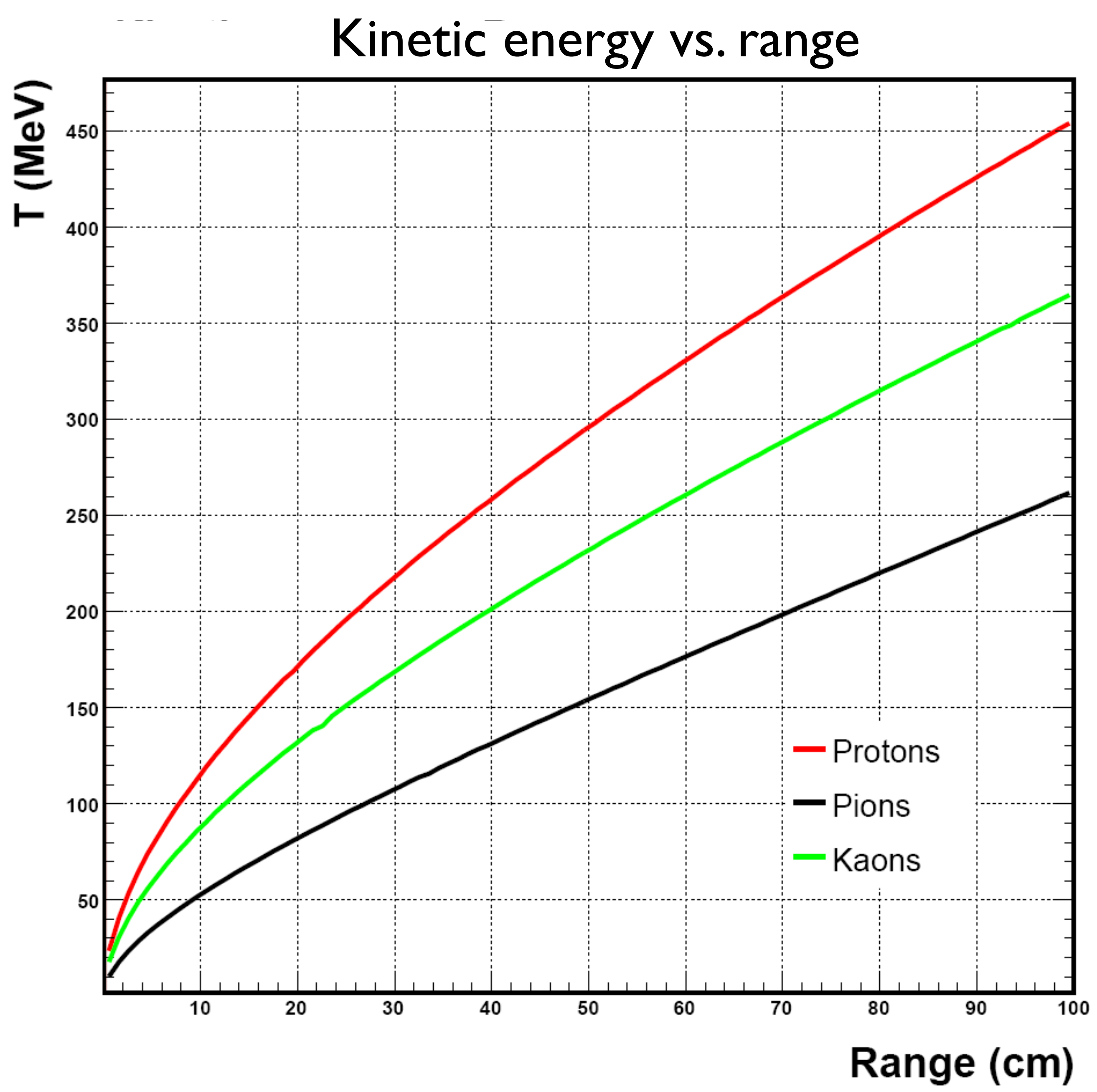


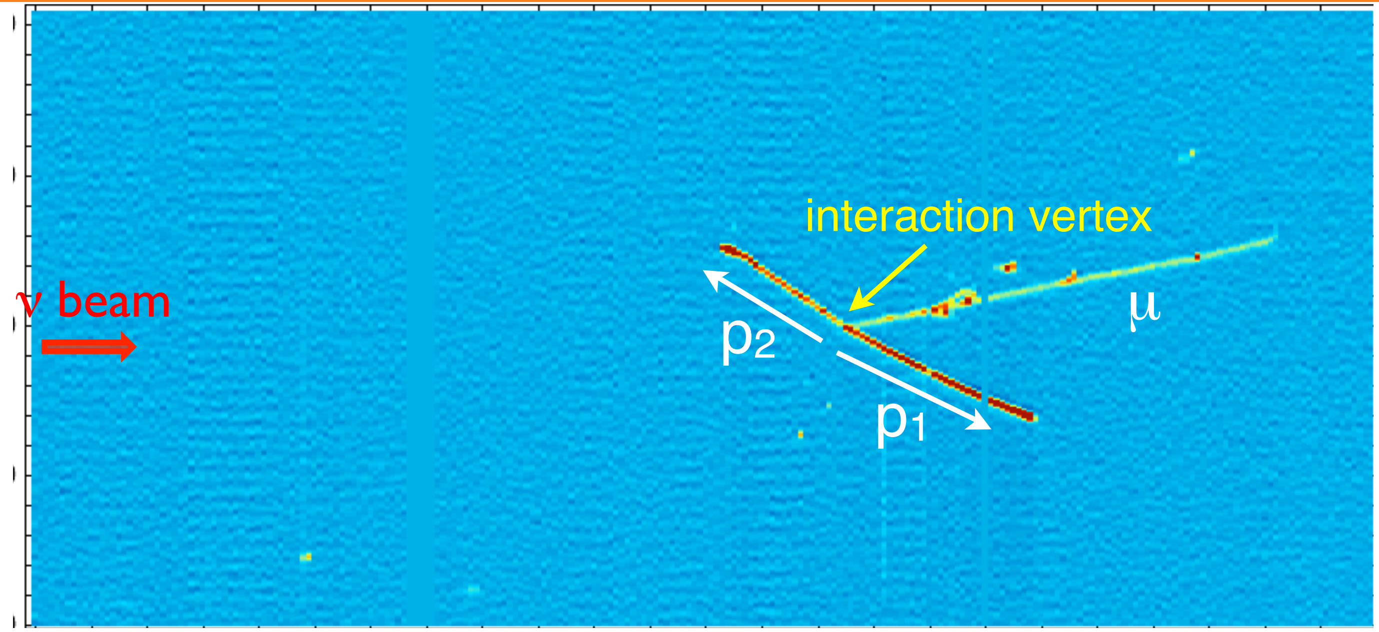
Why Noble Liquids for Neutrinos?

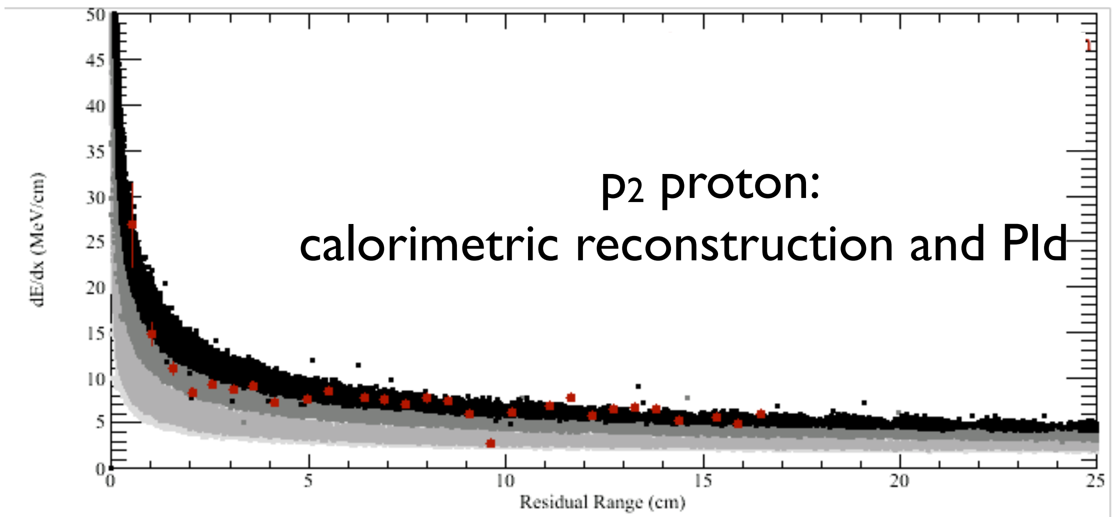
- Abundant ionization electrons and scintillation light can both be used for detection.
- If liquids are highly purified (<0.1ppb), ionization can be drifted over long distances.
- Excellent dielectric properties accommodate very large voltages.
- Argon is relatively cheap and easy to obtain (1% of atmosphere).
- Noble liquids are dense, so they make a good target for neutrinos.
- Drawbacks?...no free protons...nuclear effects.

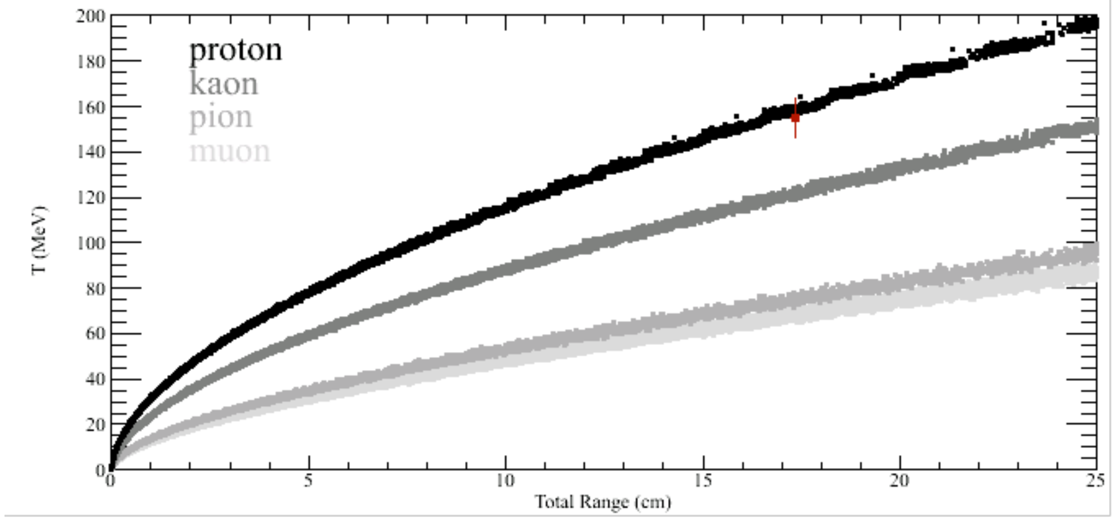
	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	
Price [$/Liter]	~10	~100	~1	~300	~3000	~1

Liquid Argon Properties

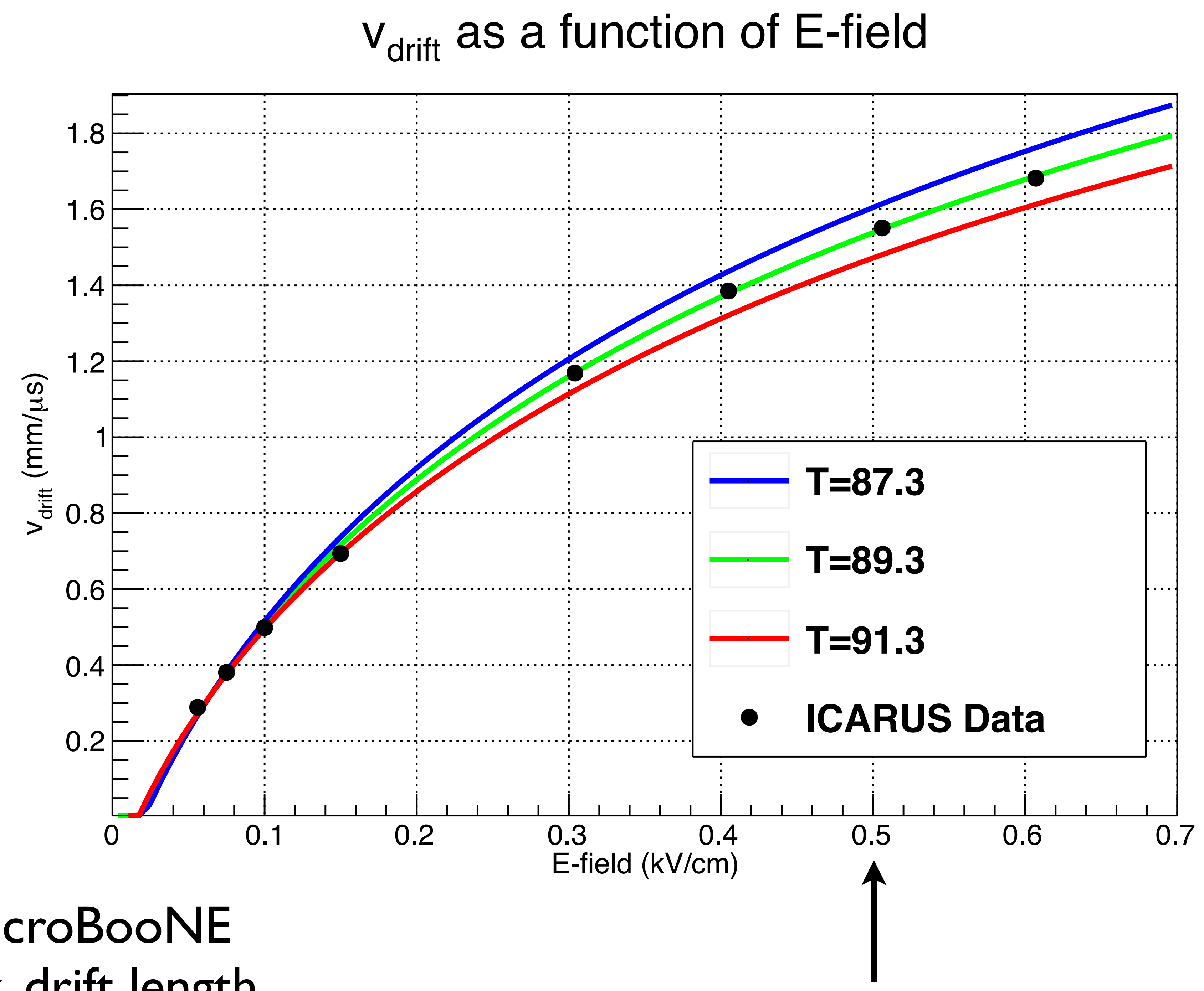








Liquid Argon Properties



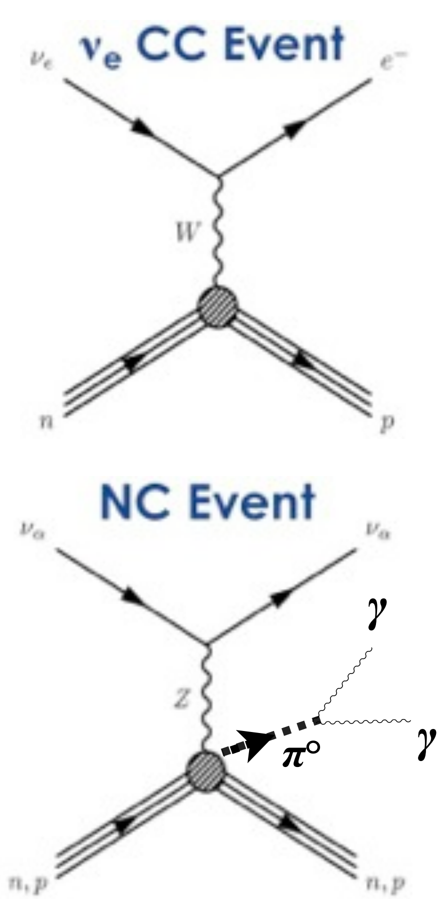
Example: MicroBooNE has 2.5m max. drift length. @ 1.5mm/μs, that will take 1.6ms.

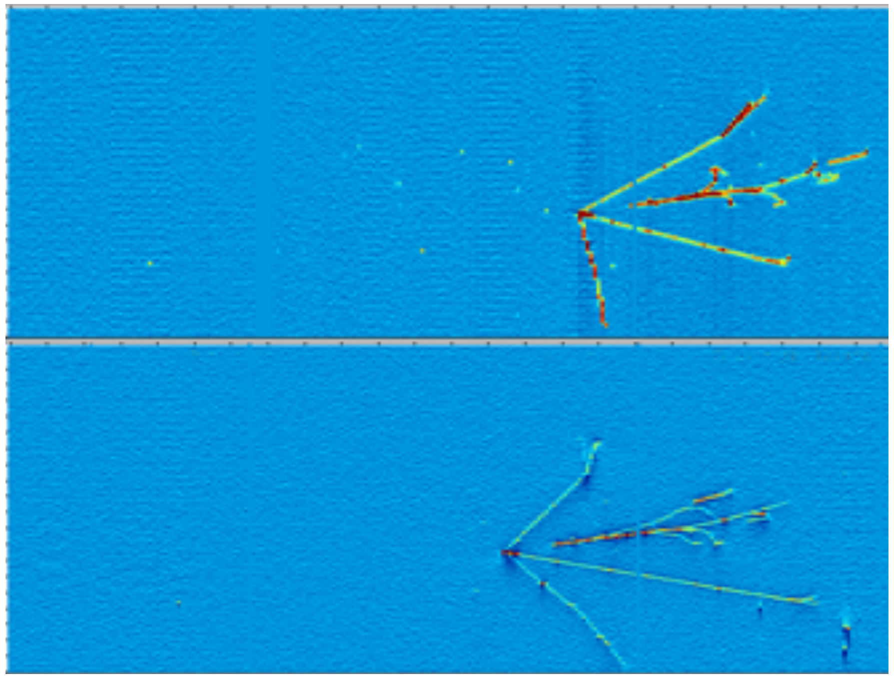
Canonical operating field of LArTPCs (500 V/cm)

Advantages of LAr TPCs

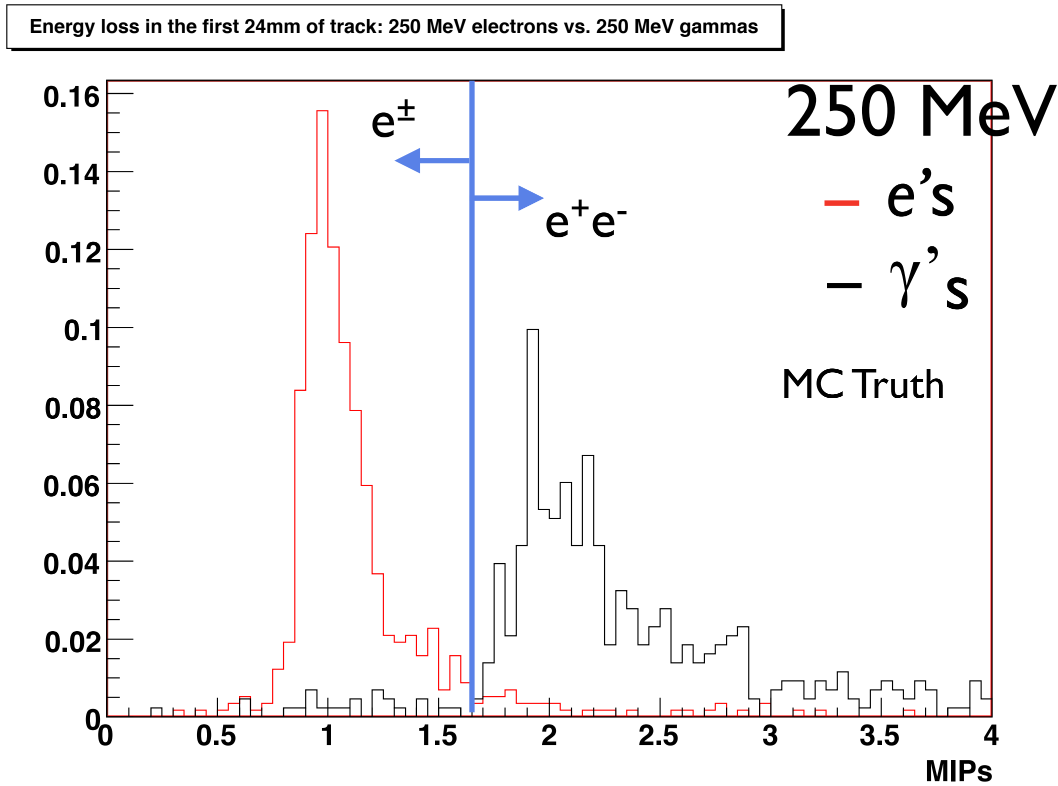
excellent e/γ separation → superior background rejection

- Particle identification comes primarily from dE/dx (energy deposited) along track.
  - Millimeter wire spacing plus appropriate sampling provides fine-grained resolution
- ν_e appearance: Excellent signal (CC ν_e) efficiency and background (NC π^0) rejection
  - Topological cuts will also improve signal/background separation
- Appear scalable to large sizes.
- Beautiful, bubble-chamber like events!





ArgoNeuT Event



dE/dx for electrons and gammas in first 2.4 cm of track

LAr Worldwide

Completed/Ongoing/Potential/Proposed/Suggested LAr Projects, separated by location of the detectors.

US

Materials Test Stand
ArgoNeuT
Liquid Argon Purity Demonstrator
MicroBooNE
LBNE
1 kTon LArTPC
Test-Beam @ FNAL (LArIAT)
Test-Beam @ Los Alamos (CAPTAIN)
GLADE
RADAR

Europe

3-ton prototype
50-liter @ CERN
$10m^3$
ICARUS
LArTPC in B-Field
LANDD @ CERN
ArgonTube @ Bern
UV Laser
GLACIER/LAGUNA
Double-LAr @ CERN-PS

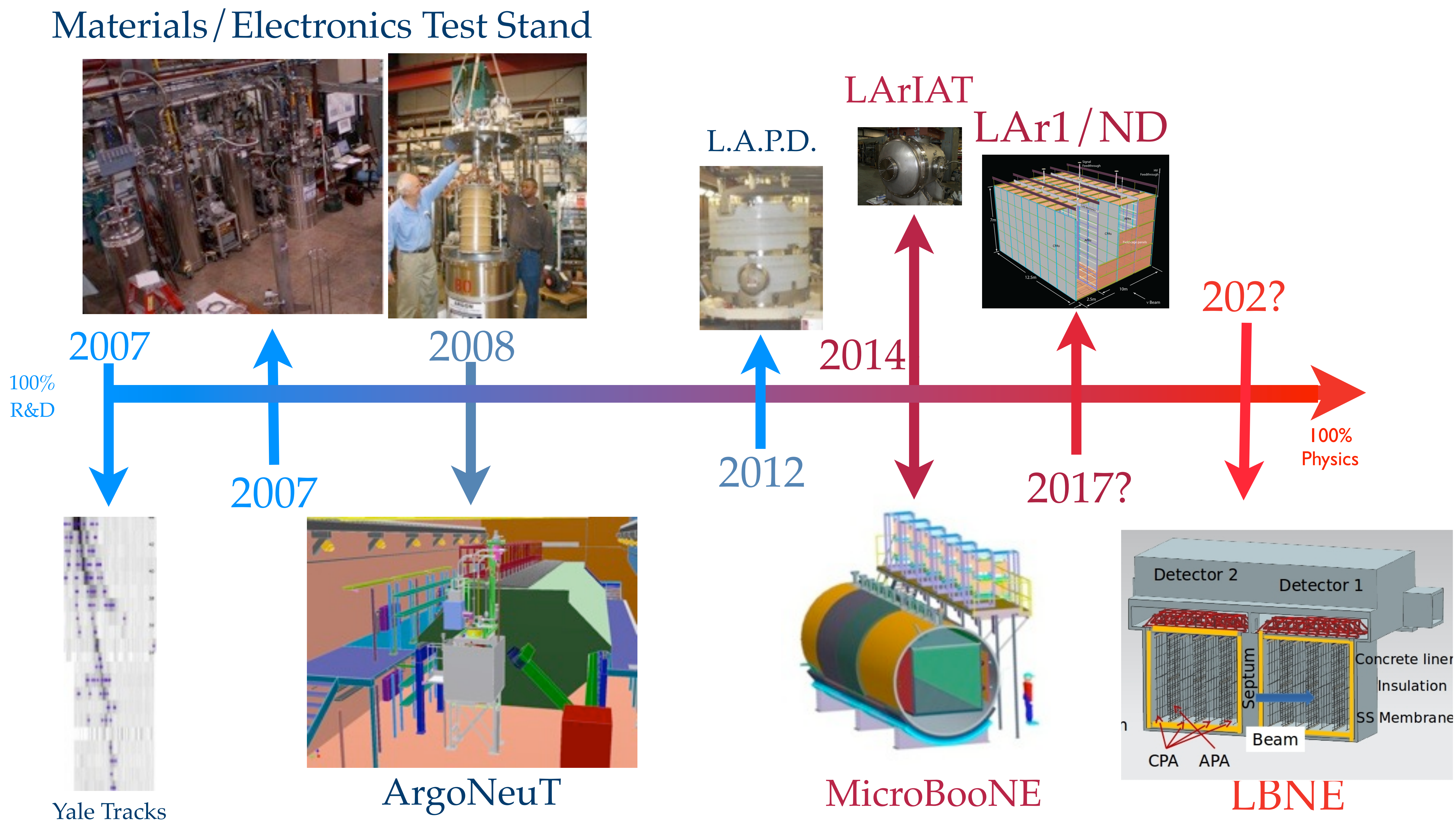
Japan

Test-Beam (T32) at J-PARC
100 kTon @ Okinoshima island

Message is that majority of these ideas are <5 years old, demonstrating growing interest.

*LAr also pursued for Dark Matter: DarkSide, ArDM, DEAP/CLEAN, WARP, Depleted Argon, ...

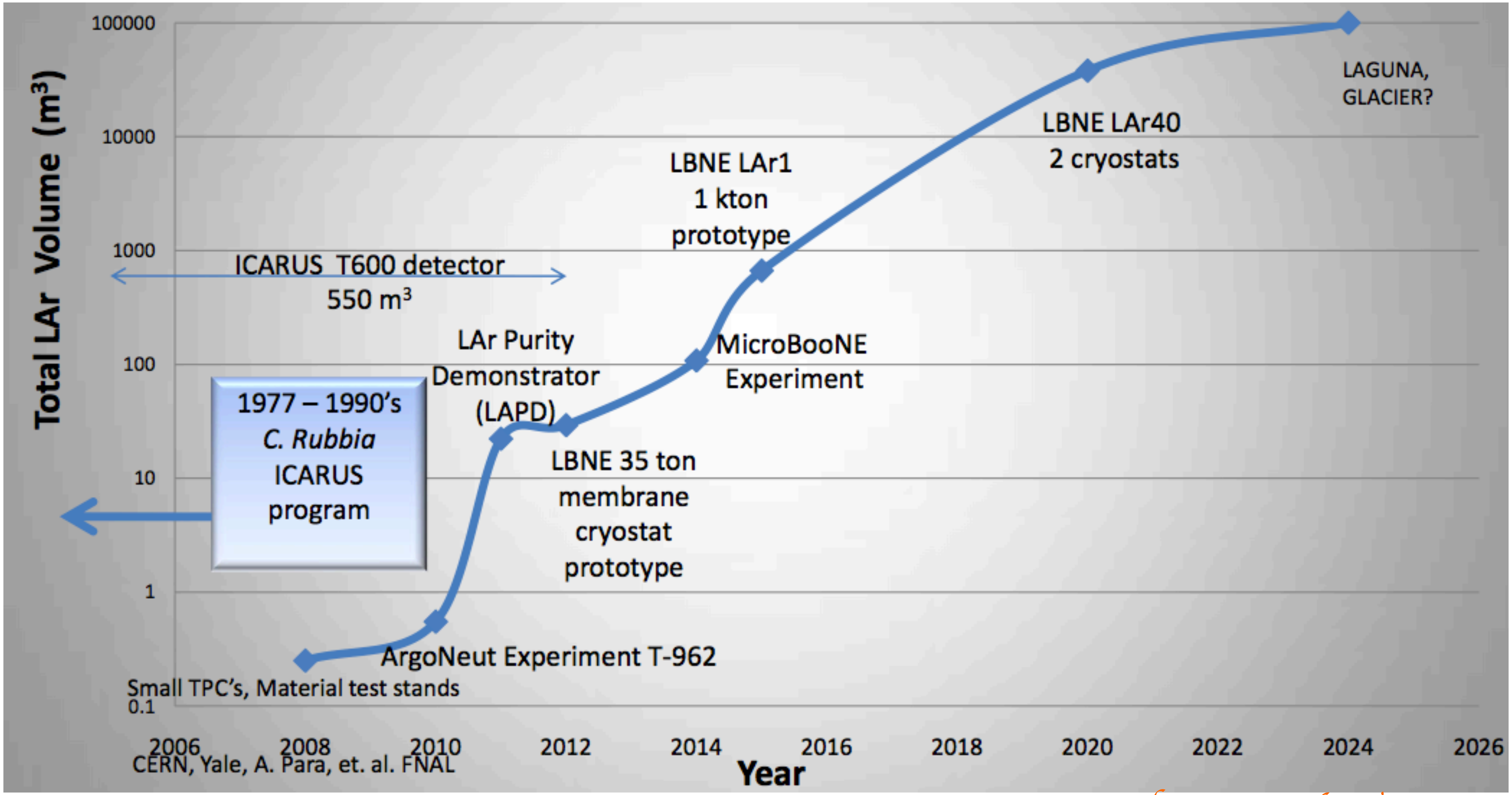
Recent / Future LAr Activity in the U.S.



Refs:
1.) *A Regnerable Filter for Liquid Argon Purification* Curioni et al, NIM A605:306-311 (2009)
2.) *A system to test the effect of materials on electron drift lifetime in liquid argon and the effect of water* Andrews et al, NIM A608:251-258 (2009)

Recent/Future LAr Activity in the U.S.

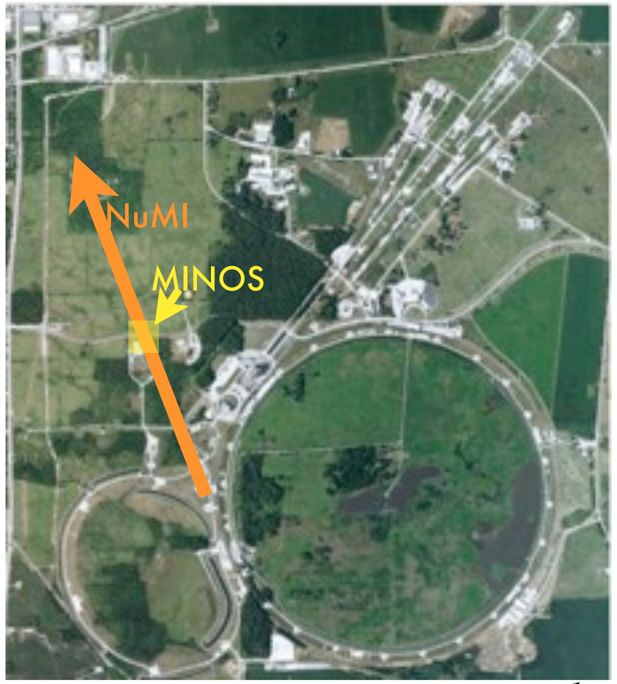
Volume of LAr TPC Detectors with Time



Russ Rucinski, TIPP 2011

The ArgoNeuT Project

- ArgoNeuT deployed a ~175 liter LArTPC in Fermilab NuMI neutrino beam.
- Located upstream of MINOS near detector, which provides muon reconstruction and sign selection.
- Collected 1.35×10^{20} Protons on Target (POT), predominantly in antineutrino mode.



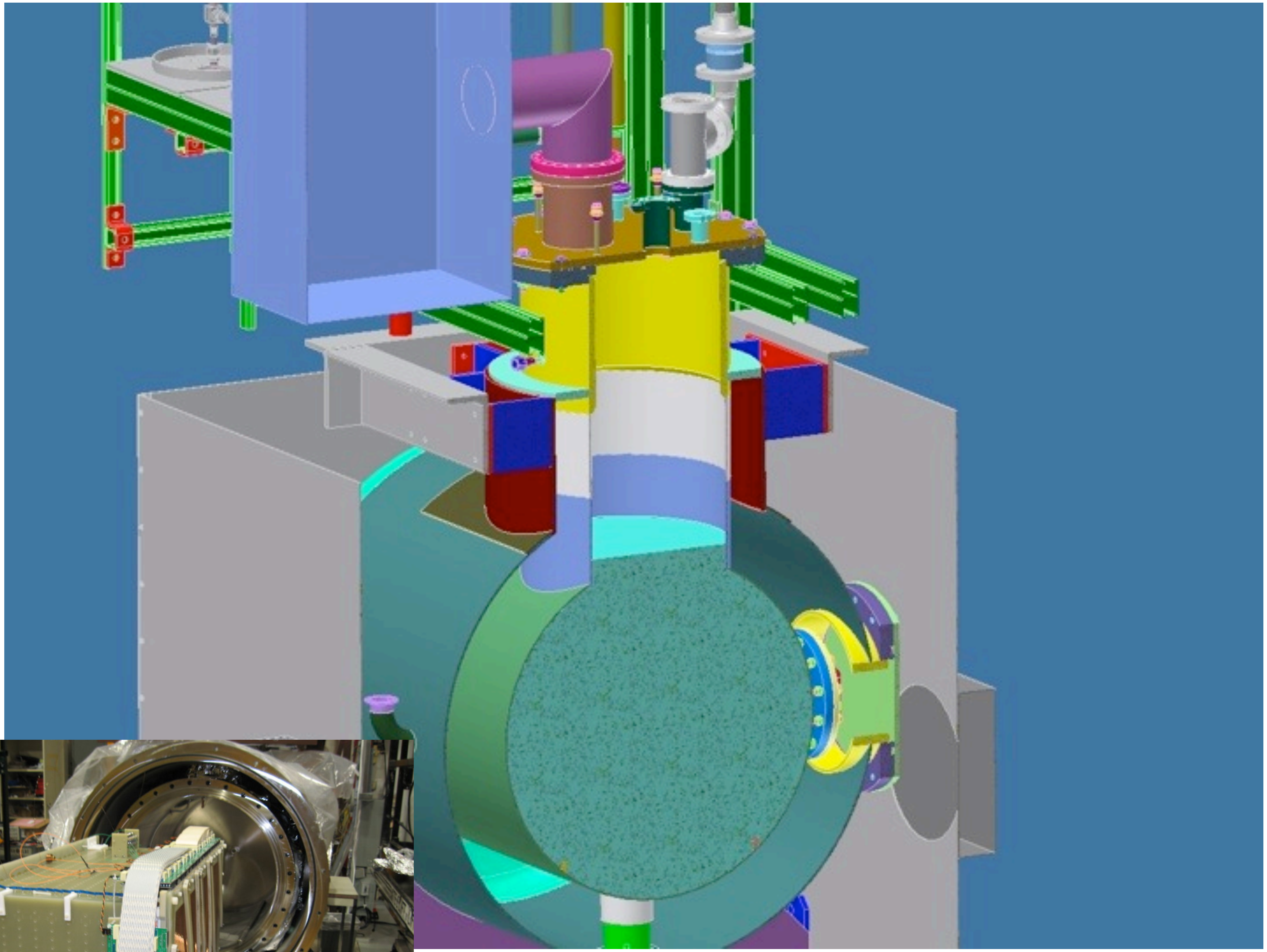
NuMI Beam at Fermilab

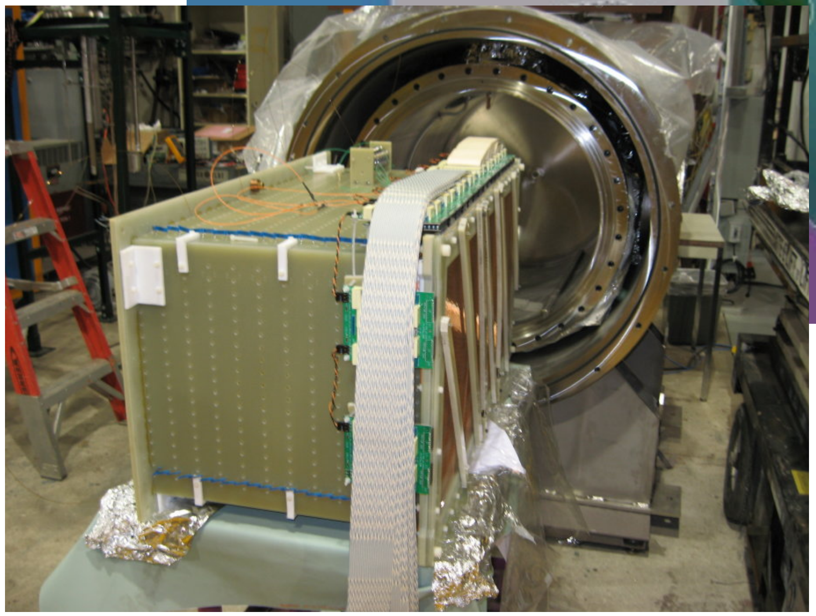
Cryostat Volume	500 Liters
TPC Volume	175 Liters (90cm x 40cm x 47.5cm)
# Electronic Channels	480
Electronics Style (Temp.)	JFET (293 K)
Wire Pitch (Plane Separation)	4 mm (4 mm)
Electric Field	500 V/cm
Max. Drift Length (Time)	0.5 m (330 μs)
Wire Properties	0.15mm diameter BeCu

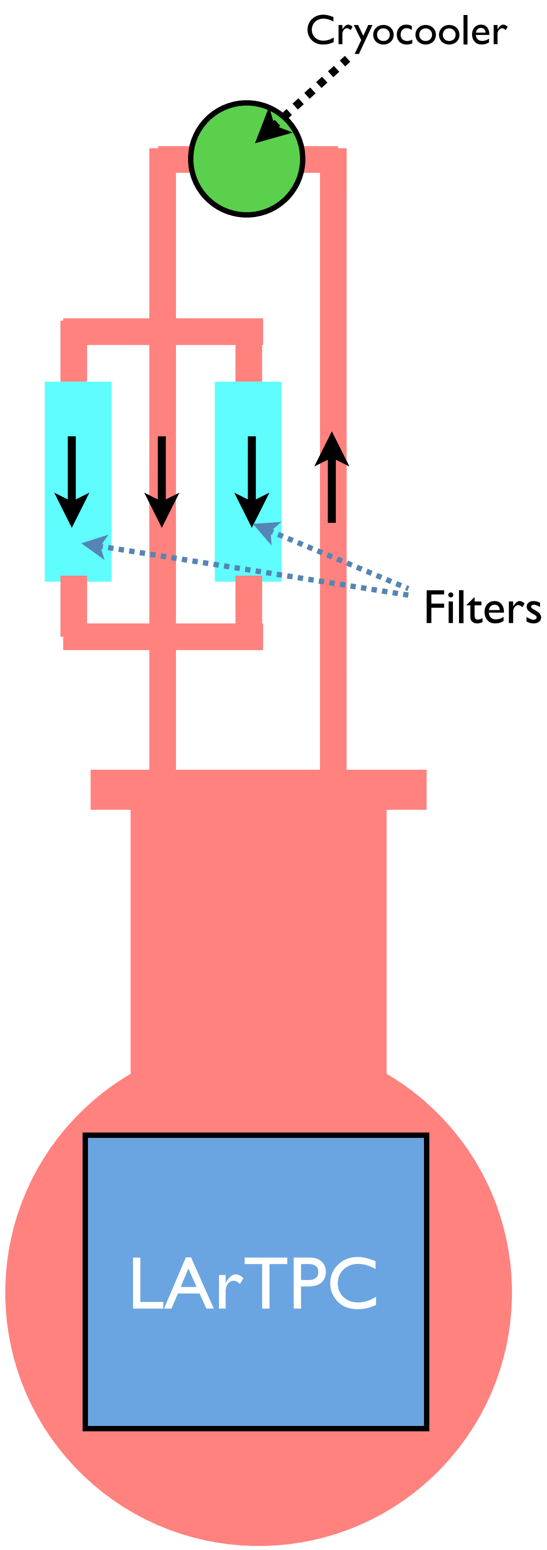
ArgoNeuT in the NuMI Tunnel

Refs:
1.) *The ArgoNeuT detector in the NuMI low-energy beam line at Fermilab*, C. Anderson et al., JINST 7 P10019, Oct. 2012, arXiv:1205.6747

The ArgoNeuT Project

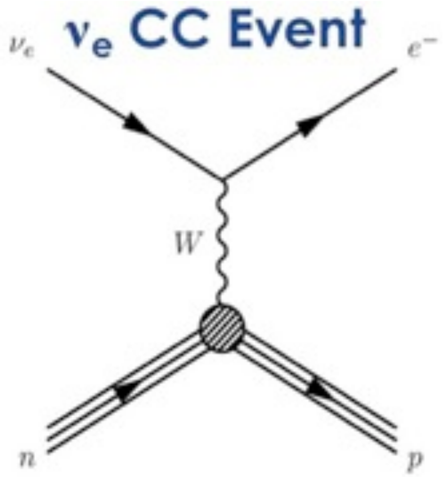


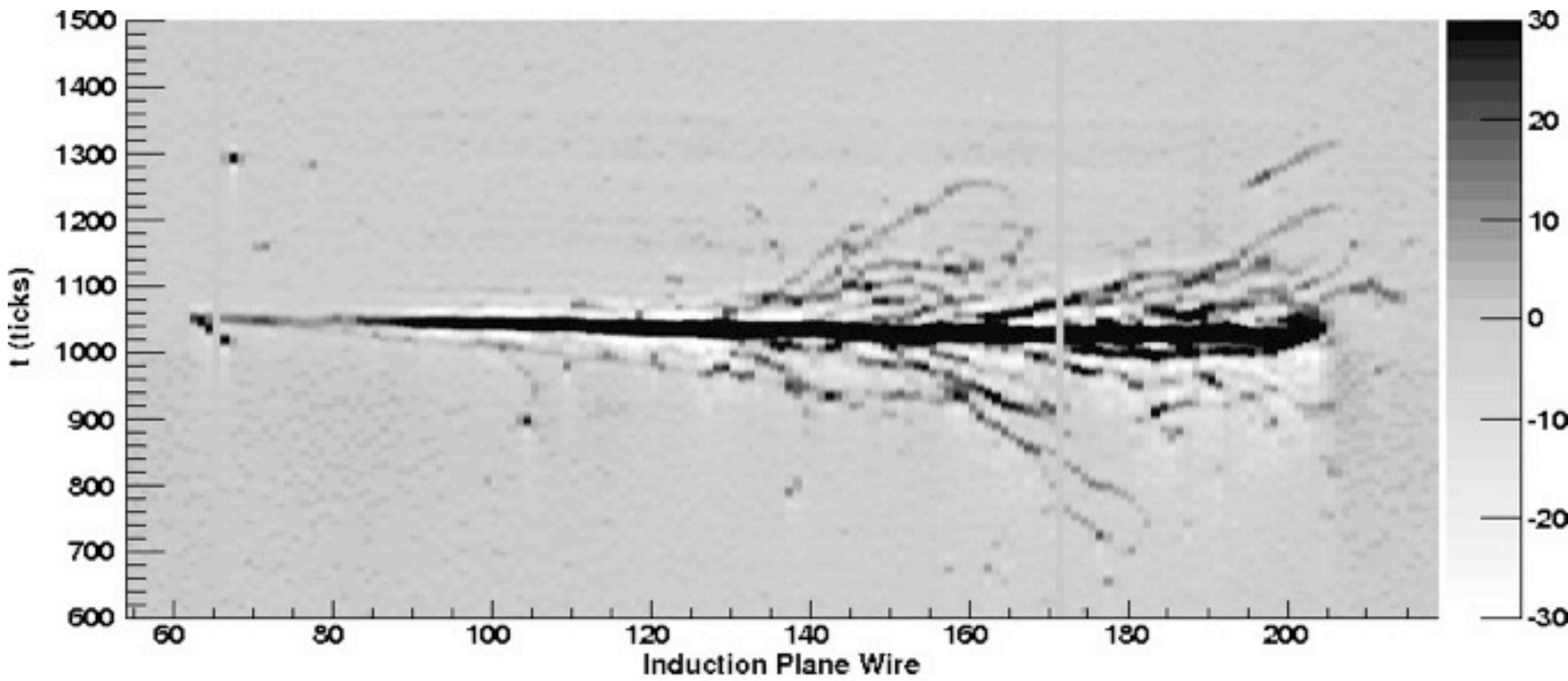


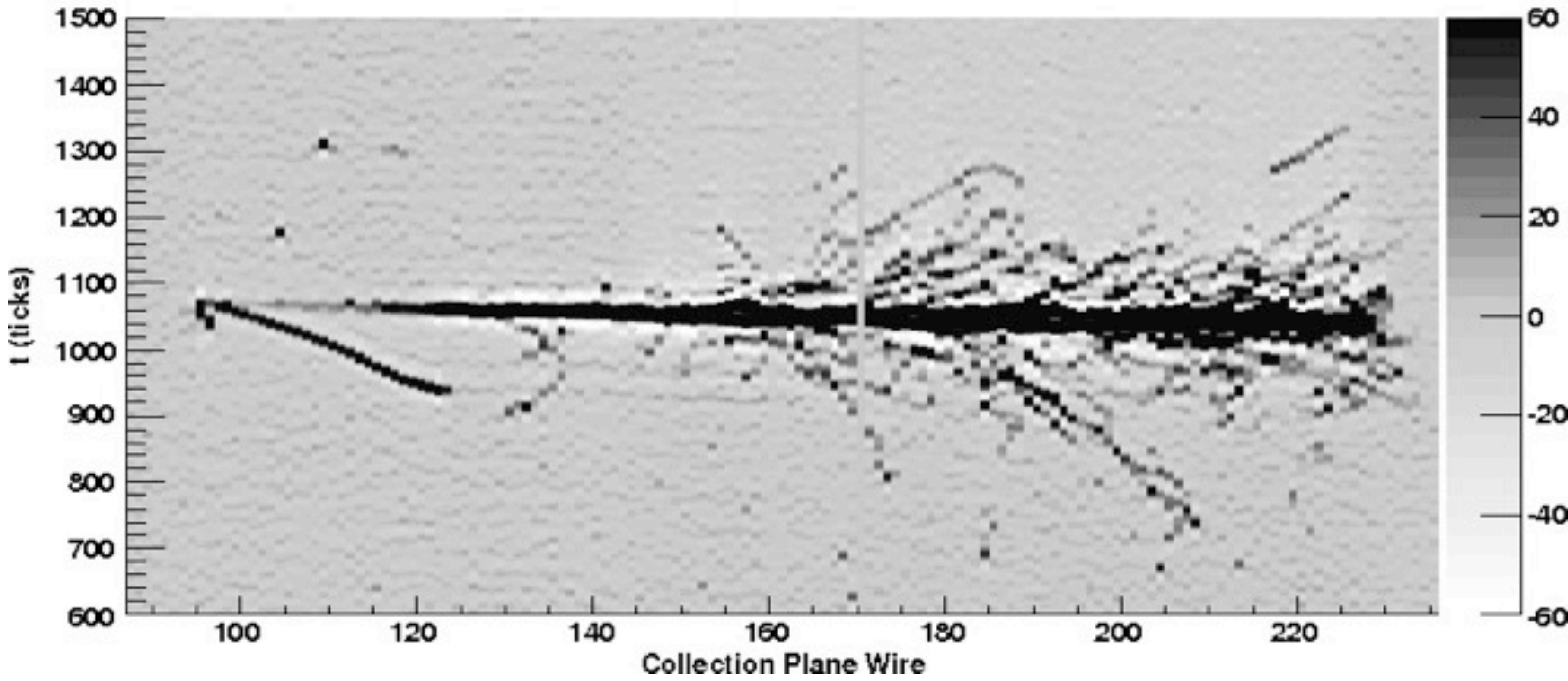


Neutrino Interaction in ArgoNeuT

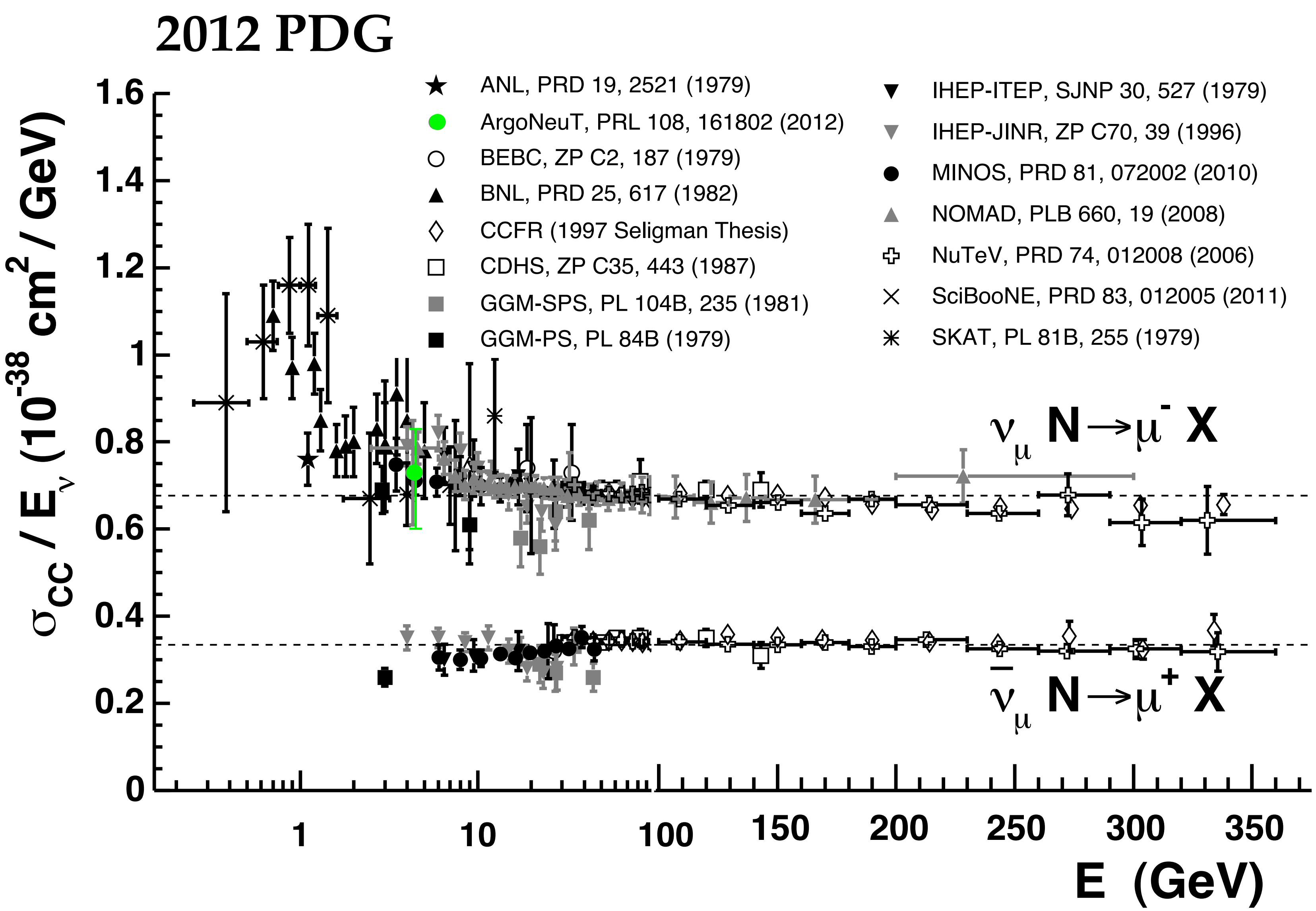
CCQE ν_e candidate
(Sept. 2009)

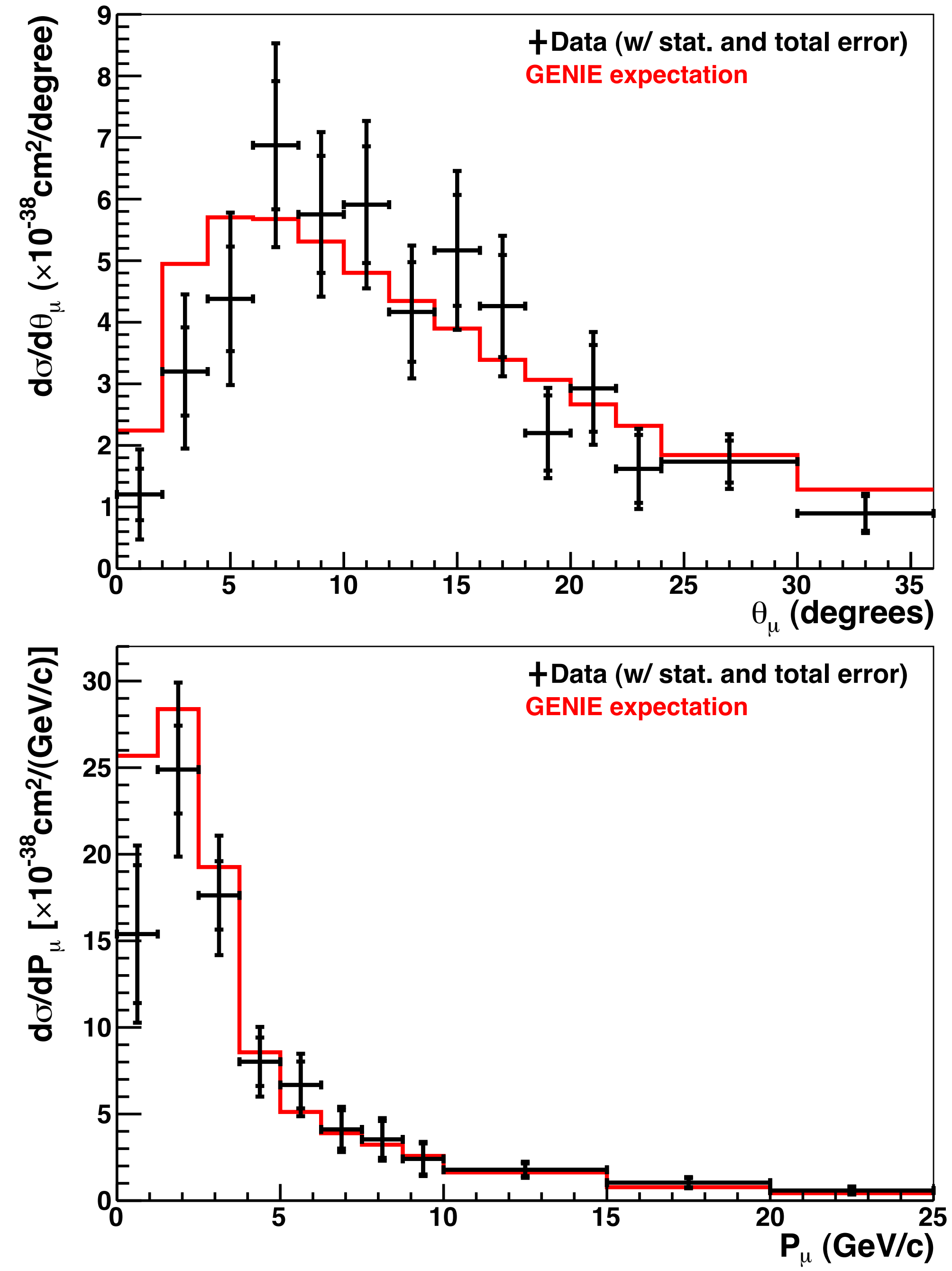






ArgoNeuT: Physics





Inclusive CC cross-section

- First Results: Using **2 weeks** of neutrino-mode data (8.5×10^{18} POT), the differential cross-section for inclusive charged-current muon neutrino production was measured.
- Analysis Selection:
  - Track originating within ArgoNeuT fiducial region.
  - Match to corresponding track in MINOS near detector.
  - MINOS track is negatively charged.

$$\frac{\partial\sigma(u_i)}{\partial u} = \frac{N_{\text{measured},i} - N_{\text{background},i}}{\Delta u_i \ \epsilon_i \ N_{\text{targ}} \ \Phi}$$

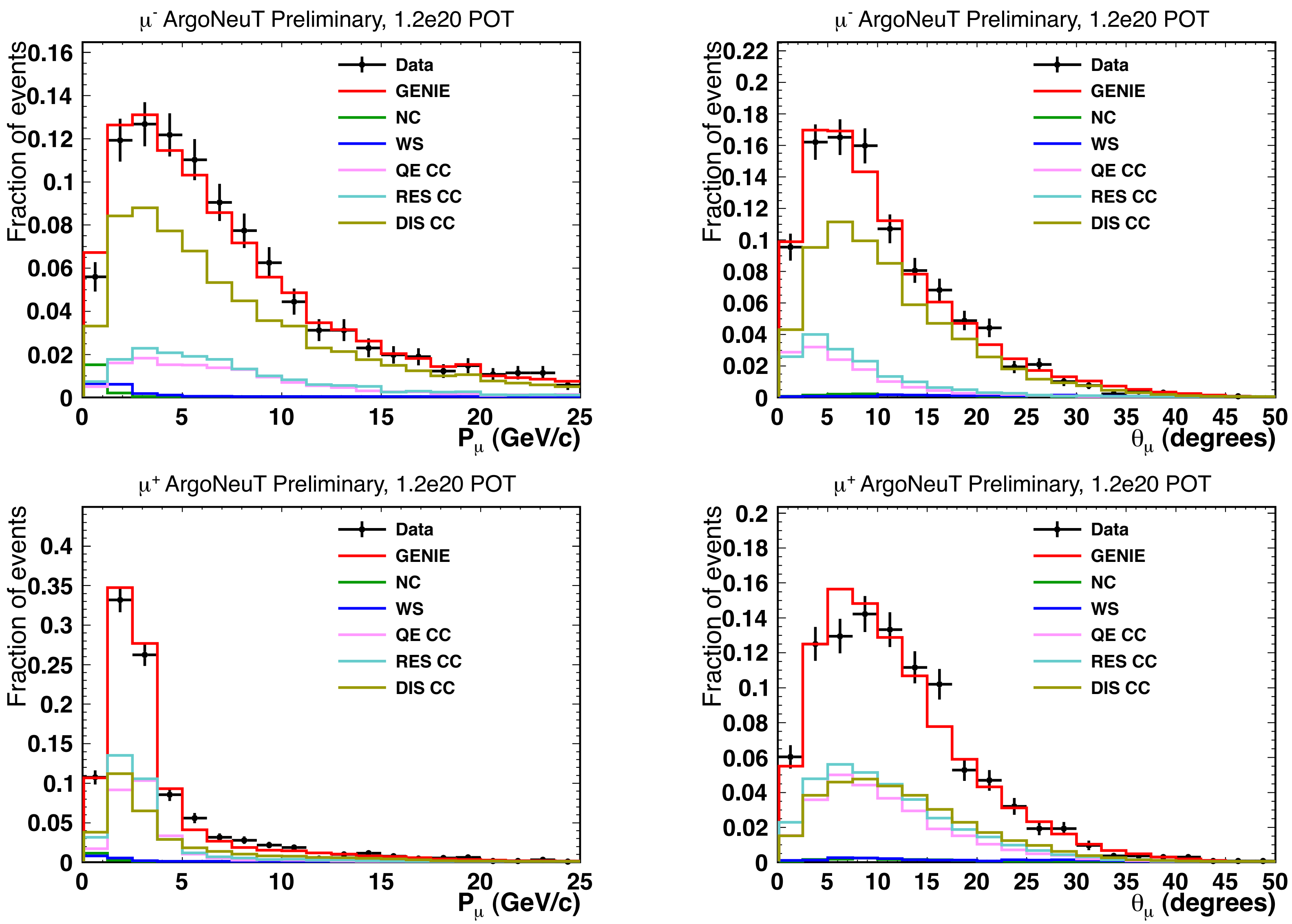
Refs:

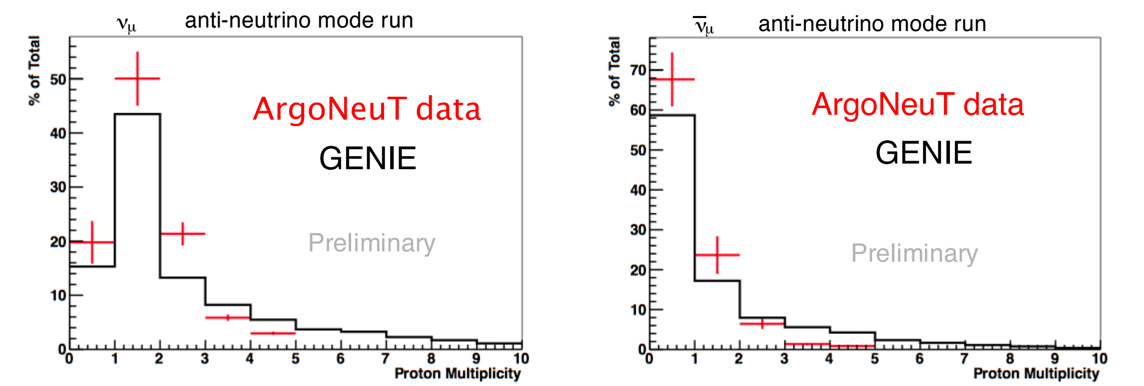
1.) *First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon*, C. Anderson et al., PRL 108 (2012) 161802, arXiv:1111.0103

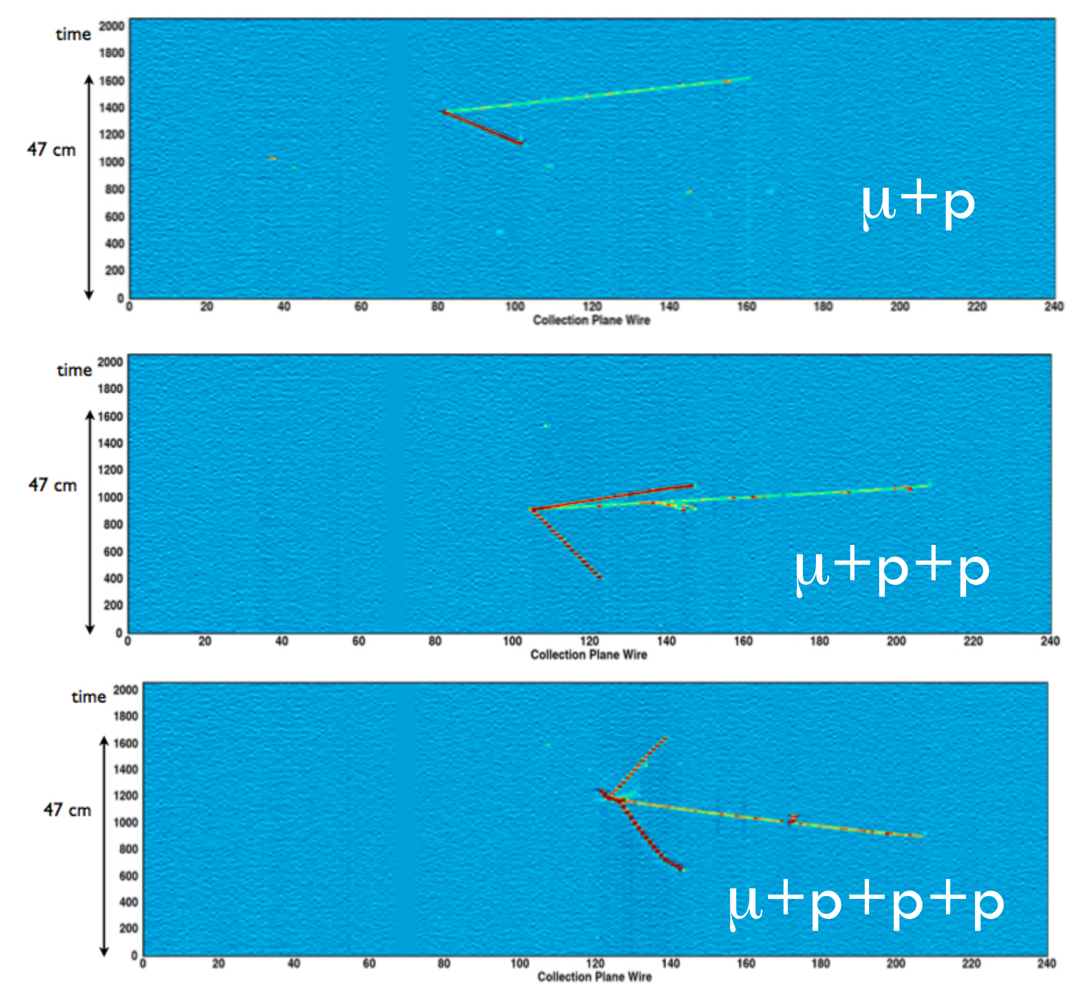
2.) *Neutrino cross section measurements*, J. Beringer et al. (Particle Data Group), Phys. Rev. D**86**, 010001 (2012)

ArgoNeuT: Physics

- ArgoNeuT has highlighted need to consider nuclear effects (e.g. - Multinucleon Correlations, final-state activity) when analyzing LArTPCs.
- Repeat of CC-Inclusive analysis in antineutrino mode.
- Papers in progress.



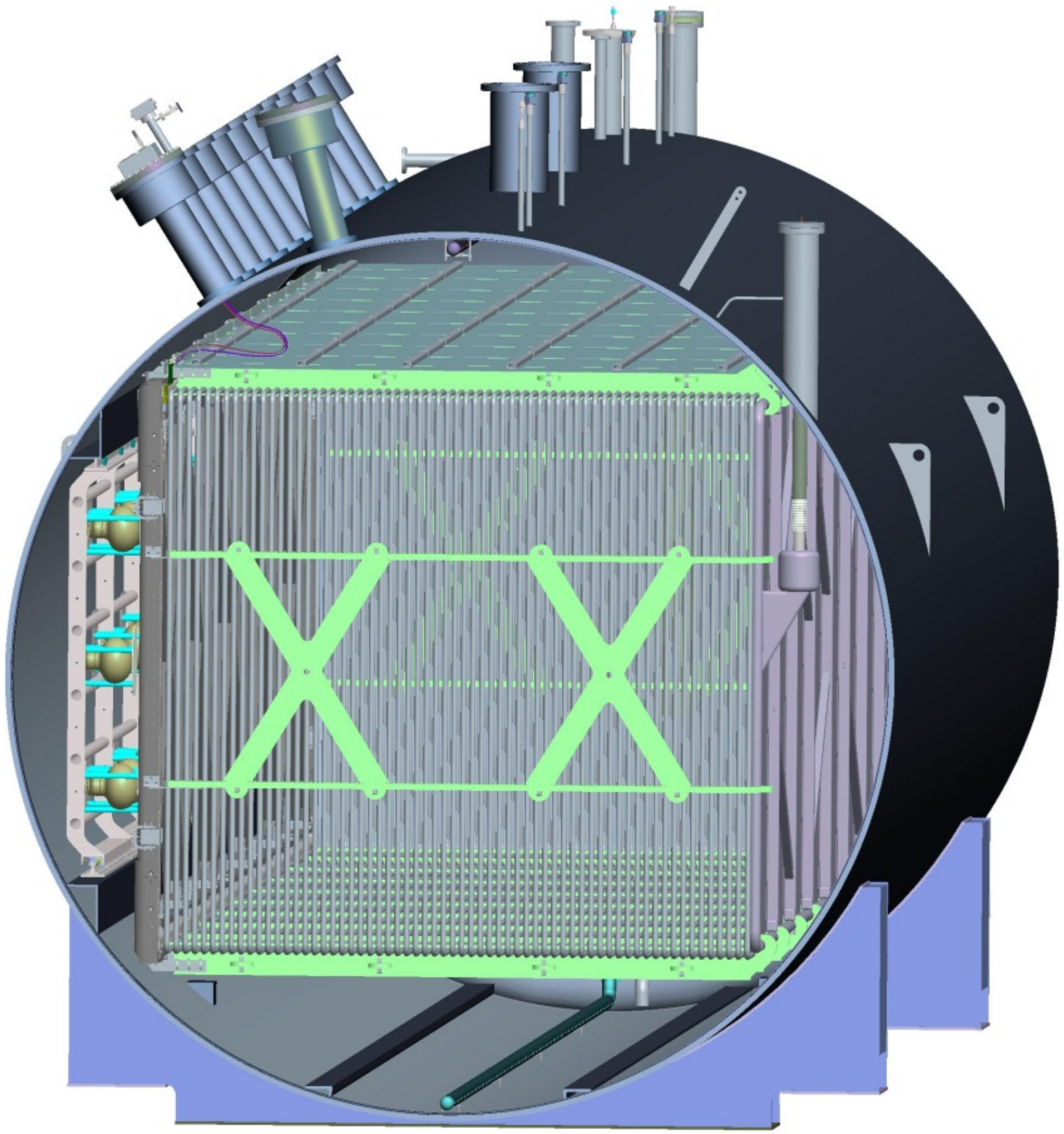




Refs:
1.) *Exclusive Topologies reconstruction in LAr-TPC experiments: a Novel Approach for precise Neutrino-Nucleus Cross-Sections Measurements*, O. Palamara, K. Partyka, F. Cavanna, arXiv:1309.7480
2.) *New Results from ArgoNeuT*, T. Yang, NuFACT2013, hep-ex/1311.2096

The MicroBooNE Experiment

- MicroBooNE will operate in the Booster neutrino beam at Fermilab starting in 2014.
- Combines physics with hardware R&D necessary for the evolution of LArTPCs.
  - MiniBooNE low-energy excess
  - Low-Energy (<1 GeV) neutrino cross-sections
  - Cold Electronics (preamplifiers in liquid)
  - Long drift (2.5m)
  - Purity without evacuation.

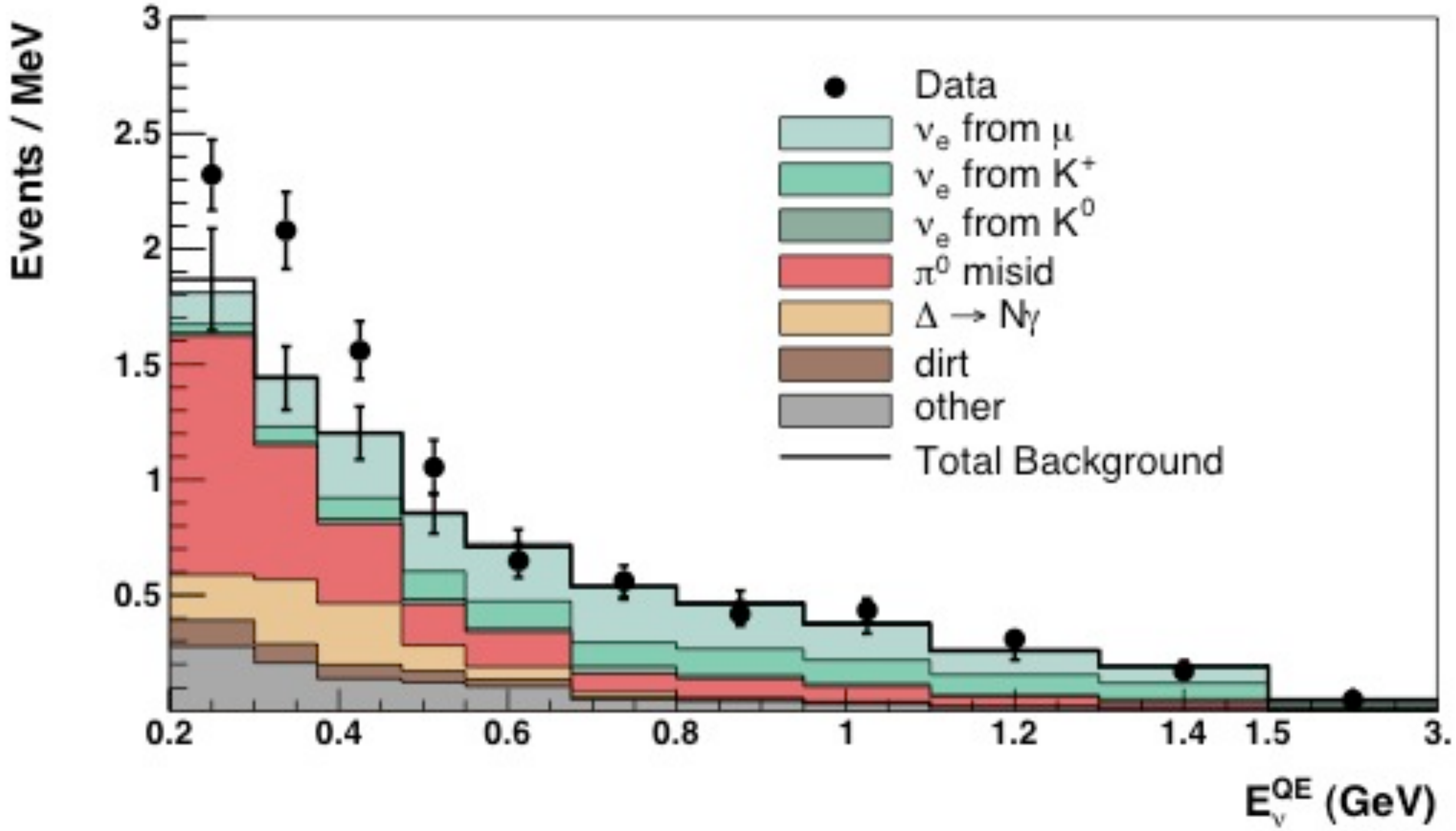


Refs:
1.) *Proposal for a New Experiment Using the Booster and NuMI Neutrino Beamlines*, H. Chen et al., FERMILAB-PROPOSAL-0974

MicroBooNE Physics

- Address the MiniBooNE low energy excess
  - MiniBoone is a Cerenkov detector that looked for ν_e appearance from a beam of ν_μ
  - Does MicroBooNE confirm the excess?
  - Is the excess due to a electron-like or gamma-like process?
- Prove effectiveness of electron/gamma separation technique (using dE/dX information).
- Low Energy Cross-Section Measurements (CCQE, NC π^o, $\Delta \rightarrow N\gamma$, Photonuclear, ...)
- Continue development of automated reconstruction (building on ArgoNeuT's effort).

MiniBooNE ν_e Appearance Result



MiniBooNE Result Excess

200-300MeV: 45.2±26.0 events

300-475MeV: 83.7±24.5 events

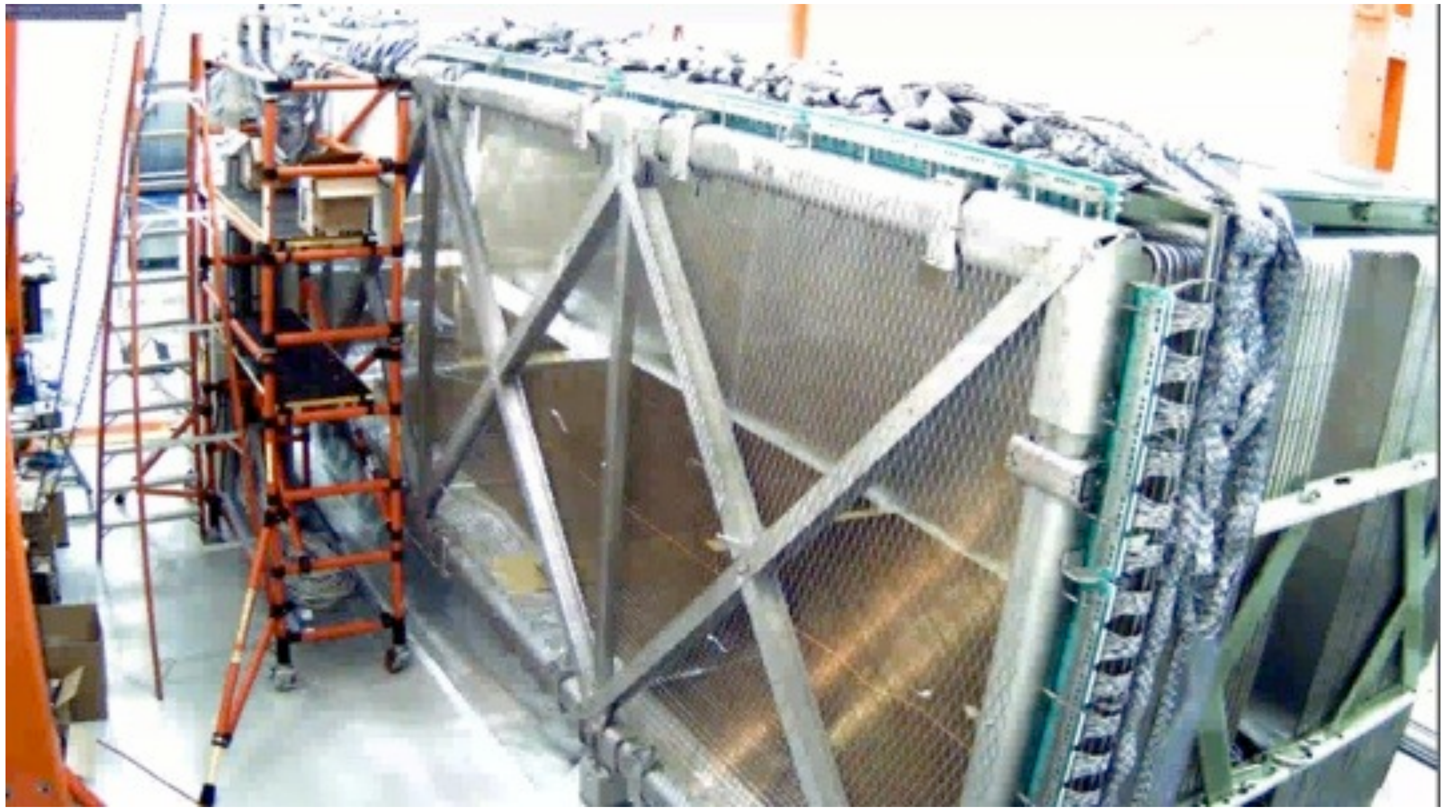
MicroBooNE will have 5σ significance for electron-like excess, 3.3σ for photon-like excess.

Refs:

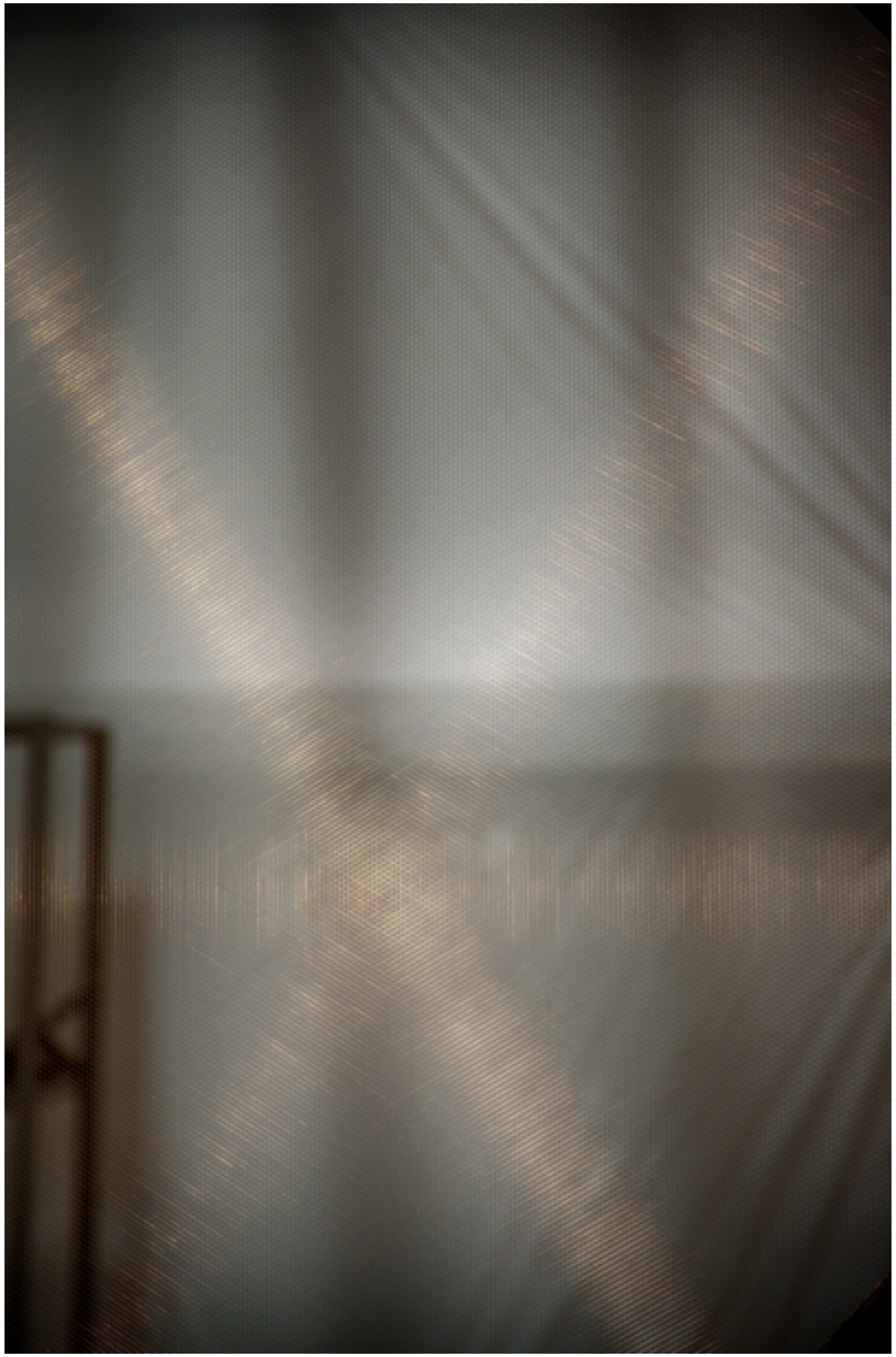
1.) *Unexplained Excess of Electron-Like Events From a 1-GeV Neutrino Beam* MiniBooNE Collaboration, Phys. Rev. Lett. 102, 101802 (2009)

MicroBooNE: TPC Detector

Cryostat Volume	150 Tons
TPC Volume (l x w x h)	89 Tons (10.4m x 2.5m x 2.3m)
# Electronic Channels	8256
Electronics Style (Temp.)	CMOS (87 K)
Wire Pitch (Plane Separation)	3 mm (3mm)
Max. Drift Length (Time)	2.5m (1.5ms)
Wire Properties	0.15mm diameter SS, Cu/Au plated
Light Collection	30 8″ Hamamatsu PMTs



MicroBooNE TPC (Nov. 2013)

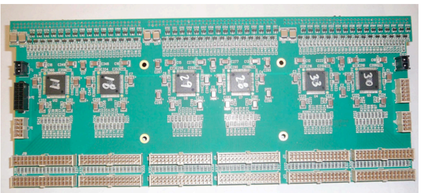


TPC Wires

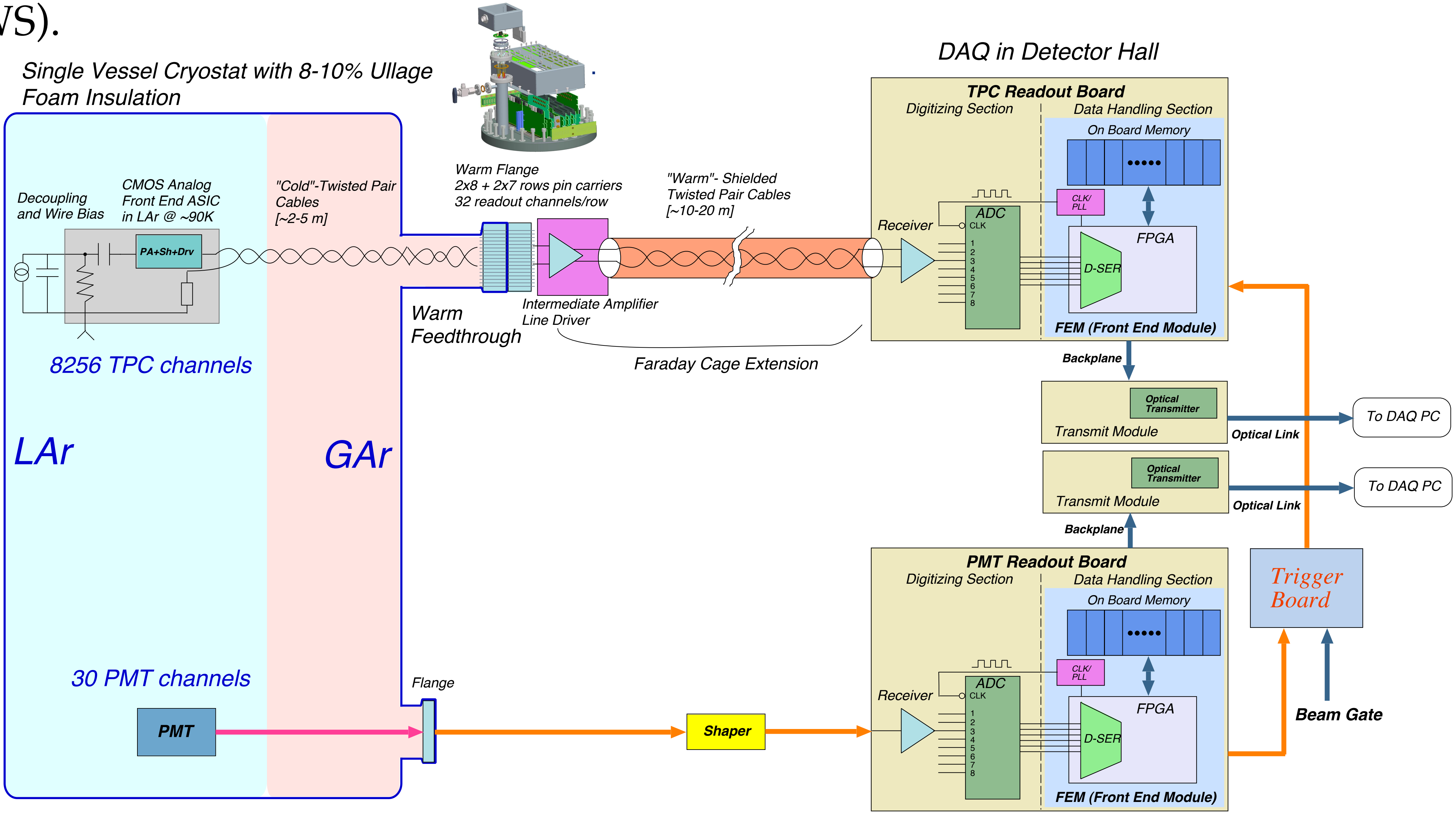
MicroBooNE: Cold Electronics

- CMOS preamplifiers located in liquid, attached to TPC, to minimize noise.
- 12-bit ADCs sampled at 2MHz (i.e. - 500ns per sample) for 4.8ms (x3 drift window).
- Several hour data buffering for Supernova analysis (triggered by receipt of alert signal from SNEWS).

Cold MotherBoards



Wire-carrier Board

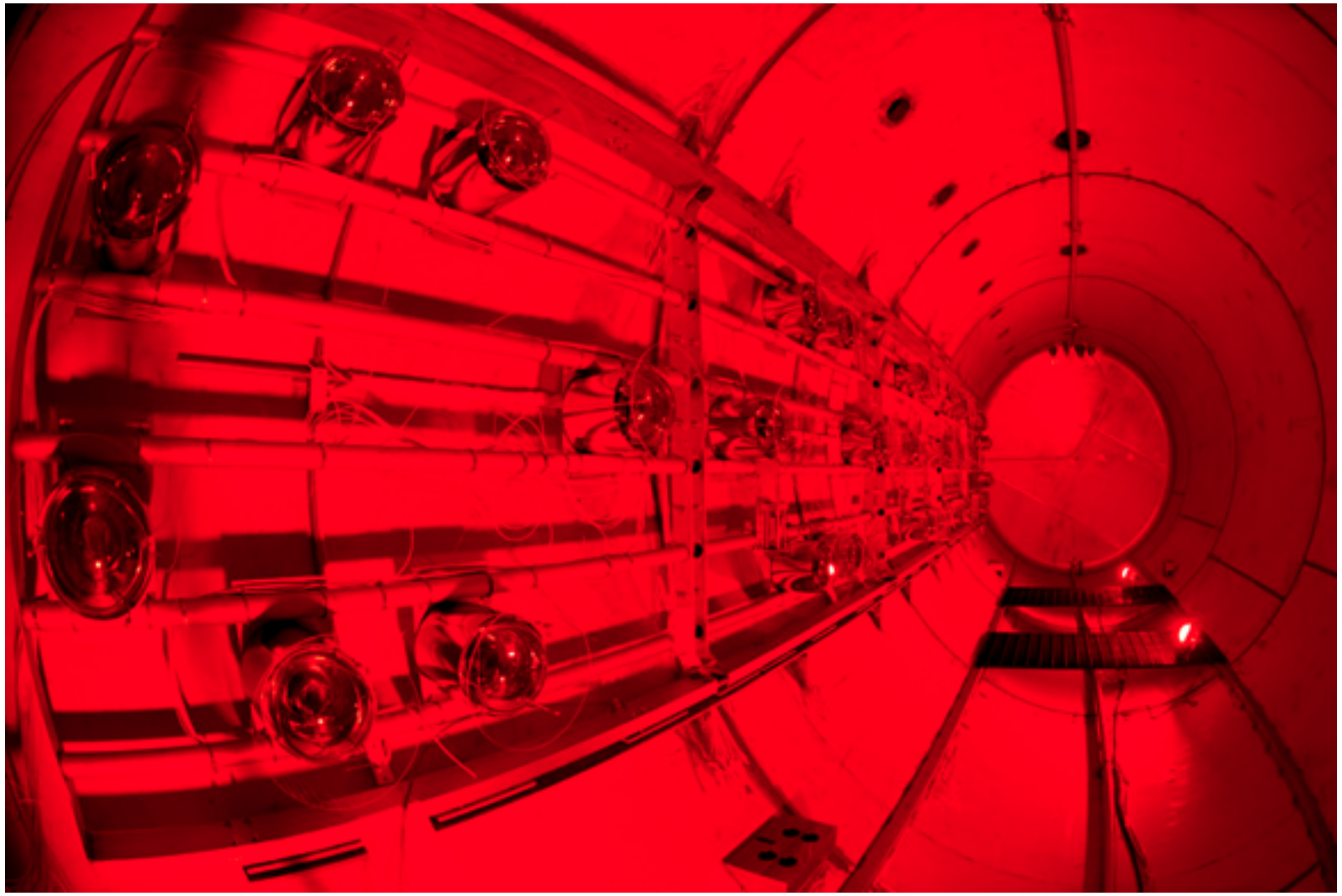


Refs:

1.) *Readout Electronics Design Considerations for LAr TPC*, H. Chen, ANT2013 Conference

MicroBooNE: Light Collection

- 30 8” Hamamatsu (R5912-02mod) cryogenic PMTs facing into the TPC volume.
- Tetraphenyl Butadiene coated plate in front of PMT to shift wavelength of UV scintillation light.
- PMTs are essential in disentangling out-of-time cosmic tracks from in-time neutrino interactions.



PMT System Installed in Cryostat (Sept. 2013).

PMT Assembly

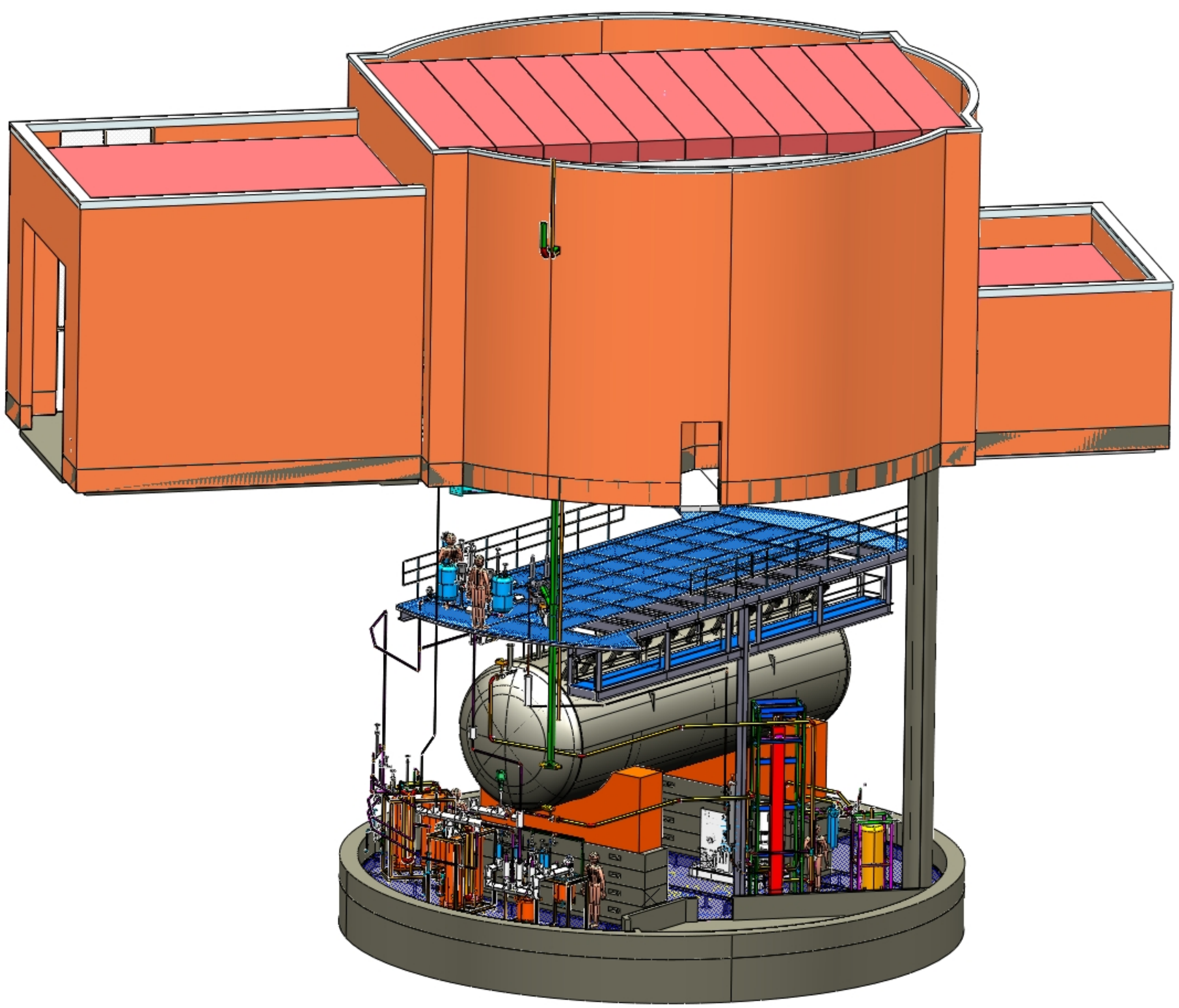
Refs:
1.) *Testing of Cryogenic Photomultiplier Tubes for the MicroBooNE Experiment*, T. Briese et al., hep-ex/1304.0821

MicroBooNE: Status

All detectors installed…finalizing a few things before sealing up.

MicroBooNE: Status

- We will move sealed-up detector over to new LArTF enclosure in Spring 2014.
- Commissioning begins in summer of 2014.
- Cryogenic recirculation system already installed and being tested prior to arrival of cryostat.



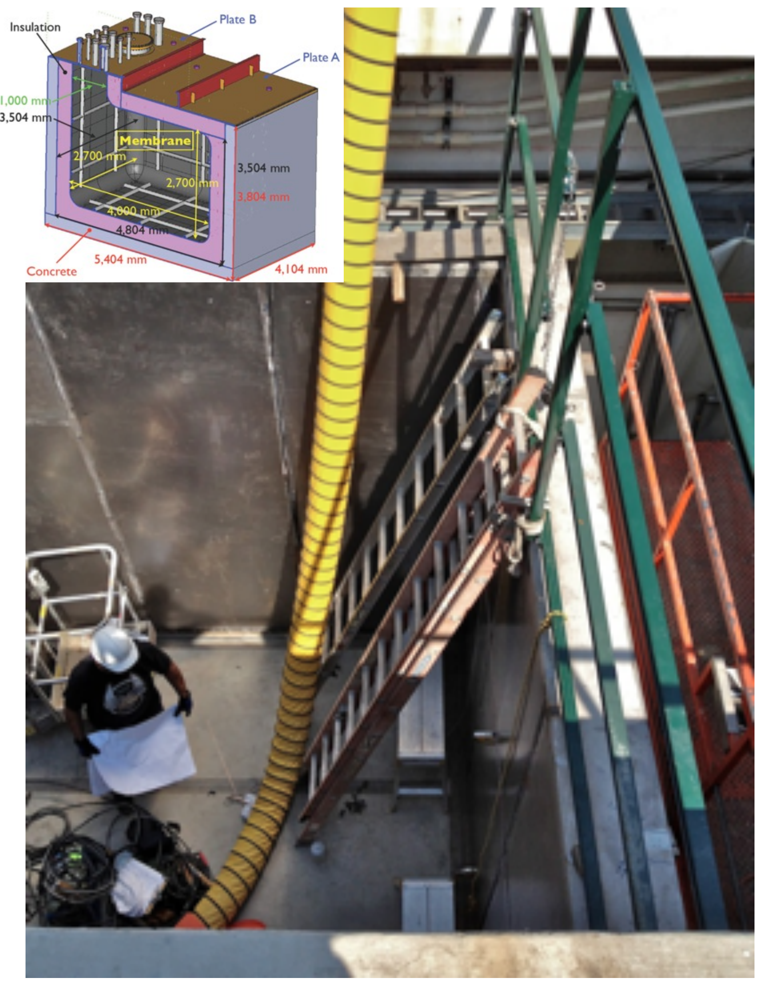
Rendering of cryostat + “hair” in LArTF

Liquid Argon Test Facility (LArTF)

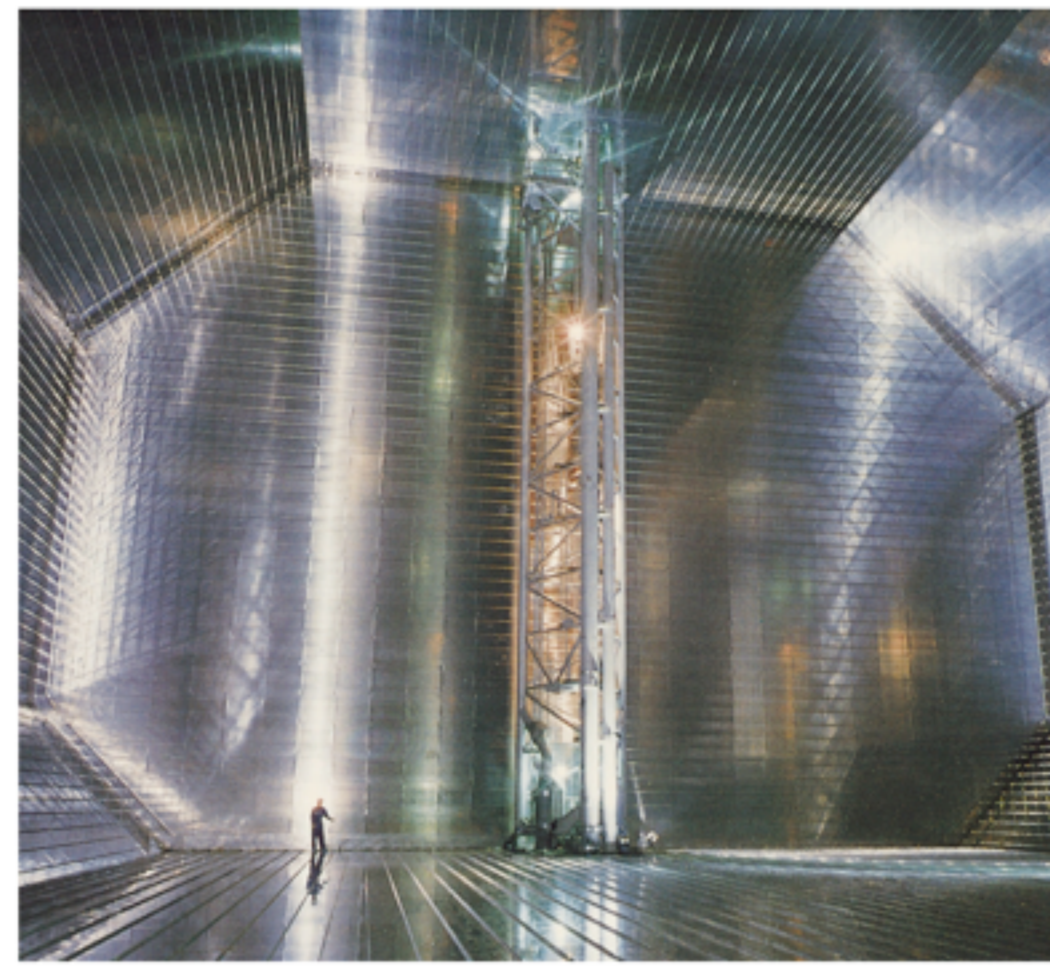
LAr Purity R&D @ Fermilab

- LBNE pursuing membrane cryostats, using experience from industry.
- Built 35-ton membrane cryostat to demonstrate liquid purity without initial evacuation as has previously been demonstrated by Liquid Argon Purity Demonstrator (LAPD) in a "traditional" cryostat.

LAPD
(30-ton cryostat)



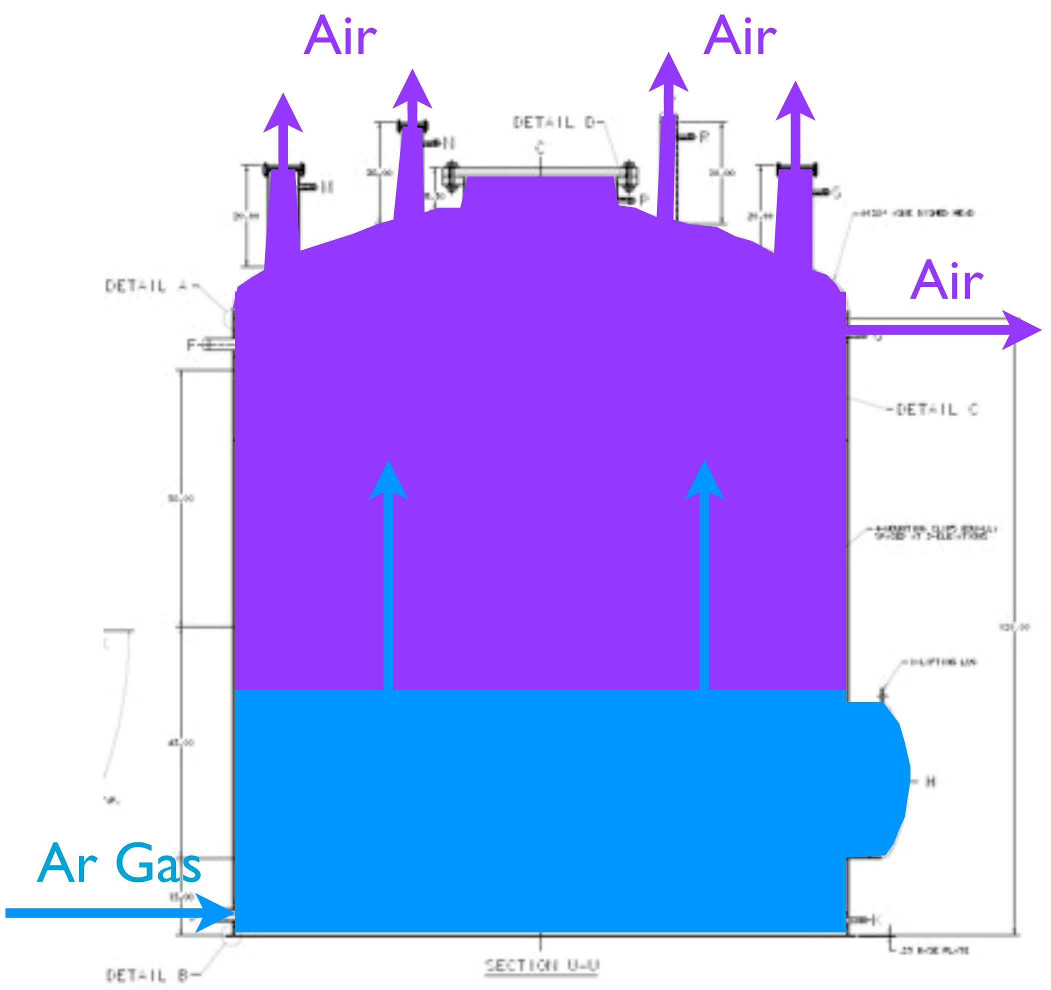
35-ton
Membrane Cryostat

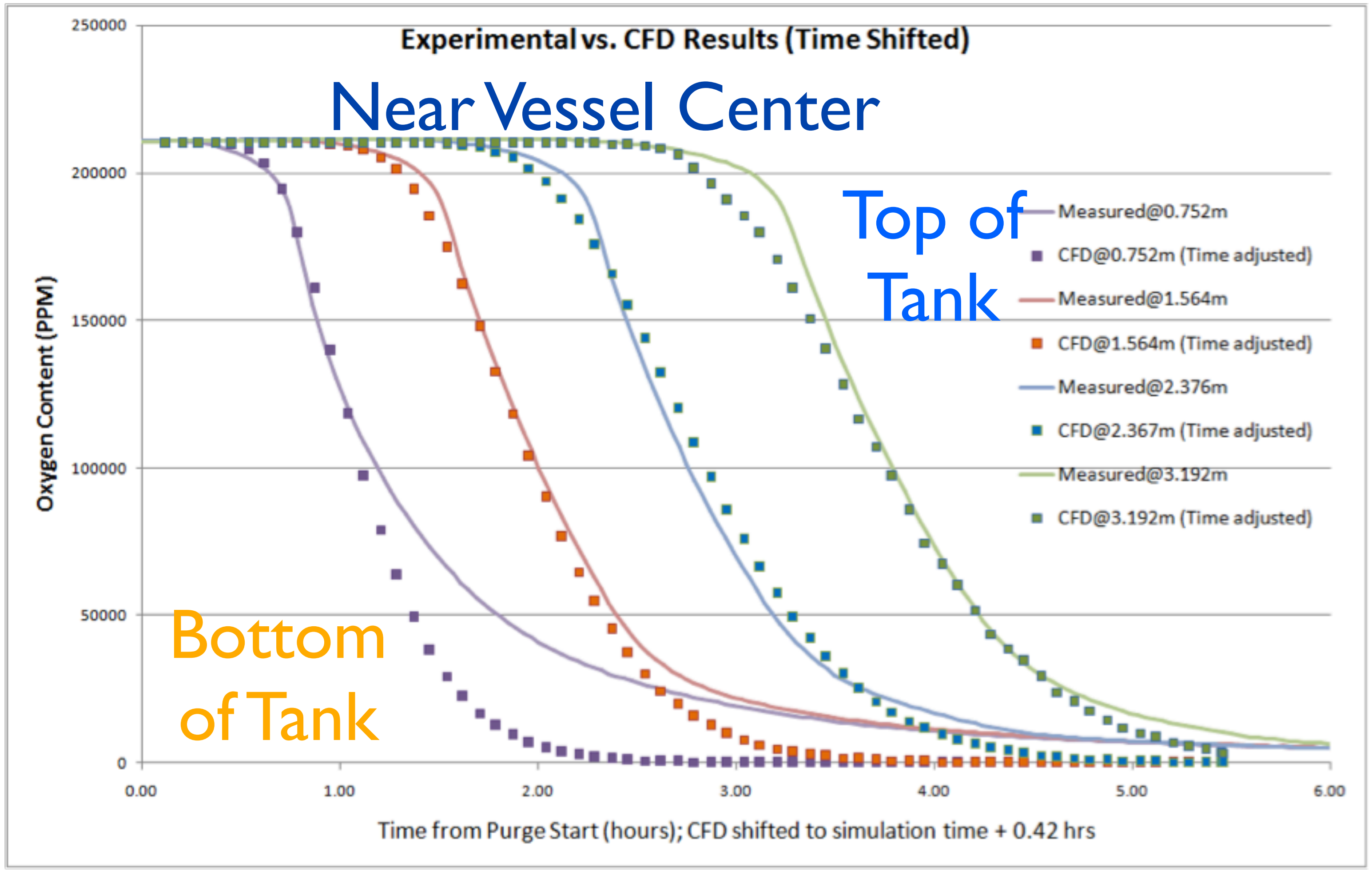


Membrane Cryostat for industrial
LNG shipping

LAr Purity R&D @ Fermilab

- Argon gas acts like a piston, pushing atmosphere up and out of cryostat.
- Gas is cycled through cryostat until desired Oxygen concentration is reached.
- LAPD has routinely achieved LAr lifetimes >3 ms, (LBNE/MicroBooNE require ~1.5 ms)

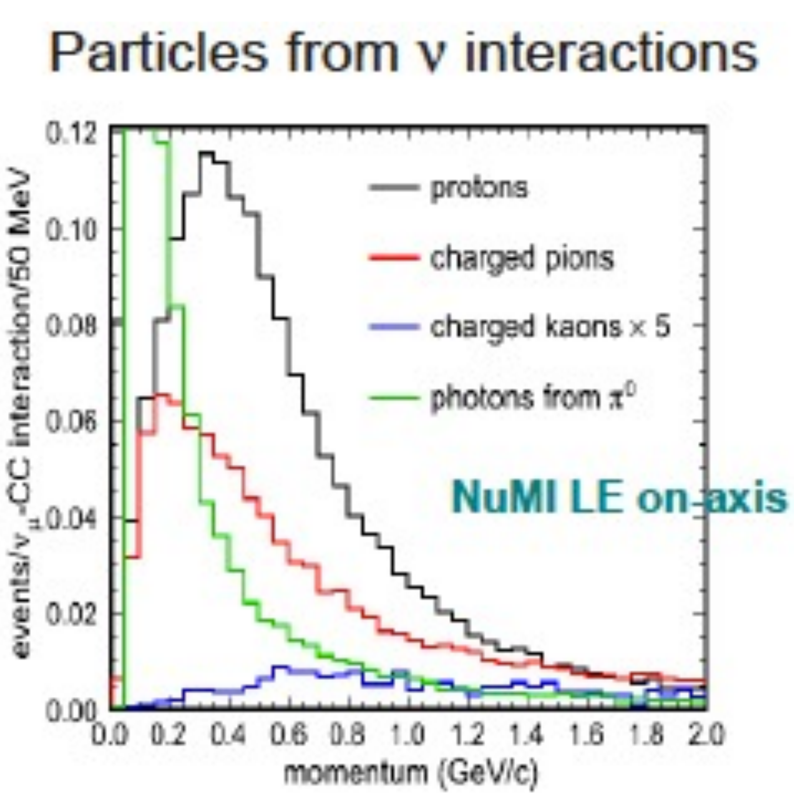


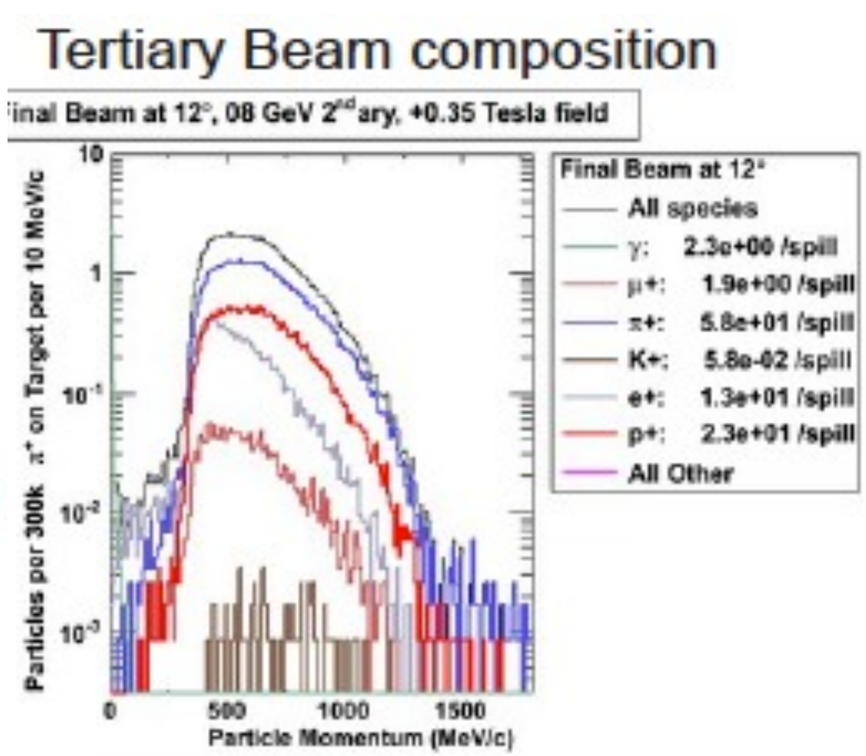


Refs:
1.) *LAPD Update*, B. Rebel, 2012 Fermilab PAC Meeting

LArIAT

- Dedicated test-beam exposure of LArTPC to charged-particles in appropriate energy regime will provide invaluable calibration information to feed into simulations.
- **L**iquid **Ar**gon **I**n **A** **T**estbeam (LArIAT) experiment envisions two phases of running...initially with a small ArgoNeuT-sized detector (starting 2014), followed by a larger MicroBooNE scale detector.

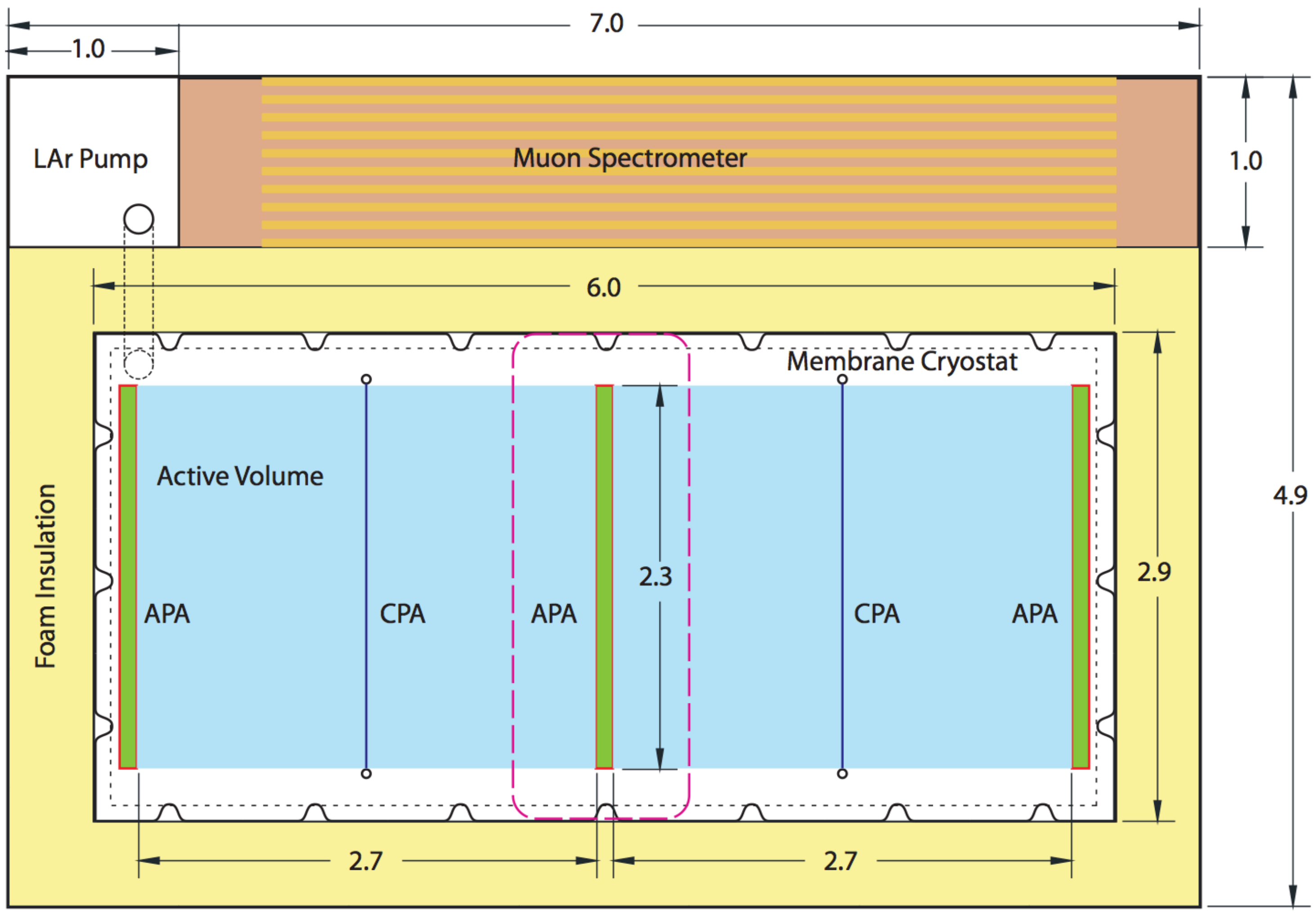




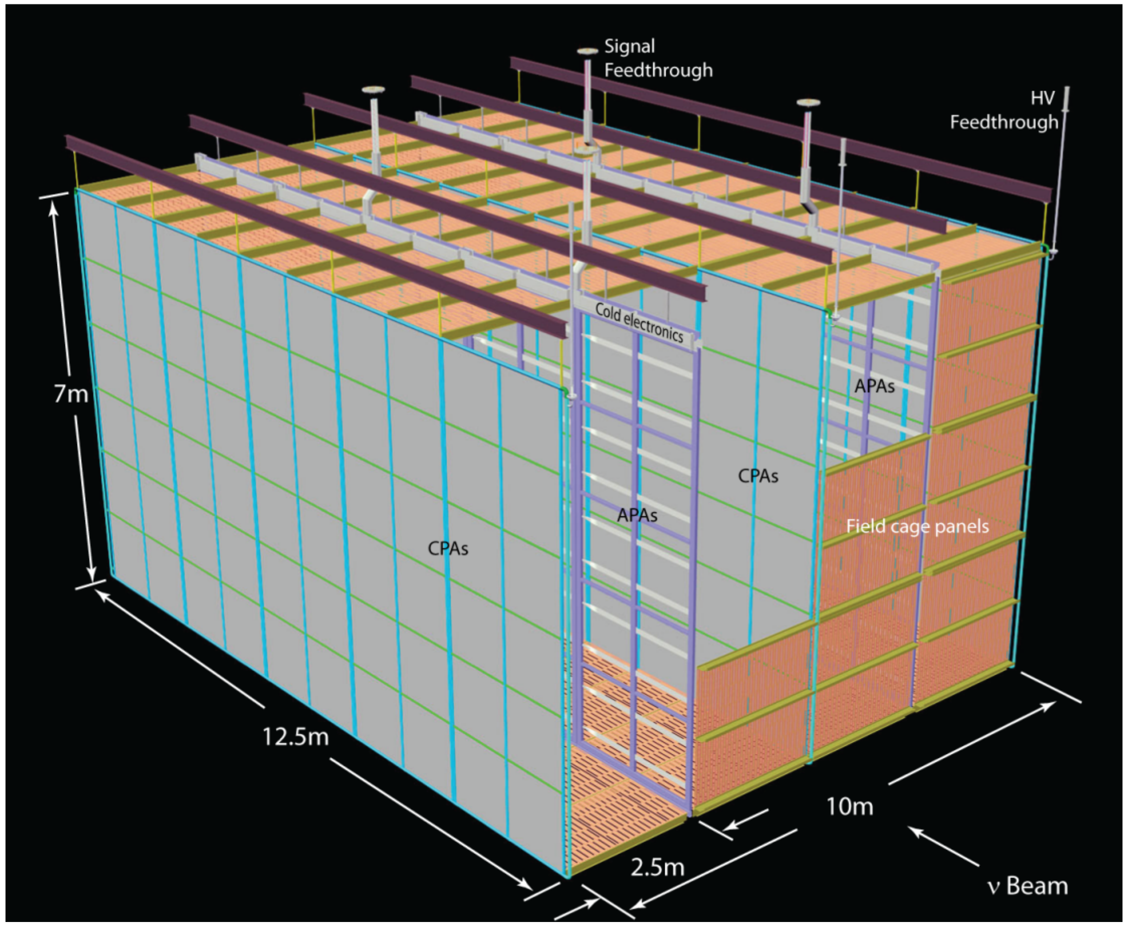
Modified ArgoNeuT Cryostat

LAr1 + LAr1-ND

- Coupling a 1-kiloton "far detector" (LAr1) with existing MicroBooNE experiment would create fantastic short-baseline neutrino program at Fermilab.
- First phase is to install "near detector" (LAr1-ND) in vacant SciBooNE enclosure. Active volume of ~75 tons.
- Leverage LBNE design work; provide beam test of the hardware.



LAr1-ND in SciBooNE Building



LAr1

Refs:

1.) *LAr1-ND: Testing Neutrino Anomalies with Multiple LArTPC Detectors at Fermilab*, C. Adams et al., arXiv:1309.7987

LAr1 + LAr1-ND

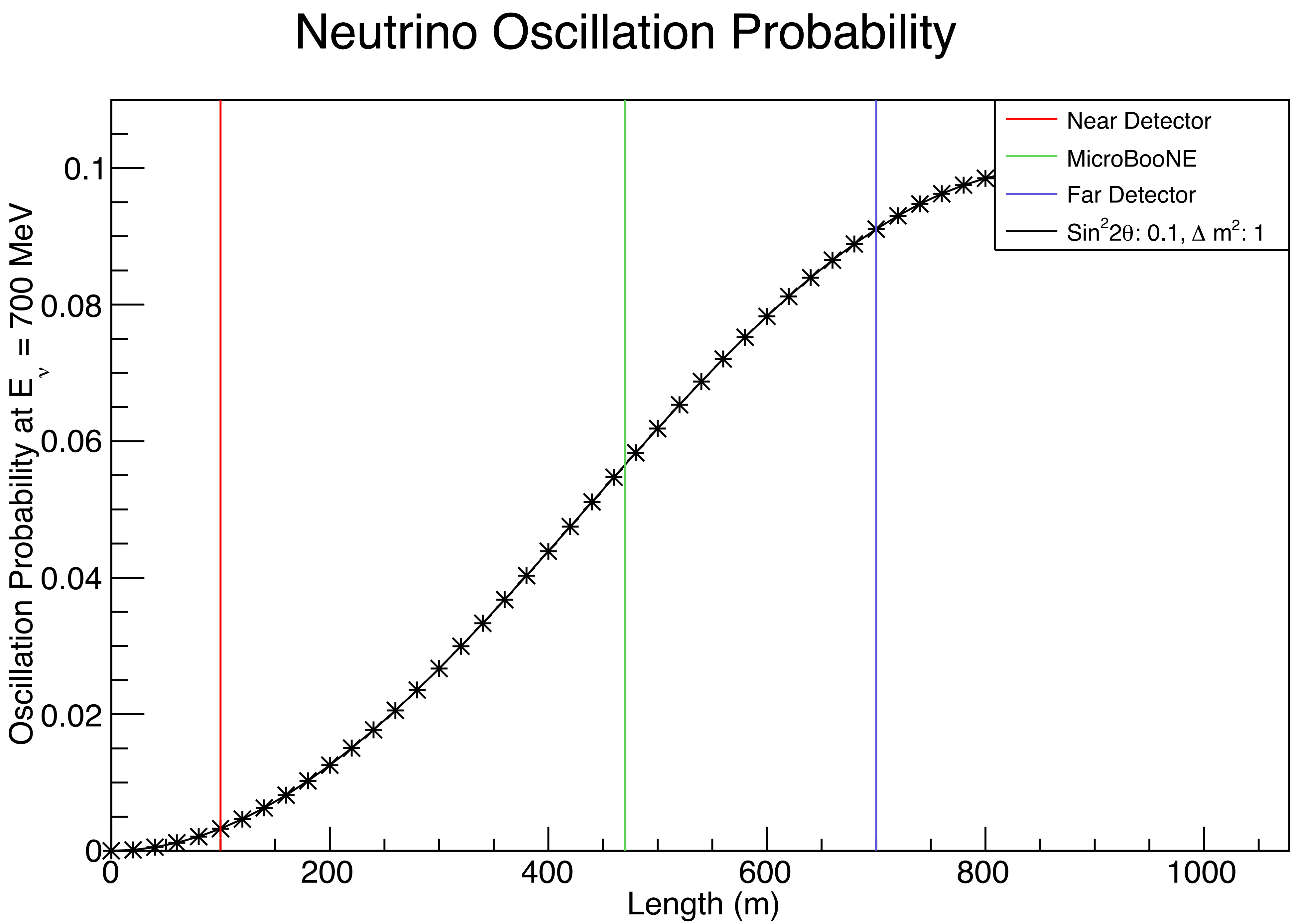
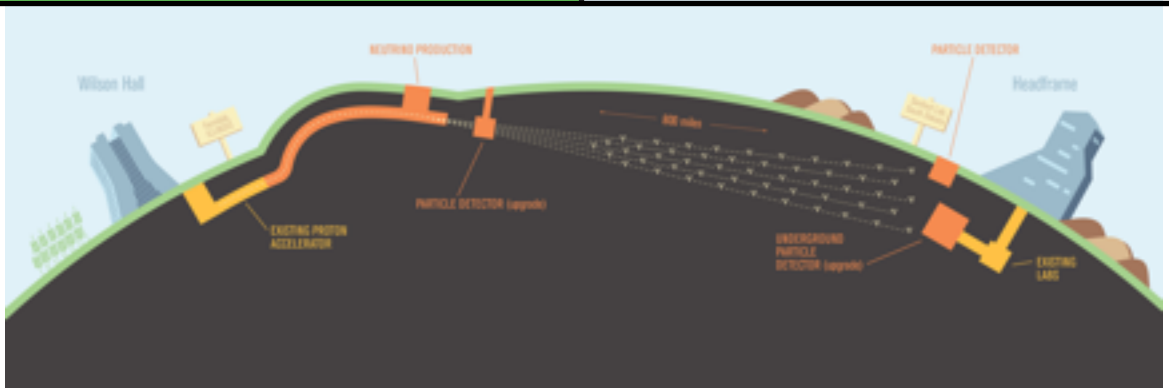


Figure 18: Sensitivity to ν_μ disappearance with the full LAr1 experiment, a program of three LArTPC detectors on the Booster Neutrino Beamline at Fermilab (left). ν_μ disappearance probability at $E_\nu = 700$ MeV as a function of distance in a sterile neutrino model with $\Delta m^2 = 1$ eV^2 and $\sin^2 2\theta_{\mu\mu} = 0.1$ (right). The vertical colored lines indicate the proposed locations of LAr1-ND, MicroBooNE and LAr1-FD.

LBNE

- All of this technology development culminates in the multi-kiloton LBNE far-detector, which will use a LArTPC to search for CP violation, proton decay, supernova neutrinos, etc...
- Detector will be located underground at 4850 ft. level in the Sanford Underground Research Facility (SURF), in the path of an intense beam originating at Fermilab.
  - Reminder: this is the site of the original Ray Davis experiment!

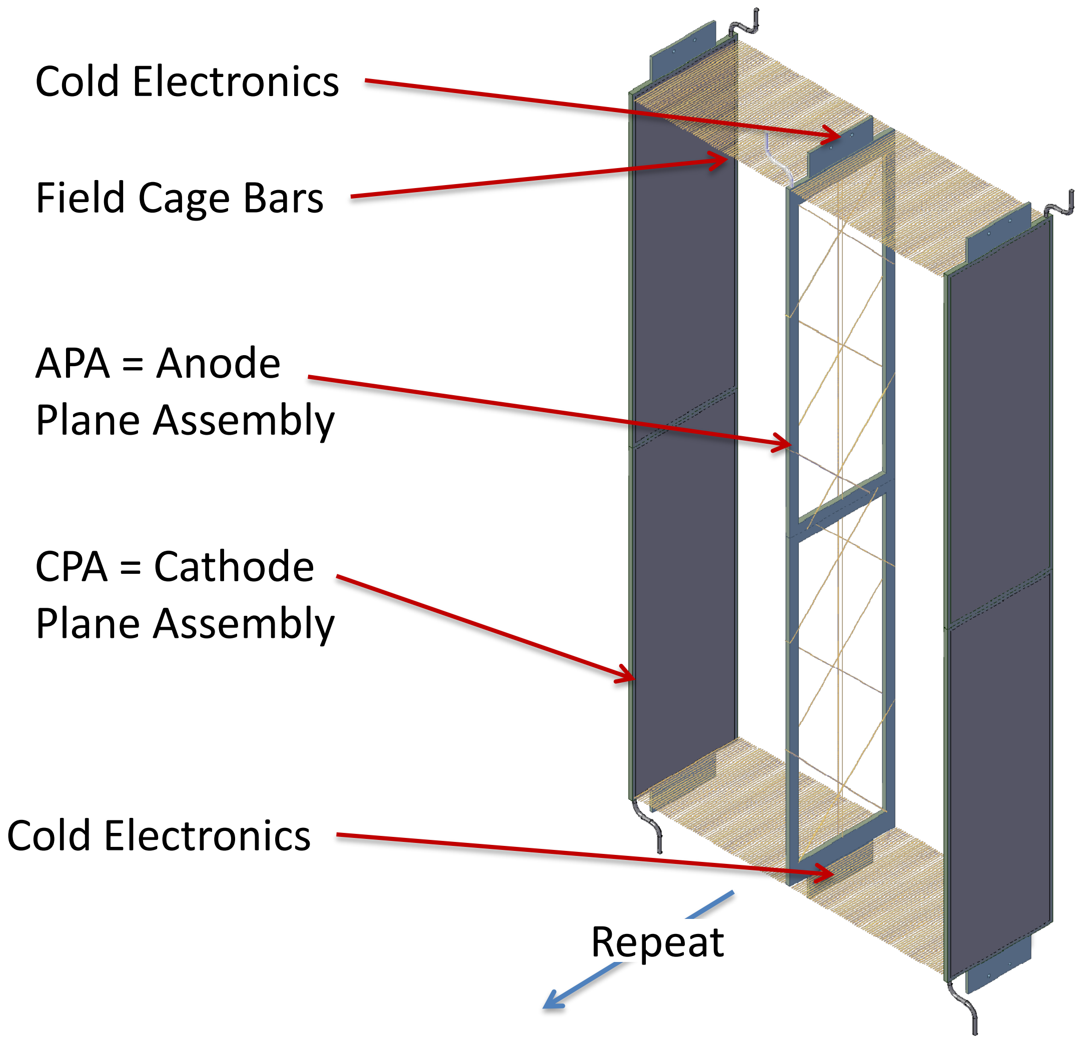
Cryostat Volume	9400 tons (x2 = 18600 tons)
TPC Volume (l x w x h)	5000 tons (x2 = 10000 tons)
# Electronic Channels	~150k/cryostat (x2 = ~300k)
Electronics Style (Temp.)	CMOS (87 K)
Wire Pitch	~5 mm
Max. Drift Length (Time)	2.3m (1.4ms)
Light Collection	Acrylic bars with TPB

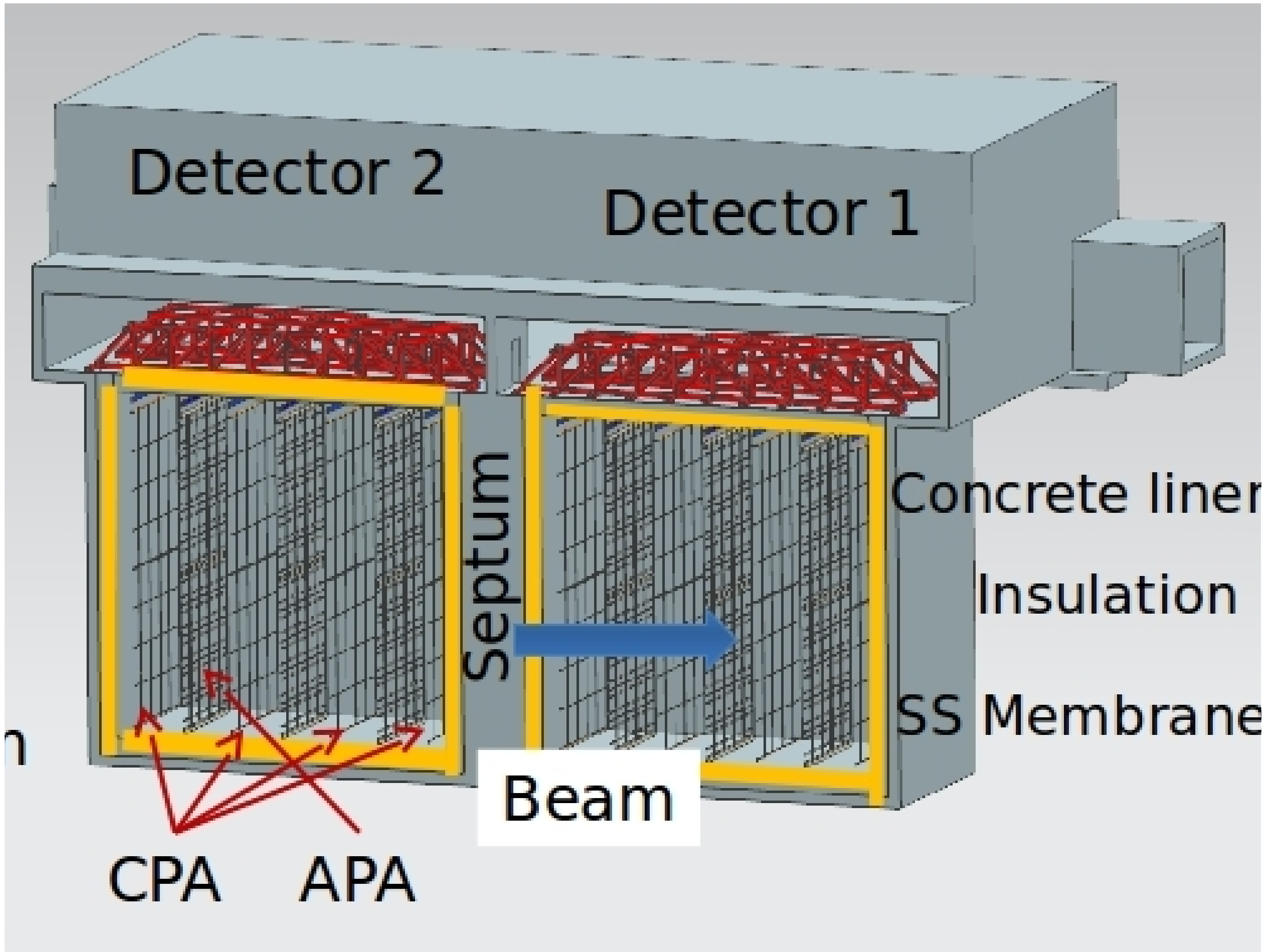


Refs:
1.) *Scientific Opportunities with the Long-Baseline Neutrino Experiement*, C. Adams et al., hep-ex/1307.7335

LBNE

- Two separate membrane cryostats each with 9.4 kiloton volume.
- TPC is formed by alternating rows of cathode (CPAs) and anode (APAs) assemblies that are hung from the ceiling of the cryostat.

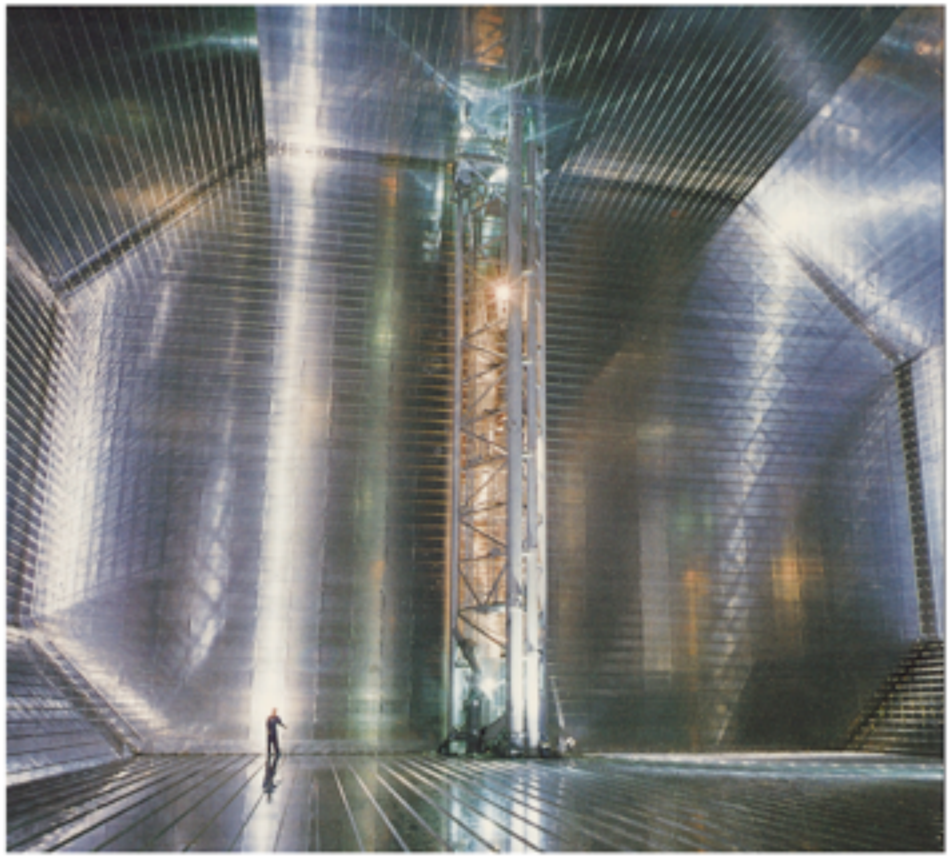




LBNE

- Massive storage of cryogenic liquids not such a crazy idea....ultra-high purity is the big unknown.
- Industrial companies use ocean liners to transport Liquified Natural Gas (LNG) since it's the most economical way (gas density is 1/600 of liquid) to move a large quantity of gas.
- LNG cooled to -162C (111 K)...almost as cold as LAr (87 K).
- "Membrane" cryostats are built piece-by-piece inside an enclosure. Small vacuum levels possible.

Q-Max LNG Carrier
Capacity: 266,000m^3



"Membrane" Interior

LBNE Physics

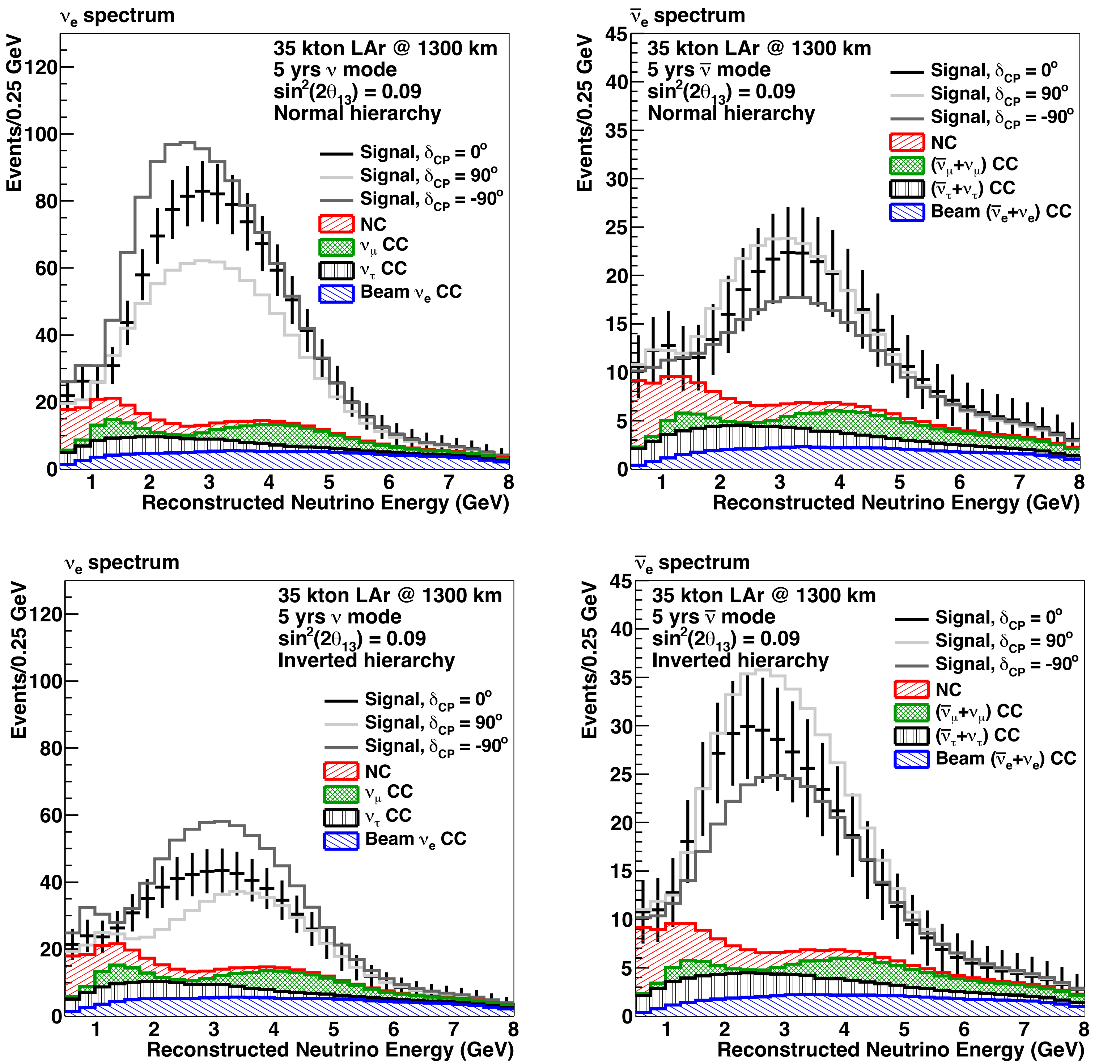
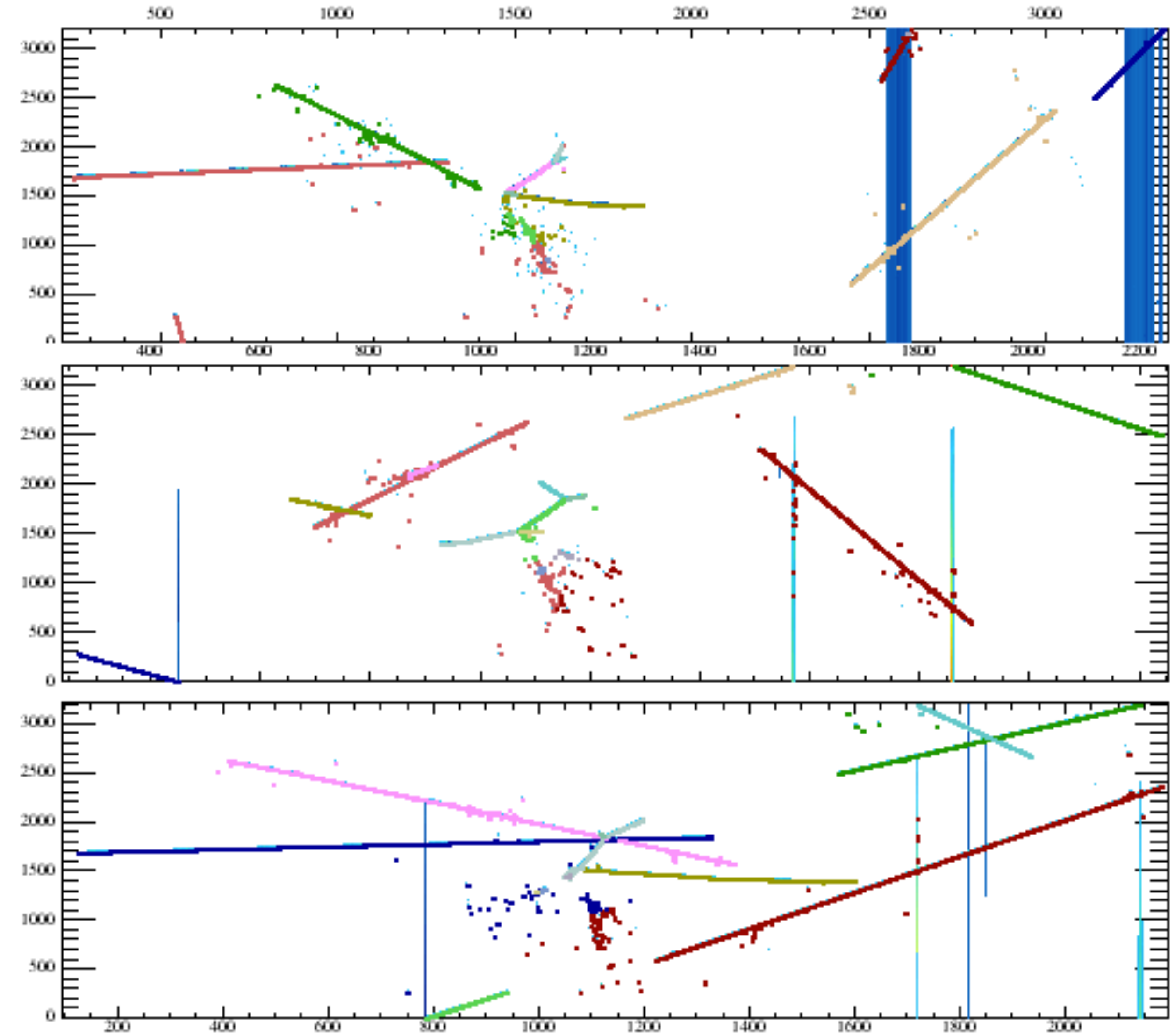
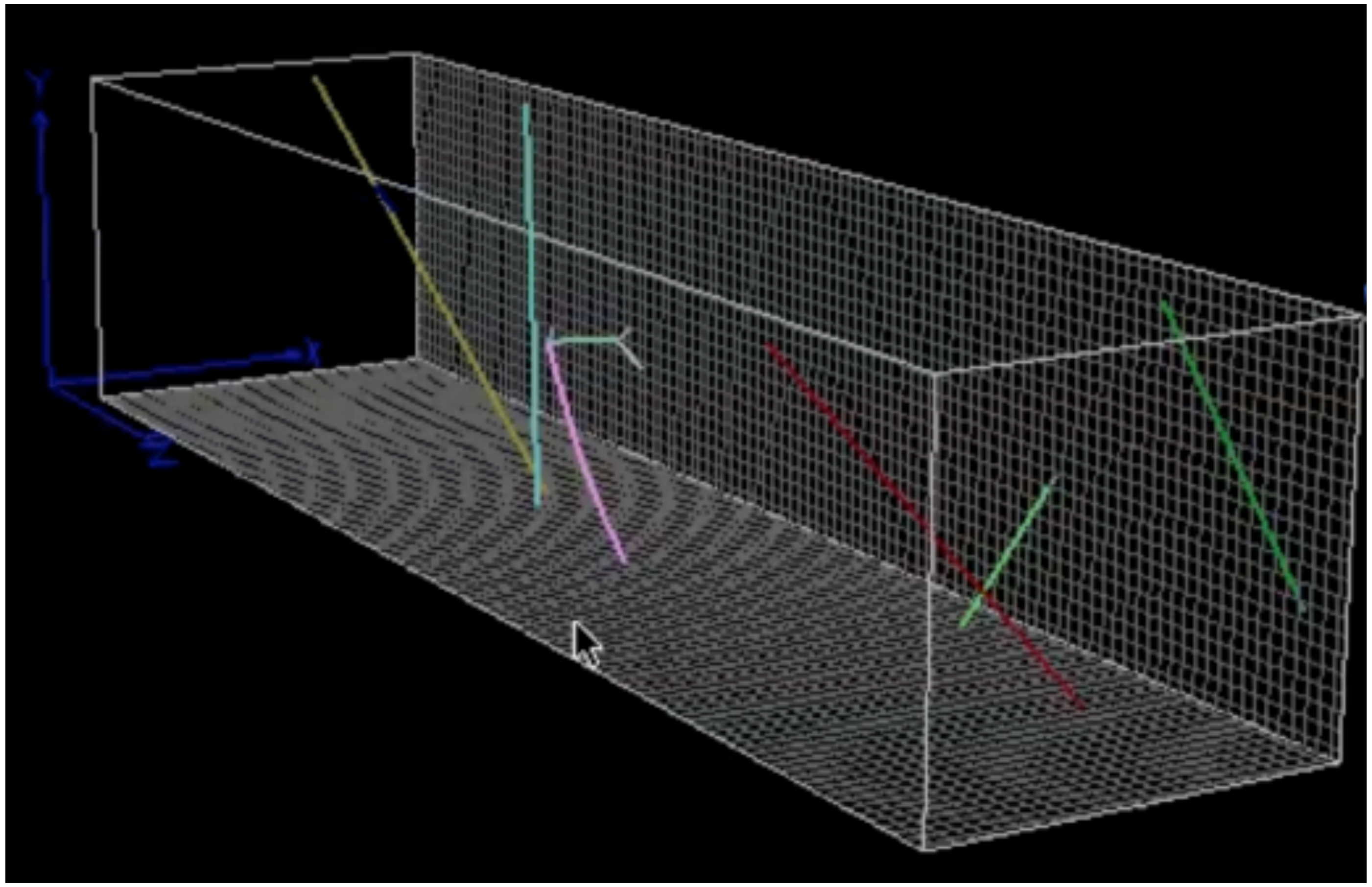


Figure 4–12: The expected spectrum of ν_e or $\overline{\nu}_e$ oscillation events in a 35-kt LArTPC for 5 years of neutrino (left) and anti-neutrino (right) running with a 708 kW, 80 GeV beam assuming $\sin^2(2\theta_{13}) = 0.09$. The plots on the top are for normal hierarhcy and the plots on the bottom are for inverted hierarchy.

Software

- Extracting physics results from LArTPC data presents its own challenges that must be overcome and will require significant effort.
- Developing generators, simulation, reconstruction, etc... that <u>fully</u> encapsulate neutrino interactions in a LArTPC is a challenge that (in my opinion) rivals the hardware development. Deserves more attention than I'm giving it here.





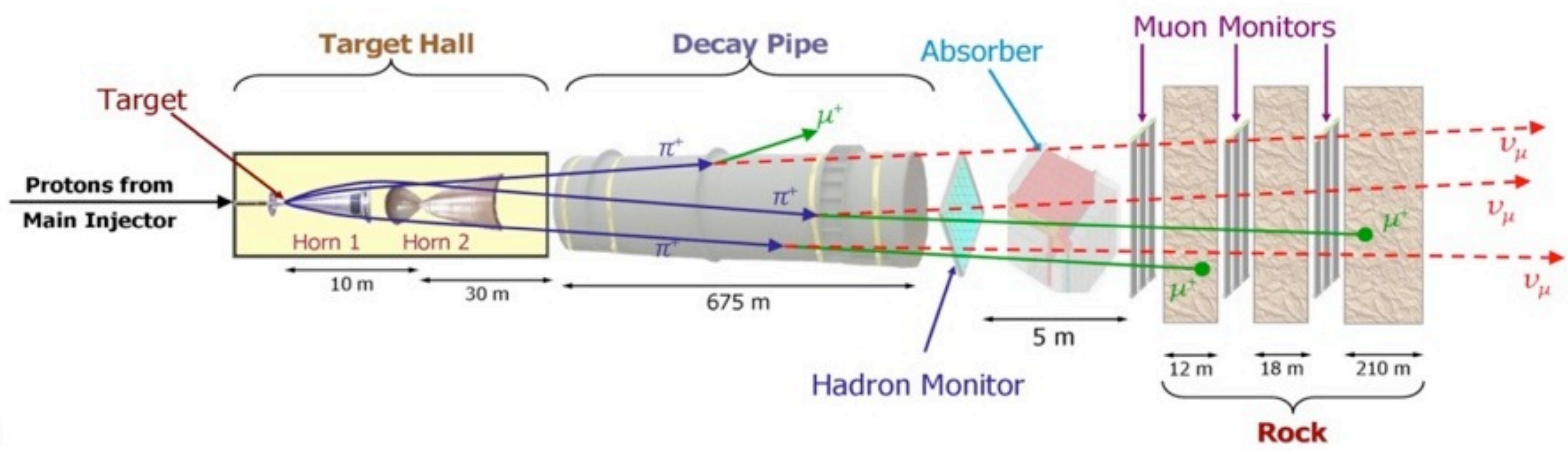
Refs:
1.) https://cdcvs.fnal.gov/redmine/projects/larsoftsvn/wiki

Conclusions

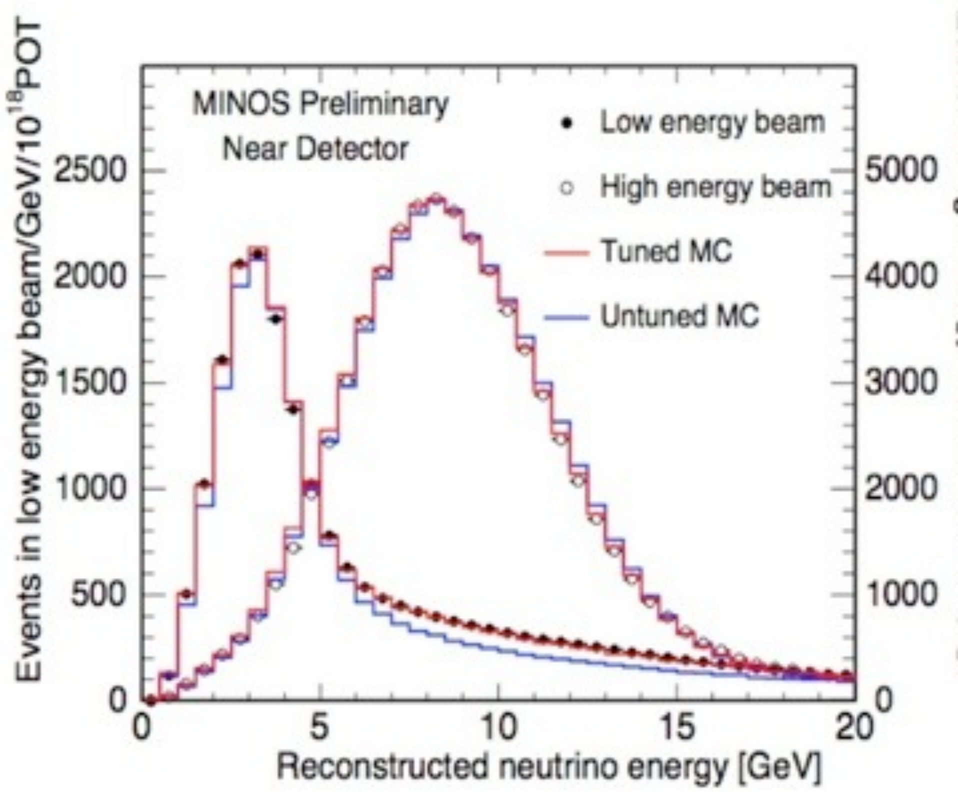
- LArTPCs are powerful detectors for studying neutrinos.
- Tremendous progress in recent years in U.S. efforts to develop this technology. Growing interest, which is good since there is lots of work to be done.
- Next few years should be very exciting as experiments come online, and as development of kiloton-scale experiments continues.

Back-Up Slides

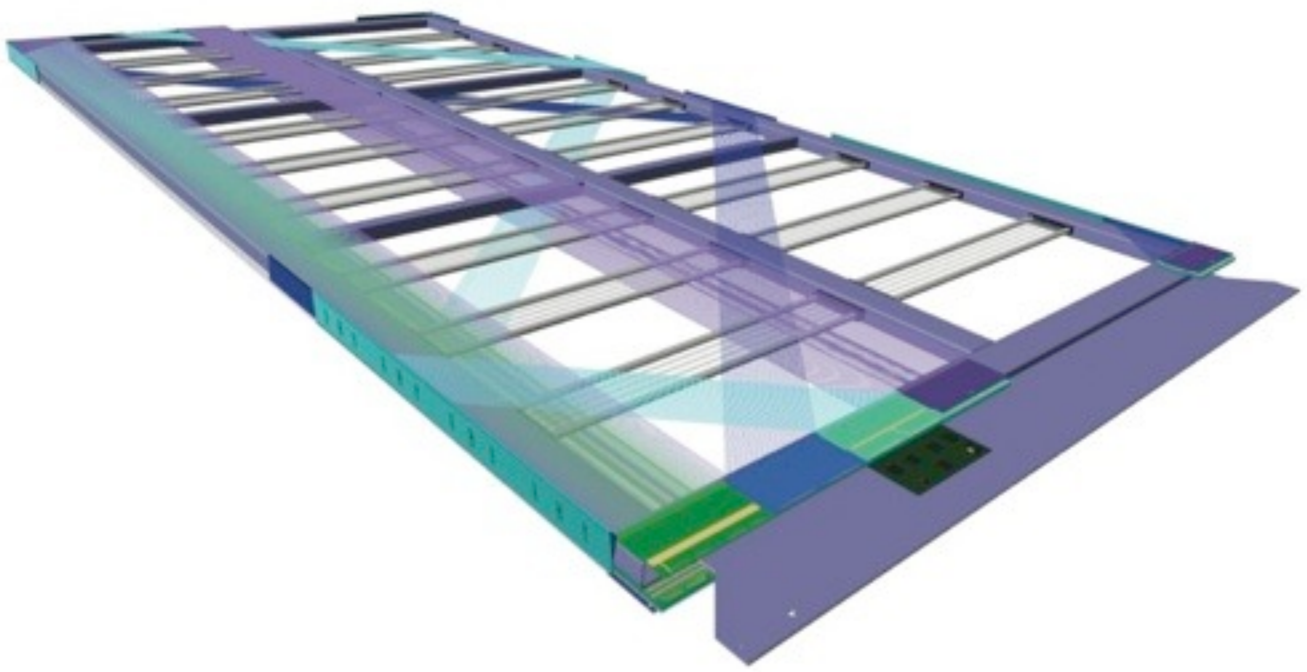
NuMI Beam



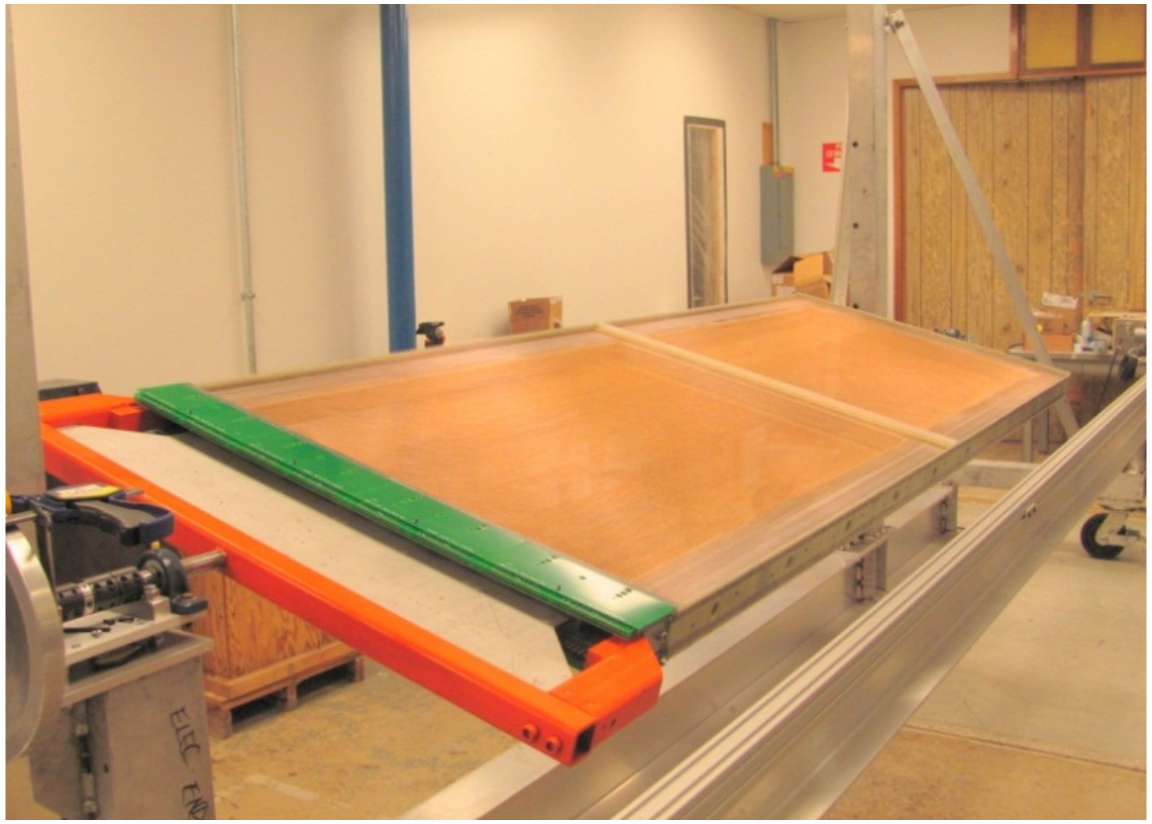
- 120GeV protons from Main Injector hit graphite target and produce pions, kaons.
- Charged mesons are focused by a pair of magnetic horns, then allowed to decay in flight.
- Absorber removes all but neutrinos.
- "Low Energy" horn configuration during ArgoNeuT's run.



- APAs are formed by wrapping angled wires around perimeter of frame. This allows readout all to come off the ends of the assembly, and helps to control the channel count.
- Light detection systems could be placed inside the APAs, minimizing their impact on active volume of LAr.



APA Design



Prototype APA at University of Wisconsin

Physical Sciences Laboratory