Liquid Argon Detectors - Performance and Technical Challenges

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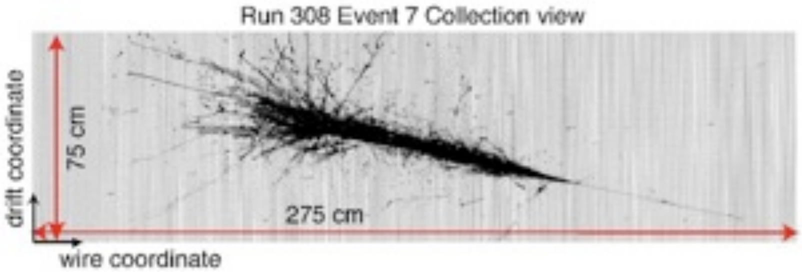
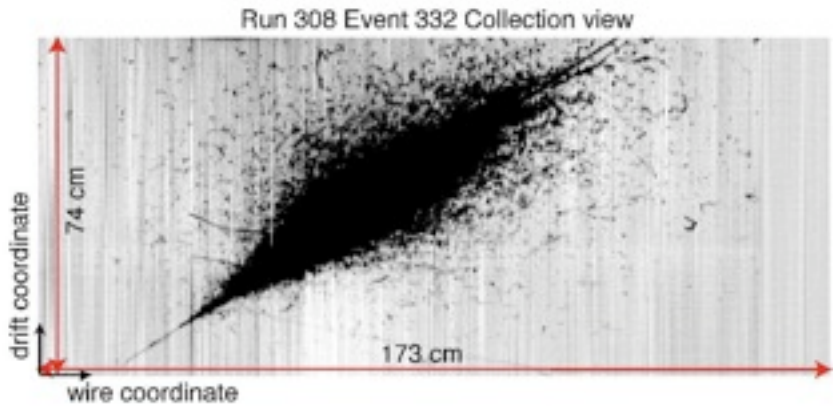
October 2010

Outline

- Advantages of LAr Time Projection Chamber
- Current detectors - ICARUS and ArgoNeuT
- Test stands for on-going R&D
- Outlook

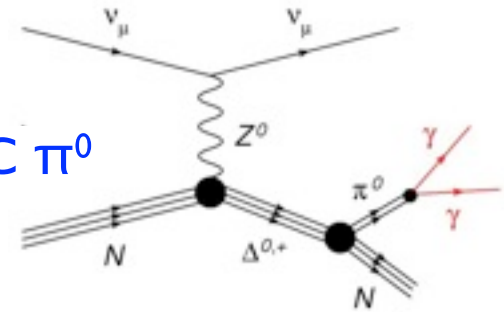
LAr TPC Benefits



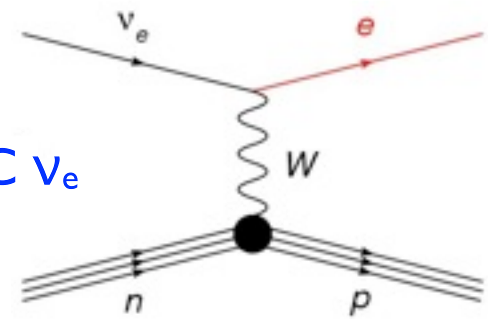


Events from ICARUS test run in 2001

NC π^0

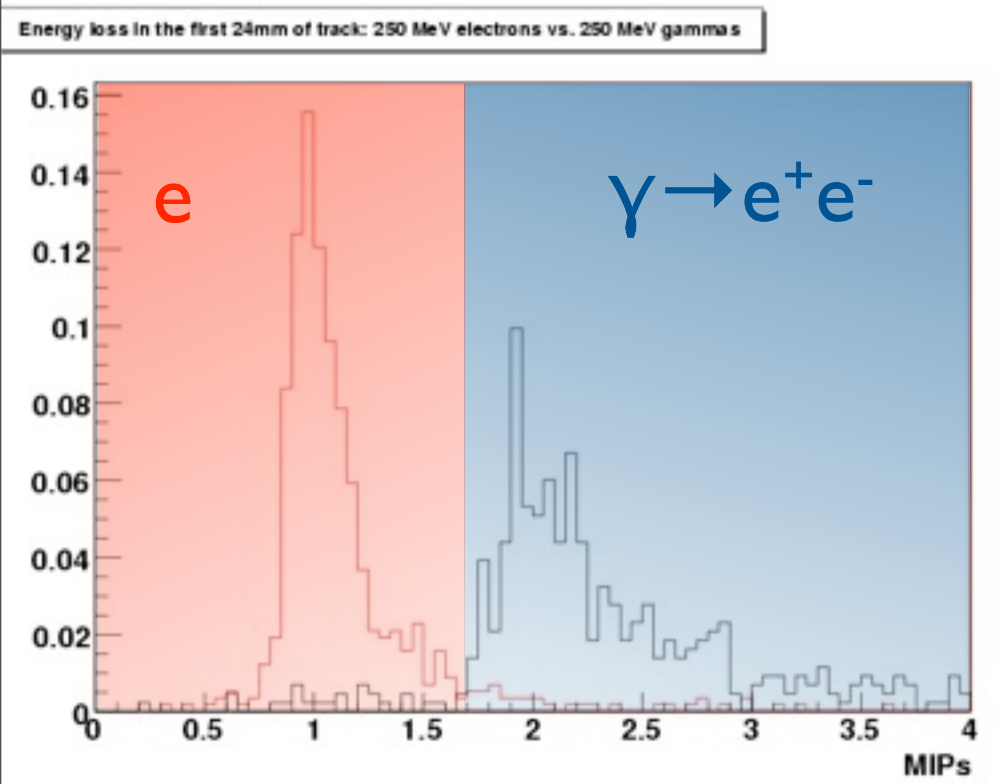


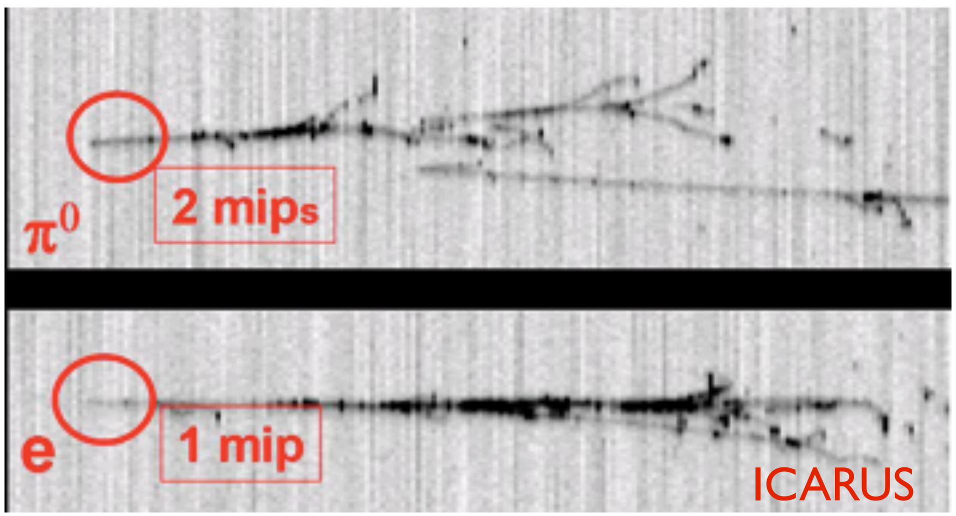
CC ν_e



- Incredible resolution in drift direction - very important for distinguishing NC π^0 events from CC ν_e
- LAr TPC resolution: ~0.05 cm
- Important for cross-section measurements as well as oscillation parameters
- Low energy threshold - $\langle dE/dx \rangle$ is 1.519 MeV cm^2/g

e/γ Separation

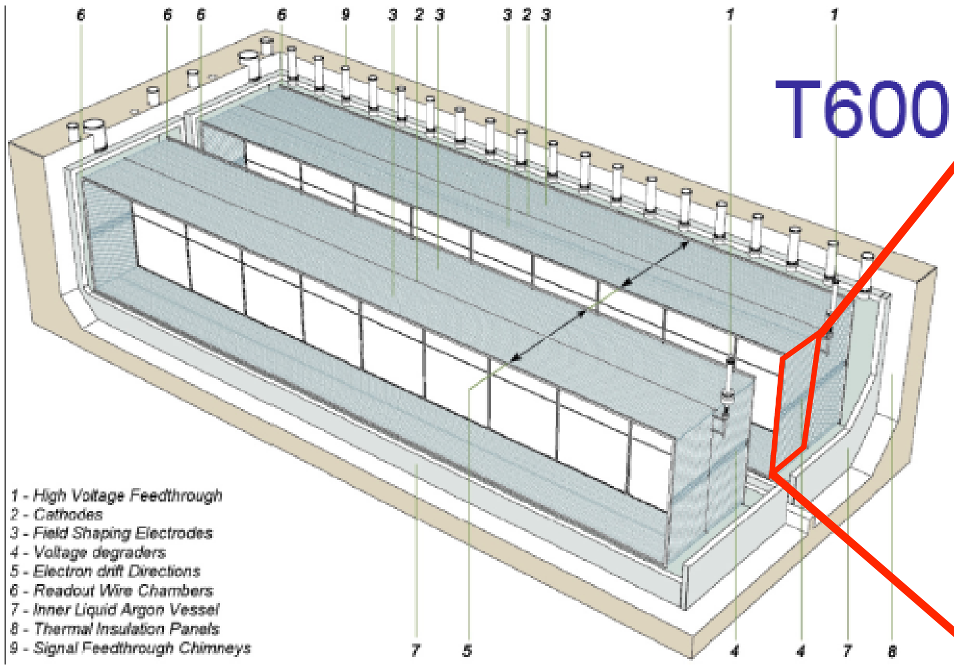




- Top plot shows MIP deposition in first 2.4 cm of track for 250 MeV e/γ
- MC studies show one can achieve 90% electron ID efficiency at cost of 6.5% γ contamination
- Best technology for e/γ separation
- Distinguishing these processes is crucial for measurements of remaining mixing matrix parameters

Current Detectors

ICARUS



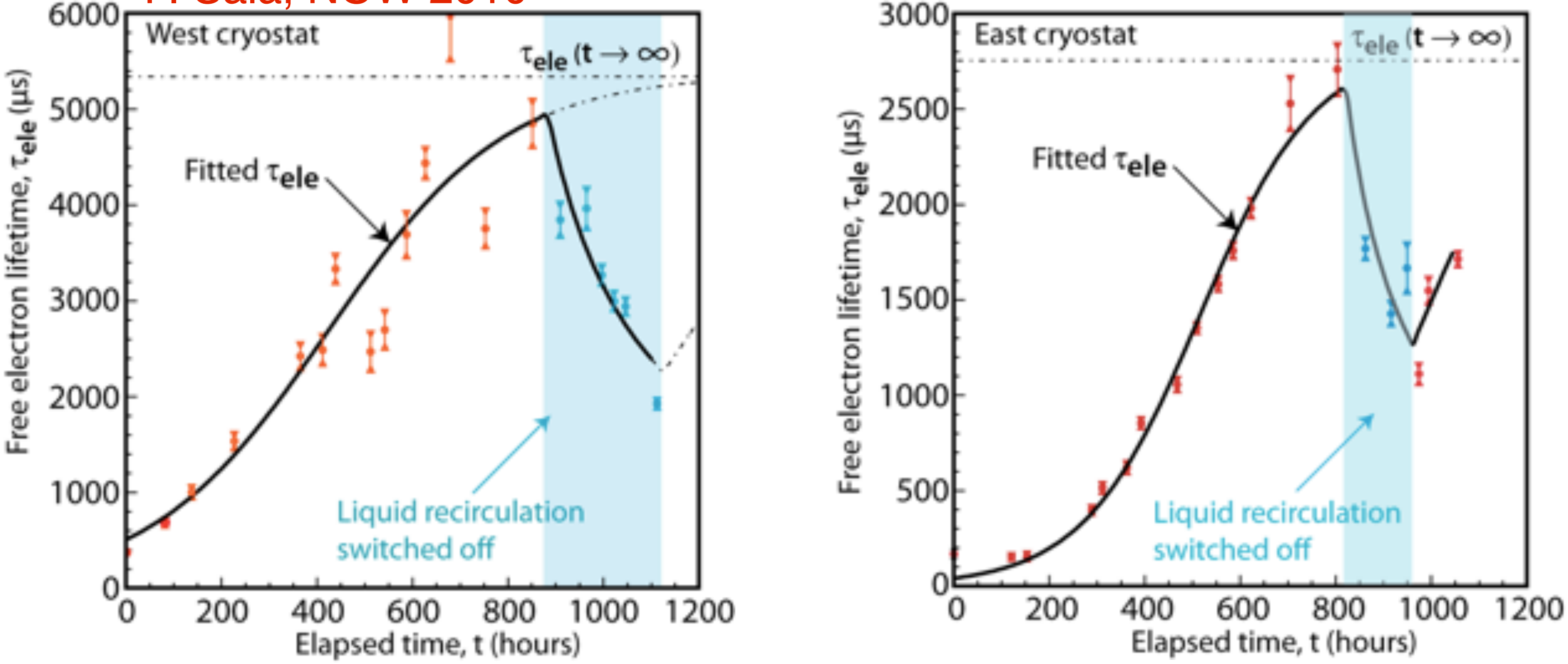
- Largest LAr detector in the world
- Culmination of 20 years of effort - 50 L → 3 t →300 t
- Made of 2 modules, 300 t each
- Filled May 18, 2010

Energy Resolution

Low energy electrons	$\sigma(E)/E = 11\%/\sqrt{E} + 2\%$
EM Showers	$\sigma(E)/E = 3\%/\sqrt{E}$
Hadronic Showers	$\sigma(E)/E = 30\%/\sqrt{E}$

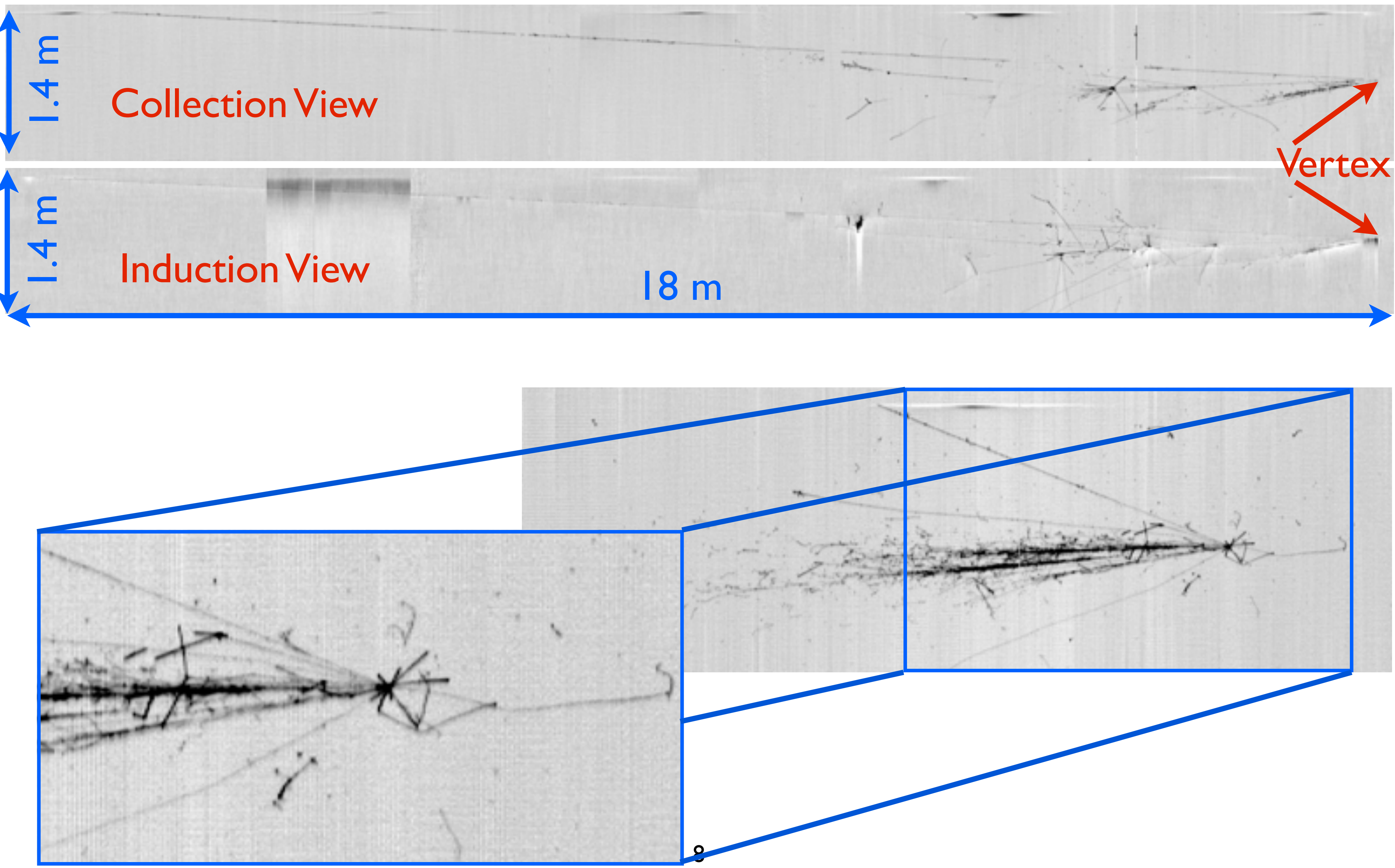
Electron Lifetime in ICARUS

P. Sala, NOW 2010



- Lifetime steadily increases in each cryostat with recirculation
- Equilibrium lifetime is 5.39 ms (West) and 2.73 ms (East)
- Recirculation time of 6.7 days (West) and 5.5 days (East)
- Difference due to different production of impurities in each module - 7.2 ppt/day (West) and 20 ppt/day (East) O_2 equivalent

LNGS Neutrinos in ICARUS

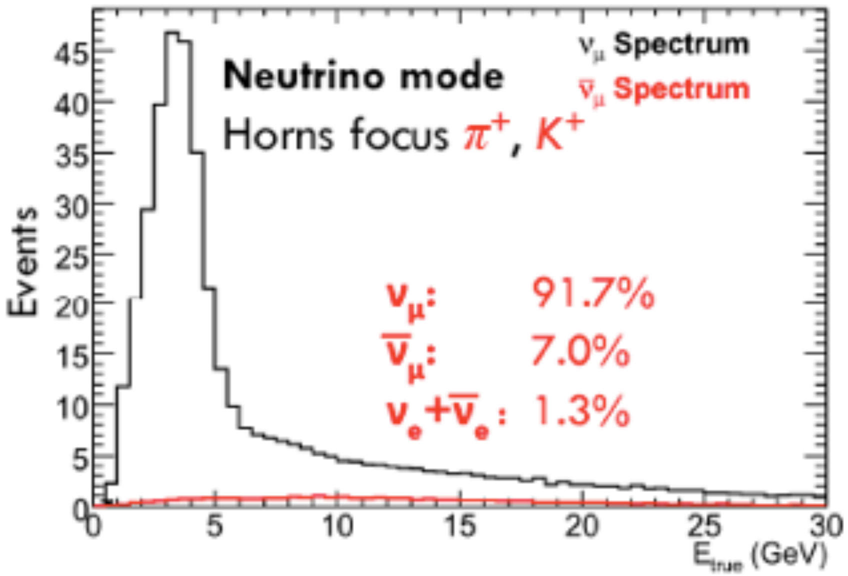


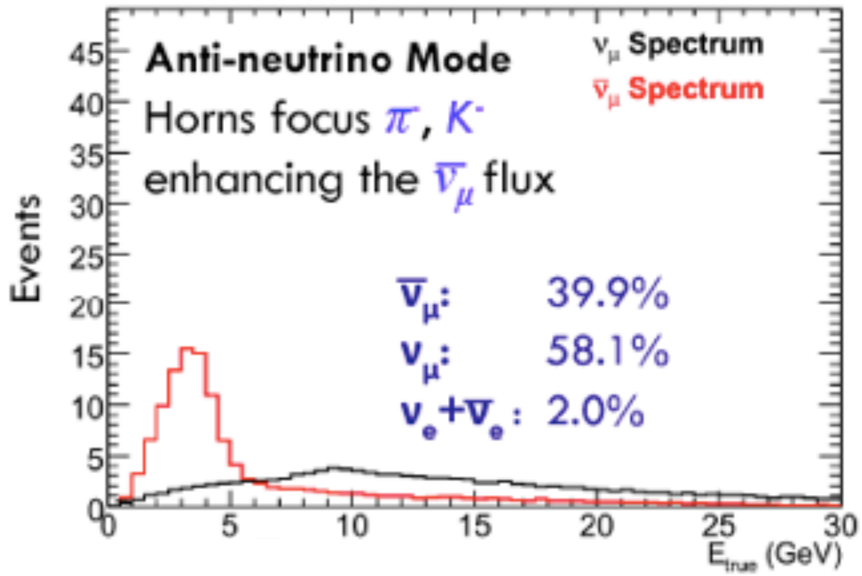
ArgoNeuT

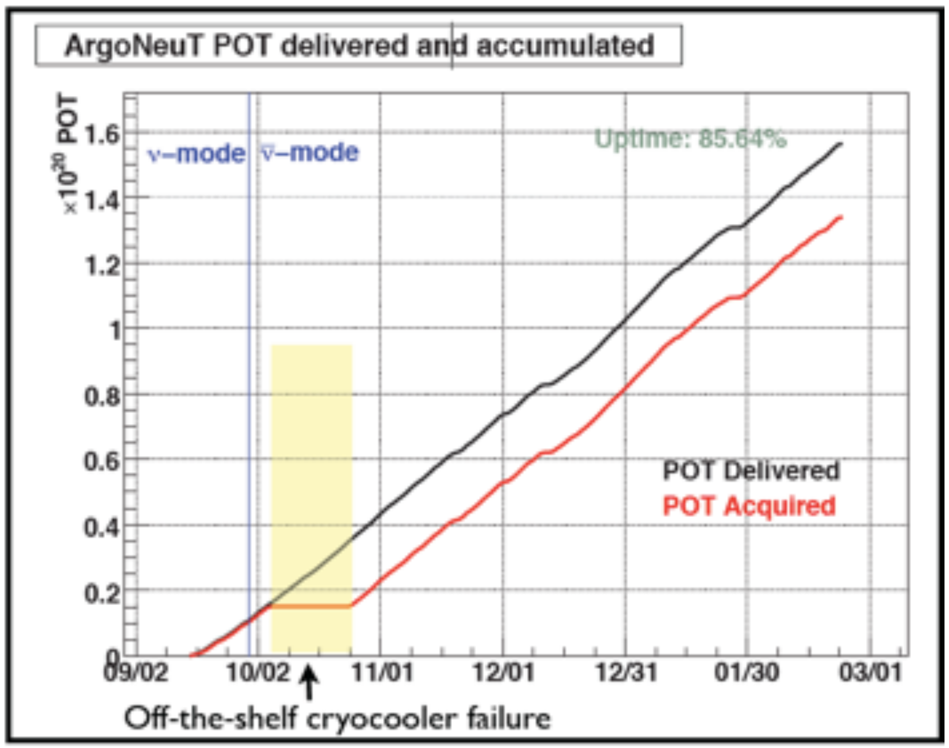
- First LArTPC in a low energy neutrino beam - mostly R&D, but with some Physics thrown in
- Cryostat went into the MINOS hall in December 2008
- Filled with LAr May 8, 2009
- Ran through February, 2010

Cryostat Volume	500 Liters
TPC Volume	175 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length (Time)	0.5m (330μs)
Light Collection	None

ArgoNeuT Data Taking in NuMI Beam



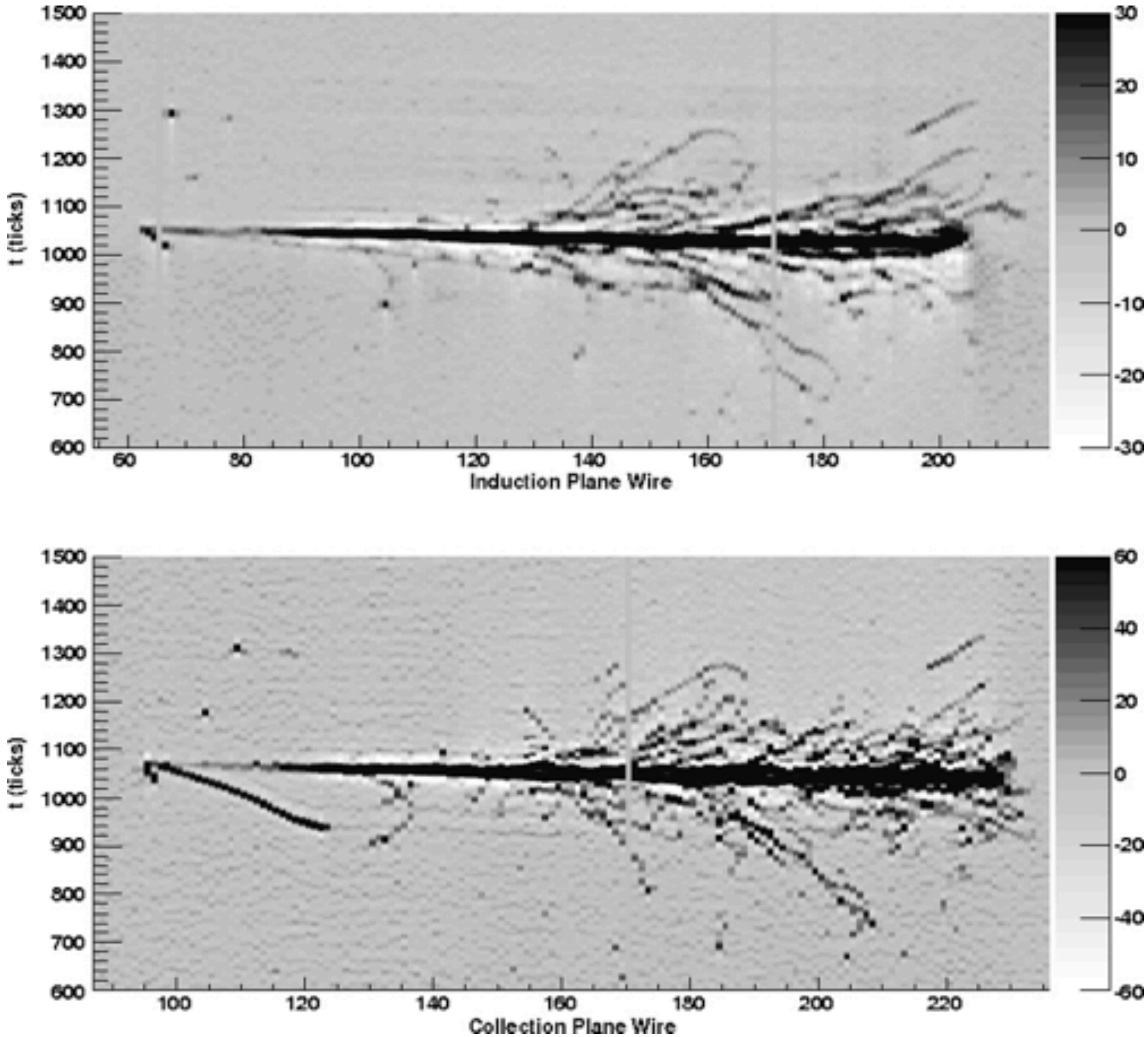




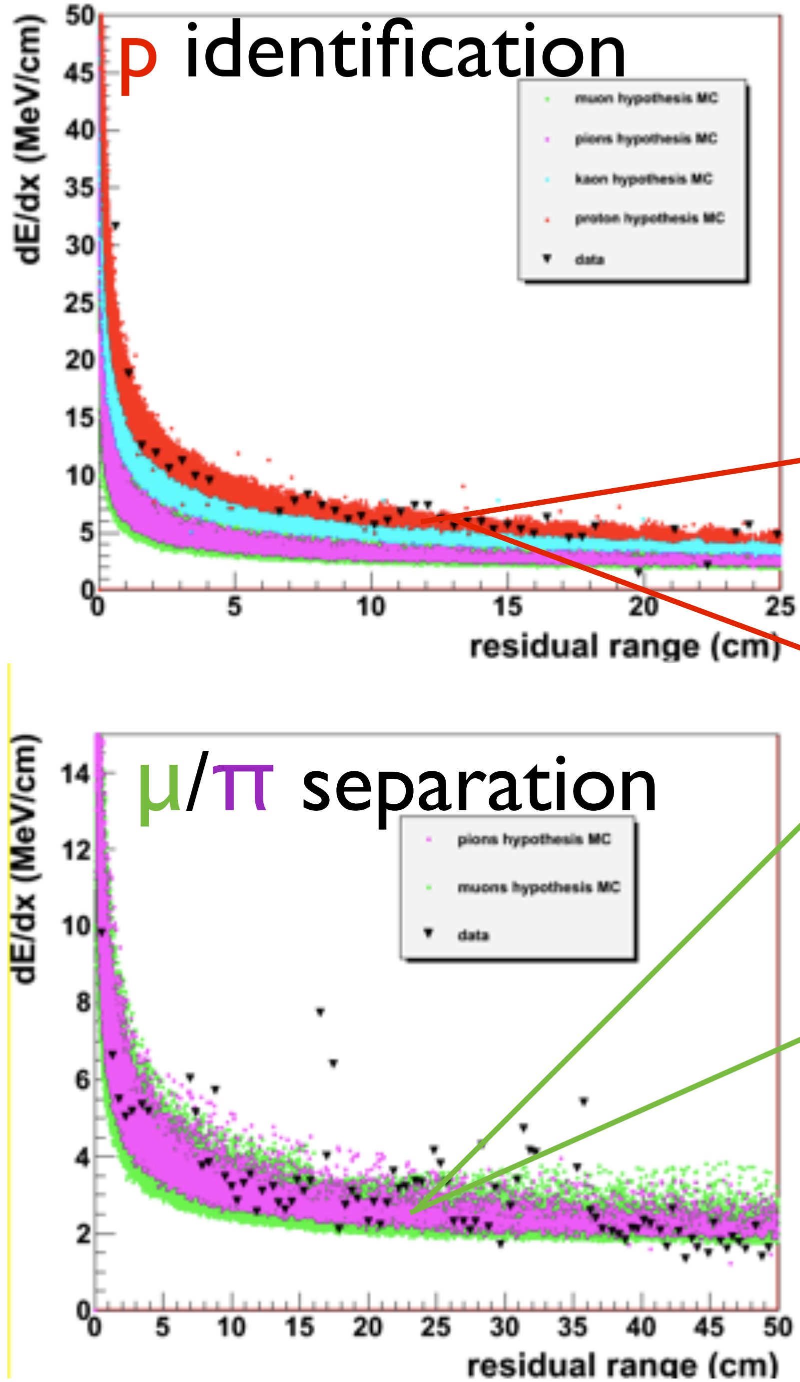
- Stable operation for nearly 5 months
- Unattended operation
- First low energy anti-neutrino events in LArTPC

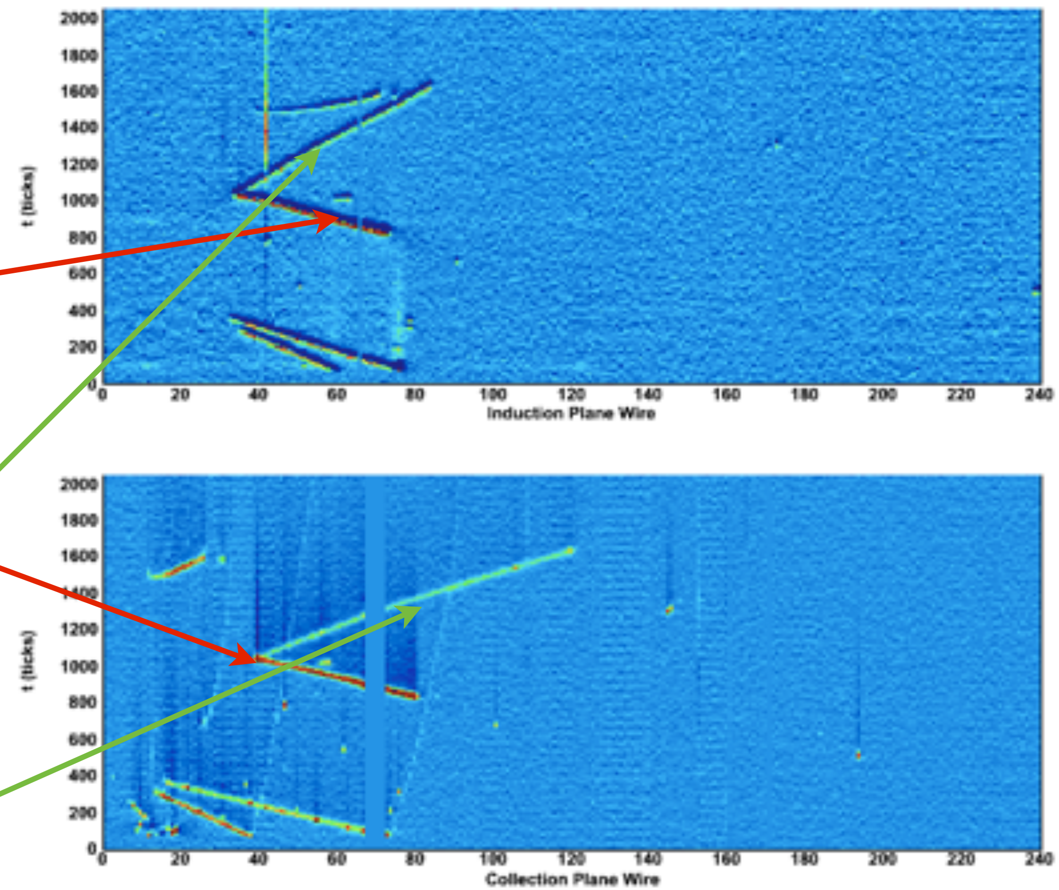
Reaction	#events in AV (~1.35E20 POT)
ν_μ CC	~6600
$\bar{\nu}_\mu$ CC	~4900
ν_μ CCQE	~600
ν_e CC	~130

ArgoNeuT Candidate ν_e Interaction



ArgoNeuT Particle Identification

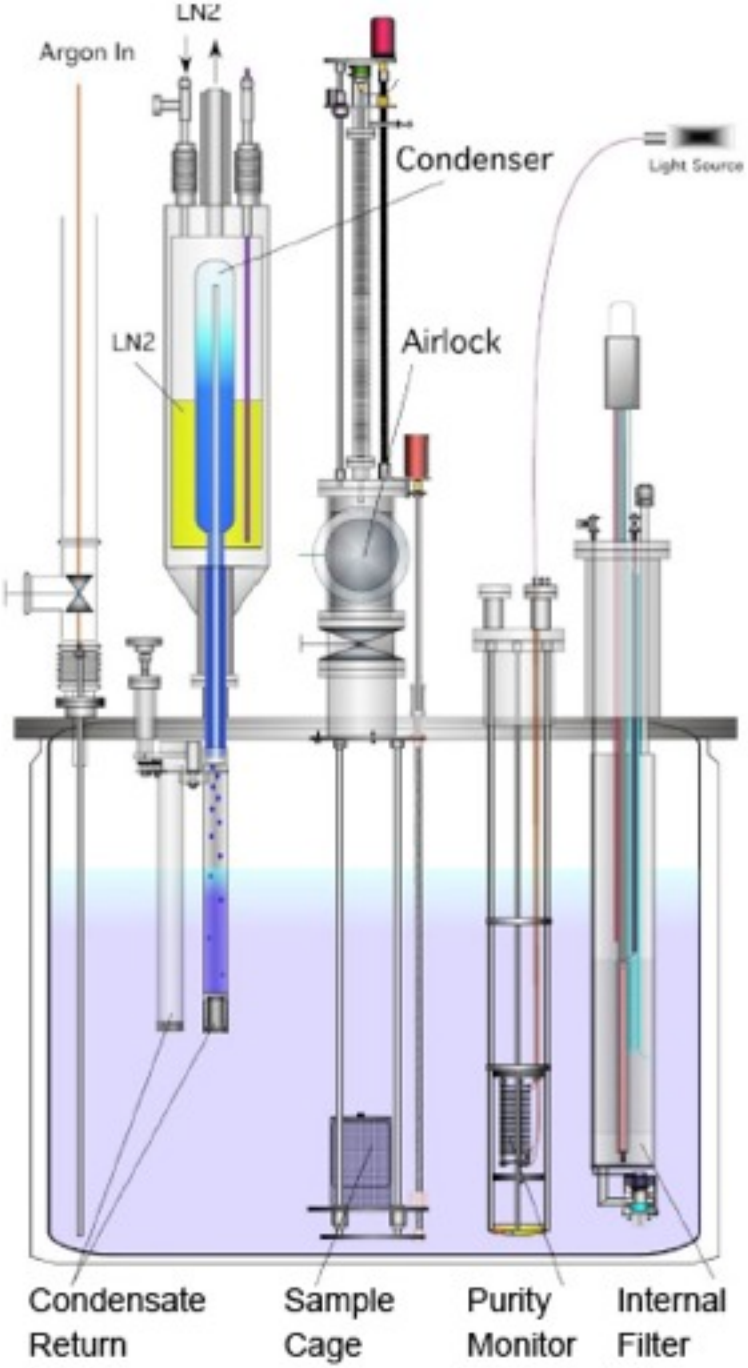




- μ/π separation very difficult
- Protons id'ed as heavily ionizing particles

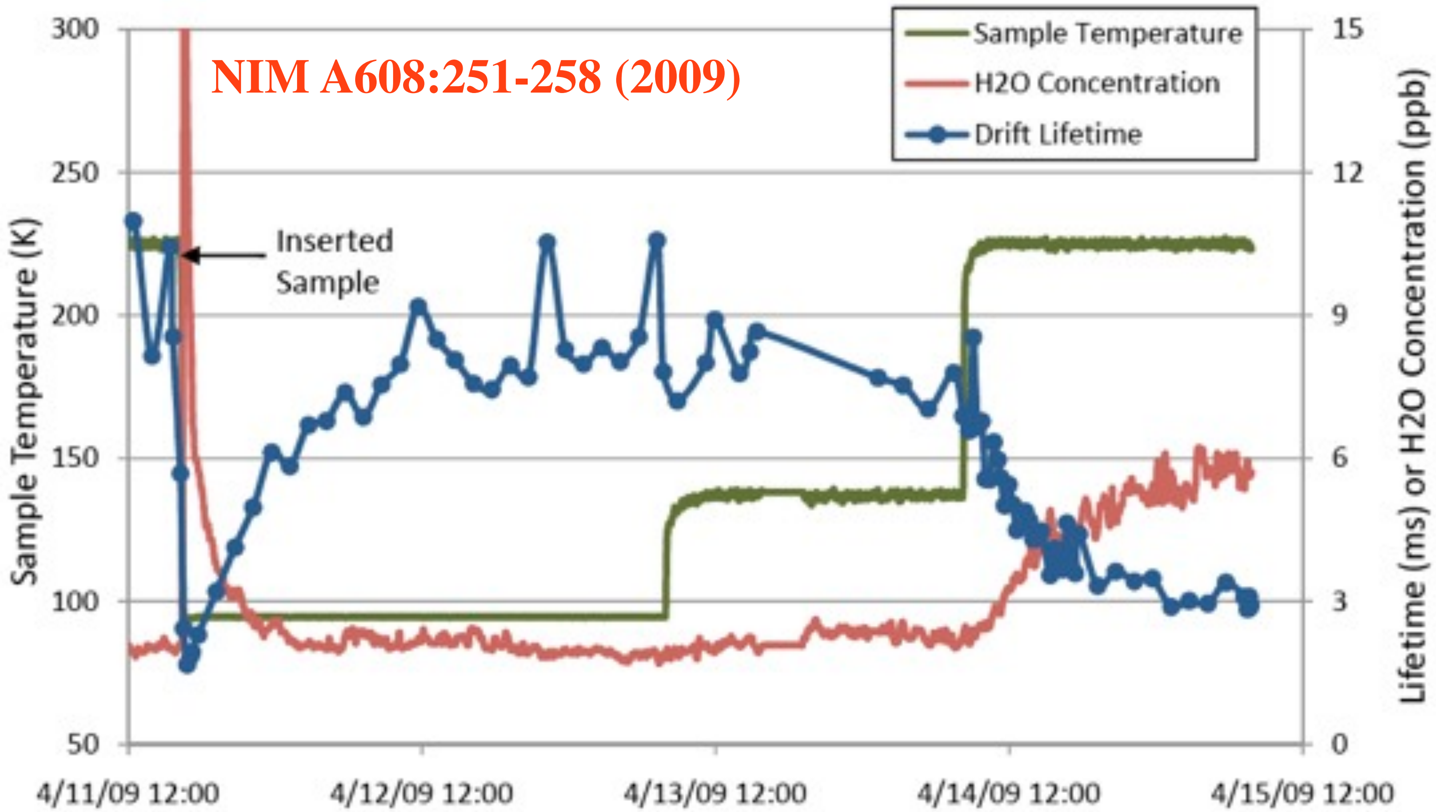
On Going Research & Development

Fermilab Materials Test Stand



- Major on-going challenge for LAr TPCs is ensuring purity of LAr
- 250 L capacity, vacuum-insulated, evacuable vessel
- Internal filter combines molecular sieve and activated copper, purifies liquid in situ
- Condenser allows closed system operation
- Airlock sits above cryostat, contains sample cage that can be lowered into the cryostat
- ICARUS style purity monitor used to determine electron lifetime

Conclusions from the MTS



- Direct relation between electron lifetime and H_2O concentration
- Water concentration in vapor space influenced by materials in vapor space
- No change in electron lifetime when materials are in liquid
- Condensed LAr should not be returned directly to the bulk liquid

Liquid Argon Purity Demonstrator

- Evacuable vessels scales the cost by at least a factor of 2 for small vessels, worse for large vessels
- Like to find an alternative to evacuation for large vessels
- Primary goal: show required electron lifetimes can be achieved without evacuation in an empty vessel - Phase I
- Will also monitor temperature gradients, concentrations of water, O_2
- Phase II will place TPC materials into the volume and show that the lifetime can still be achieved

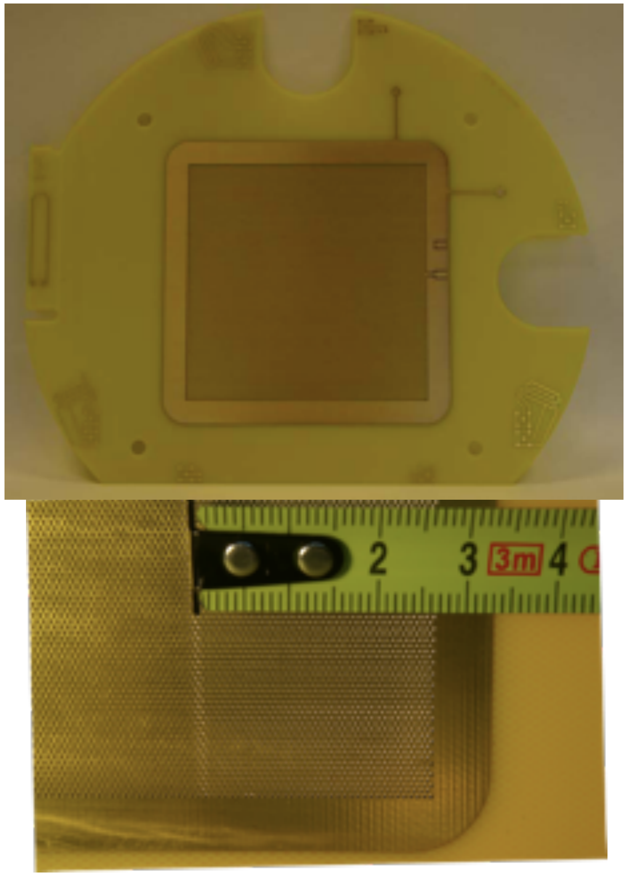
LAPD Scalability Studies

- One goal of LAPD is to understand how to scale the cryogenics system up for a multi-kiloton scale detector
- Will do studies of
  - Oxygen concentration at various depths in the tank vs time during purge
  - Number of LAr volume exchanges needed to reach necessary lifetime for 2.5m drift
  - Rate of volume exchanges necessary to maintain lifetime
  - Filter capacity as a function of flow rate
  - Ability to recover from intentional contamination

Membrane Cryostat for Multi-Kiloton TPCs

- Membrane cryostat is attractive option for large LAr detector
- Makes effective use of space
- Liquid natural gas tankers have used the technology for decades with much larger volumes
- LBNE is working with industry to develop baseline design
- Minimal evacuation, a positive result from LAPD makes this an attractive option

Large Electron Multipliers

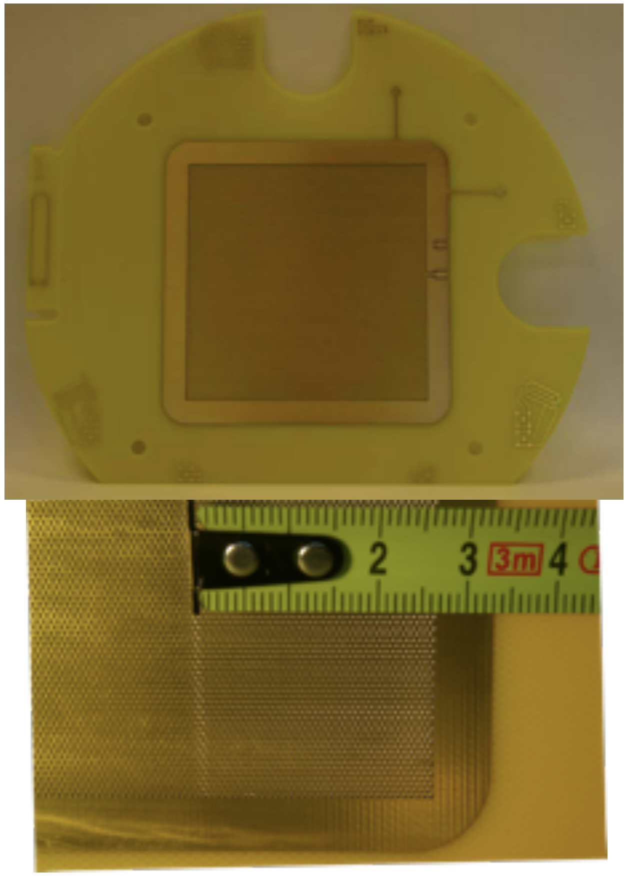


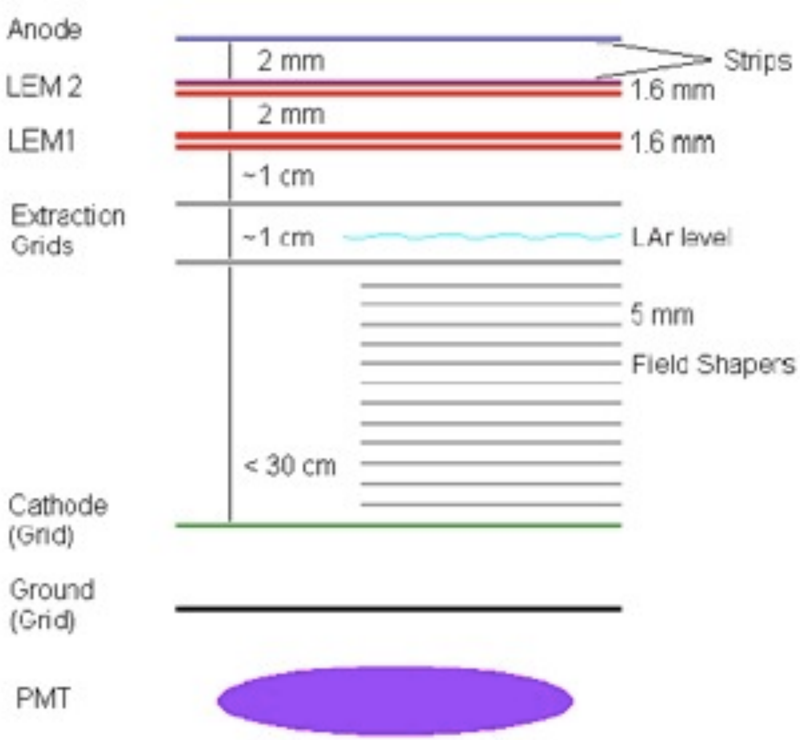
total area	10×10 cm^2
thickness	0.6, 1.0, 1.6 mm
hole diameter	500 µm
hole pitch	800 µm
rim size	~50 µm
segmentation	16 strips, 6 mm pitch

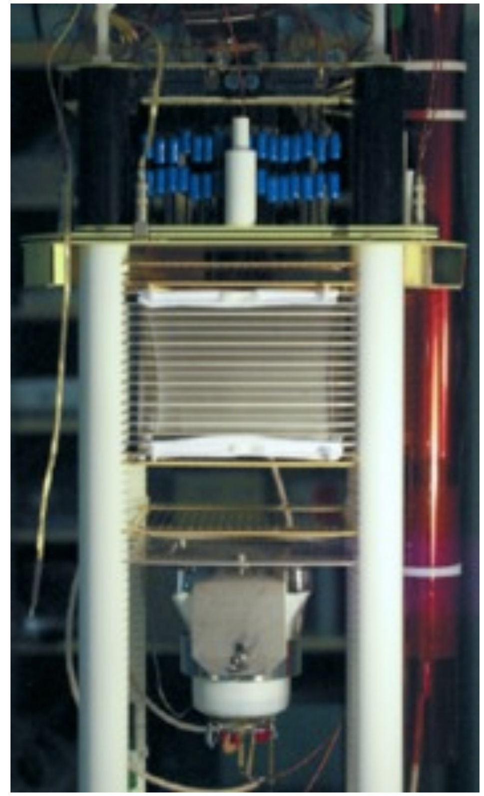
A. Badertscher *et al*., NIM A 617, 188 (2010).

- On-going R&D into alternative readout technologies
- LEM offers opportunity for electron multiplication as ionization e$^-$ are forced through the holes, S/N of 800/10 for dual phase operation
- Also potentially more mechanically robust than wire readout

Large Electron Multipliers







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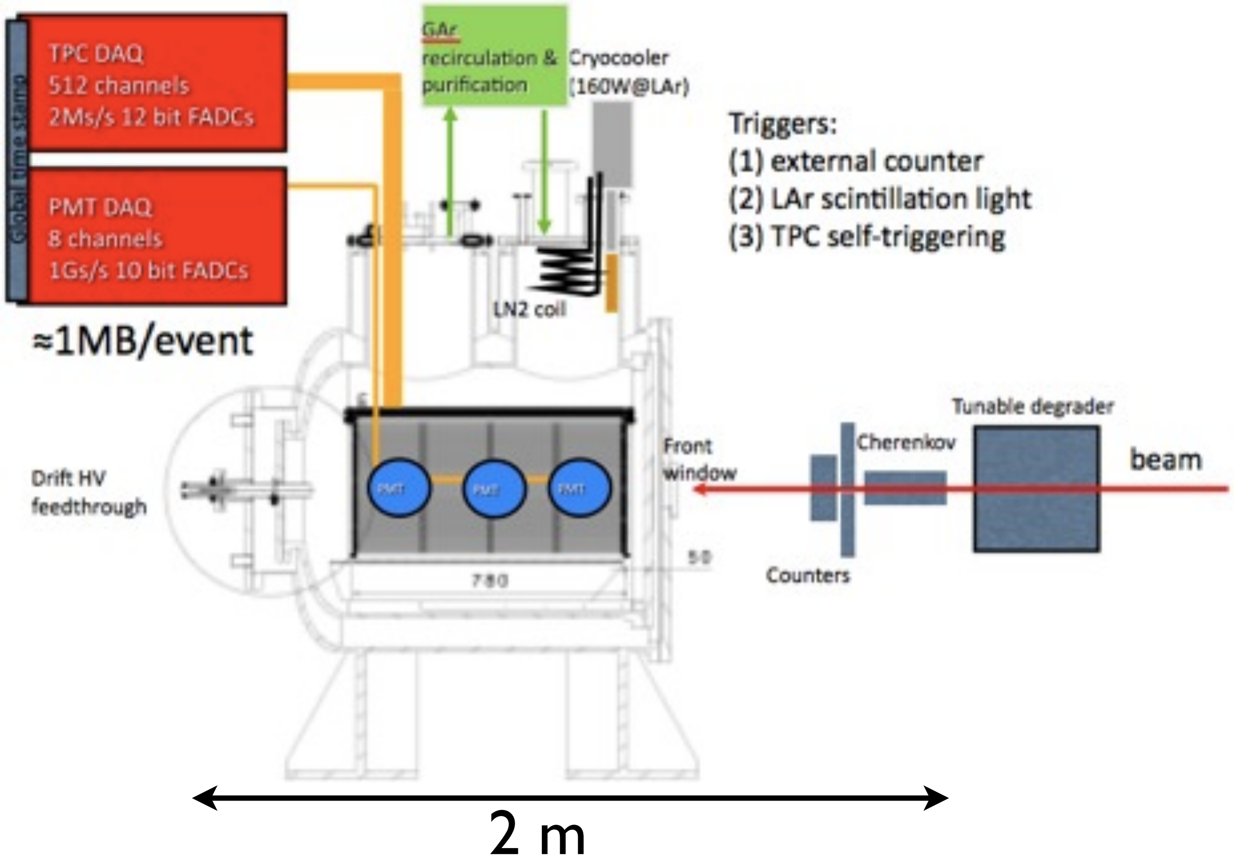
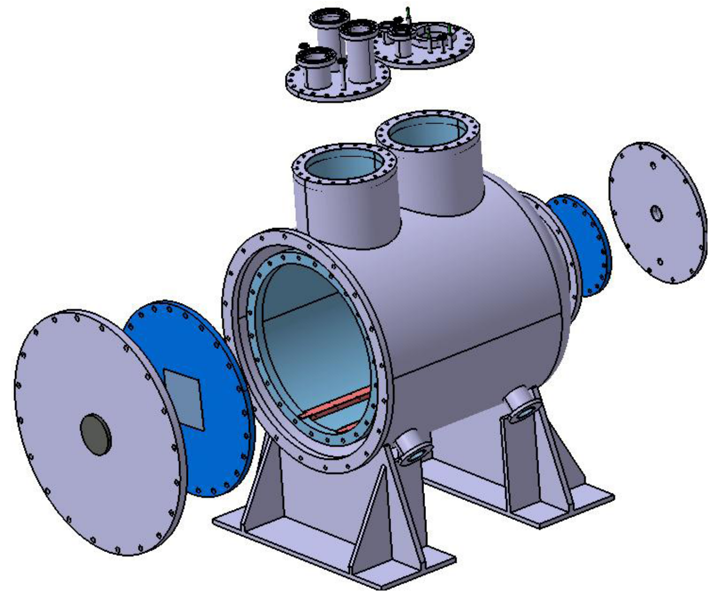
Test Beam Operation at KEK

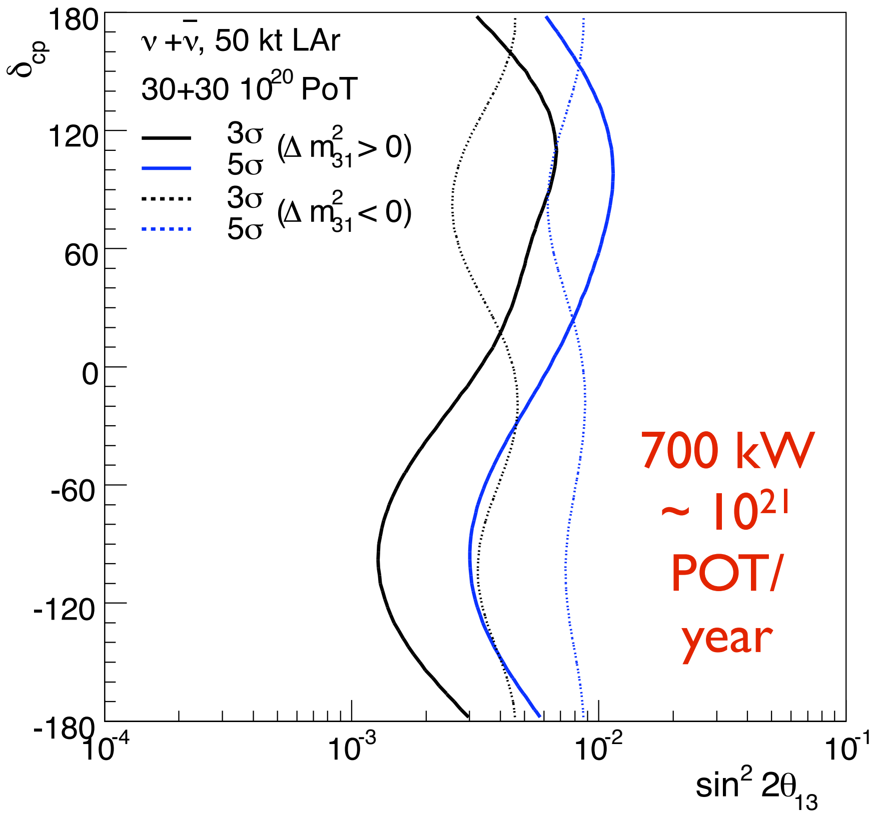


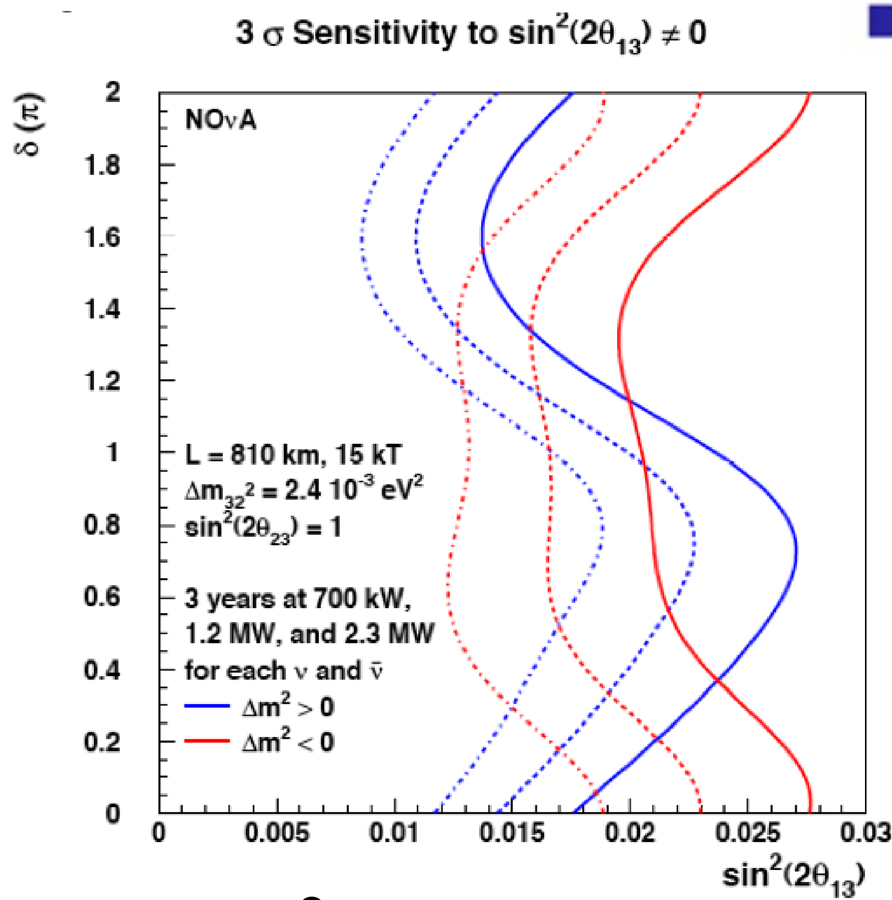


M. Tanaka at GLA 2010

- 250L LArTPC to go into K1.1BR beam @ KEK to study K+ response - relevant to proton decay studies
- Also larger scale test of dual phase readout LEMs - 0.4 m x 0.8 m
- Scheduled to go into test beam in October 2010

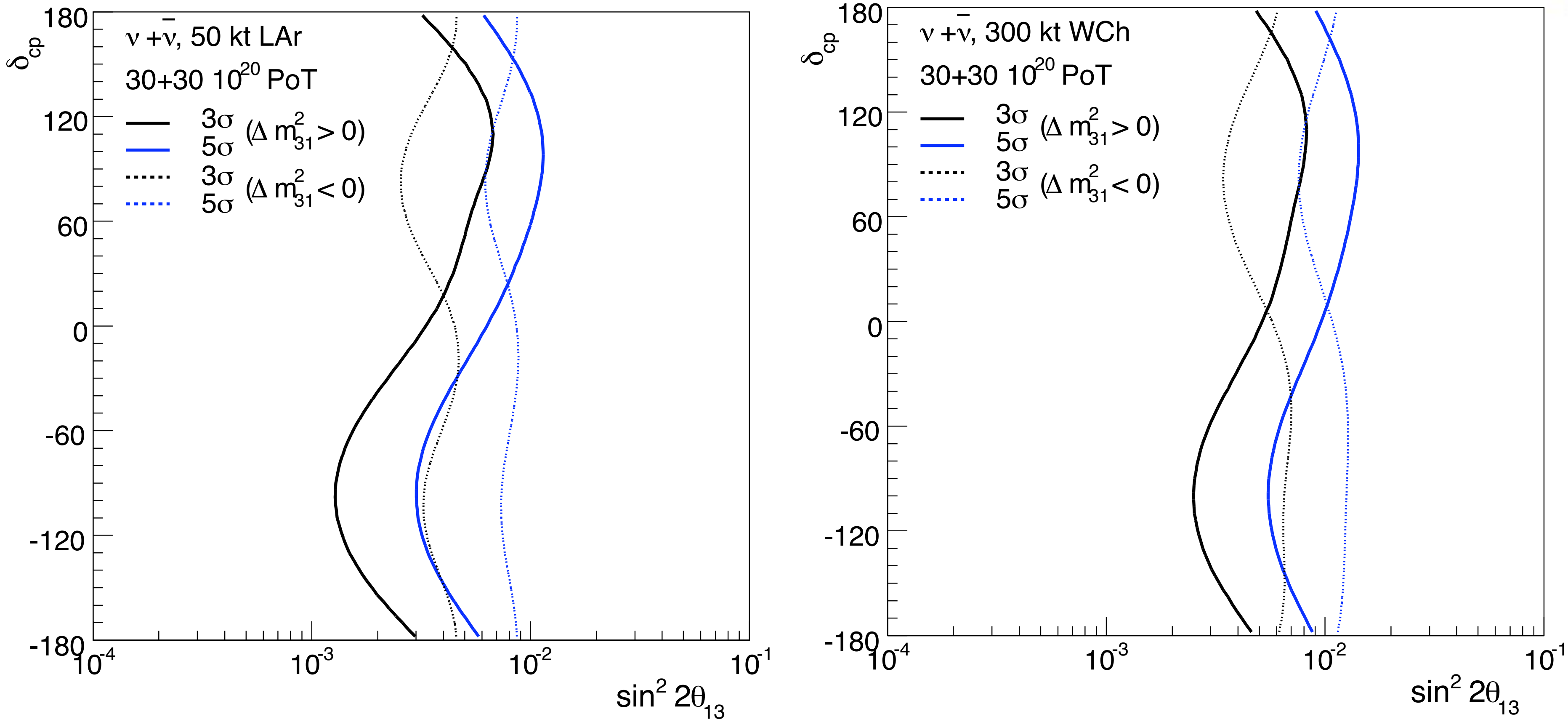
50kt LAr Vs NOνA





- Plots show sensitivity to detection of non-zero θ_{13}
- LAr offers more than order of magnitude improvements in sensitivity compared to NOνA
- Increased mass only accounts for a factor of 3 improvement in these plots, better background rejection is main reason for improvement

50kt LAr Vs Water Cherenkov

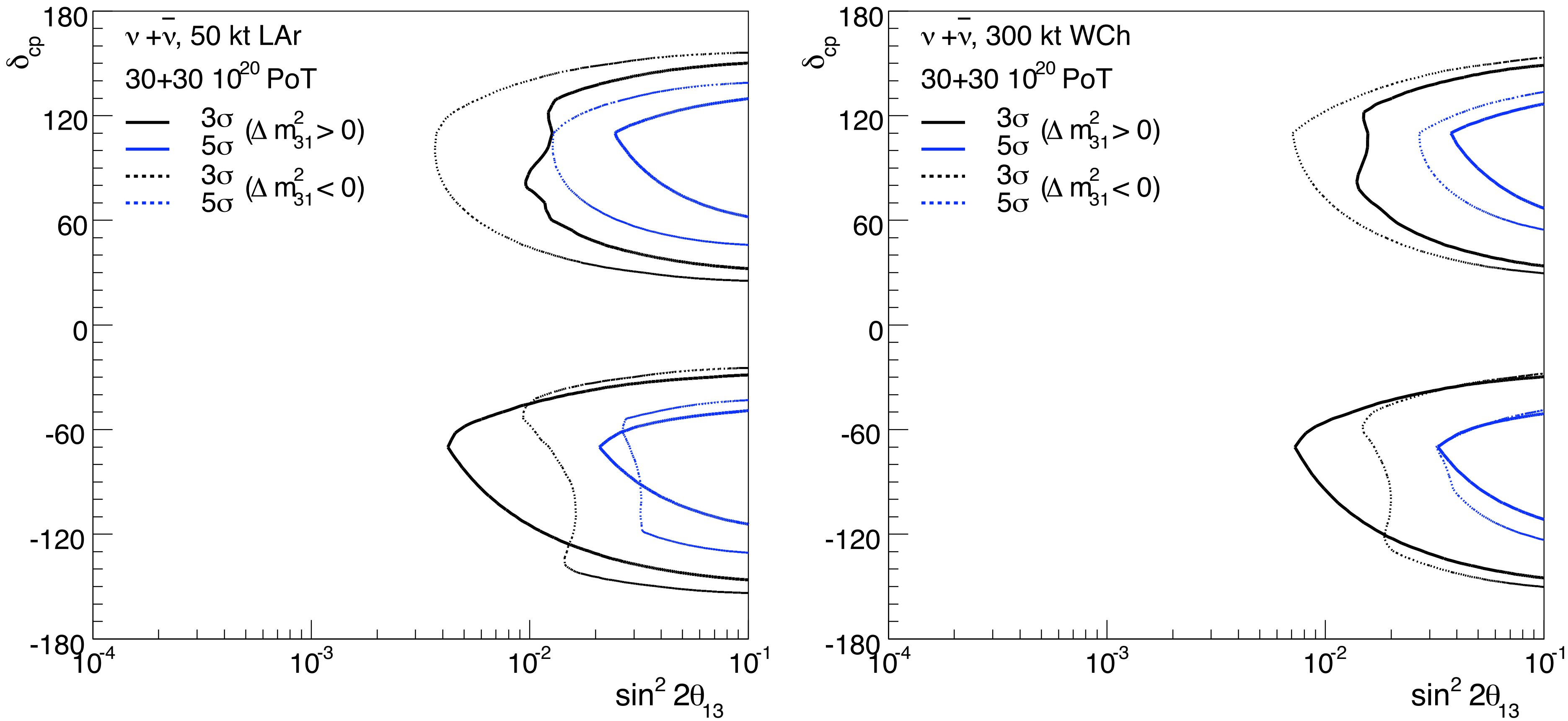


- Plots show sensitivity to detection of non-zero θ_{13}
- A LArTPC offers somewhat better sensitivity than a Water Cherenkov detector with 6x the mass
- Main advantage is due to LArTPC's increased resolution resulting in better background rejection

Outlook

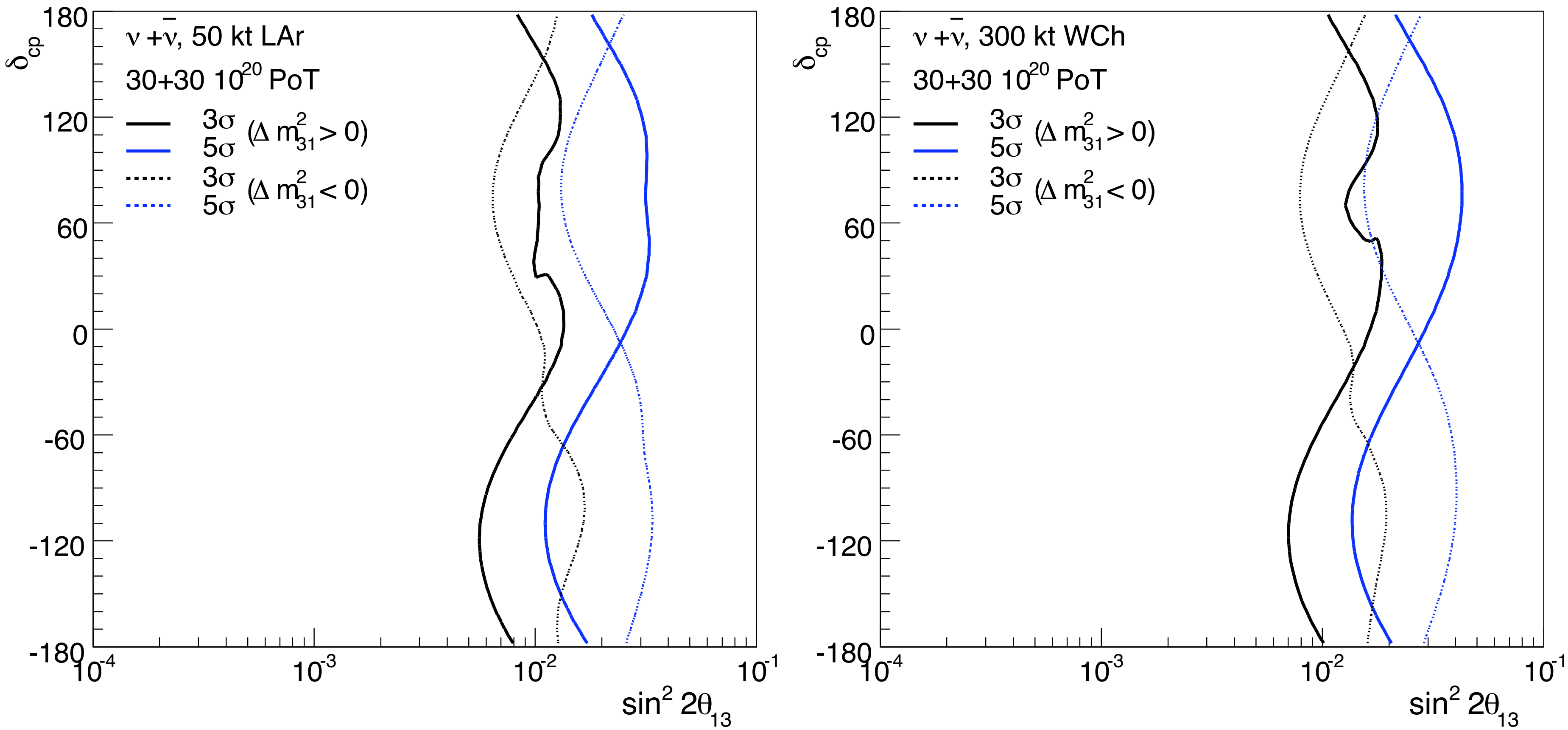
- ICARUS is running and observing LNGS neutrinos
- ArgoNeuT analysis is beginning, particle identification for proton vs μ/π results are promising
- Many test stands are pushing the technology towards a kiloton scale detector
  - Fermilab MTS provides mechanism for determining which materials should go into LArTPCs, also shown that H_2O is most worrisome contamination
  - LAPD testing whether non-evacuable vessels are viable cryostats
  - "New" membrane cryostat option being explored for LBNE
  - LEMs are possible new readout technology, provide gain and improved S/N
  - 250L TPC starting operation in KEK test beam
- Sensitivity of LArTPC rivals much larger WC detector

50kt LAr Vs Water Cherenkov



- Sensitivity to detection of CP violating phase, δ
- NOνA will not be able to measure δ

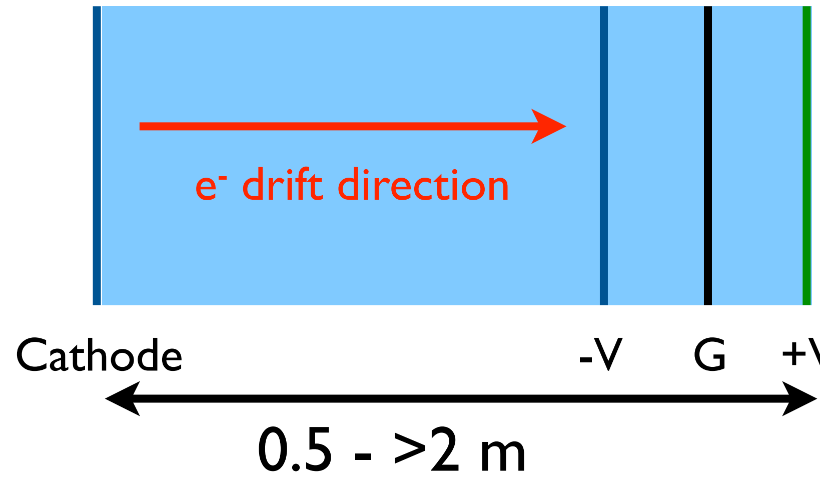
50kt LAr Vs Water Cherenkov

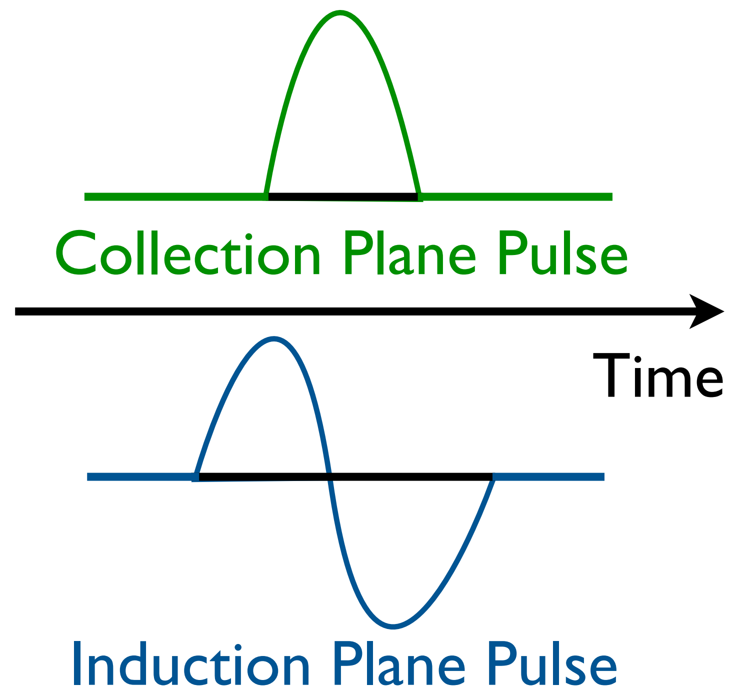


- Sensitivity to discrimination of mass hierarchy
- NOνA's reach is about a factor of 5 worse

LAr TPCs

- Electric field established between cathode and readout planes
- Field strength typically 500 V/cm
- Minimum ionizing particle releases 55k e/cm
- Electrons drift toward readout planes with velocity of 0.155 cm/μs - need > 1.6 ms for 2.5 m drift
- ⟨dE/dx⟩ for minimum ionizing particle is 1.519 MeV cm^2/g
- Attractive detector design for large detectors as channel count goes as fraction of the area rather than volume
- Primary challenge - keeping LAr pure over long drift distances



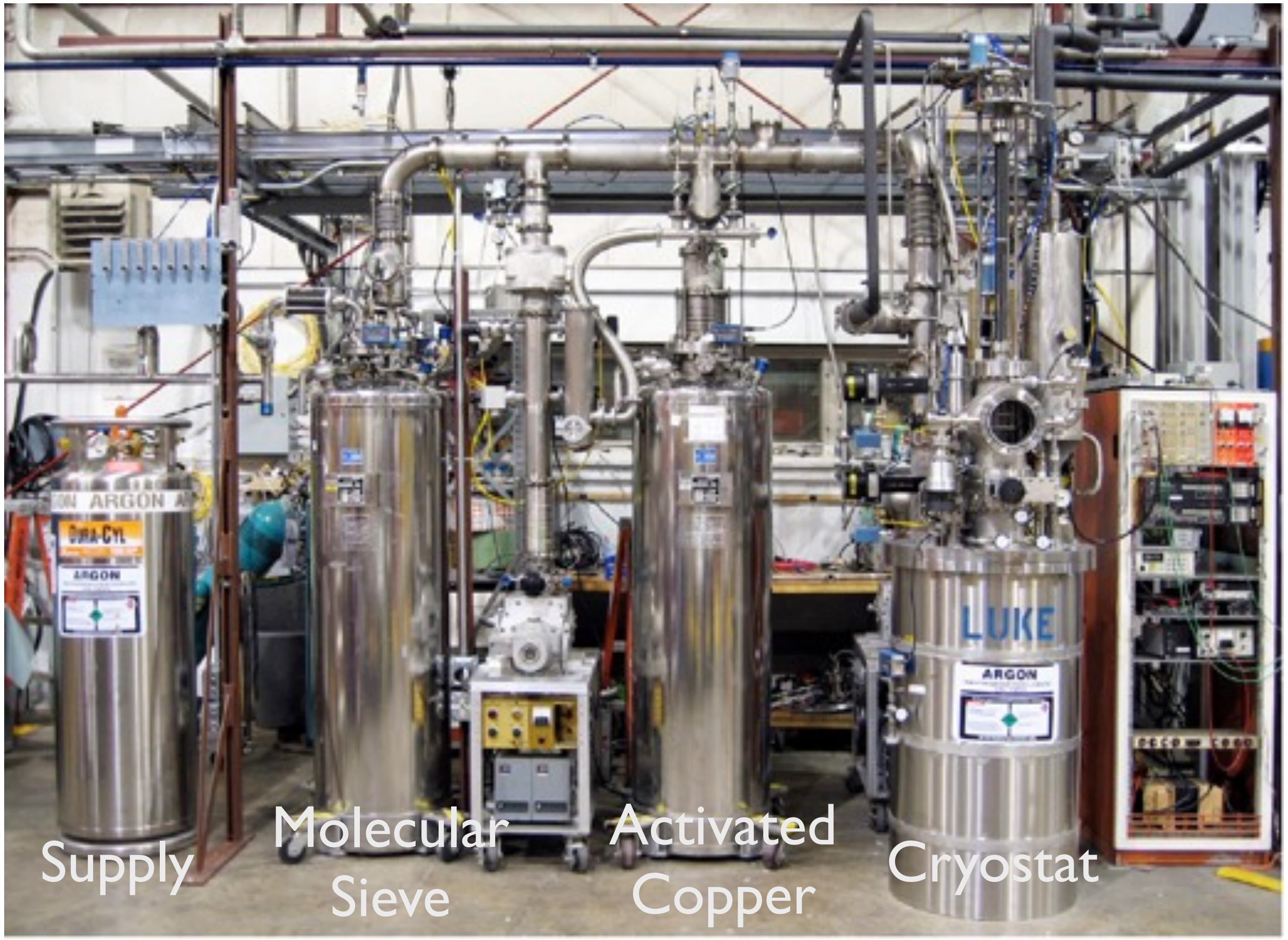


Why Argon?

	Water	He	Ne	Ar	Kr	Xe
Boiling Point [K] @ 1atm	373	4.2	27.1	87.3	120.0	165.0
Density [g/cm^3]	1	0.125	1.2	1.4	2.4	3.0
Radiation Length [cm]	36.1	755.2	24.0	14.0	4.9	2.8
Scintillation [γ /MeV]	-	19,000	30,000	40,000	25,000	42,000
dE/dx [MeV/cm]	1.9		1.4	2.1	3.0	3.8
Scintillation λ [nm]	475	80	78	128	150	175

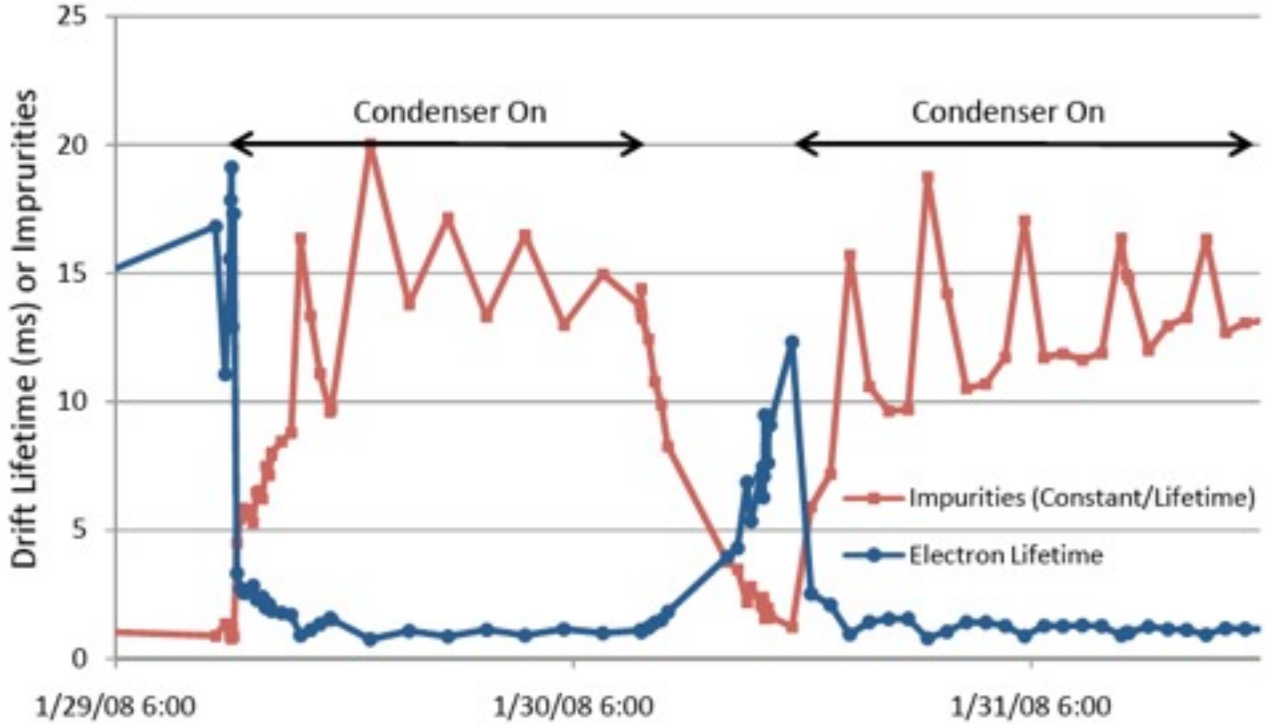
- Cheap and easy to obtain - 1% of atmosphere, $1 / L (cheaper than Pepsi)
- Relatively high boiling point
- Produces lots of scintillation light as well as ionization
- Transparent to own scintillation, useful for triggering
- Good liquid for having large electric field running through it

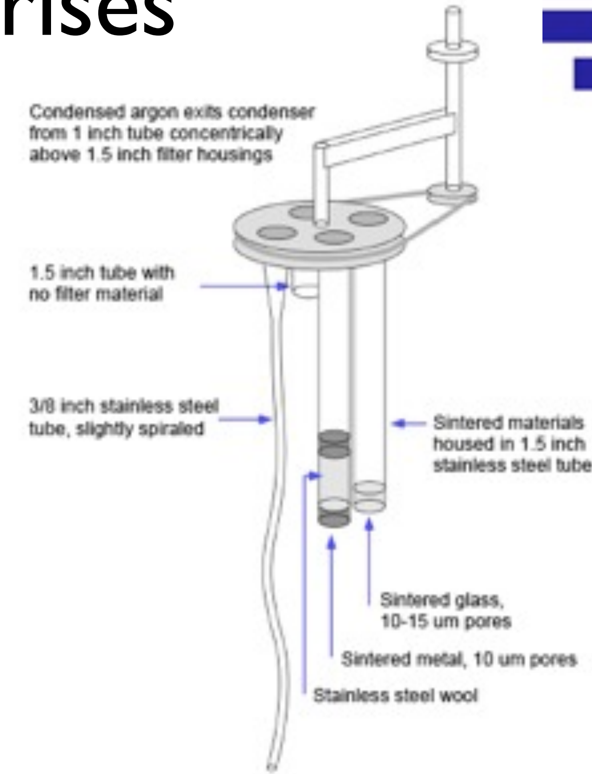
R&D Test Stand



- Goals are to develop purification techniques and qualify materials that are intended for use in LArTPCs
- Commercial LAr passes through molecular sieve to remove water then activated copper to remove oxygen

Condenser Surprises

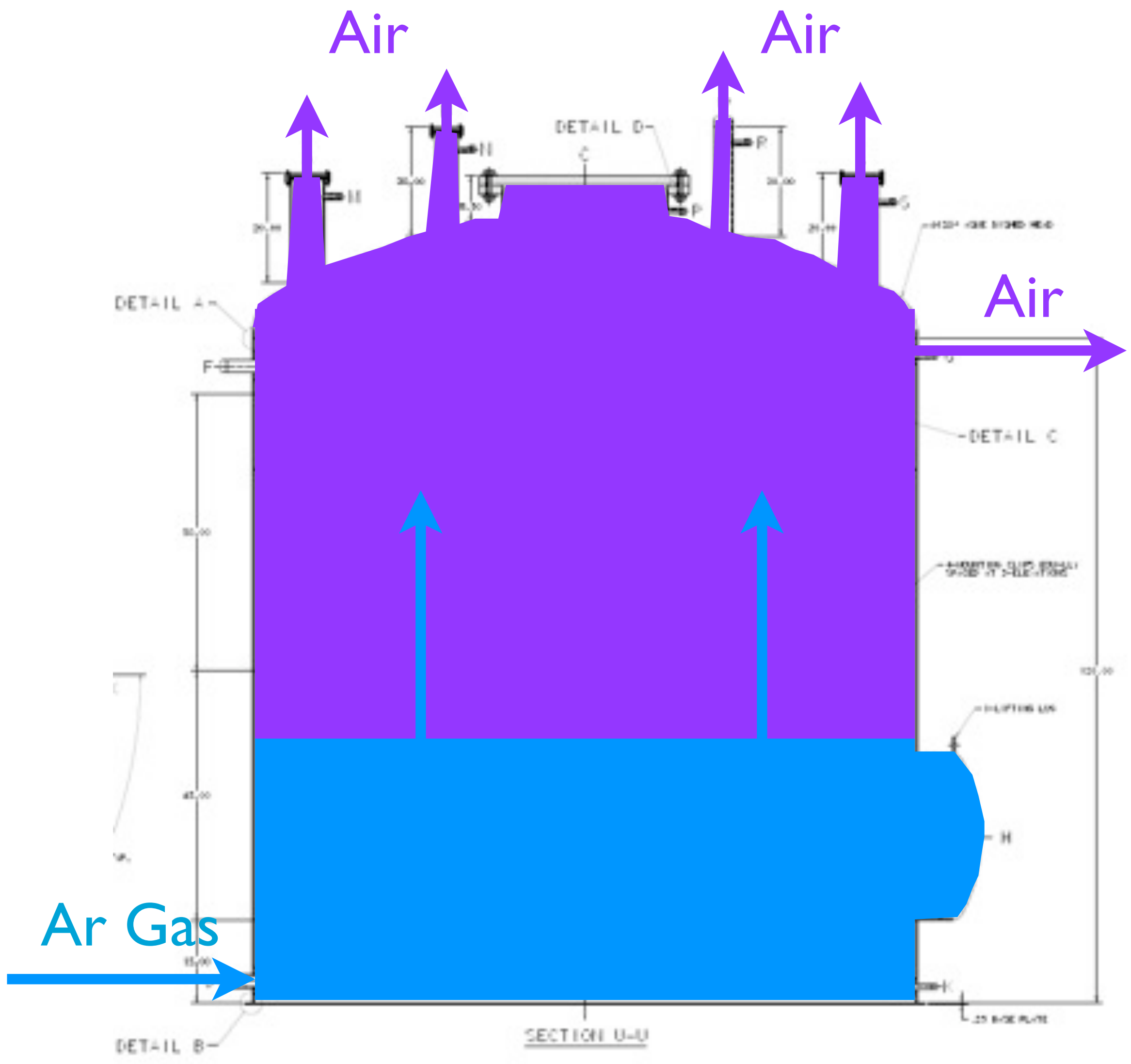




- Initially, operation of the condenser caused electron lifetime to drop
- Condensed liquid rained directly into the bulk liquid
- Several tests through various return paths showed that increasing cold metal surface area on return to liquid improved lifetime
- Hypothesis: impurity desorbs from warm surfaces, gets mixed into liquid in condenser
- Depending on return path, impurity can adsorb to cold metal on return to liquid and be removed

Phase I - Purification without Evacuation

- Basic idea is to use an argon piston for initial purification
- Cycle a few volumes of clean, warm Ar gas through the volume to push out ambient air and dry out surfaces
- Then recirculate the gas through filter system to achieve < 50 ppm contamination



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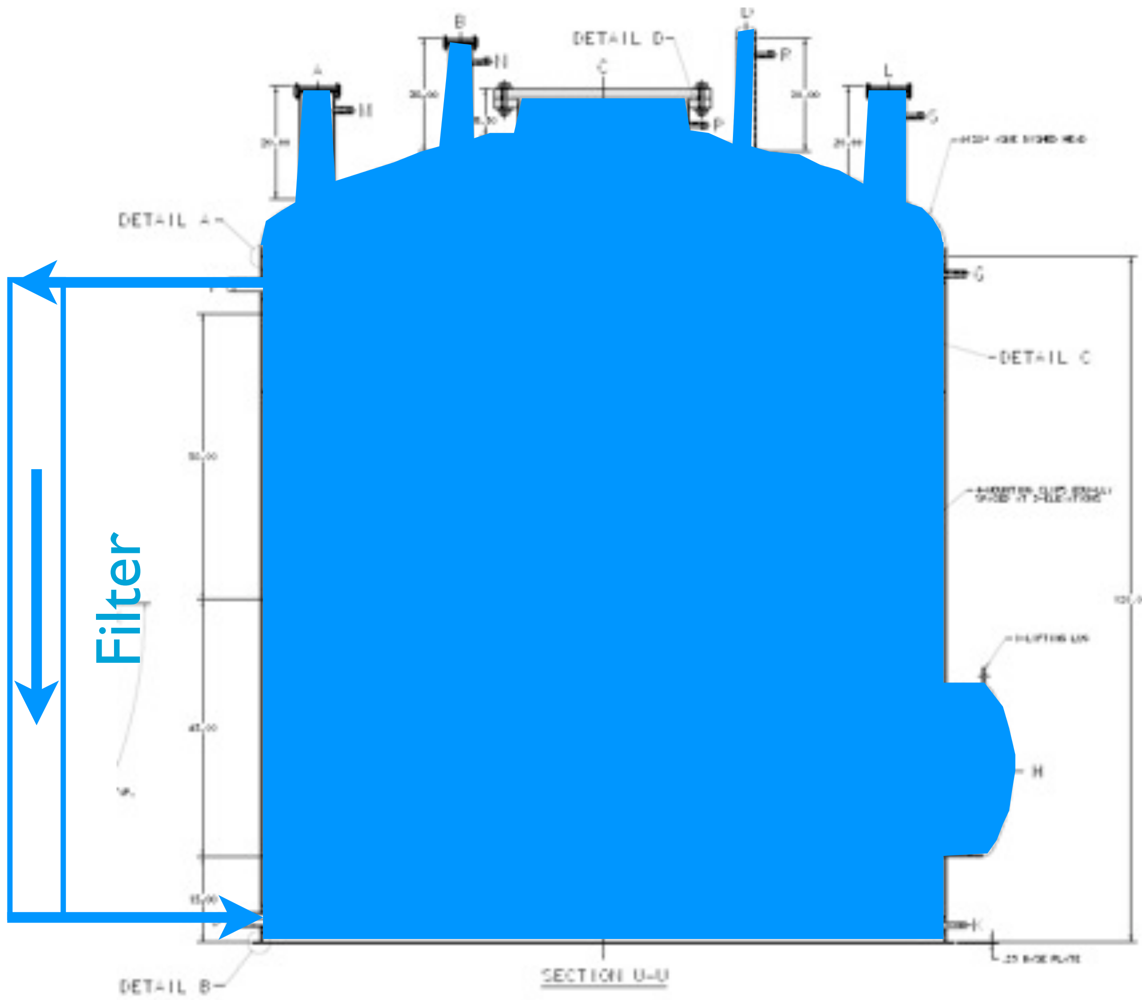
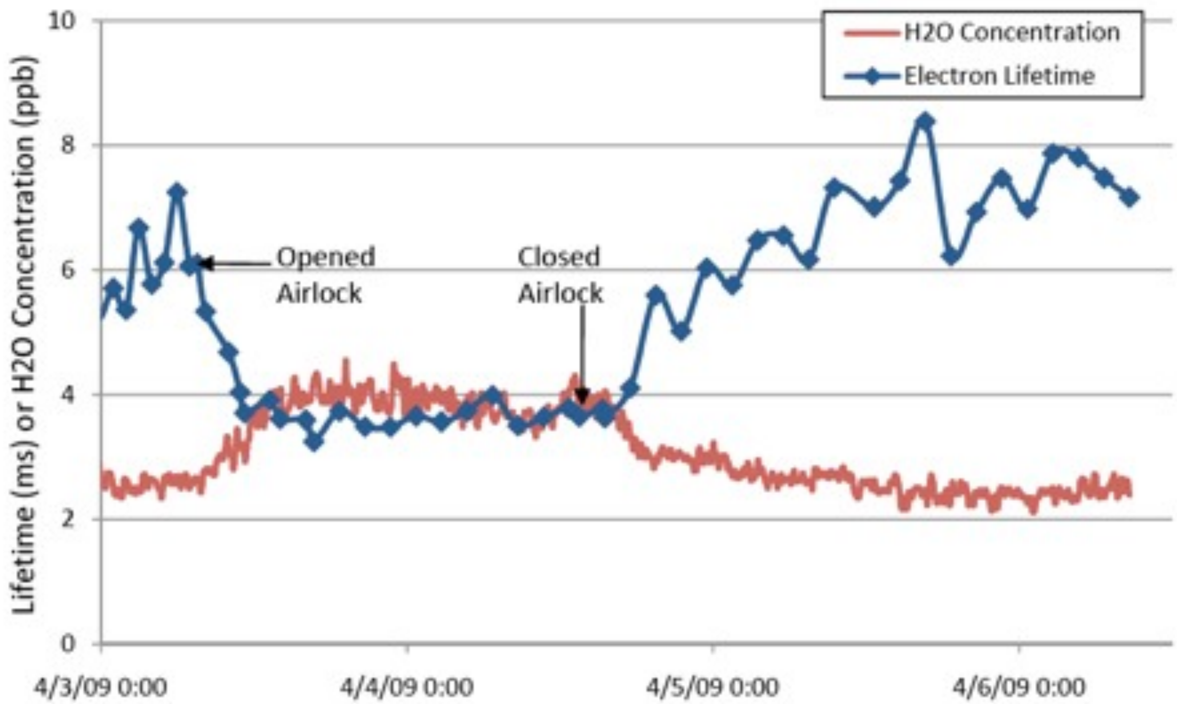
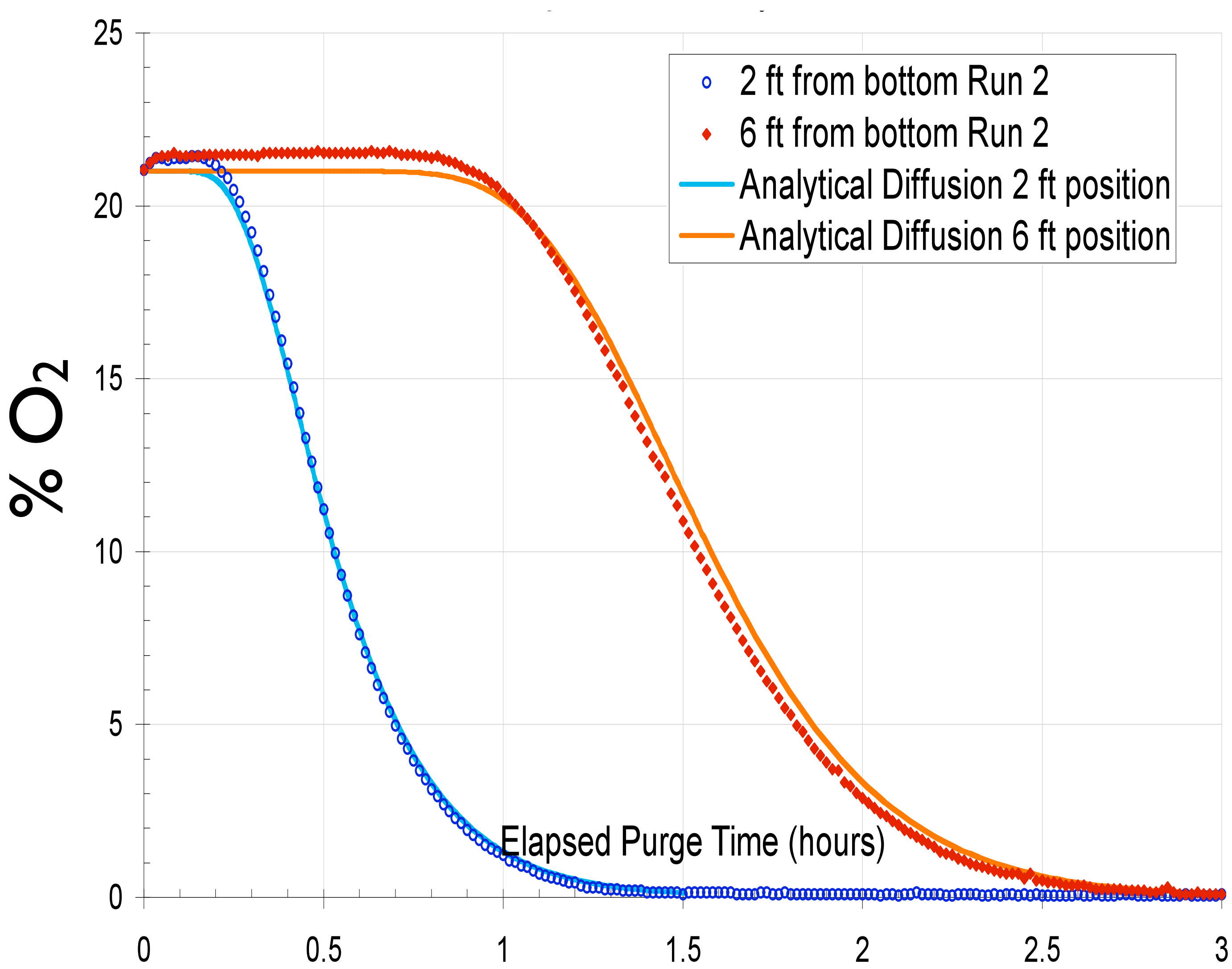


What is the Impurity?



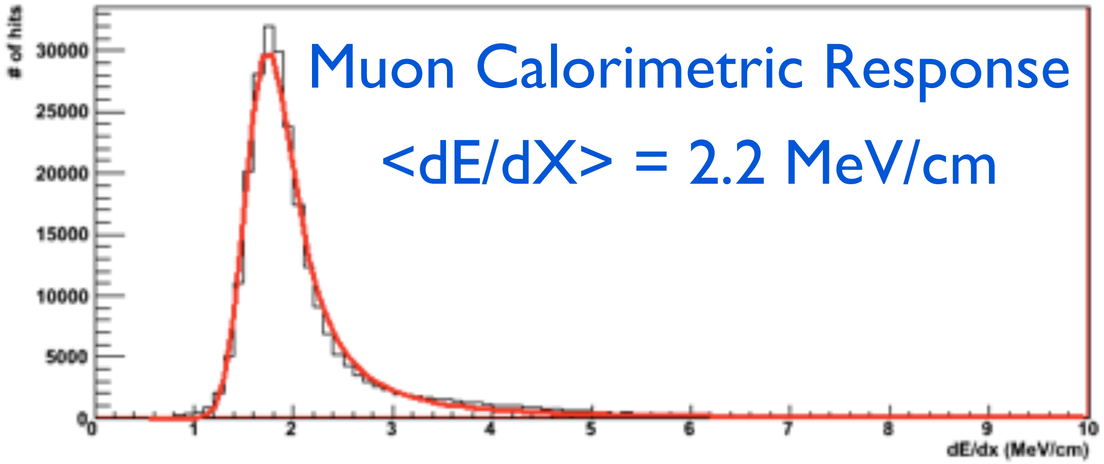
- Source must be something that remains on metal surfaces in vacuum and has an affinity for cold surfaces: Water is a clear suspect
- Moisture analyzer with 2 ppb detection limit used to monitor water concentration in cryostat
- Water concentration increases when airlock is open to cryostat, electron lifetime decreases

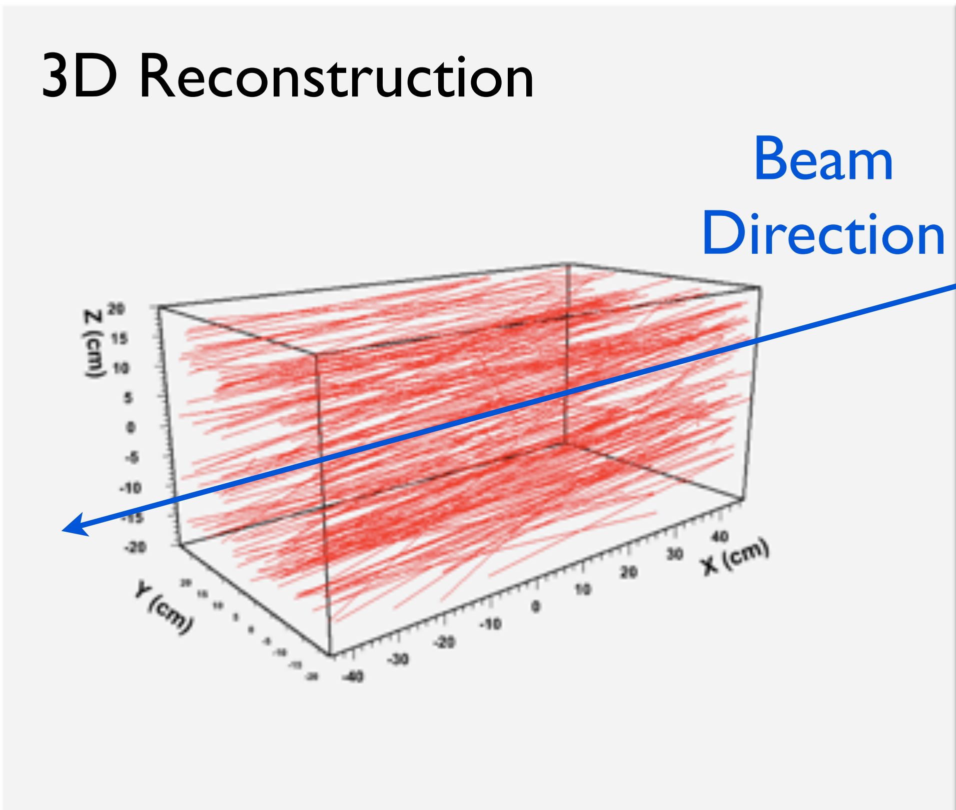
Number of Gas Volume Exchanges

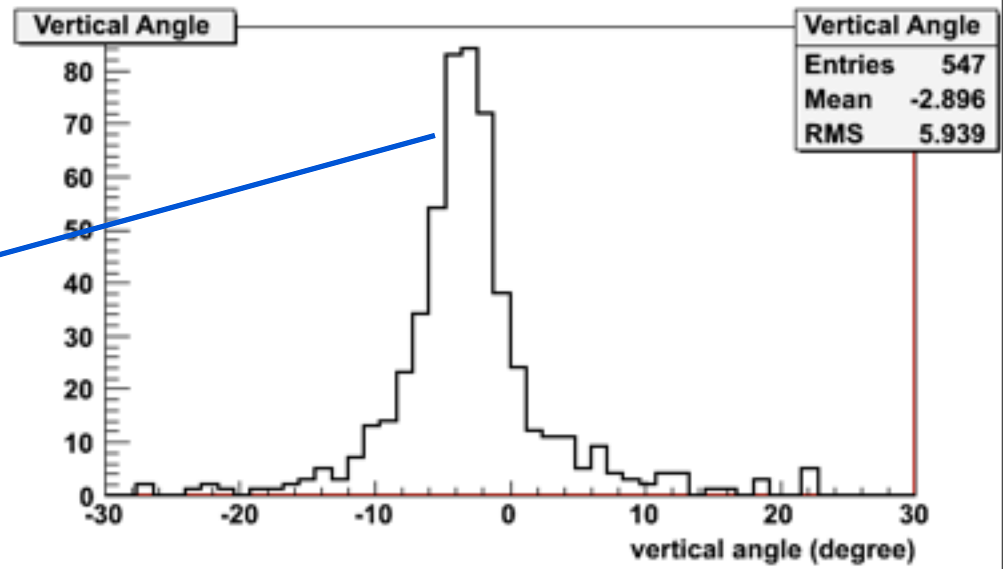


- Study by T. Tope at FNAL shows it takes 2.6 volume exchanges to reduce contaminants to 100 ppm

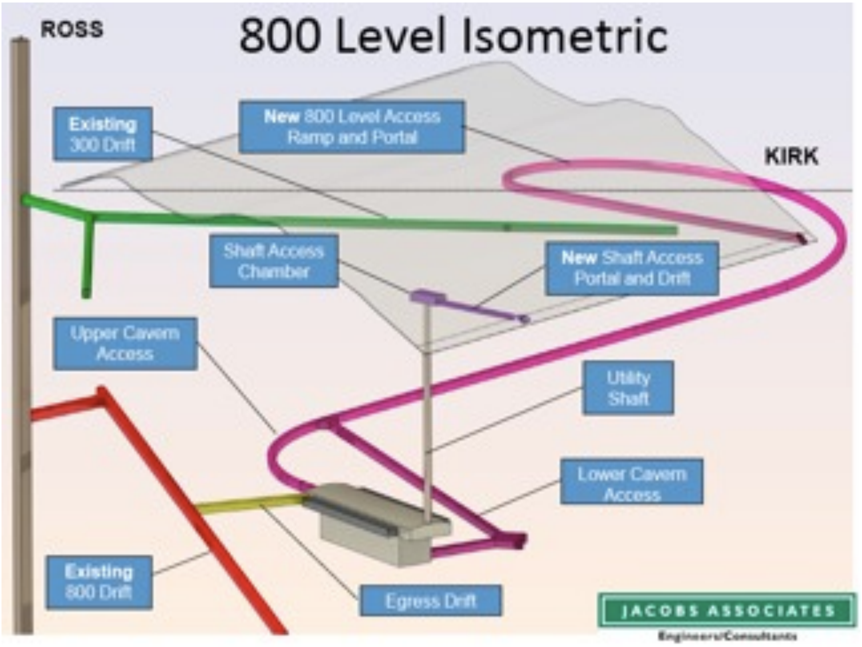
ArgoNeuT Reconstruction

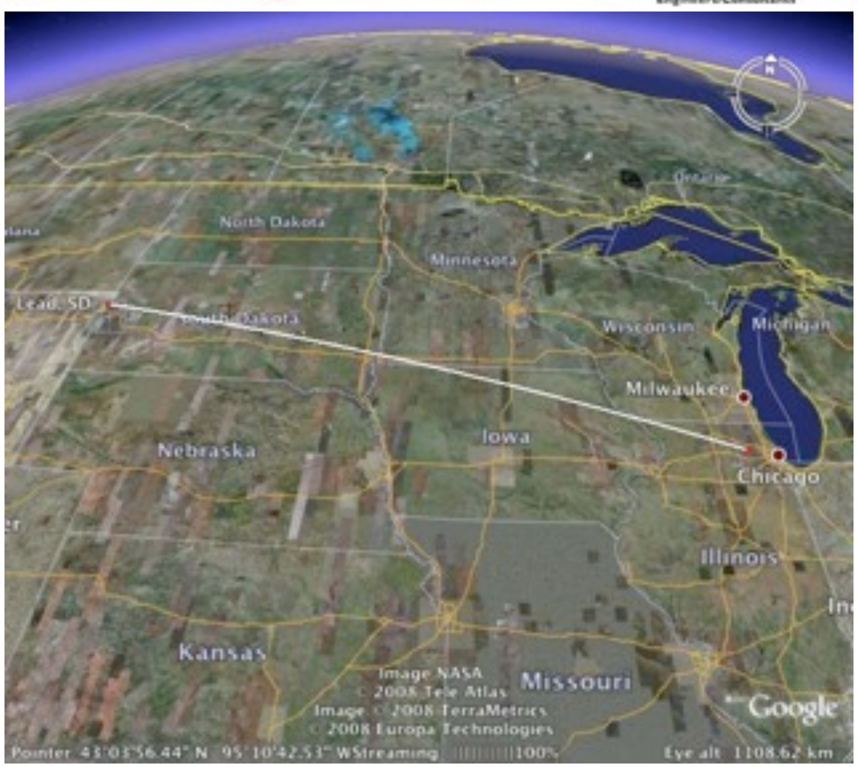






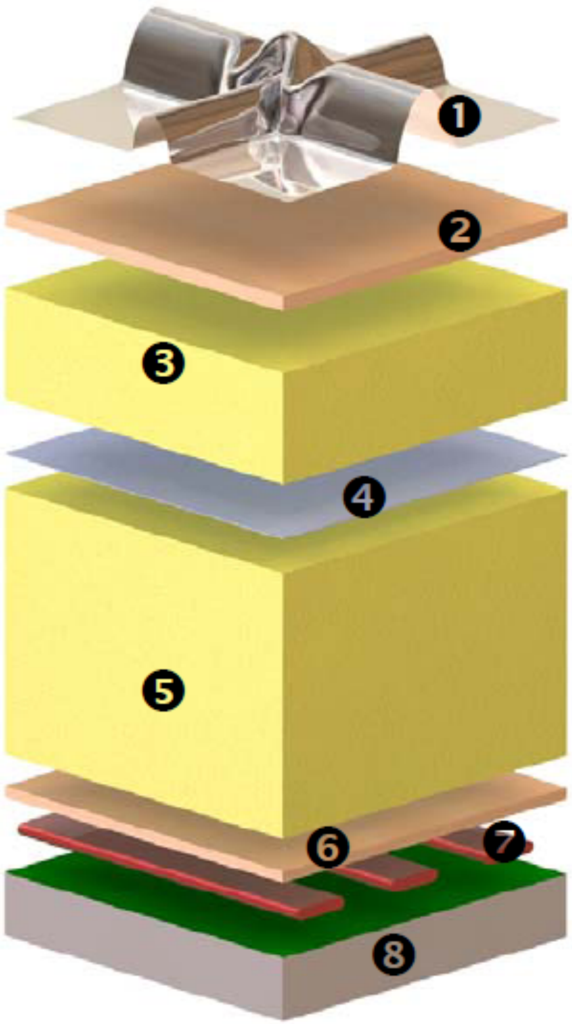
The Next Steps





- The ultimate goal is to make LAr a viable option for massive detectors
- Very large detectors needed for next generation neutrino oscillation experiments and proton decay
- Oscillation experiment will be a major component of DUSEL
- Baseline of 1300 km
- Will allow us to measure CP violation in the neutrino sector, see 1st and 2nd oscillation maxima

Membrane Cryostat



1. Stainless steel primary membrane
2. Plywood board
3. Reinforced polyurethane foam
4. Secondary barrier
5. Reinforced polyurethane foam
6. Plywood board
7. Bearing mastic
8. Concrete covered with moisture barrier