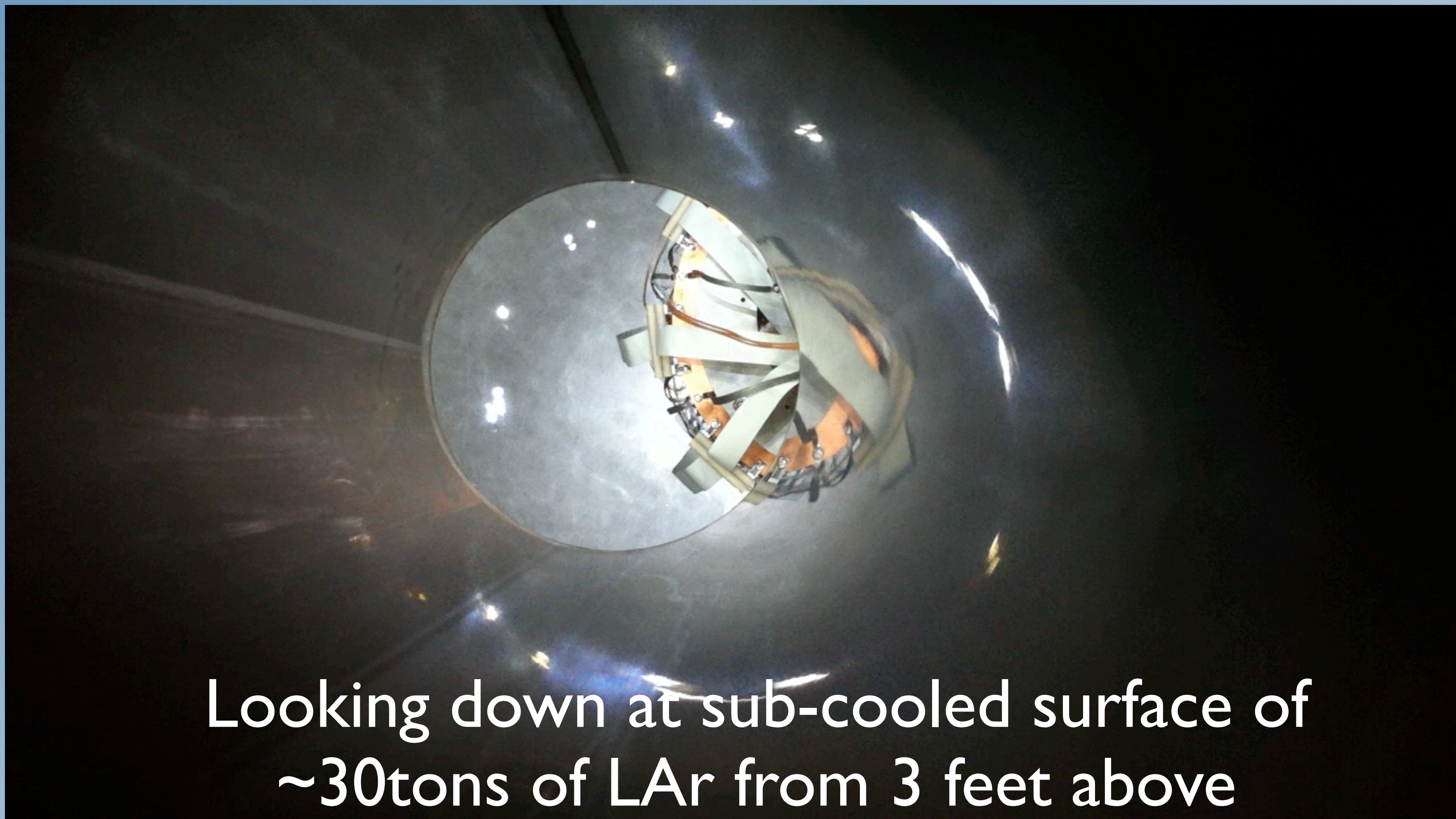
Liquid Argon Detectors at Fermilab: From R&D to LBNE



Brian Rebel
June, 2013

Outline

- Fermilab neutrino program
- Long Baseline Neutrino Experiment
- Brief introduction to LArTPCs
- Fermilab development towards LBNE
    - Purification and Cryogenics
    - Electronics,DAQ, and Triggering
    - Photon Detection
    - TPC and High Voltage
    - Calibration and Test Beams
    - Software

Neutrino Oscillations in the Future

- We have learned a lot about neutrino oscillations - measured 2 mass splittings and 3 mixing angles
- Future questions to answer about oscillations
  - Is the PMNS matrix sufficient to explain oscillations?
  - Are there more neutrinos than the 3 active flavors?
  - Is CP violated?
  - What is the mass hierarchy?
  - Is θ23 maximal?
- Background rejection is key when every CC ν_e is gold

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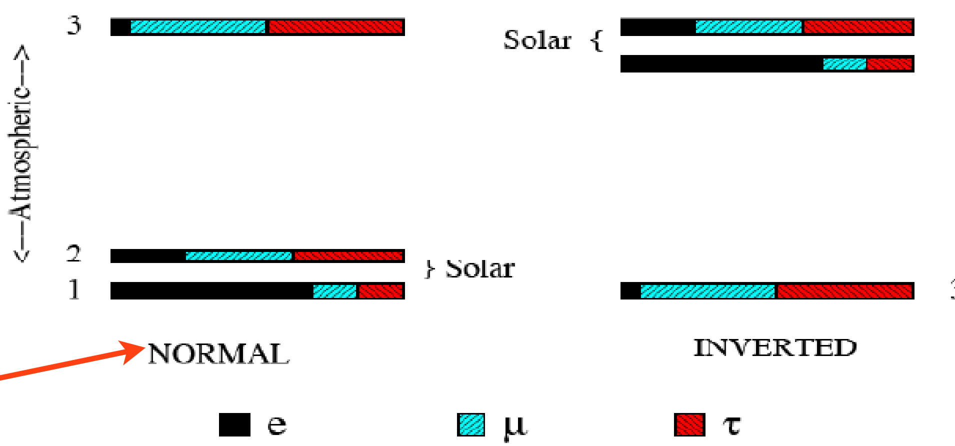
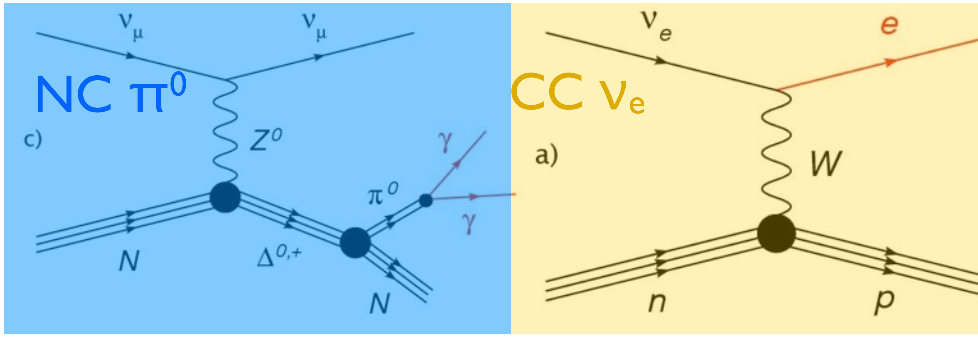
$\nu_4, \nu_5, \ldots$?

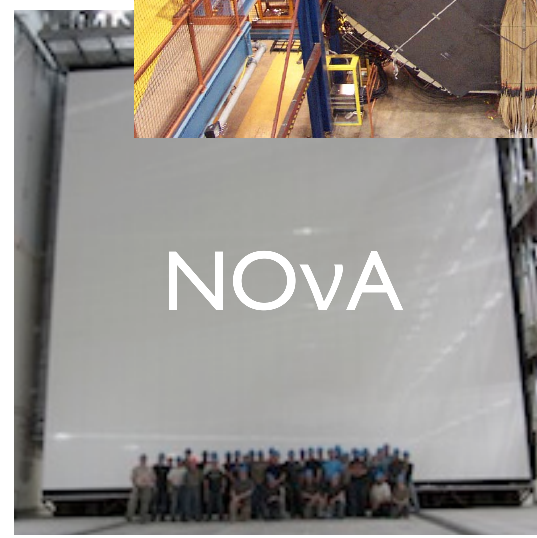
$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$

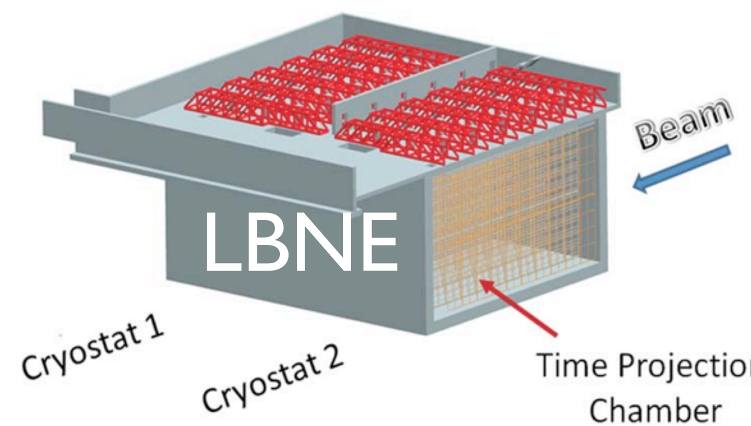




Fermilab Neutrino Program

- Fermilab long-baseline program characterizing patterns of neutrino masses and mixing
  - MINOS(+) → NOνA → LBNE
  - Will determine mass hierarchy and CPV in neutrinos
- Fermilab short-baseline program exploring whether PMNS matrix tells the whole story
  - MiniBooNE → MicroBooNE → νSTORM(?)
- Cross section measurements facilitate these goals
  - MiniBooNE → MINERνA → MicroBooNE





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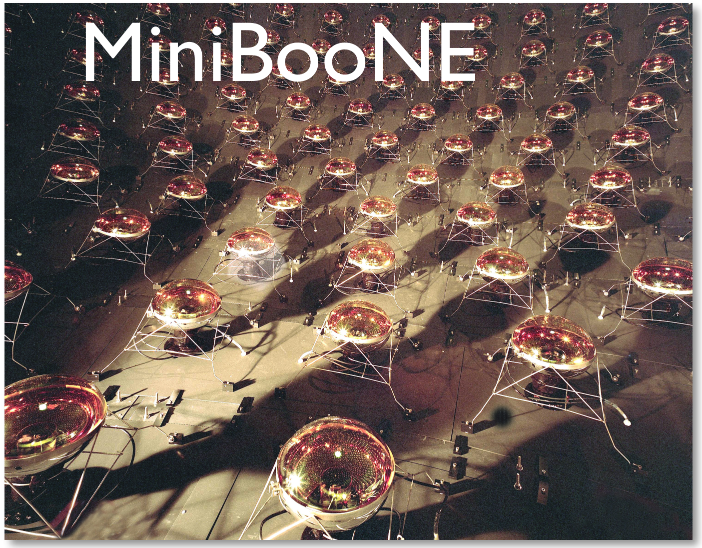

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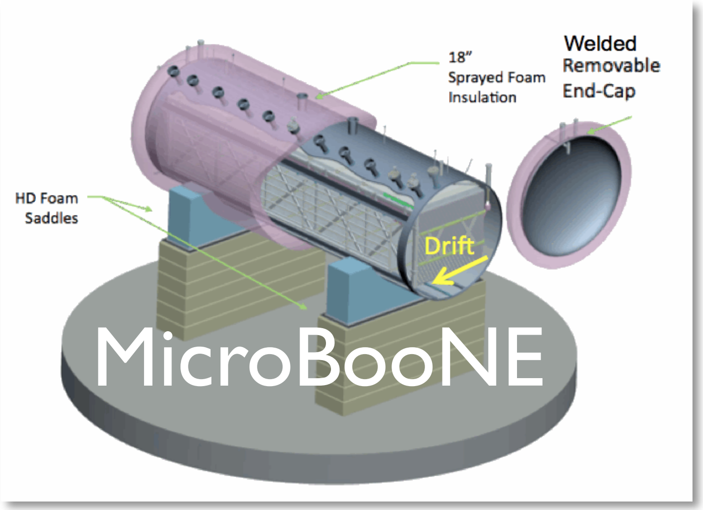

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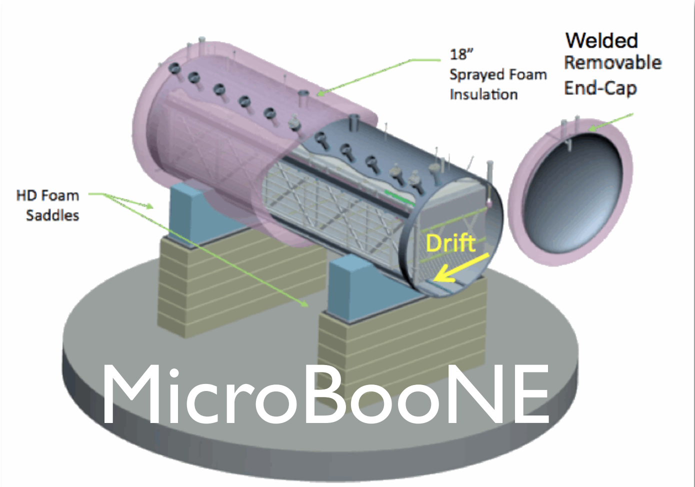
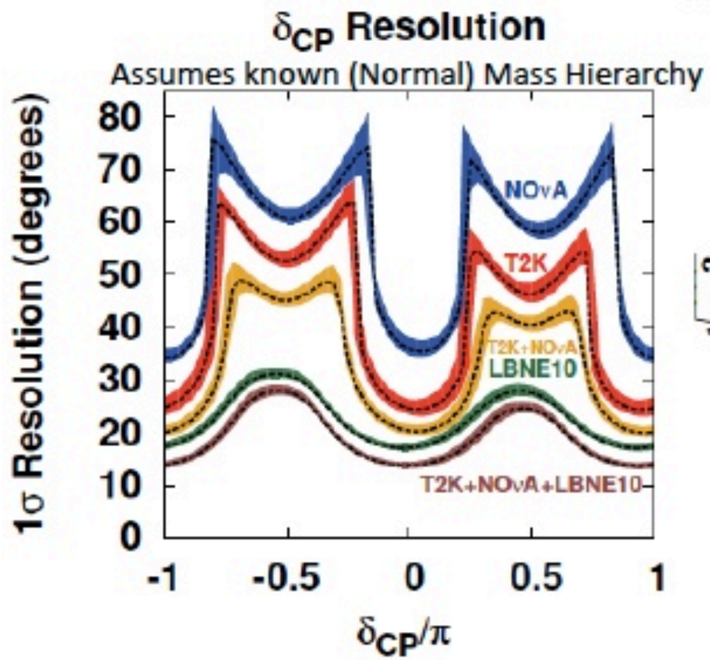
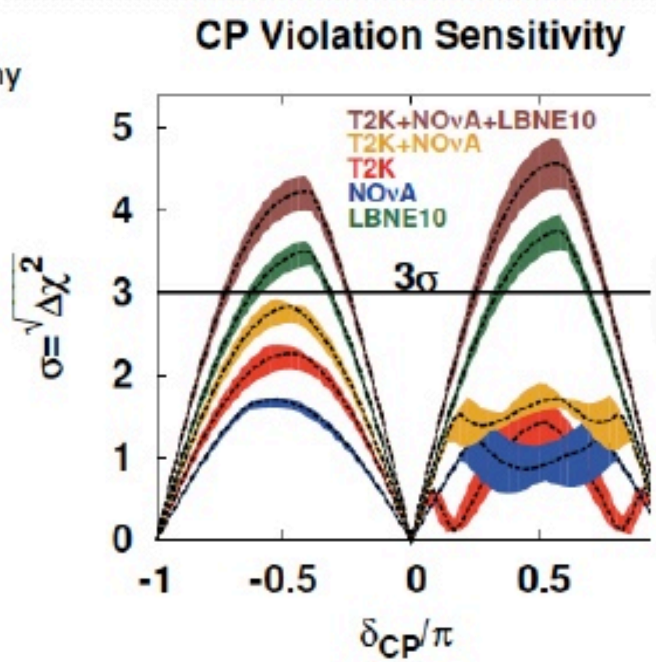


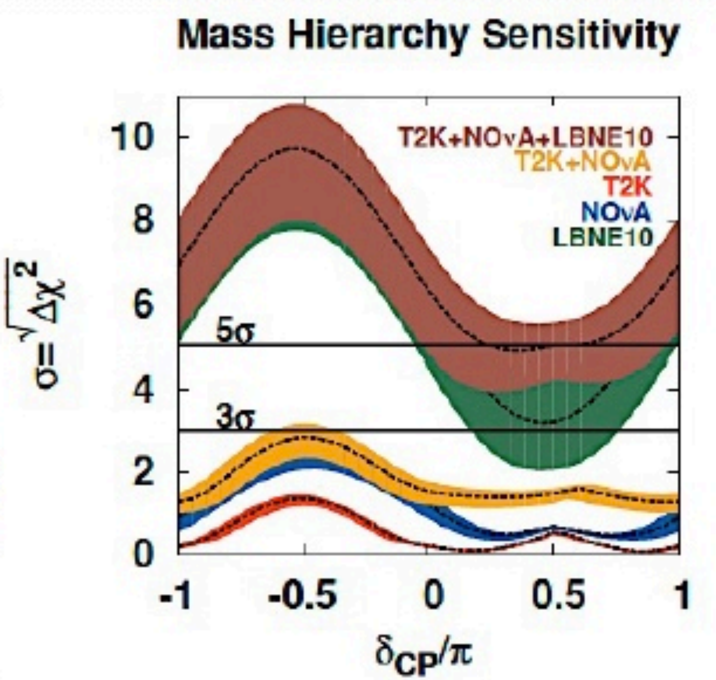
LBNE

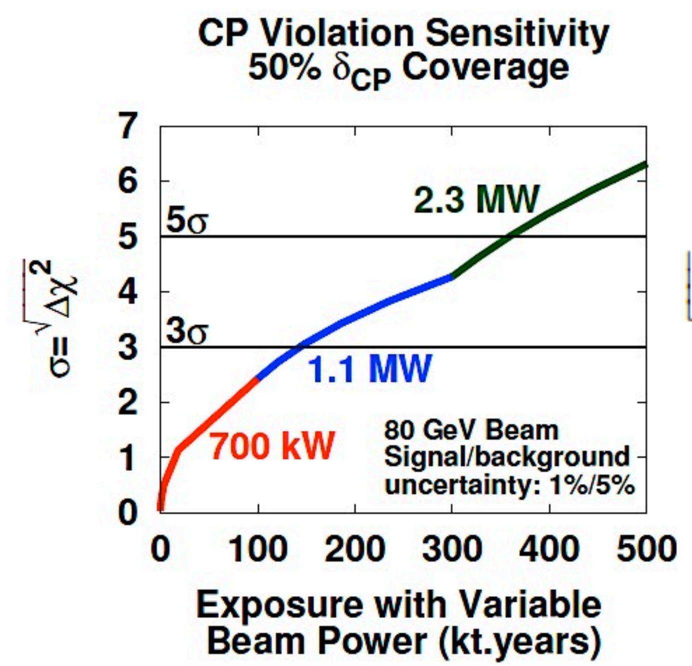
- 700kW, 60-120 GeV proton beam that can be upgraded to 2.3MW
- Near detector for neutrinos
- Far detector is at 1300km, ultimately positioned underground
- Staged process, initial approval for 10 kt LArTPC on surface but can be changed before project baseline is finalized
- Initial phase will be a major advance for neutrino oscillation physics
- Actively seeking foreign partners to accomplish these very high priority goals

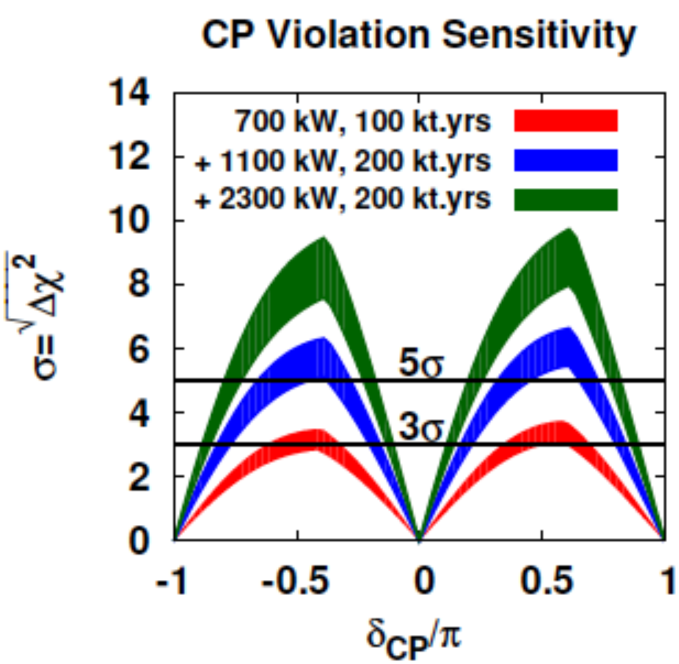
LBNE Physics Reach

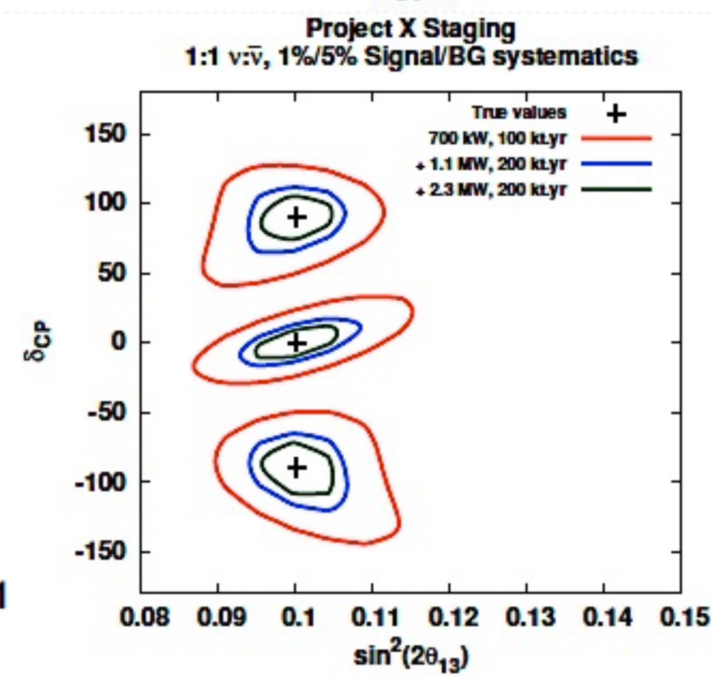






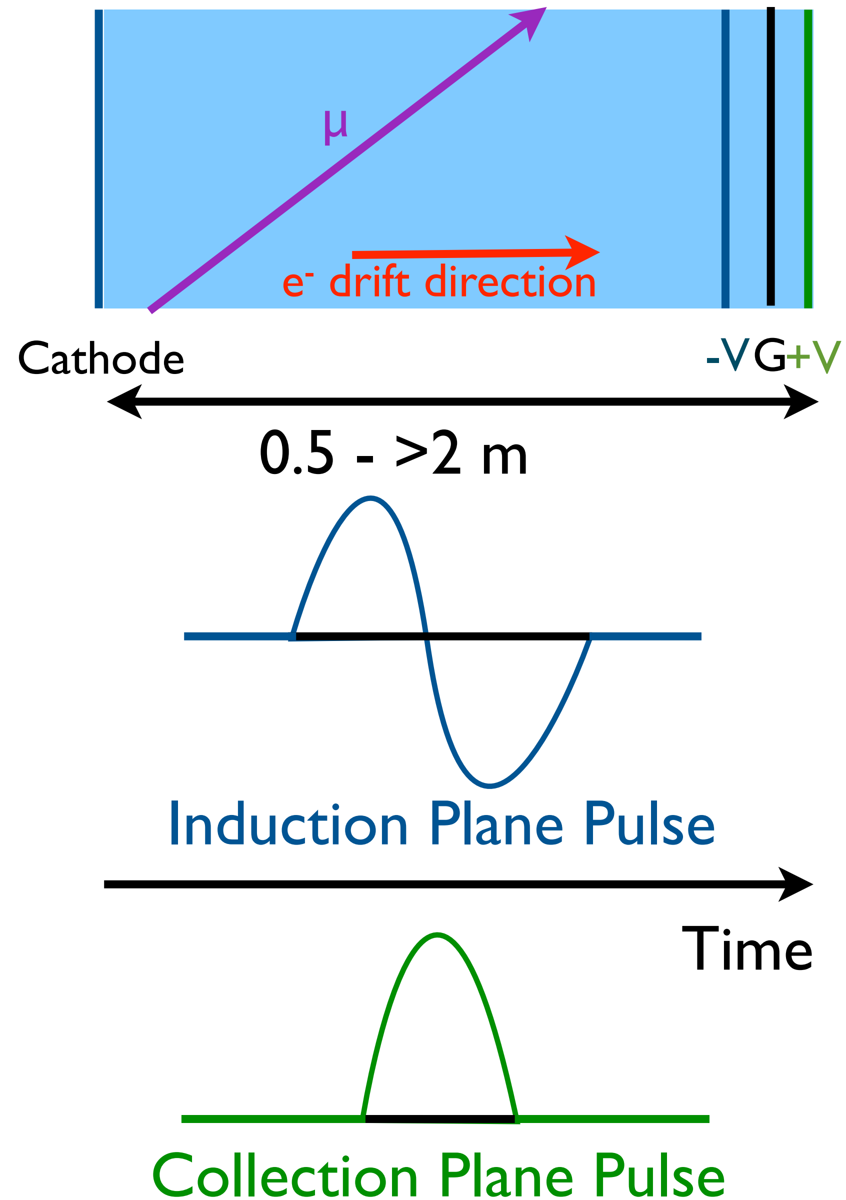






LAr TPCs

- Electric field established between cathode and readout planes
- Minimum ionizing particle releases 55k e/cm
- Electrons drift toward readout planes with velocity of 0.155 cm/μs for E = 500V/cm - need > 1.6 ms for 2.5 m drift
- ⟨dE/dx⟩ for minimum ionizing particle is 1.519 MeV cm^2/g

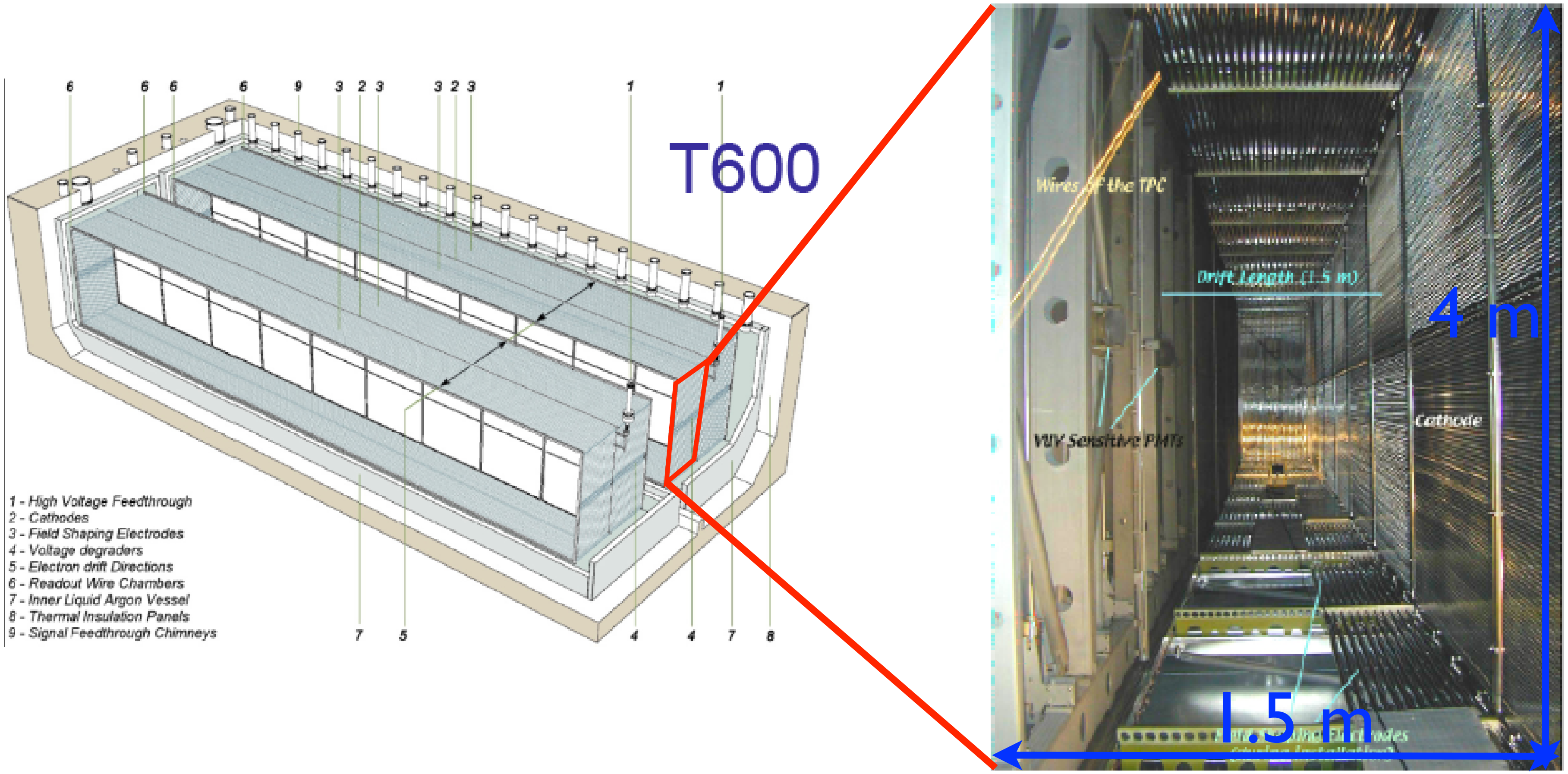


Why Argon?

	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

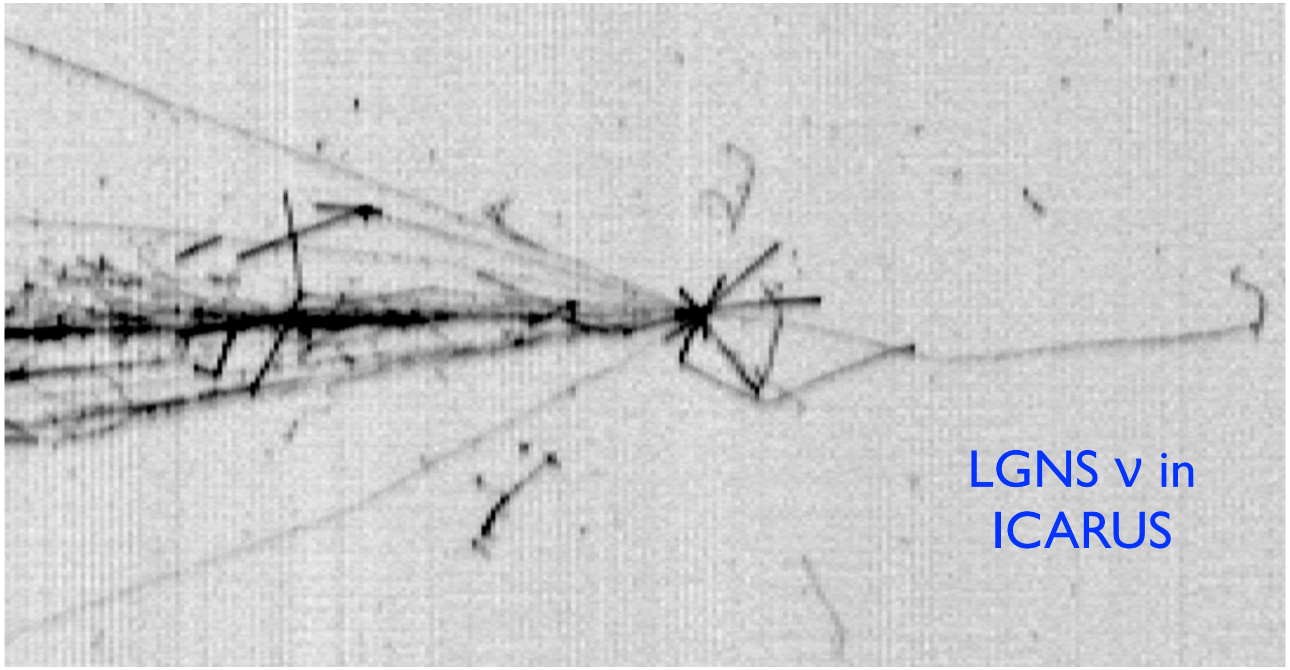
- Cheap and easy to obtain - 1% of atmosphere, $1 / L (cheaper than Pepsi)
- Relatively high boiling point
- Produces lots of scintillation light as well as ionization
- Low threshold for producing ionization electrons, good position resolution (mm)
- Good liquid for having large electric field running through it

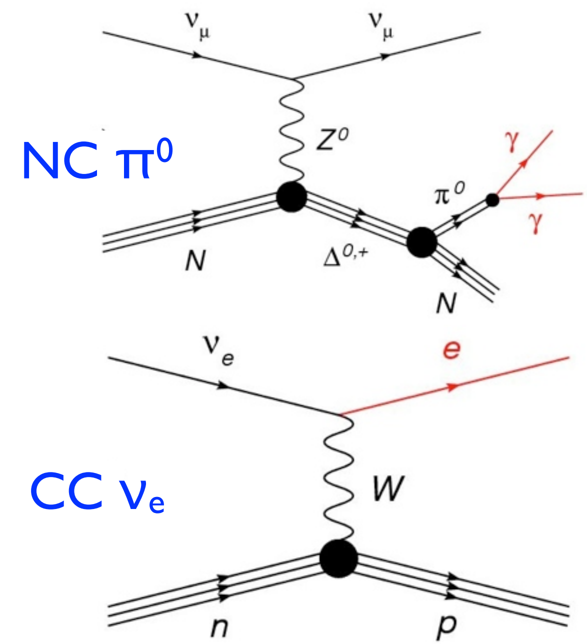
ICARUS



- First large LAr detector
- Culmination of 20 years of effort - 50 L → 3 t →300 t
- Provided solid foundation for future efforts

LArTPC Benefits



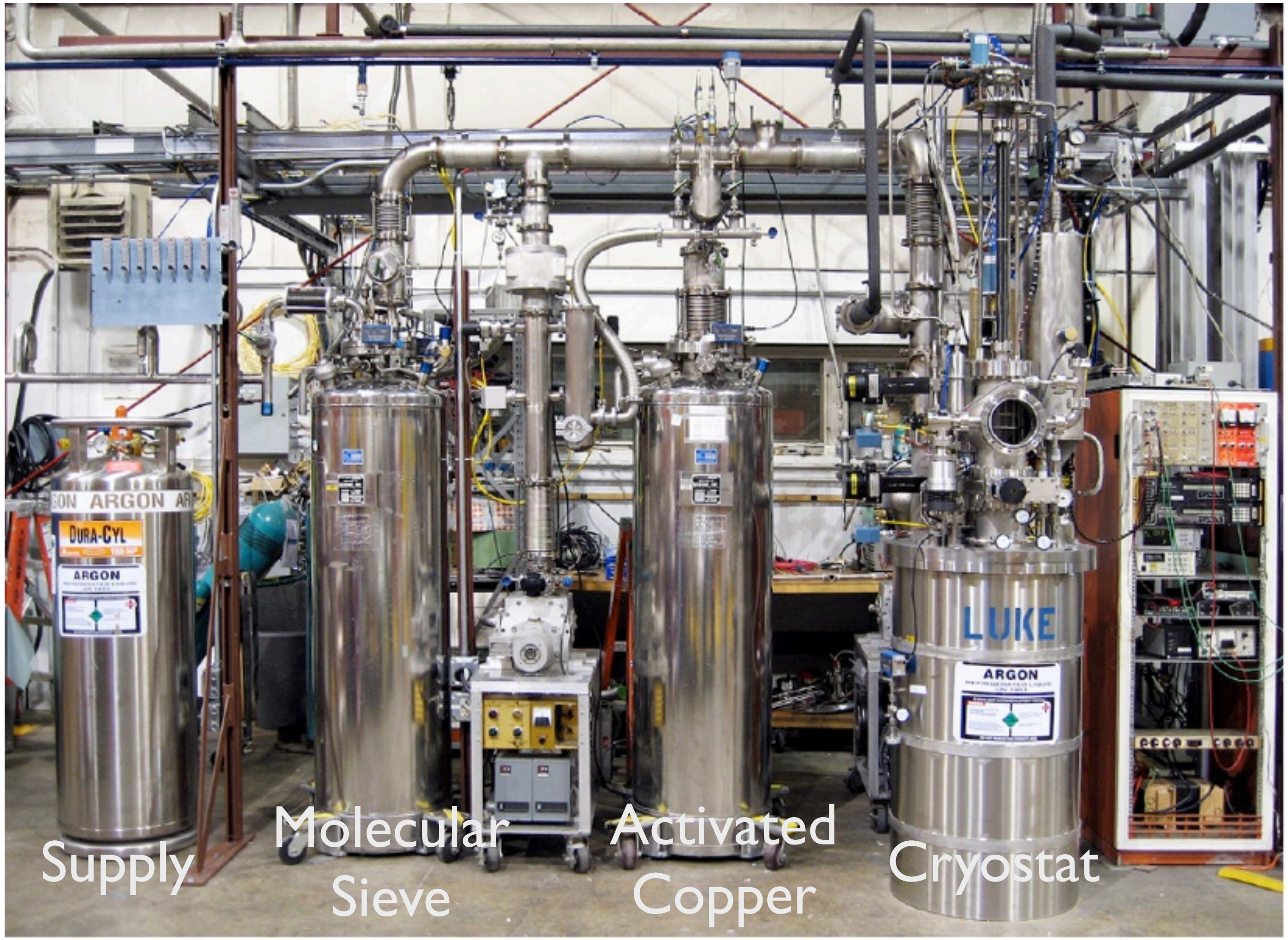


- Incredible resolution in drift direction - very important for distinguishing NC π^0 events from CC ν_e
- Important for cross-section measurements as well as oscillation parameters
- LArTPC resolution: ~0.05 cm in drift direction, transverse direction depends on detector geometry (mm)
- Low energy threshold: ~10 MeV

Purity and Cryogenics

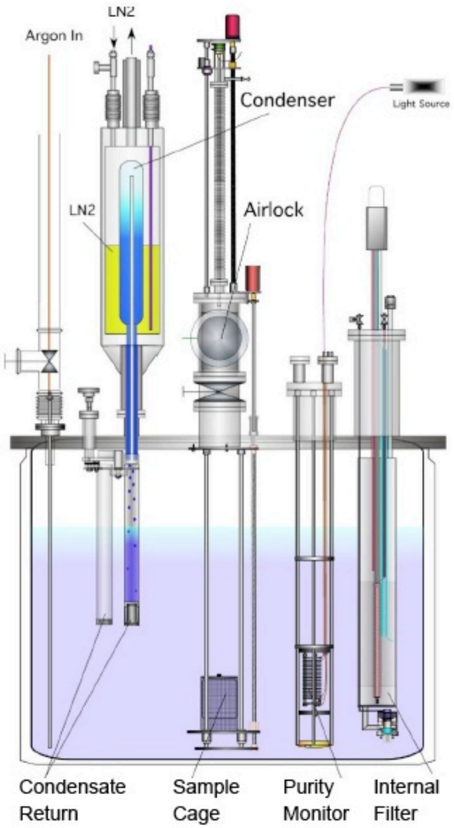
Keeping liquid argon free of electronegative impurities is crucial for operation of LArTPCs

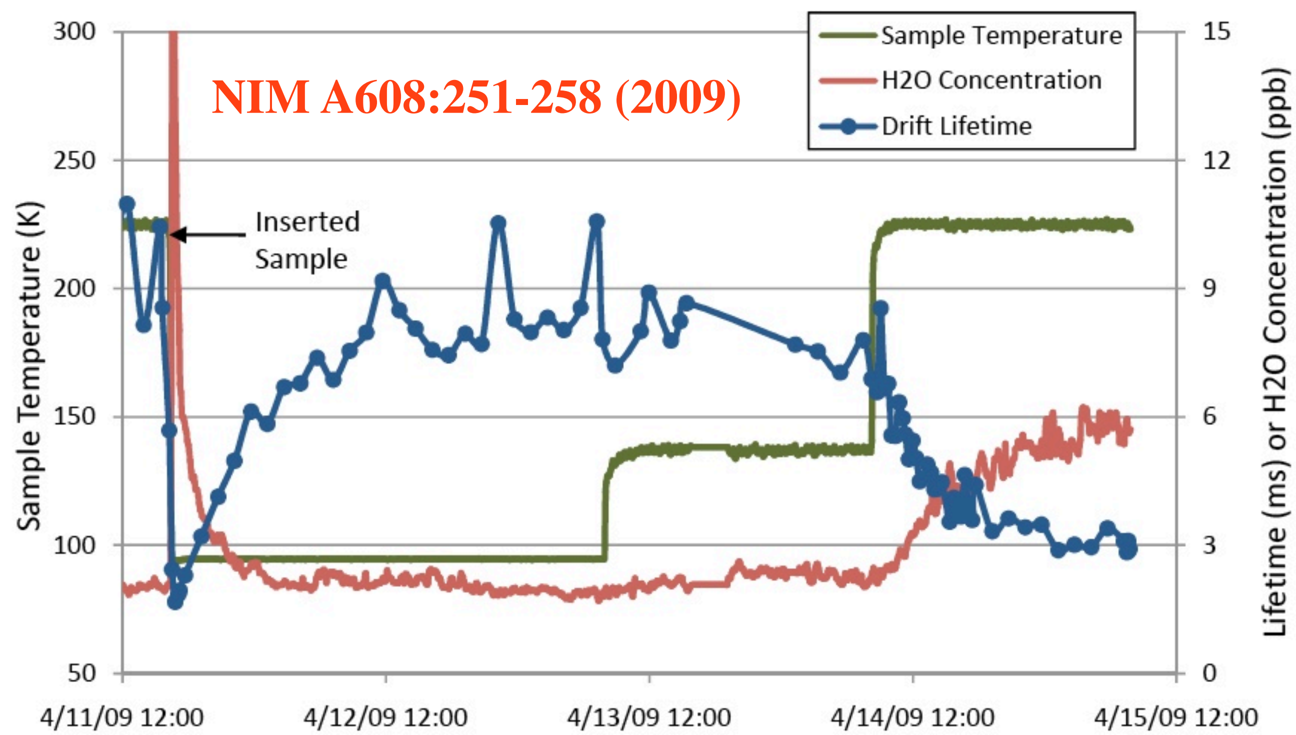
Materials Test Stand (MTS)



- 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

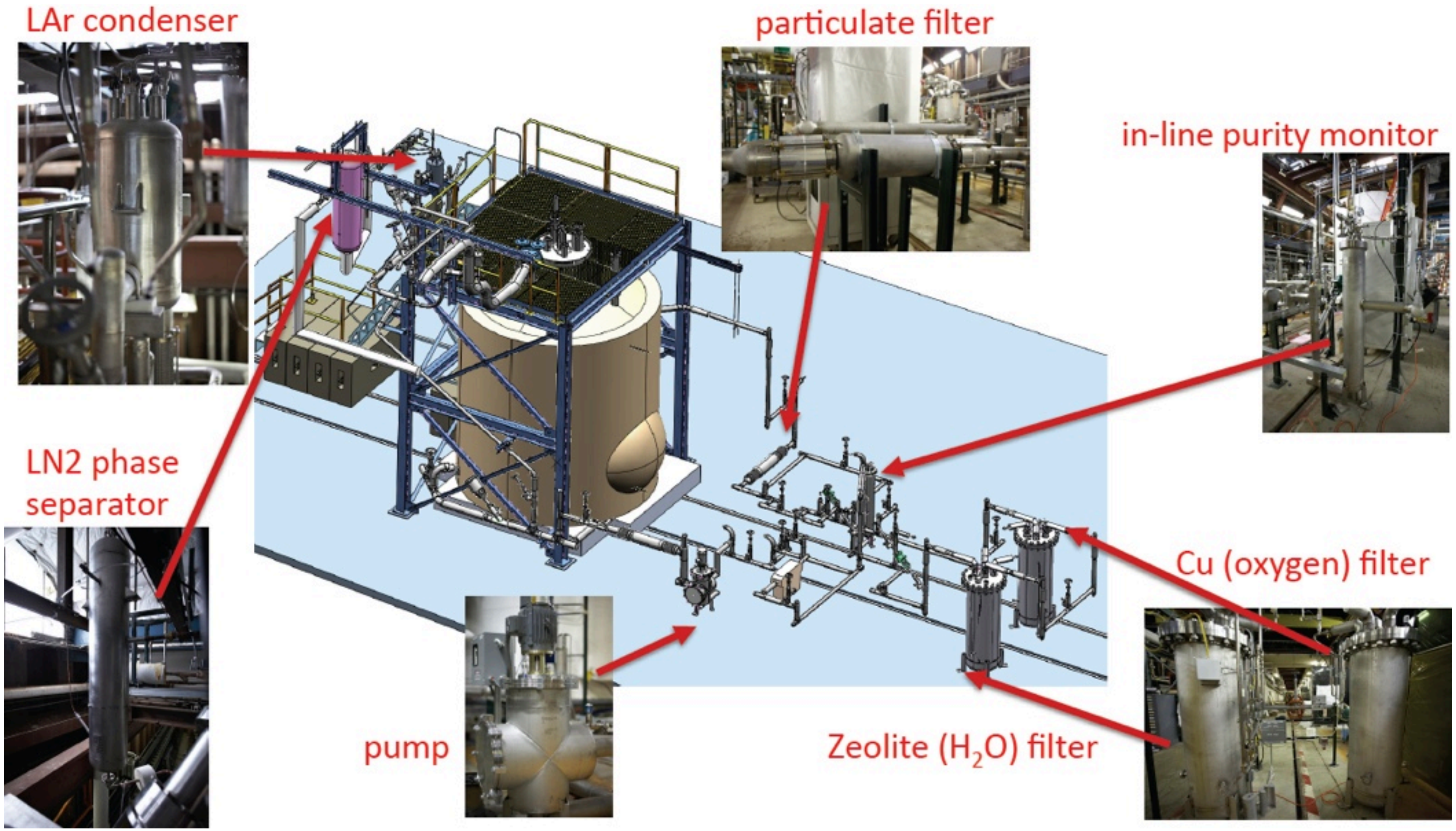
Primary Results from the MTS





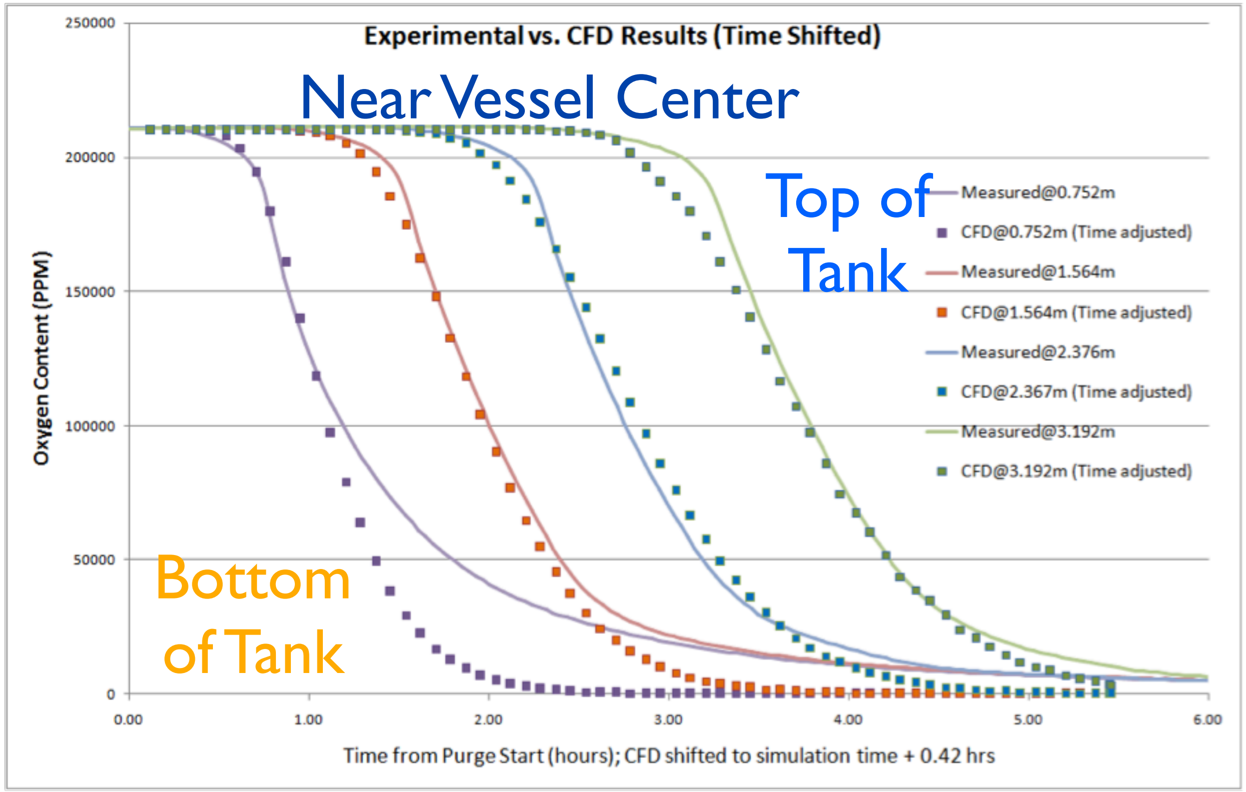
- Direct relation between electron lifetime and water concentration
- Water concentration in vapor space influenced by materials in vapor space
- No change in electron lifetime when materials are in liquid
- Condensed LAr should not be returned directly to the bulk liquid

Liquid Argon Purity Demonstrator



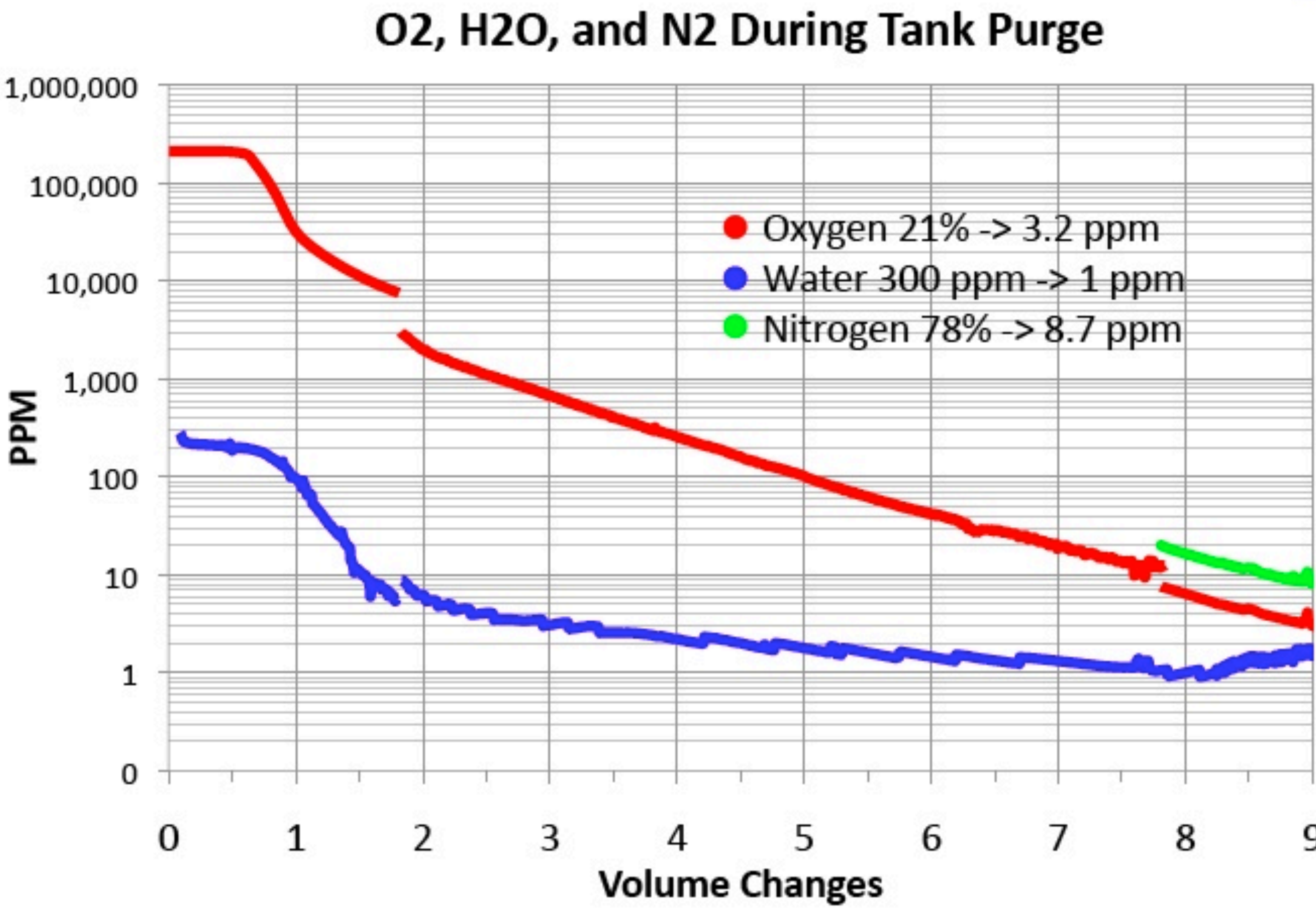
- Primary goal: show required electron lifetimes can be achieved without evacuation in an empty vessel using gaseous argon purge, followed by gaseous argon filtration, followed by liquid argon fill and filtration

Gaseous Argon Purge



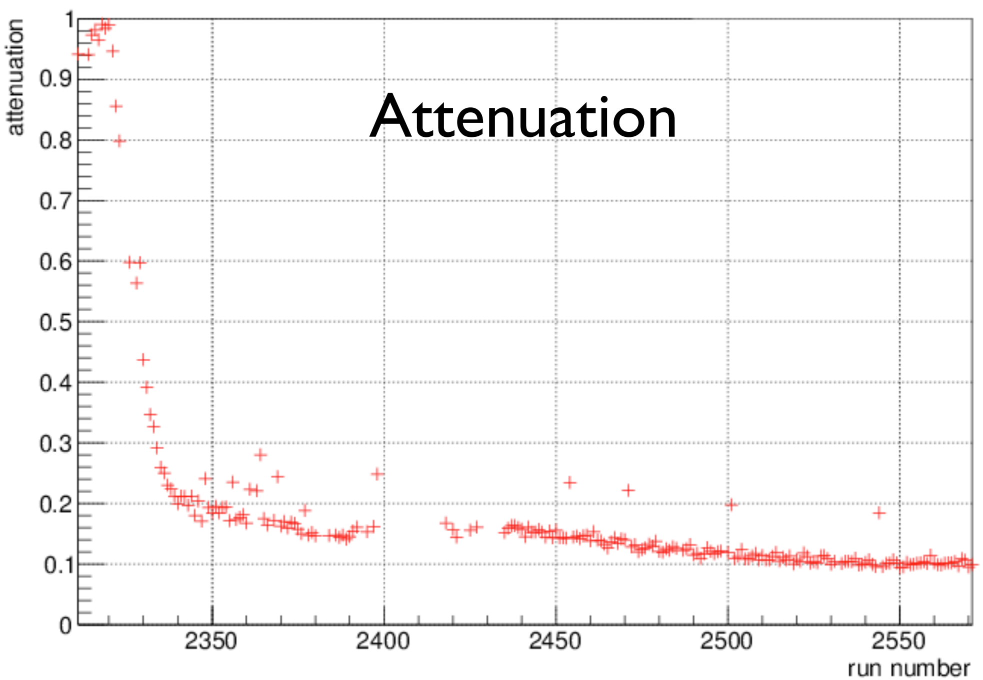
- Set of sniffer tubes monitored the oxygen content of the gas inside the vessel at various depths throughout the purge
- Plot shows the content relative to the pre-purge state of the tank in solid lines
- Clear front of argon gas moving through the vessel
- Comparison to calculations (points) shows good agreement, aside from some discrepancy in time that is likely due to 3D flow and mixing as argon gas is forced into the bottom of the tank

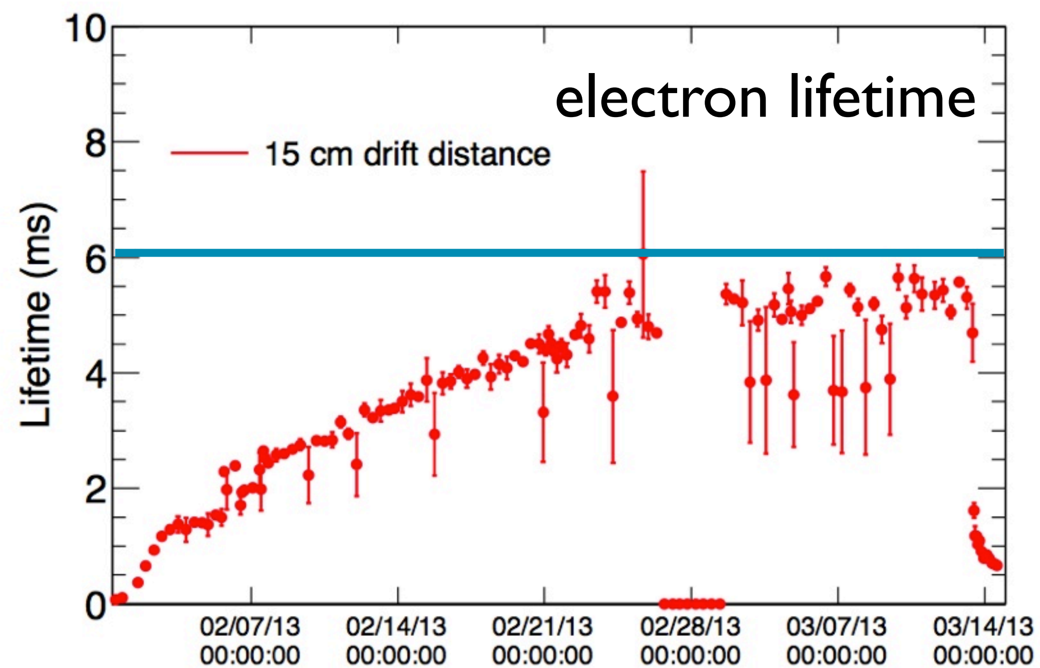
Gaseous Argon Purge



Electron Attenuation in LAPD

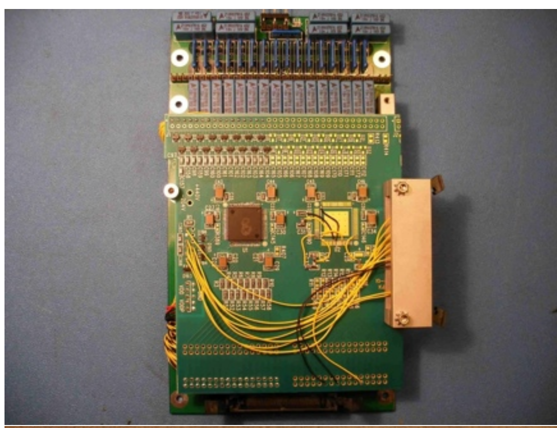
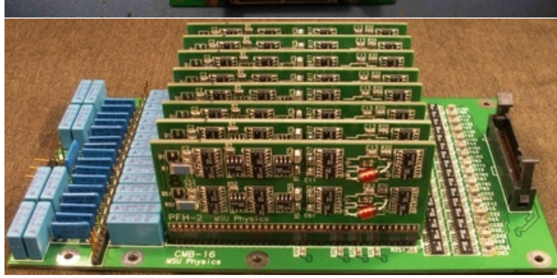
- Plots below show the clean up of the liquid argon for 15 cm drift distance
- Attenuation is at the level of 10% now, corresponds to lifetimes > 5 ms
- LAPD is first to show these lifetimes are achievable without evacuation



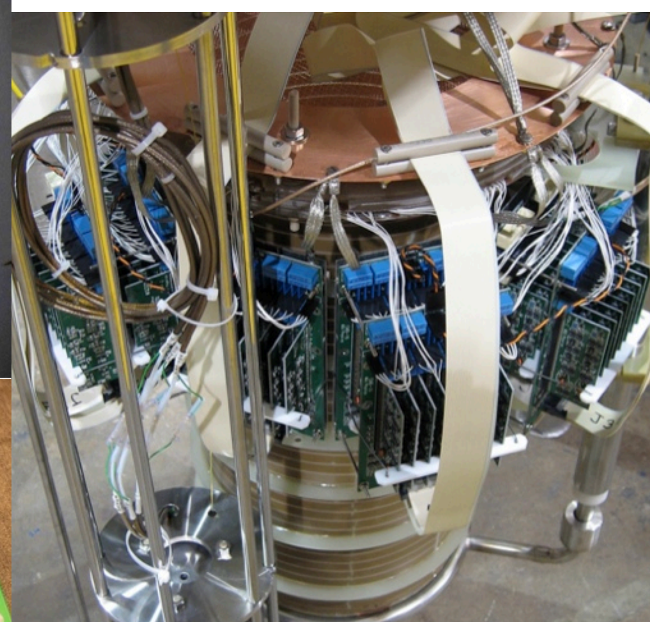


Long Bo in LAPD

- A 2 m long TPC is located in the volume - Long Bo
- Test bed for cold electronics and HV feed throughs (100 kV needed for 2m drift, currently at 75 kV)
- First tracks seen in non-evacuated vessel

Electronics from MSU

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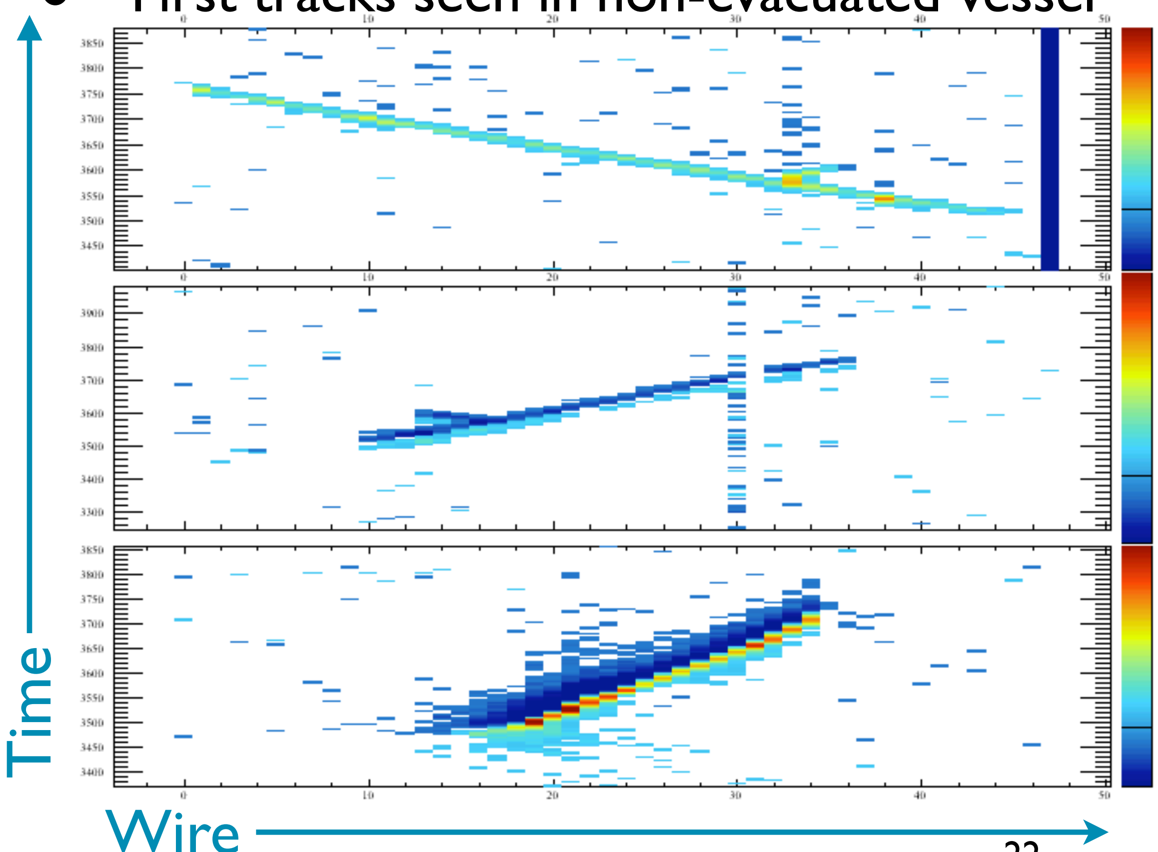
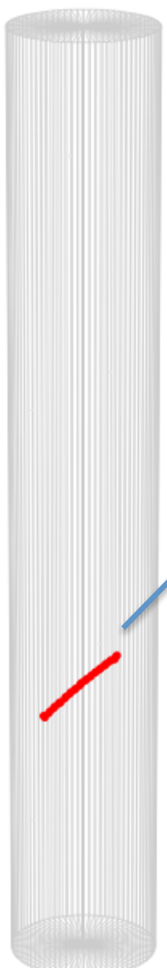
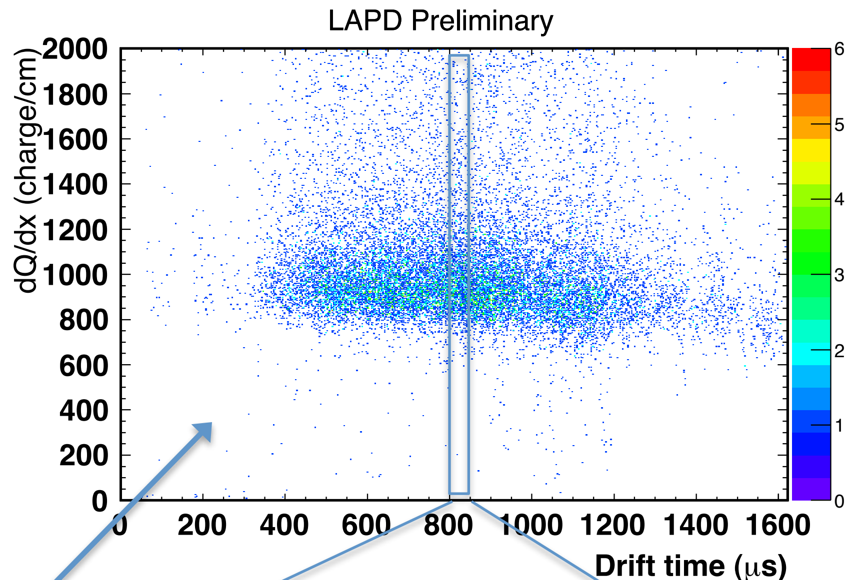
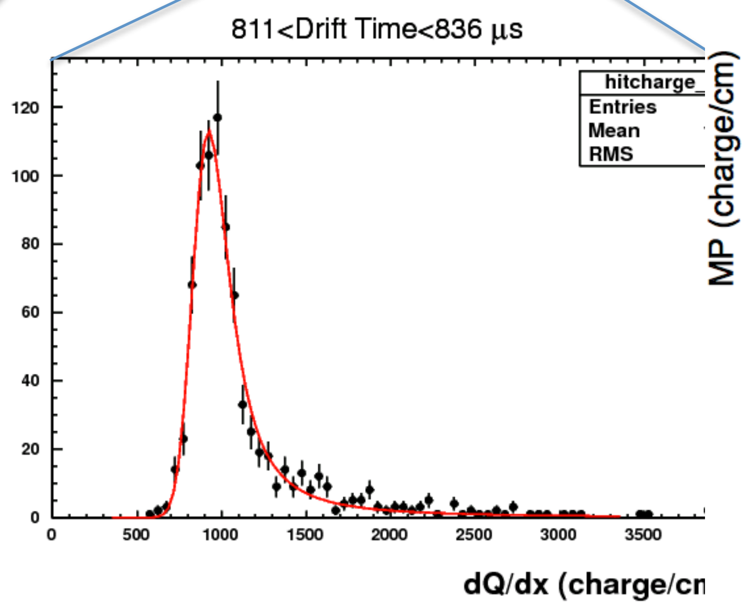


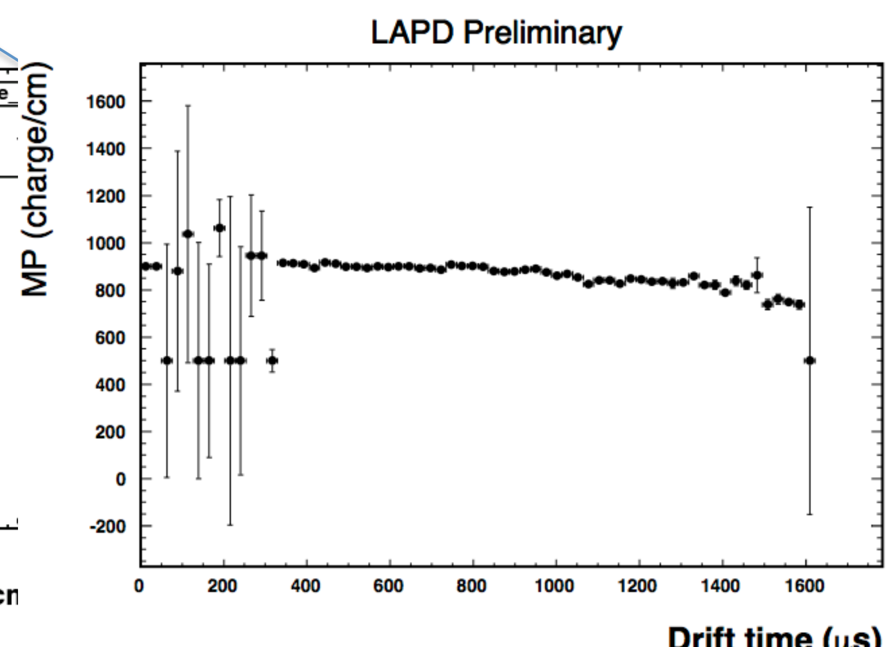
Measuring Attenuation with Long Bo





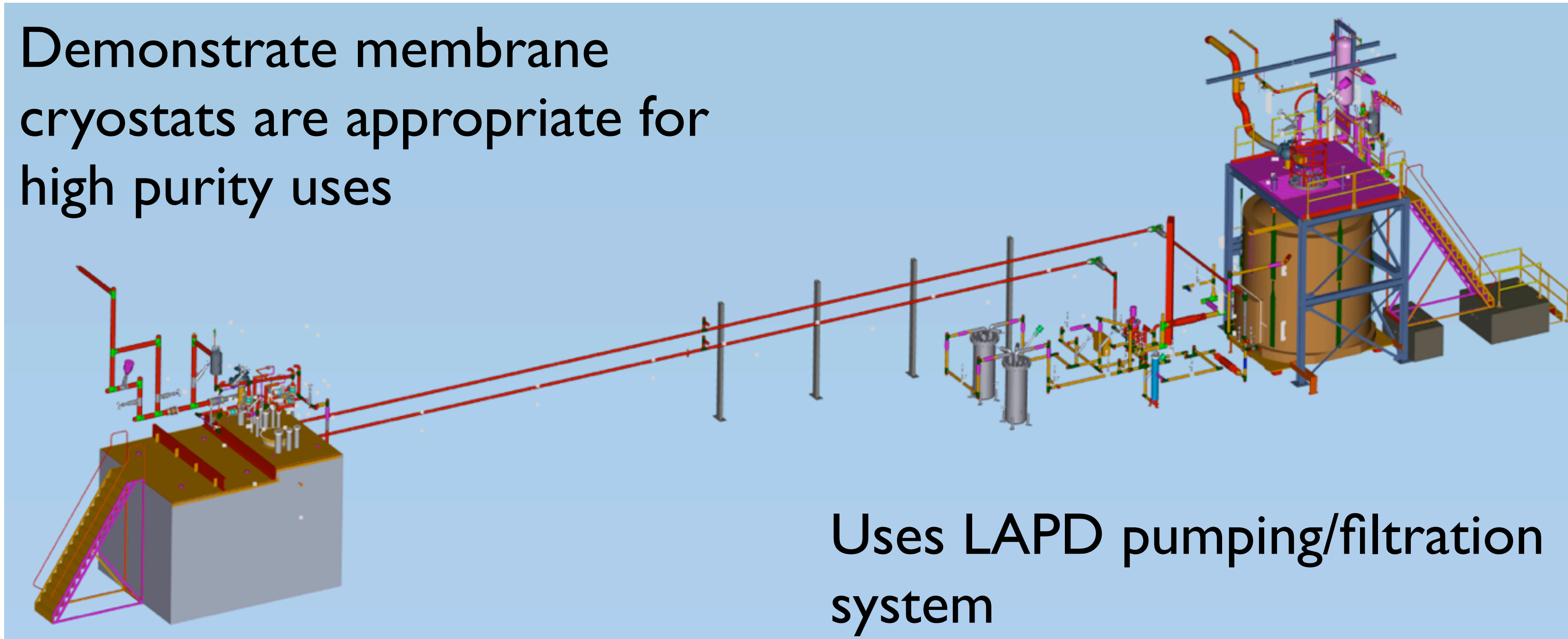
- Select single muon events in range 50 < θ < 70 and remove δ
- Use dQ/dx of muon hits as a function of drift time to measure attenuation
- Less than 20% attenuation over 1 m





35 Ton Membrane Cryostat Prototype

Demonstrate membrane cryostats are appropriate for high purity uses



Uses LAPD pumping/filtration system

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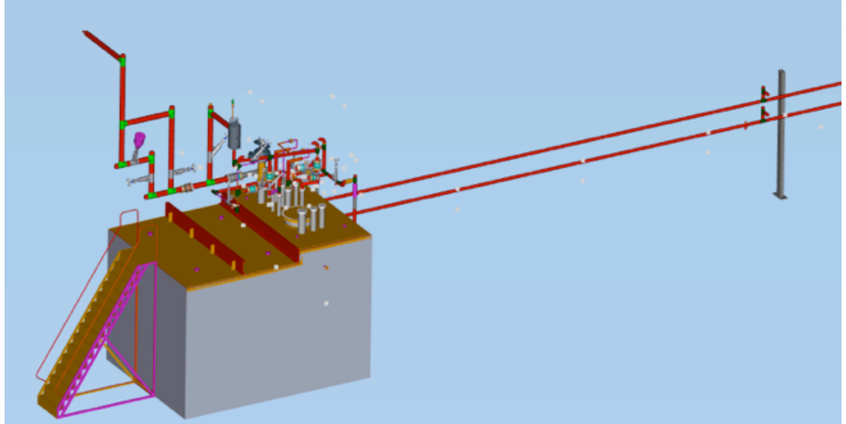

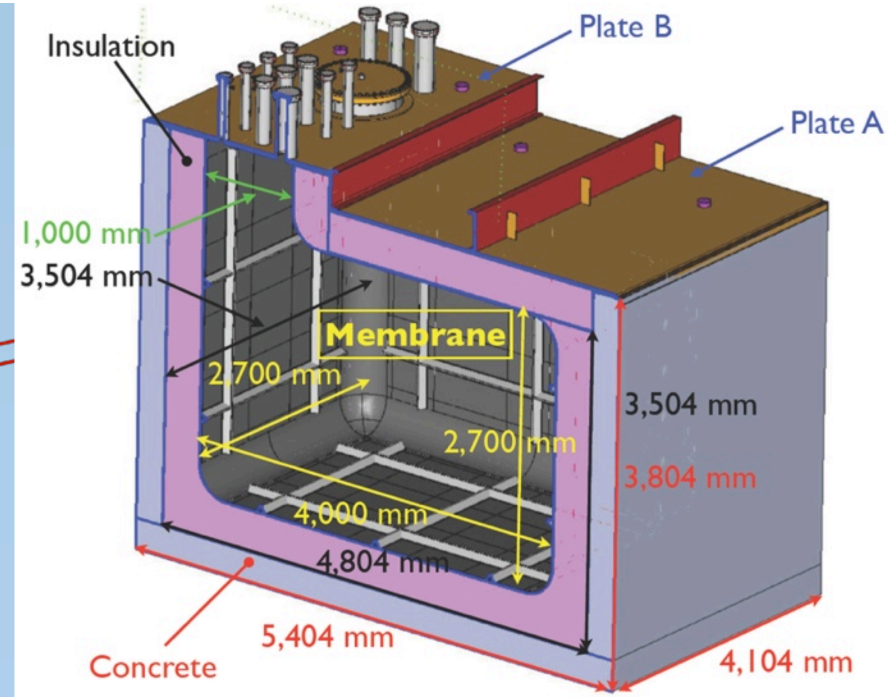

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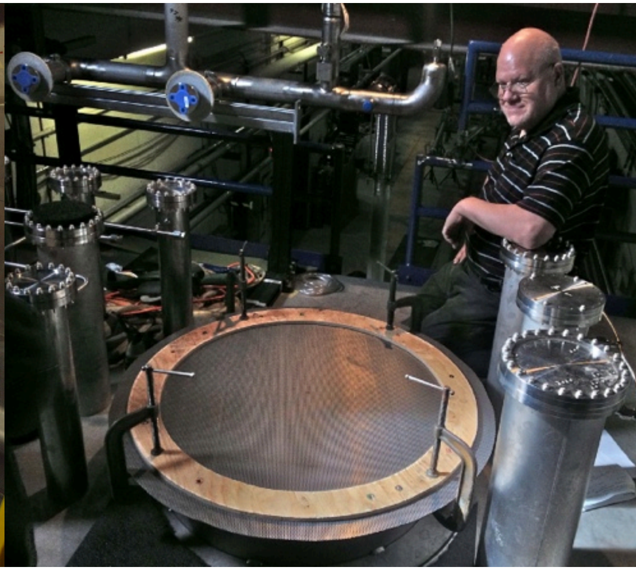


- Cryostat is now complete
- Connecting process piping to the LAPD filtration system
- First run will test use of in-liquid pumps

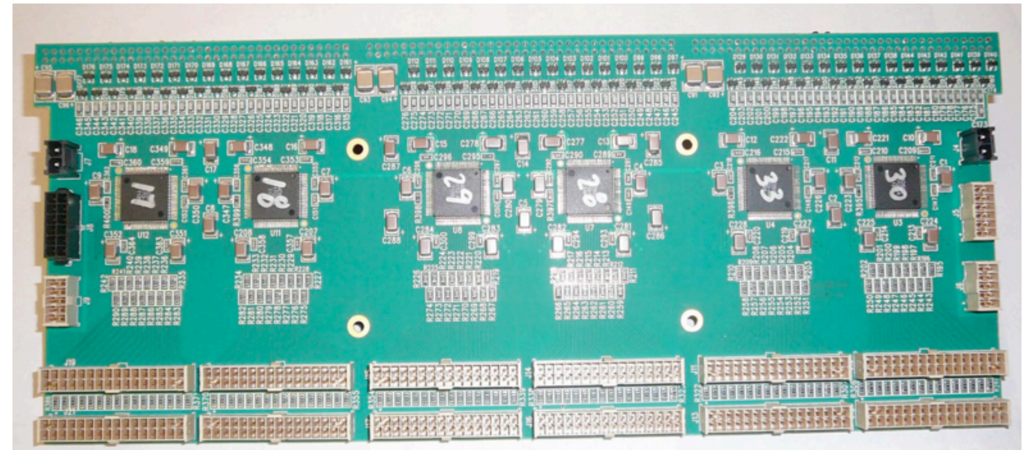
Parameter	Value
LAr Temperature	89K ± 1K
Operating Gas Pressure	70 mBar (~ 1 psig)
Vacuum	No Vacuum, we will SLOWLY purge it with GAr (See LAPD)
Design Pressure	207 mBar (~ 3 psig)
Leak tightness	10^{-6} mBar*l/sec (with NH3 leak check, ASTM standard)
Heat Leak	< 13 W/m^2 (~11.5 W/m^2)
Design Code	Applicable parts of JGA Recommended Practice for LNG In ground storage tanks FESHM 5031.5

Cold Electronics

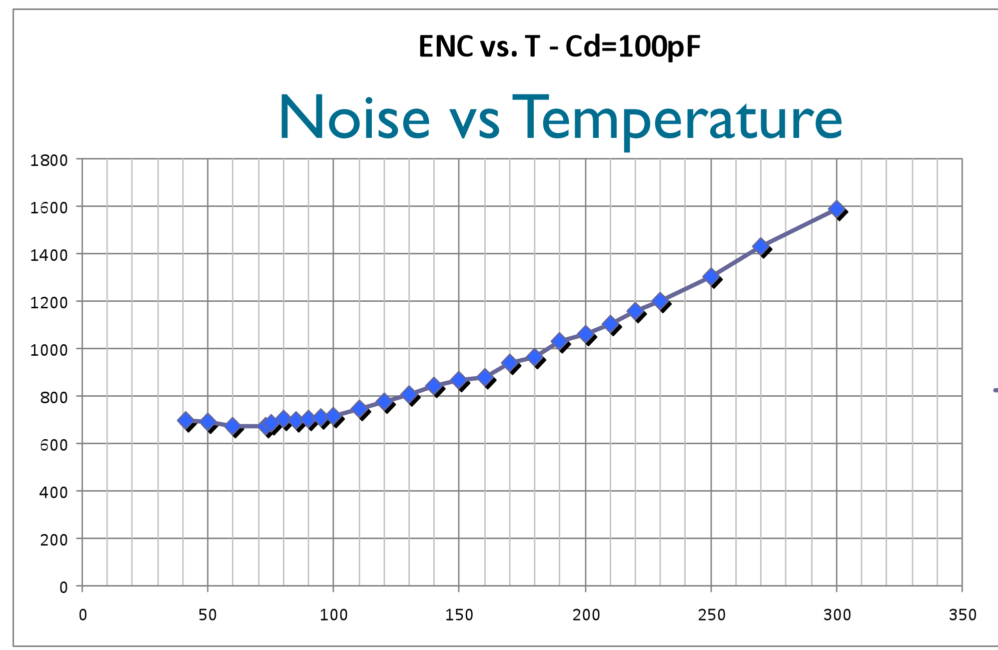
Keeping noise levels low and preventing signal degradation

μBooNE/LBNE: Cold Electronics

- A primary goal of μBooNE is to understand running cold electronics in a LArTPC
- Electronics are being designed primarily by BNL, will be used in LBNE too
- Tests show
    - Noise at 87k is half that at 300k
    - crosstalk is < 0.3%, gain variations are 7%
- Stress tests also performed show no problems after many immersions in LN_2
- BNL experience from ATLAS and NA48 calorimeters show very low failure rate over many years
- Electronics designed for > 30 year lifetime



Heat dissipation of 5 mW/channel



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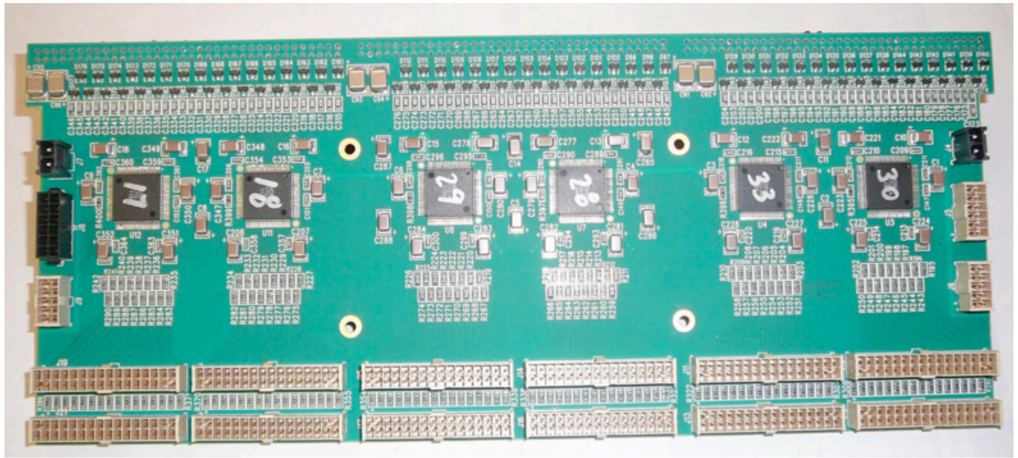
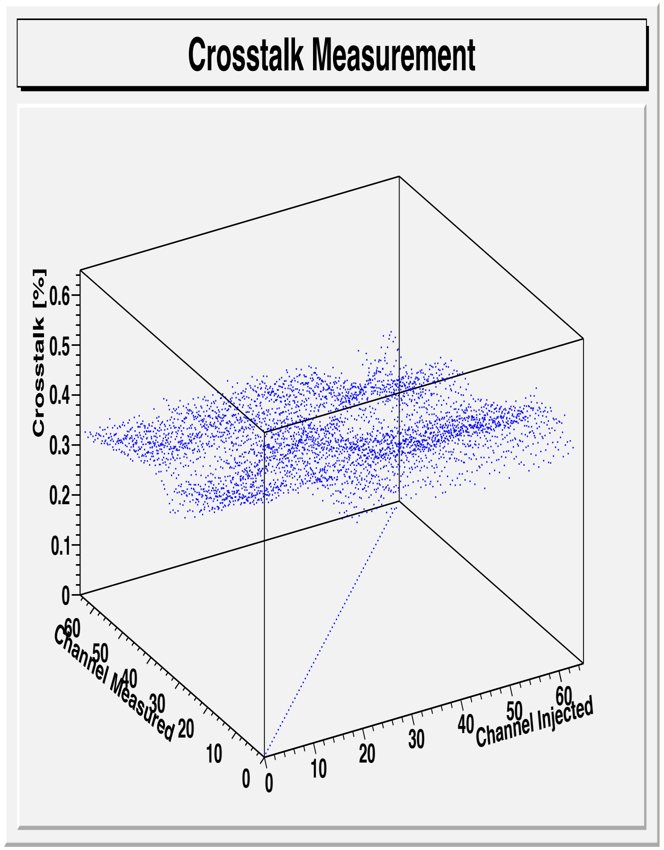




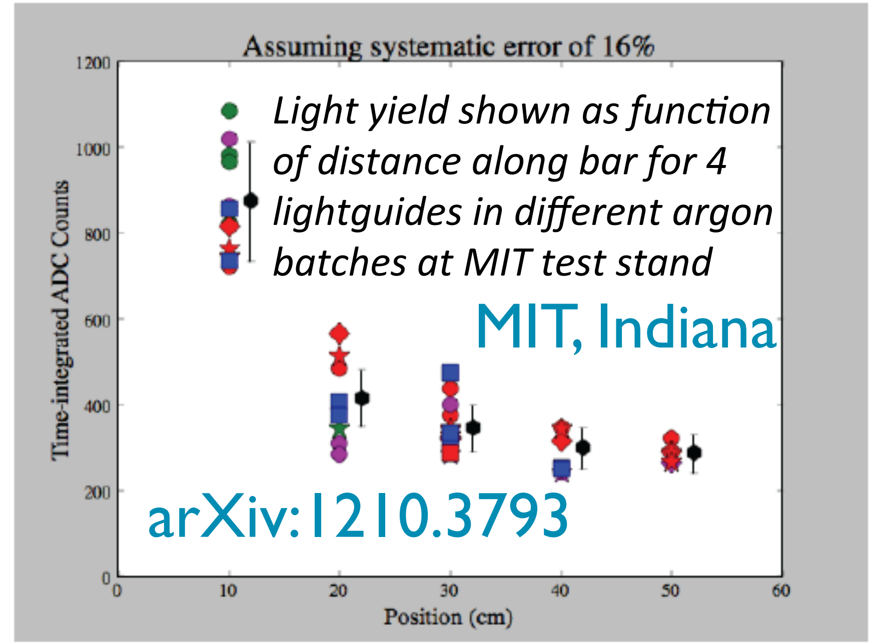
Light Collection

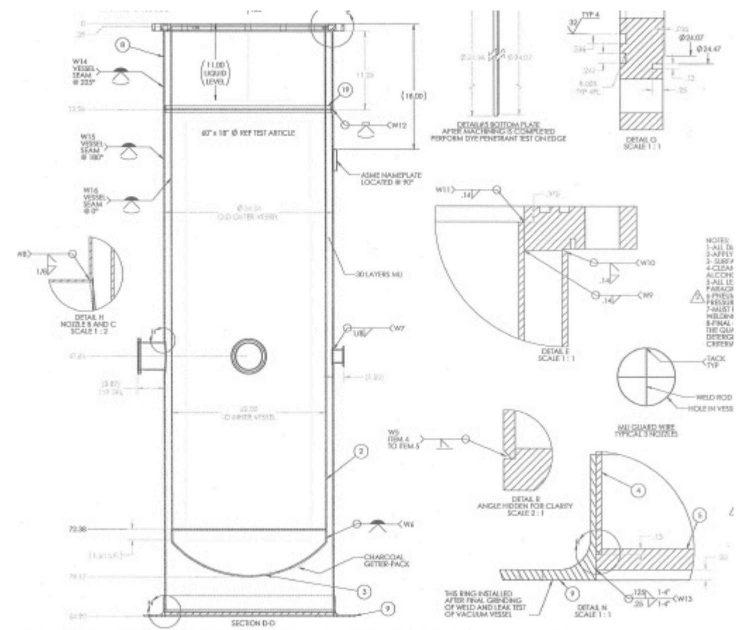
LAr produces scintillation light that can be used for triggering and possibly calorimetric reconstruction

Very useful in the absence of an accelerator signal

Light Guides

- Options for light collection include placing TBP coated plates in front of PMTs, coated bars as light guides to SiPMs, or wavelength shifting fibers connected to SiPMs
- TPB degrades when exposed to UV light, as does Bis-MSB
- New cryostat for testing various light collection techniques - 56 cm diameter and 152 cm height with argon delivery and filtration
- First customer will be Indiana University to test paddle system for LBNE
- Can be used to test other techniques like LAPPDs

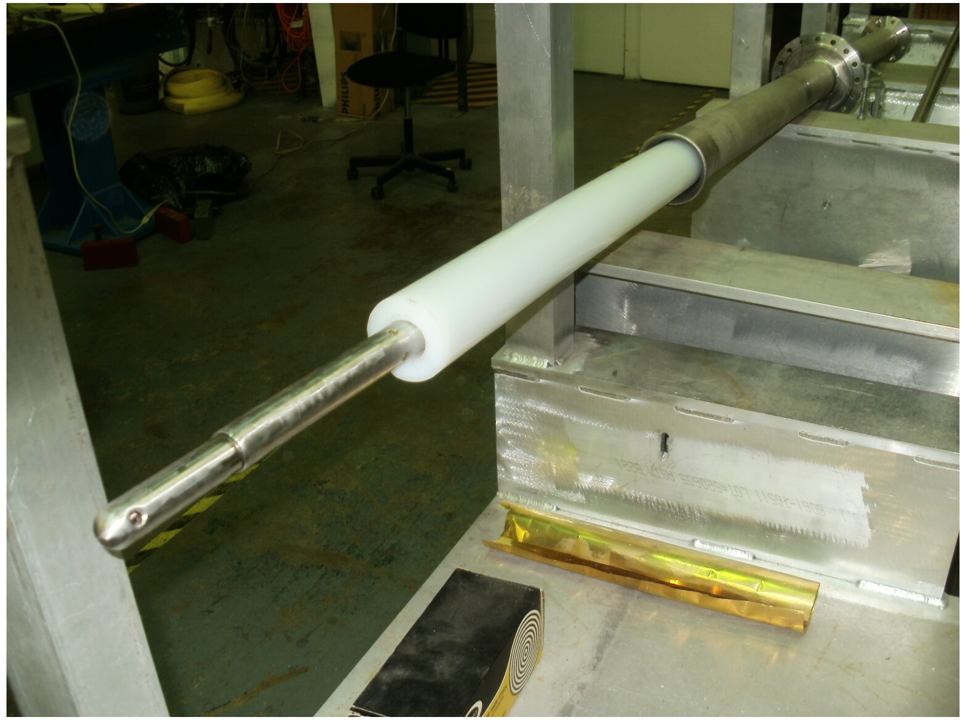




TPC and High Voltage Feed Throughs

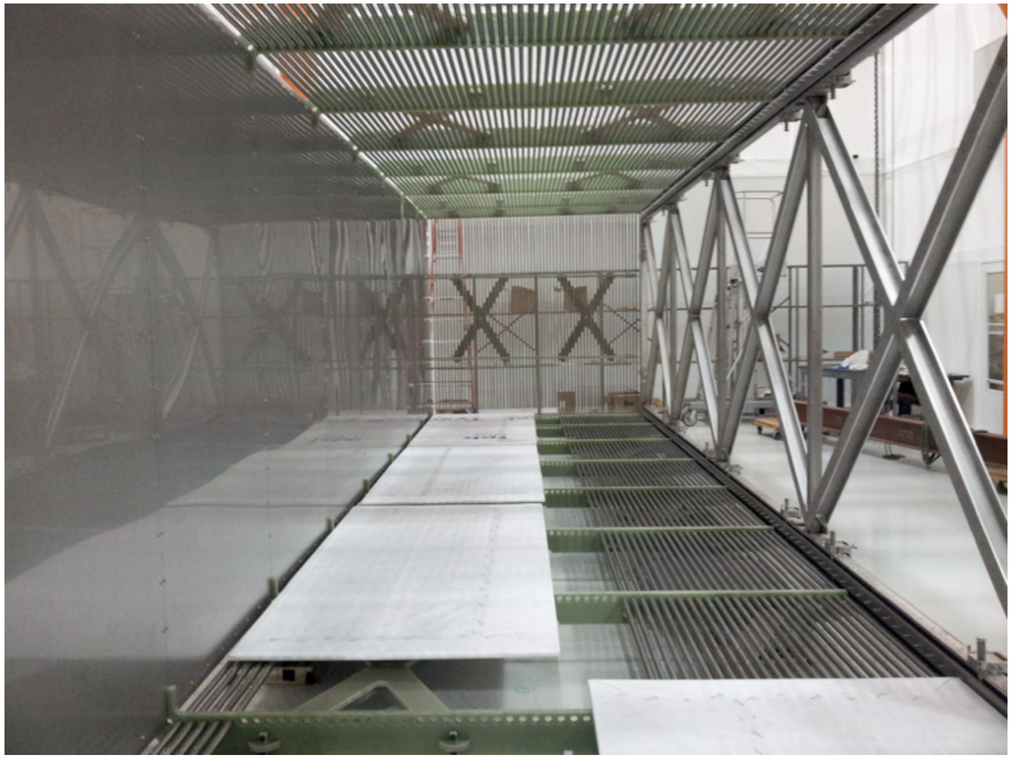
Have to create a field of order 500 V/cm over many meters for large neutrino detectors

High Voltage Feed Throughs



- Fields of 500 V/cm require 50,000 V at cathode for each meter of drift
- Several considerations when designing feed throughs
  - Commercial ceramic feedthroughs assume vacuum on one side
  - Gas or ionization near feedthrough conducive to sparking, bubbles too
- ICARUS constructed first large HV feed through for LArTPCs, operated up to -150 kV
- Prototype for Long Bo and MicroBooNE working at -70 kV

Building TPCs



- MicroBooNE TPC is built and wires attached - 2.5 m x 2.5 m x 10 m
- Lots of valuable experience gained in this process - understanding how to work with various materials, tolerances on things like the flatness of the cathode plane
- LBNE TPC has a different design - hanging planes for cathodes and anodes

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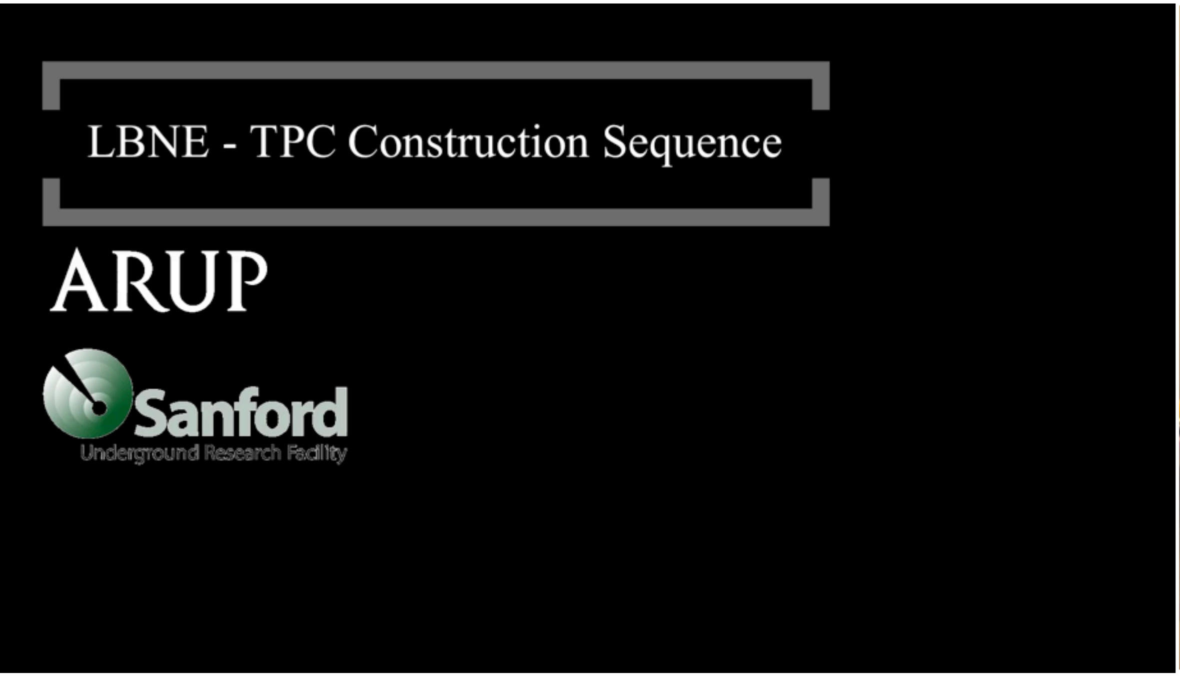

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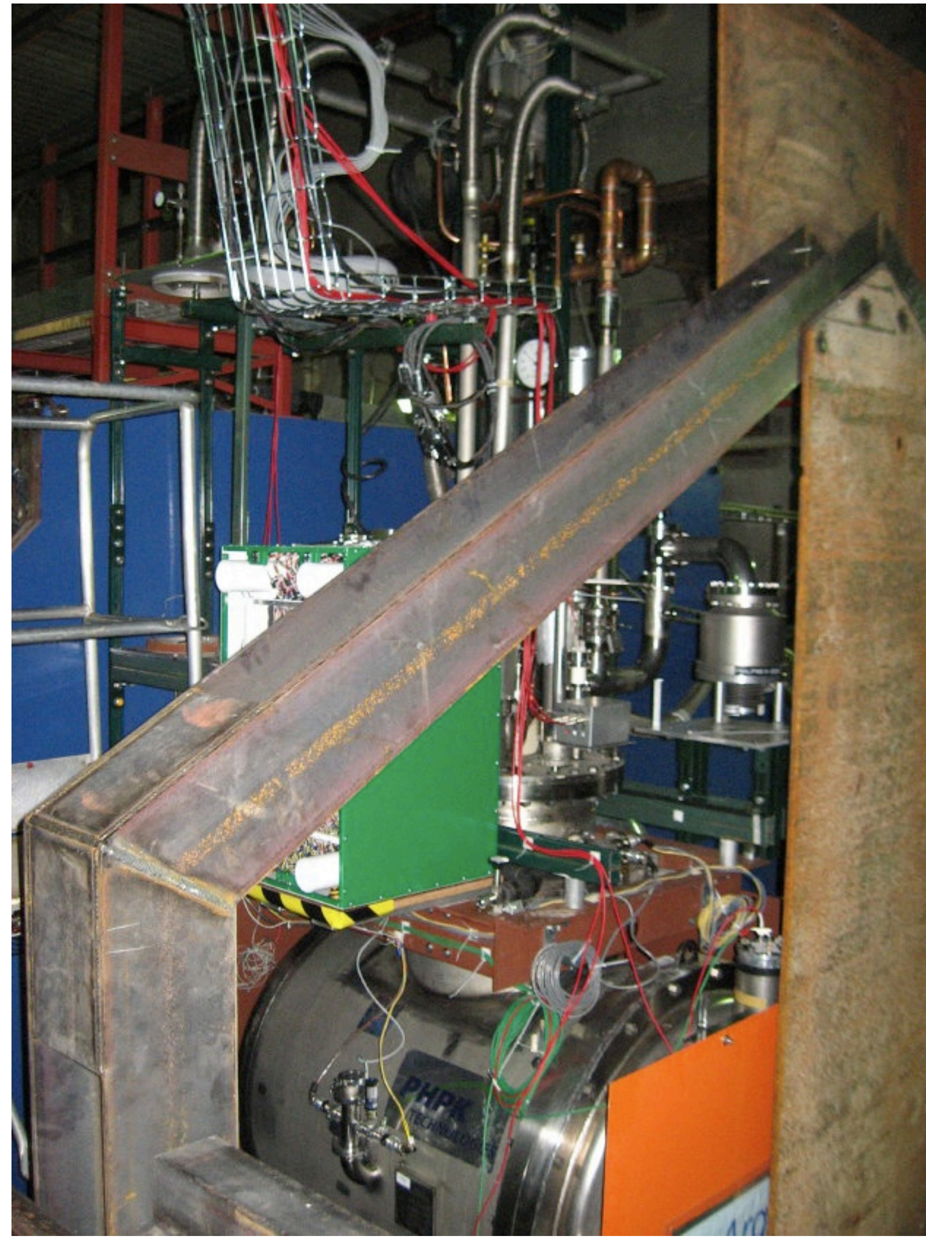
Test Beam Efforts

Understanding the performance of LArTPCs

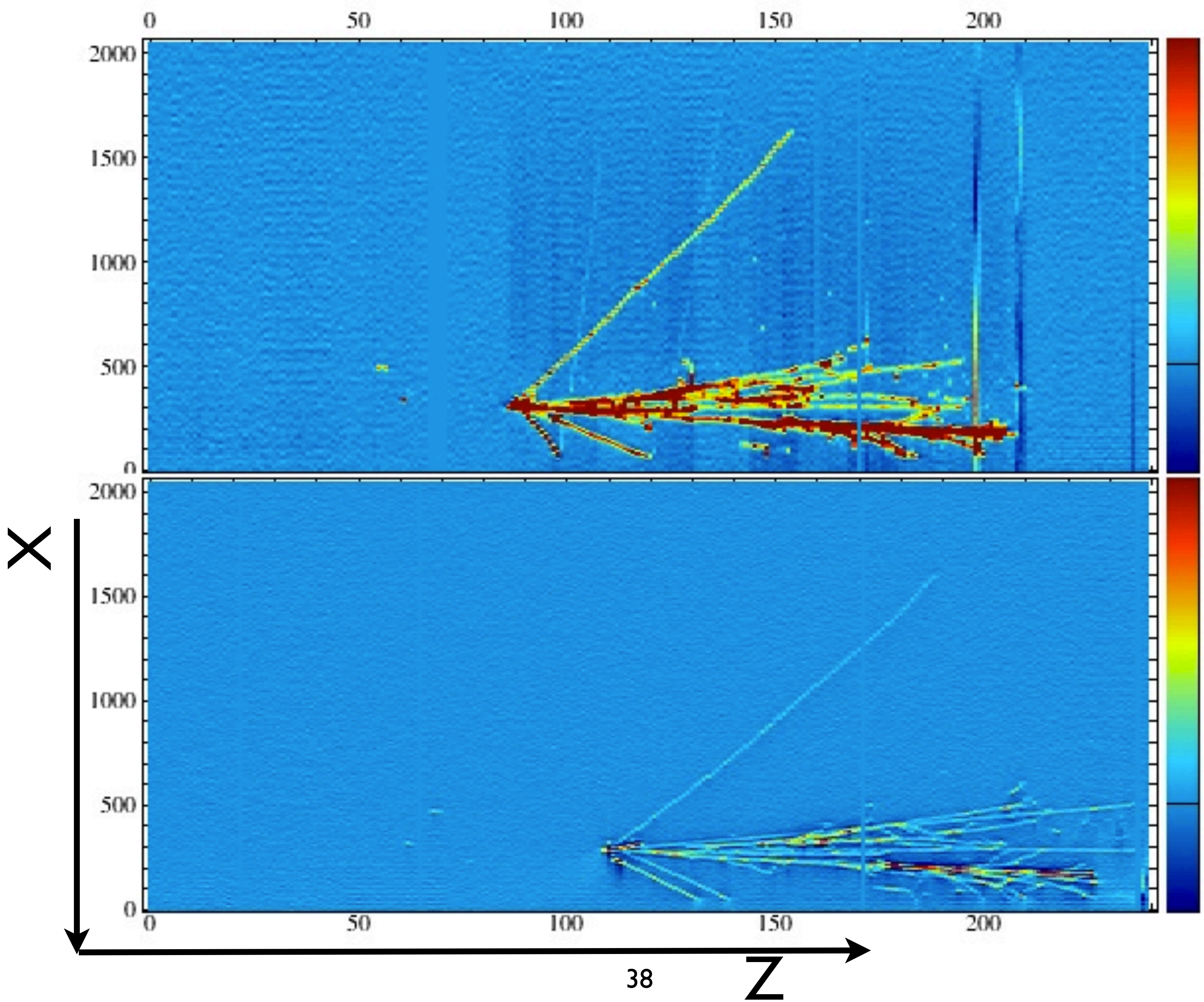
ArgoNeuT

- 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

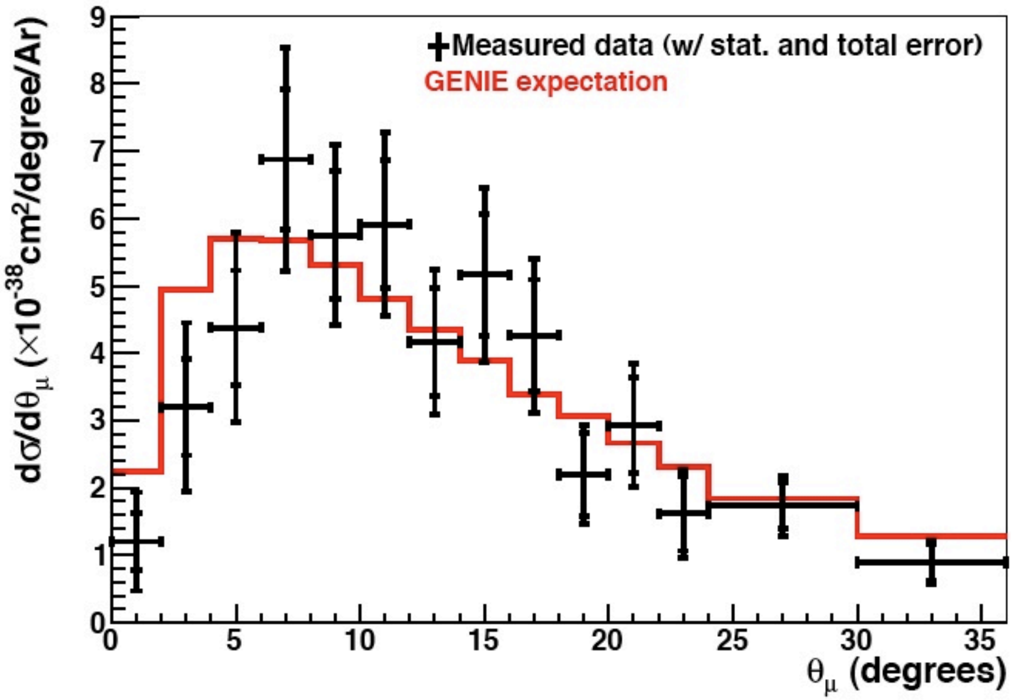
Cryostat Volume	500 Liters
TPC Volume	175 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length (Time)	0.5m (330μs)
Light Collection	None

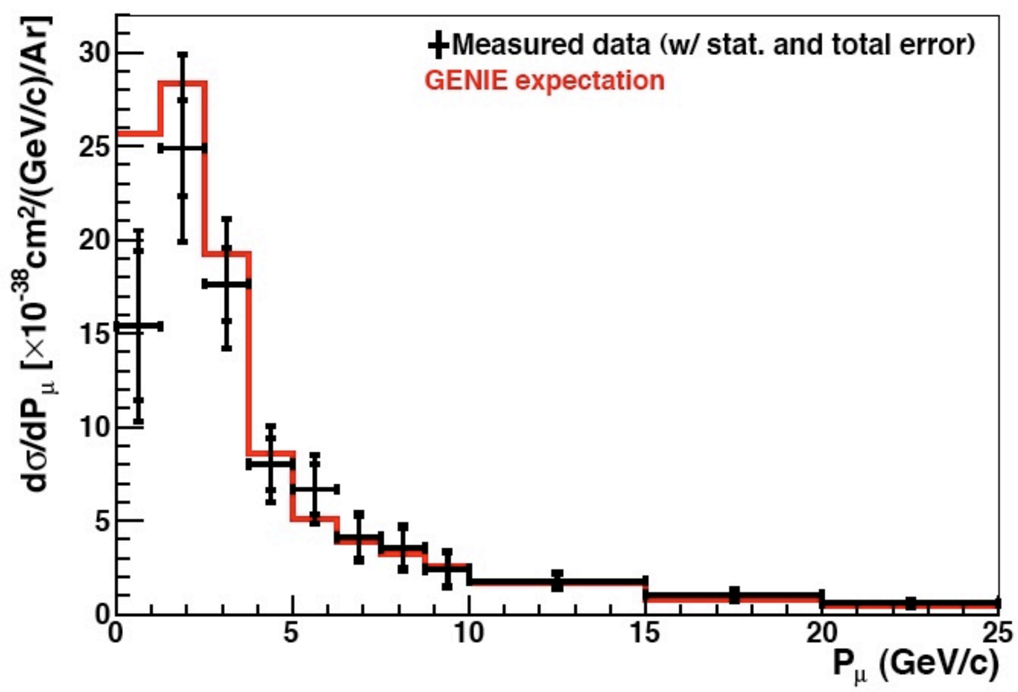


Neutrinos in ArgoNeuT



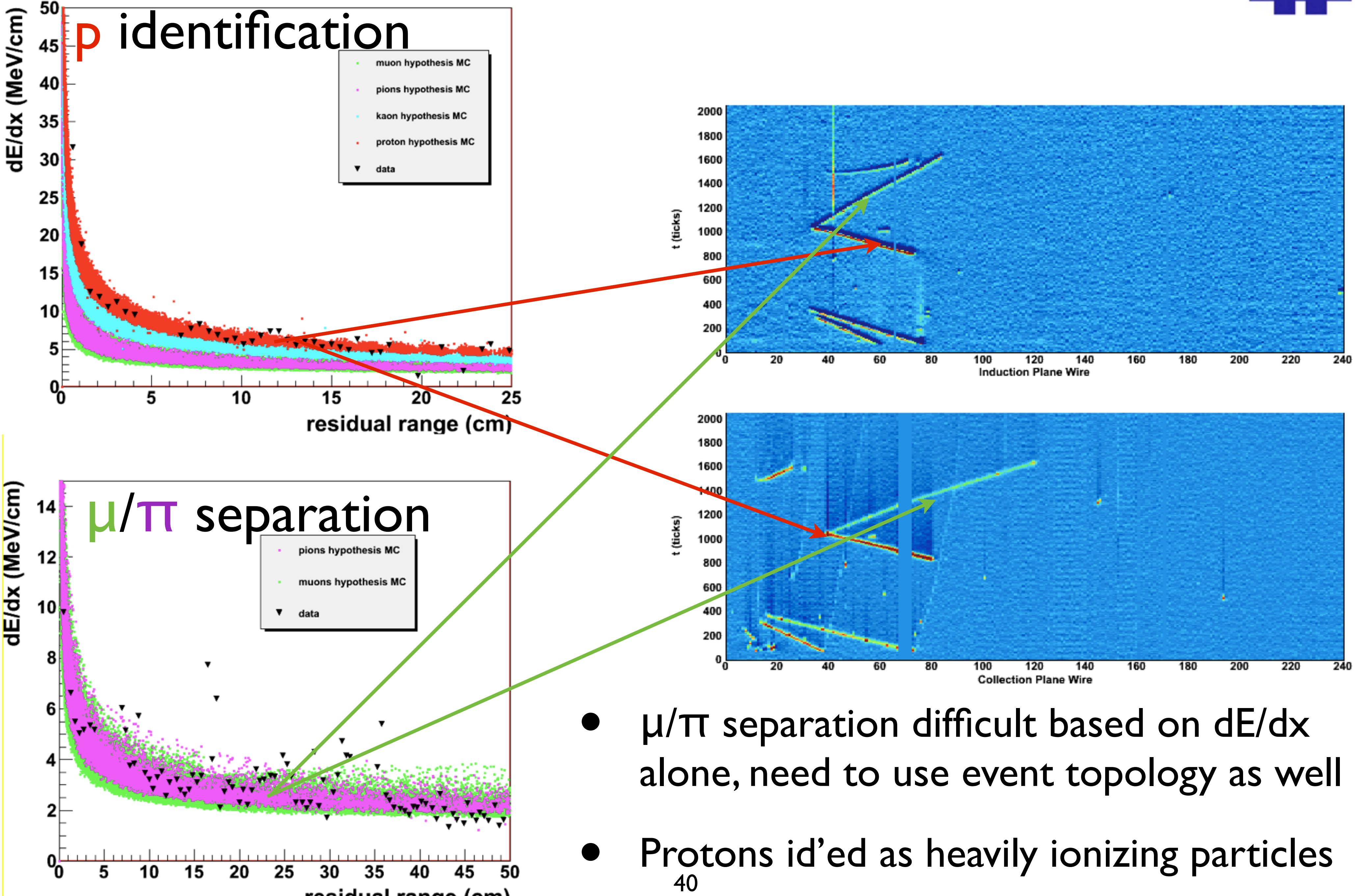
First Cross Section Measurements on Ar





- Differential cross section measurements are the industry standard
- Measurements agree well with prediction from GENIE Monte Carlo generator
- $\sigma/E_\nu = (7.3 \pm 1.2) \times 10^{-39} \frac{\text{cm}^2}{\text{GeV}} \quad \langle E_\nu \rangle = 4.3\ \text{GeV}$

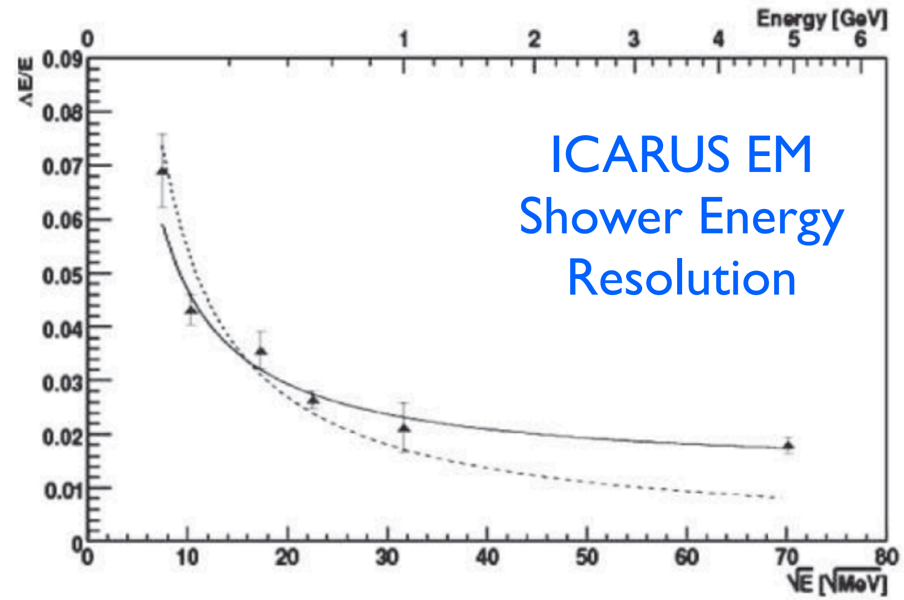
ArgoNeuT Particle Identification

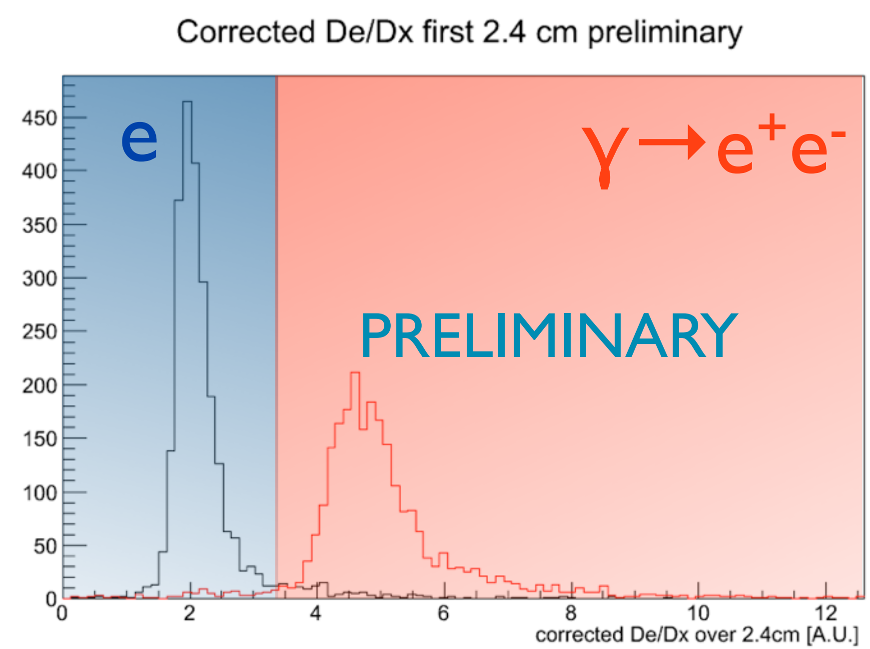


- μ/π separation difficult based on dE/dx alone, need to use event topology as well
- Protons id'ed as heavily ionizing particles

LAr In A Test Beam (LArIAT)

- A major question to come out of the 2009 Fermilab sponsored LAr R&D review was *How well known are the energy resolution and particle identification capabilities of a LArTPC?*
- Previous estimates of energy resolution from the 50L WARP test stand and ICARUS T600 run on the surface with cosmic rays
- T32 at JPARC run to understand charged particles in ArgoNeuT sized TPC
- Need data from particles and energies expected in neutrino experiments: e, p, π, μ
- Two phased approach



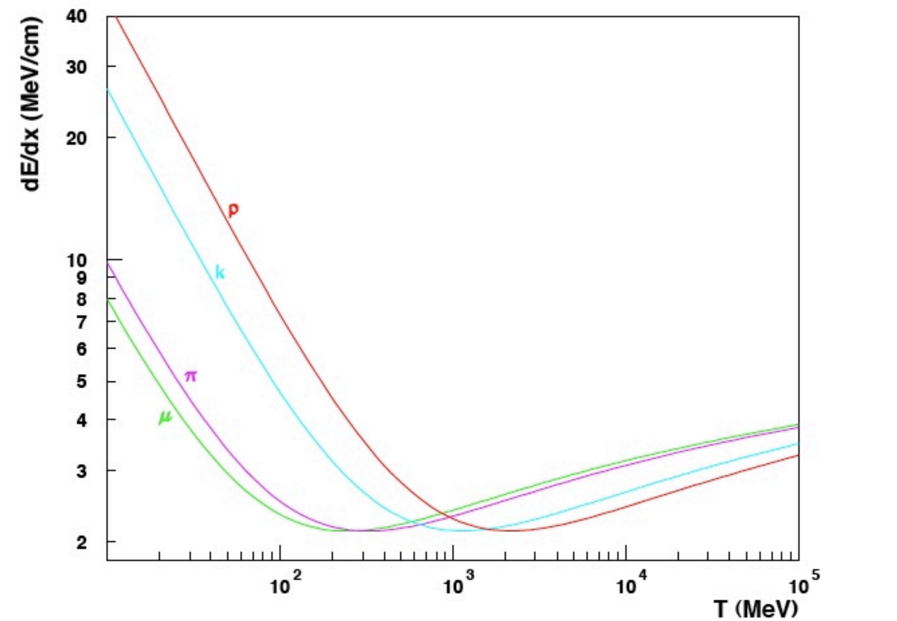


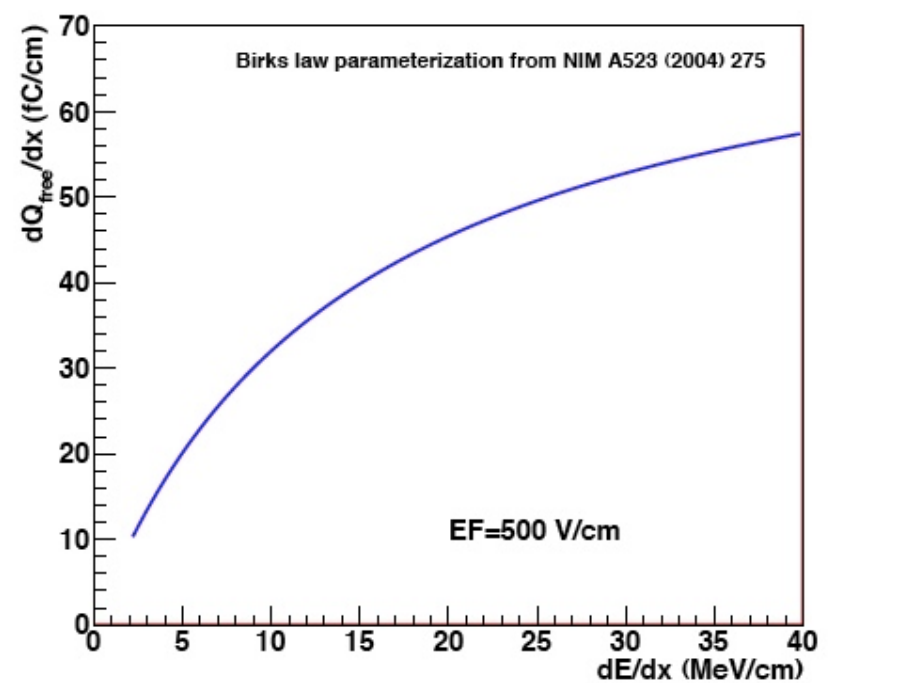
LArIAT Participants

17 Institutions
40+ physicists

Phase 1: Upgraded ArgoNeuT

- We would like to get started on understanding the calibration as quickly as possible
- Upgrade ArgoNeuT to start
  - PMT to detect scintillation light
  - Cold window to minimize amount of steel between the beam and LAr
  - Upgraded filtration system
  - Possible upgrade of the TPC to use cold electronics
- Will be used to study charge to energy conversion with single track topologies
- Also will study initial ionization in EM showers to understand e/γ separation





Phase 1: Upgraded ArgoNeuT

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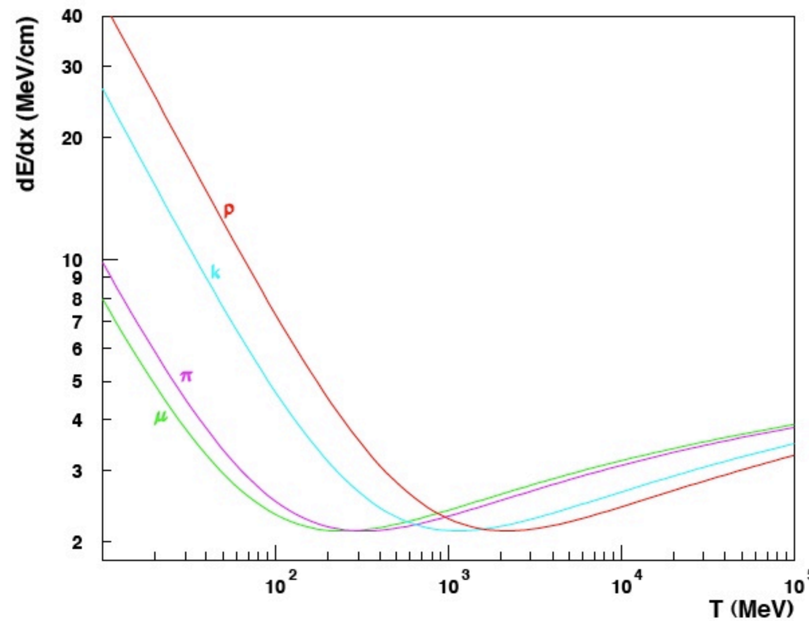
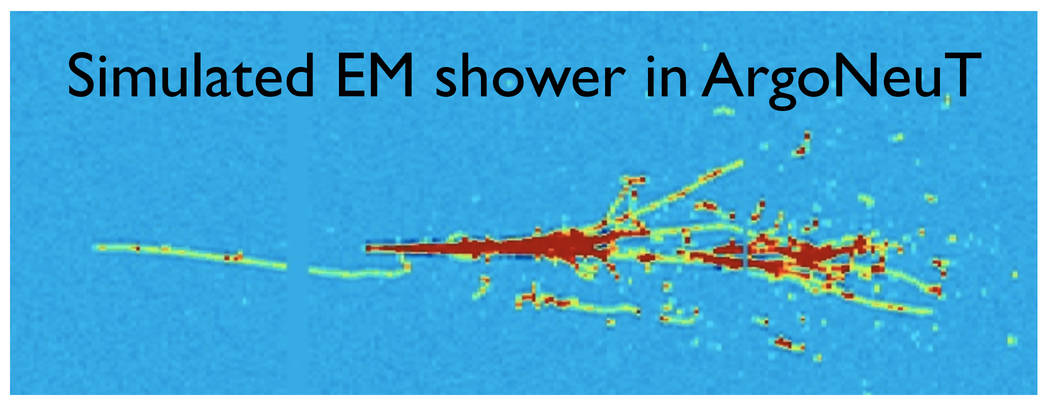
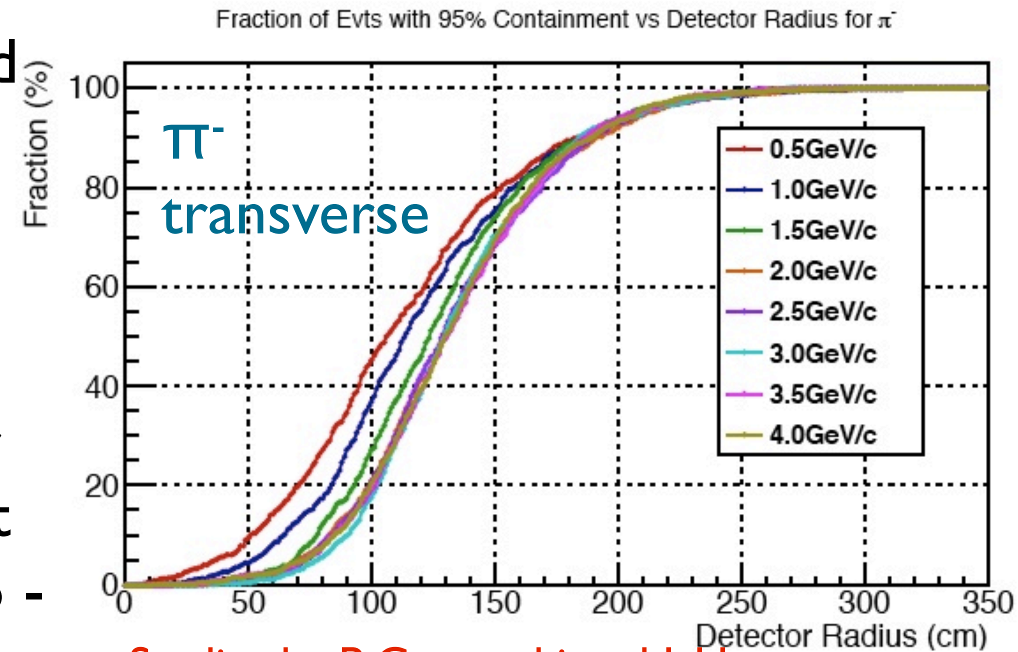


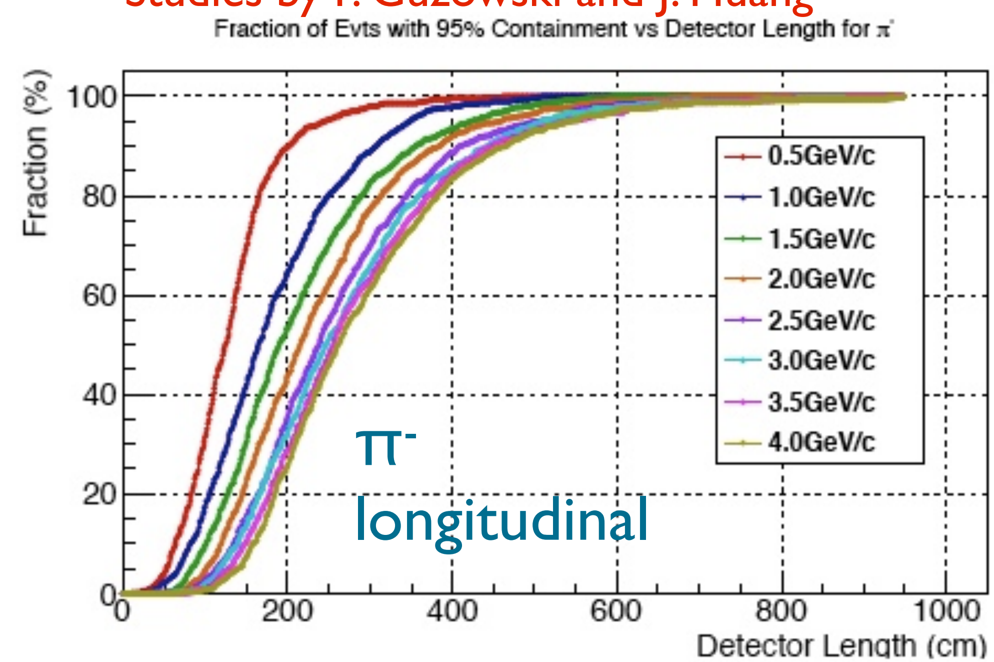

Simulated EM shower in ArgoNeuT

Phase 2: TPC Size

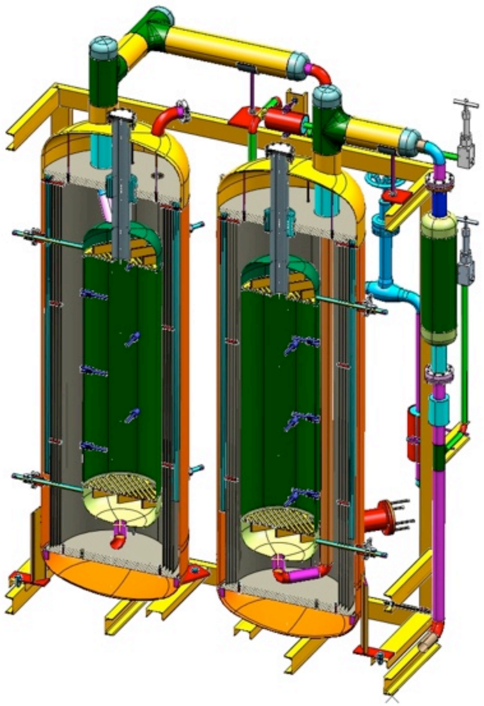
- Muons lose 2.2 MeV/cm, hadronic interaction length in LAr is 80 cm, and radiation length is 14 cm
- Hadron containment determines the scale of the detector
- MC studies show that ~2 m diameter will contain 95% of total energy for at least 20% of the interactions from 0.5 - 4 GeV pions
- Length should be ≥3 m for similar containment in that direction
- Costs and hall size combined with containment indicates TPC be on the scale of 2m x 2m x 3m
- Would make cryostat longer for upgrades

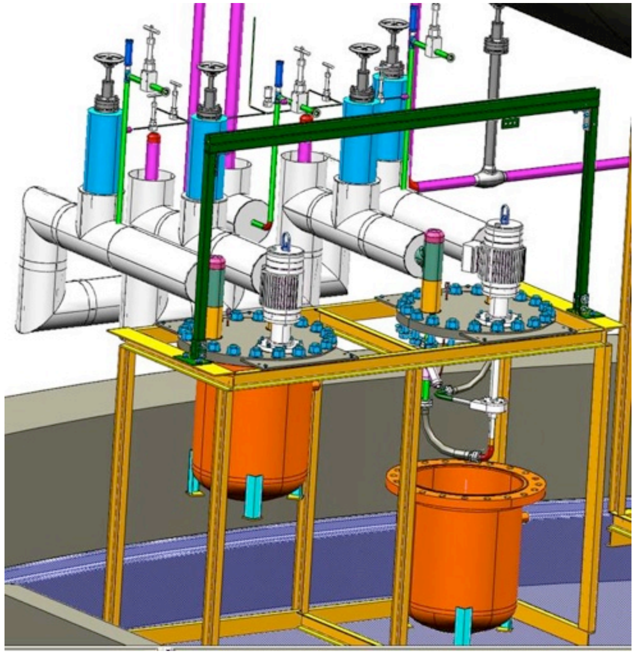


Studies by P. Guzowski and J. Huang



The Facility





- Fermilab provides the facilities, other groups provide the active detectors
- Optimization of tertiary beam used for MINERνA underway
- Use experience from LAPD and MicroBooNE for cryogenic system design
- The facility will provide a filtration and pumping system that is appropriately sized to the volume of LAr
- Build cryostat to allow convenient access to inside of vessel
- Imagine exchanging electronics, light collection systems, TPCs, etc during several year program

The Facility

Initial Filter

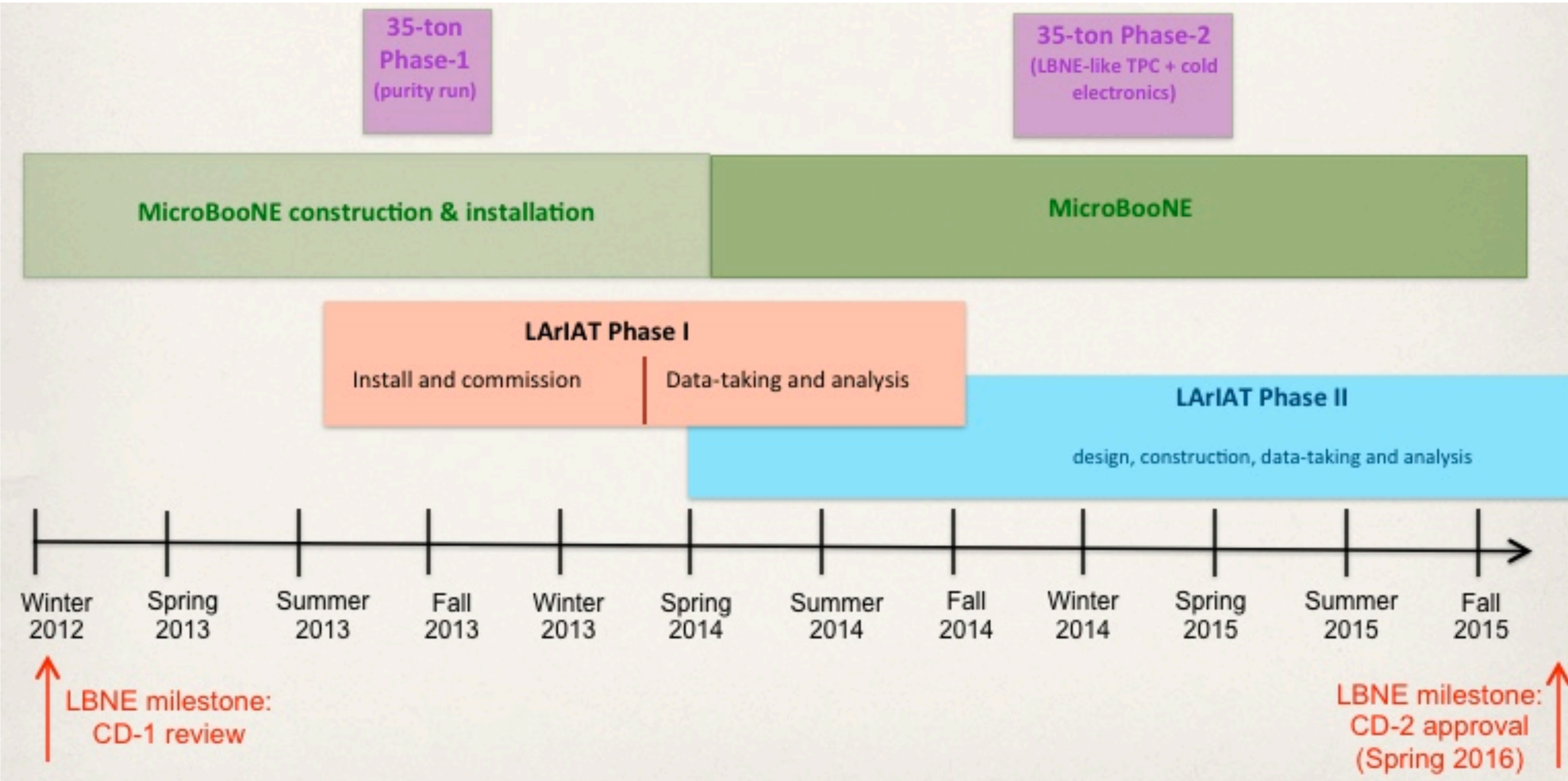
Cryogenic Pump

- Fermilab provides the facilities, other groups provide the active detectors
- Optimization of tertiary beam used for MINERνA underway
- Use experience from LAPD and MicroBooNE for cryogenic system design
- The facility will provide a filtration and pumping system that is appropriately sized to the volume of LAr
- Build cryostat to allow convenient access to inside of vessel
- Imagine exchanging electronics, light collection systems, TPCs, etc during several year program

LArIAT Physics Program

- Measurements to be made include
  - EM shower energy resolution (Phase 1, Phase 2)
  - Hadronic shower energy resolution, visible vs invisible energy (Phase 2)
  - Directionality of through going particles using delta rays (Phase 2)
  - Particle identification (Phase 1 and Phase 2)
  - dE/dx for several particle species (Phase 1 and Phase 2)
  - Light collection efficiency (Phase 1 and Phase 2)
  - Surface operation in a high cosmic ray rate environment (Phase 2)
  - Studies of proton decay backgrounds (Phase 2)
  - Diffusion studies over long drift distances (Phase 2 and beyond)

LArIAT Timeline

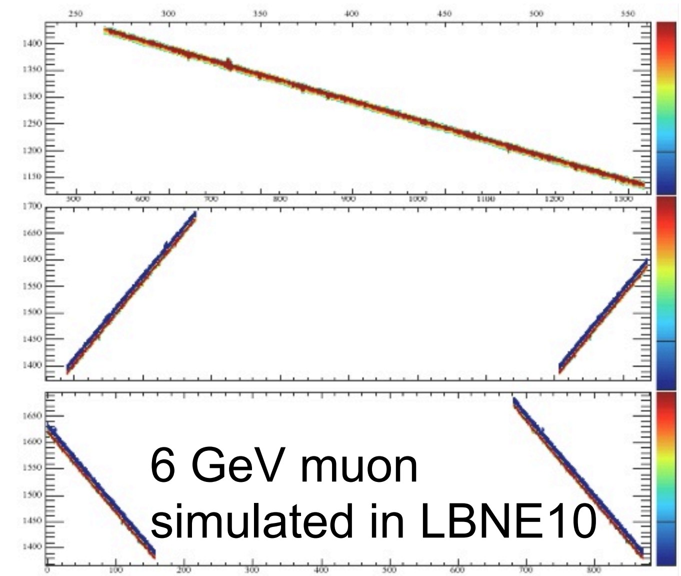


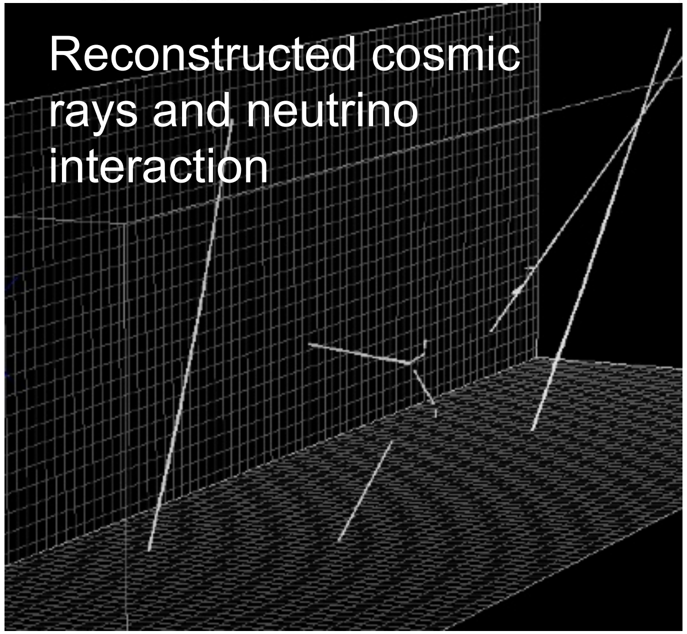
Software

Simulation, Reconstruction, and Analysis

LArSoft

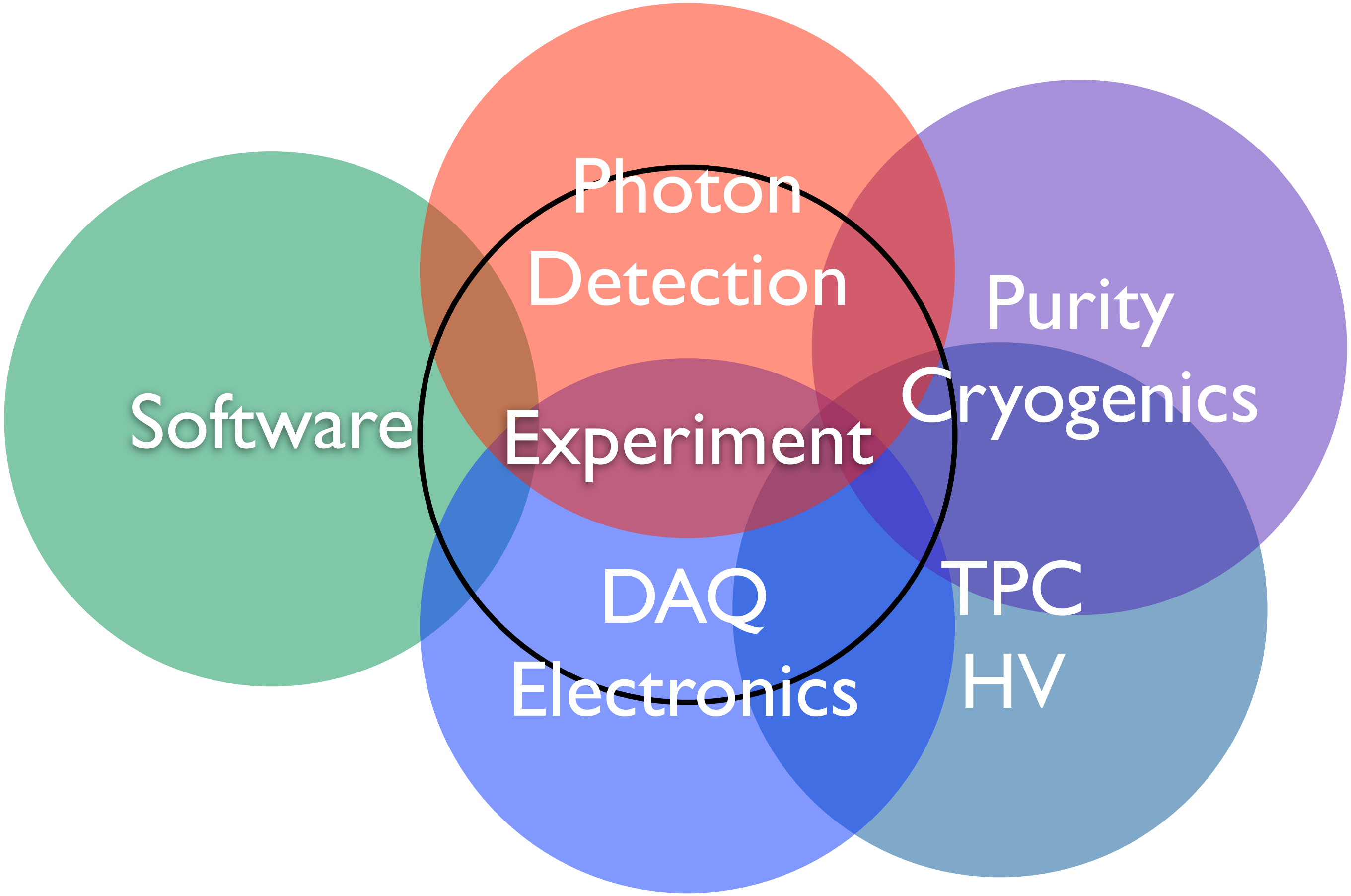
- LArSoft is a simulation, reconstruction and analysis framework for any LArTPC
- Goal is to have a fully automated simulation and reconstruction for any LArTPC
- LArSoft leverages the efforts of a variety of experiments into a single product
- Accreting a lot of new effort thanks to the LBNE technology decision and μBooNE construction
- Now managed by Fermilab Scientific Computing





LArSoft Documentation at
https://cdcvs.fnal.gov/redmine/projects/larsoftsvn/wiki

Bringing it all Together



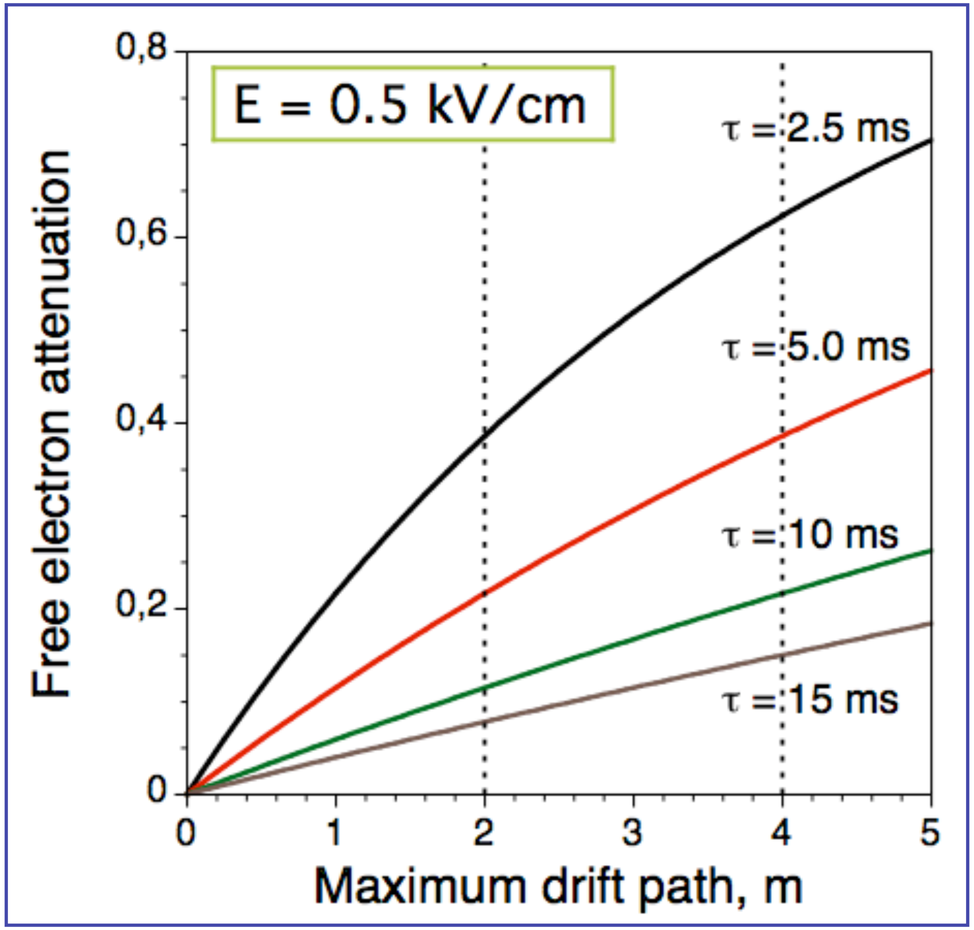
- The Fermilab LArTPC R&D is very successful - built on experience abroad and developed into a world class program
- Each area of development informs multiple other areas; new efforts emerging and older efforts being phased out
- Experiments, large scale or test beam, sit at the center of the process

Outlook

- LBNE will produce compelling results for neutrino oscillations and astrophysical topics
- Fermilab has dedicated program to make multi-kiloton scale LArTPCs
  - Materials test stand is informing choices on materials and construction
  - LAPD has shown that electron lifetimes of > 5 ms can be achieved without evacuation and in the presence of a TPC
  - Cold electronics to be tested in µBooNE before use in LBNE
  - ArgoNeuT has published first cross section results for argon
  - LArIAT will provide important input for physics analyses of LBNE
- Demonstration of the technology with the planned test stands and experiments is crucial step on the way to large neutrino detectors for LBNE and beyond

LAr Purity - How Pure?

- Poor lifetime reduces the dynamic range and strains electronics
- 100 parts per trillion (ppt) O_2 equivalent corresponds to an electron lifetime of 3 ms
- The product of the contamination and the lifetime is a constant, so for a 10 ms lifetime you need 30 ppt O_2 equivalent
- In a field of 500 V/cm the drift time for 1 m is then 0.63 ms



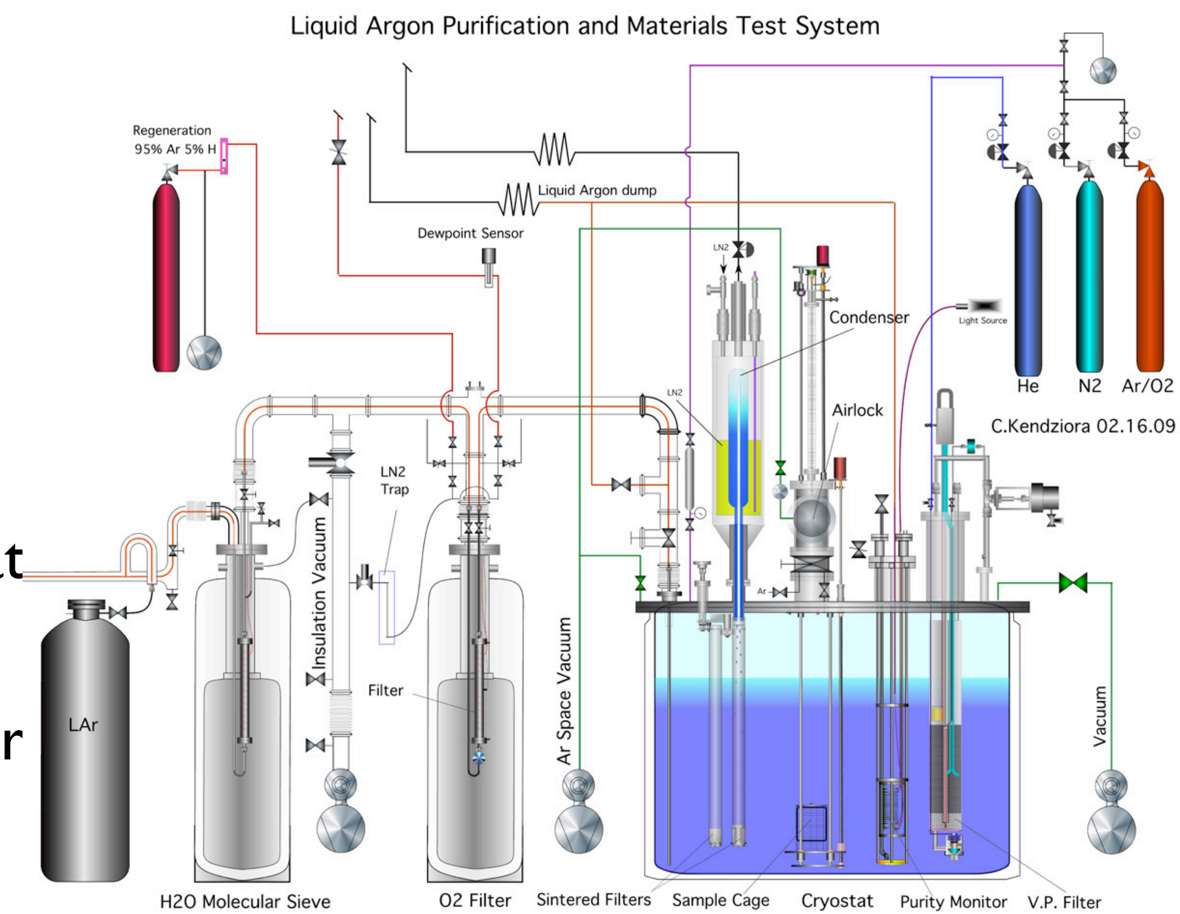
From C. Montanari, June 2007

Fermilab Program for Understanding Purity

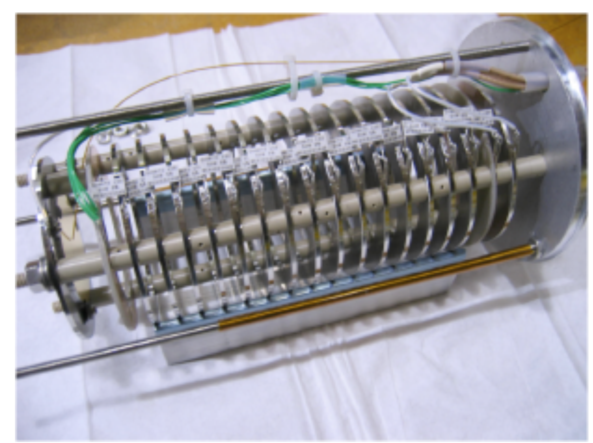
- The mantra is to learn and keep learning from existing systems, like ICARUS
- In addition, we want to develop experience with filters, cryogenics, pumps and electronics
- Use home grown test stands to get the experience and push the development
- Test stands allow us to judge suitability of materials to use in a LArTPC (MTS), and understand how to achieve large drift lifetime without evacuation

MTS Schematic

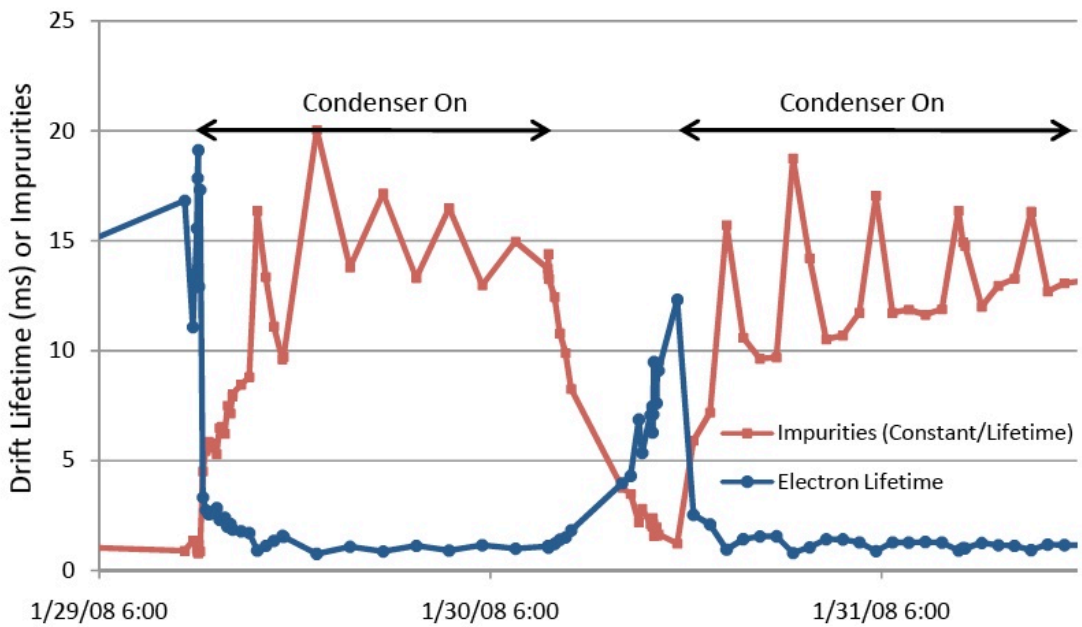
- Commercial LAr is passed through molecular sieve to remove water and copper to remove O_2
- Cryostat has airlock to allow insertion of materials, sample cage (1000 cm^3) can be placed at any depth
- LN_2 condenser used to liquify Ar boil off gas, in situ filter used to remove contaminants
- Measure H_2O and O_2 concentrations to 0.5 ppb, e lifetimes 0.3 - 10 ms
- Several locations where samples can be taken/tested for contamination
- Can inject known contamination of gases

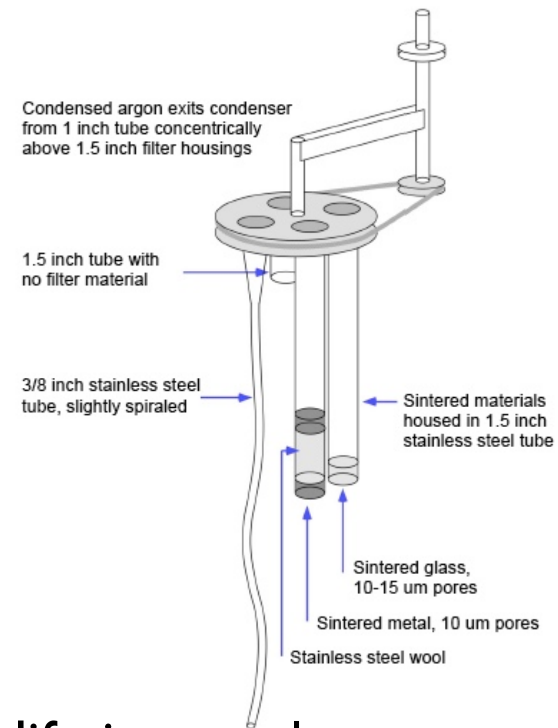


S. Pordes, C. Kendziora, T. Tope (FNAL)



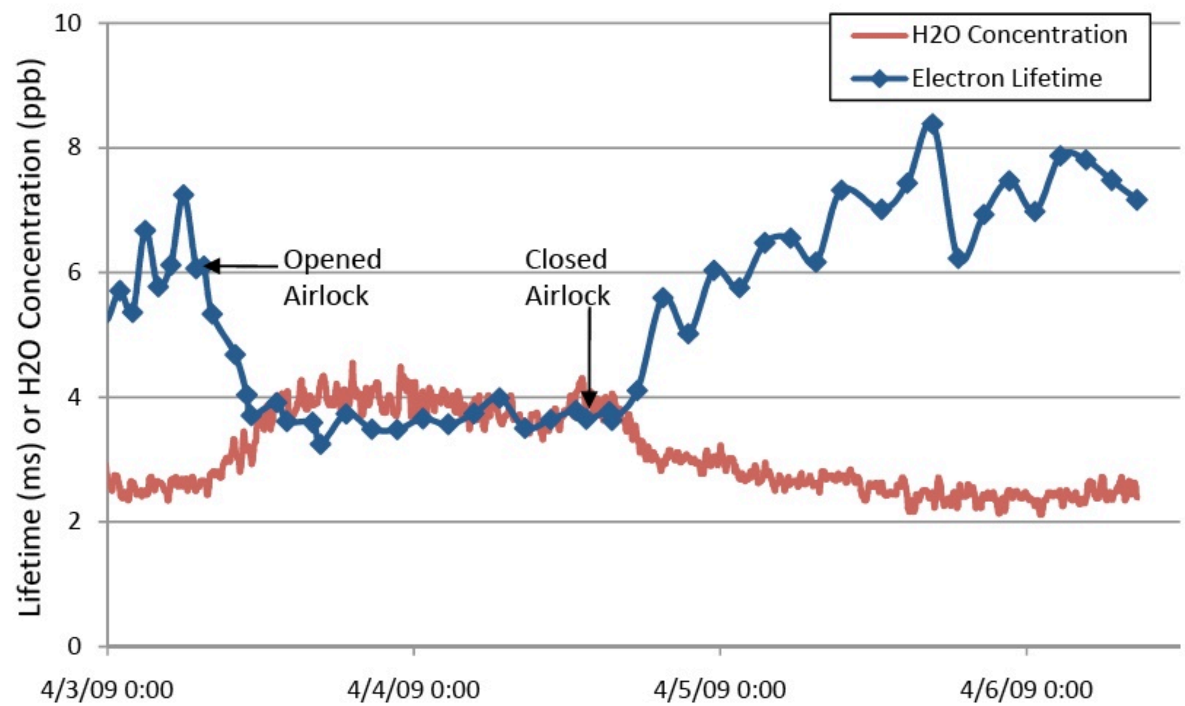
Condenser Surprises





- 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

What is the Impurity?



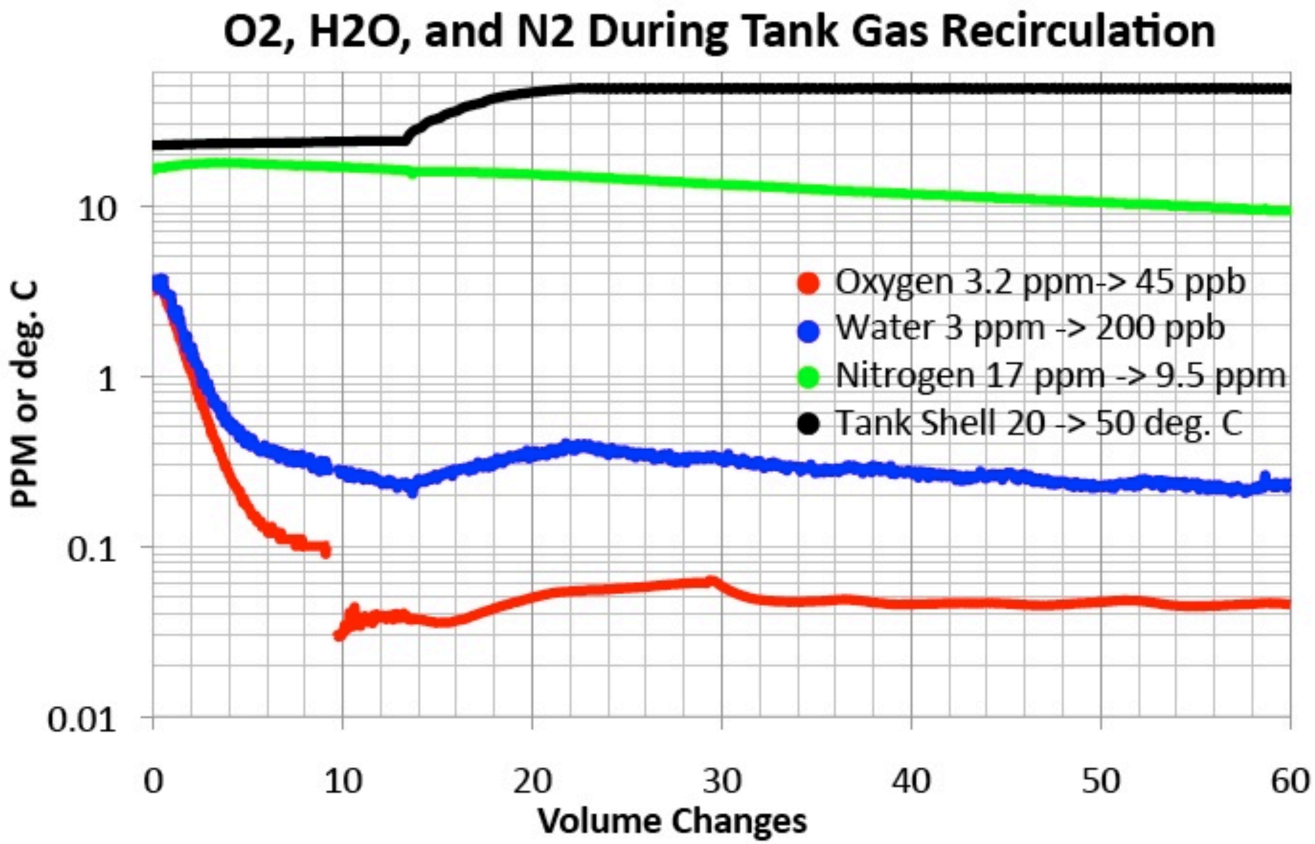
- Source must be something that remains on metal surfaces in vacuum and has an affinity for cold surfaces: Water is a clear suspect
- Moisture analyzer with 2 ppb detection limit used to monitor water concentration in cryostat
- Water concentration increases when airlock is open to cryostat, electron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

Data from Various Materials

Material	Date test started	Preparation	Tests	Water [ppb]	Lifetime [ms]	LogBook #
Cleaning Solution	6/29/09	evac. 24 h	vapor/liquid	4	5	946
Vespel	7/9/09	evac. overnite	liquid/vapor	5-7	2-5, 4-6	960
MasterBond glue	7/16/09	purged 18 h	vapor/liquid	1.6	1.3- 2.9	974
LEDs	7/31/09	purged 38 h	vapor	3.5	5	993
Carbon filter material	8/12/09	evac. 24 h	liquid/vapor	2	4-9	1000
962 FeedTru Board V2	10/12/09	evac. 24 h	vapor/warm	85	1-5	1062
Teflon cable	1/9/10	purged 28 h	warm/liquid/vapor	8-20	2-5	1175
3M "Hans" connectors	1/29/10	purged 46 h	warm/liquid/vapor	5-12	3	1198
962 capacitors	3/2/10	evac. 24 h	warm/liquid/vapor	6-14	3-6	1228
962 polyolefin cable	4/12/10	evac. 16 days	warm	25-60	2	1237
Rigaku feedthrough	4/20/10	purged 7.5 h	warm	15	3	1250
Rogers board (Teppei)	4/23/10	purged 26 h	warm/liquid/vapor	40	2, 6-10	1254
Arlon Board (Teppei)	5/14/10	evac. 0.5 h, pur.2 days	warm/vapor	300, 80	1.3, 3.5	1263
Polyethylene tubing	5/24/10	evac. 6 h, pur. 66 h	warm	300-500	1	1278
Teflon tubing	5/27/10	evac. 1 h, pur.17 h	warm	9-13	4-5	1283
Jonghee board	5/28/10	evac. 6 h, pur. 1.5 h	warm/vapor	100,28	1.2, 5-8	1285
Jonghee connectors	6/4/10	evac. 3.5 h, pur. 16 h	warm/vapor	50	2-3	1290
PVC cable	6/14/10	evac. 29 h, pur.1 h	warm	120	1-2	1296
Teppei TPB samples	8/3/10	purged 26 h	warm	600-1600	0.7	1342
Teppei TPB samples	9/4/10	purged 37 h	liquid /vapor	15, 300	6	
PrM feed tru (baked)	10/5/10	purged 25 h	warm/vapor	35, 20	3, 2	1396
Copper foil on mylar film	10/14/10	purged 26 h	warm/liquid/vapor	15, 10, 9	3, 8, 7	1409
Teppei SHV connector	10/25/10	purged 25 h	warm/vapor/liquid	35, 11, 0	2, 6, 6	1415
FR4	11/16/10	purged 25 h	warm/liquid/vapor	180, 20, 65	1.5, 6, 2.5	1429
Gaskets	3/11/11	purged 24 h	warm/liquid/vapor	8, 10	2.5, 8 , 7	1521
LBNE AP-219 Color. Developer	4/13/11	purged 25 h	warm/vapor	65, 15	4, >6	1722
LBNE RPUF Foam	4/22/11	evac. 26 h, pur.1 h.	warm	800	0.2	1729
LAPD LEDs	5/12/11	purged 49 h	vapor	0.6 ppb	10	1769

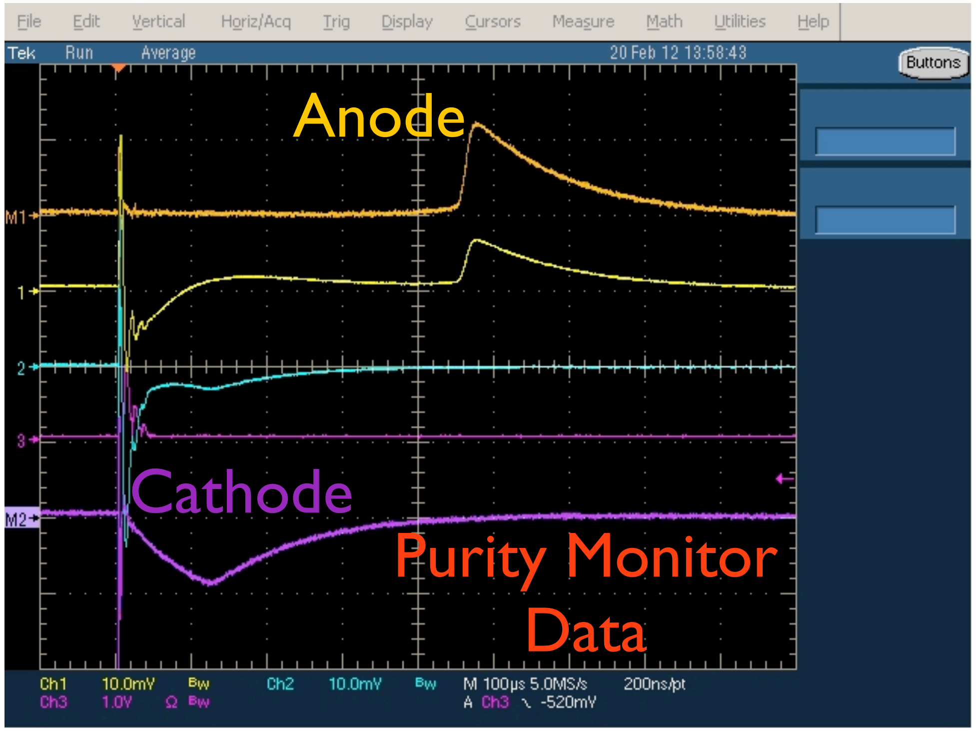
- Significant correlation with data in water-content database at outgassing.nasa.gov
- FR4 is fine to use in the liquid, don't place it in warm gas
- Teflon tubing is far superior to polyethylene tubing

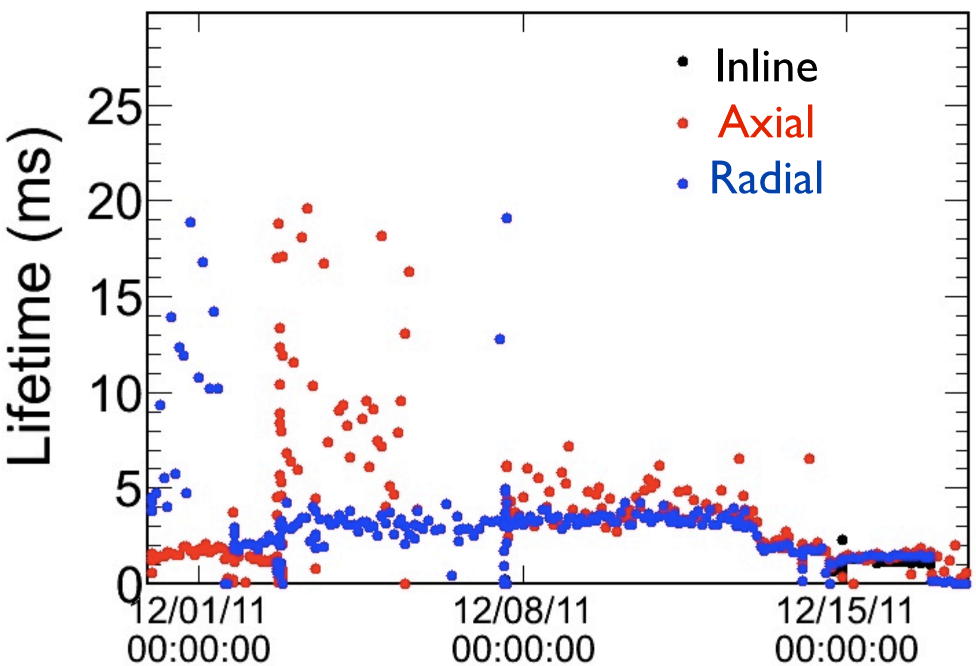
Gaseous Argon Recirculation



- The purge was very successful and brought the vapor in the tank to a contamination level that was below the specifications for the delivered liquid
- Both O_2 and H_2O contamination were well below 1 ppm after 3 volume exchanges
- Maintained sub-ppm levels in the gas for over 20 days
- Heating the tank shell allowed more contamination to be "baked" out

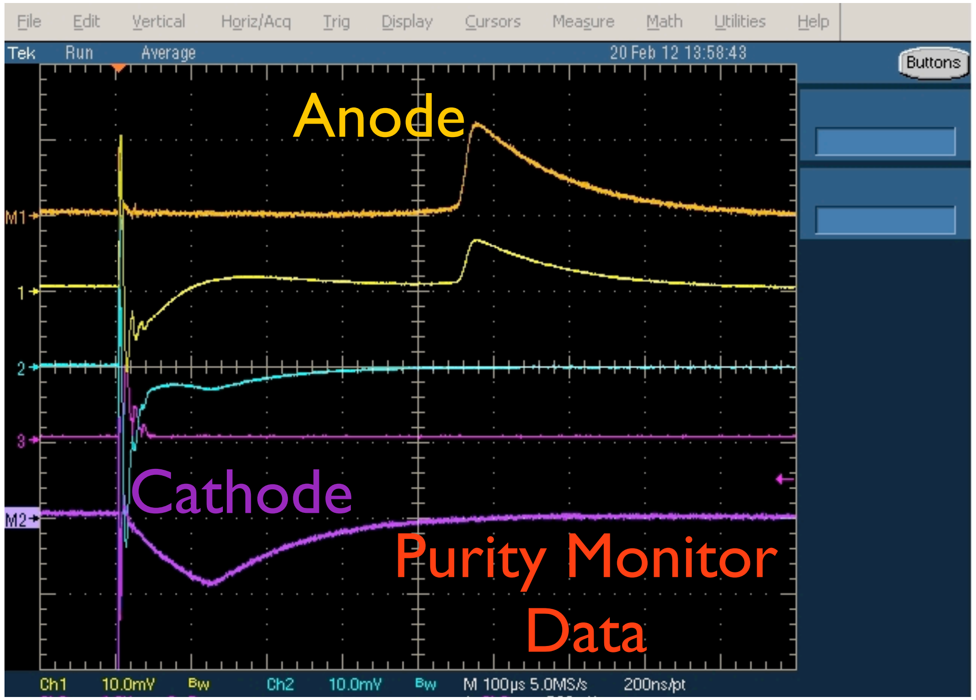
Electron Lifetime Measurement

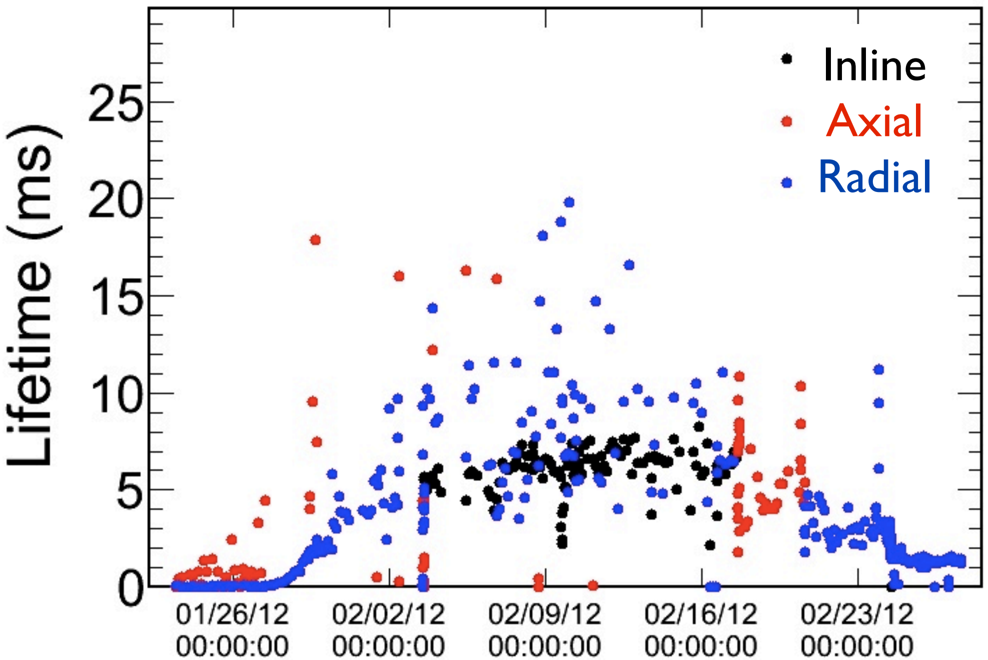




- First electron lifetime measurements made after 11 volume exchanges of liquid (66 hours)
- Lifetime during first run was stable at 3 ms or better (LBNE needs 1.4 ms)
- Lifetimes began decreasing after 2 weeks, indicating filter saturation
- Filters were regenerated and lifetimes went up to 5 ms
- Filters possibly started showing signs of saturation again, but an unplanned power outage stopped the run prematurely
- Vessel currently filled with 30 tons for the second phase run

Electron Lifetime Measurement





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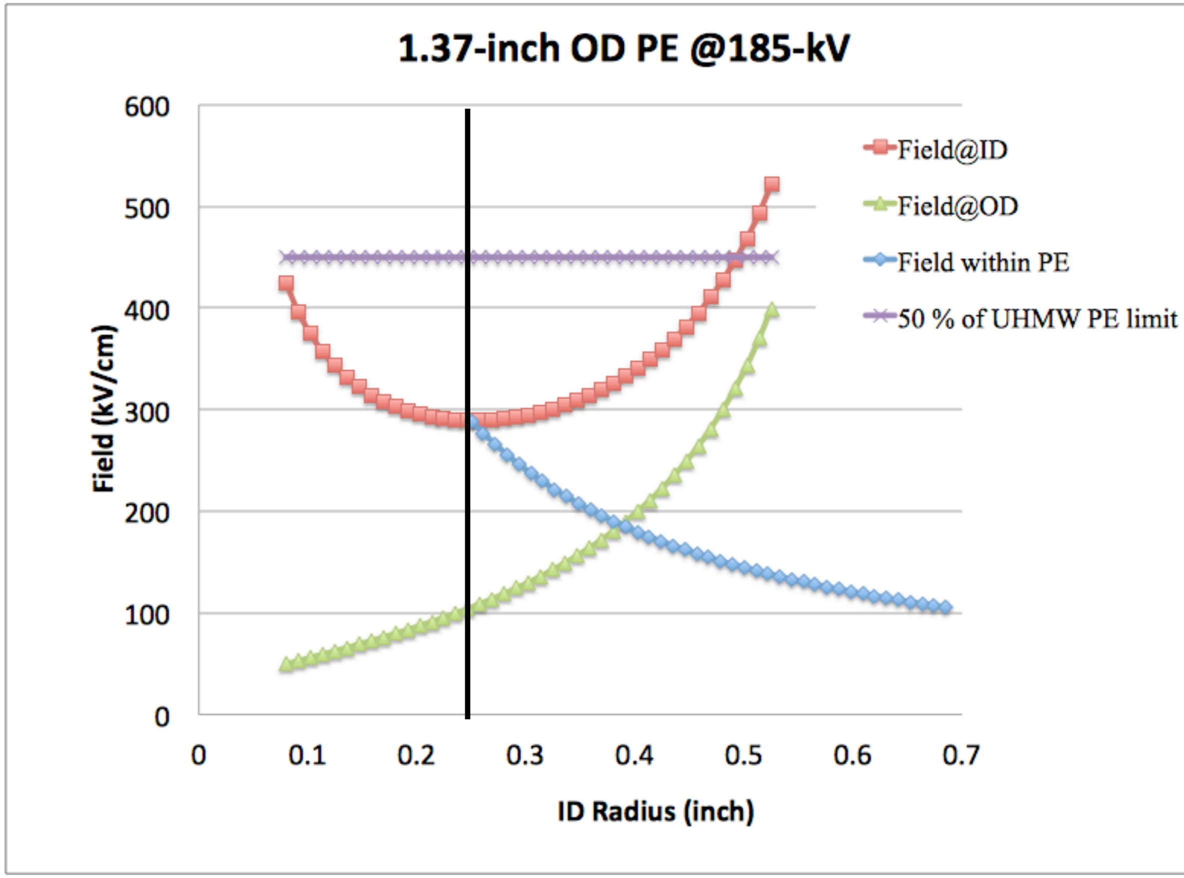
Geometry Design Considerations

- At a given outer diameter, (OD) there is an optimum inner diameter (ID) to minimize field strength on the ID surface
- Optimal ID for a 1.37 inch OD is 0.5 inch
- Blue points show field within the polyethylene (PE)
- Purple line shows 50% of dielectric strength for ultra-high molecular weight PE
- Tip geometry, TPC design and connection details also important to determining limiting HV for feedthrough



H. Wang, A. Teymourian (UCLA)

HV Filtering

- Ripples from the HV power supply will induce charge pick up by the readout electronics
- Electronics and TPC geometry will determine requirements on allowed level of ripple
- Plot shows voltage ripple for different load resistors, 0.001% peak to peak ripple
- MicroBooNE design 0.03% ripple

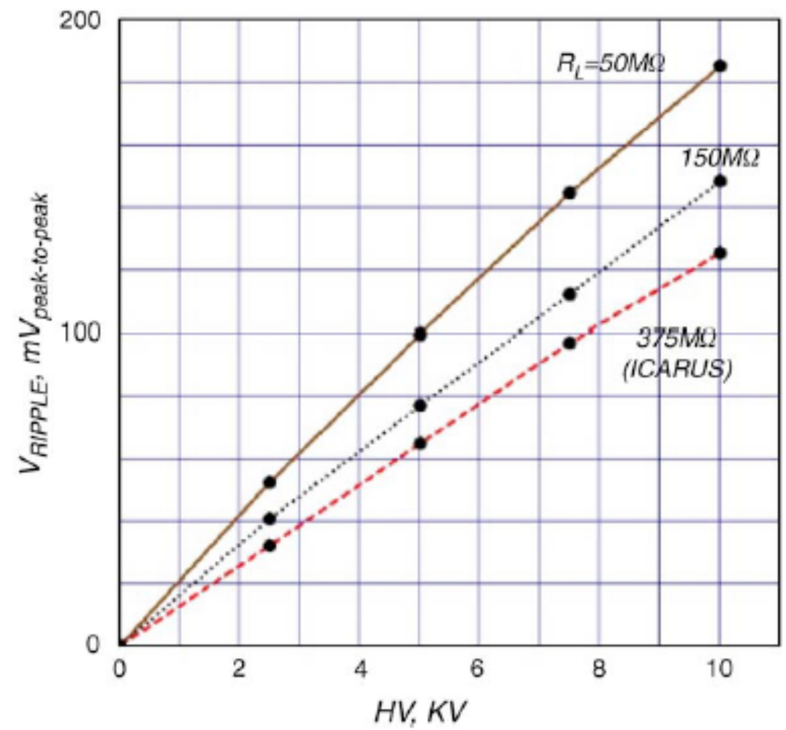
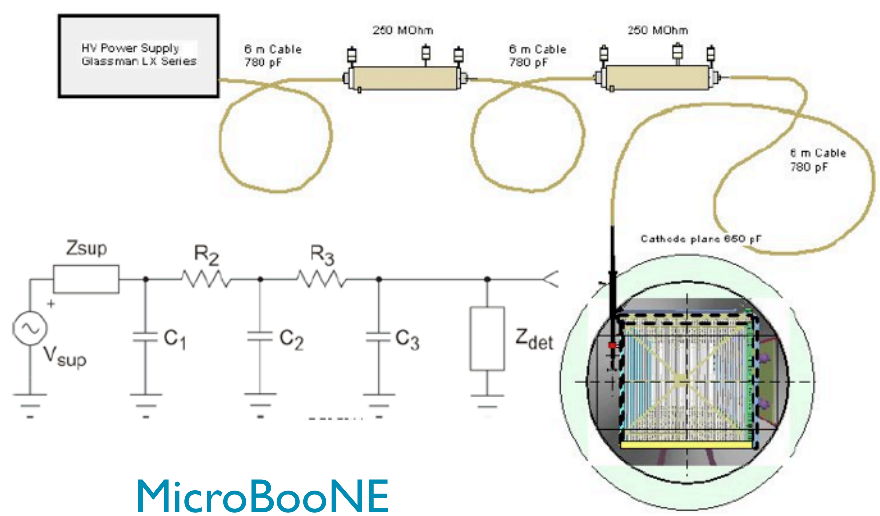


Fig. 41. Dependence of the voltage ripple (peak-to-peak) on the HV for different load resistors. (a) Solid line: $R_L = 50$ MΩ; (b) dotted line: $R_L = 150$ MΩ; (c) dashed line: $R_L = 375$ MΩ (T600 working conditions).

ICARUS



MicroBooNE

Figure 6. The circuit for the HV power supply and filter with the field cage as a load.

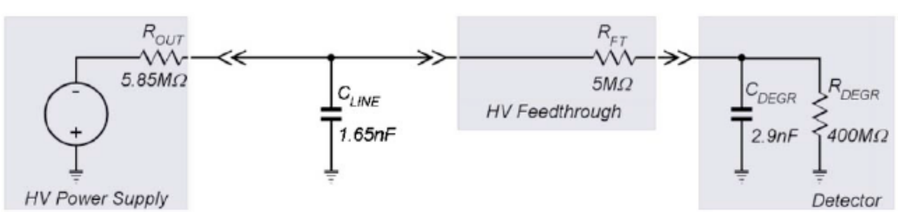
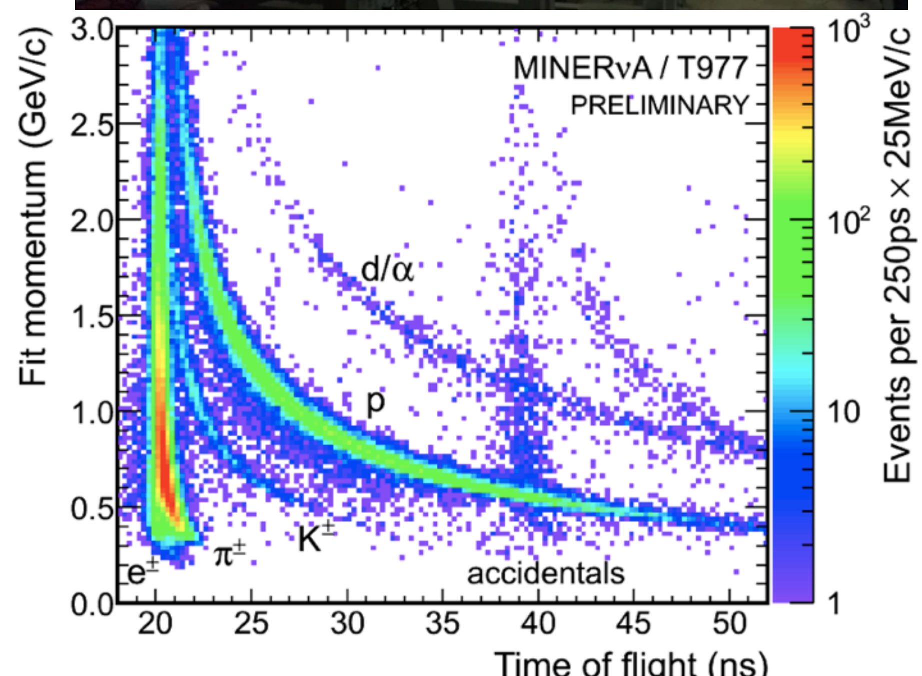


Fig. 42. Electric scheme of the external ripple rejection filter.

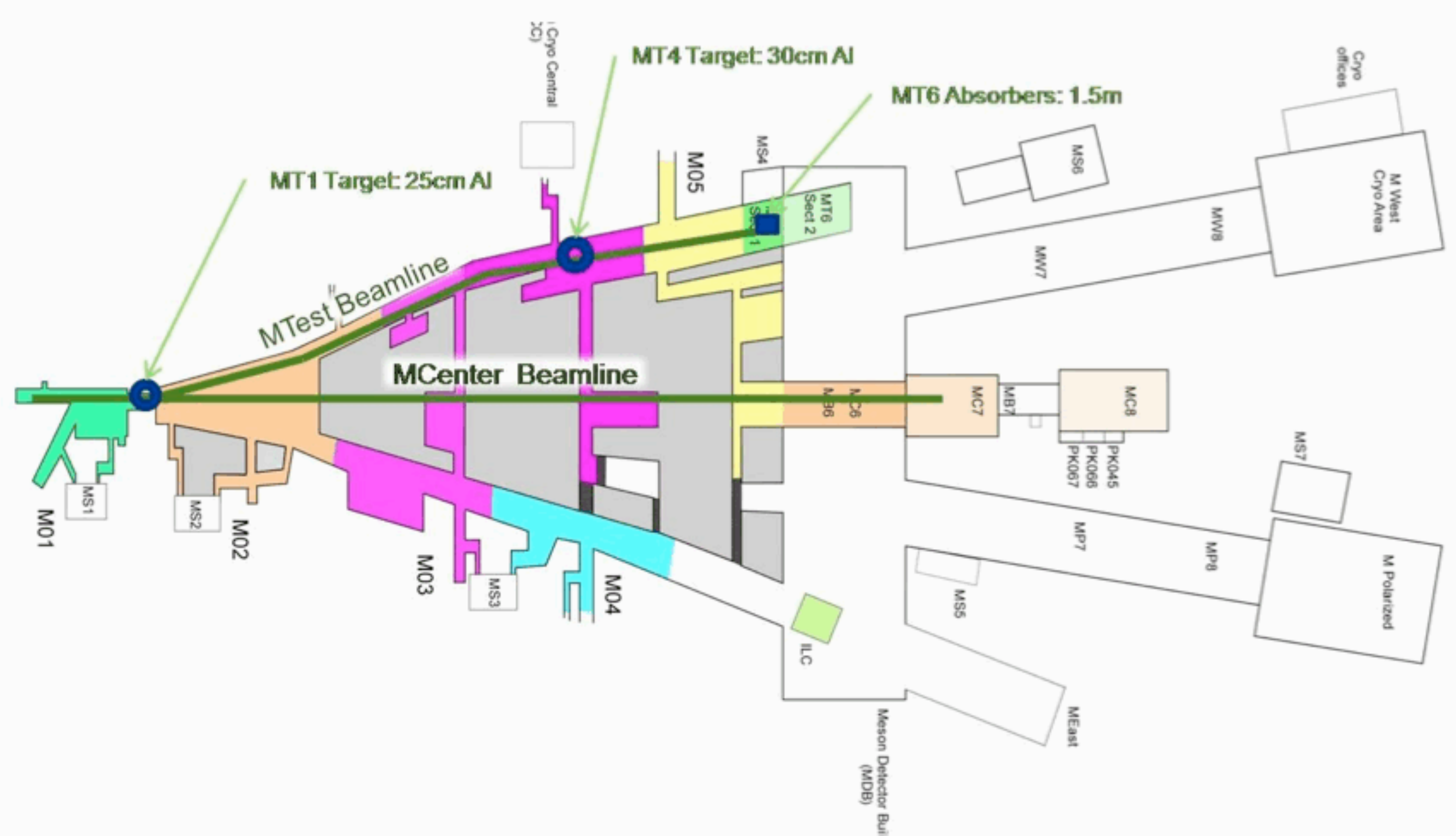
LArIAT Plan

- Create a facility for long term use where we can have the most flexible program both in terms of calibration tests and R&D related tests
- We have examined both the M-Test and M-Center areas in the Fermilab Test Beam Facility
- M-Center appears to be the better of the two locations for both size and availability over extended time periods
- Make use of the tertiary beam setup that was first used in the MINERνA test beam program

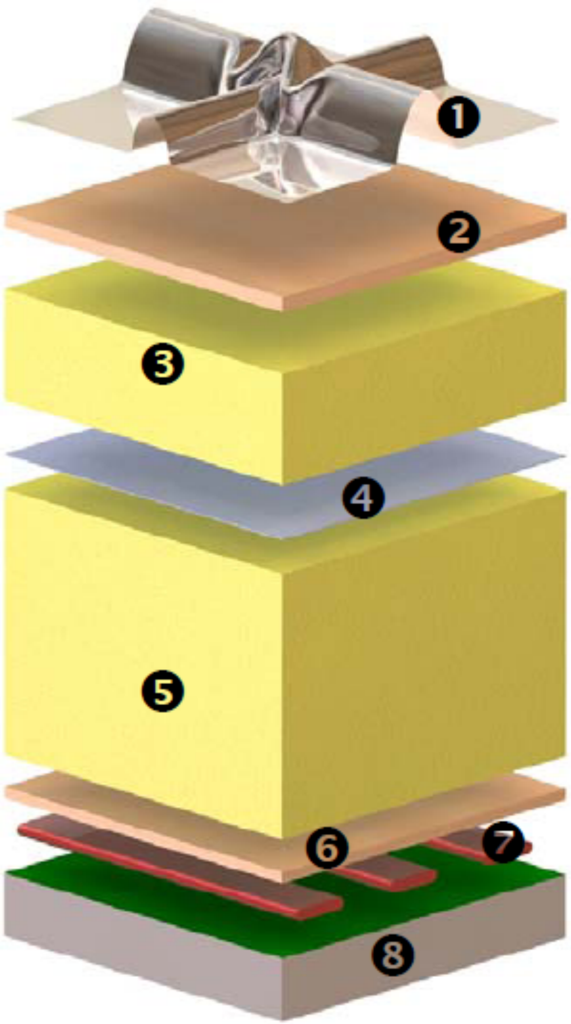


Tertiary beam composition

Fermilab Test Beam Facility



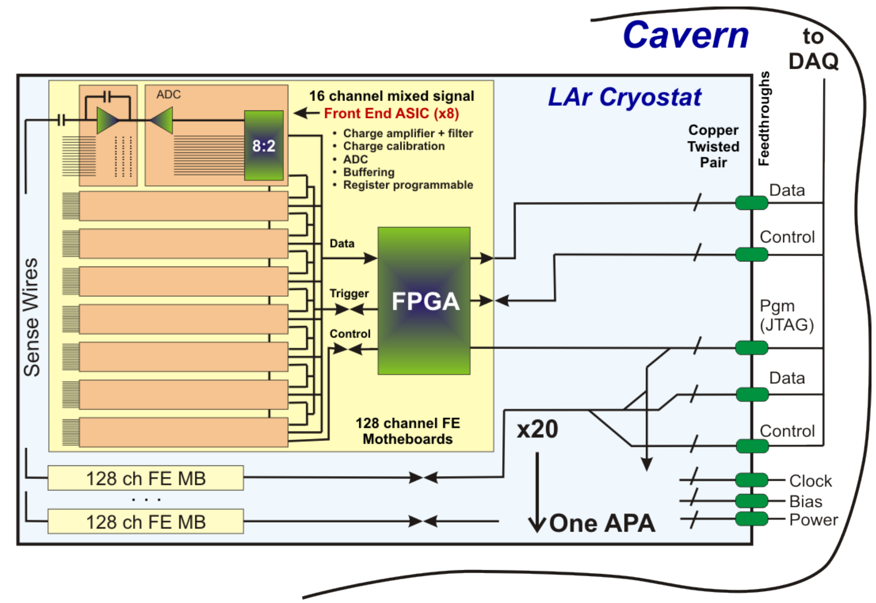
Membrane Cryostat

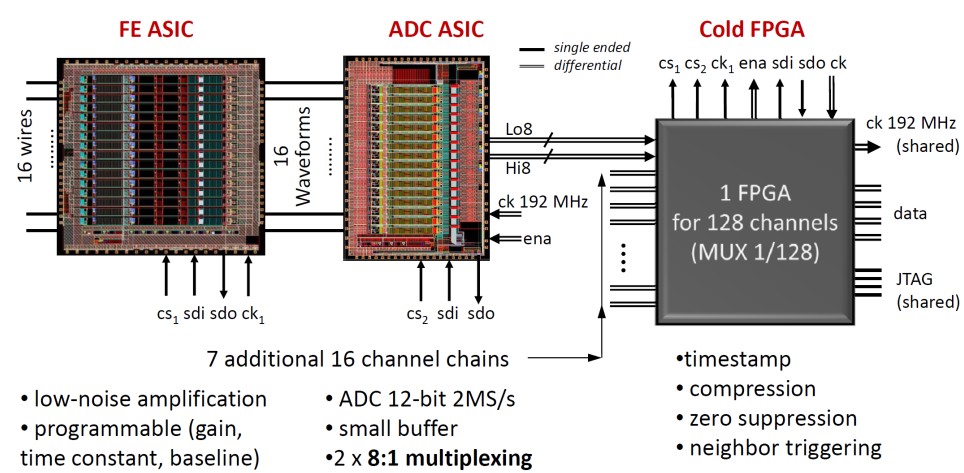


❶	Stainless steel primary membrane
❷	Plywood board
❸	Reinforced polyurethane foam
❹	Secondary barrier
❺	Reinforced polyurethane foam
❻	Plywood board
❼	Bearing mastic
❽	Concrete covered with moisture barrier

Cold Electronics

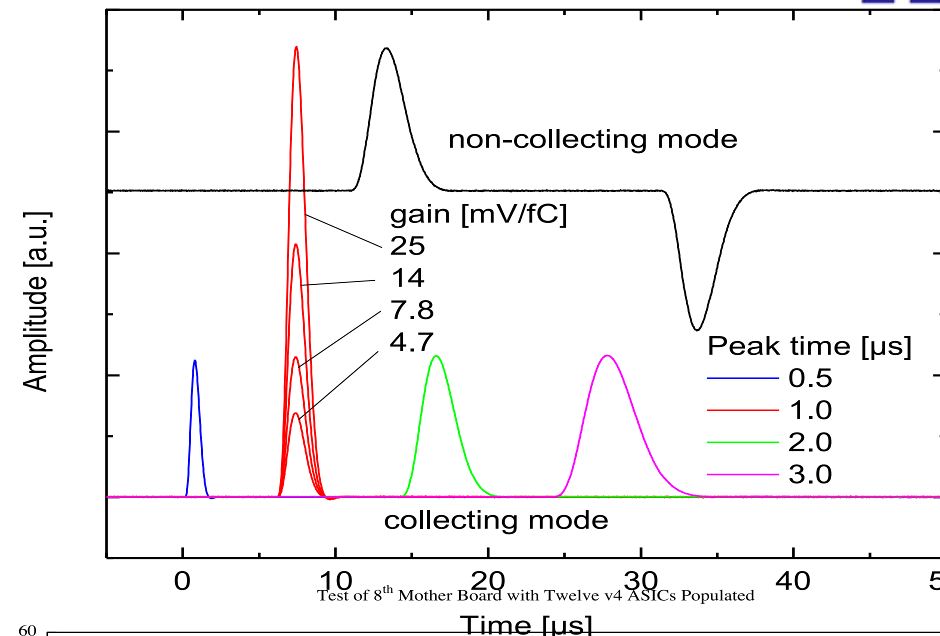
- Placing front end chips directly in the LAr minimizes capacitance and noise
- On chip digitization converts analog to digital inside the cryostat
- Multiplex signals to high speed serial link - reduces number of cables and minimizes out-gassing. This approach is important to scaling to large detectors
- Cold FPGA houses flexible algorithms for data processing and reduction
- Can use industry standard serial link to connect directly to back end system, minimizes conventional DAQ hardware

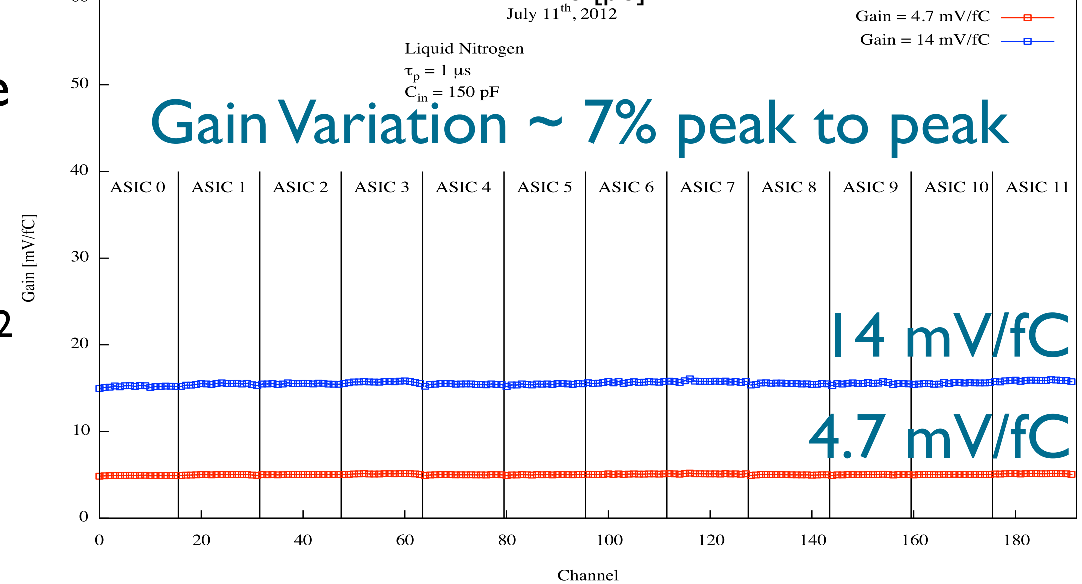




μBooNE: Cold Electronics

- A primary goal of μBooNE is to understand running cold electronics in a LArTPC
- Electronics are being designed primarily by BNL, will be used in LBNE too
- Tests show
  - Noise at 87k is half that at 300k
  - crosstalk is < 0.3%, gain variations are 7%
- Stress tests also performed show no problems after many immersions in LN_2
- ATLAS and NA48 calorimeters show very low failure rate over many years, designed for > 30 year lifetime





Wavelength Shifting

- The emitted light (128 nm) has to be shifted to a wavelength where light detectors have high quantum efficiency
- Tetraphenyl Butadiene (TPB) shifts the light to the blue (430 nm)
- TPB degrades when exposed to UV light - indicated by rising concentration of benzophenone
- Handling TPB requires care to ensure it still works when installed