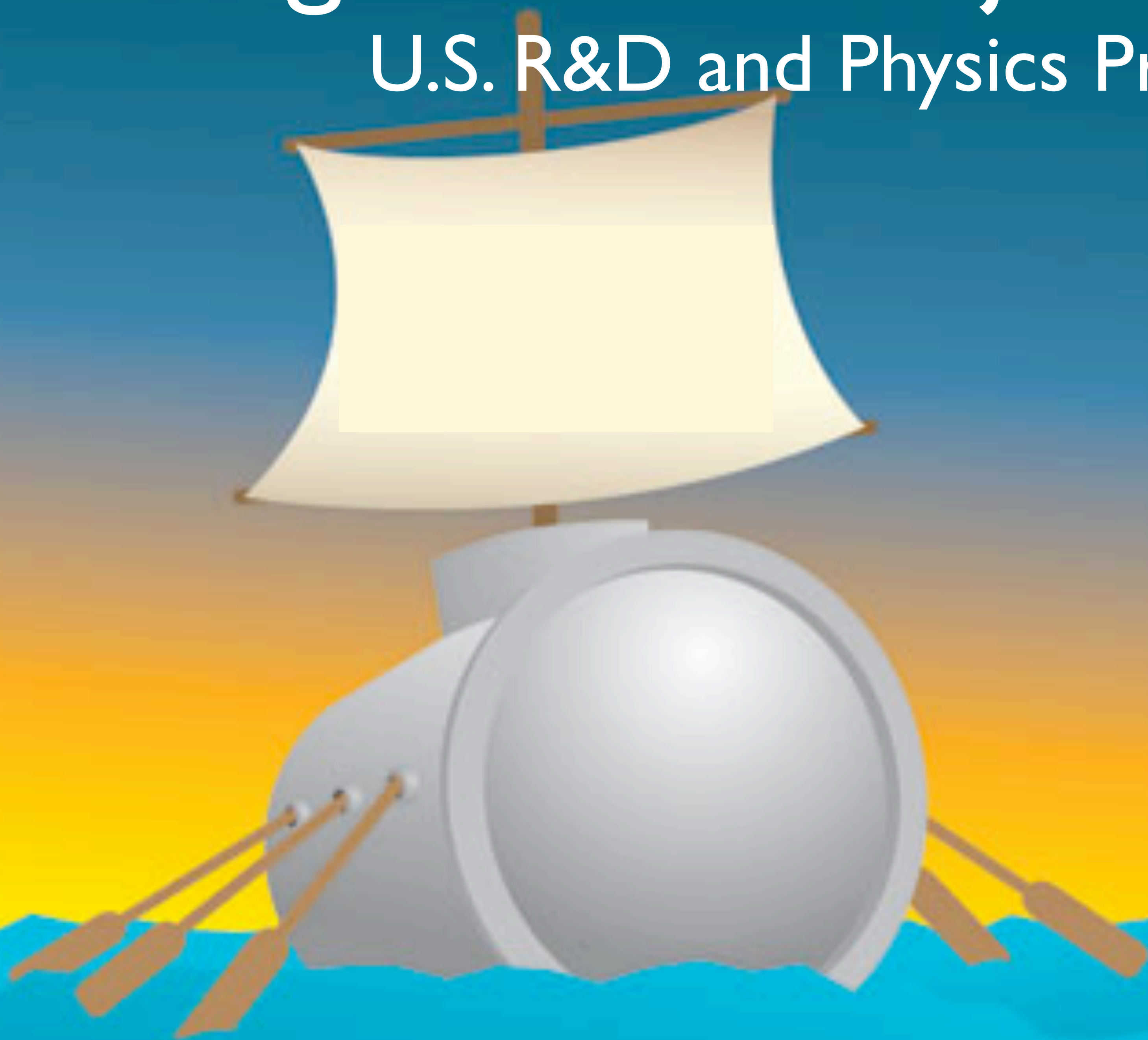
Liquid Argon Time Projection Chambers:
U.S. R&D and Physics Program



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September 15, 2008

Introduction

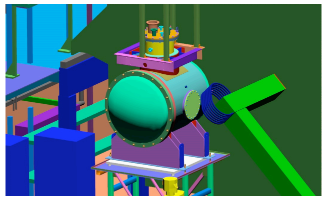
- Liquid Argon Time Projection Chambers (LArTPCs) continue to be an exciting option for future detectors.
  - ➡ combines excellent spatial resolution and calorimetry.
- Pioneering LArTPC work done in Italy by ICARUS collaboration.
- U.S. efforts to develop LArTPCs have expanded significantly in recent years.
- Several R&D efforts ongoing in U.S.
- MicroBooNE is a new LArTPC experiment to begin operating ~2011.
- Ultimate goal is to build a massive (100 kiloton) detector capable of studying neutrino oscillations and searching for nucleon decay.

Recommendations from the Report of the P5 Panel to HEPAP, May 29, 2008:

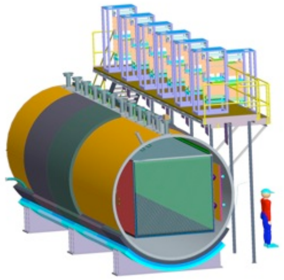
"The panel recommends support for a vigorous R&D program on liquid argon detectors and water Cerenkov detectors in any funding scenario considered by the panel. The panel recommends designing the detector in a fashion that allows an evolving capability to measure neutrino oscillations and to search for proton decays and supernovae neutrinos."

Outline

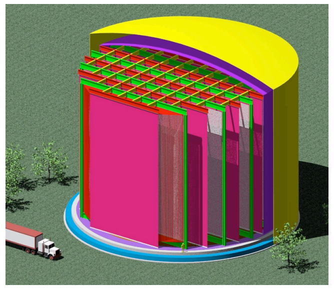
- LArTPC Basics
- Teststands in the U.S.



- The MicroBooNE Experiment



- Massive LArTPC Detectors

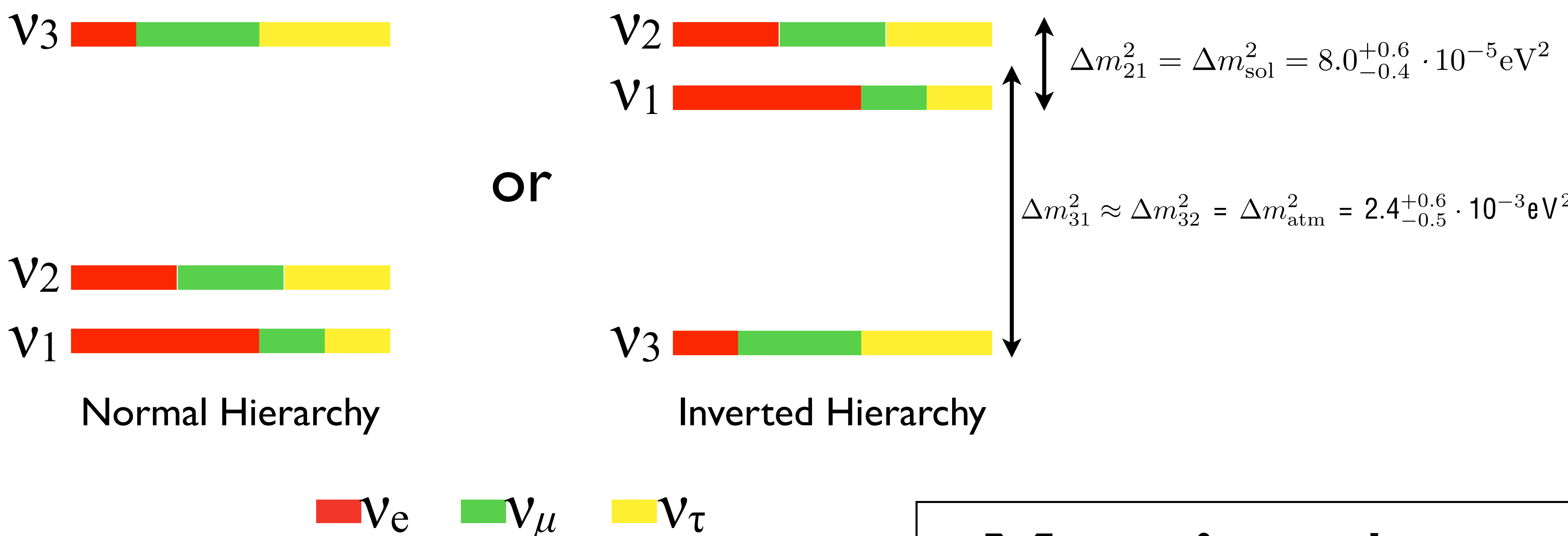


- Conclusions

Ultimate Physics Goals

Accelerator Based

- Observe $\nu_\mu \rightarrow \nu_e$ transitions, measure θ_{13}
- Measure the CP-violating phase, δ_{CP}
- Determine Mass Hierarchy:



Non Accelerator Based

- Proton Decay (e.g. - $p \rightarrow K^+ \nu_\mu$)
- Supernovae searches
- Solar neutrinos

Massive detector required for much of this physics....

"Nucleon Decay Searches with large Liquid Argon TPC Detectors at Shallow Depths: atmospheric neutrinos and cosmogenic backgrounds" - A. Bueno et. al, hep-ph/0701101

Noble Liquids: Properties

- Ionization and scintillation light used for detection (transparency to own scintillation).
- Ionization electrons can be drifted over long distances in these liquids.
- Very good dielectric properties allow high-voltages in detector.
- Argon is cheap and easy to obtain (1% of atmosphere).

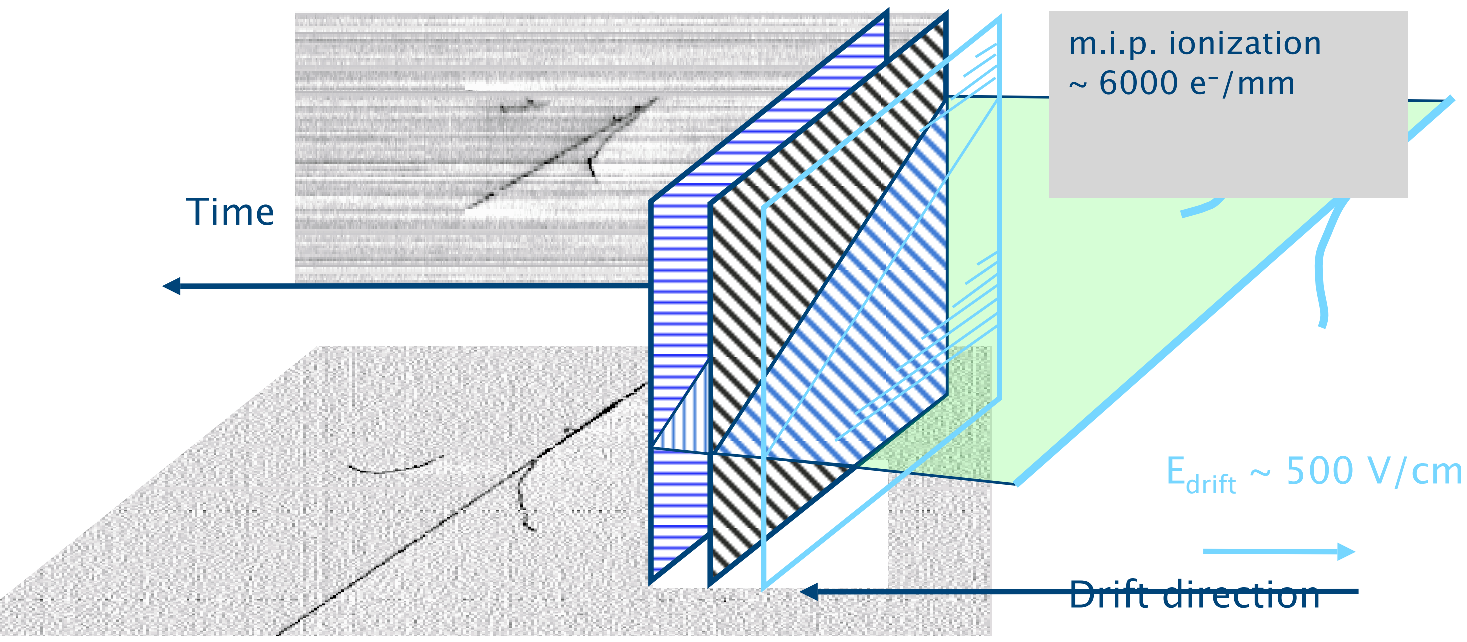
	Water	He	Ne	Ar	Kr	Xe
Boiling Point [K] @ 1atm	373	4.2	27.1	87.3	120.0	165.0
Density [g/cm^3]	1	0.125	1.2	1.4	2.4	3.0
Radiation Length [cm]	36.1	755.2	24.0	14.0	4.9	2.8
Scintillation [γ /MeV]	-	19,000	30,000	40,000	25,000	42,000
dE/dx [MeV/cm]	1.9		1.4	2.1	3.0	3.8
Scintillation λ [nm]		80	78	128	150	175

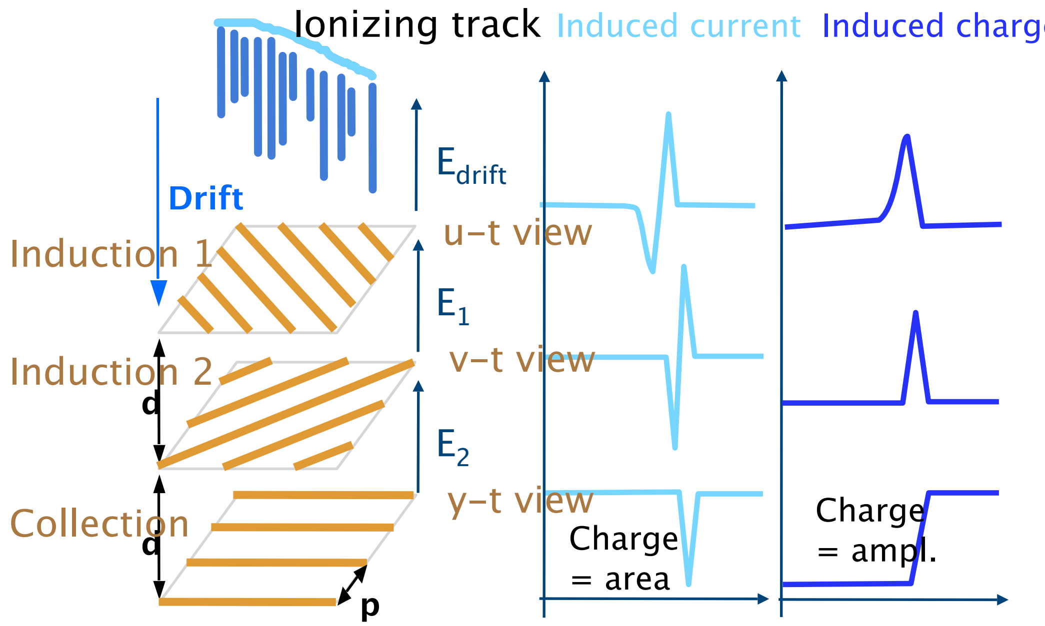
Liquid Argon Detectors appear scalable to large sizes!

LArTPC Principal

TPC = Time Projection Chamber

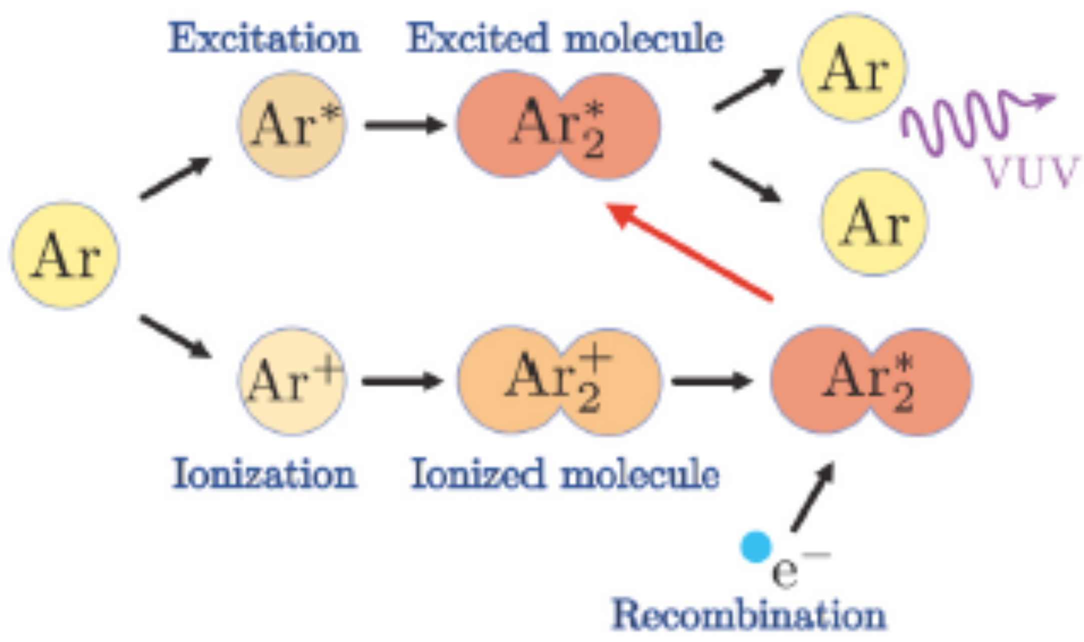
- Interactions inside TPC produce ionization particles that drift along electric field lines to readout planes.
- Knowledge of drift speed, and T_0 of events, can be used to reconstruct interaction.
- Scintillation light also present, can be collected by Photomultiplier Tubes.





Optical Properties

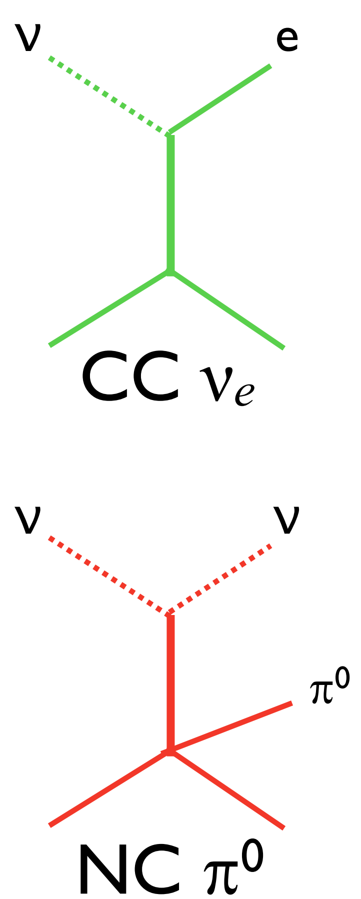
- Argon in an excellent scintillator.
- 128nm light (need to wavelength shift to collect....)
- De-excitation and recombination processes following the passage of ionizing particles in liquid Argon produce prompt scintillation radiation.

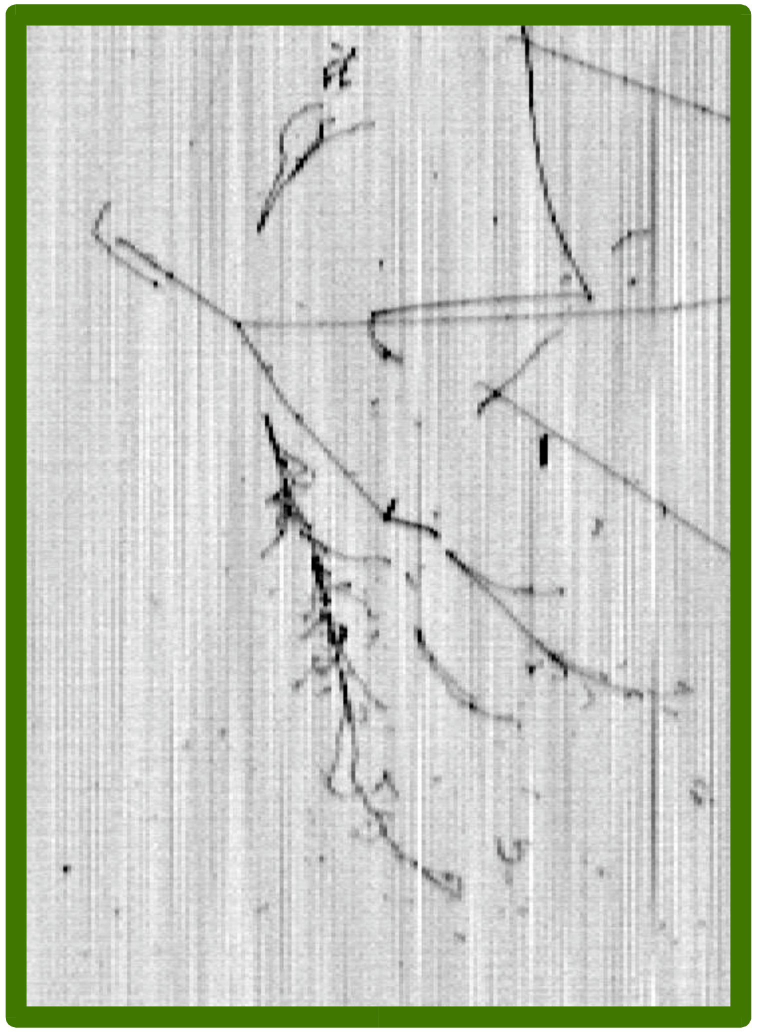


LAr TPC Advantages

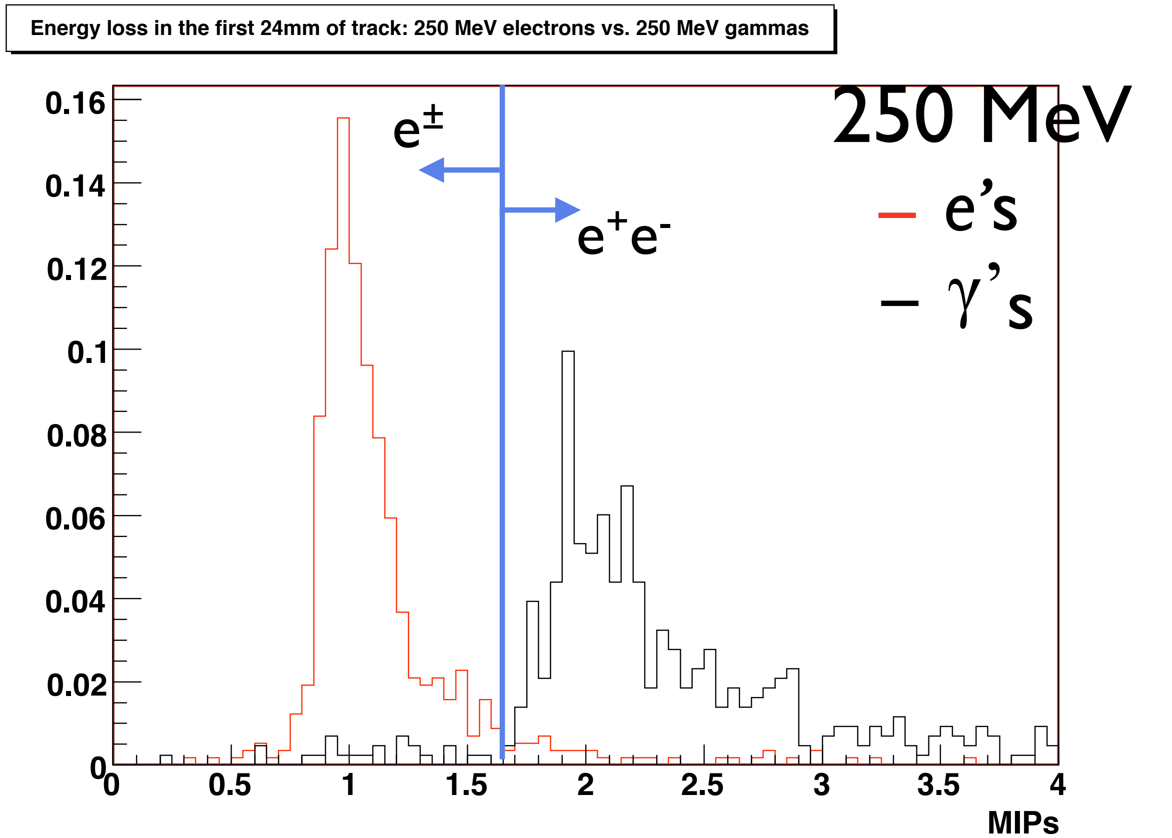
e/γ separation → reduced ν_μ induced backgrounds (NC π^0)

- 80% signal (CC ν_e) efficiency, ≈96% background (NC π^0) rejection
- Topological cuts will also improve signal/background separation
- PID from dE/dx (proton/pion/kaon/etc... separation)





ICARUS Event



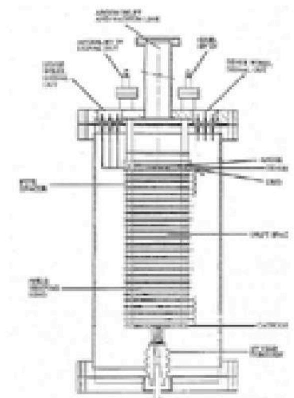
dE/dx for electrons and gammas in first 2.4 cm of track

LArTPC Challenges

- Purity level desired (ppt) is demanding.
  - Necessary to achieve long-drift (>5m)
  - Detector materials impact on purity must be understood.
- Safety issues (ODH hazards) when operating underground.
- Wire signals are small....electronics noise must be controlled.
- Vacuum/Cryogenic Environments take special care...

Current program of LArTPC development can address many of these challenges!

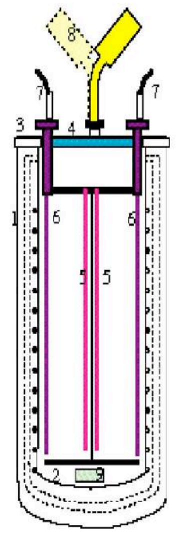
Liquid Argon in Italy



24 cm drift wires chamber

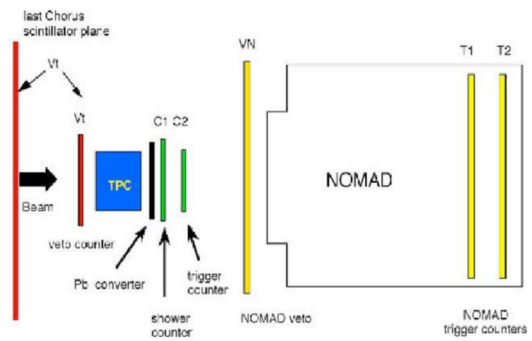
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

3 ton prototype



1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

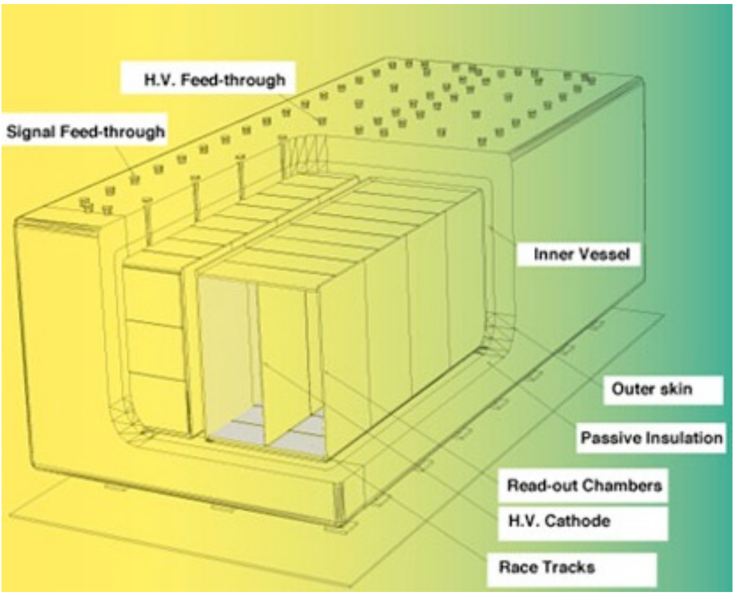
50 litres prototype
1.4 m drift chamber



1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m^3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.



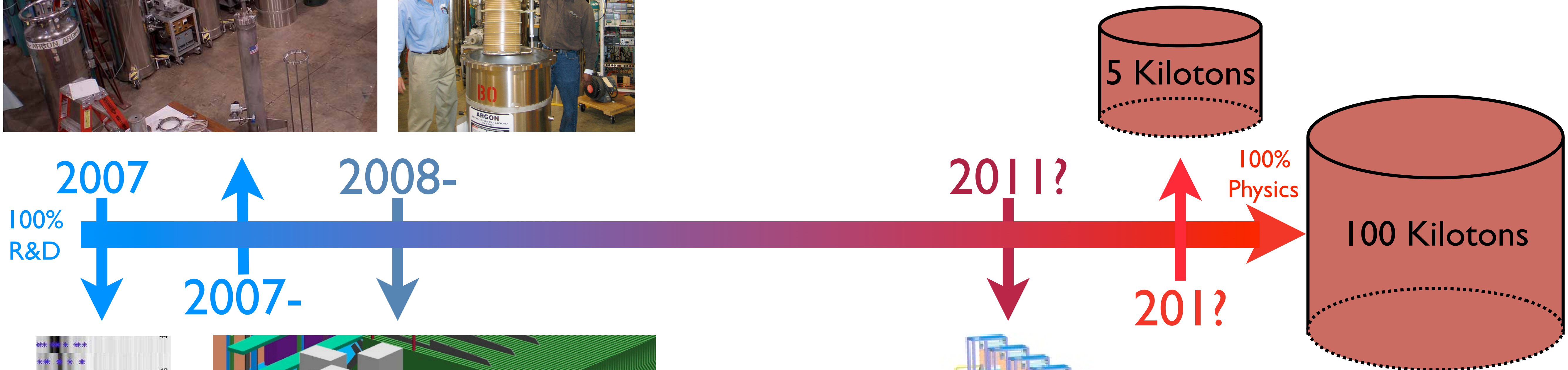
ICARUS T600

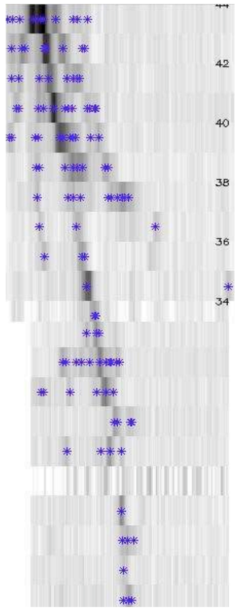
Liquid Argon in the U.S.

Materials Test Stand

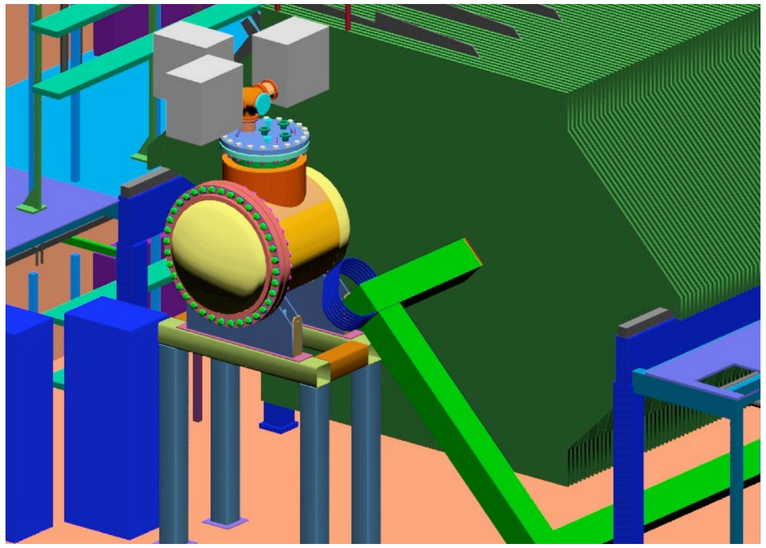
Bo

Rapid progress in LArTPC development

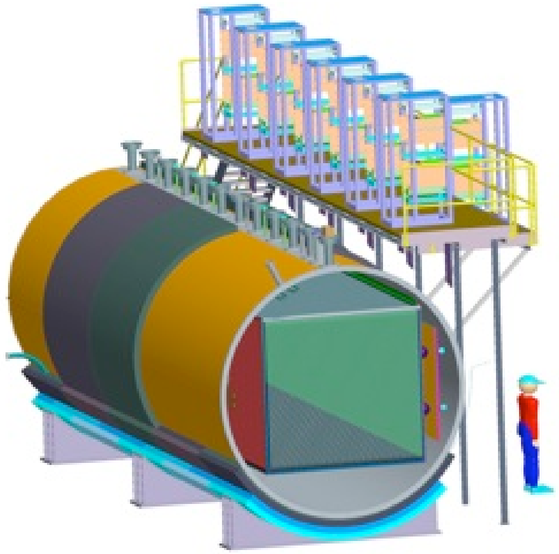




Yale Tracks



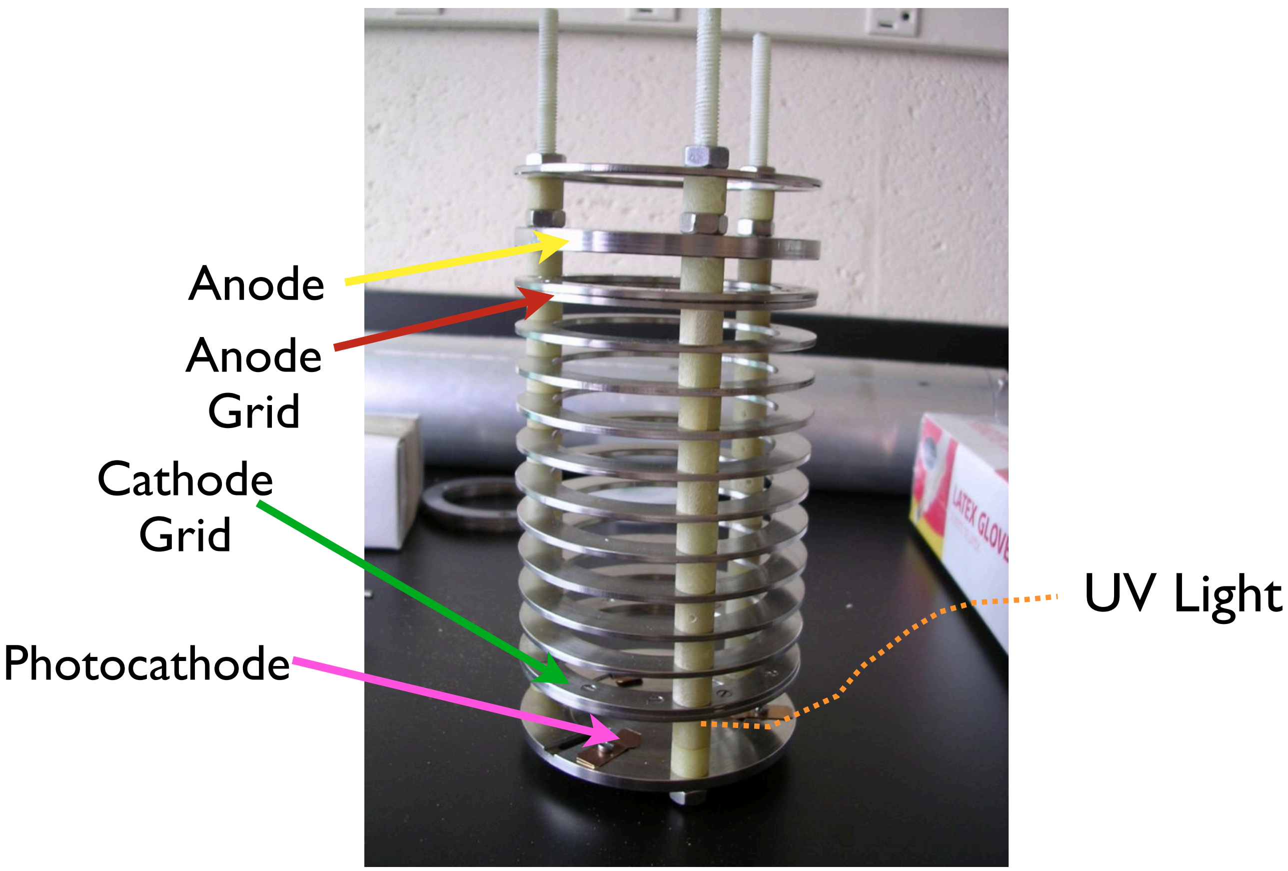
ArgoNeuT



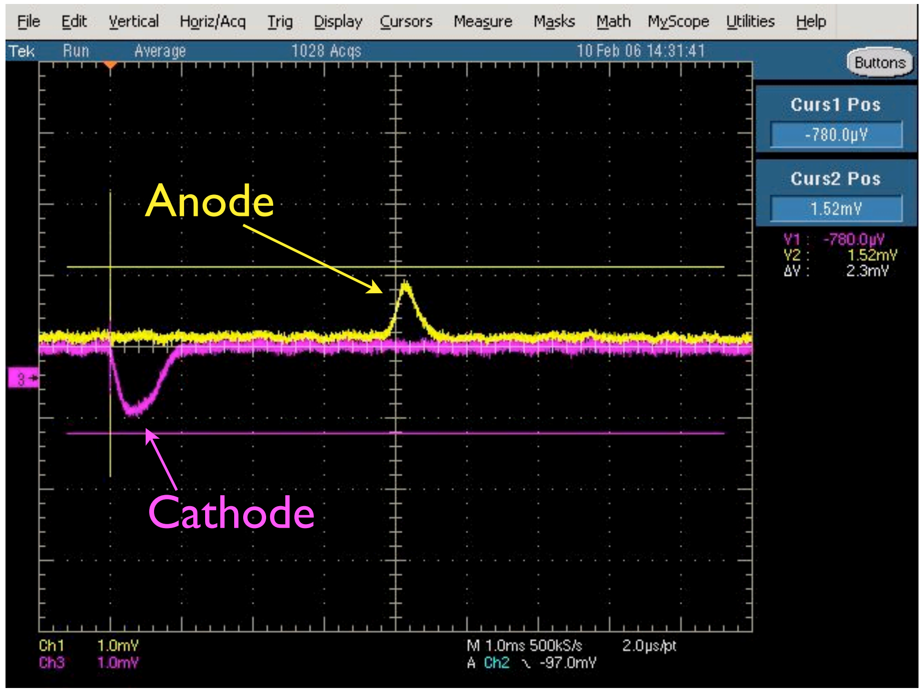
MicroBooNE

Argon Purity

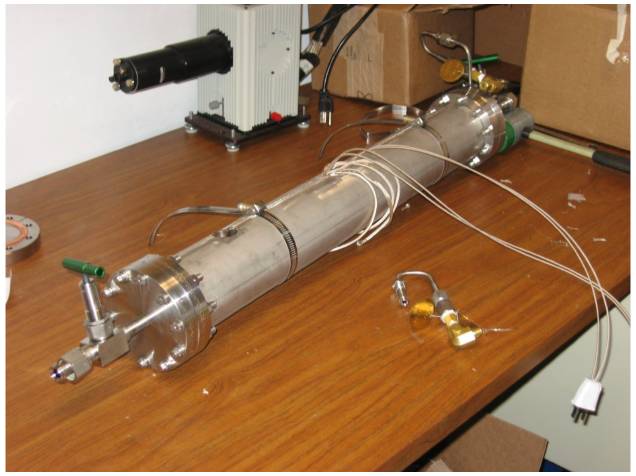
- To drift electrons through argon, impurities (Oxygen, Water, etc..) must be removed from delivered LAr to increase ionization electron lifetimes.
- Pass LAr through filter(s) to remove contaminants.
- Purity monitors used to measure charge absorbed after drifting through argon.
- Fermilab group has done extensive work to develop new filters and purity monitors.



ICARUS style Purity Monitor

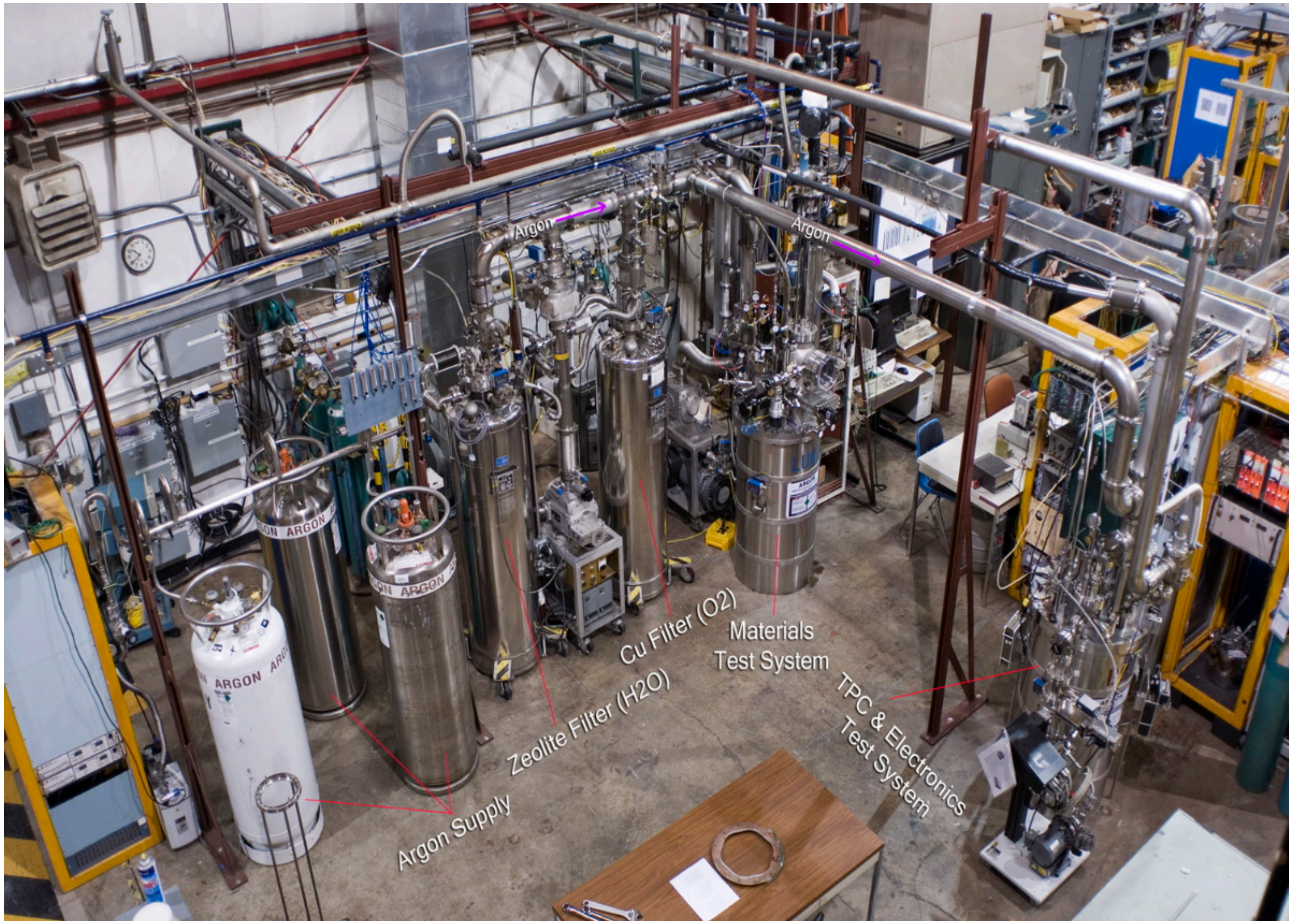


Very nice FNAL Purity signal (4ms)



TRIGON Filter

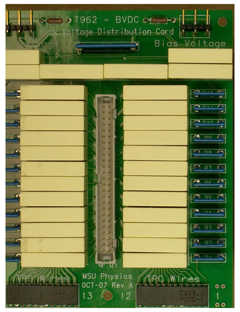
Materials Test System at Fermilab



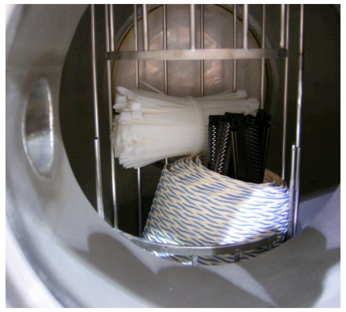
- A massive LArTPC will necessarily have large amounts of detector material, so controlling argon purity is vital.
- MTS is used to study the impact of different materials on argon purity.
- This facility also has a TPC test system for electronics.

Materials Test System at Fermilab

BNL 4-ch Amp

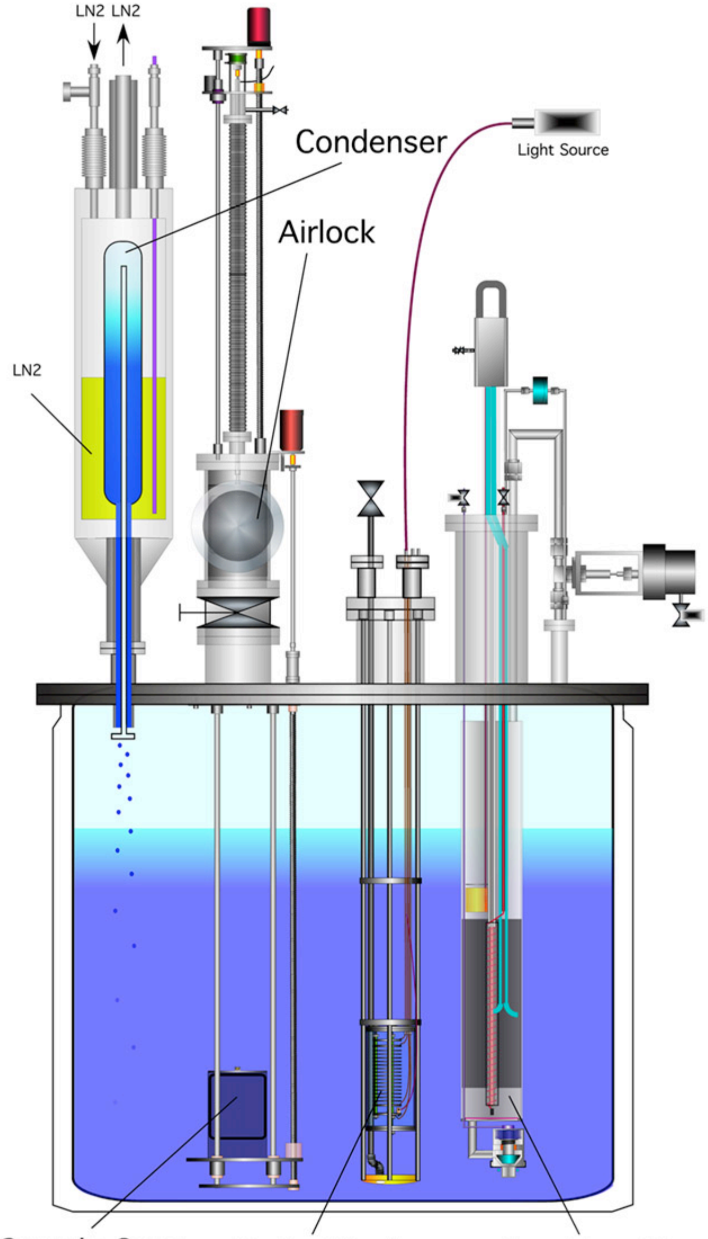


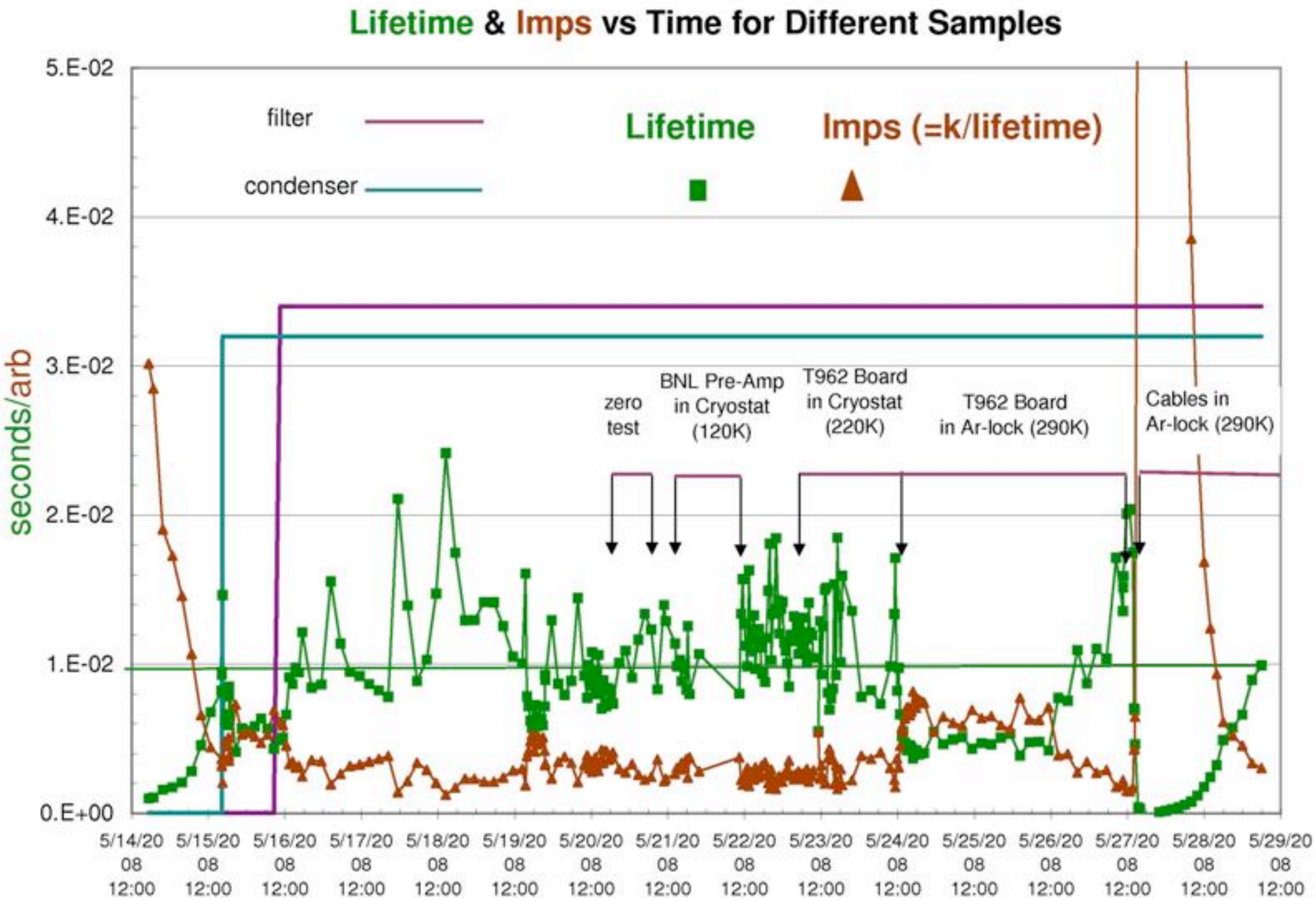
ArgoNeuT Bias Board



Cables/Cable-Tie Bundle

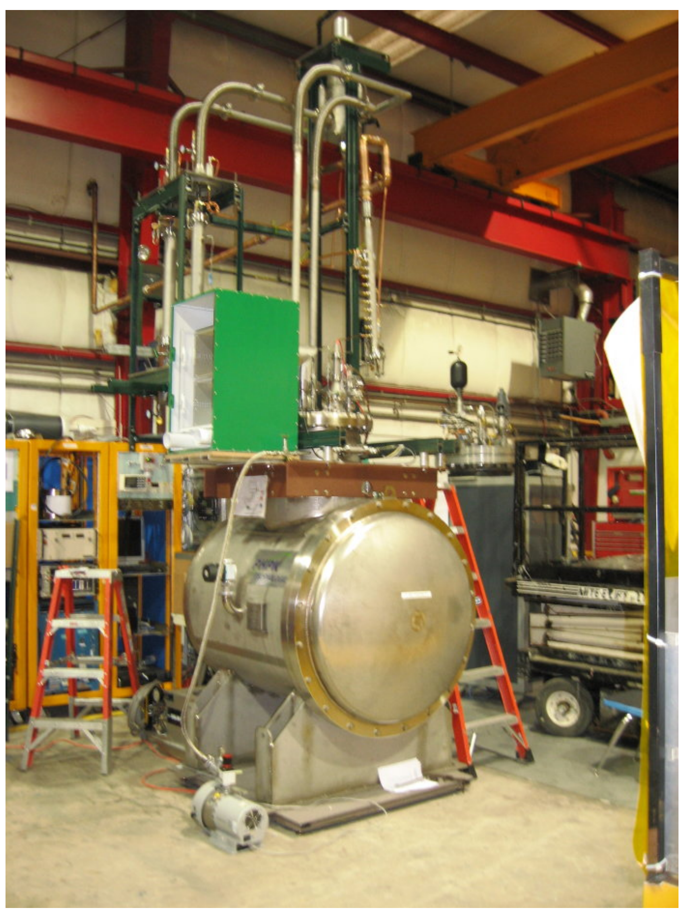
Measurements with the Materials Test System



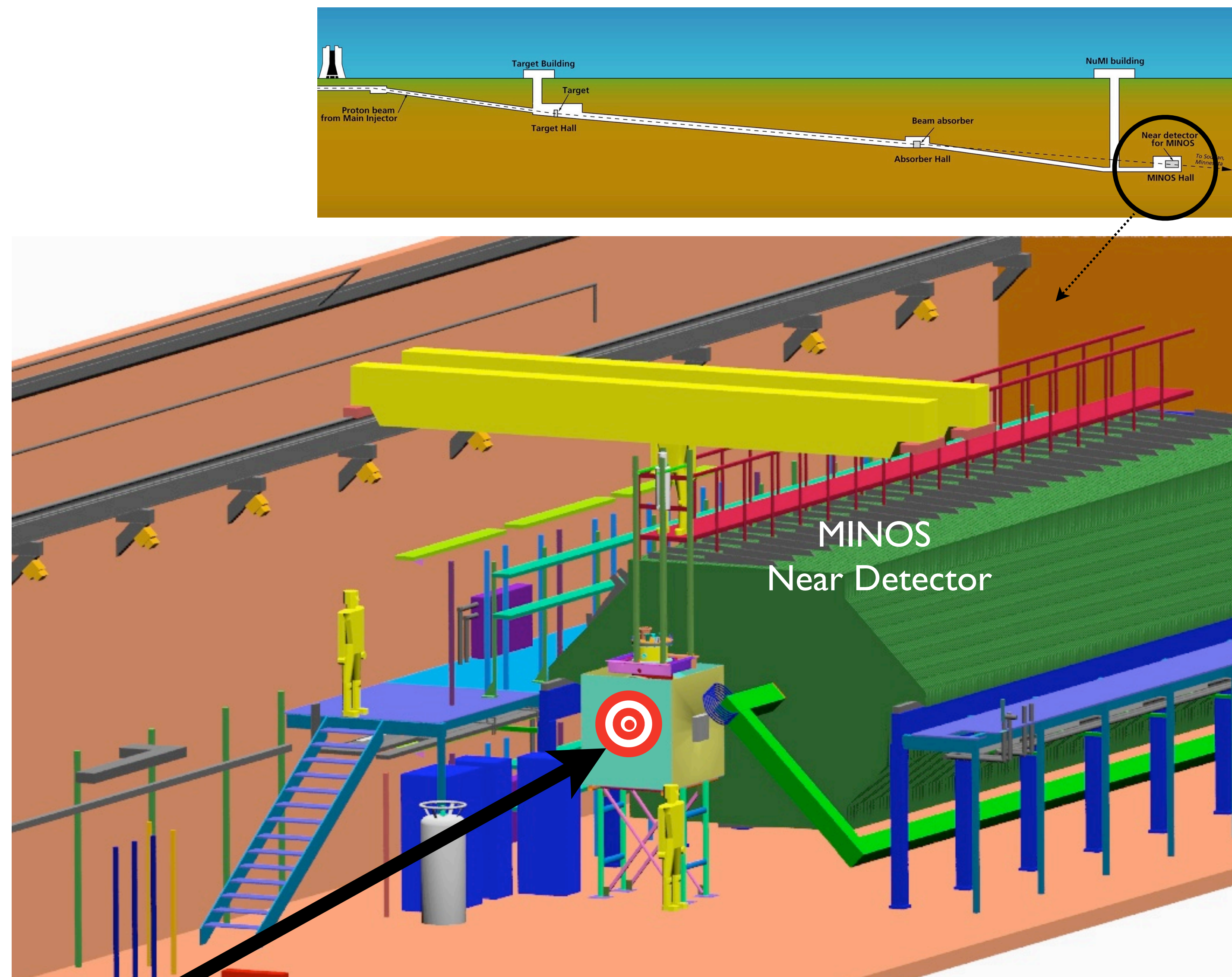


ArgoNeuT

- ArgoNeuT is a ~175 liter LArTPC (jointly funded by NSF/DOE)
- Will sit in front of MINOS near detector in NuMI beamline. Use MINOS as a range stack.
- Goals:
    - Gain experience building/running LArTPCs.
    - Accumulate a sample of 10000's neutrino events.
    - Confront many aspects of underground running and safety.
    - Develop simulation of LArTPCs and compare with data.
    - Measure CCQE cross-section



ArgoNeuT



NuMI Beam

NuMI Tunnel

ArgoNeuT: Collaboration

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University of L'Aquila

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Fermi National Accelerator Laboratory

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Gran Sasso National Laboratory

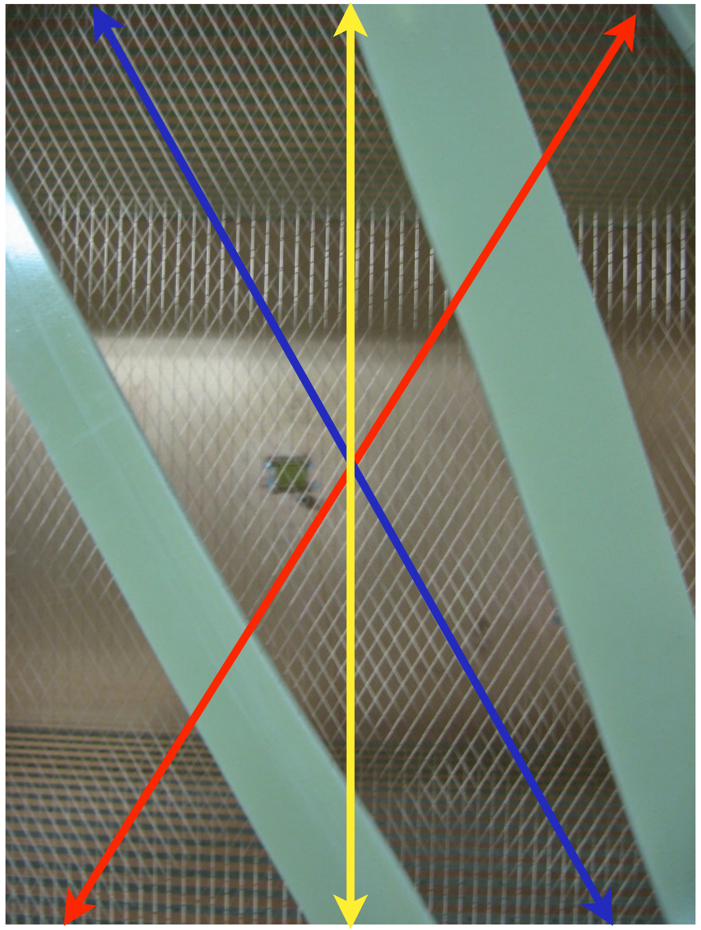
C. Bromberg, D. Edmunds, P. Laurens, B. Page
Michigan State University

S. Kopp, K. Lang
The University of Texas at Austin

C. Anderson, B. Fleming*, S. Linden, M. Soderberg, J. Spitz, T. Wongjirad
Yale University

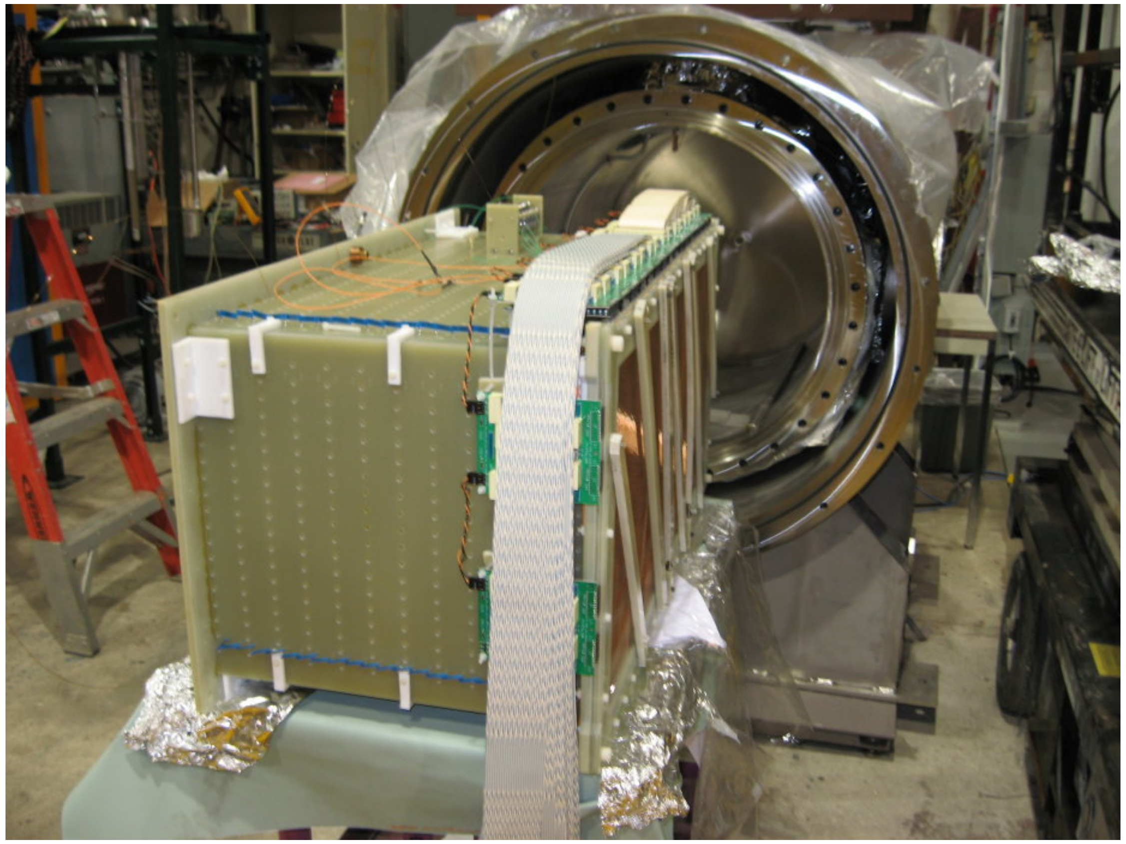
ArgoNeuT: TPC

- 175 liter active volume, 480 channels of signal.
- Collection, Induction2, Induction1 planes. Induction1 plane not read out.
- 4mm wire pitch, 4mm plane spacing.
- 500V/cm electric field.
- Max. drift of ~50cm.
- Bias voltage distribution boards located directly on TPC.
- 0.15mm diameter BeCu wire. Cu-clad G10 used for field cage.



±60° wires

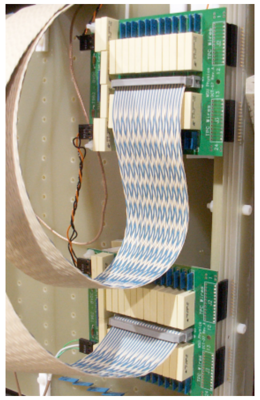
Wire Orientations



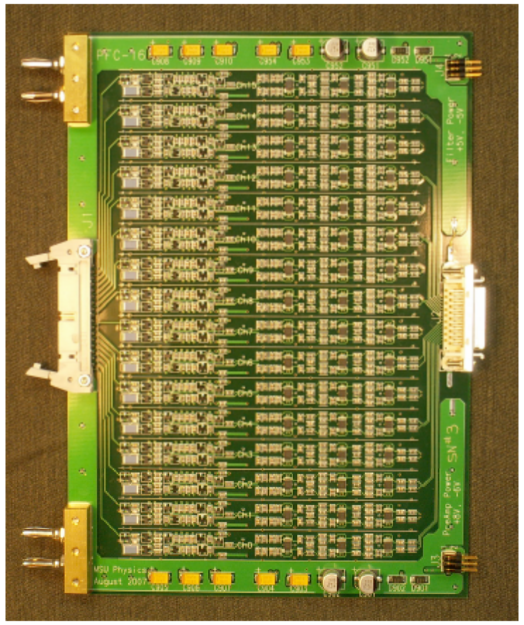
TPC About to Enter Cryostat

ArgoNeuT Electronics

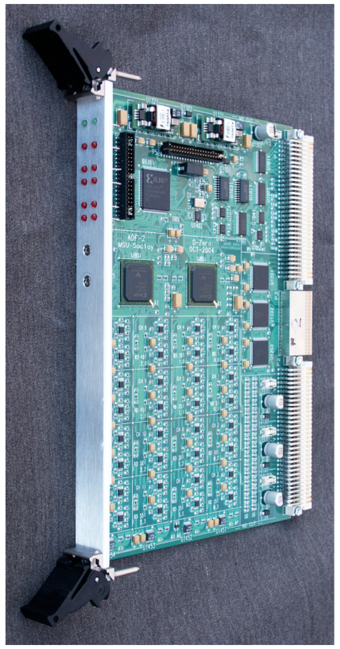
- Electronics for ArgoNeuT (480 channels)
  - Bias voltage distribution & blocking on the TPC
  - FET preamplifier similar to D0/ICARUS front-end
  - Wide bandwidth filtering (10 - 200 kHz, now)
    - Full information on most hits/tracks
    - Employ DSP to extract hit/track parameters
  - ADF2 card, sample at 5 MHz, 2048 samples/channel
  - Minimize noise sources
    - Double shielding of feed-through and preamplifiers
    - Remote ducted cooling
    - Extensive DC power filtering



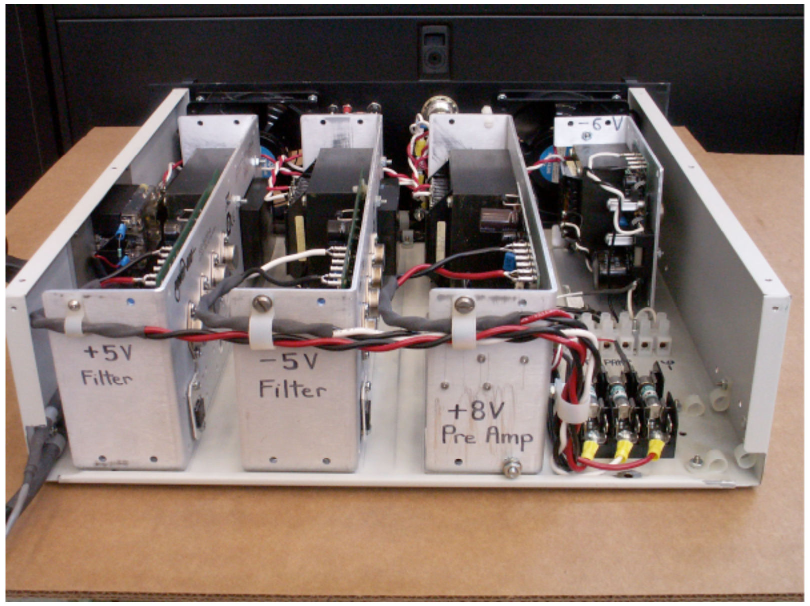
Bias Voltage R & C



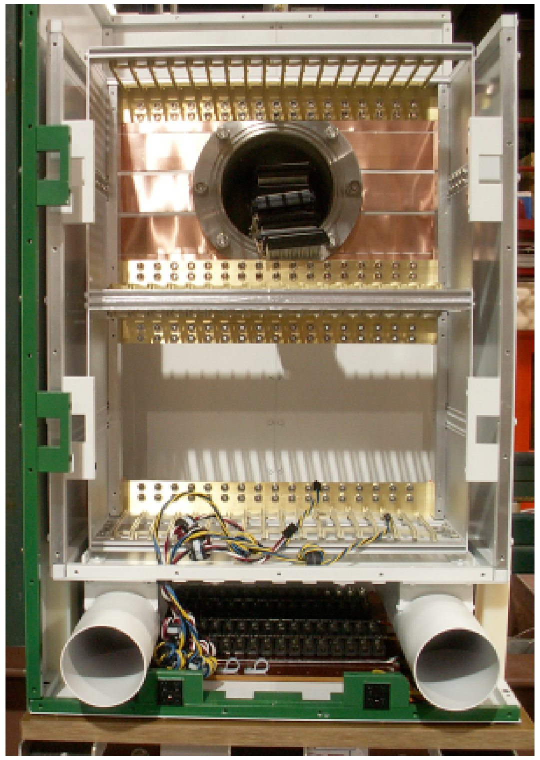
Preamp & filters



ADF2



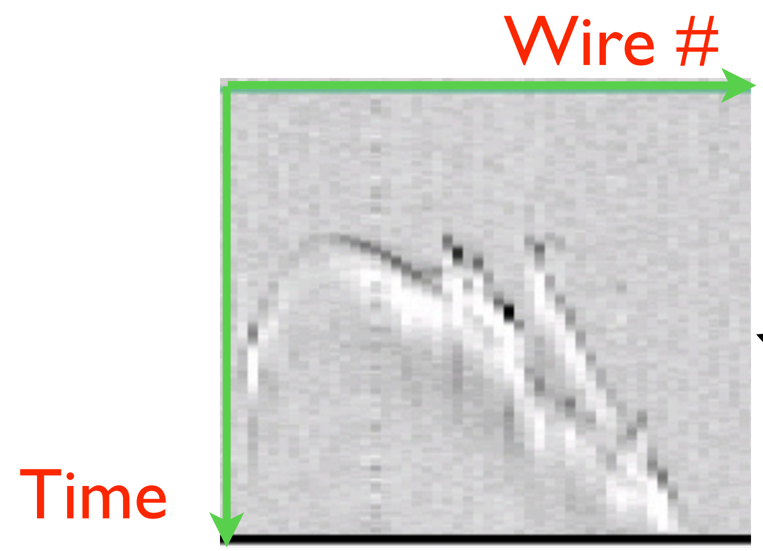
Custom power supply



RF shielding & preamp cooling

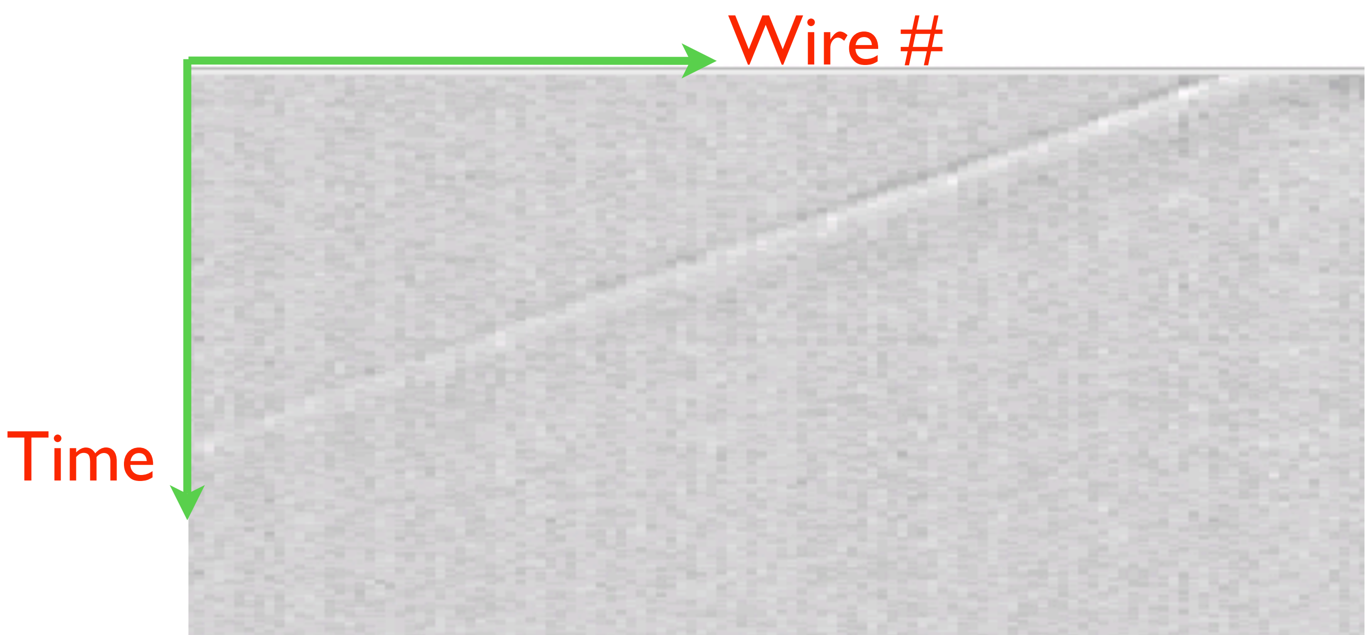
ArgoNeuT: Commissioning

- ArgoNeuT is just ending its commissioning run (~4 weeks above ground)
- We have collected many cosmic-ray events using a simple coincidence trigger.
- System has been very stable during this run!
- Plan to fix/upgrade a few items and begin move underground.

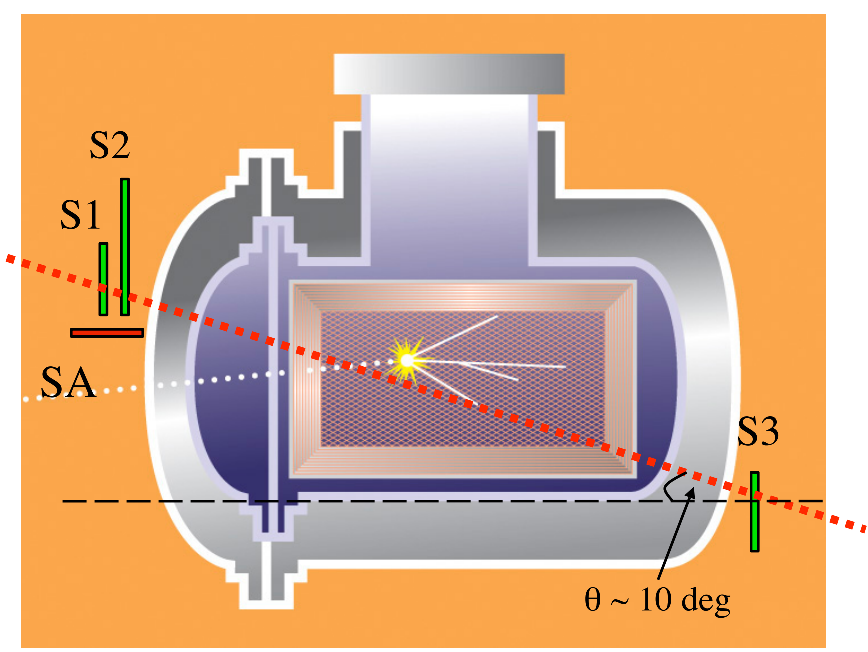


Collection View of 1st ArgoNeuT event

Event Type	# in 180 days (1.4×10^{19} PO)
ν_μ CC	28800
$\overline{\nu_\mu}$ CC	2520
ν_e CC	540
NC	9720



Induction View of Cosmic muon event

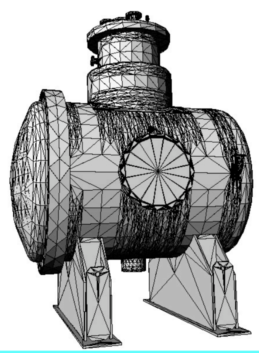


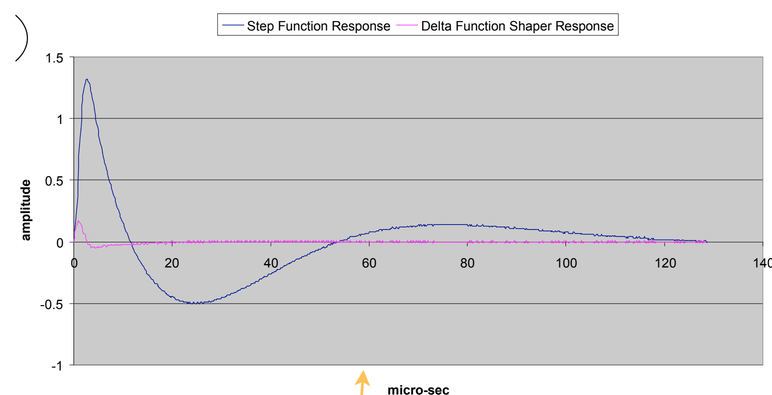
Cosmic Trigger for Commissioning

ArgoNeuT: Simulation

- ArgoNeuT members (M. Antonello, B. Baller, Yale group, etc...) developing GEANT3/4 simulations for LArTPCs
- Simulation is general purpose for future LArTPCs.
- Goal is automated event reconstruction

CAD geometry in GEANT4





Neutrino Generator Interface

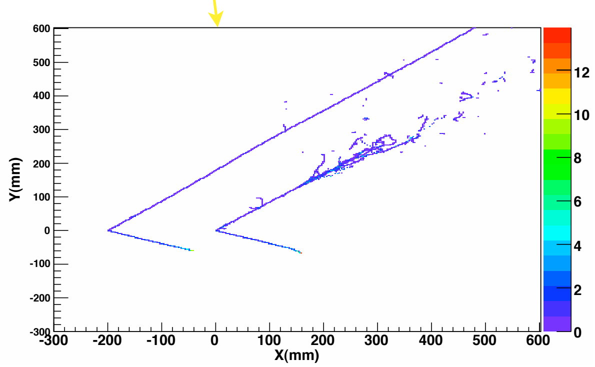
Geometry Description

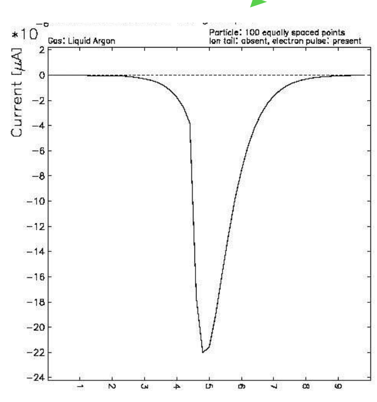
Pulse Formation

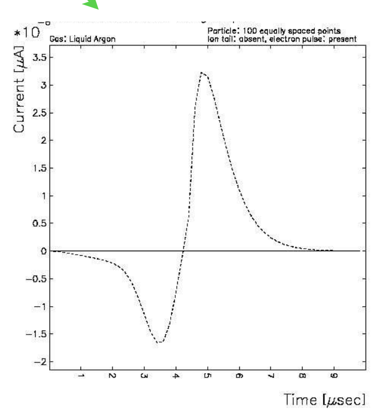
Electronics Simulation

Signal Processing

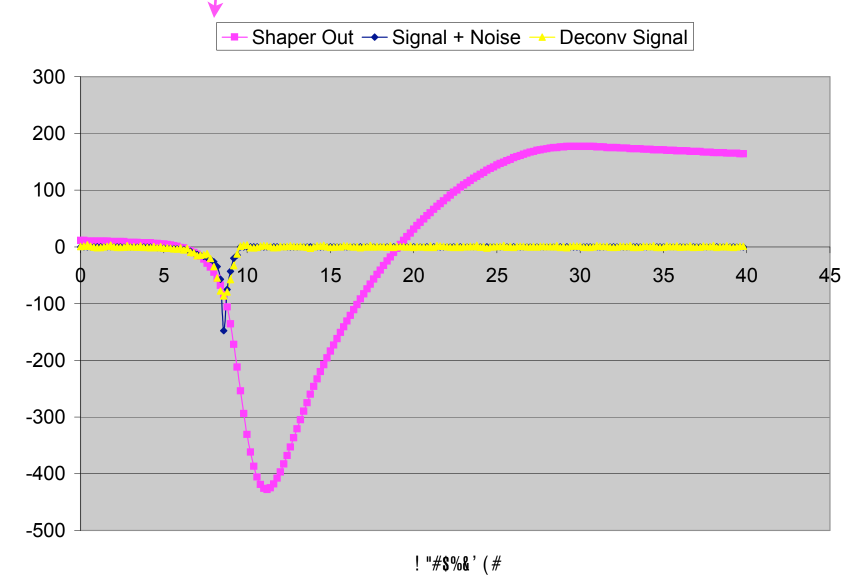
Automated Reconstruction







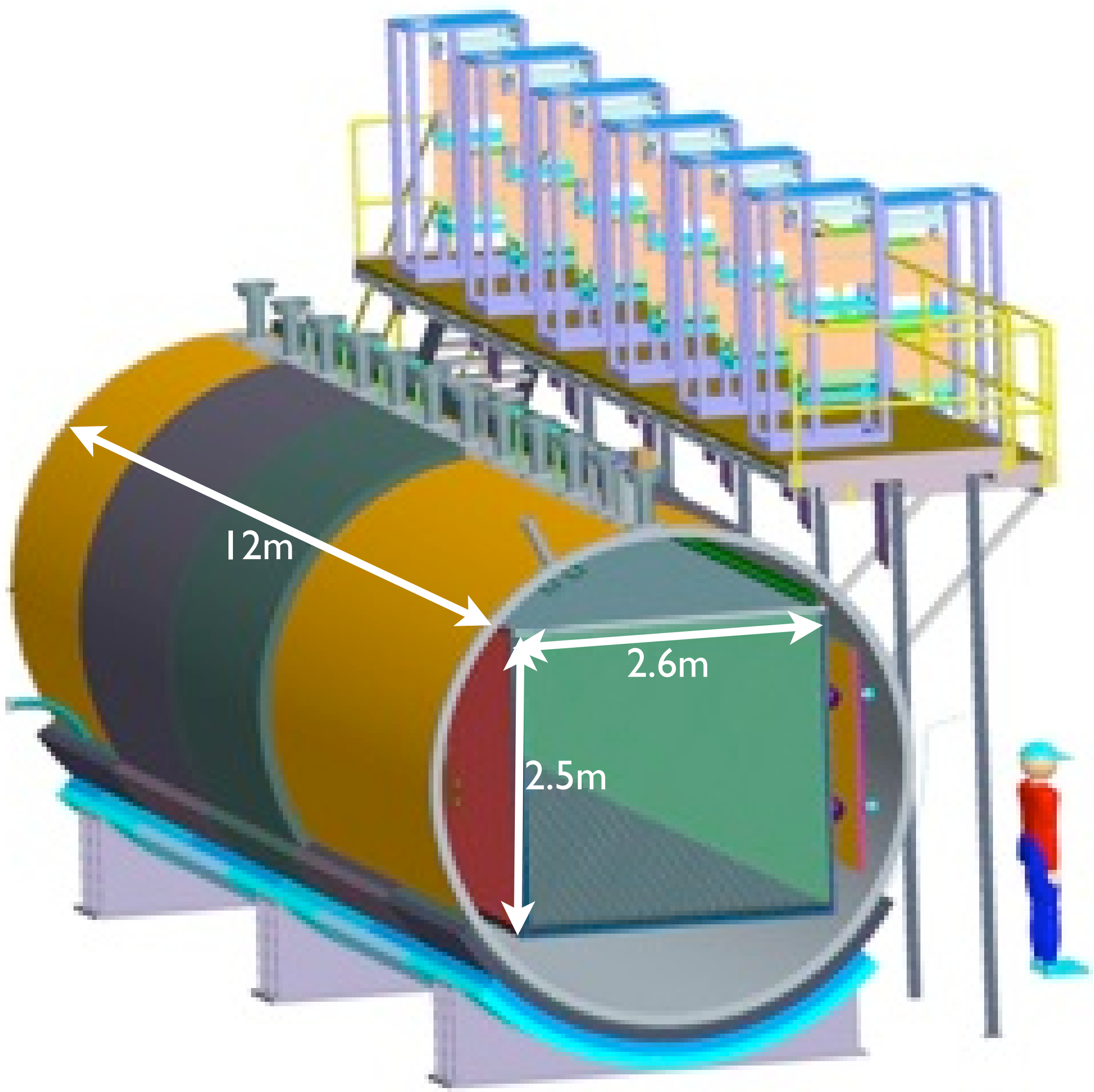
Collection/Induction Signals



MicroBooNE

- MicroBooNE is a proposed Liquid Argon Time Projection Chamber (LArTPC) detector to run in the on-axis Booster and off-axis NuMI beam on the surface at Fermilab.
- Combines timely physics with hardware R&D necessary for the evolution of LArTPCs.
  - Cold Electronics
  - Long Drift
  - MiniBooNE excess
  - Low-Energy Cross-Sections
  - etc...

Stage 1 approval from Fermilab directorate in June!



➡ Joint NSF/DOE Project
➡ NSF MRI for TPC and PMT systems

MicroBooNE Collaboration

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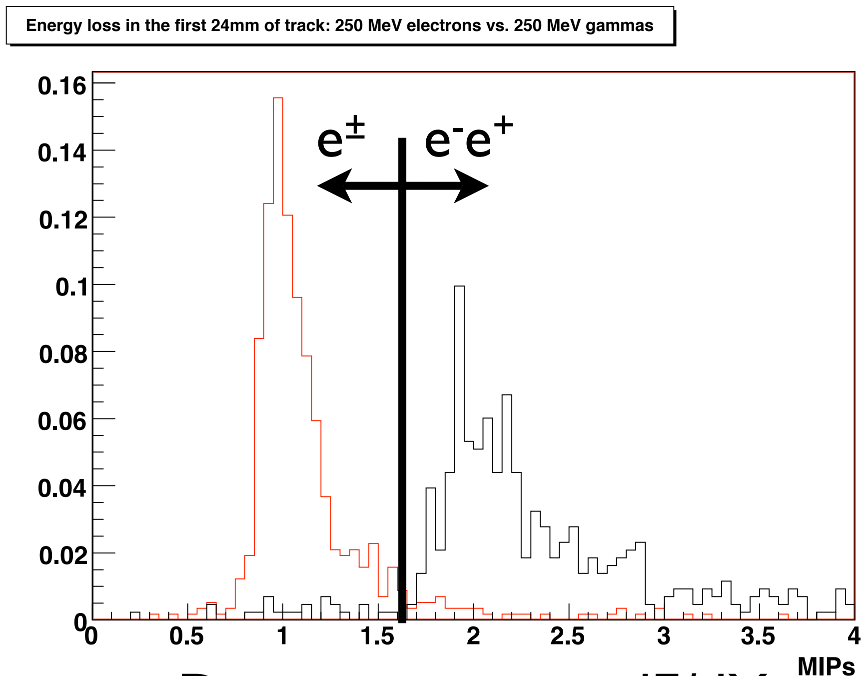
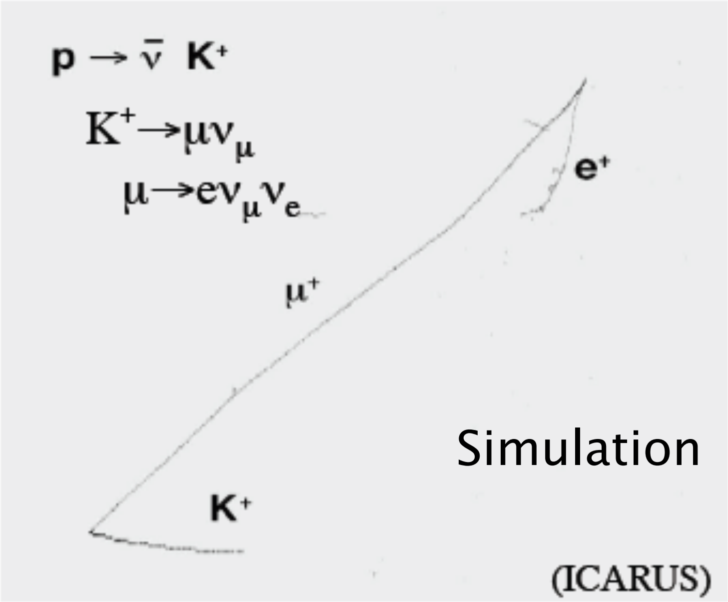
MicroBooNE: Physics Goals

- Address the MiniBooNE low energy excess
- Utilize electron/gamma tag (using dE/dX information).
- Low Energy Cross-Section Measurements (NC π^0, $\Delta \rightarrow N\gamma$,Kaon production, Photonuclear, ...)
- Use small (~500) sample of Kaons to study proton-decay sensitivity.
- Develop automated reconstruction.



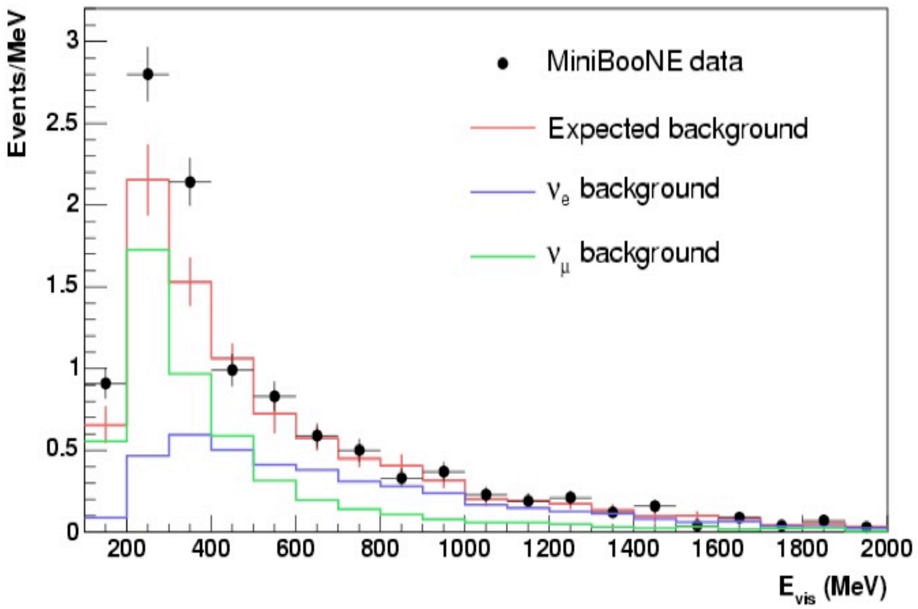
Discrimination via dE/dX



MiniBooNE Result Excess

200-300MeV: 45.2±26.0 events

300-475MeV: 83.7±24.5 events



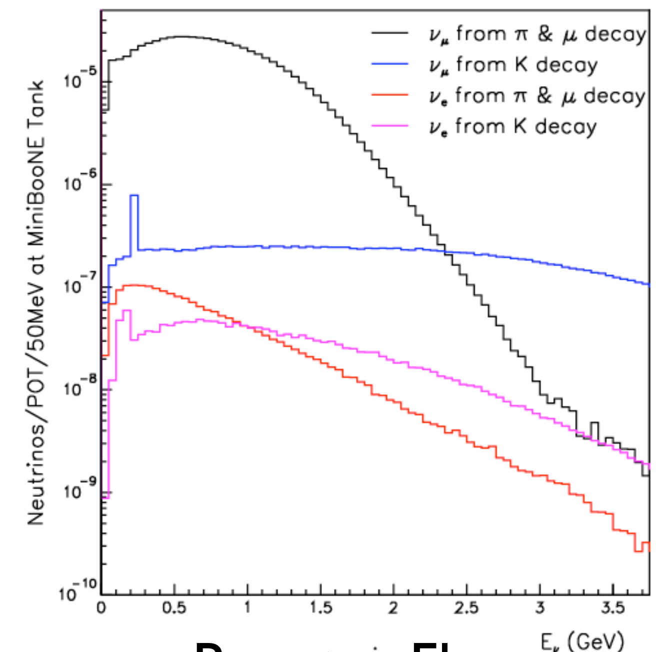
MicroBooNE will have 5σ significance for electrons, 3.3σ for photons

MicroBooNE: Location

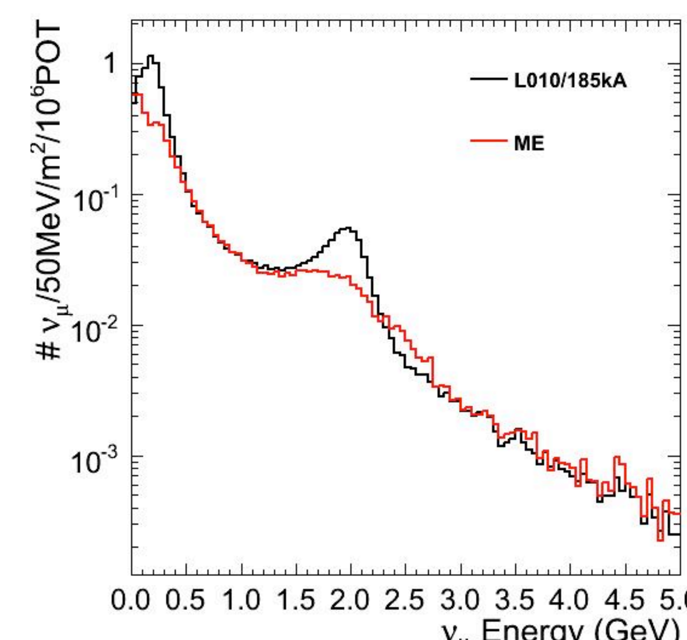
- MicroBooNE will sit on surface in on-axis Booster beam, and off-axis (LE) NuMI beam.

	BNB	NuMI
Total Events	100k	60k
ν_μ CCQE	39k	21k
NC π^o	8k	7k
ν_e CCQE	250	1.7k
POT/year	$6\text{x}10^{20}$	$4\text{x}10^{20}$

Expected Event Rates for 2-3 year run.



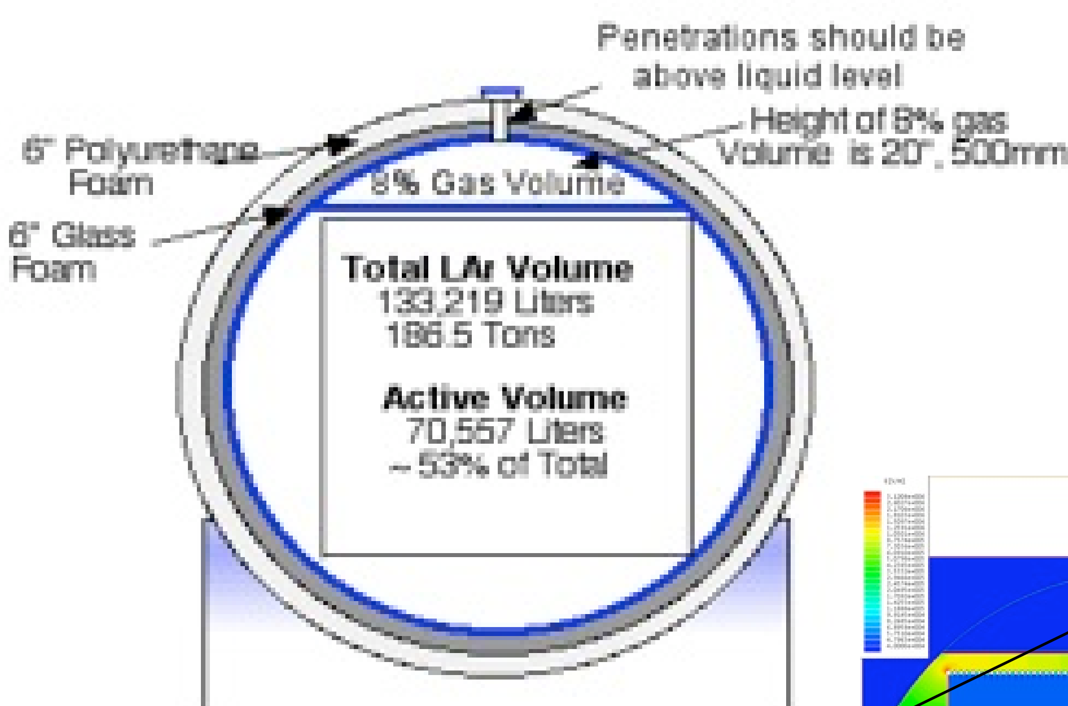
Booster Flux

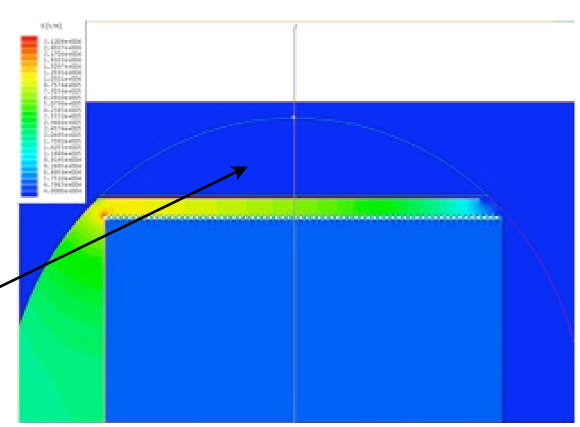


NuMI Flux

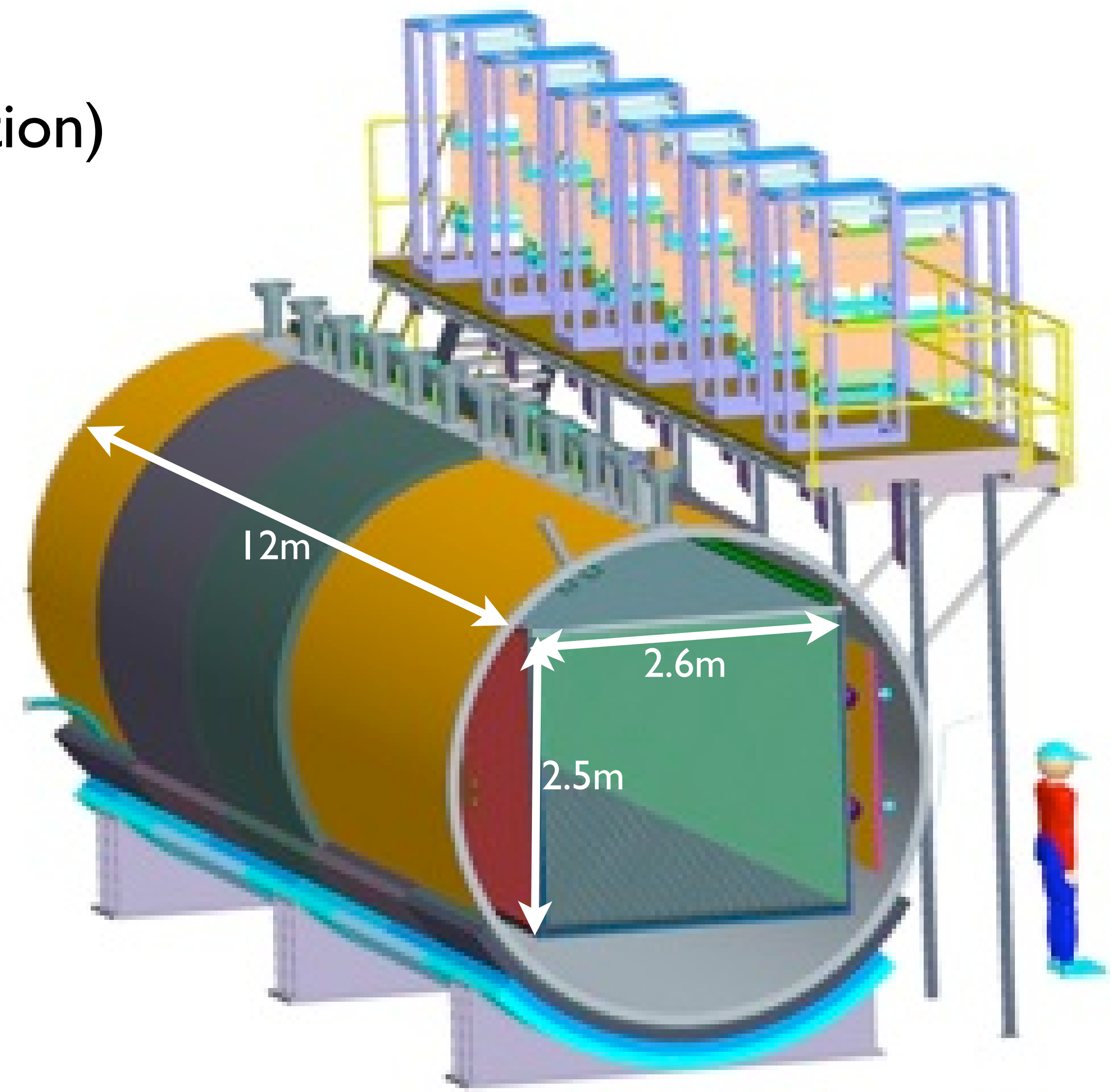
MicroBooNE: Design

- Cryostat (170 Tons LAr) as large as can be commercially built offsite and delivered over the roads.
- Evacuable vessel with foam insulation.
- To sit on surface in on-axis Booster beam, off-axis NuMI beam.
- TPC parameters
  - 70 Ton fiducial volume
  - ~2.5m drift (500V/cm)
  - 3 readout planes (±60° Induction, vertical Collection)
  - 10000 channels (using Cold Preamplifiers)
- 30 PMTs for triggering
- Purification/Recirculation system.





PreAmps in cold gas



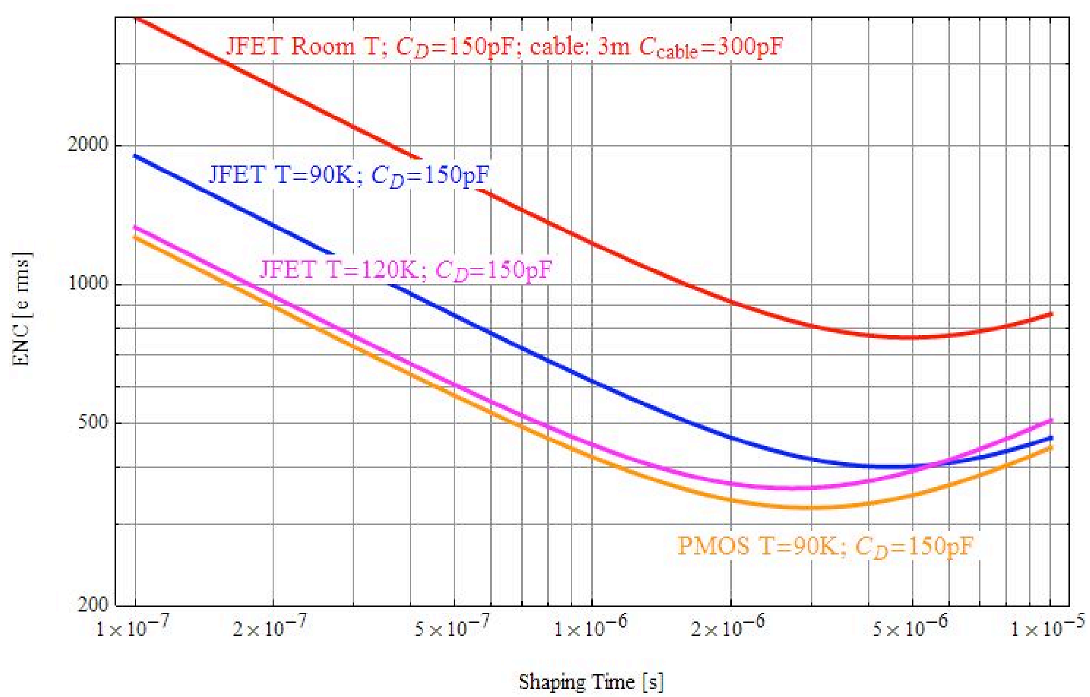
MicroBooNE: Hardware R&D

MicroBooNE will undertake R&D in two overlapping phases

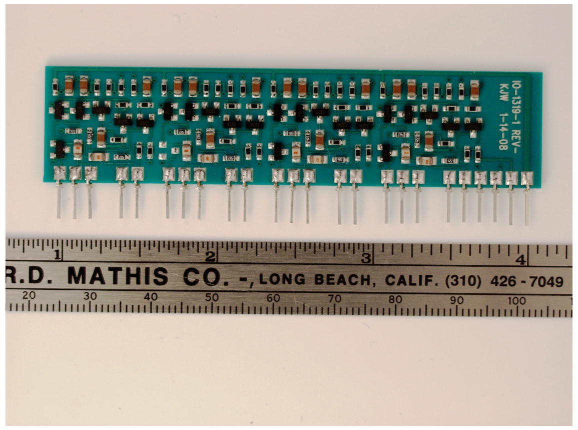
- Phase 1: Initial design relevant to MicroBooNE detector (previous slide).
- Phase 2: R&D for next generation LArTPCs
  - Cold Electronics: Next slide.
  - Purity Test: Purge vessel with argon gas, then fill with liquid, to see if high-purity liquid can be achieved without initial evacuation. Very massive LArTPCs will most likely not be evacuable, so purging will be necessary.
  - Long drift (2.5m): though not as long in massive LArTPCs, will test purity and reconstruction schemes.
- **Real data essential to understanding hardware performance!**

MicroBooNE: Cold Electronics

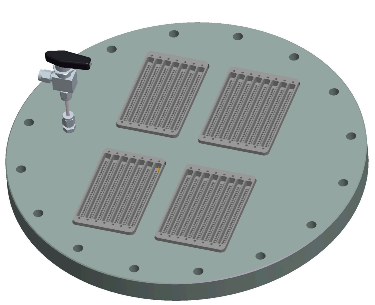
- Preamps will be placed inside of cryostat.
- x3 better S/N compared with room temperature performance.
- Necessary step along the path to large detectors where signals must make long transits.
- Many future Hardware questions can be answered by MicroBooNE.
  - JFET/CMOS performance (~4 year development required for CMOS).
  - Maintaining purity with electronics inside tank.
  - Heat load due to power output of electronics in tank.
  - Multiplexing signals.



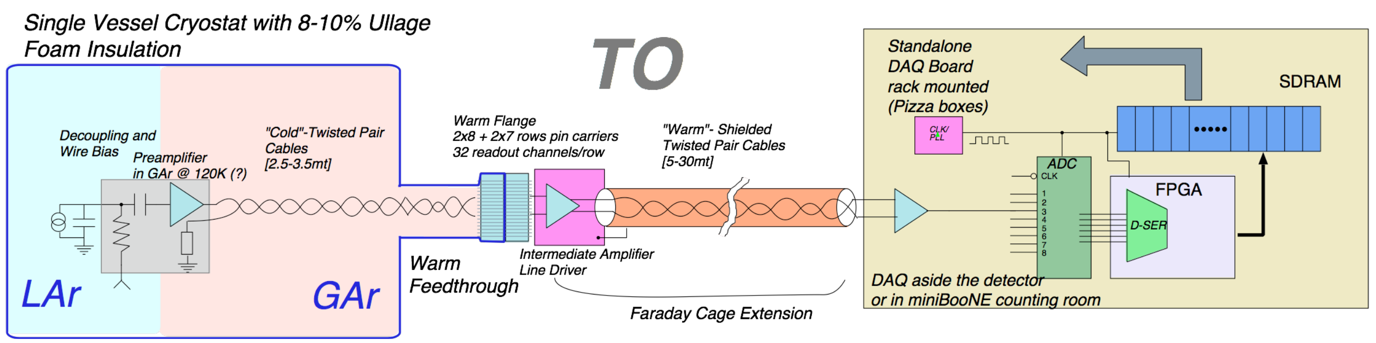
JFET (T=120 K)/pMOS (T=90K) have similar S/N performace



Quad-channel Pre-Amp prototype



ATLAS style feedthrough



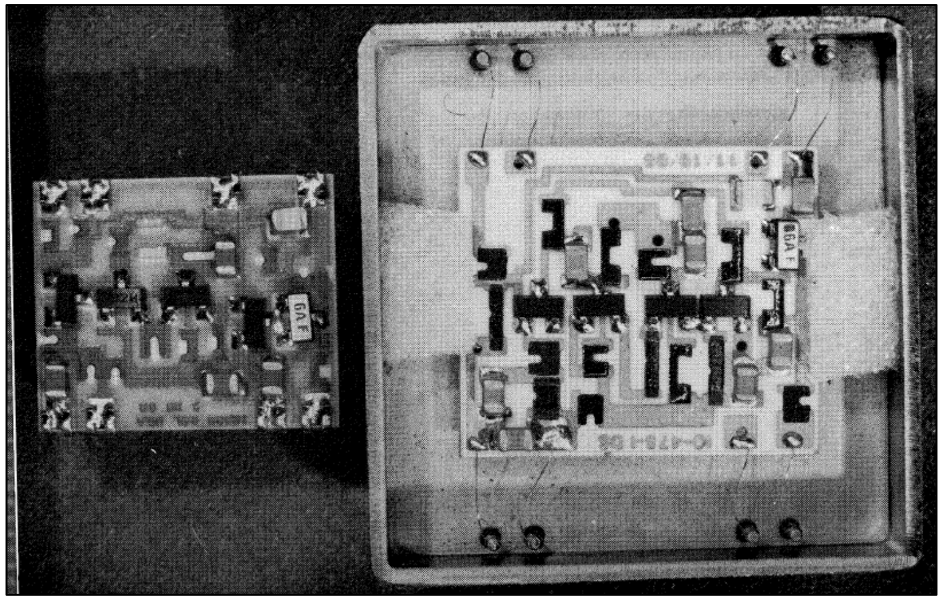
Readout Chain

MicroBooNE: Cold Electronics

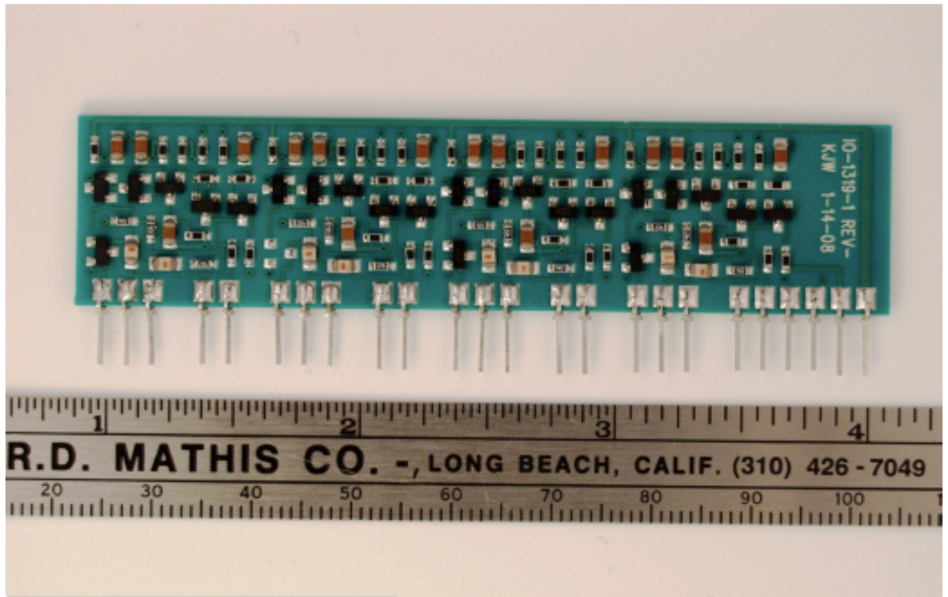
Cryogenic Front-End based on on JFET

- Technology mature and available as of today
  - Reliability issues requires a careful choice of component and high-reliability assembly
  - Ceramic hybrid with co-fired traces and surface mount components properly tested
- Several years of experience
- Helios-NA34:
  - 576 preamplifiers
  - Operations: 4 years, multiple cool-downs
  - Failure: 1
- NA48:
  - Preamplifiers in LAr: 13,000
  - Operated at very high voltage
  - Failures: ~50 because of a HV accident in 1998. Negligible failures after that
  - Always kept at cryogenic temperature

Late 80's

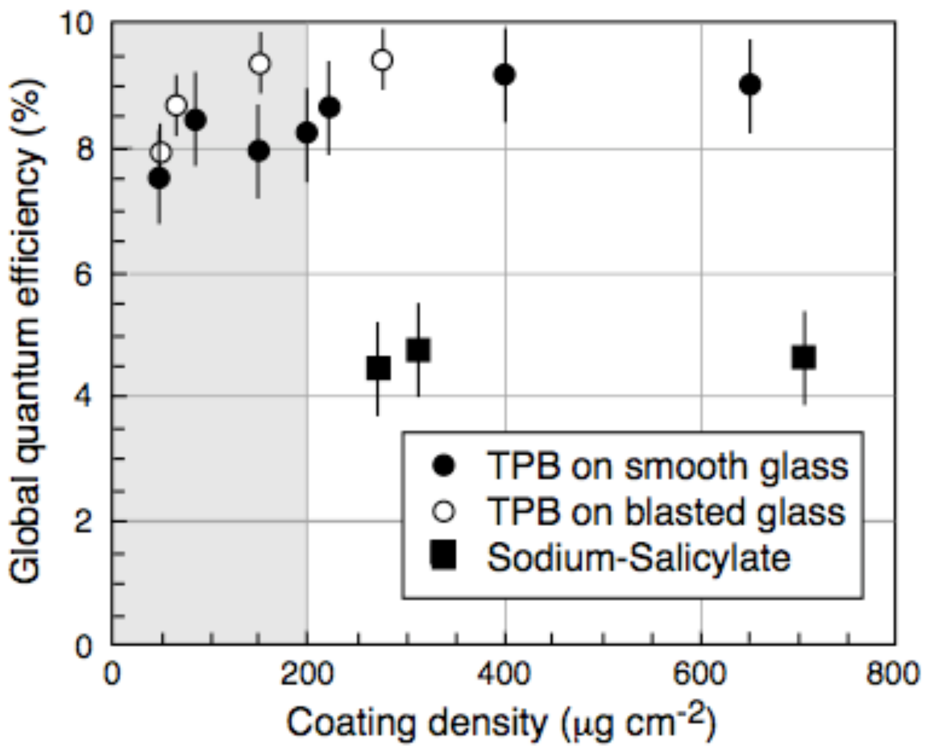


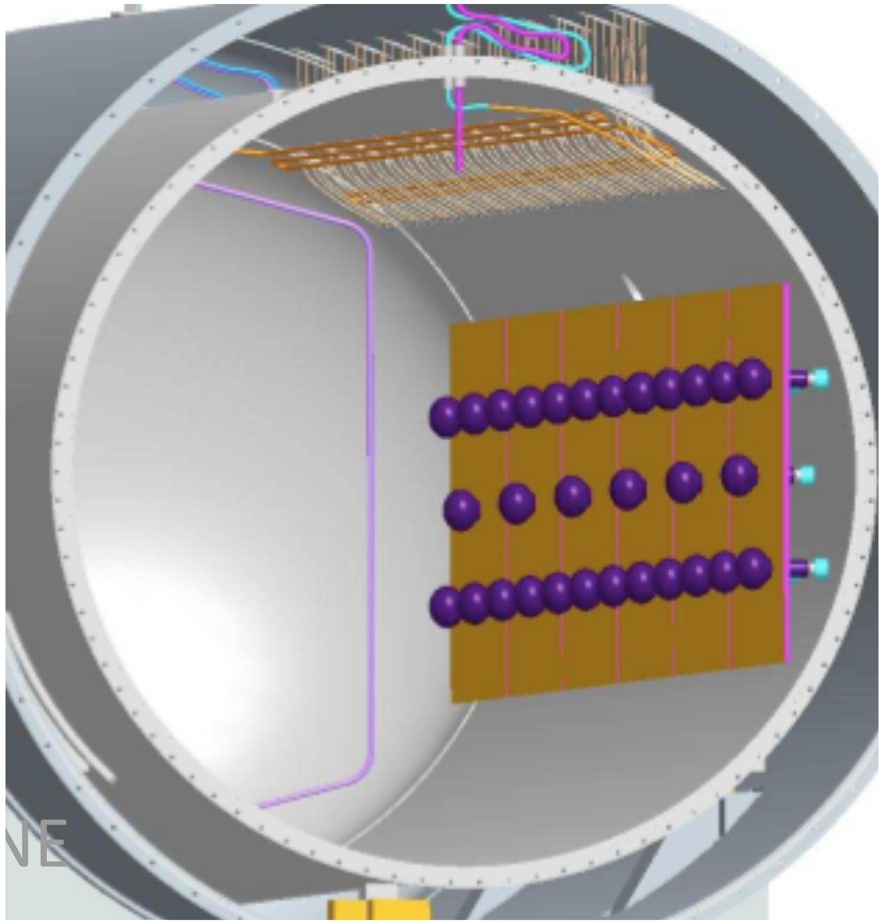
2008



MicroBooNE: Light Collection

- 30 PMTs to aid in t_0 determination.
- Most likely will use tubes from Hamamatsu (ETL seems to be out of business?)
- Coated with wavelength shifter (TPB = tetraphenyl-butadiene) to allow collection of VUV light.
- Design work on Holder/geometry/feedthroughs/etc.. ongoing.



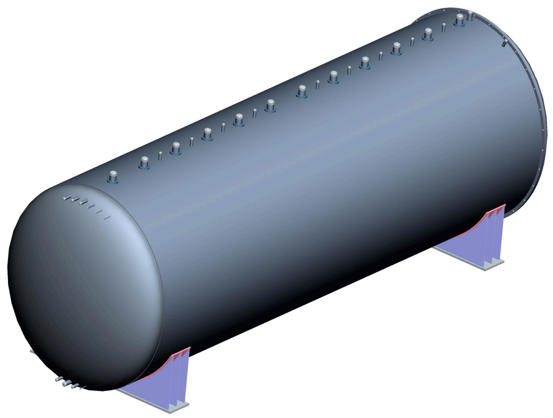


30 PMTs facing TPC

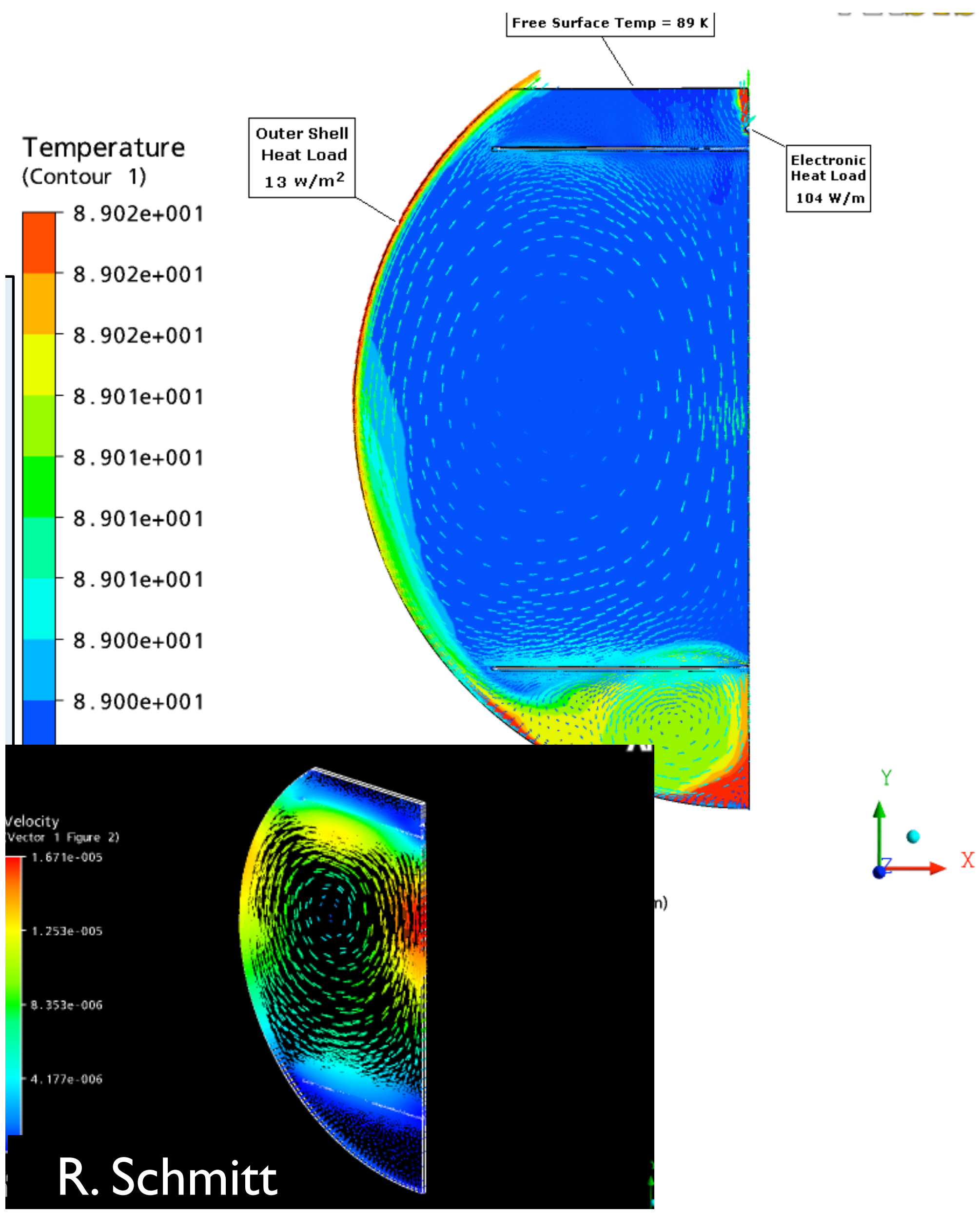
8” 9357FLA Electron Tubes PMT

MicroBooNE Cryogenics

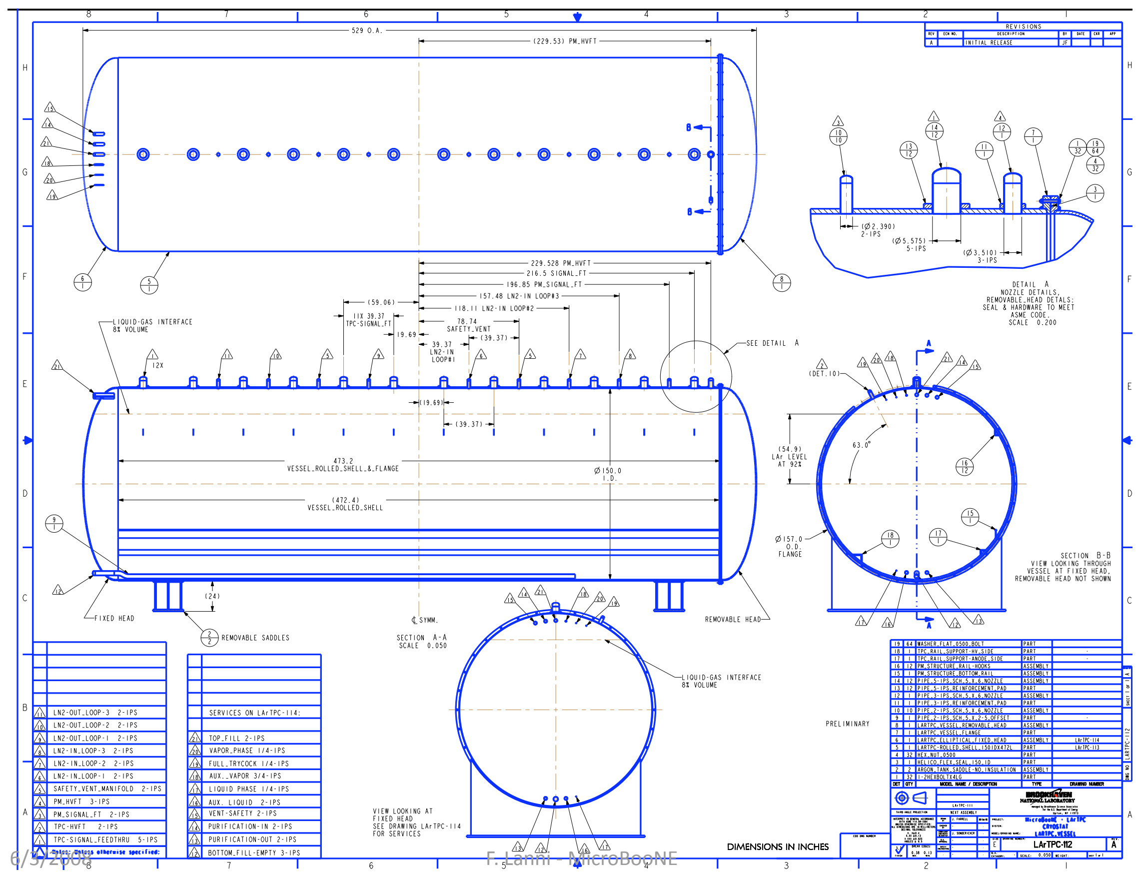
- Preliminary studies have been performed to understand thermal load of system.
- ~16 inches (~40 cm) glass foam insulation
- 3.4kW total load (13W/m^2)
- Temp. gradient <<0.1K   - crucial to reducing track distortions.



Cryostat with feedthroughs on top



Temperature/velocity distrubtions

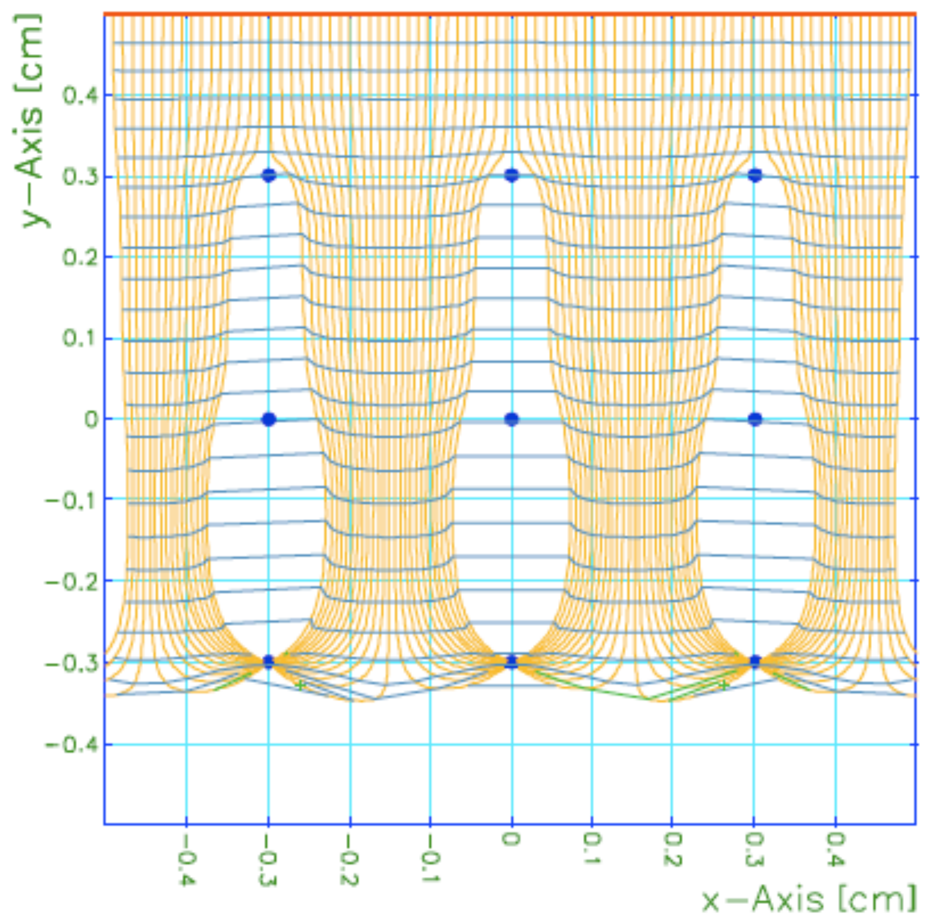


MicroBooNE: Wire Bias Voltage

- 3 wireplanes act as an electrostatic grid.
- Transparency is a function of electric fields before/after each plane.
- Choose bias voltages to keep constant field up to first induction plane, then maximum transparency between planes.

MicroBooNE bias voltages:

V1 = −205V
V2 = 0V
V3 = 440V



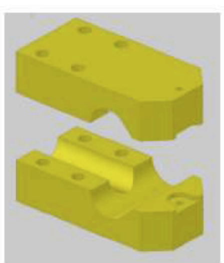
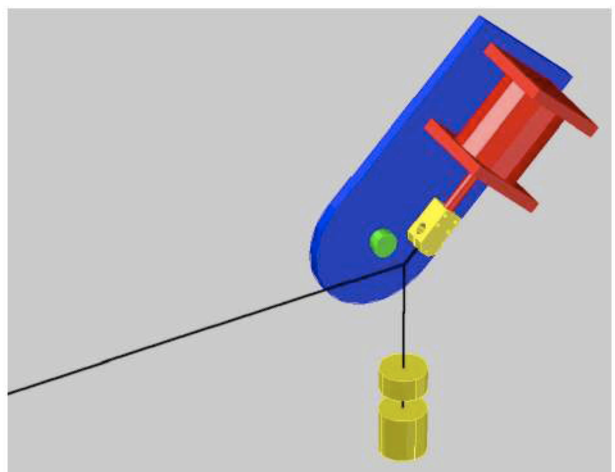
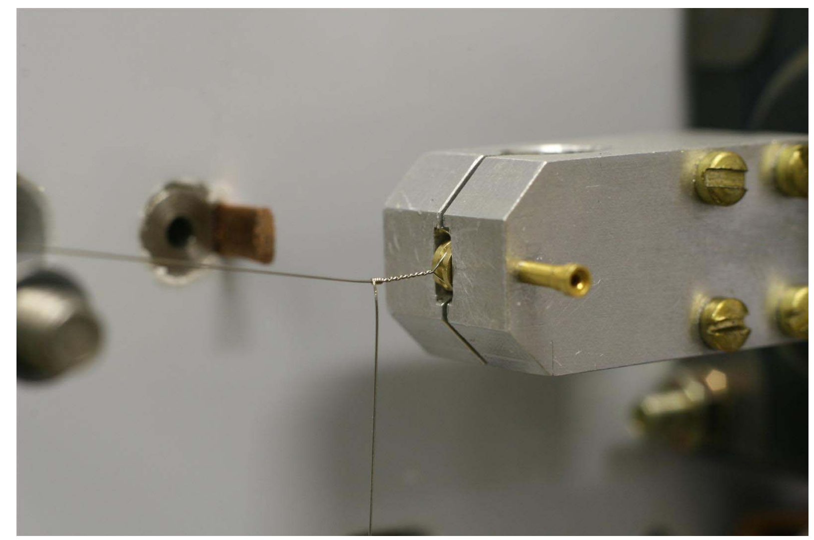
100% Transparency Condition:

$$\frac{E_2}{E_1} \geq \frac{1+\rho}{1-\rho} > 1.37 \qquad \rho = \frac{2\pi r}{d}$$

r=0.15mm
d=3mm

MicroBooNE Wire Properties

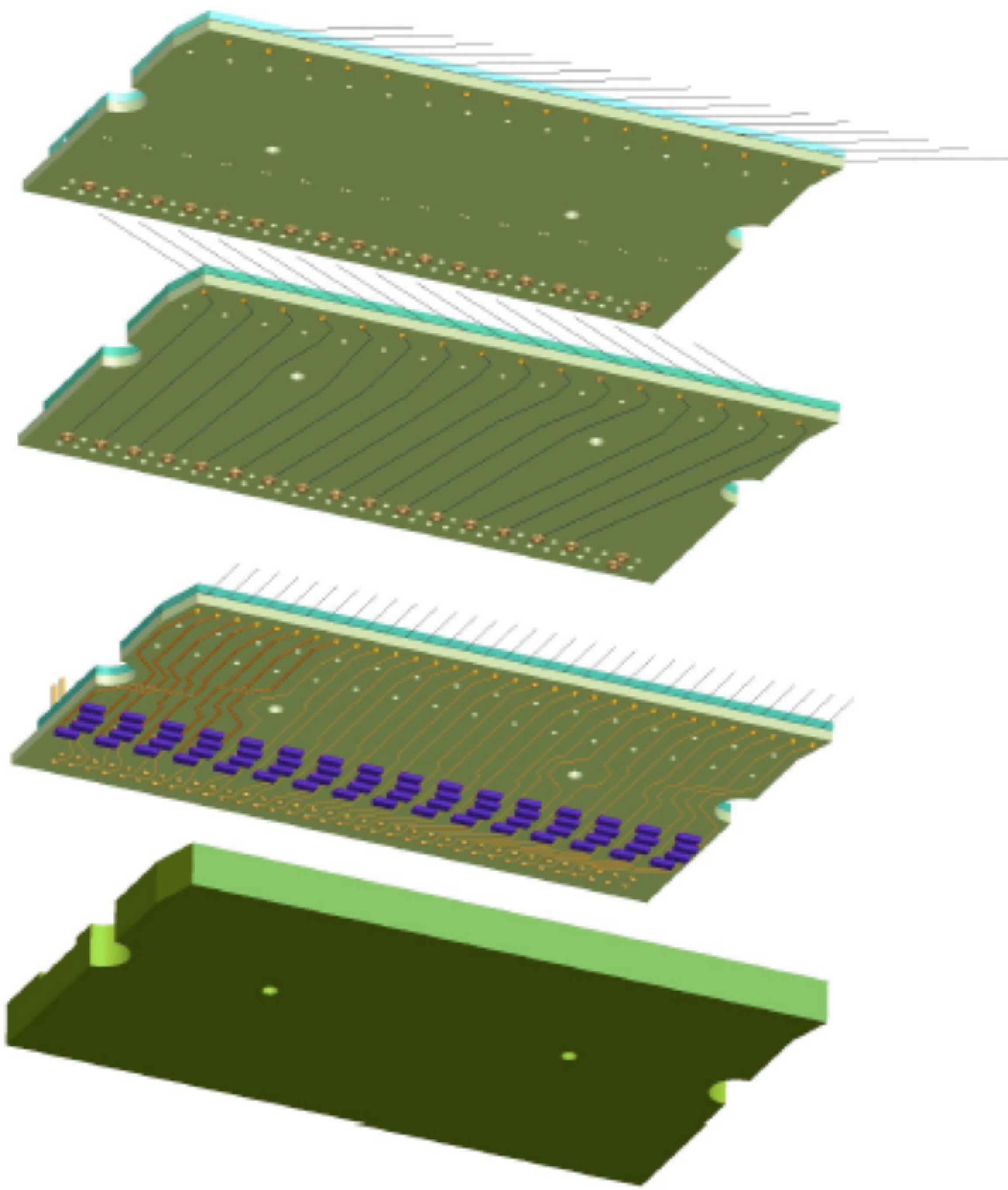
- BNL group has developed wire winding apparatus.
- Have studied properties of CuBe vs. gold-coated Stainless Steel wire.
- 1kg tension → 7mm expansion (on 2.5m long wire)
- Wire contraction when cooled to 90K (and frame is at RT): 6.8mm
- Nominal tension ~1kg

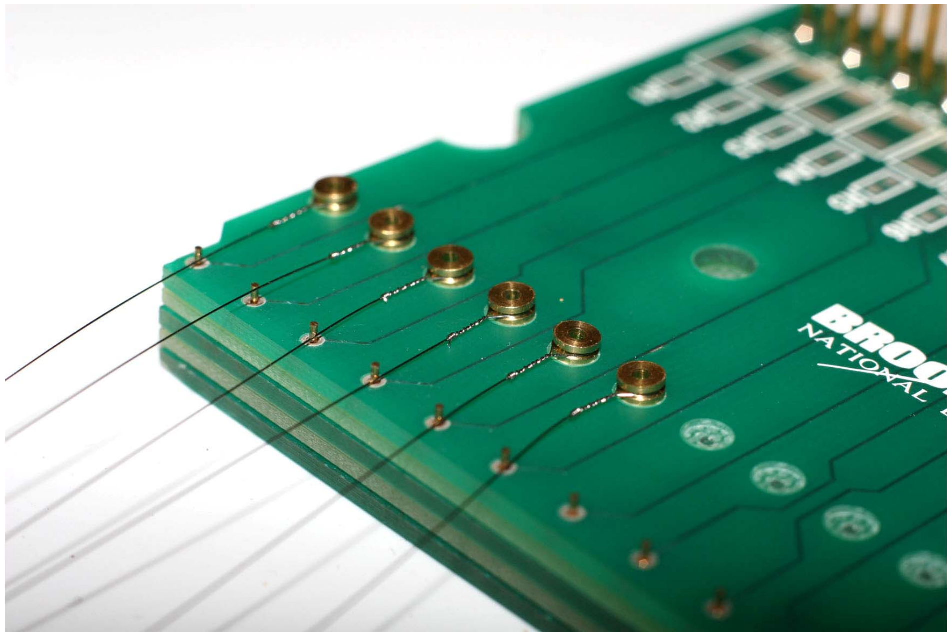





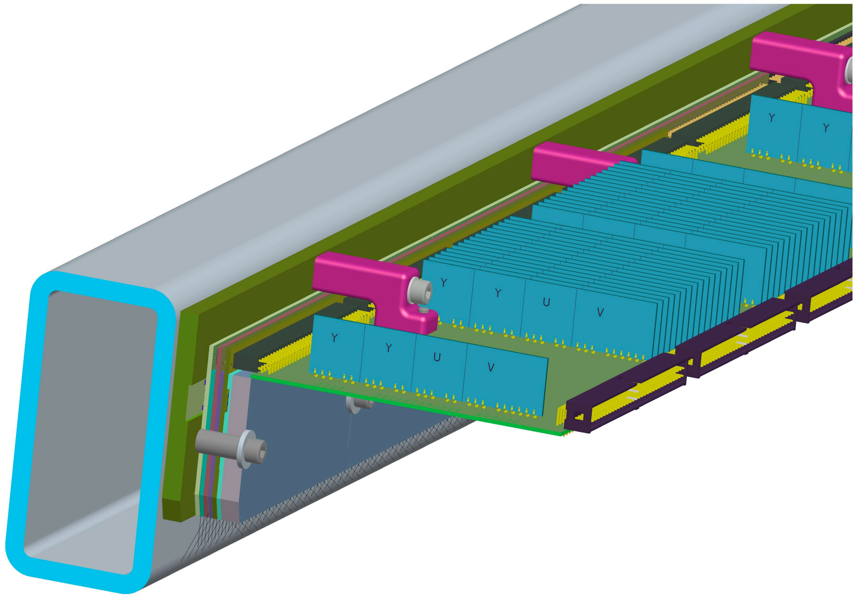
	SS304V (Fort Wayne)	CuBe (Little Falls Alloy)
Young's modulus @ RT	170GPa	121GPa
Young's modulus @ LN2	183GPa (8% increase)	136GPa (12% increase)
Integral CTE	0.22%	0.29%
Tension increase due to cooling	~750g	~730g
Max. tension with termination	~3kg	~2kg

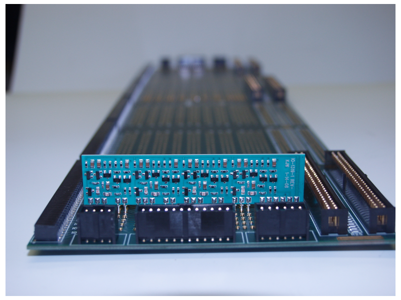
MicroBooNE: Wire Connections

- Wire connections from 3 wireplanes made in tight space
- Decoupling capacitors located on wireplane assembly.



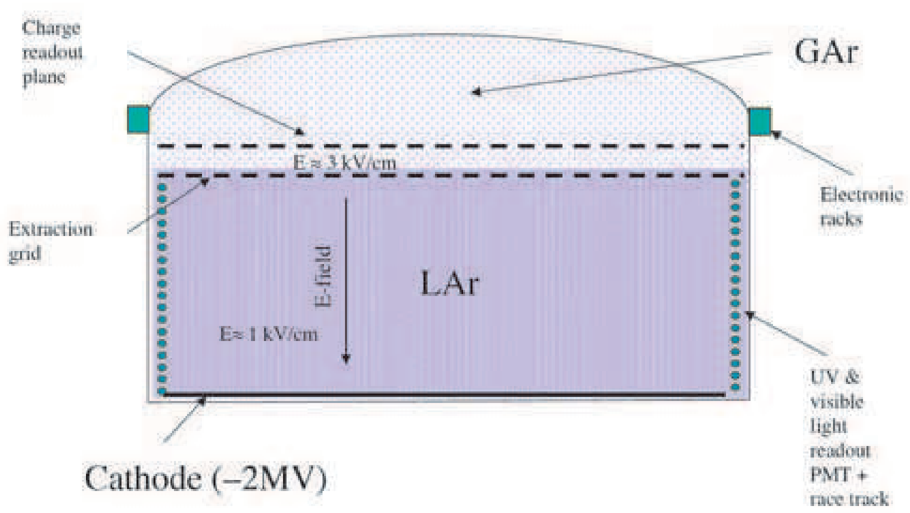




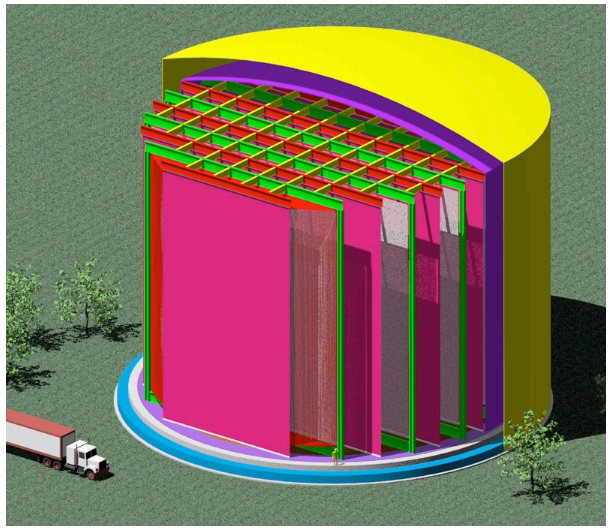


Massive Detectors

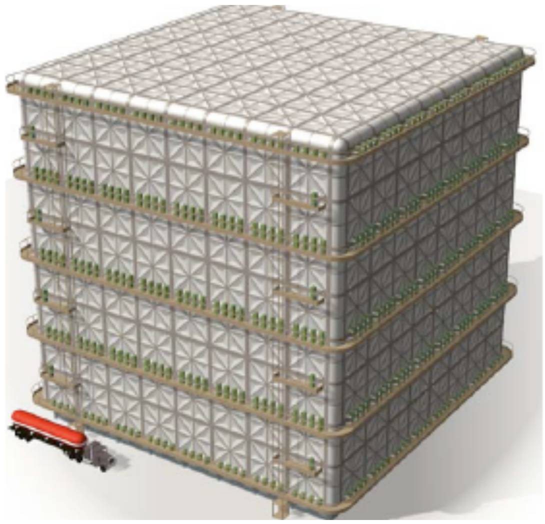
- Ultimate goal for this technology is a kiloTon class LArTPC located in a neutrino beam at a far site.
- Several detector proposals have been made...
- Reminder: Main technical challenges
  - -Safety
  - -Readout (long wires = lots of noise)
  - -Long drift
  - -Purification of large quantity of argon (not in a vacuum environment)
  - -Surface cosmic ray rates
  - -Underground construction technique
  - -...



GLACIER



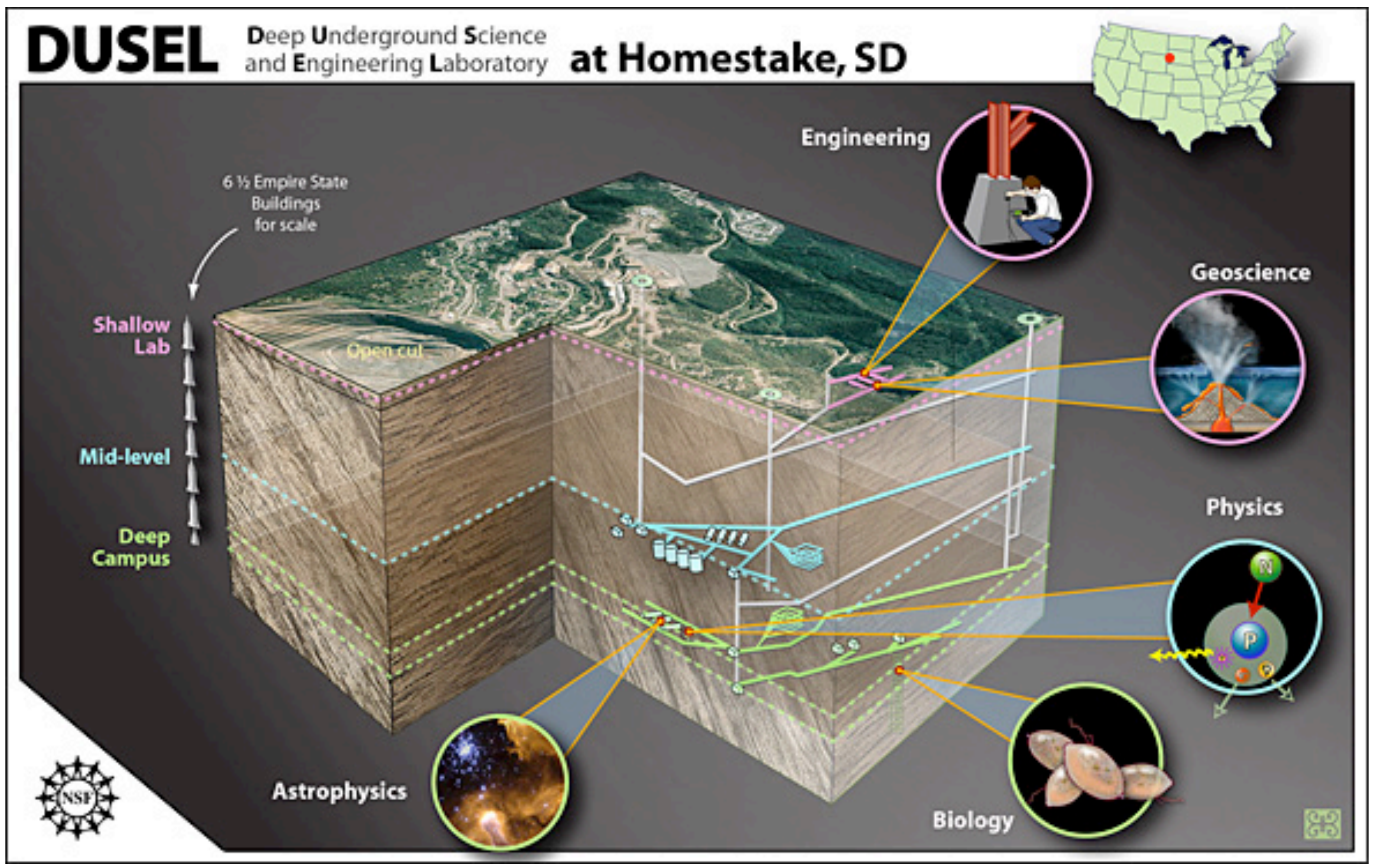
FLARE



LANNDD

Massive Detectors

- Prefer to put this huge detector someplace very deep (e.g. - Homestake Mine in South Dakota, Soudan Mine in Minnesota).
- Proposed Project X at Fermilab could send intense neutrino beam to this far-site location.
- Working groups already forming in U.S. to explore possibility of massive detector at DUSEL.



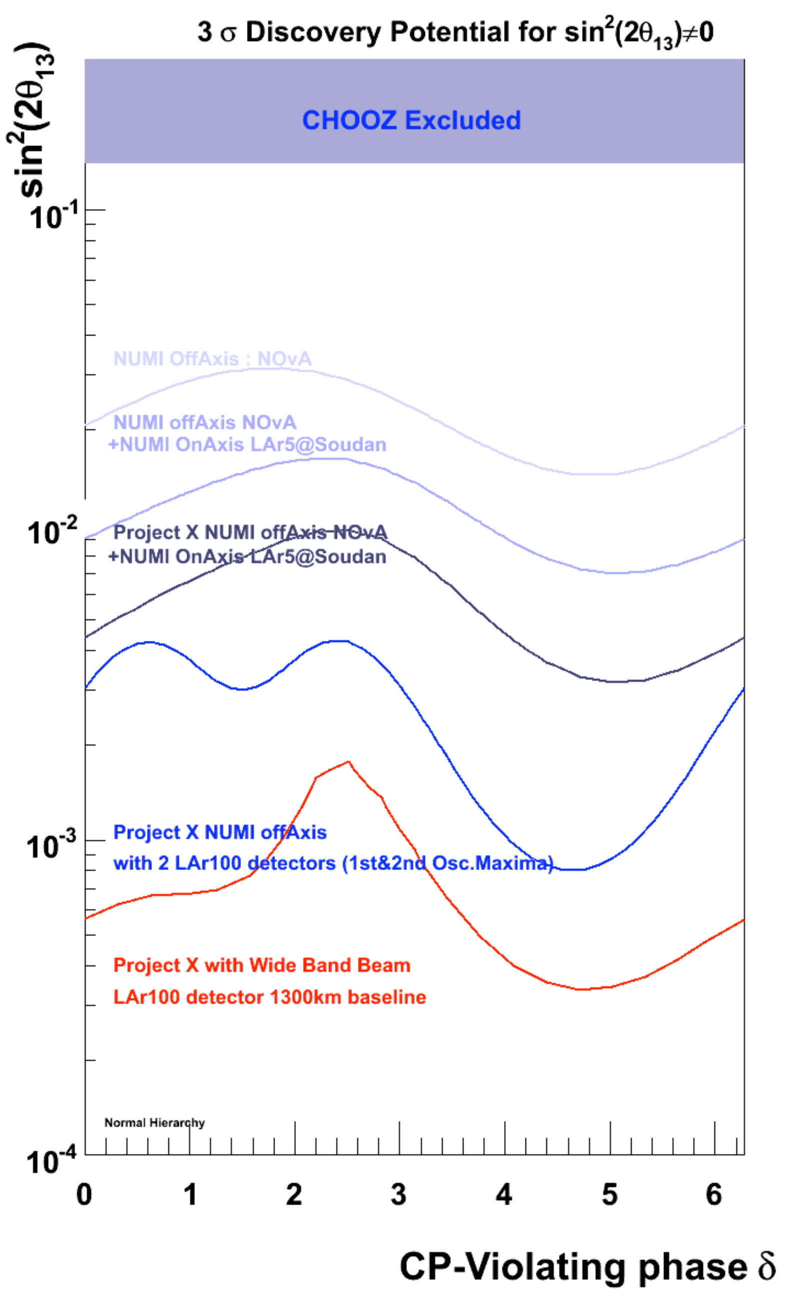
Layout of Mine in South Dakota

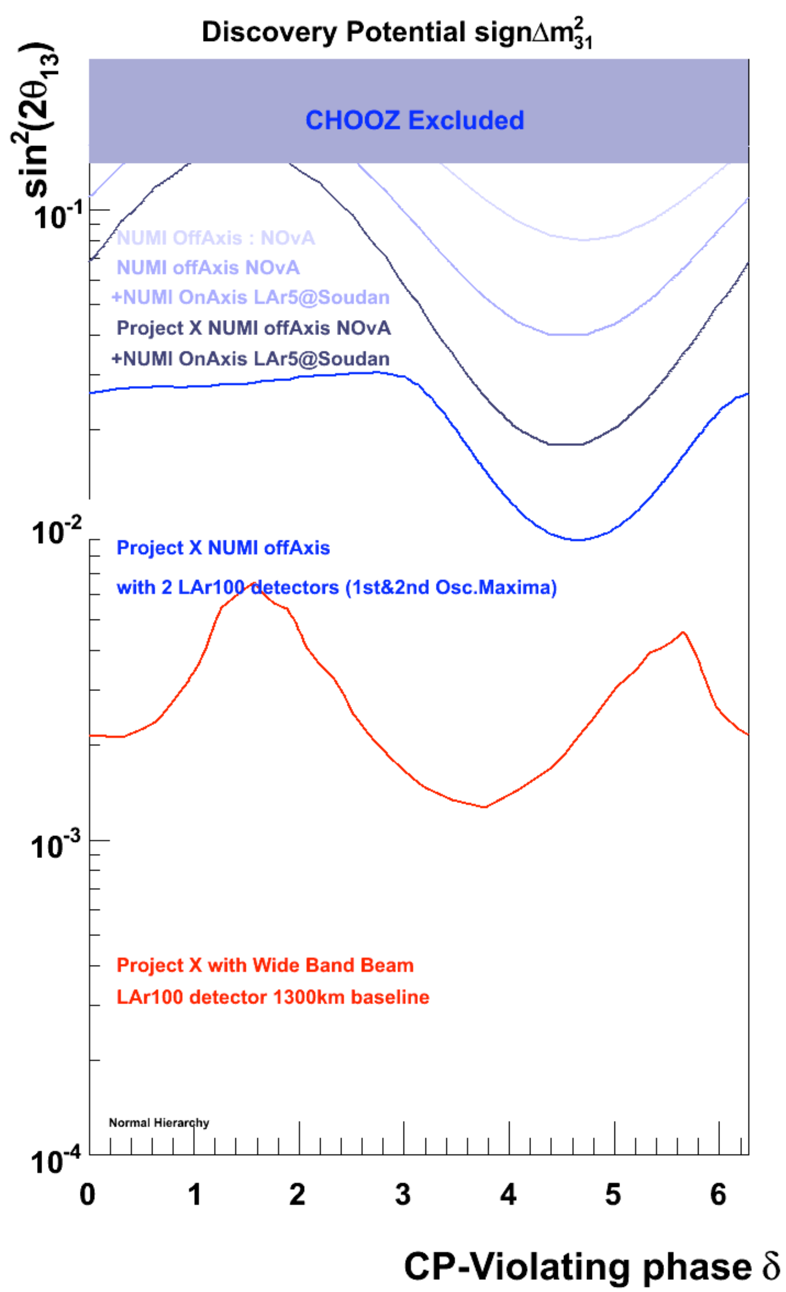
Recommendations from the Report of the P5 Panel to HEPAP, May 29, 2008:

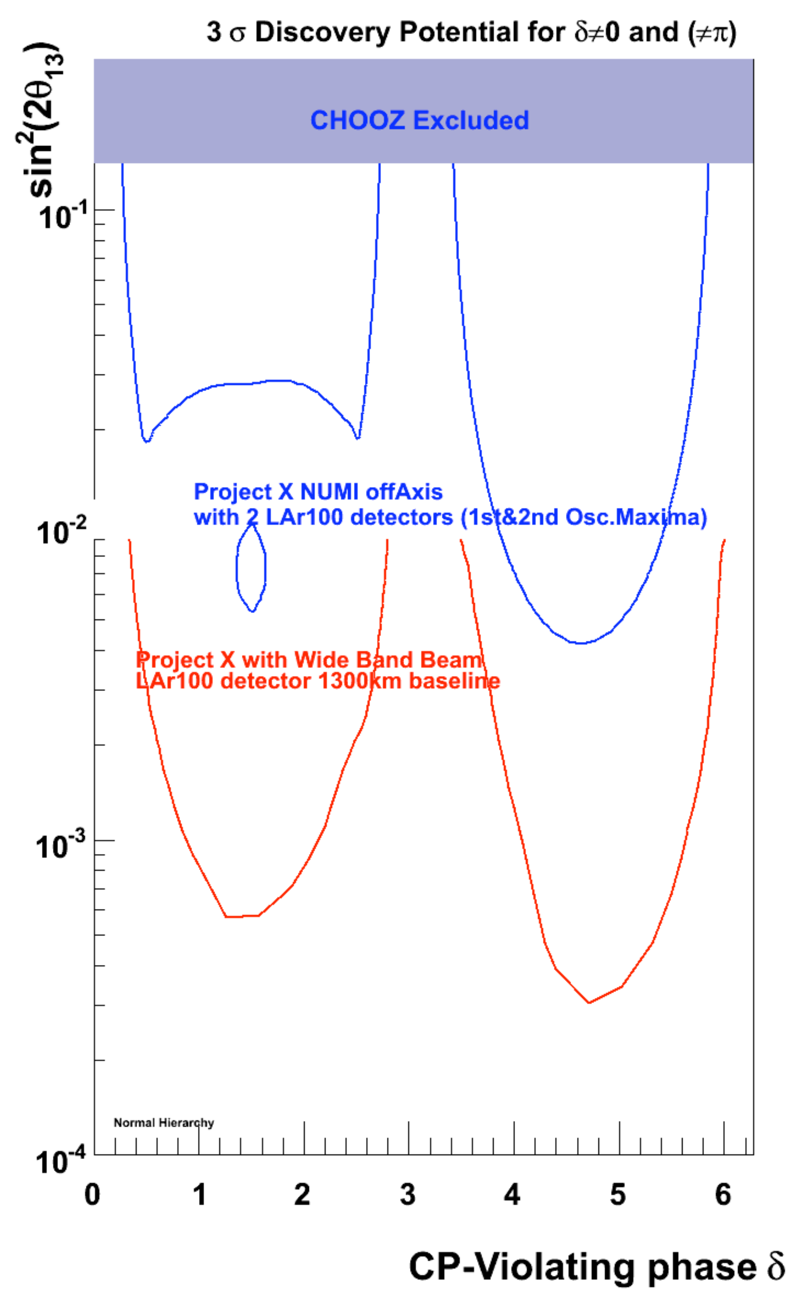
"The panel recommends proceeding now with an R&D program to design a multi-megawatt proton source at Fermilab and a neutrino beamline to DUSEL and recommends carrying out R&D in the technology for a large detector at DUSEL."

Massive Detector: Project X

- Tremendous sensitivity with large LArTPC and intense neutrino beam.
- Scenarios assume 3 years neutrino + 3 years antineutrino
- LArTPC Curves Assume:
  - 80% signal efficiency and 80% beam ν_e selection efficiency
  - no NC π^0 background and 5% systematic on background.



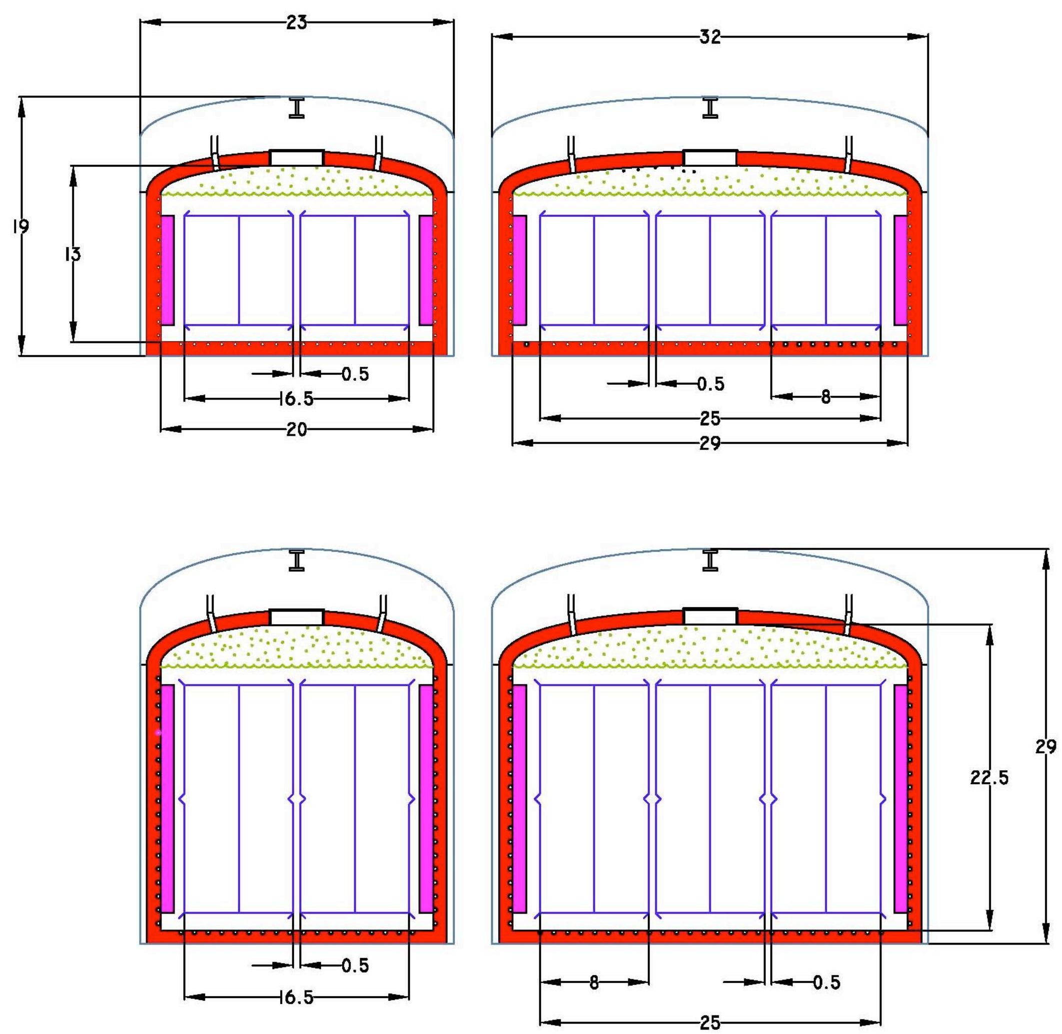




DUSEL: Cavern Layout

Some of the considerations and studies that are needed are:

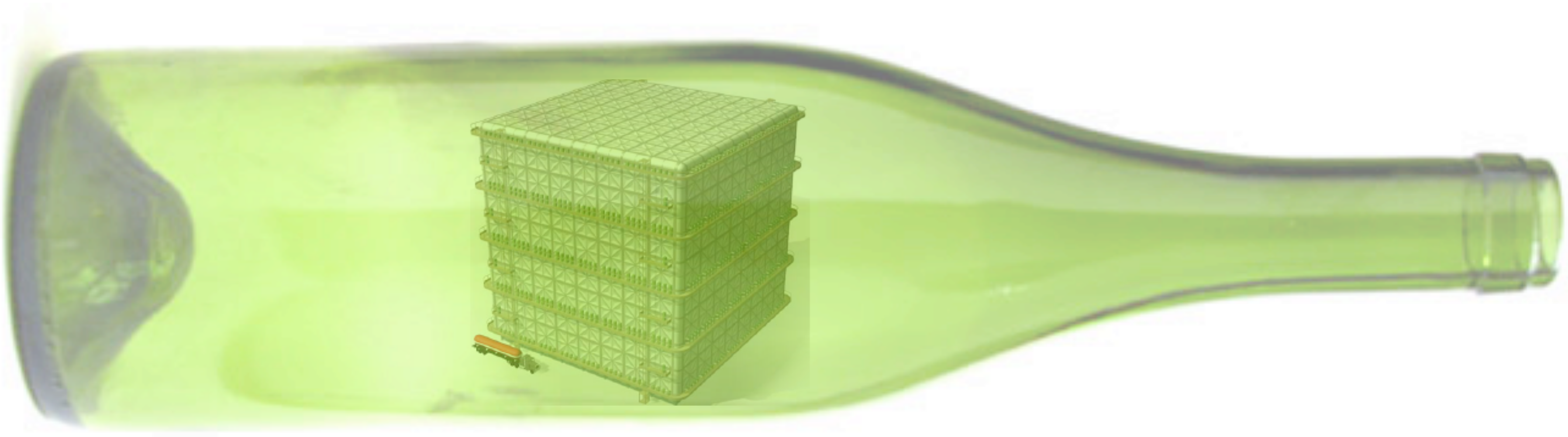
- Depth? 300 ft. , 4850 ft., or in between?
- Proton Lifetime & Supernova Neutrinos : Can they be done at 300 feet? (Backgrounds?)
- Cost differential for different depths: Excavation cost, assembly cost differential , Safety issues, ...



Cavern/Cryostat designs are coupled

DUSEL: Assembly Underground

- Space Limitation → Excavation costs drive cavern size.
- Severe Access Limitation
  - Elevator Capacity (~6 tons)
  - Limited Elevator Volume (1.4x3.7x2.2m)
- Limited Infrastructure (Machine shops, parts, etc...)
- Cryostat assembly impact on purity needs to be understood (i.e. - welding cryostat together piece by piece...)
- A very large ship in a very large bottle...



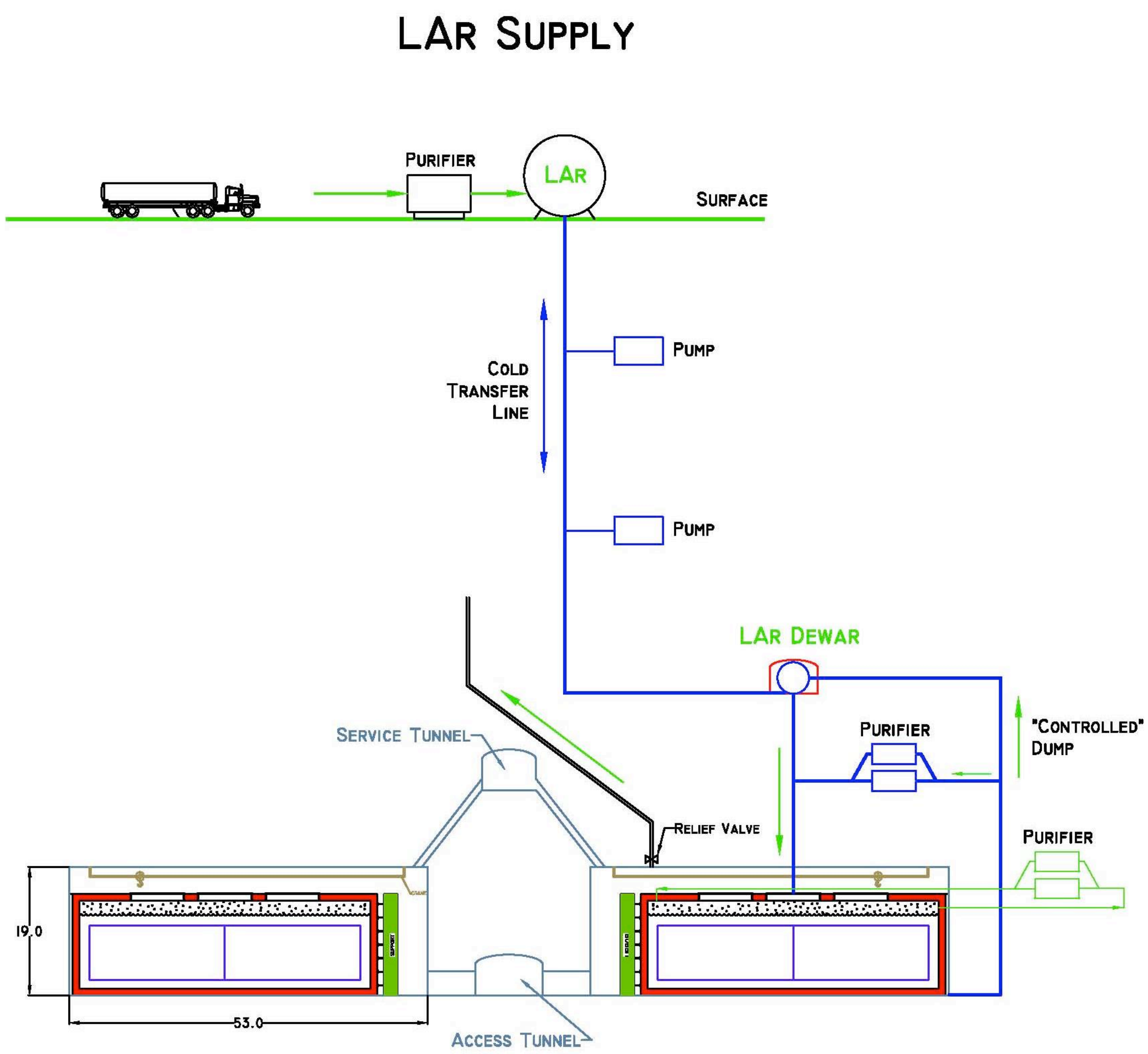
Need for a strong engineering team to fold these constrains in to the detector/cavern design from the start.

DUSEL: LAr Supply System

Procedure to supply the LAr.

Issues:

i. Cleanliness of the supply system.
ii. Ability to evacuate LAr (Accident)
iii. Acceptance tests for LAr delivery.
iv. Size and location of Buffer tanks.
v. # of buffer tanks underground.
vi. Location and size the purifiers.
vii. Cold pipe from the surface.



Example of cavern arrangement and liquid supply paths

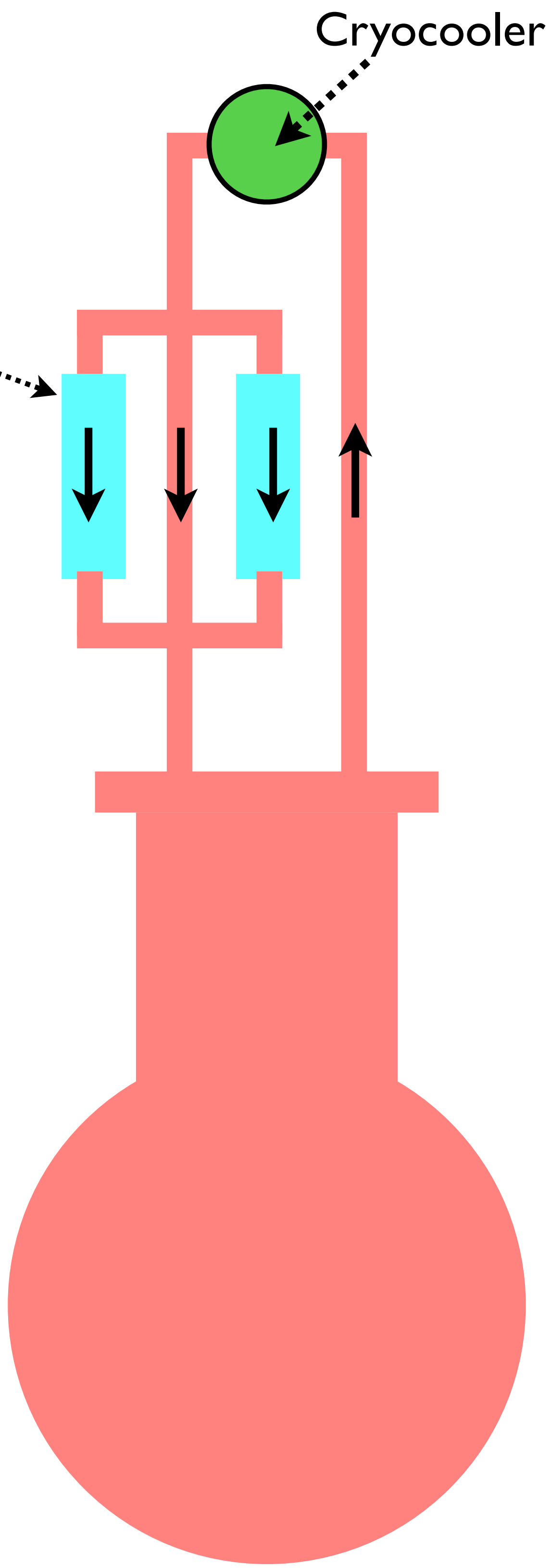
Conclusions

- Much activity in U.S. to develop LArTPC technology.
- Materials Test Stand is an excellent resource for approving materials for use in future experiments.
- ArgoNeuT is current step for LArTPCs in U.S.; will collect 10000's of events!
- MicroBooNE is next major effort in U.S., and it will teach us many things we need to understand before attempting to build a massive detector that can be used to study neutrino oscillations and nucleon decay.
- LAr collaboration for a massive detector is being discussed and preliminary meetings are starting to take place.

Back-Up Slides

ArgoNeuT: Cryogenics

- Self-contained system.
- Recirculate argon through Trigon filter.
- Cryocooler used to condense boil-off gas.
- Multiple relief paths to achieve safe running.




300W Cryocooler

Vacuum-Jacketed Cryostat

ArgoNeuT: Underground

Many safety issues addressed to prepare for move underground and maintain ODH-0 rating of NuMI tunnel:

- ArgoNeuT sits in a bathtub, which acts as tertiary containment in case both cryostats fail.
- Relief piping is routed to vent line (runs up and out shaft), to ensure no argon released in tunnel.
- 2 ODH monitors to alarm if leak is detected.
- Slow control system mirrored on screens in tunnel and surface building, and online, to alert of any ODH hazards before entering tunnel.

ArgoNeuT under construction this summer.