Liquid Argon Time Projection Chambers:

U.S. R&D and Physics Program

Mitch Soderberg

Yale University

45th Karpacz Winter School

February 11, 2009

Introduction

- Liquid Argon Time Projection Chambers (LArTPCs) are well suited to study neutrino physics and beyond.
  - Combine excellent spatial resolution and calorimetry.
  - In principle they are scalable to very large sizes.
- Pioneering work done by ICARUS collaboration
- U.S. effort to develop LArTPCs has expanded significantly in recent years.

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."

Department of Energy (DOE)

↑

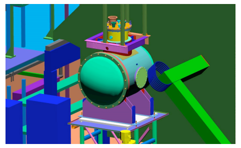
HEPAP (High Energy Physics Advisory Panel)

↑

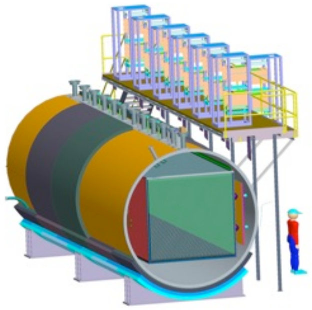
P5 (Particle Physics Project Prioritization Panel)

Talk Outline

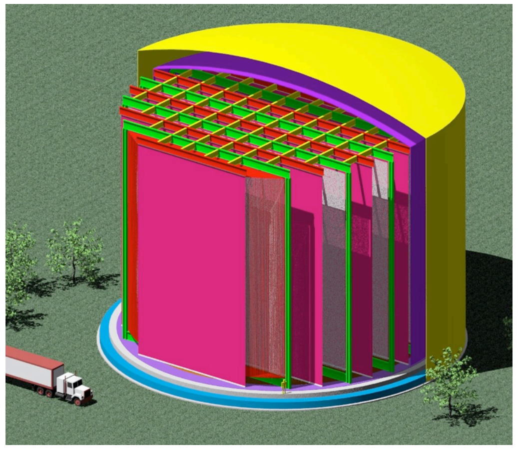
- LArTPC Basics
- Teststands in the U.S.



- The MicroBooNE Experiment



- Massive LArTPC Detectors

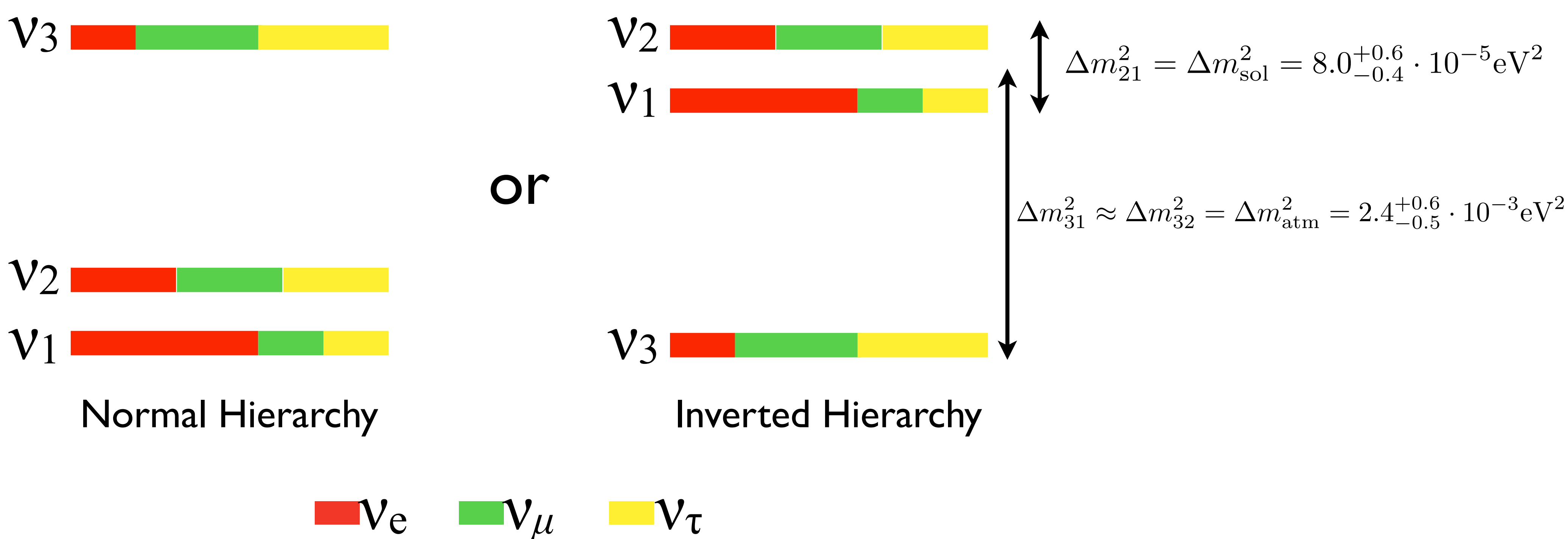


- Conclusions

Ultimate Neutrino Physics Goals

Accelerator Based Goals

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



Non Accelerator Based Goals

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

<u>Massive</u> detector with good background rejection required for much of this physics....

Noble Liquids: Properties

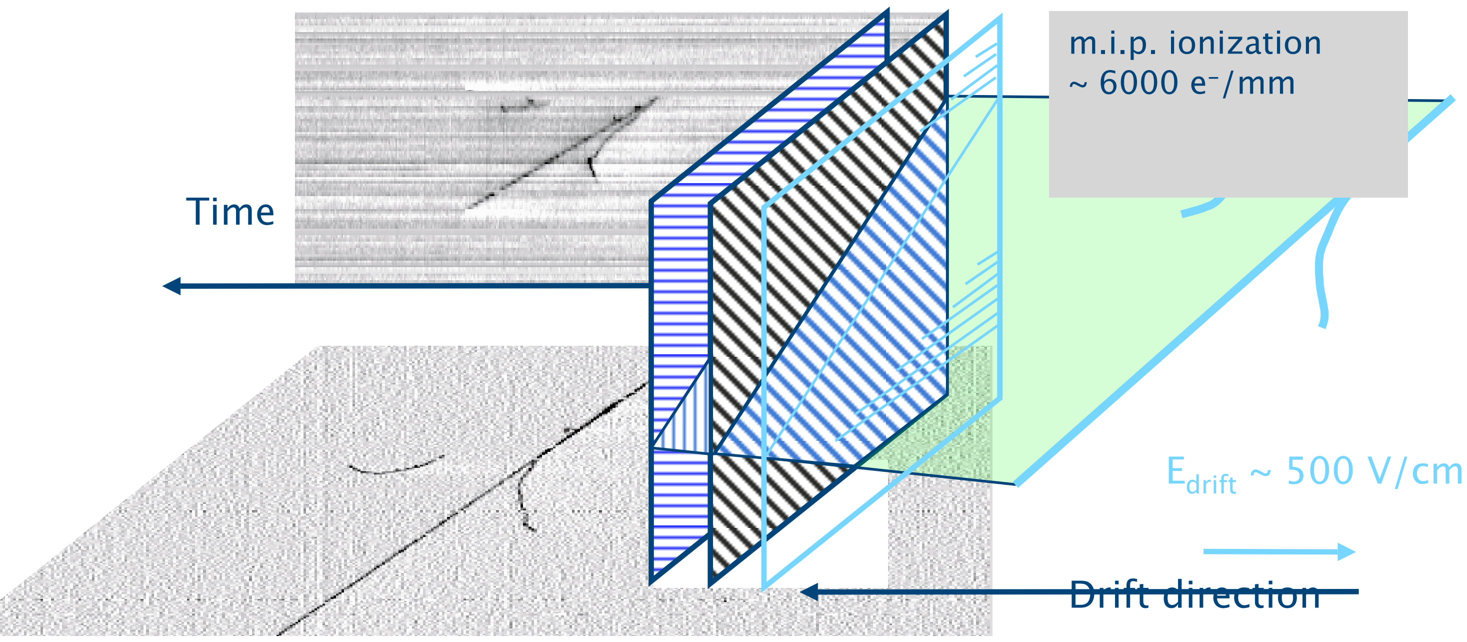
- Ionization and scintillation light used for detection (transparency to own scintillation).
- Ionization electrons can be drifted over long distances in these liquids.
- Excellent dielectric properties allow these liquids to accommodate very high-voltages.
- Argon is relatively cheap and easy to obtain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

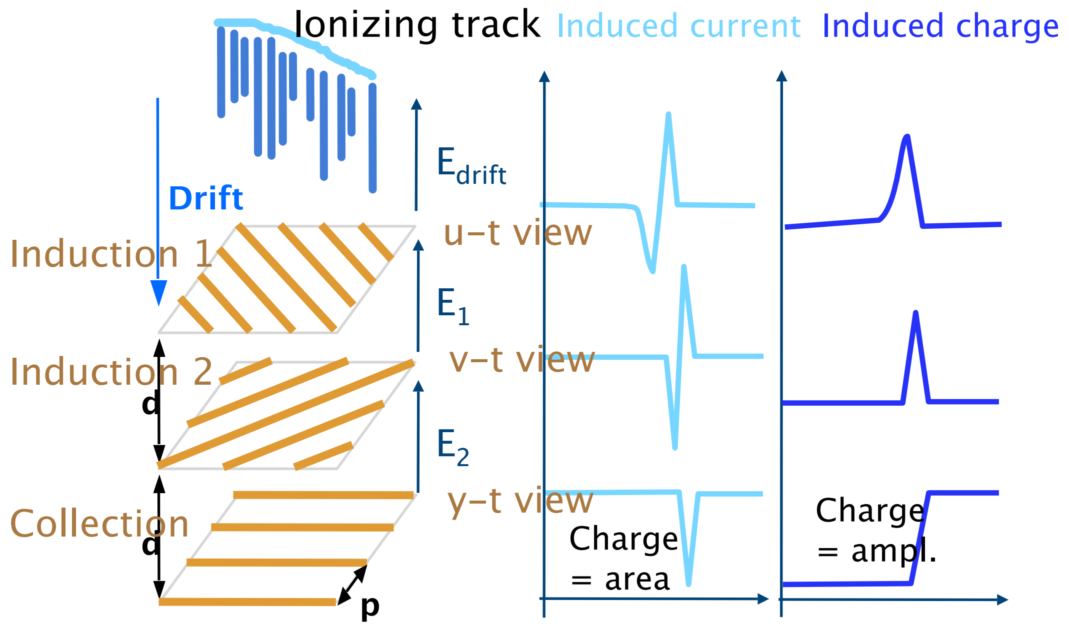
	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation λ [nm]	80	78	128	150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

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.





Refs:
1.) *The Liquid-argon time projection chamber: a new concept for Neutrino Detector*, C. Rubbia, CERN-EP/77-08 (1977)

Wireplane Bias Voltage

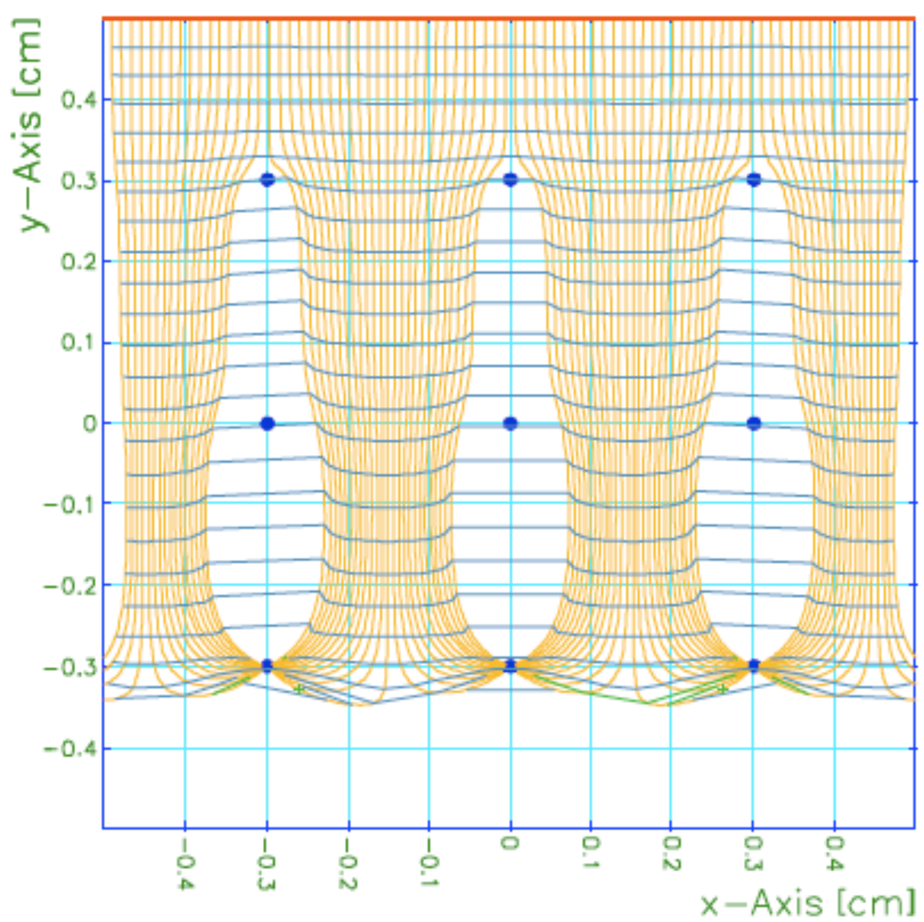
- TPC wireplanes act as an electrostatic grid.
- Transparency is a function of wire geometry and electric fields before/after each plane.
  - Transparency + Multiple wireplanes allow complimentary position measurements of same particle.
- Choose bias voltages to keep constant field up to first induction plane, then choose for maximum transparency between planes.
- Shielding effect of grid helps shape pulses.

$$\frac{E_2}{E_1} \geq \frac{1+\rho}{1-\rho}$$

100% Transparency Condition:

$$\rho = \frac{2\pi r}{d}$$

r = wire radius
d = wire pitch

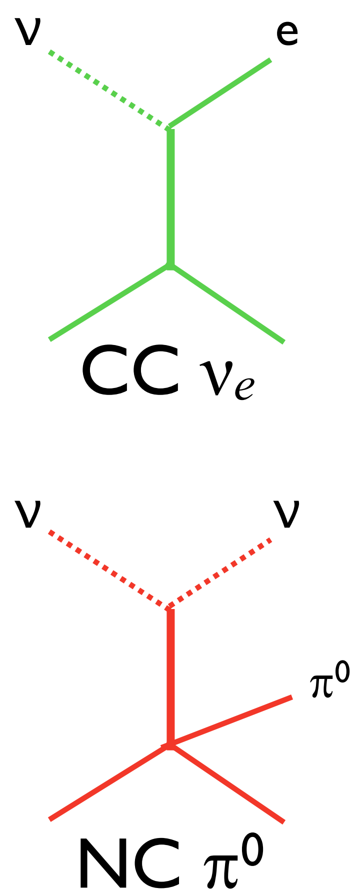


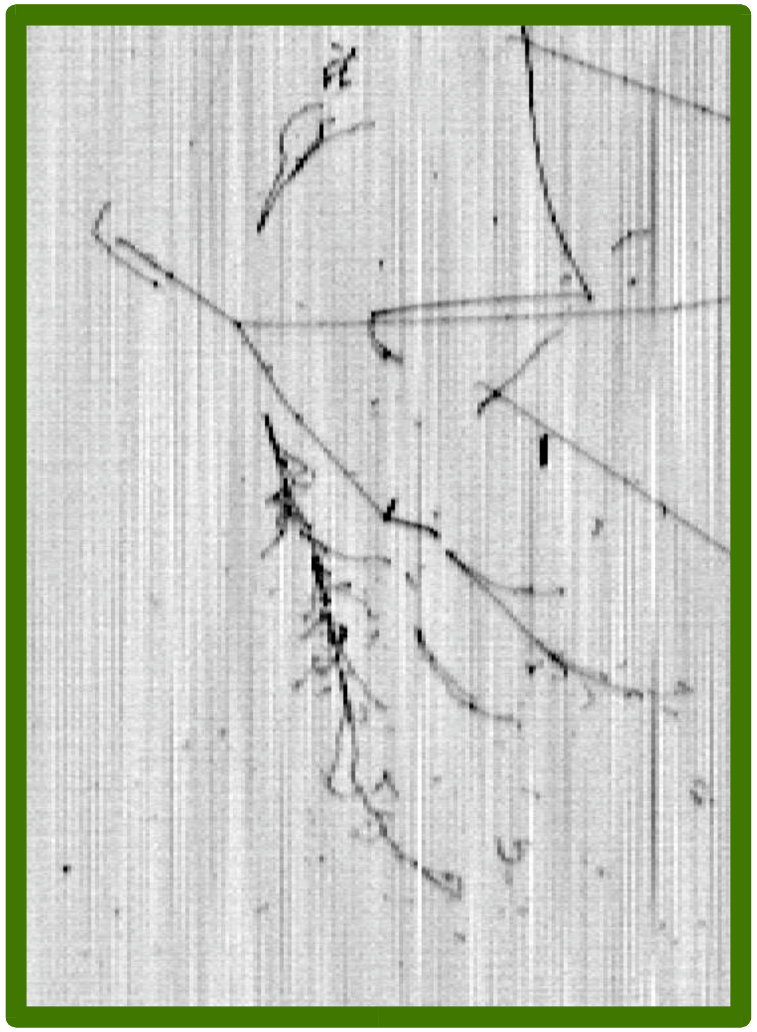
Refs:
1.) *Design of Grid Ionization Chambers*, O. Bunemann, T.E. Cranshaw, and J.A. Harvey; *Canadian Journal of Research*, 27, 191-206, (1949)

LAr TPC Advantages

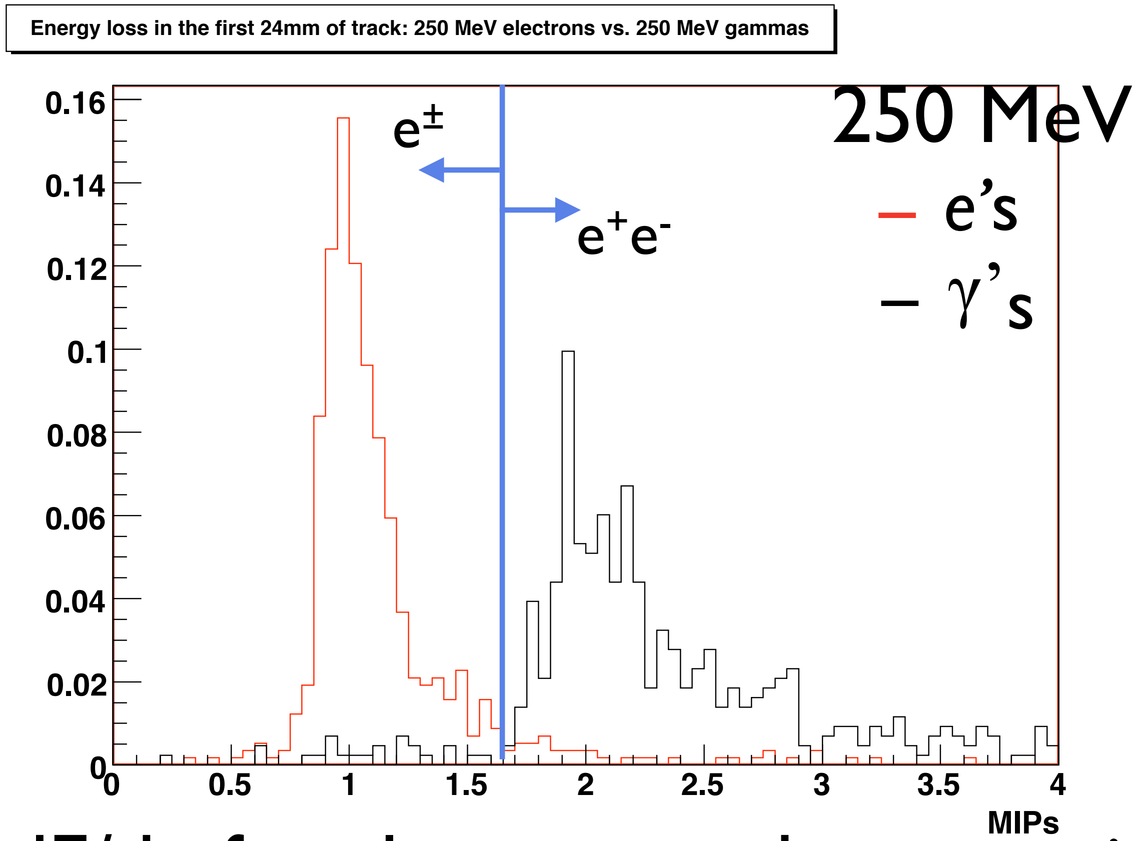
e/γ separation → superior background rejection

- Particle identification comes from dE/dx measured along track.
- ν_e appearance: Excellent signal (CC ν_e) efficiency and background (NC π^0) rejection
- Topological cuts will also improve signal/background separation





ICARUS Event



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

LArTPC Challenges

- Argon purity level required (parts per trillion) is demanding.
  - High purity necessary for long-drifts (~5m) characteristic of a very large detector.
  - Detector materials' impact on purity must be understood.
- Safety issues.
  - Oxygen Deficiency hazard if argon spills in a confined space.
  - Pressurized vessel needs to have adequate relief capability.
- Electronics.
  - Wire signals are small, so sources of electronic noise must be strictly controlled.
  - High sampling rate + many wires = Flood of raw data.
- Vacuum/Cryogenic Environments take special care...
  - Every penetration into the cryostat must be leak tight.
  - Every penetration into the cryostat increases the heat load on the system.

Current program of LArTPC development will address many of these challenges

Liquid Argon in the U.S.

Rapid progress in LArTPC development

Materials Test Stand

Bo

2007

100% R&D

2007-

2008-

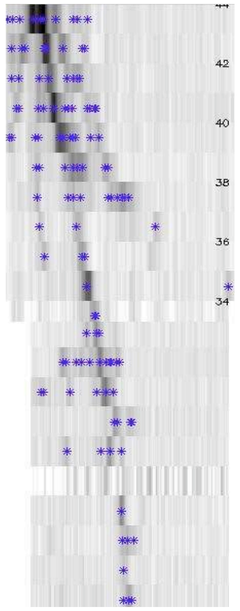
2011?

201?

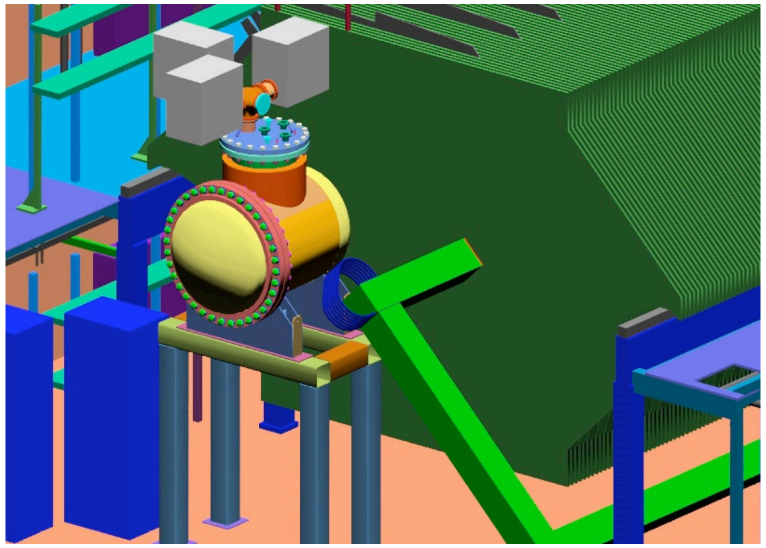
100% Physics

5 Kilotons

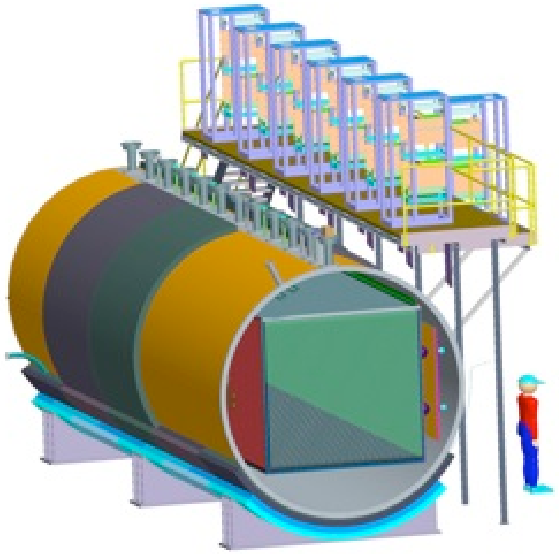
100 Kilotons



Yale Tracks



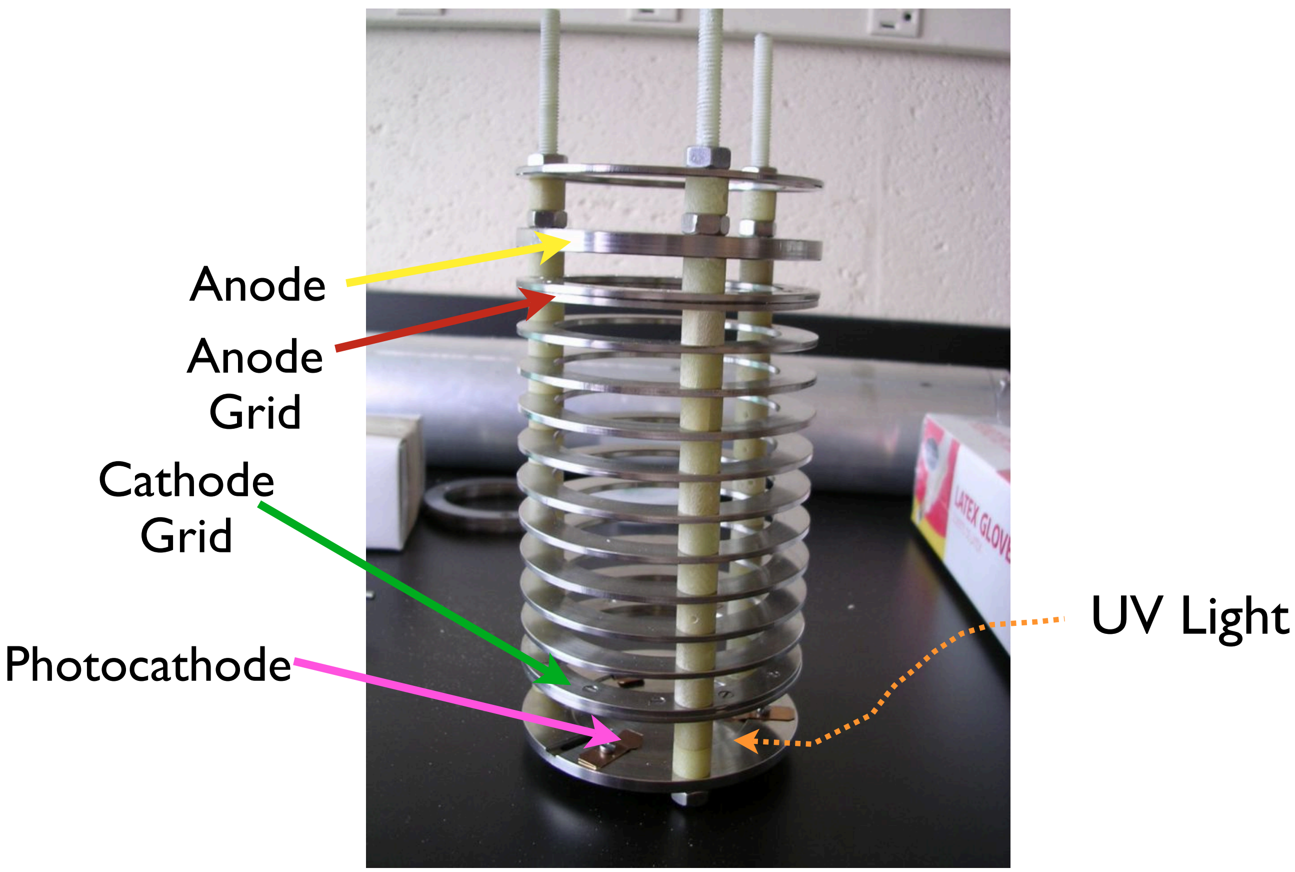
ArgoNeuT



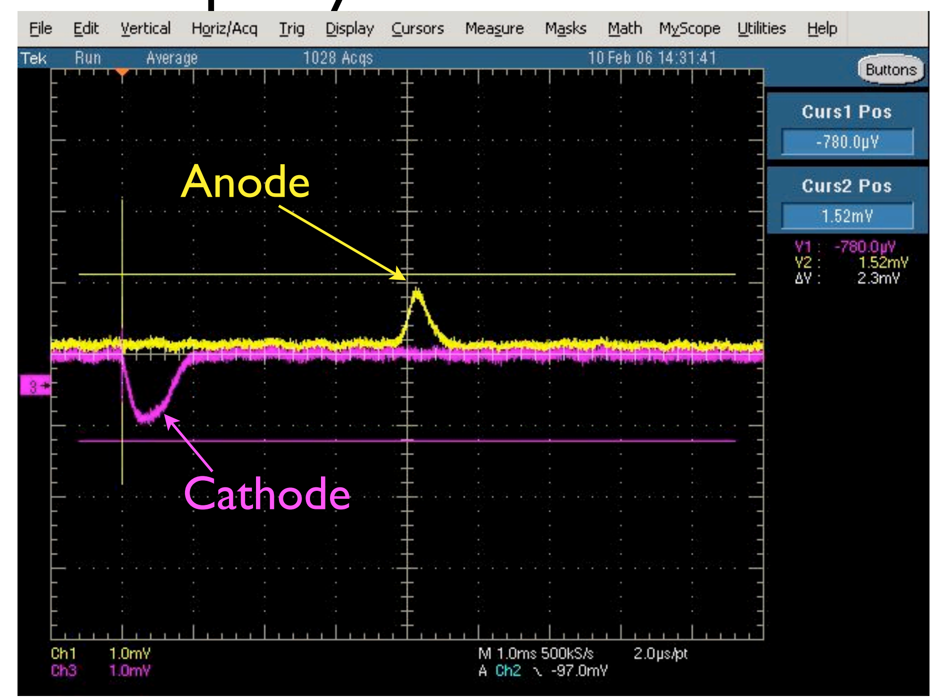
MicroBooNE

Argon Purity

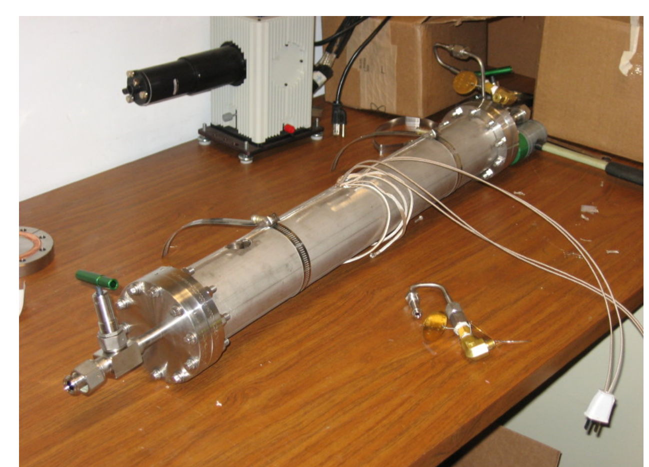
- To drift electrons through several meters of liquid argon, electronegative impurities (Oxygen, Water, etc..) must be removed to increase ionization electron lifetimes.
- Must send LAr through filter(s) to remove contaminants.
- Purity monitors are used *in-situ* to measure charge absorbed during drift through liquid argon.
- Fermilab group has done extensive work to develop new filters and purity monitors.
  - They can routinely achieve lifetimes of 10ms



ICARUS style Purity Monitor

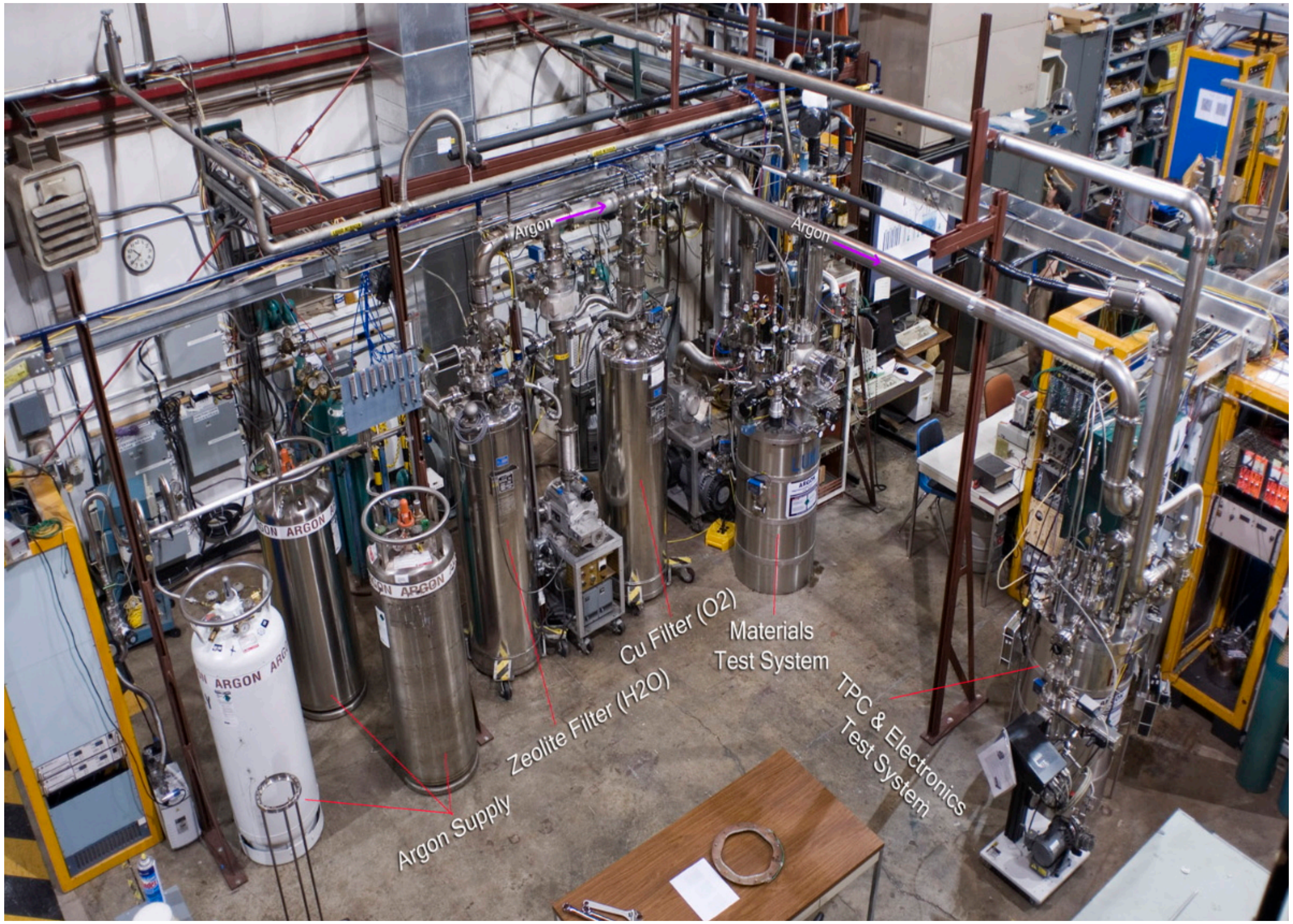


FNAL Purity signal (4ms)



TRIGON Filter

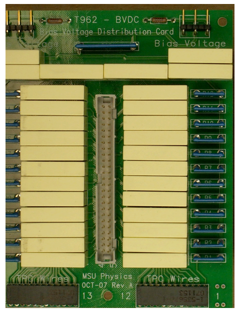
Materials Test System at Fermilab



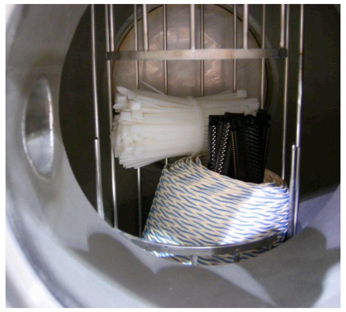
•A massive LArTPC will necessarily have large amounts of detector material, so controlling argon purity is vital.
•This system is used to study the impact of different materials on argon purity.

Materials Test System at Fermilab

BNL 4-ch Amp

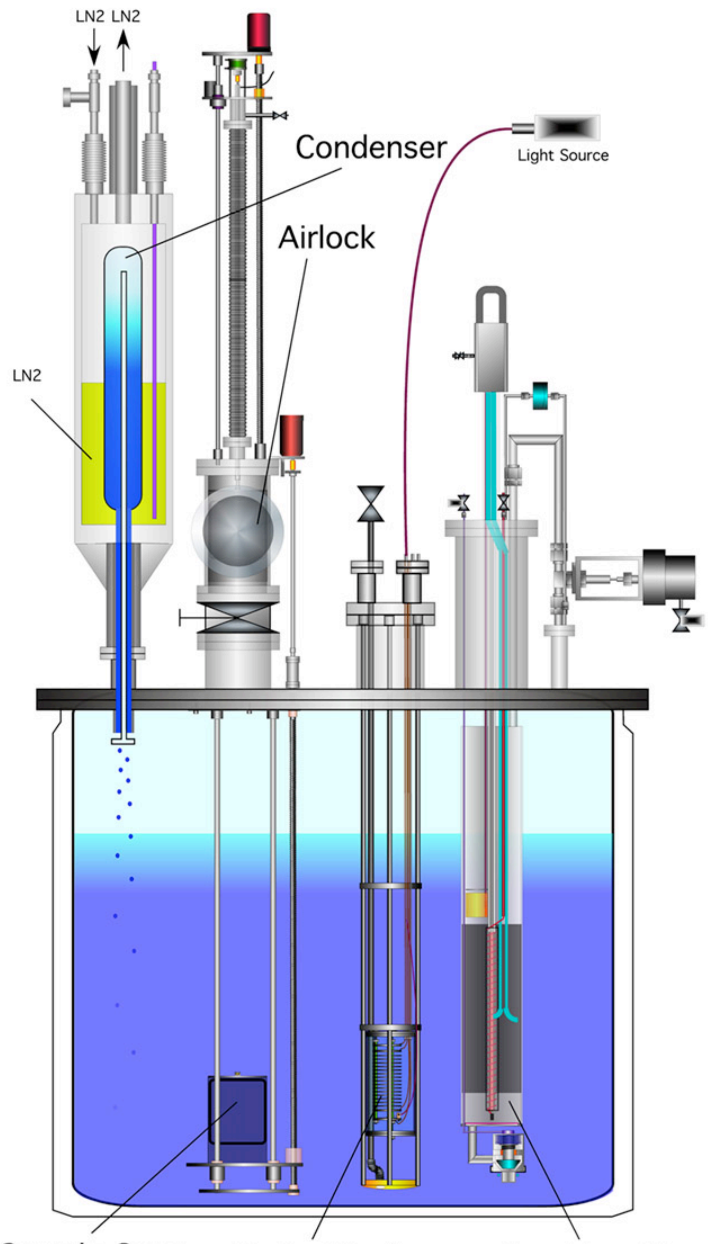


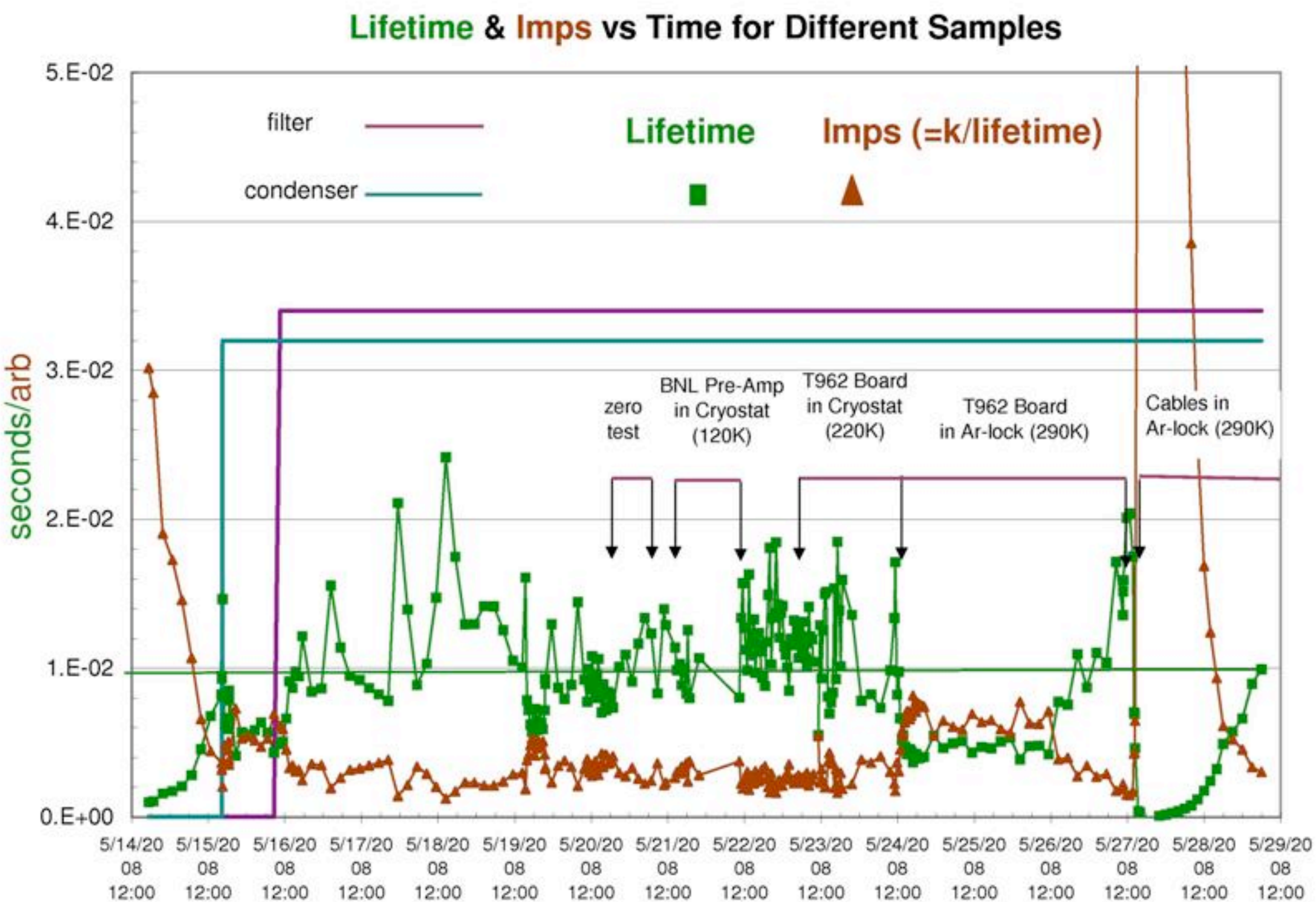
ArgoNeuT Bias Board



Cables/Cable-Tie Bundle

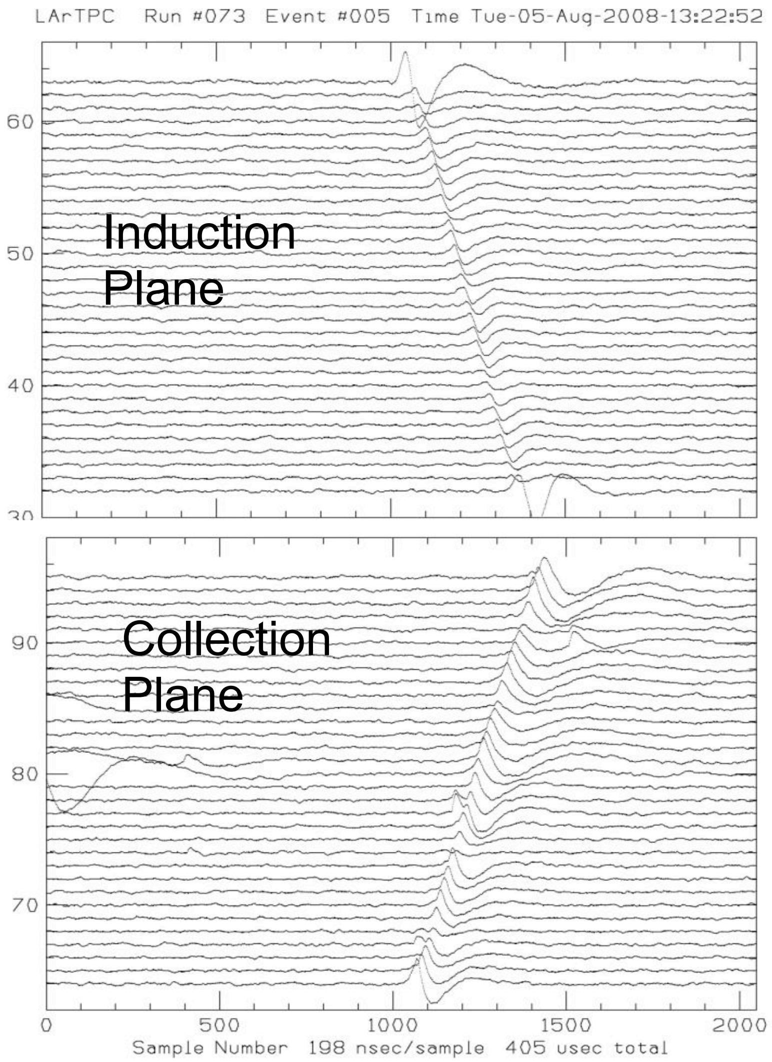
Measurements with the Materials Test System



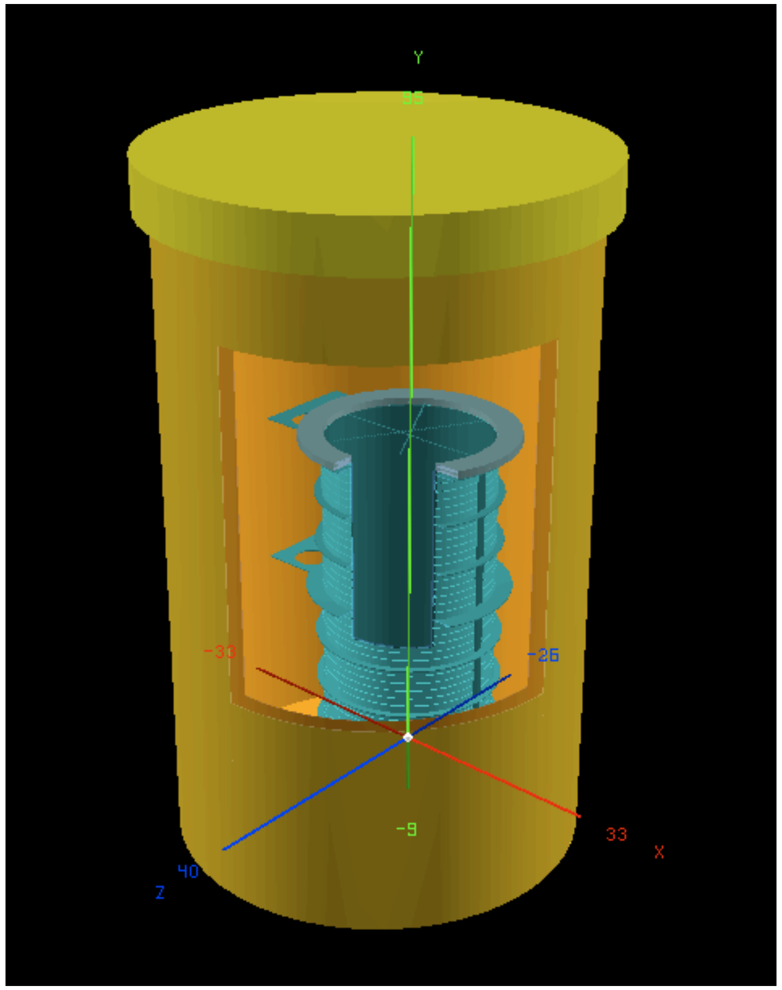


Electronics Test System

- TPC and cryostat for electronics development
- Cylindrical TPC:
  - 96 channels over 3 planes
  - 50 cm max. drift
  - 24 cm diameter
- Electronics designed and built at Michigan State University.
- Signal/Noise performance very good.



Cosmic-ray muon

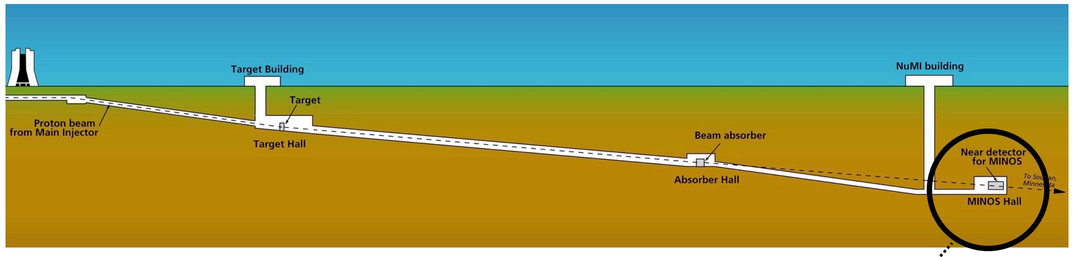

GDML Rendering of Bo TPC, for use in GEANT4 Simulation

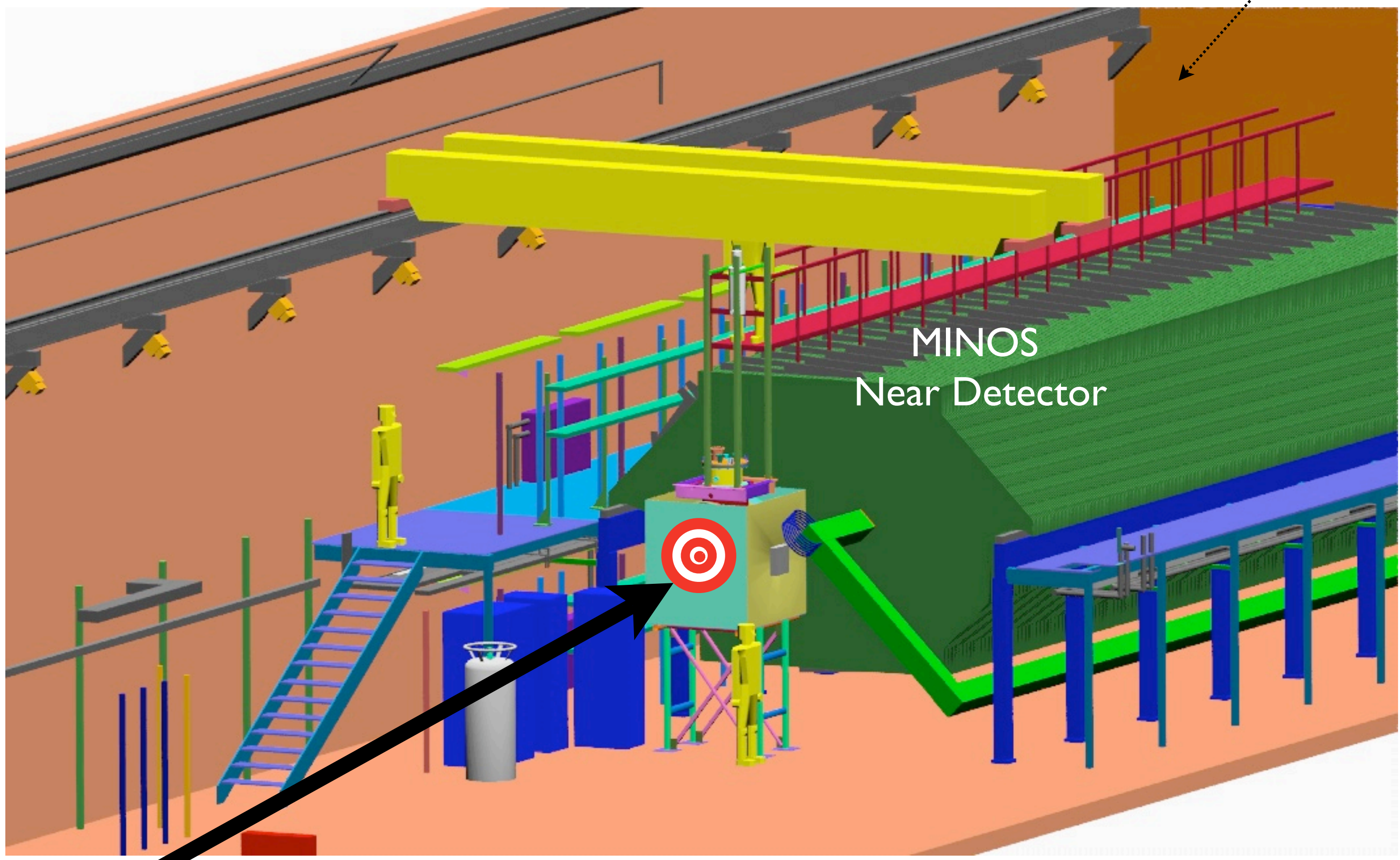
TPC being installed at Fermilab

ArgoNeuT

- ArgoNeuT is a ~175 liter LArTPC (jointly funded by NSF/DOE)
- Sits directly upstream of MINOS near detector in NuMI beamline.
    - Will use MINOS to range out muons.
- 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

F. Cavanna
University of L'Aquila

B. Baller, C. James, G. Rameika, B. Rebel
Fermi National Accelerator Laboratory

M. Antonello, R. Dimaggio, O. Palamara
Gran Sasso National Laboratory

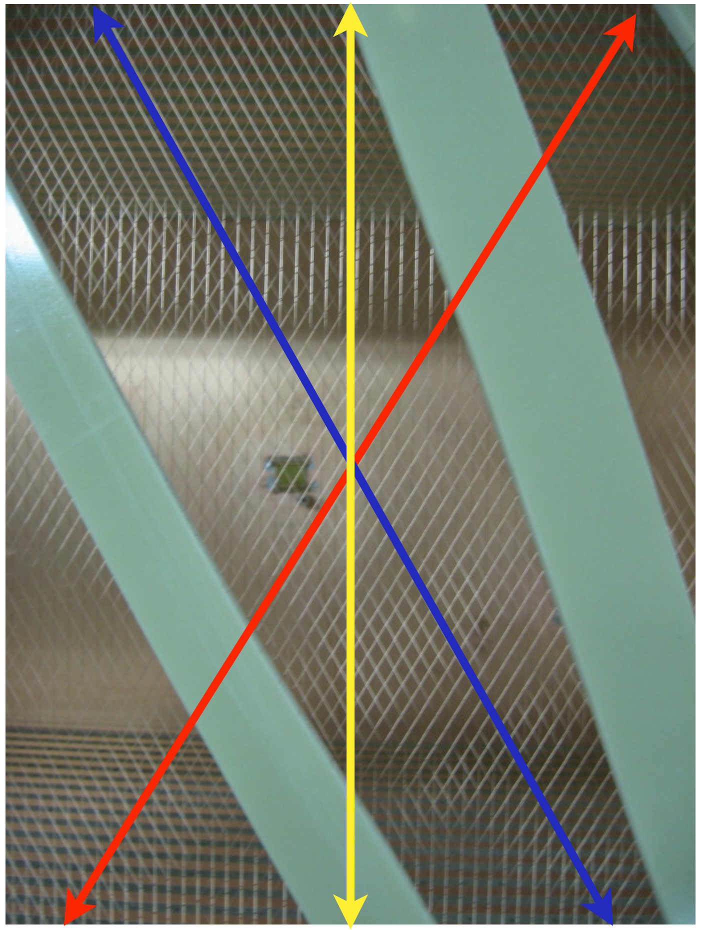
C. Bromberg, D. Edmunds, P. Laurens, B. Page
Michigan State University

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

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

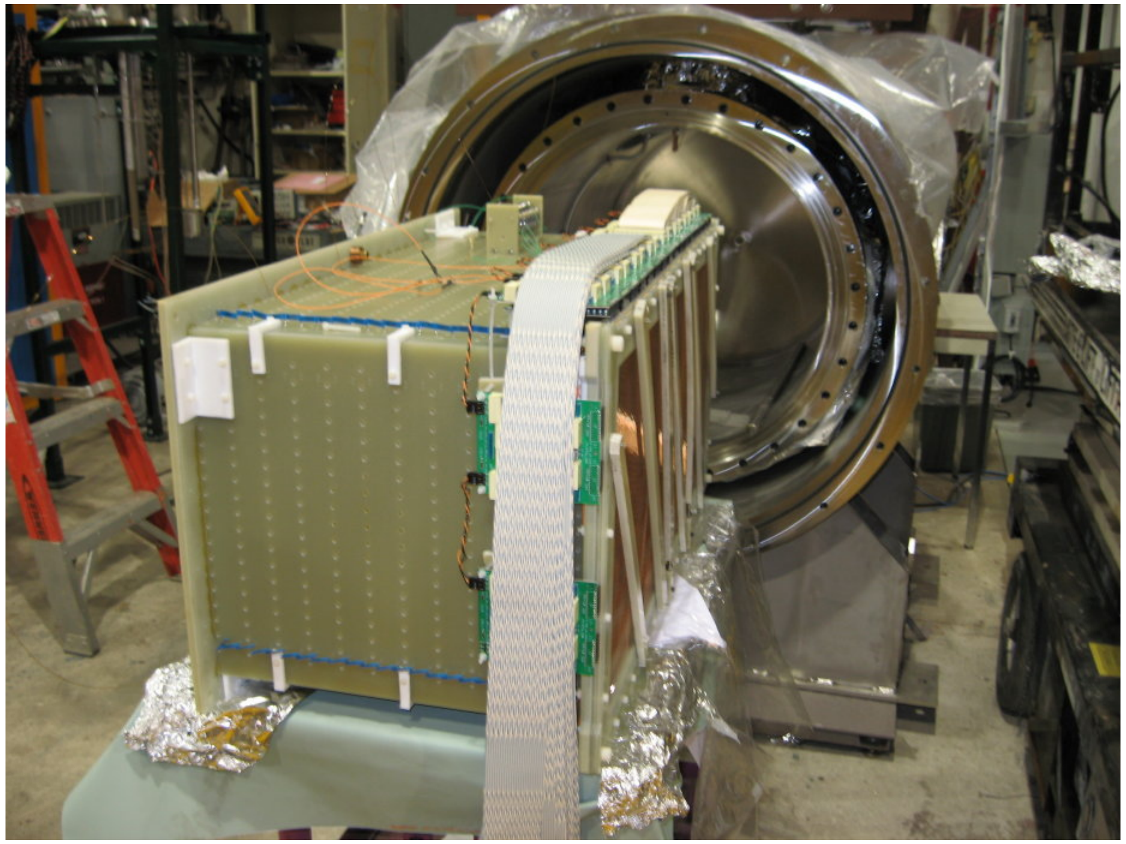
ArgoNeuT: TPC

- 175 liter active volume, 480 signal channels.
- Collection, Induction2, Induction1 planes. (Induction1 plane not read out.)
- 4mm wire pitch, 4mm plane spacing.
- 500V/cm electric field.
- Max. drift of ~50cm (corresponds to ~330μs at our drift velocity).
- Bias voltage distribution boards located directly on TPC.
- 0.15mm diameter BeCu wire. Cu-clad G10 used for field cage.



±60° wires

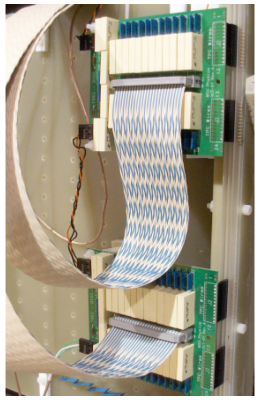
Wire Orientations



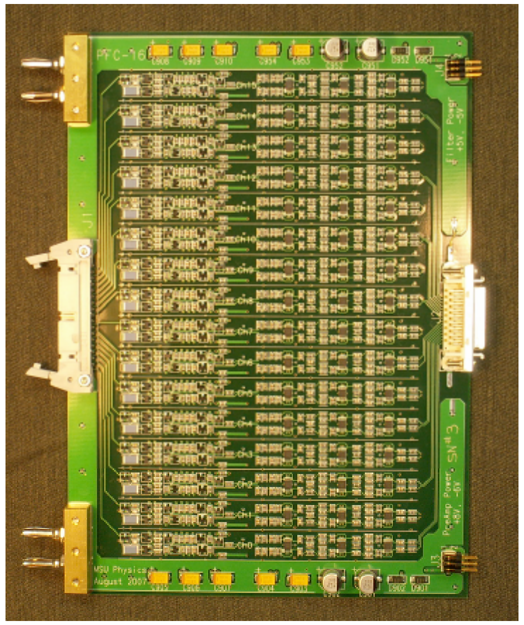
TPC About to Enter Cryostat

ArgoNeuT Electronics

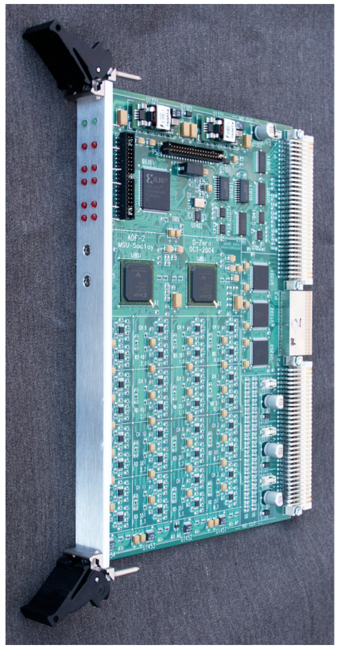
- Electronics for ArgoNeuT (480 channels)
  - Bias voltage distribution & blocking on the TPC
  - FET preamplifier similar to D0/ICARUS front-end
  - Wide bandwidth filtering (10 - 200 kHz, now)
    - Full information on most hits/tracks
    - Employ DSP to extract hit/track parameters
  - ADF2 card, sample at 5 MHz (*i.e.*- 198 ns/sample), 2048 samples/channel
  - Minimize noise sources
    - Double shielding of feed-through and preamplifiers
    - Remote ducted cooling
    - Extensive DC power filtering



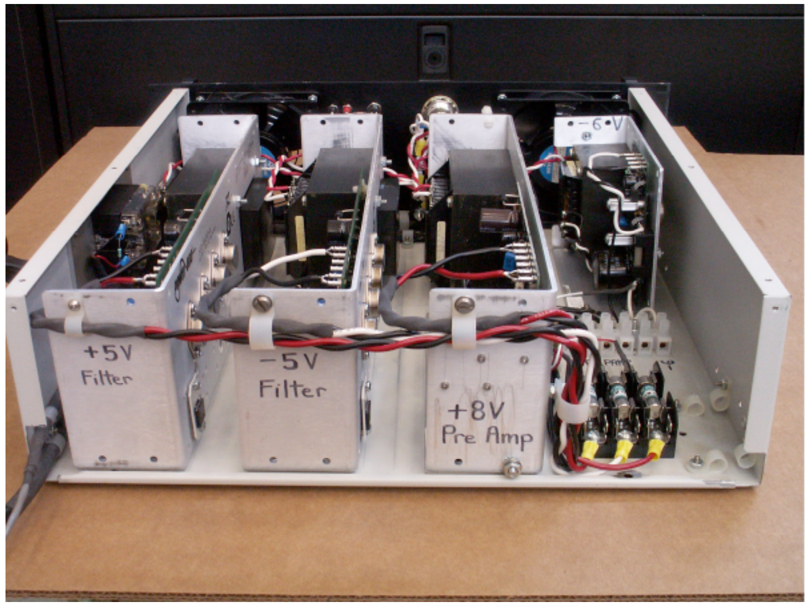
Bias Voltage R & C



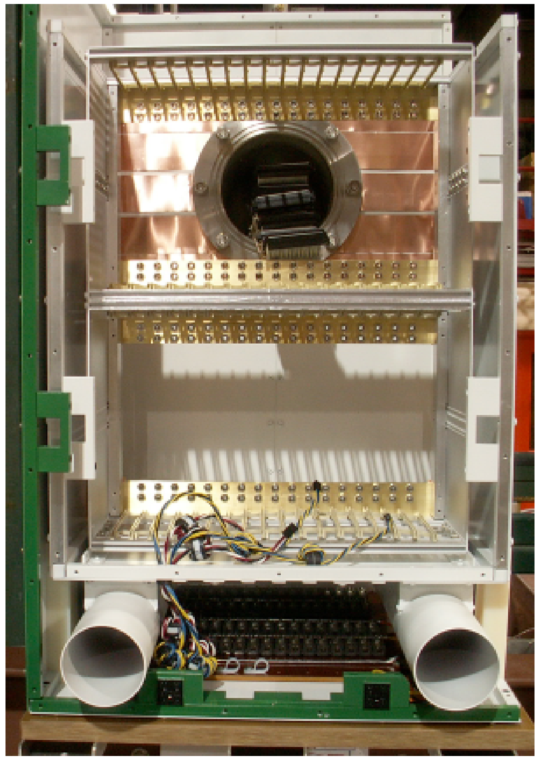
Preamp & filters



ADF2



Custom power supply

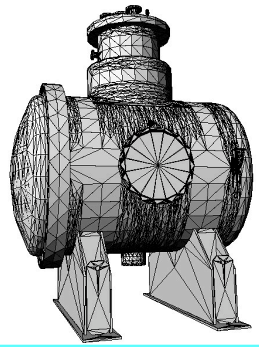


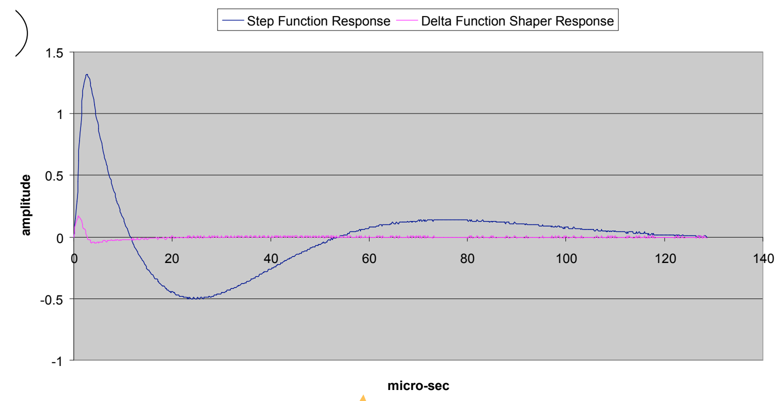
RF shielding & preamp cooling

ArgoNeuT: Software

- ArgoNeuT/MicroBooNE members developing GEANT4 simulation for LArTPCs
- Simulation is general purpose for future LArTPCs
- Would also like to begin development of automated event reconstruction

CAD geometry in GEANT4





Neutrino Generator Interface

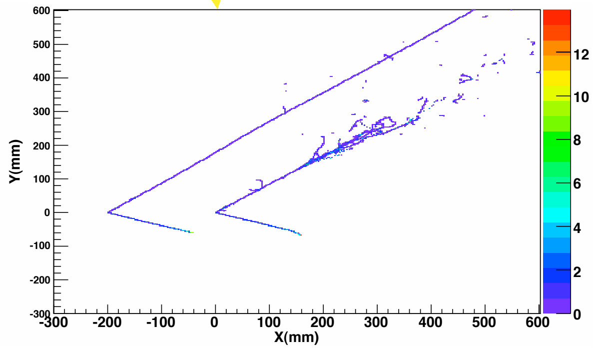
Geometry Description

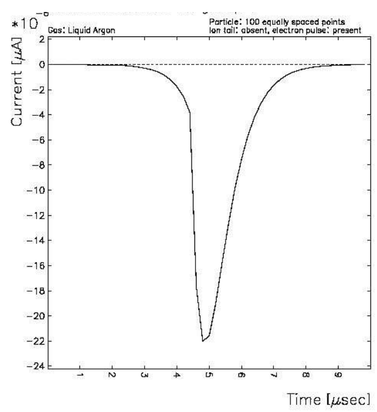
Pulse Formation

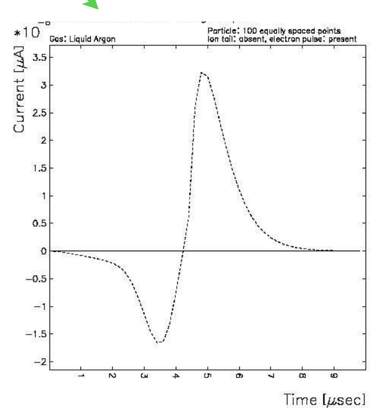
Electronics Simulation

Signal Processing

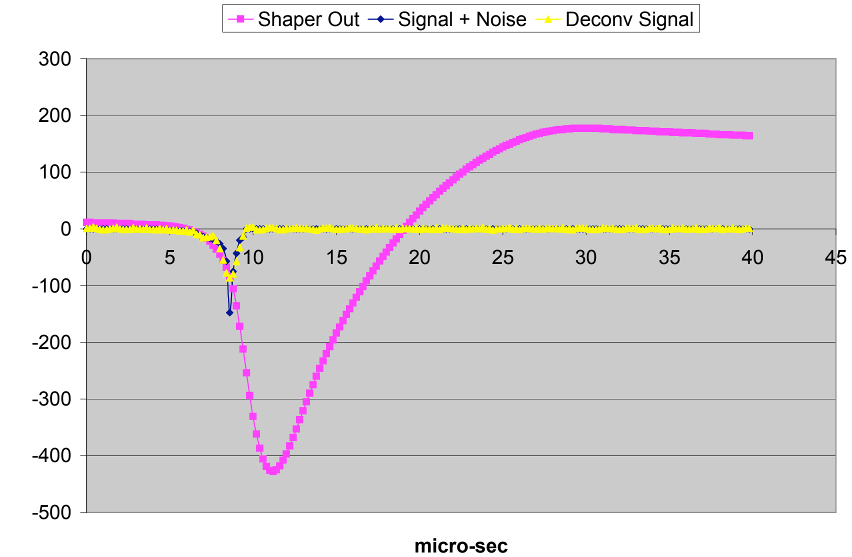
Automated Reconstruction







Collection/Induction Signals

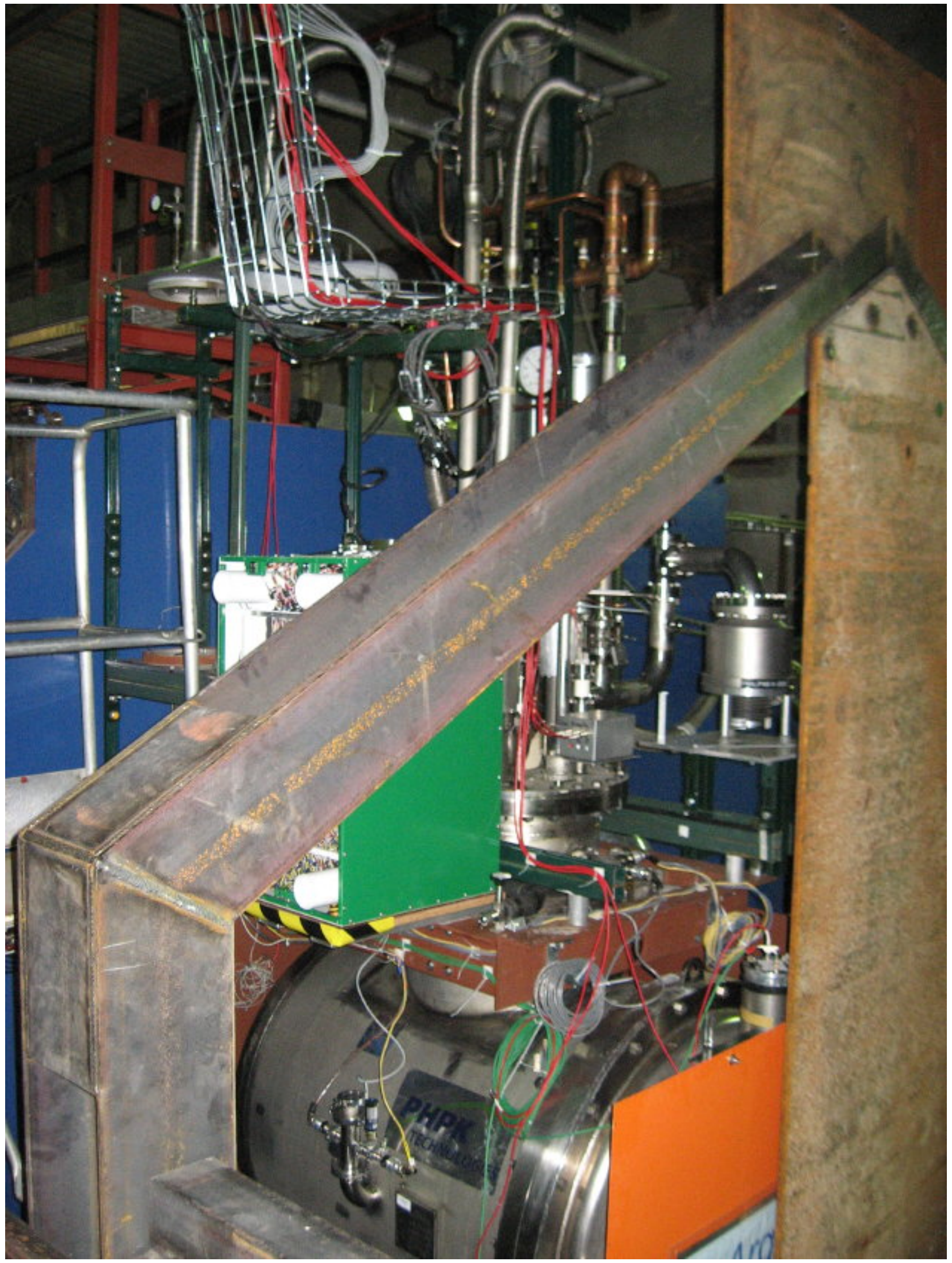


ArgoNeuT Outlook

- Flavio Cavanna will mention some details of our commissioning run last summer, and out physics potential.
- ArgoNeuT re-assembly underground almost complete
- Wedged between MINOS and Minerva.
- Expect to begin pumping down soon.

Lowering down the NuMI shaft

Event Type	# in 180 days (1.4×10^{20} PO)
ν_μ CC	28800
$\overline{\nu_\mu}$ CC	2520
ν_e CC	540
NC	9720



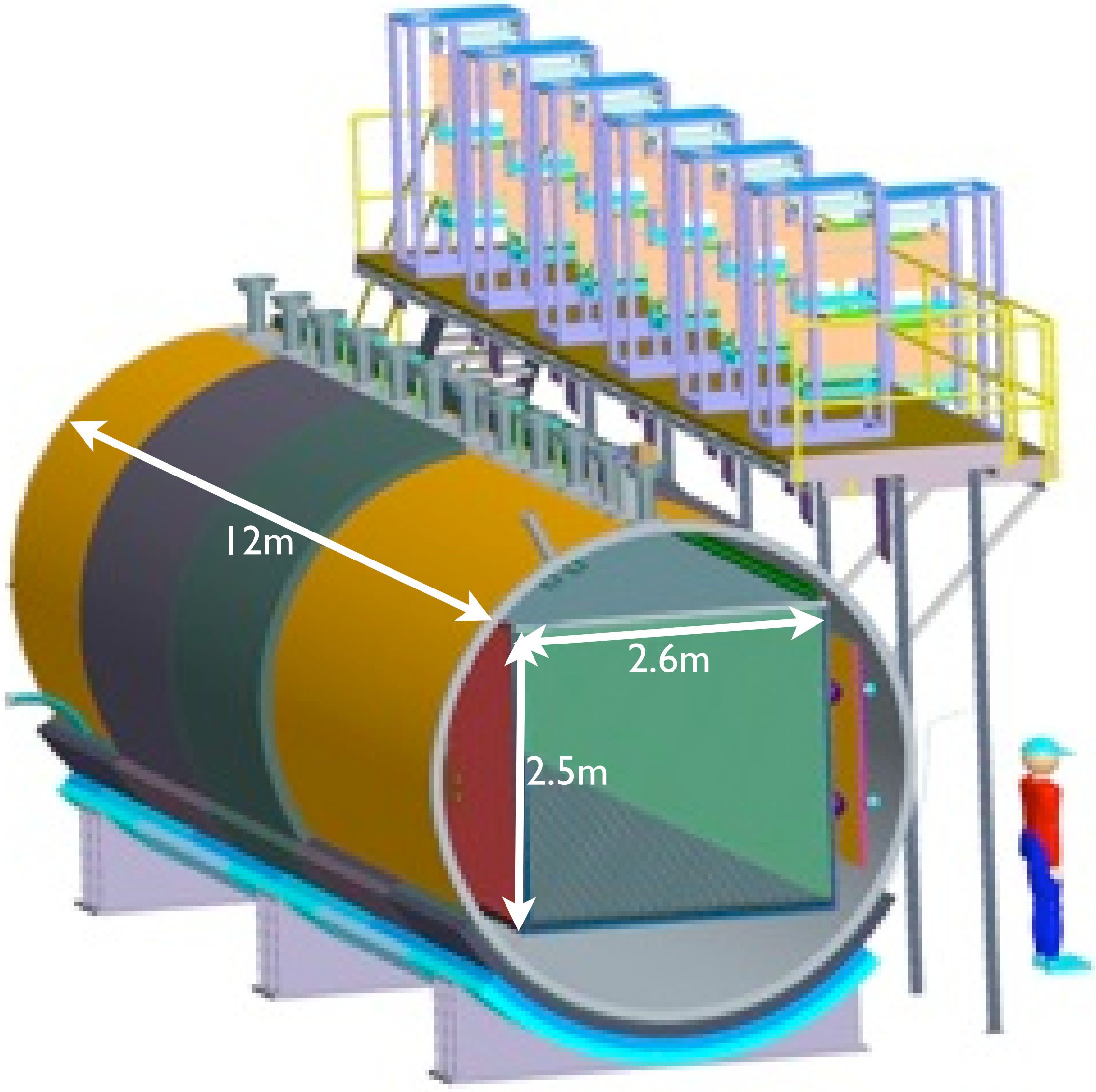
Last week: looking through Minerva frame.

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
- Purity test (purge with gas before beginning run)
- MiniBooNE excess
- Low-Energy Cross-Sections
- R&D Physics for larger detectors.

Stage 1 approval from Fermilab directorate in June 2008!



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

MicroBooNE Collaboration

H. Chen, J. Farrell, F. Lanni, D. Lissauer, D. Makowiecki, J. Mead,
V. Radeka, S. Rescia, J. Sondericker, C. Thorn, B. Yu
Brookhaven National Laboratory, Upton, NY

R. Johnson
University of Cincinnati, Cincinnati, OH

L. Camilleri, C. Mariani, M. Shaevitz, W. Willis‡
Columbia University, New York, NY

B. Baller, C. James, S. Pordes, G. Rameika, B. Rebel, D. Schmitz, J. Wu
Fermi National Accelerator Laboratory, Batavia, IL

G. Garvey, J. Gonzales, B. Louis, C. Mauger, G. Mills, Z. Pavlovic,
R. Van de Water, H. White, S. Zeller
Los Alamos National Laboratory, Los Alamos, NM

B. Barletta, L. Bugel, J. Conrad, G. Karagiorgi, T. Katori, V. Nguyen
Massachusetts Institute of Technology, Cambridge, MA

C. Bromberg, D. Edmunds
Michigan State University, Lansing, MI

K. McDonald, C. Lu, Q. He
Princeton University, Princeton, NJ

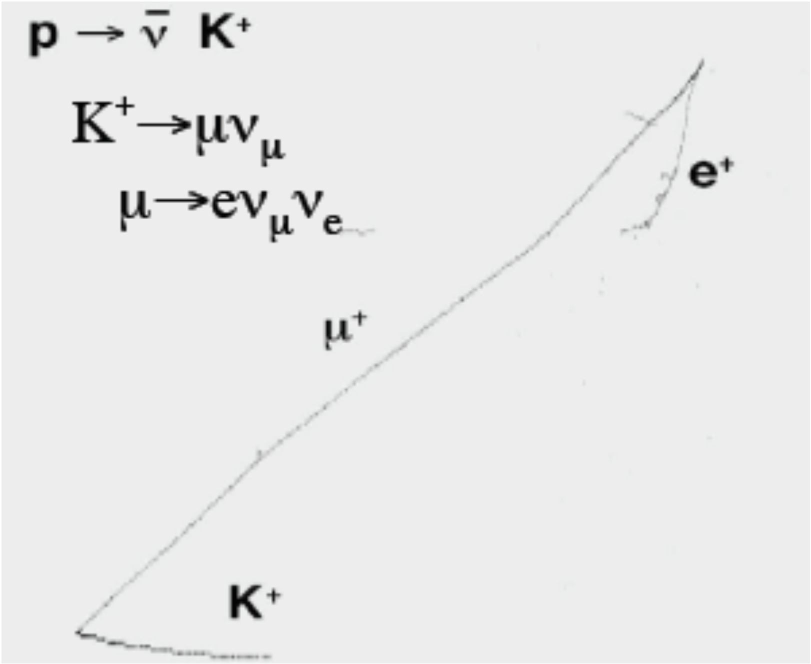
P. Nienaber
St. Mary's University of Minnesota, Winona, MN

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

C. Anderson, B. Fleming†, S. Linden, M. Soderberg, J. Spitz
Yale University, New Haven, CT

MicroBooNE: Physics Goals

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

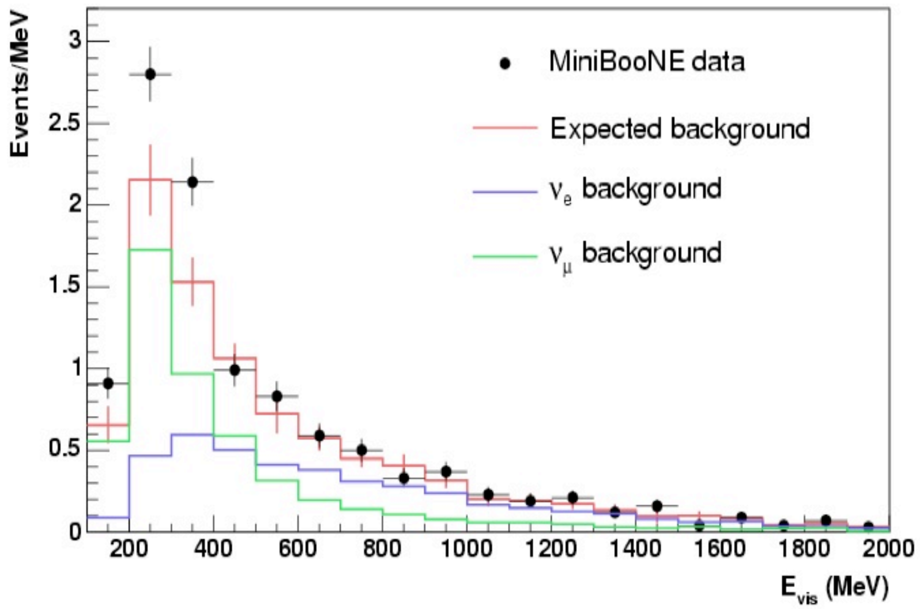


ICARUS Simulation

MiniBooNE Result Excess

200-300MeV: 45.2±26.0 events

300-475MeV: 83.7±24.5 events



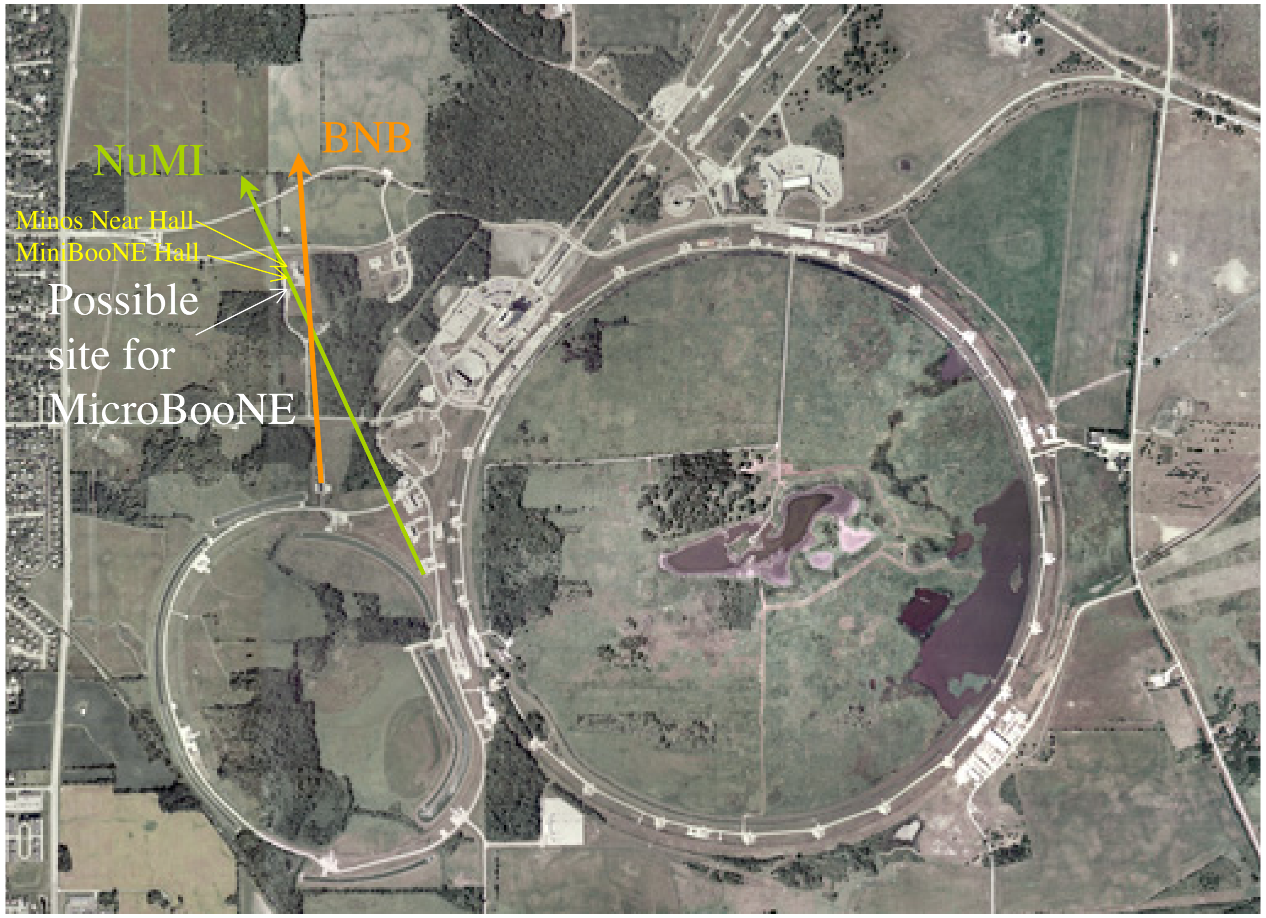
MicroBooNE will have 5σ significance for electron-like excess, 3.3σ for photon-like excess.

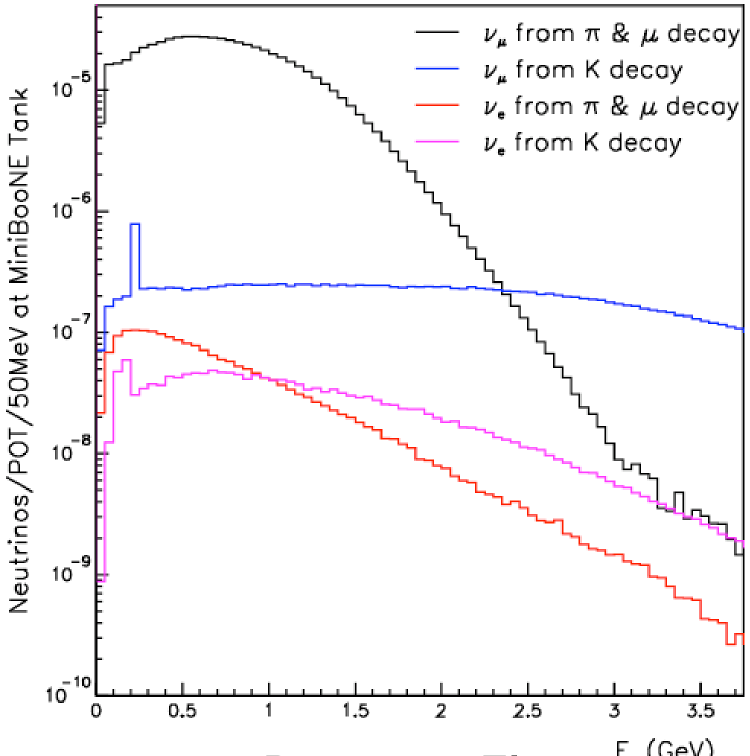
MicroBooNE: Location

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

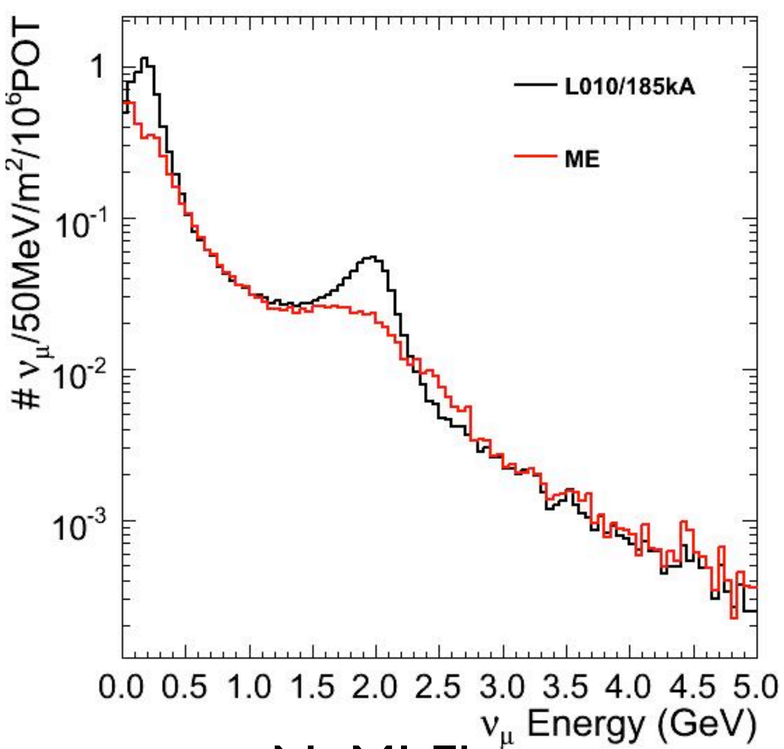
	BNB	NuMI
Total Events	145k	60k
ν_μ CCQE	68k	25k
NC π^o	8k	3k
ν_e CCQE	0.4k	1.2k
POT/year	$6x10^{20}$	$4x10^{20}$

Expected Event Rates for MicroBooNE.





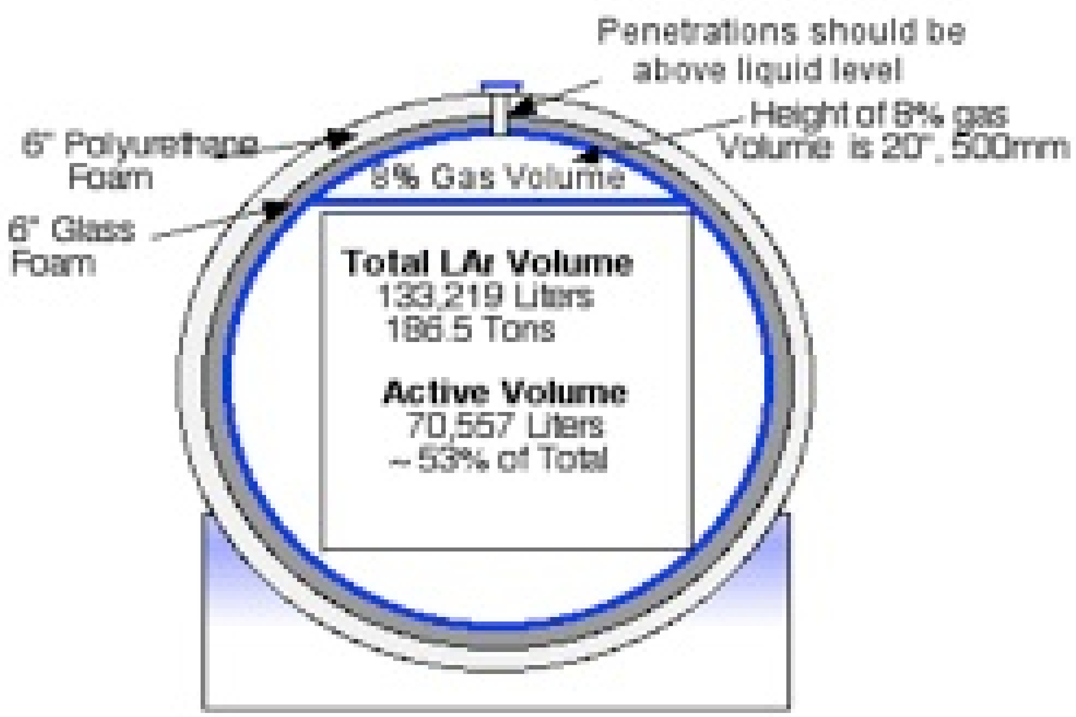
Booster Flux

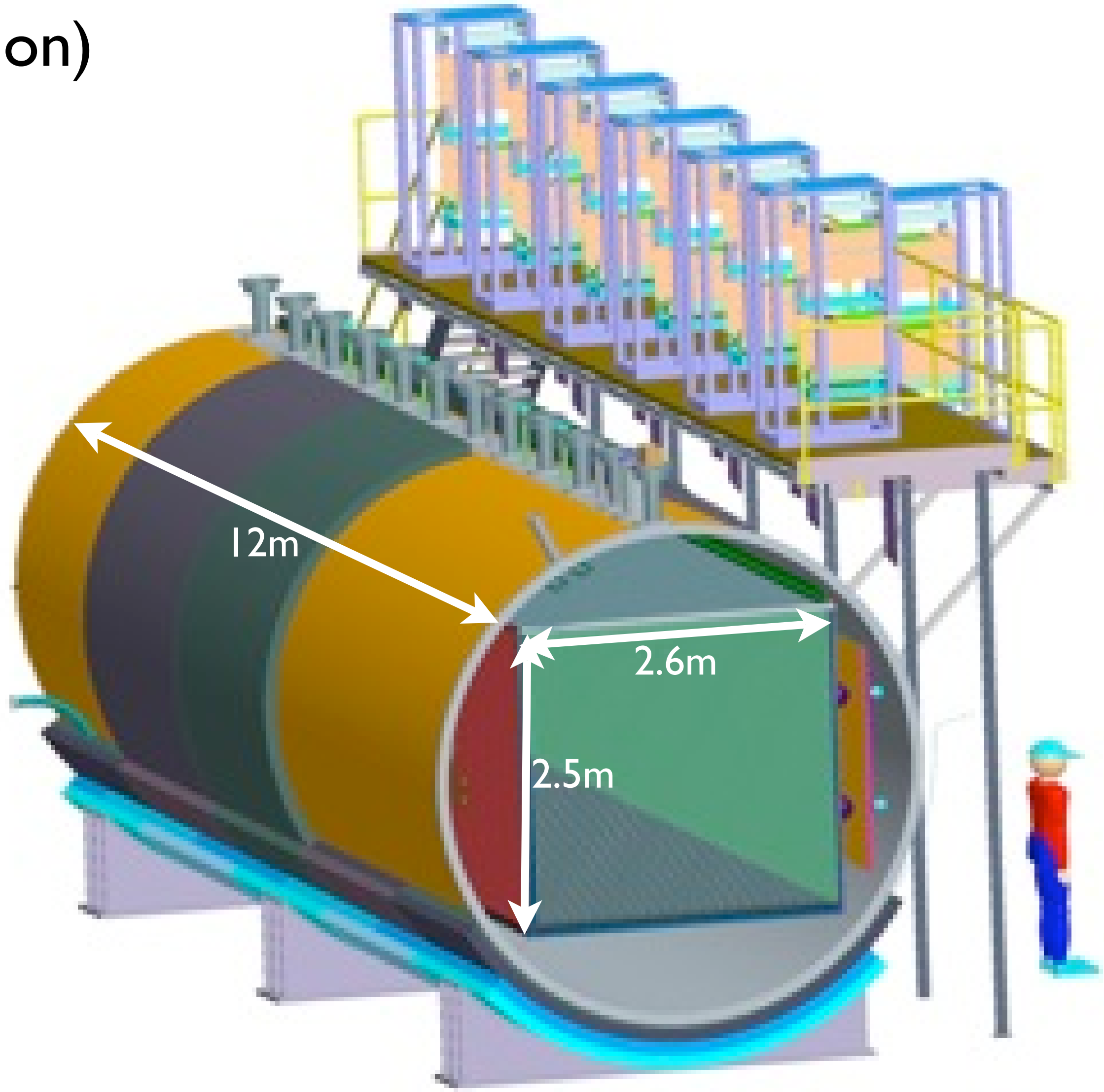


NuMI Flux

MicroBooNE: Design

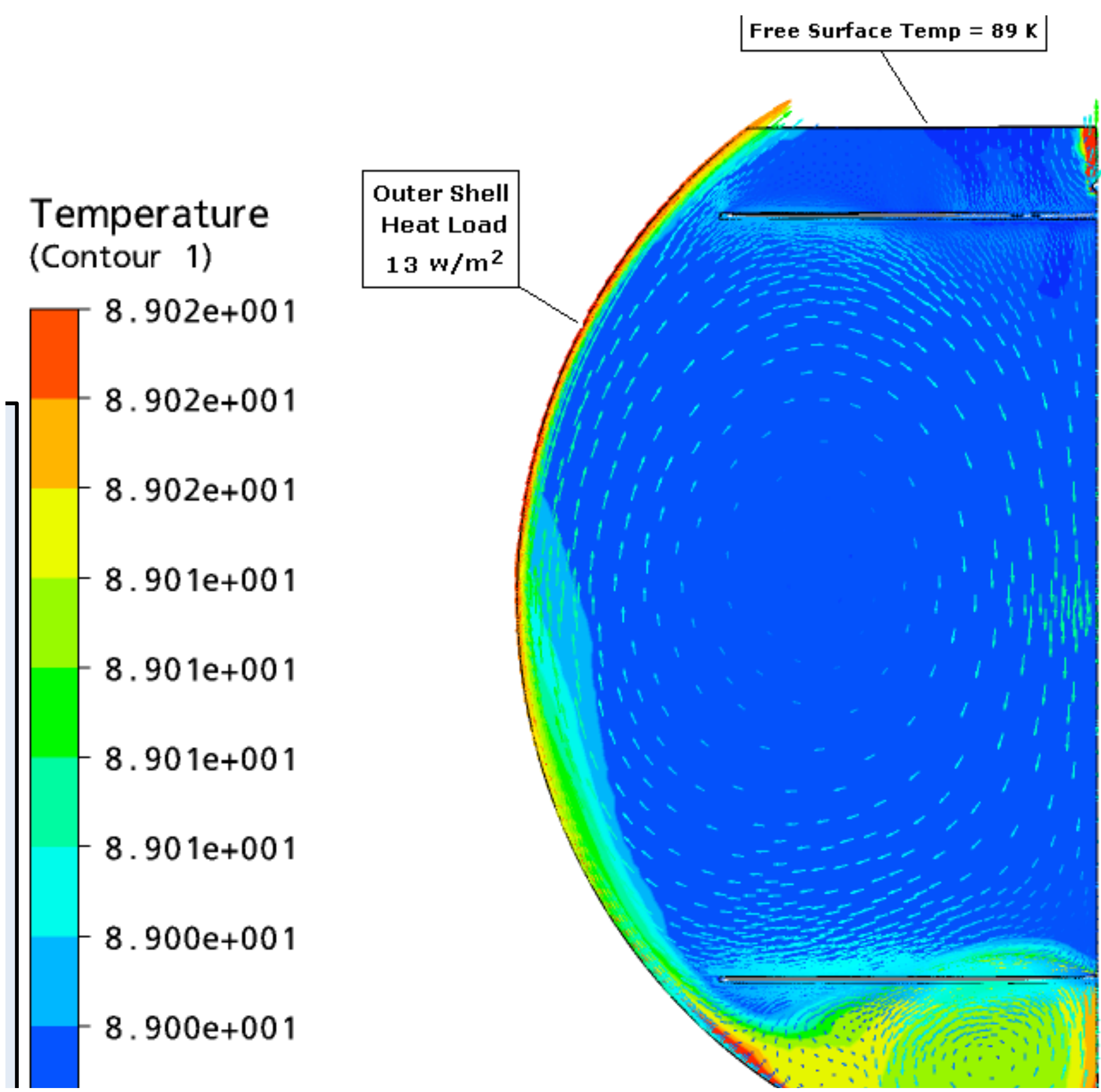
- Cryostat (170 Tons LAr) as large as can be commercially built offsite and delivered over the roads.
- TPC parameters
  - 70 Ton fiducial volume (depends on analysis definition)
  - 2.6m drift (500V/cm) ⇒1.6ms drift time
  - 3 readout planes (±30° Induction, vertical Collection)
  - 10000 channels (<u>using Cold Preamplifiers</u>)
- ~30 PMTs for triggering
- Purification/Recirculation system.



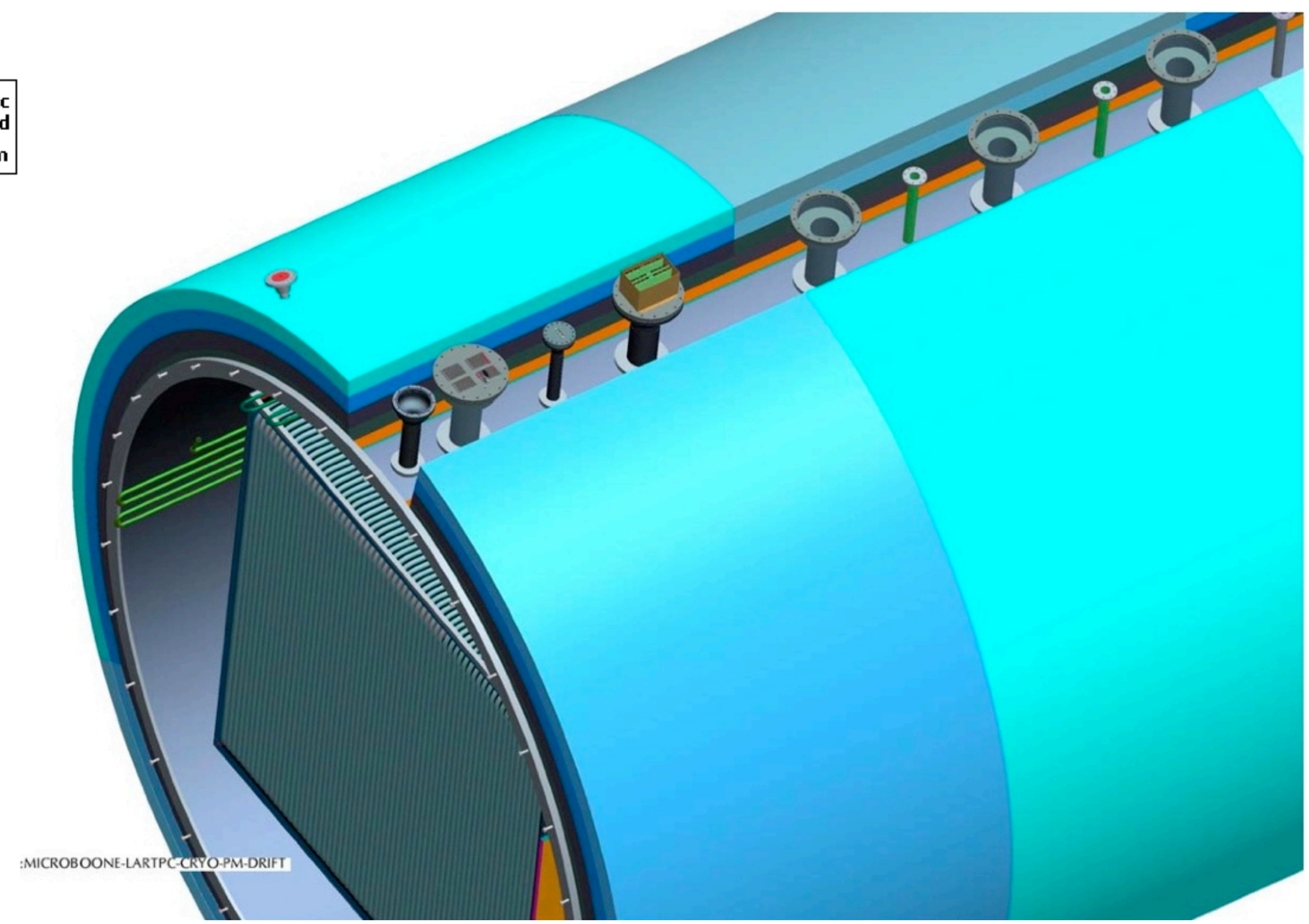


MicroBooNE Cryogenics

- 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.
- Services and TPC integration currently being designed.



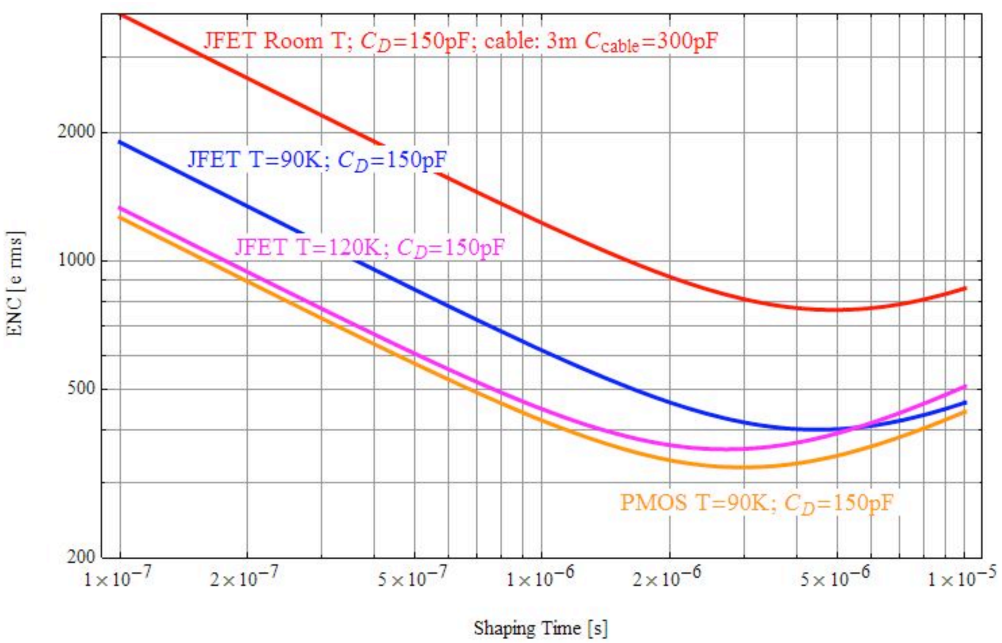
Temperature distribution



Detailed view of insulation/feedthroughs

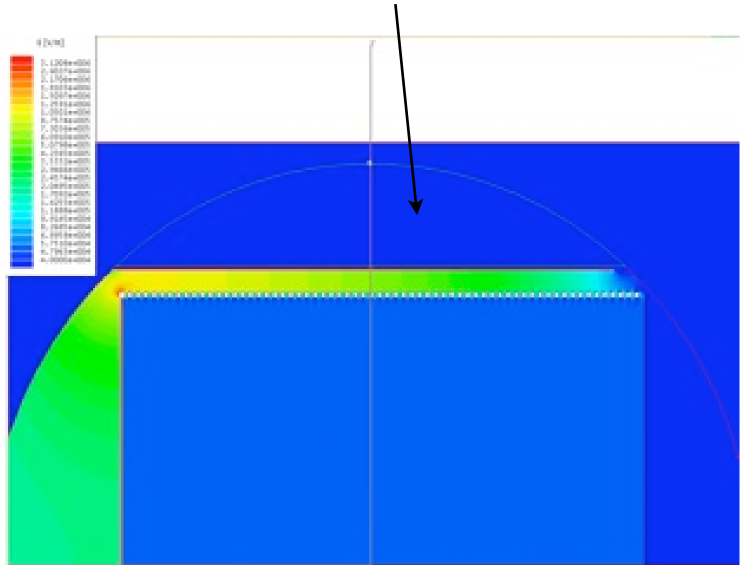
MicroBooNE: Cold Electronics

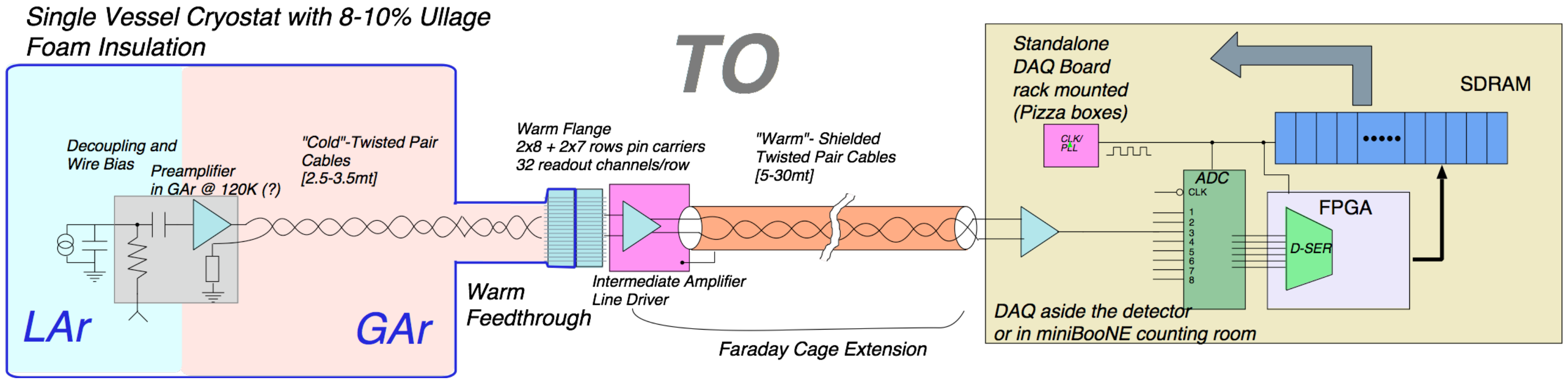
- Preamps will be placed inside of cryostat.
  - x3 better S/N compared with room temperature performance.
  - Necessary step along the path to large detectors where signals must make long transits.
- Many future Hardware questions can be answered by MicroBooNE.
  - JFET/CMOS performance (~4 year development 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

PreAmps in cold gas

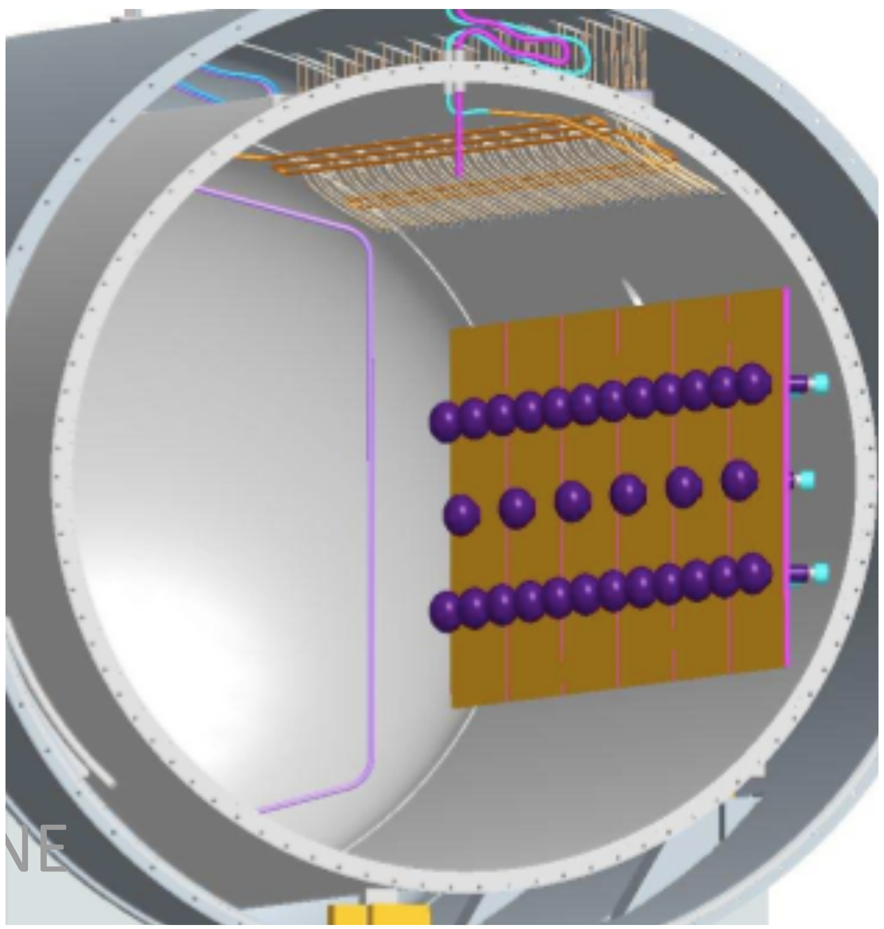




Readout Chain

MicroBooNE: Light Collection

- 30 PMTs to aid in t_0 determination and help reduce data load
  - *i.e.* - require coincidence of beam spill and light signal in PMTs
- 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 PMT holder/geometry/feedthroughs/etc.. ongoing.

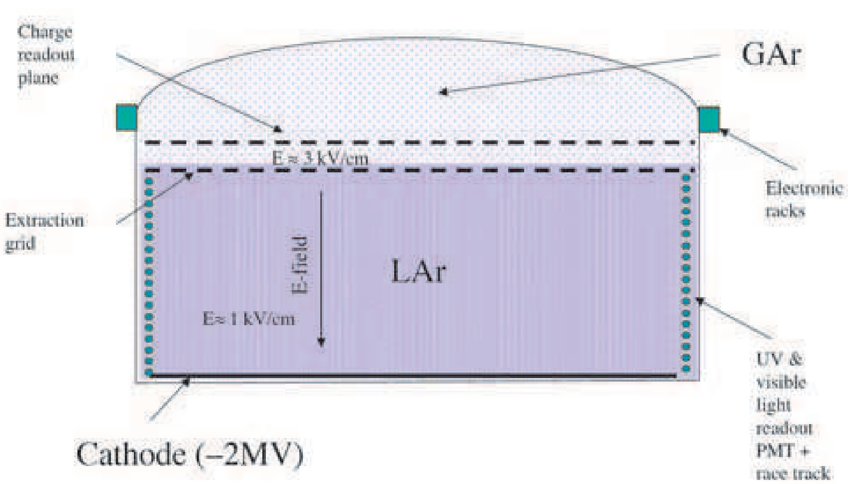


30 PMTs facing TPC

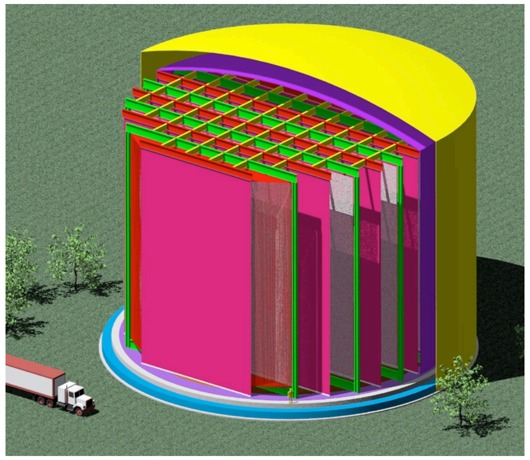
8” 9357FLA Electron Tubes PMT

Massive Detectors

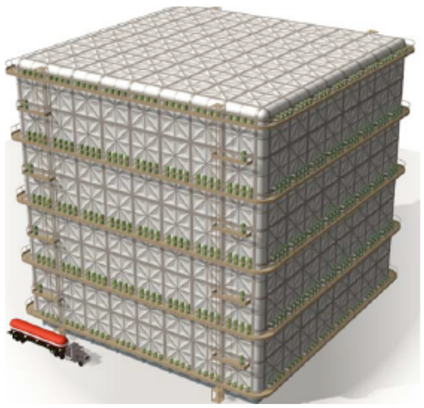
- Ultimate goal of this technology is a many kiloTon LArTPC located in a neutrino beam at a far site.
- Several detector ideas have been thought of... (see below)
- Reminder: Main technical challenges
  - Safety
  - Readout (long wires ⇒ increased capacitance ⇒ increased noise)
  - Long drift (diffusion of ionization will impact reconstruction)
  - Purification of large quantity of argon (not from a vacuum environment)
  - Surface cosmic ray rates
  - Underground construction technique
  - Huge quantities of data!



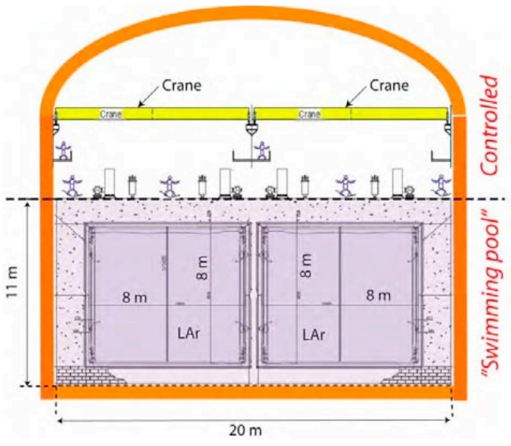
GLACIER



FLARE



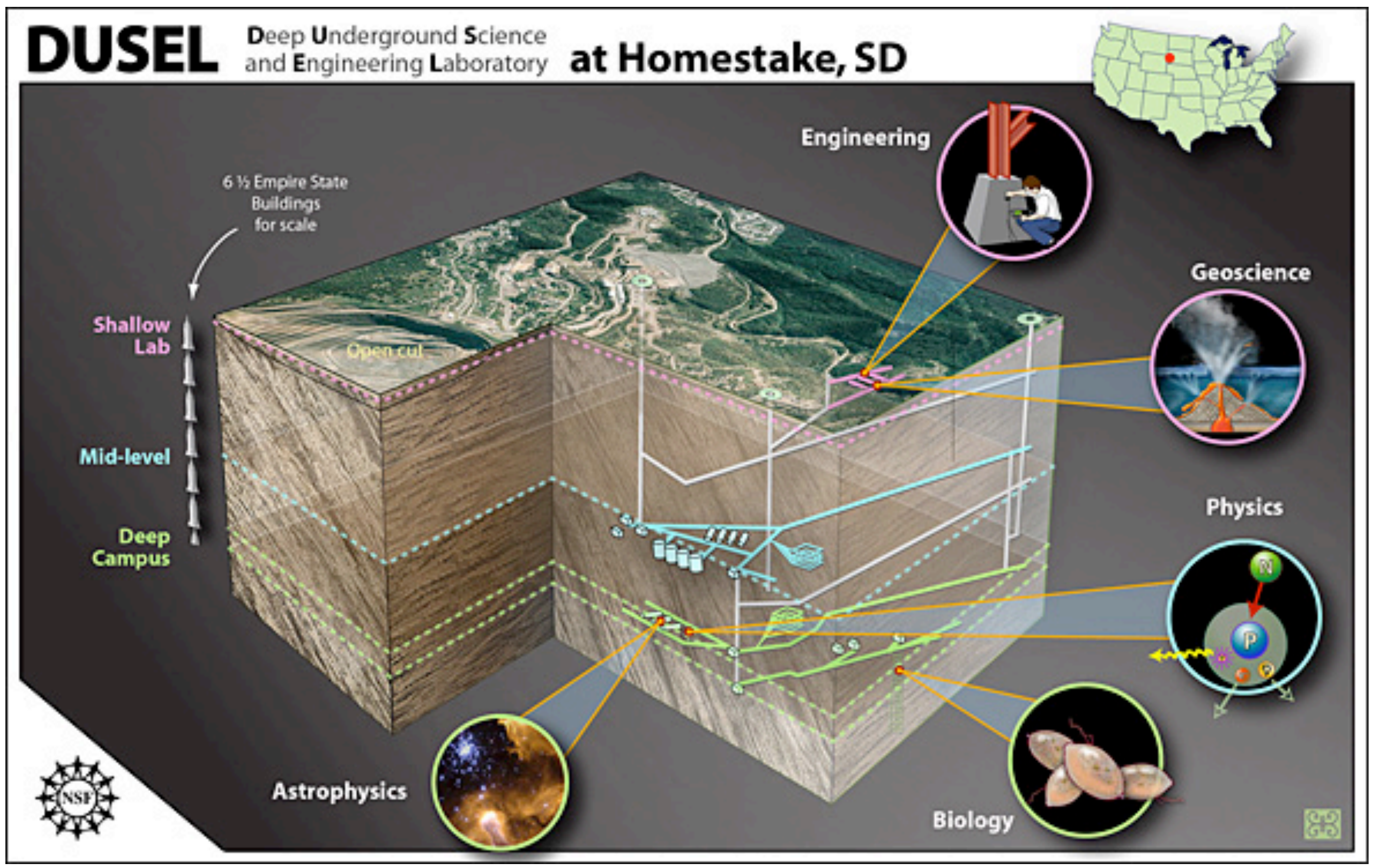
LANNDD

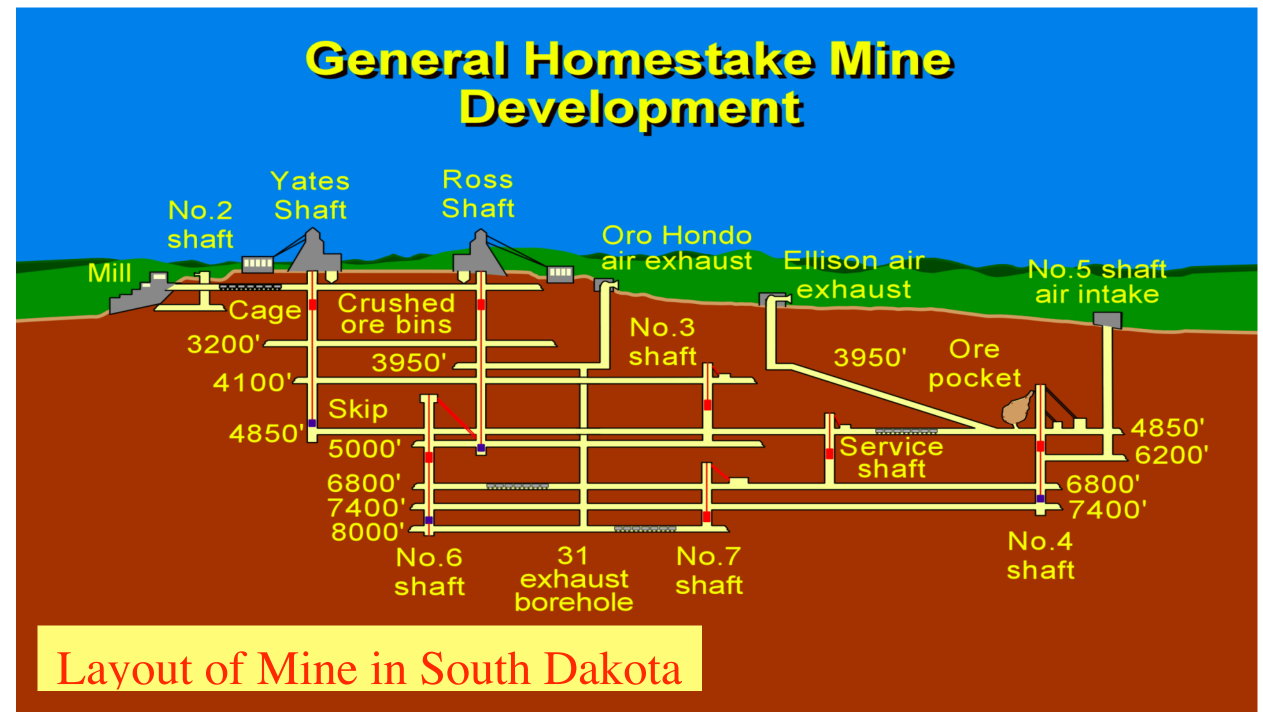


MODULAR

Massive Detector Location

•Prefer to put this huge detector someplace very deep (e.g. - Homestake Mine in South Dakota, Soudan Mine in Minnesota) to reduce cosmic background.
•Proposed Project X at Fermilab sends intense neutrino beam 1300km to this far-site location.
•Working groups already forming in U.S. to explore possibility of massive detector at DUSEL.



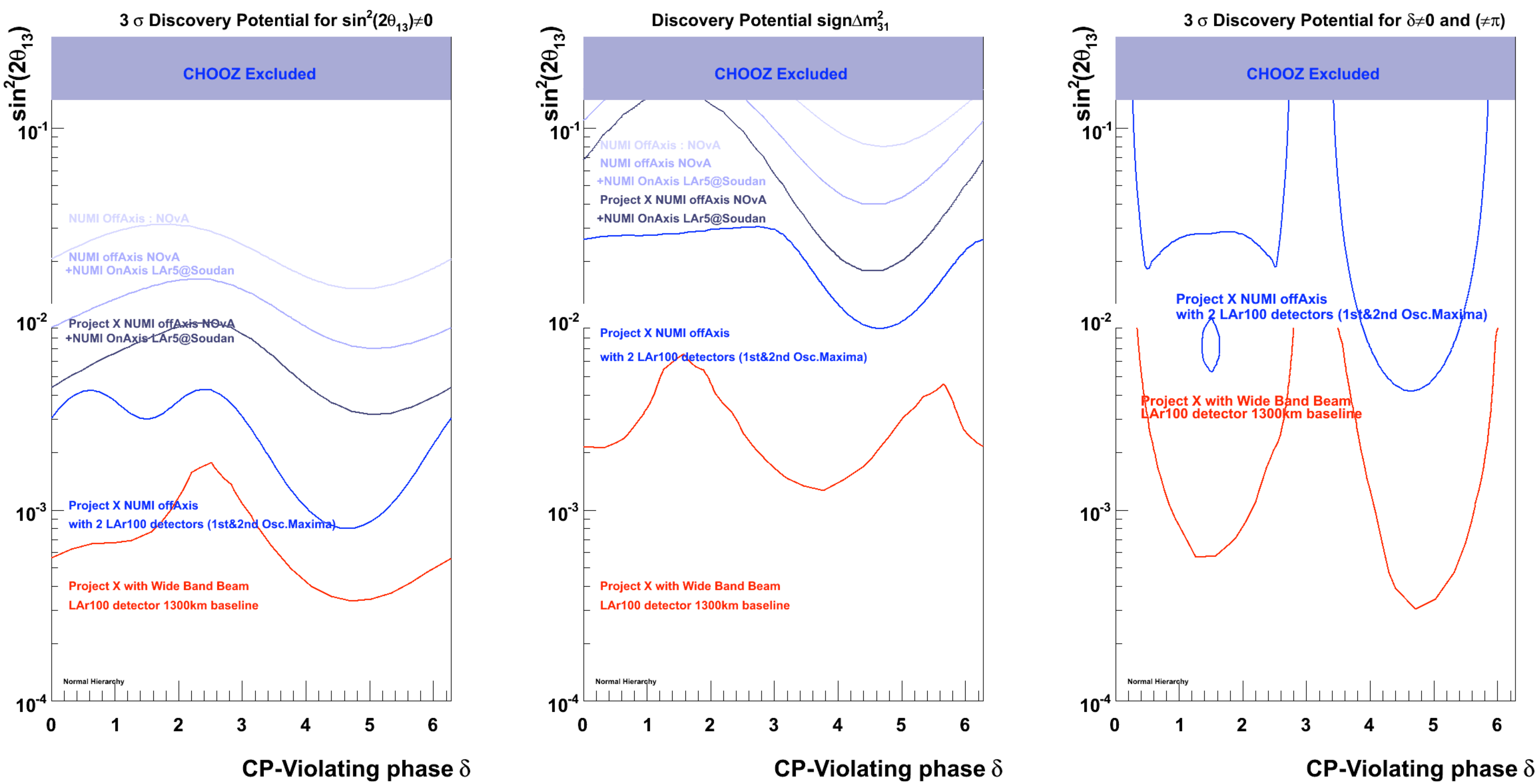


Layout of Mine in South Dakota

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

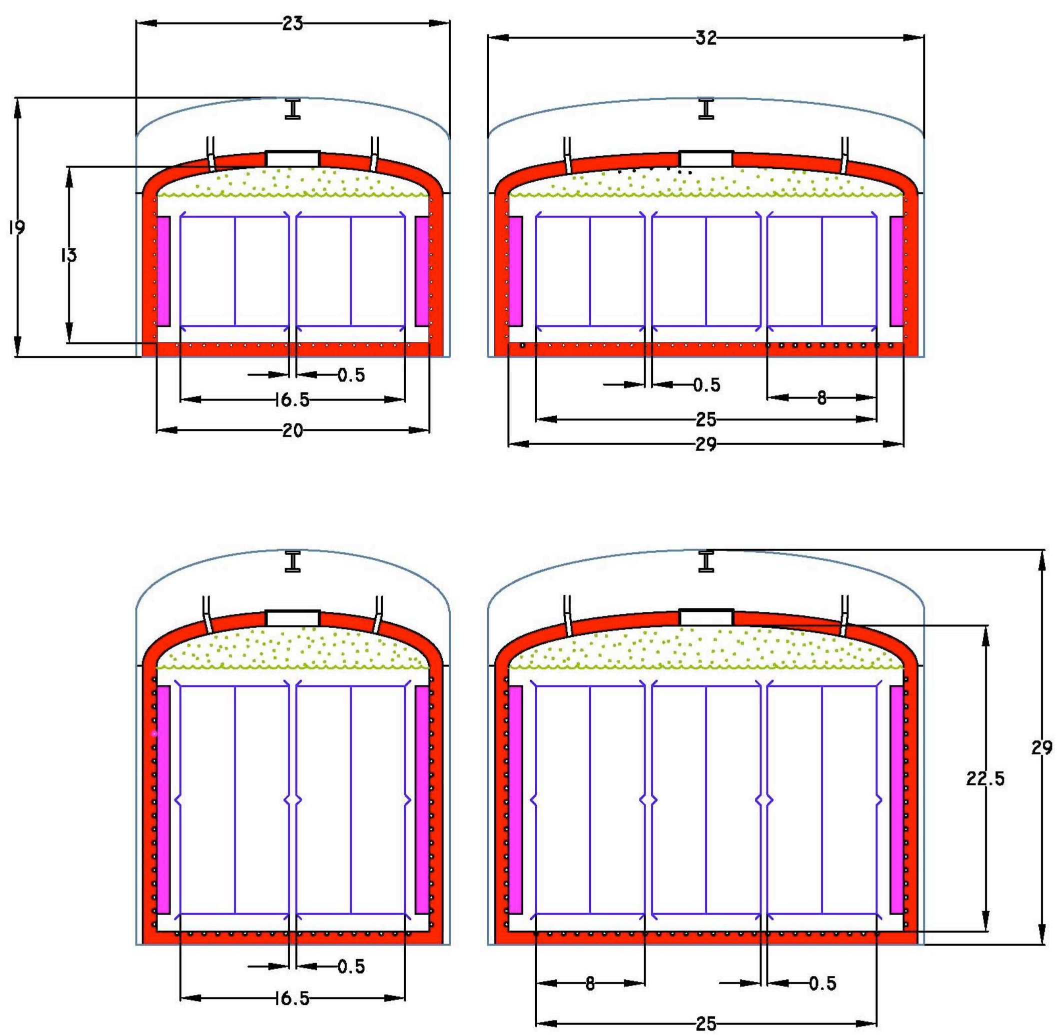
- Tremendous sensitivity when large LArTPC and intense neutrino beam are combined.
- Fermilab has proposed to build an intense neutrino source (known as Project X)
- LArTPC scenarios depicted below (thanks to Niki Saoulidou) assume:
  - 3 years neutrino + 3 years antineutrino
  - 80% signal efficiency and 80% intrinsic beam ν_e selection efficiency.
  - no NC π^0 background (thanks to dE/dx capability) and 5% systematic on background.



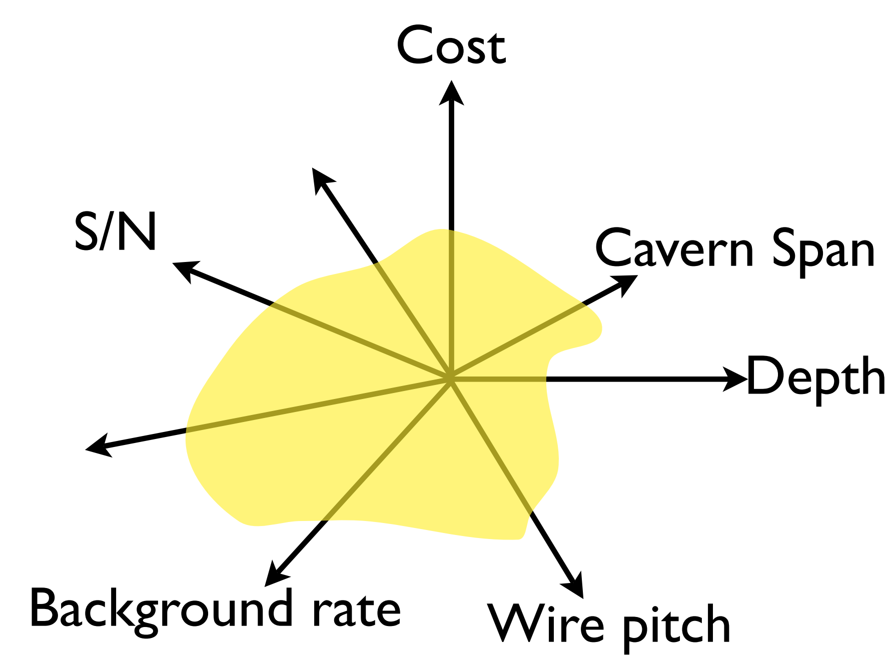
DUSEL: Cavern Layout

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? Triggering?)
- Cost differential for different depths: Excavation cost, assembly cost differential , Safety issues, ...
- Span of cavern is crucial design parameter.
- Detector design: Modular design vs. single argon volume.
- Evolution: Start with 5kiloTon detector and expand later?



Cavern/Cryostat designs are coupled.



Trying to find optimum point in N-dimensional phase space...

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 constraints into the detector/cavern design from the start.

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.;
  - will perform many physics measurements
  - will investigate important hardware questions before attempting to build very massive detector
- LAr collaboration for a massive detector is forming.

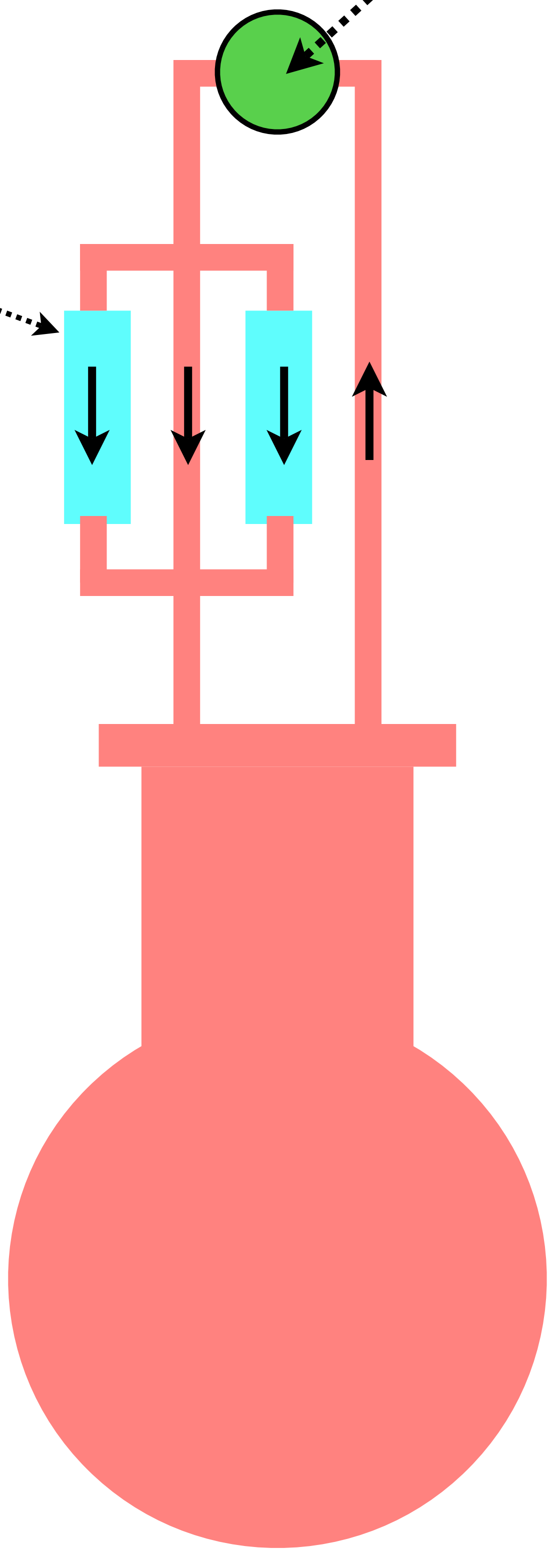
Back-Up Slides

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

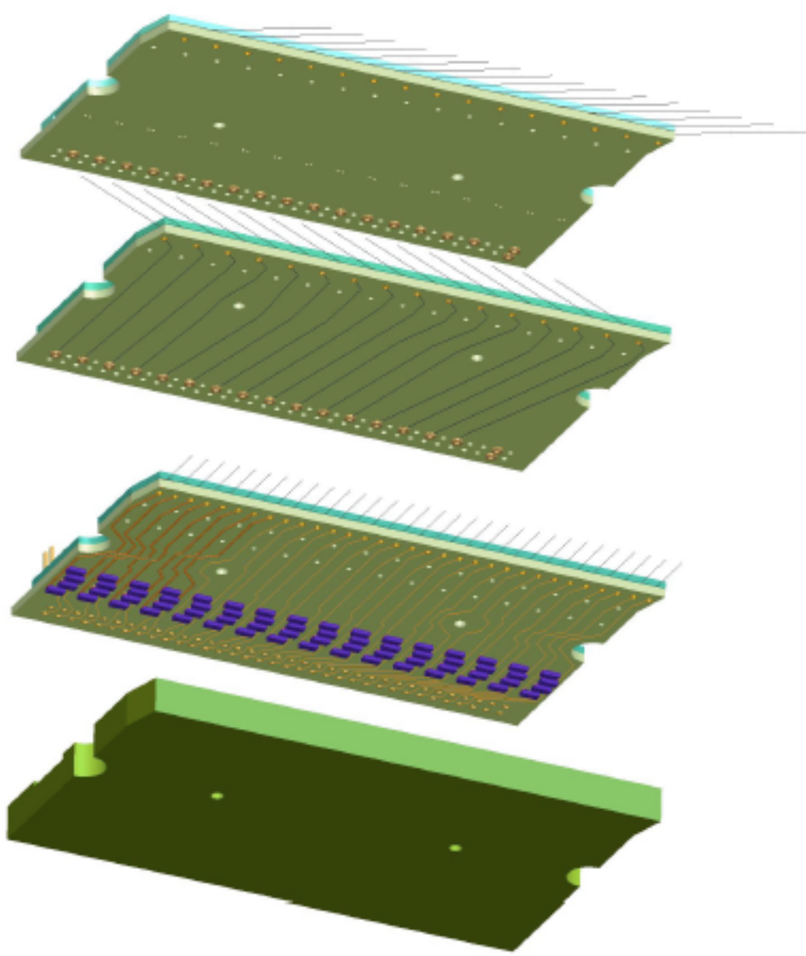
Many safety issues addressed to prepare for move underground and maintain ODH-0 rating of NuMI tunnel:

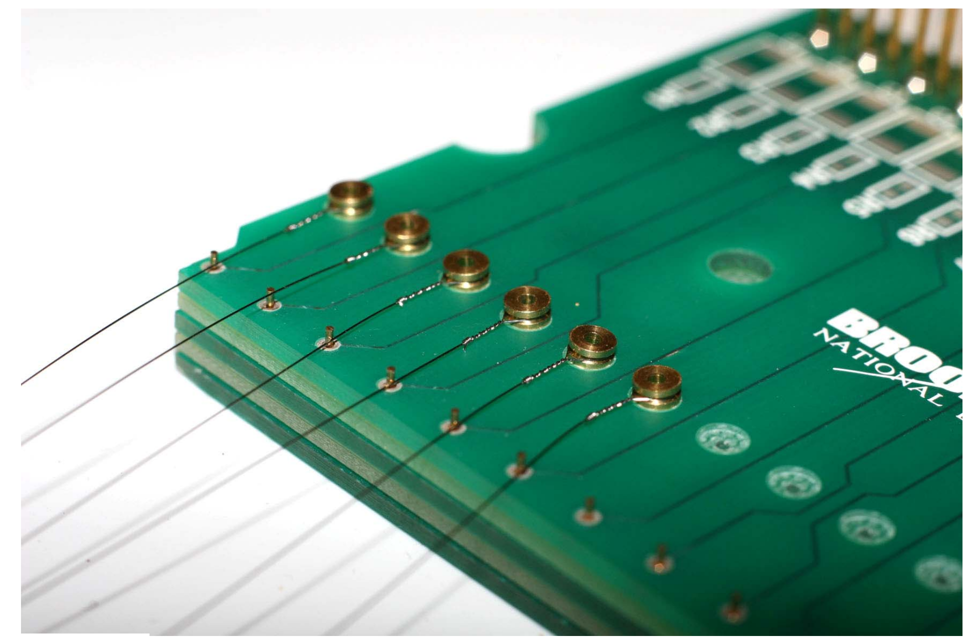
- ArgoNeuT sits in a bathtub, which acts as tertiary containment in case both cryostats fail.
- Relief piping is routed to vent line (runs up and out shaft), to ensure no argon released in tunnel.
- 2 ODH monitors to alarm if leak is detected.
- Slow control system mirrored on screens in tunnel and surface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

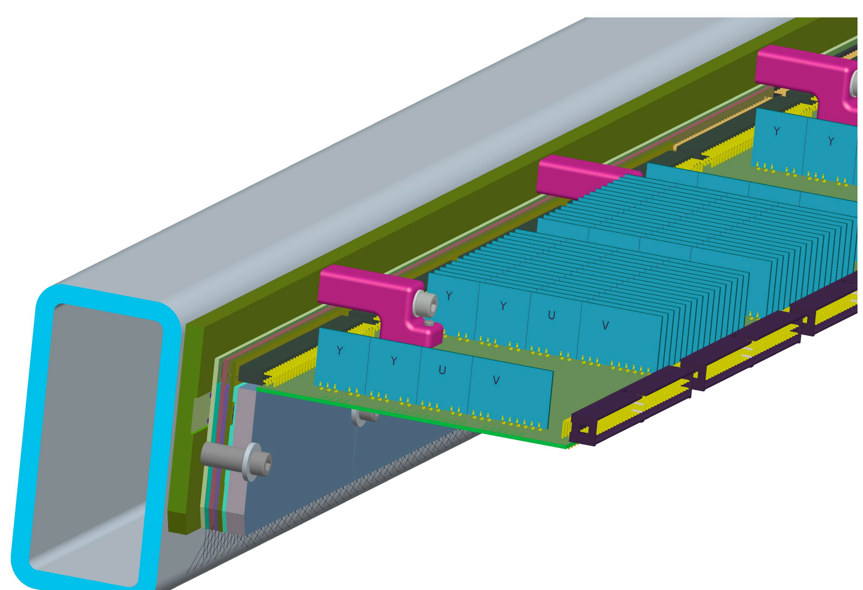
ArgoNeuT under construction this summer.

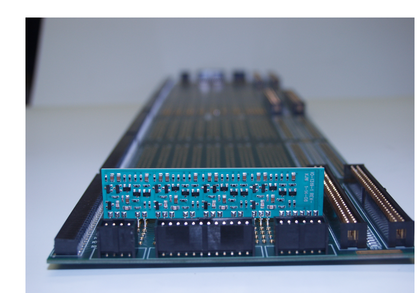
MicroBooNE: Wire Connections

- Wire connections from 3 wireplanes made in tight space
- Decoupling capacitors located on wireplane assembly.
- BNL group has developed wire winding apparatus.
- Several wires being considered. Must withstand tension increase of cooldown.



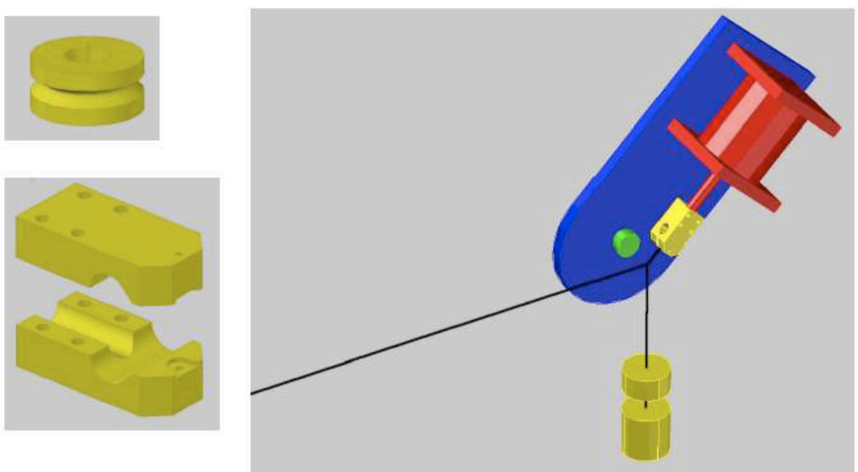


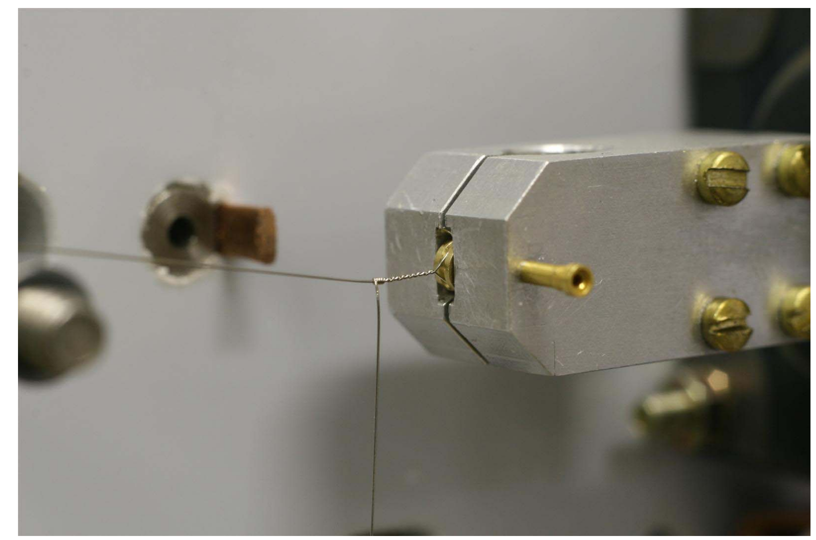




MicroBooNE Wire Properties

- 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





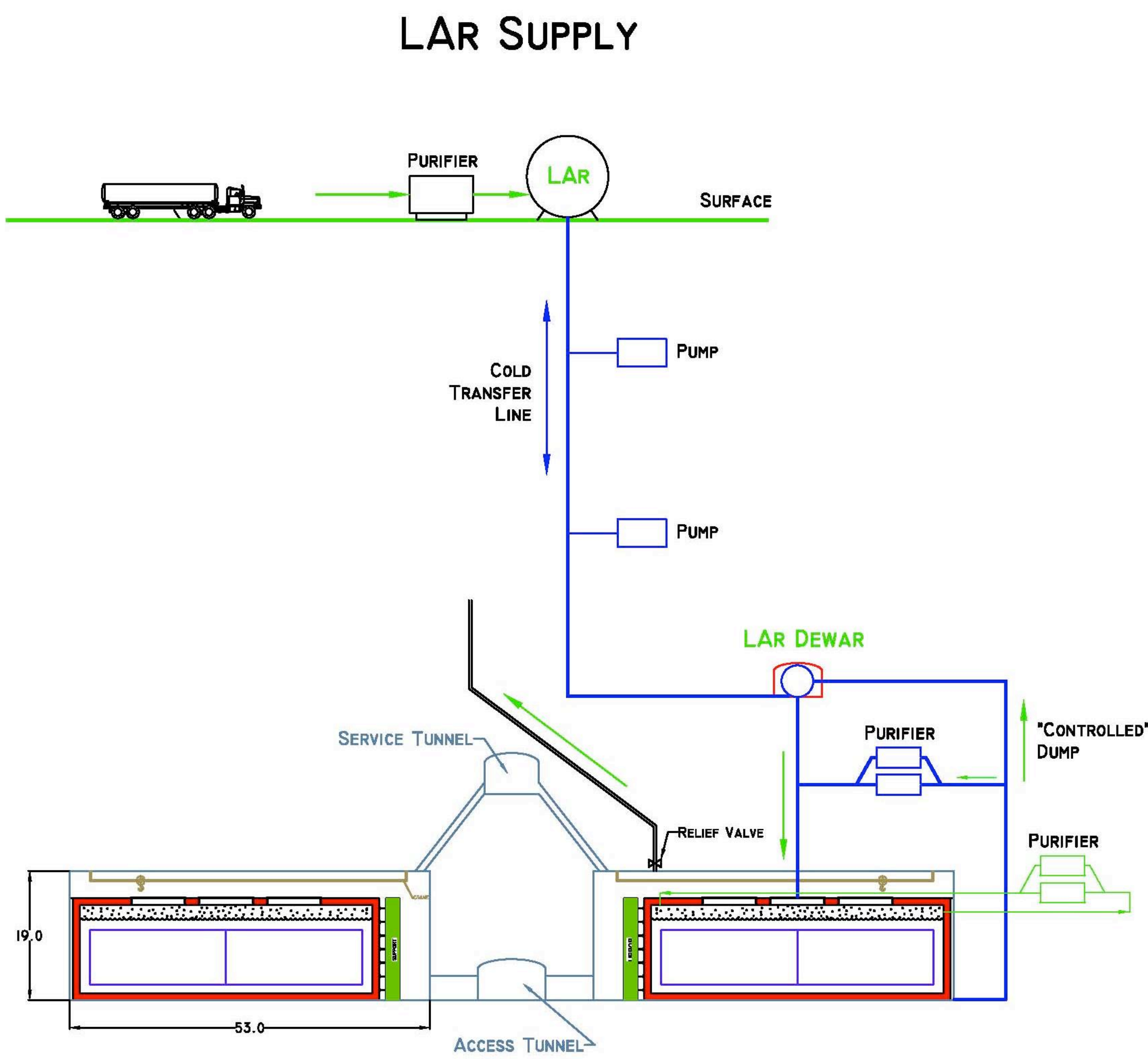
	SS304V (Fort Wayne)	CuBe (Little Falls Alloy)
Young's modulus @ RT	170GPa	121GPa
Young's modulus @ LN2	183GPa (8% increase)	136GPa (12% increase)
Integral CTE	0.22%	0.29%
Tension increase due to cooling	~750g	~730g
Max. tension with termination	~3kg	~2kg

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