Liquid Argon Detector Developments in the U.S.

Mitch Soderberg
on behalf of many colleagues in the U.S. and abroad
NNN 2013

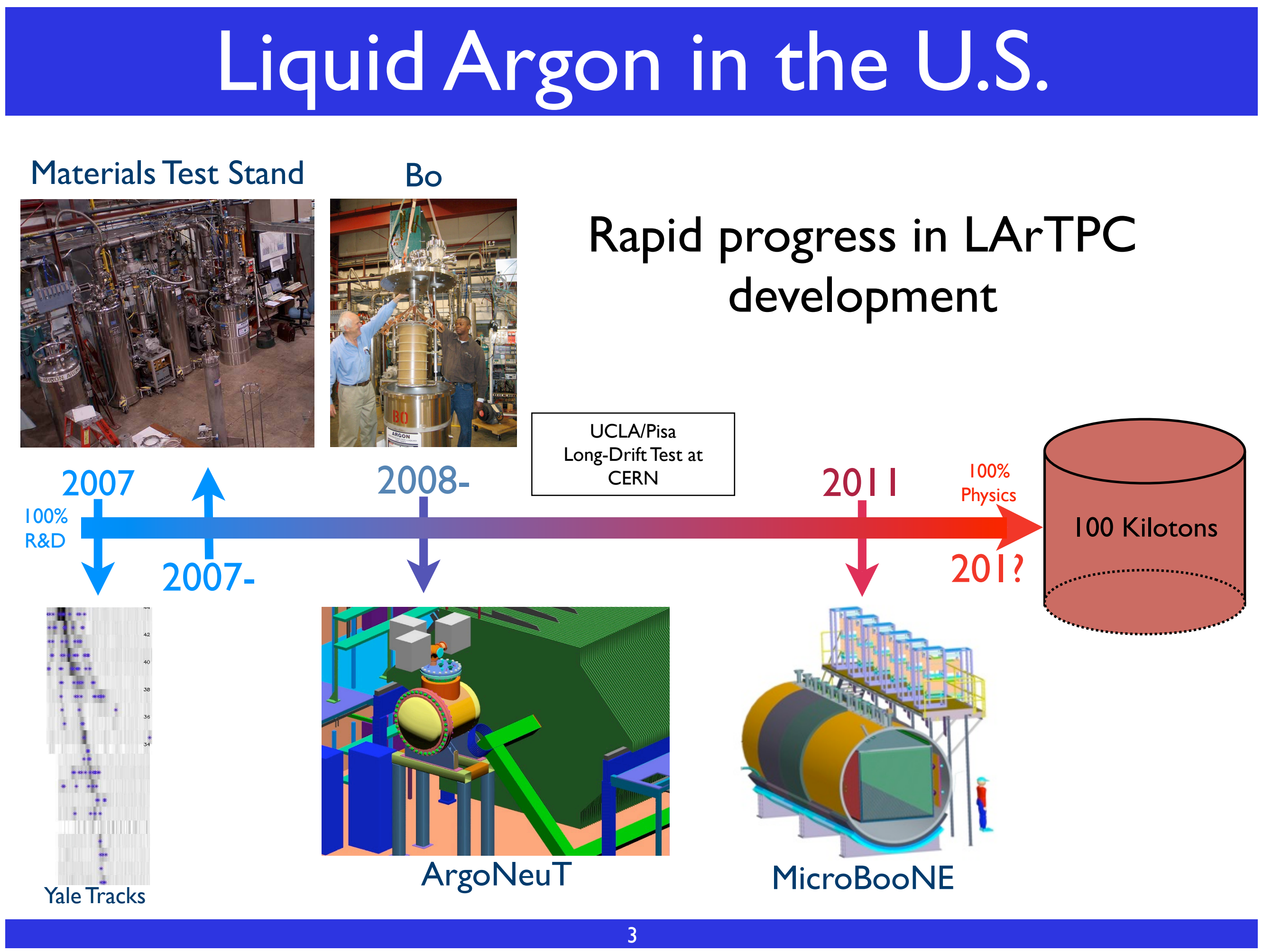
Introduction

- Liquid Argon Time Projection Chambers (LArTPCs) are imaging detectors that offer exceptional capabilities for studying neutrinos.
- In this workshop you've heard about pioneering work done by ICARUS, and you've just heard about physics potential of this technology.
- I will give an overview of recent LArTPC activities in the U.S., focusing mainly on technical developments, which has become a very daunting task due to the wide array of projects underway.

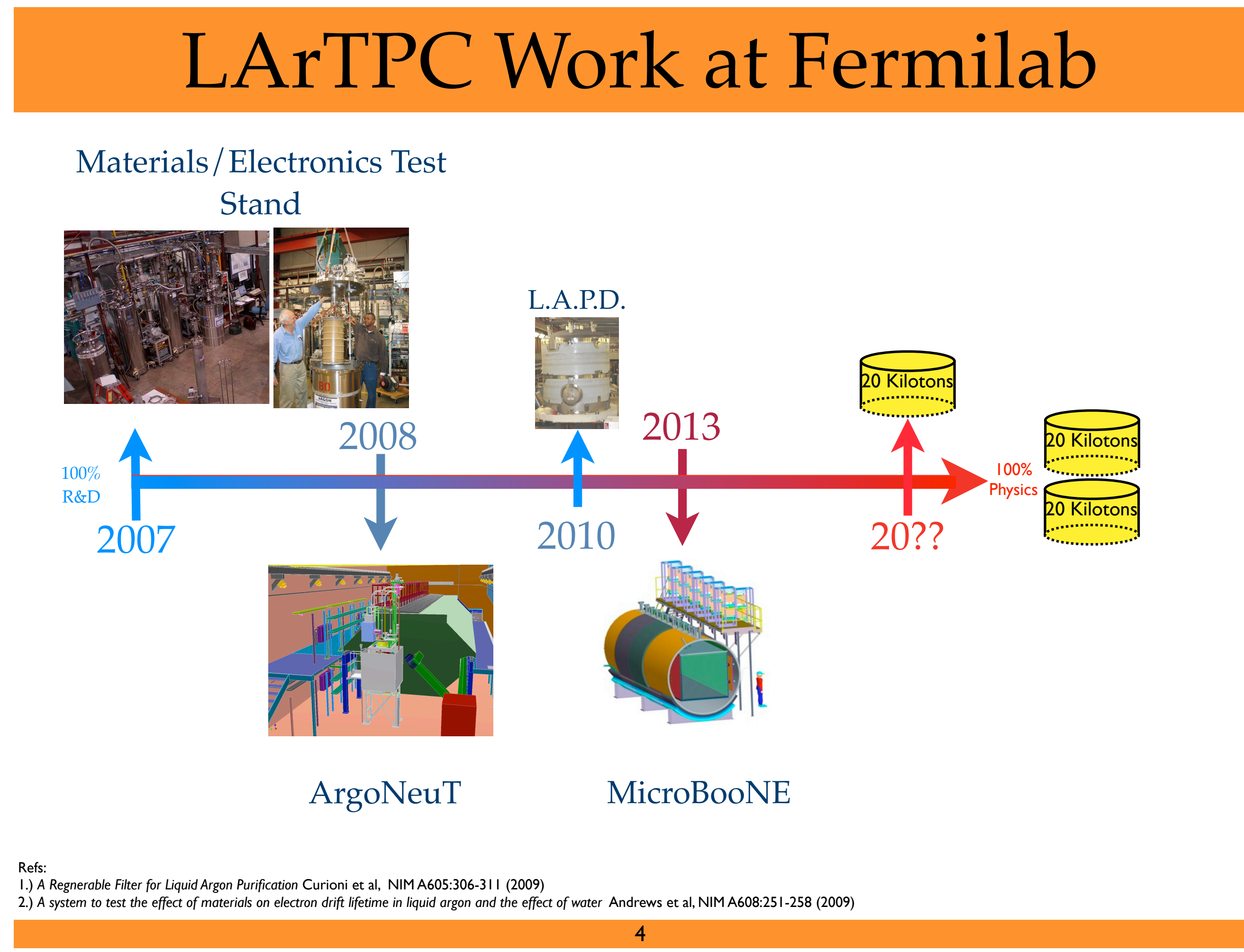
Before I Start...

It seems to be something of a tradition at NNN to have a talk that summarizes LArTPC work in the U.S. and elsewhere.

NNN 08: Paris, France



NNN 10: Toyama, Japan



Our ideas continue to evolve, and enthusiasm for this combination of physics and technology only seems to grow.

An opinion, since this is a workshop...

In the past ~2 years in the U.S. we seem (to me at least) to have crossed a "tipping point" where the idea that massive, kiloton-scale LArTPCs are technically possible has become accepted within the community.

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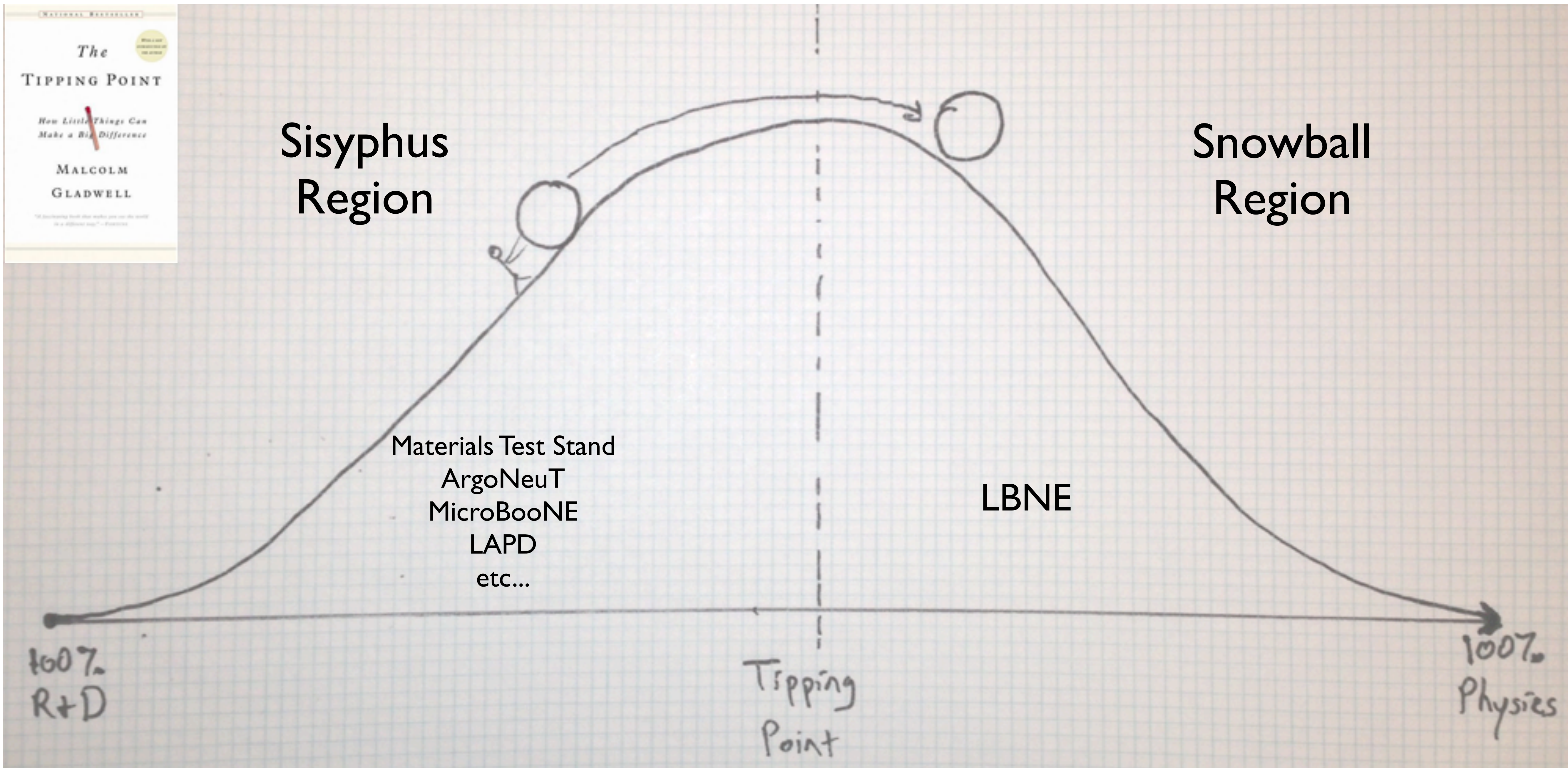

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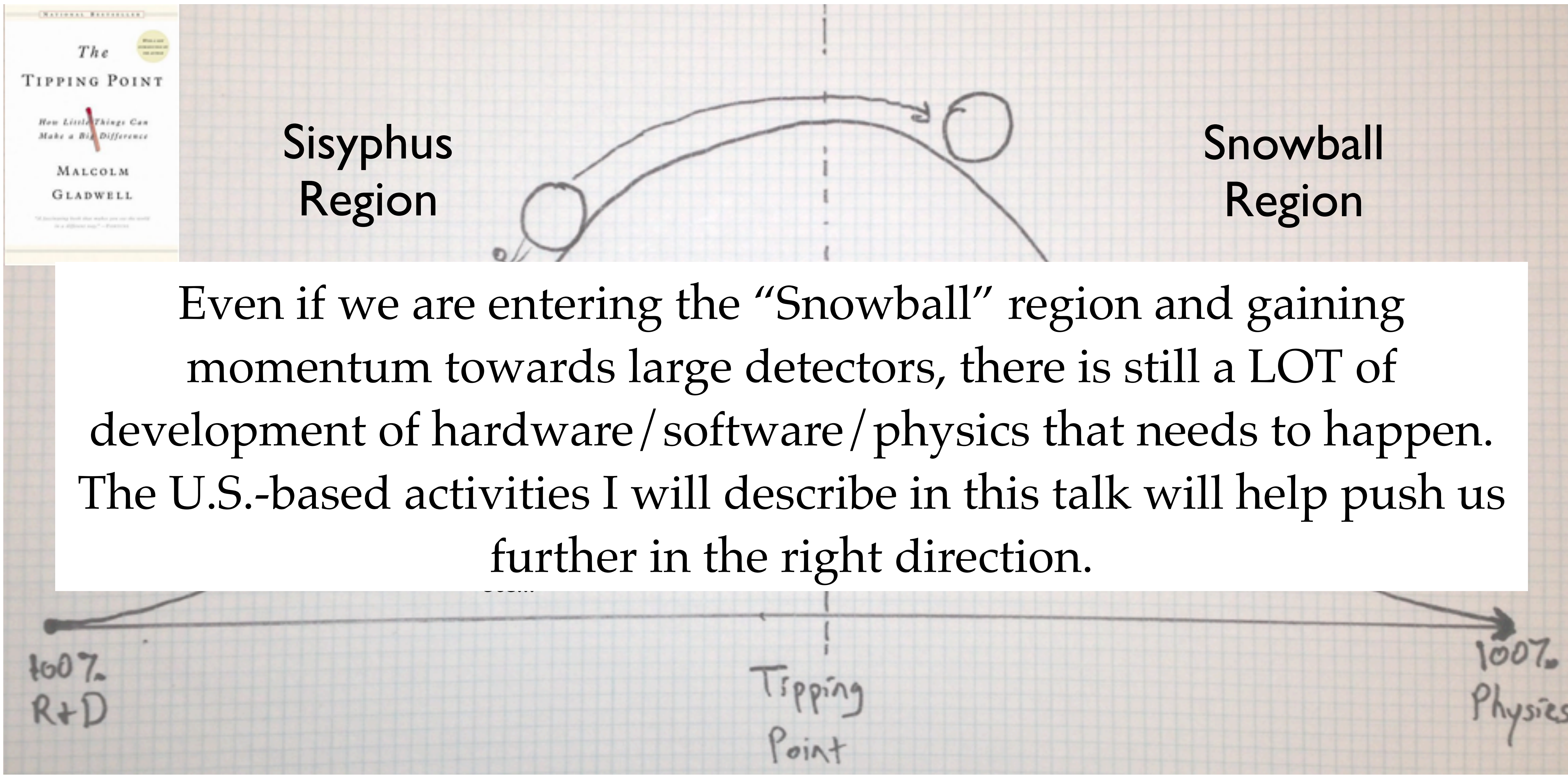
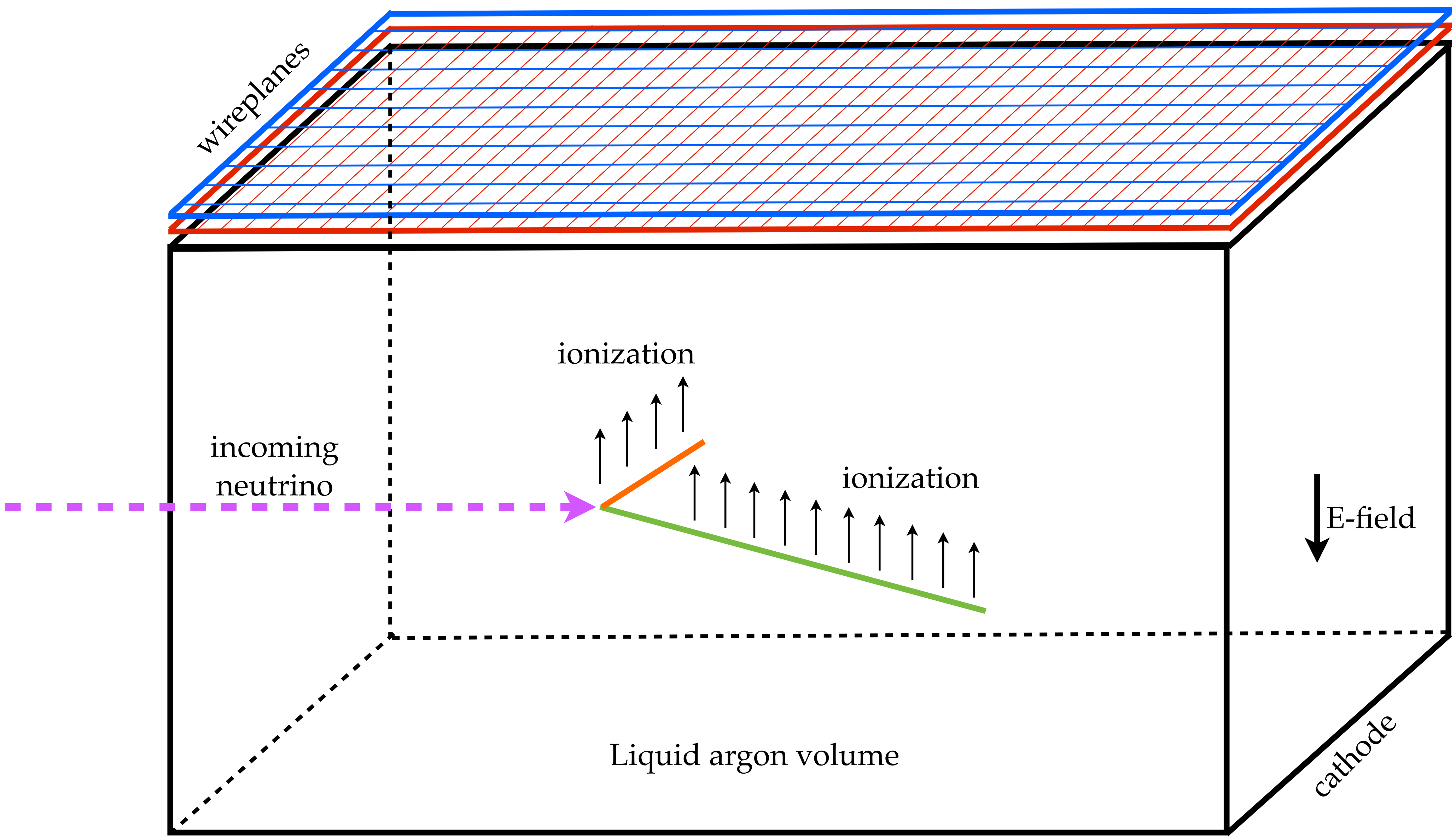


Even if we are entering the "Snowball" region and gaining momentum towards large detectors, there is still a LOT of development of hardware/software/physics that needs to happen. The U.S.-based activities I will describe in this talk will help push us further in the right direction.

Liquid Argon Neutrino Detectors

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

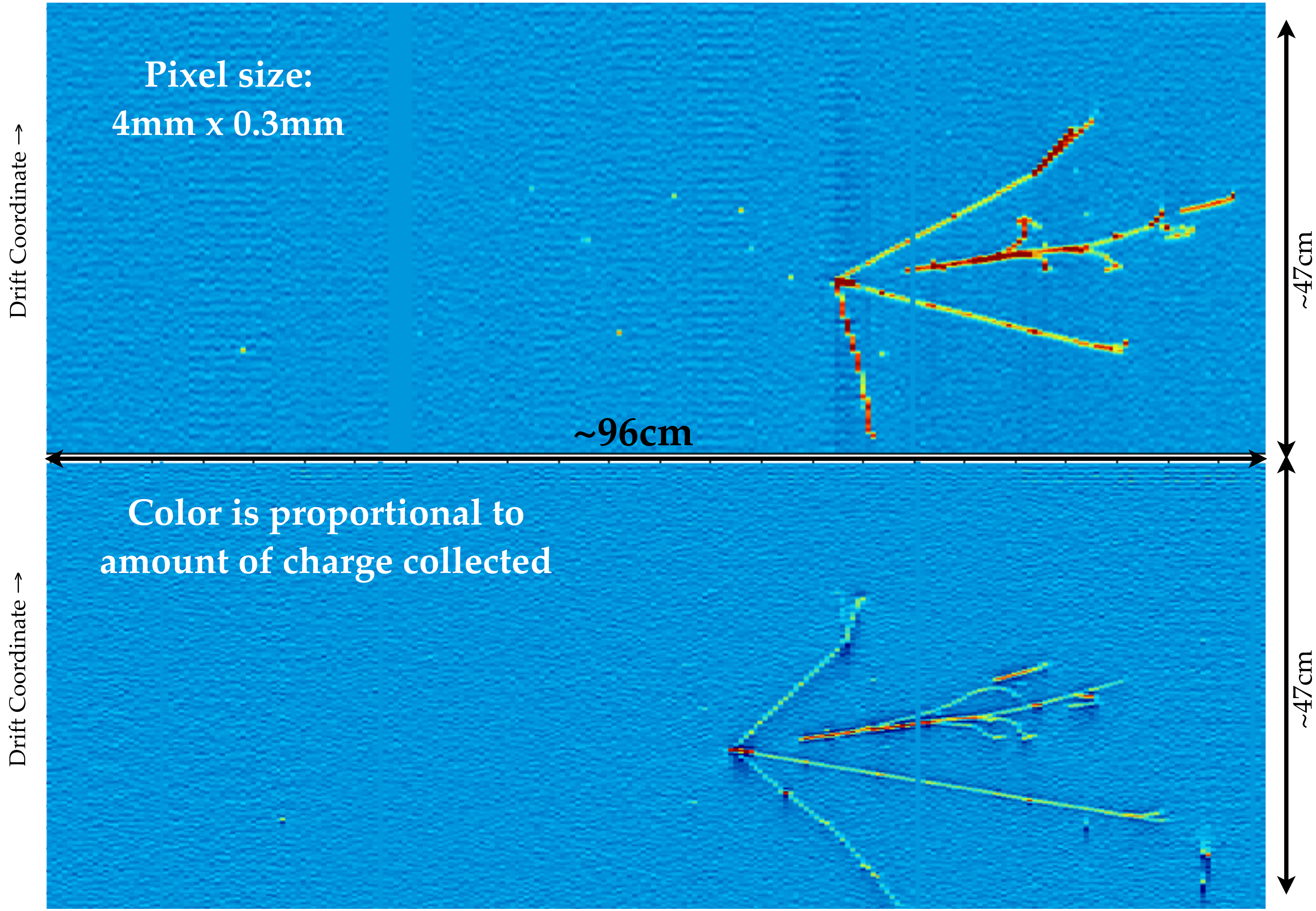


Refs:

1.) *Liquid-argon ionization chambers as total-absorption detectors*, W. Willis and V. Radeka, Nuclear Instruments and Methods 120 (1974), no. 2, 221-236.

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

Neutrino Interaction in ArgoNeuT



Why Noble Liquids for Neutrinos?

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

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

Technical Considerations for LArTPCs

- Purity: relying on Trigon "getters" and molecular sieve coupled with continuous recirculation and clean materials.
- Wires vs. "GEMs": U.S. doesn't seem to have focused on GEMs very much.
- Electronics : cold electronics for better S/N ; multiplexing ; etc...
- Light collection : lots of new and interesting ideas being pursued (PMTs, lightguides, etc...)
- High Voltage : How to test system before starting operations ; Do we understand physics of HV in ultraclean LAr?
- Cryogenics and recirculation scheme: major cost drivers. Is there ground to gain here?
- Calibration : dedicated test-beam exposures, UV lasers, flashers, etc...
- Supply of many kilotons of LAr : Where do you buy many kilotons of LAr?
- Reconstruction/Software : Need to develop tools, preferably automated, that take full advantage of the TPC event images and light collection information. Need to be able to keep up with flood of raw data.

LAr Worldwide

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

US

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

Europe

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

Japan

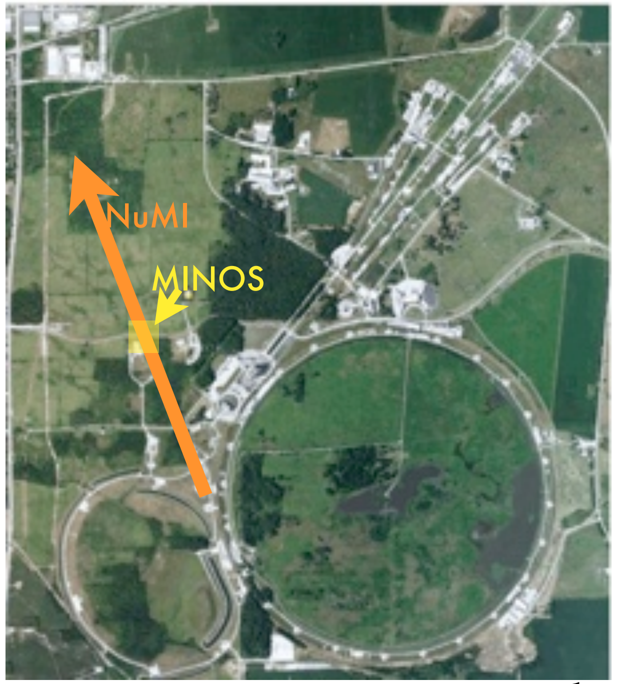
Test-Beam (T32) at J-PARC
100 kTon @ Okinoshima island

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

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

The ArgoNeuT Project

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



NuMI Beam at Fermilab

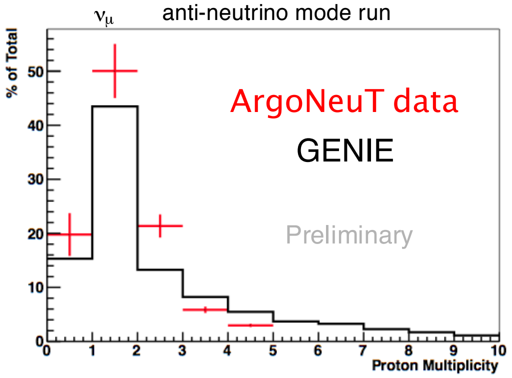

ArgoNeuT in the NuMI Tunnel

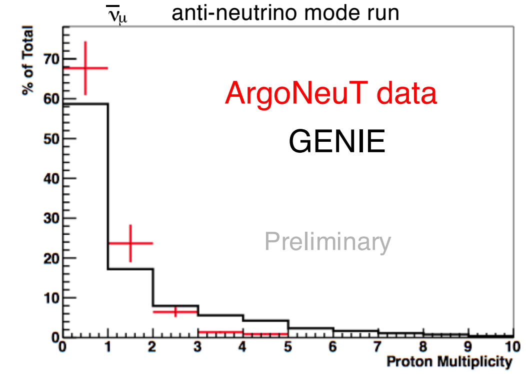
Cryostat Volume	500 Liters
TPC Volume	175 Liters (90cm x 40cm x 47.5cm)
# Electronic Channels	480
Electronics Style (Temp.)	JFET (293 K)
Wire Pitch (Plane Separation)	4 mm (4 mm)
Electric Field	500 V/cm
Max. Drift Length (Time)	0.5 m (330 μs)
Wire Properties	0.15mm diameter BeCu

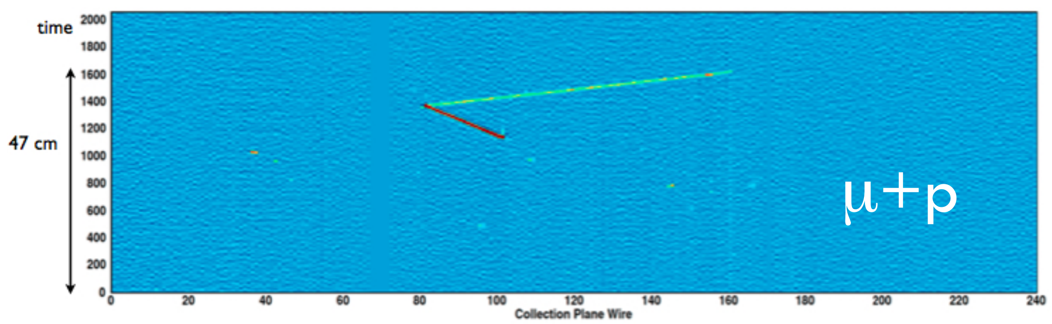
Refs:
1.) *The ArgoNeuT detector in the NuMI low-energy beam line at Fermilab*, C. Anderson et al., JINST 7 P10019, Oct. 2012, arXiv:1205.6747

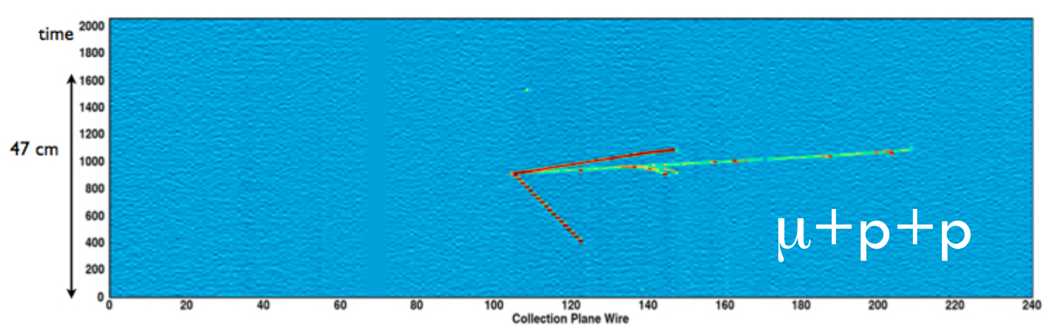
ArgoNeuT: Physics

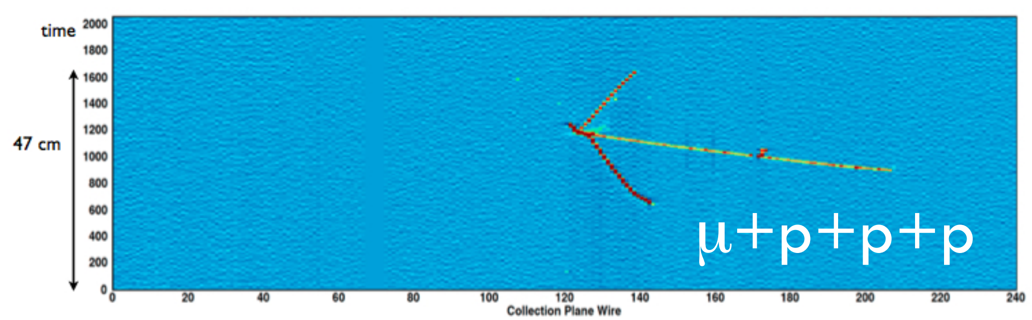
- ArgoNeuT has highlighted need to consider nuclear effects (e.g. - Multinucleon Correlations, final-state activity) when analyzing LArTPCs.
- Repeat of CC-Inclusive analysis (shown at previous NNNs) in antineutrino mode.
- Papers in progress.











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

ArgoNeuT: Physics

- ArgoNeuT has highlighted need to consider nuclear effects (e.g. - Multinucleon Correlations, final-state activity) when analyzing LArTPCs.
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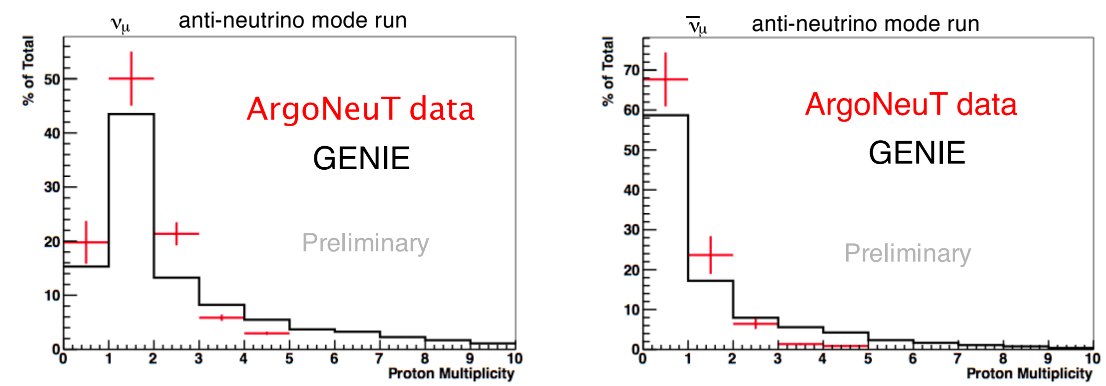

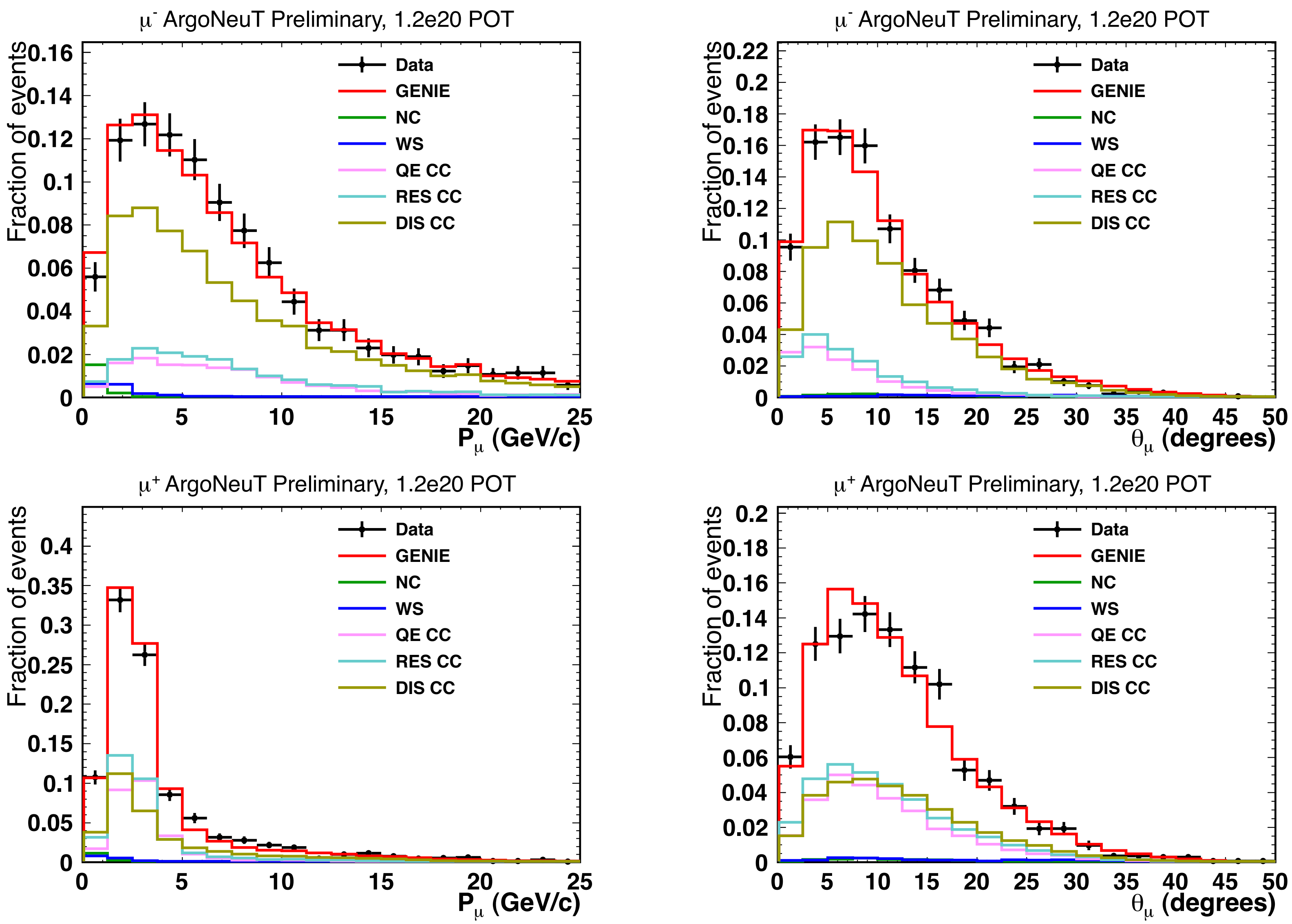

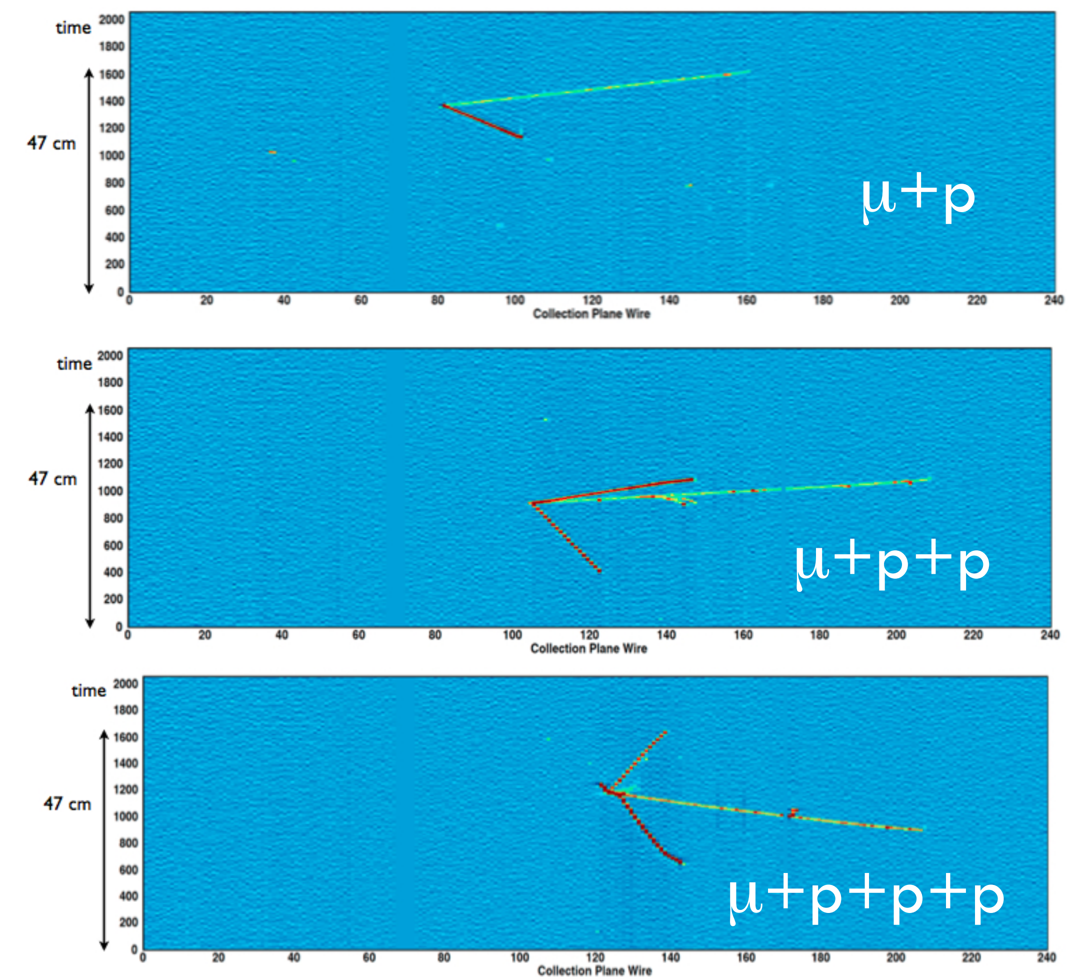

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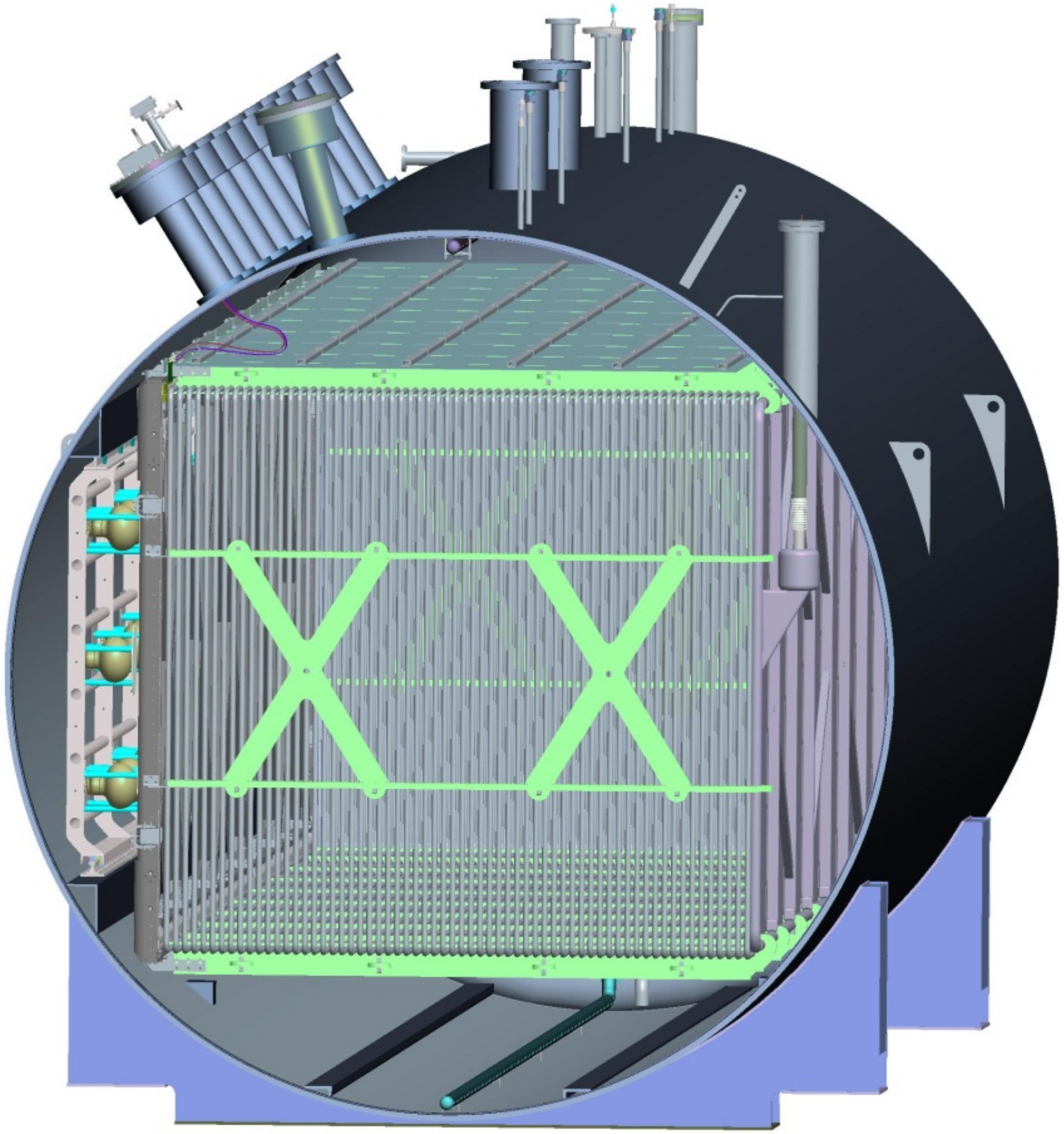
The MicroBooNE Experiment

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

MicroBooNE Construction



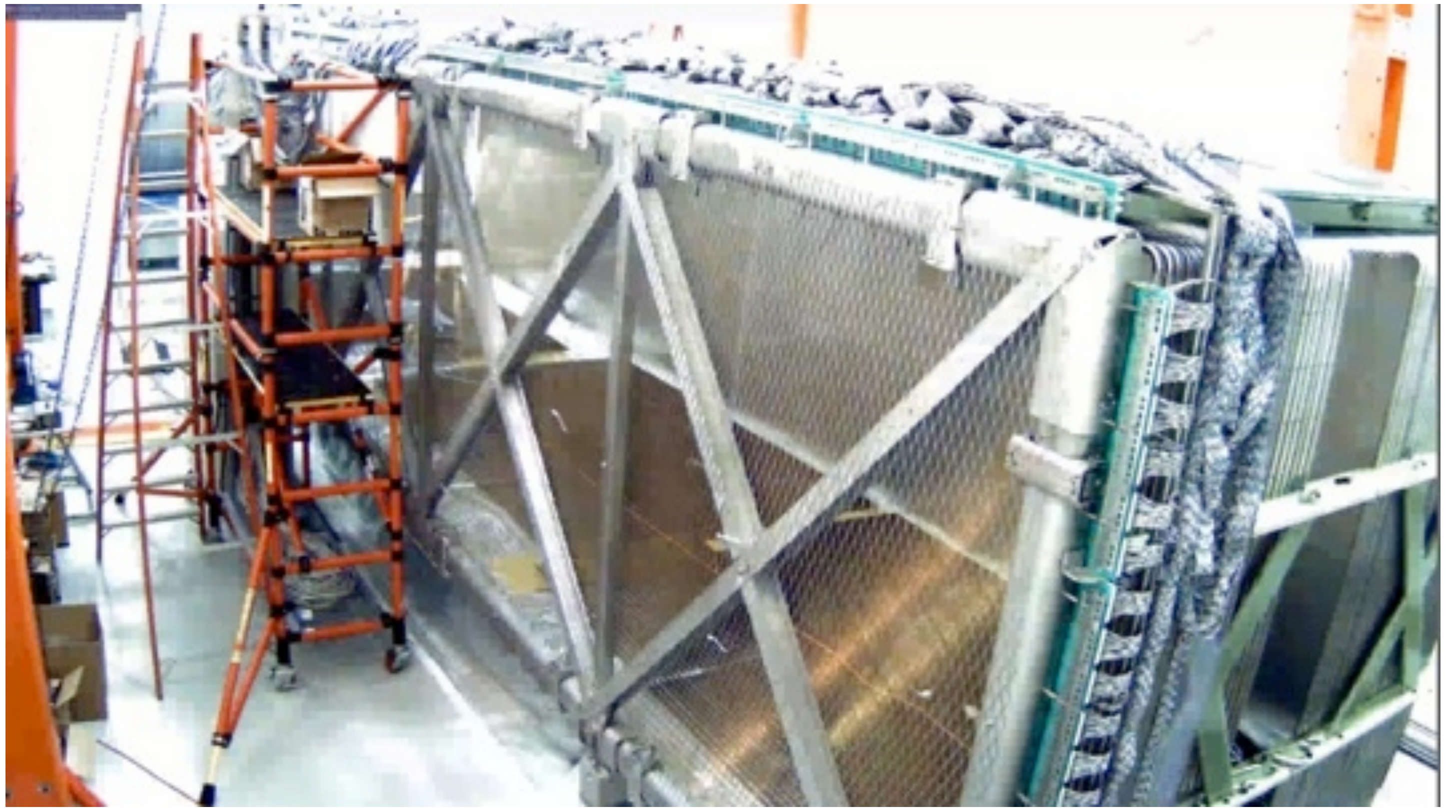
MicroBooNE Experiment

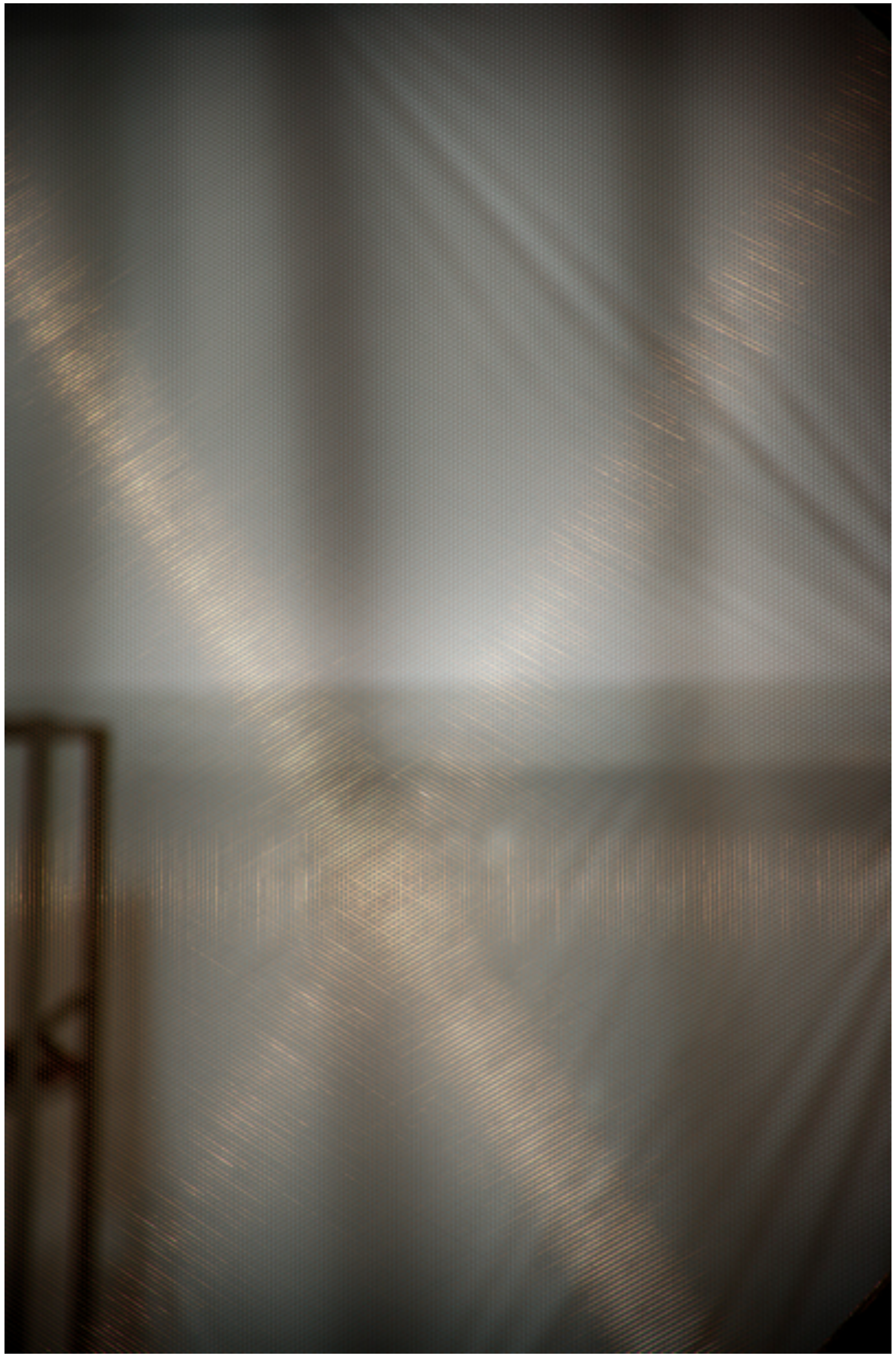
Refs:

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

MicroBooNE: TPC Detector

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

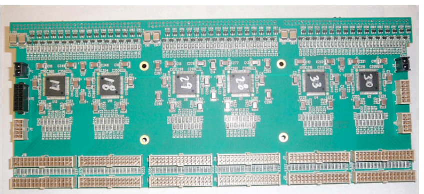

MicroBooNE TPC (Nov. 2013)


TPC Wires

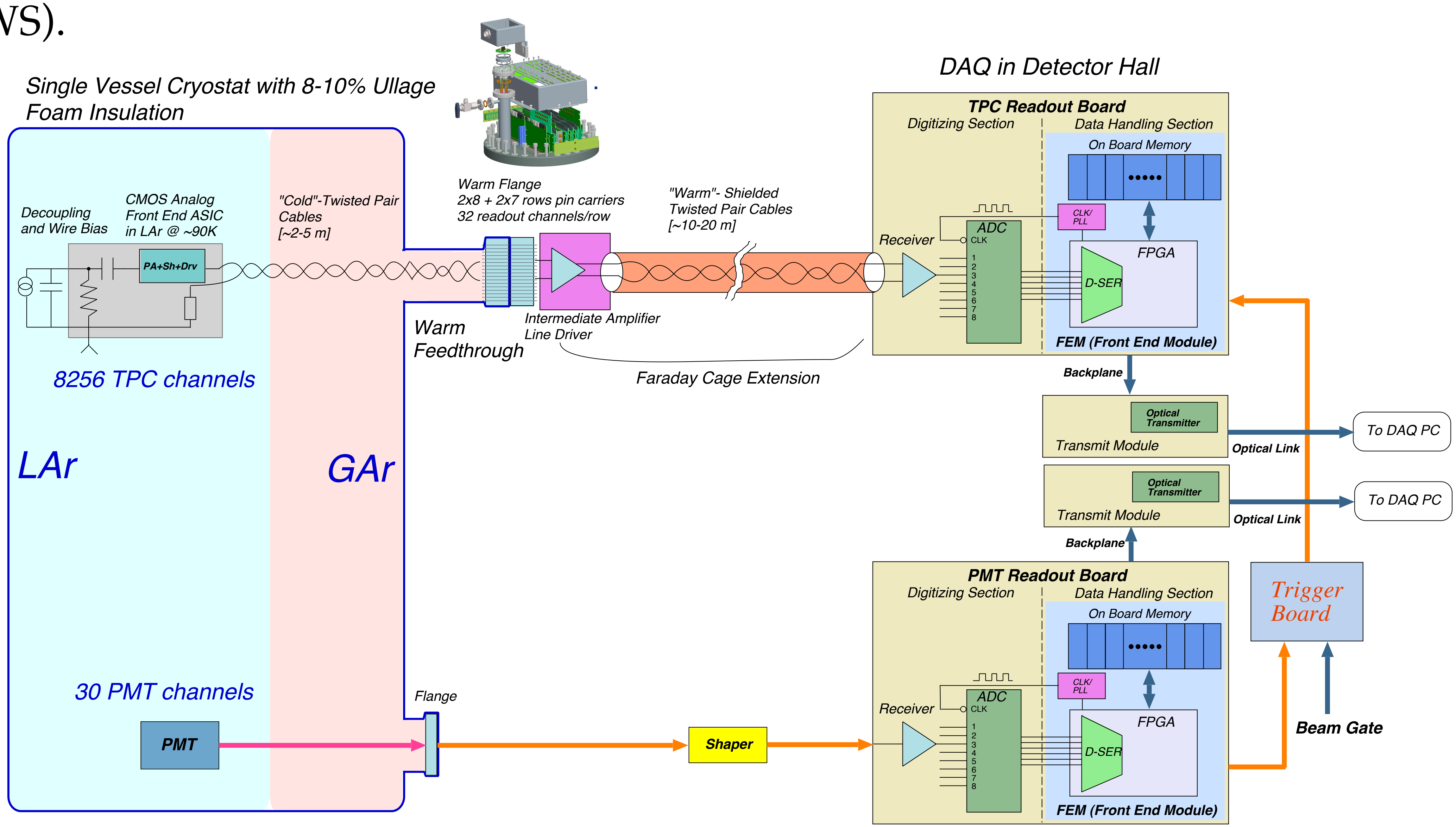
MicroBooNE: Cold Electronics

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

Cold MotherBoards



Wire-carrier Board

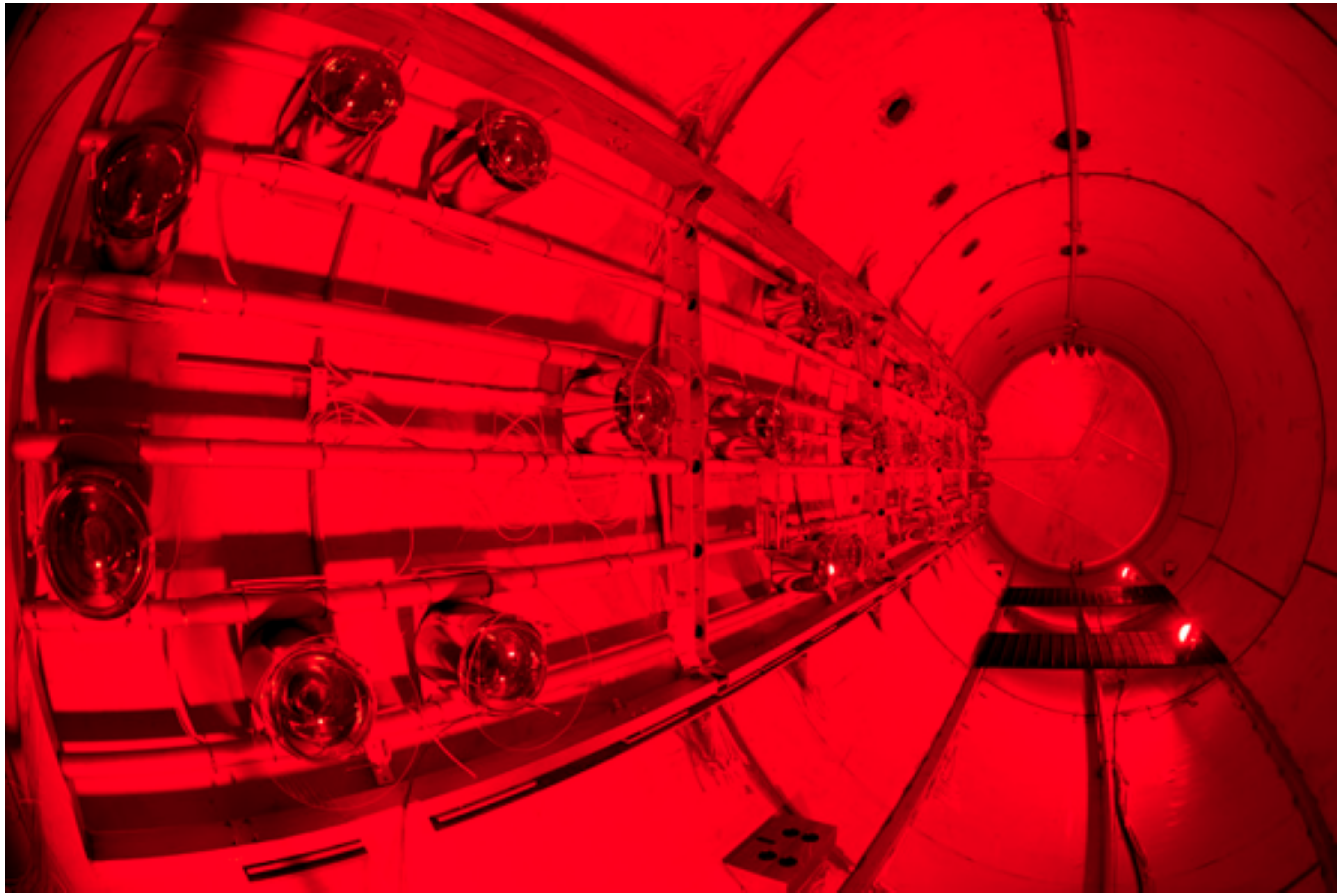


Refs:

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

MicroBooNE: Light Collection

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



PMT System Installed in Cryostat (Sept. 2013).

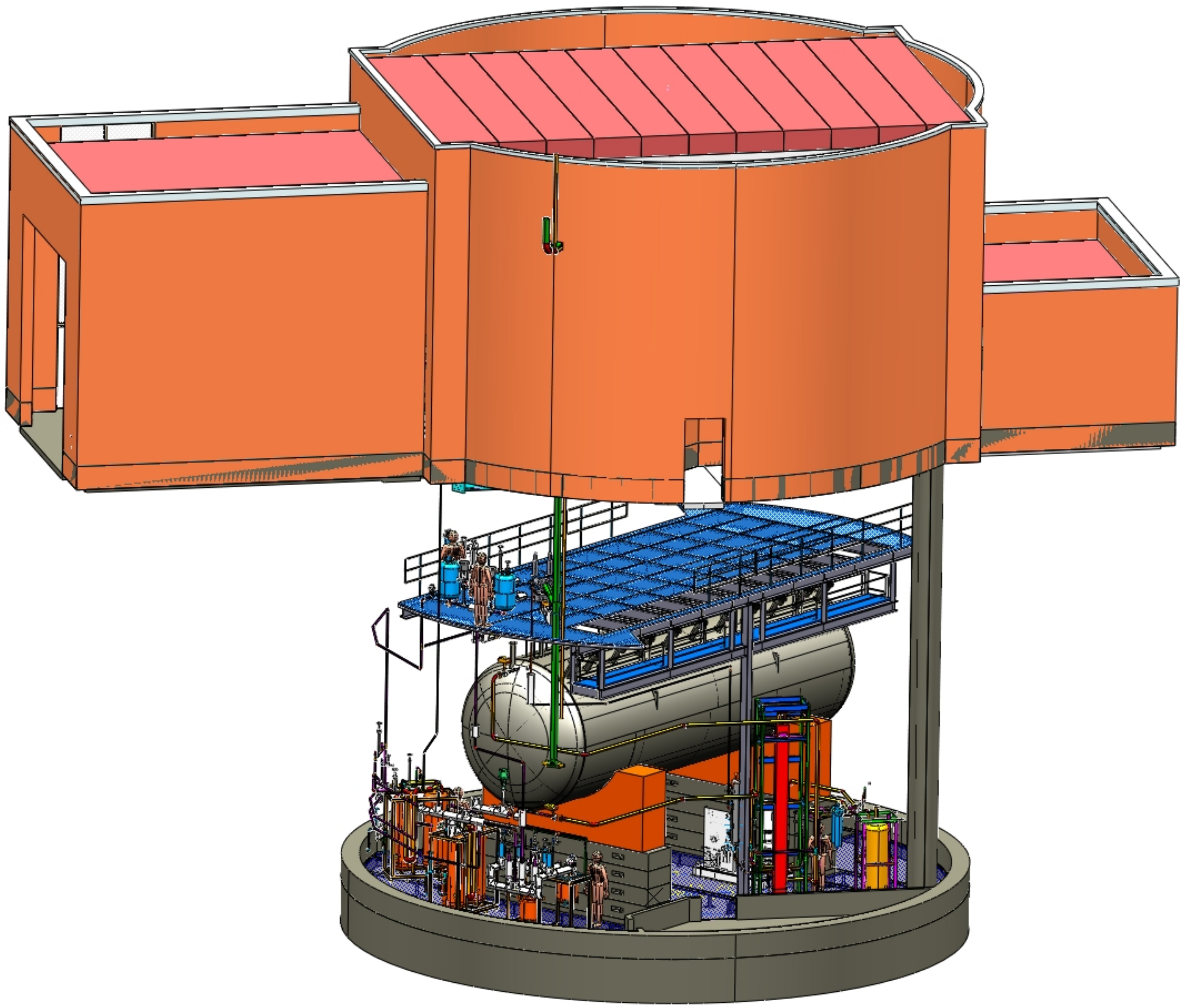
Plate (that will be) coated with wavelength shifter

PMT Assembly

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

MicroBooNE: Status

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



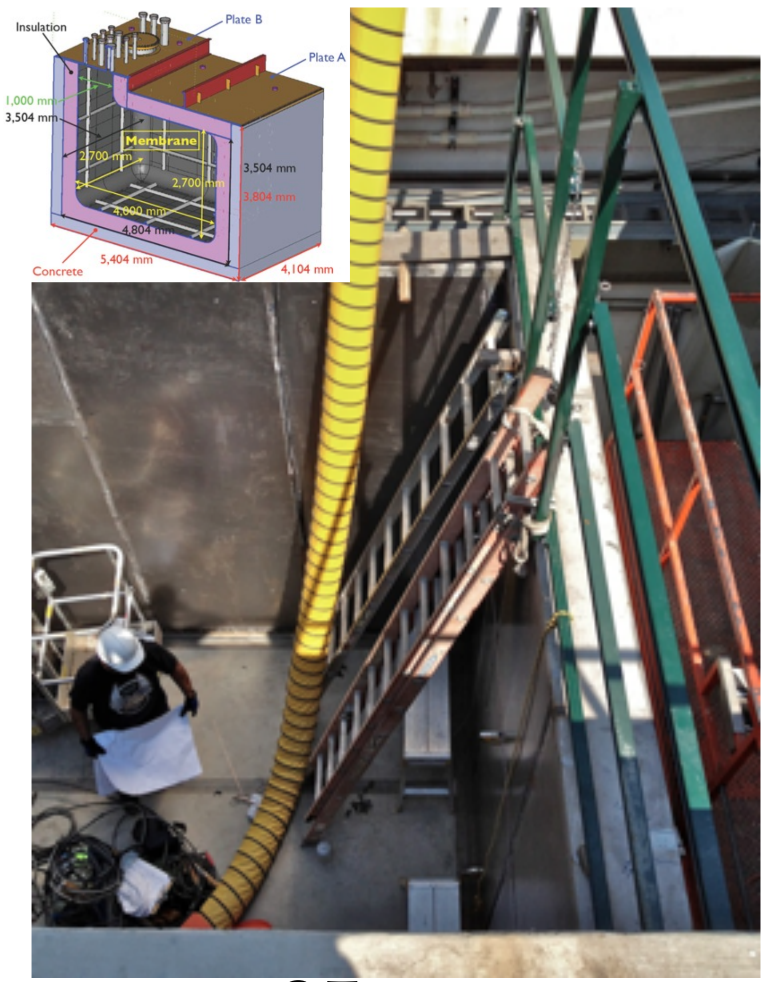
Rendering of cryostat + "hair" in LArTF

Liquid Argon Test Facility (LArTF)

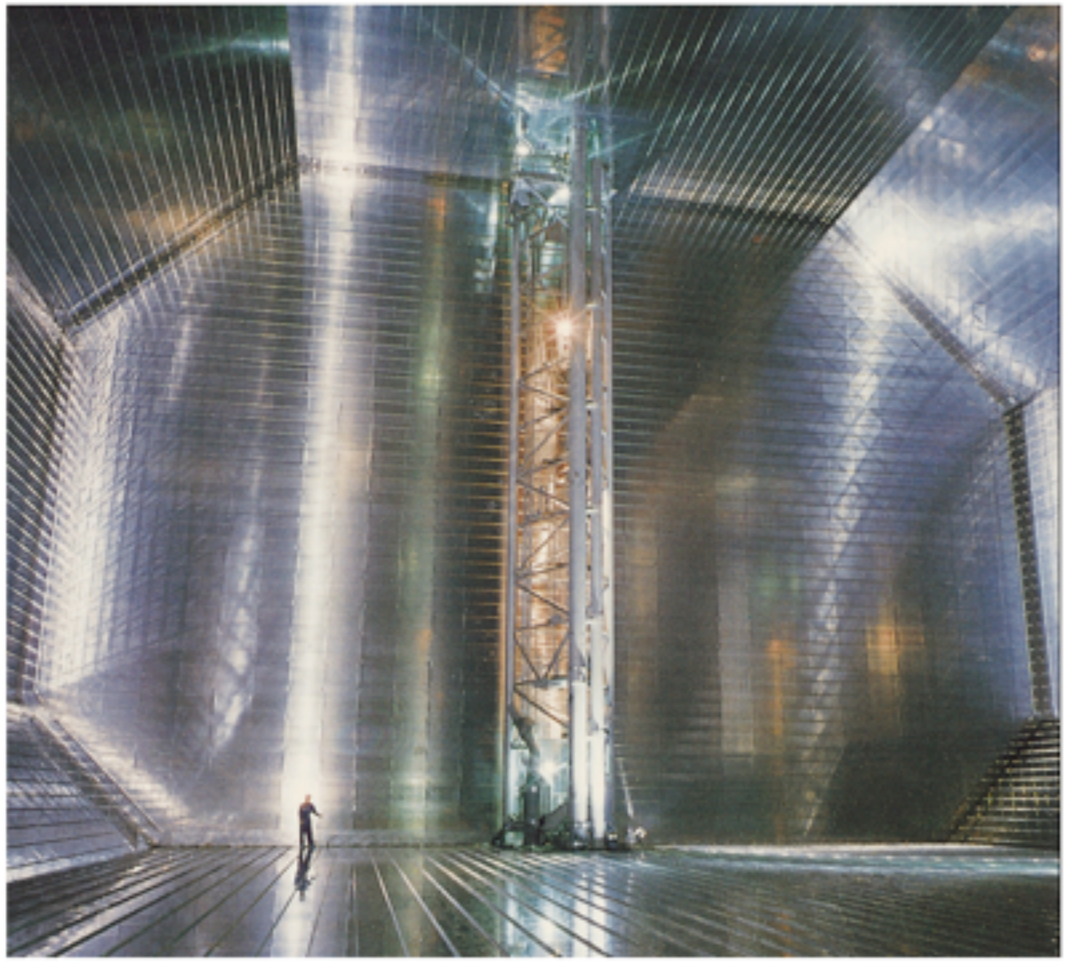
LAr Purity R&D @ Fermilab

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

LAPD
(30-ton cryostat)



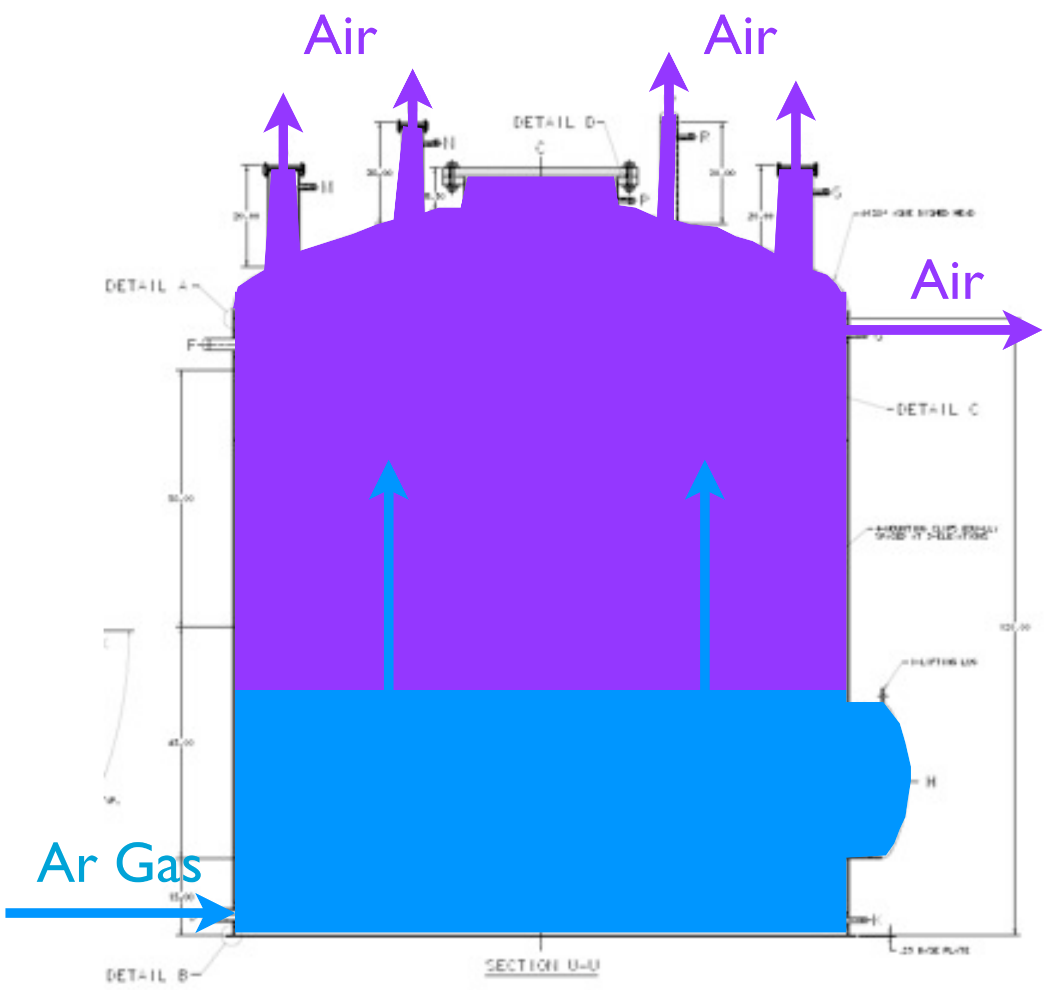
35-ton
Membrane Cryostat

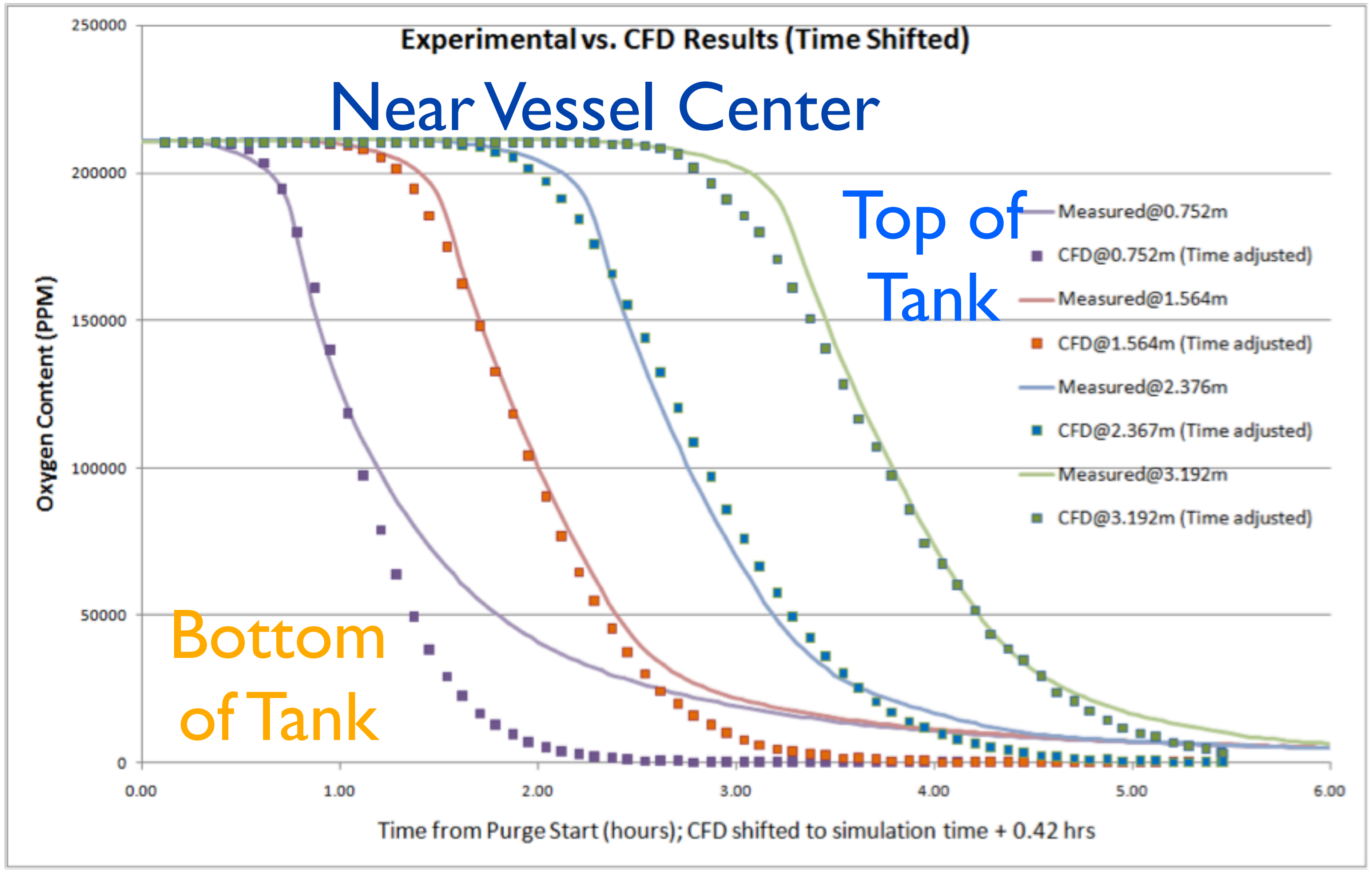


Membrane Cryostat for industrial LNG shipping

LAr Purity R&D @ Fermilab

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

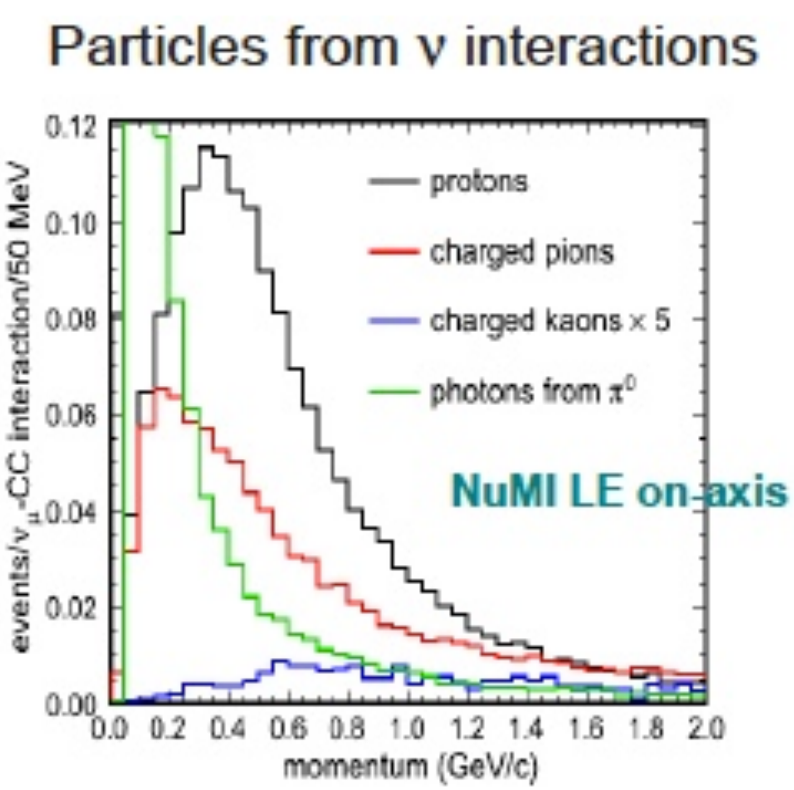


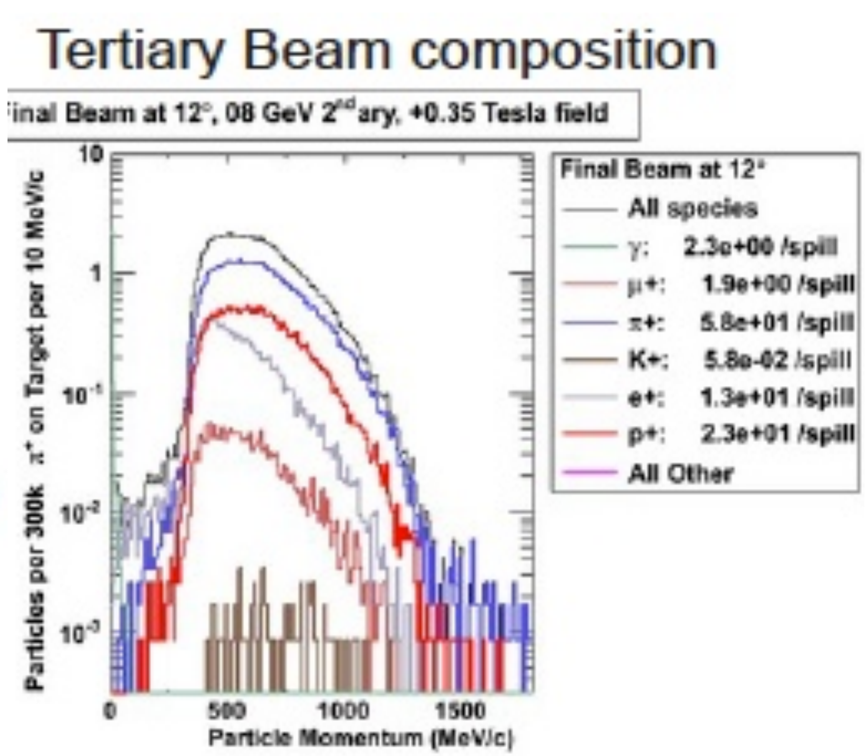


Refs:
1.) *LAPD Update*, B. Rebel, 2012 Fermilab PAC Meeting

LArIAT

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

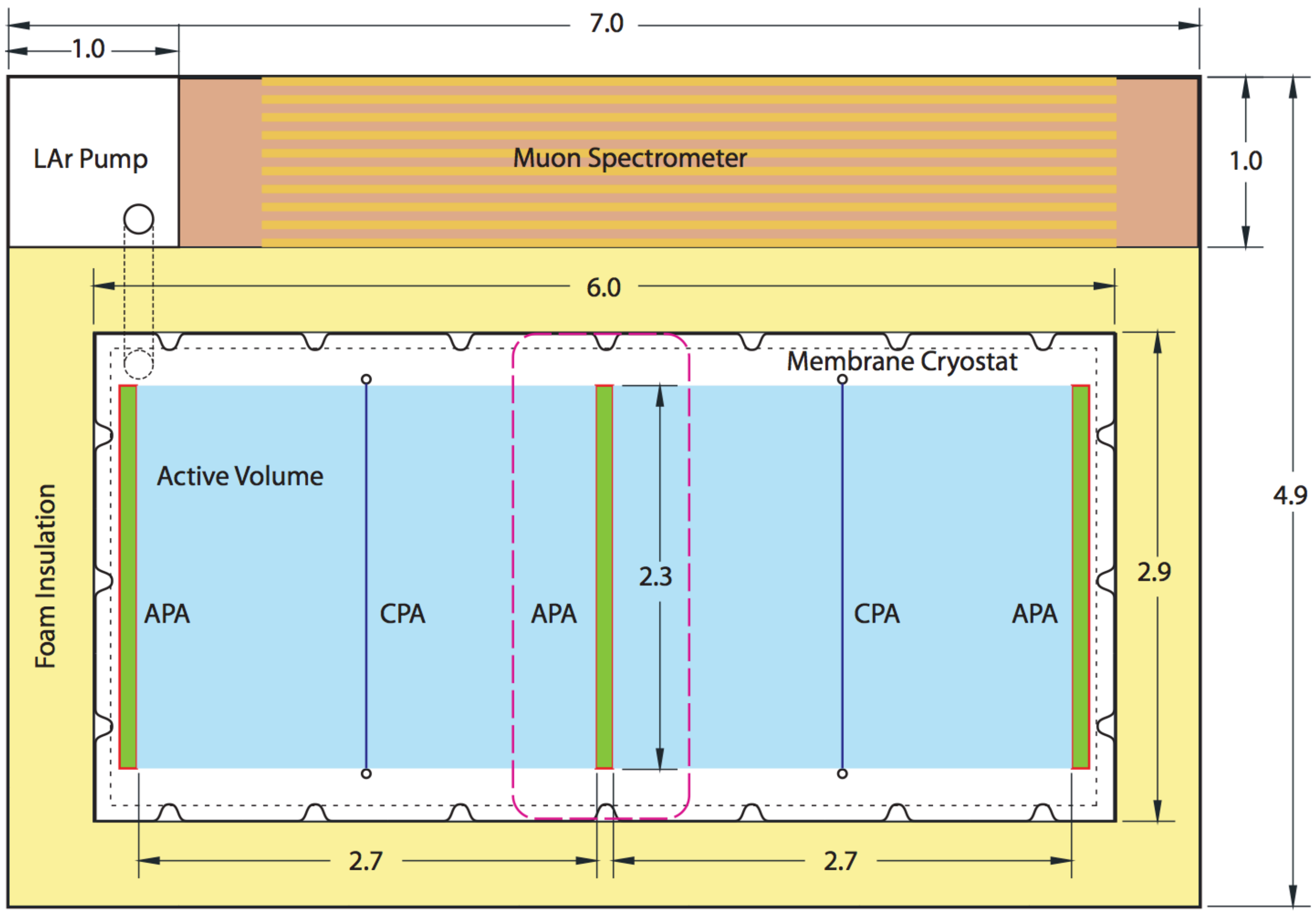




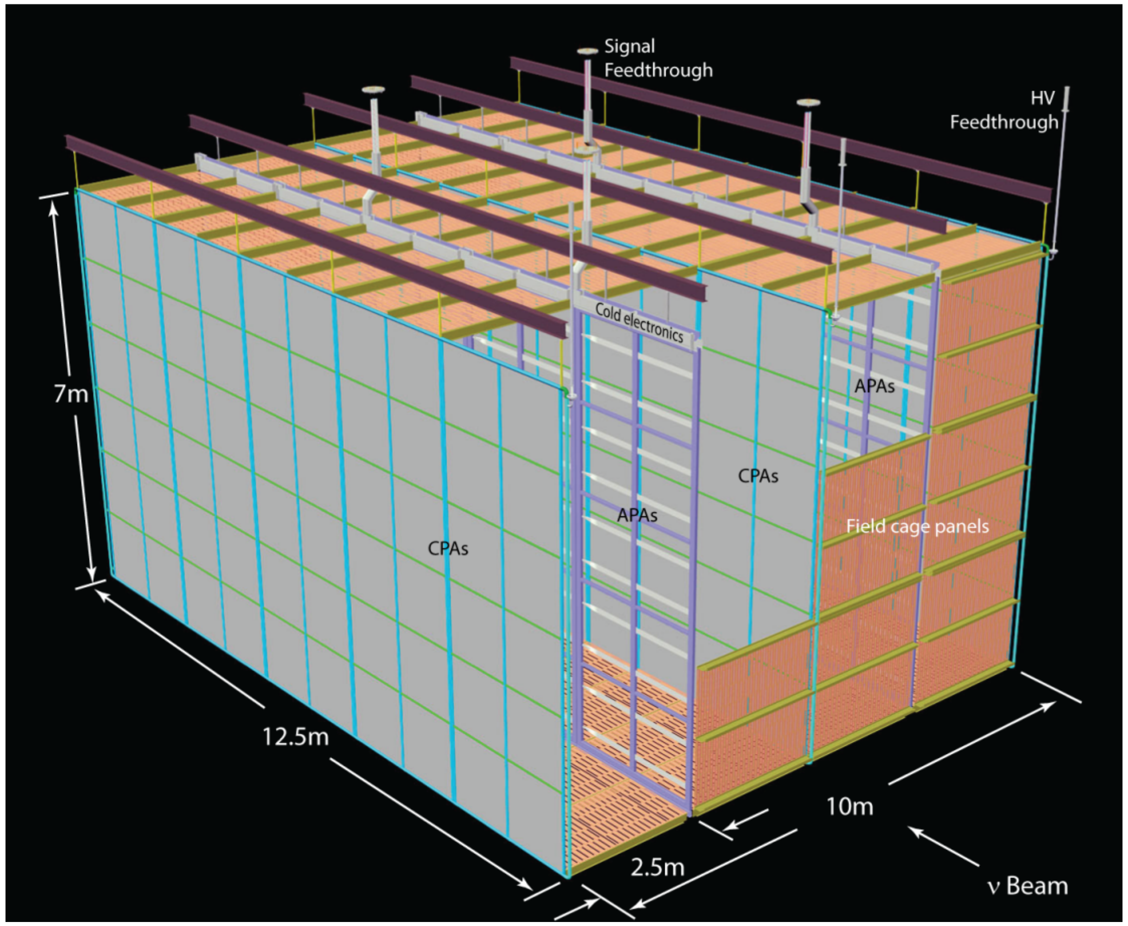
Modified ArgoNeuT Cryostat

LAr1 + LAr1-ND

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



LAr1-ND in SciBooNE Building



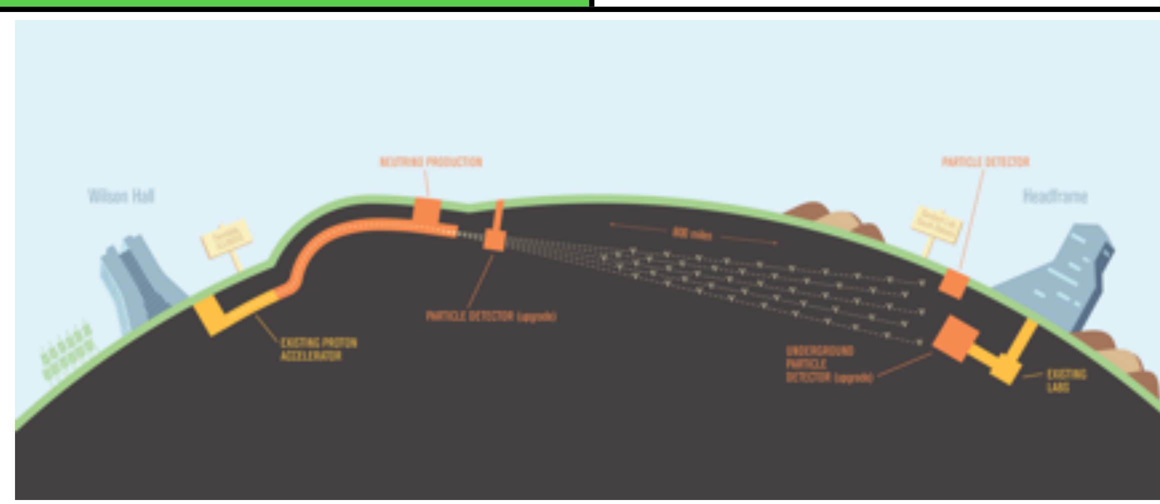
LAr1

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

LBNE

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

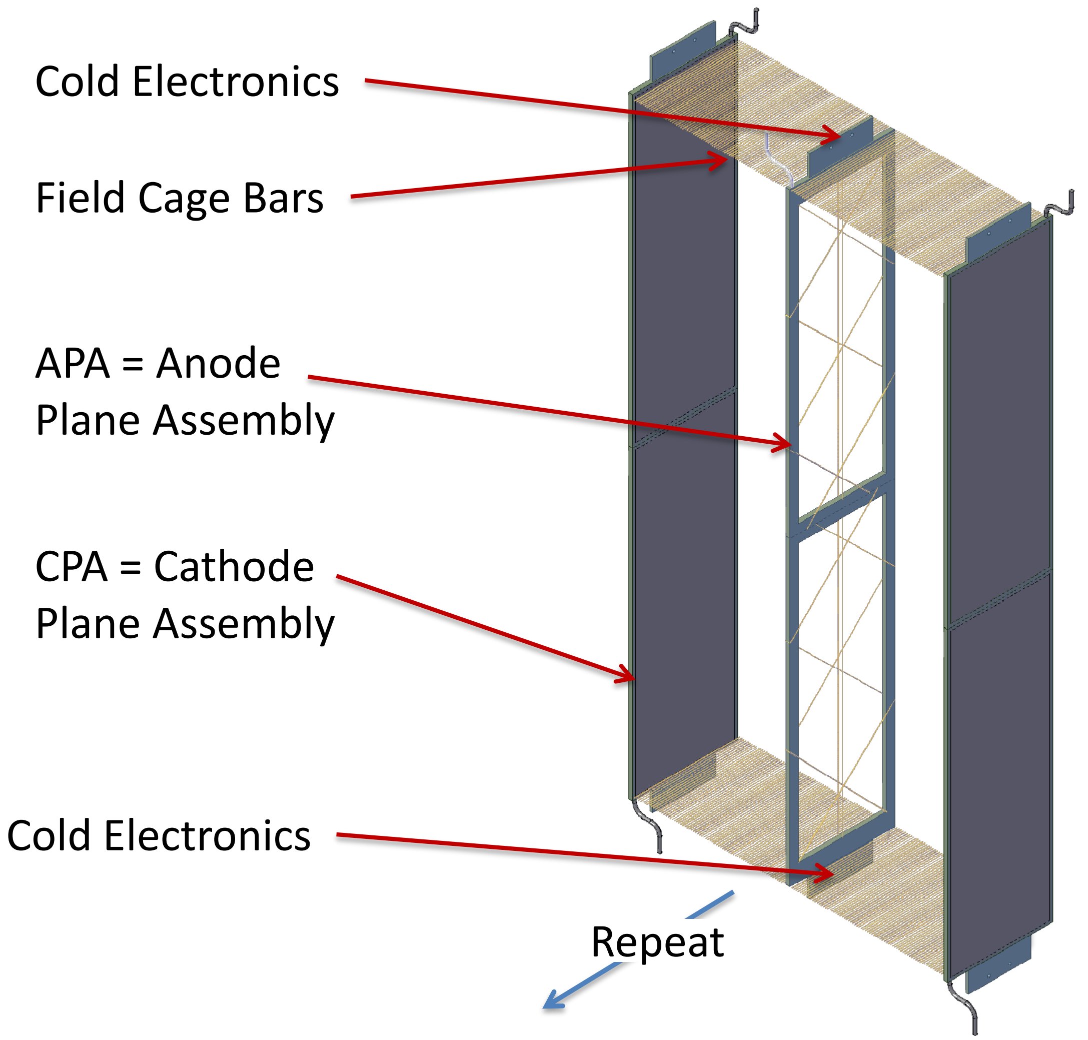
Cryostat Volume	9400 tons (x2 = 18600 tons)
TPC Volume (l x w x h)	5000 tons (x2 = 10000 tons)
# Electronic Channels	~150k/cryostat (x2 = ~300k)
Electronics Style (Temp.)	CMOS (87 K)
Wire Pitch	~5 mm
Max. Drift Length (Time)	2.3m (1.4ms)
Light Collection	Acrylic bars with TPB

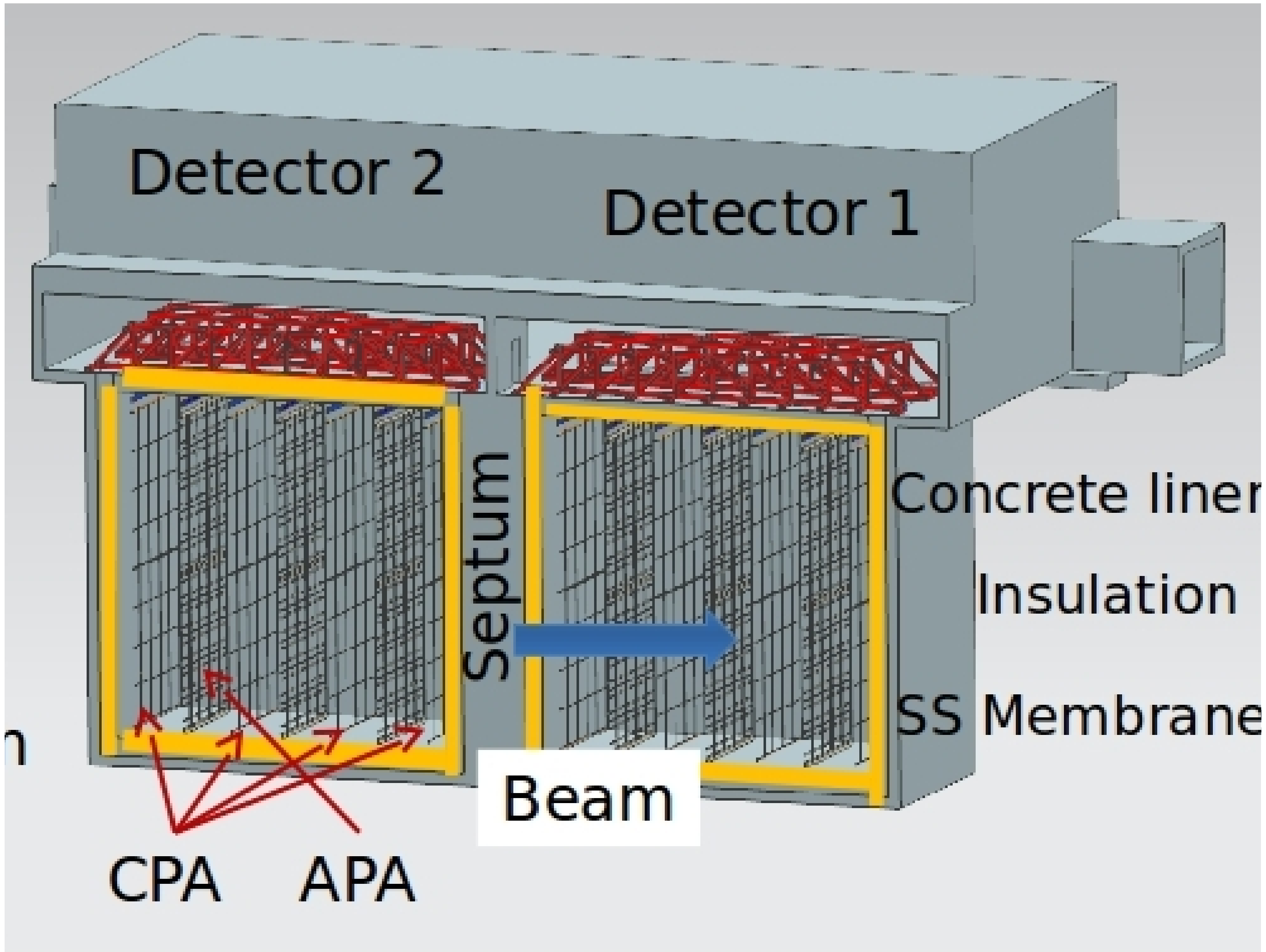


Refs:
1.) *Scientific Opportunities with the Long-Baseline Neutrino Experiement*, C. Adams et al., hep-ex/1307.7335

LBNE

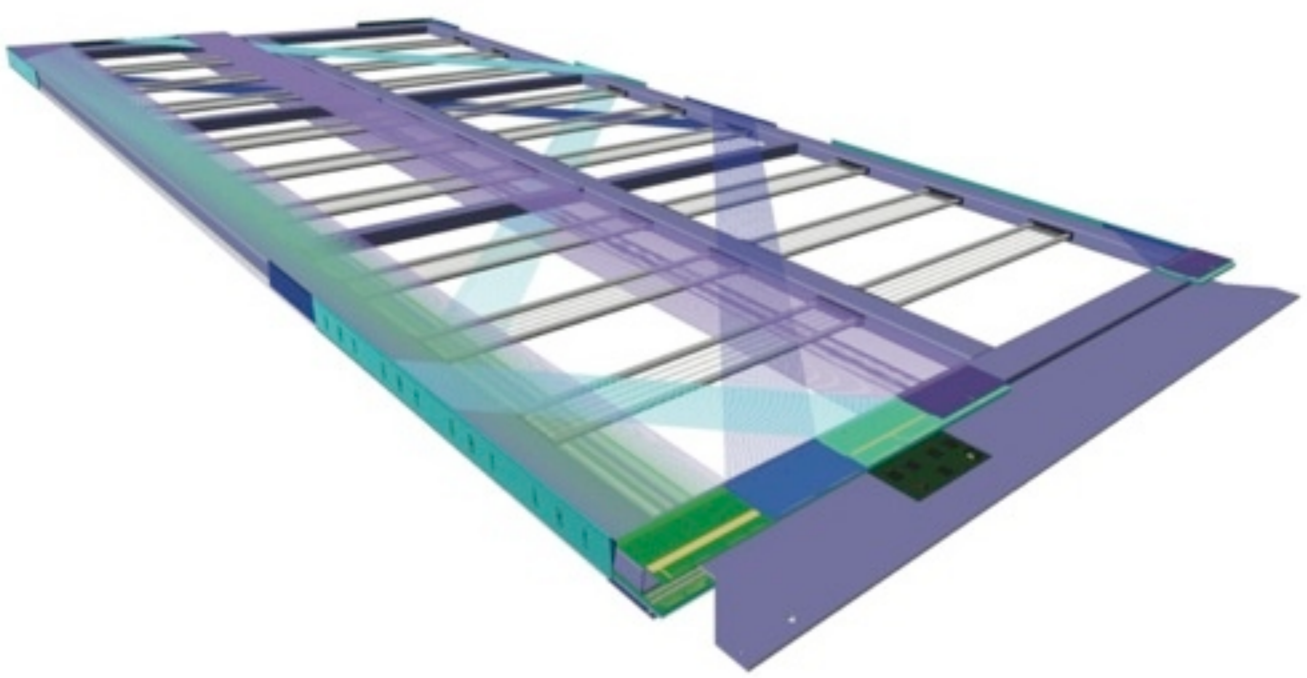
- Two separate membrane cryostats each with 9.4 kiloton volume.
- TPC is formed by alternating rows of cathode (CPAs) and anode (APAs) assemblies that are hung from the ceiling of the cryostat.



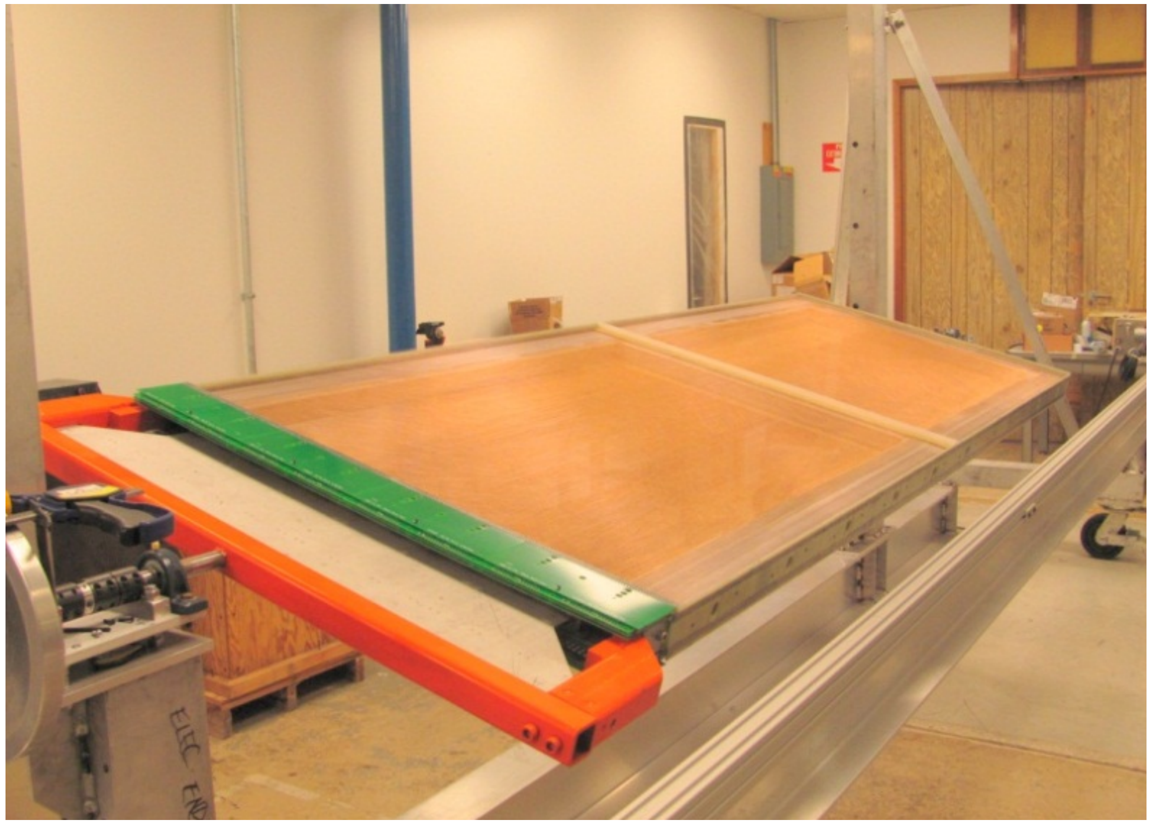


LBNE

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



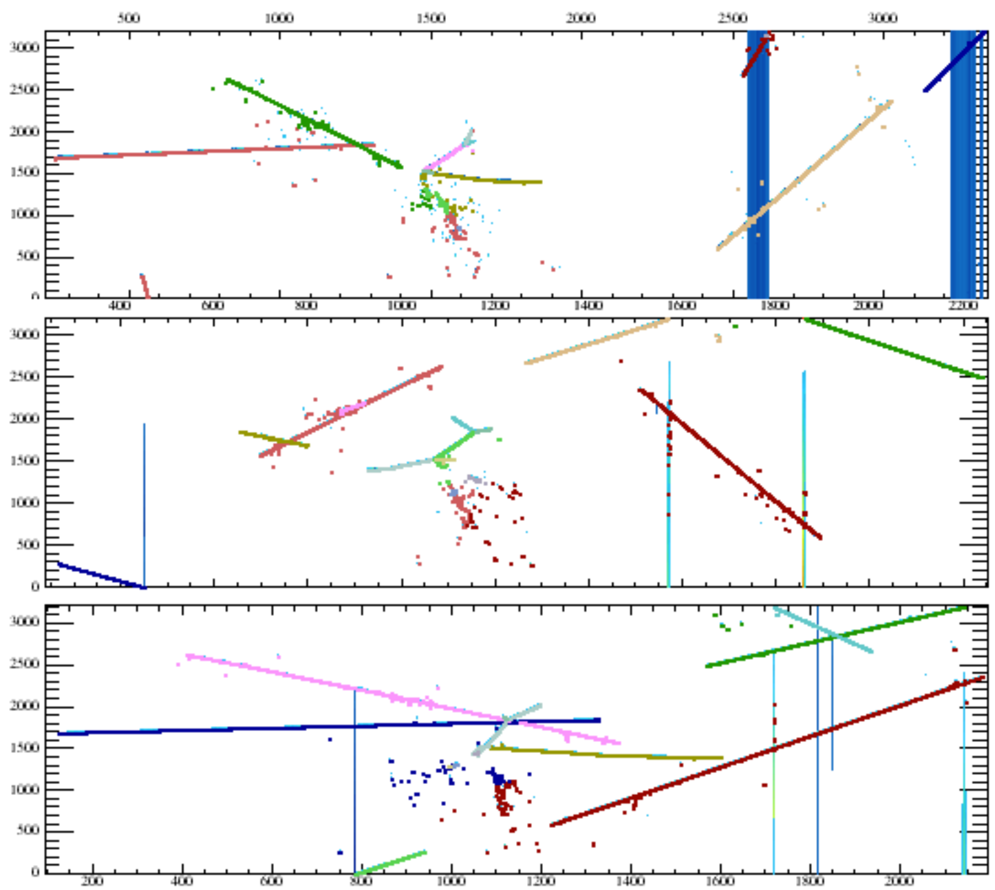
APA Design

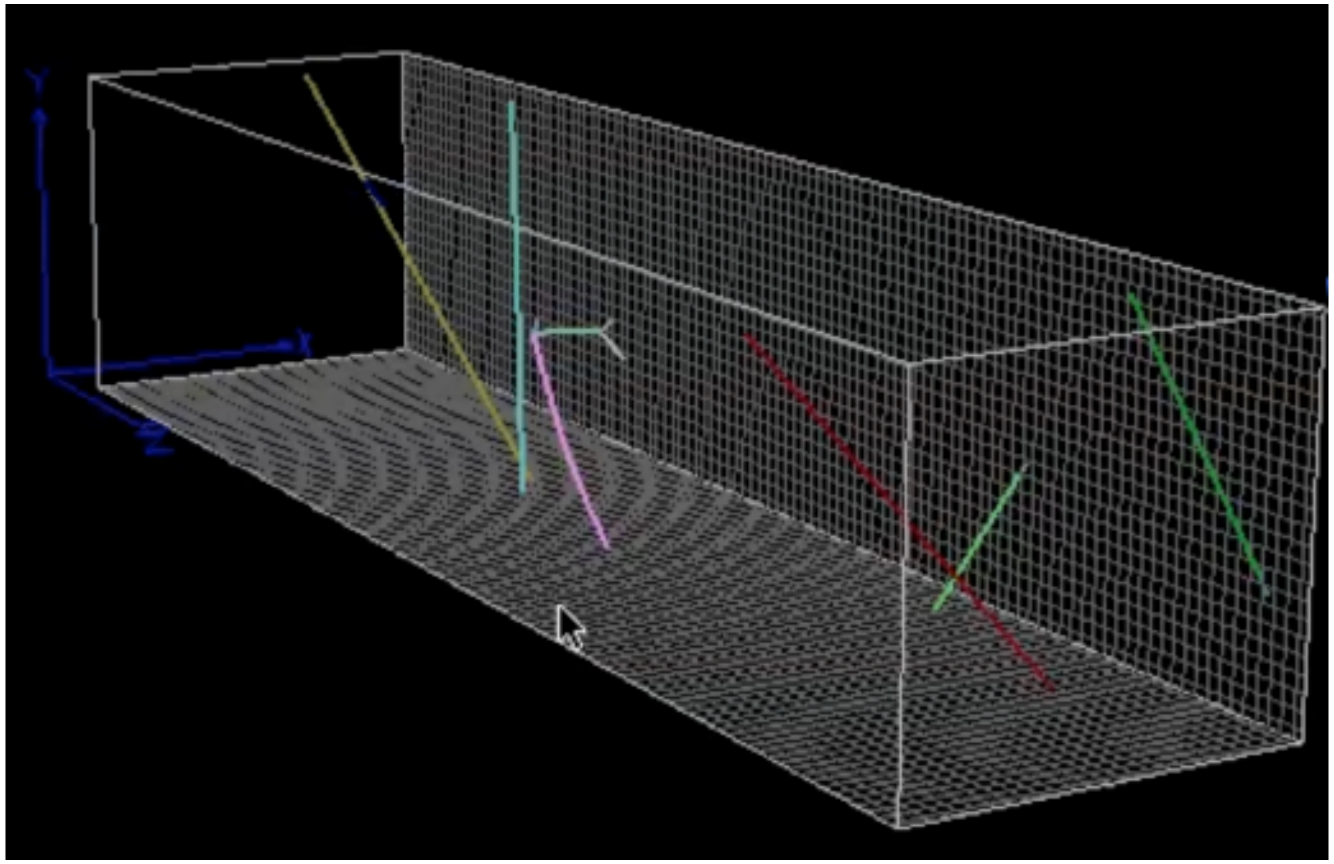


Prototype APA at University of Wisconsin Physical Sciences Laboratory

Software

- Extracting physics results from LArTPC data presents its own challenges that must be overcome and will require significant effort.
- Developing generators, simulation, reconstruction, etc... that <u>fully</u> encapsulate neutrino interactions in a LArTPC is a challenge that (in my opinion) rivals the hardware development. Deserves more attention than I'm giving it here.
- LArSoft framework is an attempt to share effort amongst experiments by developing common language and tools for analyzing LArTPCs.





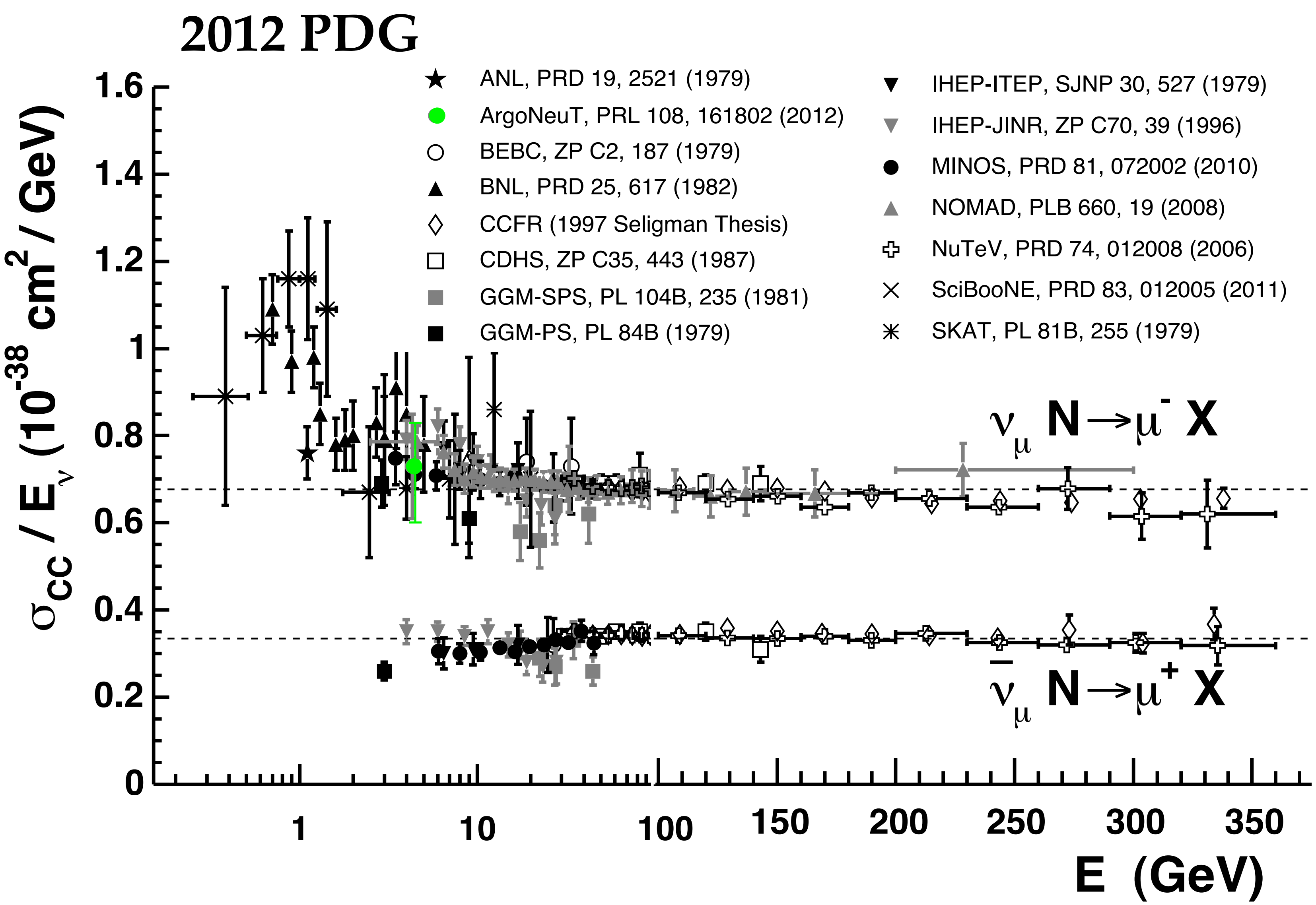
Refs:
1.) https://cdcvs.fnal.gov/redmine/projects/larsoftsvn/wiki

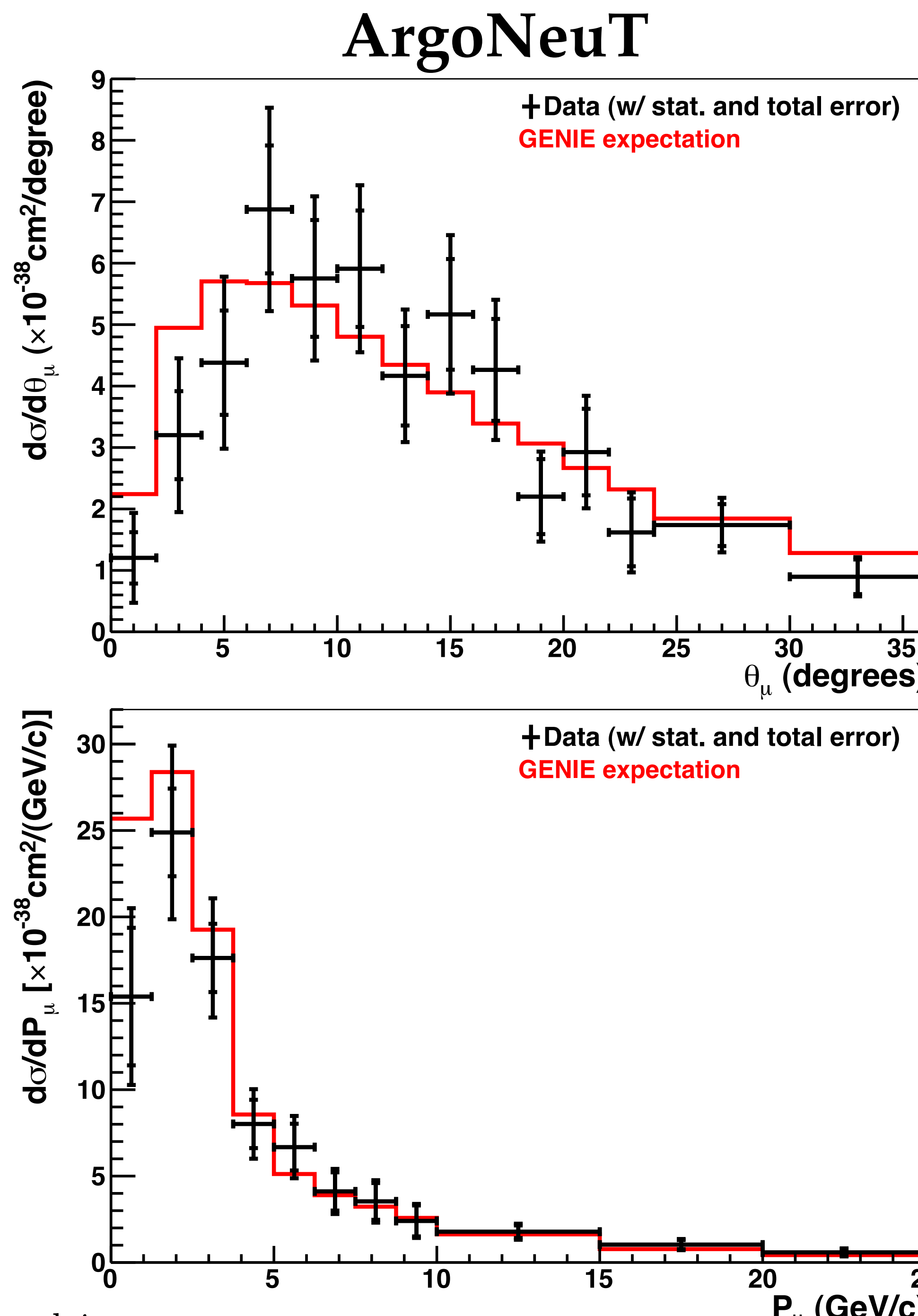
Conclusions

- LArTPCs are powerful detectors for studying neutrinos.
- Tremendous progress in recent years in U.S. efforts to develop this technology. Growing interest, which is good since there is lots of work to be done.
- My apologies to activities I didn't have time to cover at all (Materials Test Stand, CAPTAIN, Light-Collection R&D, Long-Bo in LAPD, ...others).
- Next few years should be very exciting as experiments come online, and as development of kiloton-scale experiments continues.

Back-Up Slides

ArgoNeuT: Physics





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

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

Inclusive CC cross-section

Refs:
1.) *First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon*, C. Anderson et al., PRL 108 (2012) 161802, arXiv:1111.0103
2.) *Neutrino cross section measurements*, J. Beringer et al. (Particle Data Group), Phys. Rev. D**86**, 010001 (2012)