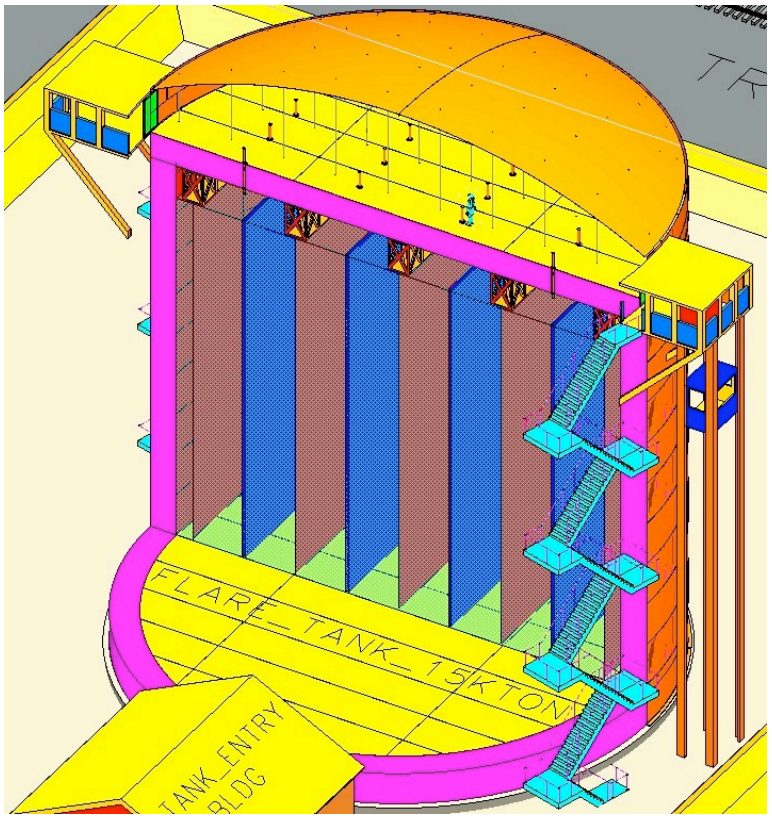
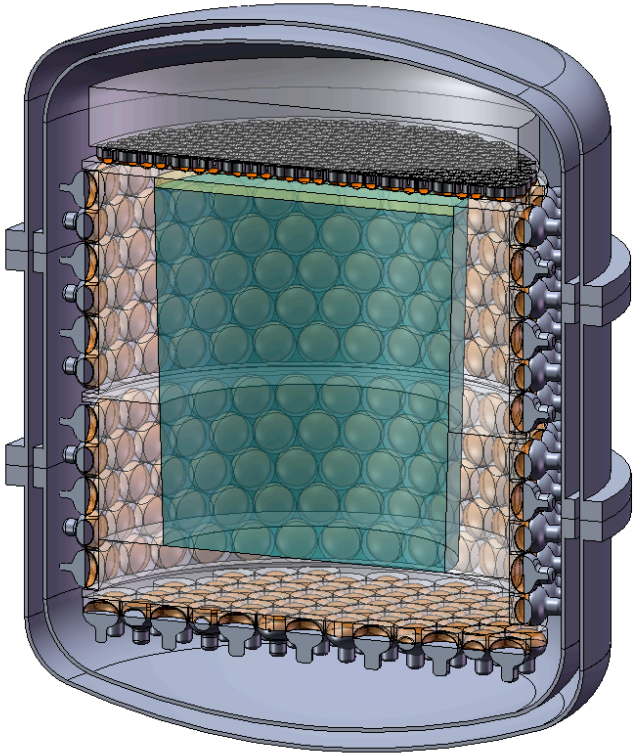
Liquid Argon at Fermilab



neutrinos



WIMPS

Outline:

Something about Liquid Argon

Present situation - Neutrinos, proton decay, WIMPS

Work/prospects at Fermilab

Bottom Lines:

Neutrinos - excellent event identification,

powerful for distinguishing neutral current π^0 from ν_e CC scatters - θ_{13} (eff > 80% cf WC ~ 20%)

- energy threshold (<5 MeV) from supernova (or ?)

Proton Decay - sensitive to Kaon modes (unlike WC)

WIMPS - large mass, powerful background rejection

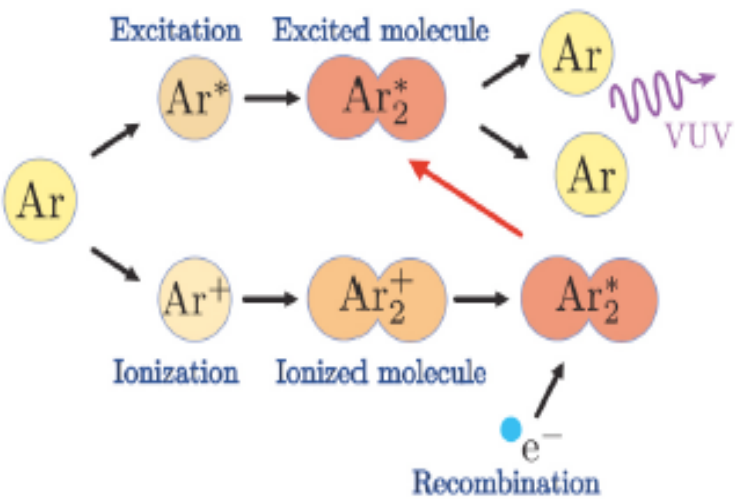
Noble Liquids: Properties

- 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).

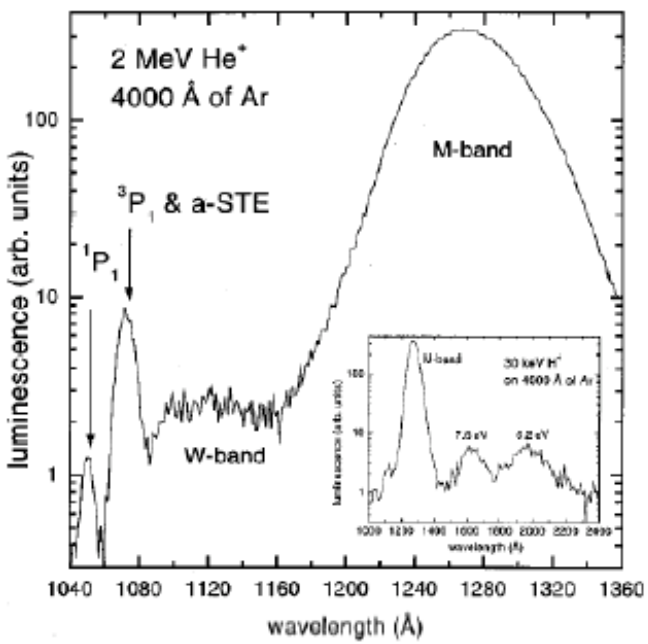
from Mitch Soderberg

	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	
ppm in air	0	12	9500	1	0.1	

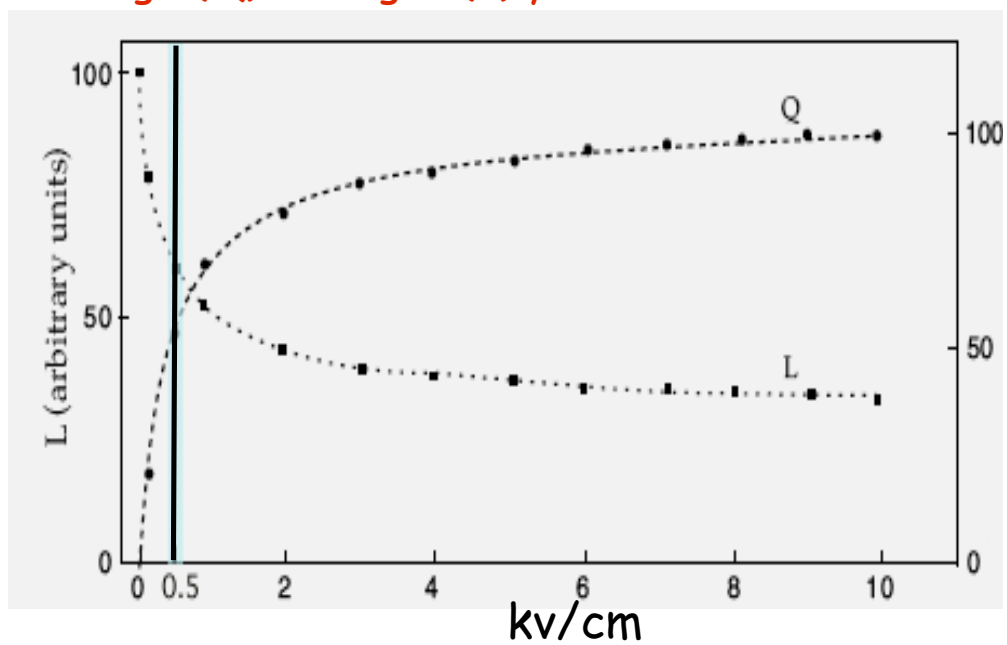
mechanism of light production



dE/dx = 2.1 MeV/cm
ρ= 1.4 gms/cm^3

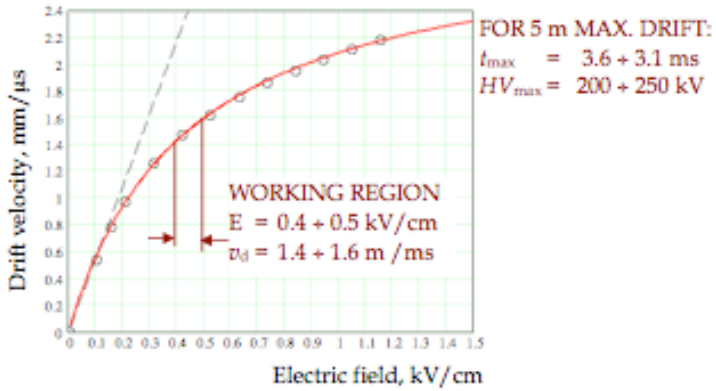


charge (Q) and light (L) yield vs electric field

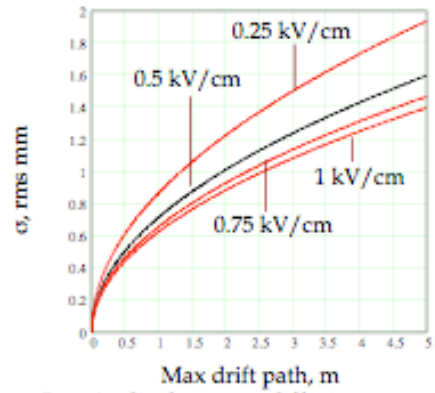


5000 e/mm and 2000 phot./mm at 0.5 kV/cm

Drift velocity, diffusion, purity and attenuation



Drift velocity versus electric field in liquid argon



Longitudinal rms diffusion spread versus drift paths at different electric field intensities

$$\sigma_D = \sqrt{2 \cdot D \cdot \frac{x}{v_d}}$$

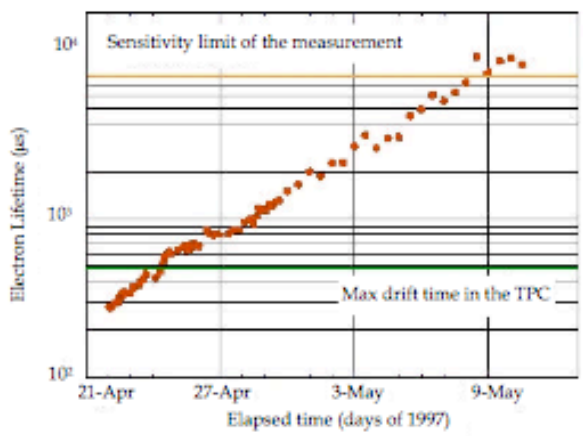
$D = 4.06\ cm^2/s$

$\sigma_D = 0.9\ mm \cdot \sqrt{T_D[ms]}$

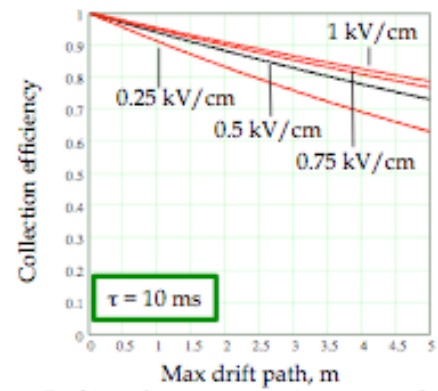
Longitudinal rms diffusion spread at 0.5 kV/cm

Average $\langle\sigma_D\rangle$ = 1.1 mm

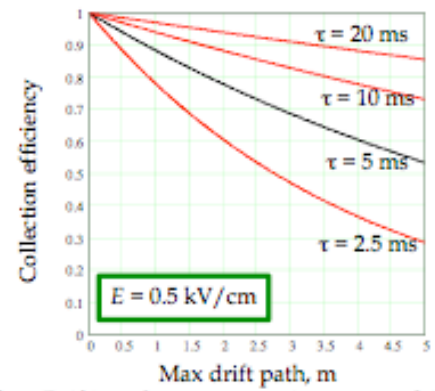
Maximum σ_{Dmax} = 1.6 mm



Purification rate for the 50L TPC



Drifting charge attenuation versus drift paths at different electric field intensities (τ = 10 ms)



Drifting charge attenuation versus drift path at different electron lifetimes (E = 0.5 kV/cm)

NuFact'01 – March 24-30, 2001 F. Sergiampietri LANNDD 22

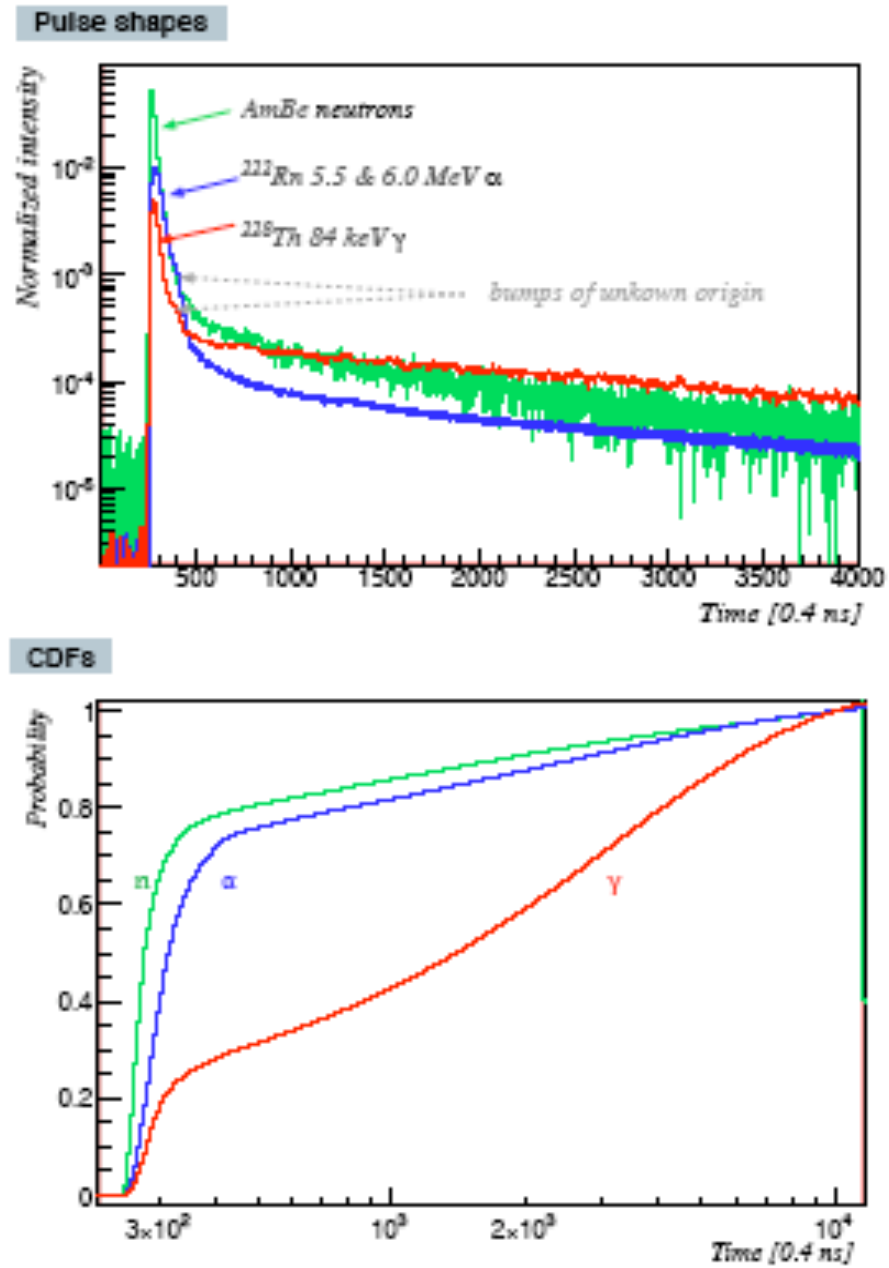
1.5 mm/μs at 500V/cm; 30 ppt O_2 -> 10 ms lifetime; $\sigma(mm)=t^{1/2}$ (ms)

Time distribution of light* output from Liquid Argon for γs, αs and neutrons

2 components:
τ(fast) = 7 ns
τ(slow) = 1600 ns

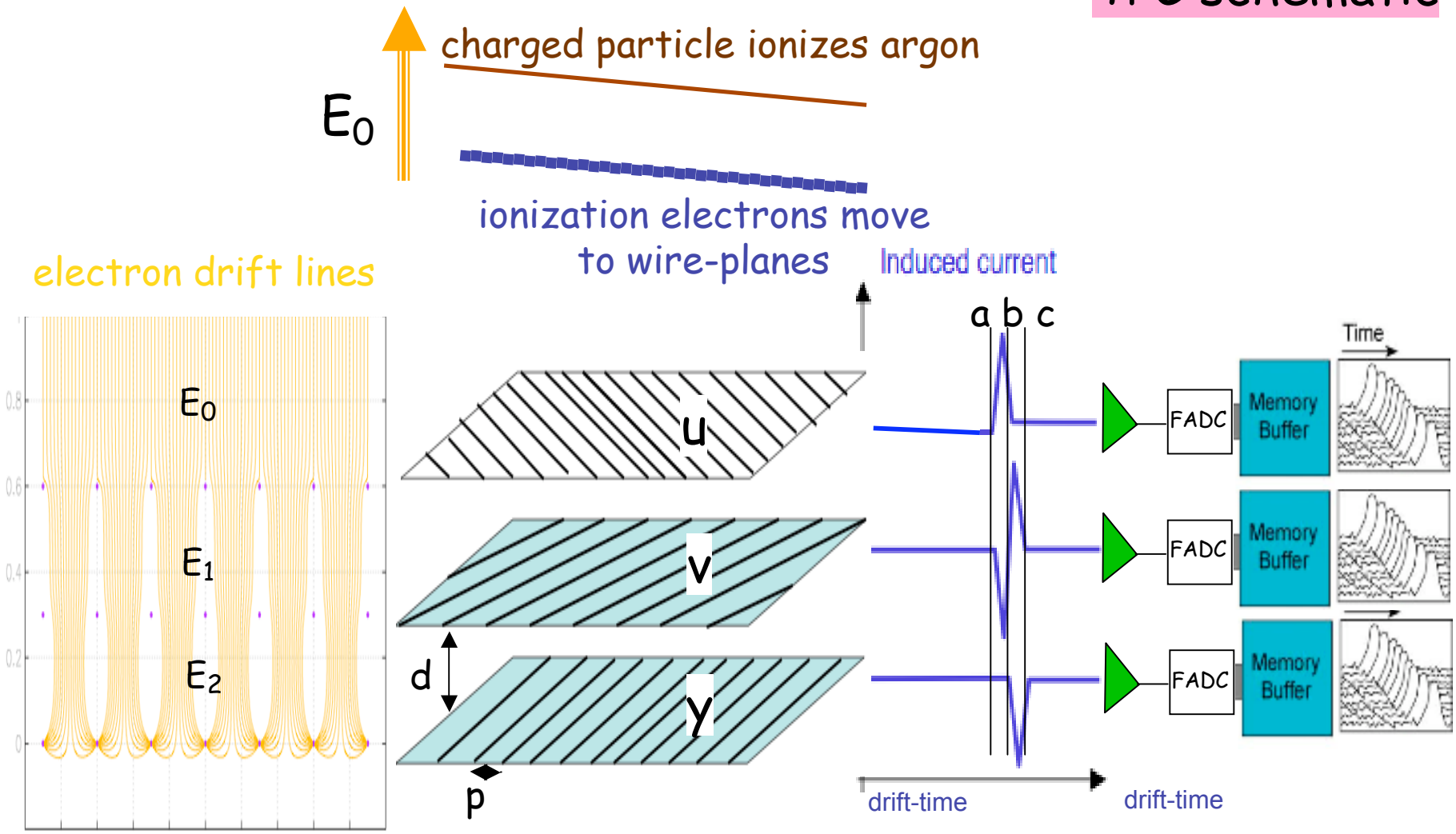
I(fast)/I(slow)
= 0.3(γ)
= 1.0(α)
= 3.0(neutrons)

*convolved with waveshifter and PMT response



from T. Pollman

TPC schematic



$E_2 > E_1 > E_0$

Bunneman, Cranshaw,Harvey, Can. J. Res. 27 (1949) 191

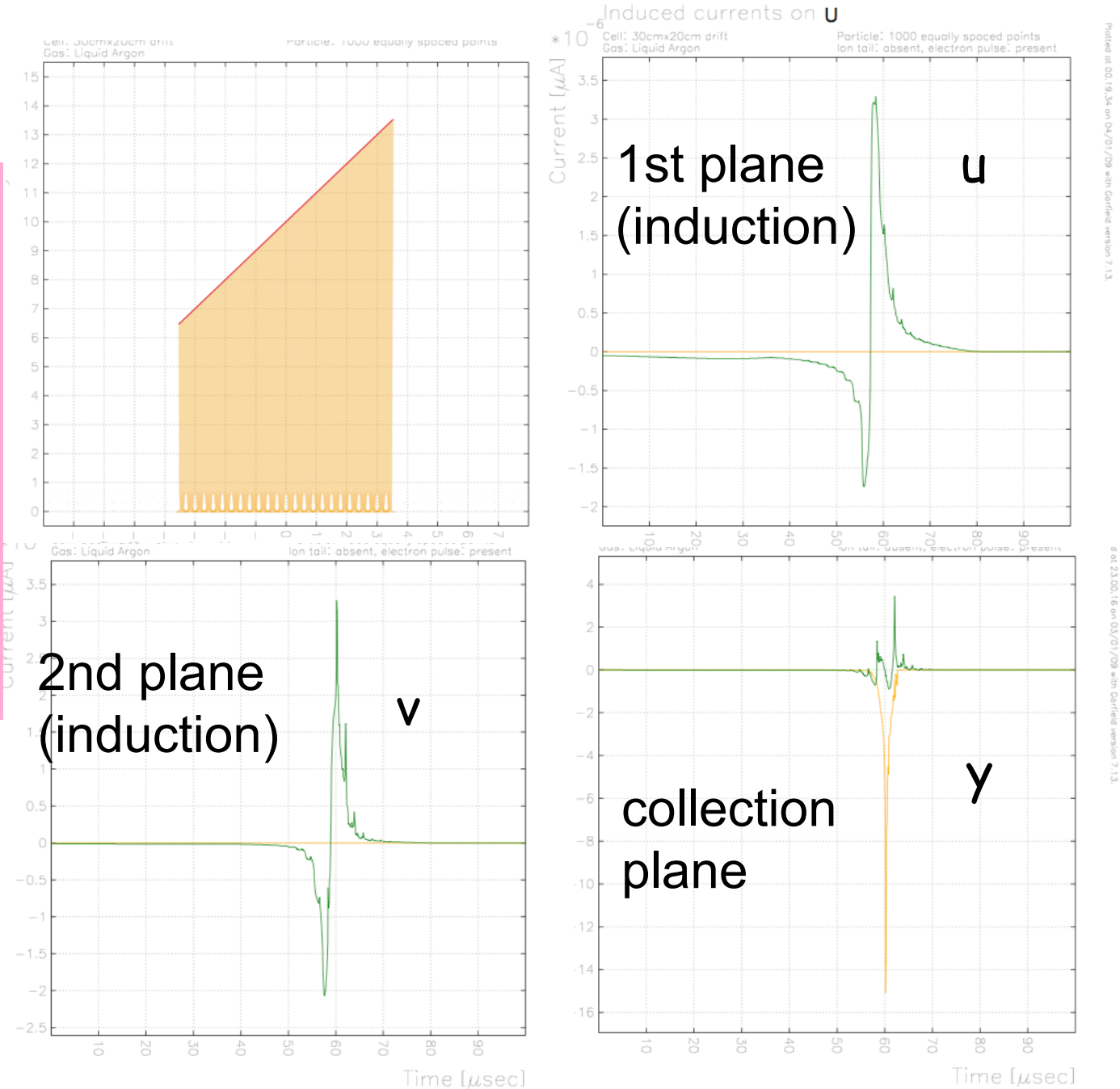
p~d~3-5 mm

Gatti, Padovini, Quartapelle,Greenlaw,Radeka IEEE Trans. NS-26 (2) (1979) 2910]

a = cross u
b = cross v
c = cross y

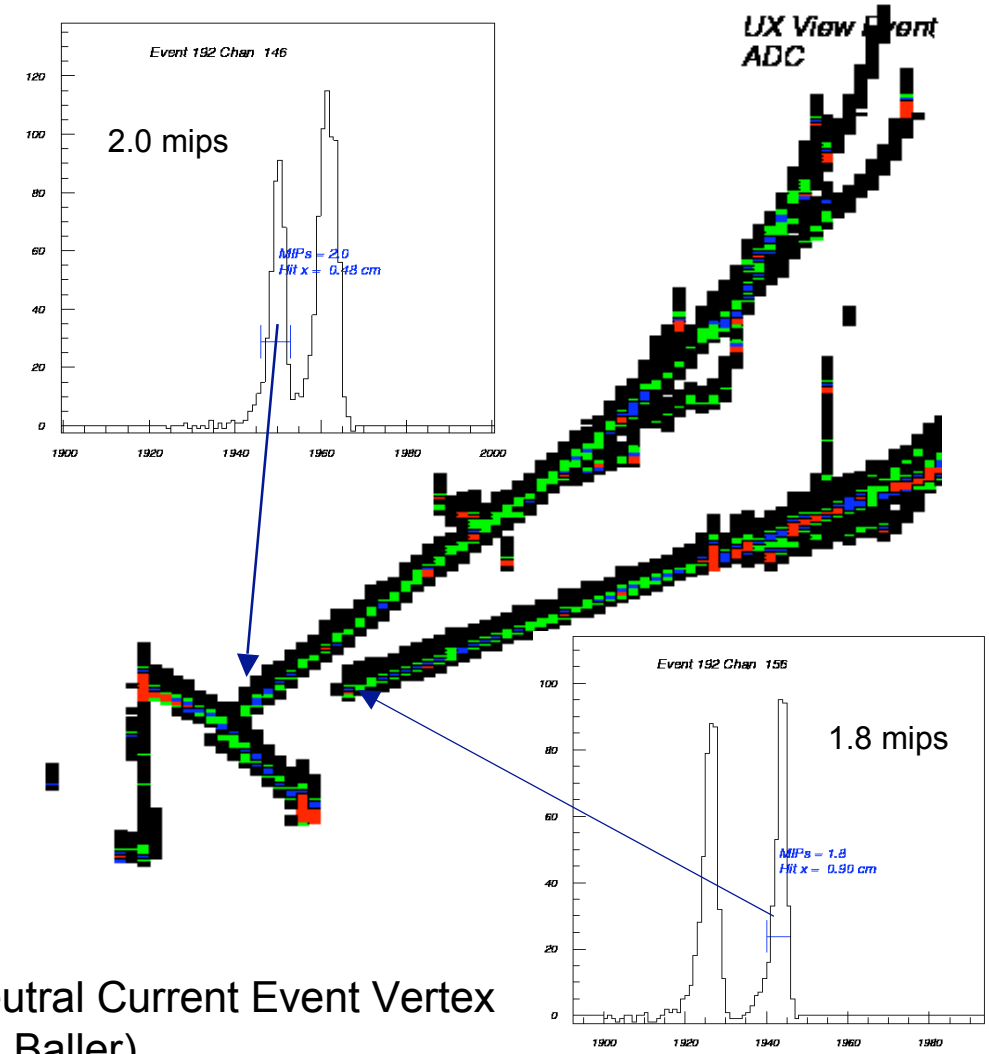
Field lines & current pulse simulations

(glitches are artifacts and removed by dispersion of electrons)

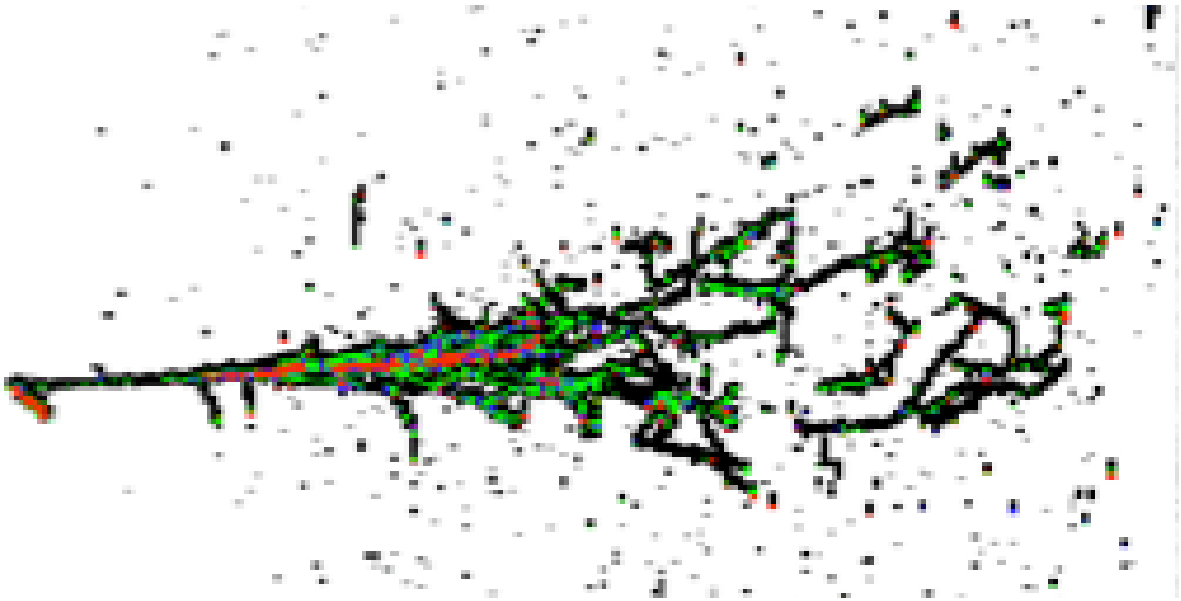


Simulation Software:

- Full Simulation of events in the detector starting from ionization through signals induced on wires through amplifier shaping and Fourier deconvolution etc
  - –know what to expect using `typical' parameters
  - –investigate alternatives (wire spacing, wire angles)
  - –develop pattern recognition and event ID algorithms

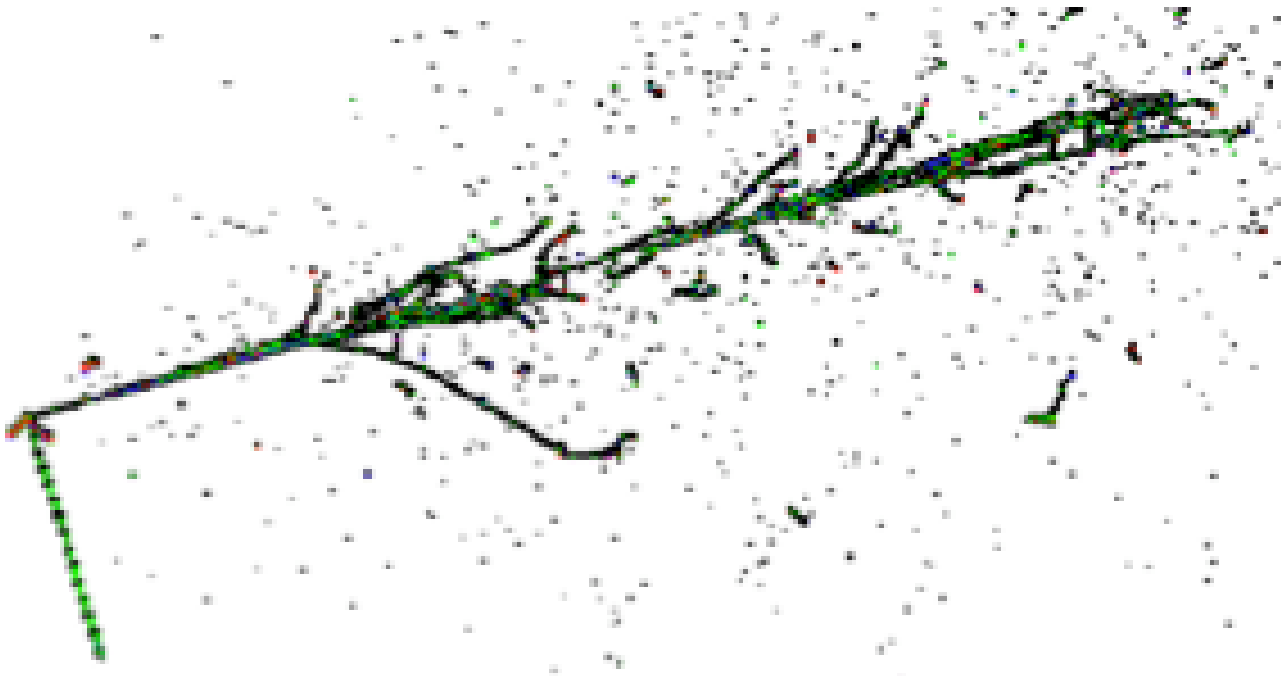


Neutral Current Event Vertex
(B. Baller)

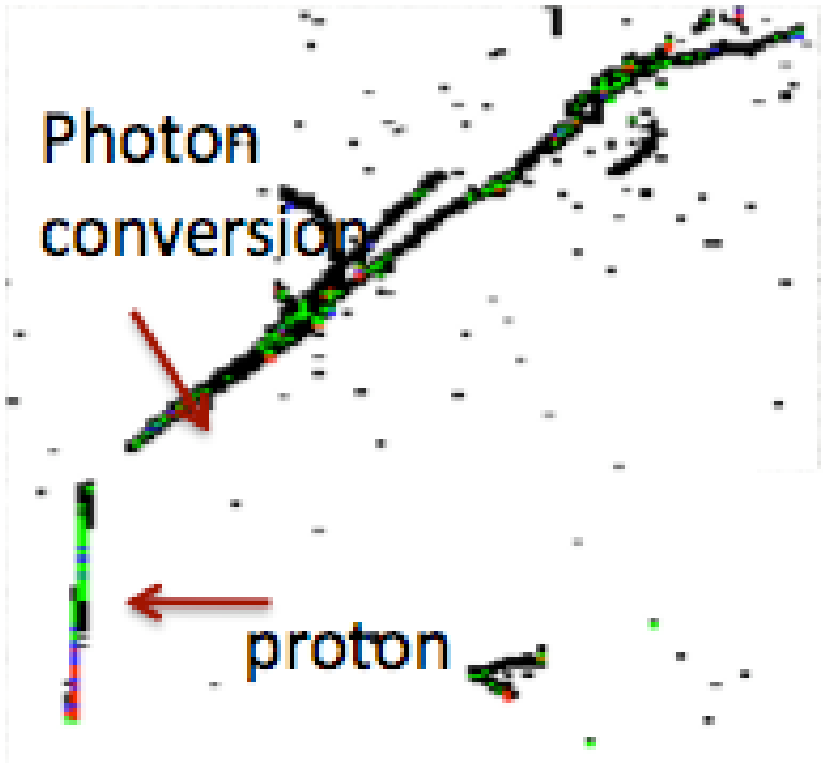


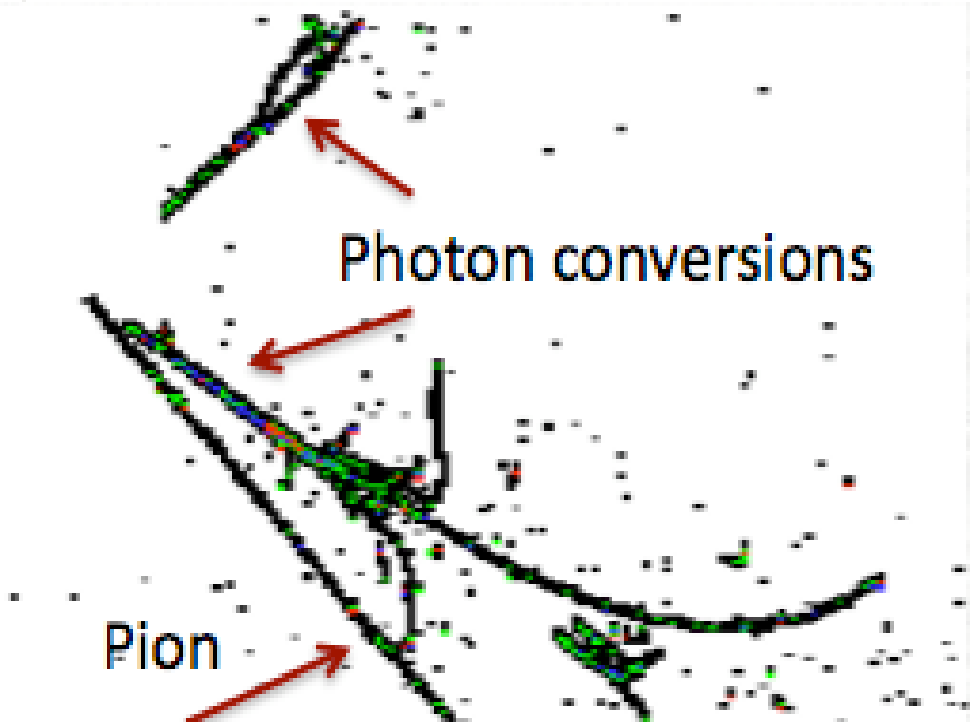
Text book
Electrons

$\nu_e + n \rightarrow e^- + p$

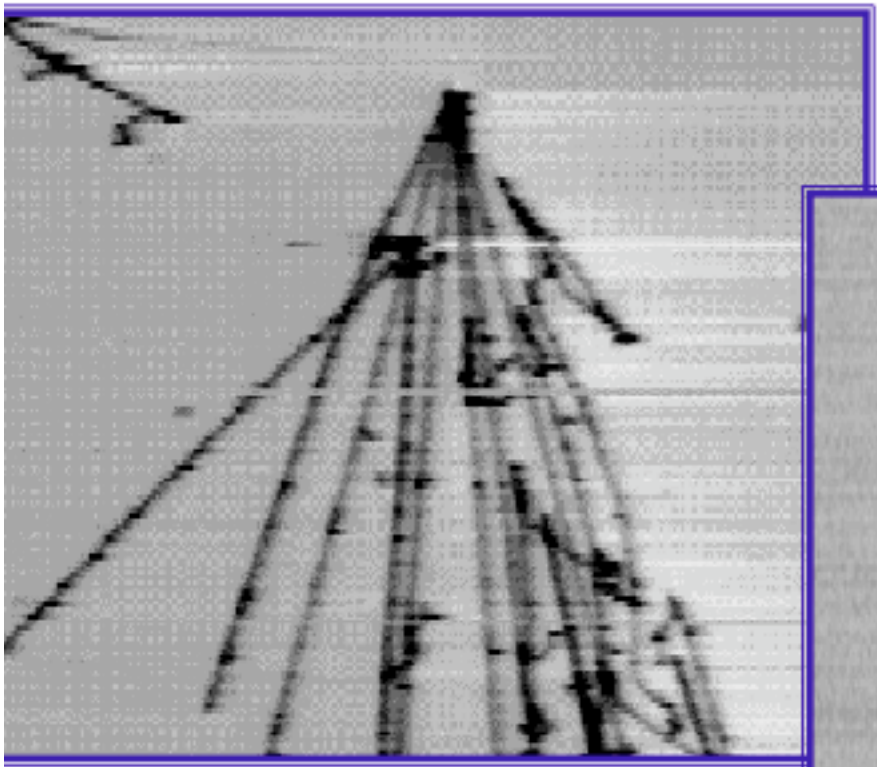


Text book photons

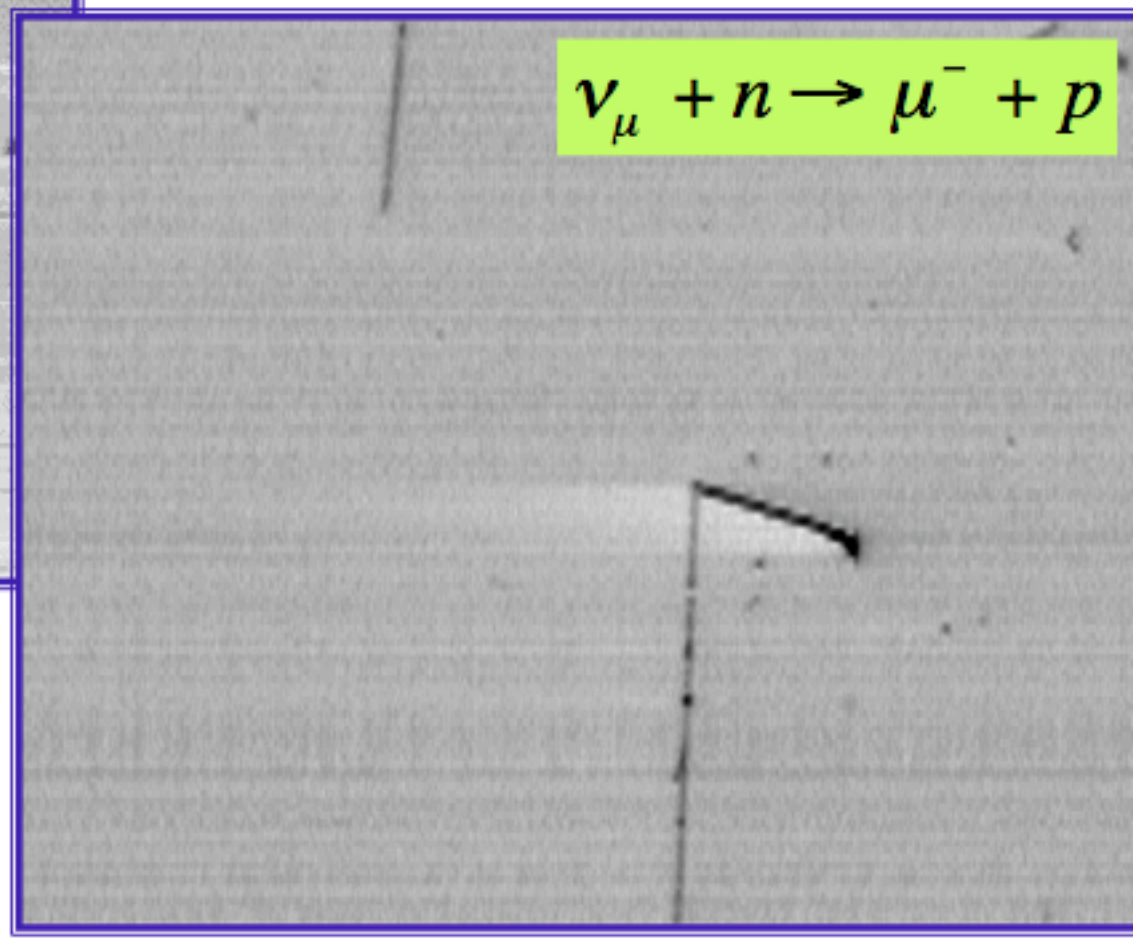




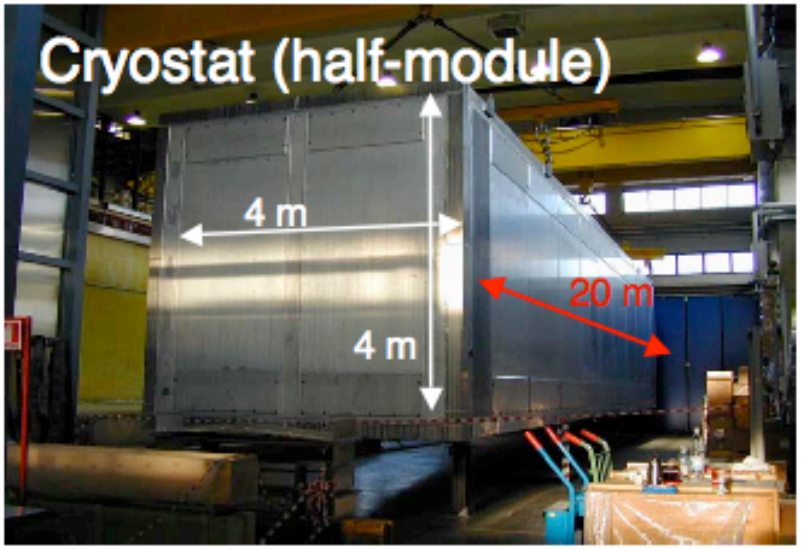
50 liter prototype in CERN West Area neutrino beam

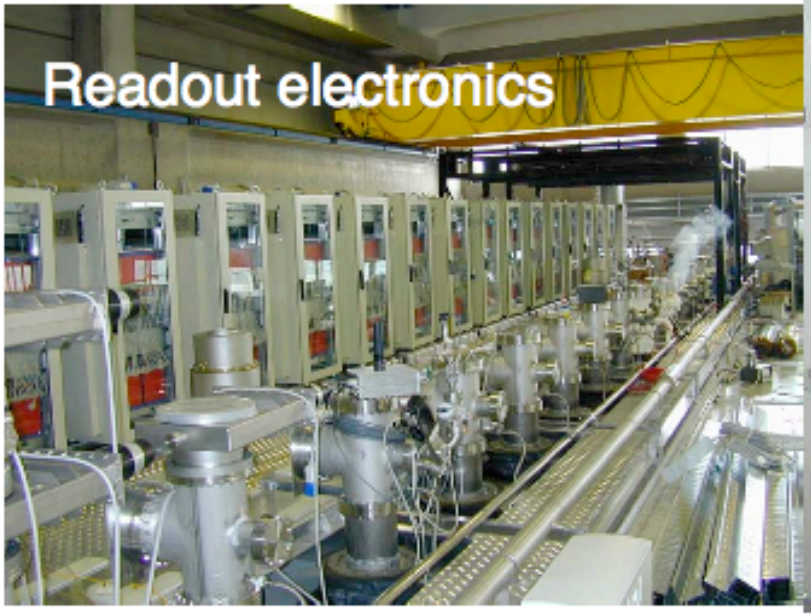


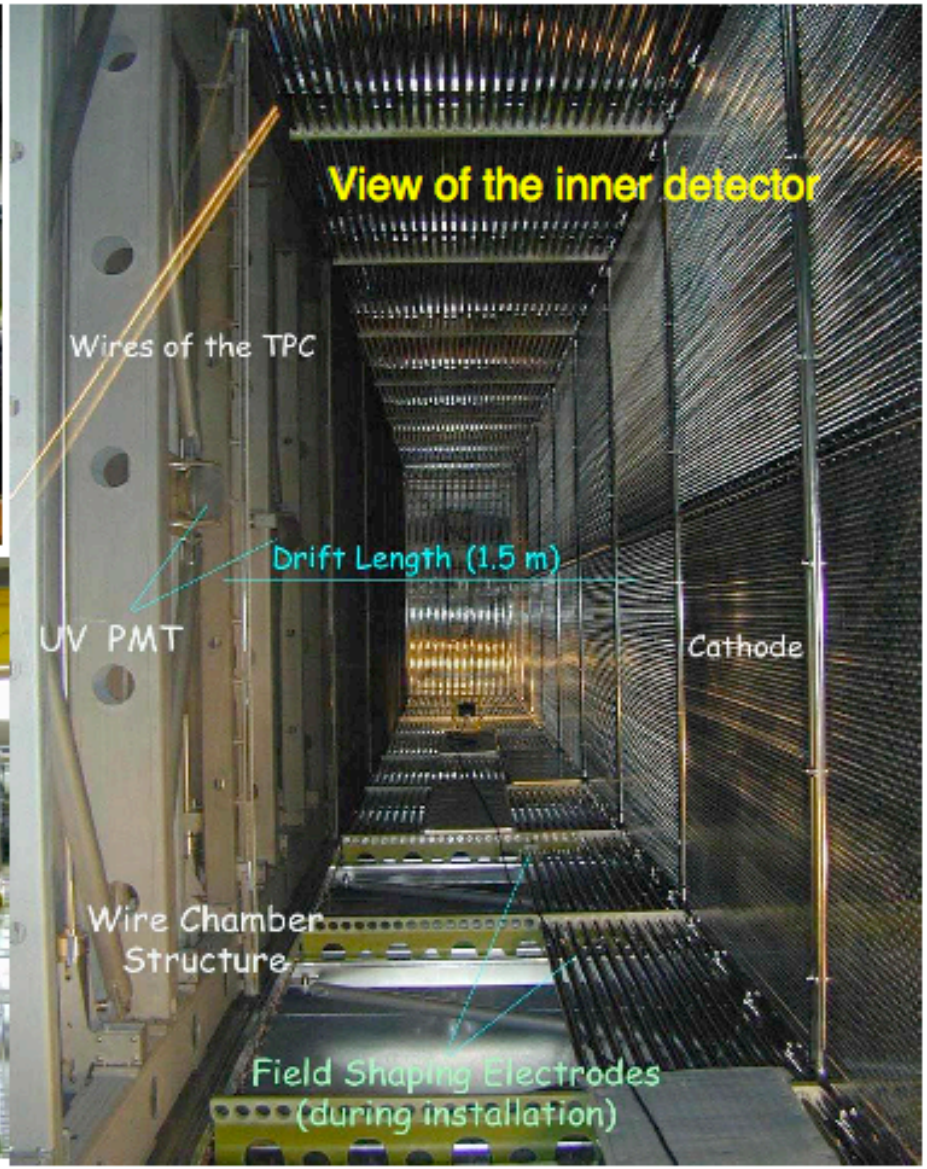
$$+ X \rightarrow \mu^- + many\ \ prongs$$



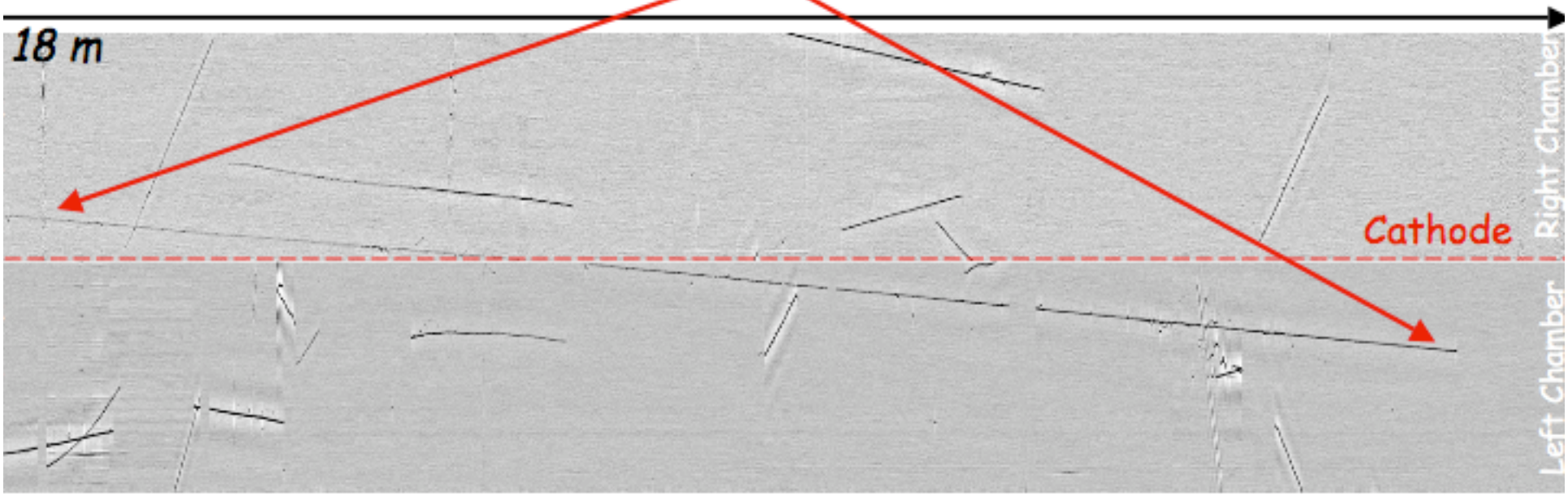
ICARUS T300 prototype



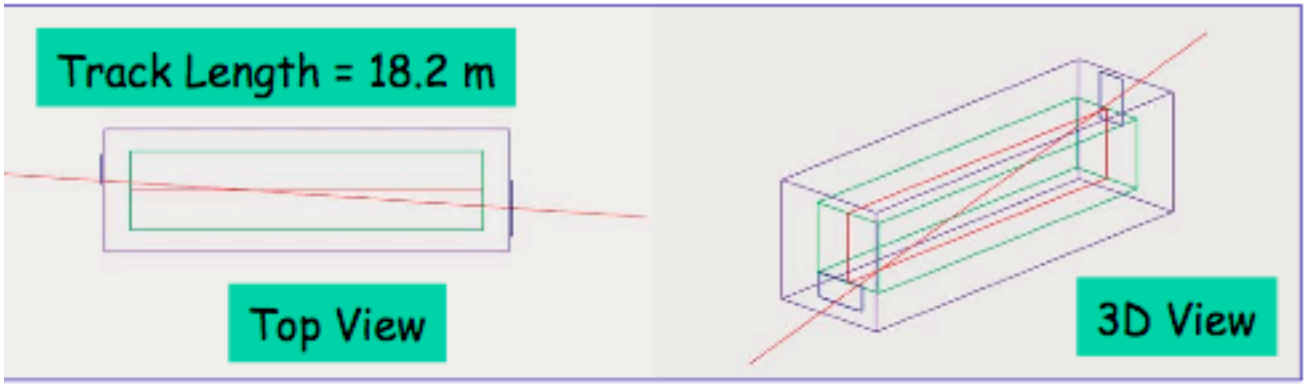




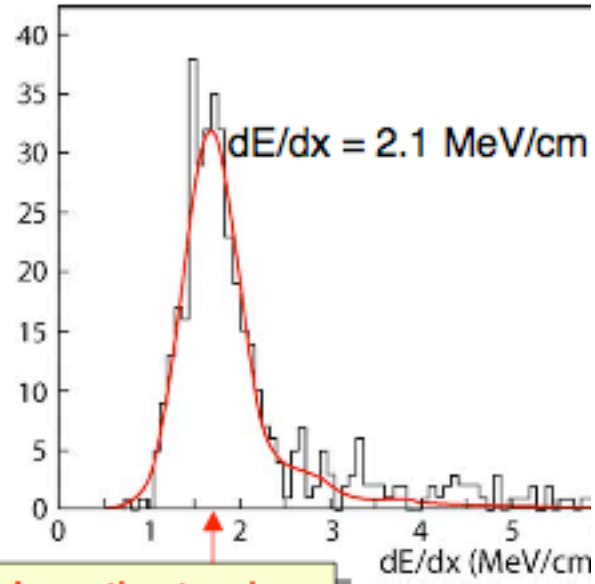
Long longitudinal muon track crossing the cathode plane



6000 points in each of the 3 readout planes !



3-D reconstruction of the long track



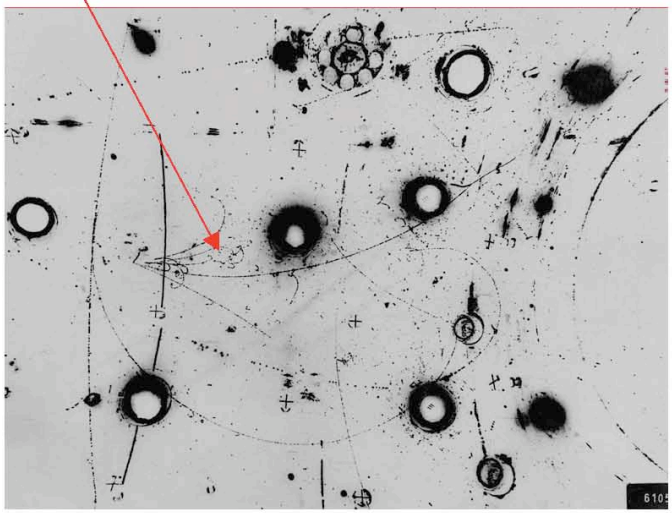
dE/dx distribution along the track

Thirty years of progress.....

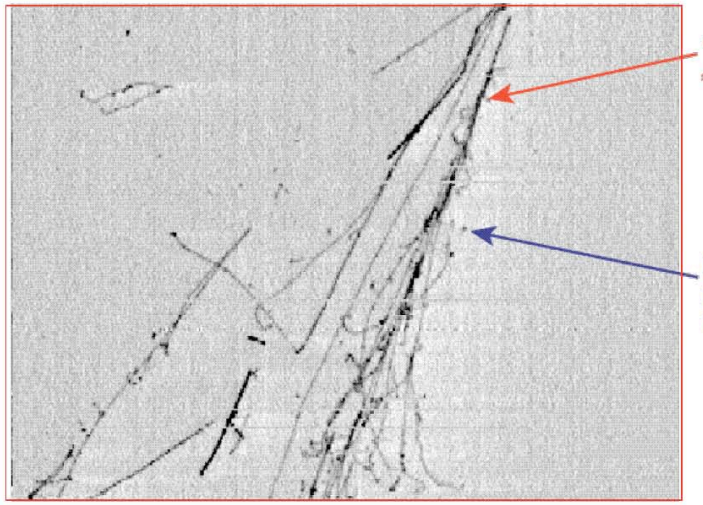
LAr is a cheap liquid (≈1CHF/litre), vastly produced by industry

Bubble diameter ≈ 3 mm (diffraction limited)

Gargamelle bubble chamber



ICARUS electronic chamber



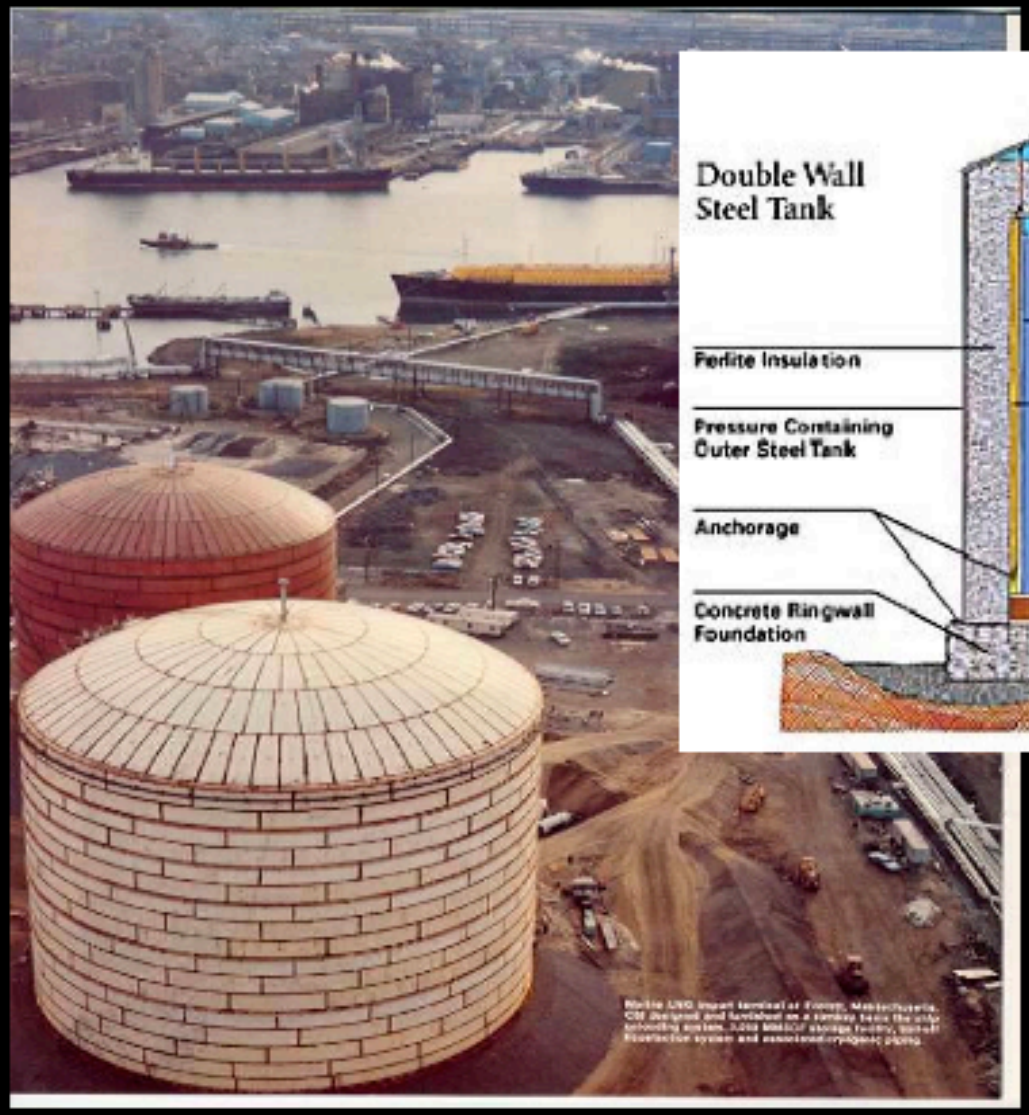
Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

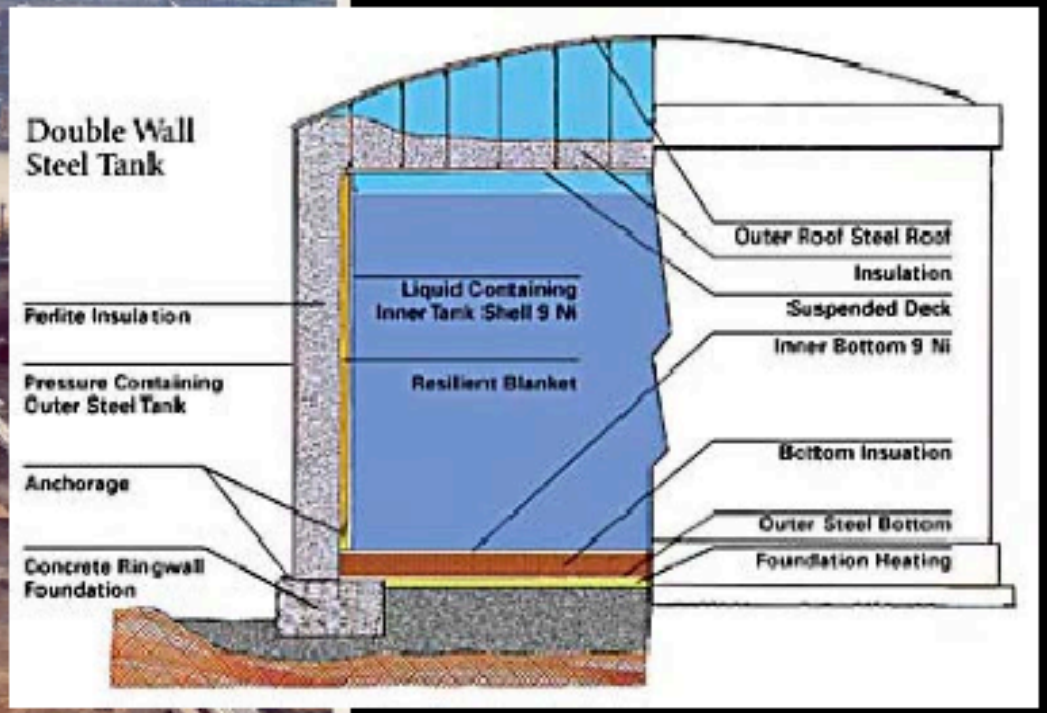
Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

from C. Rubbia

Liquid Argon in HEP has prospect of fully live Imaging Calorimeter: an electronic Bubble-Chamber

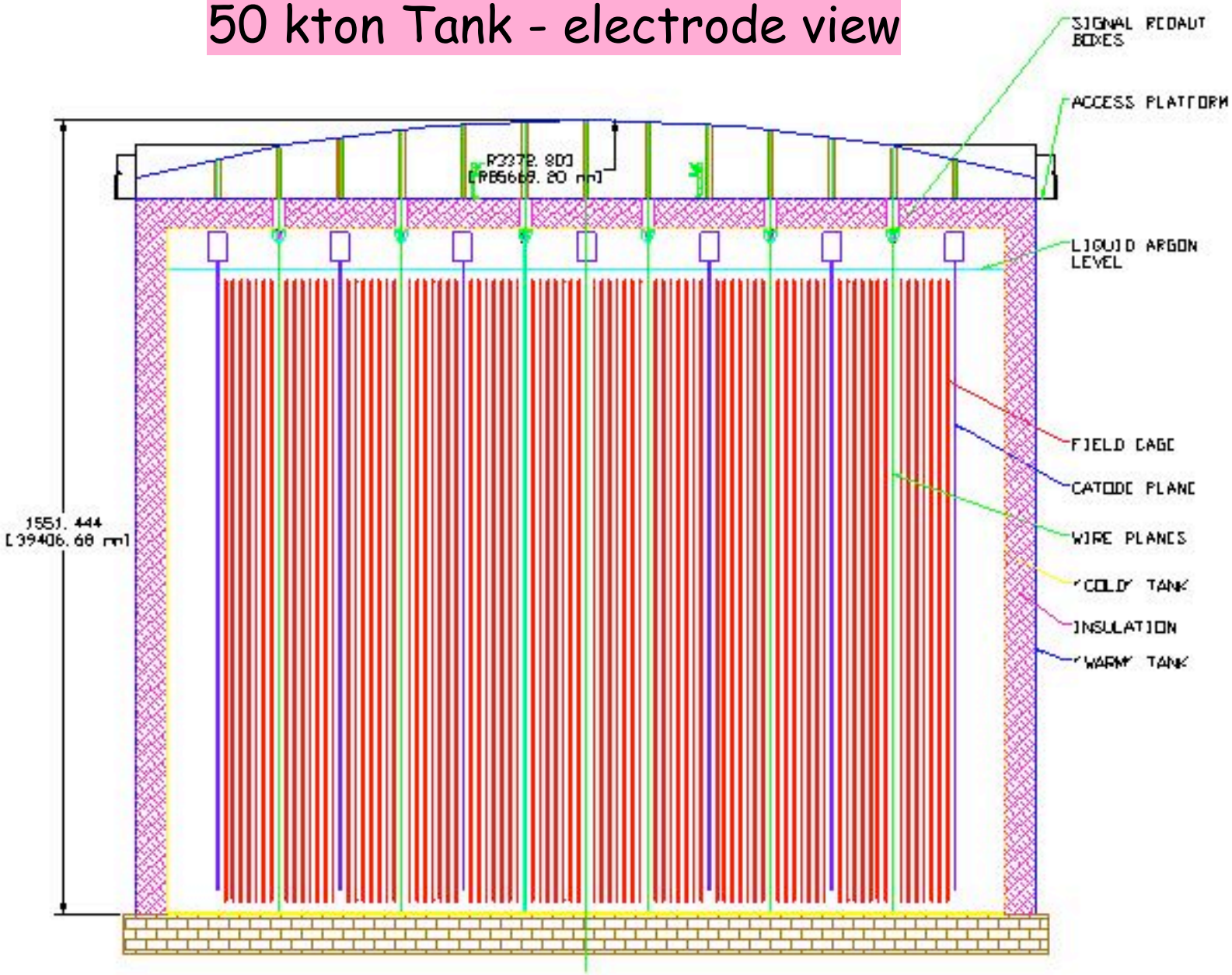
Detector Tank based on Industrial Liquified Natural Gas (LNG) storage tanks

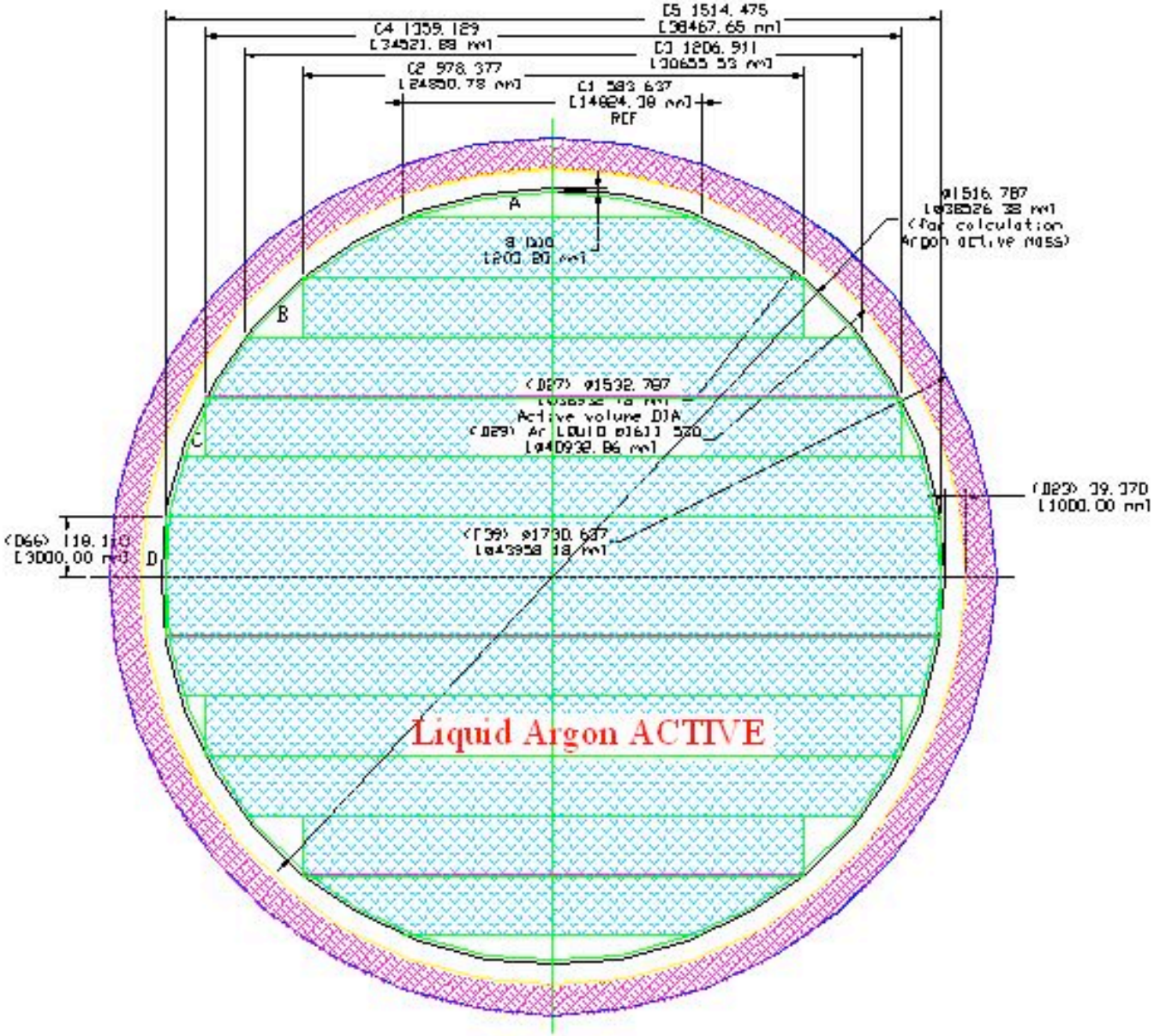




Many large LNG tanks in service.
excellent safety record;
last failure in 1940; reason
understood (wrong type of steel)

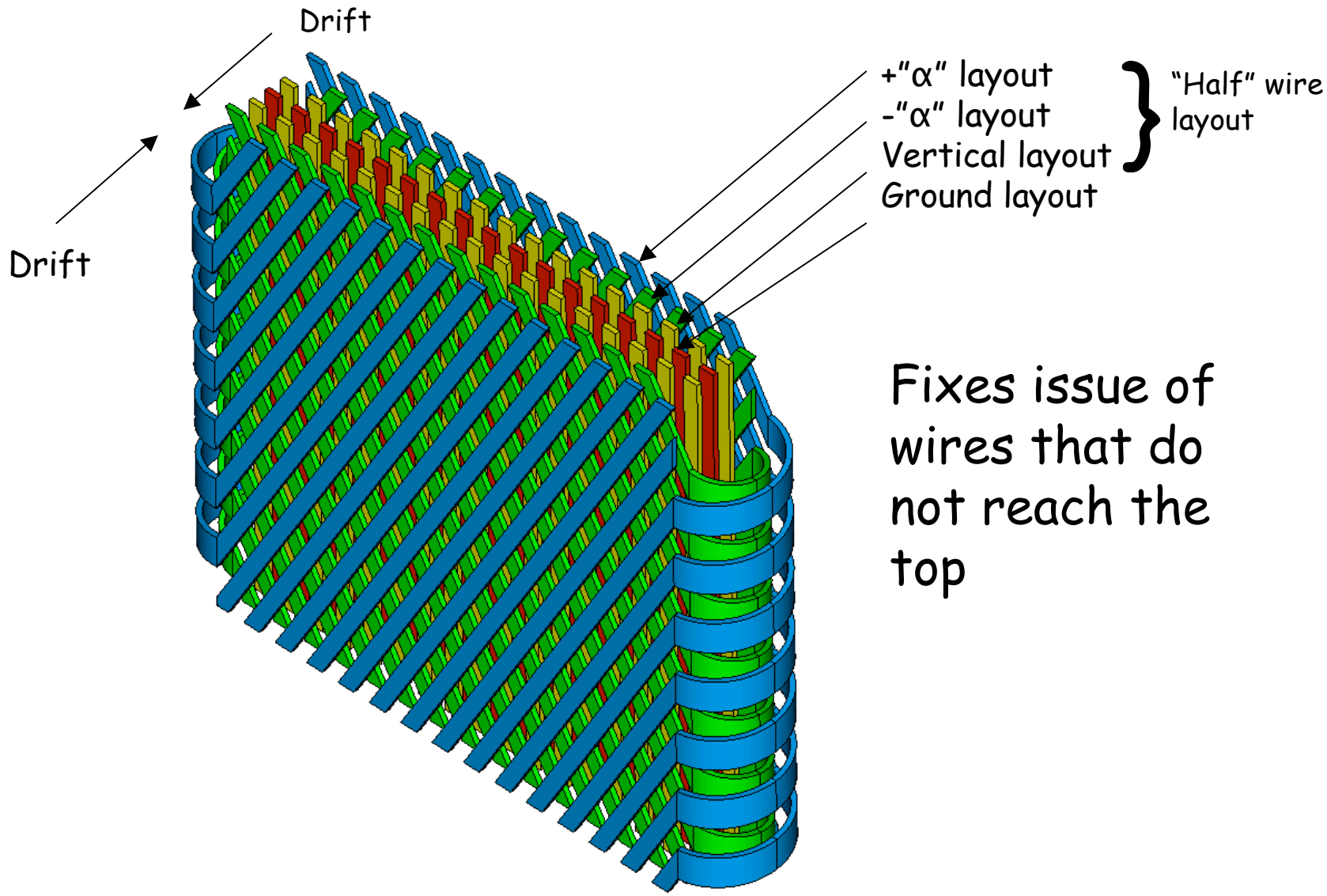
50 kton Tank - electrode view





50 kton Tank - top view

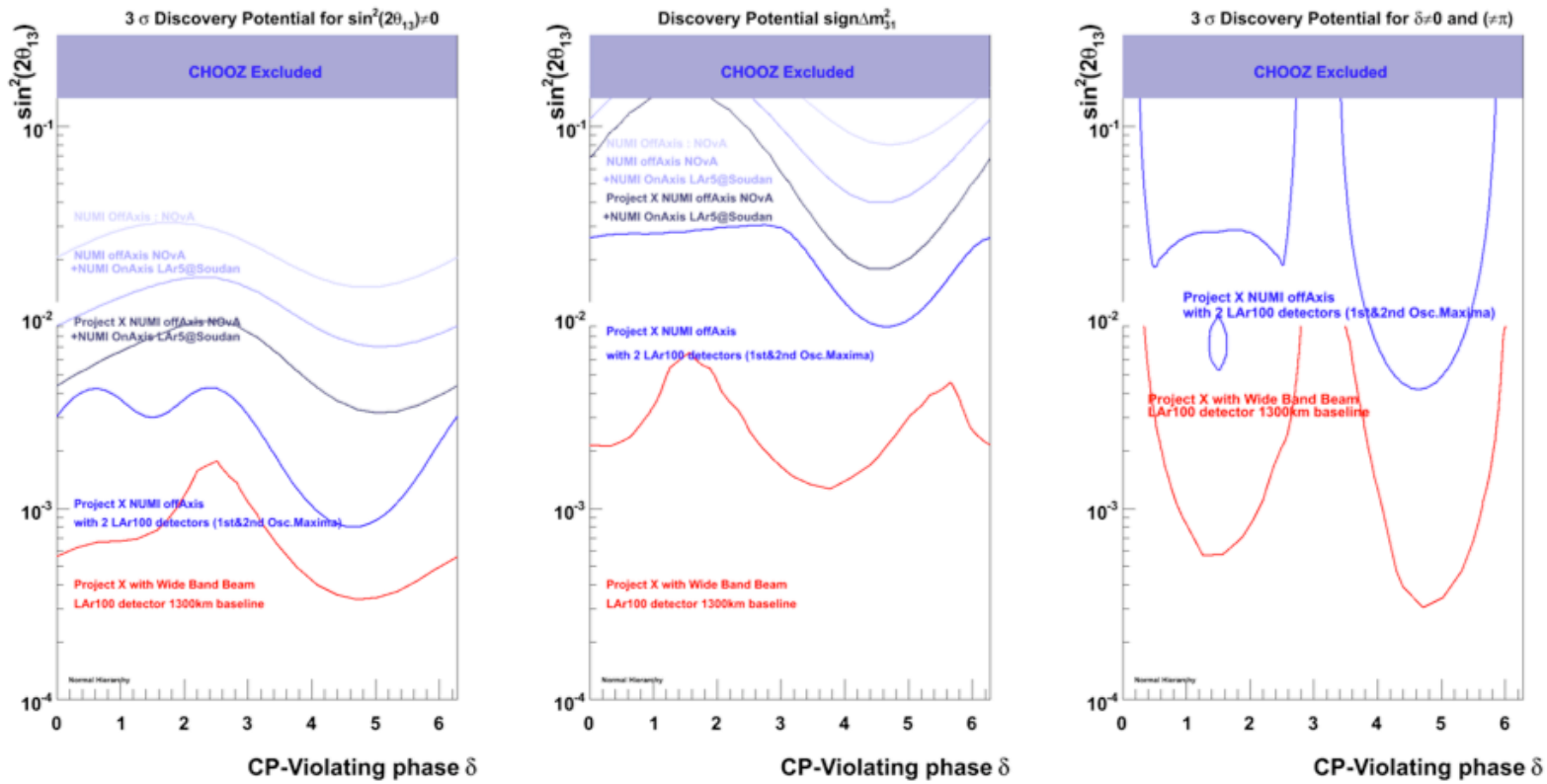
WIRE LAYOUT (proposal)



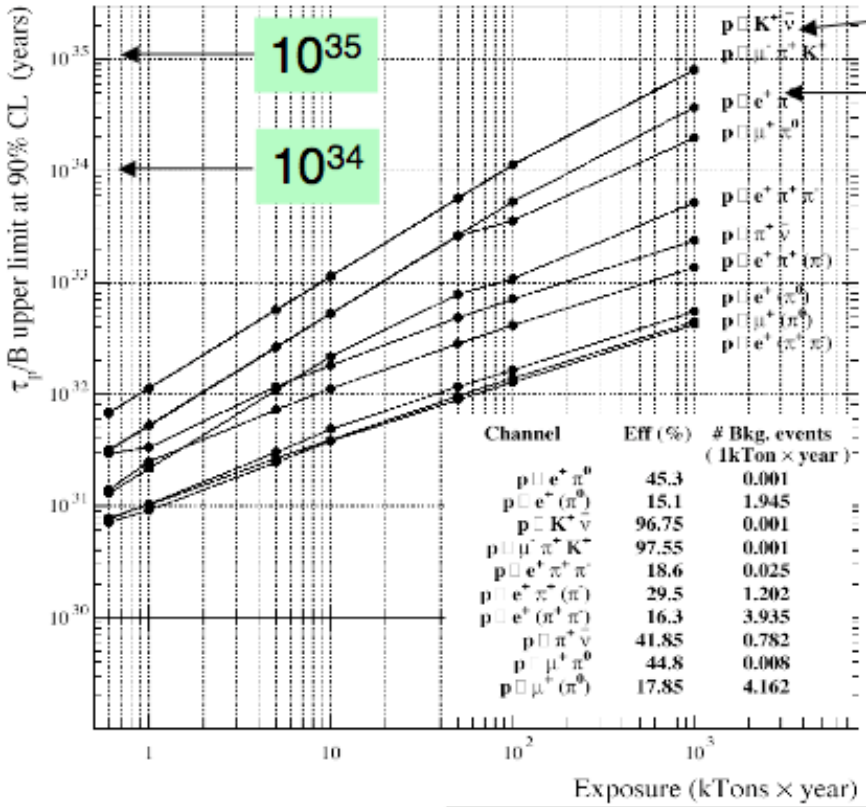
Fixes issue of wires that do not reach the top

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 assume:
  - 3 years neutrino + 3 years antineutrino
  - 80% signal efficiency and 80% beam ν_e selection efficiency.
  - no NC π^0 background (thanks to dE/dx capability) and 5% systematic on background.



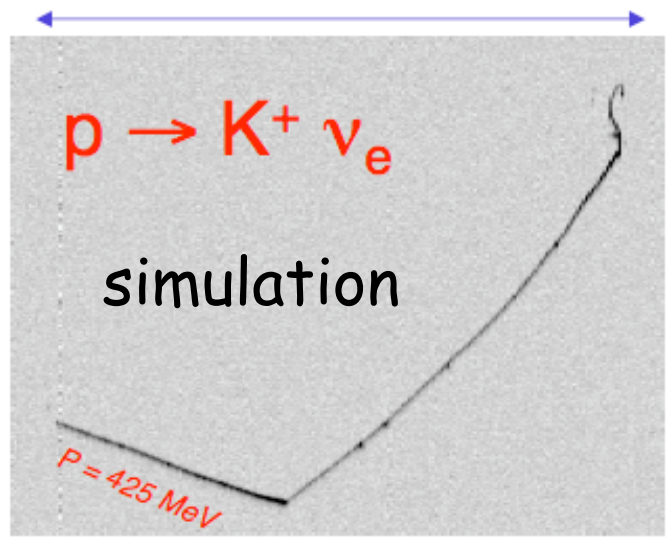
Proton decay: Sensitivity vs exposure



$p \to K^+ \nu$

$p \to e^+ \pi^0$

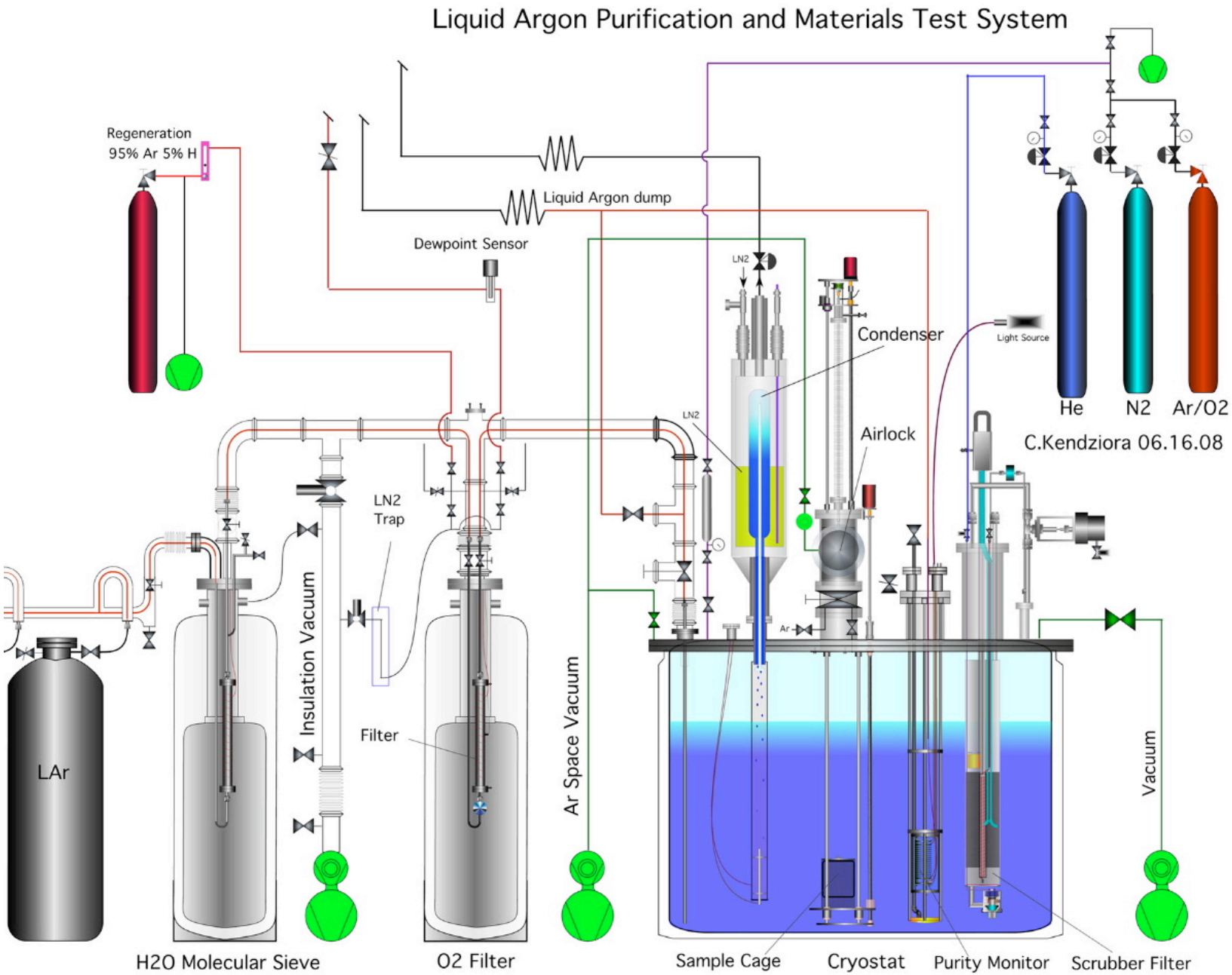
"Single" event detection capability



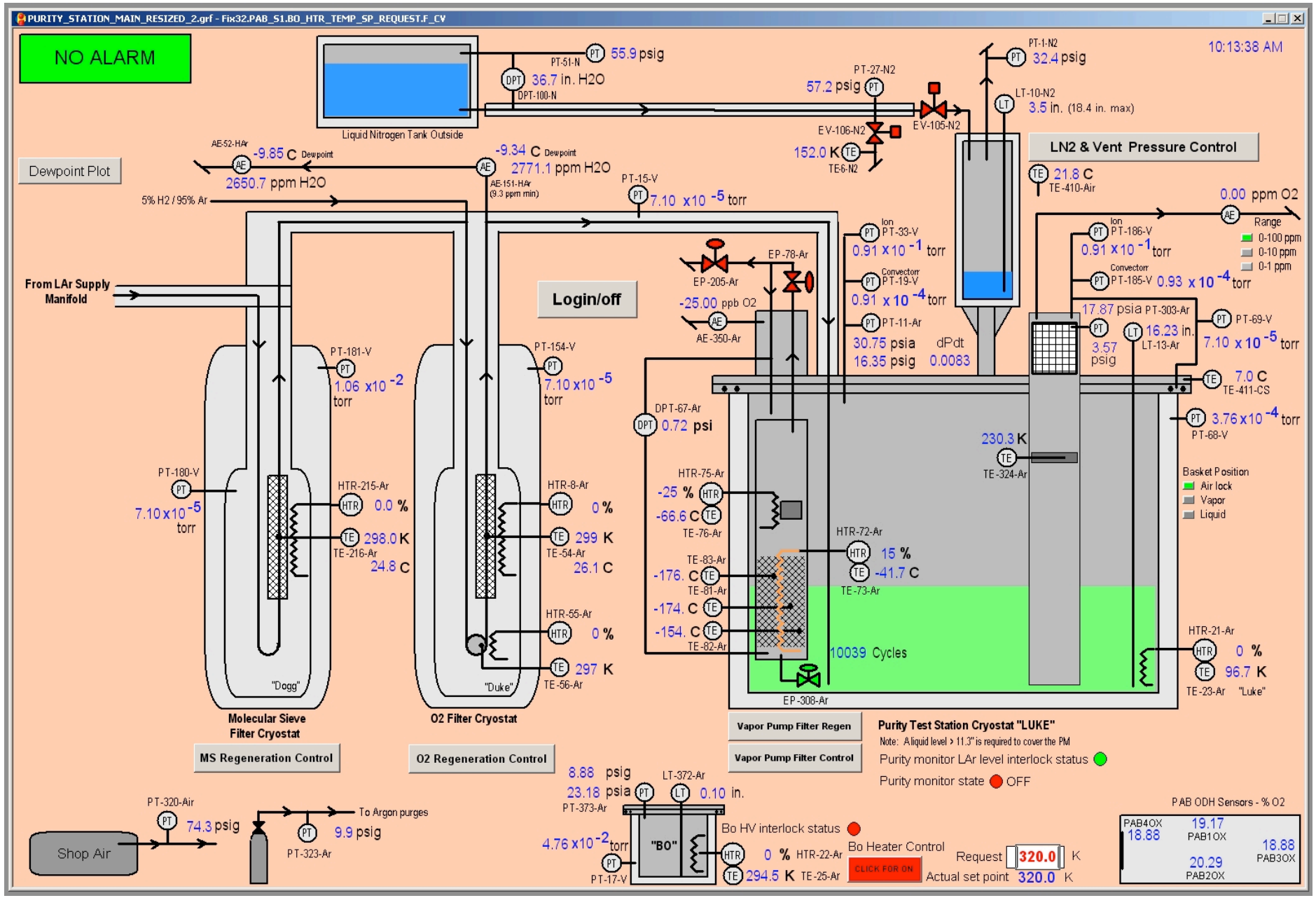
1.2×10^{35} nucleons $\Rightarrow \tau_p/Br > 2\ 10^{34}$ years × T(yr) × ε @ 90 C.L.

Some LArTPC Technical Issues for Neutrino Detectors

Argon Purity	–**From atmosphere to purity without evacuation** –How to remove impurities from Argon (filter gas as well as liquid?) –What impurities matter and how to measure drift lifetime –What are the sources of contamination and how to avoid/remove them without pumping (vessel, plastics=> surface physics)
Vessel Design	–Design, **(Underground) Construction**, Safety –Cryogenics (cooling system and insulation) –Thermodynamics (argon temperature and flow distribution)
Detector Design	–HV system –Mechanical reliability - **TPC constructed in situ or externally** –Constraints from electronics (eg readout only at top?) –Light collection scheme; (for `triggering' and pattern recognition)
Electronics & DAQ	–Amplifiers, multiplexing, digitizers - **in cryostat?** Feedthroughs –Signal/noise (large capacitance) and constraints on TPC design –Zero suppression, signal processing, local event recognition capability, **100% livetime (not just beam spill)**
Simulation & Reconstruction	–Real and simulated signals on wires; develop signal processing –Event generation in argon –Vertex and pattern recognition; cosmic ray rejection; event reconstruction

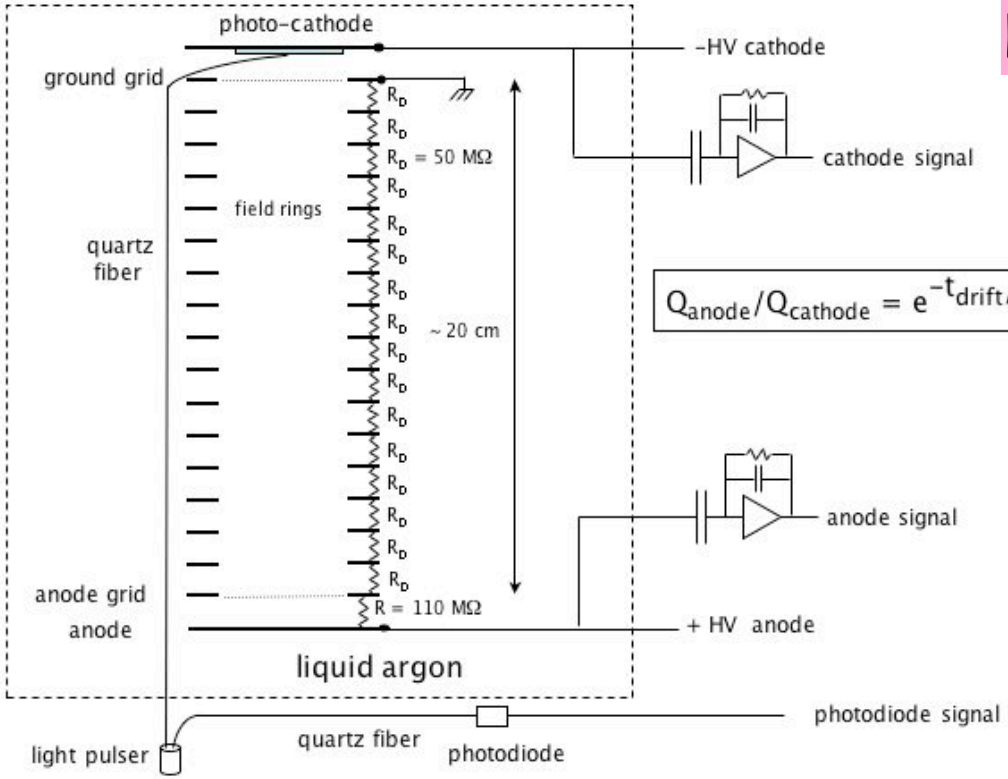

Liquid Argon Purification and Materials Test System
Regeneration
95% Ar 5% H
Liquid Argon dump
Dewpoint Sensor
LN2
Condenser
Light Source
He
N2
Ar/O2
C.Kendziora 06.16.08
Airlock
LN2
Trap
Insulation Vacuum
Filter
Ar Space Vacuum
Vacuum
LAr
Ar
H2O Molecular Sieve
O2 Filter
Sample Cage
Cryostat
Purity Monitor
Scrubber Filter

Argon
Argon
Cu Filter (O2)
Materials
Test System
Zeolite Filter (H2O)
TPC & Electronics
Test System
Argon Supply
ARGON
ARGON

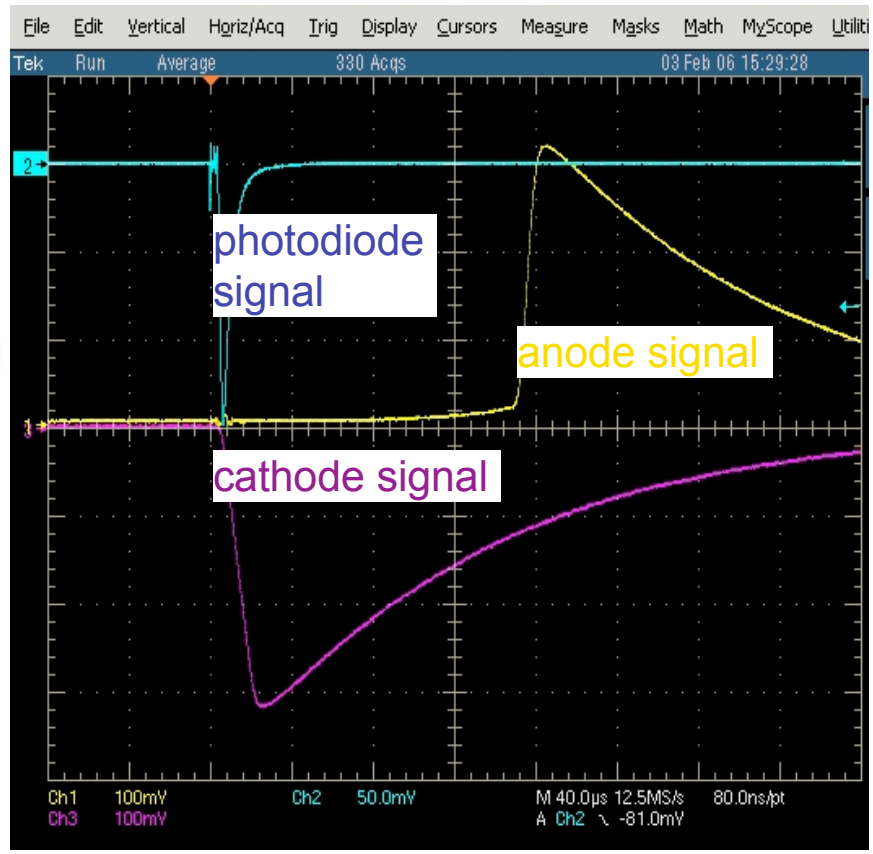

PURITY_STATION_MAIN_RESIZED_2.grf - Fix32.PAB_S1.BO_HTR_TEMP_SP_REQUEST.F_CV
NO ALARM
10:13:38 AM
Liquid Nitrogen Tank Outside
PT-51-N 55.9 psig
DPT-100-N 36.7 in. H2O
PT-27-N2 57.2 psig
PT-1-N2 32.4 psig
LT-10-N2 3.5 in. (18.4 in. max)
EV-106-N2
EV-105-N2
TE-6-N2 152.0 K
LN2 & Vent Pressure Control
TE-410-Air 21.8 C
Dewpoint Plot
AE-52-HAr -9.85 C Dewpoint 2650.7 ppm H2O
AE-151-HAr (9.3 ppm min) -9.34 C Dewpoint 2771.1 ppm H2O
5% H2 / 95% Ar
PT-15-V 7.10 x10 -5 torr
0.00 ppm O2
Range
0-100 ppm
0-10 ppm
0-1 ppm
From LAr Supply Manifold
EP-78-Ar
EP-205-Ar
Login/off
-25.00 ppb O2
AE-350-Ar
PT-33-V Ion 0.91 x10 -1 torr
PT-19-V Convectorr 0.91 x 10 -4 torr
PT-11-Ar 30.75 psia 16.35 psig dPdt 0.0083
PT-186-V Ion 0.91 x10 -1 torr
PT-185-V Convectorr 0.93 x 10 -4 torr
17.87 psia PT-303-Ar
3.57 psig
LT-13-Ar 16.23 in.
PT-69-V 7.10 x 10 -5 torr
TE-411-CS 7.0 C
PT-68-V 3.76 x10 -4 torr
PT-181-V 1.06 x10 -2 torr
PT-154-V 7.10 x10 -5 torr
DPT-67-Ar 0.72 psi
230.3 K TE-324-Ar
PT-180-V 7.10 x10 -5 torr
HTR-215-Ar 0.0 %
TE-216-Ar 298.0 K 24.8 C
HTR-8-Ar 0 %
TE-54-Ar 299 K 26.1 C
HTR-55-Ar 0 %
TE-56-Ar 297 K
HTR-75-Ar -25 %
TE-76-Ar -66.6 C
TE-83-Ar -176. C
TE-81-Ar -174. C
TE-82-Ar -154. C
HTR-72-Ar 15 %
TE-73-Ar -41.7 C
10039 Cycles
EP-308-Ar
Basket Position
Air lock
Vapor
Liquid
HTR-21-Ar 0 %
TE-23-Ar 96.7 K "Luke"
"Dogg"
"Duke"
Molecular Sieve Filter Cryostat
O2 Filter Cryostat
MS Regeneration Control
O2 Regeneration Control
Vapor Pump Filter Regen
Vapor Pump Filter Control
Purity Test Station Cryostat "LUKE"
Note: A liquid level > 11.3" is required to cover the PM
Purity monitor LAr level interlock status
Purity monitor state OFF
PT-320-Air 74.3 psig
Shop Air
PT-323-Ar 9.9 psig
To Argon purges
8.88 psig
23.18 psia PT-373-Ar
LT-372-Ar 0.10 in.
4.76 x10 -2 torr PT-17-V
"BO"
Bo HV interlock status
HTR-22-Ar 0 %
TE-25-Ar 294.5 K
Bo Heater Control
CLICK FOR ON
Request 320.0 K
Actual set point 320.0 K
PAB ODH Sensors - % O2
PAB4OX 18.88
PAB1OX 19.17
PAB3OX 18.88
PAB2OX 20.29

Drift lifetime Measurement

Schematic of Liquid Argon Purity Monitor (PrM)

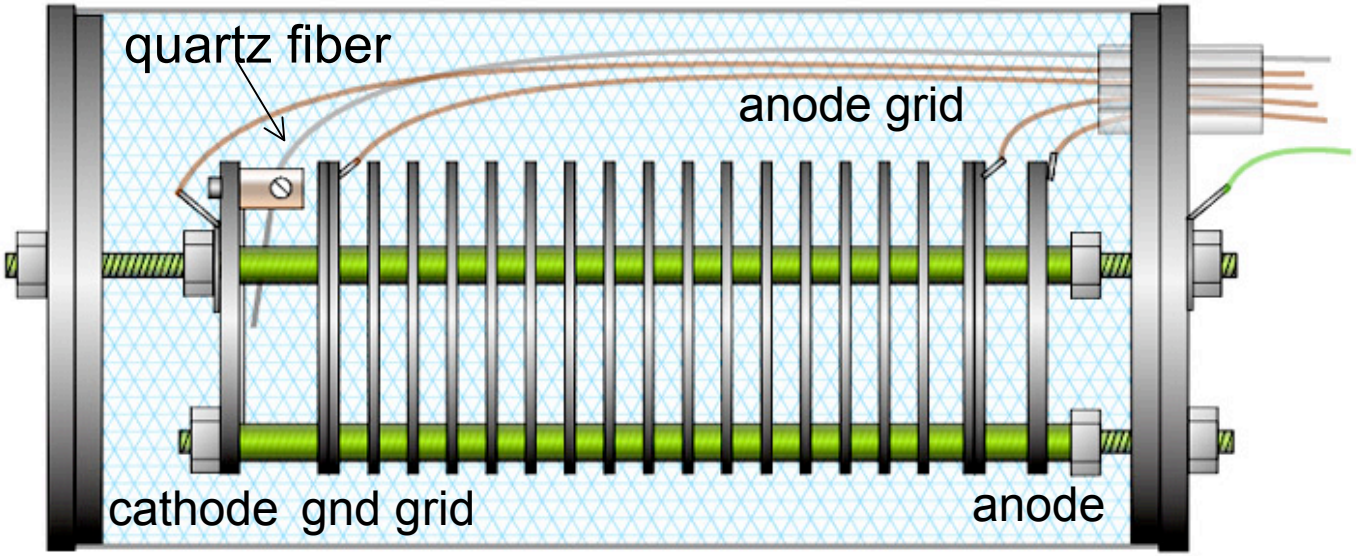


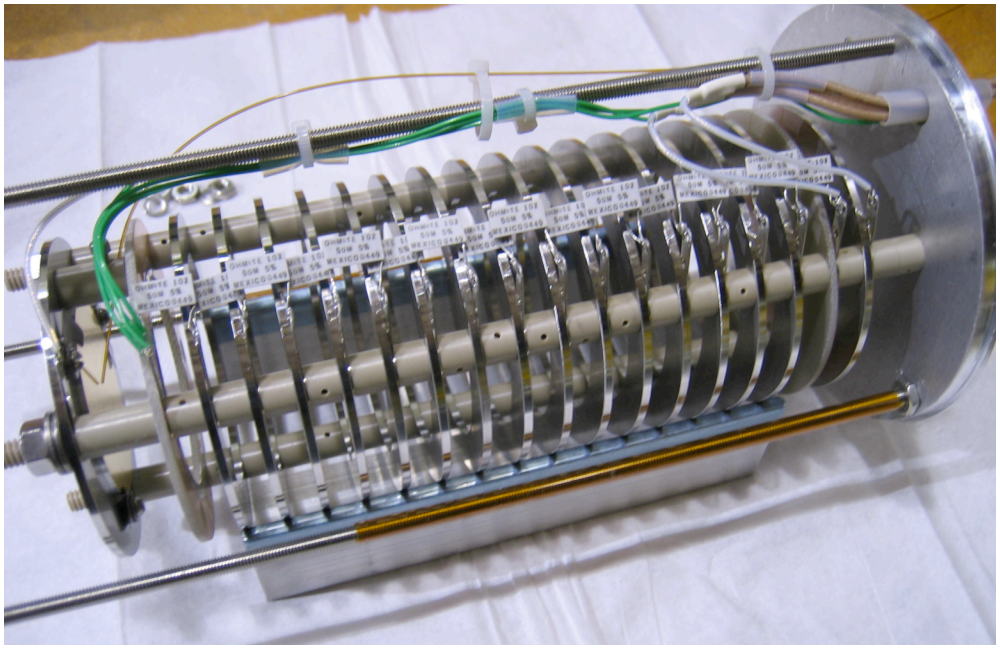
$$Q_{anode}/Q_{cathode} = e^{-t_{drift}/\tau}$$



G. Carugno, NIM A 292 (1990)

PrM drawing

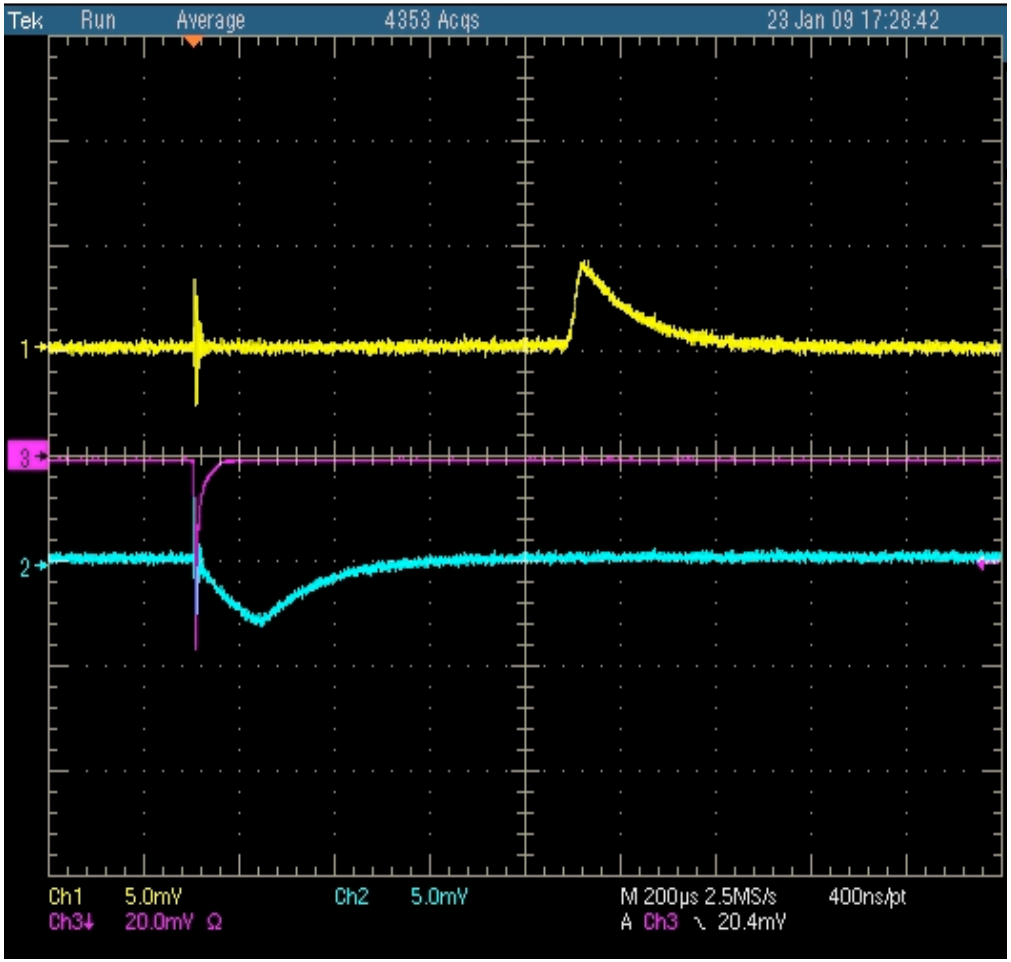


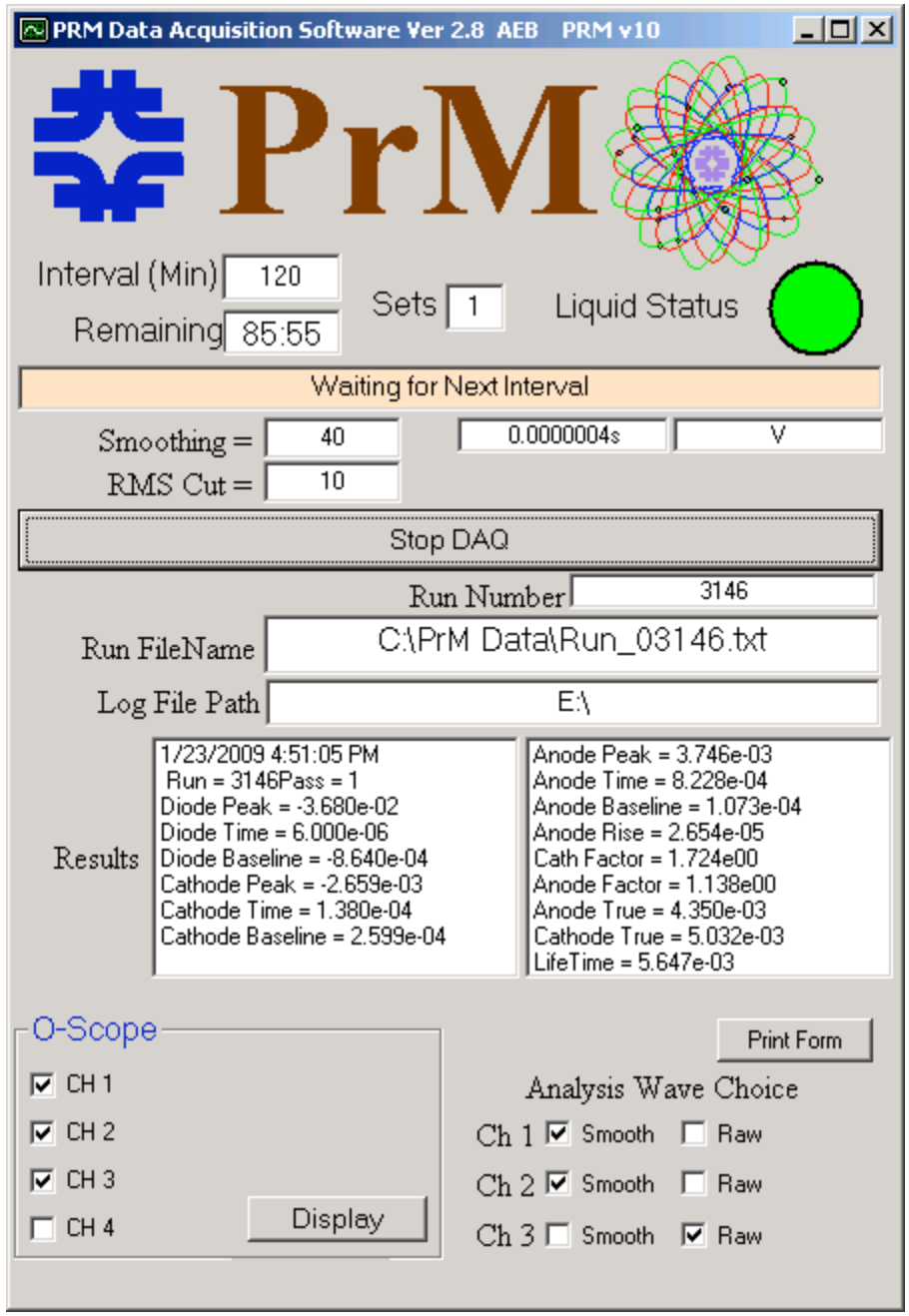


C.Kendziora2/3.05

PrM photograph

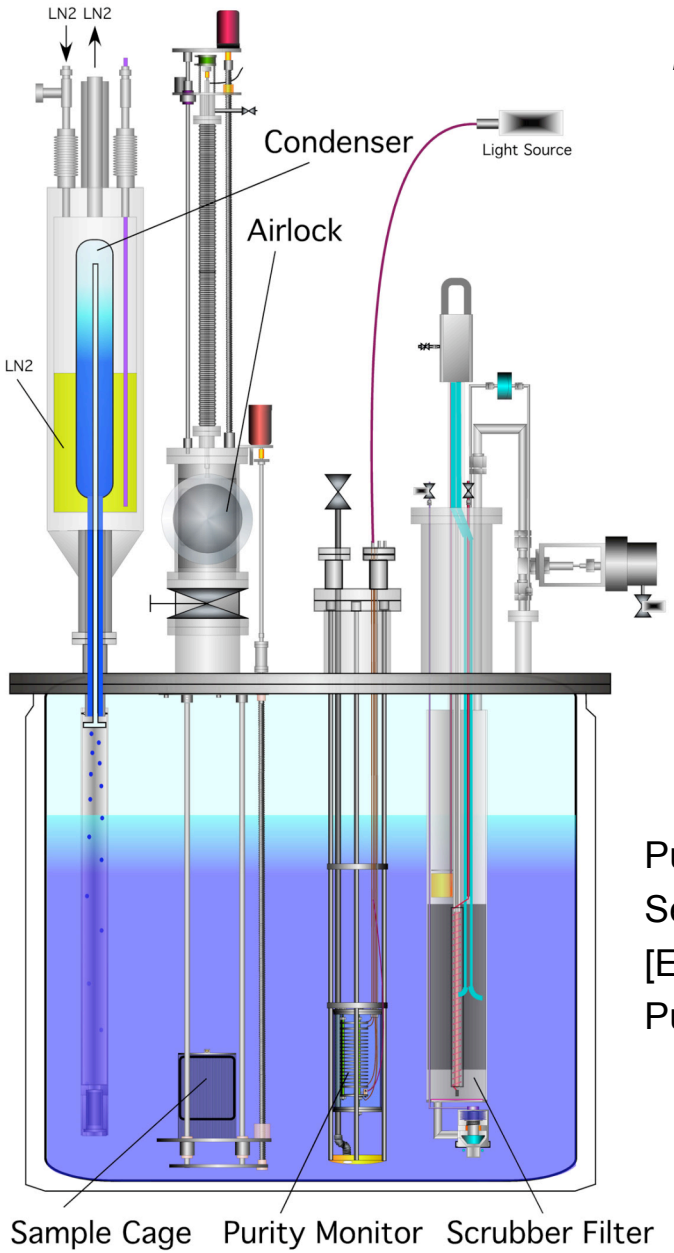
On-line data and DAQ



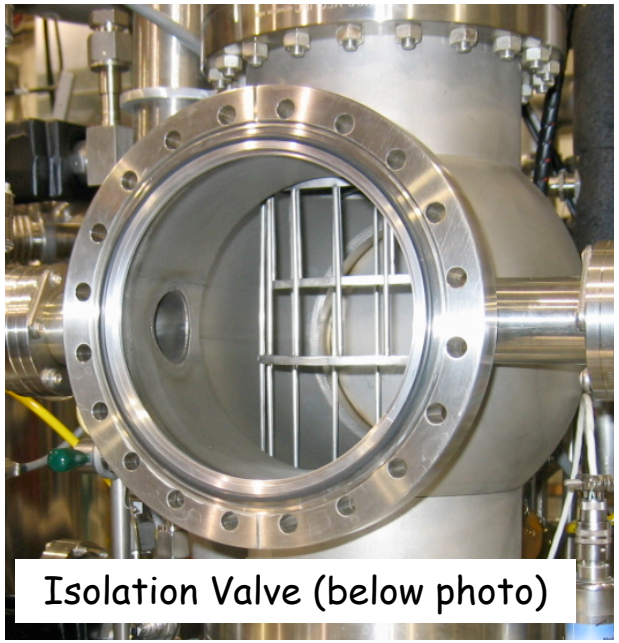


A. Baumbaugh

Luke (Materials Test System)



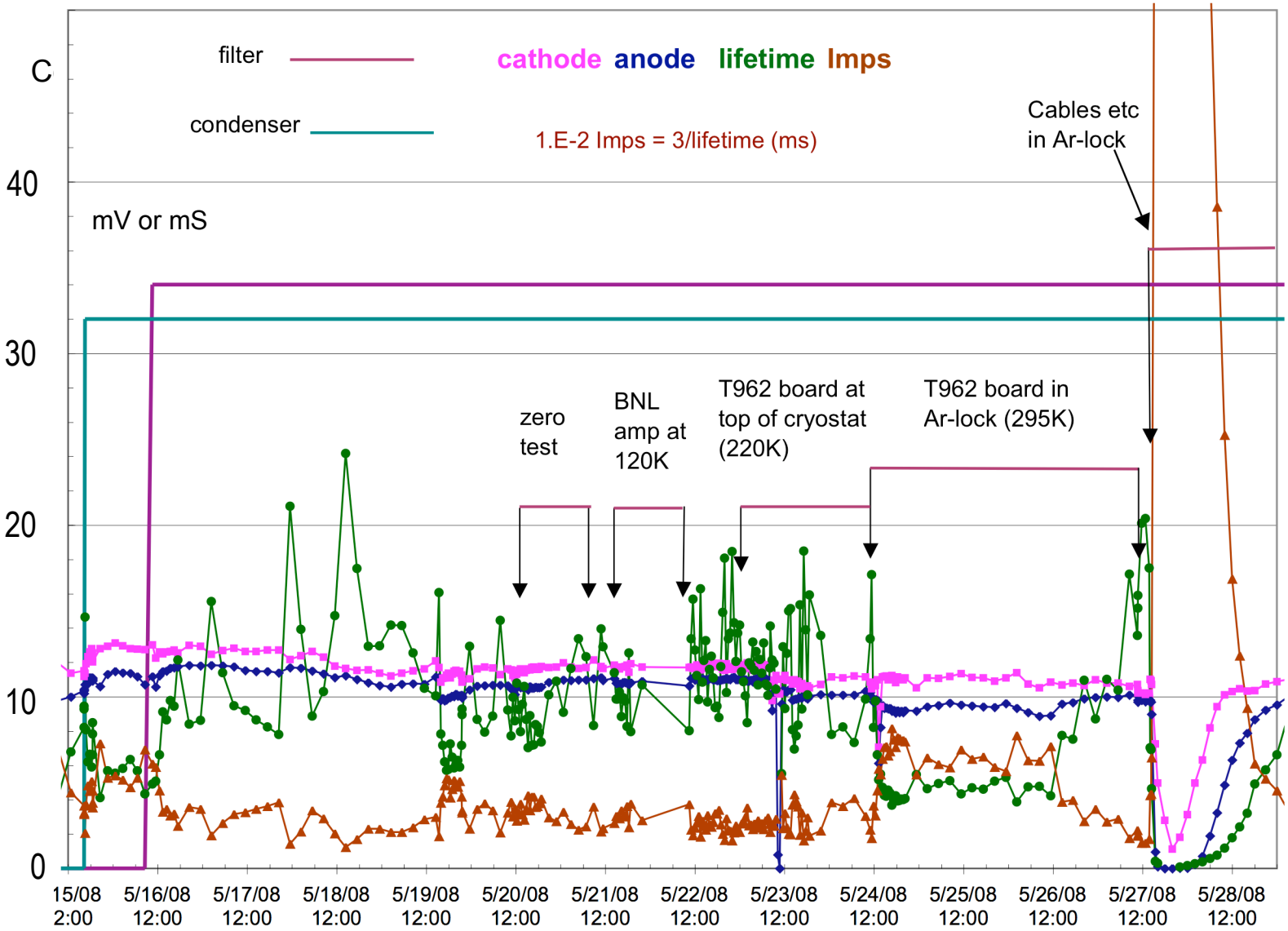
insertion of materials without exposure to vacuum

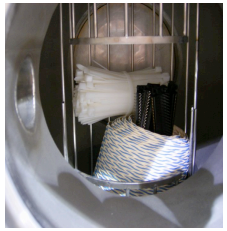


Put materials in Sample Cage in the Argon Lock
Seal the Argon Lock (open in photograph).
[Evacuate the Argon Lock (or not).]
Purge with pure argon gas (available from the cryostat).

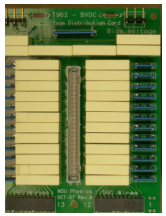
Some Measurements with the Materials Test System

Anode Signal, Cathode Signal, Lifetime & Imps vs Time





Cables and Ties



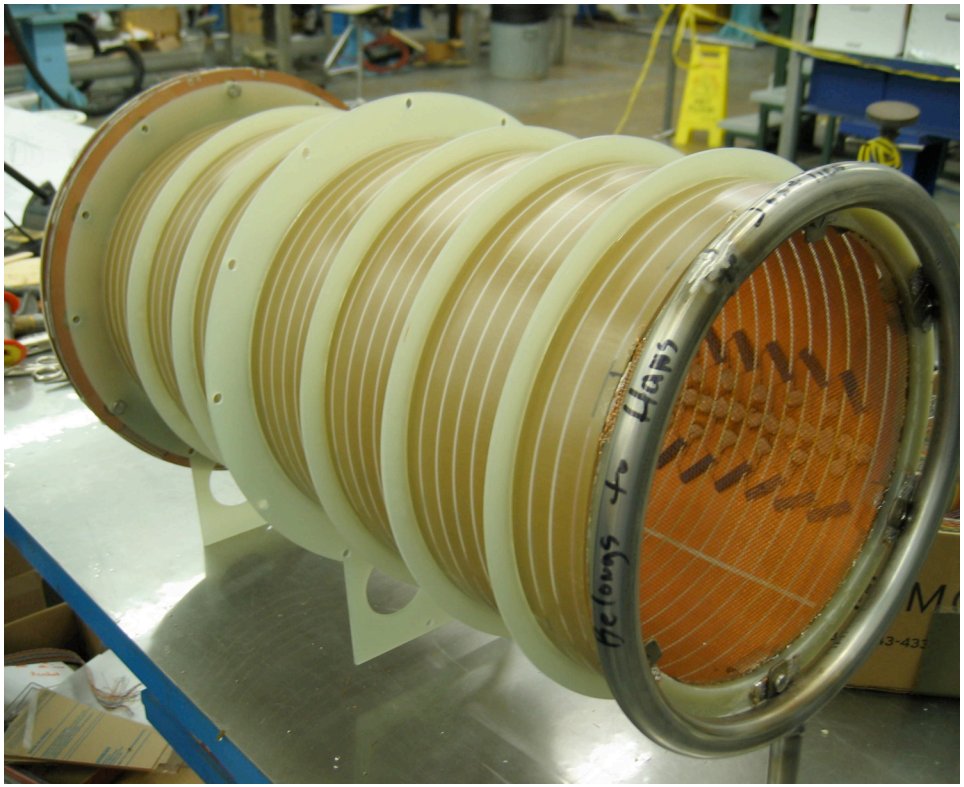
T962 Bias Card

BNL Amp

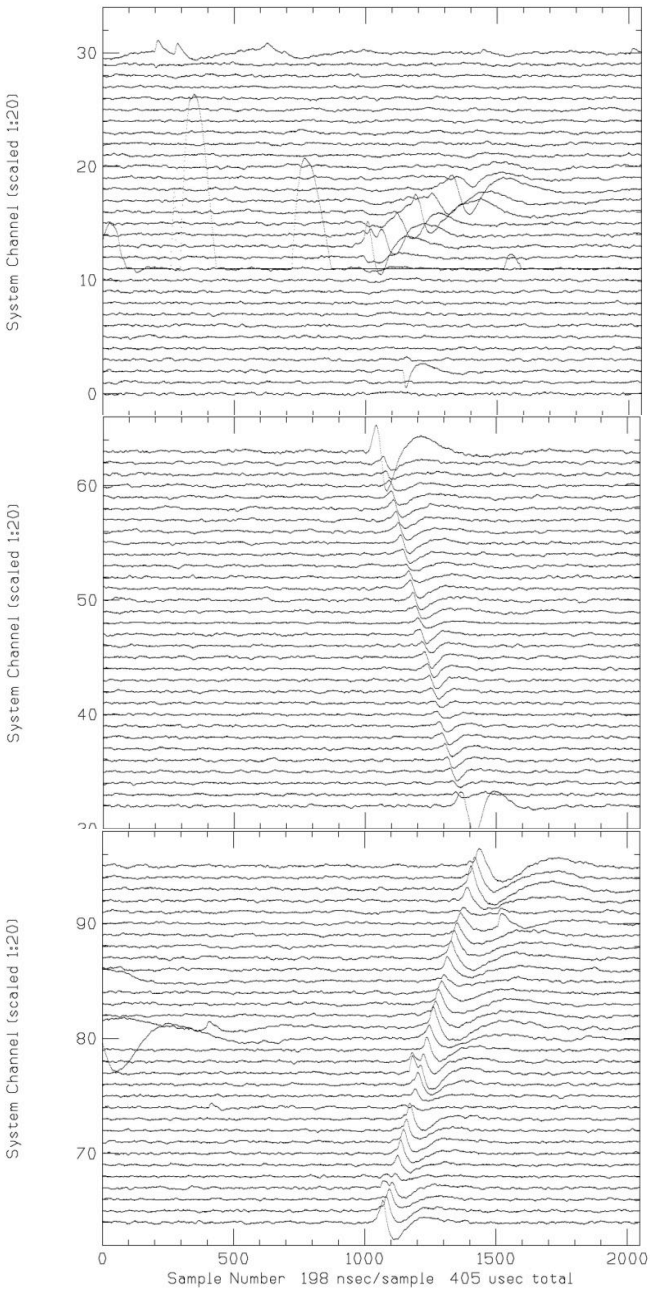
TPC (96 channels, 50 cm)
for electronics development

into Bo

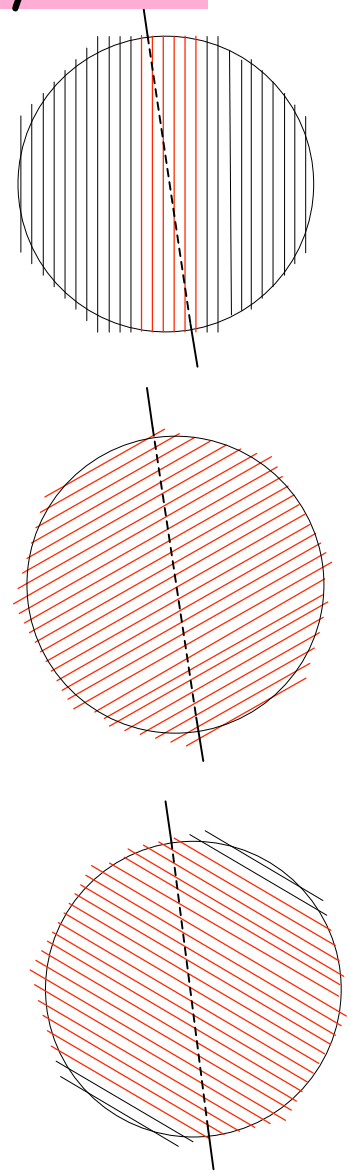
on bench



Cosmic ray in B0



5th trigger

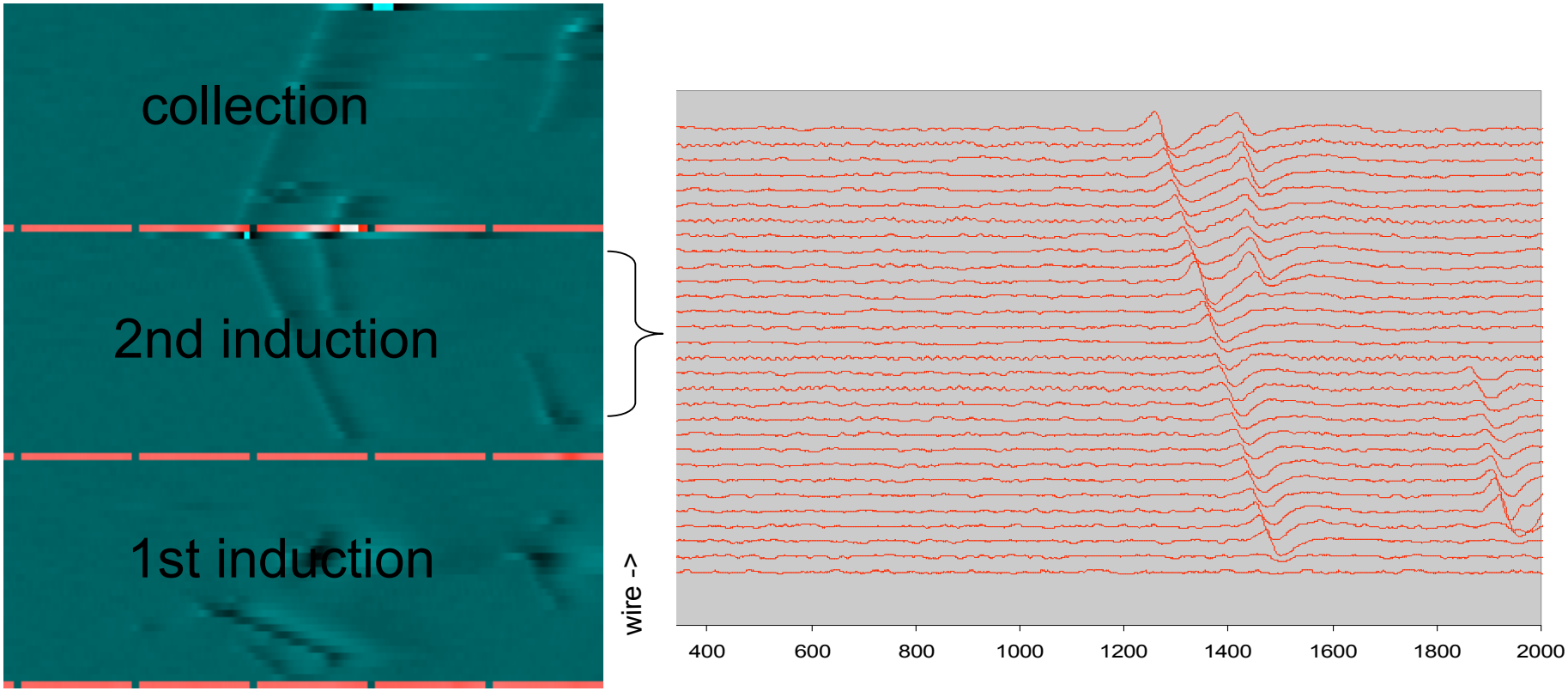


Plane 1
(Induction, 0°)

Plane 2
(Induction, +60°)

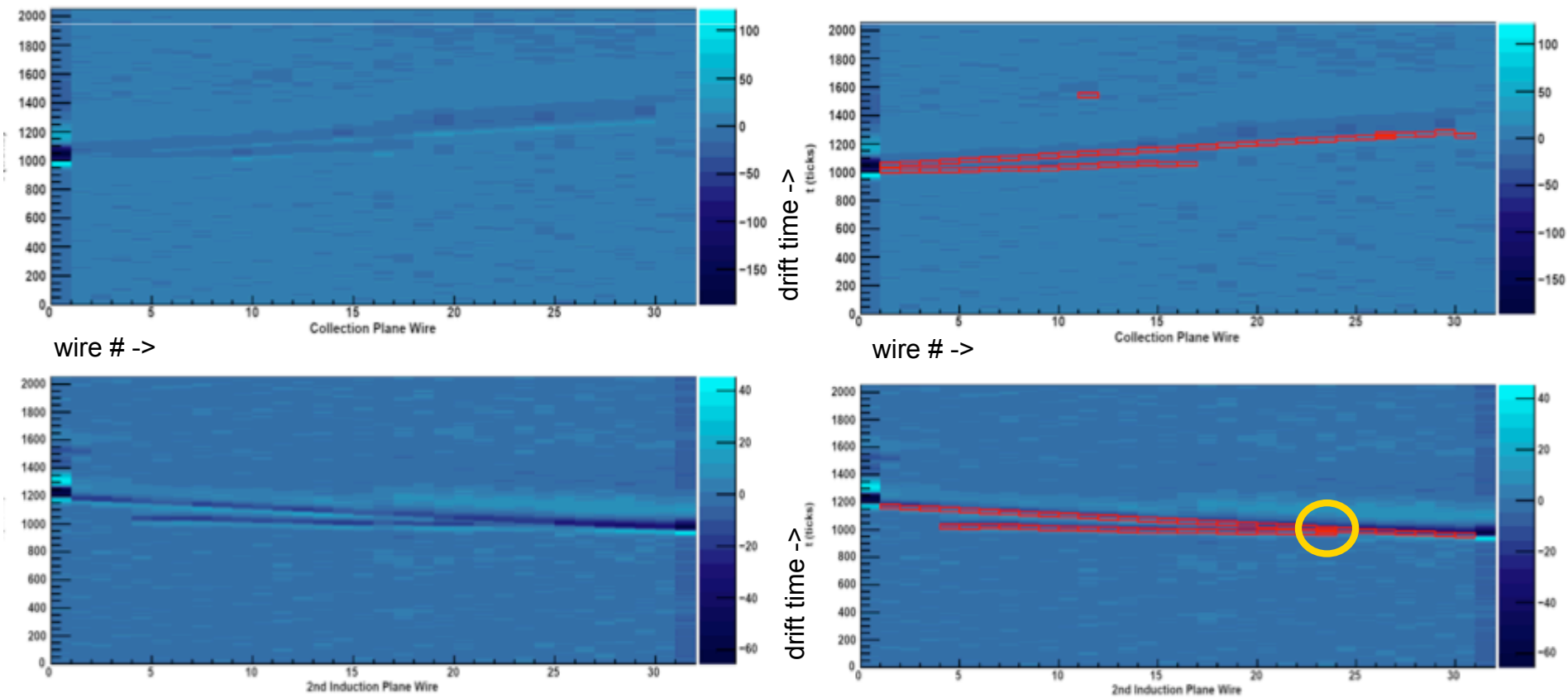
Plane 3
(Collection, –60°)

from waveform to picture



J-Y Wu

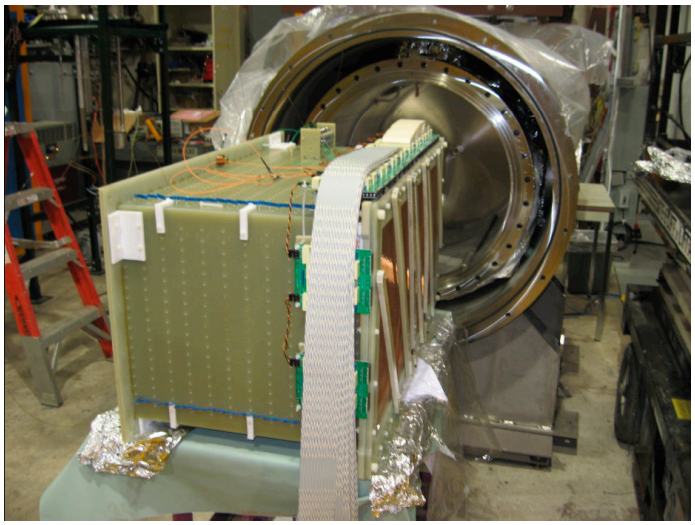
Bo Data - track finding and two track resolution



(J. Spitz, Yale)

ArgoNeuT (T-962) (Yale-FNAL-MSU-LNGS-UTA)

- 0.25 ton LAr TPC in NuMI beam u/s of MINOS ND;
  - –FNAL cryogenics & purification, MSU electronics & DAQ
  - –FNAL/YALE/LNGS simulation
  - –dealt with underground safety issues
- 800 ν_μCC, 15 ν_eCC, 250 NC per week
  - –20,000 events in 6 month run
  - –demonstrate electron/gamma separation



TPC insertion

Vessel closed

To purity without Evacuation

Motivation for Large Test System

- Current systems use vacuum evacuation as a preliminary cleaning step
- This is extremely difficult to scale to very large volumes – especially mechanically.
- Physics requirements for Liquid Argon detectors are showing that large volumes are required. (5 kTon minimum)
- Hence we must study alternative filling schemes.

R. Plunkett

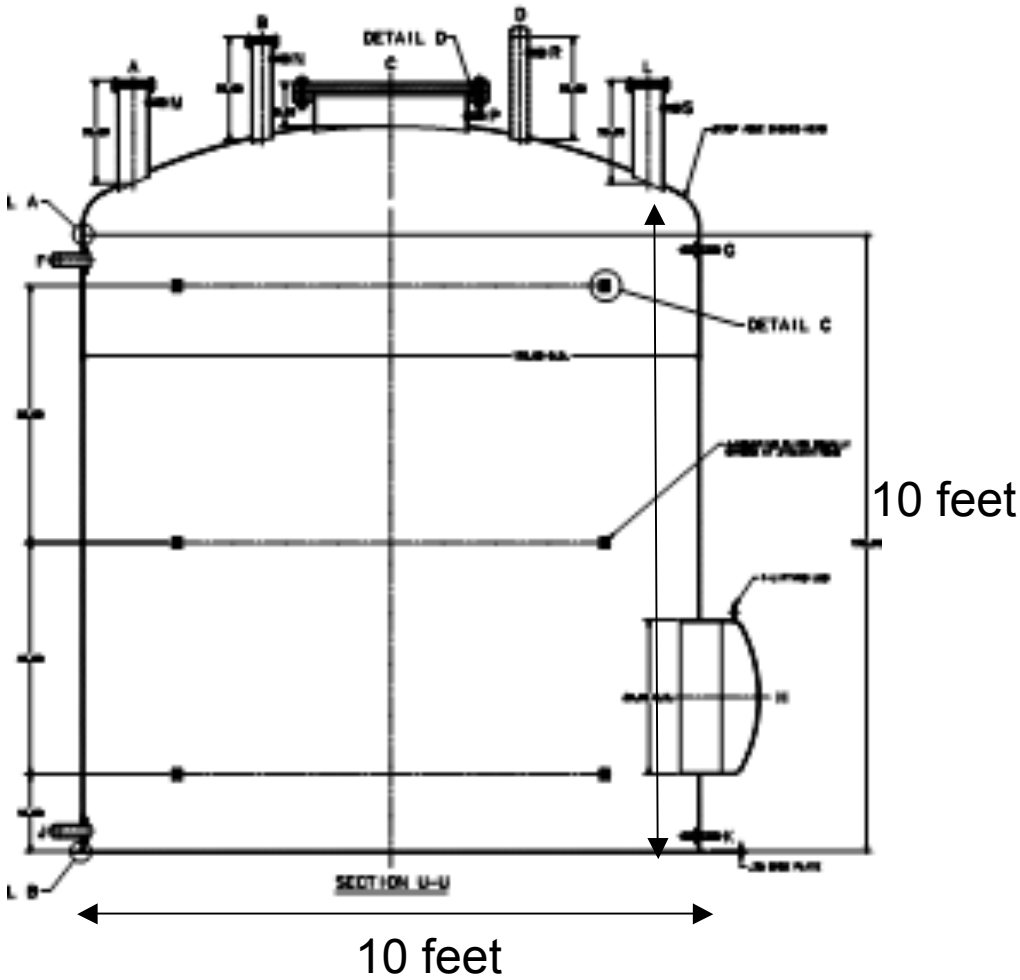
Twenty-ton purity test (LAPD)

3/16” Stainless Steel

Fermilab will add foam insulation (about 1 ft.)

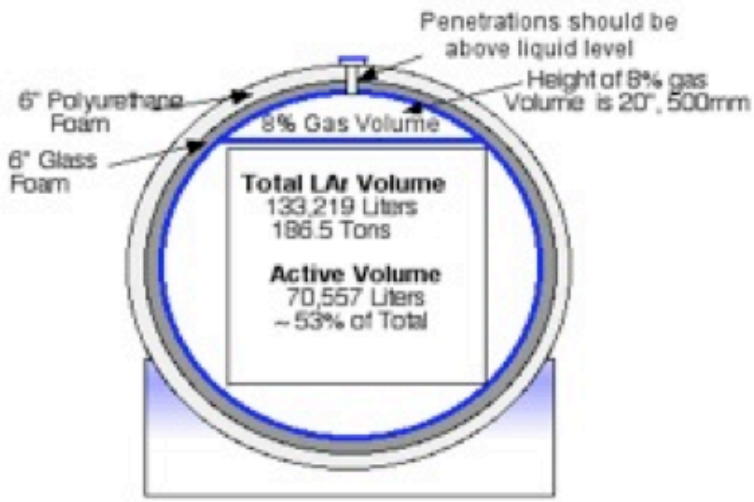
Detailed cleaning procedure specified

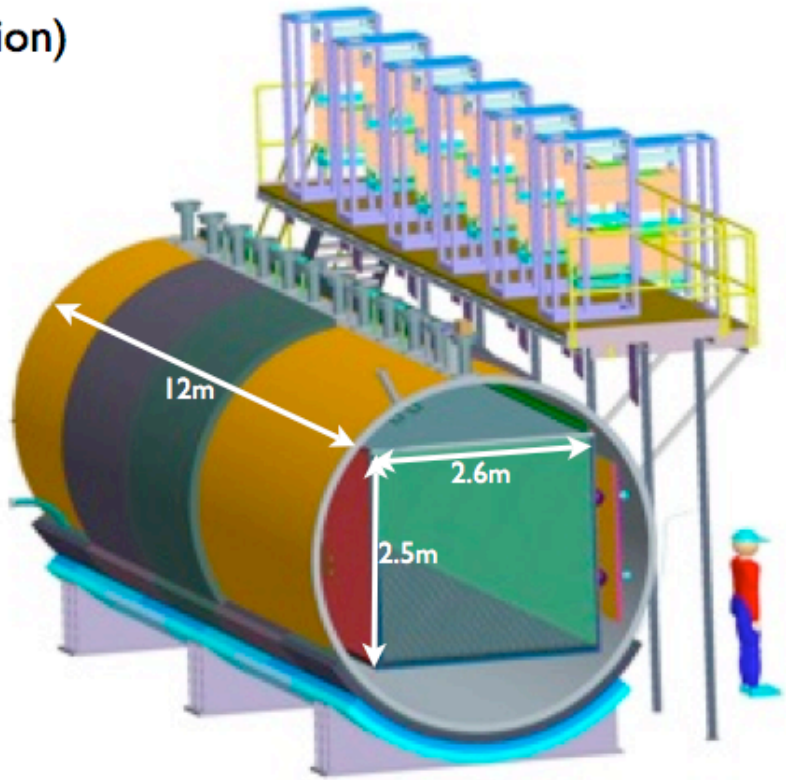
Mounted on insulated cribbing.



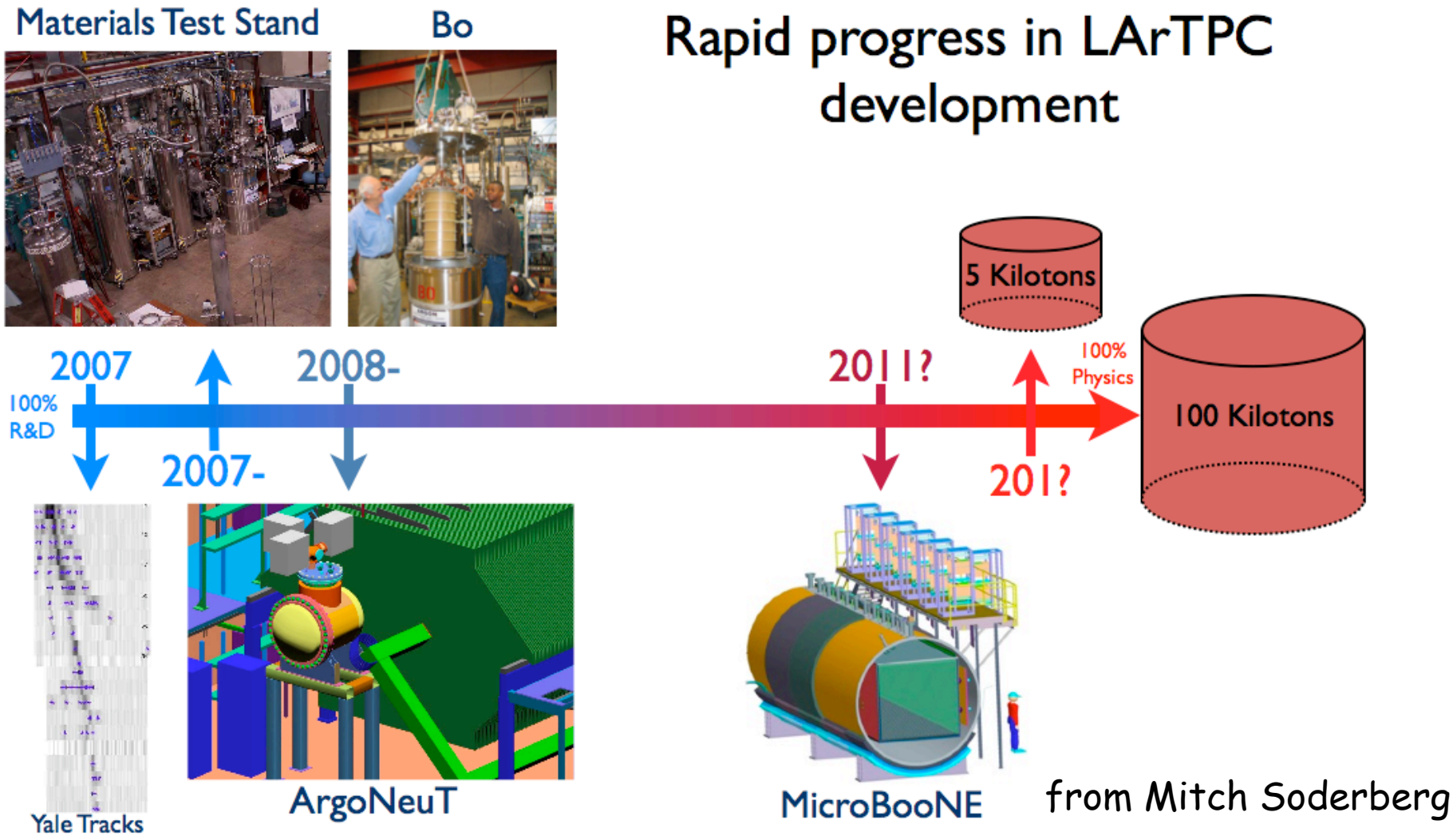
www-microboone.fnal.gov (E-974)

- 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 (using Cold Preamplifiers)
- ~30 PMTs for triggering
- Purification/Recirculation system.





Liquid Argon in the U.S.

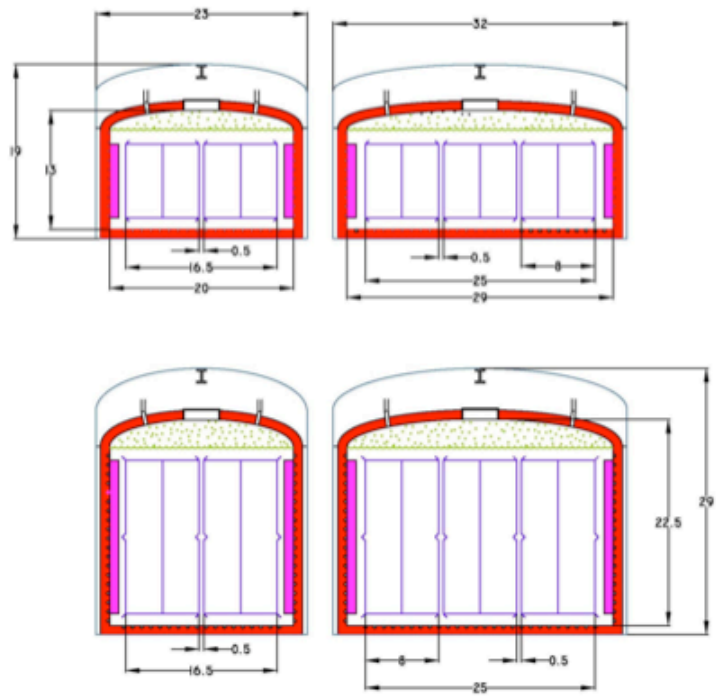


from Mitch Soderberg

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.



from Mitch Soderberg

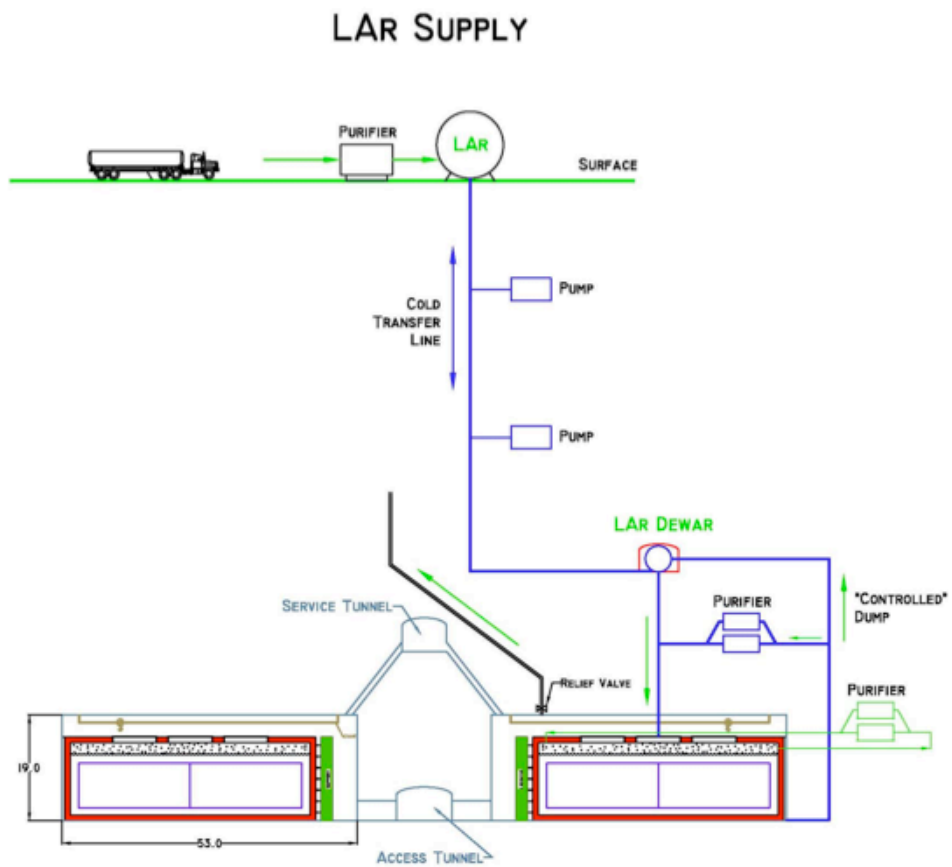
Cavern/Cryostat designs are coupled.

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

from Mitch Soderberg

Some LArTPC Technical Progress

- Argon Purity
  - **From atmosphere to purity without evacuation**
  - How to remove impurities from Argon (filter gas as well as liquid?)
  - What impurities matter and how to measure drift lifetime
  - What are the sources of contamination and how to avoid/remove them without pumping (vessel, plastics=> surface physics)
- Vessel Design
  - Design, **(Underground) Construction**, Safety
  - Cryogenics (cooling system and insulation)
  - Thermodynamics (argon temperature and flow distribution)
- Detector Design
  - HV system
  - Mechanical reliability - **TPC constructed in situ or externally**
  - Constraints from electronics (eg readout only at top?)
  - Light collection scheme; (for `triggering' and pattern recognition)
- Electronics & DAQ
  - Amplifiers, multiplexing, digitizers - **in cryostat?** Feedthroughs
  - Signal/noise (large capacitance) and constraints on TPC design
  - Zero suppression, signal processing, local event recognition capability, **100% livetime (not just beam spill)**
- Simulation & Reconstruction
  - Real and simulated signals on wires; develop signal processing
  - Event generation in argon
  - Vertex and pattern recognition; cosmic ray rejection

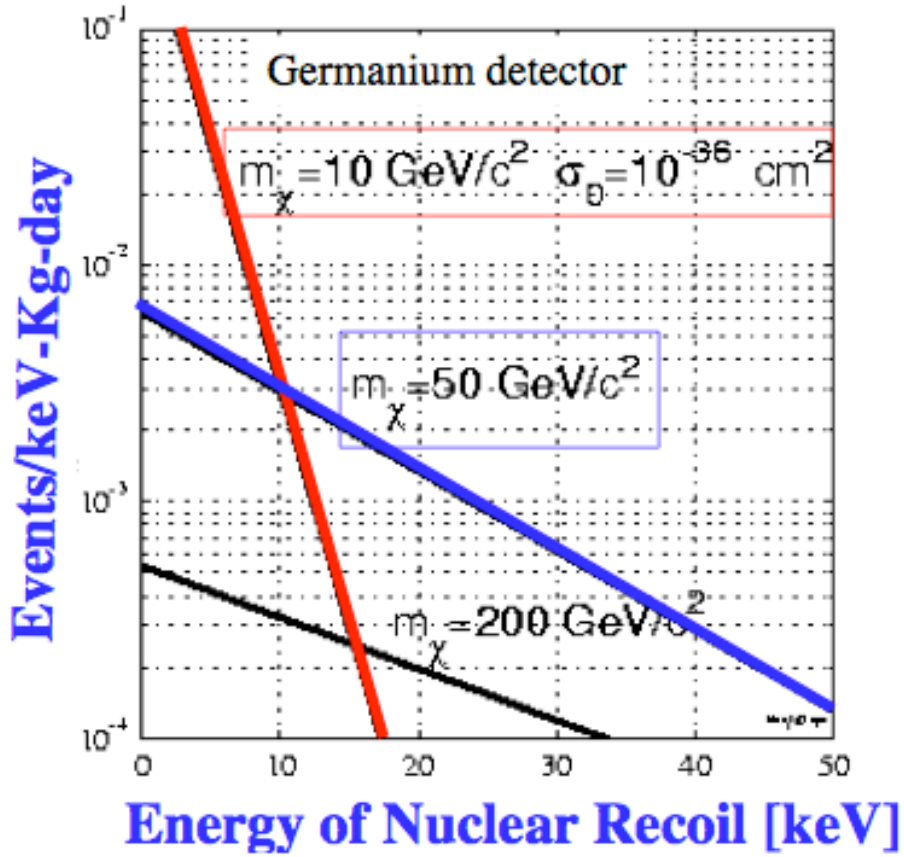
And now for something rather different and yet fully synergistic

Spectrum of WIMPs in a Detector on Earth

Based on simple assumptions:

- Particles are gravitationally bound to halo, with Maxwellian velocity distribution (V_{rms}=220 Km/s) and local density 0.3 GeV/cm^3
- WIMPs are heavy particles, 10 GeV< M_{WIMP}< 1 TeV.

⇨ Nuclear scattering can efficiently transfer energy to a nucleus, since $M_{nucleus}$~M_{wimp}.
The signal will be a nuclear recoil, with energy ~10 keV



- Scattering is non-relativistic.
- Shape of spectrum does not depend on particle physics inputs.
- Amplitude of spectrum depends on unknown supersymmetry parameters and some astrophysical uncertainties.

Technology Choices for Dark Matter Detection

Technique	Good features	Bad features
Cryogenic detectors CDMS, Edelweiss	Excellent to good (>99.9%) discrimination for alpha, beta, gamma	High cost, difficult to manufacture, scale up
Xenon TPC + Scintillation Xenon, Lux	Scalability, Easy cryogenics, high Z, good position resolution	Modest discrimination for beta, gamma (99%), expensive
Argon, scintillation only DEAP	Excellent discrimination for alpha, beta, gamma	Radioactivity of Ar-39
Argon TPC + Scintillation WARP, ARDM	Best discrimination overall, inexpensive to scale up	Radioactivity of Ar-39?
Bubble chamber **COUPP** PICASSO	Lowest cost, easy to scale best spin target (F) best gamma discrimination	Alpha backgrounds
Drift chambers DRIFT	Directionality!	Small target mass

from Andrew Sonnenschein

DUSEL Dark Matter S4 Proposals

Technology	Experiment	Target	Mass (T)	Cost (M$)
Low Temperature Ionization/Phonon	GEODM	Germanium	1	100?
Bubble Chamber	COUPP	Fluorine, Iodine	10?	1 M$/ton
Liquid Argon Scintillator	DEAP/ Clean	Argon/ Neon		
Dual Phase TPC	LZ20	Xenon	20	100?
	MAX	Argon Xenon	5 2	17 18
Gas TPC	DRIFT	Fluorine	0.1?	

Fermilab involvement

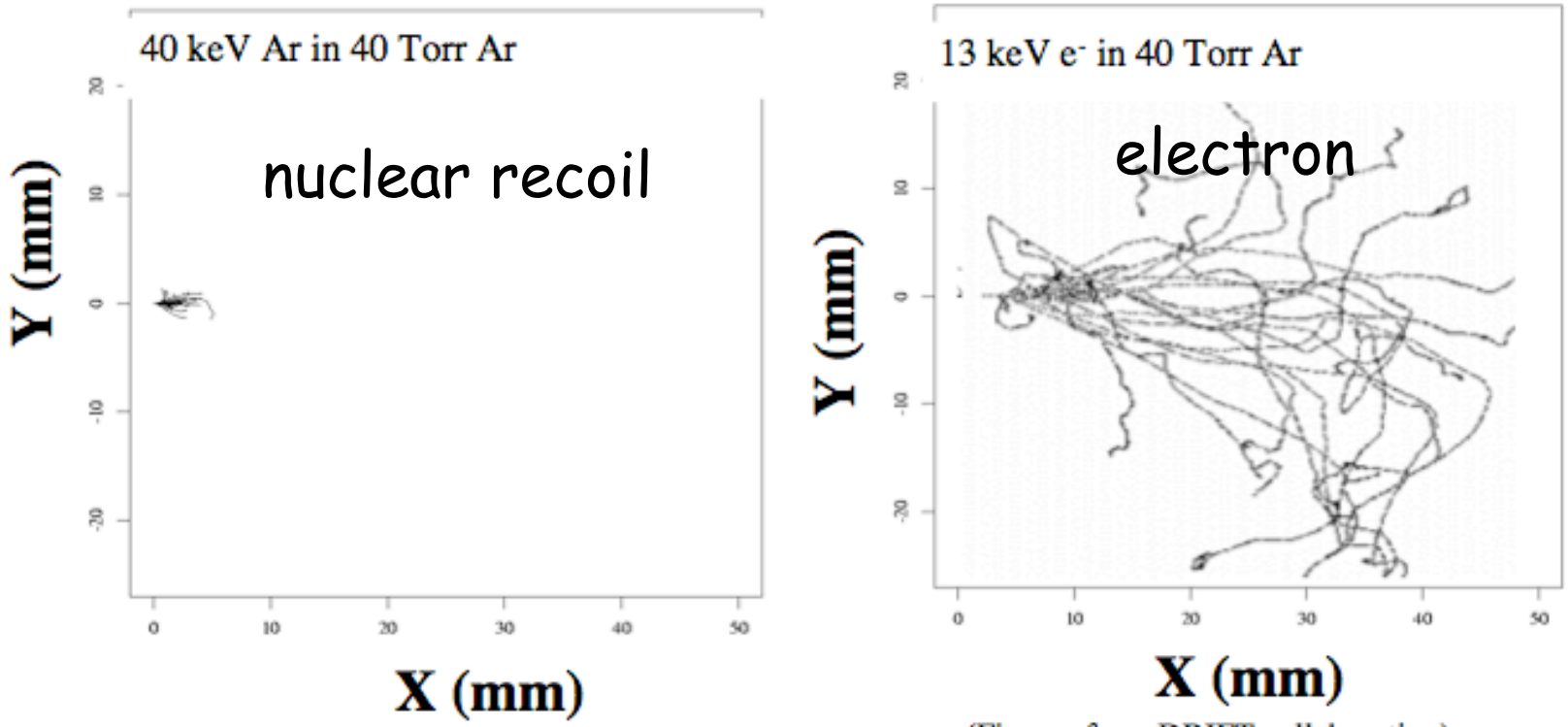
from Andrew Sonnenschein

Discriminating Against Backgrounds

- WIMPs interact with the **nucleus**, while most backgrounds are due to **electron scattering** by gamma and beta rays.

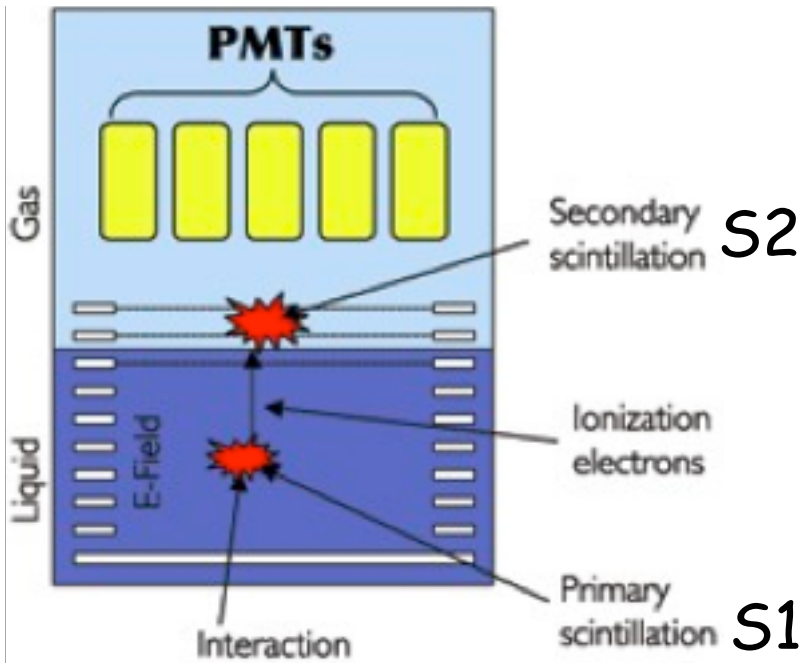
- The resulting spatial distributions of energy and charge are very different-- this is fundamental physical basis of most discrimination techniques.

Ionization distribution for nuclear recoil and electron

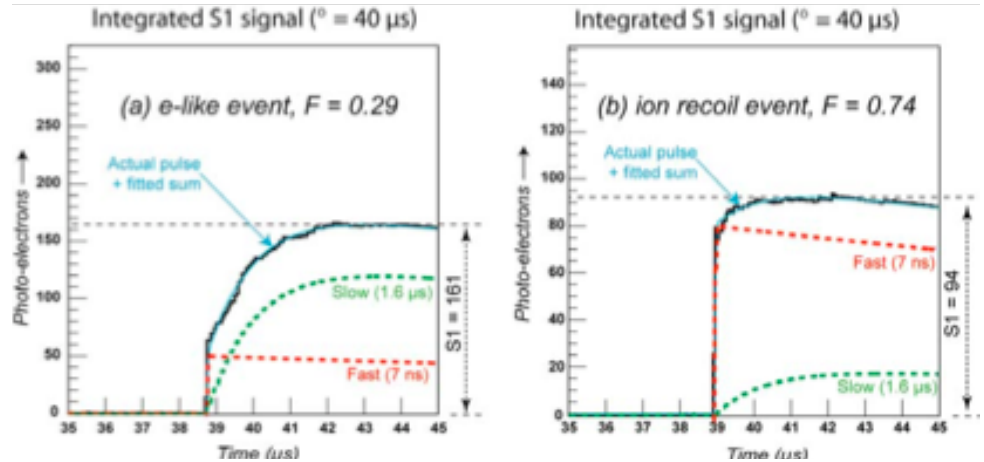


(Figures from DRIFT collaboration)

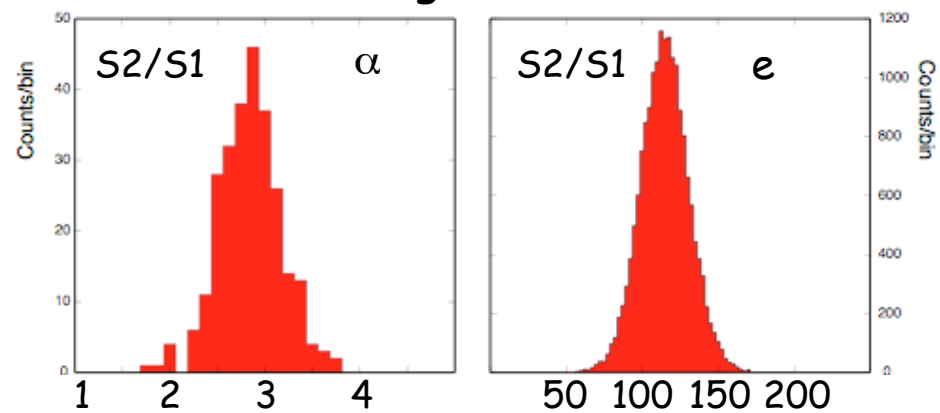
from WARP



fast/slow

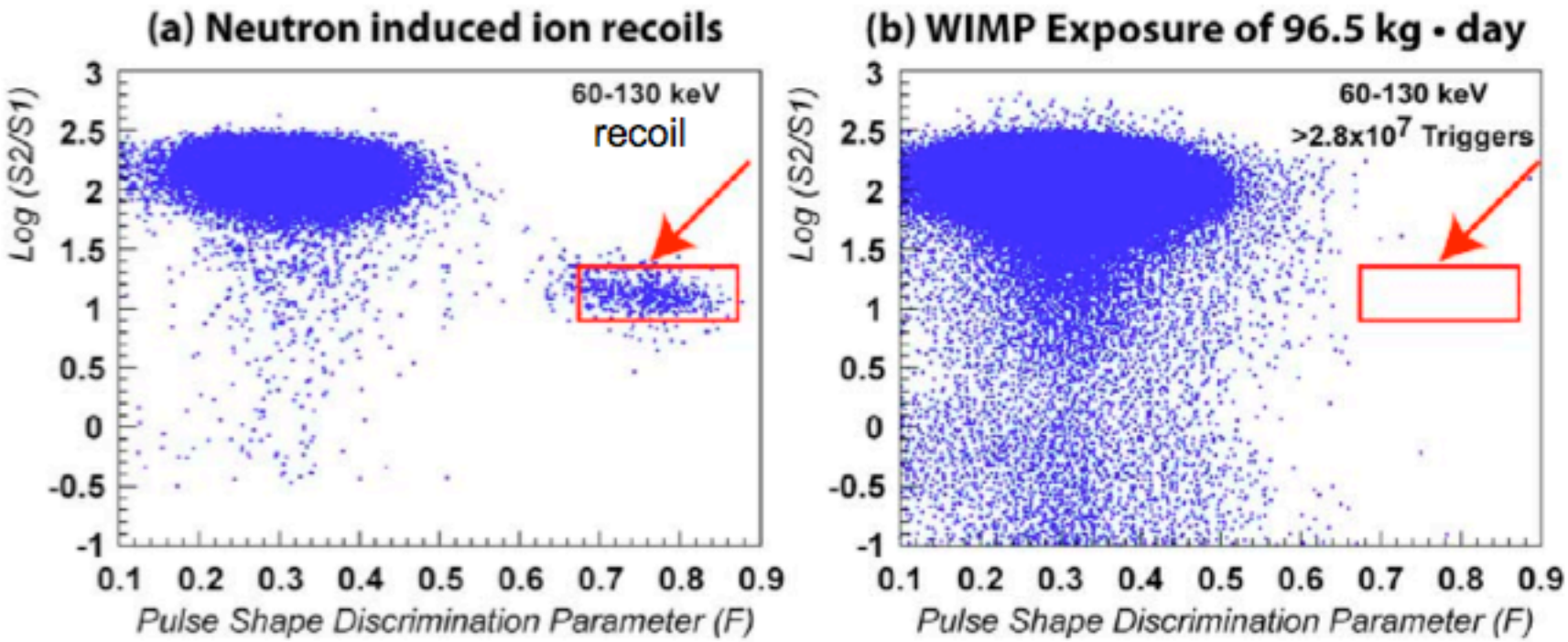


surviving ionization



S1 (energy, time distribution -> particle dE/dx)
S2 (ionization that escapes recombination -> particle dE/dx)
S1 PSD rejection ~10^{5-6}, S2/S1 rejection~10^{2}, com. 10^$^{7-8}$

Discrimination In Argon TPC: Two Independent Parameters



~ 2 p.e./keVee

WARP (Benetti et al. 2007)

WARP, Cocco, Lisboa (2005)

2.3 litre preliminary results (V)

^{39}Ar measurement

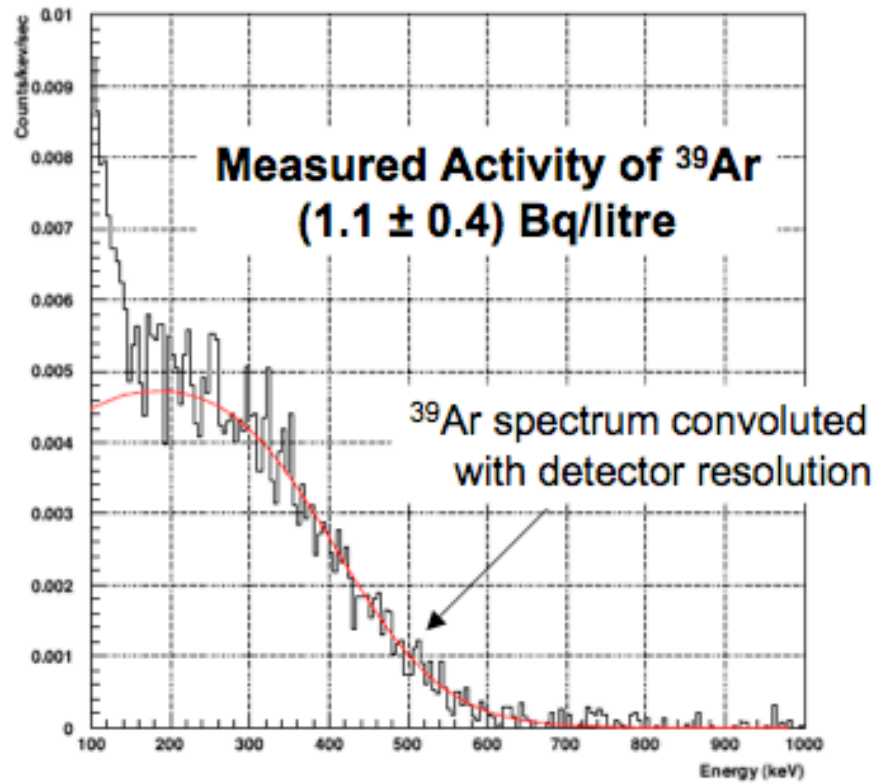
$^{39}Ar \rightarrow {}^{39}K + e^- + \bar{\nu}_e$ (Q = 565 keV)

Measured activity in agreement with the result of H.H.Loosli quoting the ^{39}Ar in natural Argon as $(8.1 \pm 0.3) \times 10^{-16}$

The fraction of ^{39}Ar decays producing an energy release in the range 30 ÷100 keV is about 3%

The expected rate due to ^{39}Ar in the ion recoil evergy window from 30 to 100 keV is given by 1.1 × 0.03 Hz/litre

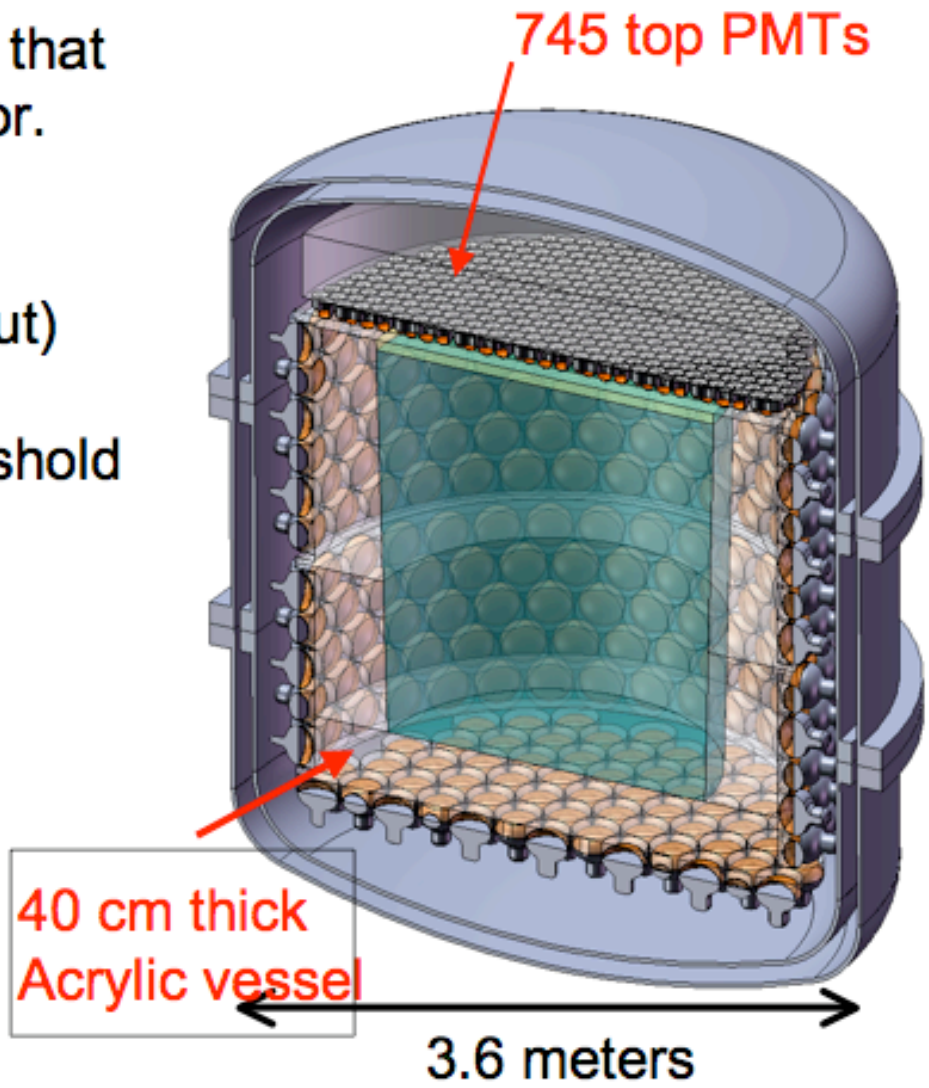
Residual spectrum after subtracting ^{222}Rn contribution and γ estimated from events without Pb shield



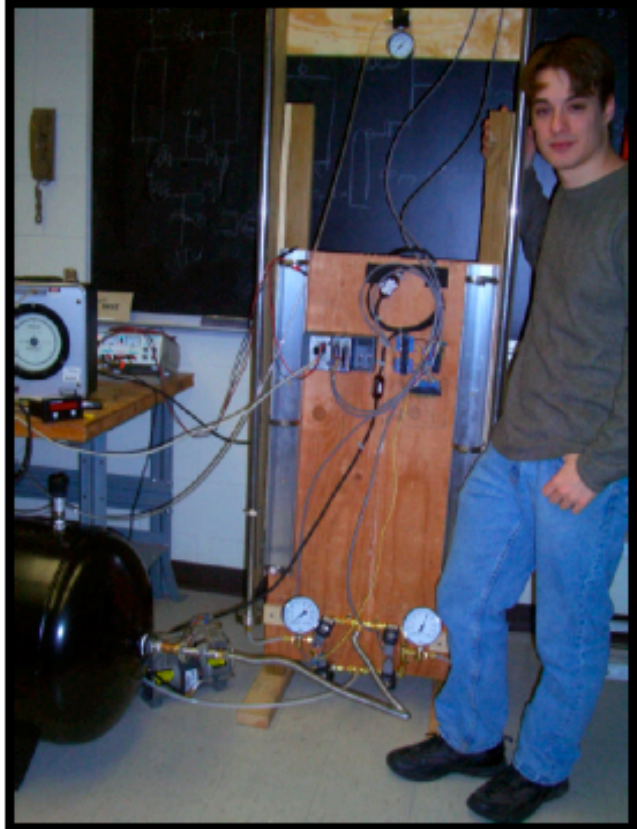
Argon Detector Concept

- Largest diameter cryostat that will fit down DUSEL elevator.
- 5 tons depleted argon (2.6 tons after fiducial cut)
- 30 keV recoil energy threshold
- ~ 2 cm position resolution
- 0.5 background events expected in 5-year run.

3 order of magnitude improvement over present CDMS/ XENON sensitivity



Discovery of underground sources of low-activity argon



← Prototype Purification Plant at Princeton

Sampling on a gas field in the West

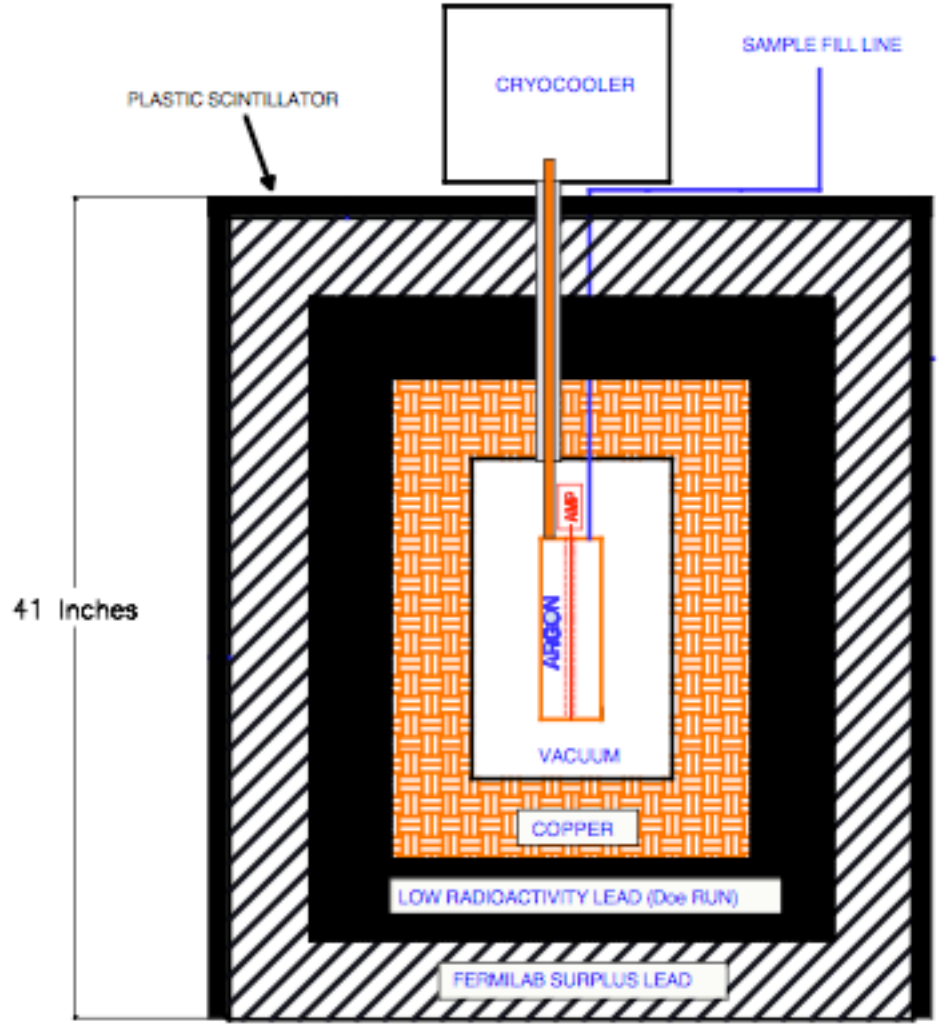
<5% atmospheric Ar-39 concentration!

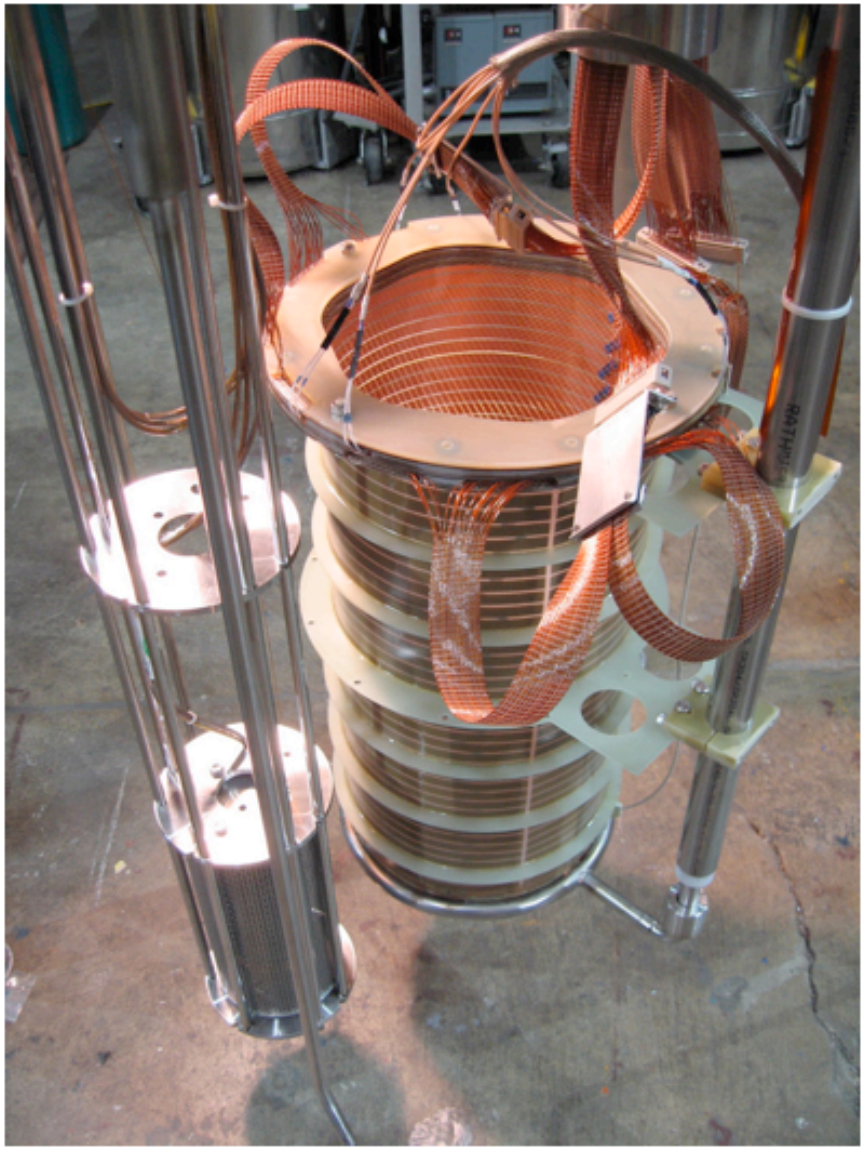
Funded by NSF

Argon-39 Counter

from Andrew Sonnenschein

- Measure ^{39}Ar isotope in 1- liter of liquid argon with a single-wire ion chamber.
- Attention to radiopurity and shielding details will allow measurement at 10^{-3} of atmospheric ^{39}Ar abundance (~100 decays/day).
- Application: screen argon from underground sources for use in a large detector at DUSEL (collaboration with Princeton University, Temple University, others)





"Bo" TPC Technology Demonstration

The TPC is a cylinder 50 cm long by 24 cm diameter. Electrons drift upwards in a field of 500 V/cm towards horizontal wire-planes at the top. There are three planes at 60 degrees to each other. The first two planes (as the electrons see them) are so-called induction planes, the very top plane is the collection plane. The vertical rod at the extreme right is the HV feedthrough – it's been tested to 50 kV in Nitrogen.

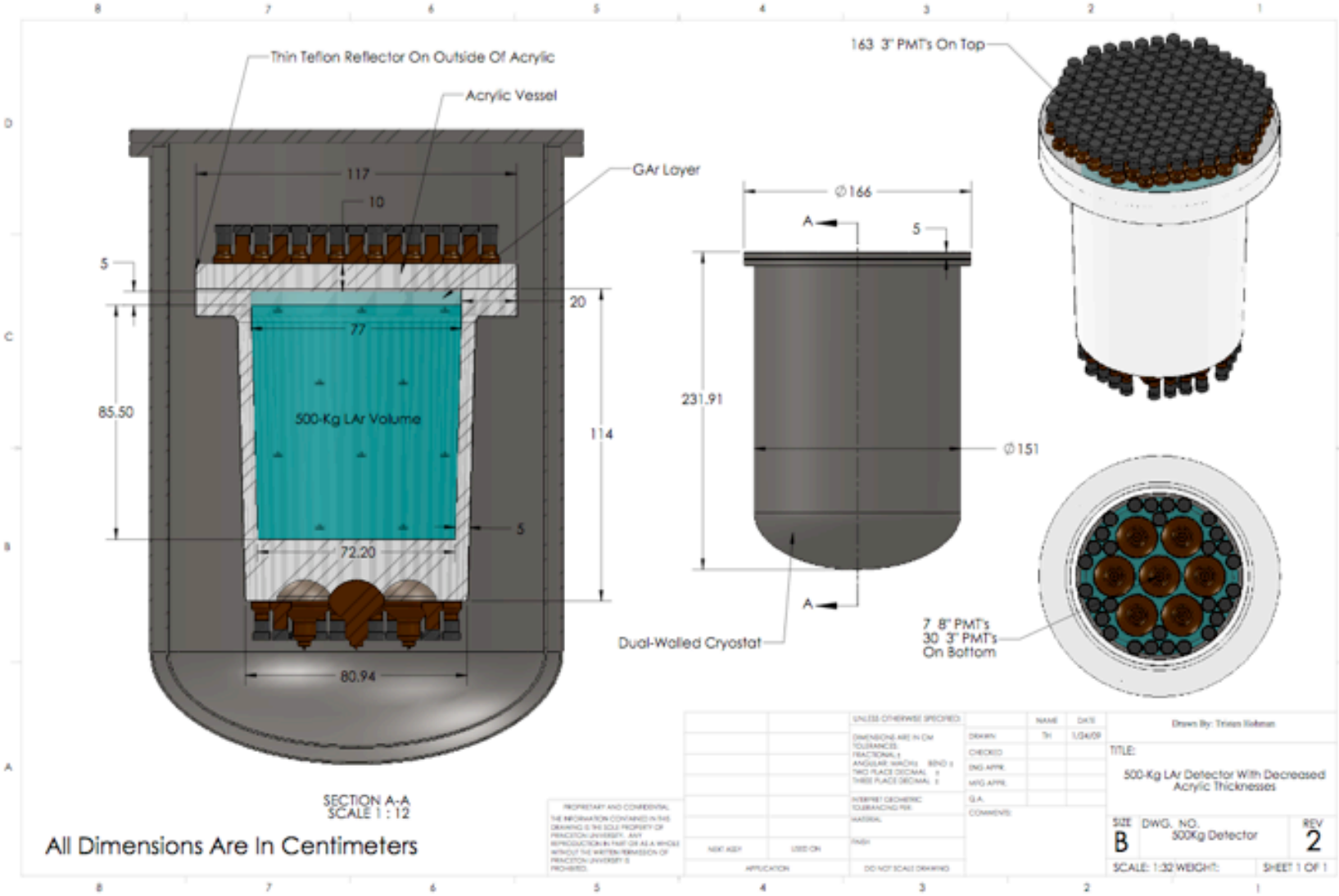
Issues for MAX:

light-yield - PMTs, geometry, WLS
PMT radioactivity
design of TPC - grids, materials
construction of acrylic vessel
chemical purity (drift lifetime)
provision of depleted argon
shielding and vetoing

Prototype MiniMax

MiniMax - prototype for MAX

10% MAX Prototype (500 -Kg)

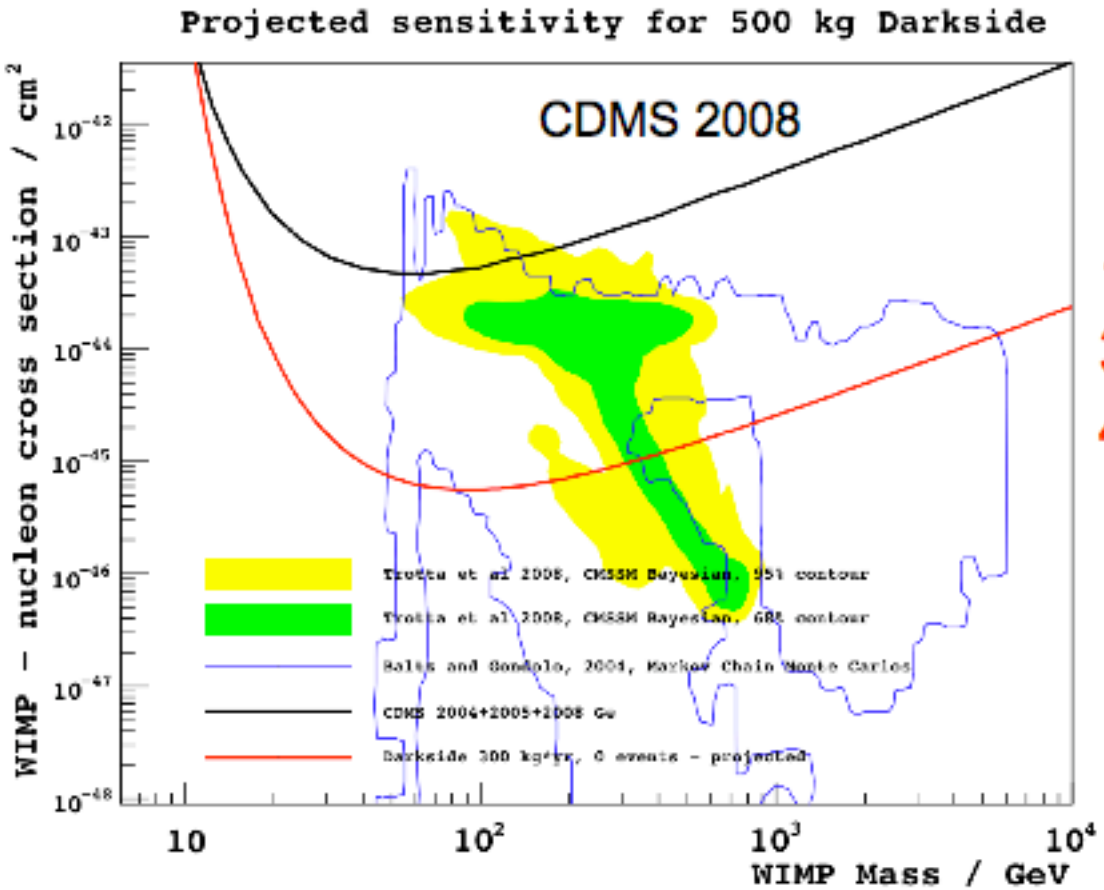


MiniMax - prototype for MAX

Phase II for 500-kg : Physics Run

Homestake (Pre-DUSEL) or Snolab

Will need large water shield



1- year run
300 kg fiducial
4 p.e./keV

Back-ups (wow)

Test Stand Work at Fermilab

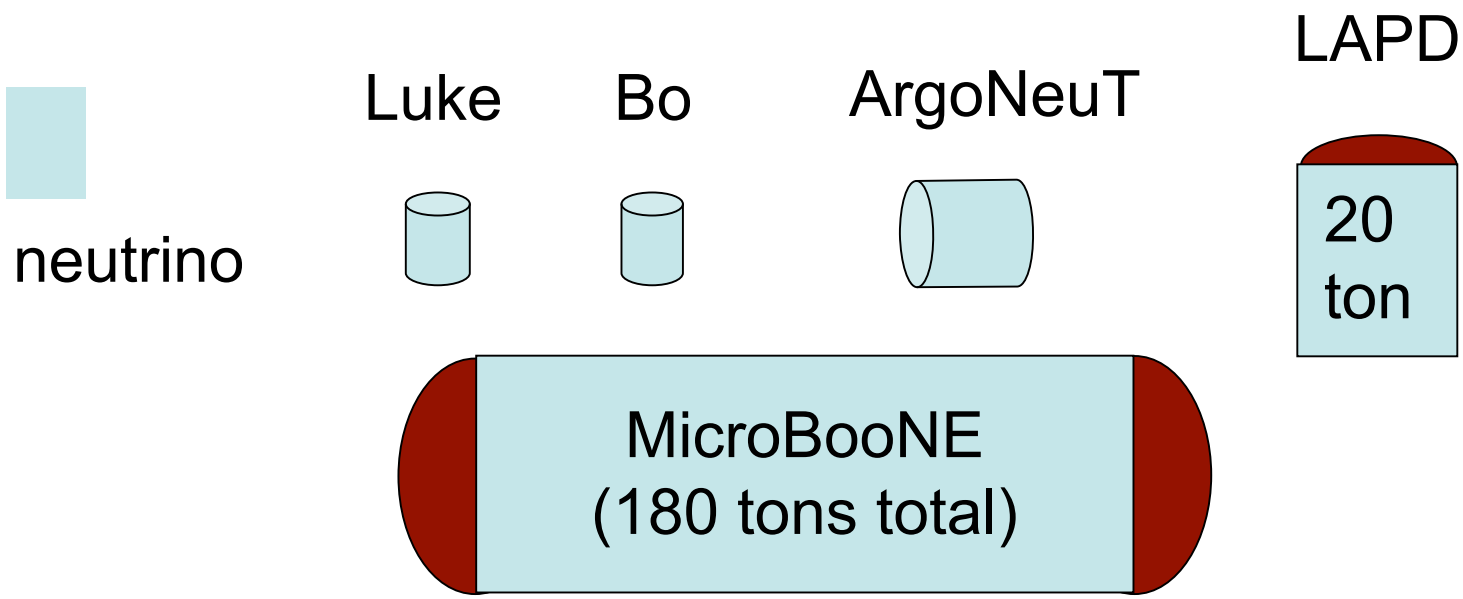
Materials Test System (MTS) - Luke
TPC for electronics development - Bo
Bell-jar for photo-cathode and light-fiber testing

Tests performed for atmosphere to purity without evacuation

- Demonstration of Argon Piston (purge to few ppm)
- Demonstration of Oxygen to few ppb and water to few ppm

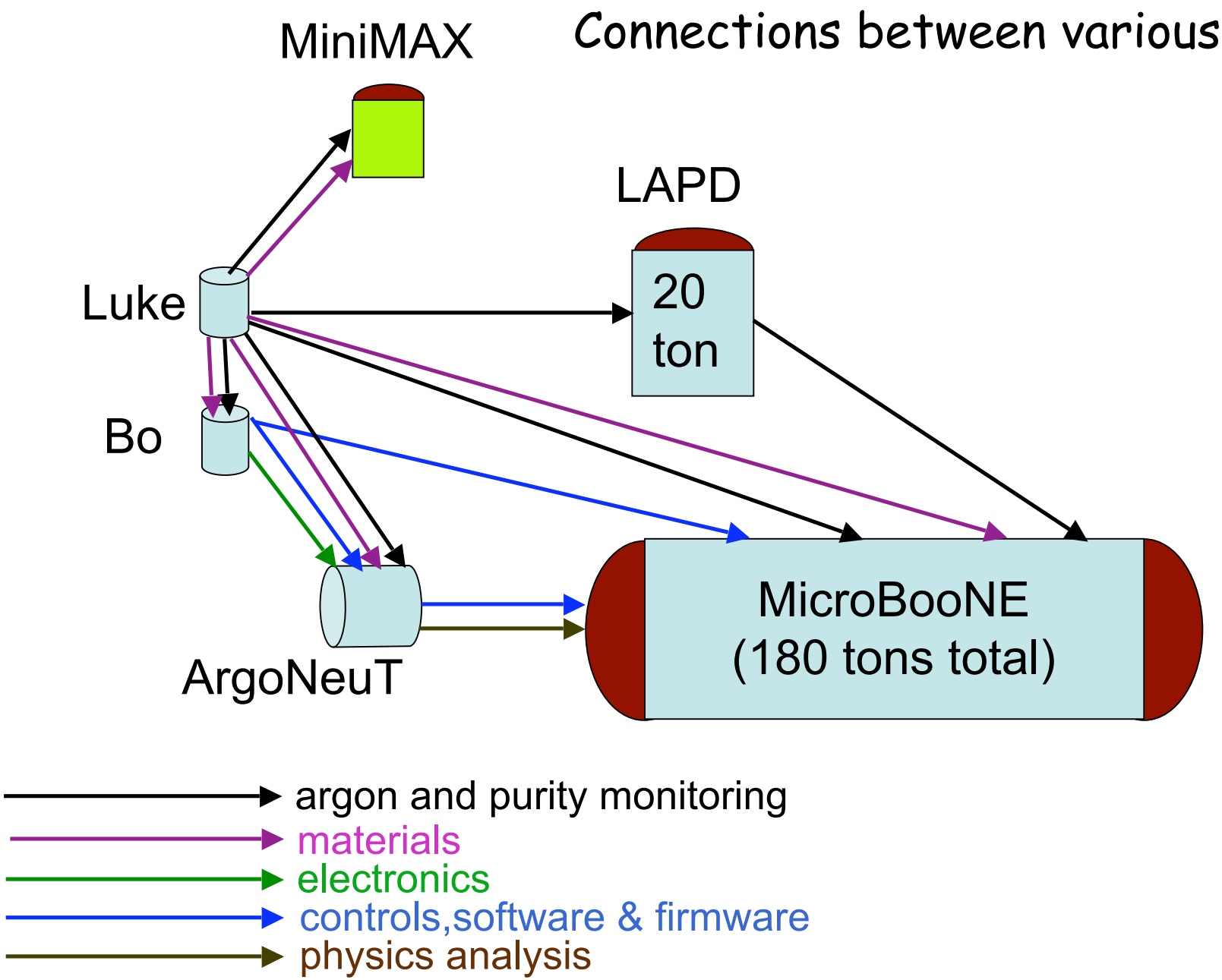
Infrastructure

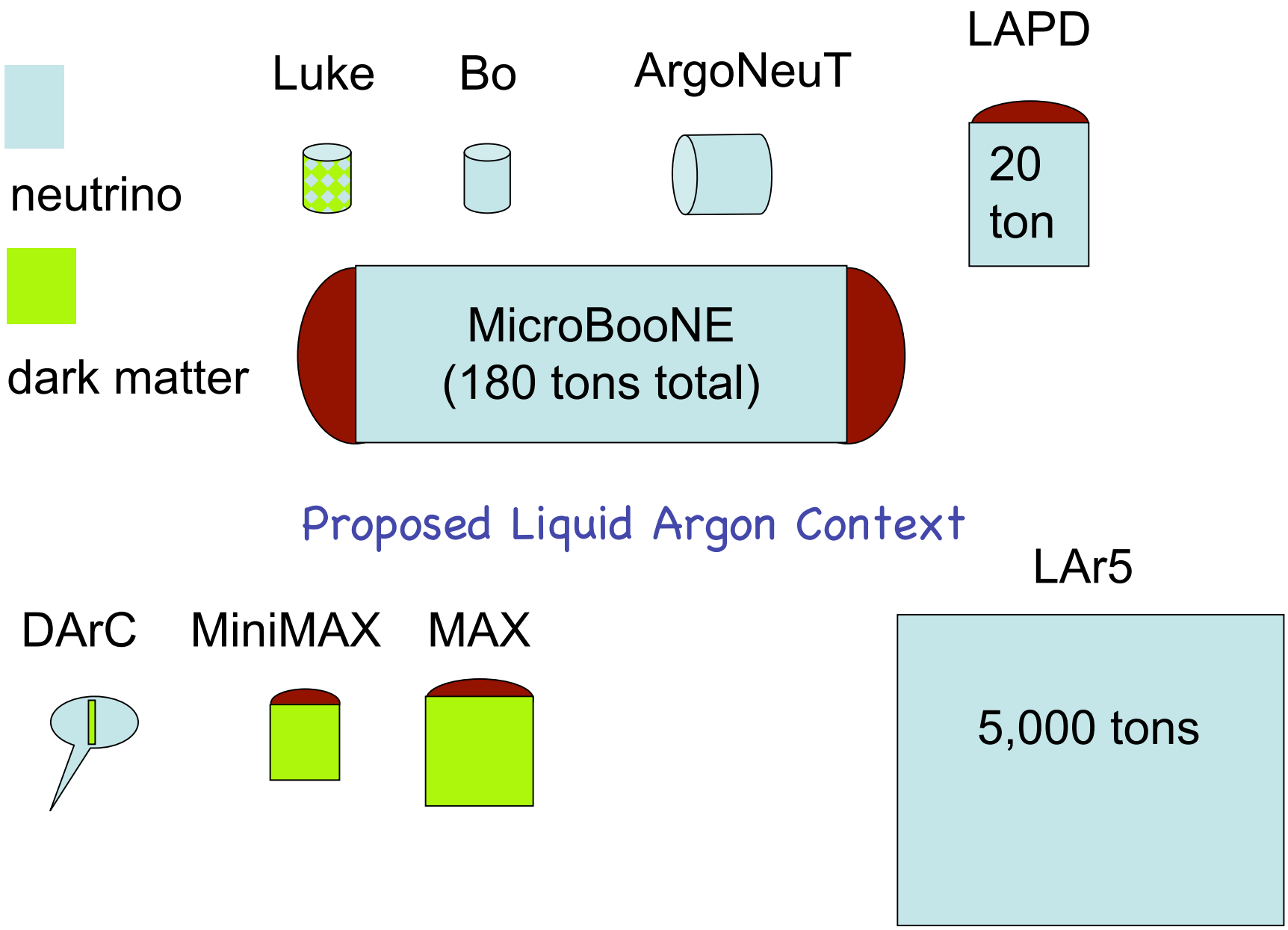
- Single Pass clean Argon Source with Oxygen and H_2O filters.
- Home-made Filters for above that can be regenerated in-situ
- Internal Filter Pump
- Controls System
- Purity Monitor DAQ
- Fermilab versions of ICARUS `purity monitor' and readout electronics
- Nitrogen concentration measurement (at the 0.2 ppm)



Present Liquid Argon Context

Connections between various devices




neutrino
dark matter
Luke
Bo
ArgoNeuT
LAPD
20 ton
MicroBooNE
(180 tons total)
Proposed Liquid Argon Context
DArC
MiniMAX
MAX
LAr5
5,000 tons

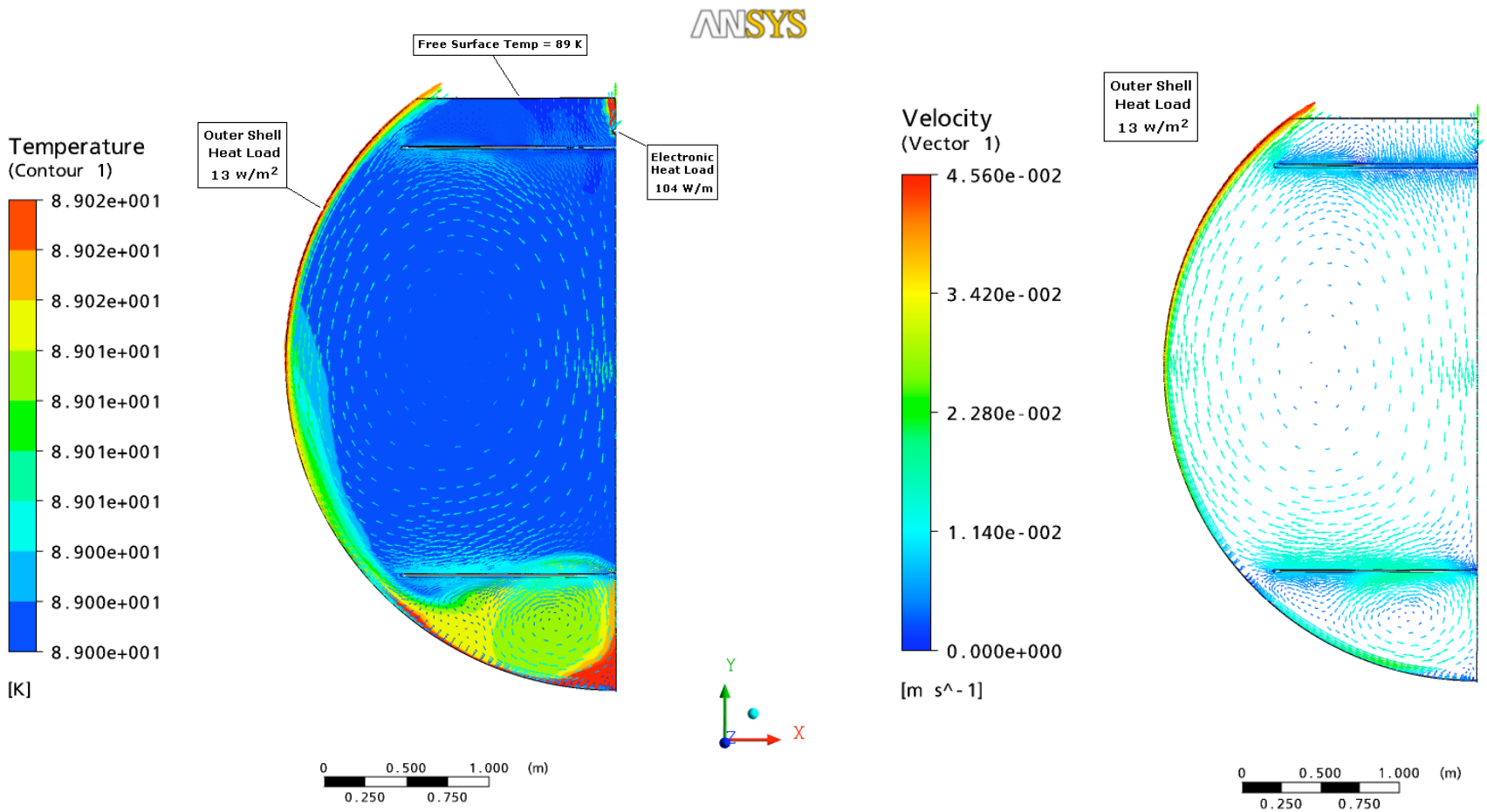
GLOSSARY

Luke	280 kg - Materials Test System	(operating)

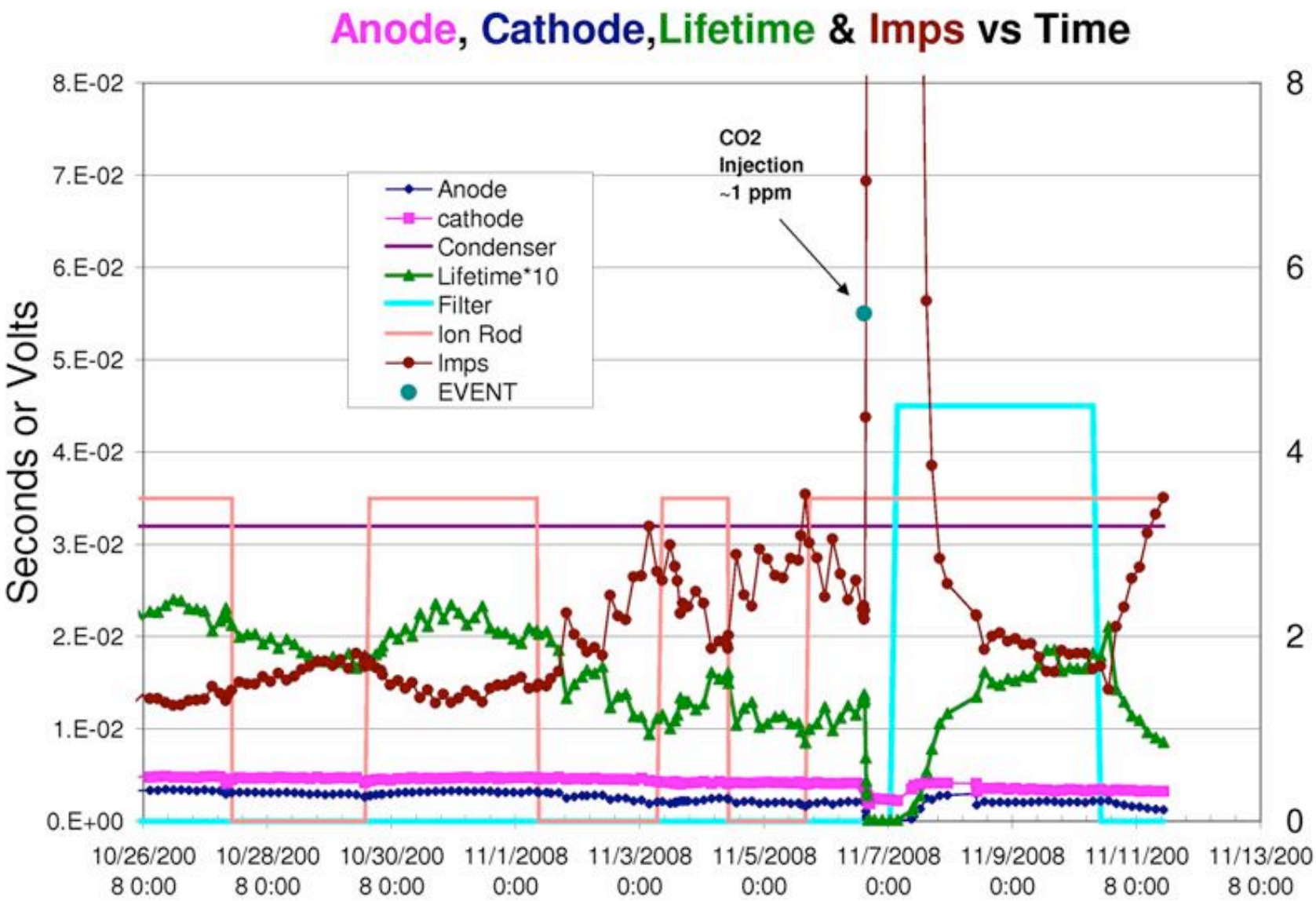
Bo	280 kg - Electronics Test System	(operating)
LAPD	20 tons - Purity without Evacuation	(parts ordered)
ArgoNeuT	0.75 tons - Neutrino Interactions	(installing)
MicroBooNE	180 tons - Physics/R & D	(phase 1 app.)
LAr5	5,000 tons - Physics/Prototype	(EOI/S4 prop)

DArC	1 kg - measure Ar39 Depletion	
miniMAX	1 ton - WIMP search/R & D for MAX	(today)
MAX	10 tons - Argon (and Xenon) WIMP search	(S4 prop)

Temperature and Velocity Profiles in MicroBooNE



The ion-rod and a contaminant injection



Work List for PAB devices for coming year:
(Purity Demonstration instrumentation separate)

Instrumentation:

- Complete long PrM
- Develop PrM electronics to operate in liquid argon
- Test UV LEDs as alternate light source for PrM
- Develop TPC modifications to take pre-amps inside cryostat
- Extend scintillator trigger for Bo (x 2)

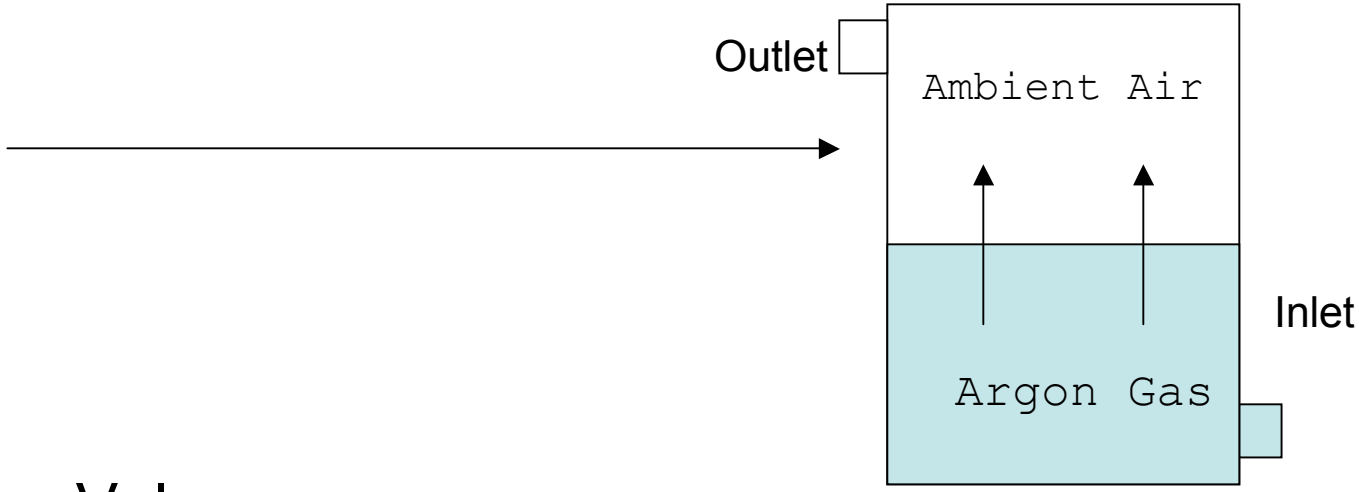
Electronics:

- Develop firmware (dynamic decimation, hit region finding) in Bo readout
- Develop and test `in-cryostat-electronics' for Bo

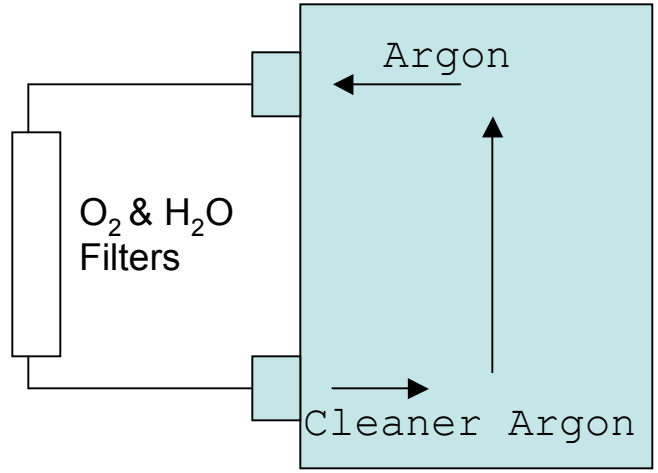
Estimate: 9 months Eng. (incl. MSU), 3 months EP, 2 months MT; $50k + MSU

Visualization of Process

- Argon Piston

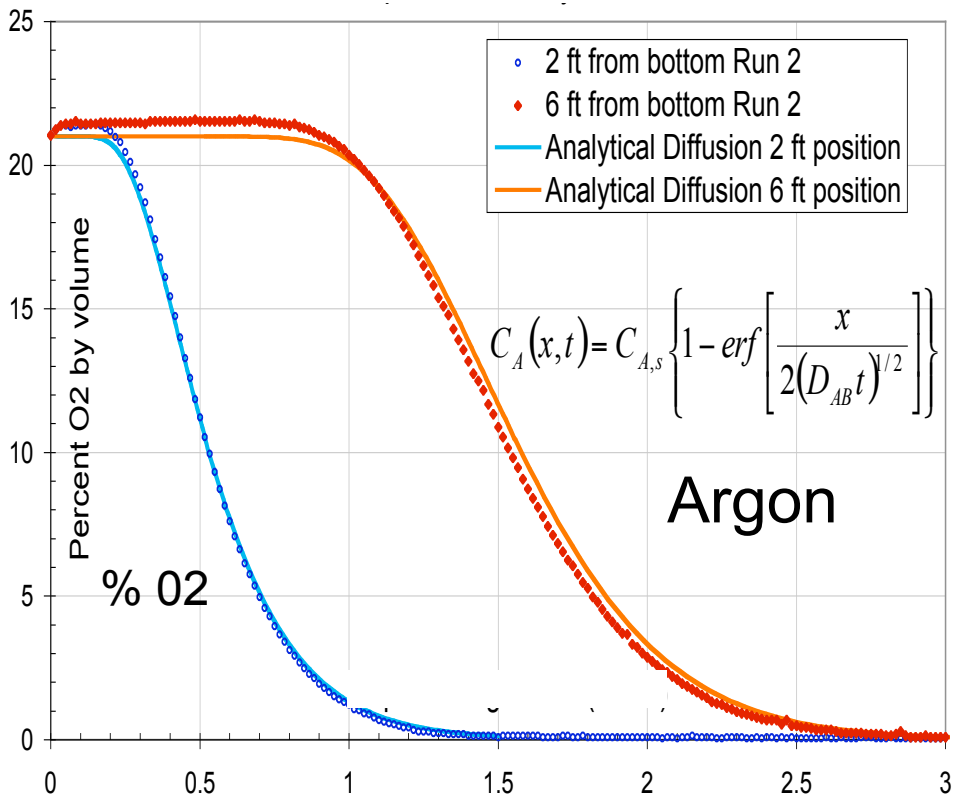


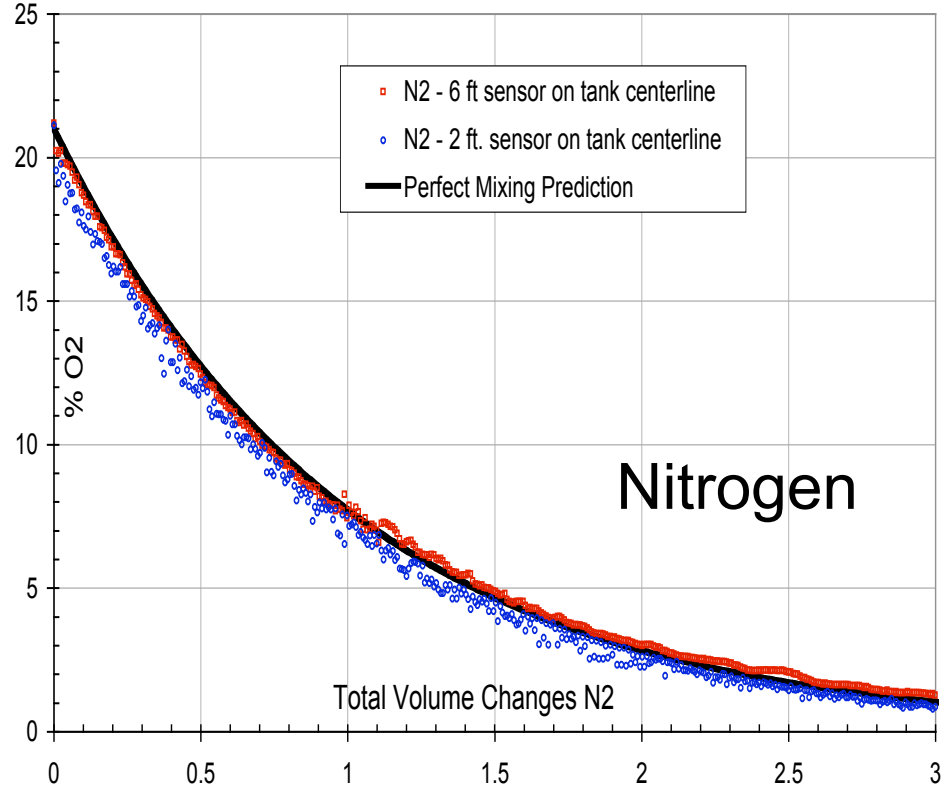
- Exchange a few Volumes
- Recirculate and Filter to <10 ppb



After Reed Andrews

Comparison of Oxygen displacement by Argon and by Nitrogen (Argon Piston)





T. Tope

- to 100 ppm (reduction of 2,000) takes 2.6 volume changes (cf simple mixing, which predicts ln(2000) = 7.6 volume changes)

Work by T. Tope