Fermilab

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Introduction to Liquid Argon Thrust

Stephen Pordes

Review of DOE-HEP supported Fermilab Detector R & D

29 October 2014

Agenda of Liquid Argon Session:

Introduction and Overview	S. Pordes (25)
Purification of Underground Argon	H. Back (20)
ScENE	H. Lippincott (15)
Light Detection Studies	M. Toups (20)
HV studies	S. Lockwitz (15)
LArIAT	B. Rebel(30)

Charge for the Fermilab Detector R&D External Review Draft v1.0

In preparation for the next triennial review of the DOE Office of High Energy Physics (OHEP) general detector R&D portfolio, anticipated for the summer of 2015, the Fermilab directorate requests a review of the associated Fermilab detector R&D program. Since the last triennial review, U.S. detector R&D researchers have developed a common vision for detector R&D manifest in the Snowmass Instrumentation Frontier report, and the broader U.S. particle physics community has strongly endorsed the Prioritization Panel for Particle Physics Projects (P5) report which contains the following two recommendations regarding detector R&D:

Recommendation 27: "Focus resources toward directed instrumentation R&D in the near-term for high-priority projects. As the technical challenges of current high-priority projects are met, restore to the extent possible a balanced mix of short-term and long-term R&D."

Recommendation 28: "Strengthen university-national laboratory partnerships in instrumentation R&D through investment in instrumentation at universities. Encourage graduate programs with a focus on instrumentation education at HEP supported universities and laboratories, and fully exploit the unique capabilities and facilities offered at each."

We request that you assess the quality and impact of Fermilab detector R&D efforts conducted in the last several years and to assess the merit, feasibility and alignment of proposed activities with the Snowmass vision and P5 recommendations for the U.S. detector R&D program. In particular we request that you:

Evaluate the impact and promise of the group's research efforts in detector R&D:

The quality and impact of the Detector R&D by the group in the past three years.

The scientific significance, merit, and feasibility of the proposed future program and the competence and promise of the group for carrying it out.
The adequacy of resources for carrying out the proposed research, and cost-effectiveness of the research investment;
How well do the group's proposed activities align with the Snowmass vision and P5 recommendations?

Assess how effectively the detector R&D effort has exploited and leveraged existing facilities at Fermilab and the importance of these facilities to the future proposed program of work. Evaluate whether additional facilities are needed.

Evaluate Fermilab's status and plans for collaborative efforts with universities, other national labs, and industry, in the general areas of detector R&D and technology transfer. Has Fermilab been effective in maintaining and seeking out additional partners for collaborative research?

Fermilab will provide relevant information in advance of the review which addresses these items and facilitates reviewer evaluations. Upon the completion of the review, we request that the review committee submit a letter summarizing their findings and evaluations.

FNALReport from DOE R & D Review of 2012

1.1 Introduction and Summary

FNAL is the only dedicated HEP laboratory in the US and plays a unique role of providing a strong, well-balanced research program designed to address critical needs for future HEP programs.

FNAL maintains facilities for: silicon detector development, liquid argon-based detectors, NICADD scintillator extrusion, CCD characterization, thin-film deposition, high power laser applications and test beams. These facilities are extremely valuable to the scientific community and the test beam will be critical for developing detectors for the LHC upgrade, ILC and rare decay physics. The lab also maintains an experienced team of engineers for ASIC development, cryogenics and data acquisition.

The projects proposed for KA15 funding are the 3D vertically integrated pattern recognition associative memory (VIPRAM), low noise CCD readout, a microwave kinetic induction detector (MKID), rad hard optical data links, a next generation data acquisition standard using the Advanced Telecommunications Computing Architecture (ATCA), simulation of high resolution calorimetry, dual readout calorimetry, and software framework for DAQ. The scientists and engineers at Fermilab have a long and distinguished record of developing innovative ideas into working systems.

FNAL has become a leader in the development and use of LAr in Intensity Frontier and Cosmic Frontier experiments. The LAr TPC test facility at Fermilab is unique, extremely valuable and doing important work such as the characteristics of the low energy response of liquid argon.

FNAL also provides an important test beam facility to the entire US HEP community for detector development studies. It is in the unique position to provide test beams in which different species of particle interactions can be studied.

The Detector Systems Group has carried out high quality research with substantial impact in the field. The Panel felt that existing program is very productive, but could be more cost-effective.

It was generally agreed that the FNAL KA15 program's management and direction was much improved since the 2009 review. There is a good internal structure with a coherent plan that emphasizes on those areas that are a good match to FNAL resources. A series of internal reviews (under a Detector Advisory Group) of the R&D projects guides the management of Detector R&D program. The panel suggested external review of new ideas would be beneficial.

The Panel noted that collaboration with other laboratories and with universities has also grown since the 2009 review.

FNAL Report from DOE Review of 2012 (cont)

1.2 Findings

- The VIPRAM project is pushing the development of 3D IC technology in order to provide the needed interconnections. This particular 3D electronics connects the associate memories needed to do pattern recognition to find tracks in silicon pixel detectors.
- FNAL continues with developing silicon tracking sensors with integrated trigger functionality.
- The low-noise CCD readout has many potential applications, both for telescopes and for dark matter detectors.
- The MKID can be used as a detector that could collect spectroscopic data in the IR, visible and UV bands simultaneously, and produce a camera far superior to any currently in existence. FNAL has an ambitious goal of developing 100,000 pixel imager MKIDs with complex readout.
- A crystal growing system has been built and has produced a 1 kg solid Xenon crystal. FNAL proposes to continue R&D to measure scintillation yield, electron drift and to compare with liquid.
- FNAL has developed extensive LAr facilities including a materials test stand, clean chamber for purity tests, and cryogenic distillation column. Liquid Argon Purity Demonstrator (LAPD) showed that LAr purity can be maintained to keep the lifetime of the electrons longer than 3 ms without requiring evacuation of the vessel.
- FNAL built an argon distillation column to separate argon from nitrogen from well gas (which is depleted in Ar-39) for use in DarkSide and DEAP dark matter experiments
- The work on optical links includes making a radiation n hard array capable or 120 Gbps aggregate rate and electro optical modulators. Much of this work is in cooperation with Argonne.
- The ATCA data acquisition system could have immediate impact in many small test setups, similar to the role the mini-DAQ played in the construction, assembly and testing of the ATLAS detector.

FNAL Report from DOE Review of 2012 (cont)

1.3 Comments

- The design of systems based on silicon sensors with 3D IC technology seems still not mature. Development of new ideas that could possibly produce the breakthrough in the field should be, however, encouraged. Since the problems to be solved are particularly challenging, a better and wider national and international collaboration would be an important added value. The Fermilab management should develop a technology roadmap to evaluate the benefits and viability of this effort.
- MKID is an exciting project which seems to have the potential to contribute substantially to experiments in the Cosmic Frontier. FNAL has unique capabilities to contribute to the project.
- Solid Xenon crystal R&D is an interesting generic detector R&D project which should be continued.
- FNAL's development of the distillation column for processing of argon gas from deep wells is likely to have great value in this area. There is a concern that if Darkside is not chosen as a Generation-2 Dark Matter search experiment, the work could be orphaned. The highly successful long-drift purity demonstration was a crucial step in the development of kiloton LAr detectors.
- A future large scale LAr detector for neutrino and proton decay physics seems ideal for a major US-based program and Fermilab is well positioned to take the lead on this.
- The ATCA work should continue, and should be closer coordinated with similar work being done at SLAC.
- FNAL has made some effort in the past year to give more support to test beams, but even more is needed to address the community need. A particular need is low energy beams with excellent particle identification.
- Fermilab should seek to work cooperatively with other laboratories that are actively pursuing in similar technologies.
- As the only U.S. laboratory with purely HEP mission, Fermilab should take leading role in organizing workshops in new detector technology to attract expertise from the other DOE labs, the university community, and non-HEP sources.

Annual LAr and 2013 HV workshops

No presentation on LAPD – JINST published on purity achievements, **JINST 9 (2014) P07005**, article in preparation for the Long Bo running.

No presentation on light readout led by Prof. Stuart Mufson at Indiana **arXiv:1408.1763, submitted to PRD**

Liquid Argon – Why

Liquid Argon is a bright Scintillator (40,000 photons/MeV) and allows free electrons to drift meters under E fields of ~ kV/cm. It has a density of 1.4 tonne/m^3, and is readily available.

Liquid Argon presents an attractive Target & Detection Medium for:

Neutrino interactions

Liquid Argon TPCs can produce bubble-chamber quality event images with topology *and* ionization density -> particle ID/calorimetry

Dark Matter searches

The time development of the light pulse and the ratio of the amount of free charge to light produced by interactions in Argon provide powerful rejection of electron and photon background in WIMP searches

Technical Challenges for Liquid Argon Detectors

- Chemical purity of Argon to allow electron drift,
- Chemical purity to allow light production and propagation
- Detector Materials Qualification
- Cryostat and Cryogenics, and associated safety issues
- TPC design
- TPC readout electronics
- HV feedthroughs (>100 kV) and distribution
- Light Detection
- Data Acquisition

Technical Challenges for Liquid Argon Detectors

- Chemical purity of Argon to allow electron drift, ***(ν and DM)*** ***IP***
- Chemical purity to allow light production and propagation ***(ν and DM)*** ***IP***
- Detector Materials Qualification ***(ν and DM)*** ***IP***
- Cryostat and Cryogenics and associated safety issues ***(ν and DM)*** ***IP***
- TPC design ***(ν and DM)*** ***oh***
- TPC readout electronics ***(ν (and DM?))*** ***oh***
- HV feedthroughs and HV distribution ***(ν and DM)*** ***IP***
- Light Detection ***(ν and DM)*** ***IP***
- Data Acquisition ***(ν and DM)*** ***IP***
- Radio purity of Argon ***(DM)*** ***IP***

IP = In Progress at FNAL, oh = on hold

(Some) Liquid Argon R & D at Fermilab

Charge Detection

- **Certification of detector materials**
  - **Materials Test System (MTS)**
- **Production of clean argon without evacuation**
  - **Liquid Argon Purity Demonstration (LAPD)**

Light Detection and Production

- **Effect of contaminants and additives (quenching, attenuation)**
- **Detector Performance (light collection, photosensors)**
  - **BO and TallBO cryostat systems**

High Voltage

- **Breakdown in noble liquids**

(Some) Liquid Argon R & D at Fermilab

Neutrino Specific

- **TPC performance with electronics and HV ->**
  BO TPC and Long BO TPC
- **Detailed behavior of particles in liquid Argon ->**
  Test beam into LArTPC (LArIAT)

Dark Matter Specific

- **Light yield from nuclear recoils at low energy (<50 keV)**
  ScENE (Scintillation Efficiency of Noble Elements) experiment
- **Argon for low-background experiments**
  Purification of underground argon

(Some) Liquid Argon R & D at Fermilab

Policies & Disclaimers

- **Relevant to `the current program' but not exclusively so**
- **Maintain close relations with University groups, encourage use of existing facilities, and support developments for new work**
- **Work in areas where we can exploit expertise at Fermilab**
- **Design equipment for R & D - if available may be used to develop equipment for a specific experiment (useful shakedown)**
- **Not the only LAr R & D at Fermilab**
  both MicroBooNE and LBNE are doing interesting stuff &
  there is a program LAr1-ND which will be covered in a separate talk


Argon Source & **Materials Test System**
Commercial Argon ~1 ppm Oxygen, Water, Nitrogen
Water removal filter
Oxygen removal filter
Pure Argon <30 ppt O2 eq.
DURA-CYL
ARGON
ARGON
REFRIGERATED LIQUID
UN 1951
LUKE

Materials Test System

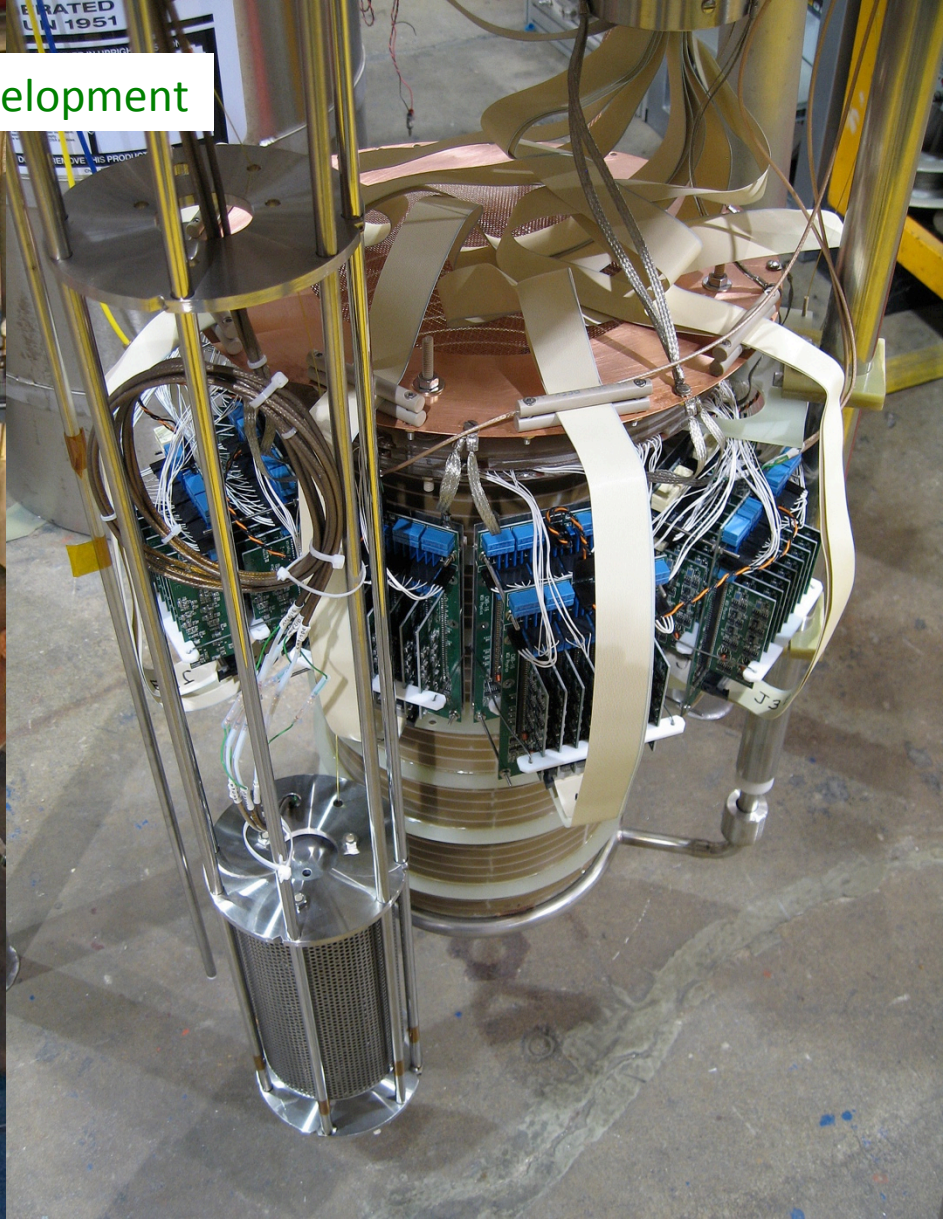
`A system to test the effects of materials on the electron drift lifetime in liquid argon and observations on the effect of **water**' R. Andrews *et al.,* Nucl.Instrum.Meth.A608:251-258,2009.

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

Sample data on different materials (bad, good,OK in liquid)

TPC Electronics Development

Original Bo TPC
Electronics outside cryostat (Michigan S.U)



Bo TPC with
Electronics in liquid argon (Michigan S. U.)

Liquid Argon Purity Demonstration

All existing LArTPC detectors have been evacuated before filling. Probably not practical for kiloton detectors

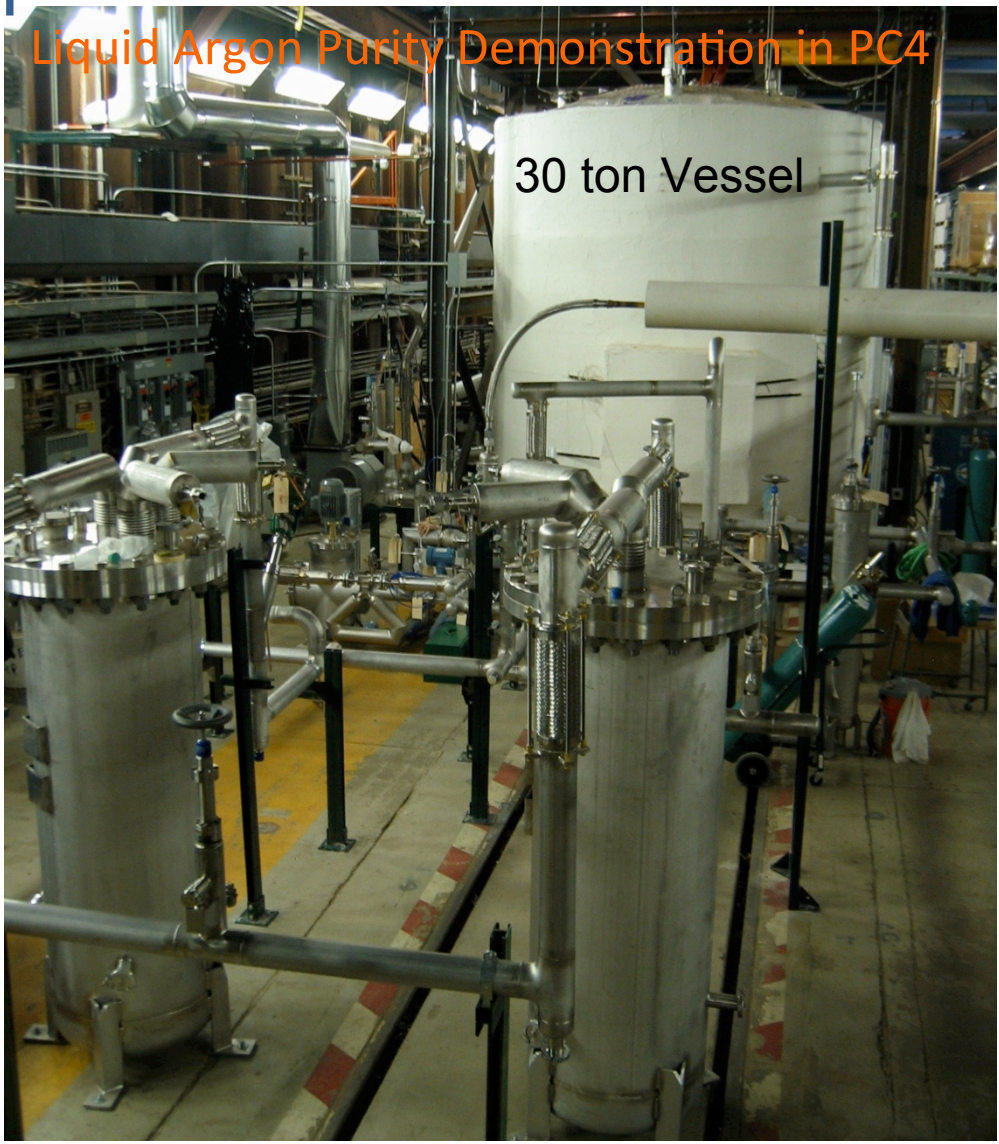
Goal: Demonstrate good life-time **in an industrial vessel without evacuation**.

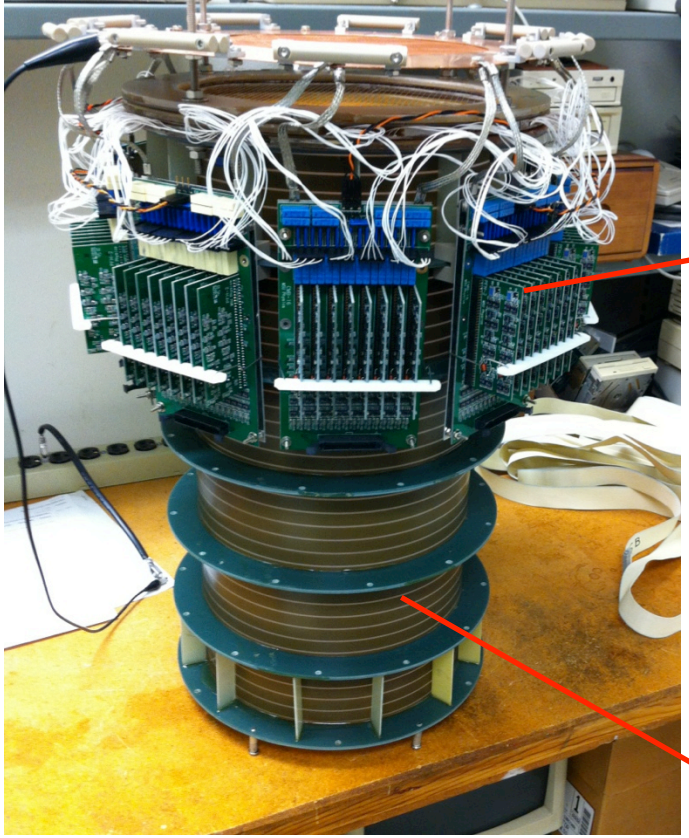
First multi-ton purification system designed and built at Fermilab.

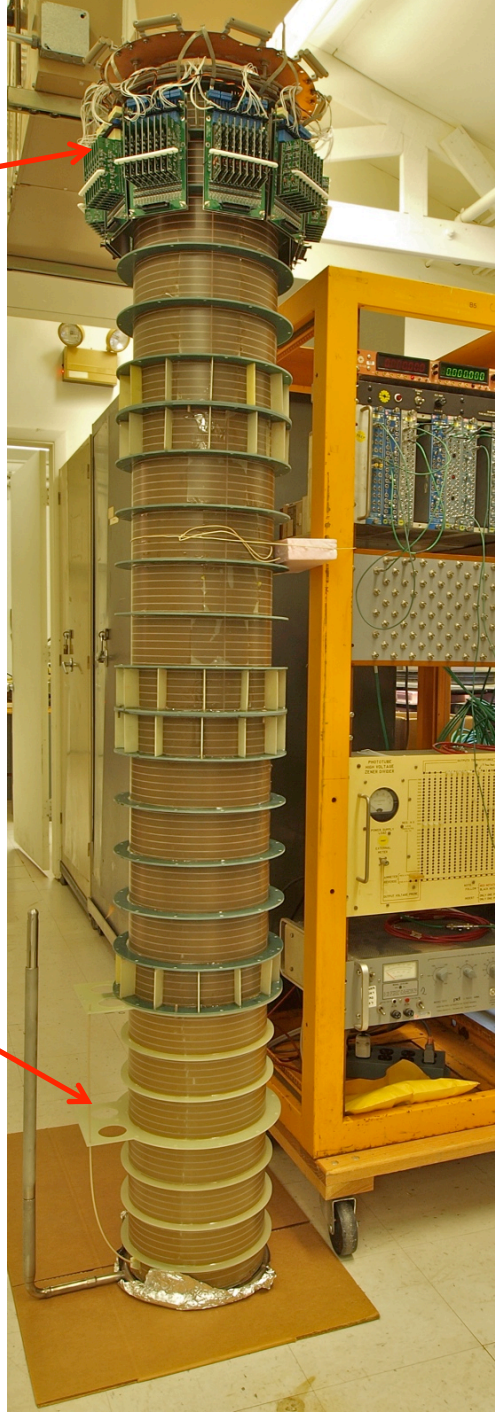
Stage 1 – bare tank & Instrumentation

- Sniffers for evolution of gas purge
- Analyzers – for O_2, N_2, and H_2O levels
- RTDs – for temperature (gradients)
- Purity Monitors - for drift-lifetime

Stage 2 – Operation with long TPC (LongBo)





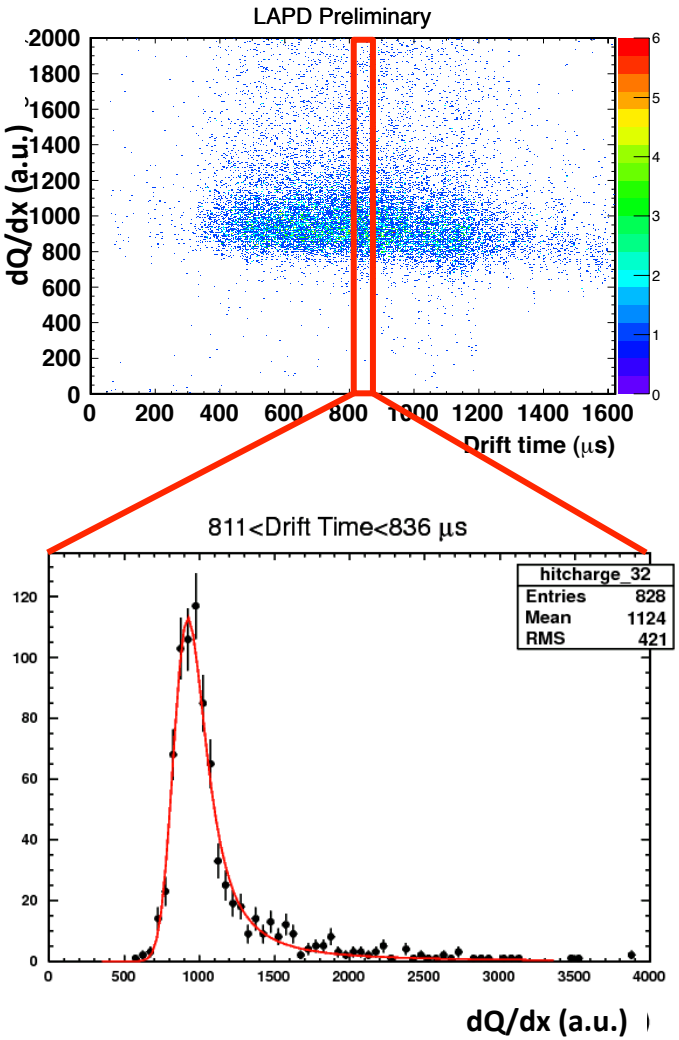


Long Bo

Bo to LongBo(w)

If you don’t watch carefully …

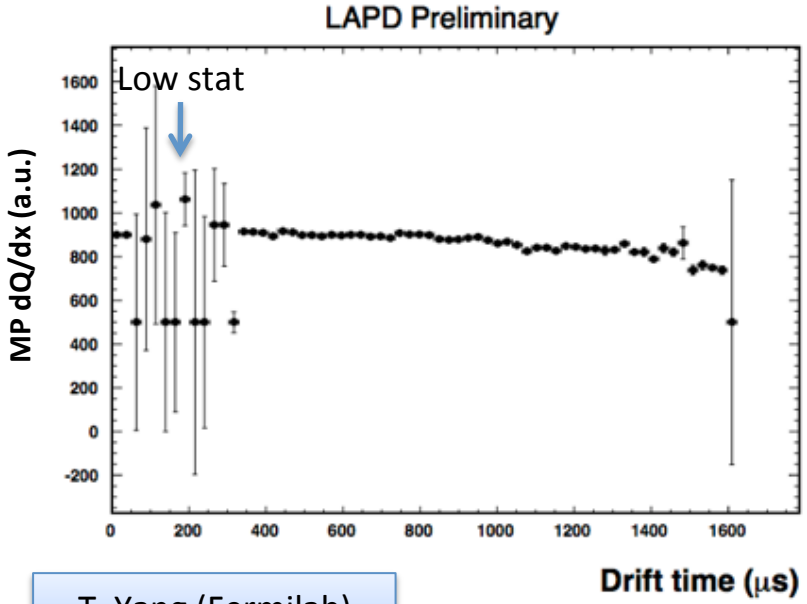
Lifetime measurement from tracks in LongBo



— Select single muon events between $50° < \theta < 70°$ and remove δ rays

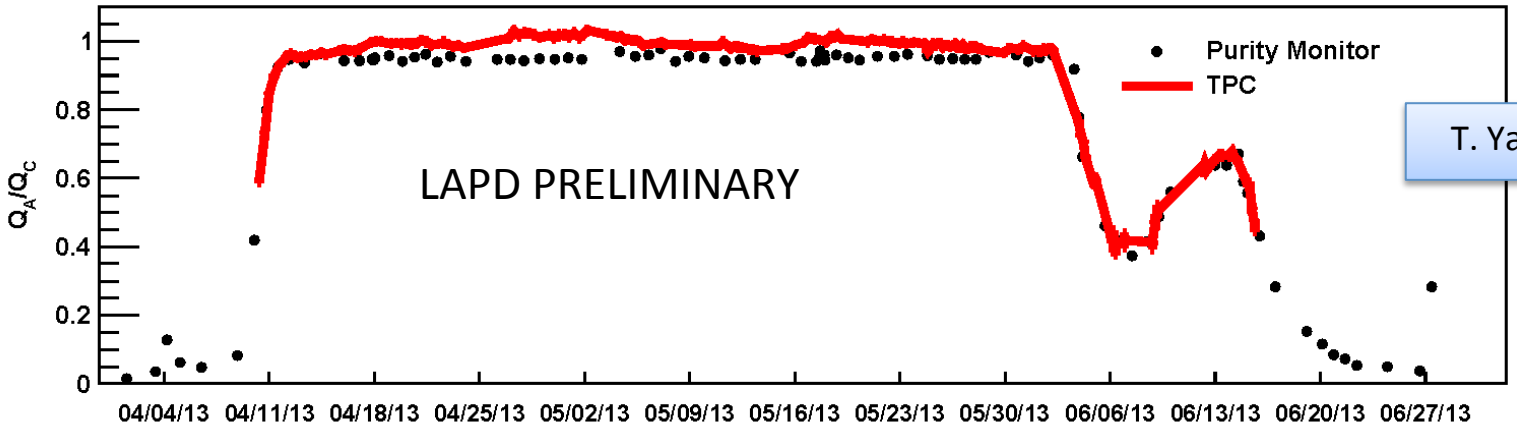
— Use dQ/dx of muon hits as a function of drift time to measure charge attenuation

— Less than 15% attenuation for 1 ms of drift time (1.3 m @ 0.35 kV/cm)



T. Yang (Fermilab)

Comparison of TPC and Purity Monitor at long (> 3 ms) lifetime



T. Yang (Fermilab)

- Electron attenuation measured in the TPC agrees with lifetime measured by the purity monitors (PrM)

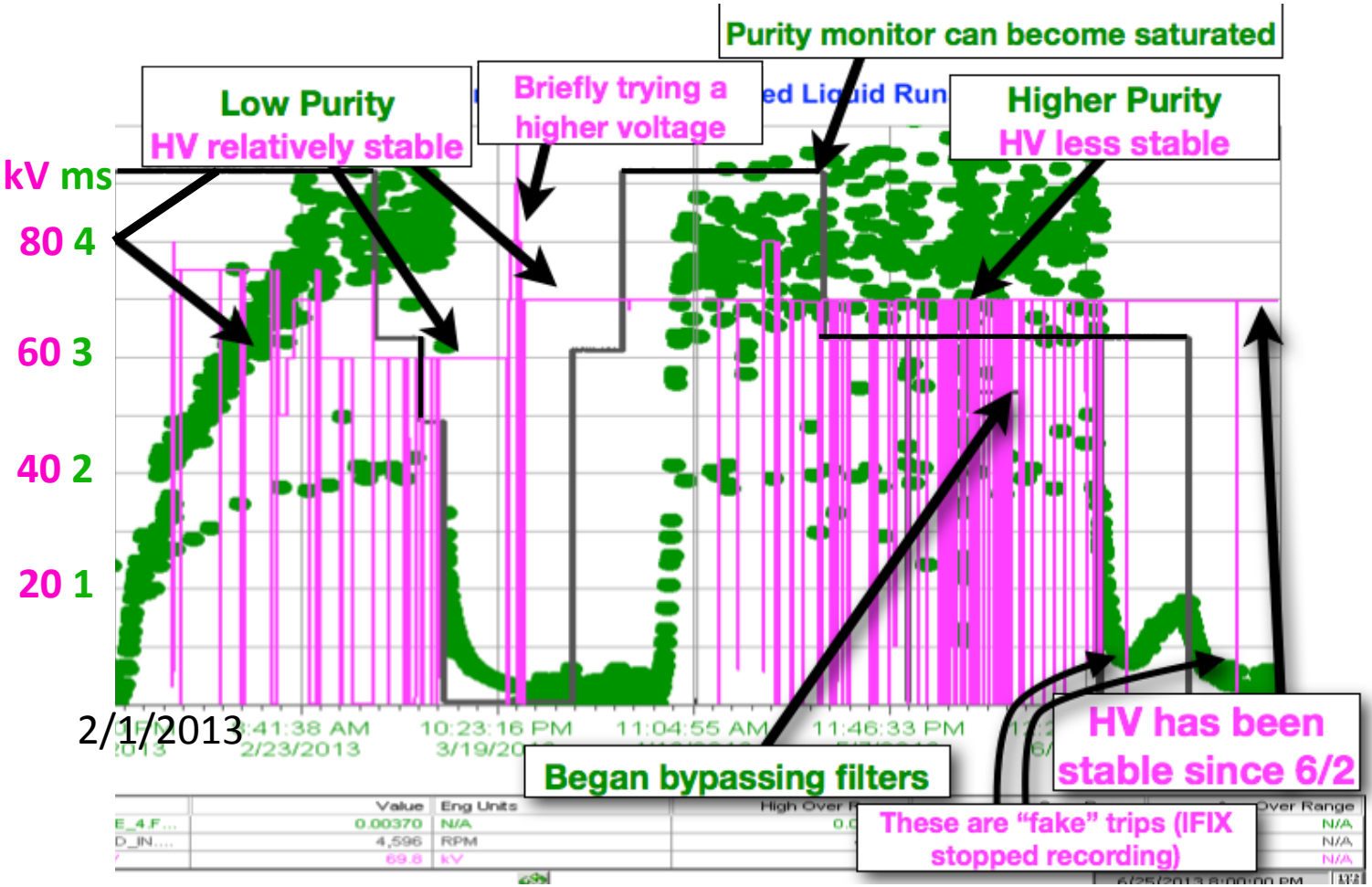
LAPD – HV stability with LongBo TPC and argon purity;

the plot that launched the question – does HV strength depend on purity?

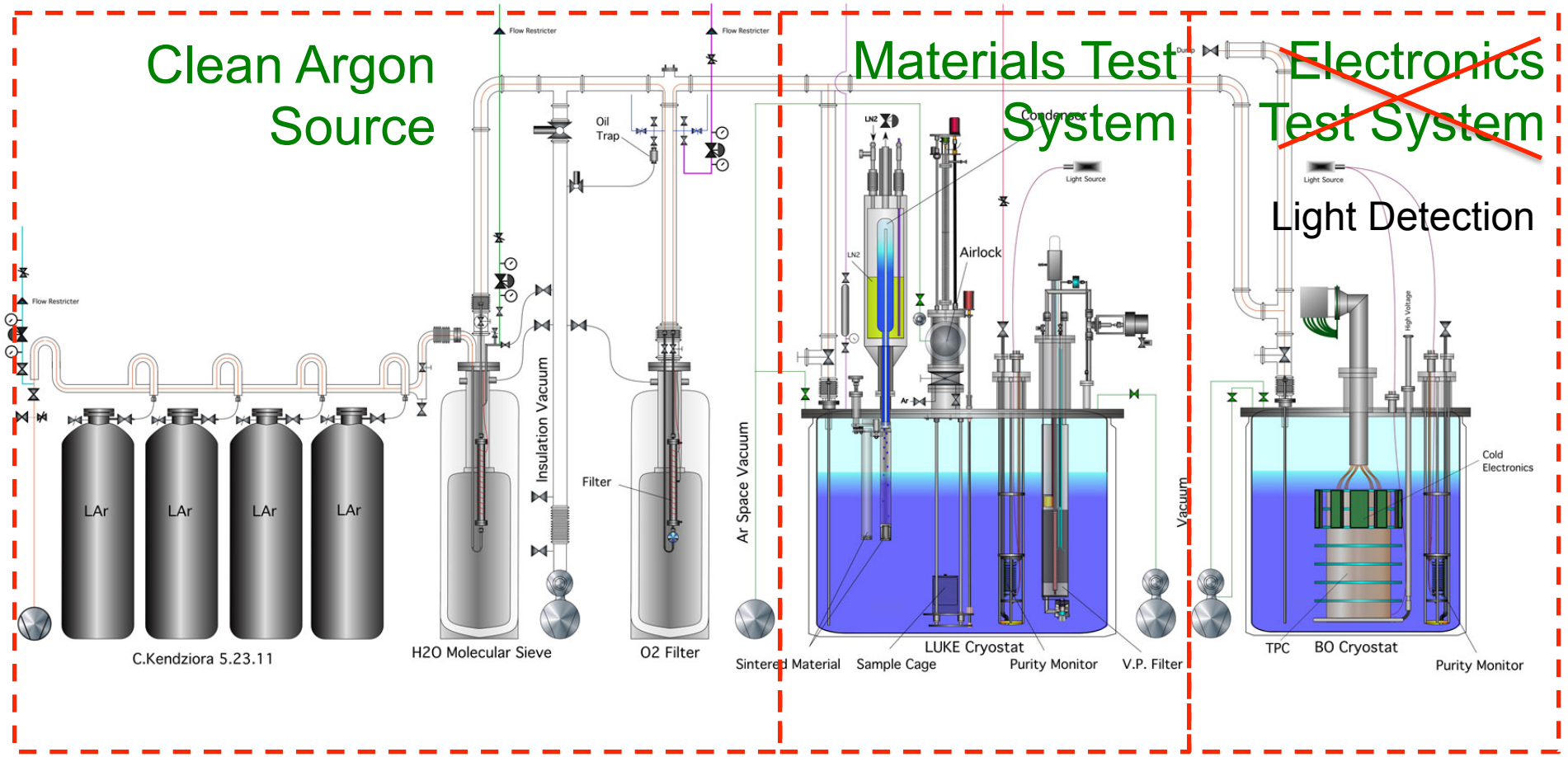
pink – HV (vertical lines are HV supply trips)

green – argon purity (lifetime in milliseconds – monitor saturates at 5, ignore low points below the bulk – bugs in analysis)

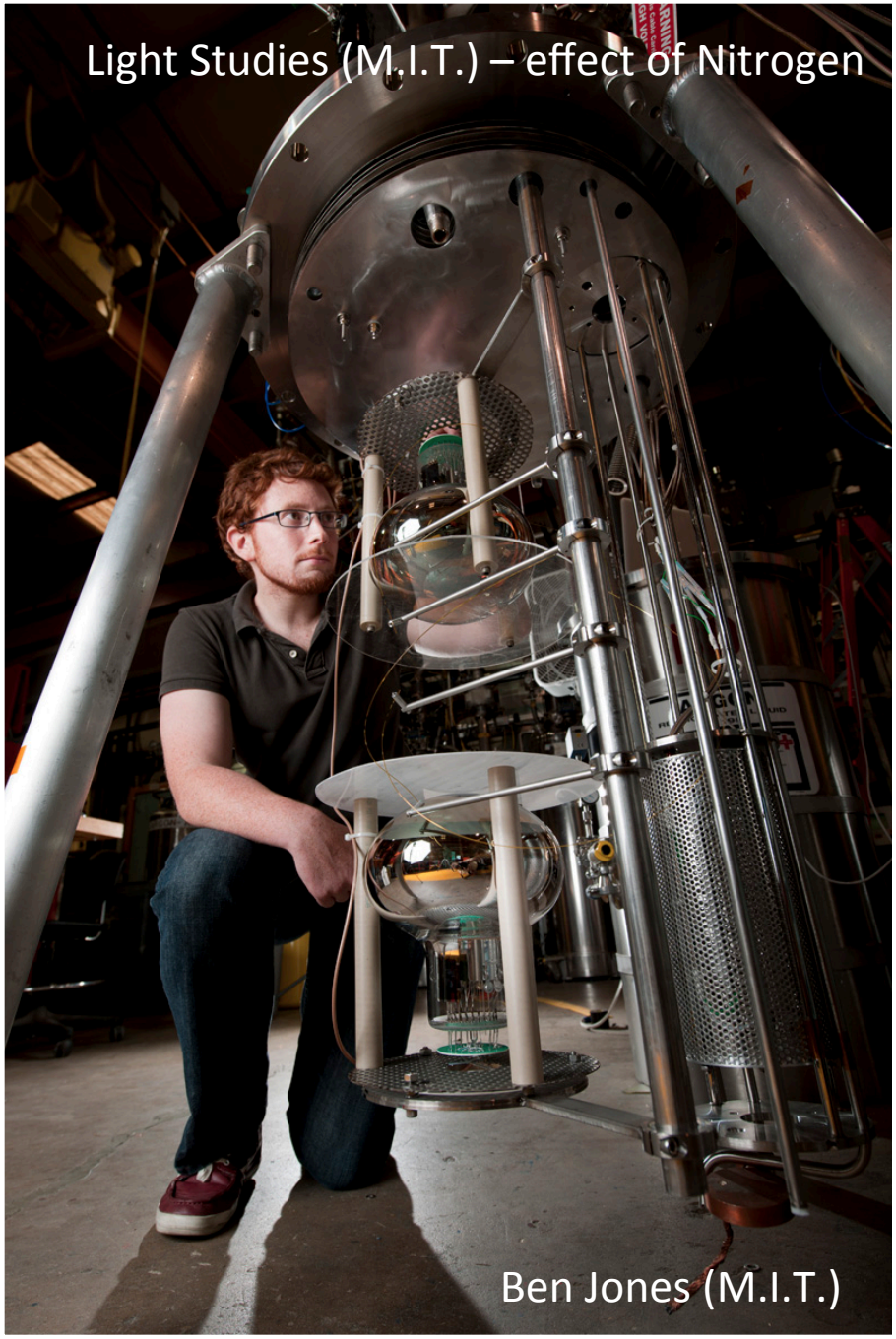
black – liquid circulation pump (arbitrary units)

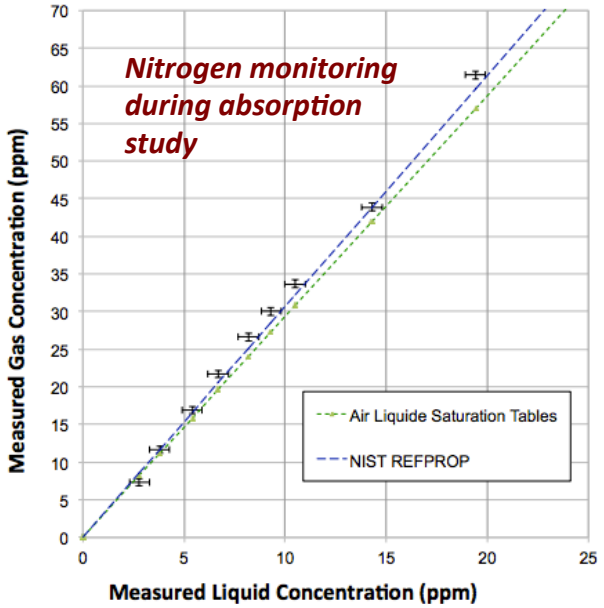


Liquid Argon Setup at the PAB



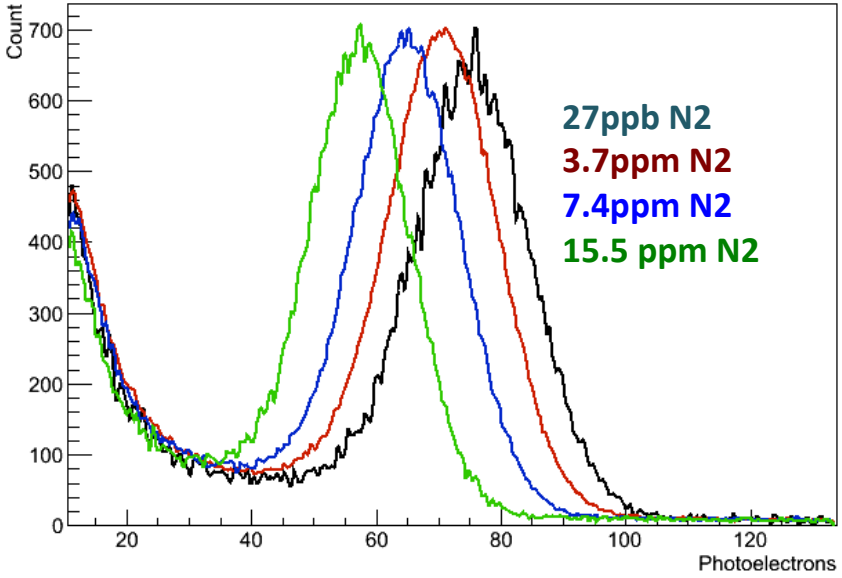
Schematic of Materials and ~~Electronics~~ Test Systems
Light Detection





JINST 8 (2013) P12015
JINST 8 (2013) P07011

Alpha particle response vs N2 conc.



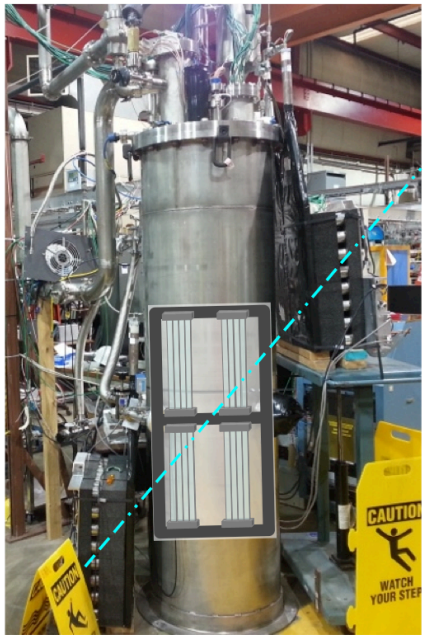
Light Detection R & D in new 80 inch cryostat, TallBo

Scintillator Paddle Prototype for LBNE hanging on TallBo lid

TallBo in operation

Promising Outlook for Large-Volume LAr Photon Detection

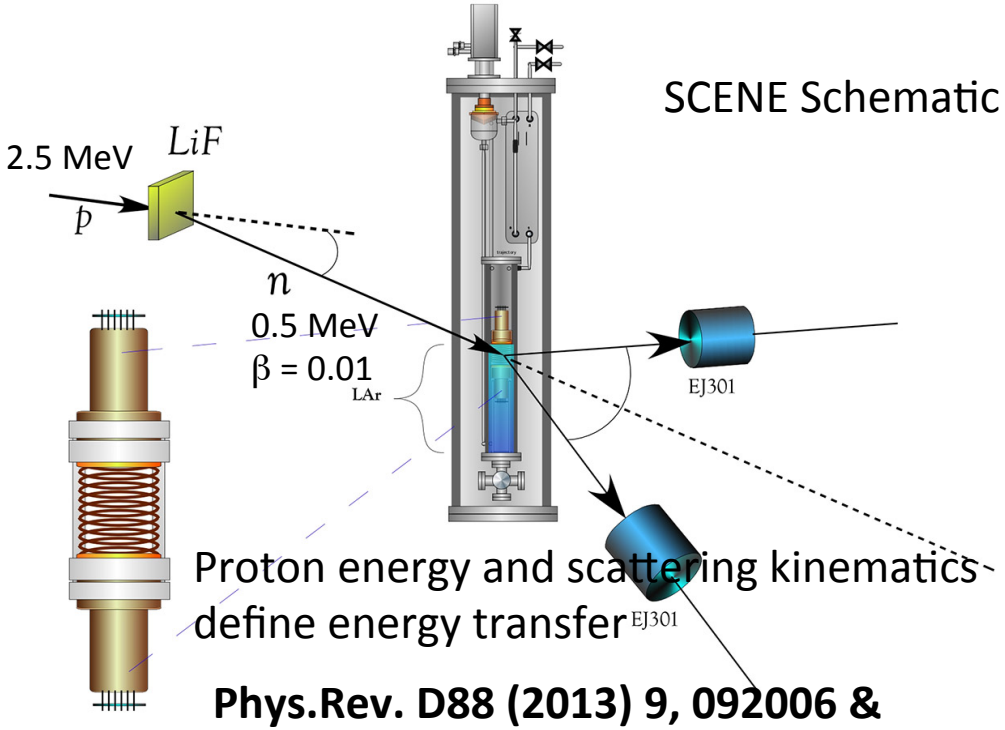
- Exploring and *converging* on detector designs
  - Effectively *evaluating* and *comparing* designs
  - Identifying and improving promising technologies
  - SiPMs exhibit many appealing features
- *Scintillation signal* provides valuable info
  - Timing for TPC
  - Potential for *particle identification*
- More exploration on the horizon
  - 35-ton Phase 2 LAr cryostat (FNAL, beginning of 2015)
  - 500-L dewar at CDDF (CSU, operating summer 2014)
  - Continuing operations at TallBo (FNAL, fall 2014)
  - Continuing work at local dewar facilities
- *Lots of effort from many folks in many groups*
  - Indiana U.
    - Stuart Mufson, Jim Musser, Mark Gebhard, Brice Adams, Mike Lang, Brian Baugh, Paul Smith, Brian Baptista, Bryan Martin, John Urheim, Jonathon Lowery, Bruce Howard
  - MIT
    - Janet Conrad, Matt Toups, Ben Jones, Len Bugel
  - Colorado State U.
    - Norm Buchanan, Dave Warner, Ryan Wasserman, Dylan Adams, Jay Jablonski, Tom Cummings, Forrest Craft, Andrea Shacklock
  - LBNL – Victor Gehman, Richard Kadel
  - Louisiana State U. – Thomas Kutter
  - Argonne Natl. Lab
    - Gary Drake, Patrick De Lurgio, Andrew Kreps, Michael Oberling, John T. Anderson, Zelimir Djurcic, Himansu Sahoo, Victor Guarino
  - Fermilab
    - Brian Rebel, Stephen Pordes, Marvin Johnson, Ron Davis, Bill Miner



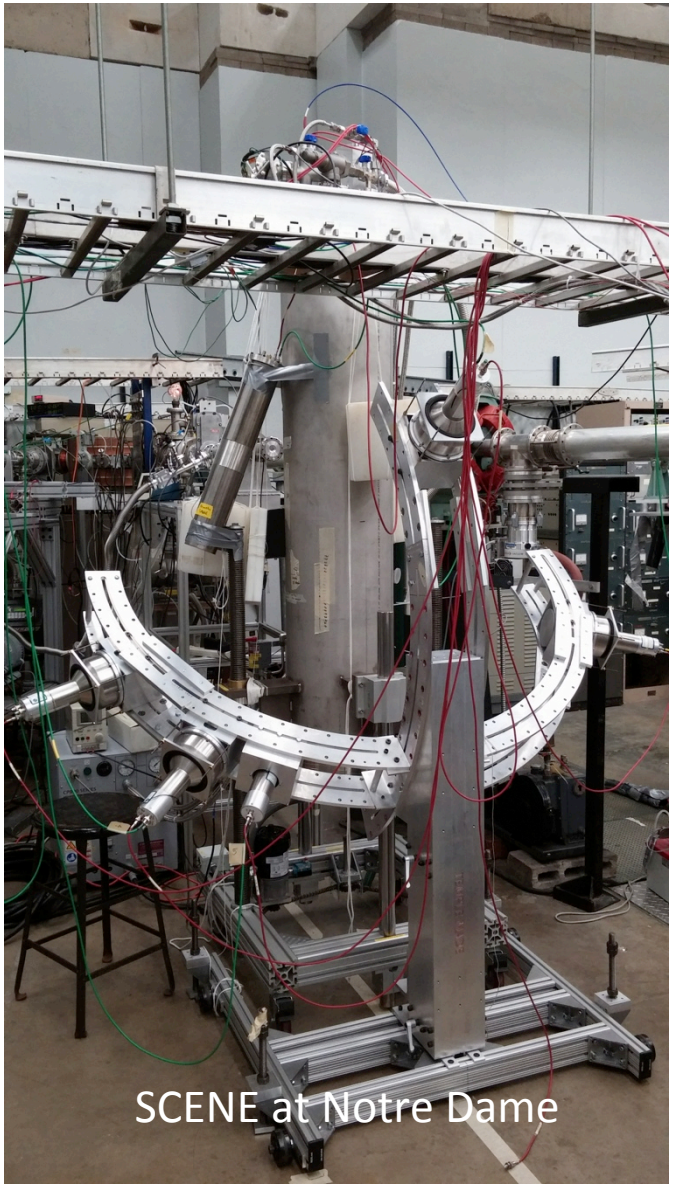
SCENE – Scintillation Efficiency of Noble Elements

Precision measurement of light output of Argon nuclear recoils in a dual-phase LArTPC using monoenergetic, low energy, pulsed Neutron Beam at Notre Dame

(Chicago, Fermilab, Princeton, Naples, Notre Dame, Temple, UCLA)

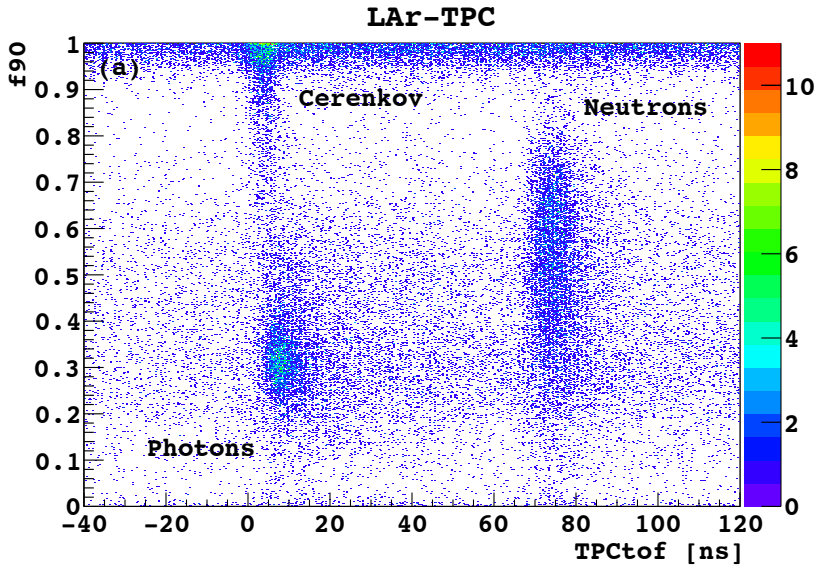


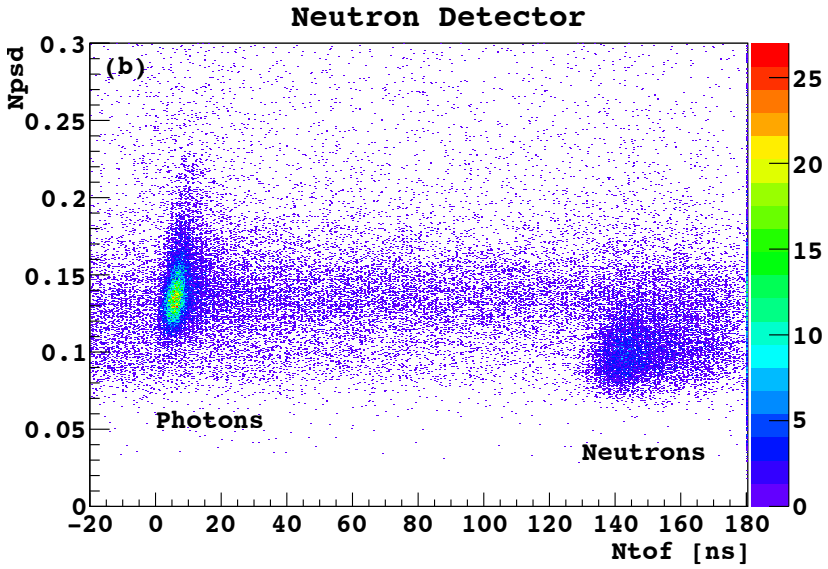
Phys.Rev. D88 (2013) 9, 092006 & arXiv:1406.4825

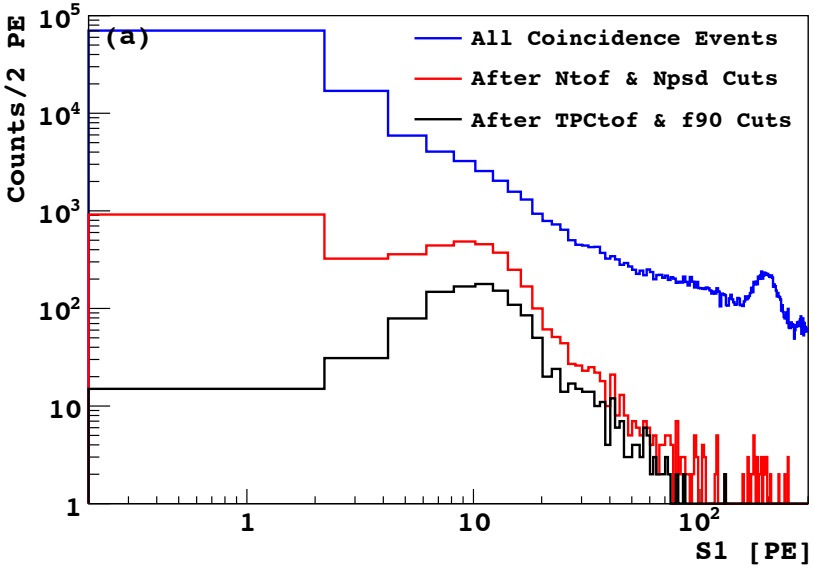


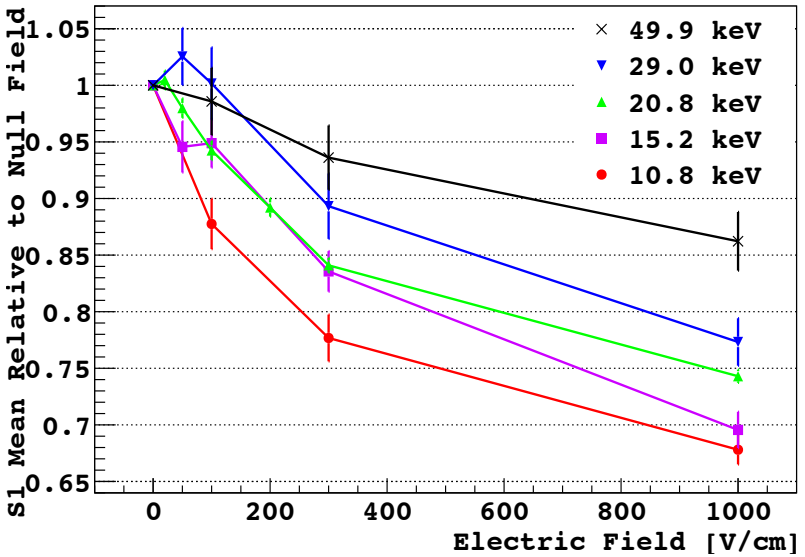
SCENE - Time of Flight vs Pulse Shape Discriminant in LArTPC & Neutron Counters

Less light from nuclear recoils in presence of electric field – **unexpected result & affects optimal operating parameters for argon (and possibly xenon) dual-phase TPCs searching for Dark Matter**









Purification of low-radioactivity argon from underground

Atmospheric argon ~ 1Bq/kg from ^{39}Ar;

This background limits the size of dual-phase Argon TPCs to < 1 tonne for dark matter searches because of pile up.

Ar (600 ppm) from certain CO_2 wells in Co has < 0.01 Bq/kg (arXiv:1204.6011) Mixture of ~4% Ar, ~5%N_2, ~90% He comes to Fermilab; have to distill the N_2 off.

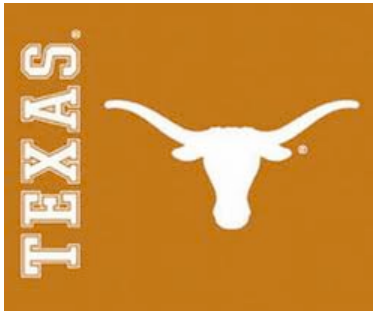
Column has processed > 100 kg Ar

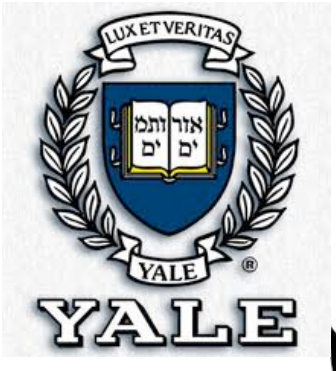
Aimed at DarkSide and DEAP programs

(other uses in Henning Back talk)

LArIAT Collaboration at time of 2012 DOE Review
(see Brian Rebel's talk for present status)

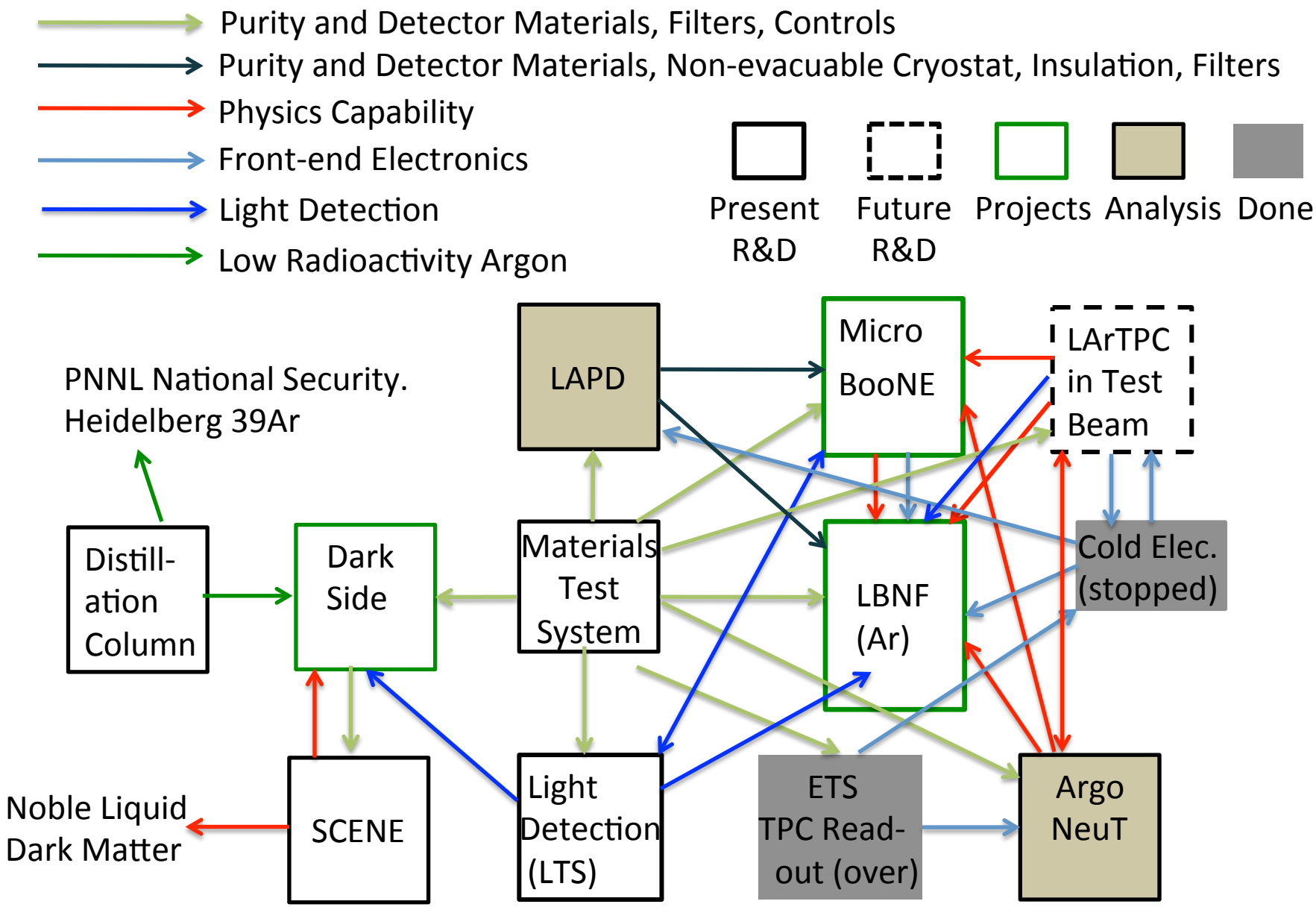
Imperial College London





L'Aquila

Relationships Between Activities



One Slide on Software

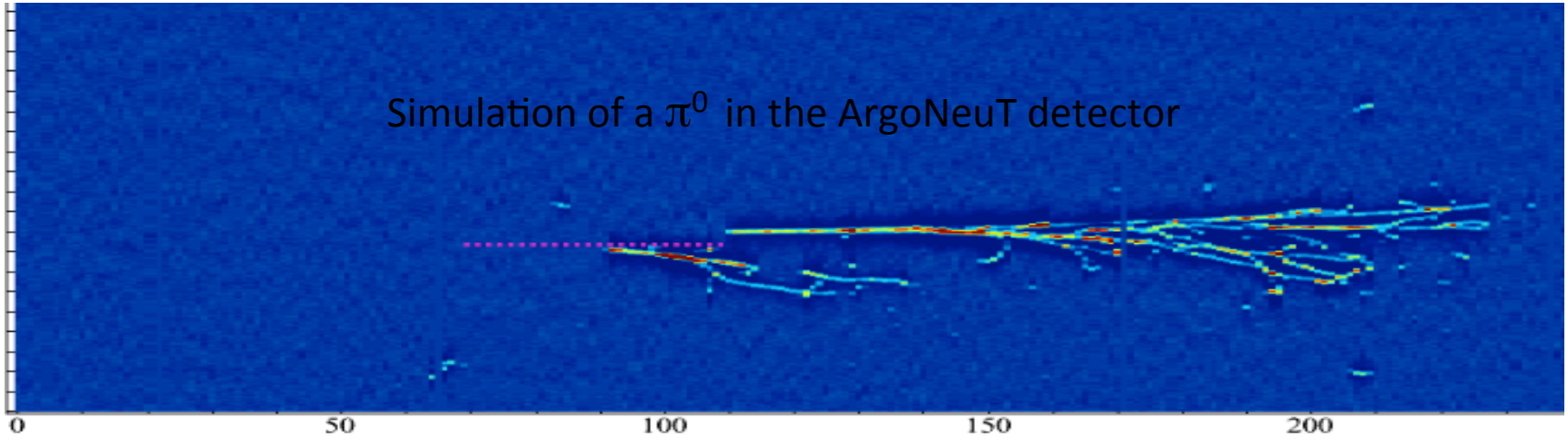
Detector simulations and event reconstruction software are important for the success of the LAr technology, and present a significant challenge given the wealth of data the detector provides.

LArSoft is a framework for Detector Simulation and Reconstruction in Liquid Argon TPCs.

Uses the Fermilab Art Framework: provides event-types (neutrino interaction, single particle, cosmic rays) propagates the charge and light to user-defined detectors

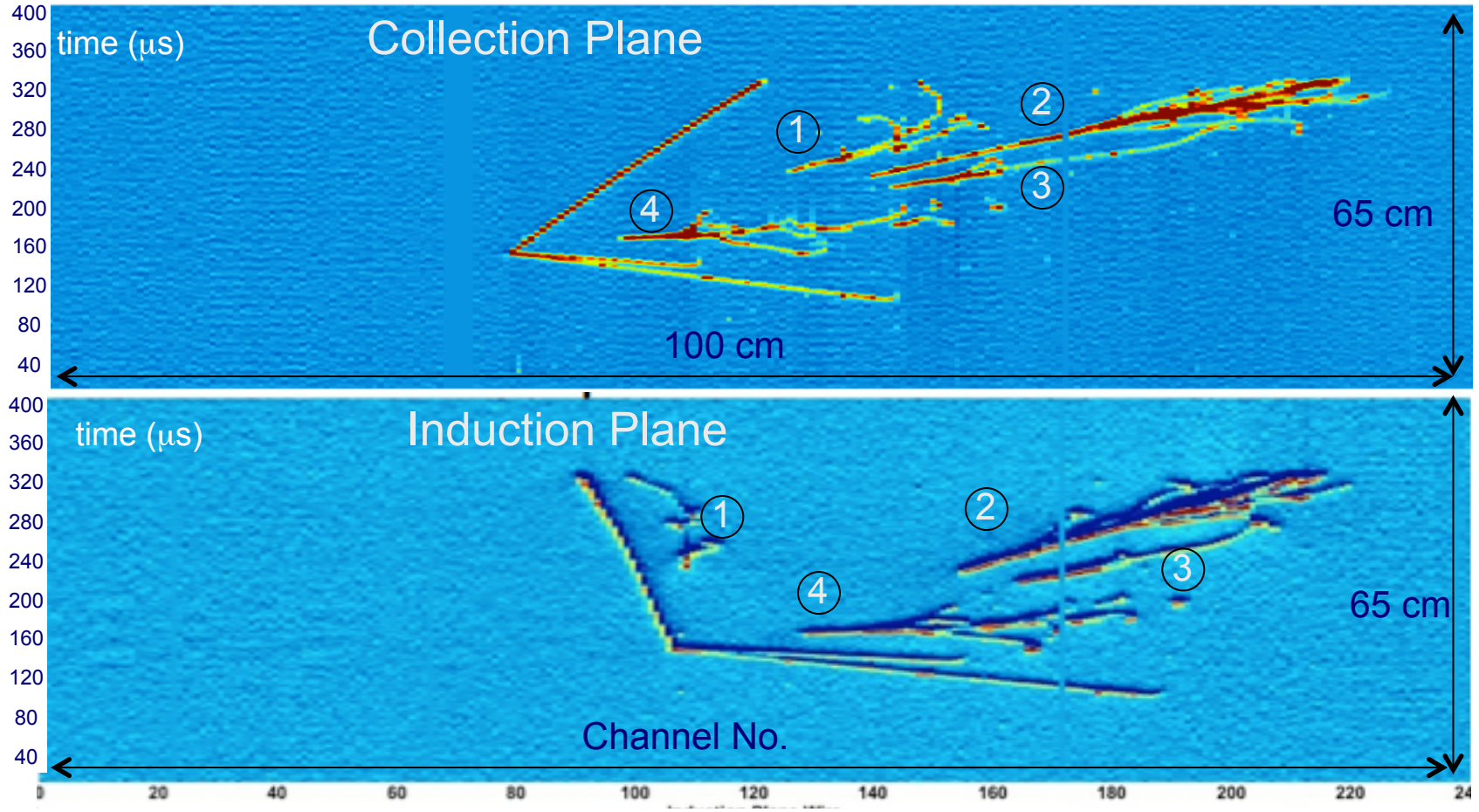
LArSoft has contributors from:

Bern (CH), Colorado State, Columbia, Duke, Fermilab, LNGS (It), Kansas State, L.A.N.L., M.I.T., Michigan State, New Mexico, U. Penn, S.M.U., Syracuse, and Yale.



ArgoNeuT in NuMI Beam

Event with 4 photon conversions (2 π^0)



Invaluable data set of ν interactions (~10,000) in Argon

Enabling factors:

- ICARUS – showed what was possible for liquid argon
- Supportive Management at Fermilab & DOE
- Significant material funding in early days for analytic equipment
- A home, and continuity of skills in workforce
- Highly competent individual personnel

  Resident engineer at the PAB for the first systems

  Resident technical group at the PAB (Leader and 4 technicians)
- Relationships with Universities and other laboratories

  BNL, Chicago, Indiana, M.I.T., Michigan State, PNNL, Princeton, Yale, UCLA, & LArIAT collaboration

Summary of Achievements of Liquid Argon R & D program

- In-house production of filtrations systems to produce pure argon (<30 ppt O_2 equivalent)
- Construction of system for measuring effects of materials on electron drift-lifetime without being exposed to vacuum
- Identification of major source of reduction of electron drift-lifetime in clean, tight systems
- Identification of useful analytic equipment (in particular H2O analysers)
- The first U.S. electronics for TPC readout - generation 1 in the warm outside cryostat and then the first CMOS, in liquid, electronics.
- An invaluable set of data from ArgoNeuT (250 kg LAr TPC in NuMI beam)
- In-house experience in construction of multi-ton pure argon production
- Demonstration of many millisecond electron drift-lifetime in an unevacuated, industrial vessel
- In-house experience in construction of HV feed-throughs and measurements on breakdown
- Measurements of effects of contaminants such as Nitrogen and Methane on light transmission
- Measurement of effect of electric field on light and ionization production by recoil argon nuclei (important for dark matter searches using noble liquids)
- Purification of underground argon for Dark Matter - and National Security and Climate Studies
- Development of new approaches to light detection – both photon collectors and transducers
- Cadre of young physicists with interest and skills in detectors and analysis of data therefrom.
- A work-force - technicians and engineers - with experience and expertise in cryogenics.
- Sliced bread .

Future Program..

Construction of LAr1-ND and completion of LArIAT are the big items.

Integration of the HV cryostat on argon source at PAB

Argon Purification
HV studies (LDRD supported)
Light detection studies
Materials Tests
ScENE studies

Infrastructure wish-list:
Device to move radioactive sources up and down inside a cryostat
Material test stand to measure water outgassing rates from – 100 C to 0 C.
Lightweight under water (argon) camera

Issues are not (only) money but availability of engineering and technician time

Fine

Mission: develop the expertise to enable a U.S Program for a multi-kiloton LArTPC

Learn as much as we can from previous work (especially ICARUS)

Develop hands-on experience and our own (new) infrastructure
- filters, cryogenics, pumps, HV feed-throughs, readout electronics

Look at technical topics which may not have been fully explored previously
- material tests, in-liquid electronics, light detection

Put a LArTPC in a neutrino beam to exercise a complete system (and physics)
- ArgoNeuT

Demonstrate good electron lifetime *in an* ***unevacuated commercial vessel***
- LAPD (Liquid Argon Purity Demonstration)

Expose LArTPC to a beam of known energy and different particle types
- LArIAT (Liquid Argon In A Test beam)

Exploit synergies with Dark Matter detectors
- DarkSide Program