Liquid Argon for Direct Detection of Dark Matter

Work and Plans at Fermilab

Why Liquid Argon

What are the technical issues

Why and What at Fermilab

Why Liquid Argon for Dark Matter Detection :

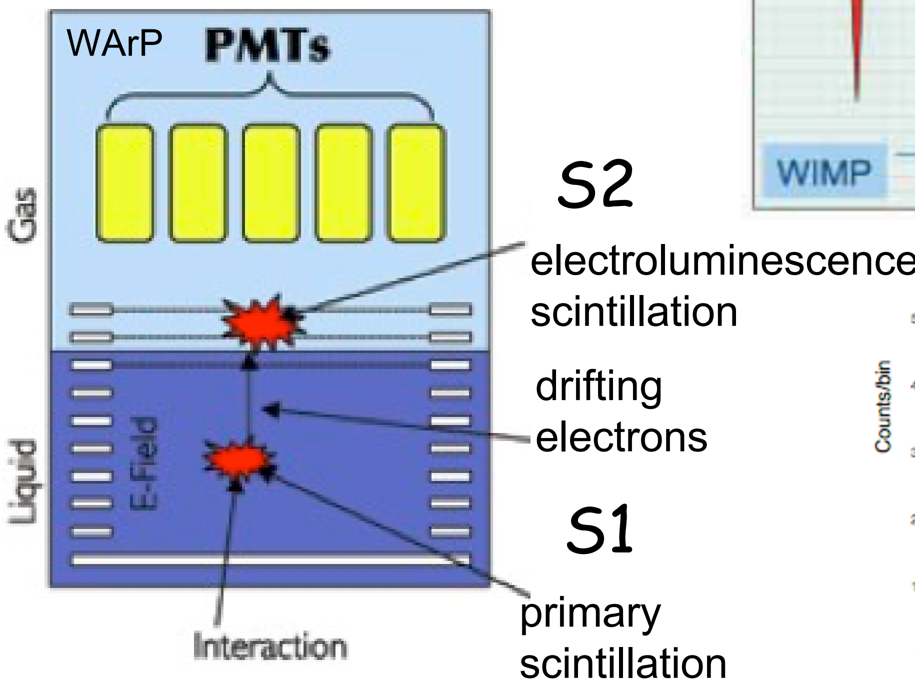
Signature of WIMP interaction: Nucleus recoiling from WIMP

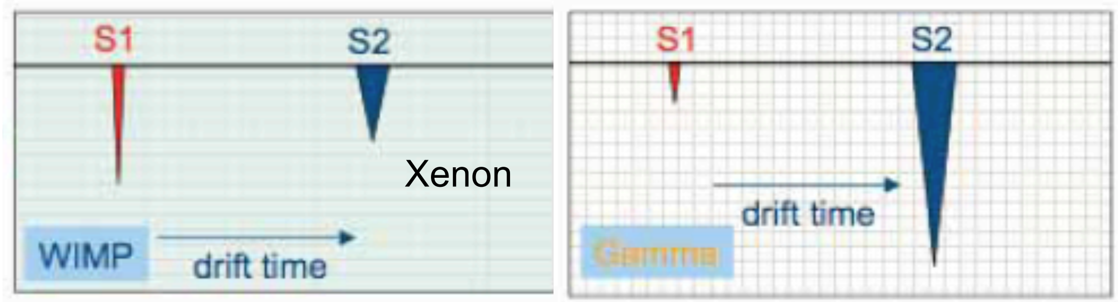
Experiment challenge is to reject backgrounds to DM signal and to have sufficient target-mass. Backgrounds come from photons (low dE/dx) and neutrons (high dE/dx)

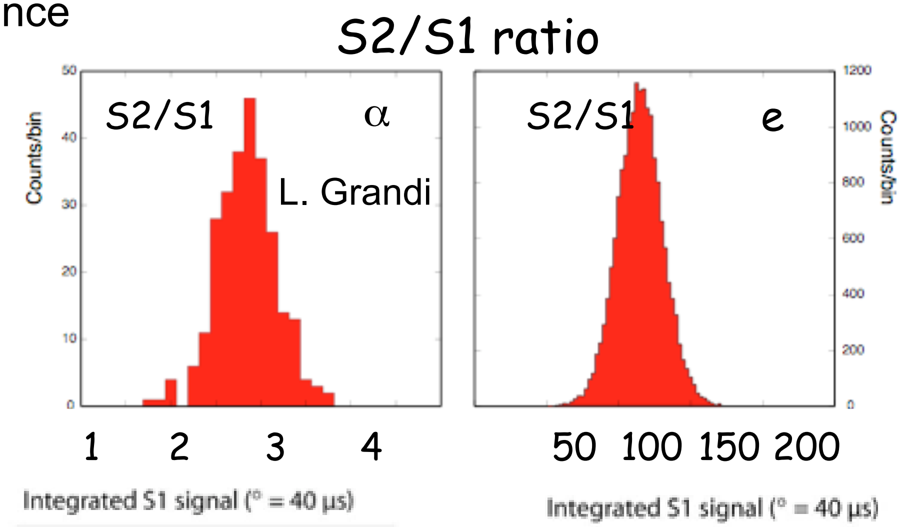
Noble Liquids

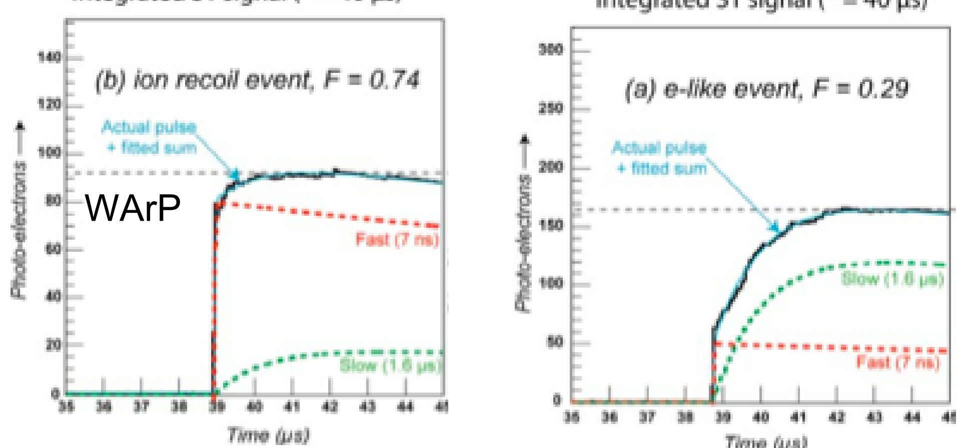
- radiation produces free charges and free photons
- charge to light ratio depends on density of energy deposition
- scintillation light has two components with different decay times whose intensity ratio depends on density of energy deposition *Argon has particularly powerful separation here (PSD)*
- Argon allows one to exploit both ionization/light ratio and scintillation time structure for maximum discrimination.

2-phase schematic









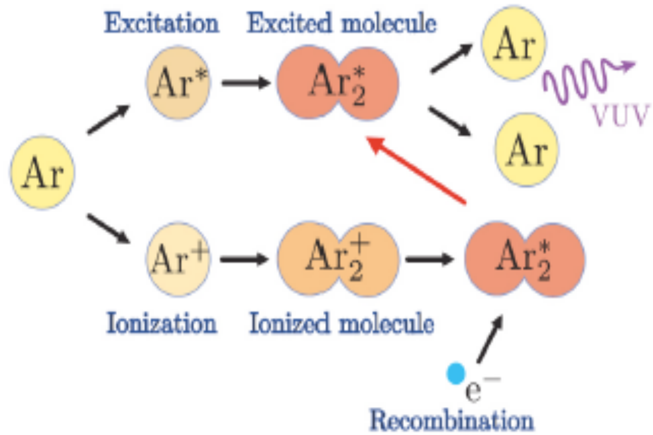
S2/S1 rejection~10^2

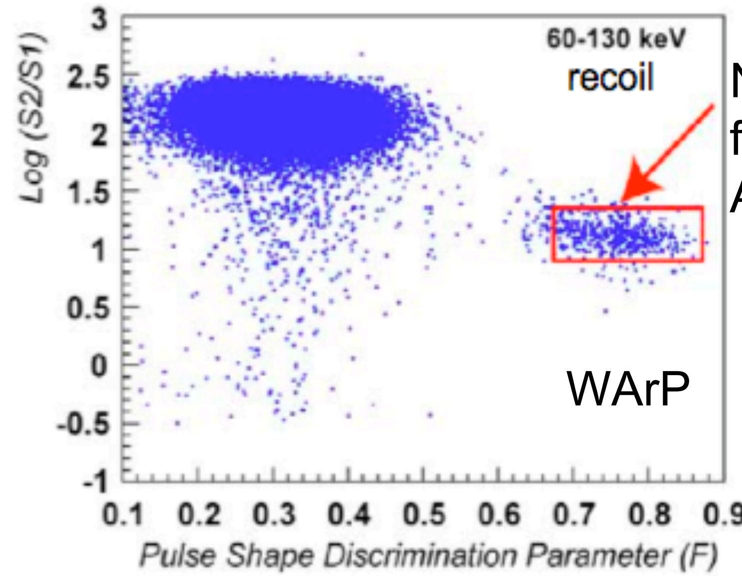
S1 PSD rejection ~10^{5-7}

$\otimes$ 10^{7-9}

Argon Light and Charge and Stuff

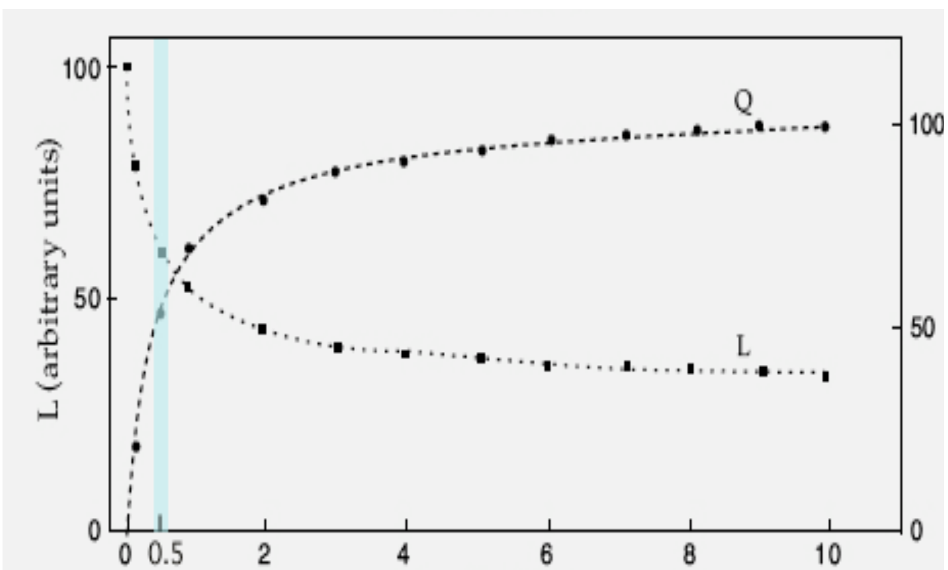
mechanism of light production



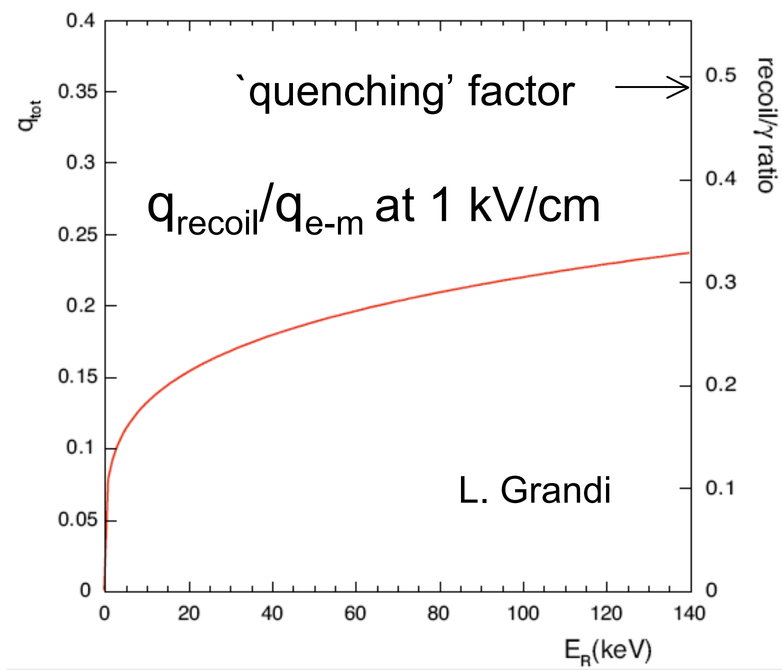


Neutrons from Am-Be

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



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



From the MAX collaboration S4 proposal

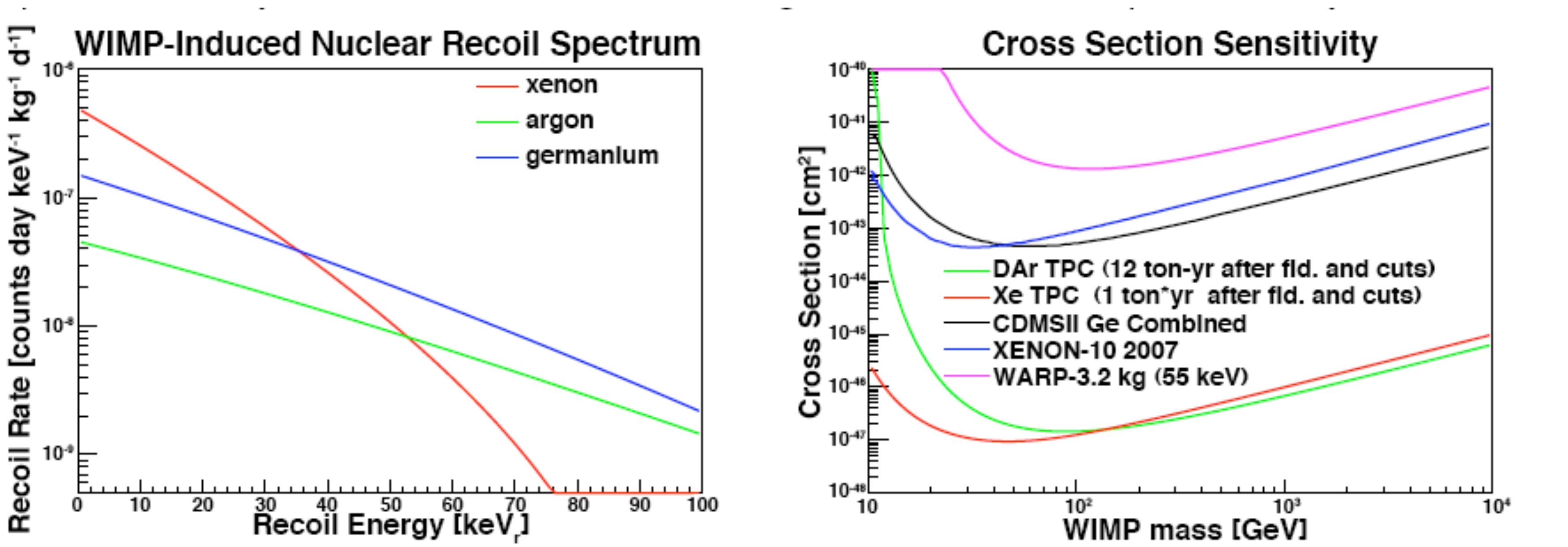


FIG. 1: **(a)** Nuclear recoil spectrum for Ar and Xe targets (M_χ=100 GeV and $\sigma_{\chi N}=10^{-47}$ cm^2). **(b)** Physics reach of the 5.0 ton DAr TPC (5-yr run, 12 ton·yr exposure after fiducial and analysis cuts) and of the 2.4 ton Xe TPC (2-yr run, 1 ton·yr exposure after fiducial and analysis cuts) presented in this proposal, compared with the limits achieved by CDMS, XENON, WARP, and ZEPLIN [4, 5, 18, 19, 25].

Argon and Xenon components of MAX detectors - Argon mass set by DUSEL access

What the technical Issues for Multi-ton Argon detector:

Chemical purity of Argon to allow electron drift (10's ppt O_2)

Chemical purity of Argon to allow light propagation(<ppm N_2)

HV feedthroughs (>100 kV) in Argon gas

TPC design

Data Acquisition

Cryogenics (and associated safety issues)

Detector Materials Qualification

Shielding from environment radiation

Radio-purity of detector material

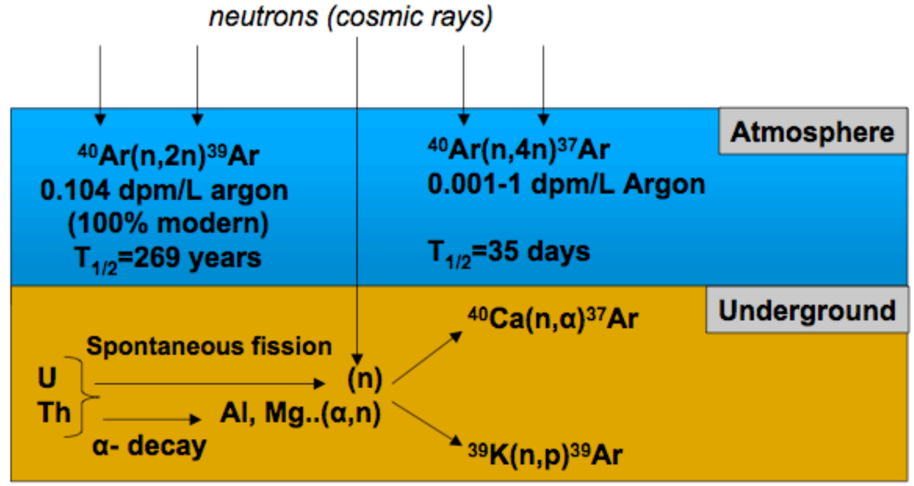
What:

Critical Technical Issues:

^{39}Ar in atmospheric Argon (1 Bq/kg) - this is a potential show-stopper: β with 565 keV endpoint, limits useful scale to ~0.5 ton

(1 ton gives 3 x 10^{10} decays/yr)

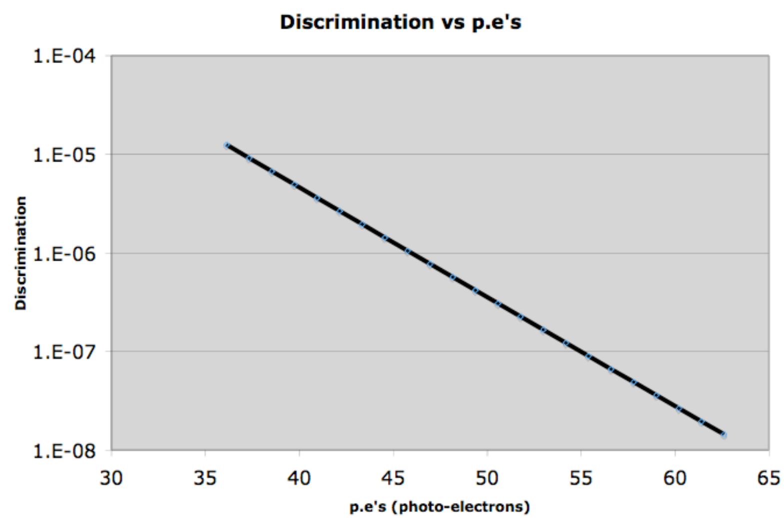
->underground sources



Light detection efficiency

Photo-electrons/keV feeds into threshold (discrimination power) and thus sensitive cross section.

-> investigate photo-detectors & optics



Why and What at Fermilab:

Interest among scientific staff

Appropriate technical expertise - in cryogenics, electronics

Synergies with Neutrino Program (prompted idea)

Why and What: Fermilab

Technical Issues for Multi-ton Argon detector:

Chemical purity of Argon to allow electron drift (10's ppt O2 equivalent),

Chemical purity of Argon to allow light propagation

HV feedthroughs (>100 kV) in Argon gas

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Radio-purity of detector materials

Why and What Fermilab

Technical Issues for Multi-ton Argon detector:

Chemical purity of Argon to allow electron drift (10's ppt O2 equivalent), ***(neutrino and DM)***

Chemical purity of Argon to allow light propagation (*DM*)

HV feedthroughs (>100 kV) in Argon gas ***(neutrino and DM)***

TPC design ***(neutrino and DM)***

Data Acquisition ***(neutrino and DM)***

Cryogenics (and associated safety issues) ***(neutrino and DM)***

Detector Materials Qualification***(neutrino and DM)***

Shielding from environment radiation *(DM)*

Radio-purity of detector materials *(DM)*

Learning how to do what has been done by others

(cryogenics, purification, purity monitoring, electronics readout (MSU) - all are now designed and built in the US)

New stuff - our own filter systems, material test systems, the effect of H_20, coating fibers with TPB (MIT)

FERMILAB-TM-2384-E: efficiency of slow purging to remove atmosphere to ppm levels

A regenerable filter for liquid argon purification

A. Curioni [b], B.T. Fleming [b], W. Jaskierny [a], C. Kendziora [a], J. Krider [a], S. Pordes [a], M. Soderberg [b], J. Spitz [b,*], T. Tope [a], T. Wongjirad [b]

[a] Particle Physics Division, Fermi National Accelerator Laboratory, Chicago, IL, USA
[b] Department of Physics, Yale University, New Haven, CT, USA

NIM-A

A system to test the effect of materials on electron drift lifetime in liquid argon and the effect of water

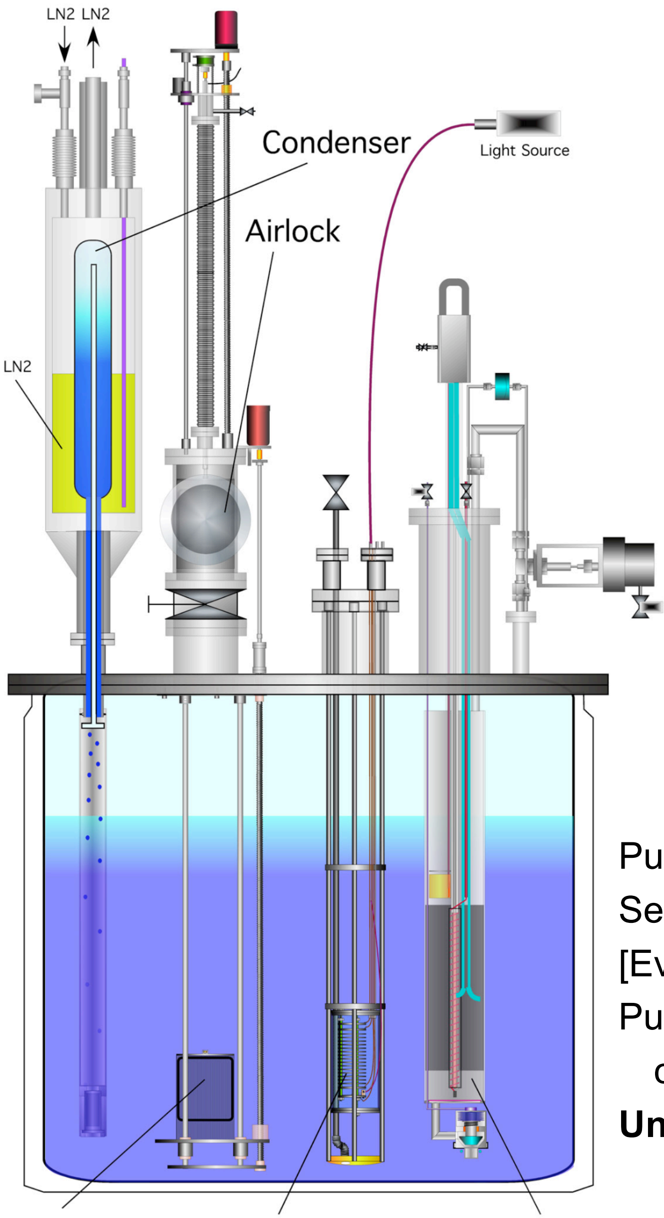
NIM-A

R. Andrews, W. Jaskierny, H. Jöstlein, C. Kendziora, S. Pordes *, T. Tope

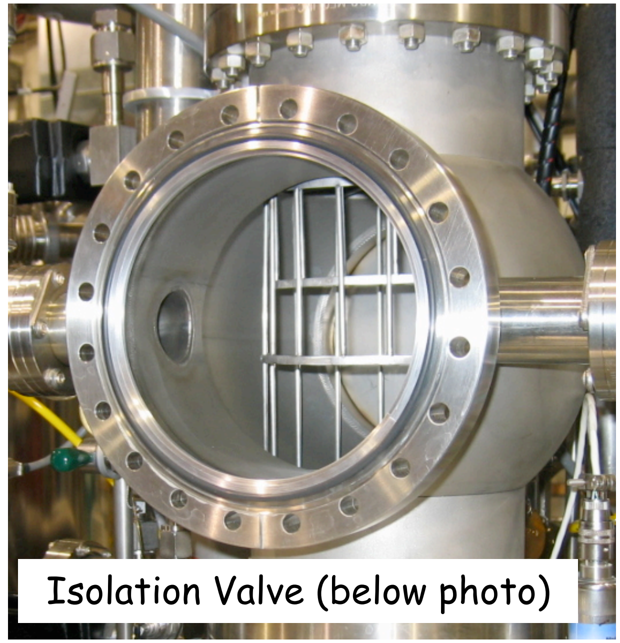
Particle Physics Division, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Liquid Argon Setup for Materials Testing and TPC Readout

Materials Test System

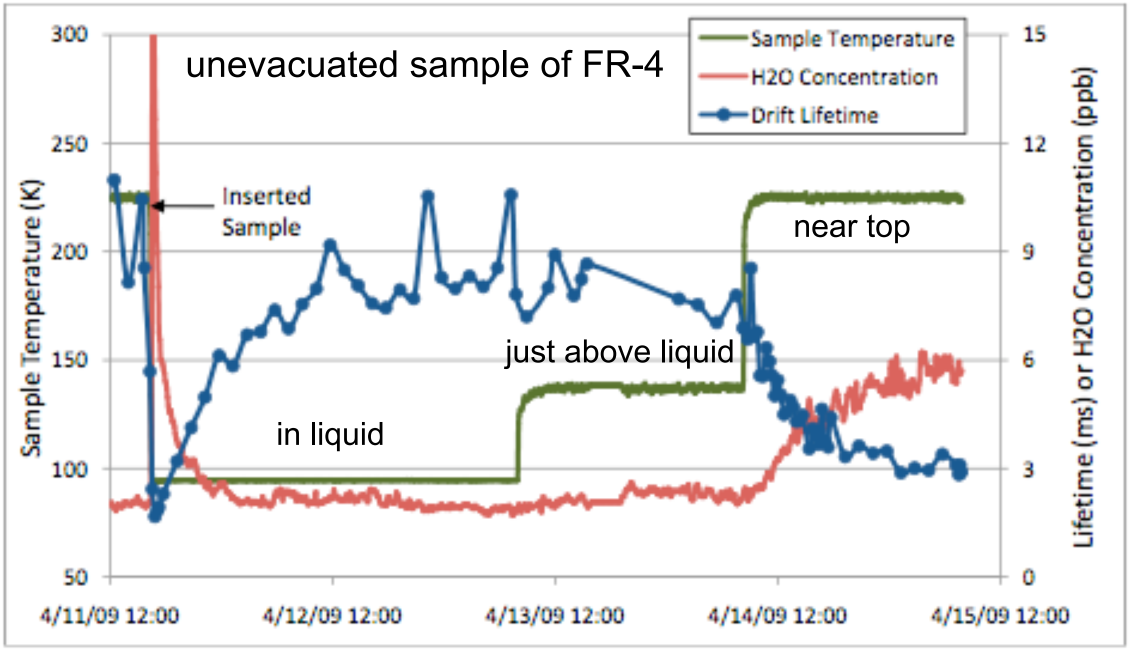


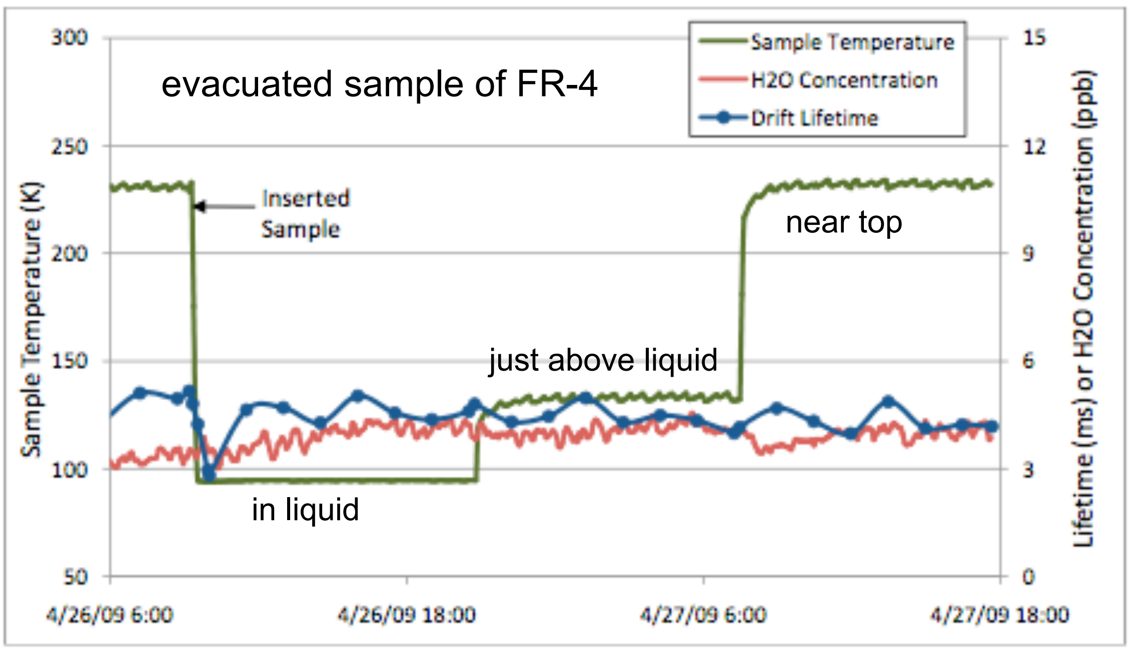
insertion of materials
without exposure to vacuum

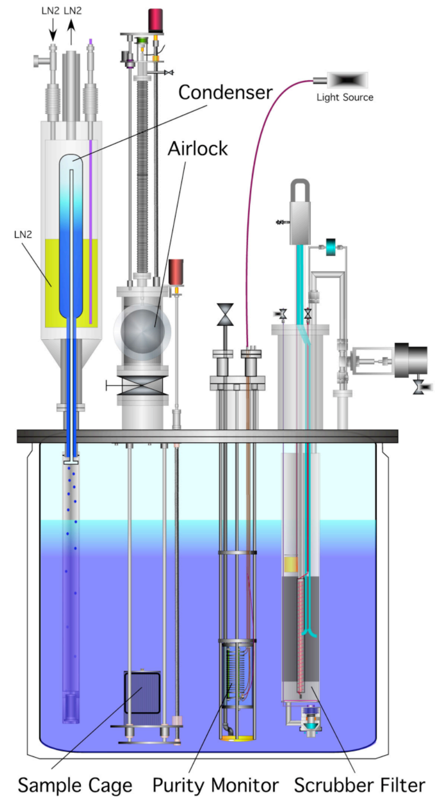


Put materials in Sample Cage in the Argon Lock
Seal the Argon Lock (open in photograph).
[Evacuate the Argon Lock (or not).]
Purge with pure argon gas (available from the cryostat).
Unique system

Data from Materials Test System







Showing effect of water concentration on drift-lifetime - we see the same effect with all materials we have tested. H20 is perfect marker.

What for Dark Matter (only) at Fermilab:

Context:
DArCSIDE Collaboration*

- characterization of depleted Argon
- preparation of 20 kg detector
  -->*treat the Most Urgent Issues (^{39}Ar, light collection)*
- preparation for next step towards MAX

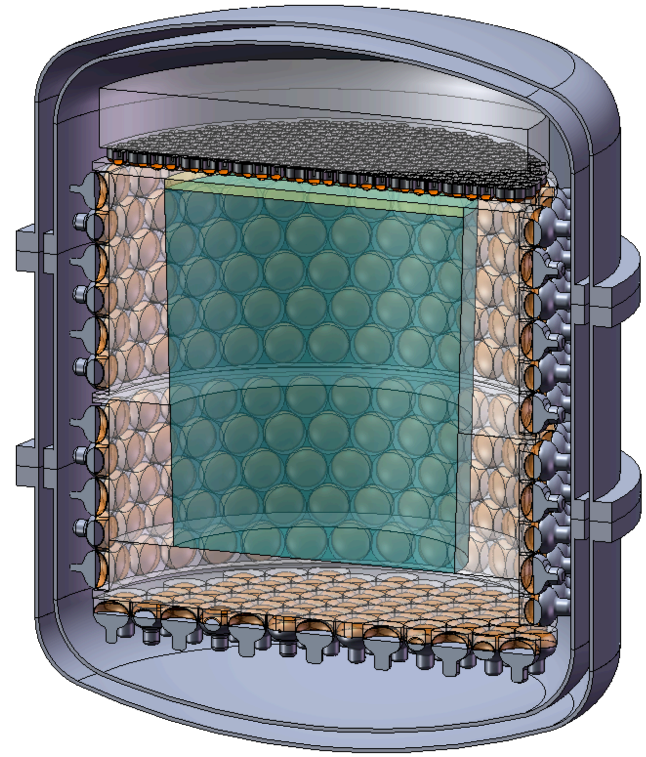
Galbiati spending sabbatical year at Fermilab

Participation in S4 proposal, MAX, 5 ton Argon, 2 ton Xenon

* **D**epleted **Ar**gon **C**ryogenic **S**cintillation & **I**onization **De**tector

What: MAX collaboration S4 Proposal for engineering of a 5 ton Argon and 2 ton Xenon detector at DUSEL

Fermilab staff in important positions in electronics, cryogenics, and purification for the LAr detector

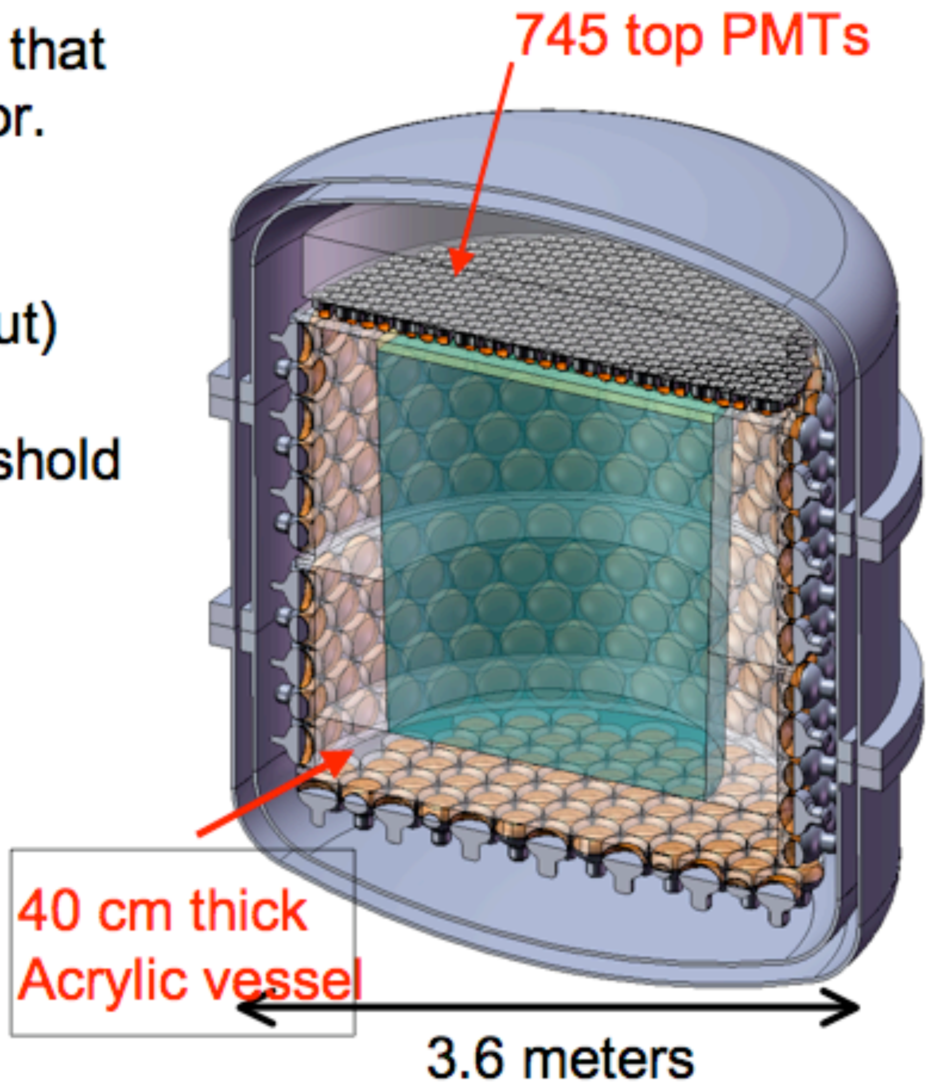


Fermilab Directorate provided letter of support.
NSF will fund

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



Element	Work package	Definition	Responsible	Class
	Noble Liquids TPCs	Project Manager	Parsells (PRI)	C
1.	Dark Matter Detectors		Parsells (PRI)	C
1.0.1	DAr TPC	Detector Manager	Sands (PRI-TEM)	C
1.0.2	Xe TPC	Detector Manager	Tajiri (COL)	C
1.1	TPCs	Level 2 Manager	Martoff (TEM)	C
1.1.1.1	Xe Electrodes	Cathode, field cage, & grids mechanics	Shagin (RIC)	XE
1.1.1.2	Ar Electrodes	Cathode, field cage, & grids mechanics	Martoff (TEM)	AR
1.1.2.1	Xe Electrostatics	Spec. & simulation of electrostatic fields	Wang (UCLA)	XE
1.1.2.2	Ar Electrostatics	Spec. & simulation of electrostatic fields	Alarcon (ASU)	AR
1.1.3.1	Xe HV interconnects	Internal connections to electrodes	Tajiri (COL)	XE
1.1.3.2	Ar HV interconnects	Internal connections to electrodes	Martoff (TEM)	AR
1.1.4.1	Xe gas & liquid interconnects	Interfaces to fill & purification system	Giboni (COL)	XE
1.1.4.2	Ar gas & liquid interconnects	Interfaces to fill & purification system	Sonnenschein (FNAL)	AR
1.1.5	Liquid level	Fill level measurement & control	Shagin (RIC)	C
1.1.6	TPC gas pressure	Gas pressure measurement & control	Sands (PRI-TEM)	C
1.1.7	Fluids	Interface to storage, fill, & empty systems	Tajiri (COL)	C
1.1.7.1	Xe specific fluids	Interface to storage, fill, & empty systems	Giboni (COL)	XE
1.1.7.2	Ar specific fluids	Interfaces to storage, fill, & empty systems	Pordes (FNAL)	AR
1.1.8	Calibration	Light & charge sources for calibration data	Monroe (MIT)	C
1.1.8.1	Xe Specific Calibration	Light & charge sources for calibration data	Oberlack (RIC)	XE
1.1.8.2	Ar Specific Calibration	Light & charge sources for calibration data	Monroe (MIT)	AR
1.1.9.1	TPC materials	Radioactivity budgets	Pocar (UMA)	C
1.1.9 .2	TPC materials	Radon plate-out	Monroe (MIT)	C
1.1.9 .3	TPC materials	Radon emanation	Pocar (UMA)	C
1.1.10.1	Xe TPC integration	Mechanical & electrical systems integration	Tajiri (COL)	XE
1.1.10.2	Ar TPC integration	Mechanical & electrical systems integration	Sands (PRI-TEM)	AR
1.2.	Inner Vessels (IV)	Level 2 Manager	Meyers (PRI)	C
1.2.1.1	Ar liner mechanical	Specifications & method of construction	Martoff (TEM)	AR
1.2.1.2	Ar WaveLength Shifter (WLS)	TPB films & their application	Galbiati (PRI)	AR
1.2.1.3	Ar liner interfaces	Interface to TPC electrodes & acrylic CV	Sands (PRI-TEM)	AR
1.2.1.4	Xe liner	Reflector, windows	Aprile (COL)	XE
1.2.2.1	Xe containment vessel	Vessel structure & manufacture	Tajiri (COL)	XE
1.2.2.2	Ar containment vessel	Acrylic vessel structure & manufacture	Sands (PRI-TEM)	AR
1.2.2.3	Mechanical seals	Top & bottom plate seals	Sonnenschein (FNAL)	C
1.2.2.4	HV & HHV seals	HV & HHV feedthrough flange seals	Wang (UCLA)	C
1.2.2.5	Vessels materials	Radioactivity budget	Pocar (UMA)	C
1.3	Photodetector	Level 2 Manager	Arisaka (UCLA)	C
1.3.1	QUPIDs radioactivity budget	Characterization of components	Oberlack (RIC)	C
1.3.2	8" PMTs radioactivity budget	Characterization of components	Pocar (UMA)	AR
1.3.3.1	Procurement	Procurement	Arisaka (UCLA)	C
1.3.3.2	Test	Test & characterization	Arisaka (UCLA)	C
1.3.3.3	Database	Database with photosensors characteristics	Arisaka (UCLA)	C
1.3.4	Photocathodes	Optimization of quantum efficiency	Suyama (Hamamatsu)	C
1.3.5.1	QUPIDs support	Mechanical support structure	Wang (UCLA)	C
1.3.5.2	8" PMTs support	Mechanical support structure	Martoff (TEM)	AR
1.3.6.1	QUPIDs signals	Thermal management of cable	Wang (UCLA)	C
1.3.6.2	PMTs signals	Cabling & thermal management	Sonnenschein (FNAL)	AR
1.4	Cryogenic Systems (CS)	Level 2 Manager	Wang (UCLA)	
1.4.1	Cooling Elements	Specifications & design	Haruyama (KEK)	C

MAX

responsibilities

More MAX responsibilities

1.4.2.1	LXe fill	Fill, empty, & purification of LXe	Giboni (COL)	**XE**
1.4.2.2	Inner LAr fill	Fill, empty, & purification of inner LAr	Pordes (FNAL)	**AR**
1.4.2.3	Outer LAr fill	Fill, empty, & purification of outer LAr	Pordes (FNAL)	**AR**
1.4.3.1	Ar dewar	SS double-walled cryostat	Sonnenschein (FNAL)	**AR**
1.4.3.2	Xe dewar	OFHC double-walled cryostat	Tajiri (COL)	**XE**
1.4.5.1	Ar top plate	HV, signal, fluid feedthroughs	Sonnenschein (FNAL)	**AR**
1.4.5.2	Xe top plate	HV, signal, fluid feedthroughs	Giboni (COL)	**XE**
1.4.6	Dewar mechanical	Support & leveling	Sonnenschein (FNAL)	**C**
1.4.7	Cooling	Steady-state & emergency cooling systems	Sonnenschein (FNAL)	**C**
1.4.8.1	Fluids	Common fill, empty, storage systems	Sonnenschein (FNAL)	**C**
1.4.8.2	Ar fluids	Ar fill, empty, storage systems	Sonnenschein (FNAL)	**AR**
1.4.8.3	Xe fluids	Xe fill, empty, storage systems	Lopes (COI)	**XE**
1.4.9	CS mechanics	Mechanical interfaces of all vessels	Sonnenschein (FNAL)	**C**
1.4.10	CS materials	Radioactivity budget & ^{222}Rn emanation	Pocar (UMA)	**C**
1.4.11	Recovery systems	Zero-boiloff gas/liquid recovery	Wang (UCLA)	**C**
1.5	**Pre-Purification (PP)**	**Level 2 Manager**	**Galbiati (PRI)**	**C**
1.5.1	Depleted argon collection	Engineering of collection system	Fitch (Linde)	**AR**
1.5.2	Cryogenic distillation of Ar & Xe	Engineering of cryogenic distillation column	Fitch (Linde)	**C**
1.6	**Runtime Purification (RP)**	**Level 2 Manager**	**Pordes (FNAL)**	**C**
1.6.1.1	Filters	Selection of filters & getters	Weinheimer (MUN)	**C**
1.6.1.2	Ar specific filters	Selection of Ar specific filters & getters	Galbiati (PRI)	**AR**
1.6.1.3	Filters	Selection of filters & getters	Weinheimer (MUN)	**XE**
1.6.2.1	Ar RP scheme	Fluid handling & control	Pordes (FNAL)	**AR**
1.6.2.2	Xe RP scheme	Fluid handling & control	Aprile (COL)	**XE**
1.6.3 .1	RP materials	Radioactivity budget & ^{222}Rn emanation	Weinheimer (MUN)	**C**
1.6.3.2	RP materials	Radioactivity budget & ^{222}Rn emanation	Pocar (UMA)	**C**
1.6.4.1	CRDS Enginering	Ultra-trace measurement of N_2, O_2, & H_2O	Lehmann (UVA)	**C**
1.6.4.2	CRDS Operations	Procedures & protocols	Zehfus (BHSU)	**C**
1.7	**Electronics**	**Level 2 Manager**	**Chou (FNAL)**	**C**
1.7.1	Voltage amplifiers	QUPIDS & PMTs	Arisaka (UCLA)	**C**
1.7.2	Digitizer layout	Specifications & design	Arisaka (UCLA)	**C**
1.7.3	Digitizer FPGA firmware	Specifications & code development	Hungerford (HOU)	**C**
1.7.4	2nd level DAr trigger board	Specifications & design	Hungerford (HOU)	**C**
1.7.5	HV supply	QUPIDS & PMTs	Pordes (FNAL)	**C**
1.7.6	Cables	QUPIDS & PMTs	Sonnenschein (FNAL)	**C**
1.7.7	Slow Controls	Monitoring of electronics & environment	Hungerford (HOU)	**C**
1.7.8	GPS Clock	Specifications & design	Hungerford (HOU)	**C**
1.7.9	Crates & racks	Specifications	Pordes (FNAL)	**C**
1.8	**DAQ**	**Level 2 Manager**	**Hungerford (HOU)**	**C**
1.8.1	Communications Links	Specifications & protocols	Hungerford (HOU)	**C**
1.8.2	Computers	Specifications	Alton (AUG)	**C**
1.8.3	On-Line Software	Specifications	Hungerford (HOU)	**C**
1.8.4	Off-Line software	Specifications	Oberlack (RIC)	**C**
1.8.5	Data Recording	Specifications & protocols	Alton (AUG)	**C**
2.	**Simulations**	**Level 2 Manager**	**Monroe (MIT)**	**C**
2.1	Common simulations	FLUKA & GEANT4 infrastructure	Hungerford (HOU)	**C**
2.1.1	Ar specific simulations	Complete simulations for Ar TPC	Monroe (MIT)	**AR**
2.1.2	Xe specific simulations	Complete simulations for Xe TPC	Baudis (ZUR)	**XE**
3.	**Shielding & Rn-free cleanroom**	Design, Coord. with Water Shield S4 Prop.	**Parsells (PRI)**	**C**
3.1	Shield design	Water-based external shield & muon veto	Parsells (PRI)	**C**
3.2	Shield interfaces	Interfaces to water shields S4 activity	Parsells (PRI)	**C**
3.3	Rn-free cleanroom	Specifications & design	Parsells (PRI)	**C**
4.	**DUSEL Interface**	**Level 2 Manager**	**Parsells (PRI)**	**C**
5.	**Radiation Screening**	**Level 2 Manager**	**Pocar (UMA)**	**C**

Depleted Argon:

Present 5% of atmosphere limit set by test volume (at Bern)

Harvesting from CO_2 wells (Princeton)

Aim is characterization to < 1% of atmospheric rate (Fermilab and Princeton)

Fermilab using high pressure (180 bar) ionization chamber of OFHC copper with muon veto and hermetic lead-shielding in NuMI tunnel

Depleted Argon harvesting (Princeton)

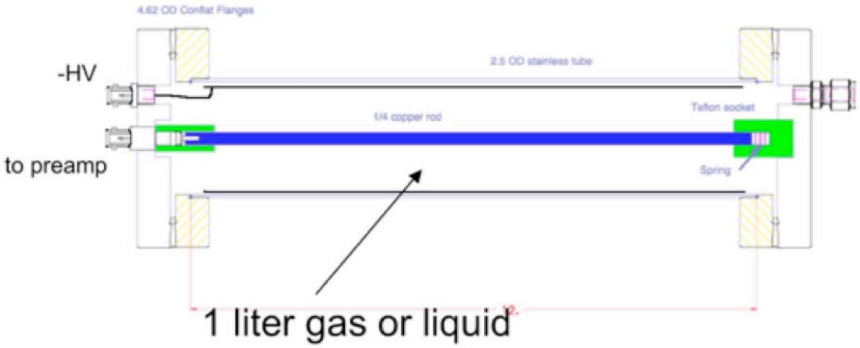
Discovery of underground sources of low-activity argon

← Prototype Purification Plant at Princeton

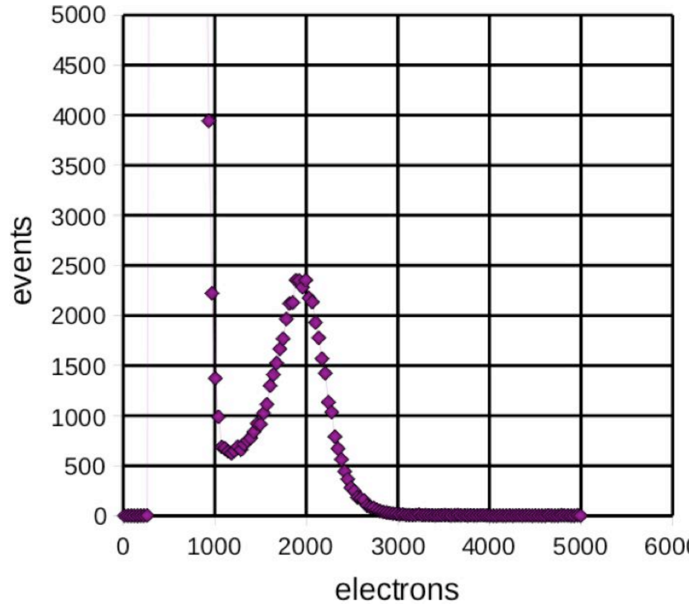
Sampling on a gas field in the West

Funded by NSF

Prototype Ionization Chamber Work (8.5 bar)



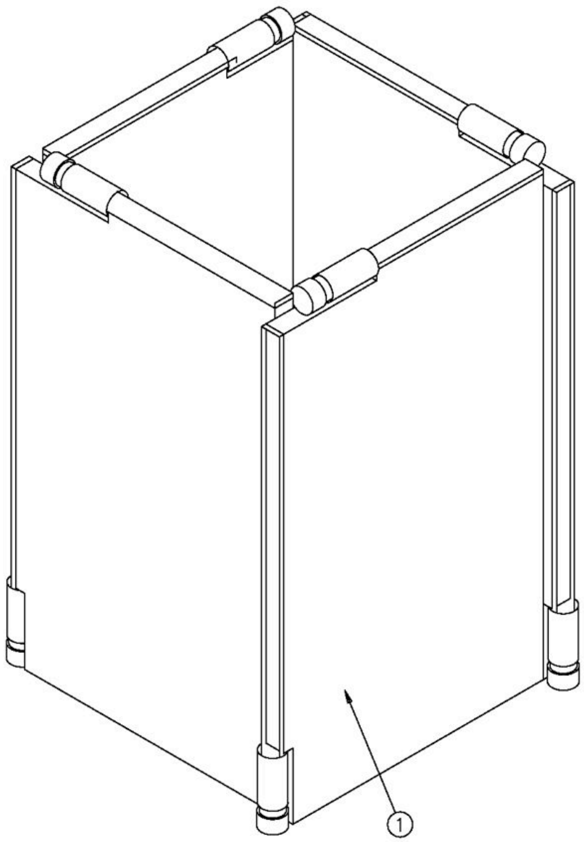
60 keV X-rays (241-Am)
in 8.5 Bar Argon



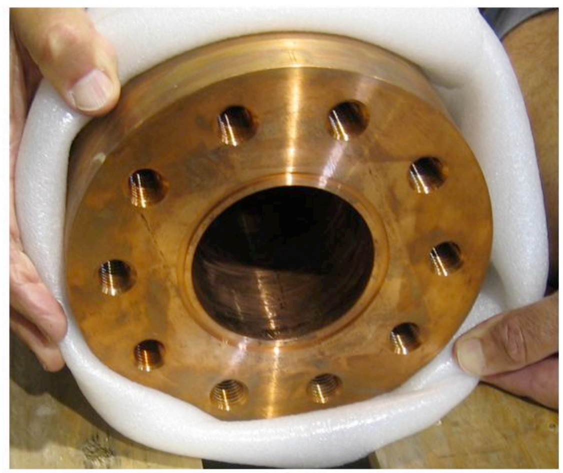
220 electrons rms noise

^{39}Ar spectrum flat to 560 keV
560 keV ~ 20,000 electrons

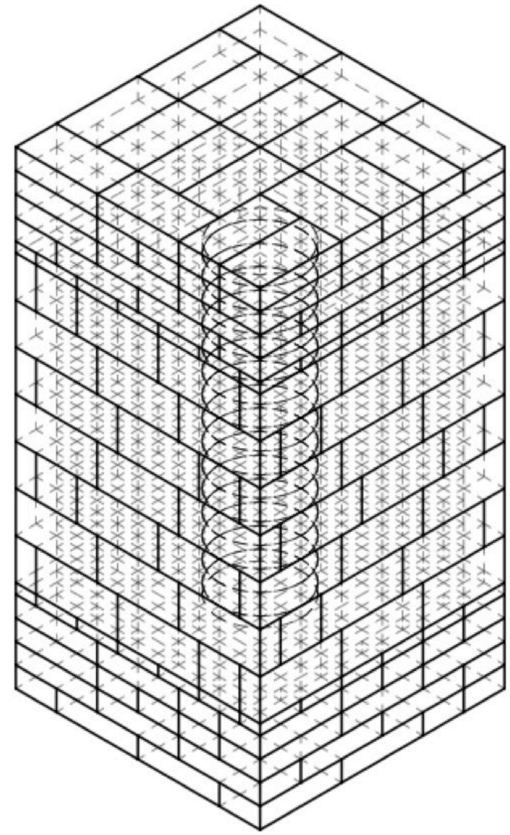
Muon Veto Drawing



Ion Chamber Body



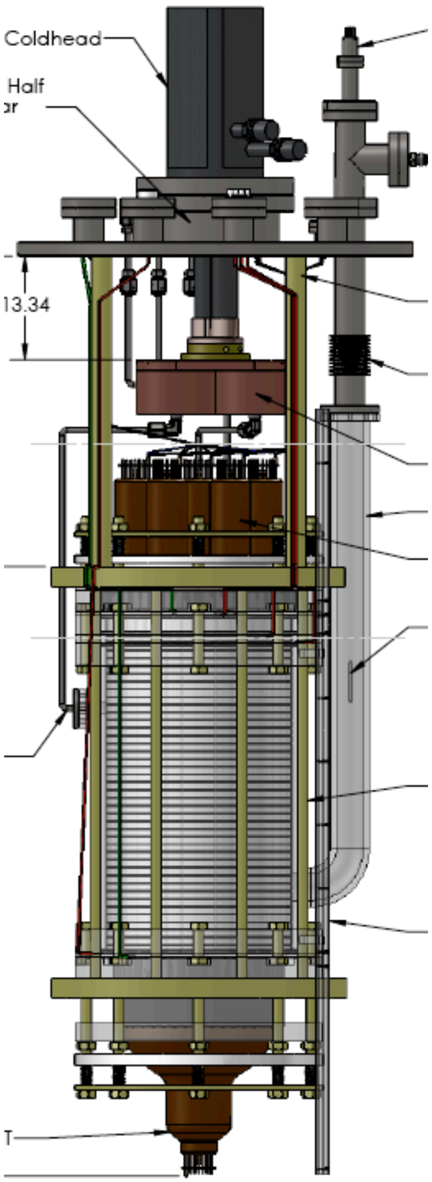
Lead Shield Drawing



Muon veto, lead shield, and low-radioactivity copper, and running in NuMI tunnel needed to achieve < 0.01 Bq/kg

more **What:**

20 kg device at Princeton -
inner TPC with depleted Argon
surrounded by normal Argon

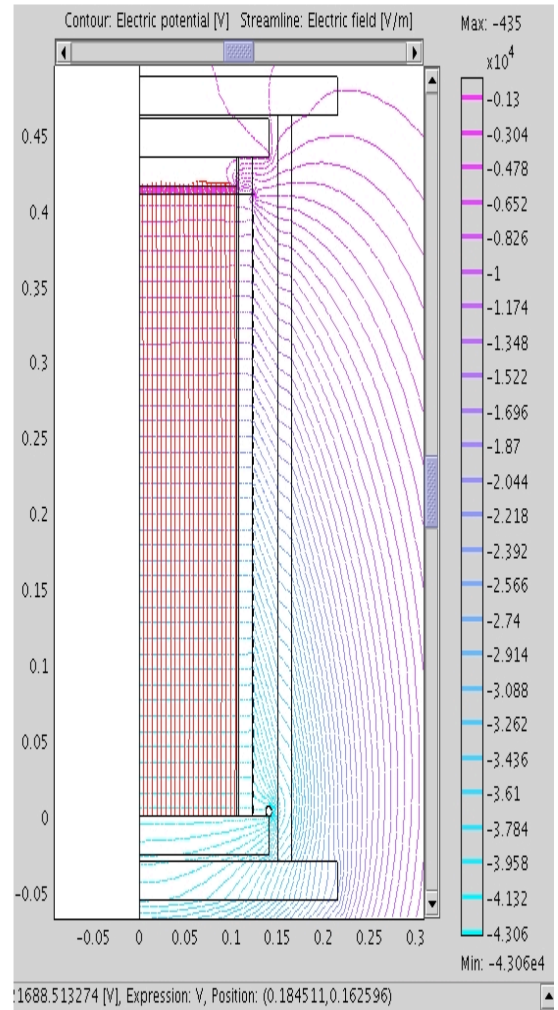


20 kg Innards

R & D on:
light-collection,
TPC design,
PMTs (new from Hamamatsu),
bases,
electronics readout,
depleted Argon

Fermilab supplying:
PMT bases,
HV feedthroughs,
TPC electrostatics design

TPC Drift-field Lines



(C.J. Martoff (guest))

Next two years:

Build, run, study 20 kg device

Characterize depleted Argon

Develop data acquisition (with CD - triggerless DA)

R & D on light collection (wave-shifter, coatings, optics)

High-level responsibilities for Electronics, Cryogenics and Purification in S4 proposal

Develop and present proposal for intermediate (~500 kg) device as prototype for MAX
(full Argon mechanical system - partial coverage with PMTs(?))

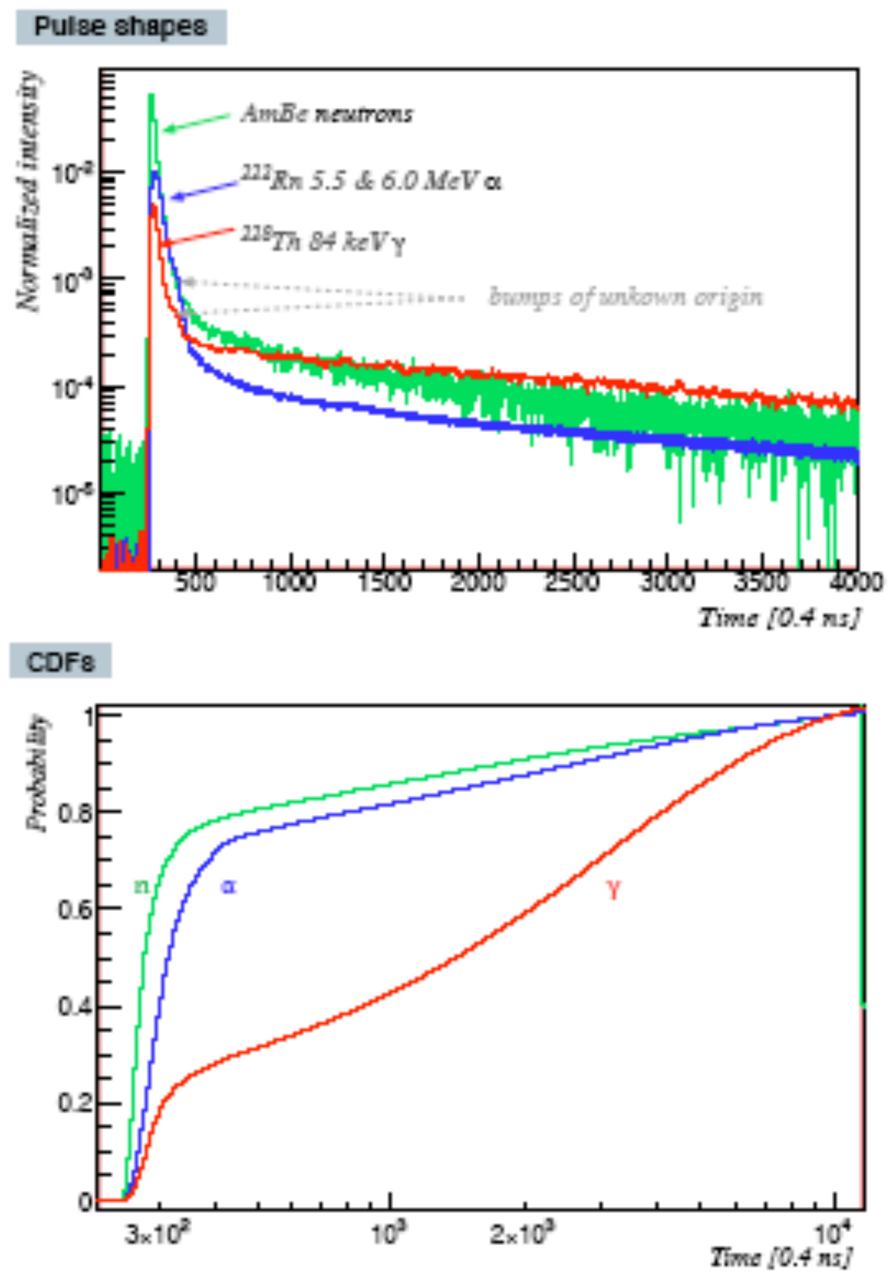
Back-ups

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



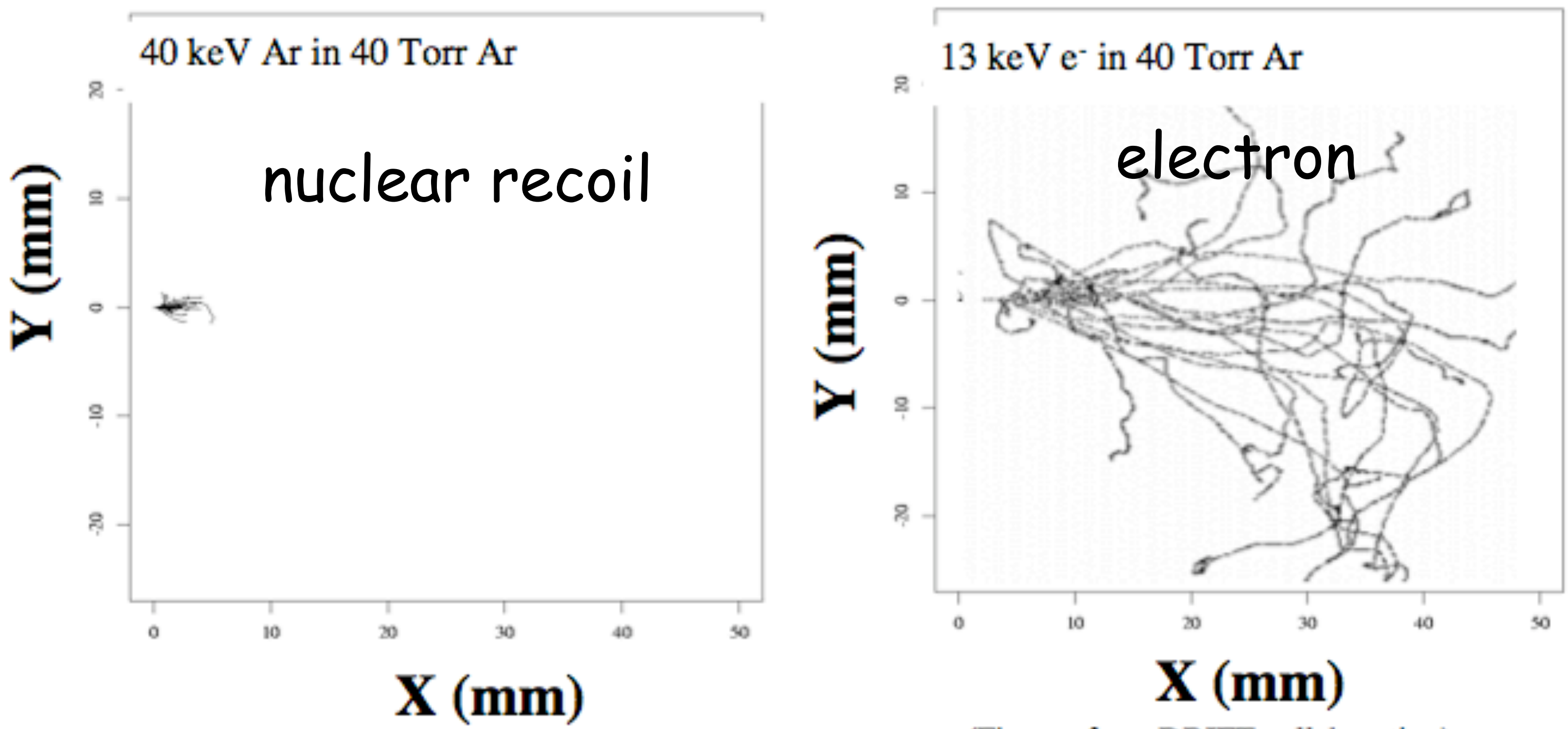
from T. Pollman

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)

Connections between different devices