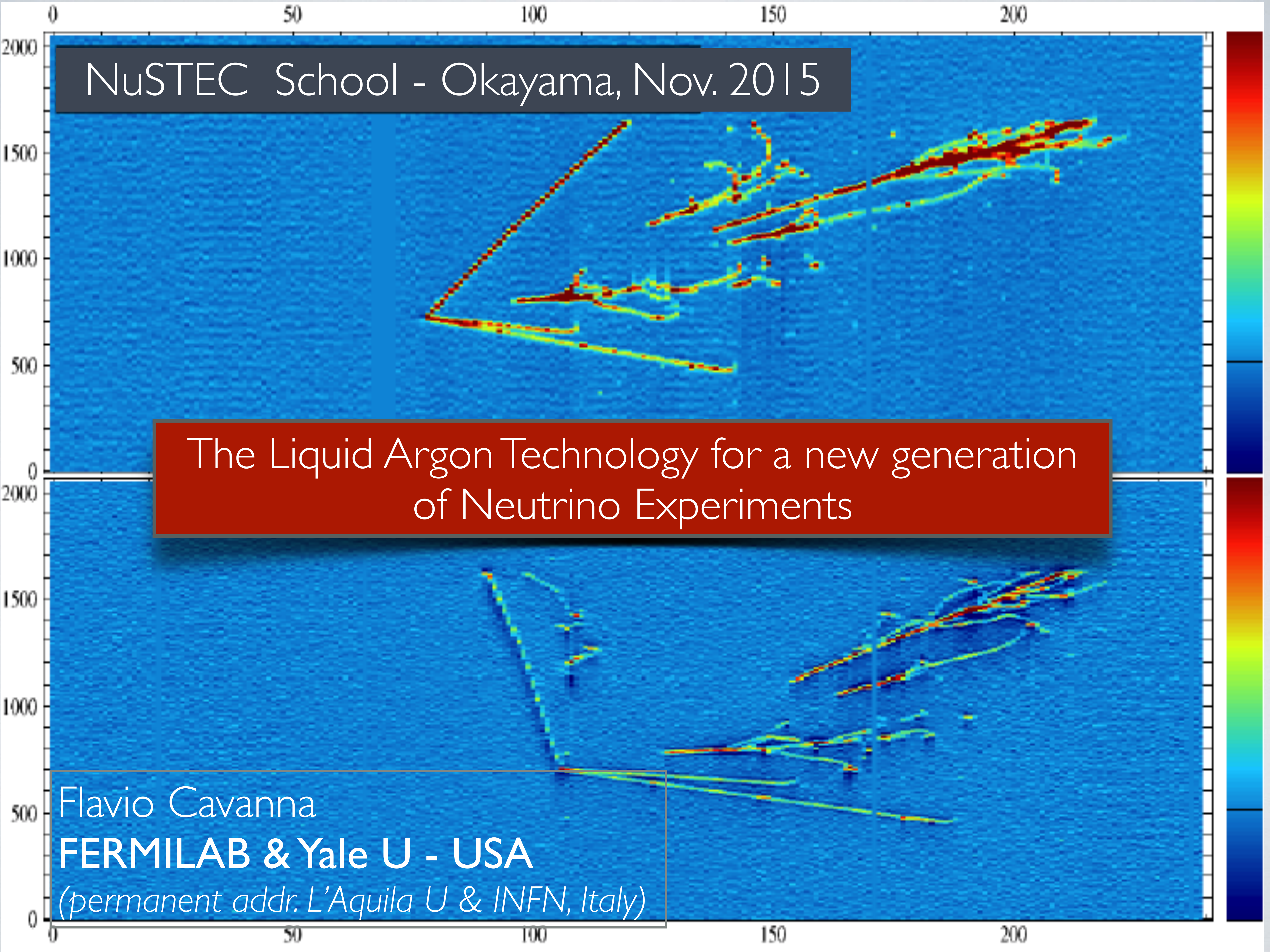

NuSTEC School - Okayama, Nov. 2015

The Liquid Argon Technology for a new generation of Neutrino Experiments

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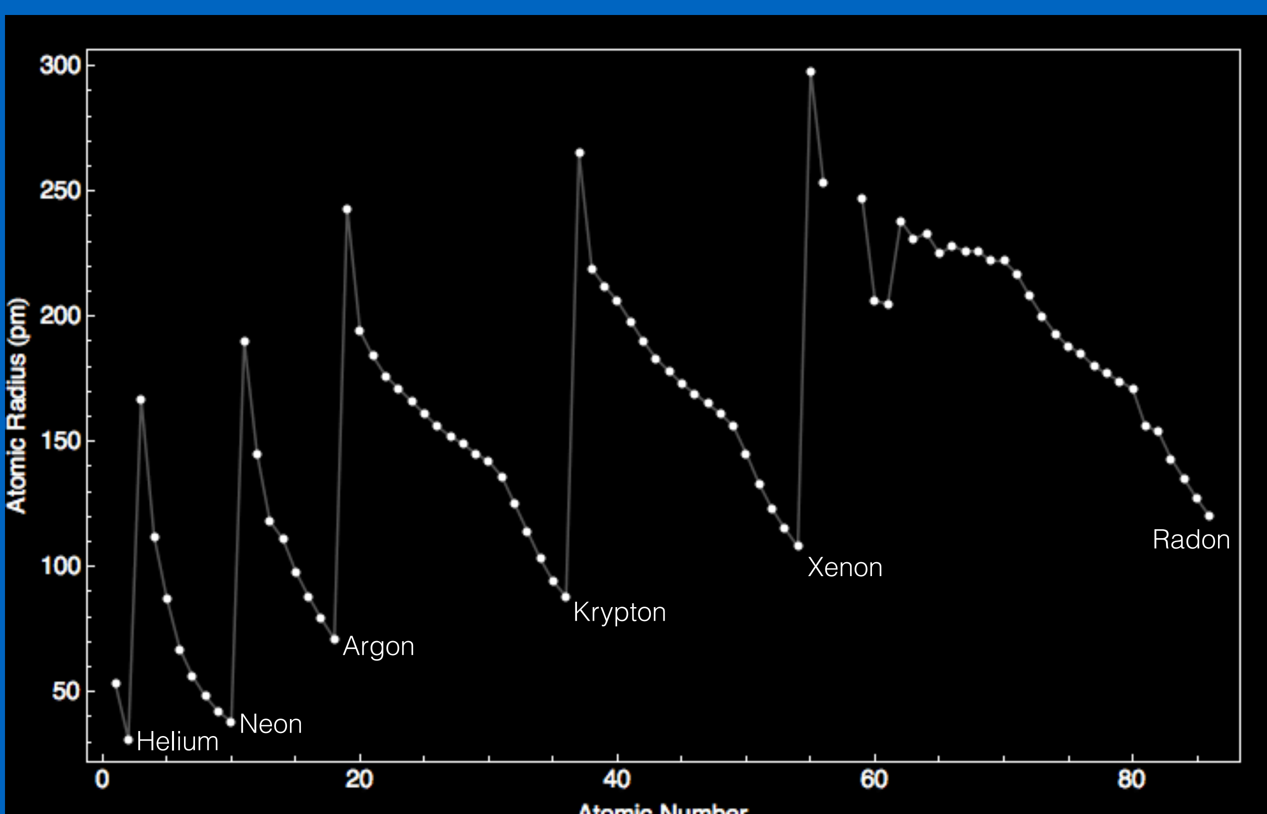
THE LIQUID ARGON DETECTOR(S)

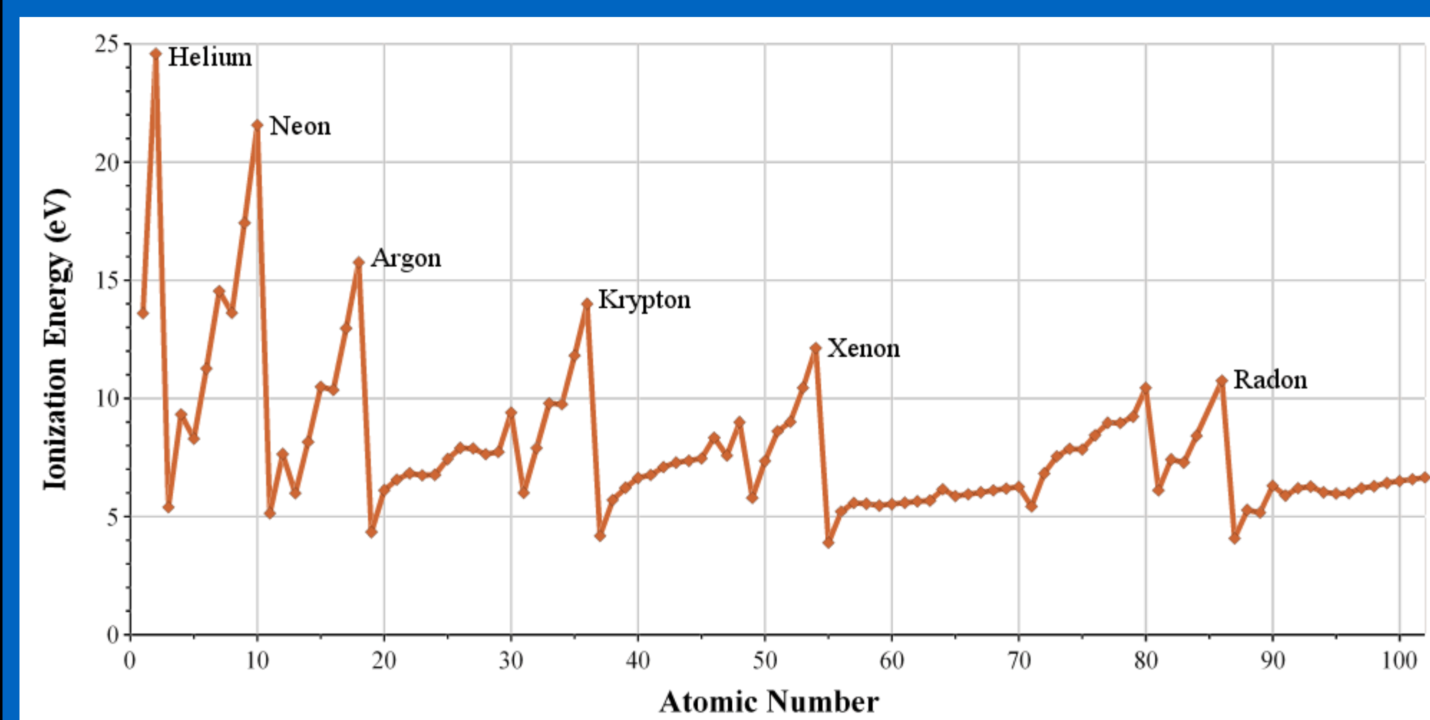
- Argon: the active medium
  - Ionization Charge
    - recombination, drift, e-attachment (el.negative impurities)
  - Scintillation Light
    - propagation (Rayleigh scattering), quenching & absorption (impurities)
- The LAr TPC
  - the Neutrino detector ``style”
- LAr TPC at work: Event reconstruction
  - imaging
  - calorimetry
  - Particle Identification
- A visual analysis session:
  - single particle identification
  - neutrino event topology
- The new wave …

- The LAr TPC
  - the Dark Matter detector ``style”

Noble Elements

- The Noble elements are characterized by their inertness, which is a reflection of their completely filled valence shells.
- These are compact atoms that hold on to their electrons tightly.
- Their almost nonexistent electron affinity indicates that free electrons <u>in a highly purified</u> noble liquid environment will be capable of traveling long distances under the influence of an electric-field.

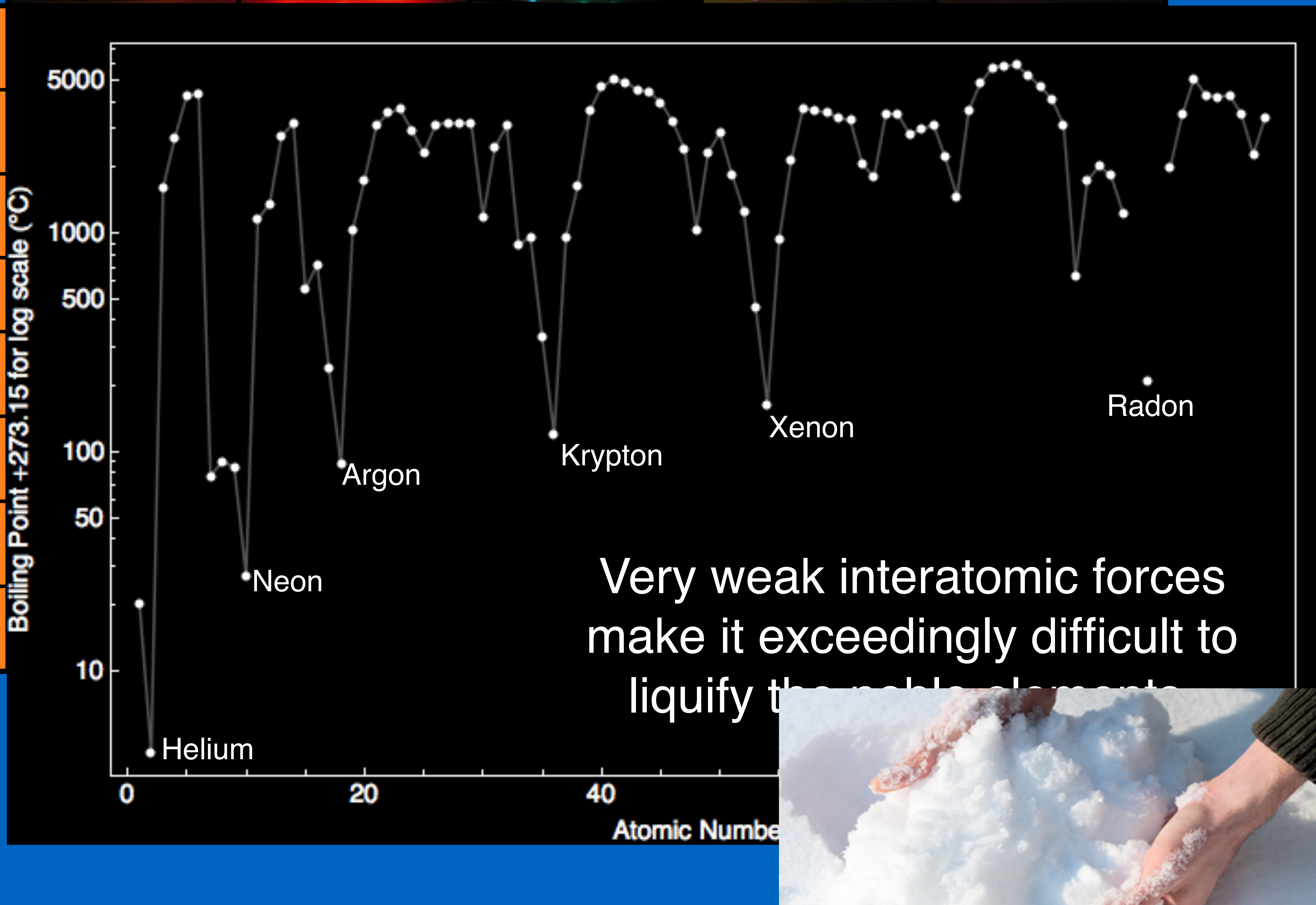




Refs:
1.) image from <u>periodtable.com</u>

Noble Liquids

Atomic Number
Boiling Point [K] @ 1atm
Density [g/cm
Radiation Length [cm]
dE/dx [MeV/cm]
Scintillation [γ/MeV]
Scintillation λ [nm]
Cost ($/kg)



Very weak interatomic forces make it exceedingly difficult to liquify t

Kind of like making a snowball out of very "powdery" snow.

Refs:
1.) images from periodtable.com

Table 1
Liquid Argon chemical and physical properties [1,2], [3–5].

Atomic number, mass	18, 40
Atomic weight	39.948 m_u
$\langle Z/A \rangle$	0.45059
Concentration in air	0.934 %

Most abundant isotope of argon on Earth? Ar40
Ar40 is primarily produced by decay (electron capture) of potassium in Earth's crust.

$$^{40}_{19}K + ^{0}_{-1}e^{-} \rightarrow ^{40}_{18}Ar + \nu_e$$

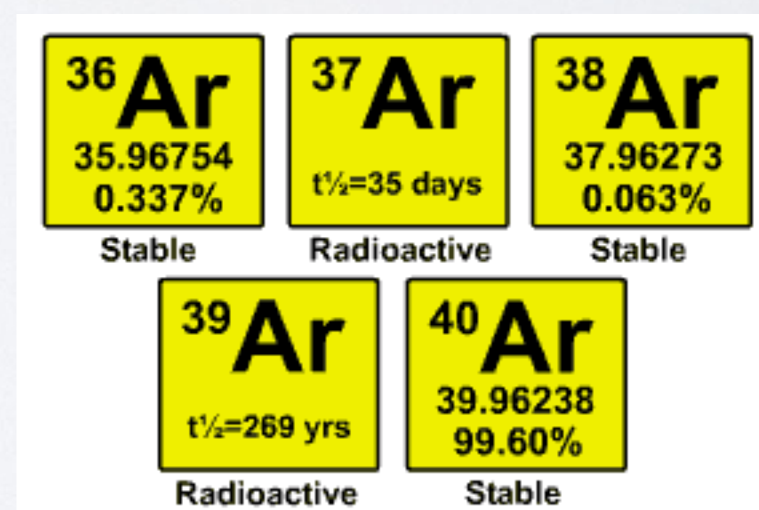


Table 2
Liquid Argon thermal and physical properties [6], [2].

	Pressure	Temperature	Density
Solid phase:		83. K	1.625 g/cm^3
Triple point:	0.689 bar	83.8 K	
Liquid phase:	1.00 bar	87.2 K	1.396 g/cm^3
Boiling point (@ 1 atm =)	1.013 bar	87.3 K	1.395 g/cm^3
	1.15 bar	88.5 K	1.388 g/cm^3
	1.20 bar	88.9 K	1.385 g/cm^3
	1.25 bar	89.3 K	1.383 g/cm^3
Critical point:	48.63 bar	150.7 K	0.553 g/cm^3
Heat capacity [Cp] (boiling point)			0.2670 cal/g K
Thermal conductivity (boiling point)			3.00×10^{-4} cal/s cm K
Latent heat of vaporization (boiling point)			38.4 cal/g
Gas/liquid ratio (1 atm, 15^o/BPT)			835 vol/vol
e^- Mobility (boiling point)			500 cm^2/V s
e^- Drift velocity (500 V/cm - nominal field, 89 K)			1.55 mm/μs
e^- Diffusion coefficient (89 K)			4.8 cm^2/s
e^-– O_2 Trapping rate (500 V/cm, 89 K)			$\sim 7.\times 10^{10}$ l/mol s

Liquid Argon as Active Target for Particle Detectors

Mechanisms of
Ionization Charge release and
Scintillation Light emission

Charged particle traversing a volume of (liquid) Argon loose energy primarily (but not exclusively) via ***Ionization*** (e^-,Ar^+) AND **Scintillation** Light production.

Charge recombination and de-excitation processes quickly follow the passage of the ionizing ptcls.
This changes the amount of both light and charge available for detection.

Solid Argon is characterized by the existence of an electron band structure and it is usually assumed that the same **band structure** also exists **in the liquid state**

*Most of what we know is due to the original work of Japanese groups, led by **Prof. Doke (Waseda U.)** since mid '70.*

Table 4
Liquid Argon Ionization and Scintillation properties [3,4,11],[4,7–9].

Mean energy loss (*mip*)	$\langle dE_{mip}/dx \rangle = 1.519$ MeV cm^2/g
Average energy for (e^-,Ar^+) pair production	$W_{ion} = 23.6$ eV
Free e^- yield [@ > 15 kV/cm]	$Y_{ion} = 4.2\times 10^4\ e^-$/MeV
[@ 500 V/cm] (*mip*)	$Y_{ion} = \sim 2.9\times 10^4\ e^-$/MeV
[@ 0-Field] (*mip*)	$Y_{ion} = \sim 1.1\times 10^4\ e^-$/MeV
Energy gap (Band Structure)	$E_{gap}=14.3$ eV
Average energy per ionizing collision	$E_+=15.4$ eV
Average energy per excited atom	$E_*=12.7$ eV
Average kinetic energy of subionization electron	$\epsilon_{kin}=6.3$ eV
Number of excited atoms to the number of ions Ratio	$N_*/N_+=0.21$
Fano Factor	0.107
Ar_2^* excited dimer states (*M*-band)	*Singlet* $^1\Sigma_u$, *Triplet* $^3\Sigma_u$
Decay γ Energy	$\langle E_{ph} \rangle = 9.7$ eV
Decay γ Spectrum	$\langle \lambda_{ph} \rangle = 127$ nm ; $\sigma_\lambda \simeq 3$ nm
Decay Time constant *(singlet)*	$\tau_S \sim 6$ ns (~ 5 ns [10])
Decay Time constant *(triplet)*	$\tau_T \sim 1.6\ \mu s$ ($\sim 1.3\ \mu s$ [10])
Decay Intensity Ratio (*mip*)	$I_S/I_T = 0.3$ (23%/77%)
Decay Intensity Ratio (α-*ptcl*)	$I_S/I_T = 3$ (75%/25%)
Average energy for γ production	$W_{ph} = 19.5$ eV
Photon yield [@ 0-Field] (ideal)	$Y_{ph} = 5.1\times 10^4\ \gamma$/MeV
[@ 0-Field] (*mip*)	$Y_{ph} =\sim 4.0\times 10^4\ \gamma$/MeV
[@ 500 V/cm] (*mip*)	$Y_{ph} =\sim 2.4\times 10^4\ \gamma$/MeV
[@ > 15 kV/cm] (*mip*)	$Y_{ph} =\sim 1.3\times 10^4\ \gamma$/MeV
Dielectric constant (@128 nm, 89 K)	$\epsilon_{Ar} = 1.5$
Refractive Index (@128 nm, 89 K)	$n_{Ar} = 1.38$
Rayleigh scattering length (@128 nm, 89 K)	$\ell_R = 90$ cm
Attenuation length (ultra-high purity)	∞

IONIZATION

LAr valence band negligibly small and conduction band with E_{gap}=14.3 eV

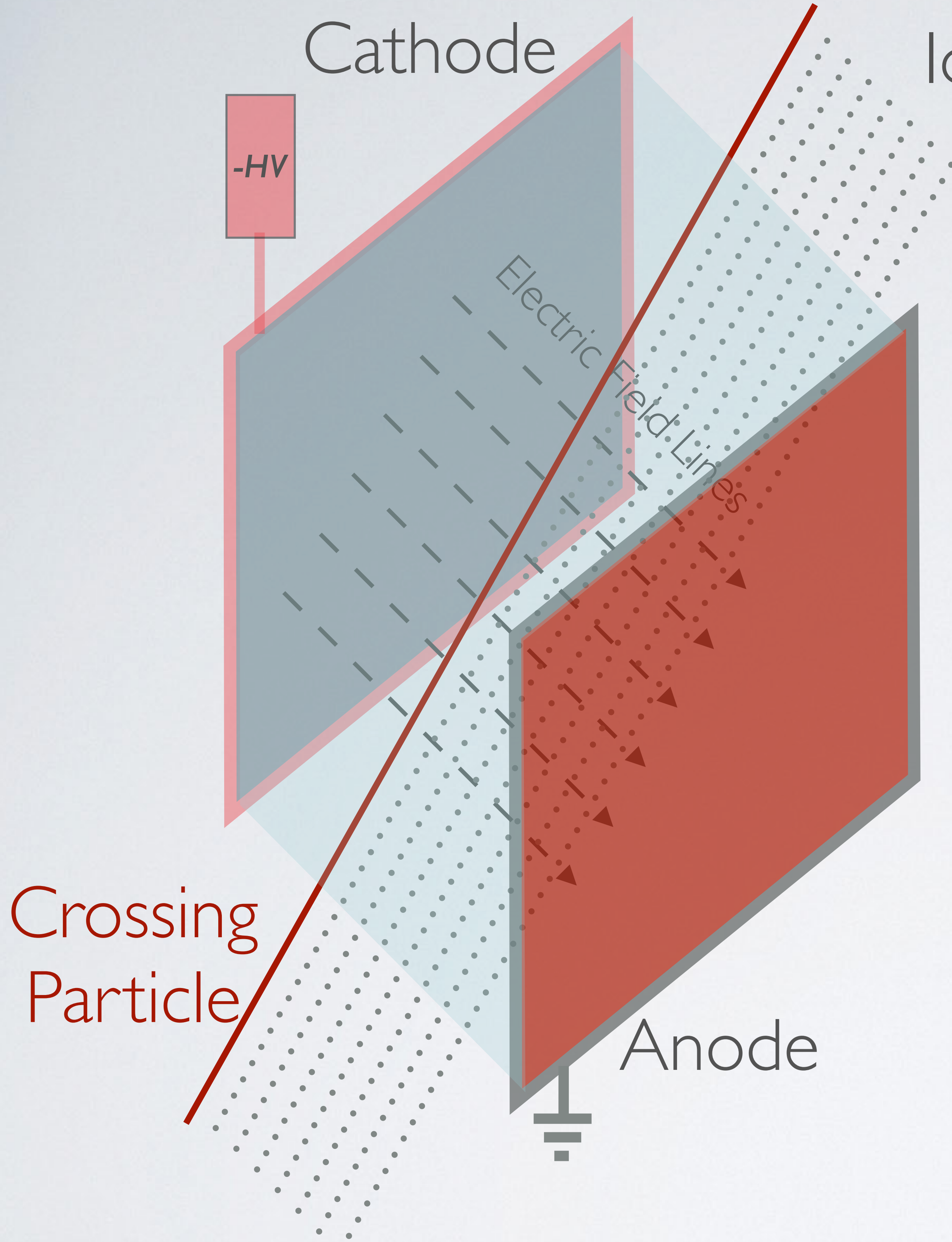
$$W_{ion} = E_+ + \epsilon_{kin} + E_*(N_*/N_+)$$

(**Note:** *the LAr band gap energy E_{gap} corresponds to the ionization potential* ***I*** *of the gaseous phase*)

SCINTILLATION

Ar^* excited atoms and Ar^+ ions produced by ionizing radiation lead to Ar_2^* low excited dimer (*"self-trapped" excitons in Singlet and Triplet state*) formation through collision with Ar atoms.

$$Ar_2^* \rightarrow \mathbf{2}\ Ar + \mathbf{1}\ \gamma$$



Liquid Argon is used as active target in particle detectors operated as **Ionization Chambers** (LAr being the dielectric medium)

When no EF is applied (EF=0) **all N_+ ions recombine**

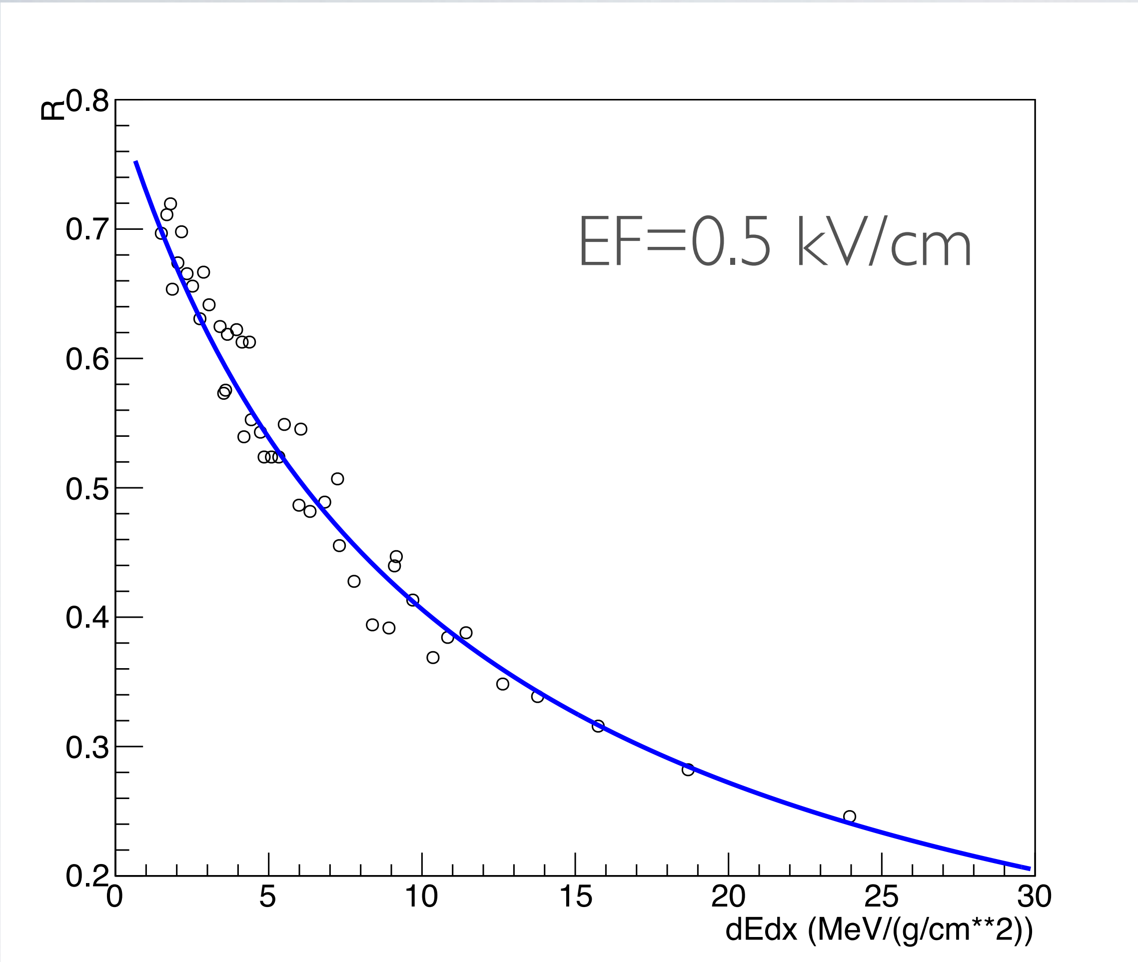
$\Rightarrow$ for a deposited energy $E_{dep} = W_{ion}$

$(1+N_*/N_+)$ photons are emitted, i.e.

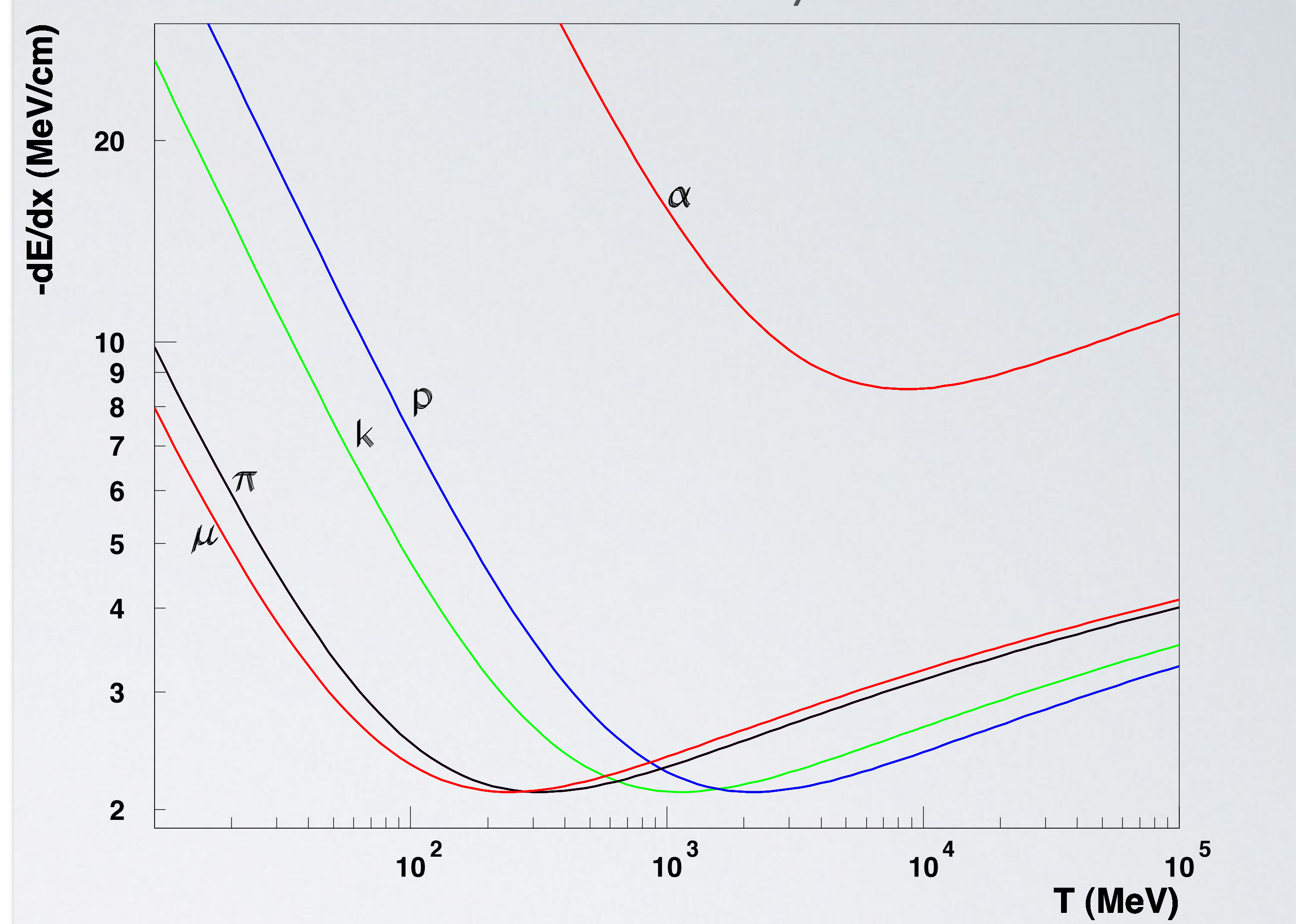
Free el-Yield: $Y_e = 10^6/W_{ion}$ [e-/MeV]

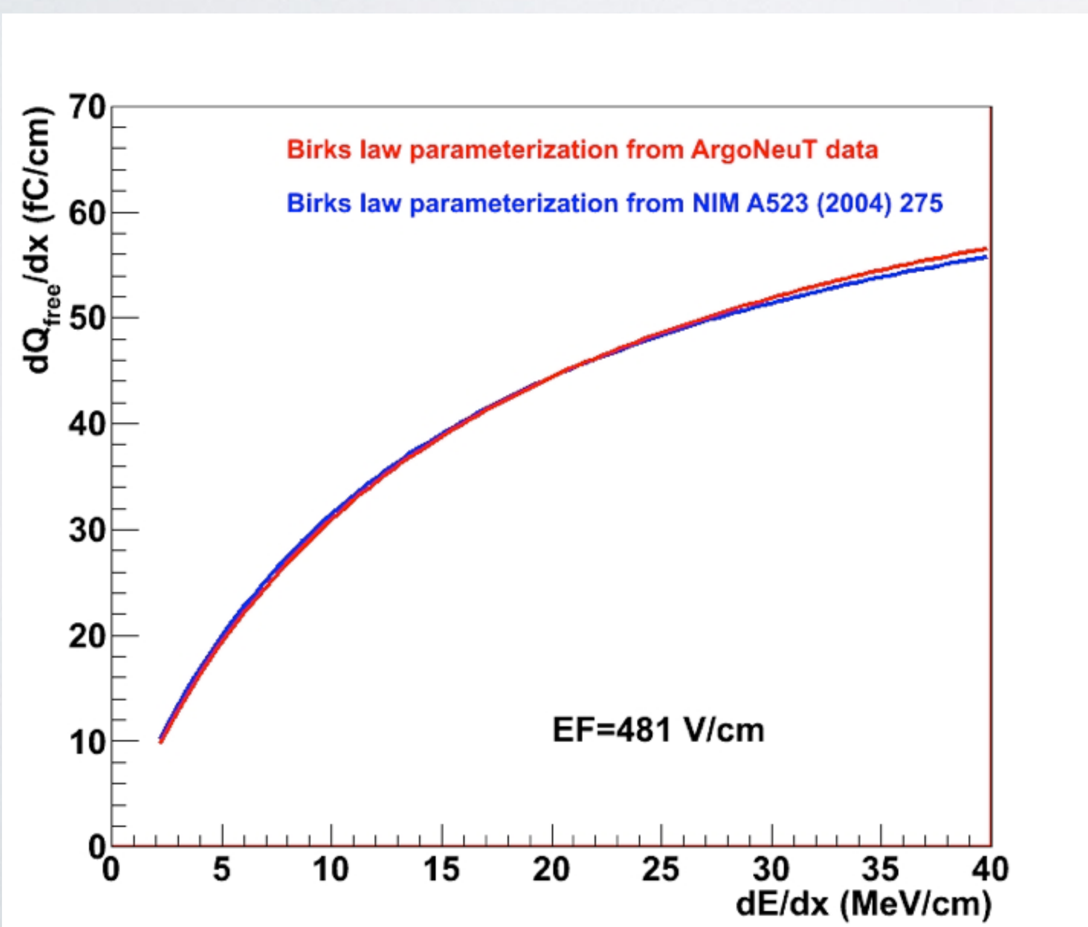
Photon Yield: $Y_\gamma = 10^6/W_{ph}$ [γ/MeV]

$W_{ph} = W_{ion} / (1 + N_*/N_+)$



Ionization Density in LAr





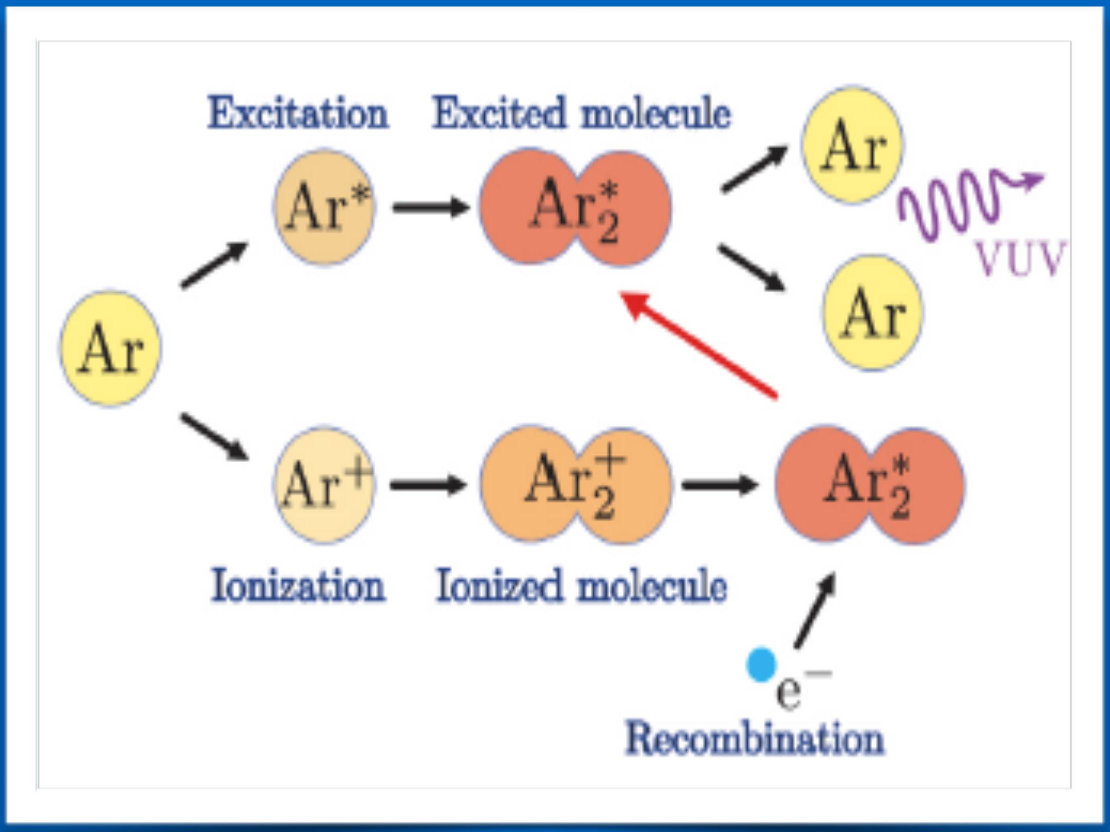
At a given EF value, the fraction **R** of ion. charge **surviving Recombination** depends (non-linearly !) on the ionization density (dE/dx).

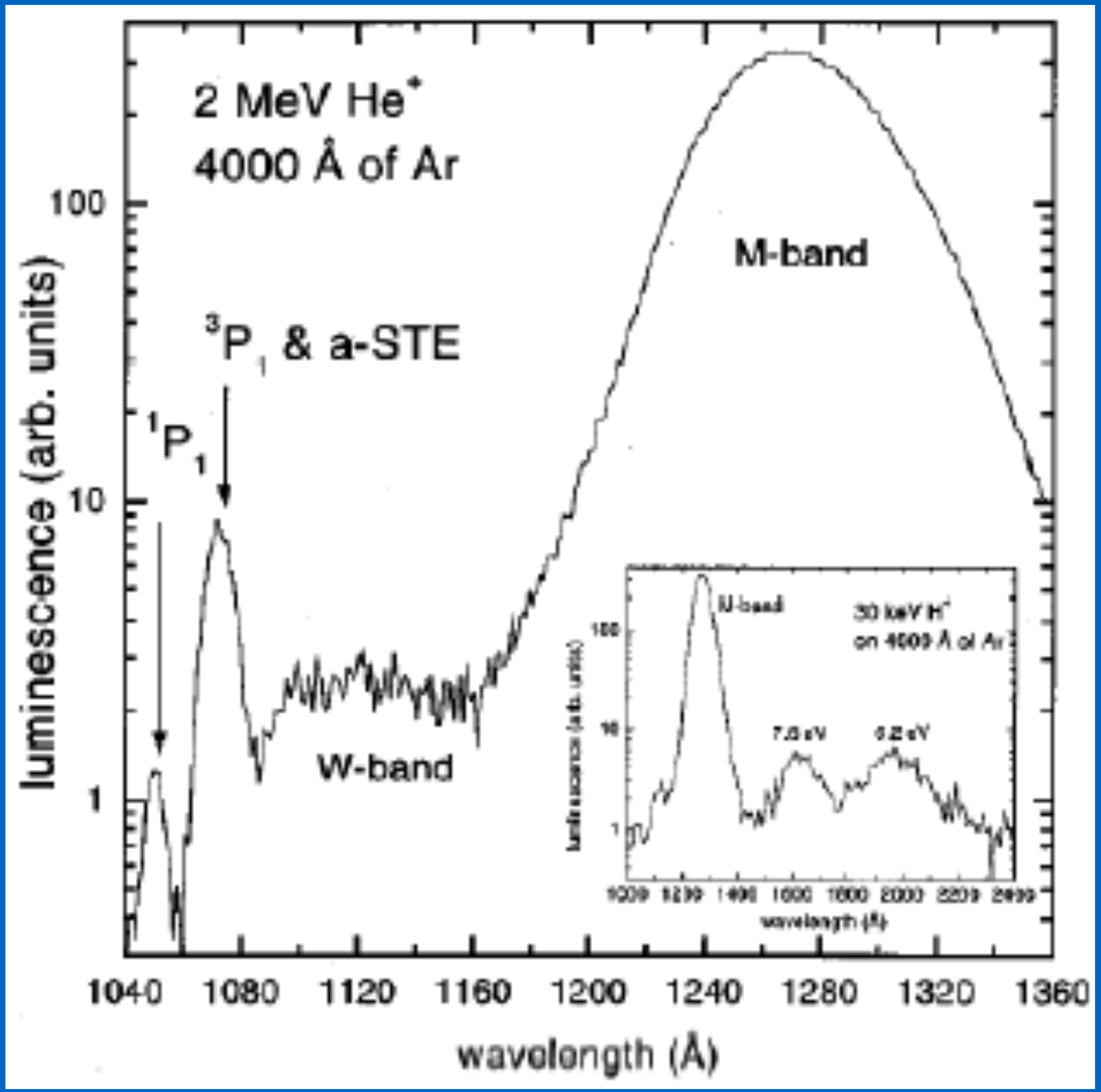
Note: different ptcls have same dE/dx at different kin. energy

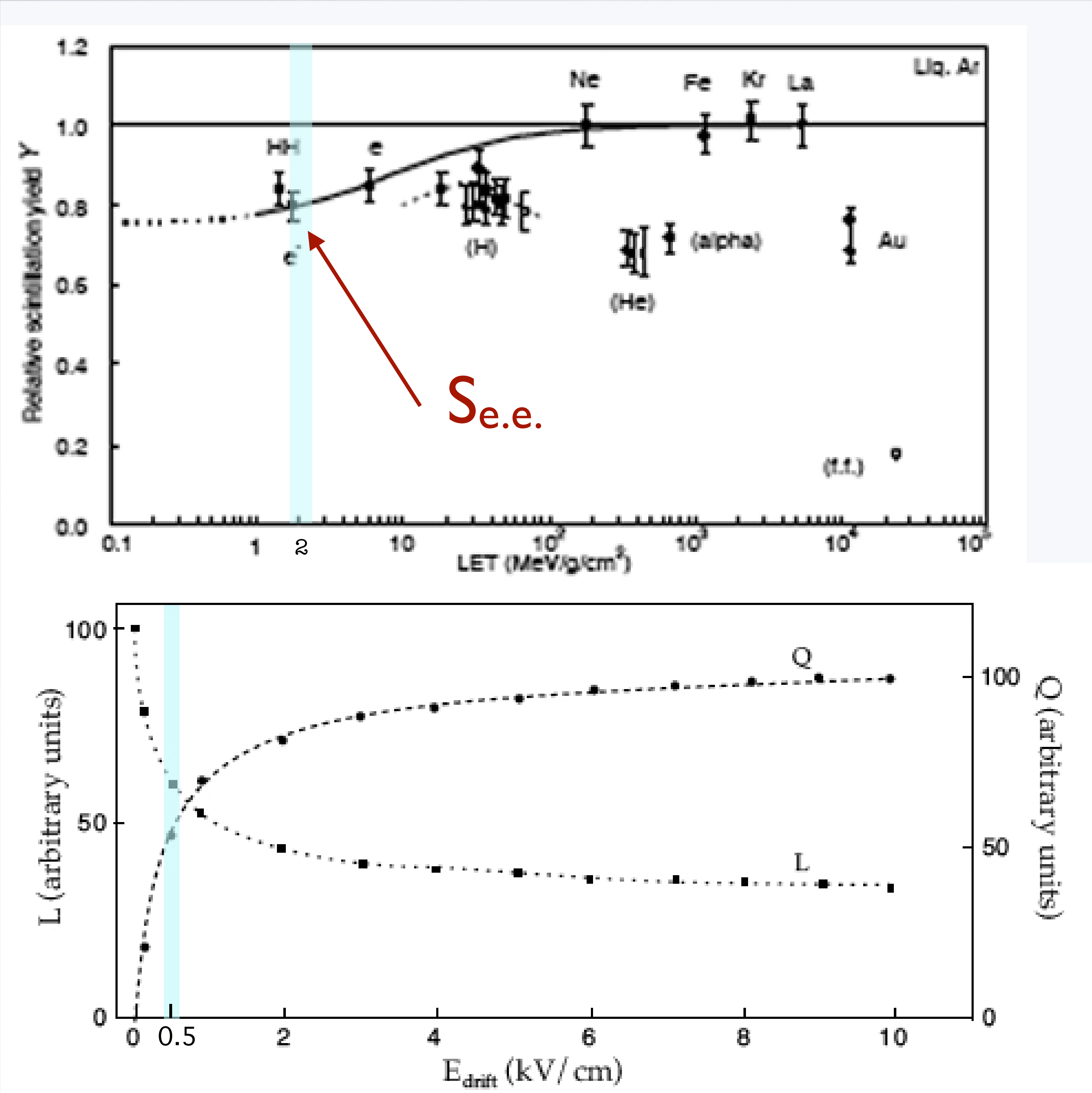
Light Production

- Prompt light from particles traversing the LArTPC allow determination of the t_0 of the interaction, as well as complimenting the TPC information during reconstruction.

- LAr is a very bright scintillator, though its predominant wavelength is deep in the UV (128nm).







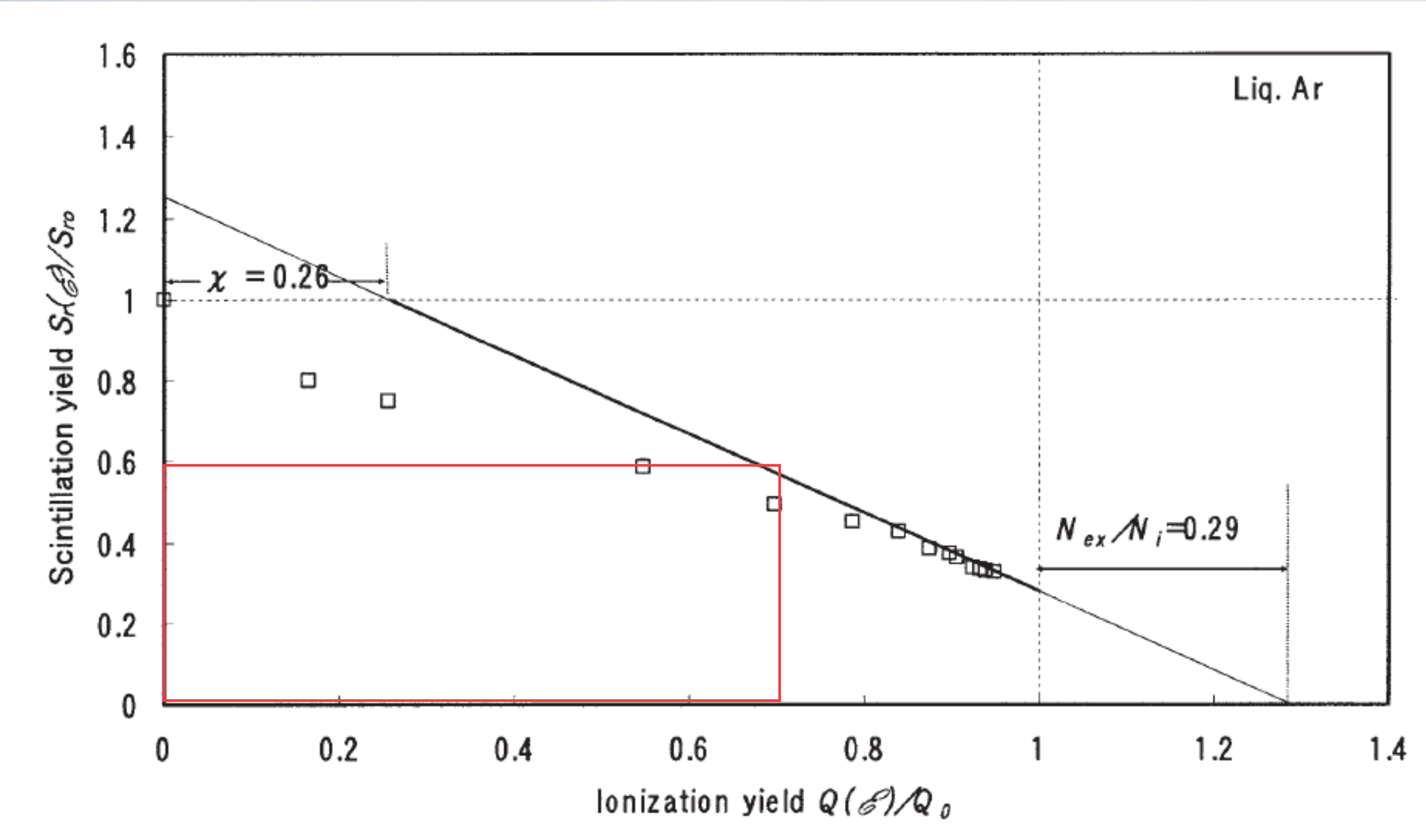
When an electric field (EF) is applied to the LAr medium the increase of the EF strength results in a *reduction of scintillation light* balanced by an *increase of free electron charge.*

The LET value (i.e. dE/dx) determines the relative amount of charge and light.

Note: Scint. Suppression due to escape electrons

$S_{e.e.}$=0.78

[Top] LET dependence of the scintillation yield, [Bottom] EF dependence of the free-electron yield and of the scintillation yield for a mip.
Shaded bands indicate the nominal EF in LArTPC detectors.



let's try a calculation..

Assumptions:

EF=0.5 kV/cm,

Crossing ptcl: muon with T_μ = 300 MeV kin energy (MIP regime) constant dE/dx = 2.1 MeV/cm along a track of length Δx = 100 cm,

- Fraction of e^- surviving recombination at EF: R=0.7 (at 0.5 kV/cm) (R equiv to $Q(EF)/Q_0$)
- Reduction of photons at EF F = 0.6 (at 0.5 kV/cm) (F equiv to $S_r(EF)/S_{r0}$)

Free electrons

$$R \cdot Y_e\,(e/MeV) \cdot E_{dep}(MeV) =$$

$$R \cdot 10^6/W_{ion} \cdot dE/dx \cdot \Delta x = \mathbf{6.2 \cdot 10^6\, e}\ (=1000\ fC) = \mathbf{Q_{free}}$$

Emitted VUV Photons

$$F \cdot Y_{ph}(\gamma/MeV) \cdot S_{e.e.} \cdot E_{dep}(MeV) =$$

$$F \cdot 10^6 \cdot (1+N^*/N+)/W_{ion} \cdot S_{e.e.} \cdot dE/dx \cdot \Delta x = \mathbf{5.0 \cdot 10^6\, \gamma_{VUV}}$$

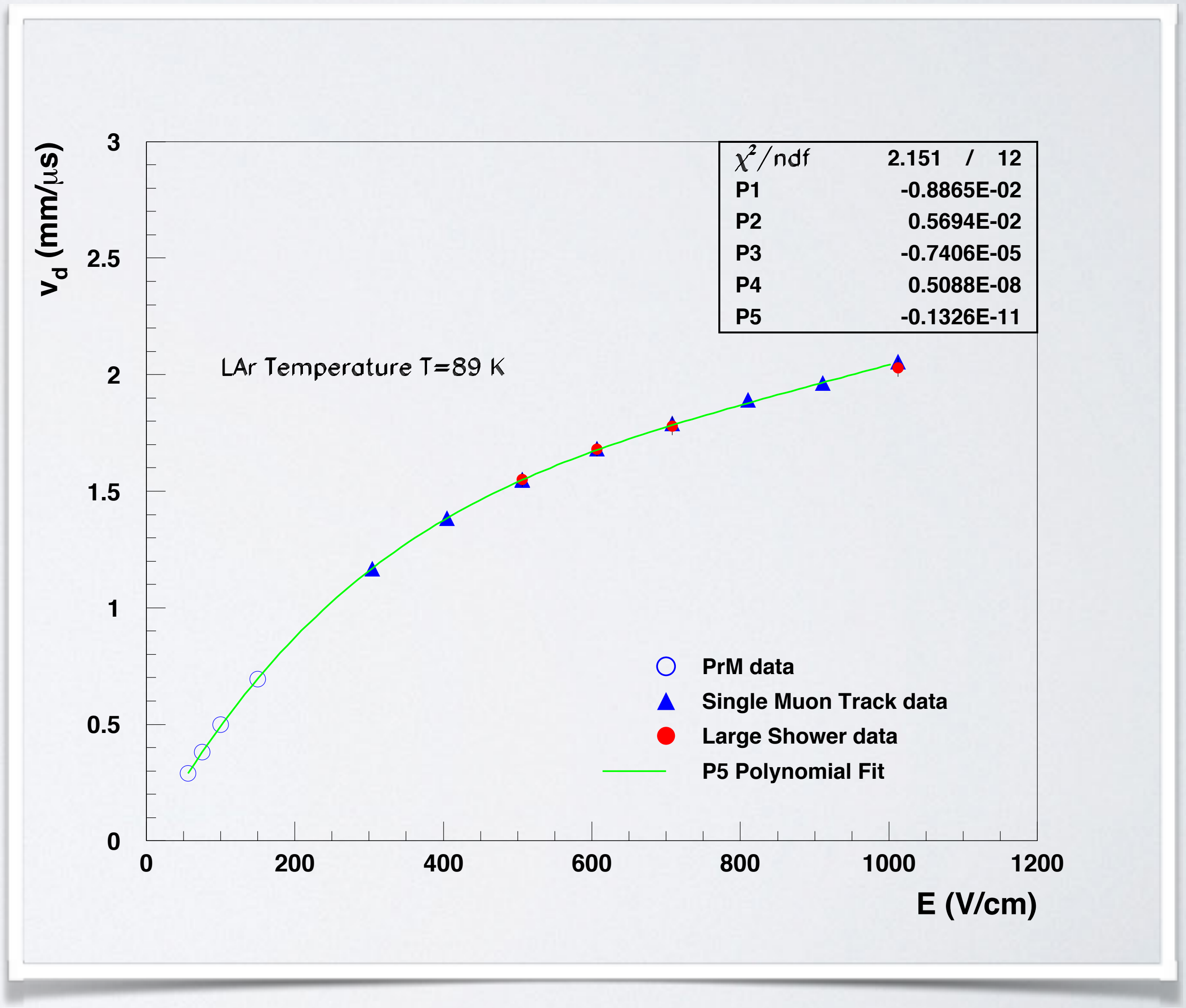
Charge transport and ***Light propagation***

through the LAr (detector) Volume

Charge Transport

from Q_{free} to Q_{Det}

- Free e-charge under influence of the EF (assumed uniform):
  - "drift" from Cathode to Anode at constant velocity, v_D
    - NB: the drift velocity in LAr is LOW (v_D ~1.5 mm/μs at nominal EF - **0.5 kV/cm**)



- The charge at the end of its drift is eventually collected by the Anode Plane

… however …

… *however*:

- e-charge is progressively reduced during drift time t_D due to
    - "attachment" to el-negative impurities (e.g. O_2)diluted in LAr:

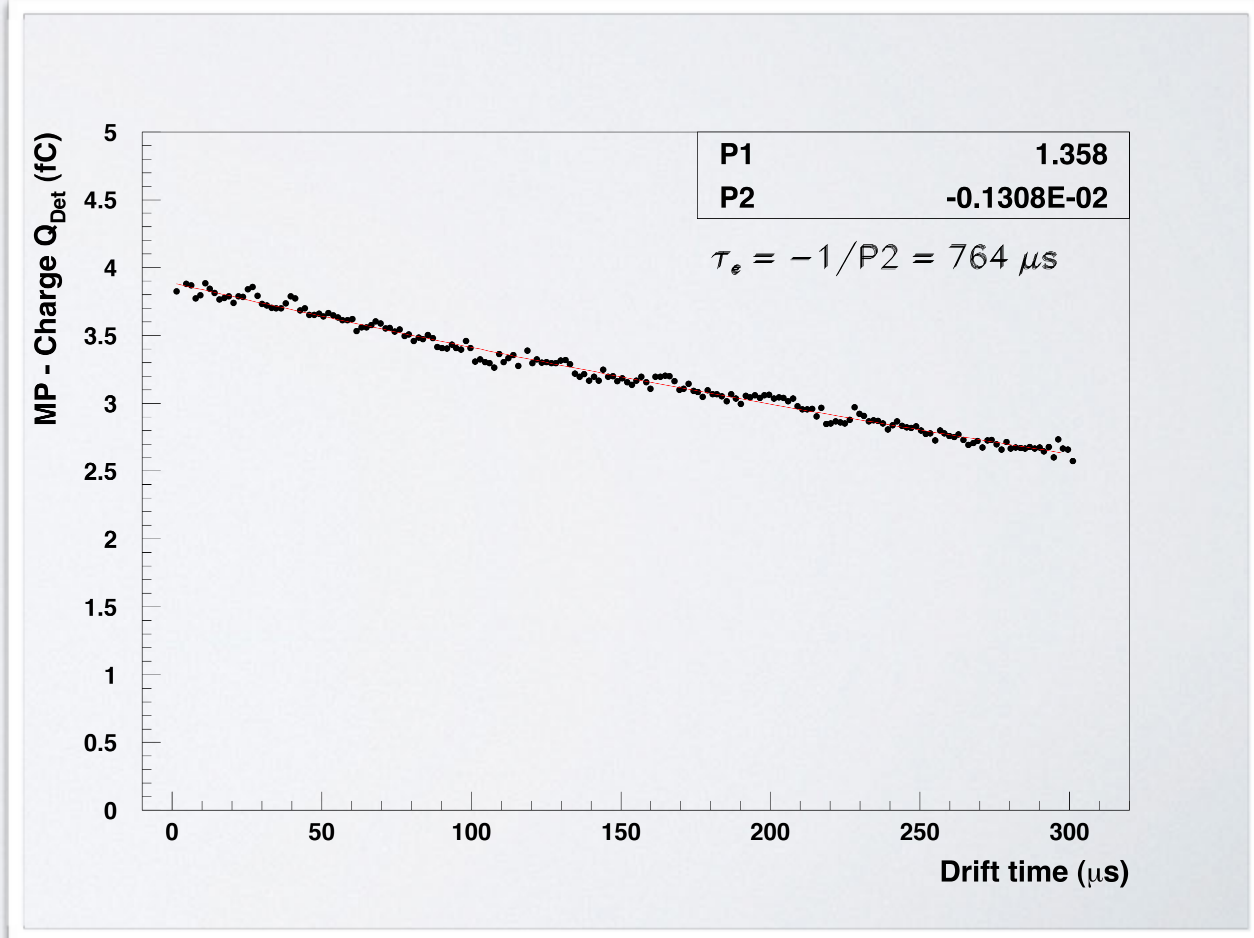
$$e^- + O_2 \rightarrow O^-_2 \quad ; \quad \text{rate constant } k_e \simeq 3.1\ \text{ppb}^{-1}\ \text{ms}^{-1}$$

$$\Rightarrow \quad Q_{Det}(t_D) = Q_{free} * \exp(-t_D/\tau_e)$$

where τ_e is the "electron Lifetime" in LAr with el-negative impurity concentration $[O_2]$ in ppb:

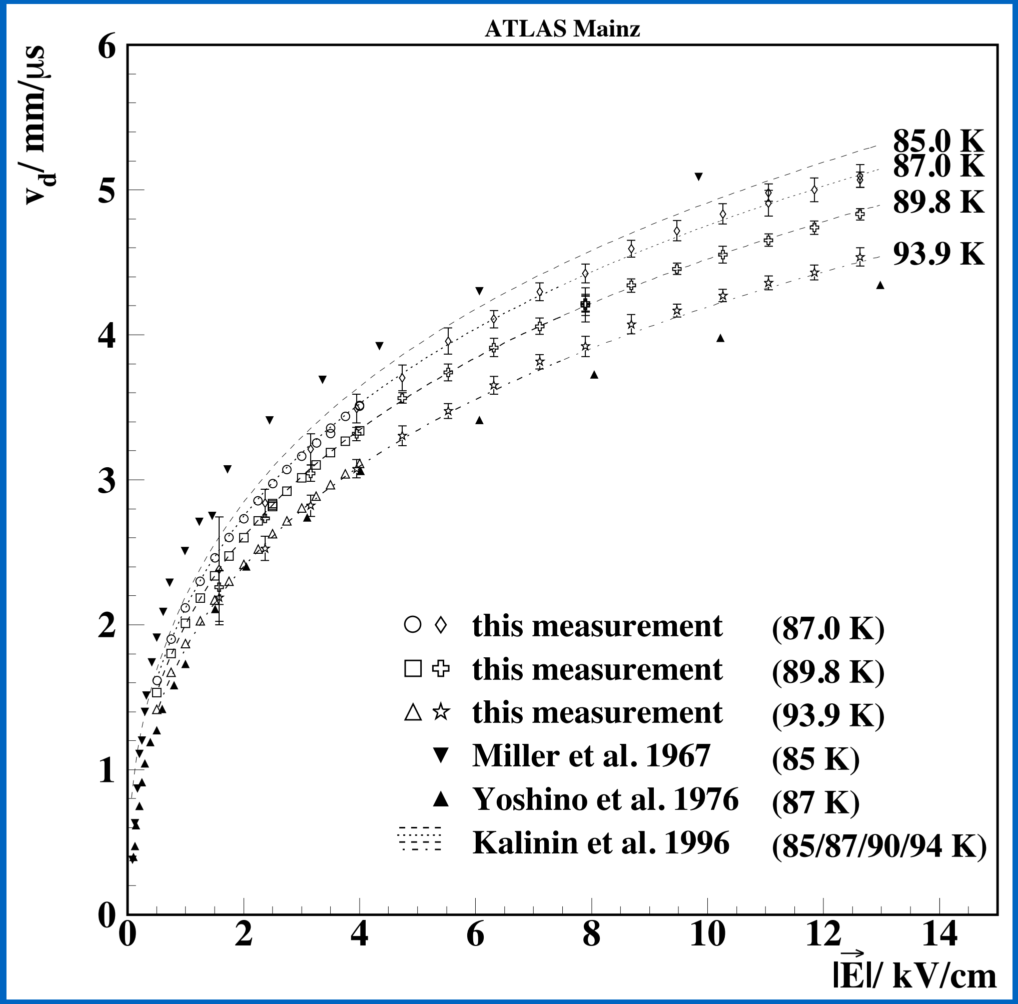
$$\tau_e = 1 / k_e\,[O2]$$

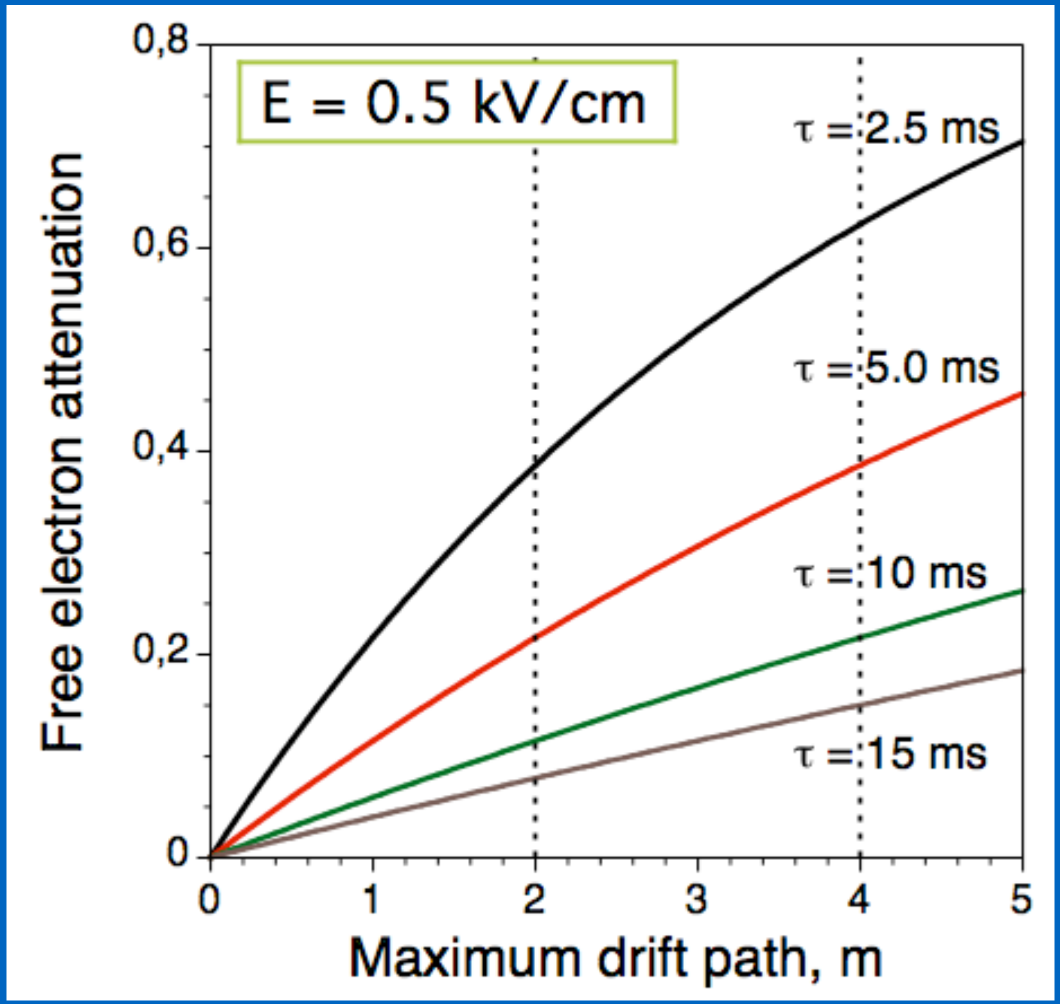
since k_e is a known, measuring the e-lifetime means measuring the impurity concentration.



LAr Purity

- The *electron lifetime* is one of the most important detector parameters.
- In 100% pure LAr, the electron lifetime should be almost infinite.
- Electronegative impurities, such as Oxygen and Water, will attach to electrons before they reach anode planes, reducing the recorded signal.



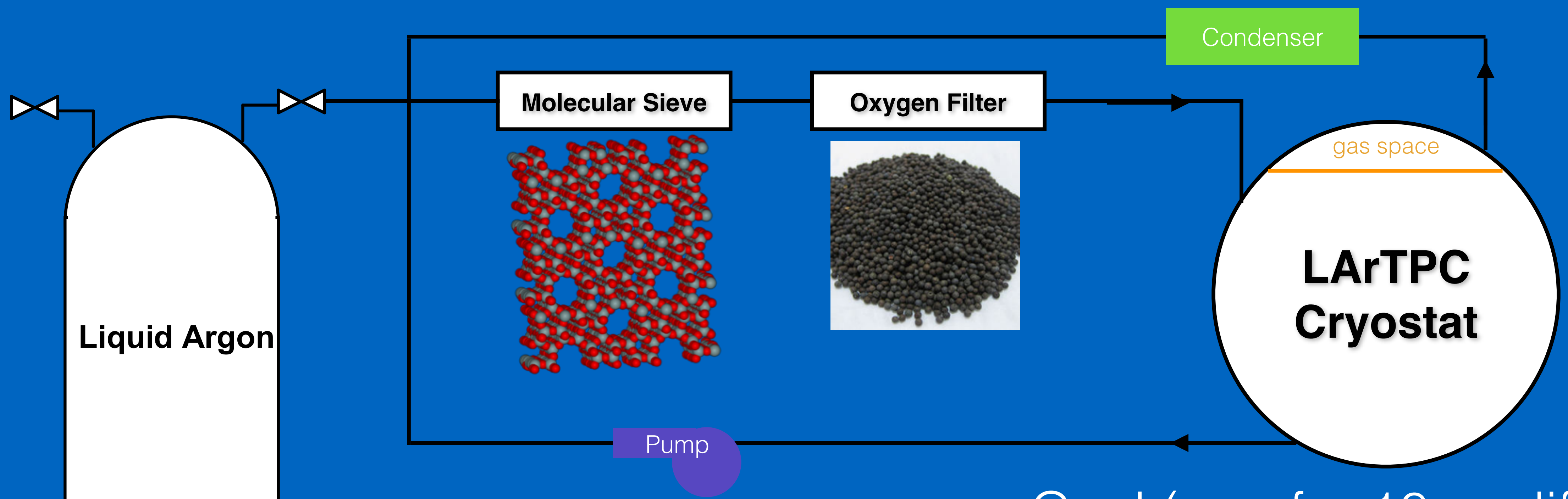


Refs:

1.) *Drift Velocity of Free Electrons in Liquid Argon*, W. Walkowiak, NIM A Vol. 449, July 2000, pp 288-294

LAr Purity

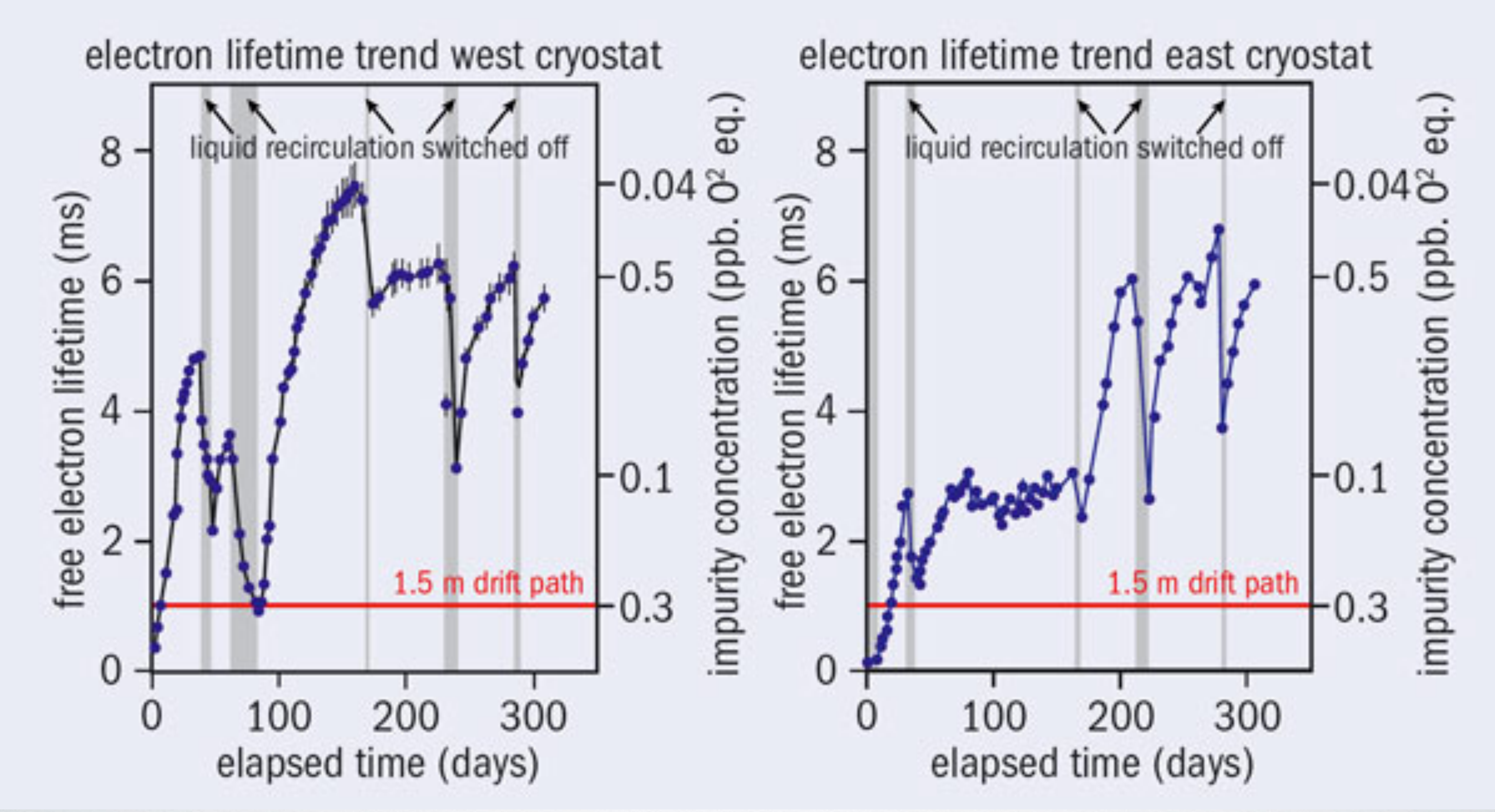
- Achieve desired purity level by passing argon through filters containing molecular sieve (to remove water) and copper (to remove oxygen).
- Detector components must also be chosen to minimize contamination.
- Continuous recirculation necessary to reach/maintain ultimate purity requirements.



Delivered: 1ppm O_2

Goal (*e.g.* for 10 ms lifetime): 30 ppt O_2

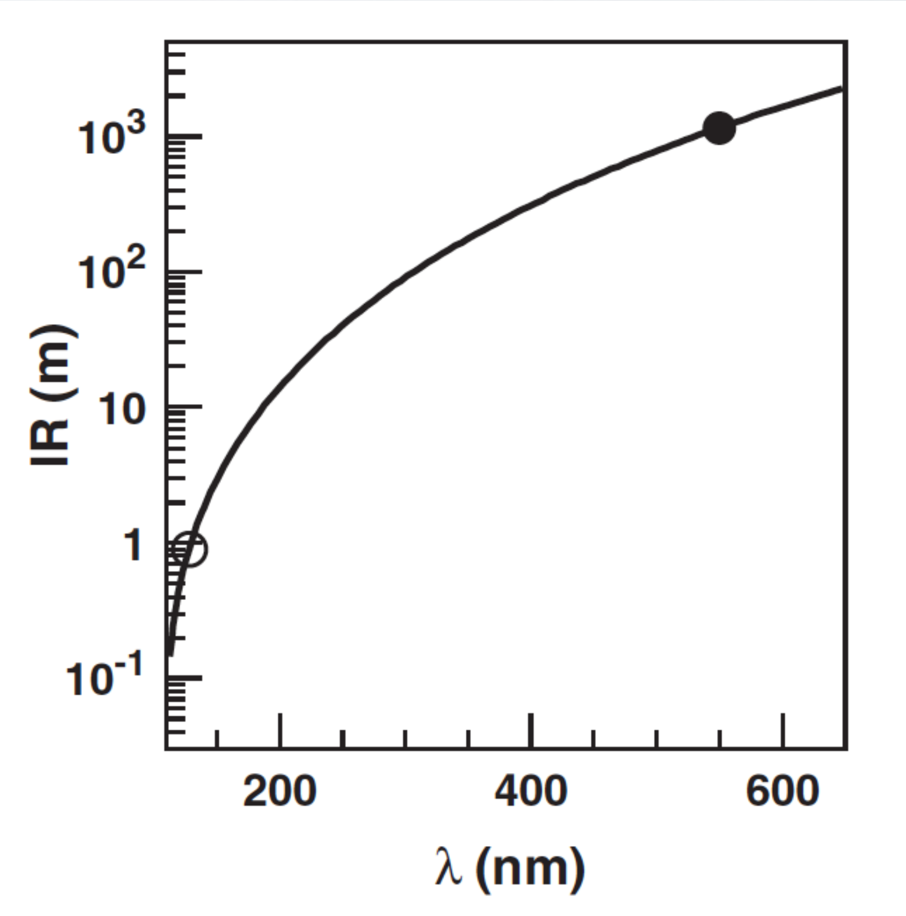
Refs:
1.) *A Regenerable Filter for Liquid Argon Purification*, A. Curioni et al, NIM A Vol. 605, July 2009, pp 306-311
2.) *ICARUS takes flight beneath the Gran Sasso*, CERN Courier, July 2011


electron lifetime trend west cryostat
liquid recirculation switched off
free electron lifetime (ms)
impurity concentration (ppb. O² eq.)
1.5 m drift path
elapsed time (days)
electron lifetime trend east cryostat
liquid recirculation switched off
free electron lifetime (ms)
impurity concentration (ppb. O² eq.)
1.5 m drift path
elapsed time (days)

Light Propagation

- LAr is transparent to its own scintillation light (128 nm VUV photon = 9.8 eV, not enough energy to re-excite another Ar atom) ⇒

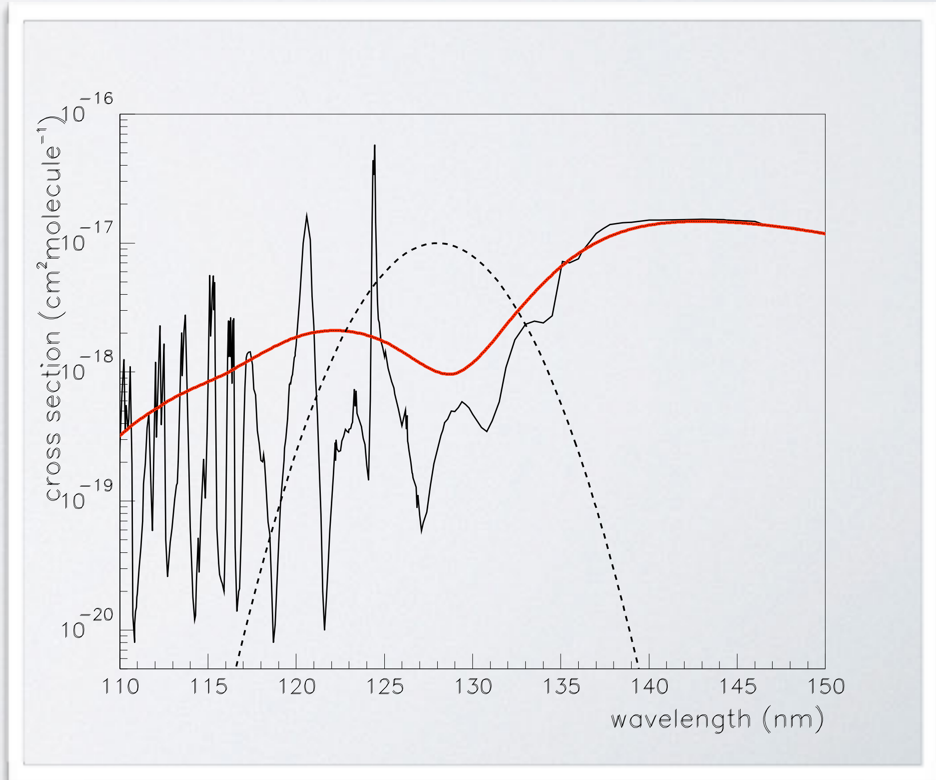
  VUV photons freely propagate through LAr



… however…

- undergo "frequent" elastic interactions with Ar atoms (***Rayleigh Scattering***): $\ell_R \simeq 60$ cm (at λ=128 nm)

- ***Absorption*** by photo-sensitive molecules (impurities, like O_2 and H_2O) diluted in LAr: $\ell_A = 1 / k_A [O_2]$



Charge ***Collection*** and Light ***Collection***

at/by the Charge- or Light-Sensitive devices.

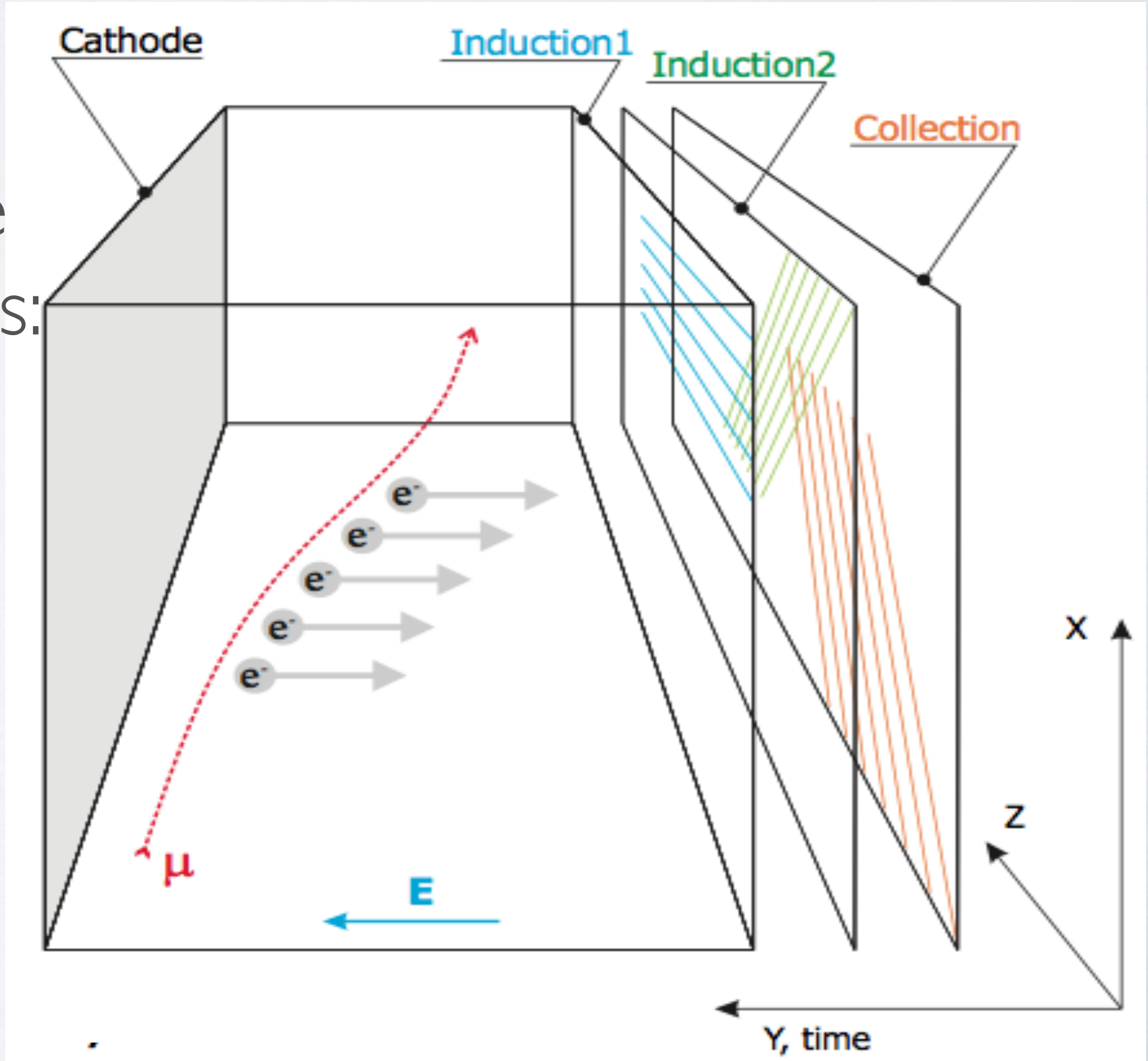
Charge ***Collection***

- The anode electrode of the Ionization Chamber collects the "detectable" charge at the end of the drift distance → Q_{det}

NB1: in LAr there is ***no charge-multiplication*** (as in GAr detectors), i.e. Q_{det} is the actual amount of ionization charge surviving Recombination ($Q_{Ion} \rightarrow Q_{free}$) and Attachment ($Q_{free} \rightarrow Q_{det}$)

NB2: the shape and geometry of the anode electrode can be chosen in a variety of ways: the one relevant here is the **Time Projection Chamber geometry** with the anode plane formed by a succession of two (or more) parallel planes of wires oriented at different angles:

☞ **the LArTPC concept**

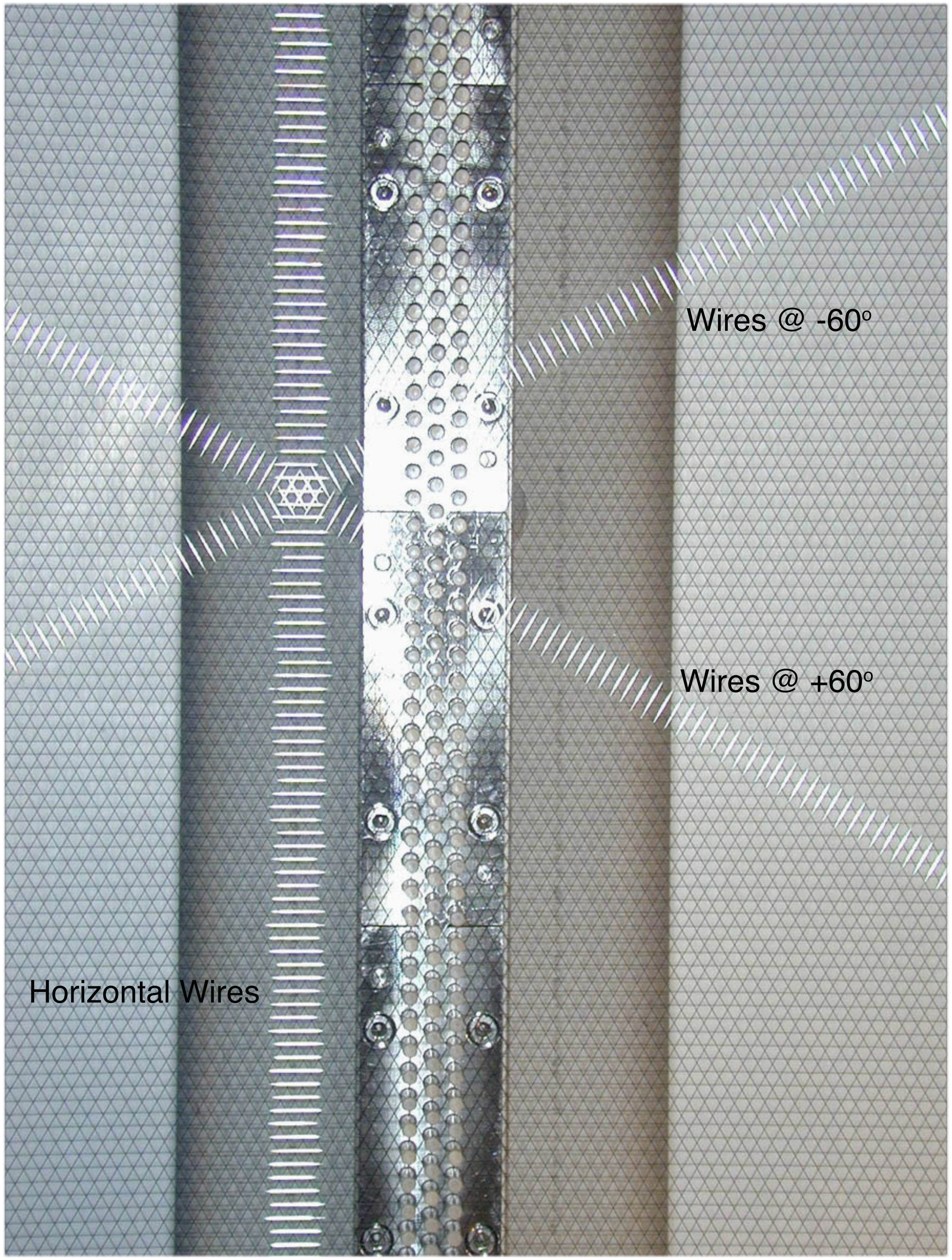


LArTPC

- **Field-cage of TPC creates uniform drift region from cathode to a anode plane.**
- Excellent dielectric properties of noble liquids allow for sustaining high cathode voltages. Example: MicroBooNE has a 2.5m drift, so a 500V/cm field requires: 125,000V on Cathode.
- Recombination of electron-ion pairs diminishes signal. Can compensate by increasing field, but this increases demand on cathode voltage.

anode plane formedThree Wire Planes 0°, ± 60°

ICARUS TPC



MicroBooNE at FNAL

The TPC – cathode and field cage

Anode wire plane

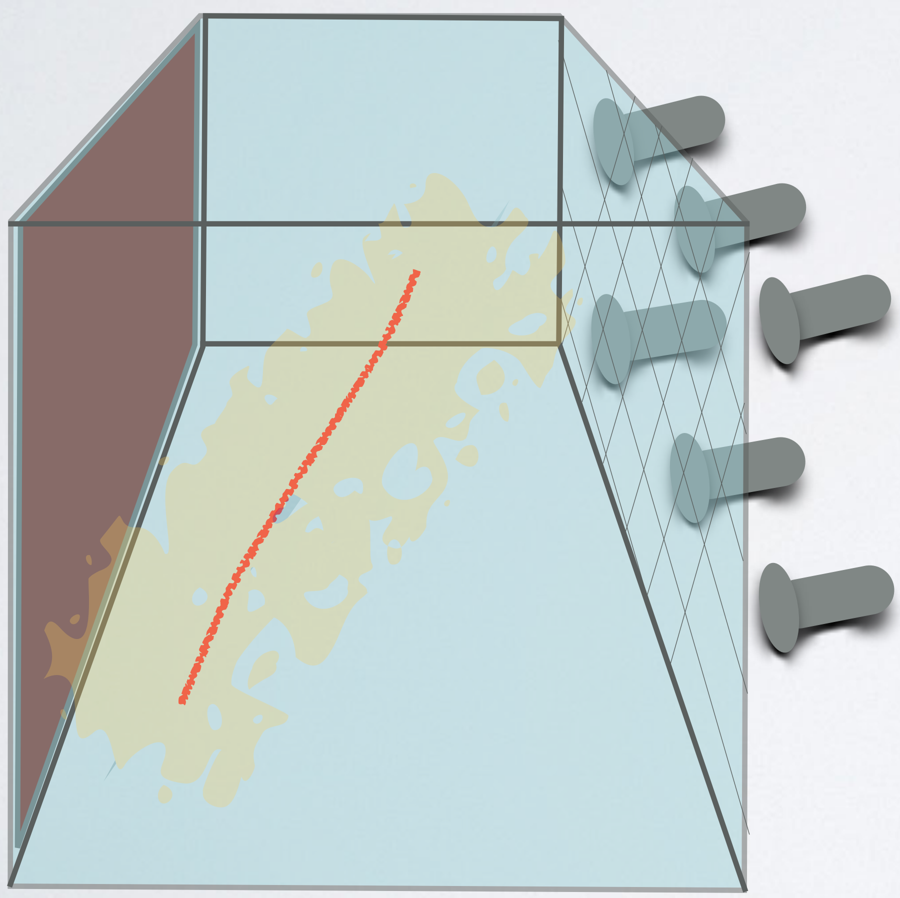
Field cage:
64 stainless steel tubes at different potential to create a uniform electric field inside "loops around the TPC volume"

Wire readout electronics boards

and Light **Collection**

- Any "PhotoCathodic" area can collect the LAr Scintillation Light

["PhotoCathodic" area is the active surface of an optical sensor where photons generate an electronic signal, typically a (photo-)electron current: e.g. ***PMT, SiPM, …]***



NB1: VUV (128 nm) light need to be wavelength-shifted into visible to be detected by PMTs (e.g. blue-sensitive). Coating PMT window with wls-material (e.g. TPB) is the most common solution.

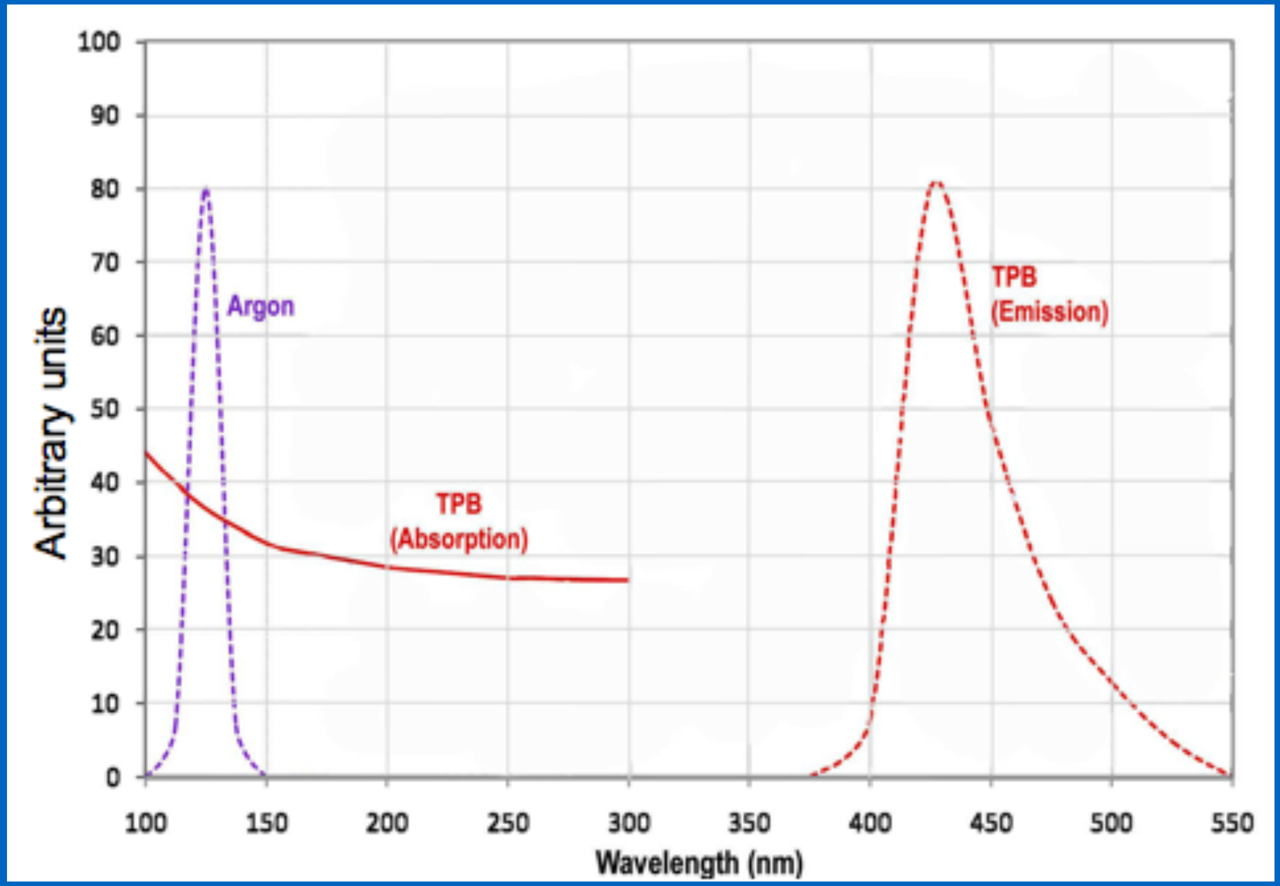
NB1: detected light is mostly DIRECT light impinging upon PMT photo-cathode
⇒ collection efficiency usually very low

$\epsilon_{coll} \approx 10^{-5}$ (for typical photo-cathodic coverage ≈ 1‰)

VUV (128 nm) light is only marginally reflected by inner detector surface (metallic cathode and field-shaping system - R≈20%)

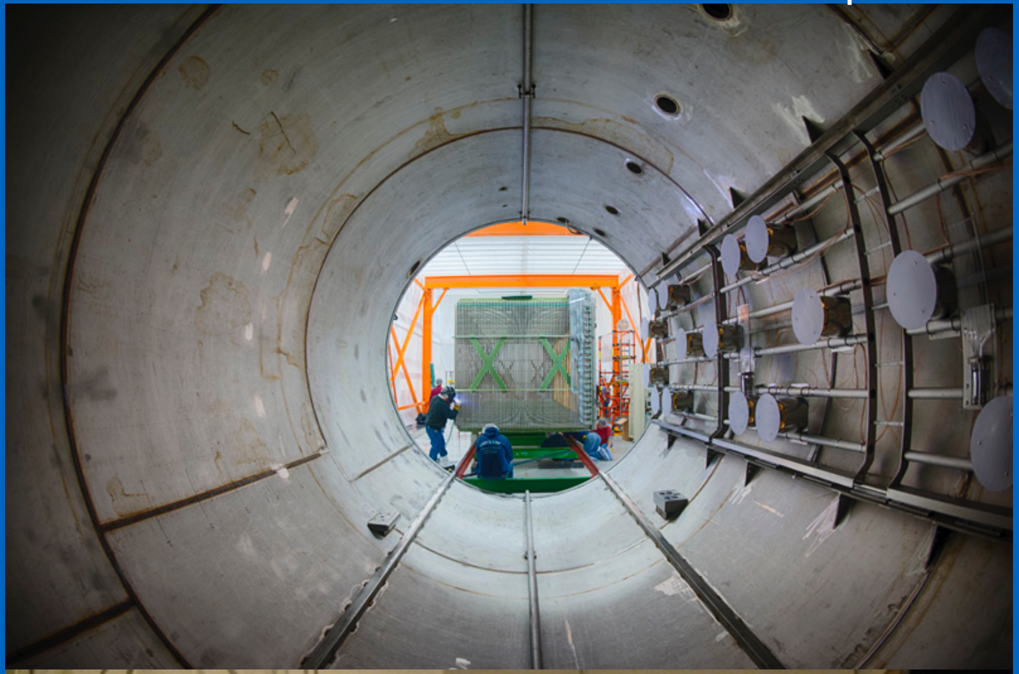
Light Collection

- Light collection devices (PMT, scintillator bar, SiPM, etc…) immersed in the LAr, which puts constraints on their robustness to cold.
- Argon scintillation light is deep in UV, so need to shift wavelength to regime where device has good efficiency.

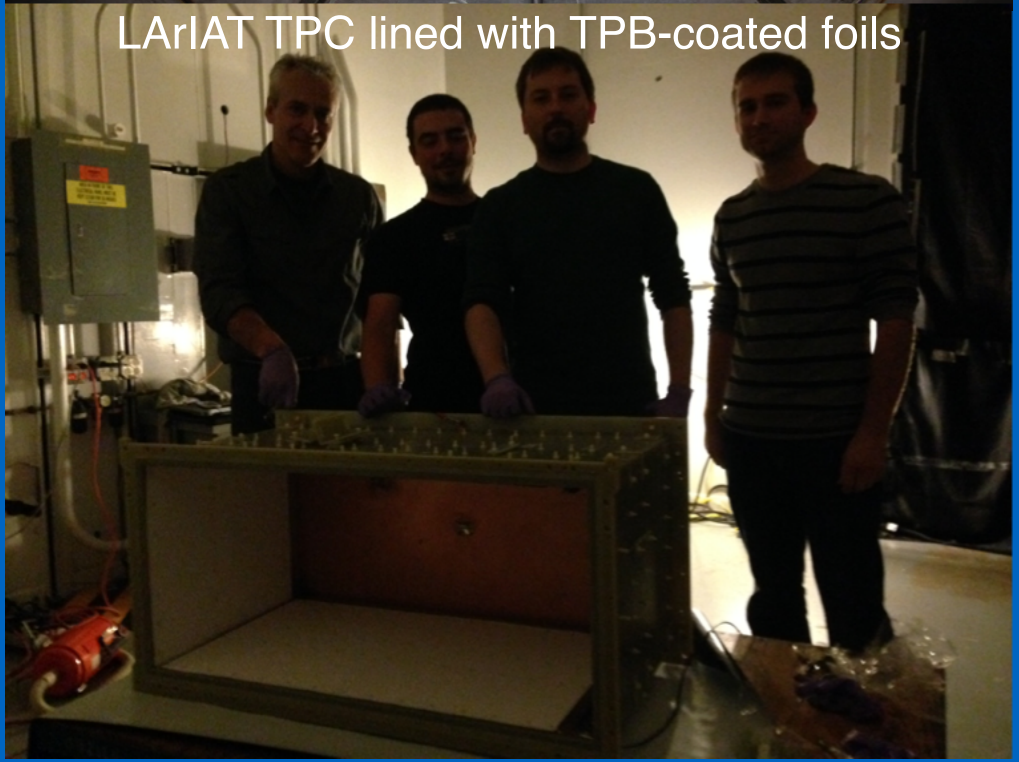


Abosrption/Emission Spectrum of Tetraphenyl butadiene (TPB)

MicroBooNE PMTs behind TPB-coated plates



LArIAT TPC lined with TPB-coated foils

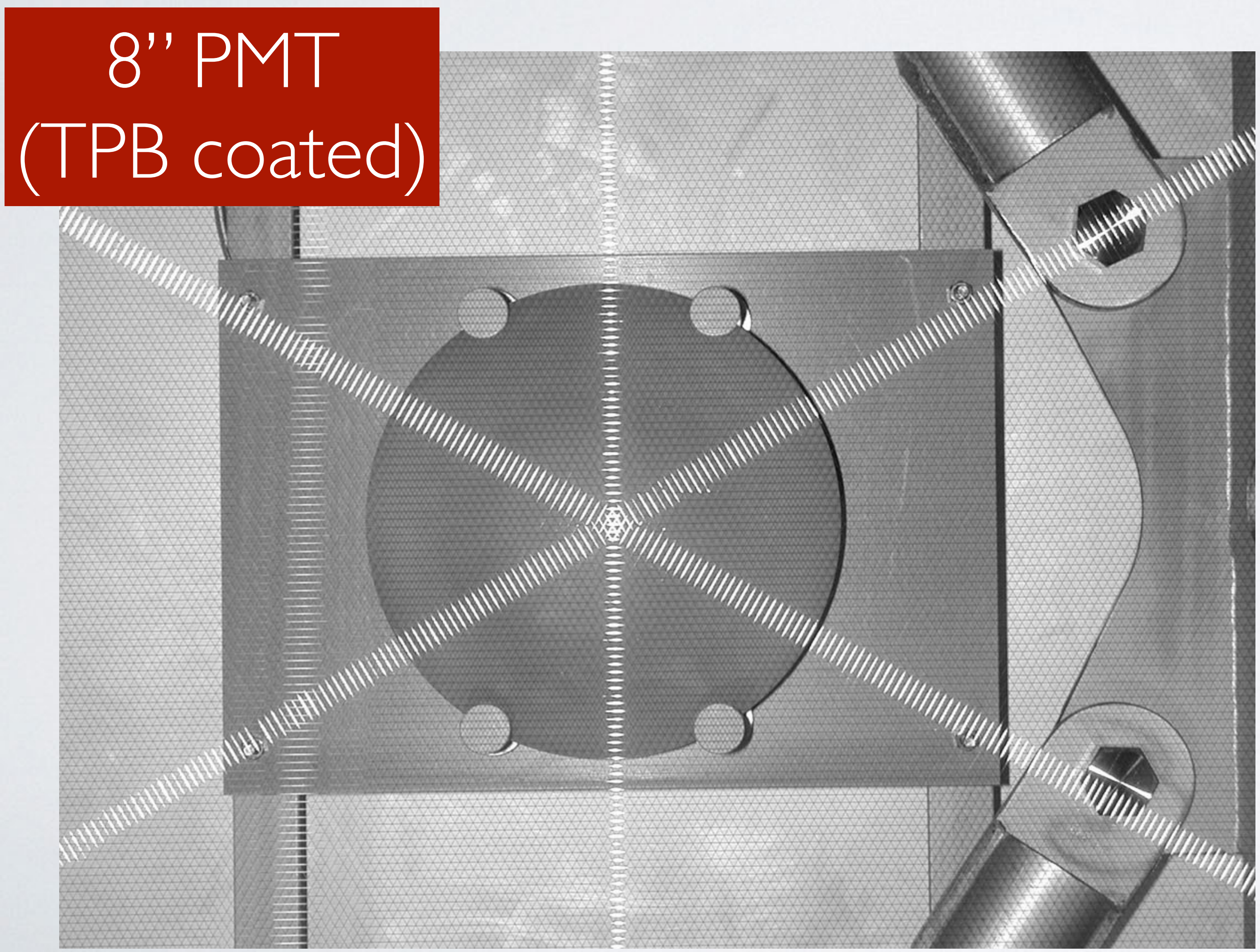


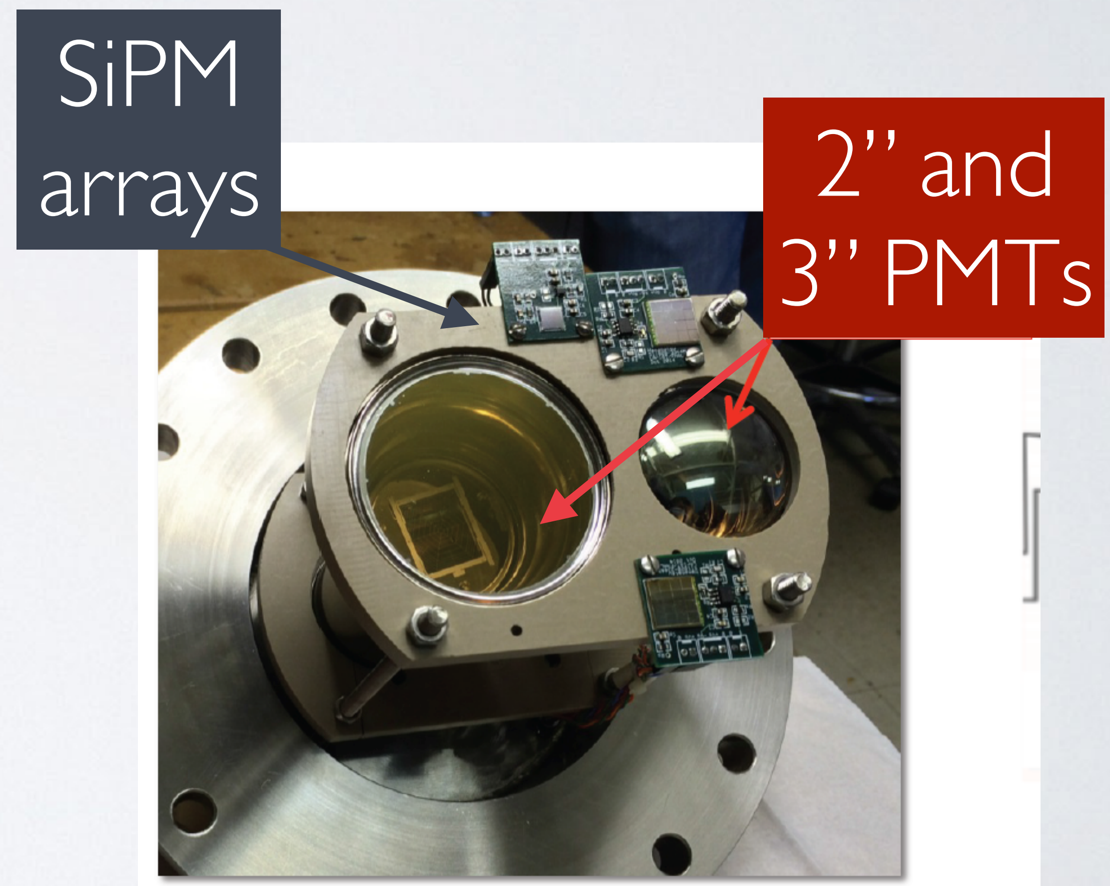
Refs:
1.)*MicroBooNE*, C. Ignarra, DPF 2011 Proceedings

Prompt Scintillation Light (fast component ~5 ns) is detected (after VUV-Vis w.l. down-conversion) by arrays of PMTs/SiPM:

* used for Triggering
* used for determining $\mathbf{t_o}$ of event (time of passage of ptcl in LAr) necessary for TPC event reconstruction: drift coordinate $\mathbf{x_D}$

$$t_D = (t_{hit} - t_o)\ ; \quad x_D = v_D * t_D$$





LArTPC technology at work

LArTPC

- One of the attractive aspects of this technology is we don't need to instrument the entire volume. Just drift liberated ionization over to anode plane.

- This allows us to scale the detector to very large sizes.

NB:

- The longer the drift length, the higher the demands on LAr purity and high-voltage capability.

Operating Principle of the LAr Time Projection Chamber

The LArTPC technology allows for ***three-dimensional image reconstruction*** and ***calorimetric measurement*** of the ionizing events.

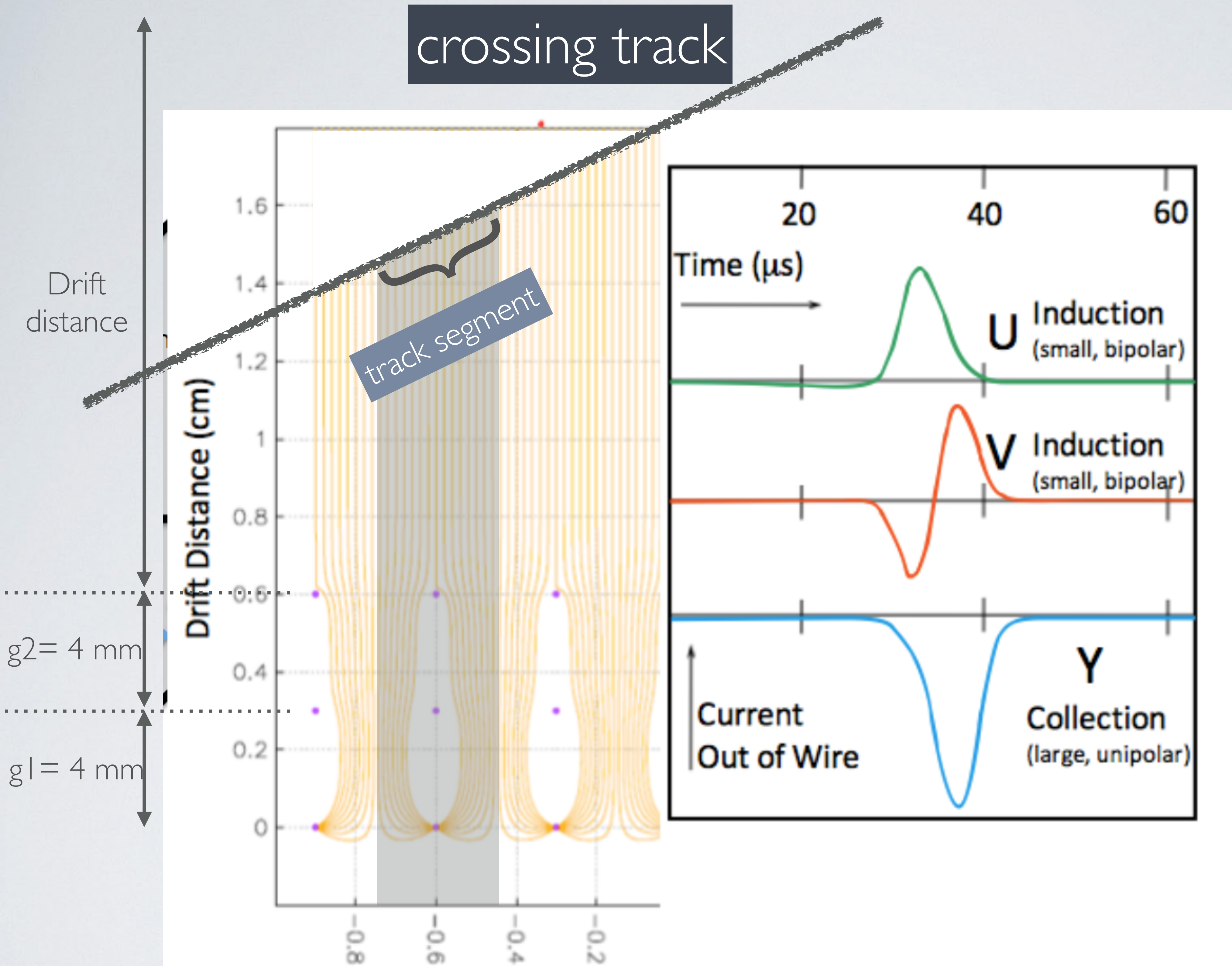
When a uniform electric field is applied, the ionization ***electron tracks are projected onto the anode*** along the electric field lines.

The read-out of the electron track image is obtained by configuring the anode as a system of parallel wire-planes (number of planes ≥ 2), biased at specific potentials to enhance ***"transparency"*** of the successive wire plane to drifting electrons.

With this configuration, each ***segment*** of a track induces a pulse signal (***"hit"***) on one wire in each plane.

The ***coordinate of the wire in the plane provides the hit position,*** so that multiple and independent localizations (y, z) of the track segment can be accomplished **("non-destructive" read-out).**

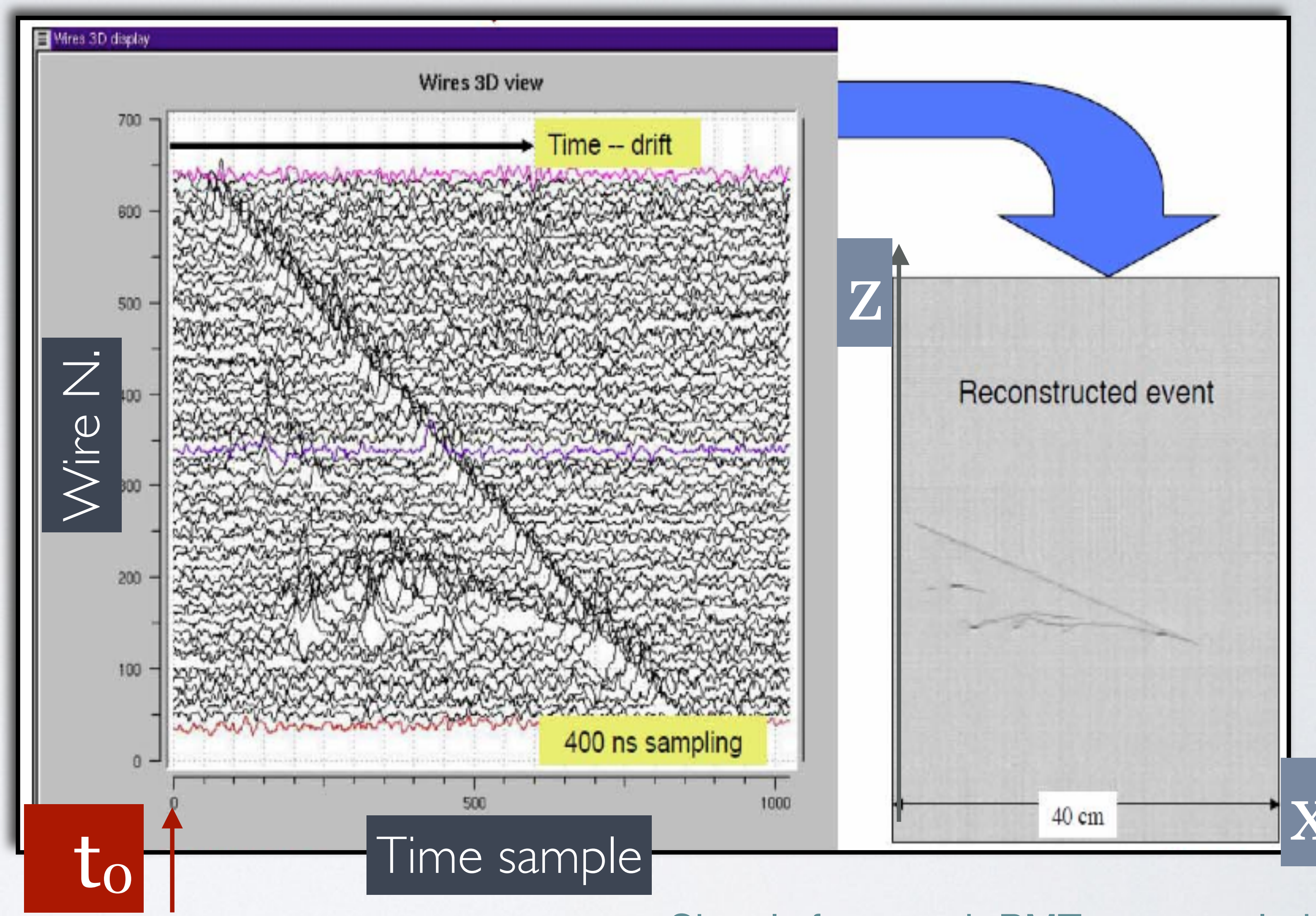
Timing of the pulse (t_0 from Prompt Scintillation Light) , combined with the drift velocity information, ***determines the drift-coordinate*** of the hit (x), thus providing full three dimensional (**3D**) image reconstruction capability.

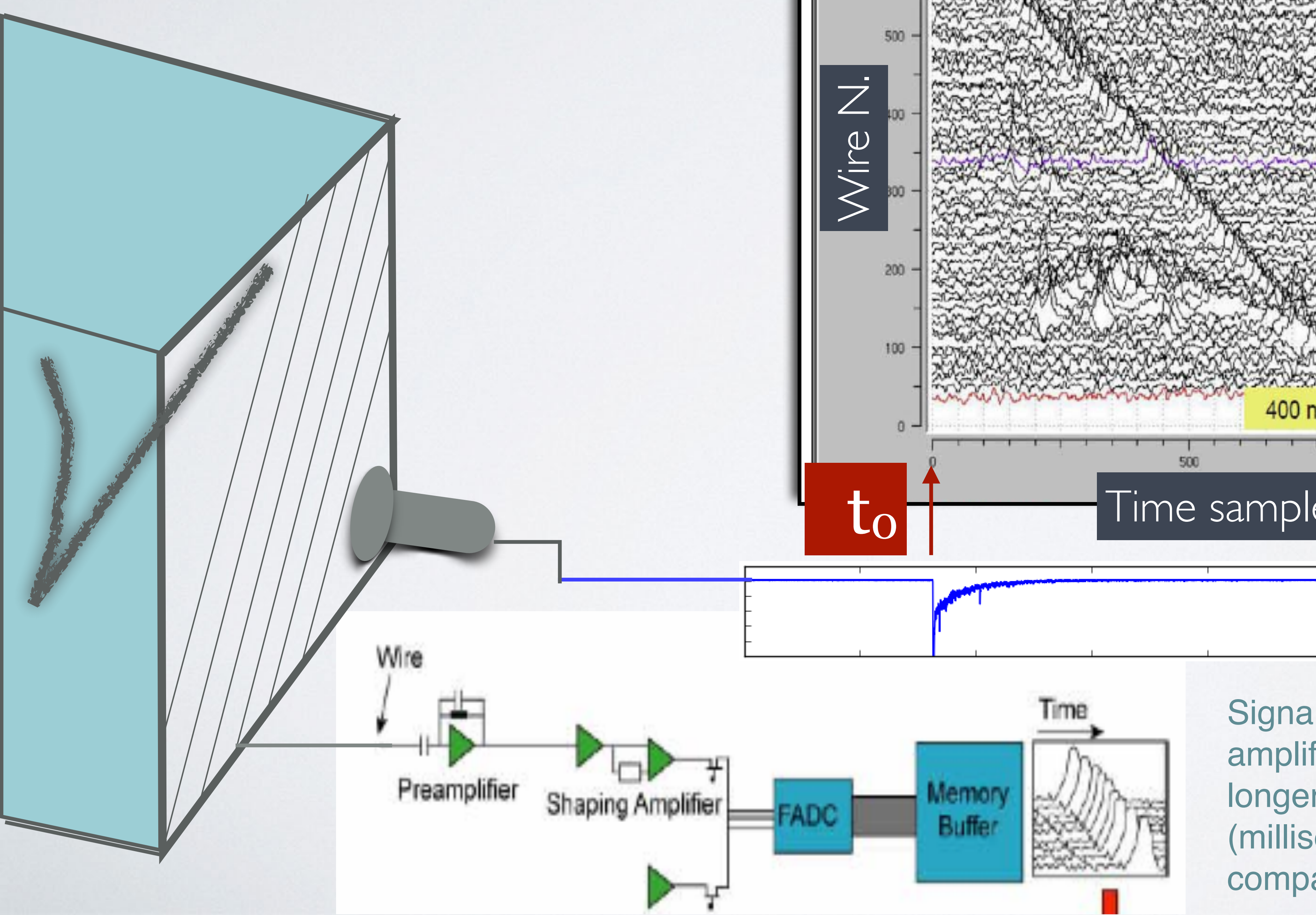


Signals from wires in different planes sensing the same track segment

Transparency is established when $E_{g2} \geq r_T E_{g1}$ and $E_{g1} \geq r_T E_d$ with $r_T \geq$ **1.3-1.4**

The electronics implemented for the LArTPC wire signal readout is structured as a ***multi-channel waveform recorder*** that continuously records charge information collected by each sense wire during the drift of ionization electrons inside the TPC.

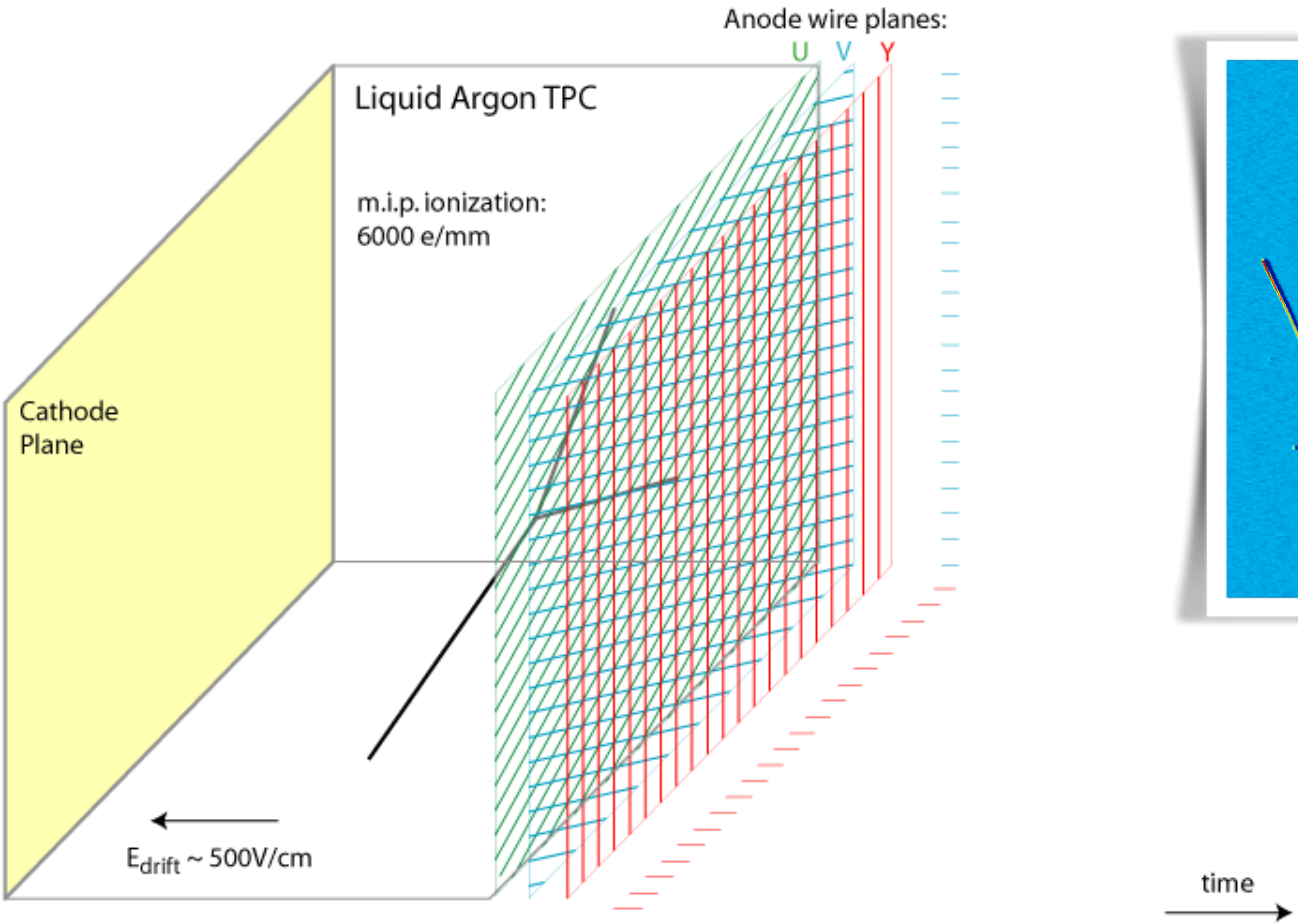


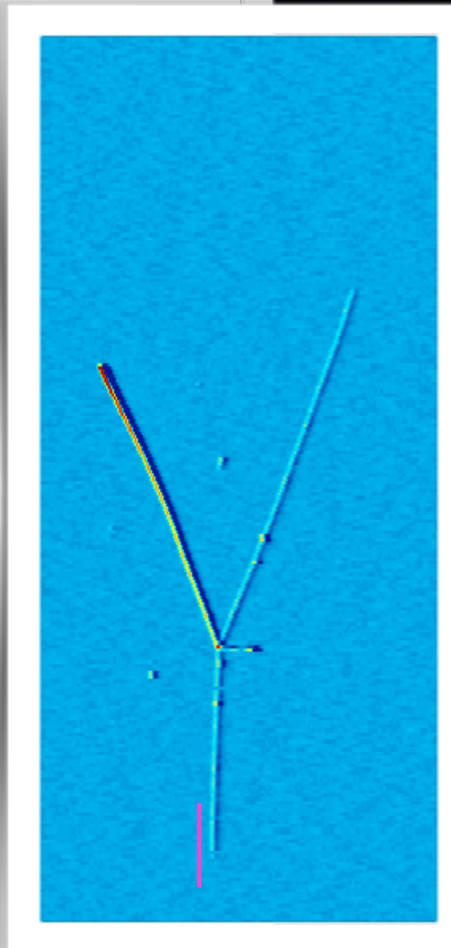


Signals from each PMT are sampled/digitized for a duration of few microseconds

Signals from each wire are sampled/amplified/shaped/digitized for a duration longer than the maximum drift time (milliseconds). This is an eternity compared to usual HEP experiments.

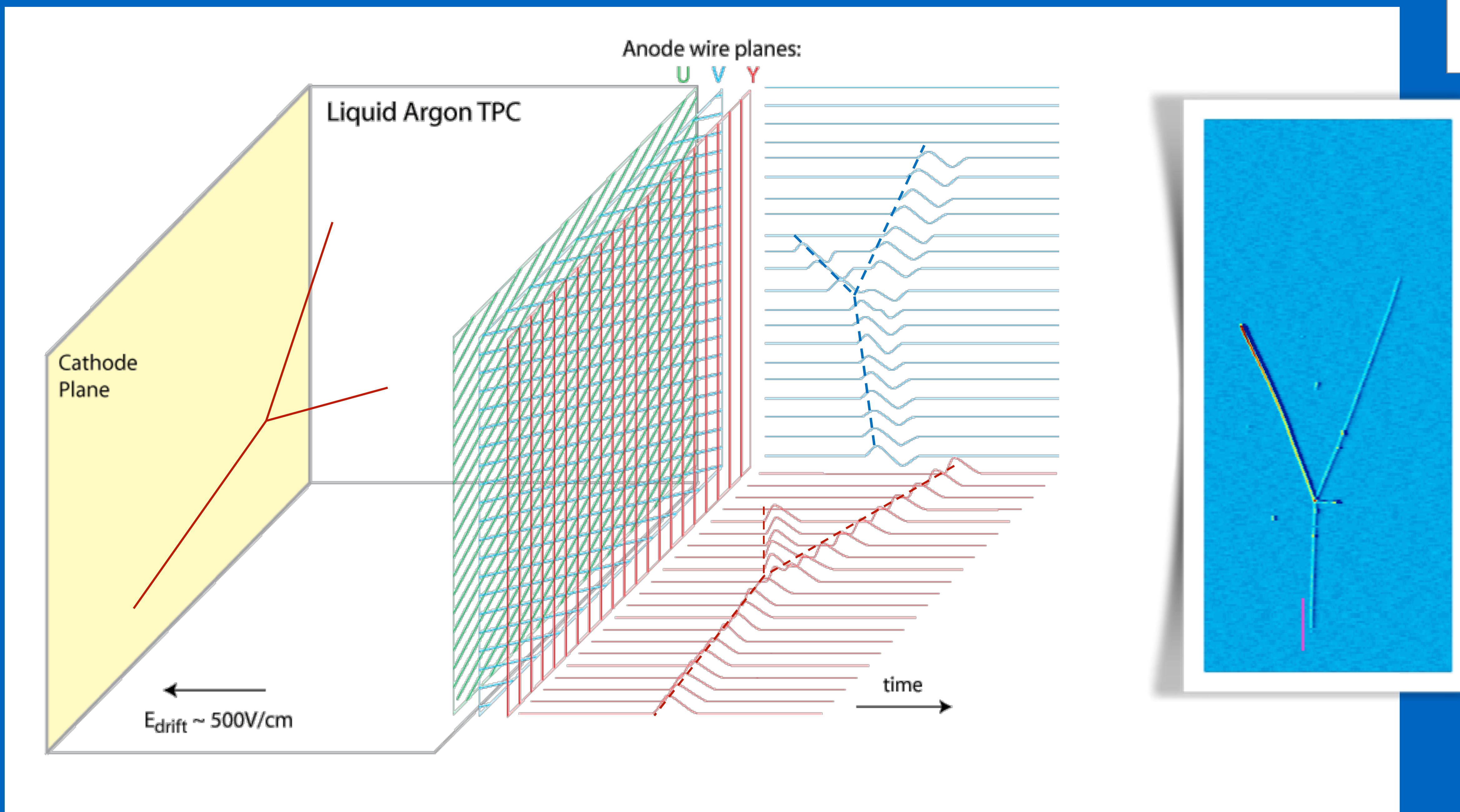
LArTPC at work

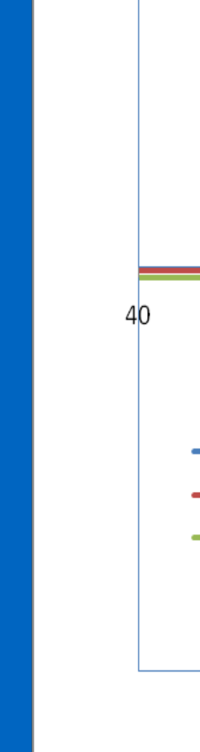




TPCs

- Drifting charge induces current in wires it is approaching/receding from.
- Wireplanes act as “Frisch” grids that shield subsequent planes from drifting charge.
- Transparency of Induction planes, and opaqueness of Collection plane, is achieved through anode geometry and bias voltages applied to wires: $E_{g2} \geq r_{T2} E_{g1}$ and $E_{g1} \geq r_{T1} E_d$ ($r_T = 1.4$)





Refs:
1.) *Design of Grid Ionization Chambers*, Bunneman, Cranshaw,Harvey, Can. J. Res. 27 (1949) 191
2.) *Design of Large LArTPCs*, B. Yu, TIPP 2011

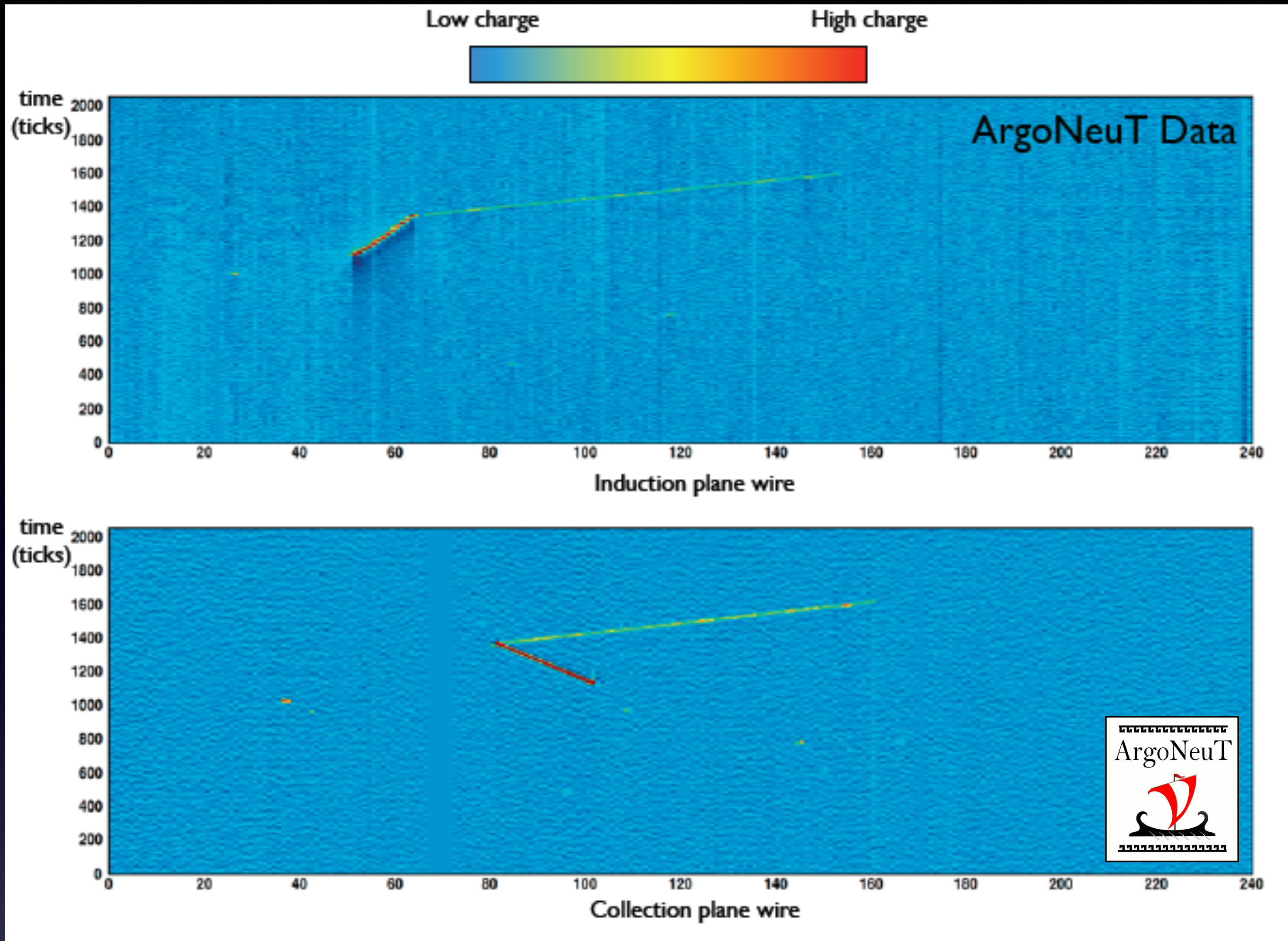
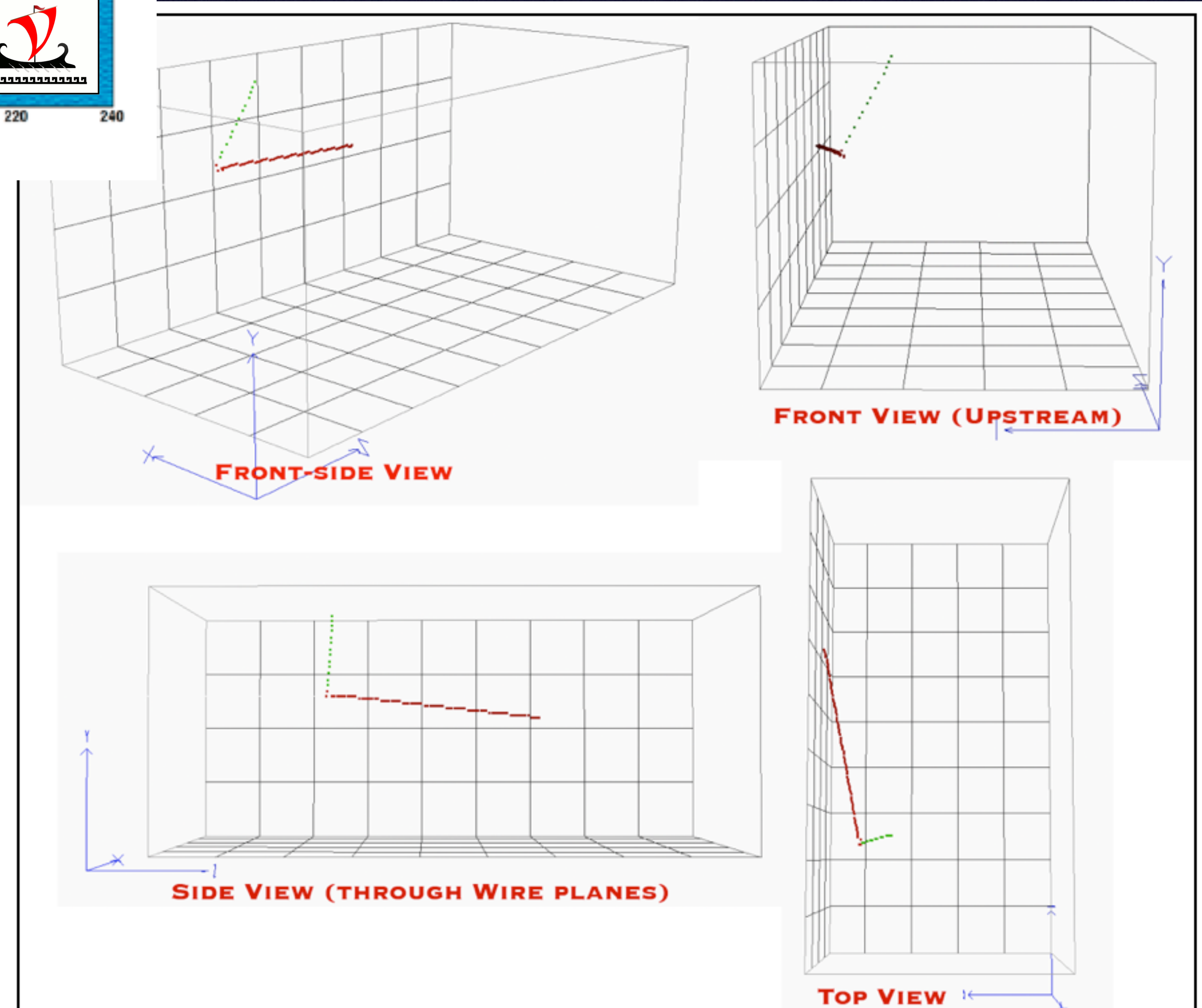


Image reconstruction in 3D is accomplished by combining information from the two 2D views



LArTPC: calorimetry

The hit amplitude (in ADC counts) in a wire of the Collection plane corresponds to the charge Q_{det} (in fC units) in the track segment $\boldsymbol{\delta x}$ detected on that wire (need calibration ADC to fC)

a first correction is applied to obtain the free charge after recombination $Q_{free} = Q_{det}/\exp(-\mathbf{t_D}/\boldsymbol{\tau_e})$

a second correction is applied to obtain the total charge released $Q_{ion} = Q_{free}/\mathbf{R}$

The charge Q_{ion} released is directly related to the energy deposited $\boldsymbol{\delta}\mathbf{E} = W_{ion} * Q_{ion}$ in the track segment $\boldsymbol{\delta x}$.
Note: $(\boldsymbol{\delta}\mathbf{E}/\boldsymbol{\delta x})$ is a measure of the energy loss of the ptcl.

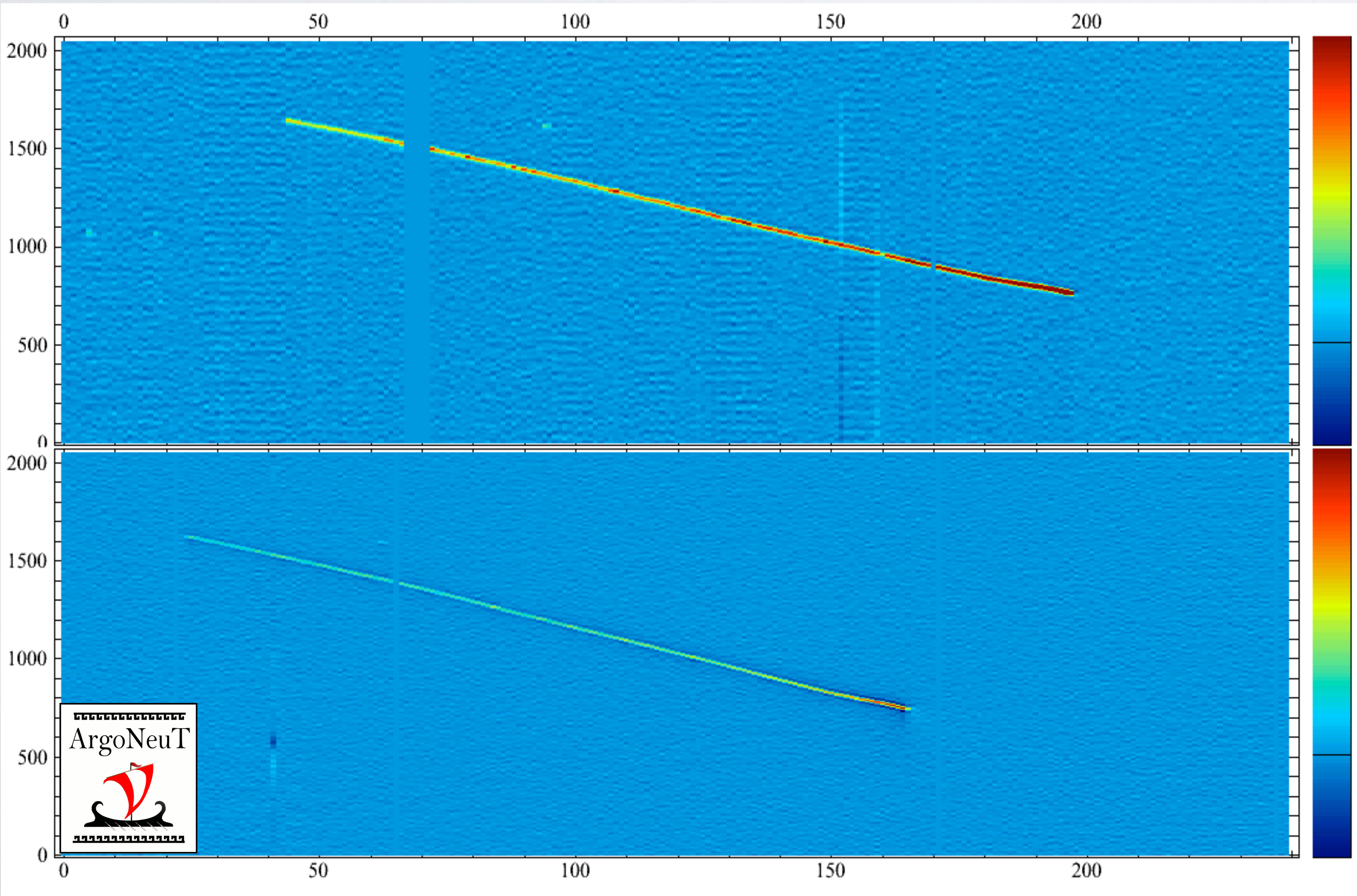
The total energy deposited $\mathbf{E_{dep}}$ is obtained by summing over all the segments along the track, $\mathbf{E_{dep}} = \sum(\boldsymbol{\delta}E/\boldsymbol{\delta x})\mathbf{i} * \boldsymbol{\delta x}$

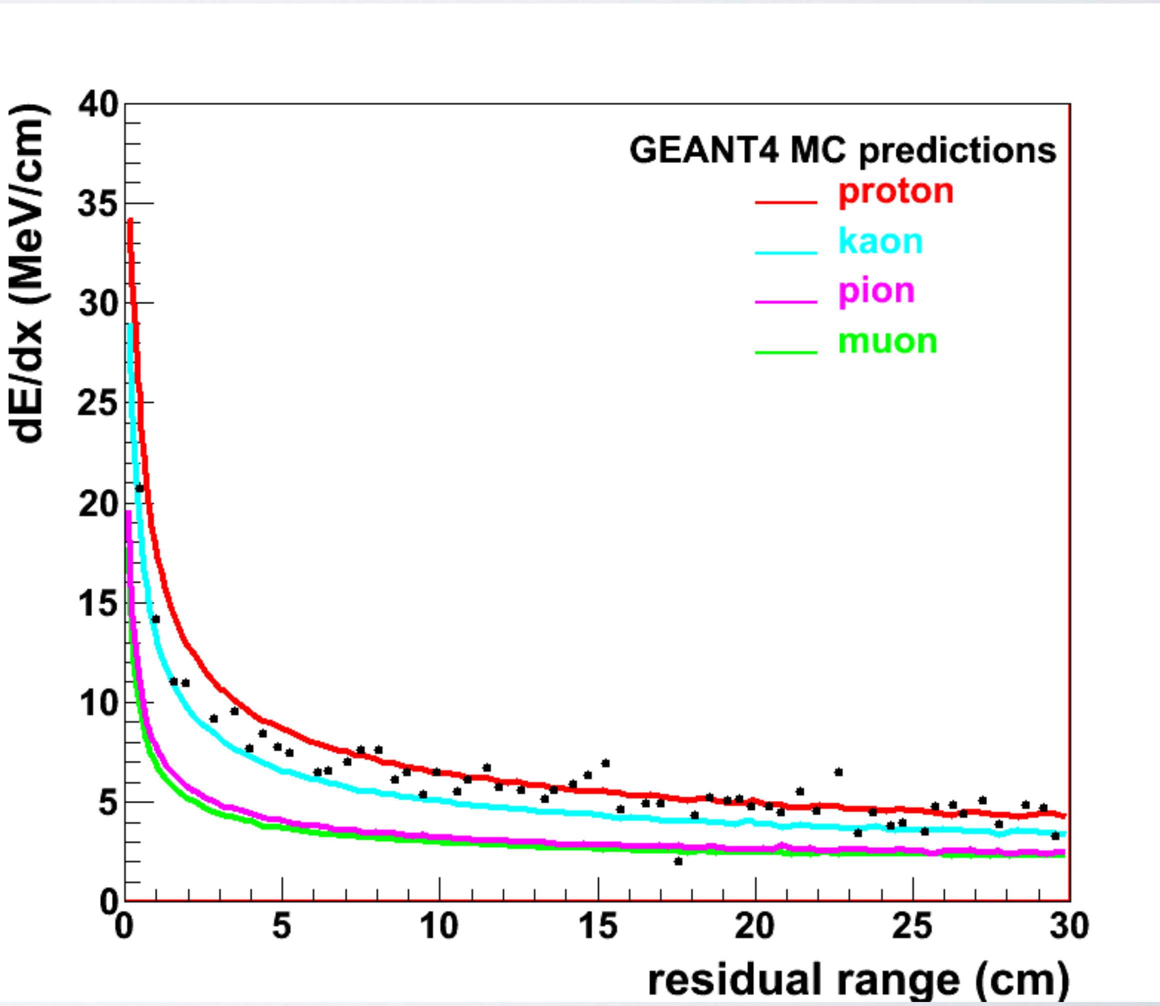
Note: $\mathbf{E_{dep}} = \mathbf{T}$ kinetic energy of the ptcl

LArTPC: Particle Identification

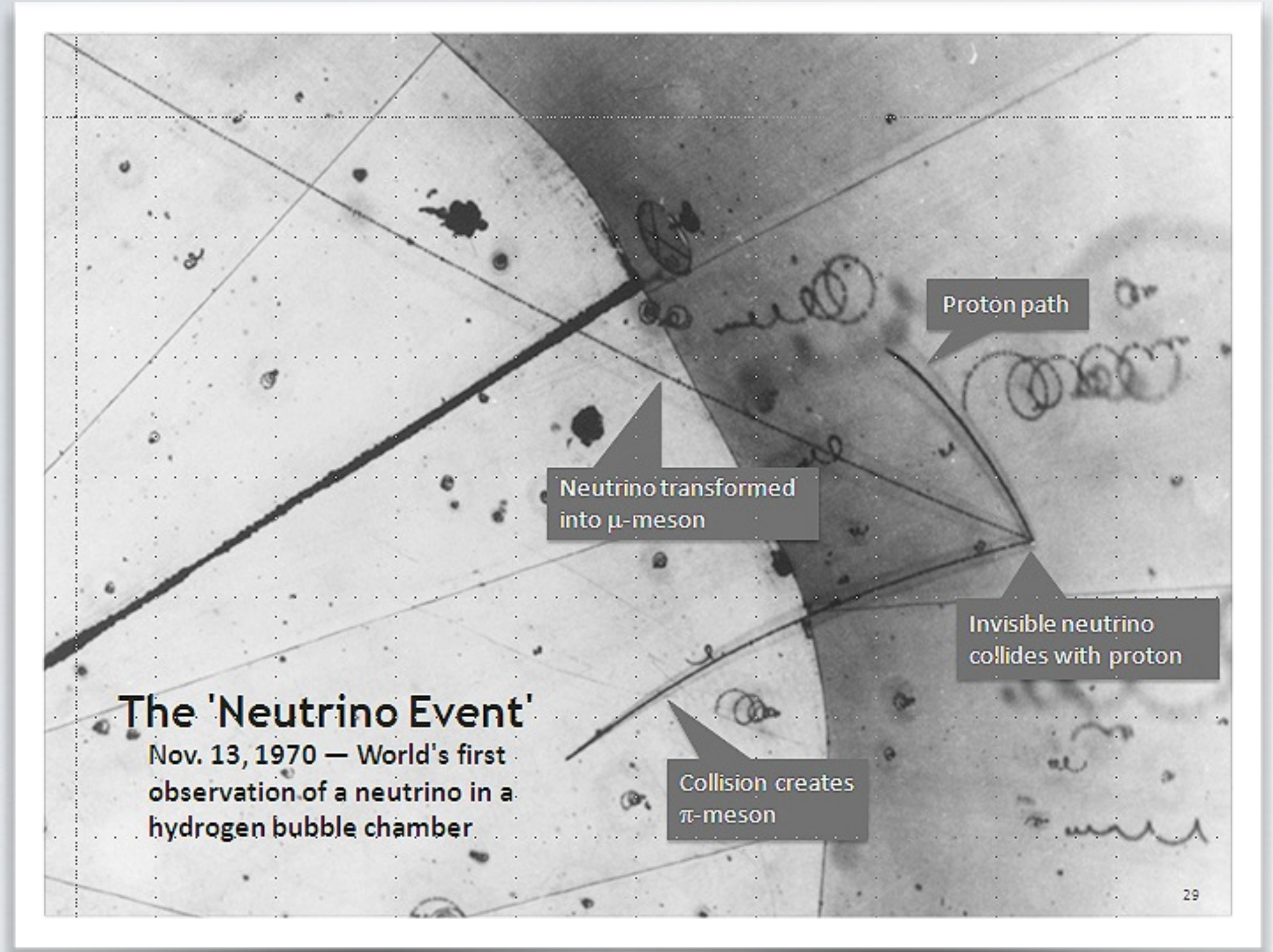
When incident particle slows down and stops in the LArTPC active volume, the energy loss as a function of the residual range (the path length to the end point of the track) is used as a powerful method for particle identification (PId).

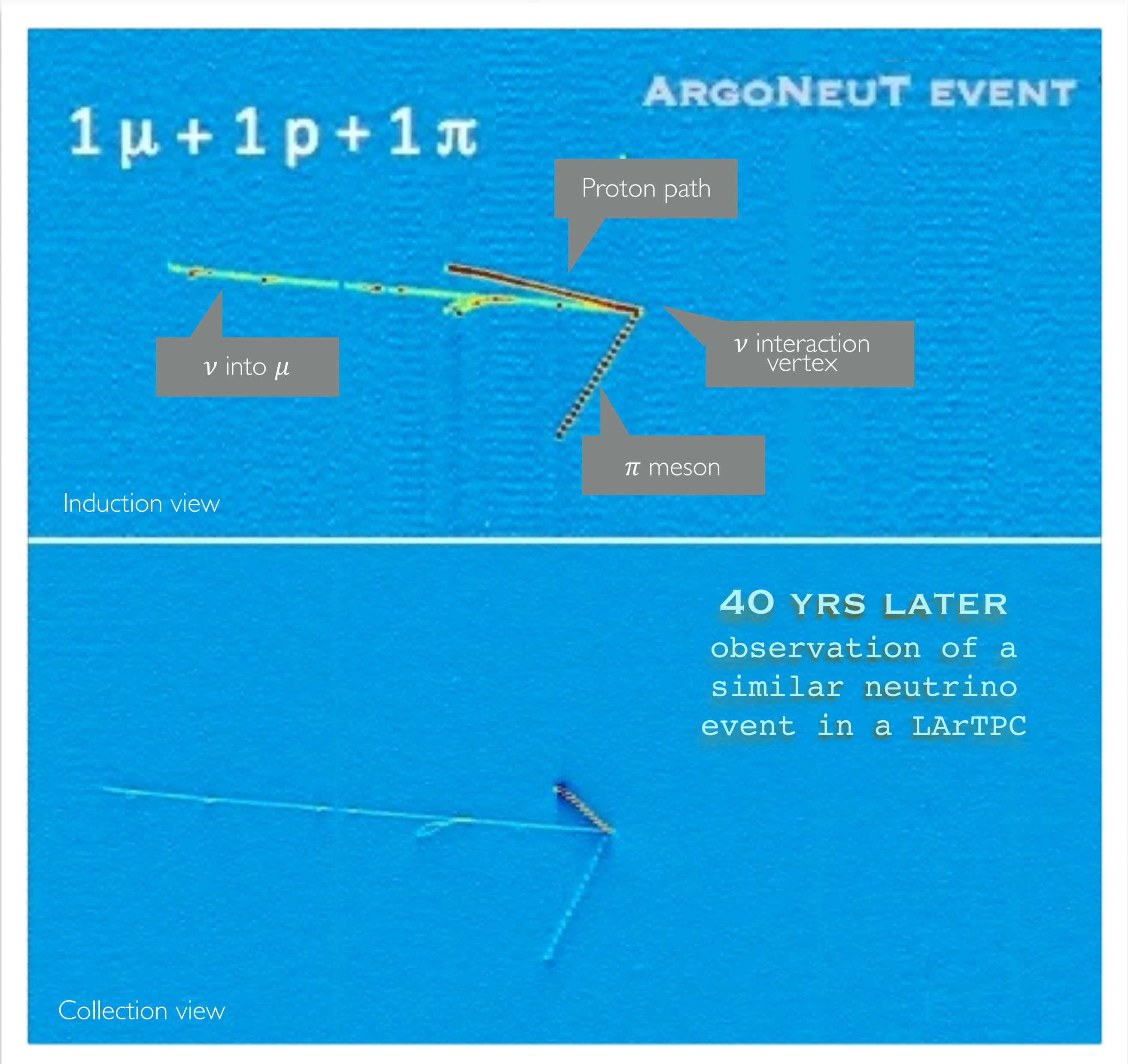
Charged particles of different mass (or charge) have in fact different increasing stopping power at decreasing distance from the track end,





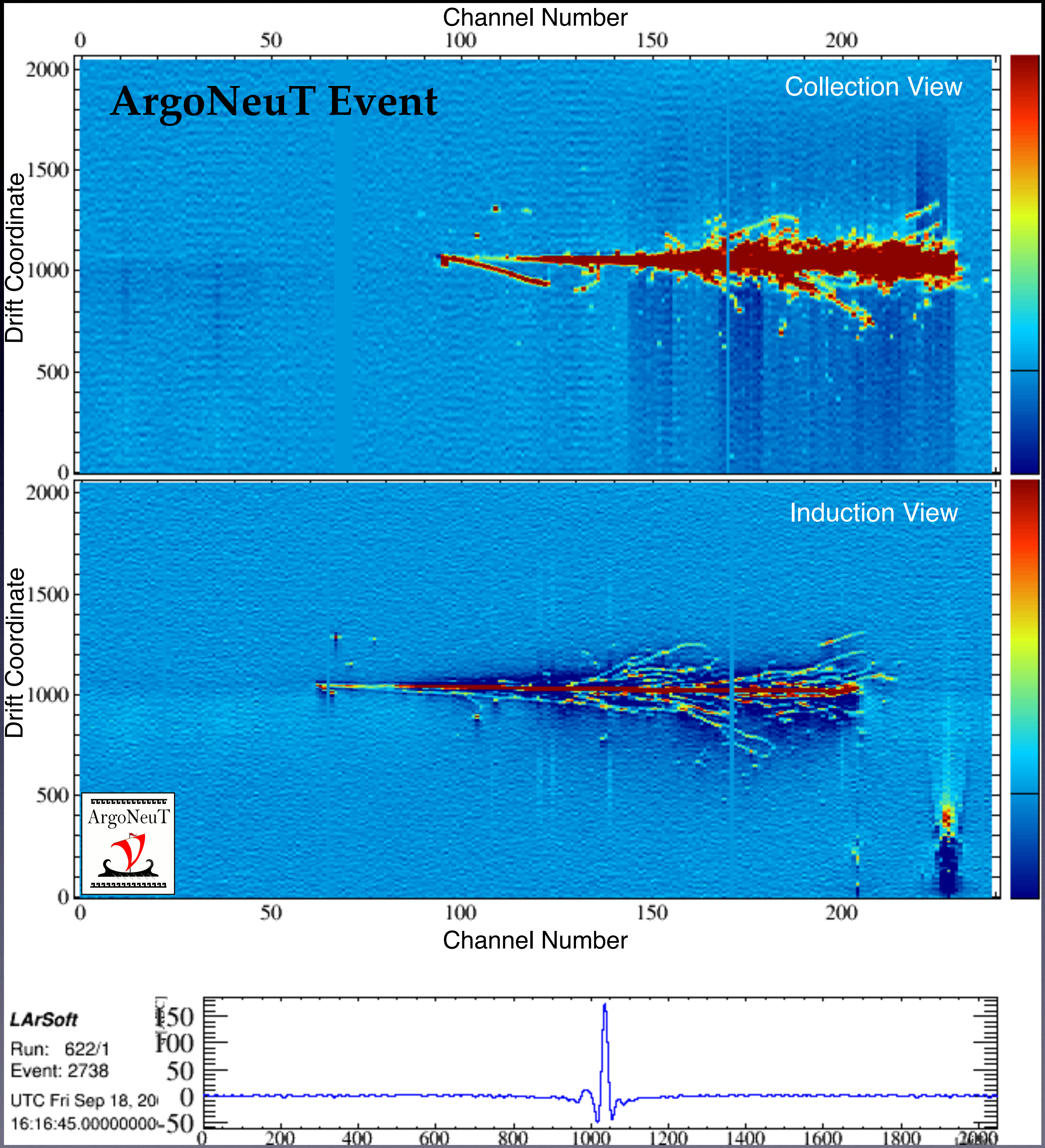
From Bubble Chamber to ArgoNeuT





Ready for studying neutrino-nucleus interactions ??

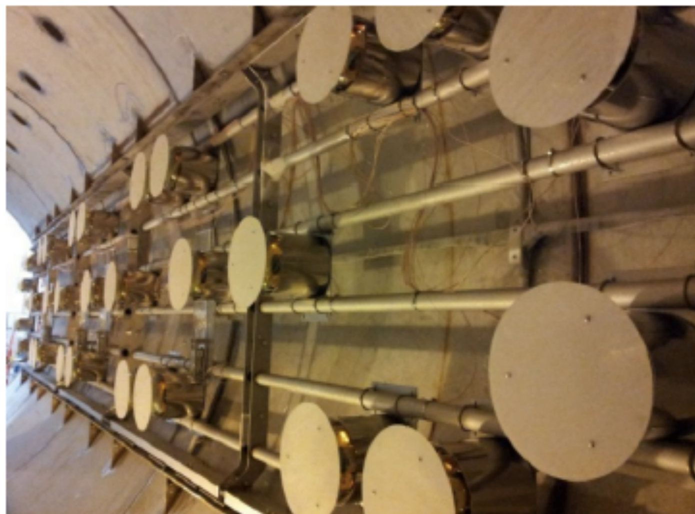
Accessing so far undetectable features of neutrino interactions with target material is the new path to the next generation Neutrino Oscillation Experiments



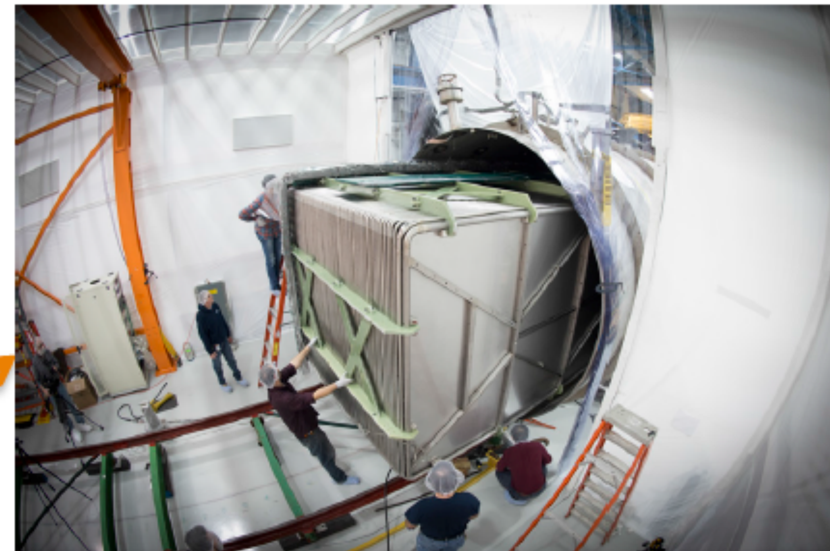
MicroBooNE at FNAL

Installation: a picture series

PMT system installation: Dec 2013



TPC insertion: Dec 23rd, 2013



Moving day! June 23rd, 2014

MicroBooNE's home in the beam line: The LAr Test Facility

Foamed in! July 2014

Cabled up! Sept. 2014

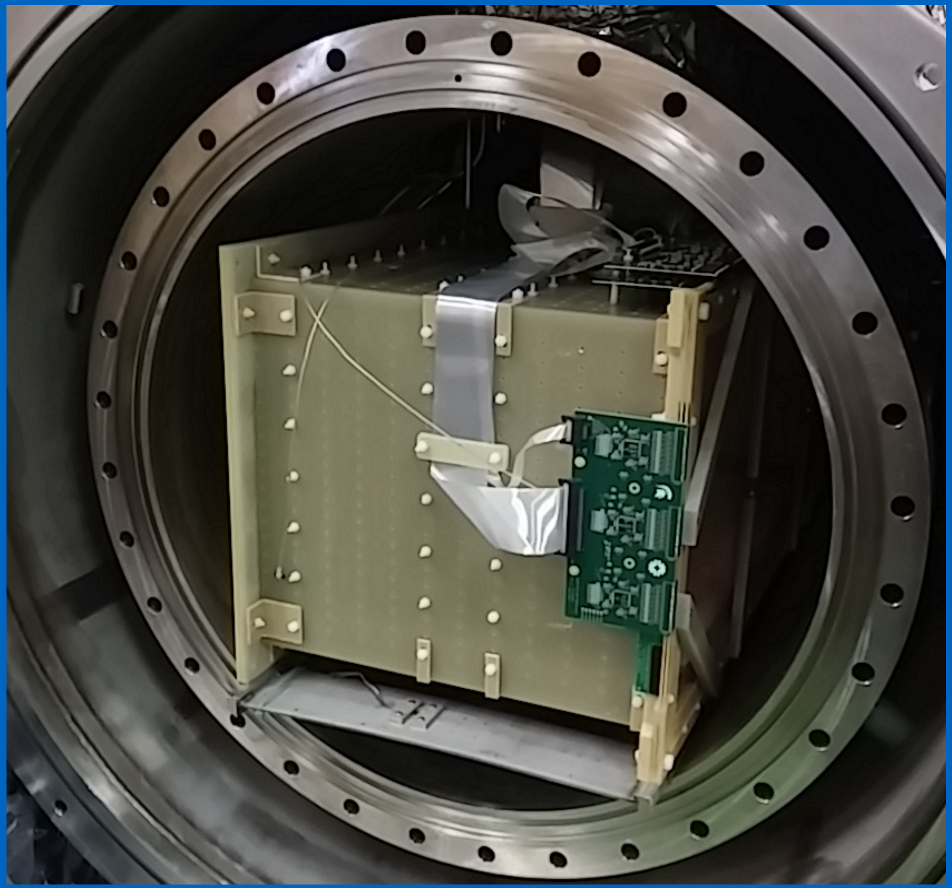
All electronics in! Dec. 10, 2014

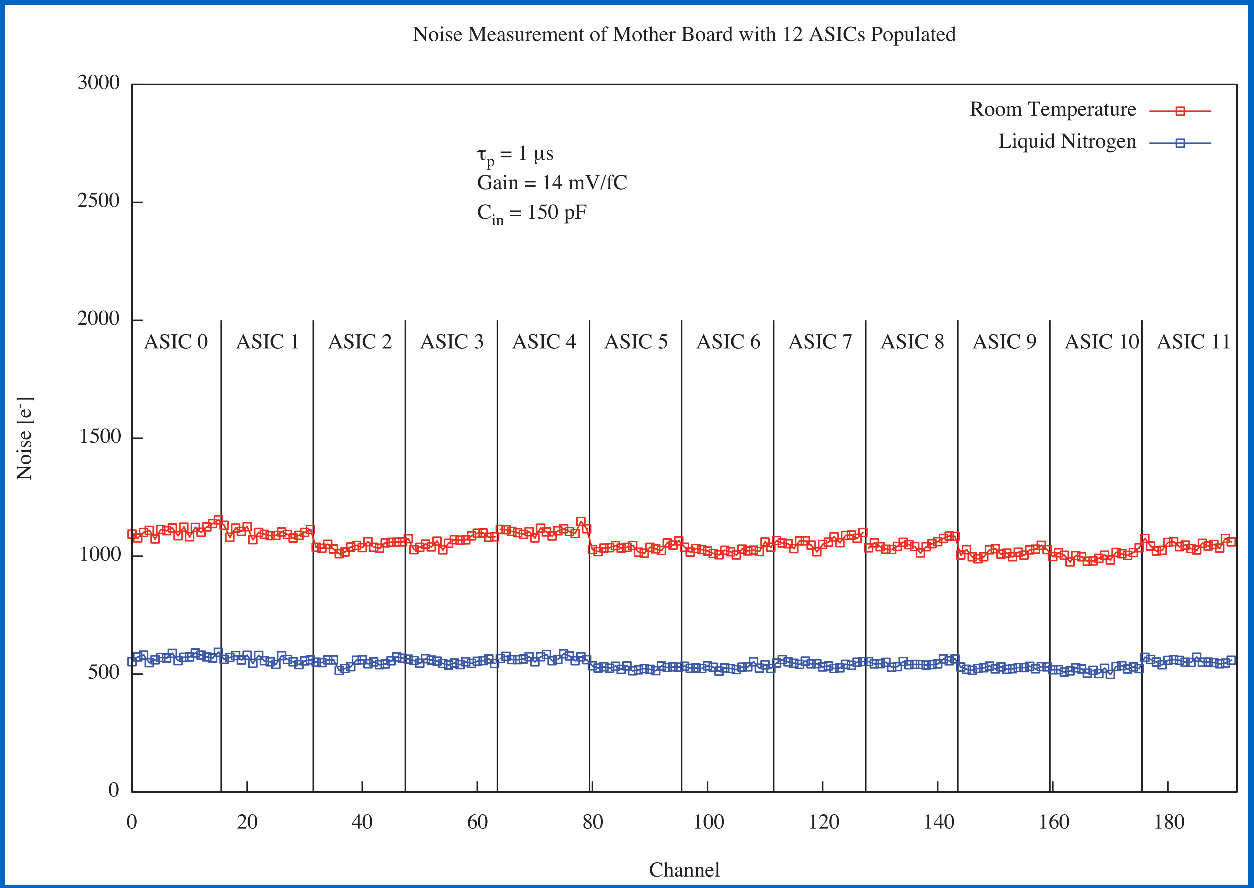
Backup

Lecture 1

Electronics

- Signals from each wire are sampled/amplified/shaped/digitized for a duration longer than the maximum drift time (milliseconds). This is an eternity compared to usual HEP experiments.
- Small signal sizes demand low-noise electronics.
- Placing the amplification circuit in the LAr, directly on the TPC, increases S/N performance.

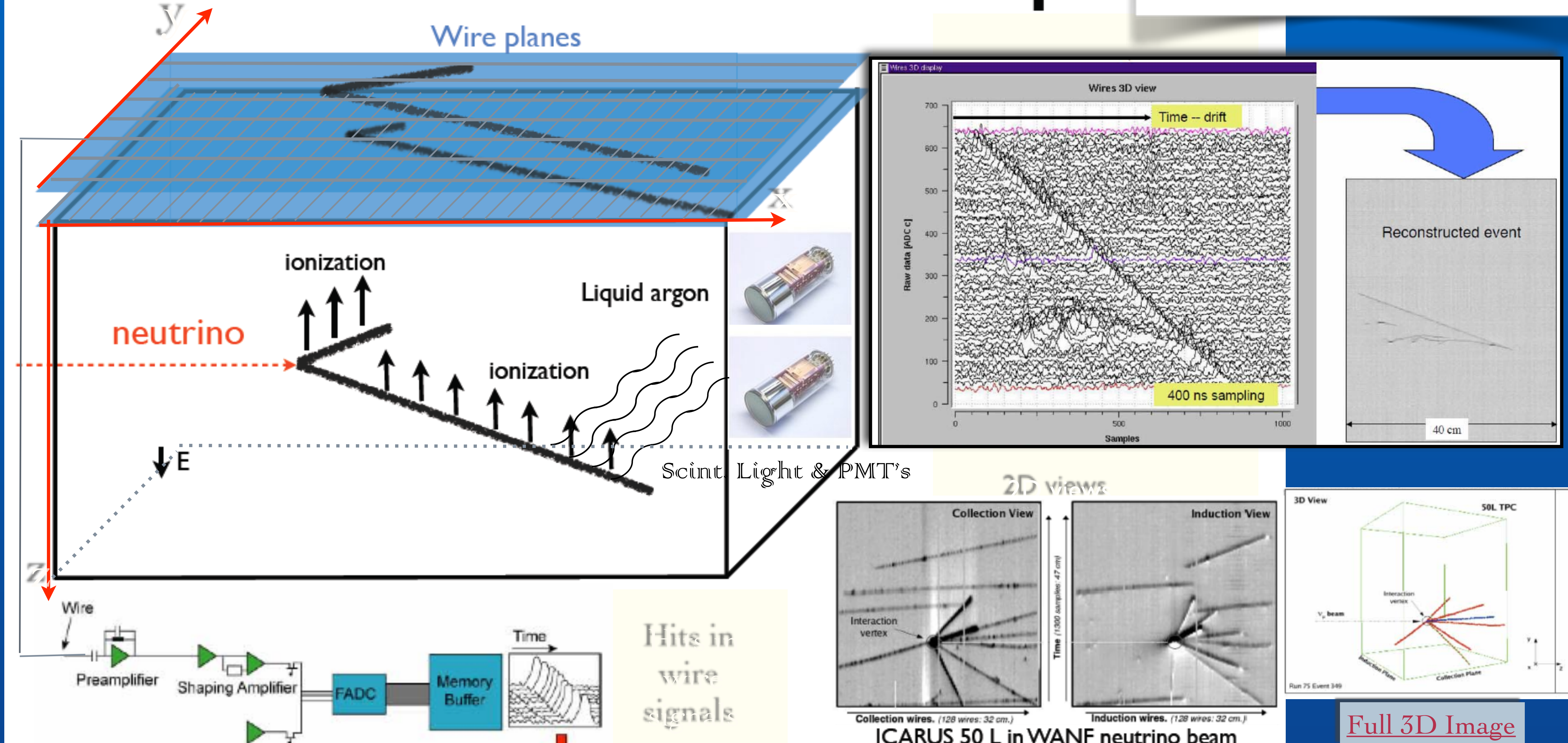




Refs:
1.) *Readout electronics for the MicroBooNE LAr TPC, with CMOS front end at 89K*, H. Chen et al, JINST 7 C12004, 2012

The LArTPC concept

FOR N PHYSICS

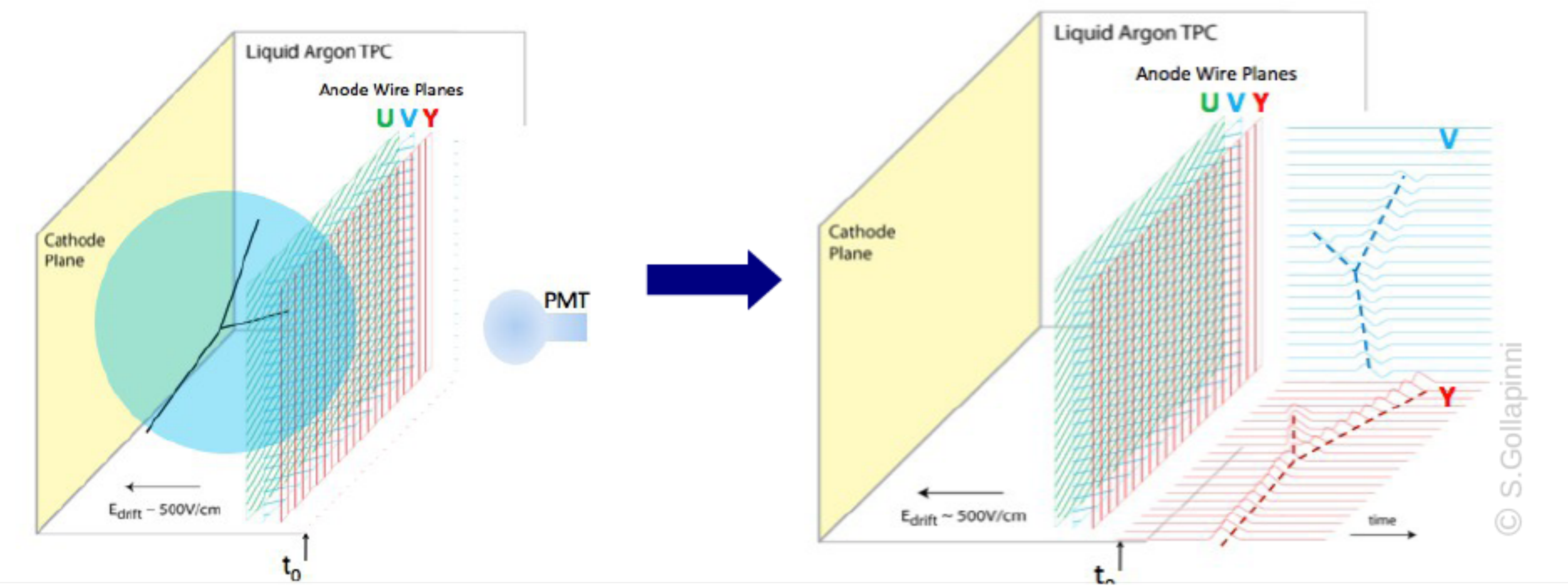


(Neutrino) interactions inside the LAr-TPC

- Prompt Scintillation Light is detected (after VUV-Vis w.l. down-conversion) by array of PMTs.
  * Scintillation light collected by PMTs is used for
- Free Ionization electrons tracks in EF drift towards anode planes of wires
  * Track segments induce hits on corresponding wires: the wire coordinate in the wire plane provide hit position.
  * Multiple (
    * Timing of pulse (T

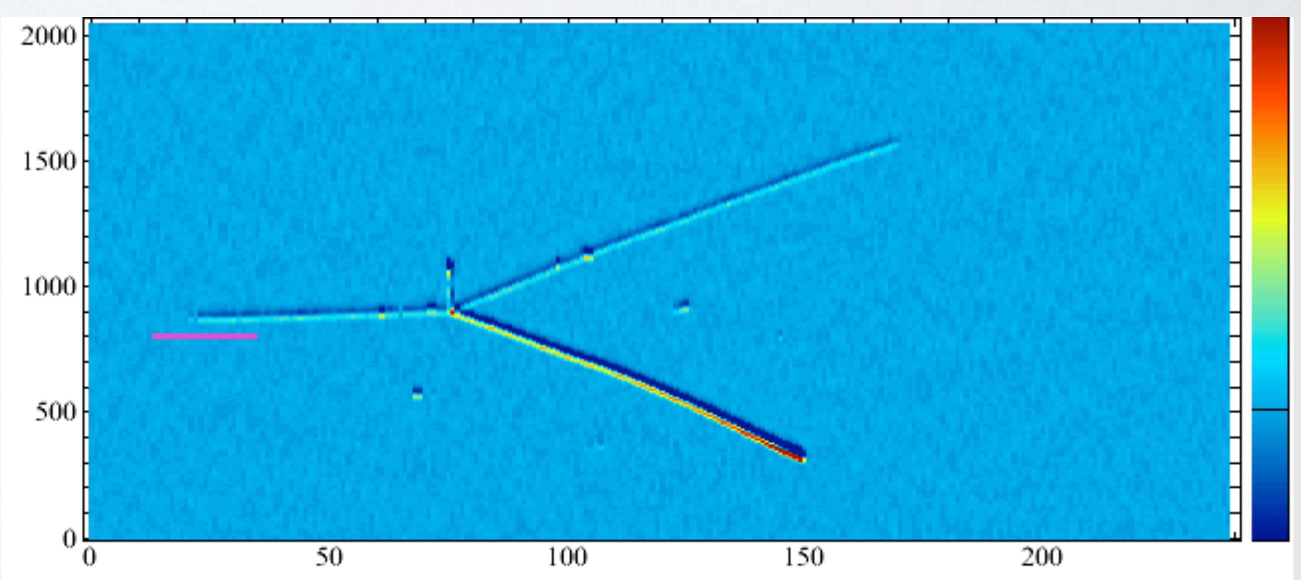
    ⇒ Multiple
  * Collection of the ionization charge on wires of the last plane (hit amplitude) measures the deposited energy

Time projection chambers

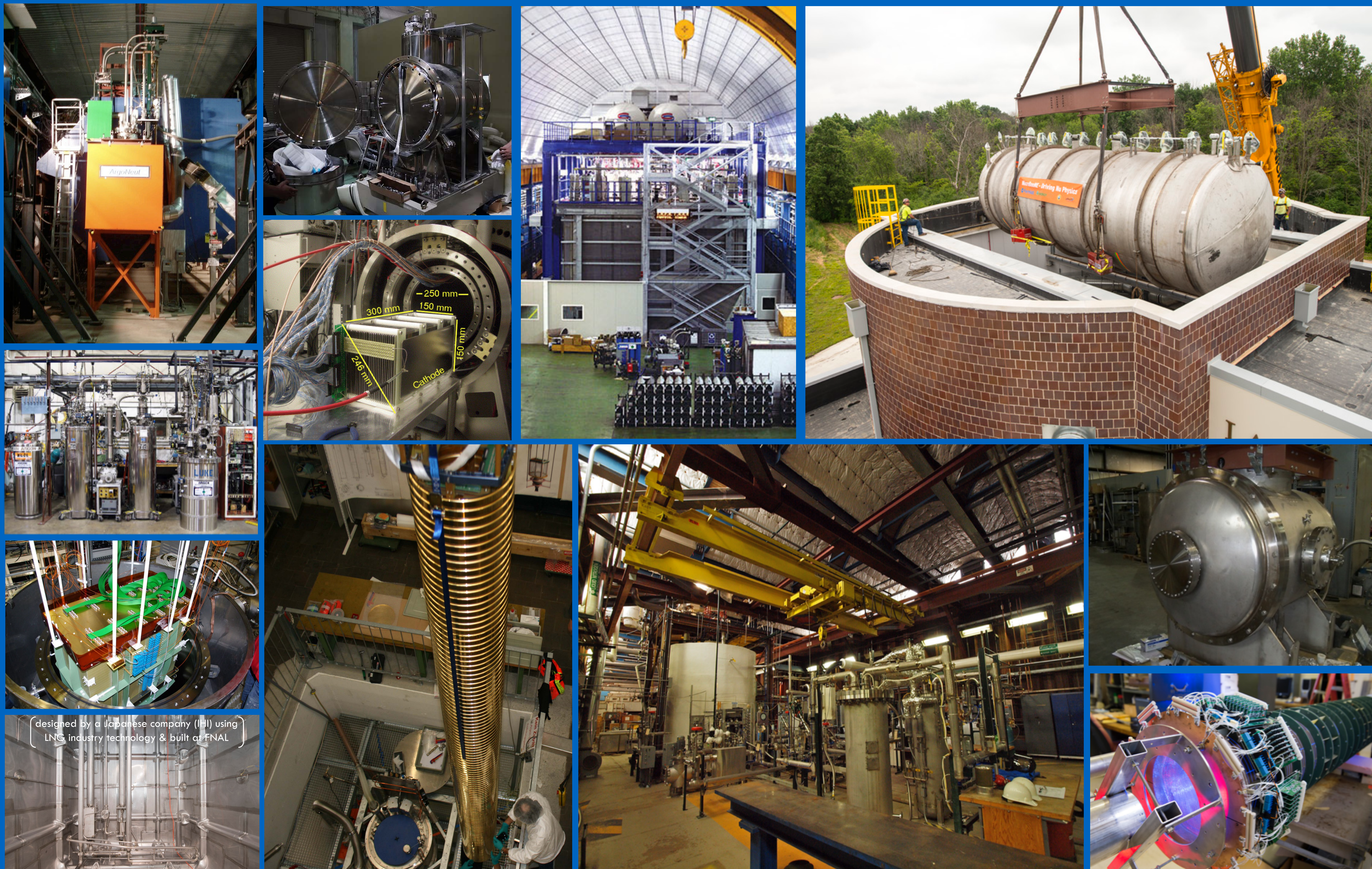


LAr-Time Projection Chambers allow multiple 2D and the 3D reconstruction of charged particles tracks.

- Charged particles crossing the detector ionize the liquid, producing free electrons that are drifted towards the readout wire-planes and produce digitized signals.
- The 3rd coordinate is determined from measuring the drift time. Scintillation light gives the reference t_0 time.
- The total charge is prop to the deposited Energy ⇒ calorimetry. (note: also scintillation light is prop to dep Energy)
- dE/dx along the track ⇒ PId

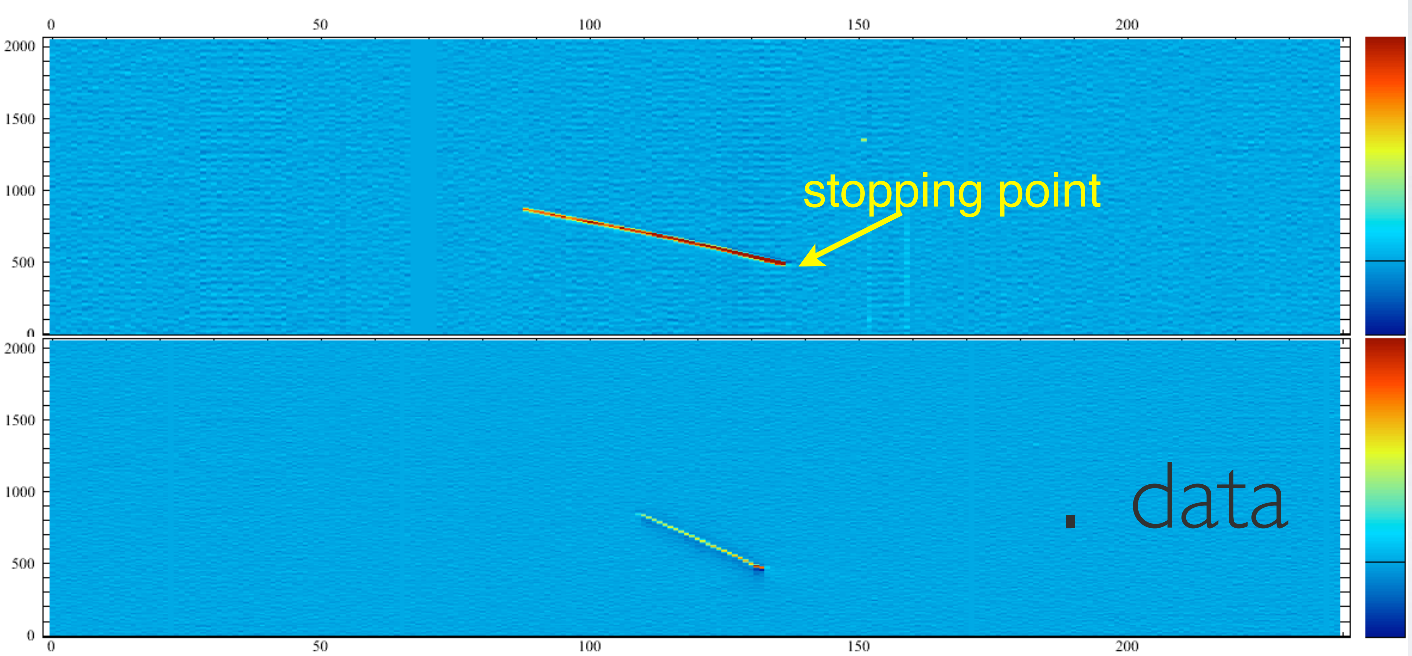


LAr Worldwide

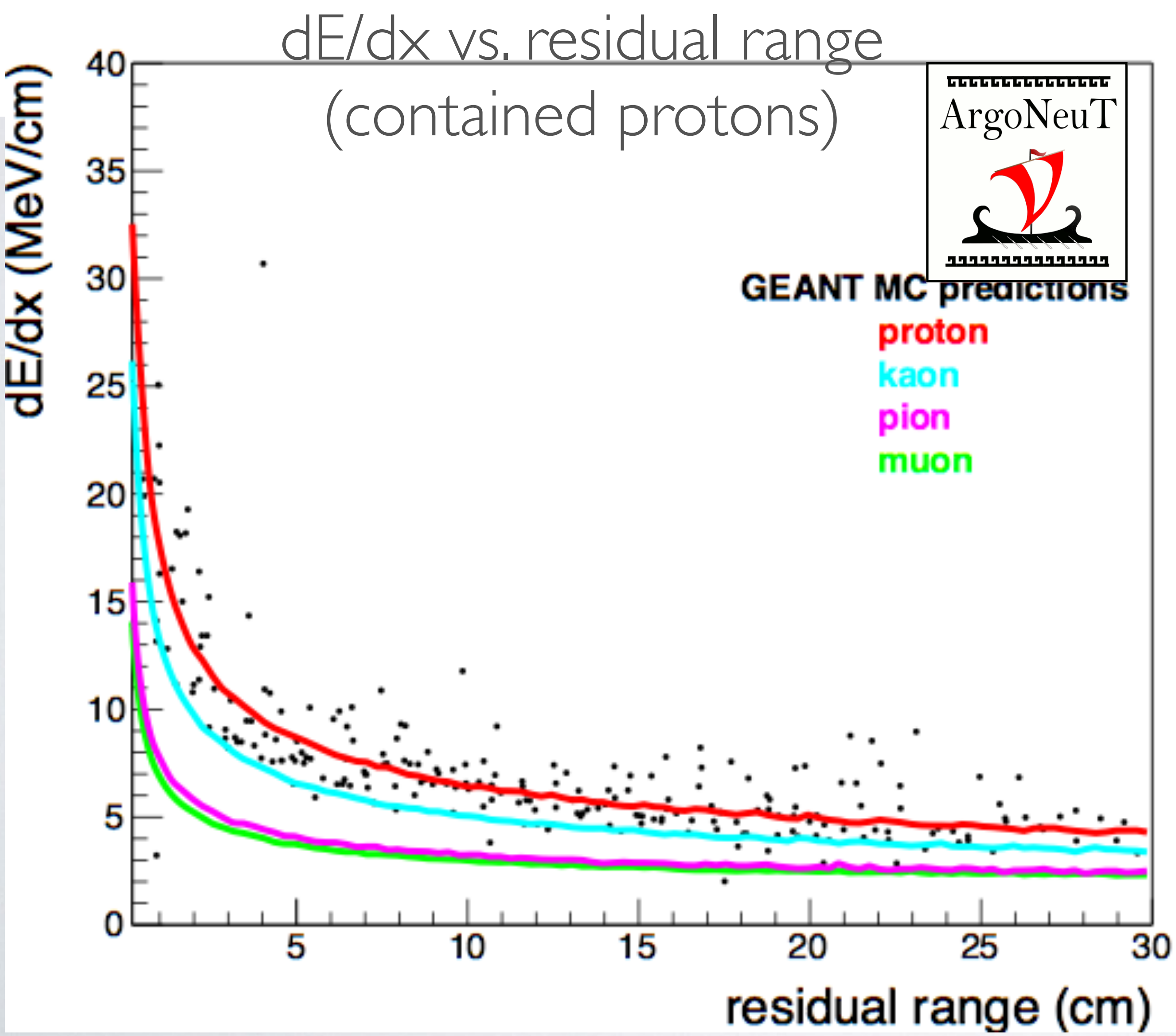


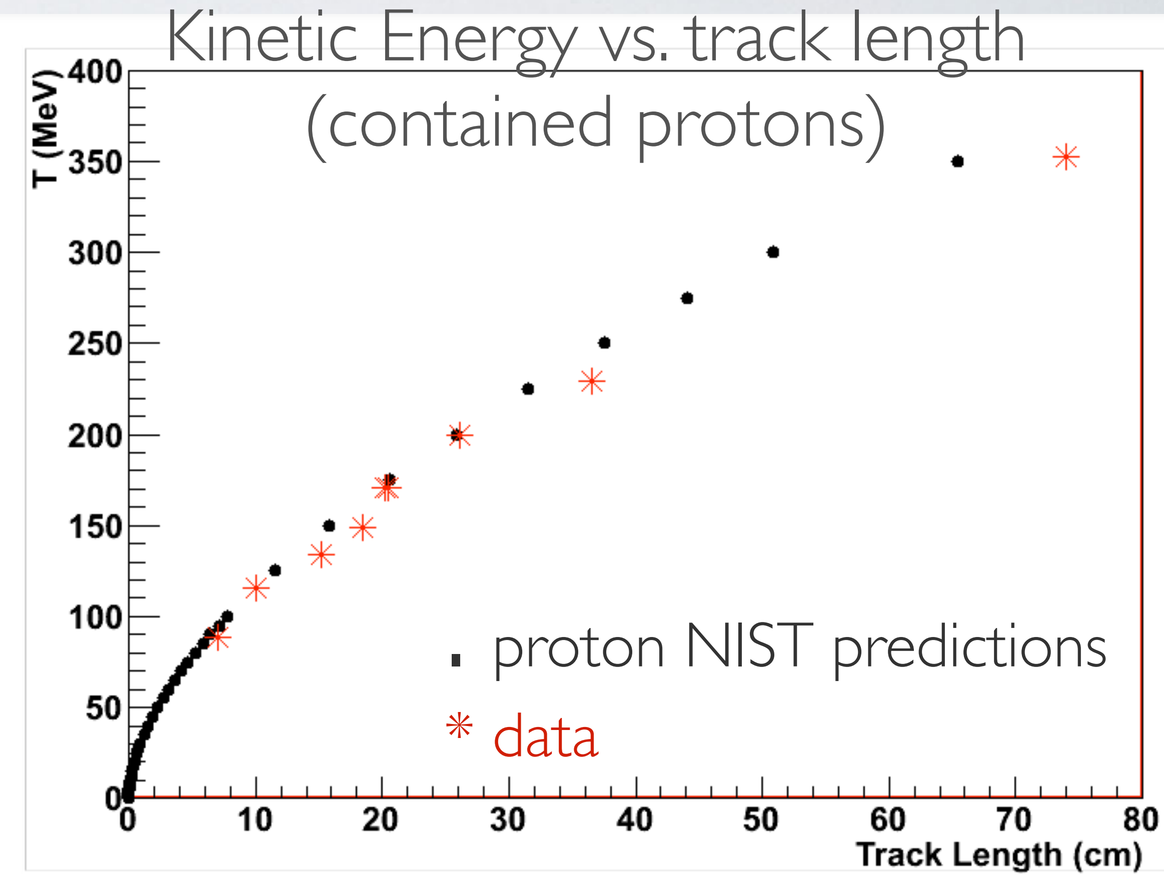
Far too much activity to cover each of these, so I'll focus on the general aspects of LArTPCs

CALORIMETRIC RECONSTRUCTION & PID



"Off-Line SW R&D"





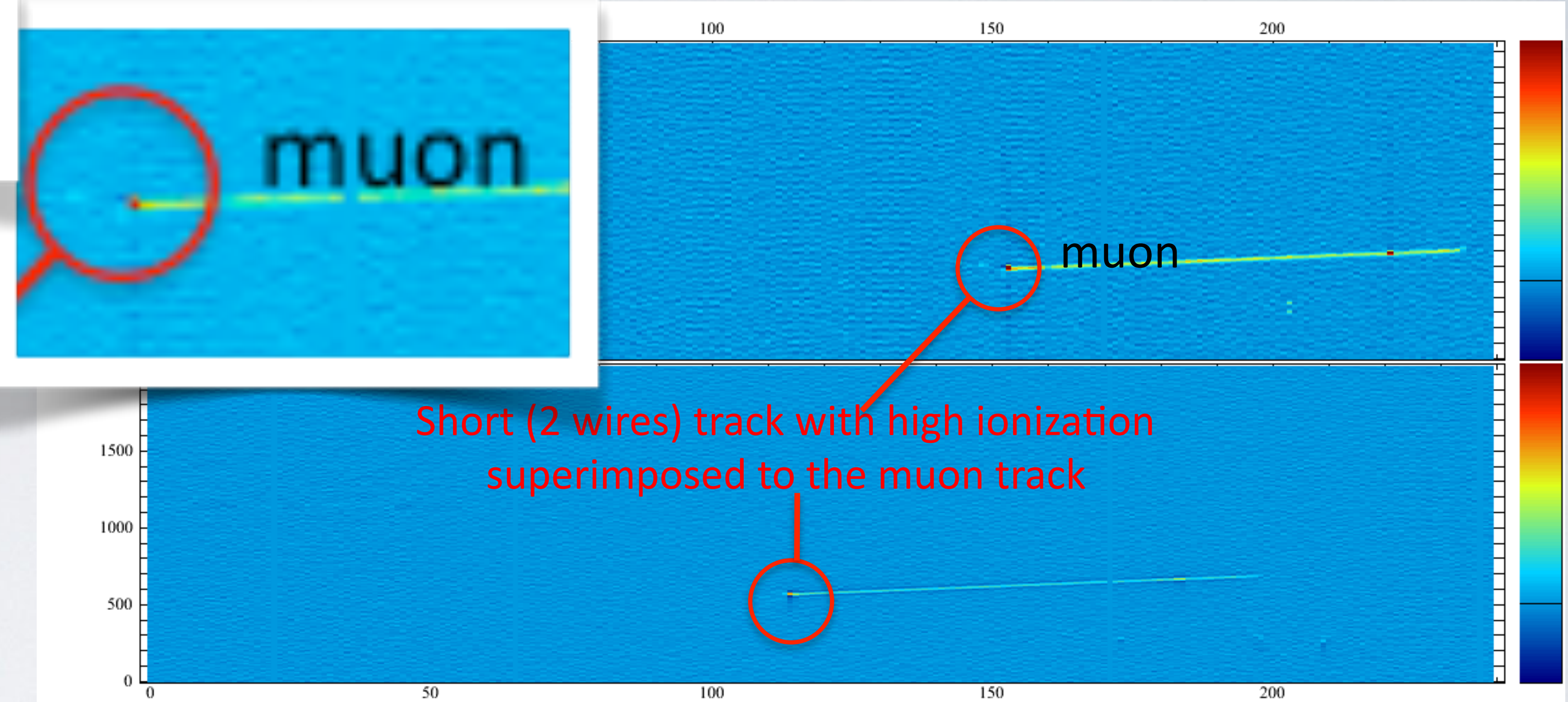
Measurement of:

- dE/dx vs. residual range along the track
- kinetic energy vs. track length

Low energy proton reconstruction

"Off-Line SW R&D"

proton threshold is 21 MeV of Kinetic Energy (ArgoNeuT)

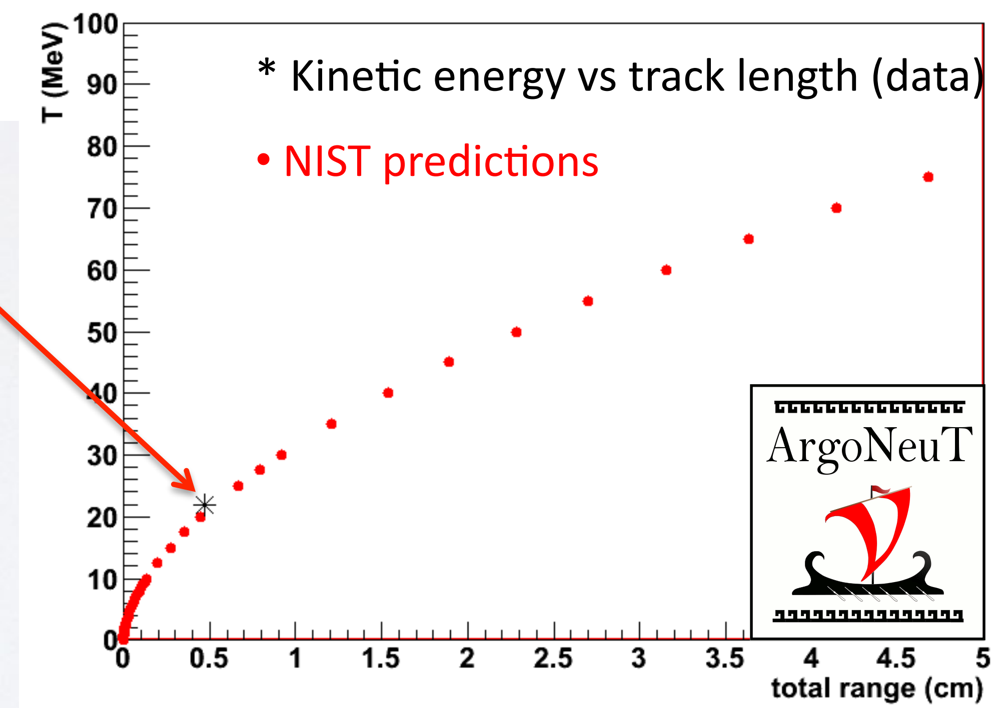


The short track behaves like proton

The event is (CCQE) 1p – 1 μ−

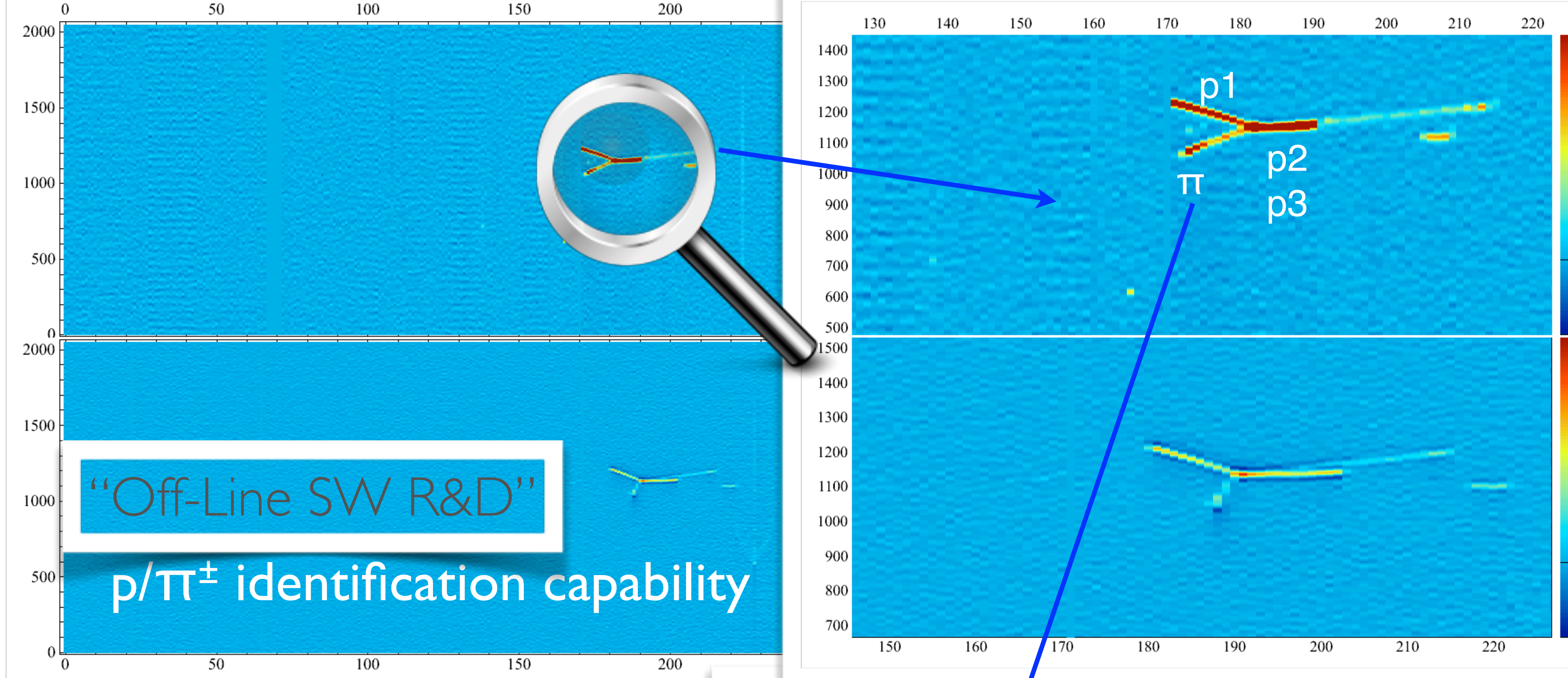
KE=22±3 MeV

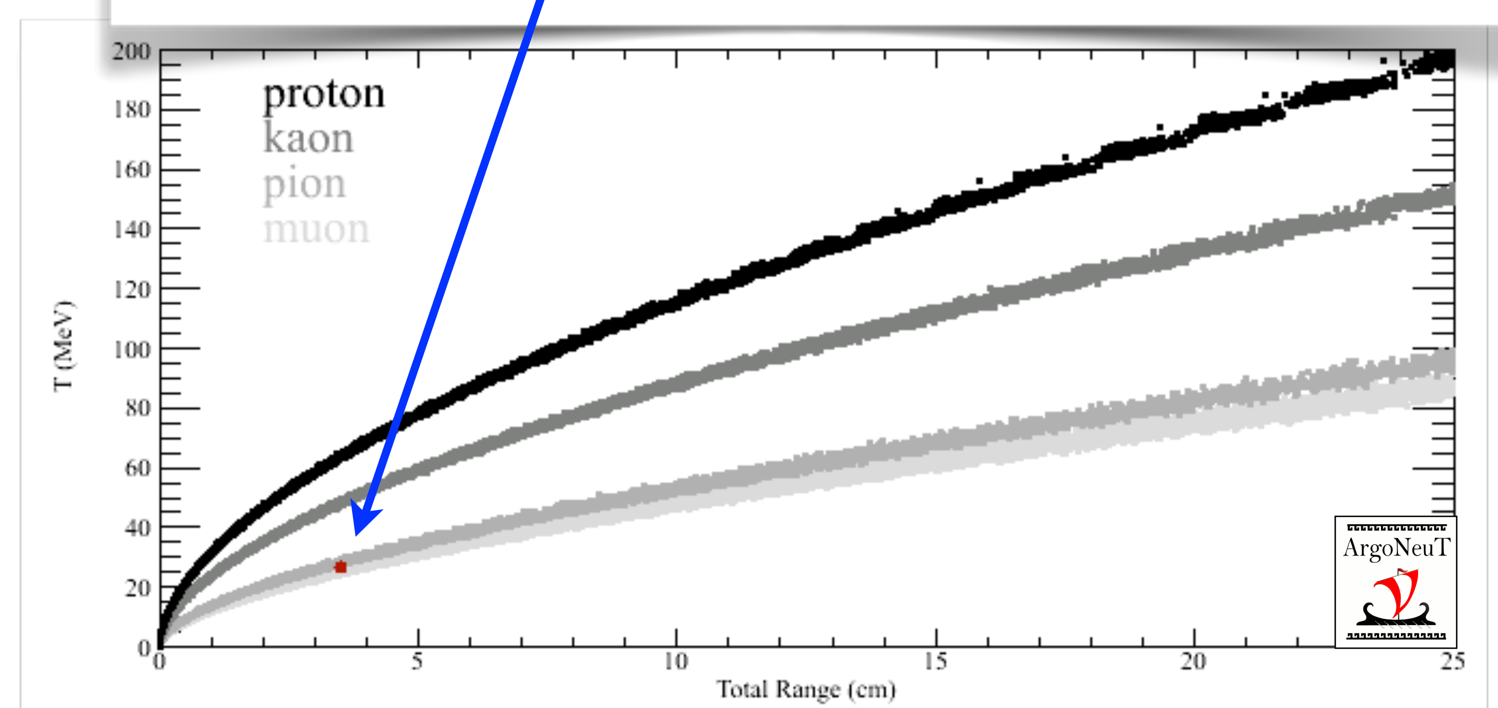
Length=0.5 cm



“Off-Line SW R&D”

p/π$^{\pm}$ identification capability





- *p1*: 4.9 cm ----> T=83±5 MeV
- *p2*: 5 cm ----> T=134±7 MeV
- *p3*: 5 cm ----> T=134±7 MeV
- **π**: 3.5 cm ----> T=26±3 MeV

1μ 3p 1π

⇒ Event not in the muon+Np sample