Integral Concept of Sensors and Electronics – Past to Future

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Caveat …

… about any historical account given by a participant:

"History will be kind to us . . .

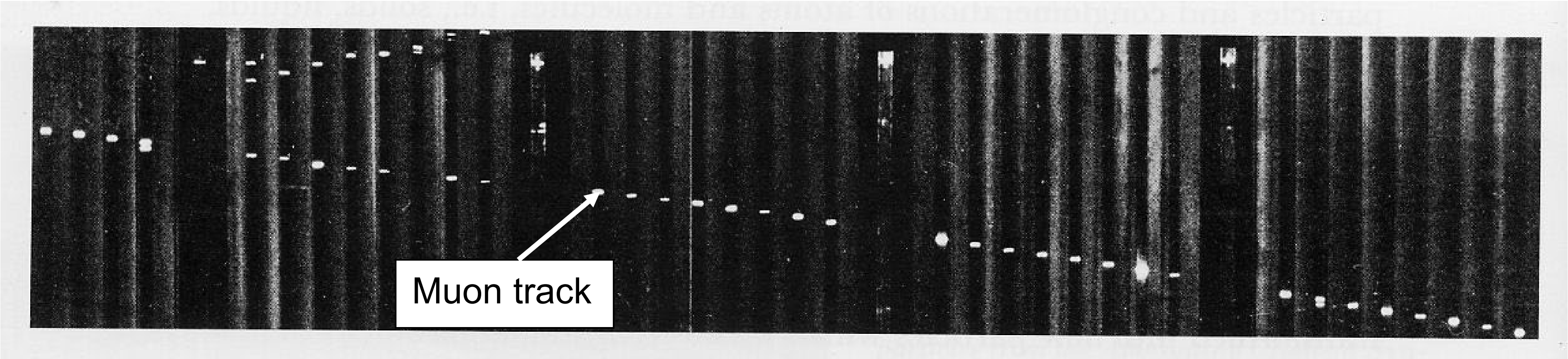
… I intend to write it"

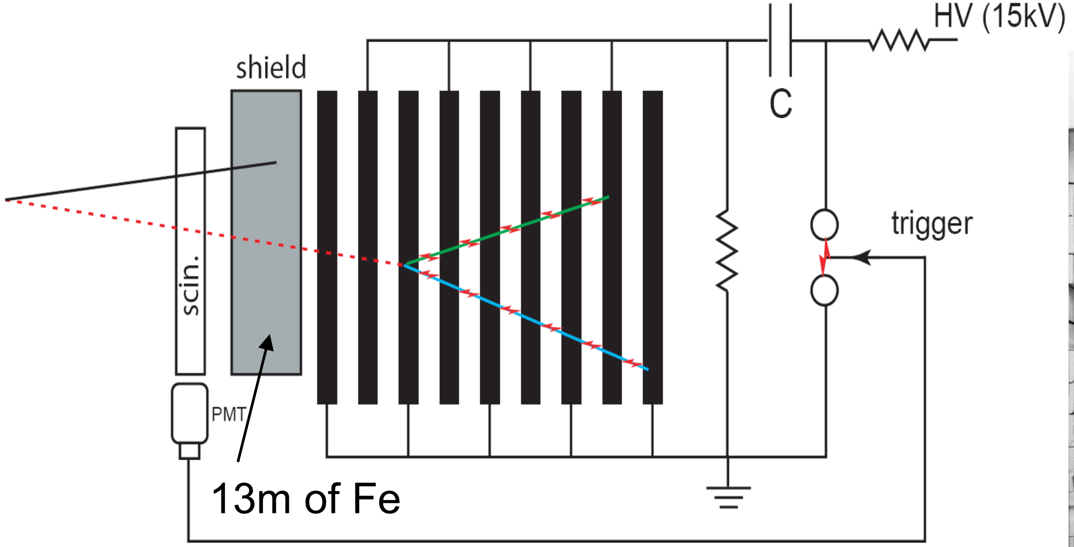
(W.C. ~1945)

Limited Selection of significant events in Detector Technology

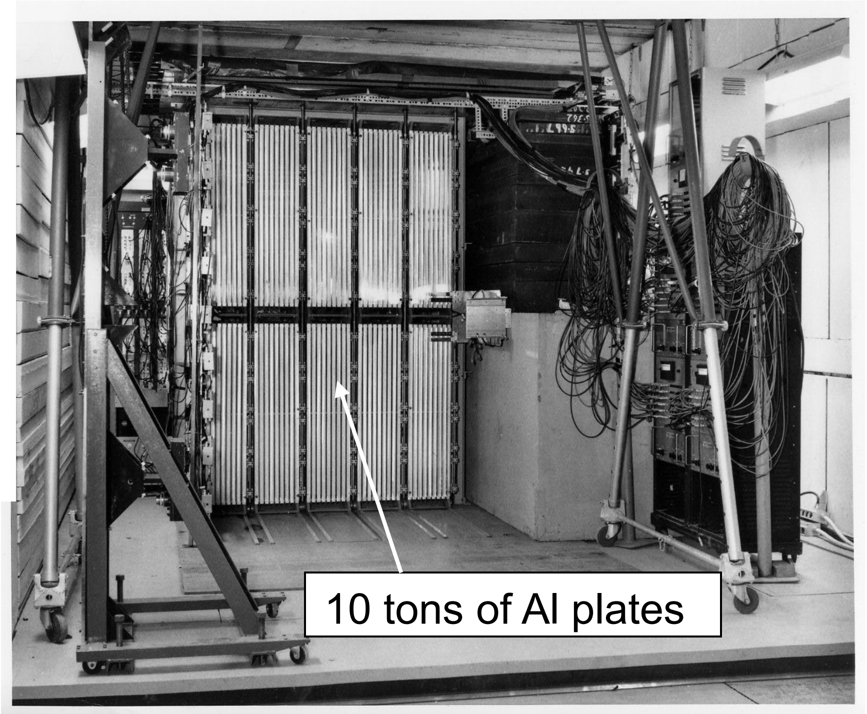
- **Germanium p-i-n detector**, Tavendale, Ewan (1963-4), gamma-ray and x-ray spectroscopy; first cold front end JFET (1965)
- **Liquid Argon Ionization Calorimetry**, Willis, Radeka (1972) → CERN ISR → ATLAS
- **TPC** , Nygren (1974), lasting impact through gas and later noble liquid TPCs
- H. Chen, C. Rubbia, independently propose **TPC with LAr** (1977) → leads to ICARUS
- H. Chen, (1985) proposal for a large LAr TPC
- Uranium-LAr hadron calorimeter (…), first use of cold electronics (JFETs),(1986)
- Major realizations at FNAL(D0), HERA(H1), SLAC(SLD), (1985-1993)
- LKr EM calorimeter for CERN NA48-NA62 (1997-today)
- MAPS and active Si-pixel detectors 2000 -
- **ATLAS LAr EM calorimeter** (2004 -); high speed-high precision; highest confidence limit on Higgs (2012)
- MicroBooNE(MB) proposal (2007) with **cryogenic electronics** (JFETs); In 2009 decision to go with cold CMOS; MicroBooNE starts operation in 2015 -
- Technology selection for LBNF(DUNE) in 2011: LAr TPCs
- MB in operation for 7 years; protoDUNE rapid realization and successful test in 2018. Technology path open for DUNE …

1962 - Spark Chambers in the Muon Neutrino Experiment





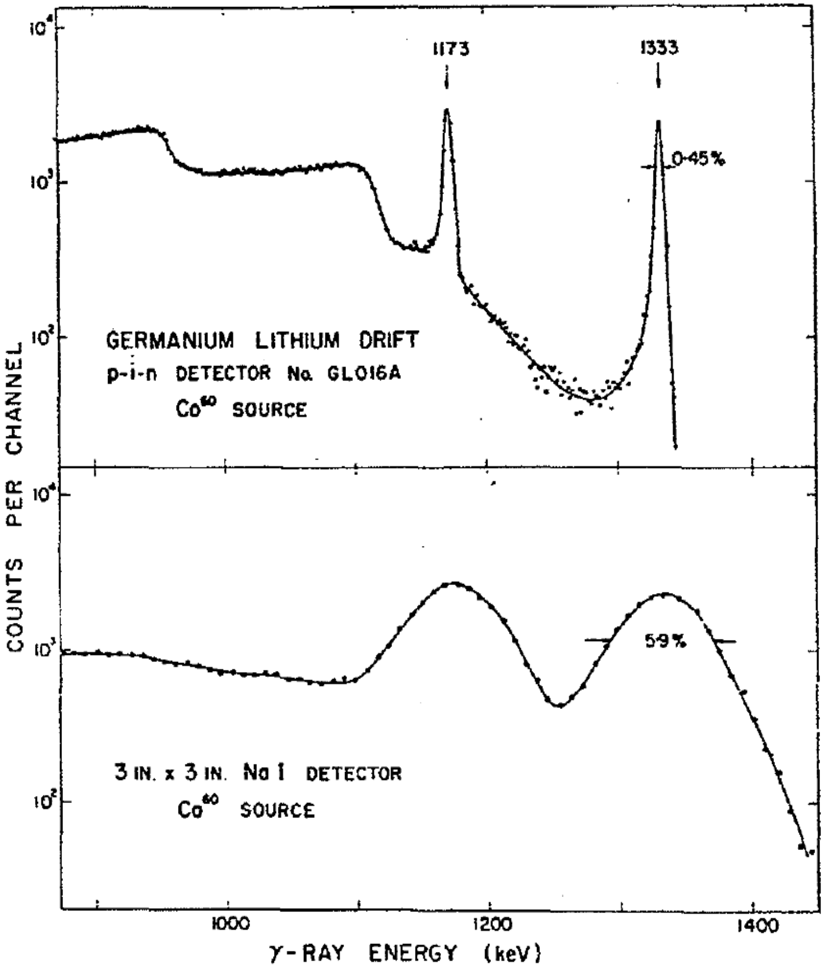
(Danby, et al., 1962)



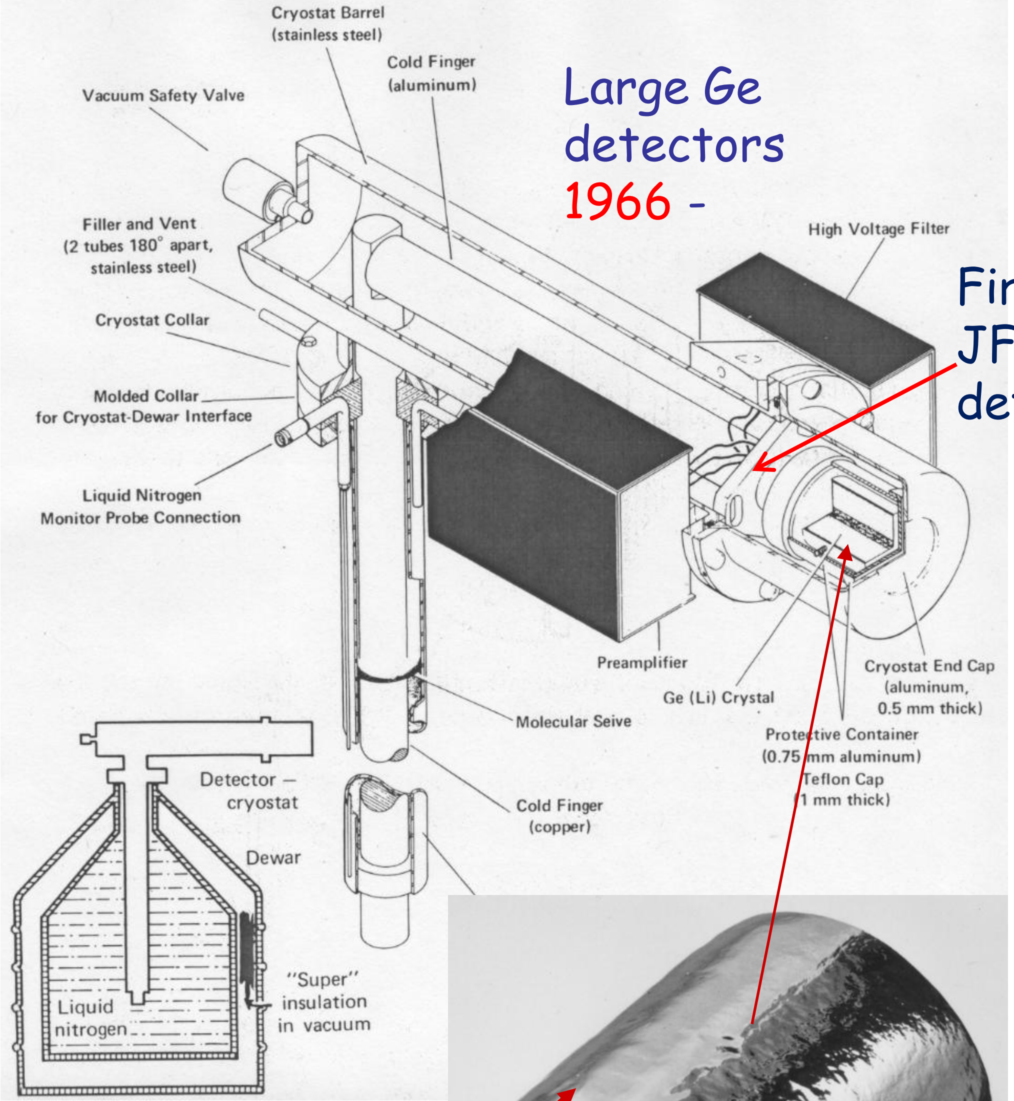
Spark chambers also used in CP violation experiment (Fitch and Cronin, 1964)

Two Nobel Prizes with such detectors!

1963 Germanium Detector Breakthrough

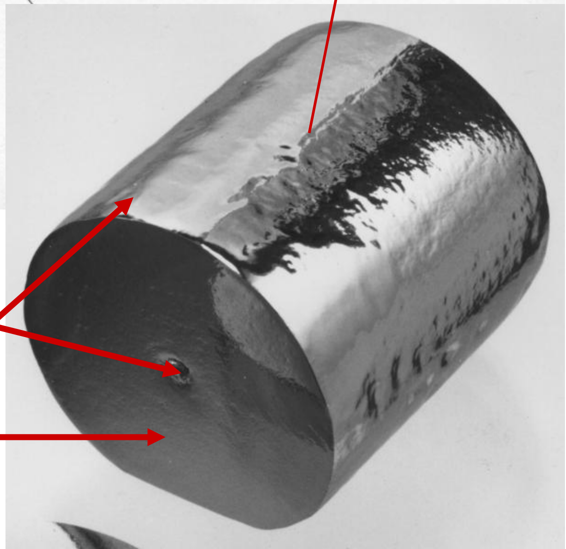


A. Tavendale, G. Ewan, NIM 25 (1963)185



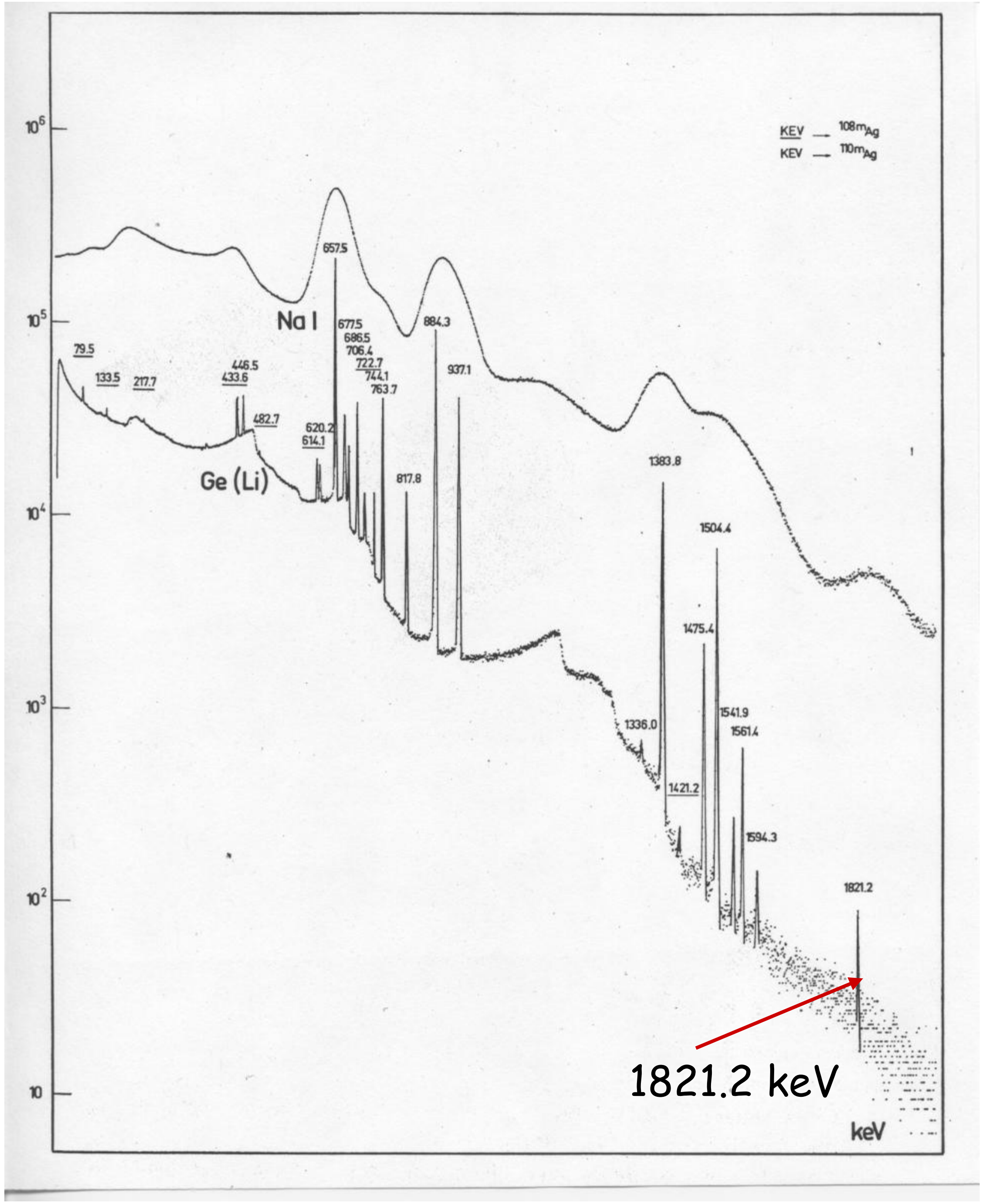
Large Ge detectors 1966 -

First cryogenic JFET on a detector



Coaxial det.contacts

Ge-crystal ~50-100 cm^3

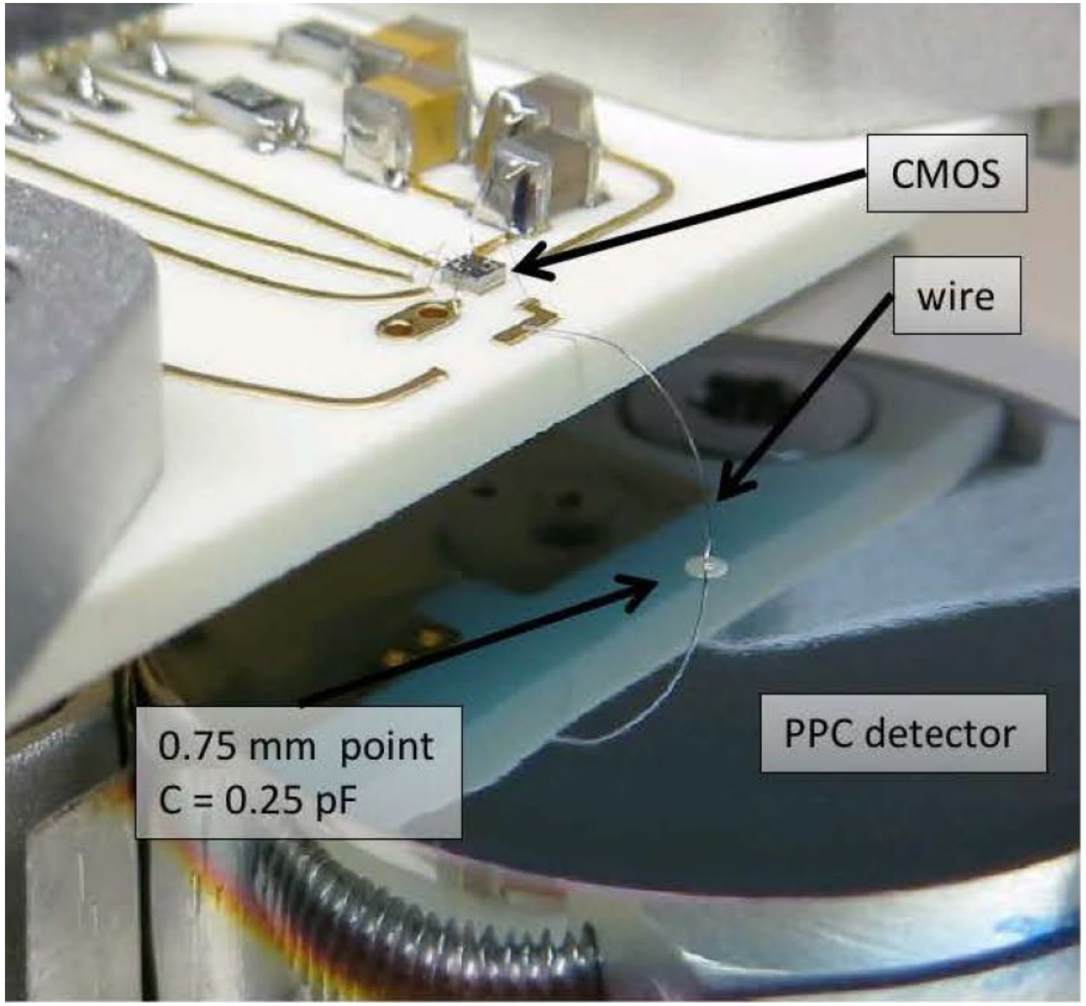


Comparison of Germanium with Sodium Iodide for gamma-ray spectrometry (~1968)

Low noise electronics and signal processing (for gamma ray energy resolution of ~0.1%) developed for germanium detectors in ~ 1965-1972 provided the basis for later use of these techniques in particle physics, solar neutrino detection, x-ray and neutron detectors … **in LAr calorimeters and later in noble liquid TPCs … and … in AGATA, LEGEND**

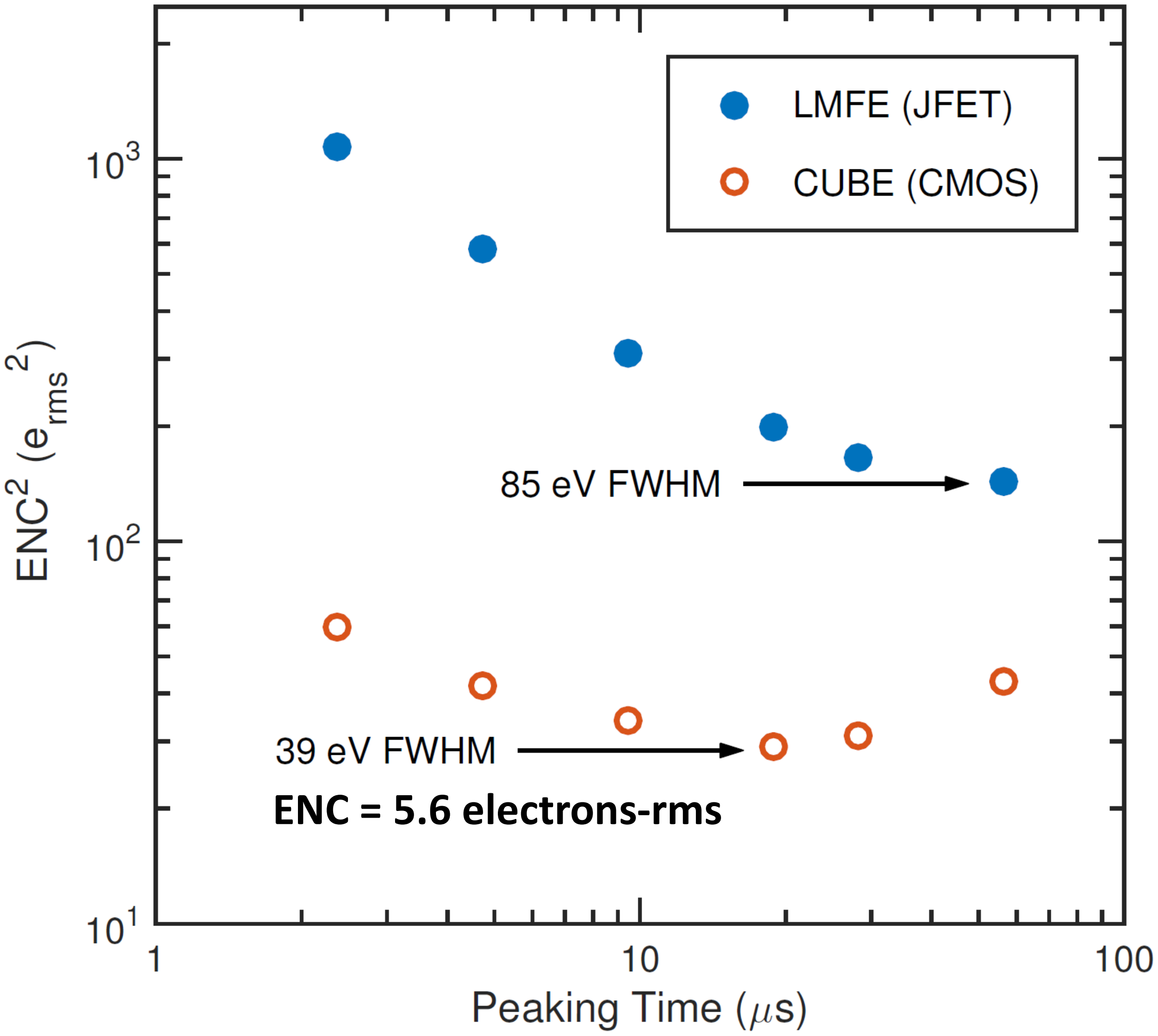
2015: Germanium detector with p+ point contact and cryogenic CMOS

Charge collection to p+ point contact

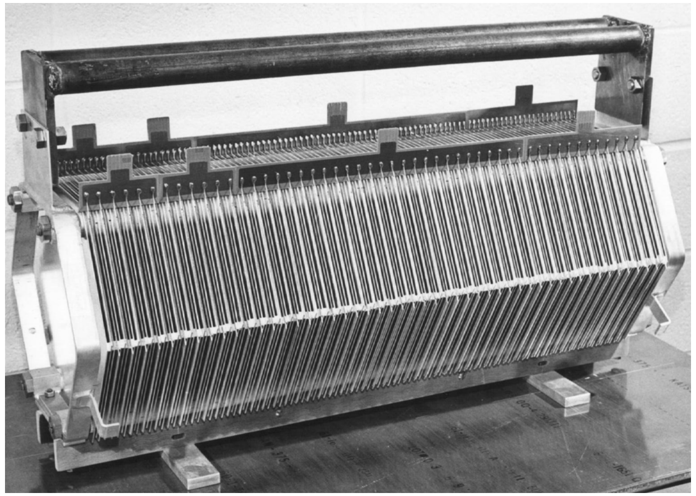


P. Barton et al., NIMA812(2016)17

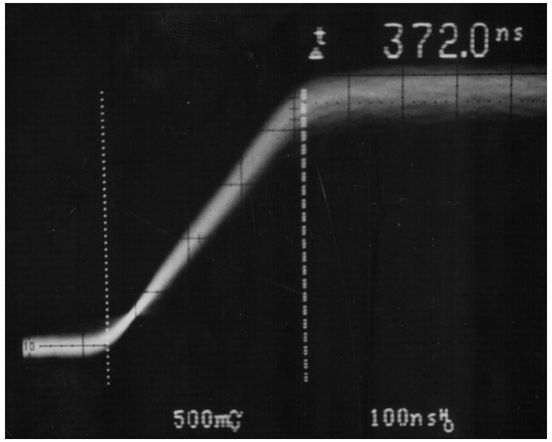
Low capacitance → low noise



Jan-Apr 1973: Design and build the first LAr sampling electromagnetic calorimeter



20 radiation lengths, 200 steel 1.6 mm plates with 2 mm LAr gaps; $\Delta E/\Delta x \approx (11.6 + 2.1)$ MeV/cm, or $0.1\ X_0$



Charge Collection and Drift Velocity Studies in LAr

Only electrons induce a signal in the time of interest <1 μs; mobility $\mu_{electron} \gg \mu_{ion}$

2 mm electrode spacing → ~400ns at 10kV/cm

W.J. Willis and V. Radeka, NIM 120 (1974) 221

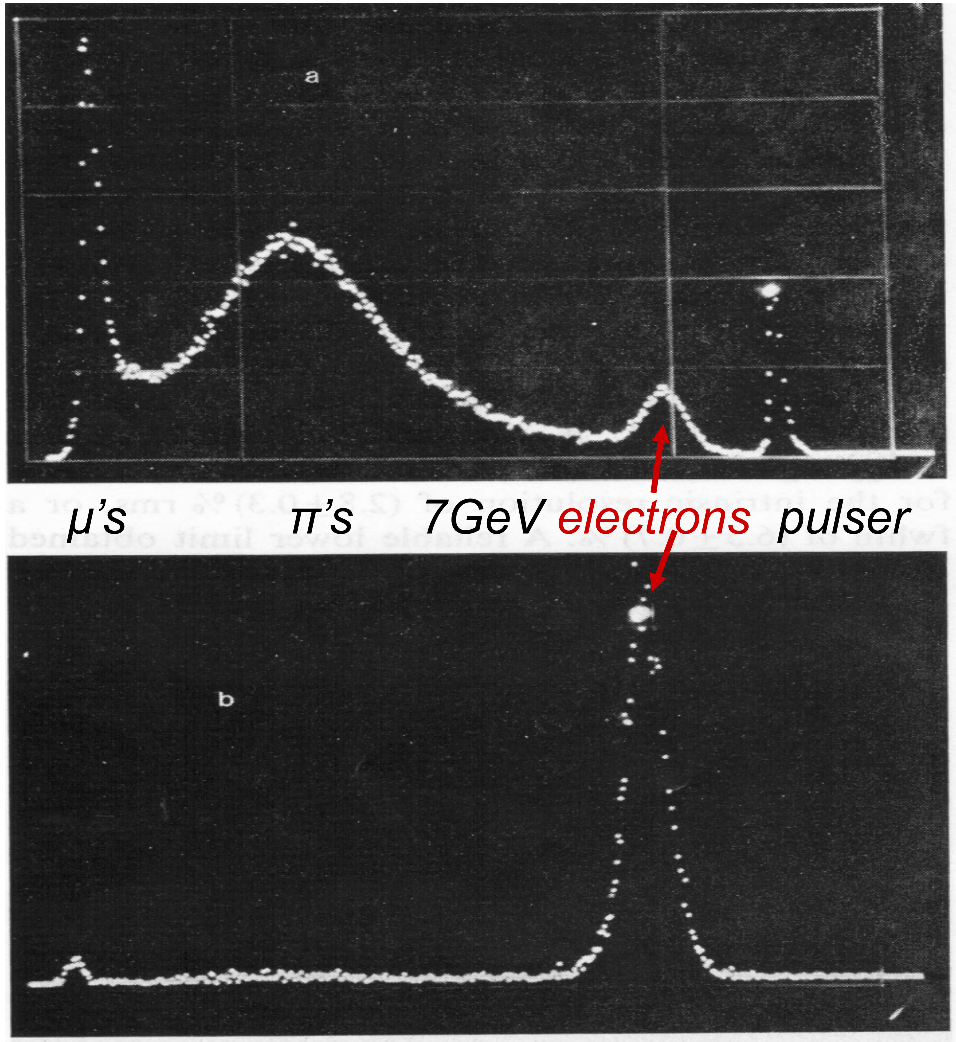
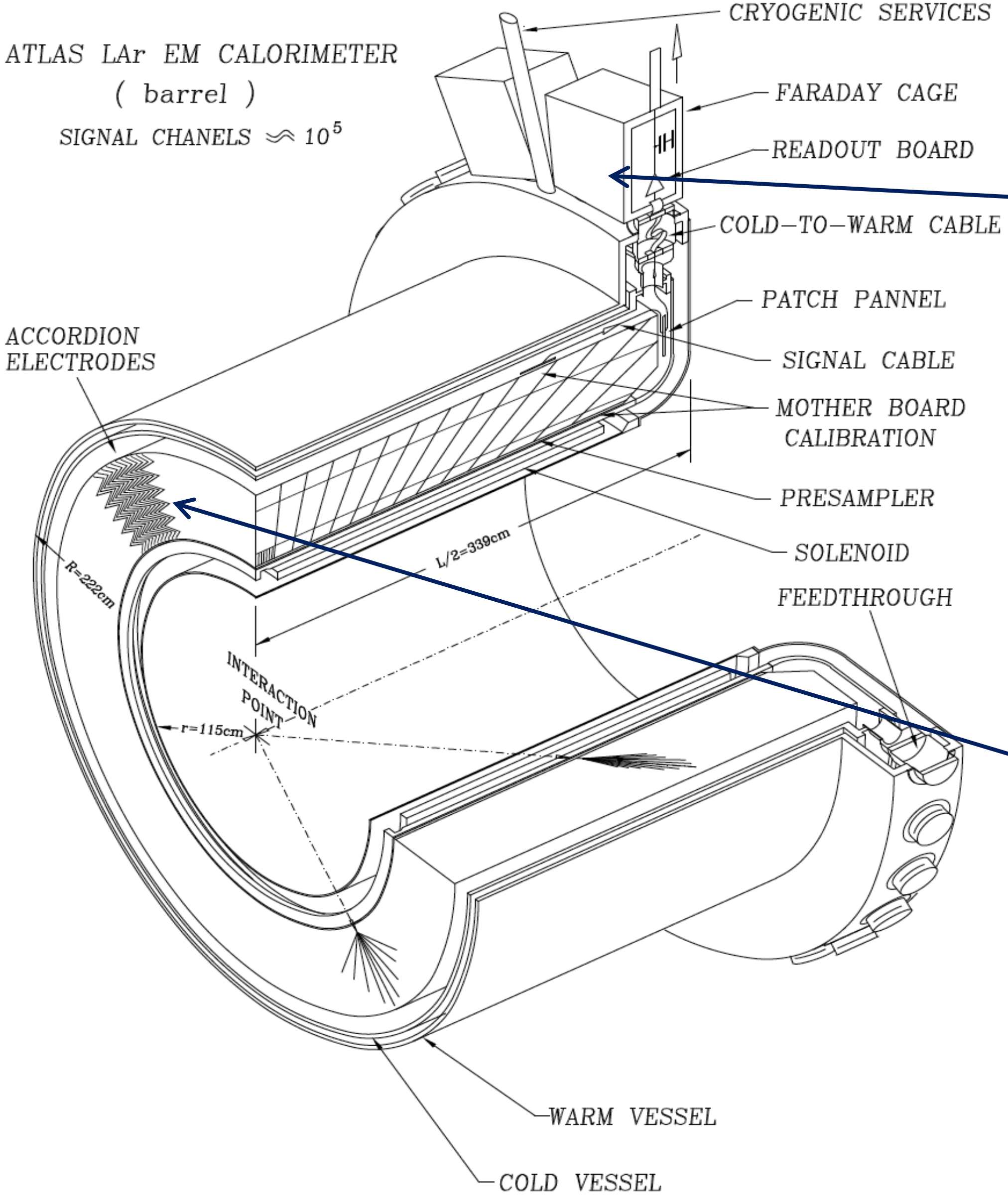
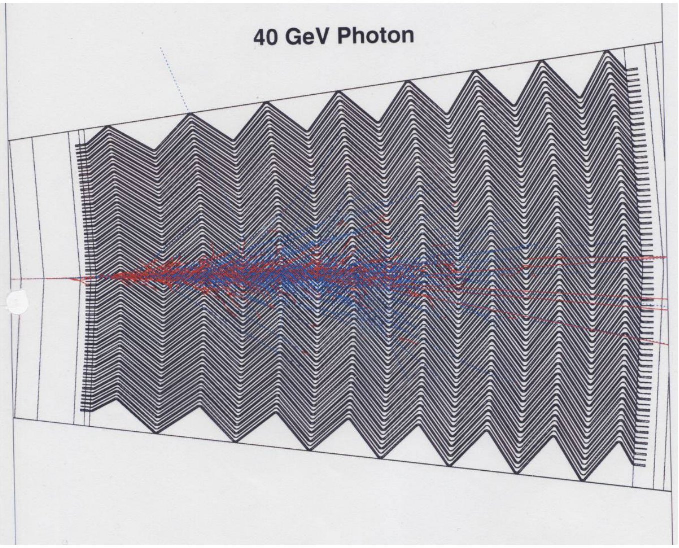


Fig. 12. Charge spectrum with large test chamber for 7 GeV/c negative beam. (a) peaks from left to right: muons, π's, electrons, calibration pulser; (b) electrons enhanced with a Cherenkov detector.

ATLAS LAr Calorimeter Readout → Faraday Cage with Cryostat

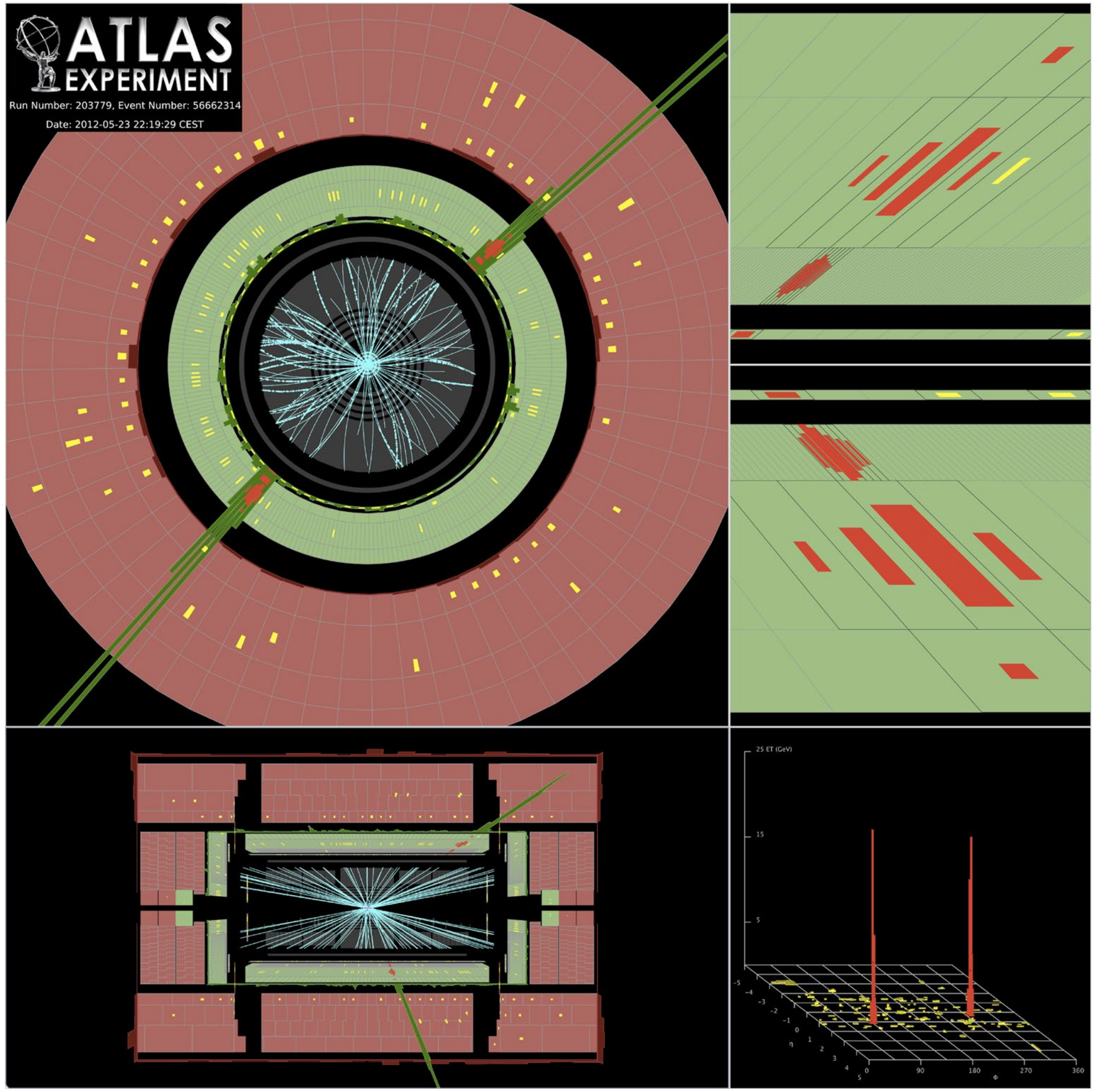


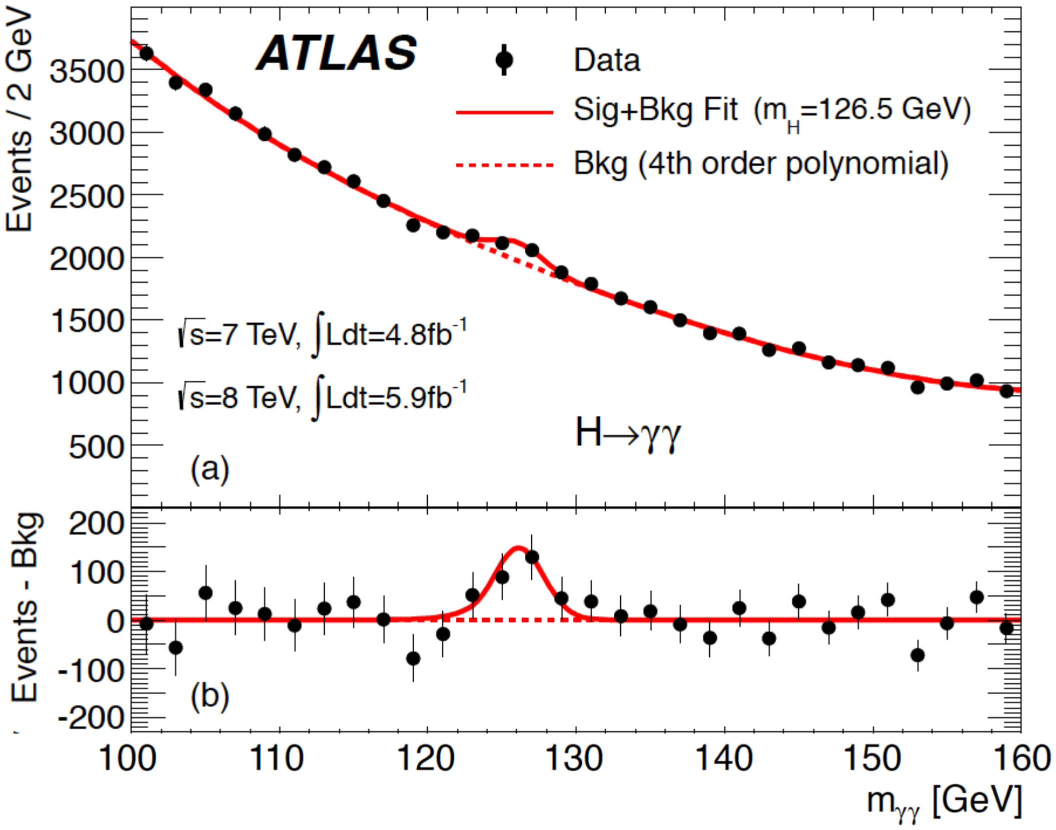
- Electrodes
  - Calibration resistors, 0.1%
- System crate: on detector electronics, Faraday cage
- An integral system design approach - from detector electrode to readout electronics. This approach was followed later in MicroBooNE and protoDUNE



Accordion Sampling EM calorimeter by <u>Daniel Fournier</u> in 1990

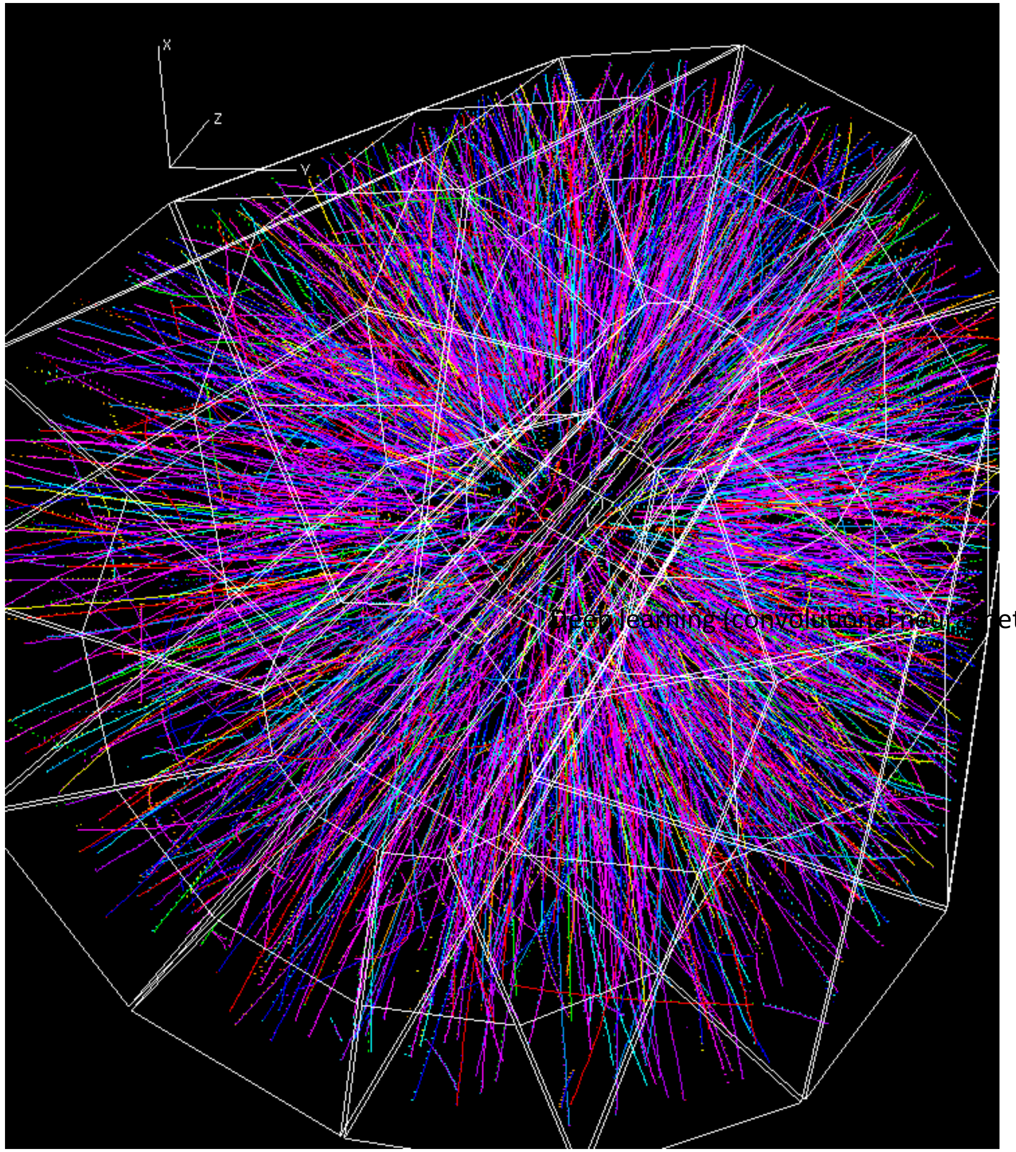
Higgs Discovery in 2012





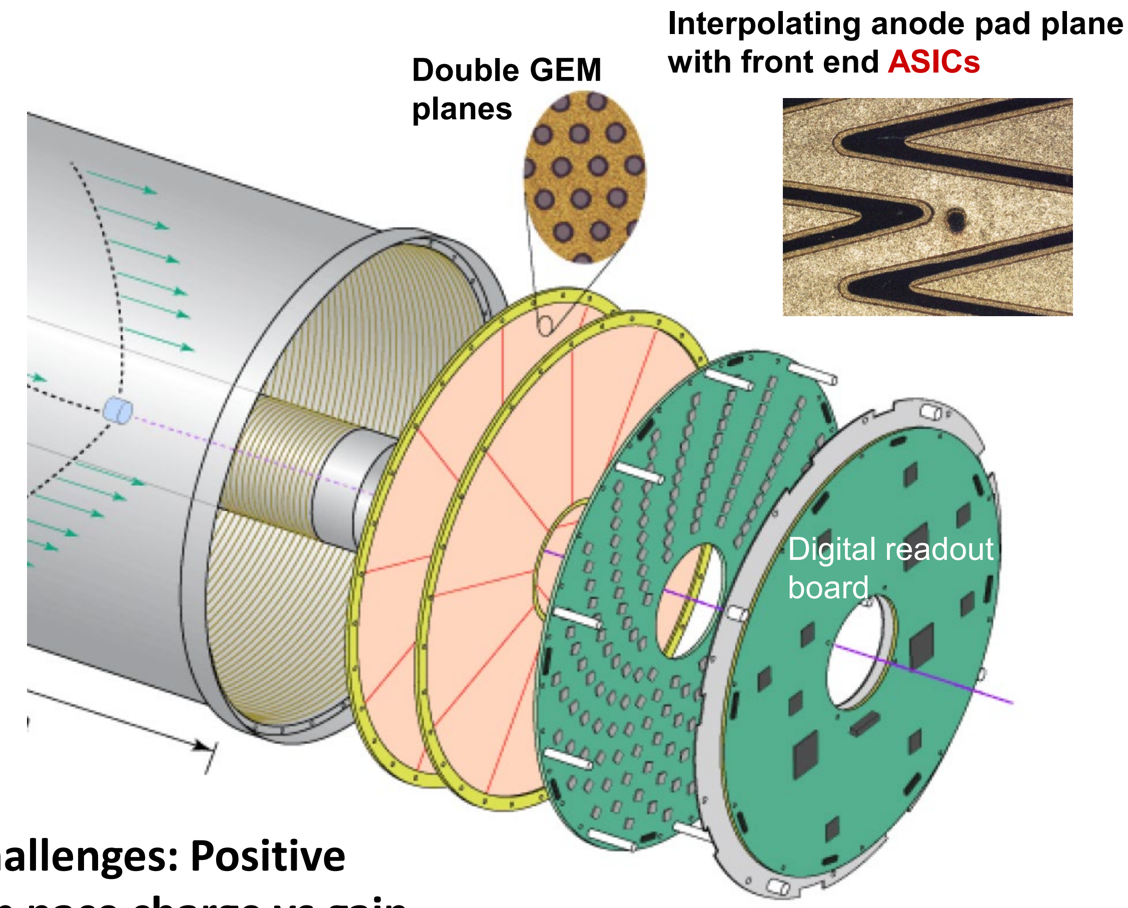
- 2012: ATLAS and CMS find evidence of Higgs-like events
- ATLAS LAr calorimeter provides more than 5σ confidence level
- Mass resolution of ~1% for the Higgs between 100 and 200 GeV
- Calibration and stability of response <0.1 %

1974: David Nygren introduces Gas Time Projection Chamber (TPC)



Deep learning (convolutional neural network) methods

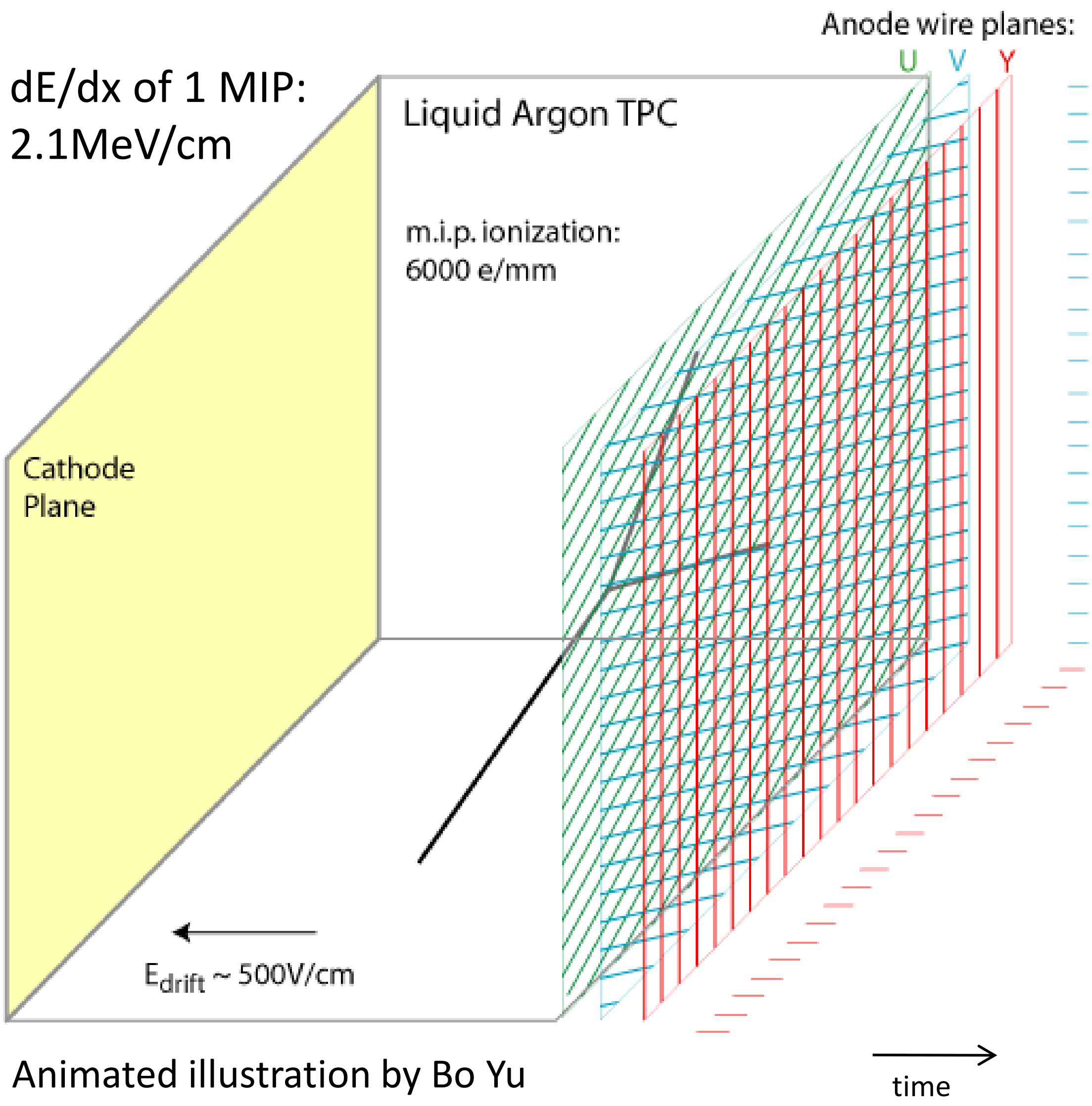
STAR TPC at RHIC: Au on Au (2000)



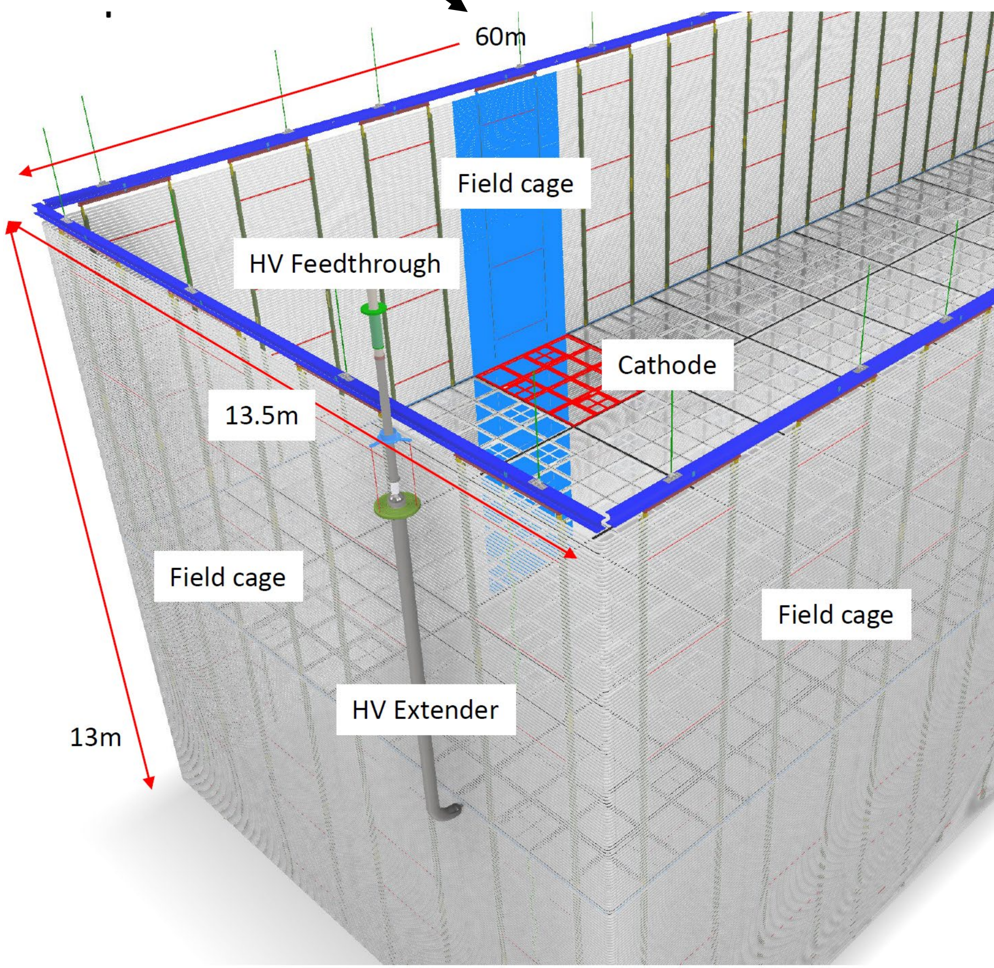
Challenges: Positive ion pace charge vs gain

1977: H.H. Chen and C.Rubbia introduce LAr TPC … leading from ICARUS to MicroBooNE, ProtoduNE, eventually to DUNE …

dE/dx of 1 MIP:
2.1MeV/cm



Animated illustration by Bo Yu



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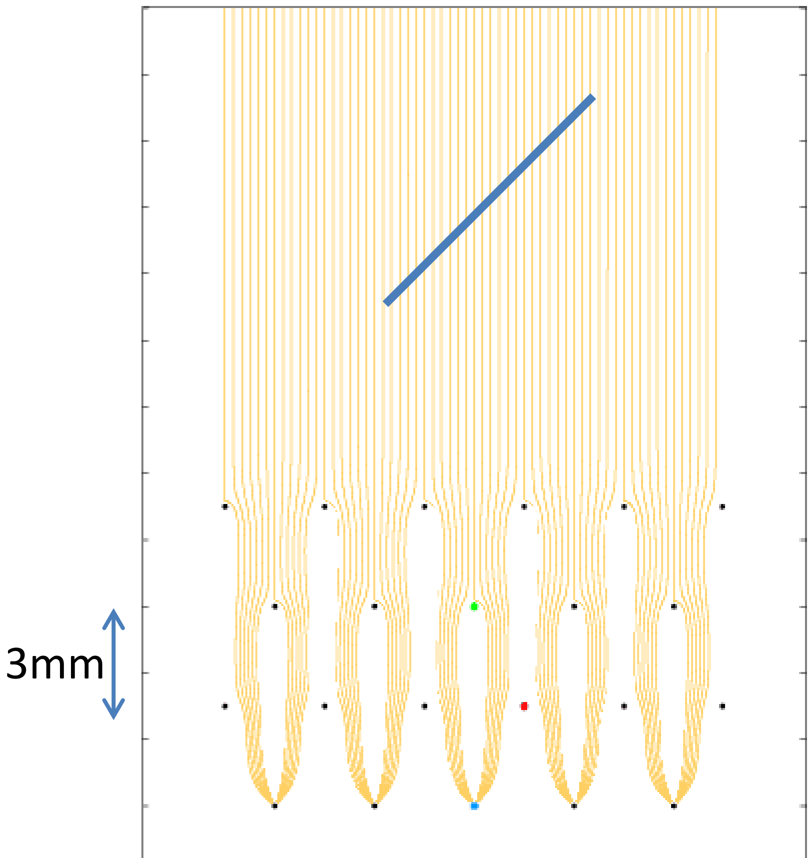
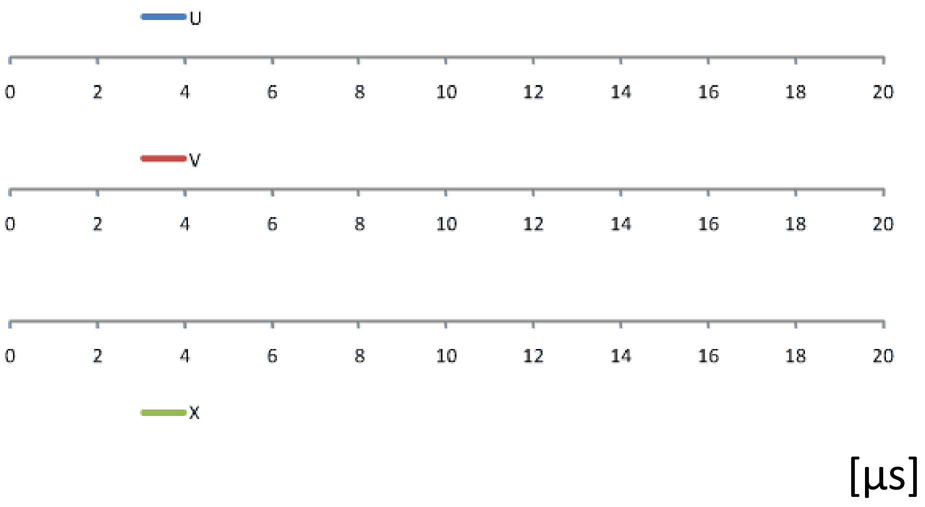
Signal Formation in LAr TPC: Induced Signals from a Track Segment



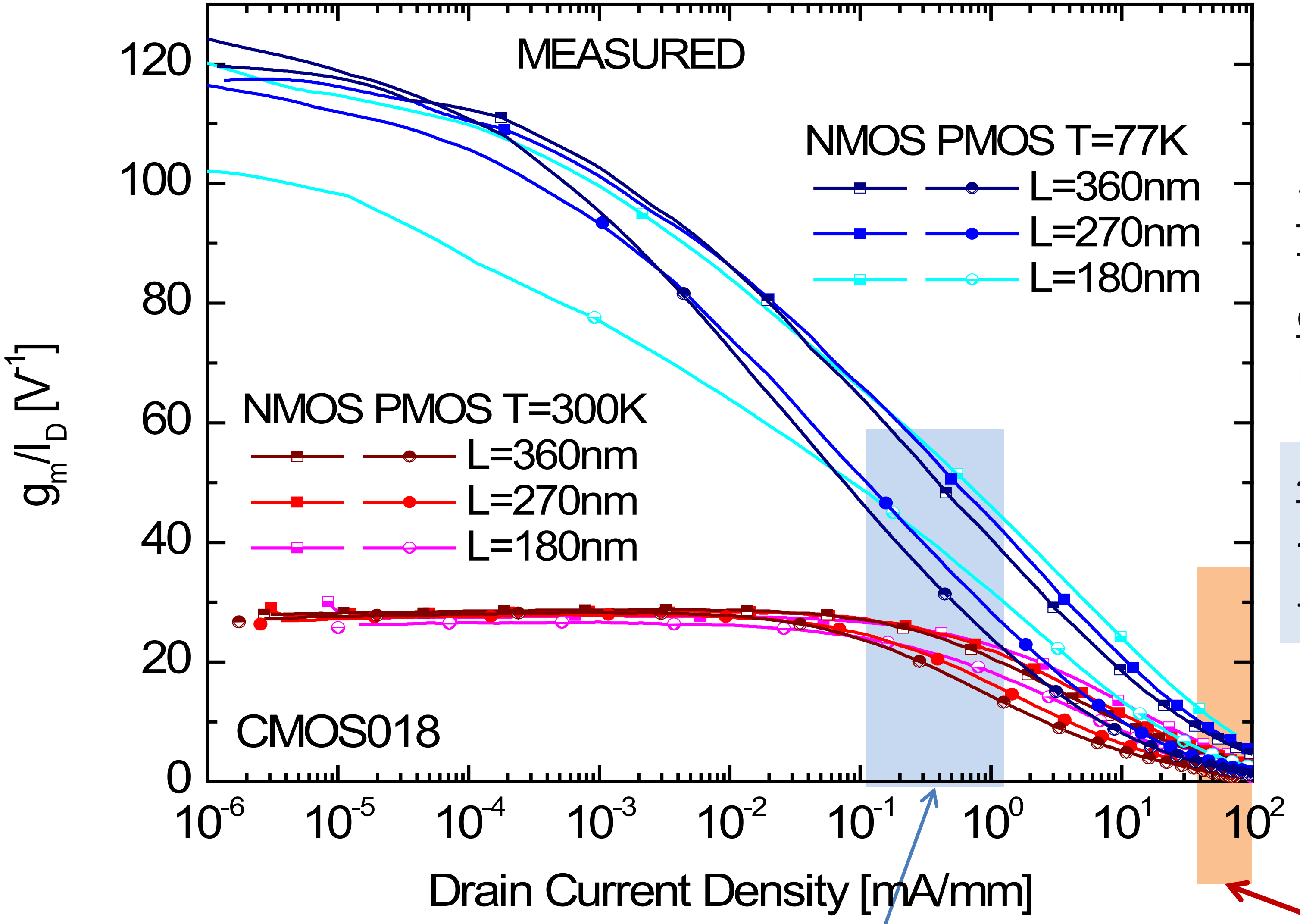
Animated illustration by Bo Yu

Time scale of signals determined by **wire plane spacing** and electron **drift velocity ~1.6 mm/µs**



LBNE style wire arrangement: 3 instrumented wire planes + 1 grid plane
Raw current waveforms convolved with a 0.5µs gaussian (~1/2 drift length) to mimic diffusion

2008: CMOS at 77K: *low power = long lifetime*



Low power and long lifetime at 77K

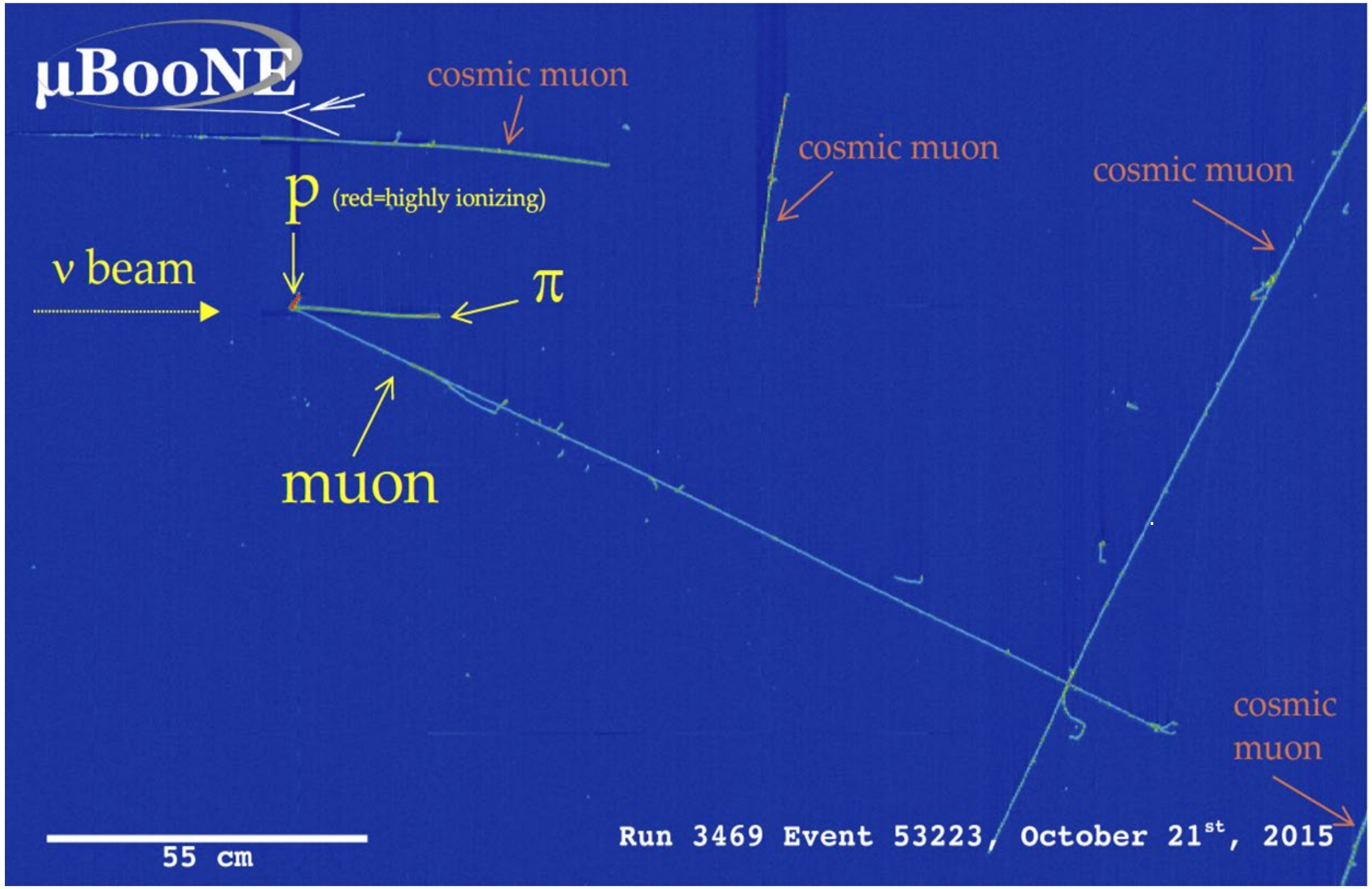
At 77-89K mobility <u>increases</u>, thermal fluctuations <u>decrease</u> with **kT/e**, resulting in:

- *<u>higher</u>* g_m/I,
- *<u>higher speed</u>*
- *<u>lower noise</u>*.

G. De Geronimo, et al., IEEE Trans. Nucl. Sci. 58 (2011)1376

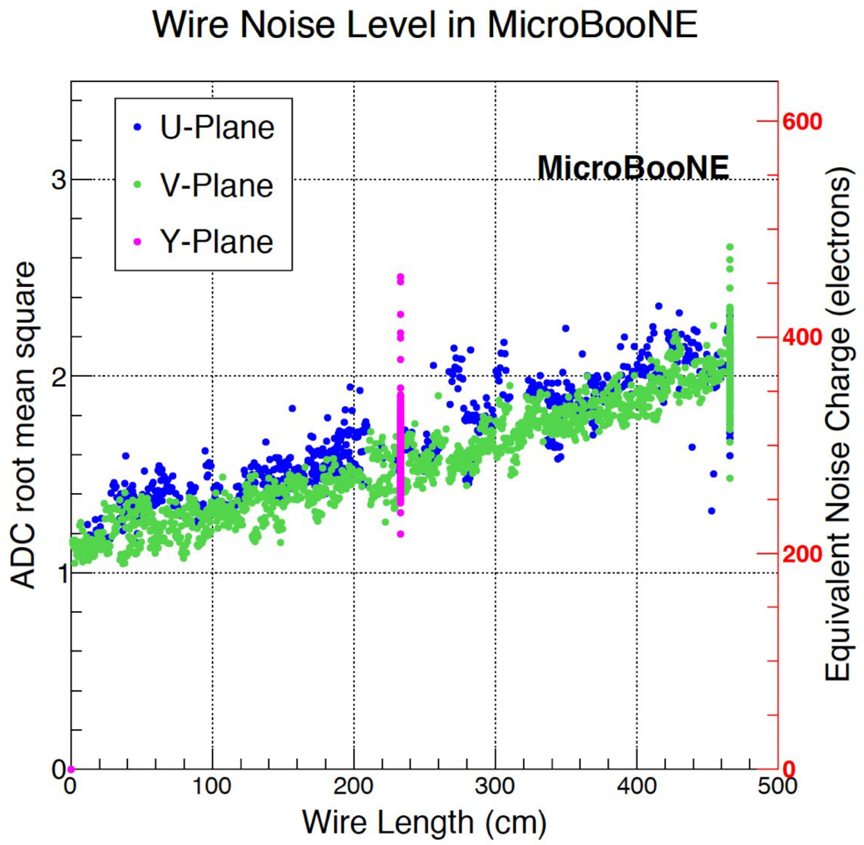
<u>Accelerated stress testing</u>

2015: MicroBooNE – First LAr TPC with cryogenic CMOS ASIC



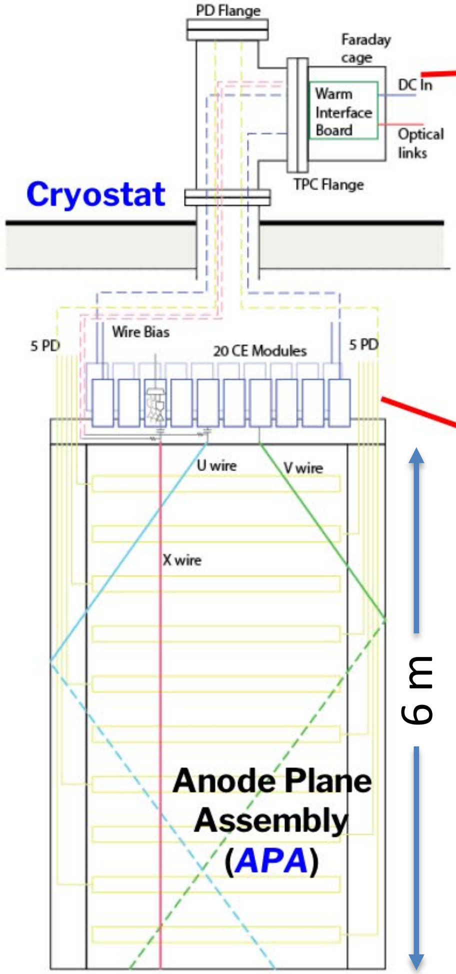
Waveform Type	U Plane PSNR	V Plane PSNR	Y Plane PSNR
Raw Data	6.6	5.7	19.5
After Noise Filtering	22.3	16.2	37.9

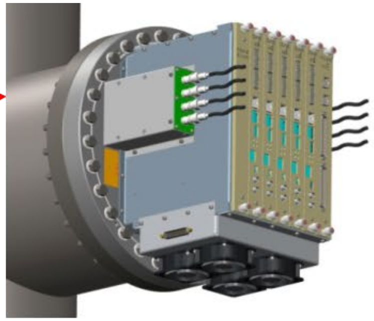
LAr 170 tons (86 tons active)
8256 sense wires



R. Acciarri, et al., JINST 12 (02) (2017) P02017.

2018: Integral system design concept for LAr TPC with cryogenic electronics in ProtoDUNE (prototype for DUNE module 1)



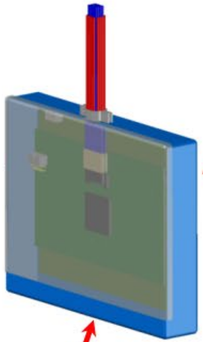


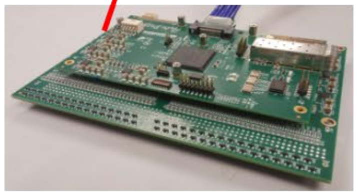
ProtoDUNE

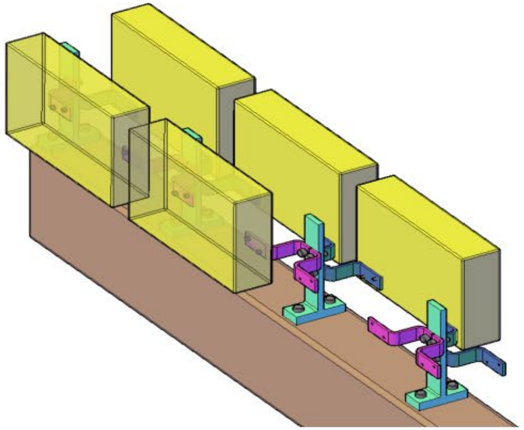
LAr 770 tons (420 tons active)
15600 sense wires

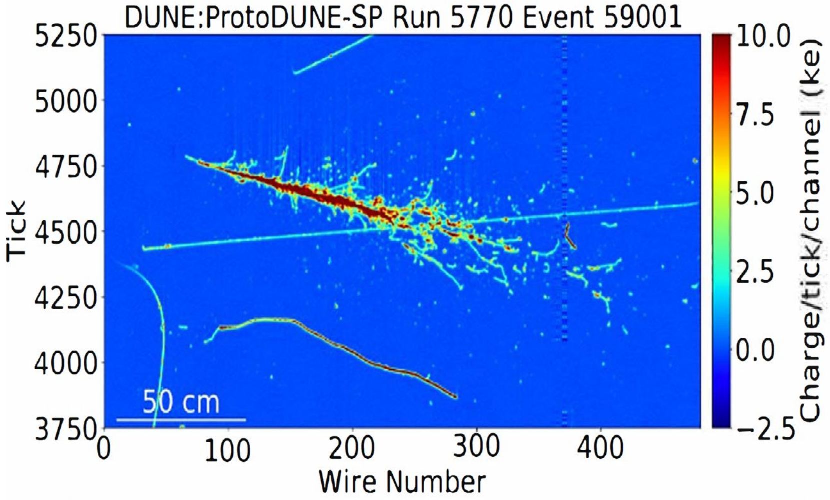
Plane	Peak signal-to-noise ratio			
	Raw Data		After noise filtering	
	MPV	Average	MPV	Average
Collection	30.9	38.3	40.3	48.7
U	12.1	15.6	15.1	18.2
V	14.9	18.7	18.6	21.2

Cold electronics (CE) module and its attachment to the APA frame



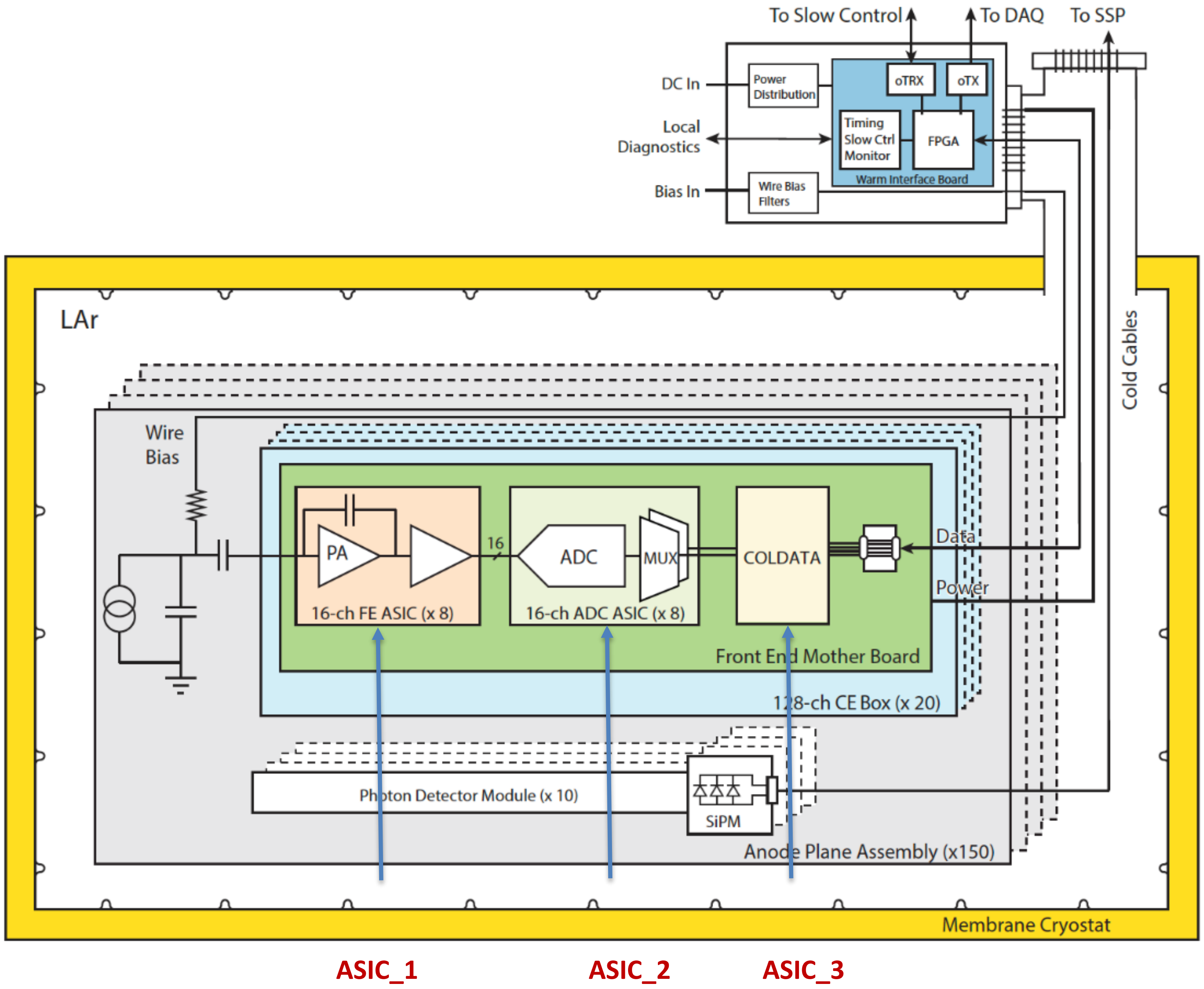






B. Abi, et al., JINST 15 (12) (2020) P12004.
A. A. Abud, et al., JINST 17 (01) (2022) P01005

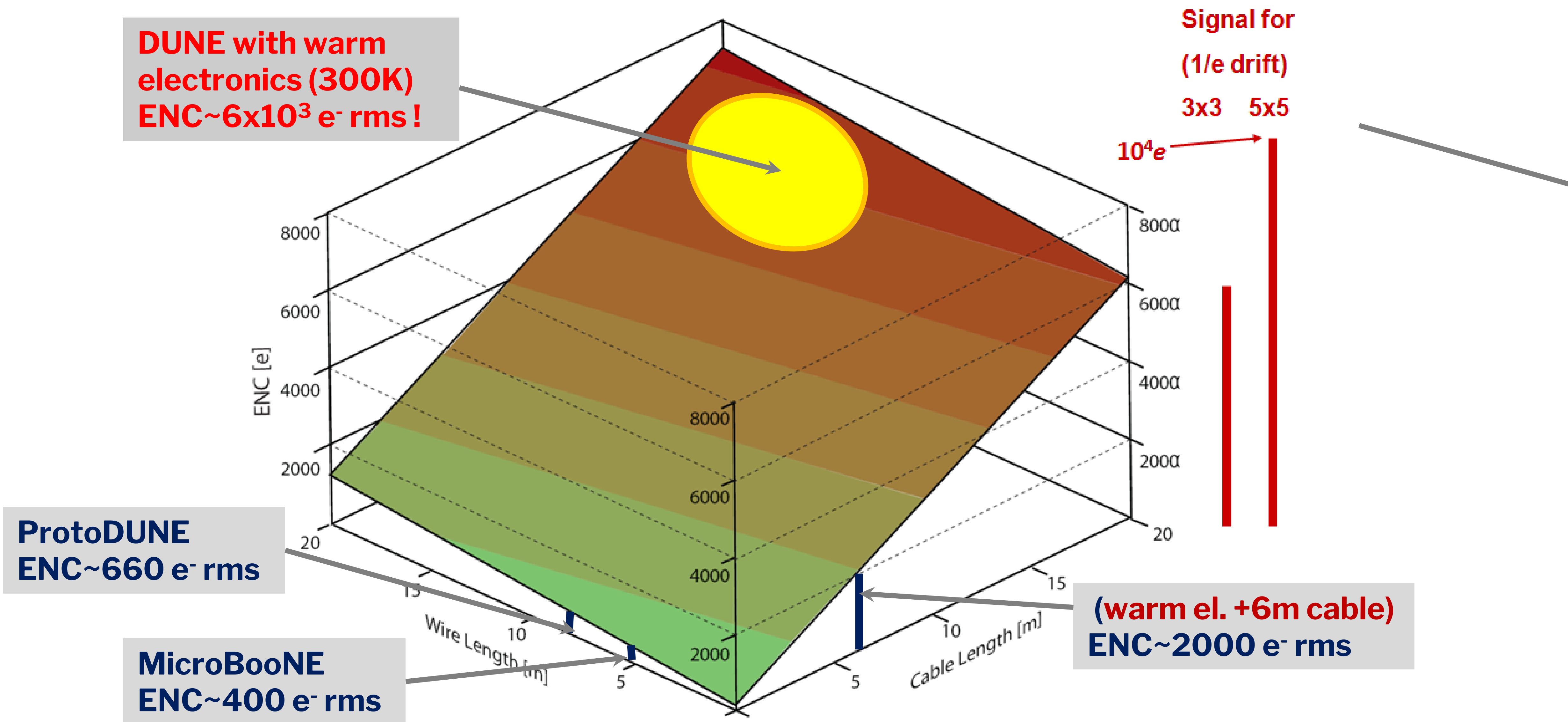
2020: Readout for DUNE

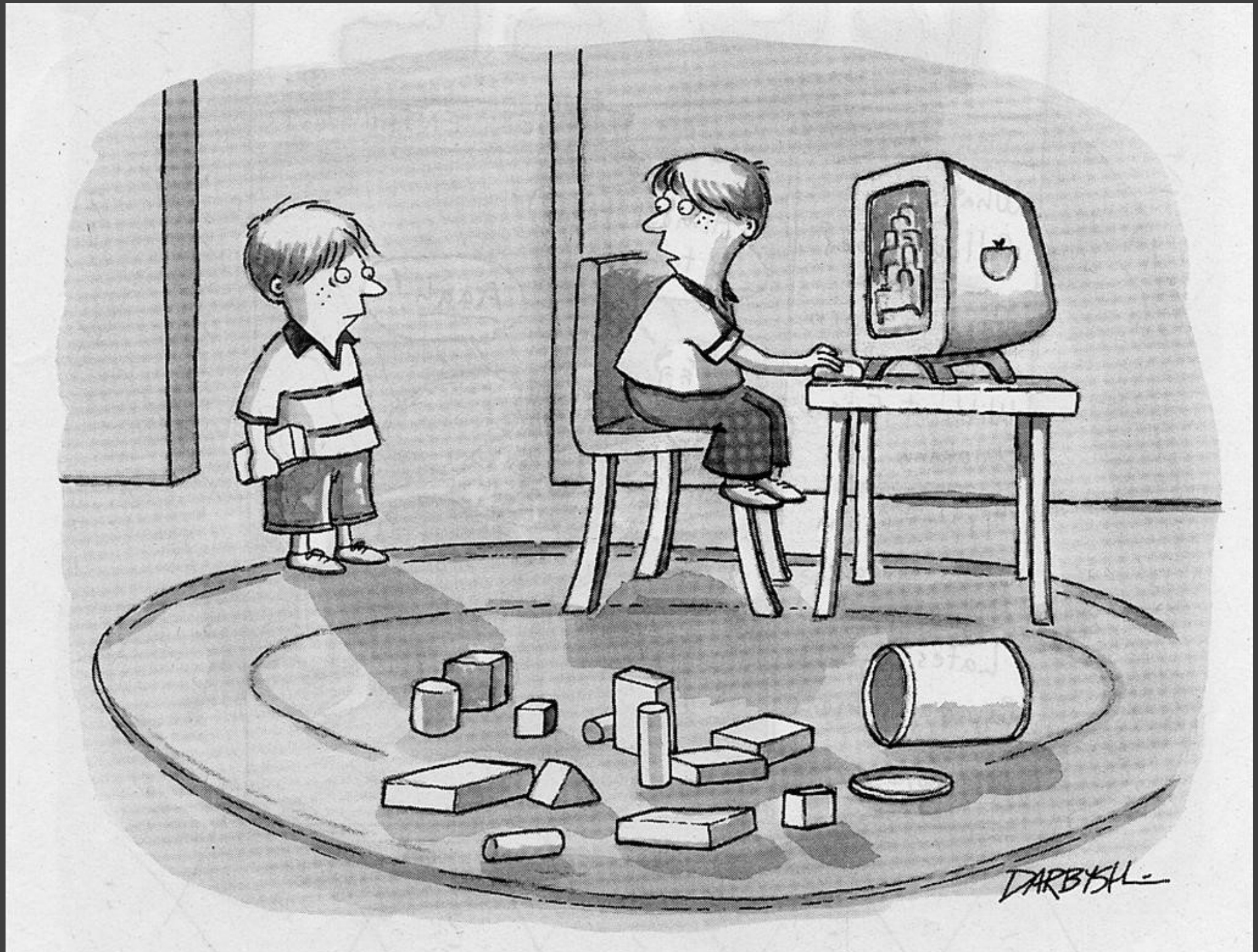


3-ASICs design allows optimal choice of CMOS nodes and supply voltages to minimize power dissipation for the large dynamic range. (An FPFA used in place of COLDATA in ProtoDUNE).

Giant LAr TPCs: The Challenge of Capacitance

Noise (ENC) *vs TPC Sense Wire and Signal Cable Length* for CMOS at 300K and 89K



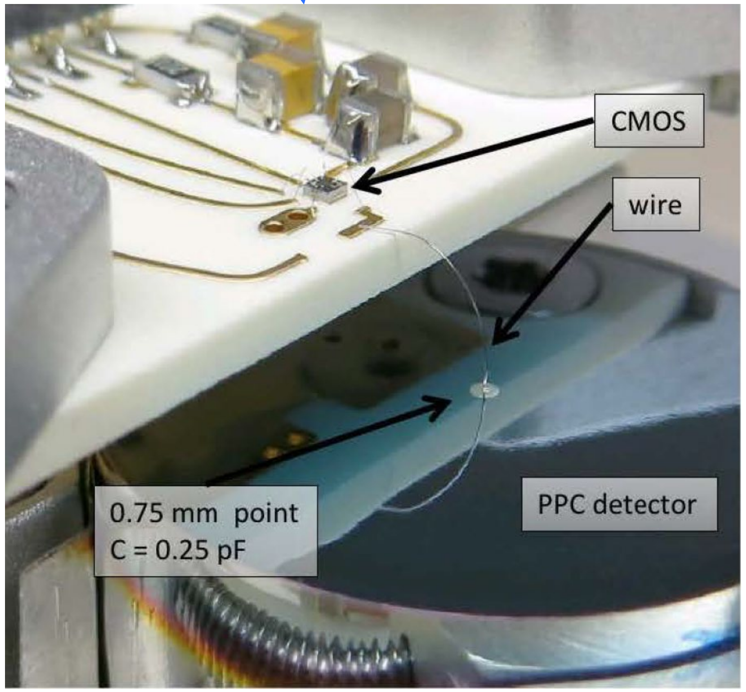


"Now, this is just a simulation of what the blocks will look like once they're assembled."

The times are changing …
… and so are interests and activities …

AI/ML methods will be dominant activities in producing *new science results* in the future, while the *ultimate detector sensitivity* will depend on ***integral design*** of sensors and electronics

- neural networks …
- deep learning (convolutional neural network) methods …
- data healing algorithms …
- neuromorphic …
- autonomous experiments …
- quantum …
- ……….



Thank You!