Charge and light sensing in noble liquid TPCs

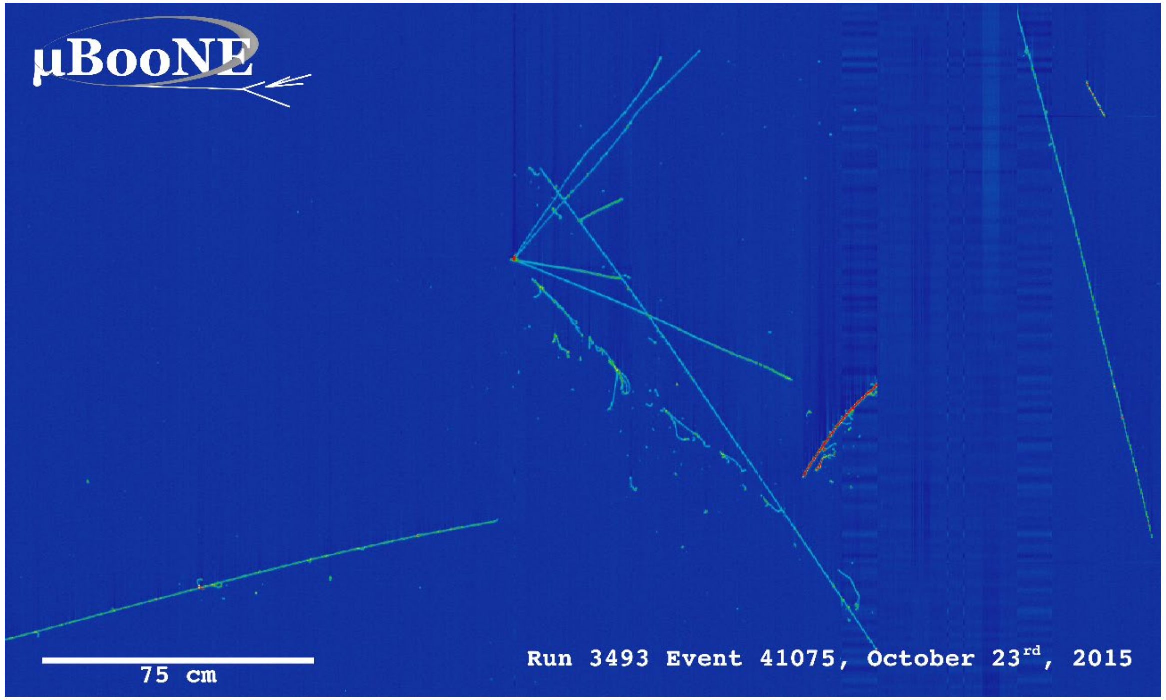
Veljko Radeka

Instrumentation Division Seminar

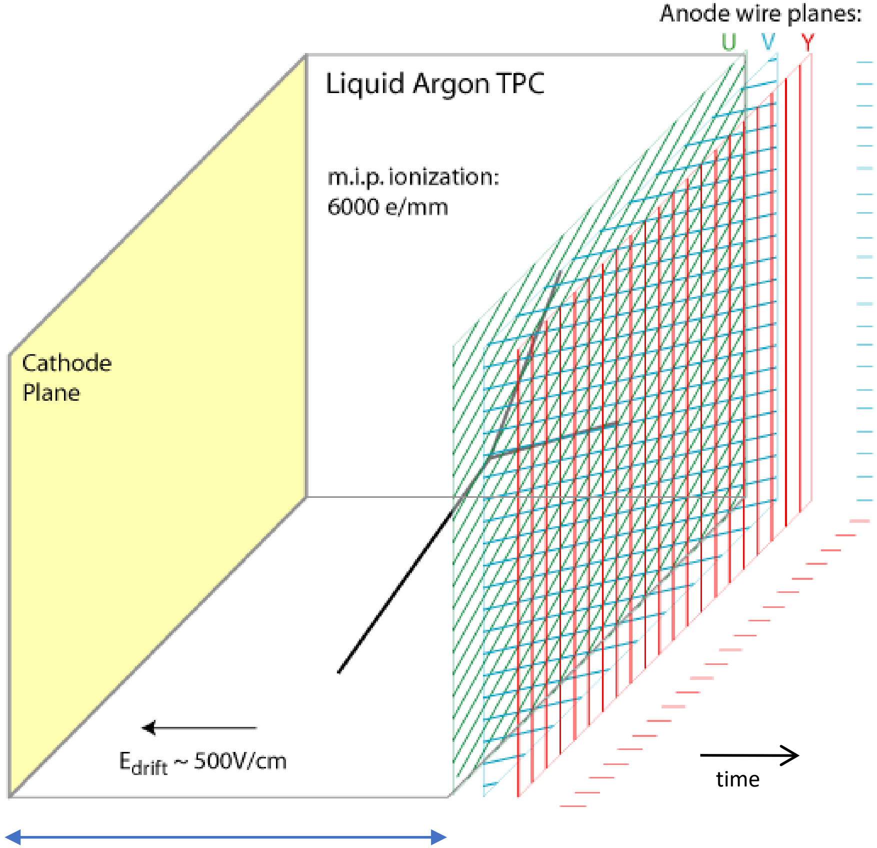
Sept 2, 2021

Principle of Liquid Argon Time Projection Chamber (LArTPC)

- ~mm scale position resolution with multiple 1D wire/strip/pad readouts
- PID with energy depositions and topologies



By Bo Yu (BNL):



1.5-2.5 m (6m?)

Drift velocity 1.6 m/ms → ms drift time

Signal Formation: Induced Signals from a Track Segment

Waveform calculation: Bo Yu

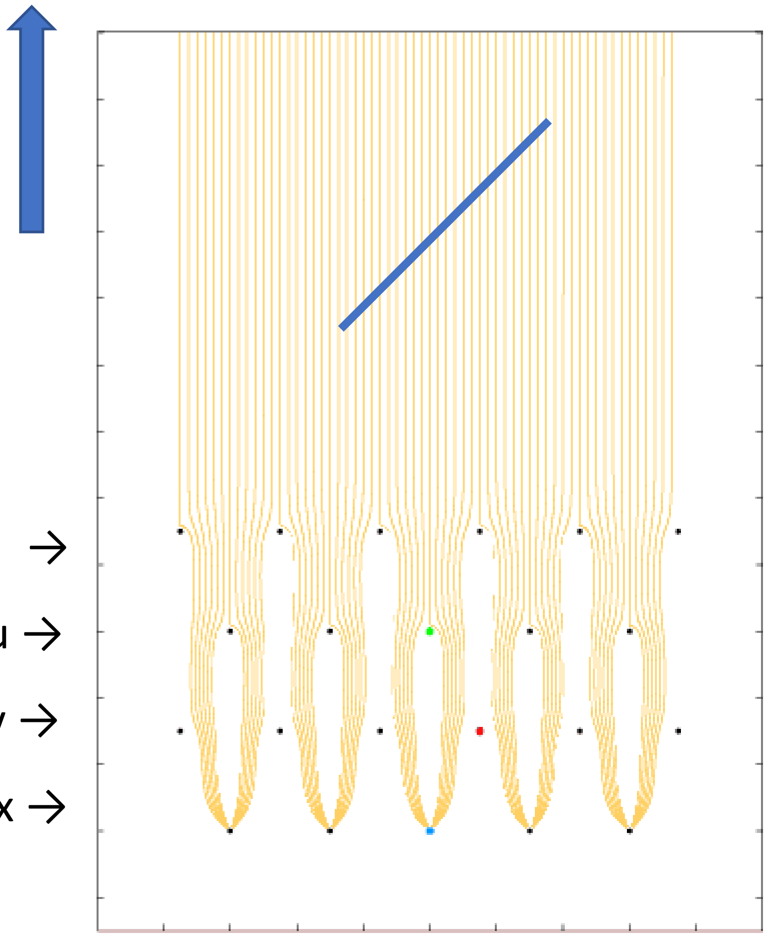
Cathode
2.5 meters
away (up
to 6 m in
DUNE FD-2

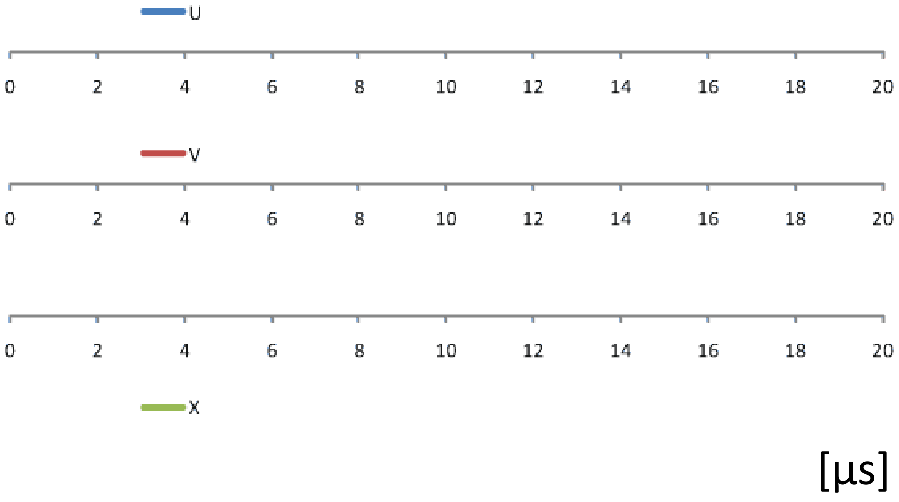
Grid →

Induction plane u →

Induction plane v →

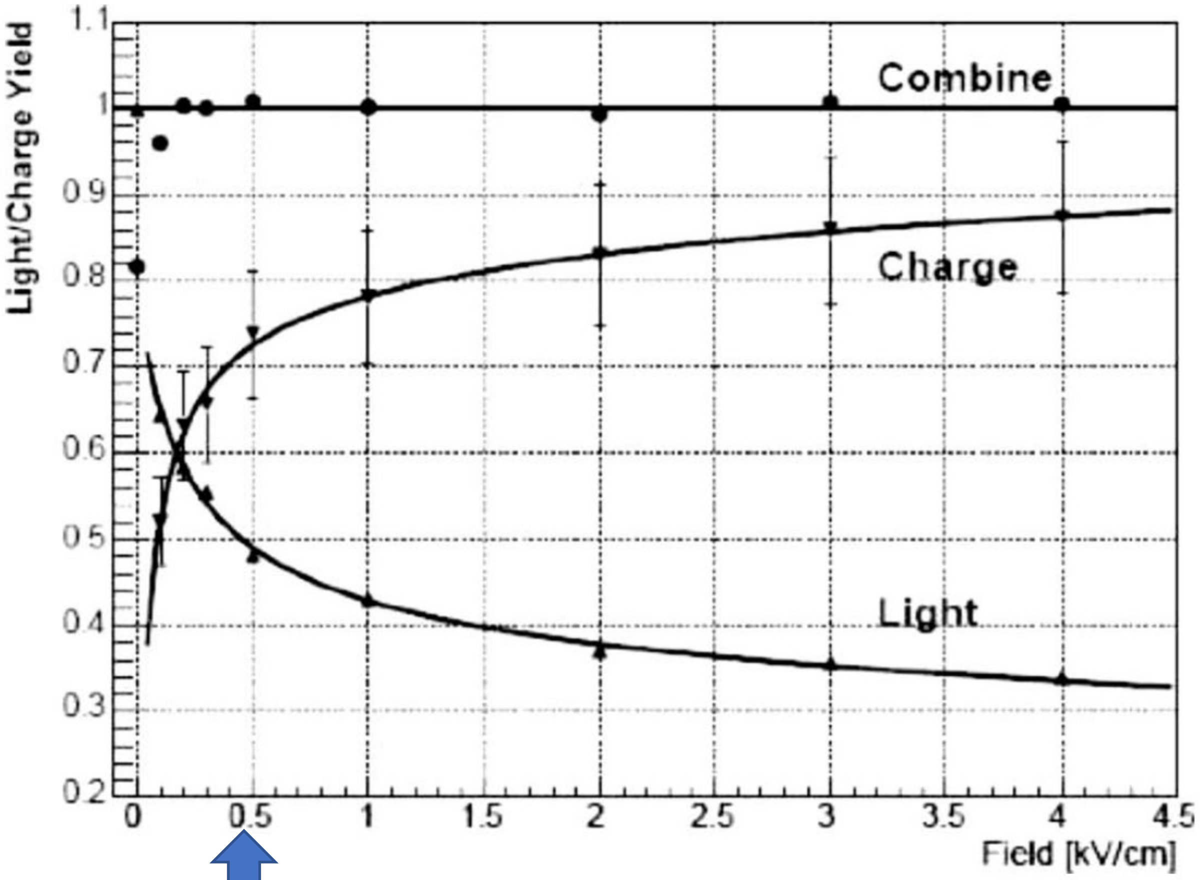
Collection plane x →





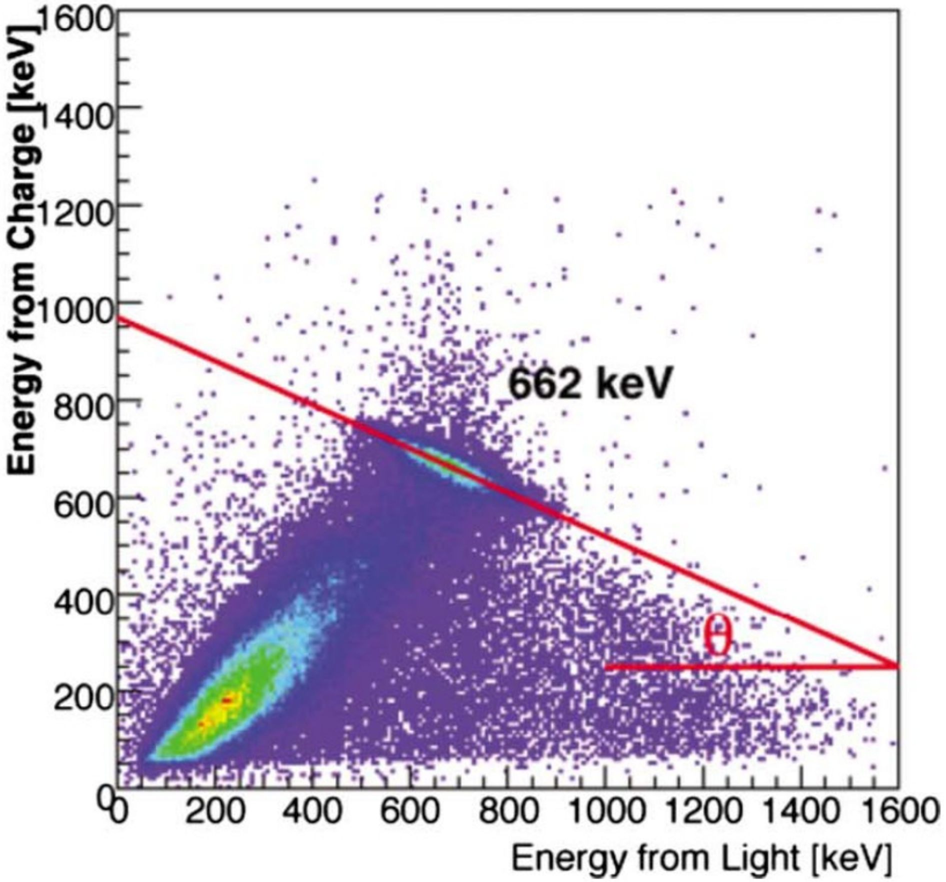
ProtoDUNE style wire arrangement: **3 instrumented wire planes (u, v, y) + 1 grid plane**
Raw current waveforms convolved with a 0.5 μs gaussian (~1/2 drift length) to mimic diffusion

Light and charge in LXe vs drift field for 137 Cs 662 kev γ-rays



TPCs

Aprile, E., et al., 2007b, Nucl. Instrum. Methods Phys. Res. B,173, 113.
E.Aprile, T. Doke, Reviews of Modern Physics, Vol. 82, July–September 2010



Combined (anticorrelated) light and charge signals to be used in nEXO to obtain better ("rotated") energy resolution.

Liquid Argon Time Projection Chambers:

The idea originated from the work of a number of people, (e.g., gas TPC Nygren, 1974; LAr calorimetry). Two focused proposals:

In **1976 Herbert H. Chen,** U.C. Irvine proposed one of the earliest uses of liquid argon in a time projection chamber (liquid Ar TPC). Chen's initial goals with such a detector were to study neutrino-electron scattering, but the goals evolved to measure solar or cosmic neutrinos or proton decay.

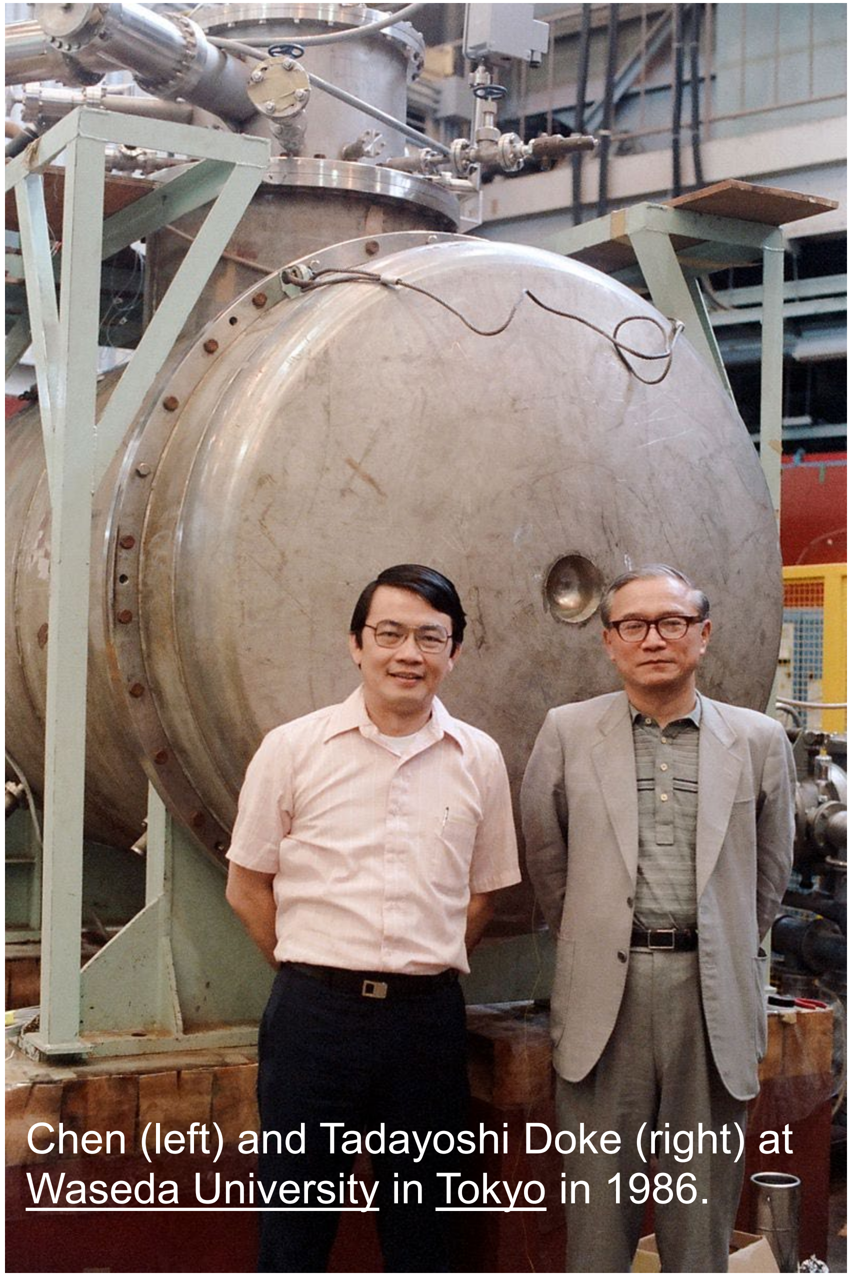
In 1978 he reported a drift distance of 35 cm (!).

In the eigthies he pursued actively a proposal for a large LAr TPC, an effort cut short by his untimely passing in 1987.

In **1977 Carlo Rubbia** proposed to construct such a device at CERN for rare event particle physics experiments. This led to ICARUS, the only large LAr TPC (600 tons) until 2007-2015.

The anode based on three planes of long wires essentially remained into the first DUNE 10 kton module.

Induced signals in LAr TPC were analyzed at Polytecnic Milan and BNL in 1978.



Chen (left) and Tadayoshi Doke (right) at Waseda University in Tokyo in 1986.

A Proposal for a New Experiment

Using the Booster and NuMI Neutrino Beamlines: MicroBooNE

October 15, 2007

H. Chen, J. Farrell, F. Lanni, D. Lissauer, D. Makowiecki, J. Mead,
V. Radeka, S. Rescia, J. Sondericker, B. Yu
Brookhaven National Laboratory, Upton, NY

L. Bugel, J. M. Conrad, V. Nguyen, M. Shaevitz, W. Willis‡
Columbia University, New York, NY

C. James, S. Pordes, G. Rameika
Fermi National Accelerator Laboratory, Batavia, IL

C. Bromberg, D. Edmunds
Michigan State University, Lansing, MI

P. Nienaber
St. Mary's University of Minnesota, Winona, MN

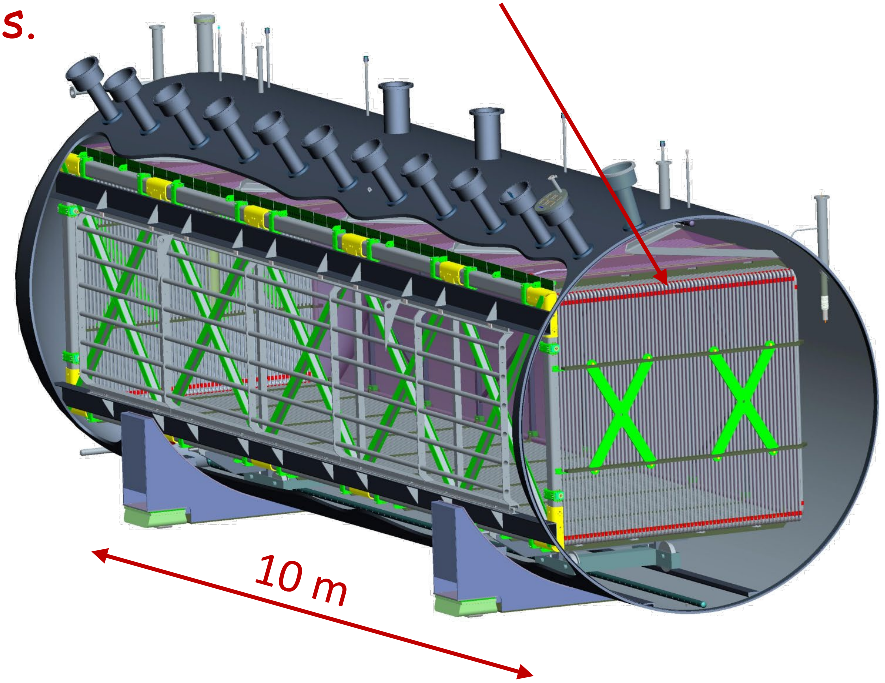
S. Kopp, K. Lang
University of Texas at Austin, Austin, TX

C. Anderson, B. T. Fleming†, S. Linden, M. Soderberg, J. Spitz
Yale University, New Haven, CT
†= Spokesperson, ‡= Deputy Spokesperson

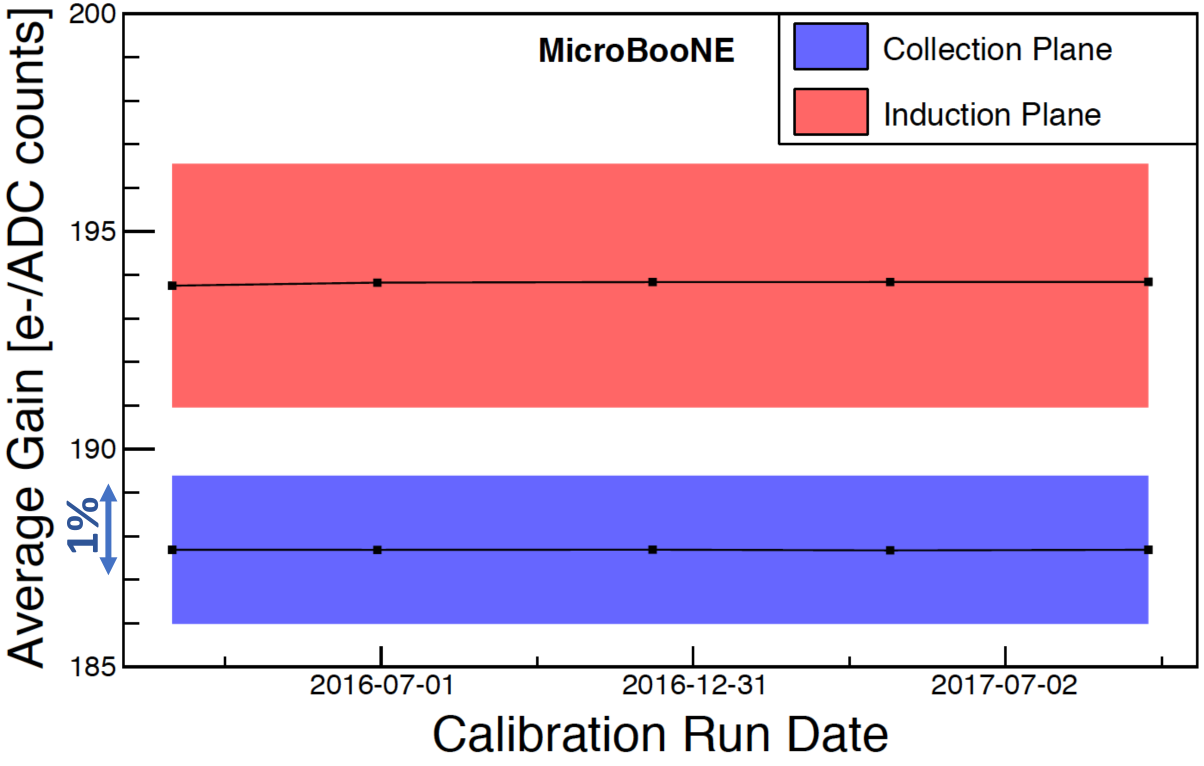
MicroBooNE: From **24 in2007** to ~**180 collaborators in 2021**

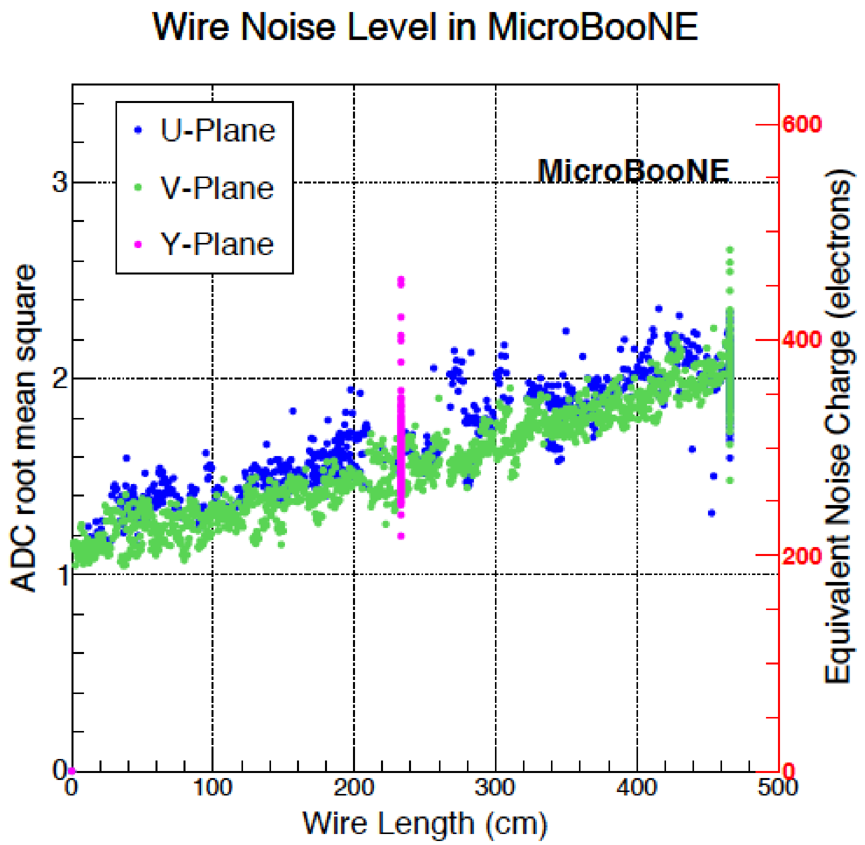
New in **MicroBooNE** (with respect to ICARUS):

- Cryostat uses **foam insulation** to simplify construction (cryostat, feedthroughs,…).
- It will be **purged with argon gas** instead of vacuum evacuation to demonstrate the feasibility of very large non-evacuable cryostat for LBNE.
- All front end analog **electronics are submerged in LAr**, directly connected to the sensing wires to reduce electronic noise (< 400e vs. ~ 2000e).
- 2.5 m maximum drift length (vs. 1.5m); LAr ~80 tons.



Stability and Performance of MicroBooNE TPC

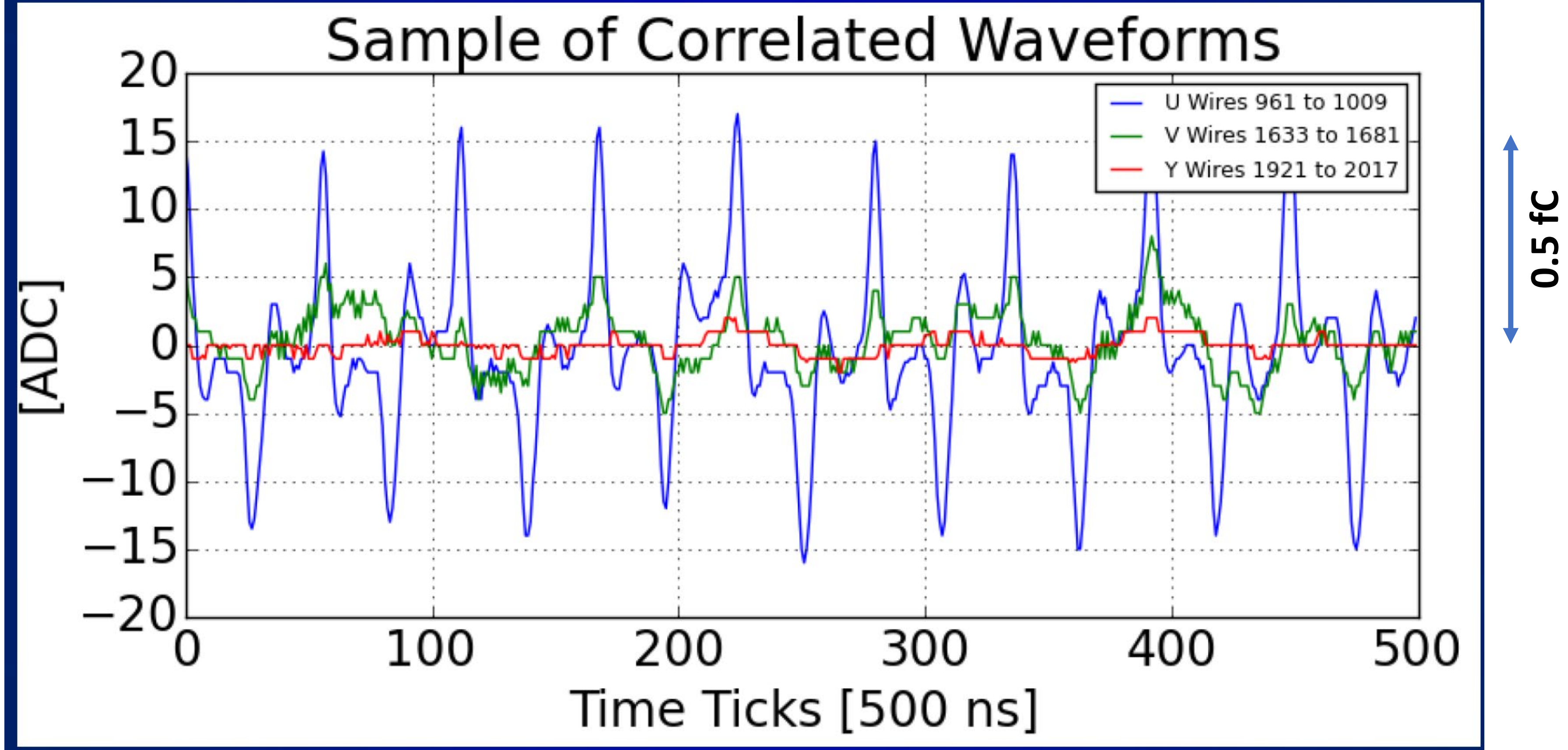




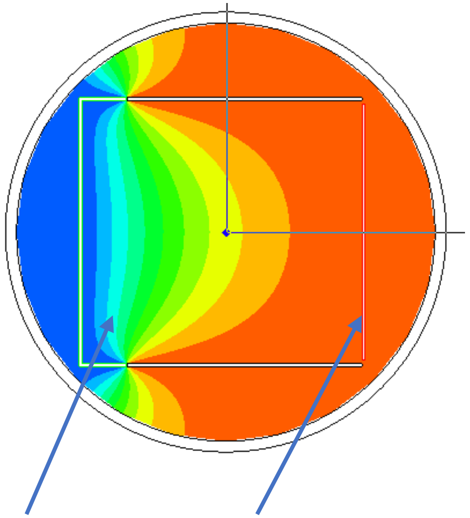
- Electronic calibration
  - Cold electronics gain stable over two year period, ***variation <0.2%.*** (Stable over ~7 years …).
- Excellent noise performance
  - ENC after ***excess noise*** filtering is < **400 e$^-$** for 85% of channels (~7000 wires).

Excess noise from cathode 2.5 m away with HV= 70 kV turned on

HV ripple (36 kHz fundamental) induced on sense wires



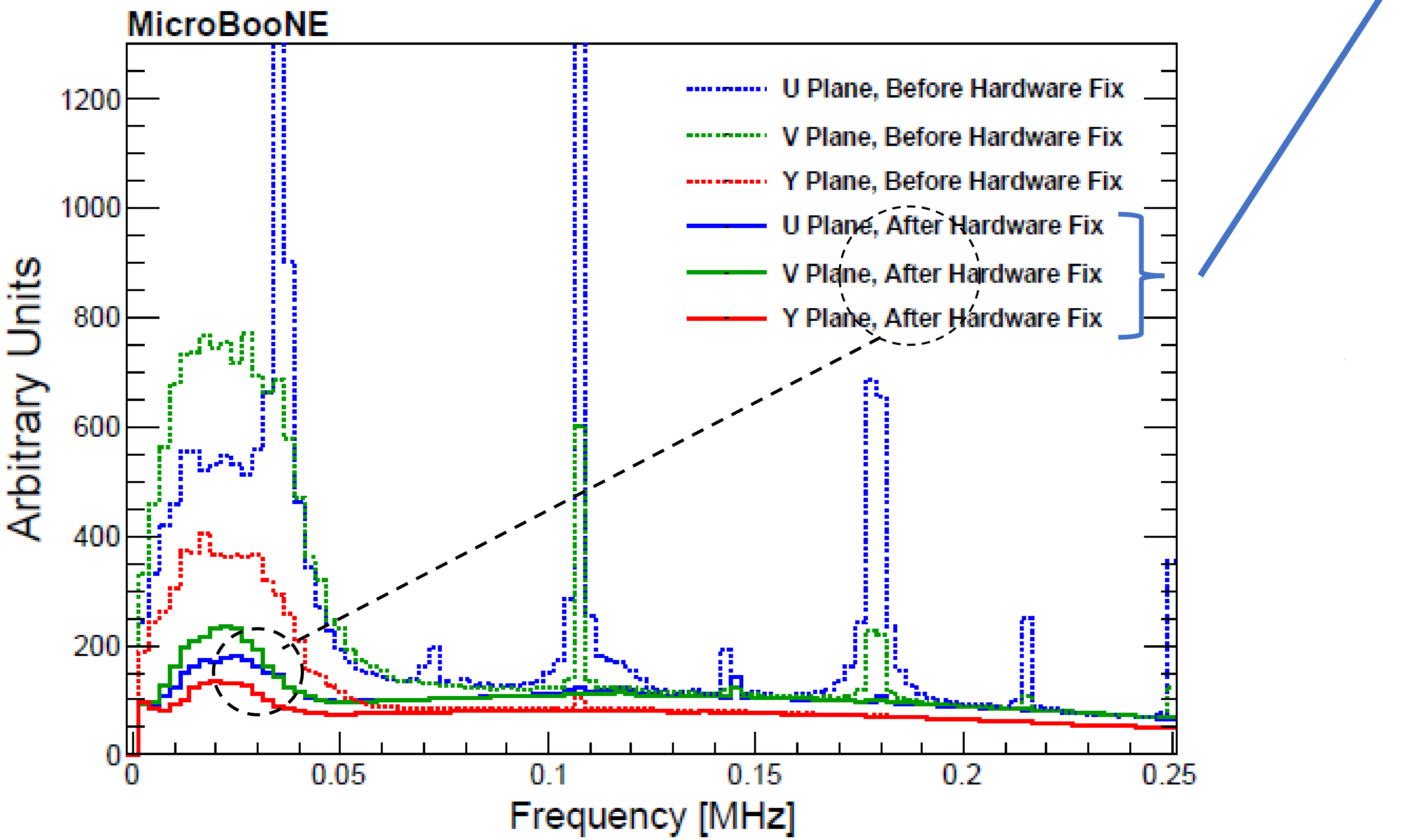
Noise induced by the cathode is progressively attenuated by the shielding effect of the wire planes



Cathode-anode coupling ~ 1 pF/m^2 ~ **20 fF/wire in the 1st wire plane**

Cathode HV ripple must be less than **1 part in 10^7!**

Excess noise removal took some work …. Better HV filters

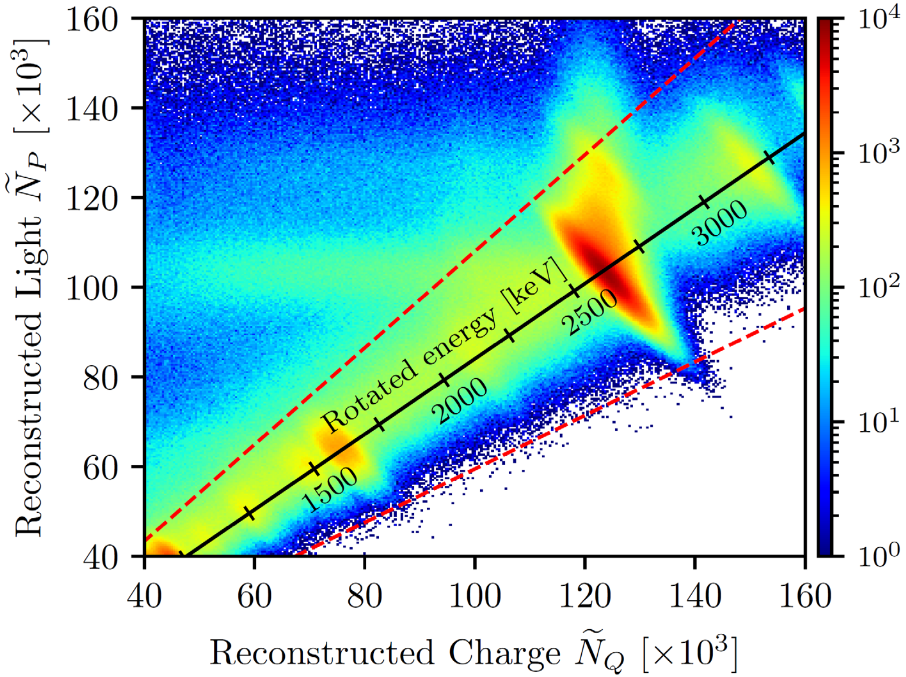


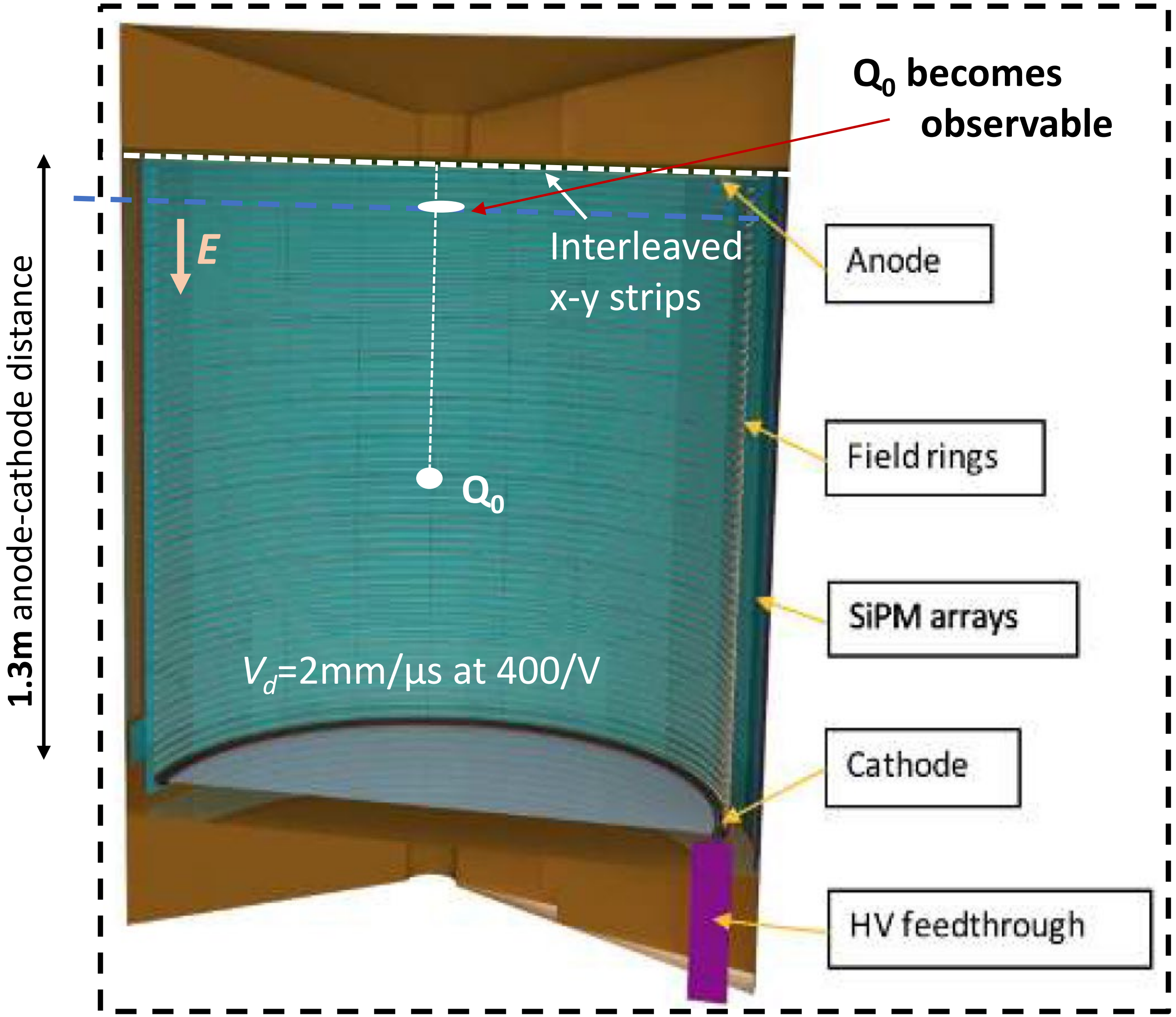
JINST 12 P08003 (2017)

nEXO “5 ton” LXe TPC – search for neutrinoless 2β decay

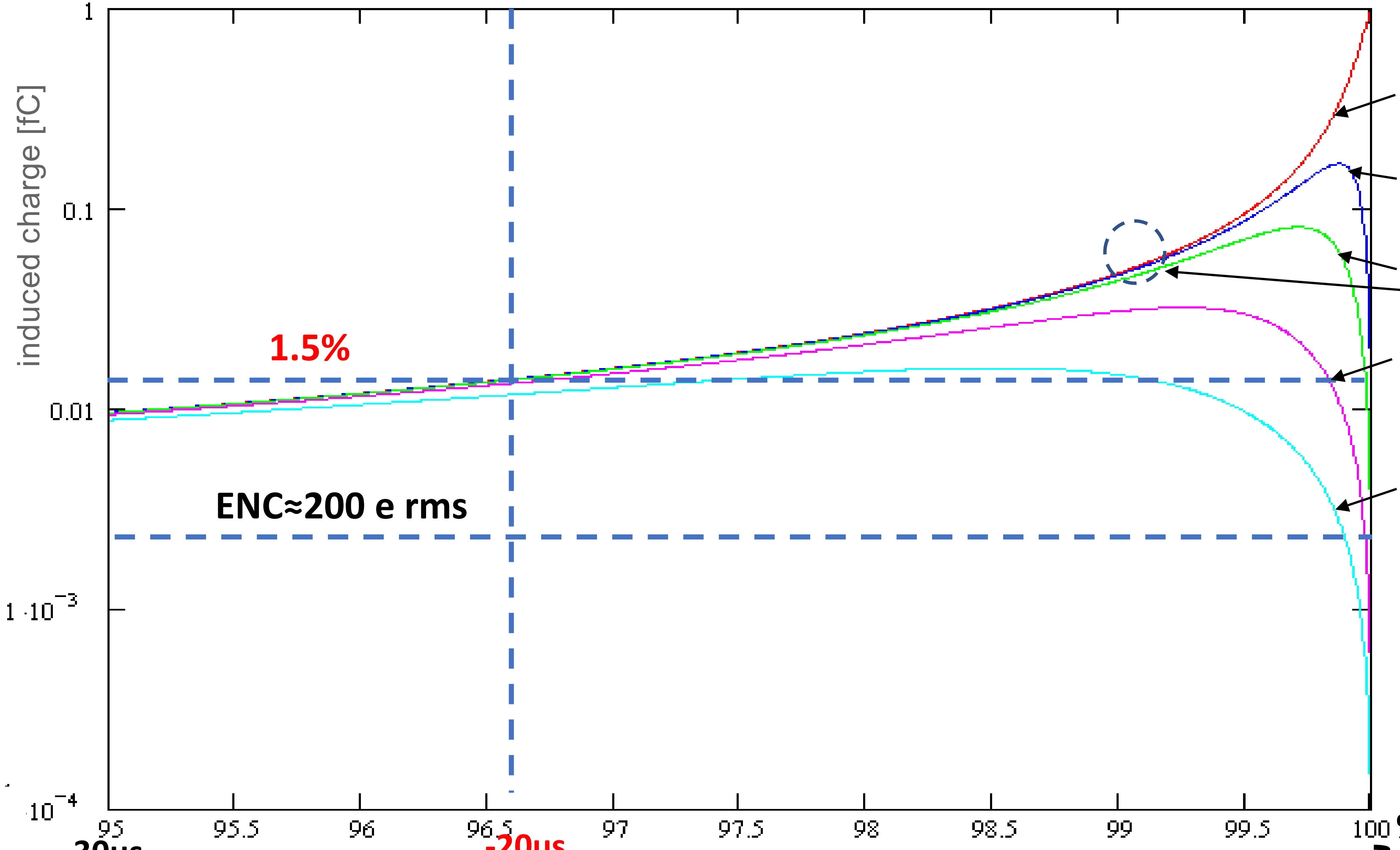
- ^{136}**Xe** is used both as the *source* and *detection* medium.

Charge: **Q_0=16fC (10^5e)** from *$0\nu\beta\beta$*
Charge from *$0\nu\beta\beta$* localized to a few *mm vs* wider spread background events
Sensing electrodes: single plane, interleaved x-y strips
Integration time: **~ 20μs** (long induced signals);
dominant noise is *1/f* from the input transistor;
ENC~200 e rms, demonstrated by LAr cold electronics





Charge induced on the collection strip and on 1^{st} , 2^{nd} , 5^{th} , and 10^{th} neighbor as a function of time and distance to the anode; 3mm strip pitch



Q_0=16fC (10^5e)

Coll.

1^{st}

2^{nd}

5^{th}

10^{th}

1.5%

ENC≈200 e rms

% (of drift from cathode)

-30us
-60mm

-24us
-48mm

-20us
-40mm

-12us
-24mm

-3us
-6mm

0
0

Time and distance to anode

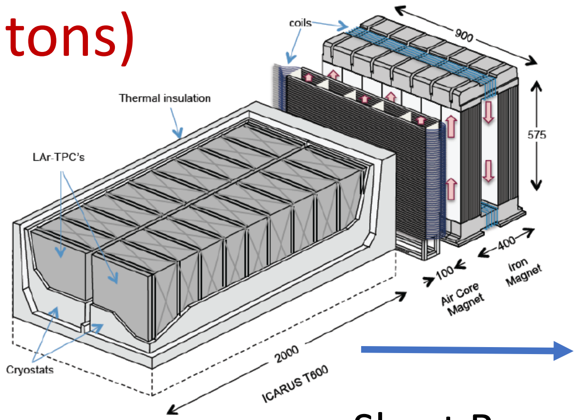
Q_0/ENC≈500

Equal charge induced on adjacent strips until ~1cm from the anode

Ballistic deficit:
1.5% at ~20 μs
1% at ~30 μs
Integration time could be reduced to 10 μs by a 2d grid – a separate study.

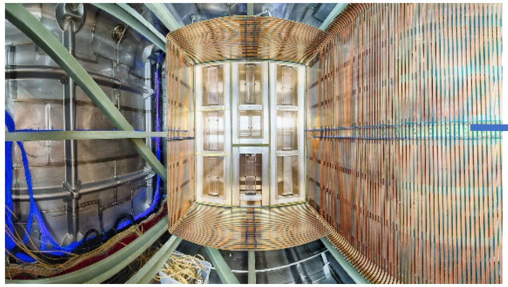
Evolution towards 10 kT ("Single-Phase") LArTPCs

ICARUS (600 tons)



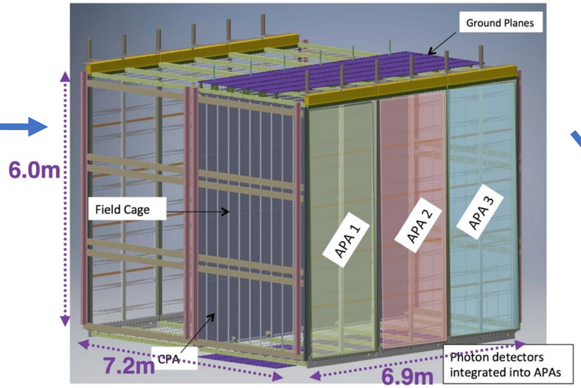
Long Base Line

35-ton prototype



2014-2018

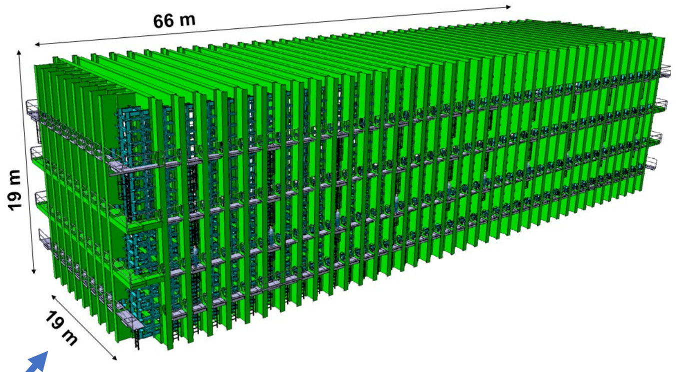
ProtoDUNE (400 tons)



2018-2020

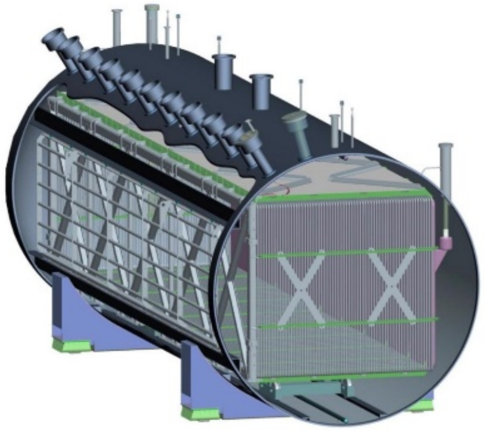
DUNE reference design

$19\text{x}19\text{x}66\ \text{m}^3$

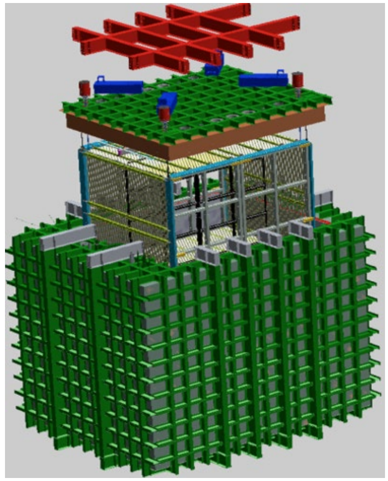


Short Base Line

ArgonNeuT at FNAL



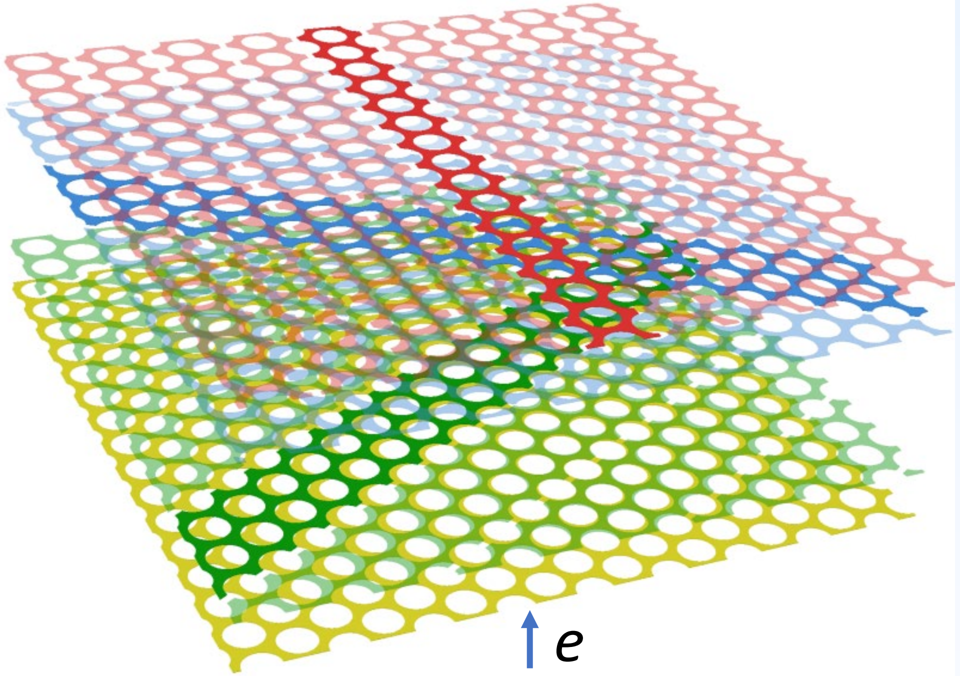
MicroBooNE (80 tons)



SBND (under constr.)

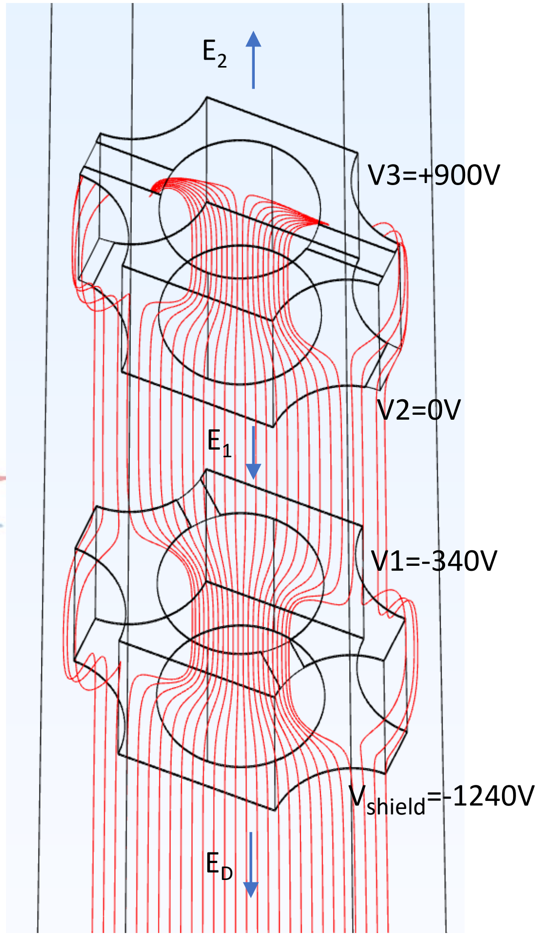
What is new for LAr DUNE-FD2 : A 3-View Perforated PCB Anode Readout Concept

A 3-view (+/-30°, 90°) strip readout. The substrate of the two PCBs are removed for clarity. One strip from each readout plane is highlighted.

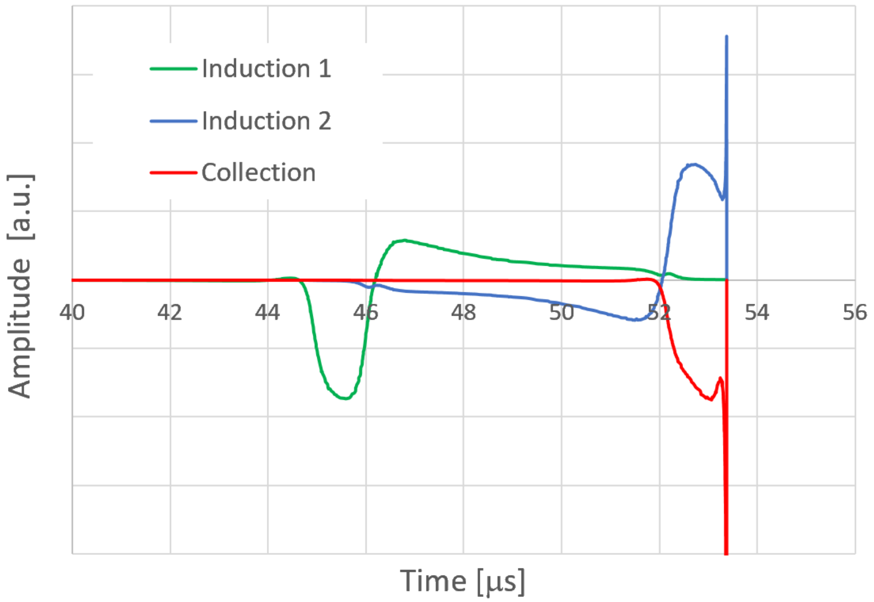


The first plane facing the drift volume is not segmented, it is used for shielding the readout strips from charge injection from the cathode.

Concept developed by F. Pietropaolo (CERN) and B. Yu (BNL)



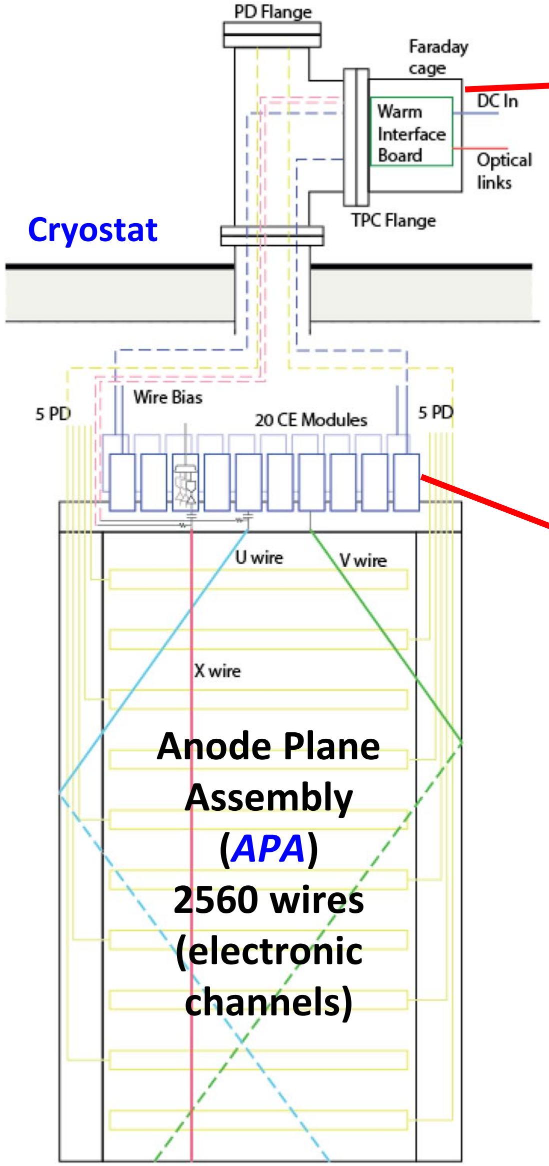
Induced current waveforms from a strip in each view for a point charge passing through the middle of each strip.

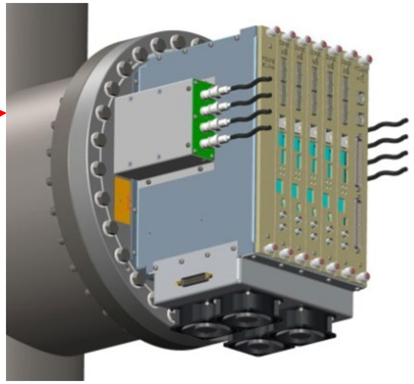


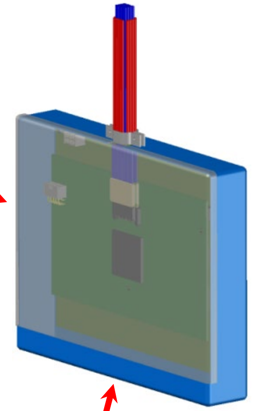
Typical PCB thickness: ~3mm
PCB separation: ~1cm
Hole size: 2-3mm

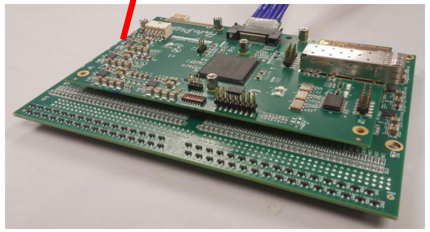
With proper bias voltage on each plane, ionization electrons can be pulled through multiple planes (induction views) without loss and be collected on the last one (collection view).

A Critical Concept: Integral Faraday Cage and Readout



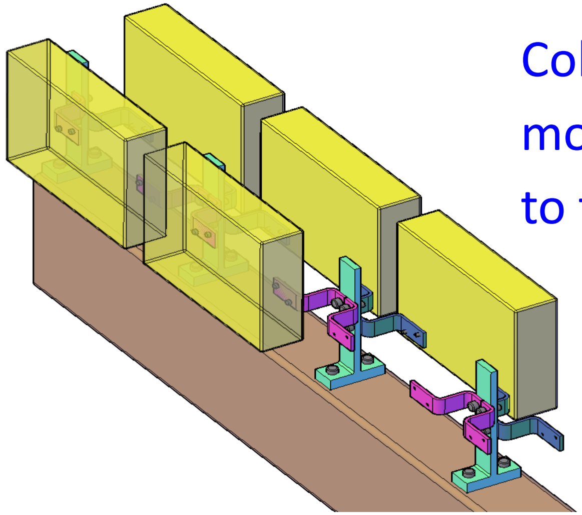






A necessary condition to achieve good system performance:

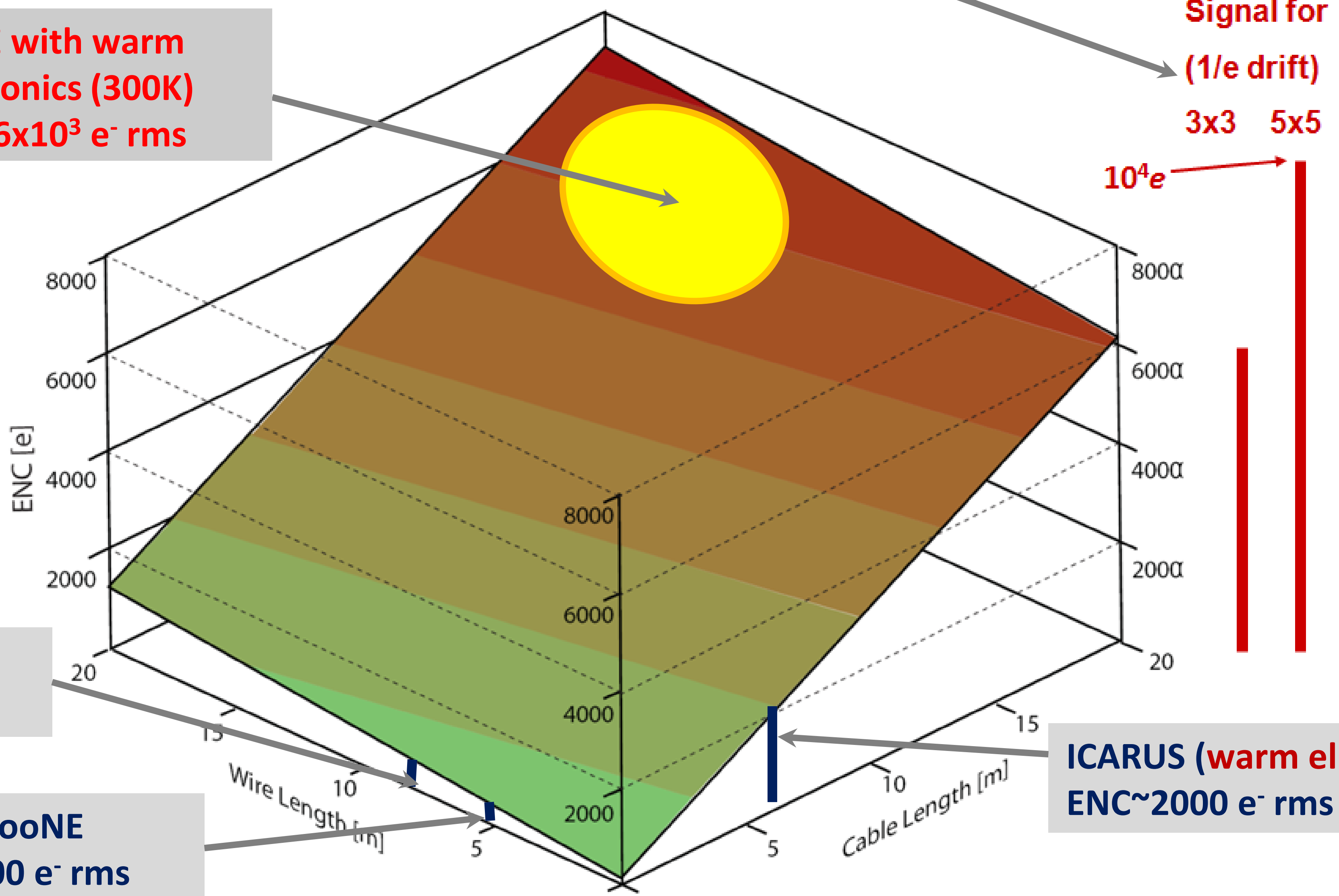
Integral design concept of APA + CE + Feed-through, plus Warm Interface Electronics with local diagnostics and strict isolation and grounding rules



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

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

MIP Signal for 3x3 and 5x5 mm Sense Wire Spacing



DUNE with warm electronics (300K)
ENC~6x10^3 e$^-$ rms

Signal for
(1/e drift)
3x3 5x5

ProtoDUNE
ENC~660 e$^-$ rms

MicroBooNE
ENC~400 e$^-$ rms

ICARUS (warm el.)
ENC~2000 e$^-$ rms

Light sensing in noble liquid TPCs by Silicon Photo Multipliers (SiPMs) for **Large Area Photo Detectors**

Literature for in-depth study of SiPMs (mostly small devices, ≤3x3 mm^2,for PET and medical imaging)

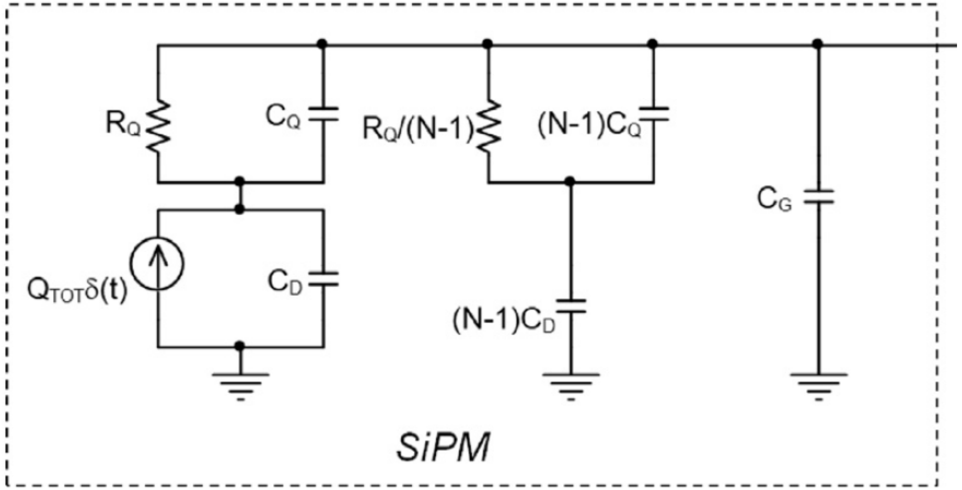
NIM A926 (2019), Special Issue on SiPMs

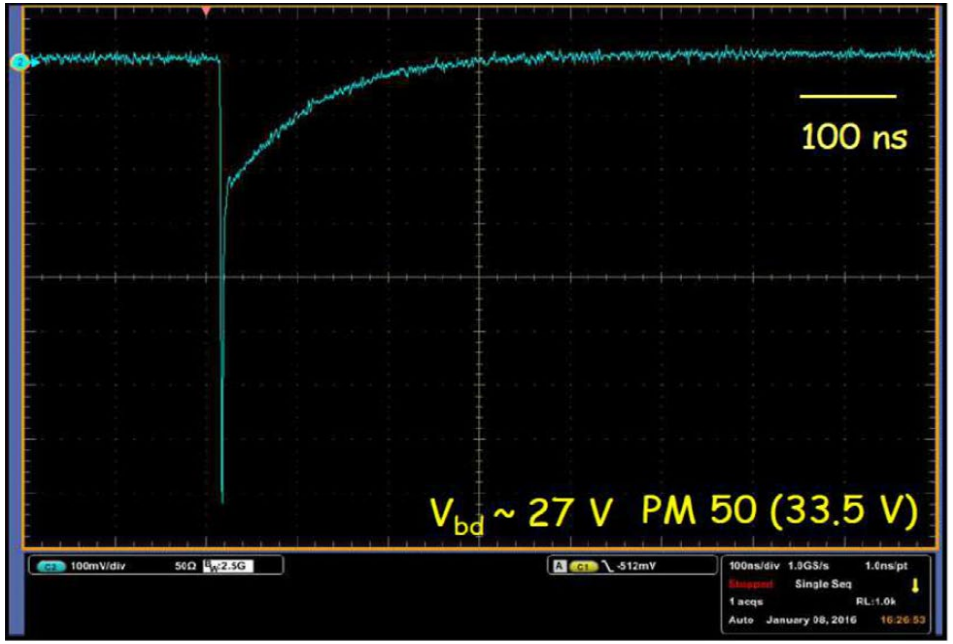
[1] R. Klanner, *Characterisation of SiPMs*

[2] F. Acerbi, S. Gundacker, *Understanding and simulating SiPMs*.

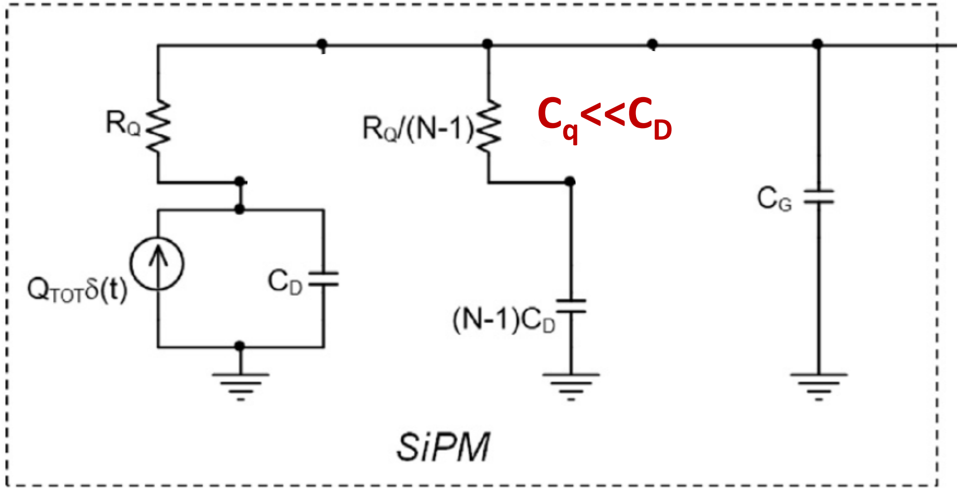
[3] P.P. Calo, F. Cicierello C. Marzocca, S. Petrognani, *SiPM Readout Electronics*.

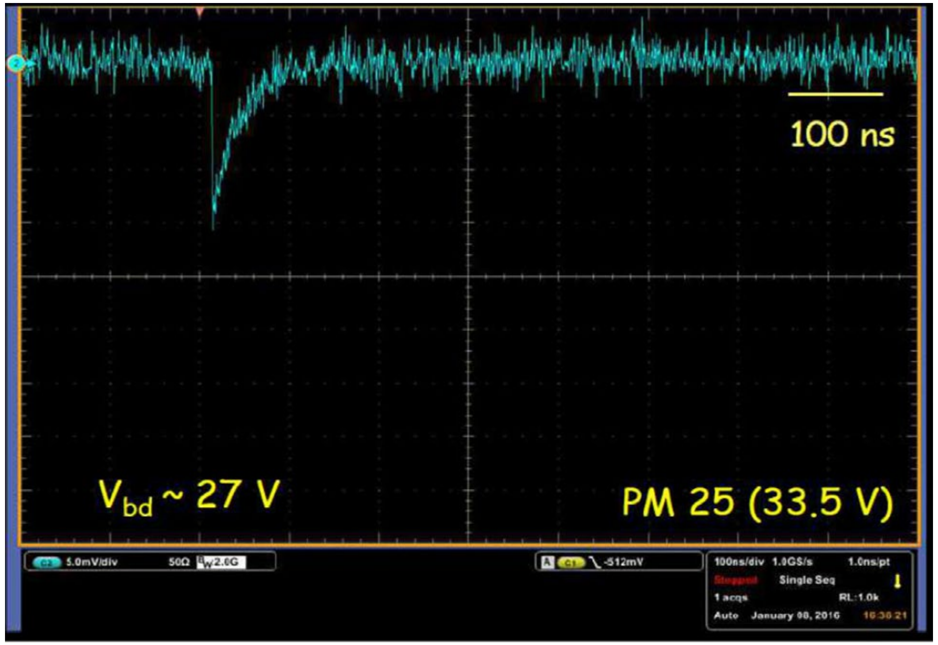
SiPMs for PET, ≤3x3 mm², Pixels ≈ 25 µm





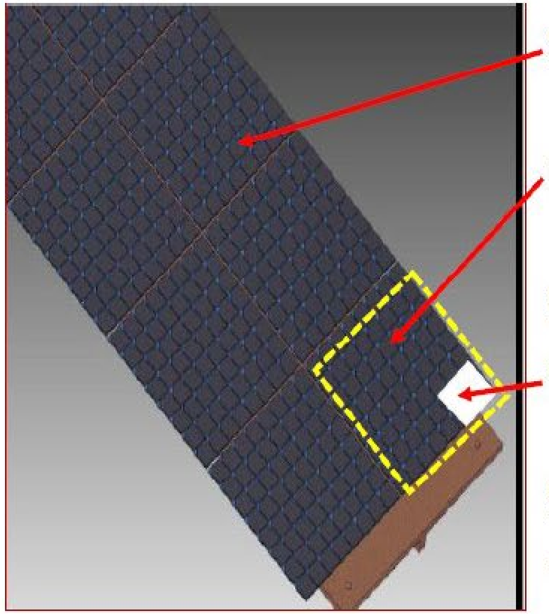
SiPMs for Noble Liquid TPCs, ≥6x6 mm², Pixels ≥ 50 µm





Adapted from: R. Klanner, NIM A926 (2019) 36

nEXO SiPM Light Detector Readout

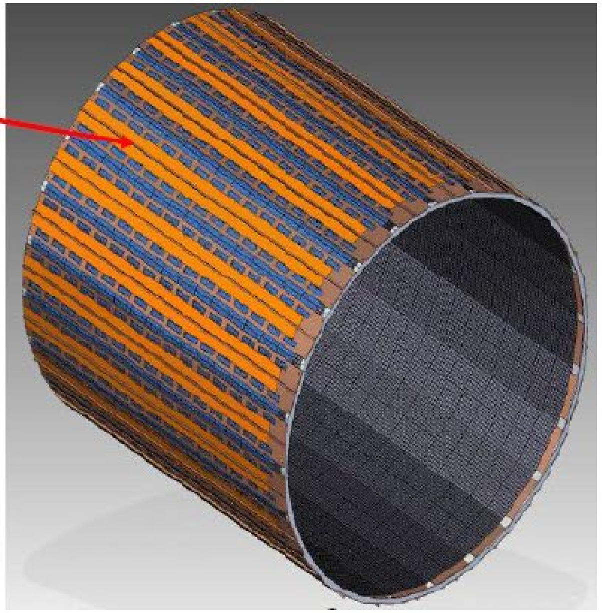


Staves: **24**

Tiles : **24** x 2 x 10 = **480**

Sub-arrays 6 cm^2:
480 x 16 = **7680**

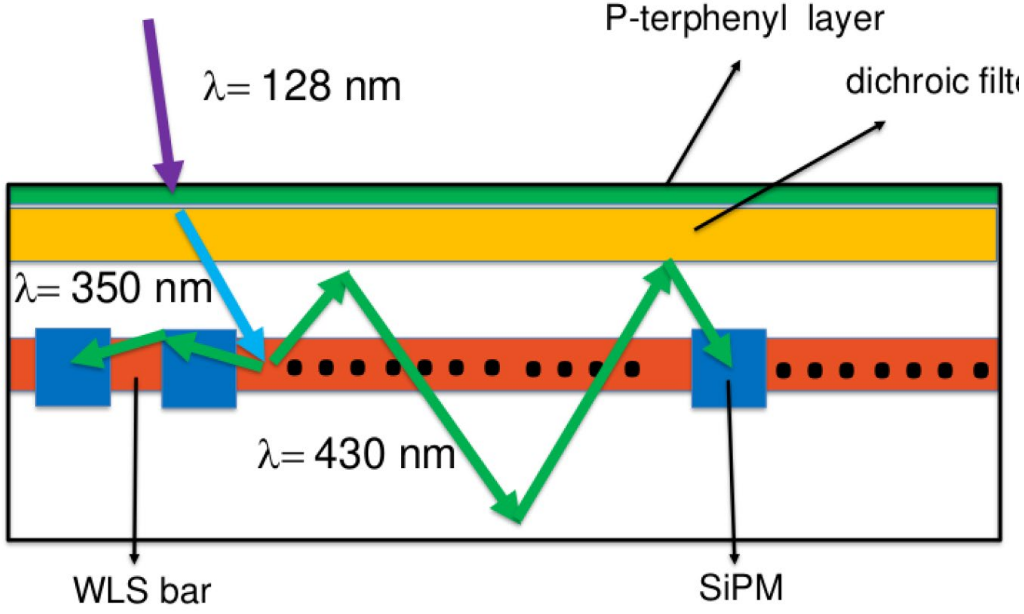
SiPM Area: **7680** x 6 cm^2=
= **= 4.6 m^2**



Technology	**“HPK”**	**“FBK”**
C/A [nF/cm^2]	3.5	8.5
V_{op} [V]	50	30
C_{6cm^2} [nF]	**21**	**51**
C_{2s} [nF]	**5**	**12.5**
V_{2s} [V]	100	60

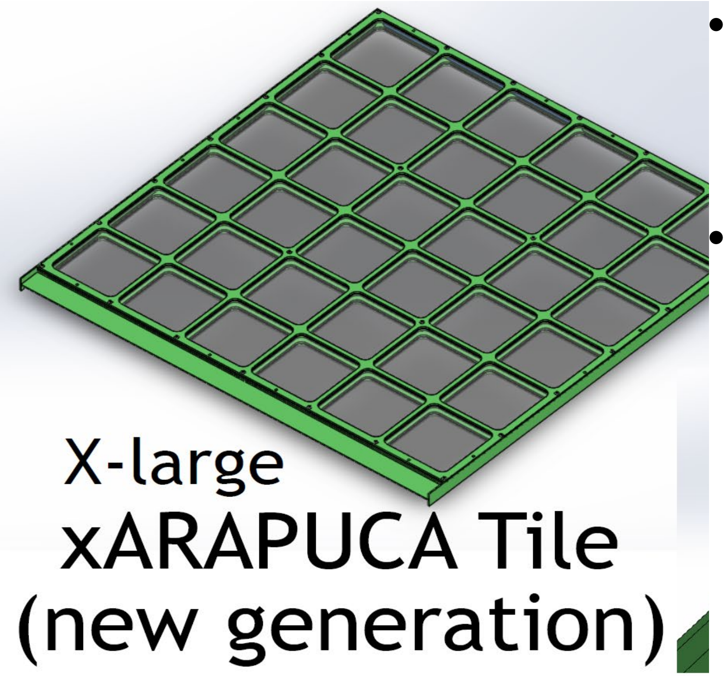
Readout challenge:
Fine segmentation, 7680 SiPM subarrays=electronic channels (<1 p.e/subarray), still results in a “giant” subarray capacitance/channel, ~**5-12 nF** in the best case (series connection C_{2s}), and ~**20-50 nF** in the worst case (SiPMs in parallel).

ARAPUCA (Argon R&D Advanced Program at UniCAmp).



Credits: F. Terranova

- ➢ 160 SiPMs (40 per side)
    - ➢ Glued to WLS Bar for improved optical contact
- ➢ SiPMs mounted on Kapton flexi-PCB

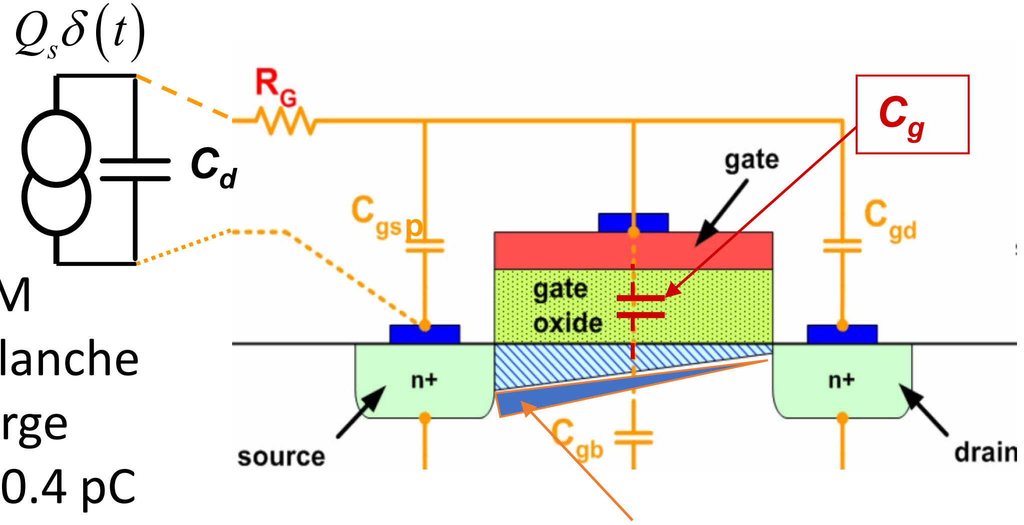


X-large
xARAPUCA Tile
(new generation)

- **Optical area**
    - **600 mm x 600 mm=3600 cm^2**
- **SiPM area**
    - **160 x 0.36 cm^2 ≈60 cm^2**
    - **≈1.7 % of opt. area**
    - **SiPM array capacitance ≈200 nF for V_{bd}~45 V;**
    - **≈260 nF for V_{bd}~37 V**

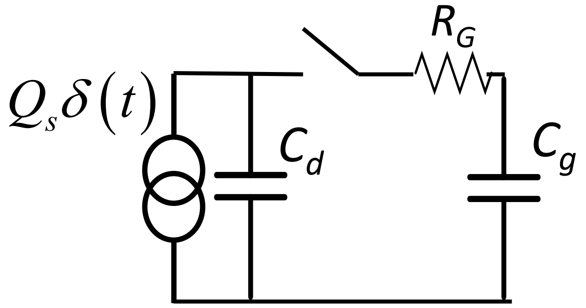
M.C. Queiroga Bazetto, V.L. Pimentel, A.A. Machado and E. Segreto, in Campinas, Brazil

How much of the avalanche charge can we really "see"?
SiPM – transistor capacitance mismatch



SiPM avalanche charge **Q_s**≈0.4 pC

"useful" charge: **Q_g** modulates the channel and with transistor noise determines S/N



$$\frac{Q_g}{Q_s} = \frac{C_g}{C_g + C_d}$$

Example:

SiPM array: C_d≥10 nF

Transistor gate: C_g =25pF (very large transistor)

$(Q_g/Q_s)=(Cg/Cd)\leq 1/400$

We "see" less than **1/400** of the SiPM avalanche charge.

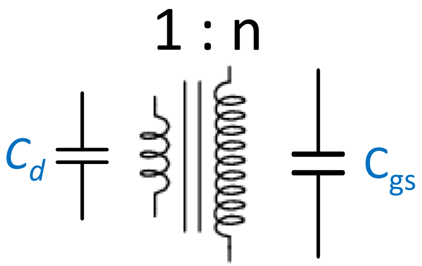
A long way to the maximum transfer of charge:

$(Q_g/Q_s)_{max}$ **= 1/2**
for ***(Cg/Cd)=1***

SiPM-to-transistor capacitance matching: *SNR* vs transformation ratio *n*

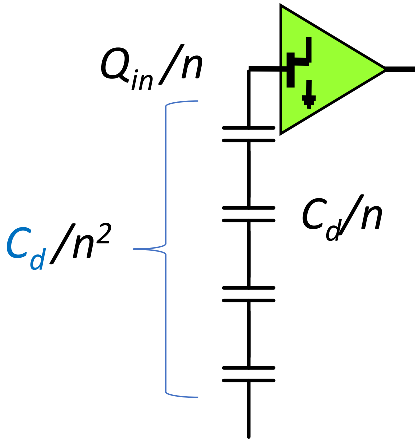
$$\left(\frac{S}{N}\right)_{(n)/(n=1)} \simeq n_{opt}\frac{n/n_{opt}}{1+\left(n/n_{opt}\right)^{2}} \qquad n_{opt}=\left(\frac{C_d}{C_{gs}}\right)^{1/2} \qquad \left(\frac{S}{N}\right)_{(\max)/(n=1)}=\frac{n_{opt}}{2}$$

n= transformation ratio for ***EM and ES transformers***; for ***transistors in parallel***: $n = n_{trans}^{1/2}.$



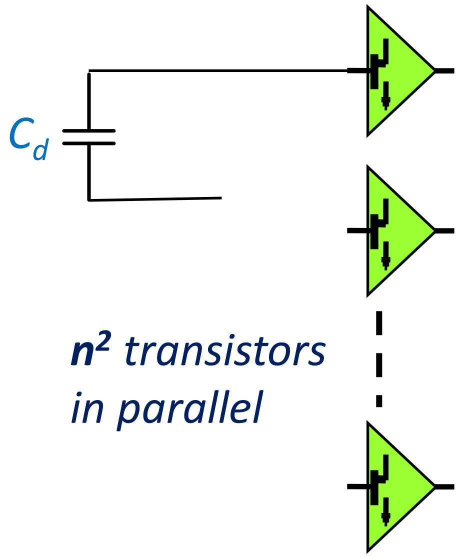
EM transformer, most effective and proven, but not radio pure (introduced 1974)

For C_d=10 nF, C_g=25 pF → n_{opt}={C_d/C_g)^1/2~**20**, *S/N* is increased by ***n**$_{opt}$***/2=10**



ES (Electrostatic) transformer (introduced 1990)

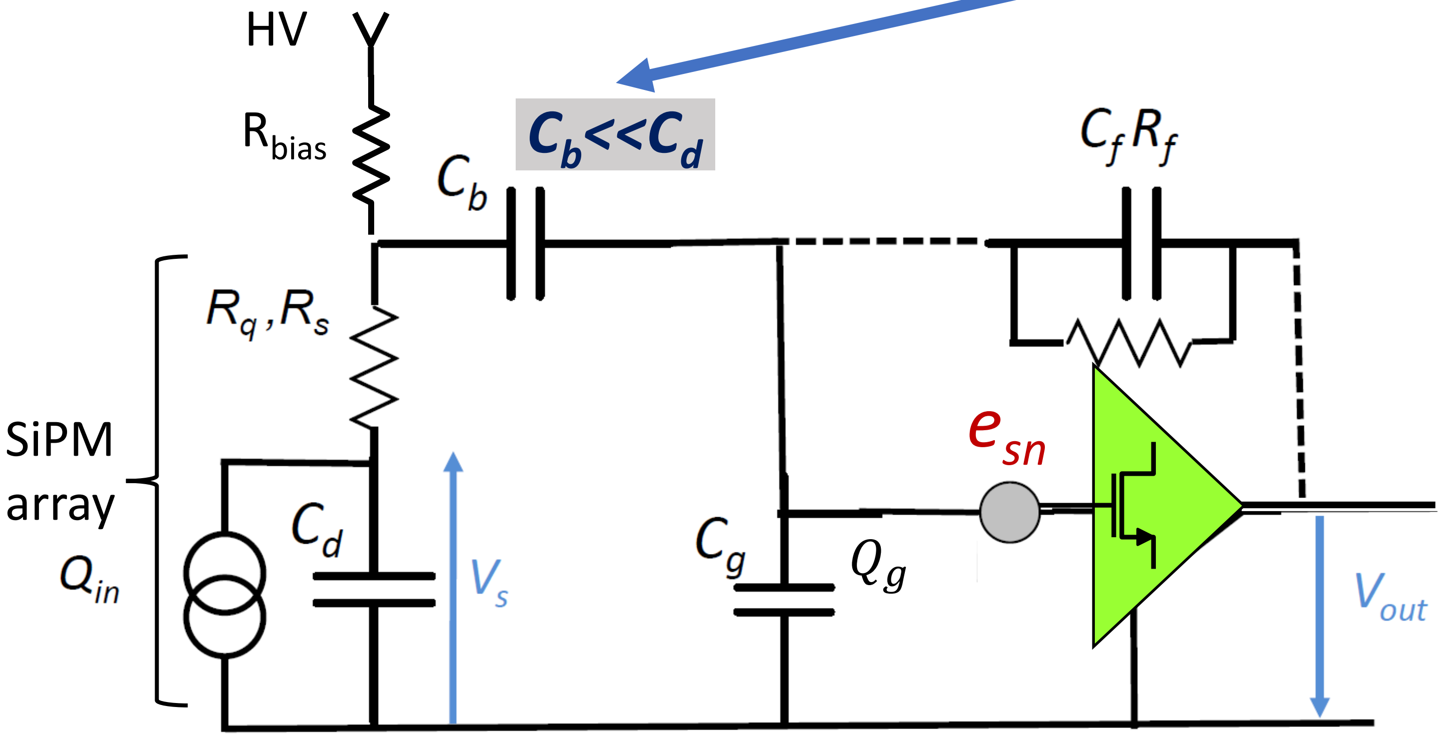
ES transformer n=4 improve *S/N* by a factor of ~ 3.95 ;
compared to parallel connection of SiPMs.



***n²** transistors in parallel*

It would take ***n*²=16** times as large a transistor area ***and power*** for the same result as with EM or ES transformer.

Optimal readout for SiPM arrays: Weak coupling to amplifier



Conventional approach: $C_b>>C_d$, resulting in (de)coupling capacitors in ***tens of nanofarads***, to elaborate electronic circuits (e.g., "current conveyor") with no benefit to S/N. Active (forced) transfer of charge is accompanied by increase in noise.

Basic limitation: Only *a fraction of avalanche charge*, $Q_g \approx \frac{C_g}{C_d} Q_{in}$ can be transferred "adiabatically" to the gate .

Q_{in}= avalanche charge

C_d=capacitance of SiPM array in parallel;

n = ES transformation ratio

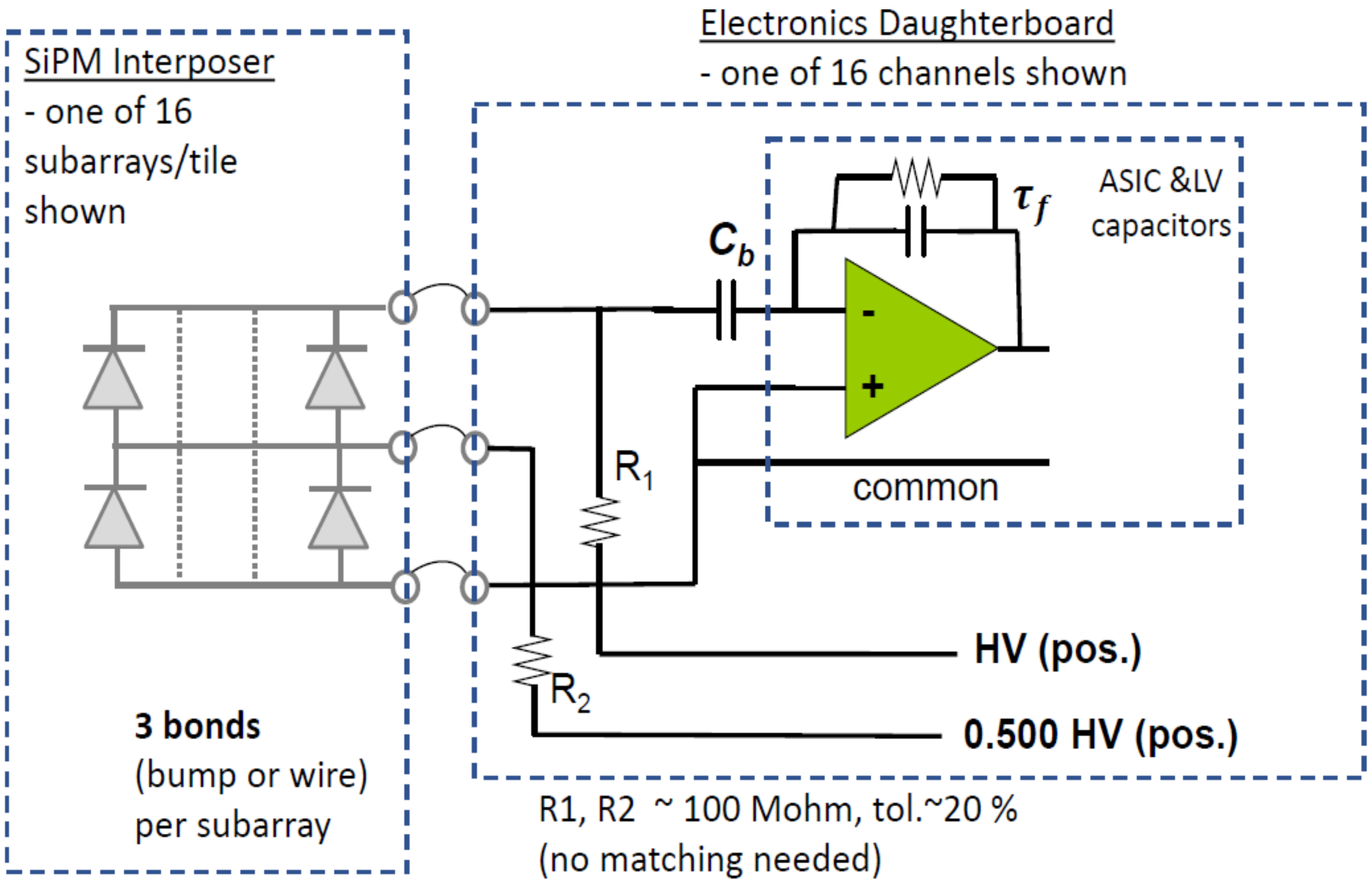
$$\left(\frac{S}{N}\right)_n = \frac{Q_{in}/C_d}{e_{sn}/t_p^{1/2}} \cdot \frac{n}{1+C_g/C_b+n^2\,C_g/C_d}$$

***S/N analysis** shows: C_b must be larger than C_g, but can be much smaller than C_d:*

$$C_d>>C_b>>C_g$$

e.g., *10 nF>>0.5 nF>>25 pF*

BNL: Demonstration of 6 cm^2 SiPM(HPK) subarrays with LArASIC in LN2



SiPM Interposer
- one of 16 subarrays/tile shown

Electronics Daughterboard
- one of 16 channels shown

3 bonds (bump or wire) per subarray

R1, R2 ~ 100 Mohm, tol.~20 %
(no matching needed)

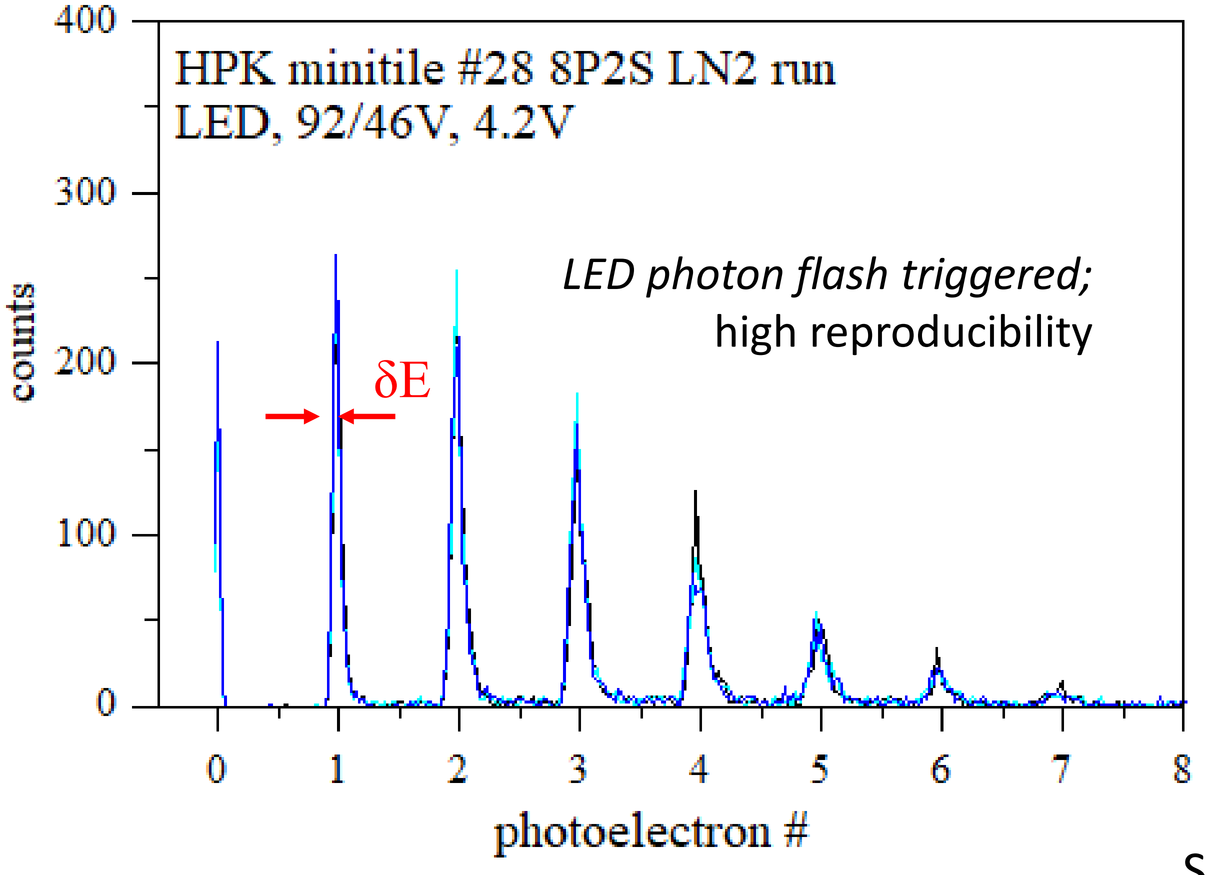
Electrostatic Transformer (series connection of SiPMs) ***n*=2** shown; readout scheme is independent of ***n***

“Weak coupling” (Cb<<Cd) vs conventional strong coupling (Cb>>Cd):

- **Radiopure 0.5 nF/100 V capacitor** easier to realize, and lower risk than 50 nF/100V;
- Calibration and diagnostics of electronics independent of SiPM capacitance and condition (open or short).
- Small C_b allows higher inductance interconnections.
- In situ SiPM array capacitance measurement

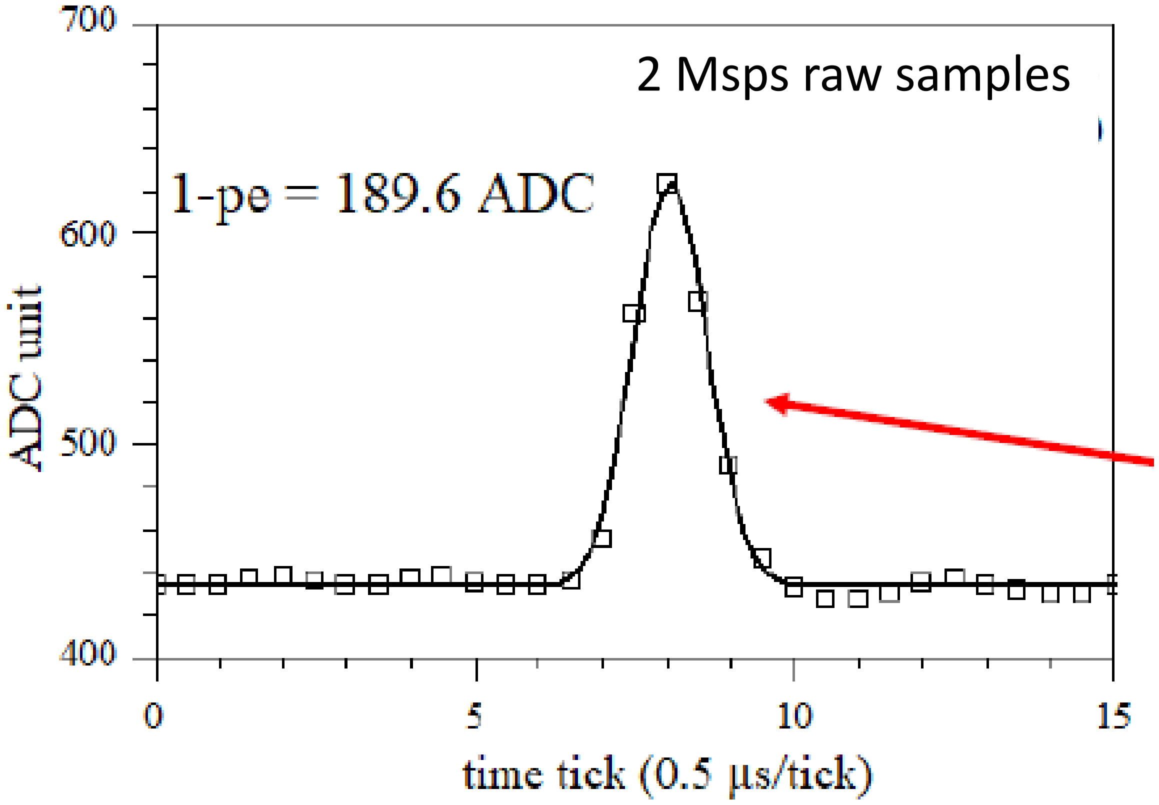
Concept, realization, tests by
H. Chen, S. Gao, V. Radeka, S. Rescia, T. Tsang

BNL: Demonstration of 6 cm^2 SiPM(HPK) subarrays with LArASIC in LN2



LED photon flash triggered;
high reproducibility

Photon rate: ~80 Hz (trigger rate 100 Hz)



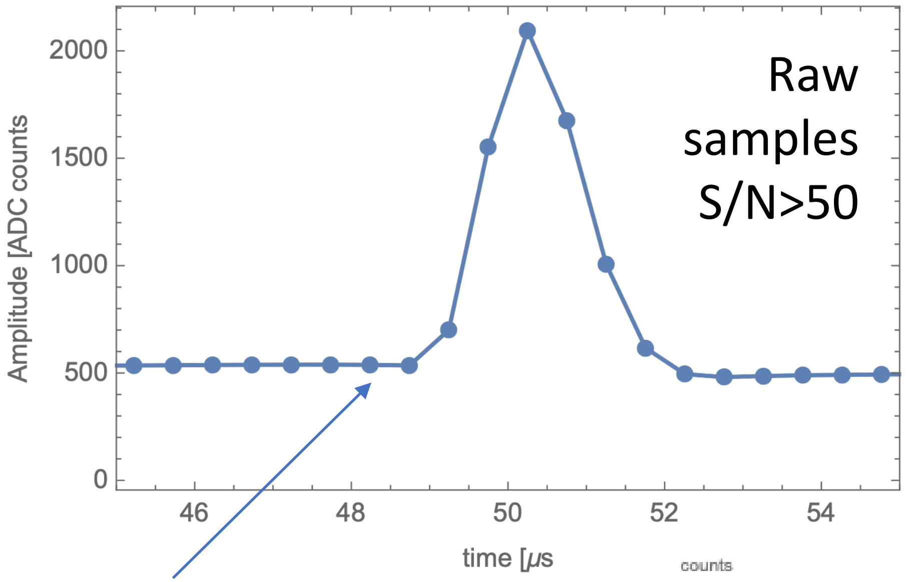
2 Msps raw samples

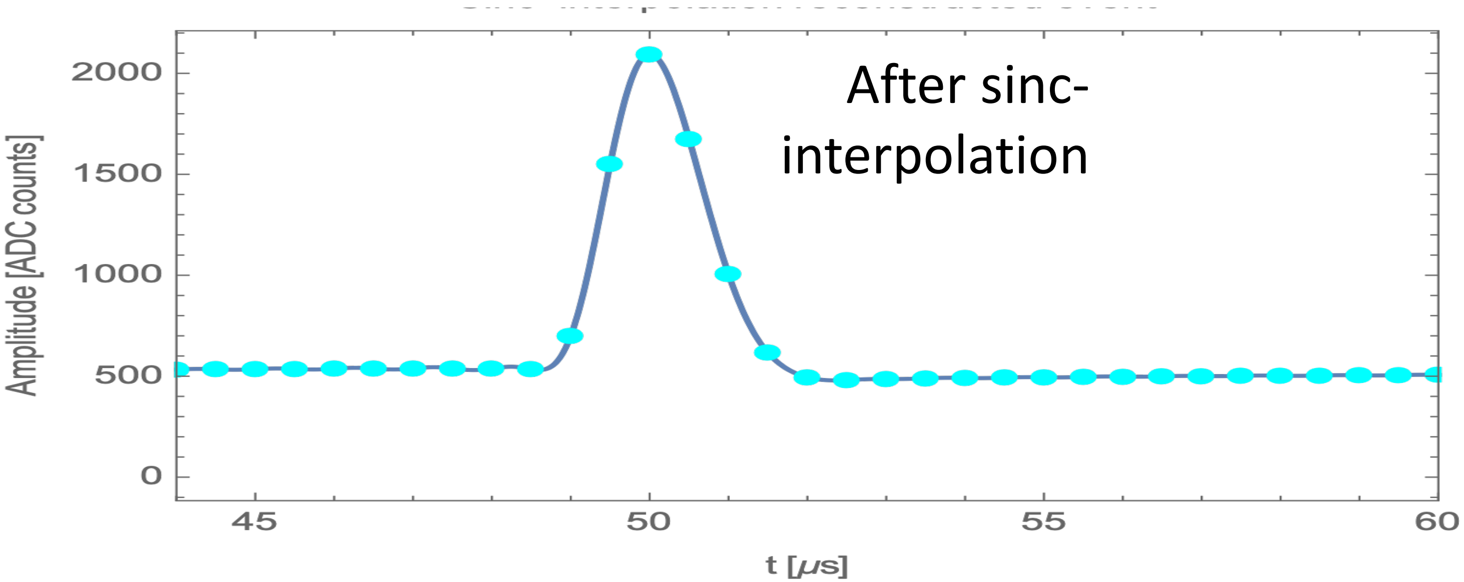
Single photoelectron waveform information provided by a “snippet” of samples :

1-pe resolution (δE): 3 to 3.5% rms

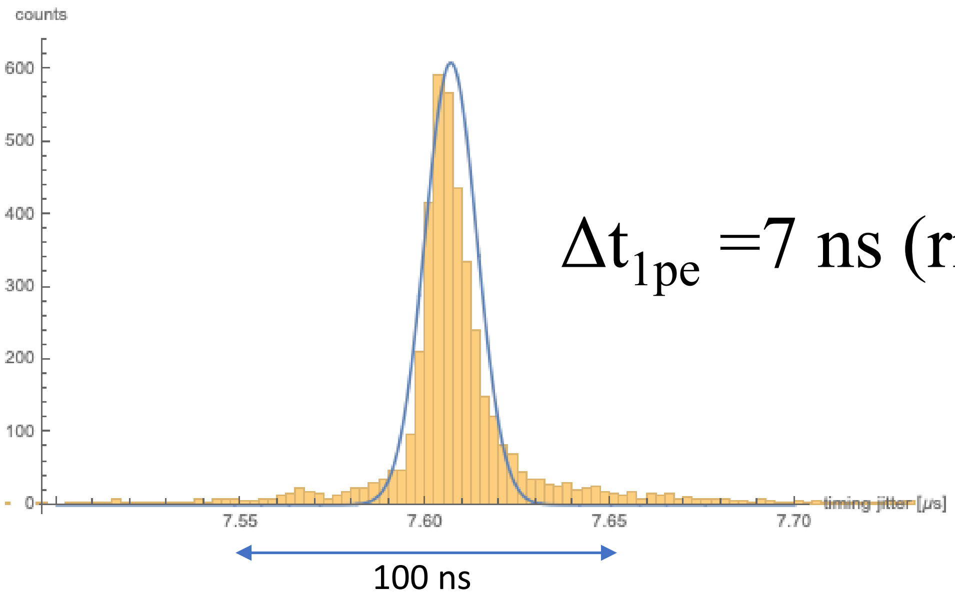
- ***S/N* ~60**
- ***coincidence resolution* between two subarrays < 19 ns**

Waveform reconstruction and single-photon timing resolution (SPTR)





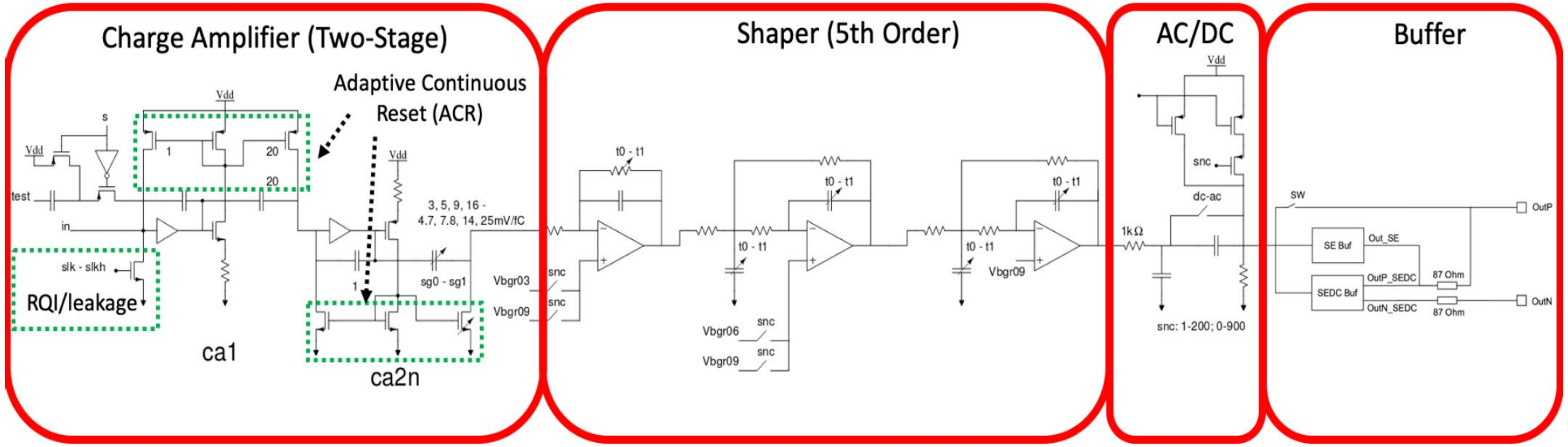
Waveform snippet:
10 μs = 20 samples
at **2Msps**;
***t*$_p$=1μs** anti-aliasing
filter

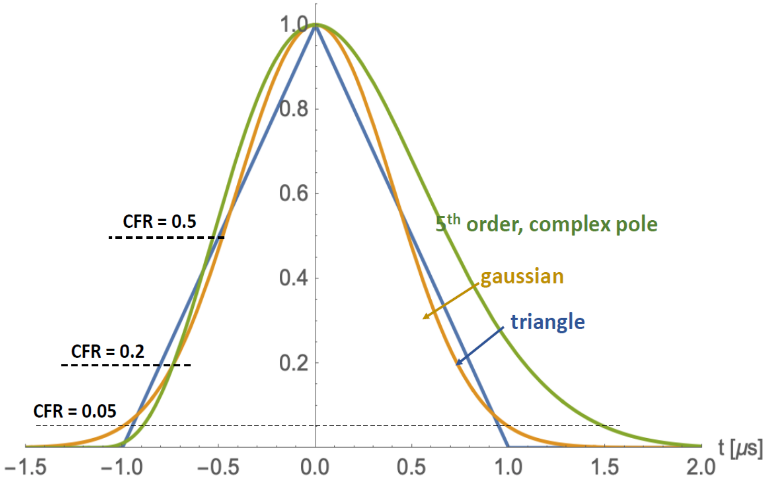


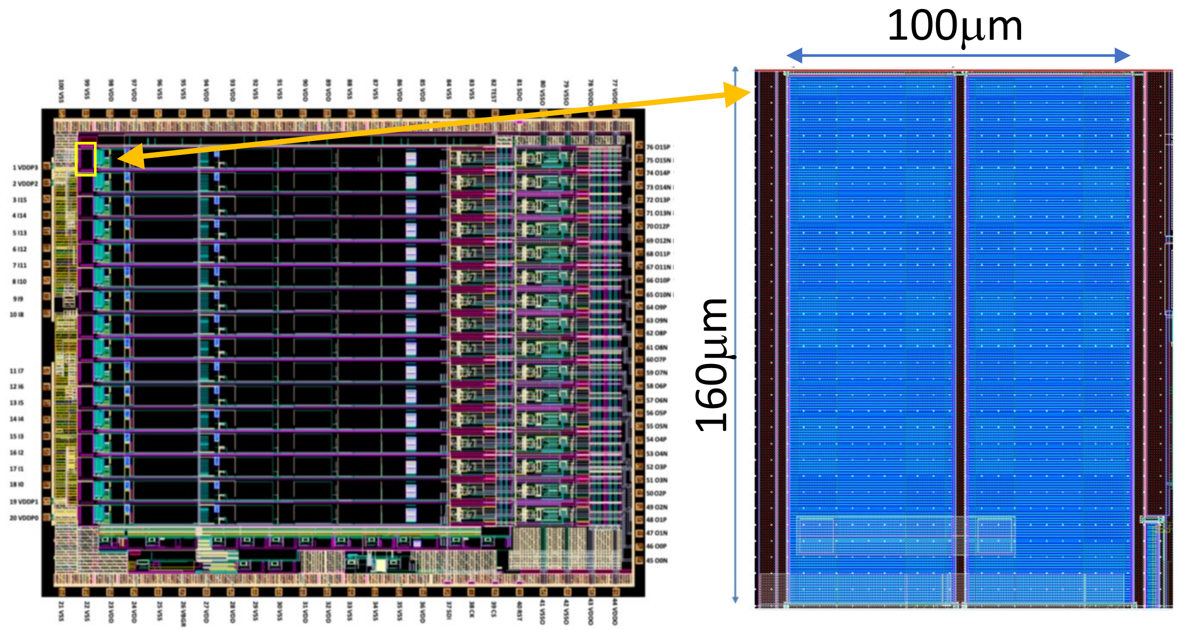
$\Delta t_{1pe} = 7$ ns (rms)

Using ***sinc-interpolation*** +
'digital' constant fraction
discriminator, results in a
low timing error (SPTR)

LArASIC = Antialiasing Filter

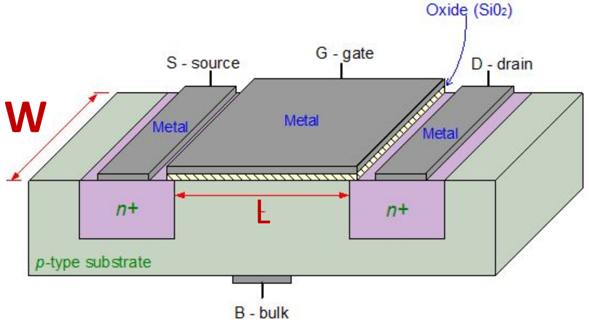






$160\mu m \times 100\mu m = 16{,}000\mu m^2$

$$W/L = \frac{20\ mm}{270\ nm}$$



For a *very large low noise PMOS transistor* W~20mm, L~270nm, W/L~4x10^4, C_g~20pF ;

This very large transistor is a small fraction (~1/400) of the SiPM capacitance.

The equivalent noise resistance is smaller than SiPM quenching resistance and interconnections resistance (<10 ohms).

Summary

- With a large SiPM array capacitance grossly mismatched to even the largest input transistor, active (forced) transfer of charge from SiPM via a large (de)coupling capacitor (**$C_b>C_d$,**i.e., strong coupling) does not benefit SNR.
- In a forced (*non-adiabatic*) transfer of charge by a "current amplifier/conveyer", "transimpedance", or any other, both the signal and the transistor noise are affected equally by amplifier feedback, and SNR remains unaffected by feedback necessary to realize such circuits. Amplifiers with unavoidable noise are used to transfer the charge.
- In case of a large mismatch, **a *weak coupling* between the SiPM and input transistor is sufficient**, where $C_d>>C_b>>C_g$. A charge sensitive amplifier (CSA), or a "voltage amplifier" is coupled to a SiPM parallel/series array by a decoupling capacitor only an order of magnitude larger than transistor capacitance, and independent of a much larger SiPM array capacitance **(C_b~200-500pF for 5-10 nF, or even 100 nF, SiPM array).**
- Experimental verification of the noise calculation, SiPM response, SNR, and timing resolution have been demonstrated.
- SiPMs with lower capacitance, higher V_{bd}, offer better SNR and timing resolution in large area photo detectors. **The cost of higher capacitance SiPMs is in higher system cost (power, cabling) for equal SNR.**

Acknowledgements:

- Support for Charge and Light Detector Studies:

  David Asner, Gabriella Carini, Grzegorz Deptuch
- Test Facilities:

  Instr. Div. Laser&SiPM Lab; Neutrino and ATLAS detector labs., Physics Dept., Hucheng Chen
- Test and Analysis Team:

  Shanshan Gao, Sergio Rescia, Thomas Tsang
- Insight into induced signal formation:

  Bo Yu
- Insight into SiPM design:

  Gabrielle Giacomini