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Improvements in the NOvA Detector Simulation based on JINR stand measurements

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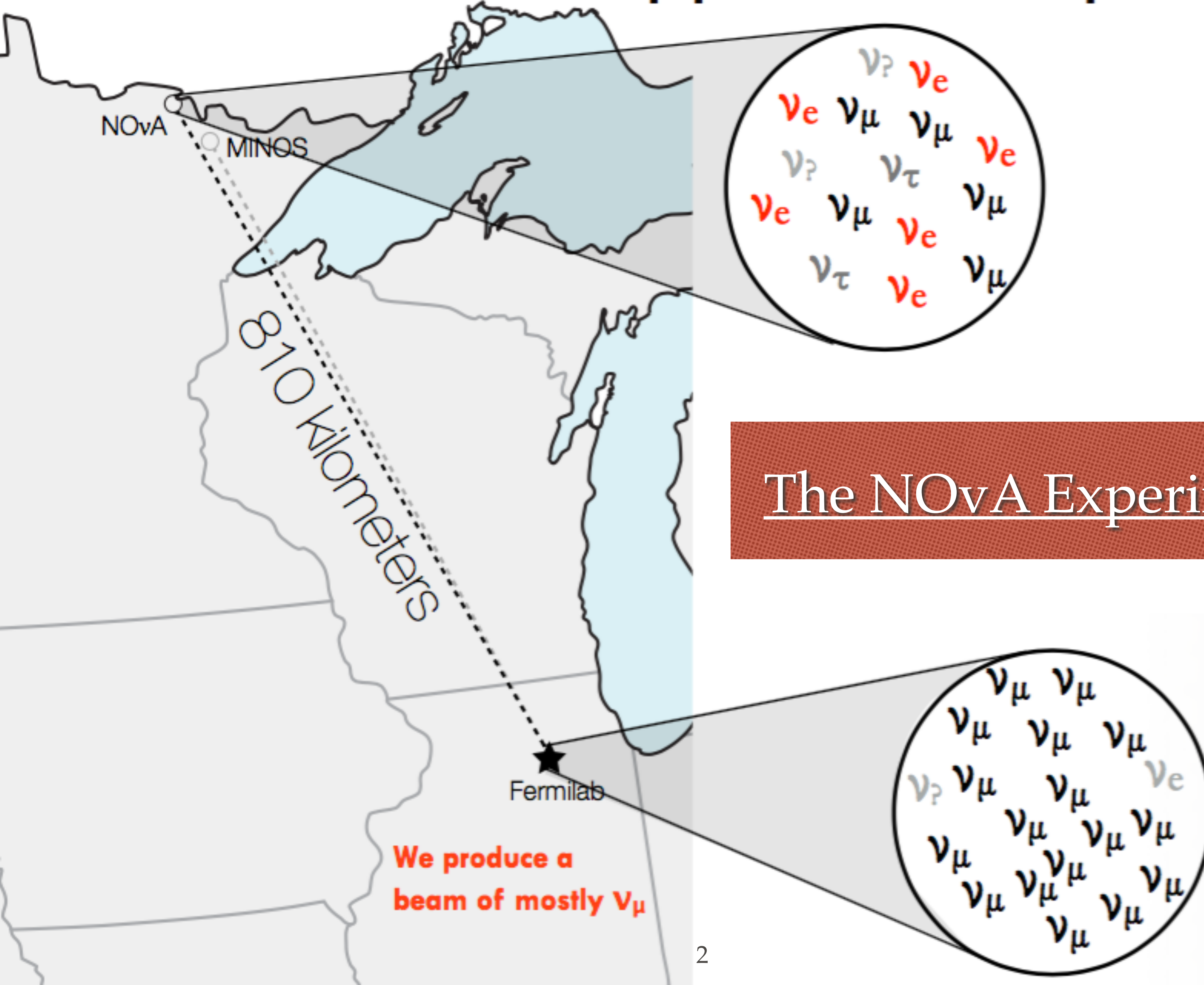
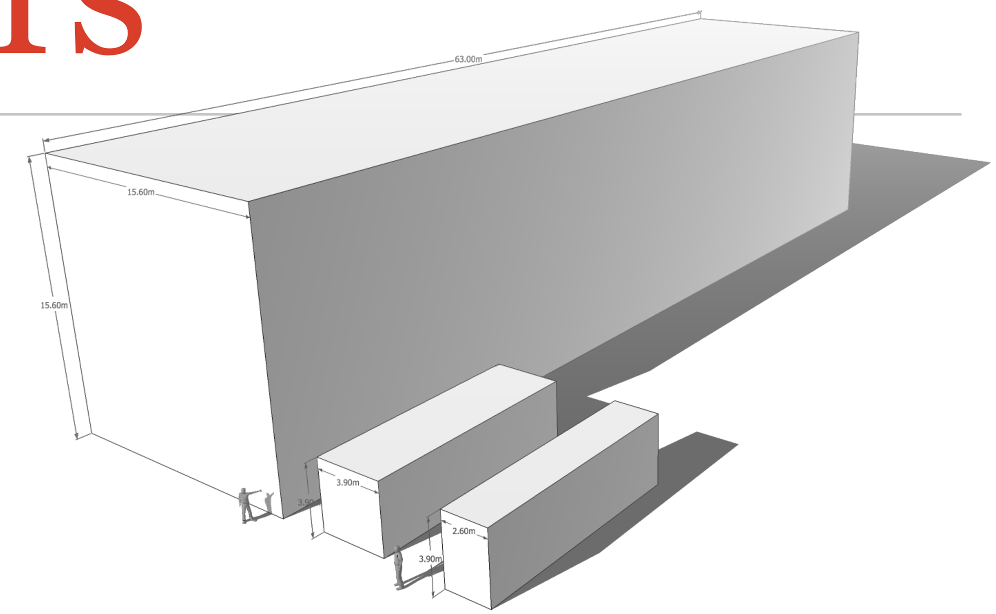
NuMI Off-axis ν_e Appearance Experiment

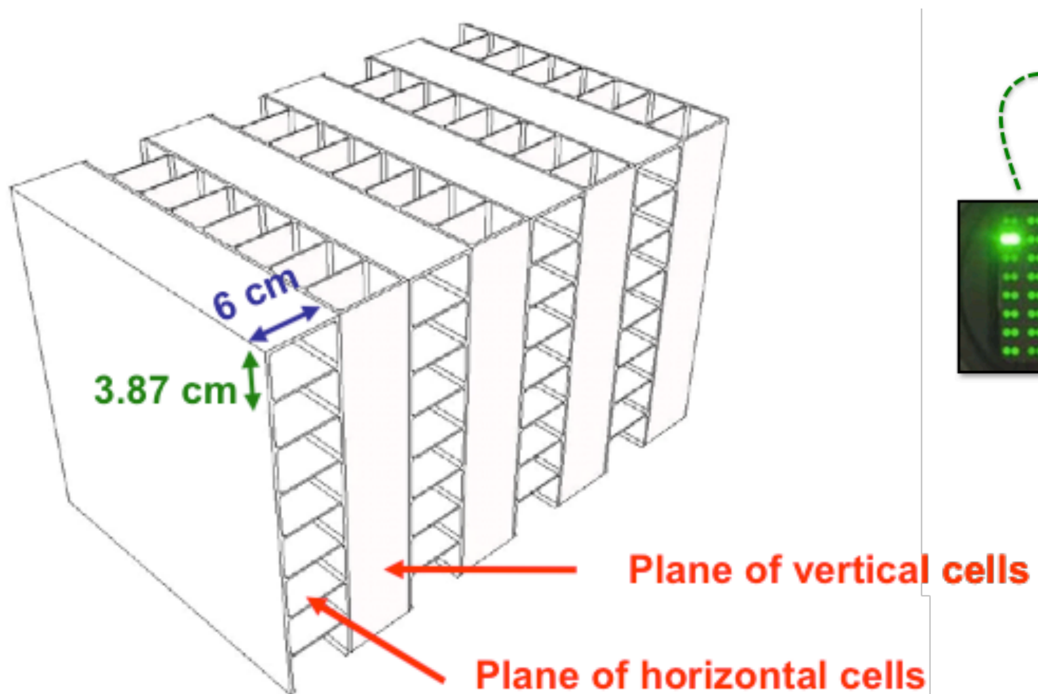


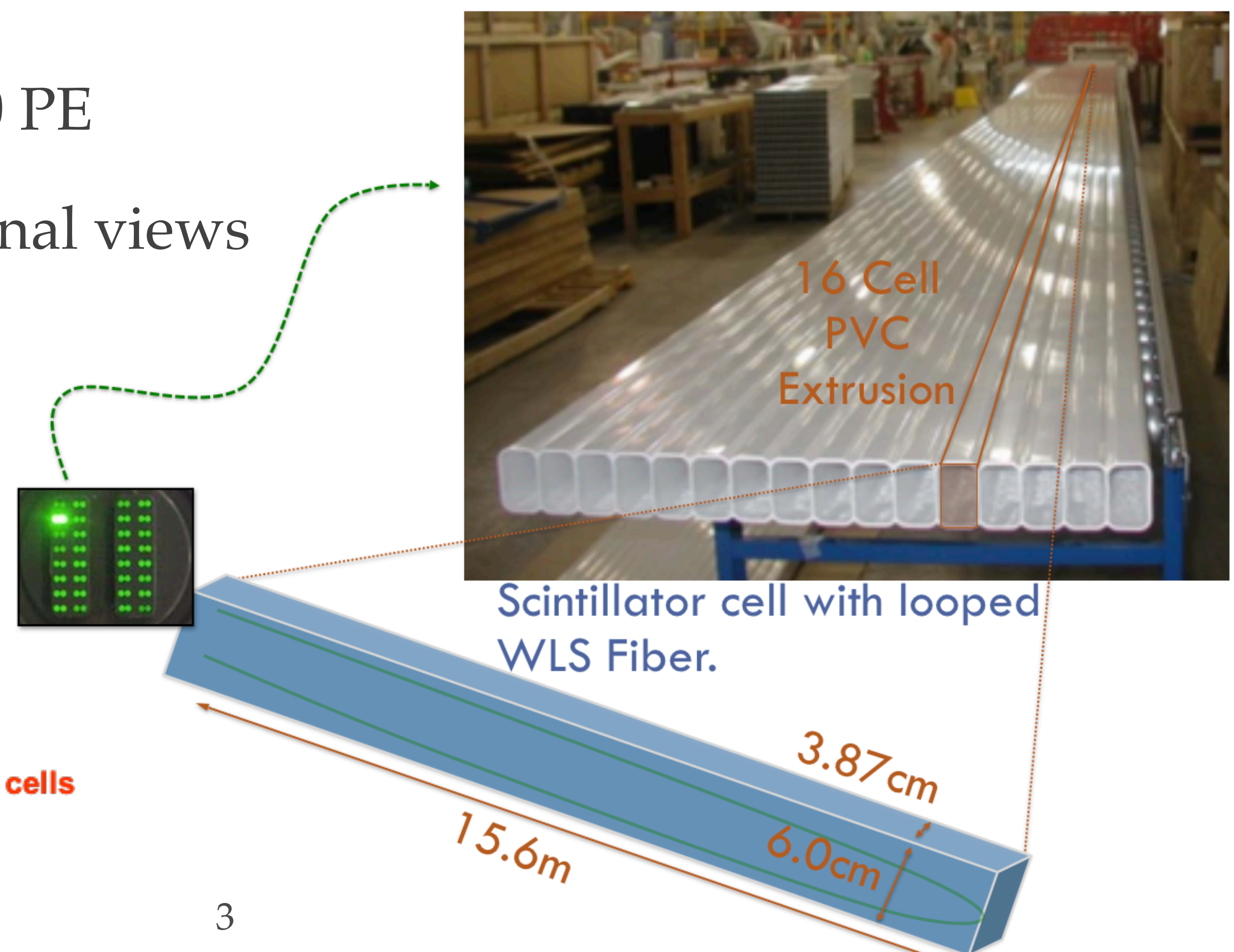
The NOvA Experiment

The NOvA Detectors



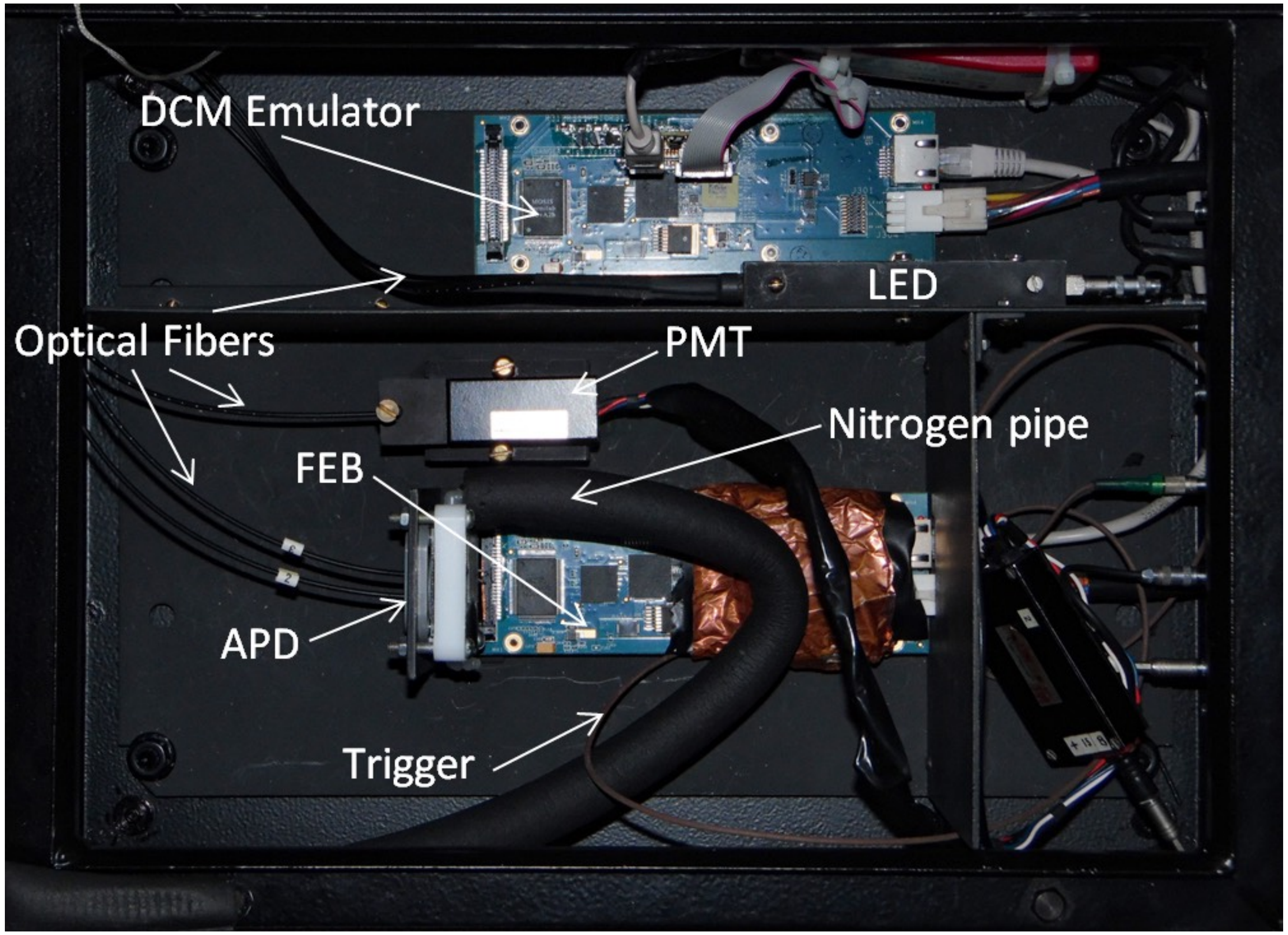
- PVC extrusion + Liquid Scintillator
  - mineral oil + 5% pseudocumene
- Read out via WLS fiber to APD
  - FD has ~344,000 channels
  - muon crossing far end ~40 PE
- Layered planes of orthogonal views



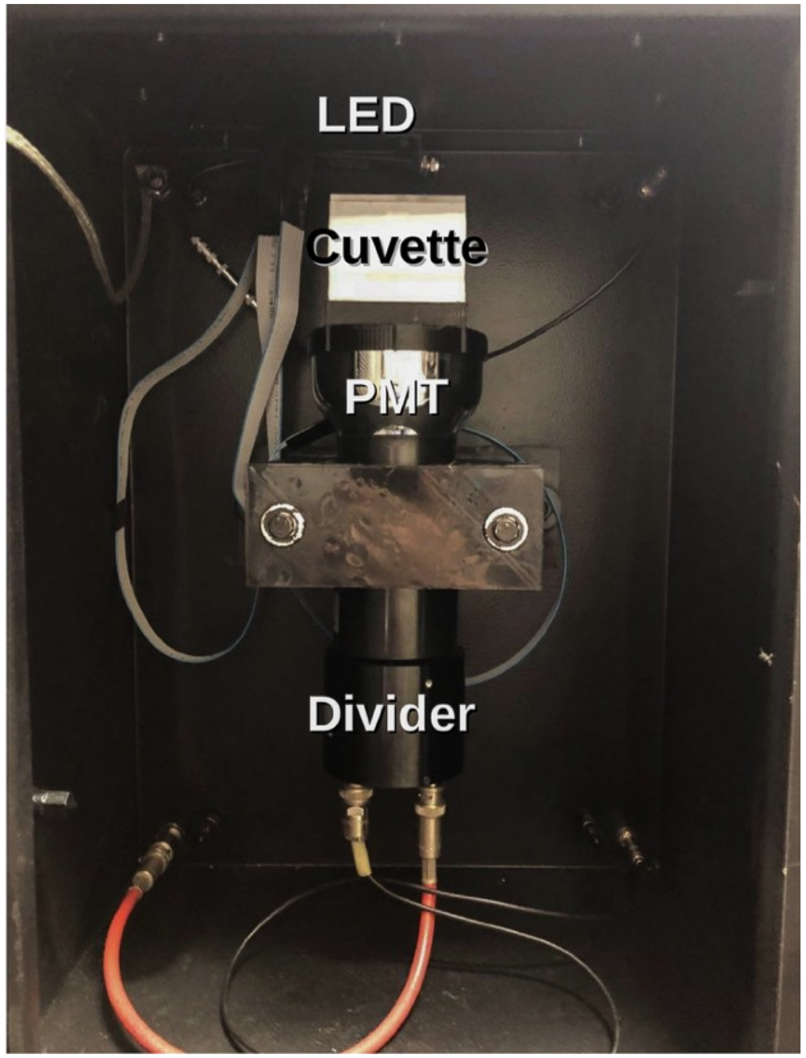


Dubna Test Stands

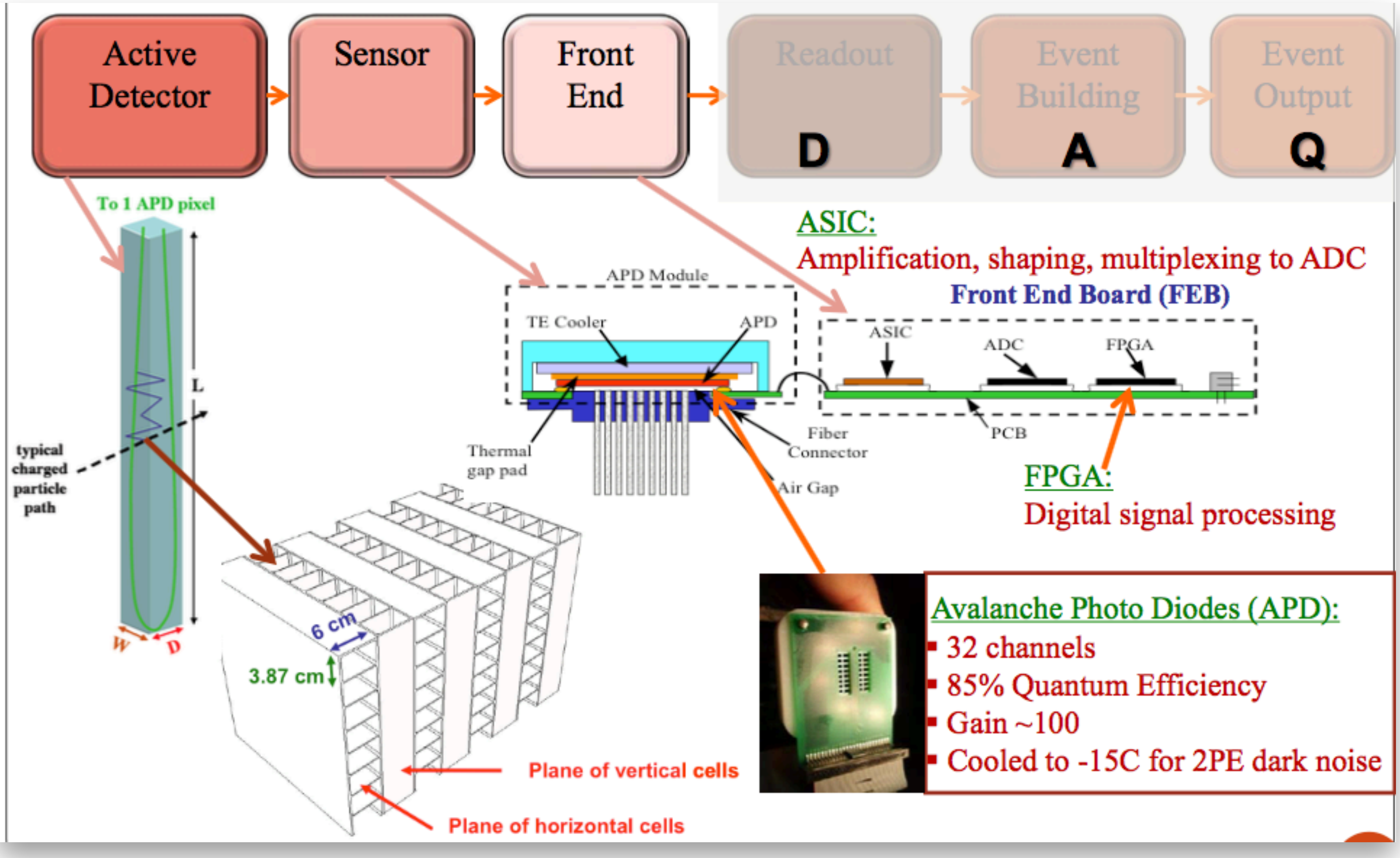
- **Stand-2015**
  - to measure electronics properties



- **Stand-2017**
  - to measure scintillator properties

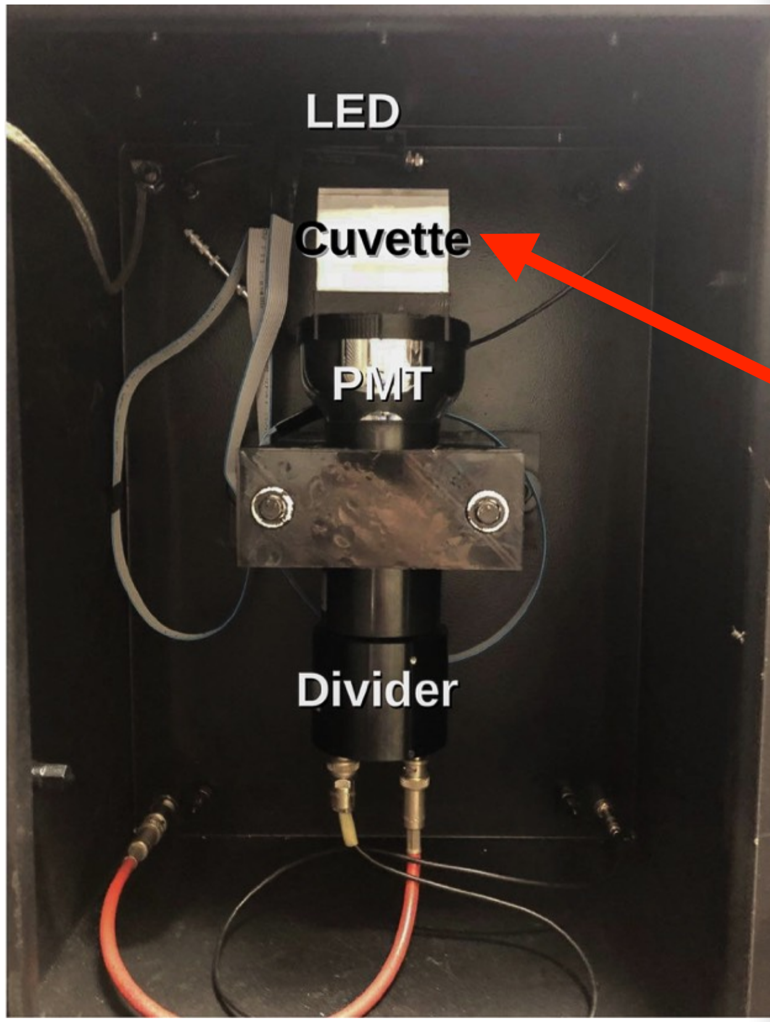


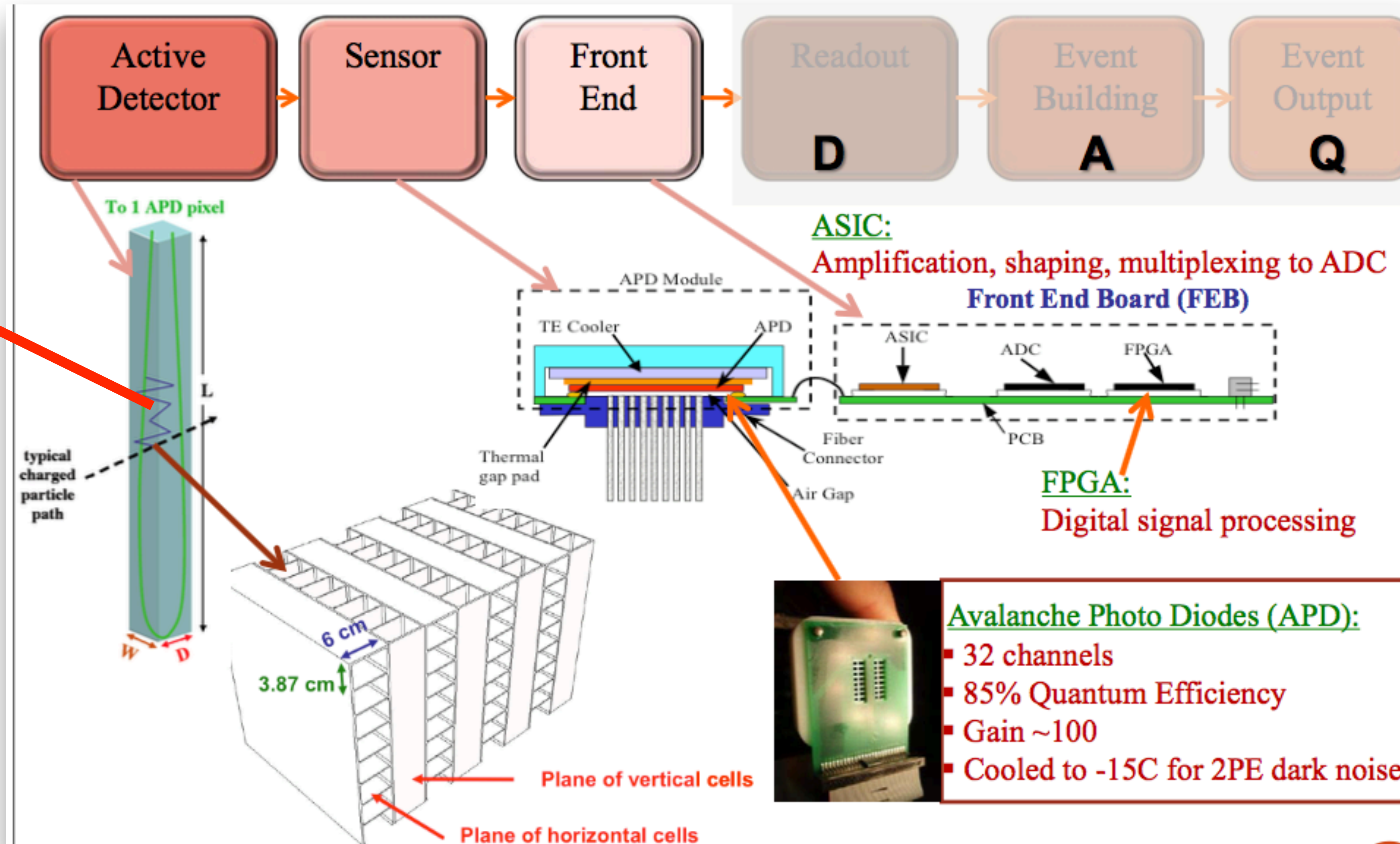
An individual cell signal shaping



SIGNAL SHAPING: Scintillator -> Fiber -> APD -> FEB (ASIC/ADC/FPGA)

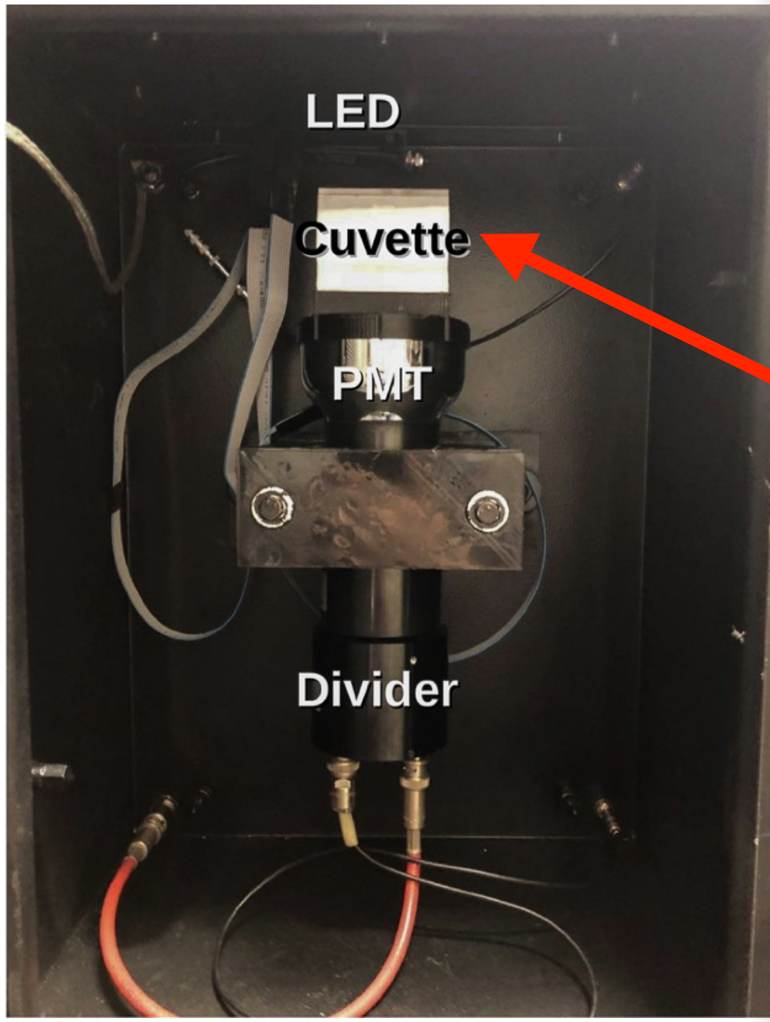
An individual cell signal shaping

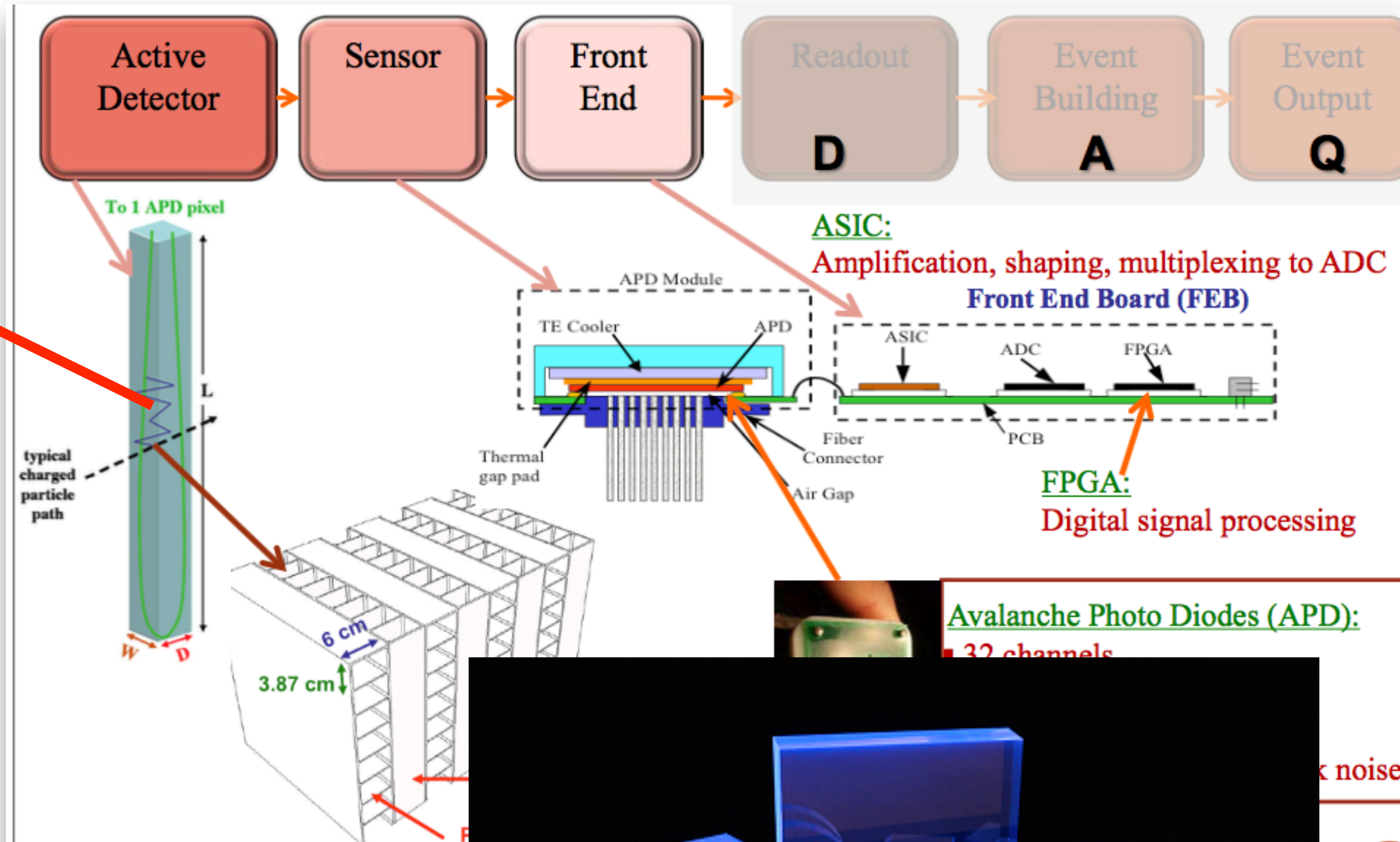




Scintillation light

An individual cell signal shaping





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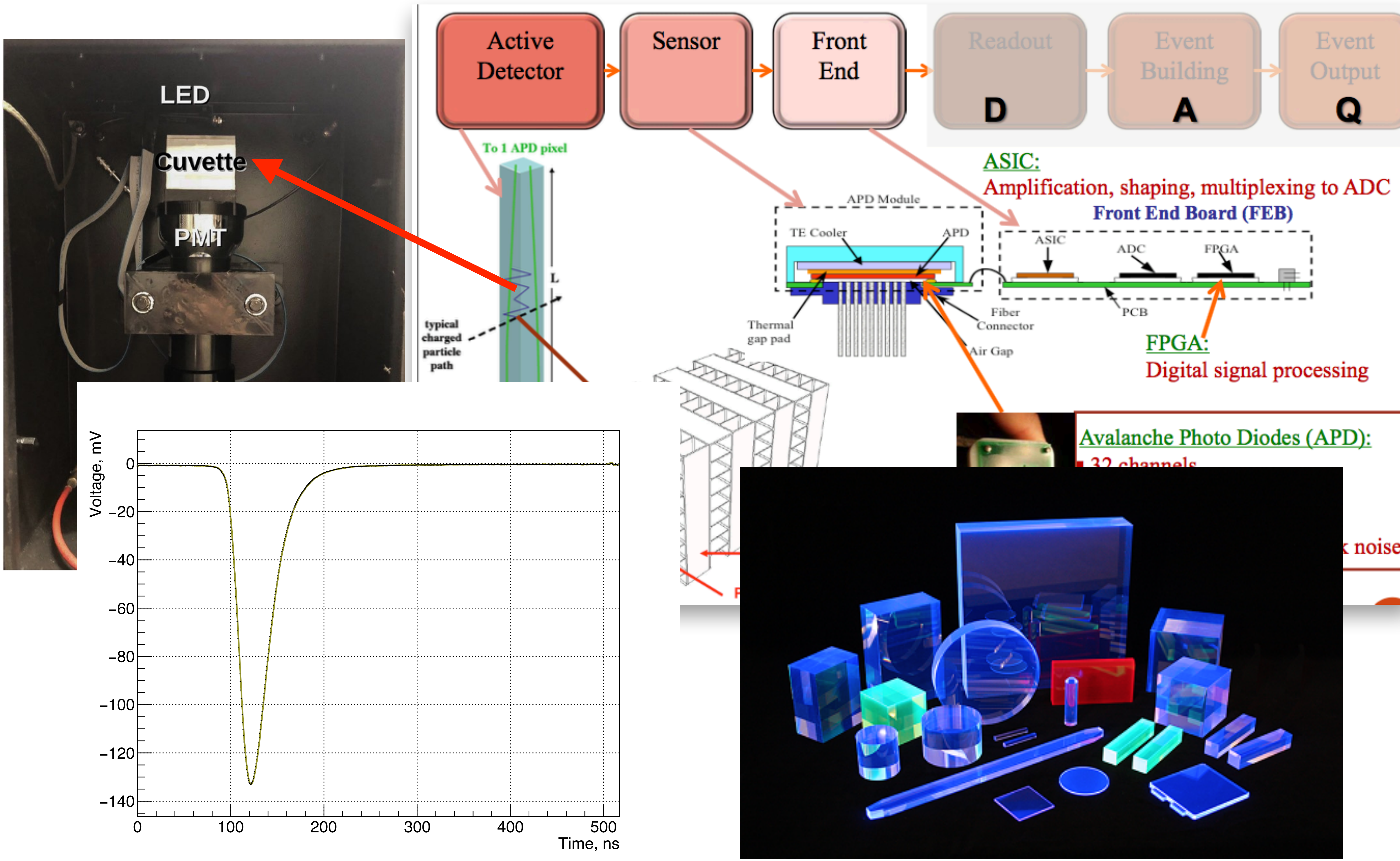
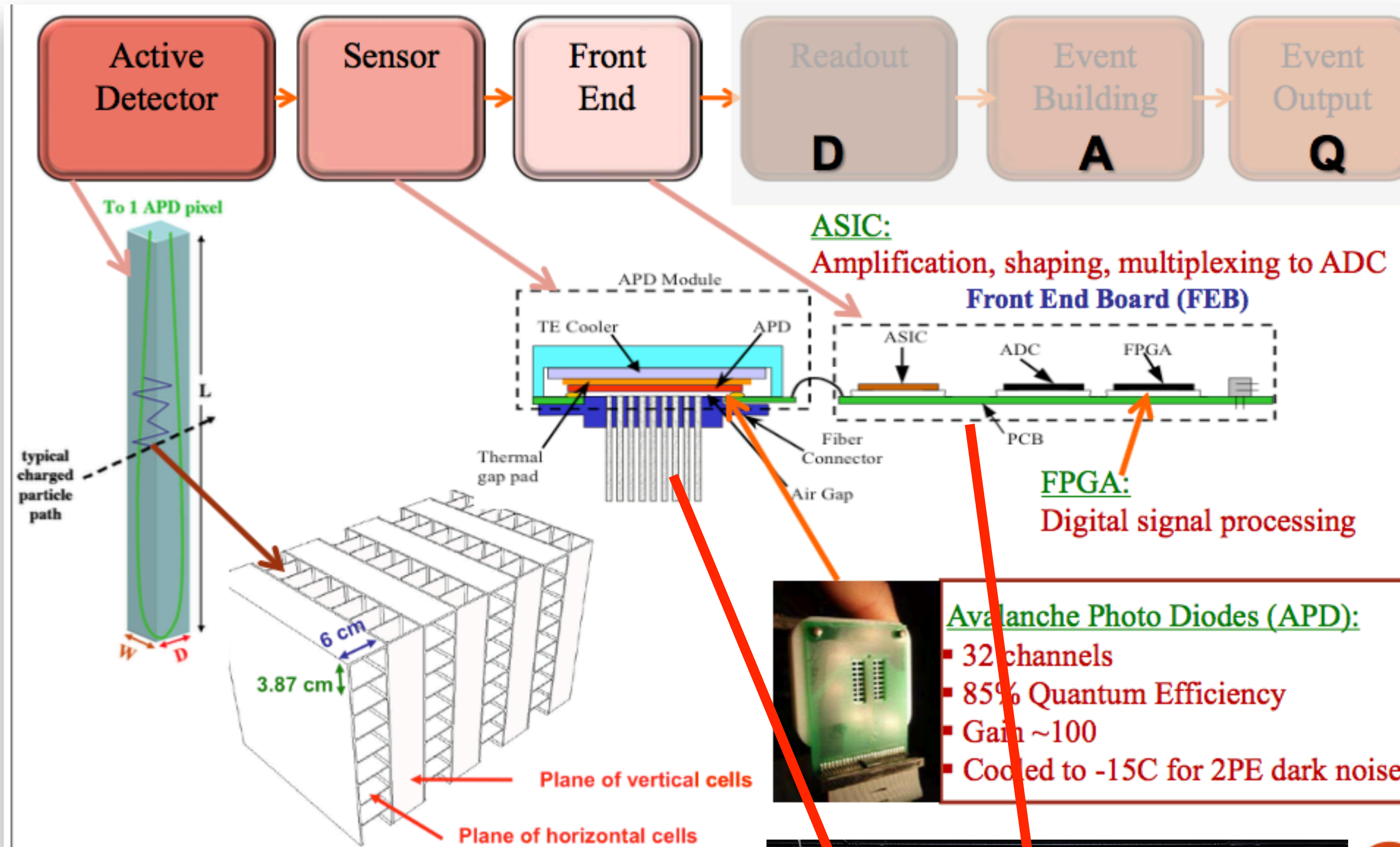
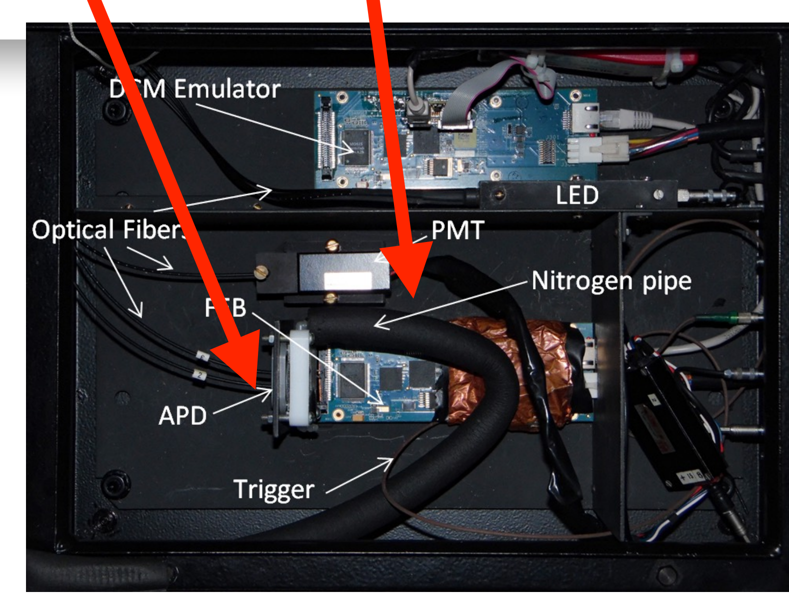


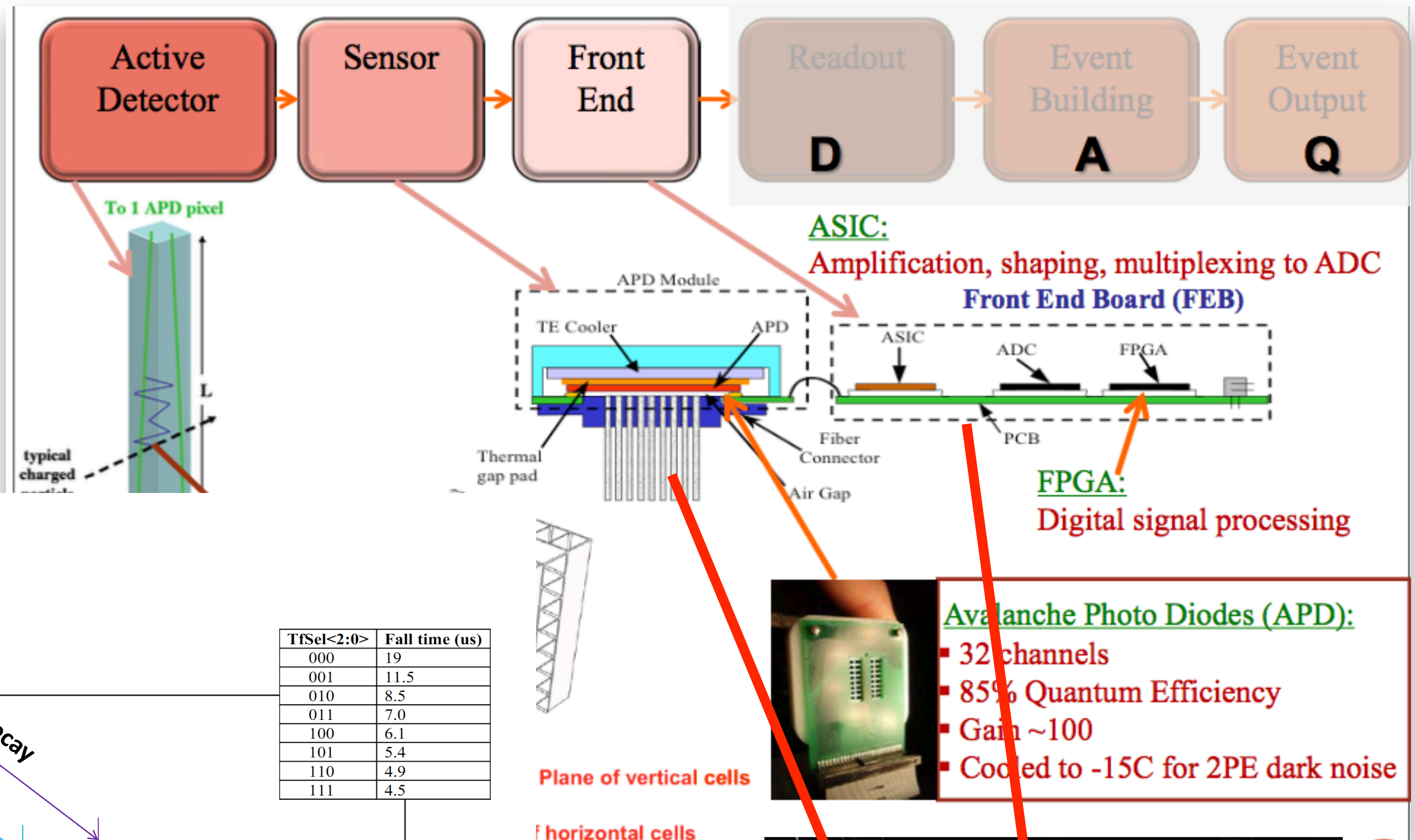
An individual cell signal shaping

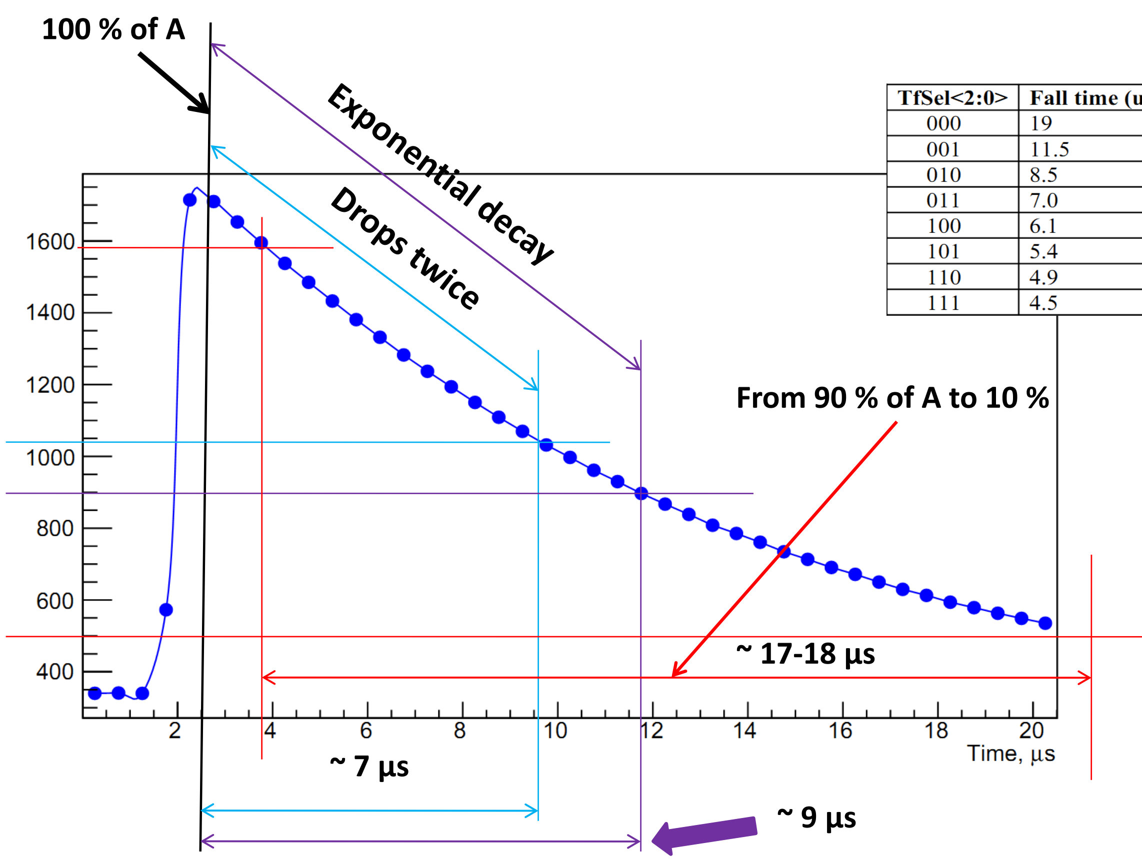




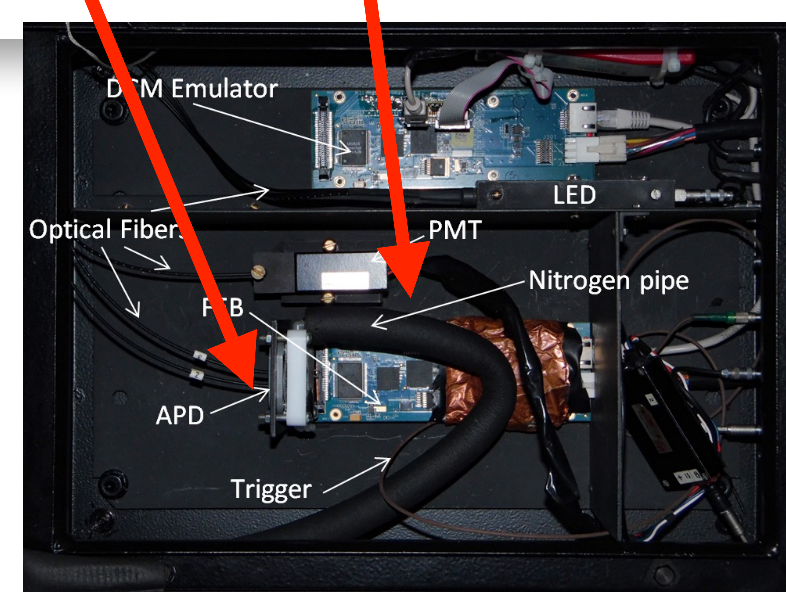
Electronics: APD + FEB

An individual cell signal shaping



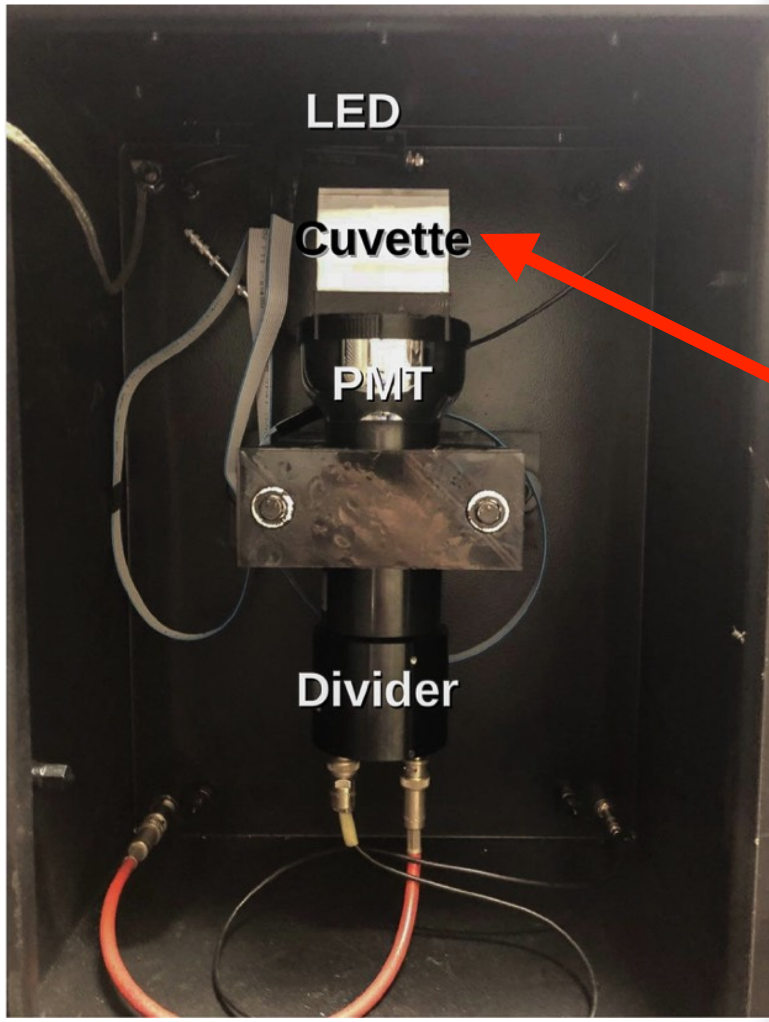


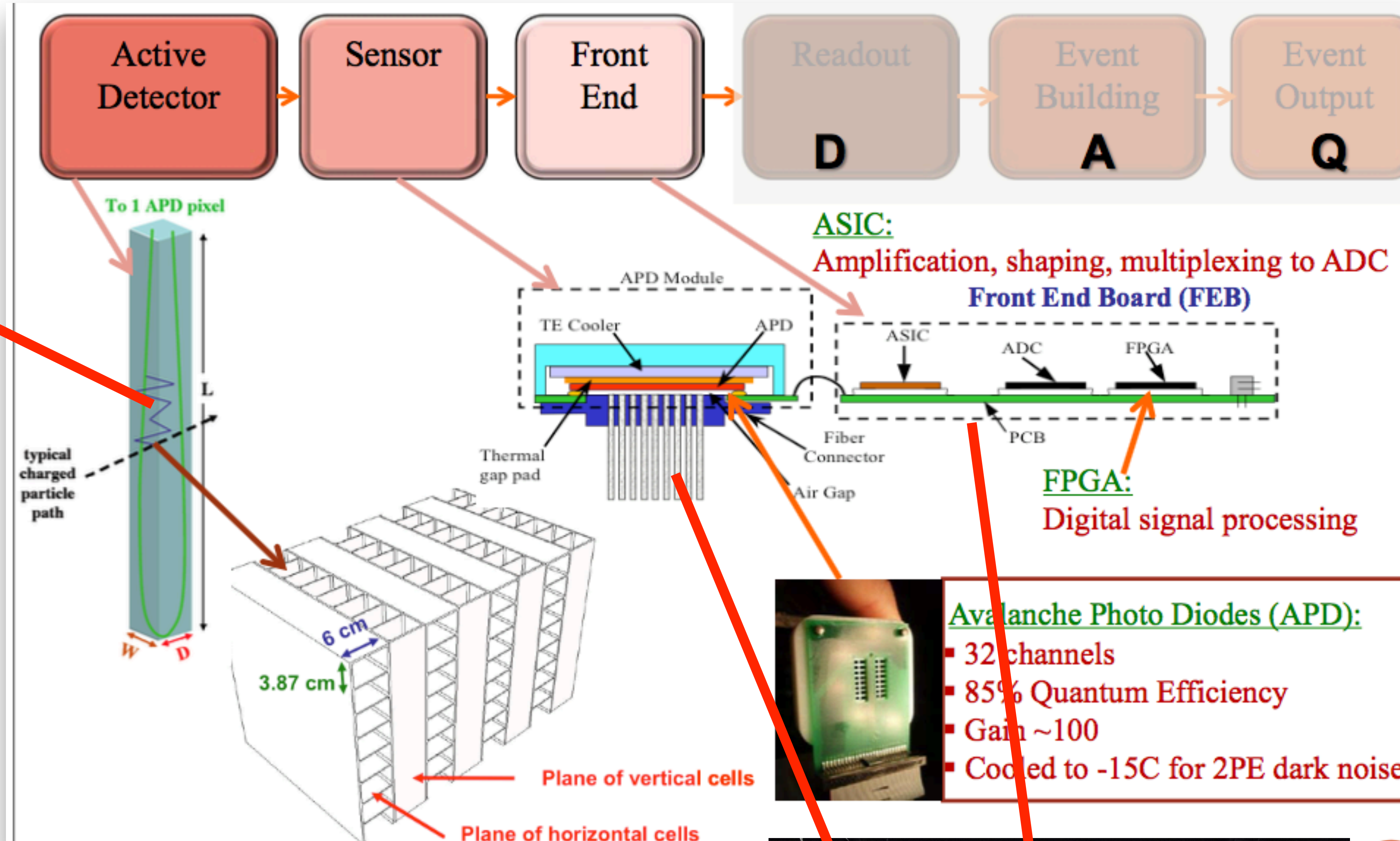
TfSel<2:0>	Fall time (us)
000	19
001	11.5
010	8.5
011	7.0
100	6.1
101	5.4
110	4.9
111	4.5

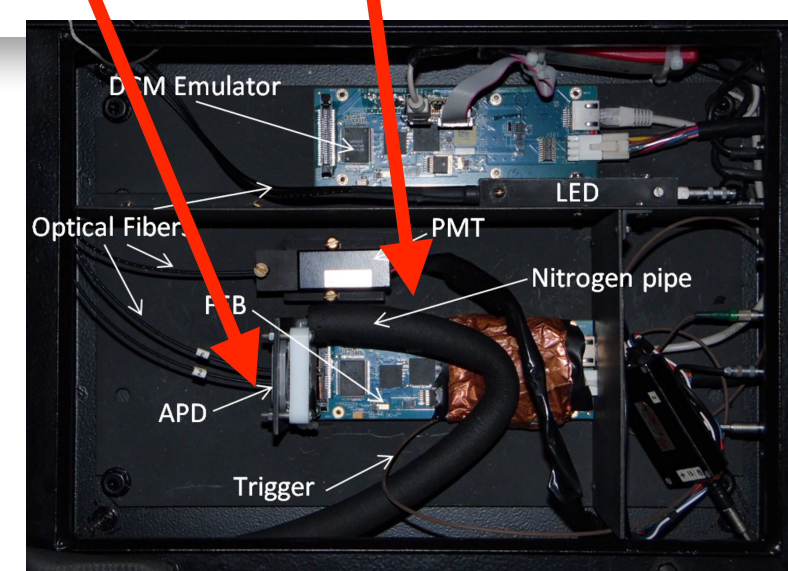


3

An individual cell signal shaping

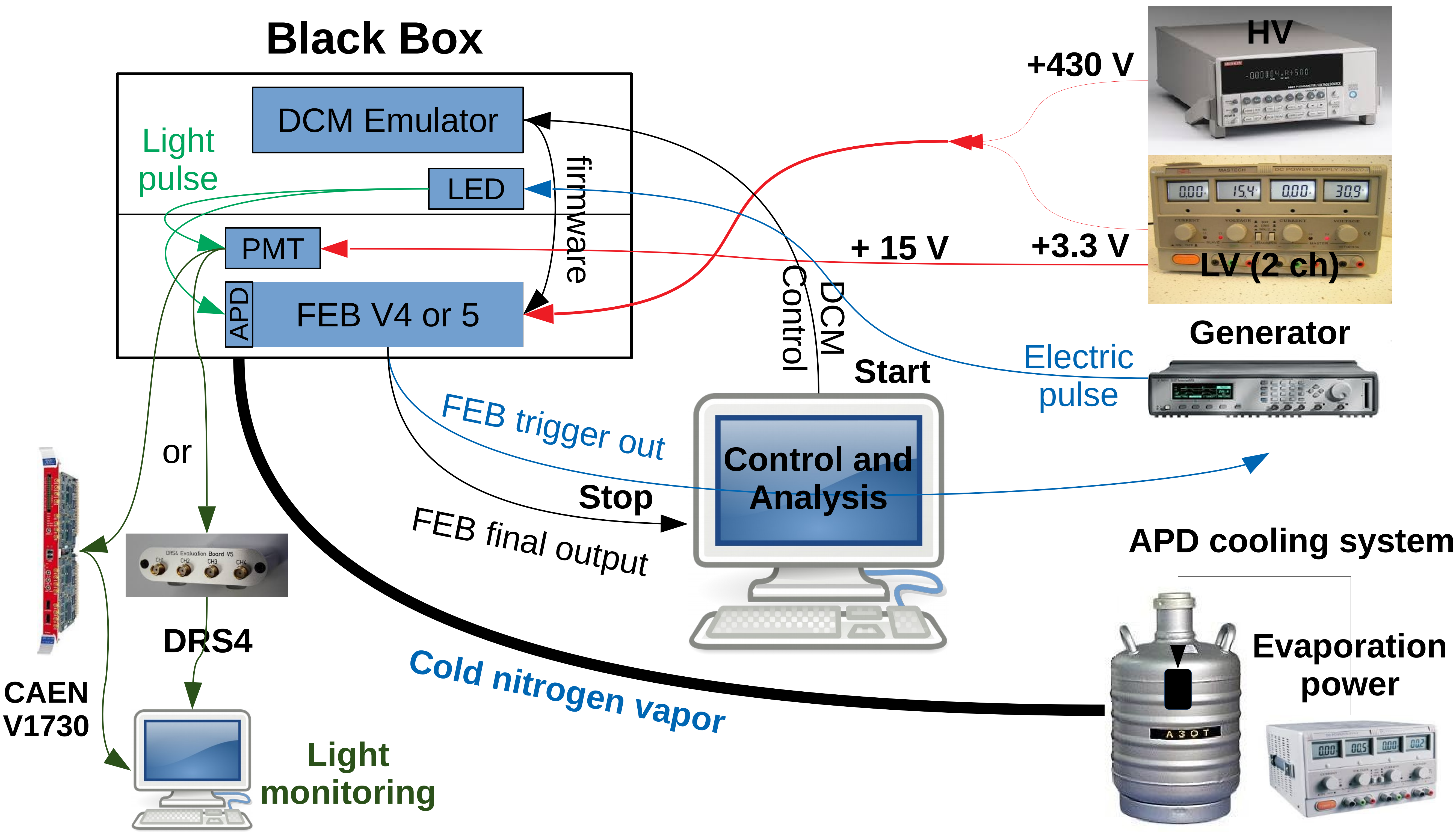






Two boxes to measure signal responses

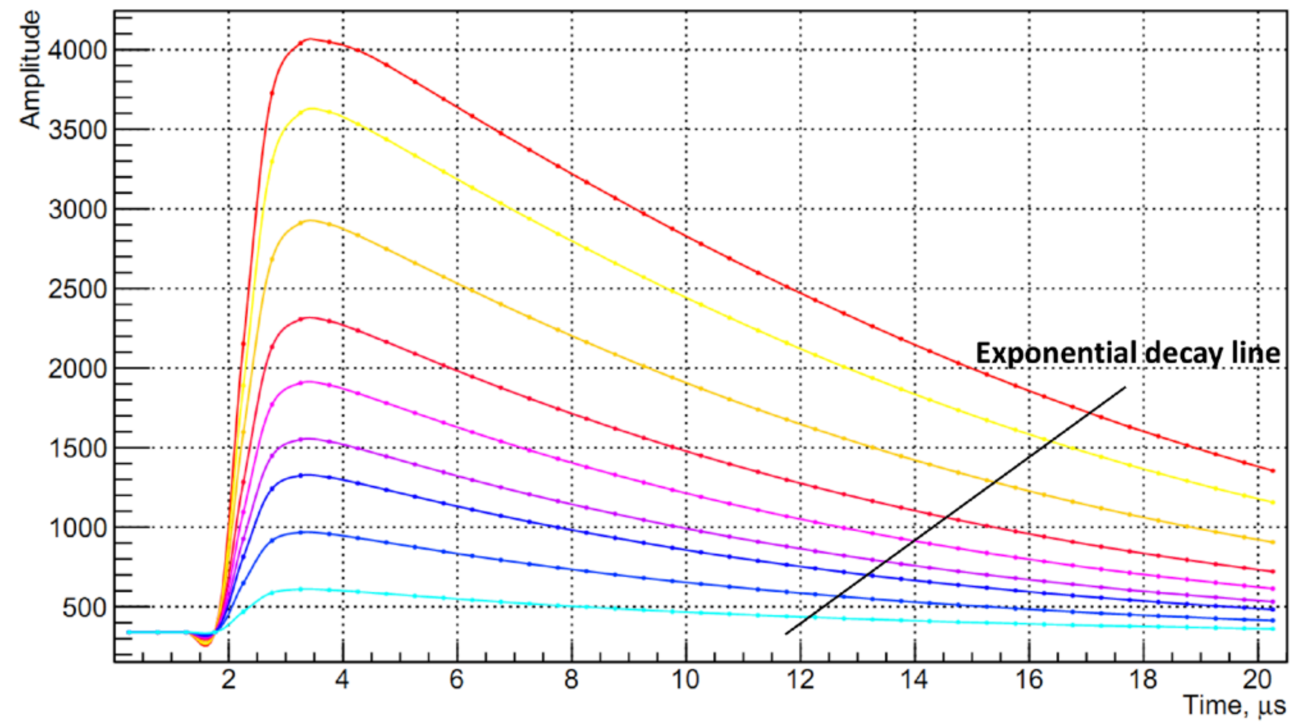
NOvA electronics test at JINR



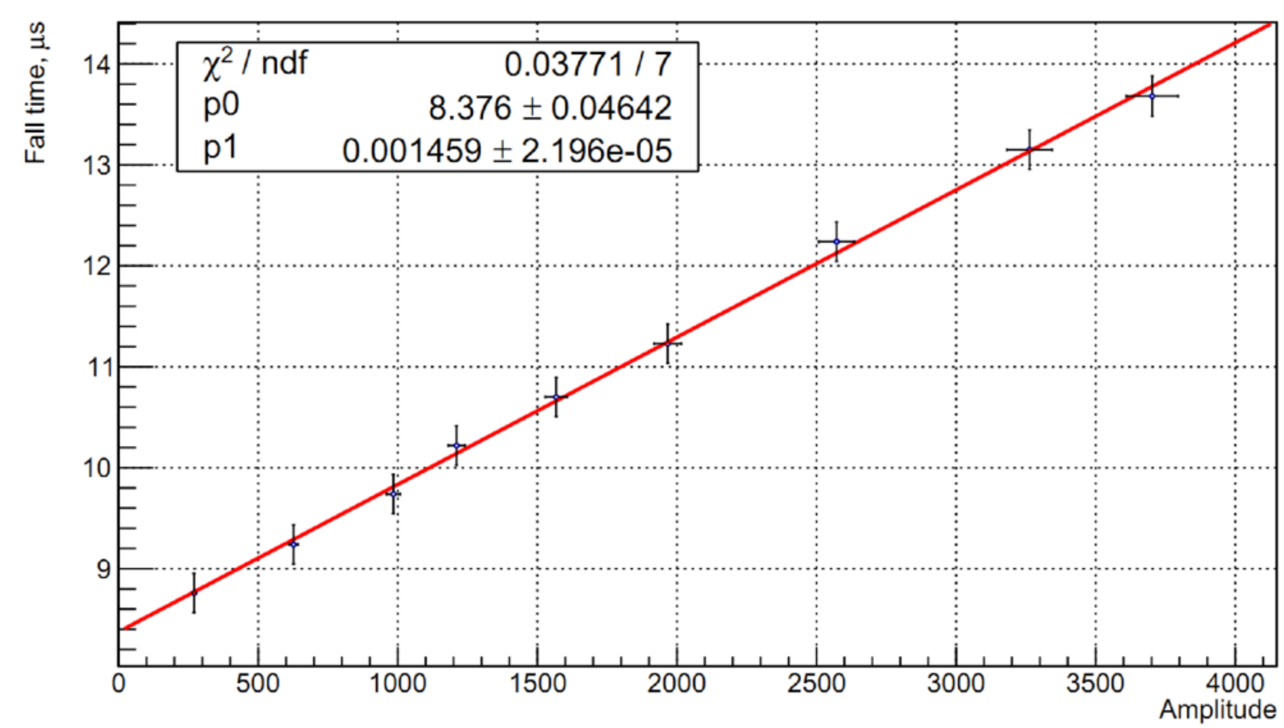
Pulse shaping

- During the design of the ASIC it was noted that the fall time of the CR-RC circuit varied as a function of the magnitude of the input.
- It was shown on the JINR test stand that the fall time scaled linearly with the number of incident photoelectrons.

Fall time dependence

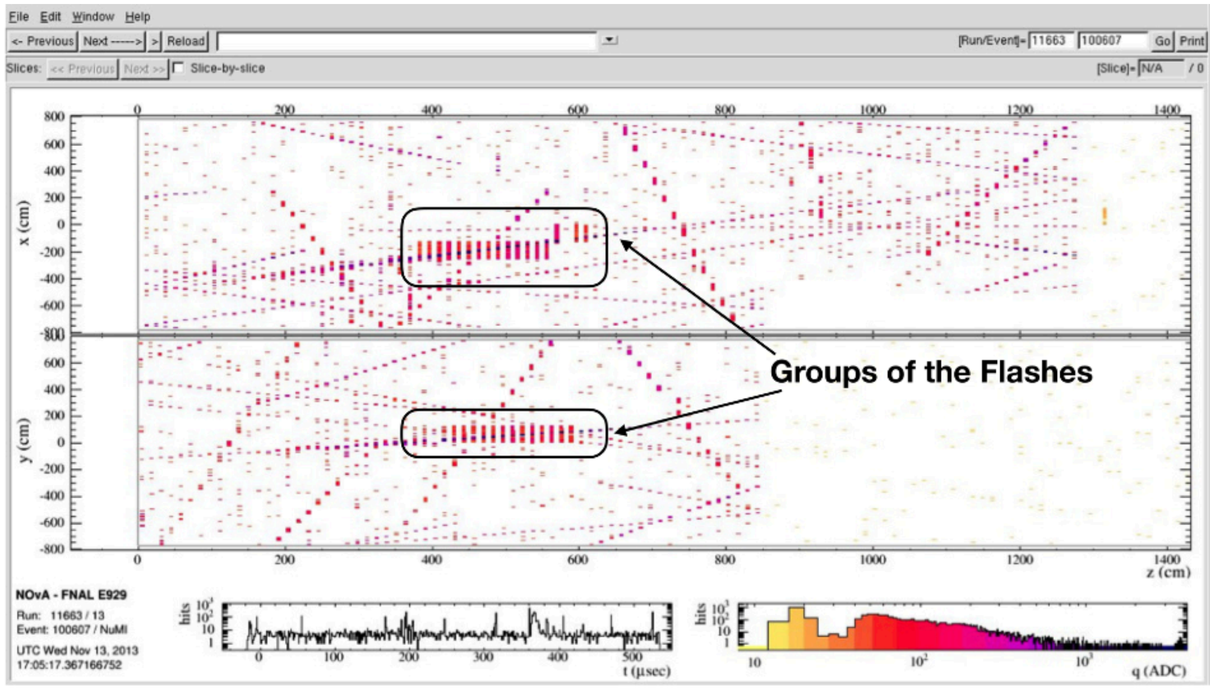


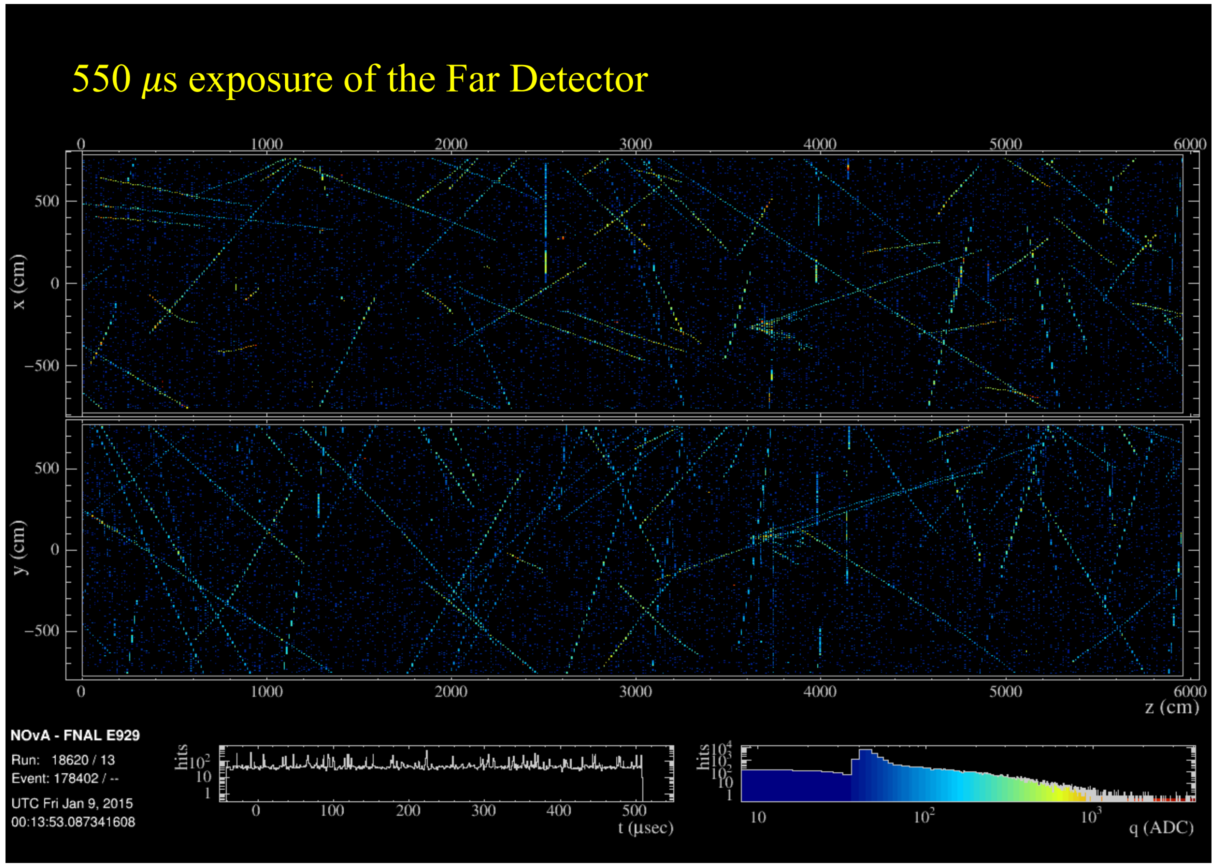
Fall time / Amplitude



APD Sag Effect

- In the beginning of the FD operation it was seen a "cross-talk" effect between APD channels for very large signal.
- When one APD channel breaks down it produces a voltage drop on the entire PCB, which passes trough the capacitance of all other APD channels.
- This effect has no impact on beam neutrino and normal cosmic background events and might need special consideration only for high energy dissipation (exotics, cosmics).





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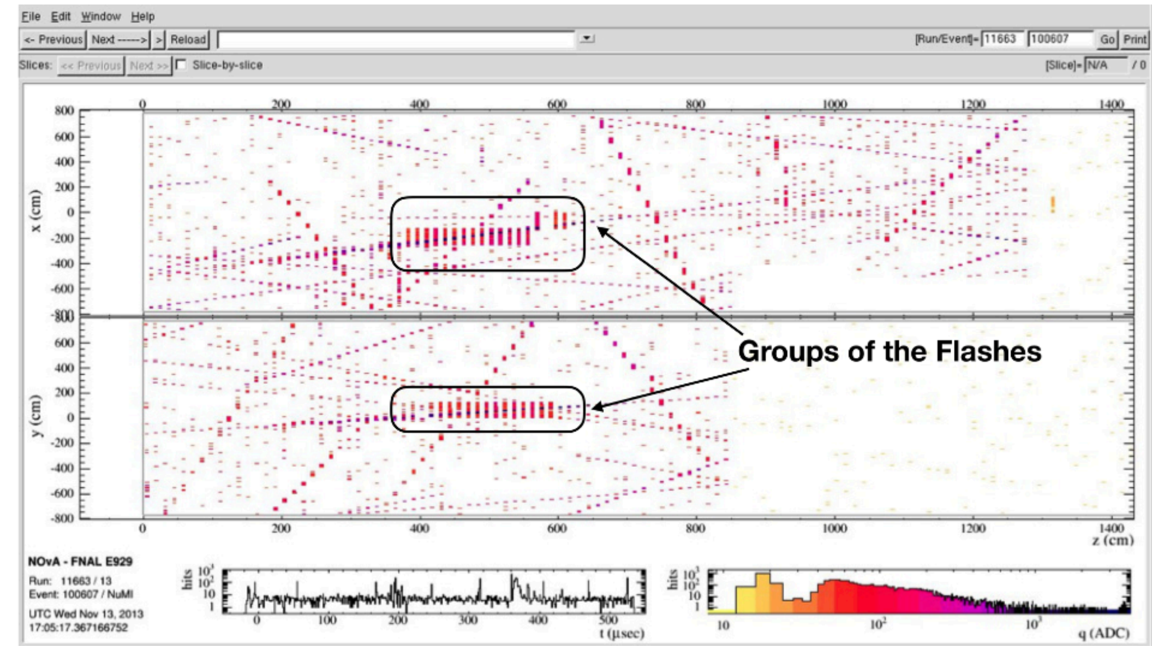
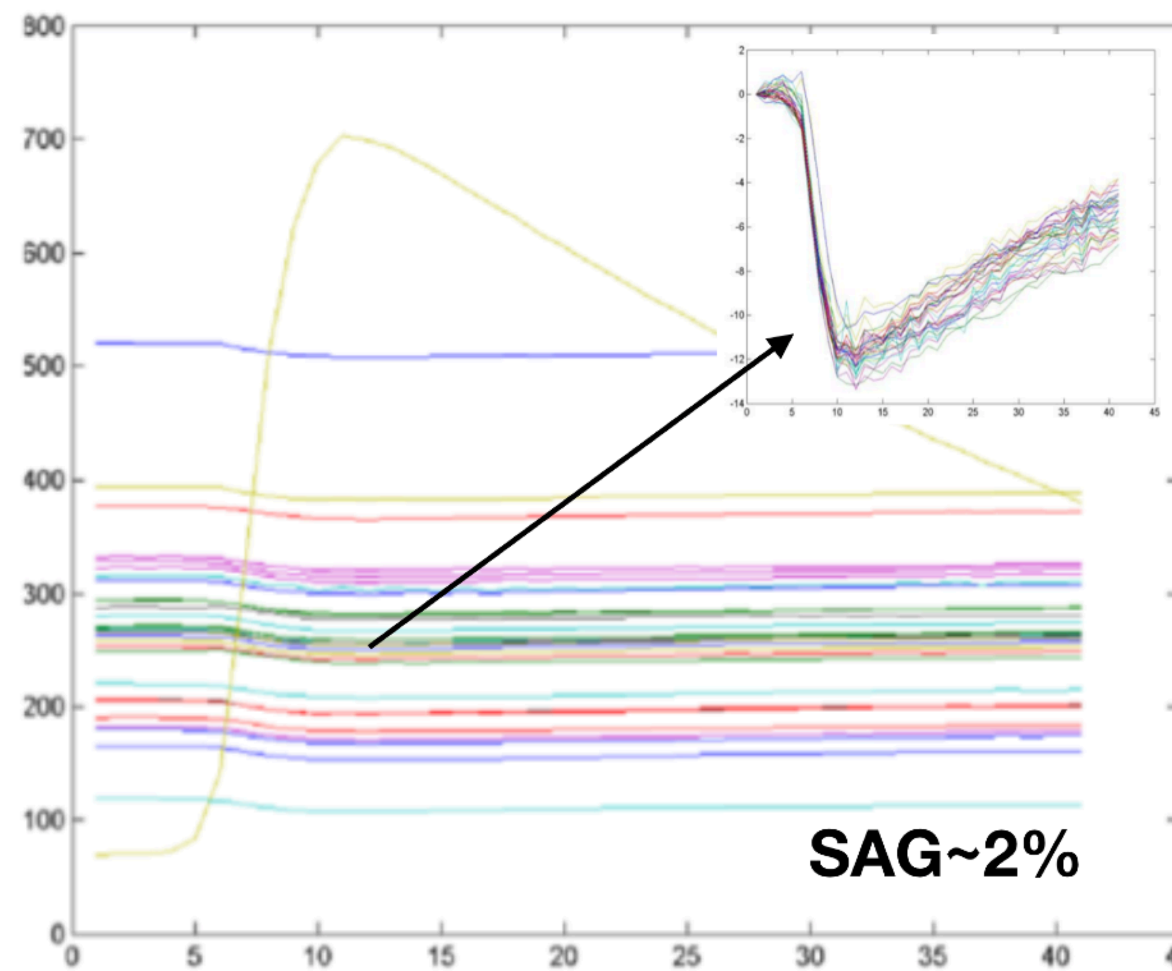
- When one APD channel breaks down it produces a voltage drop on the entire PCB, which passes trough the capacitance of all other APD channels.
- This effect has no impact on beam neutrino and normal cosmic background events and might need special consideration only for high energy dissipation (exotics, cosmics).
- This effect was dubbed “Sag”, and in NOvA's case has a contribution of ~2%.





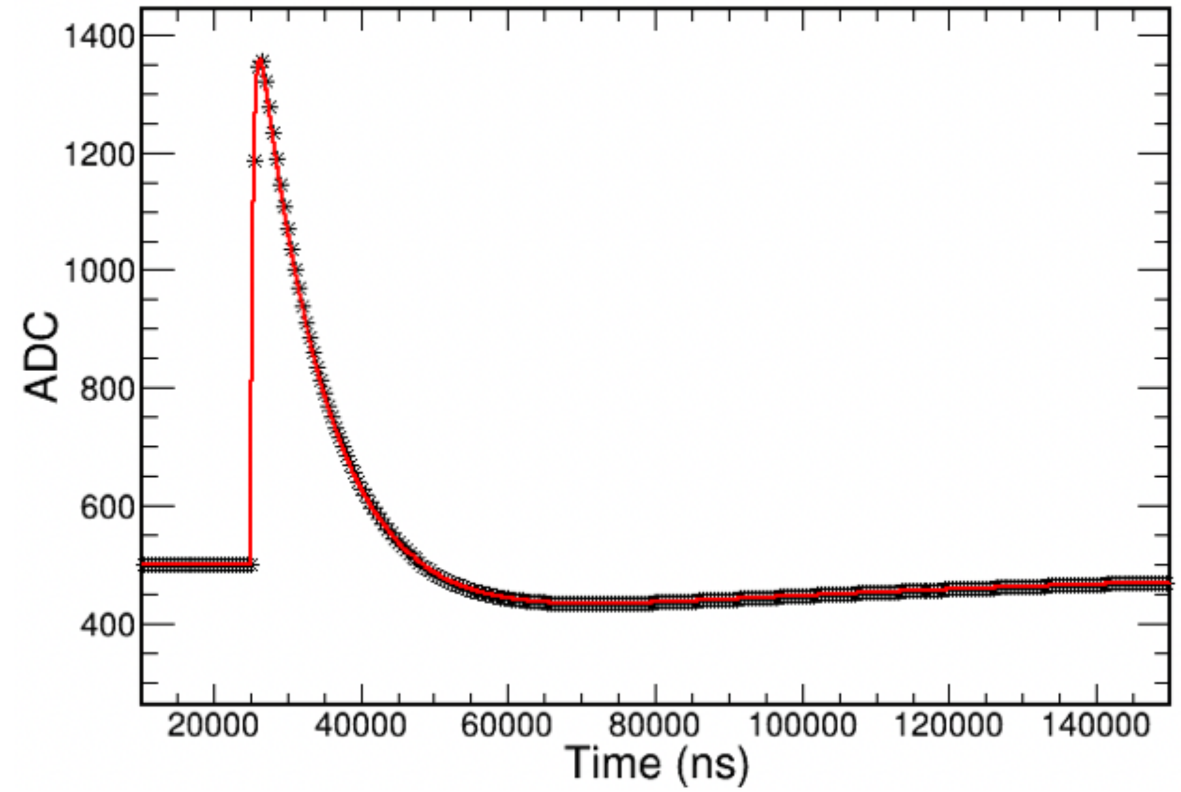
In the simulation

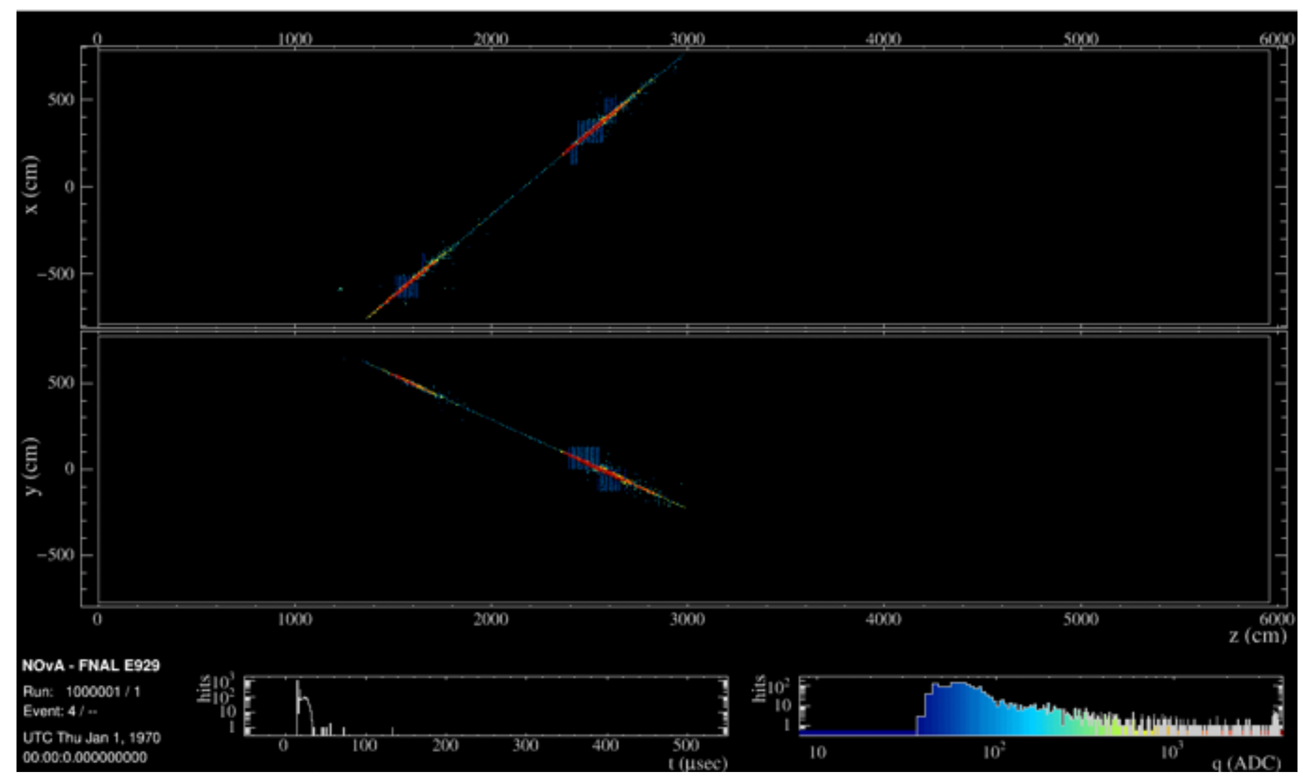
- Signal form includes pulse shaping with all effects

$$f(t) = IF\left(\frac{e^{-(t-t_0)/F}}{(I-F)(F-R)} - \frac{e^{-(t-t_0)/I}}{(I-F)(I-R)} + \frac{e^{-(t-t_0)/R}}{(I-R)(R-F)}\right)$$

  where *R*,*F* are rise and fall times, *I* is time scale over which photoelectrons should be integrated to determine how the fall time should vary, and *F* is varied over the time shift as an additional linear component F_m to the F_0.

- The "Sag" effect was implemented into the simulation in 2016 in case the total amount of light captured by all pixels of an APD exceeds 5000 ADC in any given 15 ns window. Final traces are computed for pixels in all the 32 APD channels. This models the FEB flashing behaviour seen in data when high energy cosmic rays traverse the detector.





Theory of Scintillation. Birks' law

- According to Birks[1] and Chou[2], in the liquid scintillators, the light output function **L(E)** is related to the stopping power **dE/dx** of a charged particle of **kinetic energy E**, and stopped in the scintillator, via

$$L(E) = S \cdot \int_0^E dE \left[1 + kB \left(\frac{dE}{dx} \right) + C \left(\frac{dE}{dx} \right)^2 \right]^{-1}$$

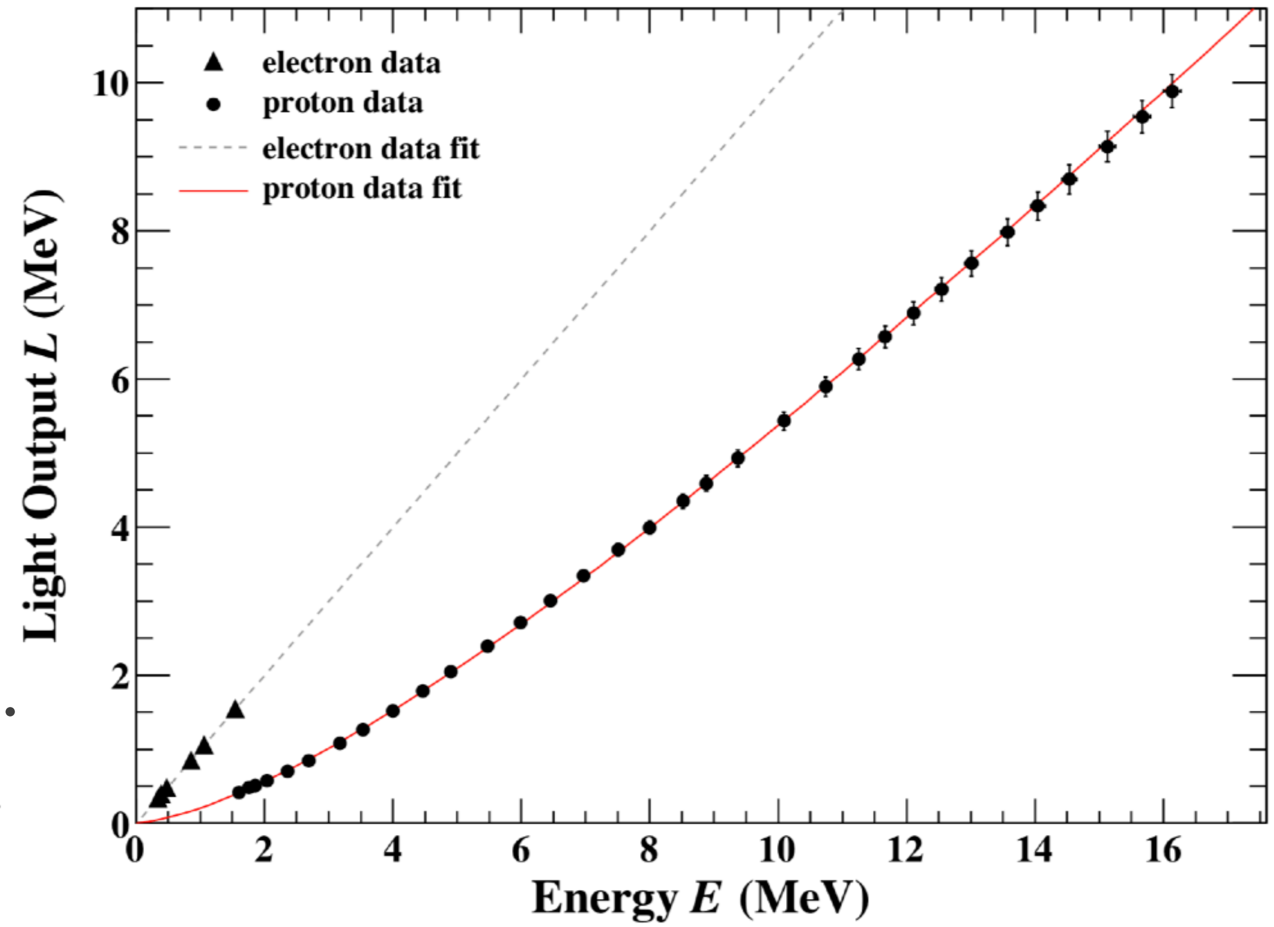
- The light output **L** is the total light emitted when a charged particle loses all of its energy **E** within the scintillator.
- **S** is the scintillation efficiency, which yields the light output, and it could be set to **S=1** if calibration procedure is applied.
- First linear suppression term is **kB** constant and a quadratic correction term is **C**, often used to take into account large values of dE/dx for heavy charged particles or hadrons.

[1] J. B. Birks. The Theory and practice of scintillation counting. Pergamon Press (1964). 662 pp.
[2] C. N. Chou. The Nature of the Saturation Effect of Fluorescent Scintillators. Phys.Rev. 87 (1952) no.5, 904-905

Previous measurement with LAB based scintillator

- In the paper[1], the proton light output function in electron–equivalent energy of various scintillators based on linear alkylbenzene (LAB) has been measured in the energy range from 1MeV to 17.15MeV for the first time.

LAB admixture	kB [cm MeV^{-1}]	C [cm^2 MeV^{-2}]
2g/l PPO, 15mg/l bis-MSB	0.0097 ± 0.0002	$\leq 5.0 \times 10^{-7}$
2g/l PPO	0.0098 ± 0.0003	$\leq 4.0 \times 10^{-7}$
3g/l PPO, 15mg/l bis-MSB	0.0098 ± 0.0003	$\leq 1.0 \times 10^{-7}$
3g/l PPO	0.0094 ± 0.0002	$\leq 6.5 \times 10^{-7}$

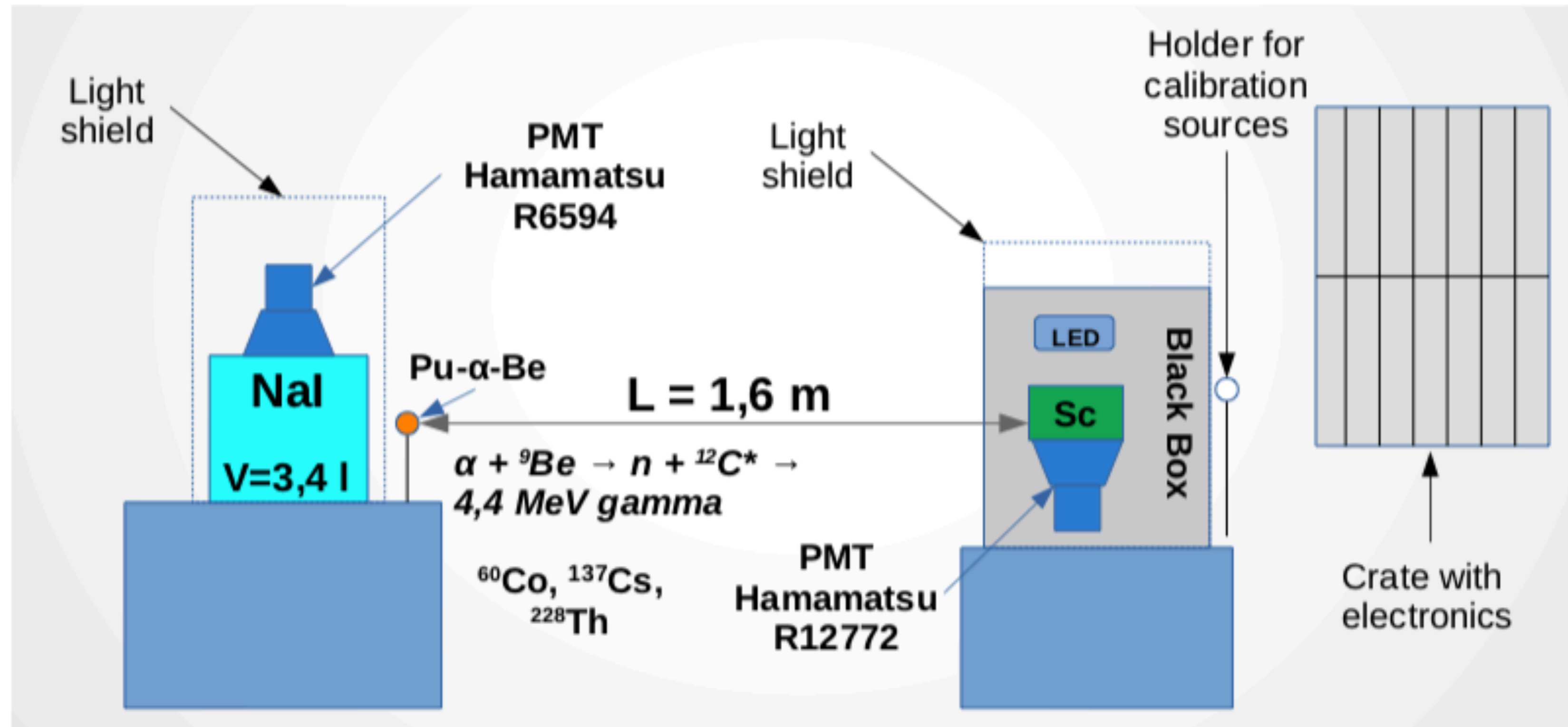


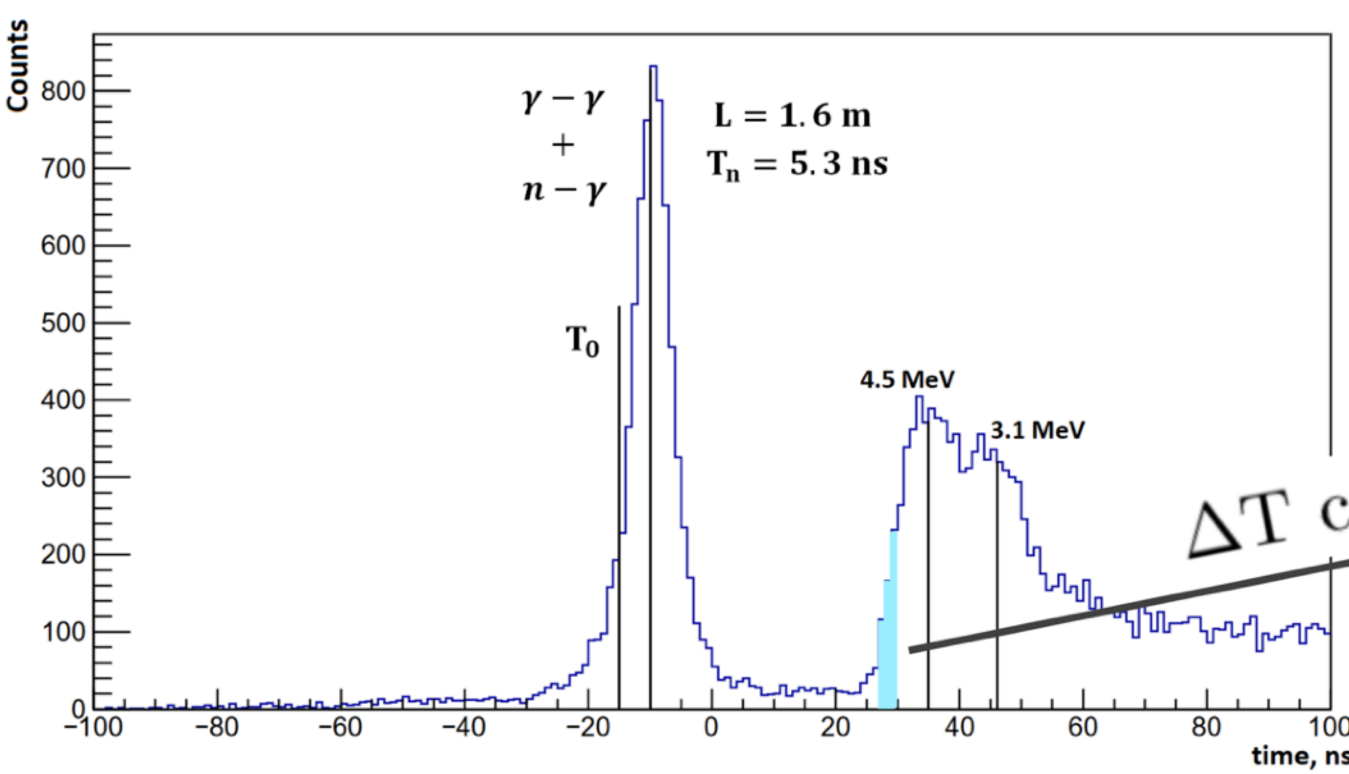
- An example on the data is taken with LAB, 2 g/l PPO and 15 mg/l bis–MSB.
- The constant **C**, quadratic Chou term, is consistent with **zero** for all investigated scintillators with an upper limit (95% CL).

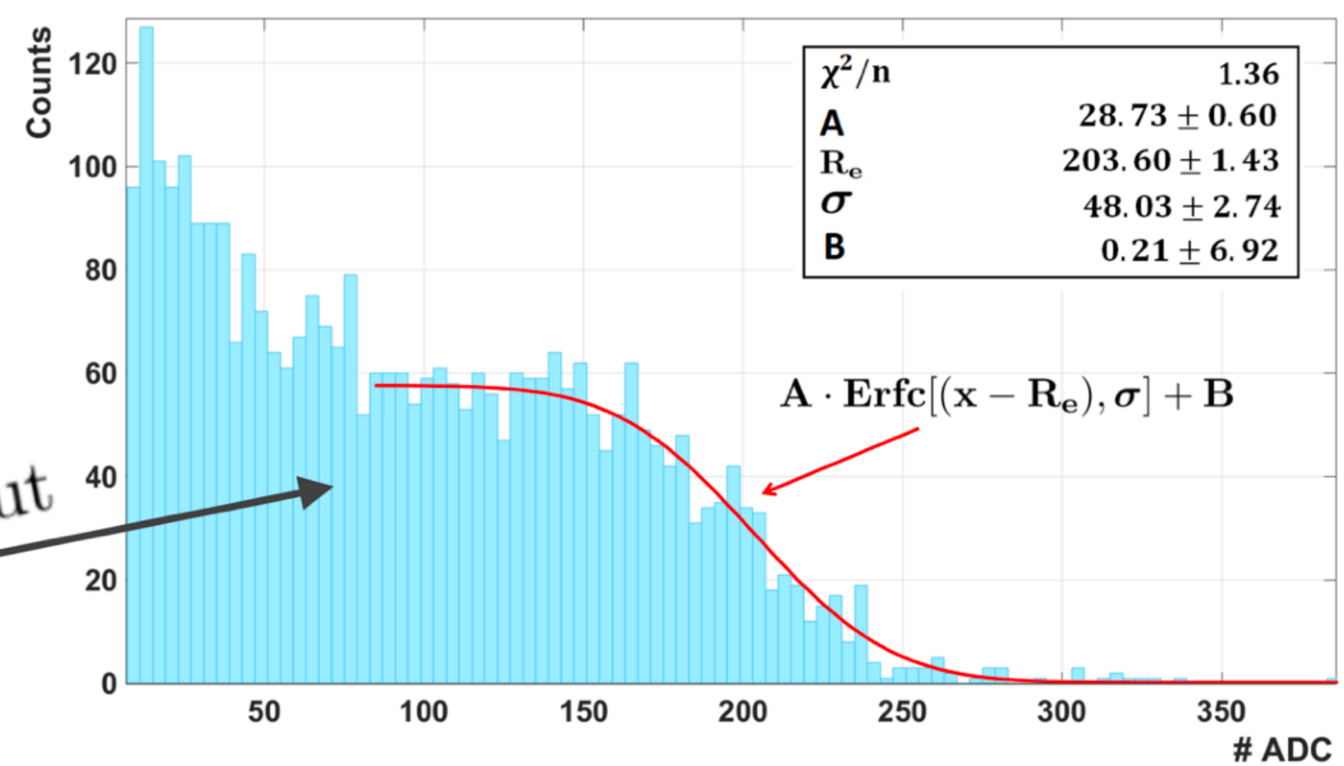
[1] B. von Krosigk, L. Neumann, R. Nolte, S. Rottger, K. Zuber. Measurement of the proton light response of various LAB based scintillators and its implication for supernova neutrino detection via neutrino-proton scattering. Eur.Phys.J. C73 (2013) no.4, 2390.

Birks measurement at JINR stand

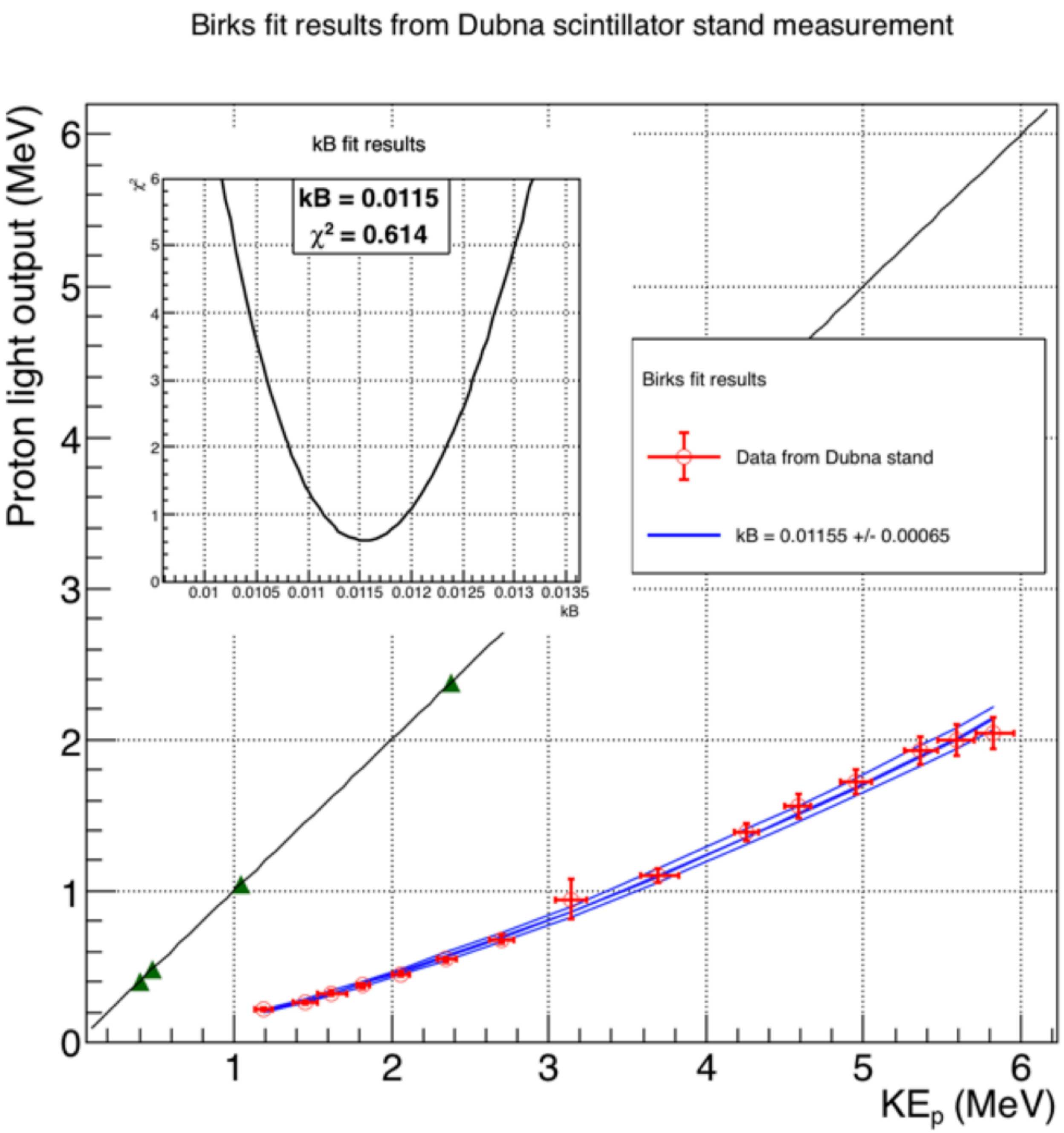
- Use PuBe source to produce sample of neutrons and photons
- Look for coincidences between pulses in NaI detector (photon) and cuvette with NOvA scintillator (neutron induced proton)
- Time of flight gives kinetic energy of neutron
- Scintillation response gives Birks suppressed energy







Fit of the stand data



- Data were analysed by using NOvA simulation software based on GEANT deposit energies and custom simulation for light output. The Birks coefficient is

$$\mathbf{k_B = (1.155 \pm 0.065) \cdot 10^{-2} \left[\frac{g}{MeV \cdot cm^2}\right]}$$

- Calculations were cross-checked by numerical integration using NIST tables accounting for NOvA LS composition

$$k_B = (1.13 \pm 0.07) \cdot 10^{-2} \left[\frac{g}{MeV \cdot cm^2}\right]$$

Summary

- Two test stands have been built in JINR (Dubna, Russia) to measure the proton light response of NOvA scintillator and the electronic signal shaping of the NOvA front-end electronics.
- The parameters measured using these test stands have been implemented in the custom NOvA simulation chain.
- Further improvements are possible with detailed studies on Cherenkov light at a new test stand.
- We are looking straightforward with running the NOvA test beam program at FNAL providing tagged electron, muon, pion, and proton beams, which will enable a detailed understanding of the detector's muon energy scale, electromagnetic and hadronic response, in addition to providing real data for the detailed study of particle identification techniques.

Current and future activities on Dubna Test Stands

- Exotic channels studies and simulations (monopole search as an very high deposit energy object).
- A new scintillator stand setup to measure Cherenkov reemission light in the scintillator.

- On behalf of the JINR group (Nikolay Anfimov, Alexander Antoshkin, Albert Sotnikov and me),

We gratefully thank N.Felt, D.M.Kaplan, M.D.Messier, A.G.Olshevskiy, R.D.Rechenmacher, P.Shanahan, R.J.Tesarek for initiation of this work, arrangements, help and valuable discussion.

We very appreciate help and providing tools for liquid scintillator measurements of our JINR colleagues from Radio-Chemical Laboratory: V.G.Egorov, S.V.Kazartcev and V.B.Brudanin.