SiPM technology

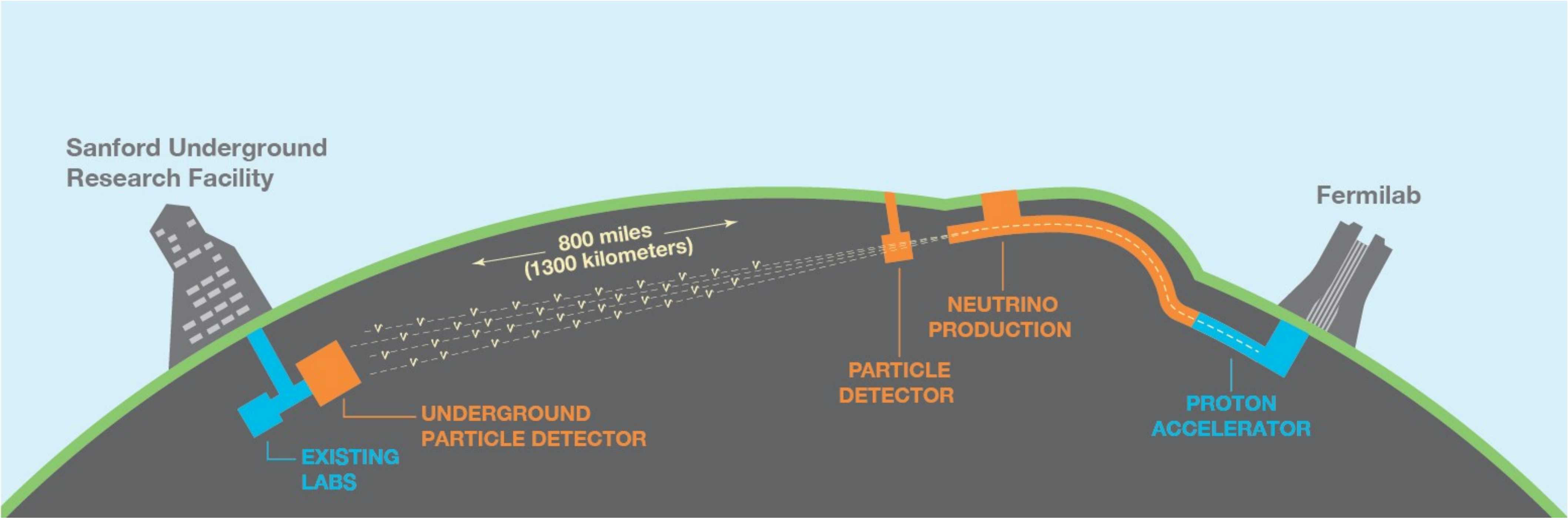
for large LAr-TPC light detection systems

DUNE / ProtoDUNE experiment
R&D at Fermilab

Dante Totani

University of L'Aquila

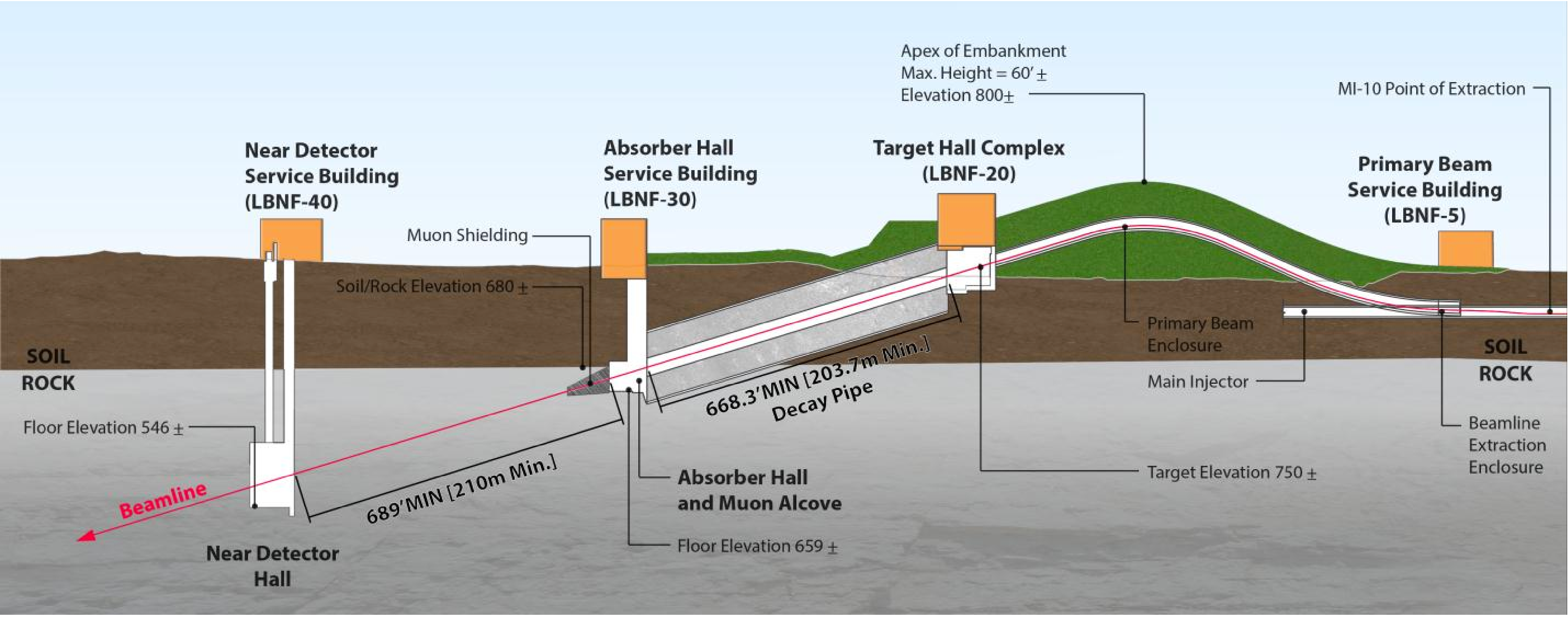
DUNE



- The **Deep Underground Neutrino Experiment** will be:

- a 40 kton fiducial liquid argon neutrino detector...
- located 1.5 km underground...
- 1300 km from Fermilab, which will host a 1.2 MW at 120 GeV neutrino beam...
- and a highly-capable near detector.

Long Baseline Neutrino Facility at Fermilab



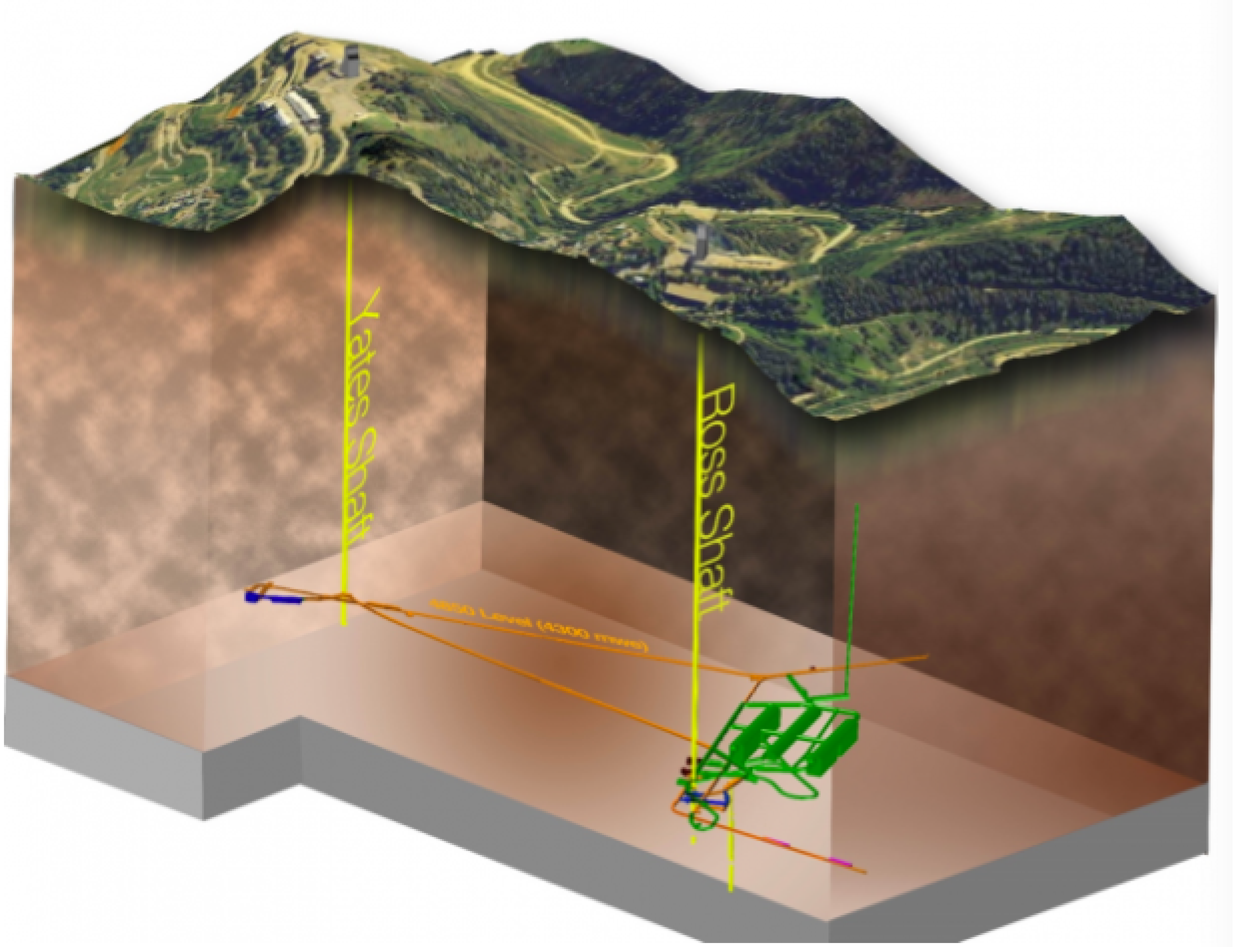
- Conventional horn-focused neutrino beam using protons from the Main Injector.
- Horn and target design being optimized with a genetic algorithm developed LBNO.
- Initially 1.2 MW, upgradeable to 2.4 MW

The far detector: Sanford Underground Research Facility

Large Excavations a Mile Underground

The Sanford Underground Research Facility (SURF) is located at the site of the former Homestake Gold Mine in Lead, SD. This facility, with underground spaces as far below ground as 8,000 ft (2,440 m), has since been repurposed and extensively modified in order to accommodate underground science experiments.

The LBNF Far Site Conventional Facilities (FSCF) effort is preparing facilities both at the surface and at 4,850 ft (1,480 m) underground — called 4850L — for the DUNE experiment's liquid argon far detector.

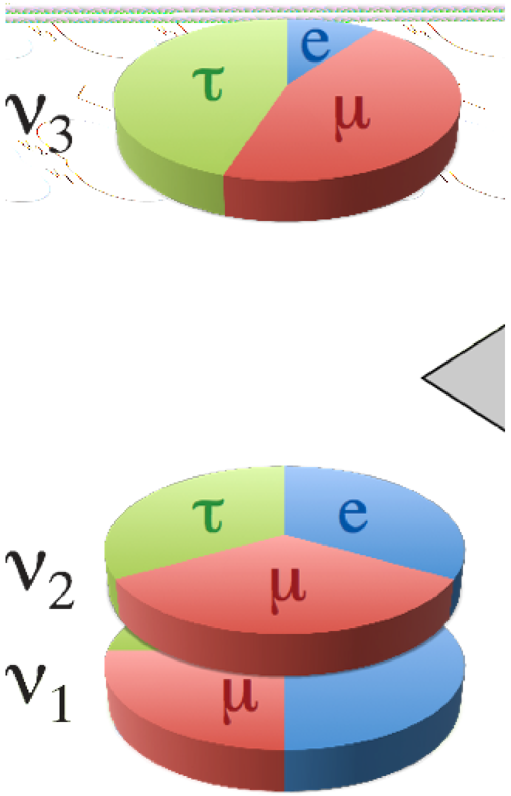


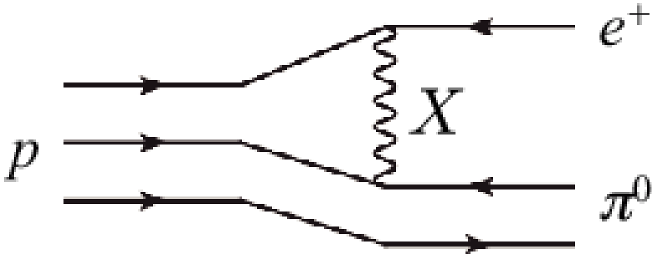
DUNE Physics Goals

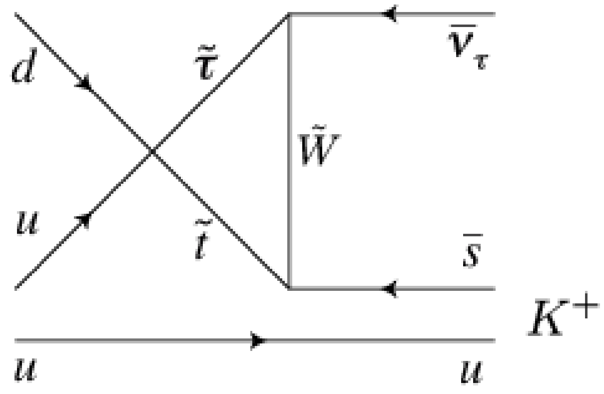
- **Make precise measurements of neutrino oscillations, including determining the mass hierarchy and the potential discovery of leptonic CP violation**

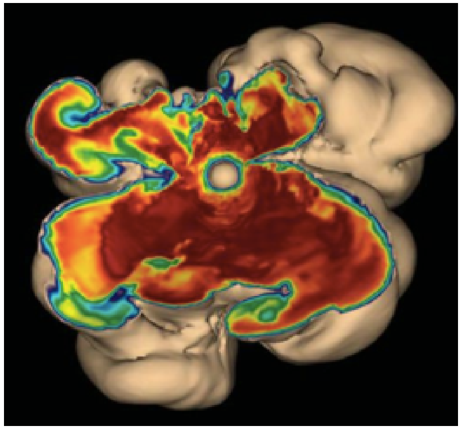
- **Measure the spectrum and flavor composition of a supernova burst in our galaxy.**

- **Search for nucleon decay**









LAr TPC Single Phase

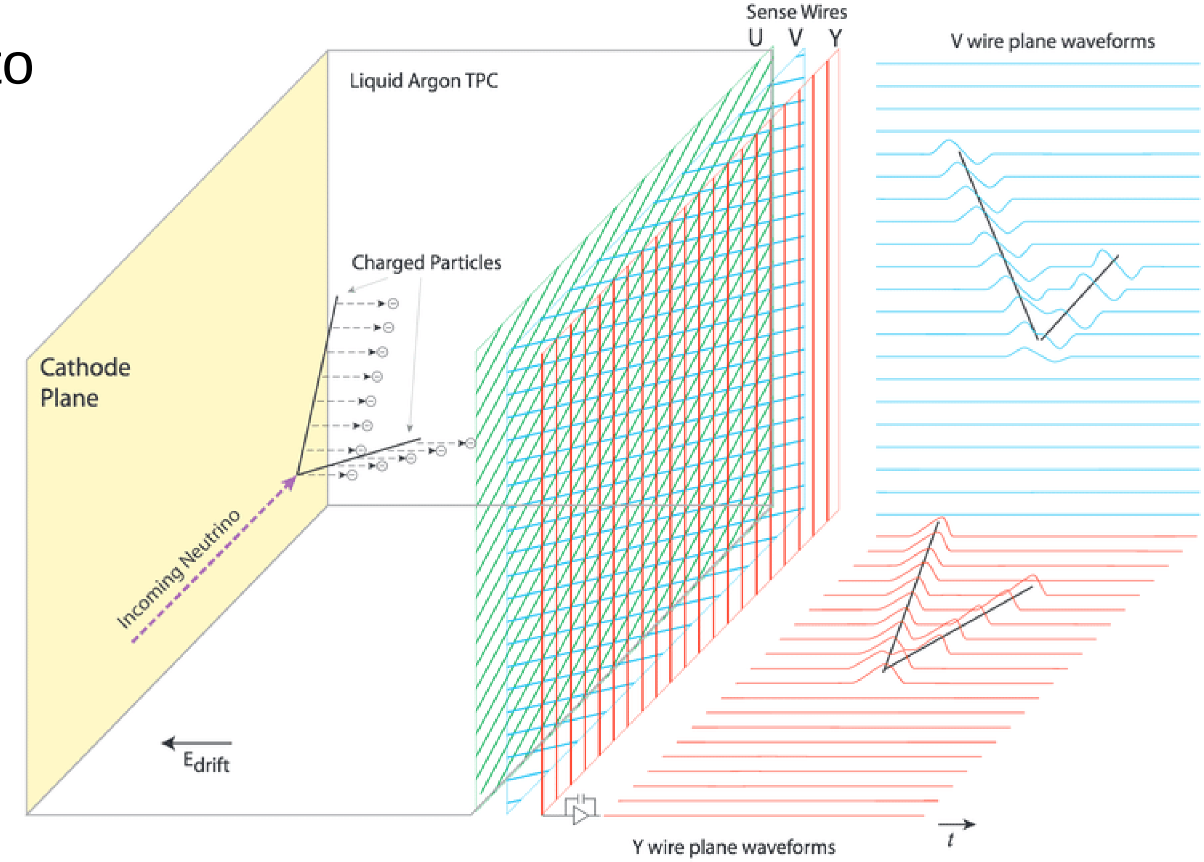
- Argon is an excellent scintillator
  - Charged particles ionize the argon atoms, which then recombine, emitting light.

- High electric field causes some (40%) of the charge to drift.

- The 2-dimensional projection of the event can be read out.

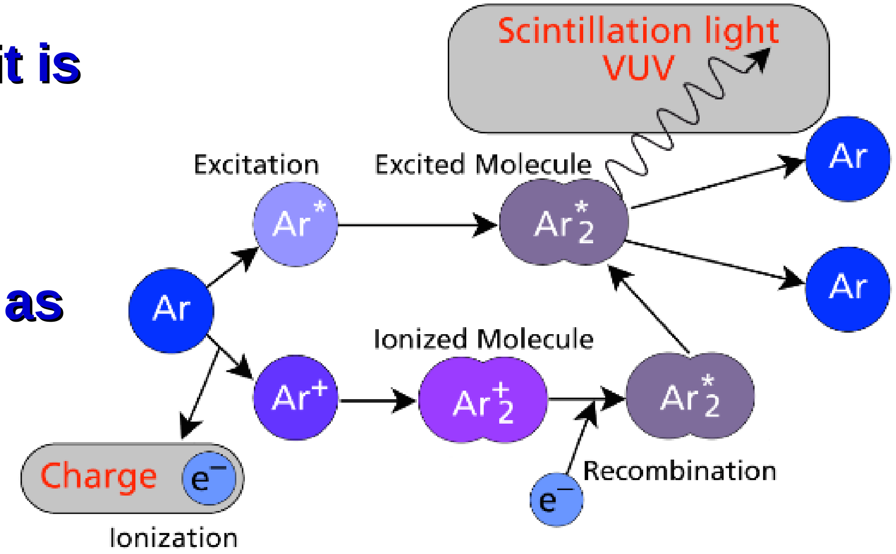
- The arrival time of the charge gives the third dimension.

- Produces high-resolution, 3-dimensional images of events.



LAr scintillation light

LAr has an high scintillation light yield and it is transparent to its own scintillation light
50 000 PE per MeV at 128 nm



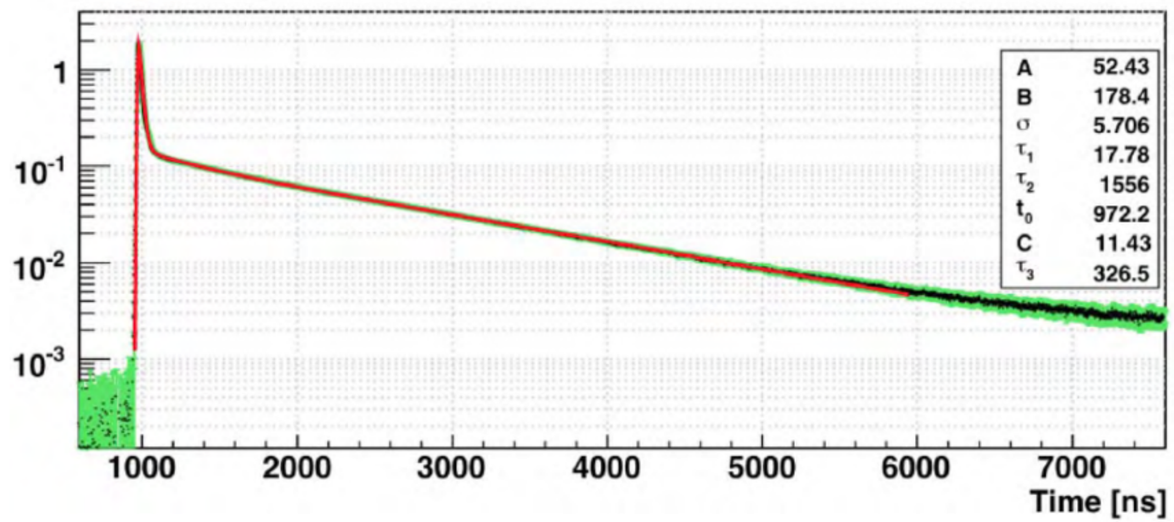
Collecting the LAr scintillation light, as well as for calorimetric energy reconstruction, is interesting for timing purposes

t0 deterination for 3D track reconstruction

Moreover the LAr fast scintillating light component can provide an excellent trigger for low energy underground events as

SuperNovae ν

Proton decay



ArDM: A ton-scale LAr detector for direct Dark Matter searches December 2010 10.1088/1742-6596/308/1/012006 - arXiv

ProtoDUNE-SP at CERN

- Main TPC Components:

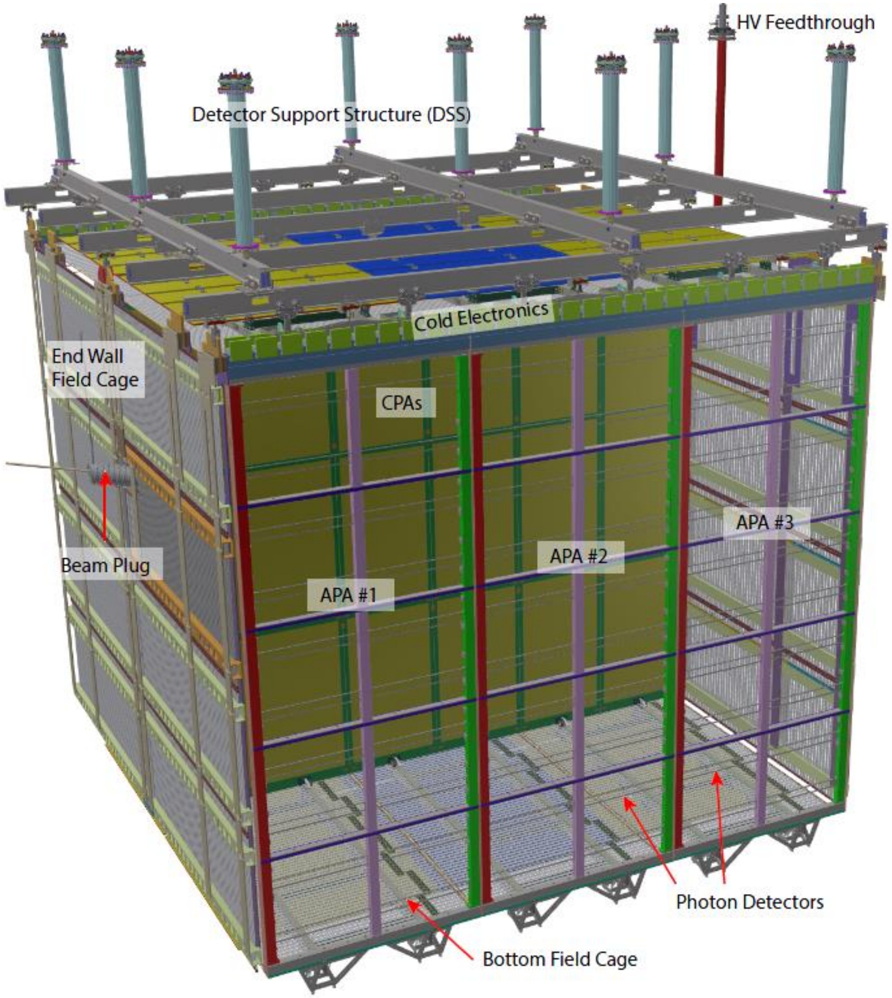
- 6 Anode Plane Assemblies (APA) with integrated photon detectors
- 15k ch. of integrated cold front-end and digitizing electronics
- 28 field cage modules, 18 Cathode Plane Assemblies (CPA)
- The entire TPC is suspended on the Detector Support System.
- The APA, CPA and field cage modules are intended to be nearly identical to the DUNE FD counterparts.

- Photon Detectors

- 10 acrylic bars with TPB WLS per APA
- SiPM readout
- Custom readout
- 1APA for detector development

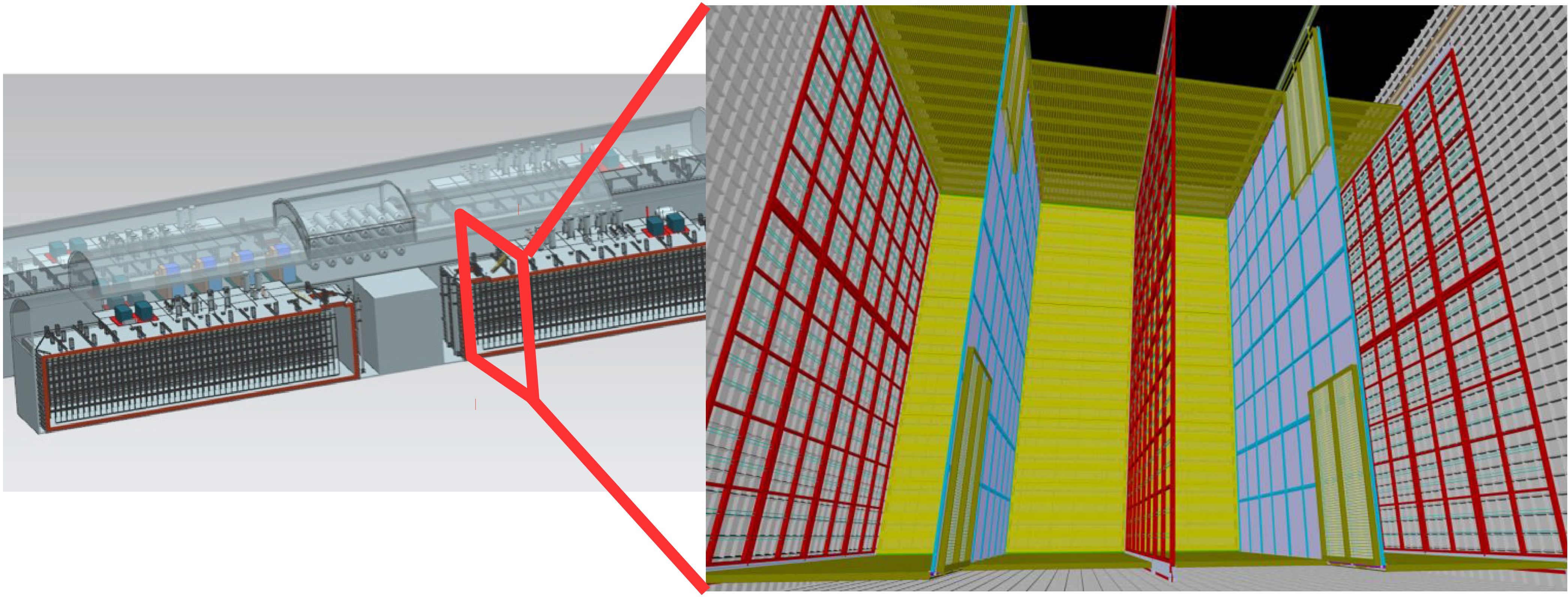
- Detector Active Volume:

- 7m (L) x 6m (H) x 2x3.6m (W)
- 420 ton active mass



Jim Stewart, Brookhaven National Laboratory
For the DUNE Collaboration
October 24, 2017

The DUNE Far Detector: Single Phase



- **Single-phase TPC design based on LBNE modular drift cells.**

- Suspended Anode and Cathode Plane Assemblies (APAs & CPAs).
- 3.6 m drift with a 500 V/cm E-field
- Cold digital electronics reduce noise.
- 3 azimuthal views: collection wires vertical, induction wires at a 35.7° wrapped around APA.
  - Wrapping reduces the cold cable plant and number of readout channels.

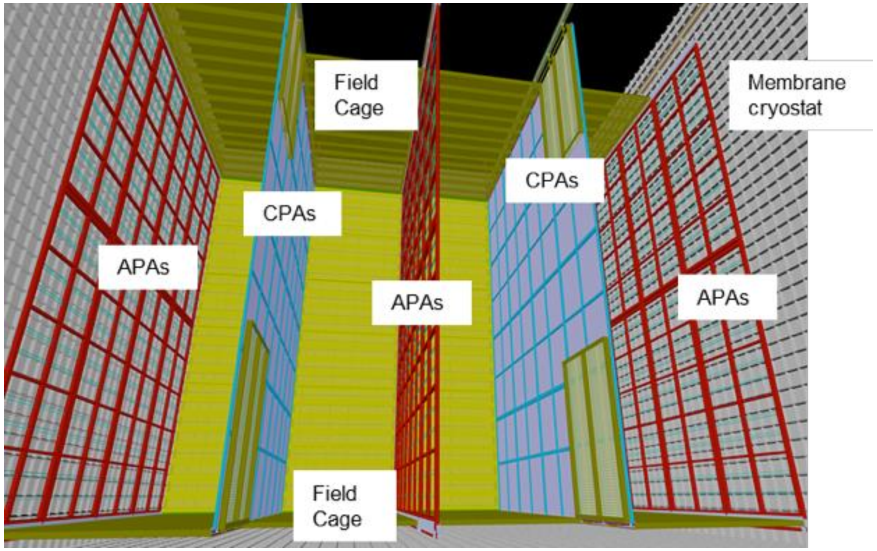
DUNE and ProtoDUNE mechanical constraints for the Light Detectors

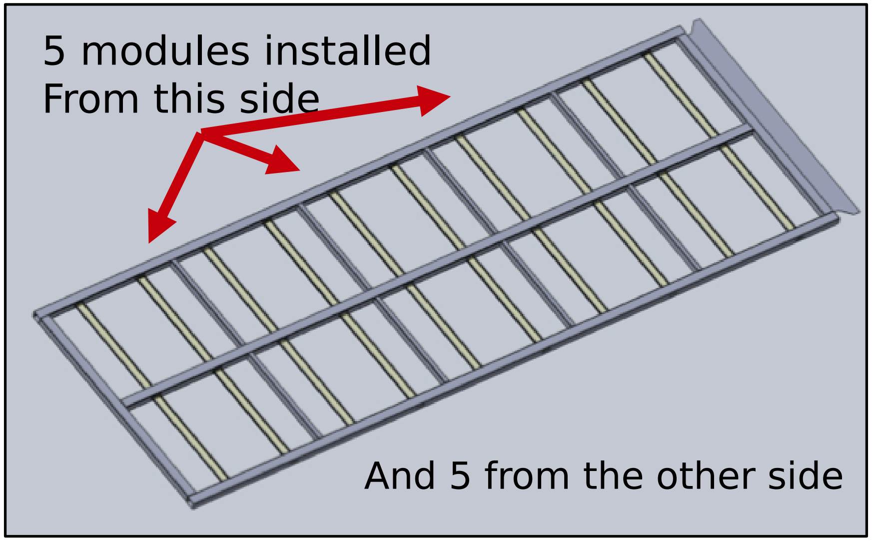
The DUNE LAr-TPC SP module geometry, as for ProtoDUNE SP, imposes substantial mechanical constraints on the Light Detectors design

Classical PMTs can not be housed inside the LAr-TPC

For this reason it is necessray to develop new Light Detector sistems with alternative design

DUNE Far Detector Conceptual Design

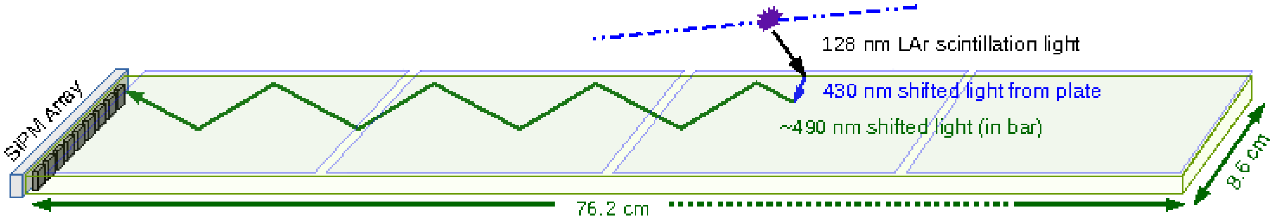


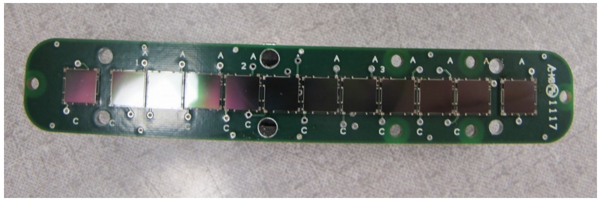


PhotoDetector Basic Concept for DUNE LAr Experiment

10 PDs per APA Frame
PD active area 2076mm X 84mm (each)
APA Frame area (Outside) 6060mm X 2300mm
PD Coverage fraction: ~12.5%

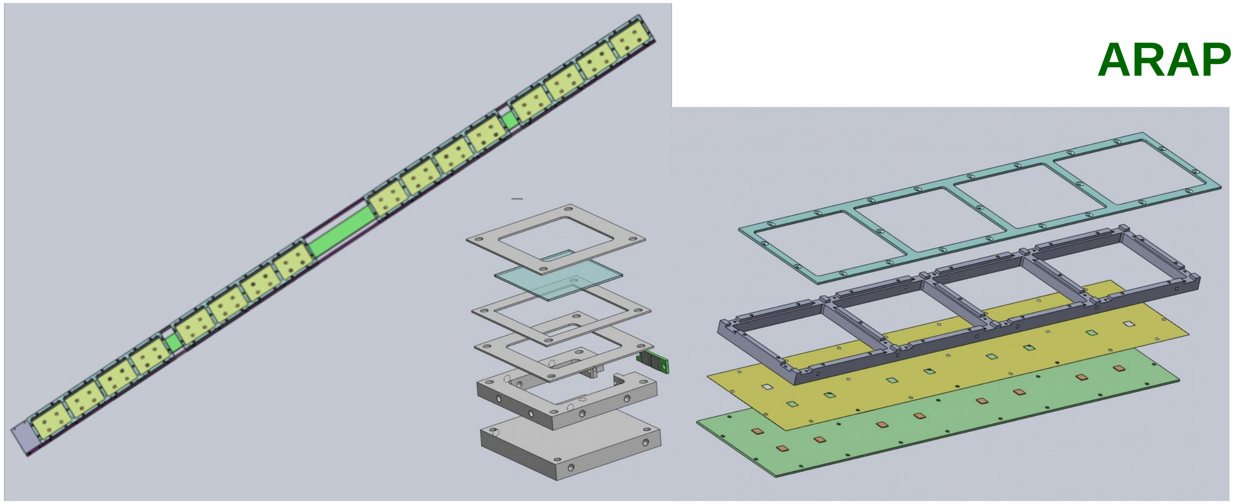
The design concept for the photon detector technology in ProtoDUNE

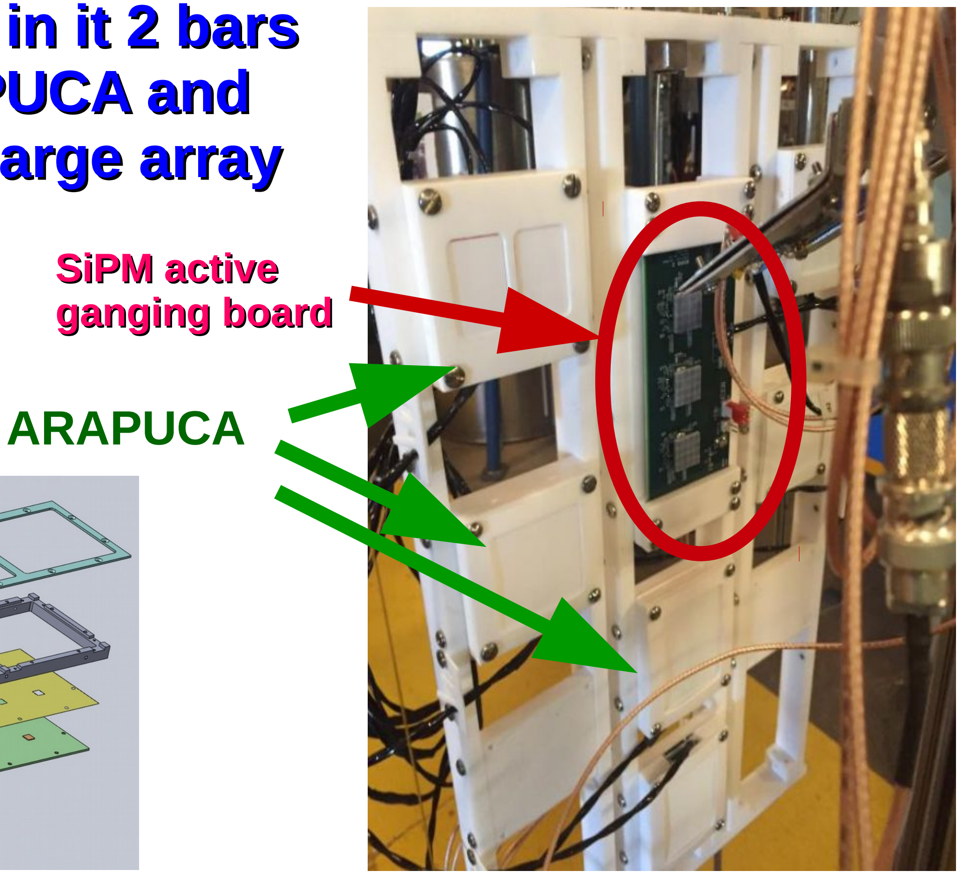




Standard Light Guides are used to instrument 5 of the 6 APA.
12 SiPM of which 3 ganged per readout channel per bar are used for the light detection

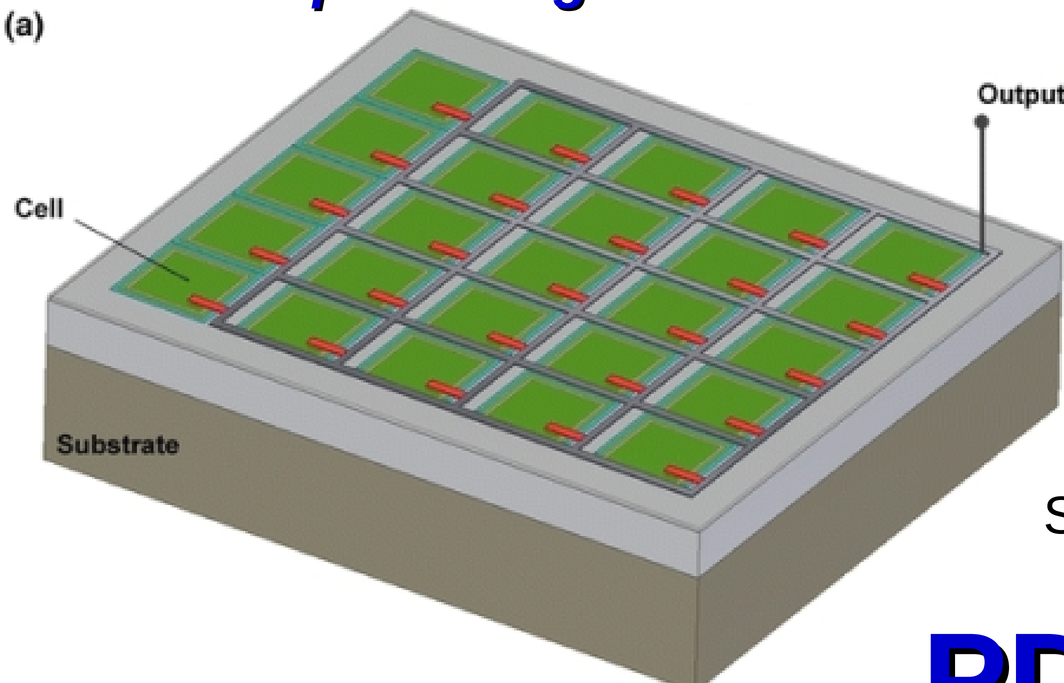
One APA is used for development and in it 2 bars will host the innovative devices ARAPUCA and in case an active ganging board for a large array of SiPMs.

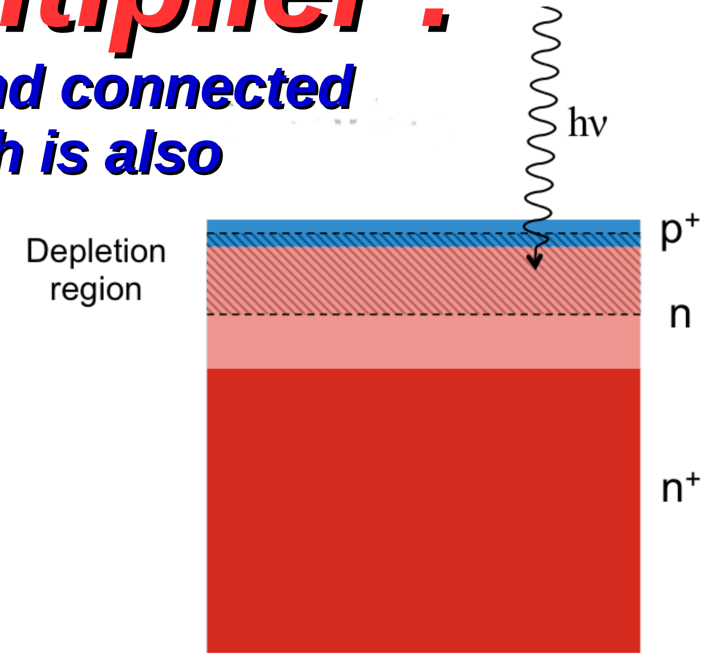




Silicon PhotoMultiplier :

A SiPM is segmented in tiny GM-APD cells and connected in parallel trough a decoupling resistor, which is also used for quenching avalanches in the cells





SensL C Series 6x6 mm^2
λ=420 nm T=T_room

PDE = 31% (V=Vbd+2.5V)

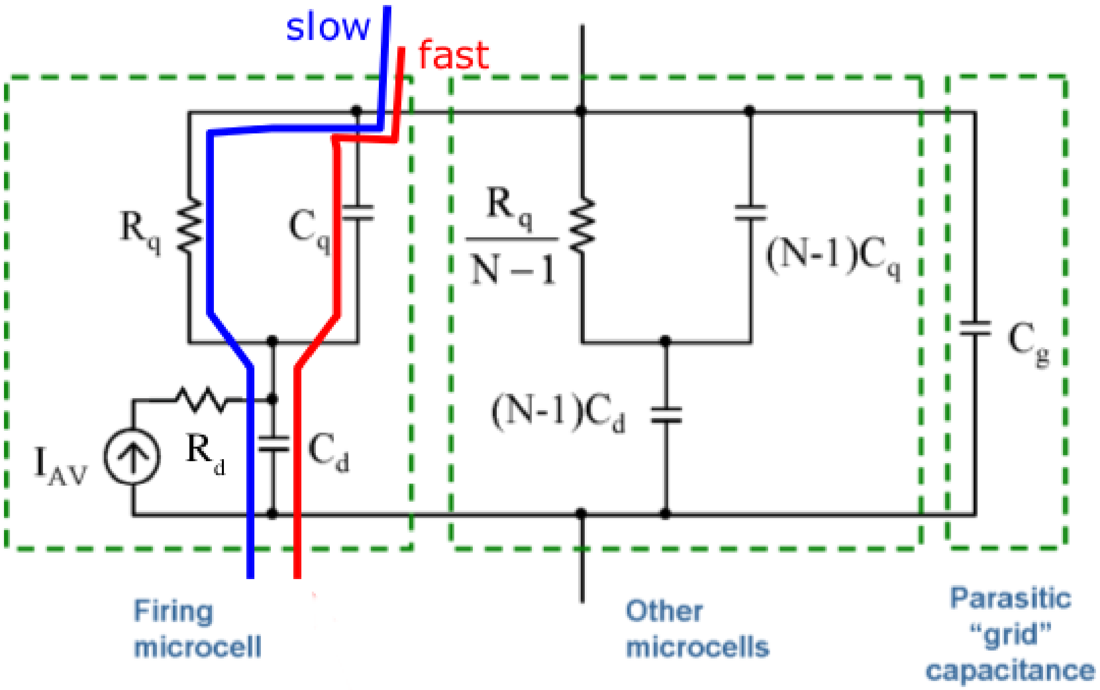
PDE = 41% (V=Vbd+5V)

G = 3 x 10^6 (V=Vbd+2.5V)

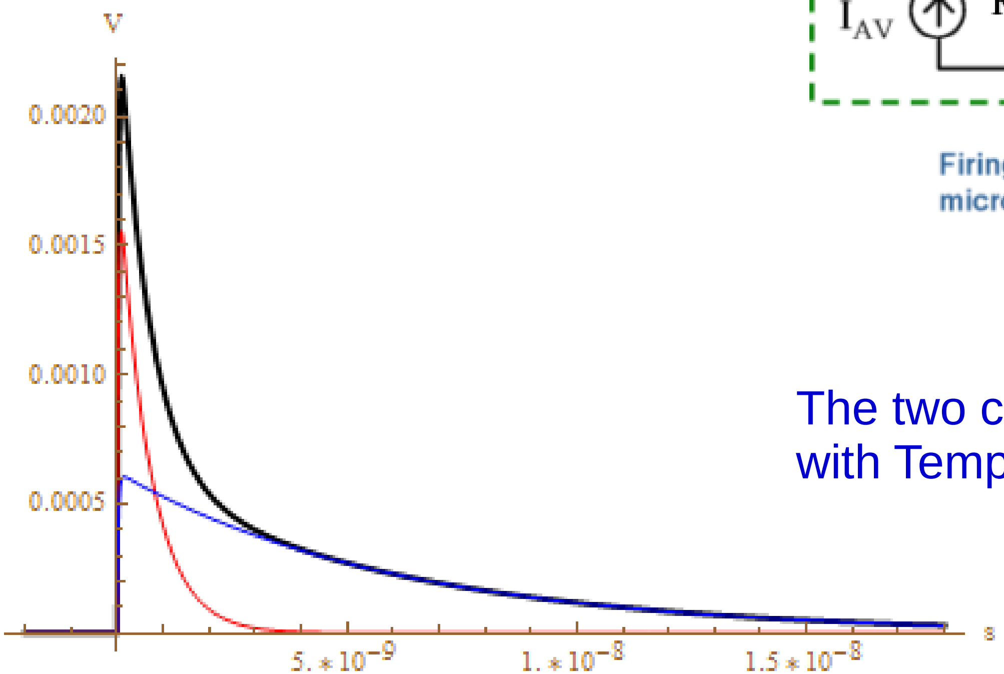
Each element is independent and gives the same signal when fired by a photon
In principle output charge is proportional to the number of of incident photons

SiPM: equivalent circuit

(G.Collazuol - “Advances in Solid State Photo-Detectors” - IDPASC School on Frontier Detectors 2013 October 4 th - 6 th)



- τ(rise) ~R_d (C_q +C_d)
- τ_fast (fall) = R_load C_tot (fast)
- τ_slow (fall) = R_q (C_q +C_d)(slow)



The two current components behave differently with Temperature

F.Corsi, et al. NIM A572 (2007) 416
S.Seifert et al. IEEE TNS 56 (2009) 3726

ARAPUCA: the photon trap mechanism

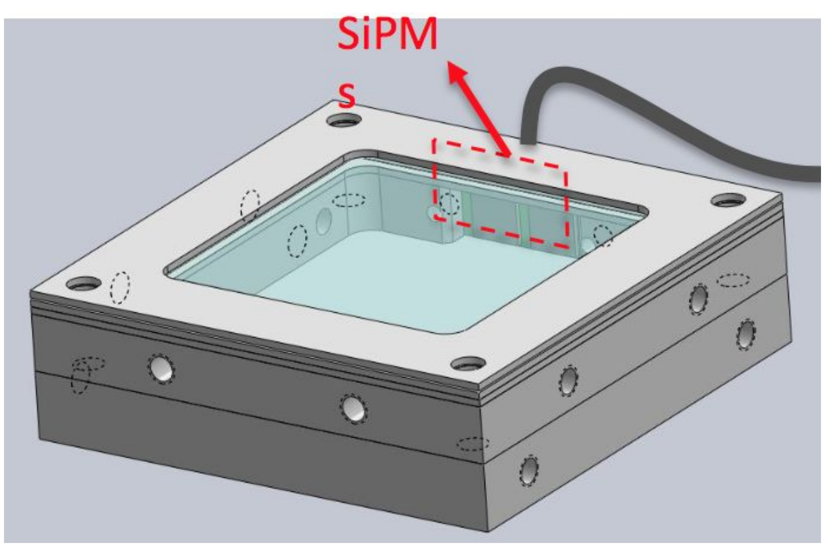
(Ernesto Kemp for the ARAPUCA collaboration – LIDINE 2017)

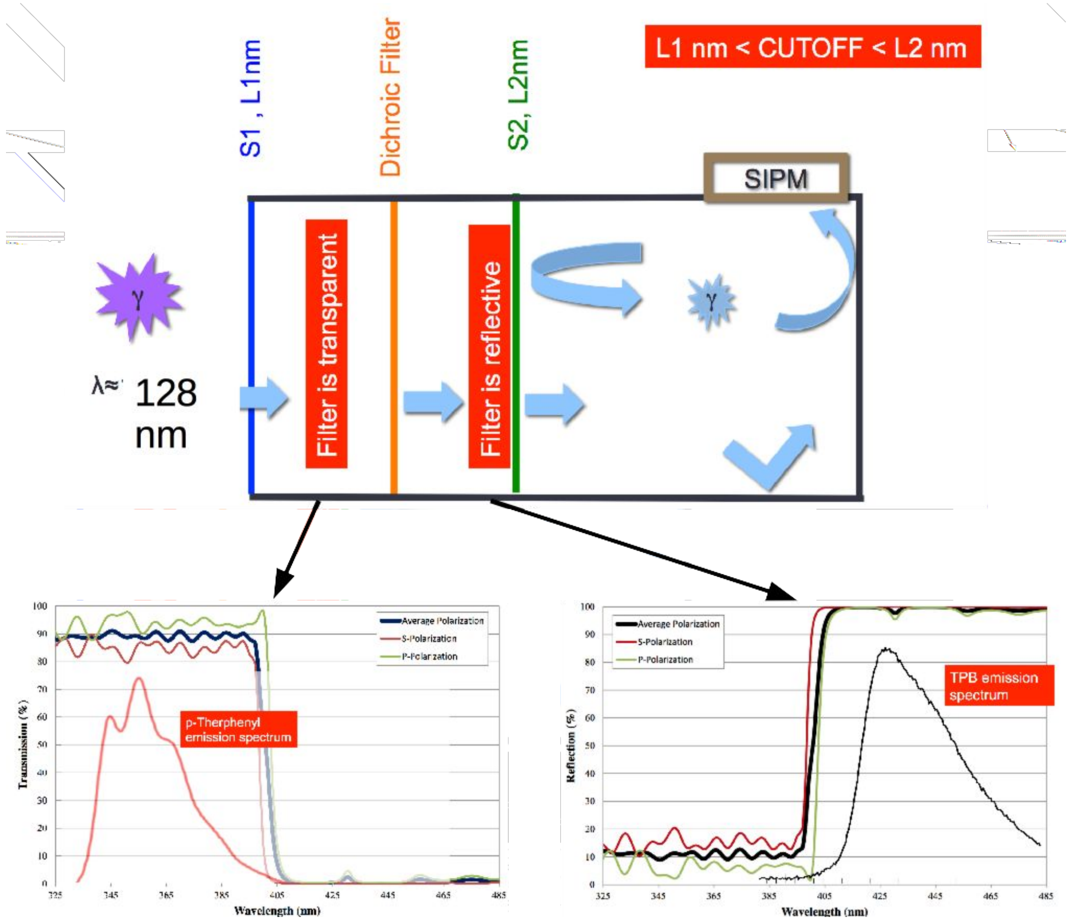
- VUV (128 nm) photons are produced in LAR

- 1st WLS interaction: downshift to λ < λ CUT
Filter is transparent, photons get into the box

- 2st WLS interaction: downshift to λ > λ CUT
Filter is reflective, photons become trapped

Photons undergo further reflections until reach the photosensor (SiPM)





ARAPUCA a new device for liquid argon scintillation light detection. A. A. Machado, E. Segreto (Campinas State U.). JINST 11 (2016) no.02, C02004

OPPORTUNITIES AT FERMILAB FOR PHOTO-DETECTOR DEVELOPMENT

- **Mechanical constraints**
- **Large area to cover**
- **Limited read-out channels**
- **Requirement of high PDE**

lead to the necessity to develop new and more efficient light detector systems which take into account these needs

Currently the development of different photon detector technology is pursued at Fermilab

Detector Design and R&D

ARAPUCA (UNICAMP) Design (light trap by dichroic glass and wls)

………

Photo Sensor Design and R&D

SiPM array with Active (cold) ganging. Parallel ganging of Series of SiPMs.

Electronics Design and R&D

Physics/Simulations

SiPM role in light detectors

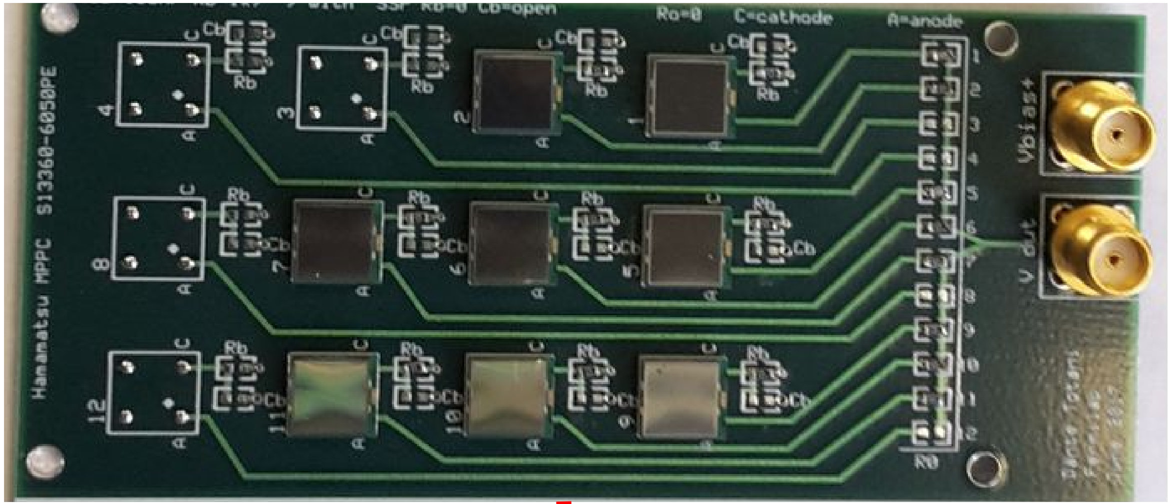
My work at Fermilab focuses on:

- design, testing and characterization of a passive ganging board for the ARAPUCA photosensor system

Aiming at an improved PD efficiency:

- R&D of an active ganging board able to read a large surface SiPM array in cold

Passive Ganging



The boards allow for passive ganging of 1 to 12 SiPMs.

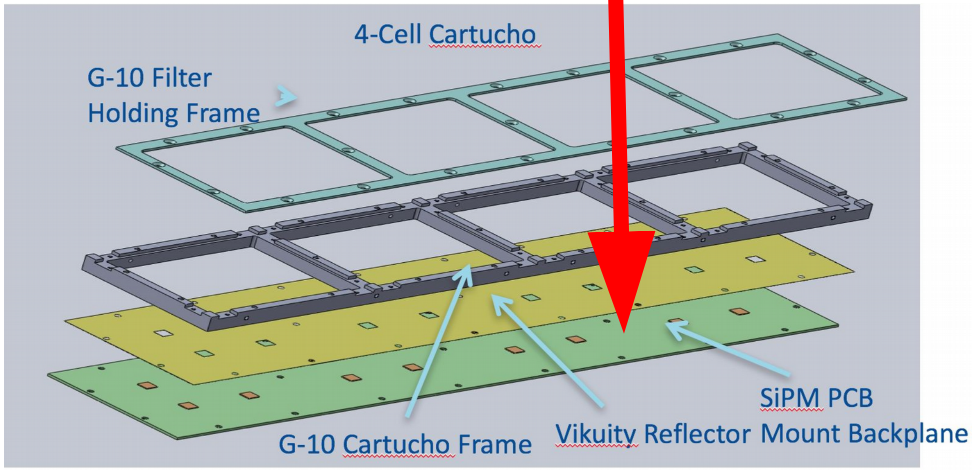
Connecting SiPM in parallel implies paralleling their capacities

↓

Longer recovery time (i.e. discharge)

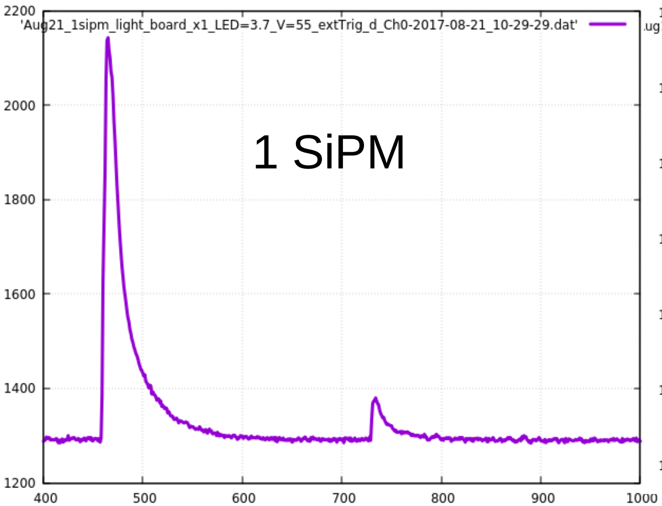
↓

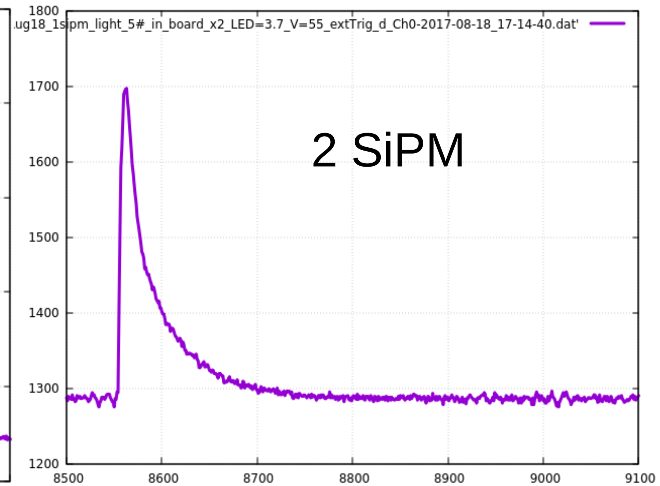
Increasing the sensitive surface would decrease the resolution on photoelectron multiplicity.

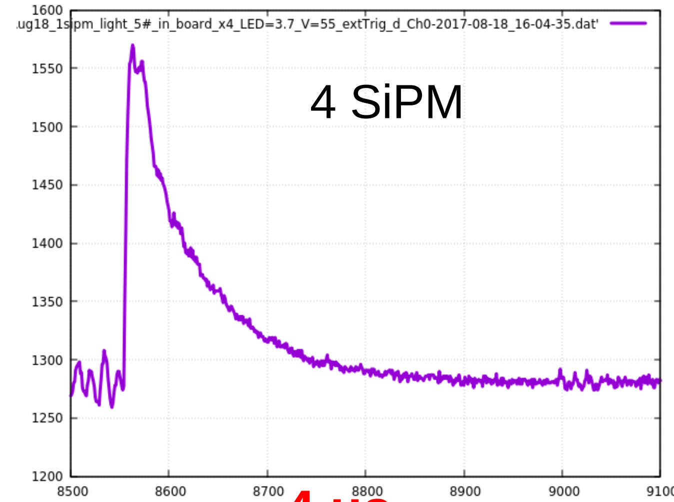


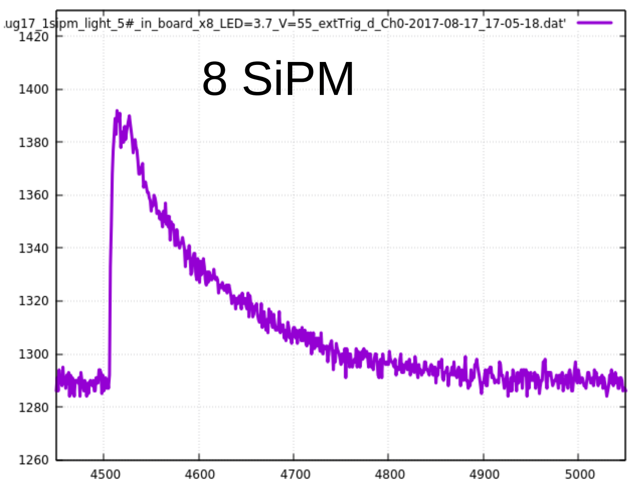
Passive Ganging

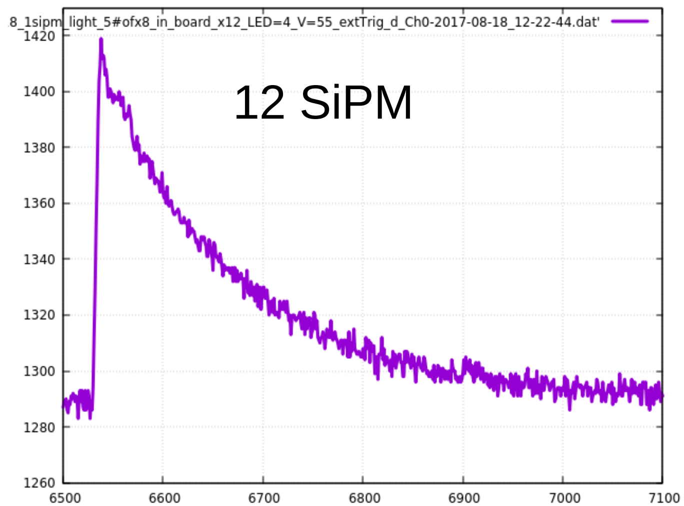
Hamamatsu: **V_bias=55 V T=-70C LED λ=400 nm**







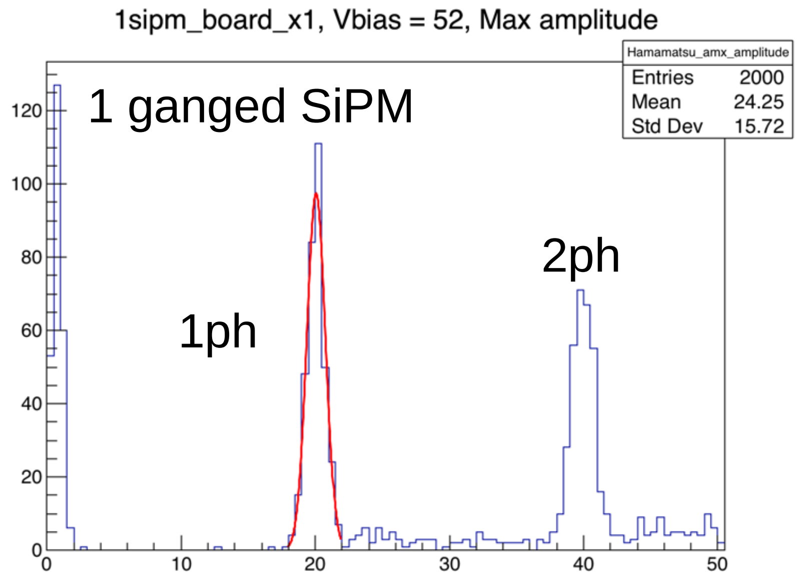


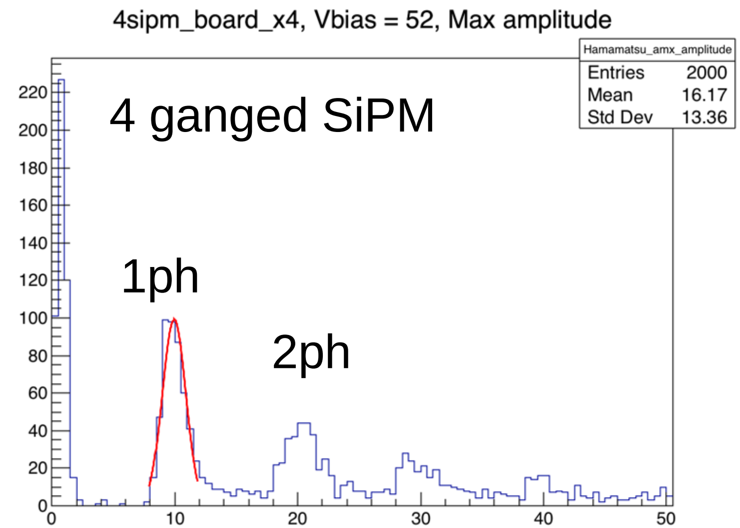


Increasing signal tails with increasing number of connected SiPMs

Passive Ganging

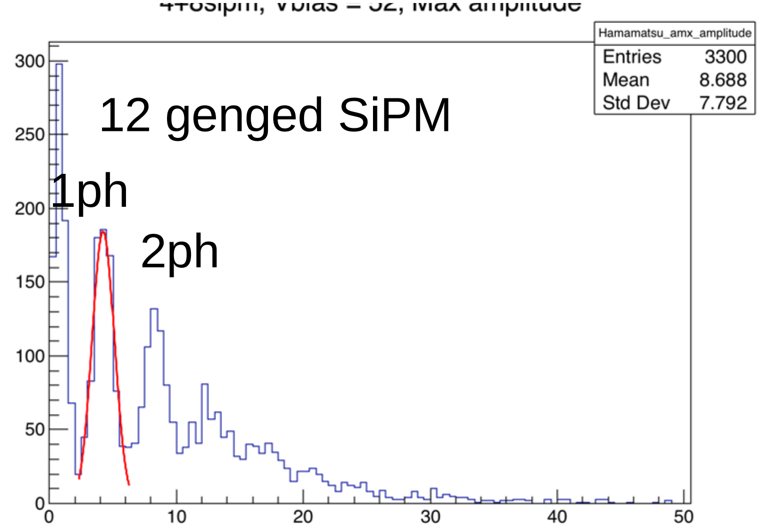
Histograms of the amplitudes:





V_bias = 52V,
T = -70C
Same bright
LED intensity

The peak are in ADU units, fitted to a Gaussian
1 ADU ~ 0.58 mV

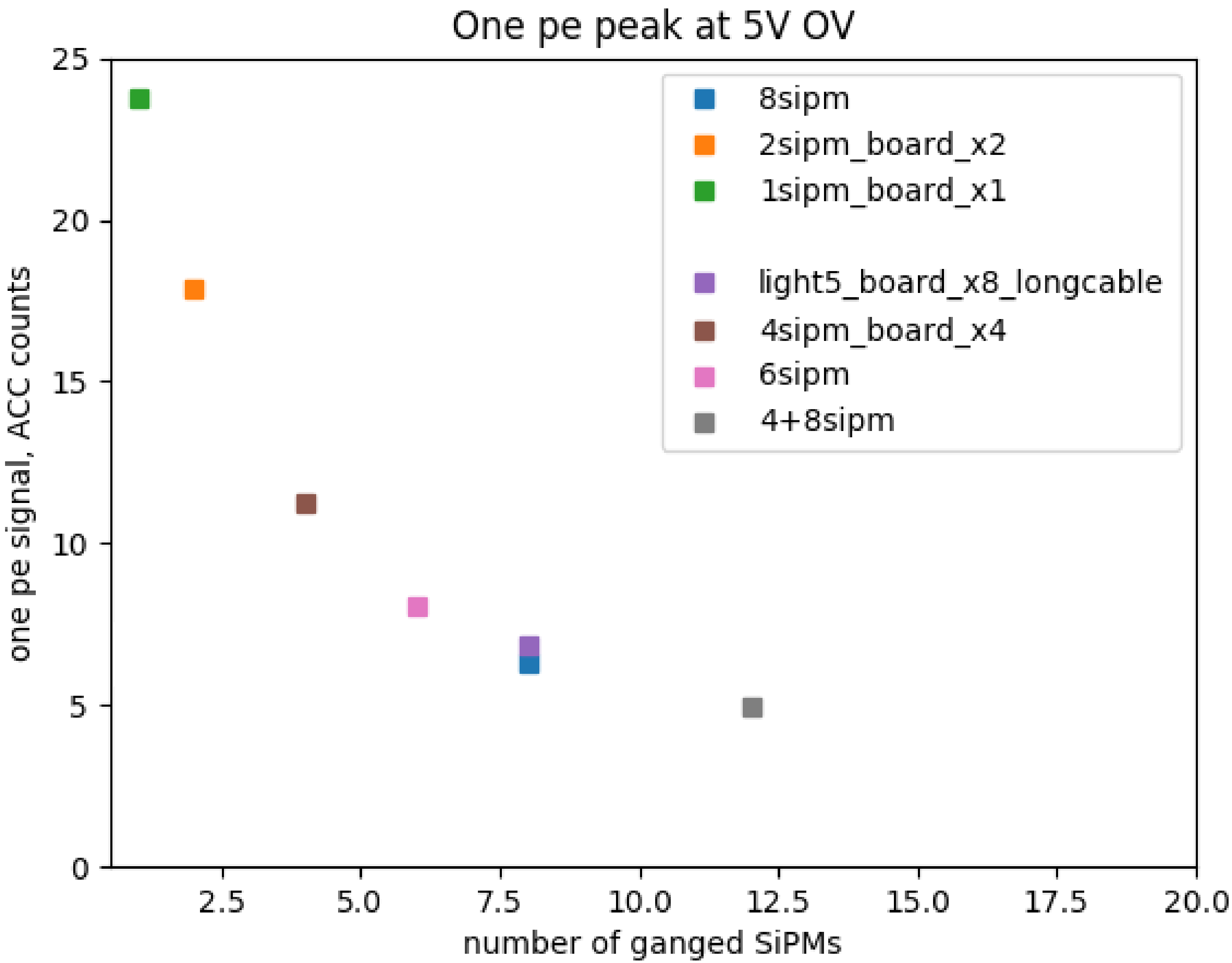


Signal amplitude decreases with increasing ganging multiplicity

The loss of resolution in photon number is evident

Passive Ganging

Single photon peak as a function of SiPM ganging

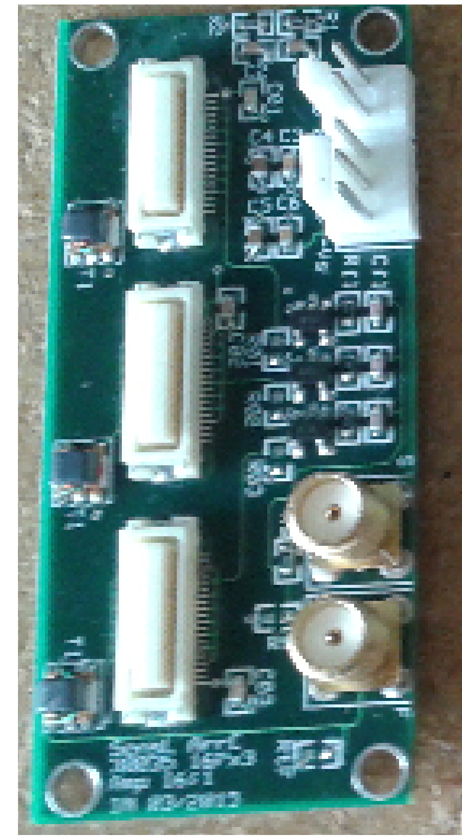


Active Ganging

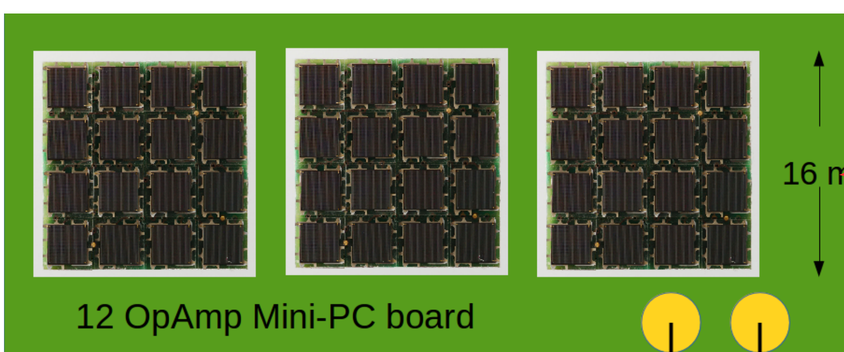
Aim at getting with SiPMs the same sensitive area as with PMT.

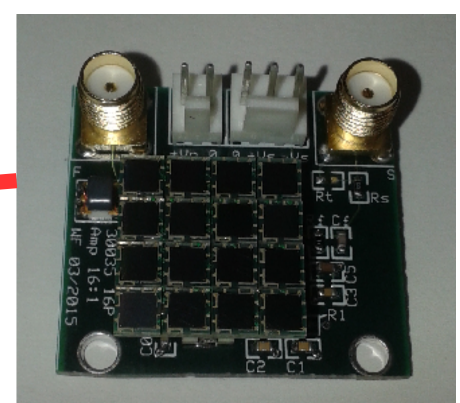
Handle:
- amplify the signal immediately

Contour conditions:
- read a large SiPM array
- work in cold (immersed in LAr)

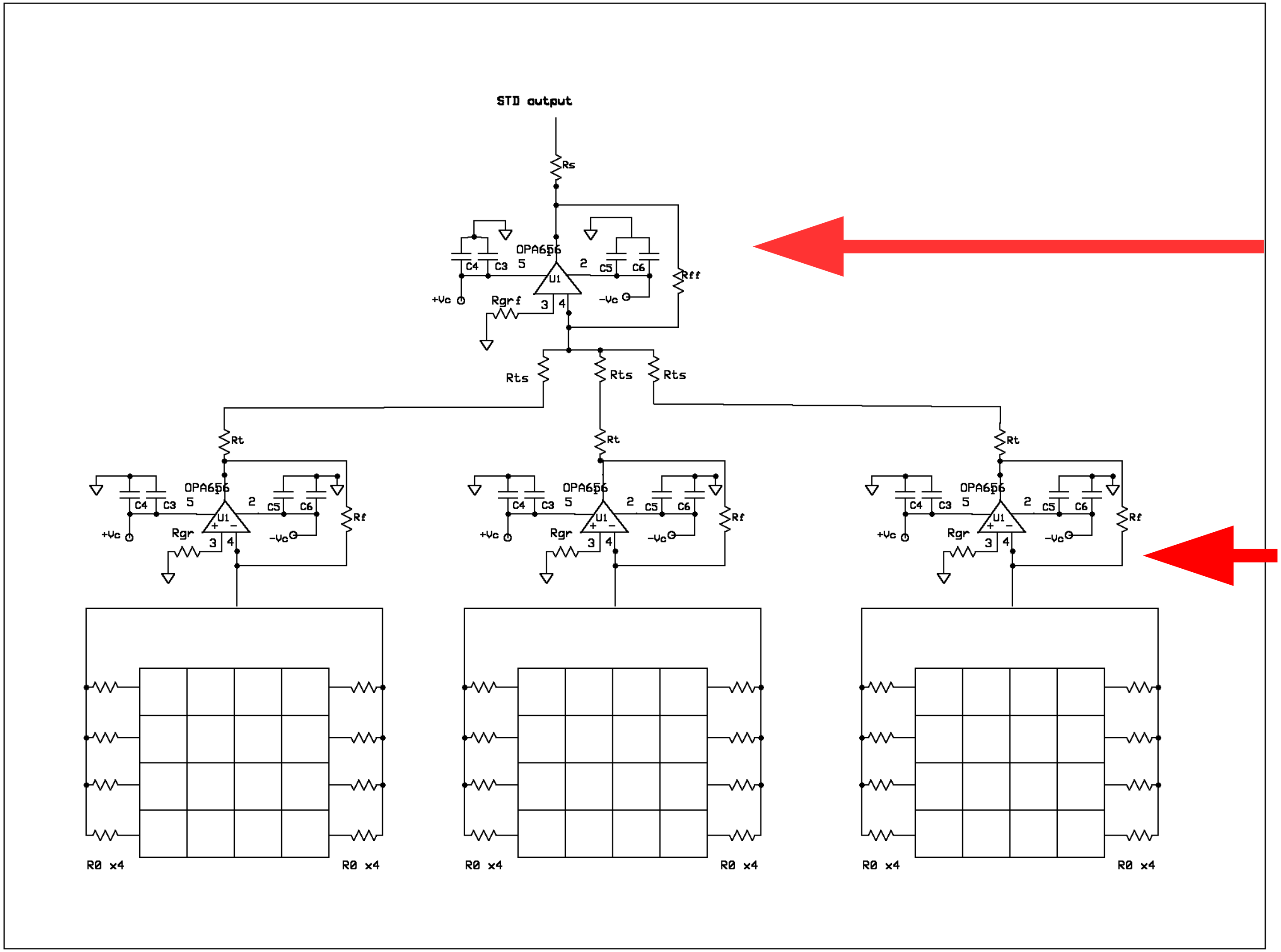


The project, started in LArIAT,
thanks to operational amplifiers working in cryogenic environment





Active Ganging

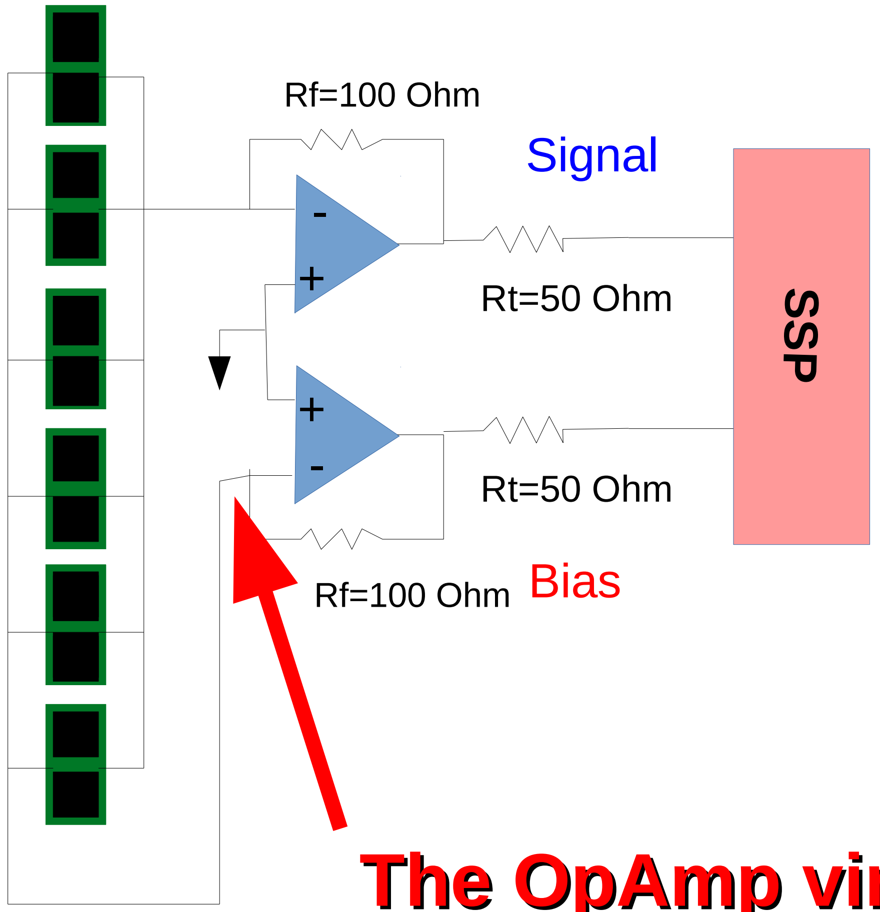


A second stage works as a buffer to sum the first stages

The virtual ground of the inverting imput allows to connect SiPMs decoupling the capacitance and hence preserving the signal shape.

Active Ganging for ProtoDUNE

To adapt the SiPM board to the ProtoDUNE DAQ, a new circuit was developed.



Since the SSP has an amplification stage based on full-differential OpAmps the front-end amplification stage was removed and the buffer was adapted.

The OpAmp virtual ground decouples the SiPM pair capacitances

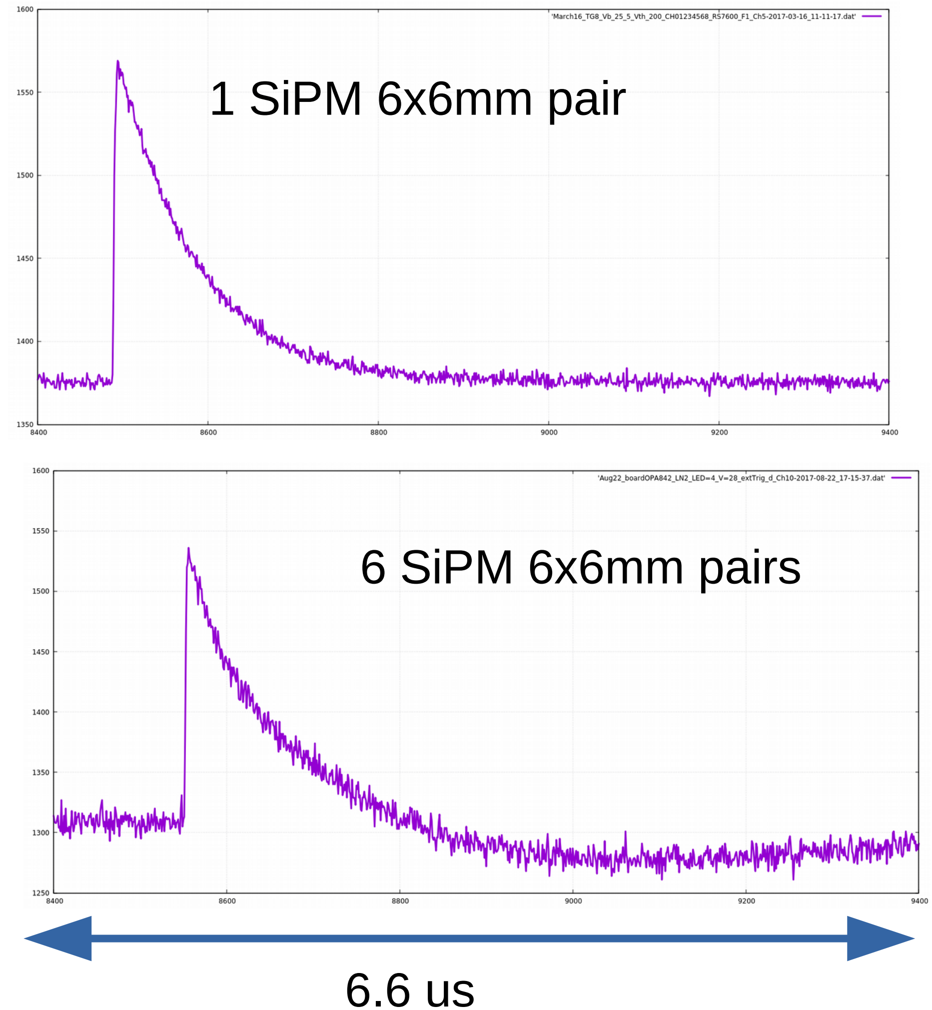
Active Ganging for ProtoDUNE

Tests results in Liquid Nitrogen.

The output signal is independent of ganging multiplicity

The R&D is still going on to improve details.

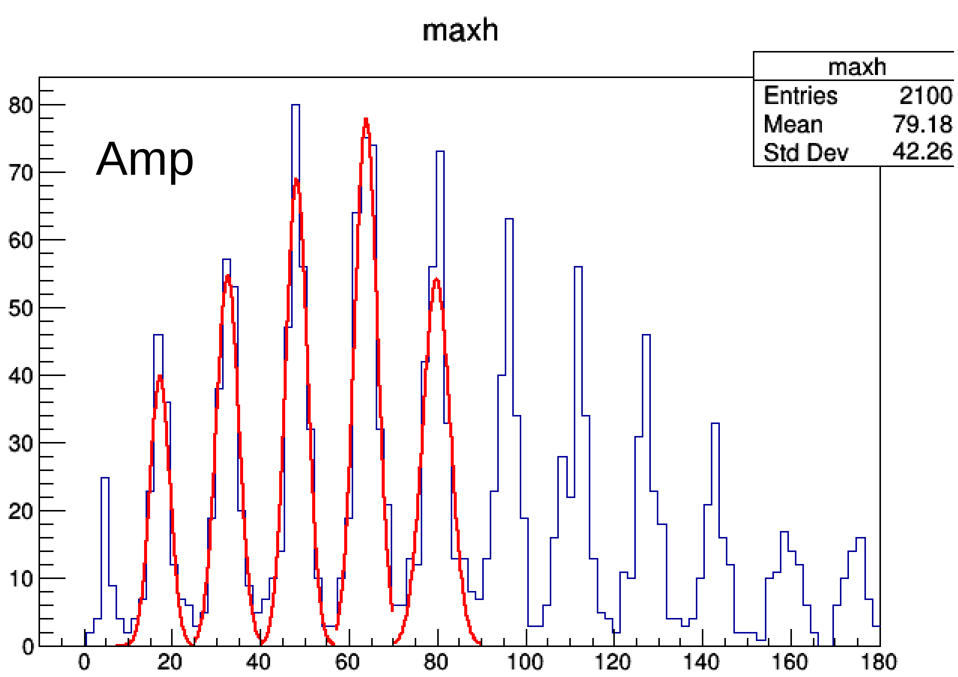
T=T_LN2 V_bias =25.5 V LED “on”

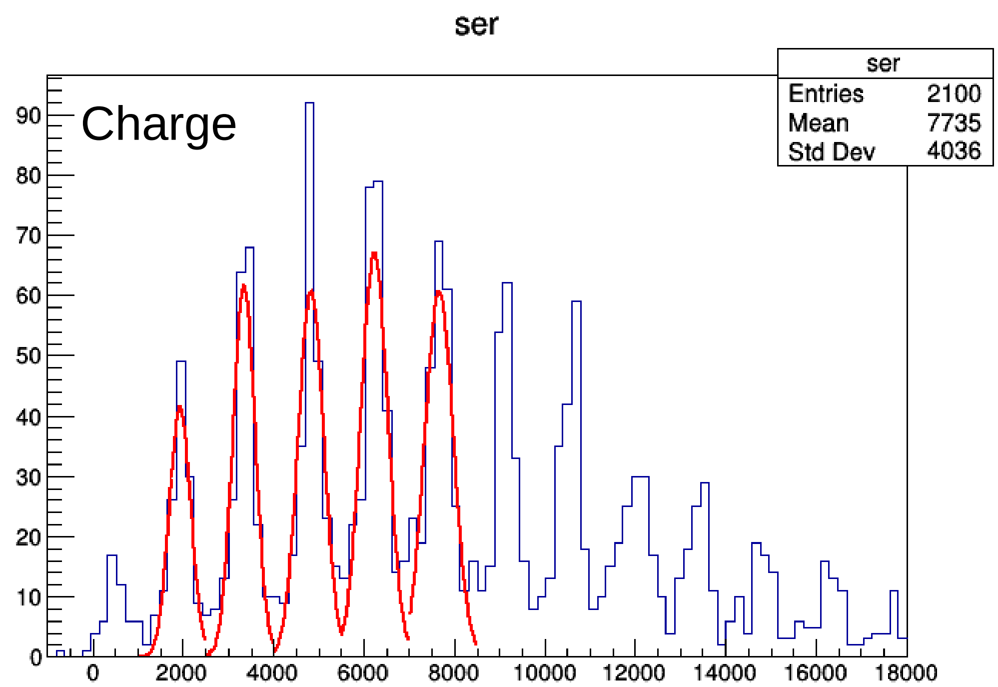


Active Ganging for ProtoDUNE

Amplitude and Charge histograms from the board with 12 SiPMs connected in active ganging (in 6 pairs)

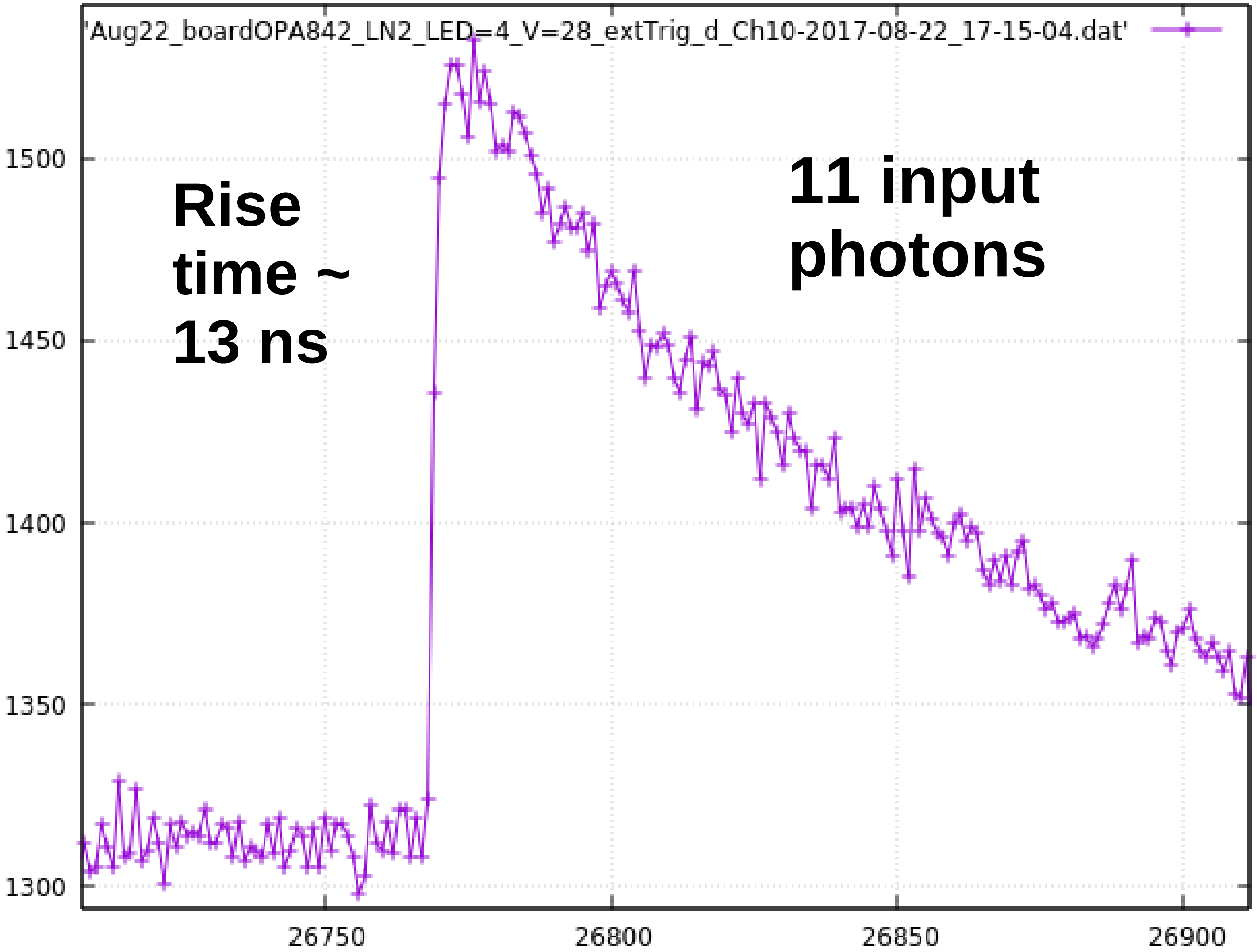
Photon multiplicity is clearly measured





Active Ganging for ProtoDUNE

The fast rise time makes the signal suitable for timing

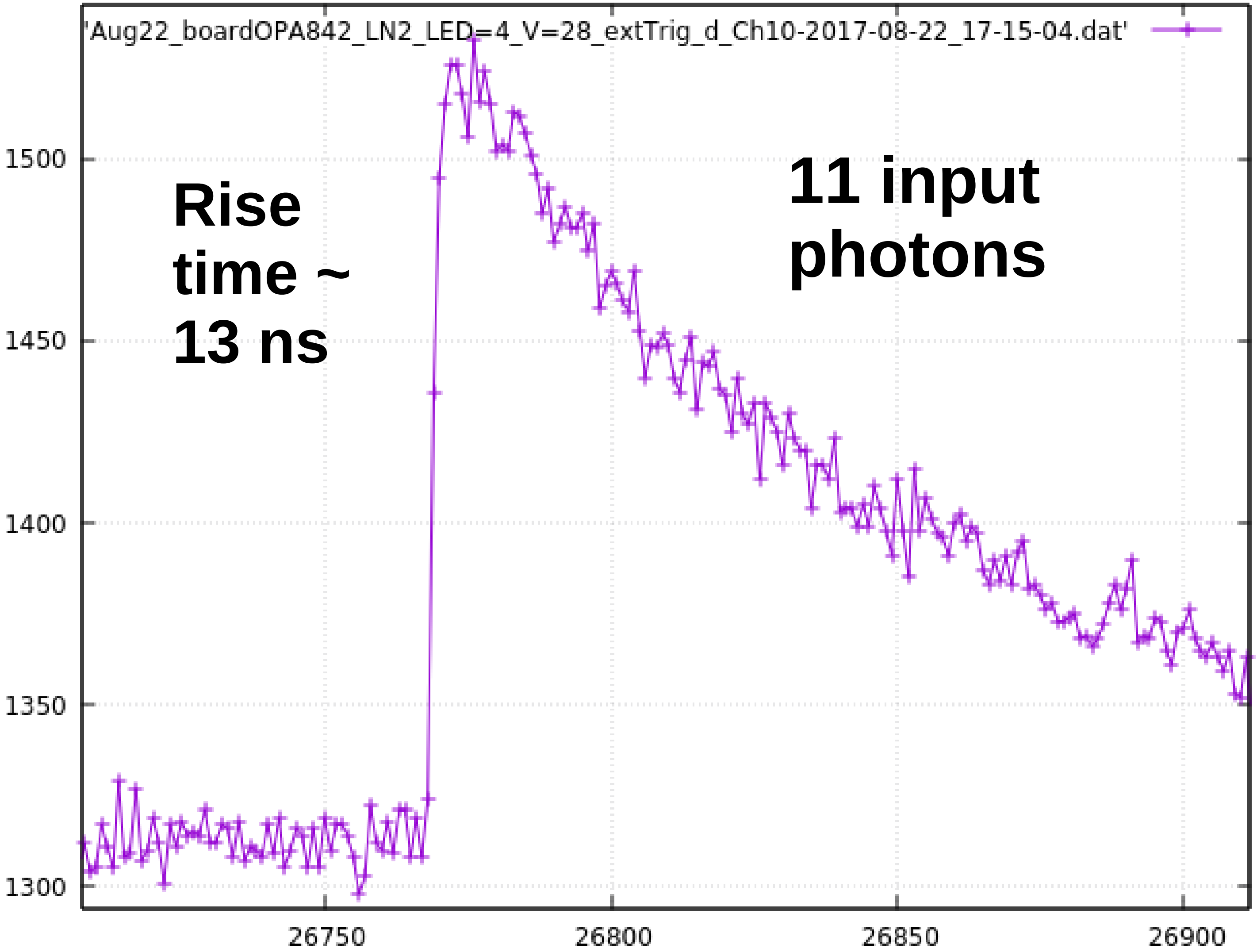


V_bd=28V
T=LN2

1 ADU=0.58 mV
1 tick = 6.67 ns

Active Ganging for ProtoDUNE

The fast rise time makes the signal suitable for timing



V_bd=28V
T=LN2

1 ADU=0.58 mV
1 tick = 6.67 ns

Progress with active ganging

-SiPMs can be ganged together with no loss in signal amplitude and photon multiplicity resolution.

-We tested a system of 6 pairs of SiPM 6x6 mm^2. but there is no reason why a larger board should not work as well.

-Active ganging R&D goes on focusing on the DUNE needs

Active ganging board for DUNE

Developing a large surface SiPM Array is an attractive solution for the DUNE light detection system

It will provide fast, high sensitivity light detecion from LAr events with large coverage.

The SiPM fast response will play a fundamental role both for triggering and for 3d event reconstraction

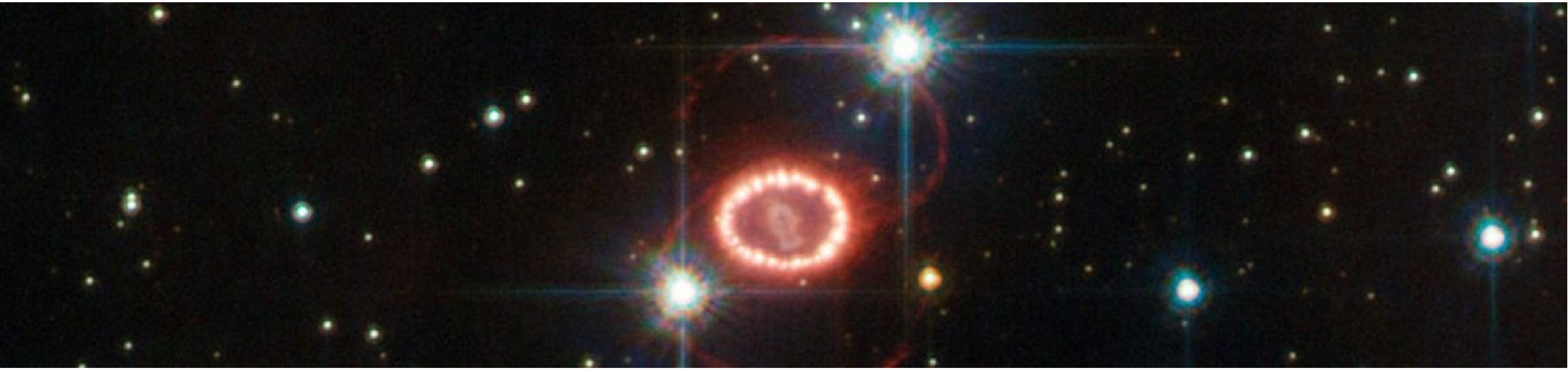
These features will make DUNE specially capable of detecting low energy undergorund events.

SuperNovae and proton decay events are hard to measure, because they will feature neutrinos of O(10 MeV) and a small number of photons (~ 1% of ν from beam events)

The discovery potential of DUNE will be substantially strangthened

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Grazie per l'attenzione



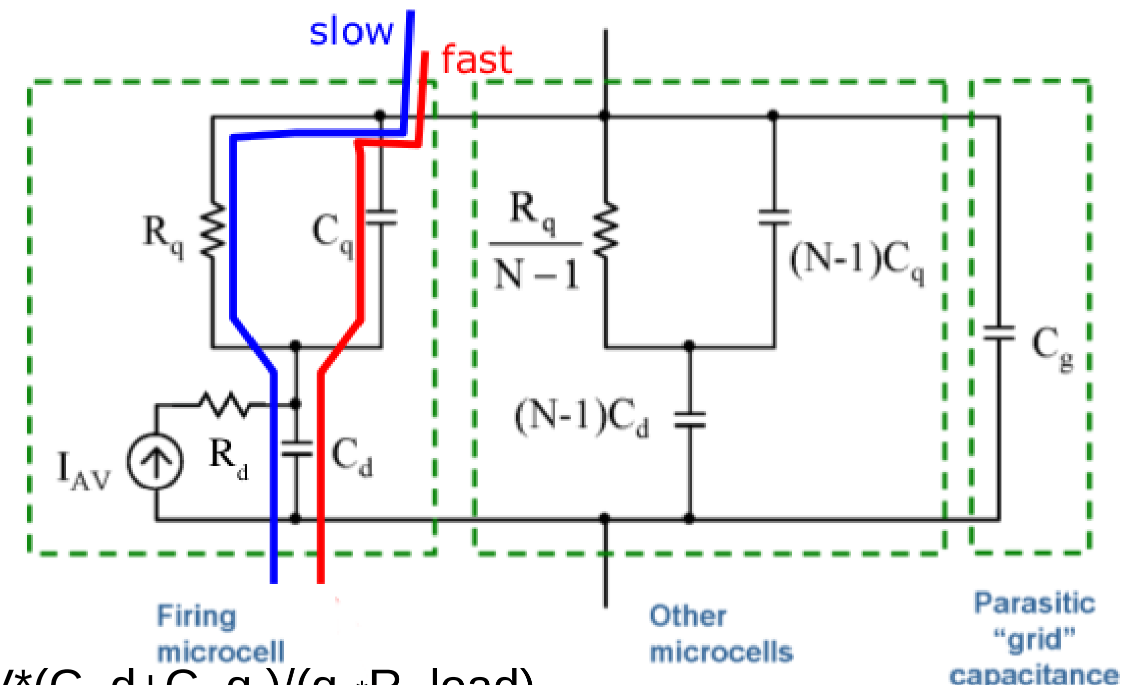
SiPM: equivalent circuit

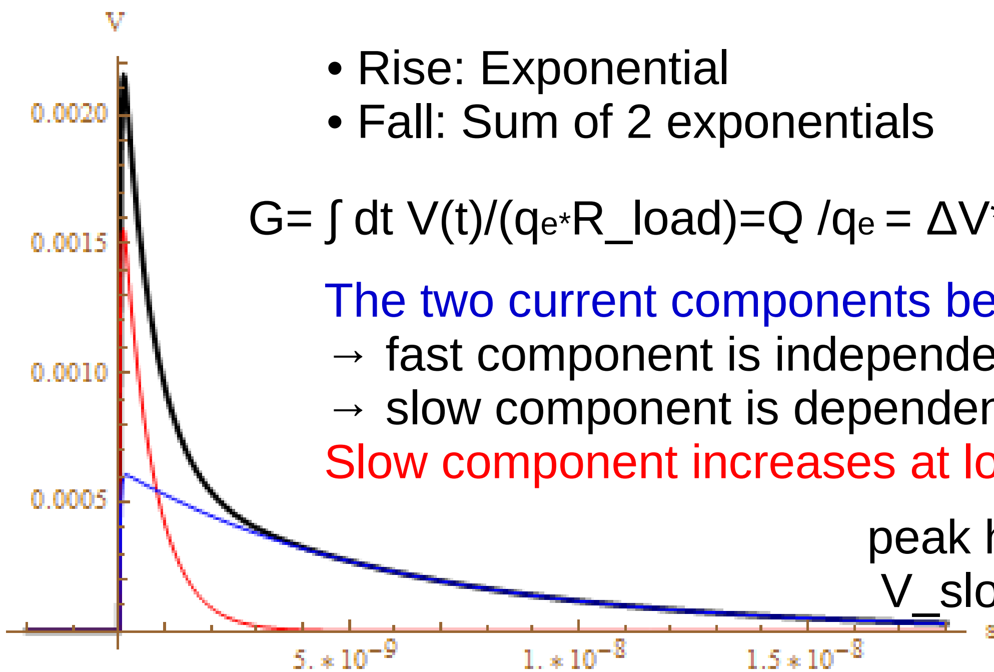
(G.Collazuol - “Advances in Solid State Photo-Detectors” - IDPASC School on Frontier Detectors 2013 October 4 th - 6 th)

Single cell model → (R_d ||C d)+(R_q ||C_q)
SiPM + load → (||Z_cell)||C_grid + Z_load

Signal = slow pulse (τ (rise), τ_slow (fall)) +
+ fast pulse(τ(rise), τ_fast (fall))

- τ(rise) ~R_d (C_q +C_d)
- τ_fast (fall) = R_load C_tot (fast)
- τ_slow (fall) = R_q (C_q +C_d)(slow)





- Rise: Exponential
- Fall: Sum of 2 exponentials

G= ∫ dt V(t)/(qe*R_load)=Q /qe = ΔV*(C_d+C_q)/(qe*R_load)

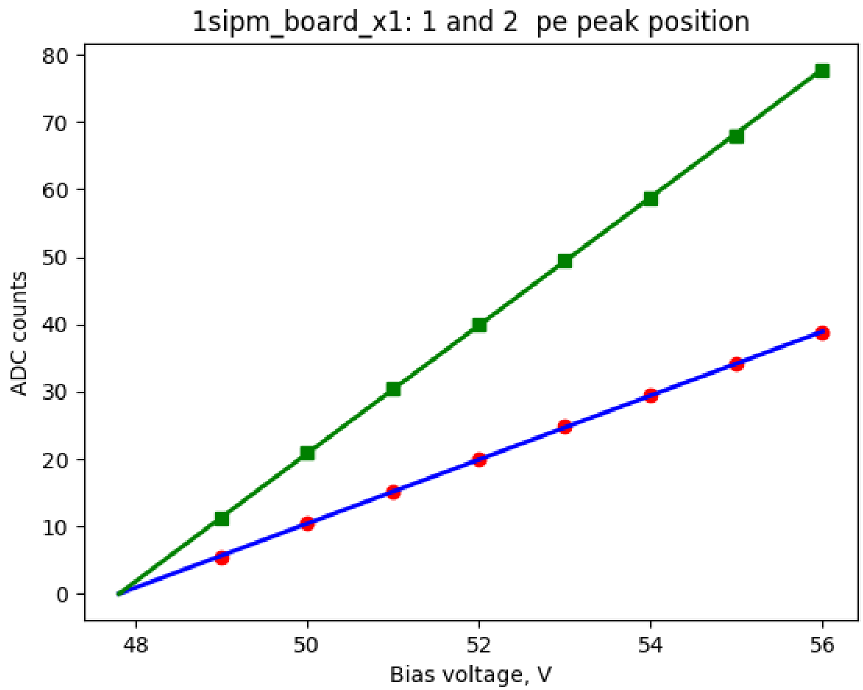
The two current components behave differently with Temperature
→ fast component is independent of T because C_tot couples to external R_load
→ slow component is dependent on T because C_d,q couple to R_q(T)
Slow component increases at low T, this causes a reduction in SPE resolution

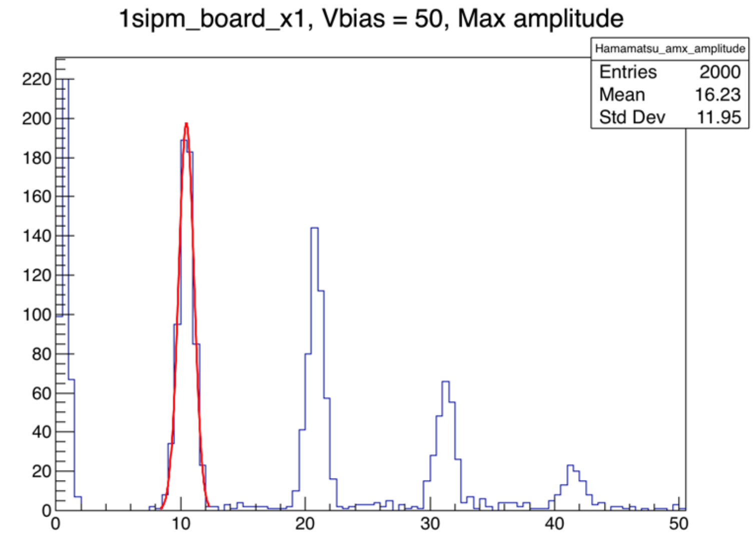
peak height ratio change with temperature:
V_slow/ V_fast ~ [C_d*C_tot*R_load] / [(C_q)^2 *R_q]

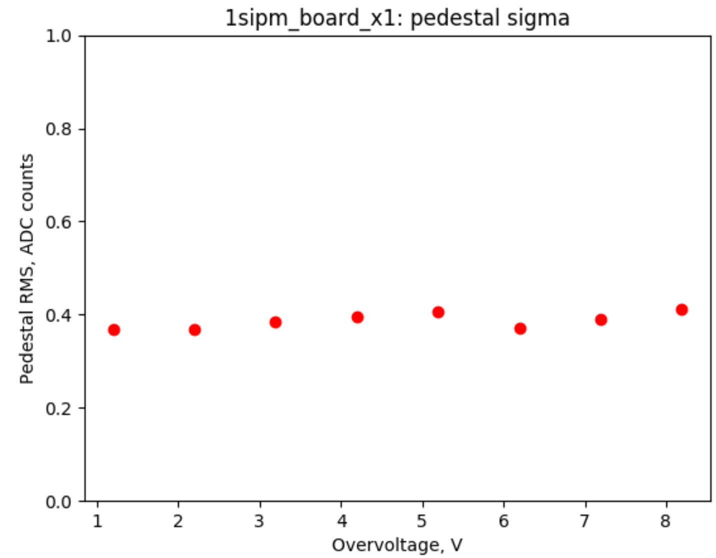
Increasing with C_d and 1/R_q

F.Corsi, et al. NIM A572 (2007) 416
S.Seifert et al. IEEE TNS 56 (2009) 3726

Passive Ganging







A complete characterization of SiPM Hamamatsu has been made to understand their behavior (T = -70C).

As we can see, their response is extremely linear with varying parameters

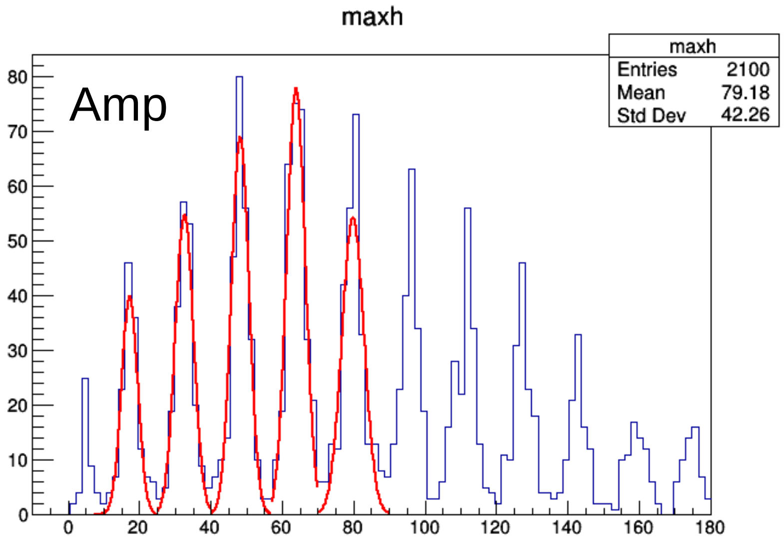
In the top left plot, the amplitude of the single PE and of 2 PEs is reported as a function of the power supply voltage for a SiPM 6x6mm.

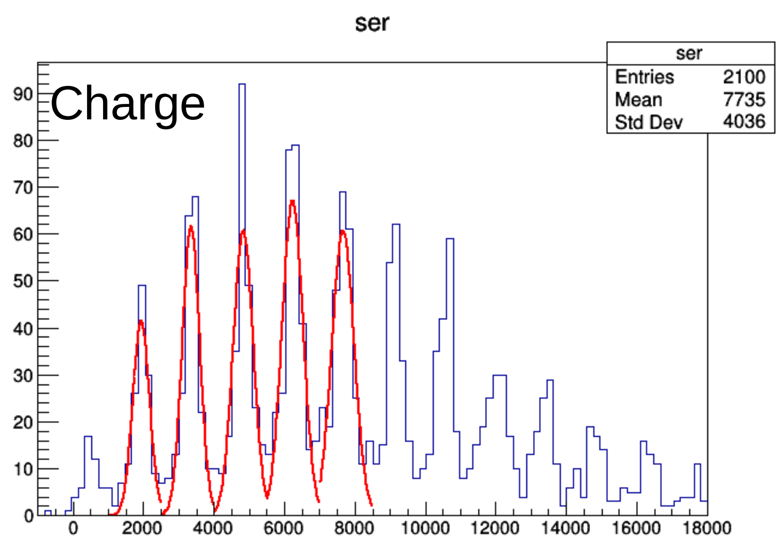
Bottom right the RMS of the baseline.

Similar results are also available for multiple SiPMs configurations in parallel

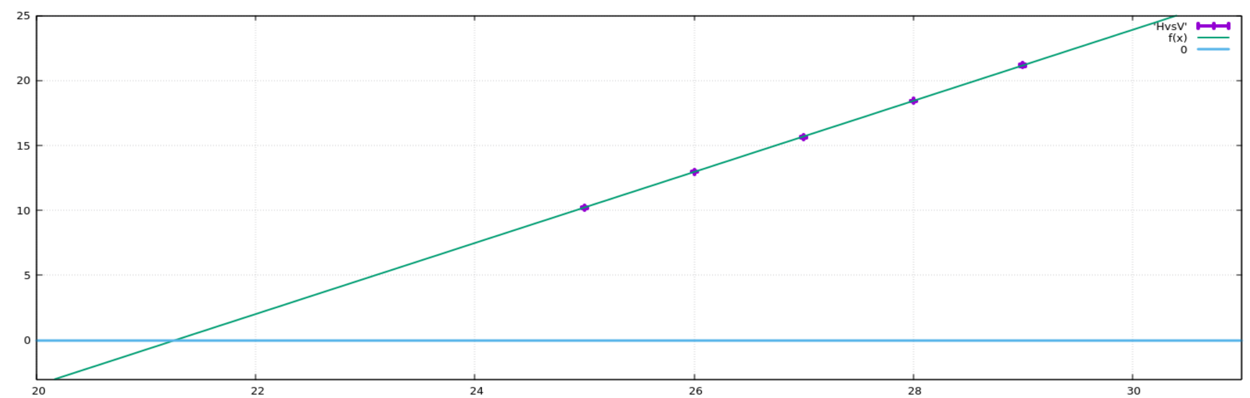
Active Ganging

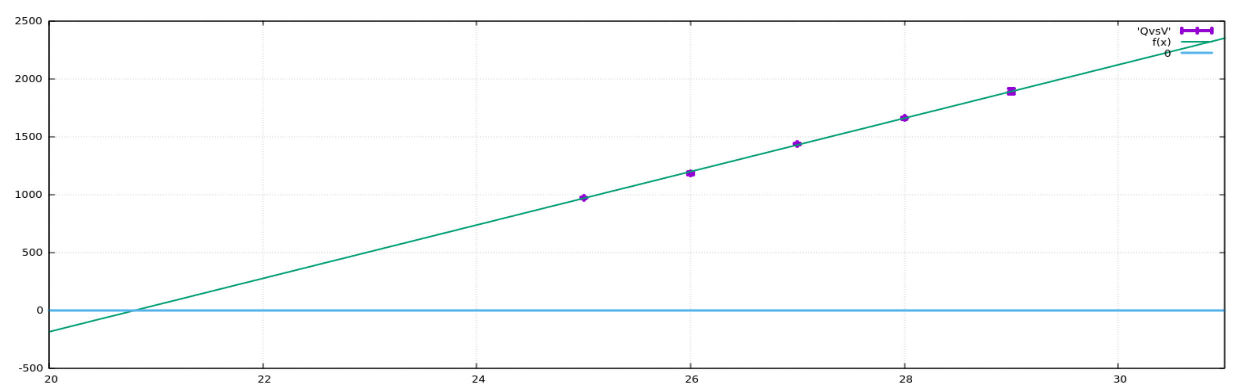
Amplitude and Charge histograms from the board with 12 SiPMs connected in active ganging (in 6 pairs)





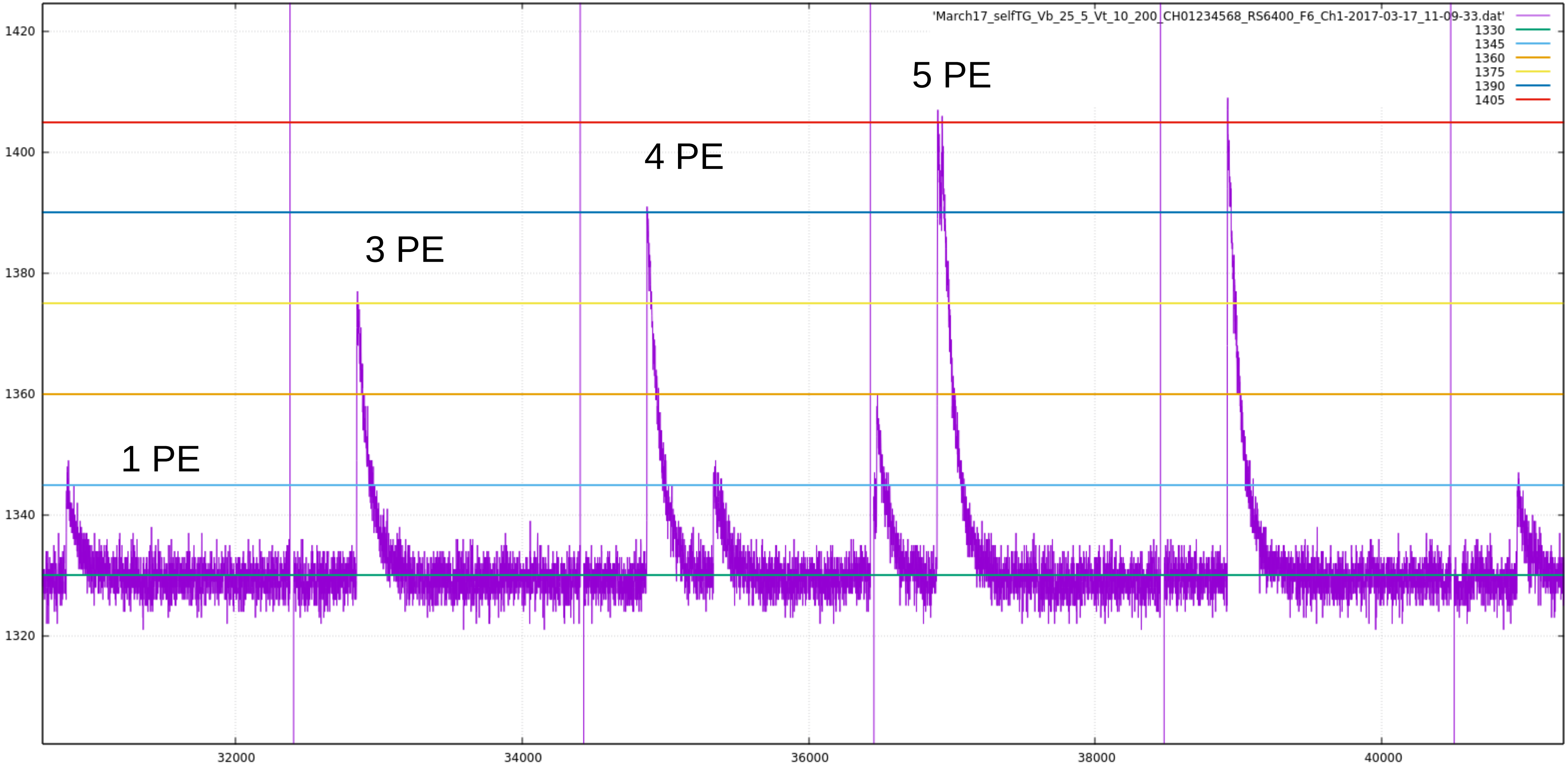
We can see a good resolution in terms of photons number





Active Ganging

Here we can see a set of waveforms to have an idea of the active ganging board PE resolution



TallBo experiment: LAr test

TallBo experiment at Fermilab:
a LAr dwear where ARAPUCA with passive ganging boards and active ganging boards are been tested in LAr using event form cosmic muons and an alpha source Am 241

Previous version of our devices was calibrated Summer 2017. Now I am waiting data about the the latest devices version taken in the Fall 2017 run just finished.