Advancements in SiPM Technology for Cryogenic Detectors for Dark Matter and Neutrino Research

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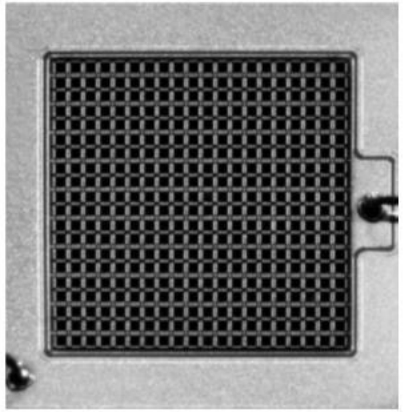
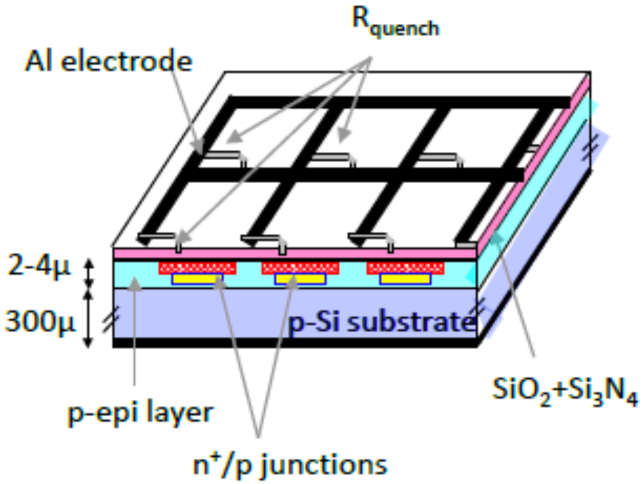
Content

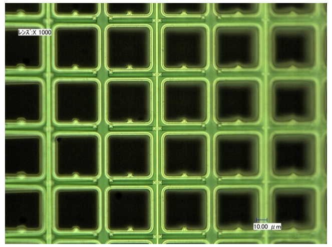
- SiPM and its advantages
- SiPM characteristics in cryogenic environment
- Experiments: past, in construction and future detectors

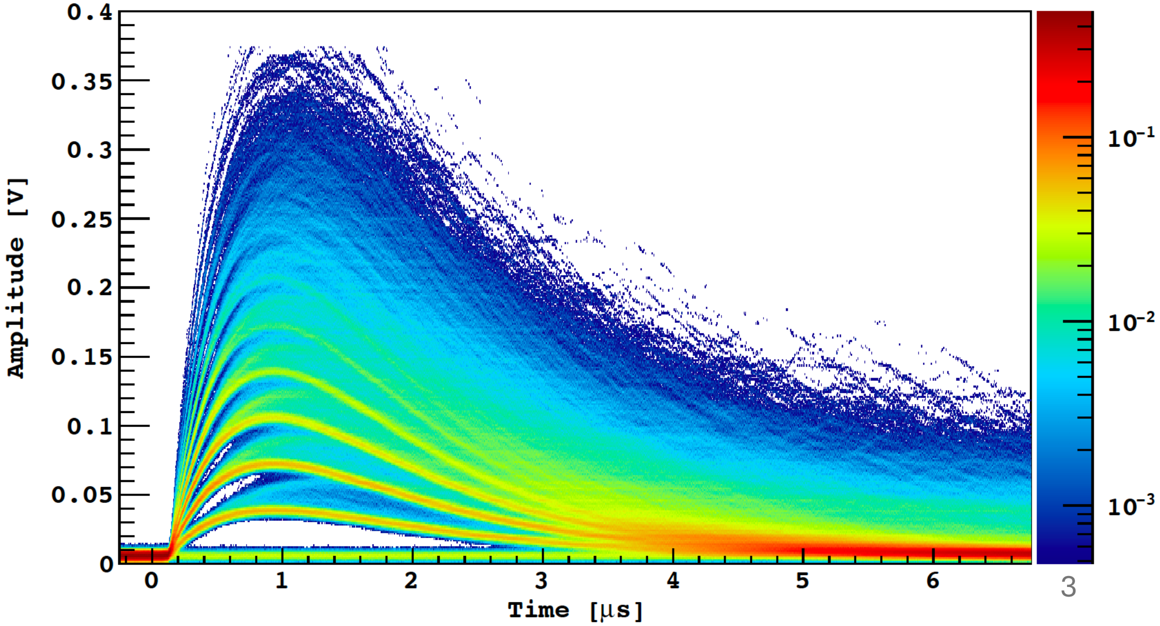
Silicon Photomultipliers (SiPM)



- **2D array** of single photon avalanche diodes (SPADs)
  - PN junctions operated in **Geiger mode**: reverse bias above breakdown voltage
  - SPAD signal is saturated, same signal when fired by photon
- SPADs tipically connected in **parallel**
  - Parallel through a decoupling resistor which is aslo used for **quenching** avalanches in single cells
  - Each array of SPADs is readout as one channel
  - Signal is proportional to number of photons detected (SPADs fired)







Excellent photon counting…and many other advantages

SiPMs in last 30 years becomes very popular in particular physics:

- Compact and mechanical robust
- Low bias voltage (<100 V)
- High Gain and high Quantum Efficiency (~50%)
- Geiger mode operation provides sub-nanosecond timing
- Excellent SNR, high single photon resolution
- Low radioactivity
- Not damaged when exposed to light
- No aging

Under improvements

- Lower dark rate (continuously improving)
- Lower optical cross-talk
- Improving VUV sensitivity
- Increasing size
- Radiation hardness

Photodetection and Noise sources in SiPMs

Signal photons:

- Electron-hole pair creation in high-field region causing avalanche
- E-h creation by photon strongly wavelength, maximum efficiency@ about 400 nm, decreasing in the UV, VUV

Dark Count Rate:

- Thermal generated e-h pair
- Quantum tunneling generated e-h pair

Internal Correlated avalanches:

- After pulsing: carrier trap (in crystal impurities) during primary avalanche and release
- Direct cross-talk: photon from primary avalanche reach neighbouring cells

External cross-talk:

- The avalanche in one SiPM generate infrared photons that travels and hit another SiPM

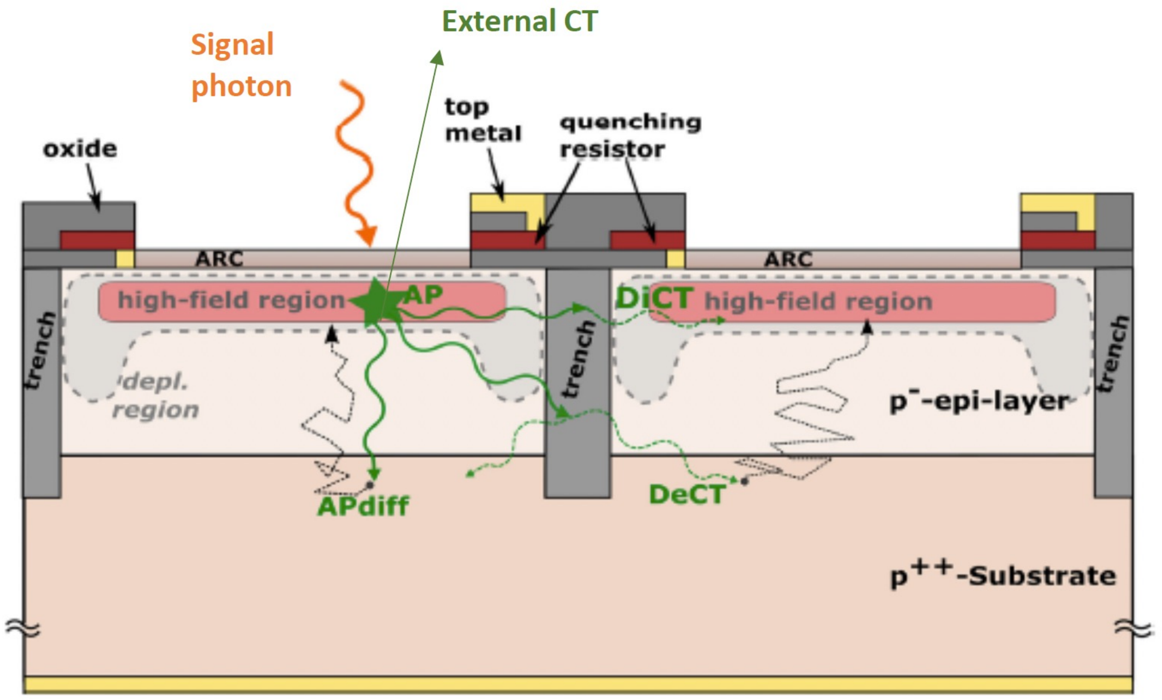


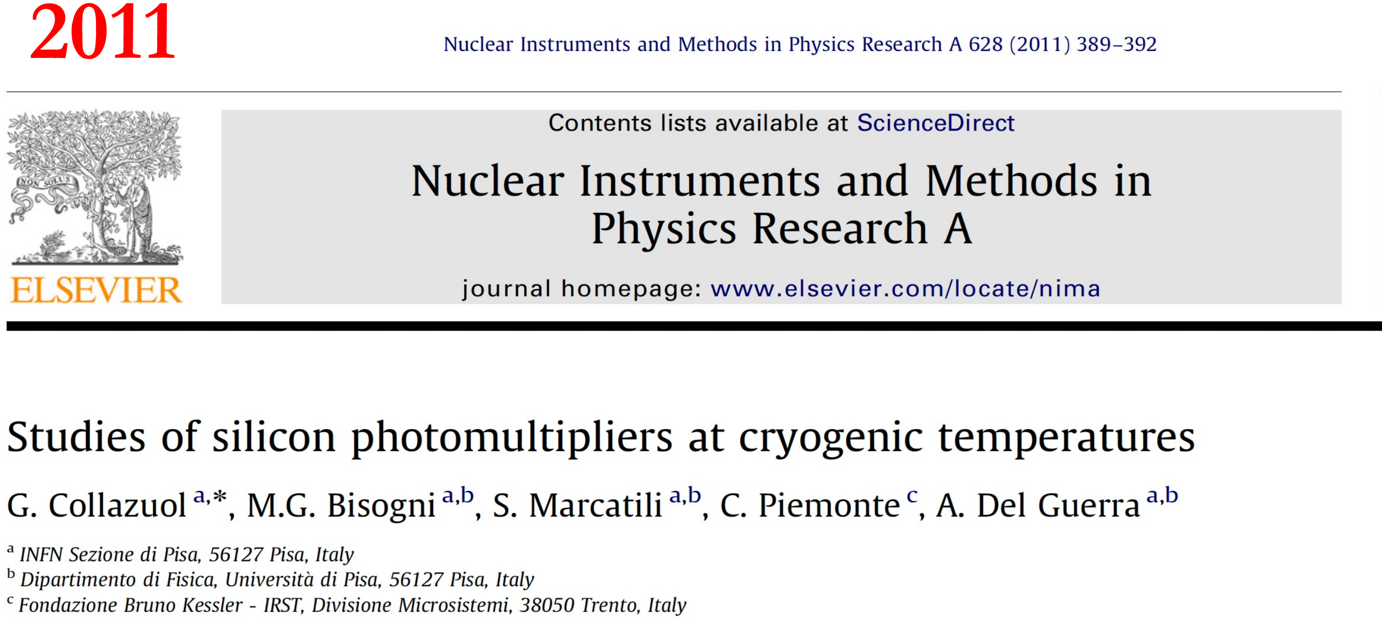
Fig. 1. Schematic representation of the internal structure of FBK Silicon photomultiplier, made in RGB-HD or RGB-UHD technology, with deep trenches between cells (SPADs).

SiPM at cryogenic temperatures

- **SiPM have been very actrattive for dark matter and neutrino experiment operating with liquid nobles**
  - Lower radioactivity budget
  - Extremely low DCR @ low T
  - Excellent photon counting
- **First pioneristic employment in cryogenic environment dates back to 2011**
- Operating at low temperature introduce several changes in SiPM characteristics wrt standard room temperature:
  - **Quenching Resistance**
  - **Signal shape**
  - **Breakdown Voltage**
  - **Dark Count Rate**
  - **Crosstalk and afterpulses**
  - **PDE**

Some pioneristic studies

2011



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Studies of silicon photomultipliers at cryogenic temperatures

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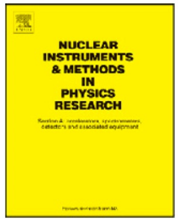
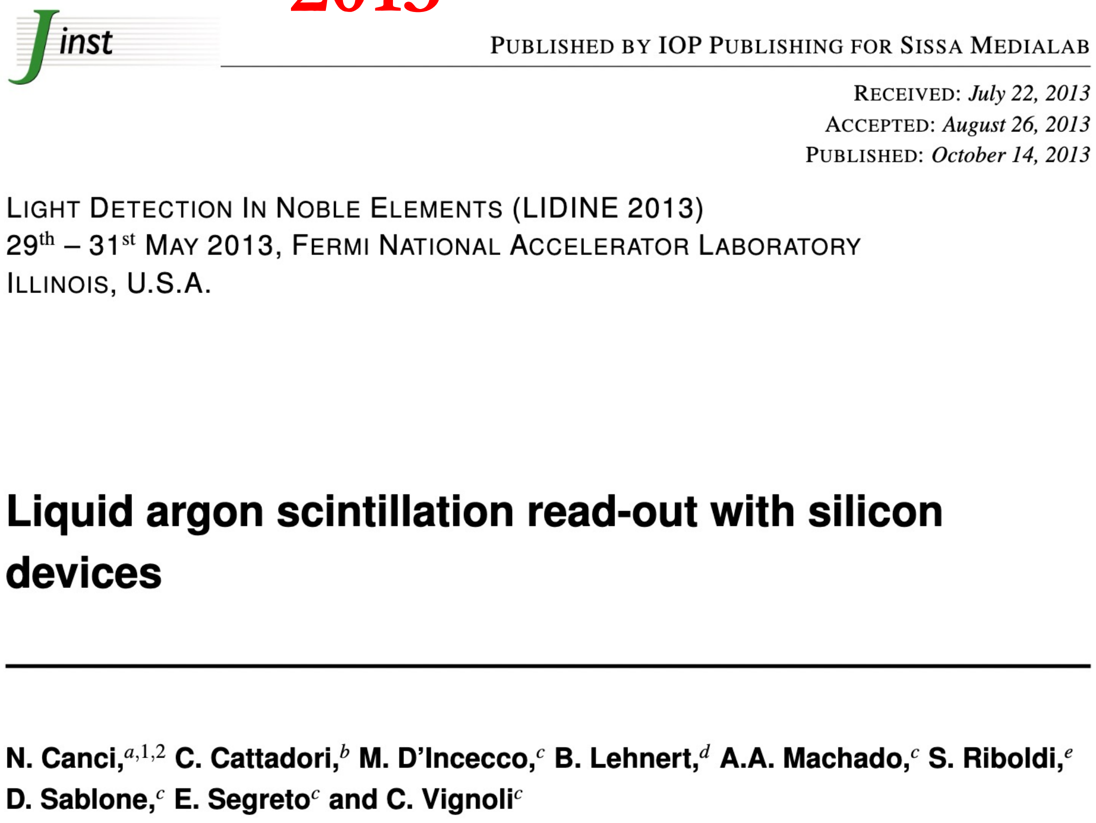


2013



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Light Detection In Noble Elements (LIDINE 2013)
29th – 31st May 2013, Fermi National Accelerator Laboratory
Illinois, U.S.A.

Liquid argon scintillation read-out with silicon devices

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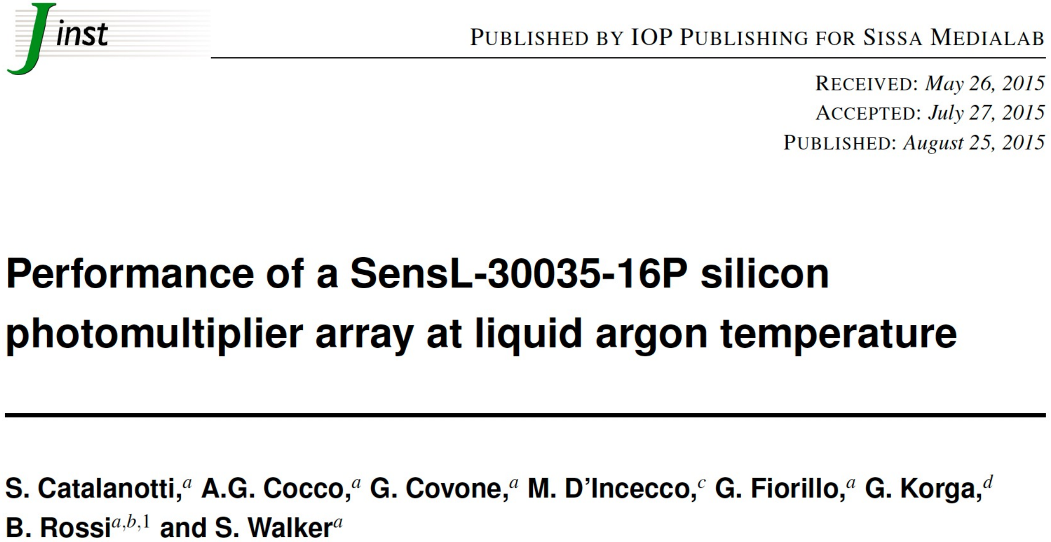
2015



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Performance of a SensL-30035-16P silicon photomultiplier array at liquid argon temperature

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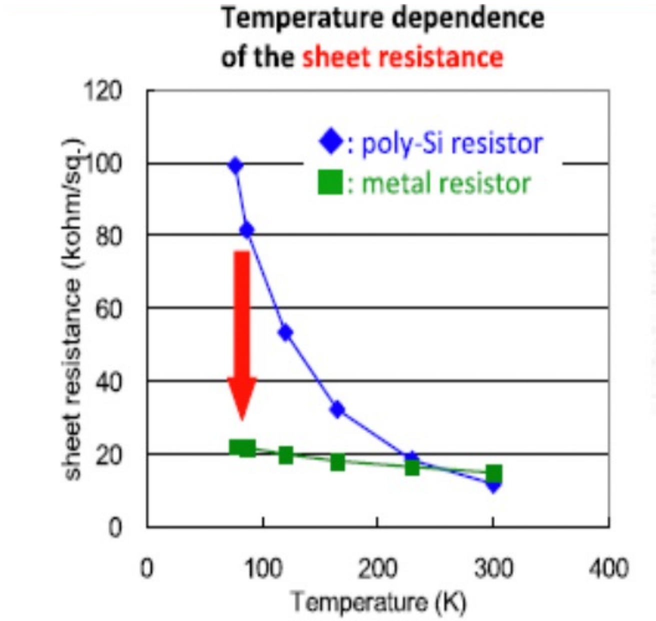
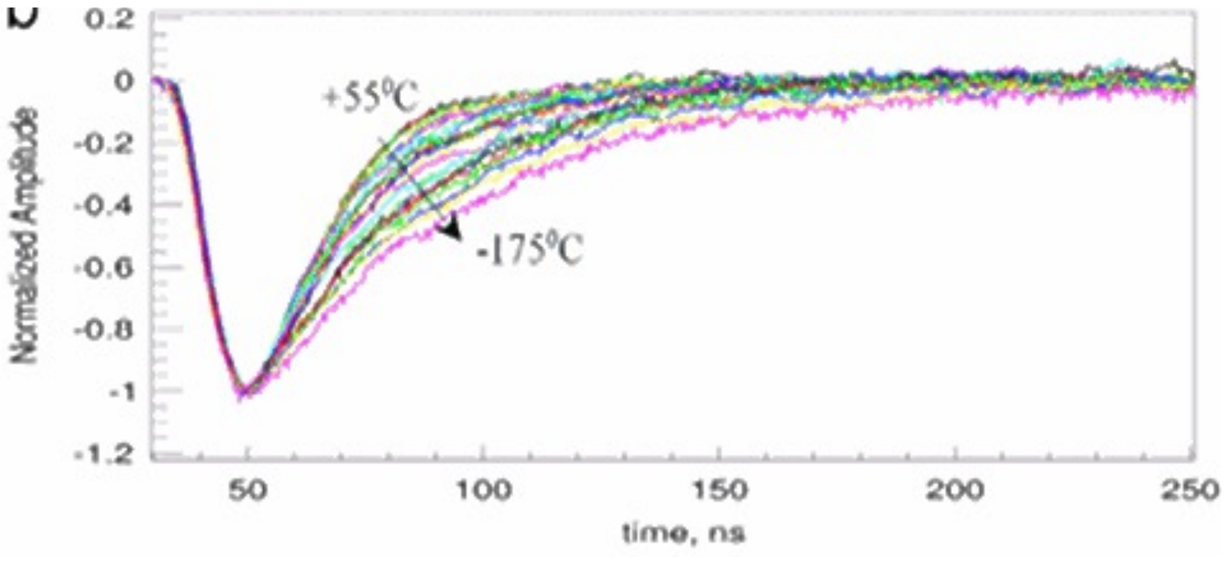
Quenching resistance and signal shape

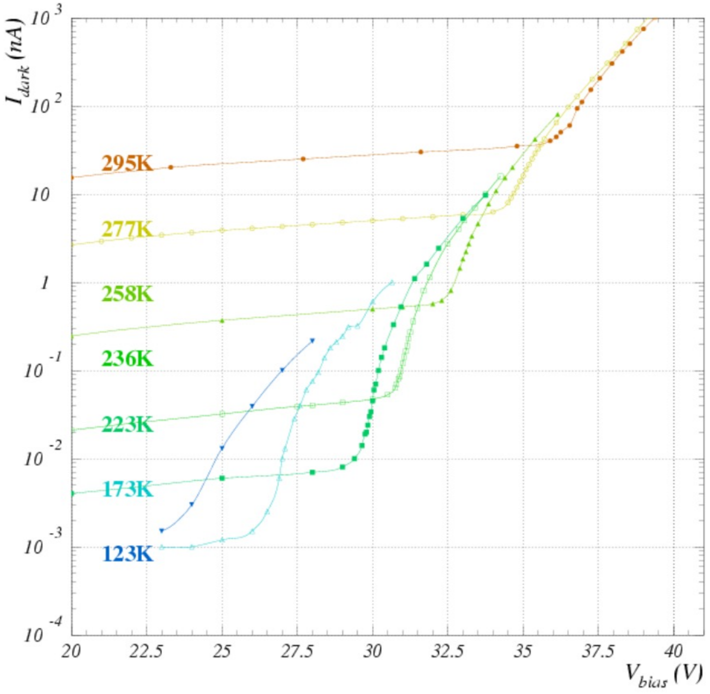
- The R_Q **increase with decreasing temperature** (from 0.1MΩ to 1 MΩ going from room to LN temperature)
- Higher R_Q and **lower is the amplitude of the single photoelectron**
- In addition, together with the junction capacitance, it affects the signal recovery **(long tail)**
- In addition, the Joule heating could reduce R_Q during fall time and this could inhibit the quenching process



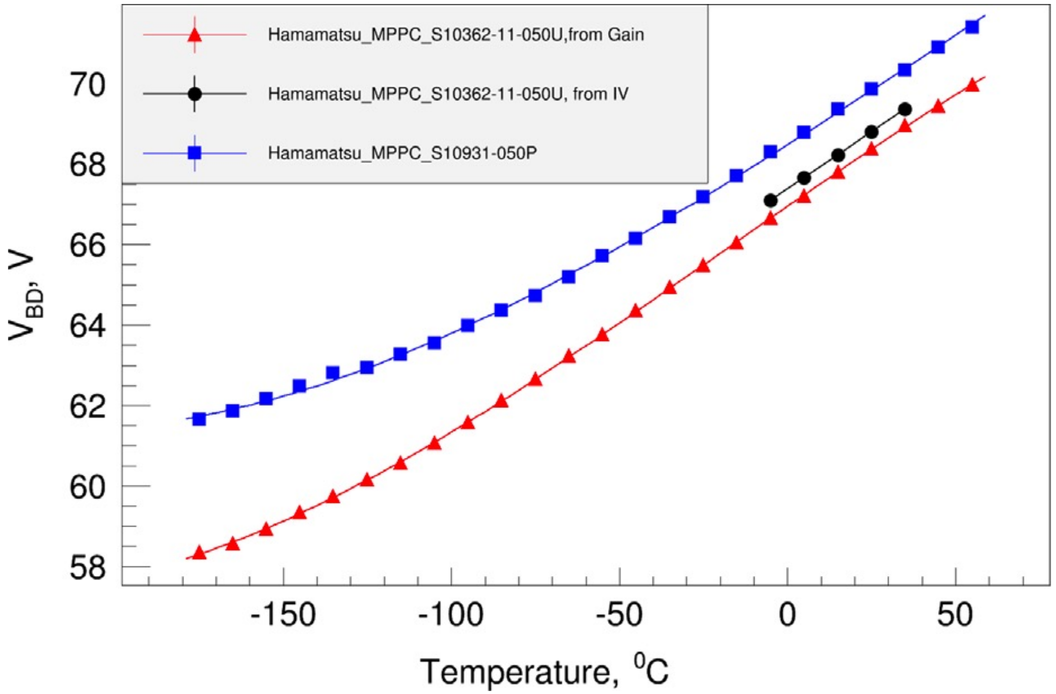


Breakdown voltage

- The breakdown voltage **decrease with decreasing temperature**
- This is due to larger carrier mobility-> larger impact ionization
- Decreasing of the V_{BD} is linear for a wide range of temperature

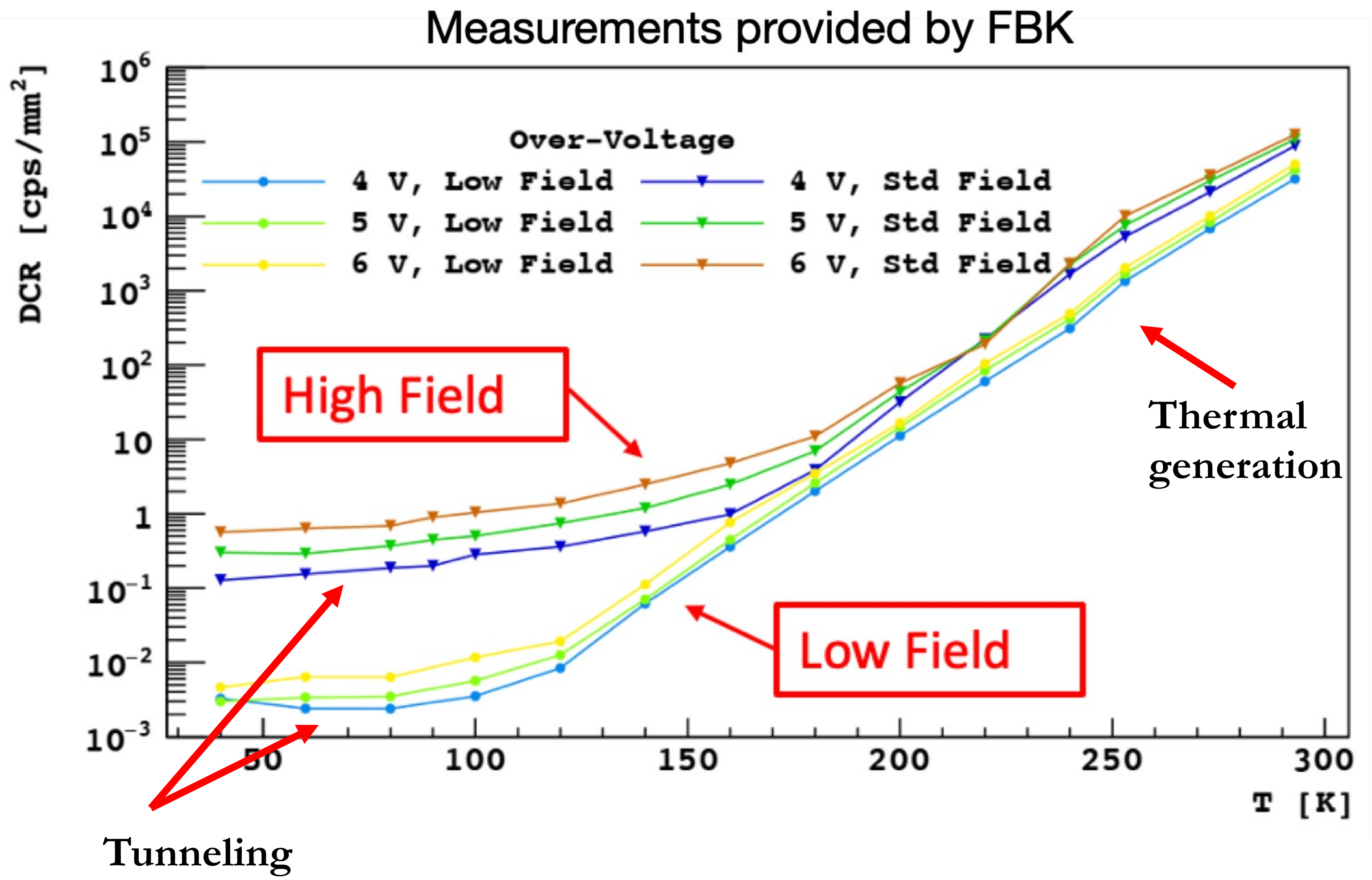


VBD vs T for a FBK SiPM



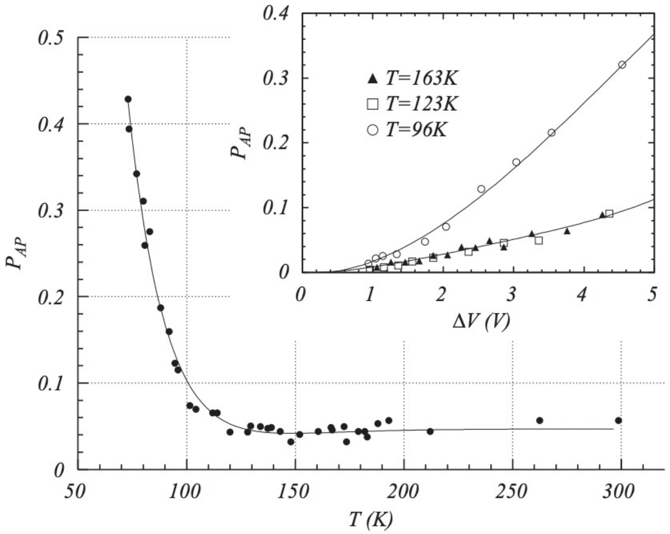
Dark Count Rate

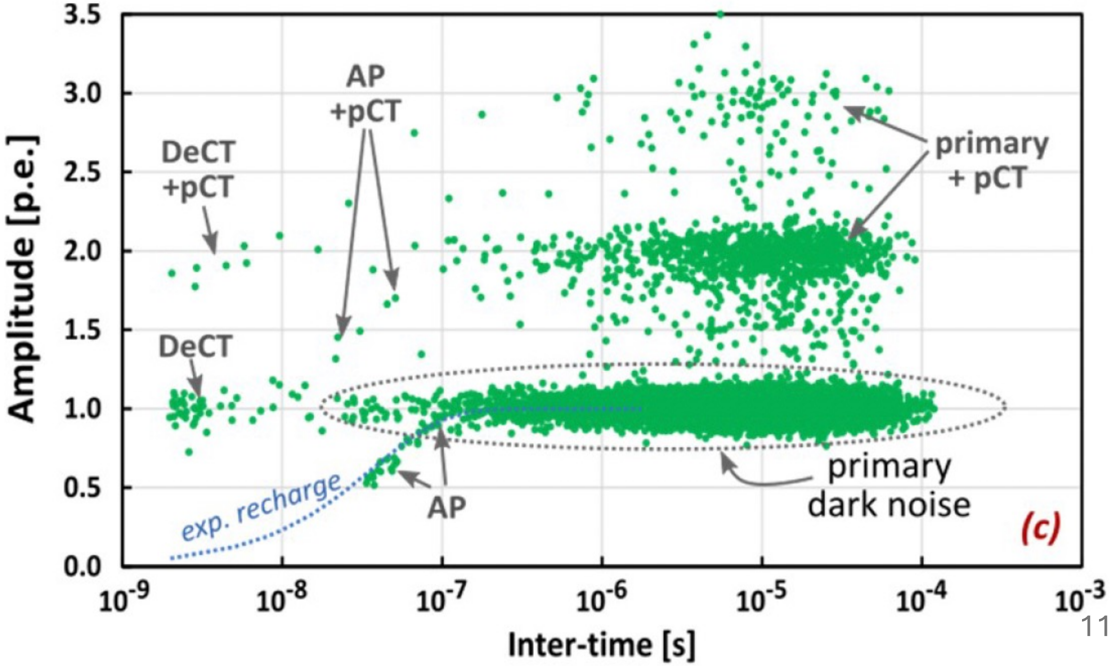
- Spontaneous avalanches can occour due to thermal generated charged carrier or due to quantum tunneling
- Dark events results in output that is indistinguishable from that obtained from absorption of a photon
- Going down in temperature (below 120K), tunneling contribution become more important than thermal generation
- Strong R&D effort performed by FBK within DarkSide-20k experiment to reduce the overall DCR up to mHz/mm^2



Secondary pulses: afterpulses and cross-talk

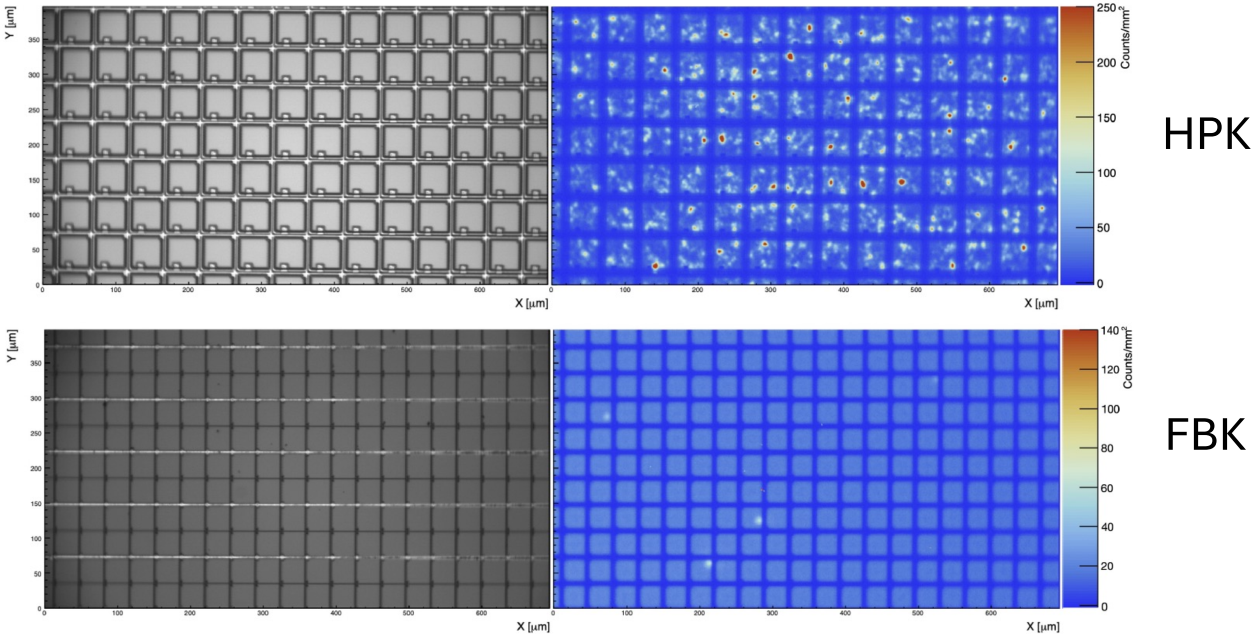
- The afterpulse probability is quite stable with temperature up to 110 K
- Down 110K start rising significantly, probably due to new traps become active related to carrier freez-out
- This behaviour of AP is not confirmed for all SiPMs models
- The probability of cross-talk do not have a significative variation at cryogenic temperatures

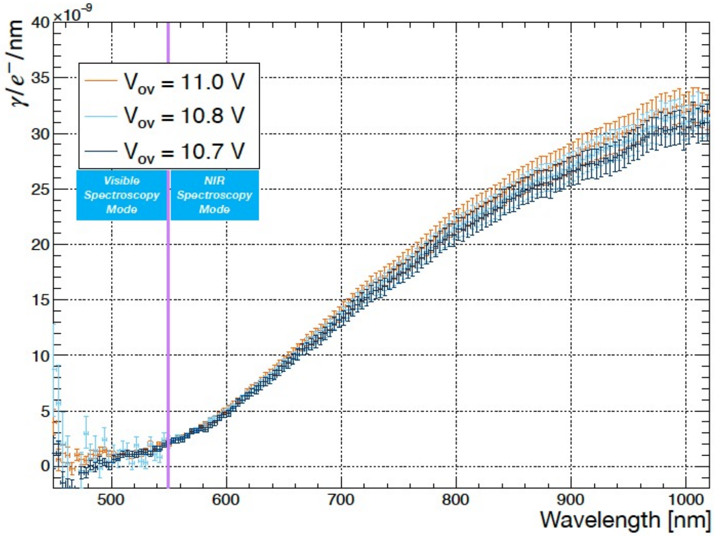




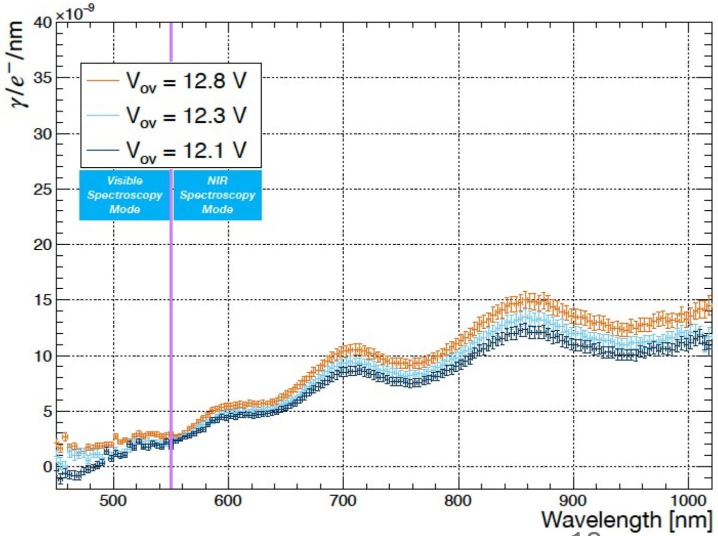
External crosstalk

- eCT could be critical in detectors with large coverage and looking for rare events
- Measured at TRIUMF with emission microscopy images and spectral analysis
- no significative variation with temperature of this effect is observed





(a) HPK VUV4



(b) FBK VUV-HD3

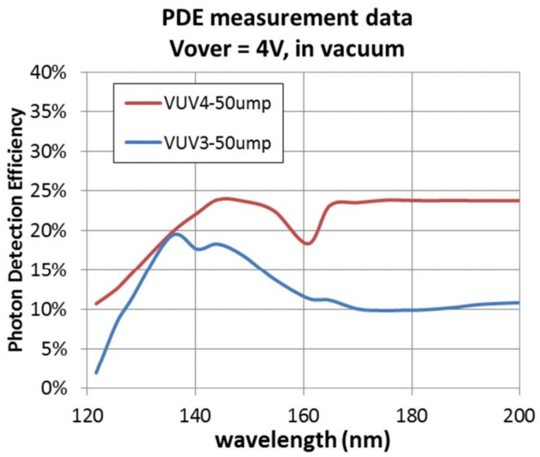
Photon Detection Efficiency and VUV sensitivity

No sensitive to VUV

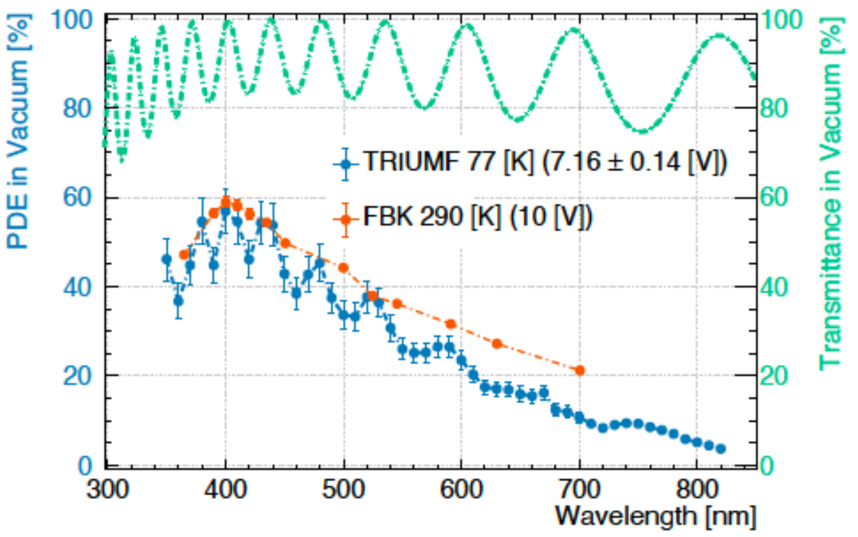
- Need for WLS as for example TPB or PEN to convert VUV light in visible

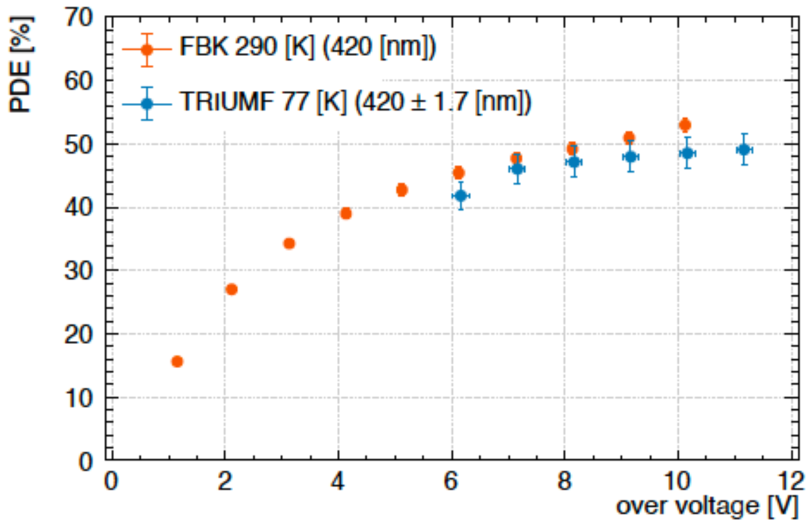
VUV sensitive

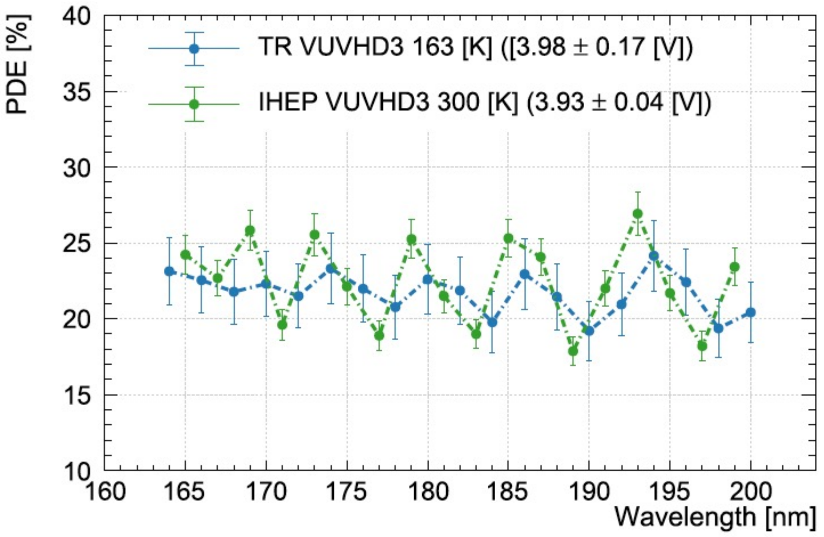
- high field region very close to the surface
- Developed by FBK and Hamamatsu

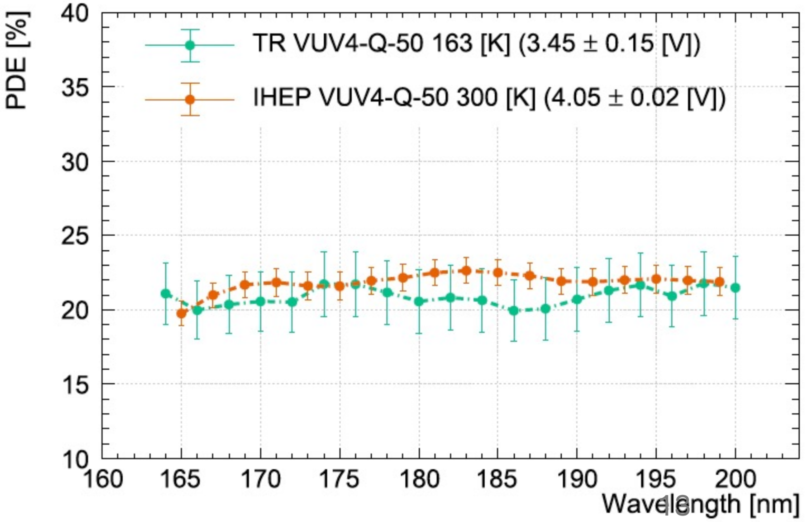


DarkSide-20k FBK@OV=7V









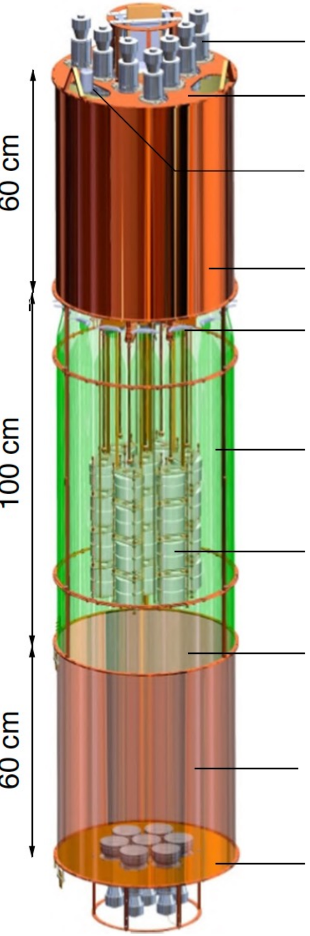
Experiments using cryogenic SiPMs.
(past, currently running and future detectors)

- **GERDA Phase II**
- **LEGEND-200**
- **MEG II**
- **ProtoDUNE** –DUNE Photon Detection System validation
- **DarkSide-20k**
- **DUNE FD1 and FD2**
- **nEXO**
- **LEGEND-1000**

GERDA Phase II

LAr veto system in GERDA Phase II

- 405 fibers readout at both end by 90 SiPMs



nine 3" PMTs (R11065–20)

top plate (Ø 49 cm)

calibration source entering slot in top plate

copper cylinder (wall thickness 0.1 mm)

SiPMs

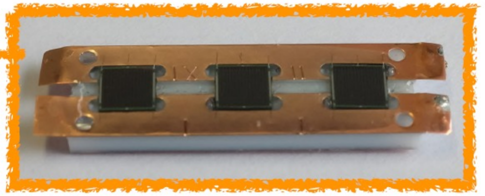
fiber curtain coated with wave length shifting TPB

Ge detector array

Tetratex lining soaked in TPB

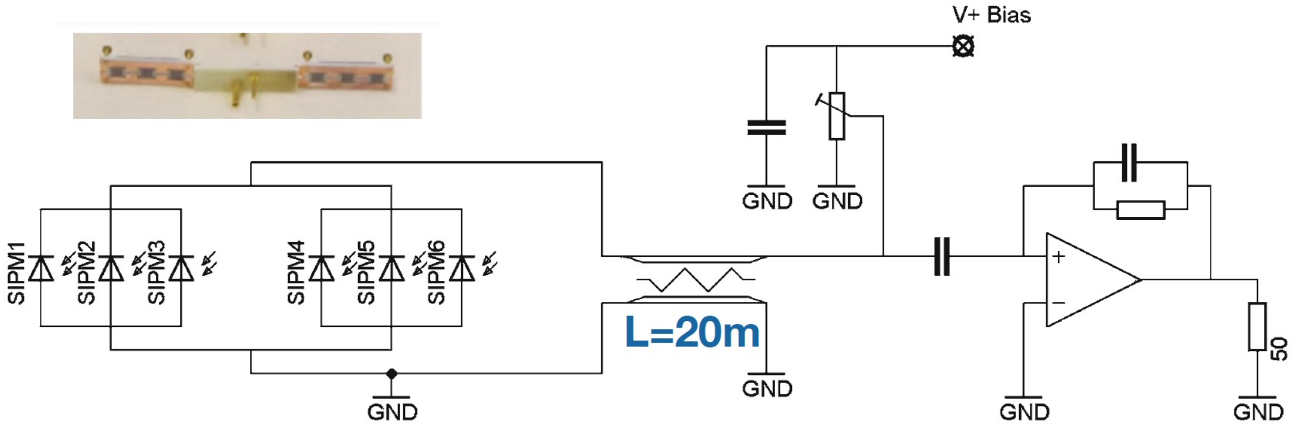
copper cylinder

bottom plate with seven 3" PMTs



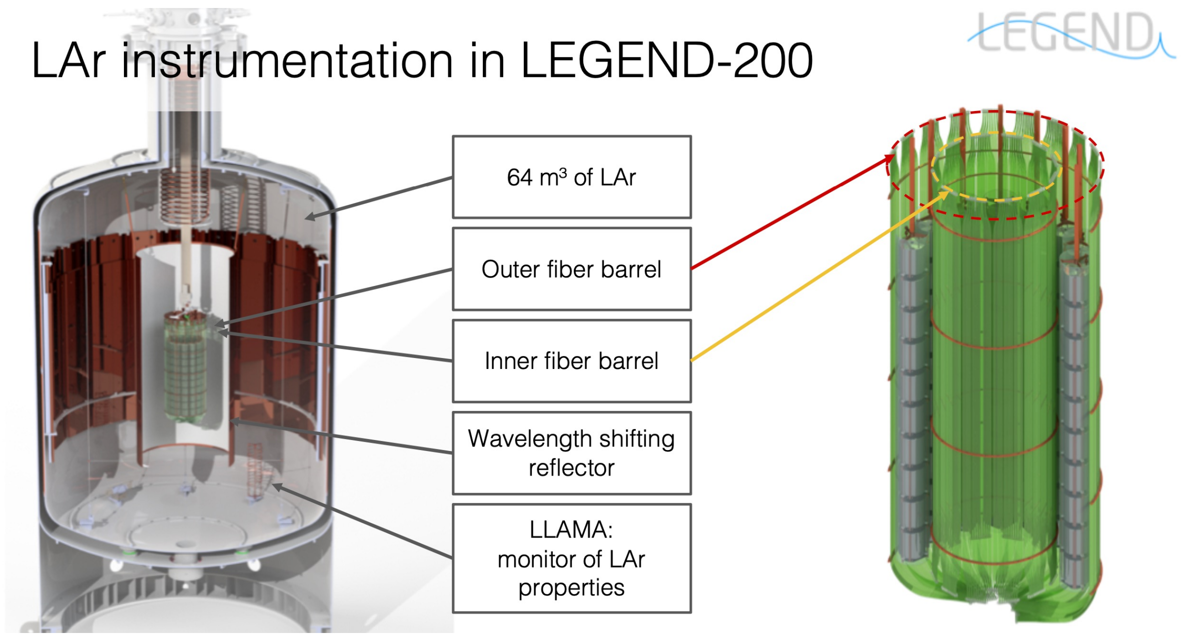
6 SiPM (3x3 mm2) connected in parallel

- no amplification in LAr



LEGEND-200

Light readout instrumentation deployed into the scintillating liquid argon (LAr) volume surrounding the Ge detectors



LAr instrumentation in LEGEND-200

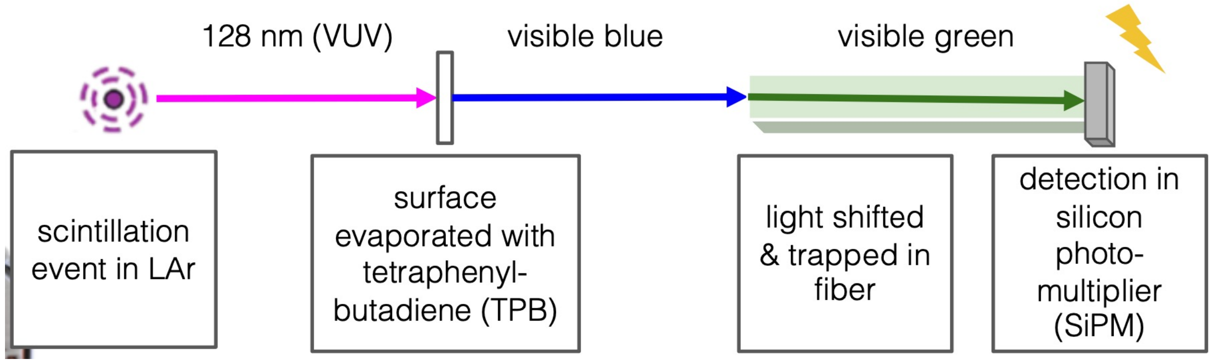
64 m³ of LAr

Outer fiber barrel

Inner fiber barrel

Wavelength shifting reflector

LLAMA: monitor of LAr properties



128 nm (VUV)

visible blue

visible green

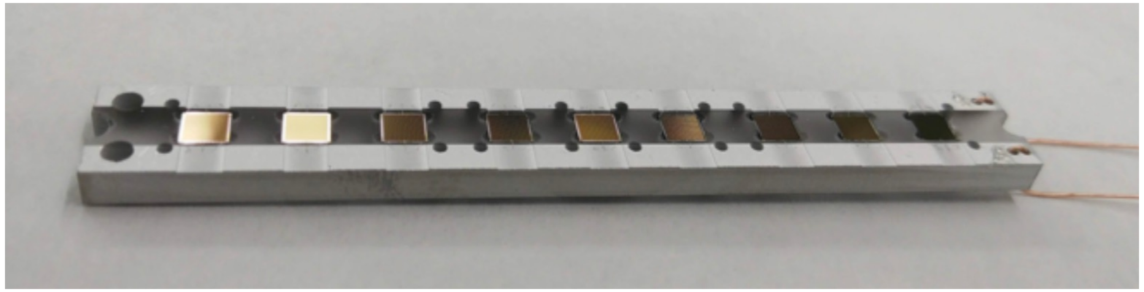
scintillation event in LAr

surface evaporated with tetraphenyl-butadiene (TPB)

light shifted & trapped in fiber

detection in silicon photo-multiplier (SiPM)

- Fibers (Saint Gobain BCF 91A) arranged in 2 barrels
- Outer barrel surrounded by a wavelength-shifting reflector TPB-coated Copper-Tetratex foil
- 20 / 9 modules for outer / inner barrel
- Read out at both ends by SiPM arrays



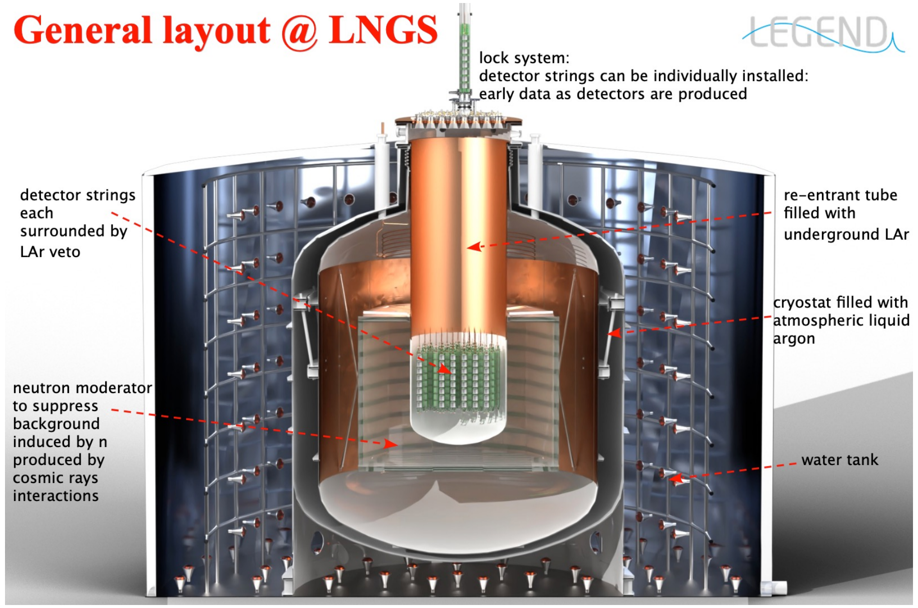
- Ketek PM33100 3x3 mm^2 SiPMs used
- 9 SiPMs mounted on one module and read out in parallel
- Suprasil-1 substrate with aluminum traces
- 58 SiPM arrays:
  - 18 arrays mounted on the inner barrel
  - 40 arrays mounted on the outer barrel

LEGEND-1000

LEGEND-1000: Light readout for Inner and Outer Liquid Argon Instrumentation (UAr in Inner – AtLAr in Outer)

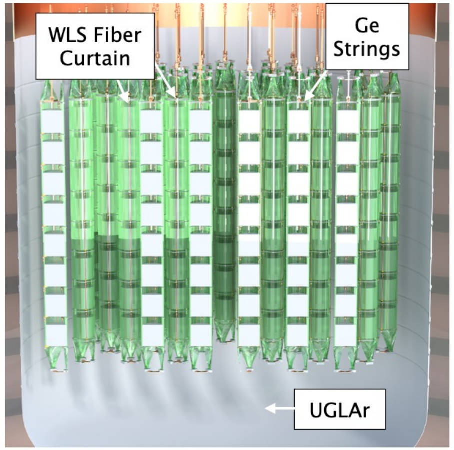
More details in the **R. Brugnera** Presentation «Neutrinoless double-beta decay search with the LEGEND experiment»

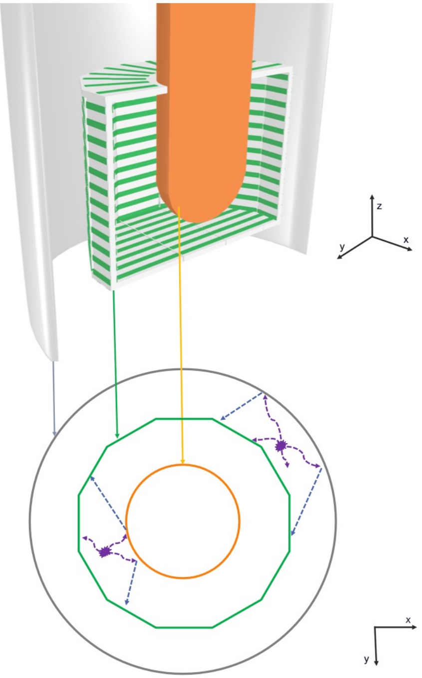
General layout @ LNGS



- 42 strings of Ge detectors
- Legend-200-like Inner veto read-out

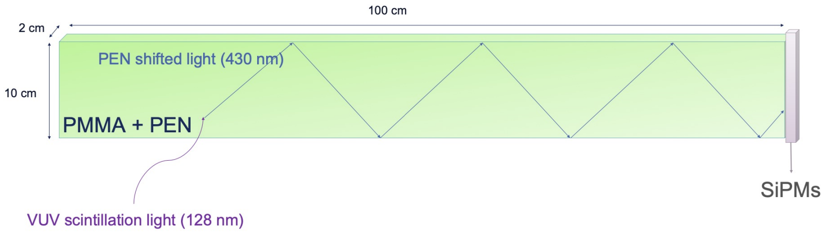
Parameters	Specifications
Operation environment	Air
Output amplitude for 1 PE	$\approx 800\ \mu V$
Low-energy noise (baseline RMS)	$\leq 100\ \mu V$
Bandwidth (3 dB)	> 120 MHz
Fall time	$>50\ \mu s$
Amplification gain	≤ 50 per polarity
Gain stability	$< 1\%$
Output driver	$100\ \Omega$ Differential
Driver load	10 m cable differential @ 100 pF/m
Adjustable bias voltage interval	15 - 31.5 V, in steps of 0.05 V





Refence Design for Outer Veto:

- $100 \times 10 \times 2$ cm^3 light guides made of PMMA and wrapped with a thin foil of PEN or TPB acting as a wavelength shifter for the VUV 128 nm Ar light (or 175 nm of Xe-doped LAr)
- Readout performed at one (or both) end(s) of the guide with 12,6×mm^2 SiPMs



- 12 horizontal light guides on each side of the moderator panel: 288 SiPMs/panel
- Each side of the top and bottom lids equipped with 24 and 45 light guides
- Cryostat surfaces facing LAr, as well as the external reentrant tube wall, lined with a wavelength-shifting reflective foil to assure a high light collection efficiency
- **Total number of SiPMs 5112**
- 852 (426) readout channels assuming groupings of 6 (12) SiPMs

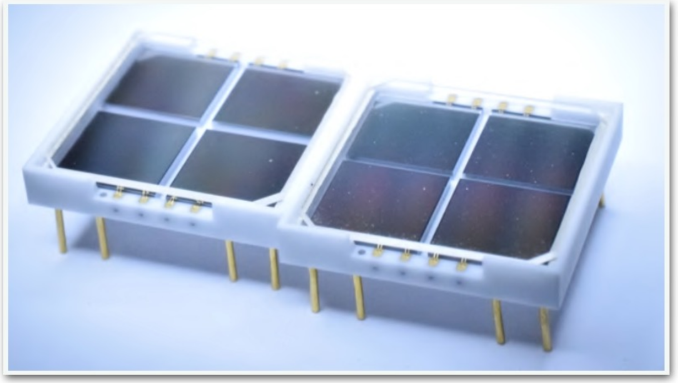
Reference design

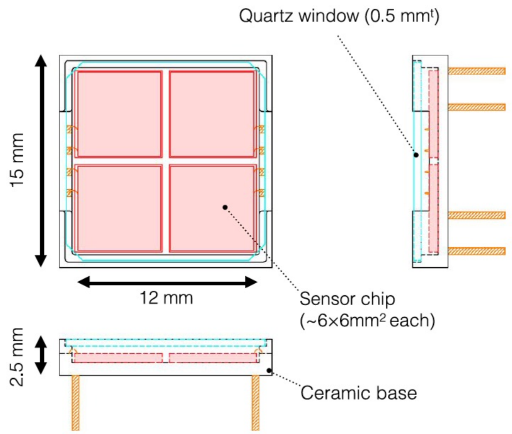
MEG II

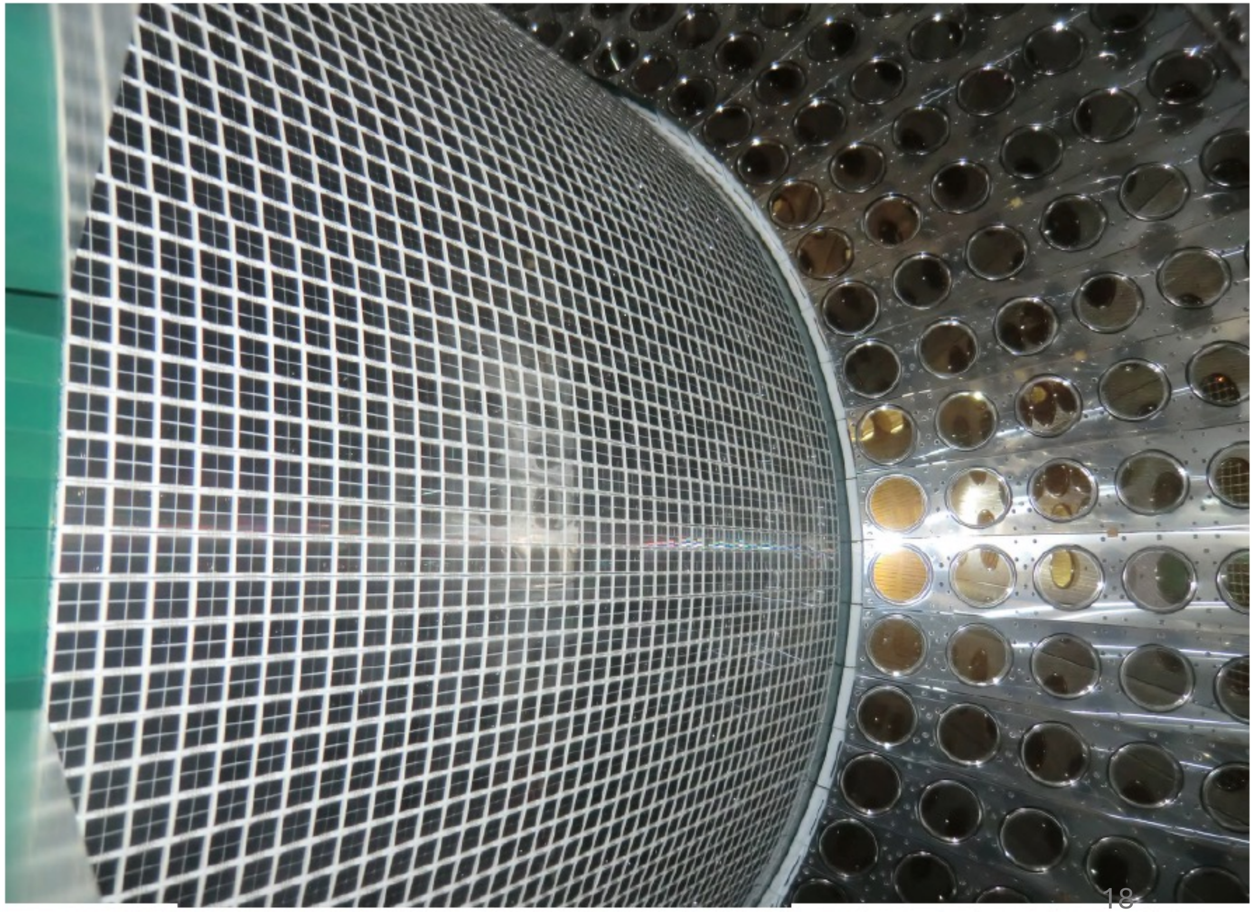
LXe scintillation light detection by VUV-MPPC

- Highly granular scintillation readout with 4092 VUV-MPPCs (139 mm^2 each)
- Covering 0.92 m^2 area (62% coverage)

S10943-4372







MEG II SiPM readout

Requirements and constraints

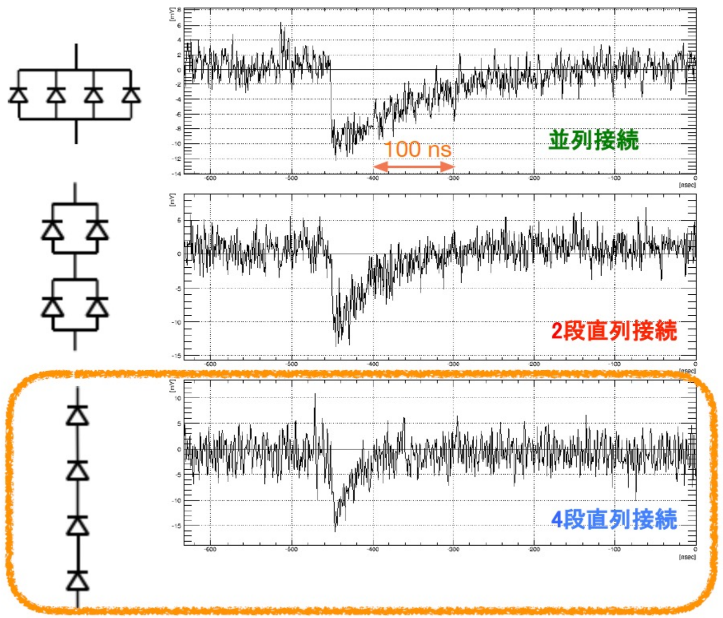
- High granularity
- Need good S/N and high speed
- No amplfication at cryo temperatures

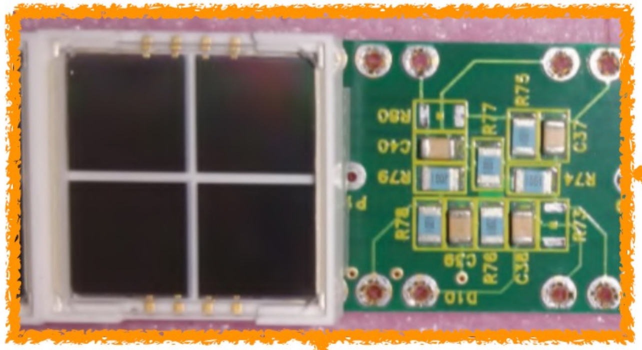
Passive ganging of 4 sensor segments (6x6 mm^2 each)

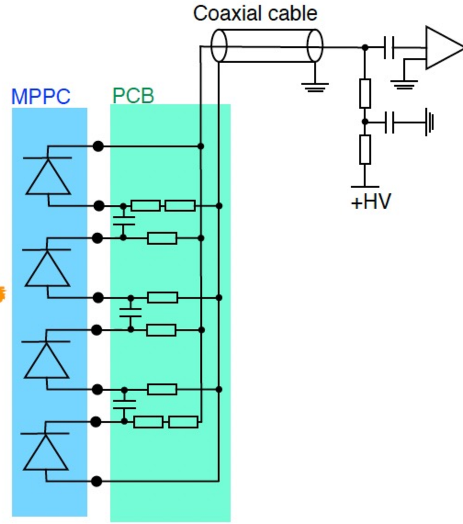
- Series connection for signal
- Parallel connection for biasing

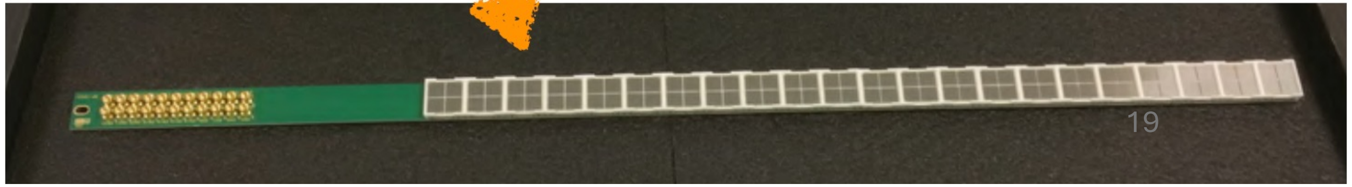
VUV-MPPCs assembled on PCB slabs

- 22 sensors on each PCB
- Precise sensor alignment

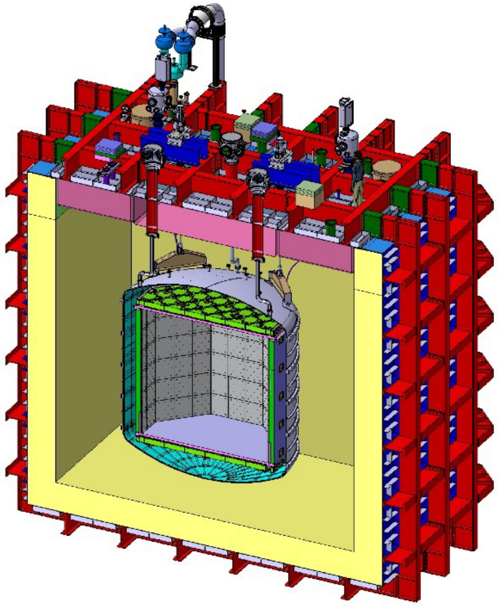








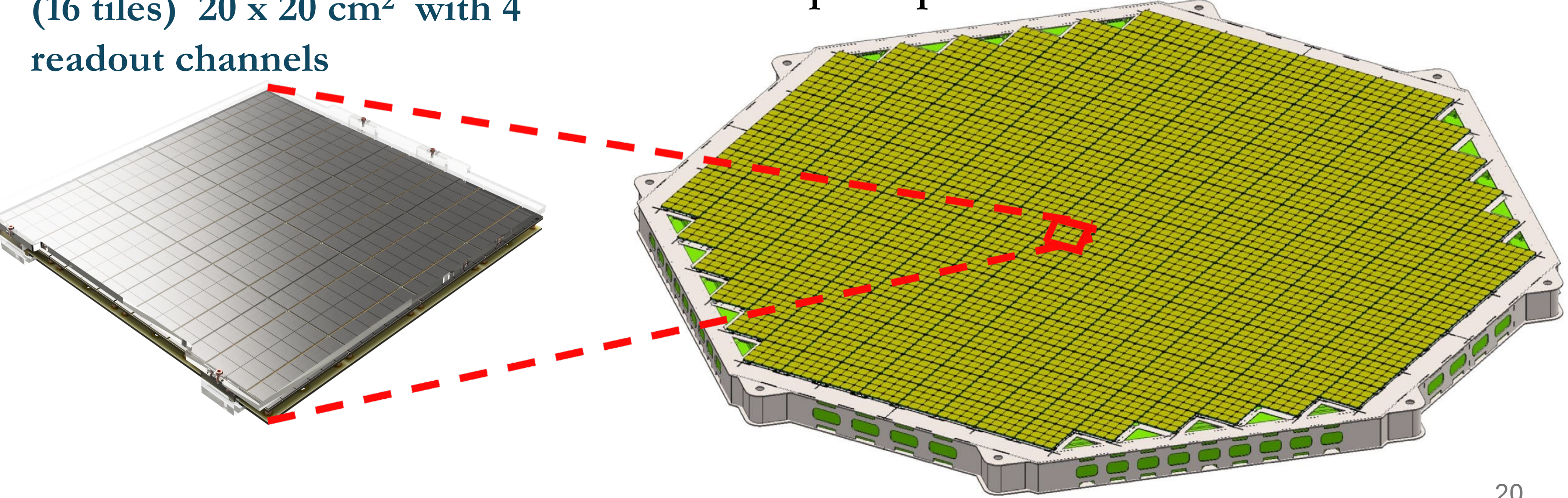
DarkSide-20k: SIPM coverage, design and requirement



- Two phase LArTPC (20t)
- Top and bottom of the TPC vessel covered by Photon Detection Units based on cryogenic SiPMs covering 21 m^2 (2112 channels)
- TPC surrounded by VETO Photon Detection Units covering 5 m^2 (480 channels)

Photon Detection Unit (PDU) (16 tiles) 20 x 20 cm^2 with 4 readout channels

Optical plane with 1056 channels

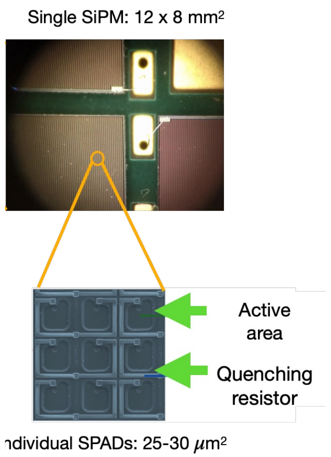


Requirements for Photon detection Units:

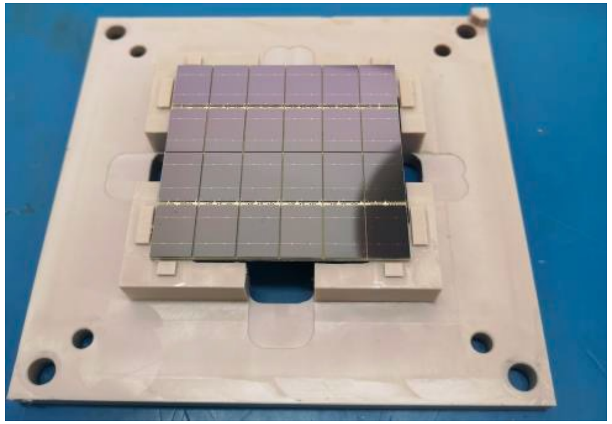
- DCR<0.1 Hz/mm^2 @87K
- PDE > 45%
- SNR>8
- Timing resolution (10 ns)
- Dynamic range >50 PE
- Power consumtion<250mW
- Radiopurtity<mBq

The Photon Detection Unit (PDU)

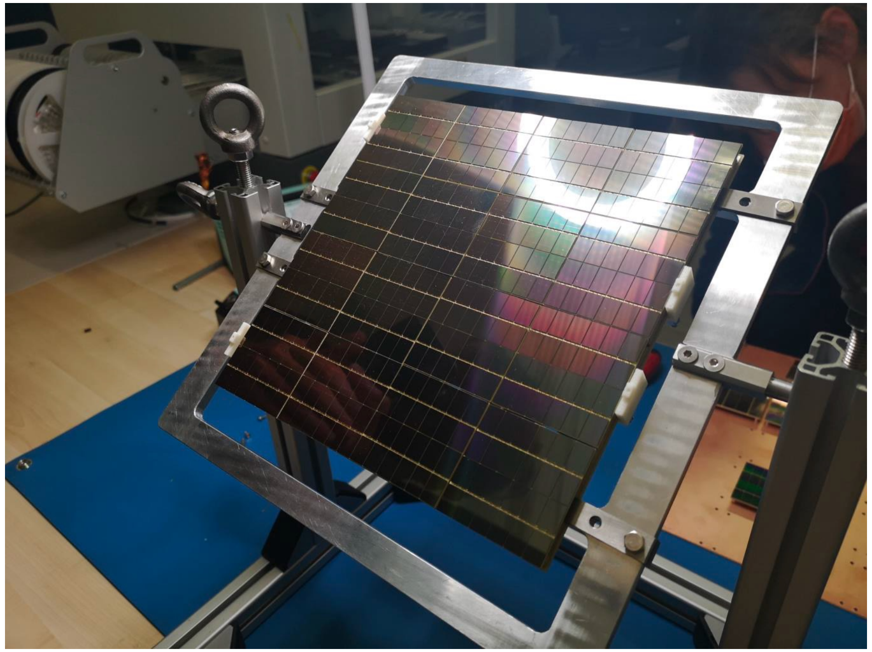
Single SiPM



PDM: 5 x 5 cm²



PDU: 20 x 20 cm²



PDU: 16 PDMs size 20x20 cm². with an overall weight of ~ 0.4 kg.

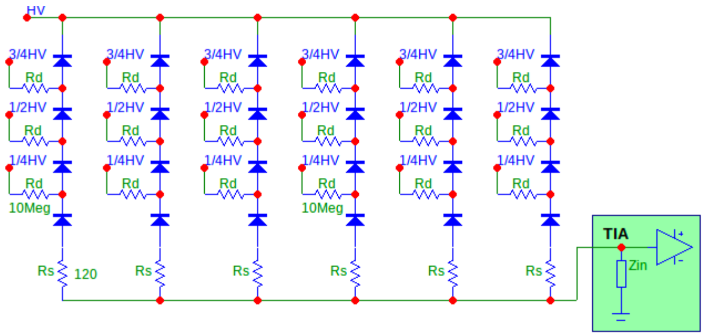
No single PDM readout. Four PDMs (1 Quadrant) are summed in one channel (100 cm²).

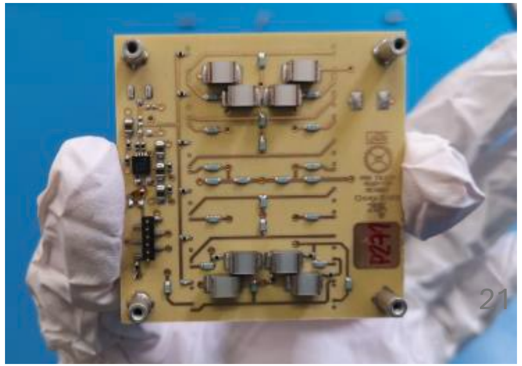
PDU has 4 output channels

Cryogenic front end electronics:

Series/Parallel ganging **4s 6p**

PDM+front-end integrated in a unique PCB

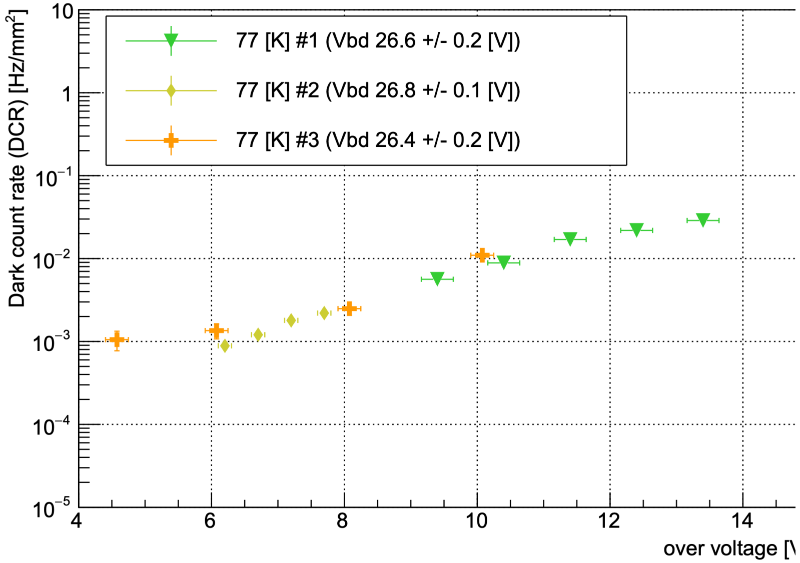




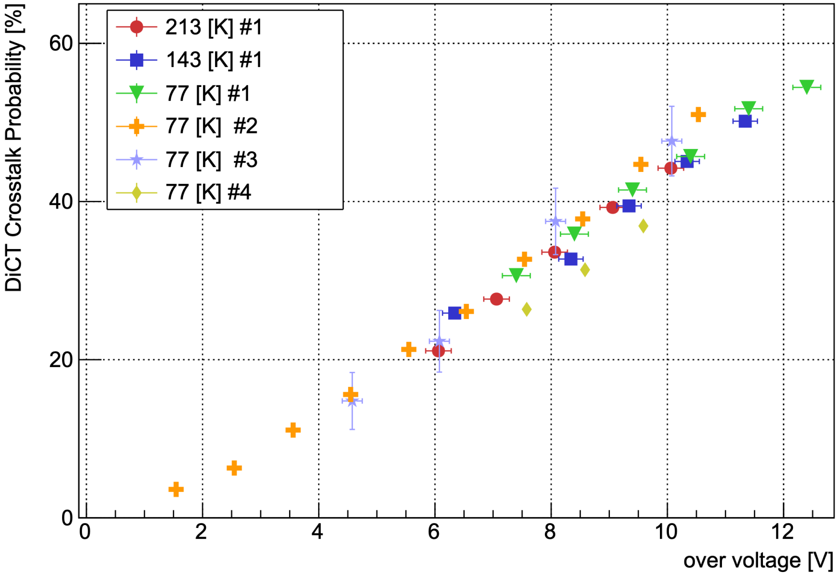
DarkSide-20k SiPM performances

Single SiPM Performaces

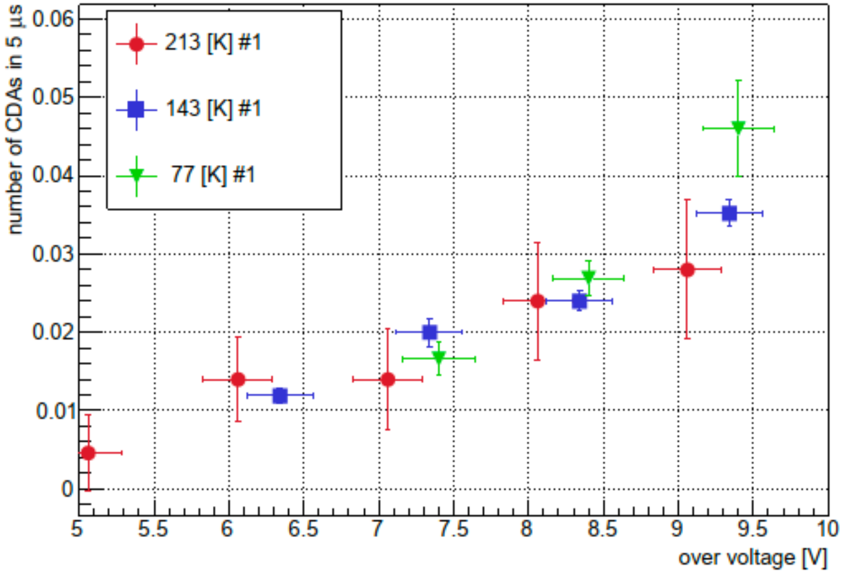
Dark Count Rate



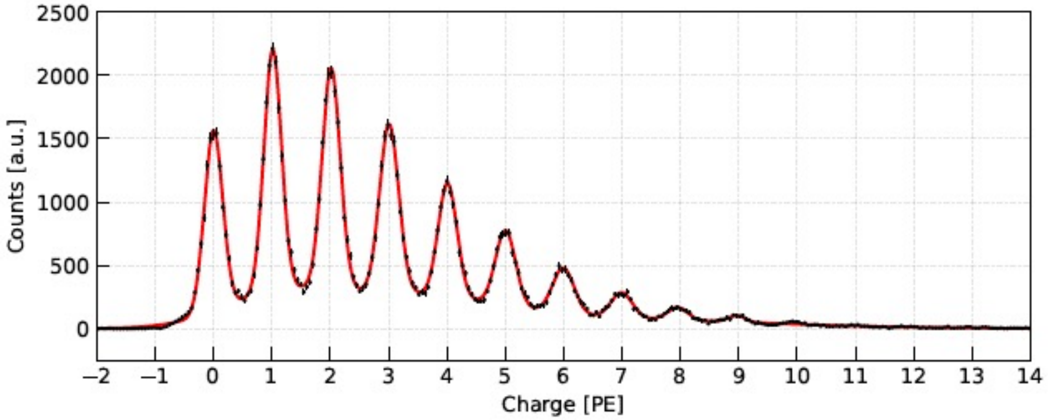
Direct Cross Talk



Afterpulse in 5 us

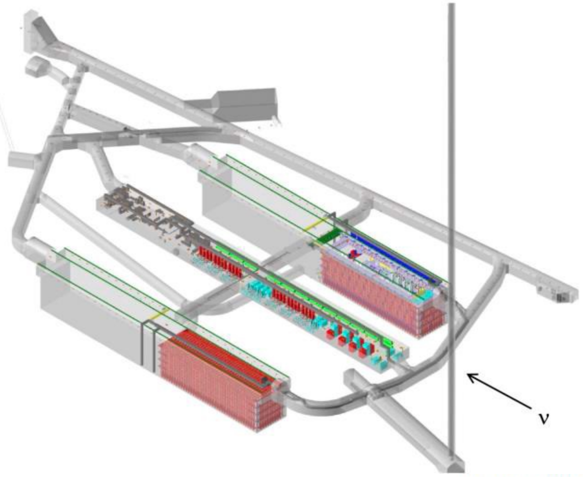


PDU: channel charge spectra

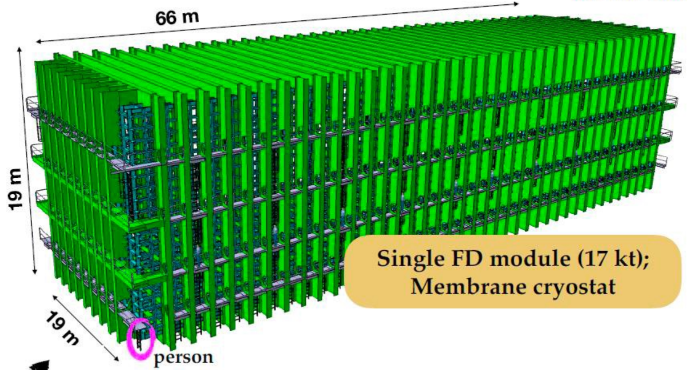


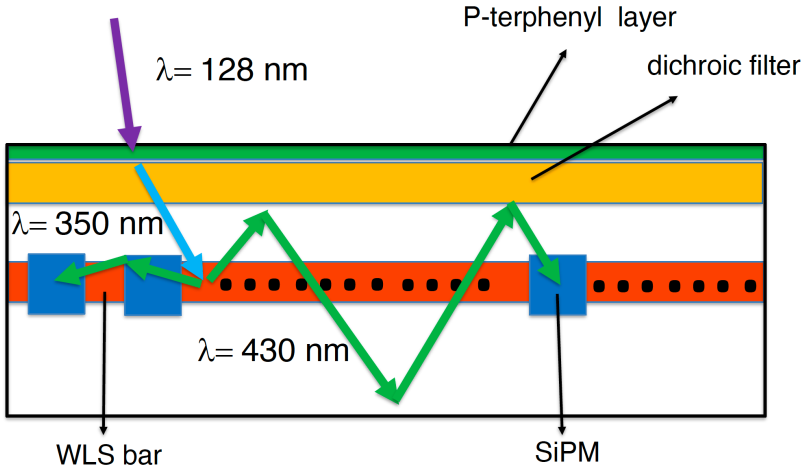
DUNE Photon Detection System

- The Photon Detection System readout of the first 2 LArTPC of 17 kton will be based on SiPM implemented in the X-Arapuca detector
- Scintillation photons after pTP wavelenght shifting are trapped in a high reflective box with dichroic window
- Inside PMMA light-guide drive photons to be detected by SiPMs at light-guide edges



JINST 15 T08010

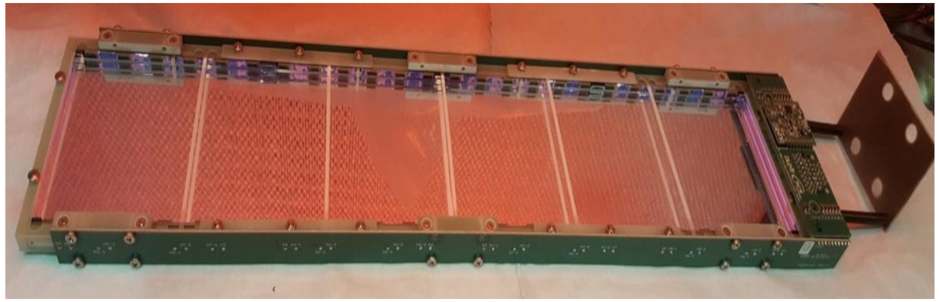


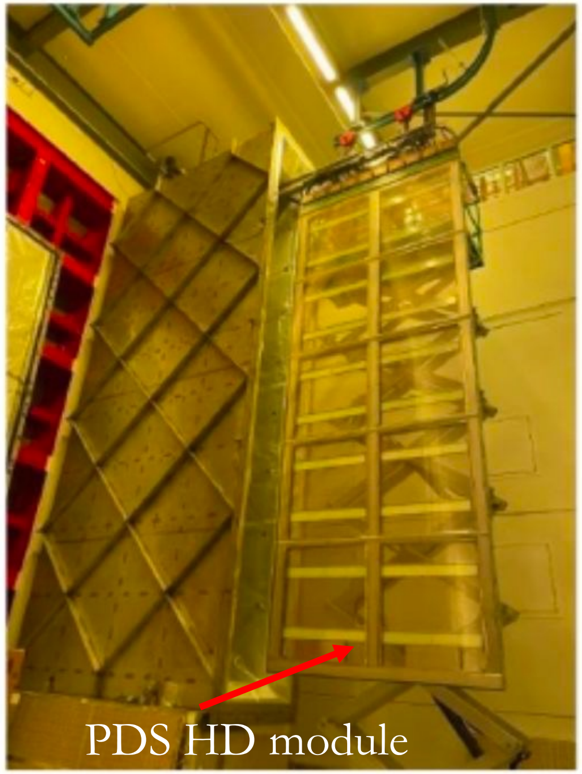


More details in the **G. Botogoske** presentation «DUNE Photon Detection System»

DUNE Photon Detection System (FD1-HD)

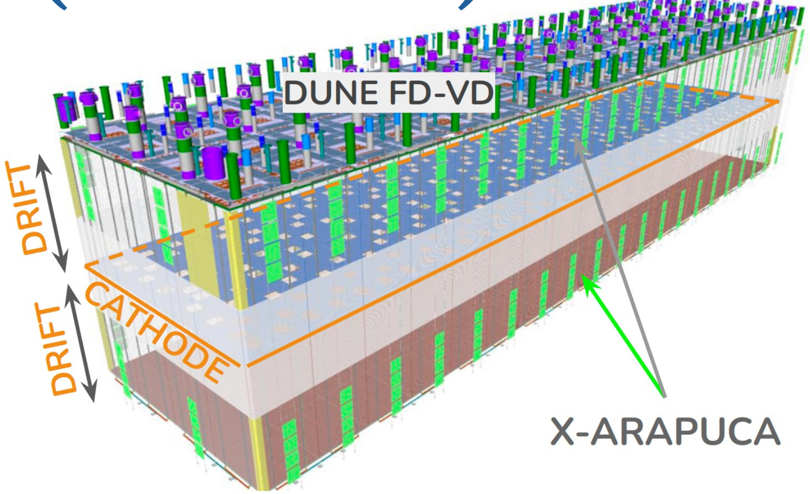
- The unit cell, Supercell (SC), have a rectanguar shape is readout by 48 SiPM (**6x6 mm^2**)
- 6 SiPM on each mounting board, 8 mounting board for SC,
- **1 readout channel (48 SiPM)** for SC
- Passive ganging of 6 SIPM on mounting board
- Active ganging: 8 mounting board (cold amplifier->differential signal)
- A PDS module is made by 4 SuperCell
- 1500 modules for **288000 SiPMs**
- Final version currently running in ProtoDUNE@CERN providing good results



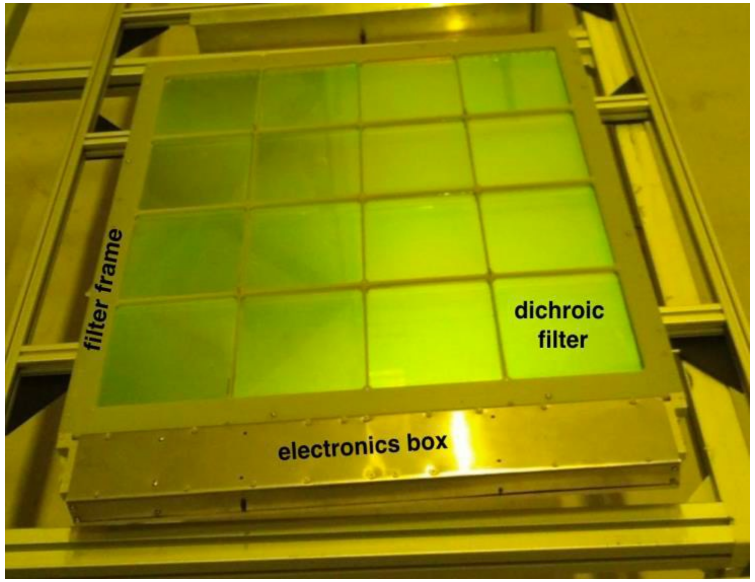

PDS HD module

More details in the **M. Guarise** presentation «Mass test setup for the DUNE FD1 SiPMs characterization and first results»

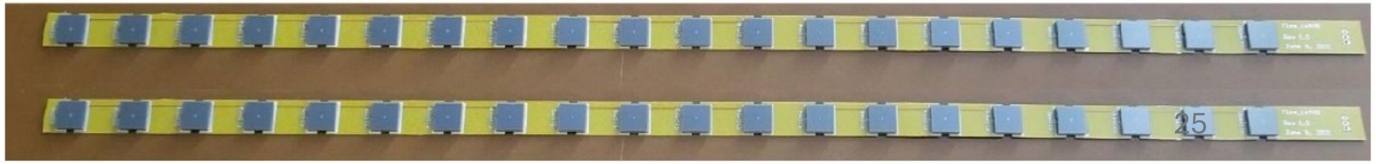
DUNE Photon Detection System (FD2-VD)



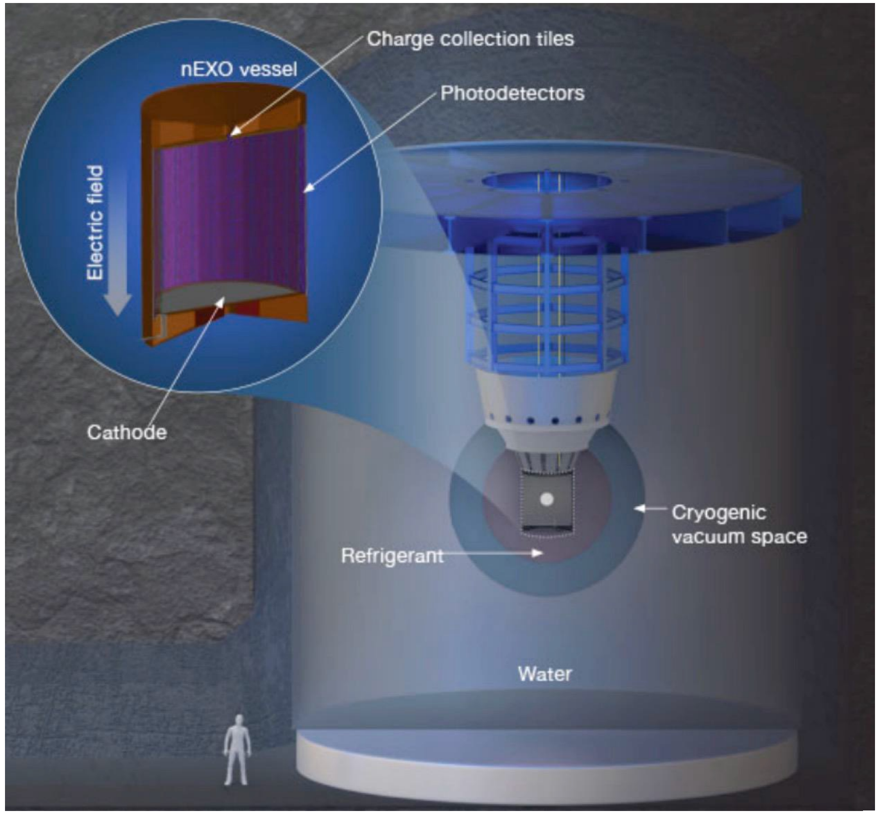
- The unit cell in FD2-VD, Megacell, has a square shape (65 cm x 65 cm) with a big light guide inside and 16 dichroic filters
- They are 352 single side (mounted on lateral cryostat membrane) and 320 double side (mounted on the central cathode)
- The Megacell is readout by 160 SiPM (40 for each side)
- On overall **107502 SiPMs**
- **2 readout channel for 1 Megacell (80 SiPM per channel)**
- 20 SiPMs passively ganged (mounted on flexible boards)
- 4 flex PCB actived ganged
- Cold transimpedance amplifier



Performances of PDS-VD in **S. Corchado** presentation «X-ARAPUCA PDE for DUNE FD-VD»

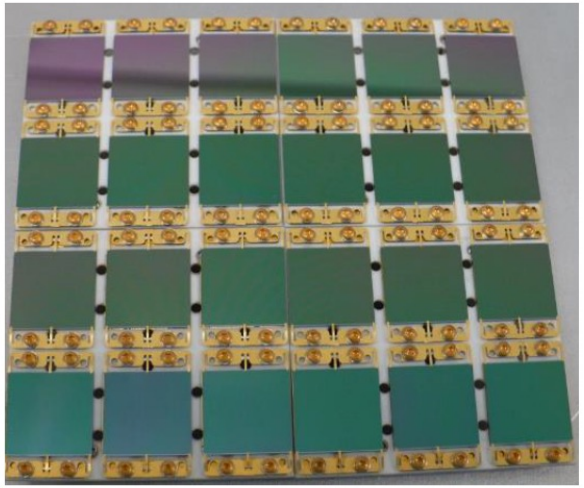


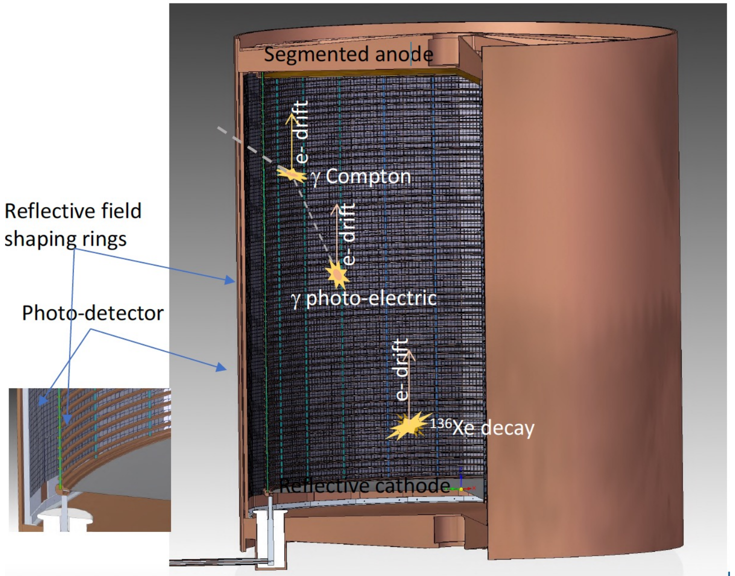
nEXO

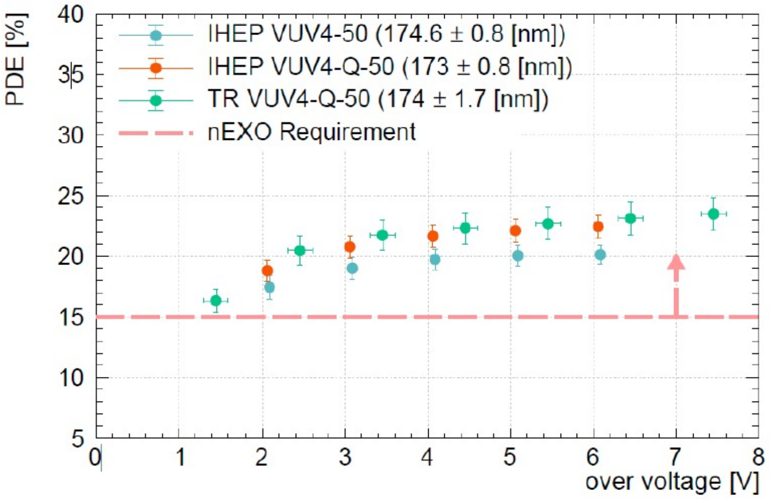


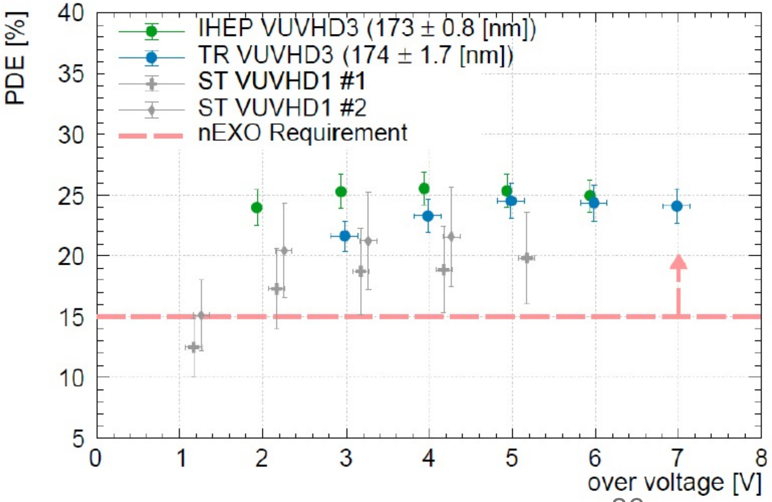
- VUV sensitive SiPMs operating @165K
- Large array covering 4.5 m^2
- Good results achieved in measured PDE for both Hamamatsu and FBK candidates

Prototype large area SiPM array (24SiPMs, 24cm^2)





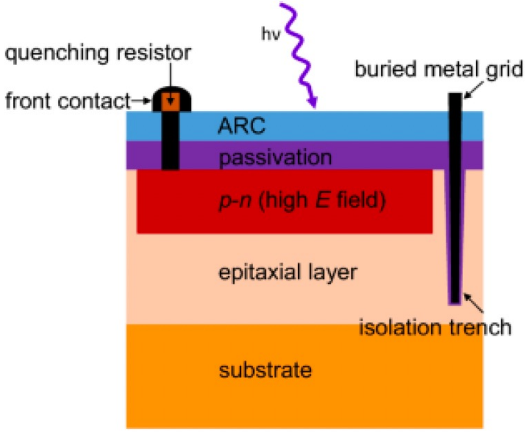


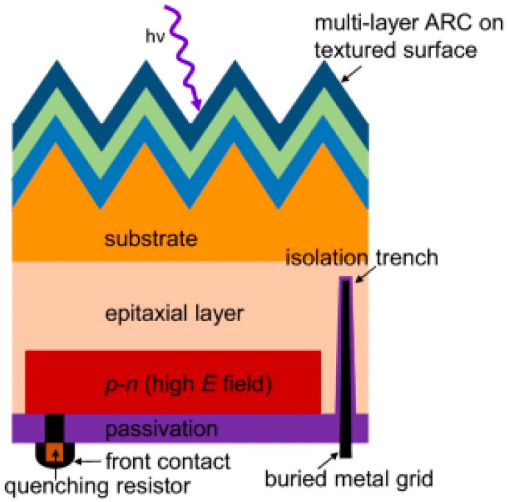


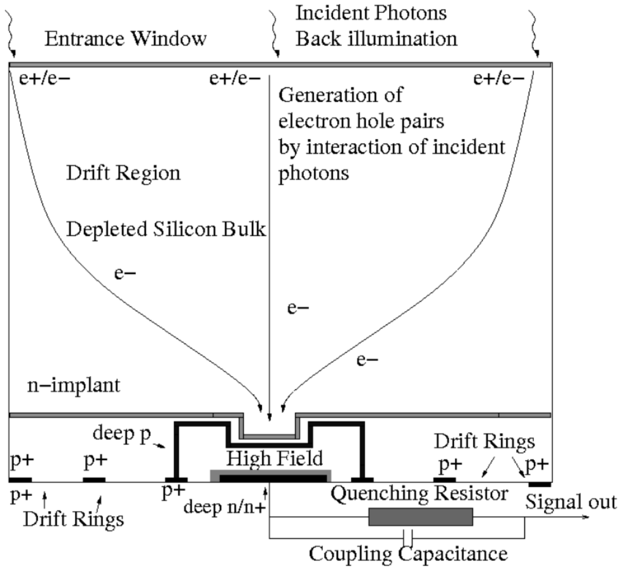
Future prospectives: back illuminated

Back illuminated SiPMs

- This new design minimize dead area
- The entrance window have ant-reflected coatings and textured surface
- Light enters through the unstructured backside and photons convert in the fully depleted n-type silicon bulk. Field shaping drift rings create an electric field in which the electrons drift into a small high field region where the avalanche multiplication occurs. This high field region is built up between the n+ contact and the deep p implant.



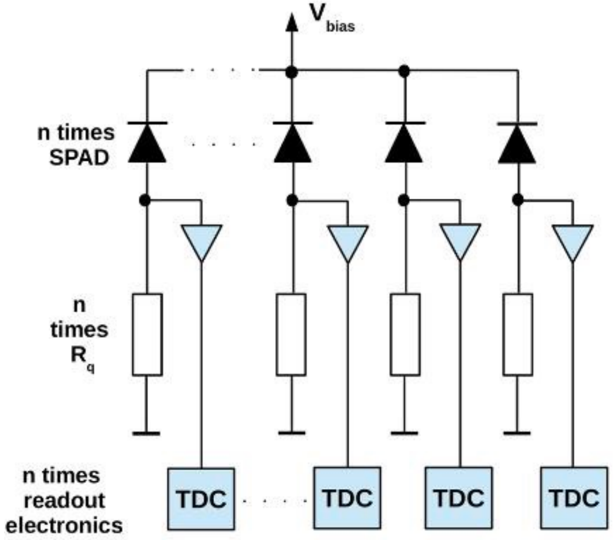




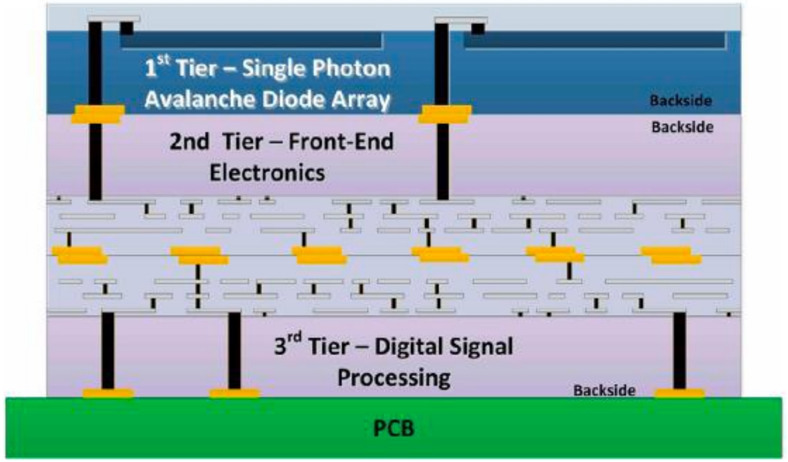
Future prospectives: digital SiPMs

Digital SiPMs

- Each pixel connected to its own readout electronics => time-stamp
- First commercial dSiPM introduced by Philips around 2010 → one time-stamp per scintillation event (PET application and Cerenkov light detection)
- Latest developments → 3D assembly → 1) pixels 2) quenching circuits 3) signal processing and readout



(a)



(b)

Conclusions

- The use of cryogenic SiPM achieved significative advancements
- In approximately 10 years from test of first prototypes of few mm^2 the Liquid Nobles community has progressed to constructing experiments with ten of m^2 SiPM coverage
- Characteristics of SiPMs in cryogenic environment have been extensively investigated
- Back-side illuminated and DSiPMs represent the next challenge for future experiments

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