SiPMs for cryogenic temperature

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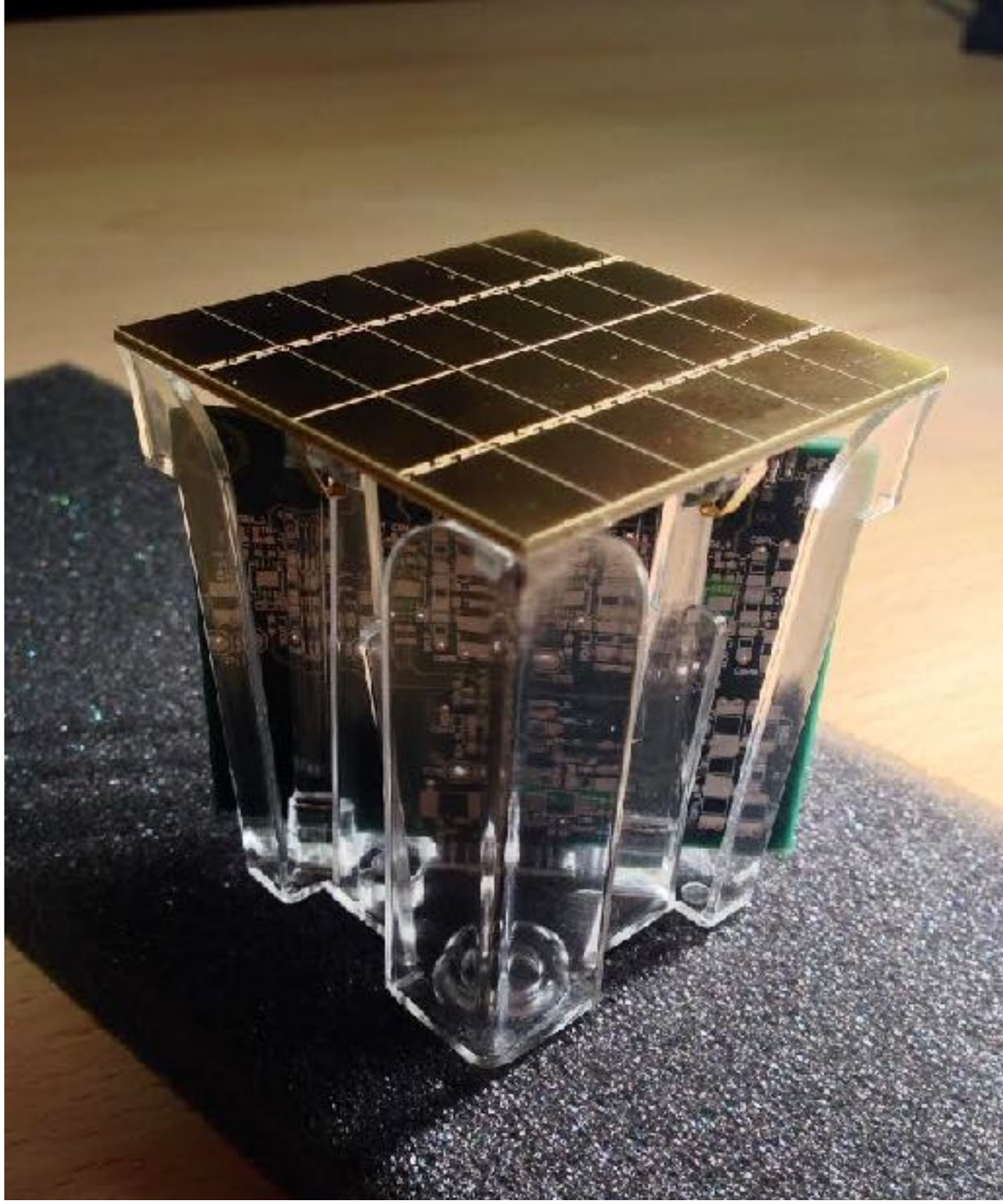
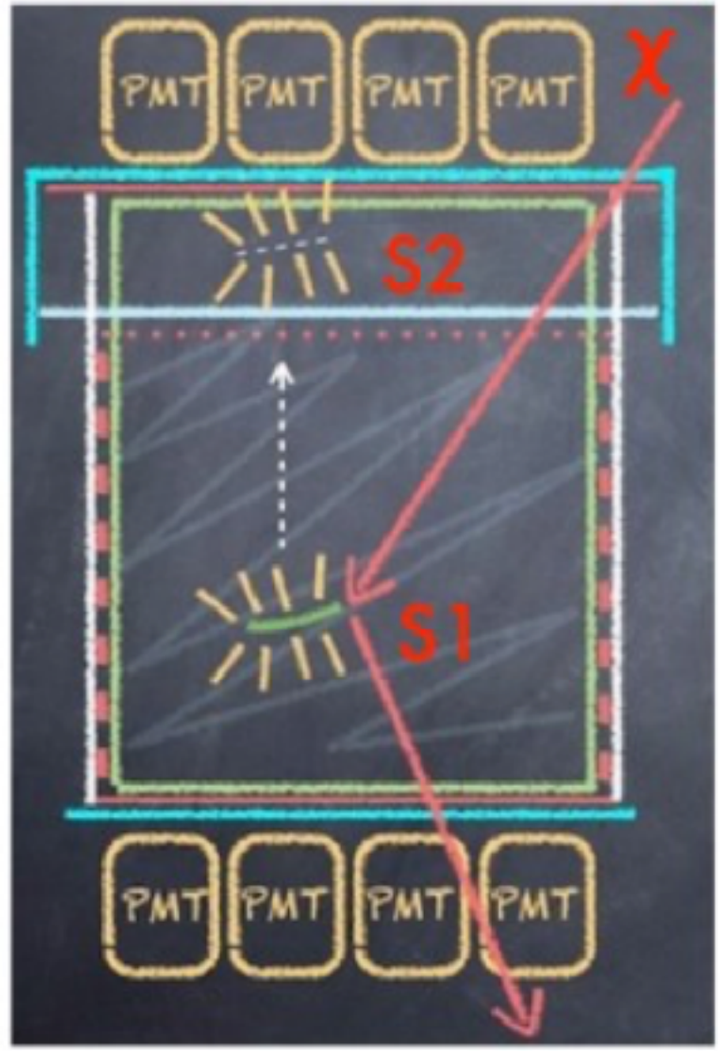
03/09/2018



2018 European Nuclear Physics Conference

Light detection in DarkSide

DarkSide is a stepped program for the realization of increasing size dark matter direct detection on a liquid argon target.
The current detector, DarkSide-50, is located at LNGS and using 50 kg of UAr inside a dual-phase Time Projection Chamber (TPC)

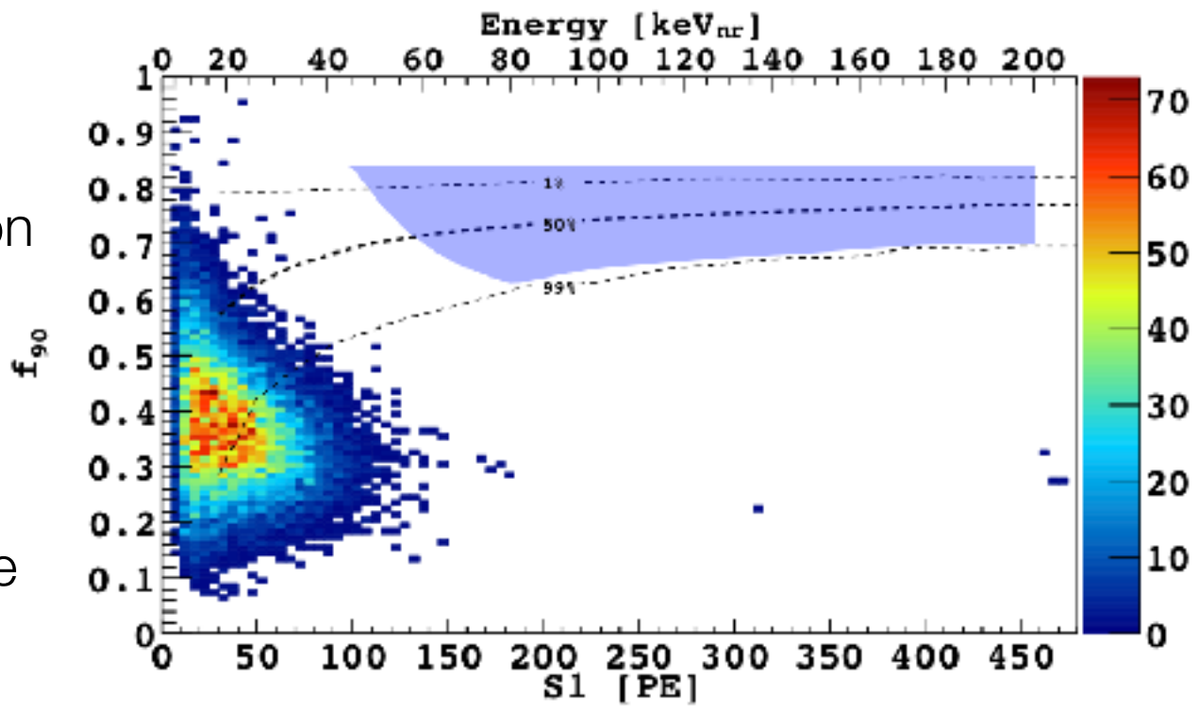


- Interaction in the active volume produces scintillation light (S1) and ionization electrons. S1 is detected by photosensors (like PMTs) on top and bottom of the TPC.

- Electrons are drifted by means of an electric field to the liquid-gas interface and extracted in the gas phase and accelerated toward the anode. The interaction between e- and the gas produces electroluminescence light (S2), detected by the photosensors.

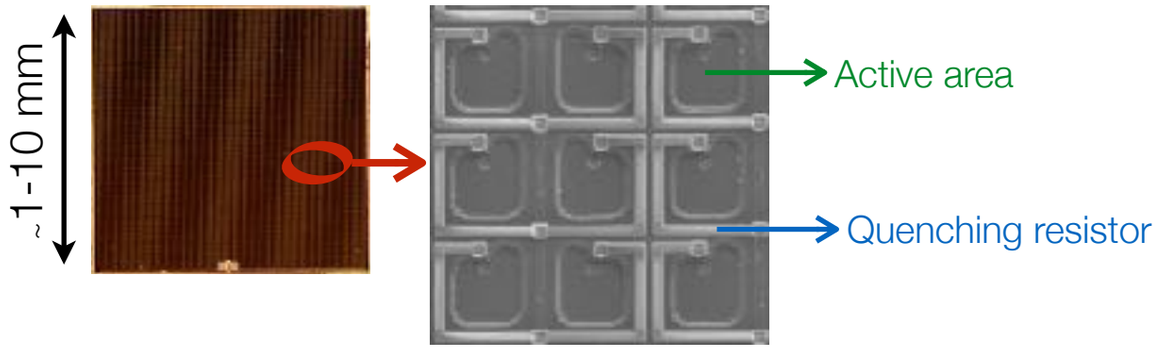
- The presence of S1 and S2 allows to reconstruct the position of the original interaction allowing fiducialization

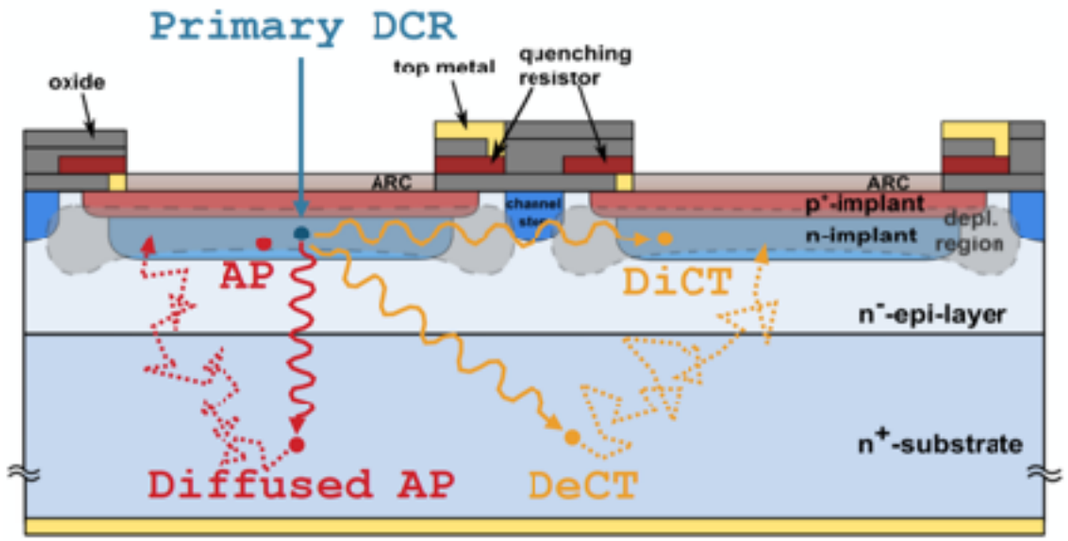
- The shape of S1 allows the discrimination of nuclear recoils from electromagnetic interaction (PSD) with a rejection better than 10^8
- Other discriminations are possible to further reduce the Background (S2/S1, multi-site interactions, …)



Therefore an accurate light detection is of primary importance for DarkSide

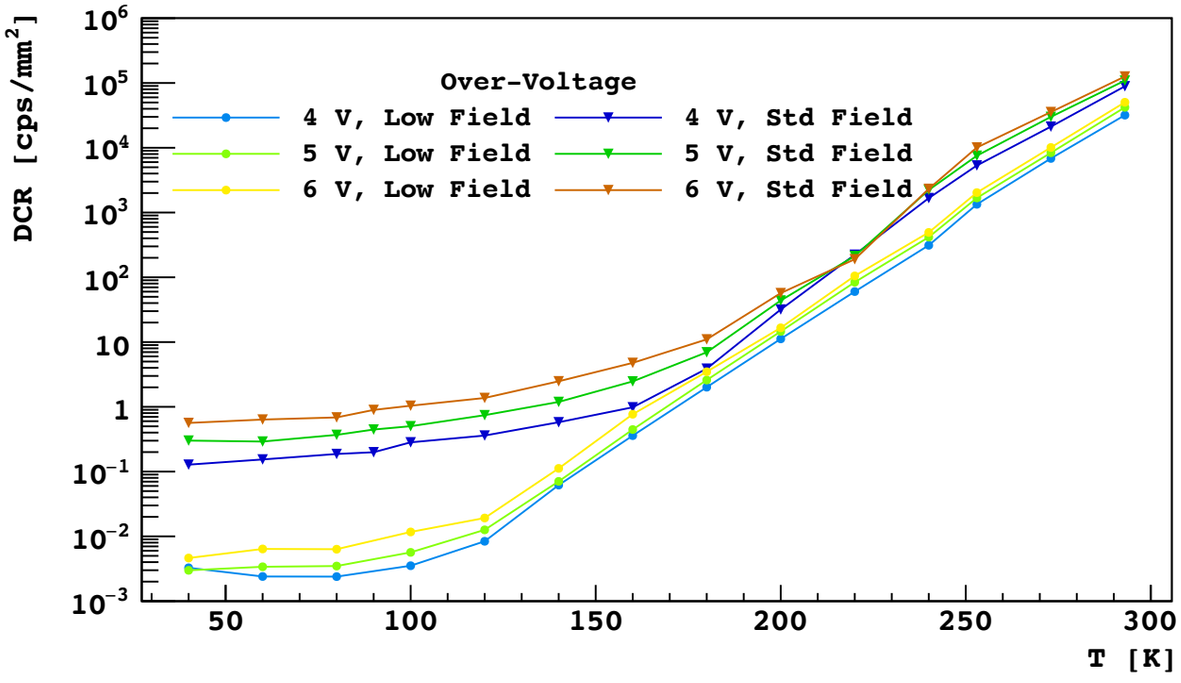
Silicon PhotoMultipliers

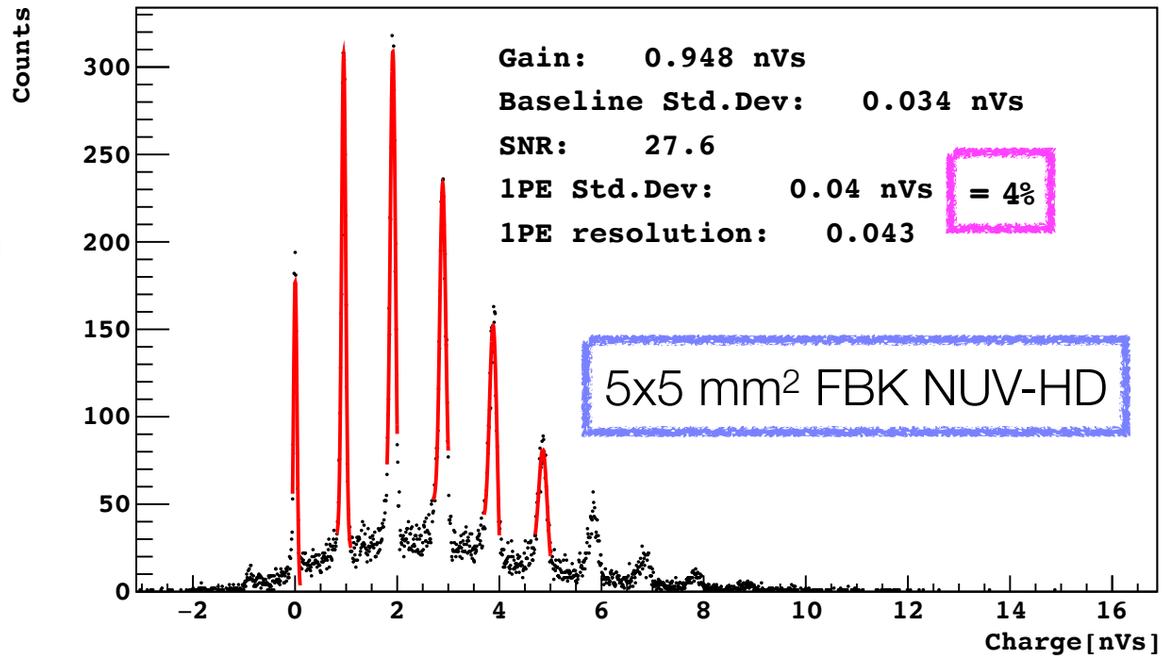




A SiPM is a collection of N SPADs of typical size 20-50 um

- A Single Photon Avalanche Diode (SPAD) is a photodiode operating in Geiger mode
  - ON or OFF
  - Resulting in extraordinary charge resolution
  - And a high dark-rate O(10^4-10^5 cps/mm^2 @ 300K)
- A signal is generated when N_f SPADs are triggered

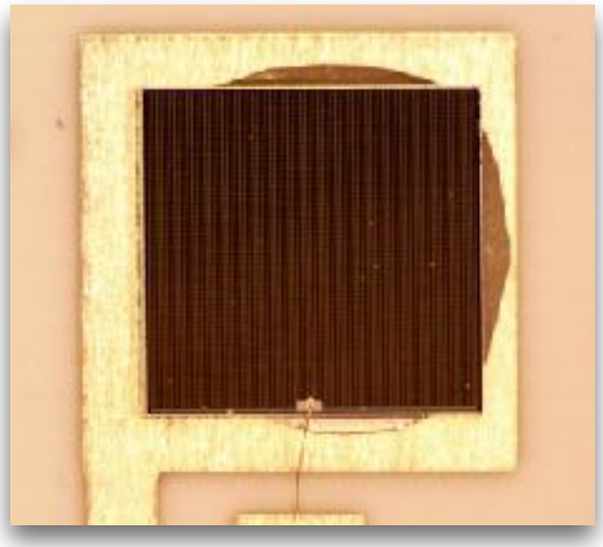




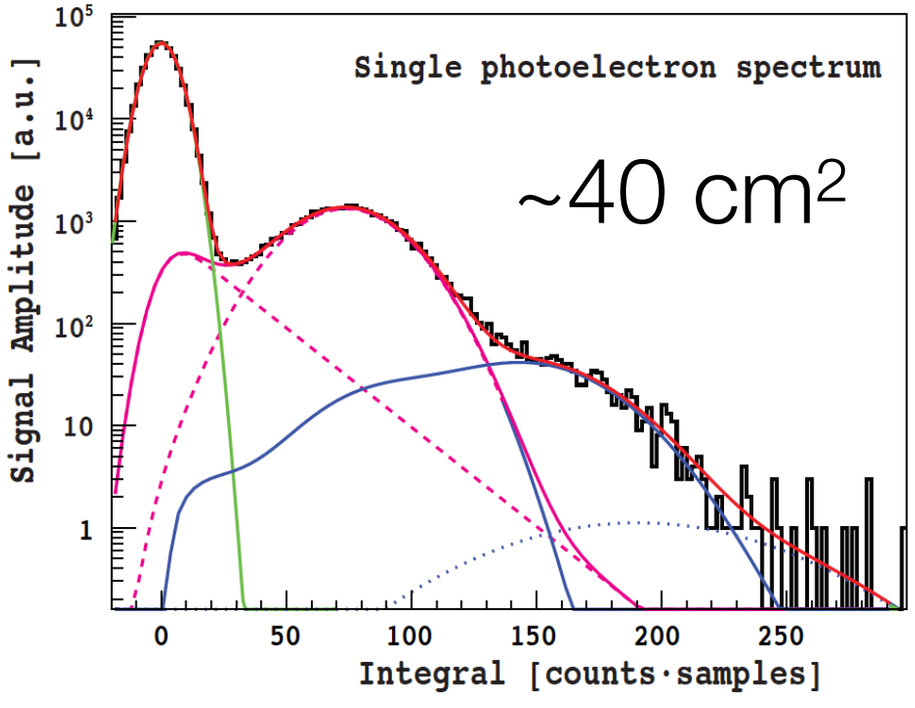
The use of SiPM in particle detectors is continuously increasing

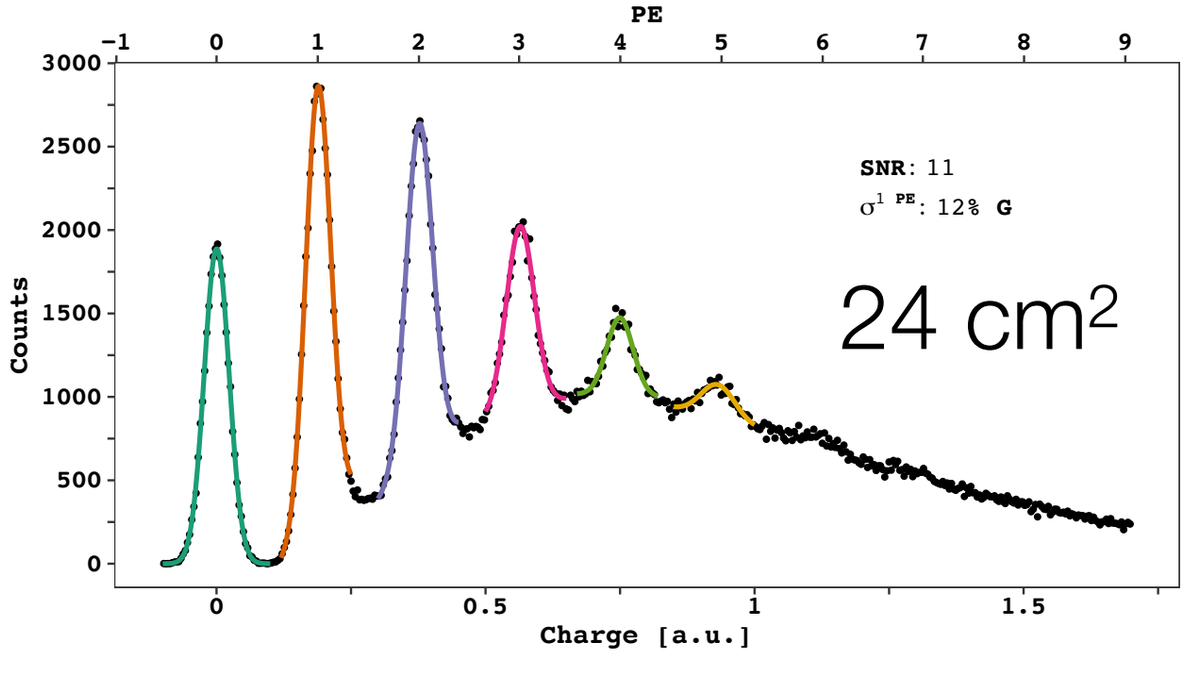
SiPMs advantages over traditional PMTs

- PMTs are the main source of neutrons in DS-50
- High operation voltage (~1 kV)
- Low SPE resolution
- Not working in LAr
  - In DS50 a special preamplifier was required

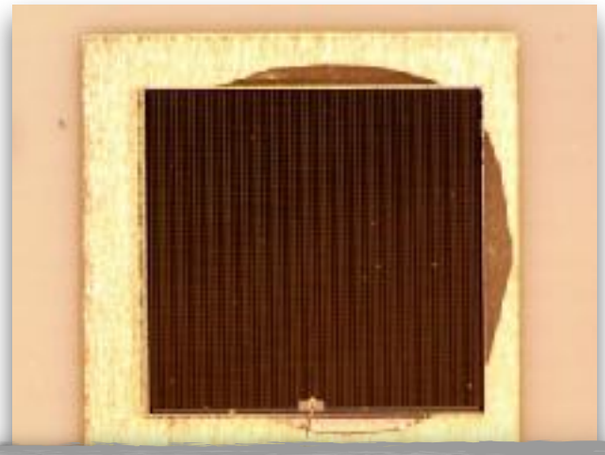


- Silicon is radiopure
- Low operation voltage (<100 V)
- High PDE wrt PMTs
  - ~40% vs ~20% (including dead-zones and packing factors)
- High SPE resolution





SiPMs advantages over traditional PMTs



- PMTs a
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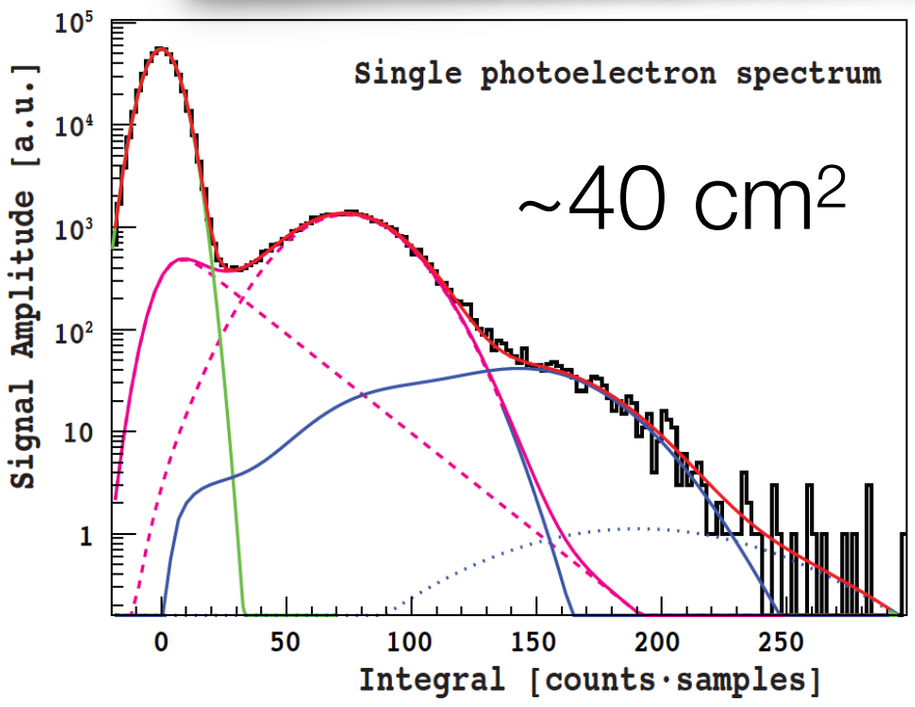
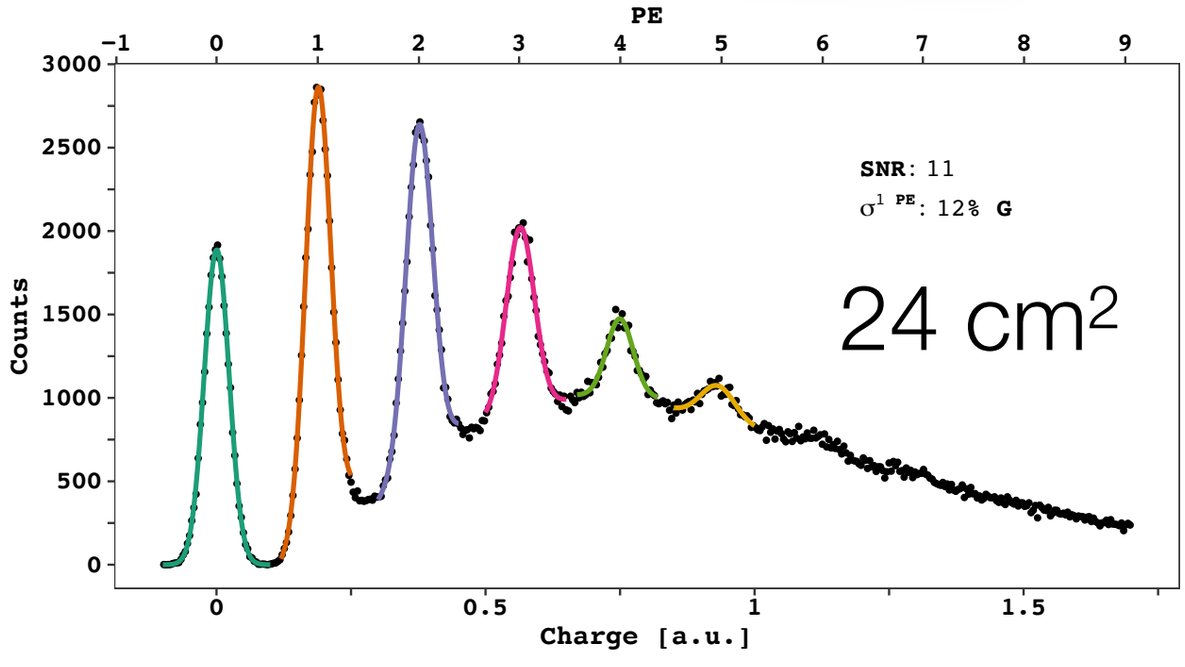
d-zones

the challenge is moving from few mm² to 25 cm²

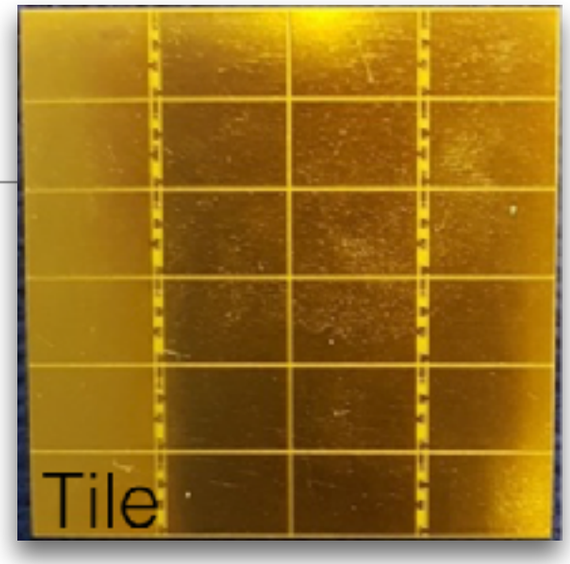
High SPE resolution

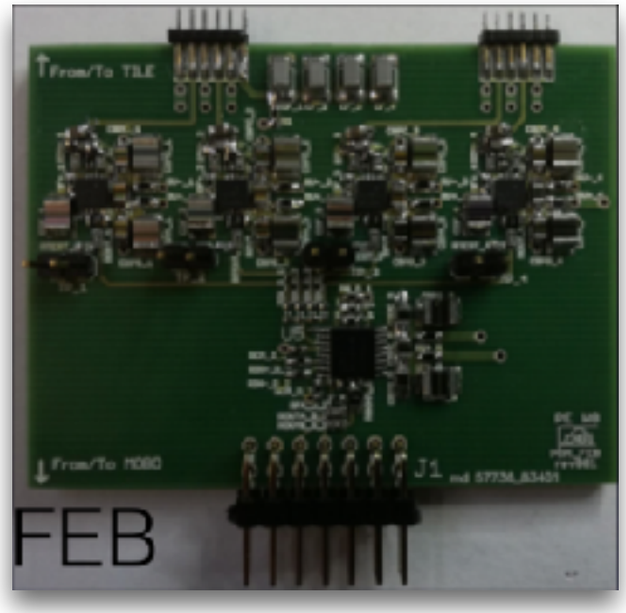




PDM photodetector module

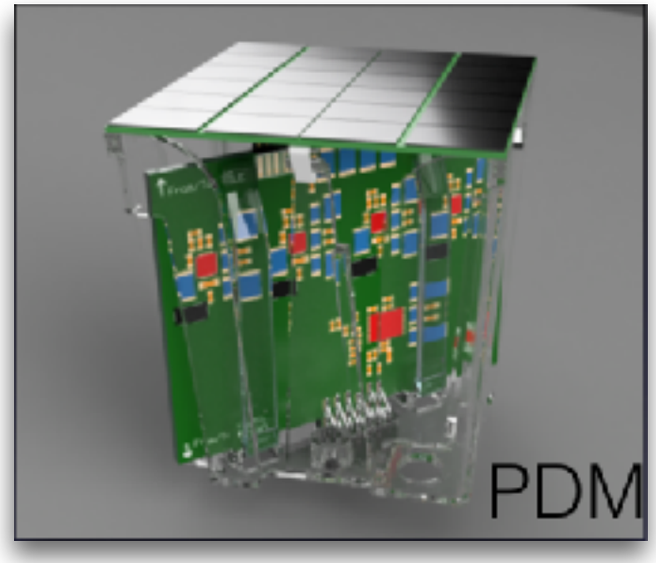
- SiPMs are small size devices (tens to hundreds of mm^2)
- A solution is to group SiPMs in arrays of size comparable to that of PMTs and read out this array (tile) as a single channel with appropriate electronics
- Tile + electronics form a PhotoDetector Module (PDM)
- About 10000 PDMs are foreseen
  - The production procedures (electronics & packaging) will require high reliability



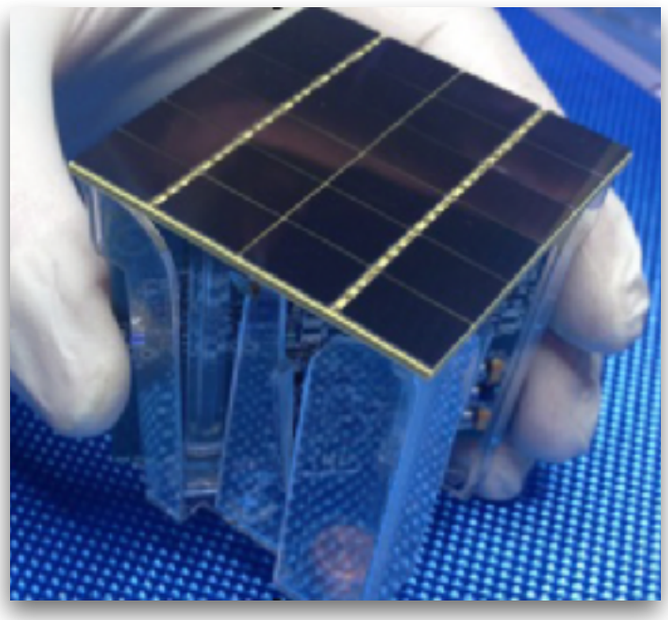


Requirements:

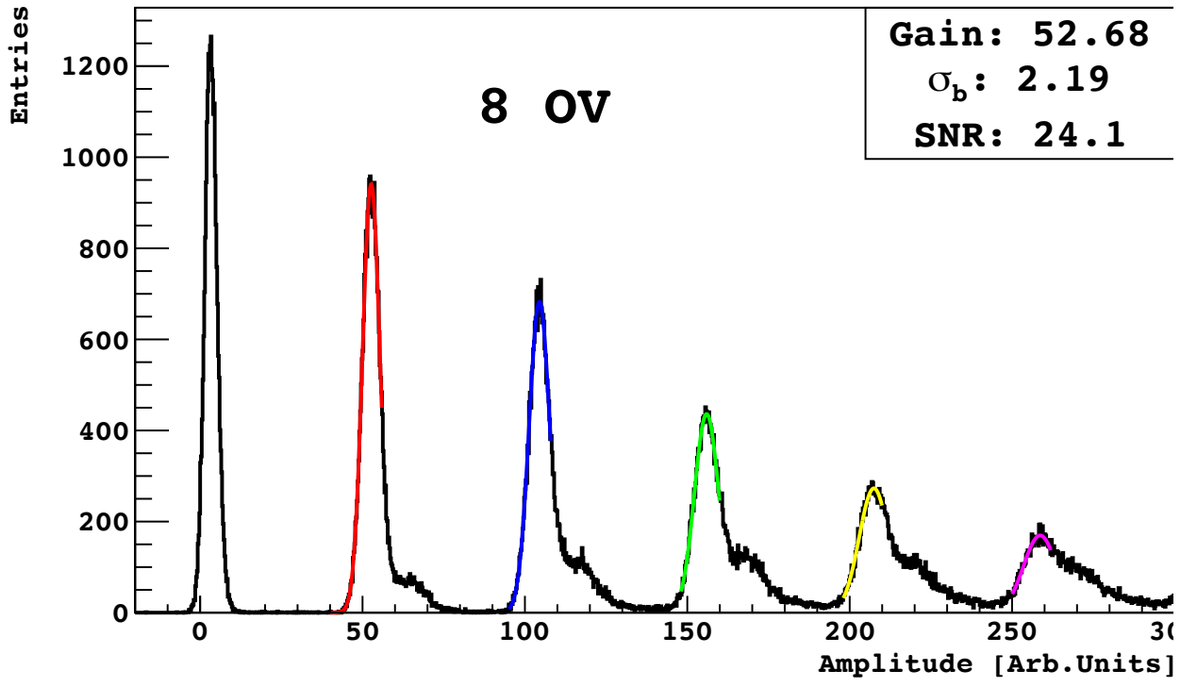
- 25 cm^2 surface (8280 channels in total)
- overall PDE > 40% at 420 nm
- dynamic range > 50 pe
- time resolution of O(10 ns)
- overall noise rate below 0.1 Hz/mm^2

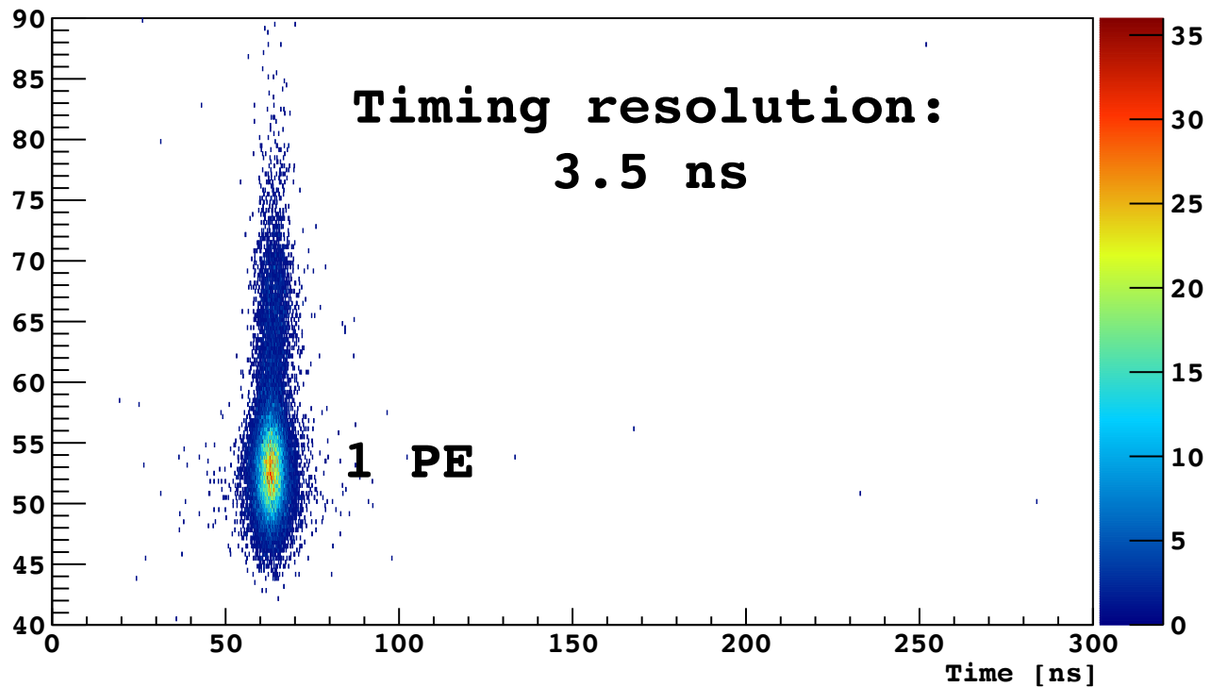


PDM performances



- The PDM integrates the SiPM tile and the readout electronics inside an acrylic cage
- 24 cm^2 total active surface
  - 24 x 8x12 mm^2 SiPMs
- SiPMs are from FBK developed for low after and low dark rate operation in liquid argon.





Motherboard

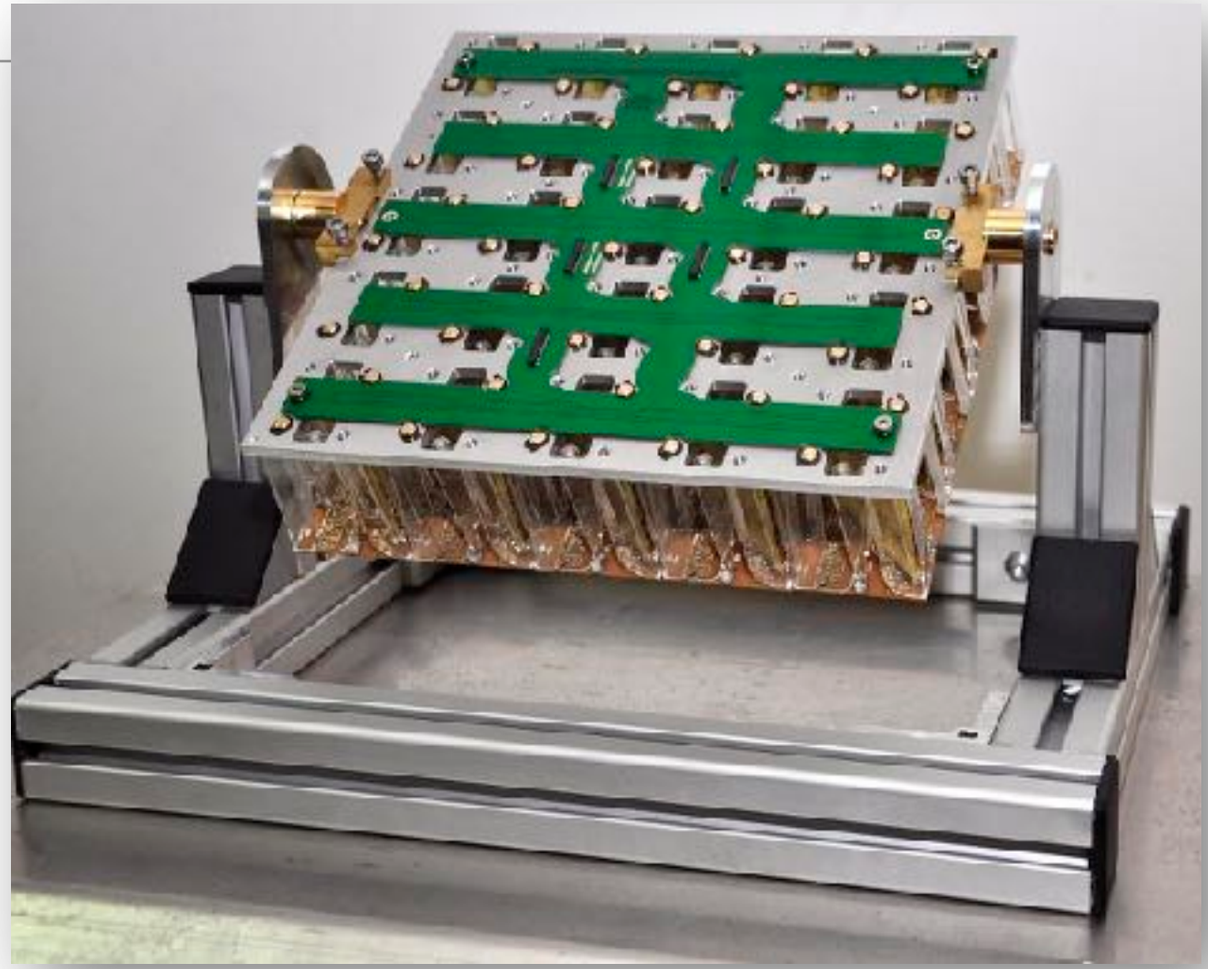
- Mechanical structure required to assemble all components and to efficiently dissipate heat in LAr target, minimizing the production of bubbles

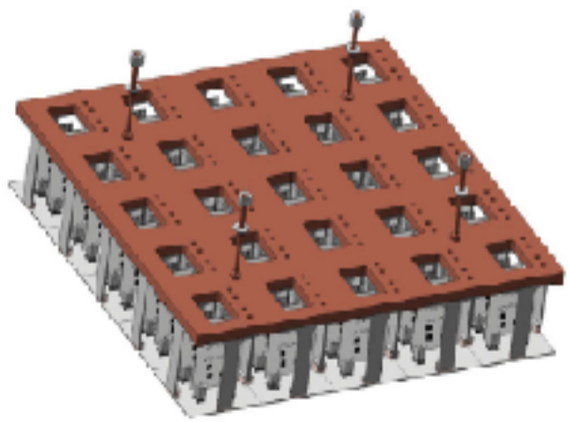
- power dissipation density limited to 100 μW/mm^2, corresponding to a total dissipated power of 250 mW per PDM

- signal extraction via analog optical transmission

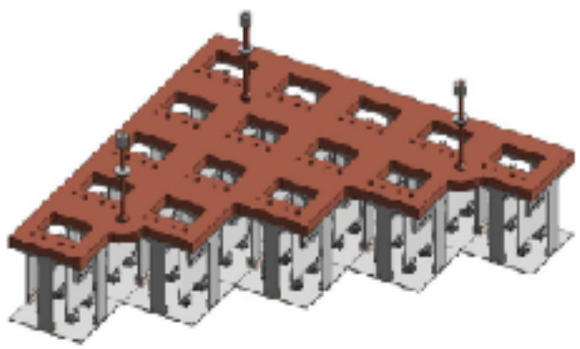
- each PDM can be turned on and off individually

- goal radio purity ~ 10 mBq/MB
  - 3” PMT can be ~ few mBq





SQB: 25 PDMs = 600 SiPMs

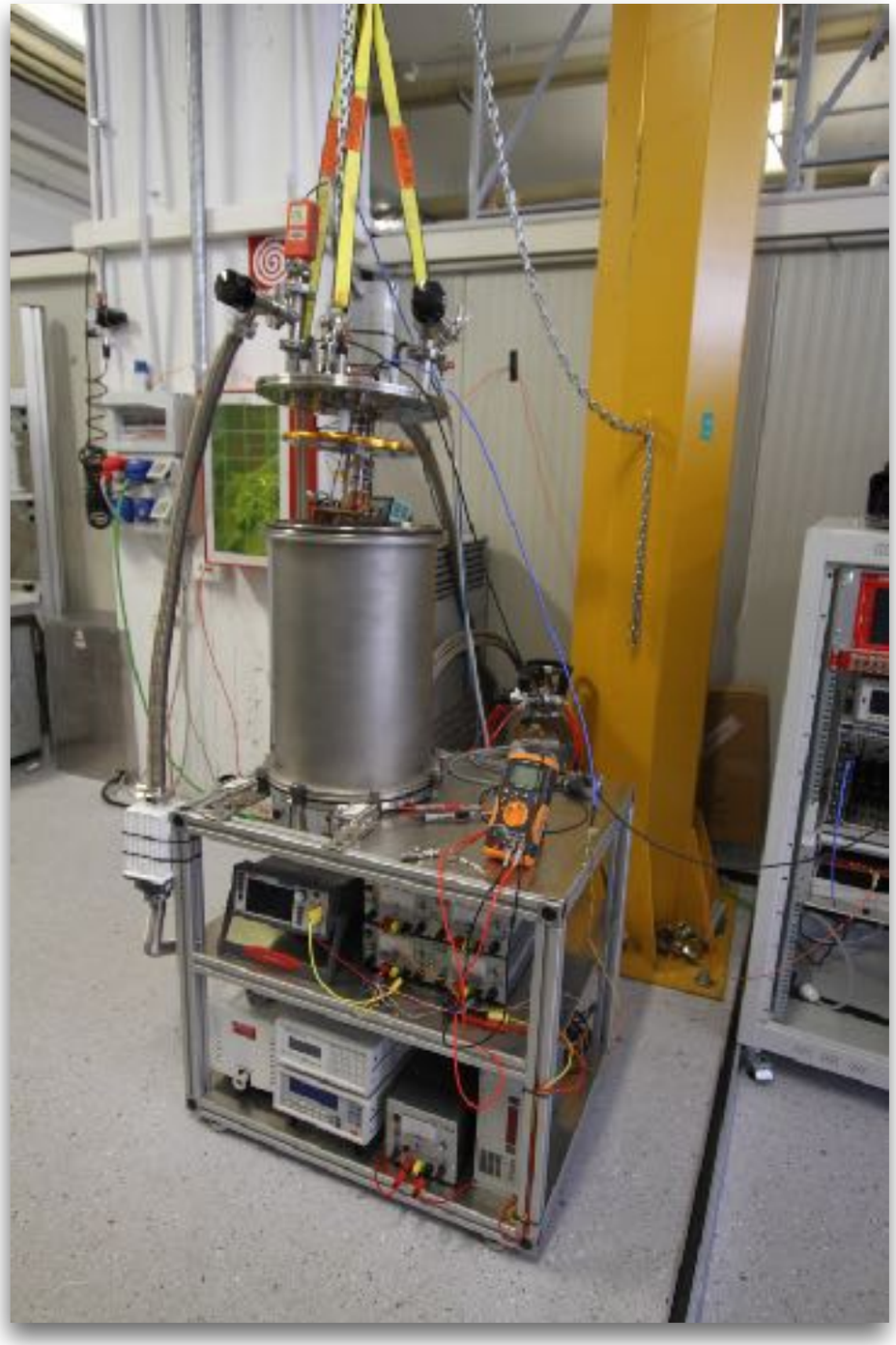


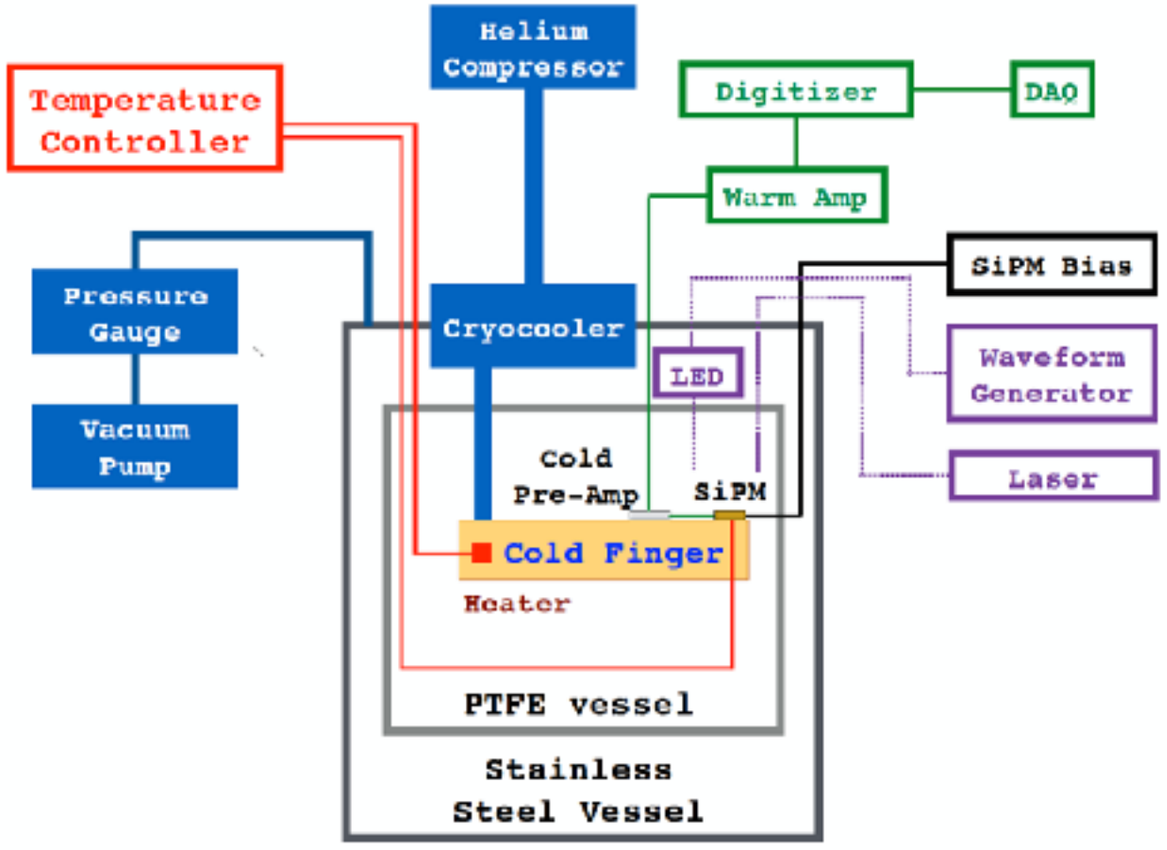
TRB: 15 PDMs = 360 SiPMs

An accurate characterization of SiPMs is required

Cryogenic setup

Full characterization of SiPMs in dark conditions was performed in a dedicated experimental setup at different over-voltages





Large temperature range

40 K < T < 300 K

Details on experimental setup at LNGS:

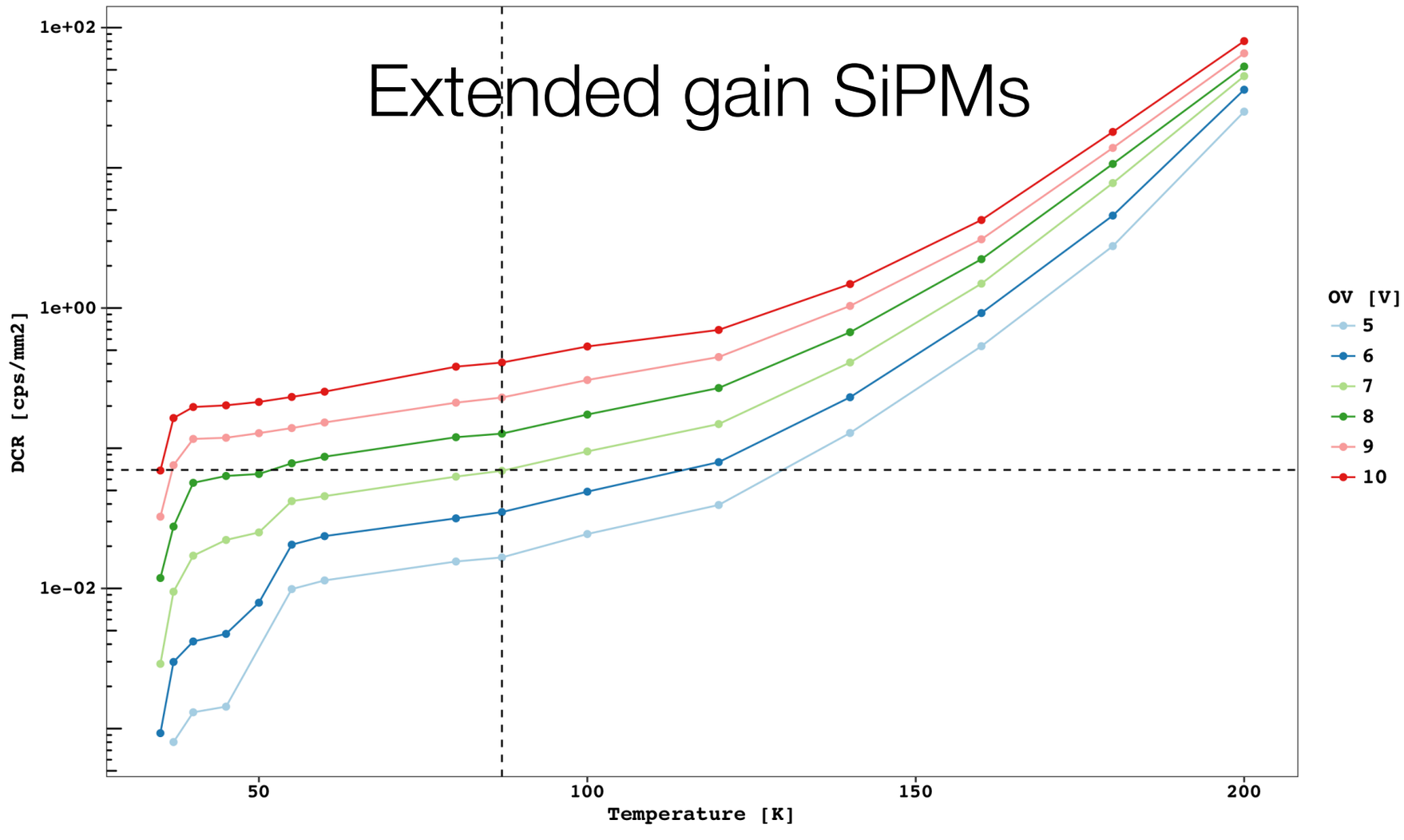
- *Cryogenic Characterization of FBK HD Near-UV Sensitive SiPMs*, IEEE Transactions on Electron Devices, vol. 64, issue:2, Feb 2017
- *Cryogenic Characterization of FBK RGB-HD SiPMs*, Journal of Instrumentation, vol.12, Sept 2017

Results

We characterize the DCR and the correlated noise of SiPMs vs temperature.

We are testing the SiPMs of the latest FBK run

- to optimize the matching with the FEB and with the requirements of DarkSide-20k

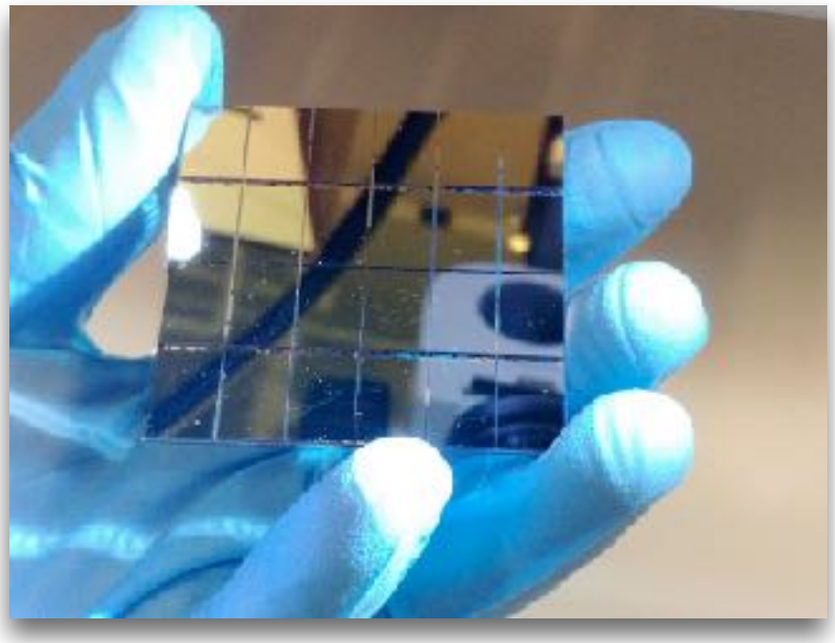


Packaging solutions for more than 240000 SiPMs

Packaging solutions for cryogenic applications

Problems:

1. CTE of substrate
2. Radio-Purity
3. Bonding reliability
4. Anode contact



Requirements:

- Low CTE substrate
  - with good rigidity
- High Radio-Purity
  - ~ few mBq/m^2 for U/Th chains and for ^{40}K
- >> 99% die bonding reliability in LAr
  - 0.99^{24} = 79% yield for PDM
- TSV to avoid wire bonding

Packaging solutions for cryogenic applications

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Material	CTE [ppm/K]	U/Th [mBq/kg]	^{40}K [mBq/kg]
Silicon	**3-5**	**very low**	**very low**
FR4	12-14	very high	very high
PTFE/Teflon	120	0.1-10	<5
Polyimide/ Kapton	20	1-10	<10
Arlon NT	5-7	100	1000
Fused Silica	0.5	5-20	-
Selected FS	0.5	0.05	-

- Stress on SiPM due to difference of CTE
- Silicon PCBs are not trivial: Si is not an insulator: R&D active
- Multilayer Fused Silica PCBs require die bonding: R&D active
- Arlon NT is readily available

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- Arlon is at the edge of DS-20k acceptance for radio-purity: R&D on other solutions is ongoing
- components ~60 μBq/kg
- main background from substrate (at this moment)

Packaging solutions for cryogenic applications

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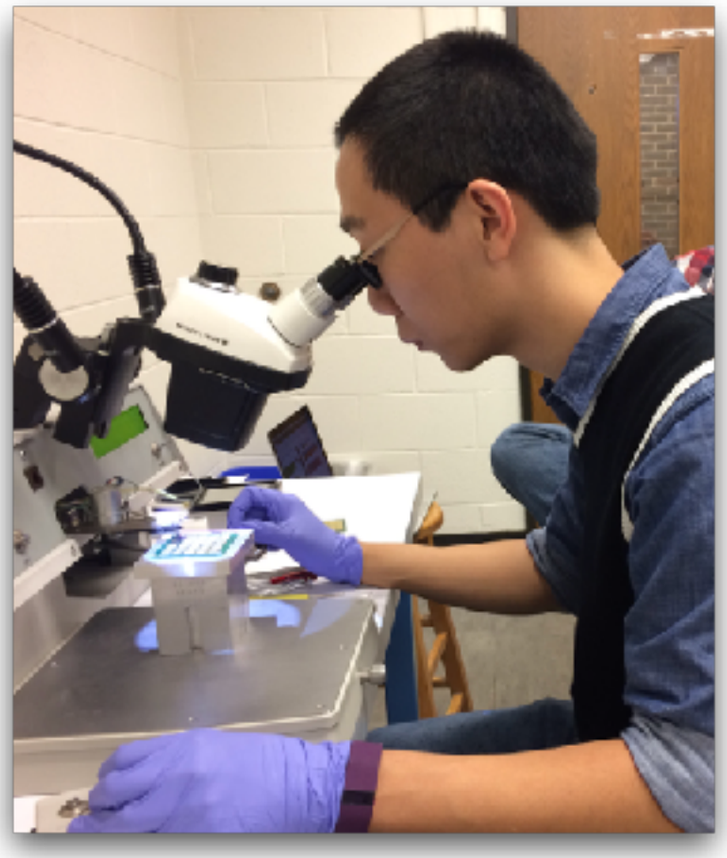

Temporary solution:

- cryo-graded conductive epoxy bonding
  - EPO-TEK EJ2189 cured at 100°C for 1h
  - the current TTiN SiPM backside does not allow other solutions.

We performed many reliability tests in LN_2

- Current reliability > 99.9%

Current procedure uses robot dispenser plus a manual die bonder.

Packaging solutions for cryogenic applications

Problems:

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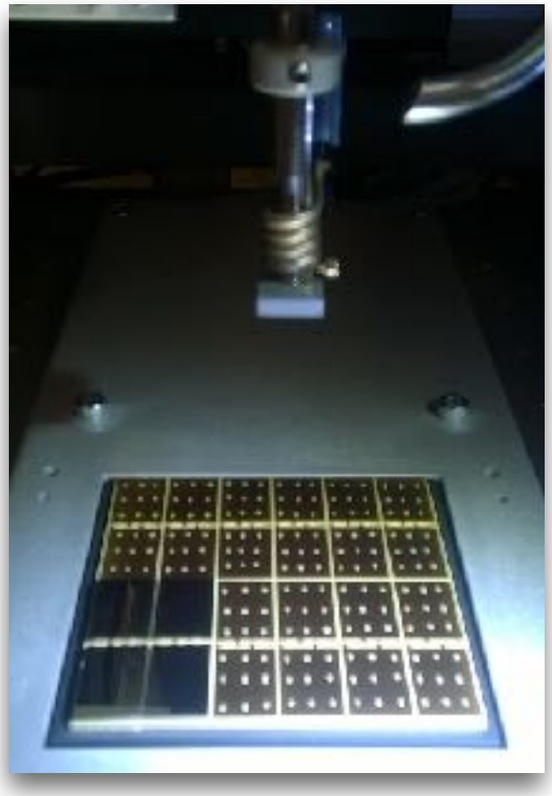


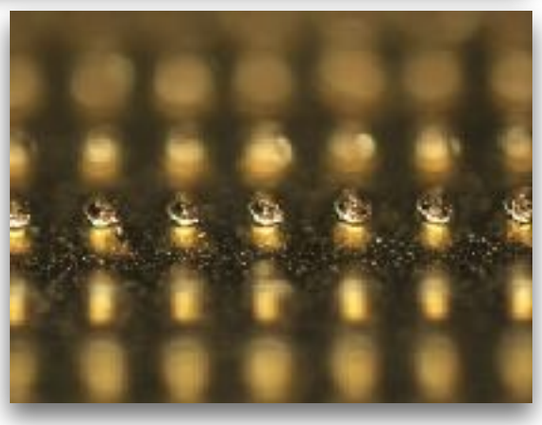
Silver loaded epoxy is not radio-pure

- and not reliable in the long term

We are moving to a new procedure:

- indium bump bonding (melting point 156.6°C)
- gold studs ball bonding

Both solutions were tested are provided very strong bonds



A procedure has already been defined. Final tests with first LFoundry wafers in October/November.

Packaging solutions for cryogenic applications

Problems:

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2. Radio-Purity
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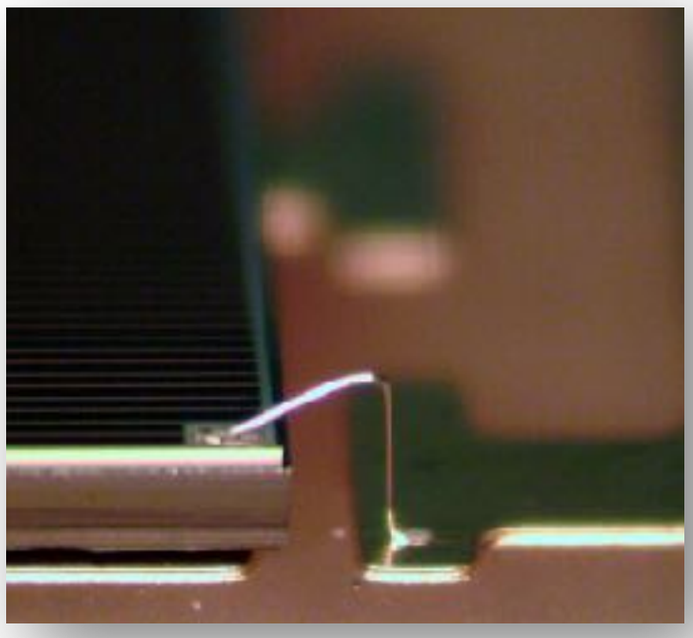
4. Anode contact



wire bonding:

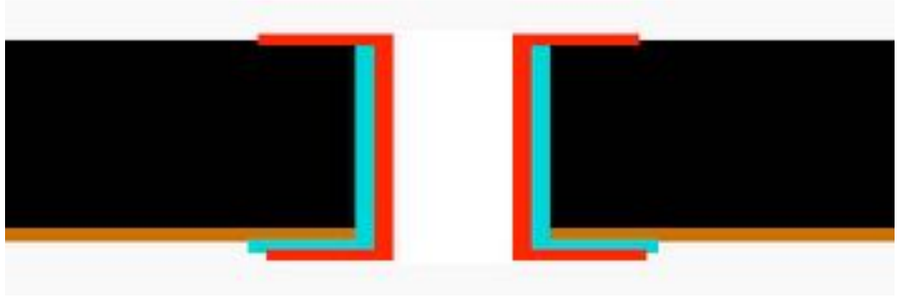
- 25 µm aluminium wire
- 24 wires per PDM

Very fragile during manipulation:

- Complicated installation of the experiment

TSV:

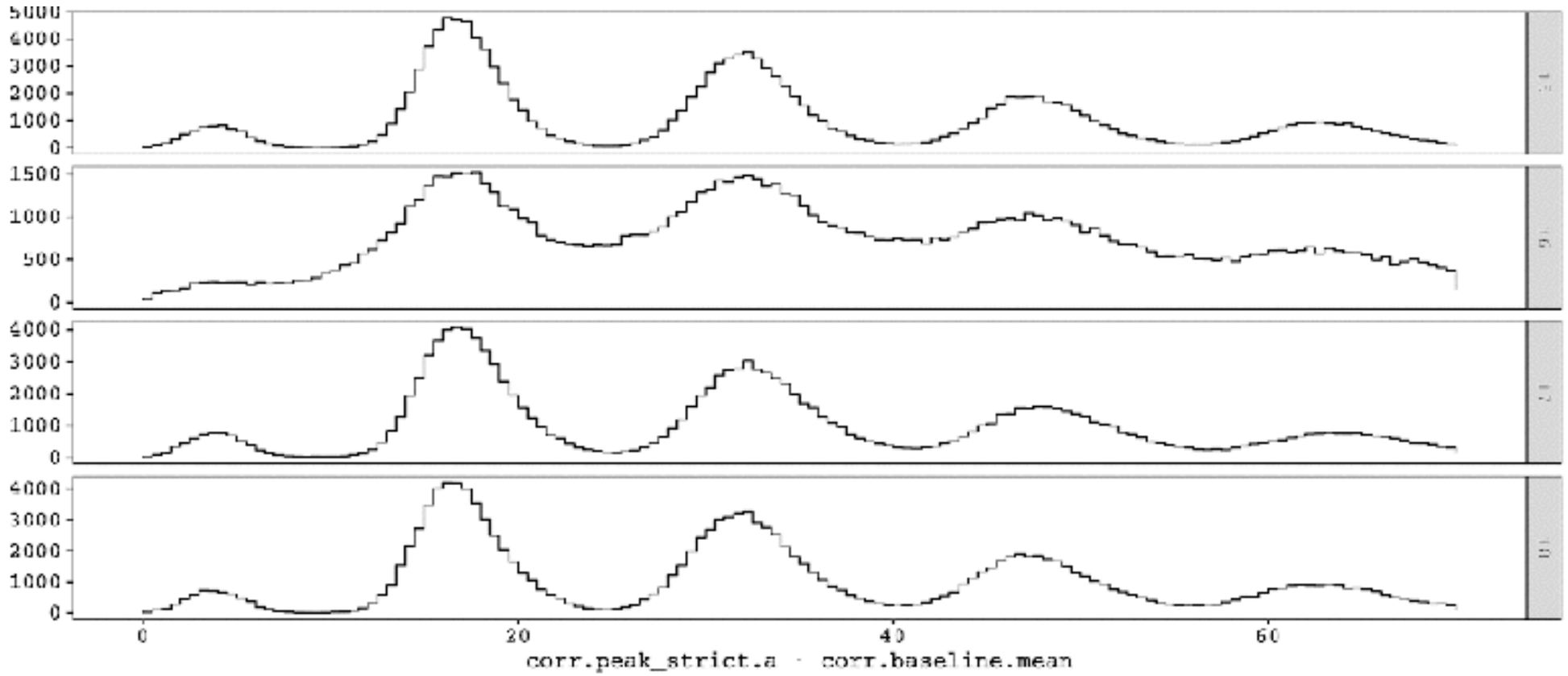
- backside
- robustness and higher fill factor (97%)



The first MB

In the last months we produced more than 30 PDMs.
Each PDM was tested independently in LN2.

Accurate characterization of the PDMs



We produced 27 tiles with NUV-HD-LF SiPMs.
Each tile was individually tested at room temperature and in LN2:

- all 24 SiPMs are working
- the single photoelectron peaks are well distinguishable
- the correlated noises are within specs

Now we have to scale the procedure in order to test 10000 PDMs.

Mass production in NOA

NOA is a project funded through the RESTART program which aims to re-launch the economy and advanced training in the 2009 earthquake region.

NOA is using top quality equipment for the packaging of silicon devices

NOA proposal starts in the framework of DarkSide-20k.

SiPMs will be produced by LFoundry and delivered to NOA CR.

NOA will include the following processes all available for wafers up to 8”:

- cryogenic and room temperature wafer probing
- dicing
- fully automated flip-chip bonding

Moreover, NOA will include radio-pure processes for SMD PCB productions and an advanced electronic testing facility.

Conclusions

DarkSide-20k succeeded in an ambitious R&D program to deploy radio-pure cryo-graded, SiPM-based, large photodetector.

The hot topics include:

- development of a specific technology of SiPM within FBK for LAr
- development of an extremely low noise preamplifier board
- selection of radio-pure components
- identification and use of the most advanced silicon packaging techniques
- deployment of a cutting edge silicon packaging facility at LNGS

As a result, we are almost ready for the mass production of the photodetector modules.