

Cryogenic SiPMs for dark matter search with DarkSide-20k

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The background image shows a scenic view of a city, likely Stockholm, with a river in the foreground, a bridge, and a dense line of green trees. In the background, several tall buildings and a telecommunications tower are visible under a blue sky with scattered white clouds.

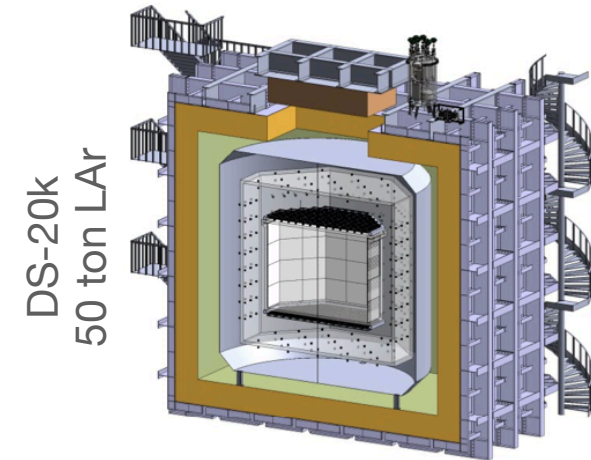
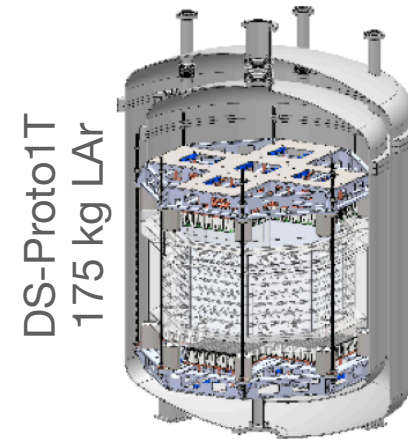
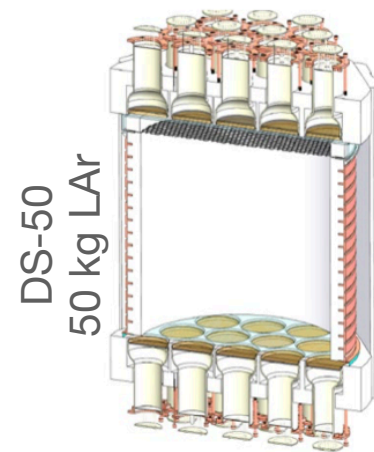
EPS-HEP Conference 2021

European Physical Society conference on high energy physics 2021

Online conference, July 26-30, 2021

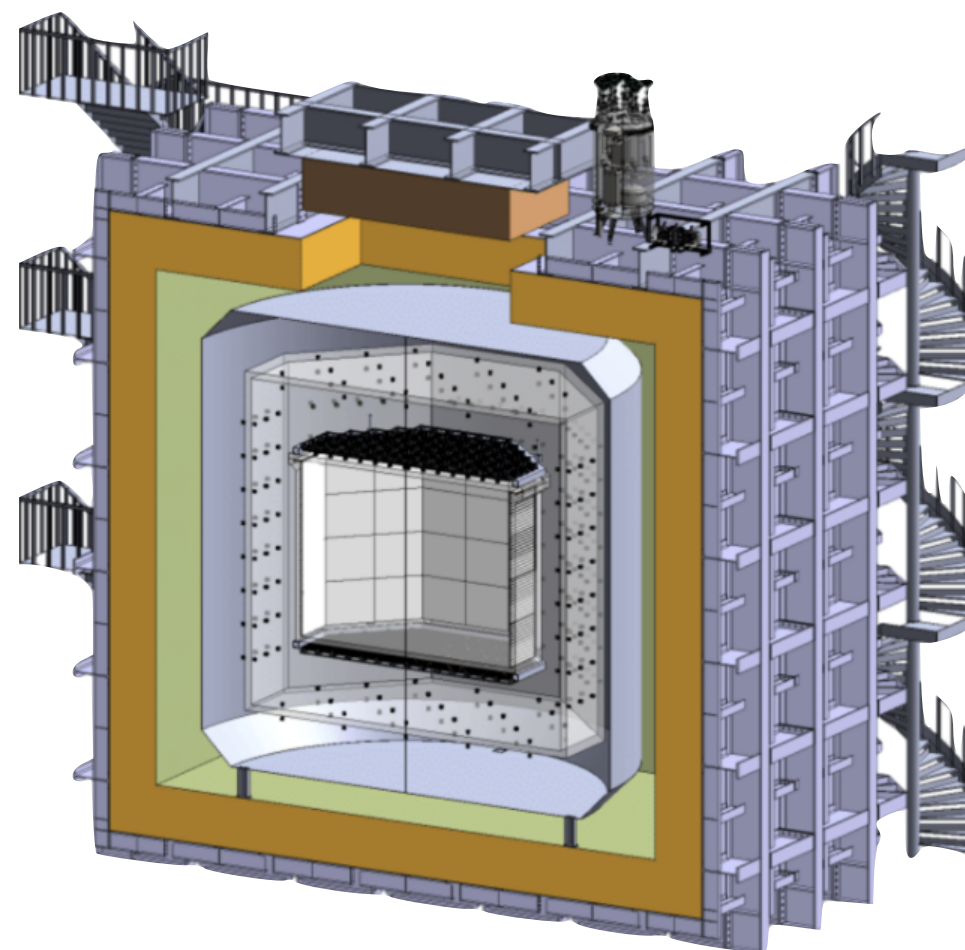
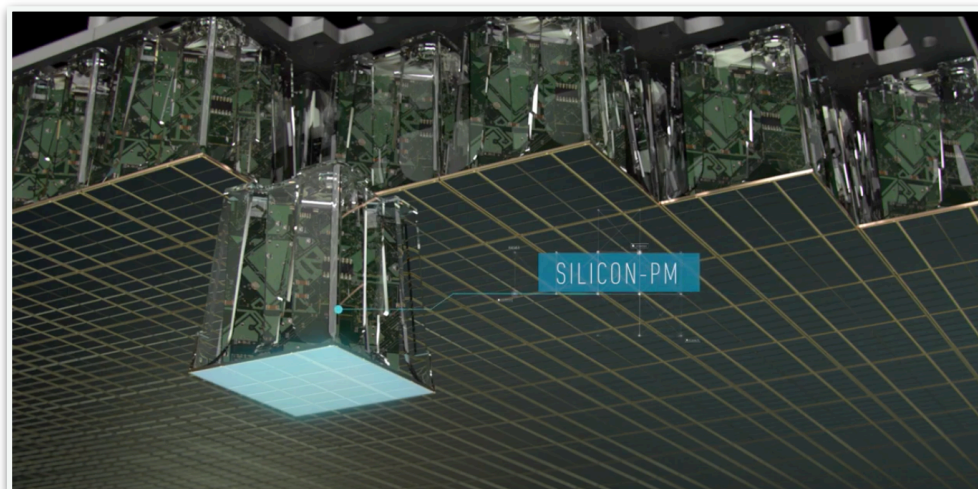
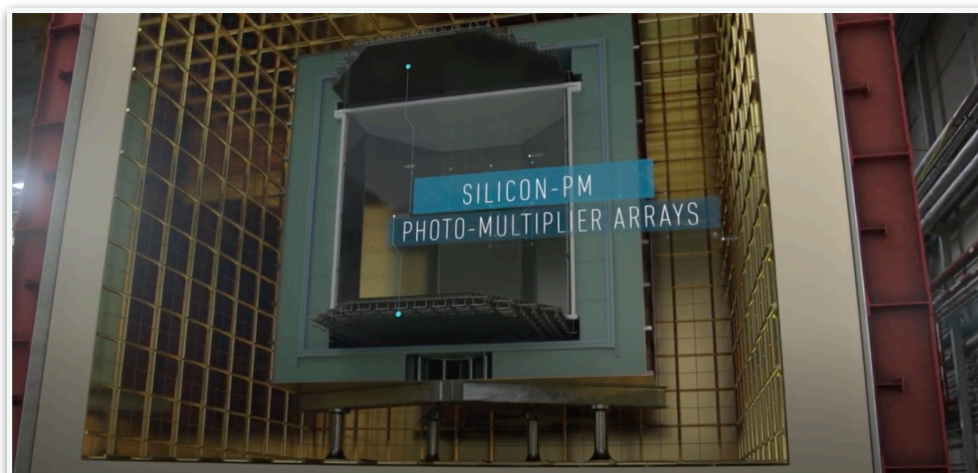
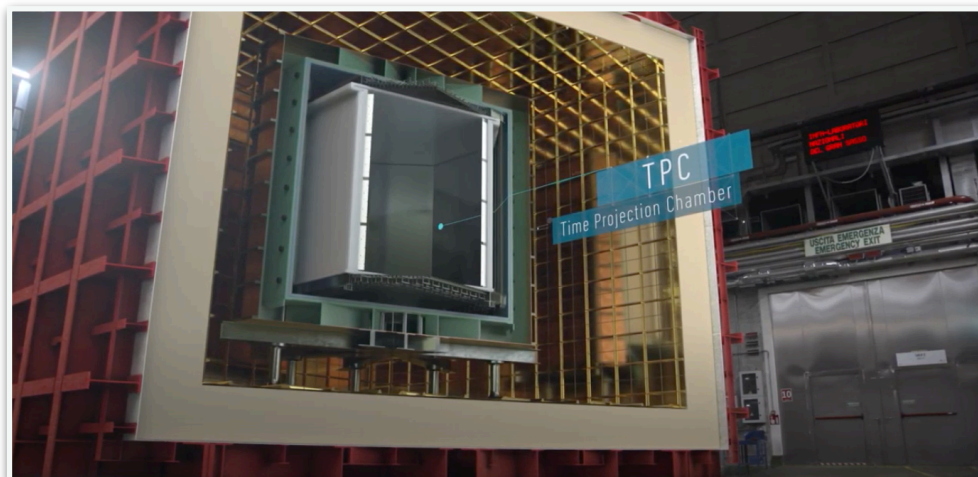
The DarkSide program

- ▶ The DarkSide collaboration aims to discover dark matter with a series of stepped size LAr-based detectors
 - ▶ From 10 kg to 300 ton



- ▶ The collaboration includes about 300 scientist from Europe, Russia, USA, Canada, China, Brazil
 - ▶ And unites all the effort for argon-based dark matter experiments
- ▶ The DarkSide collaboration has a strong R&D program to improve the detector technologies
 - ▶ Light detection based on SiPM in collaboration with FBK
 - ▶ Extraction of underground argon to eliminate ^{39}Ar
 - ▶ Naturally present isotope in atmospheric argon with a 1 Bq/kg activity

DarkSide 20k

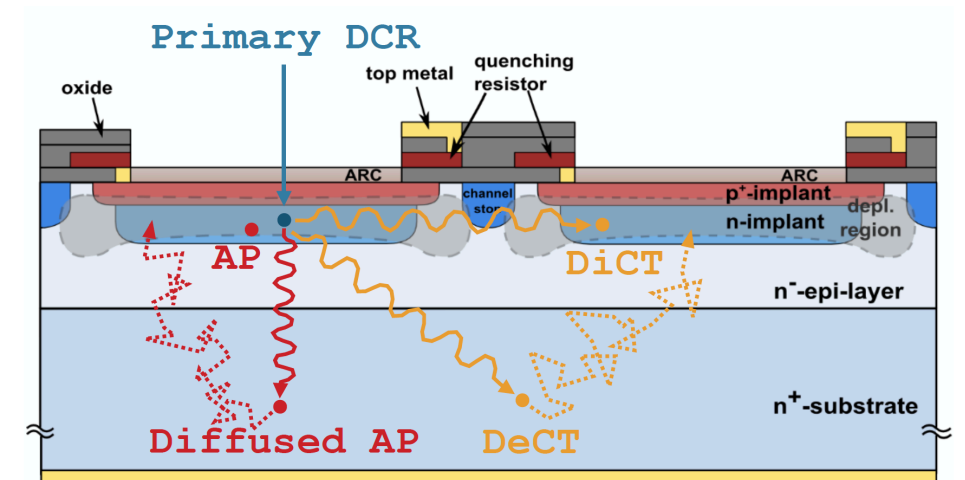
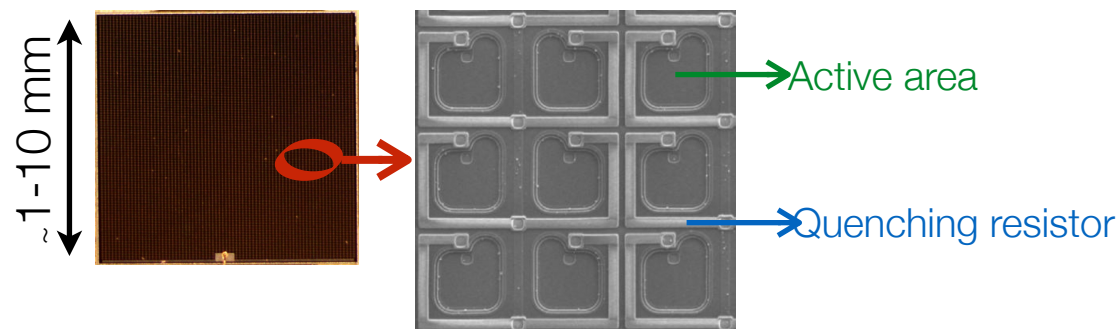


- ▶ DarkSide-20k is a dual phase TPC filled with about 50 ton of LAr
- ▶ The detector is installed in a cryogenic vessel designed for Proto-Dune
 - ▶ Containing about 700 ton of LAr
- ▶ The photo-detectors are SiPM-based
 - ▶ With a total instrumented surface of $\sim 28 \text{ m}^2$

YT: DarkSide Media

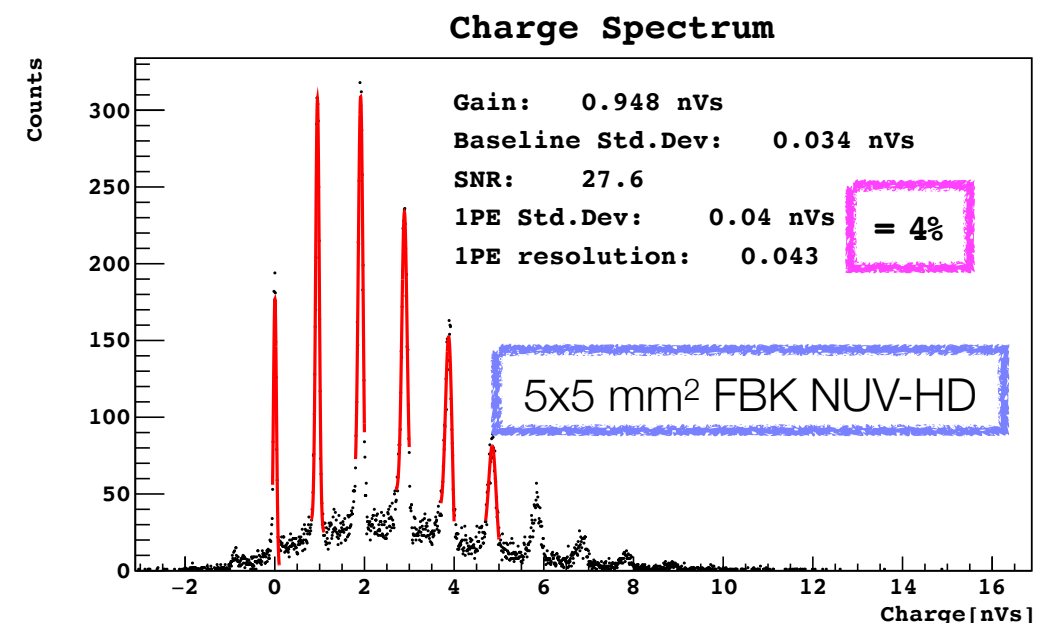
https://www.youtube.com/watch?v=sQS5ovINeEk&ab_channel=DarkSideMedia

SiliconPhoto Multipliers



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

- ▶ 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 $O(10^4\text{-}10^5 \text{ cps/mm}^2 @ 300\text{K})$
- ▶ A signal is generated when N_f SPADs are triggered

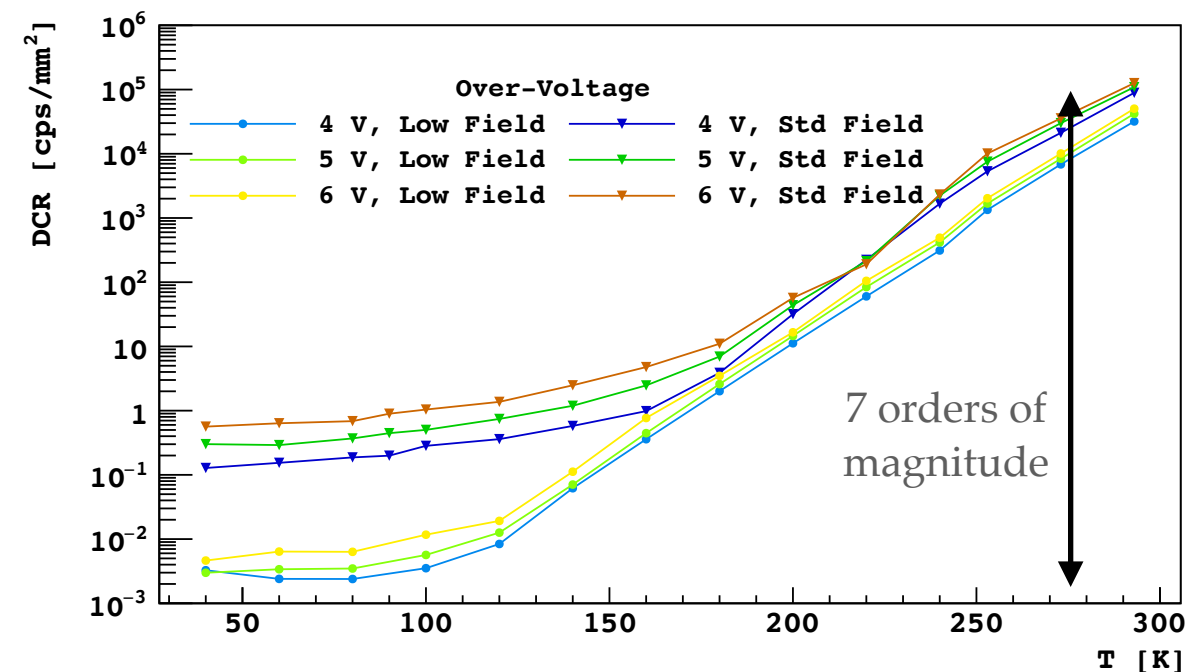
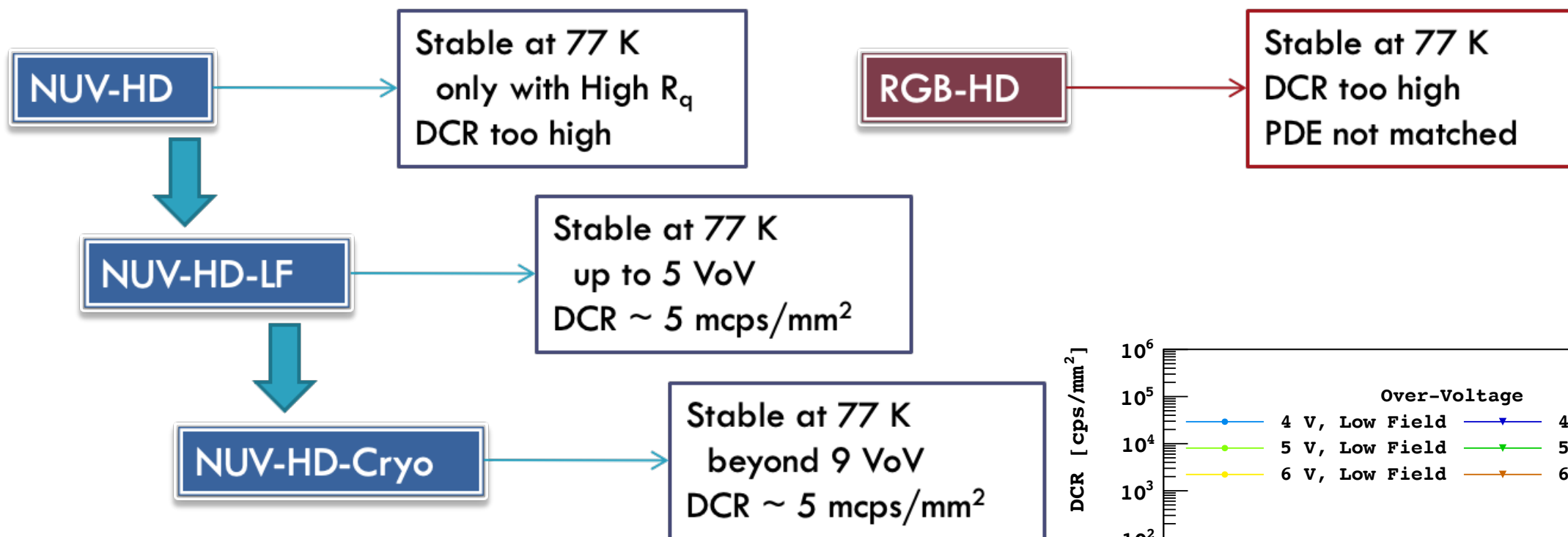


The use of SiPM in particle detectors is continuously increasing

- ▶ We need to use SiPMs at 86K
- ▶ We have a strong R&D on SiPMs centered at LNGS
- ▶ We want PMT replacement with large area and single readout

Collaboration with FBK

- Collaboration with FBK started in 2014
 - A shared R&D path started to improve the performances of SiPMs at cryogenic temperature



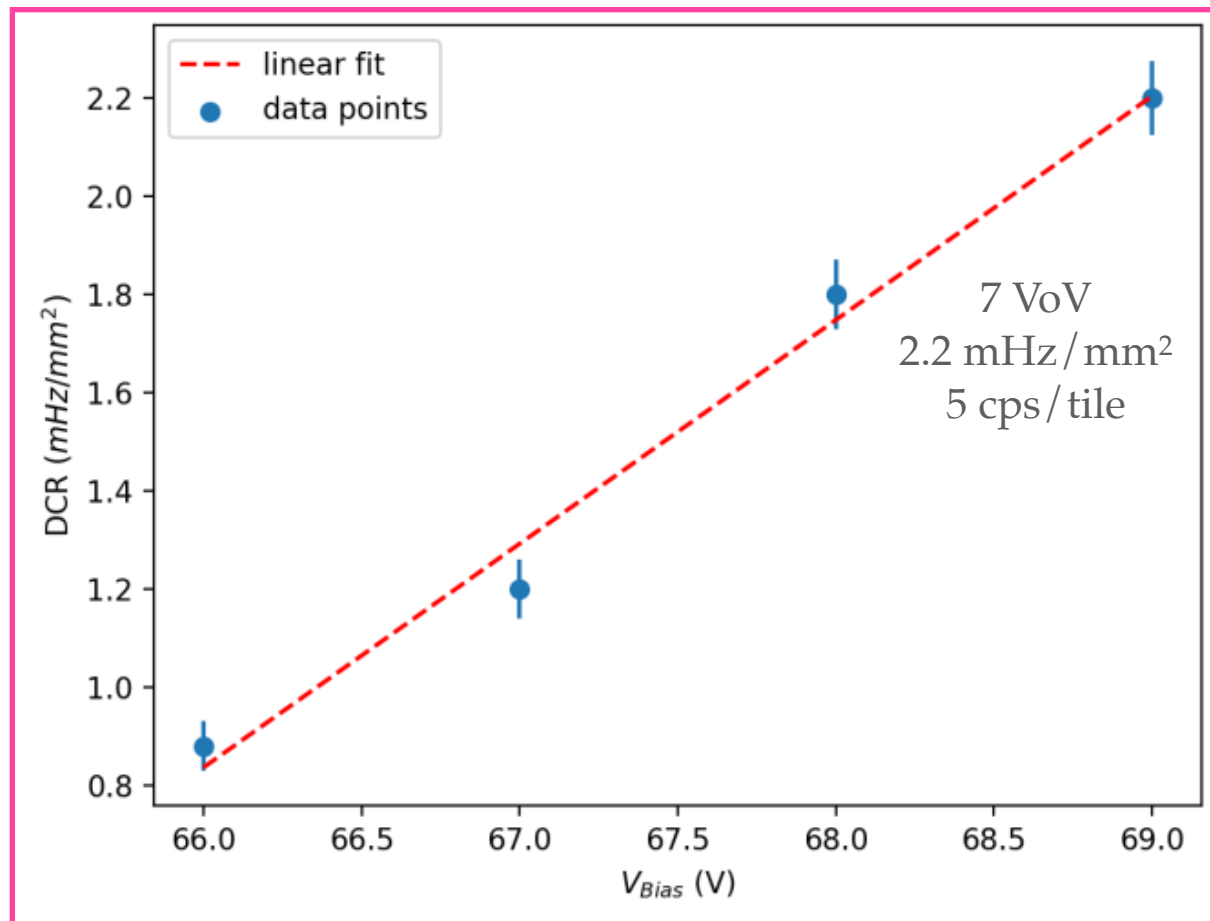
Cryogenic Characterization of FBK HD Near-UV Sensitive SiPMs

IEEE Transactions on Electron Devices, Vol. 64, No. 2, 7807295, 02.2017, p. 521-526

LFoundry

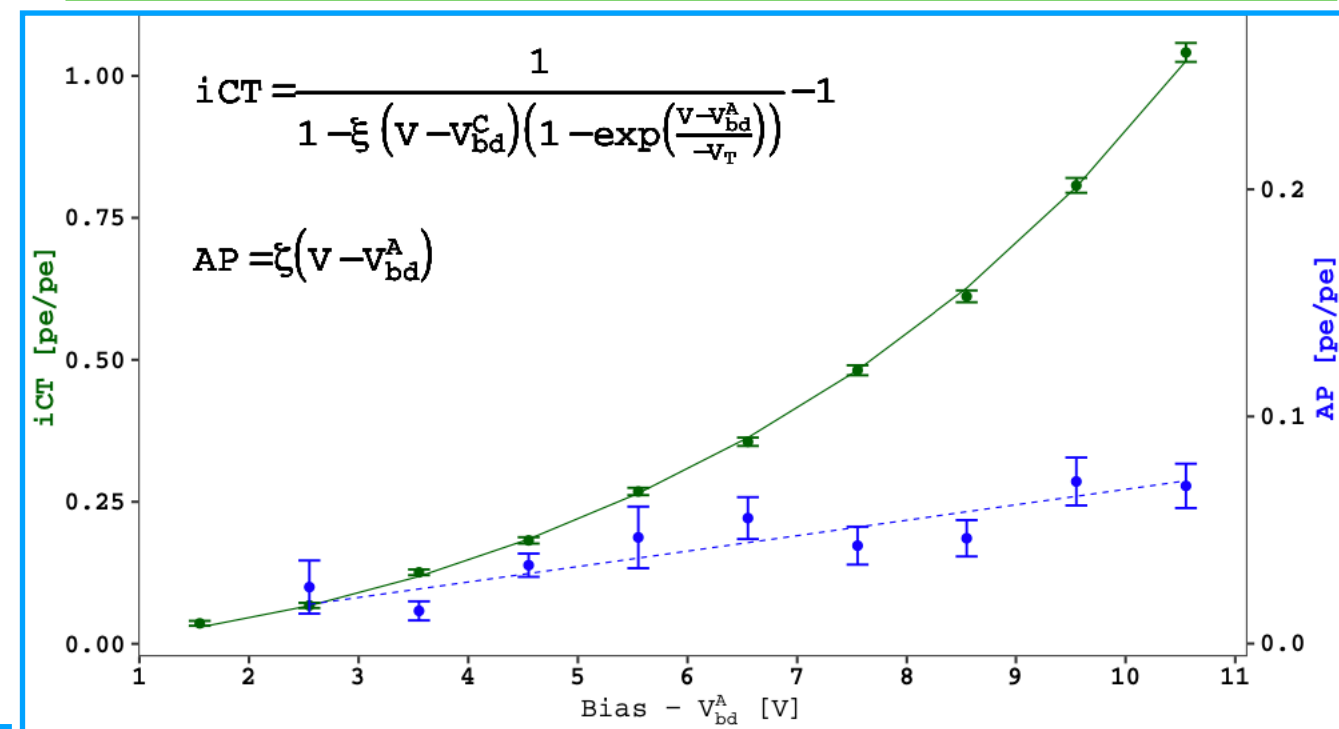
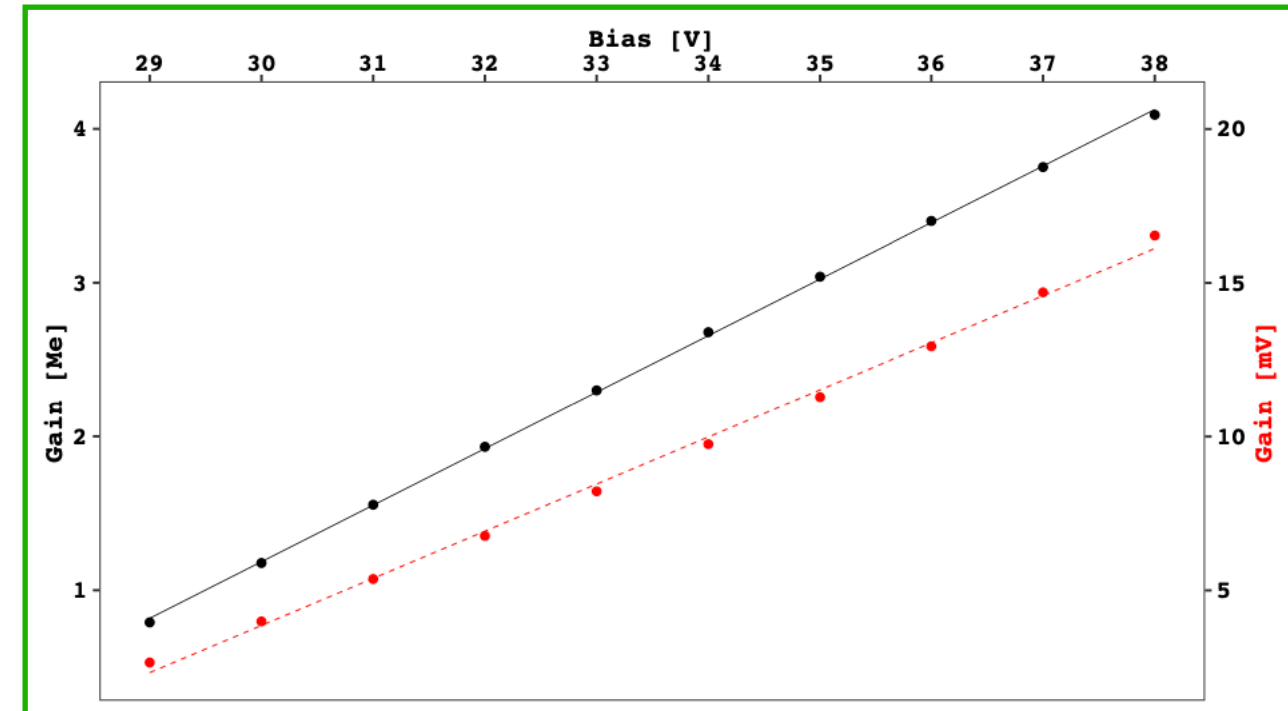
- ▶ For DarkSide-20k around 28 m² of SiPMs are required
 - ▶ The collaboration opted to produce them in an industrial grade foundry
 - ▶ LFoundry won the INFN tender for silicon production
- ▶ FBK started transferring the NUV-HD-Cryo technology to LFoundry in 2018
 - ▶ A first test run was produced and verified in FBK
 - ▶ 1x1 mm² with several variants to qualify the processes
 - ▶ The results are very positive
- ▶ 3 runs 8x12 mm² were delivered within 2020
 - ▶ 25 8" wafers each corresponding to ~ 250 * 75 SiPMs
 - ▶ Smaller issues were found with the backside metallization
 - ▶ other 4 runs produced in 2021 to debug the problem
 - ▶ using gold / silver backside + indium bonding

DCR and correlated noises



Primary dark rate at 77 K as a function of the overvoltage for the NUV-HD-Cryo SiPMs

Gain in amplitude (red dashed) and in charge (black) for the photo-detectors in liquid nitrogen

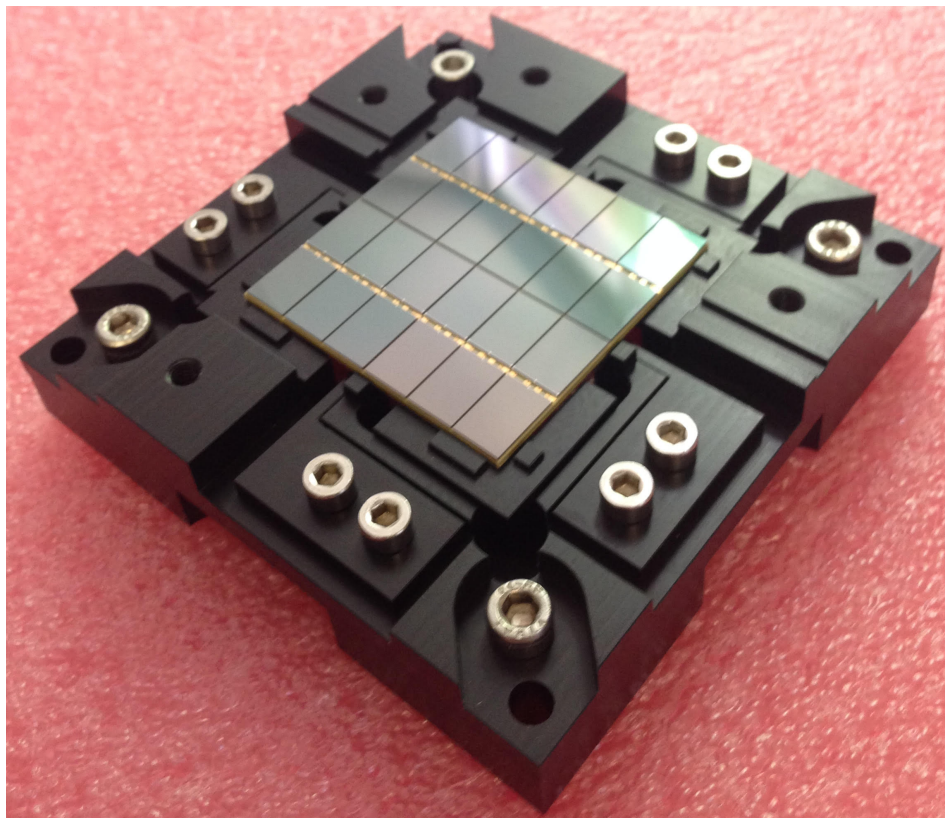


Correlated noises for the NUV-HD-Cryo SiPM at 77 K as excess of photo-electrons measured in a gate of 7 μ s for single photo-electron events

Direct comparison of PEN and TPB wavelength shifters in a liquid argon detector

<https://arxiv.org/pdf/2106.15506.pdf>

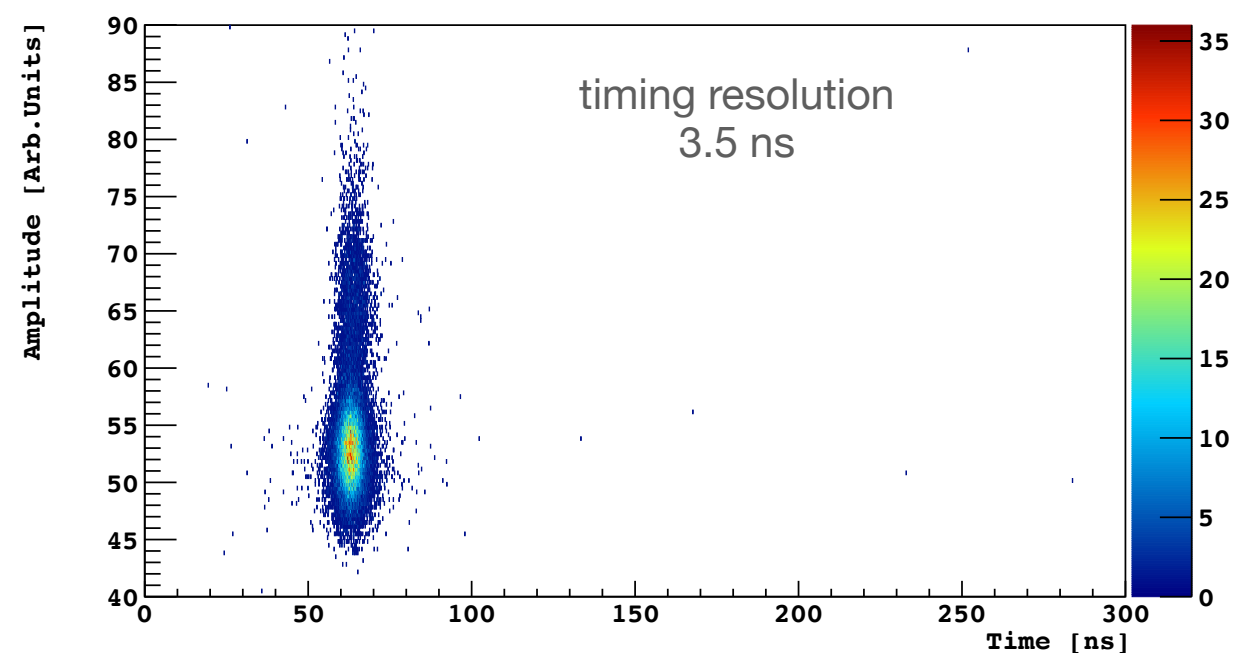
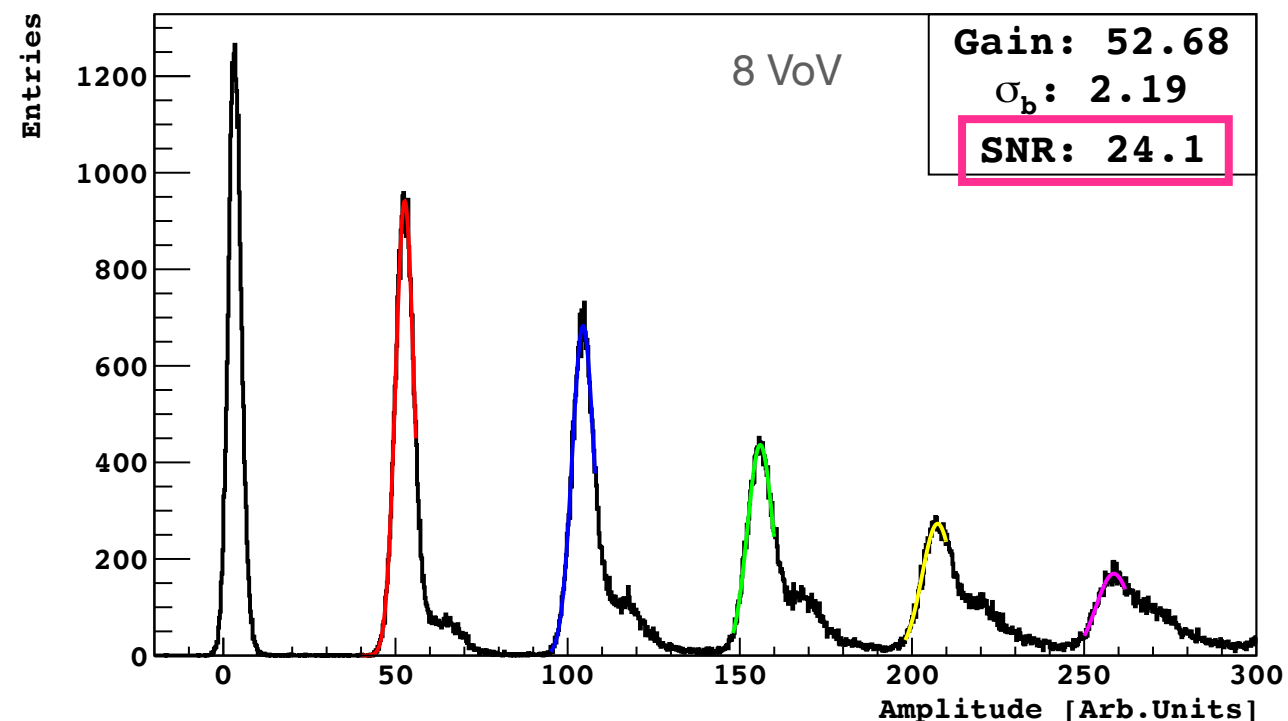
24 SiPM tile



25 cm² TILE formed by 24 SiPMs
in 4 quadrants grouped in a 2s3p ganging
configuration

NUV-HD-Cryo 12 x 8 mm²

SiPMs optimized for LAr temperature, designed in collaboration with
FBK, are now mass produced by LFoundry

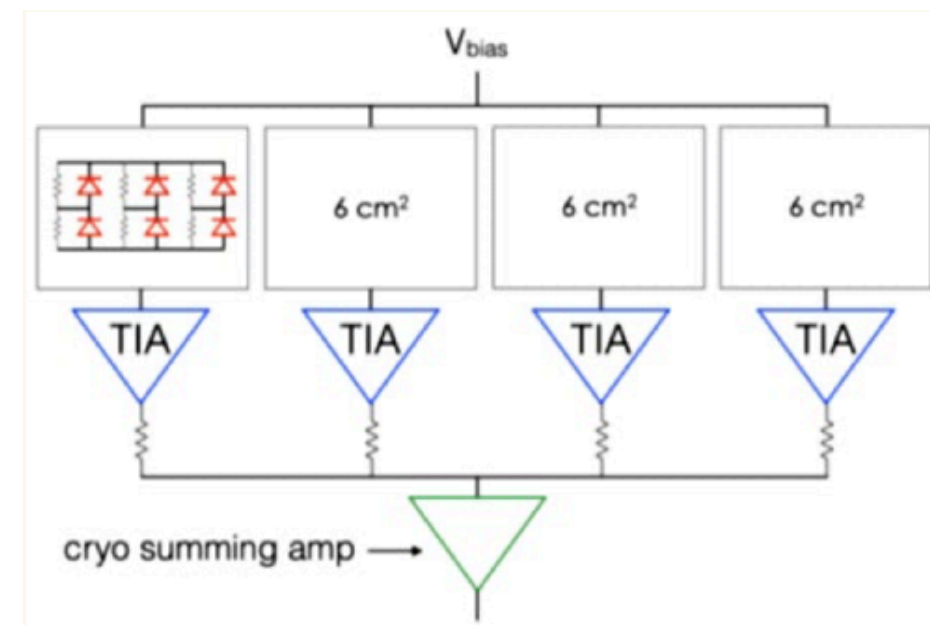
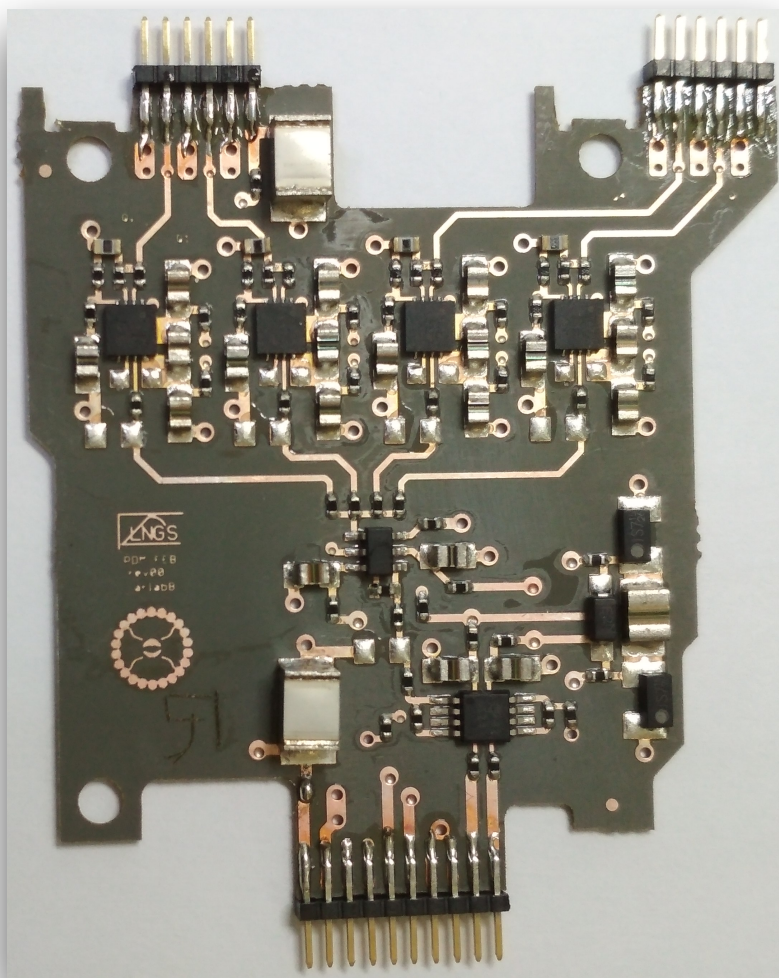


Cryogenic electronics

Front end electronics developed by the collaboration @LNGS.

SiPM can be considered as a current generator with an output capacitance $\sim 50\text{pF}/\text{mm}^2$

- ▶ Transimpedance amplifier (TIA) with high bandwidth and low noise for each quadrant of the tile
- ▶ Each TIA is summed into a single differential output
- ▶ Si/Ge technology active components
- ▶ All the components are screened for radio activity
- ▶ Quantum limited amplifier: the Johnson noise from resistor in the SiPMs dominates

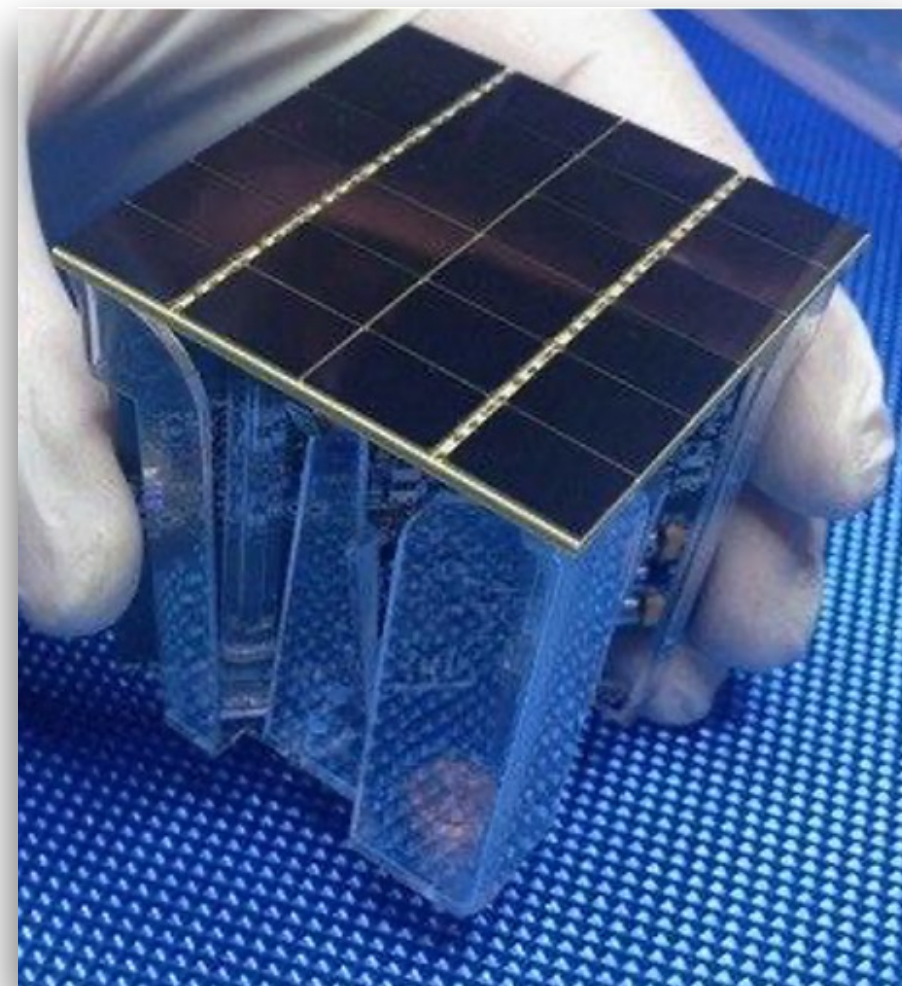


Development of a very low-noise cryogenic pre-amplifier for large-area SiPM devices

IEEE Transactions on Nuclear Science (Volume: 65, Issue: 4, April 2018)

Photo Detector Module

- ▶ The Photo Detector Module (PDM) is the light sensitive unit of DarkSide-20k
 - ▶ 24x SiPM 12x8 mm² mounted on a tile
 - ▶ A front-end cryogenic pre-amplifier with differential output
- ▶ PDMs are sensitive to the single photons
 - ▶ Up to a total of few thousands photons
- ▶ Each PDM is connected to a 120 MS/s digitizer
 - ▶ the acquired waveform is digitally processed
 - ▶ To extract only the photon arrival time & charge
- ▶ Offline the collected times & charges are summed
 - ▶ To reconstruct the original shape of light emission
 - ▶ Extracting the physical data of the interaction



ReD: characterisation of a SiPM based Liquid Argon TPC for directional dark matter detection studies

Yury Suvorov

T12: Detector R&D and Data Handling: Instrumentation, 26 Jul 2021, 17:30

DarkSide-20k and the Future Liquid Argon Dark Matter Program
Bianca Bottino

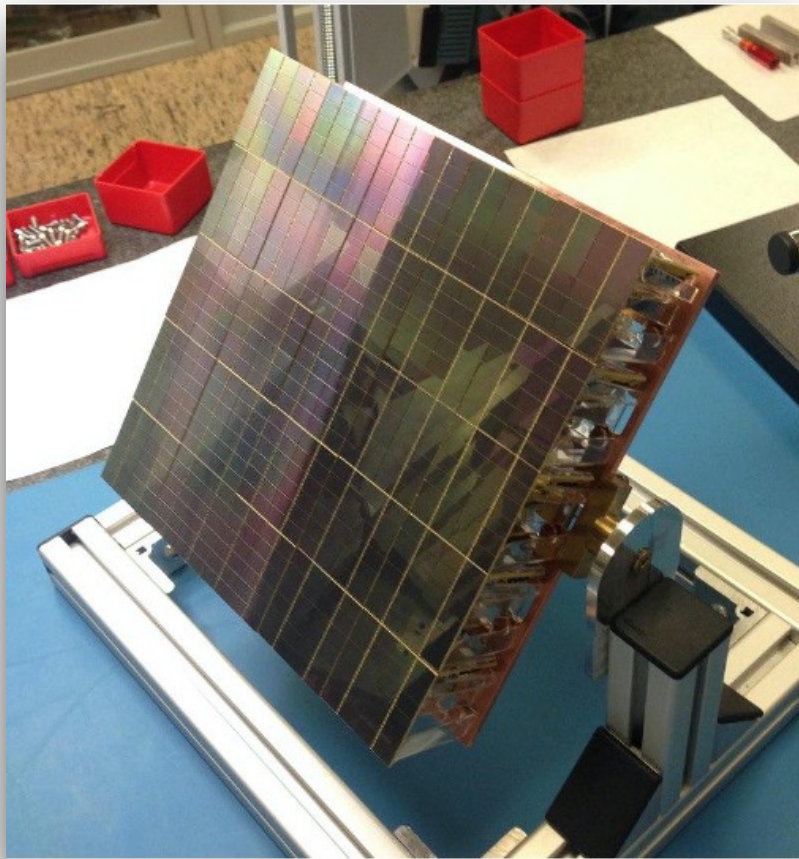
T03: Dark Matter, 27 Jul 2021, 11:10

PDM specifications

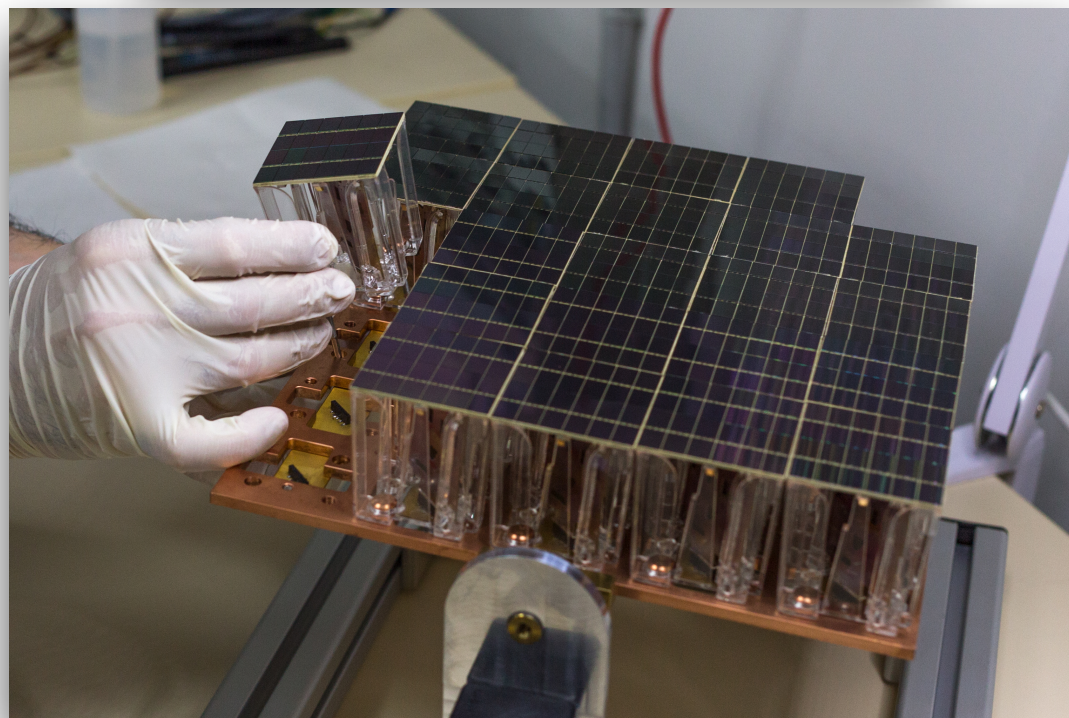
- ▶ The specifications for the PDMs of DS20k require
 - ▶ 5x5 cm² surface
 - ▶ PDE @ 420 nm > 40% -> achieved ~45%
 - ▶ DCR < 200 cps -> achieved < 20
 - ▶ Baseline hit rate ≤ DCR
 - ▶ SNR > 8 -> achieved 25
 - ▶ Timing resolution ~ 10 ns -> achieved 3 ns
- ▶ These parameters directly impact the PSD
 - ▶ In the integration window of 6 μs
 - ▶ 20.7 m² ◦ 6 μs ◦ DCR = 10 pe
 - ▶ Larger random hits could spoil the PSD at low energy

Baseline hit happens when the baseline noise (gaussian) goes above threshold emulating a real photo-electron.
Can be reduced with low noise front-end

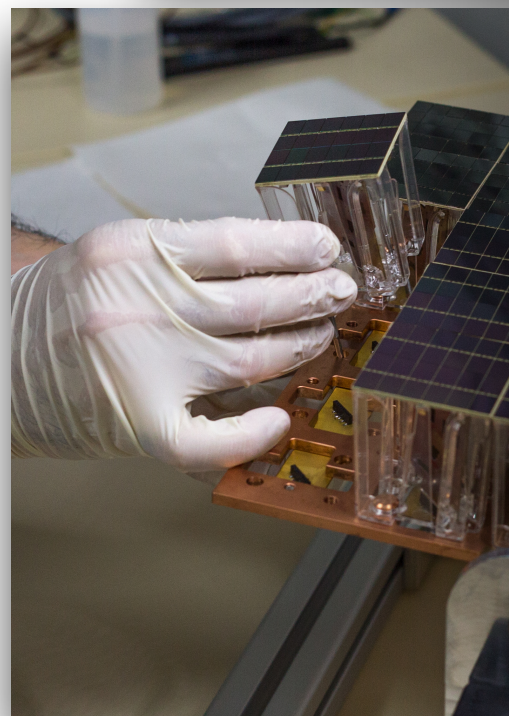
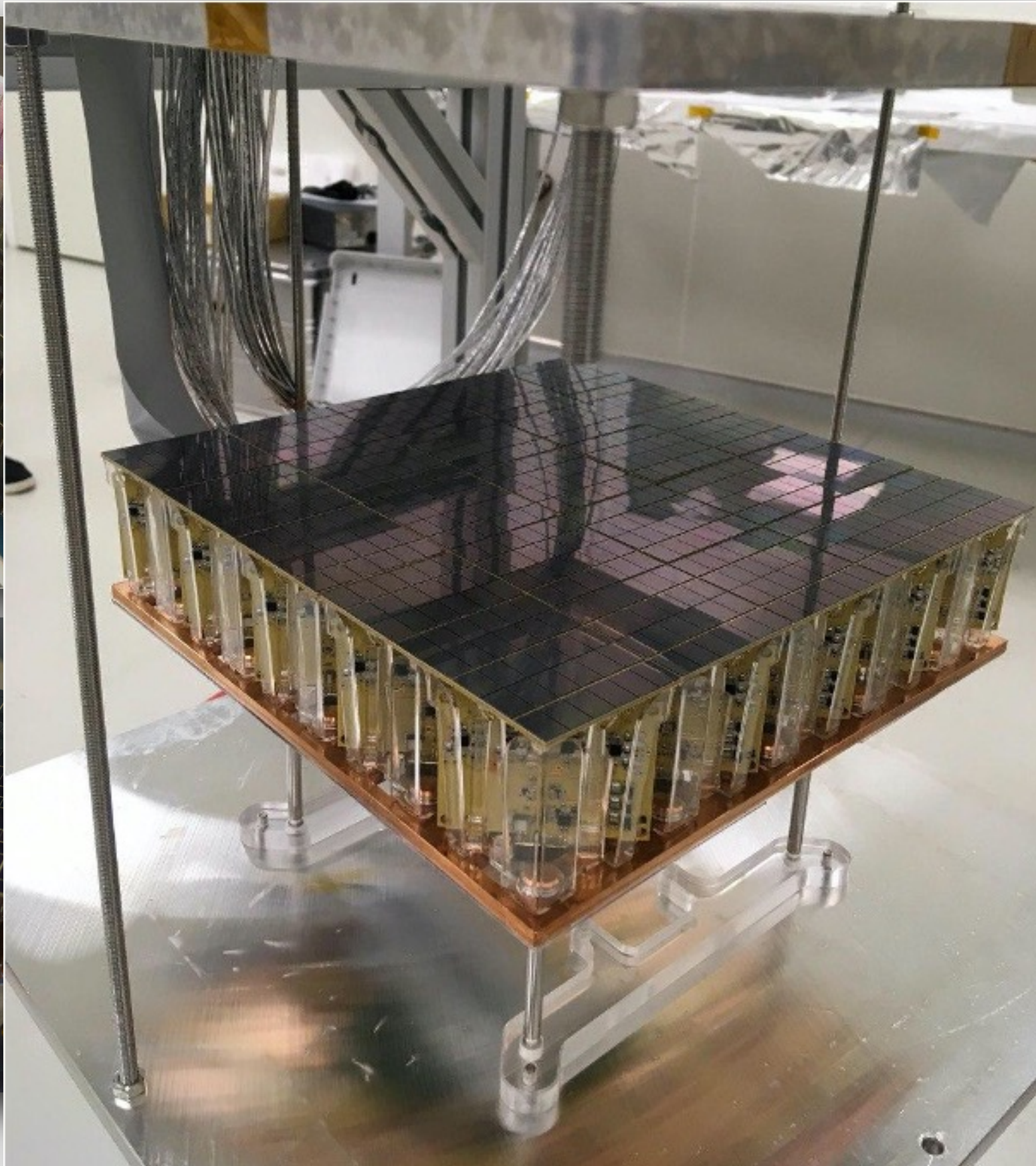
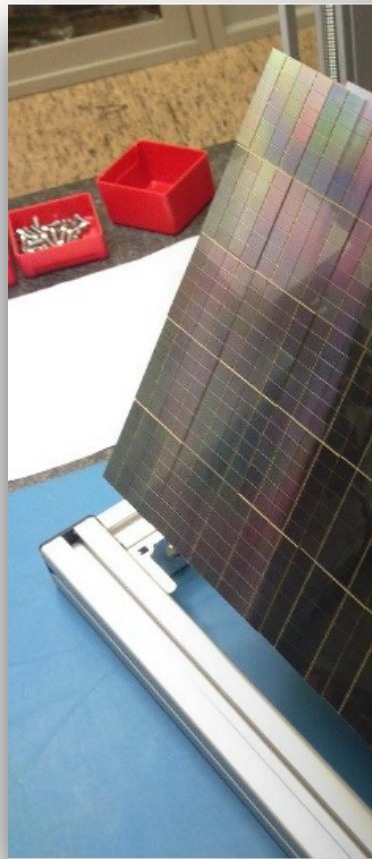
25 PDMs matrix



- ▶ PDMs are mounted on motherboards
 - ▶ 25 PDM per motherboard
- ▶ Each motherboard has
 - ▶ A power distribution hub capable of disabling individually each PDM
 - ▶ Called steering module
 - ▶ A differential to optical linear transmitter
 - ▶ Signals are extracted over high purity optical fibers
 - ▶ No faraday cage penetration, no ground loop
→ less noise
- ▶ The PDMs are installed on a high purity copper frame



25 PDMs matrix



boards

able of disabling

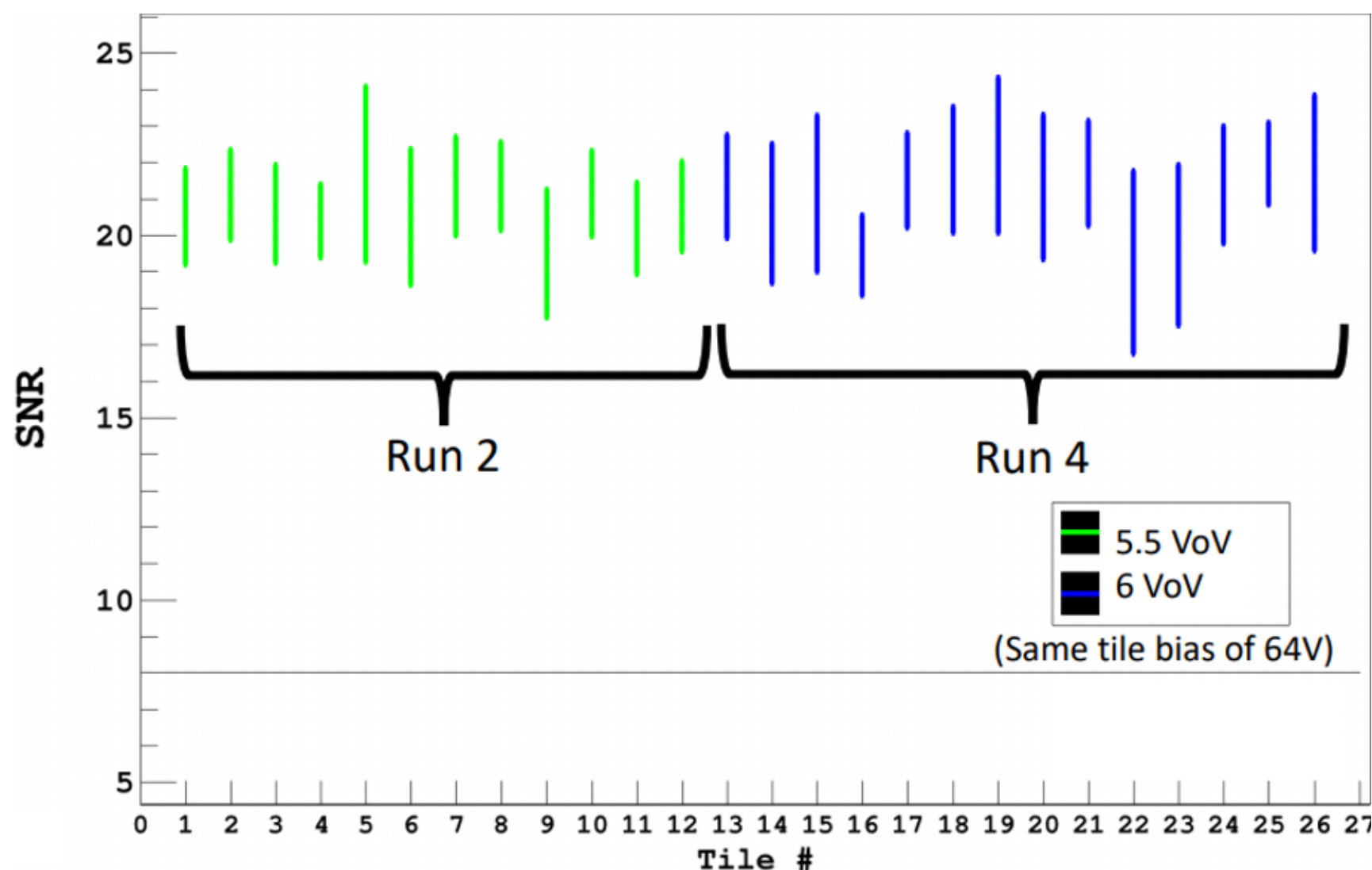
r transmitter

high purity optical

on, no ground loop

h purity copper

MB performances

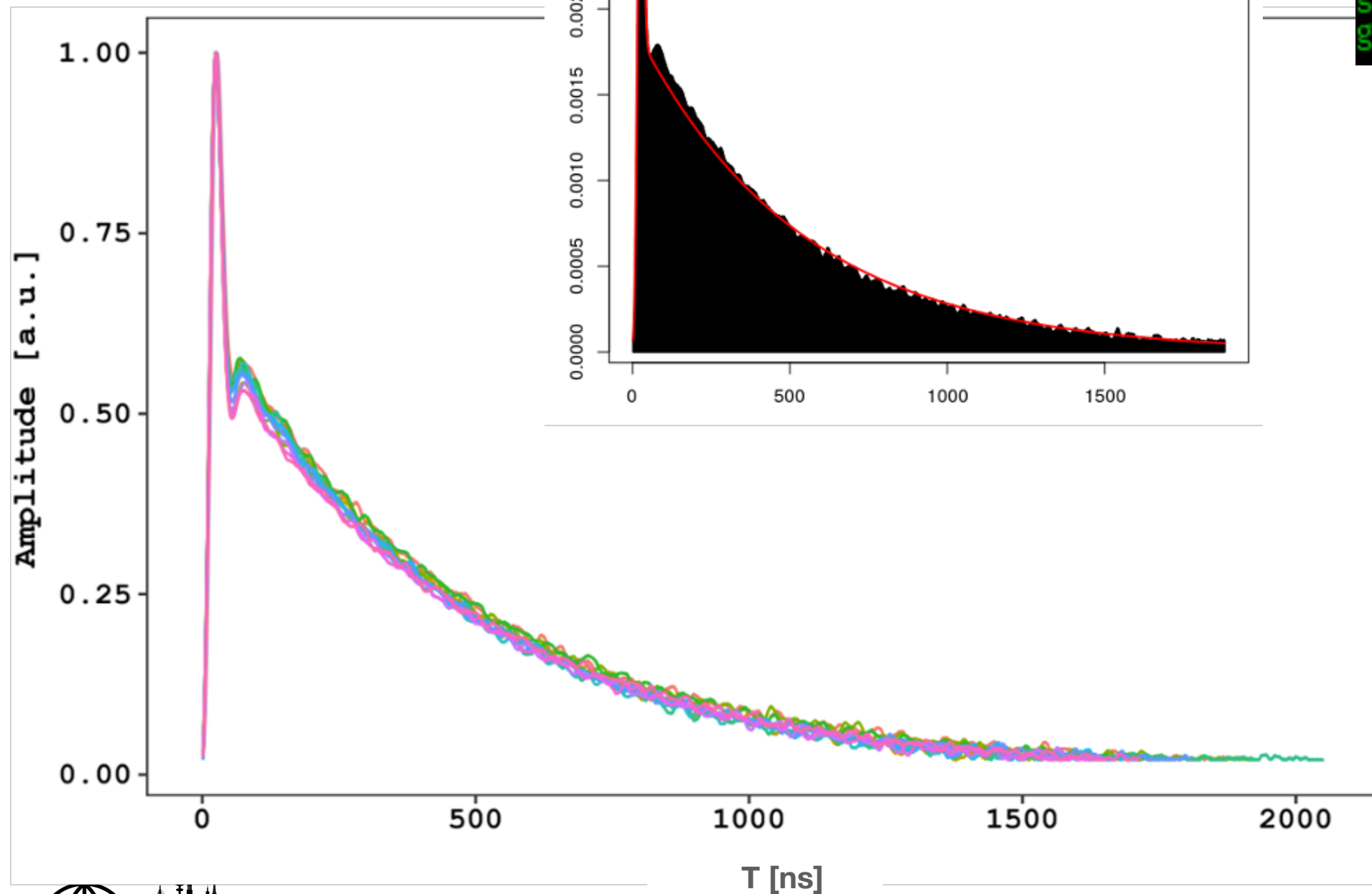


NUV-HD-LF 30 μm 5 M Ω

- ▶ MB2 built from 2 FBK runs
 - ▶ The break-down voltage of the 2 runs is 0.5 V different
- ▶ Darkside-20k MBs have a common bias
 - ▶ Run 2 SiPM are slightly underbiased
- ▶ The performances are well beyond expectation
 - ▶ SNR \sim 20
 - ▶ Timing \sim 3 ns
 - ▶ 600 SiPMs @ 77 K

Signal shape

NUV-HD-LF 30 μm 5 M Ω



Parameters:

	Estimate	Std. Error
emg.w	9.440e-01	3.632e-03
emg.m	3.141e+01	1.319e+00
emg.sd	3.954e+00	8.817e-01
emg.t	5.224e+02	1.156e+00
gaus.w	6.486e-02	2.995e-03
gaus.m	2.411e+01	4.150e-01
gaus.sd	8.403e+00	1.530e-01

Tile:

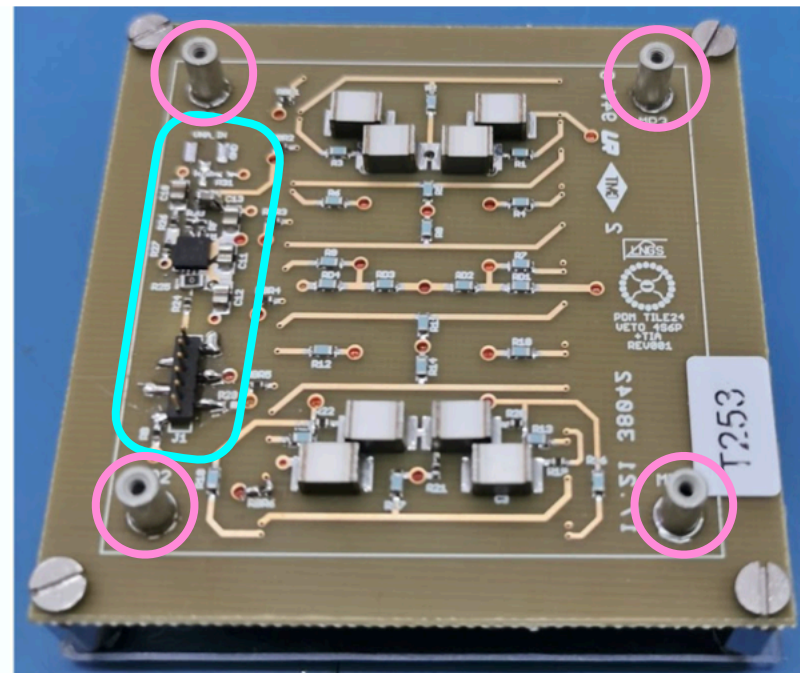
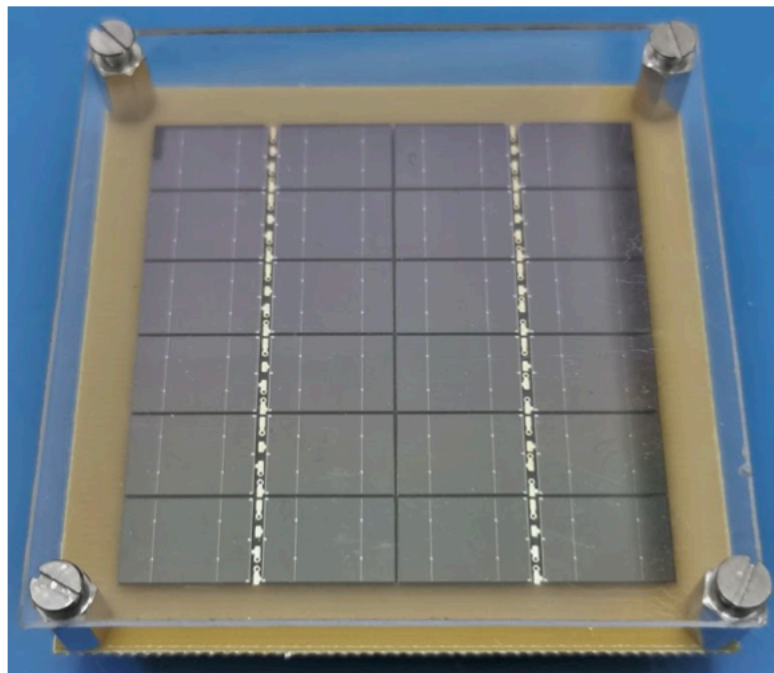
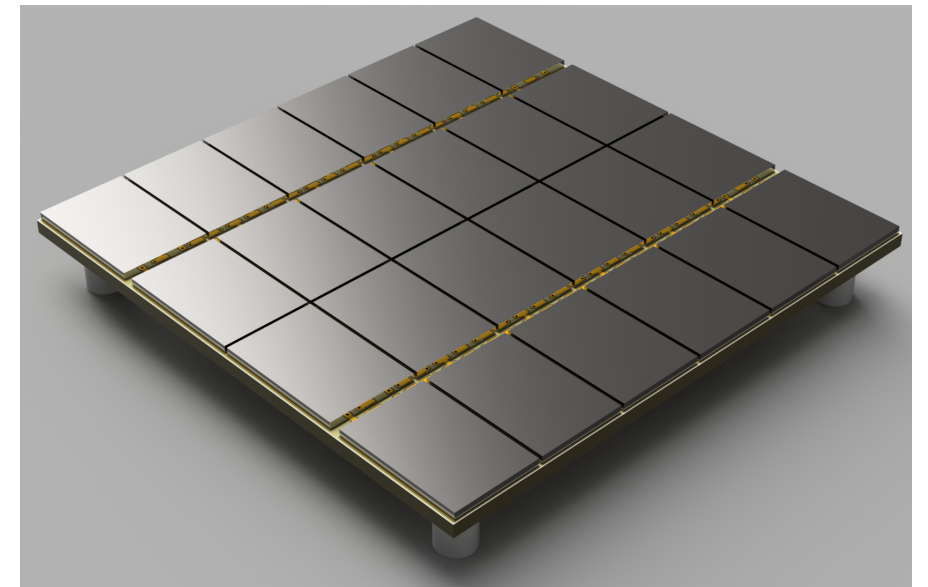
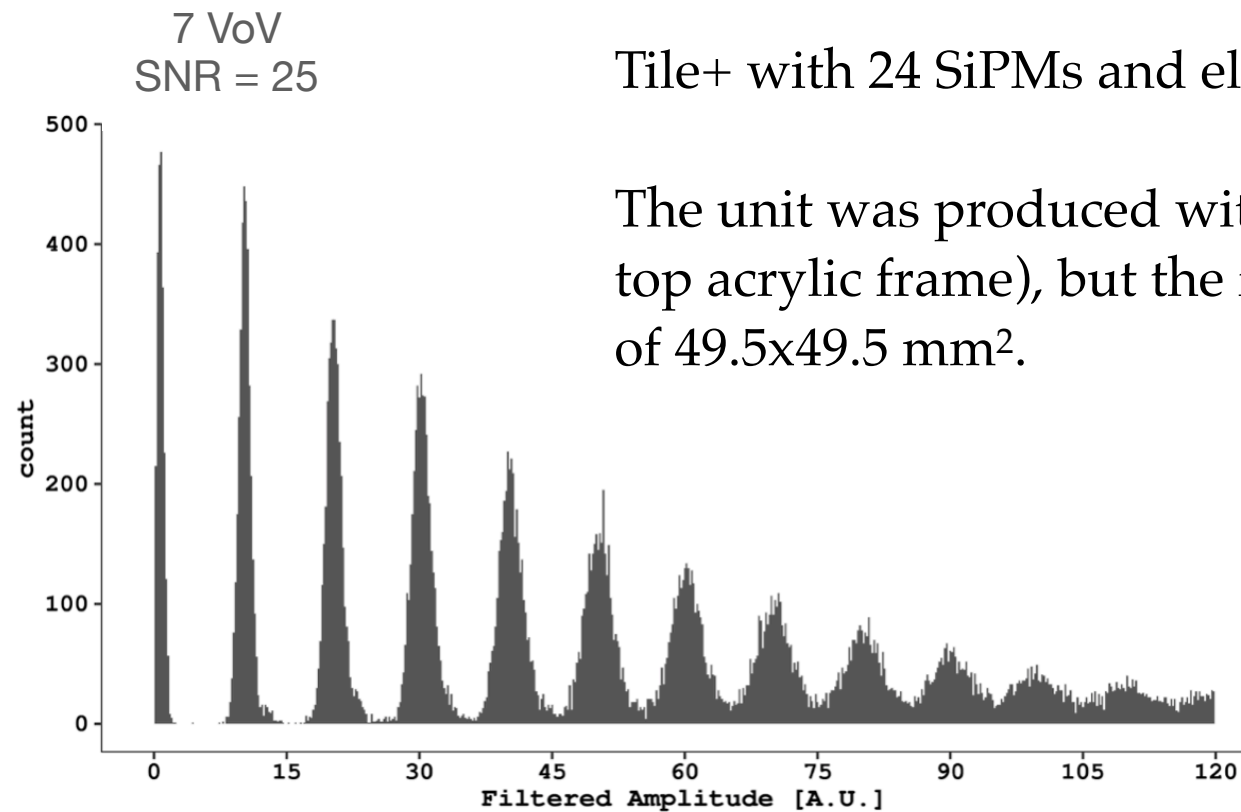
- 29
- 30
- 31
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- 41
- 42

bandwidth 26 MHz

Tile+

Tile+ with 24 SiPMs and electronic components on the backside.

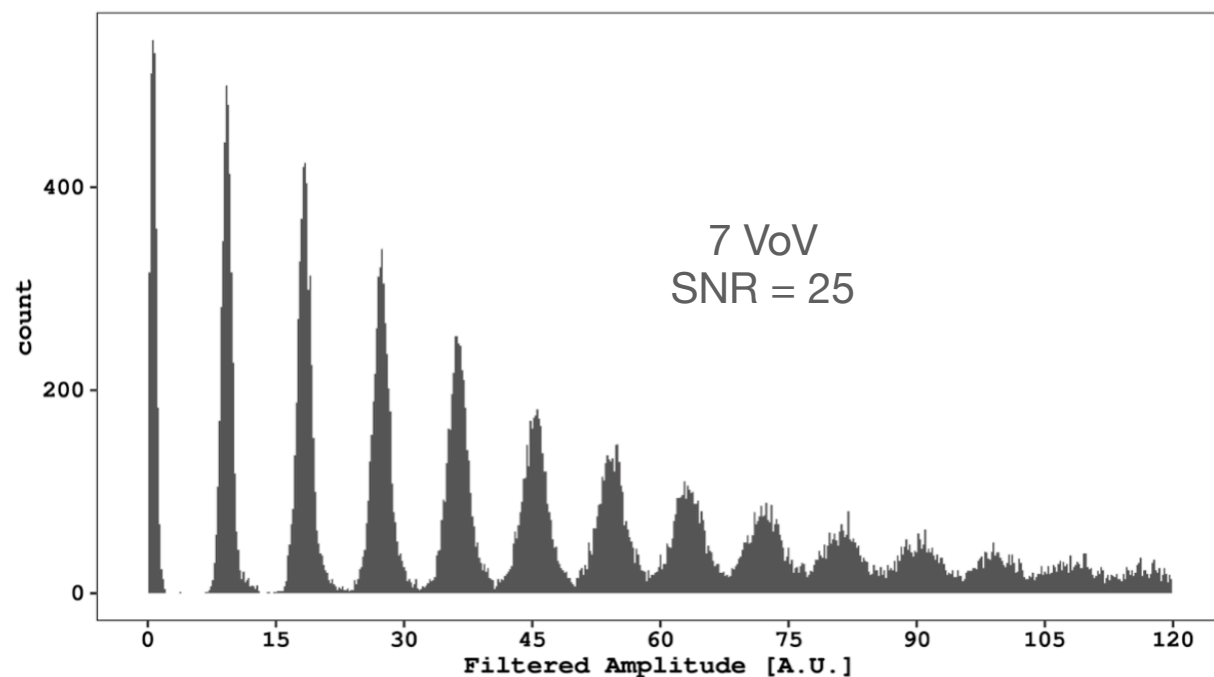
The unit was produced with borders (5 mm) to simplify the testing (including a top acrylic frame), but the final version will be borderless with a total dimension of 49.5x49.5 mm².



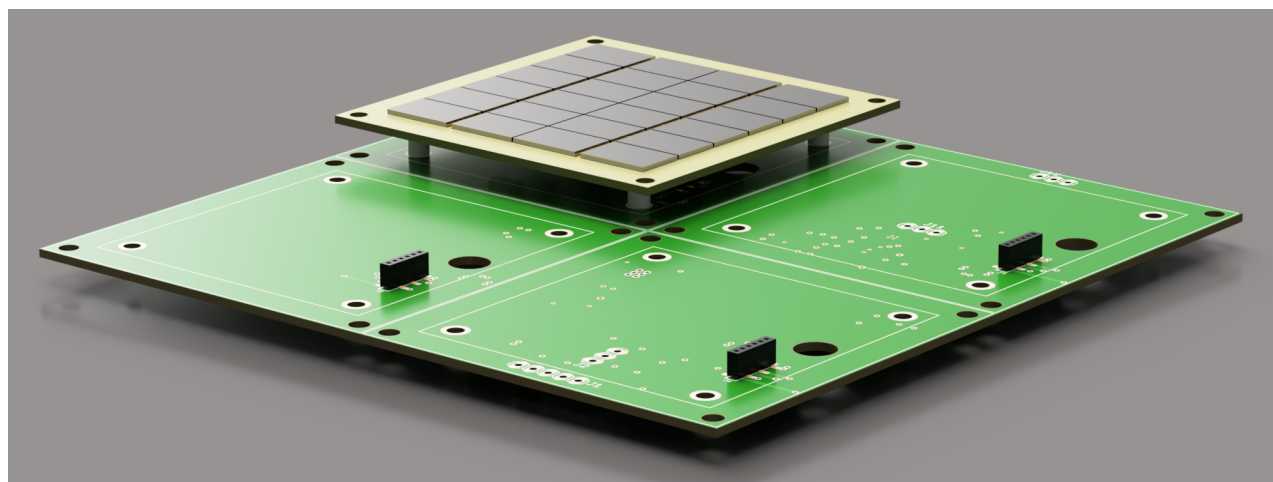
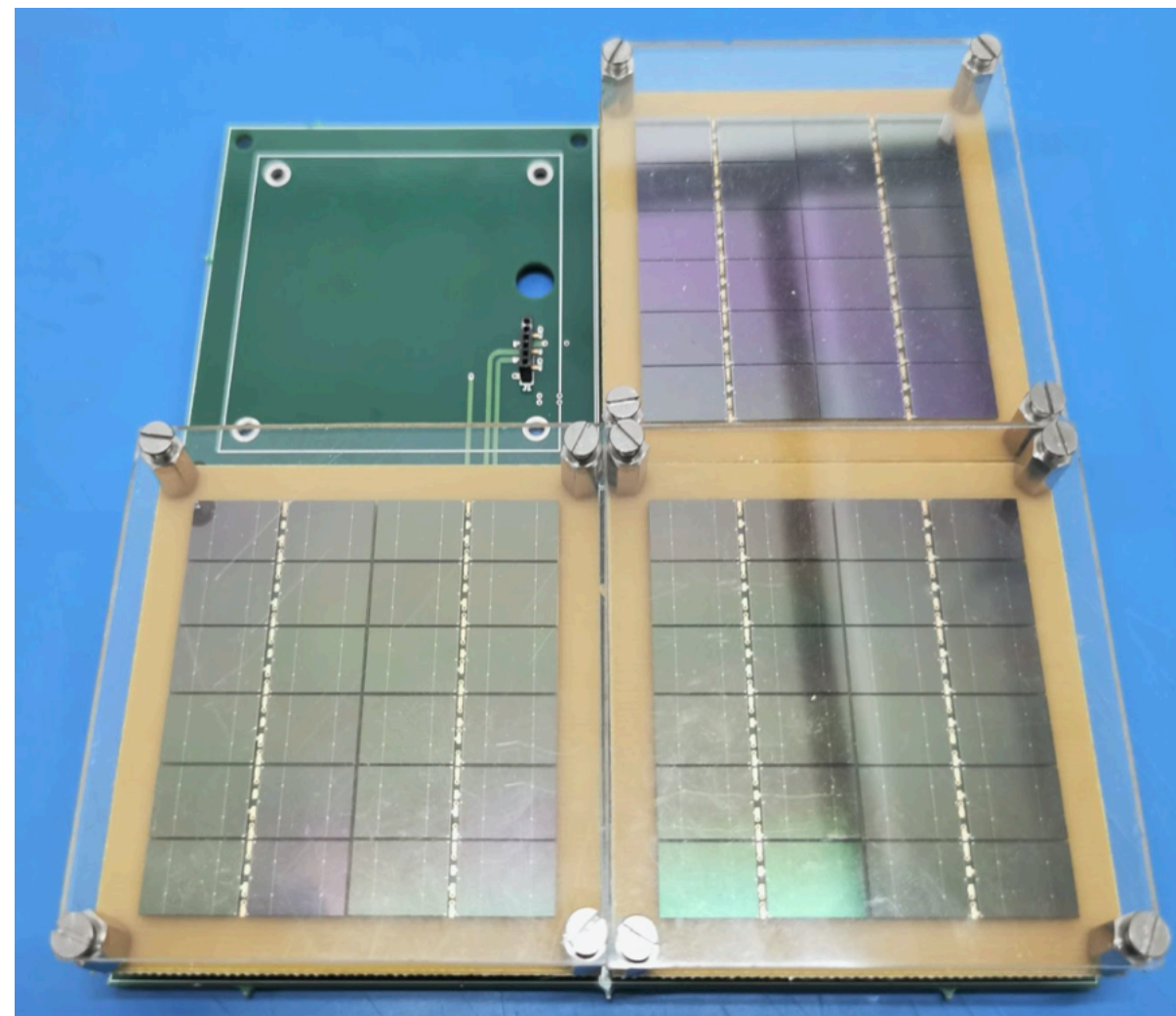
TIA and the connector on the left side

Four 5x3 mm threaded pillars are soldered to the PCB to allow a reliable connection with the motherboard

PDU/4

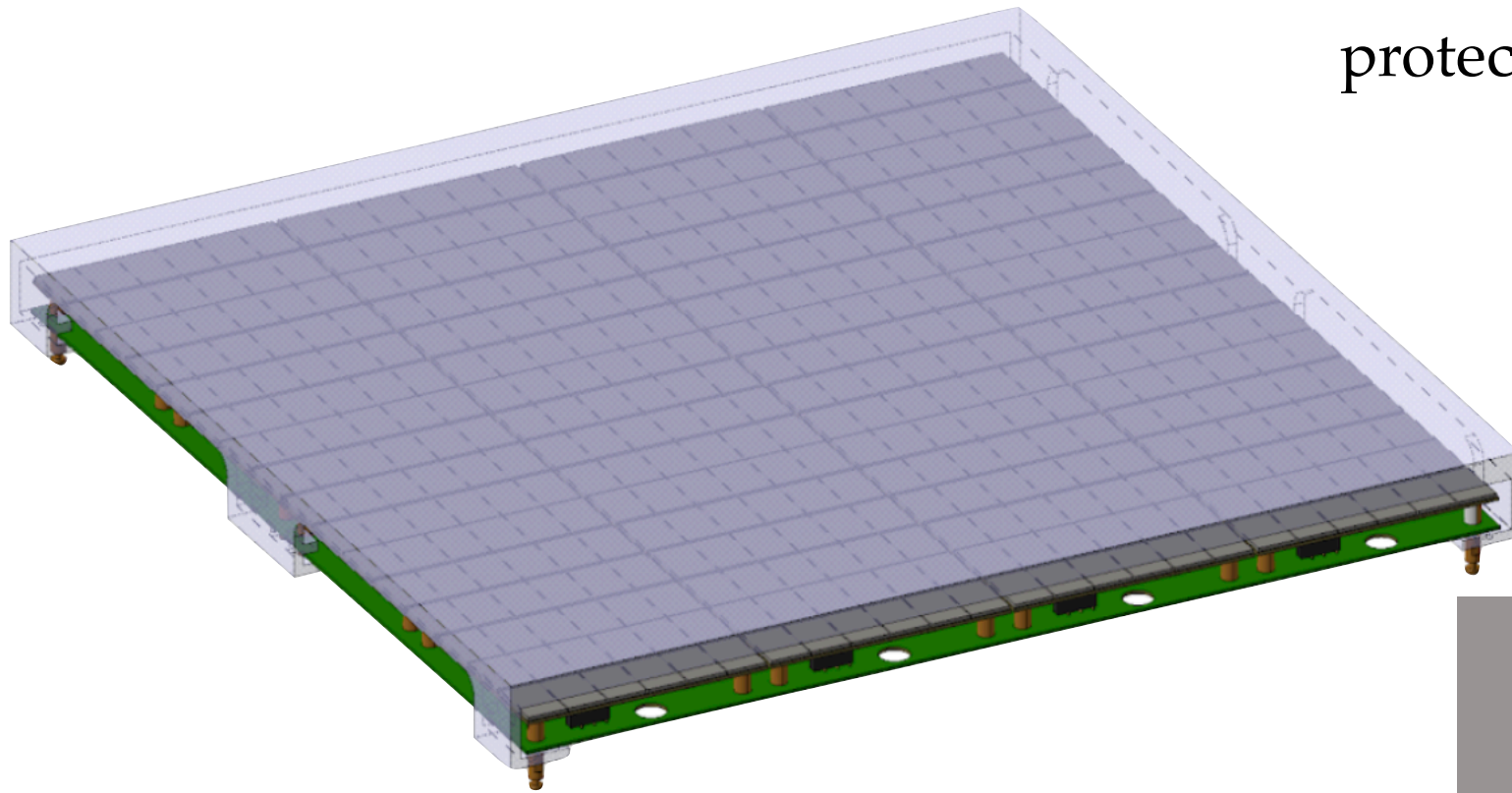


4 tiles summed in a single analog channel corresponding to 100 cm²



Three tile+ are mounted with the protection border to simplify the R&D. The final MB+ will assemble 16 tile+ without empty spaces

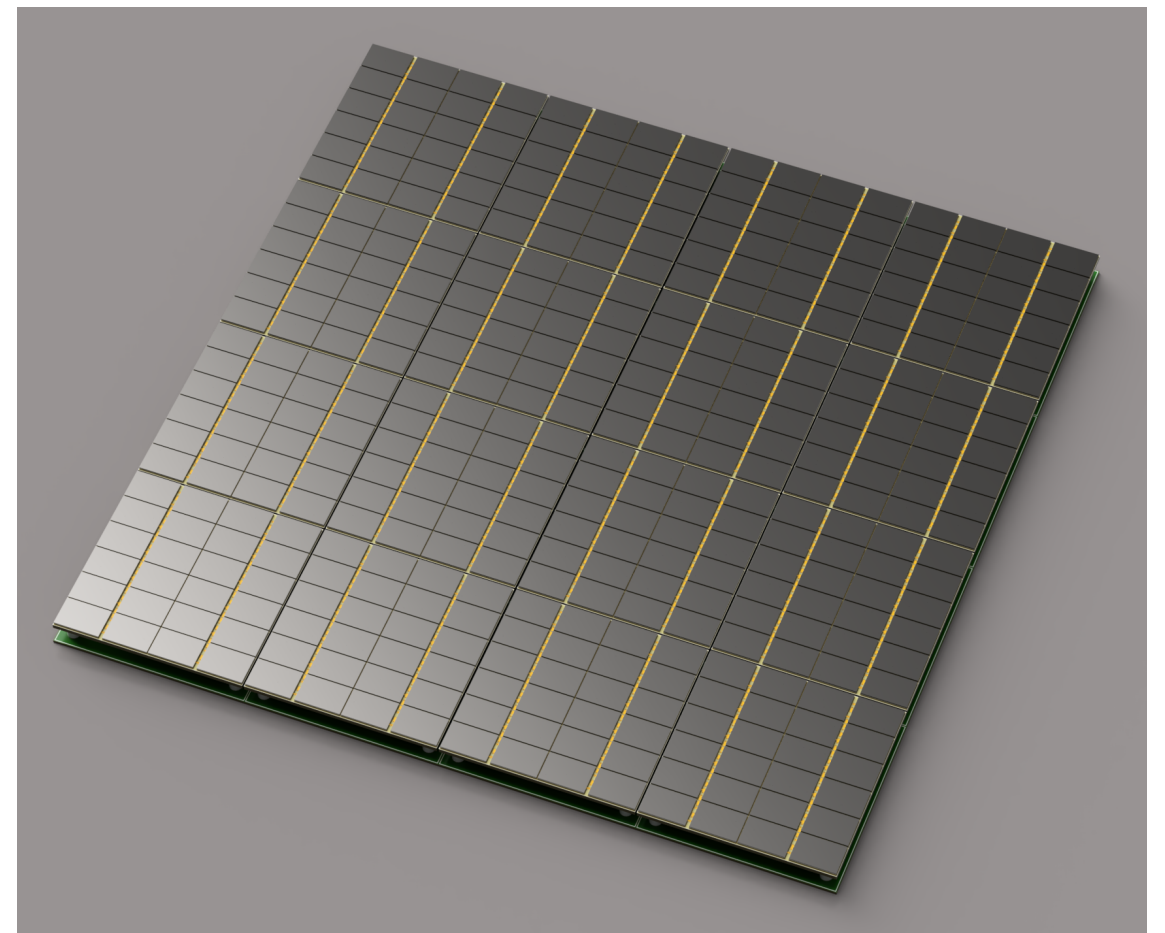
PDU+



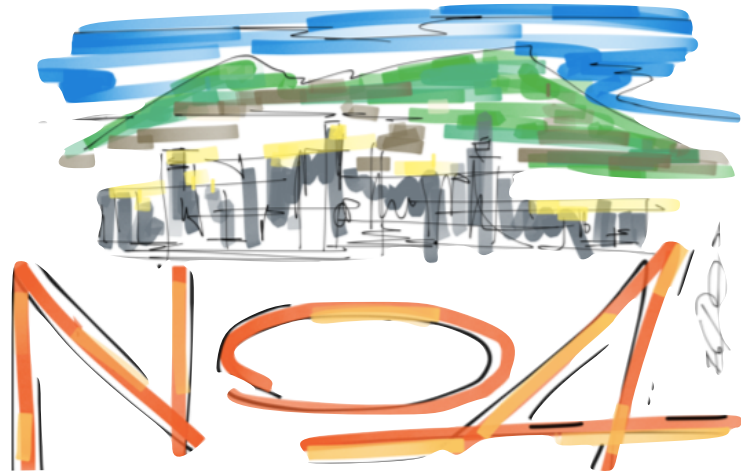
protection in acrylic for the wire bondings

all components are firmly connected by the pillars

- ▶ smaller ($20 \times 20 \text{ cm}^2$ vs $25 \times 25 \text{ cm}^2$),
- ▶ lightweight (less than 350 g)
- ▶ made out of only 2 components: the tile+ and the MB+
- ▶ total height of a PDU+ is 1.5 cm



Mass production



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 with 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

We are now ready to build 12000 tiles of 25 cm².

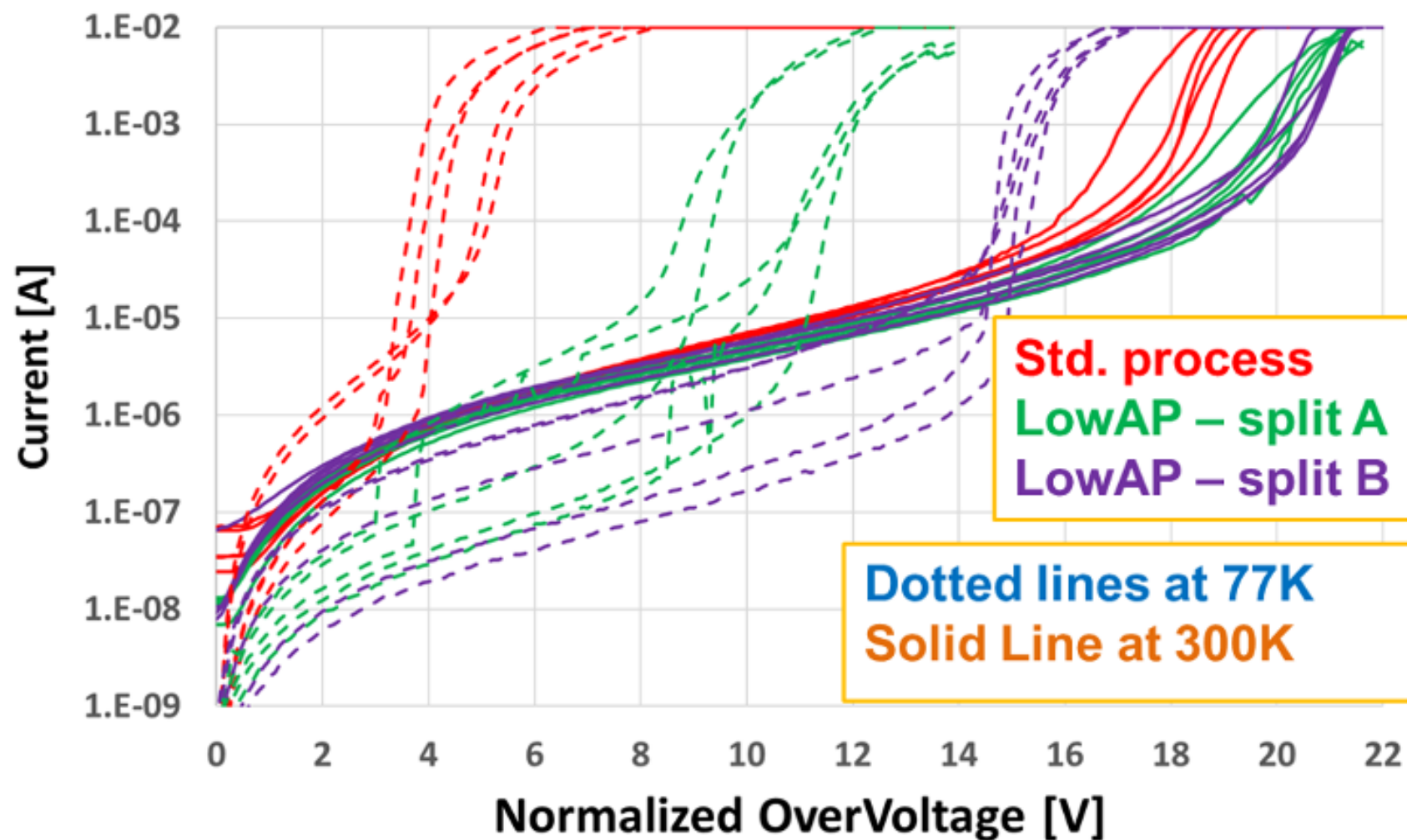
DarkSide 20k facts

DS-20k TPC Dimensions	
TPC Drift Length	350 cm
Octagonal Inscribed Circle Diameter	355 cm
Total LAr Mass	51.1 t
Active LAr Mass	49.7 t
Fiducial Cut Distance (vertical)	70 cm
Fiducial Cut Distance (radial)	30 cm
Fiducial LAr Mass	20.2 t
Nominal TPC Fields and Settings	
Drift Field	200 V/cm
Extraction Field	2.8 kV/cm
Luminescence Field	4.2 kV/cm
Cathode Voltage	-73.8 kV
Extraction Grid Voltage	-3.8 kV
Anode Voltage	ground
Gas Pocket Thickness	7 mm
Grid Wire Spacing	3 mm
Grid Optical Transparency	97%
SiPM PDM	
Number of PDM on TPC Top	4140
Number of PDM on TPC Bottom	4140
PDM Effective Area	50 x 50 mm ²

ProtoDUNE Cryostat parameters for AAr	
ProtoDUNE Cryostat inner width	8548 mm
ProtoDUNE Cryostat inner height	7900 mm
LAr height in ProtoDUNE Cryostat	7500 mm
Total AAr in ProtoDUNE Cryostat	700 t
ProtoDUNE Cryostat Insulation per unit area	6.5 W/m ²
Thermal Heat Load of ProtoDUNE Cryostat	2.7 kW
TPC PDM Cold Electronics Power	1.5 kW
Veto PDM Cold Electronics Power	0.5 kW
AAr System Design Mass Circulation Speed	10000 stdL/min
Minimum heat recovery efficiency of AAr heat exchanger	>95%
AAr Turn Over Time	30 d
Total Cooling Power Required	10 kW
LAr boiling threshold at 3 m depth	60 mW/cm ²
Minimum AAr condenser cooling power to hold LAr inventory	2.7 kW
ProtoDUNE AAr top pressure	1.075 bar

NUV-HD Cryo

- ▶ The main limitation of NUV-HD-LF is the narrow overvoltage for stable operation at 80 K with short recharge time (small R_q)
 - ▶ 5 VoV with recharge time ~ 300 ns



- ▶ NUV-HD-Cryo were developed to overcome this limitation
 - ▶ Up to 14 VoV

NOA

Cryo probe

Dicer

Flip chip bonder

Wire bonder

total area
~ 400 m²

Pick&Place
+
Reflow oven

Work tables