FONDAZIONE BRUNO KESSLER

FUTURE BUILT ON KNOWLEDGE

Development and characterization of customized NUV-HD-Cryo SiPMs for the DUNE experiment

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Presentation
Outline

1. ## FBK Silicon photomultipliers
   - General info
   - Applications
   - DUNE requirements and FBK SiPM Technologies

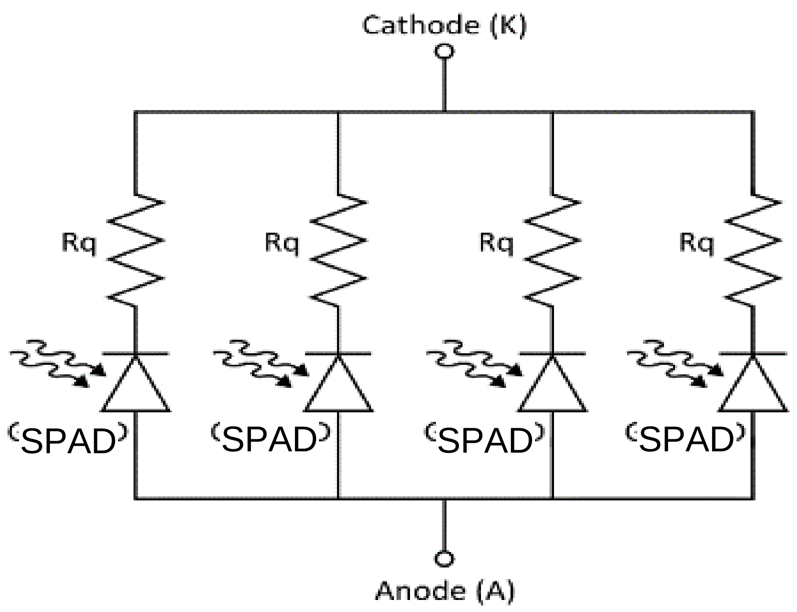
2. ## DUNE SiPM characterization
   - Room temperature characterization
   - Cryogenic characterization

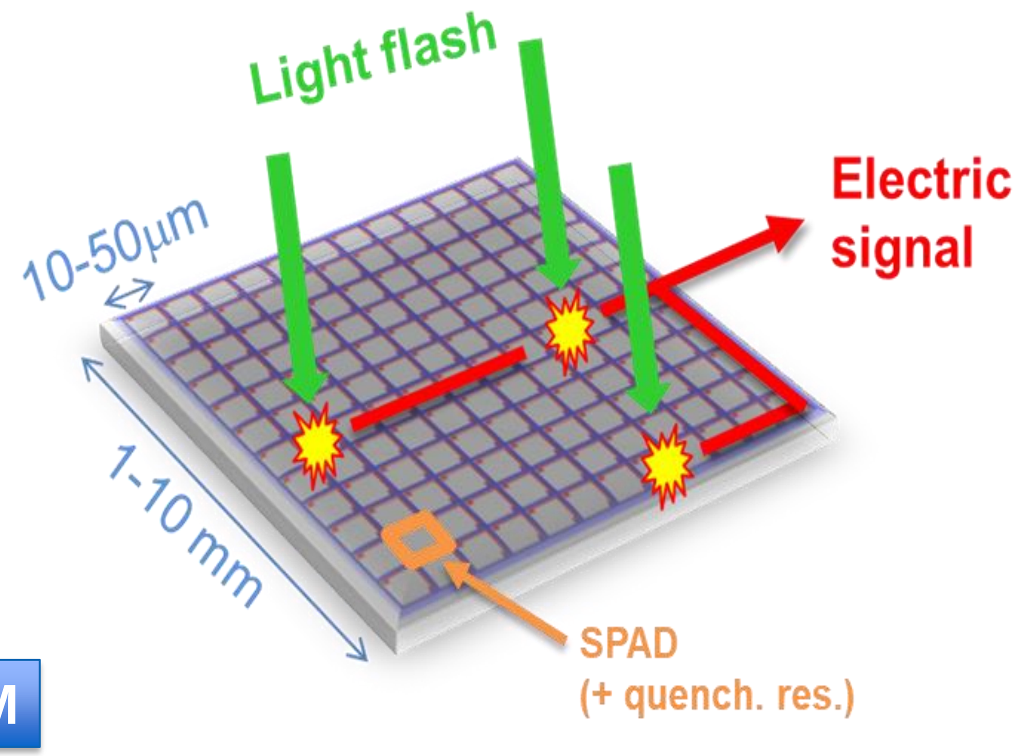
3. ## Wafer level measurements
   - Breakdown voltage
   - Dark current at 5V overvoltage
   - Value of quenching resistor

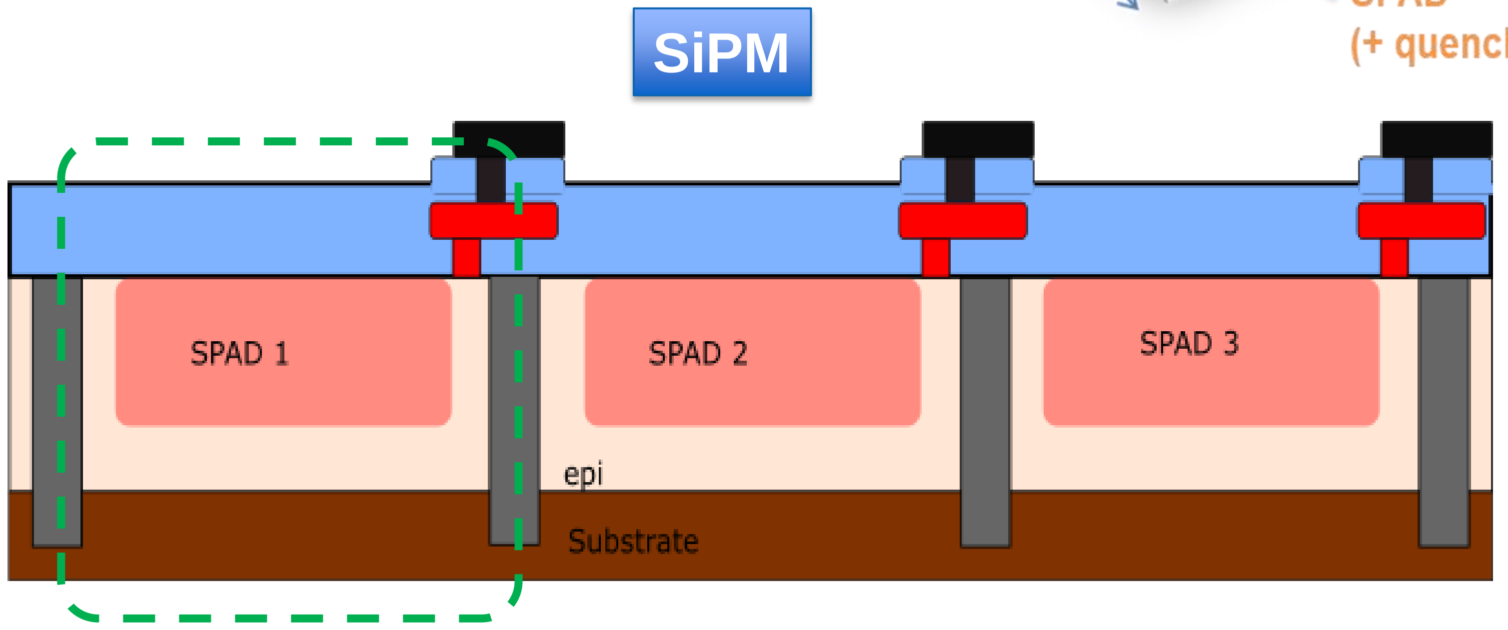
4. ## Conclusions

1. FBK Silicon Photomultipliers

FBK Silicon Photomultipliers
Silicon Photomultipliers (SiPM)

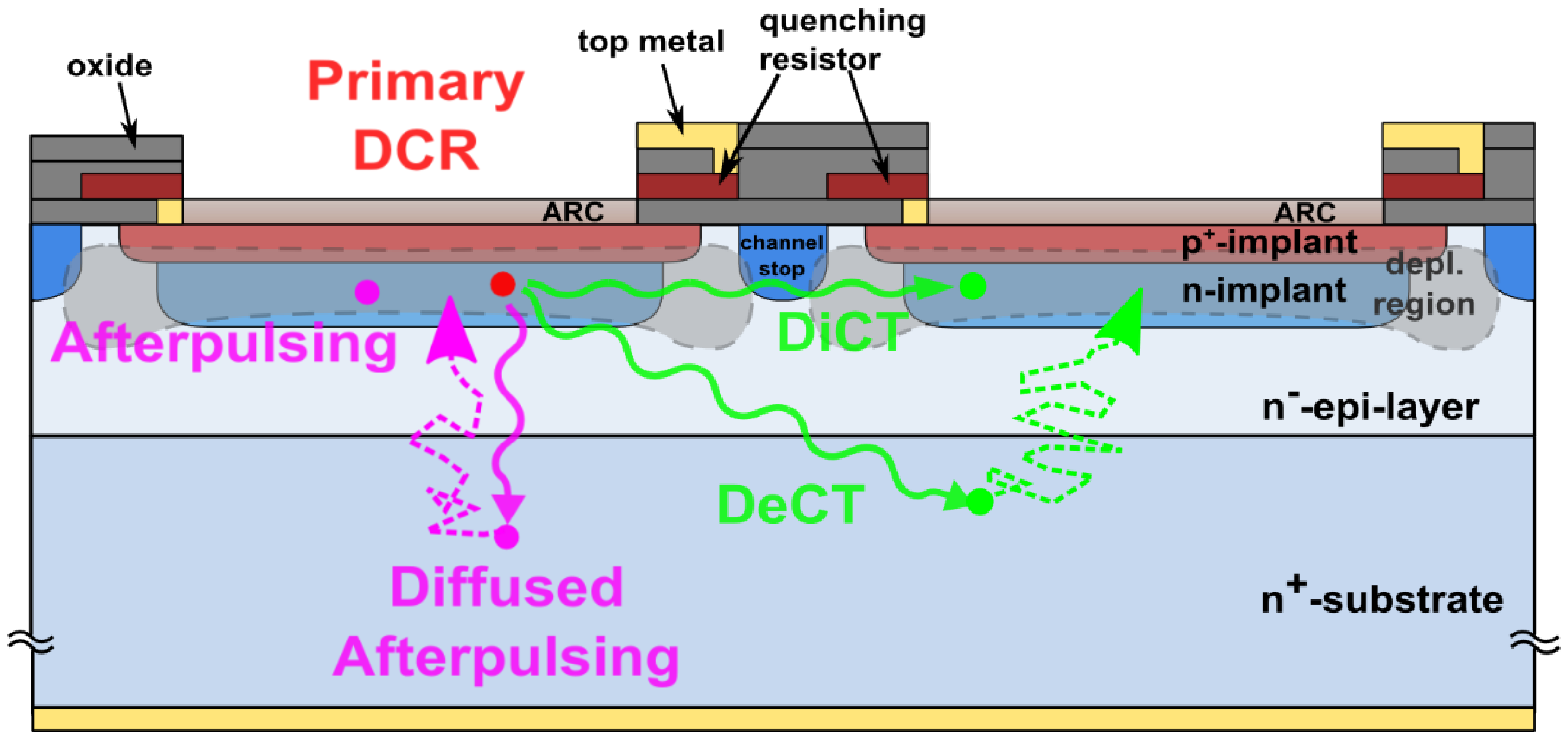






SiPM (Silicon photomultiplier)
thousands of SPADs in parallel

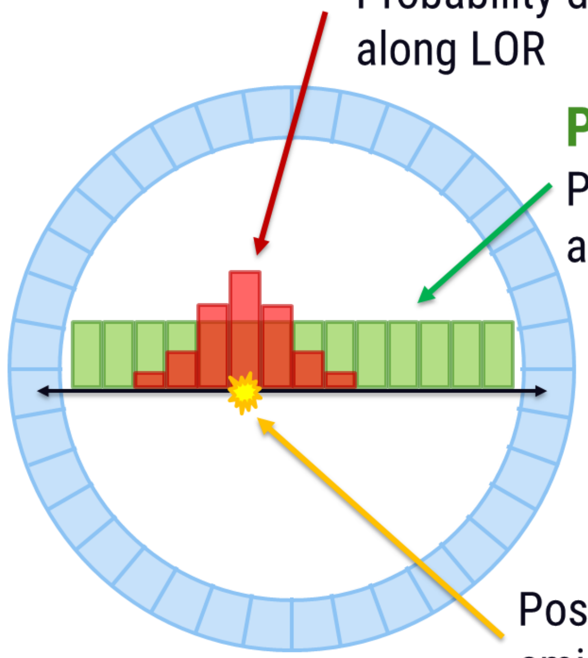
$$P(correlated) \propto Gain(OV)$$



Different SiPM noise components are related to *different physical phenomena*

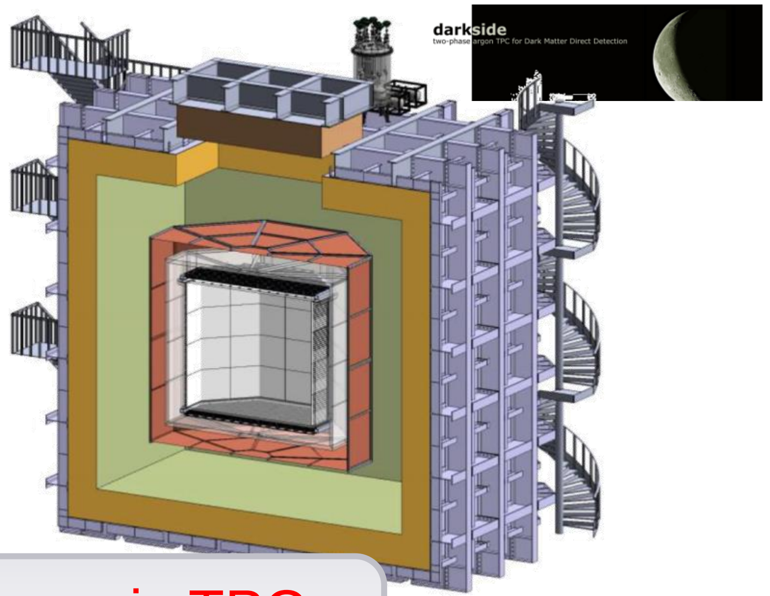
FBK Silicon Photomultipliers
SiPM Applications

Positron Emission Tomography

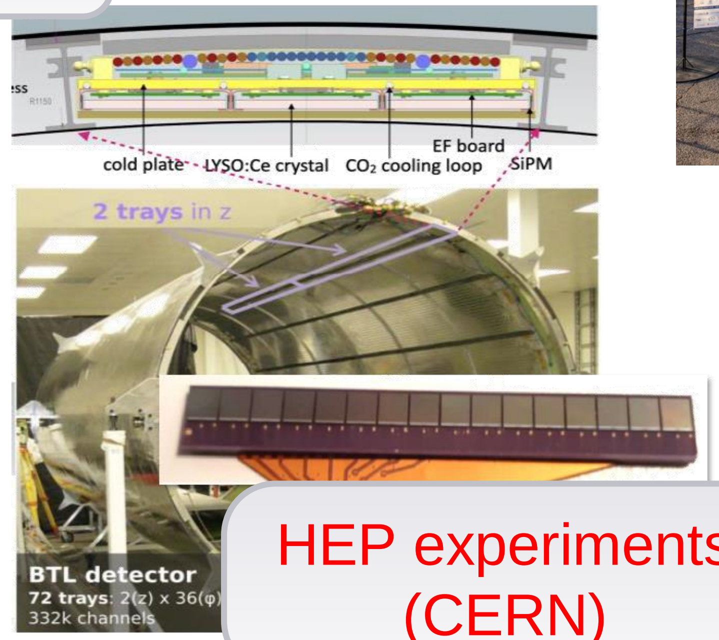


LIDAR Systems

Big Physics Experiments



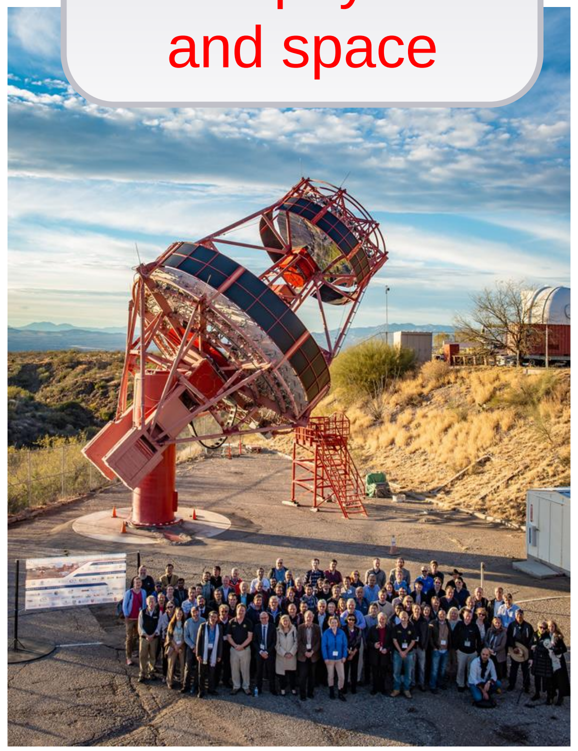
Cryogenic TPCs



Source: Nan Lu- ICHEP 2020

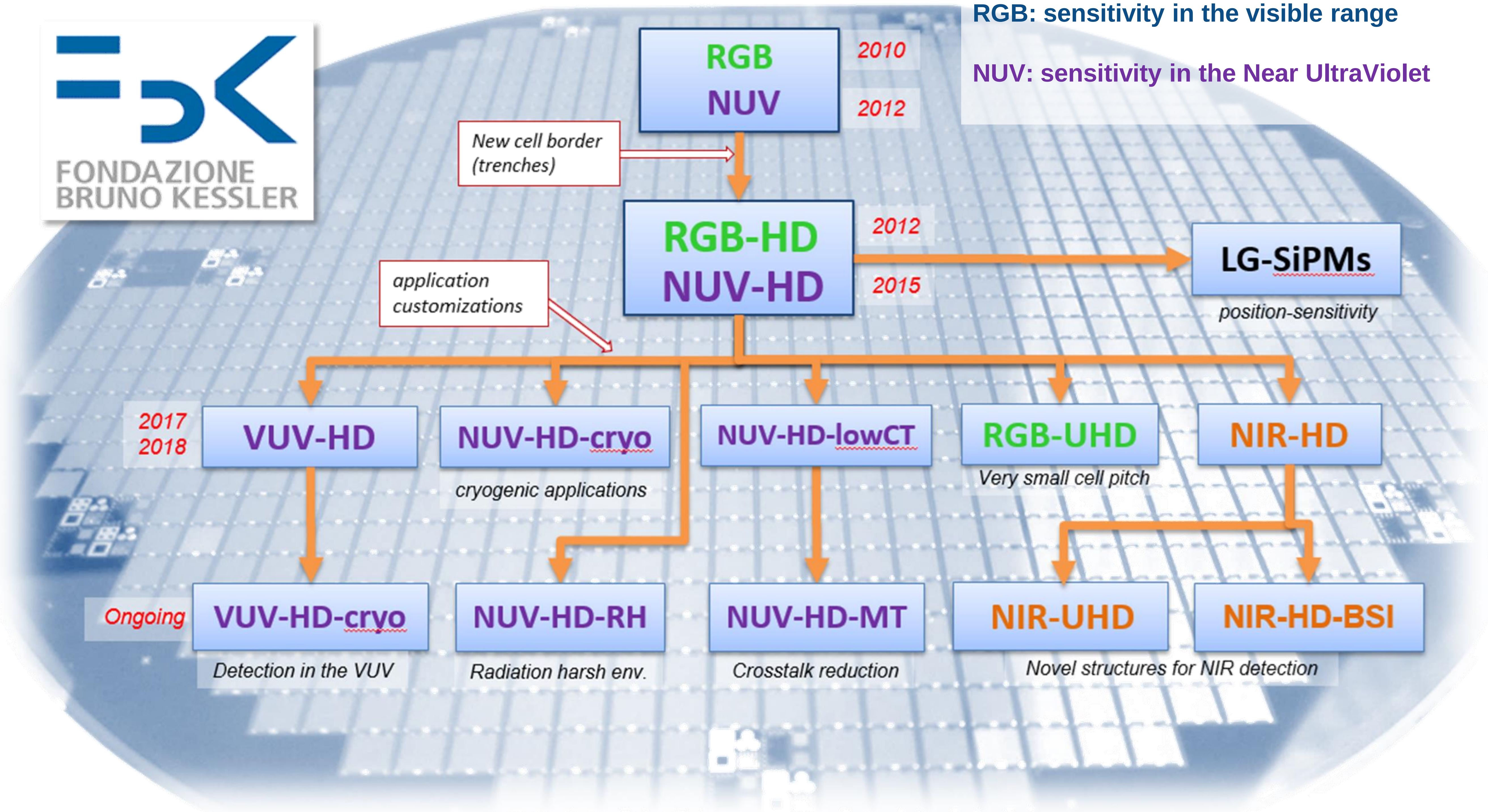
HEP experiments (CERN)

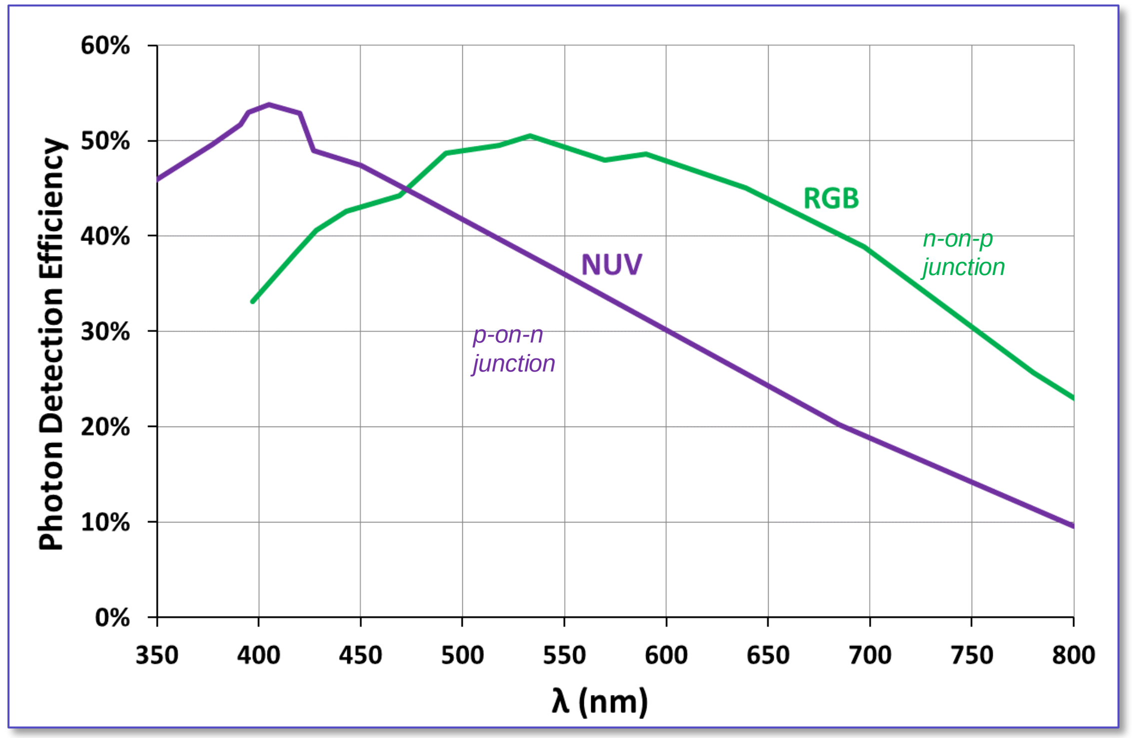
Astrophysics and space

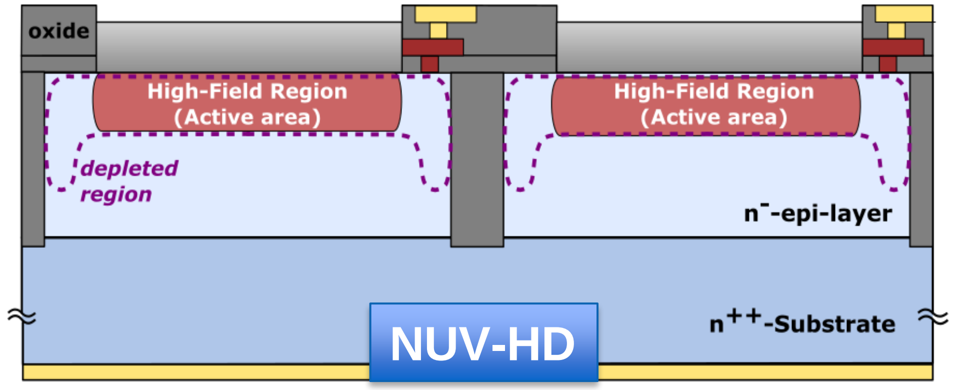


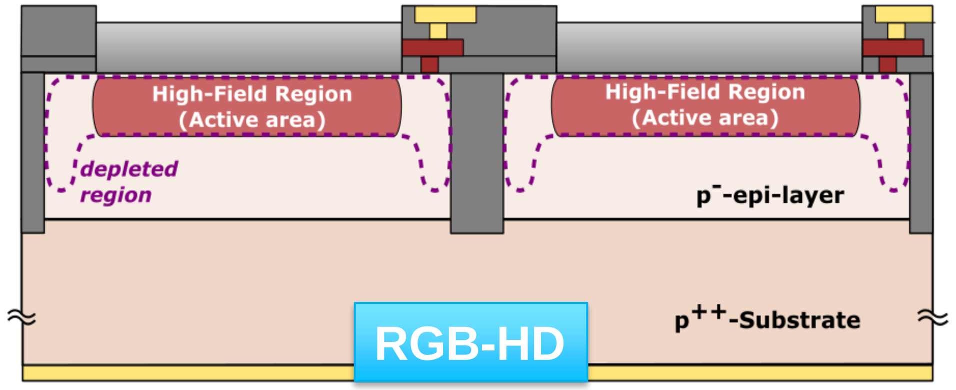
Examples of Big Physics experiments FBK is currently working on.

FBK Silicon Photomultipliers
FBK SiPM technologies



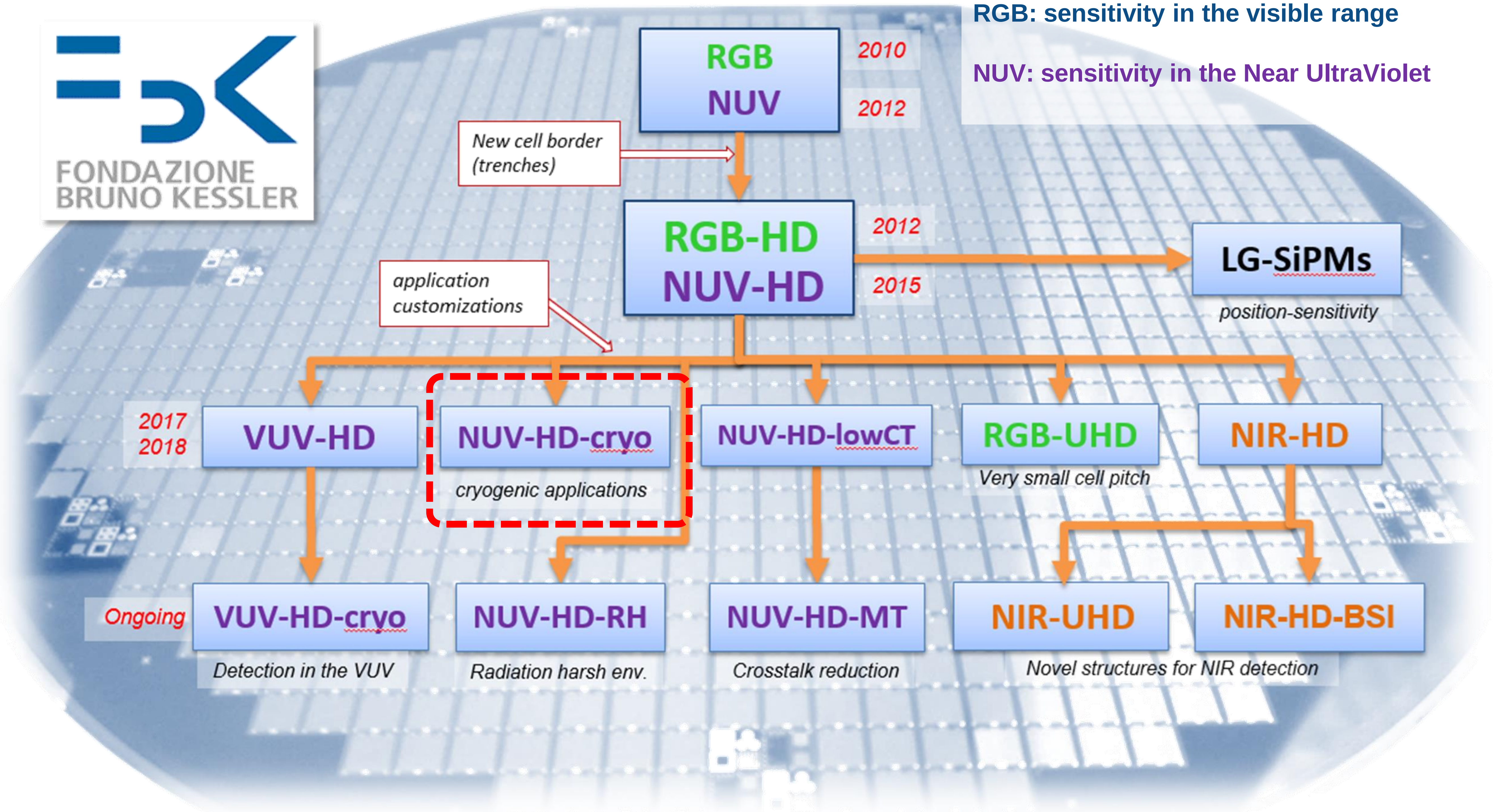


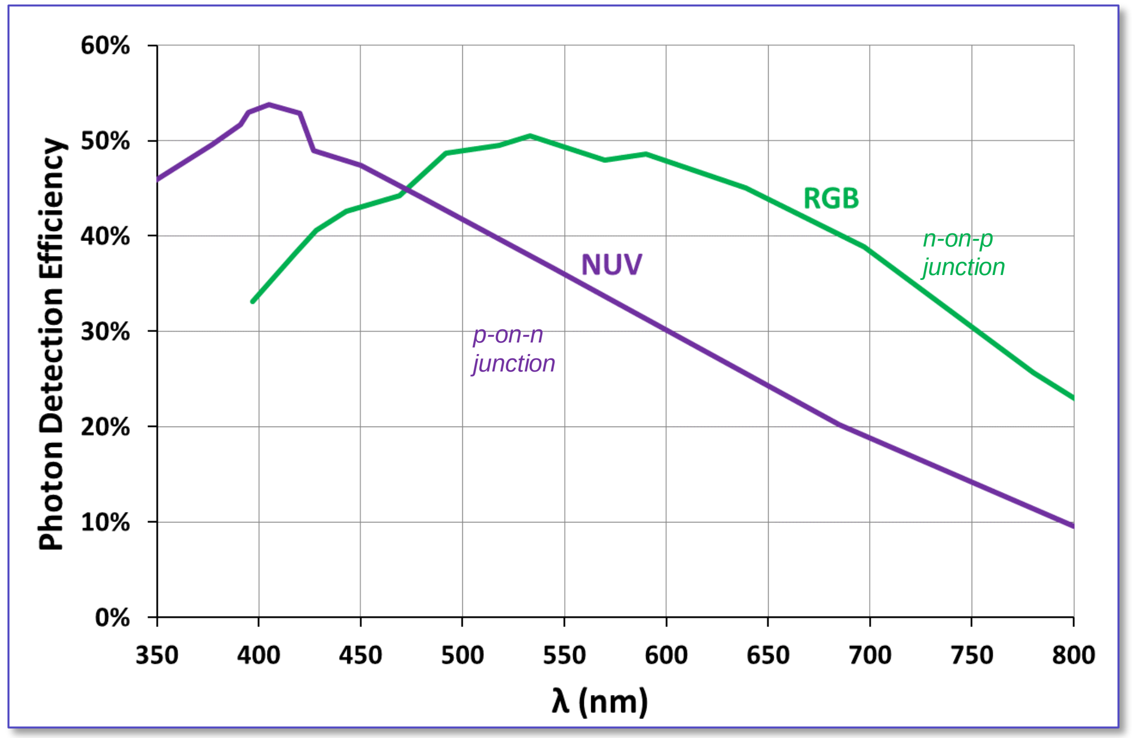


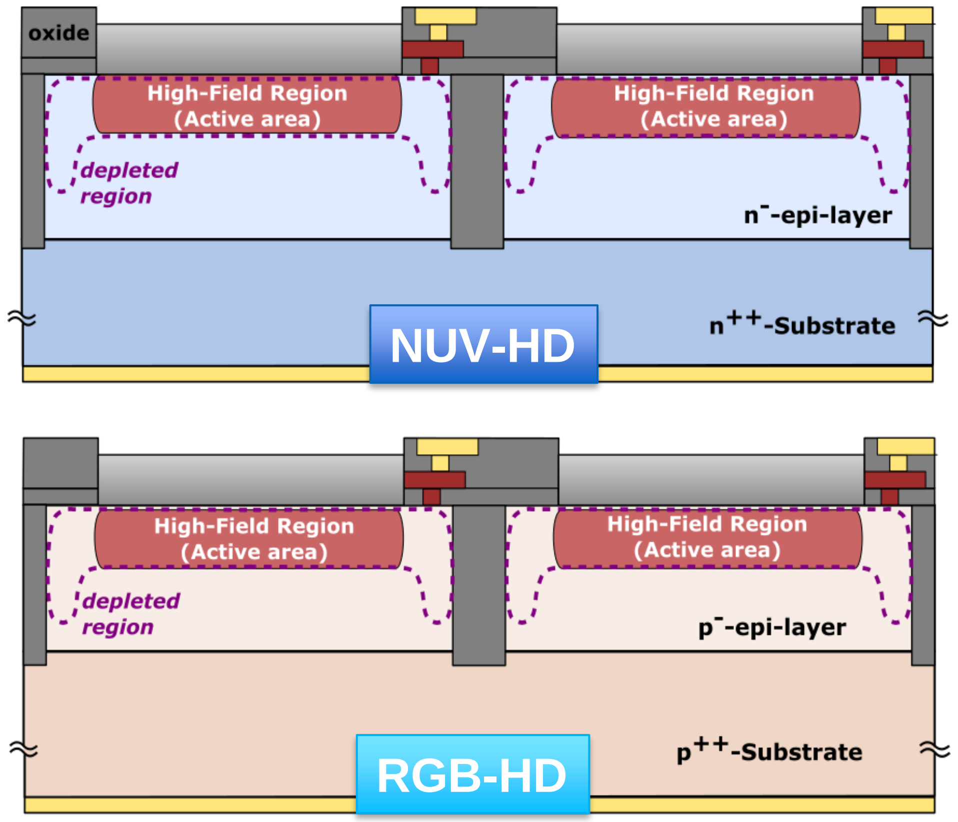


Many different SiPM technologies, tailored for different applications

FBK Silicon Photomultipliers
FBK SiPM technologies







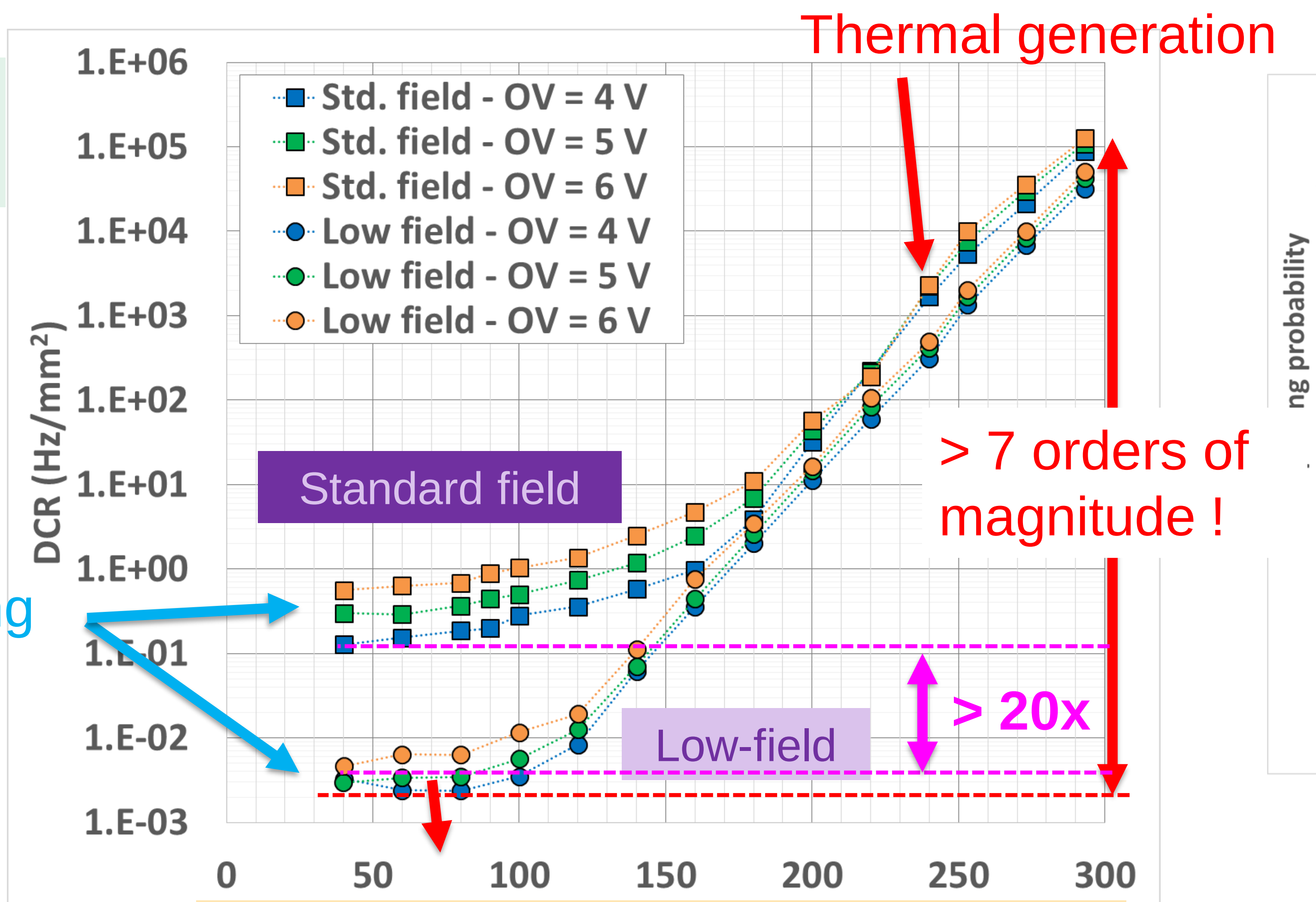
Many different SiPM technologies, tailored for different applications

FBK Silicon Photomultipliers
FBK NUV-HD-Cryo technology

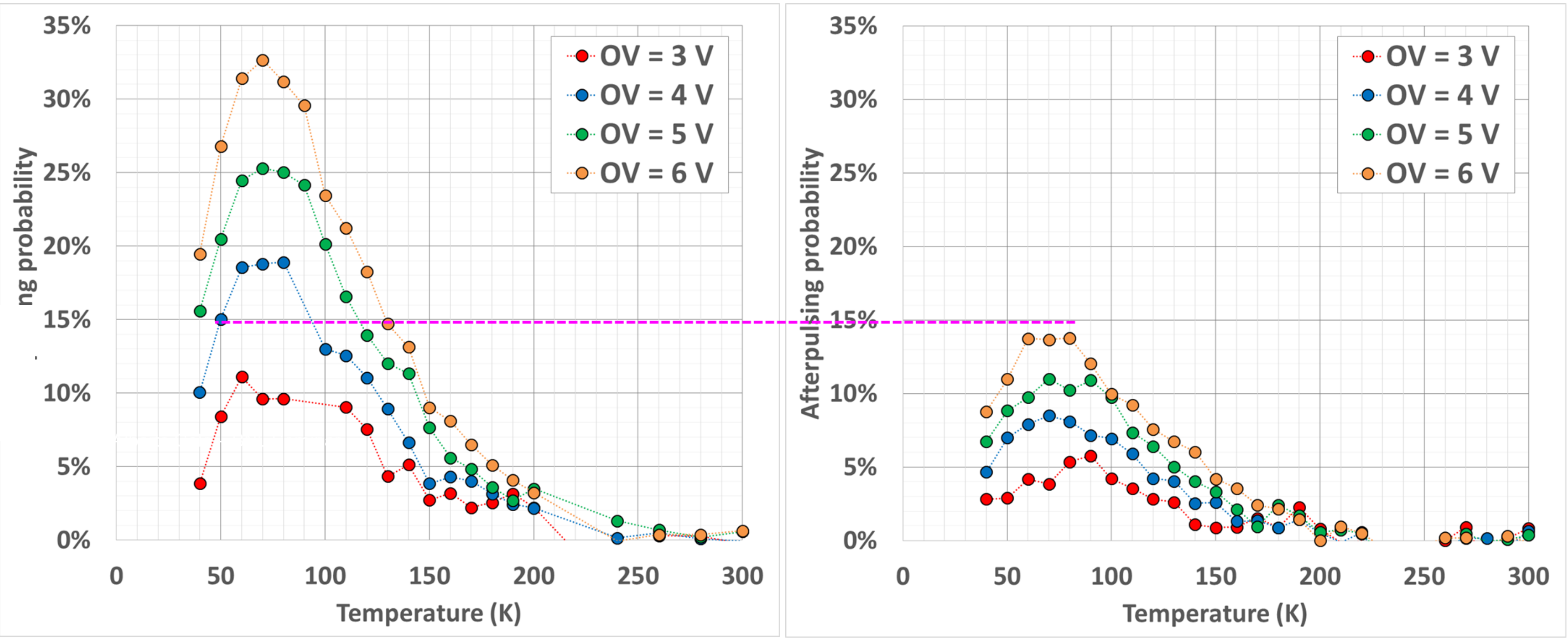
NUV-HD-Cryo SiPM technology is an enabling technology for the DarkSide-20k experiment, currently under construction, developed for cryogenic application (Starting point for DUNE SiPM customization)

25 um cell

Tunneling



0.3 counts per day per cell at 77 K!



Standard field   Low-field

Reduction of Dark Count Rate at cryogenic temperature thanks to electric field engineering

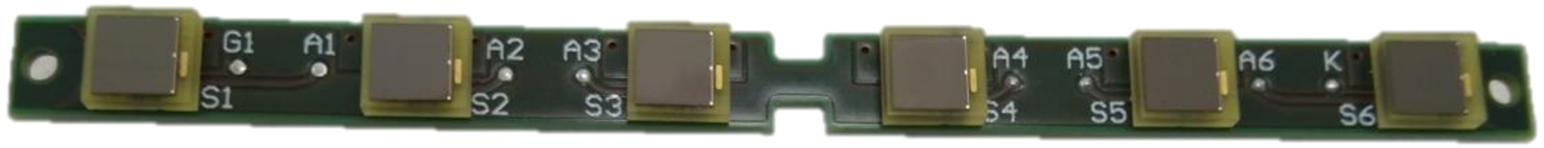
Gola, Alberto, et al. "NUV-sensitive silicon photomultiplier technologies developed at Fondazione Bruno Kessler." Sensors 19.2 (2019): 308.

Acerbi, Fabio, et al. "Cryogenic characterization of FBK HD near-UV sensitive SiPMs." *IEEE Transactions on Electron Devices* 64.2 (2017): 521-526.

FBK Silicon Photomultipliers
DUNE experiment

The Deep Underground Neutrino Experiment (DUNE) is an international experiment that uses Liquid Argon Time Projection Chambers (LArTPCs) for advanced neutrino science

6-ch board



The scintillation light readout basic component is a 6-channel board composed by CSP SiPMs

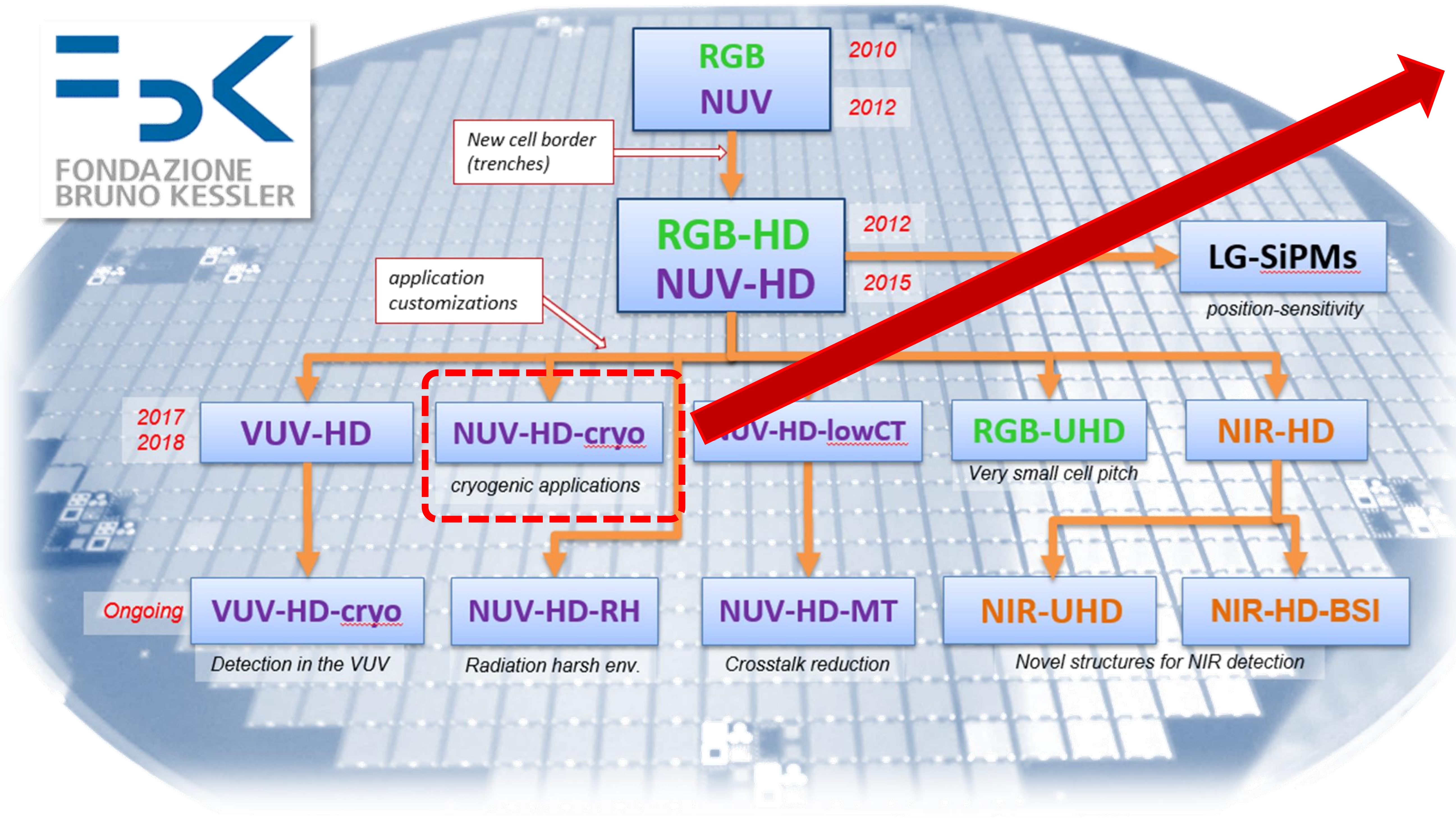
DUNE – SiPM requirements	
SiPM cell pitch	50-100 μm
PDE @ Vop	>35% @435nm
DCR	<200 mHz/mm² @77k <200 kHz/mm² @RT
Crosstalk probability	<35% at Vop @RT
Afterpulsing probability	<5% at Vop @77k
Gain	>2 10^6 at Vop @RT
Fall time constant	600ns +/- 250ns @77k

NUV-HD-Cryo customization to meet the DUNE specs → 54 μm triple trench SiPM

DUNE - mass production	
Breakdown voltage spread	<200mV (on groups of >32 boards) <2V (on the entire lot)
Silicon area	5 sqm
Number of channels	140k
Number of 6-ch boards	23k
Number of 8” wafers	300
Duration	2.5 years

Production assigned to Lfoundry for cost reduction and to meet the tight schedule

FBK Silicon Photomultipliers
FBK SiPM technologies



Starting point

NUV-HD-Cryo SiPM technology

DUNE SiPM Customization

Gain increase (better SNR in ganging) without the increase of the crosstalk probability → 54um triple trench

DUNE down selection

DUNE preliminary evaluation (30µm single trench vs 54µm triple trench)

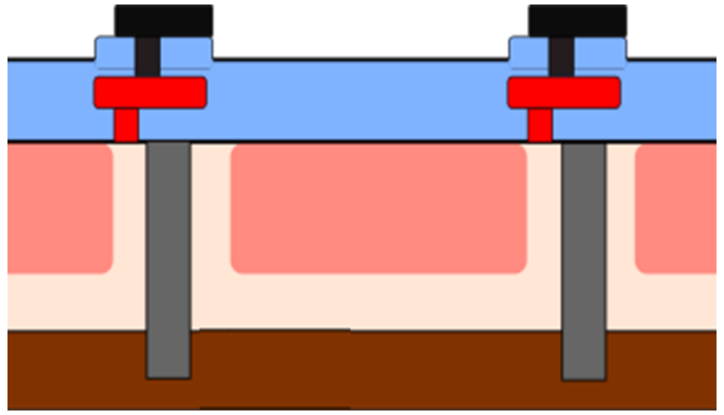
[Publication on the down selection in preparation with the DUNE collaboration]

CT reduction evaluation

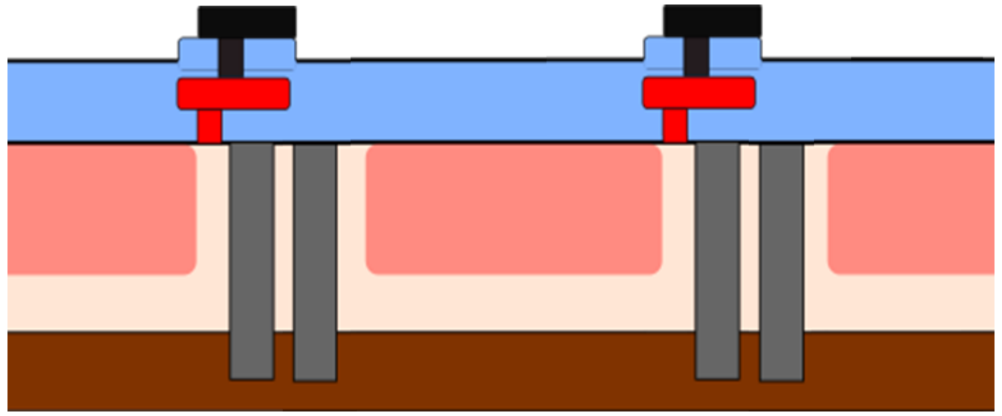
Test structures characterization to evaluate the CT reduction with multiple trenches (Same Gain different numbers of trenches)

FBK Silicon Photomultipliers
FBK SiPM technologies

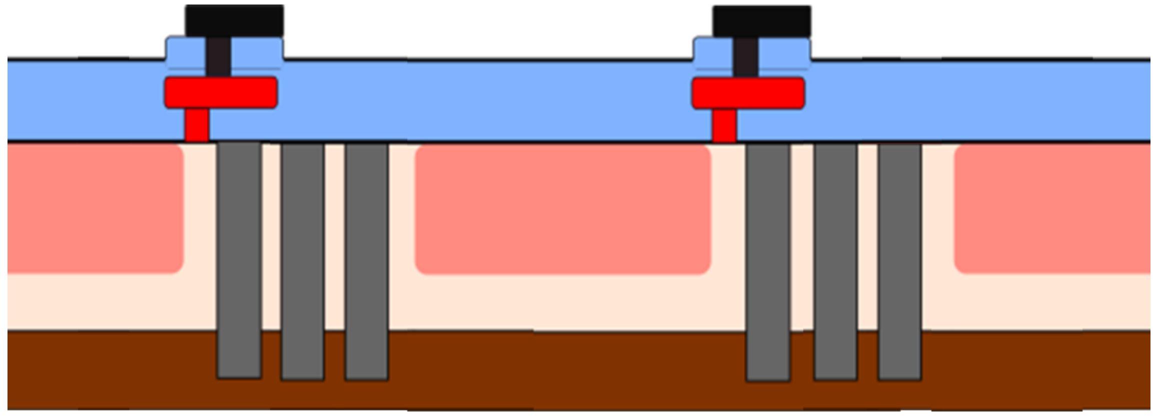
Single Trench (1T)



Double Trench (2T)



Triple Trench (3T)



Starting point

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Test structures characterization to evaluate the CT reduction with multiple trenches (Same Gain different numbers of trenches)

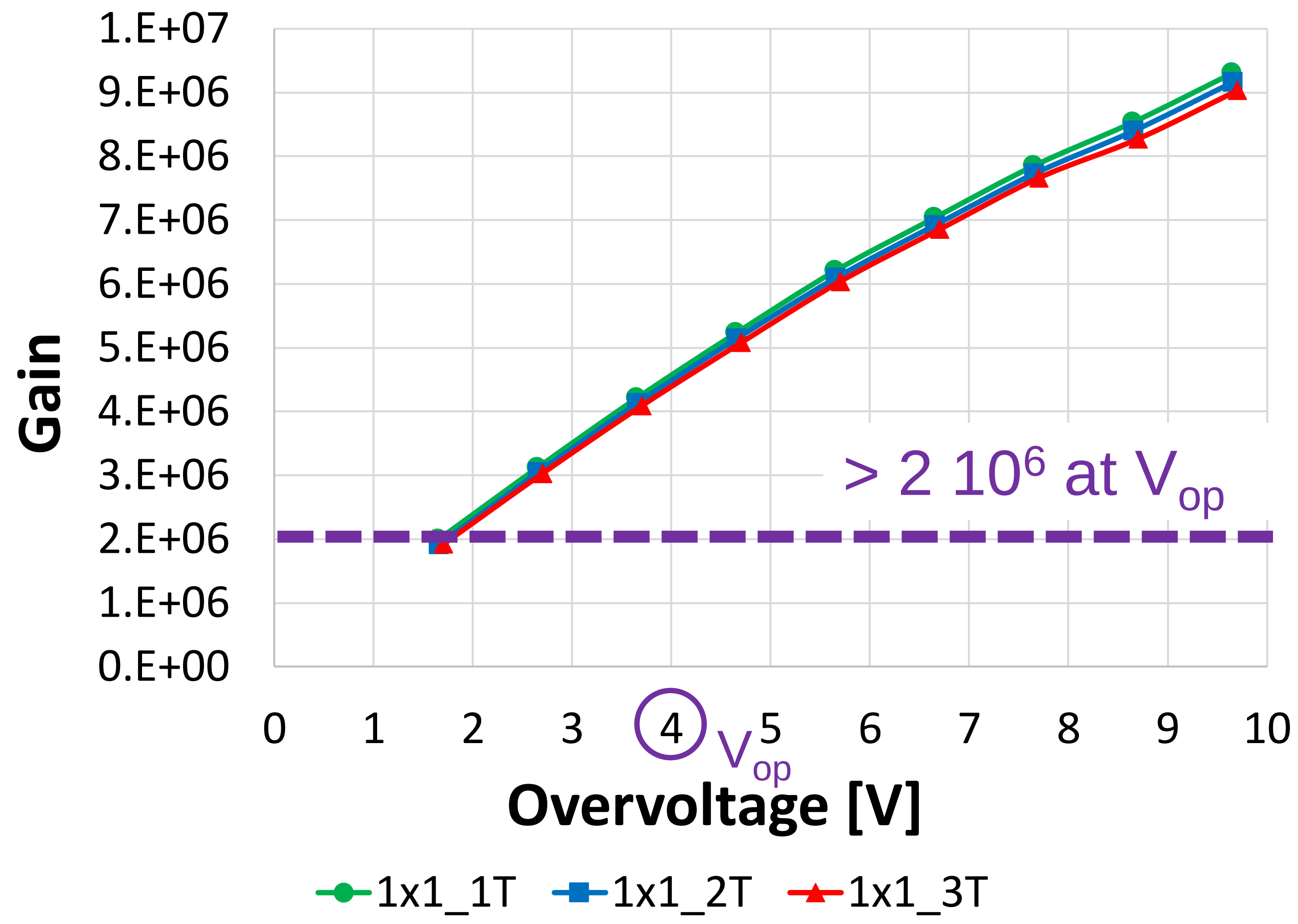
1. DUNE SiPM Characterization

DUNE SiPM Characterization
Room Temperature Characterization

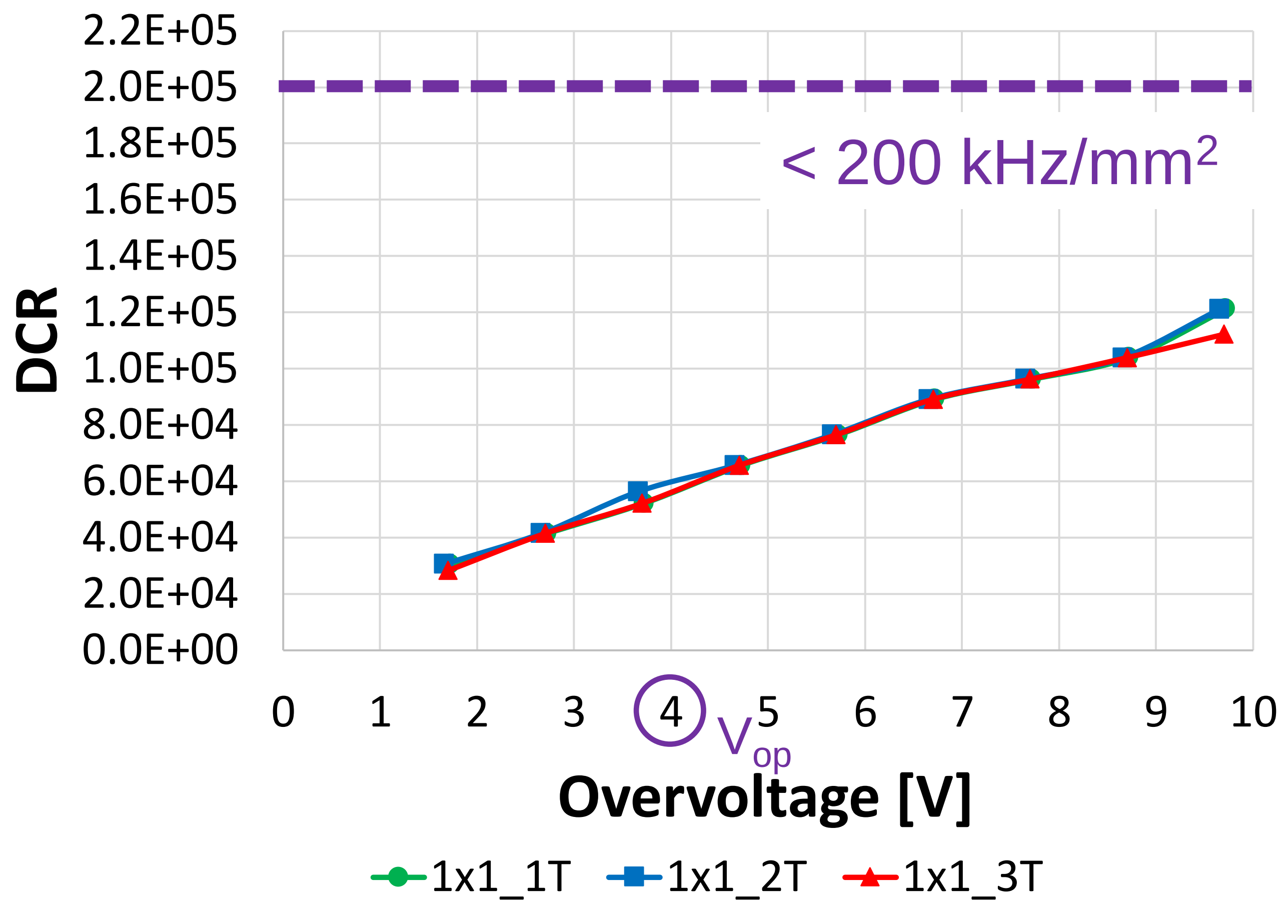
All the preliminary runs produced for the evaluation of the DUNE customized technology were composed of 6x6mm^2 SiPMs (The die dimension that will be used in the DUNE experiment)

Test structures with SiPM of 1x1mm^2 different features were included for detailed characterization and for further investigations

Gain



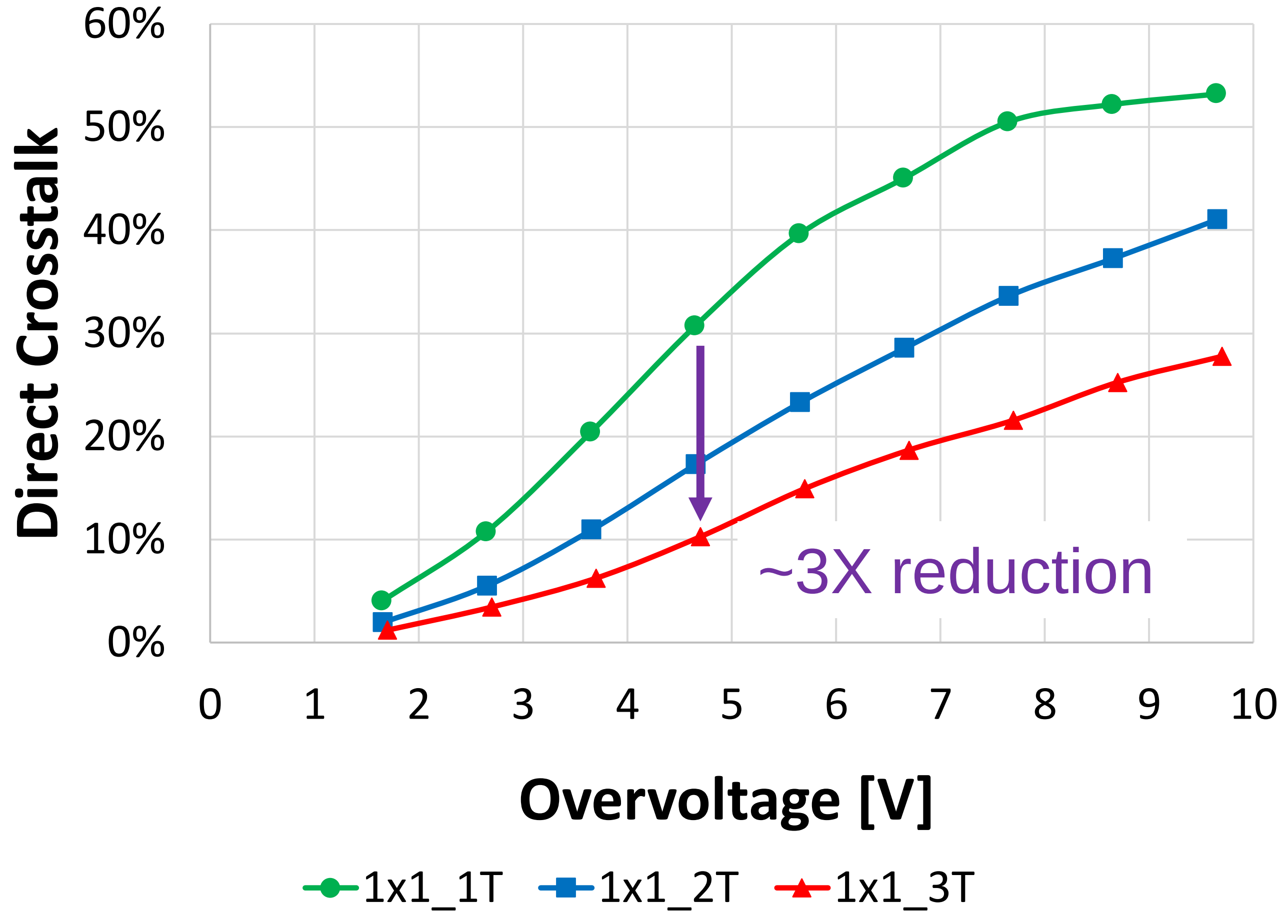
DCR at Room Temperature



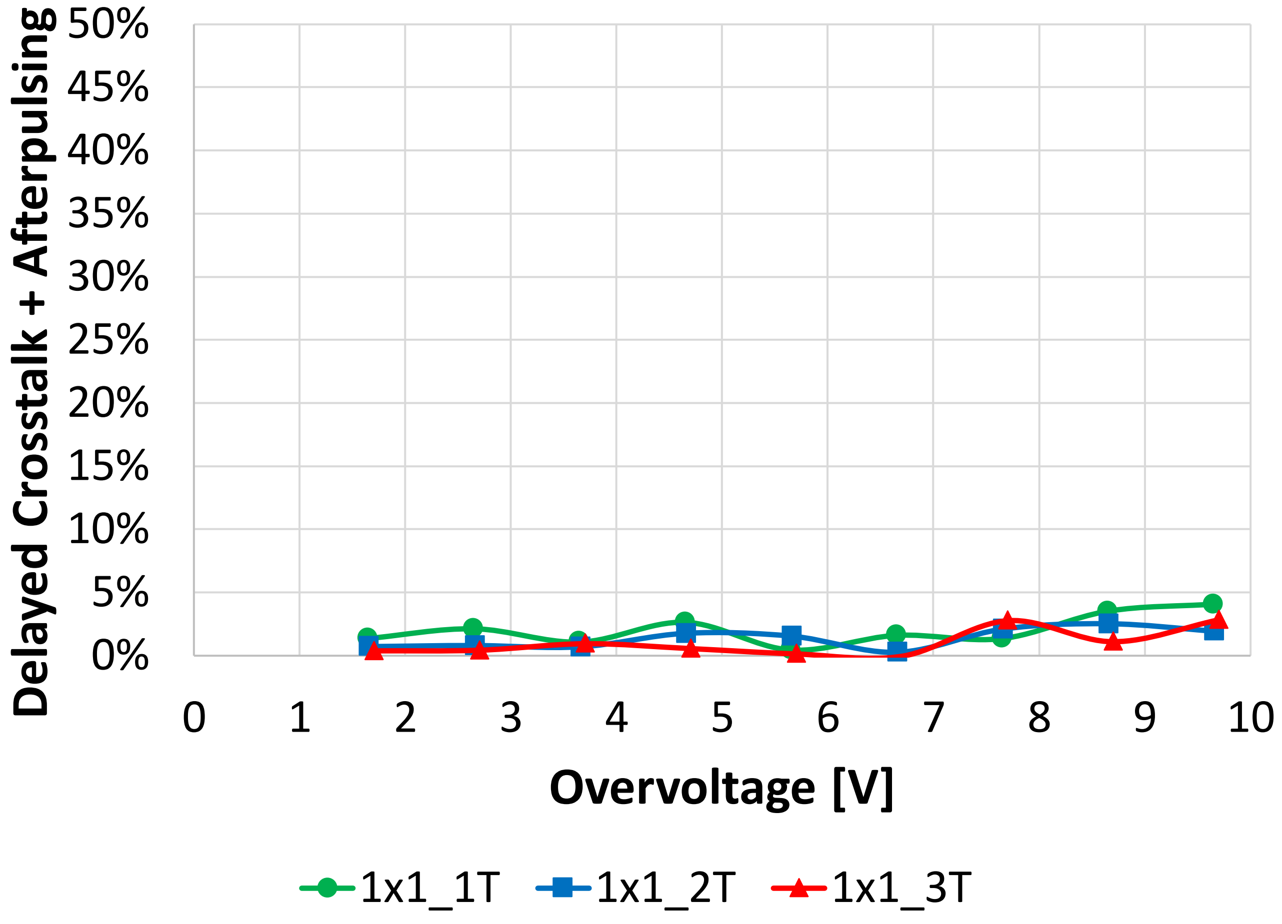
Comparison of three different 1x1mm^2 SiMPs with same gain but different number of trenches (1 trench, 2 trenches, 3 trenches)

DUNE Characterization
Room Temperature Characterization

Direct Crosstalk



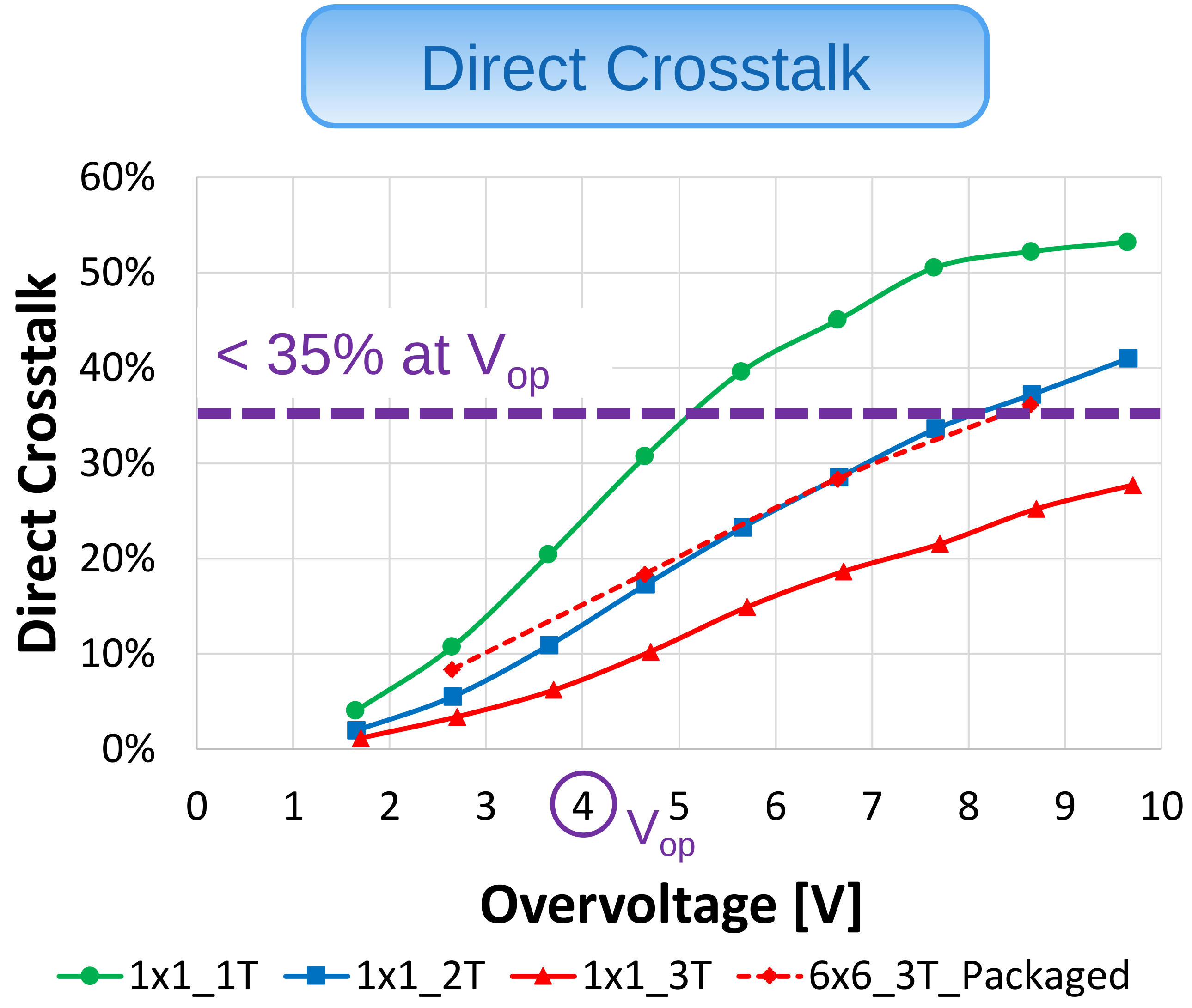
Delayed crosstalk and Afterpulsing

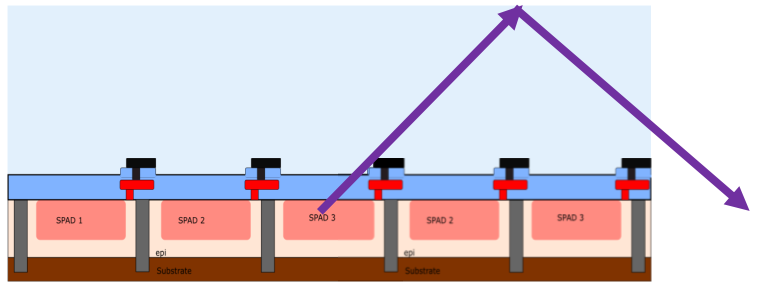


The triple trench SiPM exhibits a reduction of a factor of 3 of the direct crosstalk

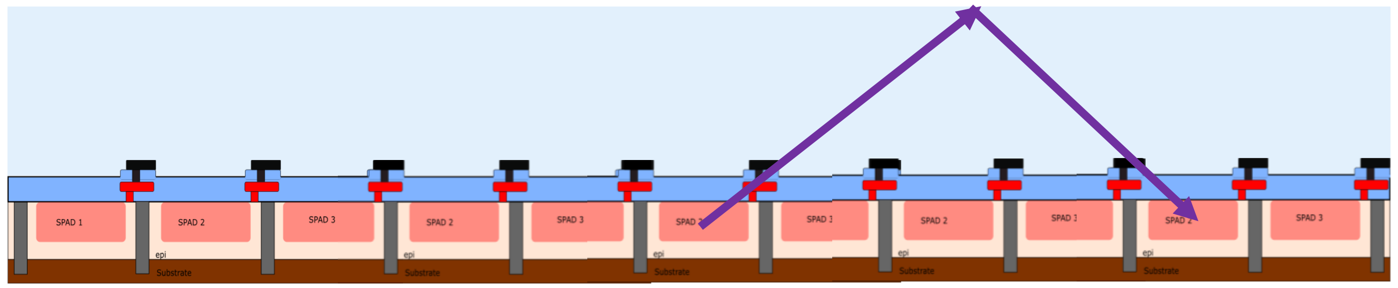
Delayed crosstalk and afterpusling probability are less of 5% in all the overvoltage tested

DUNE Characterization
Room Temperature Characterization





In a 1x1mm^2 SiPM the reflected photon at the surface of the encapsulation resin is reflected outside the SiPM without increasing the crosstalk probability



In a 6x6mm^2 SiPM the reflected photon at the surface of the encapsulation resin can be reflected inside the SiPM thus increasing the crosstalk probability

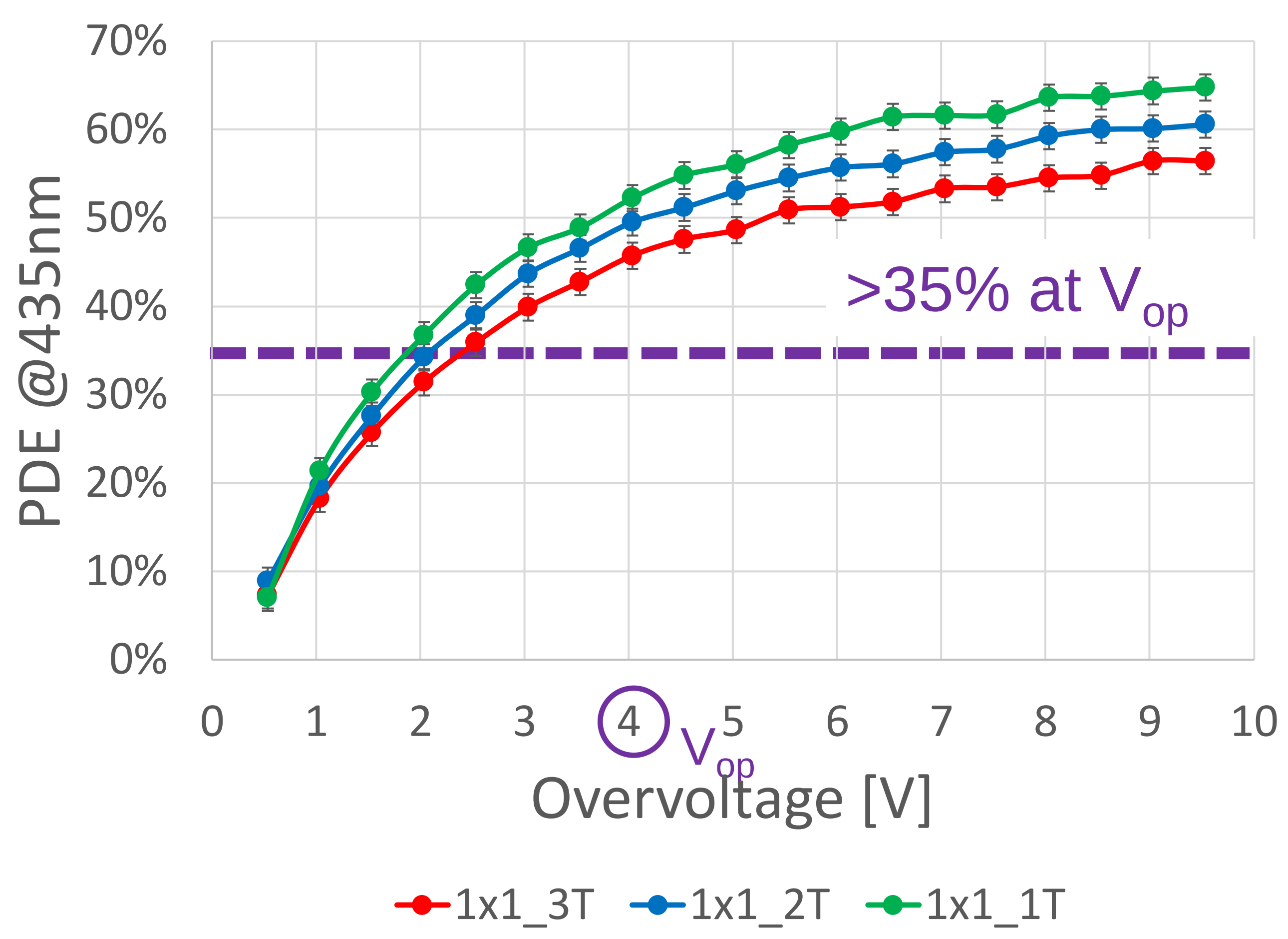
Because of the external crosstalk, the *Optical Crosstalk probability measured with different sizes of SiPM (but same technology) can be different*

Even with the CT increase caused by the packaging the Crosstalk probability remains in spec with the DUNE requirements

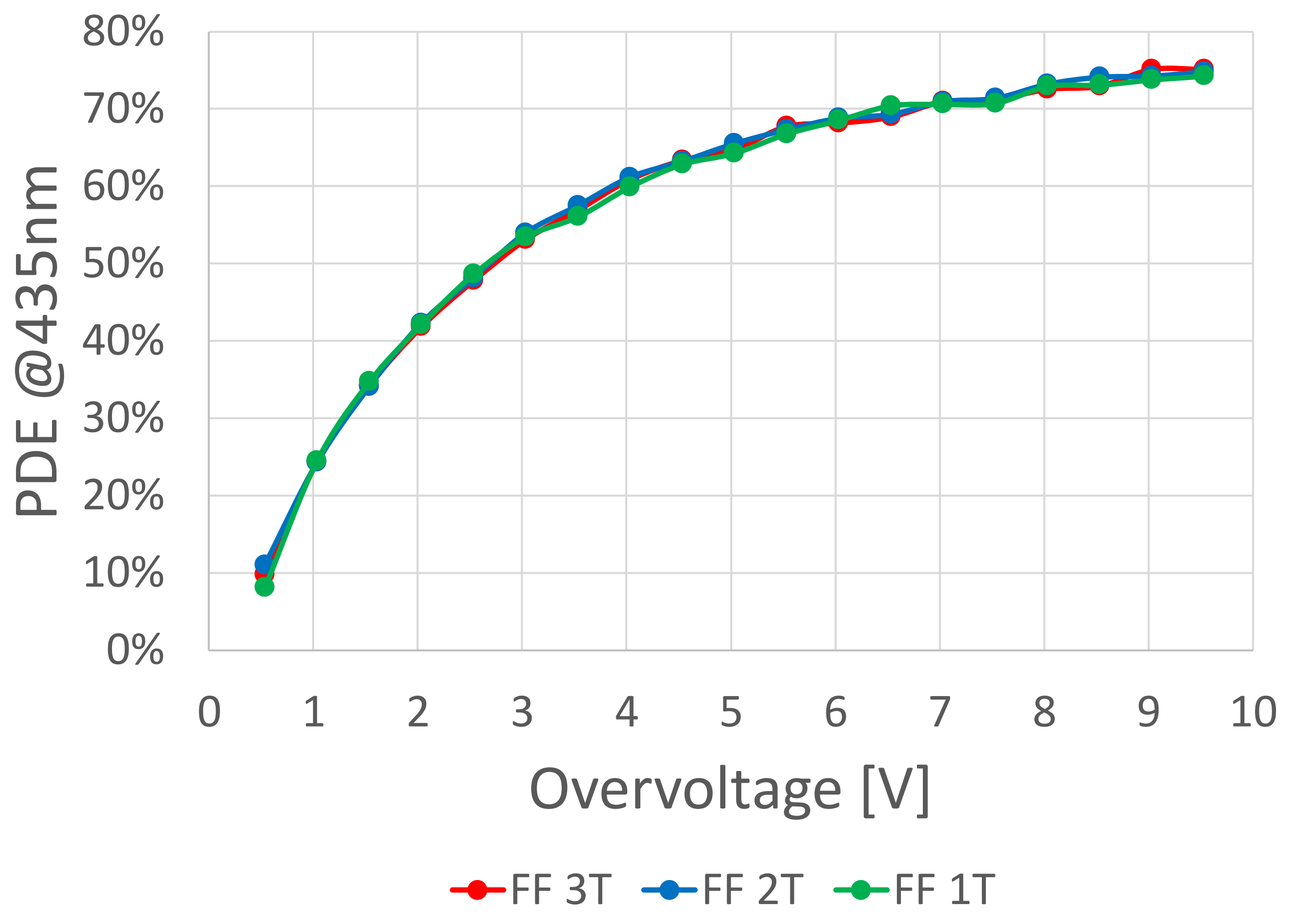
DUNE Characterization
Photo Detection Efficiency @435nm

PDE = QE × Tp × ~~FF~~

PDE @435nm comparison



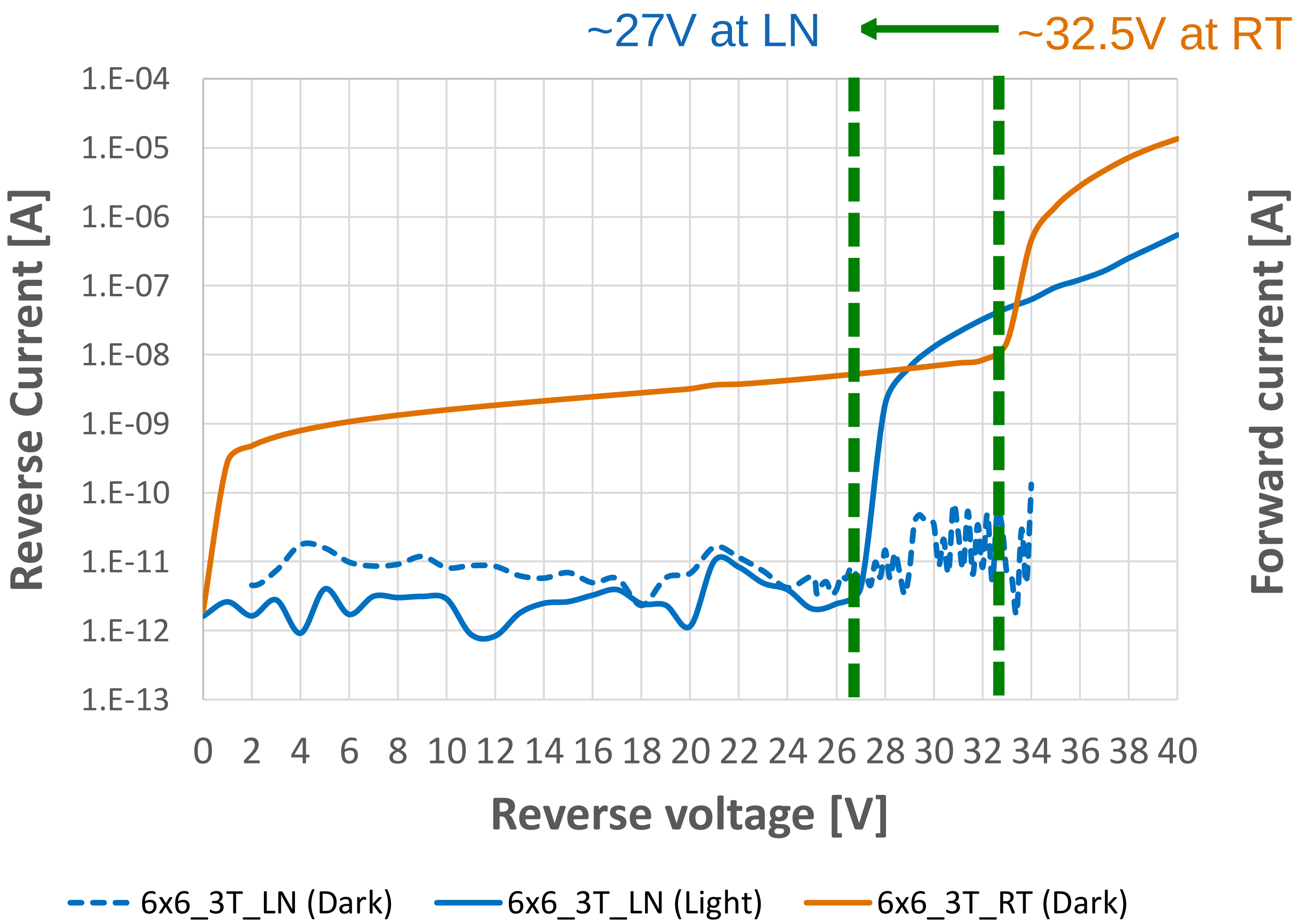
PDE normalized with FF

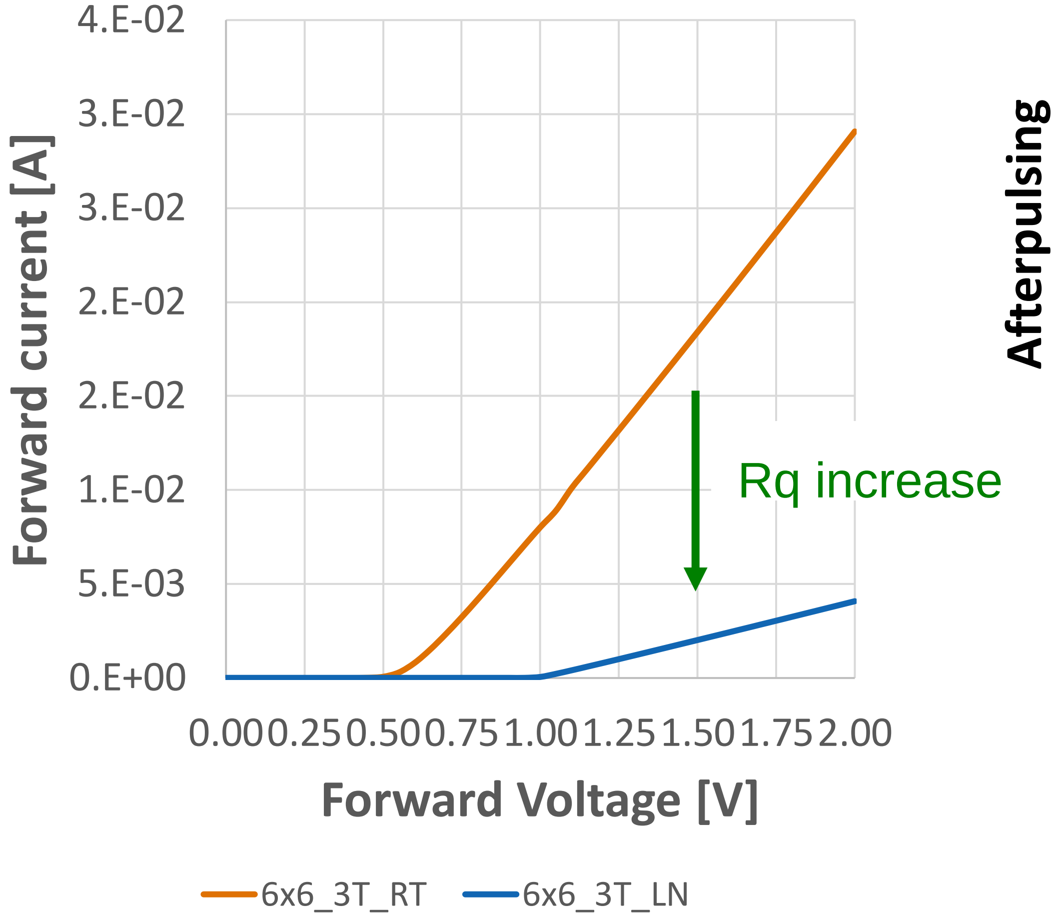


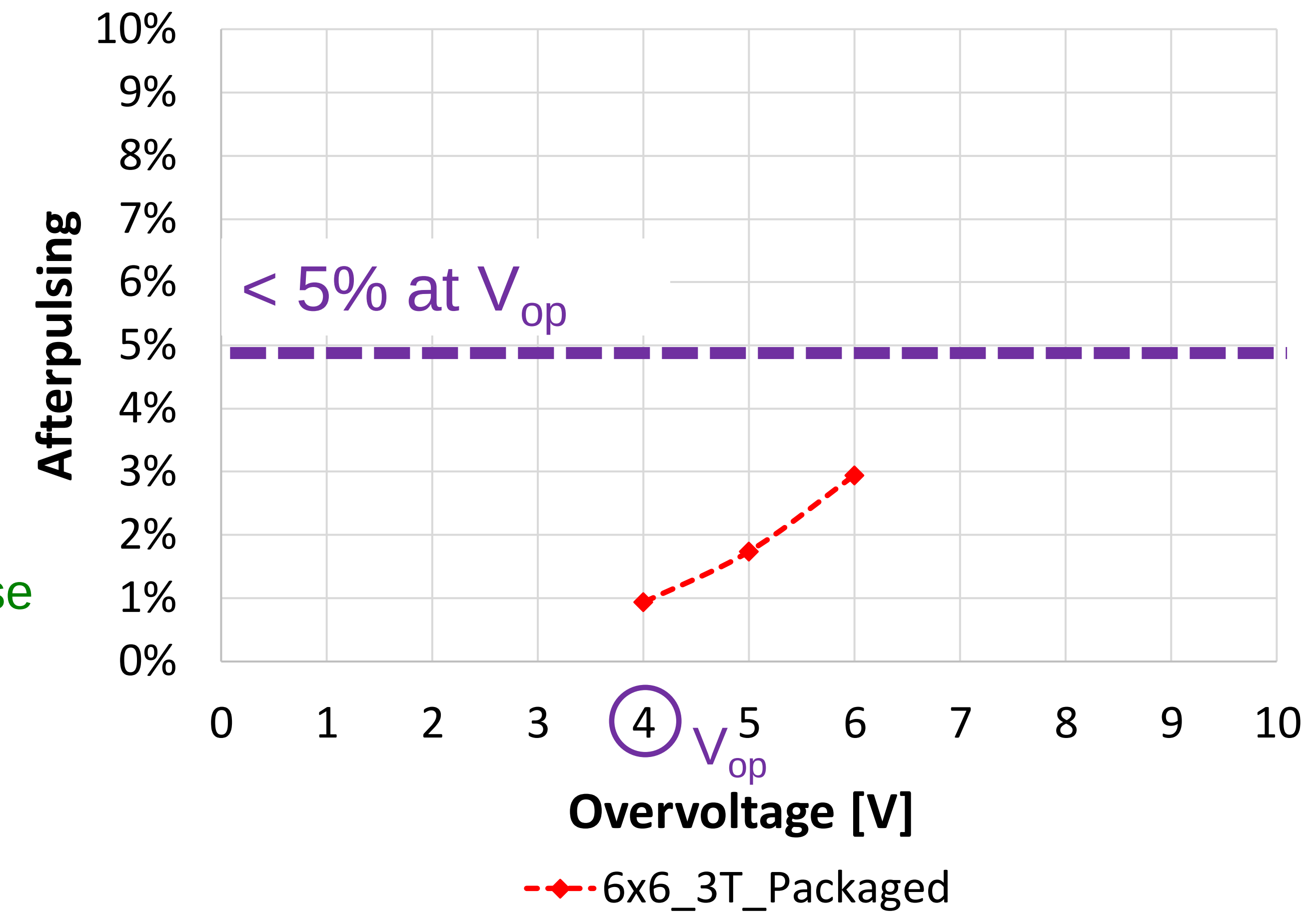
The Photo Detection Efficiency results from the product of three factors: Quantum efficiency (QE), Triggering probability (Tp), and Fill Factor (FF) of the detector

The three different detectors feature the same SiPM technology and differ only in the Fill Factor → The PDE normalized by the fill factor is the same (same QE and Tp)

DUNE Characterization
Cryogenic measurements in LN





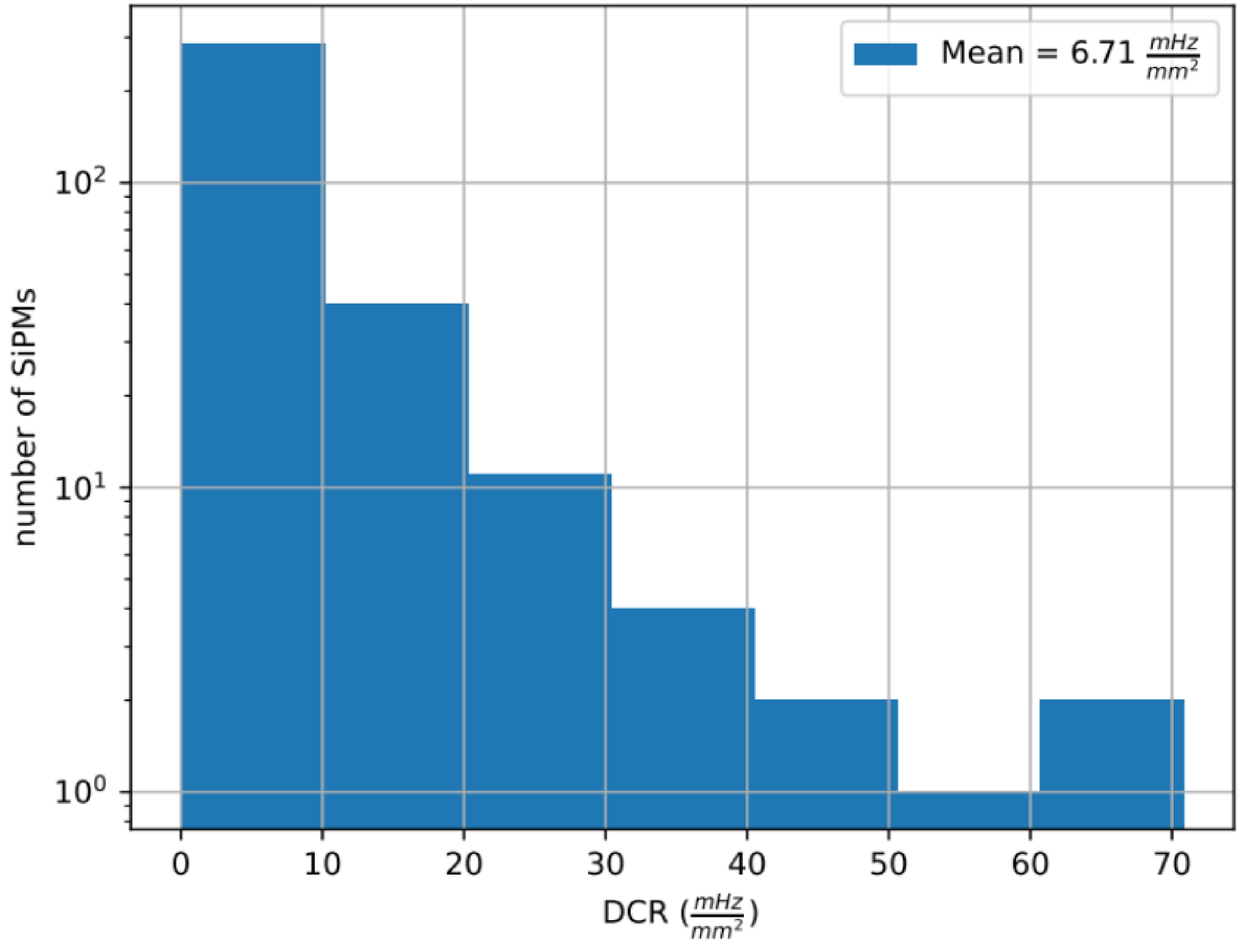


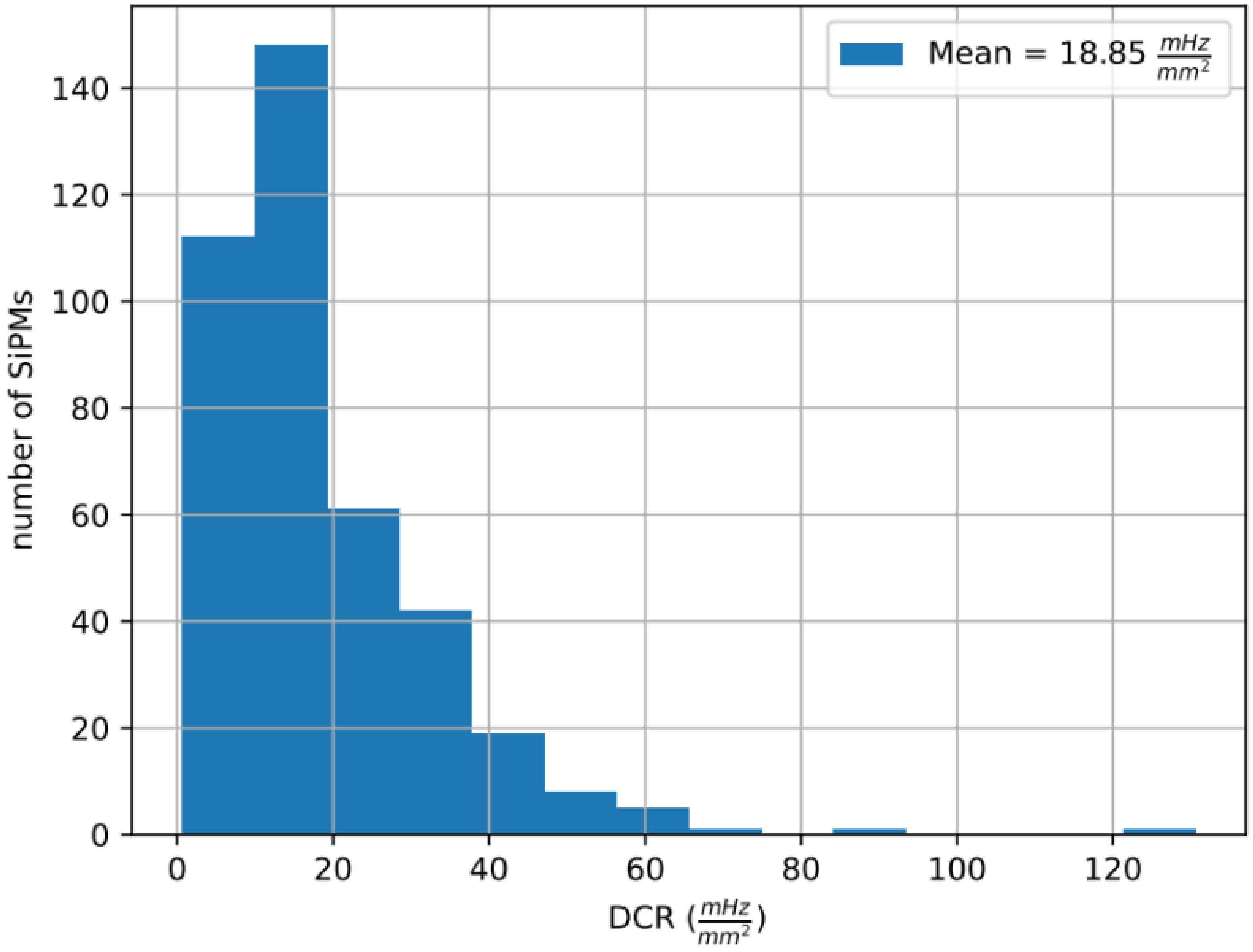
Breakdown voltage reduction from 32.5V at Room Temperature down to 27V at Liquid Nitrogen

Quenching resistor increases by a factor of approximately 5

Afterpulsing probability at 77 K is in the order of few percent → fulfills DUNE requirements

DUNE Characterization
Cryogenic measurements



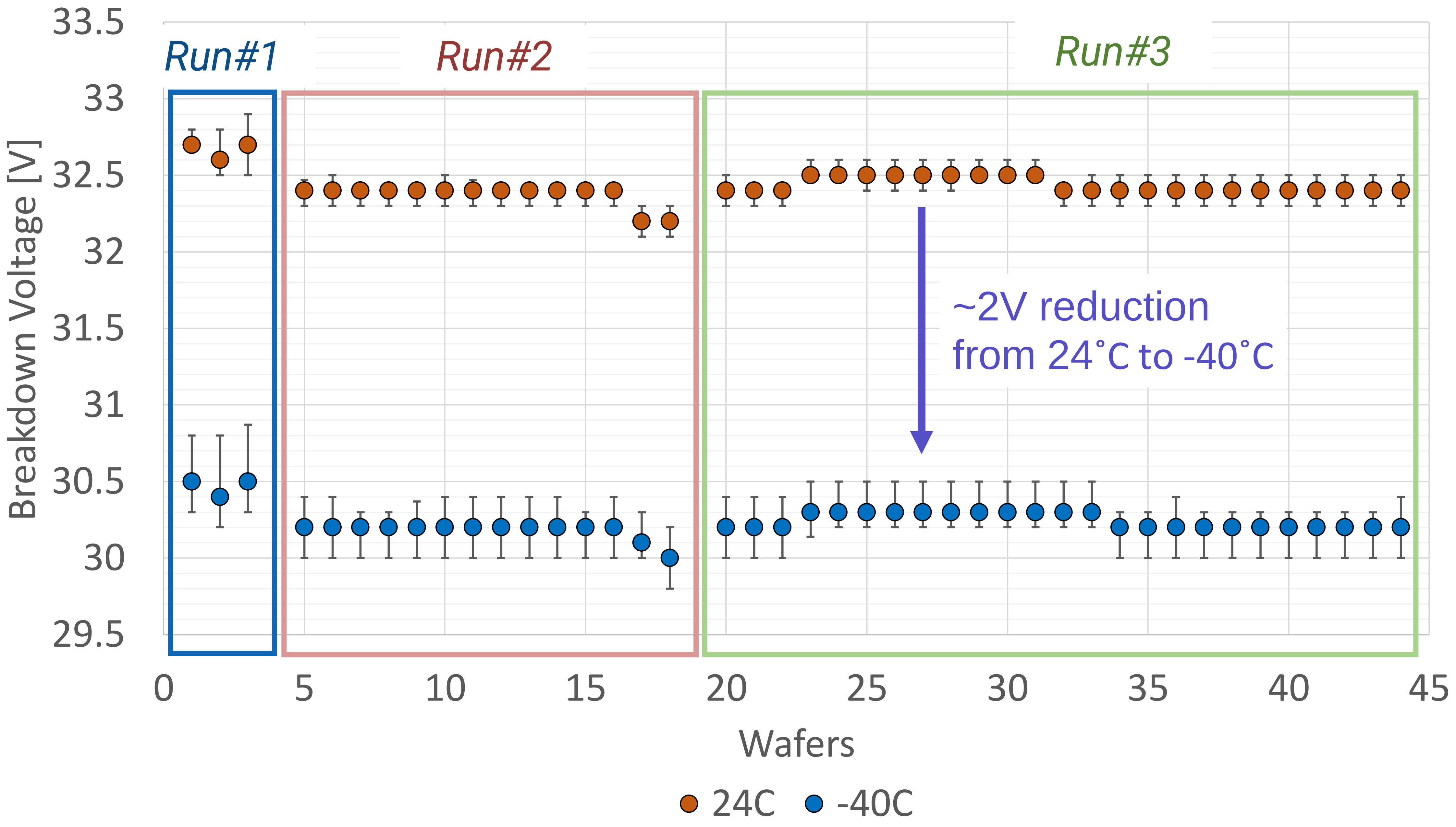


DCR is in the order of few tens of mHz/mm2 meets DUNE requirements (<200mHz/mm^2)

Measurements performed by the DUNE collaboration on FBK 6ch boards prototypes

1. Wafer level analysis

Wafer level analysis
Breakdown voltage



Sample to sample V_{BD} variation

Within same wafer

Peak to peak variation <400mV

Within same run

Median value intra-run variation <200mV

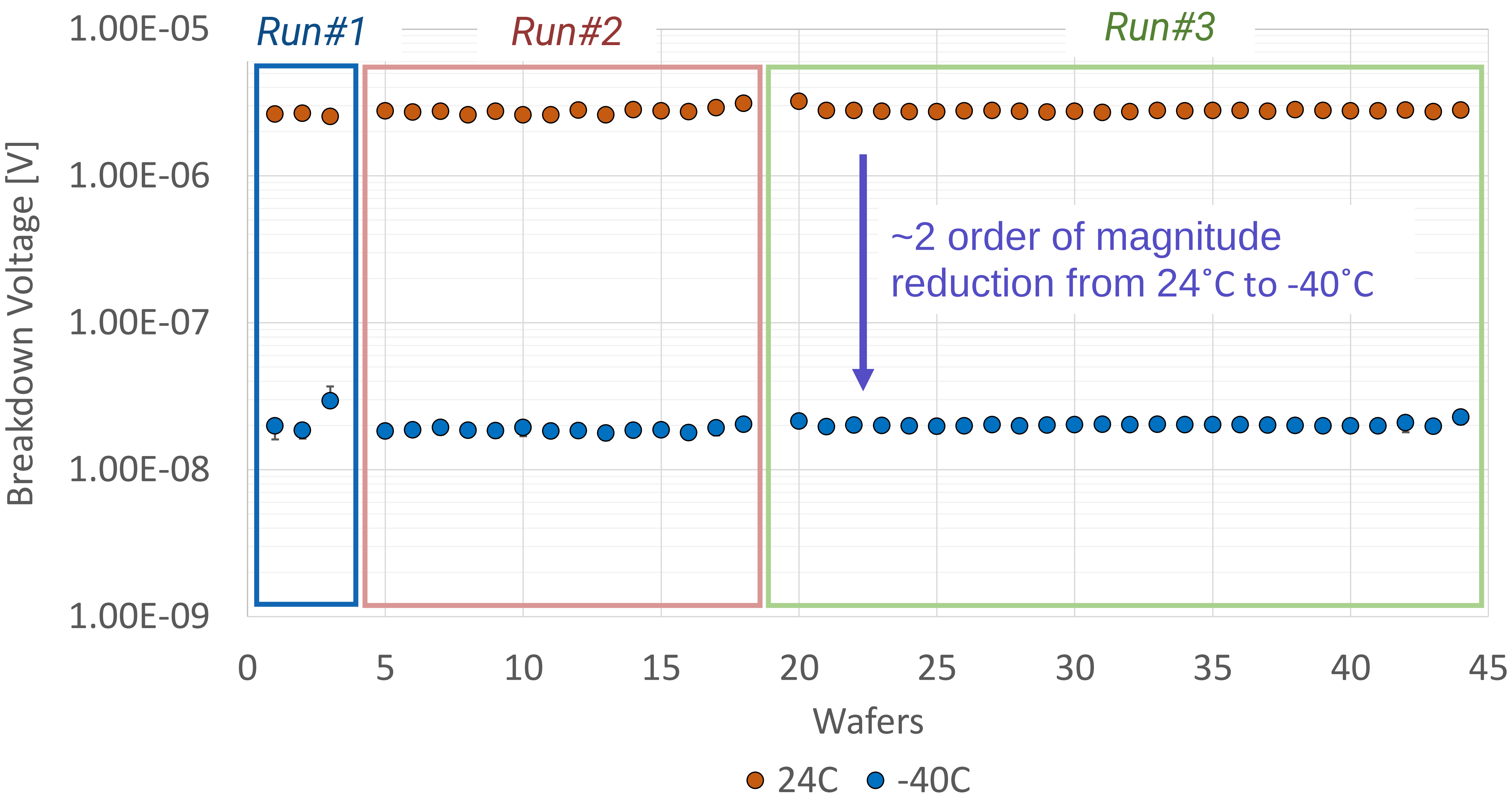
Between different runs

Median value inter-runs variation <500mV

DUNE - mass production	
Breakdown voltage spread	<200mV (on groups of >32 boards) <2V (on the entire lot)

Dots are the median value for each wafer, error bars indicate the spread over the selection of good devices

Wafer level analysis
Dark current at 5V overvoltage



Sample to sample dark current variation

Within same wafer

Relative variation less than a factor of 2

Within same run

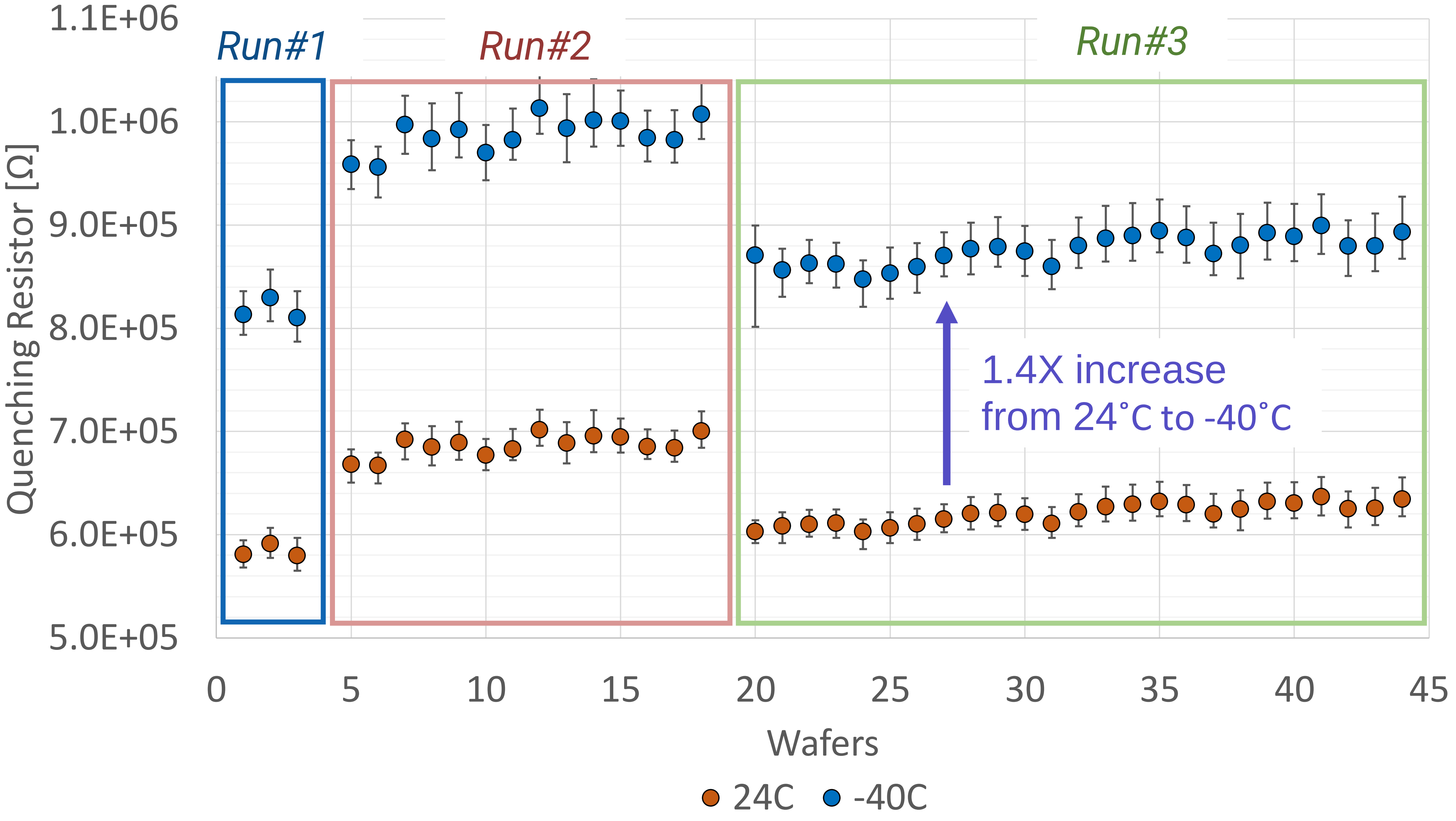
Relative variation: 55% R1, ~15% others

Between different runs

Median value inter-runs variation <7%

Dots are the median value for each wafer, error bars indicate the spread over the selection of good devices

Wafer level analysis
Value of quenching resistor



Sample to sample Rq variation

Within same wafer

Total variation <6%

Within same run

Median value intra-run variation <6%

Between different runs

Median value inter-runs variation <22%

DUNE – SiPM requirements	
Recharge time constant	600ns +/- 250ns @77k

Dots are the median value for each wafer, error bars indicate the spread over the selection of good devices

Conclusions

Conclusions

1 Silicon photomultipliers are widely used in several applications thanks to their versatility and high sensitivity

2 In order to meet the DUNE experiment requirements a customization of FBK NUV-HD-Cryo technology was carried out and the production of SiPMs at Lfoundry was characterized, to meet DUNE specification, volume and schedule requirements.

3 FBK NUV-HD-Cryo SiPM characterization results in terms of DCR, Optical Crosstalk and Afterpulsing meets DUNE specification.

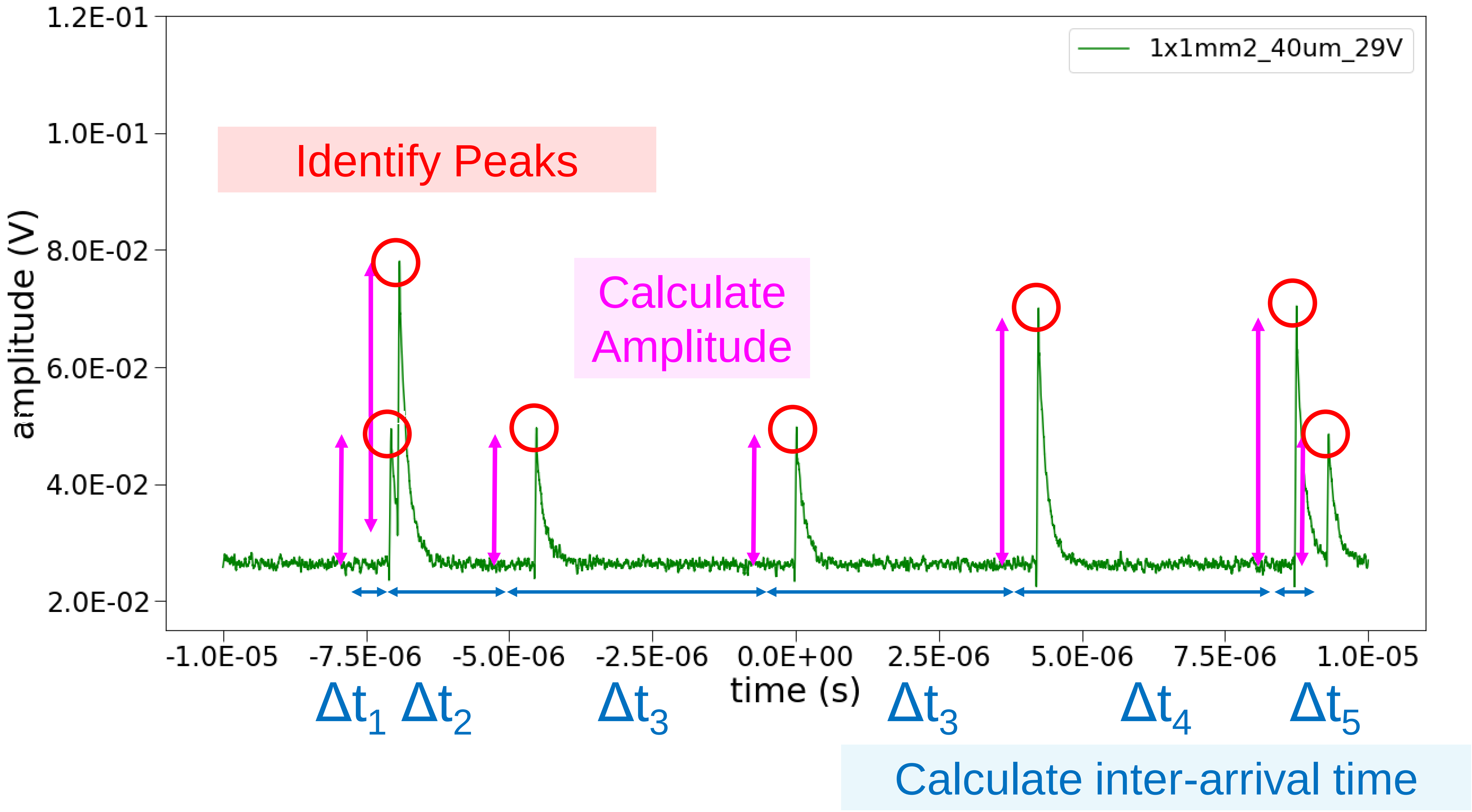
4 Wafer level measurements on pre-series runs fulfilled the requirements of the DUNE experiment ensuring the feasibility / reliability of a mass production

Thank you

Backup Slides

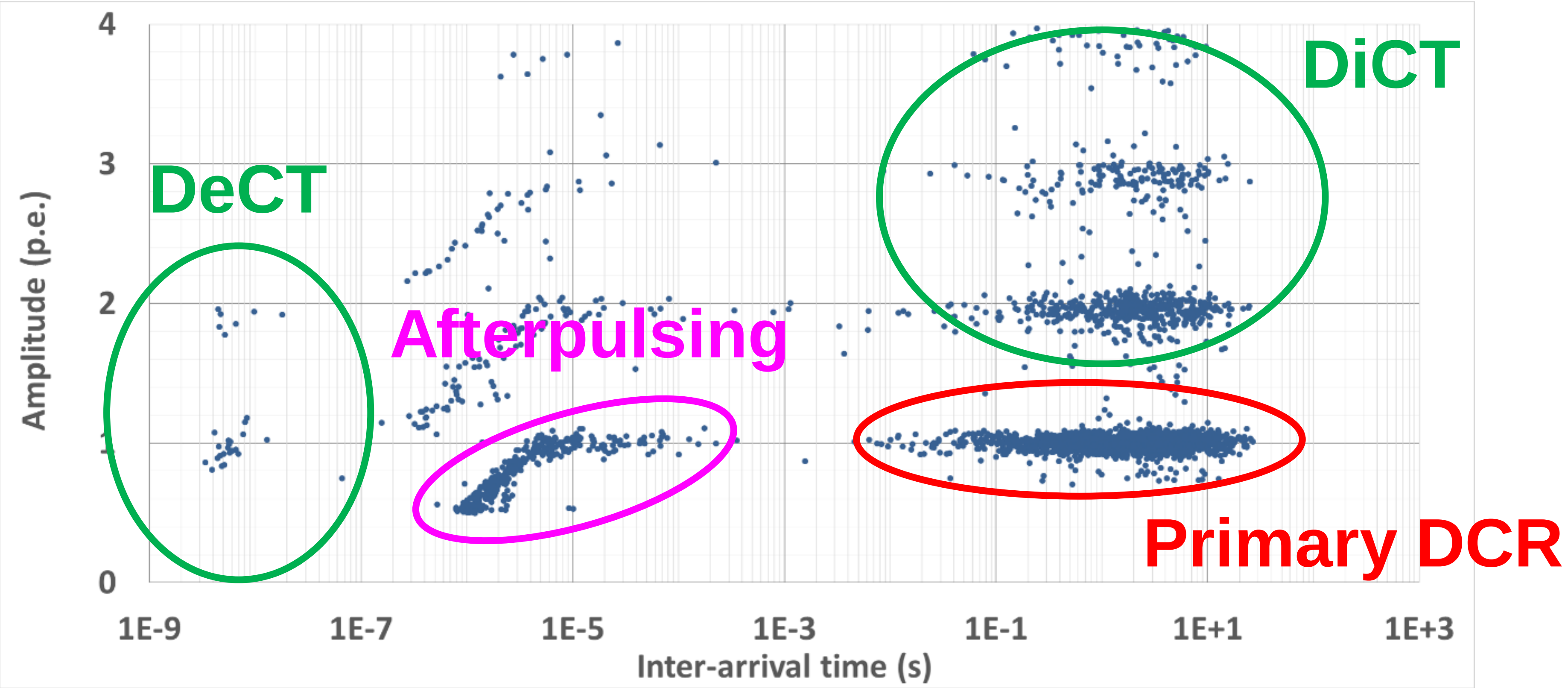
DUNE Characterization
Dark characterization technique

Acquire *continuous waveform*, filter and post-process data to identify peaks corresponding to dark counts. Then calculate inter-arrival times.

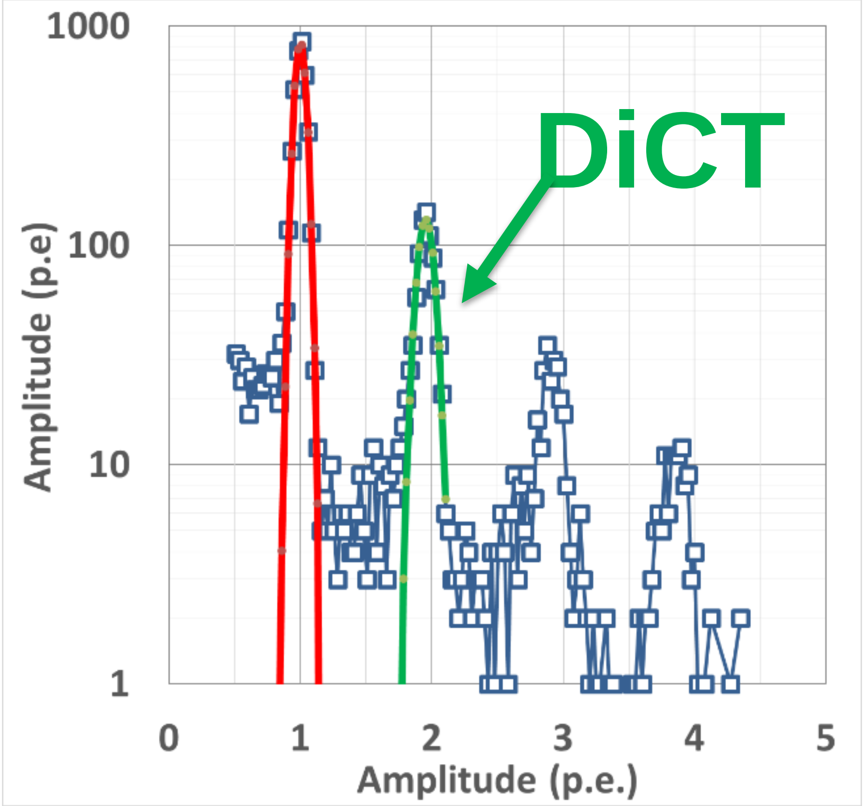


DUNE Characterization
Dark acquisition

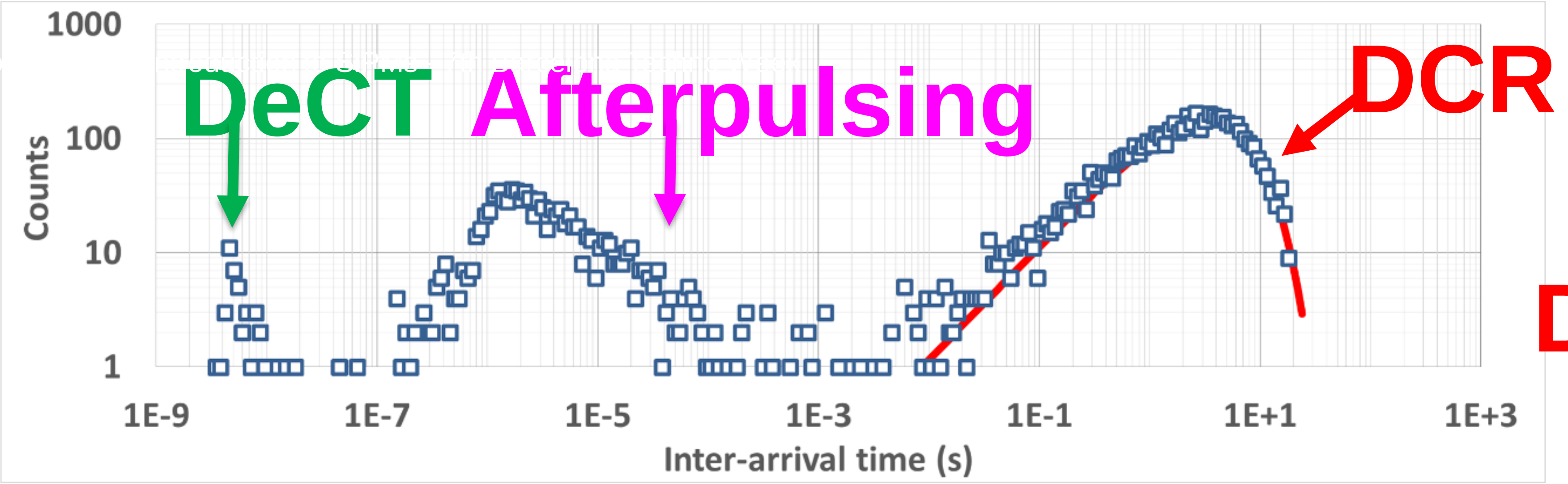
Scatter plot

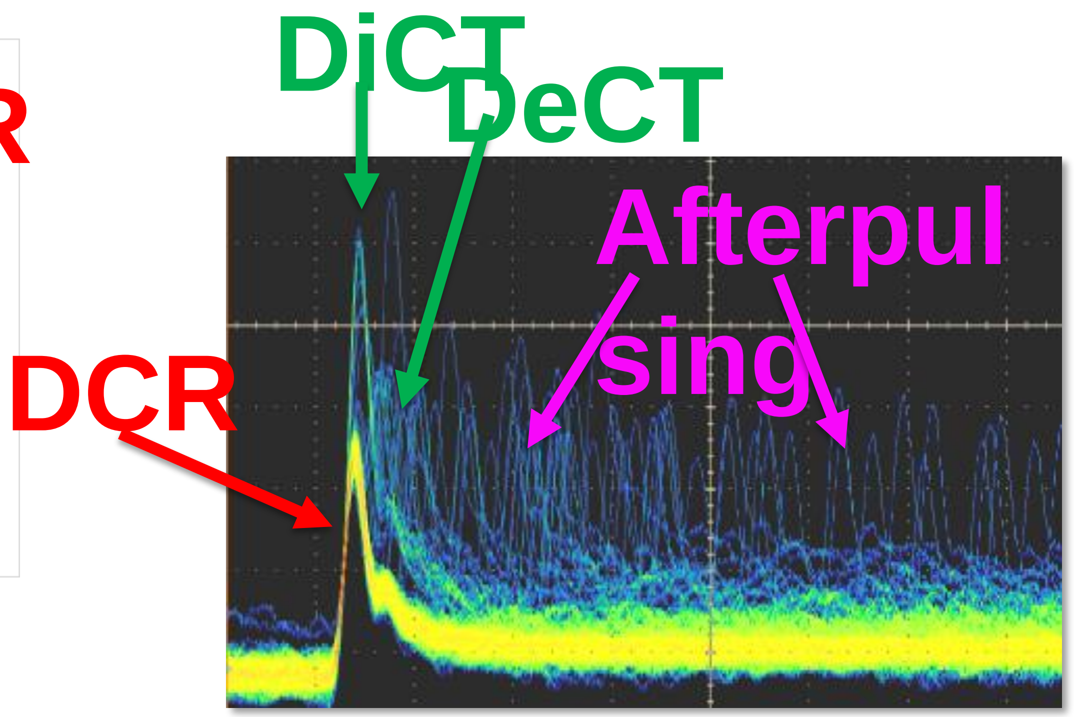


Amplitude histogram



Inter-arrival time histogram





← Sensitivity ≥ 12 orders of magnitude! →