FBK roadmap towards the next-generation of 3D-integrated SiPM and SPAD technologies

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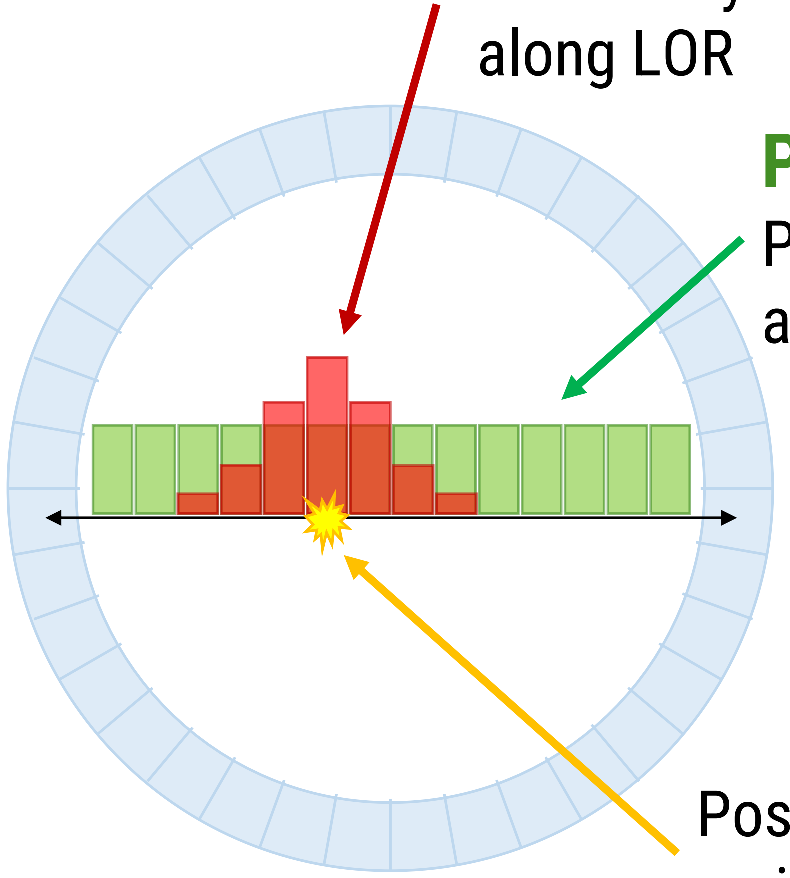
FBK SiPM technologies
Typical Applications

The traditional application of SiPMs is the ToF-PET. In addition, thanks to the *constant improvement of SiPM performance*, they are being evaluated in the *upgrade of several Big Physics Experiments*.

Positron Emission Tomography

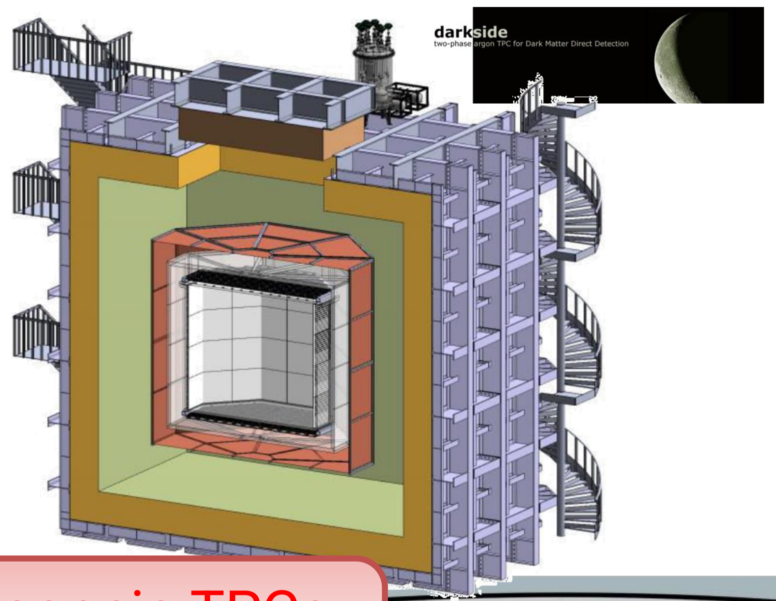
TOF-PET
Probability distribution along LOR

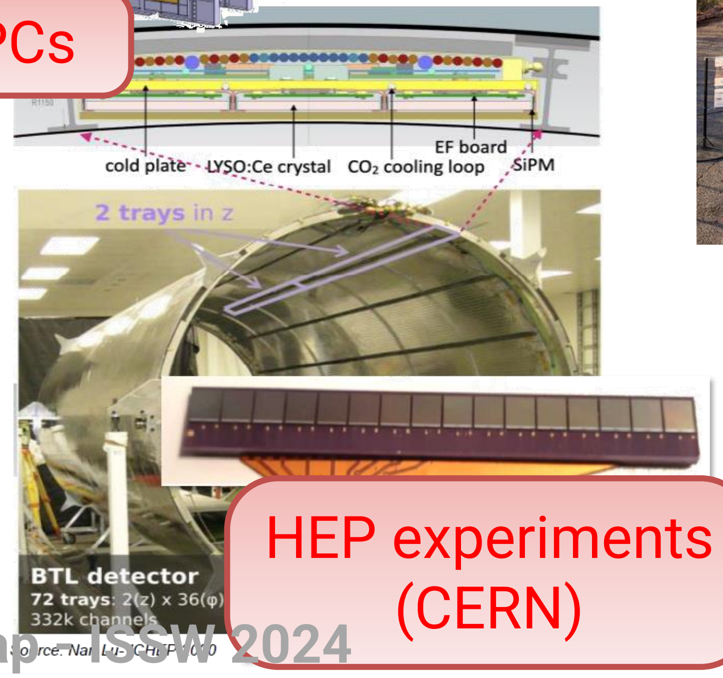
PET
Probability distribution along LOR



Position of gamma emission

Big Physics Experiments





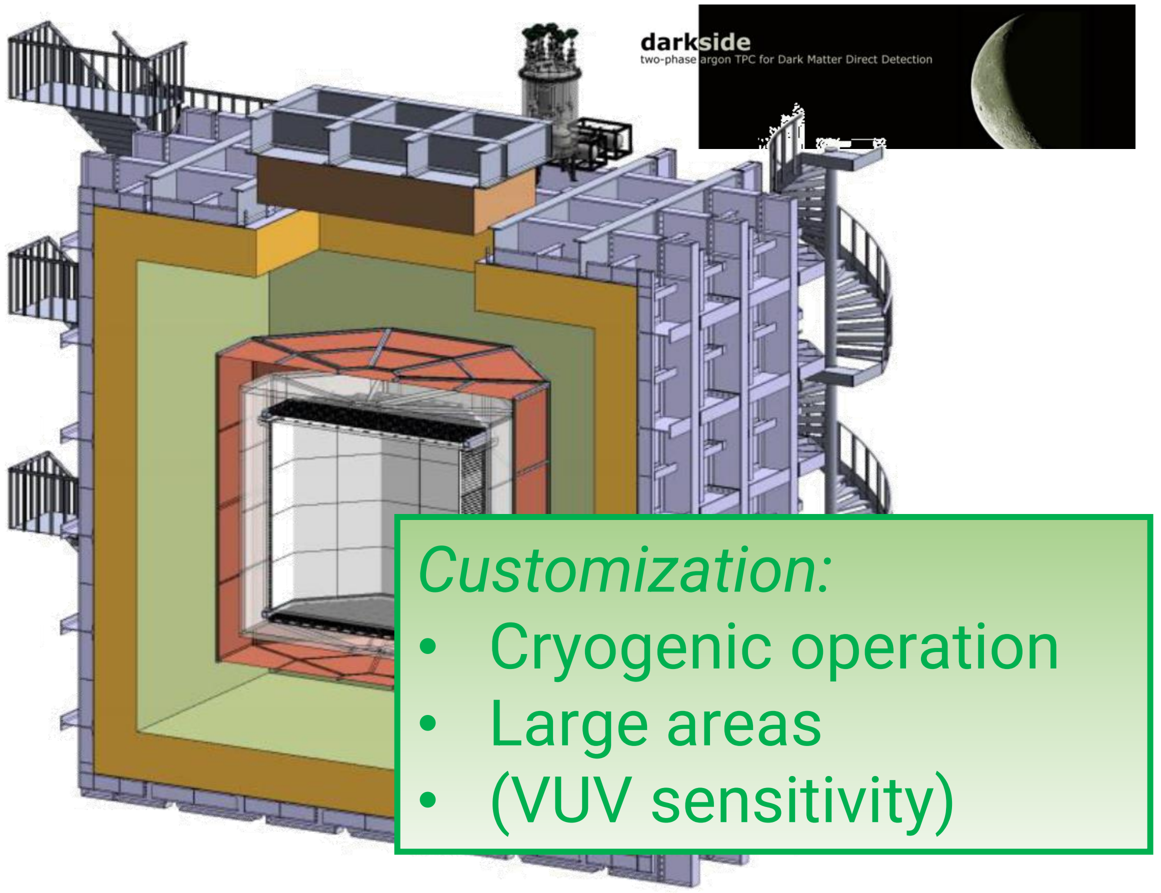
Examples of Big Physics experiments FBK is currently working on.

FBK SiPM technologies
Use in Big Physics Experiments

Especially for Big Physics Experiments, *deep customization of the detector is often required.*

Strong argument in favor of a *custom sensing layer in a 2.5D / 3D integration configuration*, *optimized for specific applications*.

Cryogenic TPCs



Customization:
- Cryogenic operation
- Large areas
- (VUV sensitivity)

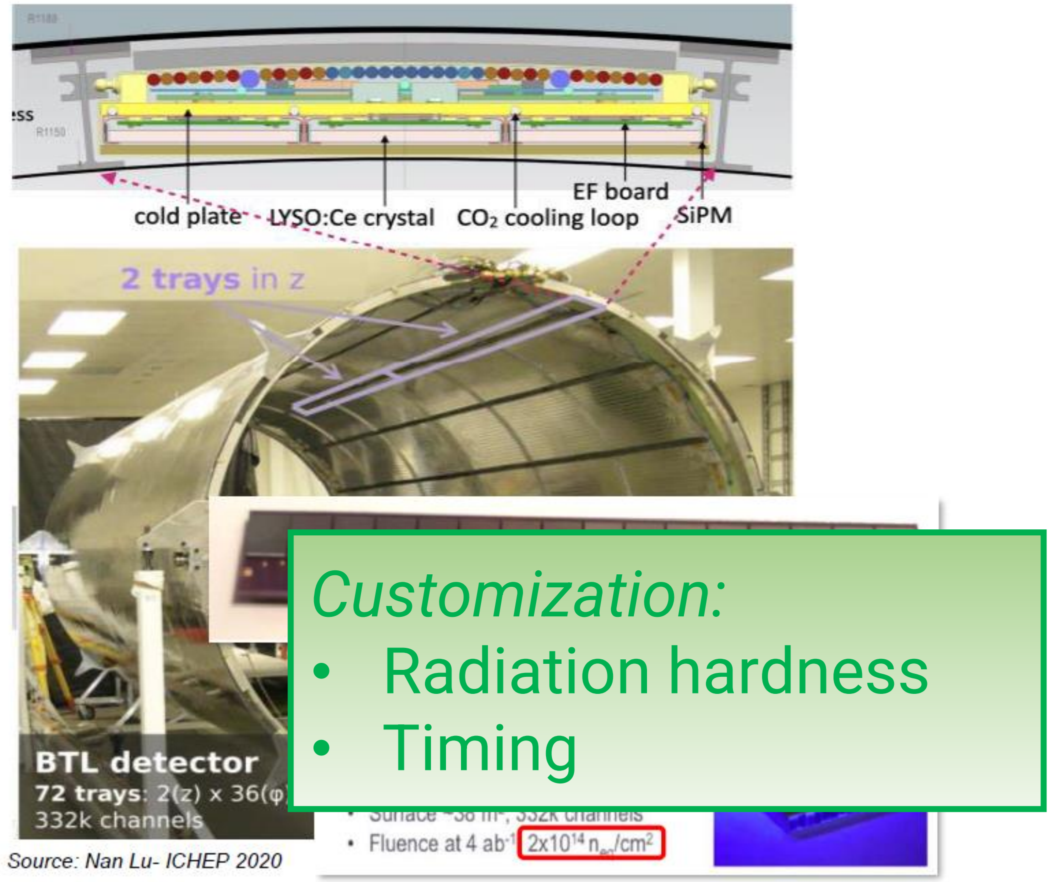
Cryogenic SiPMs will be employed in experiments such as DarkSide-20k

CTA

Customization:
- Low CT
- Maximum PDE

Prototype pSCT installed in the VERITAS, equipped with FBK SiPMs.

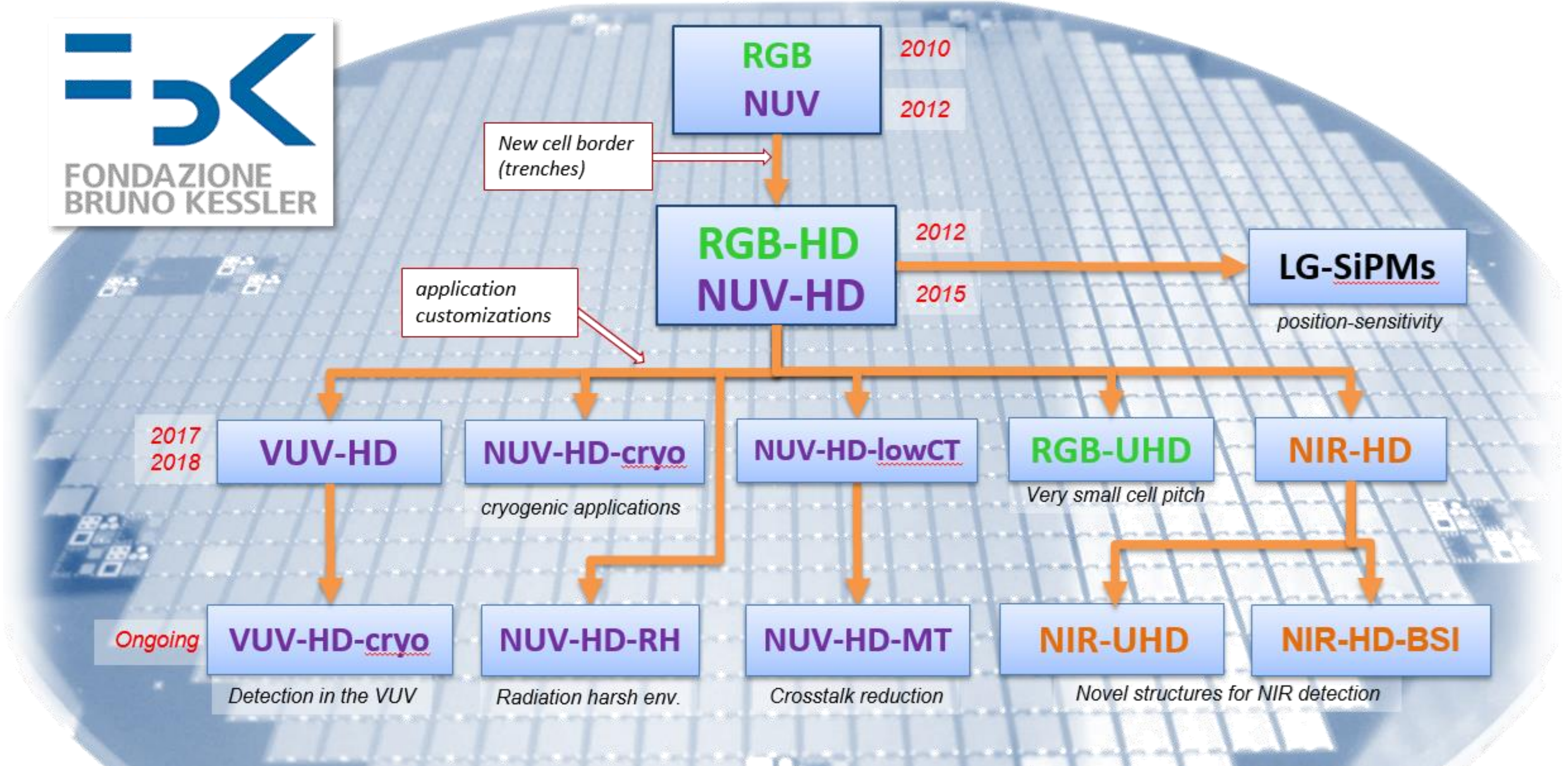
HEP



Customization:
- Radiation hardness
- Timing

NUV-HD SiPMs are being evaluated for the MIP timing detector of CMS (LYSO scintillator readout).

Fondazione Bruno Kessler
Custom SiPM technology roadmap



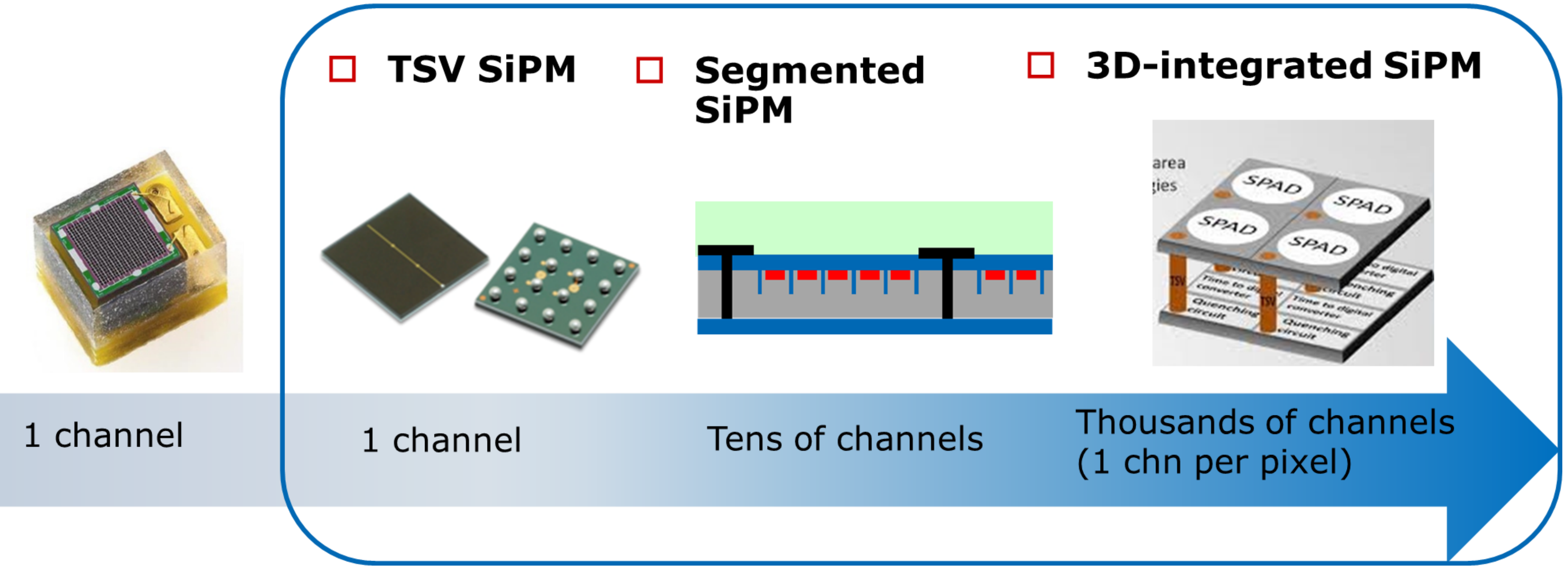
2.5D and 3D integration

2.5D and 3D Integration
FBK IPCEI clean-room upgrade

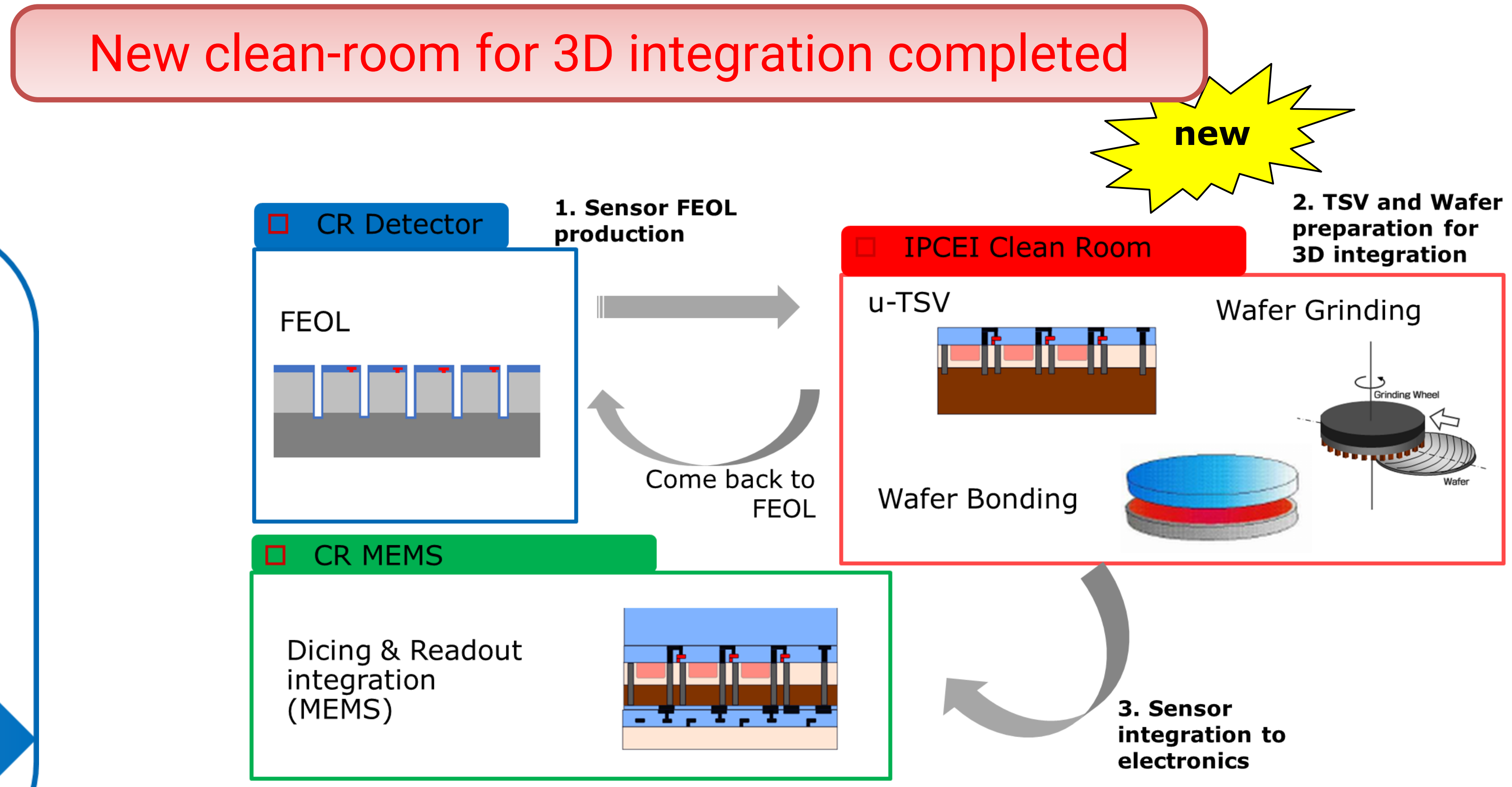
FBK is part of the *IPCEI on microelectronics* project (Important Project of Common European Interest - €1.75 billion total public support, 12 M€ to FBK).

The goal for FBK is upgrading its optical sensors technologies, by *developing TSVs, micro-TSV and Backside Illuminated SiPMs*. This will allow high-density interconnections to the front-end and high-segmentation.

Customized TSVs will be optimized to preserve the NUV-HD electro optical and timing performance.



Range of technologies being developed within IPCEI

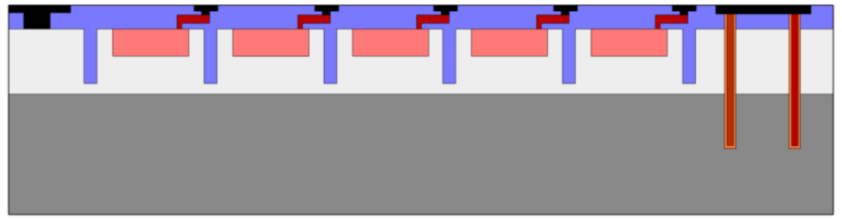


The complete system composed of 3 research clean-rooms in FBK.

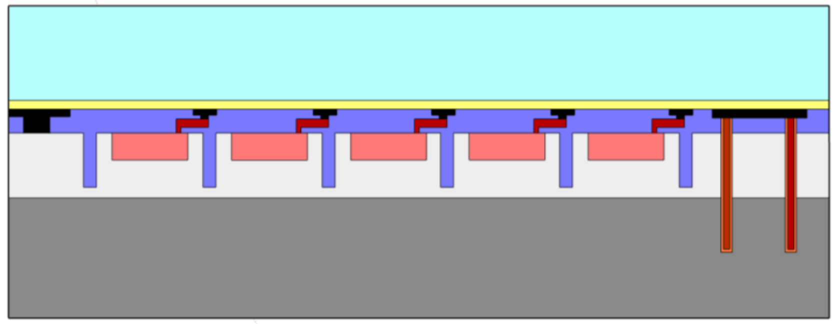
2.5D and 3D Integration
TSV – via mid: process flow

In the via-mid process, the *TSV is formed during the fabrication of the SiPM, modifying its process flow*.
In the via, the *conductor is the highly-doped silicon bulk*.

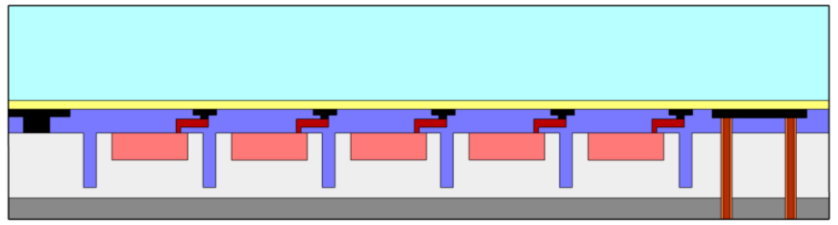
- SiPM fabrication + TSV formation



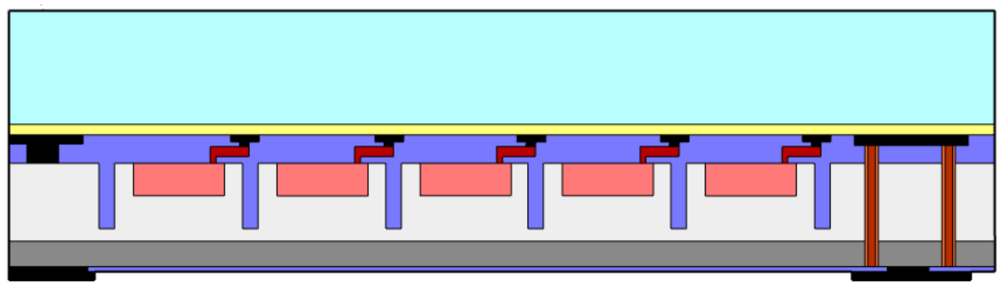
- Edge Trimming + BONDING



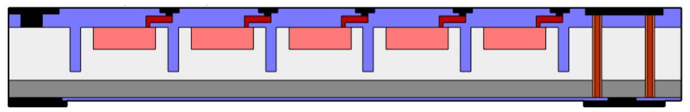
- THINNING



- Contacts formation



- DEBONDING

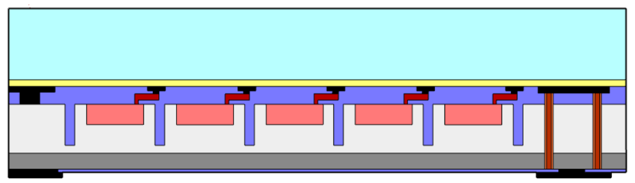


Thickness at least 150 um

Glass-less TSV
concept

500 um SiPM pitch

- NO-DEBONDING

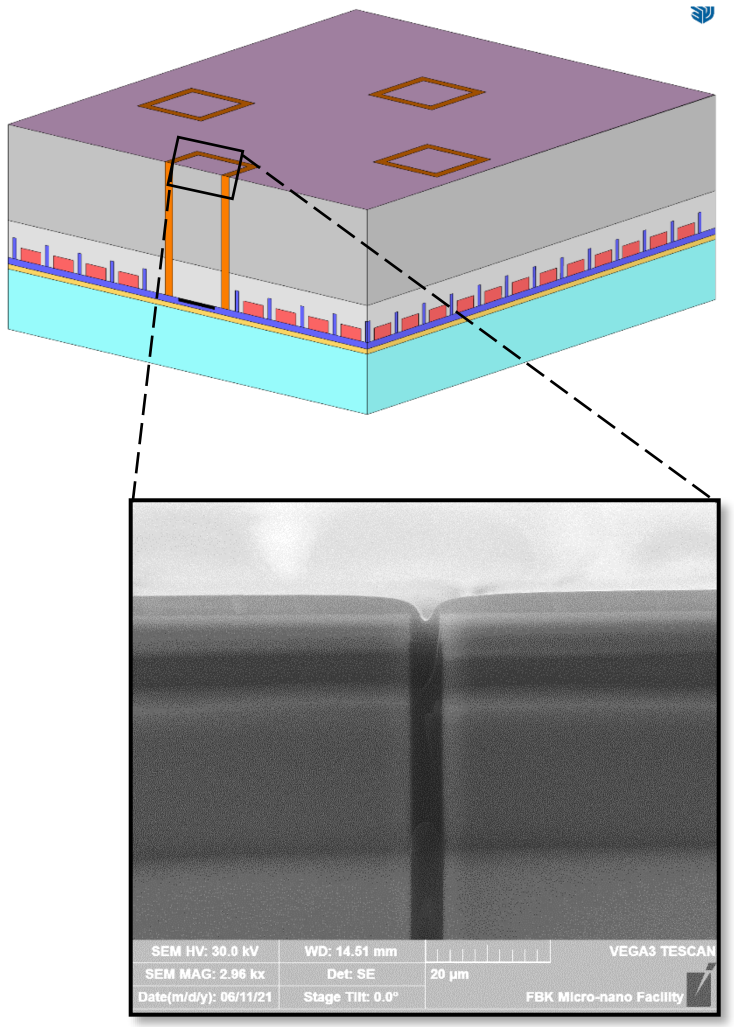


Thickness 10-50 um

Standard TSV

microTSV

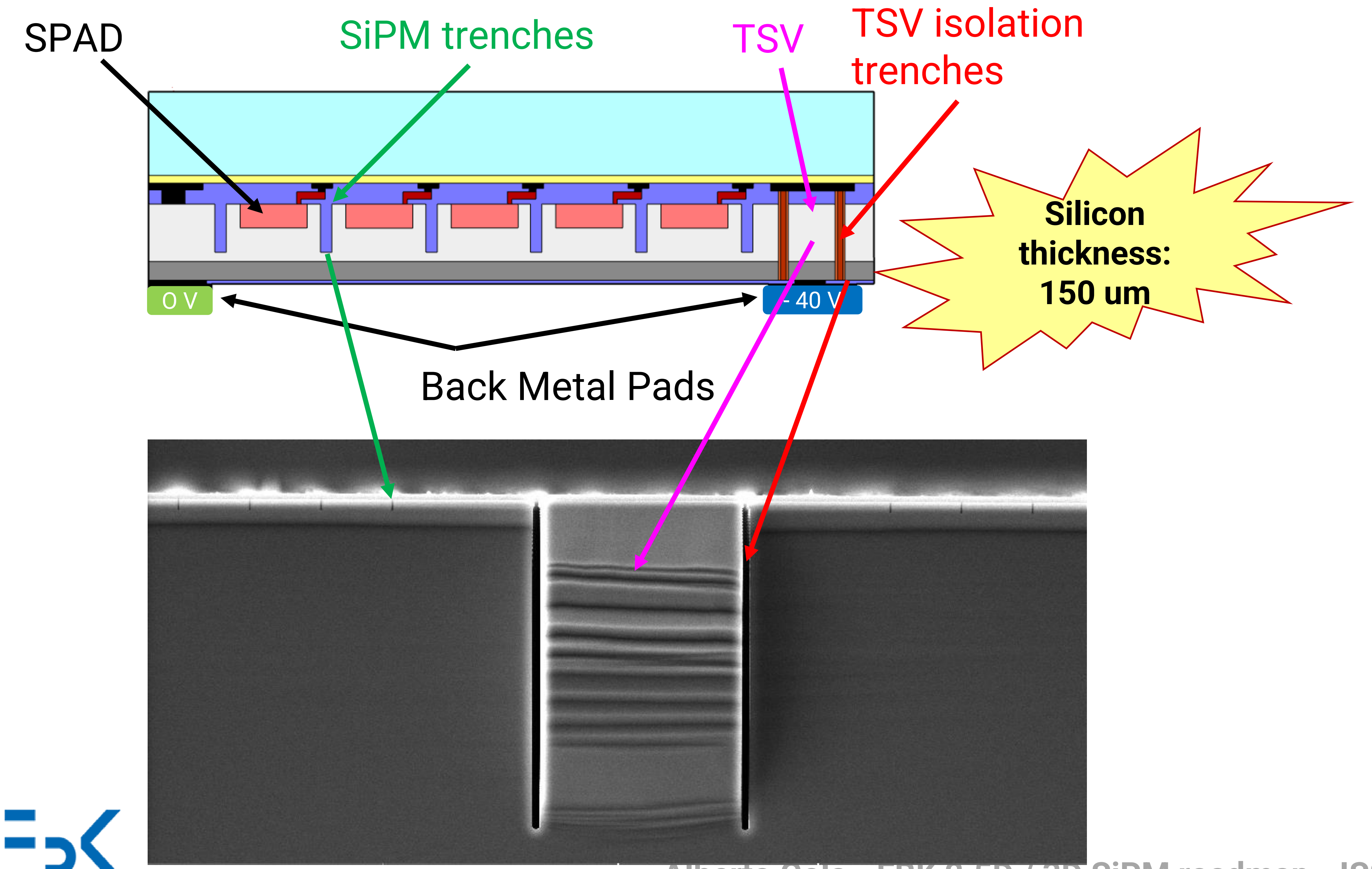
< 50 um SPAD pitch



- Metal-free TSV
- Flexible TSV layout and size
- Low bulk resistivity

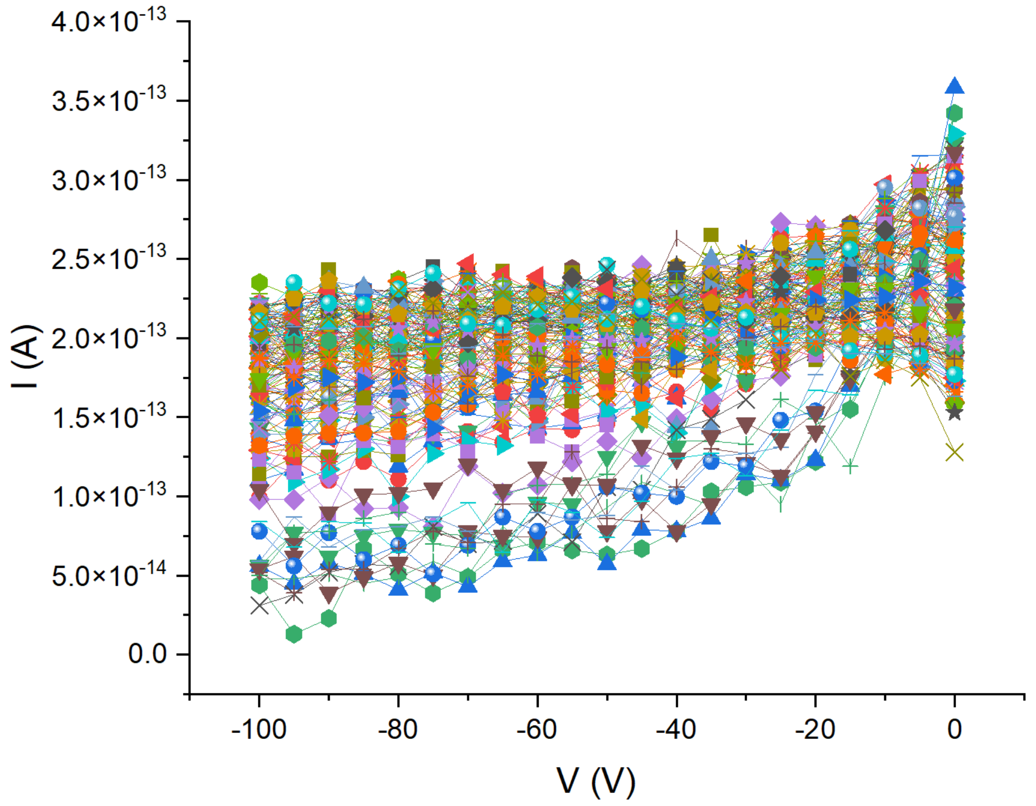
2.5D and 3D Integration
TSV – via mid: first results

Preliminary results on TSV via-mid development, with partial SiPM process, to *check isolation and continuity* (no Geiger-mode multiplication).



At **-100 V** of bias applied the intensity varies from **30 to 200 fA**

Trough Silicon Vias – Via Mid are isolated from the bulk silicon contact

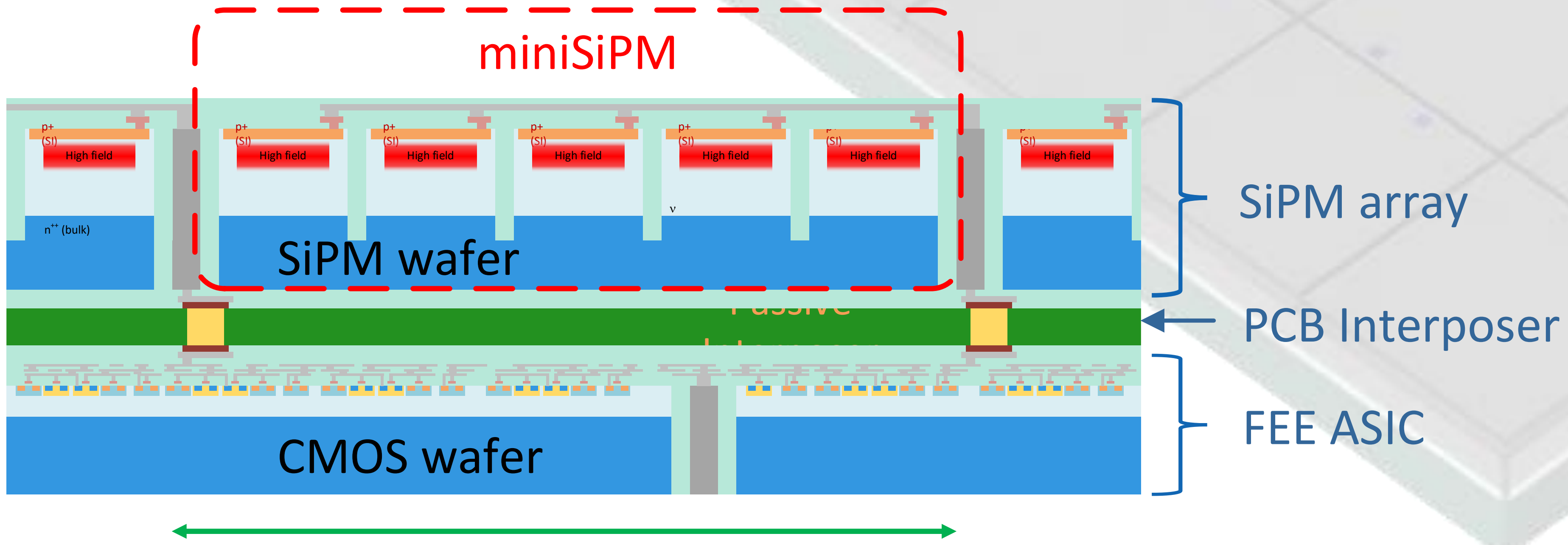


2.5D and 3D Integration
2.5D integrated SiPM tile

In the *short and medium term*, medium density interconnection seems the sweet spot to obtain *excellent performance (e.g. timing) on large photosensitive areas while not increasing complexity and cost too much*.

We propose a Photon Detection Module (PDM) in which *SiPMs with TSVs down to 1 mm pitch* are connected to the *readout ASIC on the opposite side of a passive interposer*, in a *2.5D integration scheme*.

Integrated Photon Detection Module



Core partners:

Jožef Stefan Institute

ICCUB
Institut de Ciències del Cosmos

MASSACHUSETTS GENERAL HOSPITAL

ONCO VISION

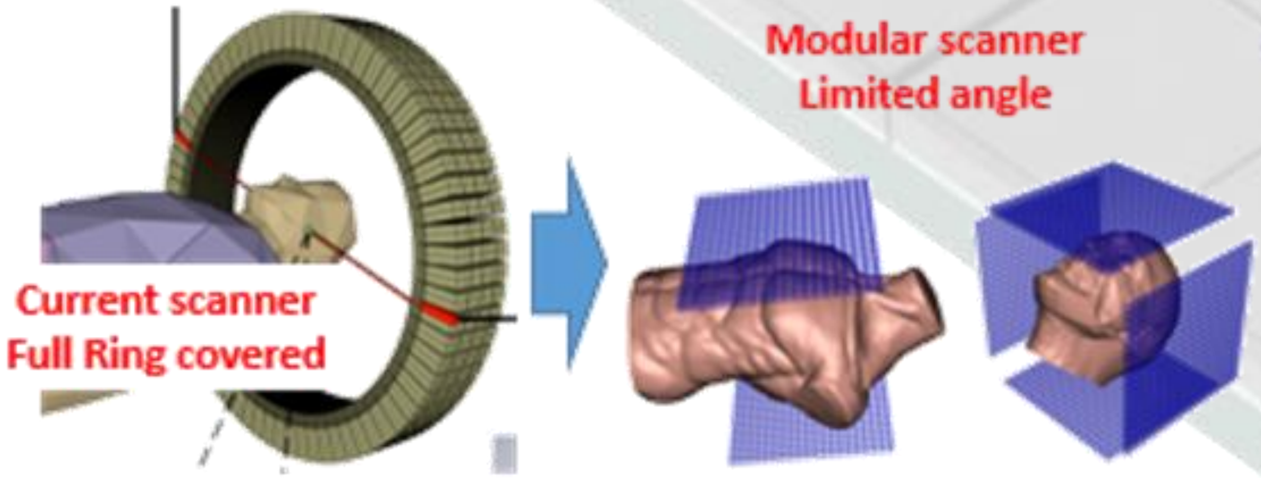
Hybrid SiPM module being developed for ultimate timing performance in ToF-PET

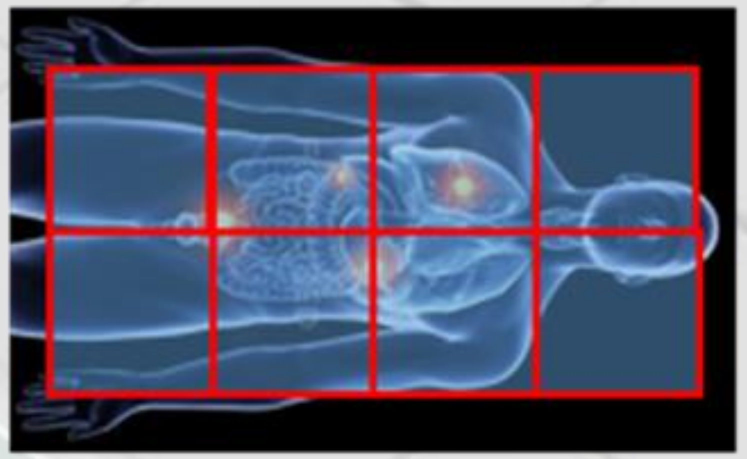
2.5D and 3D Integration
2.5D integrated SiPM tile for timing

The 2.5D integrated PDM (50x50 mm^2) will be the basis of a *30x30 cm^2 ToF-PET panel*, which will be used to build limited-angle ToF-PET systems, for brain PET, Cardiac PET and full-body scanners.

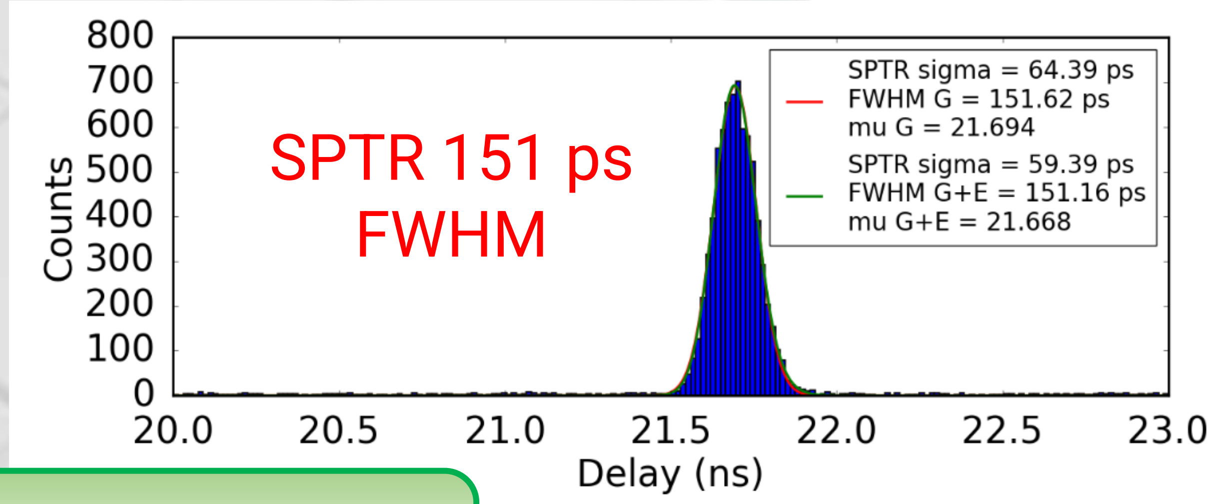
We *expect very good timing performance*, supported by preliminary measurements achieved with NUV-HD SiPMs coupled to FastIC ASIC.

ICCUB Institut de Ciències del Cosmos

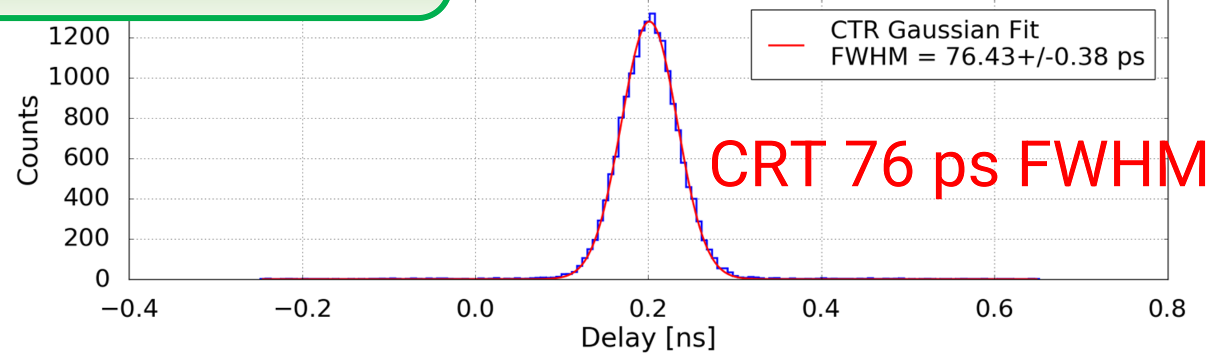


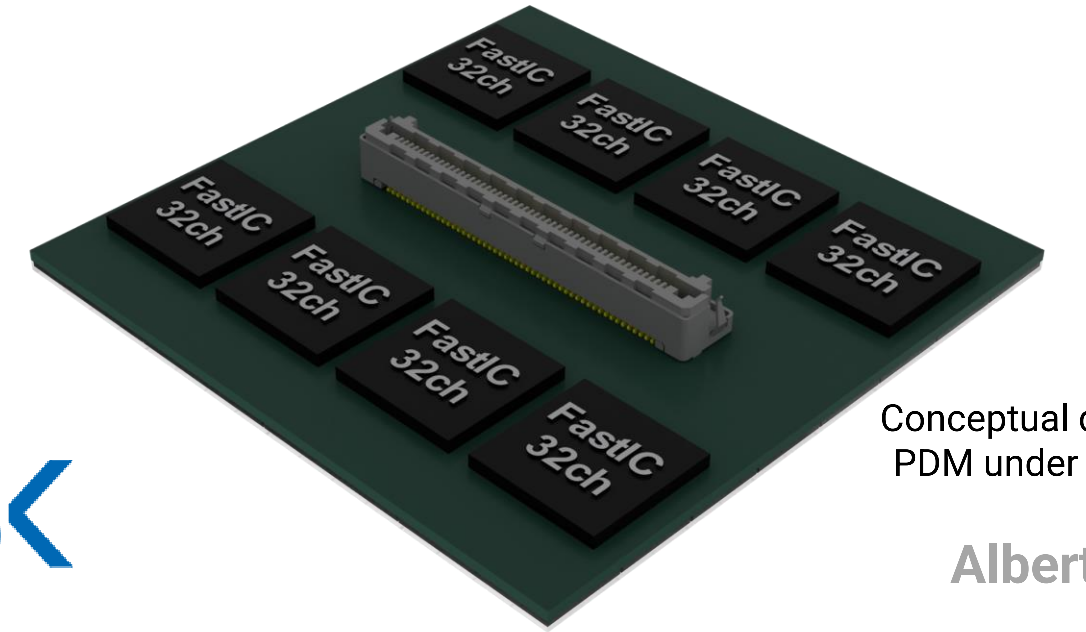


Application of the PDM to build large panes used in new, limted-angle PET applications: Brain Pet, Cardiac PET, while-body PET

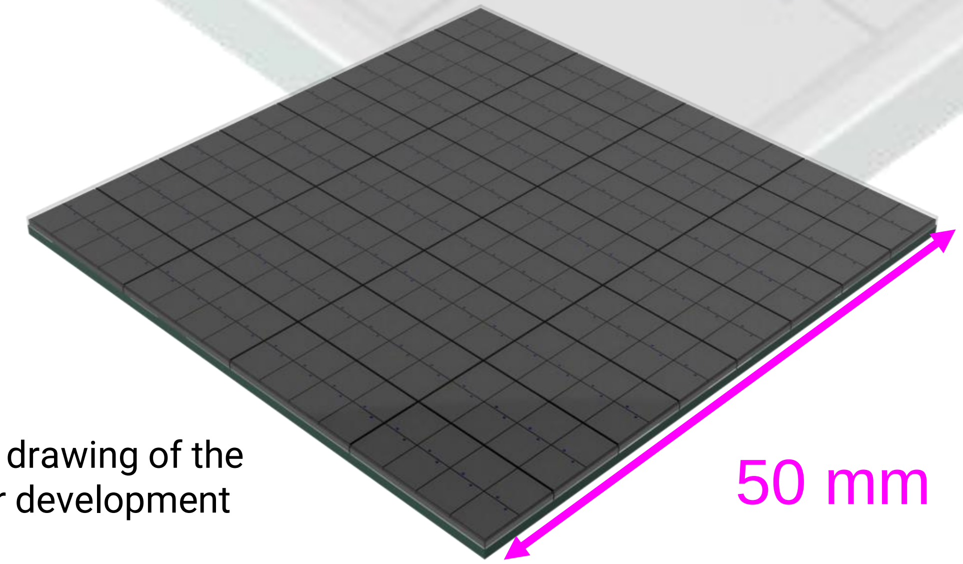


2x2x3 mm^3 LSO:Ce,Ca





Conceptual drawing of the PDM under development



SPTR and CRT measured at FBK NUV-HD-SiPMs read by the FastIC ASIC developed by ICCUB.
Sensor: NUV-HD-LFv2 SiPMs, 3x3 mm^2
Scintillator: 2x2x3 mm^3 LSO:Ce,Ca
Power consumption: 3 mW / channel

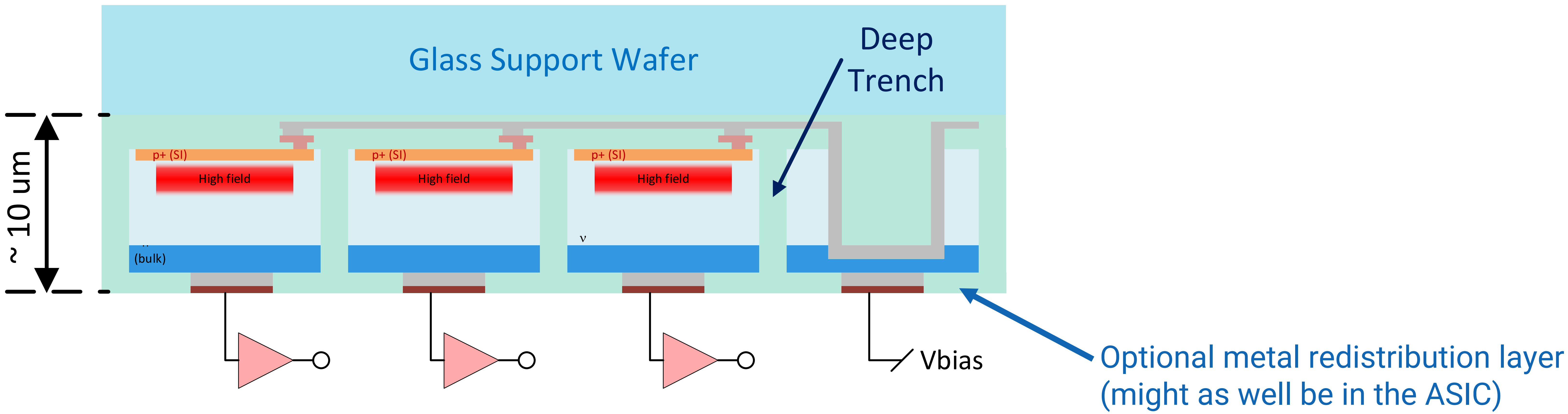
Single-SPAD TSV
Cross-section

Exploiting the Deep Trench Isolation, which is anyway present between adjacent SPADs in most SiPMs, we can achieve single SPAD isolation if we thin the wafer down sufficiently (use of a glass support wafer is needed).

We can exploit this isolation to *build a "bulk" TSV just below and coincident with each single SPAD*.

The *resistors* are still on the front-side (no change in signal shape is expected).

Common connection for bias is on the front and requires a TSV to bring it from the bottom.



Single-SPAD TSV
Advantages / Drawbacks

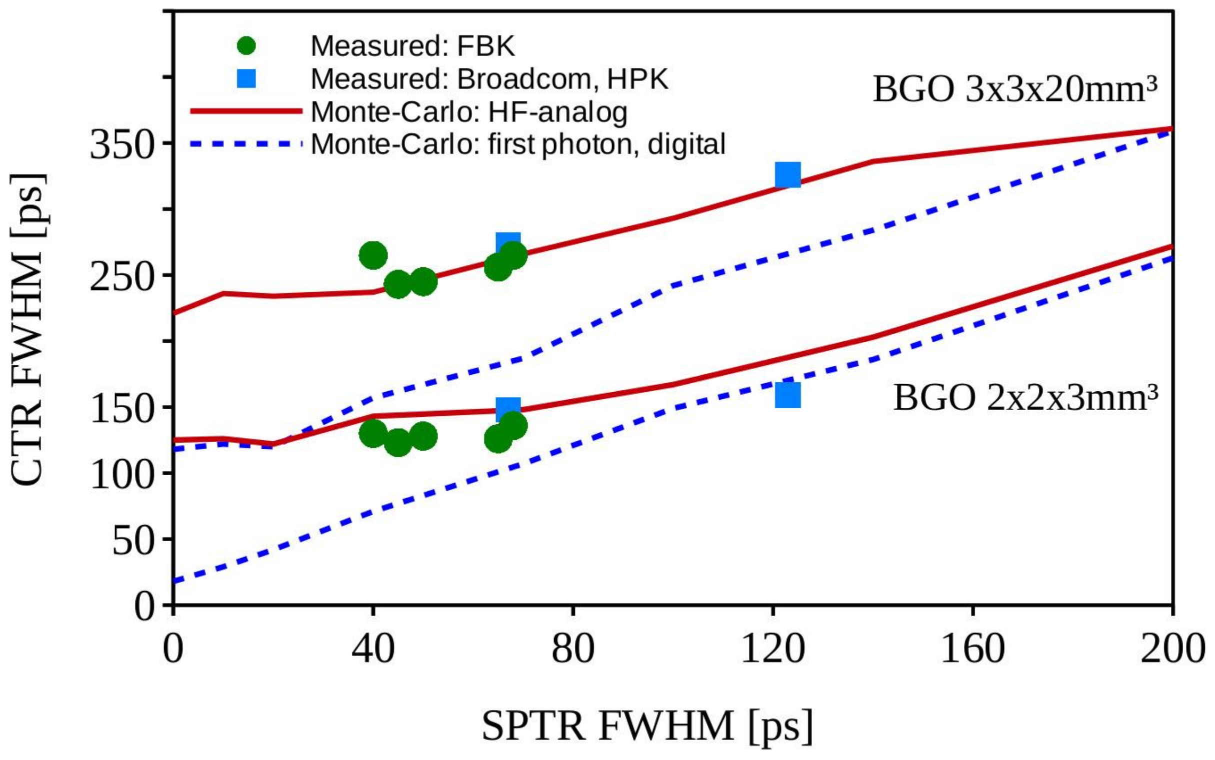
Advantages:

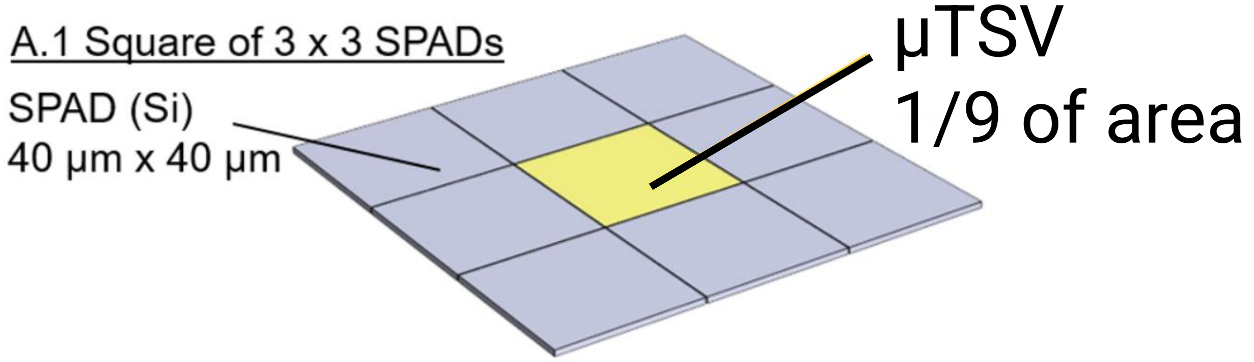
- (Almost) *no changes to the state-of-the-art, FSI, NUV-sensitive SiPMs* → conservative approach.
- It might be the only wat to have fine-pitch TSVs (around 50 um) with ***no loss of FF*** for the SiPMs.
- No additional trenches needed → simpler.
- Flexibility to have single-cell access, when needed, but also miniSiPMs and ***microSiPMs***, through *either a redistribution layer* on the SiPM backside or directly in the *3D integrated ASIC*
- *Connection for the topside metal* can be obtained through the same type of vias (possibly with epitaxial layer removal).

2.5D and 3D Integration
High-density integration: DIGILOG

DIGILOG investigates higher density interconnections to *approach the dSiPM performance without the complexity of single-SPAD access*.

Single-SPAD TSV will be investigated in the DIGILOG project, removing the need to replace the central SPAD in the uSiPMs with a TSV, thus achieving the *highest PDE possible*.



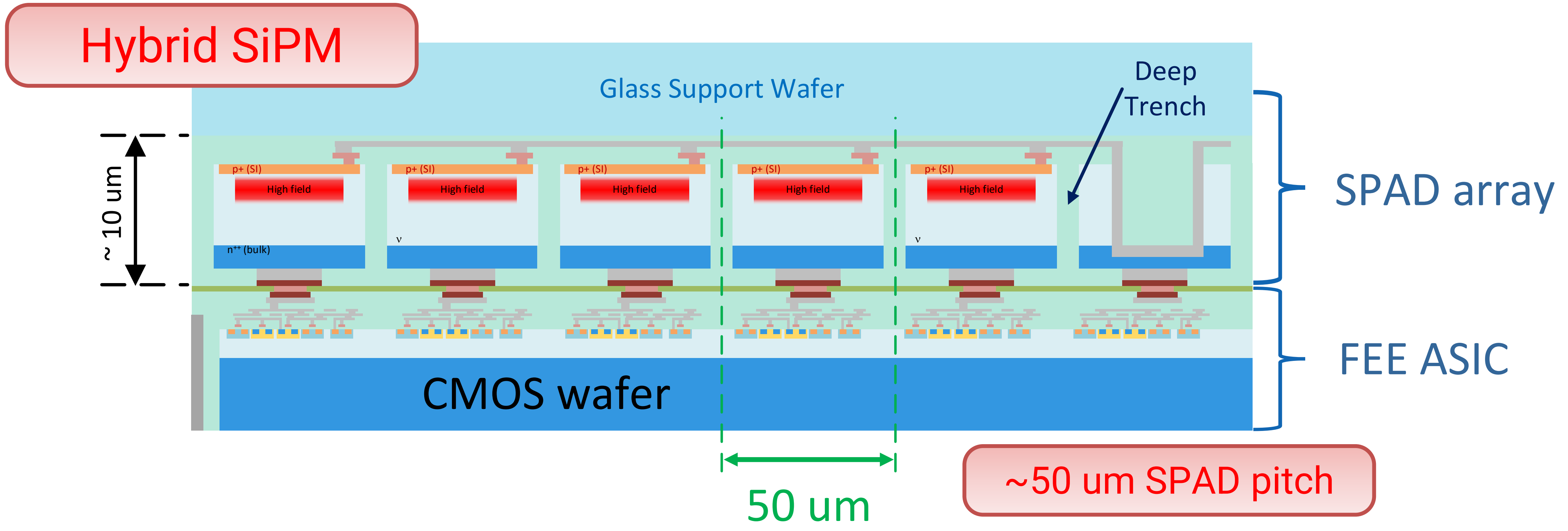


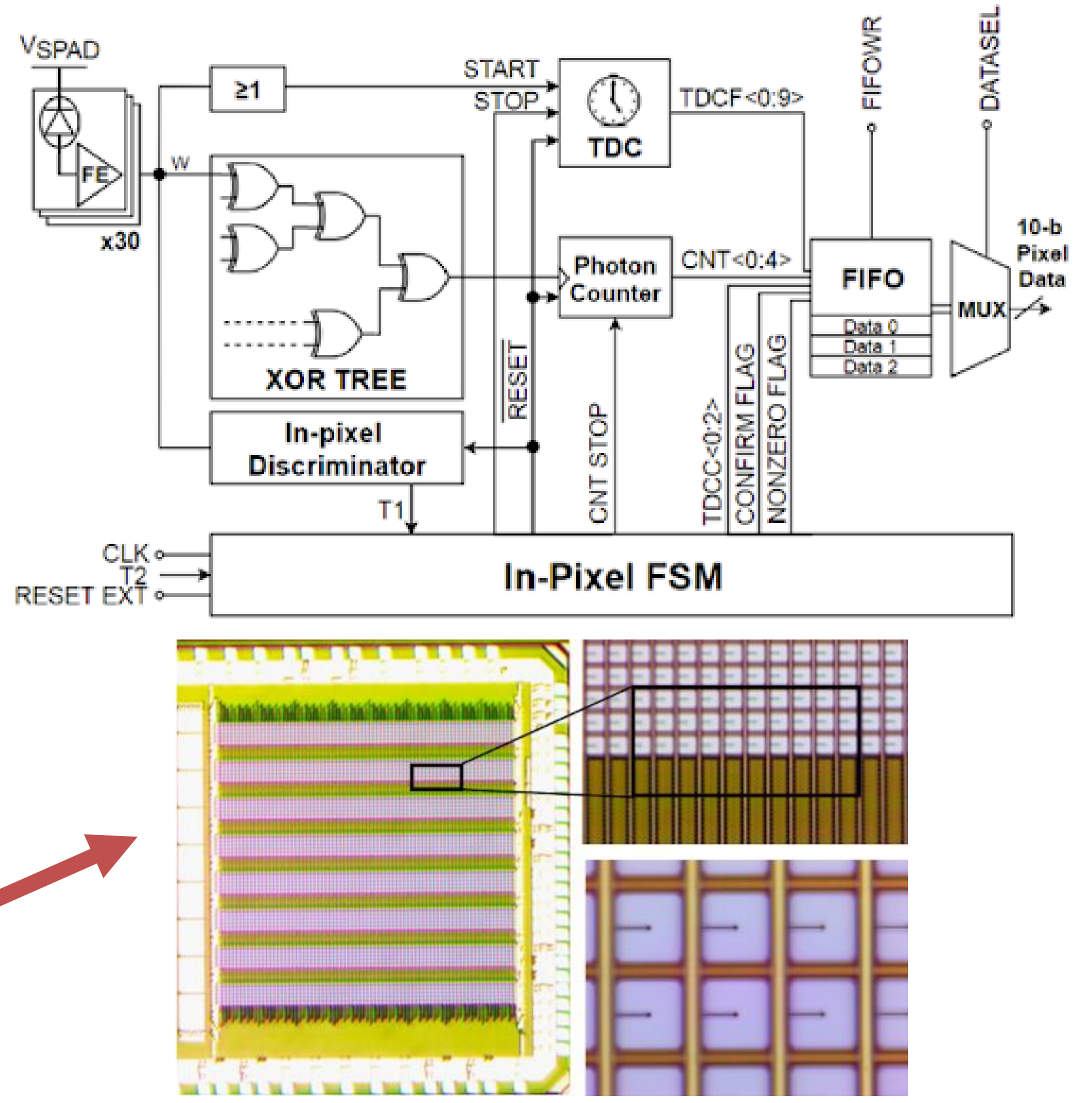
- µSiPMs with µTSVs
- µASICs with *in situ* TDCs
- Embedded ANNs
- **Distributed computing**

S. Gundacker, et al., A. Gola, E. Charbon, V. Schultz *NSS* 2023
S. Gundacker, et al., *to be published* 2023

2.5D and 3D Integration
Full 3D integration with micro TSVs: Hybrid SiPM

FBK will also employ the single-SPAD TSV to achieve *single cell connection*. While complexity of the system increases, it might provide *ultimate timing performance*.



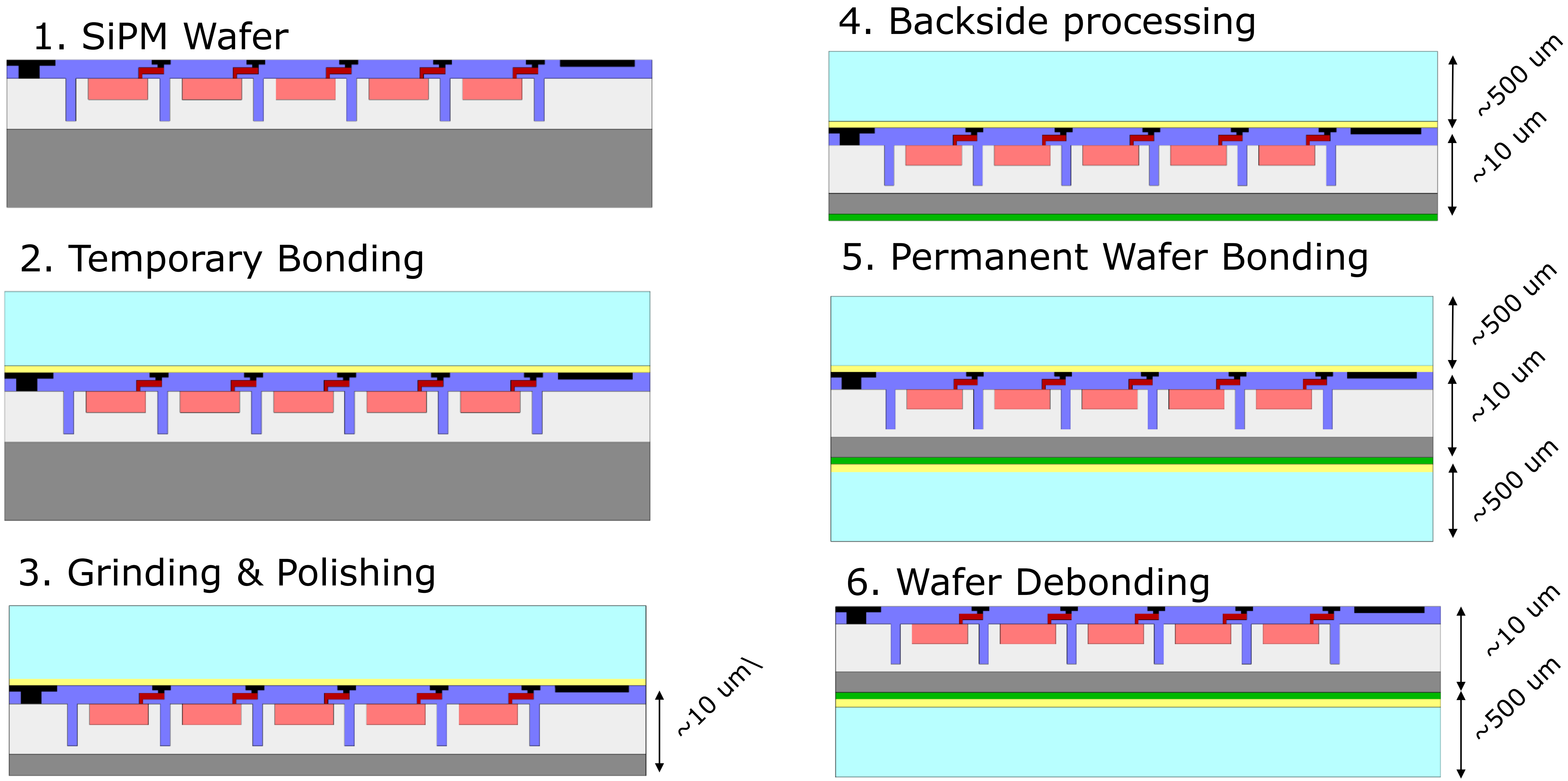


Example of dSiPM architecture developed at FBK (SBAM project)

- FBK can apply all the *know-how on system architecture* already developed in the filed of digital SiPMs.
- Finally solve the duality between analog and digital SiPM: *Hybrid SiPM concept*.

2.5D and 3D Integration
Backside Illuminated NIR-SiPMs: process flow

BSI development started on *NIR-sensitive SiPMs* → *no need to create a new entrance window* on the backside with high efficiency in the NUV.

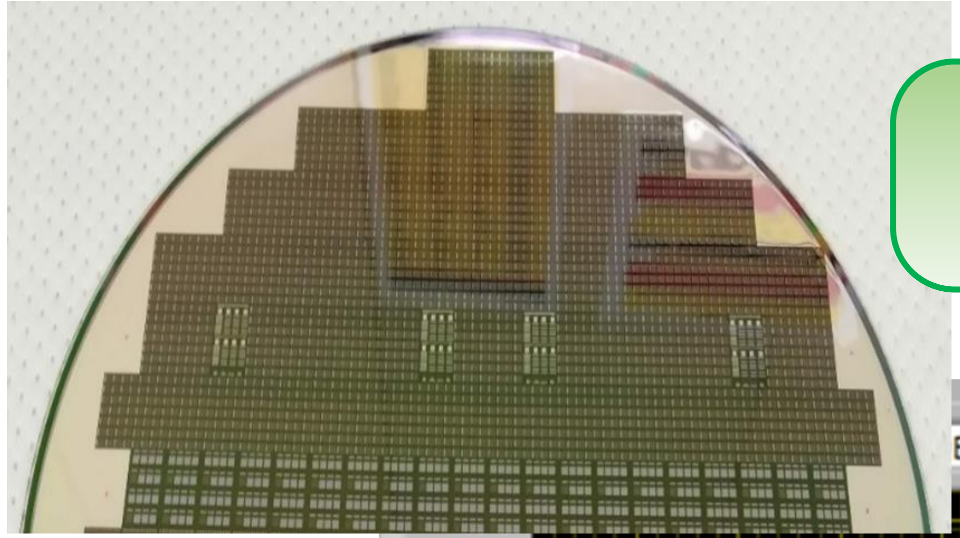


2.5D and 3D Integration
BSI NIR SiPMs: first results

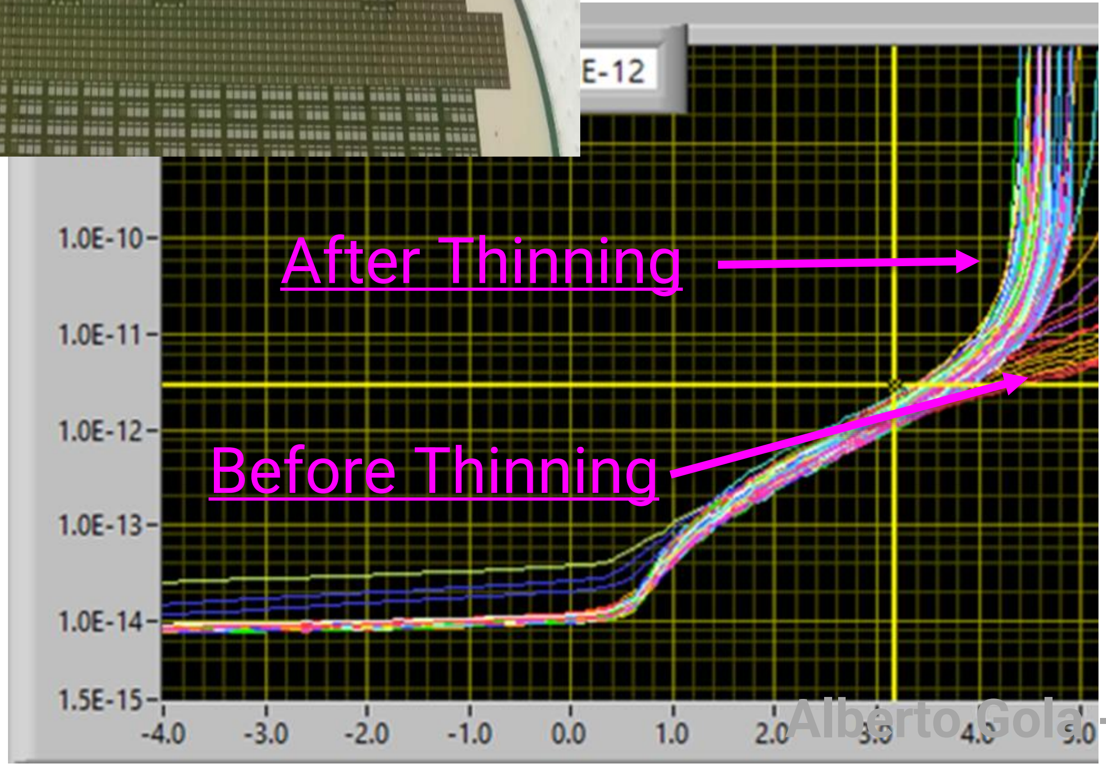
The *first NIR-sensitive BSI wafers were fabricated* in FBK clean room (1x1 mm^2 devices).

Minor differences in the IVs after thinning, compared to the FSI devices (without thinning).

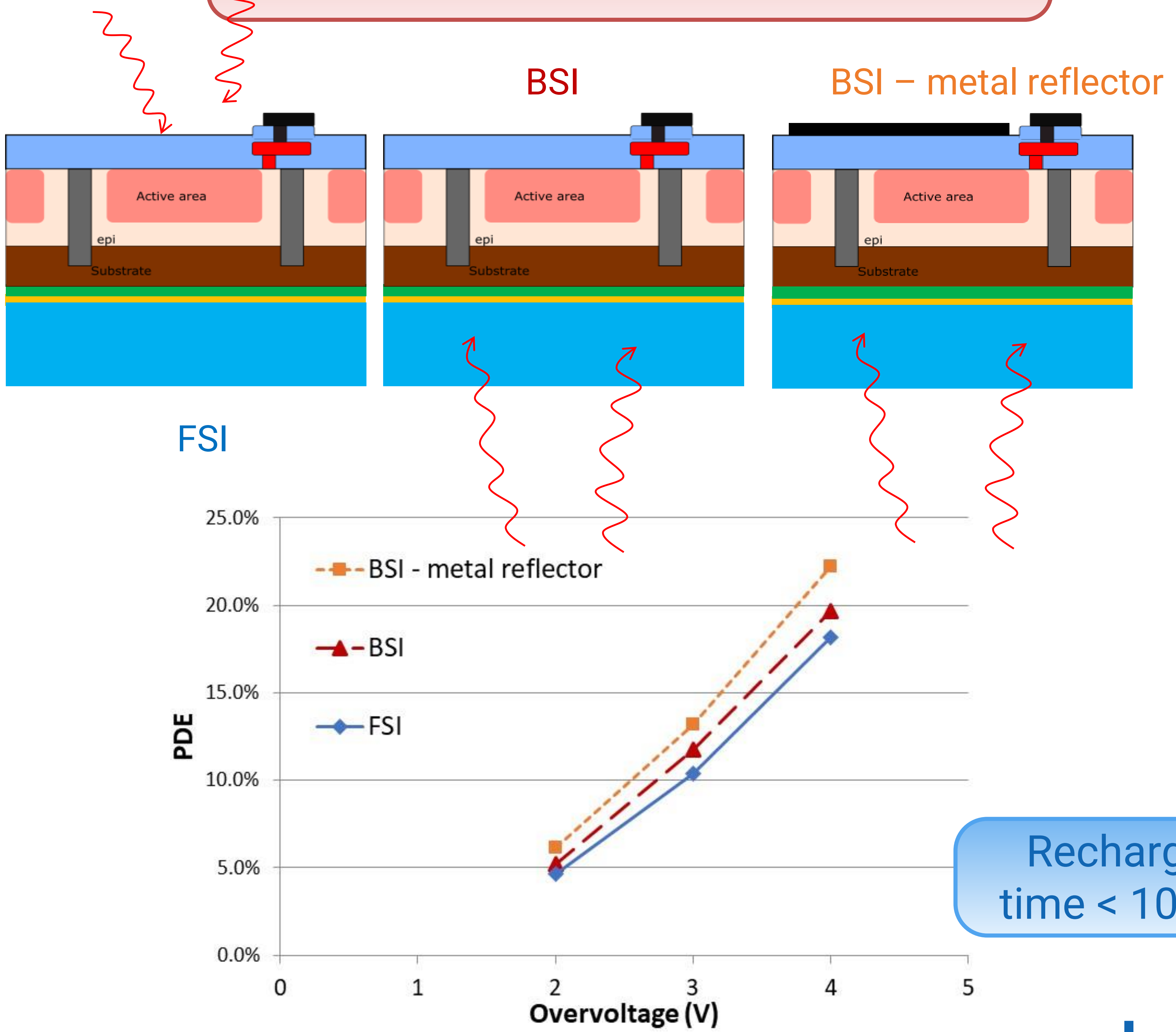
Ultrathin substrate (~ 10 um)



NIR BSI process is working!



NIR PDE comparison at 905 nm

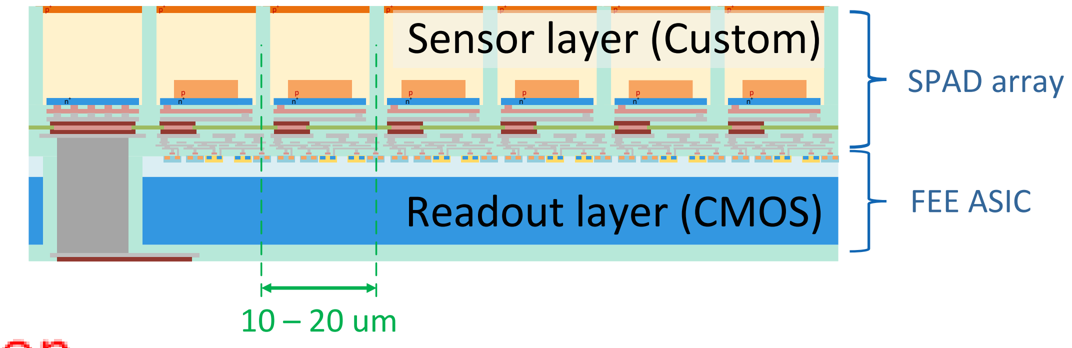


Recharge time < 10 ns

2.5D and 3D Integration
Next-generation development: Backside Illuminated SiPMs

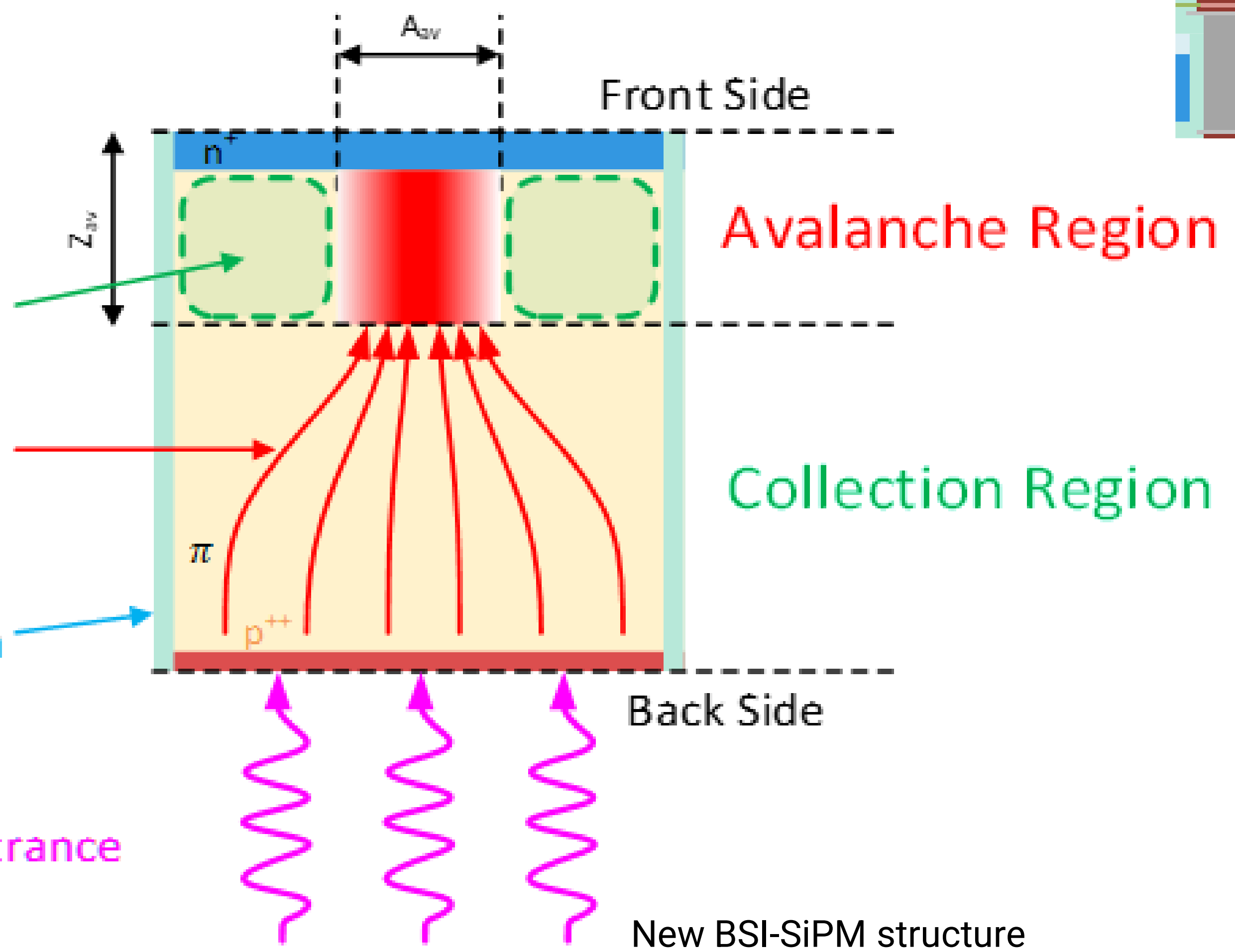
The next-generation of developments, currently being investigated at FBK, is building a *backside-illuminated, NUV-sensitive SiPM*. Several technological challenges should be overcome.

Clear *separation between charge collection and multiplication regions*.



Potential Advantages:

- Up to 100% FF even with small cell pitch
- Ultimate Interconnection density: < 15 um
- High speed and dynamic range
- Low gain and external crosstalk
- (Uniform) entrance window on the backside, ideal for enhanced optical stack (VUV sensitivity, nanophotonics)
- Local electronics: ultra fast and possibly low-power.



New BSI-SiPM structure

Development Risks:

- Charge collection time jitter
- Low Gain → SPTR?
- Effectiveness of the new entrance window

Radiation hardness:

- The SiPM area sensitive to radiation damage, is much smaller than the light sensitive area
- **Assumption**: the main source of DCR is field-enhanced generation (or tunneling).

Thank you!

Thanks to all the members of the team working on custom SiPM technology at FBK:

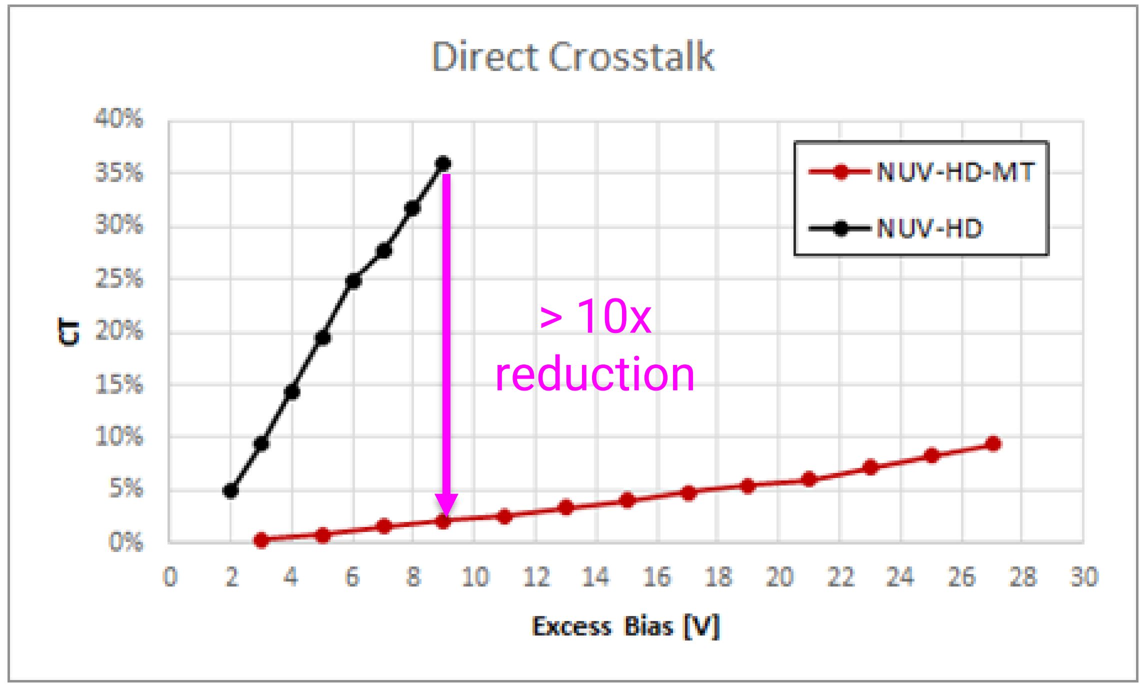
- **Fabio Acerbi**
- **Ibrahim Mohamed Ahmed**
- **Lorenzo Barsotti**
- **Andrea Ficorella**
- **Priyanka Kachru**
- **Oscar Marti Villareal**
- **Stefano Merzi**
- **Elena Moretti**
- **Giovanni Palù**
- **Laura Parellada Monreal**
- **Giovanni Paternoster**
- **Michele Penna**
- **Maria Ruzzarin**
- **Gianluca Vedovelli**
- **Nicola Zorzi**

Customized sensing layers

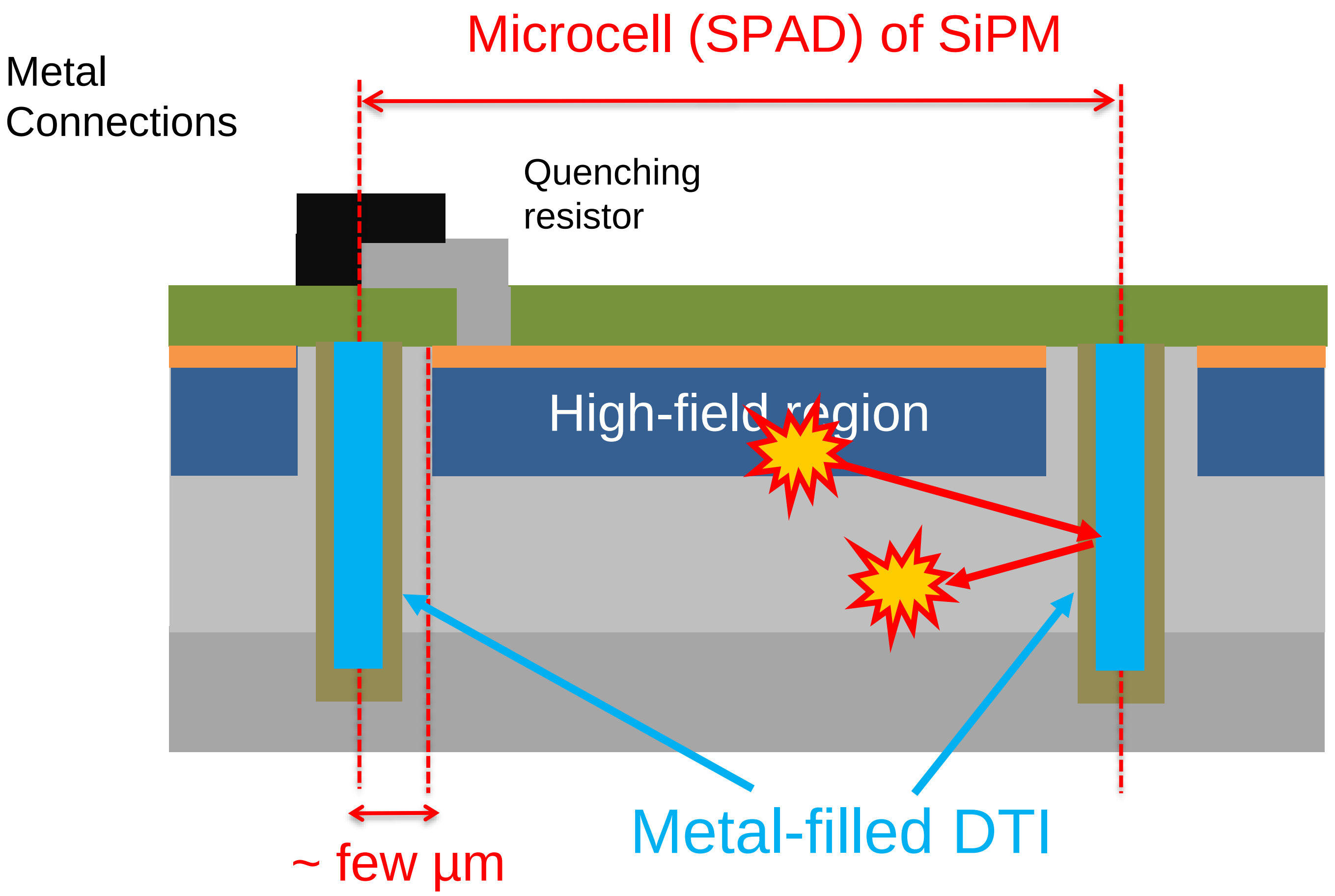
Reduction of optical crosstalk
NUV-HD-MT development

Starting from the NUV-HD technology, FBK and Broadcom jointly developed the NUV-HD-MT technology, adding *metal-filled DTI isolation to strongly suppress optical crosstalk*.

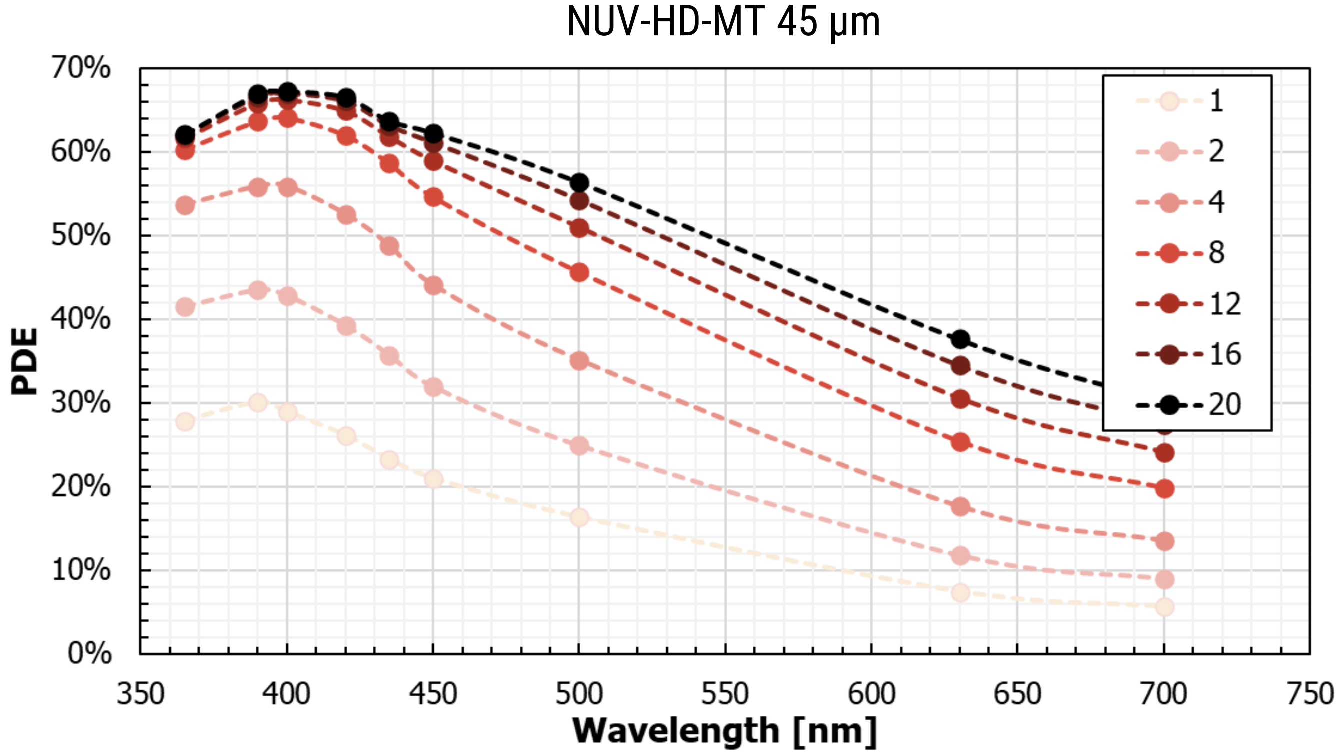
Other changes: low electric field variant, layout optimized for timing.



Reduction of optical crosstalk probability in NUV-HD-MT, compared to the "standard" NUV-HD. Measurement without encapsulation resin, i.e. *only considering internal crosstalk probability*.



Conceptual drawing of the NUV-HD-MT, with the addition of metal-filled Deep Trench Isolation.



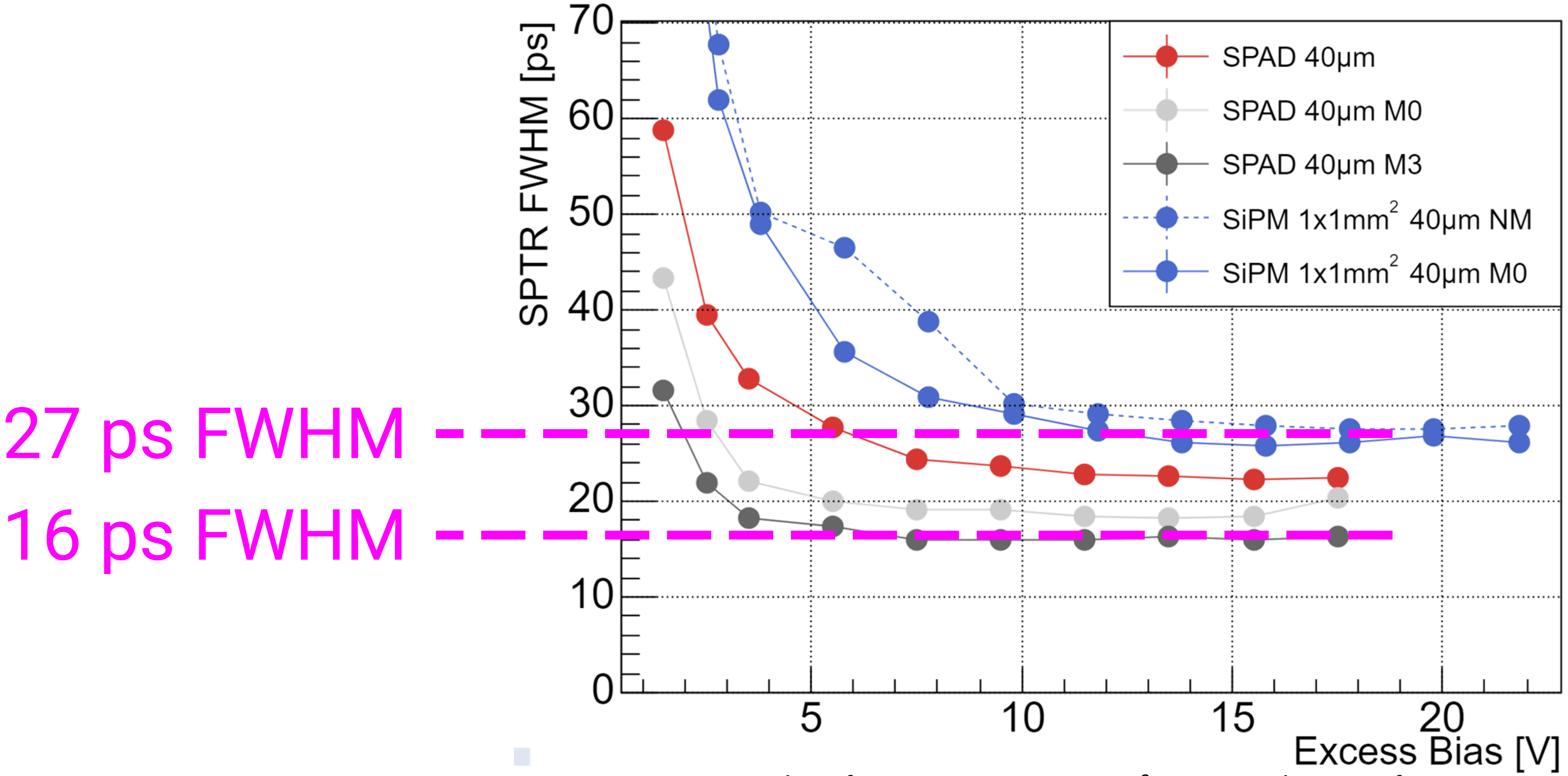
PDE vs. wavelength measured on the NUV-HD-MT technology with 45 um cell size with different values of the excess bias.

Merzi, Stefano, et al. "NUV-HD SiPMs with metal-filled trenches." *Journal of Instrumentation* 18.05 (2023): P05040.

Timing performance
Improvement of SPTR

Single Photon Time Resolution (SPTR) was improved with a *layout that enhances signal extraction* and signal integrity, in combination with *small SiPM active area* and a high frequency readout.

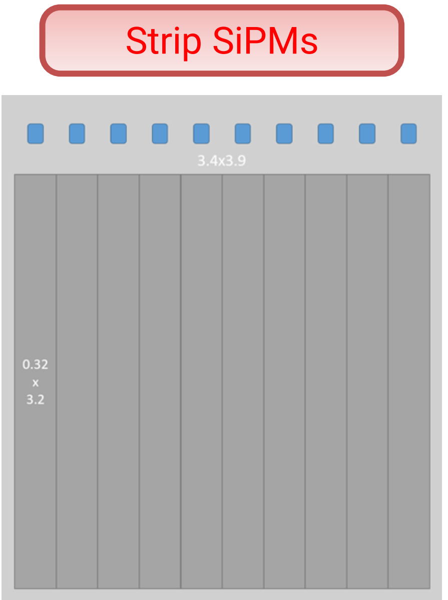
With *larger SiPMs*, the SPTR can be preserved by *segmenting the active area into smaller pixels, or miniSiPMs*, with *separate 3D connection to readout*, followed by *suitable combination of time pick-off* information.



SPTR vs. excess bias for NUV-HD-MT 1x1 mm² SiPMs and SPADs, featuring a *layout optimized for timing and using a high-frequency amplifier*.

High potential of achieving ultimate timing performance thanks to segmentation and 3D integration

10 strips 0.32 x 3.2 mm² each, no dead border between strips

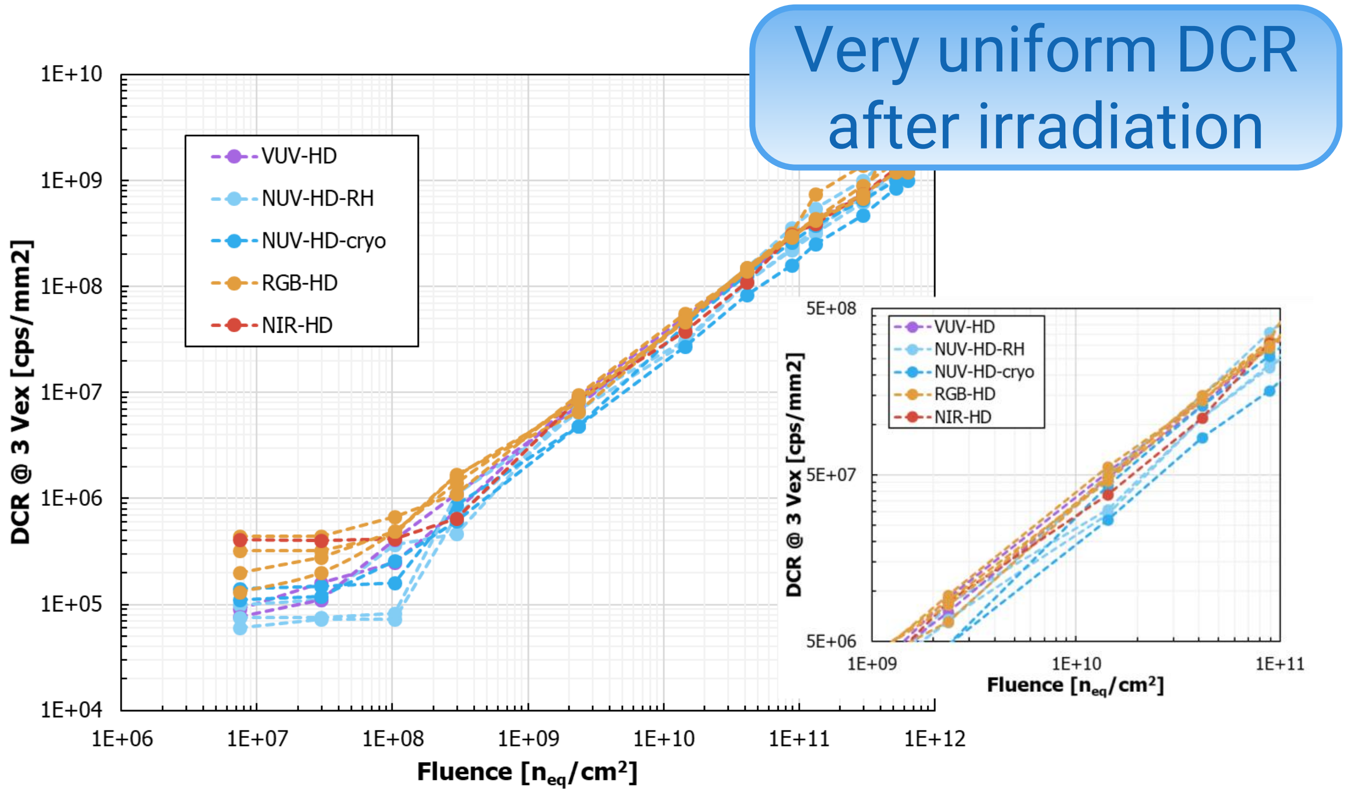


Gundacker, Stefan, et al. "High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET." *Physics in Medicine & Biology* 64.5 (2019): 055012.

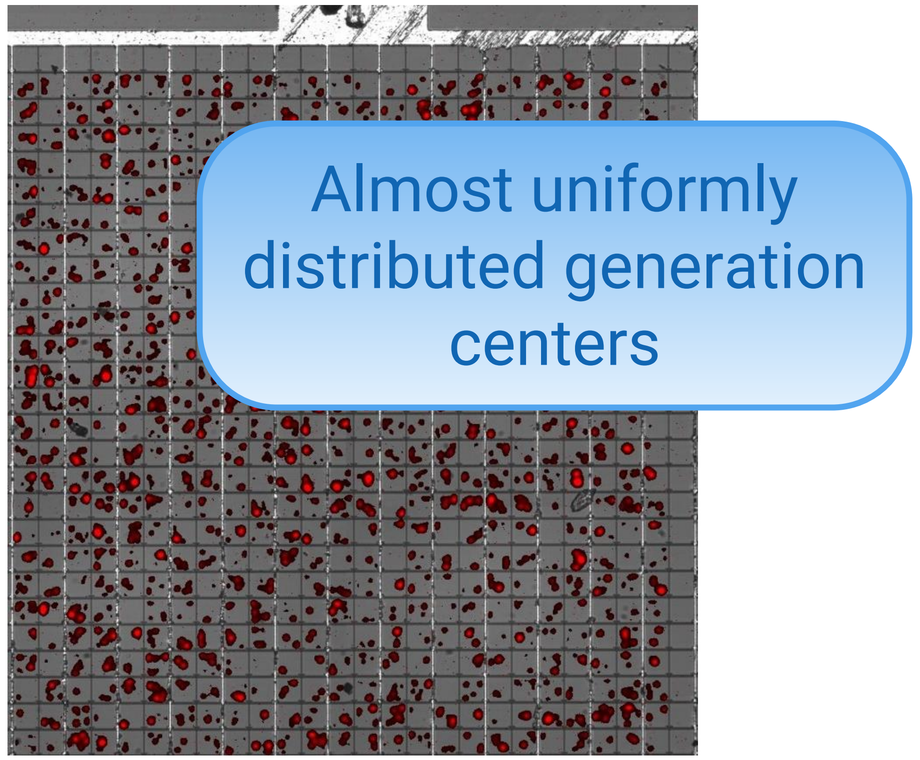
Radiation Hardness of SiPMs
Single SPAD switch-off to reduce the DCR after irradiation

Whether switching off "screamer" SPAD is effective to reduce DCR after irradiation depends on whether the increase of DCR is caused by:

a. *few, very rare, very "bad" bulk damage events*, each one causing a large increase of the DCR → single SPAD switch-off is useful.
b. *the sum of many, uniformly distributed, smaller events*, each one responsible for smaller DCR increments → single SPAD switch-off is not very useful.



DCR vs Fluence for different FBK technologies: all plots converge to similar values above approximately 1e8 n_{eq}/cm^2



Emission microscopy measurement on a NUV-HD SiPM irradiated at $1 \cdot 10^{11}$ n_{eq}/cm^2, at 4V excess bias, showing *almost uniform cell activation*.

Additional R&D ongoing to characterize SPAD population after irradiation:
AIDAinnova SiPM run

Reports on non-uniform SPAD DCR after irradiation presented at NSS2023 by L. Ratti

Altamura, Anna Rita, et al. "Radiation damage on SiPMs for space applications." NIM-A 1045 (2023): 167488.

Acerbi, F., et al. "Characterization of radiation damages on Silicon photomultipliers by X-rays up to 100 kGy." NIM-A 1045 (2023): 167502.