Large Area Low Power Photodetector Based on 3D Digital SiPM

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Outline

- SPAD, SiPM and digital SiPM
- Why go 3D?

  … and what is 3D

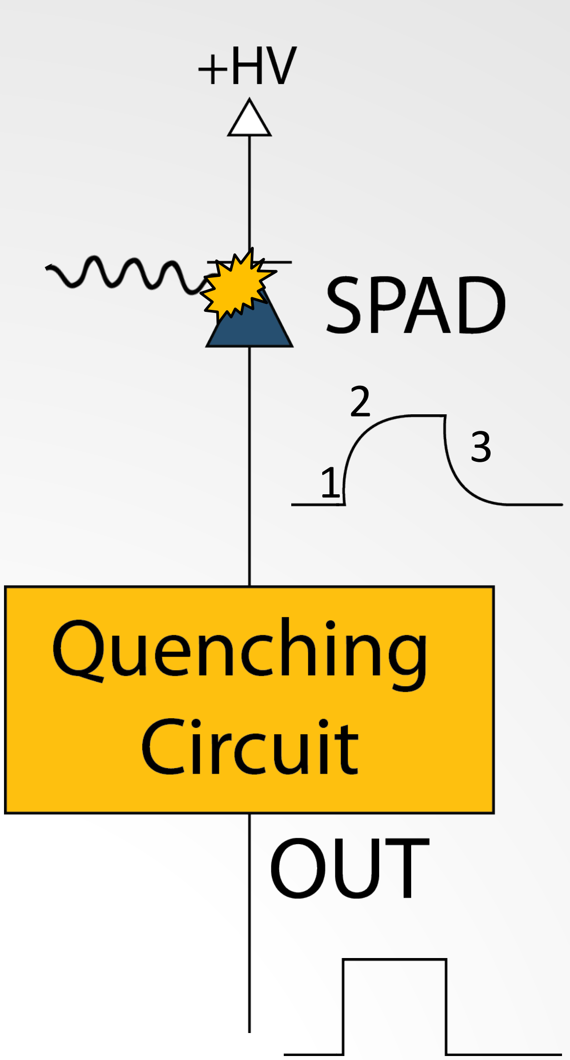
  - our first prototype
- Relevance and advantages for

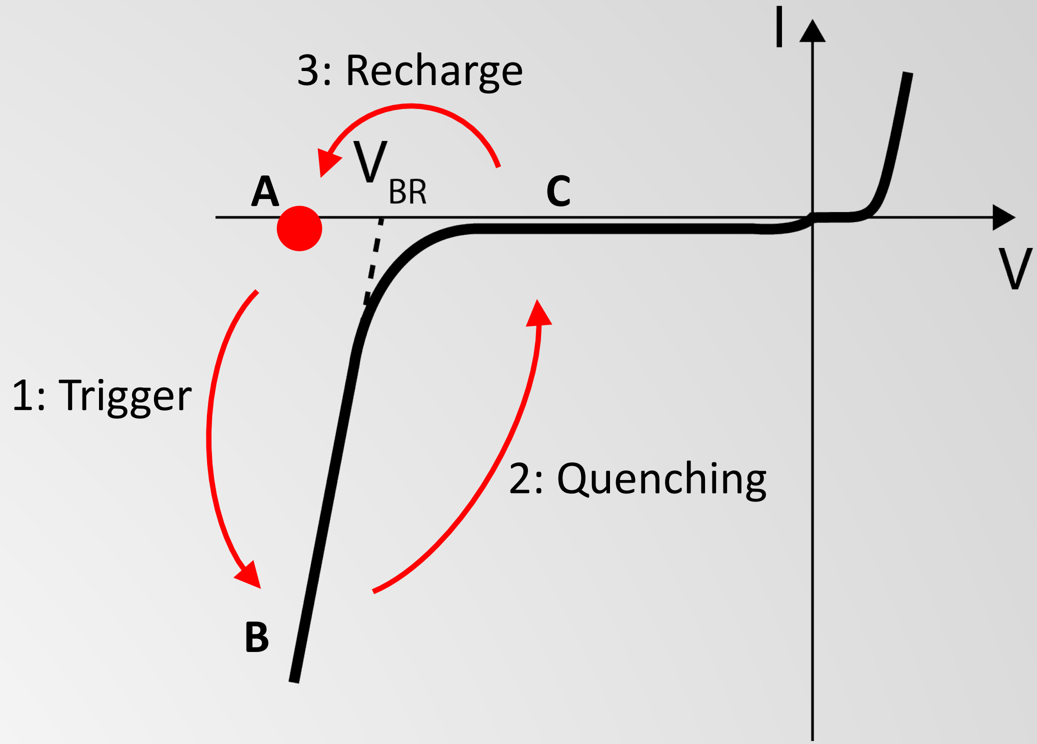
  large area

  low background

  experiments

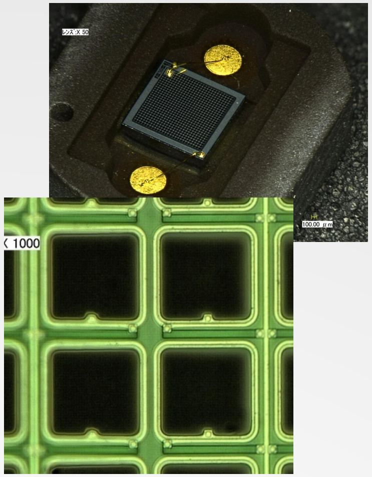
Single Photon Avalanche Diode Operation Cycle

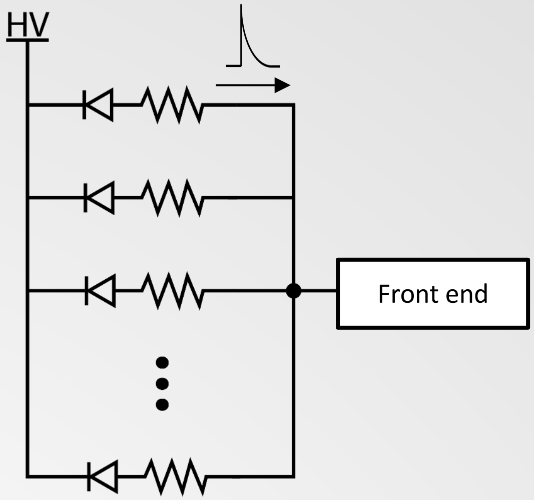




1. Time precision
2. Sensitivity – single photon
3. Low cost

Digital SiPM





Analog SiPM

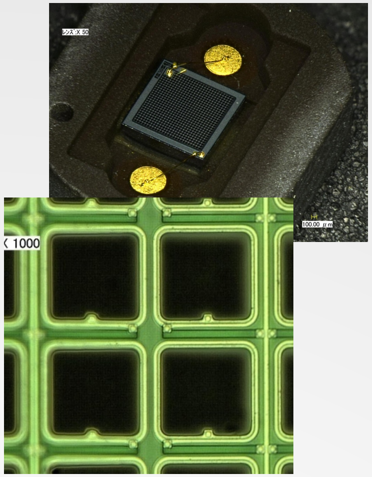
Advantages

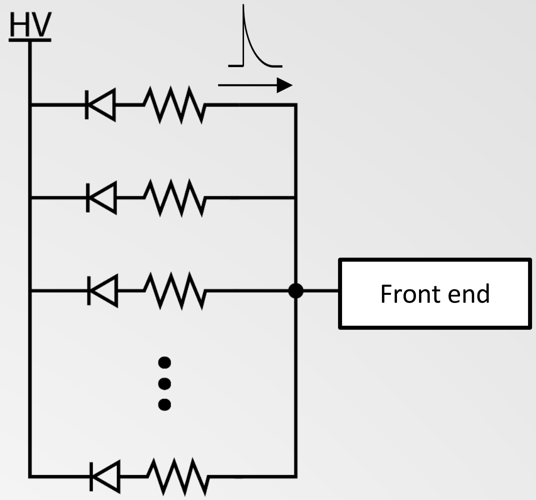
- Low cost
- High fill factor
- Low complexity

Limited to ~100ps SPTR

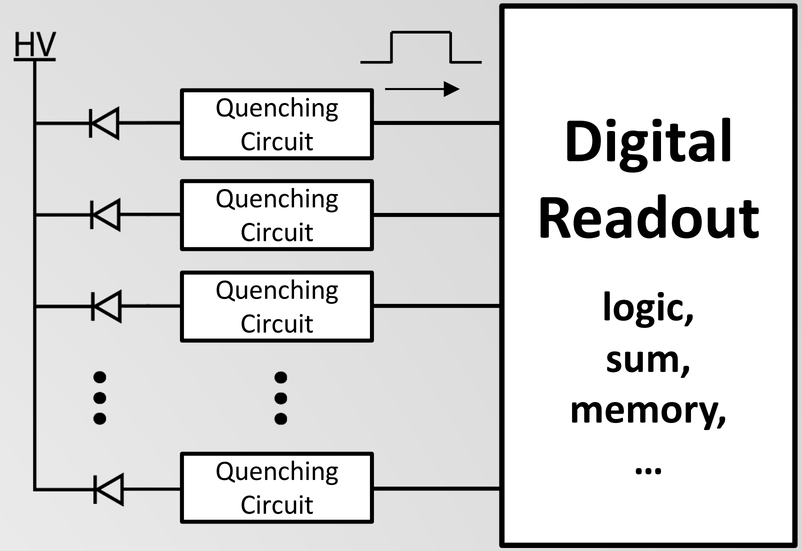
- SPAD to SPAD skew
- High output capacitance

Digital SiPM





Analog SiPM



Digital SiPM

Advantages

- Low cost
- High fill factor
- Low complexity

Limited to ~100ps SPTR

- SPAD to SPAD skew
- High output capacitance

Early digitization

- No gain dependence – more stable
- Full dynamic range (no digit'zd. noise)

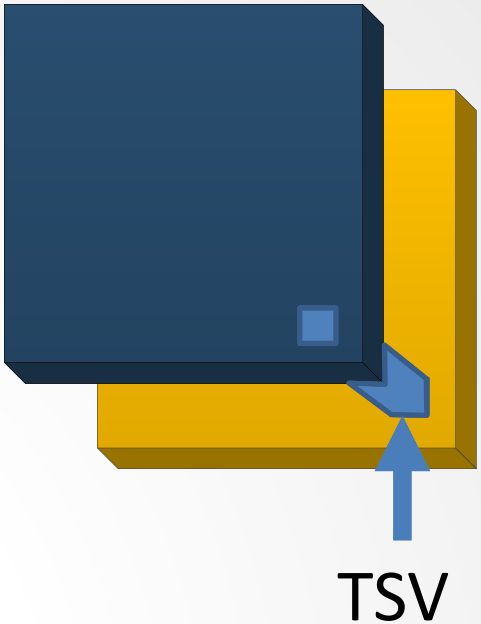
Fast quenching circuit

- Less crosstalk, afterpulse mitigation

Digital SiPM controls each SPAD

Why in 3D?

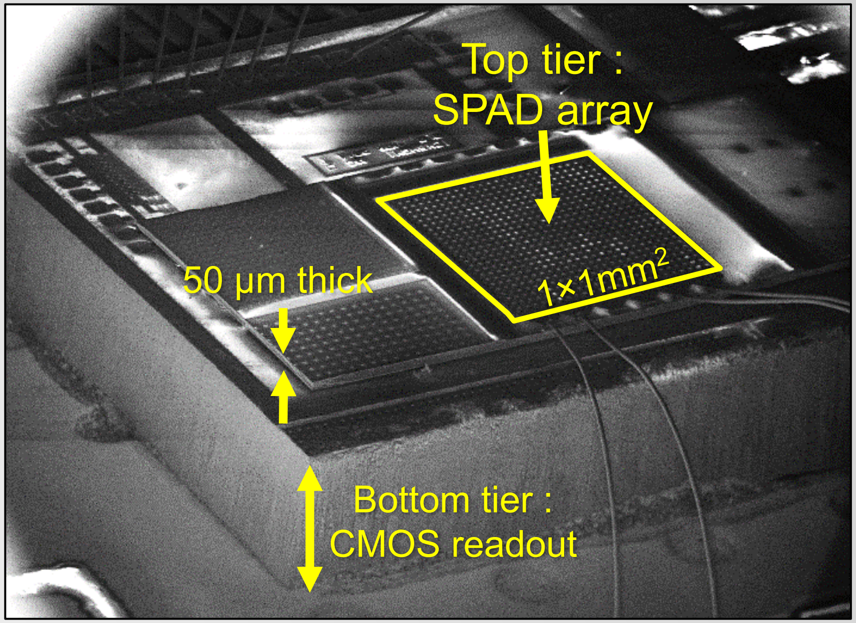
Ideal case:
3D



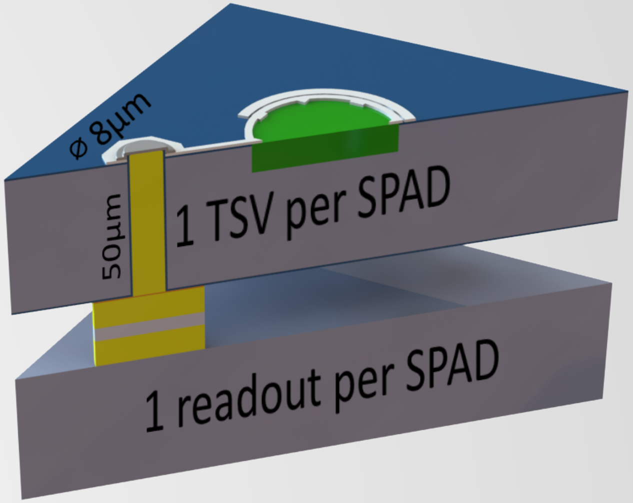
- No tradeoffs between electronics functionalities VS photosensitive fill factor.
- No compromise between electronics and SPAD processes: choose the most appropriate independently.

Sherbrooke's 3D digital SiPM

- 1st proposal in 2010*
- Prototype completed
- Embedded features
  - adjustable hold-off time
  - adjustable "gain"
  - single SPAD enable/disable



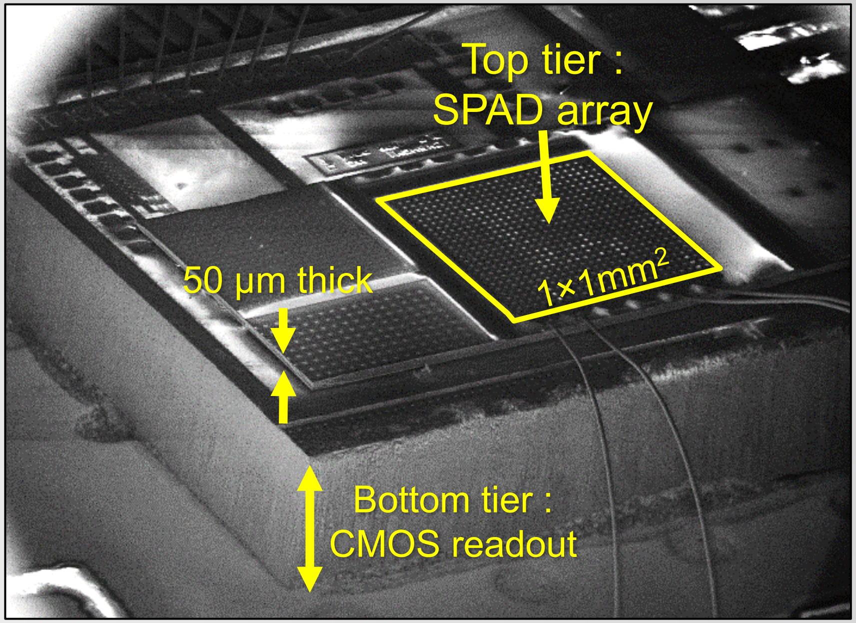
- 1st process run
  - some low-R, SPAD always "on"
  - some high-R, in series with SPAD
  - no fundamental issues
  - industrial development started

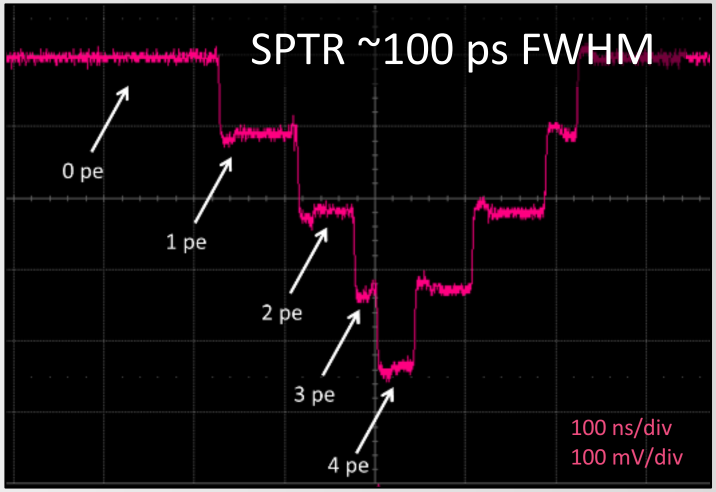


*Pratte et al. « High sensitivity fully digital photodetector », 3D Systems Integration Conf. 2010 IEEE Inter. (3DIC), Germany

Sherbrooke's 3D digital SiPM

- Anticipated risks
  - dramatic increase in DCR
  - dramatic increase in AP
  - loss of SPTR by capacitive loading
- No dramatic performance deterioration
  - DCR and AP comparable even with active screamers
  - SPTR increased in accordance to high series resistance with SPAD
- Prototype with analog sum output for simplicity
  - Sharp single p-e peeks
  - Full dynamic range expected

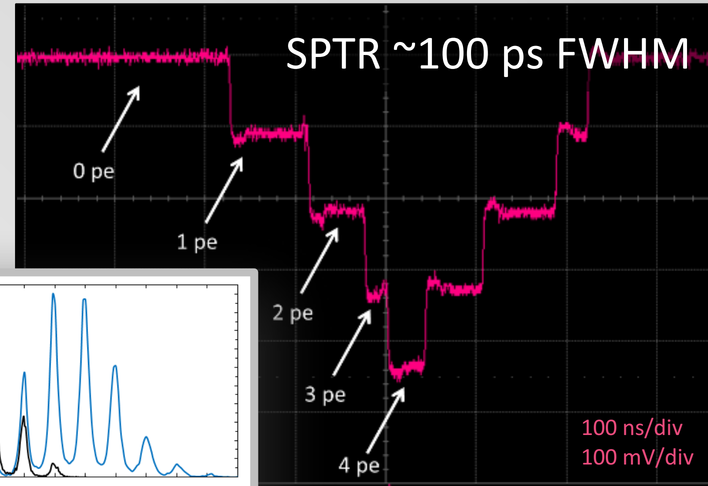


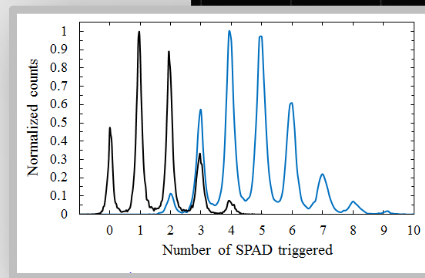


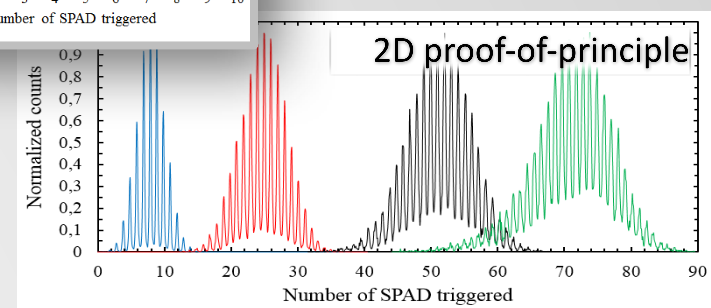
*Pratte et al. « High sensitivity fully digital photodetector », 3D Systems Integration Conf. 2010 IEEE Inter. (3DIC), Germany

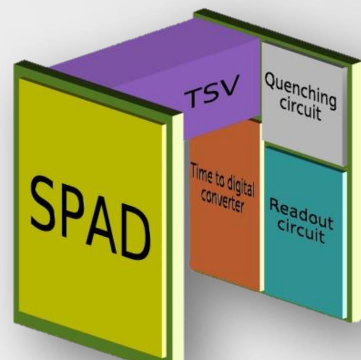
Sherbrooke's 3D digital SiPM

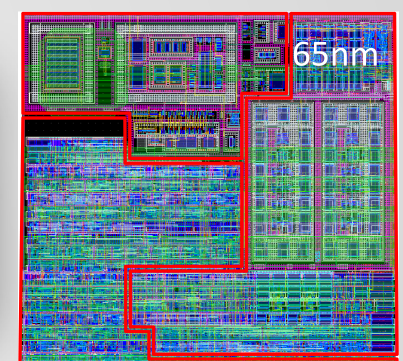
- 1st proposal in 2010*
- Basic functionalities
  - hold-off time, "gain", SPAD en/disable
- Advanced functionalities
  - 10 ps TDC per SPAD
  - phase-locked loop for TDC stabilization
  - digital signal processing
- Low power for large area detectors
  - 0.25 W/m^2 for digitization











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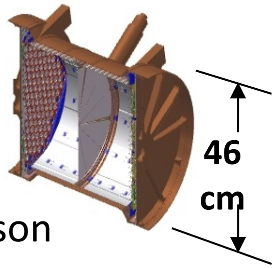
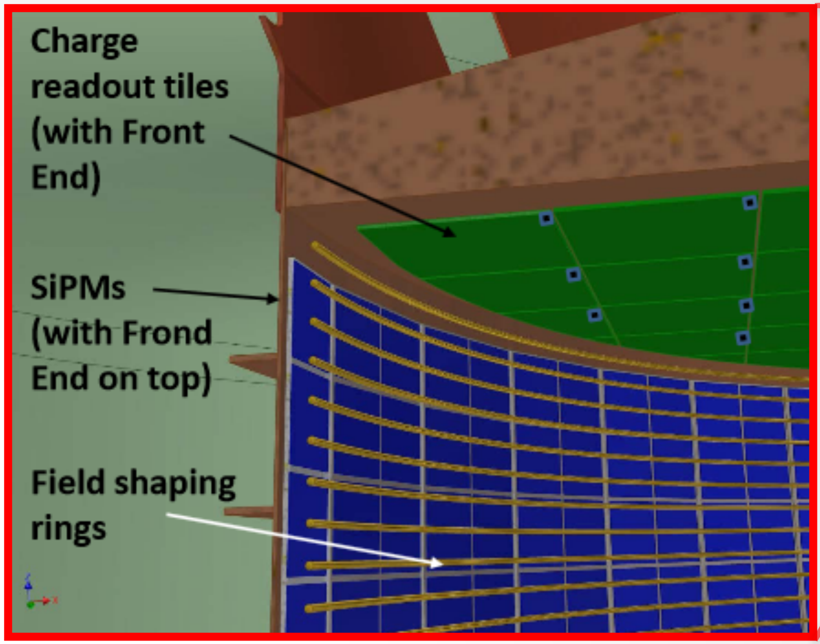
nEXO baseline design – Search for 0νββ

- 5T liquid Xenon, enriched 90% ^{136}Xe
- Charge TPC and scintillation readout
- Analog SiPM on quartz/silicon interposer
  - Photosensitive surface: ~4 m^2
  - SiPM in tiles ~10x10 cm^2 per channel in LXe
  - Power budget for scintillation readout: **40 W** / 4 m^2

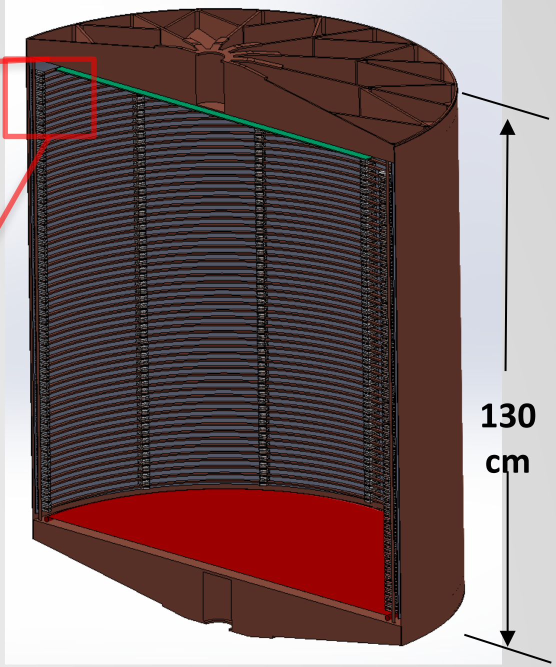
See talk by T. Brunner

EXO-200 for size comparison





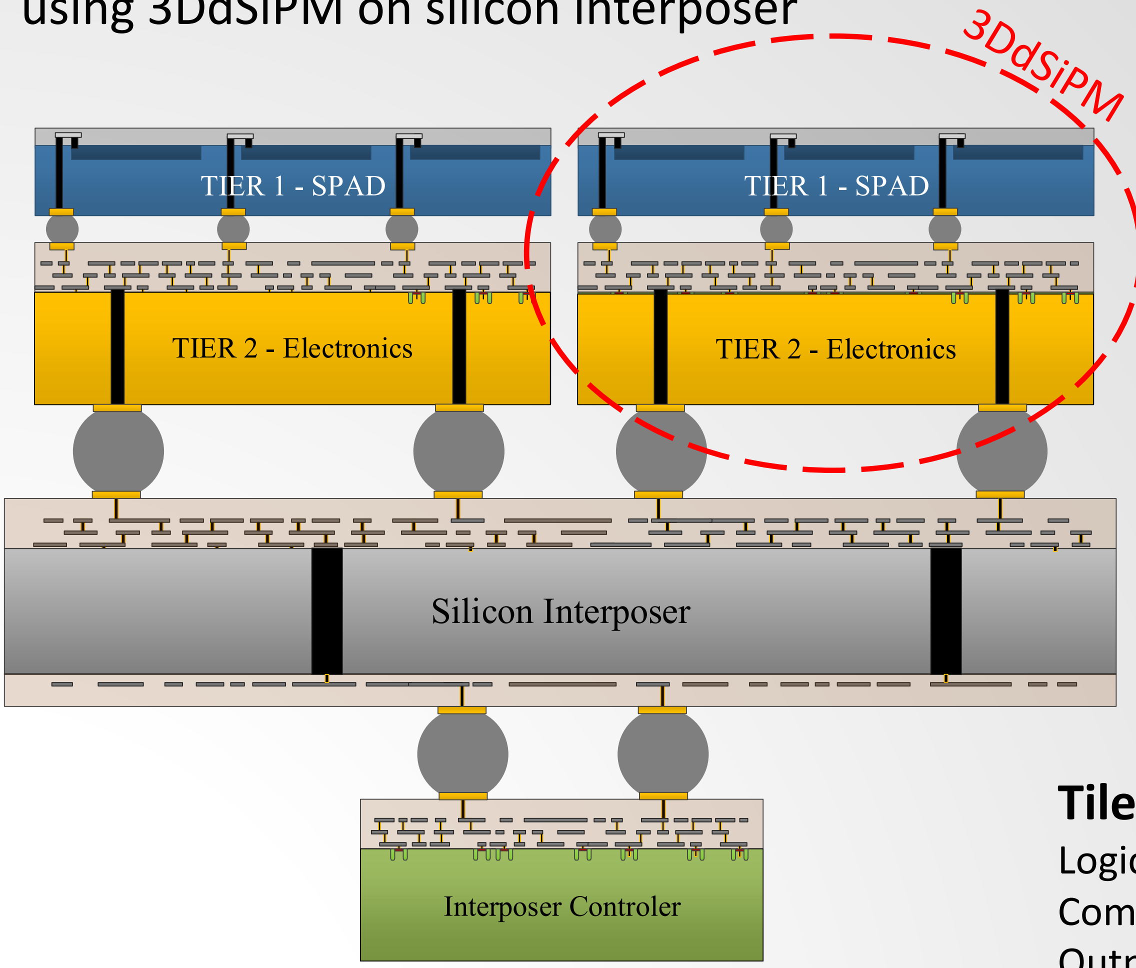
Source: nEXO collaboration



nEXO TPC

3DdSiPM based scintillation detector

We propose a fully digital scintillation readout using 3DdSiPM on silicon interposer



Application opti'zd SPAD

Readout circuit

Signal lines

Tile controller

Logic for the coincidence
Communication management
Output buffer to the DAQ

3DdSiPM designed for Low background Astroparticle Experiment

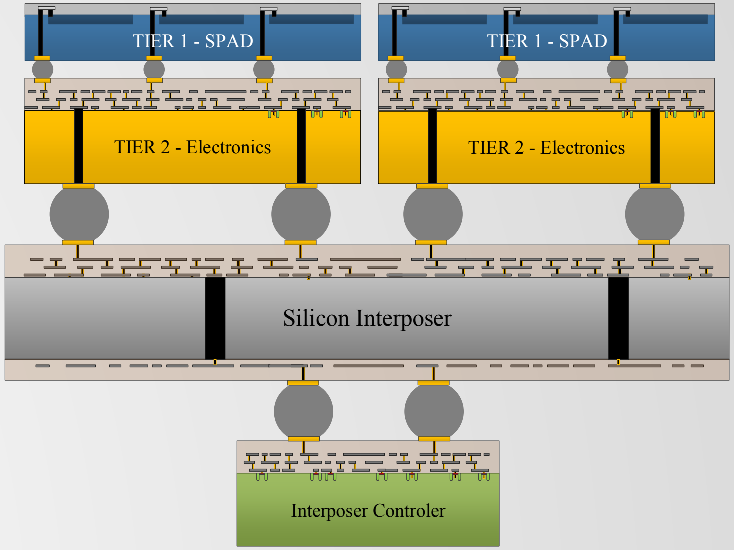
- Facility for Development of Cryogenic Detectors and Readout Systems for Subatomic Physics and Particle Astrophysics
  - CFI grant proposal (Boulay)

3DdSiPM axis:

- VUV sensitive (LXe, LAr)
- 100 cm^2 tiles of 3DdSiPM
- In cryogenic liquid
- Scalable to large area:
  - nEXO: 4-5 m^2 DEAP 200t: 150 m^2
- Tile integration validation
  - thermal stress mitigation
  - tile assembly process
  - testing protocoles
  - radio and chemical purity

3 modalities:

- low power (nEXO)
- timing and granularity (DEAP)
- luminescence (dual phase)



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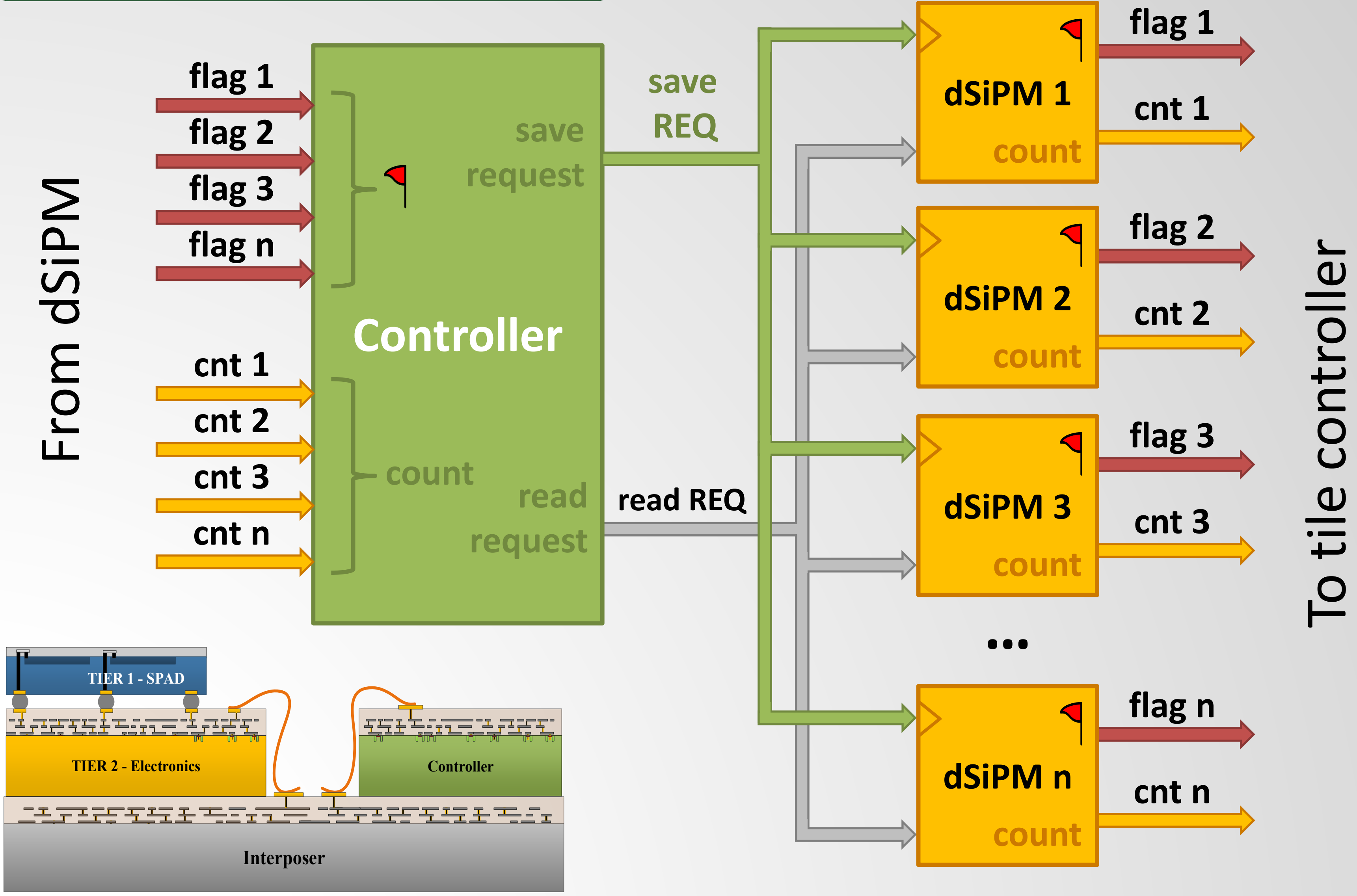
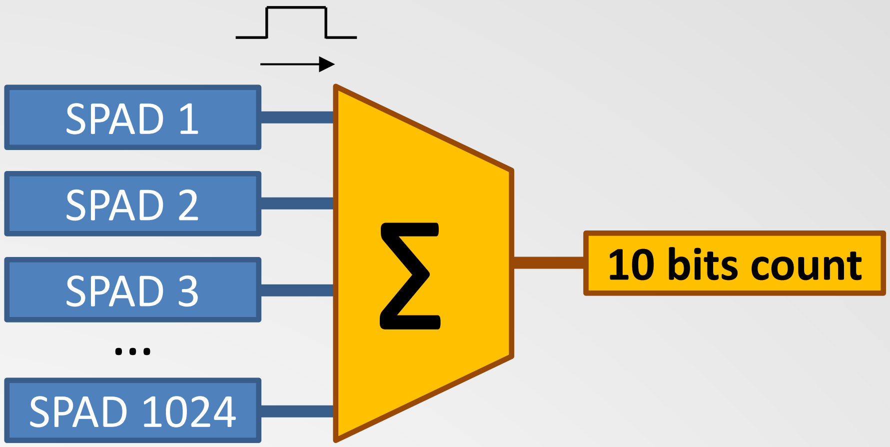
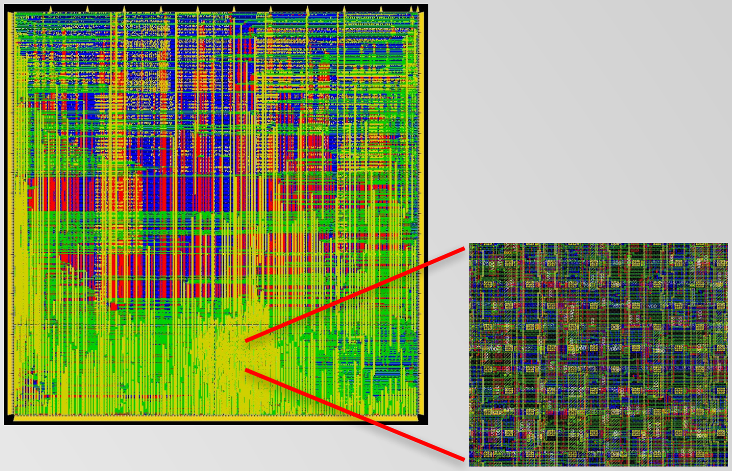
Tile Architecture



3DdSiPM power consumption estimations





- Total power consumption < 40W / 4 m²
  - Quenching 0.5 - 1 W / 4 m²
  - Sum 0.5 - 1 W / 4 m²
  - Memory to do
  - Transmission to do (protocol dependant)
  - Tile controller to do

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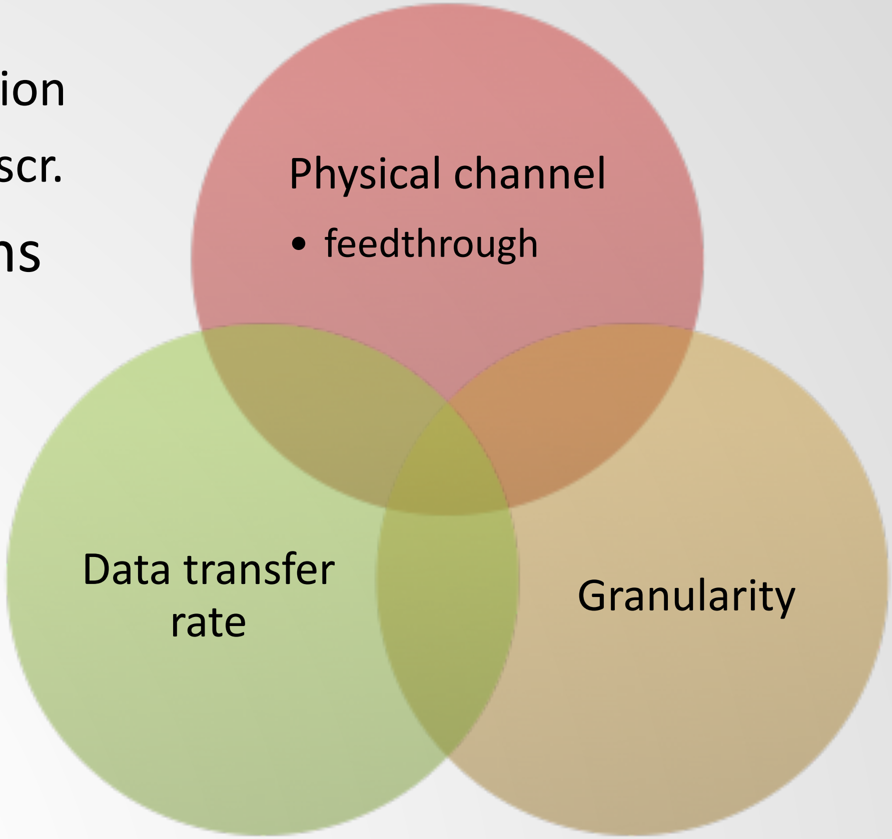
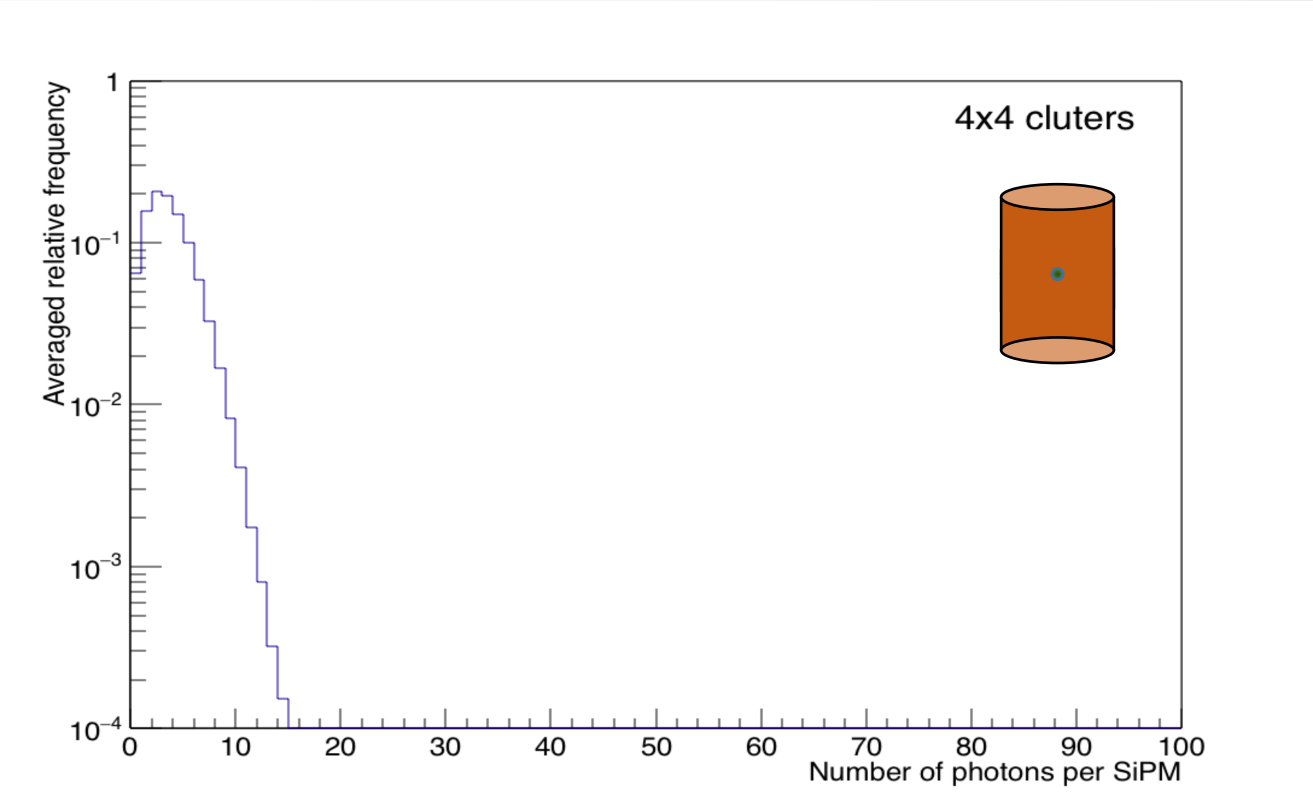
Clusters, channels and granularity

- Designing an experiment requires optimizing under many constraints
- from physics
  - energy resolution
  - background discr.
- to configurations
  - feedthrough
  - data rate



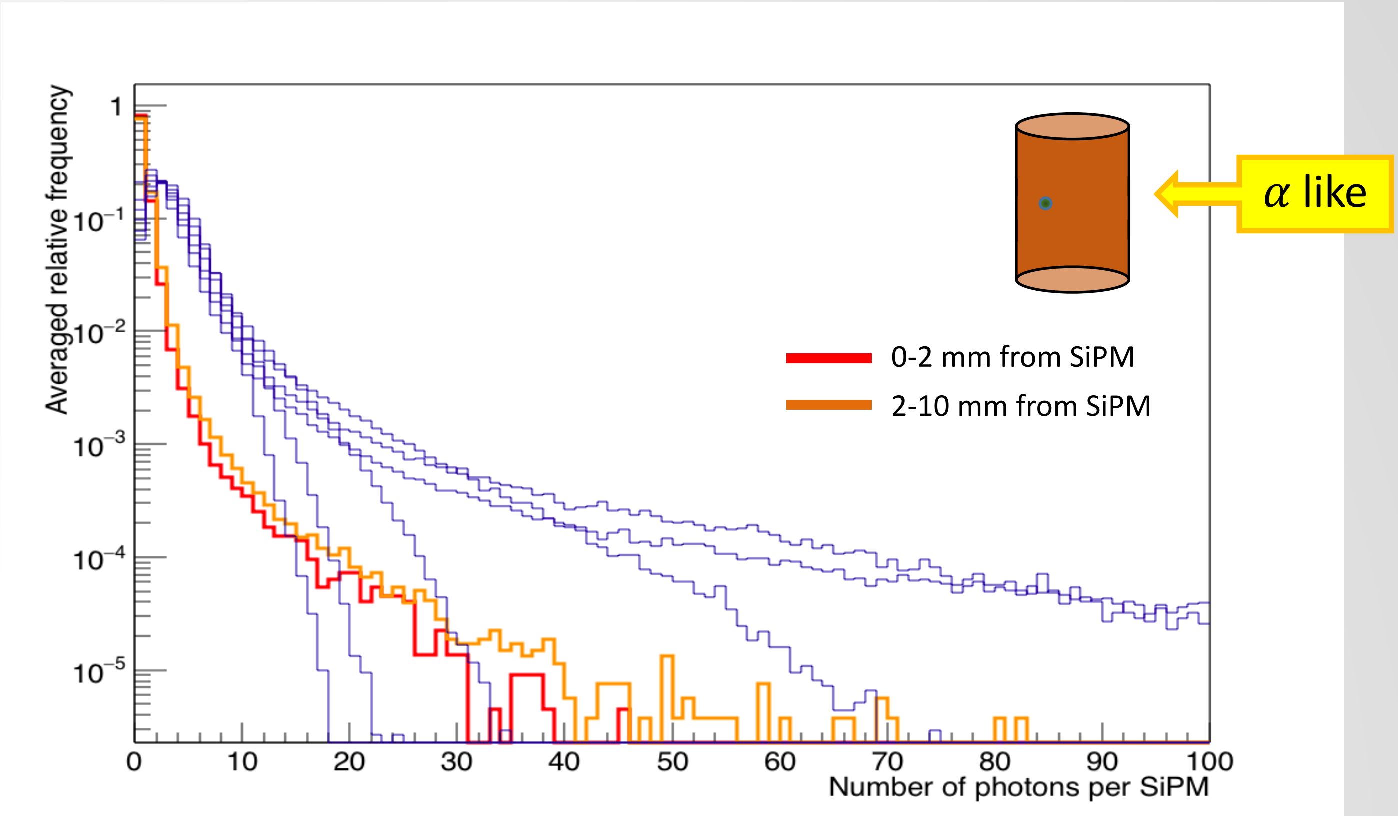
Granularity in a digital system…

- Granularity ≠ number of physical channels
- The Photons-per-SiPM histogram holds qualitative position information



Granularity in a digital system…

- Discriminating locally for “close-to-SiPM” events
  - eg. alpha decay
- Improving light-map and energy resolution
  - eg. including influence of field shaping rings



Clusters, channels and granularity

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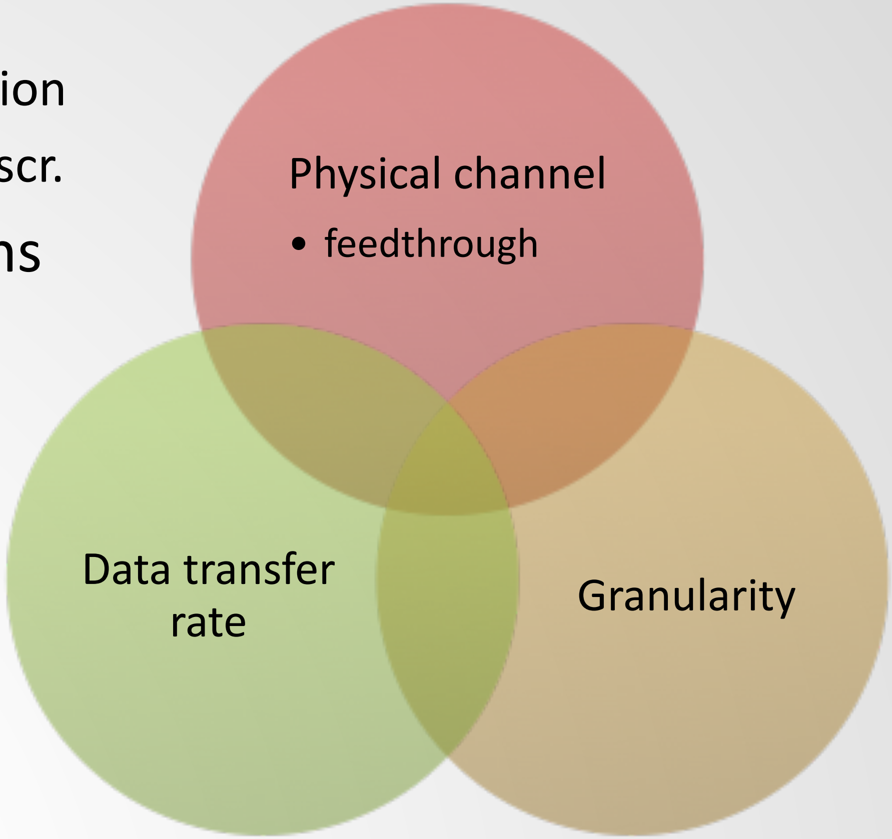
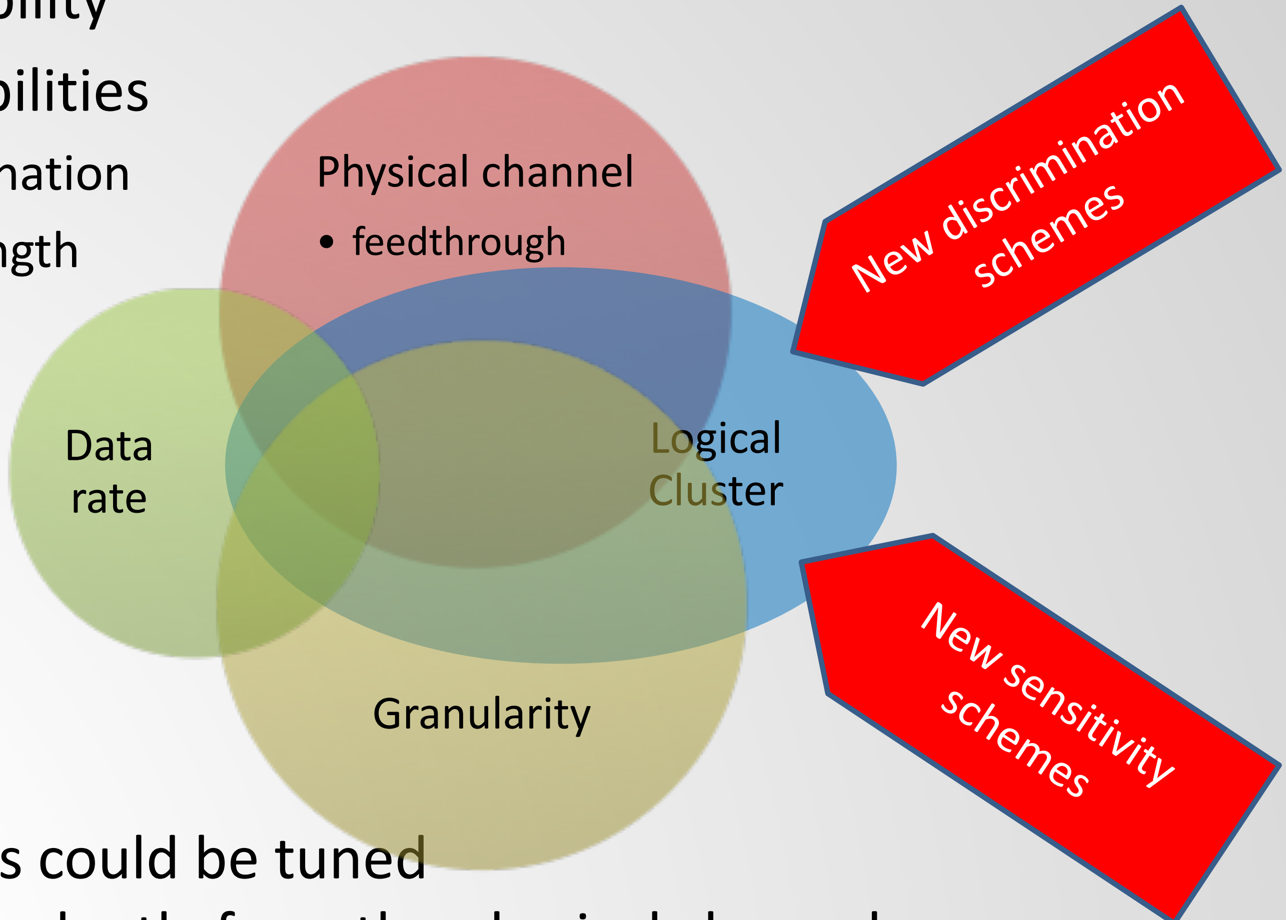


Clusters, channels and granularity

The distributed computing allow for

- for more flexibility
- for new possibilities
  - new discrimination
  - multiwavelength
  - cerenkov

  …



- Logical clusters could be tuned almost independently form the physical channels

Conclusion: 3DdSiPM to enable large area detectors

- Basic **digital SiPM** benefits
  - No gain dependence – more stable
  - Full dynamic range (no digit'zd. noise)
  - Less crosstalk, afterpulse mitigation
  - Control over each SPAD

- Implementation into tiles is a challenge
  - Prototypes demonstrated (Sherbrooke, Hamamatsu)
  - 3D industrial process exists:
    - volume production is feasible
    - validate for cryogenic use

- Opens new possibilities for advanced modalities
  - local data processing (background discrimination)
  - logical clustering
  - energy resolution
  - enables large scale integration
    - are shown to have acceptable radiopurity, low organic content

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BACKUP SLIDES

3DdSiPM designed for Low background Astroparticle Experiment

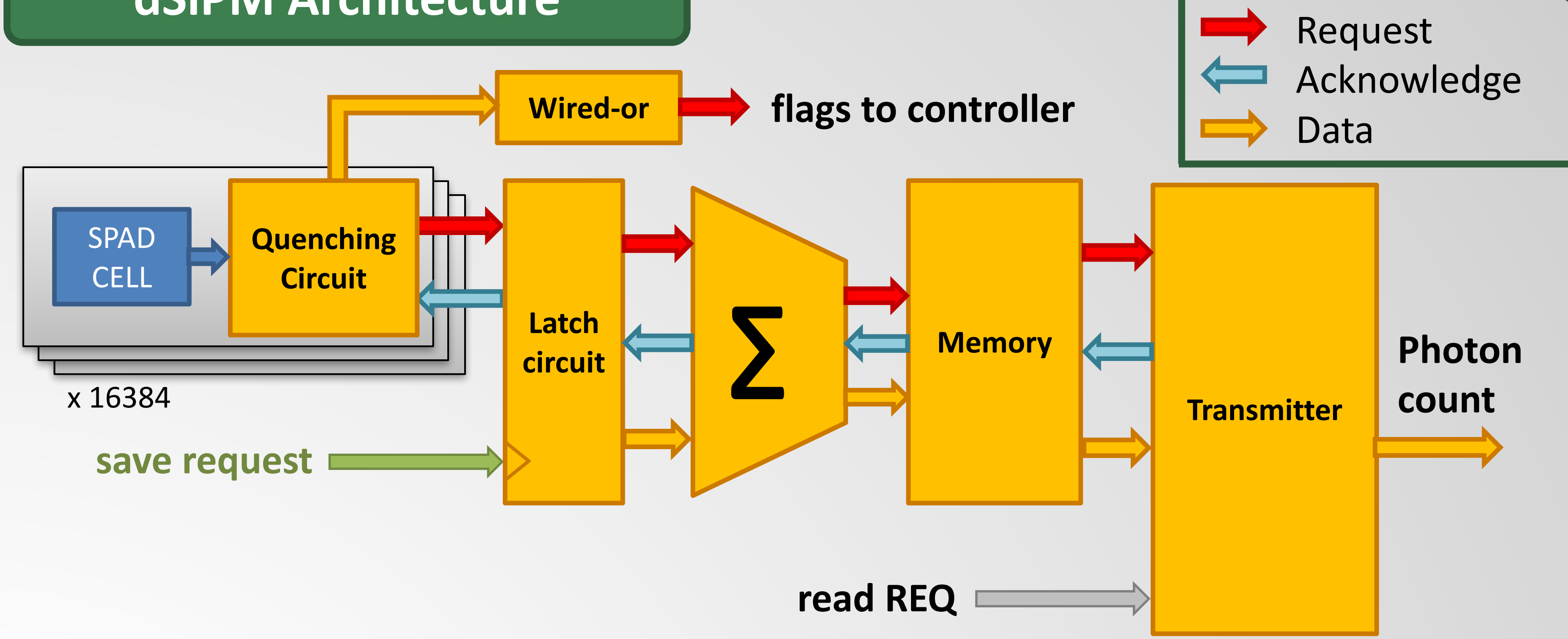
- Modality 1: low power low light (nEXO)
  - photon counting
  - 1 μs time sampling
  - < 20W/m^2
  - channel ~100 cm^2 but no granularity spec.

Preliminary specifications

- Modality 2: high timing, high granularity (DEAP)
  - first photon timing res. 250 ps (<5 cm TOF reconst.)
  - granularity 1 cm^2 (mainly for α decay from surface)
  - < 5 ns time sampling (pulse shape discrimination)
  - photon scope output

- Modality 3: dual phase TPC – charge readout with EL
  - fine granularity (5×5 mm^2)
  - < 50ns time bins
  - photon scope output

dSiPM Architecture



1. Photons hit the SPAD
2. Quenching circuit detects it and keeps the information
3. A flag is sent to controller
4. On « save request » signal, SPAD states are sent to the sum module
5. When sum is done, photon count is sent to memory
6. On « read request » signal, data (photon count) is sent to controller

7. Each step is sequential and done after the previous one **NO CLOCK!**

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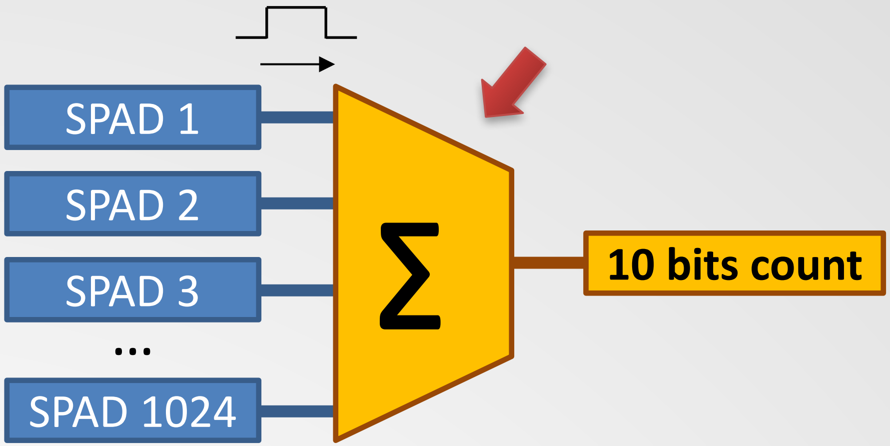
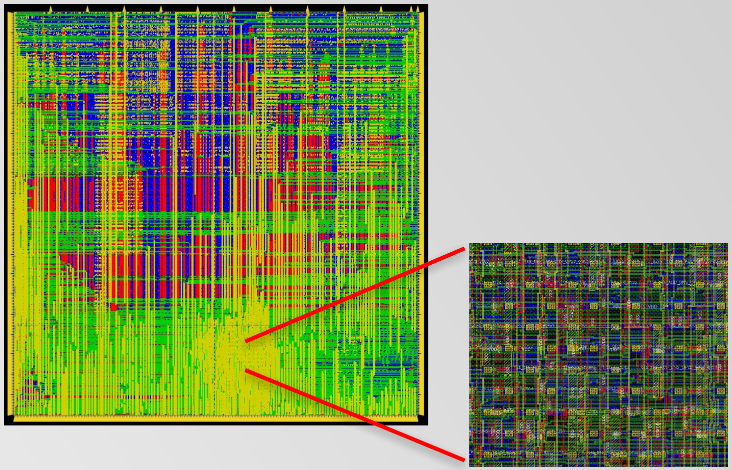
Simulation Parameters - Preliminary





- Based on a real layout (Digital Library Cells voltage = 5V)
- 1024 SPAD
- 10 bits output
- Duration = 1 sec
- DCR = 50 and 100 counts / s mm^2

Simulation Results

Switching power : depends on the events rate
Leakage power : static power consumption independant of events rate

	Simulation **1024 SPAD Matrix**	
	DCR = 50	DCR = 100
Switching (nW)	10	20
Leakage (nW)	625	625
Total Power (nW)	635	645

% Switching	1,6	3,1
% Leakage	98,4	96,9

Less than **500 mW** estimated for the TPC !

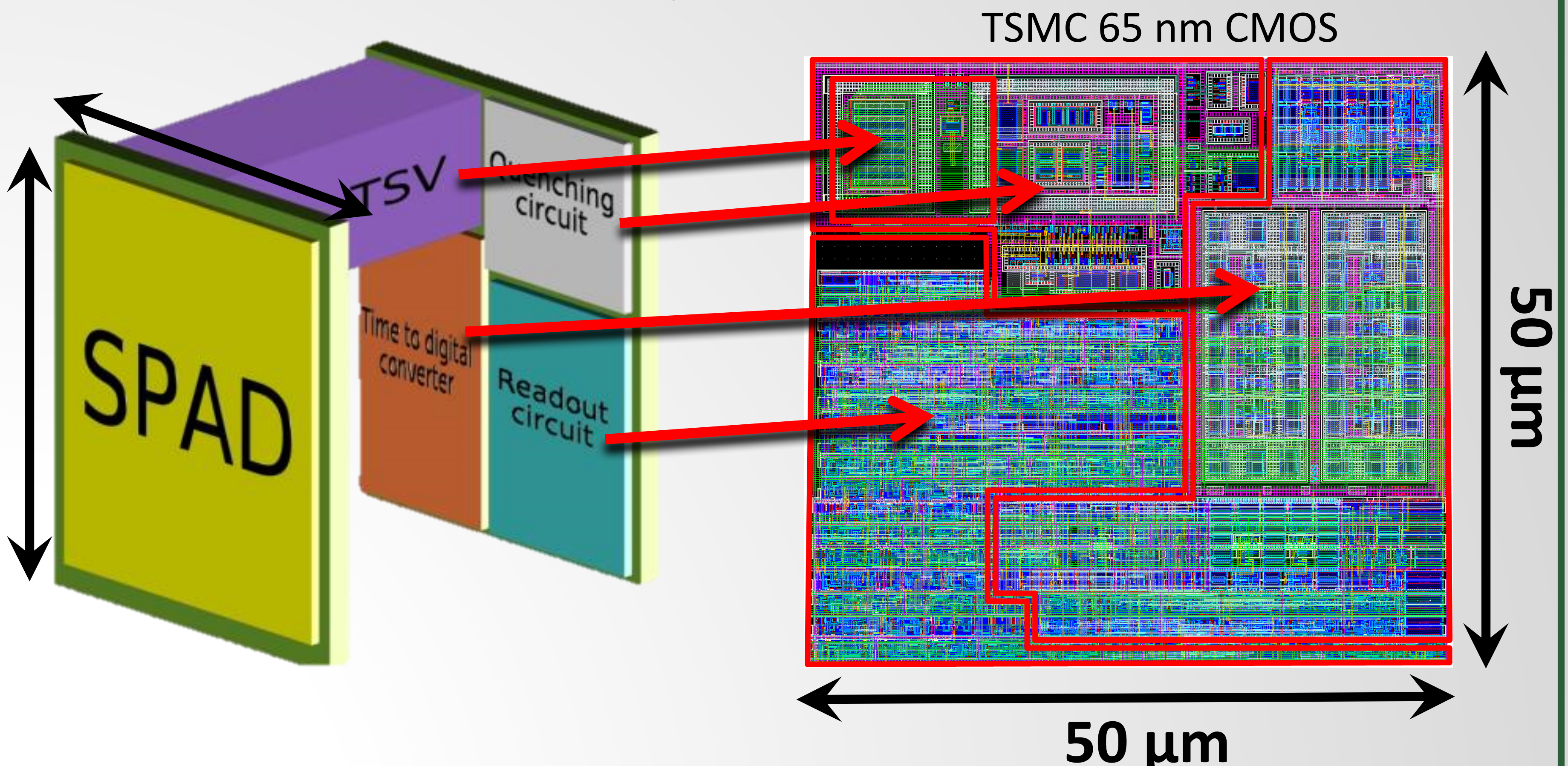
Simulation Conclusion

- Summing a full 3DdSiPM
  - < 500 mW to count photons at dSiPM level for the complete TPC
  - Leakage power is dominant for low counts

- Total power consumption < 40W / 4 m^2
  - Quenching 0.5 - 1 W / 4 m^2
  - Sum 0.5 - 1 W / 4 m^2
  - Memory to do
  - Transmission to do
    - Protocol dependant
  - Tile controller to do

Readout Integrated Circuit

- Need to timestamp as many prompt photons as possible
  - ➢ 1 TDC per SPAD
- 3D SPAD readout to eliminate timing skew
  - ➢ Readout size determined by the SPAD size



3D digital SiPM Proof of Concept Architecture

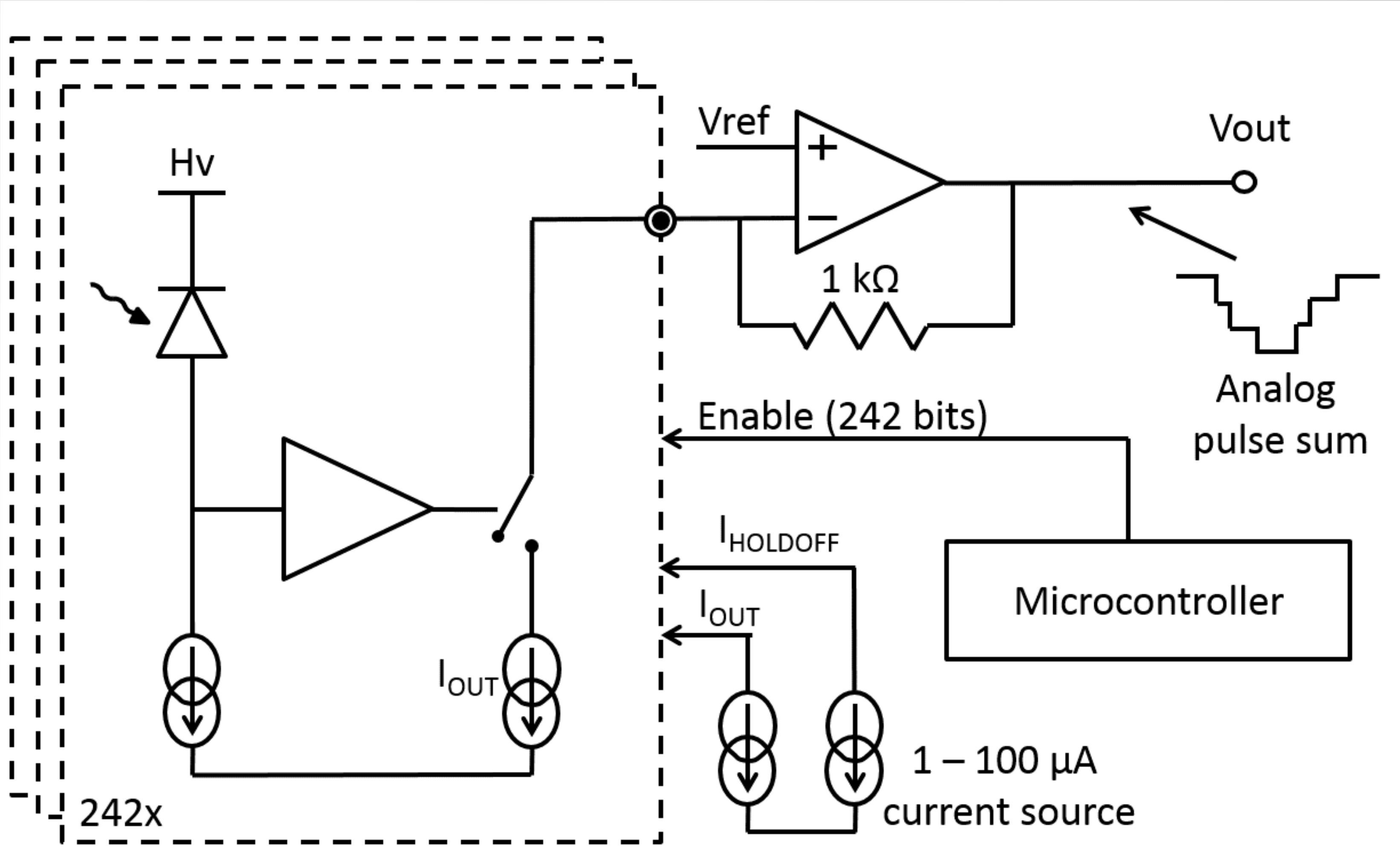
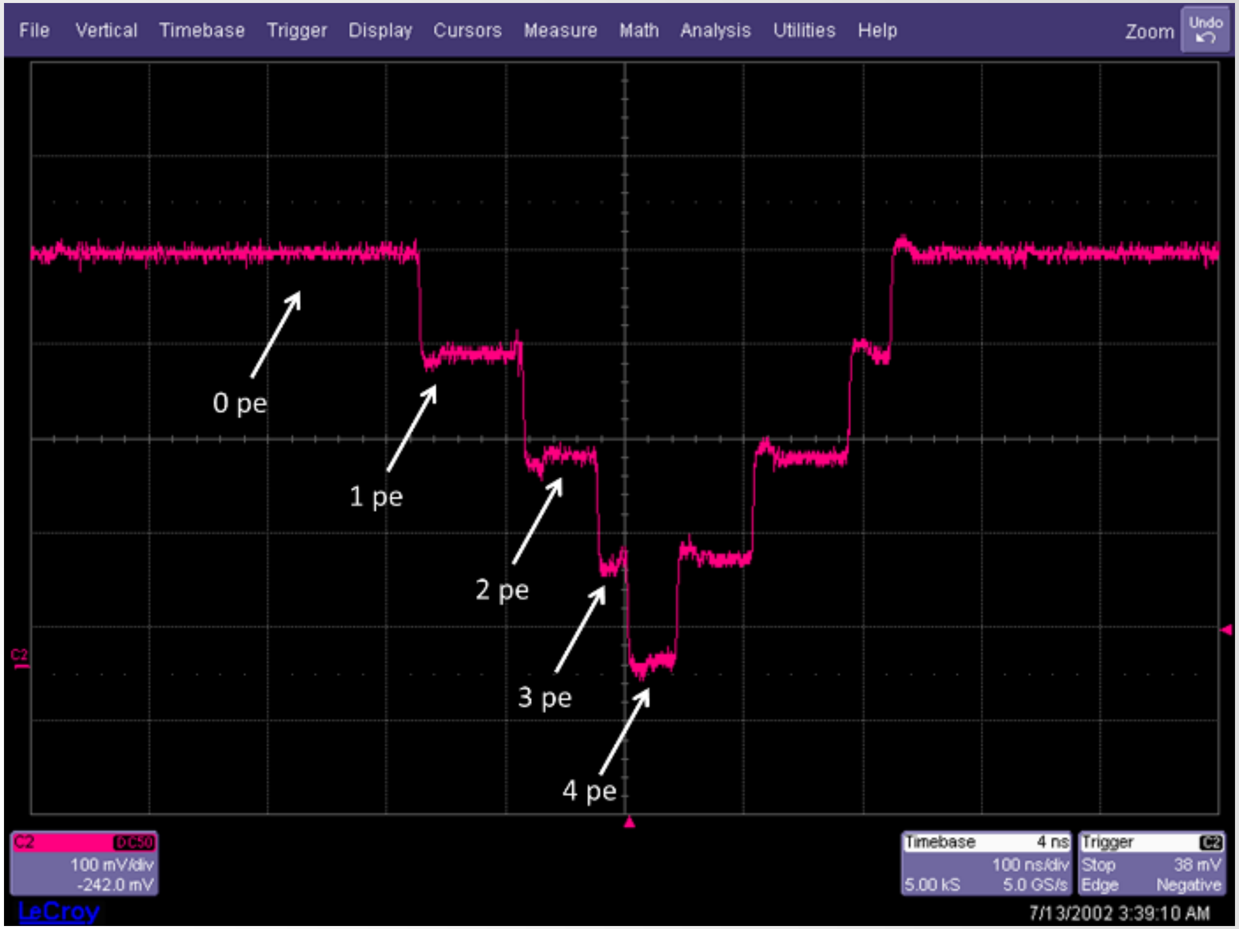


Fig. 1. Block diagram of the 3DdSiPM. In the dashed box: the 3DdSiPM. Outside the dashed box: PCB.

It works!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Timebase
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100 ns/div
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5.0 GS/s
Trigger
C2
Stop
38 mV
Edge
Negative
7/13/2002 3:39:10 AM

X-Ray Image


Handle wafer
50 µm thick SPAD array at 50 µm pitch. TSV visible in black
Indium bumps
CMOS readout circuit

Output Signal Histogram

- Pulsed laser, two intensities.