PHILIPS

GSI SiPM workshop
October 7th, 2011

sense and simplicity

Integrated Arrays of Digital SiPM's: the next solid state revolution?

Dr. York Haemisch, Anja Schmitz
york.haemisch@philips.com
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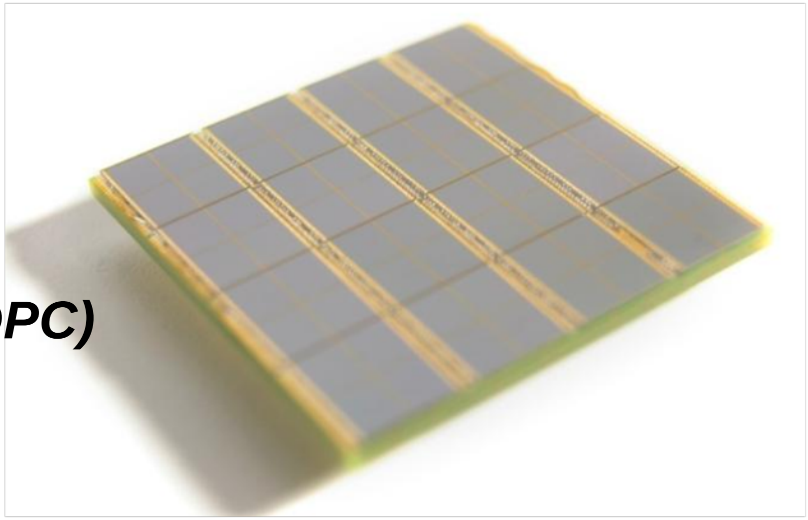
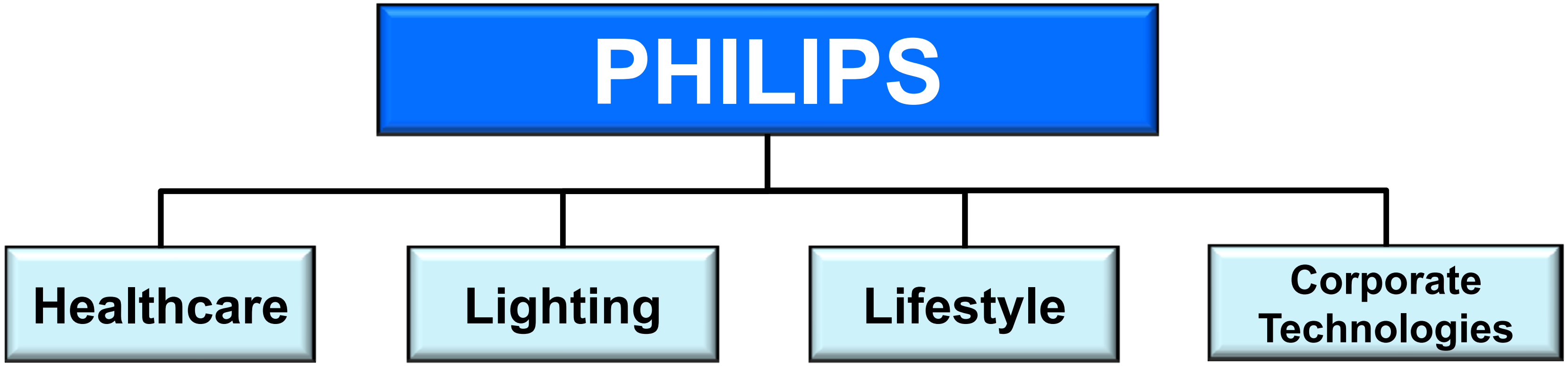
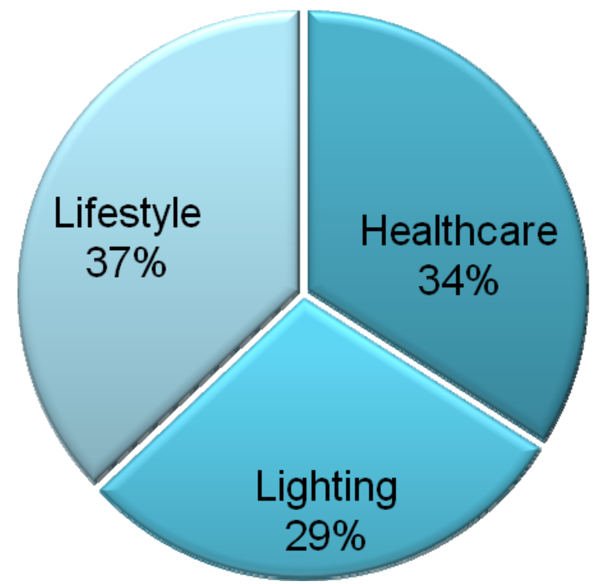
Philips Digital Photon Counting (PDPC)
Philips Corporate Technologies



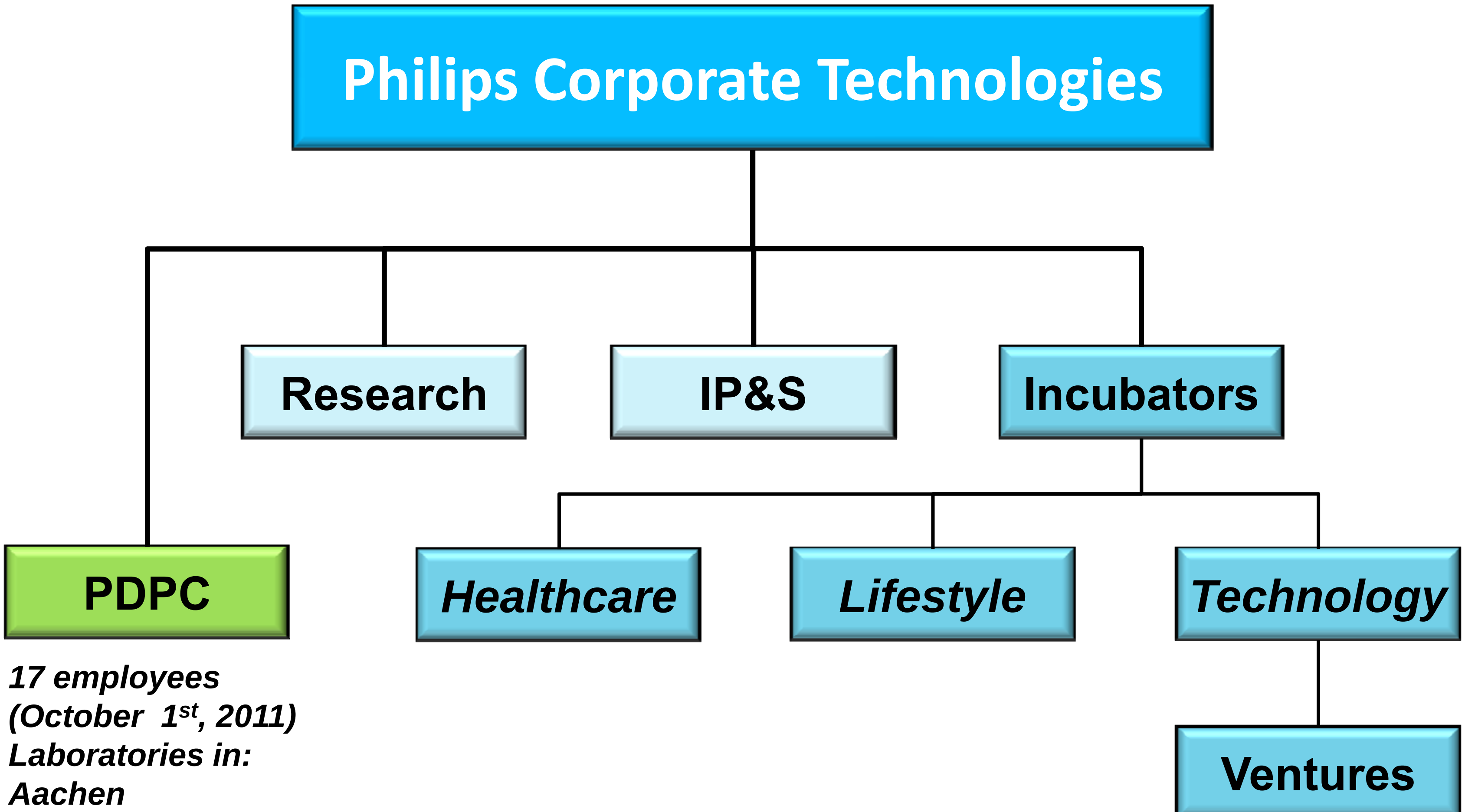
Koninklijke Philips Electronics B.V.



FY	2009	2010
Employees	115,924	119,000
Sales	23,189	25,419 Mio. €
Profit	424 Mio	2.065 Mio. €



Philips Digital Photon Counting (PDPC)



17 employees
(October 1st, 2011)
Laboratories in:
Aachen
Eindhoven

outline

- Introduction to Philips Digital Photon Counting (PDPC)
- Introduction to Positron Emission Tomography (PET)
- Analog Silicon Photomultipliers (a-SiPM)
- PDPC's digital Silicon Photomultipliers (d-SiPM)
  - principle
  - performance
  - integration
- Outlook

Solid State, Digitization and Integration Always Win

Transistor

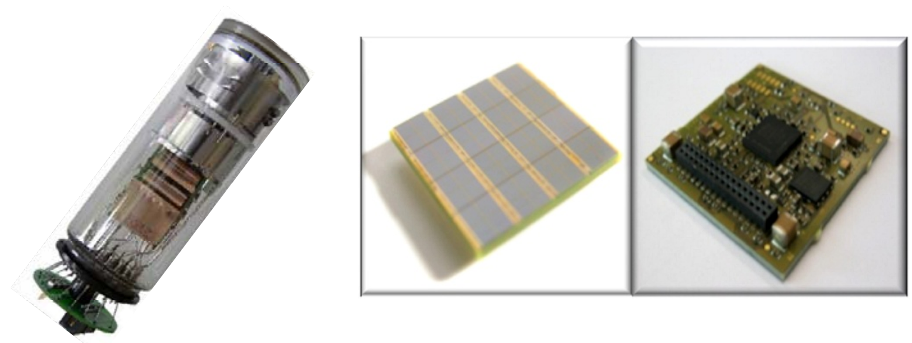
Television

Photography

Telephony

X-Ray imaging

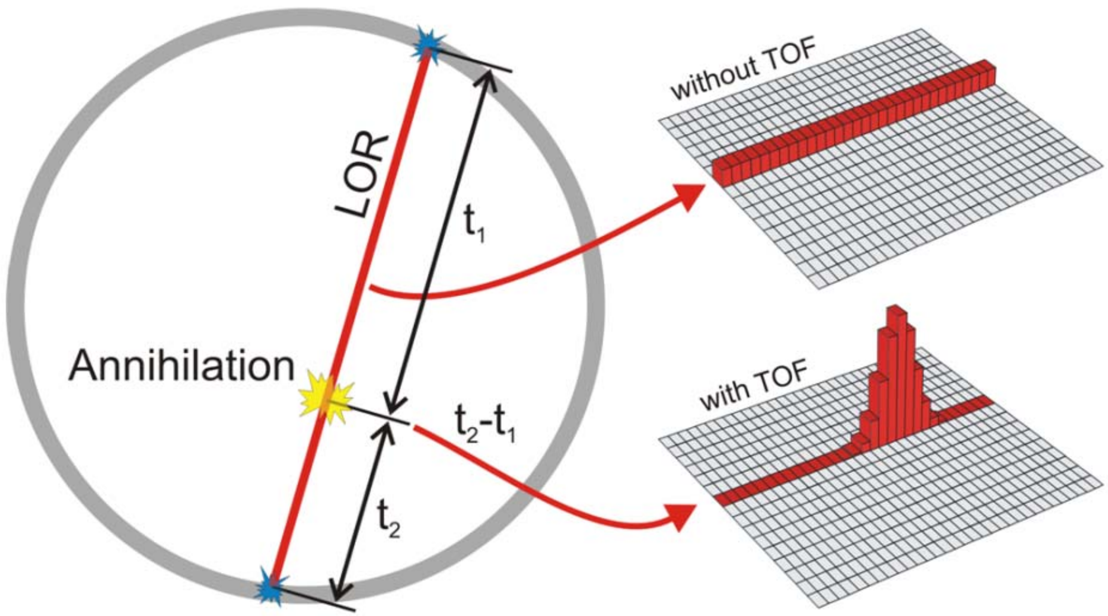
Next: Light Detection

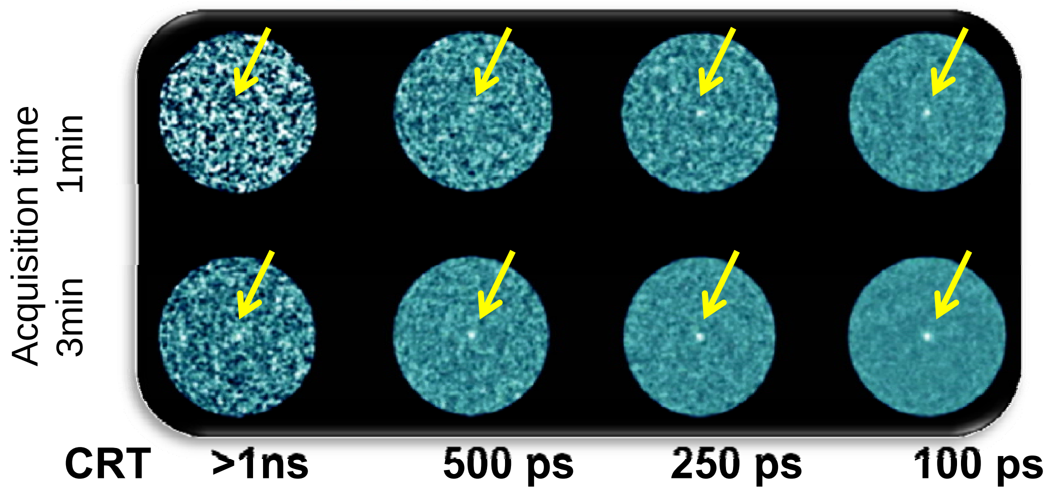


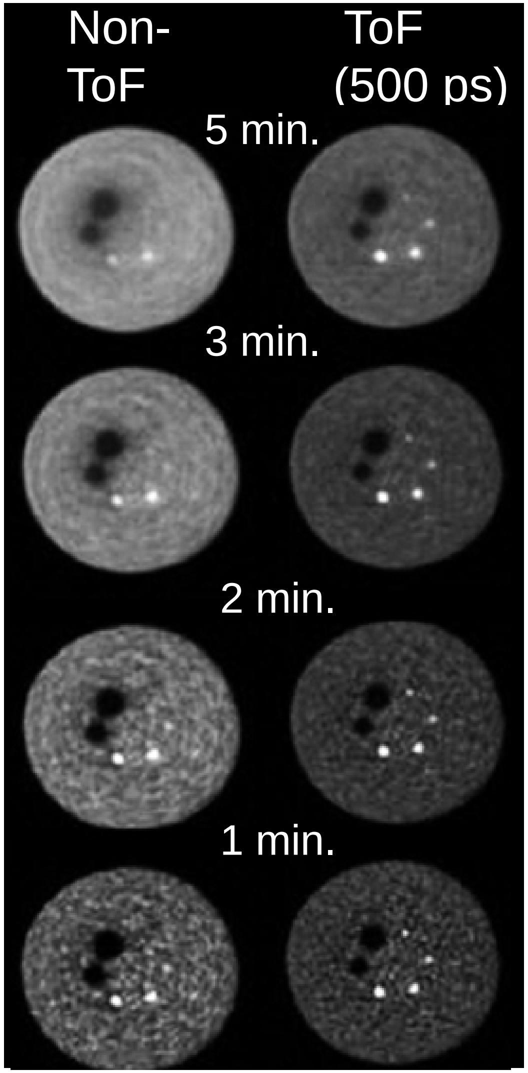
PDPC: Short history

2004	Research project: “Novel technologies for future PET systems”
2005	***Dr.Thomas Frach*** invented the digital SiPM
2006	Research project: “Integrated digital light sensor”; first test chip with promising results ***(incubator)***
2006	Disentanglement of Philips Semiconductors – now NXP
2007	Start of the PDPC ***venture***
2008	Proof of concept
2009	**Technology launch** at IEEE NSS-MIC sensor V1.0
2010	**PDPC separate unit** of Philips Corporate Technologies
2011	Introduction of **PDPC-TEK** (Technology Evaluation Kit), **sensor version 2.0** and **PET detector module**

Initial Motivation: A better detector for Positron-Emission-Tomography (PET) with Time-of-flight (TOF)

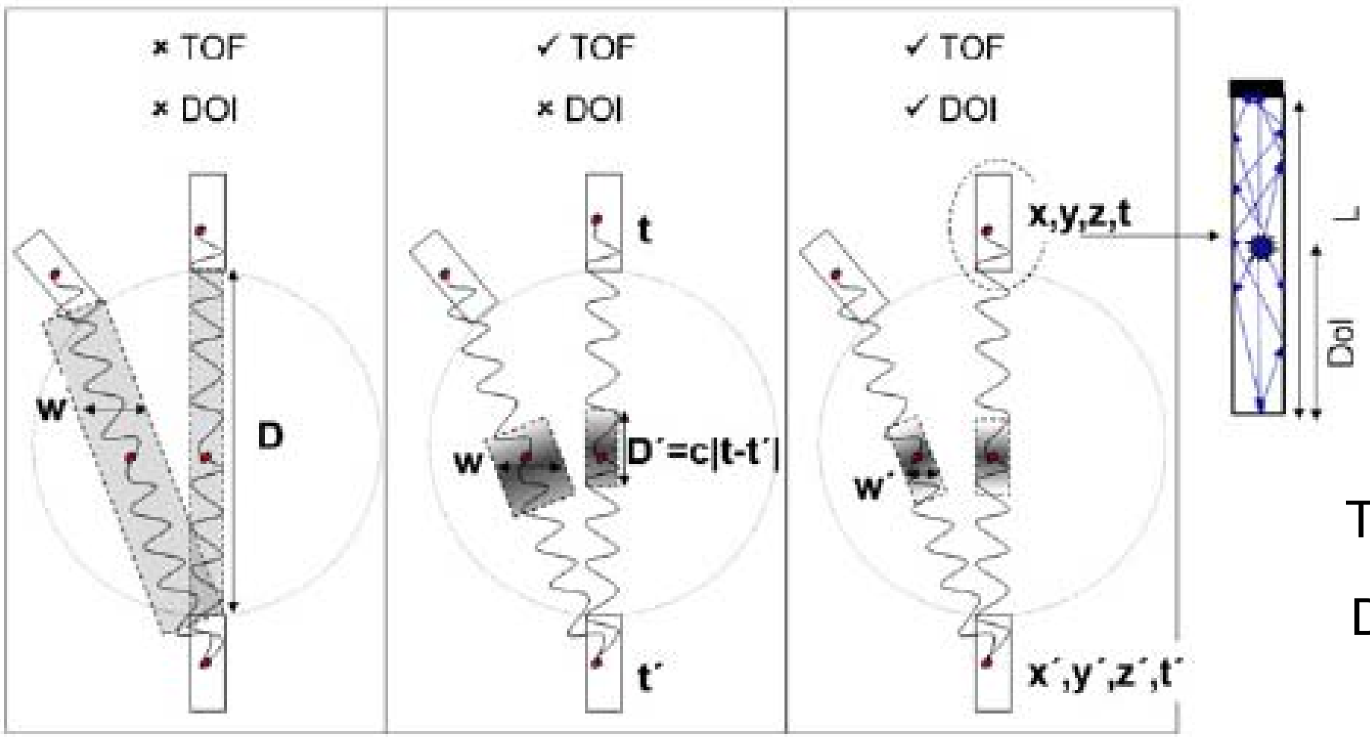






S. Surti , J. Karp, et al., IEEE TMI, 2006, vol. 25, nº5, pp. 529-538

The optimal detector for Positron-Emission-Tomography (PET) provides **TOF** and **DOI** detection



TOF – time-of-flight

DOI – depth of interaction

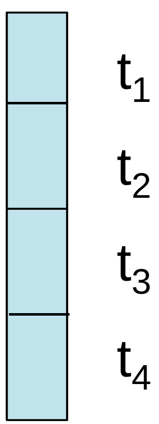
Graphics courtesy of Spanoudaki & Levin, Stanford, in: Phys. Med. Biol. (56) 2011

High sensitivity → long crystals
High spatial resolution → small cross section

High aspect ratio → needs DOI

PET with TOF and DOI implemented with PMT's

Uses 4-layer scintillator
→ very expensive !



Nakazawa et.al., in: Nuclear Science Symposium Conference Record (NSS/MIC), 2010 IEEE

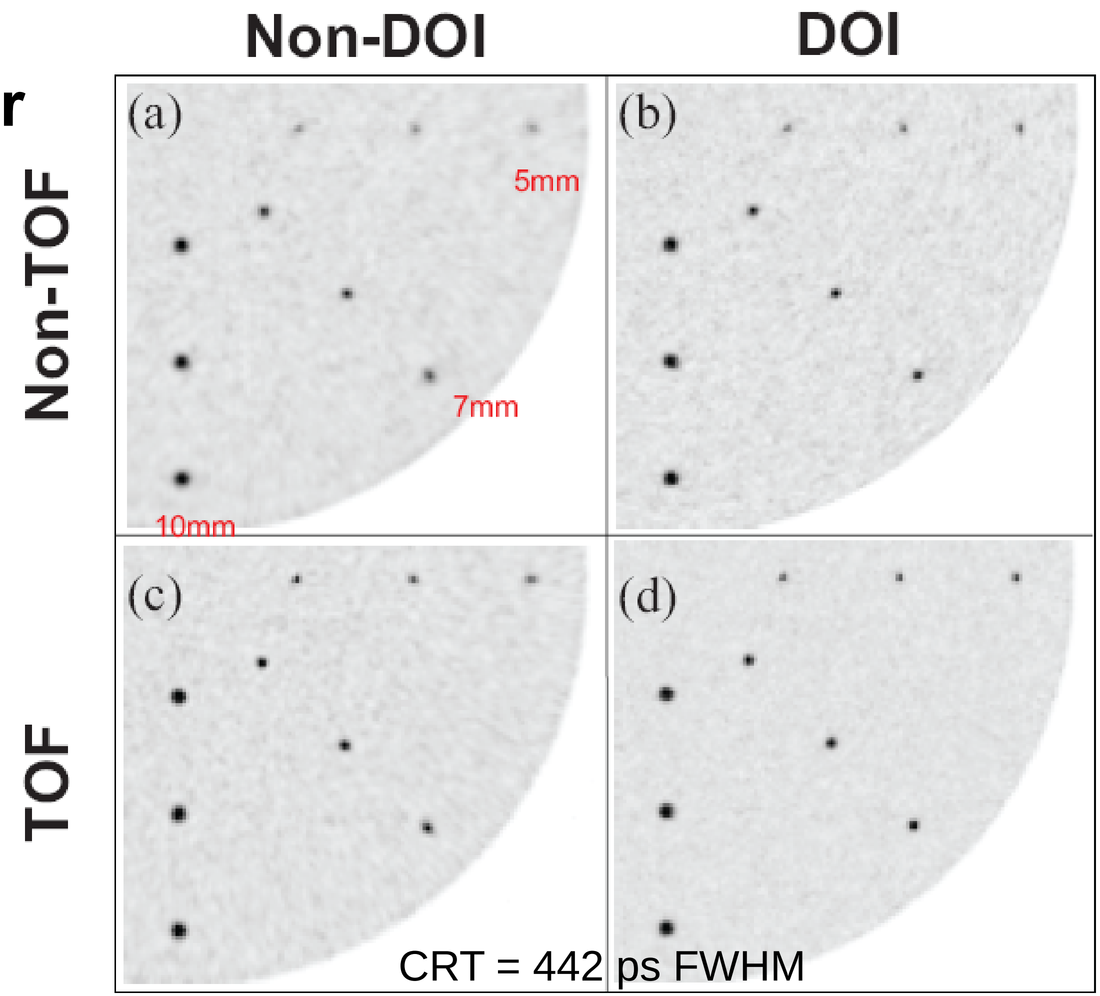
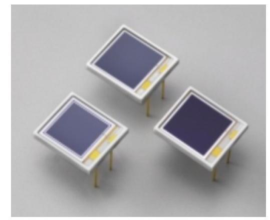
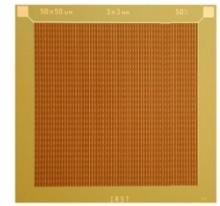
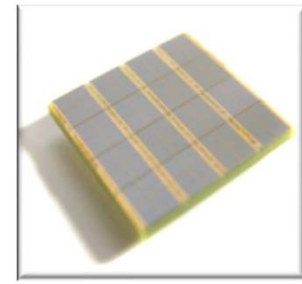


Fig. 13 Reconstructed images with-/without-DOI-TOF (a) nonDOI-nonTOF, (b) DOI-nonTOF, (c) nonDOI-TOF, (d) DOI-TOF

Scintillation light detectors

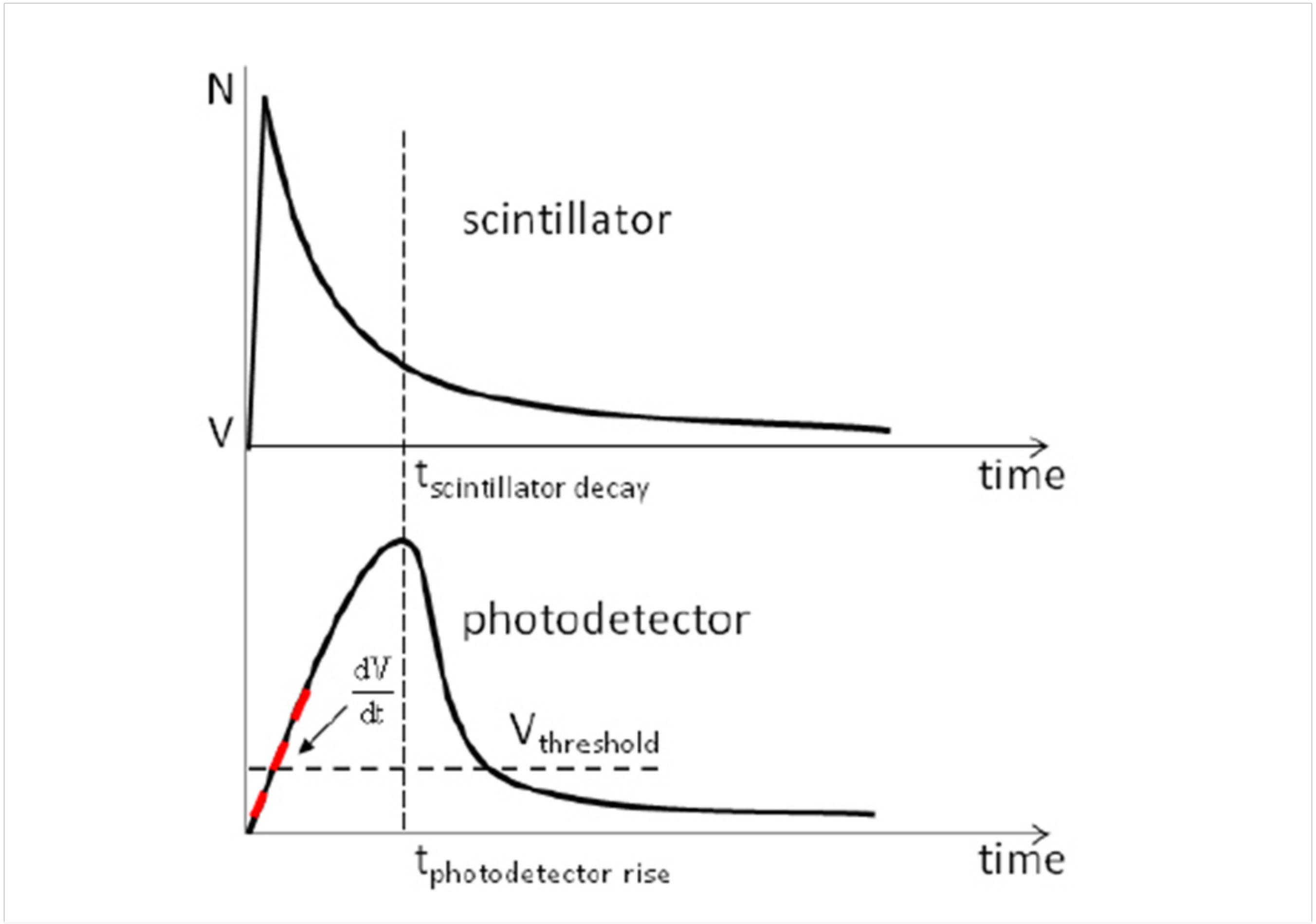






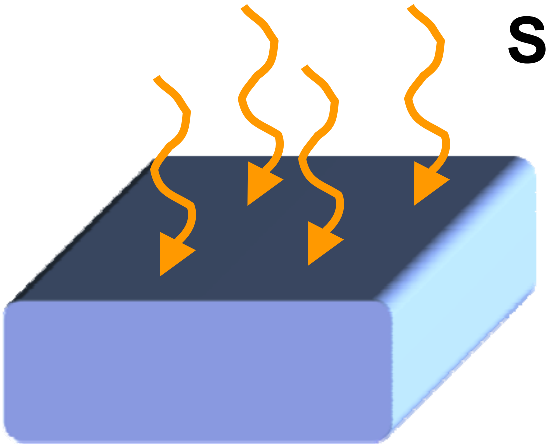
Type	PMT	APD	anal. SiPM	dSiPM
MR compliance	**No**	**Yes**	**Yes**	**Yes**
ToF compliance	limited	No	Yes	Yes
Operational stability	medium	low	low	high
Amplification	High (10^6)	Low (10^{2-3})	High (10^6)	meaningless
Compactness	bulky	compact	very compact	very compact
Power/Readout	HV, ASIC, analog	HV, ASIC, analog	LV, ASIC, analog	LV, simple, digital

(Not only) for scintillators a fast reacting light detector is desired



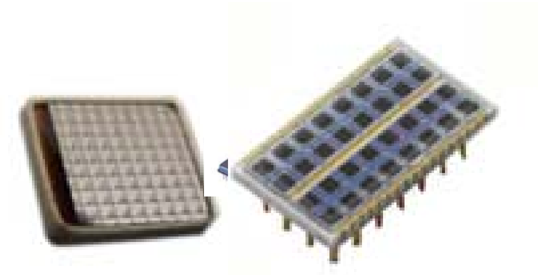
Graphs courtesy of Spanoudaki & Levin, Stanford, in Sensors, 10, 2010

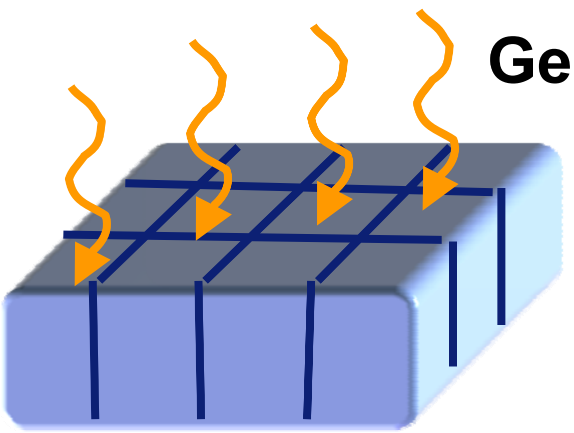
From single APD to (multiple) SPAD's:



Single Geiger-mode APD

- fully analog
- poor timing
- high bias voltage, but **below breakdown**





Geiger-mode APD Array (SPAD's):

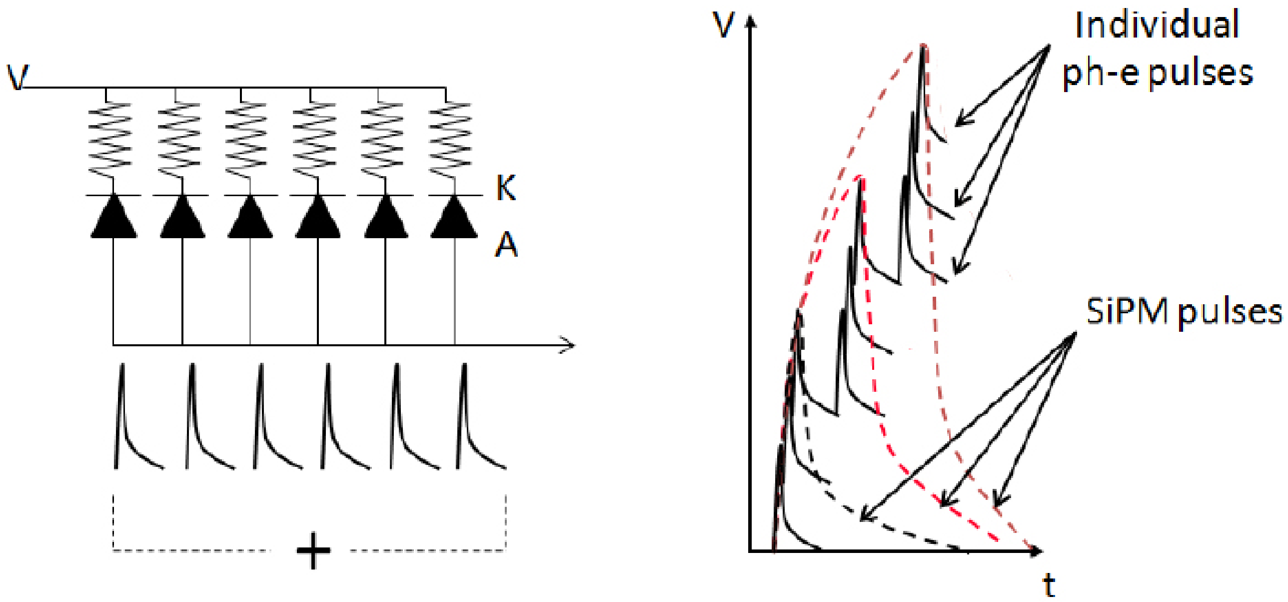
"Silicon Photomultiplier"

- single photon resolution
- binary, but still analog
- better timing
- low bias voltage, **above breakdown**

B. Dolgoshein, V. Saveliev, V. Golovine
First idea: Russia, early 80's

Signal formation in (analog) SiPM’s

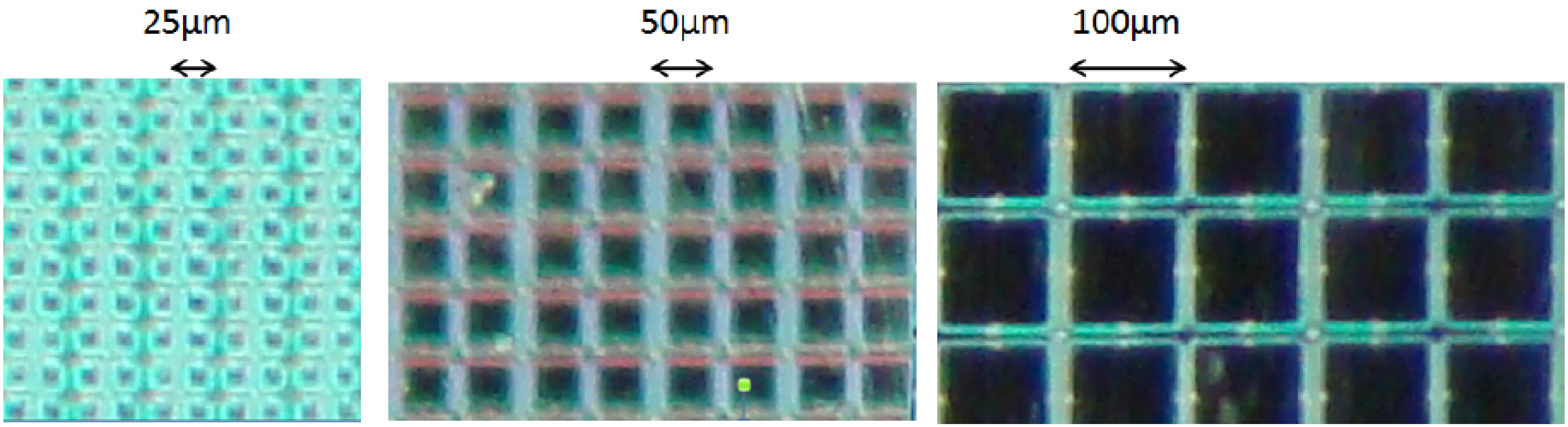
Figure 10. Left: schematic of the equivalent electrical circuit of a SiPM. Only 6 micro-cells, each represented by a diode symbol, are shown. Right: illustration of the signal formation in a SiPM. The pile-up of the individual micro-cell pulses is achieved by means of summing via a common readout line.



Graphics courtesy of Spanoudaki & Levin, Stanford in: Sensors, 10, 2010

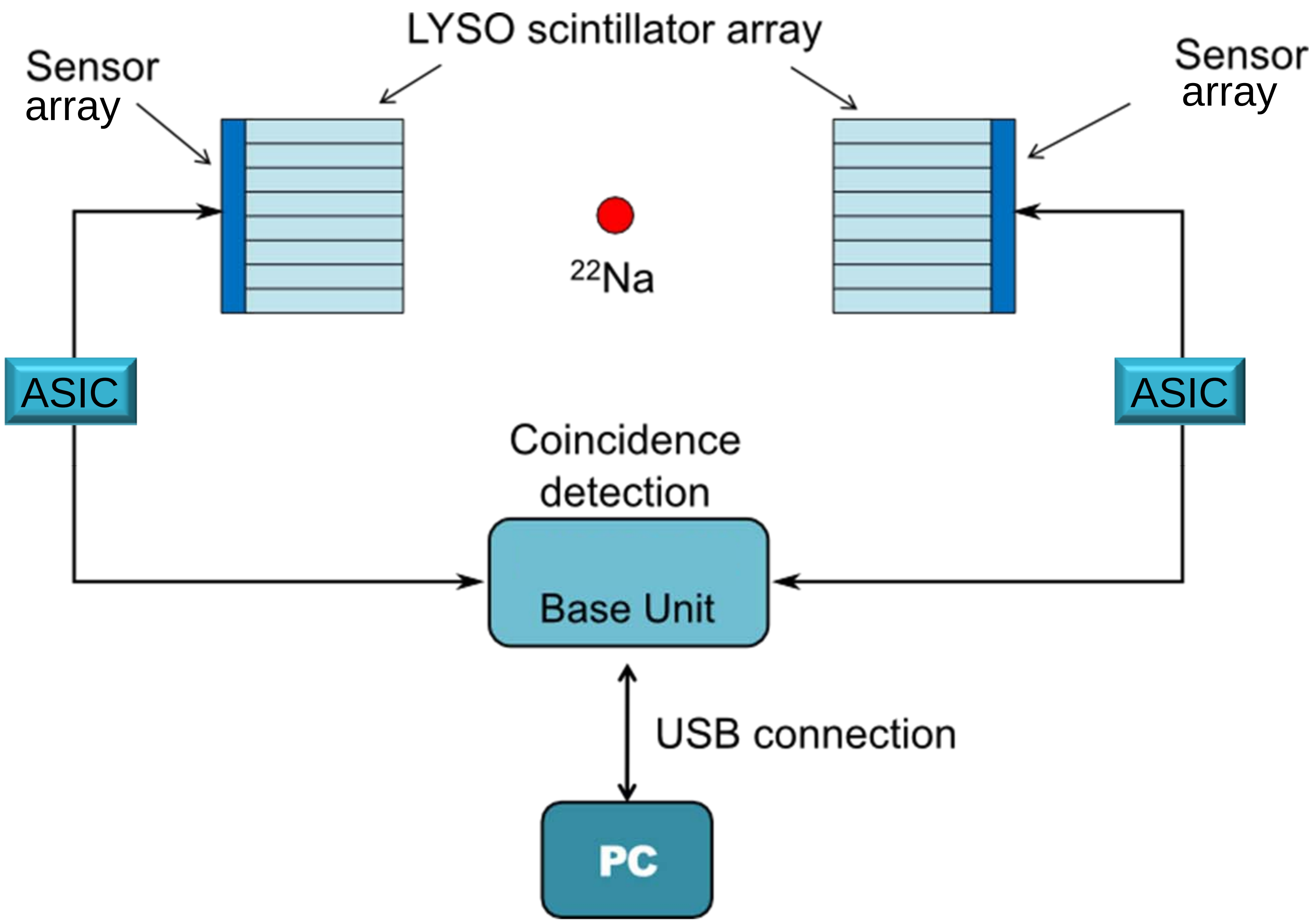
SiPM-SPADs: sensitivity vs. dynamic range vs. DC

Figure 13. Microscope captures of sensitive areas of SiPMs with micro-cell size of 25 μm (left), 50 μm (middle) and 100 μm (right). The fill factor increases with increasing micro-cell size, while the dynamic range (number of available micro-cells within a given area) decreases.



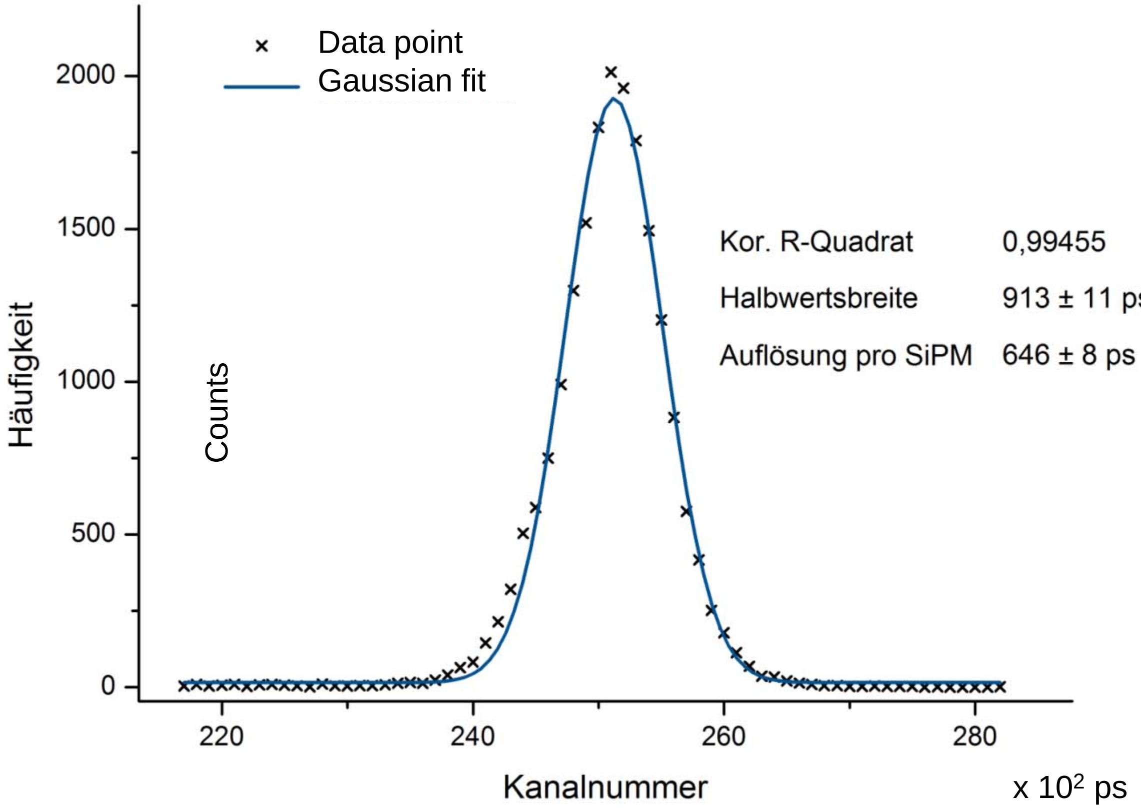
Photographs courtesy of Spanoudaki & Levin, Stanford Sensors, 10, 2010

Scintillator & SPAD Coincidence Setup



Coincidence Time Resolution

Hamamatsu MPPC S10362-11-050C, 400 cells



CRT (FWHM):

913 ± 11 ps

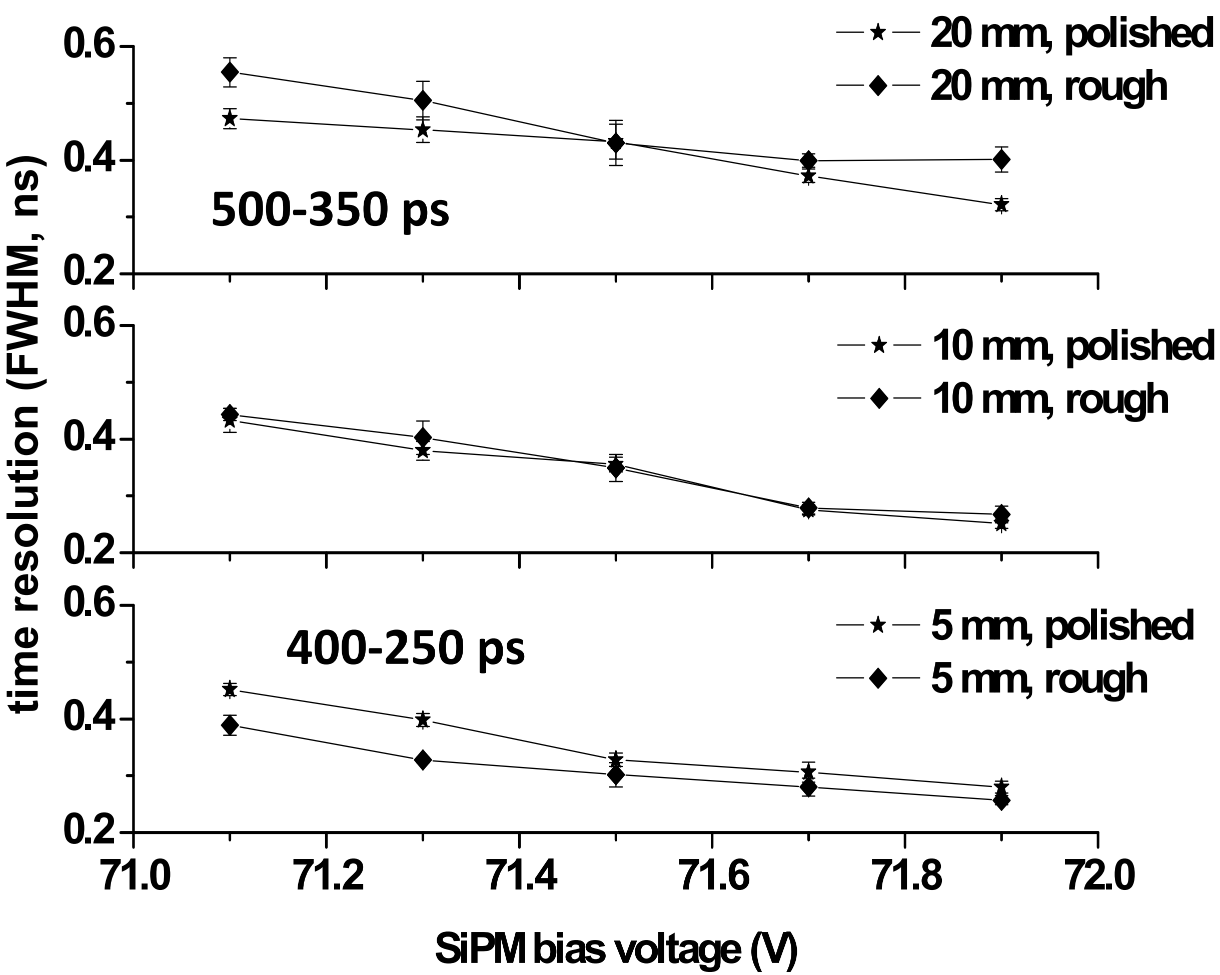
FWHM for single MPPC:

646 ± 8ps

- **2 MPPCs coupled to 1 x 1 x 20 mm³ LYSO**
- **Measured with ^{18}F**

Katja Zechmeister, "Evaluierung neuer Detektoren für die kombinierte PET/MR-Bildgebung, basierend auf SiPM und schnellen Szintillationskristallen", Diplomarbeit, Klinikum rechts der Isar, 2010

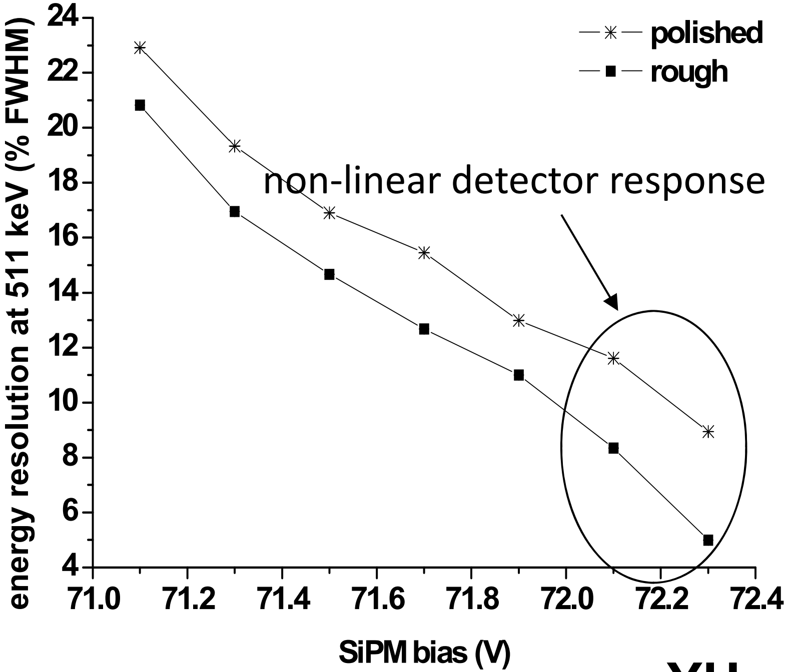
Measurements: time resolution (I)



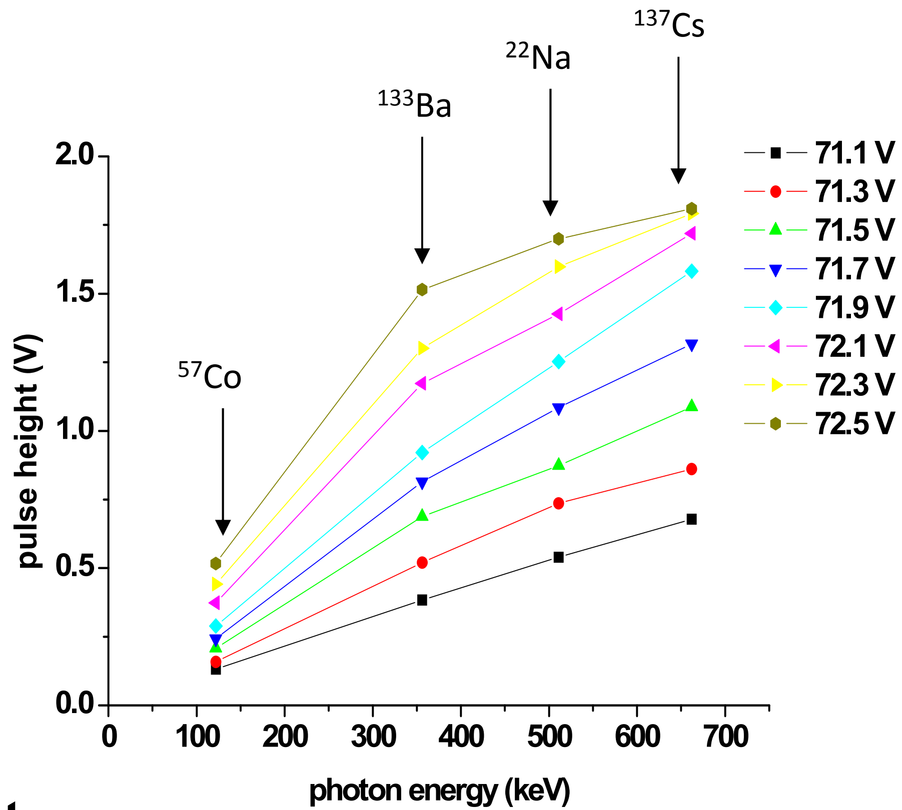
Effect of crystal surface treatment dependent on crystal thickness

Measurements: energy resolution and linearity

detector energy resolution



detector response

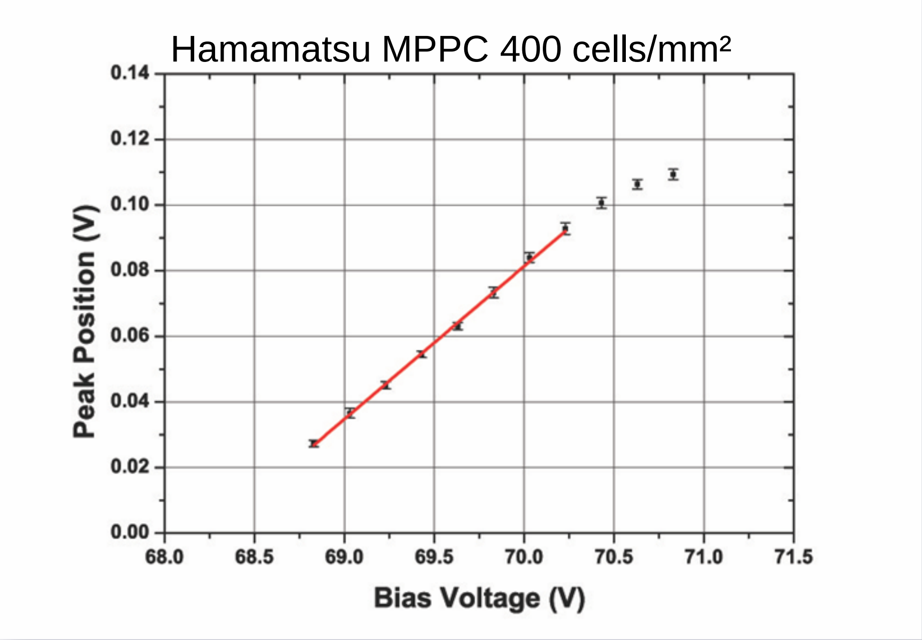


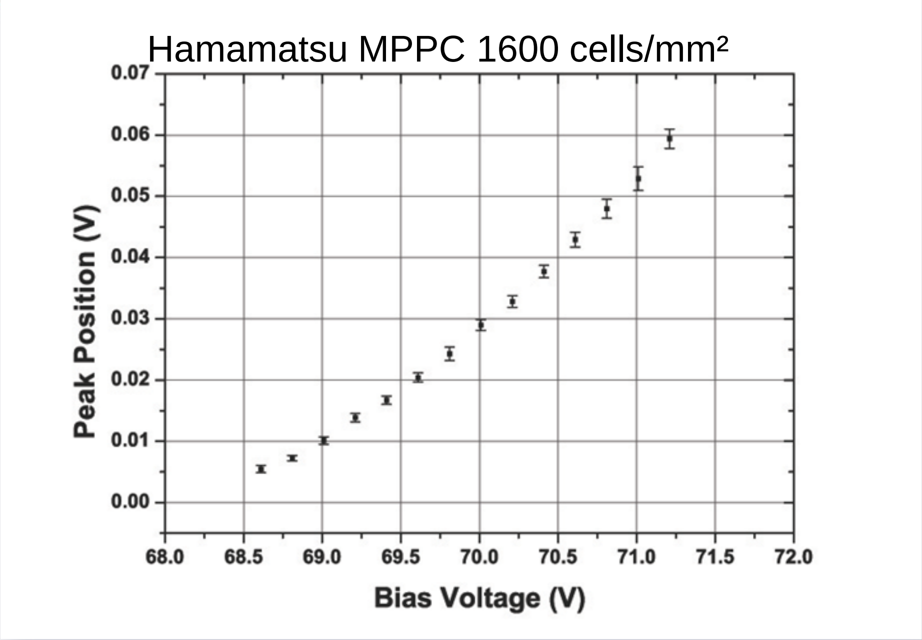
YH comments:

Non-linearity caused by
- saturation, recovery effects
- multiple "firing" of single SPADs

Bias Voltage Dependency

Pulse Height





- Illumination with blue pulsed LED
- Temperature was kept constant at 25 C in both series of measurements
- Bias voltage coefficient:
  - 400 cells: 63 ± 2 %/V @ 69.83 V

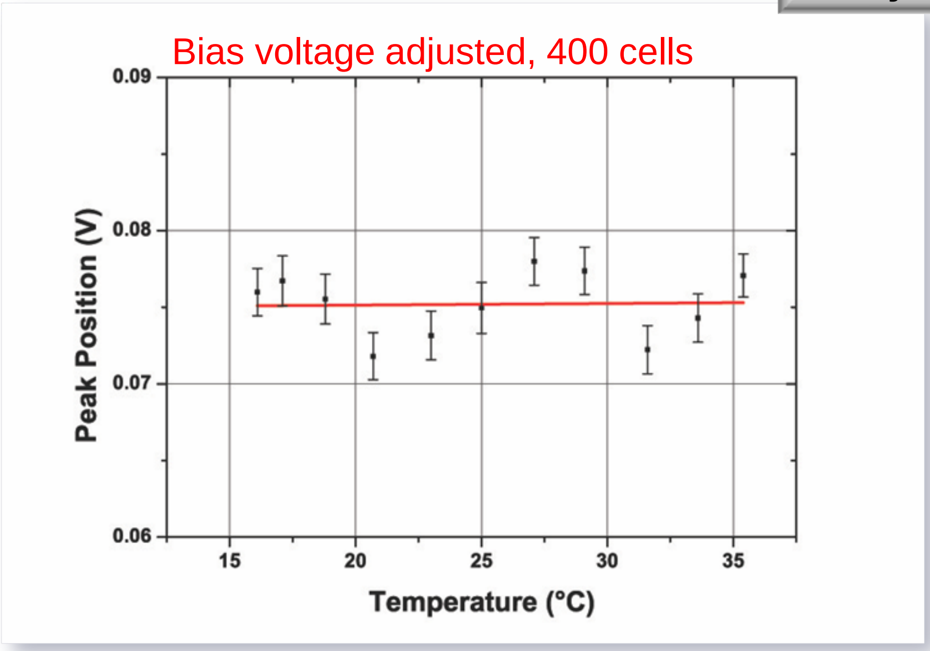
Sebastian Fürst, "Development and Evaluation of Novel Detectors for Combined PET/MR Imaging,Based on SiPMs and Fast Scintillation Crystals", Diplomarbeit, Klinikum rechts der Isar, 2009

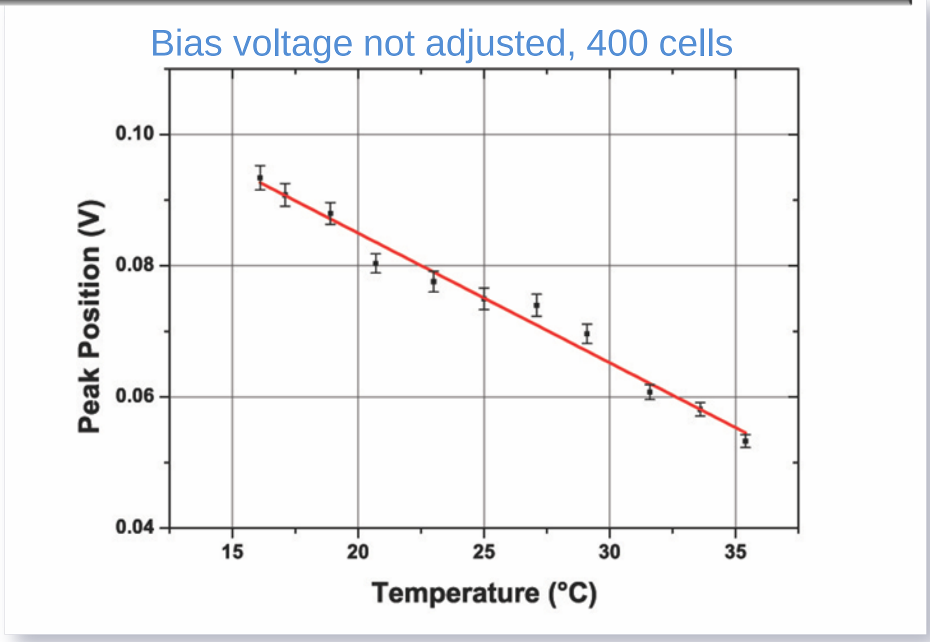
Temperature Dependency

YH comments:

- correction requires sophisticated ASIC
- correction is time critical
- adjusting bias changes PDE → non-linearity

Pulse Height





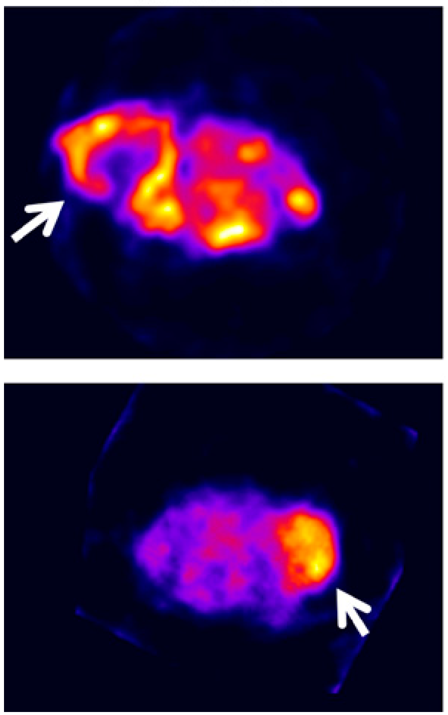
- Temperature coefficients, illuminated with blue pulsed LED
  - 400 cells
    - 0.0 ± 0.2 %/K and -2.7 ± 0.2 %/K @ 25 ° C
  - 1600 cells
    - 0.2 ± 0,6 %/K and -2.5 ± 0.4 %/K @ 25 ° C

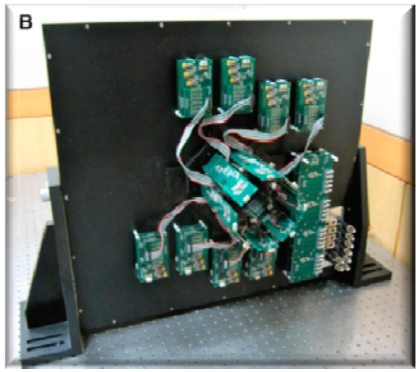
Sebastian Fürst, “Development and Evaluation of Novel Detectors for Combined PET/MR Imaging,Based on SiPMs and Fast Scintillation Crystals”, Diplomarbeit, Klinikum rechts der Isar, 2009

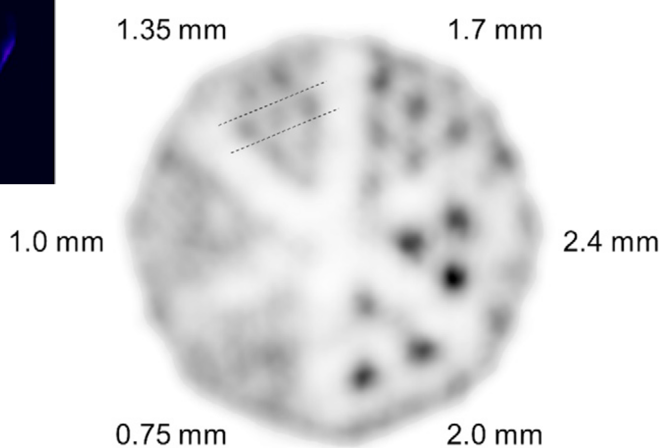
Analog SiPM's: Only a few prototype devices exist

Analog SiPM

SiPM PET

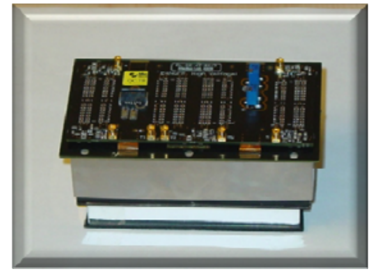


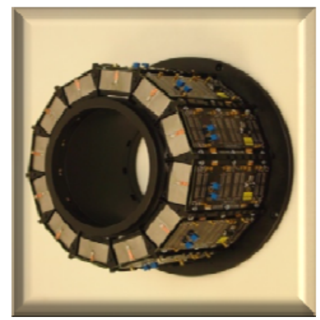


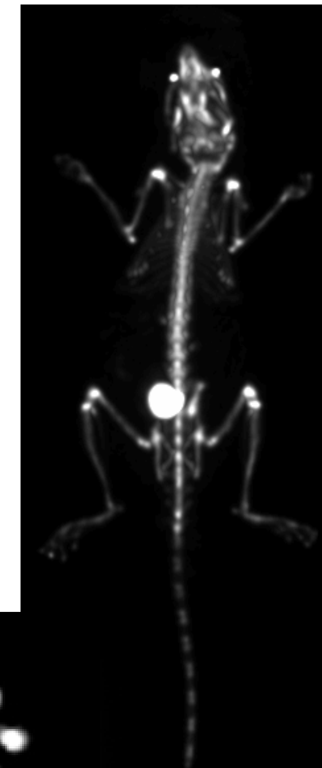


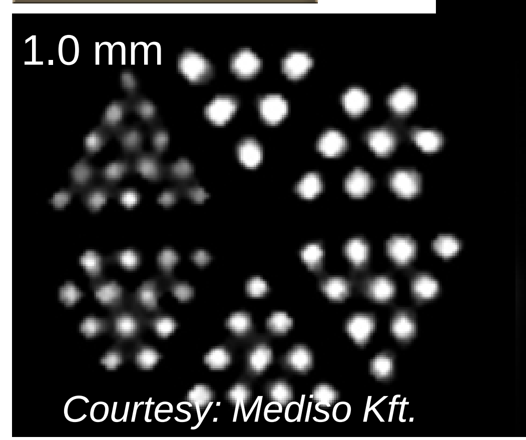
JNM, Vol. 52, No. 4, April 2011, 572-579

Analog PS-PMT



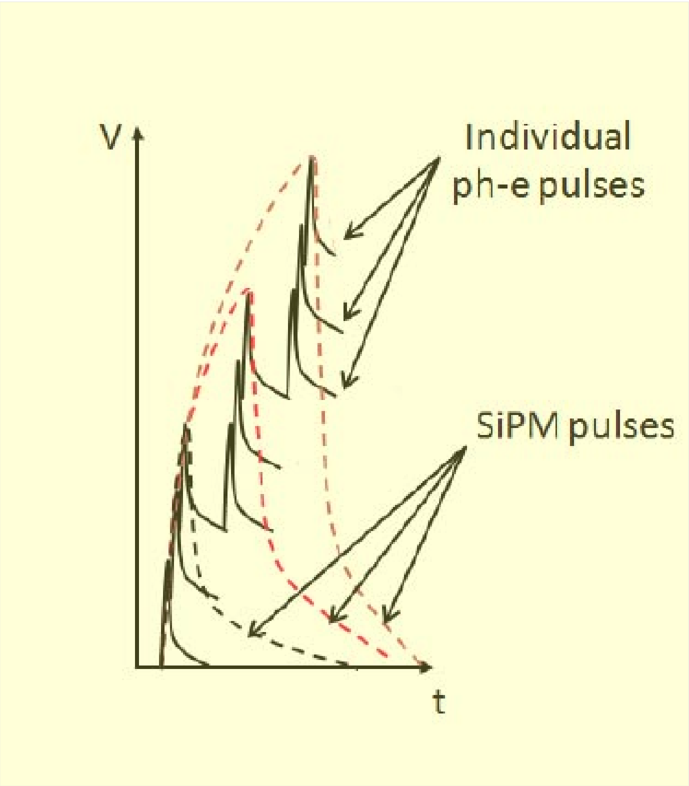




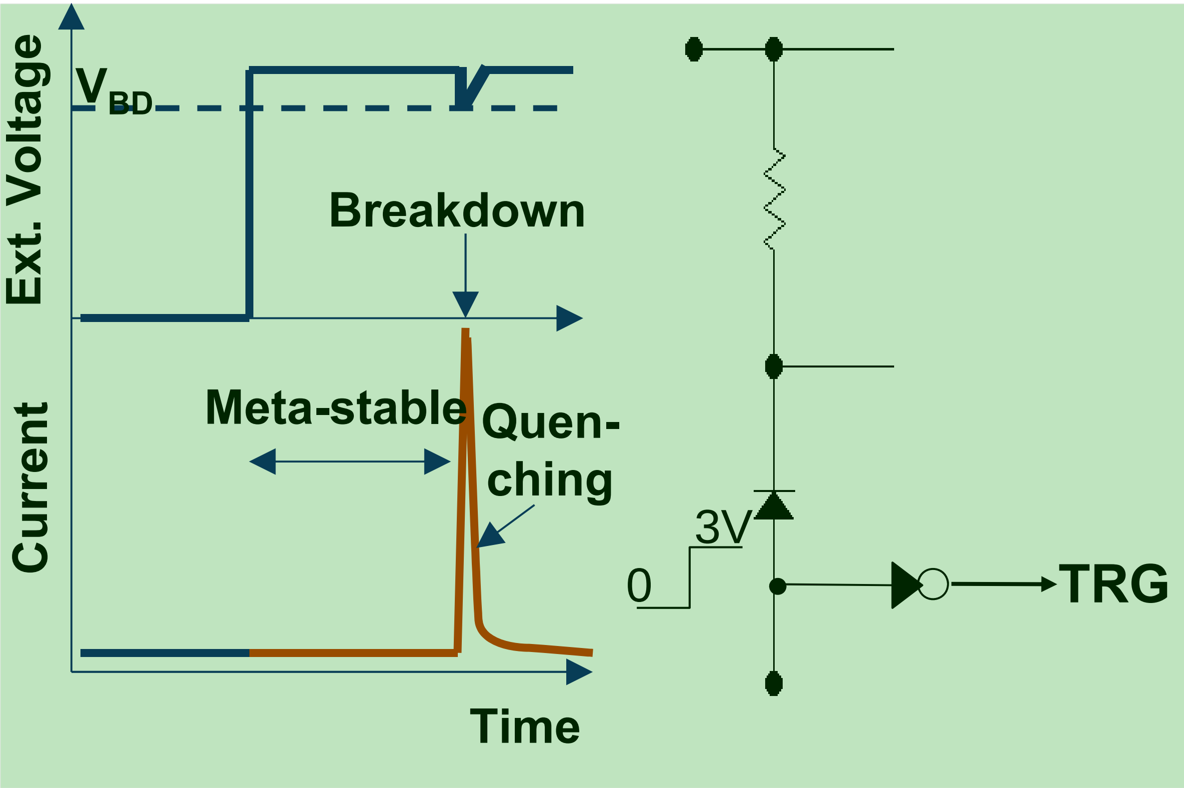


SiPM (SPAD) principles

analog

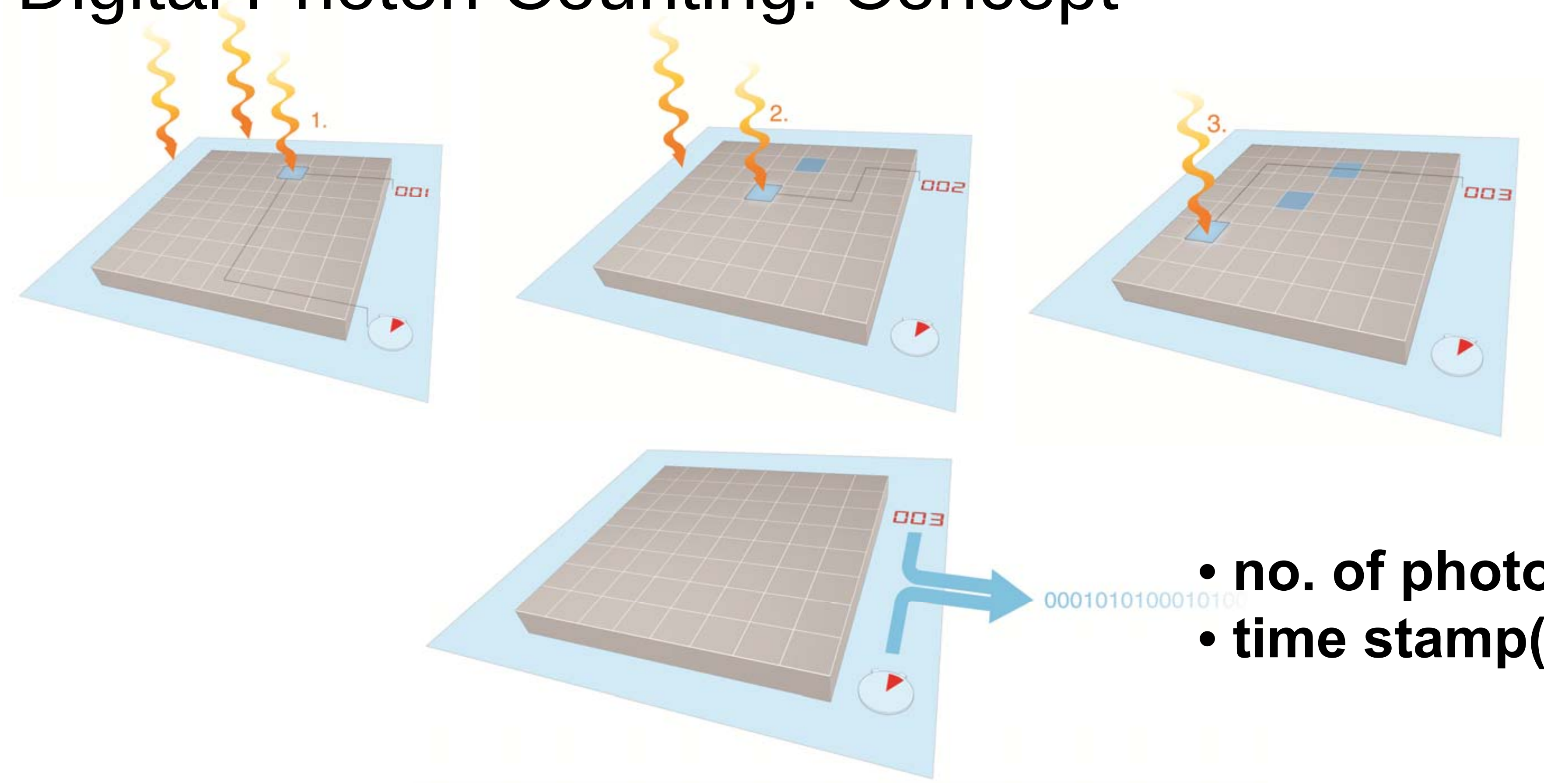


digital



"Therefore, while the APD is a linear amplifier for the input optical signal with limited gain, the SPAD is a trigger device so the gain concept is meaningless." ***(source: Wikipedia)***

Digital Photon Counting: Concept

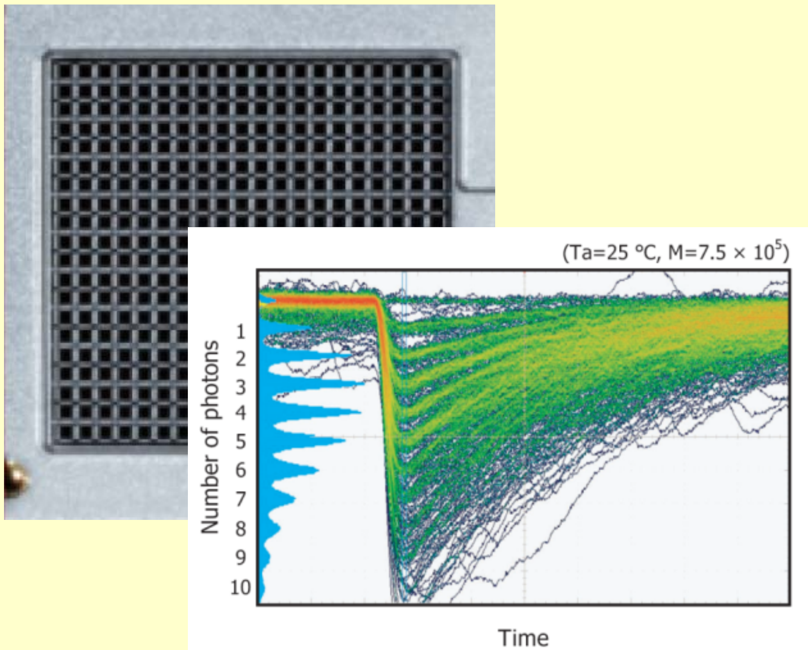


- **no. of photons**
- **time stamp(s)**

"Therefore, while the APD is a linear amplifier for the input optical signal with limited gain, the SPAD is a trigger device so the gain concept is meaningless." *(source: Wikipedia)*

Digital Photon Counting: Realization

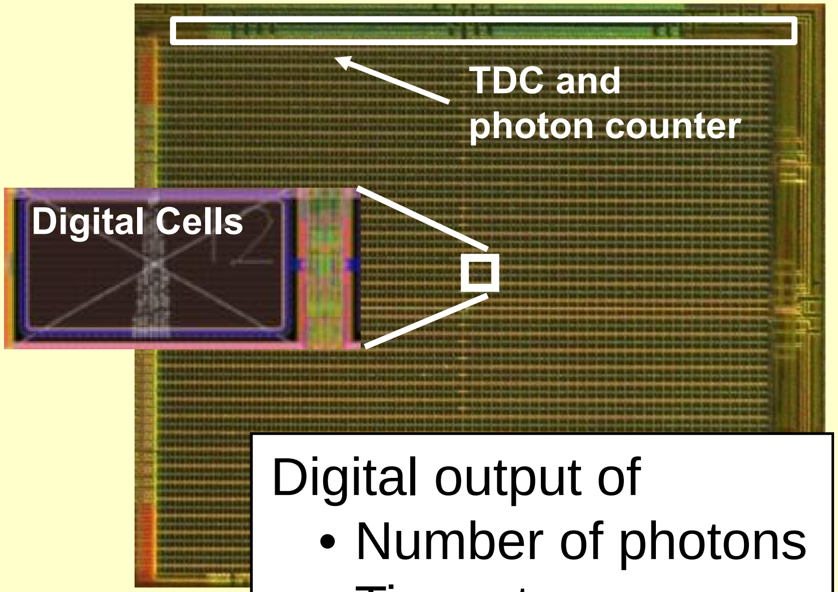
analog SiPM



www.hamamatsu.com

Summing all cell outputs leads to an analog output signal and limited performance

digital SiPM (dSiPM)

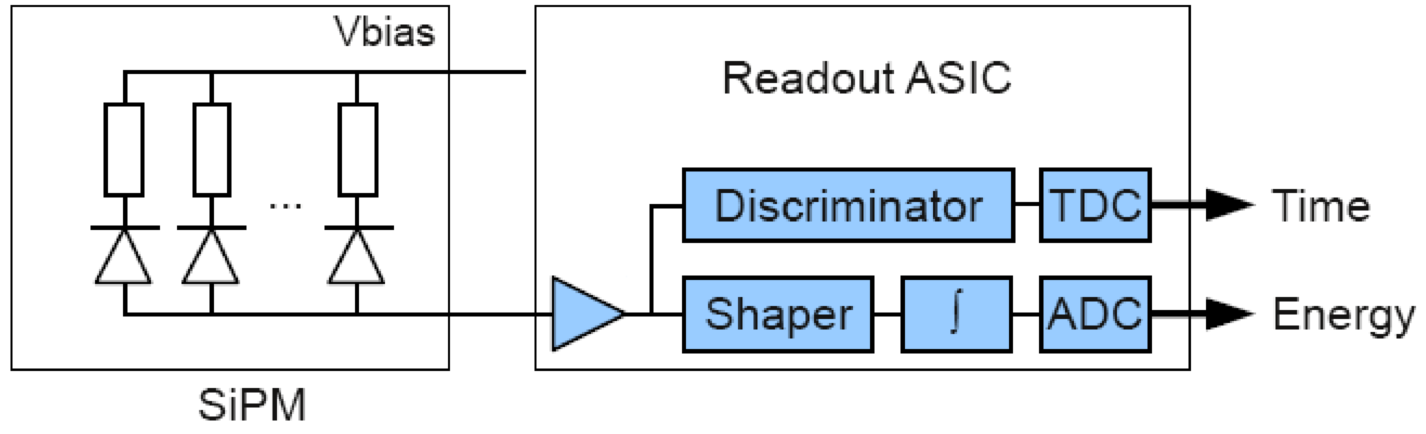


Digital output of
- Number of photons
- Time-stamp

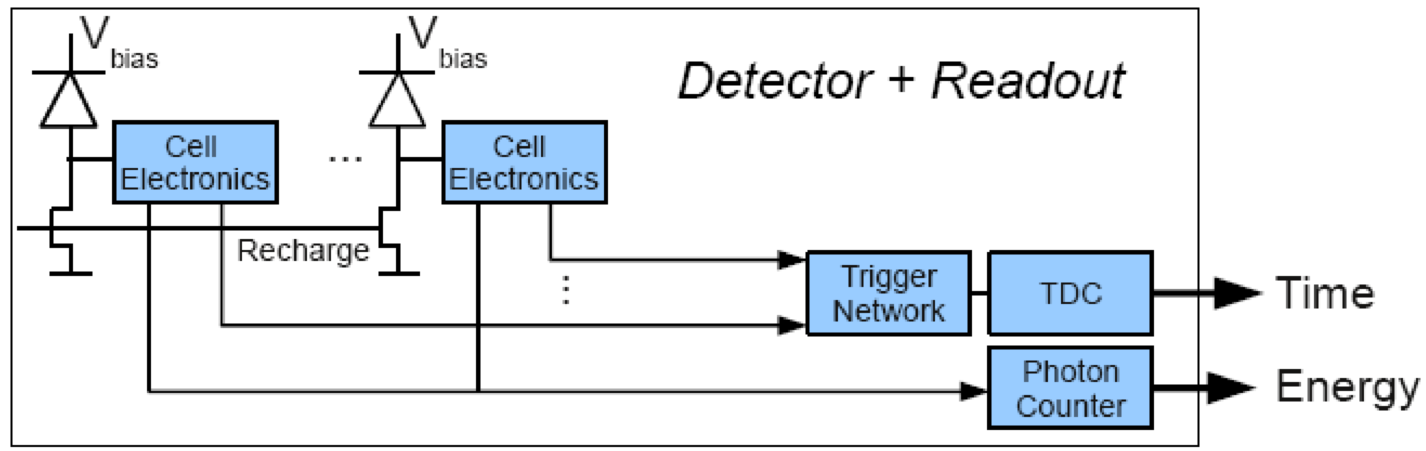
Integrated readout electronics is the key element to superior detector performance

Analog vs. Digital SiPM: Layout

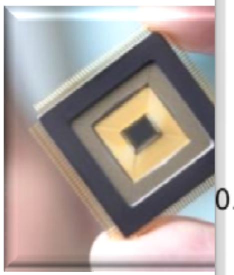
Analog Silicon Photomultiplier Detector

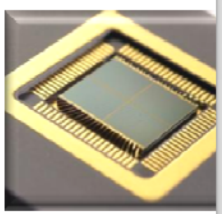


Digital Silicon Photomultiplier Detector

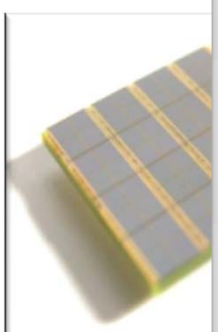


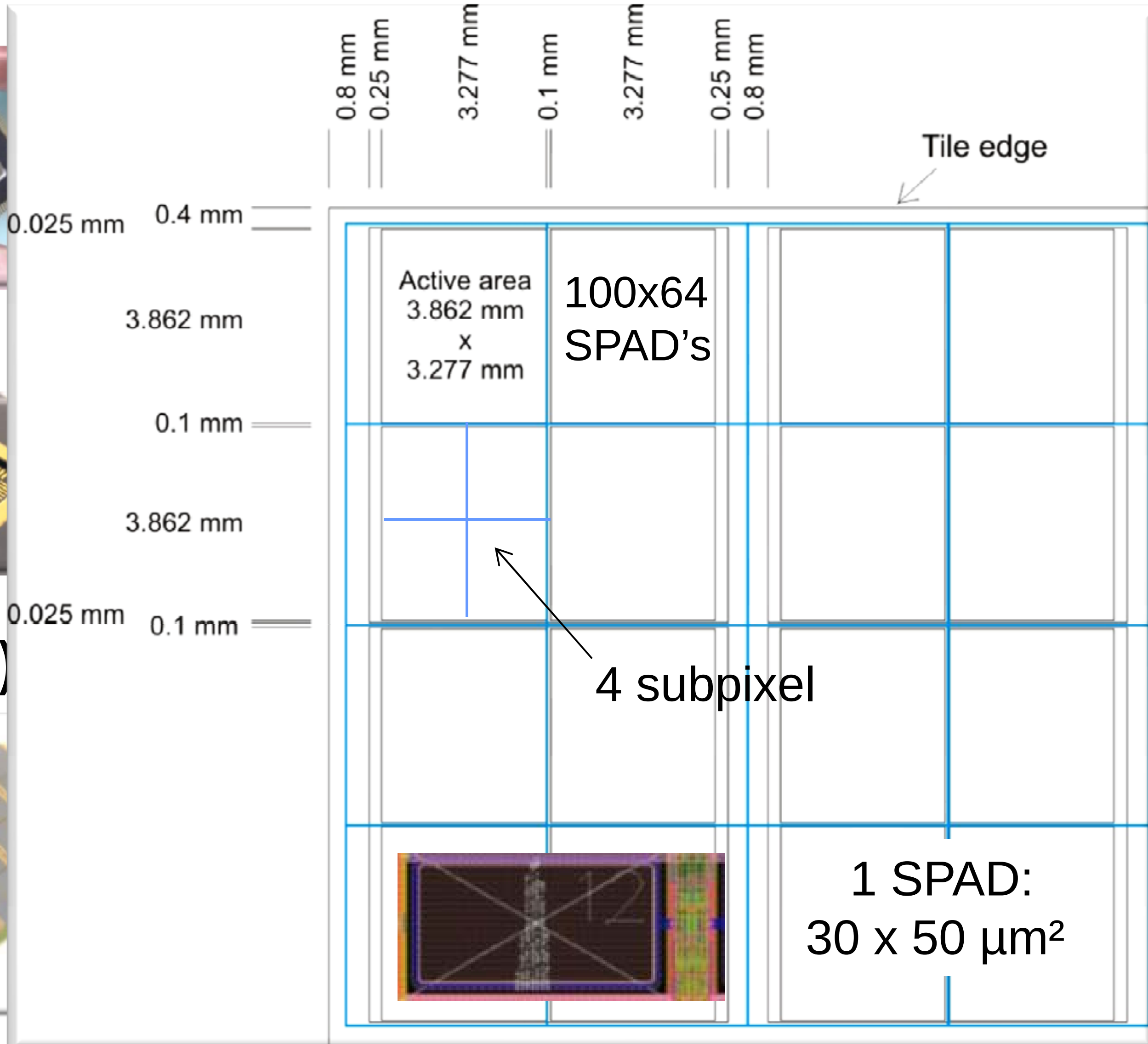
Digital SiPM: Architecture and Pixel Diagram

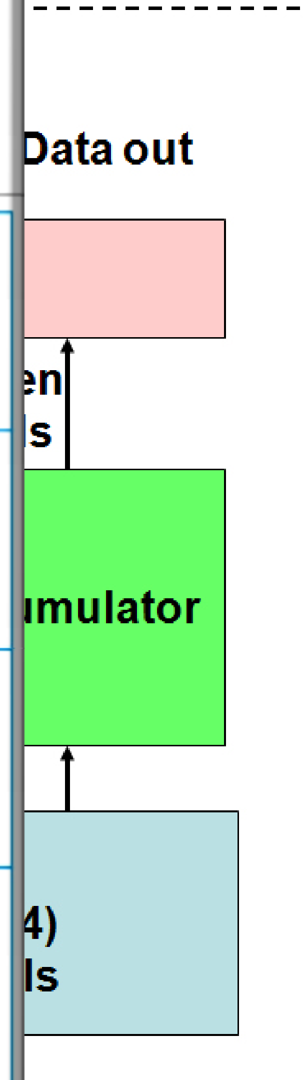




(smart)

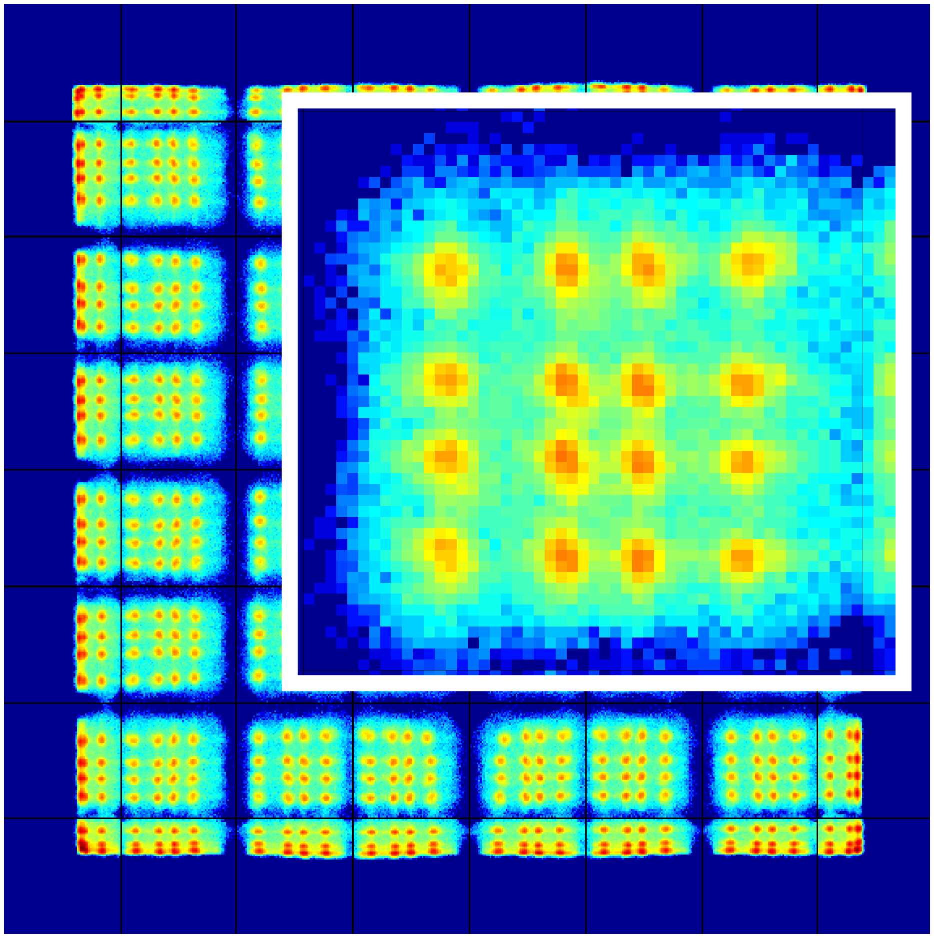


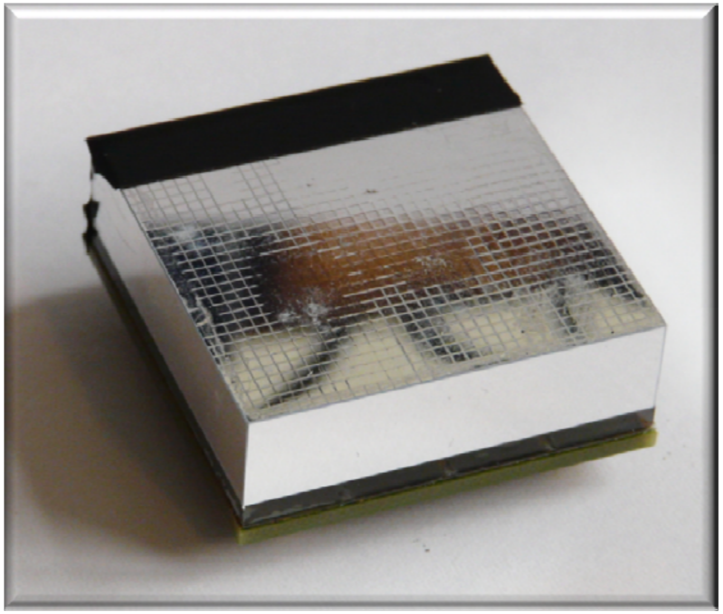




PDPC dSiPM: Small Crystal Readout

LYSO array, 30 x 30 crystals, 1 mm x 1 mm pitch, 10 mm length

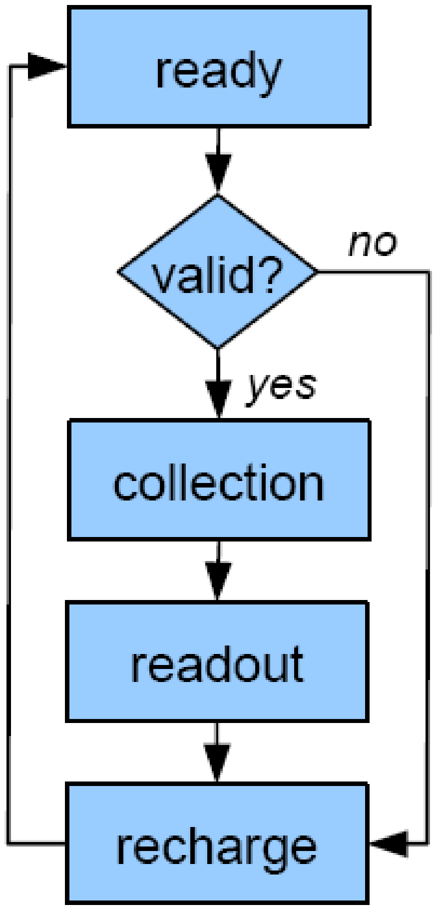




Log scale

Data analysis by P. Düppenbecker, Philips Research

Digital SiPM: Typical Acquisition Sequence (example)



5ns – 80ns

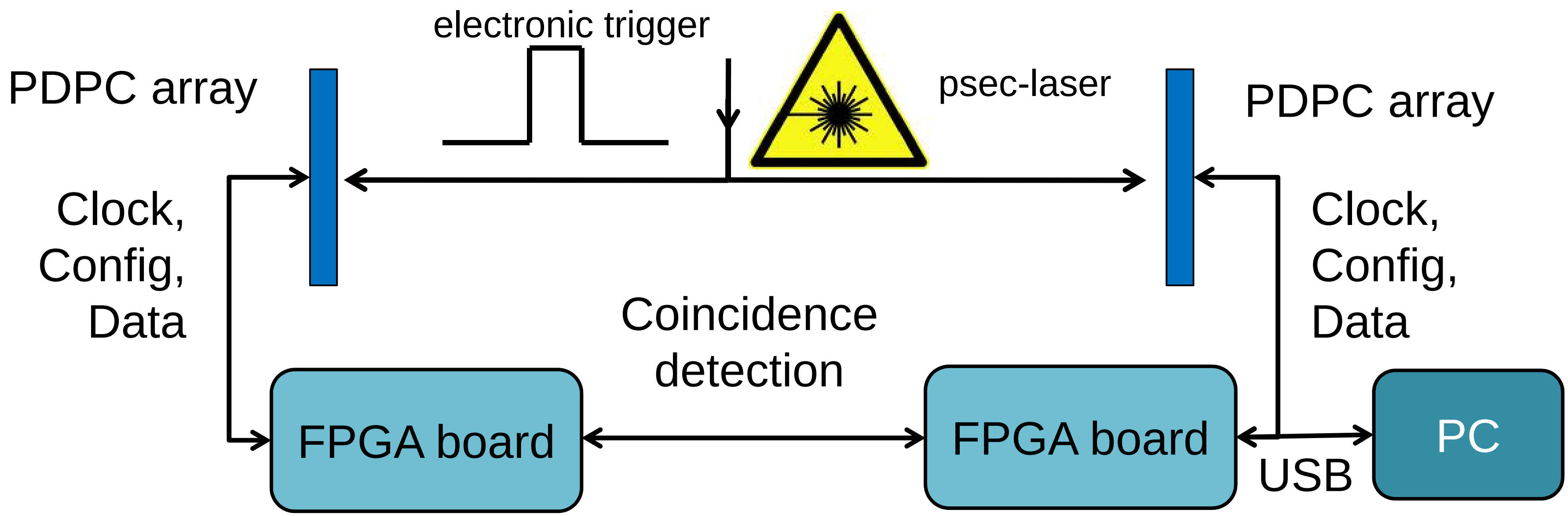
0ns – 20µs

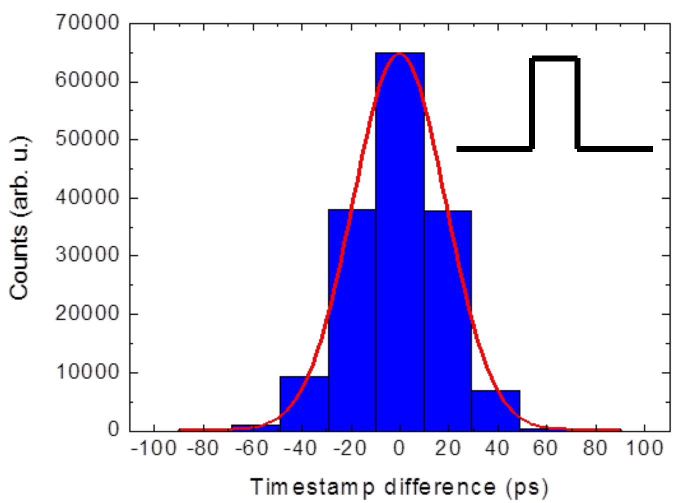
680ns

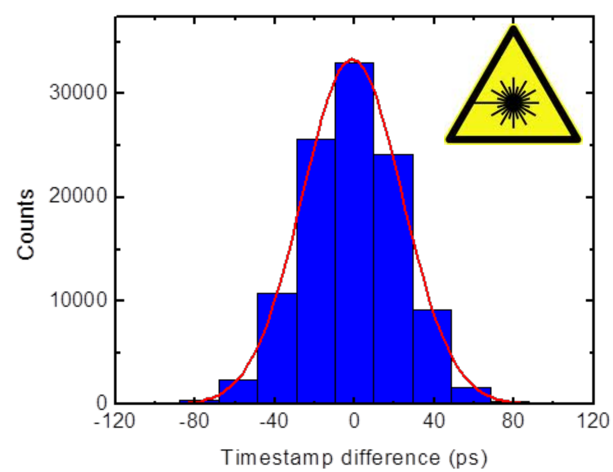
10ns – 40ns

- *200MHz (5ns) system clock*
- *Variable light collection time up to 20µs*
- *20ns min. dark count recovery*
- *dark counts => sensor dead-time*
- *data output parallel to the acquisition of the next event (no dead time)*
- *Trigger at 1, ≥2, ≥3 and ≥4 photons*
- *Validate at ≥4 ... ≥64 photons (possible to bypass event validation completely)*

PDPC dSiPM: Intrinsic Timing Resolution

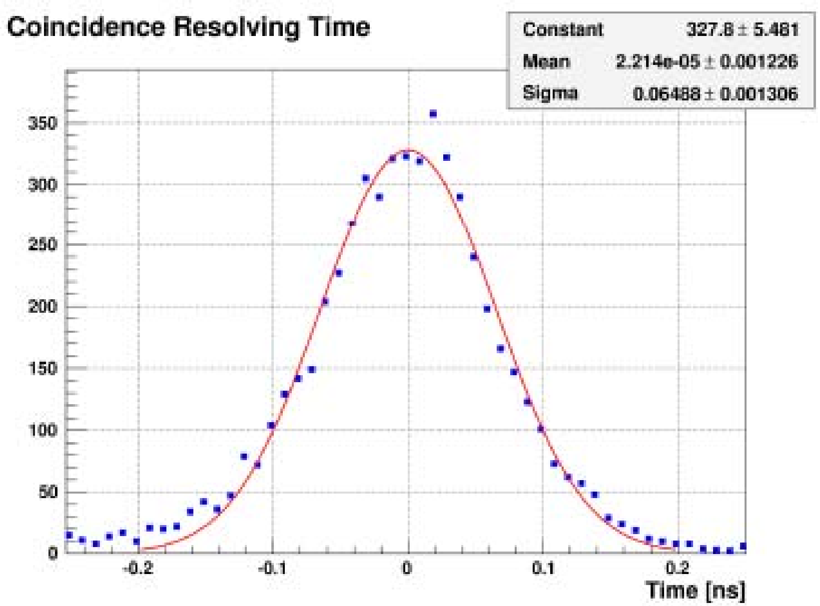


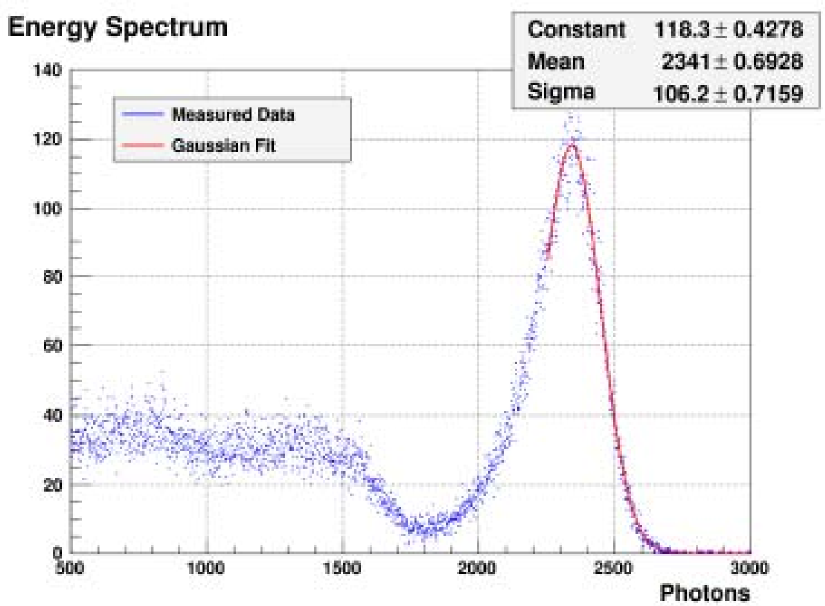




Timing jitter: **44 ps FWHM** **59 ps FWHM**

PDPC dSiPM: Coincidence Timing & Energy Resolution

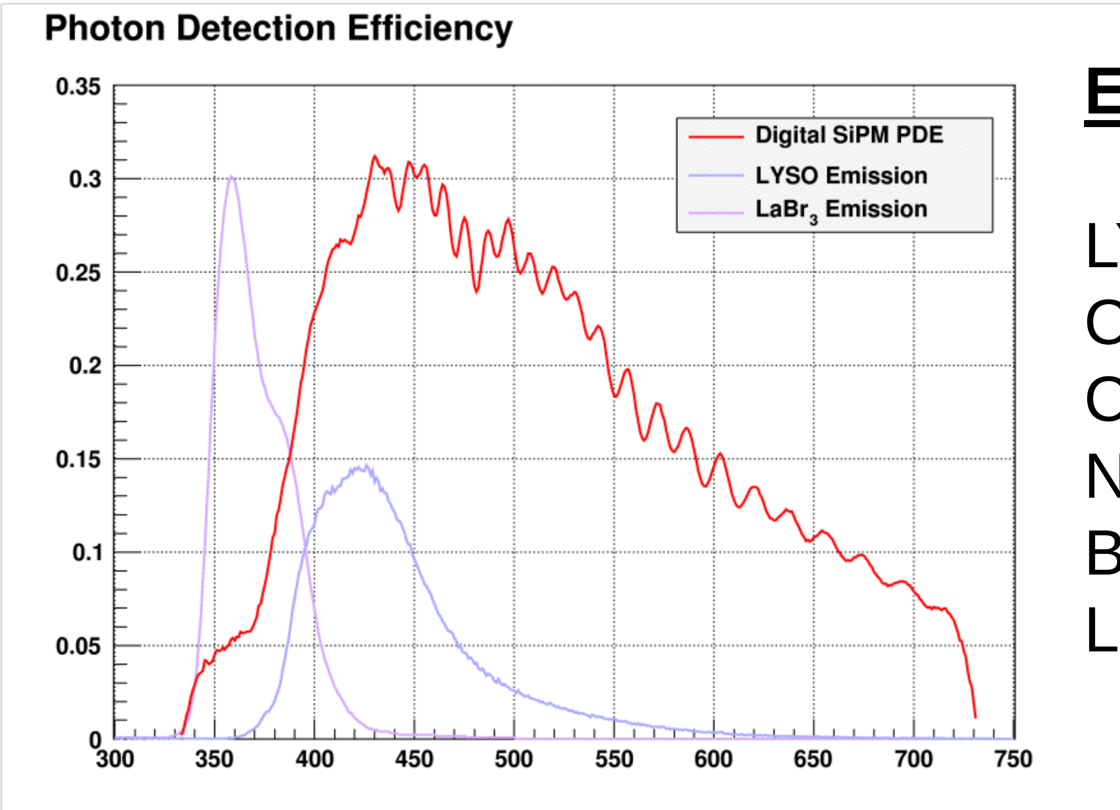




- Scintillator: 3x3x5 mm³ LYSO in coincidence, ^{22}Na source
- Time resolution in coincidence: **153 ps** FWHM*
- Energy resolution (excluding escape peak): **10.7 %**
- Excess voltage: 3.3 V, 98.5% active cells
- Measured at room temperature (31°C board temperature, not stabilized)

*** Achieved with single die, typical tile levels: 250-350 ps**

PDPC dSiPM: Spectral Sensitivity

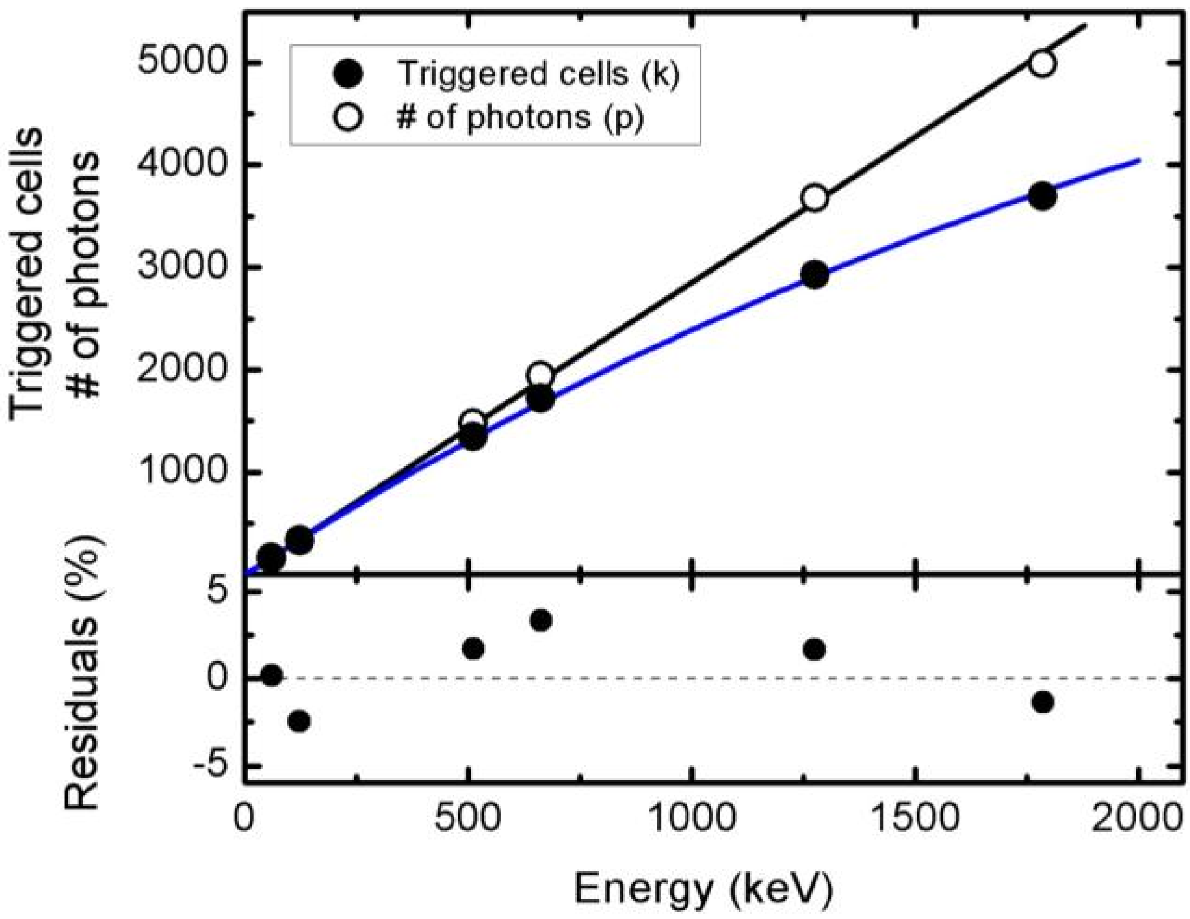


Effective PDE:

LYSO(Ce)	~30%
CsI(Na)	23.7%
CsI(Tl)	20.5%
NaI(Tl)	24.2%
BGO	24.2%
$LaBr_3$(Ce)	9.6%

- Peak PDE ~30% at 430 nm and 3.3 V excess voltage
- Conservative diode design (54 % fill-factor)
- No anti reflection coating used

PDPC dSiPM: Linearity only Affected by Saturation → Correction Possible

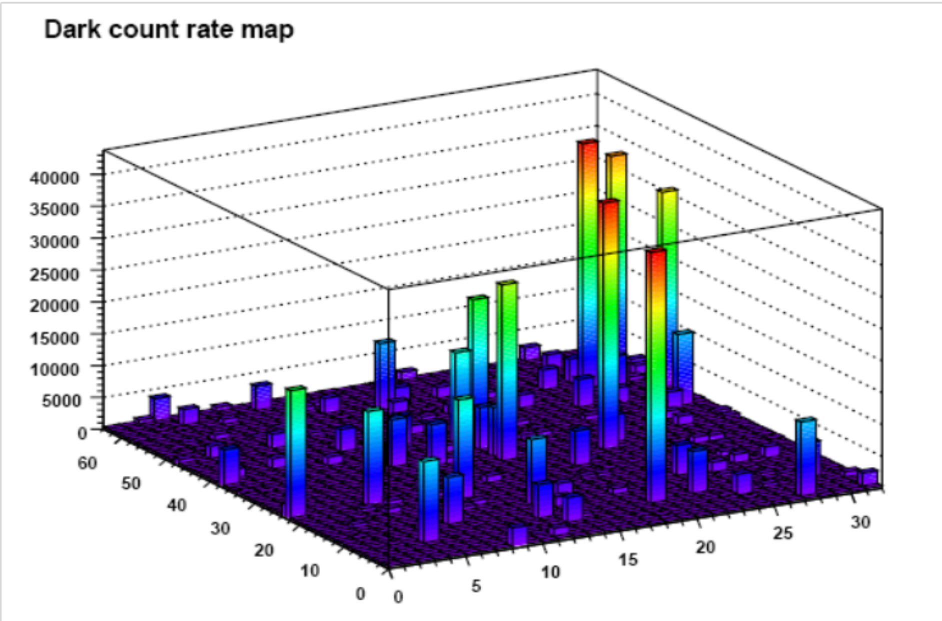


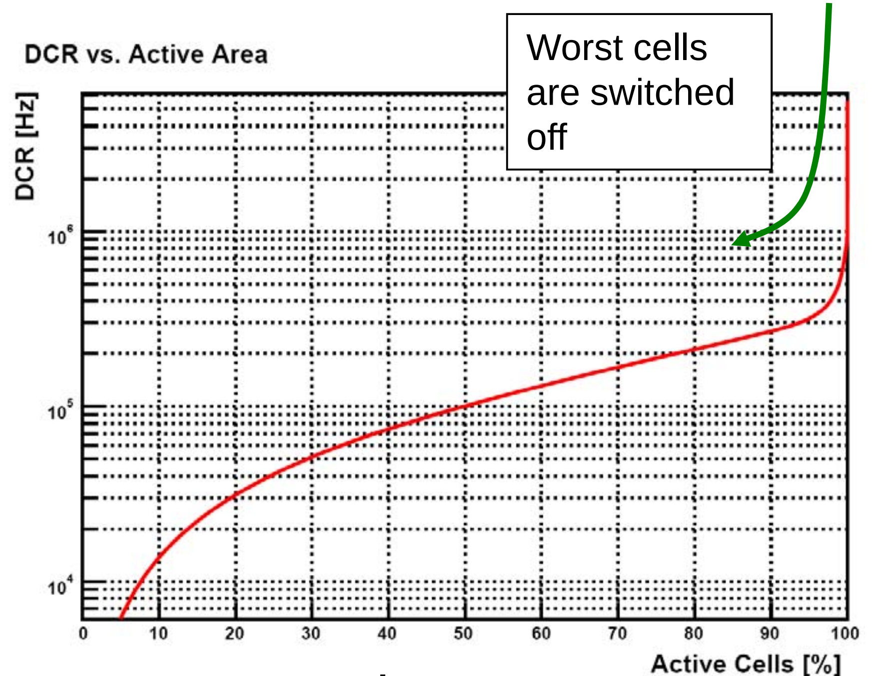
$$p = -N \cdot \ln\left(1 - {k}/{N}\right)$$

N: active cells (6400)
k: triggered cells
p: # of photons

- Experiments taken at room temperature
- No temperature stabilization

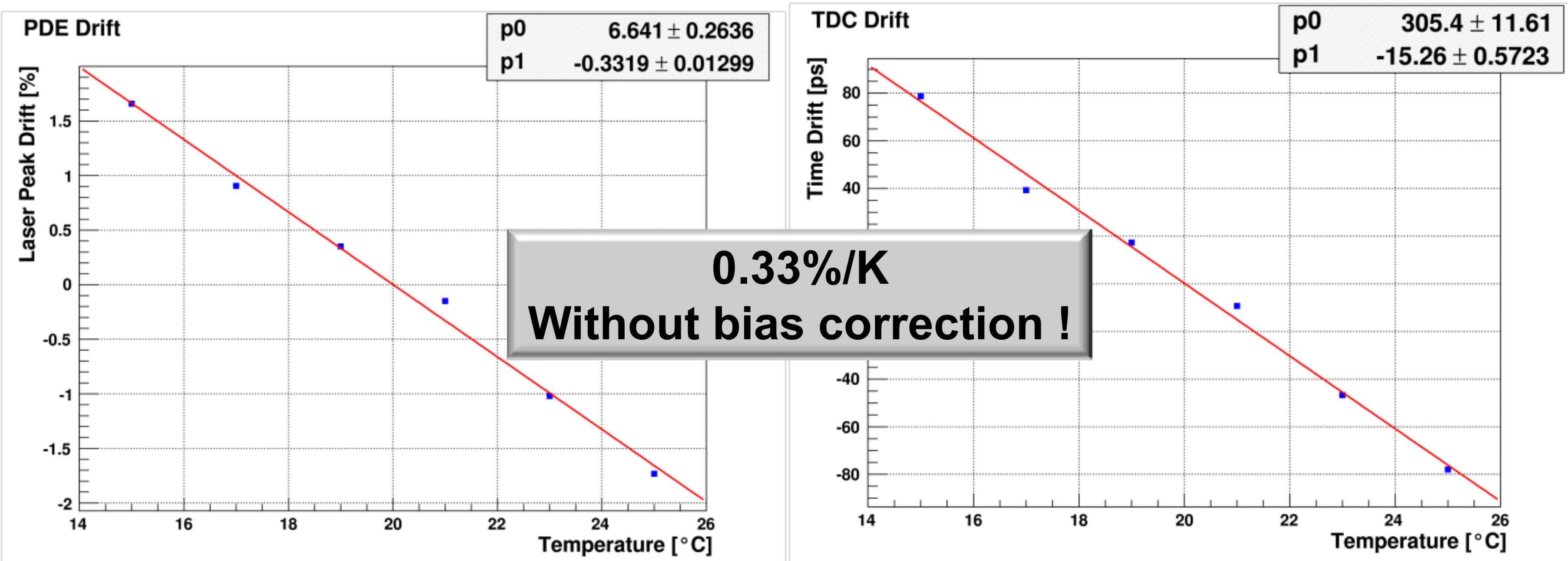
PDPC dSiPM: Dark Count Mapping/Tuning





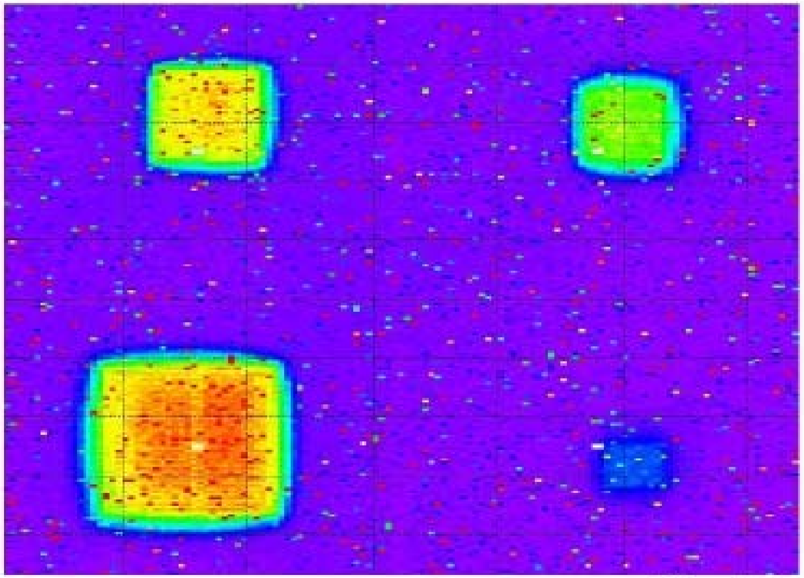
- Dark counts per second at 20°C and 3.3V excess voltage
- ~ 95% good diodes (dark count rate close to average)
- Typical dark count rate at 20°C and 3.3V excess voltage: ~150Hz / diode
- Dark count rate drops to ~1-2Hz per diode at -40°C
- **Cells with high DC can be switched off individually → DC control**

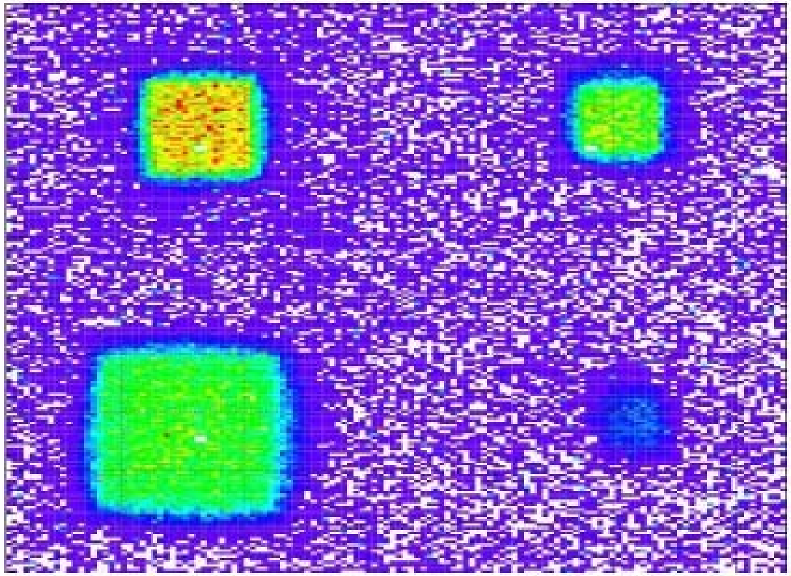
PDPC dSiPM: Reduced Thermal Sensitivity



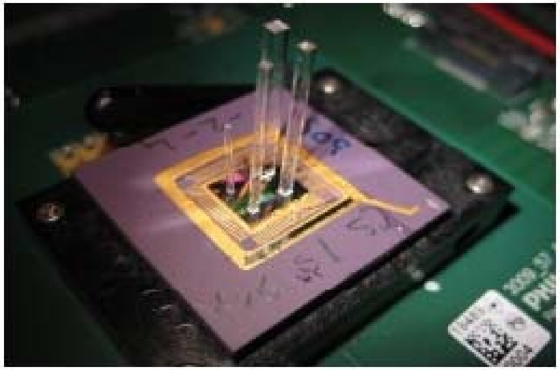
- **24 ps** full-width at half-maximum timing resolution of ps-laser
- Photopeak changes **0.33%** per degree C due to changing PDE **(values of analog SiPM's are ranging from 2-8%)**
- Time changes **15.3 ps** per degree C (TDC + trigger network drift)
- PDE drift can be easily compensated by adapting the bias voltage
- TDC offset can be periodically re-calibrated using the SYNC input

PDPC dSiPM: slow scan imaging mode


Singles


Coincidences

- *Spatial sampling of the light distribution*
- *Similar to dark count map measurement*
- *Dark count map can be used for correction*
- *Alternatively, use coincidence to reduce noise*
- *Potentially useful for light guide design*



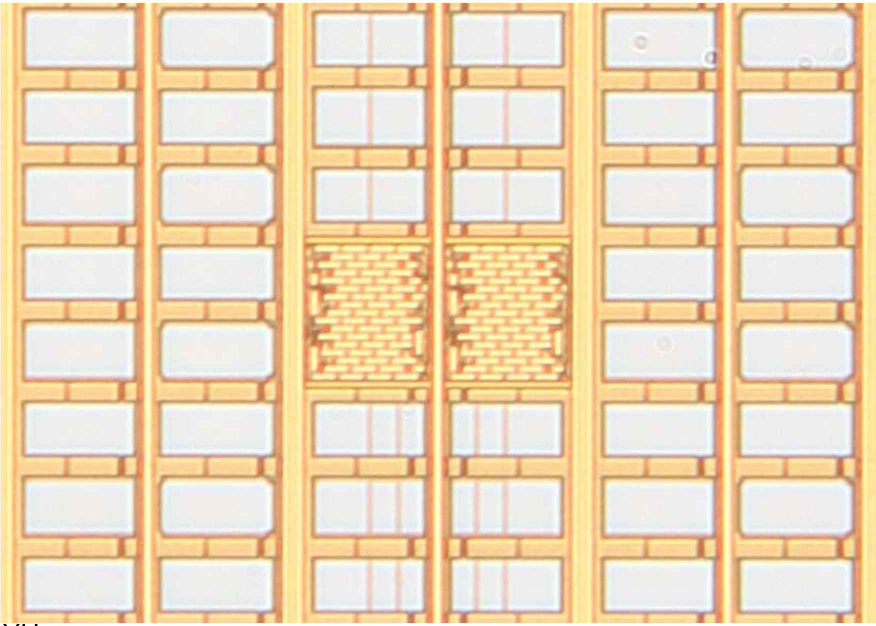
PDPC dSiPM: 2nd version with fewer/larger SPADs

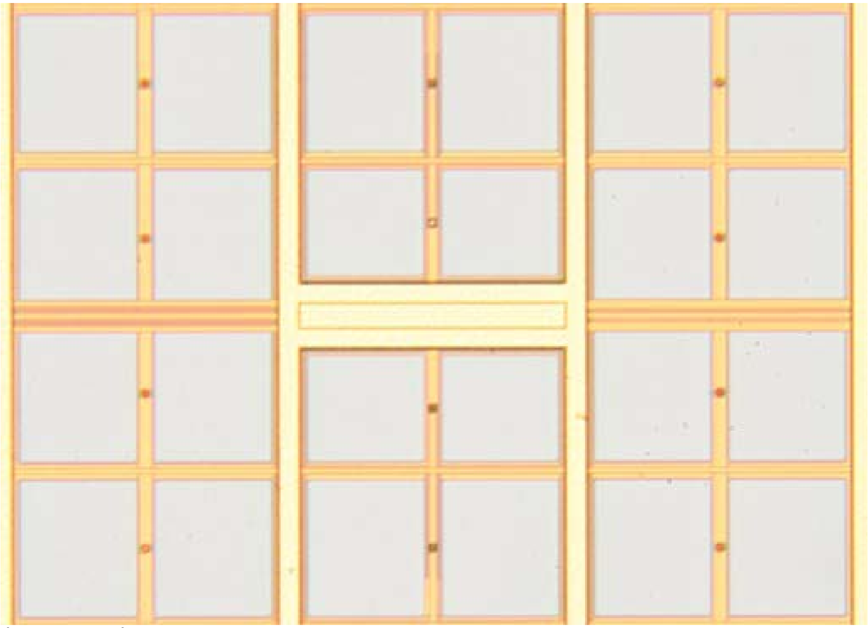
DLS 6400-22 (1st version):

- 6400 cells per pixel
- 54% fill factor
- ~ 30% PDE @ 430 nm

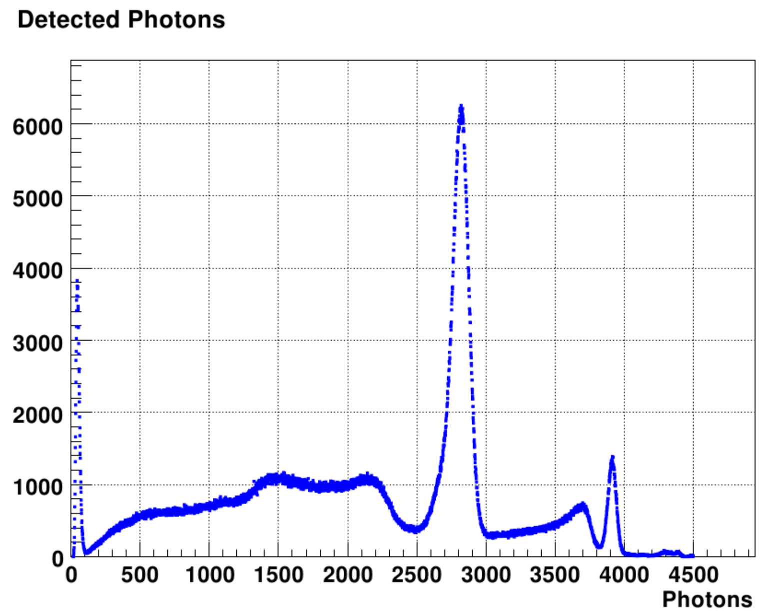
DLS 3200-22 (2nd version):

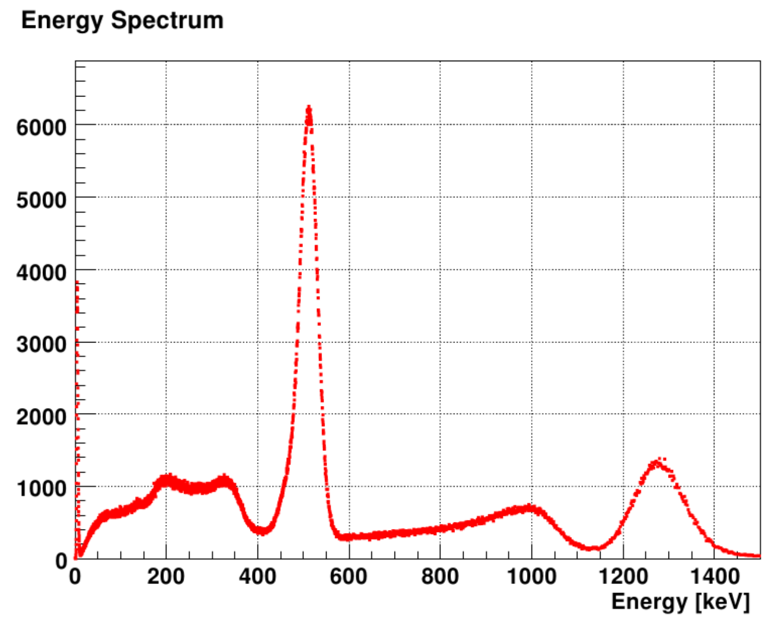
- 3200 cells per pixel
- 78% area efficiency
- anticipated PDE: >> 30% @ 430 nm
- Based on (and compatible to) DLS 6400-22 (same die size, bond pads, interface)



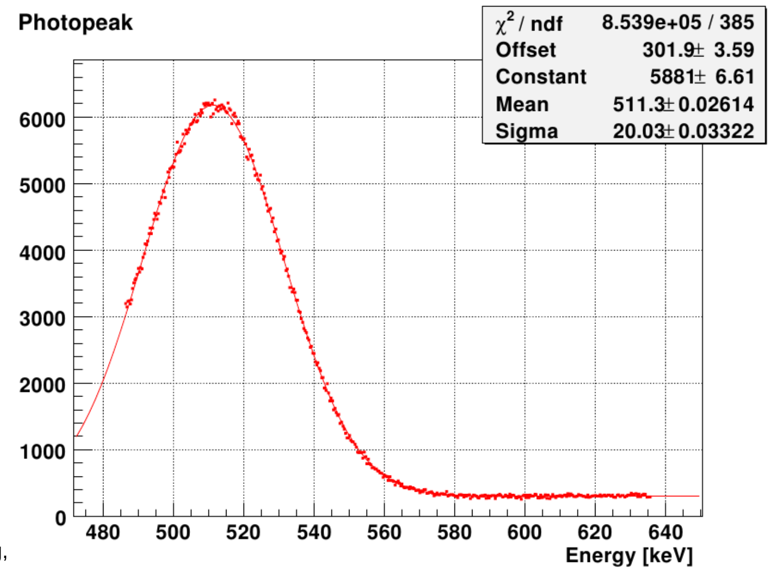


DLS3200-22: Superior Energy Resolution



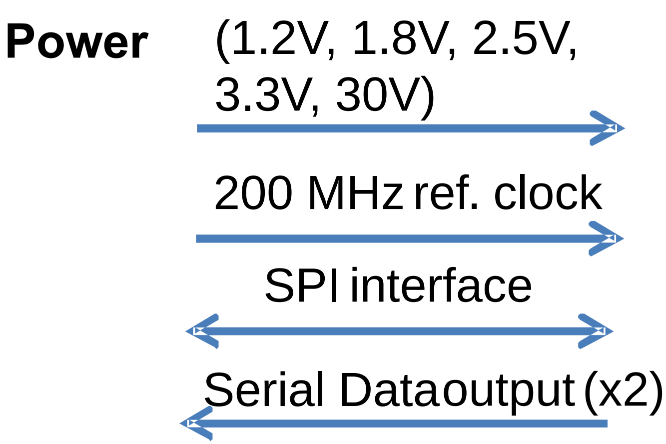


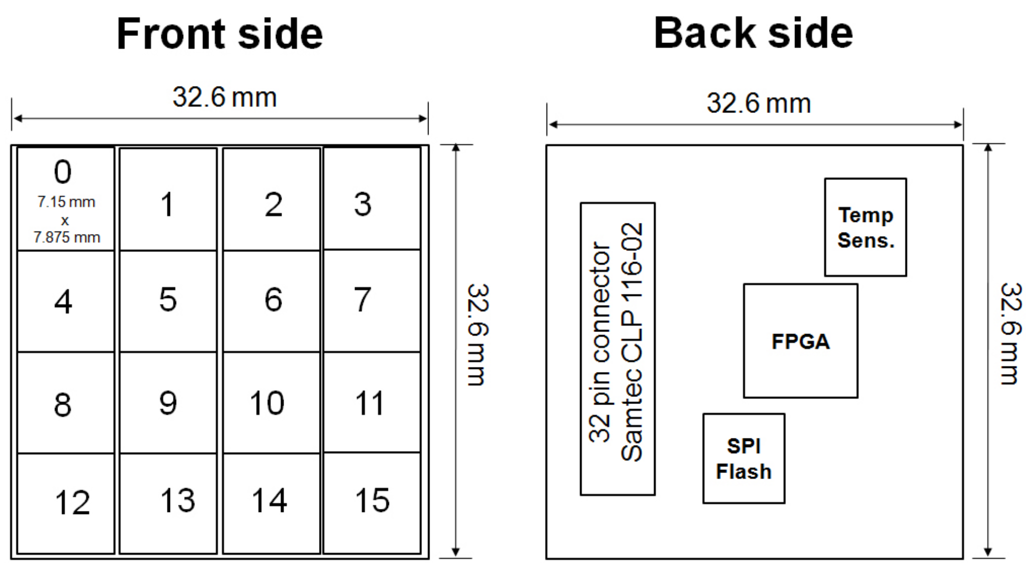
- 3.3V excess voltage, 20°C
- 99% active cells
- 4 x 4 x 20 mm³ LYSO
- Non-linearity correction
- Optical crosstalk included [Burr et al.]
- **ΔE/E = 9.2%**



PDPC dSiPM: Sensor Array (tile V2.1, 8x8 pixel)

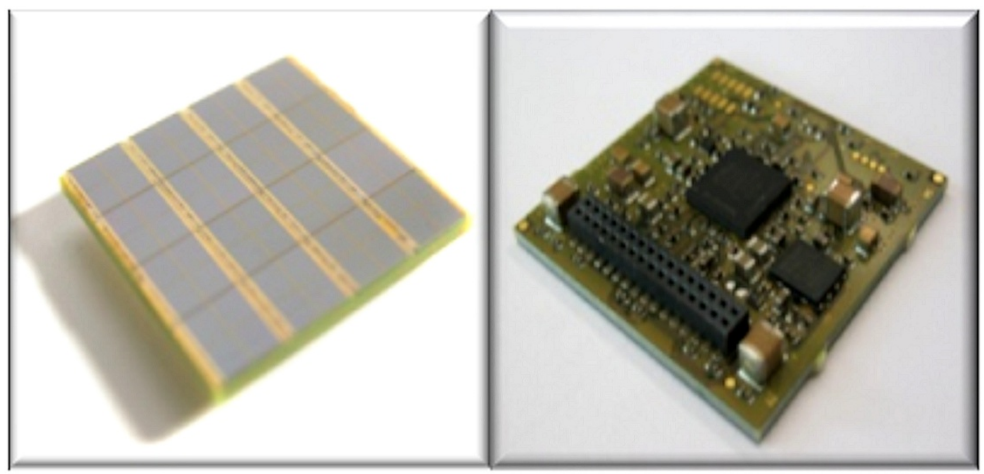
advanced integration





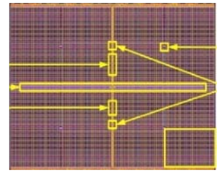
FPGA/Flash:

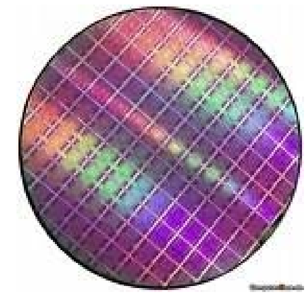
- tile firmware
- data collection/concentration
- Skew correction
- Saturation correction
- configuration
- temperature measurement
- dark count maps



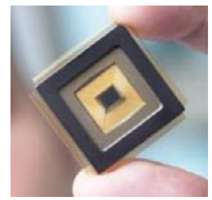
PDPC: Integrated sensors/detectors workflow

- Sensor design (PDPC)

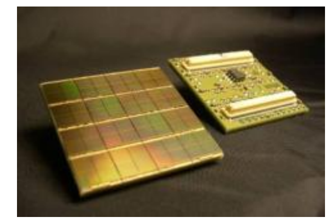




- Silicon processing (180 nm fab, 38 masks, > 500 steps)



- Die testing (PDPC)



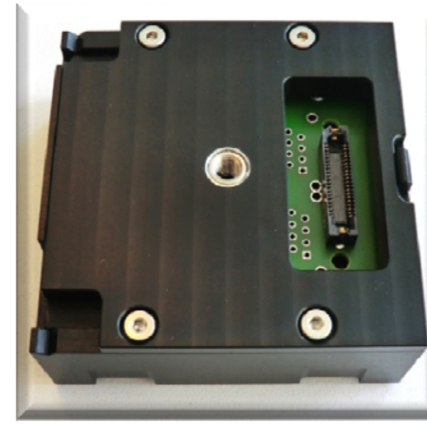
- Tile manufacturing (packaging experts)
- Tile testing (PDPC)

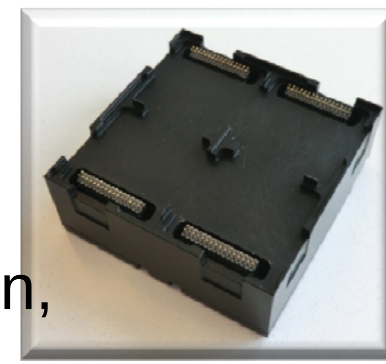
- Scintillator attachment (packaging esperts)
- Module assembly (packaging experts)

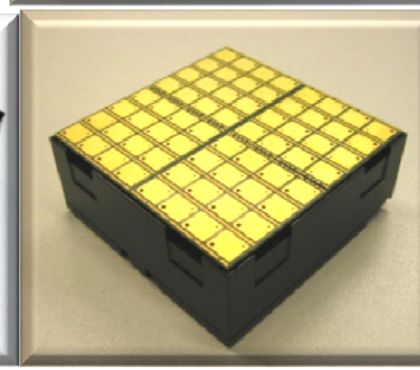
- Final module testing (PDPC), overall system design

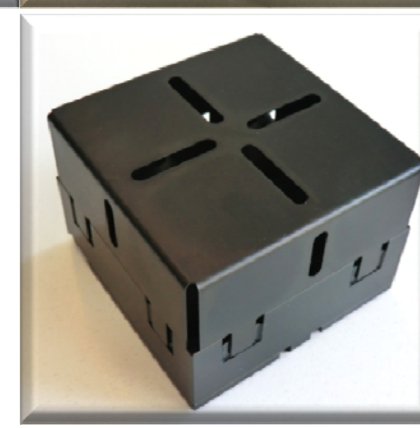
PDPC dSiPM: POC (PET) Detector Module & Ring

advanced integration









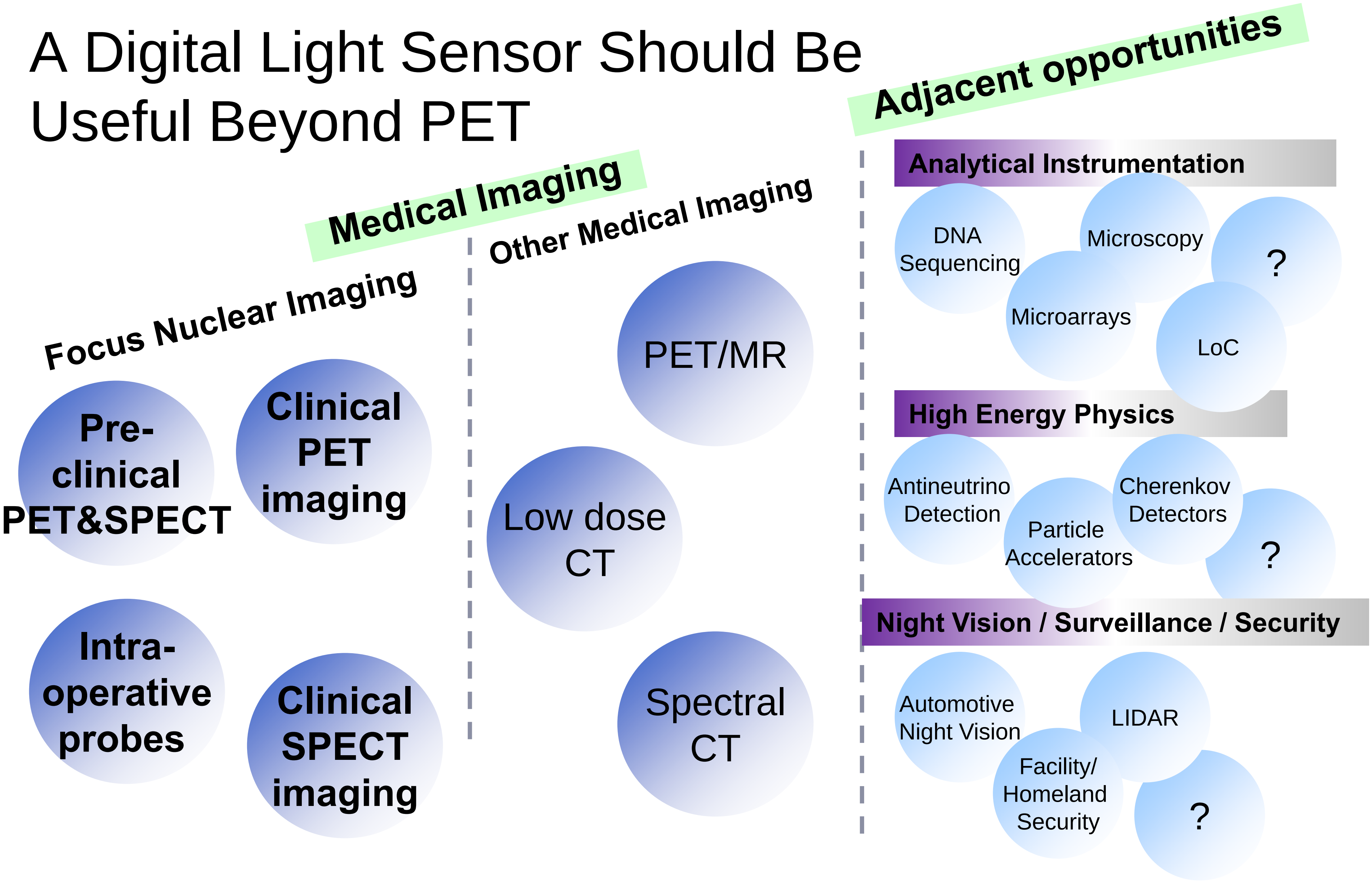
- modular design incl. 2 x 2 tiles
- integrated cooling
- module PCB for data concentration, processing & corrections
- list mode or raw data output (see also poster no. 68)
- prototype PET ring with 10 modules under construction

Comparison of light detectors – which one is going to win?

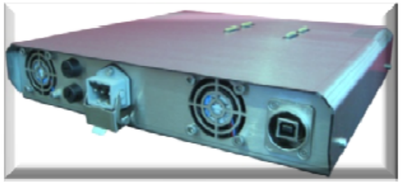
	PMT	APD	SiPM	**PDPC dSiPM**
Gain	10^6	50–1,000	$\sim 10^6$	meaningless
rise time (ns)	~ 1	~ 5	~ 1	first photon
QE @ 420 nm (%)	~ 25	~ 70	$\sim$25–75 (PDE)	25-60
Bias (V)	>1,000	300–1,000	30–80	< 35
Temperature sensitivity ($\frac{\%}{^\circ C}$)	<1	~ 3	1–8	0.33
Magnetic field sensitivity	yes	no	no	No
Sensitive area	cm^2	mm^2	mm^2	mm^2-m^2
Price/channel ($)	>200	~ 100	~ 50	Currently: ~25

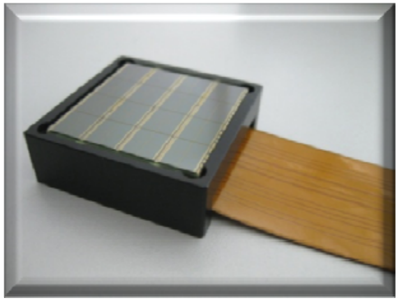
Table courtesy of Spanoudaki & Levin, Stanford in: Sensors, 10, 2010

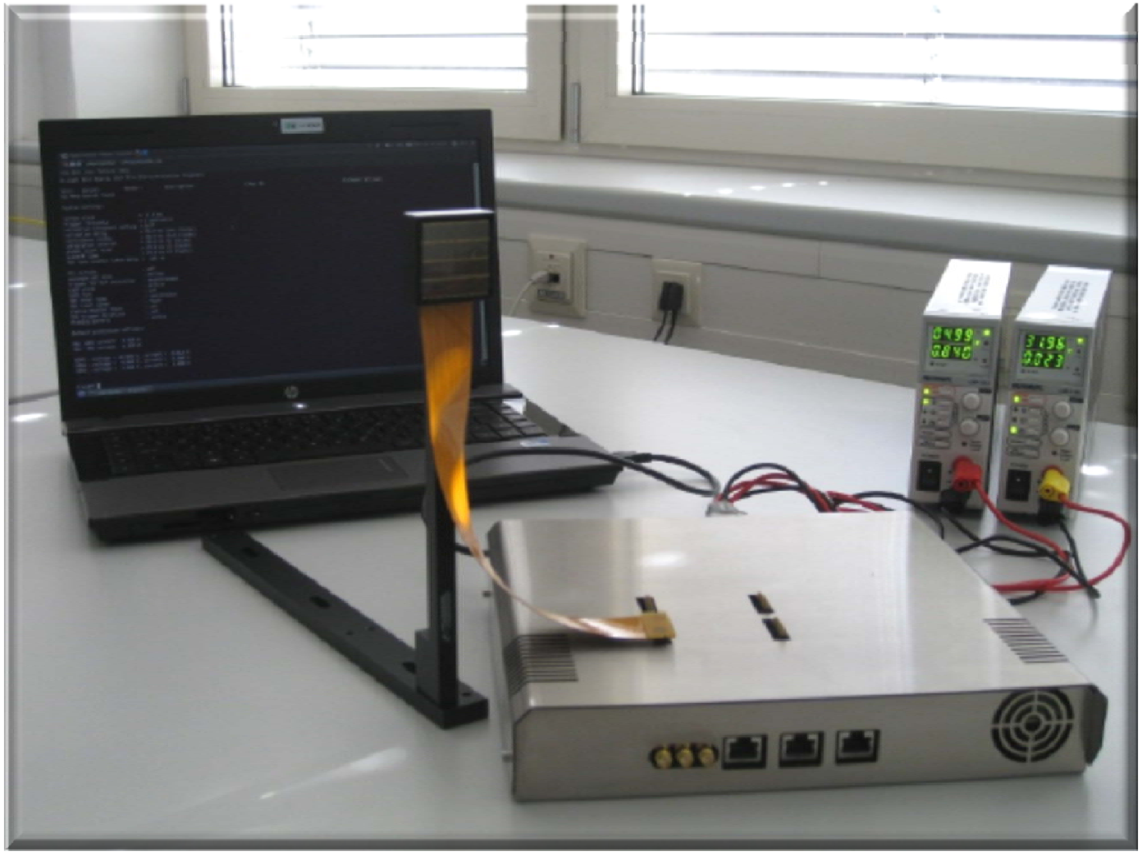
A Digital Light Sensor Should Be Useful Beyond PET



A way to explore the technology…







PDPC-TEK
(Technology Evaluation Kit)
Launched Q2/11-available now!

And perhaps this might happen…

Video showing glass PMT burning into flames and PDPC sensor evolving

Thank you for your attention!

PHILIPS

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www.philips.com/digitalphotoncounting