RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG

(Amplifying) Photo Detectors:

Avalanche Photodiodes
Silicon Photomultiplier

Peter Fischer

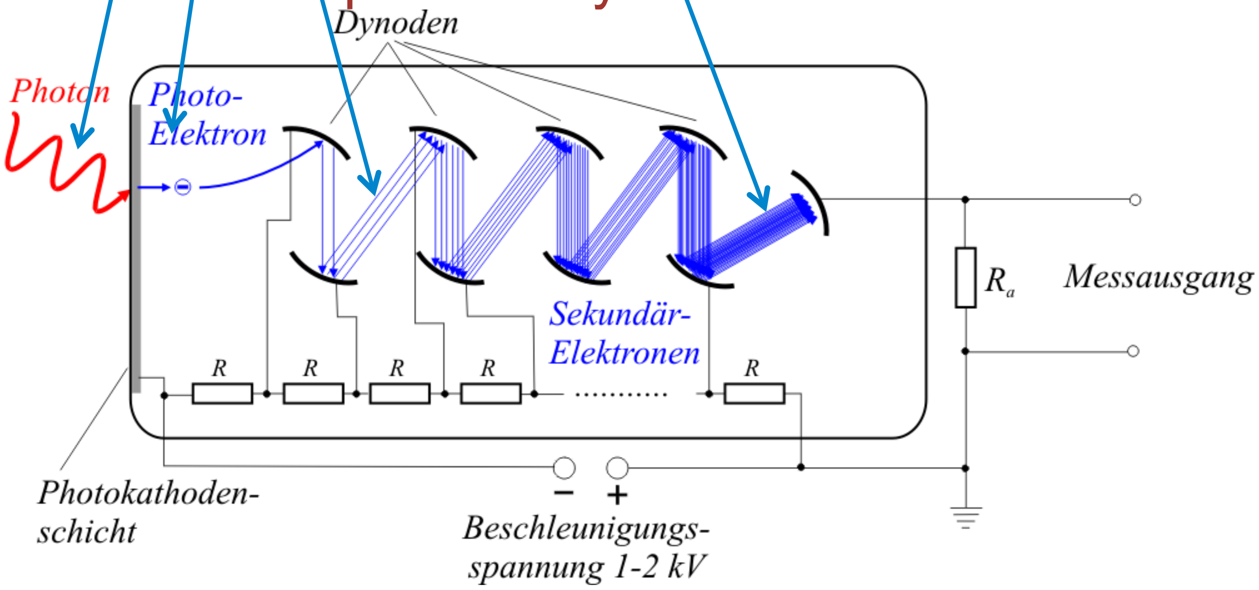
Overview

- Reminder: Classical Photomultiplier
- APD Working Principle
- Classical SiPM
  - Working Principle & Properties
  - Recent Developments
- SiPMs in CMOS Technologies
- Applications
  - Mainly work of my own groups

PHOTO MULTIPLIER TUBE

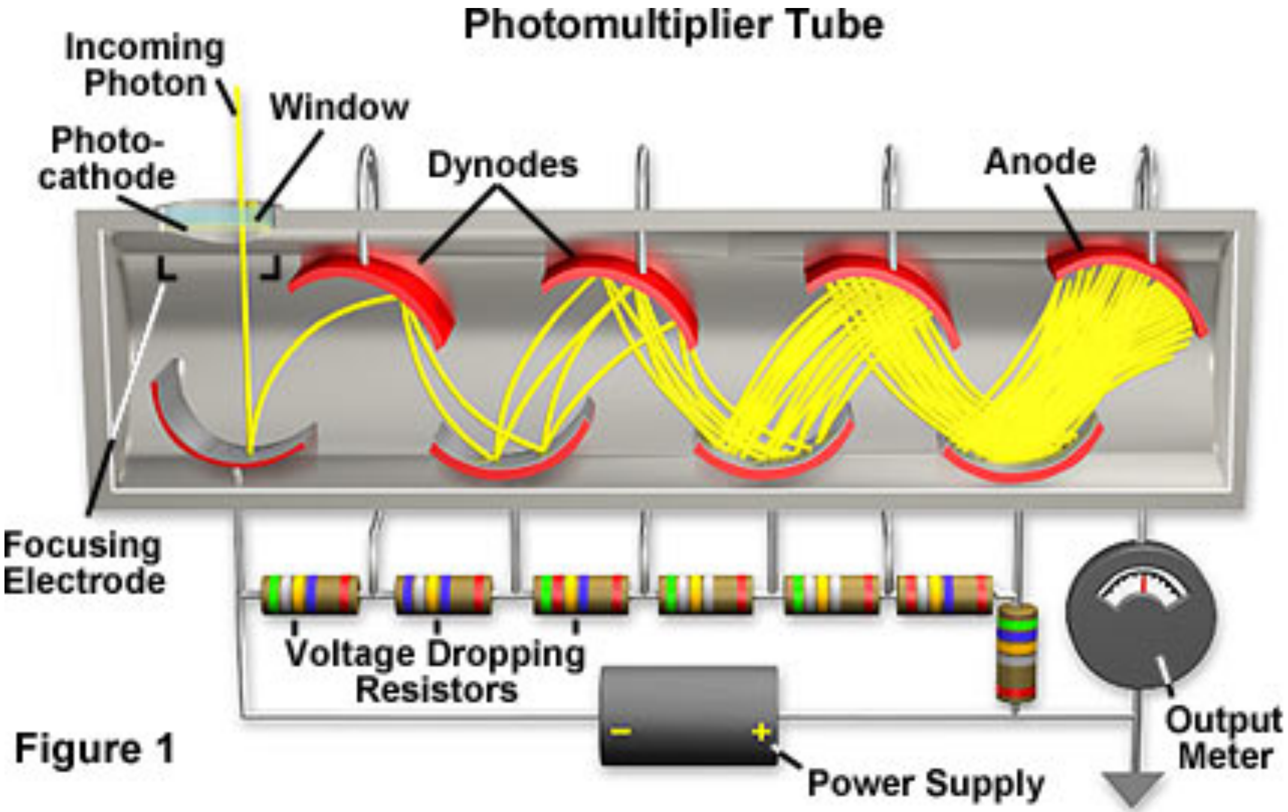
‚Classical‘ Photomultipliers

- Photons hit photo cathode and generate electrons
- Electrons are accelerated in electrostatic field
- Fast electrons hit ‘dynodes’ and produce further (secondary) electrons
- Number of electrons increases exponentially



PMT Working Principle 'Artists View'

Entrance Window

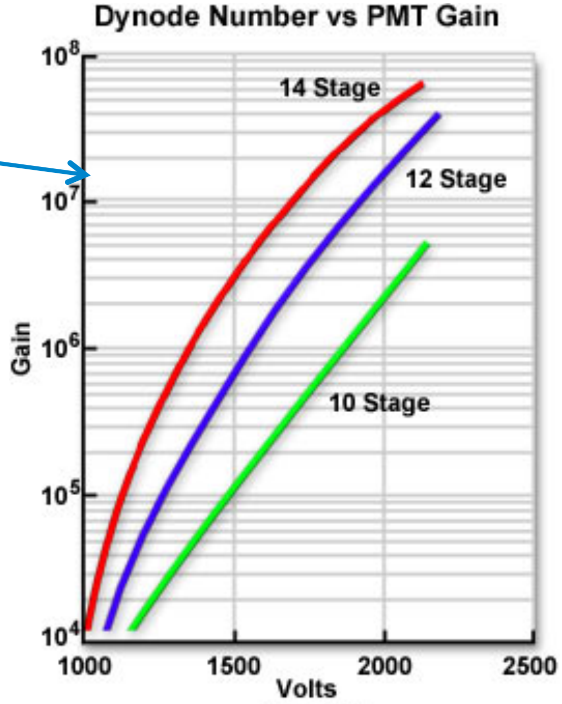


Hamamatsu

Photomultipliers

- 10 -14 'Dynodes'
- Amplification 10^6 - 10^7
- Signal is ~ proportional to # photons

- Mostly round, ∅ from 1...50 cm
- Segmented anodes available ('Multi Anode PMT'):



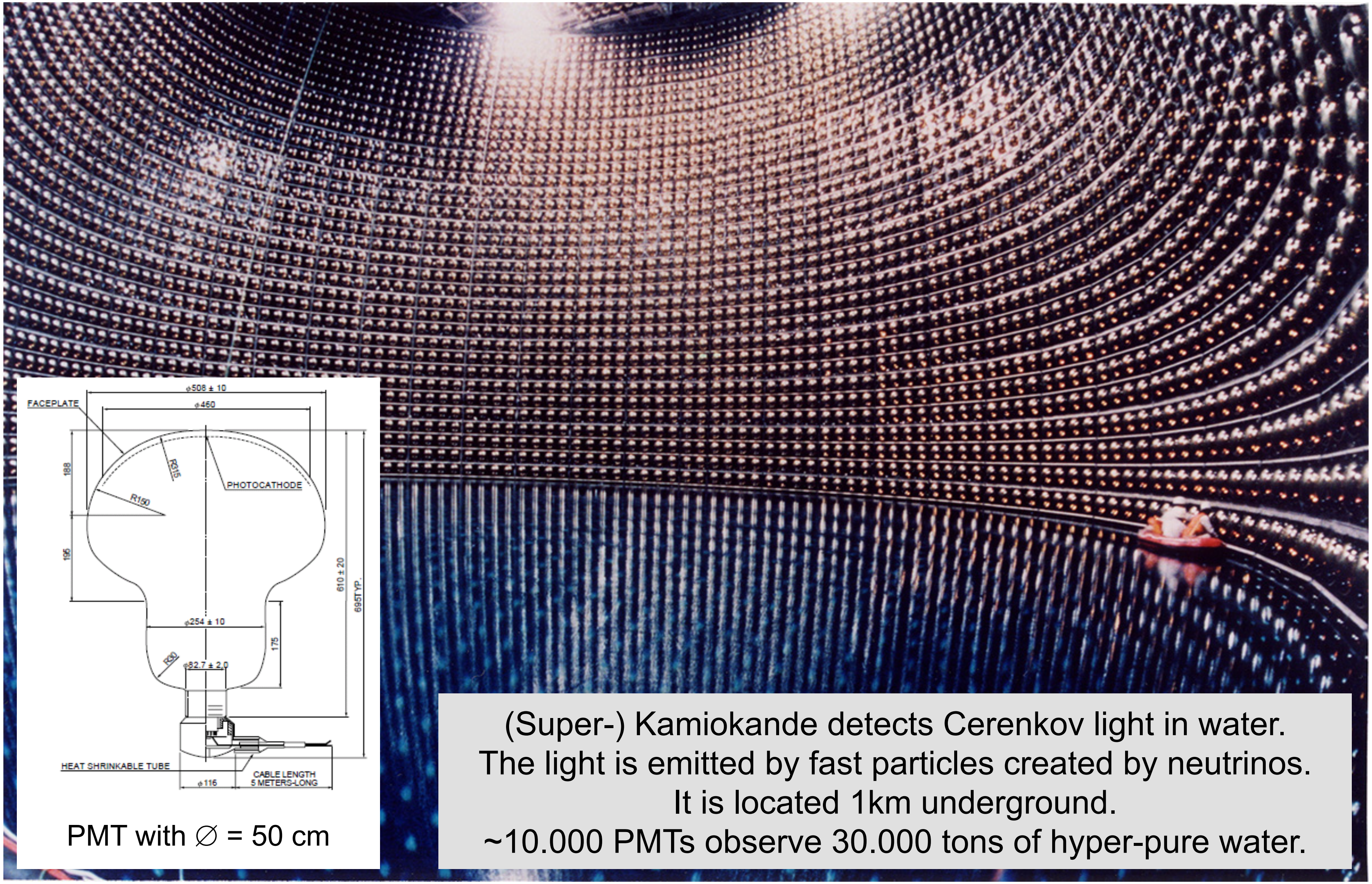
Hamamatsu

Multi-Anode PMT
Hamamatsu H8500D
5 × 5 cm^2, 8 × 8 pixels
12 Dynodes
185 nm…650 nm
Gain 1.5 × 10^6

Photomultiplier Pros & Cons

- Pros
  - Single Photon sensitivity
  - Low 'dark noise' (e.g. hits with no photons)
  - UV and IR sensitive (depends on window and photocathode)
  - Fast (rise time < ns)
- Cons
  - Mechanically sensitive, breakable
  - Expensive (but not per area!)
  - Need high voltage (kV) / large power (divider for dynode volt.)
  - Large
  - Sensitive to (even low) magnetic fields
    - Depends on orientation wrt field
    - Can be a KILLER for many applications (HEP experiments often have strong magnets, MRT, …)

Example: Very Large PMTs at Super-Kamiokande



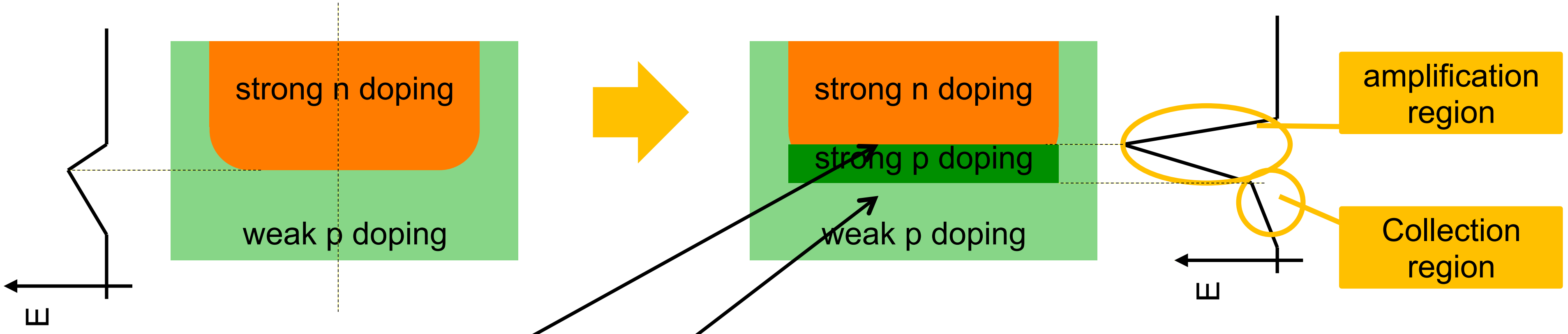
PMT with ∅ = 50 cm

(Super-) Kamiokande detects Cerenkov light in water.
The light is emitted by fast particles created by neutrinos.
It is located 1km underground.
~10.000 PMTs observe 30.000 tons of hyper-pure water.

AVALANCHE PHOTO DIODES (APDS)

The Idea

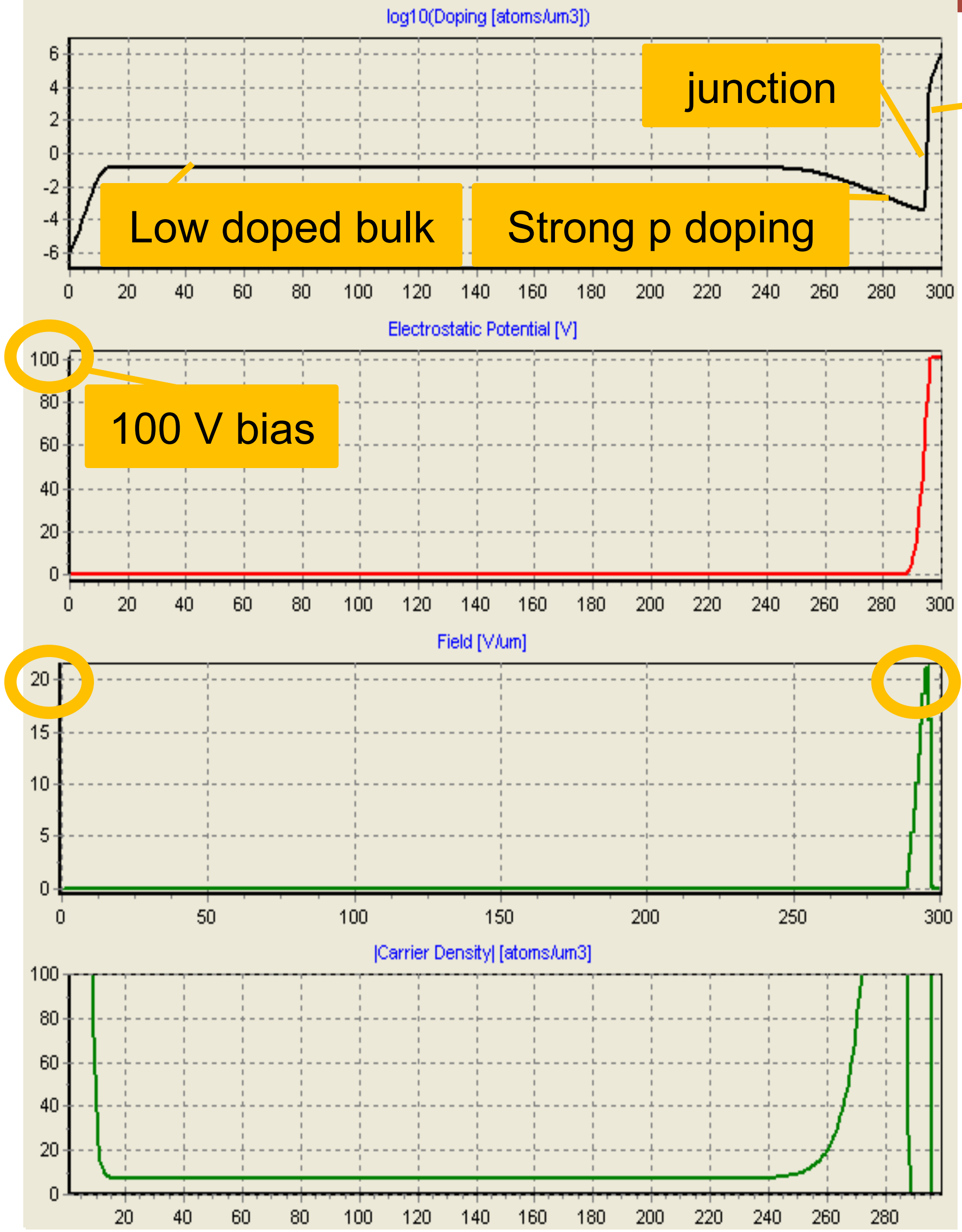
- Create a region with very high field by strong doping & external voltage

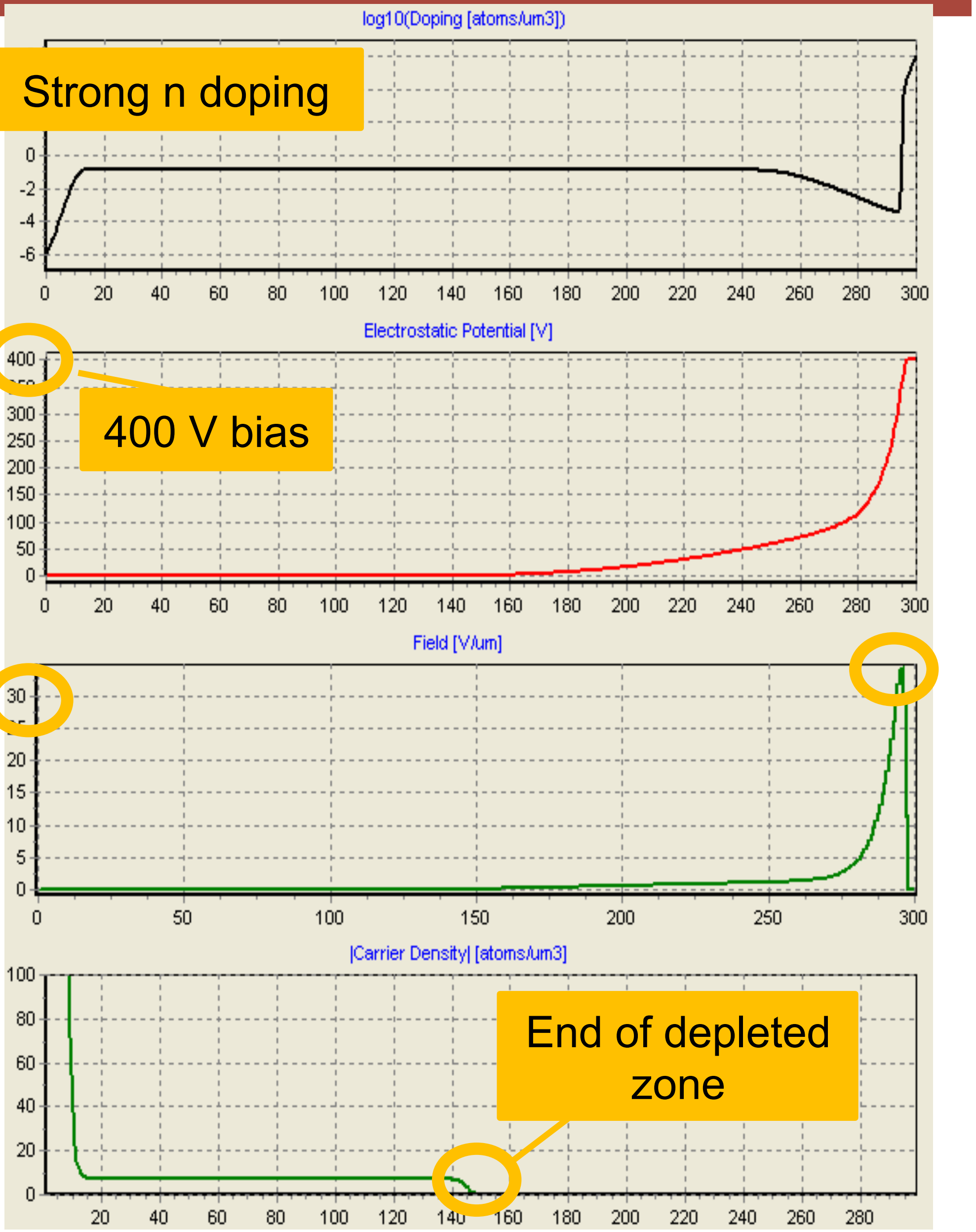


- Carriers drift from the depletion (collection) region to the amplification region
- Charge carriers are accelerated and create secondary ionization → an ***avalanche*** is created, leading to a large charge (10^5-10^6 eh pairs)
- $n^+/p^+/p^-$ or $p^+/n^+/n^-$ structure possible (amplify via electrons / holes)

- Some issues:
  - Field strength must stay below breakdown. Critical at edges
  - Photon feedback can keep avalanche 'burning'. It must be stopped by lowering the voltage on the device

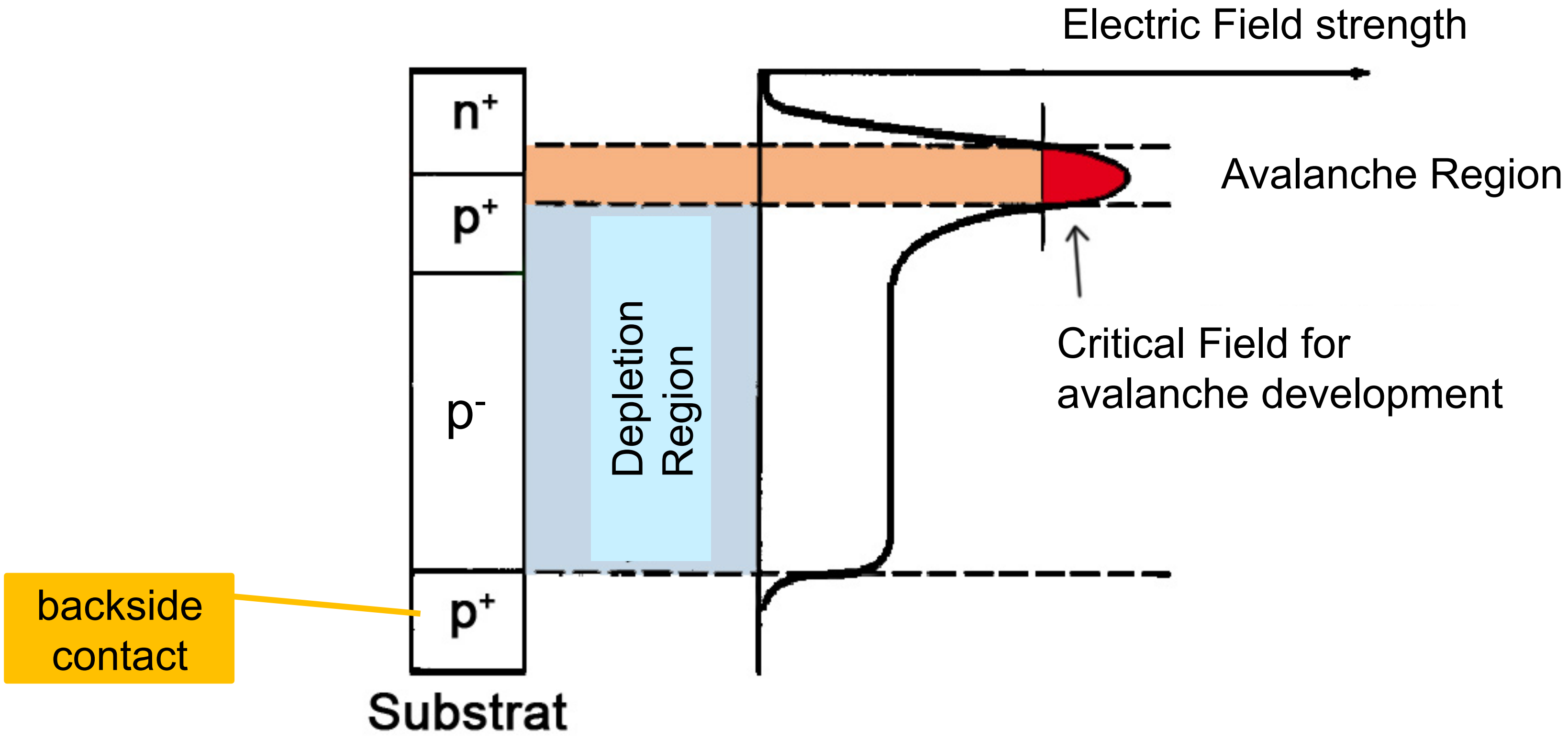
Field in Avalanche Diode (100V / 400V)





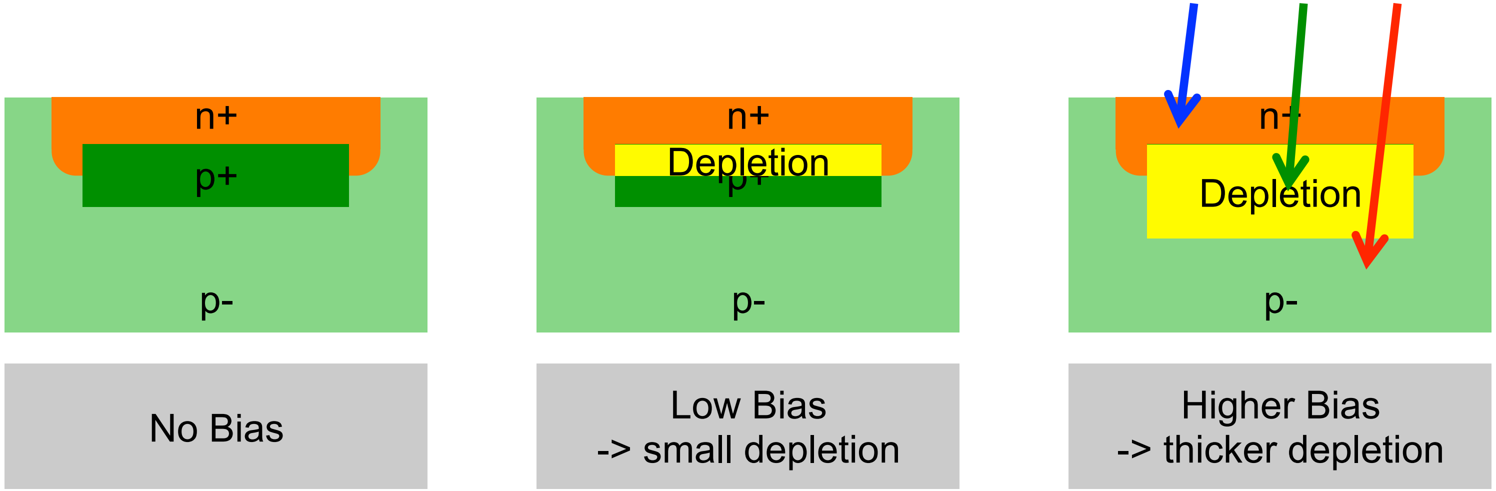
APD Construction

- Absorption / Drift region should be thick (sensitivity)
- High field region is created by strongly doped pn-junction
  - High field must still be below Si-breakdown (3 × 10^7 V/m)
  - Typical field ~10^7 V/m = 10^5 V/cm = 10 V/µm



Sensitivity (for photons)

- Device is sensitive for photons ‘only’ in depletion region (DR) (some carriers may be seen by diffusion)
  - DR starts in some depth, given by depth of (here) p^+ implant
  - DR ends somewhere in the p- region (depending on bias)



No Bias

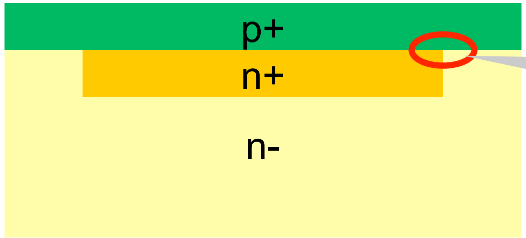
Low Bias
-> small depletion

Higher Bias
-> thicker depletion

- Photon illumination is normally from the top
  - UV photons are absorbed at the surface and may not reach the DR (jargon: ‘dead layer’)
  - IR photons may be absorbed ‘below’ the DR

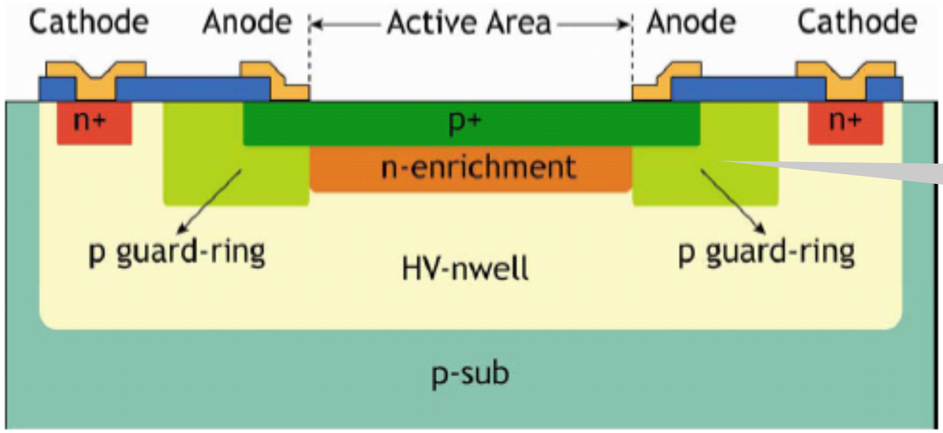
Edge Breakdown

- At the edge of the high field region, the field changes from ‘parallel plate’ to ‘1/r’. This produces highest field at the *edge*. There may be breakdown at the edge before the area reaches amplification!



High field

- The usual solutions is a lower doped region at the edge ('guard ring’):

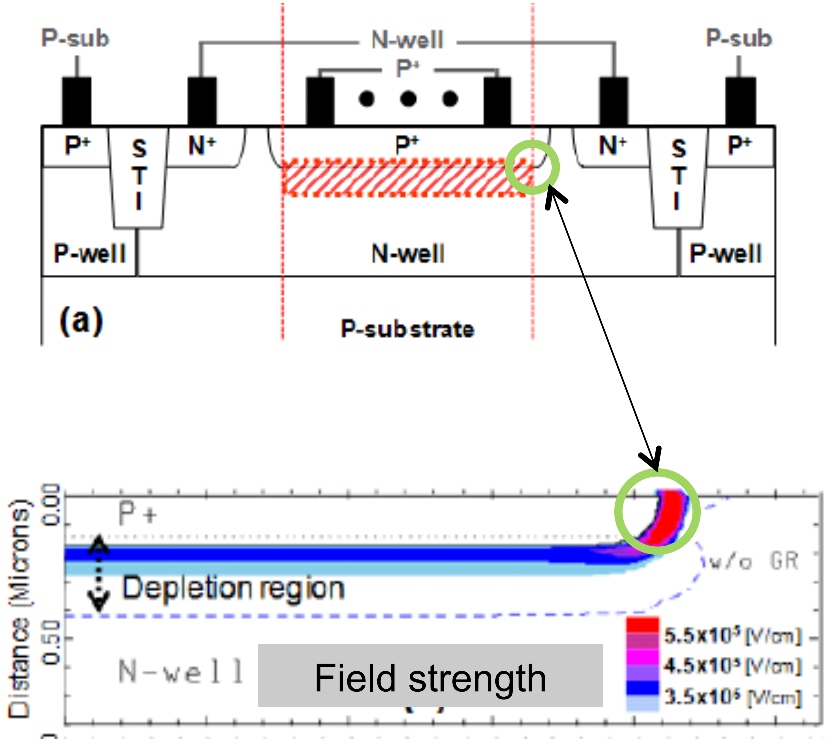


guard ring

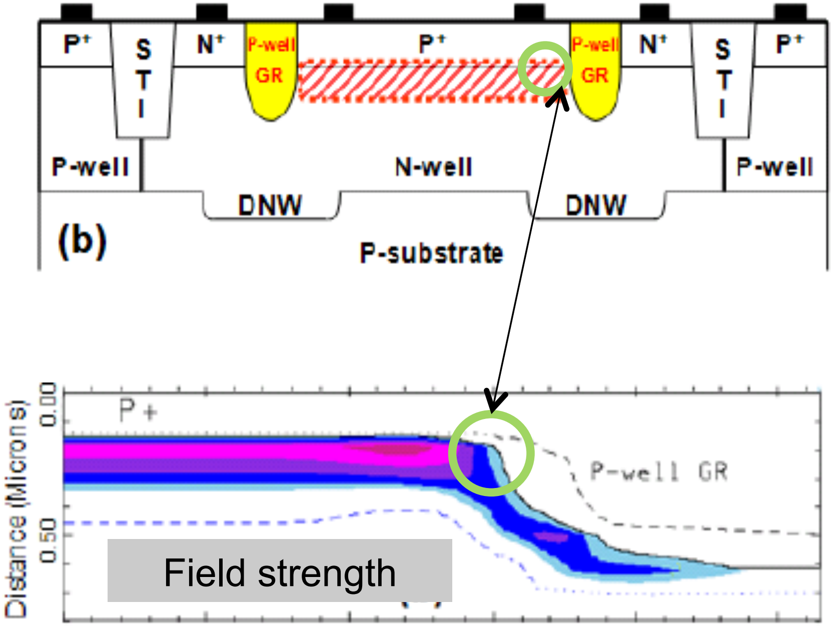
Effect or Guard Ring

- Compare structures without / with guard

No guard implants



With guard implants



From: Lee, Rücker, Choi:
Effects of Guard-Ring Structures on the Performance of Silicon Avalanche Photodetectors Fabricated With Standard CMOS Technology
IEEE Electron Device Letter, Volume: 33 , Issue: 1, Pages: 80 - 82

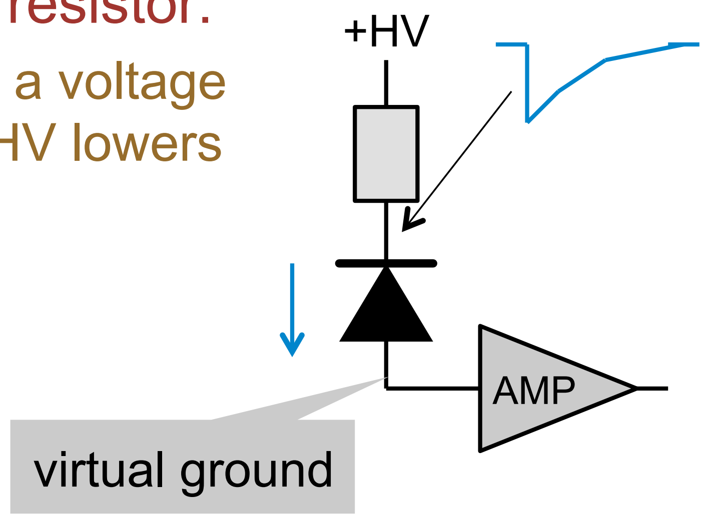
Operation Modes of an APD

- **Linear (Proportional) Mode**
  - Bias is below ‚breakdown voltage‘
  - Moderate Gain ~10^1-10^3
  - Signal is *proportional to number* of photons
  - Required for instance in Calorimetry (measure scintillation light)

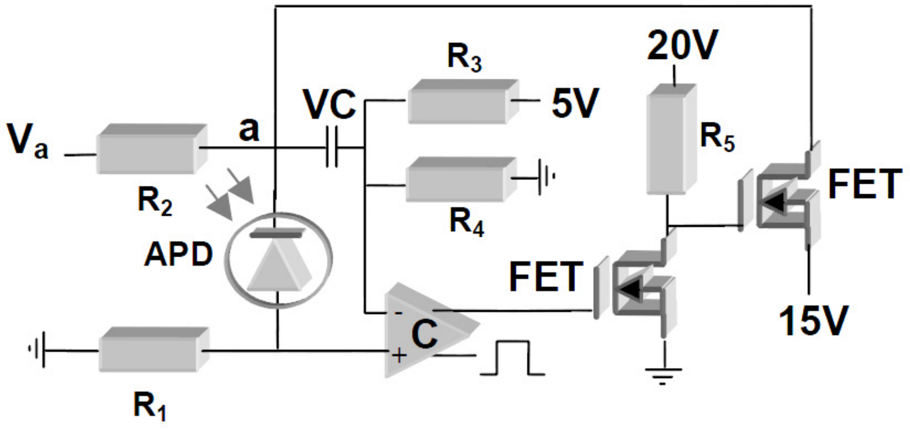
- **Geiger Mode = Photon Counting Mode**
  - Bias voltage is (slightly) above breakdown voltage
  - Single photons lead to ‘infinite’ signal (by re-triggering through (photon) feedback mechanisms)
  - Very high gain ~ 10^6
  - Signal is *independent* of primary # of photons
  - Needs ‘quenching’ circuit to lower bias voltage after a hit to stop the avalanche
  - APD is insensitive after ‘quenching’ (until HV is back again)

Quenching Methods (Geiger Mode)

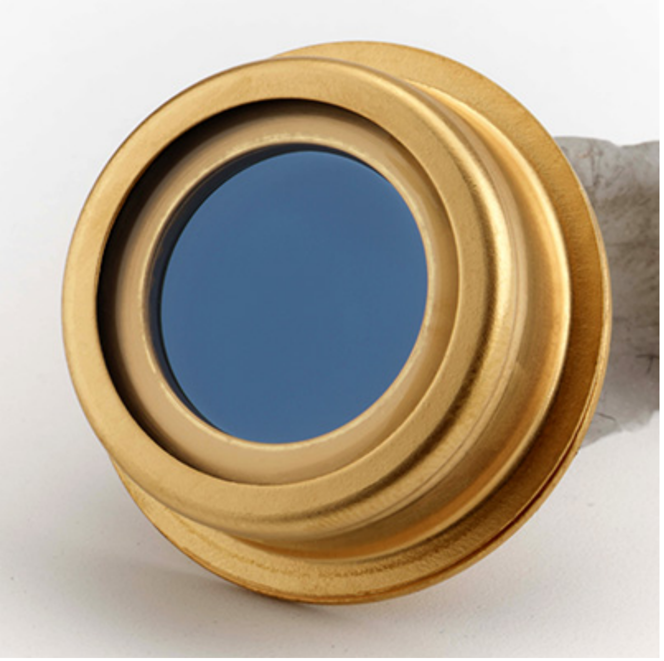
- Passive quenching with series resistor:
  - The large signal current leads to a voltage drop at the bias resistor so that HV lowers



- Active quenching:
  - A circuit detects a hit
  - A switch (transistor) lowers the voltage
  - Better control
  - Lower ‘afterpulsing’
  - But more complicated



Summary: Pros/Cons of of APDs



- Operation at low gain ('*linear mode'*)
  - signal is proportional to primary charge, i.e. we get a pulse height information.
  - But gain is lower
- Operation at high gain (‘*Geiger Mode*’)
  - High gain / sensitivity
  - No amplitude information
  - HV must be lowered when a signal occurs (normally with series resistor)
  - This leads to long dead times
- A single defect kills to hole device!
  - Large area APDs are very expensive (>1000€)
- HV setting is delicate
  - Changes with temperature

RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG

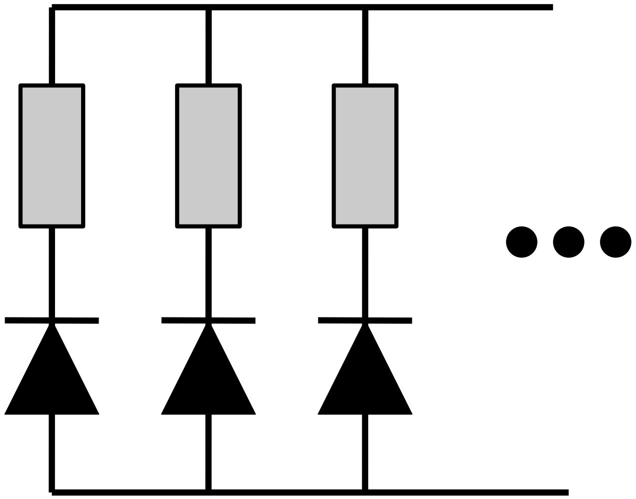
SILICON PHOTO MULTIPLIERS (SIPM, MPPC, SI-SSPM…)

Idea SiPM

- Problem of APD: gain is *low* in (often preferred) *linear mode*

Therefore:

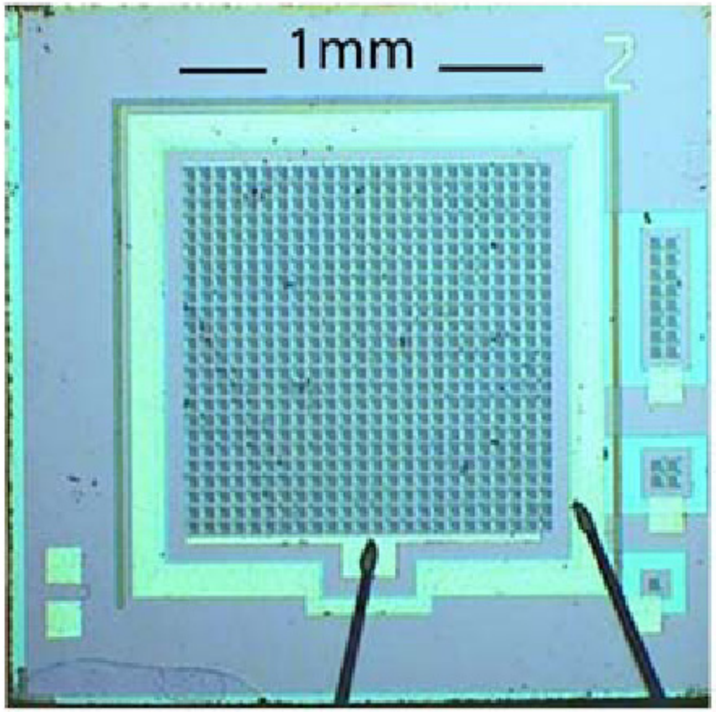
- Add *many APDs in parallel* with *separate quench resistors*
- Each SPAD (Single Photon APD) works in *Geiger Mode*
- Breakdown of a *single* SPAD creates only a *small signal*
- The *total signal* is *proportional* to the number of fired cells, i.e. *to the number of detected photons*



- Devices are called
  - SiPM: Silicon Photo Multipliers
  - MPPC: Multi-Photon Pixel Counter
  - Si-SSPM: Silicon Solid State PMT
  - ...
  - (name depends on vendor..)

SiPM Geometry

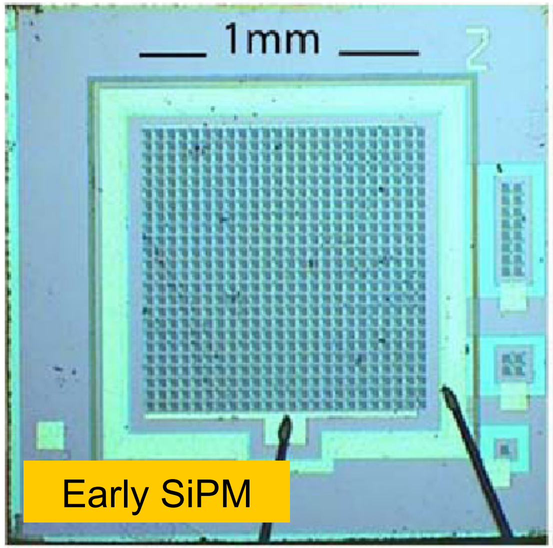
- SPAD cell size is in the order of 50 × 50 μm^2
  - → ~ 10^2 -10^3 SPADs per mm²
- Device area can be up to 8 × 8 mm^2
  - > 10.000 SPADs
  - *Single* cell/photon signal becomes very small for large SiPM!



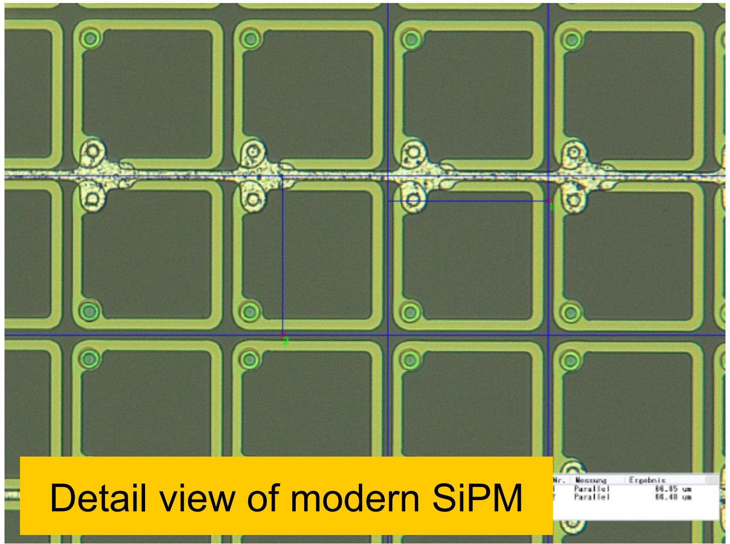
Properties SiPMs

- + Each SPAD operates in Geiger mode @ highest gain (→ sensitivity!)
- + Output = Sum of individual signals, i.e. proportional to # of fired cells!
- + Only fired SPADs are insensitive after a hit until they recharge
- + No external resistor/quenching required
- + Fault tolerant to single bad SPADs

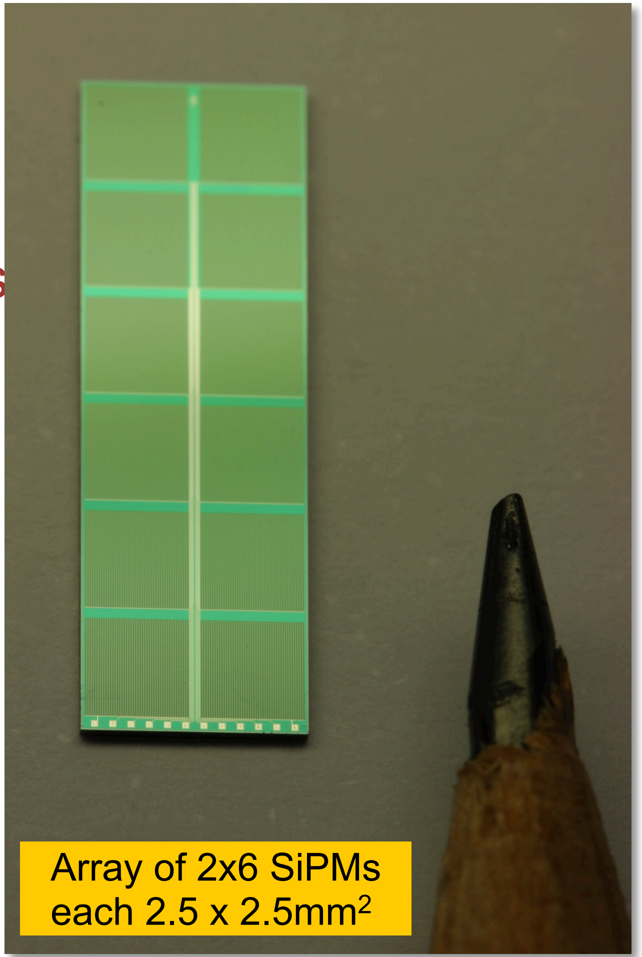
- – Fill factor is reduced (resistors, guard structures



Early SiPM



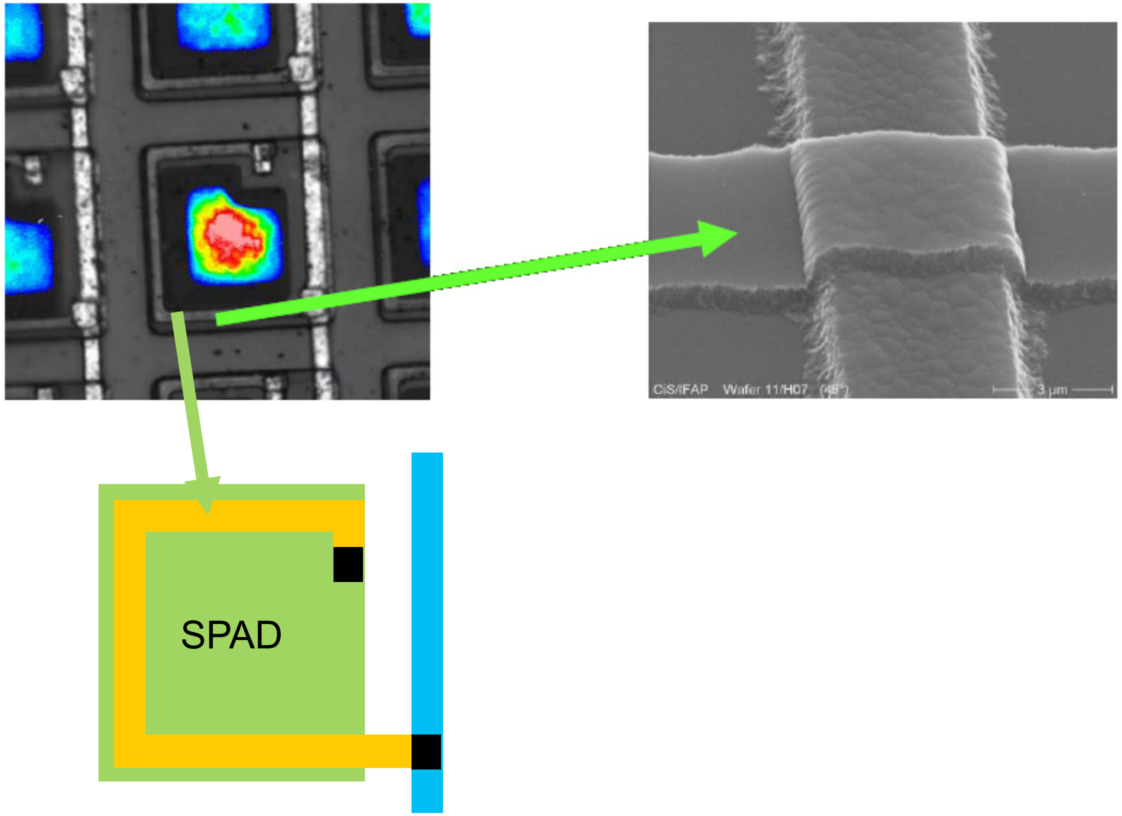
Detail view of modern SiPM

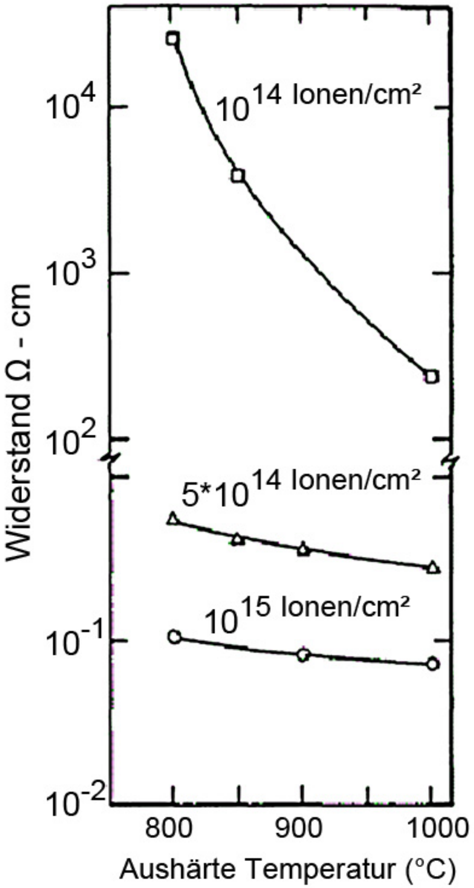


Array of 2x6 SiPMs
each 2.5 x 2.5mm^2

Quench Resistor

- Mostly Poly-Silicon
- Resistor value critical for operation
- Manufacturing is difficult: strong dependence of sheet resistance on doping concentration





Breakdown Voltage, Gain

- When $V_{bias} > V_{BR}$ (the breakdown voltage), the device starts to amplify
- V_{BR} depends on temperature
- The interesting quantity defining gain is the overvoltage

$$\Delta V = V_{OV} := V_{bias} - V_{BR}$$

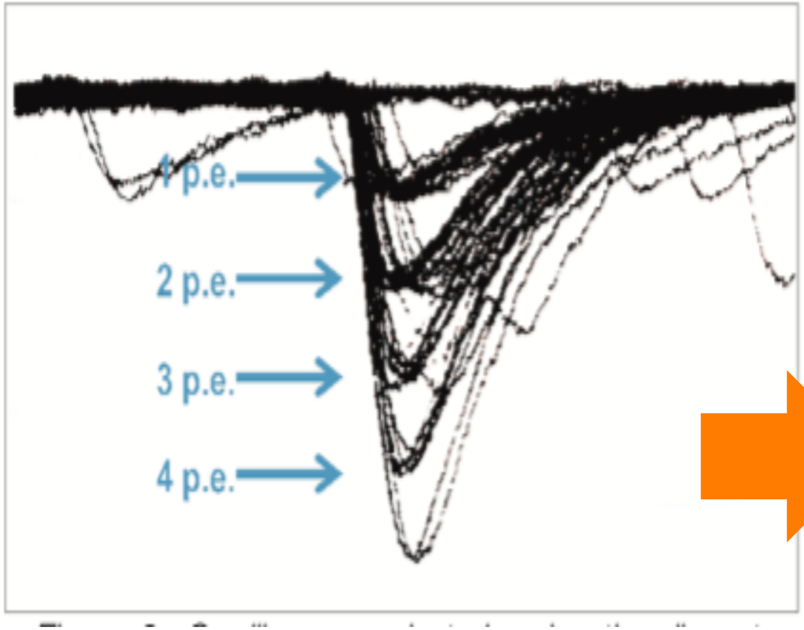
- A firing cell will develop an avalanche until V_{bias} drops to V_{BR}, i.e.:

an avalanche discharges a cell by ΔV

- The charge needed for this is just $Q = C_{cell} \times \Delta V$.
- Because this charge is generated starting with one electron (charge q), the gain is just $g = Q/q$ an thus $\sim \Delta V$
- (Small) cells with small capacitance need lower gain and typically have less dark counts

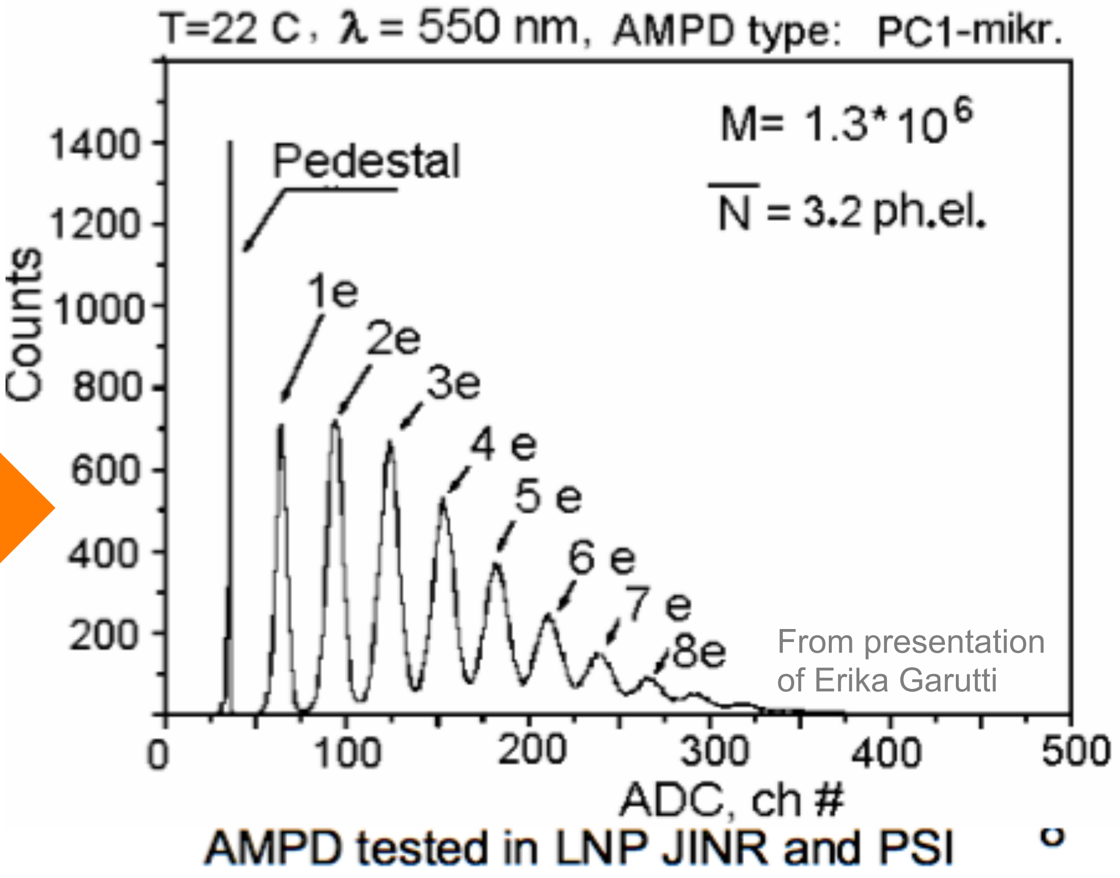
Signals of multiple photons

- A SiPM can resolve the number of photons = number of fired cells
  - This works if each firing cell produces exactly the same signal at the SiPM terminals



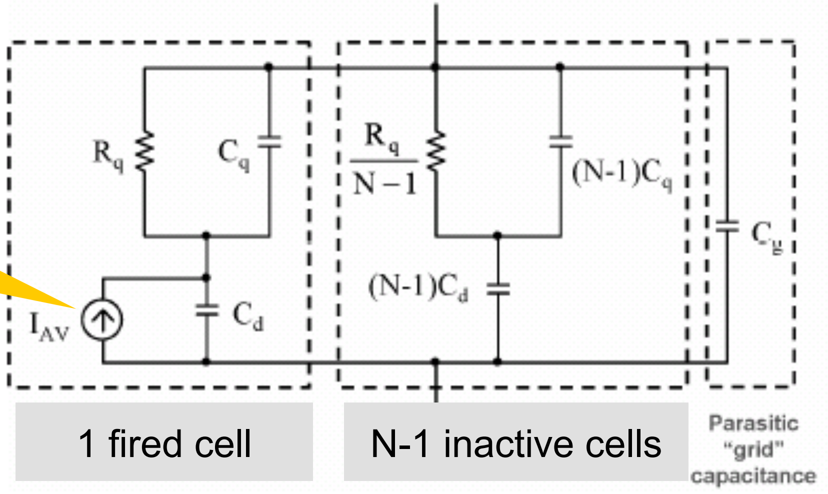
Oscilloscope Trace.

From SensL Overview Article



From presentation of Erika Garutti

Equivalent Electrical Circuit



Avalanche current spike

Typical values:

Model parameter	SiPM ITC-irst N=625, Vbias=35V
Rq	393 kΩ
Vbr	31.2 V
Q	175.5 fC
Cd	34.6 fF
Cq	12.2 fF
Cg	27.8 pF

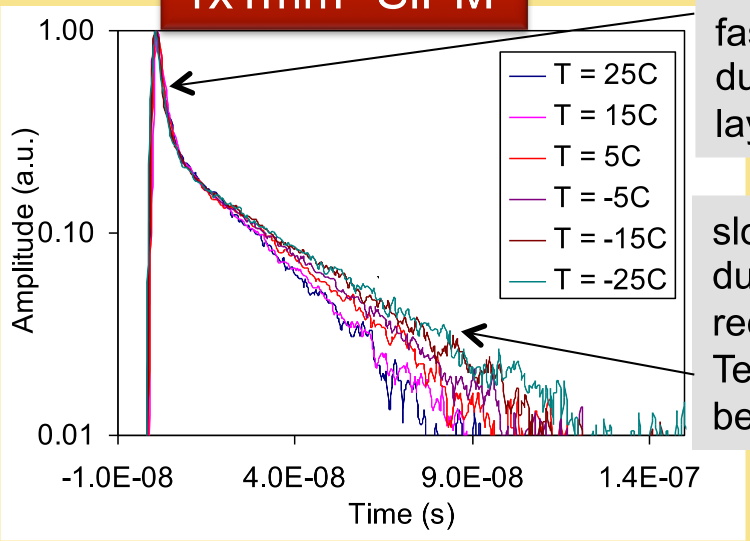
Overvoltage = 3…6 V

- Each cell has
  - Diode capacitance C_d (of SPAD)
  - Quenching resistor R_q
  - A parasitic capacitor C_q between SPAD and bias line
- The firing can be modeled by a current spike which discharges C_d from the overvoltage until the discharge stops
- The parasitic C_q capacitor is ***very*** important to make the discharge current visible as a voltage signal!!!
  - Not further discussed here in details… - sorry

Signals of one cell for small / large SiPM

- The N-1 ‘other’ cells are a (capacitive) load to the ‘firing’ cell
- Signal shape depends on
  - N (area of device)
  - termination resistor (here 50 Ohm)

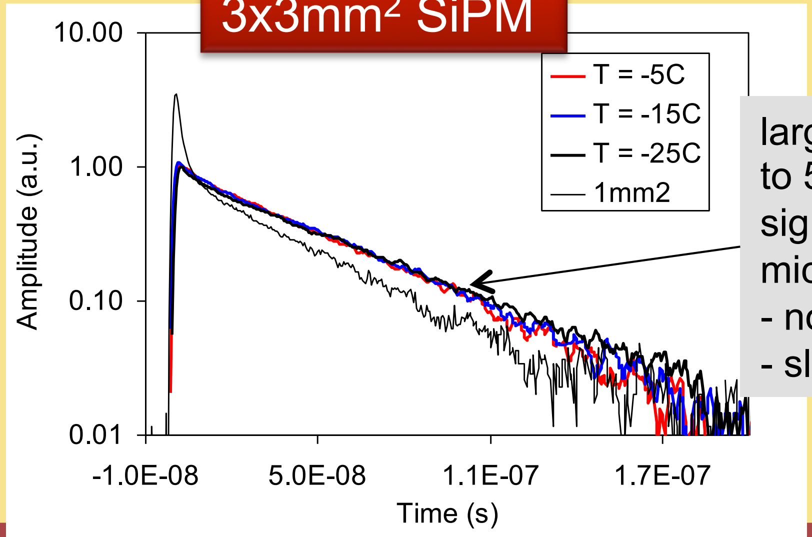
1x1mm^2 SiPM



fast component due to CQ layout dependent

slow component due to microcell recharge Temp. dependent because of poly res.

3x3mm^2 SiPM



larger cap. in parallel to 50Ω reshapes the signal from the micro-cell:
- no fast comp.
- slower signal

Images by Claudio Piemonte (PBK)

Fill Factor

- Depends on size of Micro Cells (smaller -> more edge -> worse fill factor)

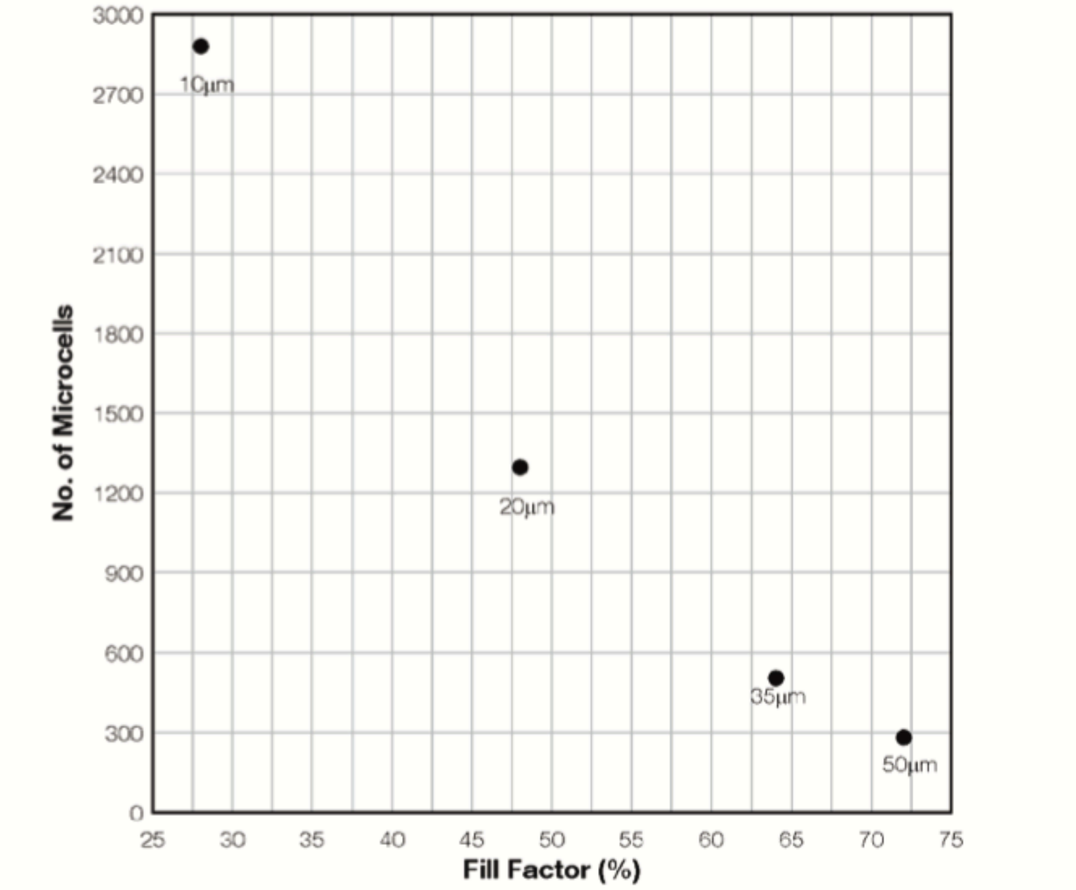


Figure 11, Typical fill factors and microcell numbers for a 1mm sensor from the C-Series product family.

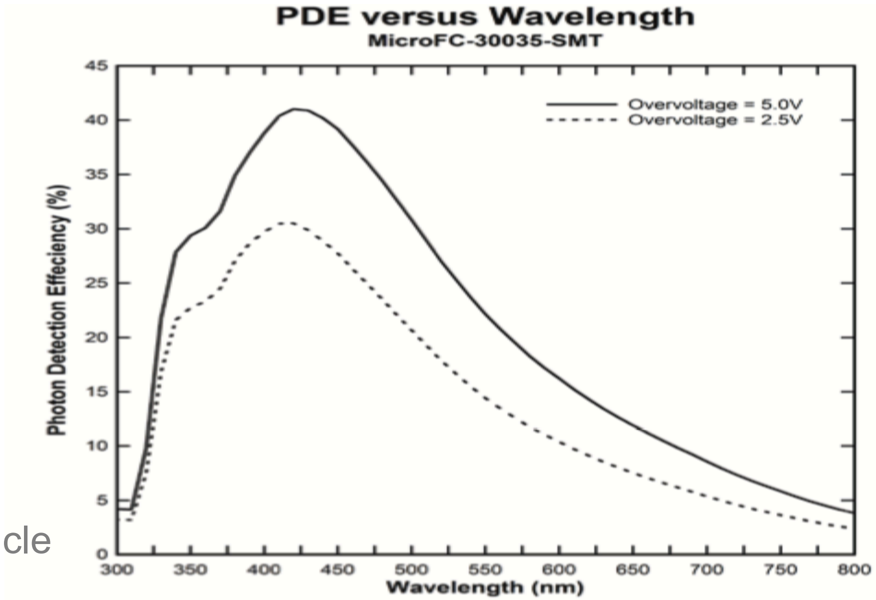
From SensL Overview Article

Photon Detection Efficiency (PDE)

= Fraction of detected photons. Depends on

- Fraction of really sensitive area (cell-cell isolation, losses from traces, resistor)
- Photon reflexion at surface (→ Anti Reflex Coating, ARC)
- Probability for Photon-Absorption (depends on wavelength) < 1
- Probability to trigger an avalanche < 1
- Dead time after a pulse or a dark hit (up-charging)

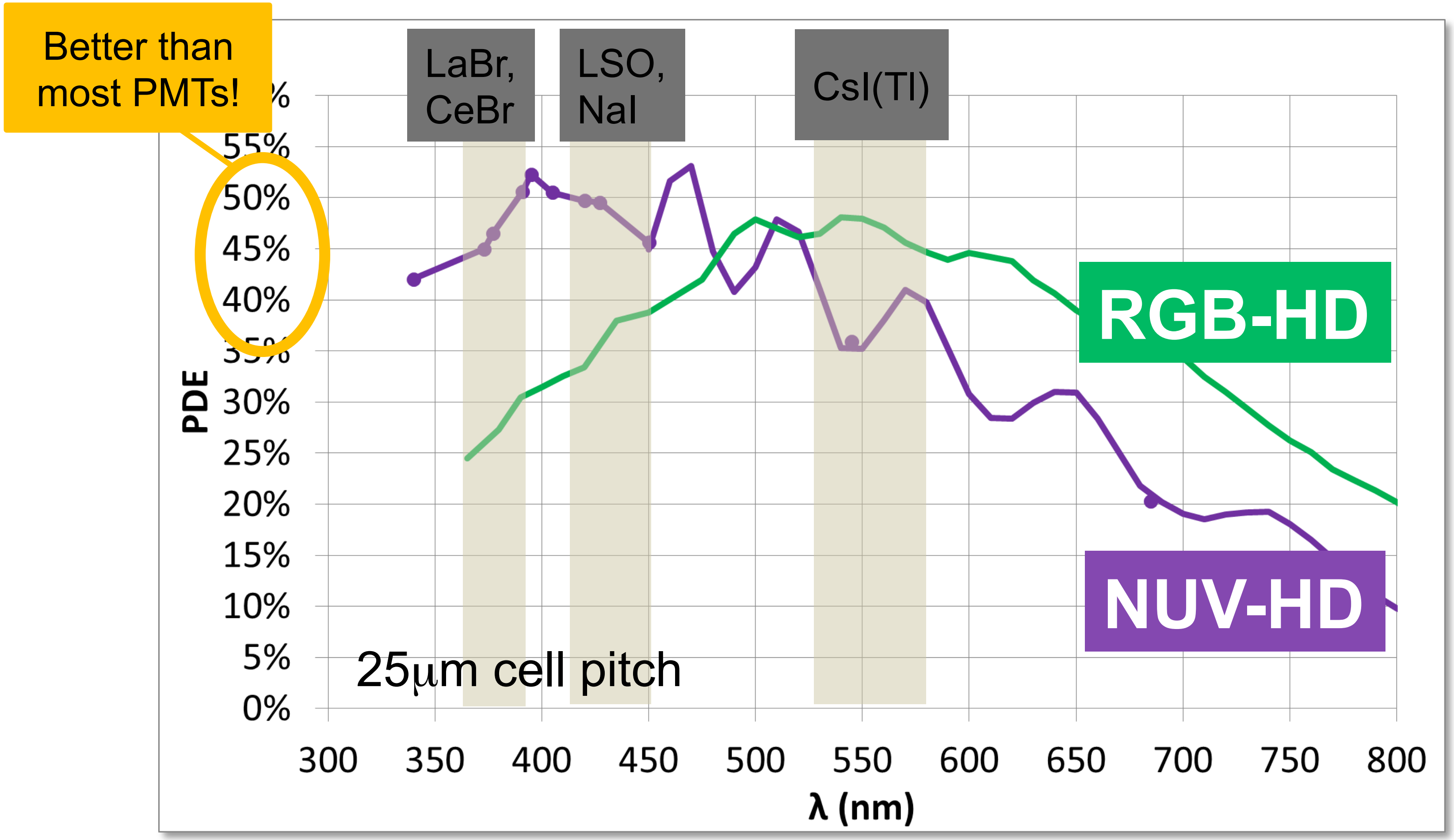
- PDE increases with overvoltage (but noise also increases!)
  - Cooling helps!



From SensL Overview Article

Spectral Sensitivity

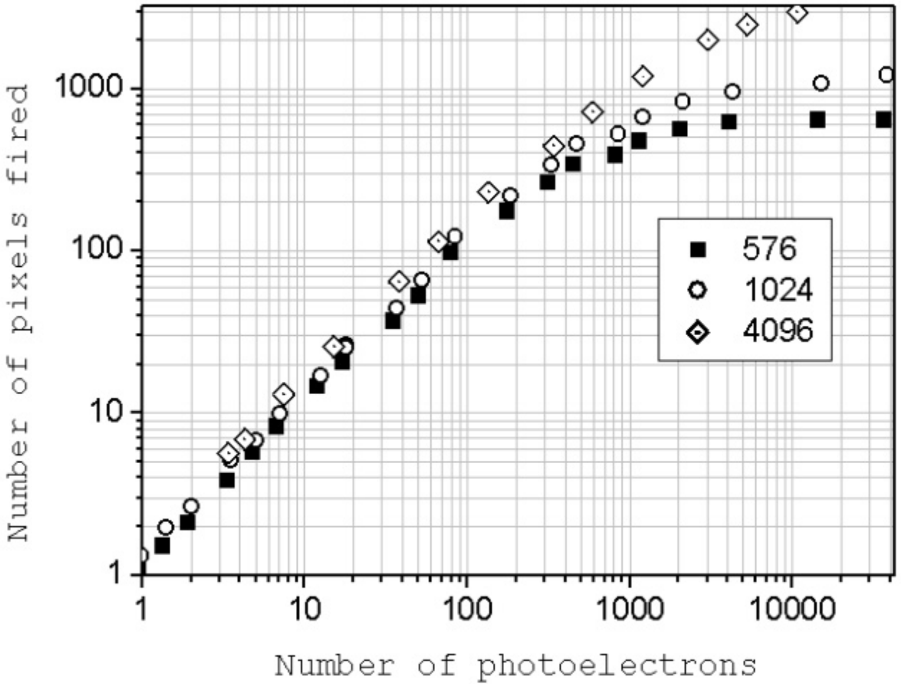
- Another Example PDE vs. λ (on active area, must add fill factor!):



(Two types of SiPMs from FBK, Trento)

Linearity

- Fired cells cannot fire again (in short time)
- This reduces the ‘detected’ signal for many photons
  - Largest signal is obviously = # of SPAD cells
  - SiPMs with many cells are better here (but have smaller PDE)
- This effect makes amplitude spectra artificially ‘narrow’
  - Must be corrected for



On average:

$$N_{seen} = N\left(1 - e^{-\frac{N_{fired}}{N}}\right)$$

(Linearity Formula: Derivation)

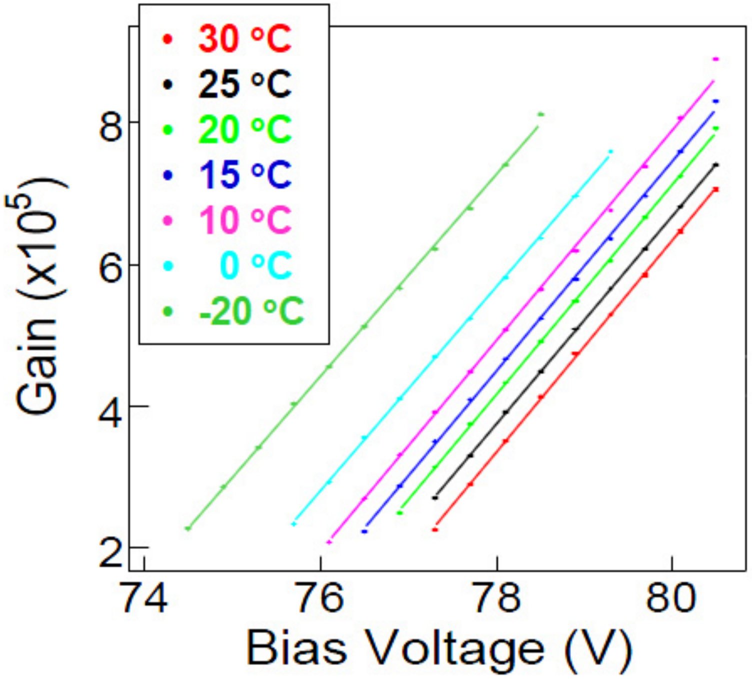
- Assume **N** cells on the detection area
- The probability of a cell to fire when hit by a photon is ε.
- We drop k Photons on the detection area.
- We look what happens in one particular cell, say, cell 13:
  - The ***probability*** that ***one*** photon fires ***that*** cell is ε/N.
  - The prob. to ***not*** hit ***that*** cell by the one photon is 1-ε/N
  - The prob. to **not** hit ***that*** cell by ***all k*** photons is (1-ε/N)^k
  - Therefore the prob. to ***hit*** that cell by any of the k photon is 1-(1-ε/N)^k.
- We add up this probability for all N cells. Therefore, the average number of hit cells is N times this value:

$$\langle \mathrm{Signal}(k) \rangle = N\left(1 - \left(1 - \frac{\epsilon}{N}\right)^{k}\right)$$

- For large N and small ε, this converges to $N\left(1 - \mathrm{Exp}\left[-\frac{\epsilon\, k}{N}\right]\right)$

Temperature Dependence

- Breakdown voltage rises ~linear with temperature
  - This leads to a gain shift
  - Strong effect: Needs correction



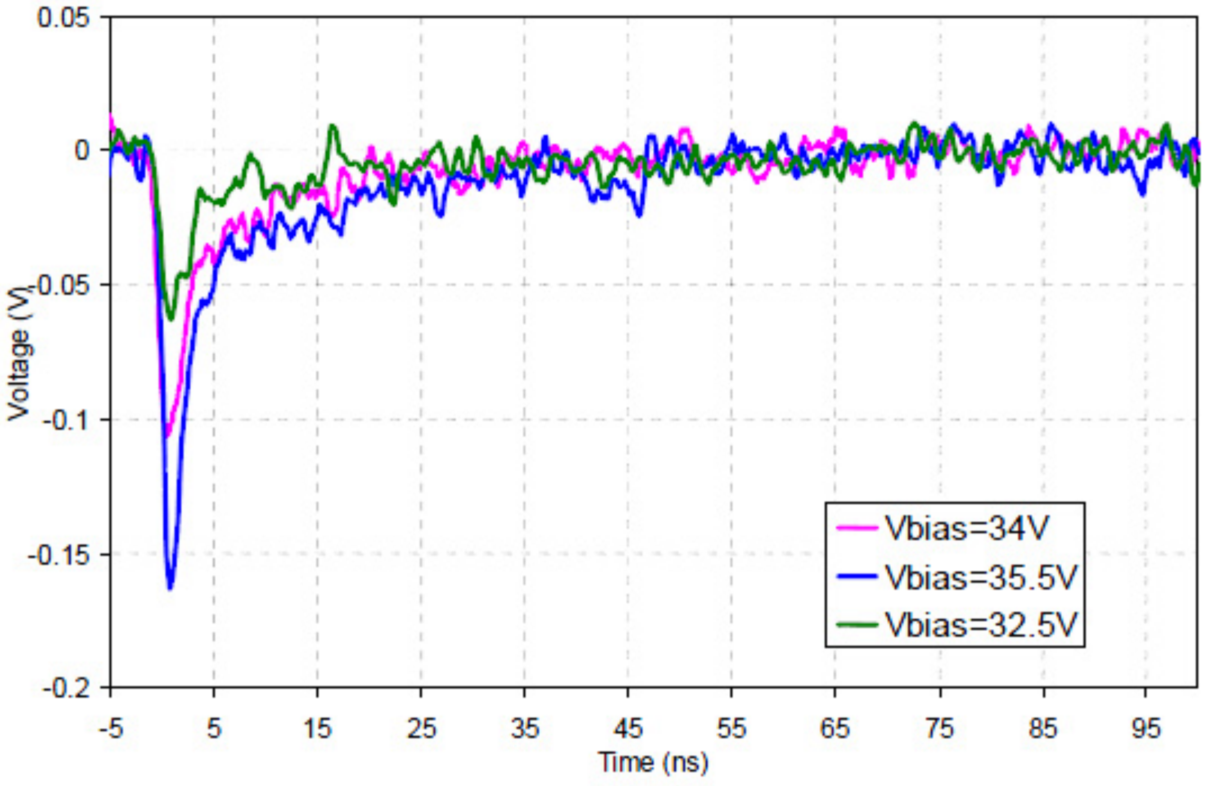
Gain = C $(V_{bias}-V_0)$ / e

C : Pixel capacity

V_0 : Breakdown voltage

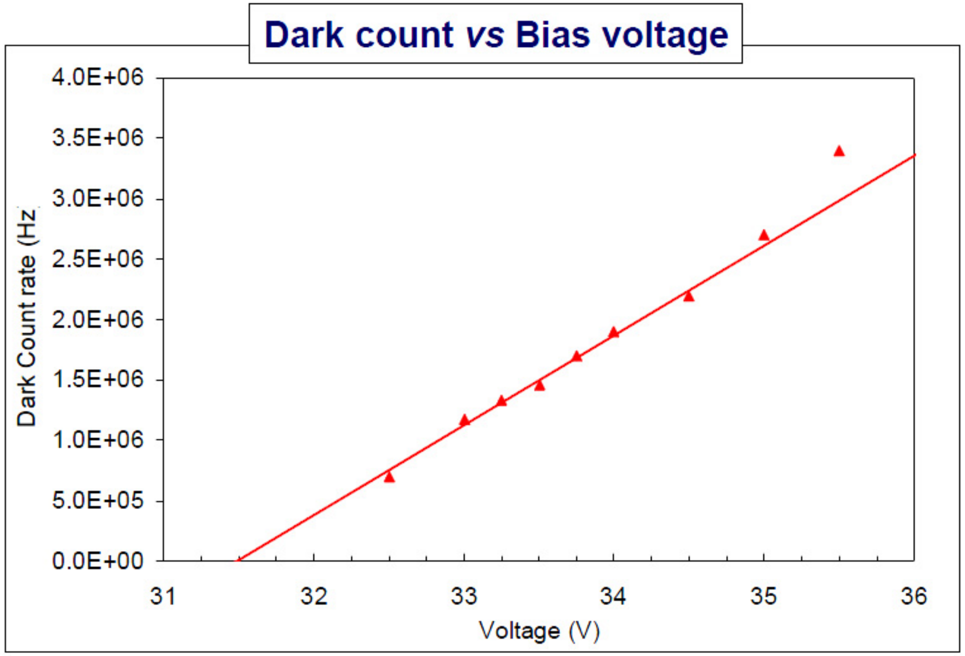
Time Behavior

- **Very fast!**
- Rise time <1ns (depends on readout circuit)
- Recovery time ~ 70ns
- At very fast recovery: After-pulsing / Crosstalk (?)



Noise / Dark Count Rate (DCR)

- Thermally generated electrons (‘leakage current’) can trigger avalanches
- Their # depends on depleted volume and thus of $\sqrt{\Delta V}$
- Depends on temperature (low T → low leakage current)
- Depends on gain (high gain → higher trigger probability)
- Typical DCR are ~100 KHz – 1 MHz / mm^2



Summary SiPM

Pros

- High Sensitivity (higher QE than 'most' classical PMTs)
- Linear Signal (up to saturation limit)
- Low Bias voltage
- Insensitive to magnetic field
- Small
- Cheap (?, not for large area)
- Short recovery time

Drawback:

- Larger dark noise wrt. PMT
- Small electrical signal requires amplifier
- Requires control of temperature

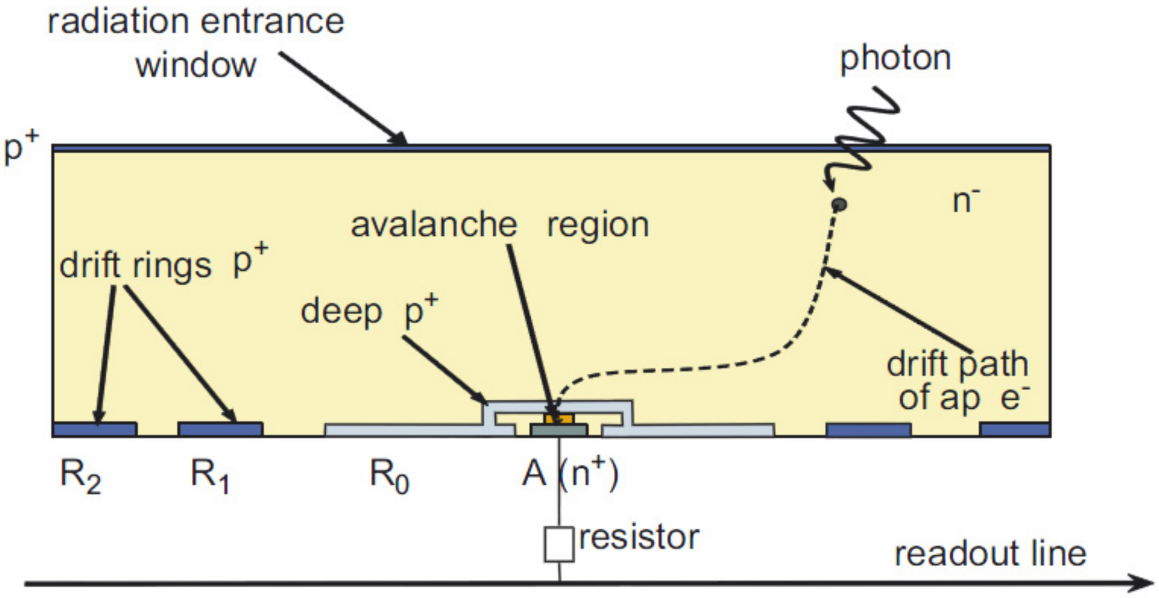
Not discussed here

- Noise in avalanche process
- Crosstalk between pixels (an avalanche in one SPAD creates photons which trigger another SPAD)
- After-pulsing (similar, but delayed)
- Timing jitter from SPAD to SPAD
- Homogeneity of parameters (overvoltage)
- …

NOVEL / FUTURE DEVICE VARIATIONS

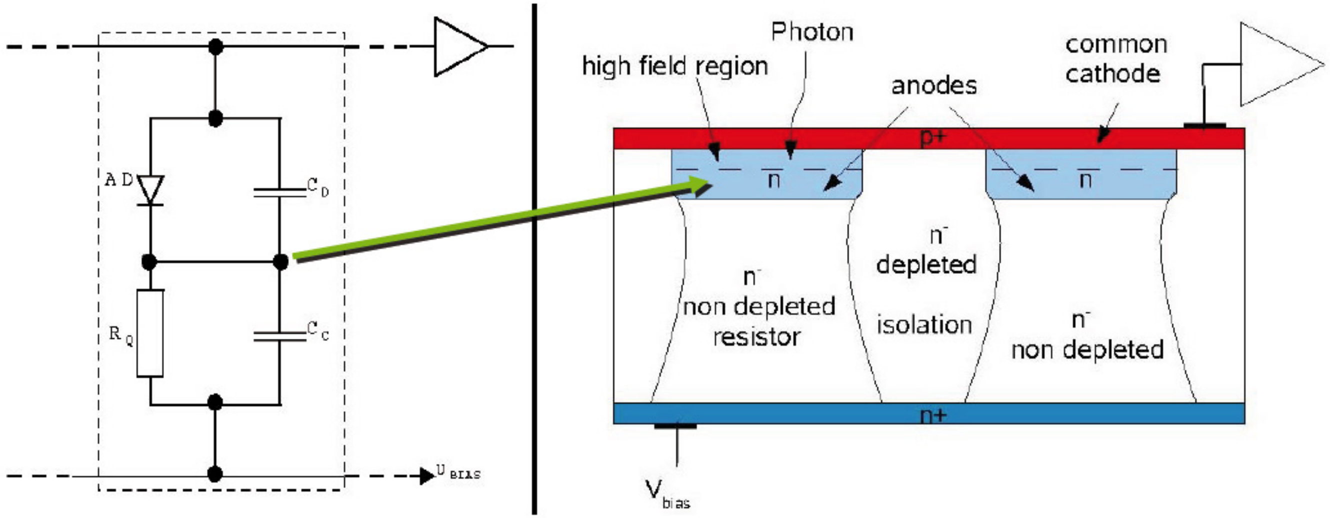
New Development: Avalanche Drift Diode

- Carriers first *drift laterally* to an amplification region
  - Device is sideward depleted
  - Electrons first drift ‘vertically’ to potential minimum, then laterally
- Only small avalanche regions
- large area, full depletion → very high PDE > 80%
- Bad time resolution (drift time depends on position)
- High dark rate (large depleted volume, ‘more than needed’)



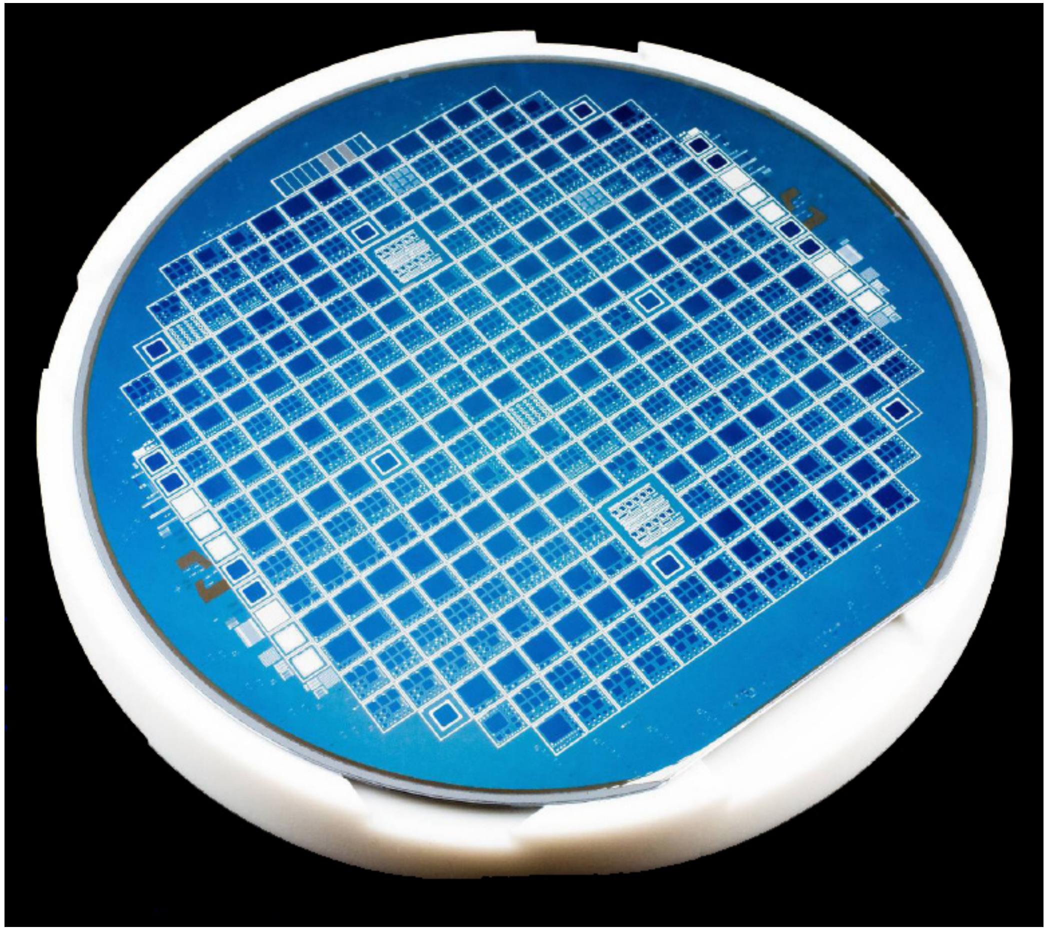
New Development: Vertikal ‚SiMPI‘ (@ HLL Munich)

- Quench resistor is vertical to backside of device
  - Value is given by device area, wafer thickness, bulk resistivity
- p$^+$ und n$^+$ electrodes on array are also contacts
- Cells are isolated by depletion regions



- Requires very thin (50-100µm) wafers
- Very high fill factor!
- Very simple technology (except thin wafer..)
- Backside contact ! → Could flip readout chip

SiMPI Wafer

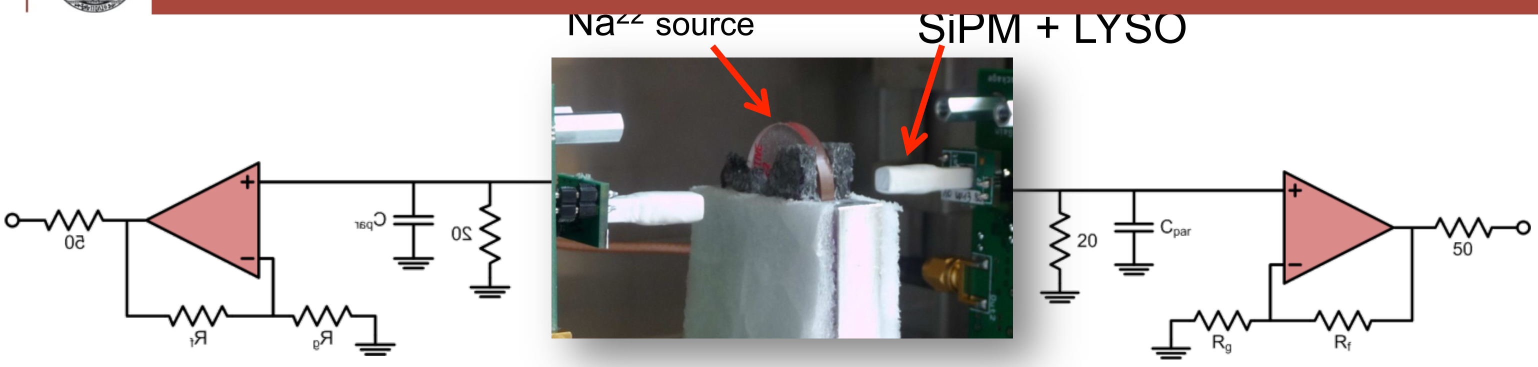


- Pros
  - Very high fill factor
  - Simple technology, no Polysilicon required, coarse lithography → high yield, low cost
- Cons
  - Vertical quench resistor
    - Depends on wafer thickness → thin wafers for small SPAD
    - is a JFET → rel. large recovery times
- Work in progress (@2012). Further improvements expected.

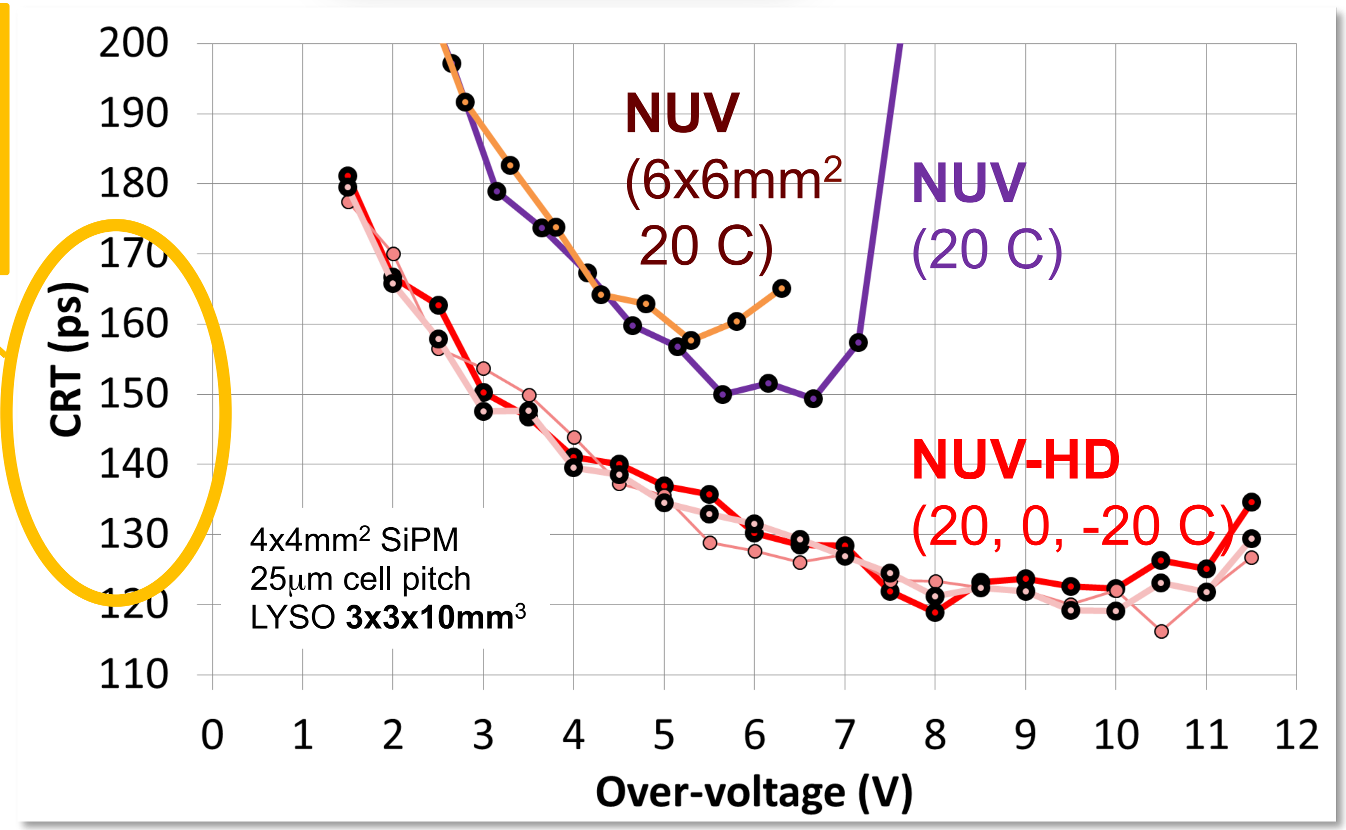
APPLICATIONS:

(CALORIMETRY), PET

Time Resolution with Crystals



Coincidence Resolving Time: FWHM of time differences

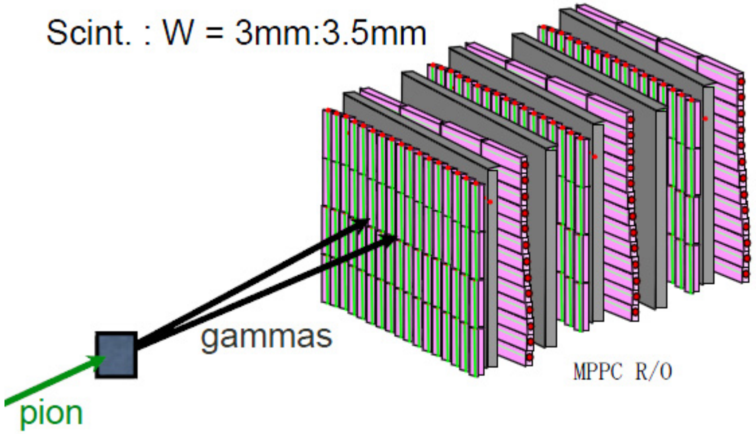


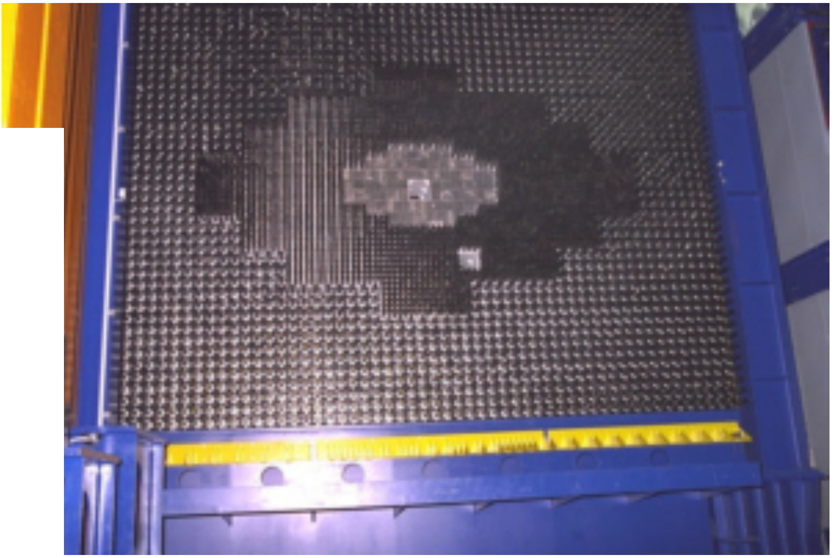
FBK result

Application: Calorimeter

- Calorimeters measure the energy of particles
- These are stopped in an absorber

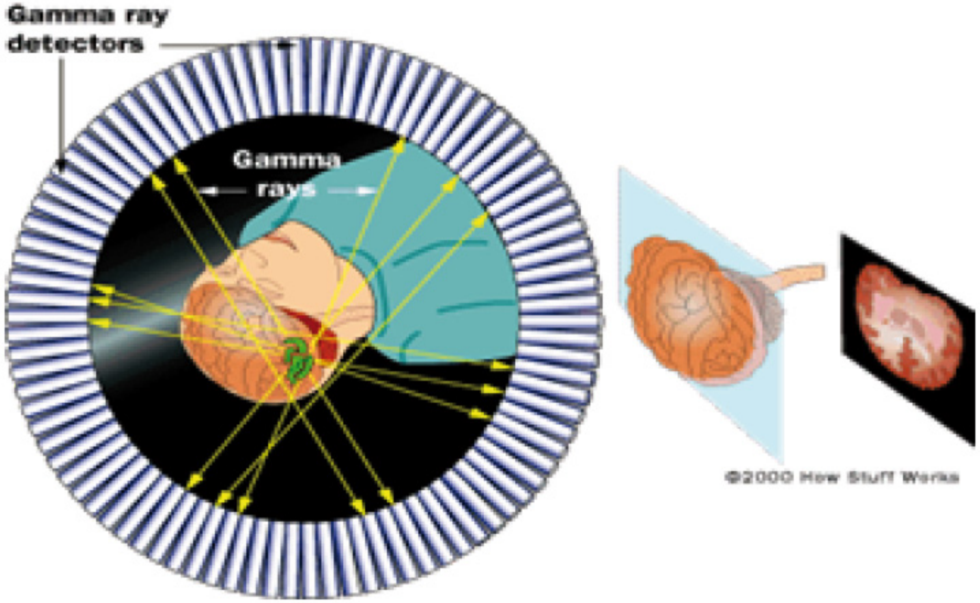
  (by electromagnetic and strong interactions)
- Absorbers are often *scintillators* which produce light proportional to deposited energy
- Light must be detected
  - In magnetic field
  - Fast
  - Many channels



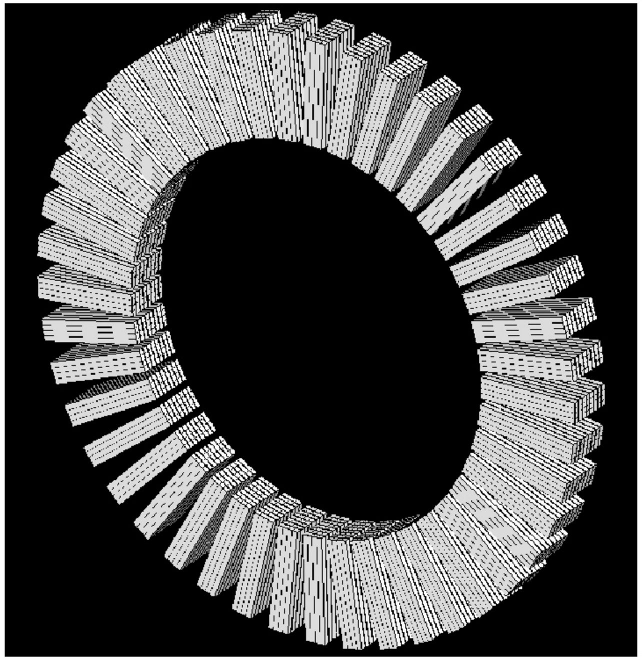


Application: Tomography (PET)

- Detection of scintillation photons (von 511 keV γ)
- Time resolution required
  - For coincidence: some 5-10 ns
  - For time of flight: some 100 ps
- Compact
- Works in magnetic field (MRI)

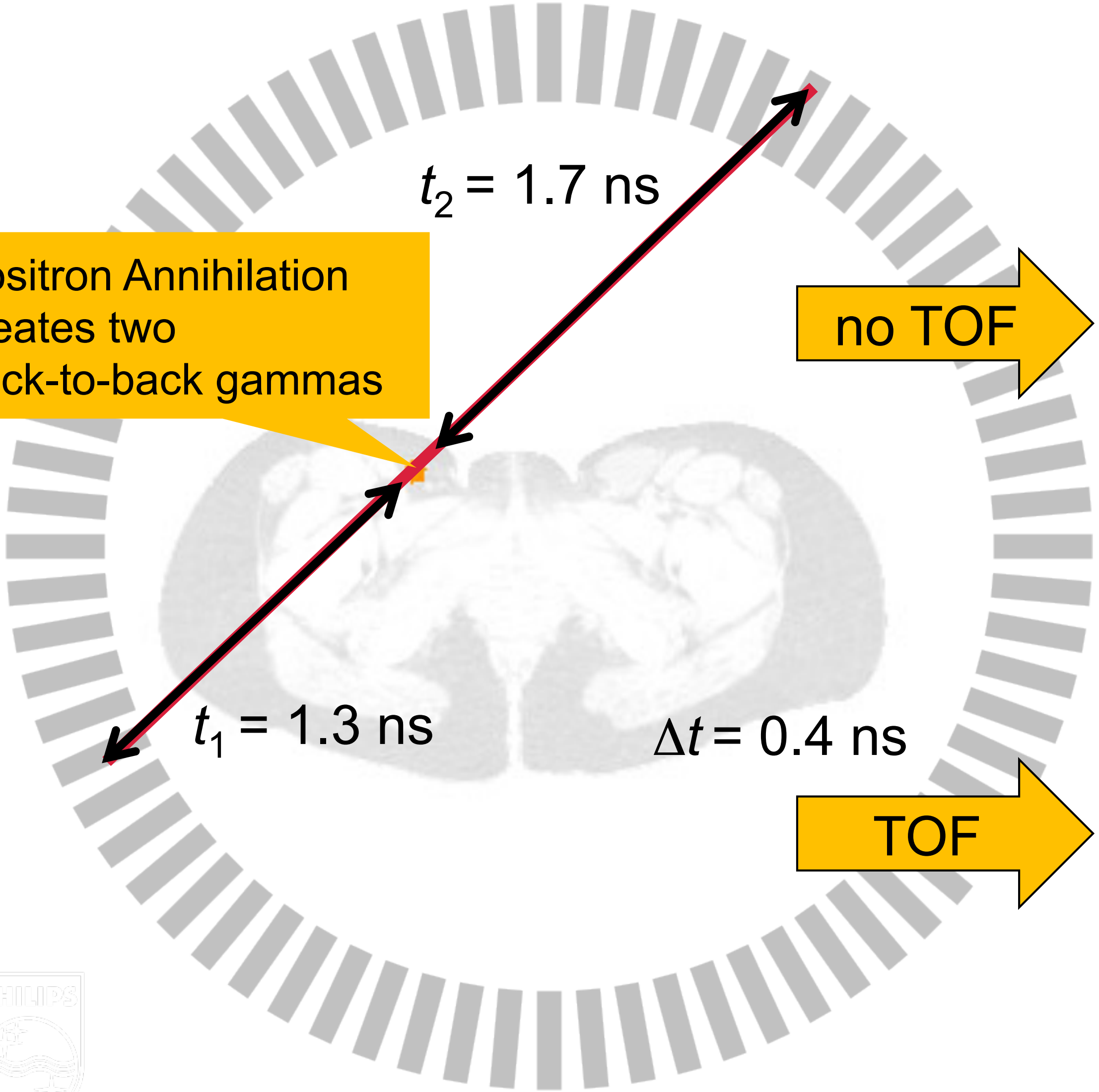


©2000 How Stuff Works



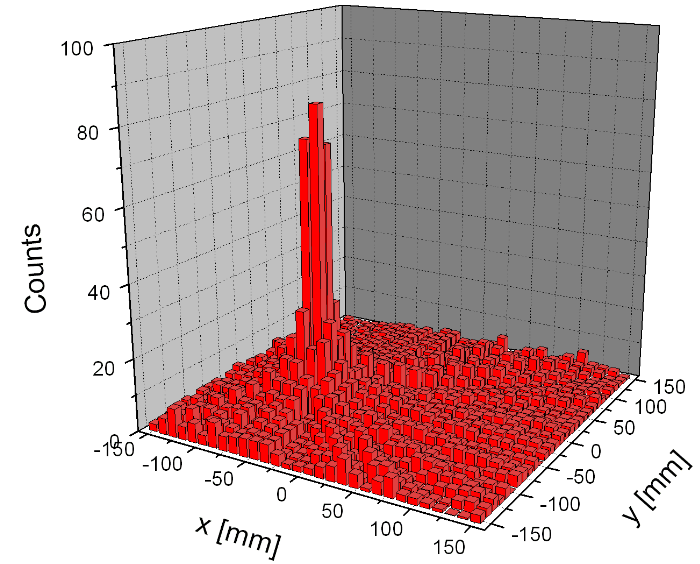
Tomograghgeometrie mit 45 Detektormodulen

Positron Emission Tomography (PET)

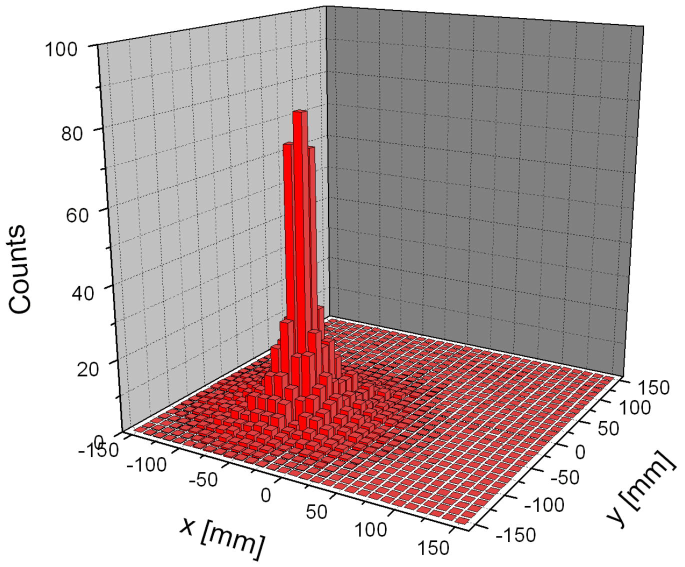


Positron Annihilation creates two back-to-back gammas

no TOF

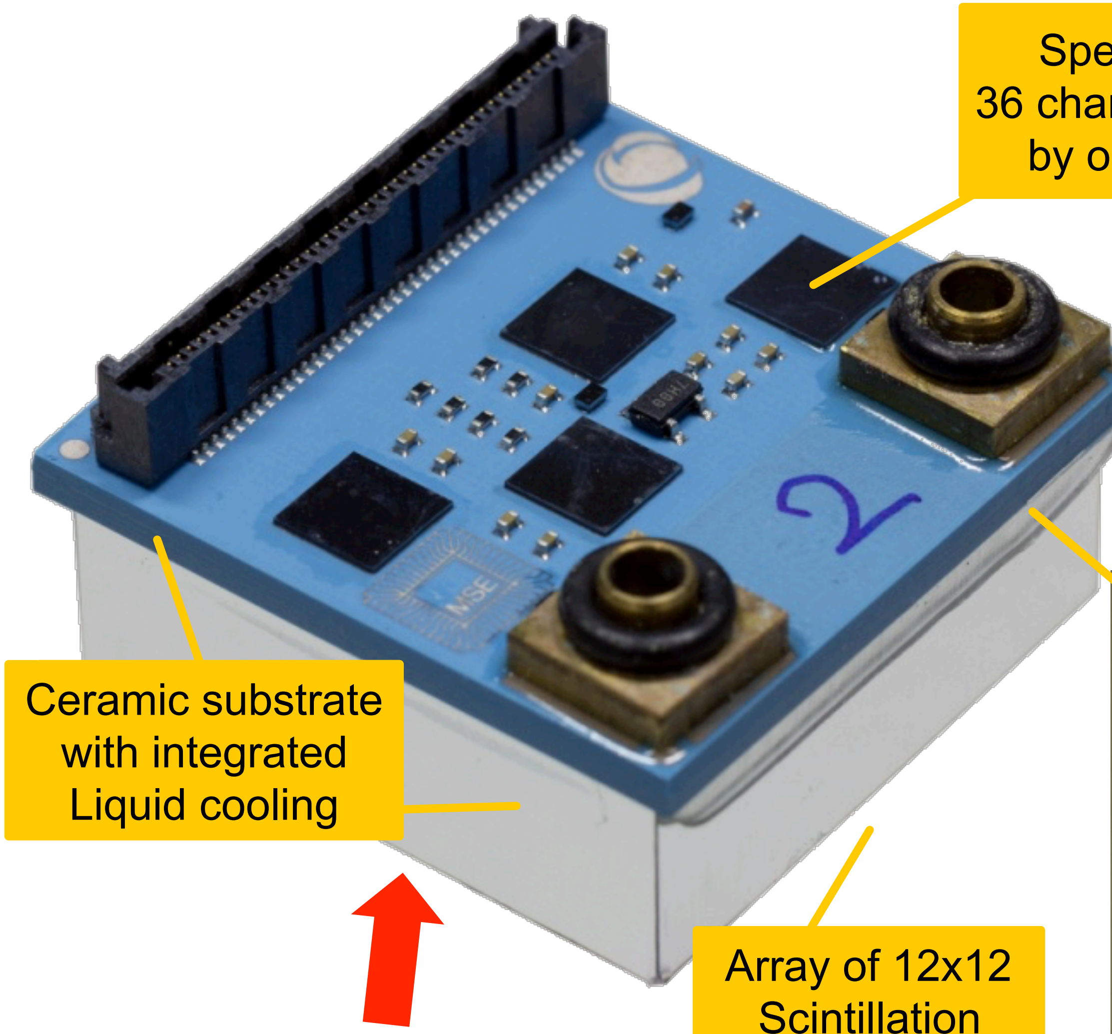


TOF

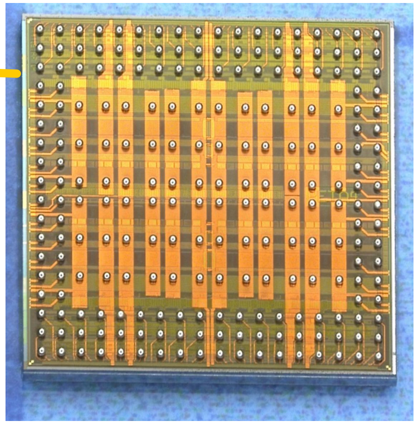


Gamma Detection Module

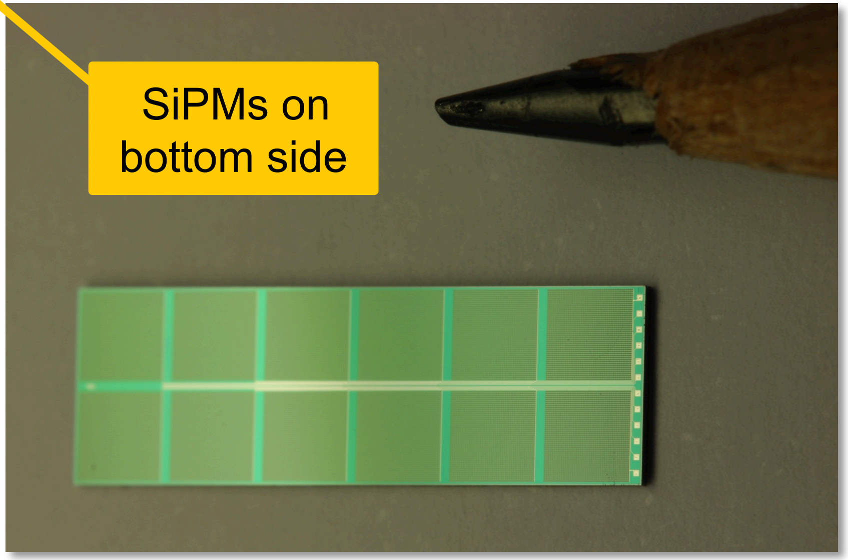
- We have built a very compact module for detection of 511 keV gammas:



Specialized 36 channel ASICs by our group



SiPMs on bottom side



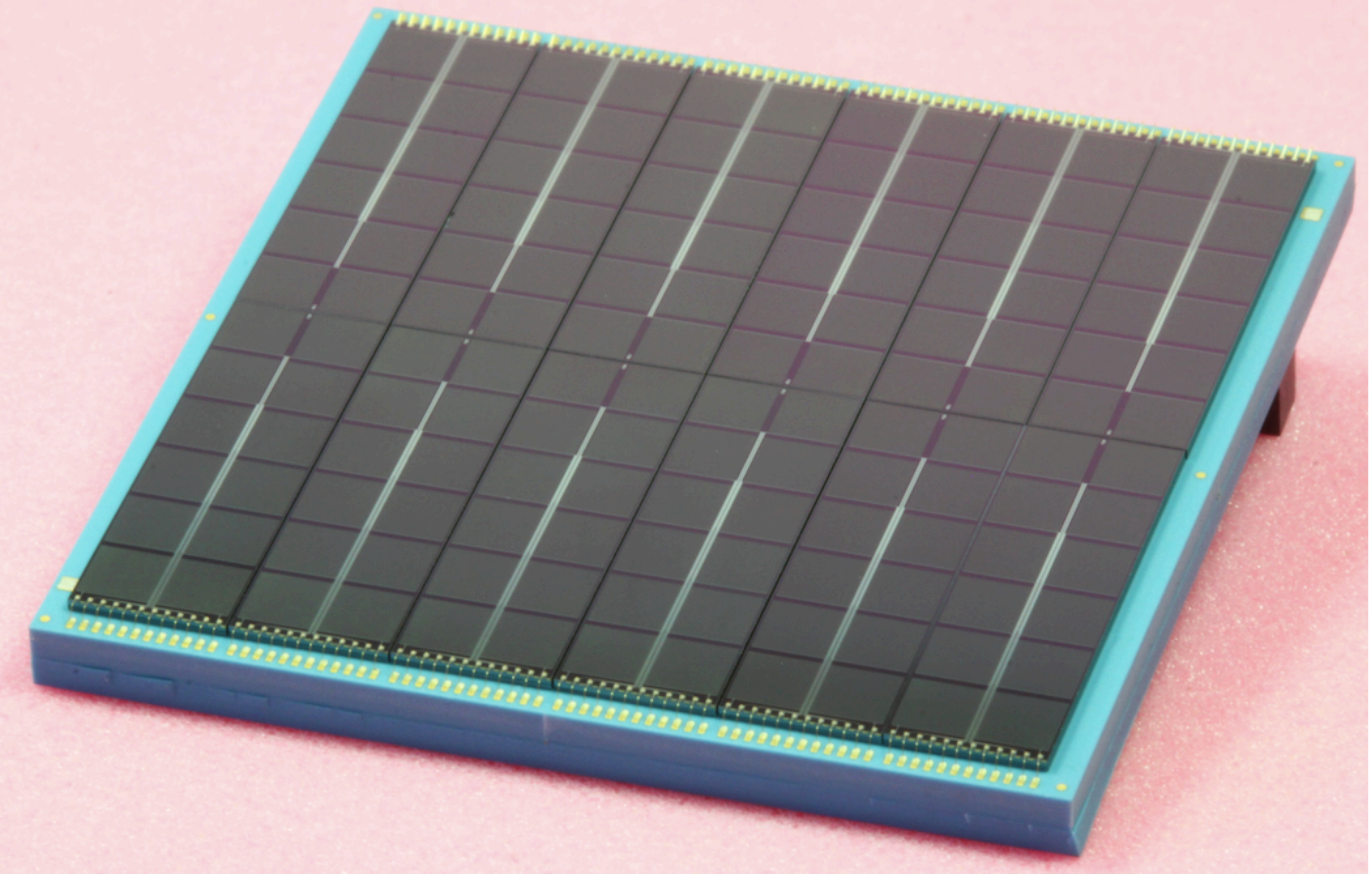
Ceramic substrate with integrated Liquid cooling

γ (511 keV)

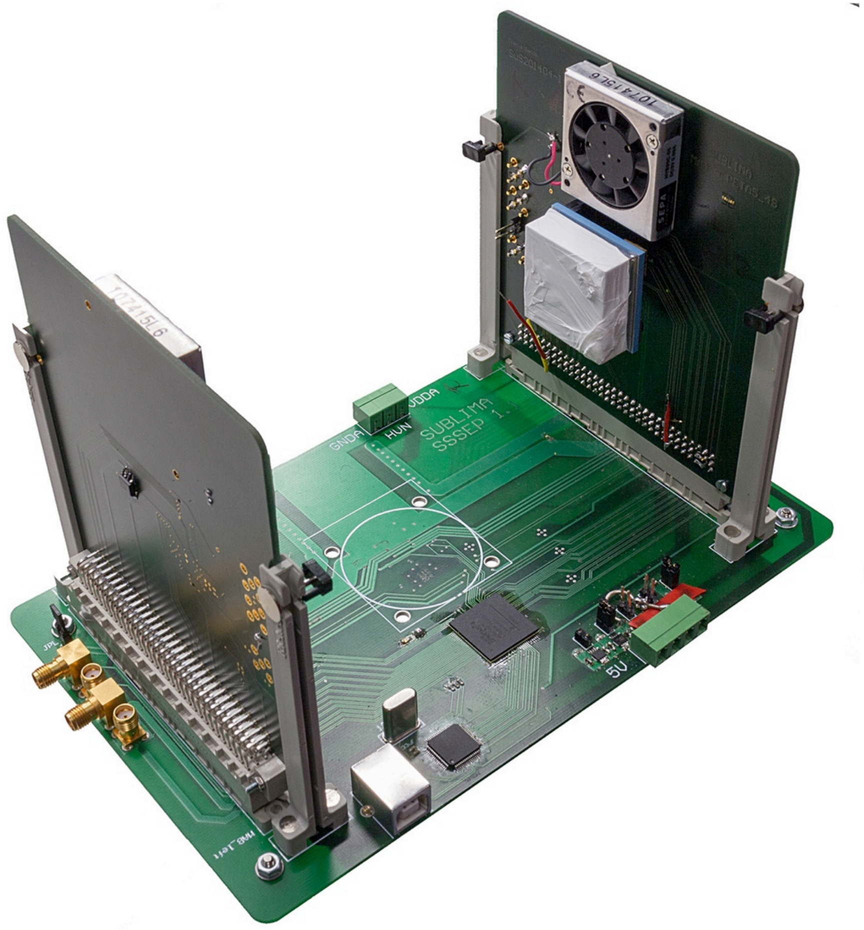
Array of 12x12 Scintillation Crystals (LYSO)

Backside: SiPM Arrays

- Challenging assembly!



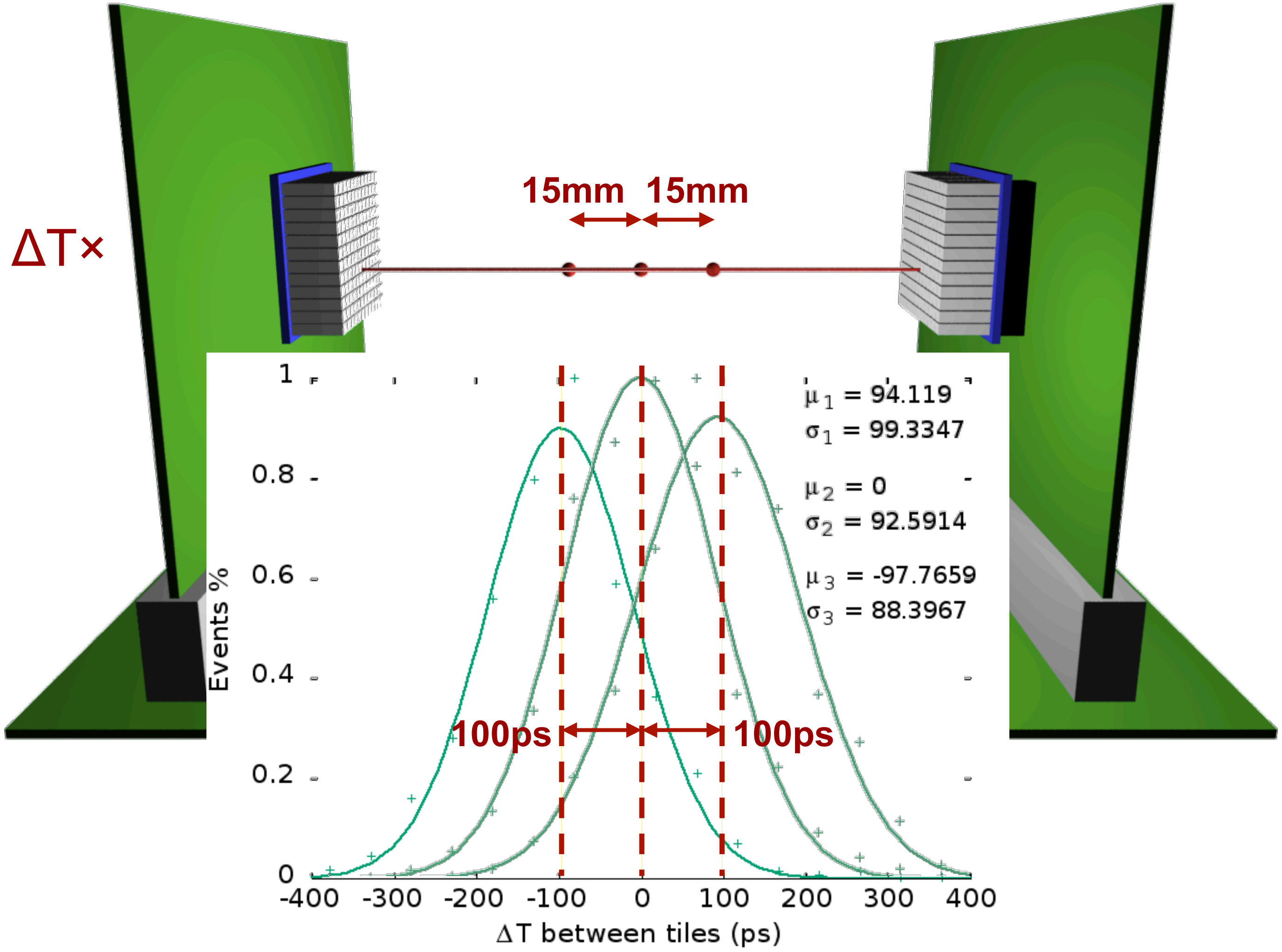
Performance in 1:1 coupling



- CRT ~210 ps (@ 30°C) is State of the Art!
  - Note that this corresponds to a single channel sigma of ~65 ps!

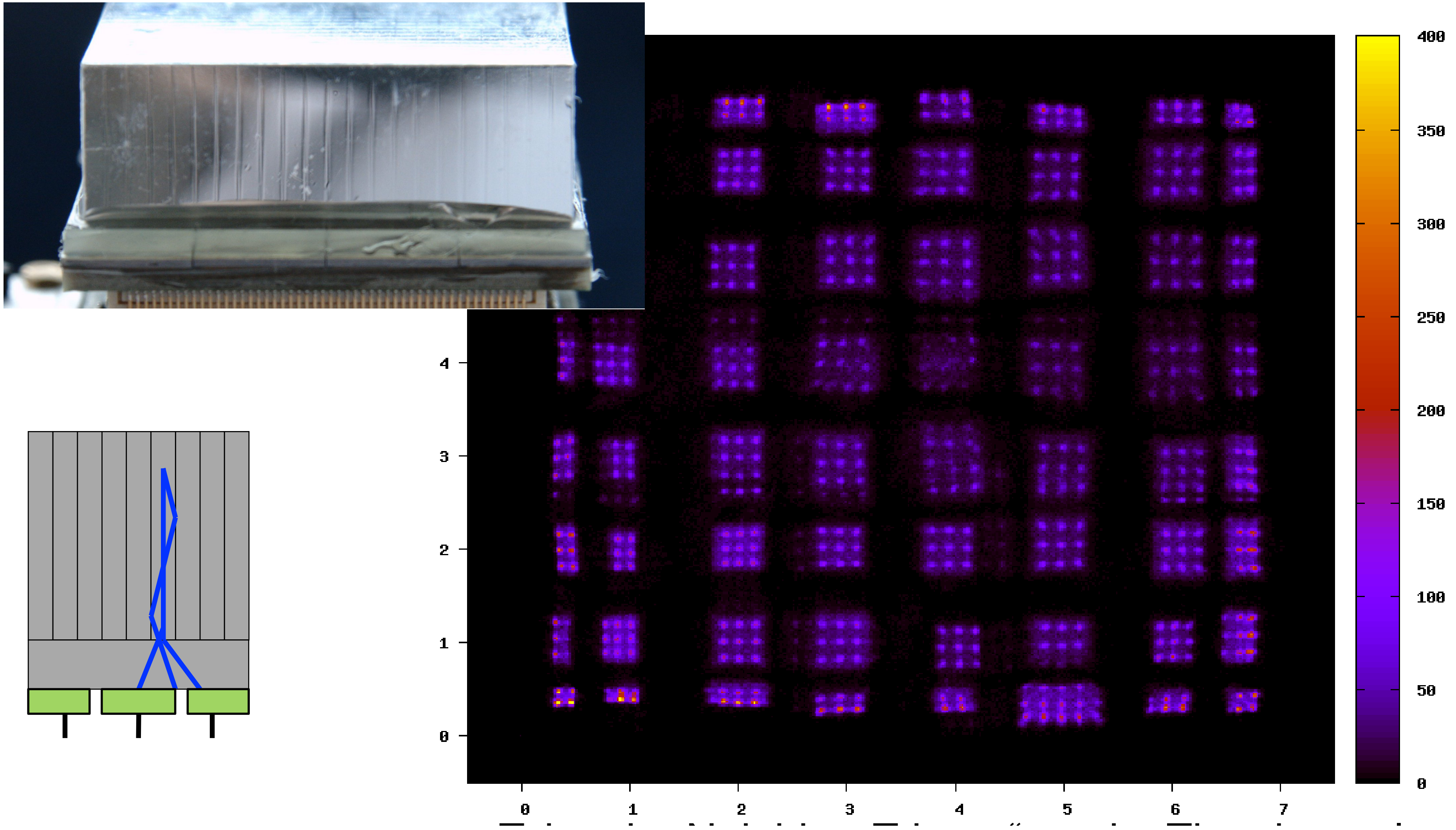
Direct Time-of-Flight Measurements

$\Delta x = 0.5 \times \Delta T \times c$



Position Resolution

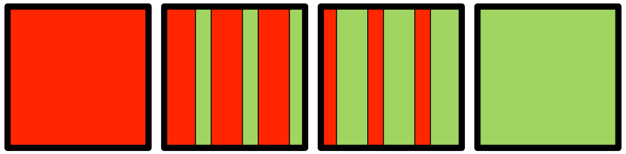
- 8 x 8 SiPMs, crystals of 1.3 x 1.3 x 10mm^3, Simple 2D Gauss fit.



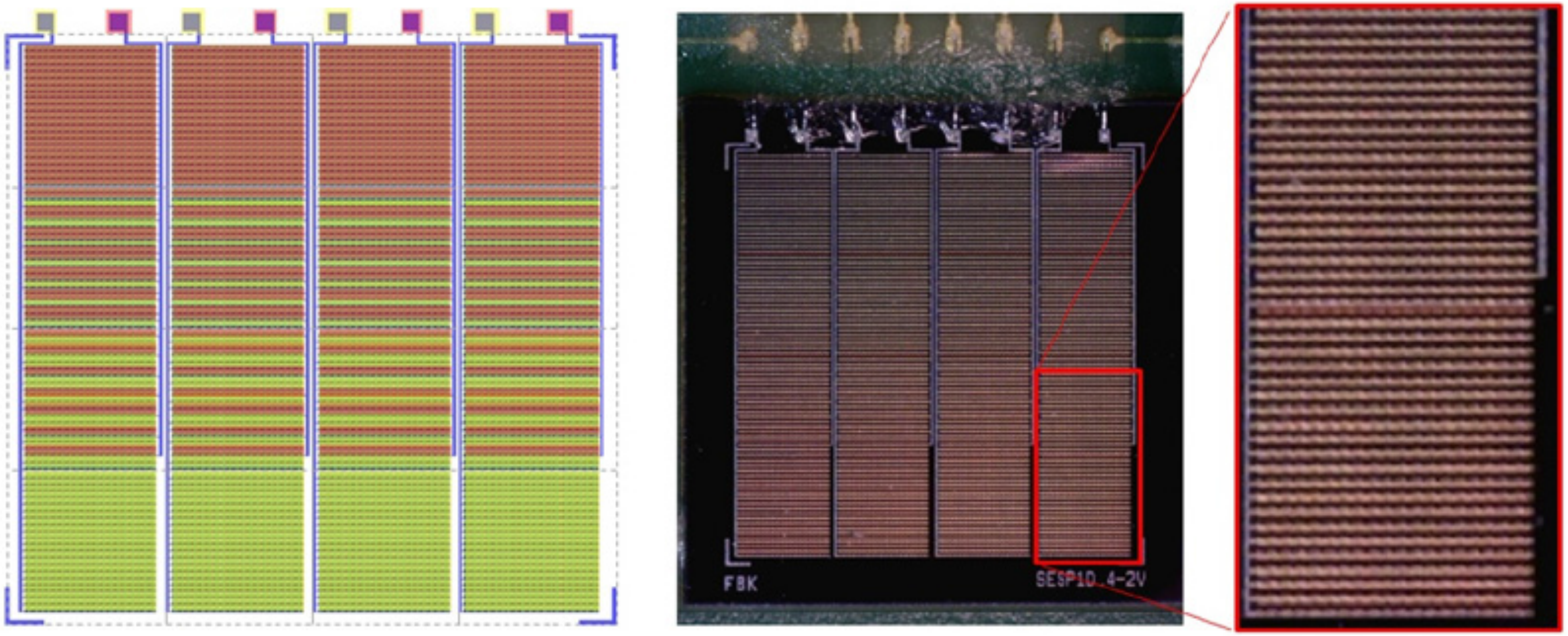
MAKING SIPMS POSITION SENSITIVE

A first Idea

- Define regions with different fraction of SPADs assigned to 2 outputs



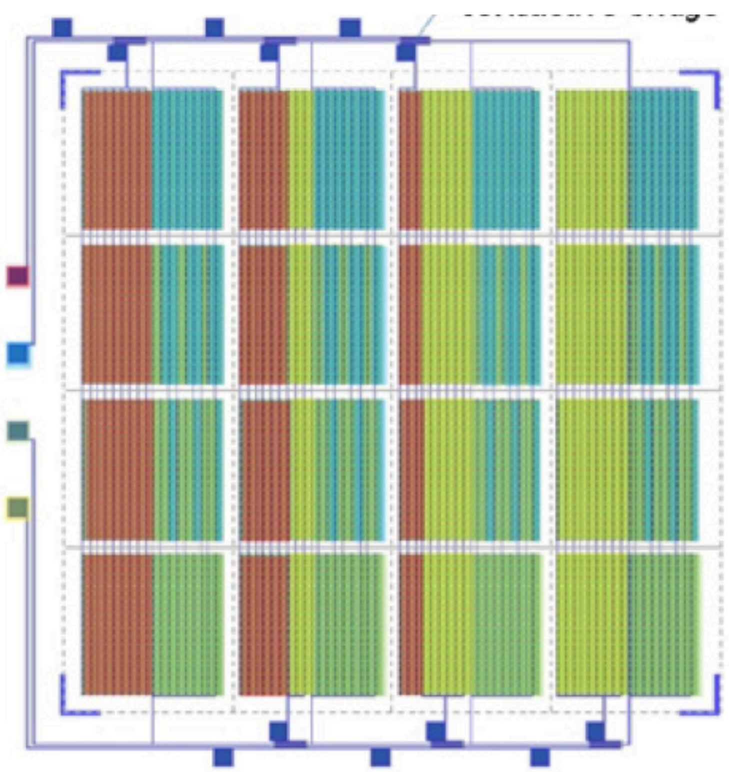
- Linear ‘SeSP’ (Sensitivity Encoded SiPM)

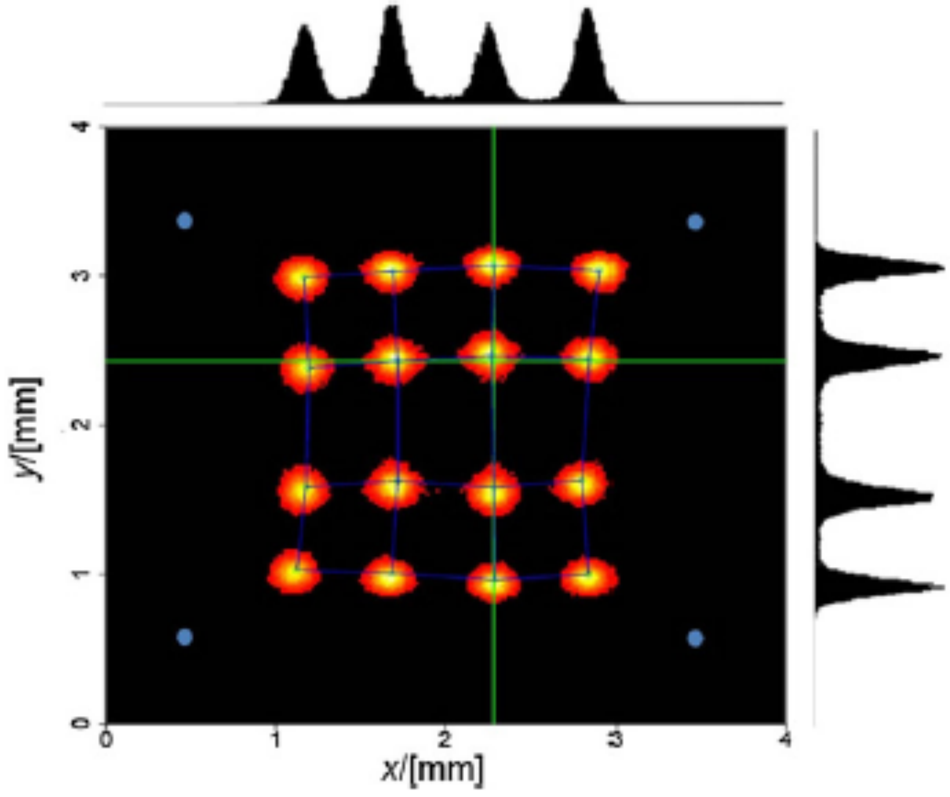


V. Schulz et al., Sensitivity encoded silicon photomultiplier—a new sensor for high-resolution PET-MRI, Phys. Med. Biol. 58 (2013) 4733–4748

2D SeSPs

- Extension to 2D device





- Works in principle. BUT: Crystals must be placed very precisely…

Omidvari & Schulz: Characterization of SESP with 1-D and 2-D Encoding for high Resolution PET/MR, IEEE TNS, Vol. 62, No. 3, June 2015

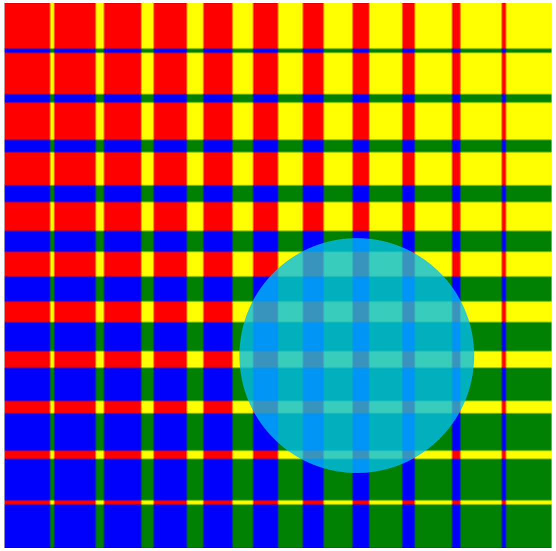
Homogeneous Devices

- Find more ‘general’ assignments of SPADs to readout channels (‘colours’)

Classical: Wedge & Strip

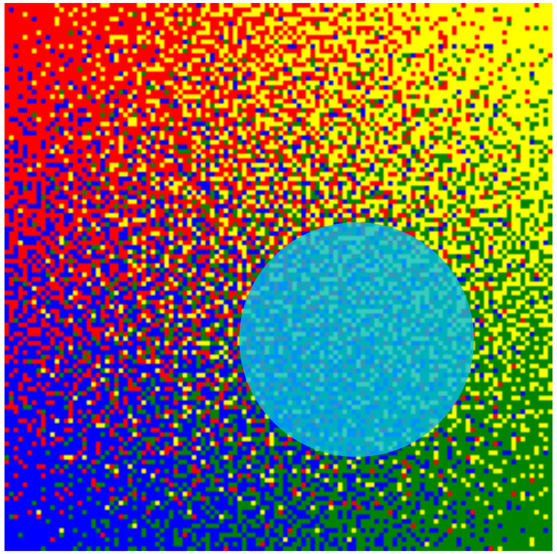
- Top/Bottom: Blue fraction
- Left/Right: Green fraction

Linear strip gradients



- Top/Bottom: G+B fraction
- Left/Right: R+B fraction

ISiPM



- Top/Bottom: G+B fraction
- Left/Right: R+B fraction

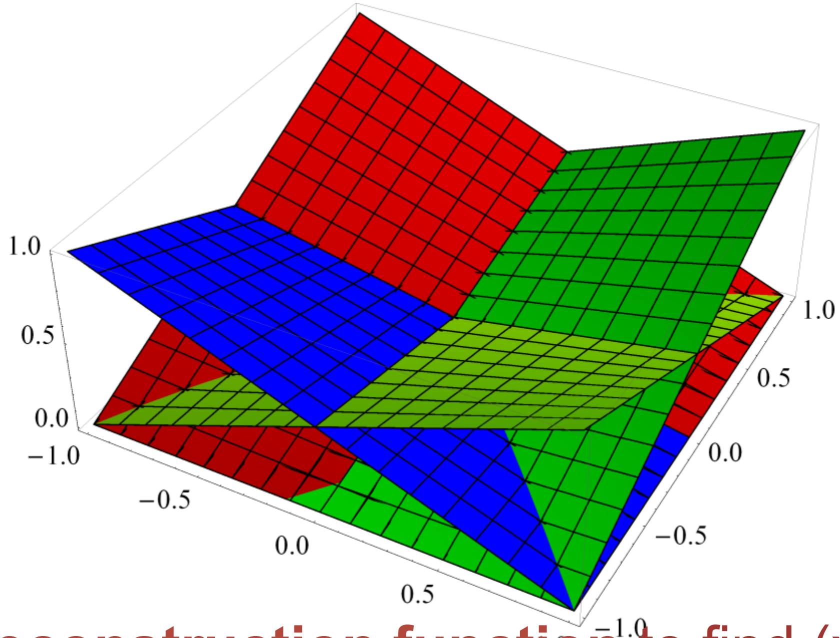
ISiPM Idea

- Chose 4 **weight functions** $S_{i,j}$ (x,y) (amplitude in corner (i,j) for hit at (x,y))

$$S_{i,j}(x,y) = \frac{(i \cdot x + 1)(j \cdot y + 1)}{4}$$

with corners at

$$\vec{C}_{i,j} = \begin{pmatrix} i \\ j \end{pmatrix}, \quad \text{with} \quad i,j = \pm 1,$$



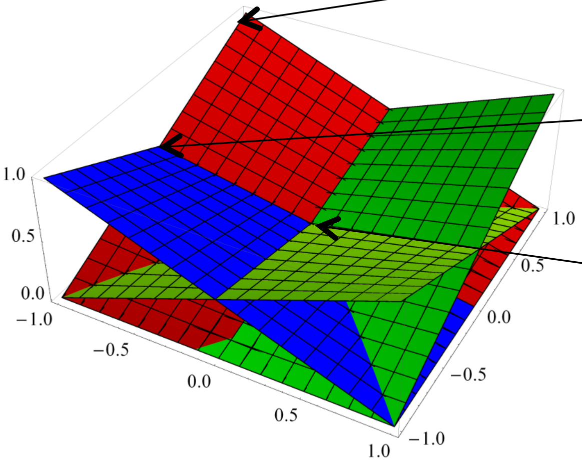
- Get a *corresponding* **reconstruction function** to find (x,y) from the 4 $S_{i,j}$.

Here: $$\vec{r}_{rek} = \sum_{i,j} S_{i,j} \, \vec{C}_{i,j}$$ (center of Gravity, CoG)

- Note: Other functions & only 3 corners are possible!

Discretizing the Weight Function

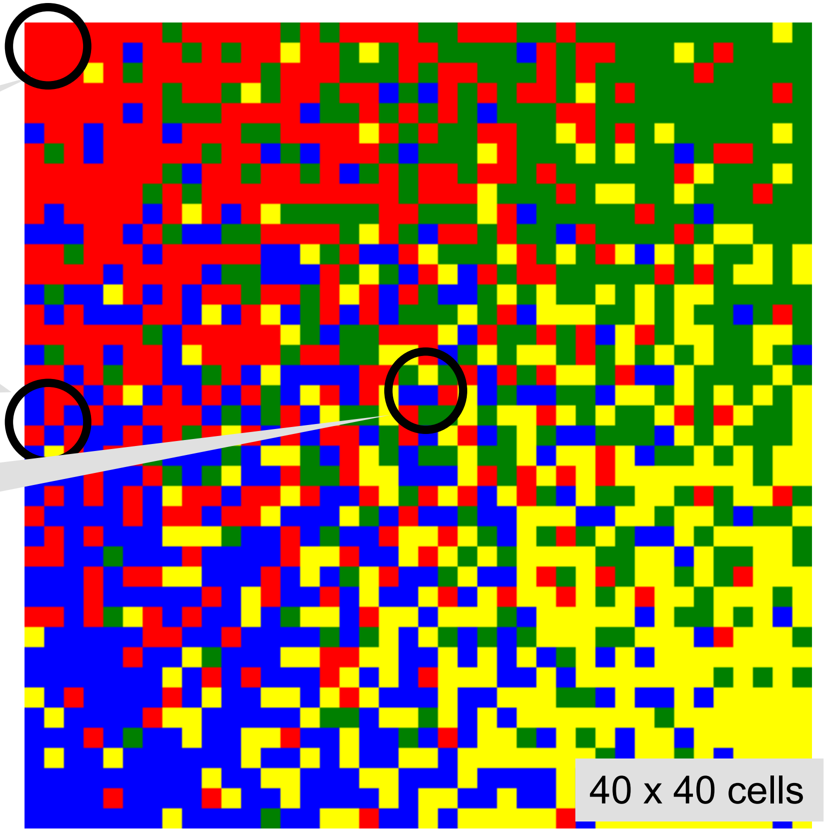
- Assign each SiPM cell to ***one*** of N = 4 corners (🟨, 🟥, 🟩, 🟦)
- Do this such that the *local* density of cells matches the Weight Function(s)
  ‘as good as possible’…



🟨 / 🟥 / 🟩 / 🟦
0 / 100 / 0 / 0 (%)

🟨 / 🟥 / 🟩 / 🟦
0 / 50 / 0 / 50 (%)

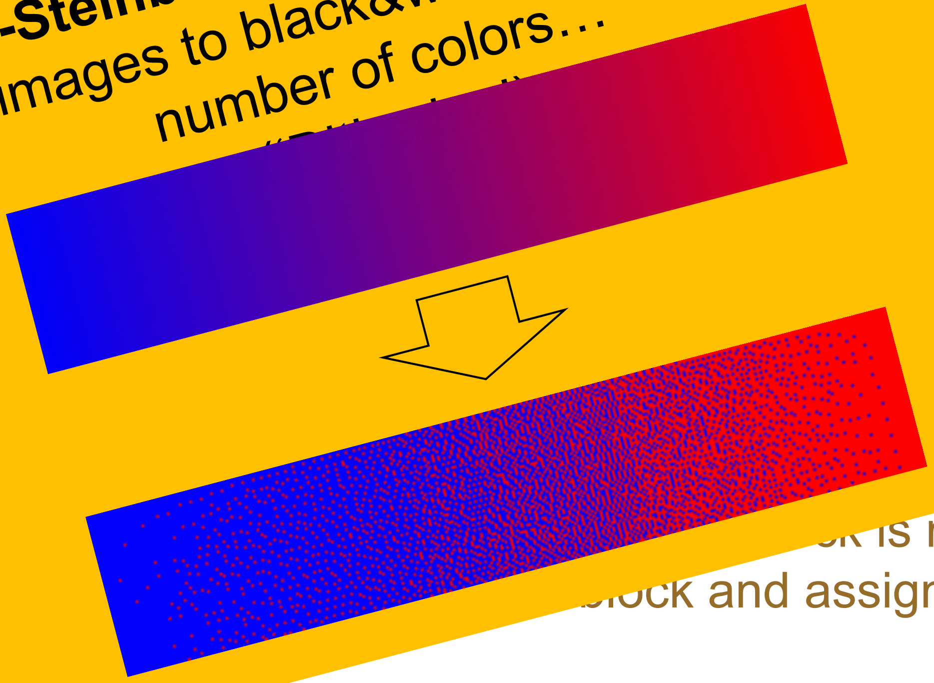
🟨 / 🟥 / 🟩 / 🟦
25 / 25 / 25 / 25 (%)

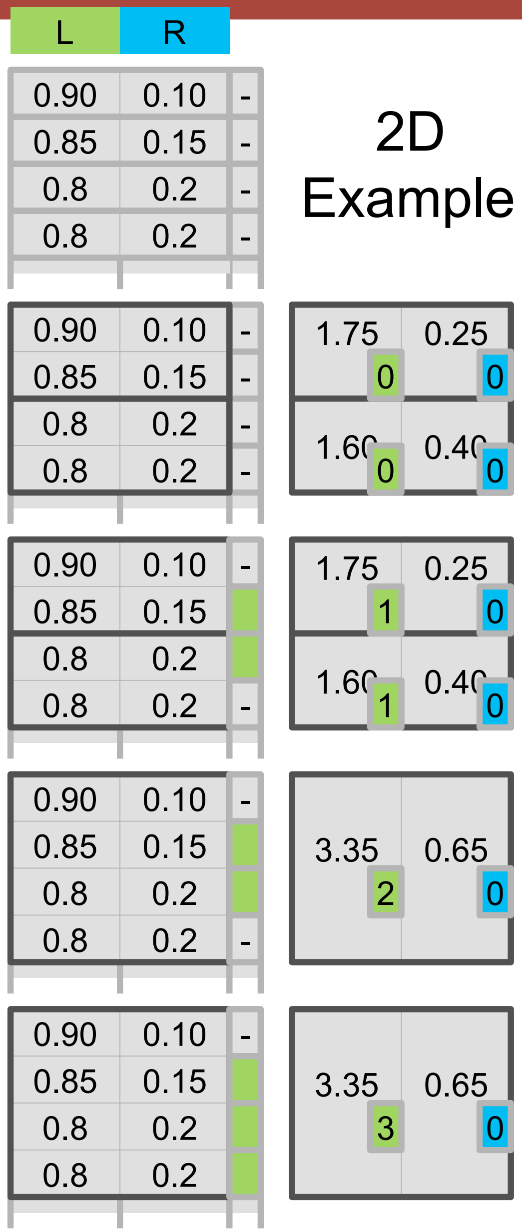


Algorithm to Obtain Cell Assignment

- For each SiPM cell, calculate the ideal … ner assignments according to th … hting function. (The su … be 1.)
- Assign
- I
- C … to
- As … are tha … ck is missing. Pick … block and assign it to corn
- Doubl … clustersize and repeat the above until all cells are assigned

This algorithm is somewhat related to the **Floyd-Steinberg-Algorithm** used to map color images to black&white or to a limited number of colors…





2D Example

L	R	
0.90	0.10	-
0.85	0.15	-
0.8	0.2	-
0.8	0.2	-

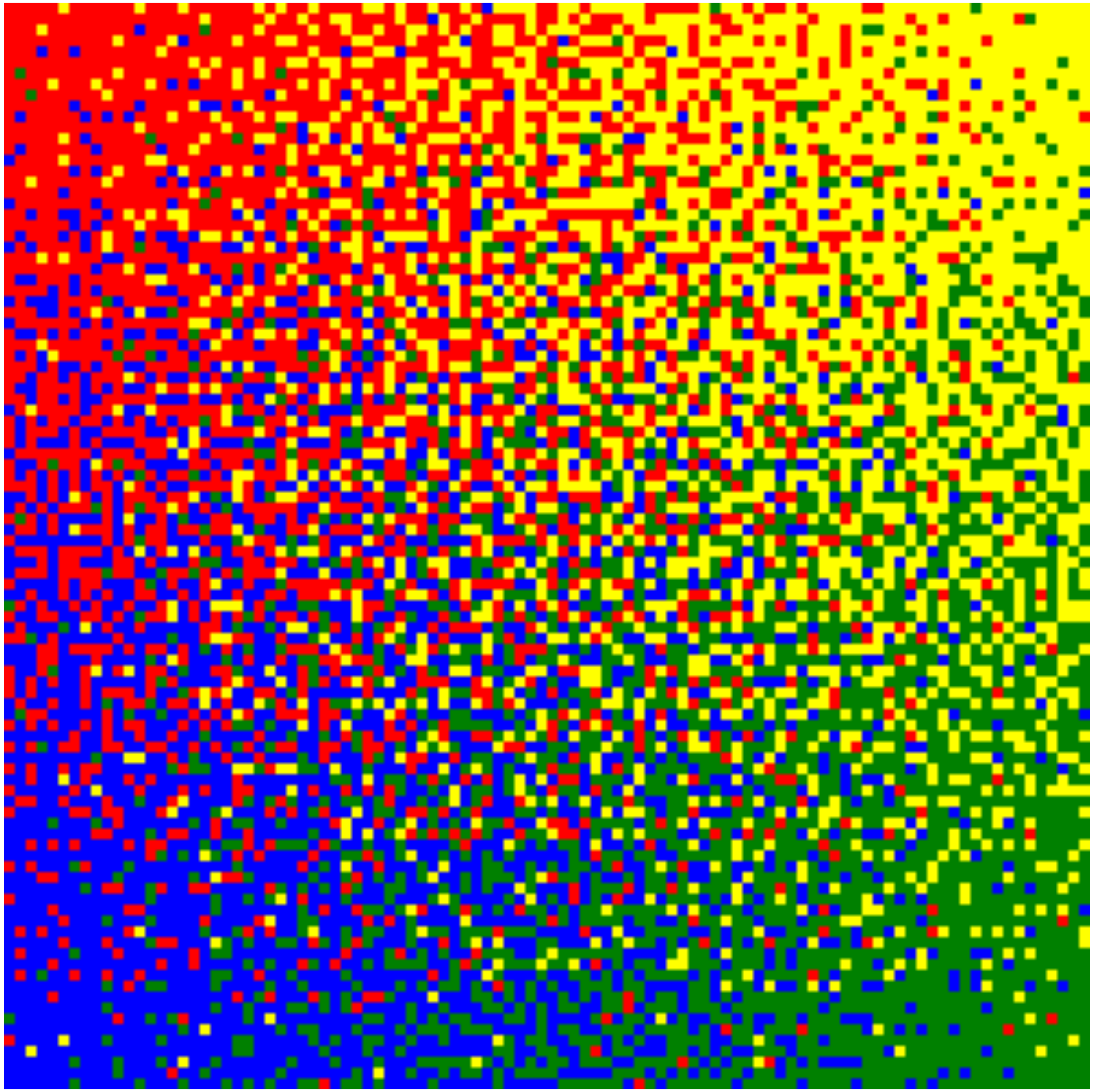
L	R				
0.90	0.10	-	1.75	0.25	
0.85	0.15	-	0	0	
0.8	0.2	-	1.60	0.40	
0.8	0.2	-	0	0	

L	R			
0.90	0.10	-	1.75	0.25
0.85	0.15	🟩	1	0
0.8	0.2	🟩	1.60	0.40
0.8	0.2	-	1	0

L	R			
0.90	0.10	-		
0.85	0.15	🟩	3.35	0.65
0.8	0.2	🟩	2	0
0.8	0.2	-		

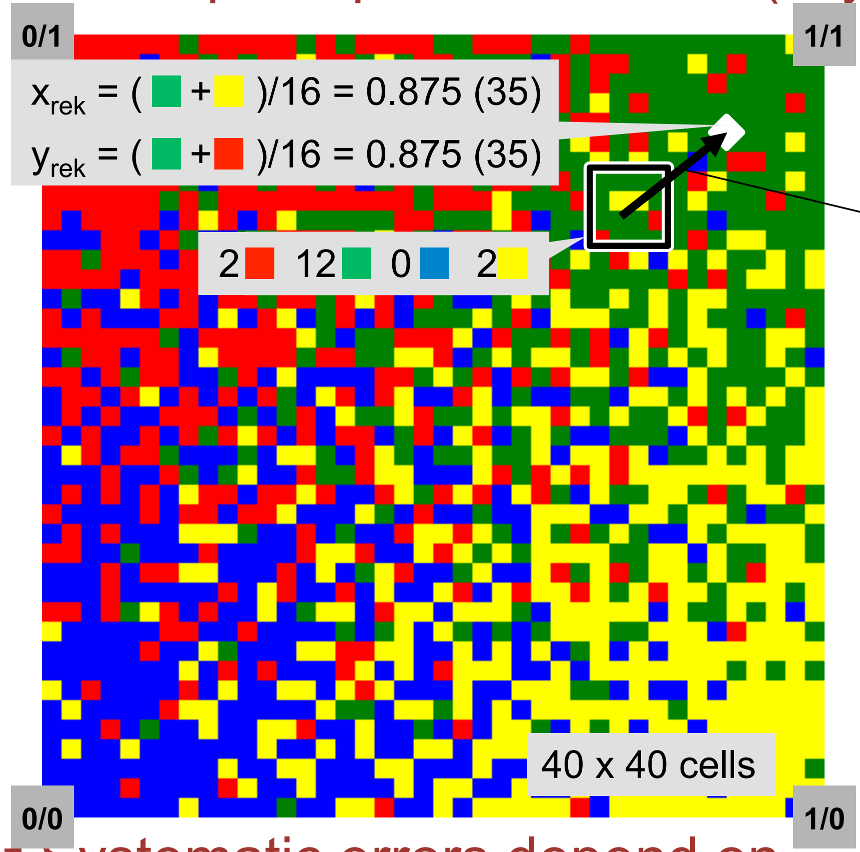
L	R			
0.90	0.10	-		
0.85	0.15	🟩	3.35	0.65
0.8	0.2	🟩	3	0
0.8	0.2	🟩		

Larger Maps (100 × 100)



Systematic Reconstruction Error

- *Discretized* weight function → *systematic* reconstruction errors
- Use square photon clusters (‘crystals’) for simple study

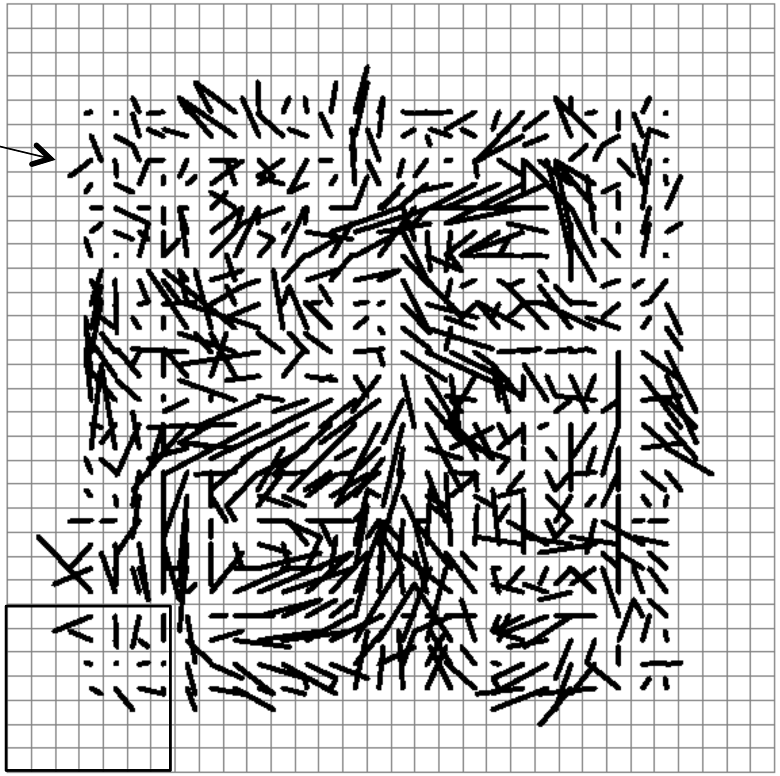


x_{rek} = (🟩 + 🟨)/16 = 0.875 (35)

y_{rek} = (🟩 + 🟥)/16 = 0.875 (35)

2 🟥 12 🟩 0 🟦 2 🟨

Picture of all ‘offset’ arrows

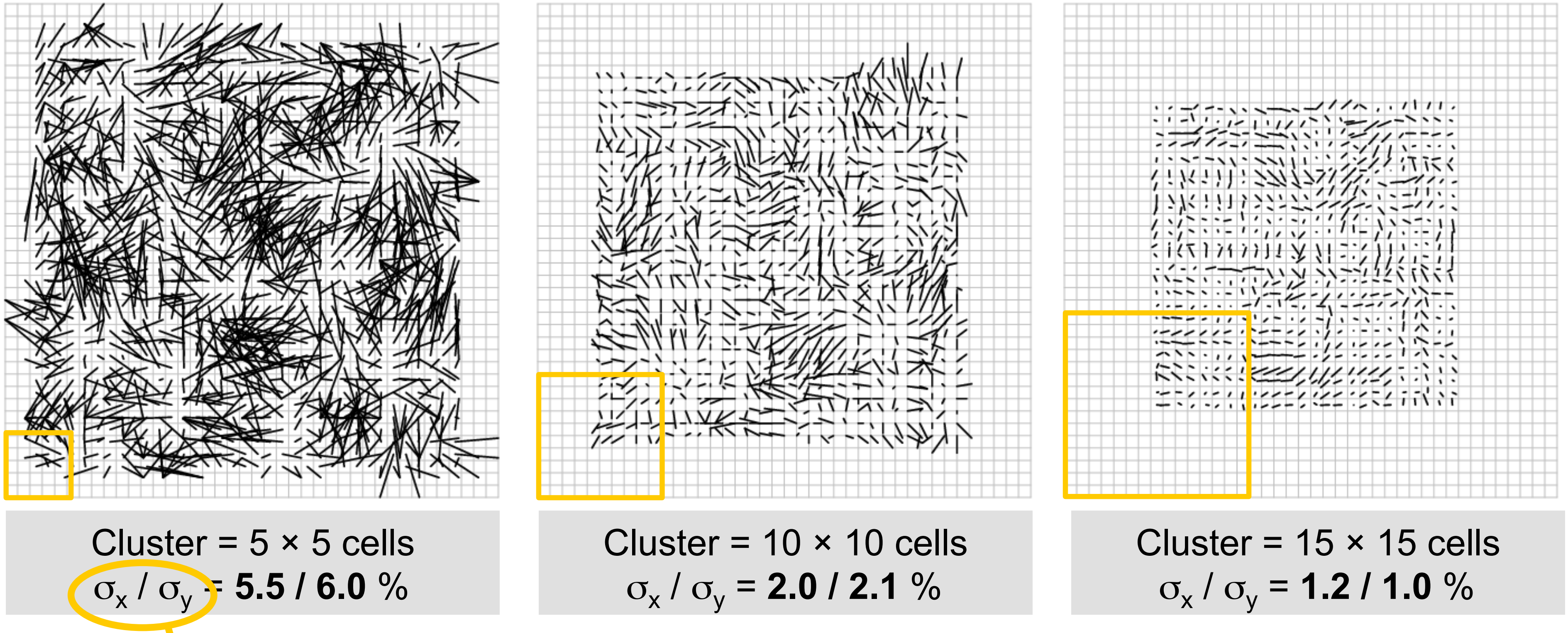


ISiPM with 32 × 32 cells
Clusters of 7 × 7 cells

- Systematic errors depend on
  - # cells on ISiPM (many: better)
  - Size of cluster (large: better)
  - *Quality of cell assignment algorithm*

A: Systematic Reconstruction Error vs. Cluster Size

- Example: ISiPM with 40 × 40 cells



Cluster = 5 × 5 cells
σ_x / σ_y = **5.5 / 6.0** %

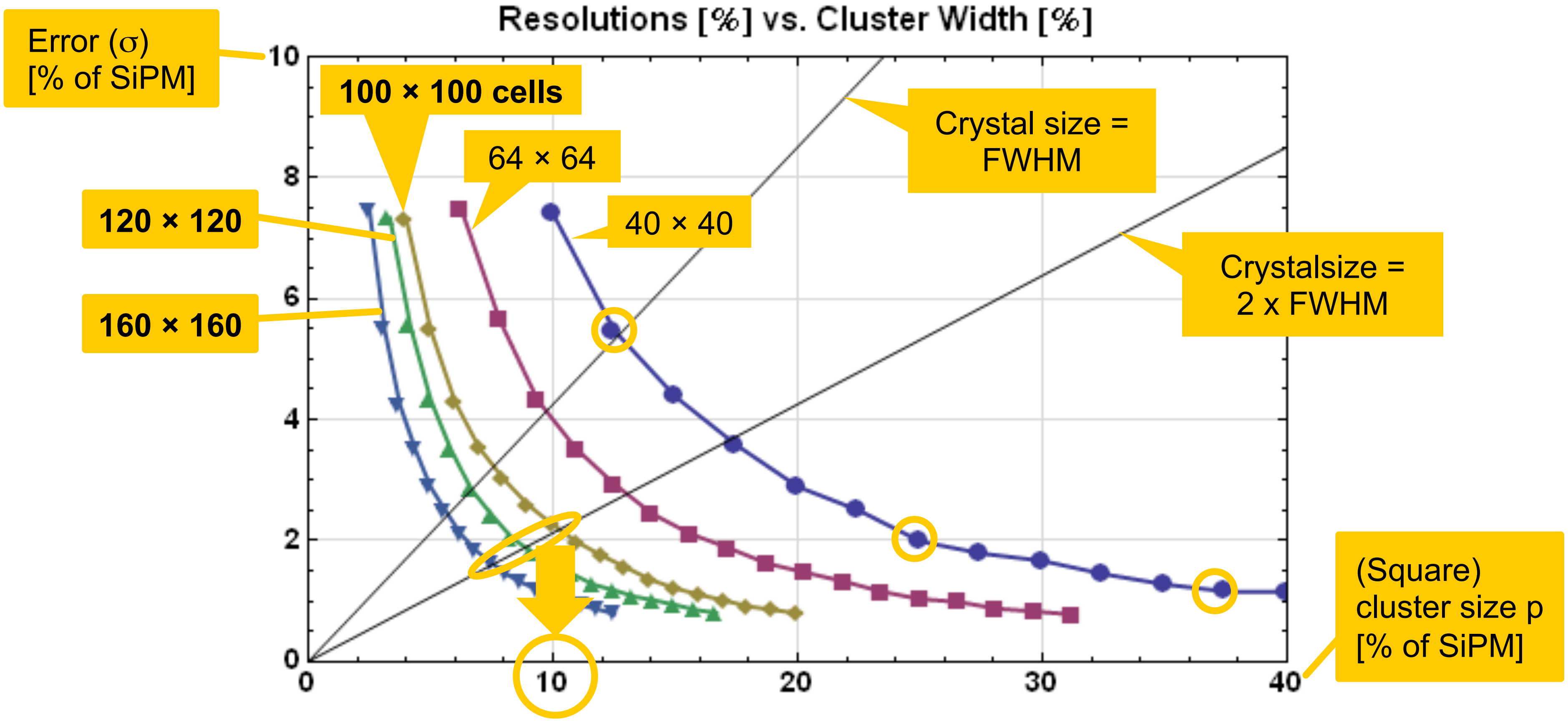
Cluster = 10 × 10 cells
σ_x / σ_y = **2.0 / 2.1** %

Cluster = 15 × 15 cells
σ_x / σ_y = **1.2 / 1.0** %

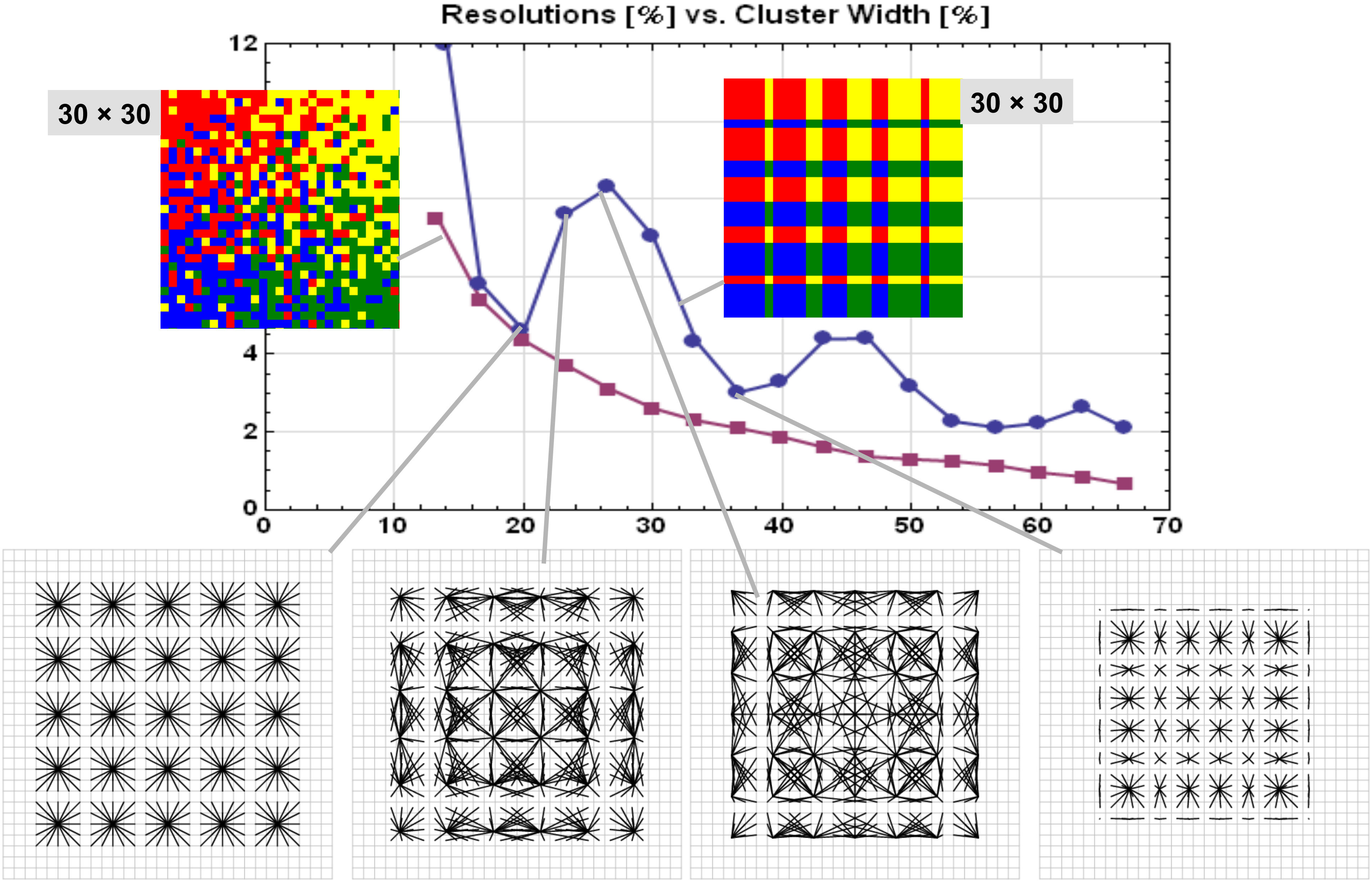
Averaged over all (integer) cluster positions fully on SiPM
(σ given in % of SiPM size)

Systematic Reconstruction Error vs. Cluster Size

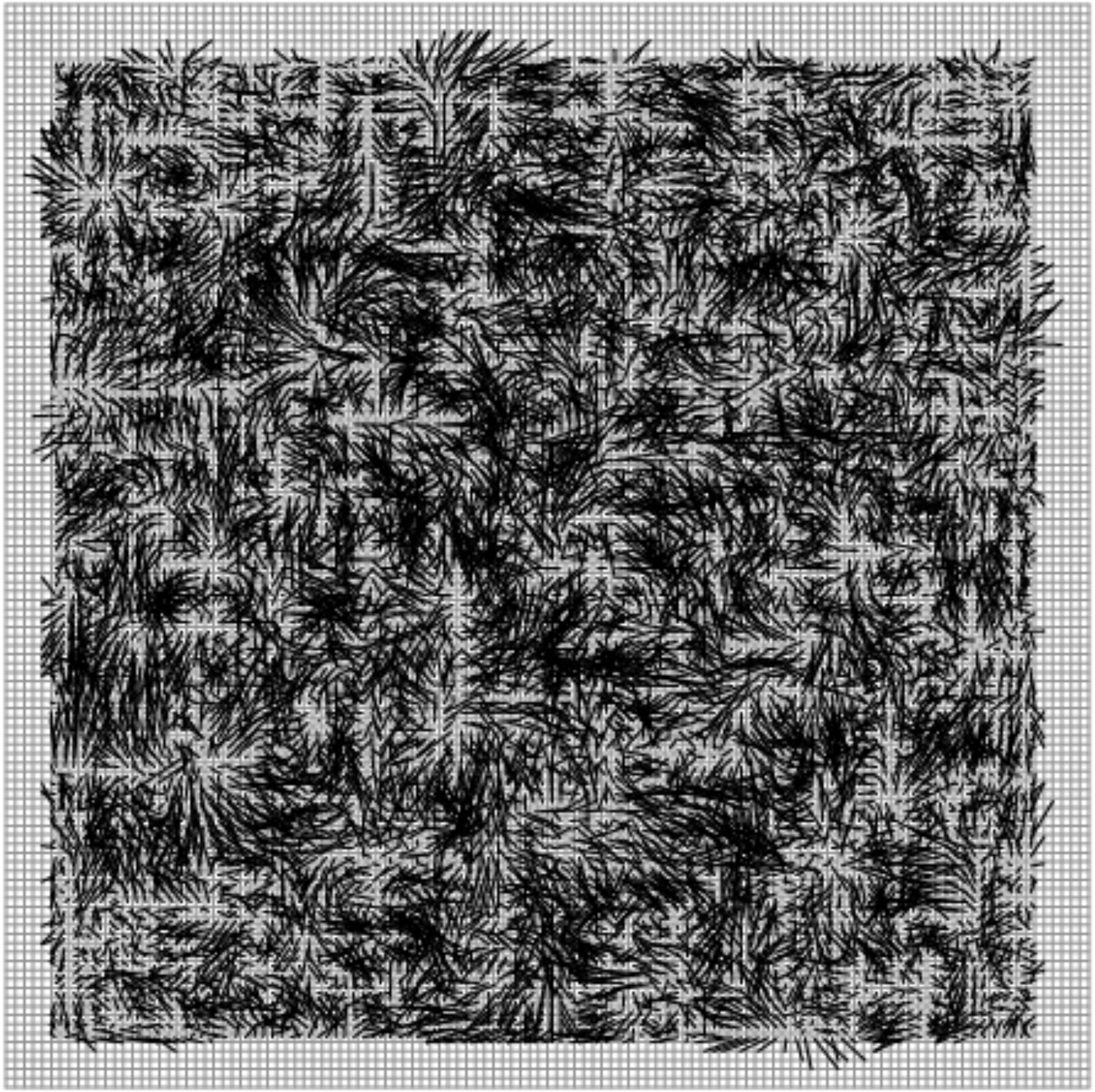
- How small crystals can we identify?
  - Crystals with pitch p can be identified if $\sigma_{Err} \ll p$



ISiPM Mapping is ‘smoother’ than ‘Stripe’ Mapping:

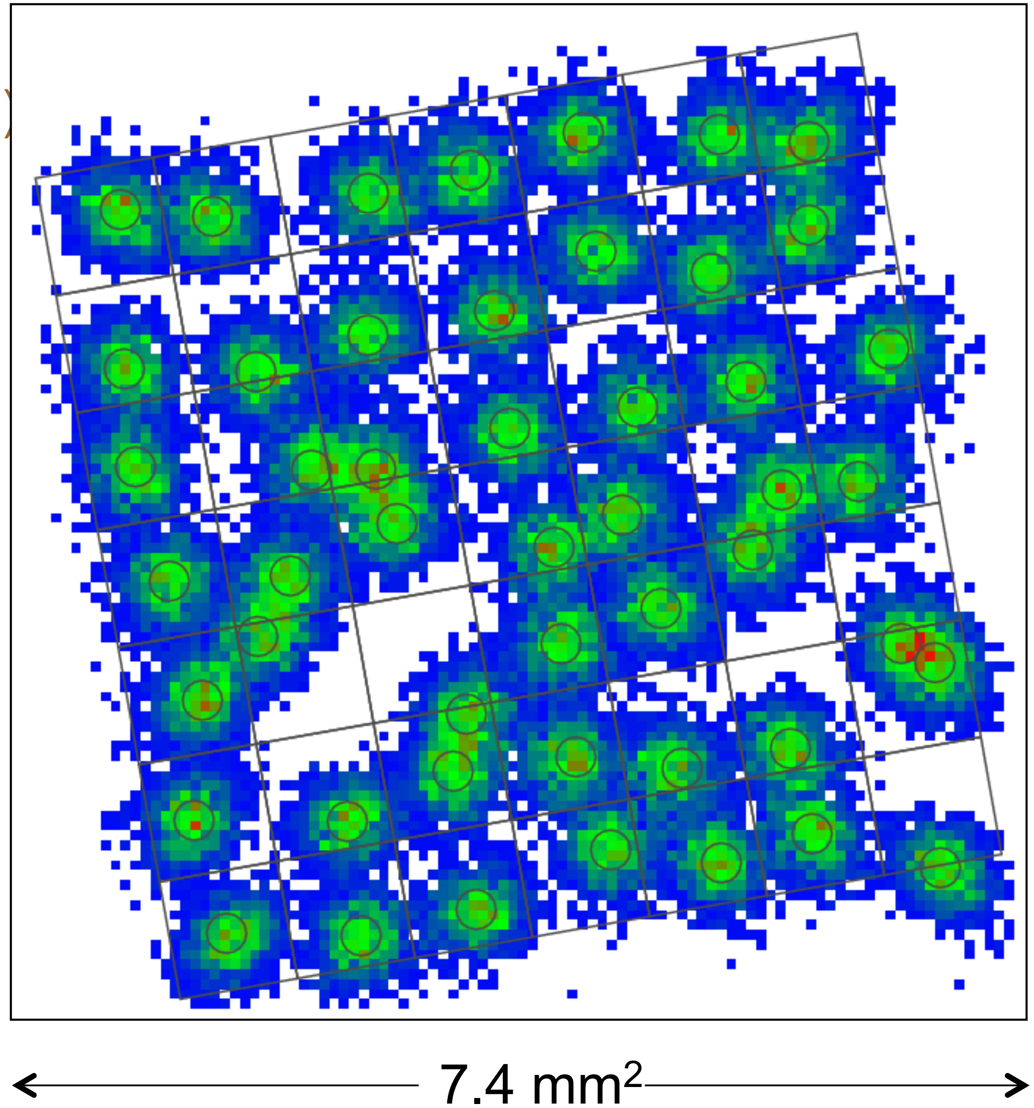


Large SiPM



Putting all together: Flood Map Simulation

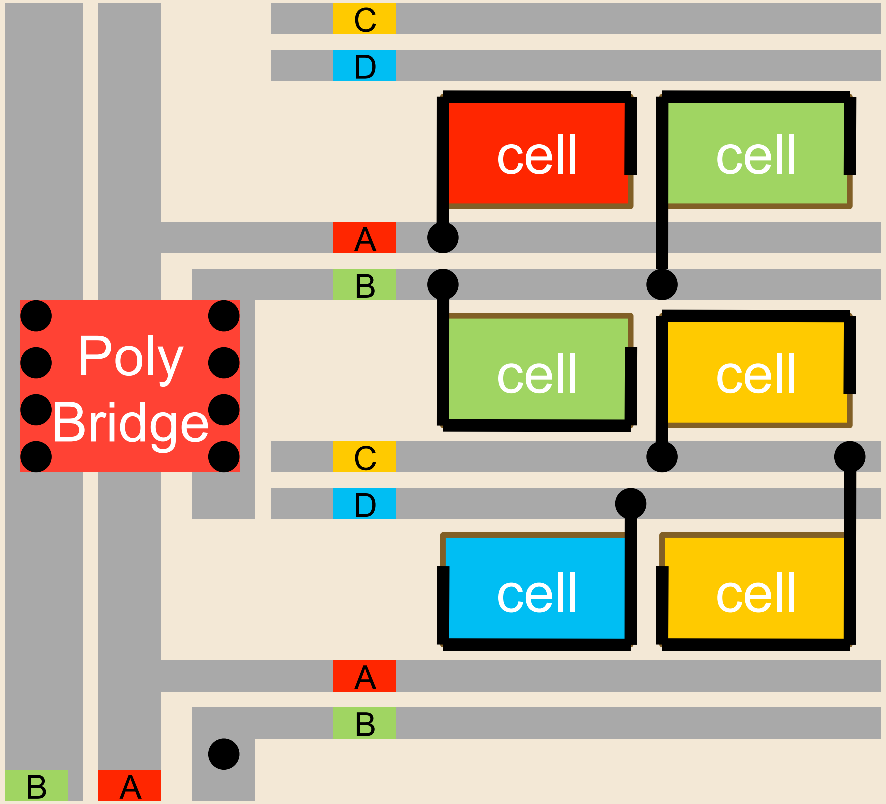
- Example for device simulation:
  - ISiPM with 100^2 cells (e.g. 7.4 mm^2)
  - crystals of 12 × 12 cells (0.9 mm^2)
  - Array of 7 × 7 crystals (tilted to show robustness)
  - Fire 250 random cells / crystal
  - noise per corner: 2 cells (rms)
- Circles ○ show systematic, (known) offsets
- Hit is associated to closest ○
- 7% of hits are associated to wrong crystal (offset by 1)



MAKING REAL DEVICES…

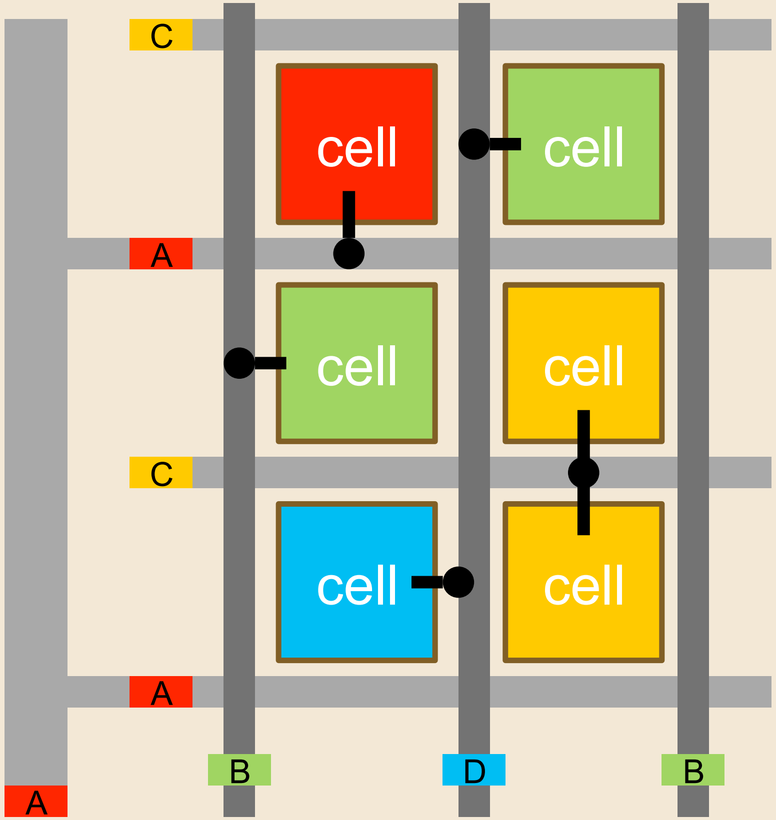
Technology Limitations

With **one** available metal layer



- − large capacitances, series resistance
- − short circuit risk, crosstalk
- − area loss

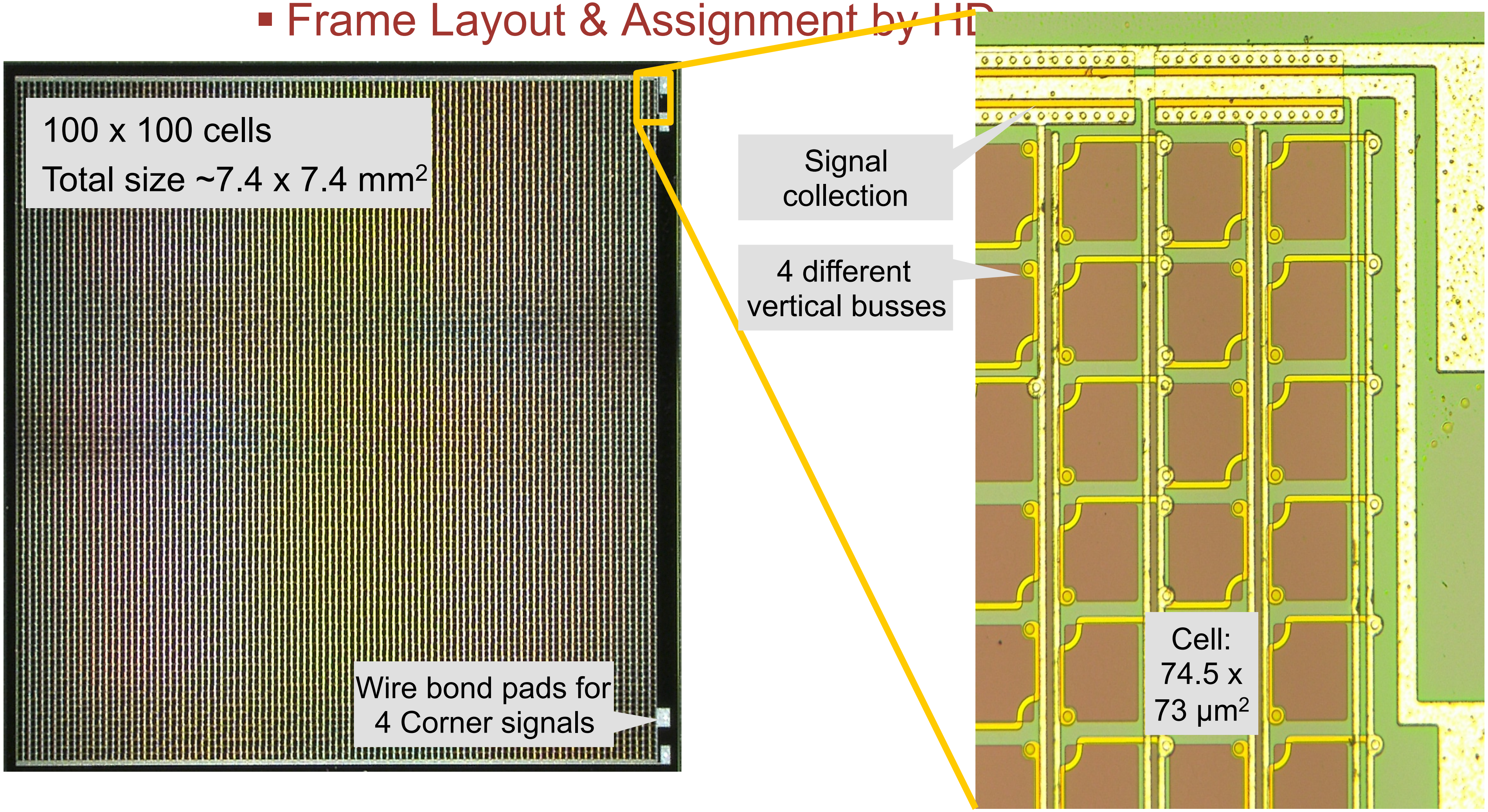
With **two** available metal layers



- − more complex technology
- \+ higher fill factor
- \+ less crosstalk

One Metal Layer Design

- Fabricated at FBK, Trento, Italy
- Frame Layout & Assignment by H



100 x 100 cells

Total size ~7.4 x 7.4 mm^2

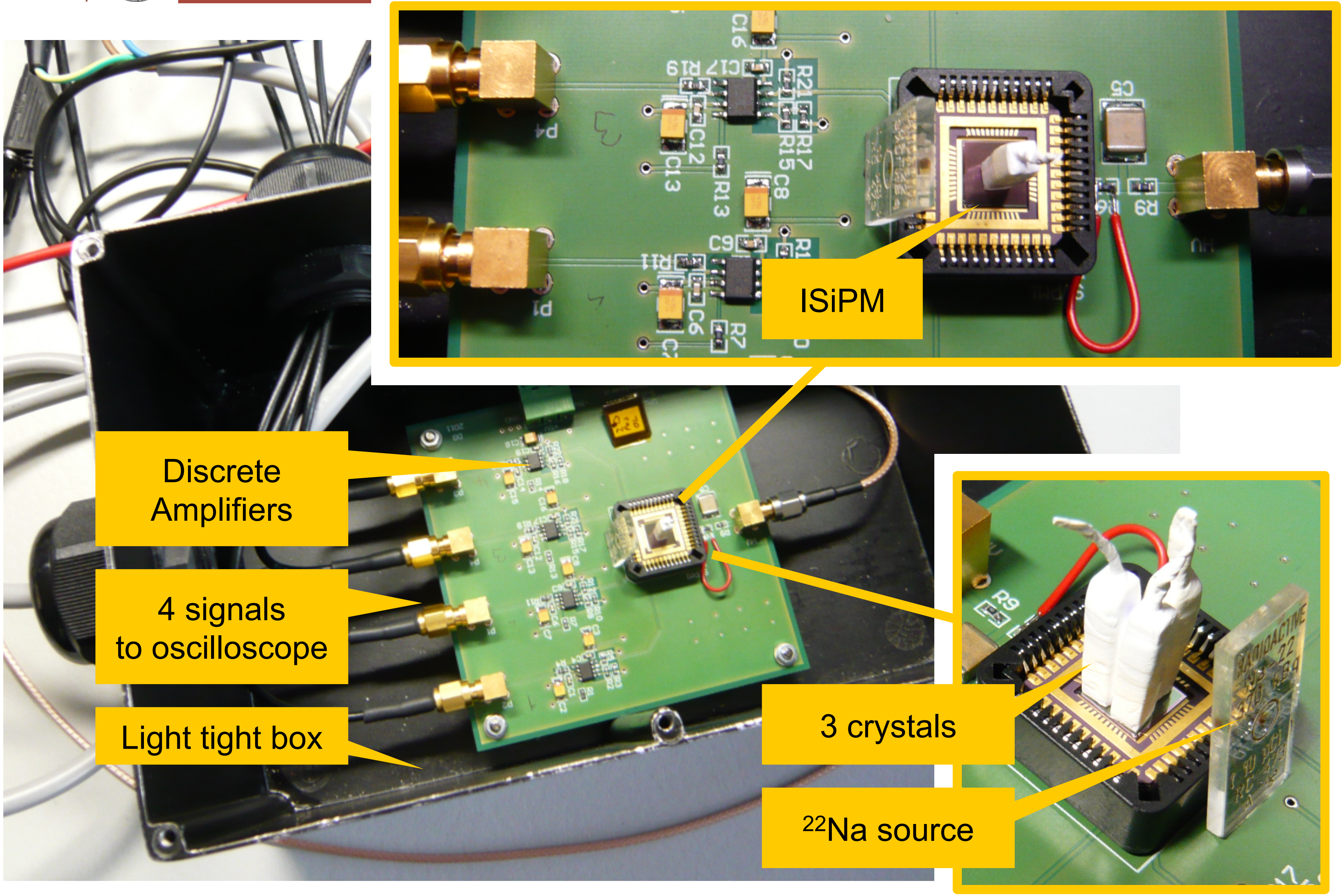
Wire bond pads for 4 Corner signals

Signal collection

4 different vertical busses

Cell: 74.5 x 73 µm^2

The First Test….



ISiPM

Discrete Amplifiers

4 signals to oscilloscope

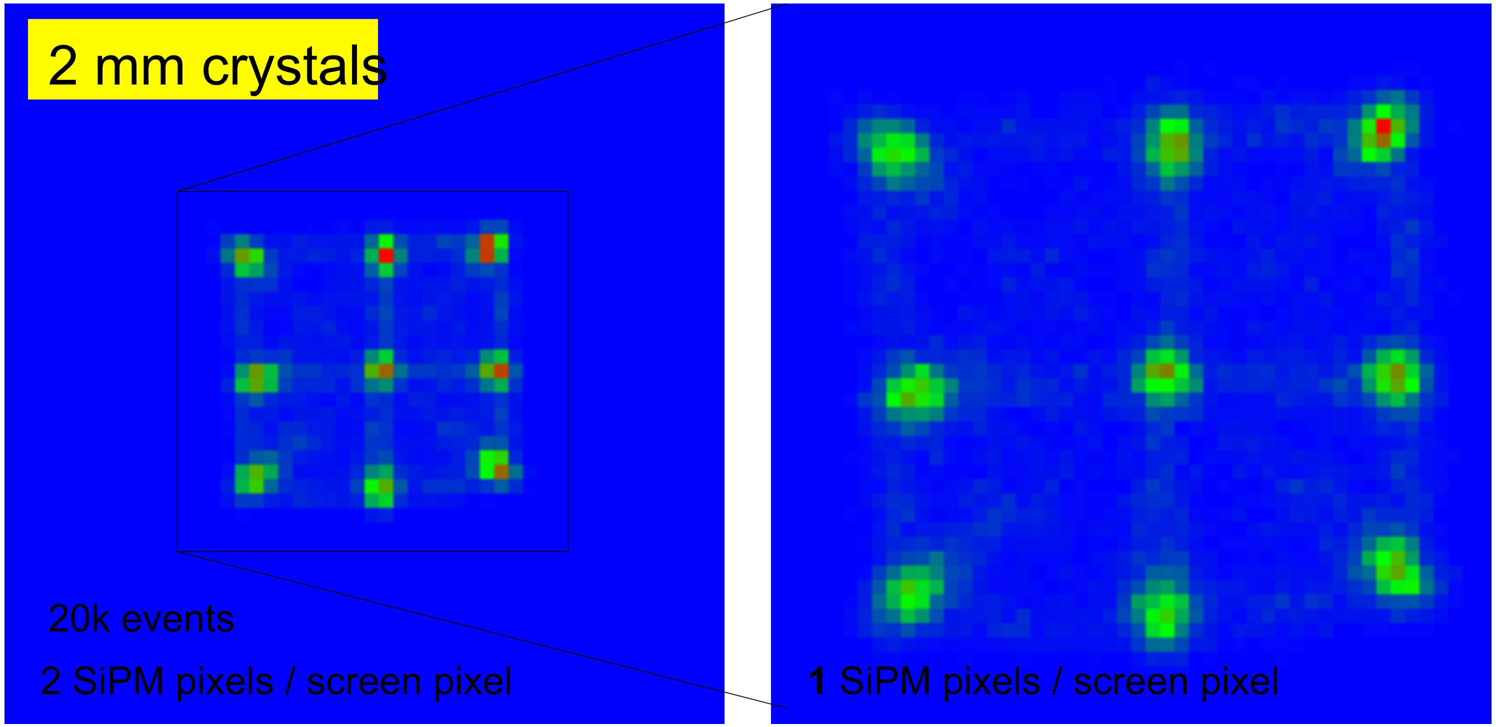
Light tight box

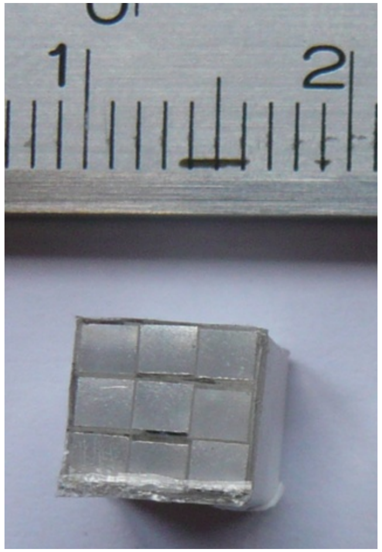
3 crystals

^{22}Na source

Array of 2 mm Crystals

- No source (natural LYSO radioactivity, mix of many amplitudes.)
- No cuts on data (energy, odd events)



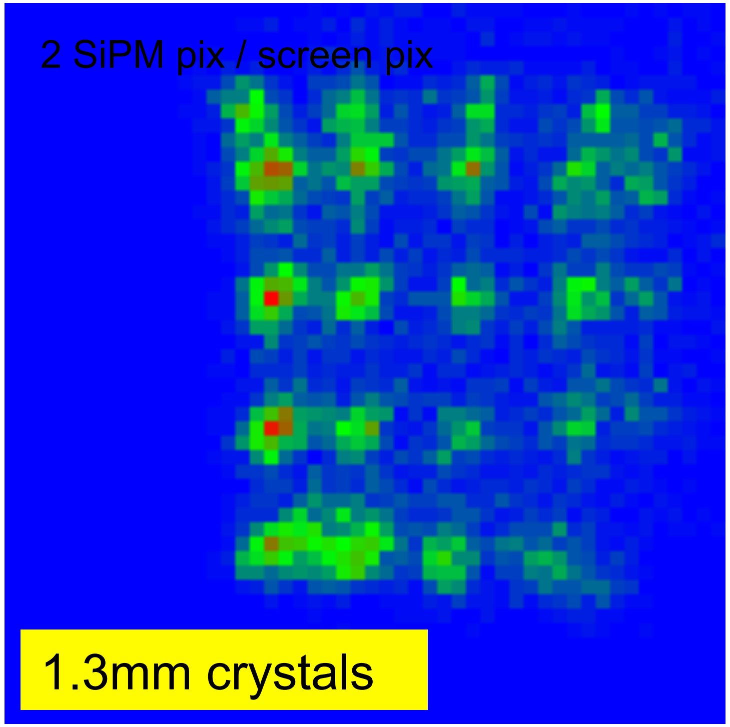


(3×3) × $(2\text{mm})^2$

- Observation: Positions compressed to center

Array of 1.3 mm Crystals

- ^{22}Na source



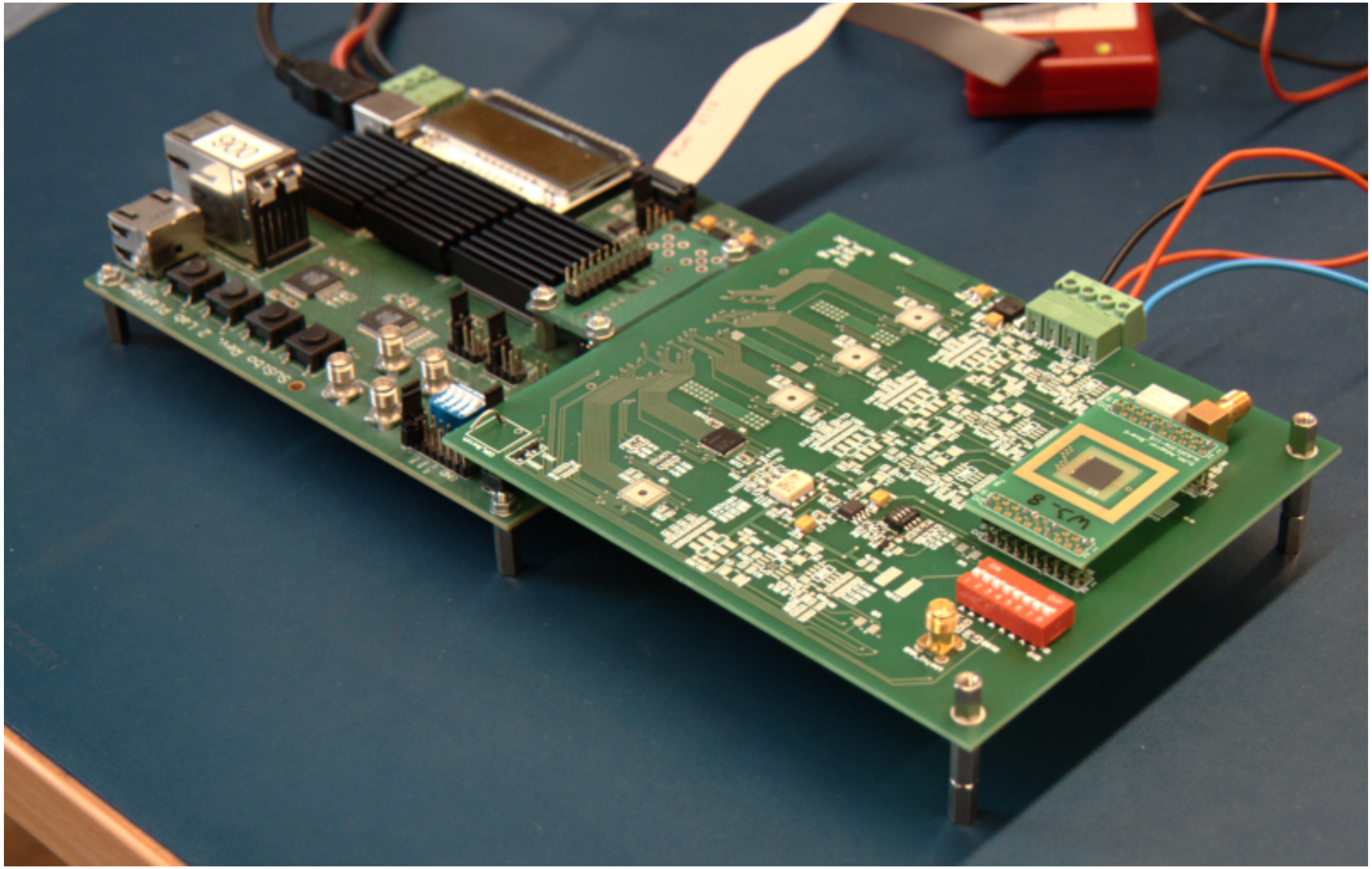
10k events, integral, COG, *No* cuts.

(5x5)
x
(1.3mm)^2

- 1.3mm crystals can still be resolved on 7.4mm device with 100^2 cells
- Note: Scope Trigger favors one corner!

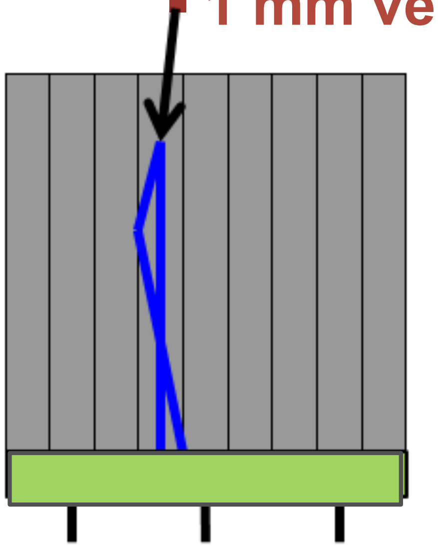
A Better & Faster Setup

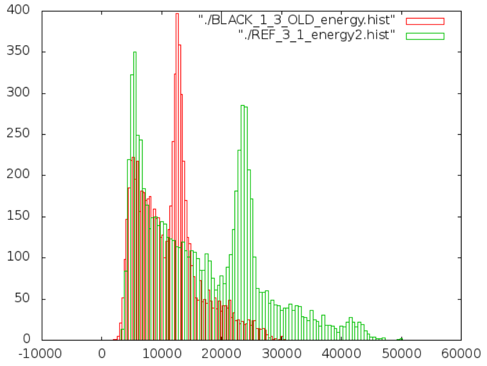
- Use discrete ADCs & USB readout
- 'Fair' trigger

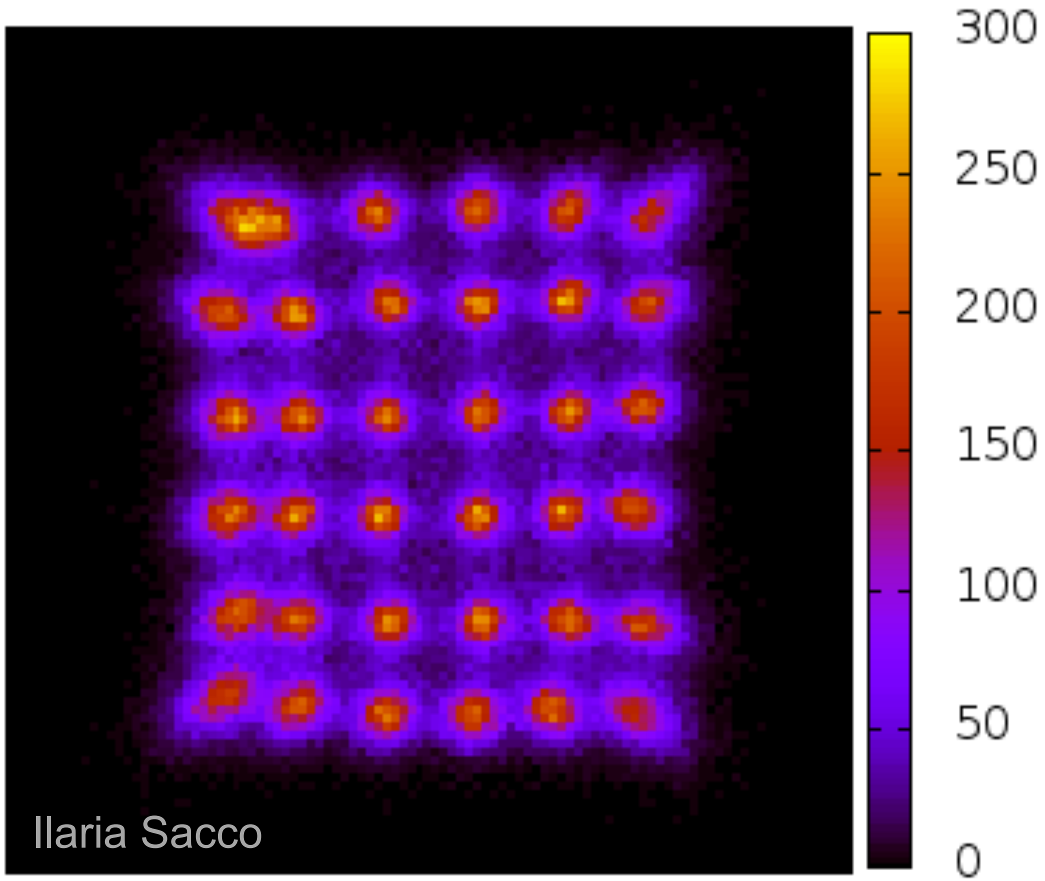


1.0 mm LYSO Crystals

- Flood map: Place source over array, plot reconstructed COGs
- **1 mm very clearly resolved** (~ 7.4mm active area)





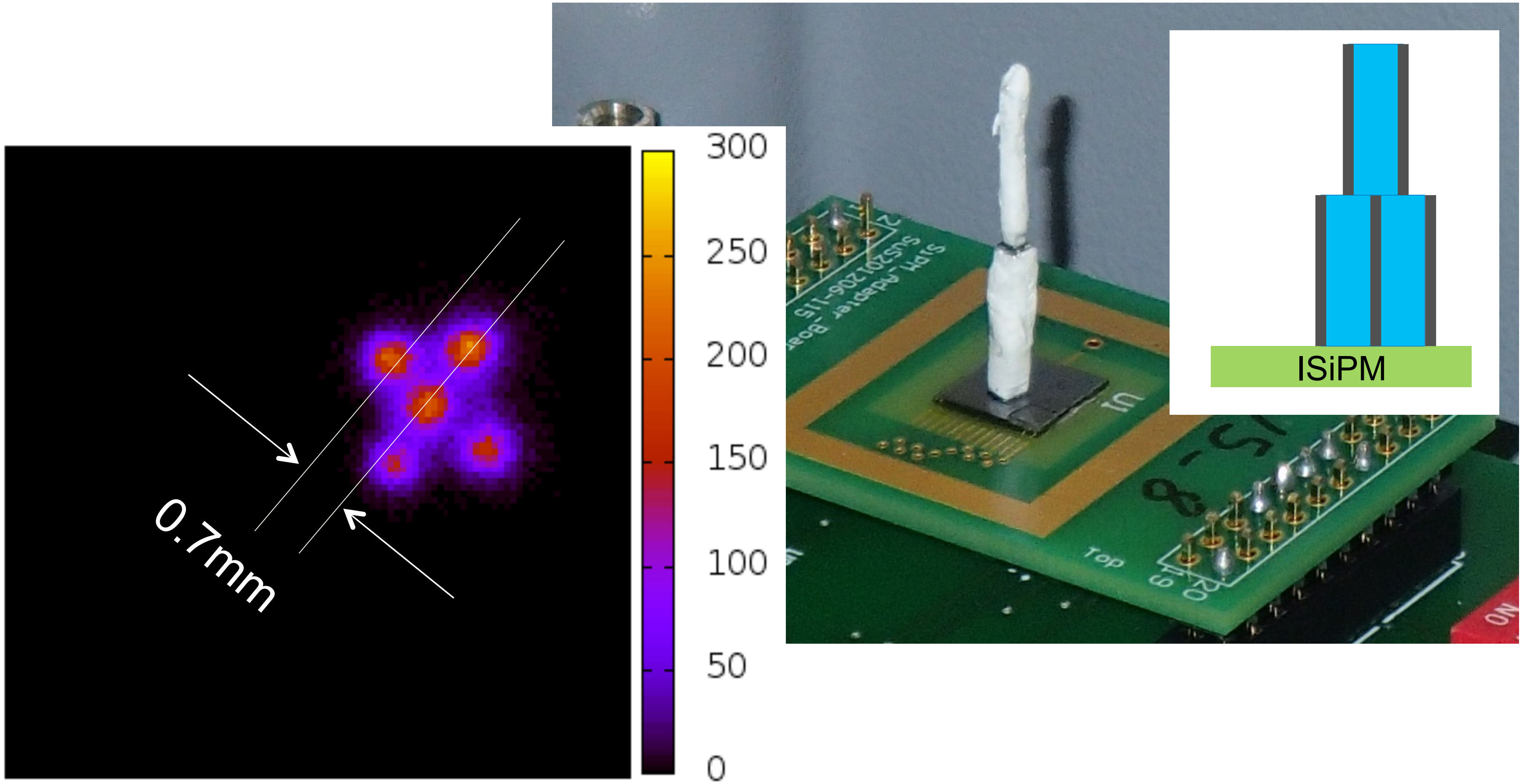


Ilaria Sacco

RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG

Sub-mm Resolution and DOI

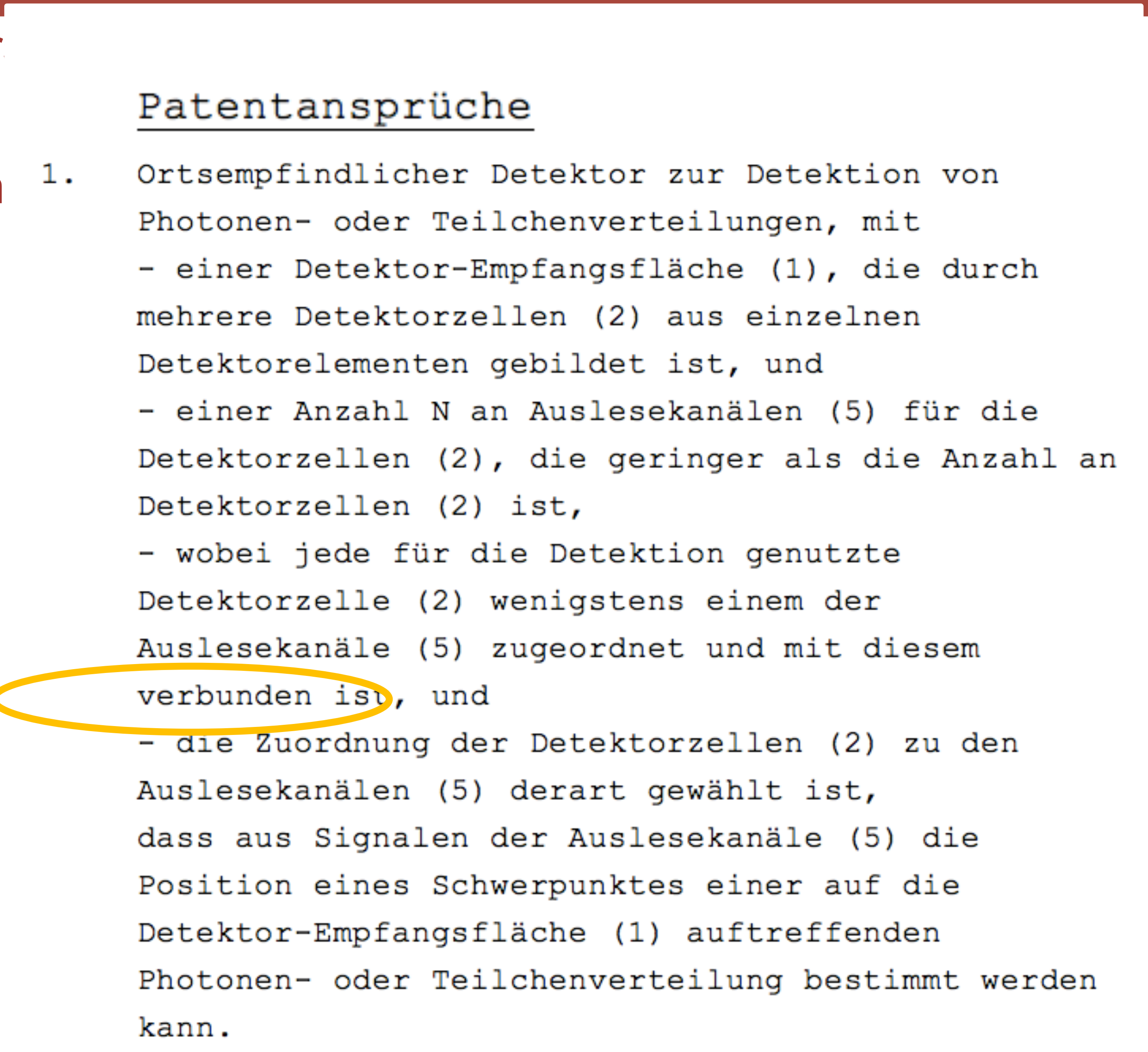
- Stack 1mm crystals (very improvised, but it works!)



- 0.7mm distance clearly resolved !
- DOI ('Depth of Interaction') works !

A Patent…

- Professor
- I tried…
- After man



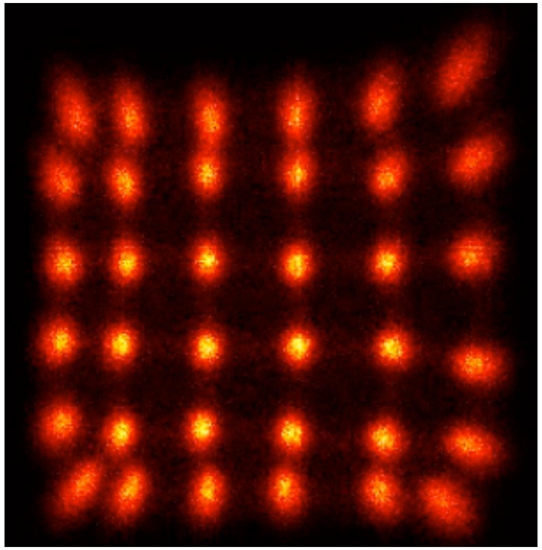
Patentansprüche

1. Ortsempfindlicher Detektor zur Detektion von Photonen- oder Teilchenverteilungen, mit
- einer Detektor-Empfangsfläche (1), die durch mehrere Detektorzellen (2) aus einzelnen Detektorelementen gebildet ist, und
- einer Anzahl N an Auslesekanälen (5) für die Detektorzellen (2), die geringer als die Anzahl an Detektorzellen (2) ist,
- wobei jede für die Detektion genutzte Detektorzelle (2) wenigstens einem der Auslesekanäle (5) zugeordnet und mit diesem verbunden ist, und
- die Zuordnung der Detektorzellen (2) zu den Auslesekanälen (5) derart gewählt ist, dass aus Signalen der Auslesekanäle (5) die Position eines Schwerpunktes einer auf die Detektor-Empfangsfläche (1) auftreffenden Photonen- oder Teilchenverteilung bestimmt werden kann.

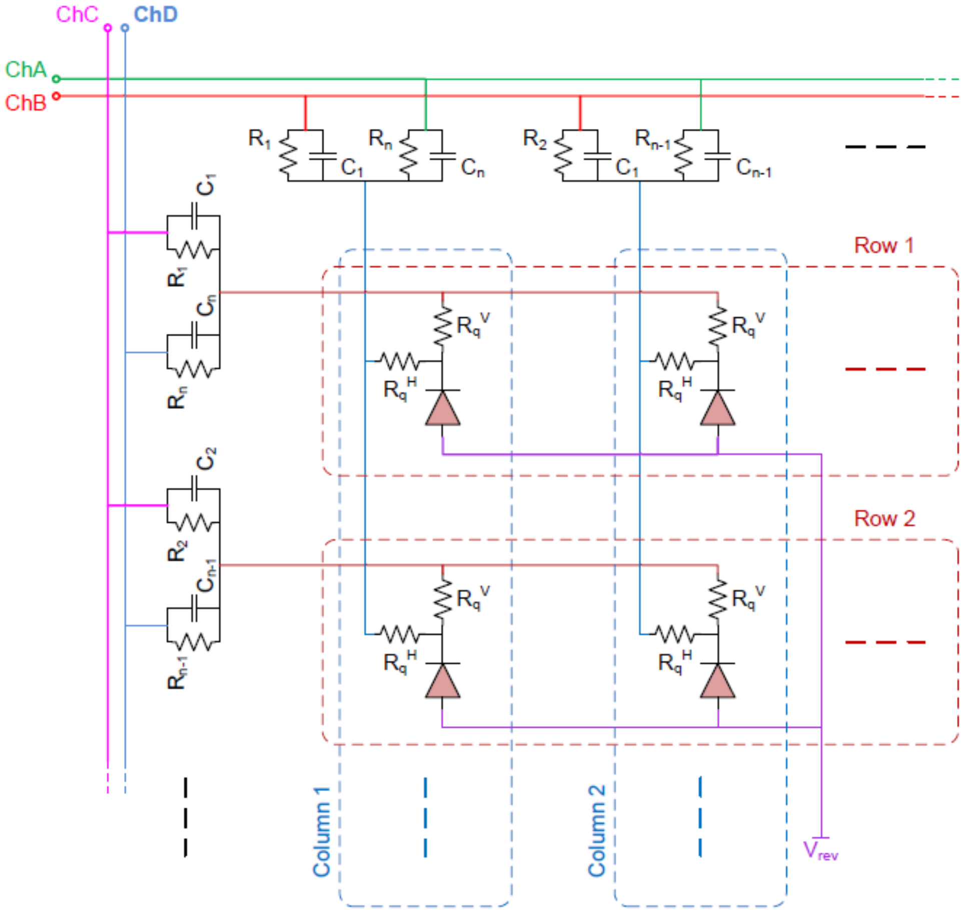
This restriction was a big mistake

Competition: Linear Graded SiPM (LG-SiPM)

- Collect row/column contributions with (equal) *resistors* in pixels
- Generate linear gradients in x- and y in periphery
- More complicated, but one pixel already is reconstructed correctly!



LG-SiPM, (4 mm)^2 area
Array with **0.53 mm** pitch



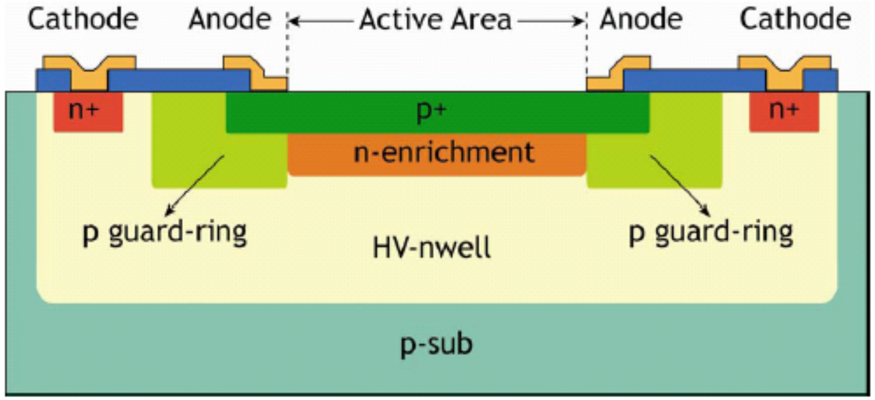
A. Gola, *A. Ferri, A. Tarolli, N. Zorzi, C. Piemonte:*
A Novel Approach to Position-Sensitive Silicon Photomultipliers: First Results

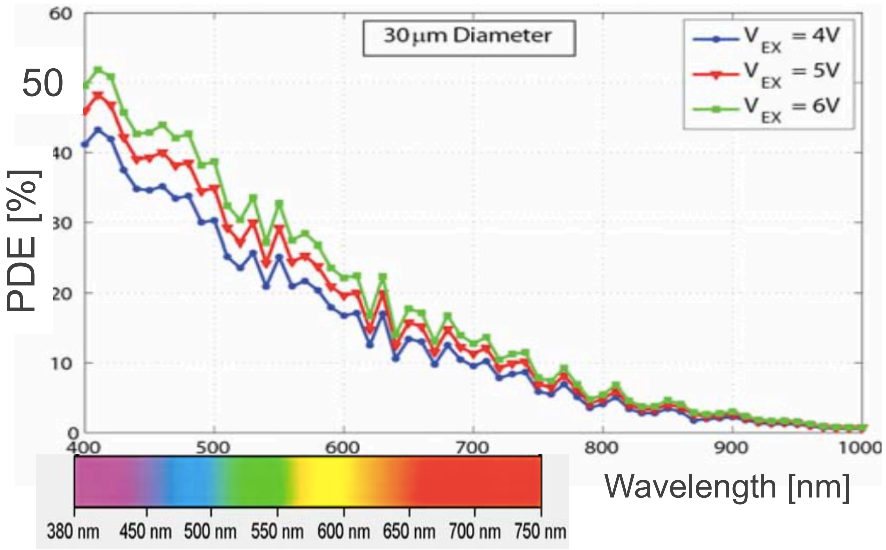
RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG

SIPM IN A CMOS TECHNOLOGY

The Fraunhofer SPAD process

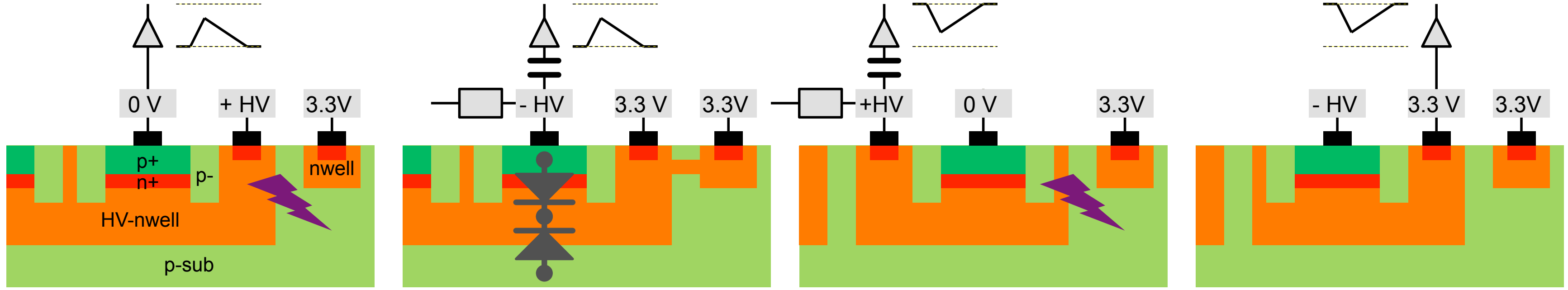
- Fraunhofer Institute IMS (Duisburg, Germany) has modified their in-house 0.35µm 4M2P-CMOS technology to obtain good SPADs





- Very encouraging properties were published:
  - Low Dark Count Rate ('DCR') (~ 20kcps / mm^2 @ RT)
  - Good uniformity (~ 95% SPADs have similar DCR)
  - Low after pulsing (< 1%)
  - Good Photon Detection Efficiency ('PDE')(~ 40% for blue light)

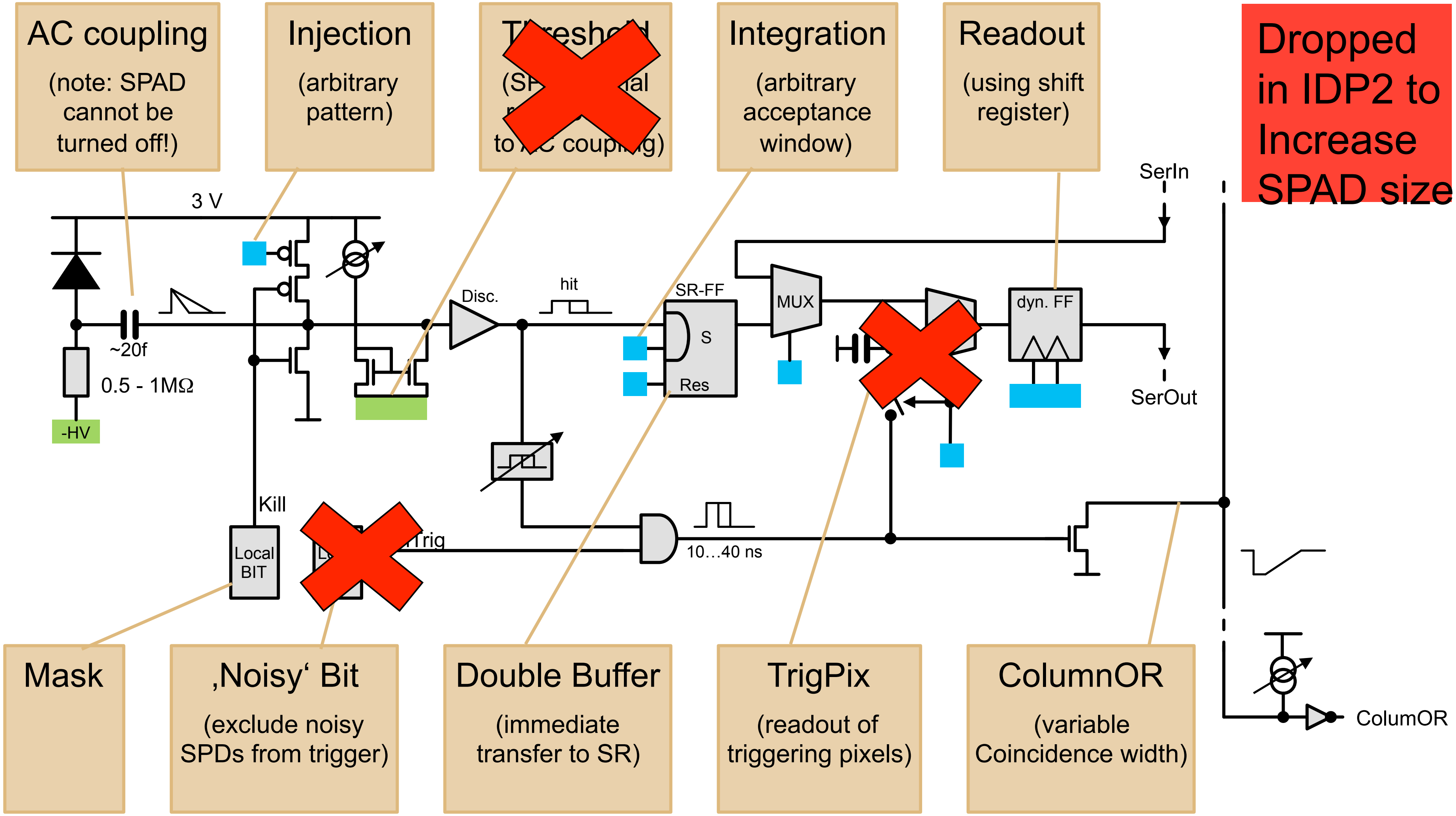
SPAD Readout: 4 Options



Readout at p+ anode = Pixel		Readout at Cathode = nwell	
HV @ nwell	HV @ Pixel	HV @ nwell	HV @ Pixel
Well spacing (HV-3.3V)	Can merge wells	Well spacing (HV-3.3V)	Well Spacing (signal!)
Small SPAD capacitance		Large SPAD capacitance	
No crosstalk		Crosstalk risk	
DC coupling, Quenching	Requires R and HV-C, No active quenching		Dc coupling, Quenching
☹	☺	☹	😐

CHOSEN for highest Density
UNUSUAL!

Pixel Architecture



AC coupling
(note: SPAD cannot be turned off!)

Injection
(arbitrary pattern)

~~Threshold~~
~~(SP al r to AC coupling)~~

Integration
(arbitrary acceptance window)

Readout
(using shift register)

Dropped in IDP2 to Increase SPAD size

Mask

‚Noisy‘ Bit
(exclude noisy SPDs from trigger)

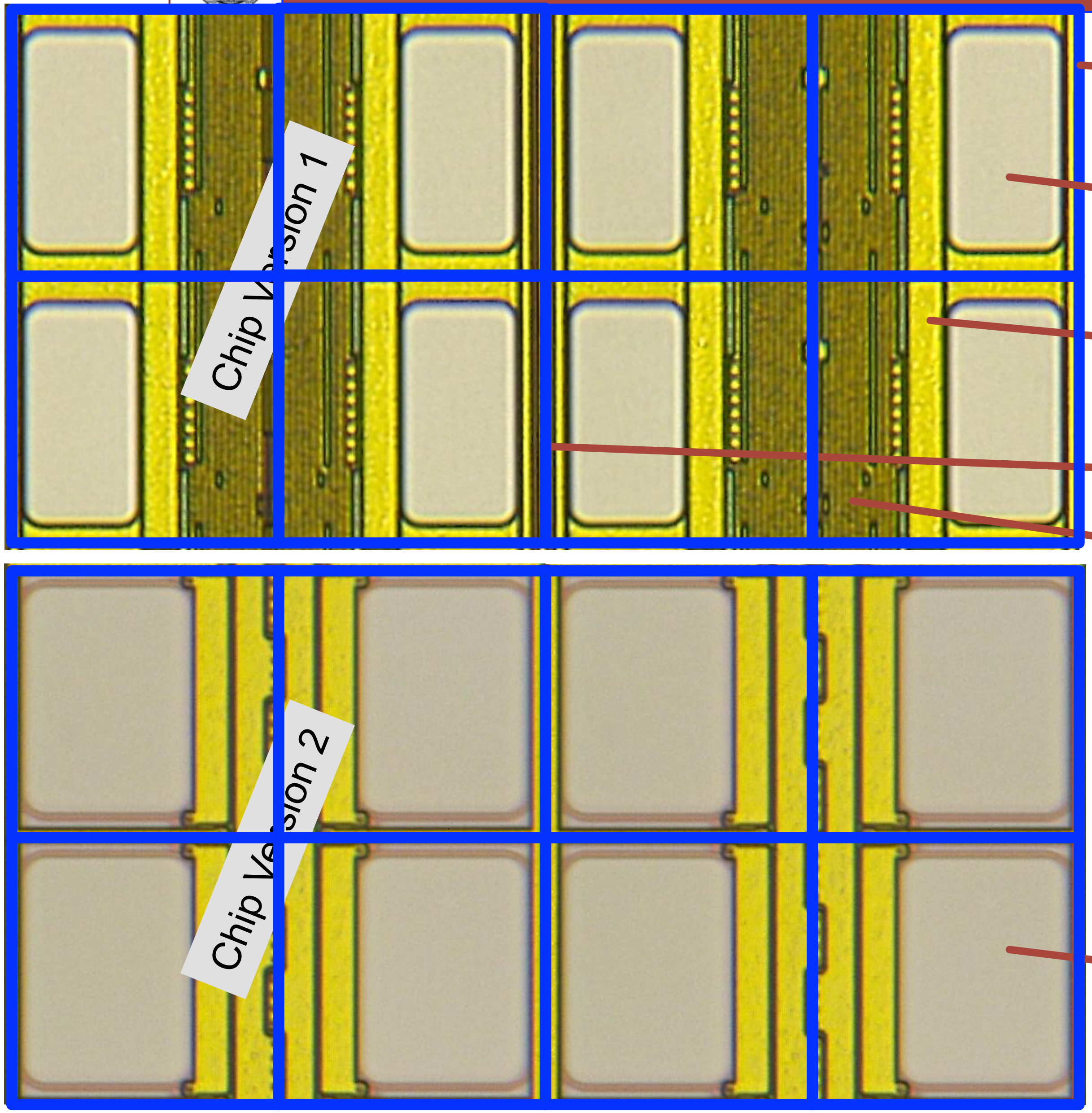
Double Buffer
(immediate transfer to SR)

TrigPix
(readout of triggering pixels)

ColumnOR
(variable Coincidence width)

(slightly simplified schematic)

Chip Photo: Pixel Array



Pixel
56.44 × 56.44 µm^2

SPAD
38% fill factor

AC coupling
Cap M1-M2-M3

HV

Readout Busses

SPAD
55% fill factor

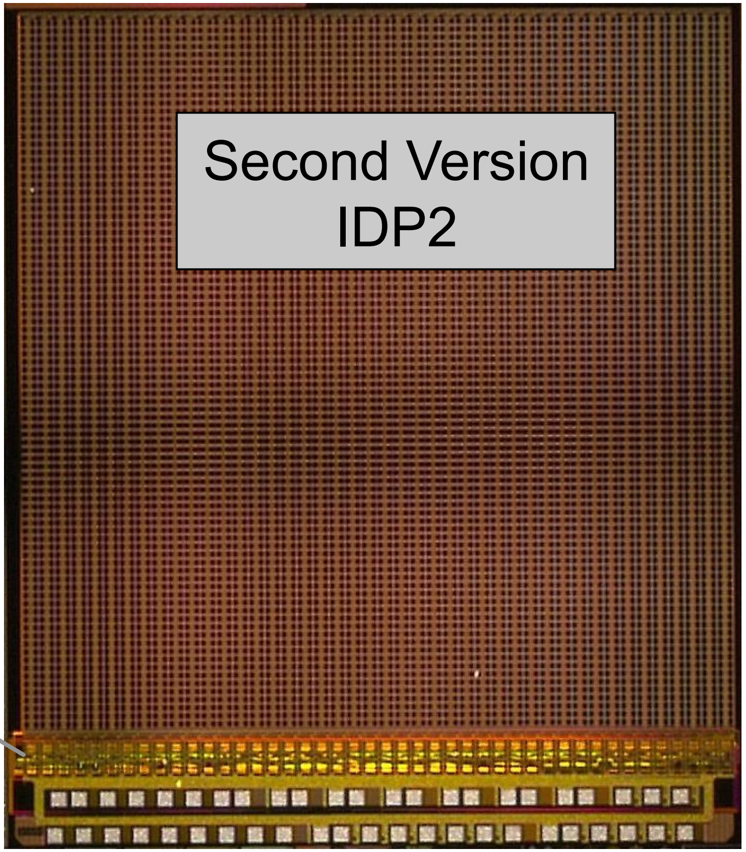
Chip Photo: Top

3 side buttable

88 × 88 Pixel
56.44 × 56.44 µm²

Pixel Area
~ 5 × 5 mm²

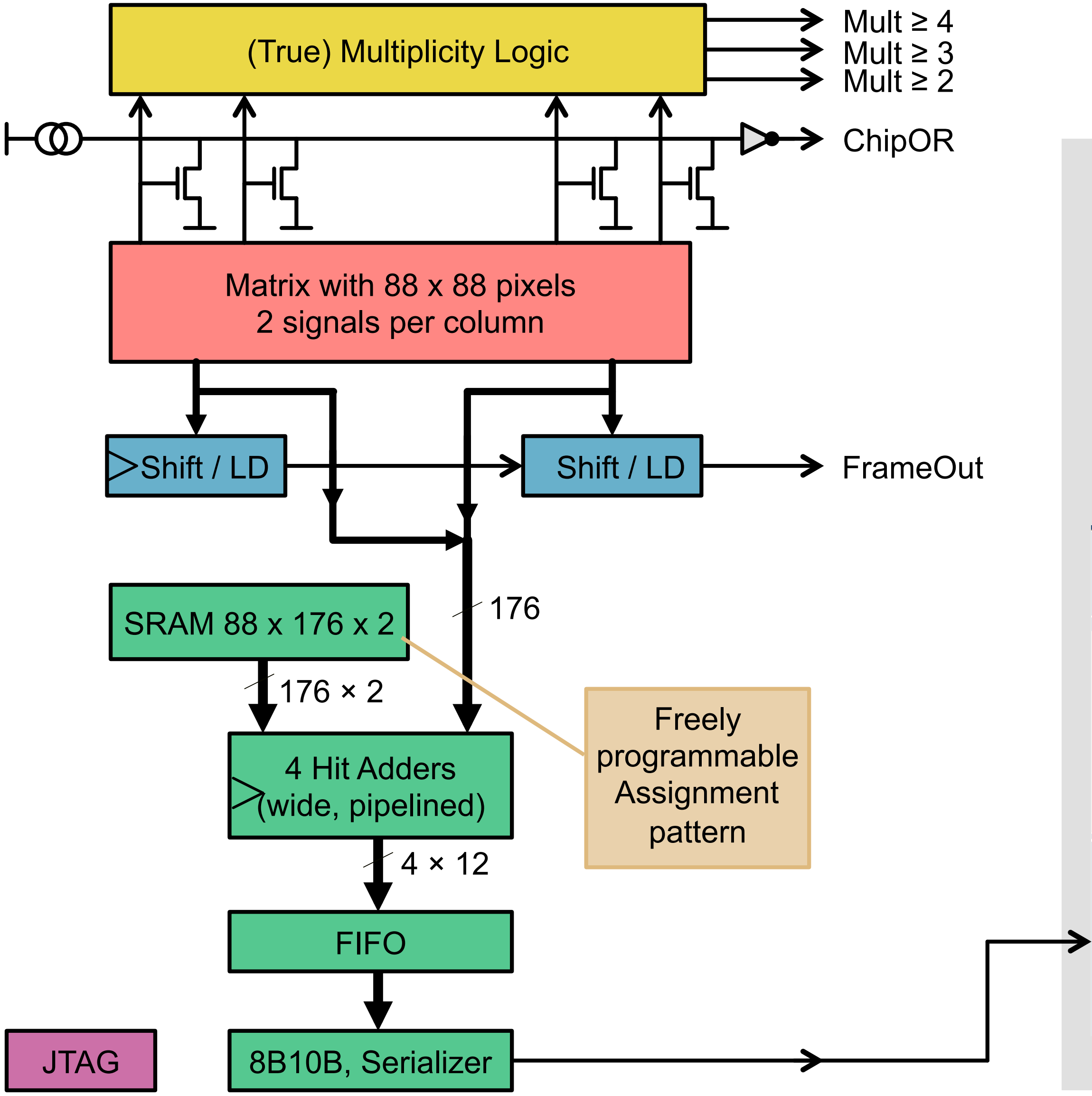
Hit-OR, Multiplicity



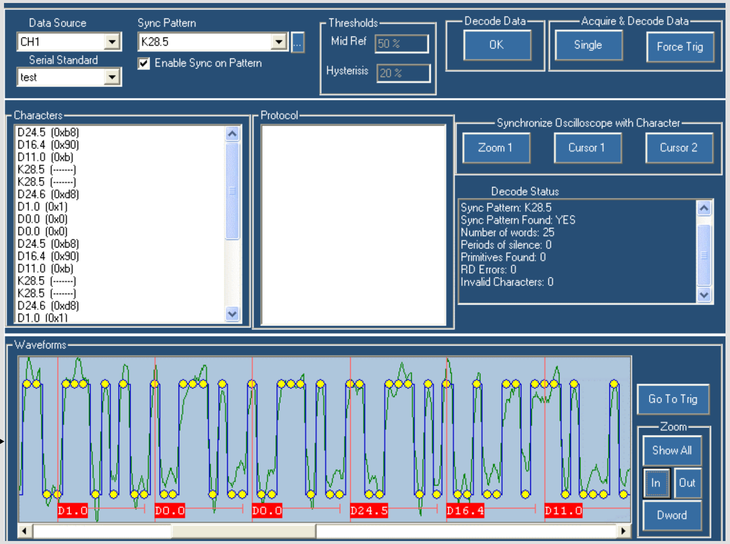
Synthesized, fully Autonomous Readout

Periphery
~ 1.5 mm

Overall Architecture IPD1



- Design bug:
  x-addressing in matrix forgotten
  → can only kill full rows
- All other tested parts work as expected

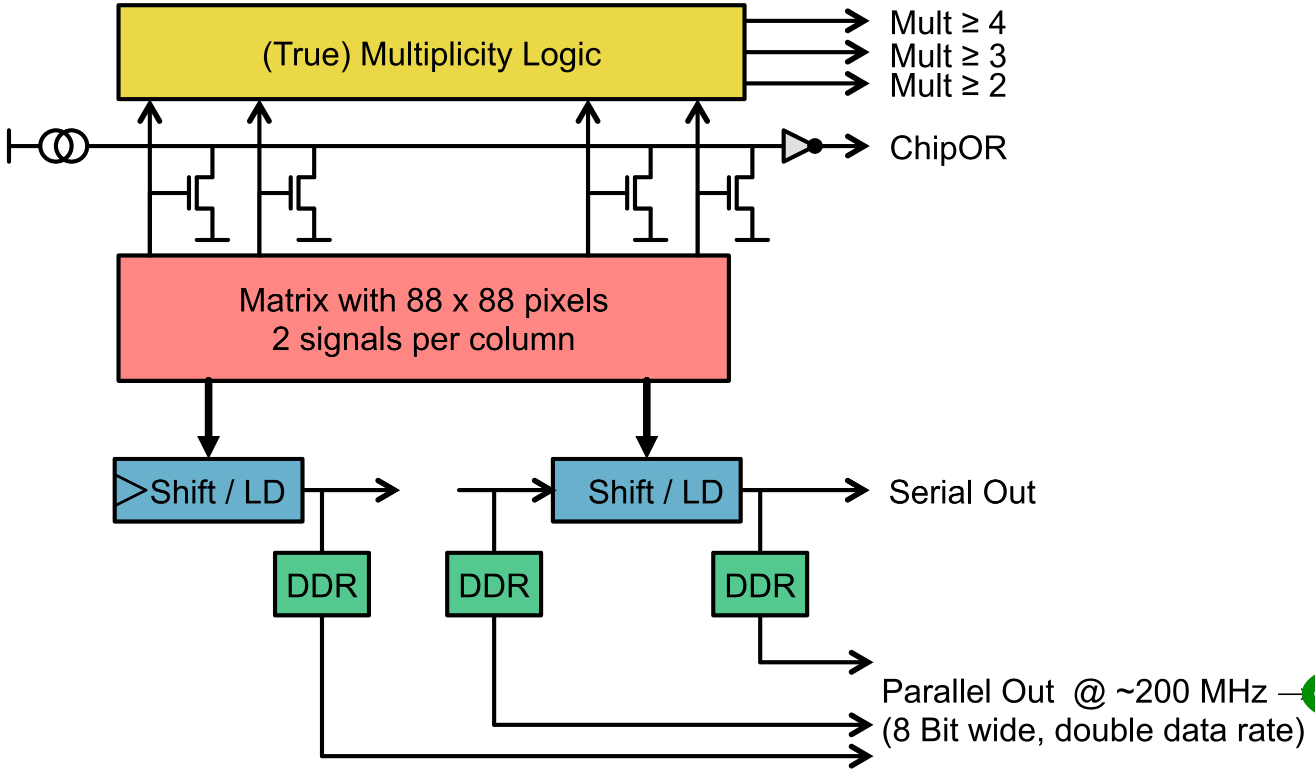


Data Source: CH1
Serial Standard: test
Sync Pattern: K28.5
☑ Enable Sync on Pattern
Mid Ref: 50 %
Hysterisis: 20 %

```
D24.5 (0xb8)
D16.4 (0x90)
D11.0 (0xb)
K28.5 (-------)
K28.5 (-------)
D24.6 (0xd8)
D1.0 (0x1)
D0.0 (0x0)
D0.0 (0x0)
D24.5 (0xb8)
D16.4 (0x90)
D11.0 (0xb)
K28.5 (-------)
K28.5 (-------)
D24.6 (0xd8)
D1.0 (0x1)
```

```
Sync Pattern: K28.5
Sync Pattern Found: YES
Number of words: 25
Periods of silence: 0
Primitives Found: 0
RD Errors: 0
Invalid Characters: 0
```

Overall Architecture IPD2



(True) Multiplicity Logic

Mult ≥ 4
Mult ≥ 3
Mult ≥ 2

ChipOR

Matrix with 88 x 88 pixels
2 signals per column

Shift / LD

Shift / LD

Serial Out

DDR

DDR

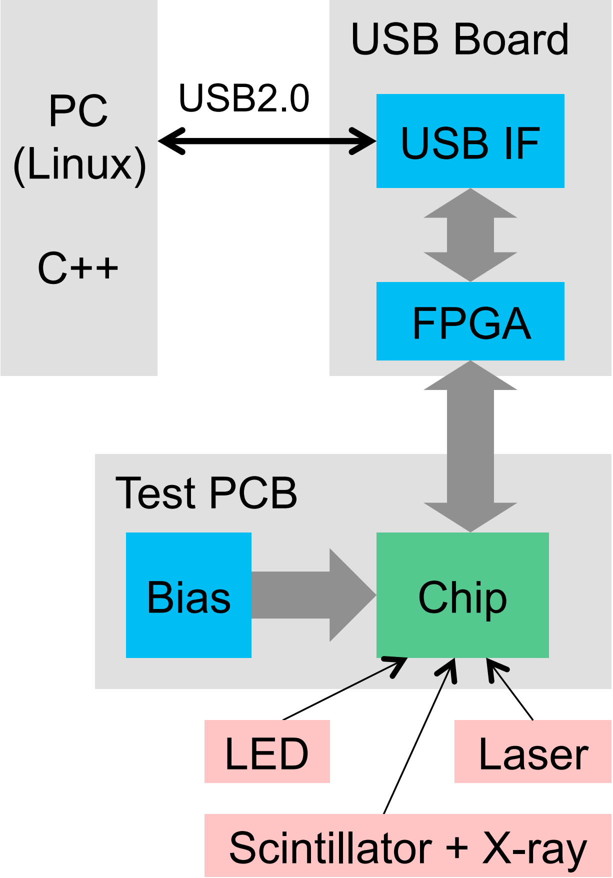
DDR

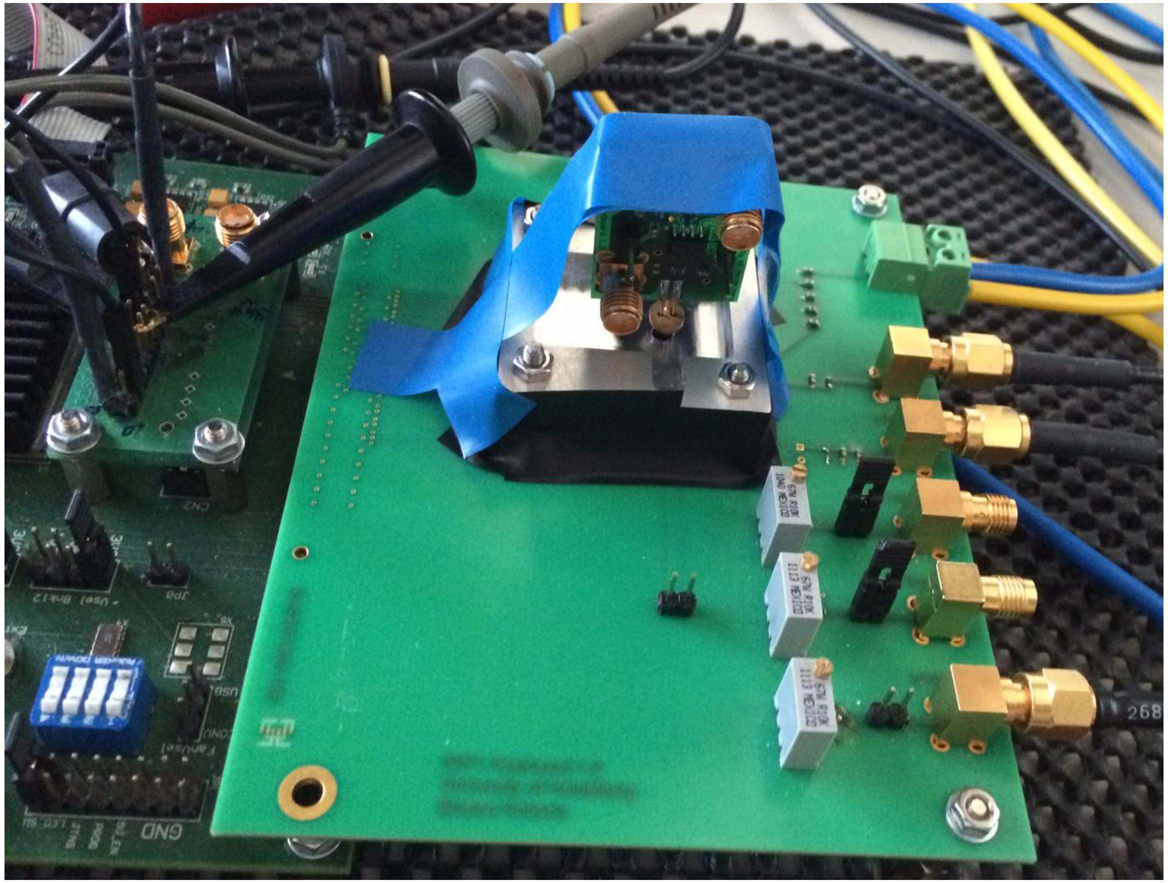
Parallel Out @ ~200 MHz → 400.000 full images / second
(8 Bit wide, double data rate)

This is really fast…

First test setup

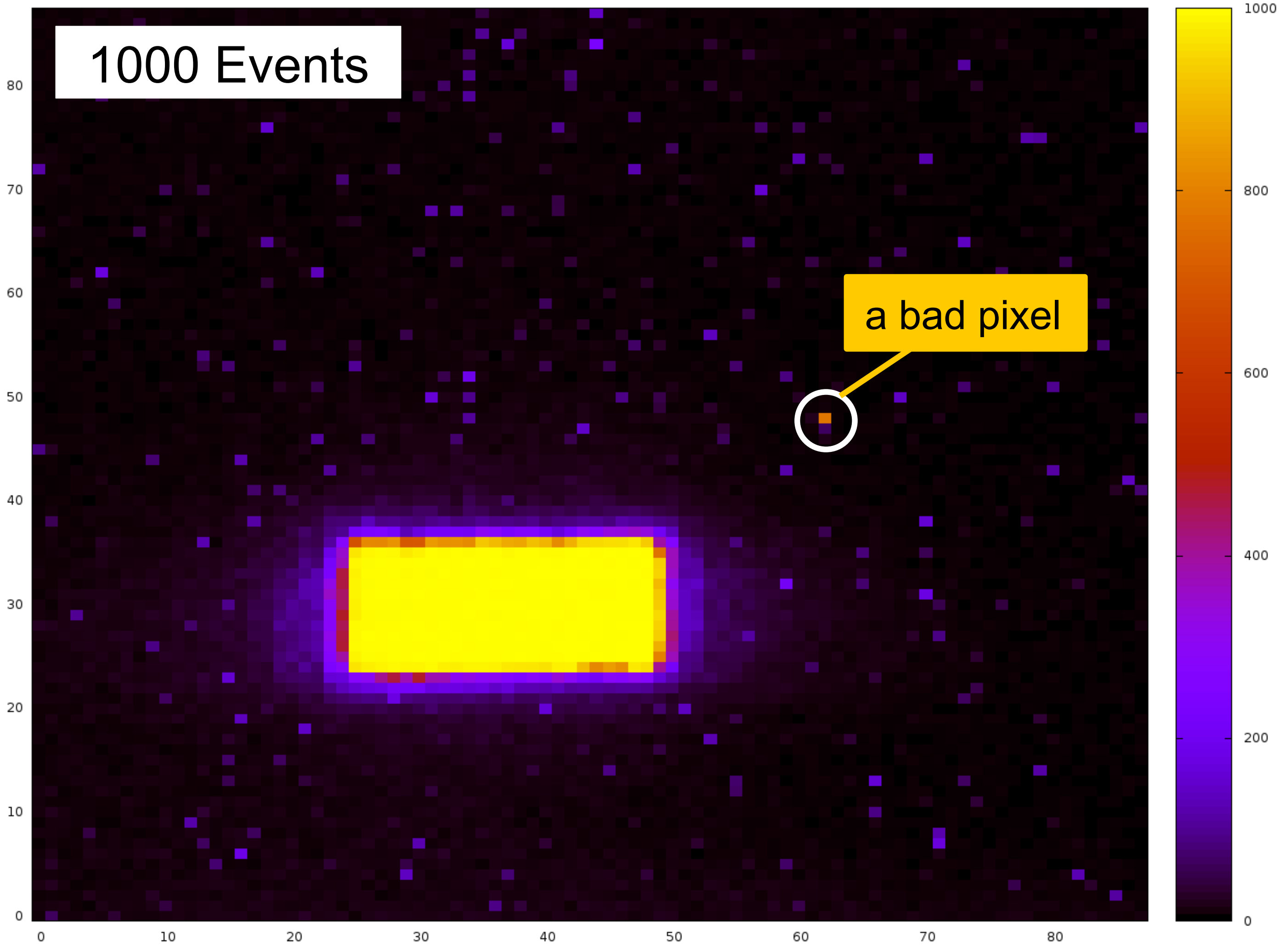
- ‘quick & dirty’: recycle FPGA board from our group….
- no cooling → run mostly @ ~30°C
- ‘low’ data rate (USB2.0)





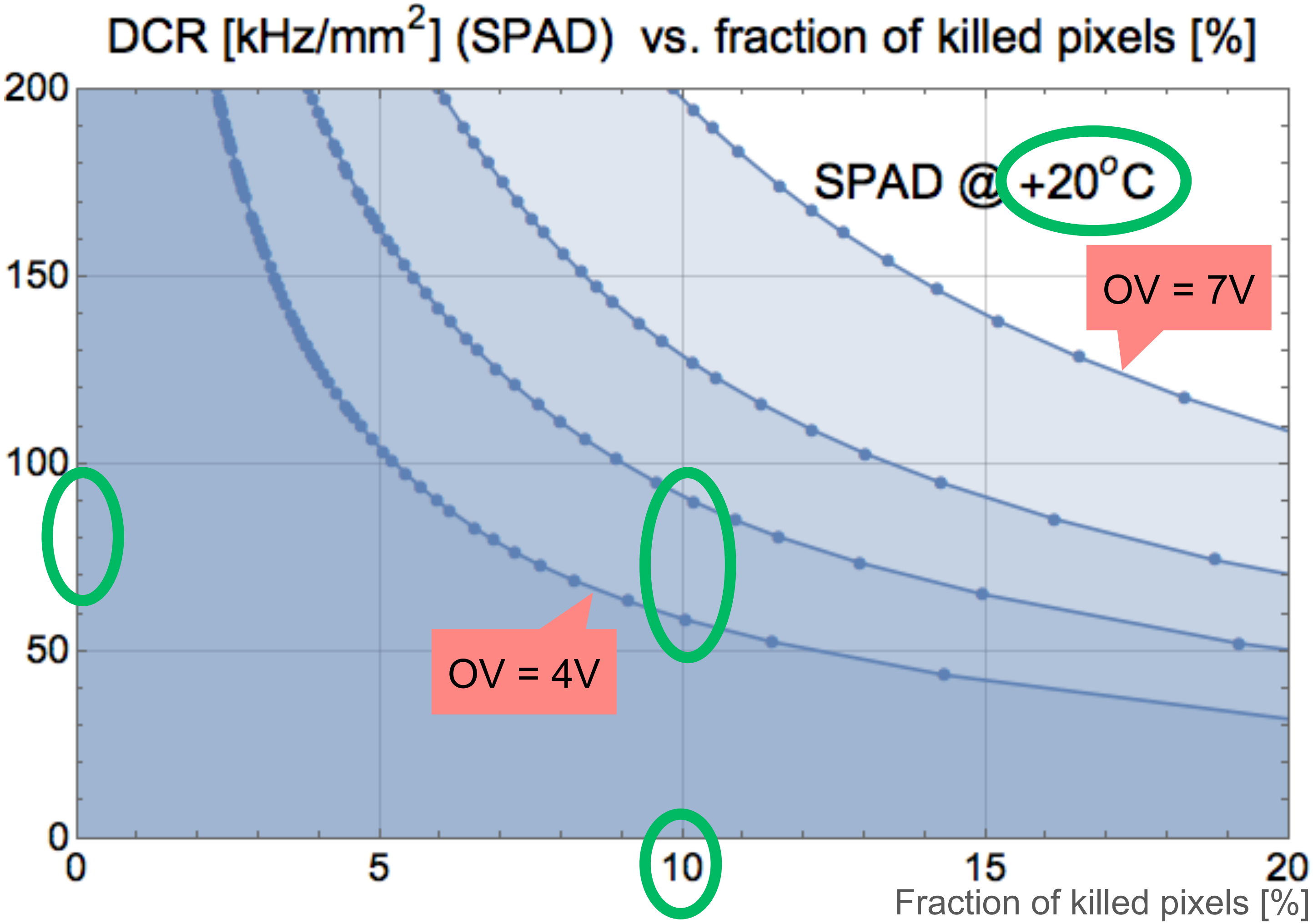
‘First Light’…

- Cover Chip with Alu-Mask with rectangular hole
- Illuminate Chip during integration window



DCR at Various Overvoltages

- Overvoltage = OV = 4,5,6,7 V, Measured @ 20°C (DCR is lower when cold)
- DCR is referred to useable **SPAD** area (inner border of M1 shield)

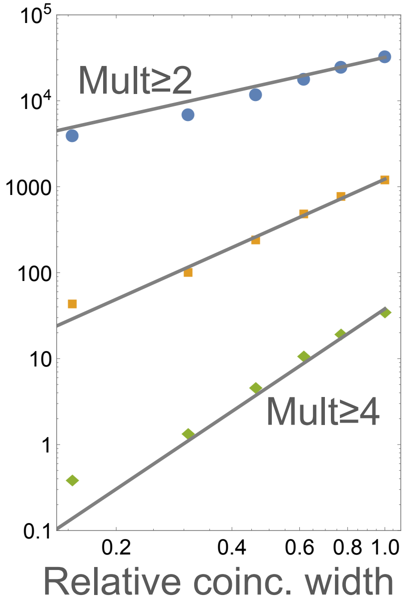


Multiplicity Rates

- Chip generates a *true* multiplicity of ColumnOR signals (i.e. groups of 88)
- Rates depend *strongly* on Coincidence *time window* (set by pixel monoflop)

Multiplicity Output	**Coinc. ~20ns**	**Coinc. ~40ns**	**Coinc. ~60ns**	**Coinc. ~80ns**	**Coinc. ~100ns**	**Coinc. ~130ns**
≥ 1	217882	324620	451114	528760	591078	652704
≥ 2	4075	7192	12370	18721	25583	34005
≥ 3	43	99.9	238	479	767	1203
≥ 4	0.4	1.4	4.8	11.2	20.1	36

Rates in Hz, T~30°C, OV = 4.0 V

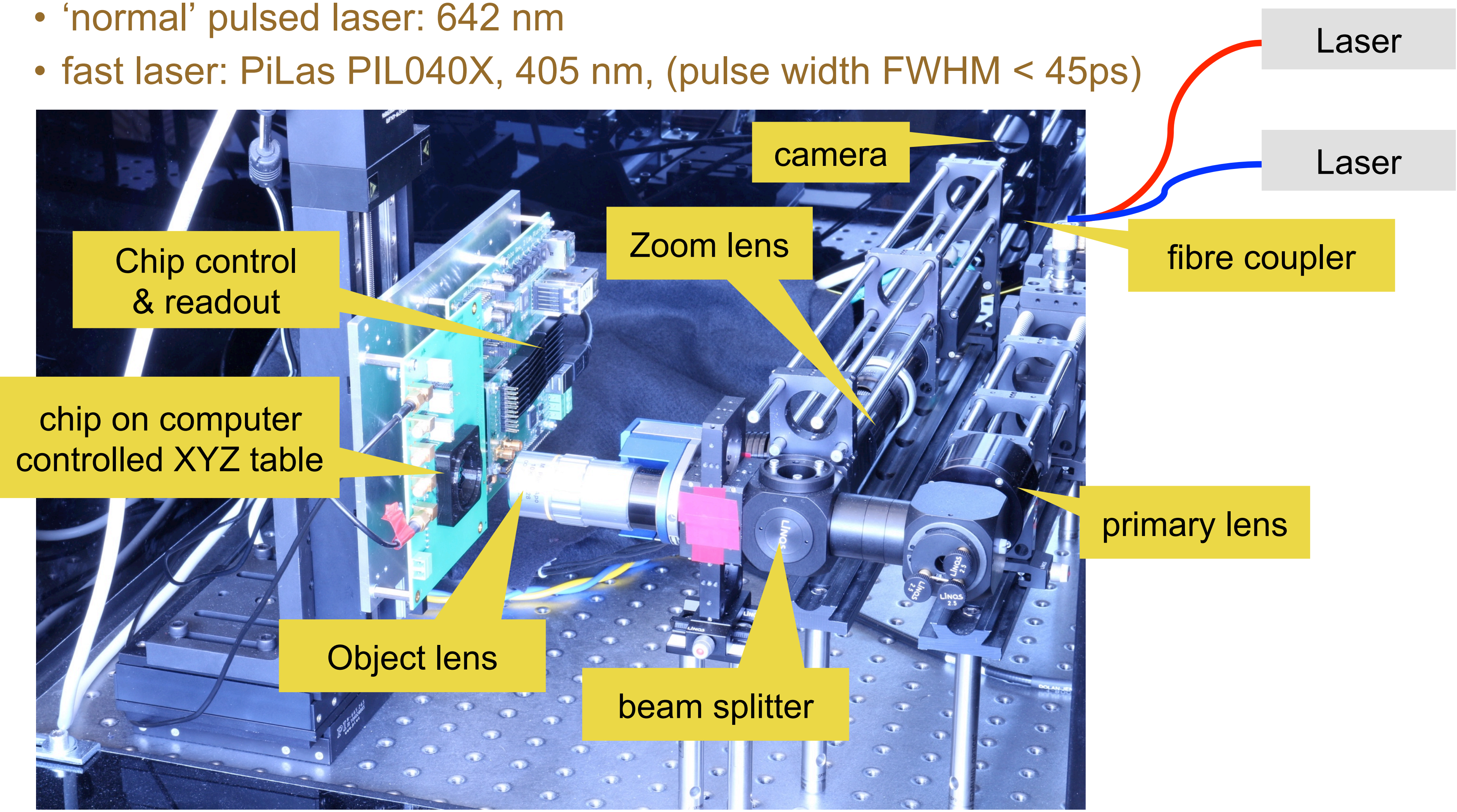


- ***No*** pixels killed in this measurement
- Can reach very low noise trigger rates of ~Hz!

- Measurement agrees quite well with theory
- Issue: dispersion in coincidence times (improved in IDP2)

Laser Setup

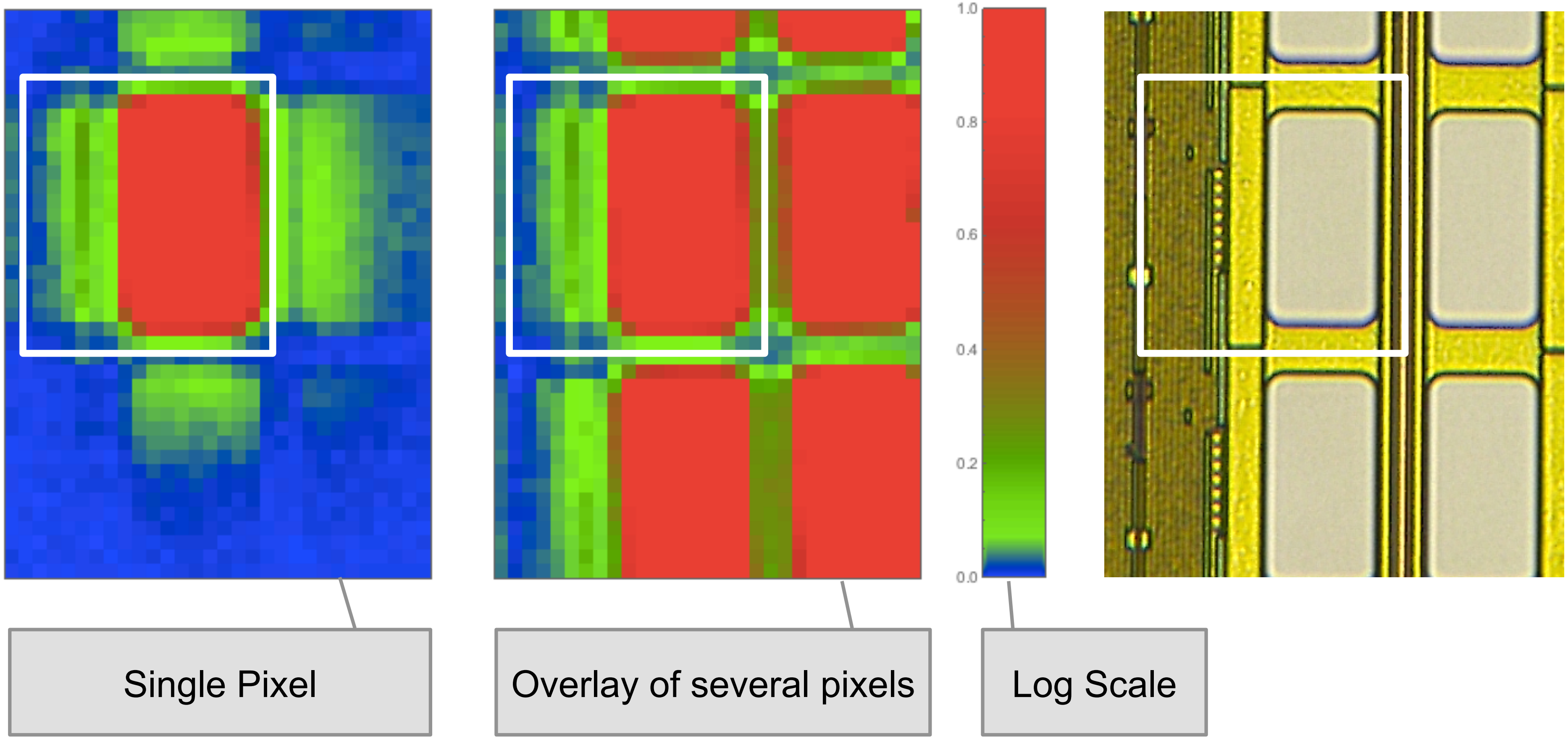
- Our microscope setup can focus a laser on a <5 µm spot
  - ‘normal’ pulsed laser: 642 nm
  - fast laser: PiLas PIL040X, 405 nm, (pulse width FWHM < 45ps)



Setup & Measurements by Manfred Kirchgessner and Michael Schork

Laser Scan: 2D Response

- Scan over region of 1.5 × 2.0 pixels in 30 × 40 steps (~ 2.8 μm / Step)
- Plot # hits in one pixel for 3000 laser shots (~ 4V overvoltage, I_{SPAD} ~6μA)
  - Notes: still need to calibrate x-y-steps better & run @ lower intensitiy..



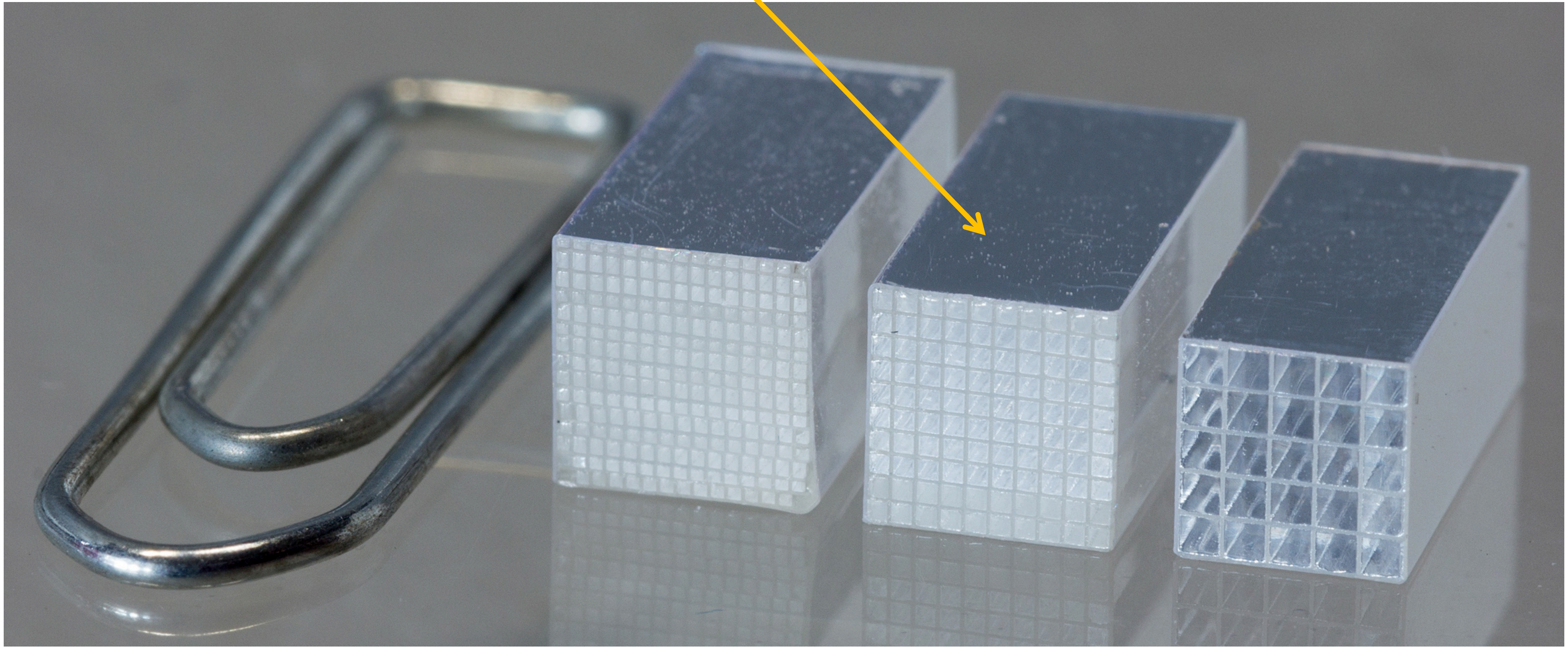
Single Pixel

Overlay of several pixels

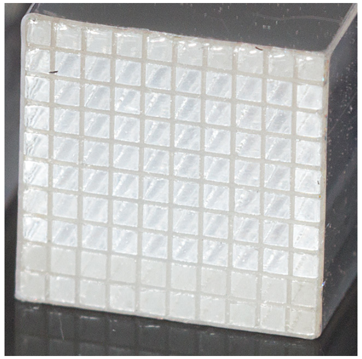
Log Scale

LYSO Arrays with VERY small pitches

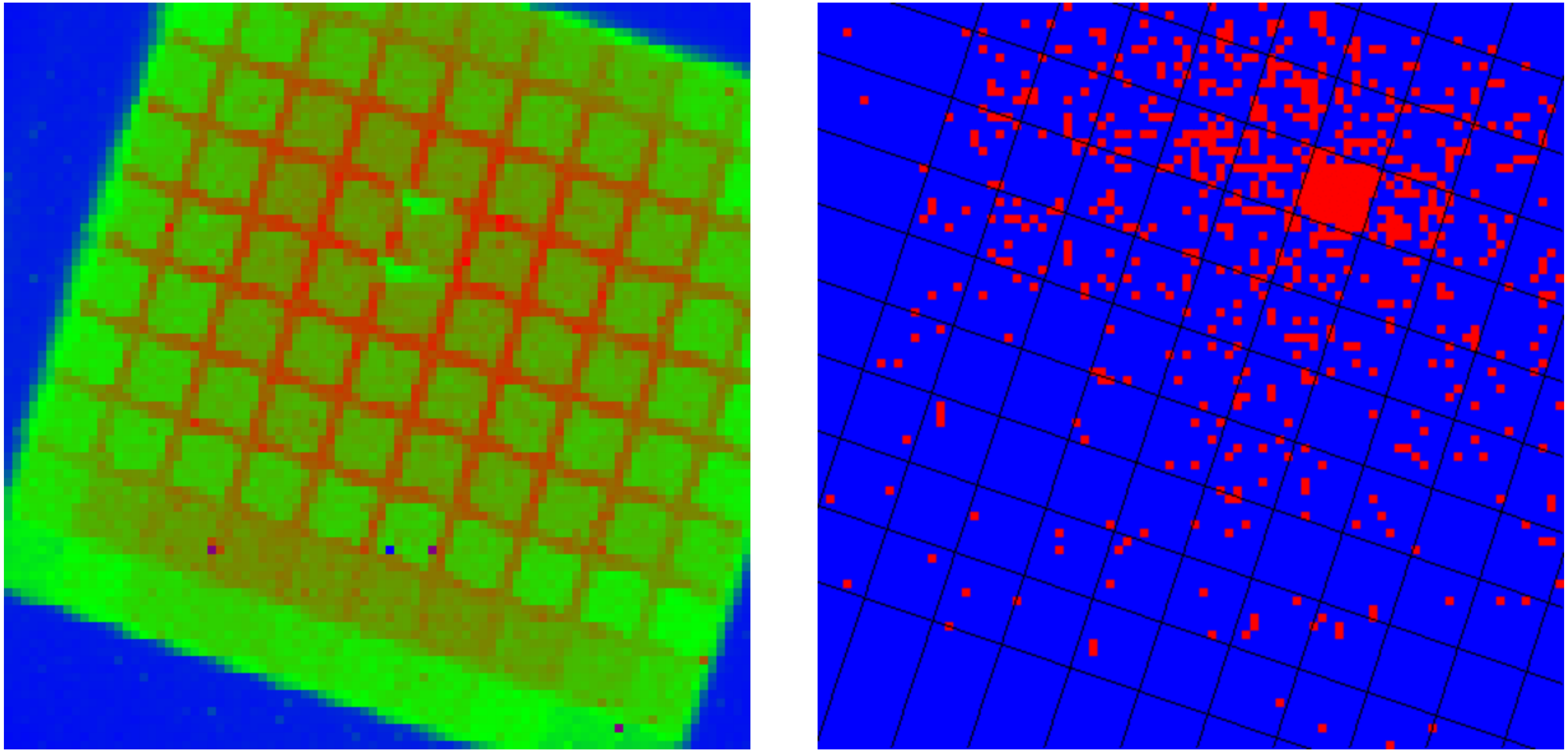
- Crystal Pitches: 0.33 / 0.48 / 0.88 mm, height = 10 mm
- 65µm thick ‘Enhanced Specular Reflector’ foils



LYSO Arrays with 0.48 mm pitch (!)



- Measured at ~30°C, OV = 3 V
- Trigger on Mult ≥ 4, 200 ns integration



Overlay of 20k events

Single events

Reserve

RE