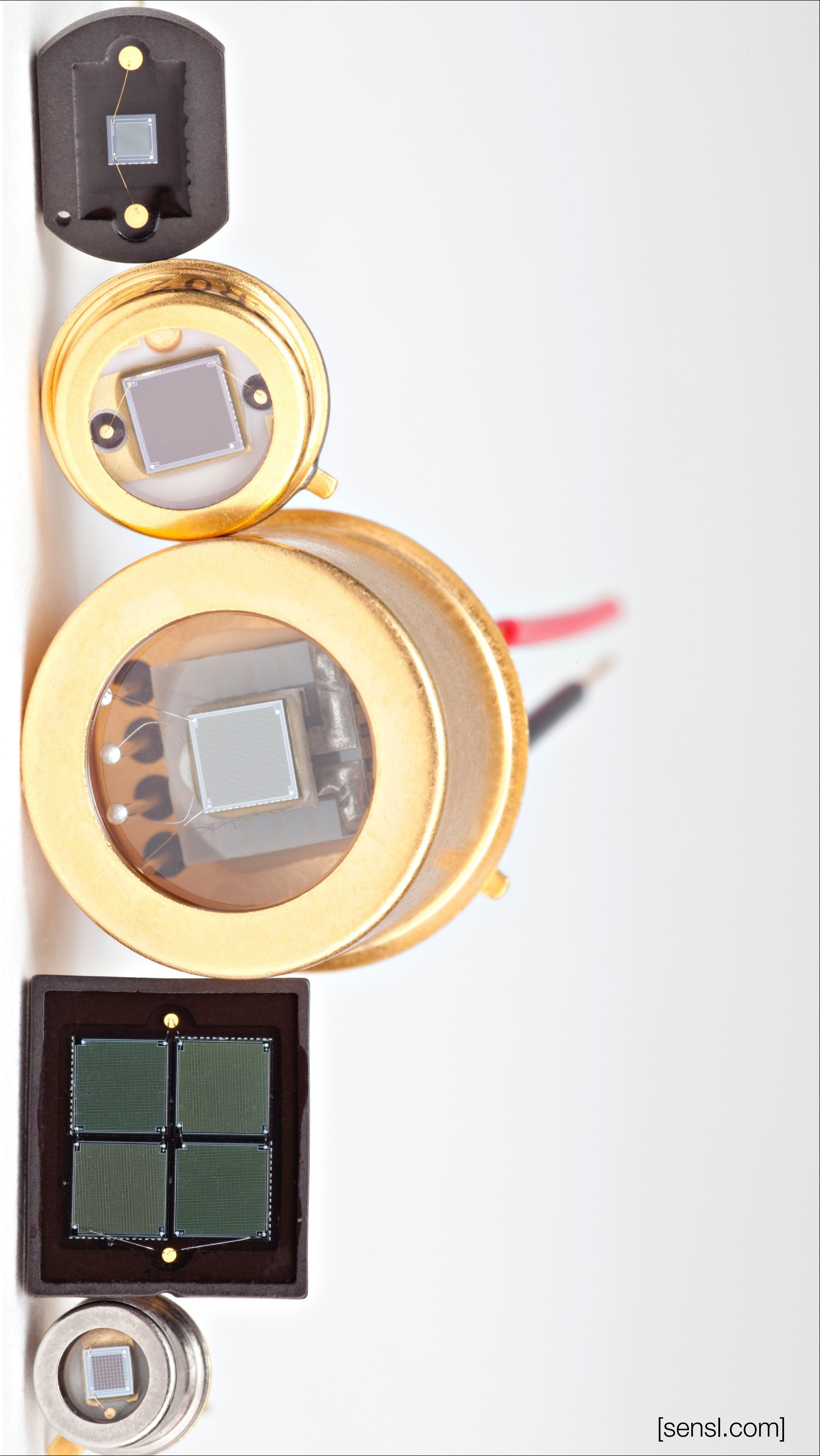
Silicon Photomultipliers

and their application in HEP and Medical Imaging


[sensl.com]

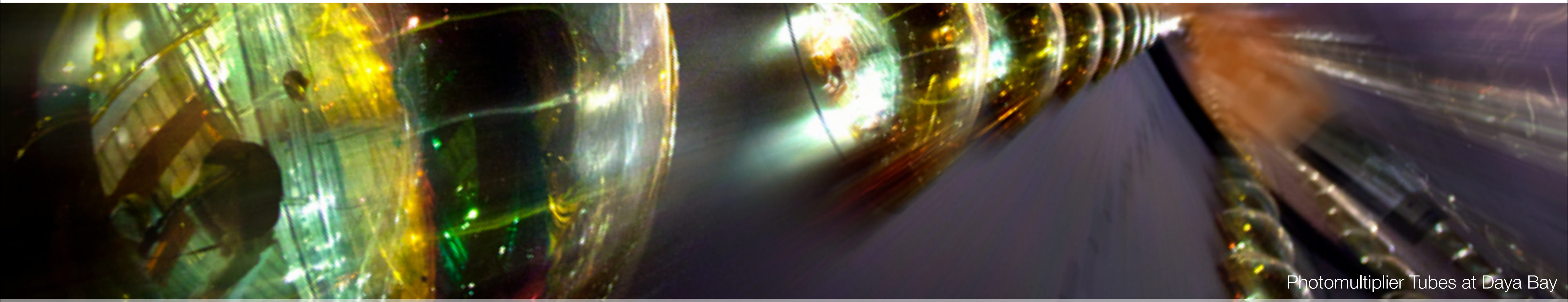
LHCb Retreat

Neckarzimmern, March 2014

Hans-Christian Schultz-Coulon
Kirchhoff-Institut für Physik, Universität Heidelberg

Setting the Scene

The Standard: Photomultiplier Tubes (PMTs)



Photomultiplier Tubes at Daya Bay

Photon Detection

Purpose : Convert light into a detectable electronic signal

Principle : Use photo-electric effect to convert photons to photo-electrons (p.e.)

Requirement :

High Photon Detection Efficiency (PDE)

i.e. high quantum efficiency [Q.E. = $N_{p.e.}/N_{photons}$]
low surface reflection, …

Available devices [Examples]:

- Photomultipliers [PMT]
- Micro Channel Plates [MCP]
- Photo Diodes [PD]
- Hybrid Photo Diodes [HPD]
- Visible Light Photon Counters [VLPC]
- Silicon Photomultipliers [SiPM]

Photomultipliers

Principle:

Electron emission

from photo cathode

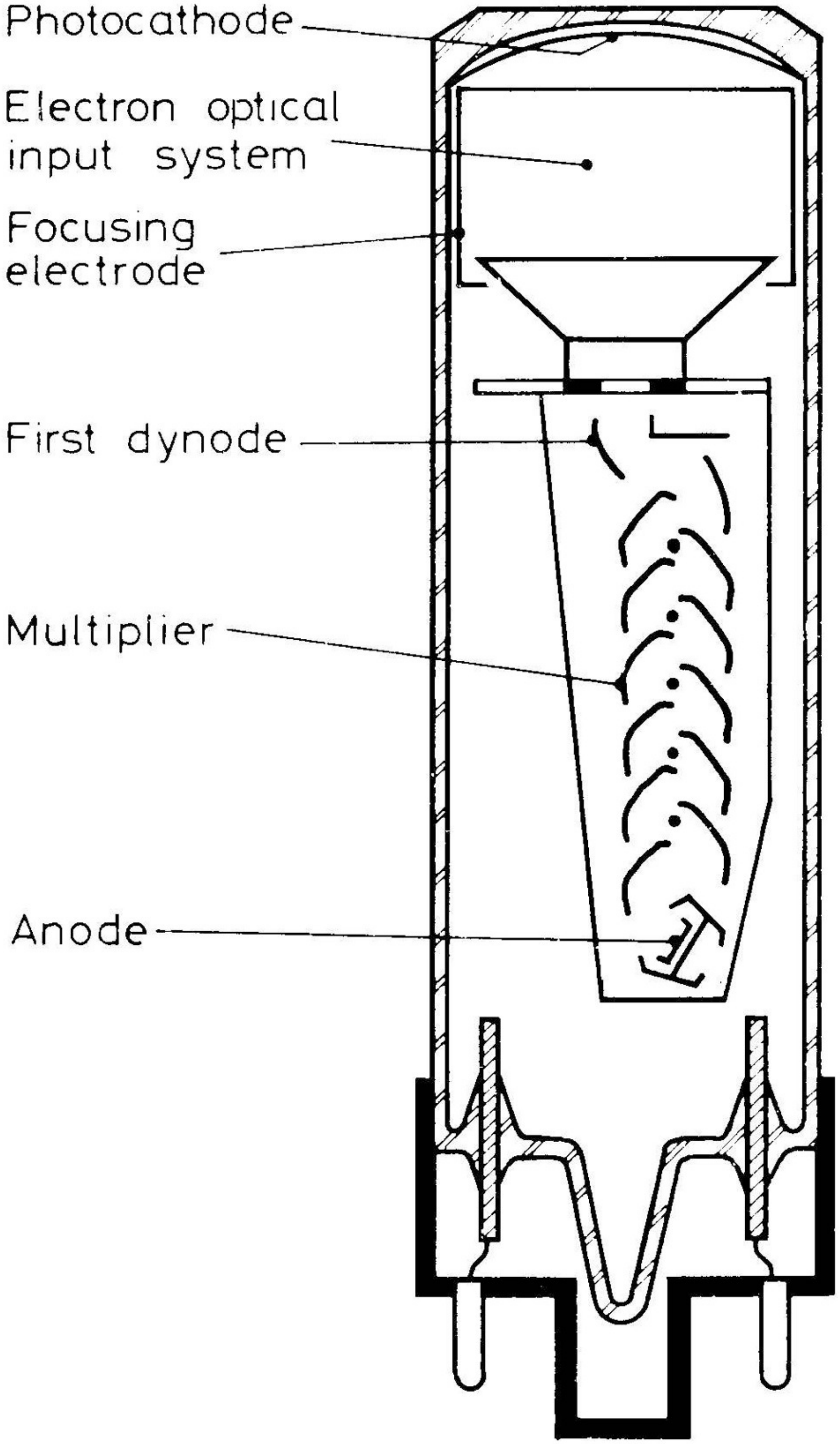
Secondary emission

from dynodes; dynode gain: 3-50 [f(E)]

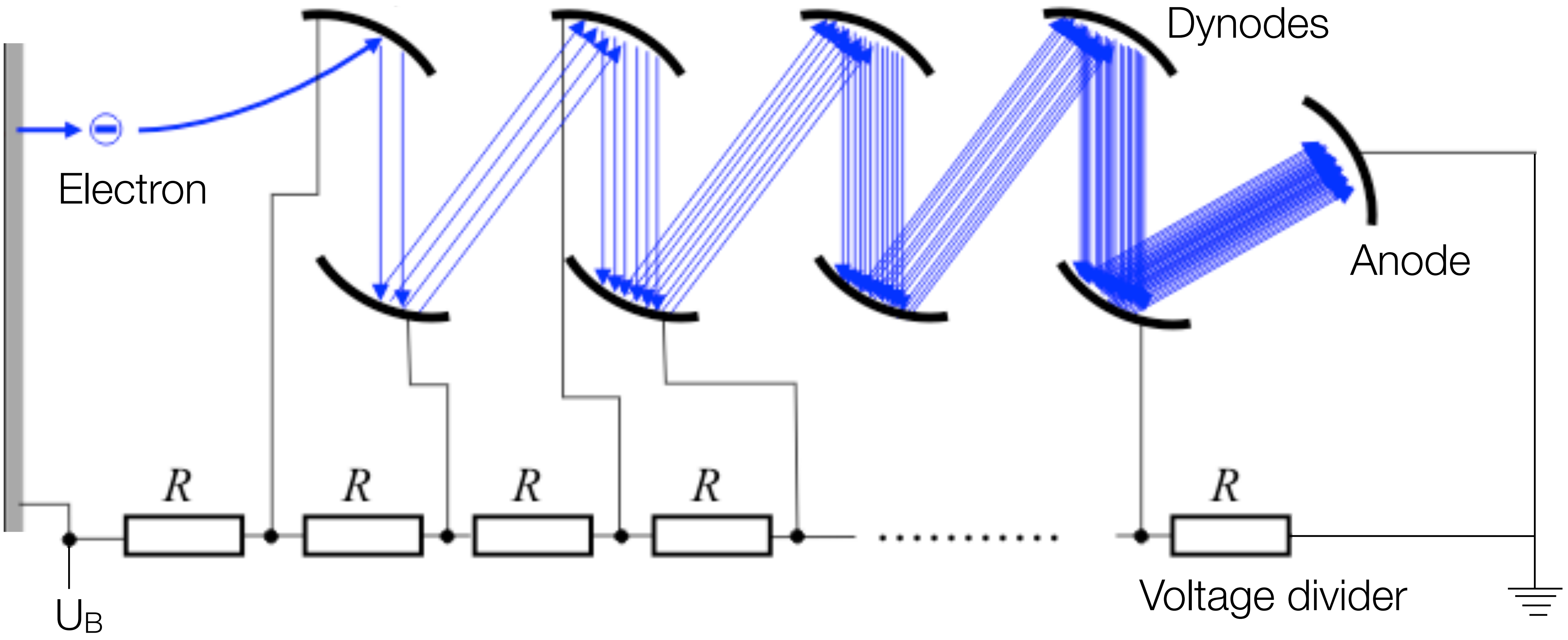
Typical PMT Gain: > 10^6

[PMT can see single photons ...]

PMT
Collection



Photomultipliers – Dynode Chain



Multiplication process:

Electrons accelerated toward dynode
Further electrons produced ➛ avalanche

Secondary emission coefficient:
$\delta = \#(e^- \text{ produced})/\#(e^- \text{ incoming})$

Typical: $\left.\begin{array}{l}\delta = 2 - 10 \\ n = 8 - 15\end{array}\right]$ ➛ $G = \delta^n = 10^6 - 10^8$

Gain fluctuation: $\delta = kU_D;\ G = (kU_D)^n$

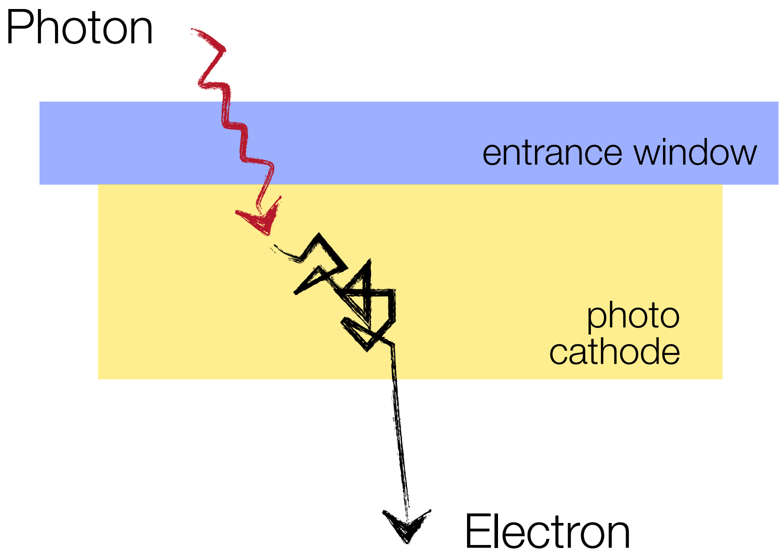
$$dG/G = n\,dU_D/U_D = n\,dU_B/U_B$$

Photomultipliers – Photocathode

Bialkali: SbRbCs; SbK_2Cs

γ-conversion

via photo effect ...

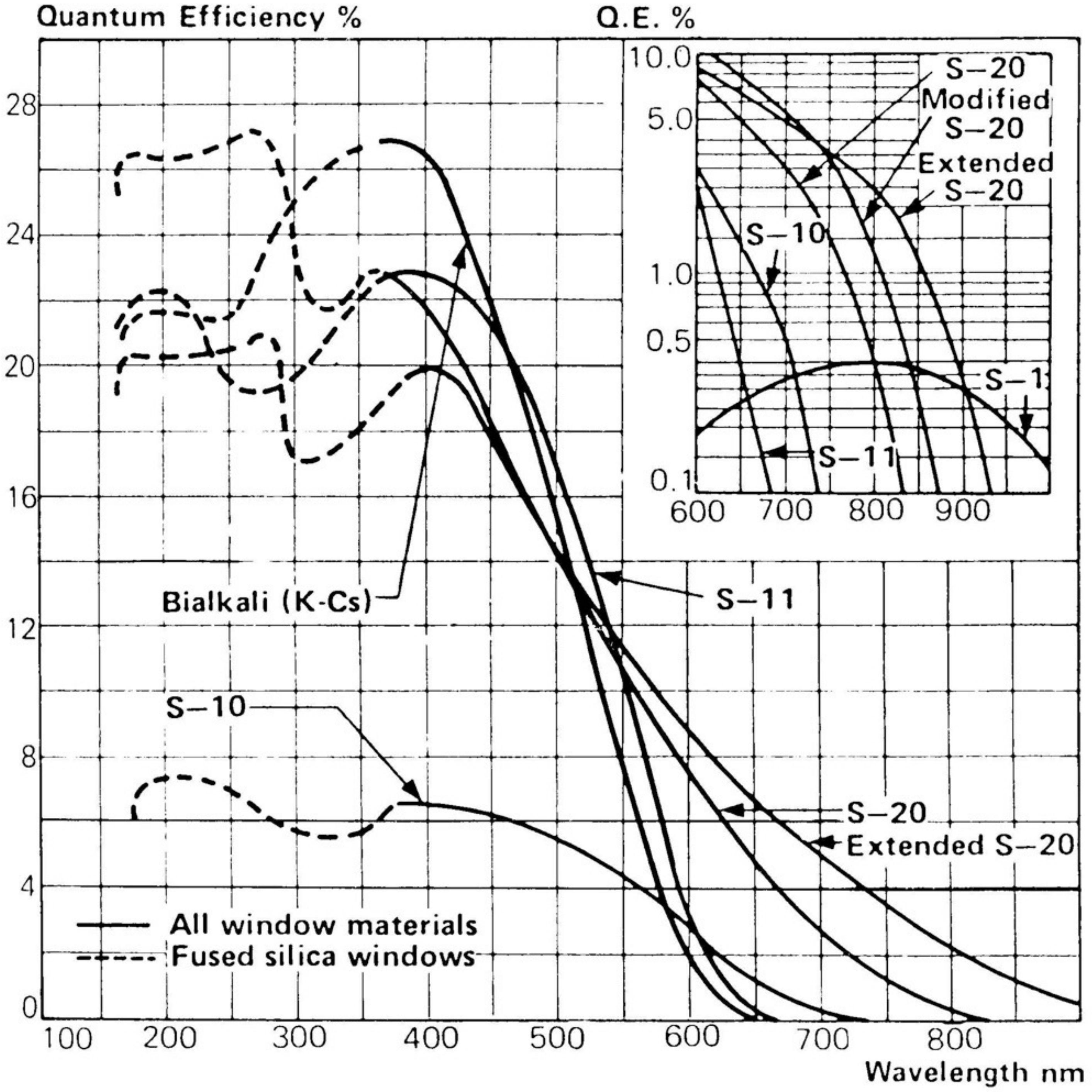


3-step process:

- Electron generation via ionization
- Propagation through cathode
- Escape of electron into vacuum

PDE ≈ 10-30%

[need specifically developed alloys]



Photomultipliers – Dynode Chain

Optimization of

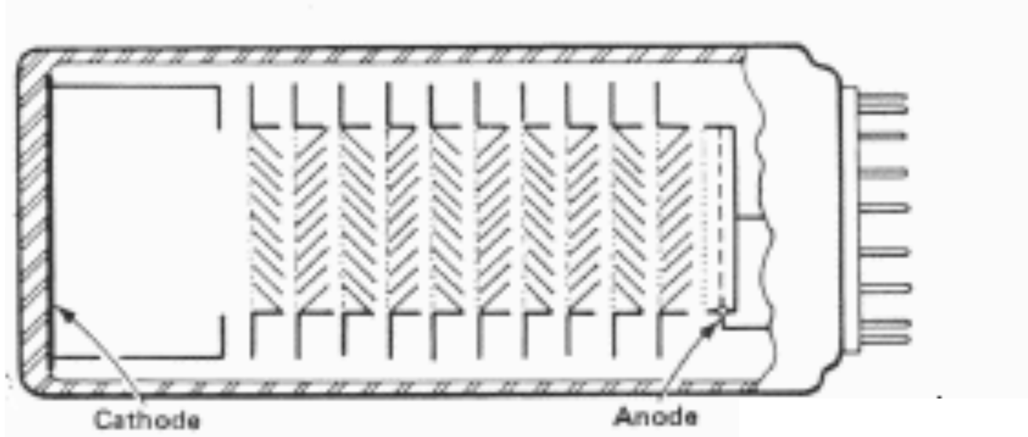
PMT gain
Anode isolation
Linearity
Transit time

B-field dependence

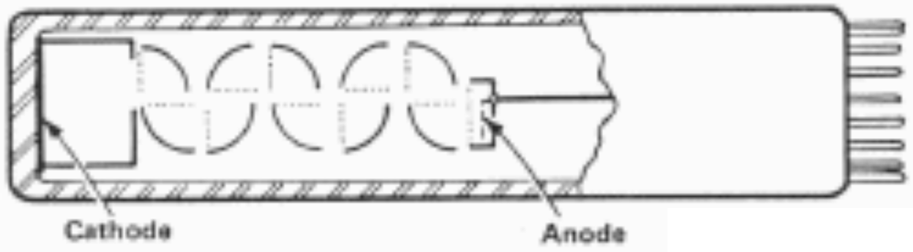
PM's are in general
very sensitive to B-fields !

Even to earth field (30-60 μT).
μ-metal shielding required.

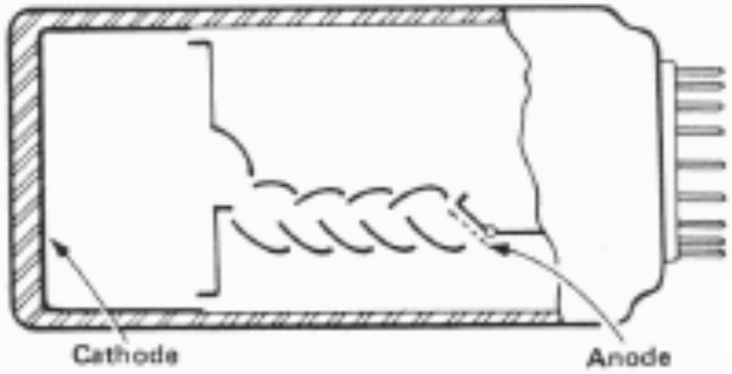
Venetian
blind



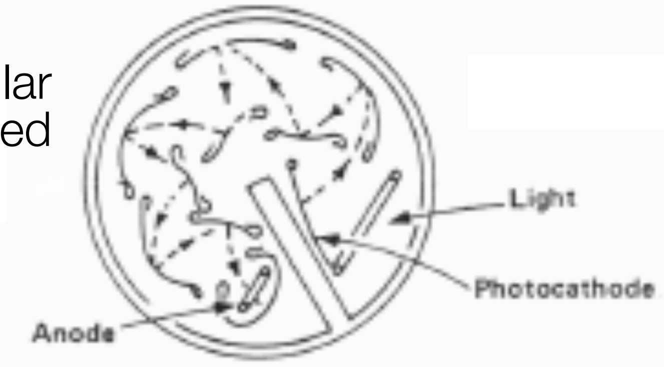
Box and
grid



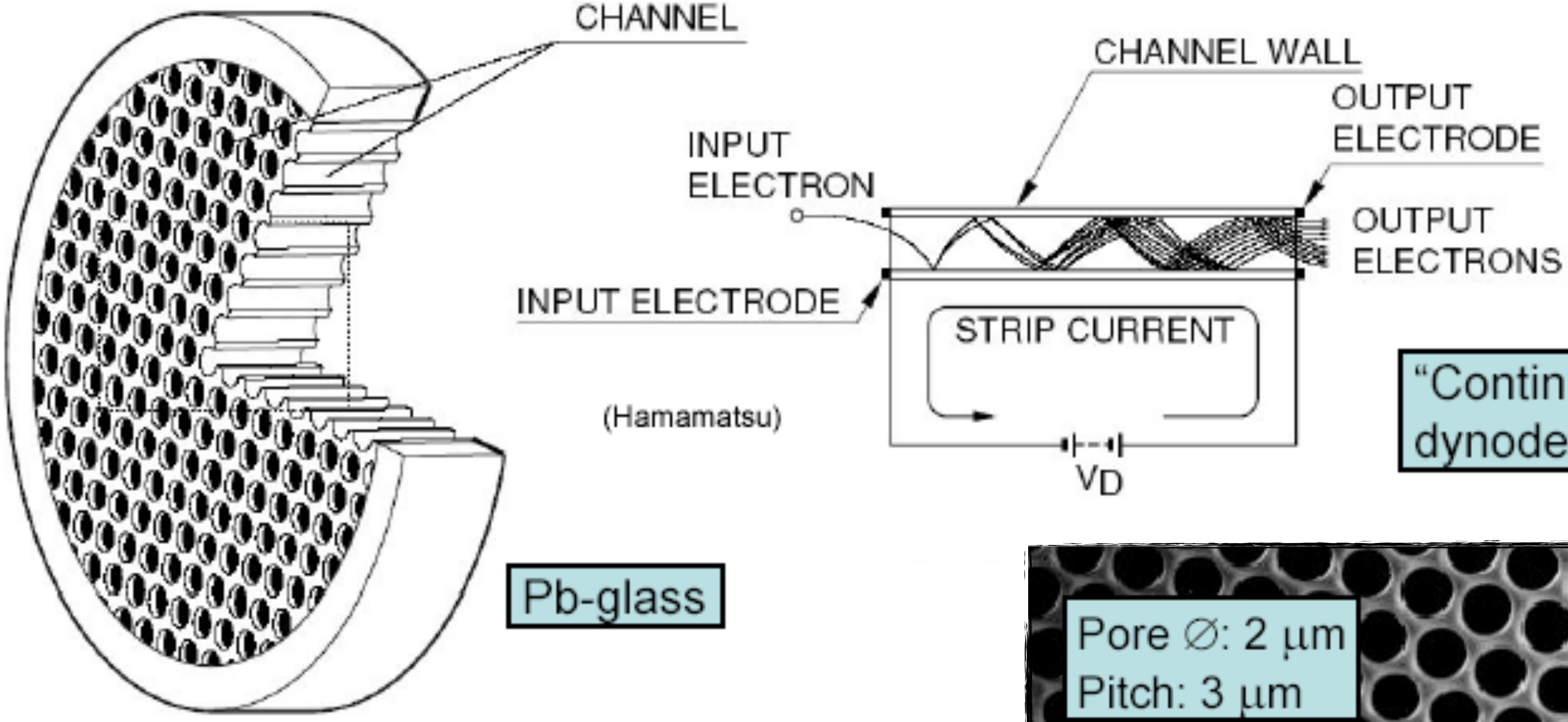
Linear
focused



Circular
focused



Micro Channel Plate



(Hamamatsu)

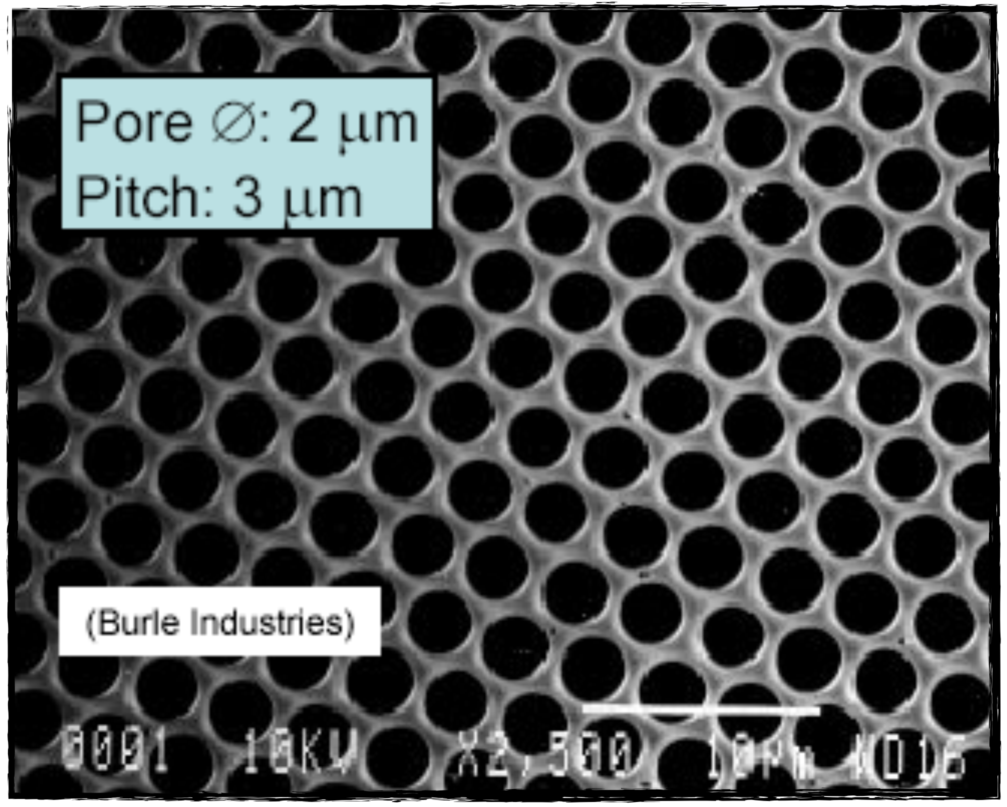
Pb-glass

"Continuous" dynode chain

"2D Photomultiplier"

Gain: $5 \cdot 10^4$
Fast signal [time spread ~ 50 ps]
B-Field tolerant [up to 0.1T]

But: limited life time/rate capability

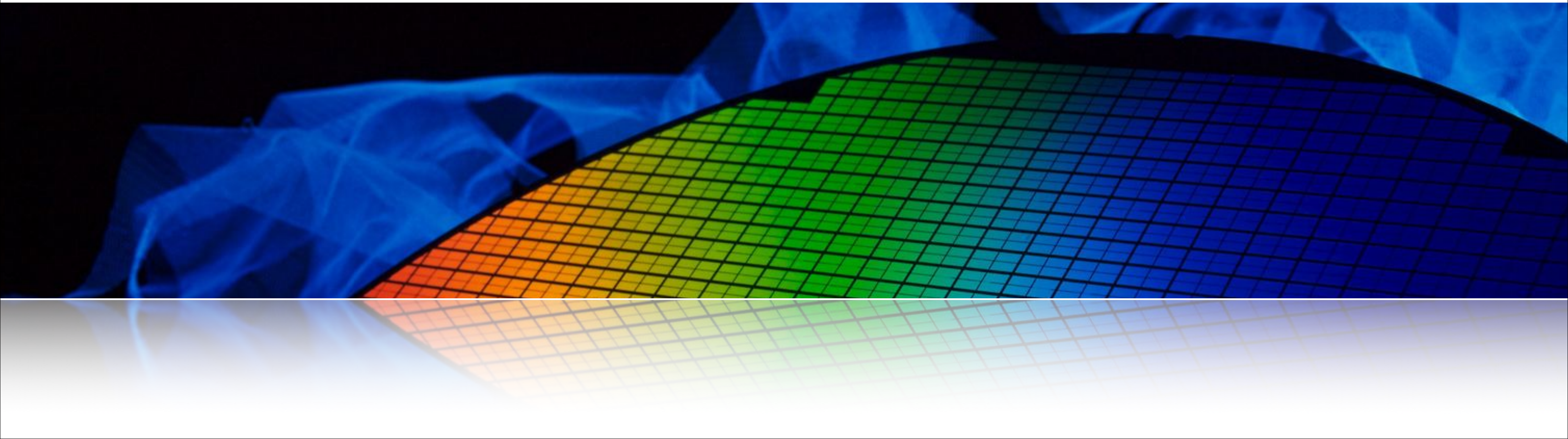


Pore ∅: 2 μm
Pitch: 3 μm

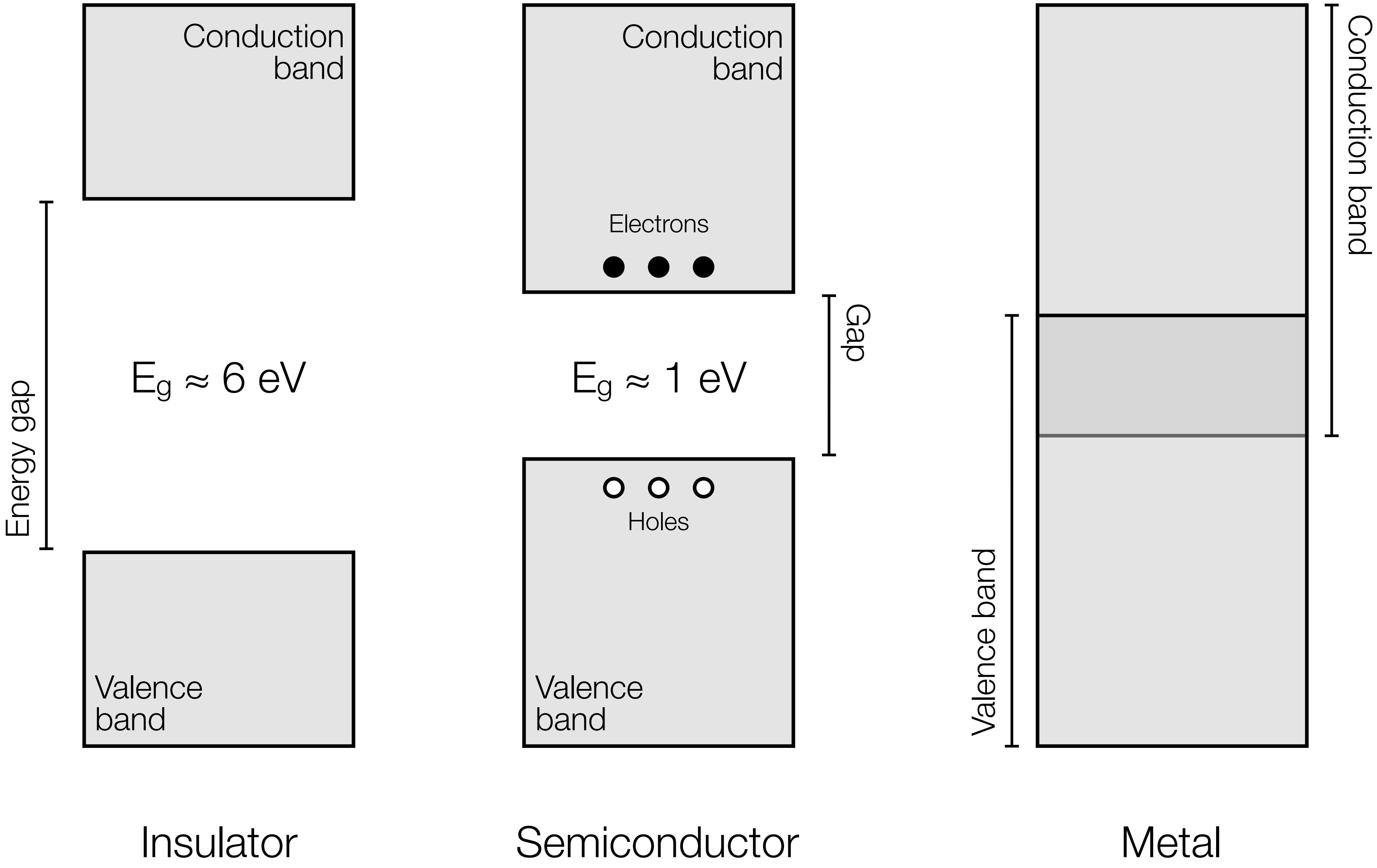
(Burle Industries)

Solid State PDs

From pn-Junctions to Silicon Photomultipliers



Basic Semiconductor Properties



Basic Semiconductor Properties

Intrinsic semiconductor:

Very pure material; charge carriers are created by thermal, optical or other excitations of electron-hole pairs; $N_{electrons} = N_{holes}$ holds ...

Commonly used: Silicon (Si) or Germanium (Ge); four valence electrons ...

Doped or extrinsic semiconductor:

Majority of charge carriers provided by donors (impurities; doping)

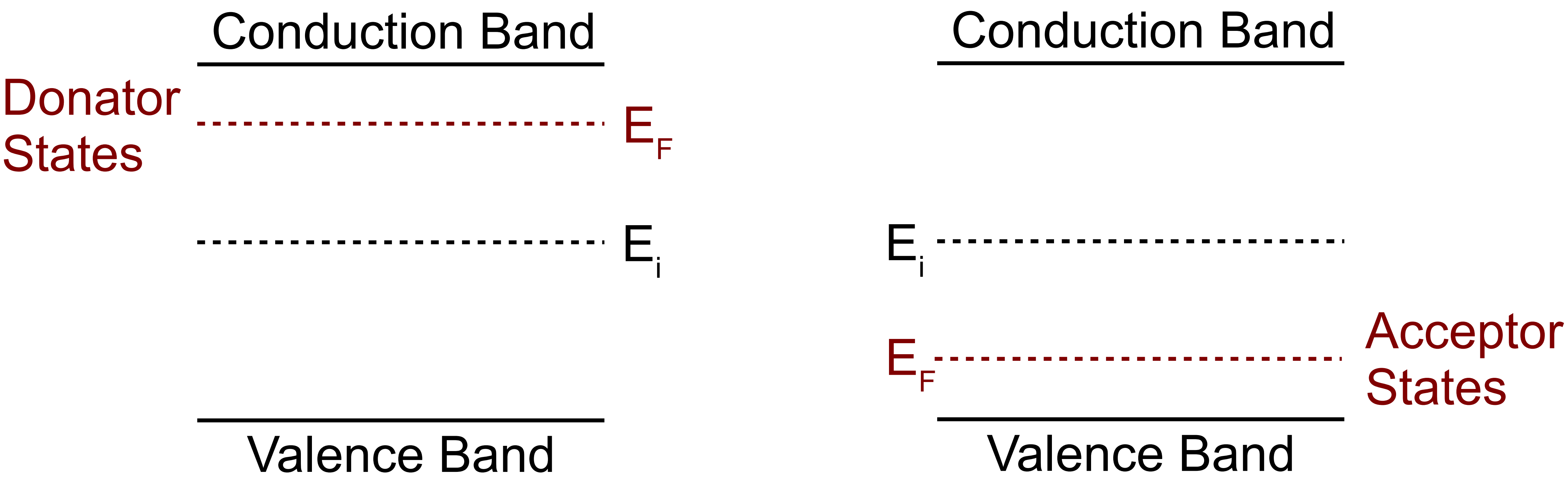
n-type : majority carriers are electrons (pentavalent dopants)
p-type : majority carriers are positive holes (trivalent dopants)

Pentavalent dopants (electron donors): P, As, Sb, ...
[5th electron only weakly bound; easily excited into conduction band]

Trivalent dopants (electron acceptors): Al, B, Ga, In, ...
[One unsaturated binding; easily excepts valence electron leaving hole]

Basic Semiconductor Properties

[source: P. Eckert]



n-doped

Conduction Band

Donator States

E_F

E_i

Valence Band

p-doped

Conduction Band

E_i

E_F

Acceptor States

Valence Band

The pn-Junction

Equilibration process:

Electrons diffuse from n- to p-type semiconductor and recombine ...

Holes diffuse from p- to n-type semiconductor and recombine ...

Resulting electric field counteracts and stops diffusion process ...

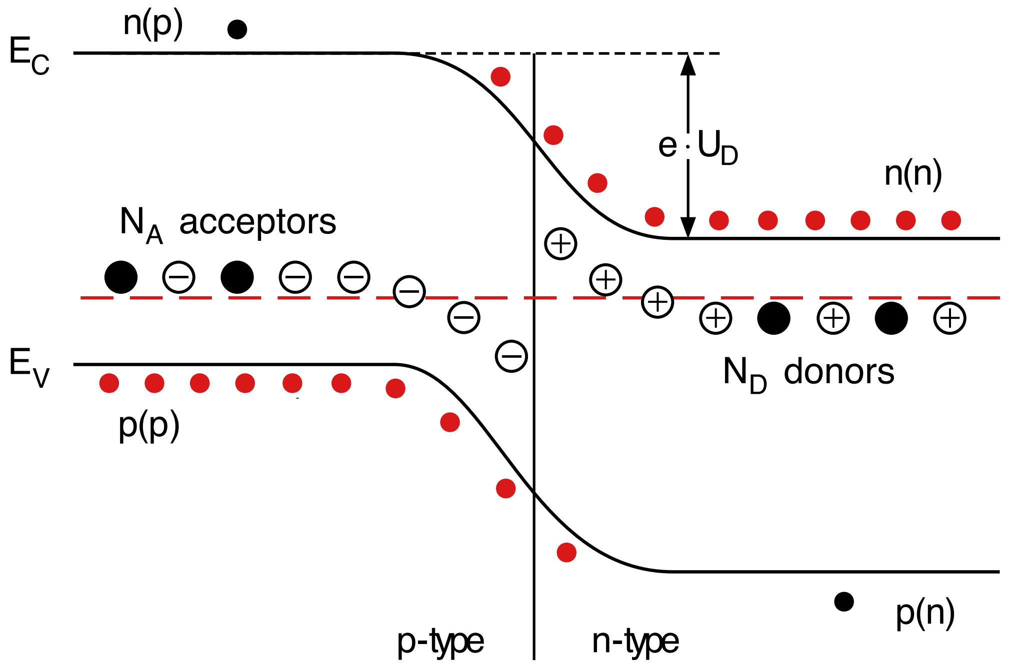
$$eU_D = \Delta E_{\text{pot}} = E_C^{(p)} - E_C^{(n)}$$

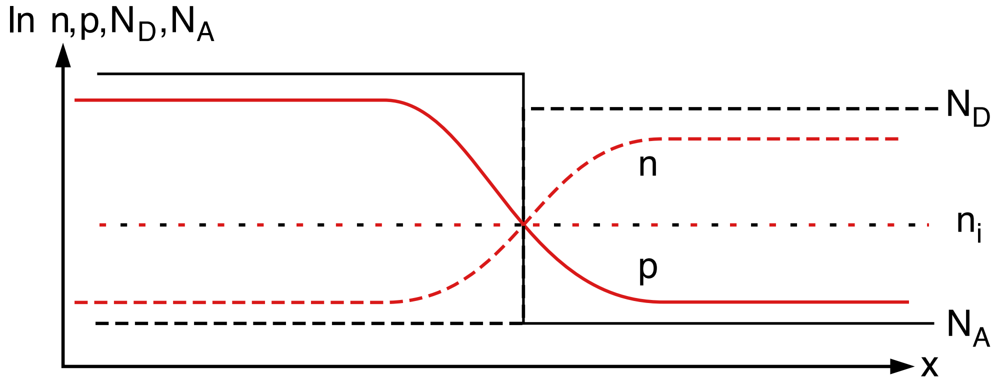
$$= k_B T \cdot \ln \frac{n_{\text{n–type}}}{n_{\text{p–type}}} = k_B T \cdot \ln \frac{N_D N_A}{n_i^2}$$

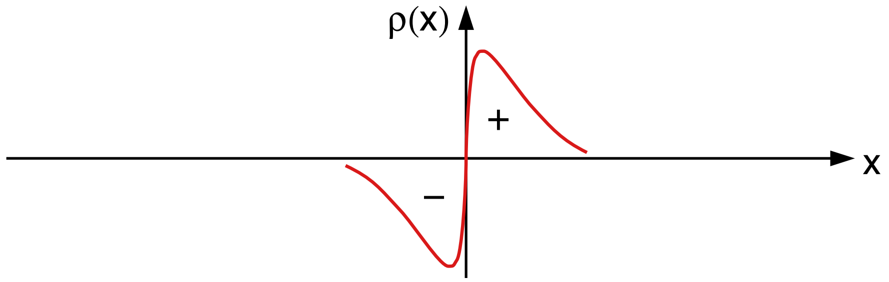
$$\left[\text{using } \; n = N_C \cdot e^{-(E_C - \mu)/k_B T}, \; p = ...\right]$$

At the boundary concentration of mobile carriers is depleted ... [depletion layer]

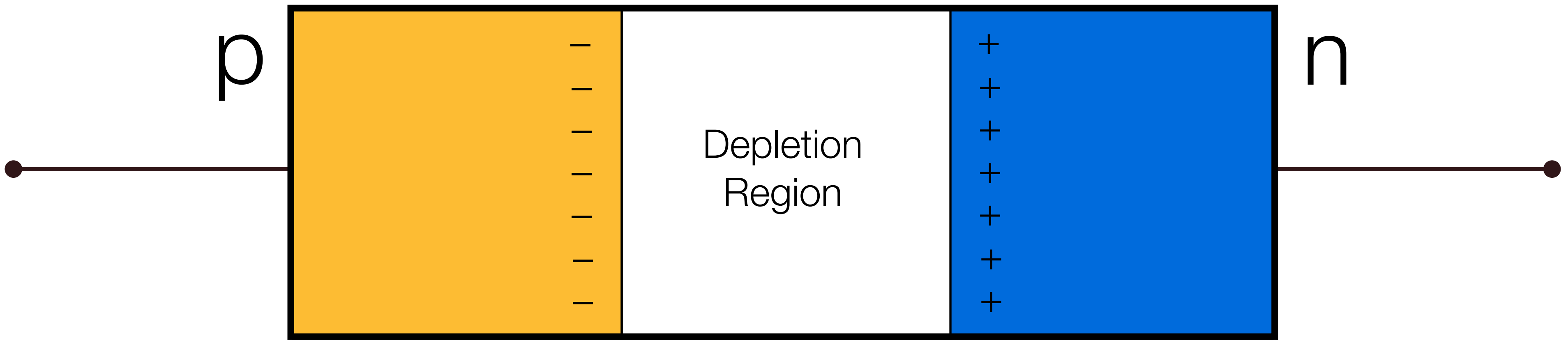
[source: Demtröder]





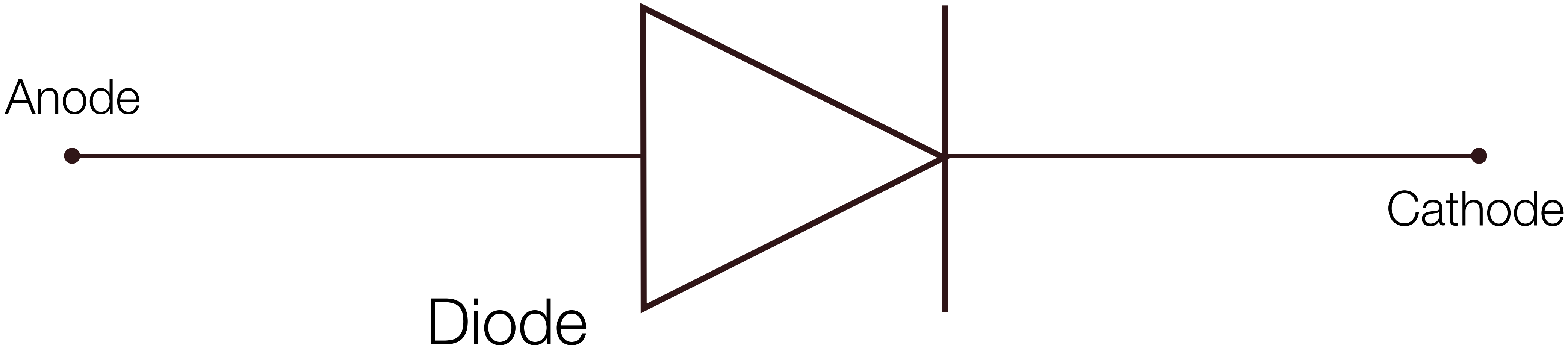


The pn-Junction


p

Depletion Region

n

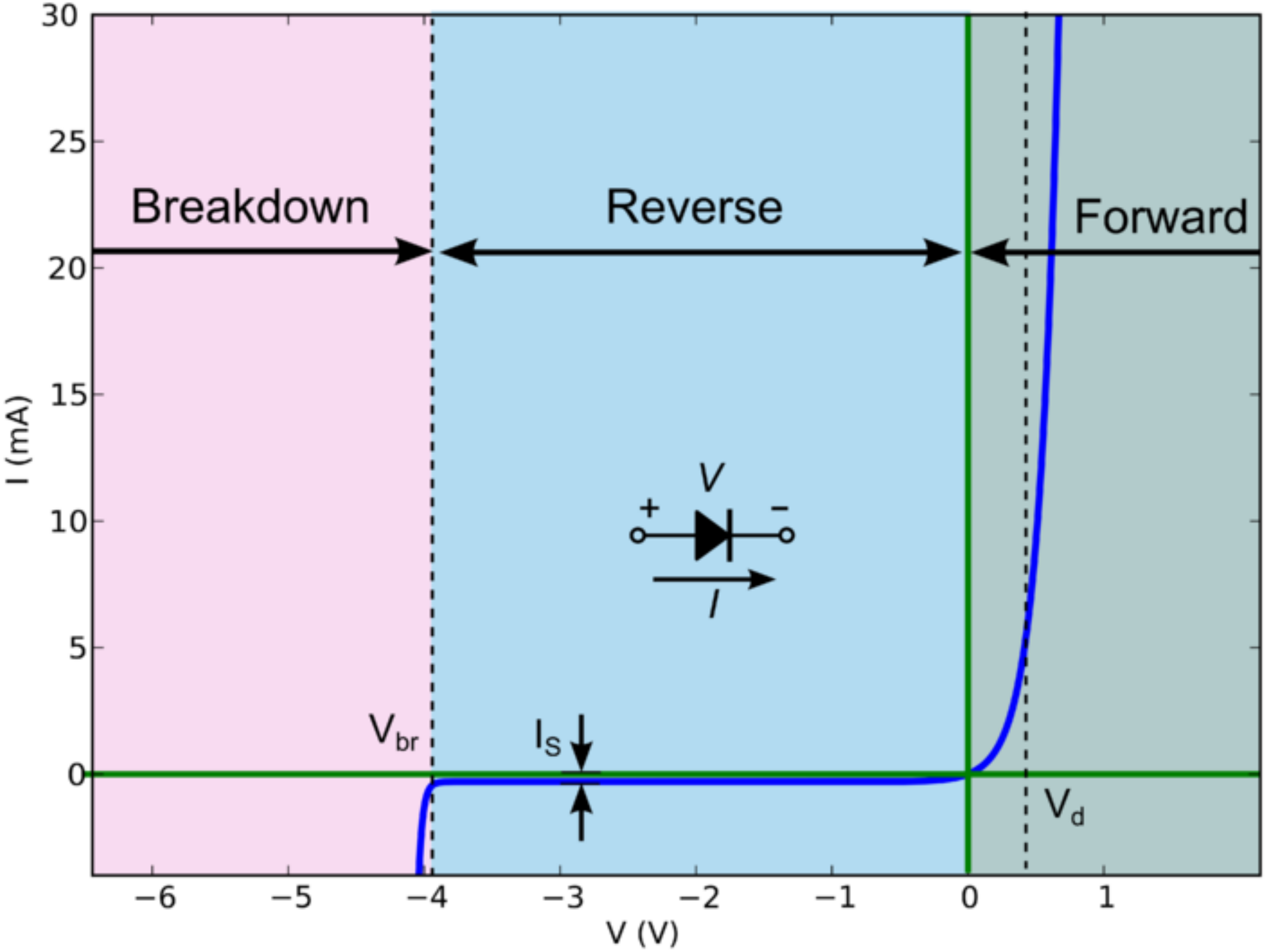

Anode

Cathode

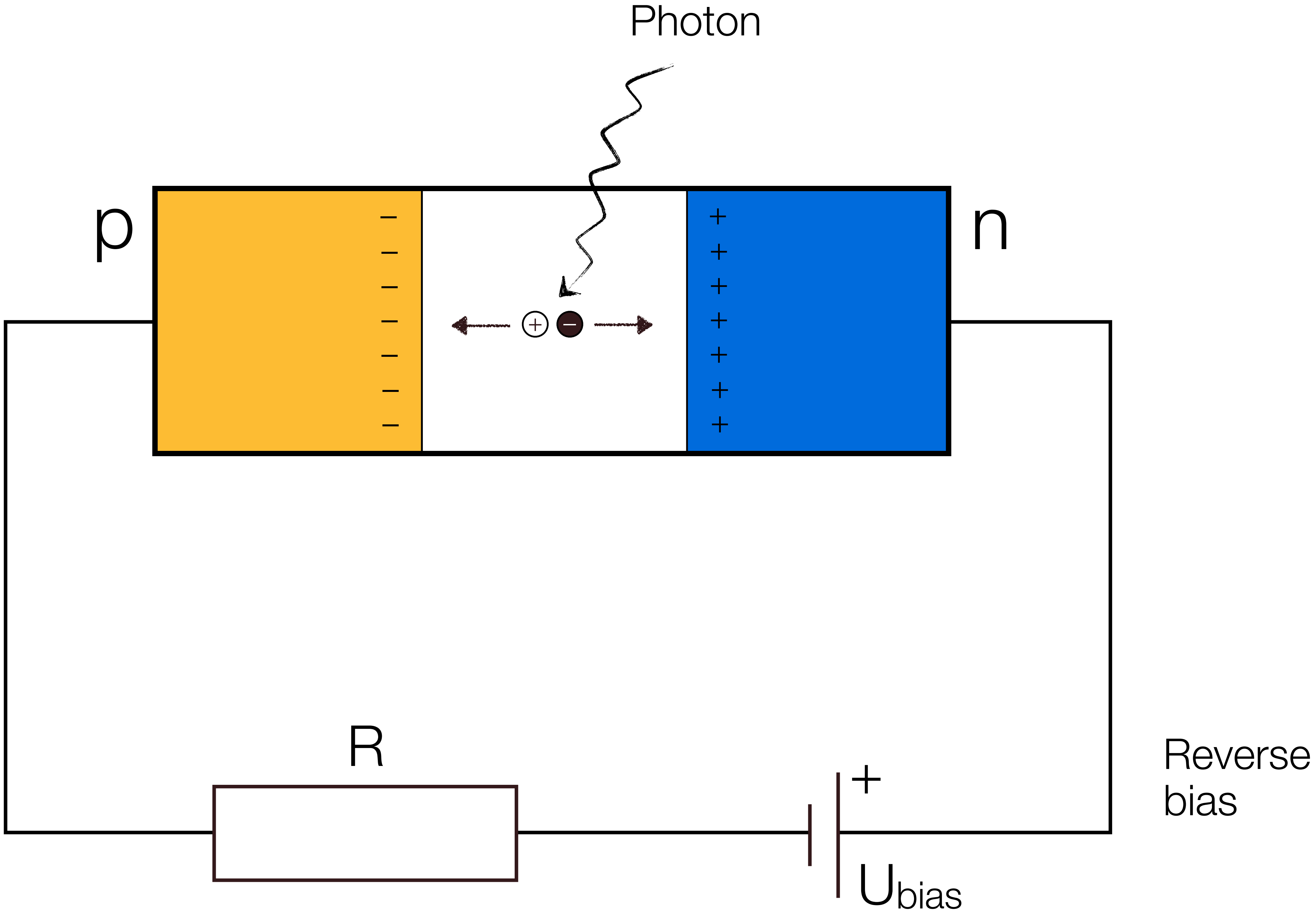
Diode

The pn-Junction

[picture source: Wikipedia]

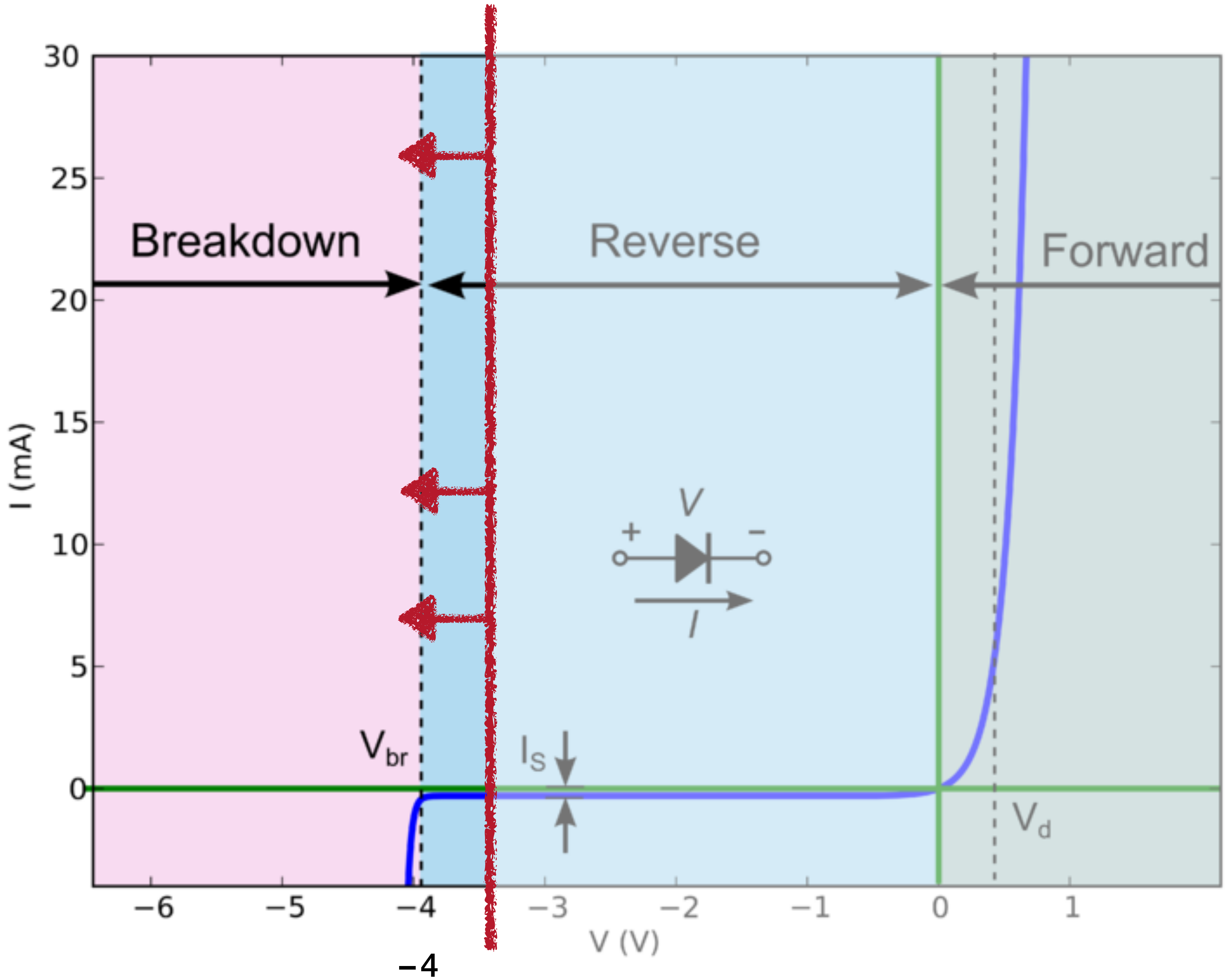


The pn-Junction – Photo Detection Principle



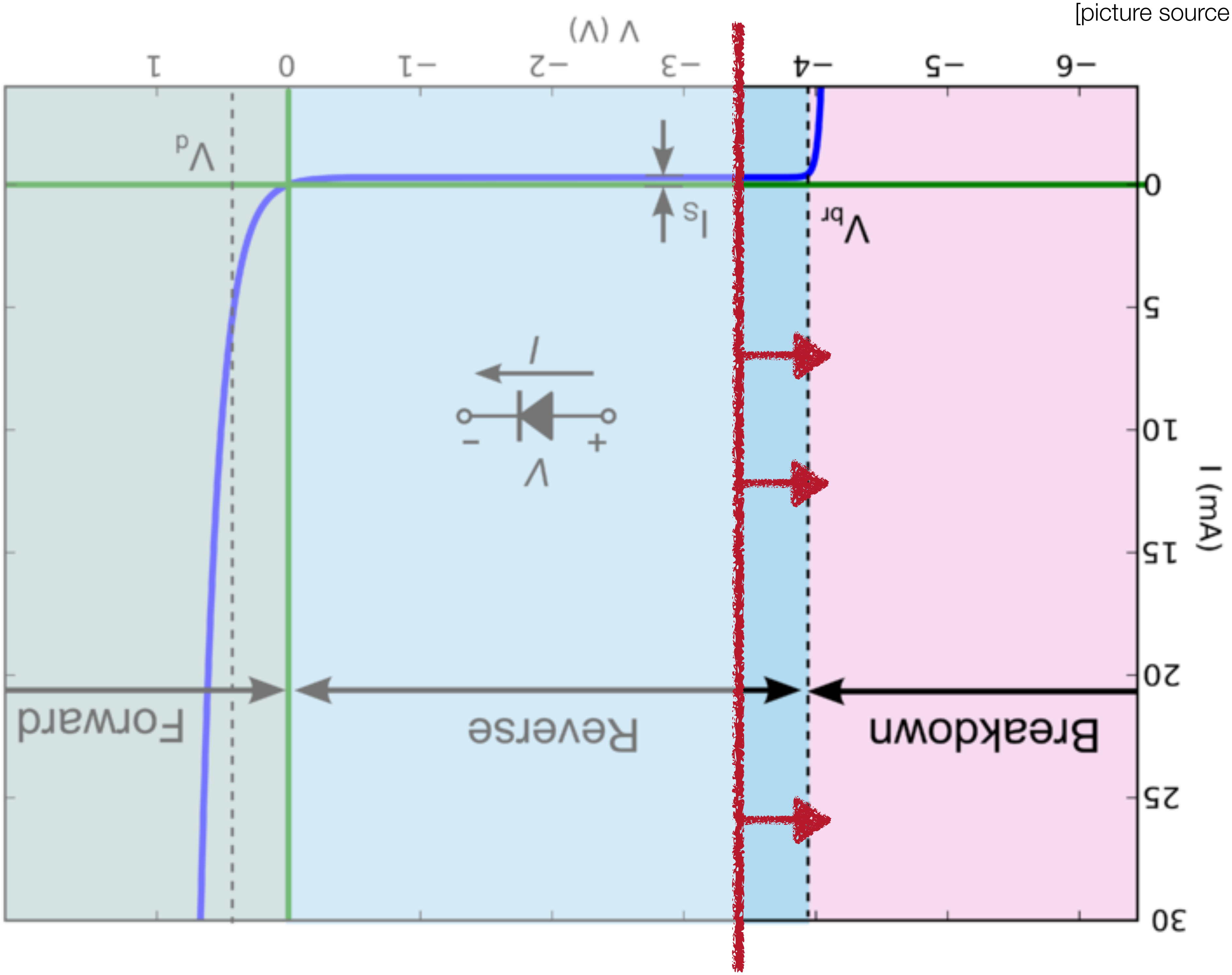
The pn-Junction – Photo Detection Principle

[picture source: Wikipedia]

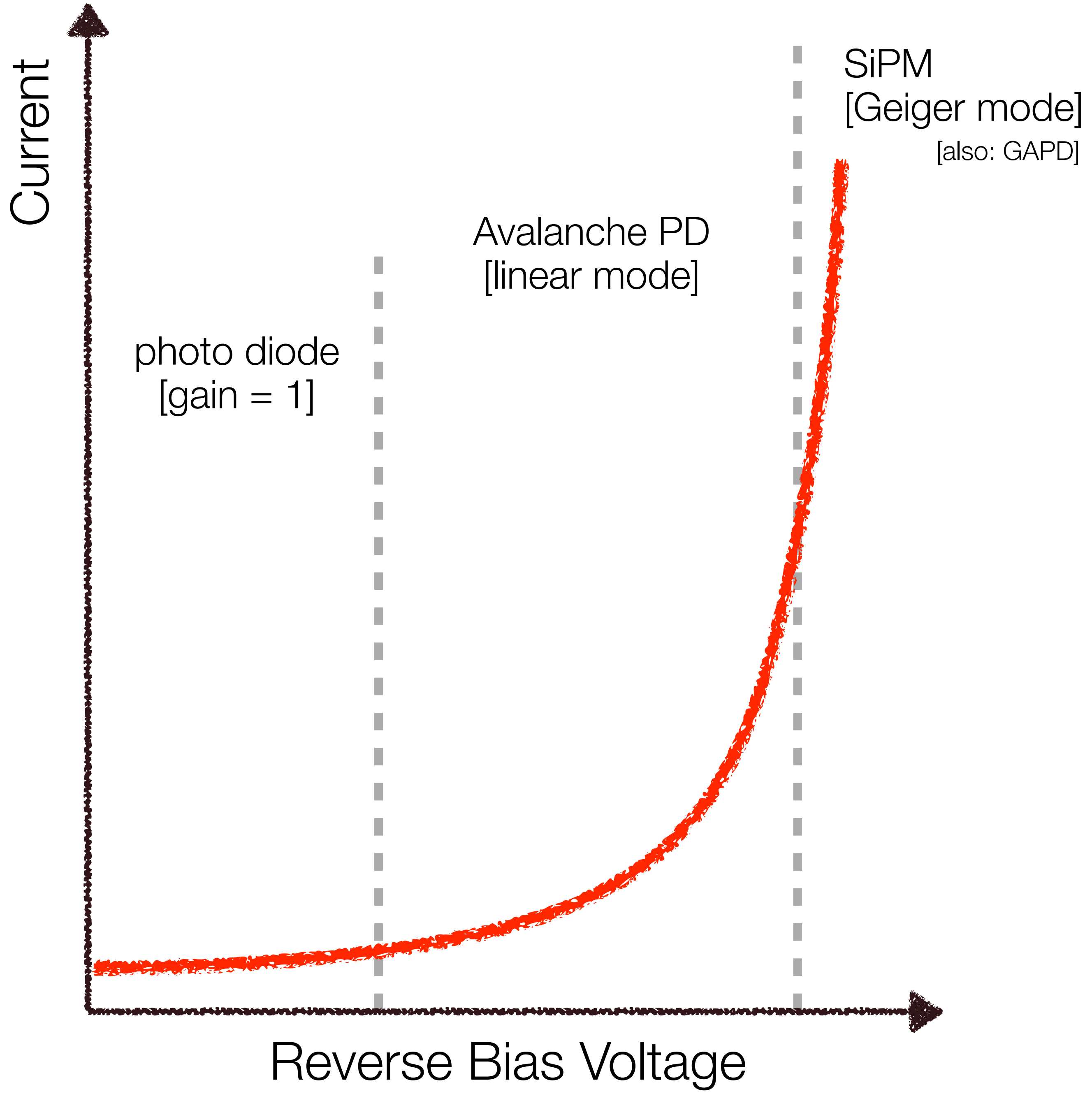


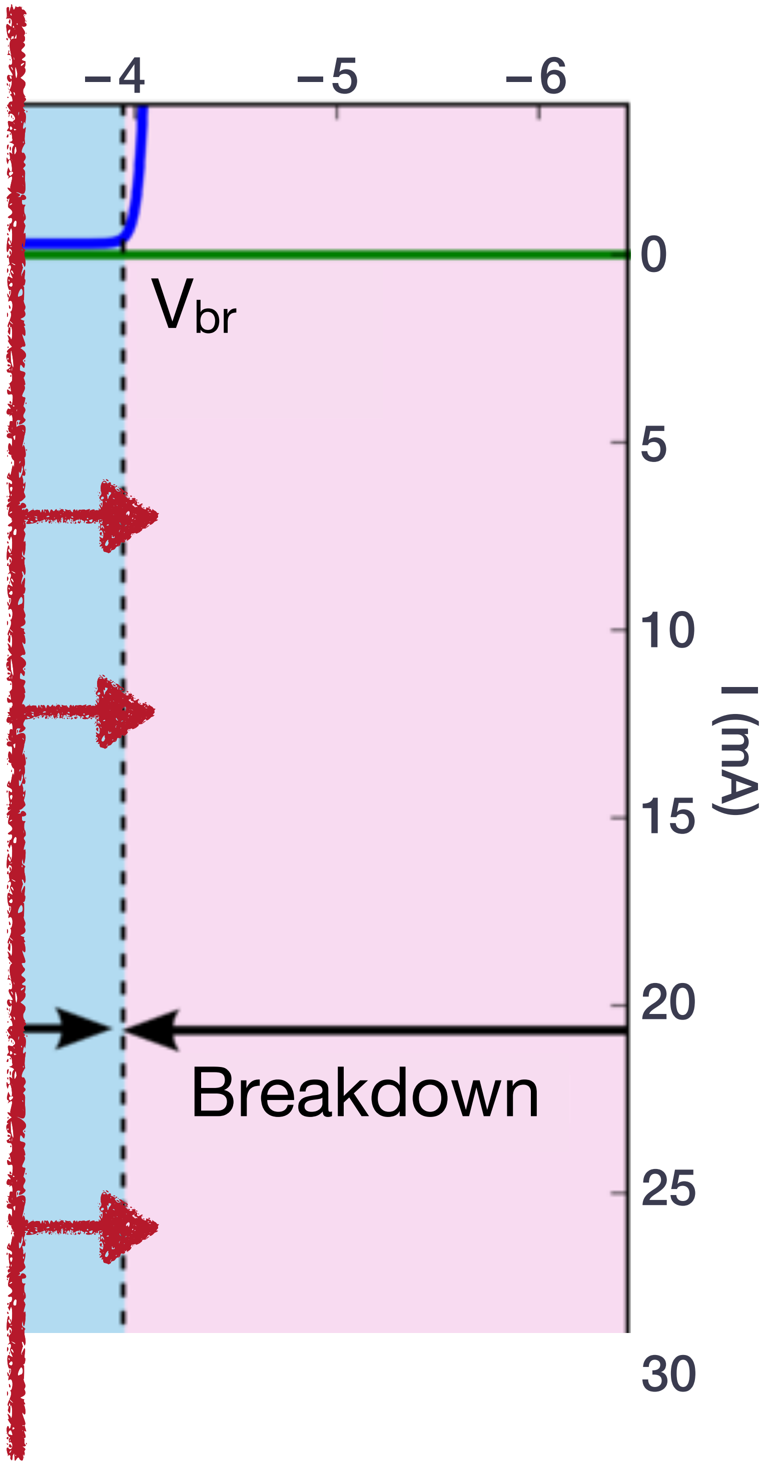
The pn-Junction – Photo Detection Principle

[picture source: Wikipedia]



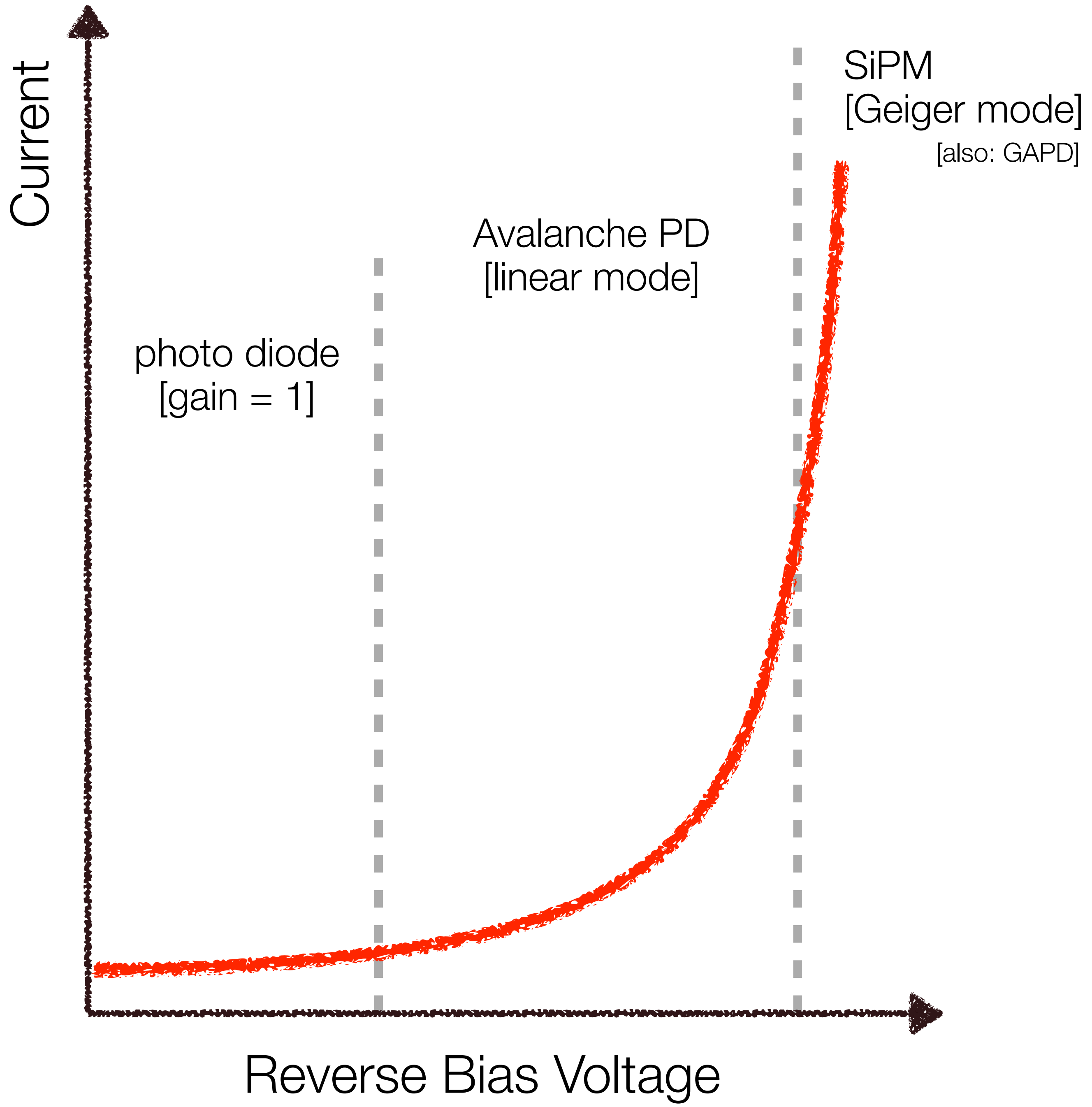
The pn-Junction – Photo Detection Principle



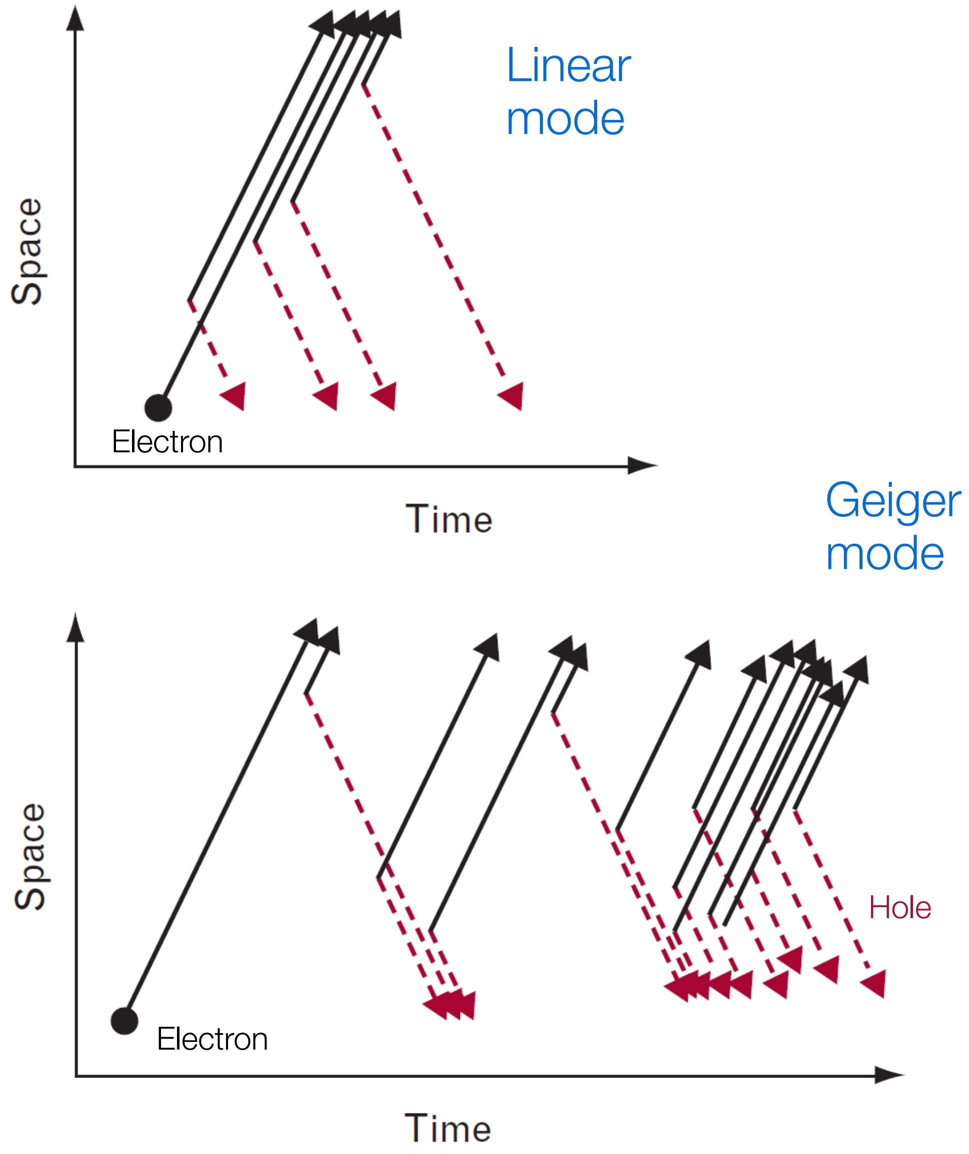


The pn-Junction – Photo Detection Principle

[source: P. Eckert]

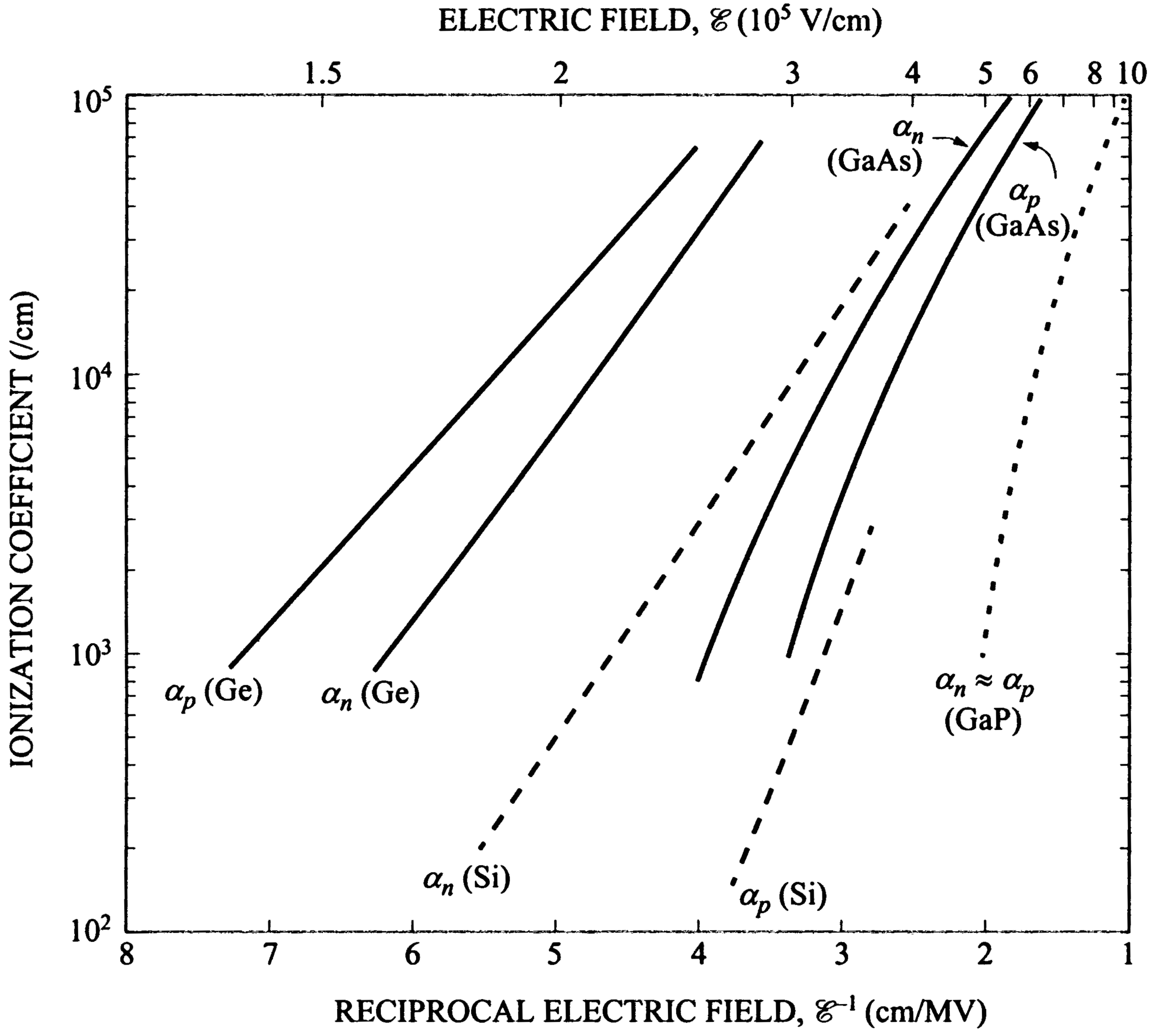


Avalanche
multiplication process …



Impact Ionization of Electrons and Holes …

[Kwok K. Ng, Complete Guide to Semiconductor Devices]



Empirical electric field dependence …

$$\alpha_i \approx a_i \cdot \exp\left[\left(-\frac{b_i}{E}\right)^{\beta_i}\right]$$

i = p,n

Silicon Photomultiplier

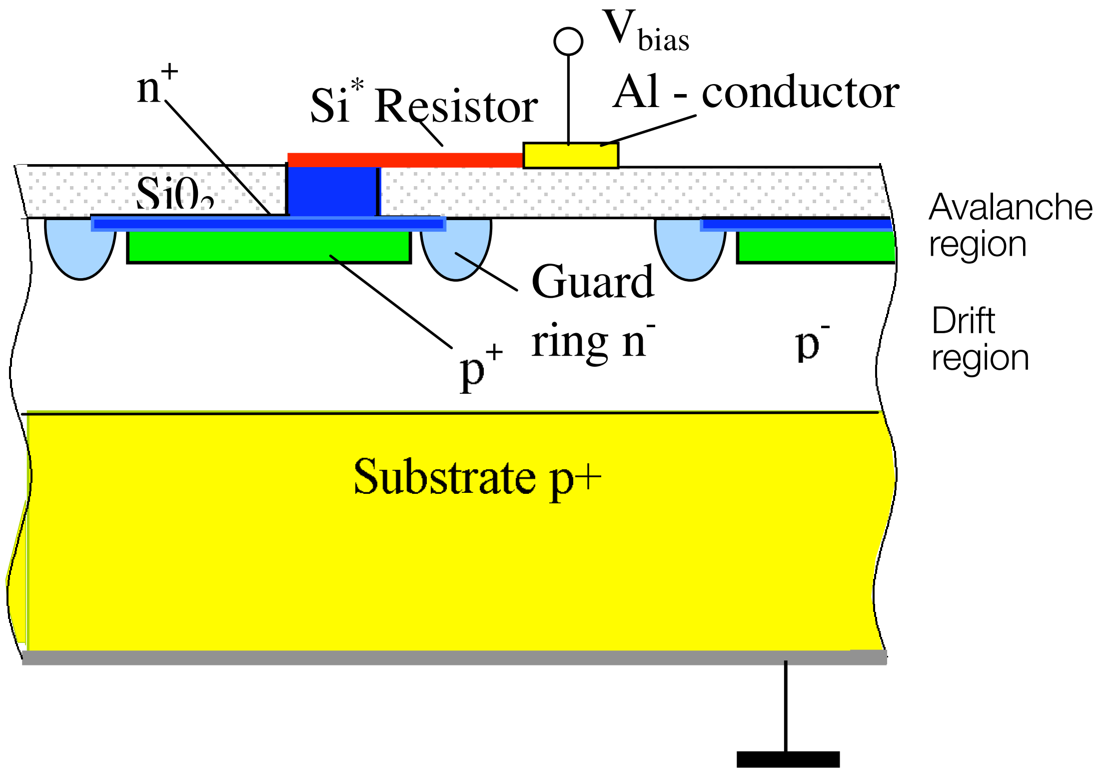
[P. Buzhan et al., ICFA Inst. Bull. 23 (2001) 28]

Principle:

Pixelized photo diodes operated in Geiger Mode

Single pixel works as a binary device

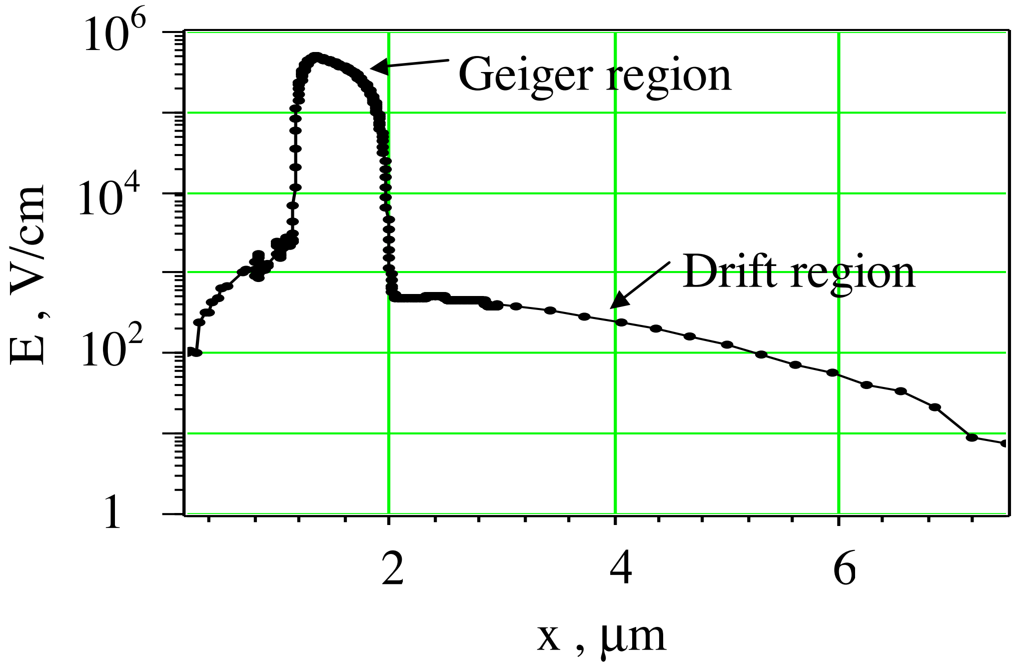
Energy = #photons seen by summing over all pixels



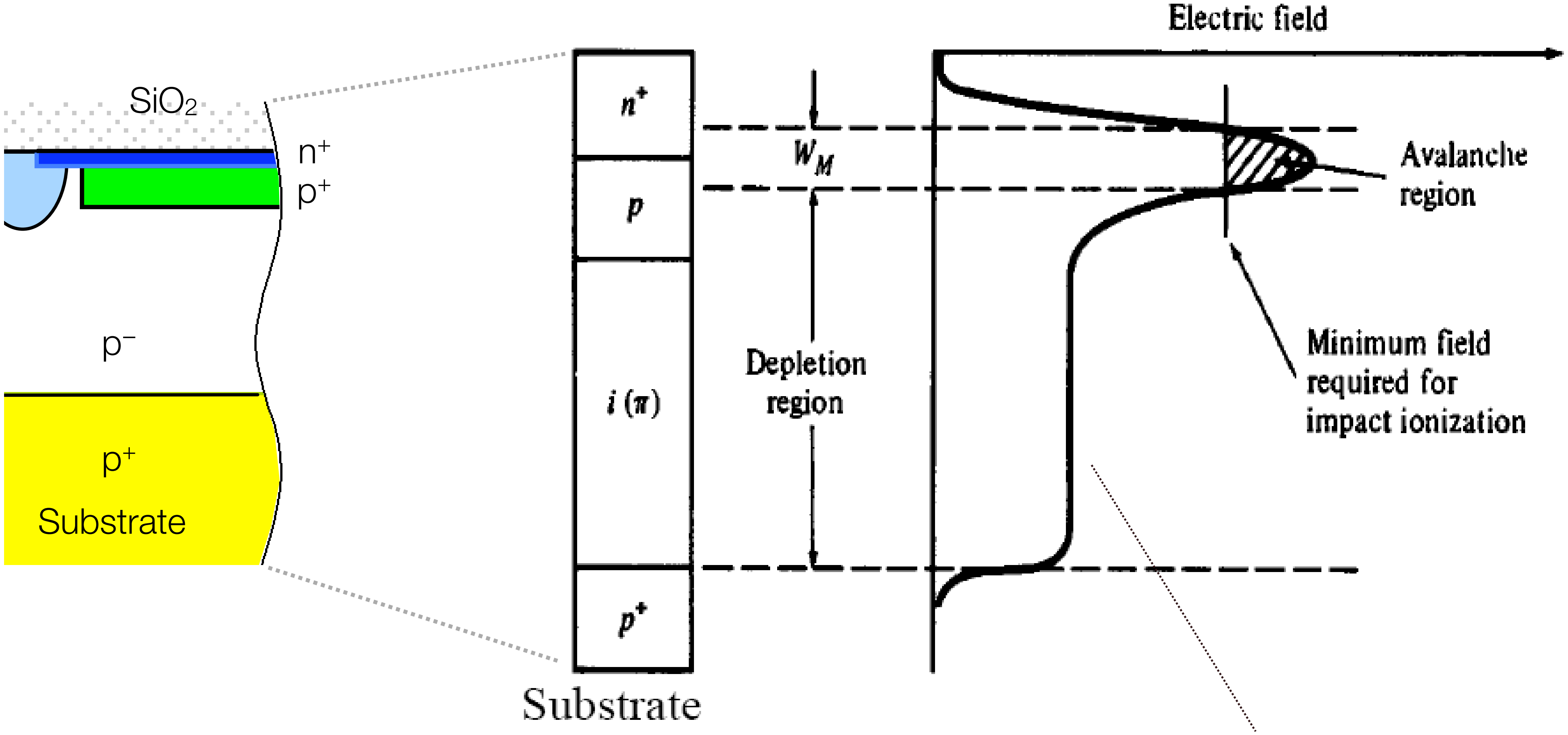
Features:

Granularity : 10^3 pixels/mm^2
Gain : 10^6
Bias Voltage : < 100 V
Efficiency : ca. 30 %

Insensitive to magnetic fields!
Works at room temperature ...

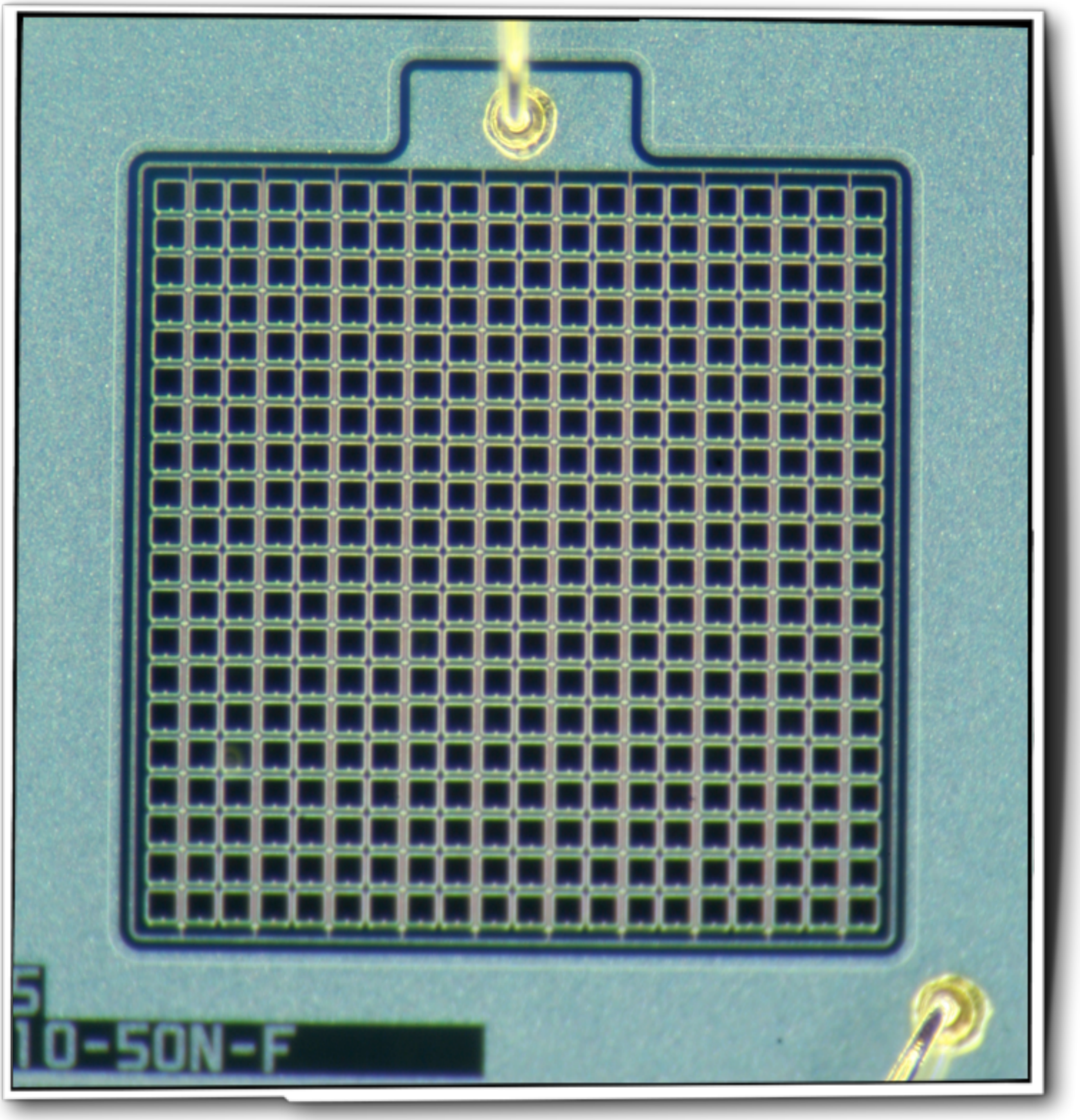


Silicon Photomultiplier



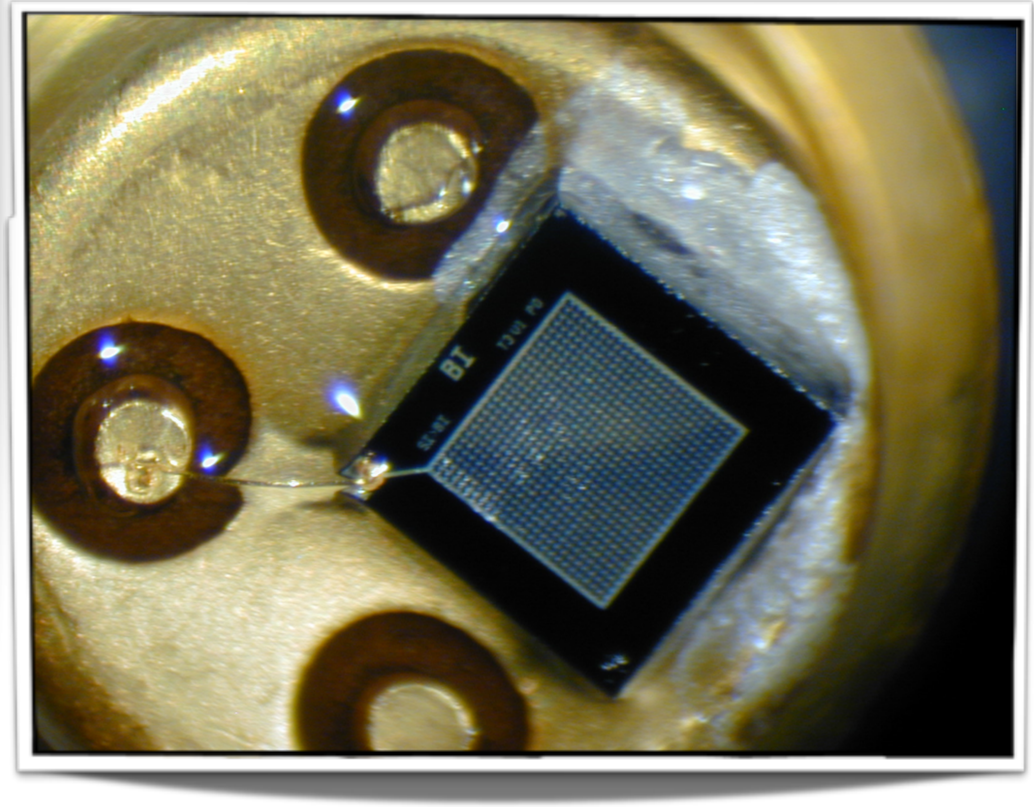
$$\frac{dE}{dx} = \frac{\rho(x)}{\epsilon}$$

Silicon Photomultiplier

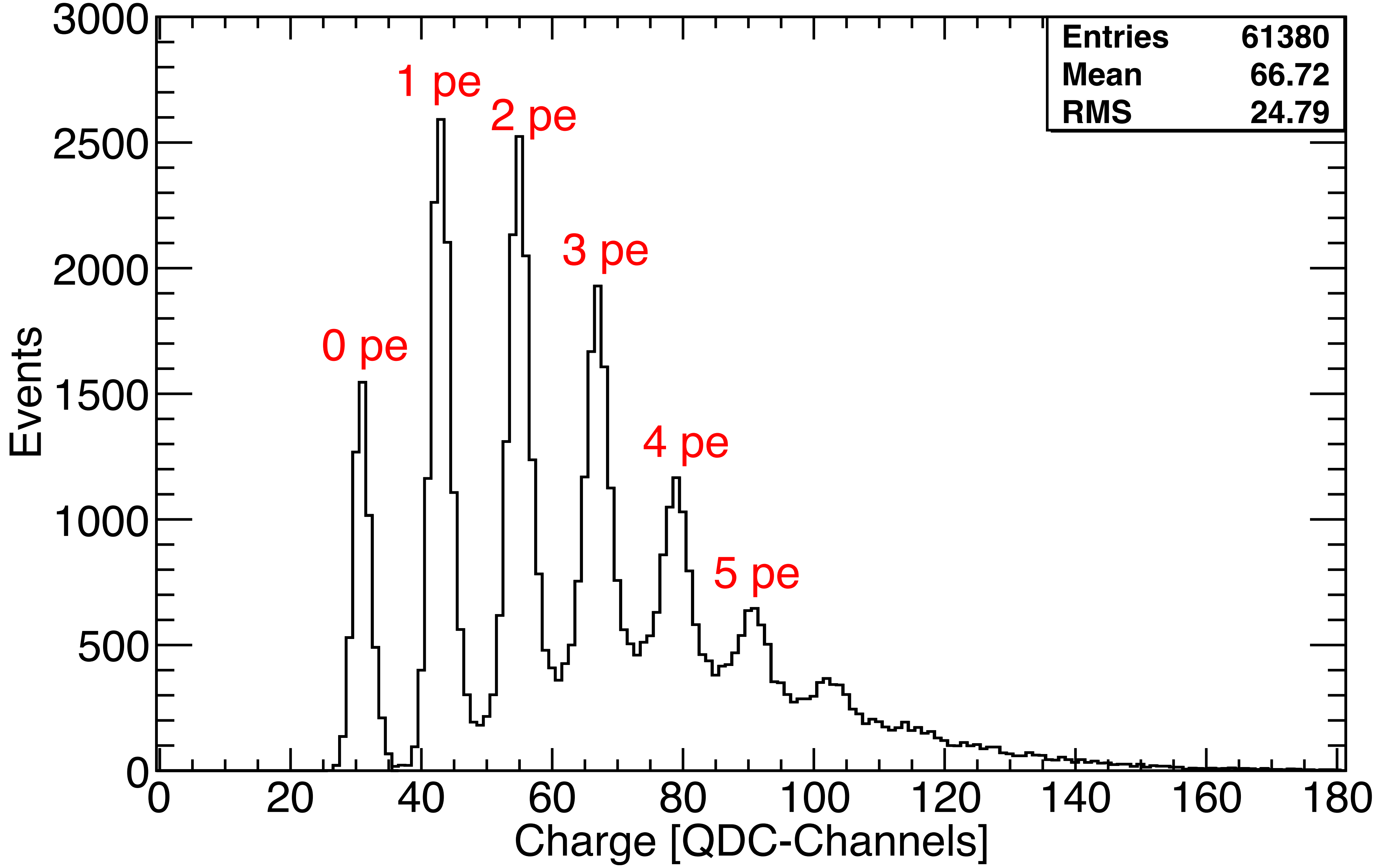


HAMAMATSU
MPPC 400Pixels

One of the first SiPM
[FBK, Trento, Italy]

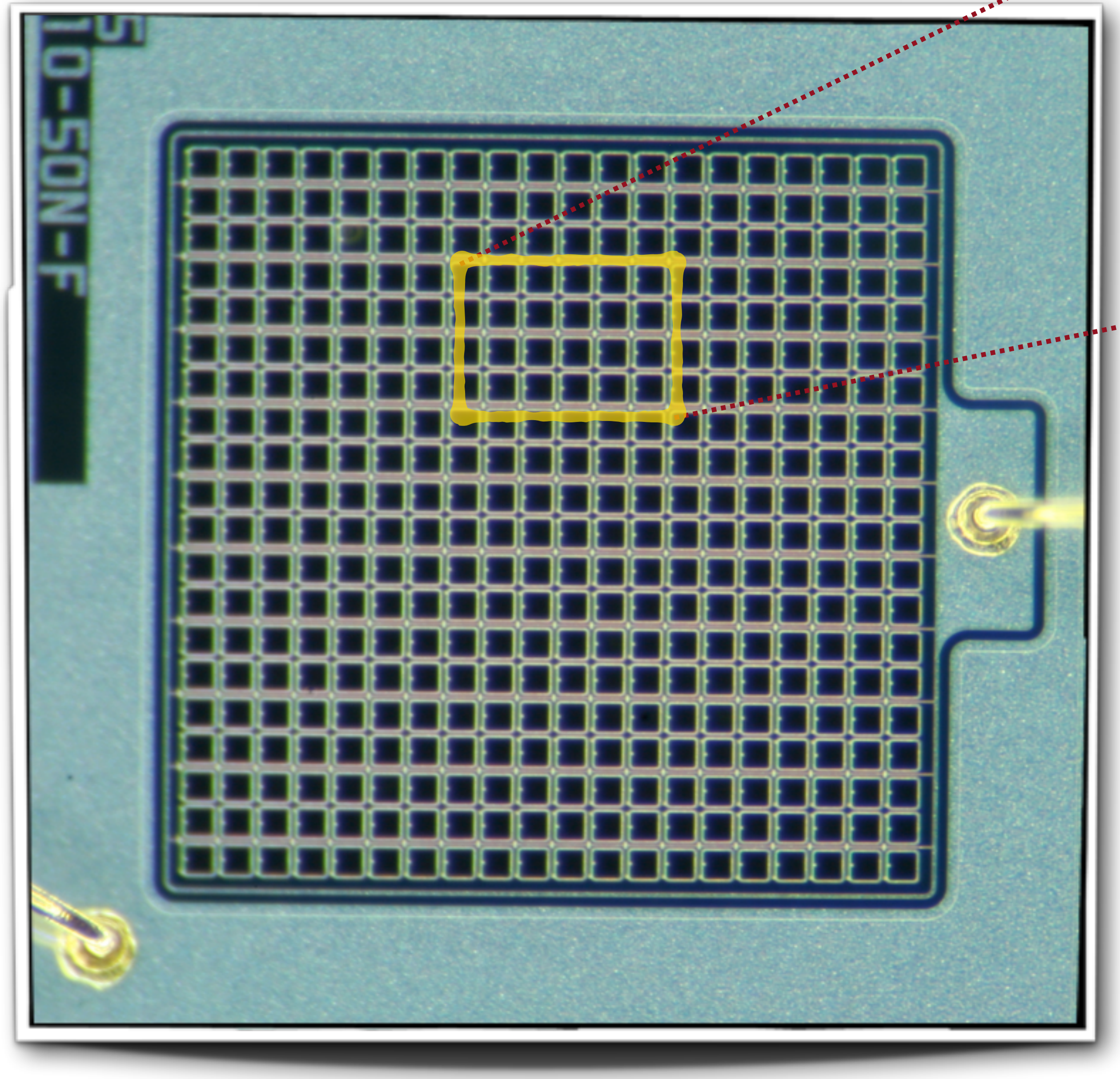


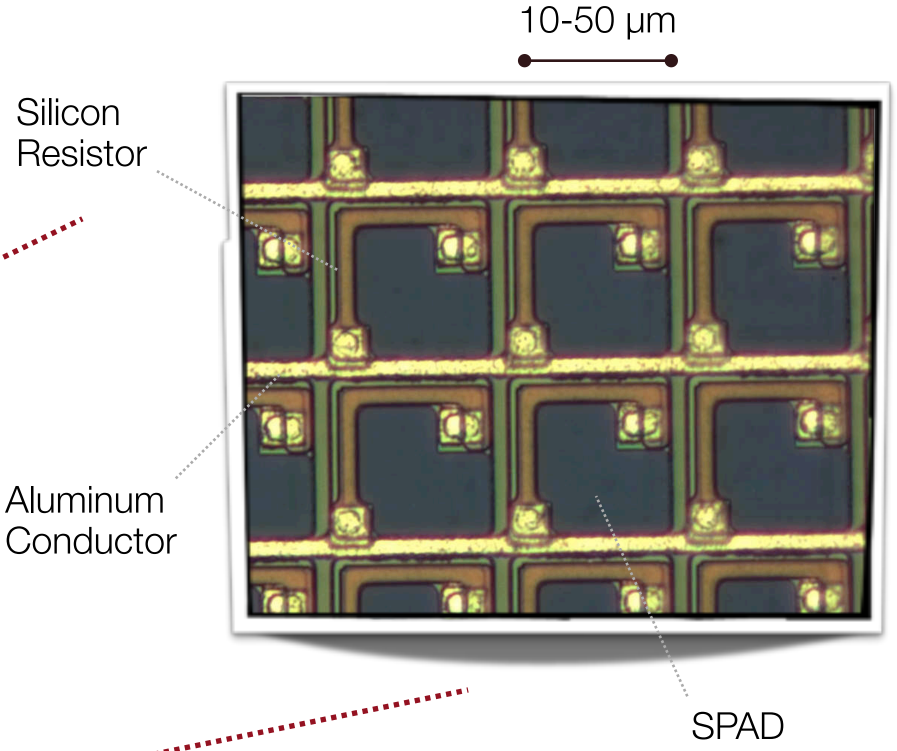
SiPM – Single Photon Spectrum

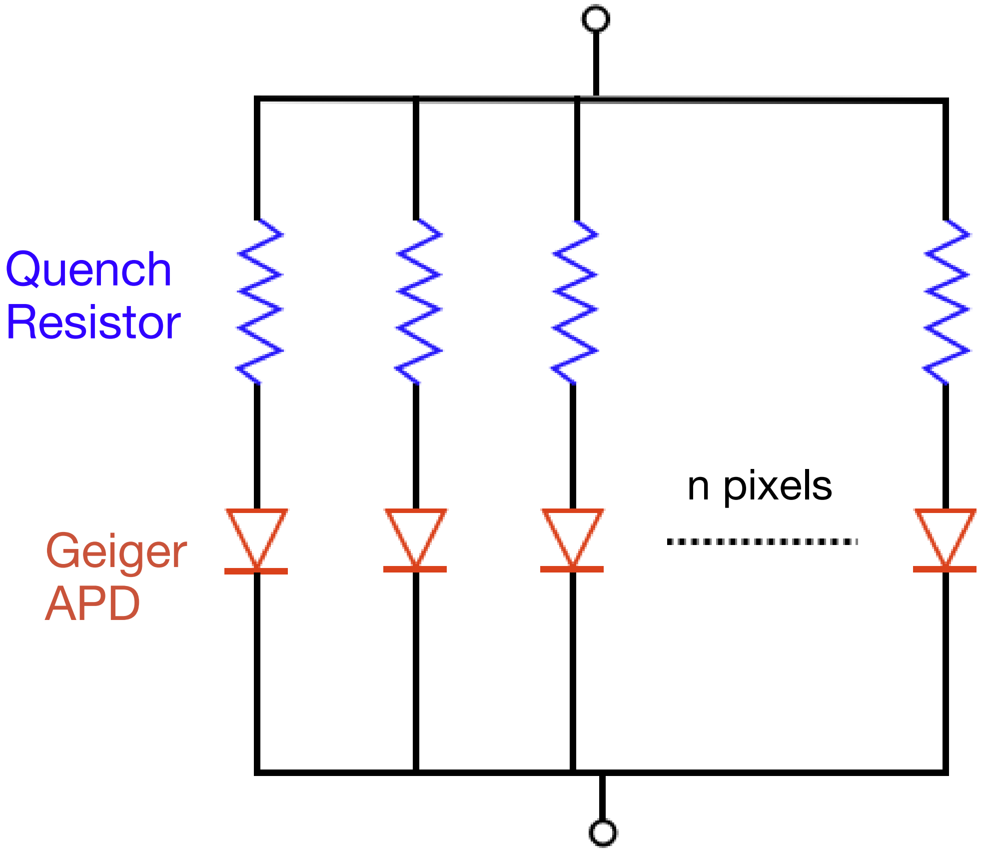


Silicon Photomultiplier

[400 pixel SiPM device; Hamamatsu]







$U_{bias} > U_{break}$

SiPM: array of SPADs connected in parallel …

[SPAD: single pixel avalanche diode]

Silicon Photomultiplier

SiPM:

Array of SPADs connected in parallel …

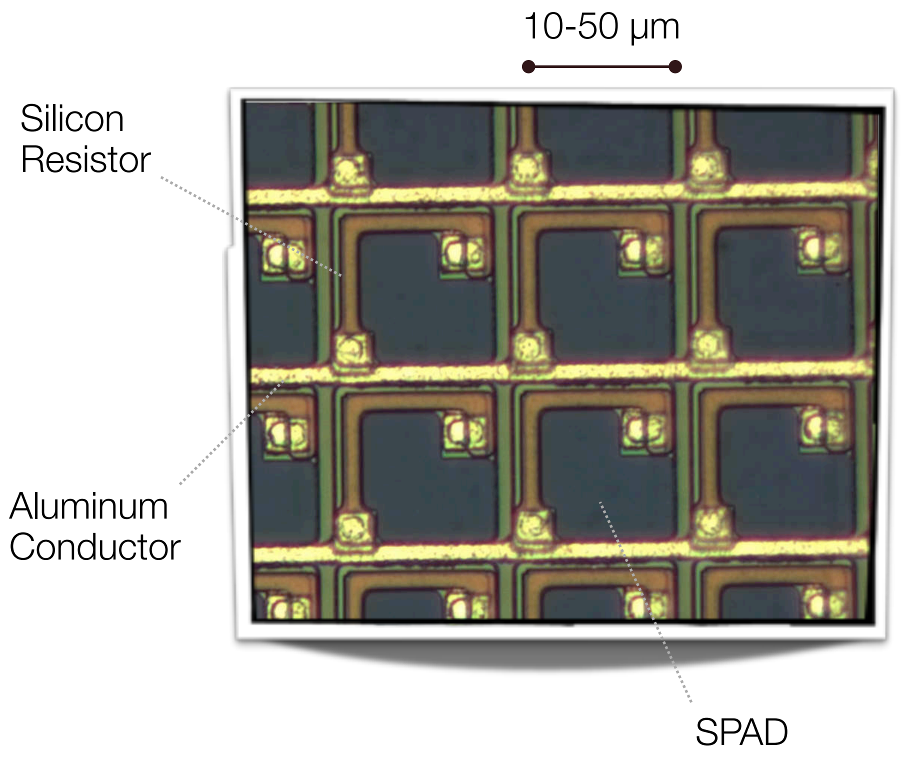
One quenching resistor per SPAD
[from 100kΩ to several MΩ]

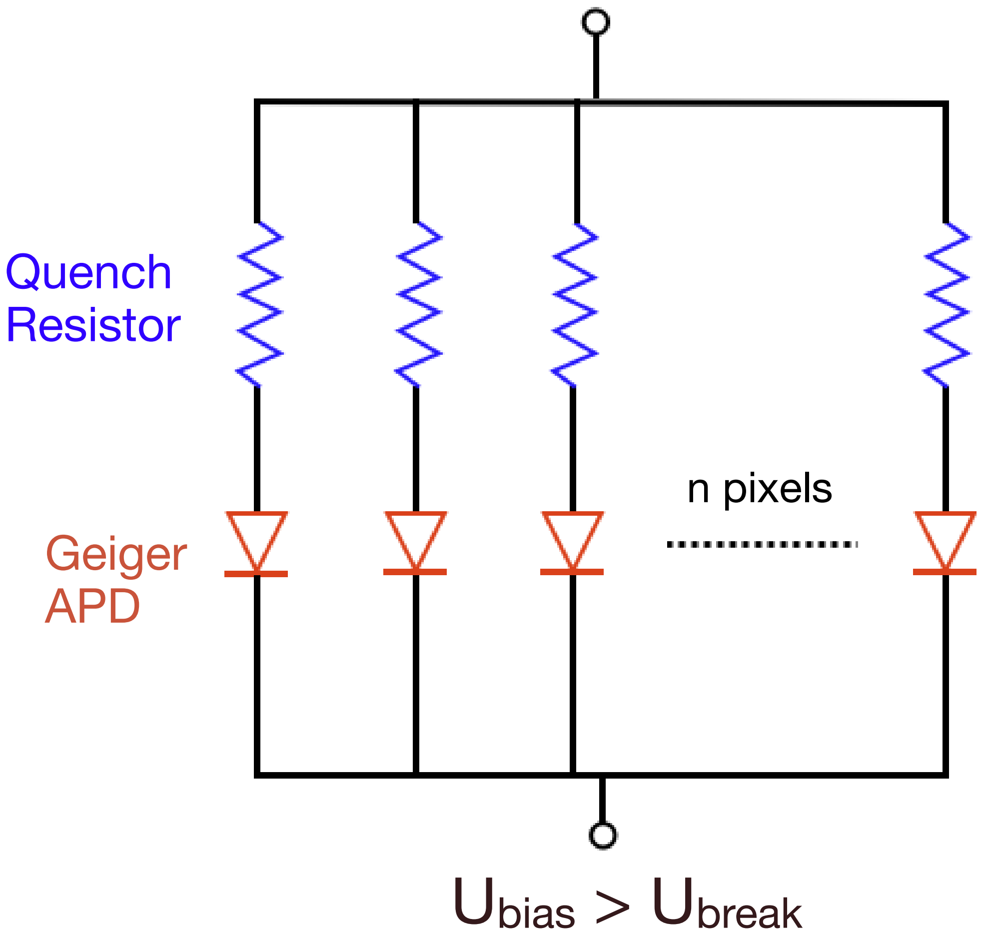
Common bias applied to SPADs …
[10-20% over breakdown voltage]

SPADs fire independently …

Output:
Sum of signals by individual cells …

i.e: for small light pulses ($N_\gamma \ll N_{pixels}$)
SiPMs work as analog photon counters …





SiPM – Quenching Process

Point A:

SiPM biased at $U_{bias} > U_{br}$ …

[$U_R = 0$, $U_D = U_{bias}$]

As long as no charge carrier is present in the high electric field region, no current flowing …

Point B:

Avalanche breakdown …

[initiated by photon, thermal noise …]

[$U_R = I \cdot R_q$; $U_D = U_{bias} - U_R$]

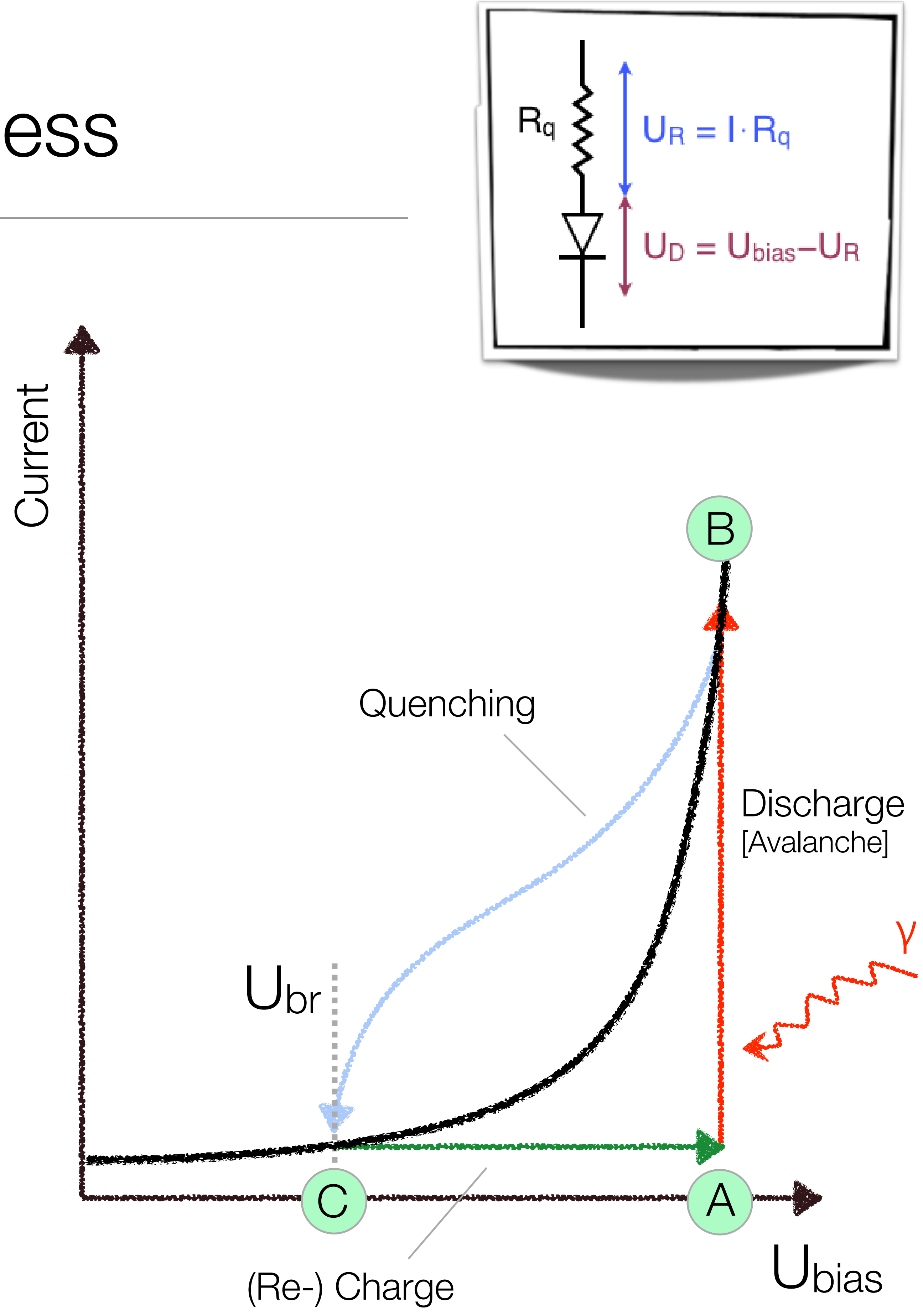
Internal diode capacitance starts to discharge, the rising current flowing through the device induces voltage drop at voltage drop at R_q …

Point C:

Avalanche quenched …

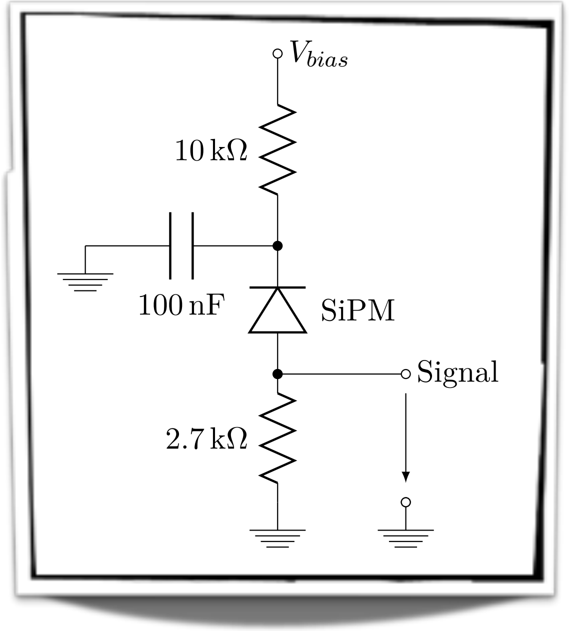
[$U_D = U_{br} \rightarrow U_D = U_{bias}$]

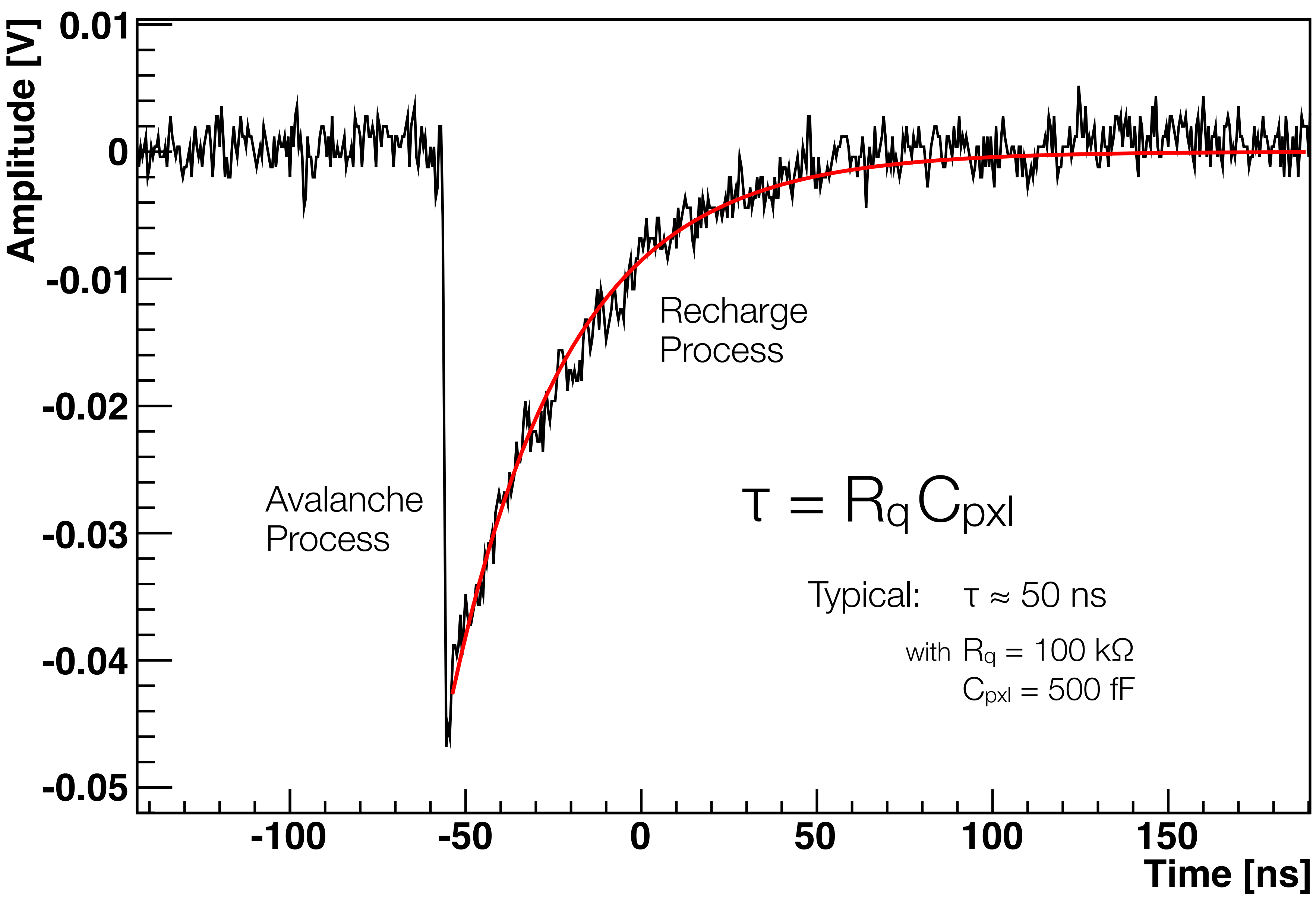
Recharge of internal device capacitance …
Return to initial state …



[source: A. Taddday]

SiPM – Typical Signal Shape





Avalanche Process

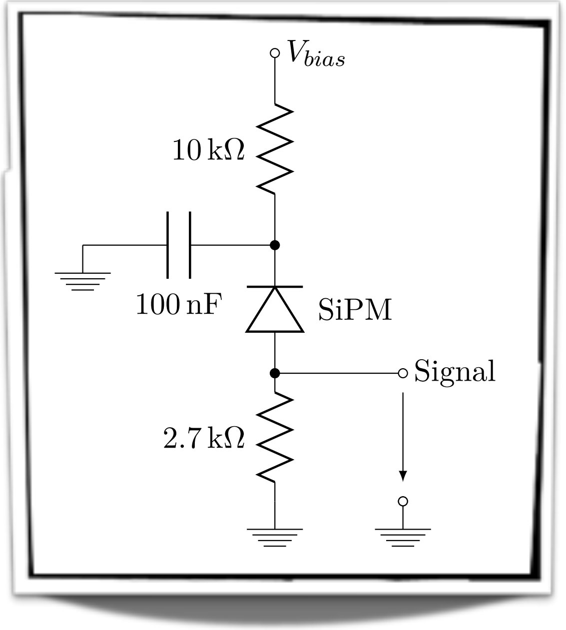
Recharge Process

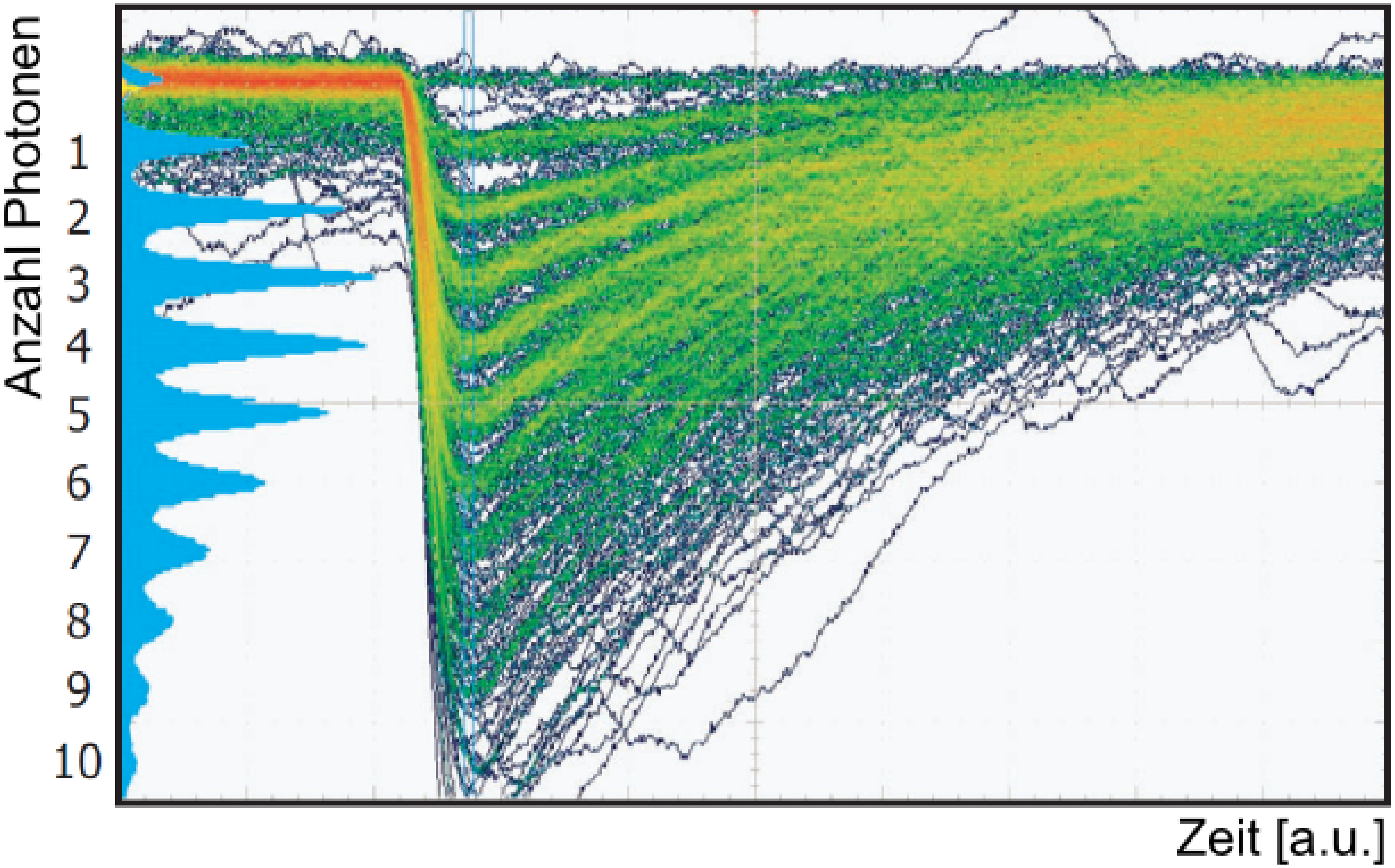
$$\tau = R_q C_{pxl}$$

Typical: $\tau \approx 50$ ns

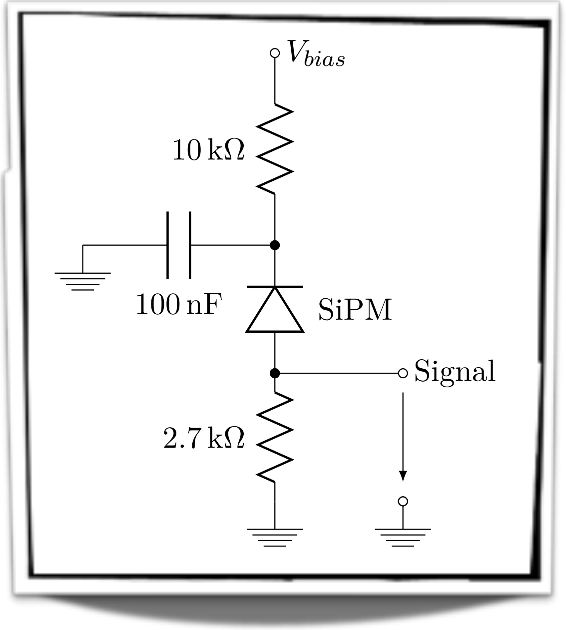
with $R_q = 100$ kΩ
$C_{pxl} = 500$ fF

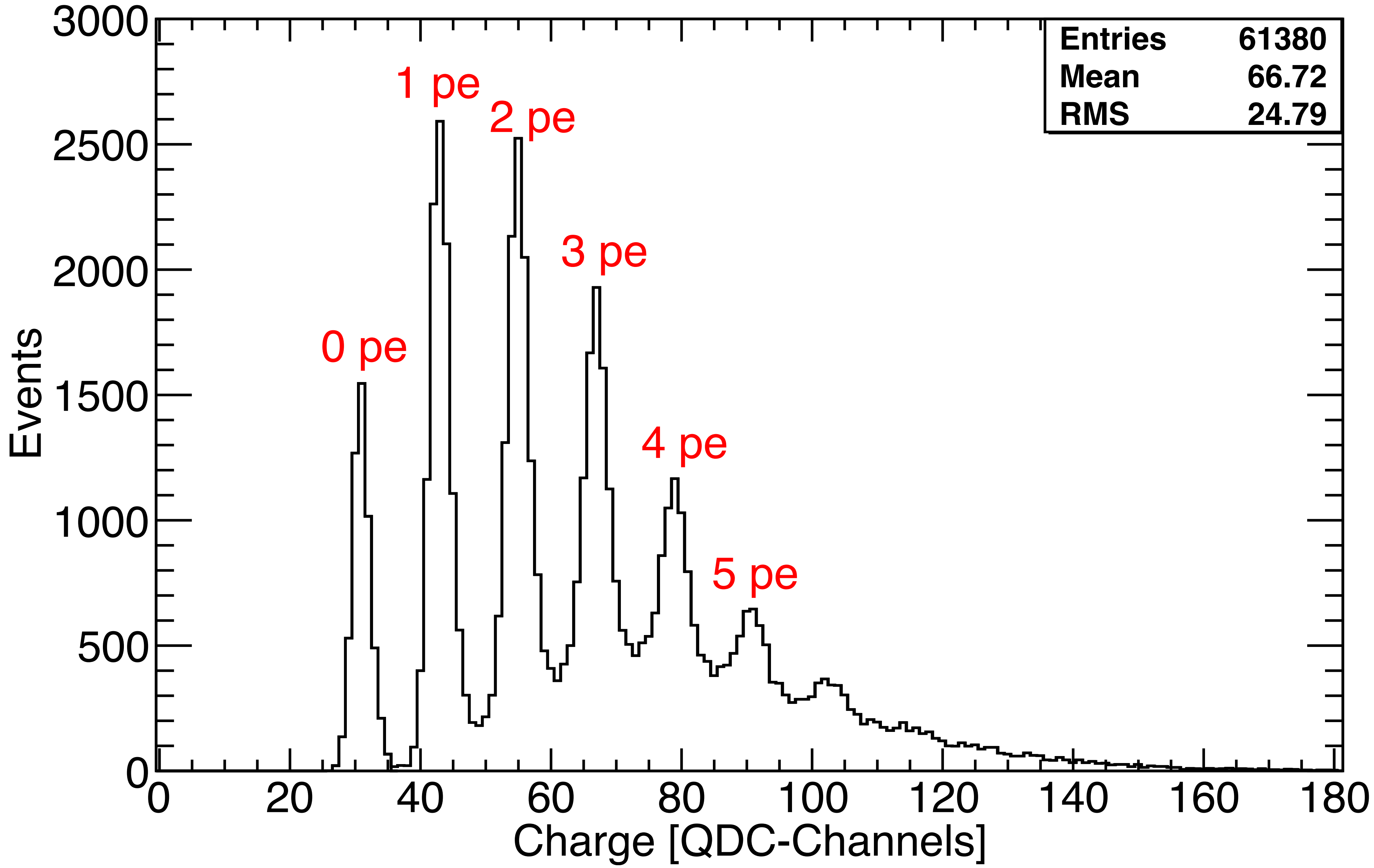
SiPM – Single Photon Spectrum





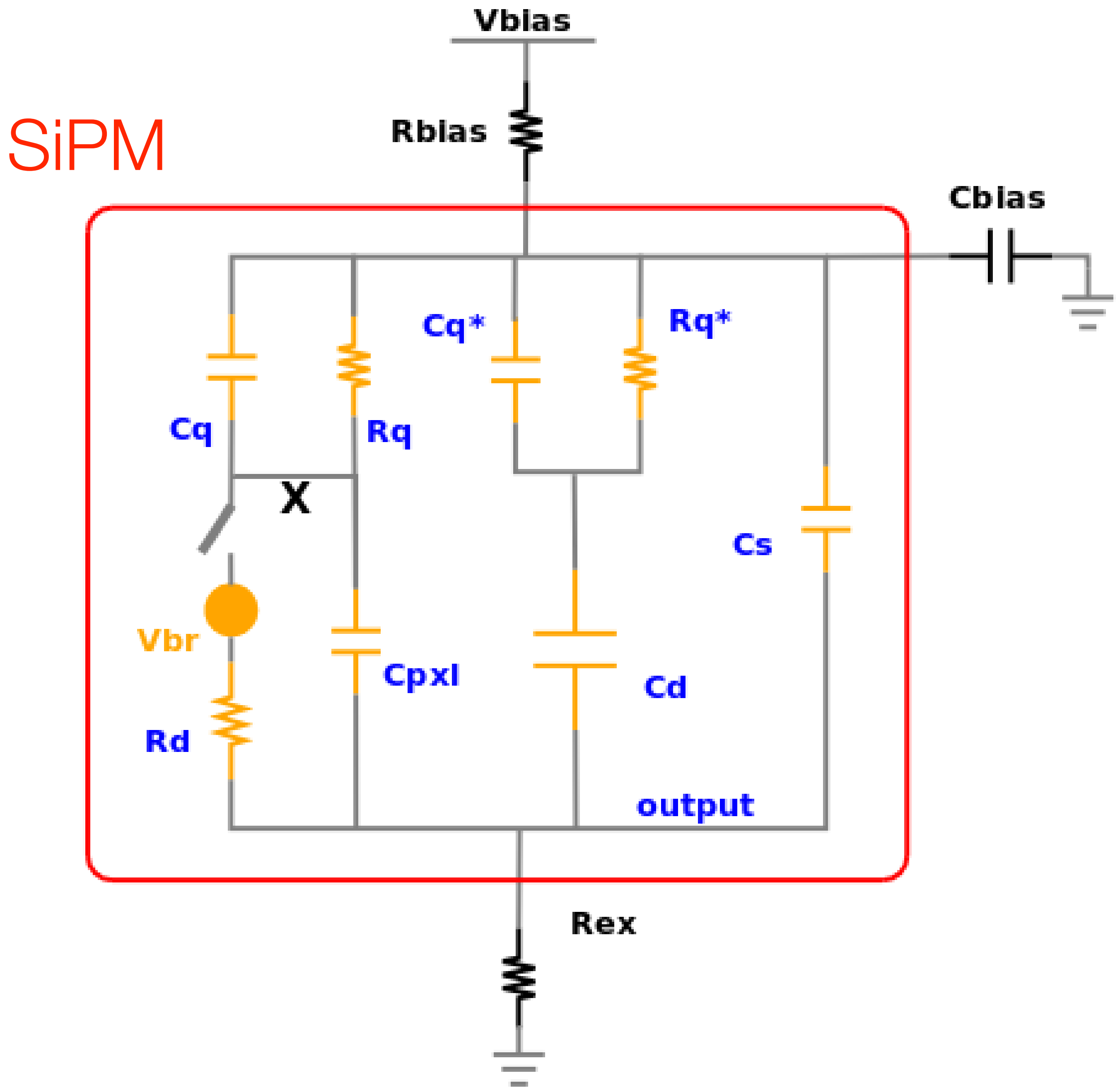
SiPM – Single Photon Spectrum



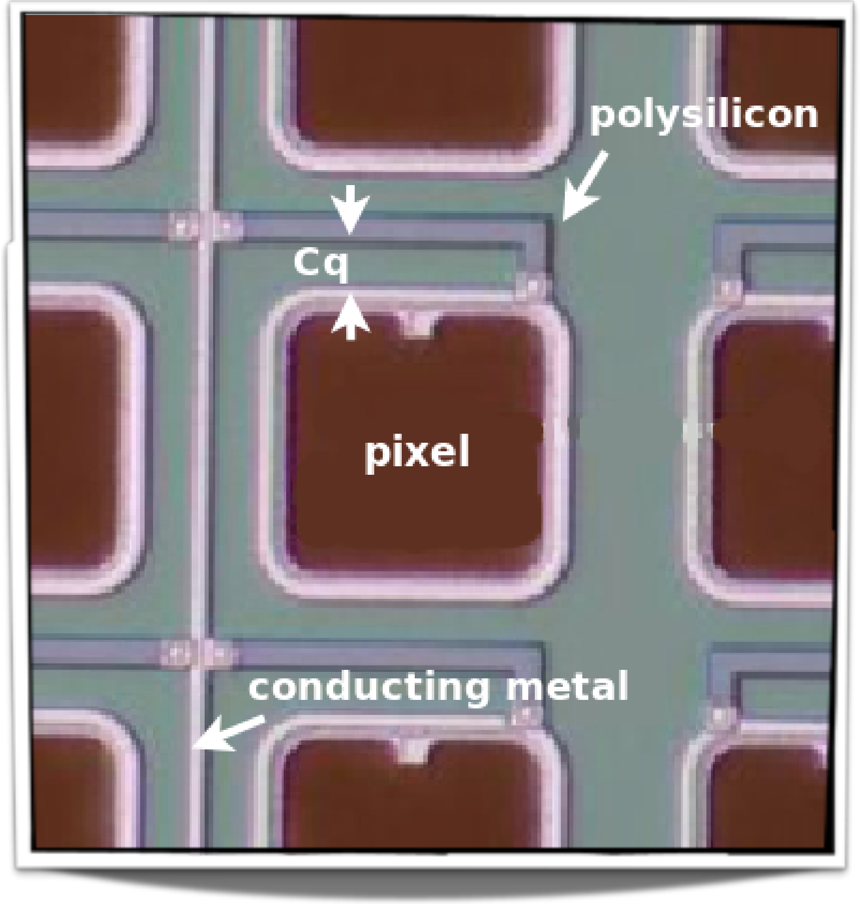


SiPM – Electrical Model

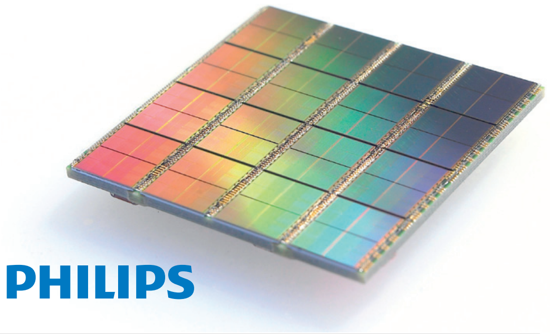
[source: W. Shen]

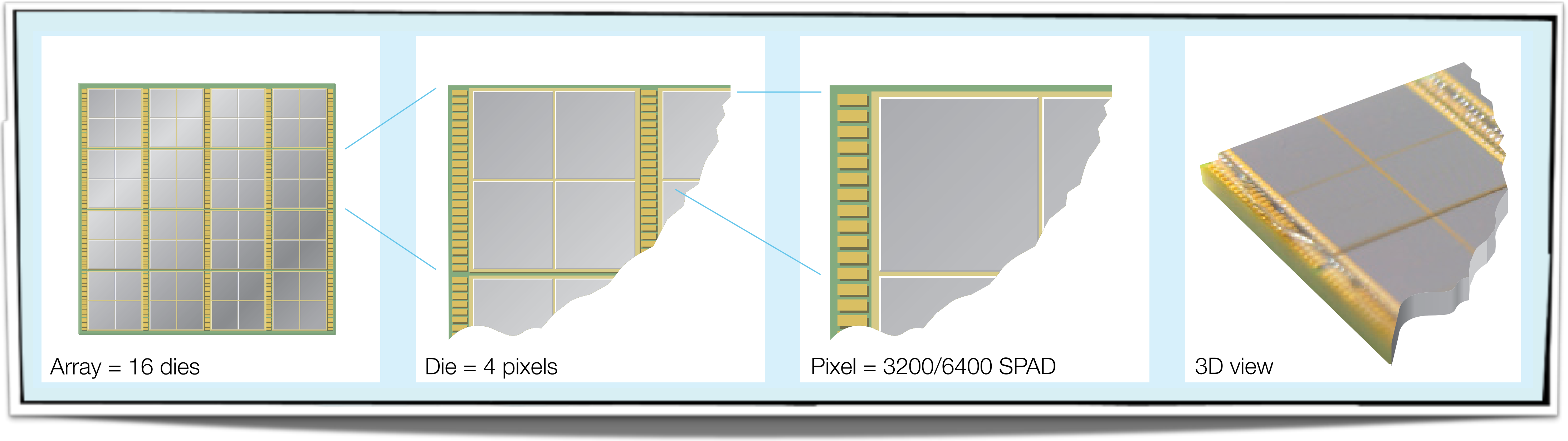


C_{pxl}	Pixel capacitance
C_q	Parasitic capacitance
C_d	Capacitance of inactive pixels
C_s	Stray capacitance
R_q	Quench resistor
R_d	Space charge resistance



Philips – Digital SiPMs



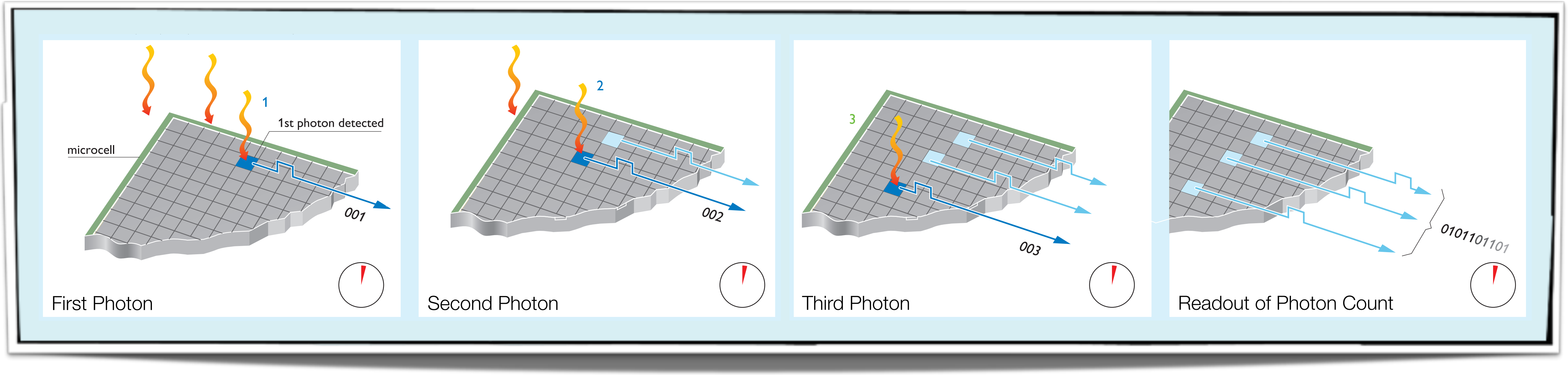


Array = 16 dies

Die = 4 pixels

Pixel = 3200/6400 SPAD

3D view



First Photon

Second Photon

Third Photon

Readout of Photon Count

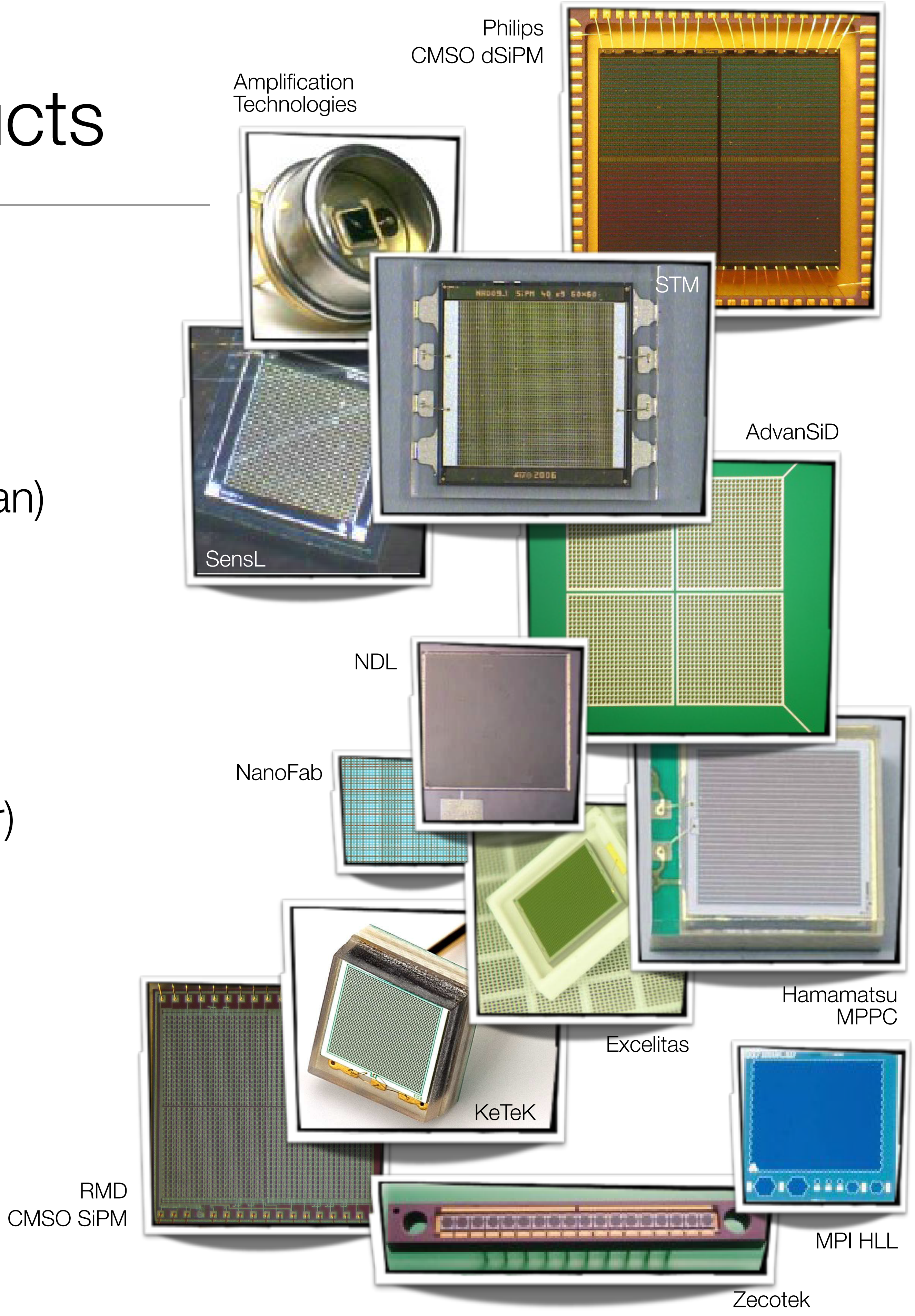
[source: Collazuol]

SiPM Developers & Products

MEPhI/Pulsar (Moscow) - Dolgoshein
CPTA (Moscow) - Golovin
Zecotek (Singapore) - Sadygov
Amplification Technologies (Orlando, USA)
Hamamatsu Photonics (Hamamatsu, Japan)
SensL (Cork, Ireland)
AdvanSiD (former FBK-irst Trento, Italy)
STMicroelectronics (Italy)
KETEK (Munich)
RMD (Boston, USA)
ExcelitasTechnologies (former PerkinElmer)
MPI Semiconductor Laboratory (Munich)
Novel Device Laboratory (Beijing, China)
Philips (Netherlands)
....

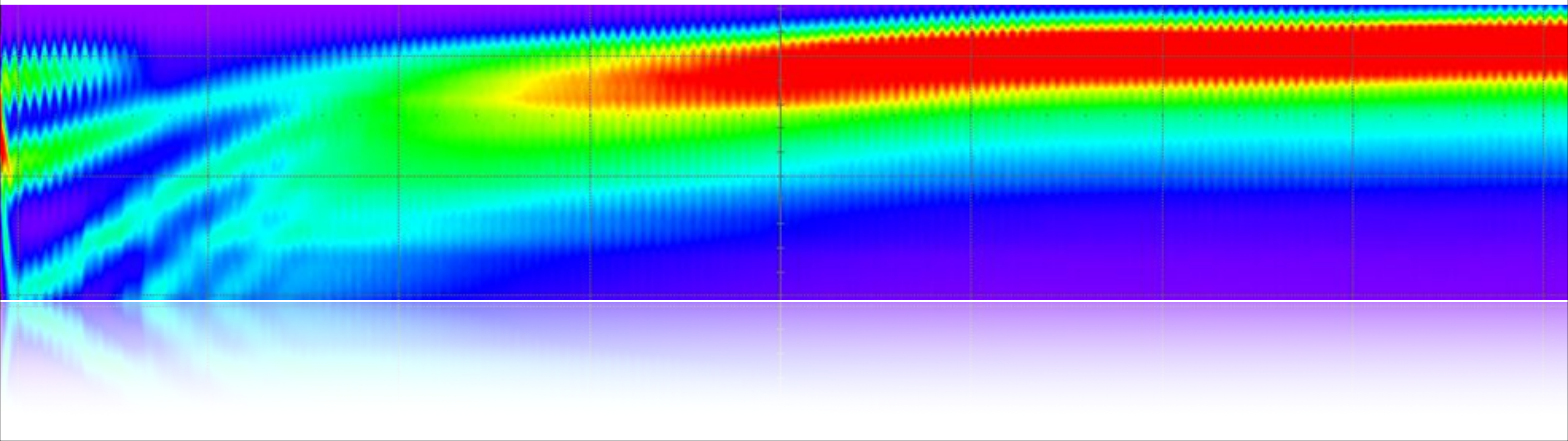
Note:
Every producer uses its own name …

MRS APD, MAPD, SiPM, SSPM,
MPPC, SPM, DAPD, PPD, SiMPl , dSiPM …



SiPM Features

Dark Count Rates, After Pulsing, PDE …



Summary of Properties

Pros:

High gain	[10^5 to 10^7
Compactness	[1 to 3 mm^2
Insensitive to magnetic fields	[up to few T
Low operation voltage	[30 - 70 V

Cons:

Limited dynamical range	[$N_{pxl} = O(1000)$
Cross-talk, after-pulsing	[1-10%
High dark-rate	[0.1 to few MHz
Temperature sensitivity	[20-50 mV/K

Gain and Single Pixel Charge

Every pixel works as digital device …

Single pixel charge:

$$\begin{aligned} Q_{\mathrm{pxl}} &= C_{\mathrm{pxl}} \cdot (U_{\mathrm{bias}} - U_{\mathrm{br}}) \\ &= C_{\mathrm{pxl}} \cdot U_{\mathrm{over}} \end{aligned}$$

SiPM Output:

[for low N_{pe} …]

$$Q_{\mathrm{out}} = N_{\mathrm{pe}} \cdot Q_{\mathrm{pxl}}$$

SiPM Gain:

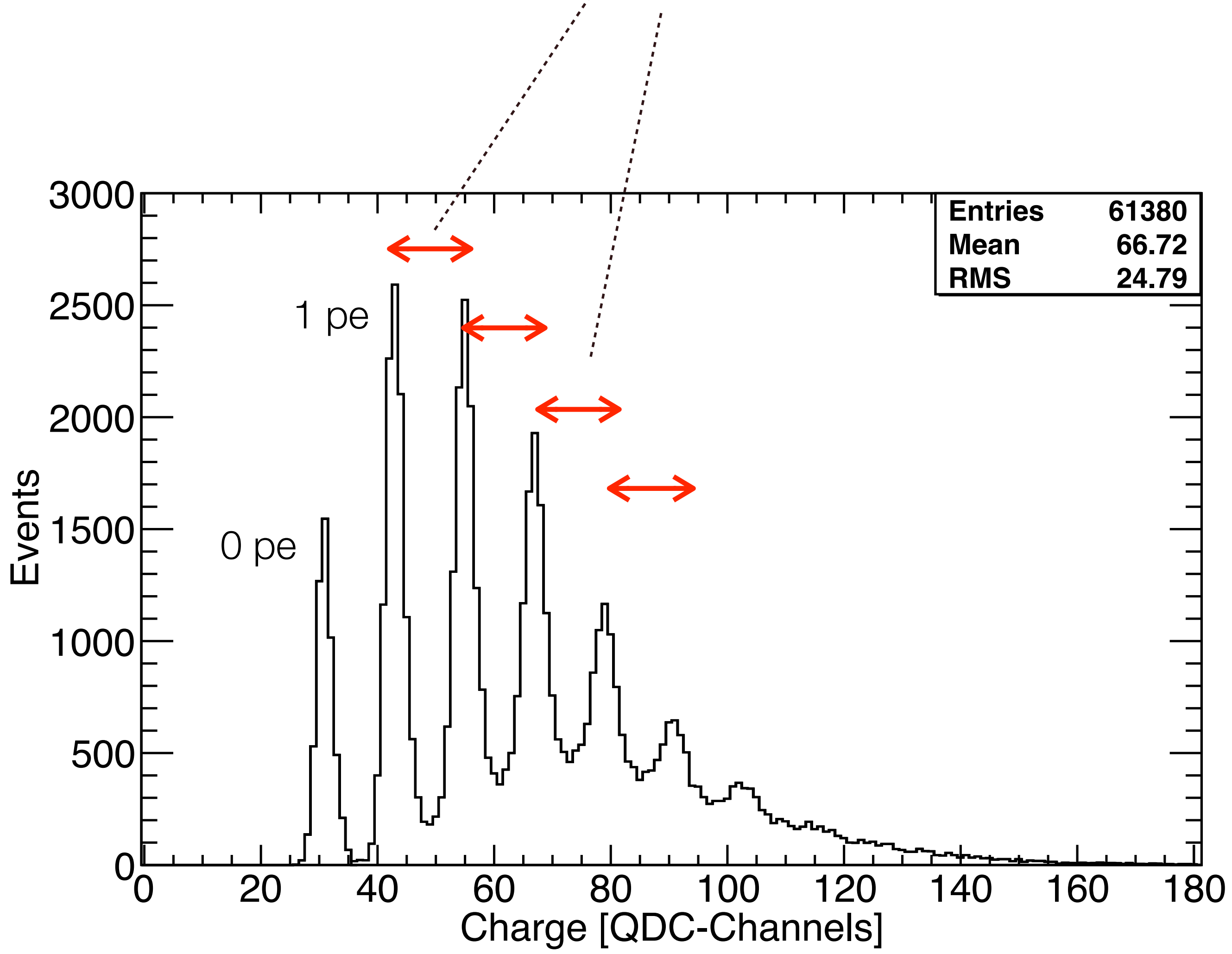
[for low x-talk; after-pulsing …]

$$G = Q_{\mathrm{pxl}}/Q_e$$

$$\text{i.e } G \sim U_{\mathrm{over}}$$

Gain

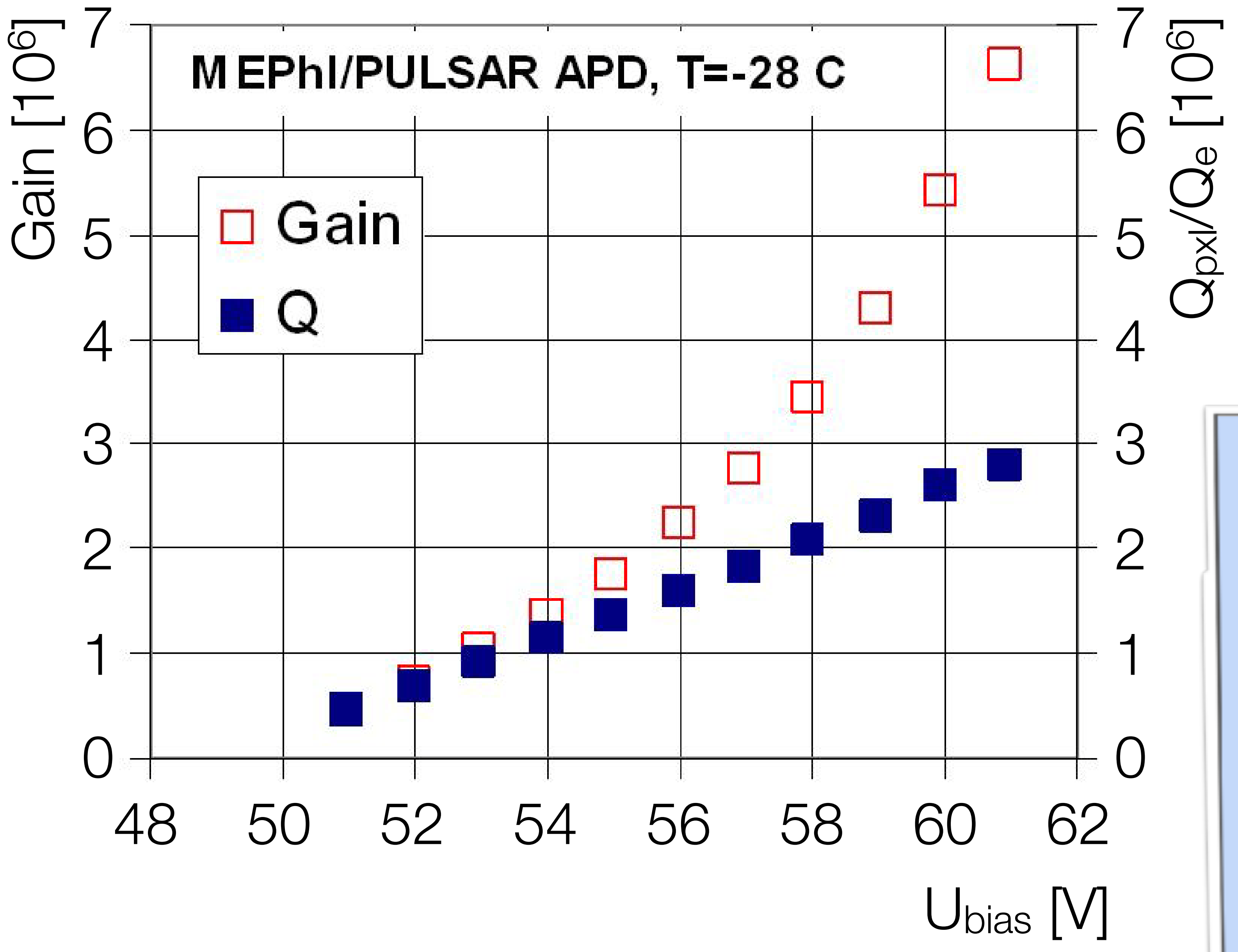
[Typical: $G \sim 10^5 - 10^7$]



Gain and Single Pixel Charge

[source: Y. Musienko, FNAL]

But …



Modification
for large U_{bias} …

$G = Q_{pxl}/Q_e \cdot n_p$

[n_p: #pixels fired one primary p.e. …]

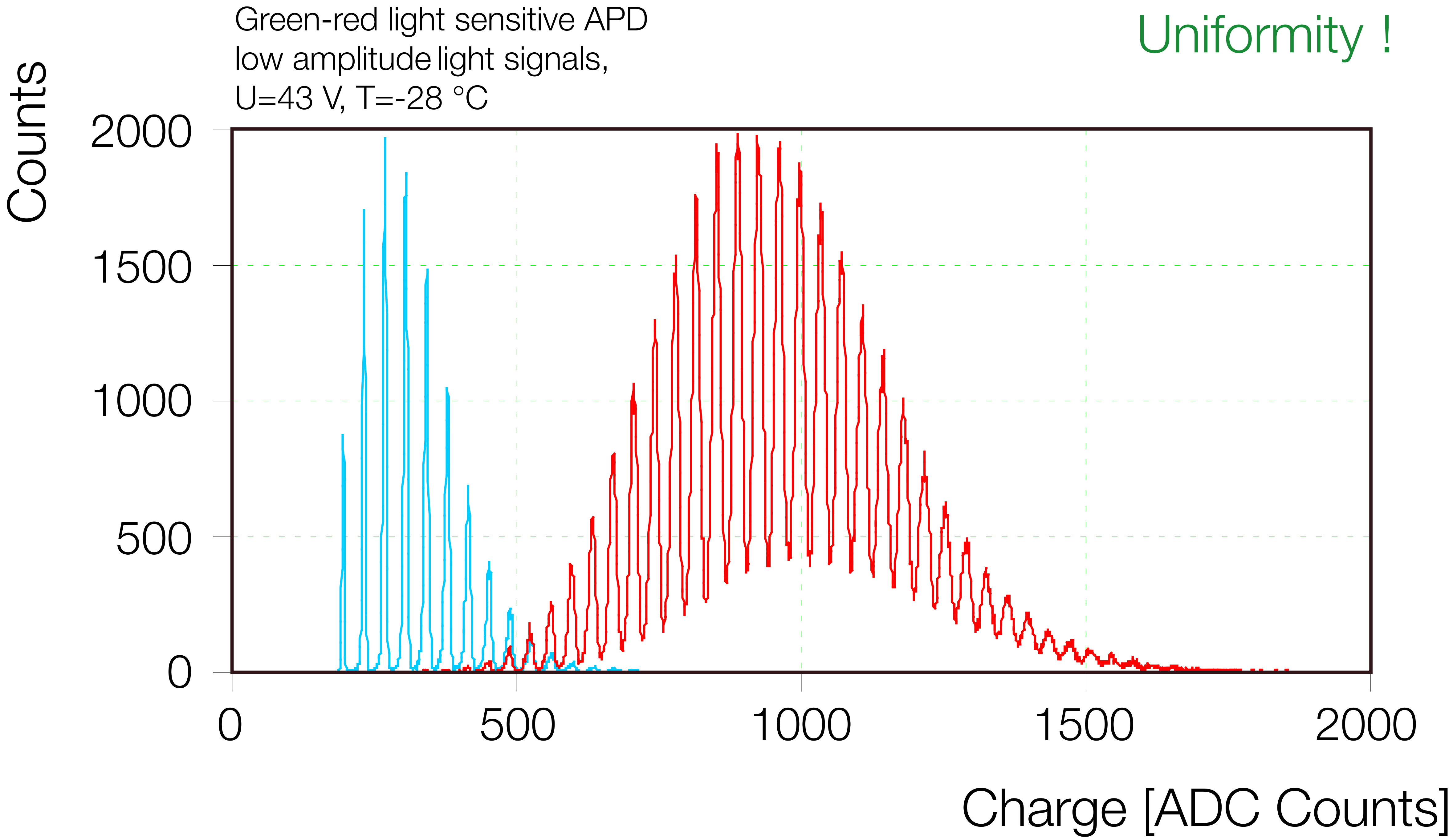
Reasons:

- Optical cross-talk …
- After-pulsing …

Pixel-to-Pixel Uniformity

[source: Y. Musienko, FNAL]

Good
Uniformity !



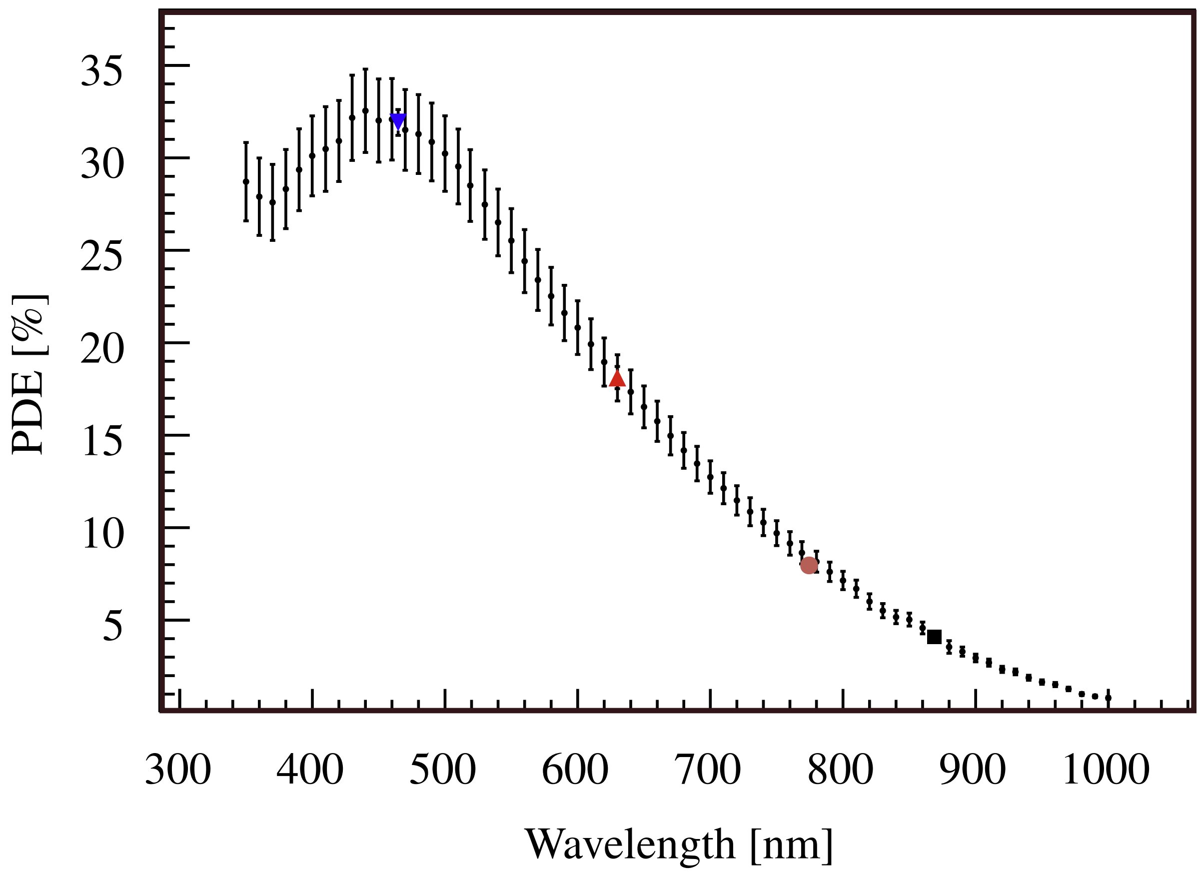
Photon Detection Efficiency

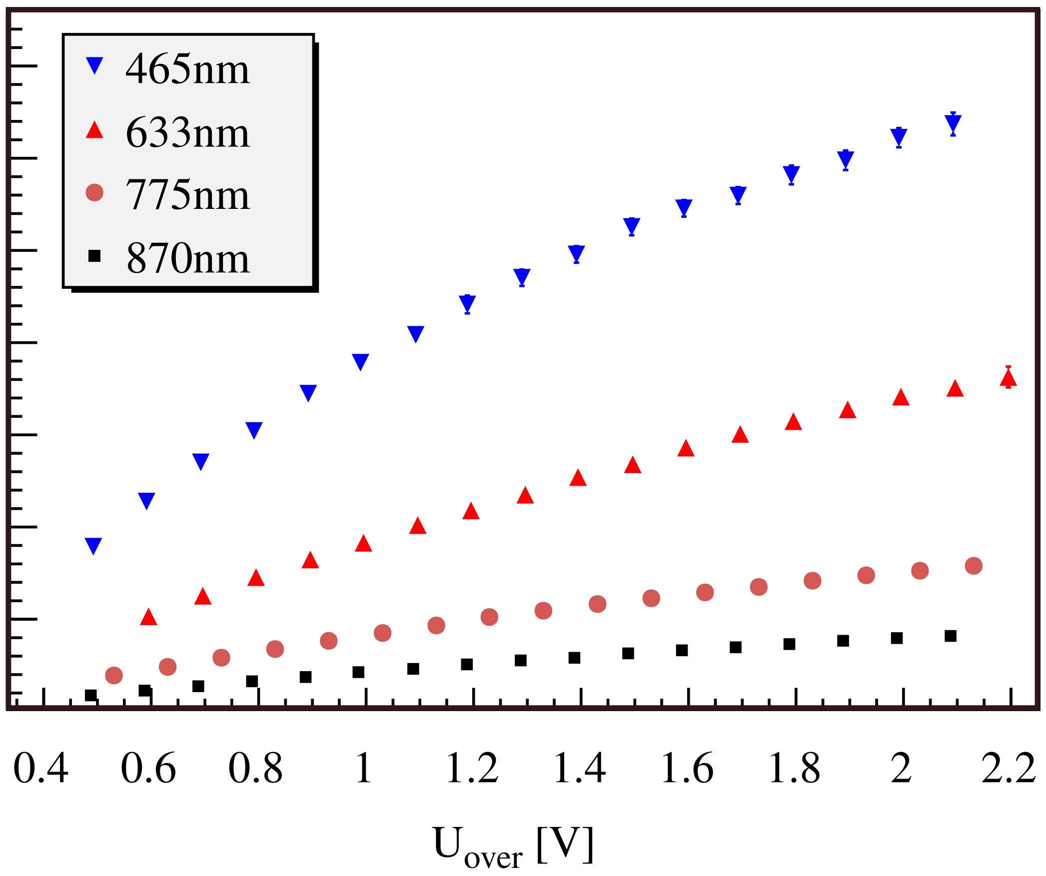
Quantum Efficiency

$$\boxed{PDE = \varepsilon_{geo} \cdot QE(\lambda,T) \cdot \varepsilon_{trig}(\lambda,U,T)}$$

Geometrical
Factor

Avalanche
Trigger Probability

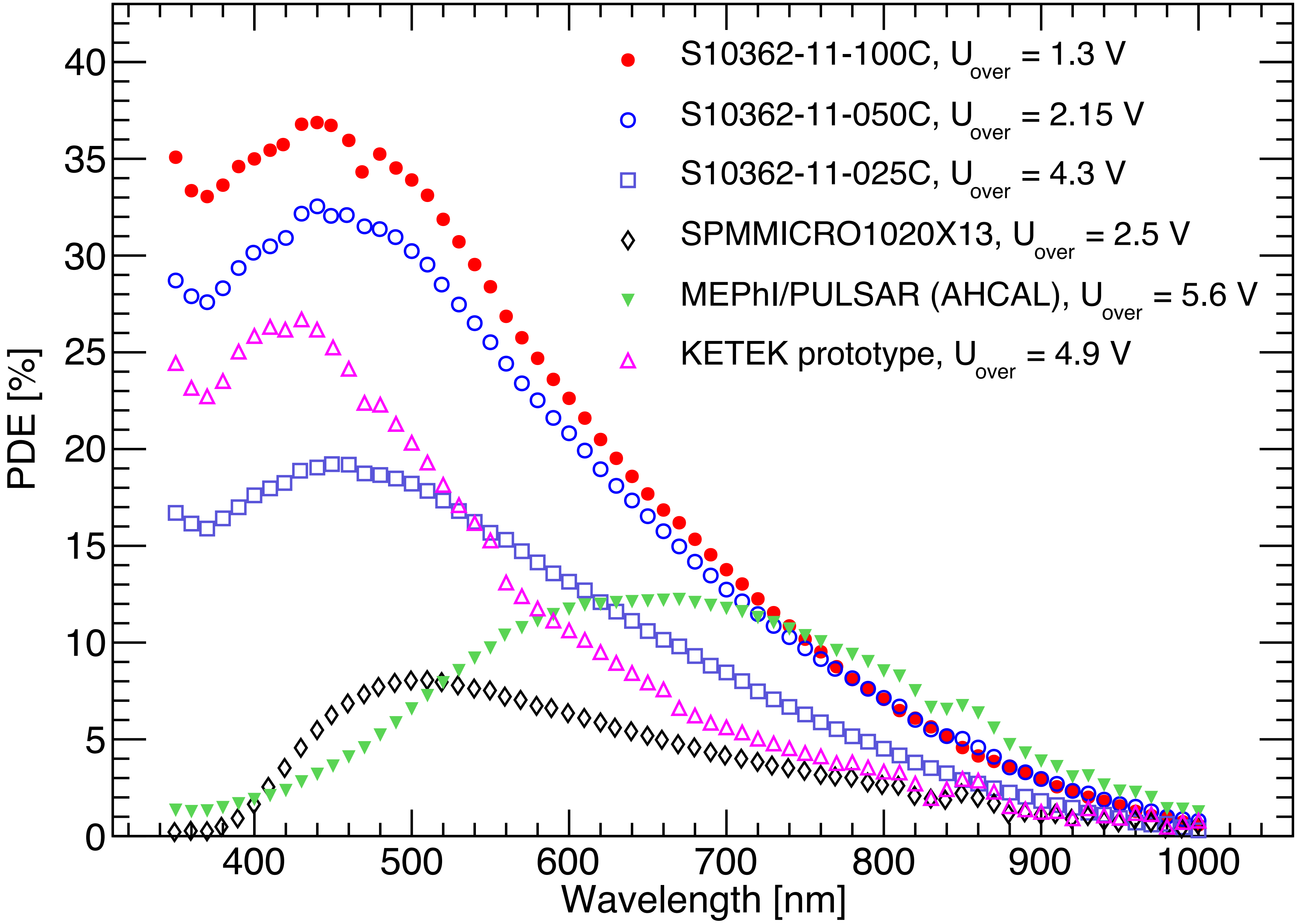




[P. Eckert et al., NIM A620 (2010) 217]

Photon Detection Efficiency

[source: A. Tadday]



Geometrical or Fill Factor

Non-sensitive zones between cells reduce Photon Detection Efficiency …

Silicon resistors and aluminum conductors are not photon-sensitive and hence reduce the active area …

Smaller pixel size yields small ε_{geo} …

[Tradeoff between dynamic range and PDE …]

Typical: ε_{geo} = 60-80%

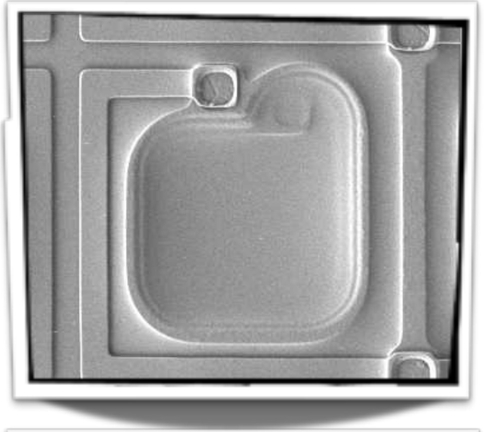
[for 50-100 µm cell pitch]

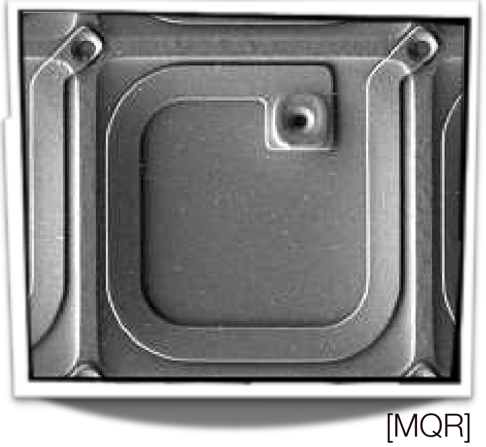
Improved ε_{geo} using MQR technique …

[Metal quench resistors …]

[Hamamatsu, IEEE 2013]

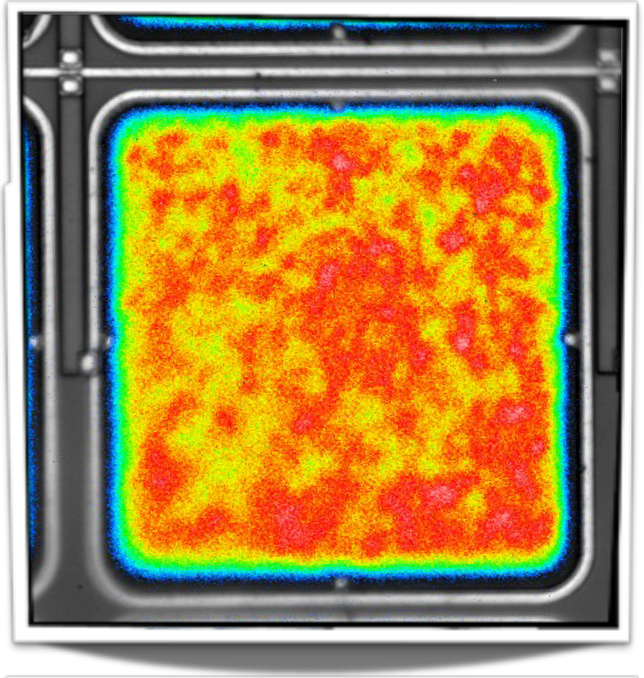
[Polysilicon Resistor]



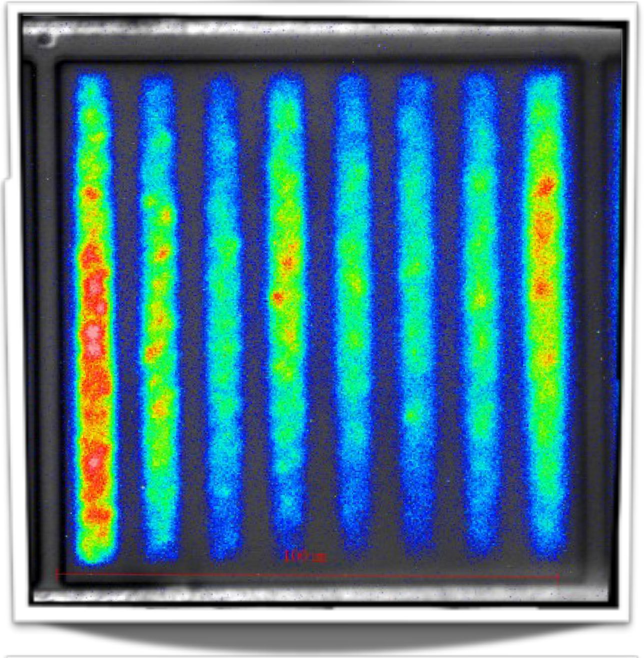


MPPC
25 µm pixels

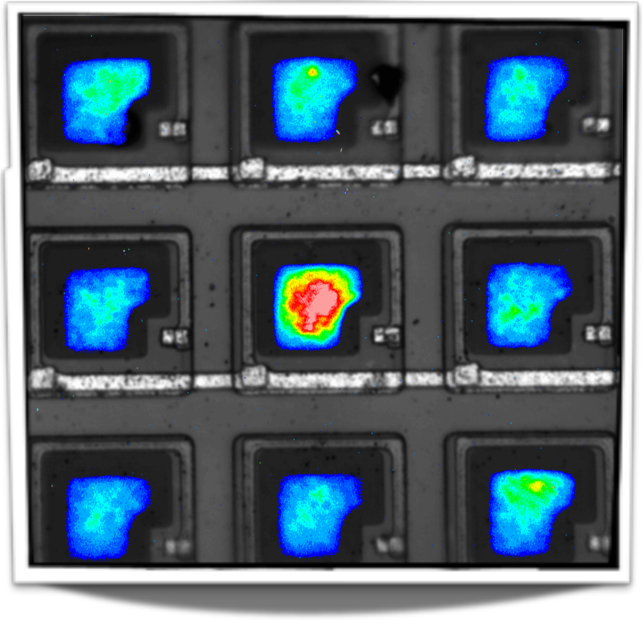
[MQR]



MPPC
100 µm pixels



SensL
35 µm pixels



Pulsar SiPM
42 µm pitch

Quantum Efficiency

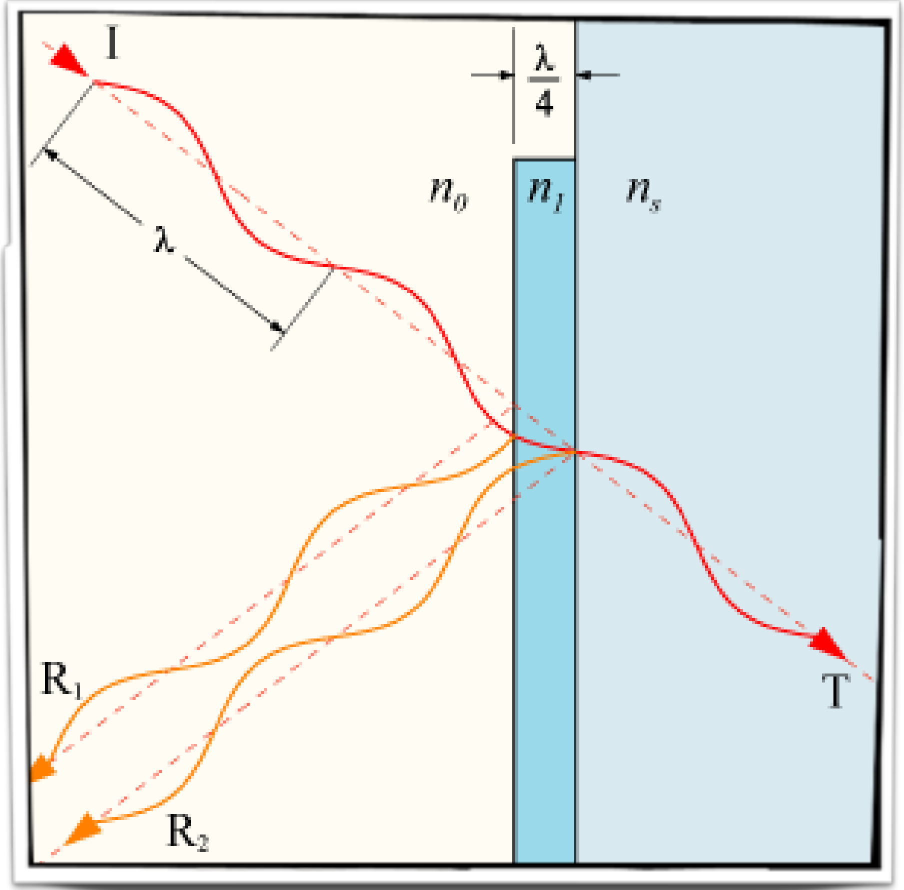
[source: W. Shen]

Reflectance

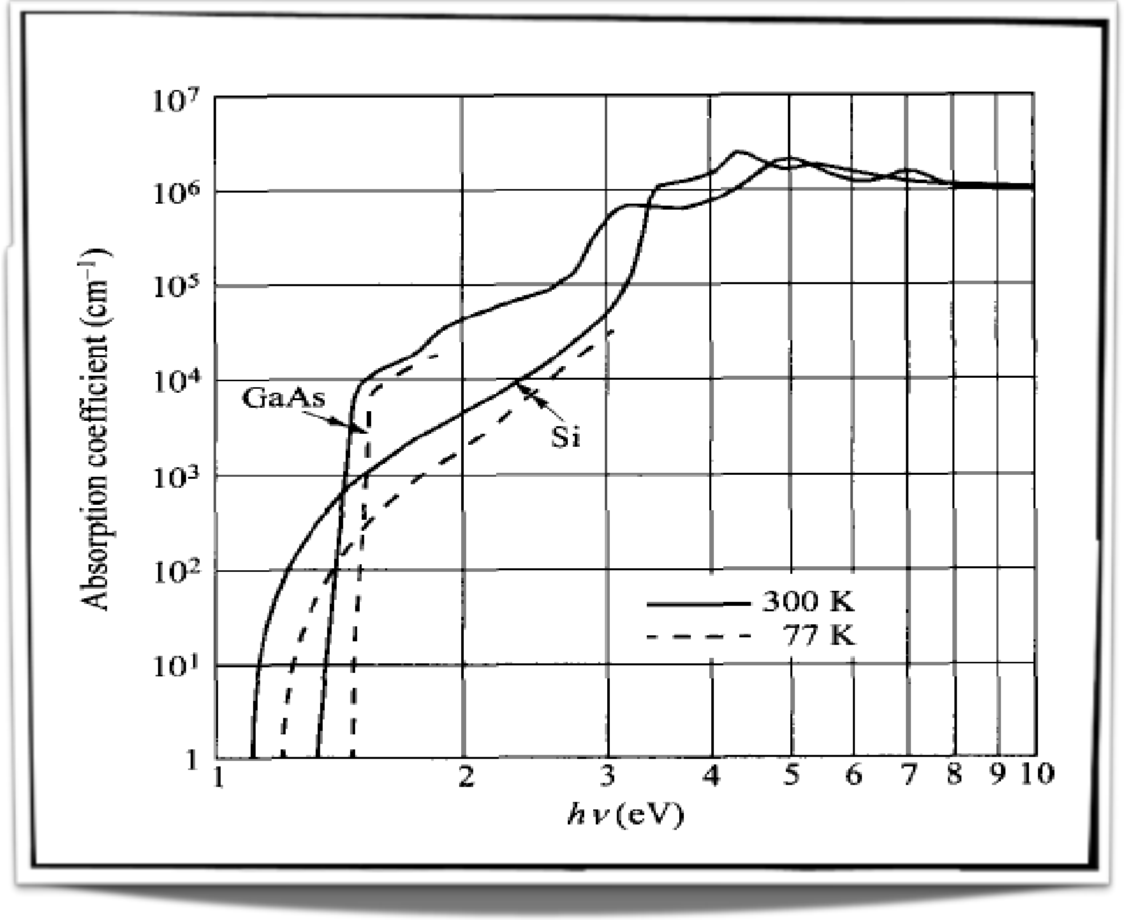
$$QE = P_0 \cdot (1 - R) \cdot (1 - e^{-\alpha x})$$

Normalization

Absorption



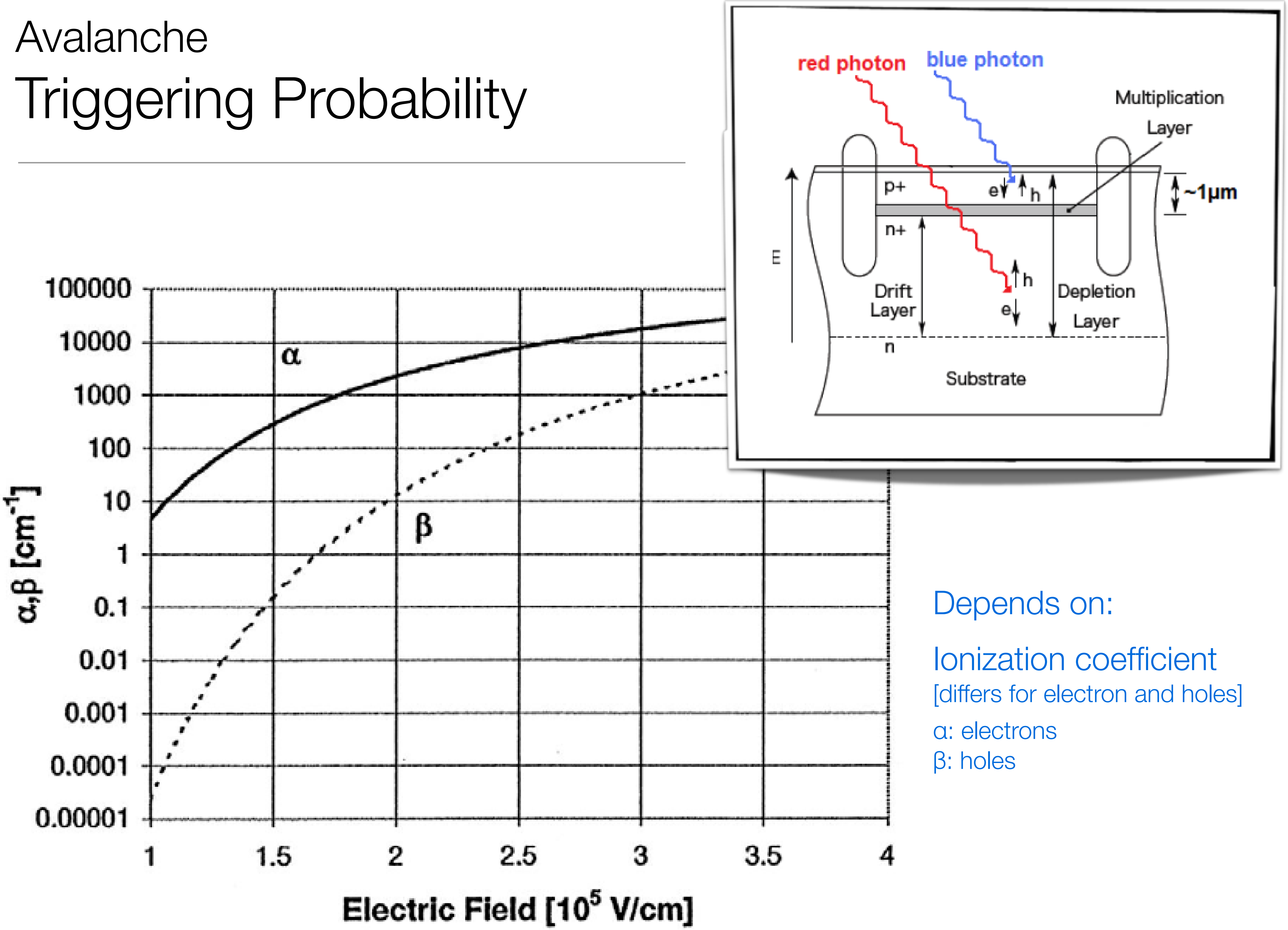
ARC
[anti-reflective coating]



Absorption Coefficient
[vs. γ-energy]

Avalanche

Triggering Probability



Depends on:

Ionization coefficient

[differs for electron and holes]

α: electrons

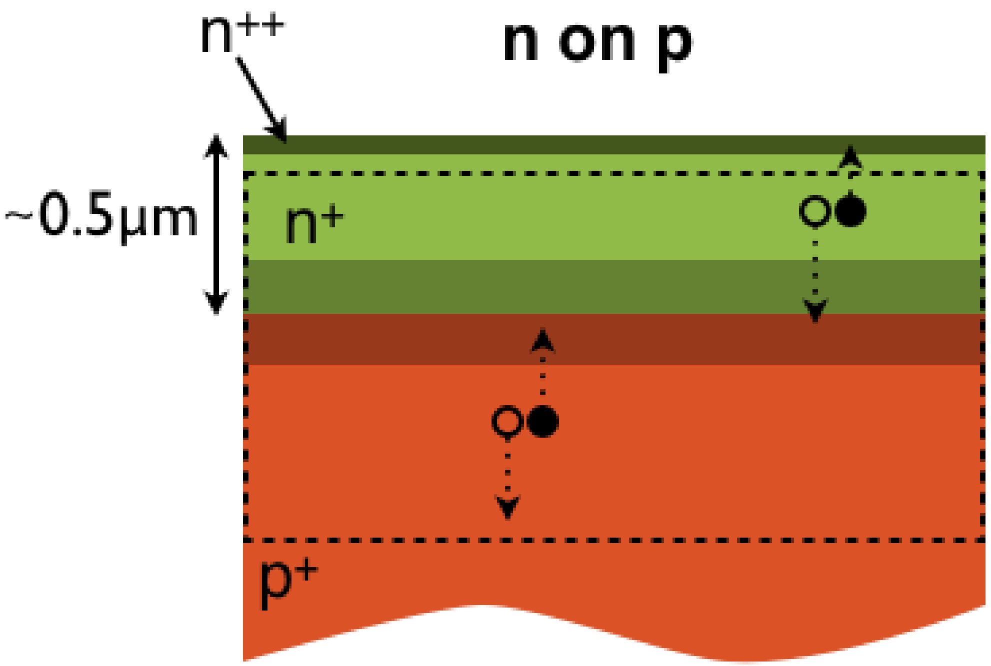
β: holes

Avalanche

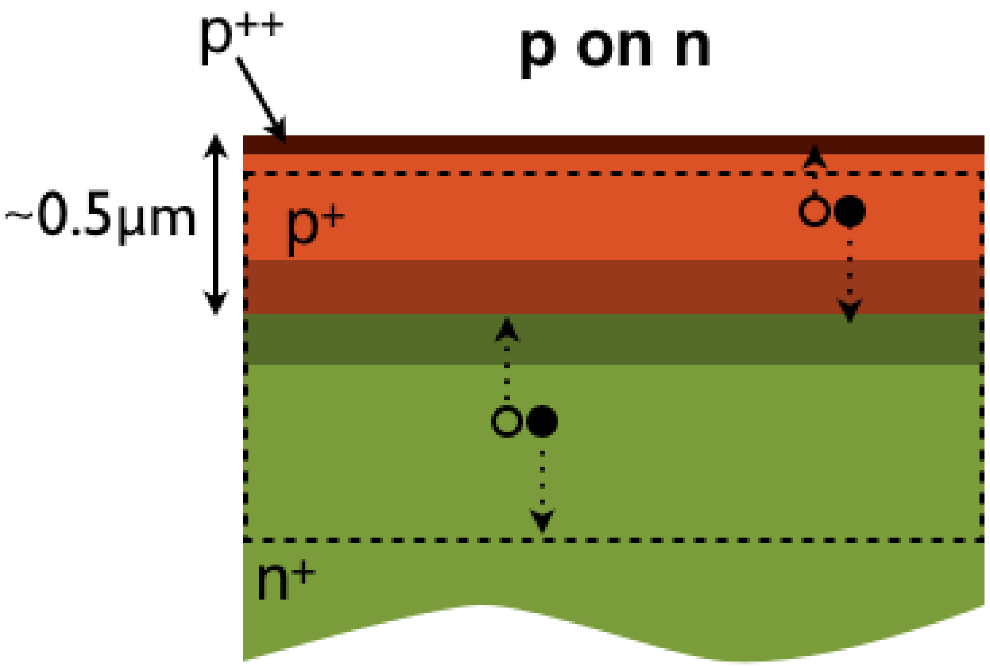
Triggering Probability

[source: A. Tadday]

Green/red sensitive



Blue/UV sensitive



● electron

○ hole

depletion region

avalanche region

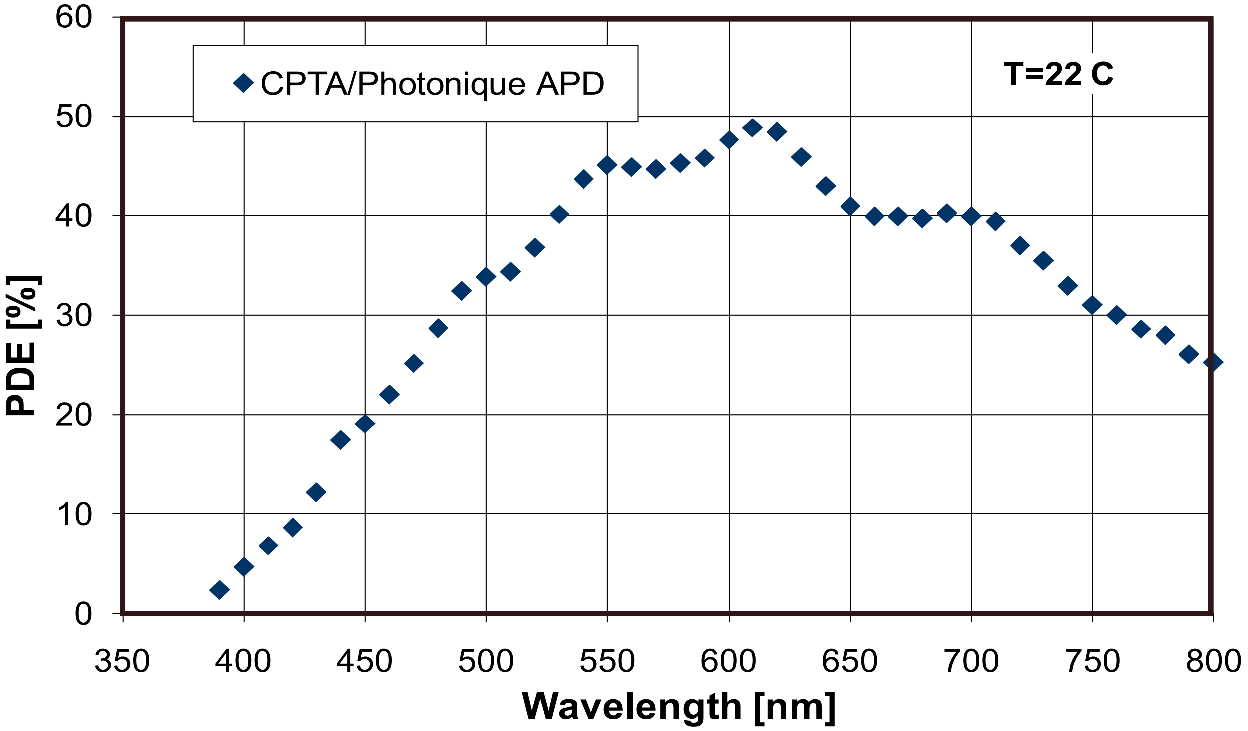
Photon Detection Efficiency

[source: Y. Musienko, FNAL]

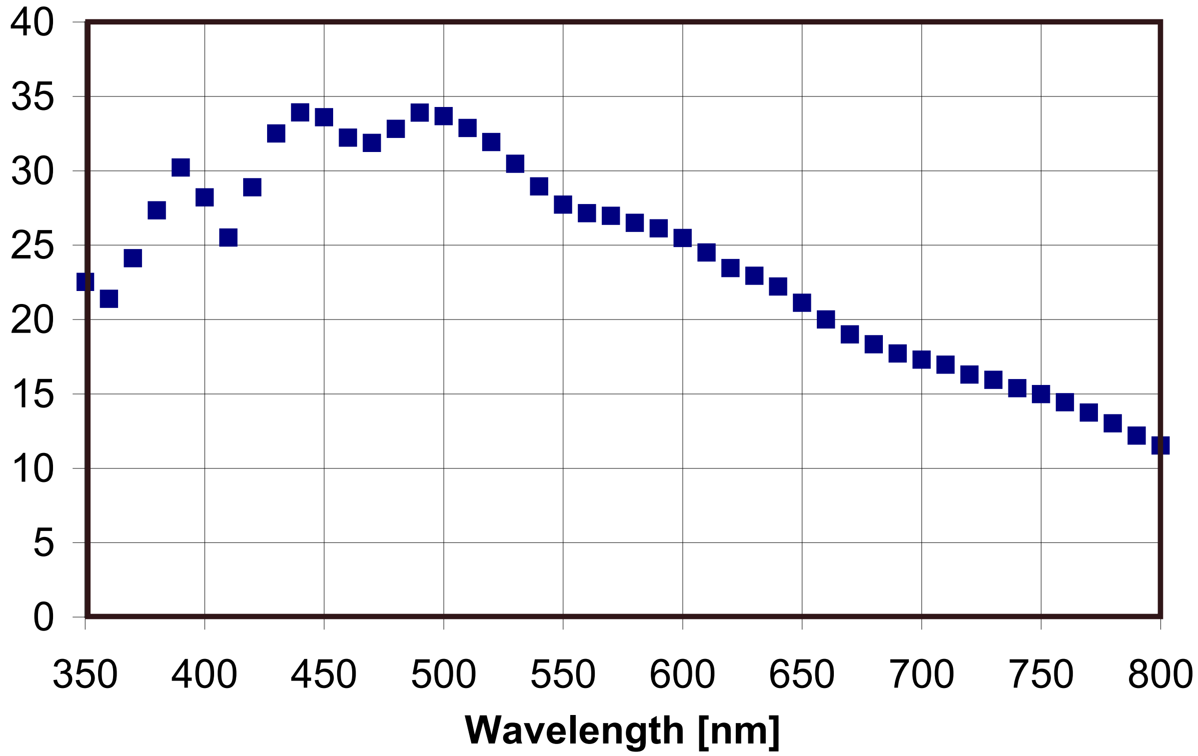
Green/red sensitive

Blue/UV sensitive

CPTA/Photonics APD
[Y.Musienko, PD-07]



CPTA SSPM; 43 μm cell pitch
[Y.Musienko, SCINT-07]



Dark Count Rate

Unwanted noise due to creation of electron hole-pairs without involvement of photon …

Possible processes:

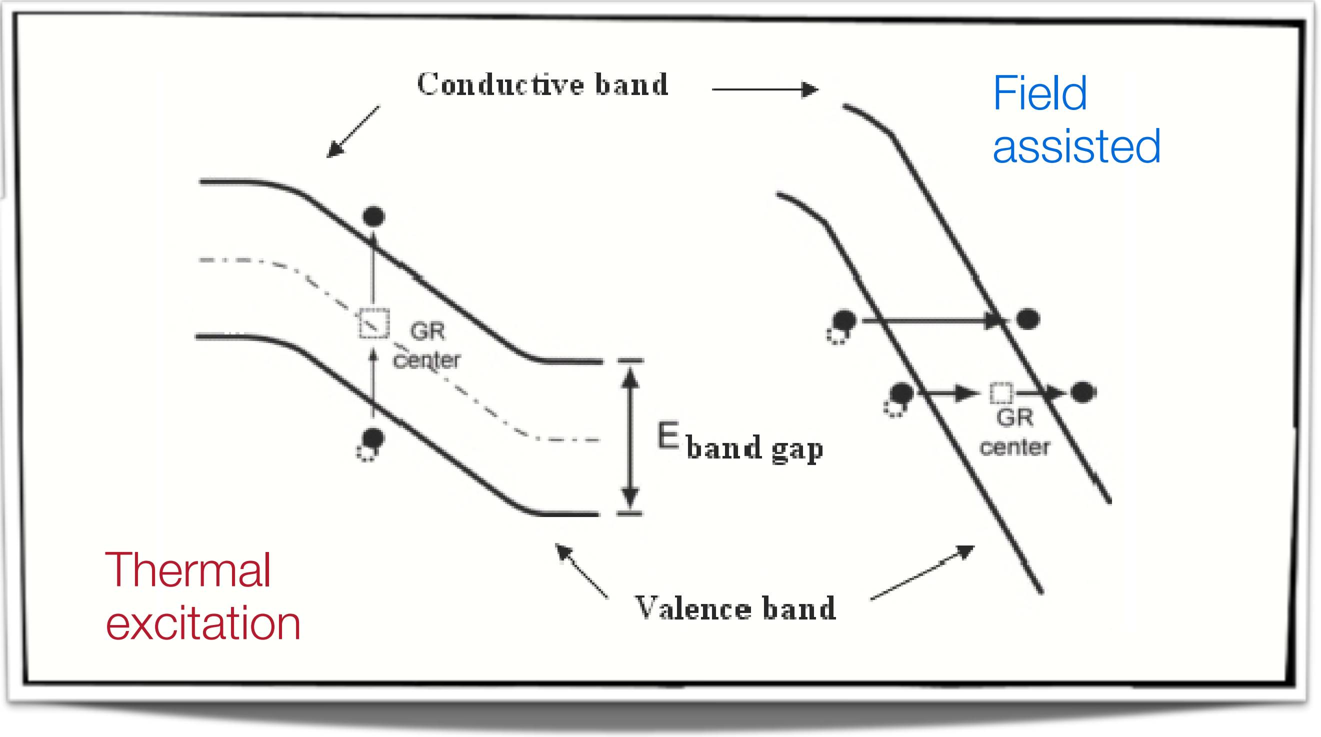
Thermal excitation

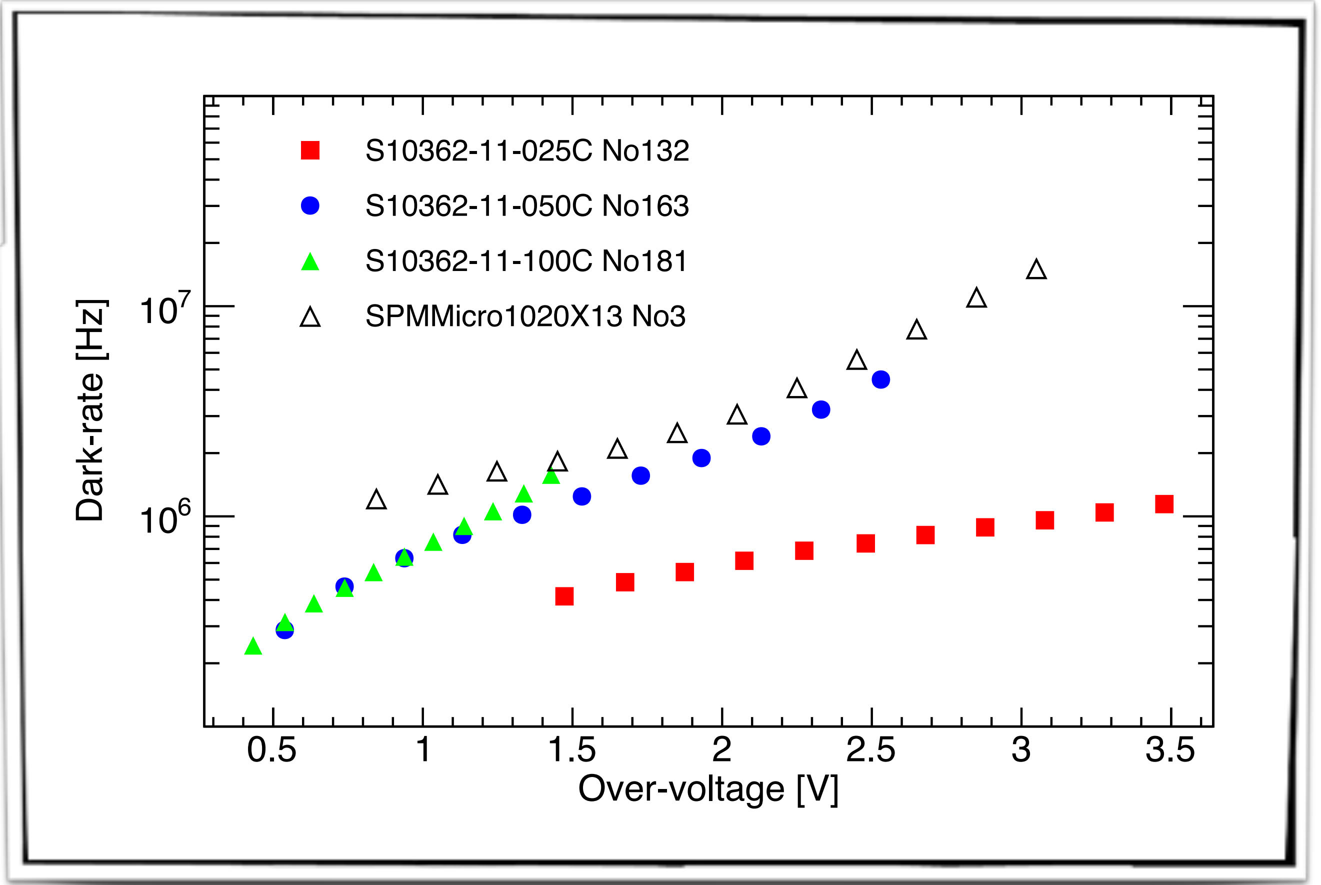
Field assisted excitation

[Tunneling Process]

Electron (hole) drifts to high-field area creating avalanche …

Resulting signal indistinguishable from genuine photon induced SiPM signal …

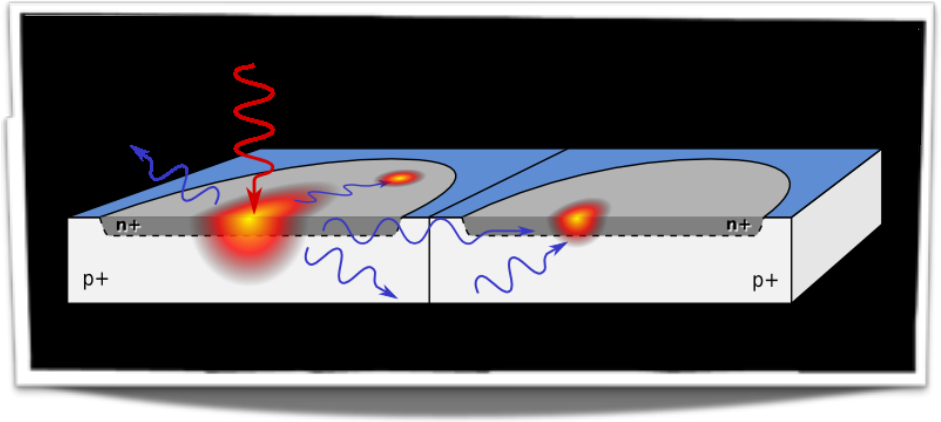




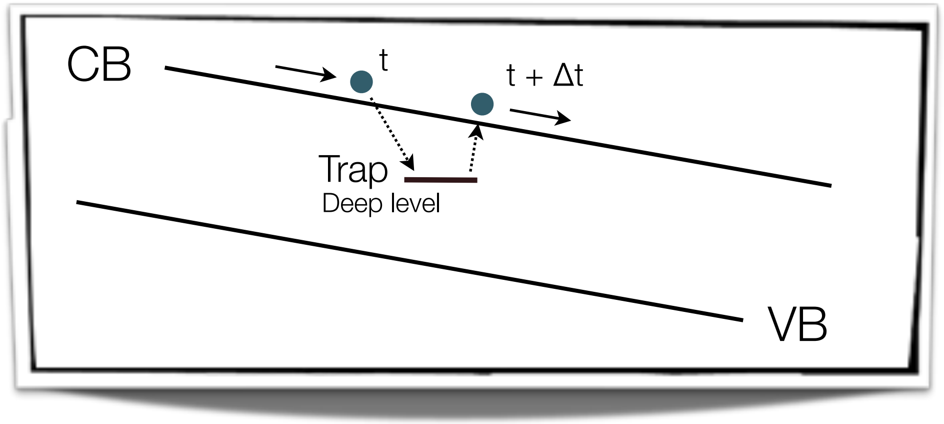
[source: A. Tadday]

Optical Cross Talk & After-Pulsing

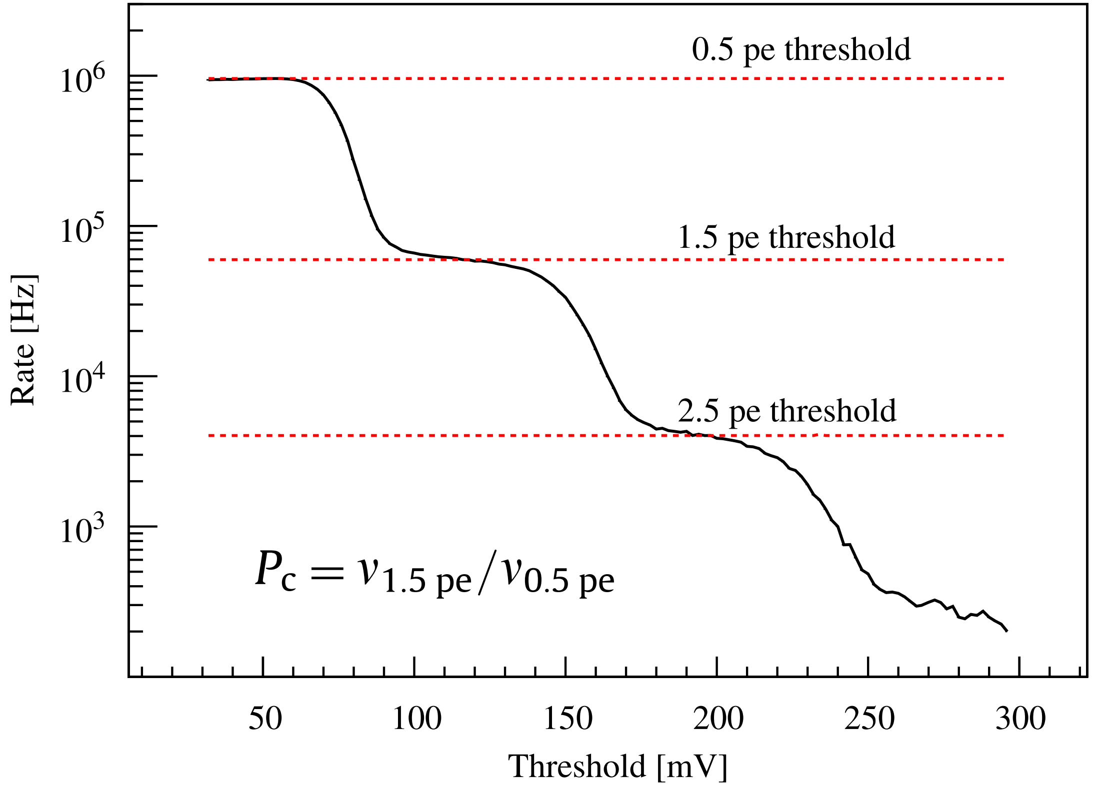
Cross Talk



After-Pulsing

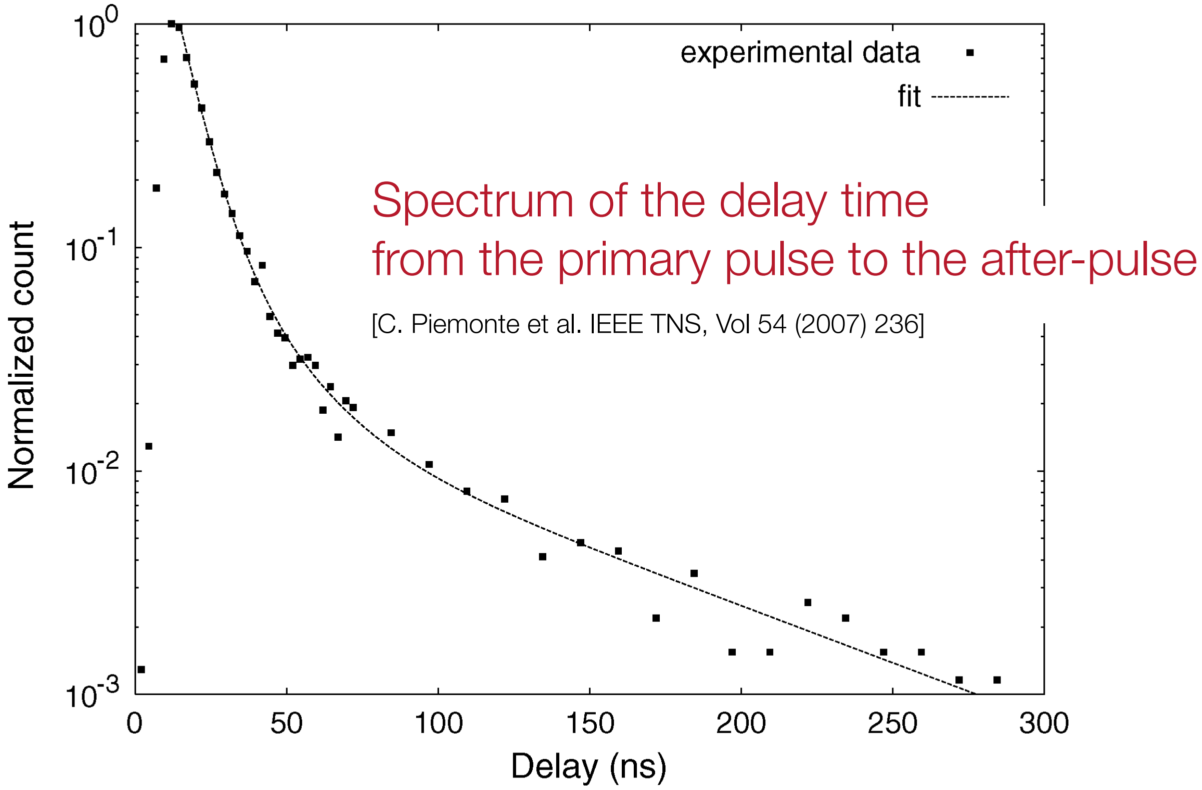


Thermal noise spectrum



$$P_c = \nu_{1.5\ \mathrm{pe}} / \nu_{0.5\ \mathrm{pe}}$$

[P. Eckert et al., NIM A620 (2010) 217]

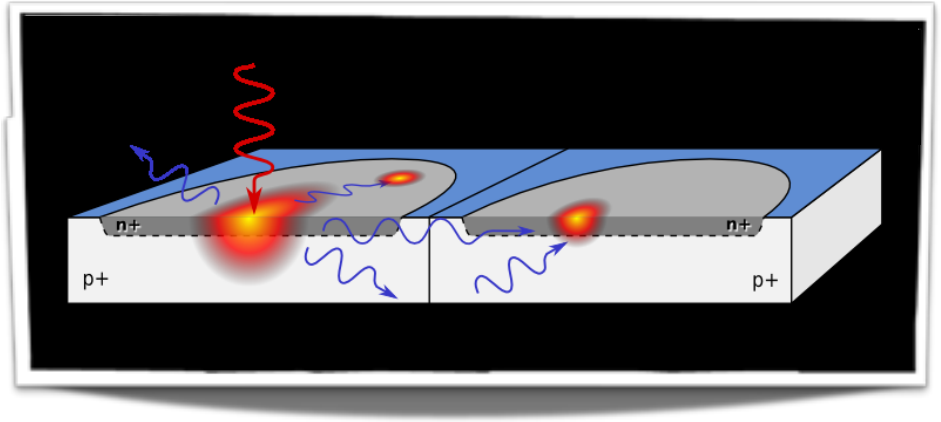


Spectrum of the delay time
from the primary pulse to the after-pulse

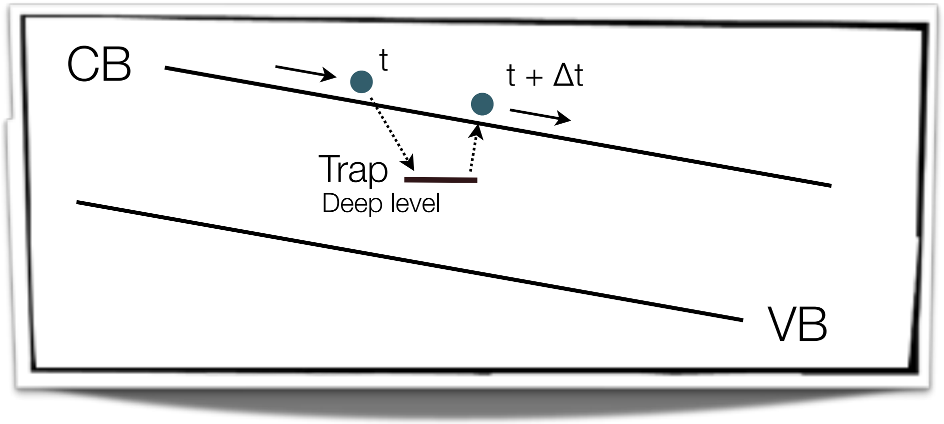
[C. Piemonte et al. IEEE TNS, Vol 54 (2007) 236]

Optical Cross Talk & After-Pulsing

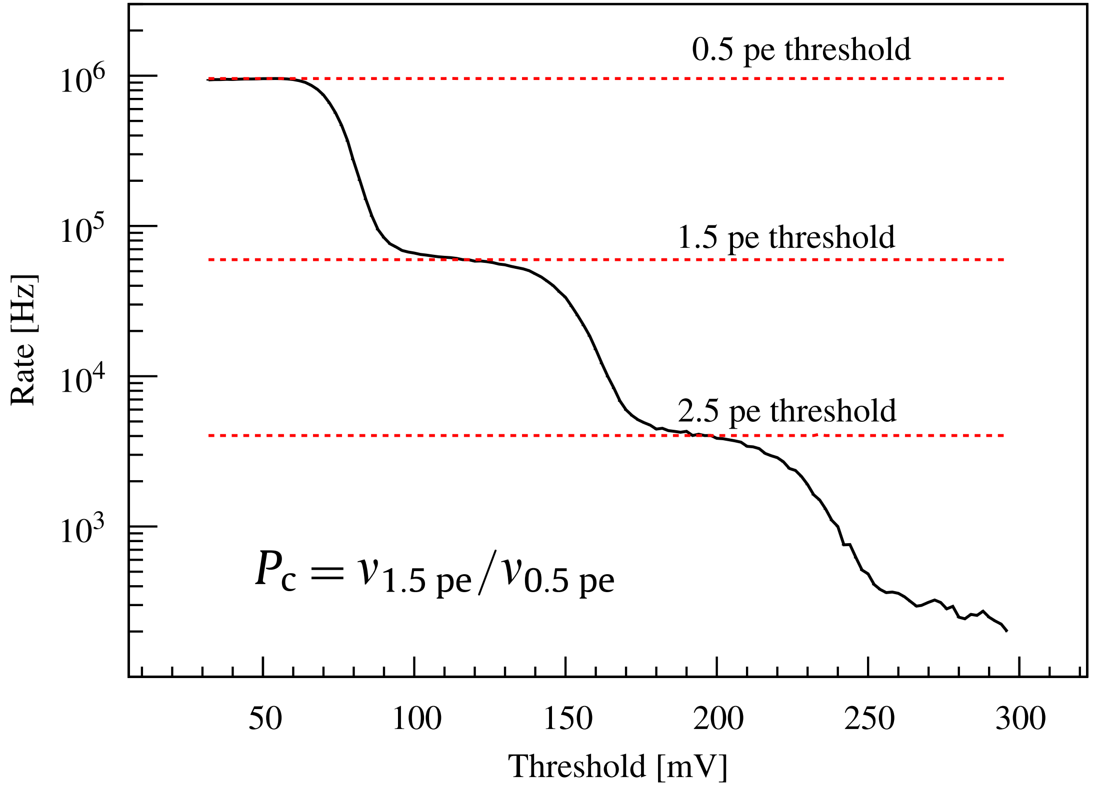
Cross Talk



After-Pulsing

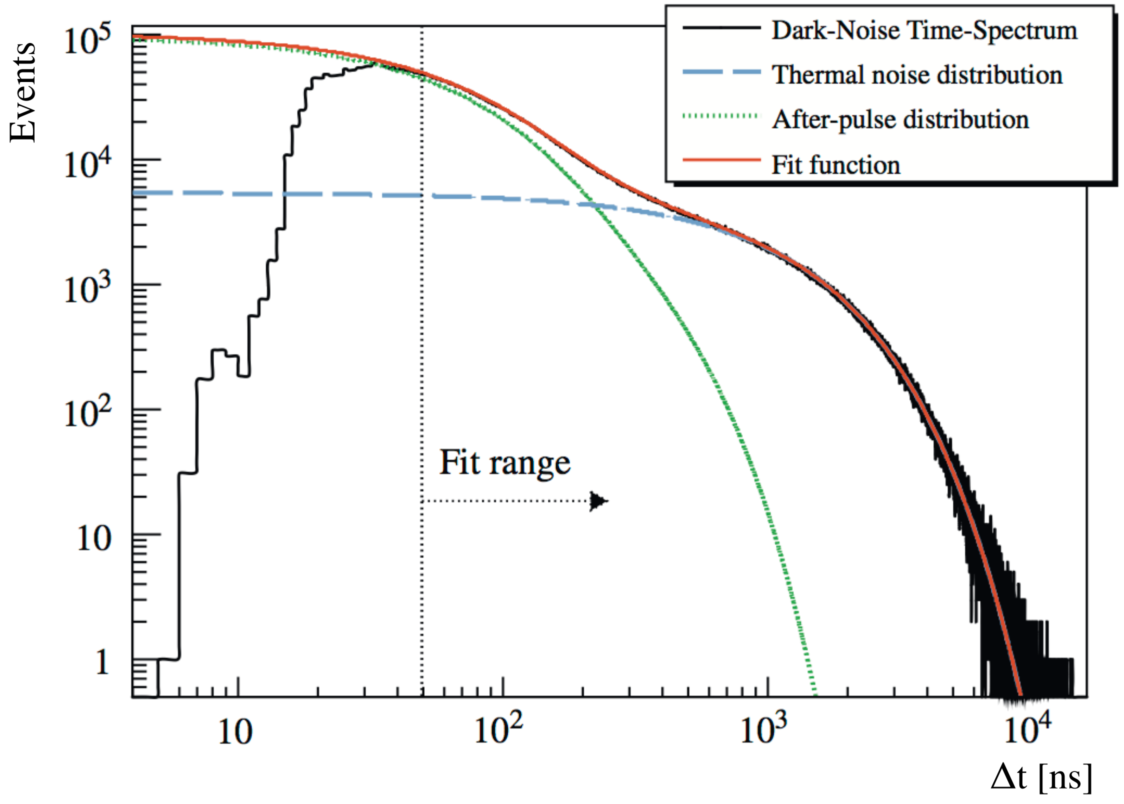


Thermal noise spectrum



$$P_c = \nu_{1.5\ \mathrm{pe}} / \nu_{0.5\ \mathrm{pe}}$$

[P. Eckert et al., NIM A620 (2010) 217]

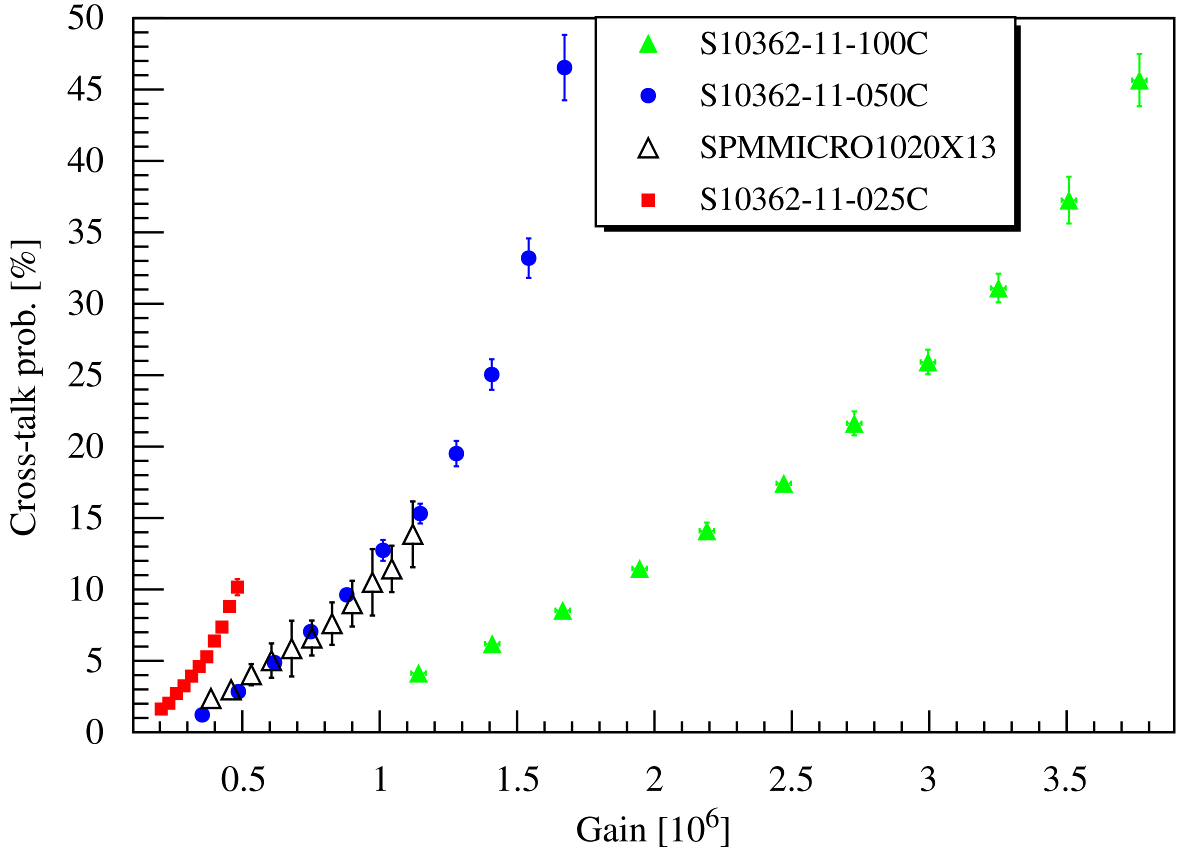


Optical Cross Talk & After-Pulsing

[P. Eckert et al., NIM A620 (2010) 217]

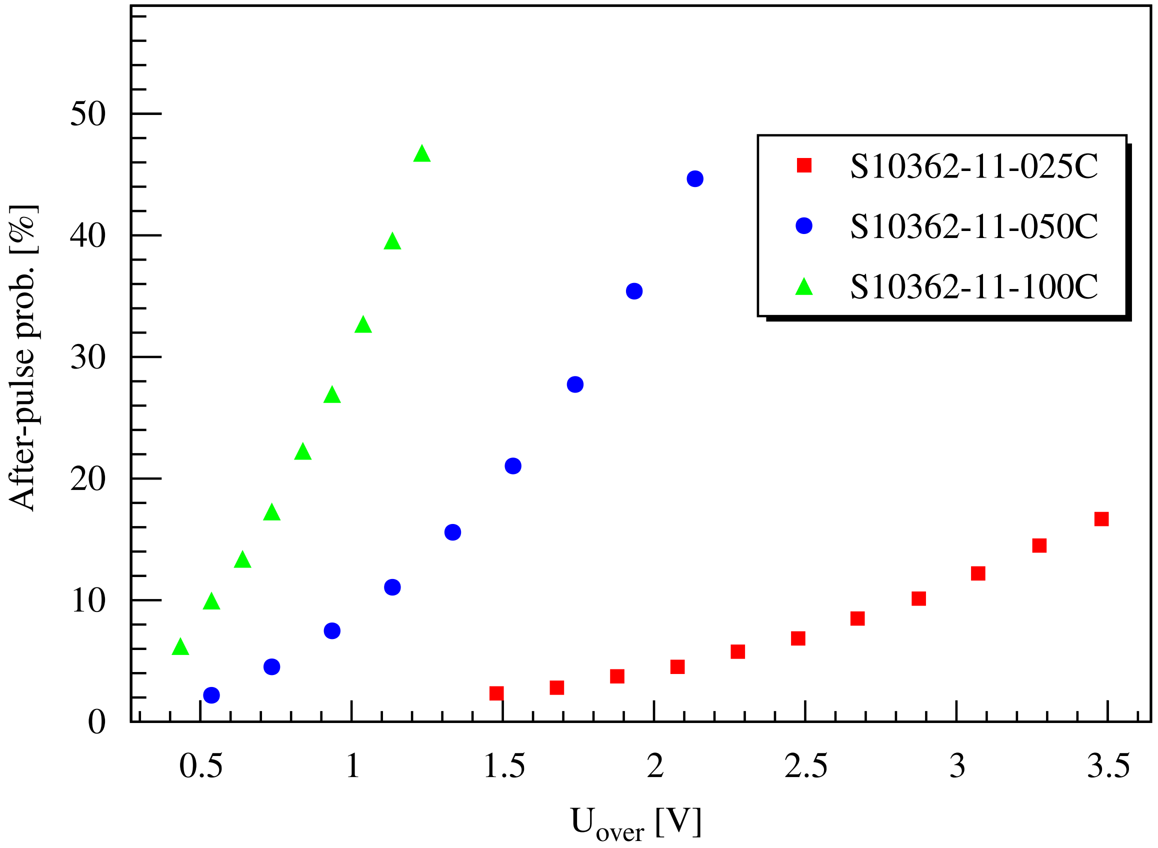
Cross Talk

Cross-talk probability for different SiPM sensors
as a function of the SiPM gain



After-Pulsing

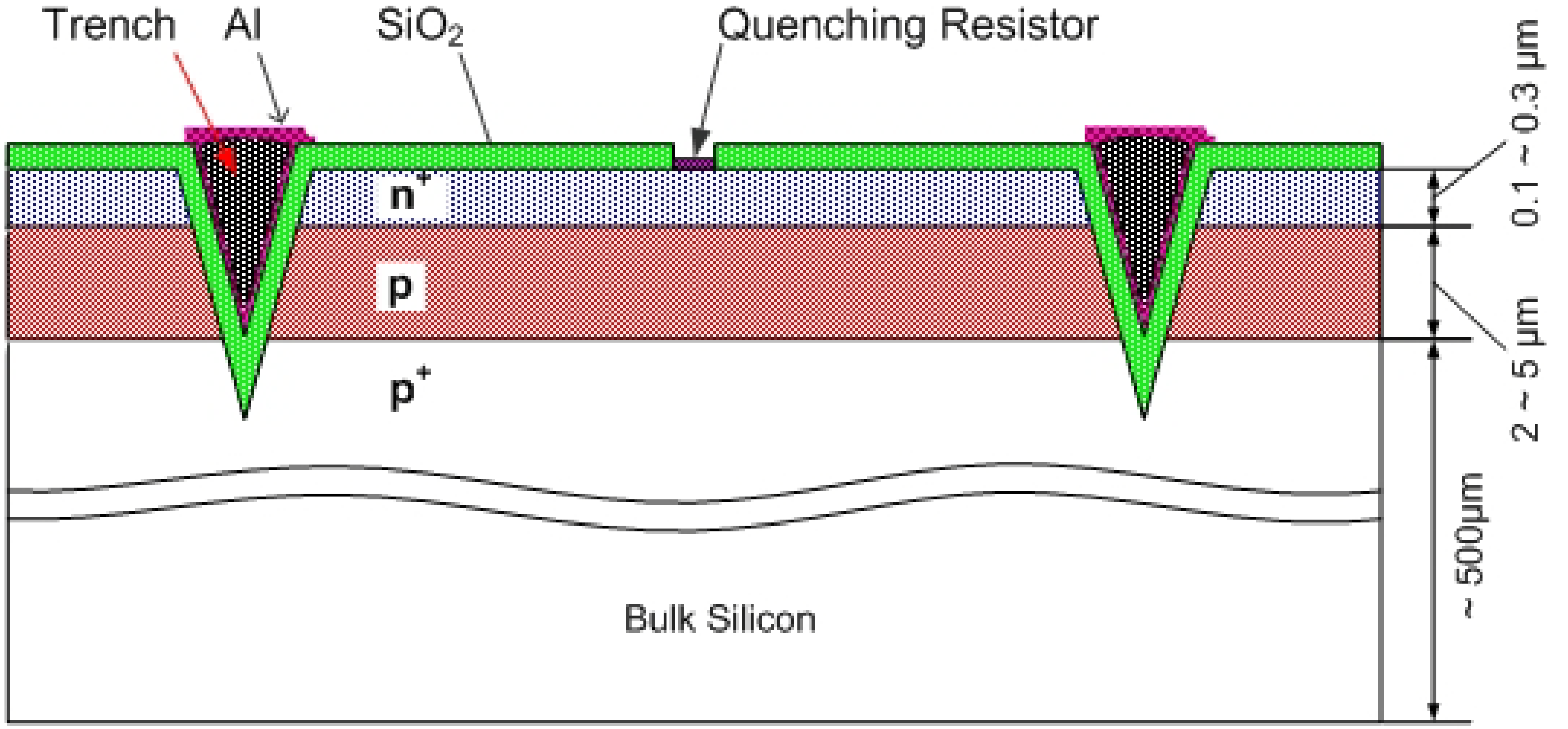
After-pulse probability
as a function of the over voltage



Optical Cross Talk & After-Pulsing

[D. McNally, G-APD workshop, GSI, Feb. 2009]
[source: Y. Musienko, FNAL]

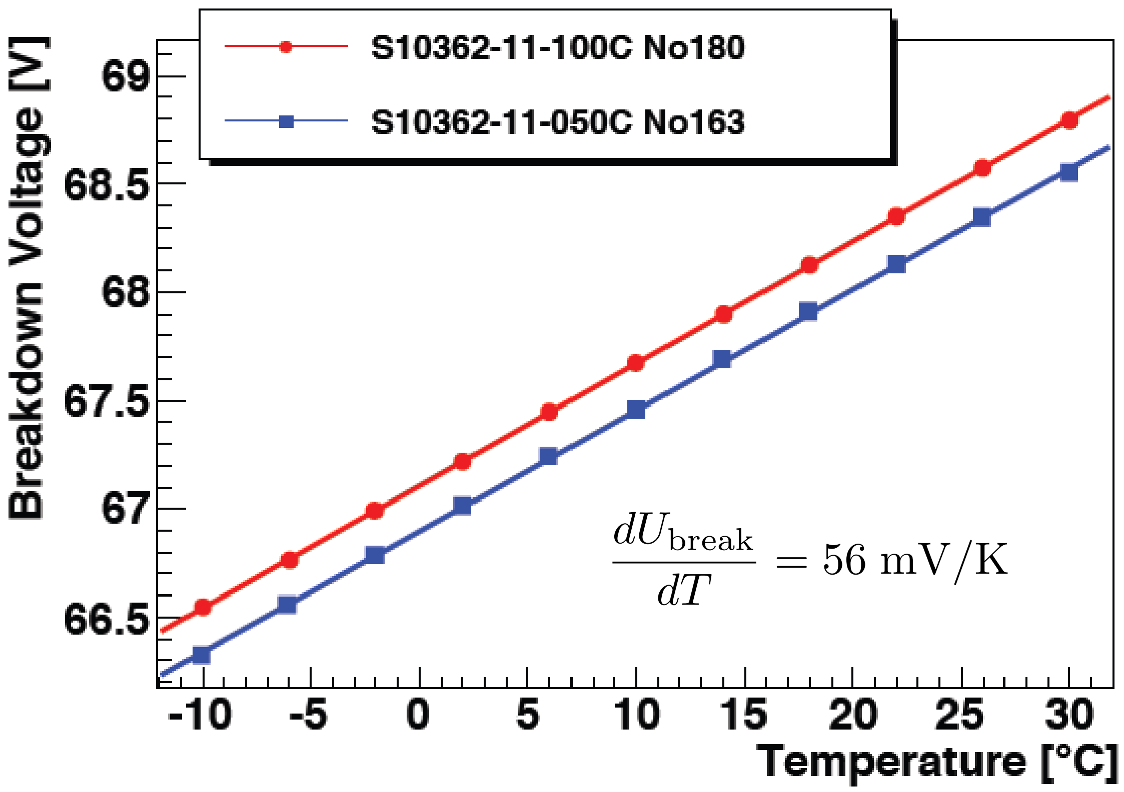
To reduce optical cross-talk trenches are introduced to separate neighboring pixels …



Temperature Sensitivity

[source: A. Tadday]

[]Hamamtsu MMPCs]

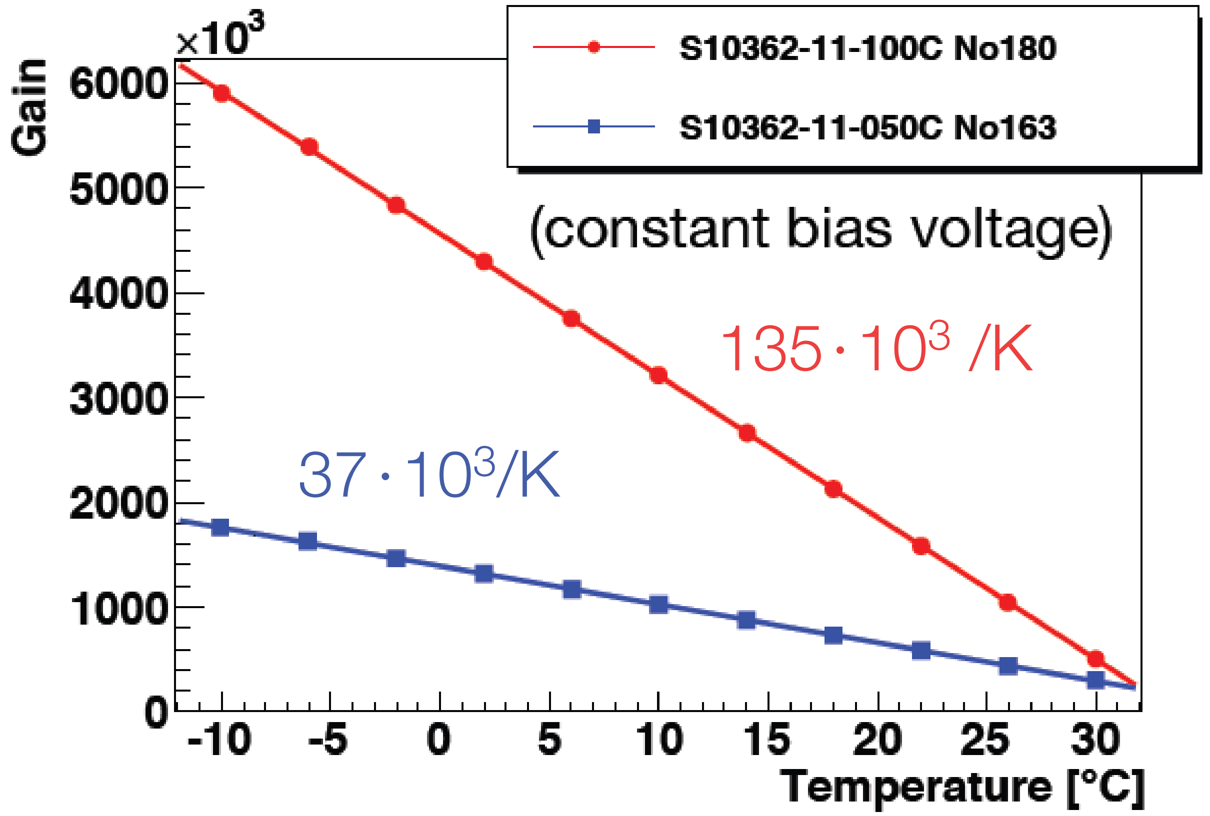


$$\frac{dU_{\text{break}}}{dT} = 56 \text{ mV/K}$$

Breakdown voltage increases with temperature

Interactions with lattice vibrations
i.e. phonons slows down charge carriers;
higher field needed for breakdown

[]Hamamtsu MMPCs]



(constant bias voltage)

$135 \cdot 10^3$ /K

$37 \cdot 10^3$/K

SiPM gain decreases with temperature

Large pixel capacitance causes
extra large temperature dependence

$$\frac{dG}{dT} = -\frac{dC_{\text{pxl}}}{q_e} \cdot \frac{dU_{\text{break}}}{dT}$$

Linearity and Dynamic Range

SiPMs respond linearly only
if number of detected photons
is significantly below number of cells …

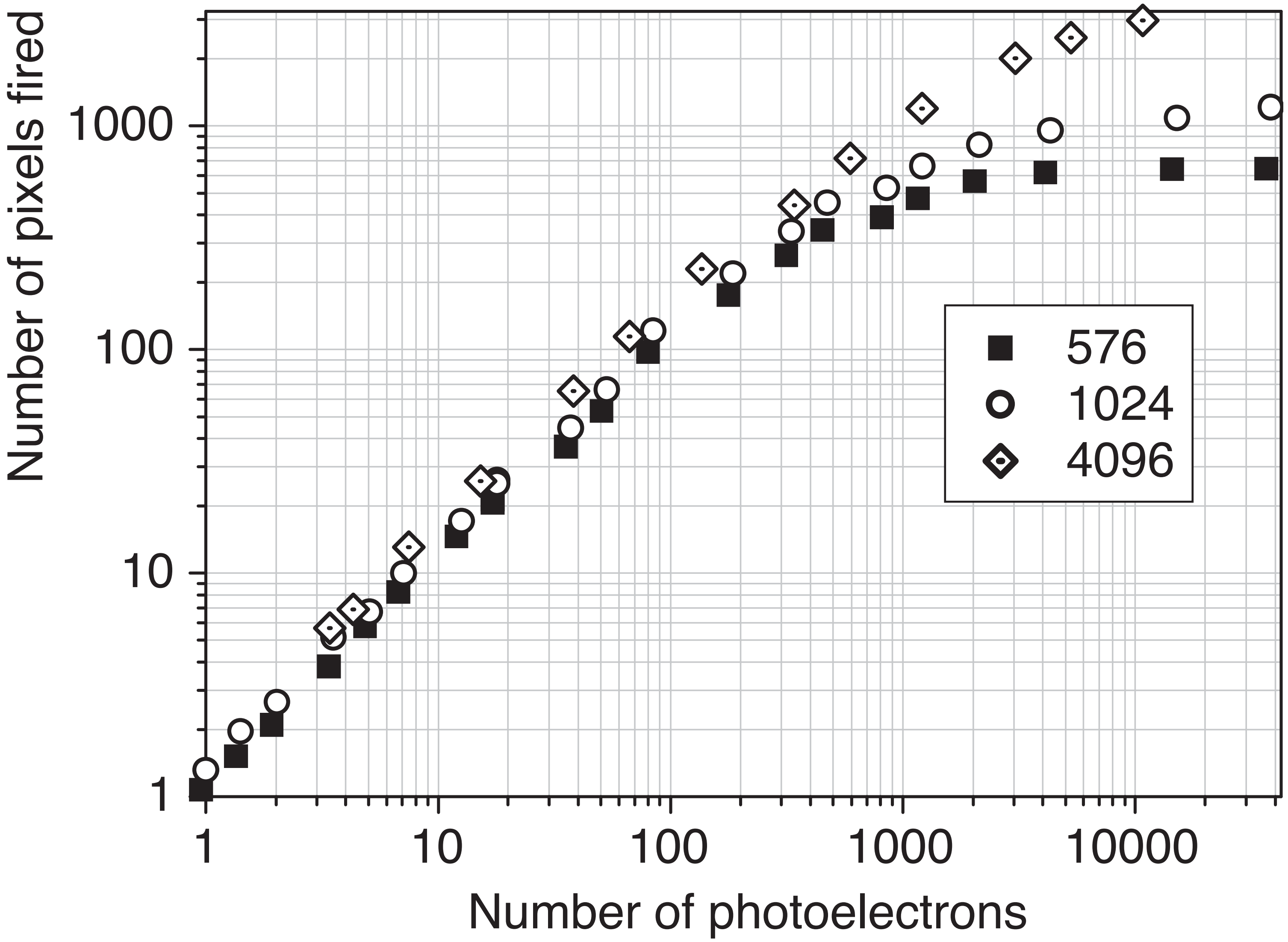
$$N_{\text{fired}} = N'_{\text{tot}} \cdot \left[1 - \exp\left(-\frac{N_\gamma \cdot \text{PDE}'}{N'_{\text{tot}}}\right)\right]$$

Otherwise
correction needed …

N_{fired}: # fired pixels
N_γ: # incident photons

N'_{tot}: effective # pixels
PDE′: effective PDE

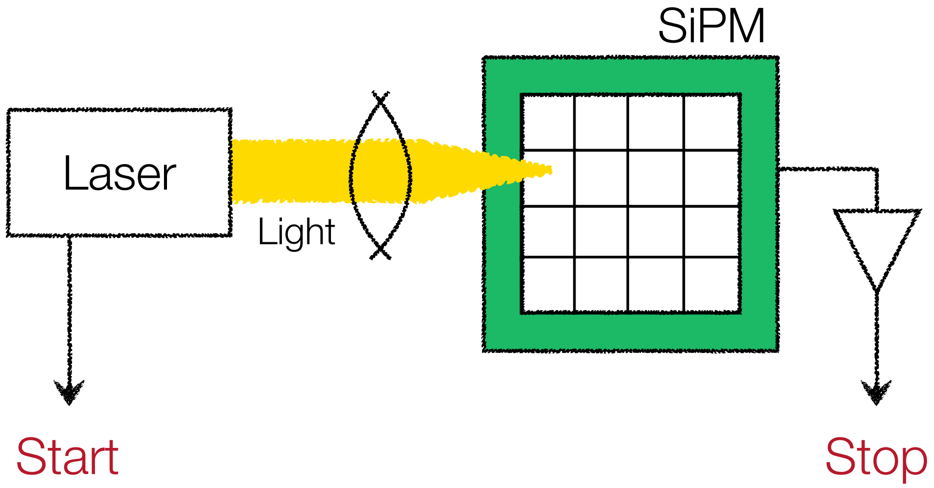
Effective Quantities account for
dark count rate, after-pulse probability,
light pulse time and spacial structure,
operation conditions etc. …



[V. Andreev et al., NIM A540 (2005) 368]

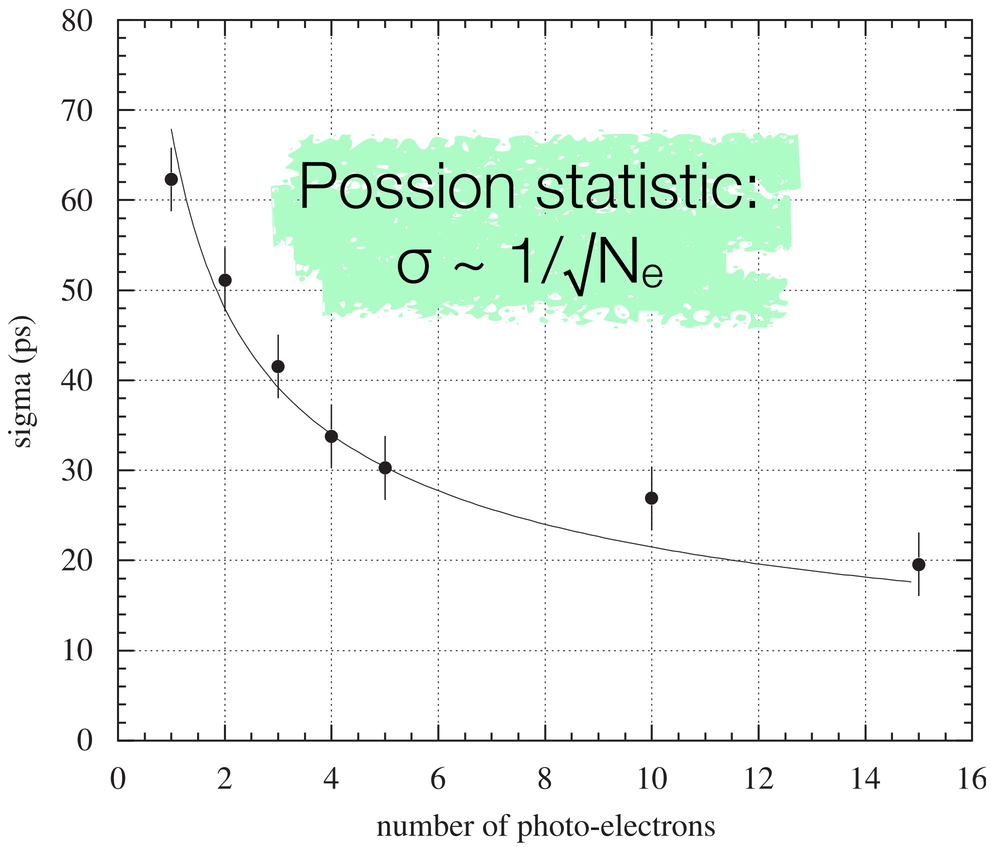
Single Photon Time Resolution

[source: Y. Musienko, FNAL]



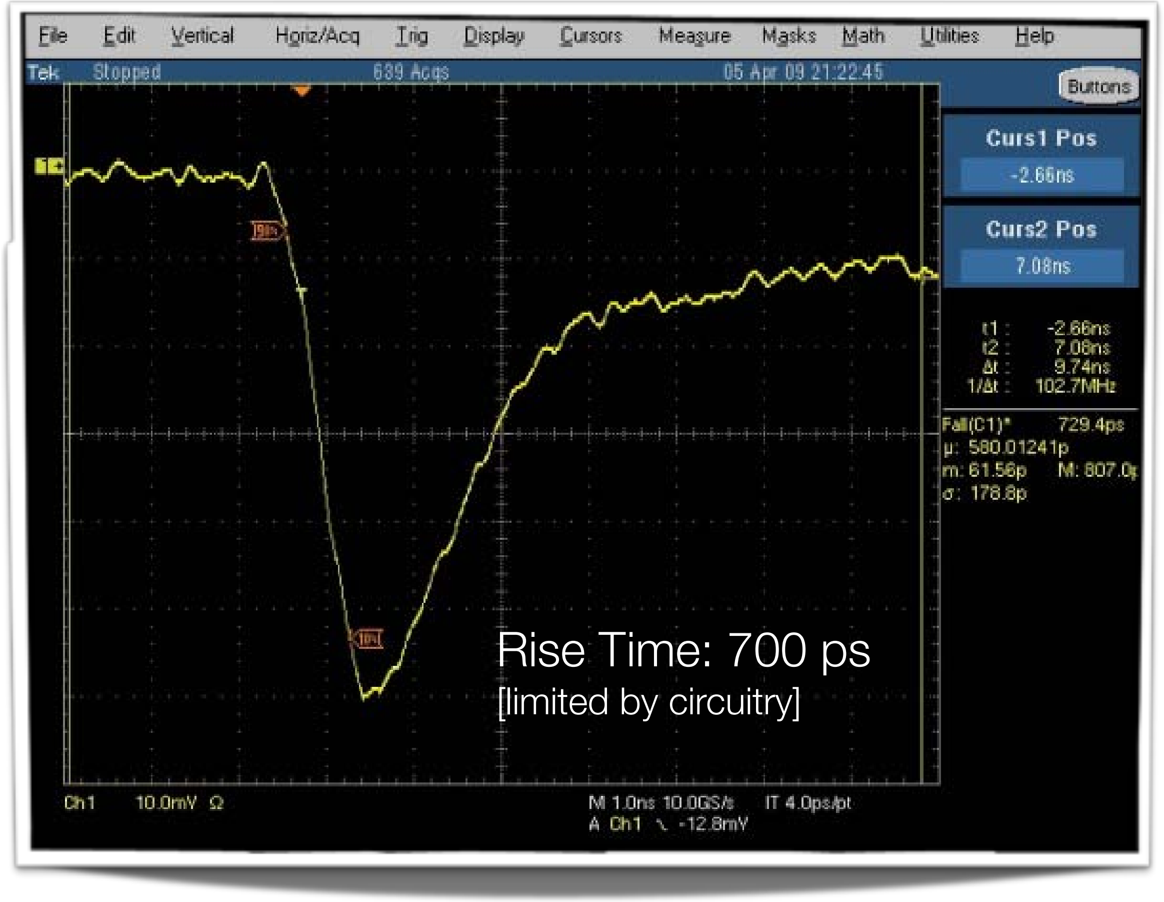
Start

Stop



Possion statistic:
$\sigma \sim 1/\sqrt{N_e}$

CPTA/Photonique 1 mm^2 SSPM
response to a 35 ps FWHM laser pulse (λ=635 nm)

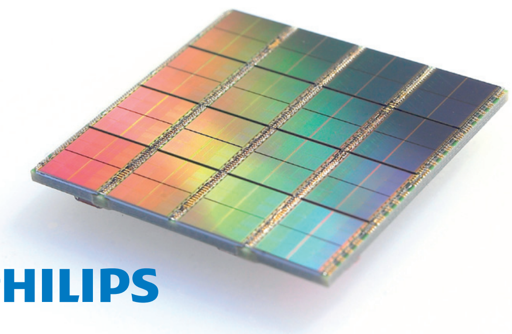


```
Tek   Stopped   639 Acqs   05 Apr 09 21:22:45
Curs1 Pos  -2.66ns
Curs2 Pos  7.08ns
  t1 :   -2.66ns
  t2 :    7.08ns
  Δt :    9.74ns
1/Δt :  102.7MHz
Fall(C1)*     729.4ps
μ: 580.01241p
m: 61.56p     M: 807.0
σ: 178.8p
Ch1    10.0mV  Ω        M 1.0ns 10.0GS/s    IT 4.0ps/pt
                        A  Ch1  ↘  -12.8mV
```

Rise Time: 700 ps
[limited by circuitry]

SiPMs have
excellent timing properties!

Philips – Digital SiPMs



PHILIPS

PHYSICAL CHARACTERISTICS	DPC6400-22-44	DPC3200-22-44
OUTER DIMENSIONS	32.6 x 32.6 mm^2	32.6 x 32.6 mm^2
PIXEL PITCH (H X V)	4.0 mm x 4.0 mm	4.0 mm x 4.0 mm
PIXEL ACTIVE AREA	3.9 x 3.2 mm^2	3.9 x 3.2 mm^2
NUMBER OF CELLS PER PIXEL CELL SIZE	6396 59.4 x 32 μm^2	3200 59.4 x 64 μm^2
SPECTRAL RESPONSE RANGE	380 nm – 700 nm	380 nm – 700 nm
PEAK SENSITIVITY WAVELENGTH (λ_P)	420 nm	420 nm
PHOTON DETECTION EFFICIENCY (PDE) @ λ_P (PIXEL LEVEL)	30 %	40 %
PIXEL FILL FACTOR (ALREADY INCLUDED IN PDE)	54 %	74 %
TILE FILL FACTOR	75%	75%
DARK COUNT RATE (95% CELLS ACTIVE)	< 5 MHz / pixel at room temperature	< 7 MHz / pixel at room temperature
OPERATIONAL BIAS VOLTAGE	27 +/- 0.5 V	27 +/- 0.5 V
TEMPERATURE DEPENDENCE OF PDE	-0.33%/°C in the range of 15°C - 25°C	-0.33%/°C in the range of 15°C - 25°C
INTRINSIC TIMING RESOLUTION*	44 ps	44 ps

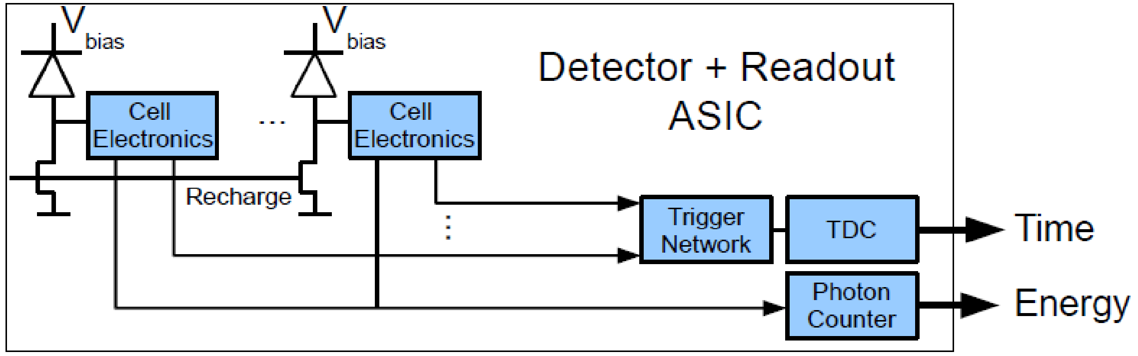
Main Features:

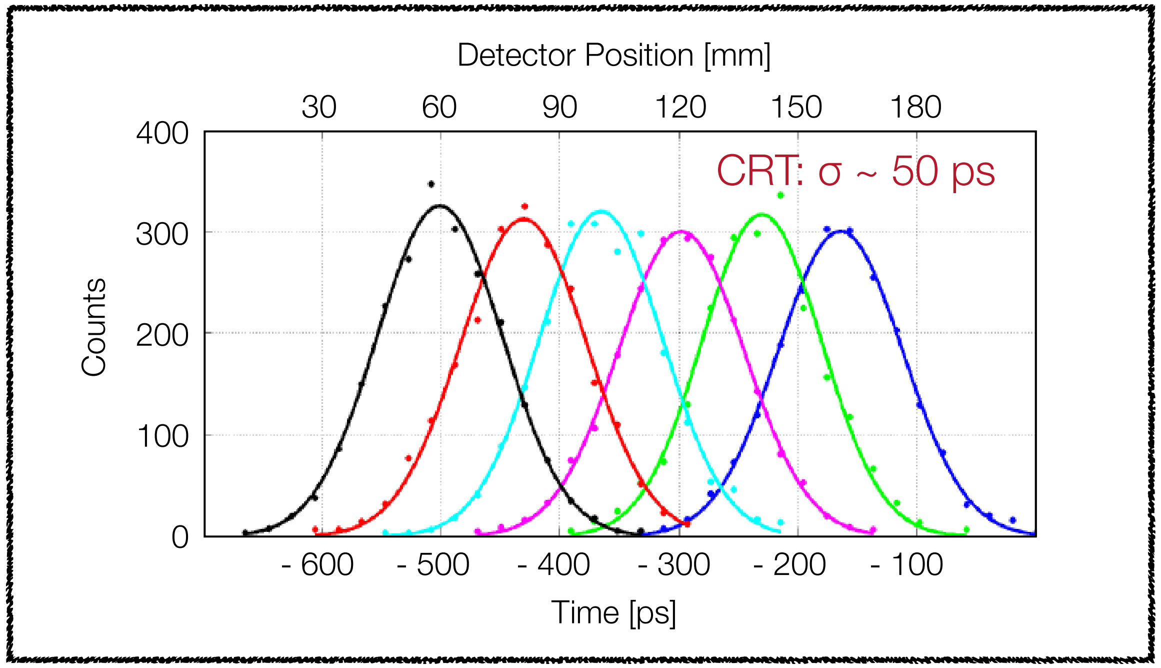
Geometric factor: > 50%
Tile fill factor: > 70%
Dark Rate: < 5(7) MHz

Disabling of individual cells
Active quenching & recharge

Integrated TDC [σ = 8 ps]
Variable trigger [1-4 photons]

Digital Silicon Photomultiplier Detector





CRT with dSiPMs and 3x3 x5 mm^3 LYSO crystals; dSiPM = DPC-3200-44-22
[D. Schaart et al., SNM 2012]

SiPM Response Simulation

GosSiP Framework:

[2012 JINST 7 P08011]

Detailed model of SiPM response for arbitrary operation conditions ...

Customizable SiPM properties ...

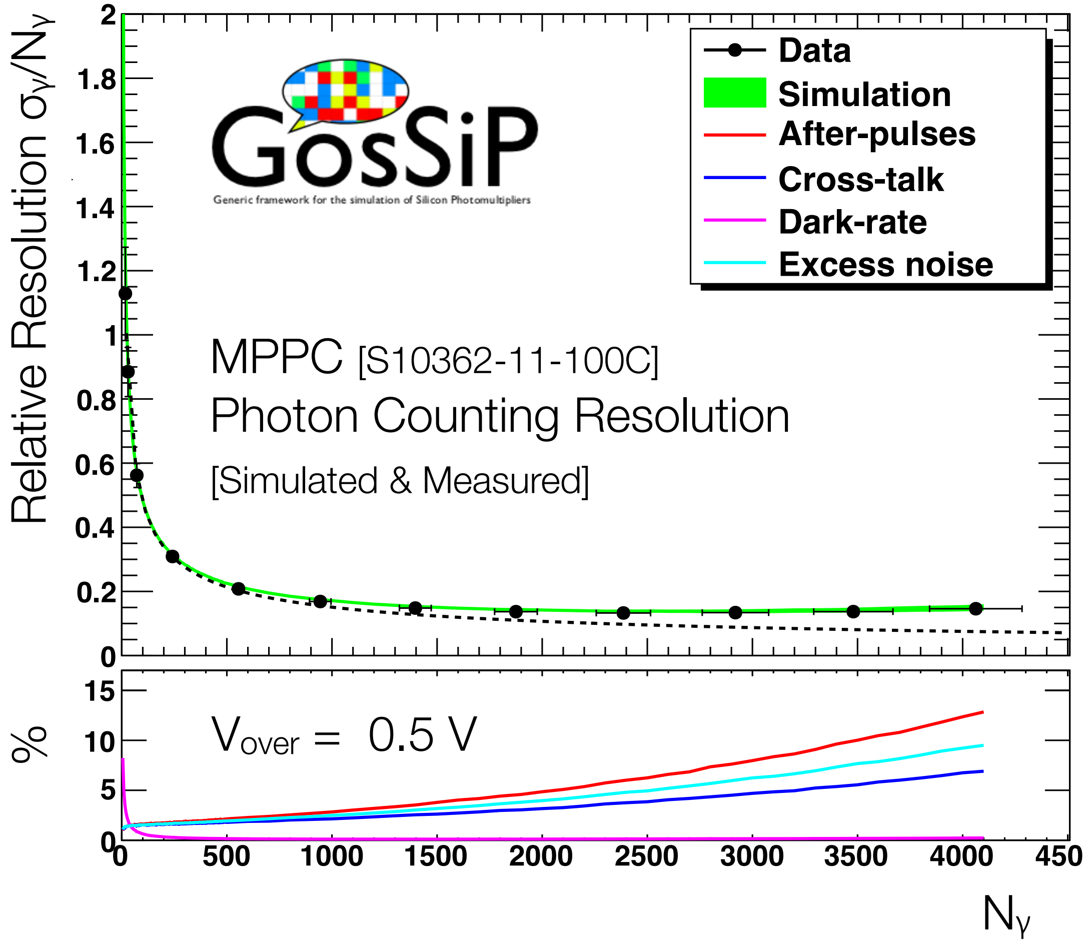
Input parameters from basic characterization measurements ...

Model for whole dynamic range including saturation region ...

Integrable into Geant4 ...

Framework allows:

Detailed studies and optimization of SiPM and combined scintillator/SiPM response ...



[Eckert et al., 2012 JINST 7 P08011]