P.N.Lebedev Physical Institute of the Russian Academy of Science

SENSE Ultimate Low-Light Level Sensor Development

Principles of Detection and Characteristics of Photosensors

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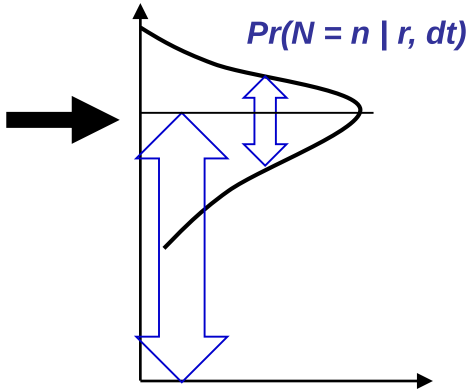
Outline

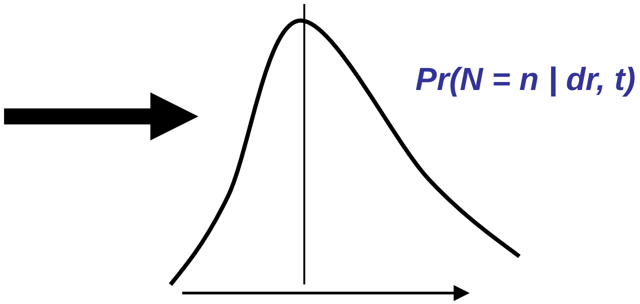
- My focus: probabilistic consideration of detection and detectors
  - Photon-number-resolving photodetectors
    - Silicon Photomultipliers (SiPM)

Flux of photons – stochastic process
Number of photons – random variable



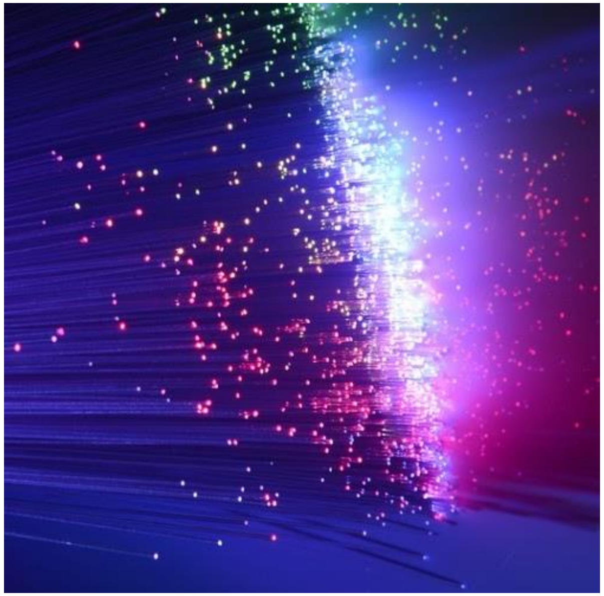
Probability distribution of number of photons in space

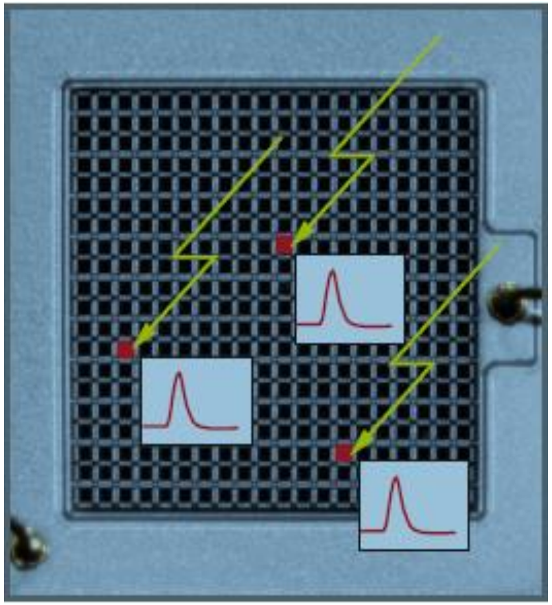
- Probability distribution of a random variable fully characterize the random variable

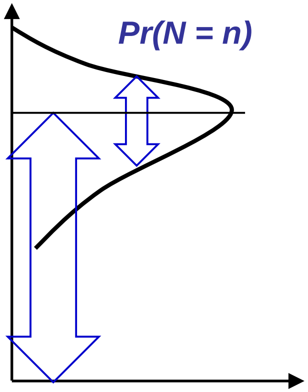


Probability distribution of number of photons in time

Detection of photons – stochastic process
Detector response (photoelectrons) – random variable







Probability distribution of number of photoelectrons in the response

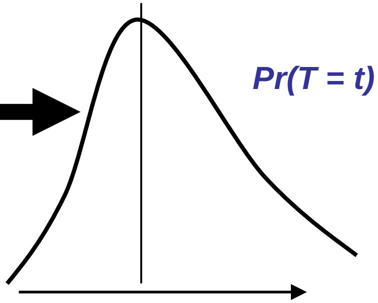
- Statistical results of photodetection:

1. Random number of photoelectrons in a time interval (pulse duration) N

=> Energy resolution

2. Random time of the pulse arrival T

⇒ Time resolution



Probability distribution of the response arrival time

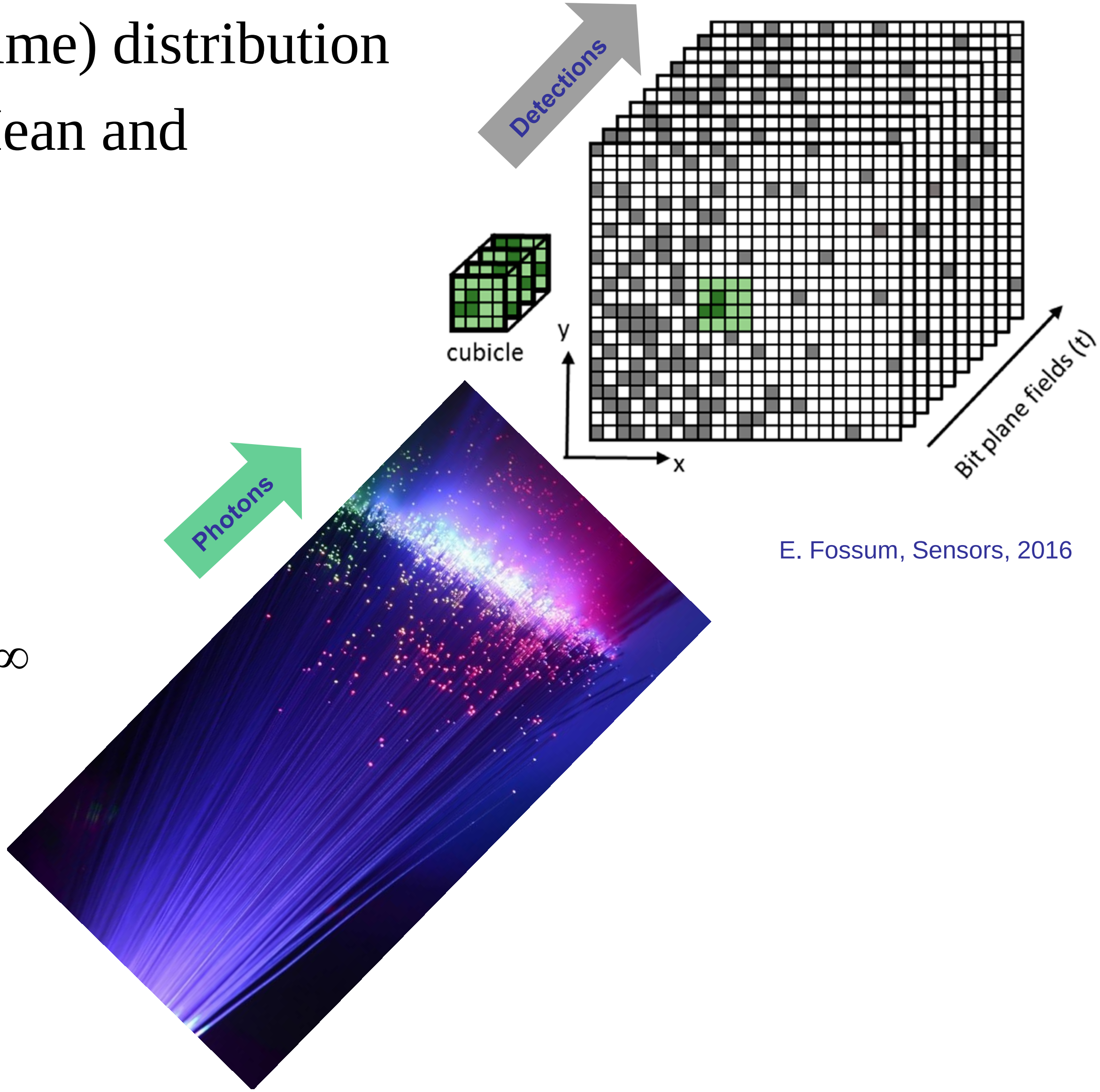
Spatial resolution ~ pixel / detector size (non-random) in the most of photodetector designs

Ultimate photon detection at quantum level

To determine 3D (space-time) distribution of photons with precise Mean and lowest possible StdDev

- In numbers
- In time
- In space

- Ideally:
  - From single photons to ∞
  - Without losses
  - Without noises



E. Fossum, Sensors, 2016

Input-dependent characteristics of output (SNR, RES) Internal characteristics of photodetection (DQE, ENF)

- SNR→ DQE
- Resolution → ENF

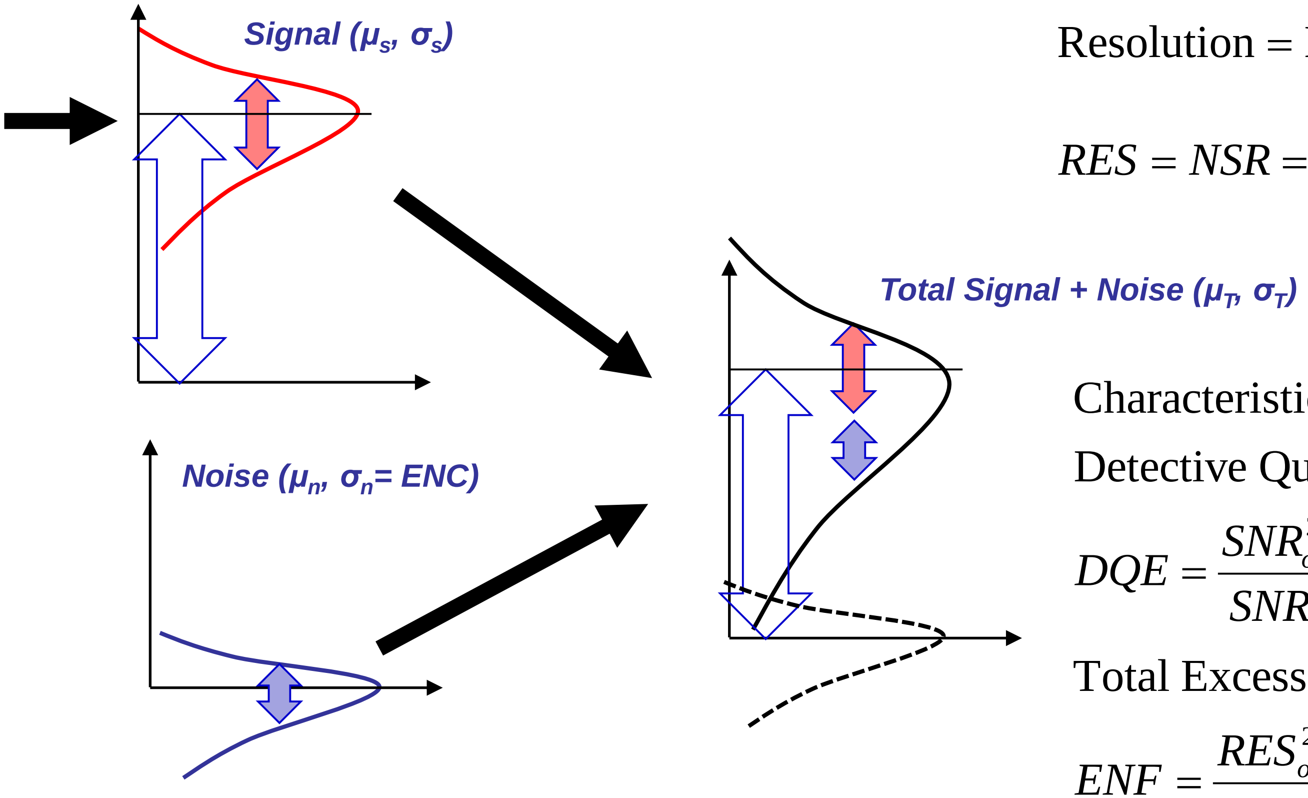
Characteristics of output signal

Signal-to-Noise

$$\mathrm{SNR} = \frac{\mu_T - \mu_n}{\sigma_T} = \frac{\mu_S}{\sigma_T} = \frac{\mu_S}{\sqrt{\sigma_S^2 + ENC^2}}$$

Resolution = Noise-to-Signal

$$RES = NSR = \frac{\sigma_T}{\mu_S} = \frac{\sqrt{\sigma_S^2 + ENC^2}}{\mu_S}$$



Characteristics of photodetection

Detective Quantum Efficiency

$$DQE = \frac{SNR_{out}^2}{SNR_{in}^2} = \frac{1}{ENF}$$

Total Excess Noise Factor

$$ENF = \frac{RES_{out}^2}{RES_{in}^2} = \frac{1}{DQE}$$

Resolution (RES) and Excess Noise Factor (ENF) of stochastic processes in photodetection

Total Excess Noise Factor

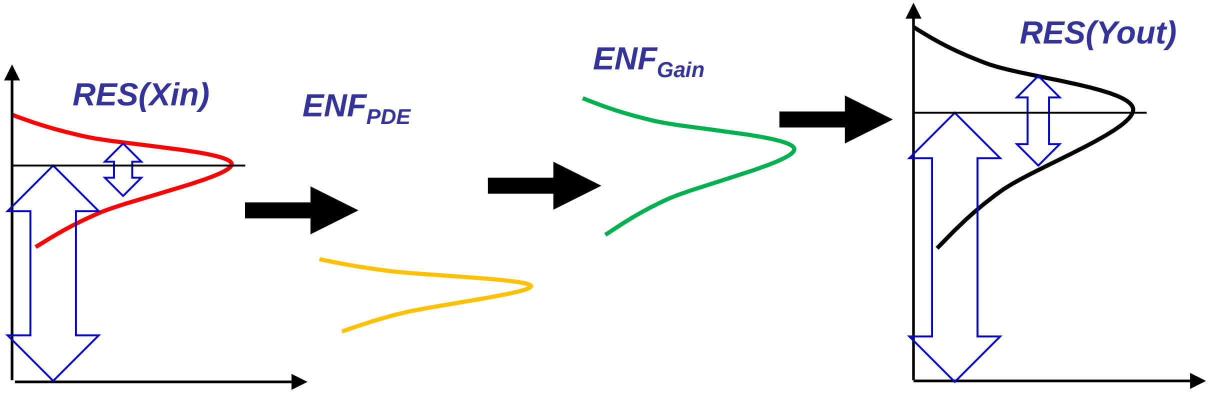
$$ENF(X_{in} = random) = \frac{RES_{out}^2}{RES_{in}^2}$$

Specific Excess Noise Factor

$$ENF(X_{in} = 1) = 1 + \frac{\sigma_{out}^2}{\mu_{out}^2}$$

- **Resolution at output = Total ENF-times degraded Resolution at input**
- **Total ENF is a product of Specific ENFs**

$$RES(Y_{out}) = RES(X_{in}) \cdot \sqrt{ENF_{total}} = RES(X_{in}) \cdot \sqrt{ENF_{process1} \cdot ENF_{process2} \cdots}$$



Input photon distribution **Photodetection processes** **Output charge distribution**

Resolution of single photon requires detection with Gain

Input: single photon $\mu_{in} \equiv 1, \quad \sigma_{in} \equiv 0$

Output: some total signal $\mu_T, \quad \sigma_T$

Total signal is a sum of photosignal (μ_S, σ_S) and electronic noise (0,ENC)

ENC - equivalent noise charge (electrons)

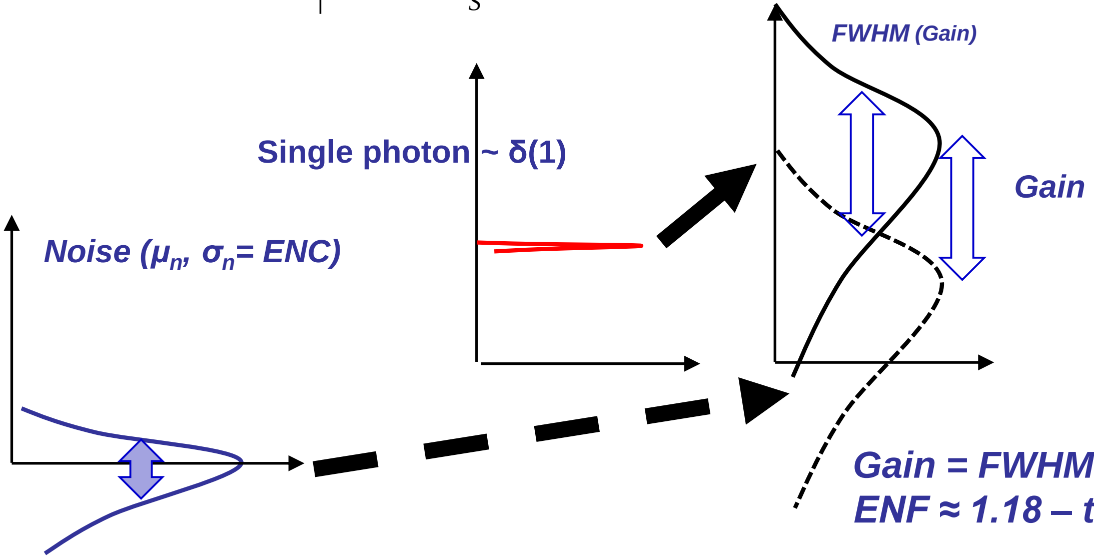
Single photon resolution demands for Gain:

Mean photosignal > Noise => Gain > ENC (FWHM)

$$RES = \frac{\sigma_T}{\mu_S} = \frac{\sqrt{\sigma_S^2 + ENC^2}}{\mu_S} \Bigg|_{Ideal:\,\sigma_S = 0} = \frac{ENC}{\mu_S} = \frac{ENC}{Gain}$$

ENC ~ 10^4 @ BW ~ 1 GHz or Δt = 1 ns

ENC ~ 10^2 @ BW ~ 100 KHz or Δt = 10 μs



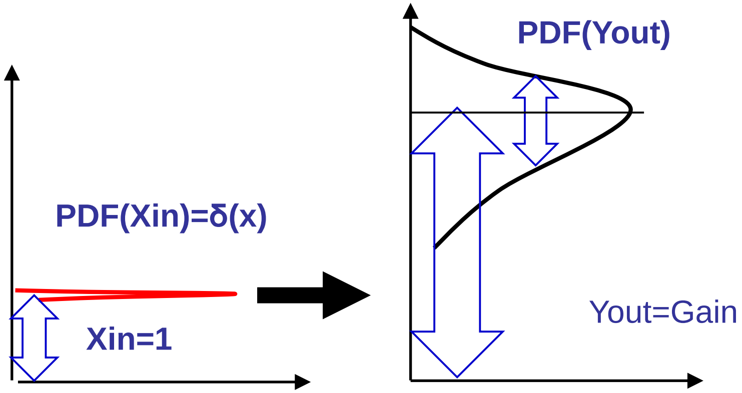
Gain = FWHM = 2.35 σ_{Gain} =>
ENF ≈ 1.18 – threshold ENF

ENF of specific detection processes

- Multiplication (*Xin=1*)

Yout of any distribution

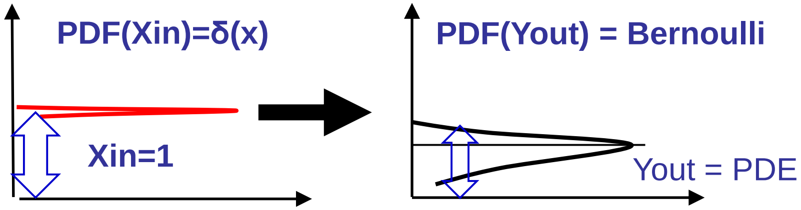
$$ENF_{gain} = 1 + \frac{\sigma_{gain}^2}{Gain^2}$$



- Photon detection (*Xin=1*)

Bernoulli distribution

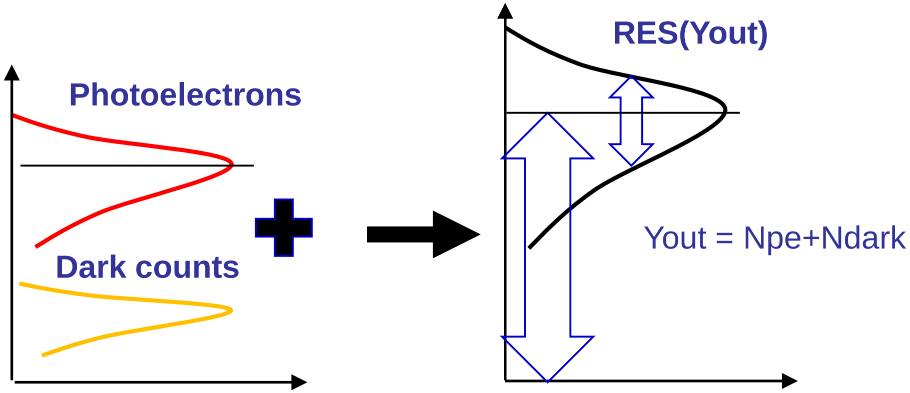
$$ENF_{pde} = 1 + \frac{PDE \cdot (1 - PDE)}{PDE^2} = \frac{1}{PDE}$$



- Dark counts (*Xin=Npe*)

Npe and Ndark ~ Poisson distribution

$$ENF_{dark} = 1 + \frac{N_{dark}}{N_{pe}}$$



Resolution of photodetector for Poisson photons

Incident photons - Poisson (N_{ph}); Output signal - electrons - $(\mu_{out}, \sigma_{out})$

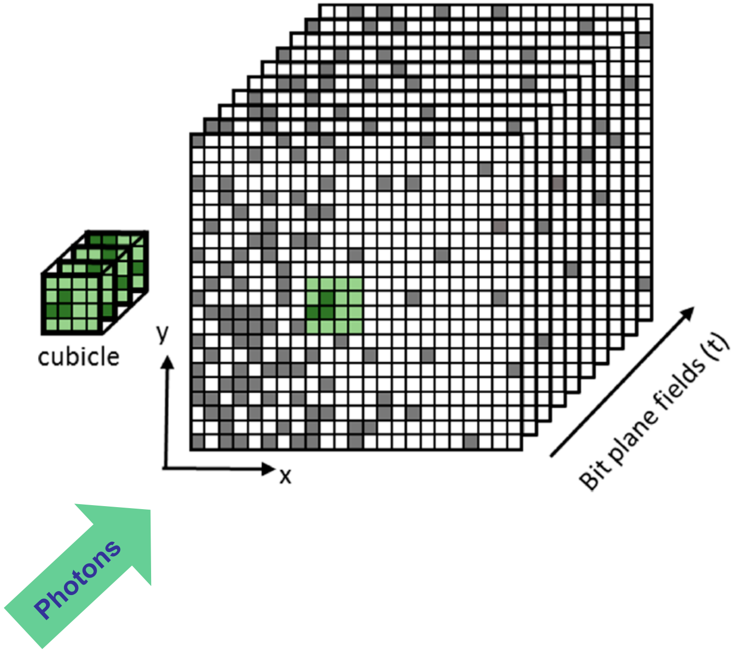
$$\mu_{out} = N_{ph} \cdot PDE \cdot Gain \qquad \sigma_{out}^2 = N_{ph} \cdot PDE \cdot Gain^2 \cdot ENF + ENC^2$$

$$RES_{out} = \frac{\sigma_{out}}{\mu_{out}} = \sqrt{\frac{ENF}{N_{ph} \cdot PDE} + \frac{ENC^2}{\left(N_{ph} \cdot PDE \cdot Gain\right)^2}}$$

PDE – Photon Detection Efficiency

ENC – Equivalent Noise Charge, electrons

ENC $\sim 10^4$ @ $BW \sim 1GHz$



- Contributions:
  - Shot noise of photoelectrons
  - Excess noise of multiplication
  - Electronic noise ENC

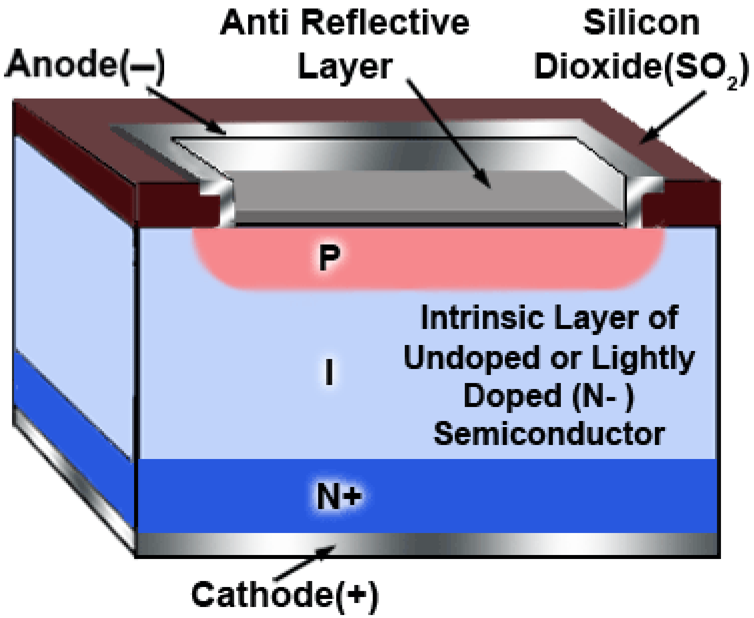
✓ **Ideal photon detector:**

- ✓ ***PDE = 100%***
- ✓ ***ENC / Gain → 0***
- ✓ ***ENF = 1***

$$RES_{out} = RES_{in} = \sqrt{\frac{1}{N_{ph}}}$$

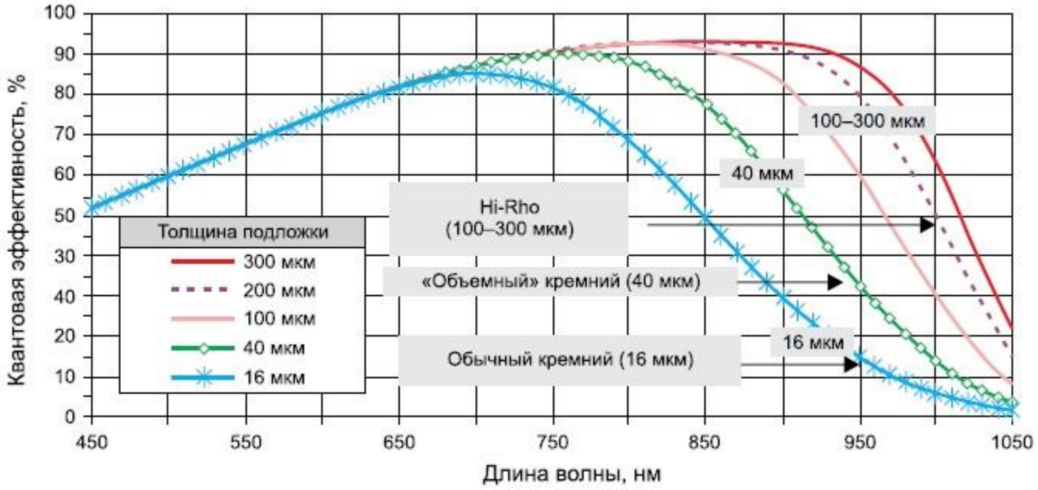
Optimization of Photodiode

$$RES_{out} = \frac{\sigma_{out}}{\mu_{out}} = \sqrt{\frac{ENF}{N_{ph} \cdot PDE} + \frac{ENC^2}{\left(N_{ph} \cdot PDE \cdot Gain\right)^2}}$$



- ✓ **Focus on max *QE* and large signals**
  - ✓ ***Nph >> ENC***
  - ✓ *Gain = 1, ENF = 1*
  - ✓ *PDE ~ 80% - 90%,*

$$RES(N_{ph}) = \sqrt{\frac{1}{N_{ph} \cdot PDE}}$$



Optimization of Avalanche Photodiode (APD)

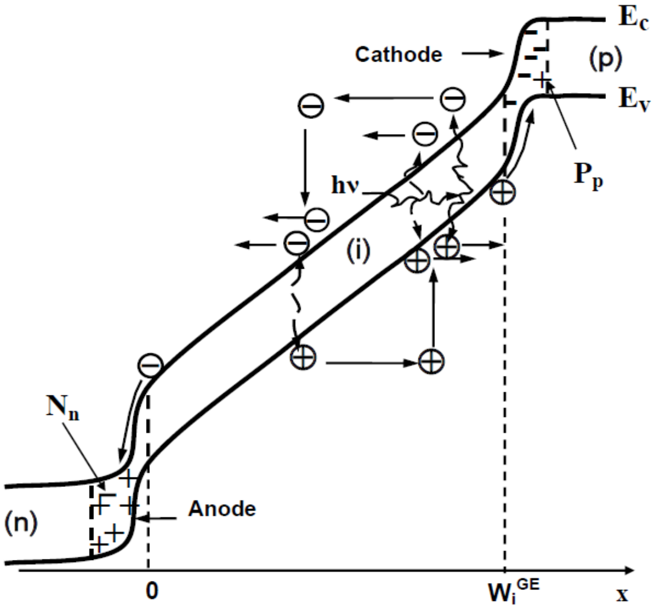
$$RES(N_{ph}) = \frac{\sigma_{out}}{\mu_{out}} = \sqrt{\frac{\boxed{ENF}}{N_{ph}\cdot PDE} + \frac{ENC^2}{\left(N_{ph}\cdot PDE\cdot \boxed{Gain}\right)^2}}$$

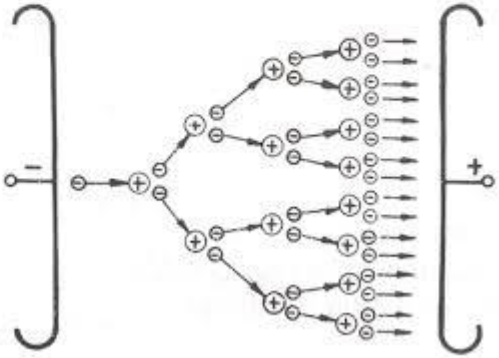
- ✓ <u>**Focus on optimal balance:**</u> ***Gain*** **vs** $\boldsymbol{ENF_{Gain}}$

  Conventional APD: $ENF(Gain) \sim Gain$

  $Min\ R$ at $\quad Gain \sim \sqrt[3]{2\frac{ENC^2}{N}}\Bigg|_{ENC=100,\,N=1} \sim 27$

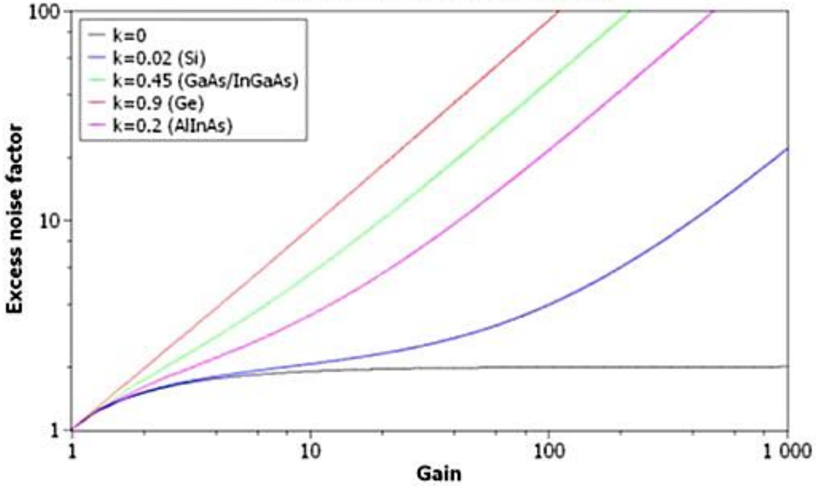
  Optimal gain ~ 30 – typical practical value





$$ENF_{gain} = 1 + \frac{\sigma^2_{gain}}{Gain^2}$$

Excess noise factor vs APD gain for various semiconductors



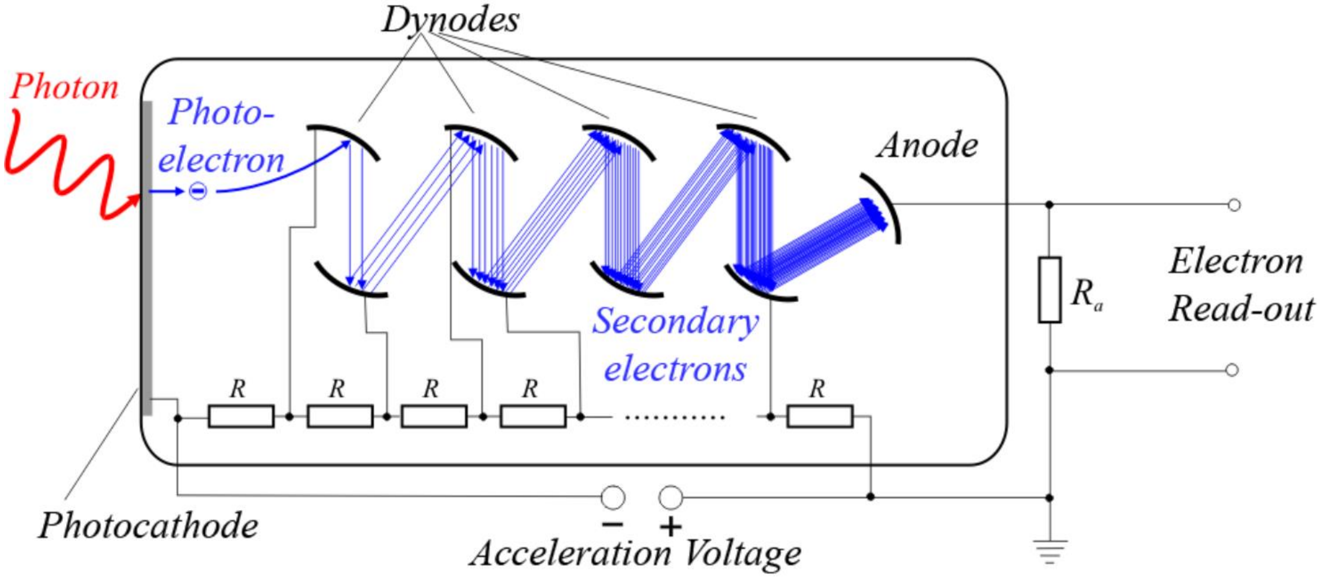
Optimization of vacuum photomultiplier

$$RES(N_{ph}) = \frac{\sigma_{out}}{\mu_{out}} = \sqrt{\frac{ENF}{N_{ph}\cdot PDE} + \cancel{\frac{ENC^2}{\left(N_{ph}\cdot PDE\cdot Gain\right)^2}}}$$

- **Focus on max *QE*:**
  - ✓ ***Gain >> ENC***
  - ✓ *$ENF \approx 1.1 \ldots 1.3$ - is determined by dynode emission of ~ 4 electrons*
  - ✓ *QE ~ 20% - 30%*

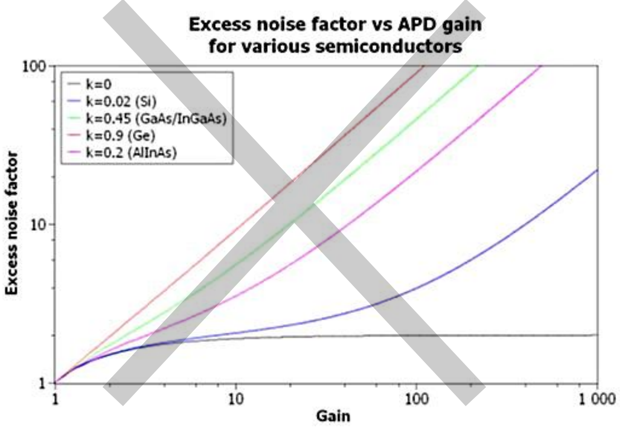
$$ENF \sim 1 + \frac{4}{4^2} \sim 1.25$$

$$RES(N_{ph}) = \sqrt{\frac{ENF_{Gain}}{N_{ph}\cdot PDE}}$$



Optimization of Geiger mode APD array

$$RES(N_{ph}) = \frac{\sigma_{out}}{\mu_{out}} = \sqrt{\frac{\xcancel{ENF}}{N_{ph}\cdot PDE} + \xcancel{\frac{ENC^2}{\left(N_{ph}\cdot PDE\cdot Gain\right)^2}}}$$



- ✓ **1. Focus on triggering of Geiger breakdown** and binary detection of single photons

$$RES(N_{ph}) = \left.\sqrt{\frac{1}{N_{ph}\cdot PDE}}\right|_{N_{ph}\le 1}$$

$PDE = FF \cdot QE \cdot P_{AV}$

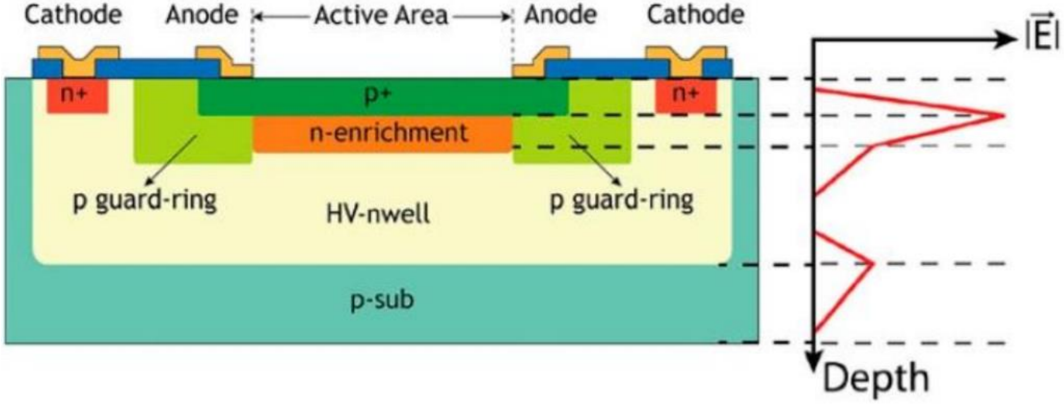
FF – fill factor, geometric efficiency

FF = Active Area / Total Area

QE – quantum efficiency

P_{AV} – probability of avalanche

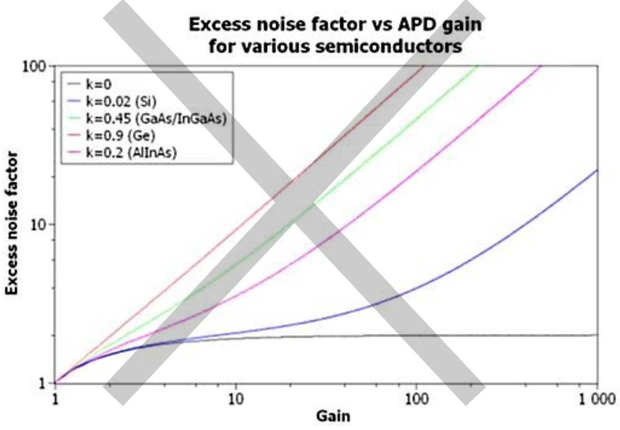
Single Photon Avalanche Diode (SPAD)



A. Tosi, F. Zappa, MiSPiA: microelectronic single-photon 3D imaging arrays, Proc. SPIE (2013)

Optimization of Geiger mode APD array

$$RES(N_{ph}) = \frac{\sigma_{out}}{\mu_{out}} = \sqrt{\frac{\cancel{ENF}}{N_{ph}\cdot PDE} + \xcancel{\frac{ENC^2}{\left(N_{ph}\cdot PDE\cdot Gain\right)^2}}}$$



- ✓ **<u>2. Focus on active quenching of Geiger breakdown</u>** (electronics => inactive area)

$$RES(N_{ph}) = \sqrt{\frac{1}{N_{ph}\cdot PDE}}$$

$$PDE = FF\cdot QE\cdot P_{AV}$$

FF – fill factor, geometric effciency

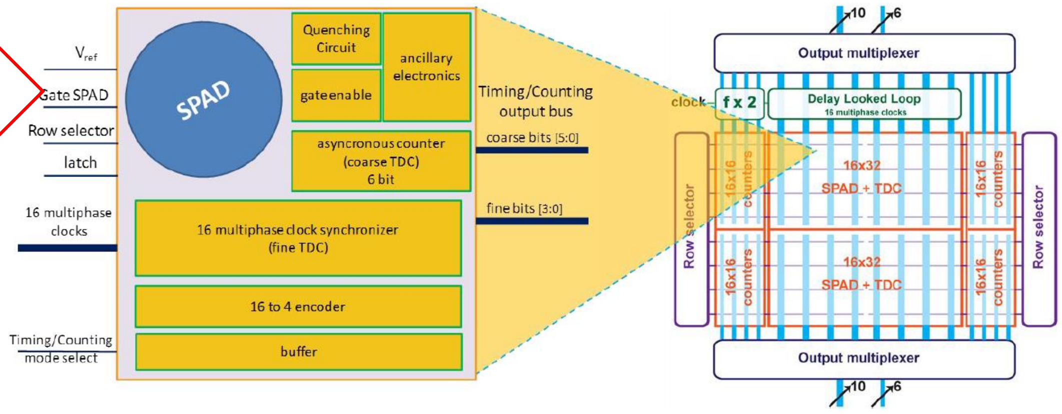
FF = Active Area / Total Area

QE – quantum effciency

P_{AV} – probability of avalanche

FF = 3%

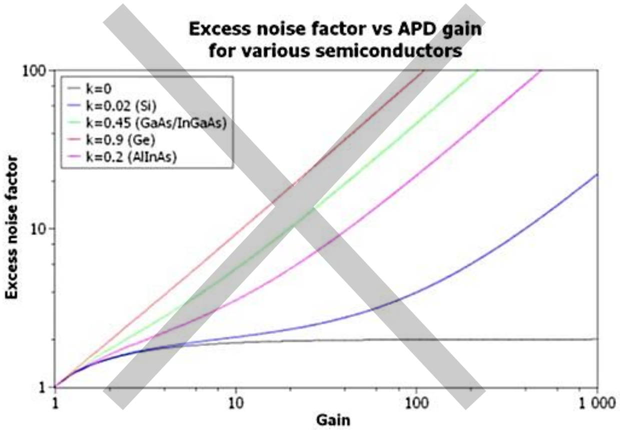
Single Photon Avalanche Diode (SPAD)



A. Tosi, F. Zappa, MiSPiA: microelectronic single-photon 3D imaging arrays, Proc. SPIE (2013)

Silicon Photomultiplier

$$RES(N_{ph}) = \frac{\sigma_{out}}{\mu_{out}} = \sqrt{\frac{\boxed{ENF}}{N_{ph}\cdot PDE} + \frac{ENC^2}{\left(N_{ph}\cdot PDE\cdot \boxed{Gain}\right)^2}}$$

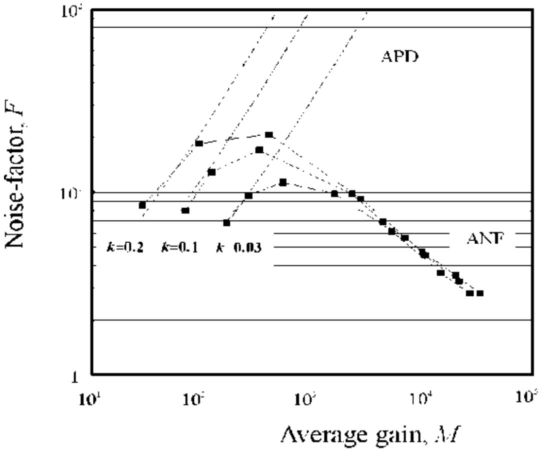


✓ **Focus on high Gain low excess noise Geiger breakdown**

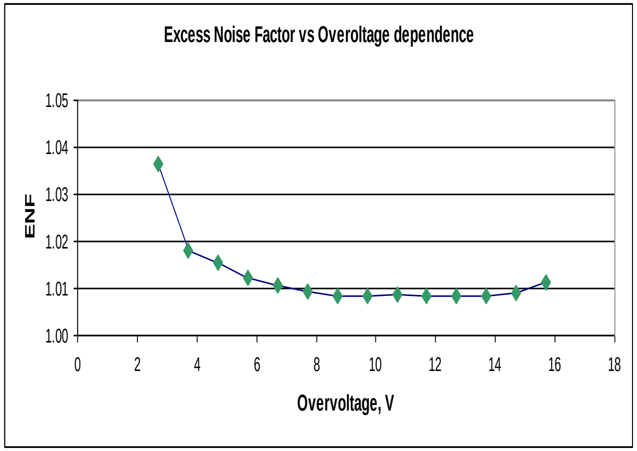
- ✓ $Gain >> ENC$
- ✓ $ENF_{Gain} \rightarrow 1$
- ✓ $PDE \rightarrow max$

$$RES(N_{ph}) = \sqrt{\frac{ENF}{N_{ph}\cdot PDE}}$$

Model



Experiment



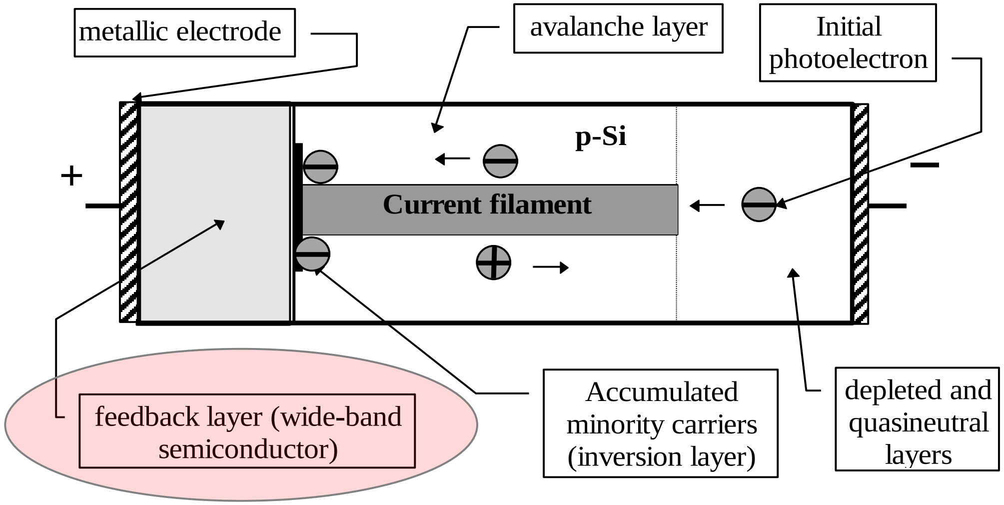
[Model] D. Shushakov, V. Shubin, Proc. SPIE (1995)
[Experiment] K. Linga, E. Godik, J. Krutov, D.A. Shushakov, V. Shubin, S. Vinogradov, E. Levin, Proc. SPIE (2006)

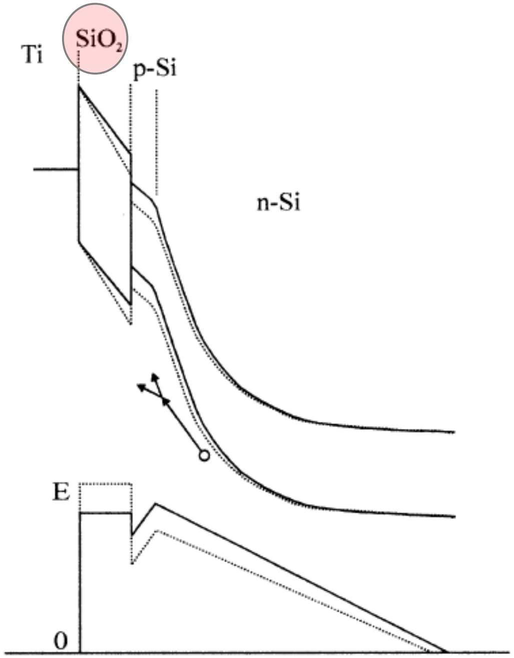
SiPM concept:
Basic studies at Lebedev Physical Institute (1970s-1990s)

Avalanche with Negative Feedback (ANF) concept:

- Avalanche development by strong positive feedback
  → Geiger mode avalanche breakdown with high overvoltage
- Avalanche quenching by strong negative feedback
  → Passive quenching by built-in elements (ANF APD)
  Capacitive (feedback ~ avalanche charge)
  Resistive (feedback ~ avalanche current)

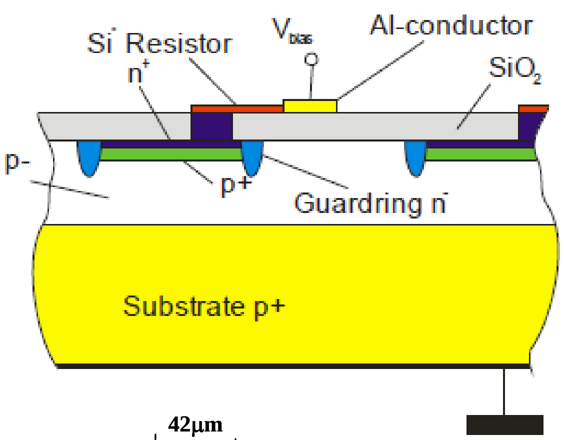
ANF
=>
High gain
+
Low noise
+
Fast time

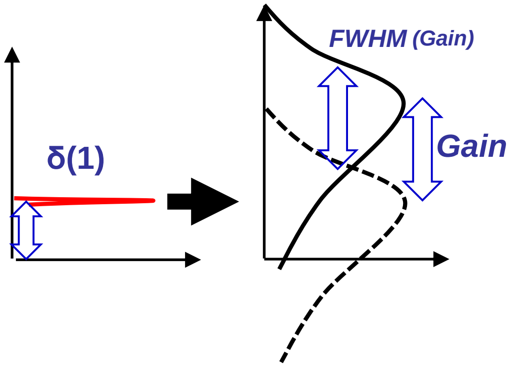




V. Shubin, D. Shushakov, Encyclopedia of Optical Engineering 2003; DOI: 10.1081/E-EOE 120009727

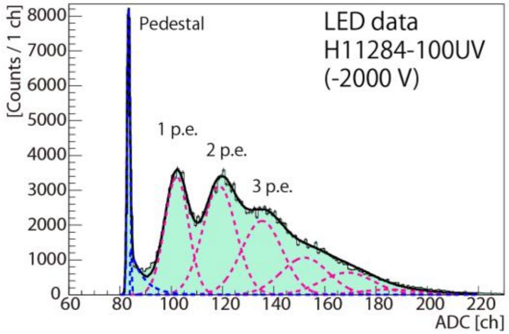
Кремниевый фотоумножитель
Silicon Photomultiplier (SiPM)



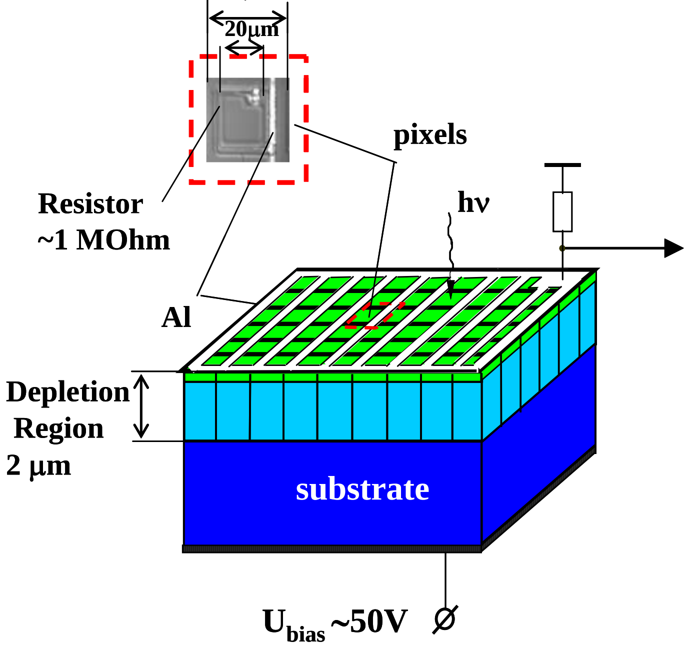


Gain = FWHM = 2.35 σ_{Gain} =>
ENF ≈ 1.18 - порог разрешения 1 фотона

PMT H11284-100UV (*ENF ≈ 1.14*)

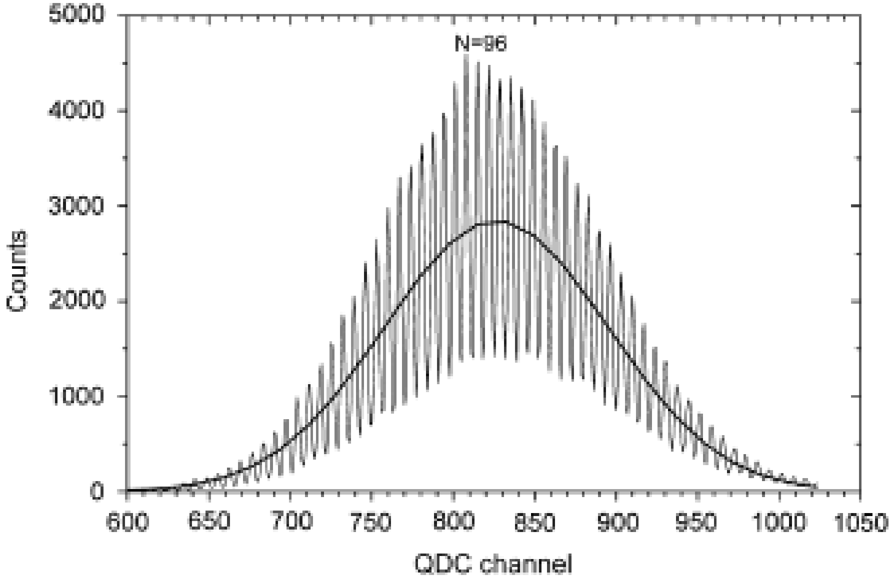


T. Cogami et al, NIMA 2016



SiPM, B. Dolgoshein et al., MEPhI / Pulsar, 2000-2003

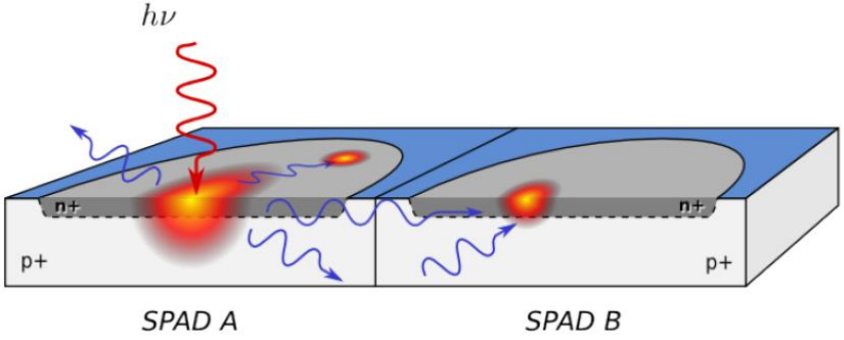
SiPM (MEPhI/Pulsar)



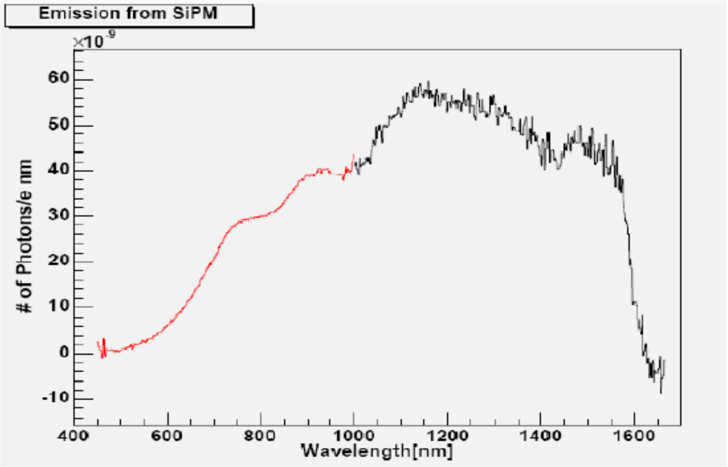
R. Mirzoyan et al., NDIP, 2008

Correlated avalanche events:
SiPM crosstalk (CT) → ENF_{CT}

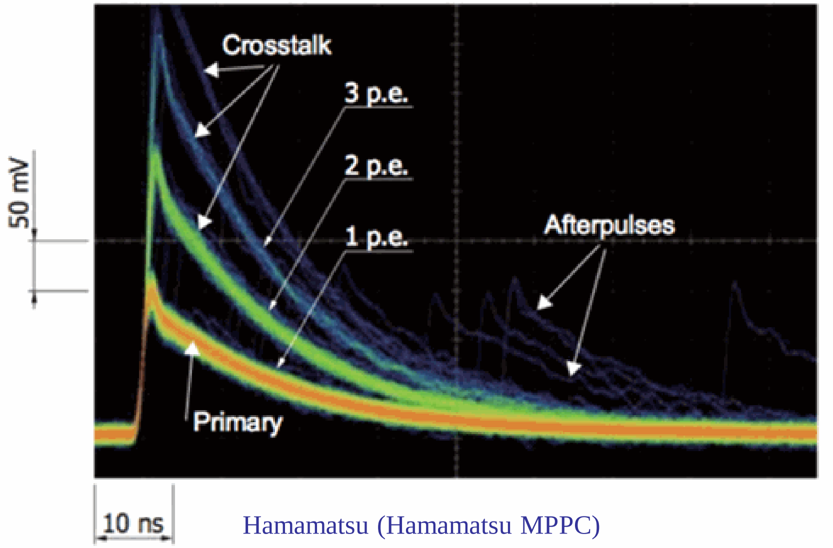
Hot carrier photon emission



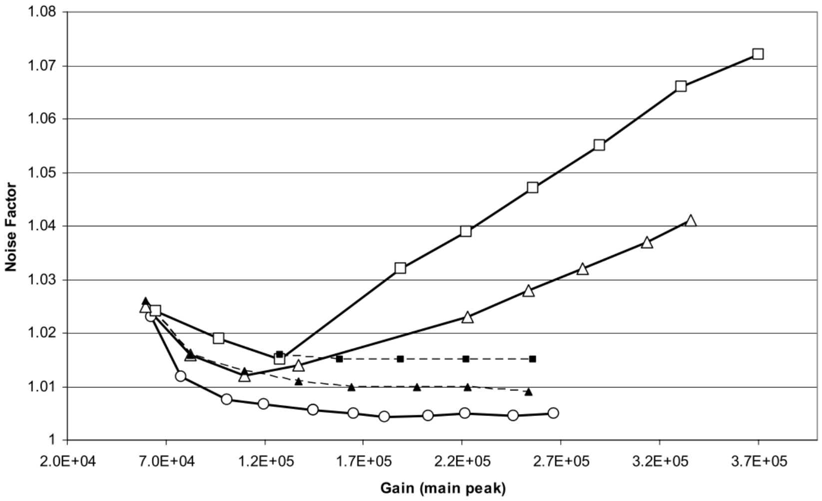
A. Lacaita et al., IEEE TED, 1993



R. Mirzoyan, NDIP, 2008



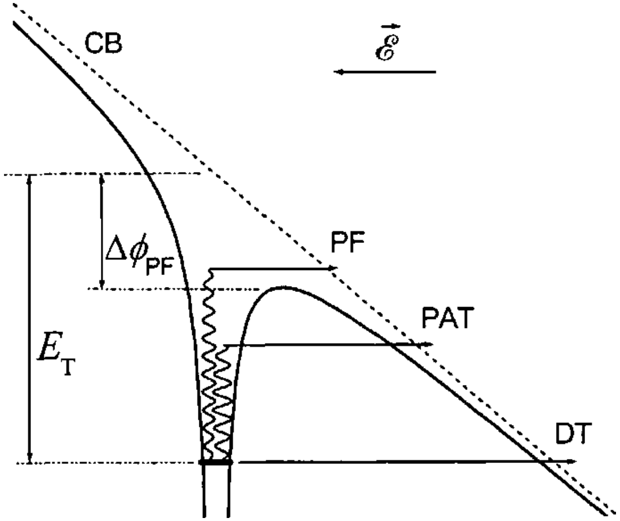
Hamamatsu (Hamamatsu MPPC)

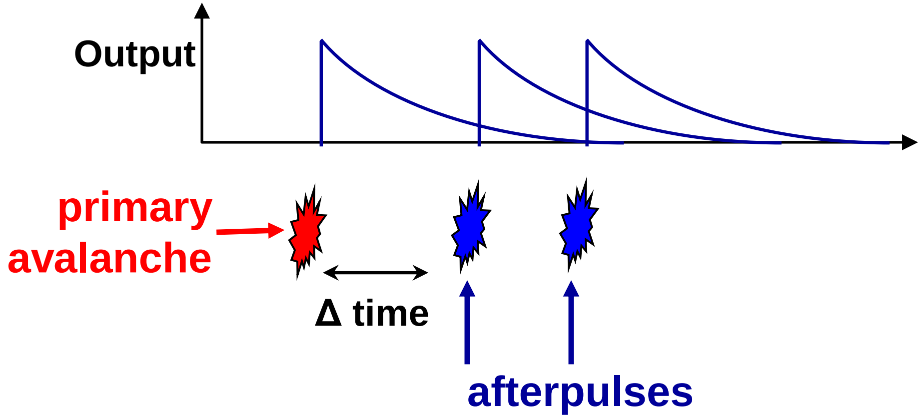


K. Linga et al, Proc. SPIE (2006)

Correlated avalanche events:
SiPM afterpulsing (AP) → ENF_{AP}

- Afterpulsing: electron/hole trapping – emission – new avalanche

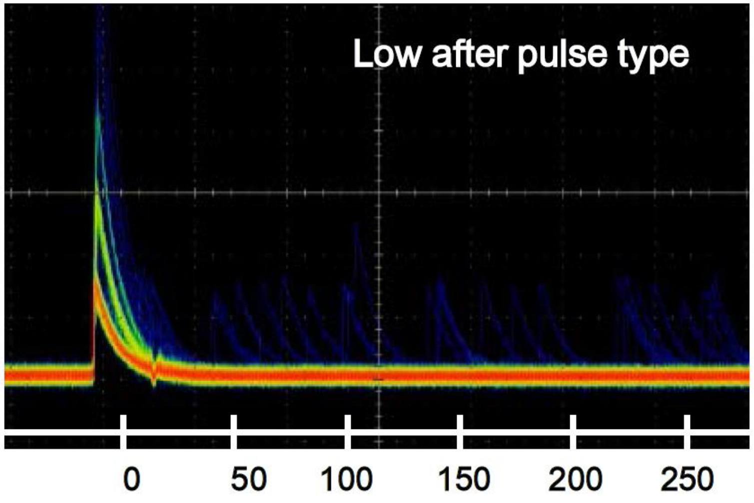


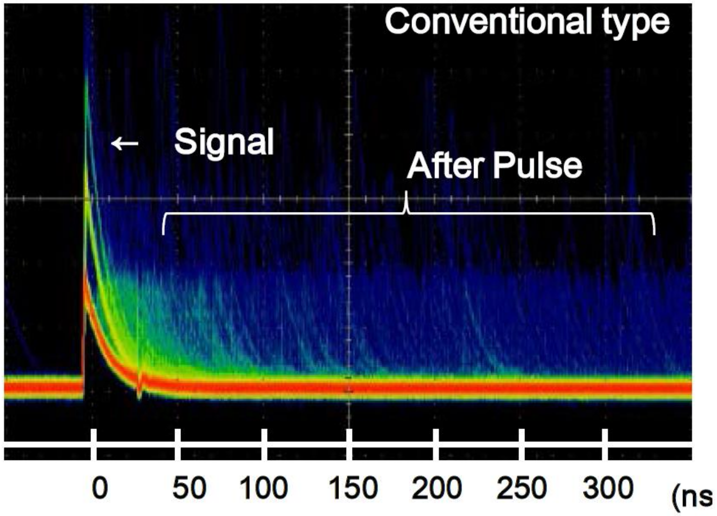


primary avalanche

Δ time

afterpulses



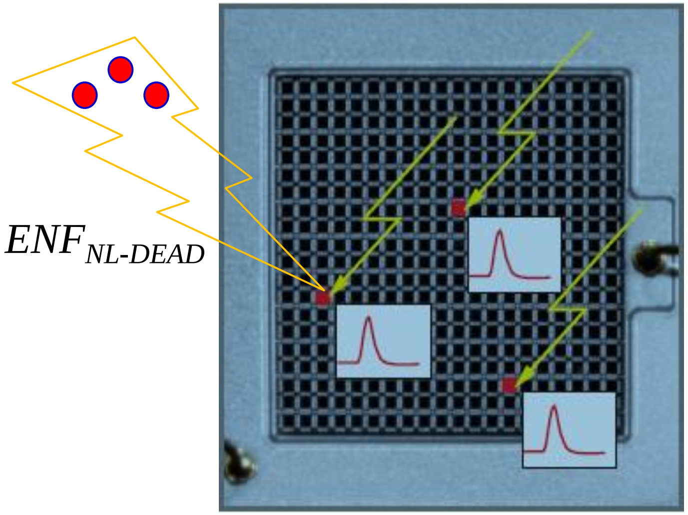


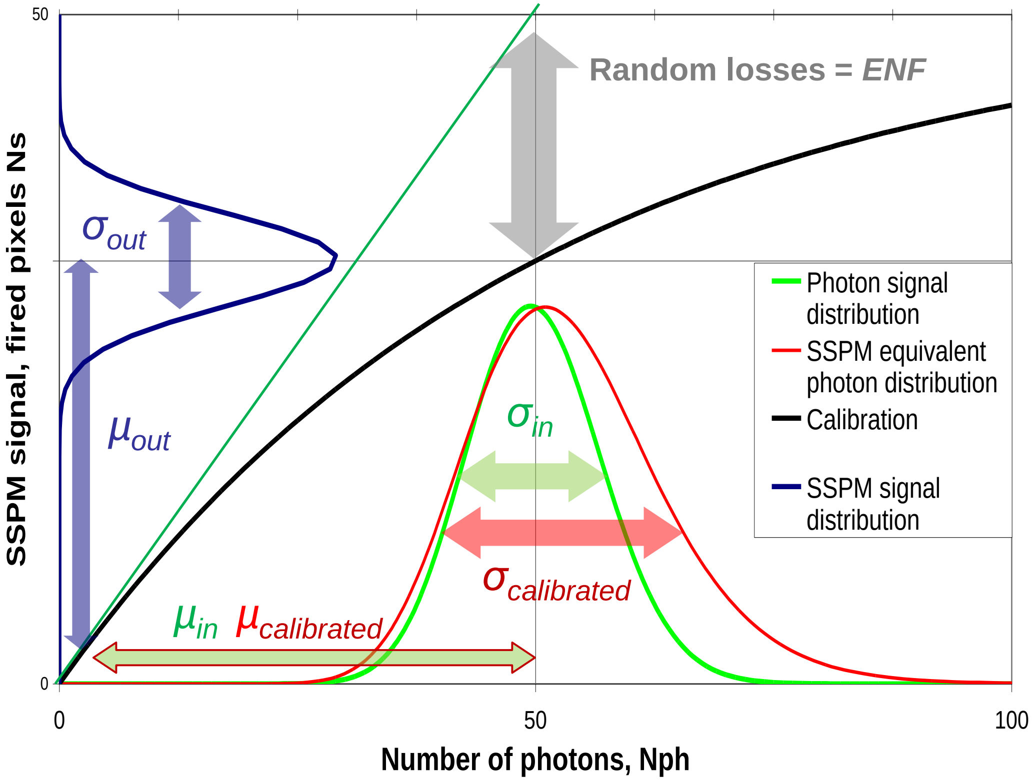
SiPM nonlinearity:
Random losses → ENF_{NL}

- Нелинейность => потери фотонов => ENF_{NL}

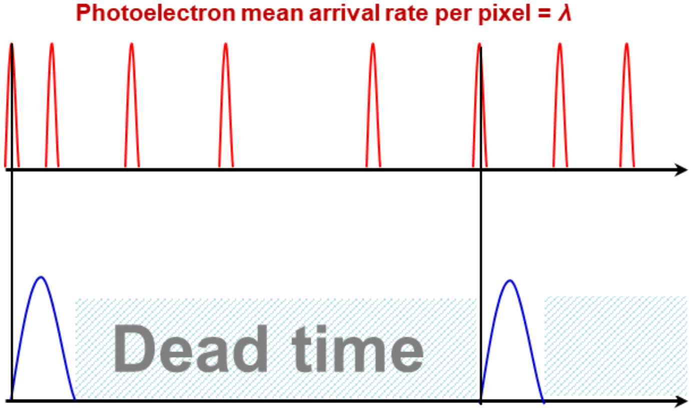
  ENF => деградация разрешения *Nph*
- Нелинейность SiPM:
  - 1) Из-за ограниченного числа ячеек $ENF_{NL\text{-}PIX}$
  - 2) Из-за мертвого времени (восстановления ячейки) $ENF_{NL\text{-}DEAD}$

1) По ячейкам





2) По мертвому времени



Detective Quantum Efficiency (DQE)

- Resolution SNR DQE

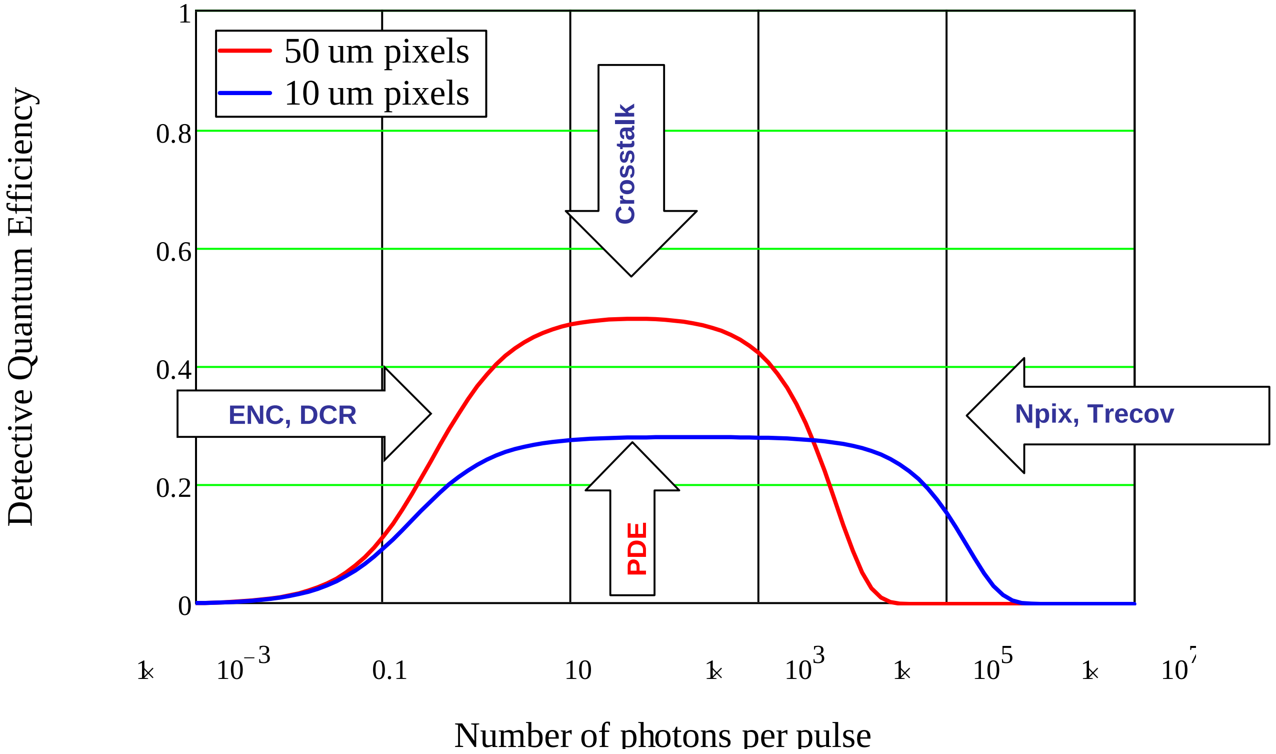
$$RES_{out} = \frac{\sigma_{out}}{\mu_{out}} = \sqrt{\frac{ENF}{N_{ph} \cdot PDE} + \frac{ENC^2}{\left(N_{ph} \cdot PDE \cdot Gain\right)^2}}$$

$$SNR_{out} = \frac{\mu_{out}}{\sigma_{out}}$$

$$DQE = \frac{SNR_{out}^2}{SNR_{in}^2}$$

- SiPM (and others with Gain >> ENC):

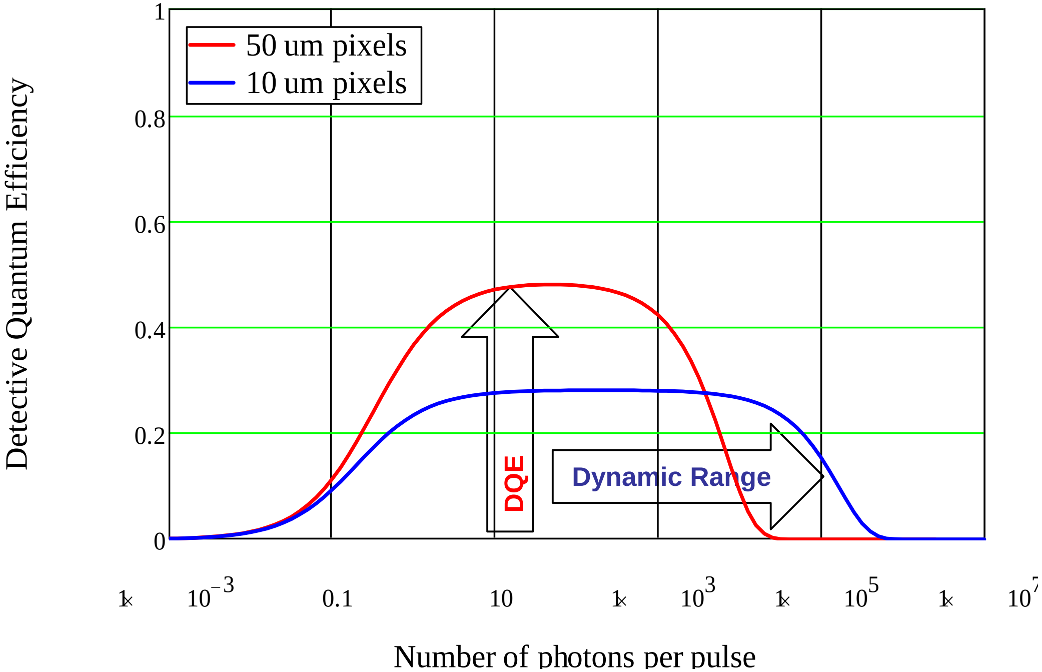
$$DQE = \frac{PDE}{ENF} = \frac{FF \cdot QE \cdot P_{AV}}{ENF_{Gain} \cdot ENF_{CT} \cdot ENF_{AP} \cdot ENF_{NL} \cdot ENF_{DCR}}$$



Main trends in SiPM R&D

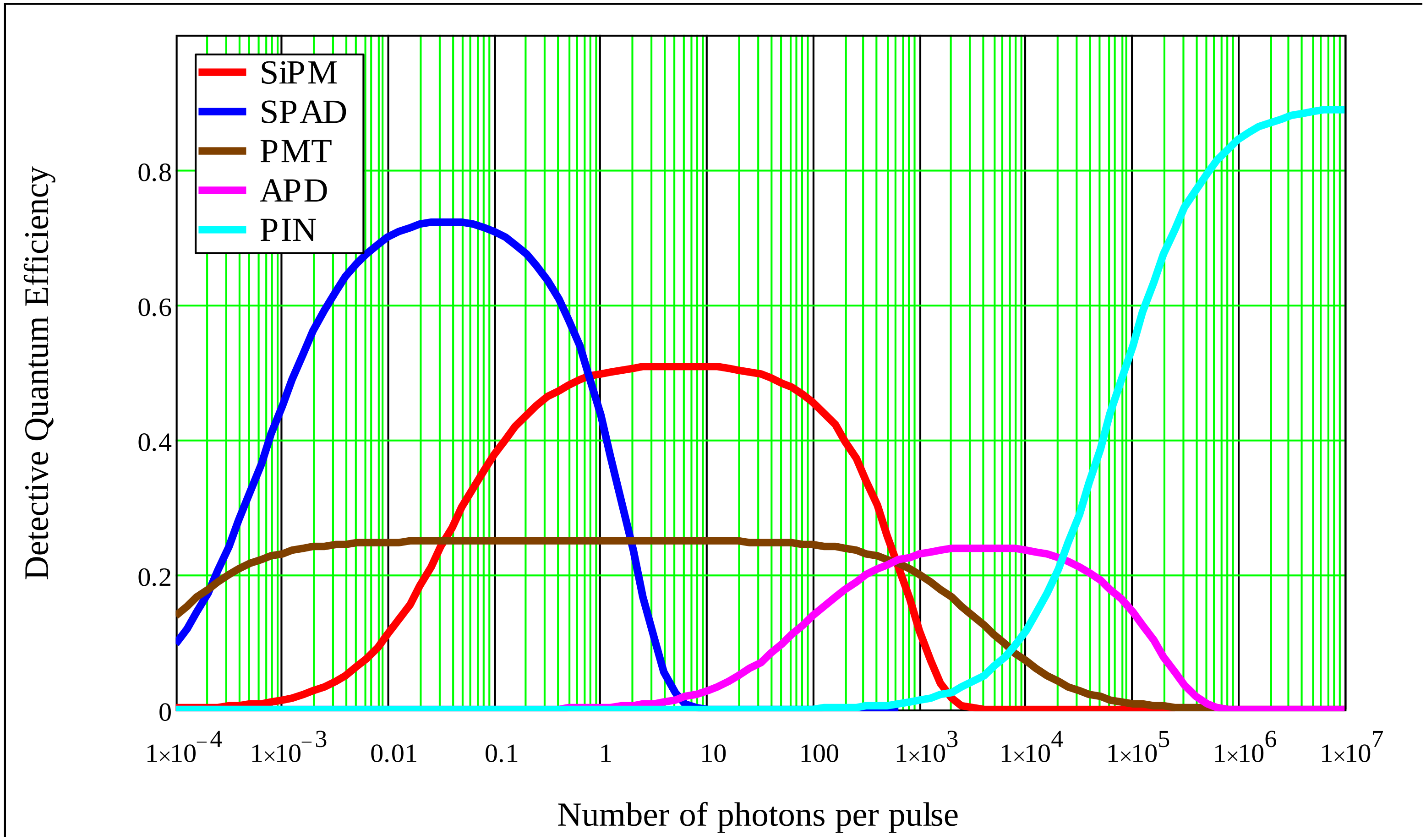
1. Max *QE*, P_{AV} => *max* PDE & DQE – beneficial for any applications and designs
2. High DQE (~ in a limited Dynamic Range)
   - «Big cells», “Scientific SiPM”
3. High Dynamic Range (~ with a limited DQE)
   - «Small cells», “HDR / UHDR SiPM”

$$DQE = \frac{PDE}{ENF} = \frac{FF \cdot QE \cdot P_{AV}}{ENF_{Gain} \cdot ENF_{CT} \cdot ENF_{AP} \cdot ENF_{NL} \cdot ENF_{DCR}}$$



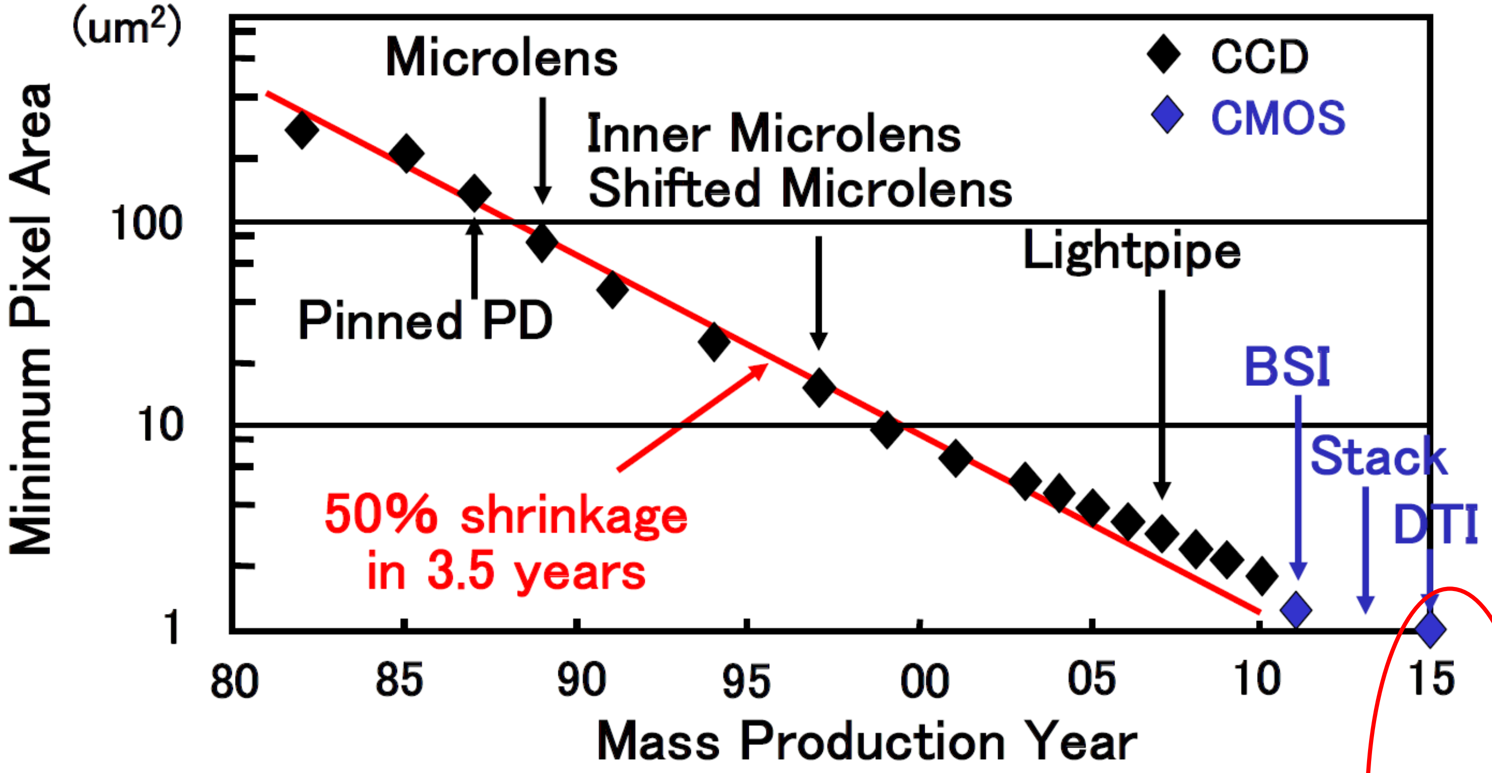
DQE of photodetectors: Map of competitiveness

- Detection of 10 ns pulse @ max spectral sensitivity



Evolution of CCD/CMOS imagers

- **Shrinkage speed becomes slower recently.**
- **In 2017, 0.9 um pixel began to be mass produced.**



- In 2015, several organization reported low noise < 0.3 e- rms

N. Teranishi, Recent Progresses of Visible Light Image Sensors, Cern Detect. Semin. (2018).

$$RMS_{noise} = \frac{\sqrt{kTC}}{q}[electrons] \qquad Si - \text{photodiode of } 1x1x10\ \text{um}^3 \Rightarrow RMS_{noise} \sim 1.3\ e$$

Pinned Photodiode (PPD) and modern CMOS imagers

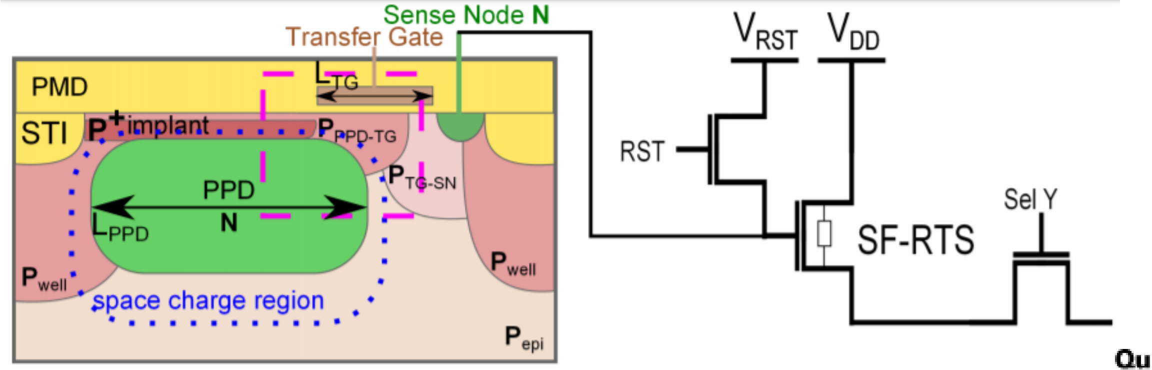
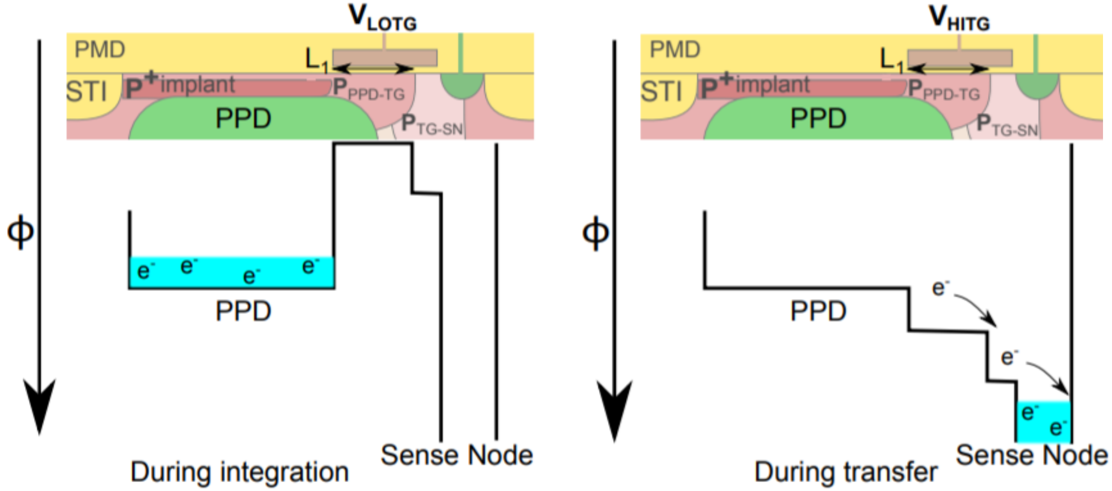
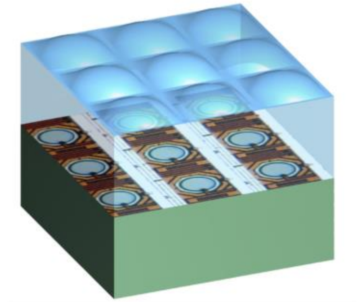
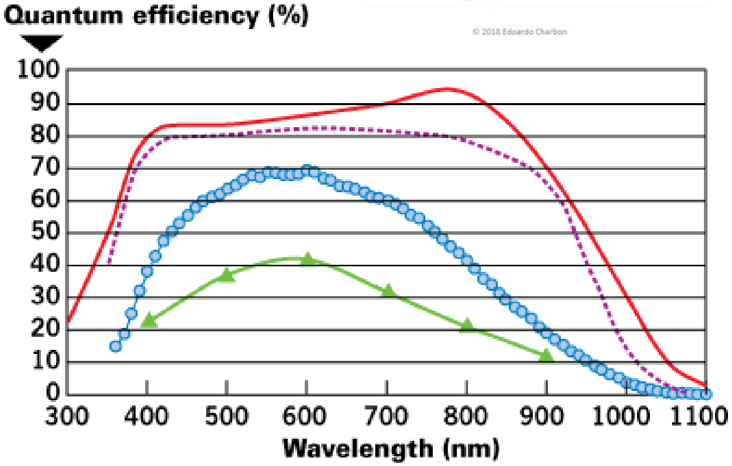


Fig. 2. Pixel architecture and cross section of the pinned photodiode used as a reference. L_{TG} is the transfer gate length and L_{PPD} is the PPD length.



Fill Factor Recovery: Microlenses





CMOS QE:
triangles – front-side illumination without microlenses,
circles – front-side illumination with microlenses,
dashed line – back-side illumination imager,
solid line – back-side illumination imager IMEC

Y. Bai, et al "Silicon CMOS imaging technologies", Proc. SPIE 2008

Quantum Image Sensor: photon-number-resolving CMOS imager (Eric Fossum)

- Sensing node size < 500 nm !!!
- Capacitance < 1 fF
- Gain ~ C/q ~ 1mV/e
- Noise ~ 0.15 e RMS
- => ENF < 1.02

FIGURE 2. A Dartmouth QIS test chip contains 20 different 1 Mjot QIS arrays and was fabricated by TSMC in a modified 45/65 nm 3D-stacked BSI CIS process.

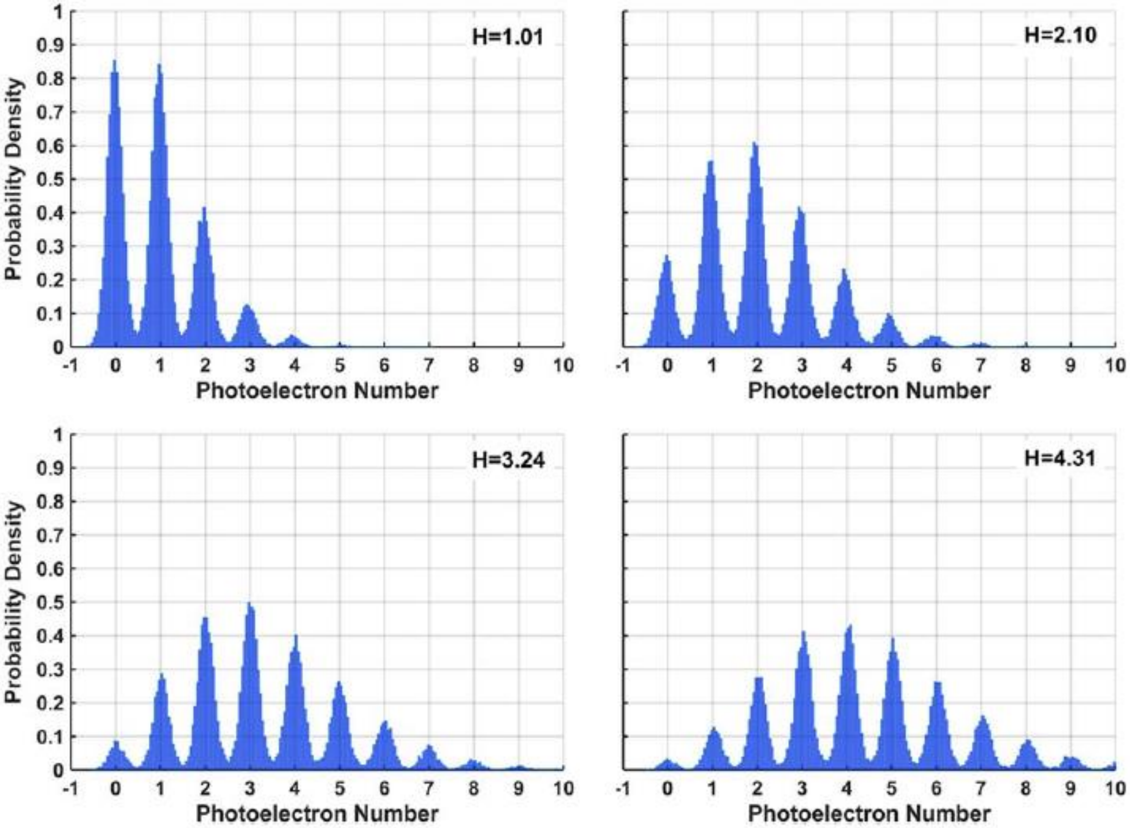


Fig. 4. Experimental demonstration of photoelectron counting.

J. Ma et al., Photon-number-resolving megapixel image sensor at room temperature without avalanche gain, O

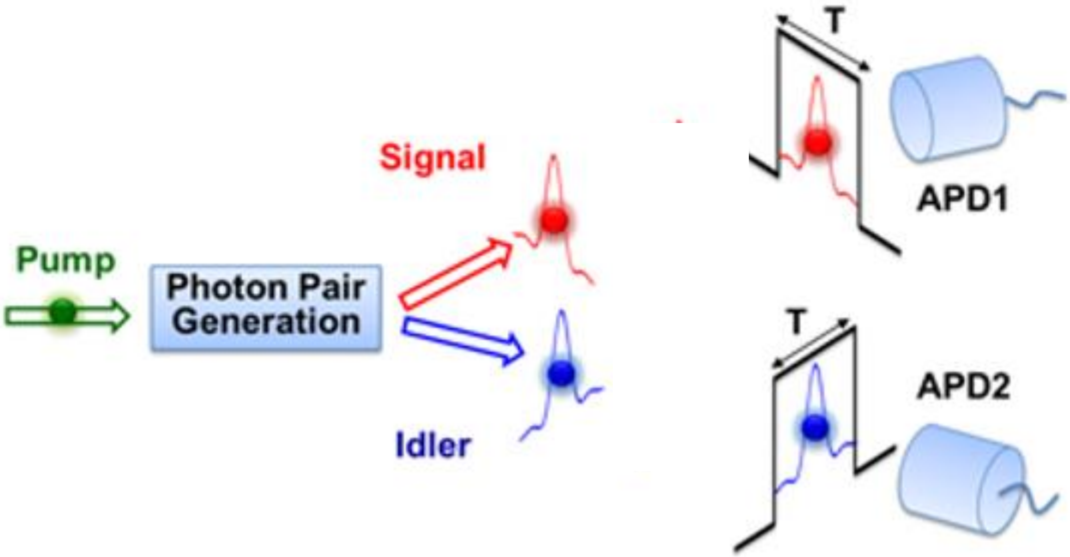
E. Fossum, Advances in Detectors: The Quanta image sensor (QIS): Making every photon count, Laser Focus

Characterization of photon-number-resolving detectors

- Characterization of SiPM and photon-number-resolving detectors

Characterization: PDE

- Photon Detection Efficiency ~ probability to detect single photon
- Absolute calibration of PDE of your photodetector
  - 1. “Single photon-on-demand” source or
  - 2. “Paired photons” down conversion technique (Alan Migdal, NIST)



Detection of paired photons

$$N(\det 1) = N_{pairs} \cdot PDE_1$$

$$N(\det 2) = N_{pairs} \cdot PDE_2$$

$$N(coin12) = N_{pairs} \cdot PDE_1 \cdot PDE_2$$

$$\Rightarrow PDE_1 = \frac{N(coin12)}{N(\det 2)}$$

$$\Rightarrow PDE_2 = \frac{N(coin12)}{N(\det 1)}$$

Characterization: PDE

- Photon Detection Efficiency ~ probability to detect single photon
- Reference calibration of PDE of your photodetector
  - 3. Calibrated photodetector and uncalibrated Poisson light source
    - — From metrology center (e.g. NIST) (PIN or others e.g. SiPM)
    - — Zero-peak method is recognized as the best for SiPM
    - — Attention to integration time - TBD

Poisson photons μ_N with dark counts μ_D

$DUT:$

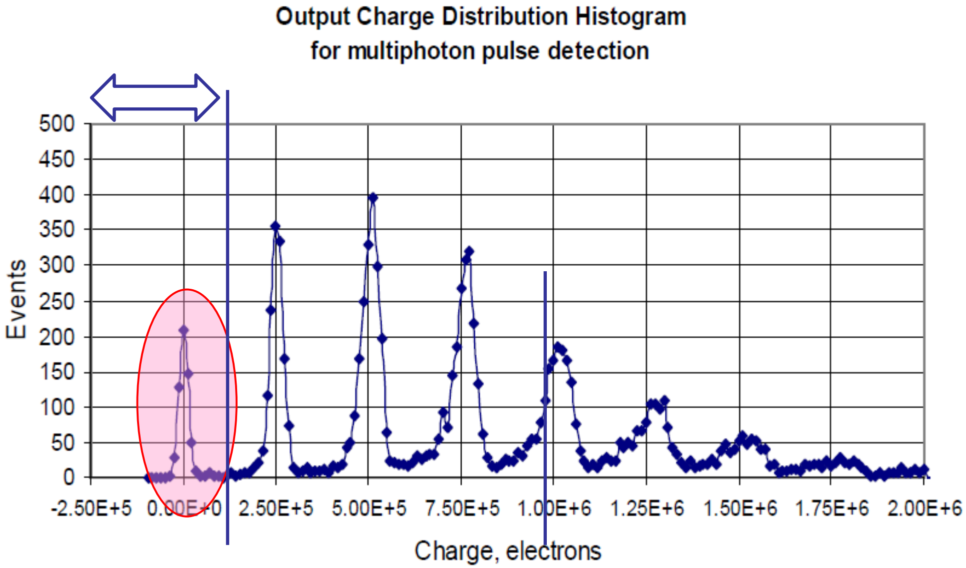
$$P_{DUT}(N_{N+D}=0)=\mathrm{e}^{-(\mu_N PDE_{DUT}+\mu_D)}$$

$$P_{DUT}(N_D=0)=\mathrm{e}^{-\mu_D}$$

$$PDE_{DUT}=-\frac{1}{\mu_N}\ln\left[\frac{P_{DUT}(N_{N+D}=0)}{P_{DUT}(N_D=0)}\right]$$

Reference detector:

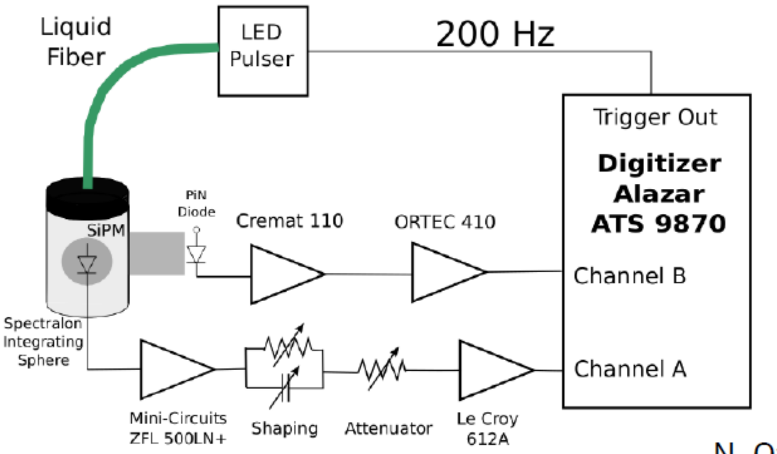
$$\mu_N=-\frac{1}{PDE_{REF}}\ln\left[\frac{P_{REF}(N_{N+D}=0)}{P_{REF}(N_D=0)}\right]$$



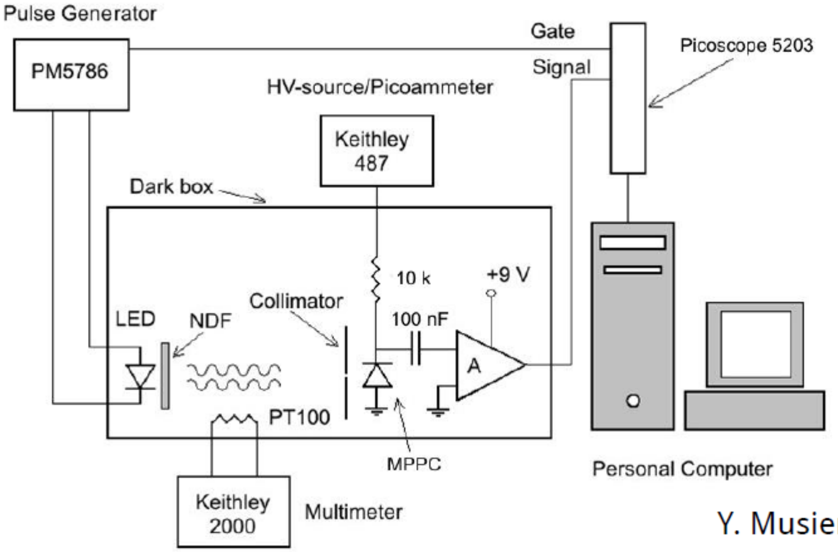
Characterization: PDE

- ICASiPM-2018

Swapping Sensors vs. Optical Splitter



N. Otte



Y. Musienko

Pro:
- Measure reference and DUT simultaneously

Contra:
- Possible wavelength dependent splitting ratio
- Photons can trickle out over long time from integrating sphere

Pro:
- no beam splitter

Contra:
- reference and DUT need to be measured in sequence
→ need a monitoring device

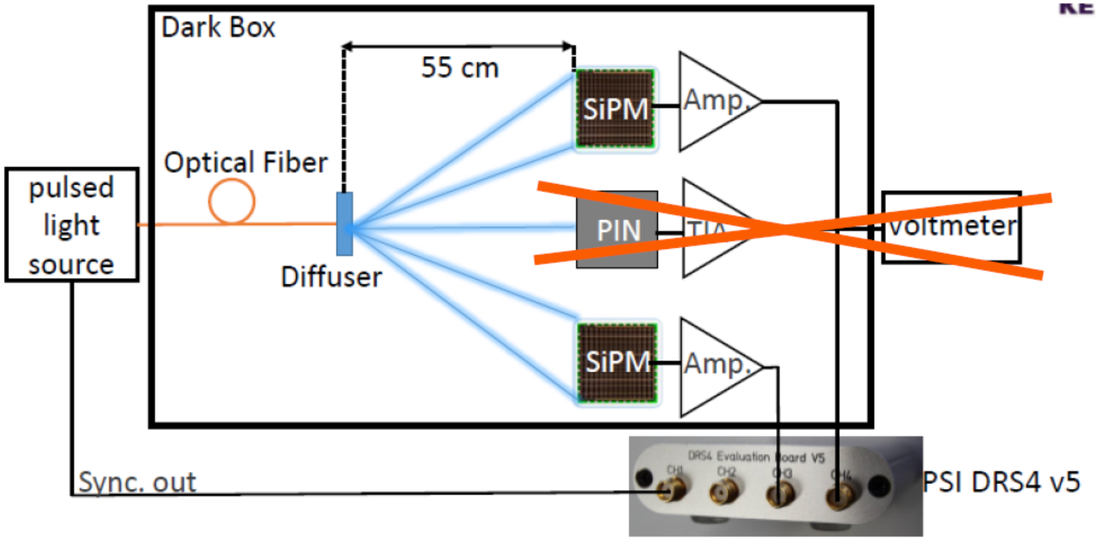
Characterization: PDE

- ICASiPM-2018

Summary of the Photon Detection Efficiency Working Group

Proposed Standard Setup

- Use calibrated SiPM as reference (i.e. no PiN diode) → splitting ratio of ~ 1
- Standard “PDE Box“

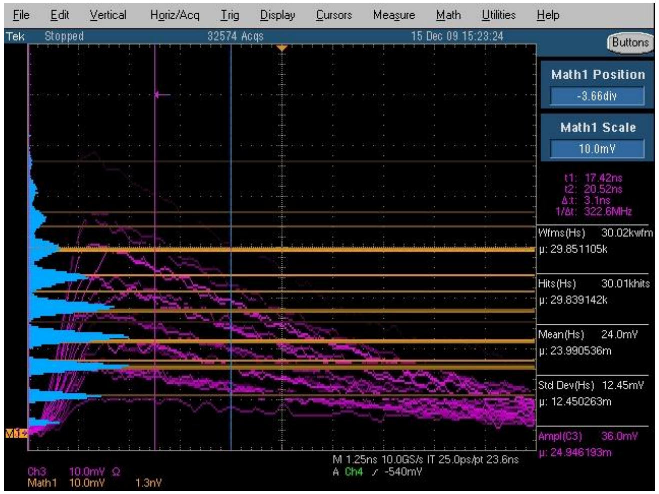


s. E. Engelmann

Nepomuk Otte

Characterization: Gain

- <u>Gain</u>: Mean Gain and Variance of Gain (ENF)
- Mean = $\overline{Gain} = \mu_1 - \mu_0$ = distance between peaks (0-1, 1-2…)



Tek Stopped 32574 Acqs 15 Dec 09 15:23:24

Math1 Position -3.66div

Math1 Scale 10.0mV

t1: 17.42ns
t2: 20.52ns
Δt: 3.1ns
1/Δt: 322.6MHz

Wfms(Hs) 30.02kwfm
μ: 29.851105k

Hits(Hs) 30.01khits
μ: 29.839142k

Mean(Hs) 24.0mV
μ: 23.990536m

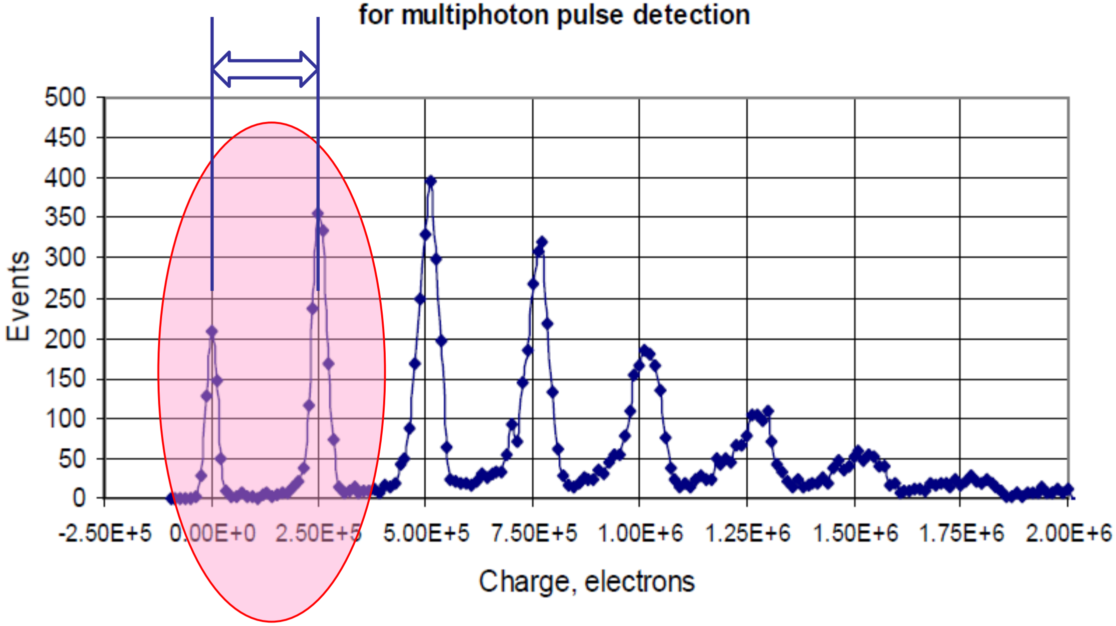
Std Dev(Hs) 12.45mV
μ: 12.450263m

Ampl(C3) 36.0mV
μ: 24.946193m

M 1.25ns 10.0GS/s IT 25.0ps/pt 23.6ns
A Ch4 ⁄ -540mV

Ch3 10.0mV Ω
Math1 10.0mV 1.3nV

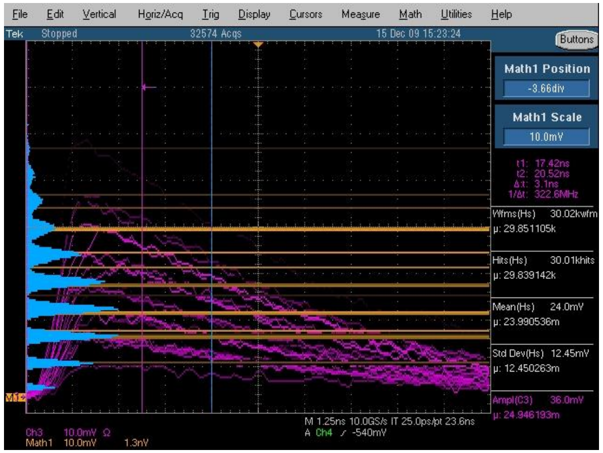
Output Charge Distribution Histogram
for multiphoton pulse detection



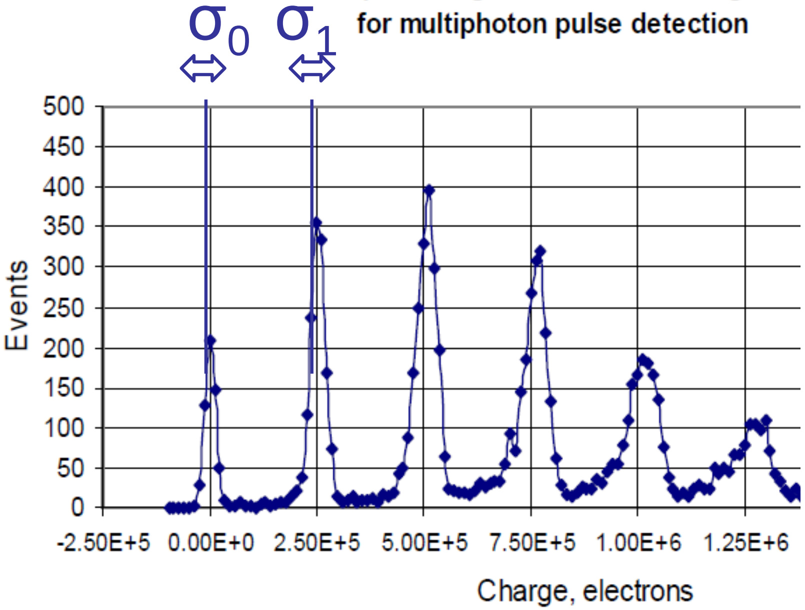
Characterization: ENF of Gain

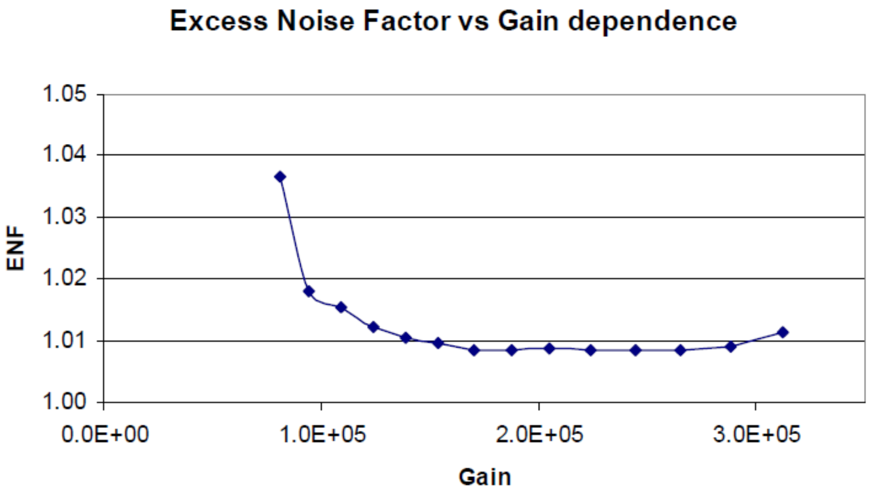
$$ENF_{gain} = 1 + \frac{\sigma_{gain}^2}{\overline{Gain}^2}$$

- Variance = $Var(Gain) = \sigma_{Gain}^2 = \sigma_1^2 - \sigma_0^2$
  - Correct if zero-peak dispersion is exclusively due to electronic noise
  - Baseline fluctuations of zero-peak due to preceding dark events (TBD)



Math1 Position -3.66div
Math1 Scale 10.0mV
t1: 17.42ns
t2: 20.52ns
Δt: 3.1ns
1/Δt: 322.6MHz
Wfms(Hs) 30.02kwfm
μ: 29.851105k
Hits(Hs) 30.01khits
μ: 29.839142k
Mean(Hs) 24.0mV
μ: 23.990536m
Std Dev(Hs) 12.45mV
μ: 12.450263m
Ampl(C3) 36.0mV
μ: 24.946193m
M 1.25ns 10.0GS/s IT 25.0ps/pt 23.6ns
A Ch4 ⁄ -540mV
Ch3 10.0mV Ω
Math1 10.0mV 1.3nV


Output Charge Distribution Histogram for multiphoton pulse detection

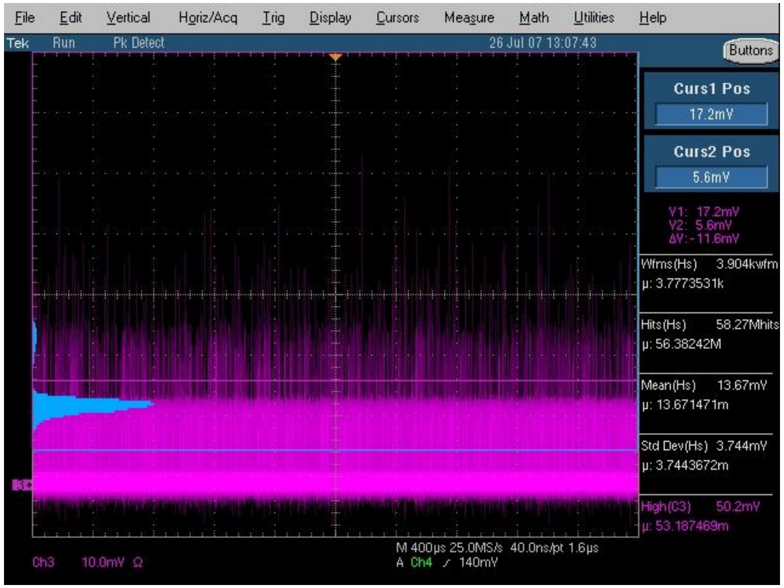

Excess Noise Factor vs Gain dependence

Characterization: crosstalk

- Crosstalk events initiated by a single primary avalanche event

- Counting mode

Triggering mode



Tek Run Pk Detect 26 Jul 07 13:07:43

Curs1 Pos 17.2mV

Curs2 Pos 5.6mV

V1: 17.2mV
V2: 5.6mV
ΔV: -11.6mV

Wfms(Hs) 3.904kwfm
μ: 3.7773531k

Hits(Hs) 58.27Mhits
μ: 56.38242M

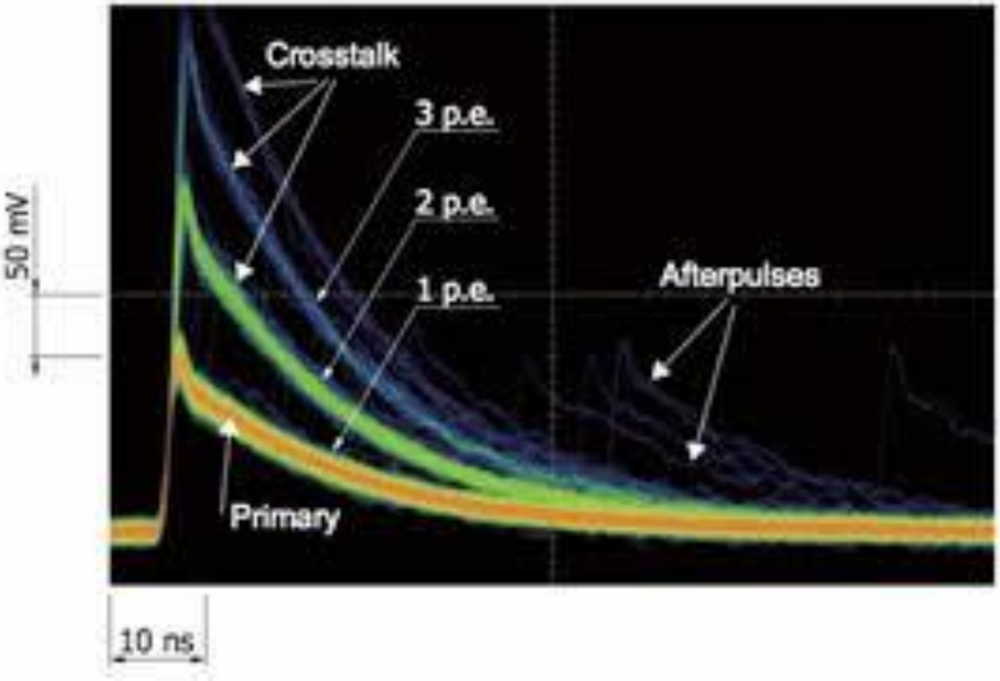
Mean(Hs) 13.67mV
μ: 13.671471m

Std Dev(Hs) 3.744mV
μ: 3.7443672m

High(C3) 50.2mV
μ: 53.187469m

Ch3 10.0mV Ω

M 400μs 25.0MS/s 40.0ns/pt 1.6μs
A Ch4 ⁄ 140mV



Characterization: crosstalk initiated by non-random primary

- Crosstalk initiated by non-random primary =>

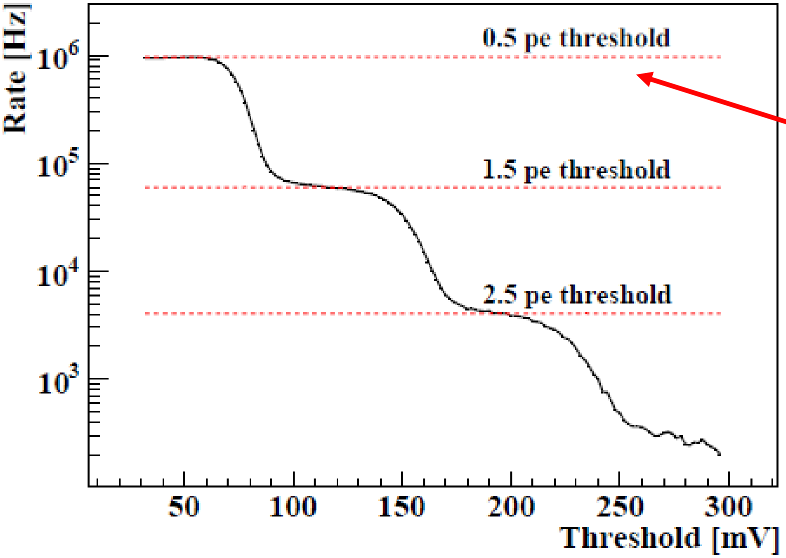
All events are crosstalk except some extra dark counts =>

to be subtracted as Poisson events (if not negligible)

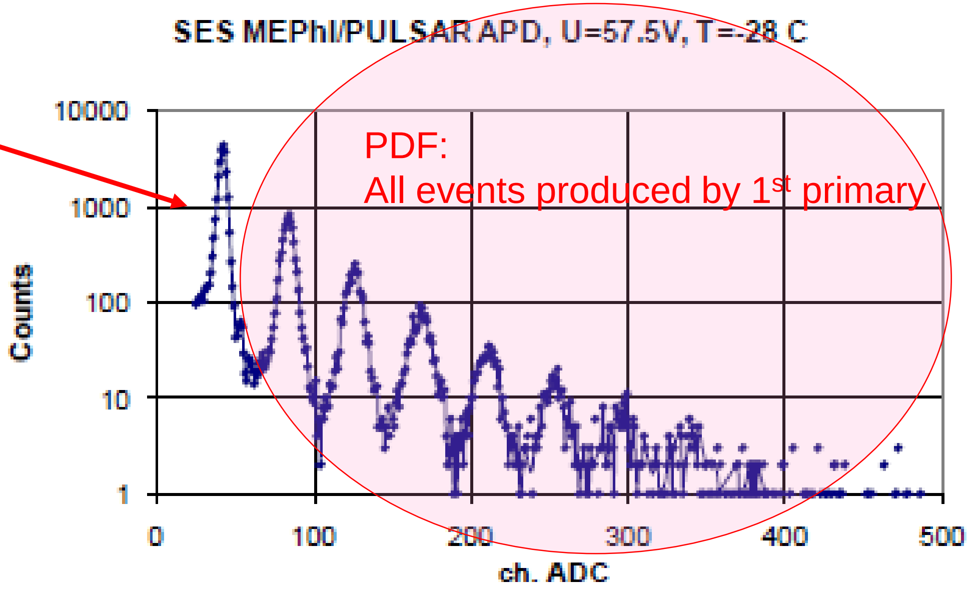
$$Pct = \frac{\sum Ndrk(>1)}{Ndrk(1)} \qquad \textit{Dark amplitude histogram}$$

$$Pct = \frac{DCR(>1.5)}{DCR(>0.5)} \qquad \textit{DCR vs threshold}$$

$$p = 1 - \left[1 - \frac{DCR_{1.5}}{DCR_{0.5}}\right] \cdot \exp(DCR_{0.5} \cdot \tau)$$



P. Eckert et al, nima.2010.03.169].



PDF:
All events produced by 1st primary

Characterization: crosstalk initiated by Poisson primaries

- Crosstalk initiated by Poisson primaries =>

Photo- and CT events in the 1st peak are independent

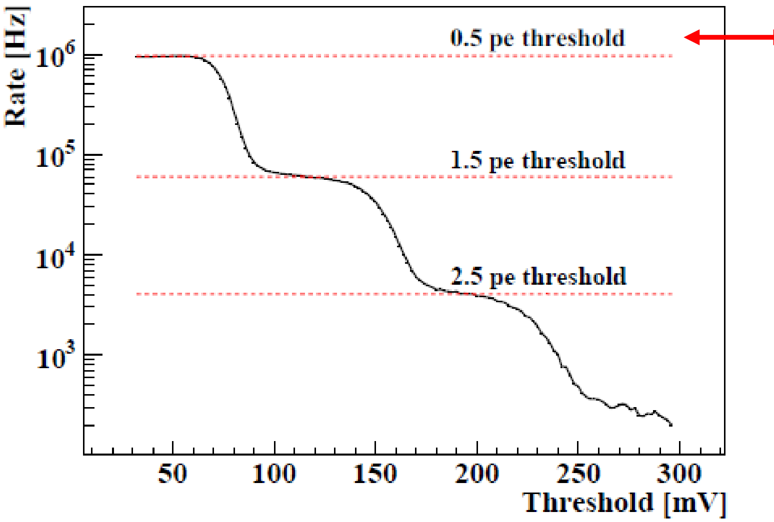
P(1) = Ppois(1)·Pct(0)

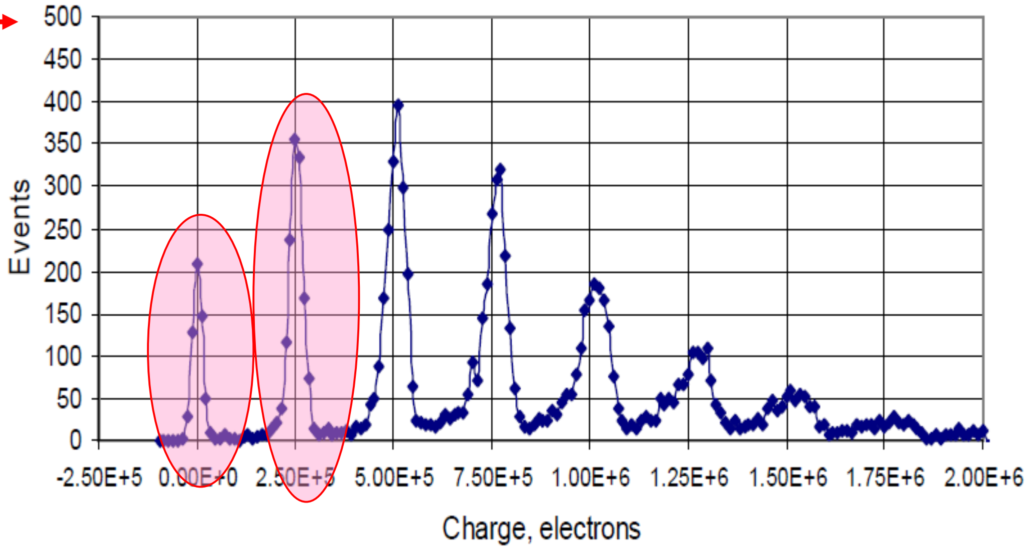
Multiphoton histogram

$$P(1) = Ppoisson(1) \cdot (1 - Pct)$$

$$Pct = 1 - \frac{P(1)}{Ppoisson(1)}$$

Output Charge Distribution Histogram for multiphoton pulse detection

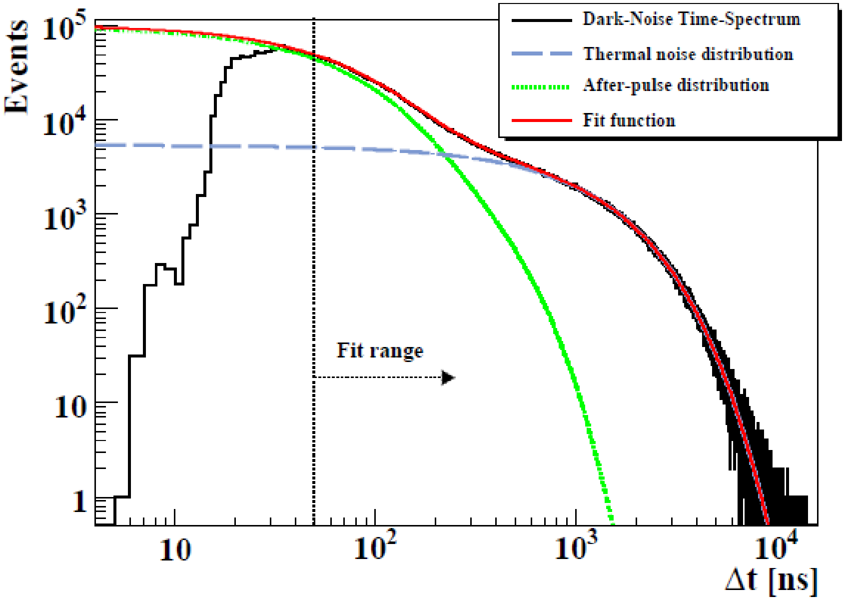




P. Eckert et al, nima.2010.03.169].

Characterization: afterpulsing by histogram of interarrival times

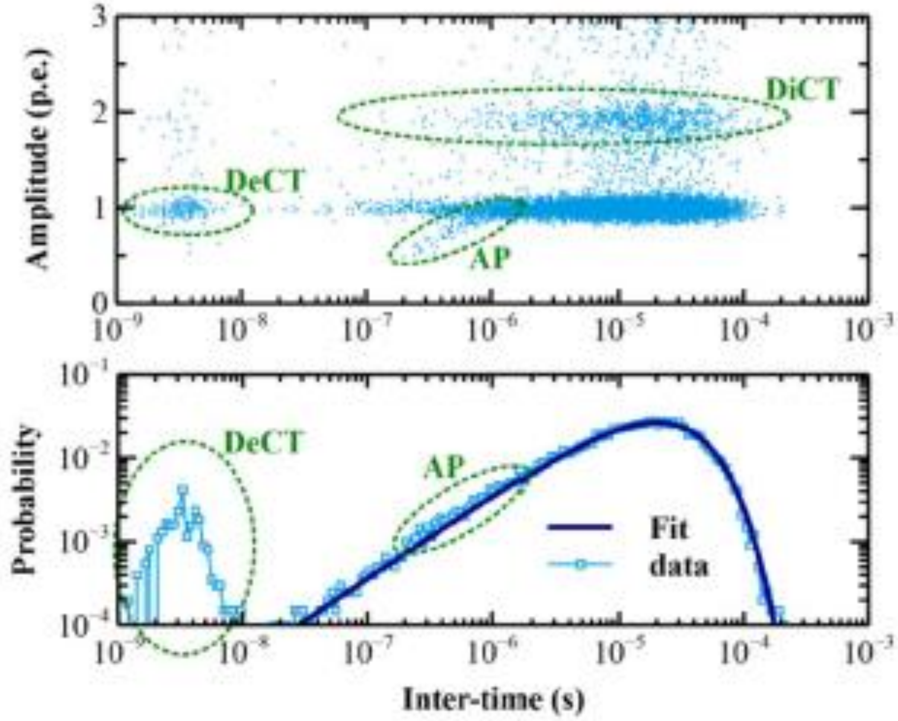
- Common-sense analysis of correlated events
- Contributions are fitted separately in specific time frames
  - Correctness of expressions as a sum of fast + slow AP (?order statistics?)



P. Eckert et al, NIMA 2010

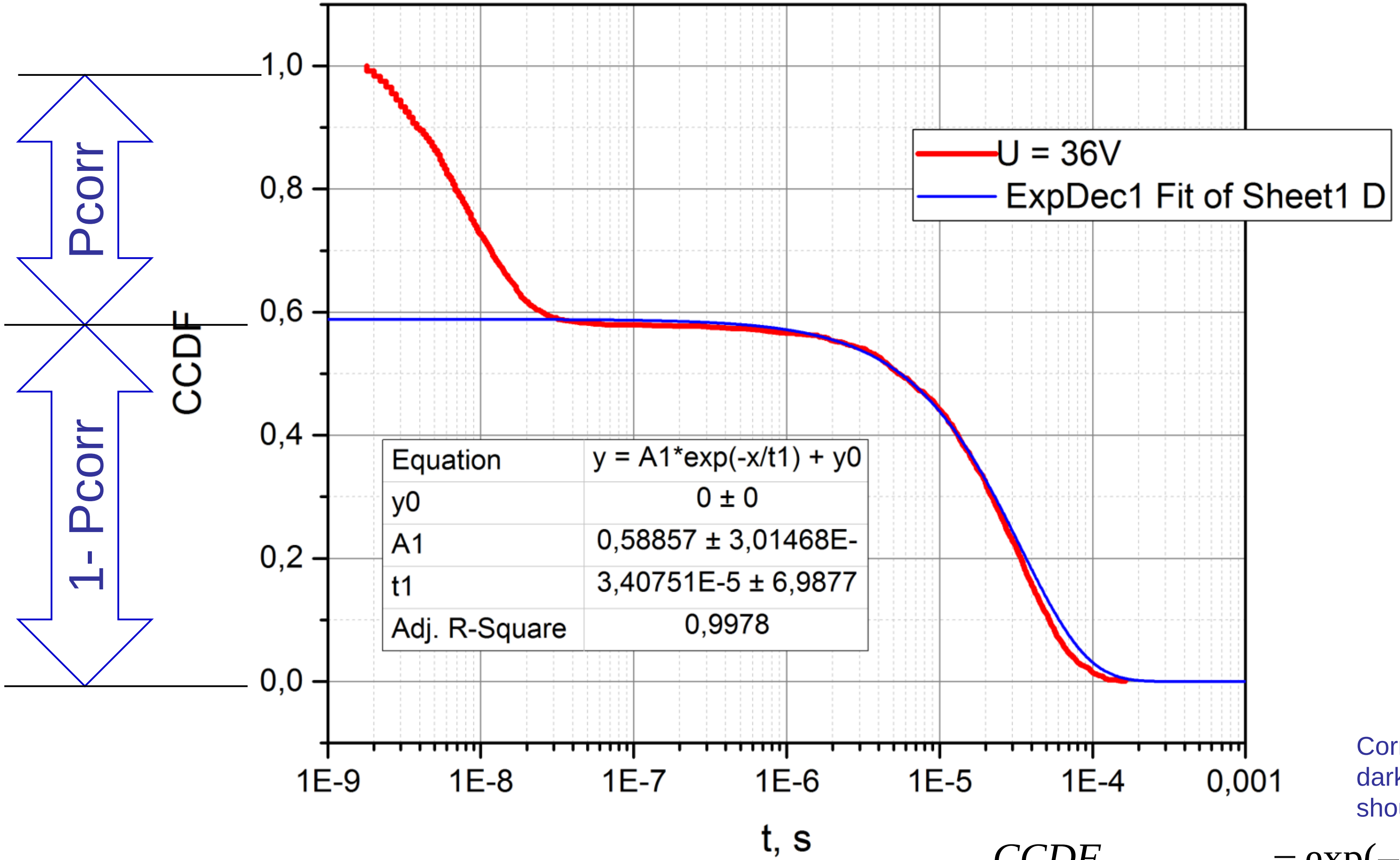
$$n_{tp}(\Delta t) = N_{tp}/\tau_{tp} \cdot e^{-\frac{\Delta t}{\tau_{tp}}}$$

$$n_{ap}(\Delta t) = N_{apf}/\tau_{apf} \cdot e^{-\frac{\Delta t}{\tau_{apf}}} + N_{aps}/\tau_{aps} \cdot e^{\frac{-\Delta t}{\tau_{aps}}}$$



F. Acerbi et al, TNS 2016

Characterization: afterpulsing by cumulative distribution of interarrival times



Equation	y = A1*exp(-x/t1) + y0
y0	0 ± 0
A1	0,58857 ± 3,01468E-
t1	3,40751E-5 ± 6,9877
Adj. R-Square	0,9978

Correction on lost dark counts at Tmax should be applied:

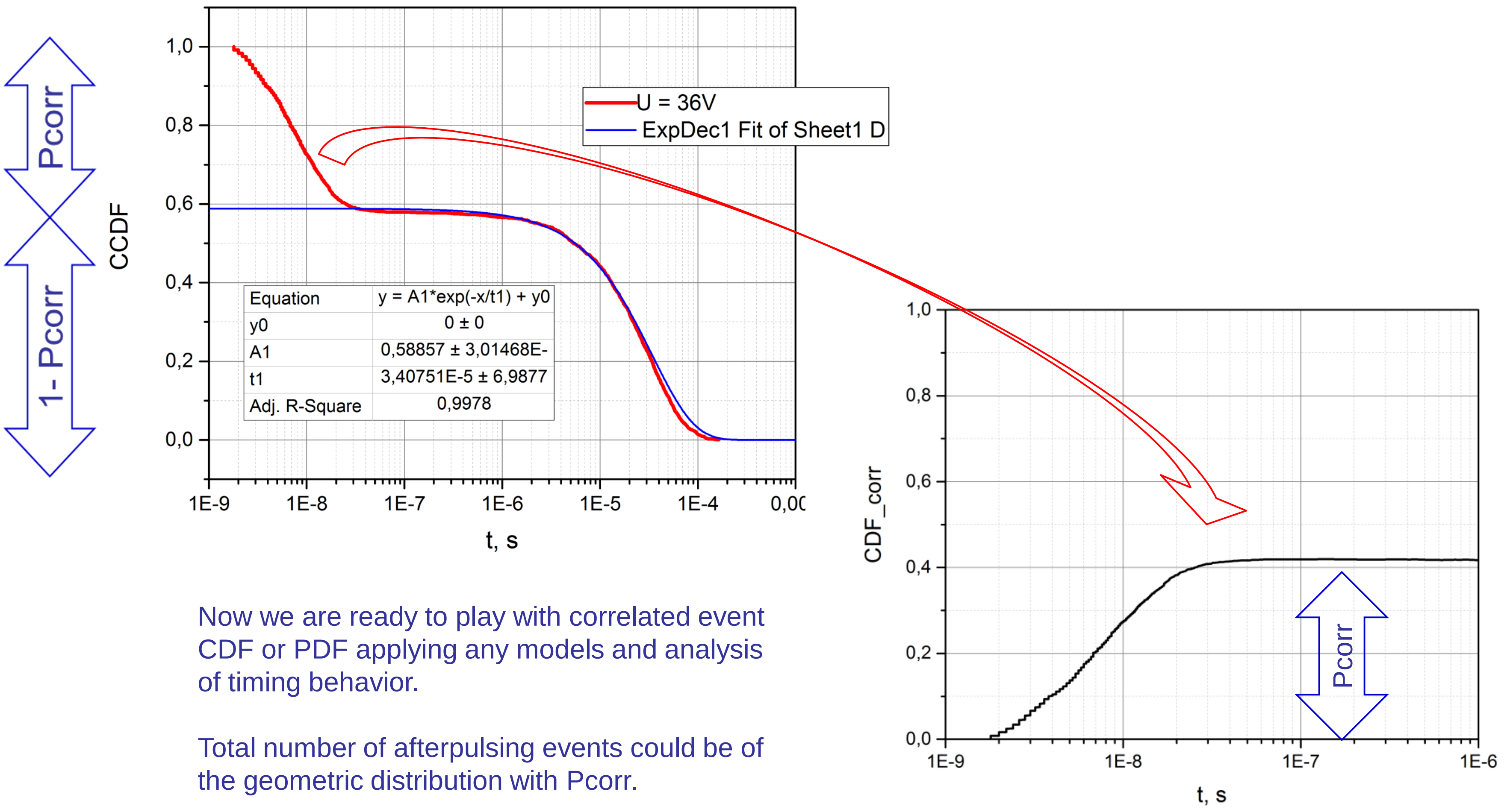
$$CCDF_{dark\_correction} = \exp(-DCR \cdot T_{\max})$$

S. Vinogradov, NSS/MIC 2016

Experimental example – courtesy of E. Popova, D. Philippov… , NSS/MIC 2016

Characterization: afterpulsing by cumulative distribution of interarrival times

$$F_{corr}(t,P_{corr}) = 1-\left(1-F_{total}(t,N_{ph},DCR)\right)\cdot\exp(DCR\cdot t)$$



Equation	y = A1*exp(-x/t1) + y0
y0	0 ± 0
A1	0,58857 ± 3,01468E-
t1	3,40751E-5 ± 6,9877
Adj. R-Square	0,9978

Now we are ready to play with correlated event CDF or PDF applying any models and analysis of timing behavior.

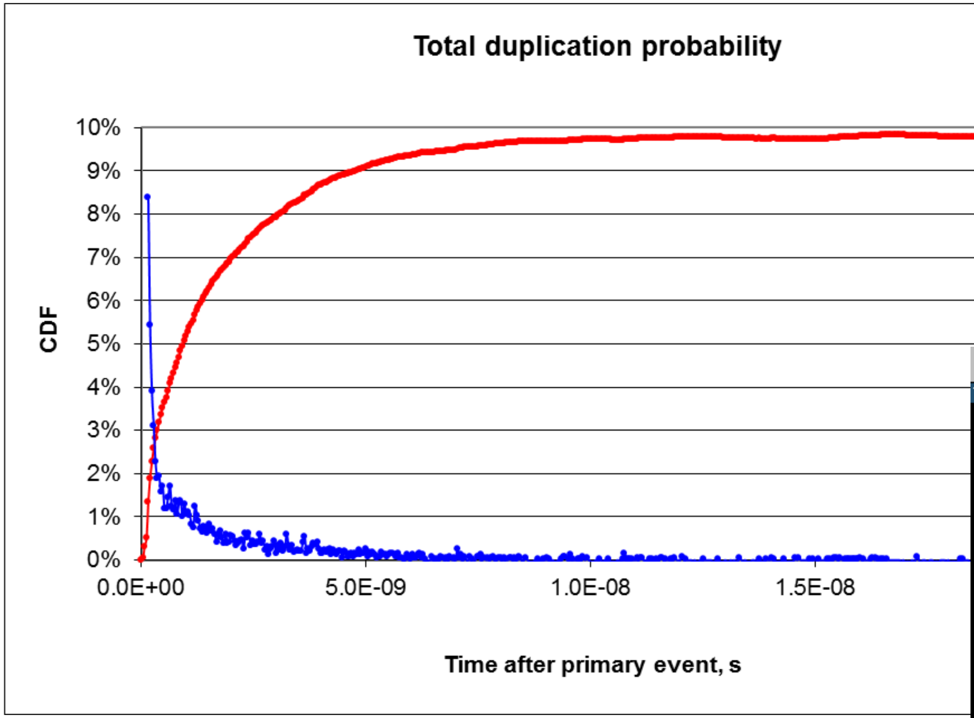
Total number of afterpulsing events could be of the geometric distribution with Pcorr.

S. Vinogradov, NSS/MIC 2016

Experimental example – courtesy of E. Popova, D. Philippov , NSS/MIC 2016

Joint characterization of CT & AP by CCDF time distribution

Seamless measurement of CT+AP at short times: Q(t) instead of I(t) measurement of time interval from primary to secondary event



$$1-Ptotal(\Delta t)=(1-Pdrk(\Delta t))\cdot(1-Pap(\Delta t))$$

$$Pap(\Delta t)=1-\frac{1-Ptotal(\Delta t)}{e^{-DCR\cdot\Delta t}} \qquad CDF$$

$$\rho(\Delta t)=\frac{dPap(\Delta t)}{d\Delta t} \qquad PDF$$

P.N.Lebedev Physical
Institute of the Russian
Academy of Science

UNIVERSITY OF LIVERPOOL

The Cockcroft Institute
of Accelerator Science and Technology

SEVENTH FRAMEWORK PROGRAMME

SiPM

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

FAST
Fast Advanced Scintillator Timing

SENSE Ultimate Low-Light Level Sensor Development

The end

Thank you for your attention!

Questions?
Objections?
Opinions?
…

vin@lebedev.ru