SiPM Characterization

Alexander Tadday
Patrick Eckert
Kirchhoff-Institute for Physics
Heidelberg University

KIRCHHOFF-
INSTITUTE
FOR PHYSICS

CALICE
Calorimeter for ILC

Outline

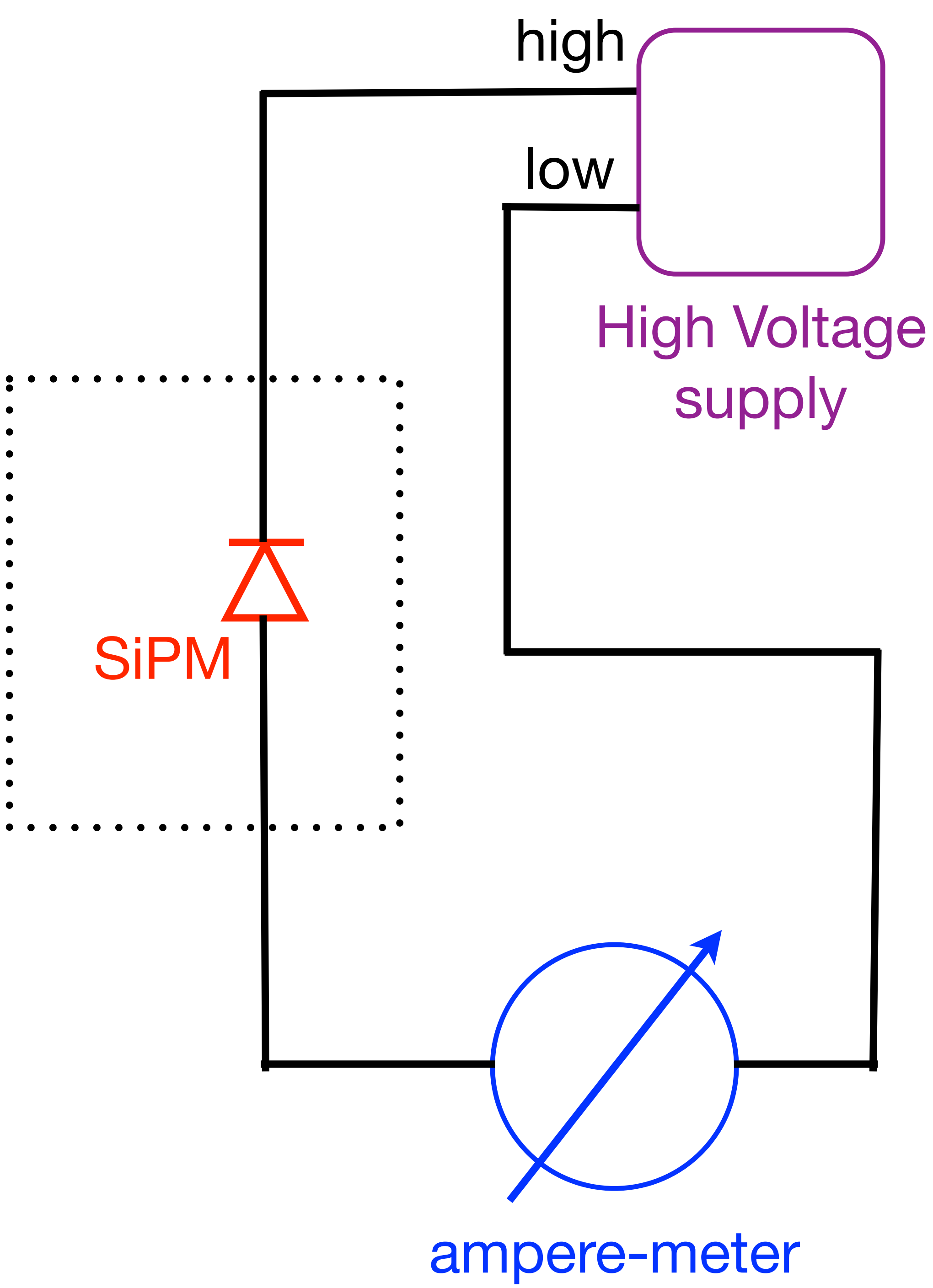
- Characterisation, why?
- Measurements without light (noise)
  - Current-voltage characteristics
  - Dark-rate
  - Cross-talk & after-pulse probabilities
- Measurements with light
  - Gain-voltage dependence
  - Photon detection efficiency
  - Surface uniformity tests

Characterisation, why?

- There are many different types of SiPM on the market
- Precise information is needed in order to choose the best device for a certain application
- Most manufacturers provide a data-sheet, however
  - Sometimes relevant information is missing
  - Manufacturer uses different definition of a property *(PDE with cross-talk & after-pulse)*
  - Large device to device variations
- Quality assurance for large scale experiments
- Learn something about SiPMs

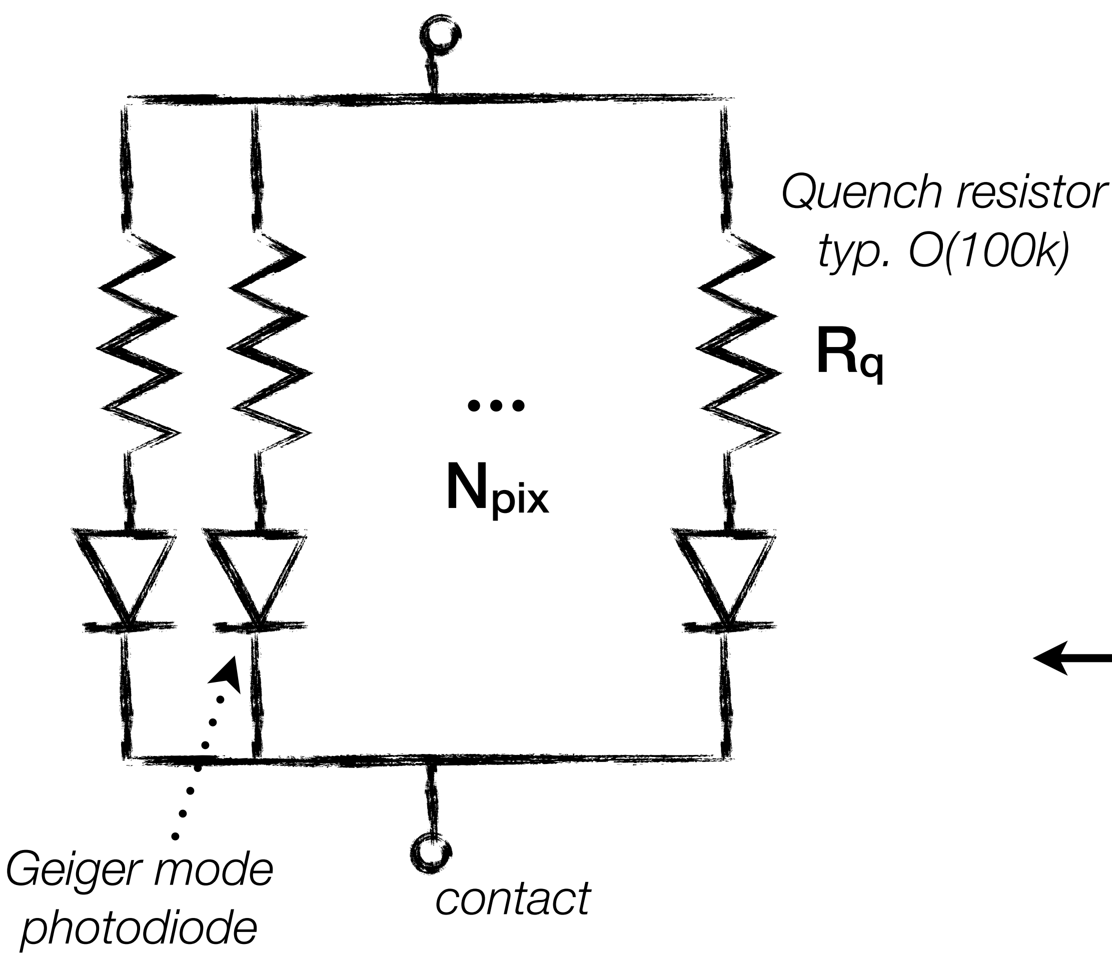
IV measurement setup

- SiPM in light-proof box
- Usually voltage source and current meter is combined in a single device
- Measure SiPM current as a function of bias voltage (forward and reverse)
- Determine the polarity of the SiPM
- Always start with low voltages ~1V and monitor the current



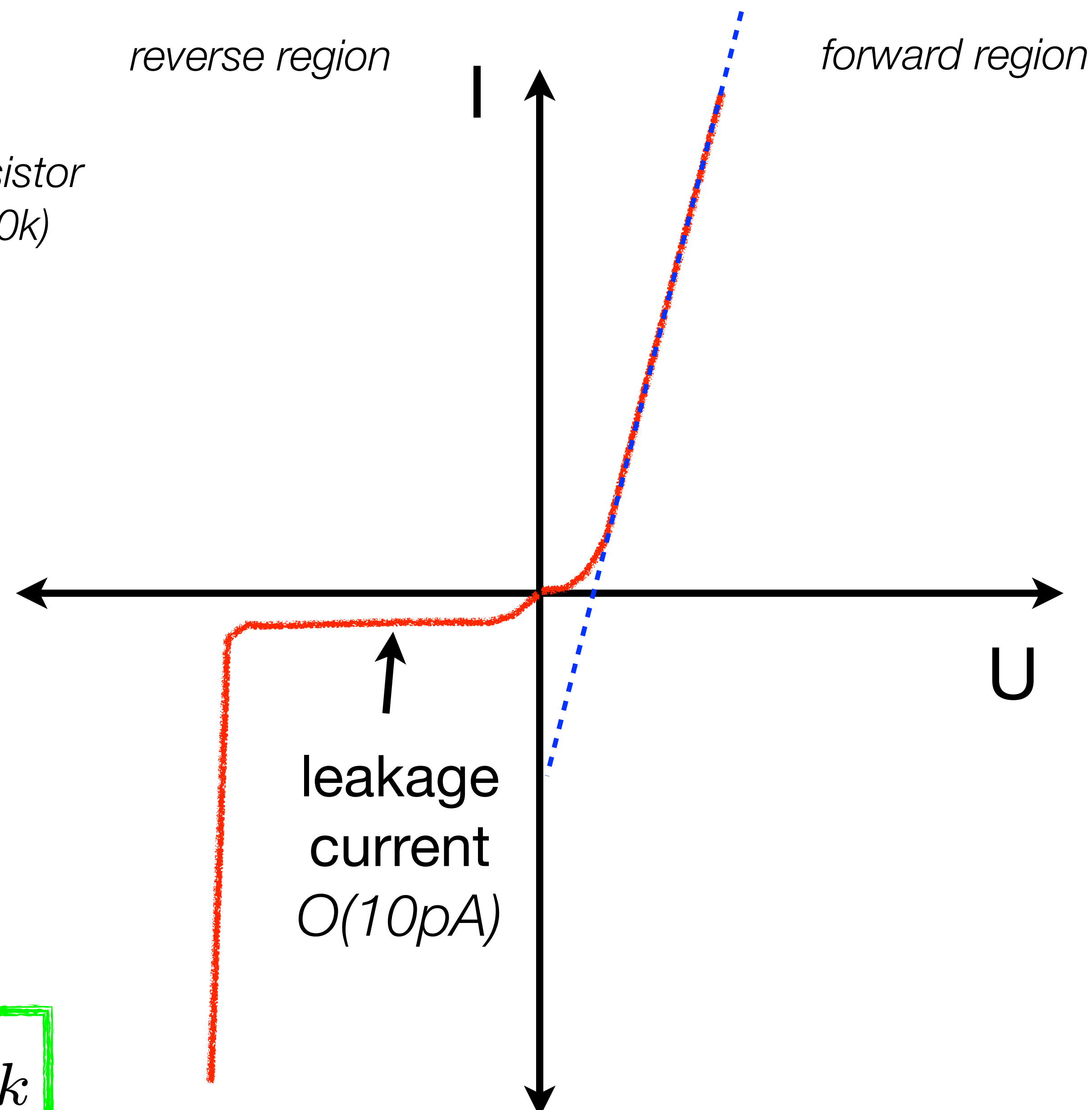
IV diagram

SiPM equivalent diagram



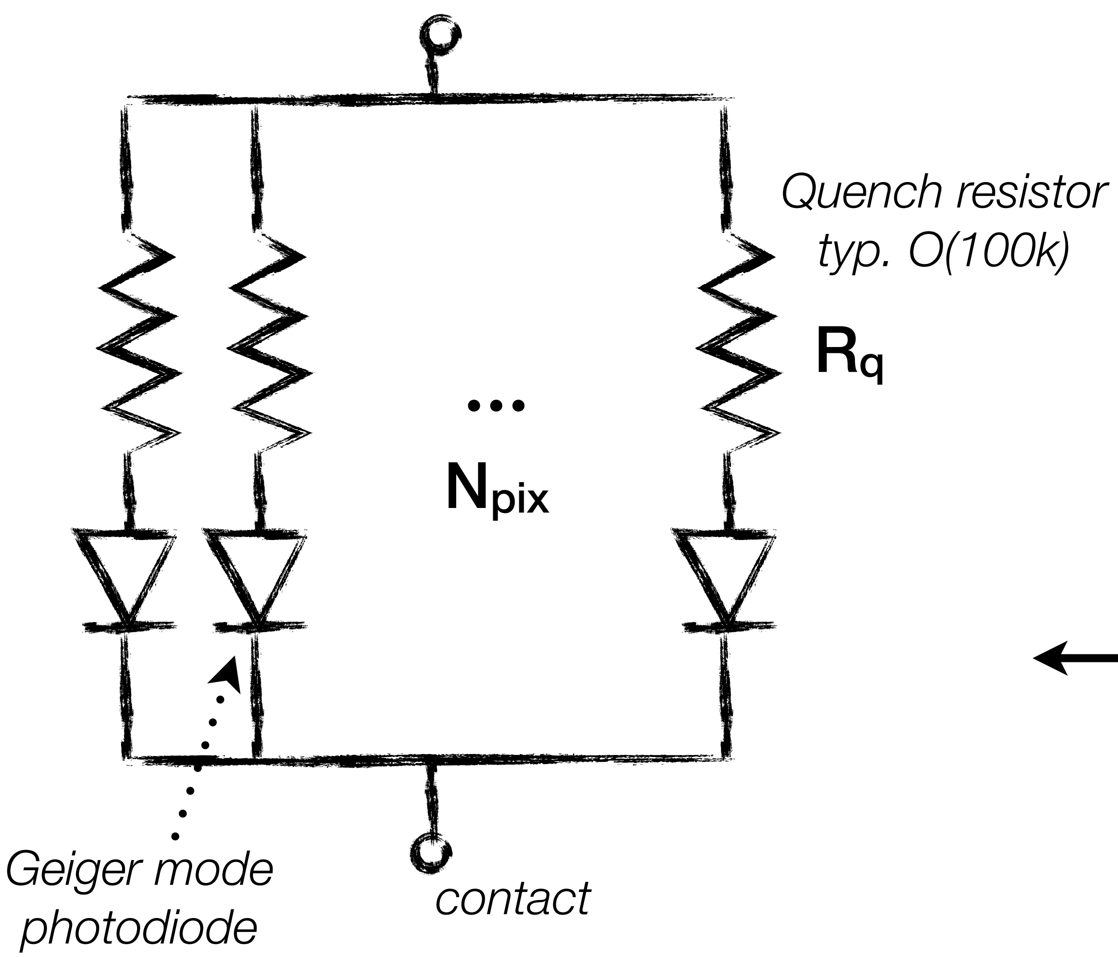
$$U_{over} = U_{bias} - U_{break}$$

qualitative IV diagram (currents are not in scale)



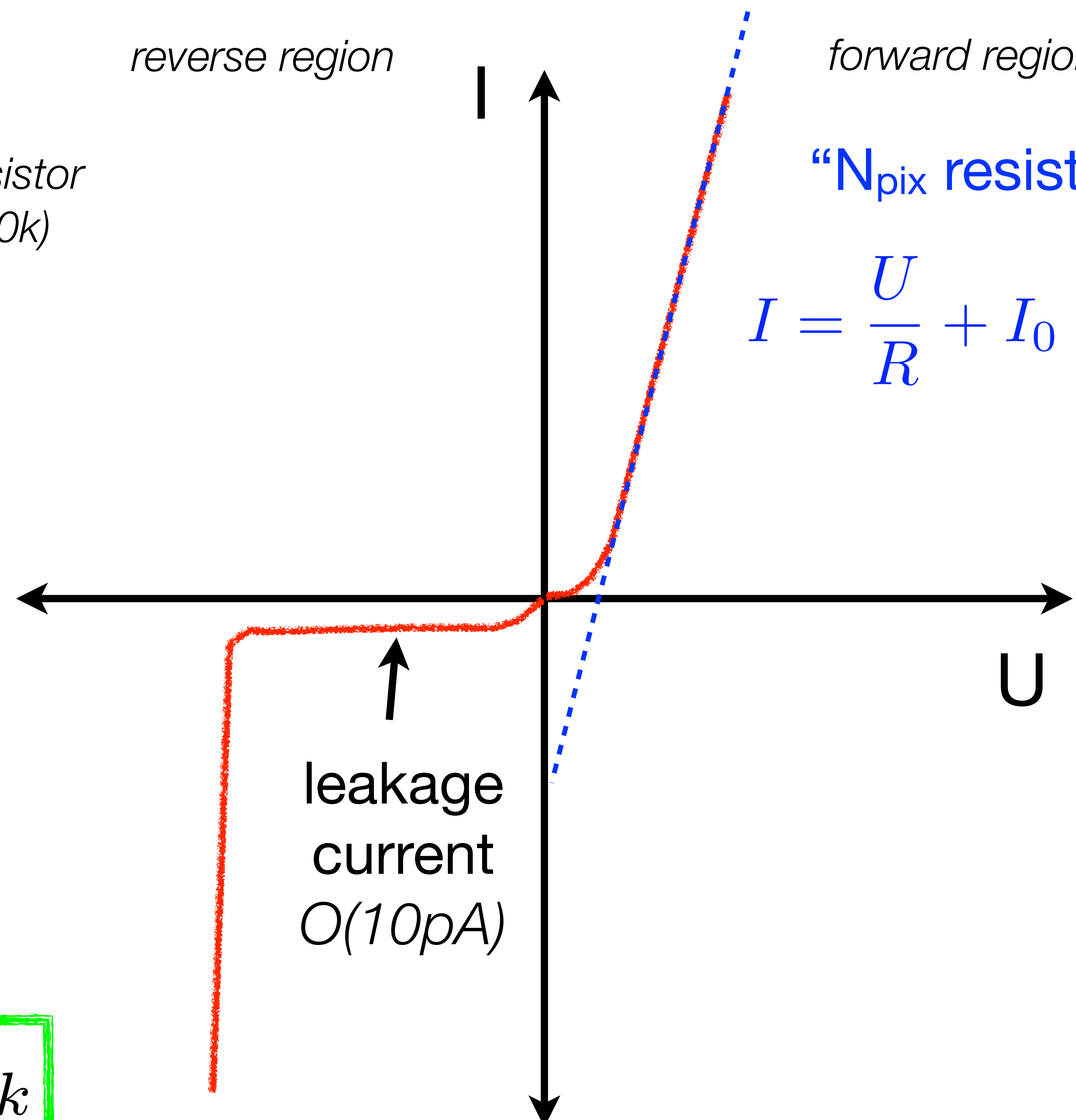
IV diagram

SiPM equivalent diagram



$$\boxed{U_{over} = U_{bias} - U_{break}}$$

<u>qualitative IV diagram (currents are not in scale)</u>

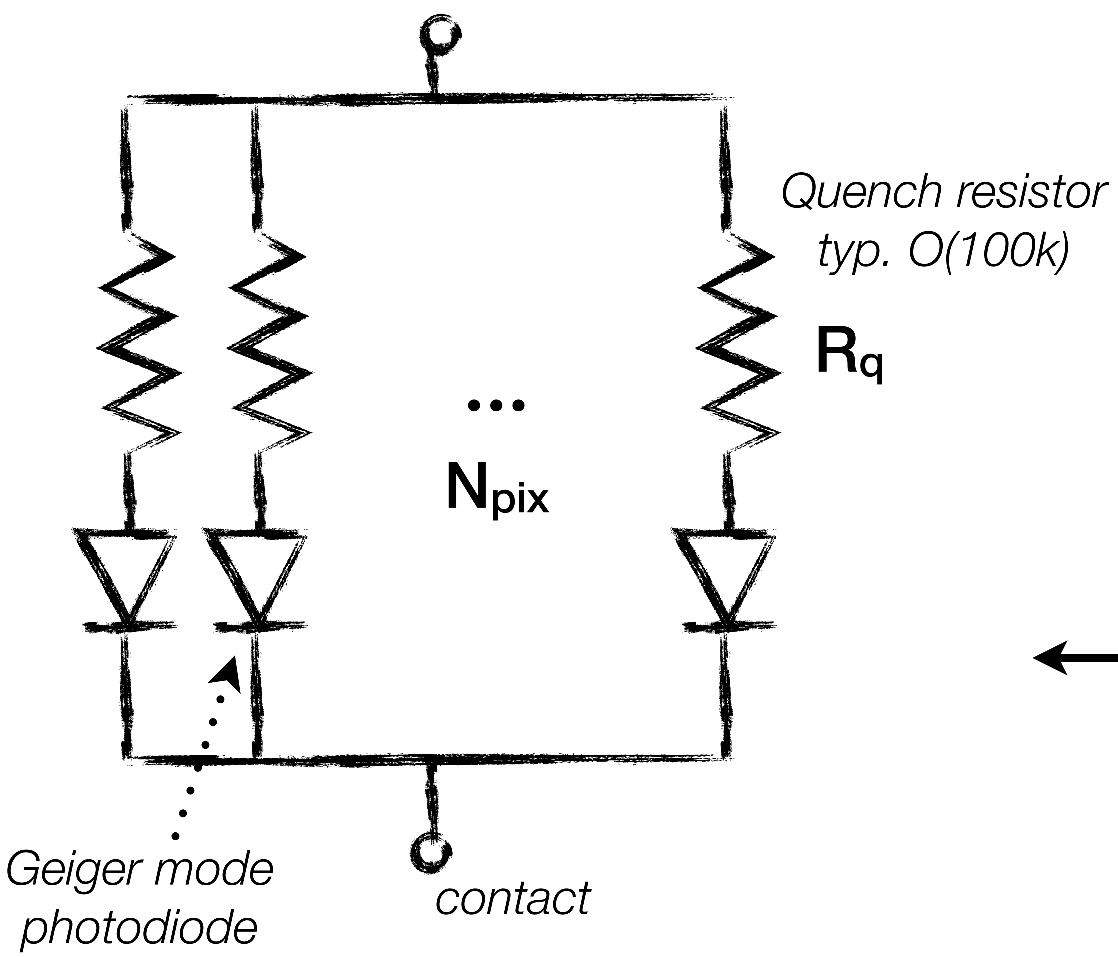


"N_{pix} resistors in parallel"

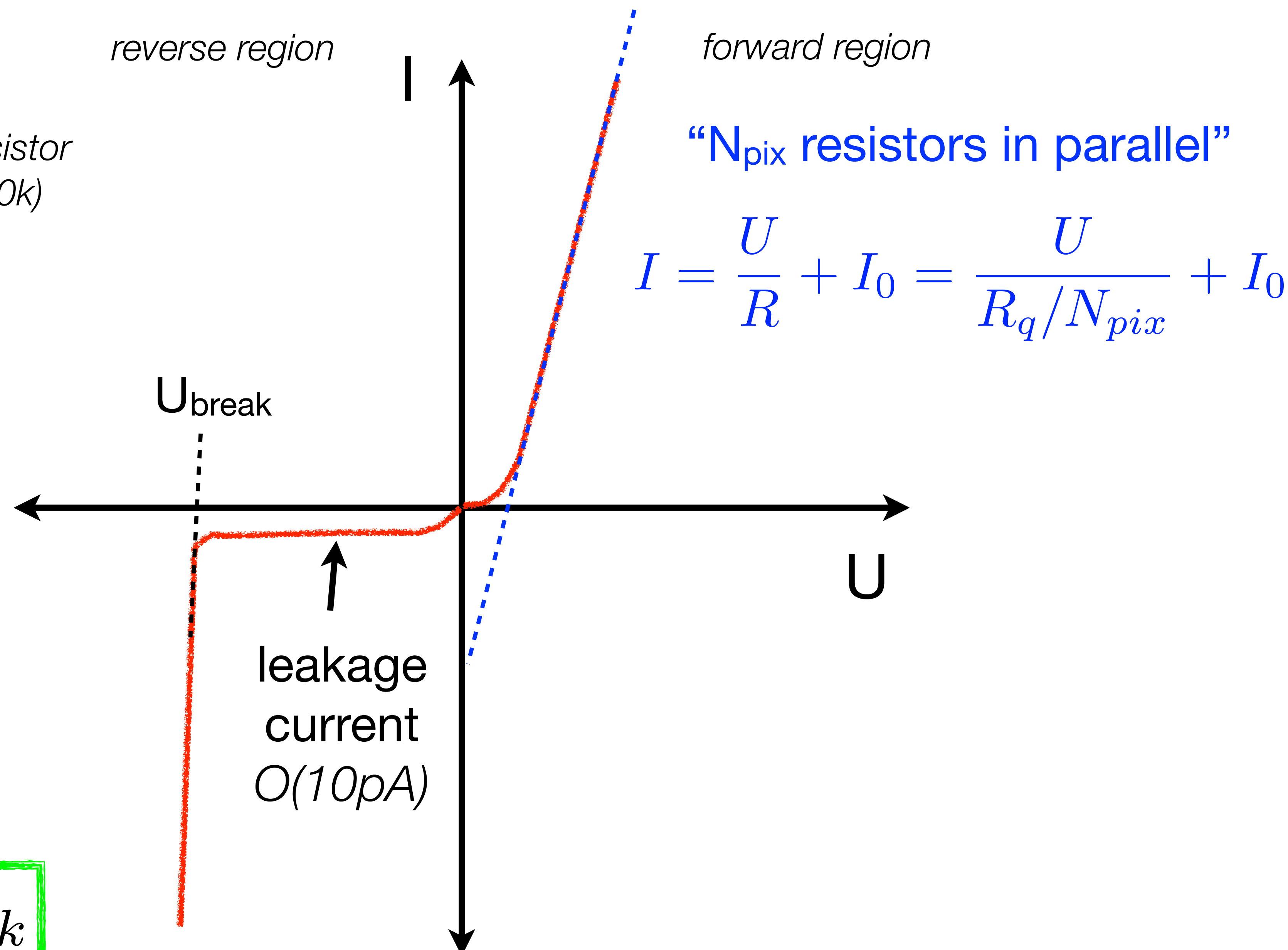
$$I = \frac{U}{R} + I_0 = \frac{U}{R_q/N_{pix}} + I_0$$

IV diagram

SiPM equivalent diagram



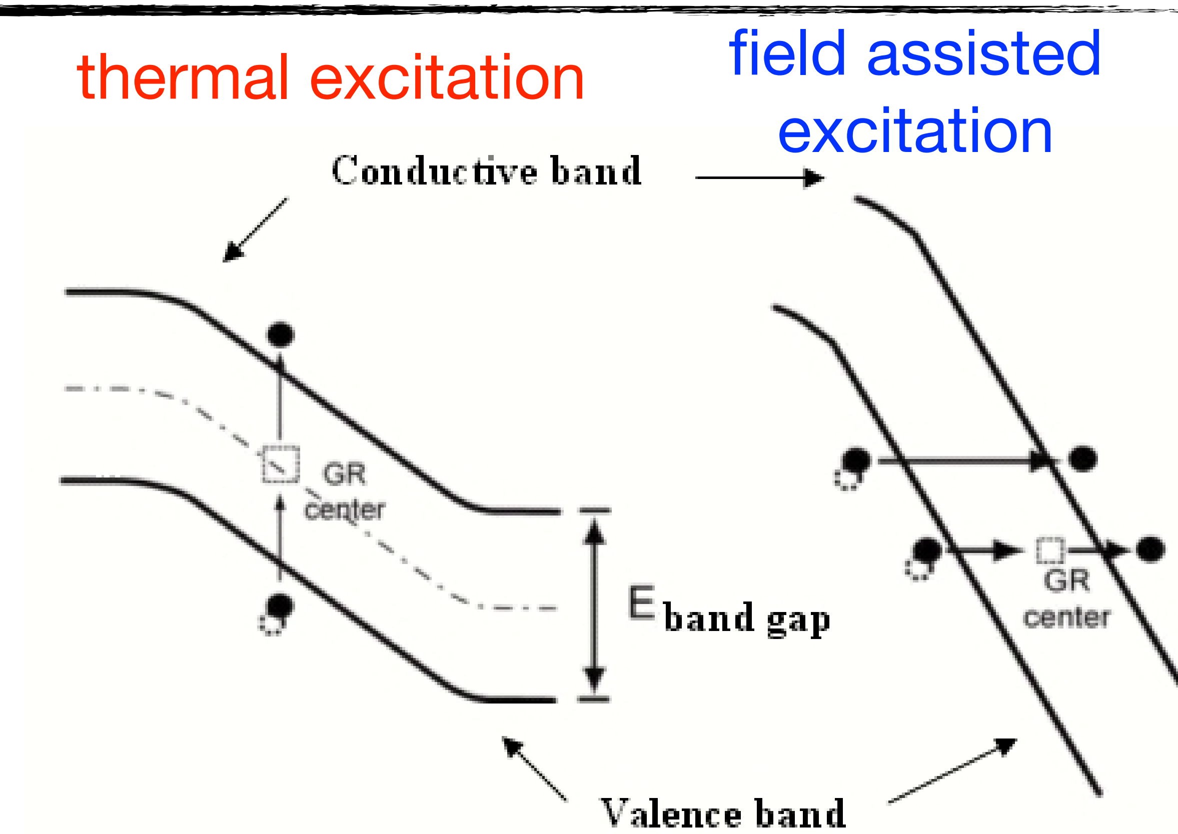
qualitative IV diagram (currents are not in scale)

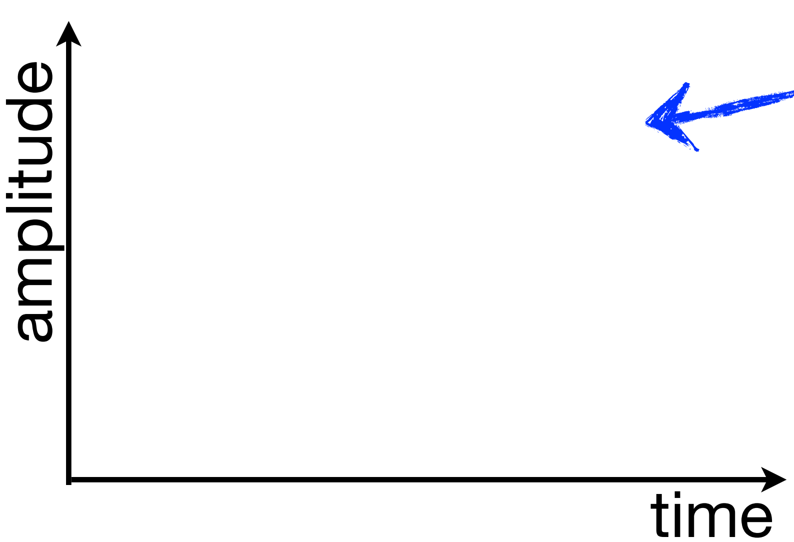


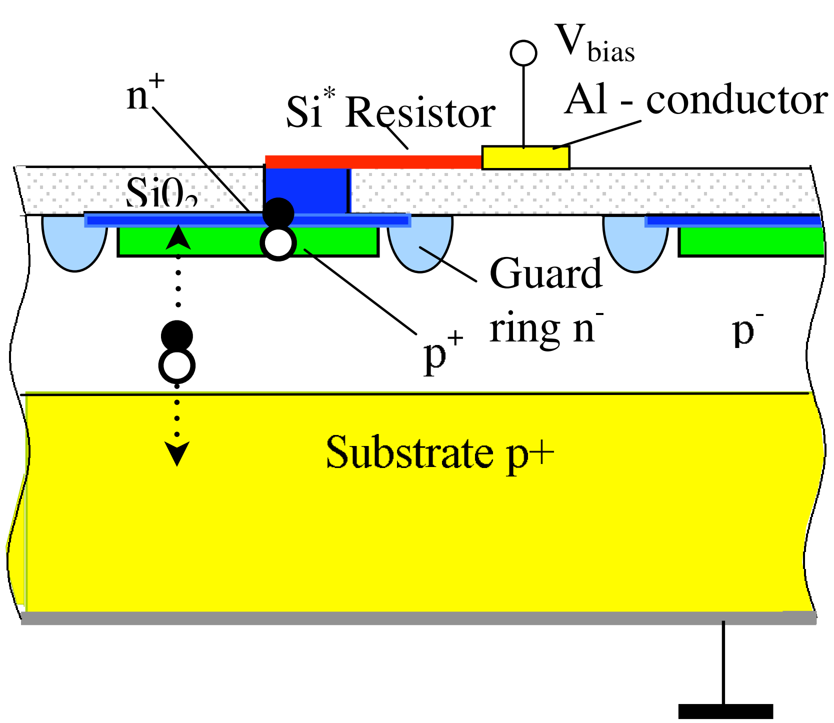
$$\boxed{U_{over} = U_{bias} - U_{break}}$$

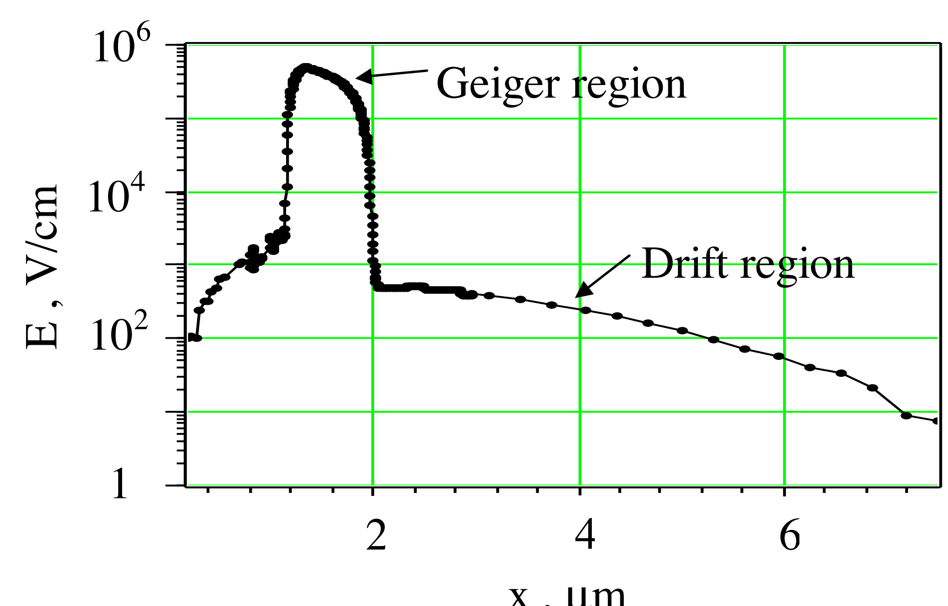
Dark-rate

- Electron hole pairs generated without the involvement of photons give rise to unwanted noise
- Two processes
  - Thermal excitation
  - Field assisted excitation (tunneling)
- Electron (hole) drifts into the high field region and causes avalanche breakdown
- Resulting signal is indistinguishable from a photon induced signal





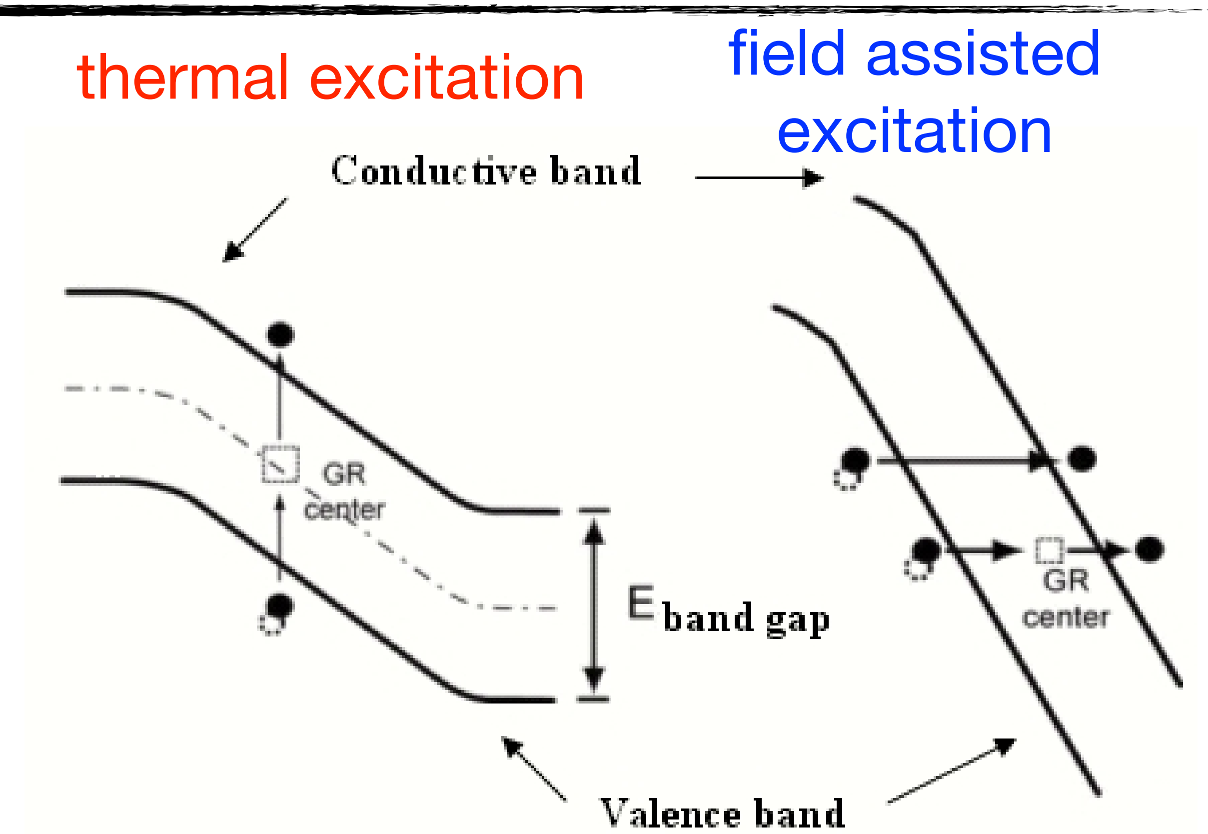


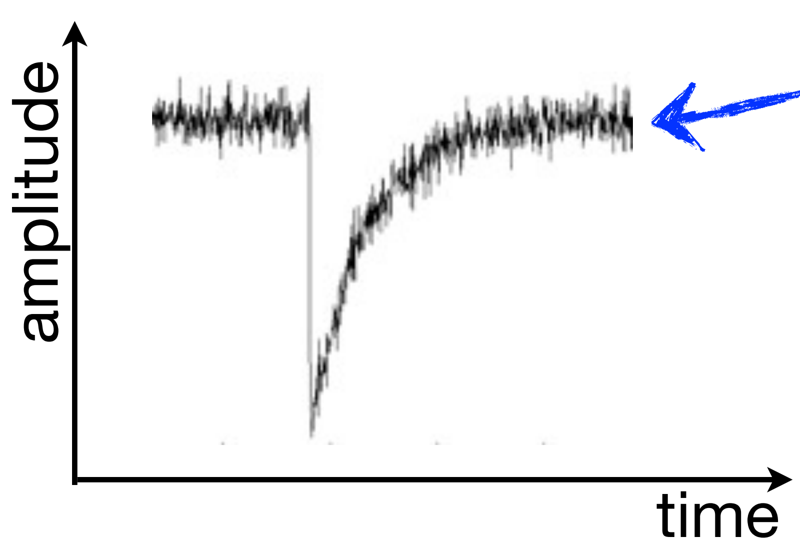


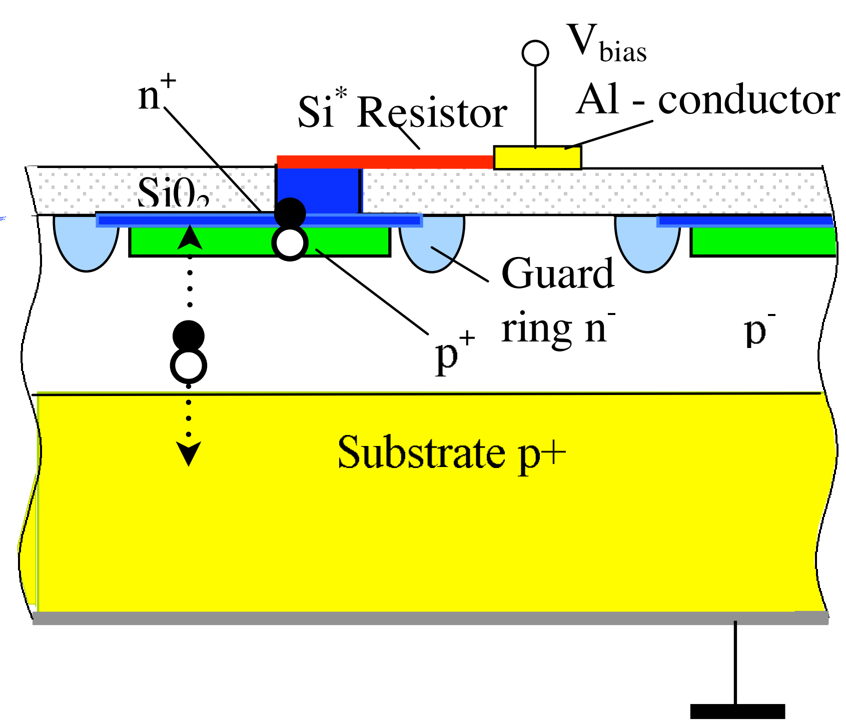
P. Buzhan et al. An advanced study of silicon photomultiplier. ICFA Instrum. Bull., 23:28–41, 2001

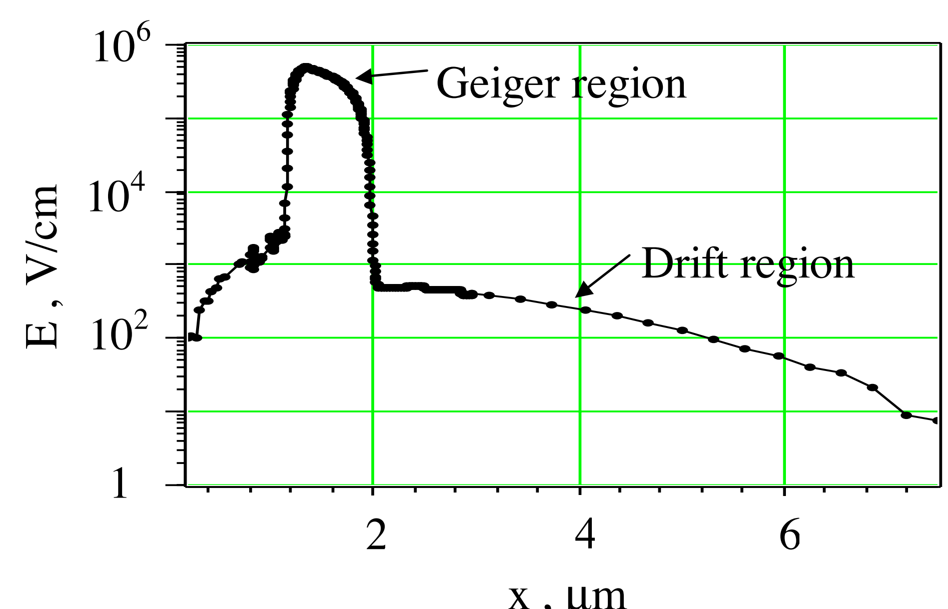
Dark-rate

- Electron hole pairs generated without the involvement of photons give rise to unwanted noise
- Two processes
  - Thermal excitation
  - Field assisted excitation (tunneling)
- Electron (hole) drifts into the high field region and causes avalanche breakdown
- Resulting signal is indistinguishable from a photon induced signal







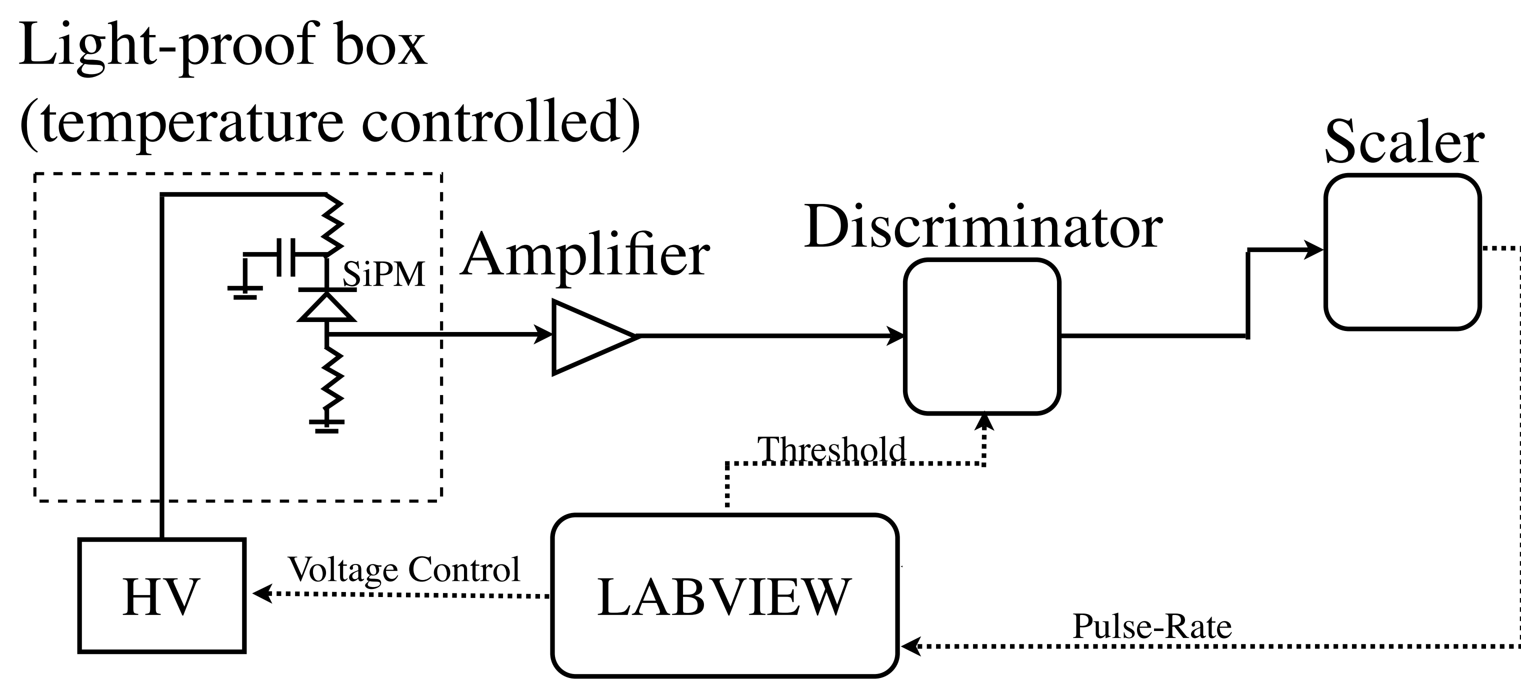


P. Buzhan et al. An advanced study of silicon photomultiplier. ICFA Instrum. Bull., 23:28–41, 2001

Laboratory setup

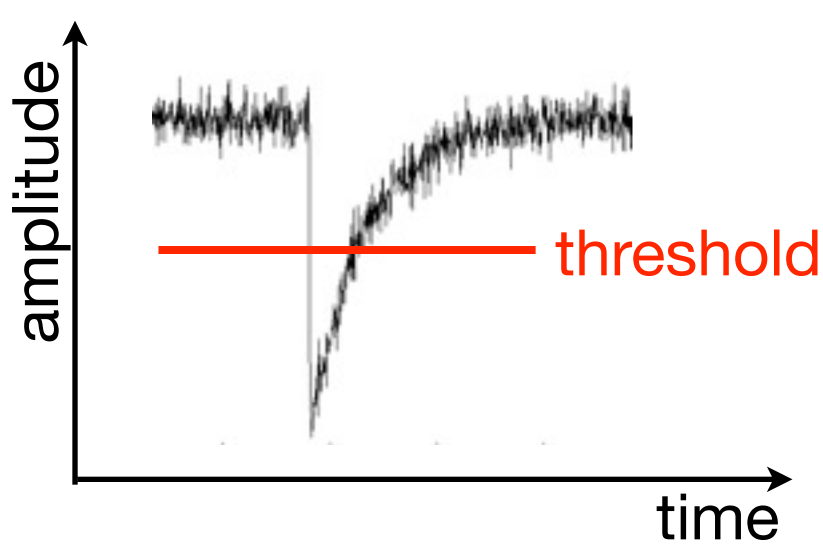
- Discriminator generates logic pulse if input signal passes threshold
- Logic pulses are counted during fixed time interval -> calculate rate
- Dark-noise depends on:
  - Temperature
  - Reverse bias voltage (tunnel probability)
  - Discrimination threshold
- Automated with LABVIEW program

<u>typical dark-rate & cross-talk setup</u>

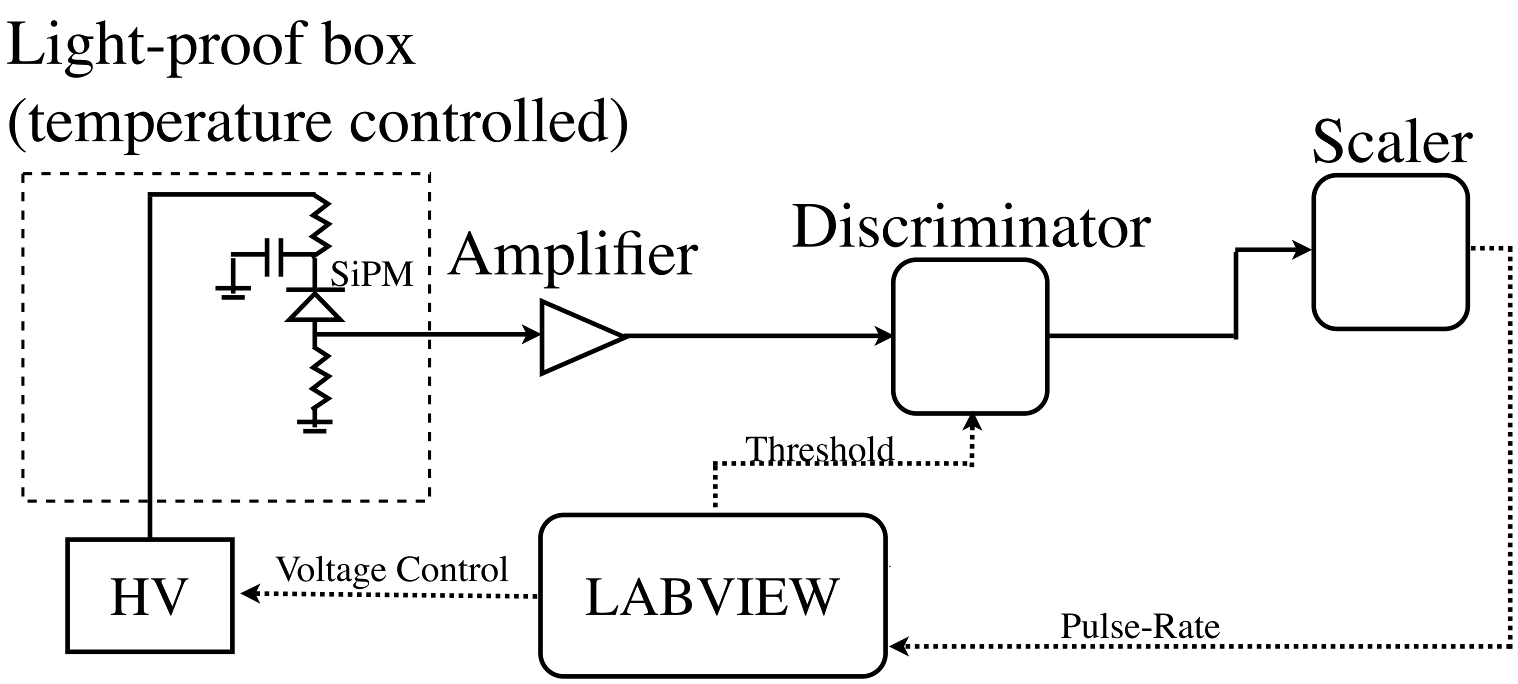


Laboratory setup

- Discriminator generates logic pulse if input signal passes threshold
- Logic pulses are counted during fixed time interval -> calculate rate
- Dark-noise depends on:
  - Temperature
  - Reverse bias voltage (tunnel probability)
  - Discrimination threshold
- Automated with LABVIEW program



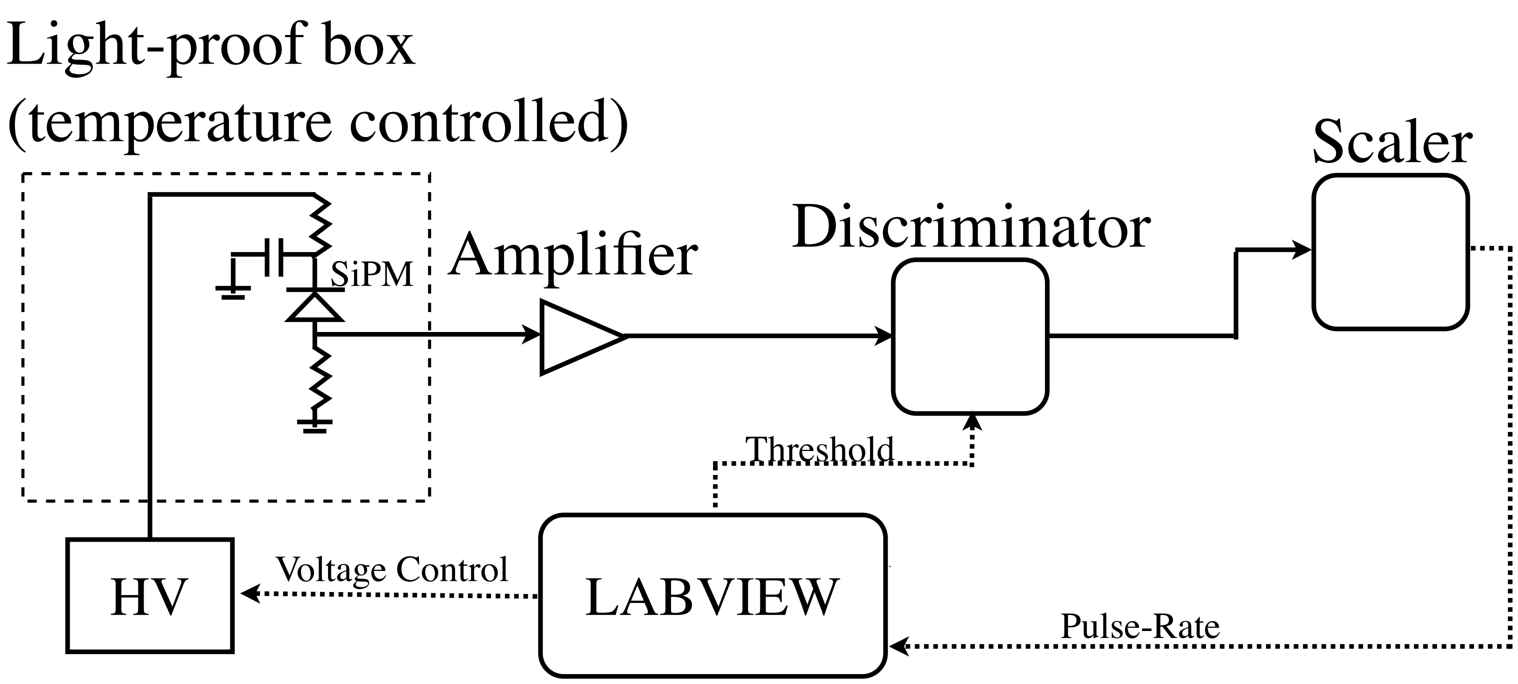
typical dark-rate & cross-talk setup

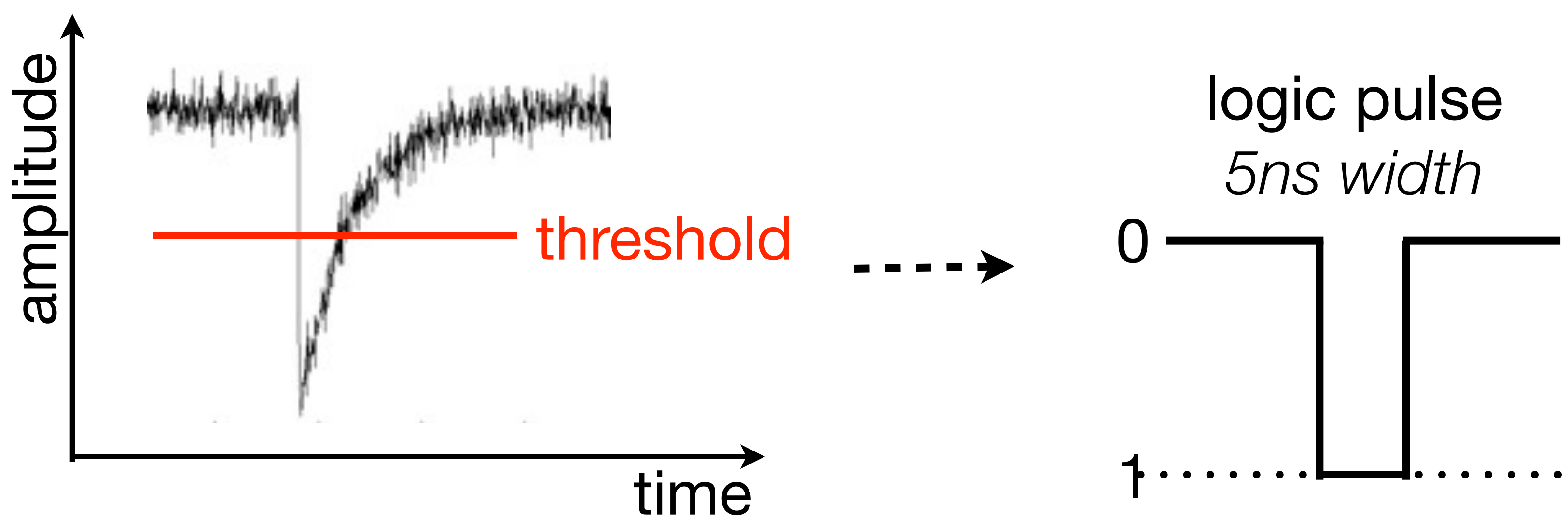


Laboratory setup

- Discriminator generates logic pulse if input signal passes threshold
- Logic pulses are counted during fixed time interval -> calculate rate
- Dark-noise depends on:
    - Temperature
    - Reverse bias voltage (tunnel probability)
    - Discrimination threshold
- Automated with LABVIEW program

<u>typical dark-rate & cross-talk setup</u>

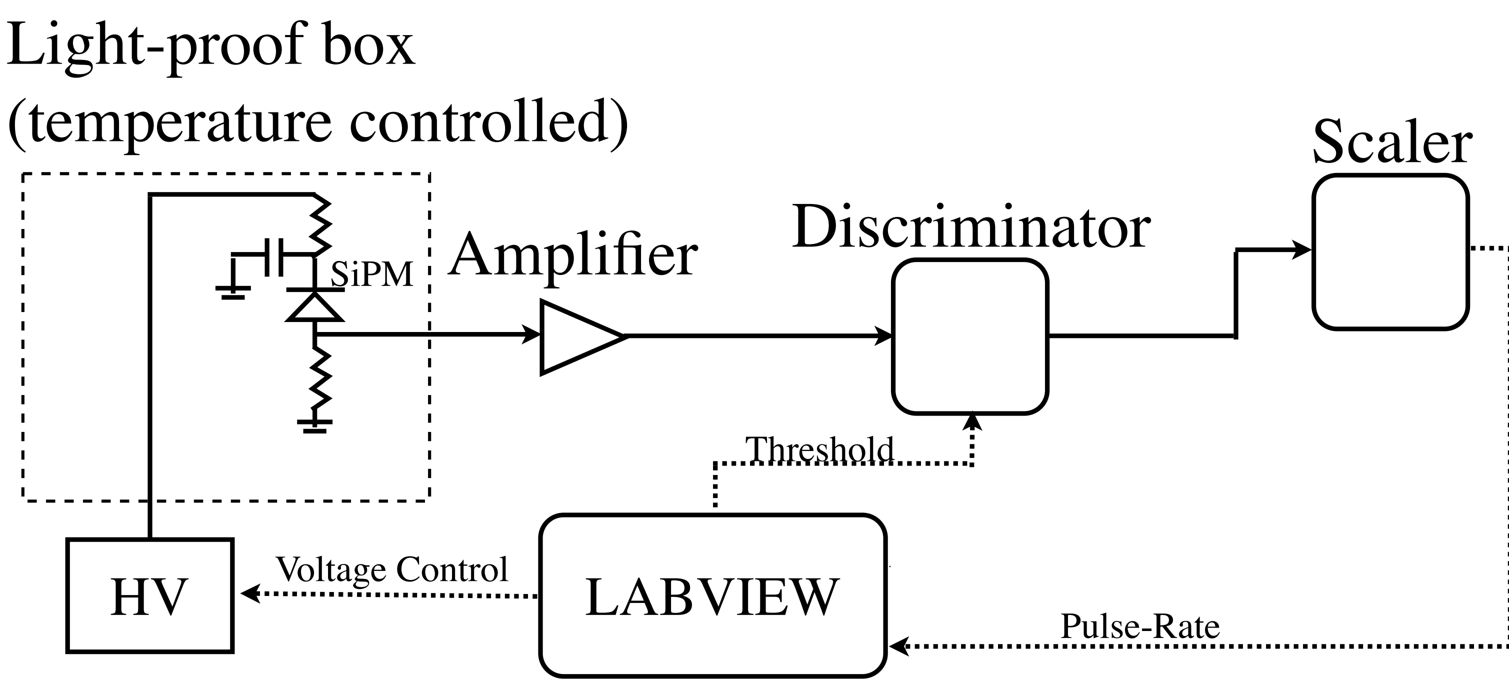


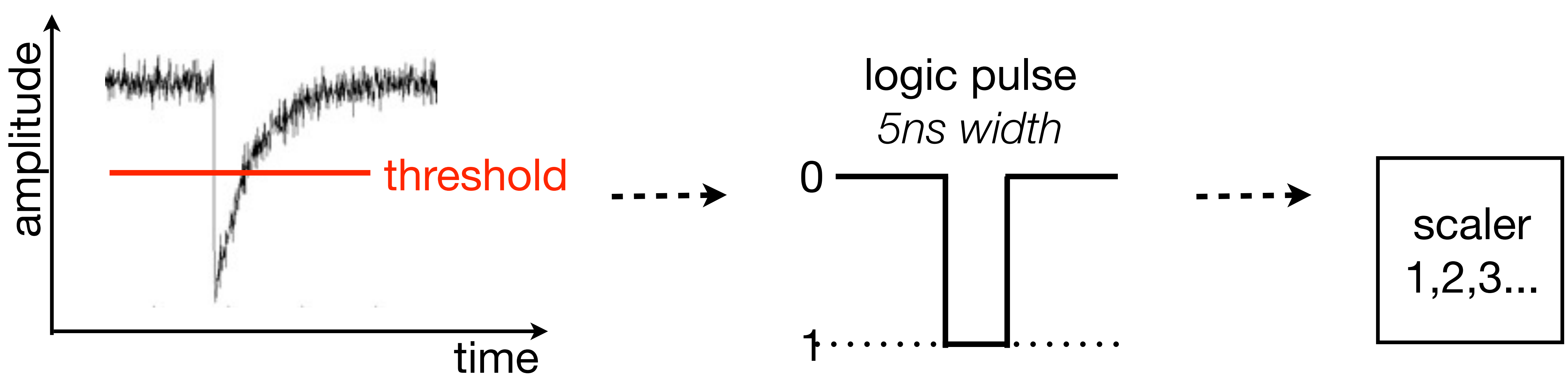


Laboratory setup

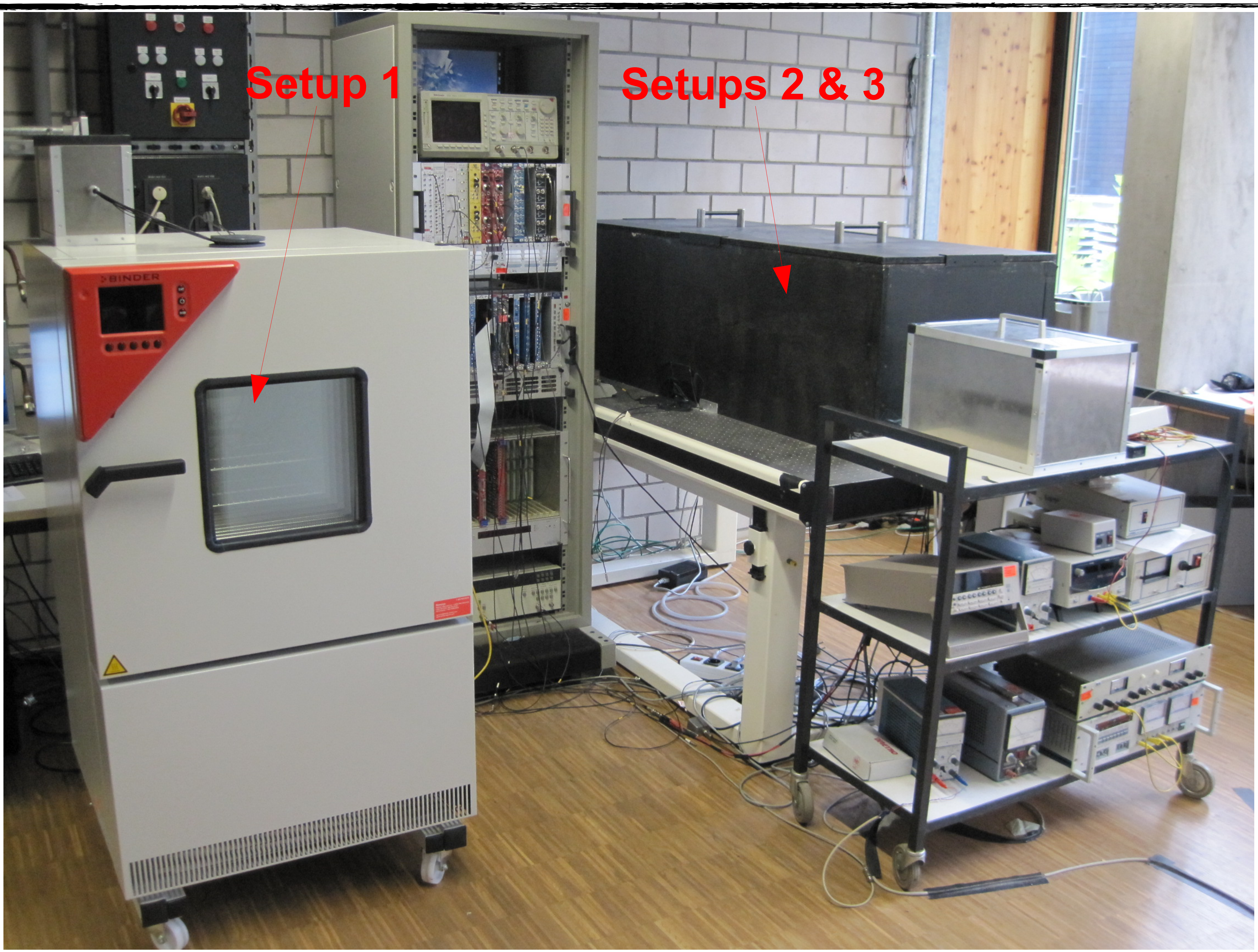
- Discriminator generates logic pulse if input signal passes threshold
- Logic pulses are counted during fixed time interval -> calculate rate
- Dark-noise depends on:
  - Temperature
  - Reverse bias voltage (tunnel probability)
  - Discrimination threshold
- Automated with LABVIEW program

<u>typical dark-rate & cross-talk setup</u>





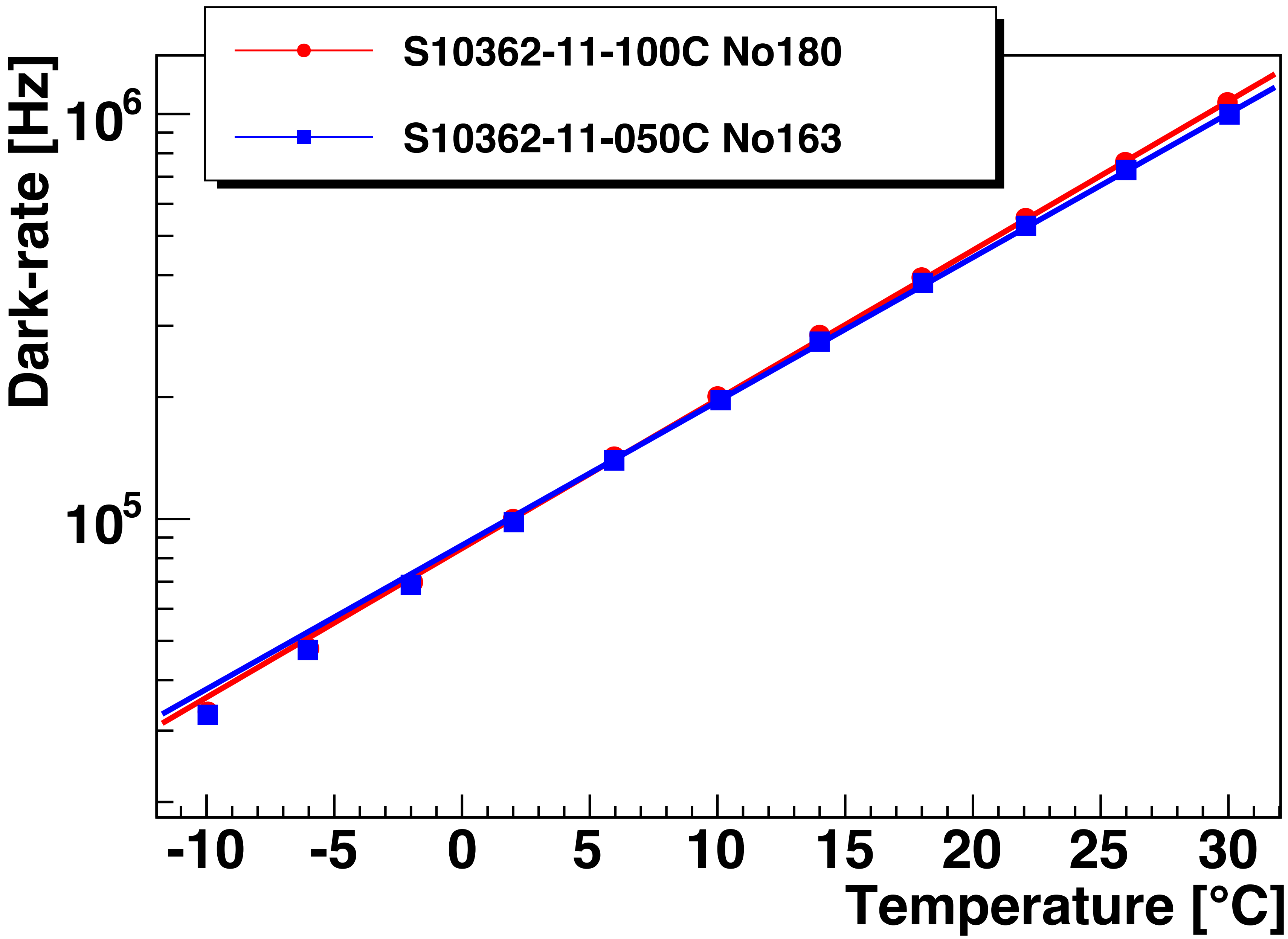
Experimental setup



Temperature dependence

Dark-rate vs. temperature

100 pixel (-100C) and 400 pixel (-050C) MPPC at U_{over} = 1V, 0.5pe threshold



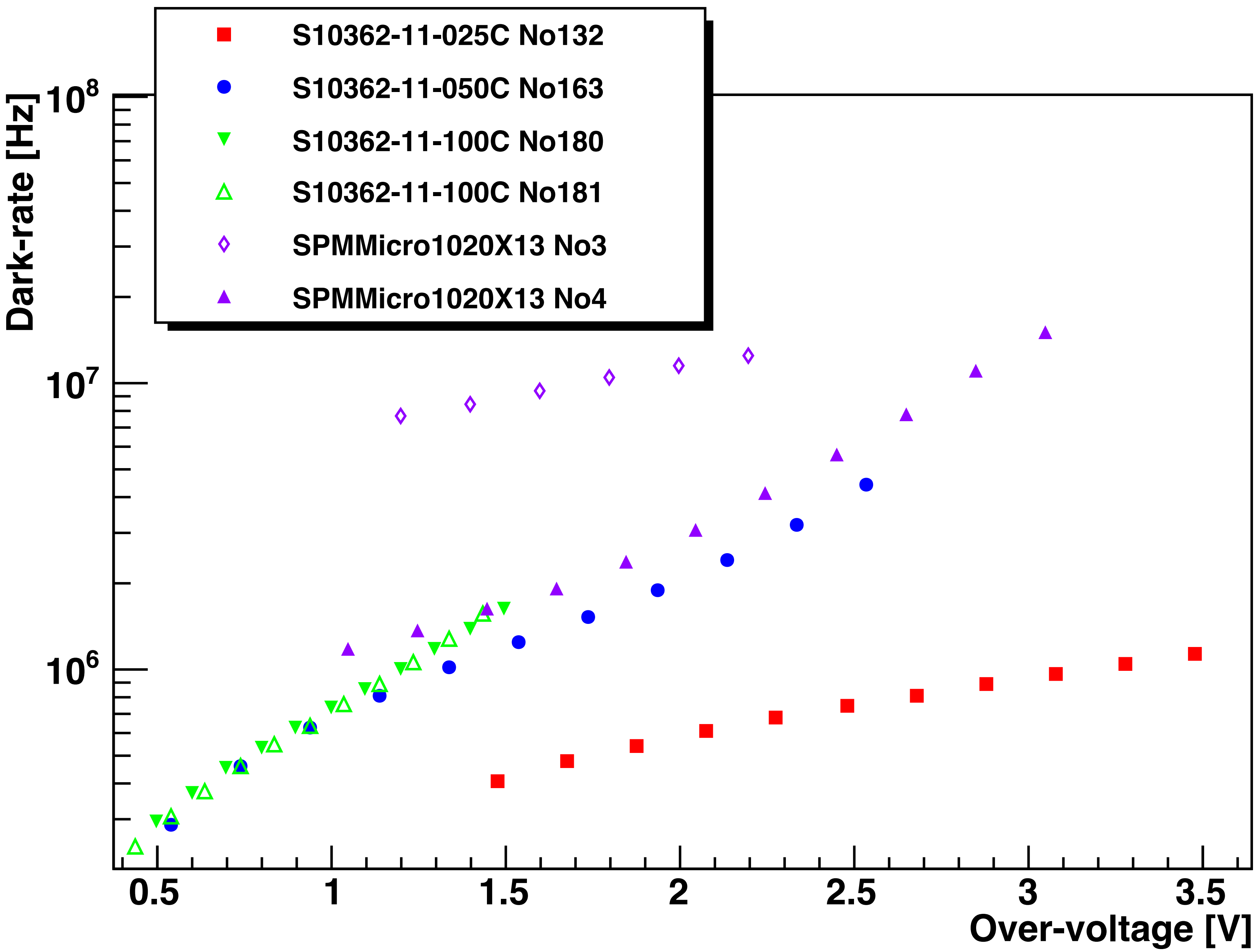
Rule of thumb:
The thermal generated dark-rate doubles for each temperature increase of 8 °C

-> Cooling (if possible)

Voltage dependence

Dark-rate vs. over-voltage

at room temperature, 0.5pe threshold

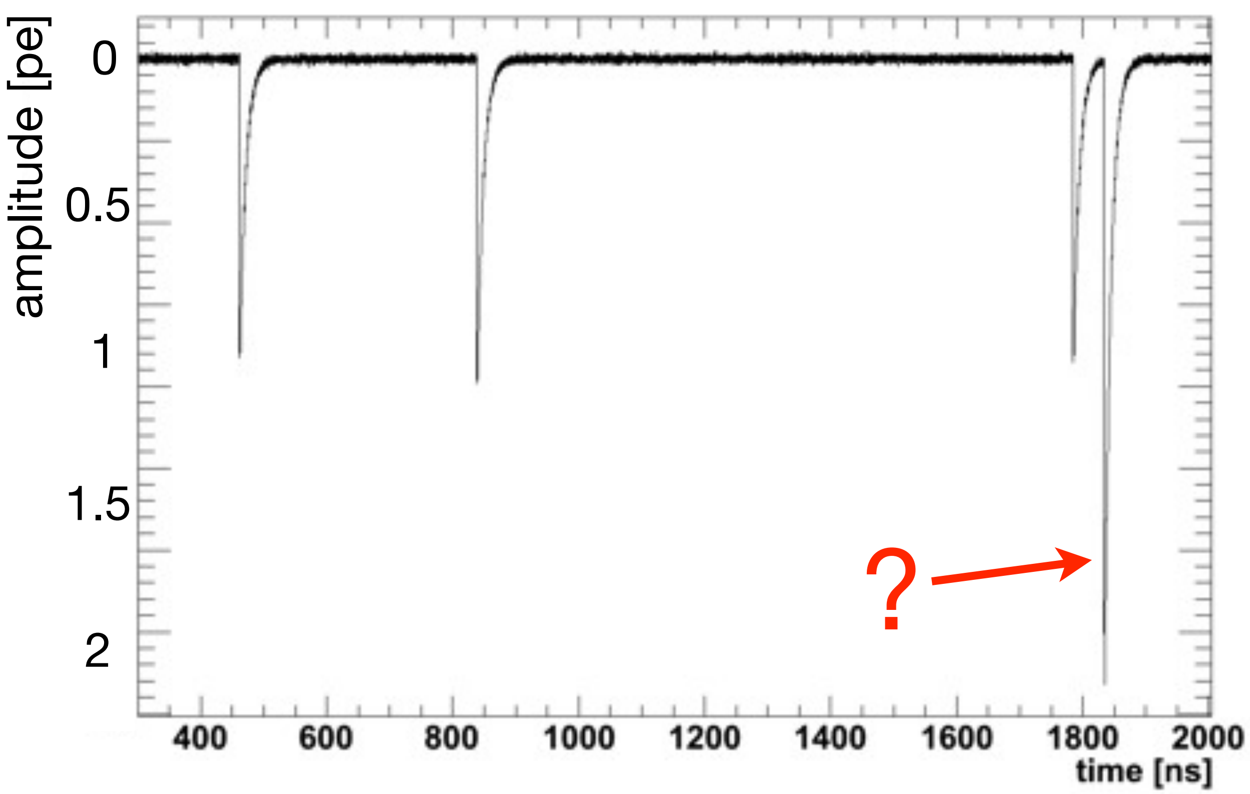


Dark-rate rises exponentially with the applied over-voltage

-> reduce over-voltage (this will lower the gain and the PDE!)

Threshold dependence (Optical cross-talk)

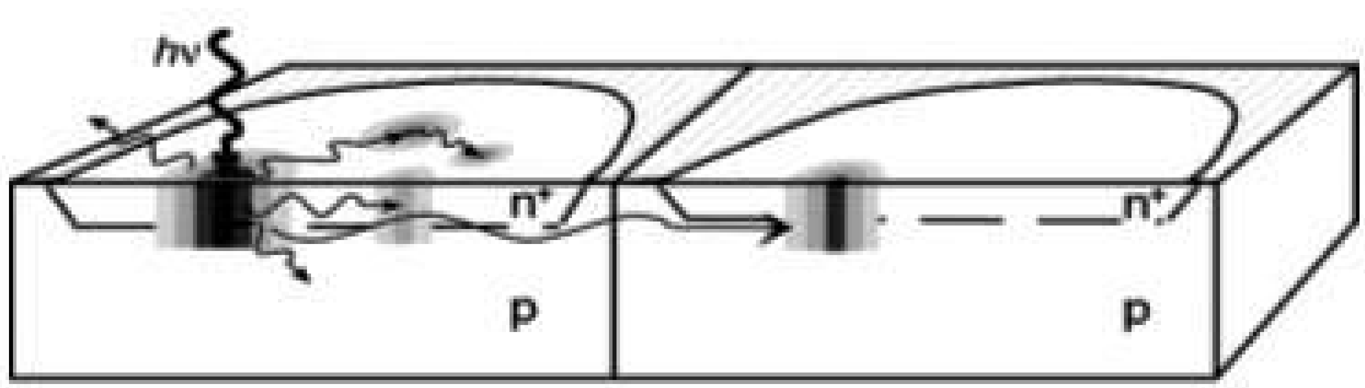
typical oscilloscope picture (dark-rate)



Expected probability for two pixels firing at the same time (~5ns) very low

$P_{2pixel} \approx \nu_{dark} \times \delta t$ = 1MHz x 5ns = 0.05%
But you see a O(10%) effect

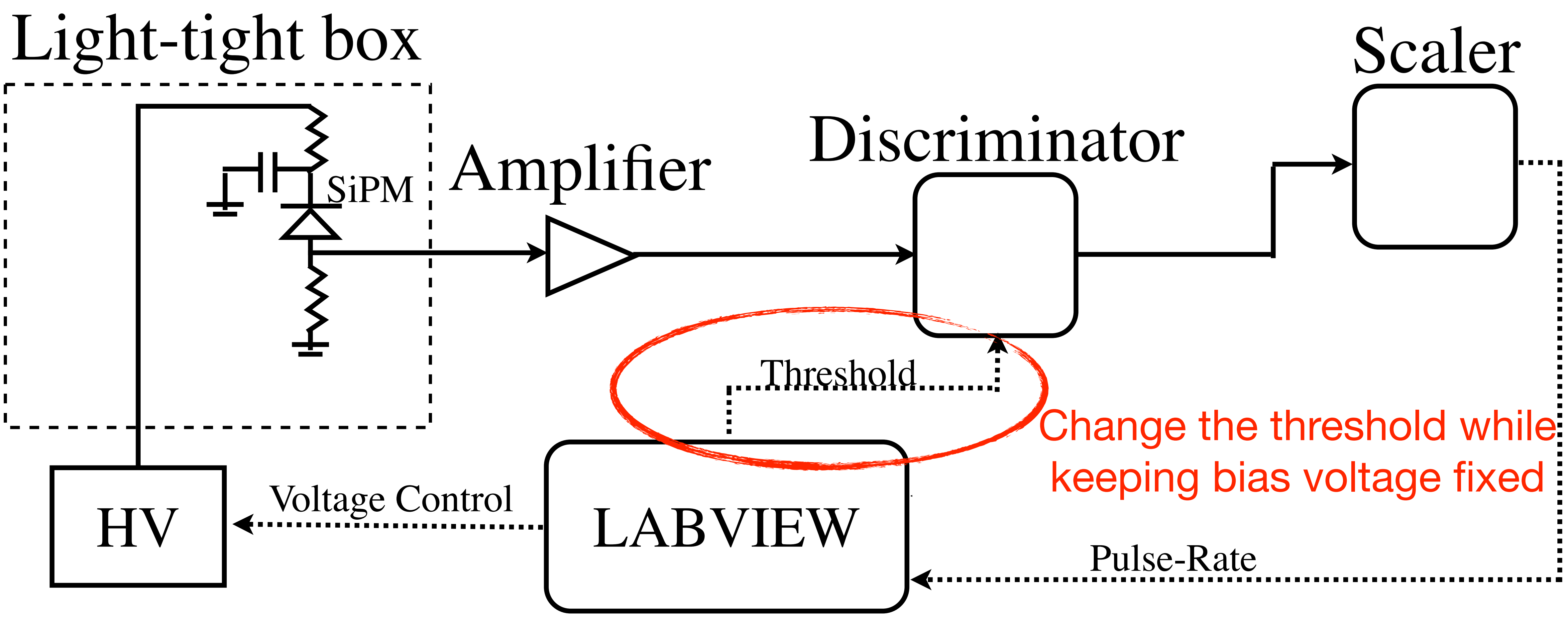
Reason: optical cross-talk
A p-n junction in breakdown emits photons in the visible range (~ 3 x 10^{-5} per charge carrier*)
If they reach a neighboring pixel additional breakdown can be caused
Instantaneous effect!



How often do more than two pixels fire?
-> threshold scan

* A. Lacaita, et al., IEEE Trans. Electron Devices ED-40 (1993) 577

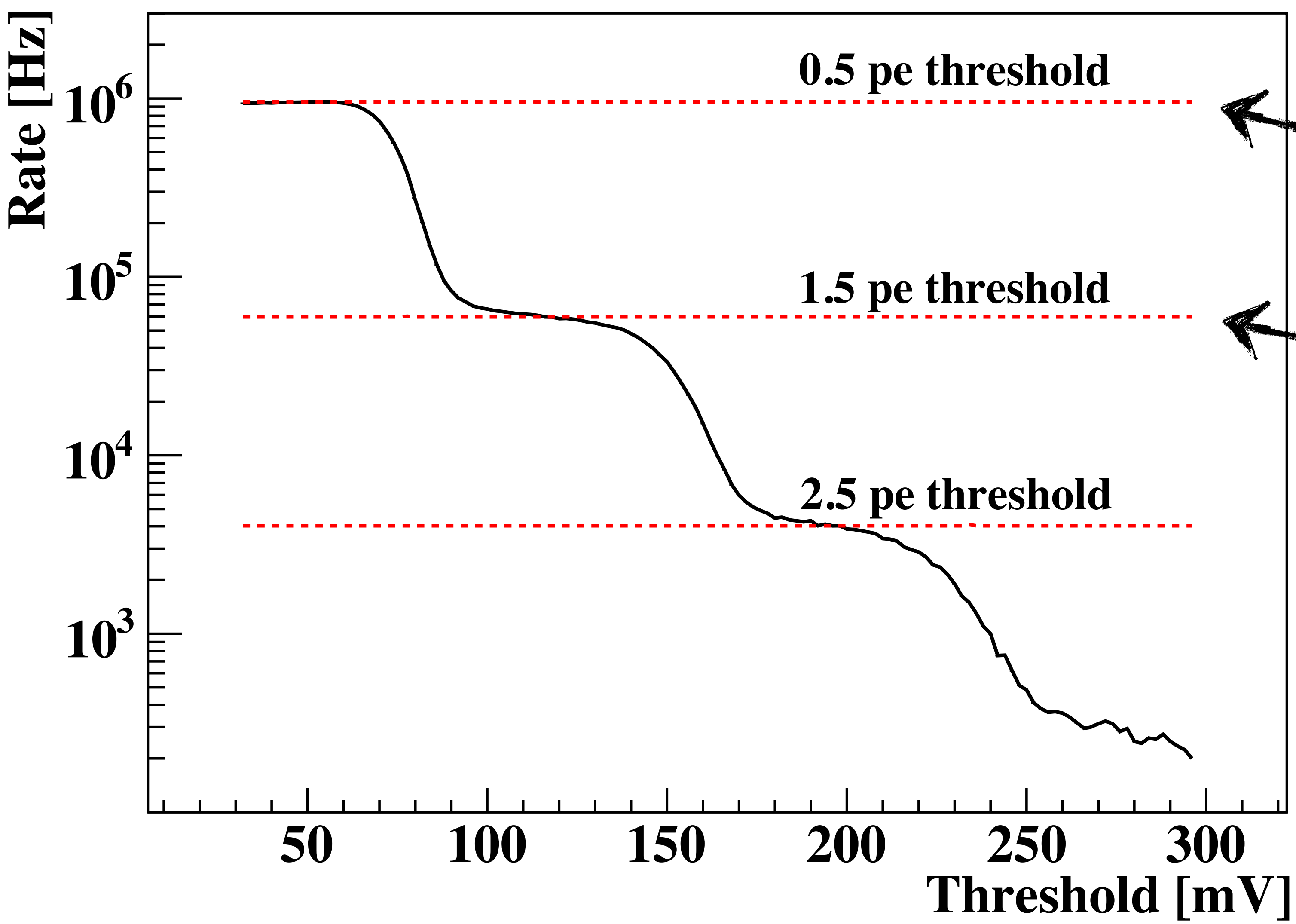
Threshold-scan setup

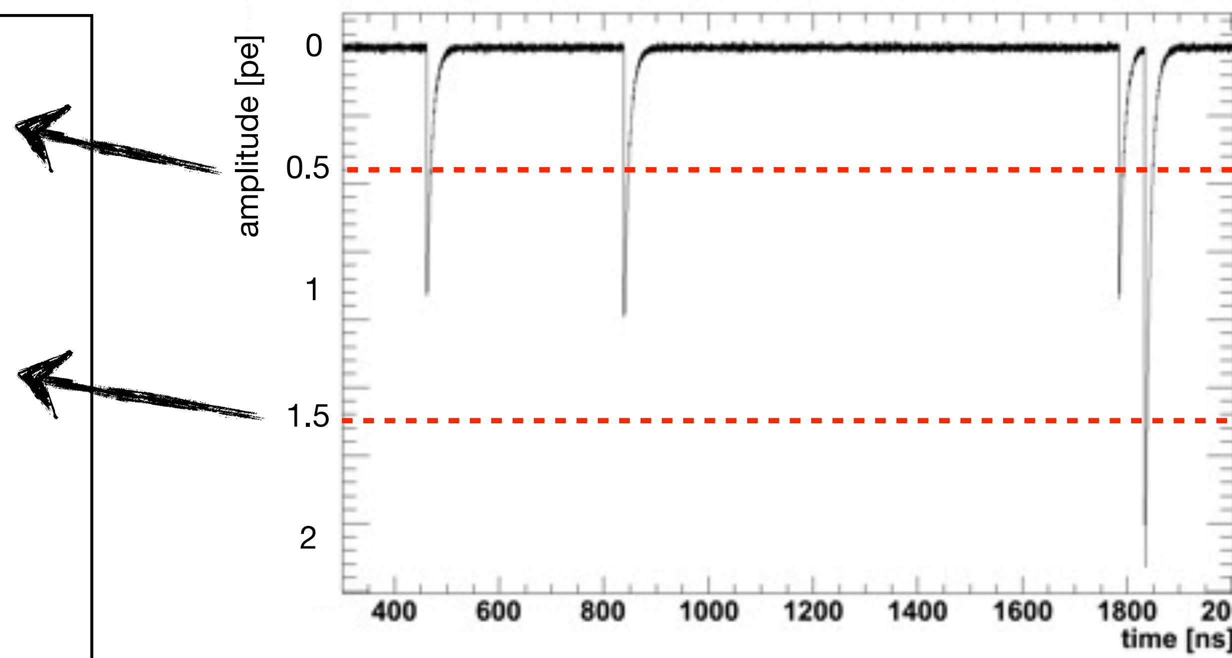


Threshold scan

threshold-scan

400 pixel MPPC U_{over} = 1.3V, room temp.



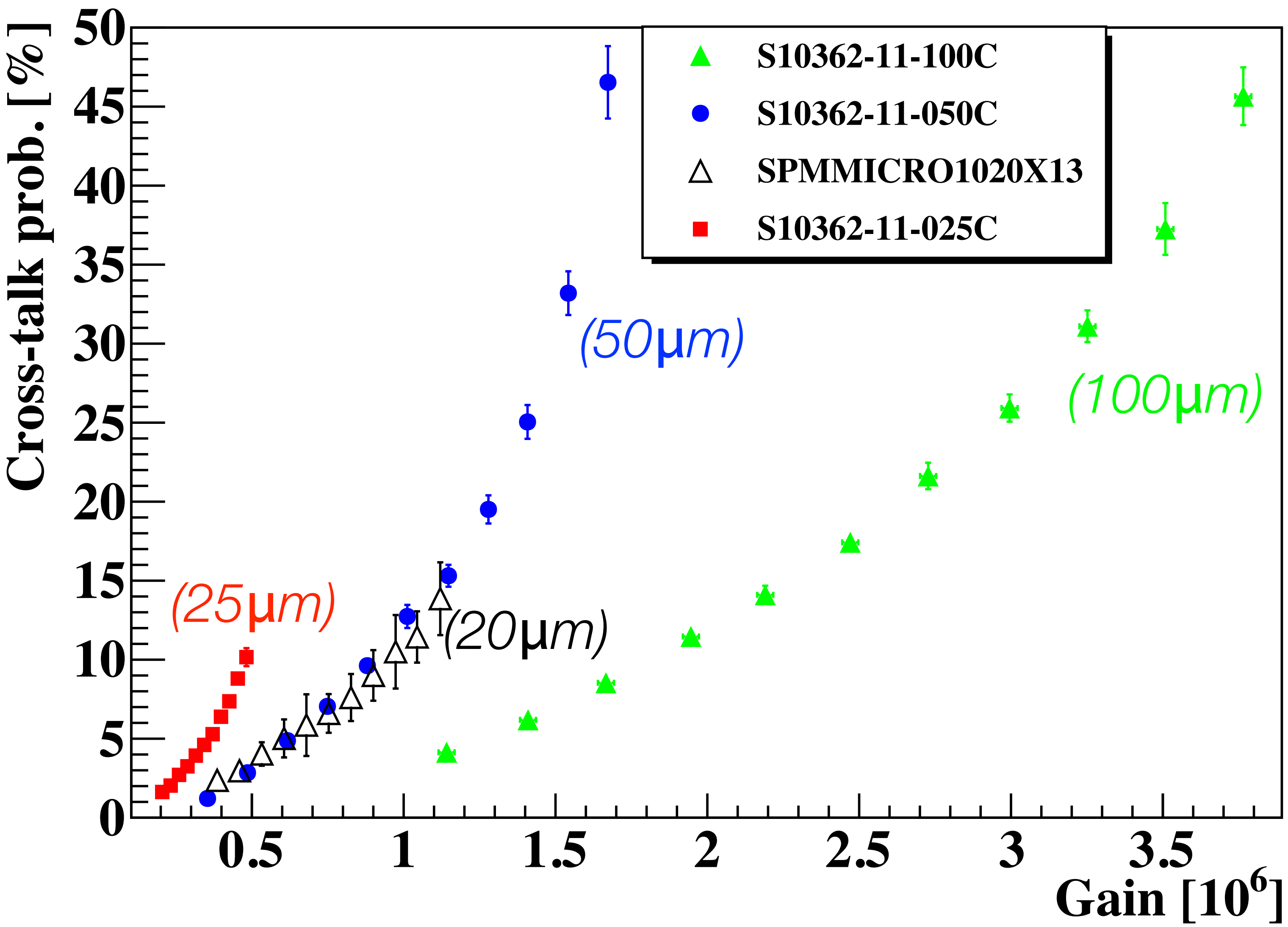


$$P_c = \frac{Number\ of\ cross - talk\ events/time}{Total\ number\ of\ events/time} = \frac{\nu_{1.5\,pe}}{\nu_{0.5\,pe}}$$

Cross-talk probability

Cross-talk probability vs. gain

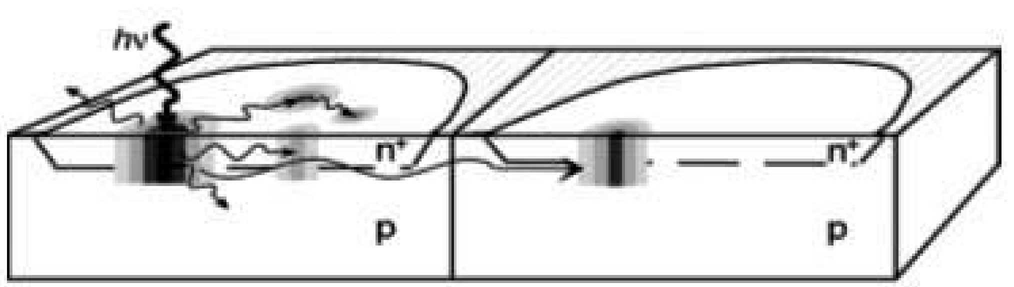
gain = C_{pixel} x U_{over}, room temp. *(pixel pitch)*



Higher gain -> more photons
+ higher geiger efficiency
(U_{over} = Gain/C_{pixel})

MPPC: At fixed gain values, small pixel devices have a higher cross-talk probability
(average photon travel distance shorter)

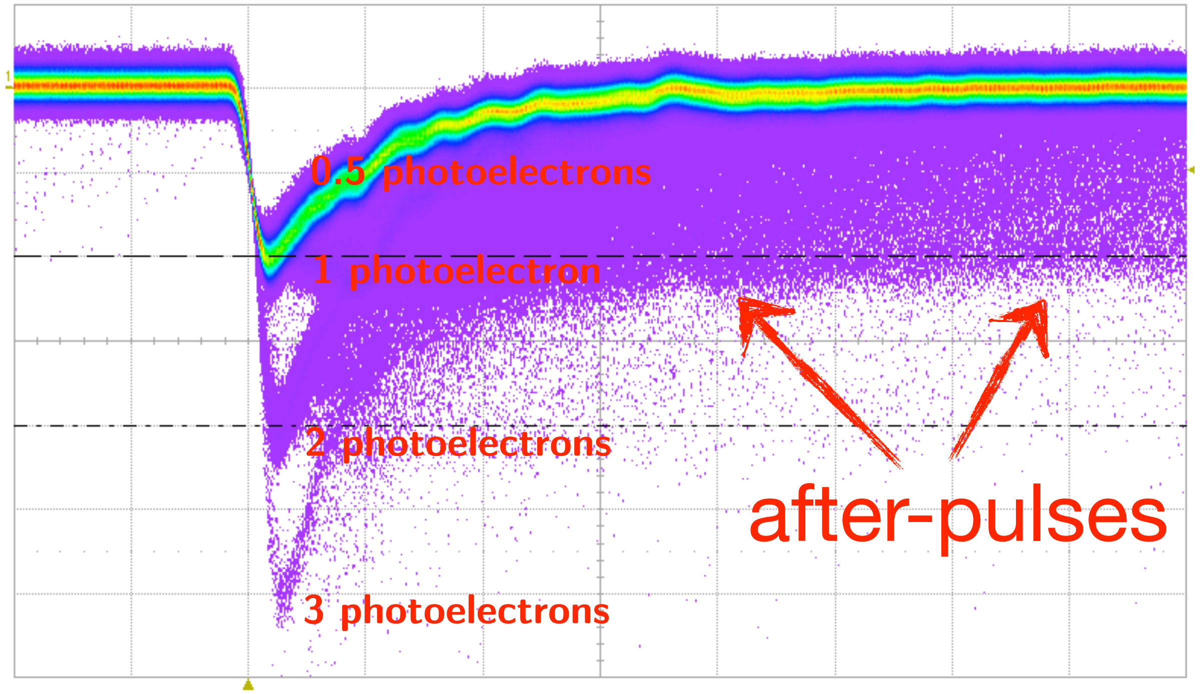
SensL: small cross-talk due to trenches between pixels

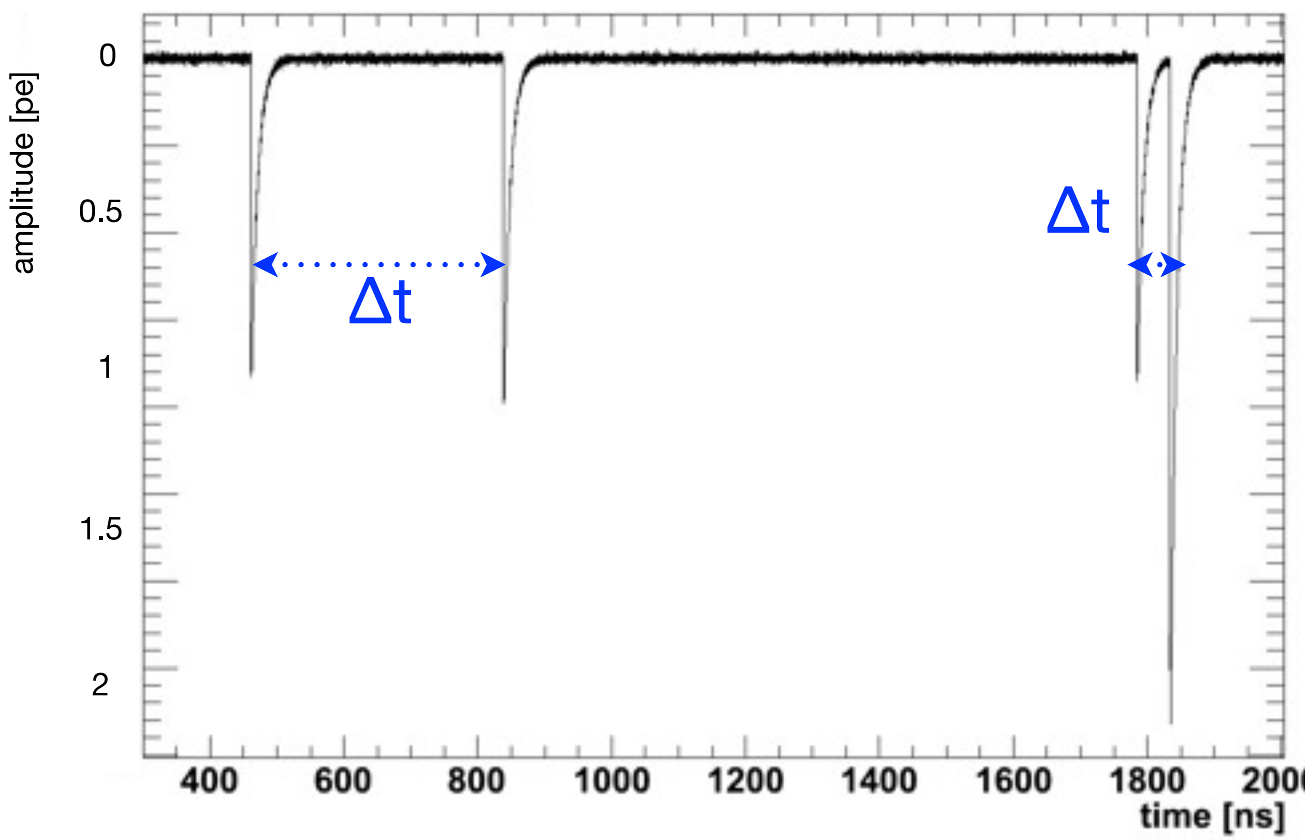


After-pulses

- During avalanche breakdown charge carriers can be trapped in silicon defects
- If they are released after a time which is longer than the pixel recovery time, a second avalanche can be initiated
- After-pulses cannot be separated on an event basis
- However it is possible to identify after-pulses in a statistical analysis of the SiPM dark-rate
- Measure the time difference between subsequent pulses

Overlaying waveforms (no light)





Noise probability density distribution

Probability to measure ***n*** dark-counts within ***t*** at a given dark-rate of $\boldsymbol{\nu_d}$:

$$P_\mu(n) = \frac{\mu^n e^{-\mu}}{n!}$$

average number of counts

$$\mu = t \cdot \nu_d$$

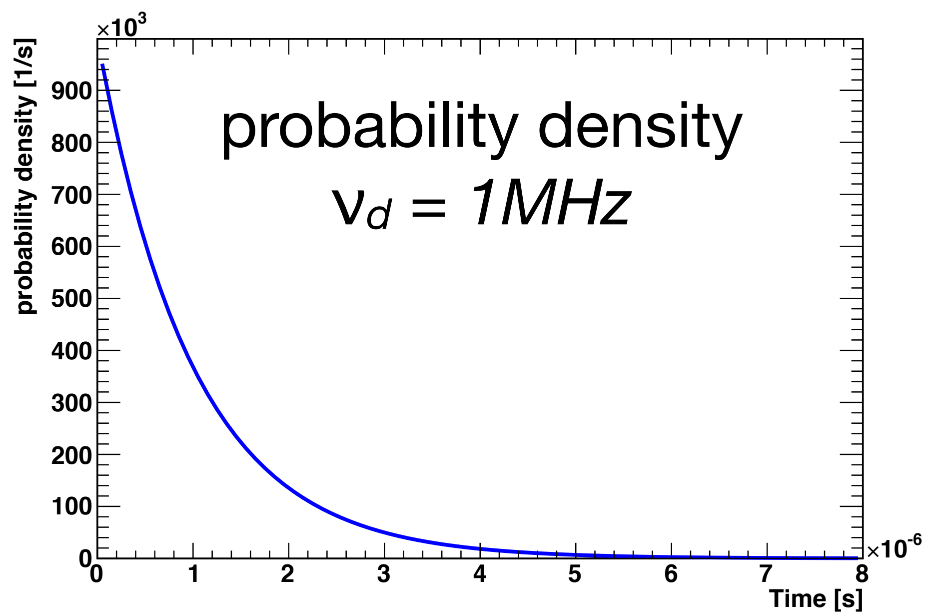
Probability to measure zero dark-counts:

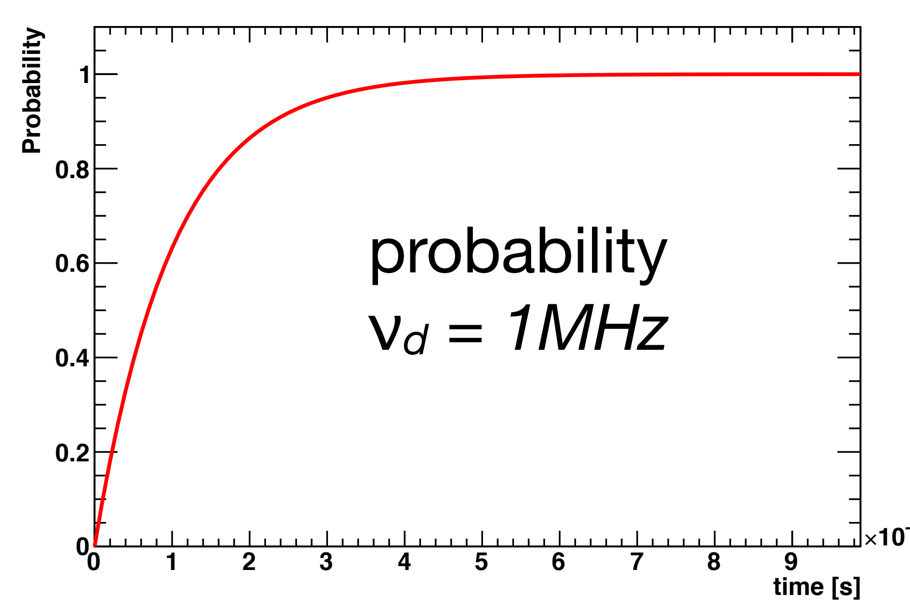
$$P_\mu(0) = e^{-t\,\nu_d} = 1 - \int_0^t p_d\, dt'$$

probability density

From the above equation we can derive $\boldsymbol{p_d}$

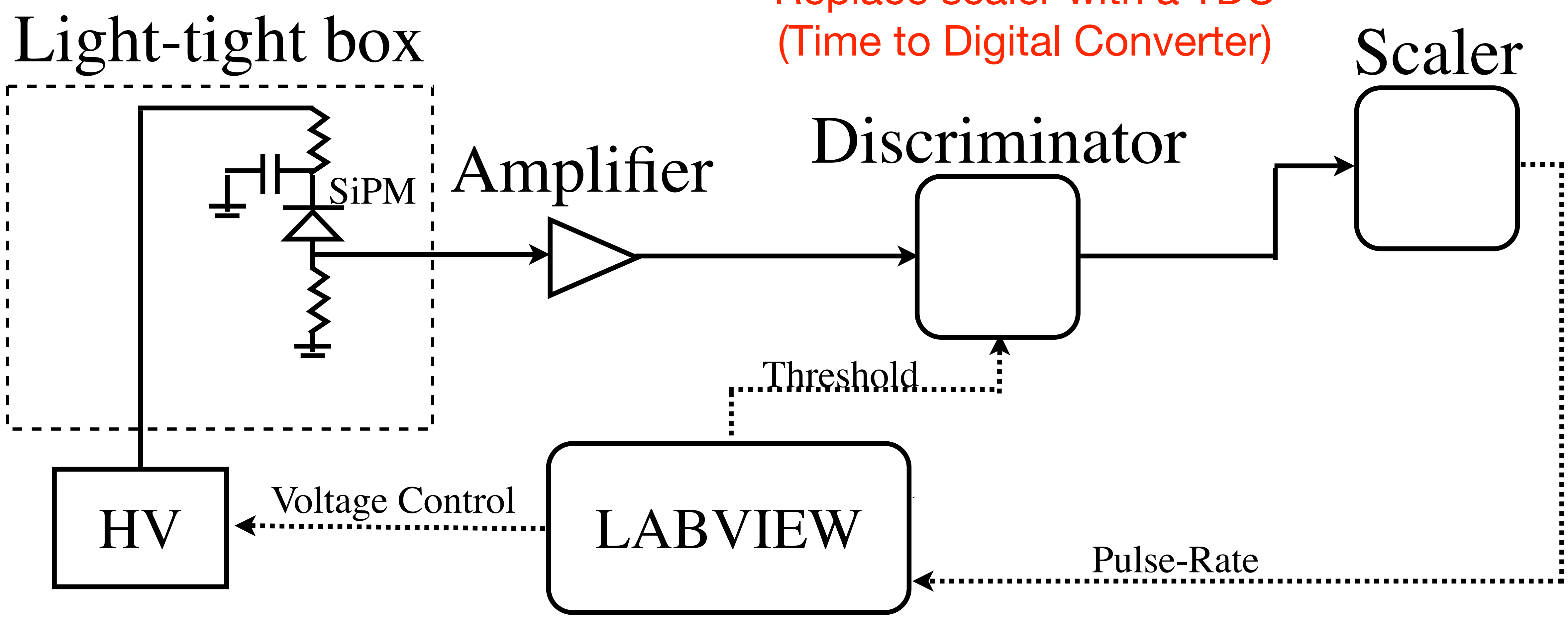
$$\boxed{p_d = \nu_d\, e^{-t\,\nu_d}}$$





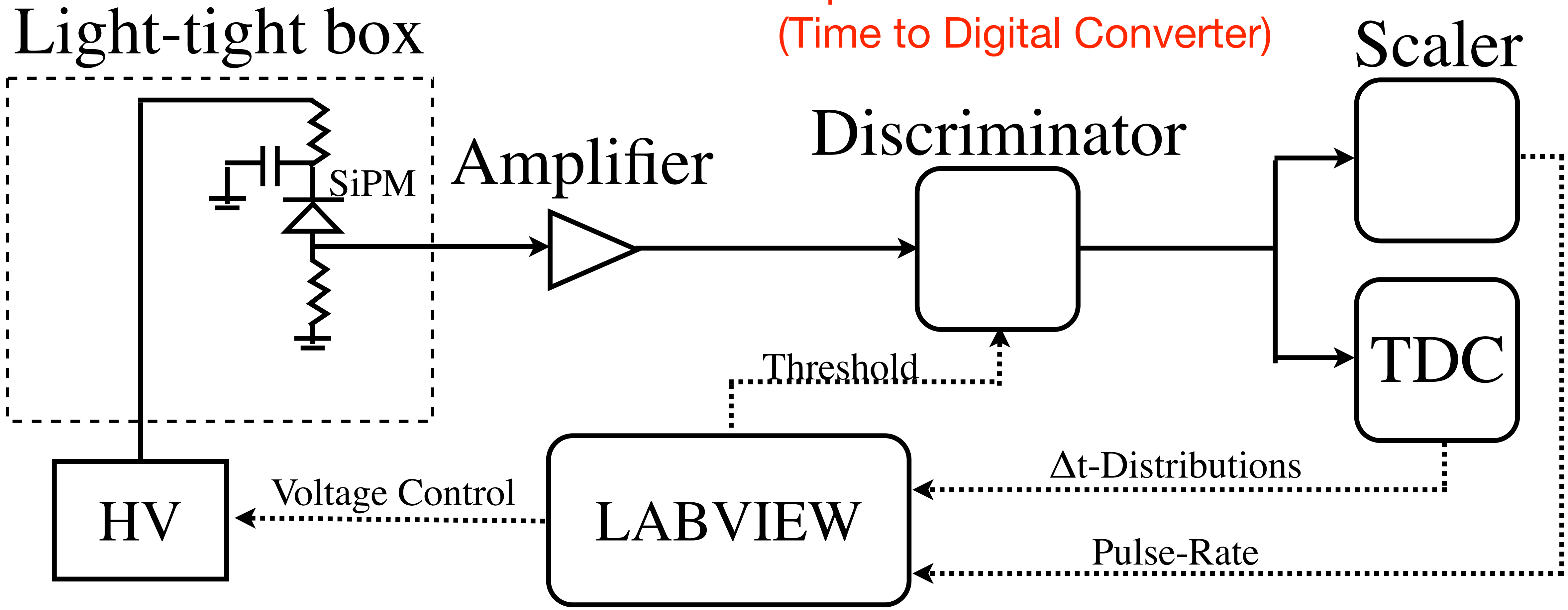
After-pulse setup

Replace scaler with a TDC
(Time to Digital Converter)



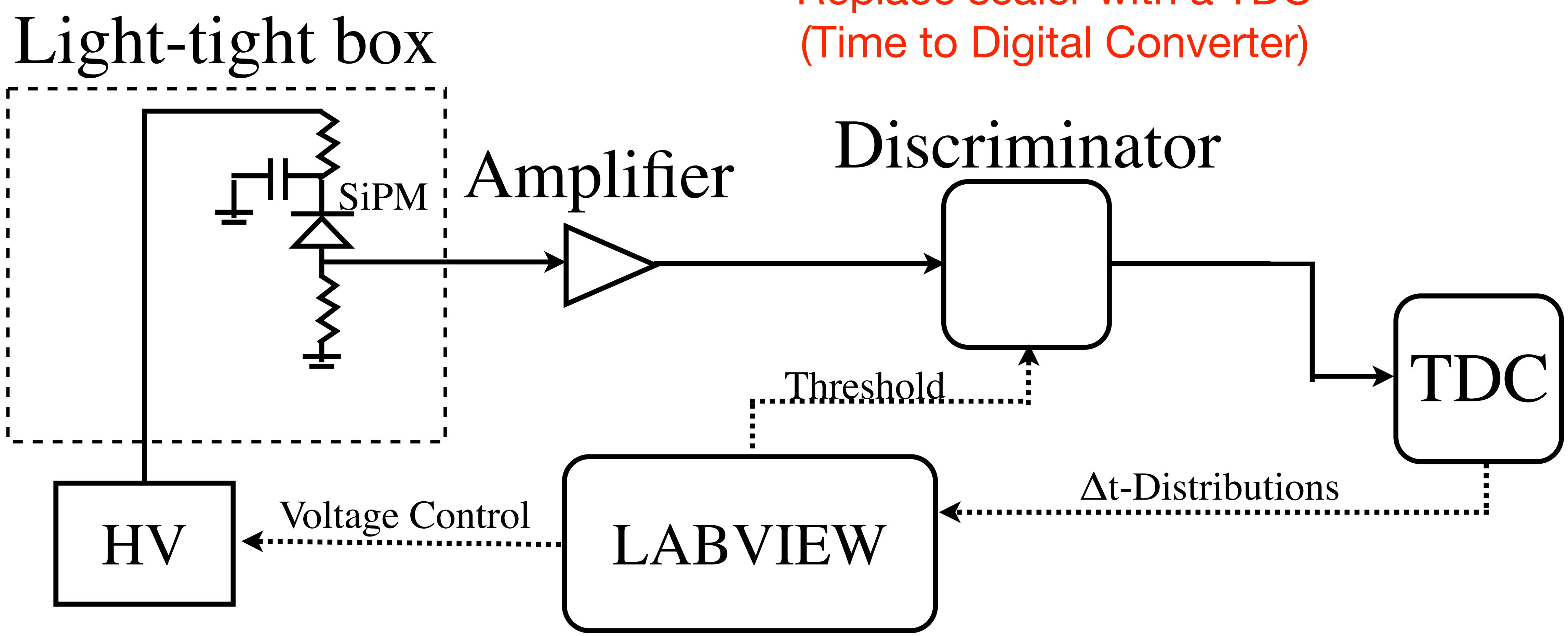
After-pulse setup

Replace scaler with a TDC
(Time to Digital Converter)



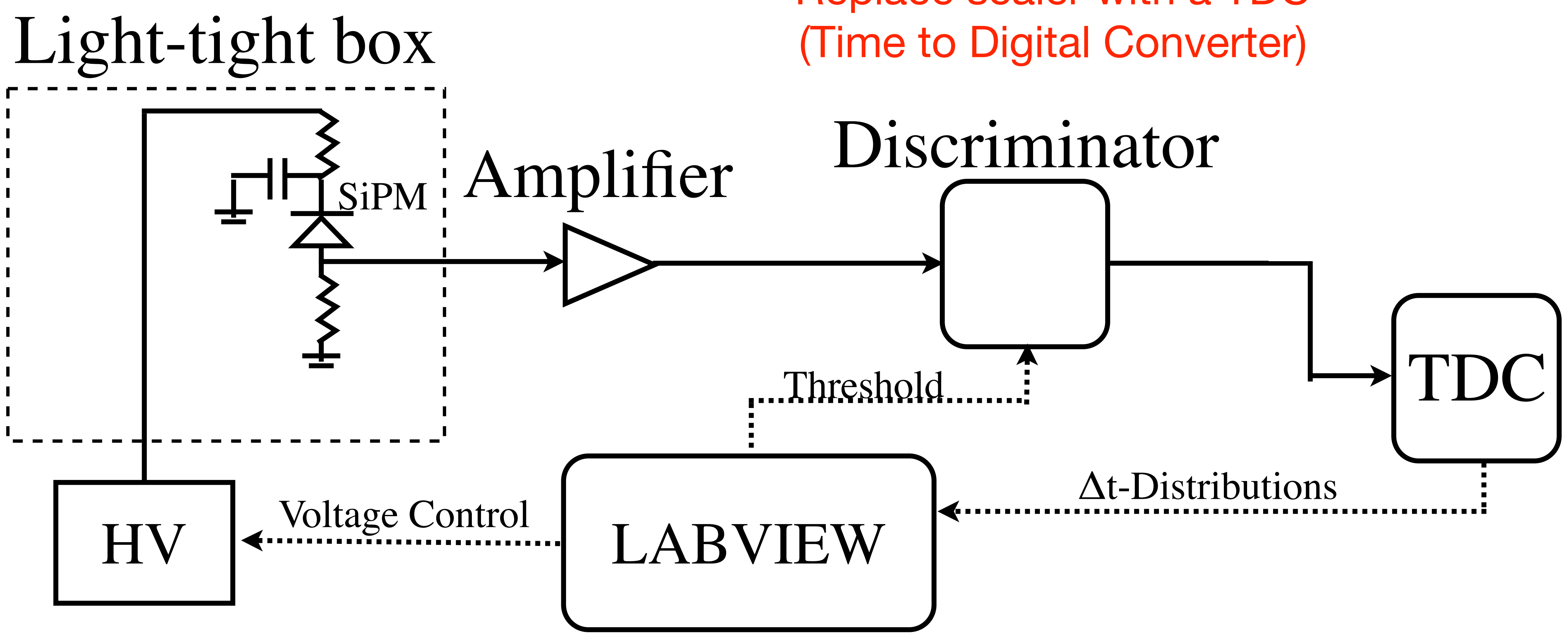
After-pulse setup

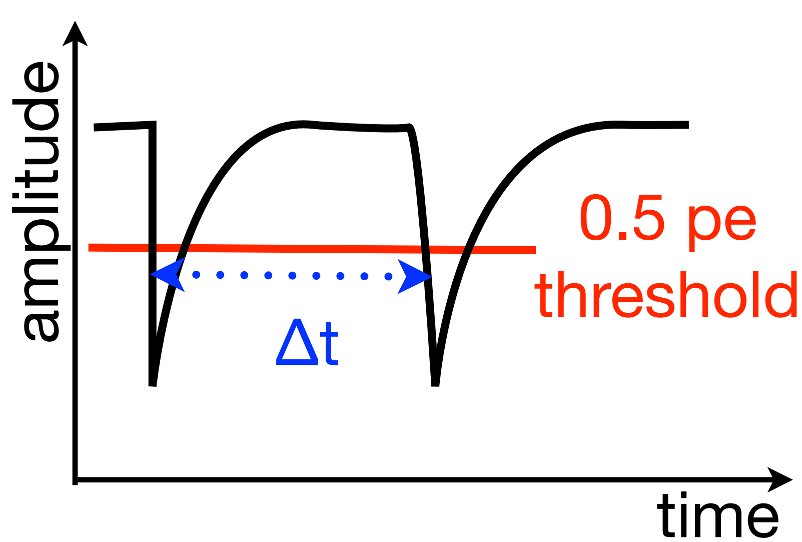
Replace scaler with a TDC
(Time to Digital Converter)



After-pulse setup

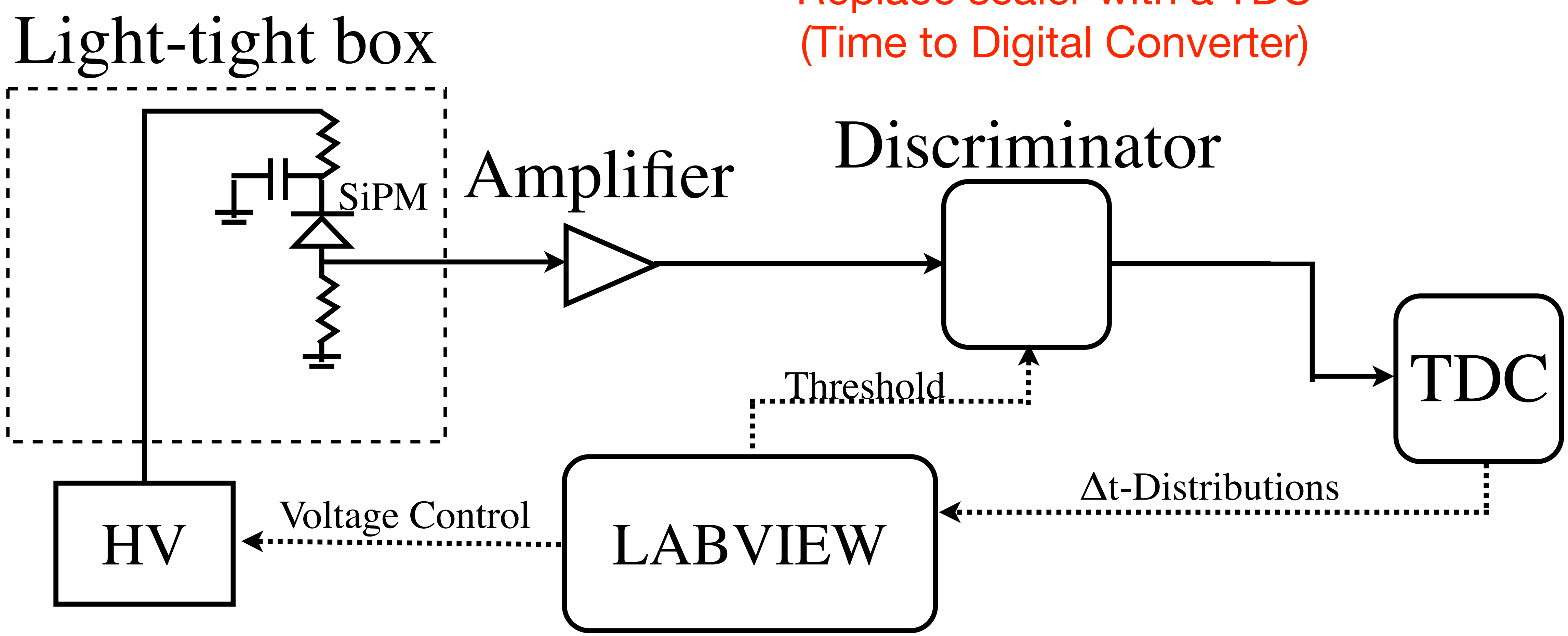
Replace scaler with a TDC
(Time to Digital Converter)

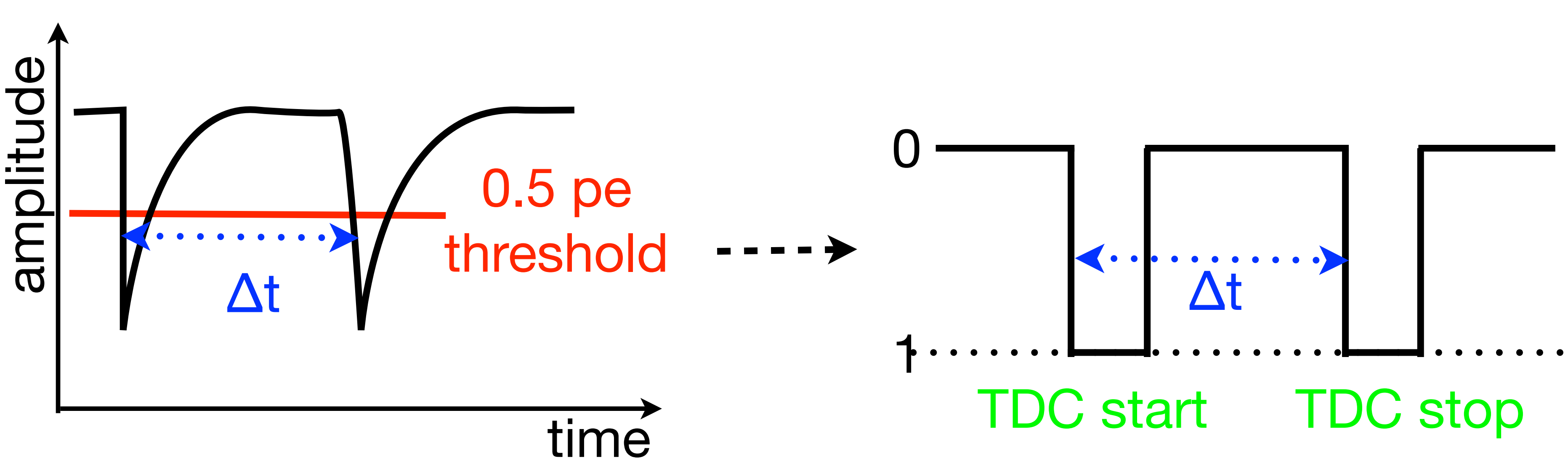




After-pulse setup

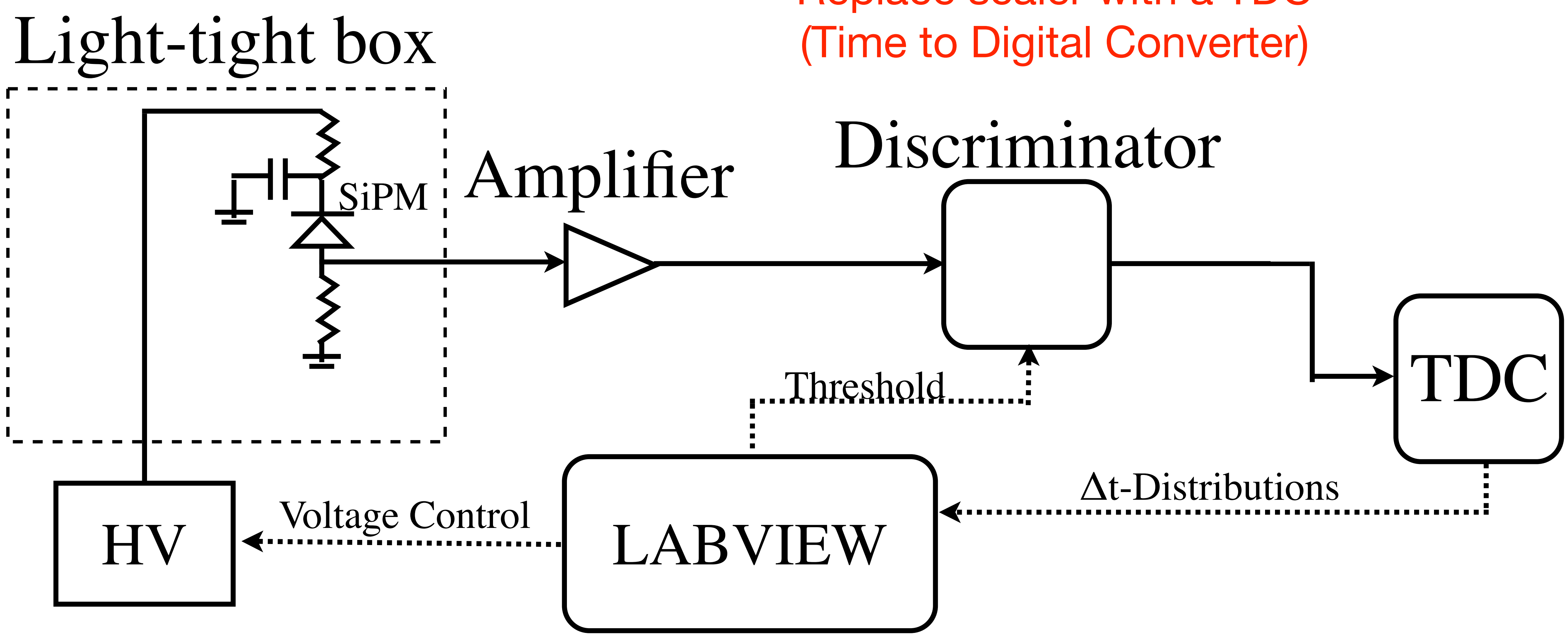
Replace scaler with a TDC
(Time to Digital Converter)

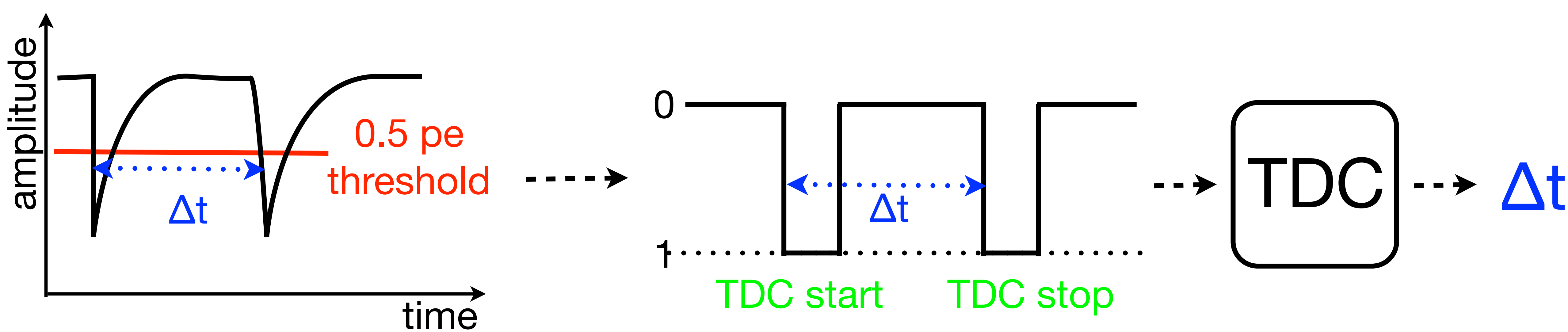




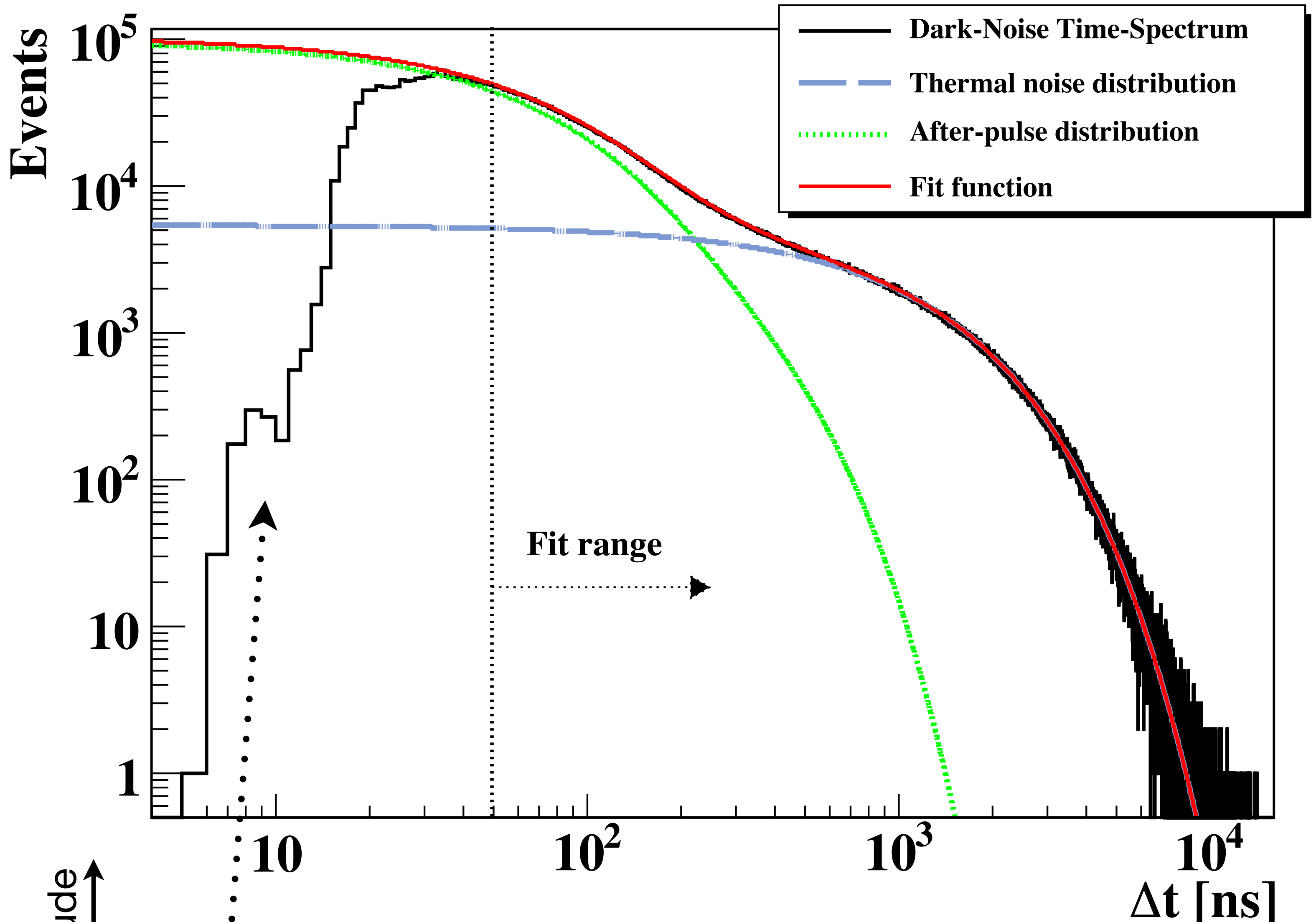
After-pulse setup

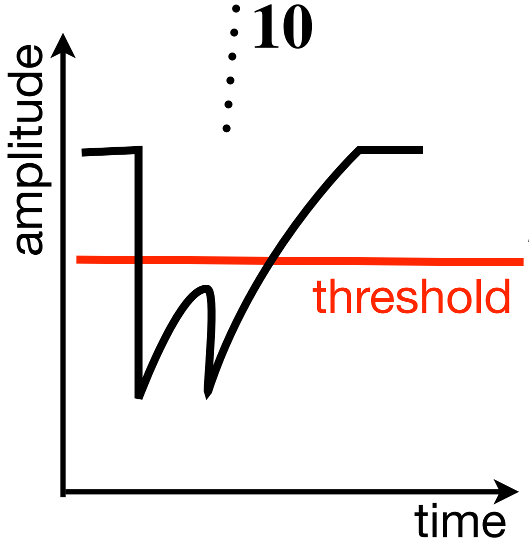
Replace scaler with a TDC
(Time to Digital Converter)





Δt distribution





fast after-pulses cannot be resolved

Result cannot be described by thermal noise only (blue curve)

Two more components needed
- fast after-pulses (apf)
- slow after-pulses (aps)

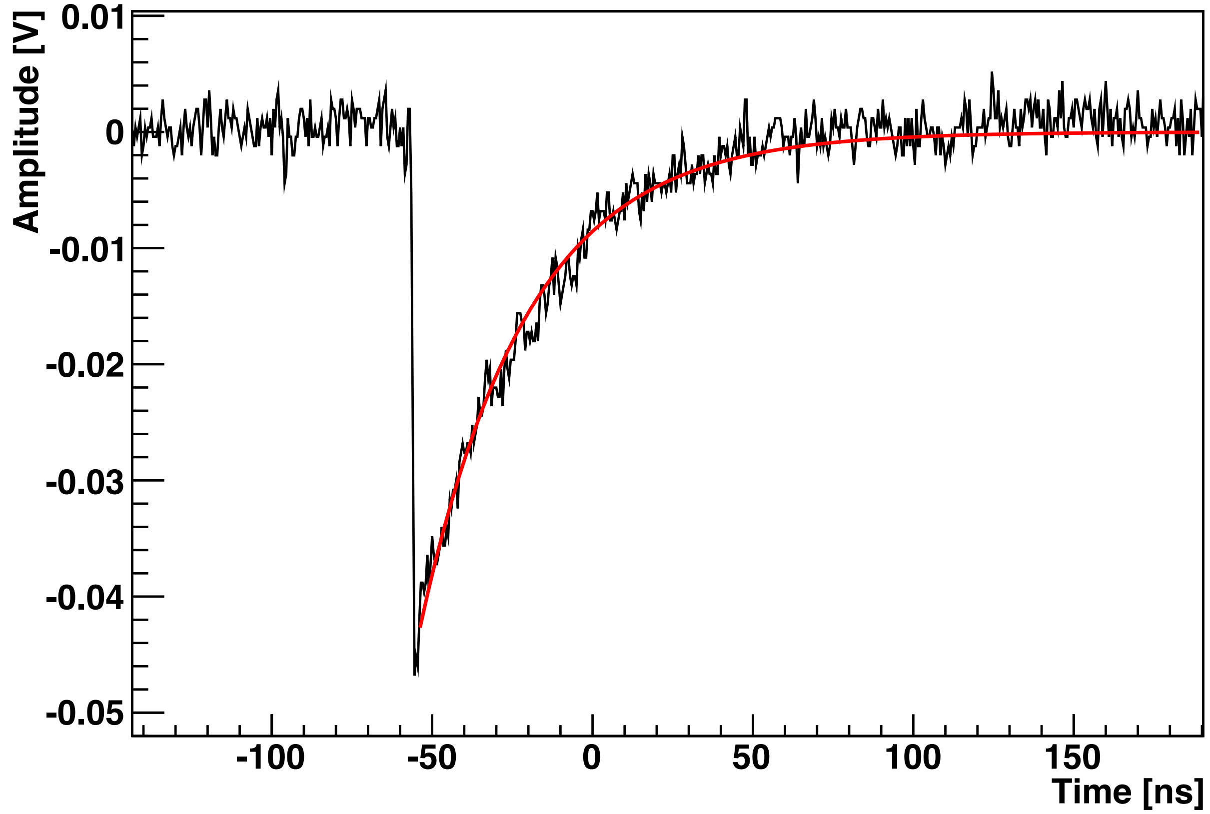
$$n(\Delta t) = N_{tp}/\tau_{tp} \cdot e^{-\Delta t/\tau_{tp}} + N_{apf}/\tau_{apf} \cdot e^{-\Delta t/\tau_{apf}} + N_{aps}/\tau_{aps} \cdot e^{-\Delta t/\tau_{aps}}$$

$N_{...}$: normalisation factors
$\tau_{...}$: time constants [1/rate]

First approximation of after-pulse probability

$$\boxed{P_{ap} = \frac{N_{apf} + N_{aps}}{N_{apf} + N_{aps} + N_{tp}}}$$

Additional corrections



Fast after-pulses will generate a smaller charge because of the pixel recovery time

effective gain:

$$G(\Delta t) = G_\infty \cdot \xi(\Delta t)$$
$$= G_\infty \cdot (1 - e^{-\Delta t/\tau_r})$$

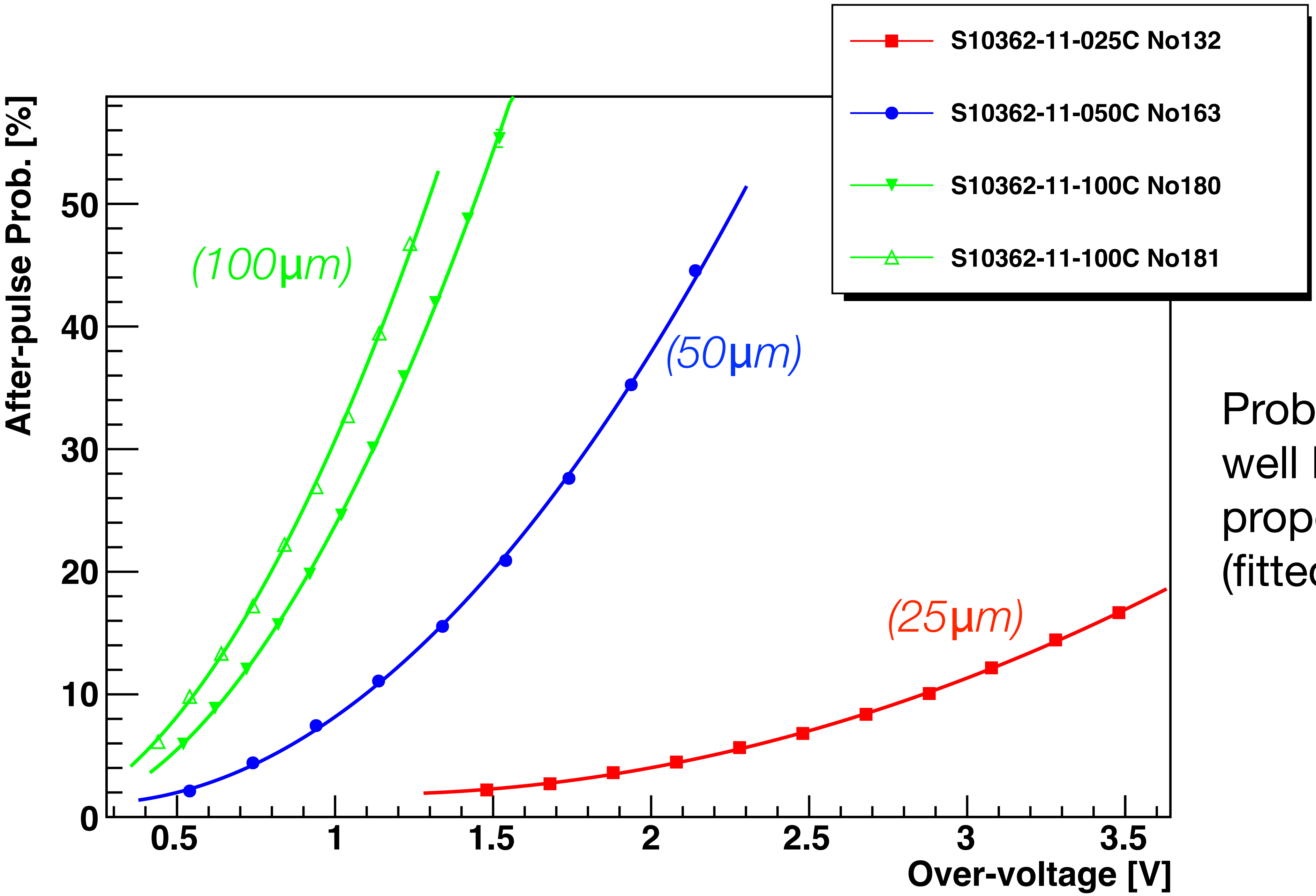
τ_r : pixel recovery time (R_q x C_{pixel})

Use ξ to correct P_{ap}

$$\boxed{P_{ap} = \frac{\int_0^\infty \xi \cdot n_{ap} \, d\Delta t}{\int_0^\infty \xi \cdot (n_{ap} + n_{tp}) \, d\Delta t}}$$

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

After-pulse probability



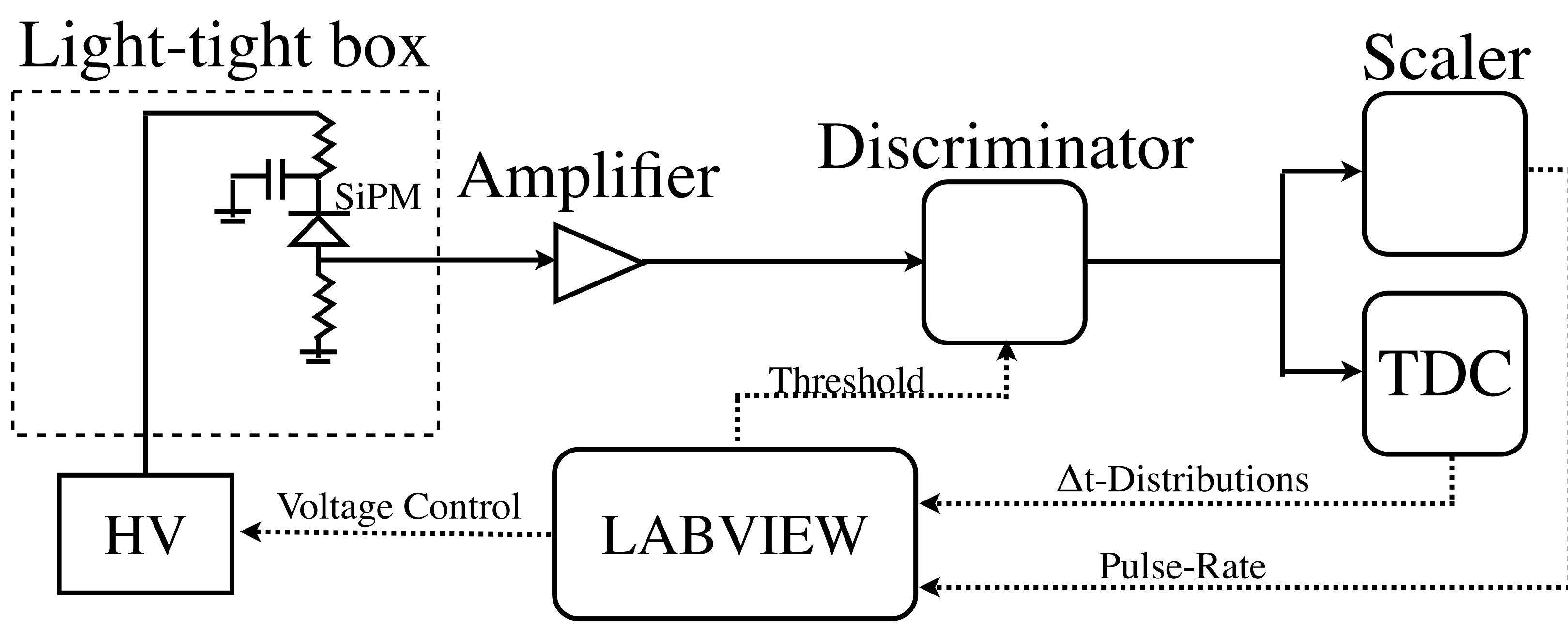
Probability can be described well by a function proportional to V_{over}^2 (fitted lines)

Measurements with light

Gain measurement

- SiPM is illuminated with short O(ns) LED pulses
- Amplified signal is fed into a charge to digital converter (QDC)
- Integration gate *(typ. 20 - 100 ns)*
- Integrate charge for each light pulse

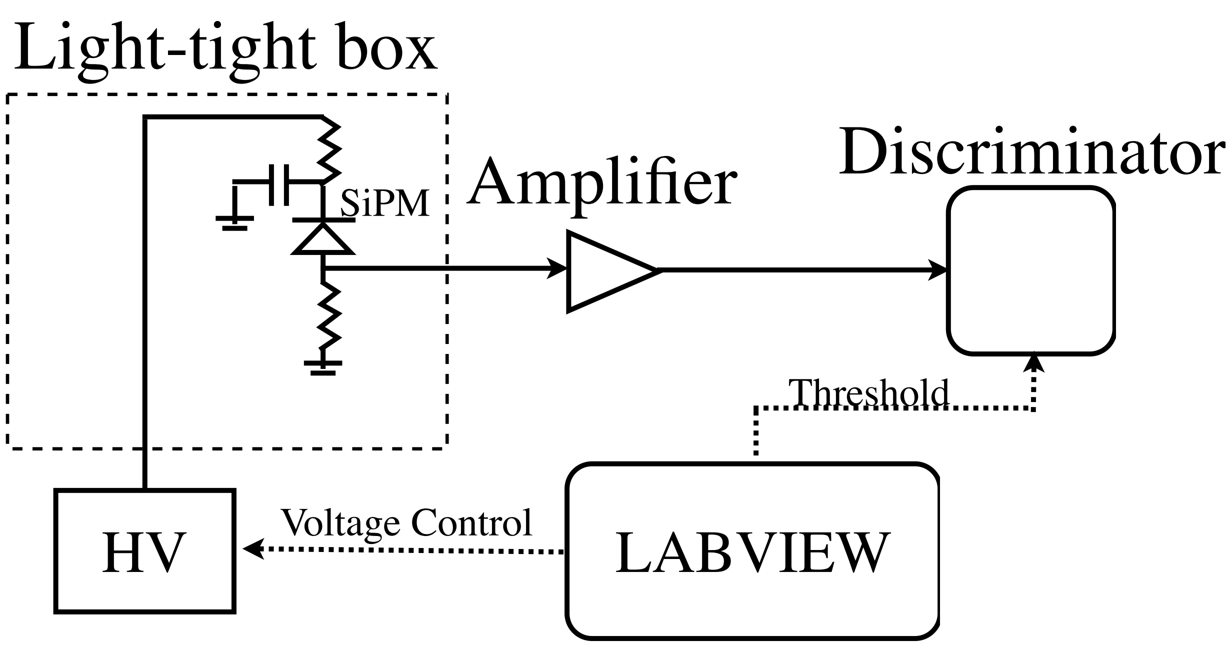
start with the dark-rate setup



Gain measurement

- SiPM is illuminated with short O(ns) LED pulses
- Amplified signal is fed into a charge to digital converter (QDC)
- Integration gate *(typ. 20 - 100 ns)*
- Integrate charge for each light pulse

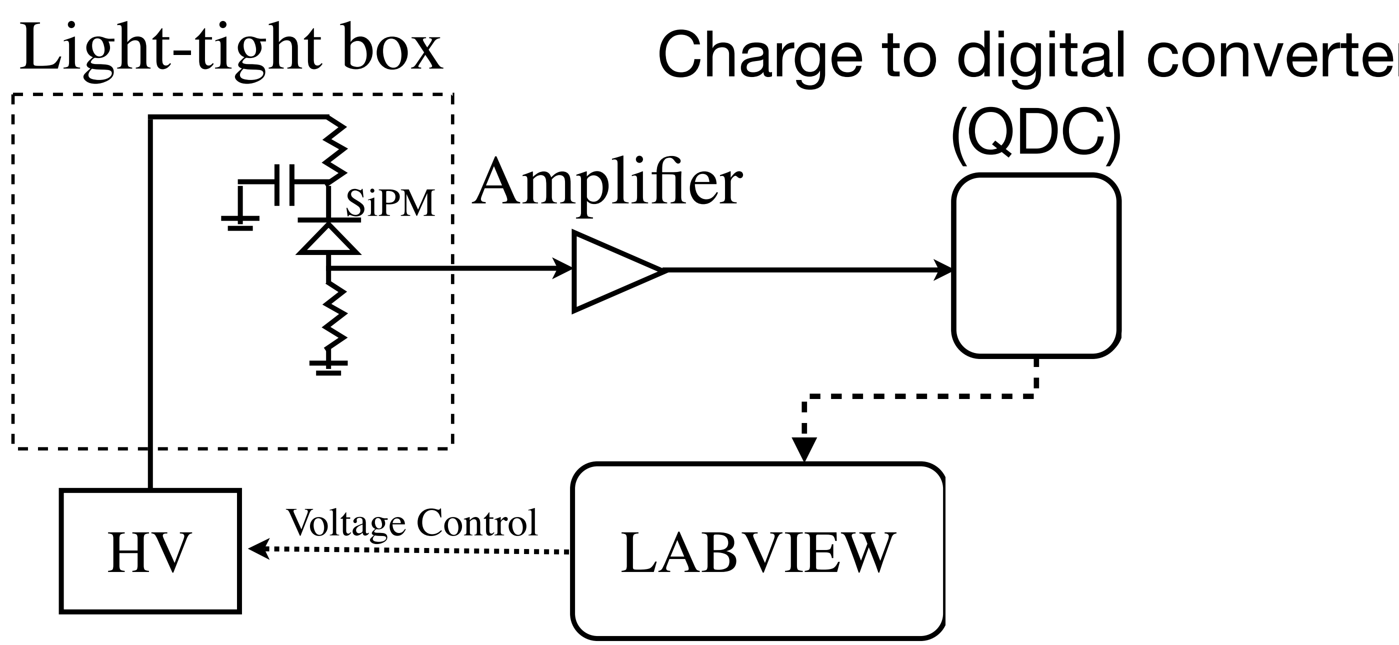
start with the dark-rate setup



Gain measurement

- SiPM is illuminated with short O(ns) LED pulses
- Amplified signal is fed into a charge to digital converter (QDC)
- Integration gate *(typ. 20 - 100 ns)*
- Integrate charge for each light pulse

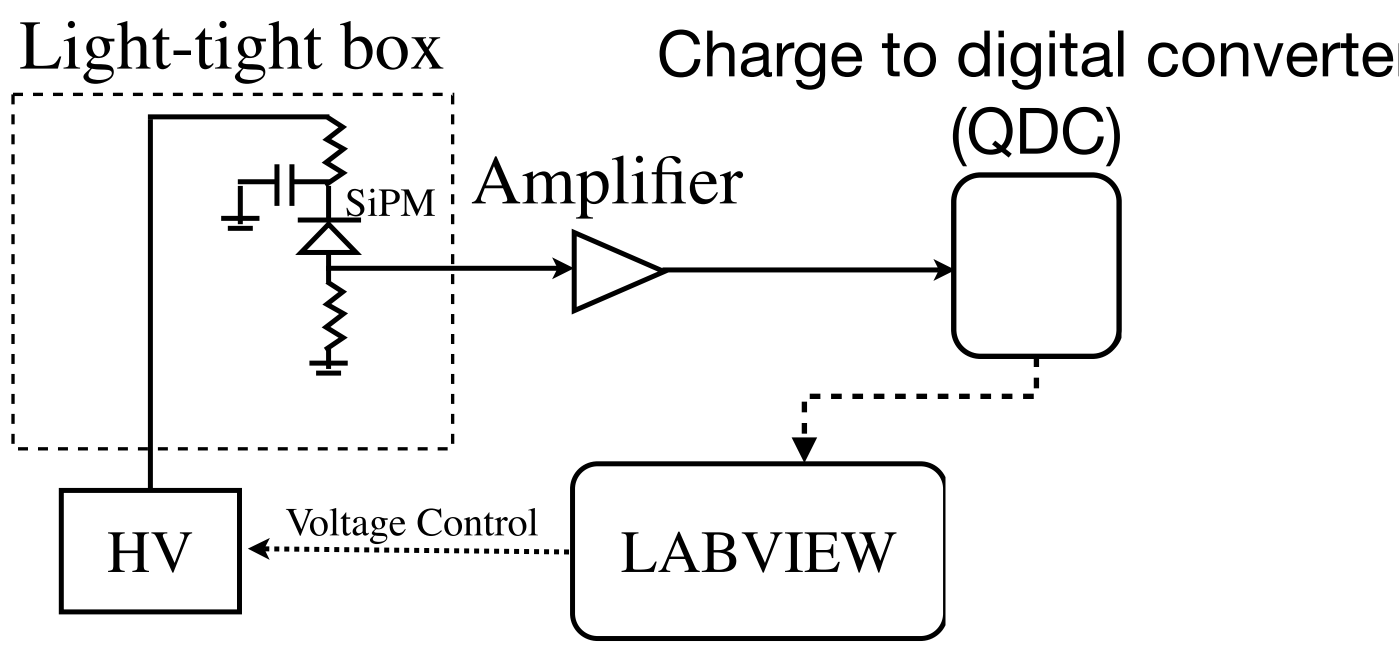
start with the dark-rate setup



Gain measurement

- SiPM is illuminated with short O(ns) LED pulses
- Amplified signal is fed into a charge to digital converter (QDC)
- Integration gate *(typ. 20 - 100 ns)*
- Integrate charge for each light pulse

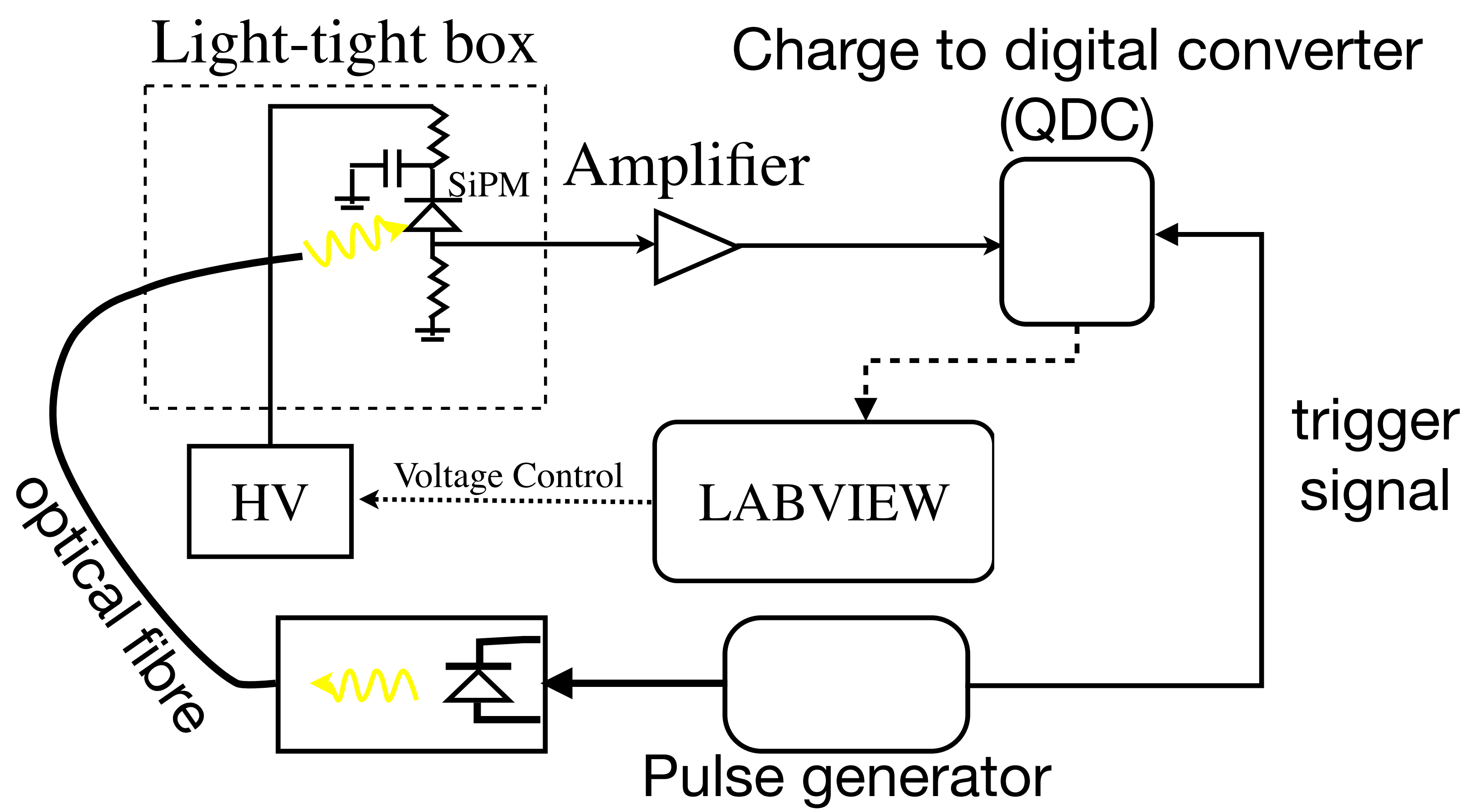
add a light source



Gain measurement

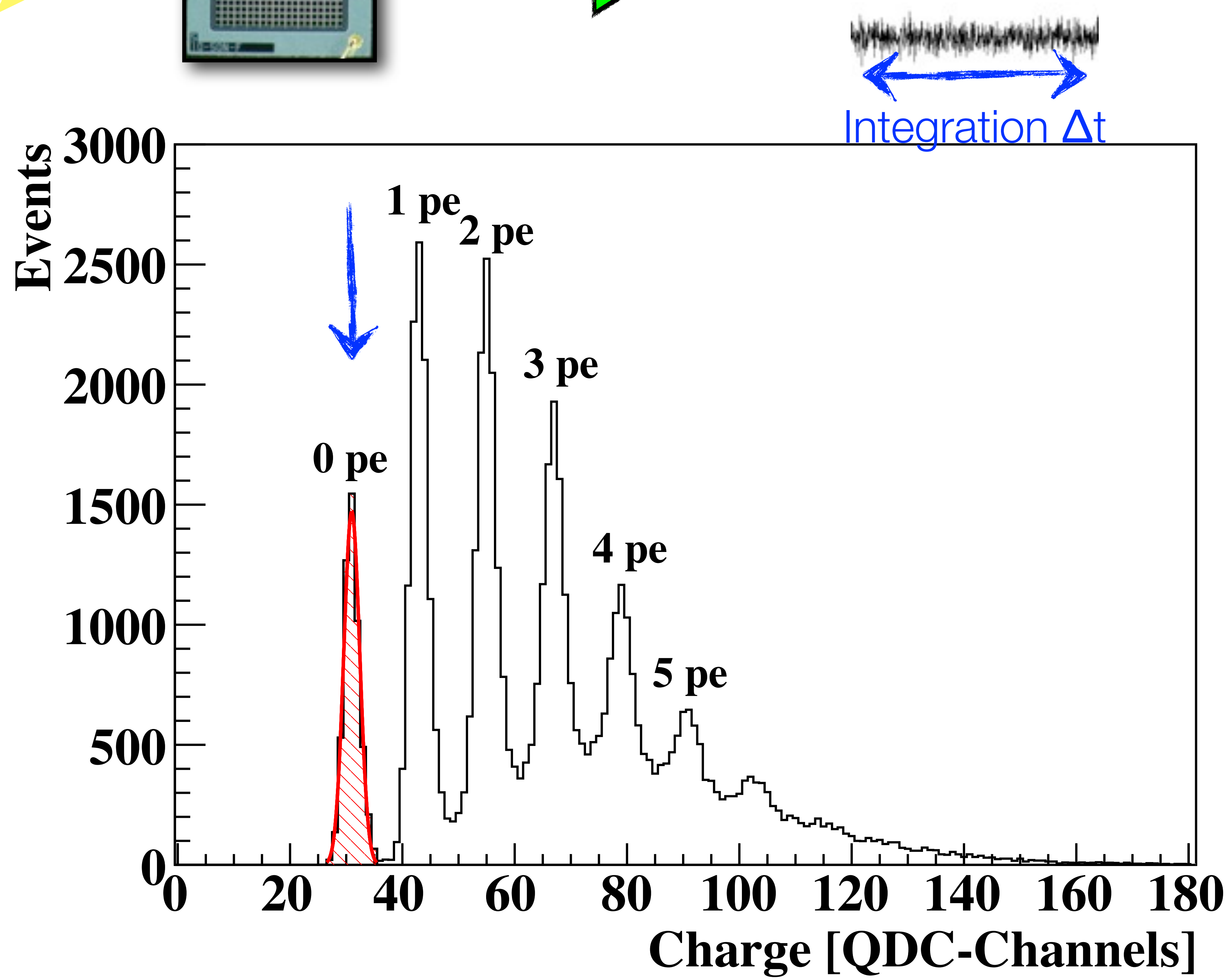
- SiPM is illuminated with short O(ns) LED pulses
- Amplified signal is fed into a charge to digital converter (QDC)
- Integration gate *(typ. 20 - 100 ns)*
- Integrate charge for each light pulse

add a light source

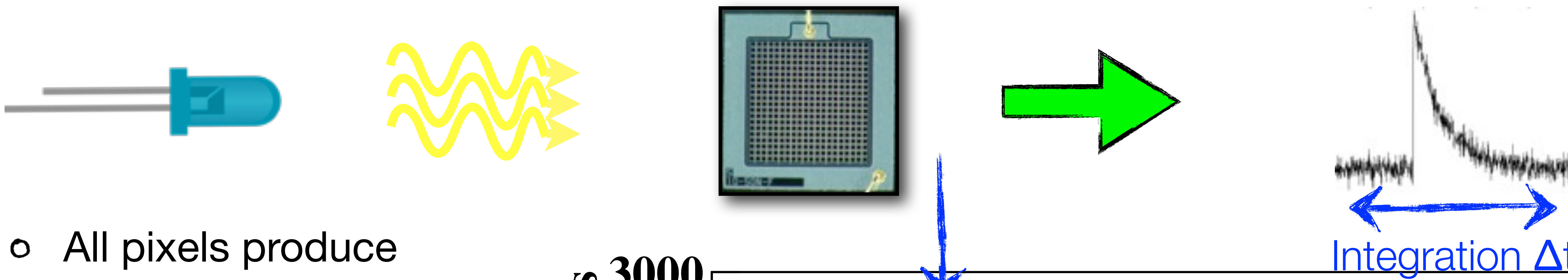


Photoelectron spectrum

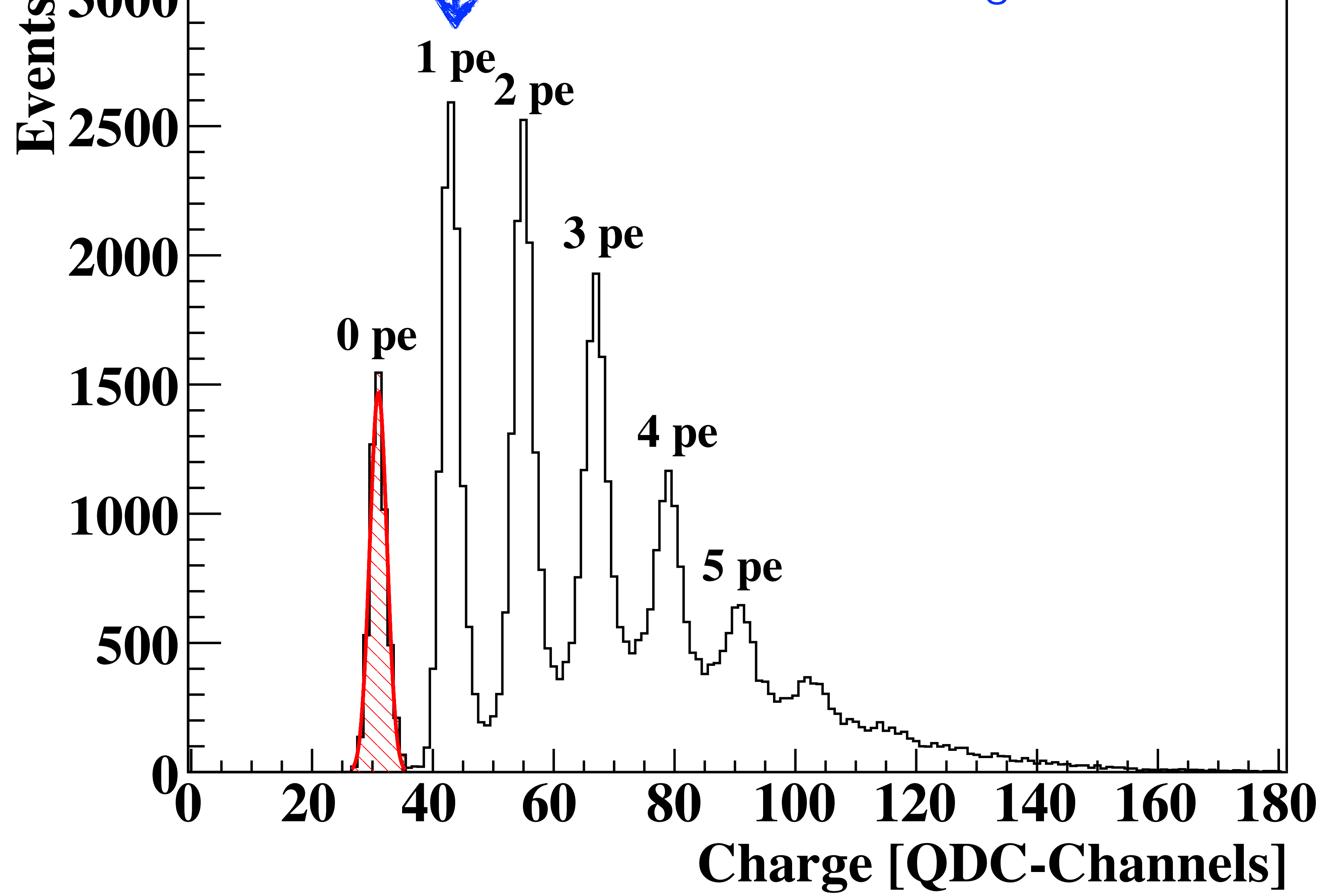
- All pixels produce nearly the same charge *(peaks can be easily separated)*
- Amplification (gain) can be determined from the diagram
  - Peak fitting
  - Fast Fourier transformation



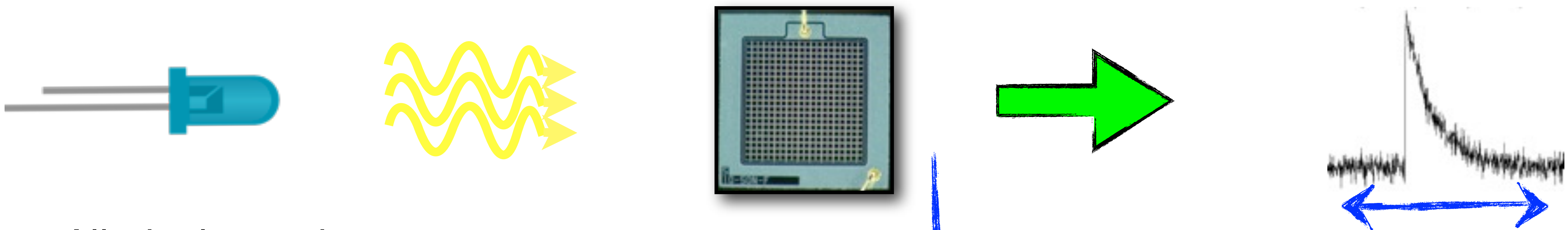
Photoelectron spectrum



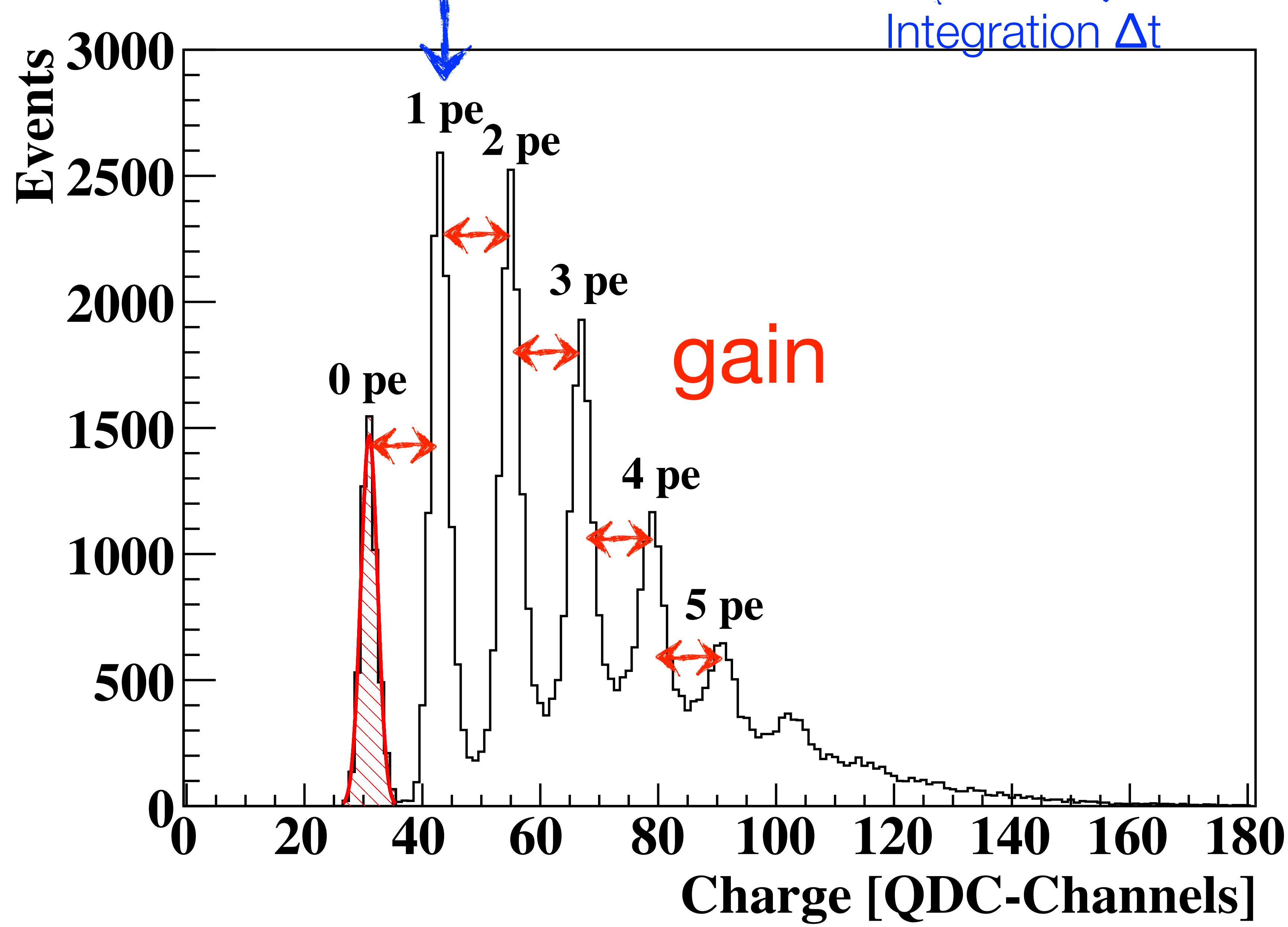
- All pixels produce nearly the same charge *(peaks can be easily separated)*
- Amplification (gain) can be determined from the diagram
  - Peak fitting
  - Fast Fourier transformation



Photoelectron spectrum

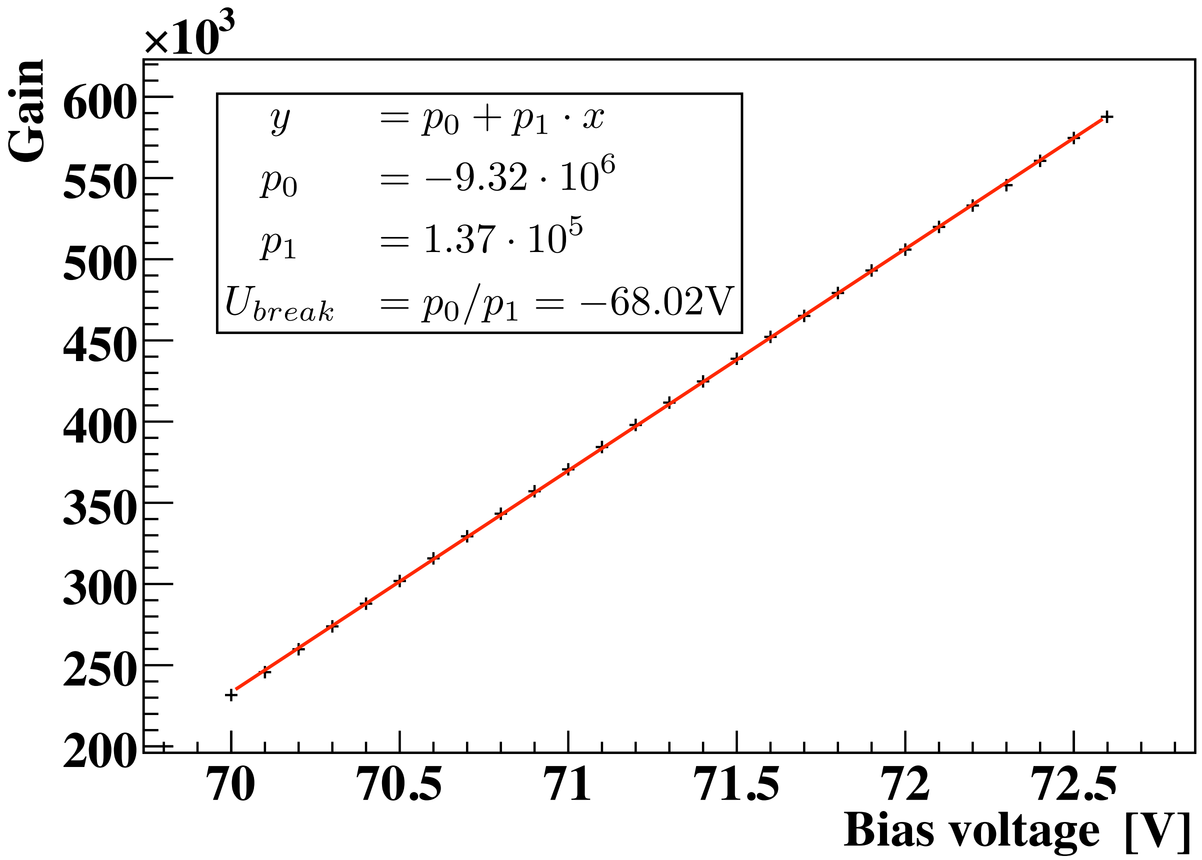


- All pixels produce nearly the same charge *(peaks can be easily separated)*
- Amplification (gain) can be determined from the diagram
  - Peak fitting
  - Fast Fourier transformation

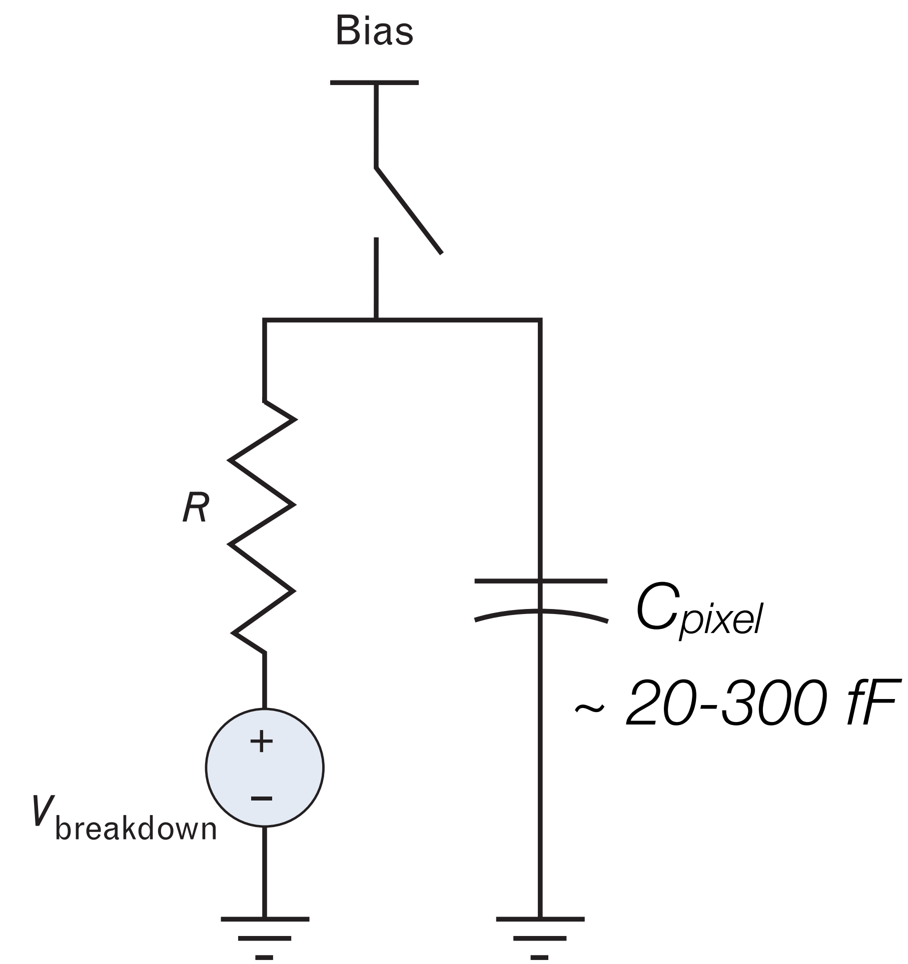


Gain-voltage dependence

Gain vs. over-voltage



simple SiPM pixel model

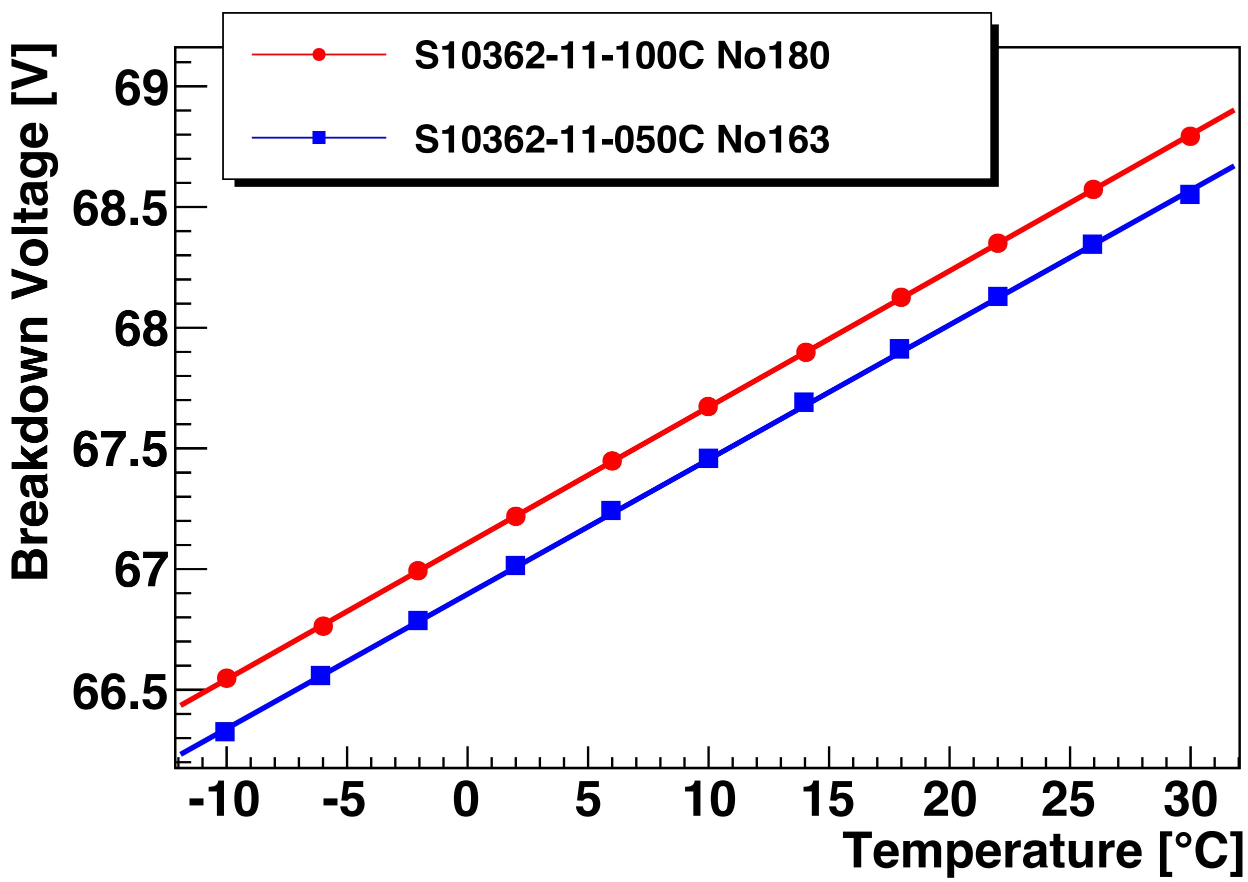


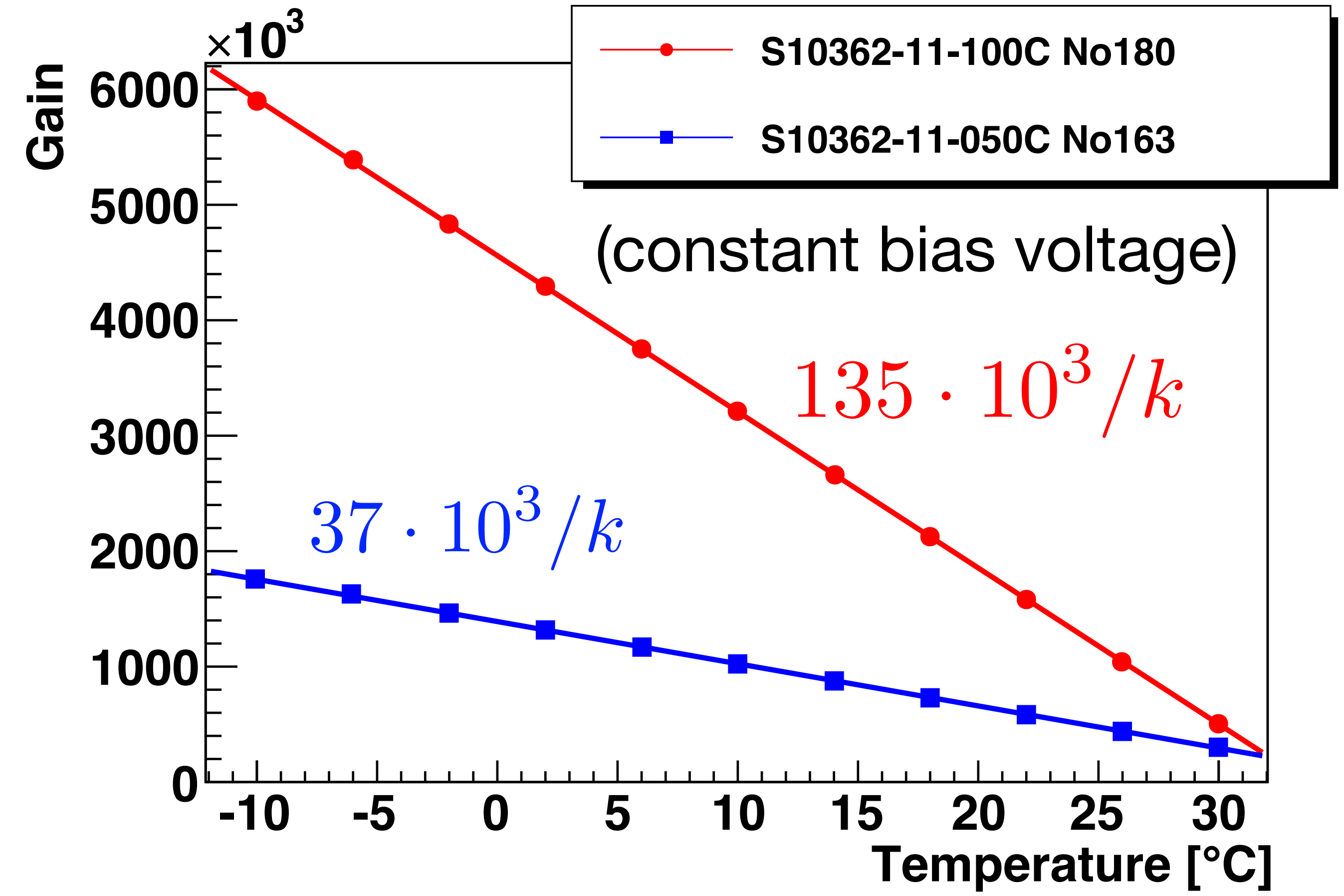
Fit function:

$$G = \frac{C_{pixel}}{q_e}(U_{bias} - U_{break})$$

➟ determine breakdown voltage and pixel capacitance from the fit parameters

Temperature dependence





Temperature coefficient

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

Interaction with phonons (vibrations) slows down the charge carriers -> Higher field needed for breakdown

Large pixel capacitance causes large temperature dependence

$$\frac{dG}{dT} = -\frac{C_{pixel}}{qe} \cdot \frac{dU_{break}}{dT}$$

Photon detection efficiency

- Definition:

$$PDE = \frac{Number\ of\ detected\ photons}{Number\ incident\ photons}$$

- In case of a SiPM:

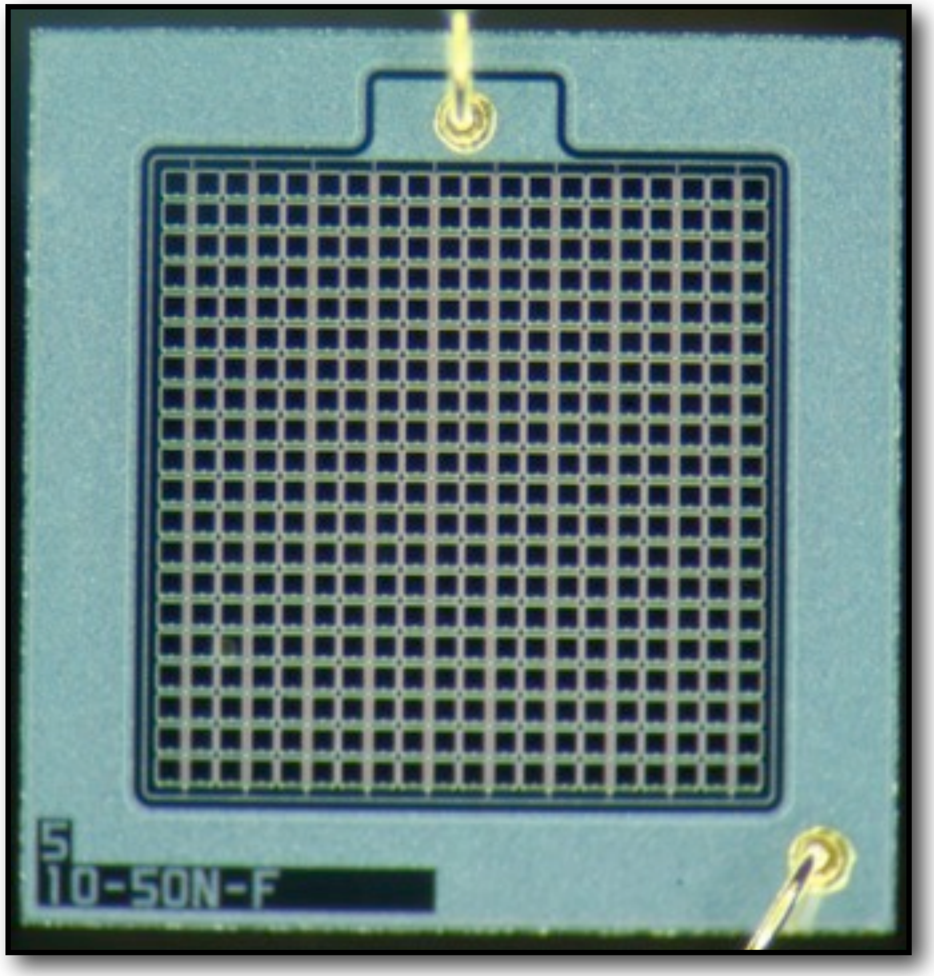
$$\boxed{PDE = \epsilon_{geo} \cdot QE \cdot \epsilon_{trigger}}$$

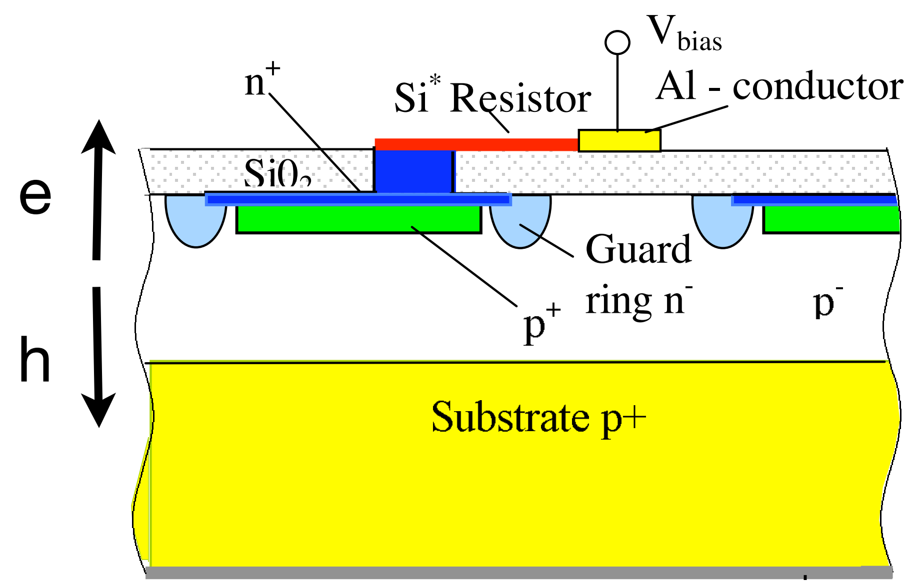
$$\epsilon_{geo} = \frac{A_{sensitive}}{A_{total}}$$

$$QE = Quantum\ efficiency$$

$$\epsilon_{trigger} = \text{avalanche trigger probability}$$

depends on U_{over} and position (λ)





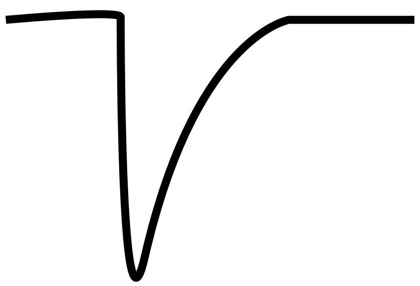
Measurement technique

- PDE measurement is difficult because of cross-talk and after-pulsing

Measurement technique

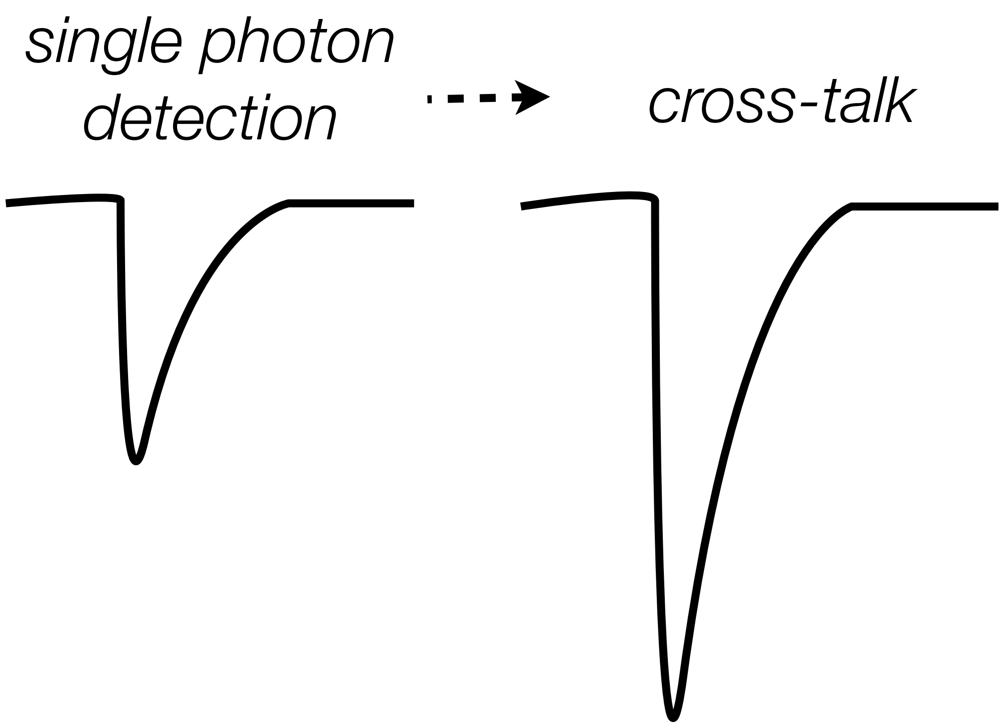
- PDE measurement is difficult because of cross-talk and after-pulsing

single photon detection



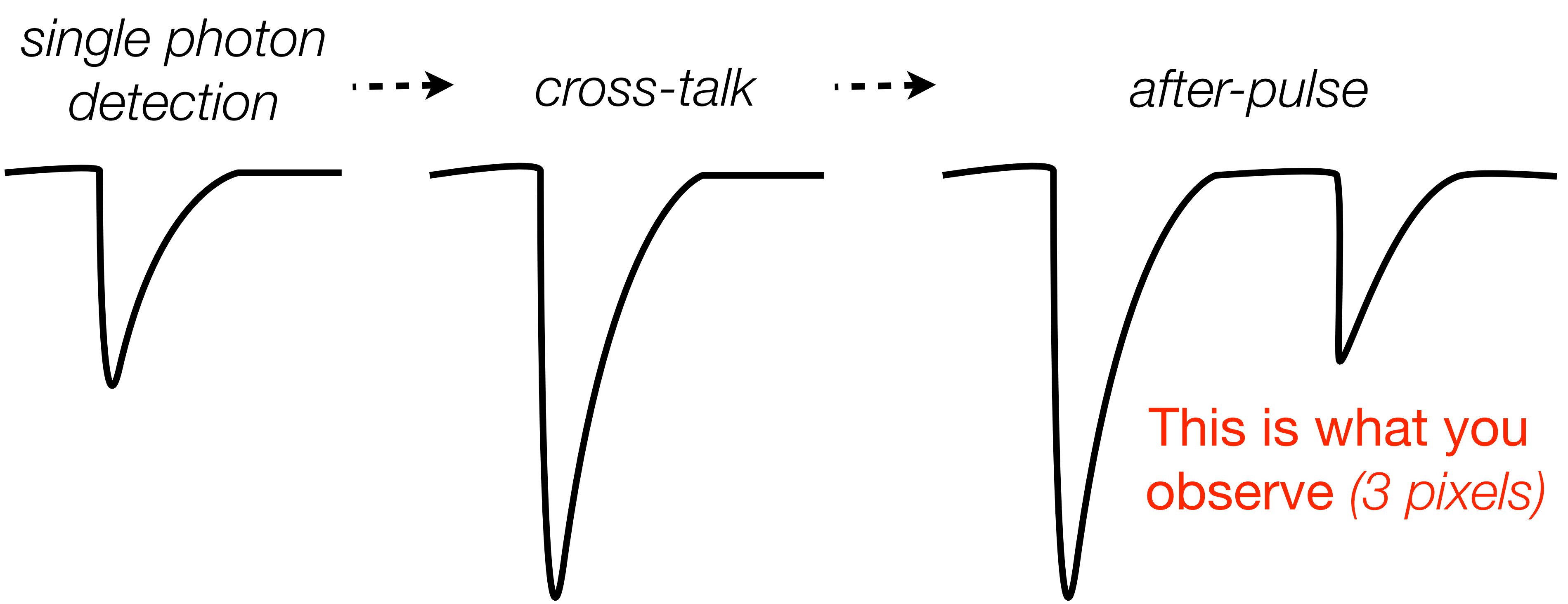
Measurement technique

- PDE measurement is difficult because of cross-talk and after-pulsing



Measurement technique

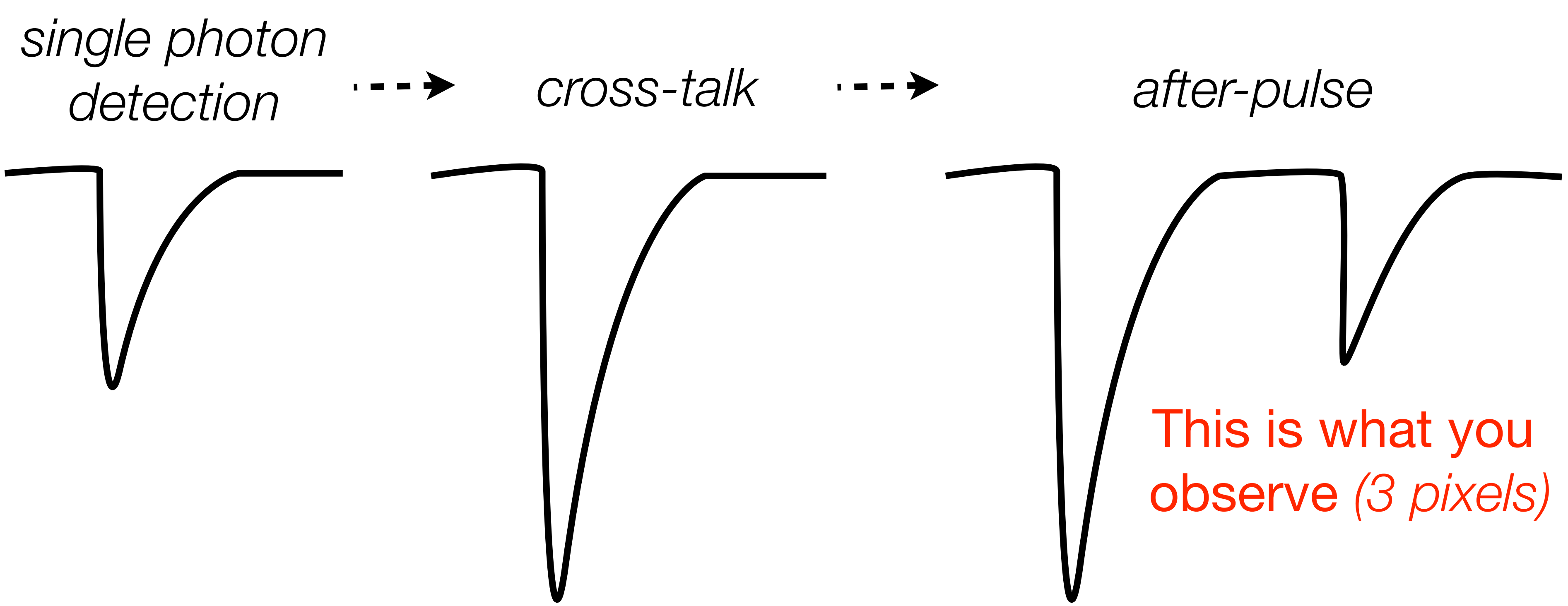
- PDE measurement is difficult because of cross-talk and after-pulsing



How many photons have been detected?

Measurement technique

- PDE measurement is difficult because of cross-talk and after-pulsing



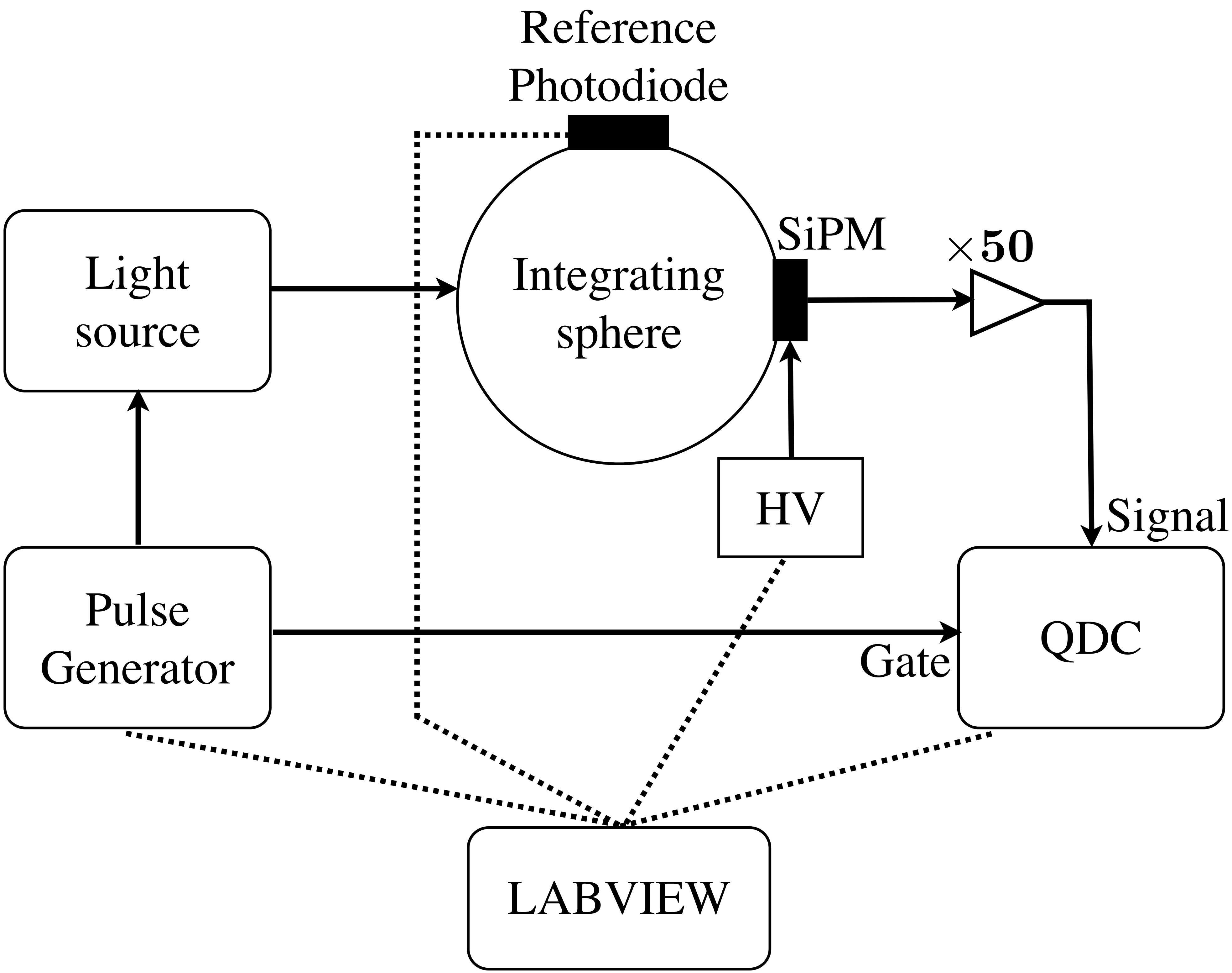
This is what you observe *(3 pixels)*

How many photons have been detected?

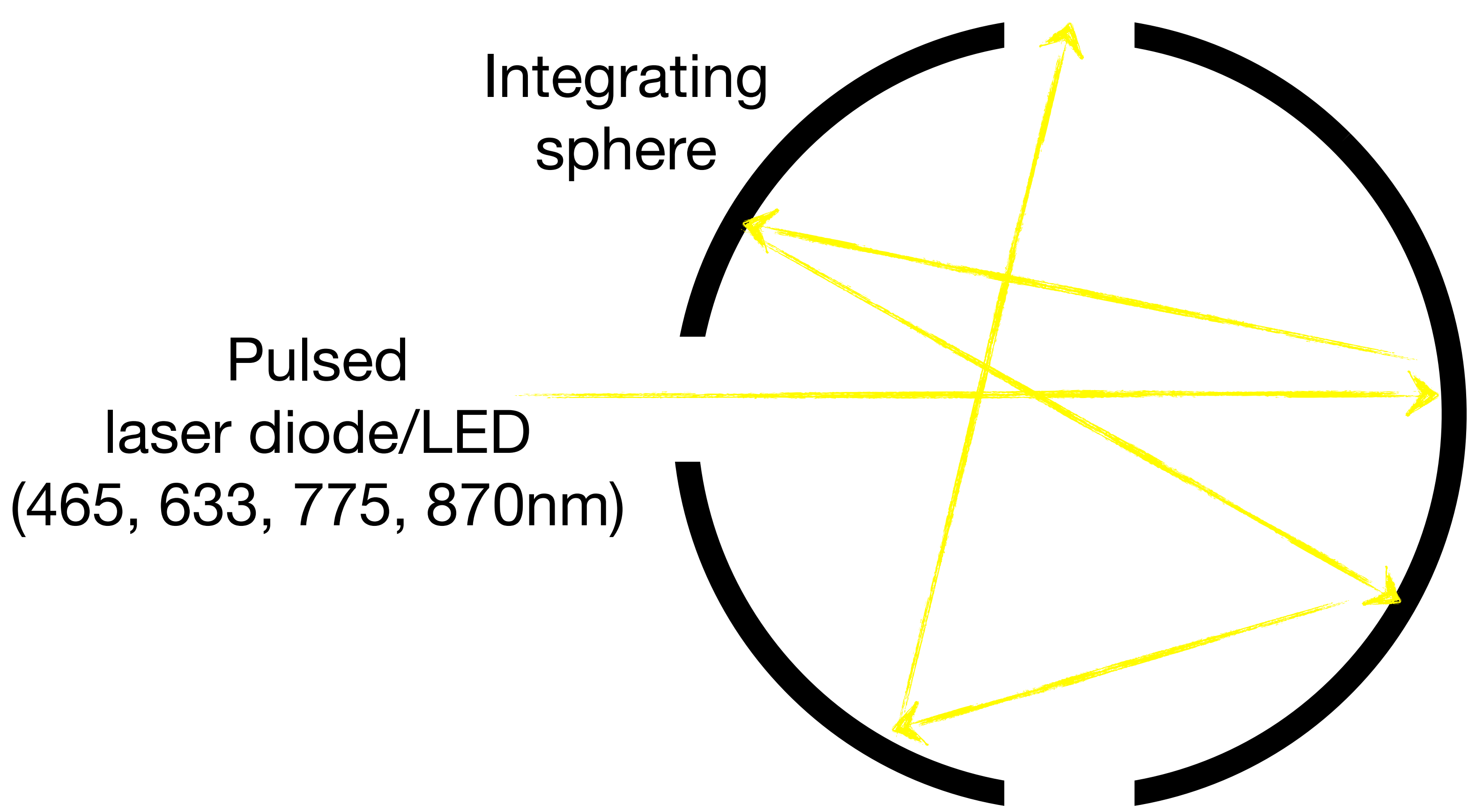
If this effect is not considered in the measurement you will measure too large values for the PDE *(values larger than one possible)*

➟ Need a method which is insensitive to cross-talk and after-pulses

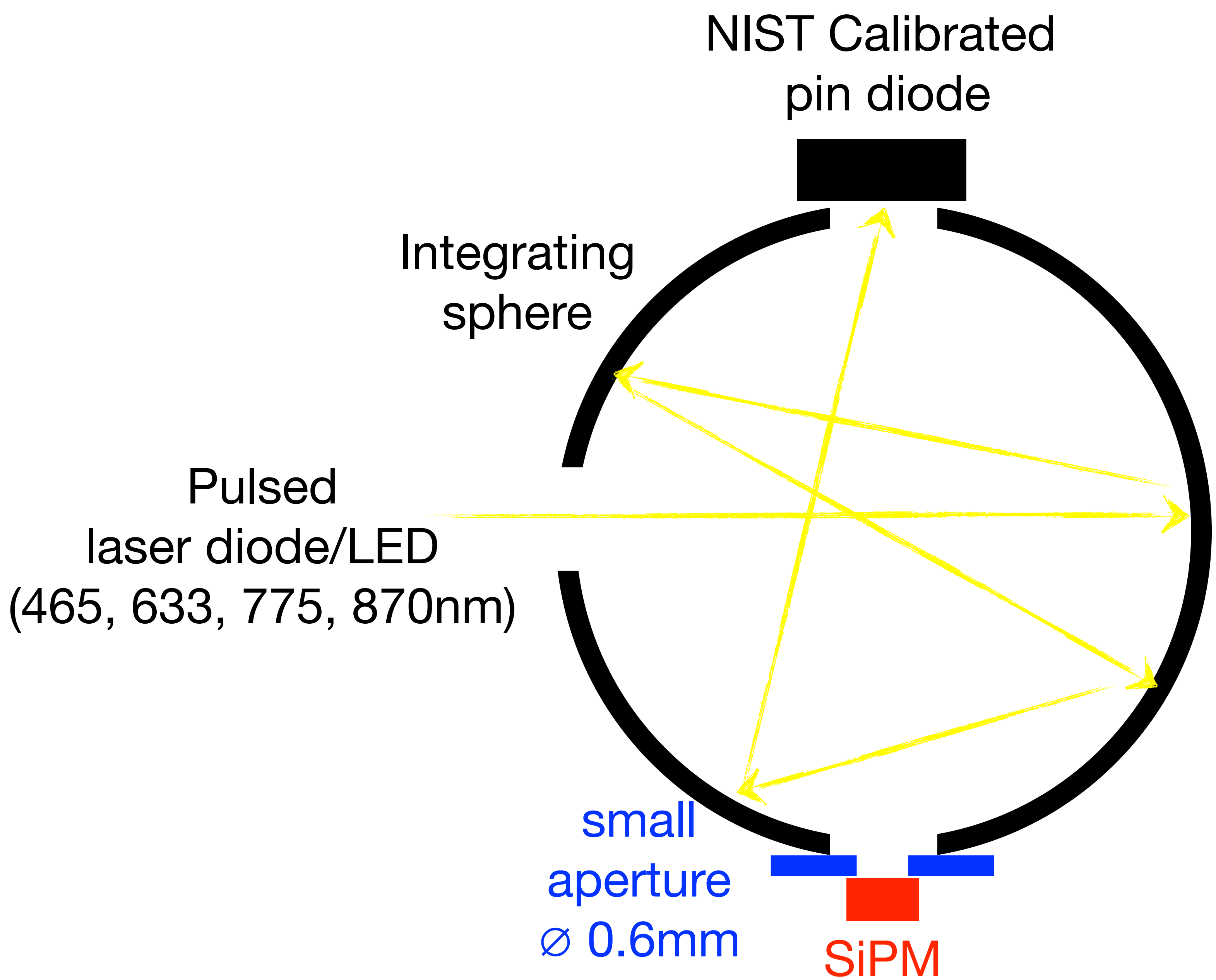
PDE measurement setup



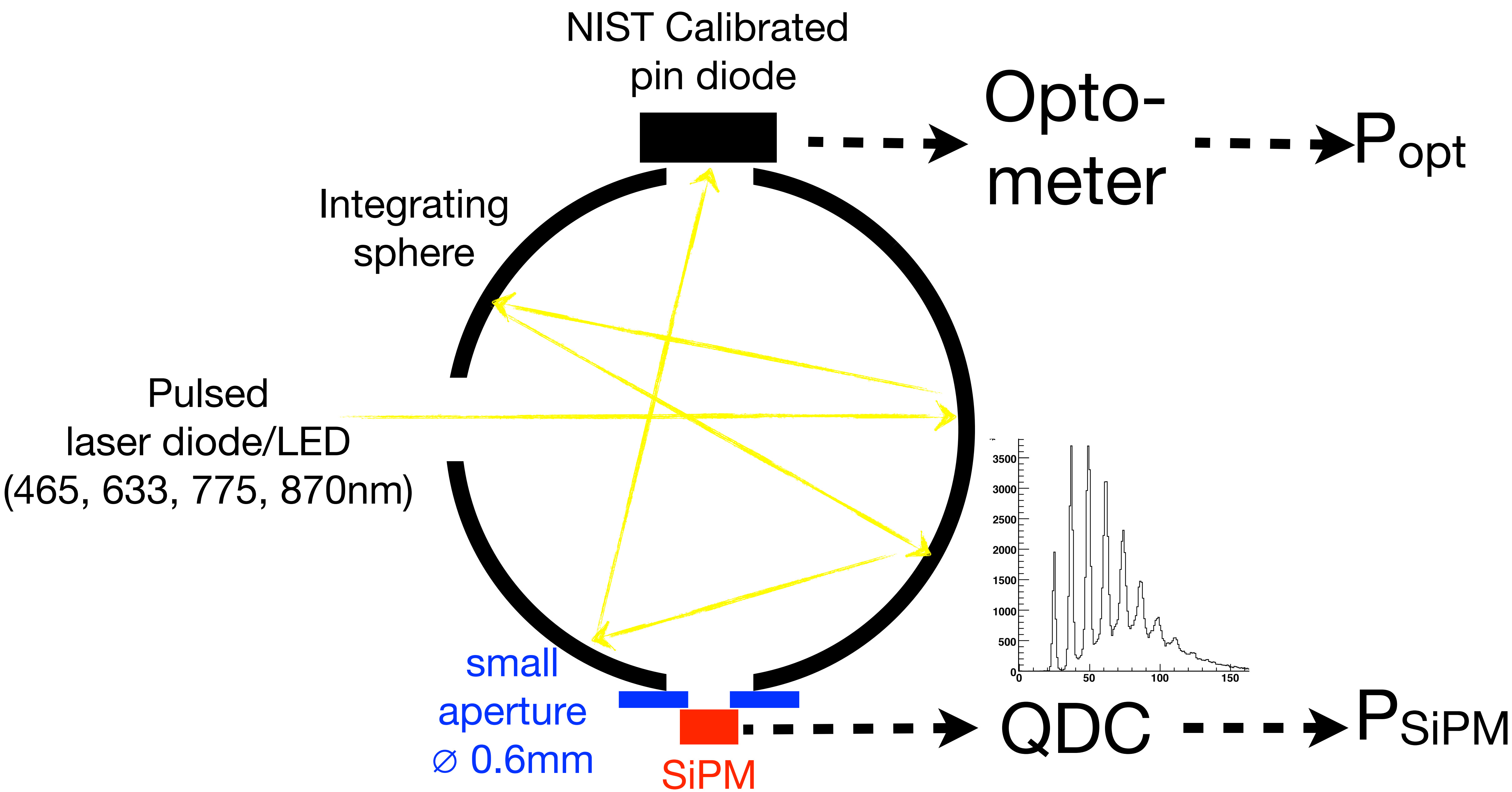
Setup: Absolute PDE



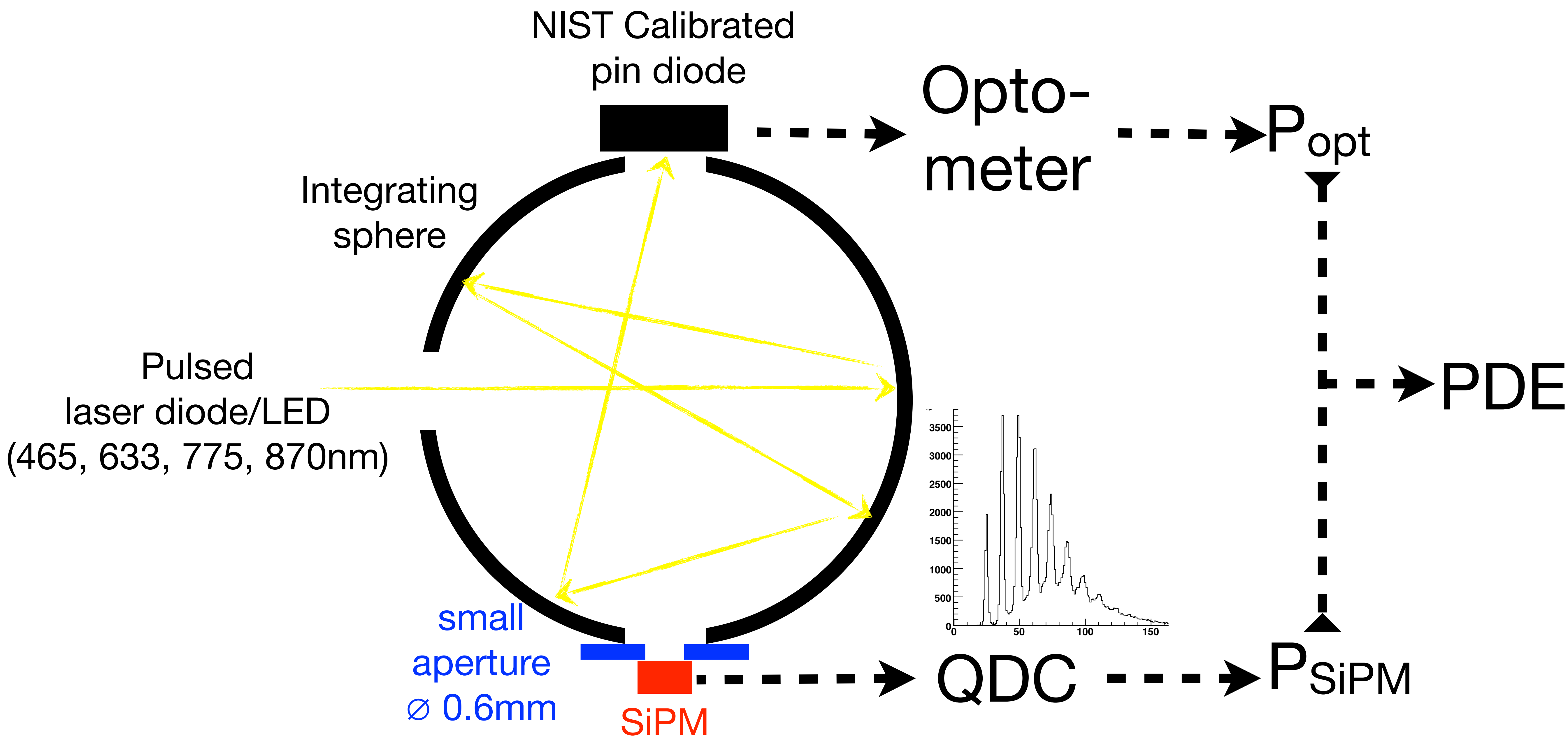
Setup: Absolute PDE



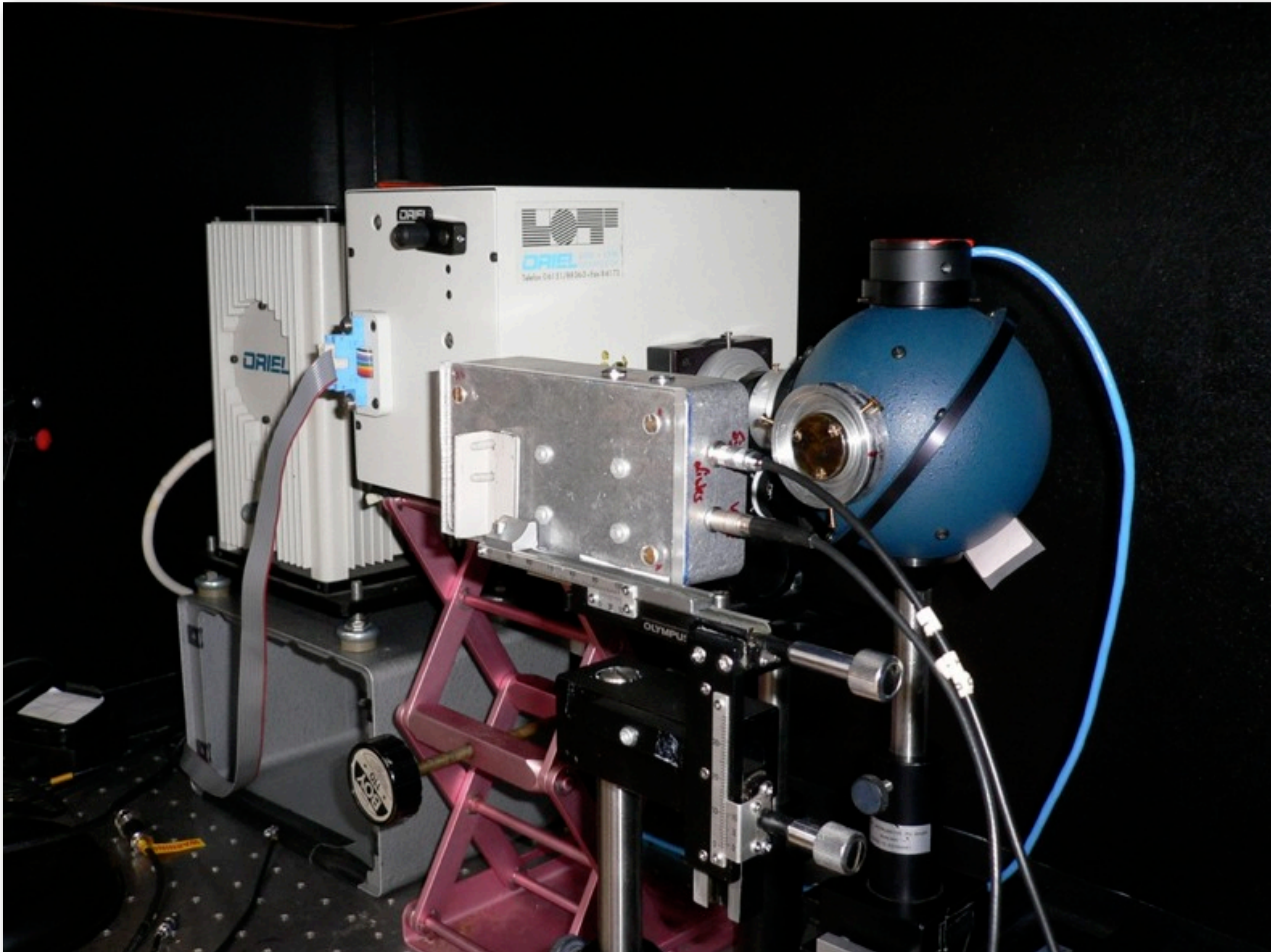
Setup: Absolute PDE



Setup: Absolute PDE



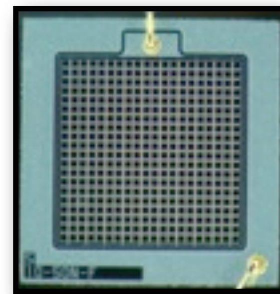
PDE Setup

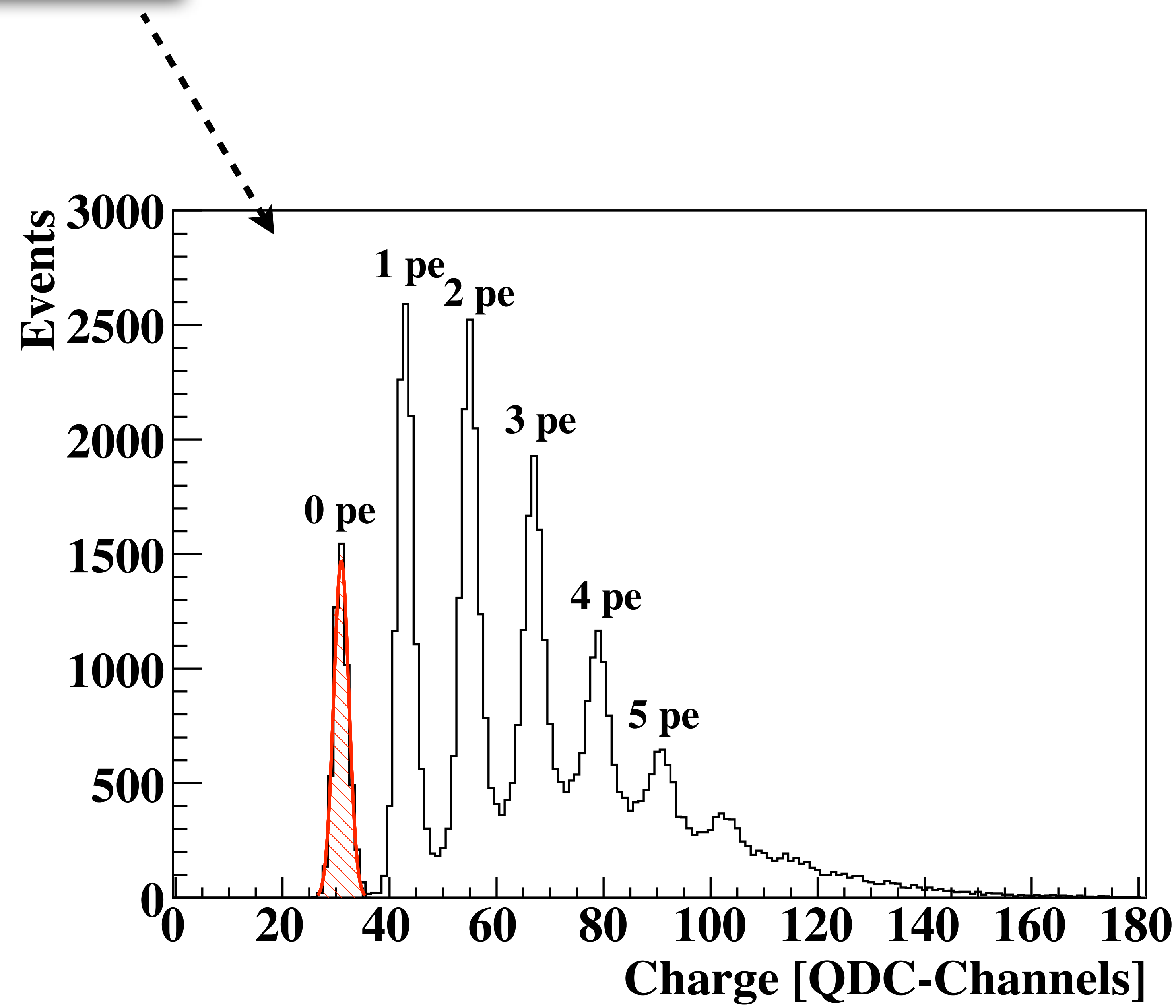


Statistical Analysis

Poisson distributed

$$P_\mu(n) = \frac{\mu^n \cdot e^{-\mu}}{n!}$$

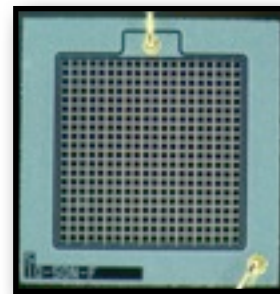




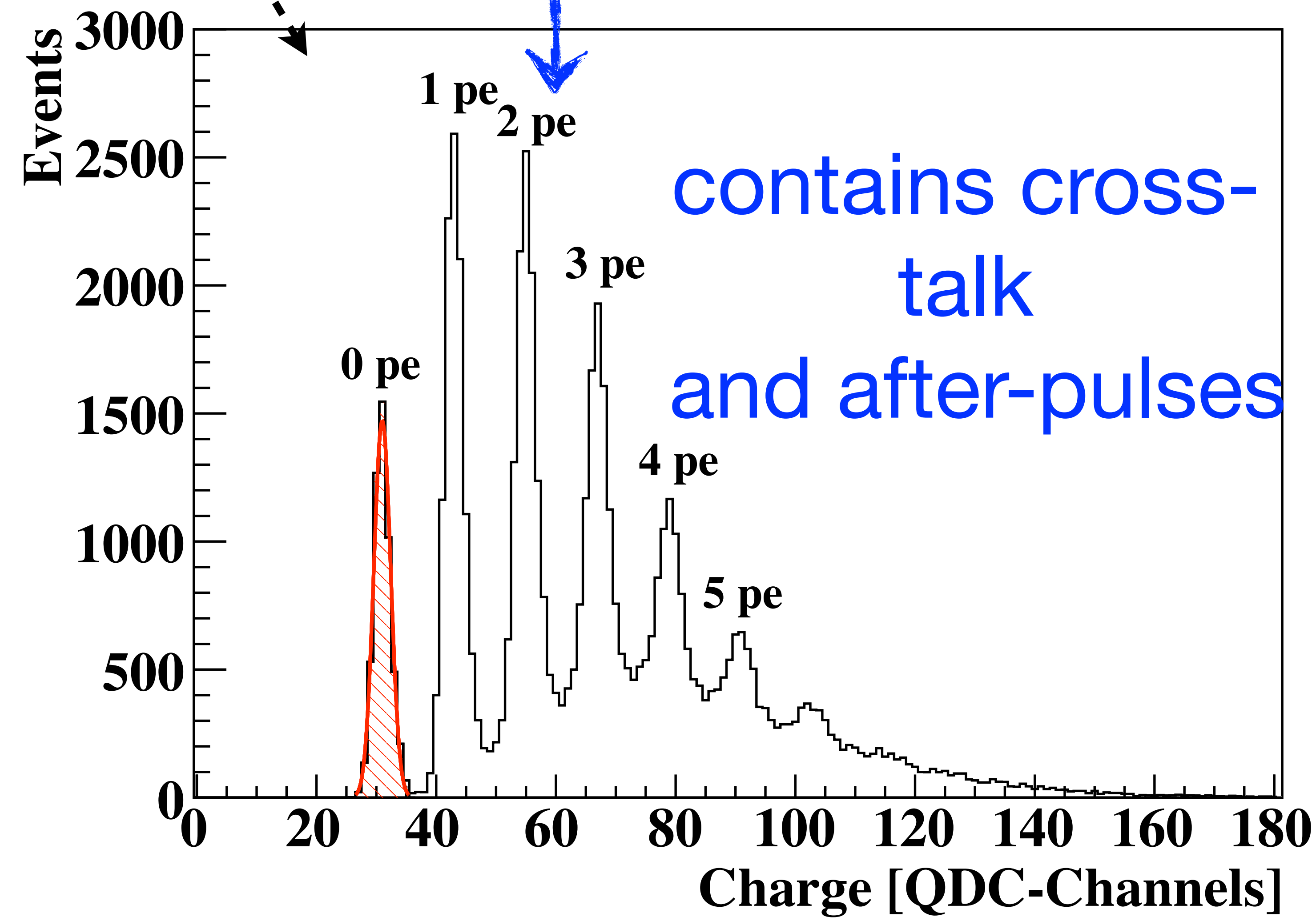
Statistical Analysis

Poisson distributed

$$P_\mu(n) = \frac{\mu^n \cdot e^{-\mu}}{n!}$$



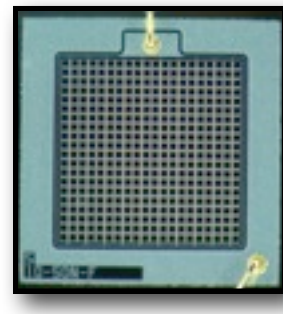
mean



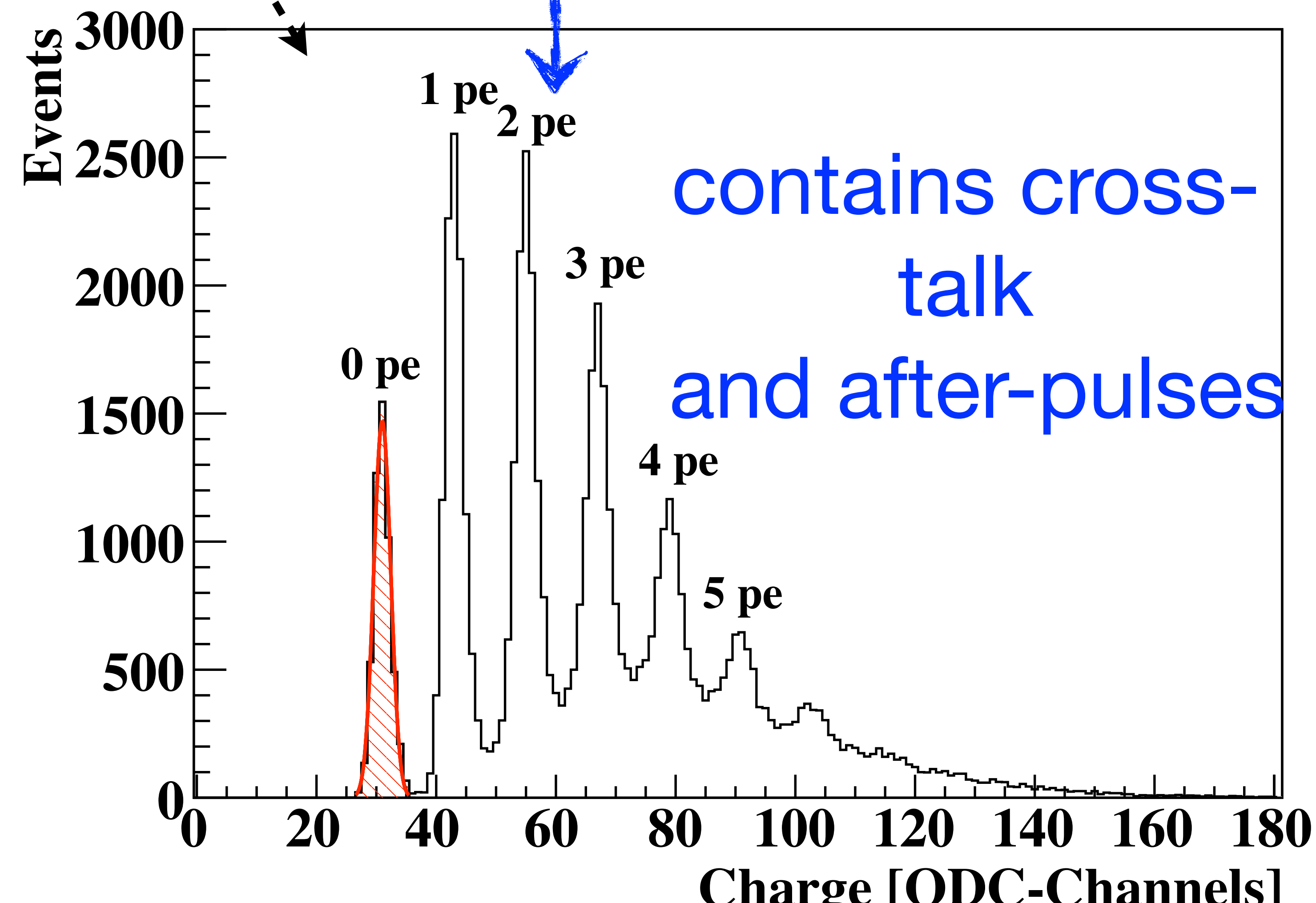
Statistical Analysis

Poisson distributed

$$P_\mu(n) = \frac{\mu^n \cdot e^{-\mu}}{n!}$$



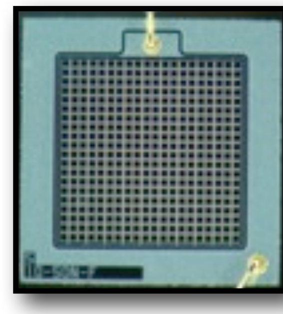
~~mean~~

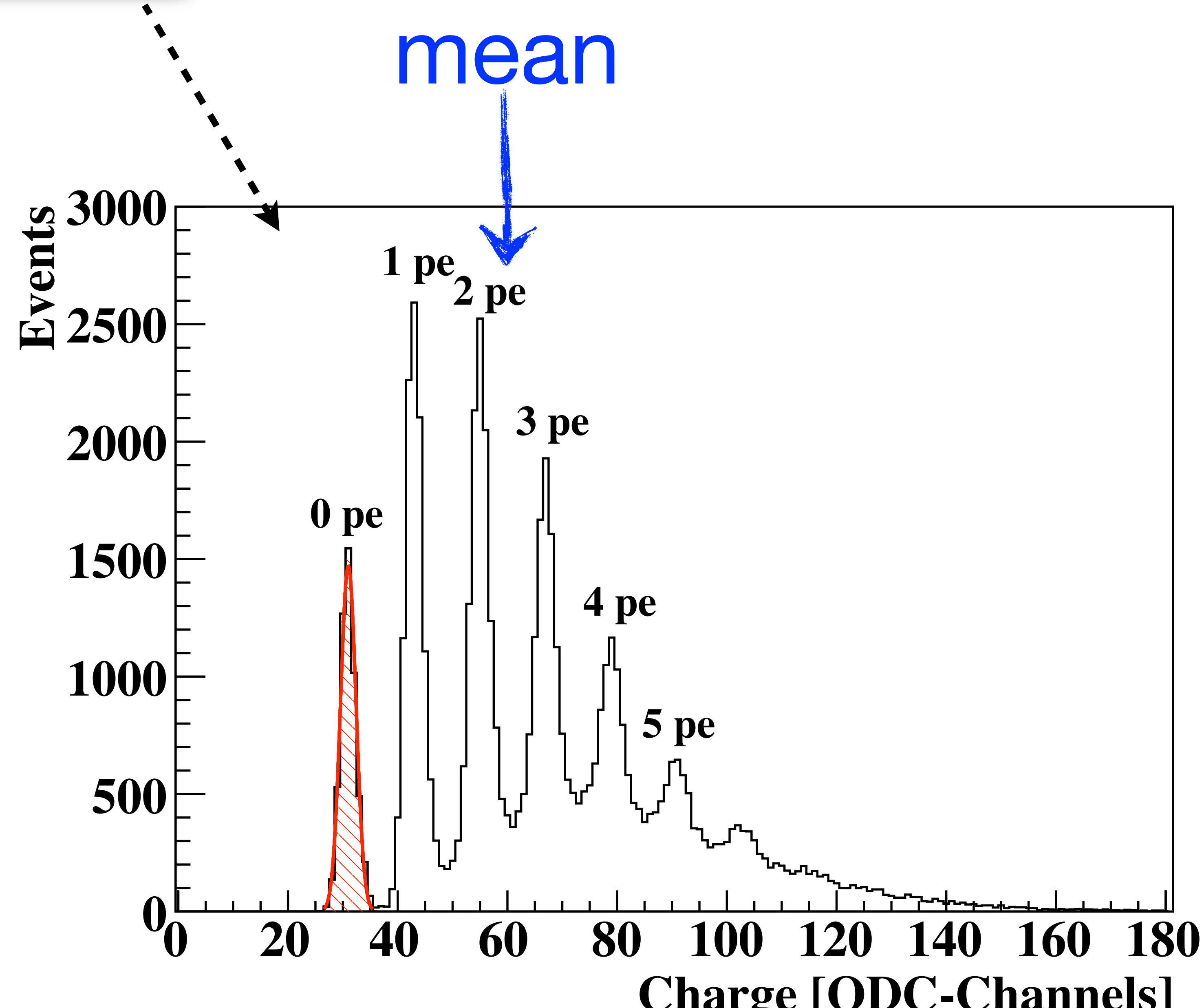


Statistical Analysis

Poisson distributed

$$P_\mu(n) = \frac{\mu^n \cdot e^{-\mu}}{n!}$$

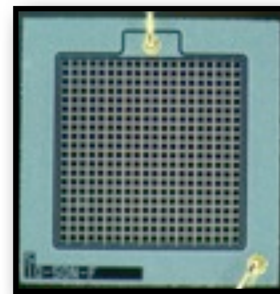




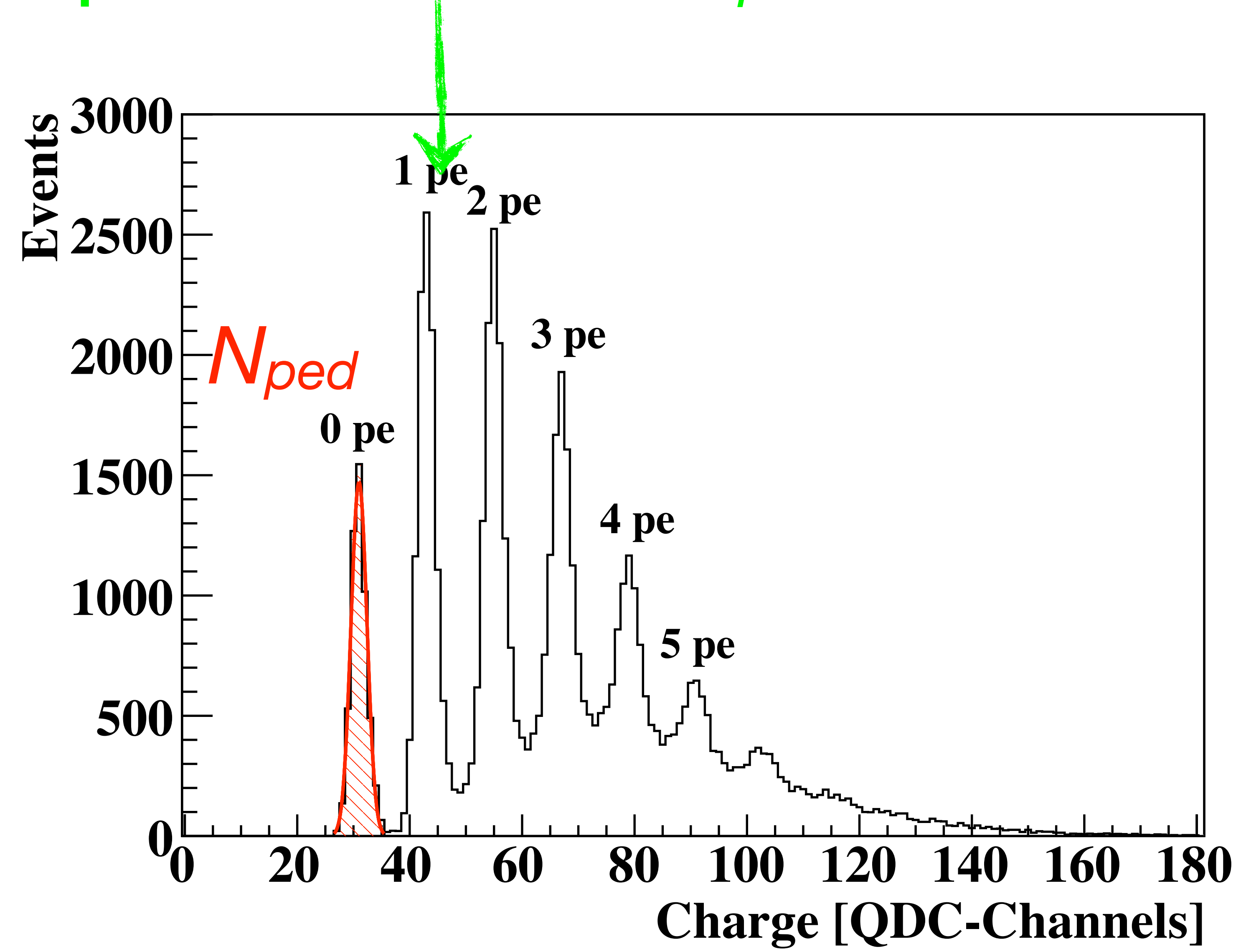
Statistical Analysis

Poisson distributed

$$P_\mu(n) = \frac{\mu^n \cdot e^{-\mu}}{n!}$$



poisson mean n_{pe}

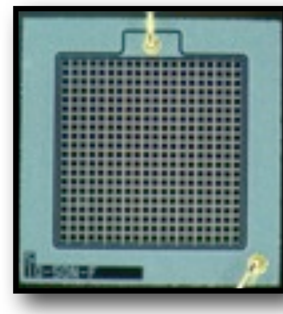


Number of pedestal events, N_{ped}, not influenced by cross-talk and after-pulses!

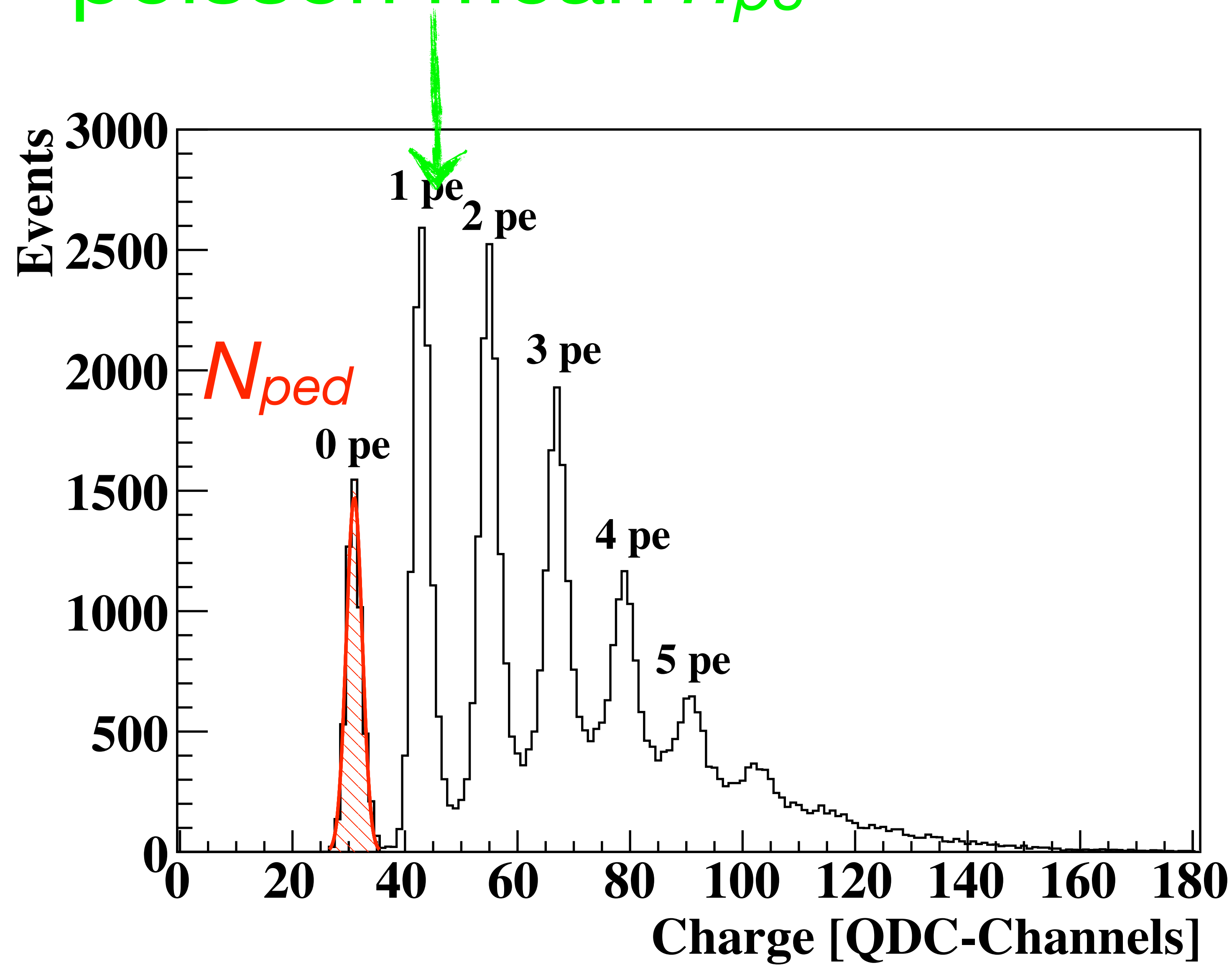
Statistical Analysis

Poisson distributed

$$P_\mu(n) = \frac{\mu^n \cdot e^{-\mu}}{n!}$$



poisson mean n_{pe}



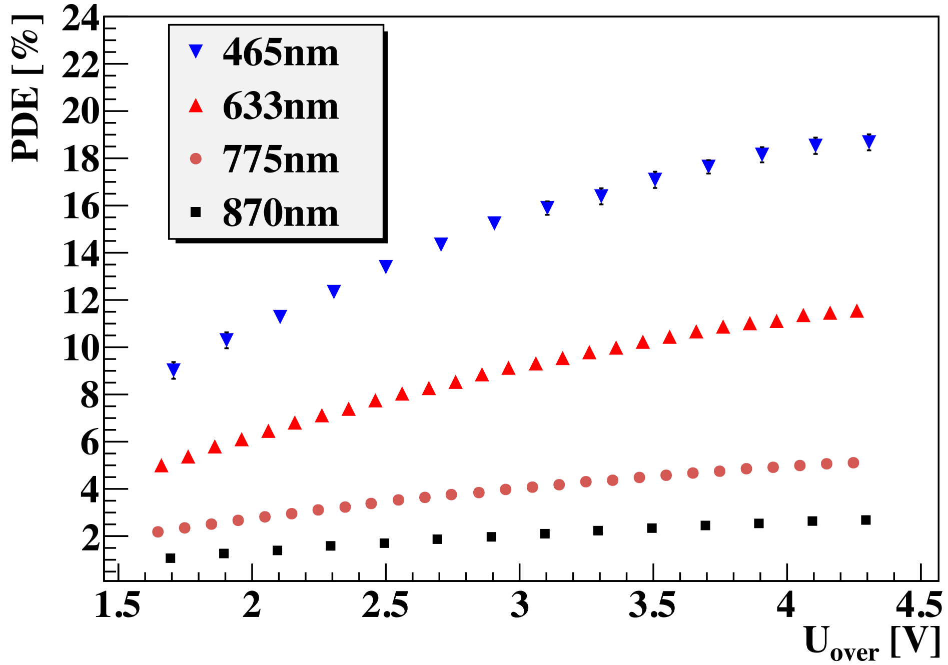
$$\boxed{\begin{aligned} P_{n_{pe}}(0) &= e^{-n_{pe}} \\ \rightarrow n_{pe} &= -ln(P_{n_{pe}}(0)) \\ &= -ln\left(\frac{N_{ped}}{N_{tot}}\right) + ln\left(\frac{N^{ped}_{dark}}{N^{tot}_{dark}}\right) \end{aligned}}$$

Dark-rate correction

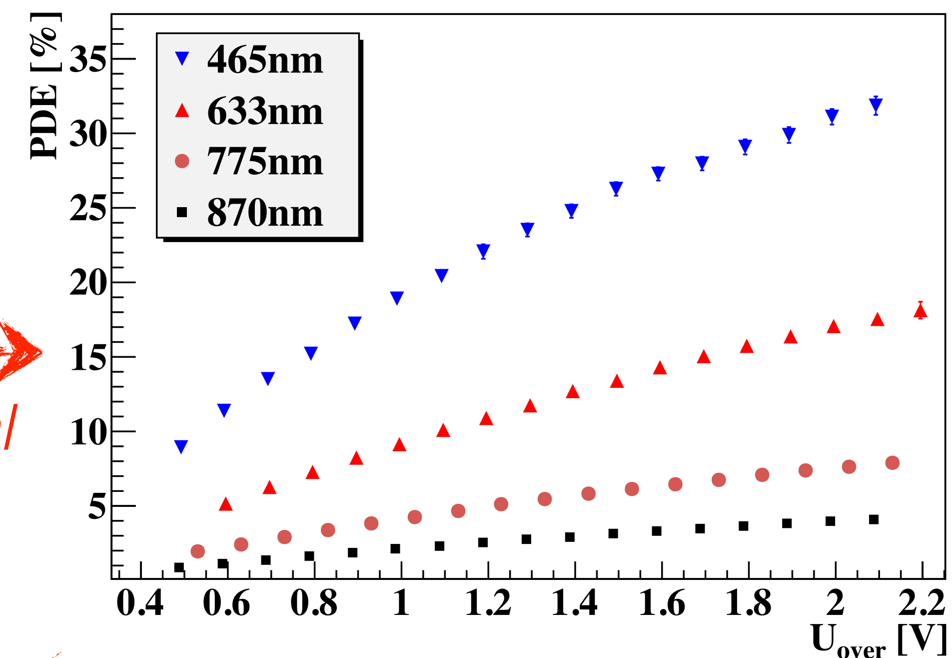
Number of pedestal events, N_{ped}, not influenced by cross-talk and after-pulses!

PDE vs. U_{over}

MPPC 1600 pixels

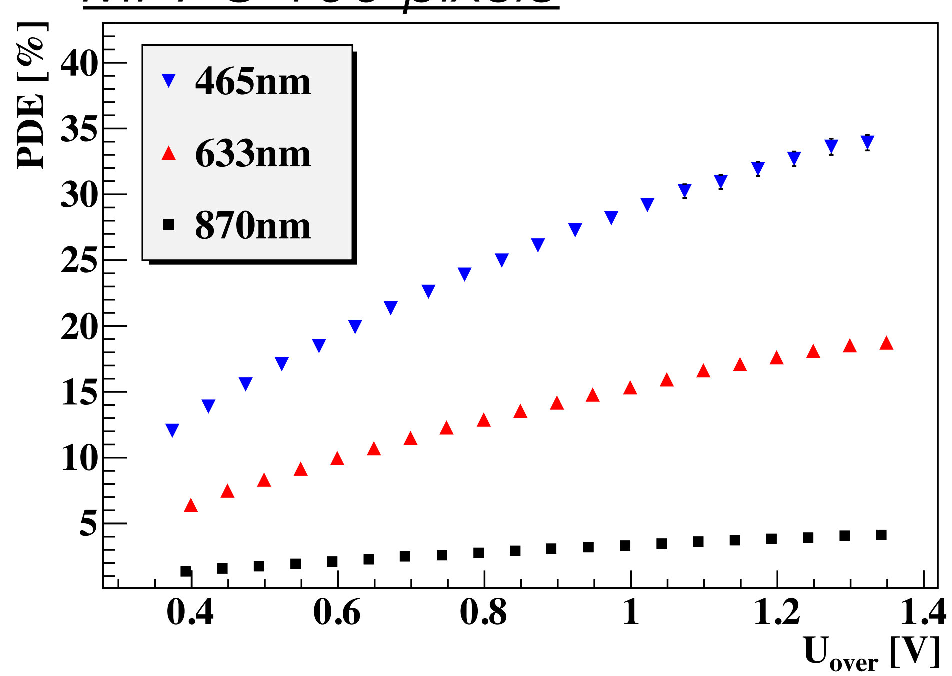


MPPC 400 pixels



higher geometrical efficiency

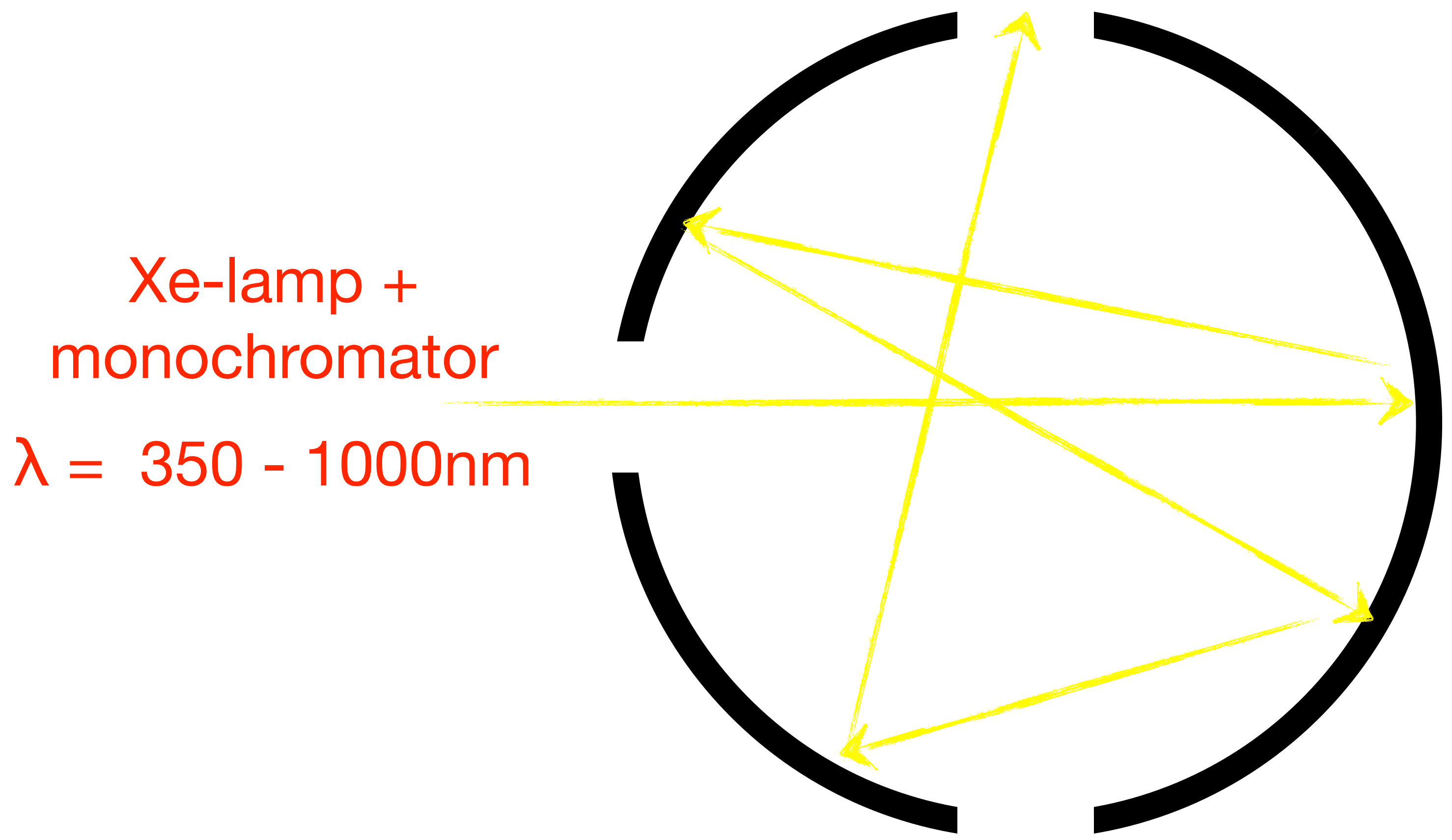
MPPC 100 pixels



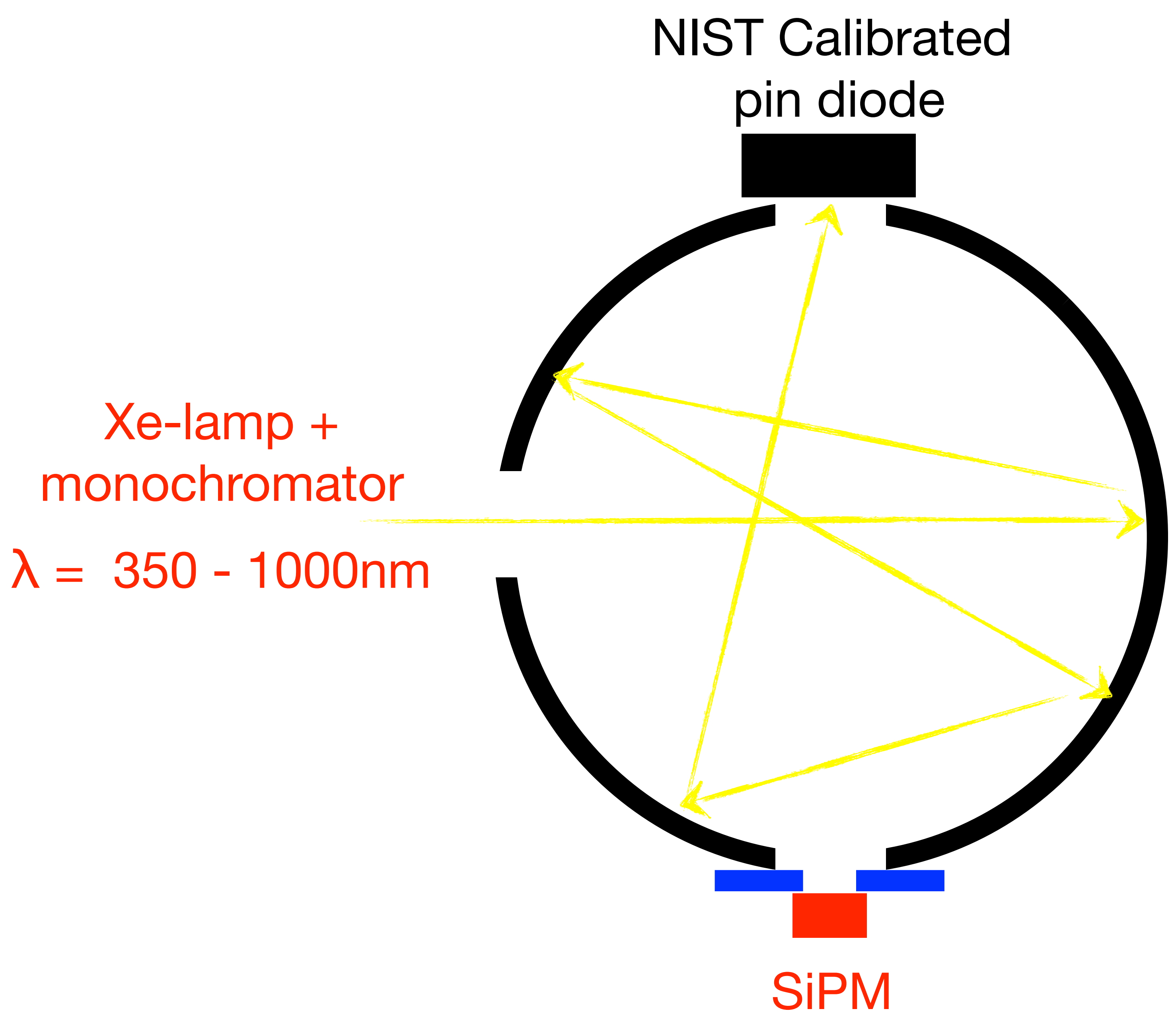
$$PDE = \frac{P_{SiPM}}{P_{opt}} = \frac{n_{pe} \cdot h\nu \cdot R \cdot f}{P_{opt}}$$

R: Power ratio
f: Pulsing frequency

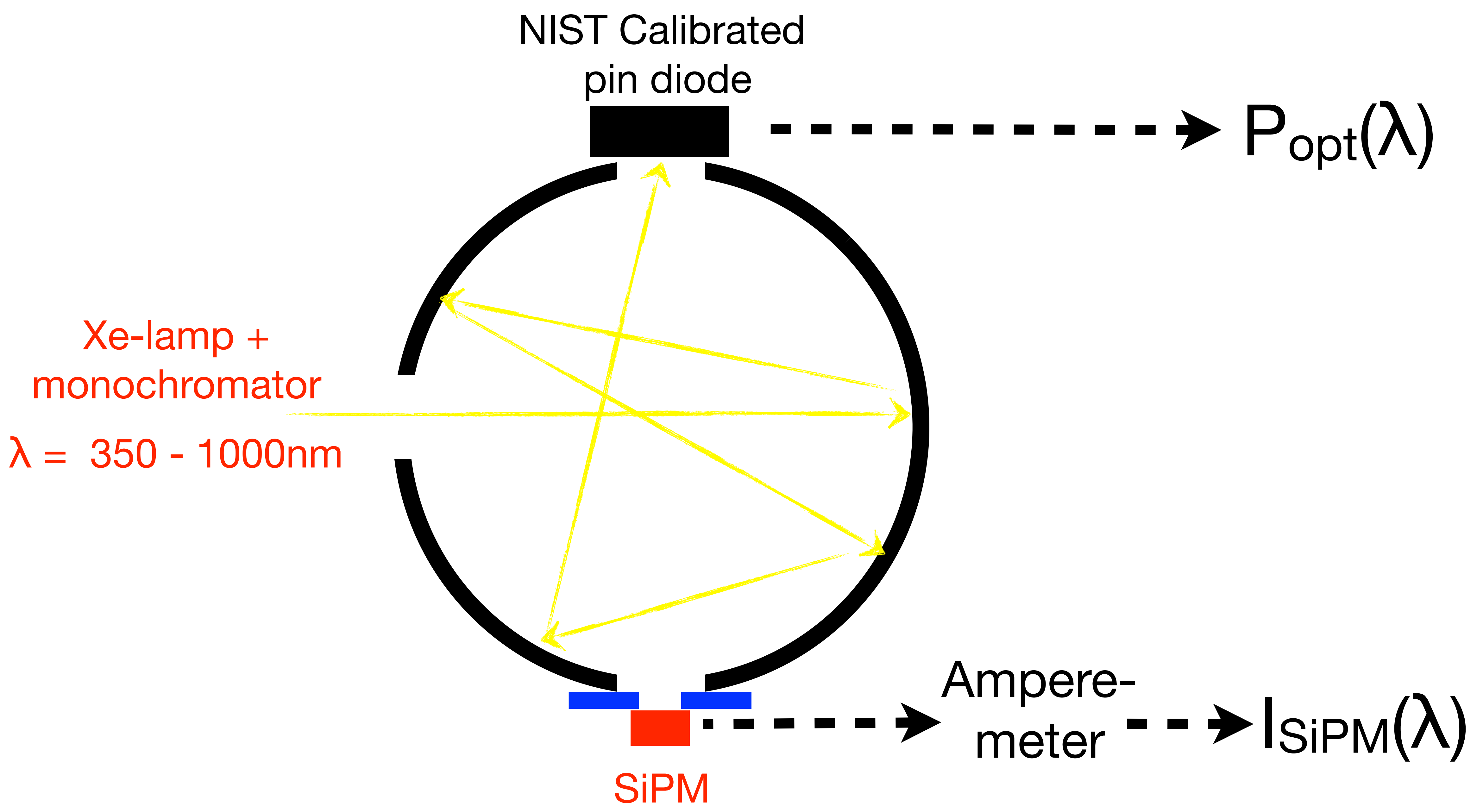
Setup: Spectral Sensitivity



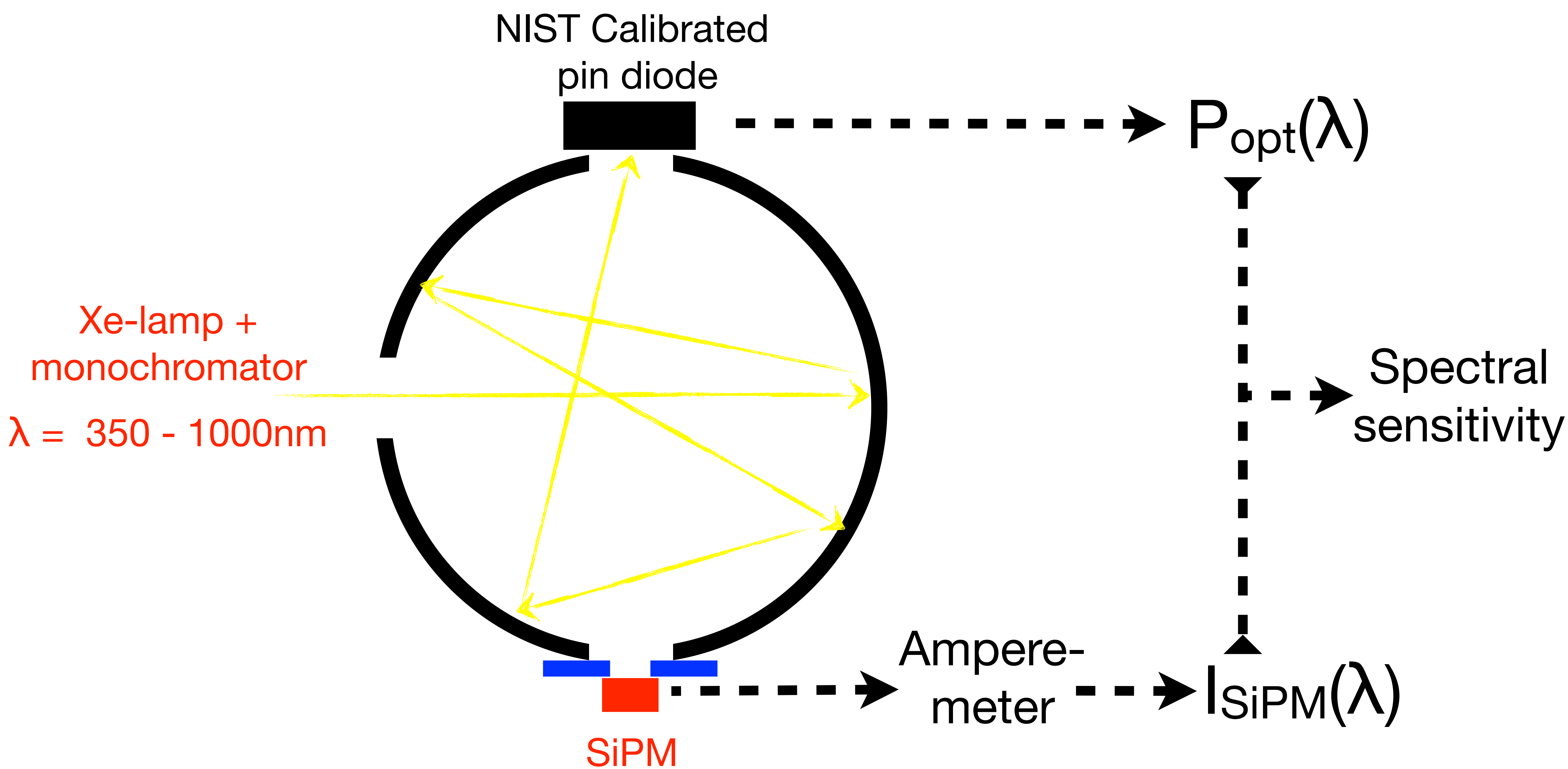
Setup: Spectral Sensitivity



Setup: Spectral Sensitivity

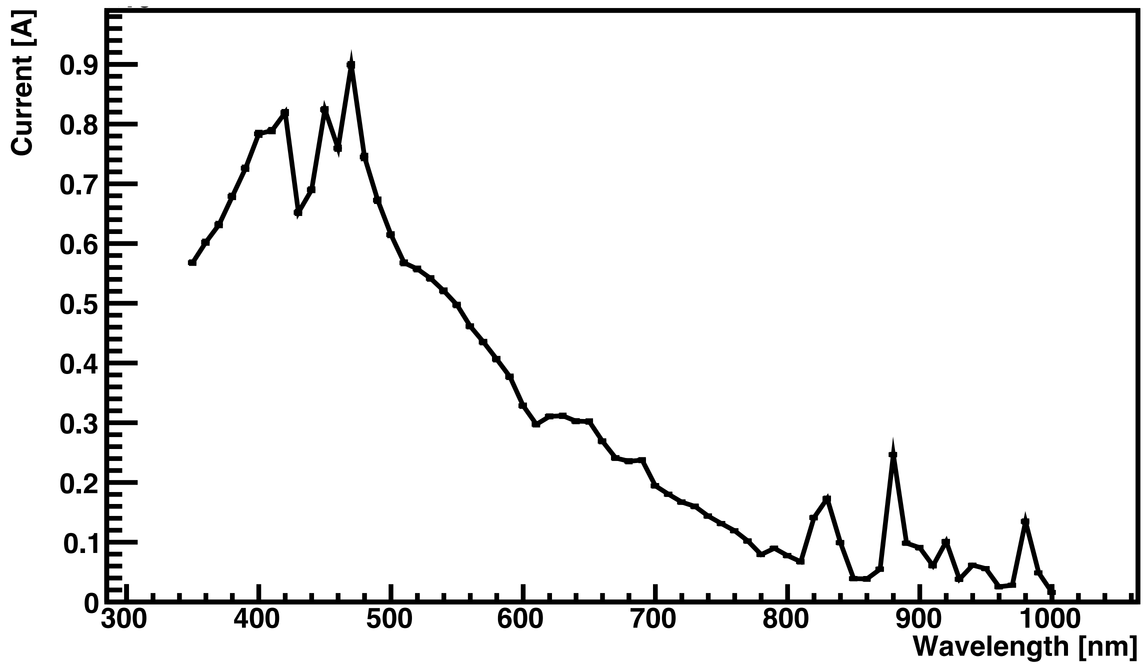


Setup: Spectral Sensitivity

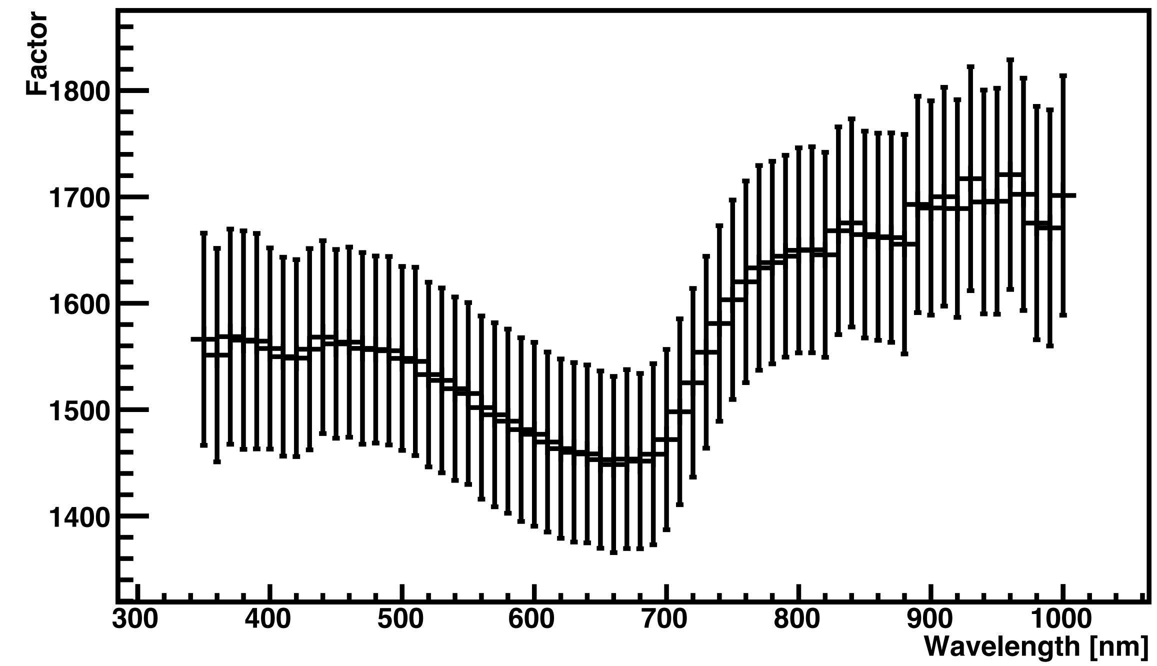


Spectral Sensitivity

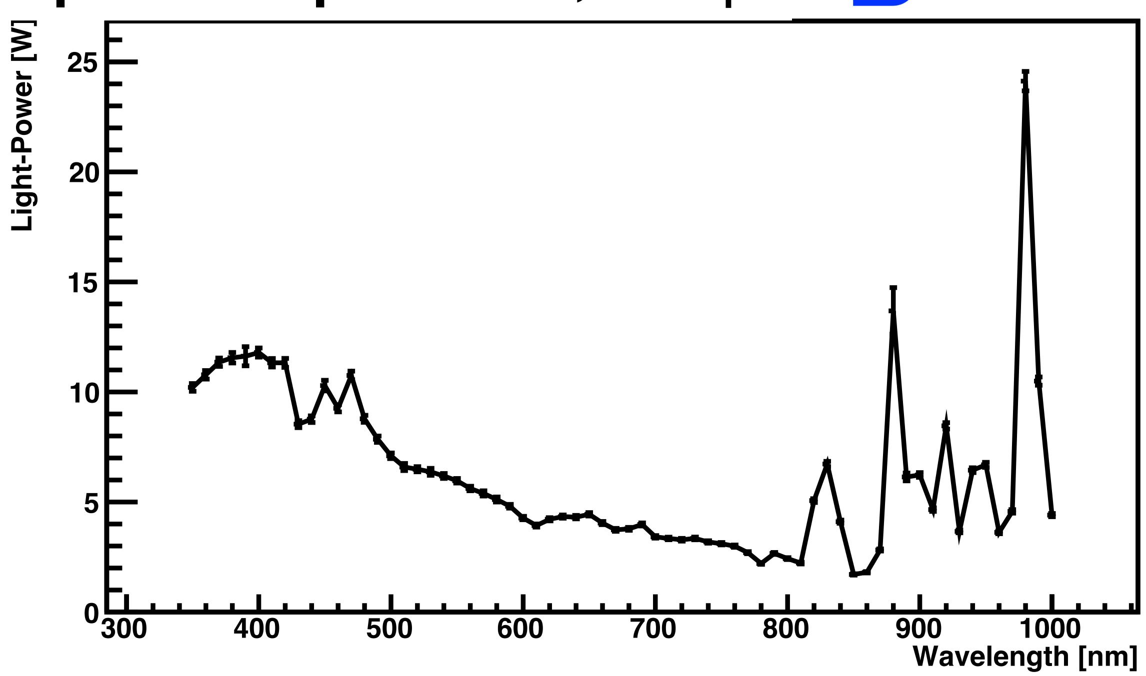
SiPM current, I_{SiPM} A



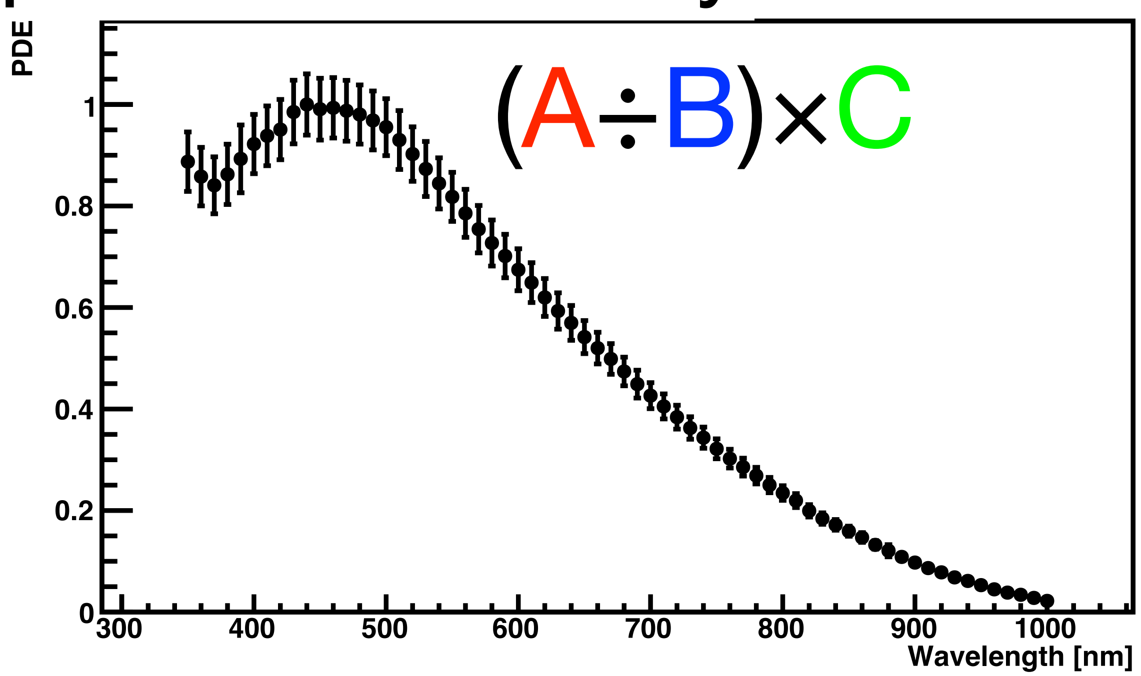
Power ratio C



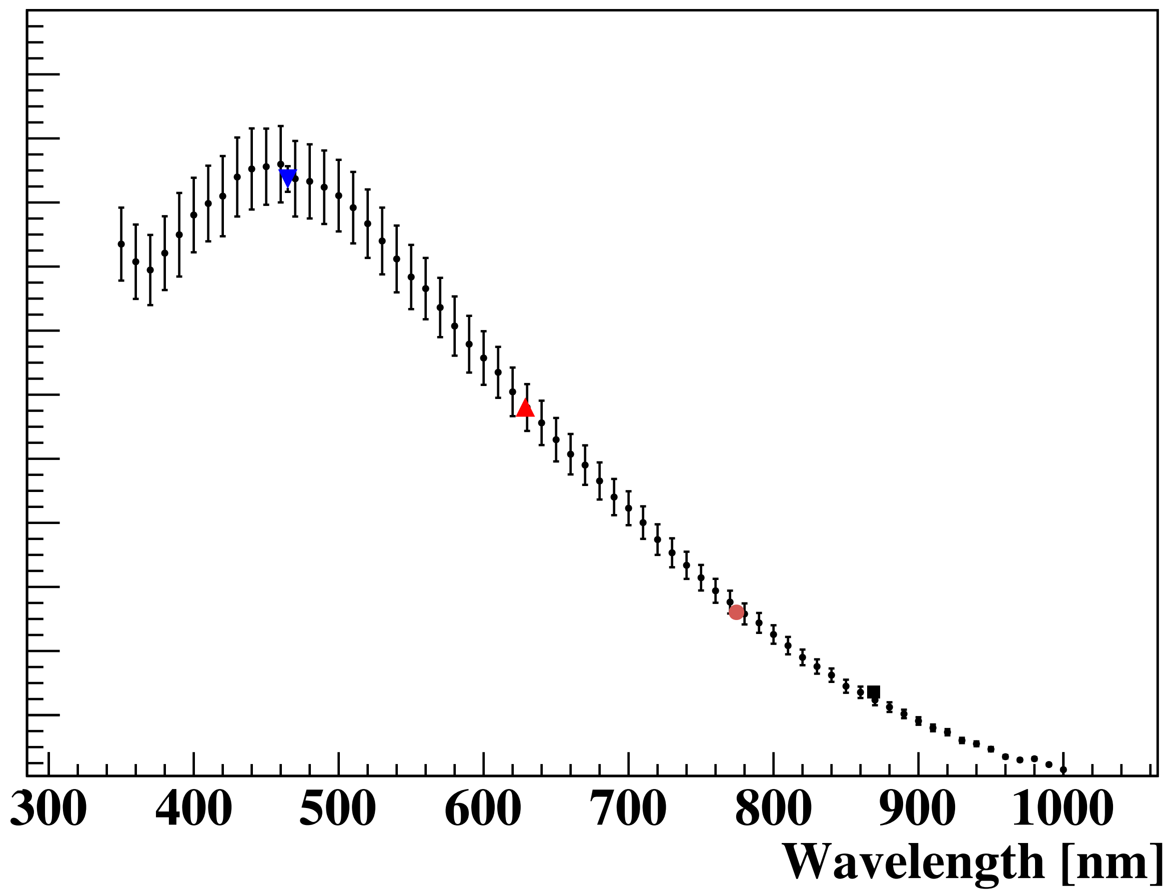
Optical power, P_{opt} B



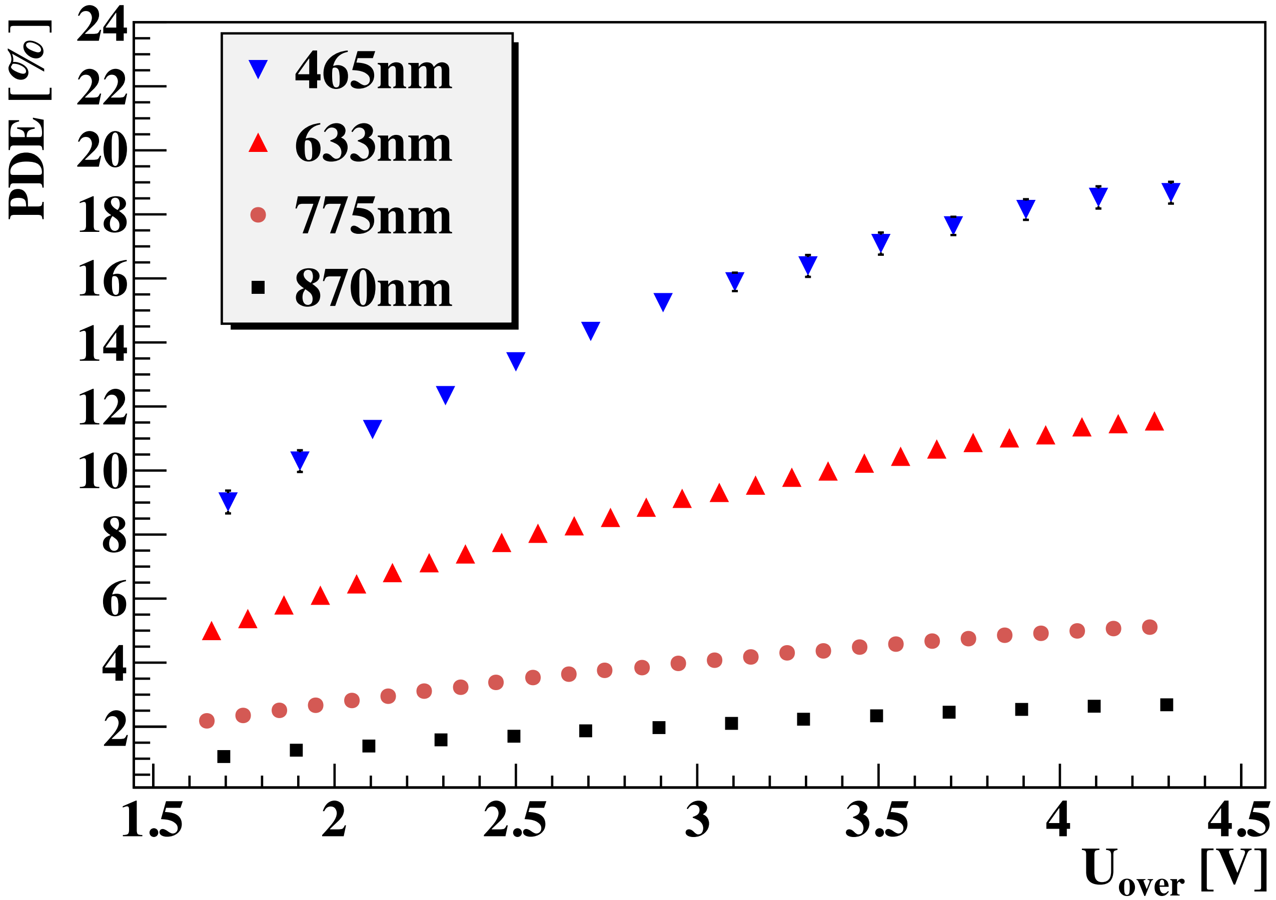
Spectral sensitivity



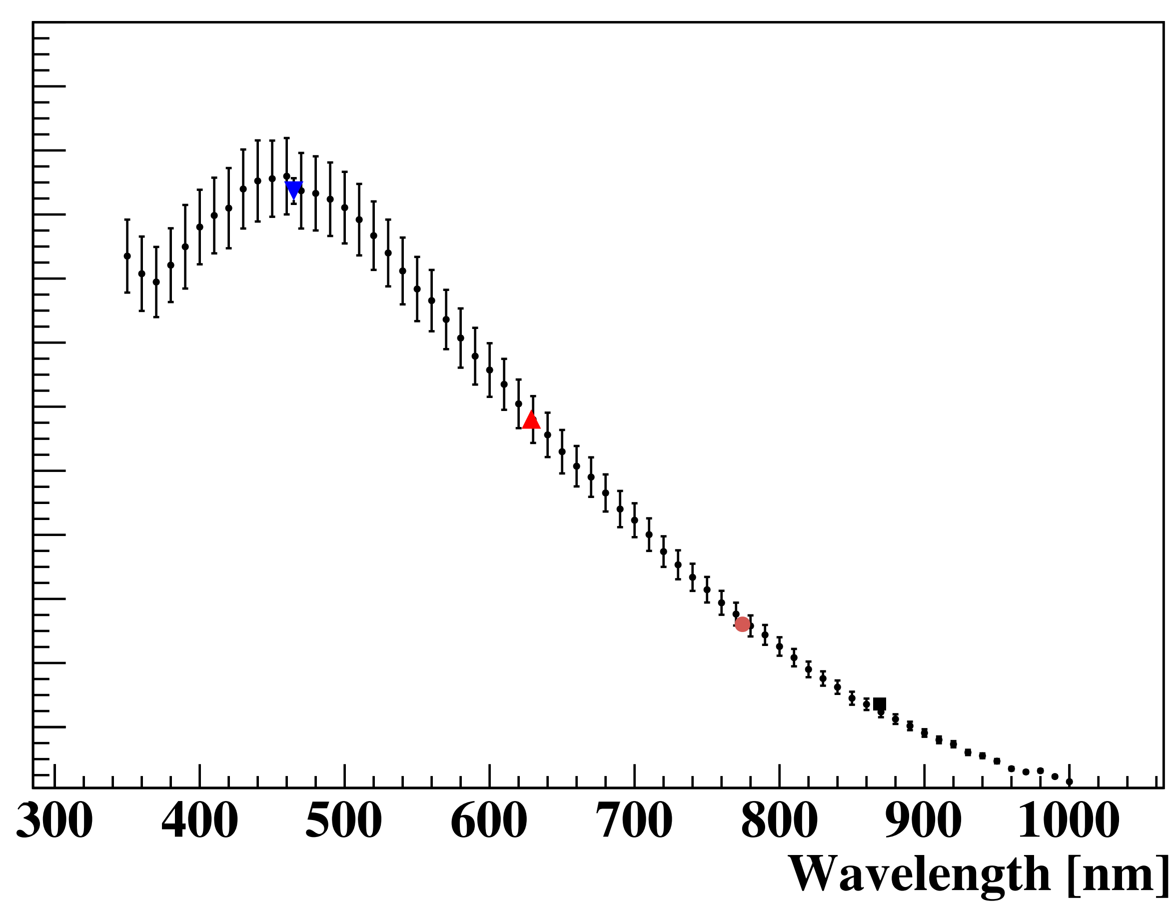
PDE Scaling



PDE Scaling

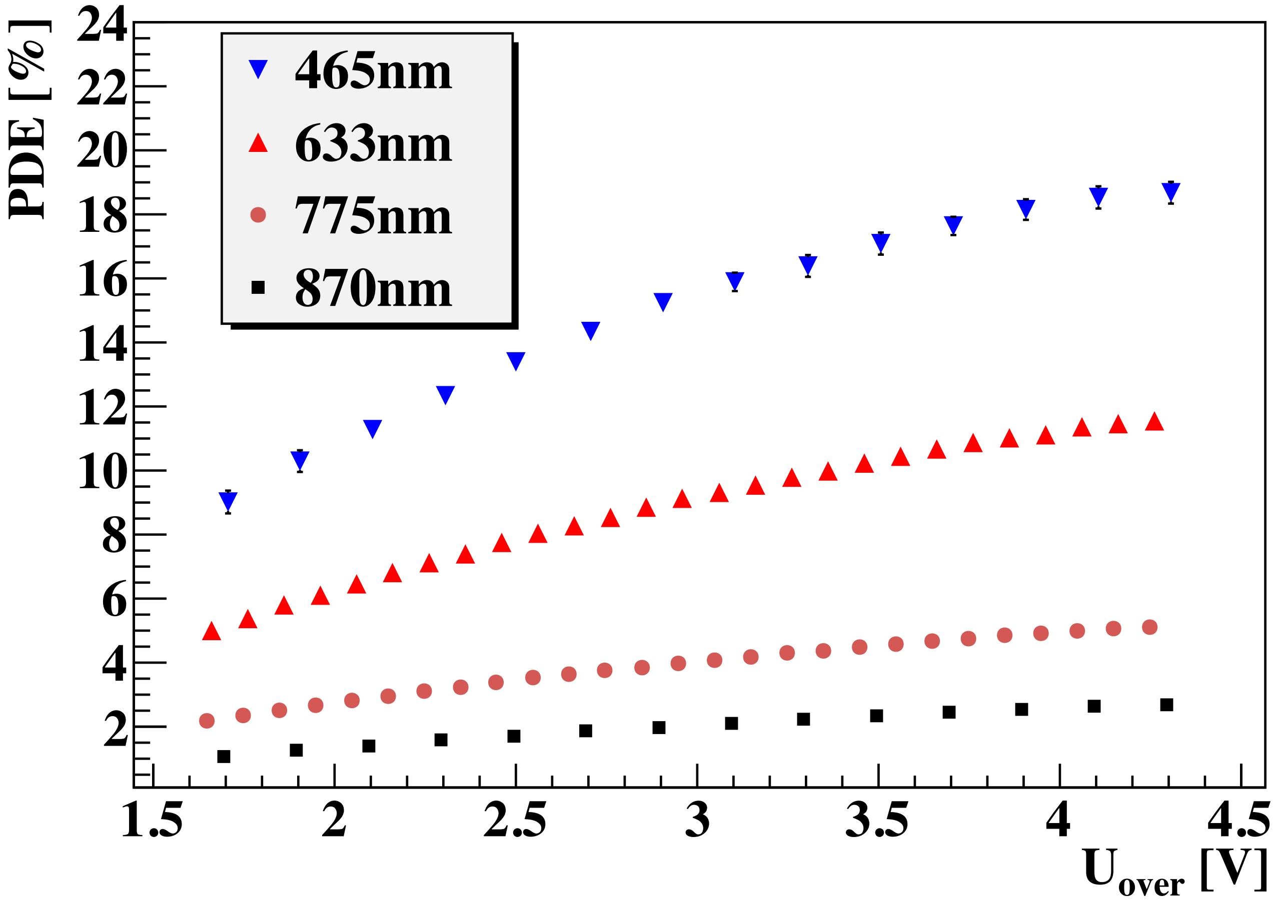


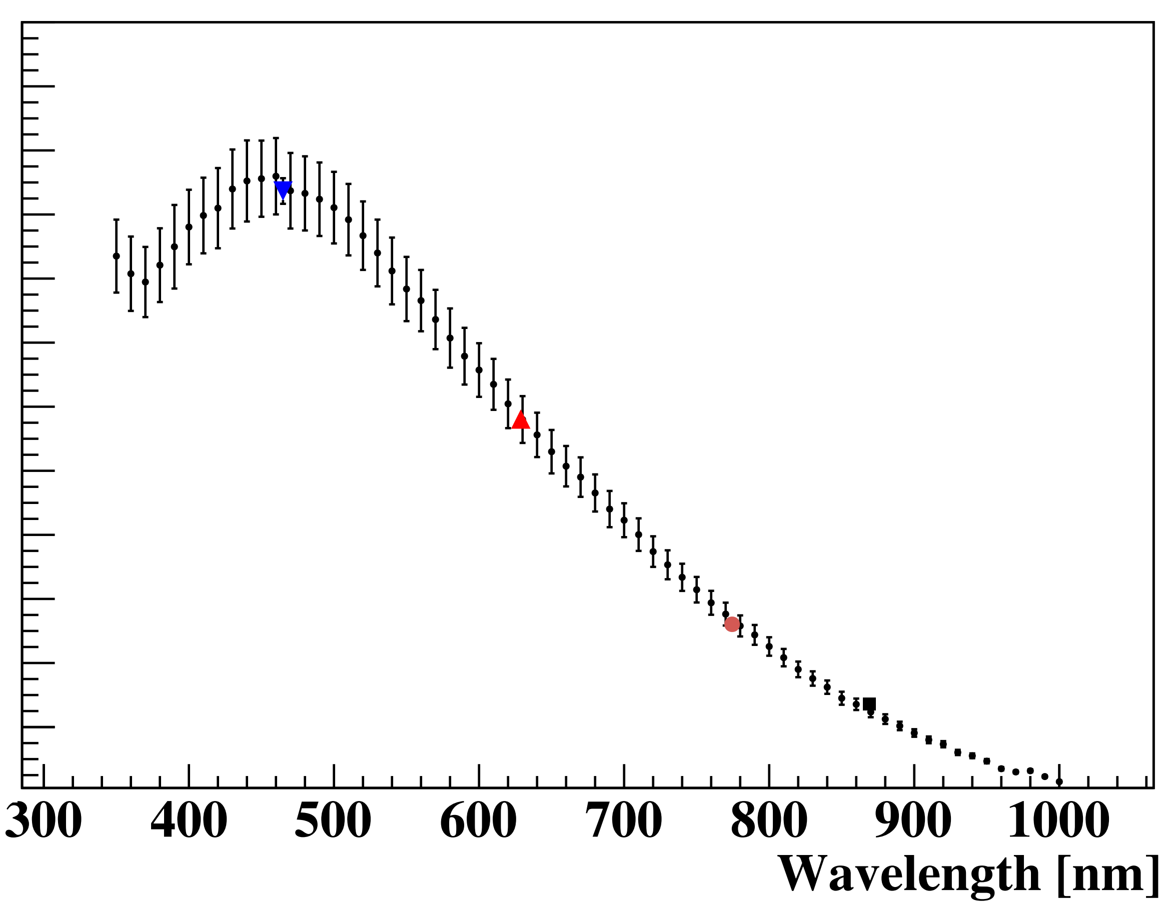
PDE [%]
24
22
20
18
16
14
12
10
8
6
4
2
465nm
633nm
775nm
870nm
1.5
2
2.5
3
3.5
4
4.5
U_{over} [V]



300
400
500
600
700
800
900
1000
Wavelength [nm]

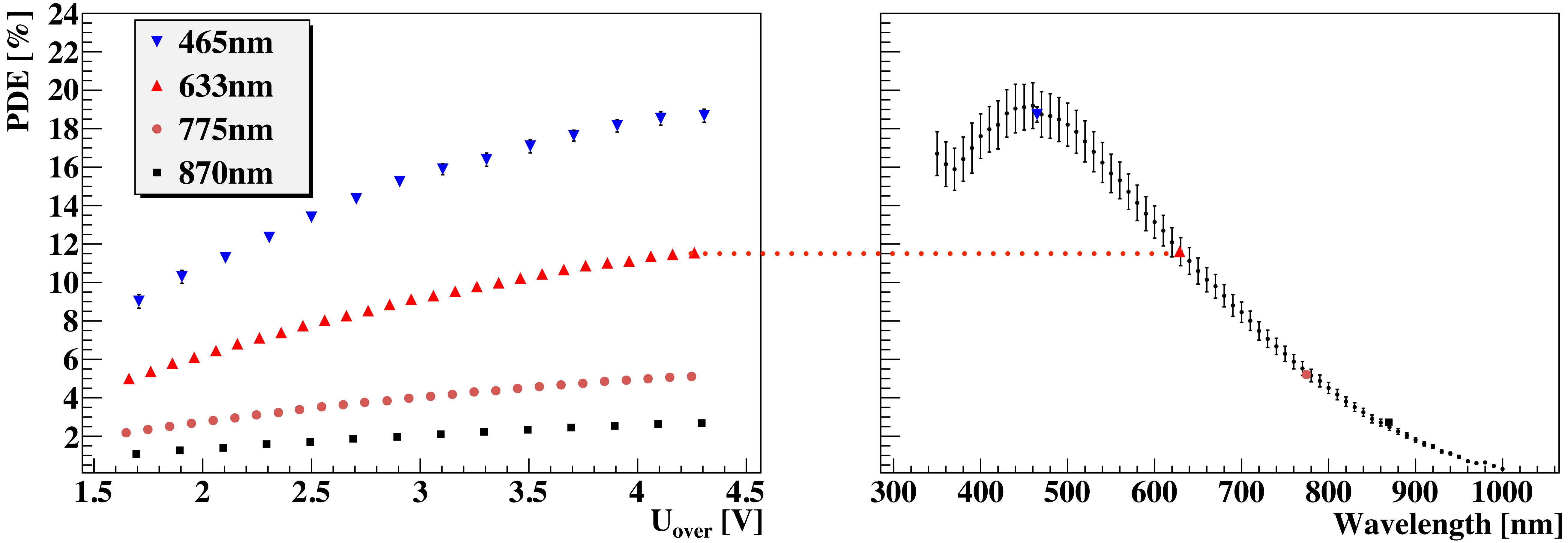
PDE Scaling





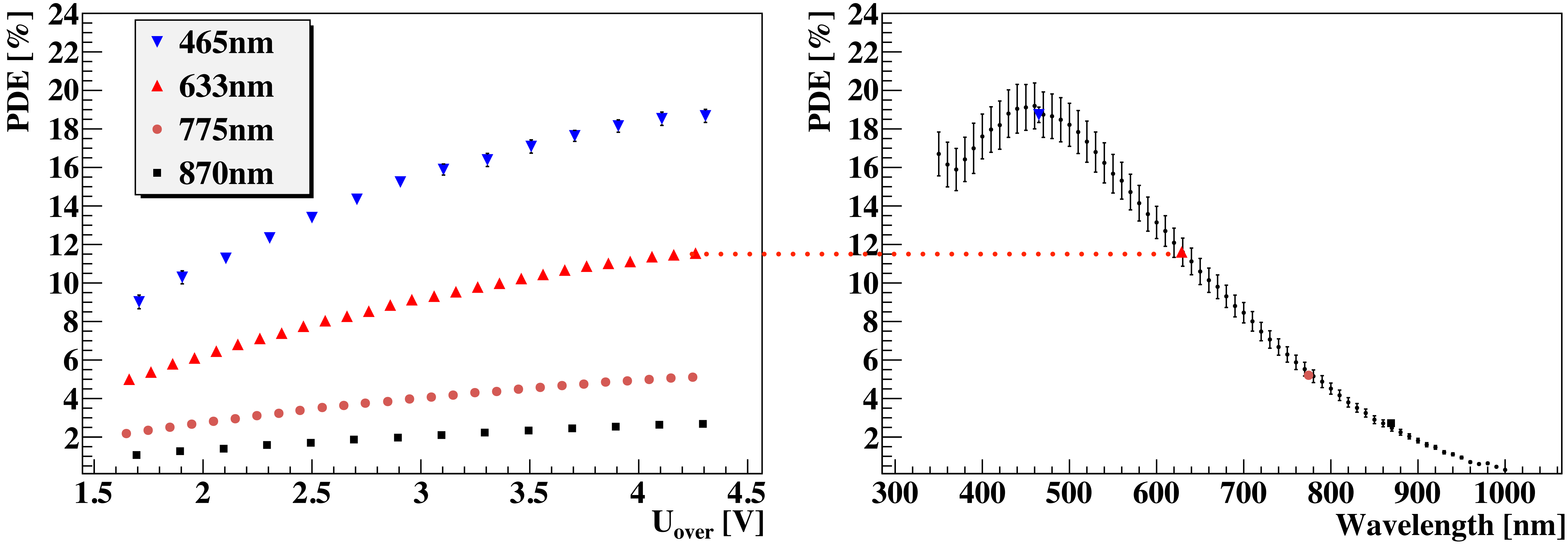
Scale to max. PDE value measured at 633nm

PDE Scaling



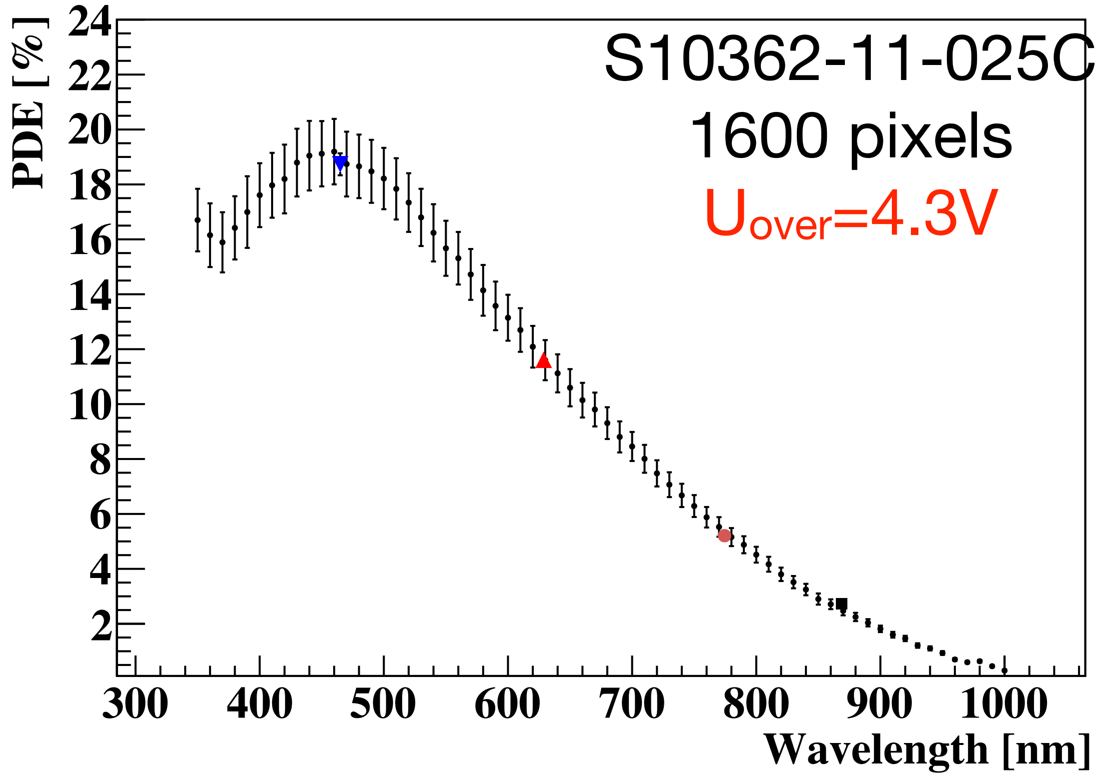
Scale to max. PDE value measured at 633nm

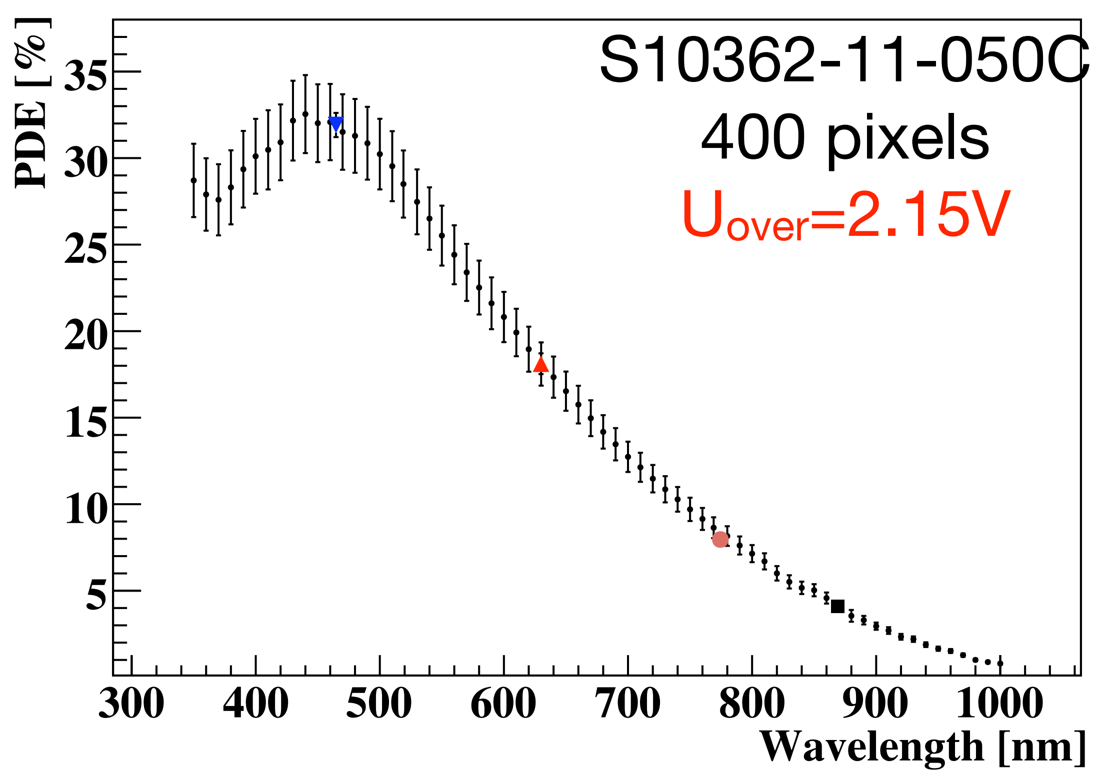
PDE Scaling

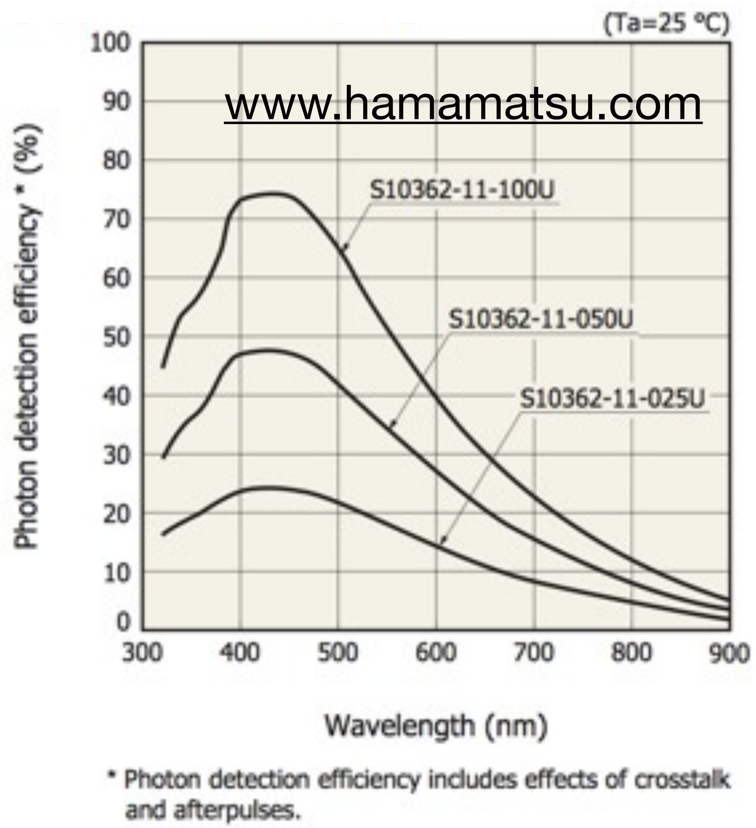


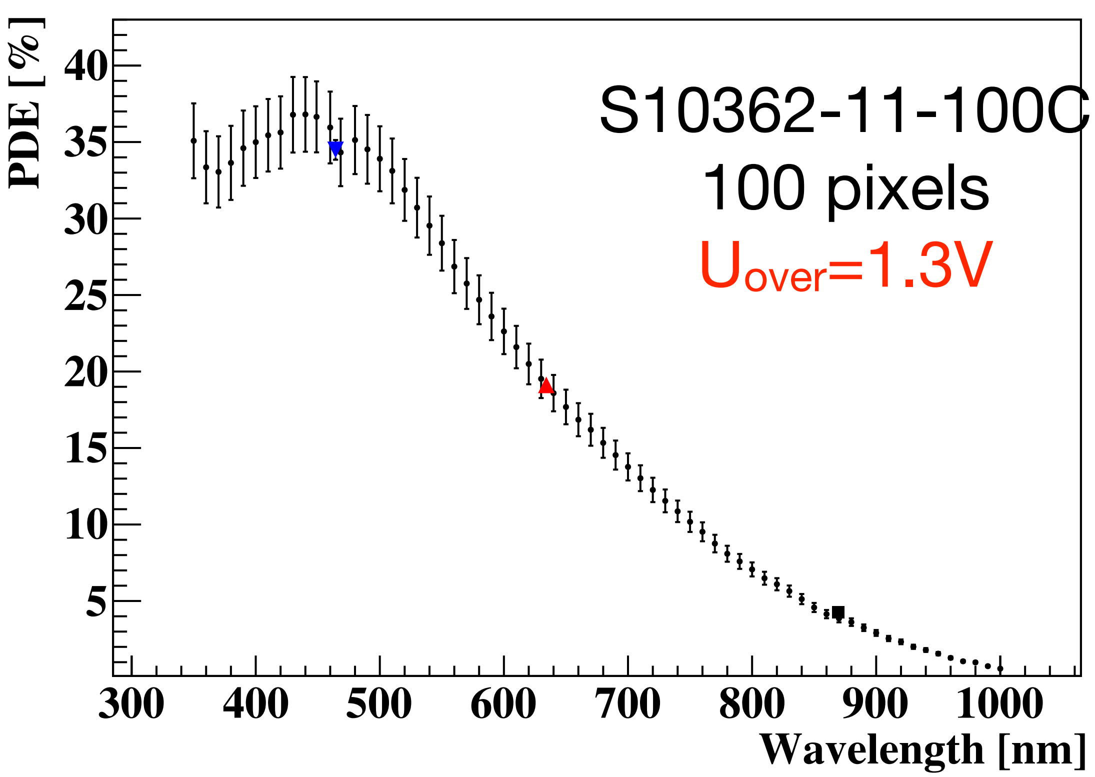
Scale to max. PDE value measured at 633nm

PDE Results: MPPC

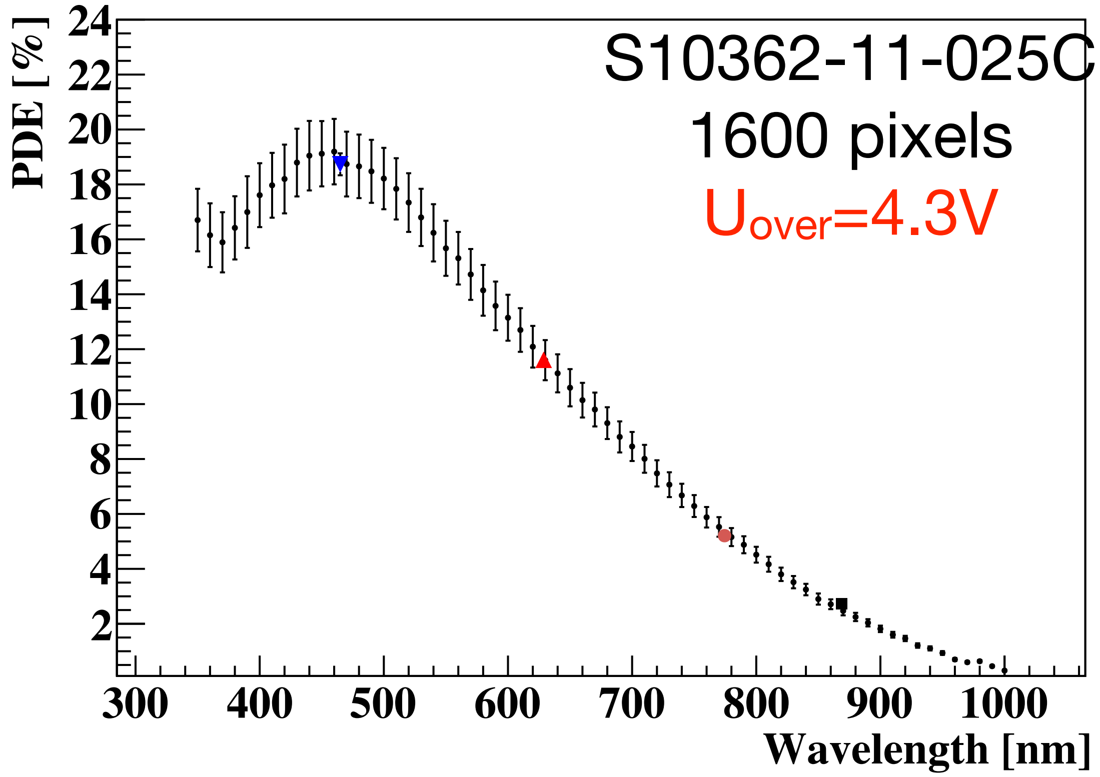


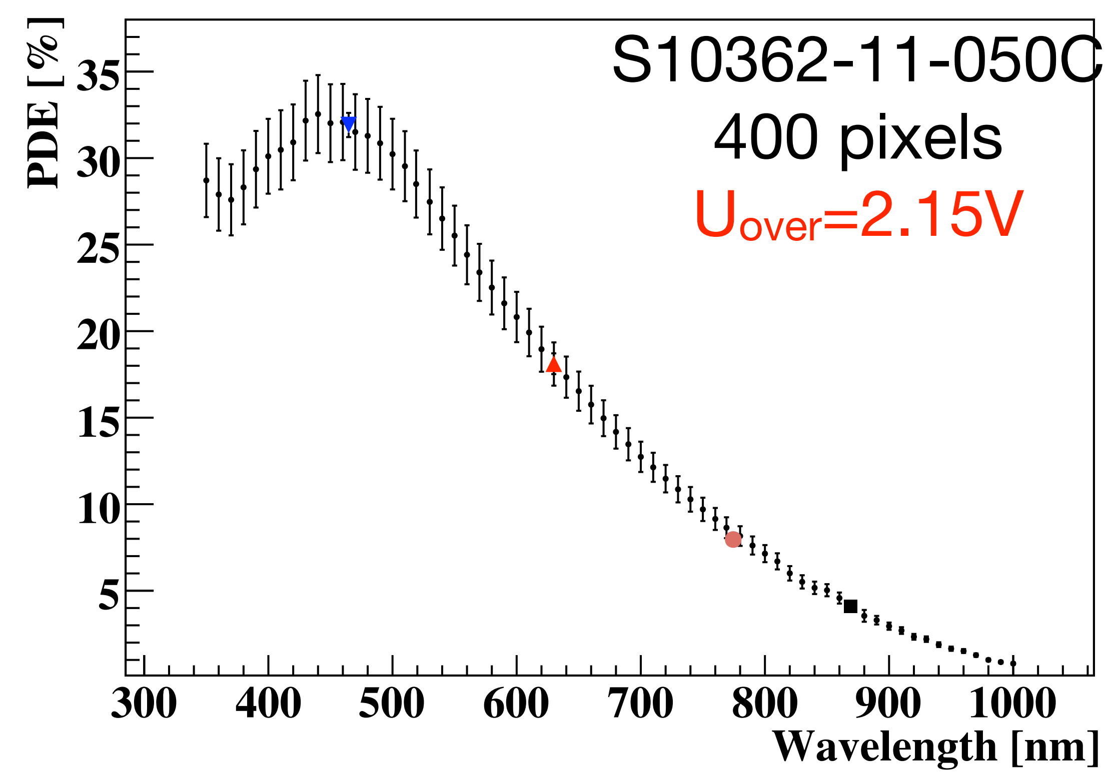


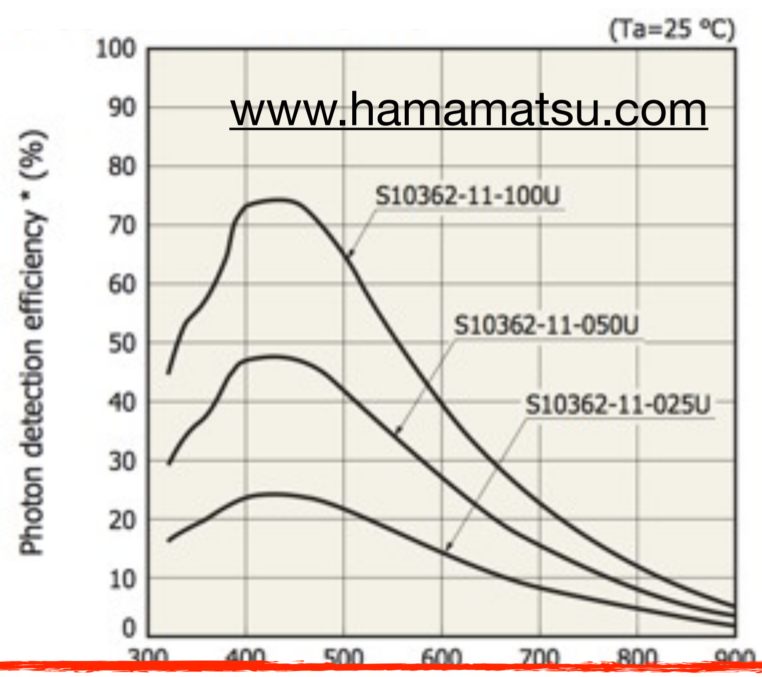




PDE Results: MPPC

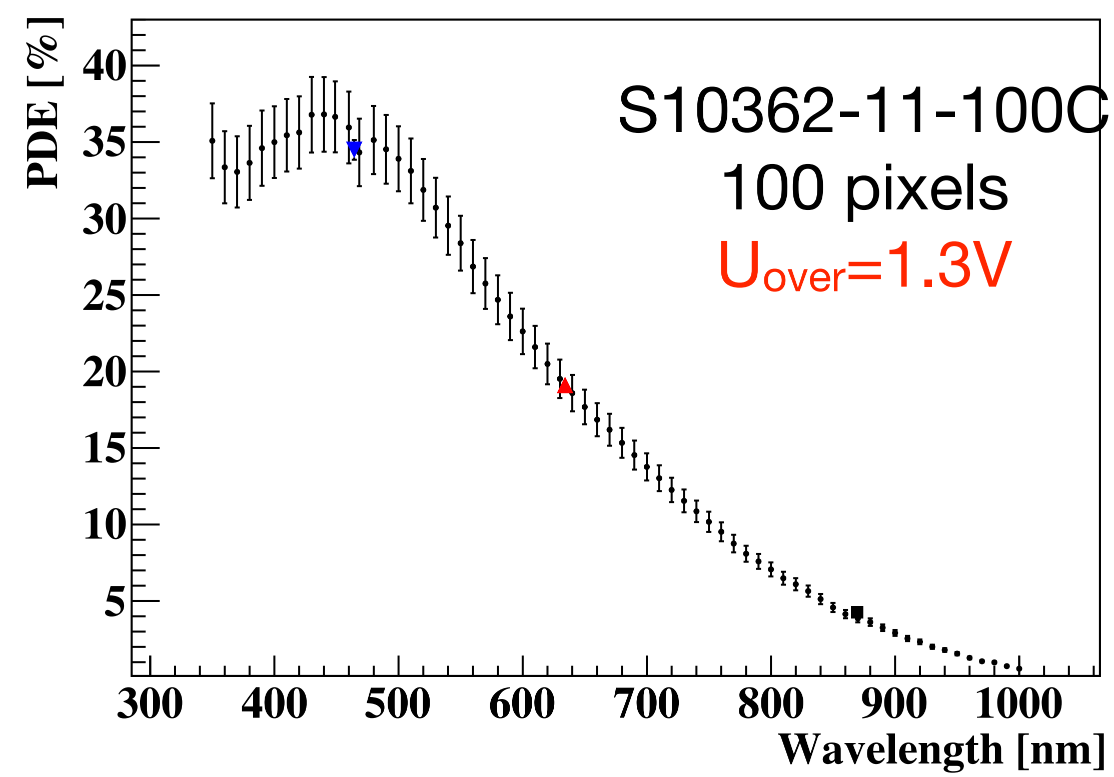






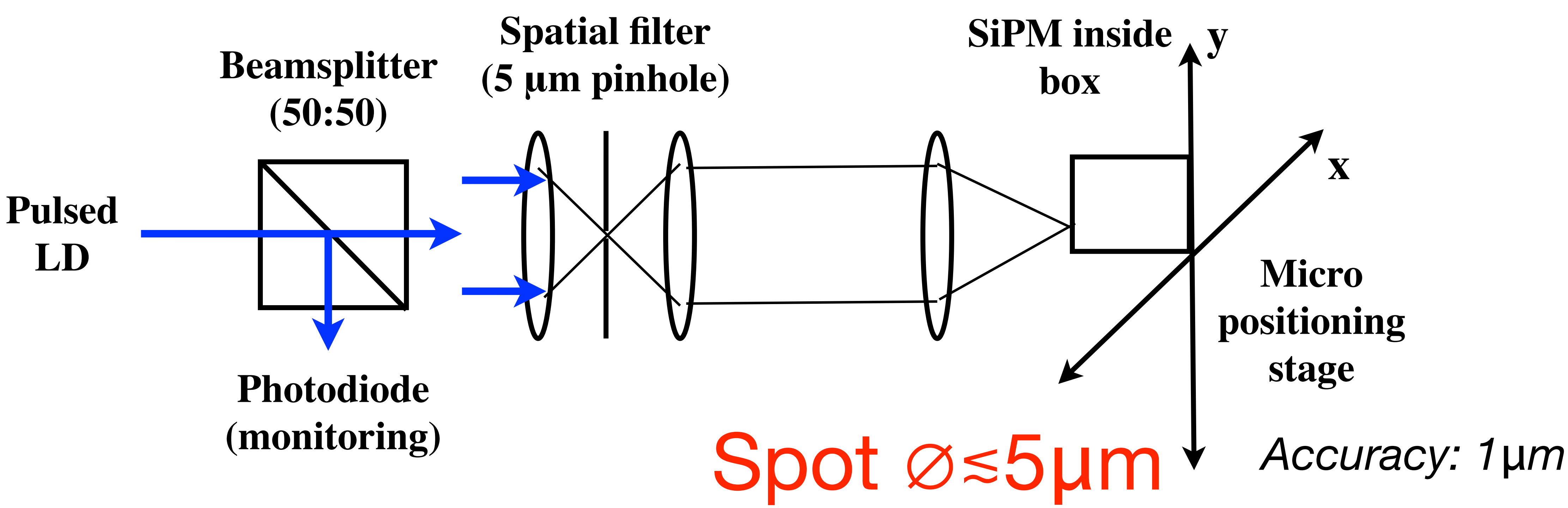
* Photon detection efficiency includes effects of crosstalk and afterpulses.

and afterpulses.



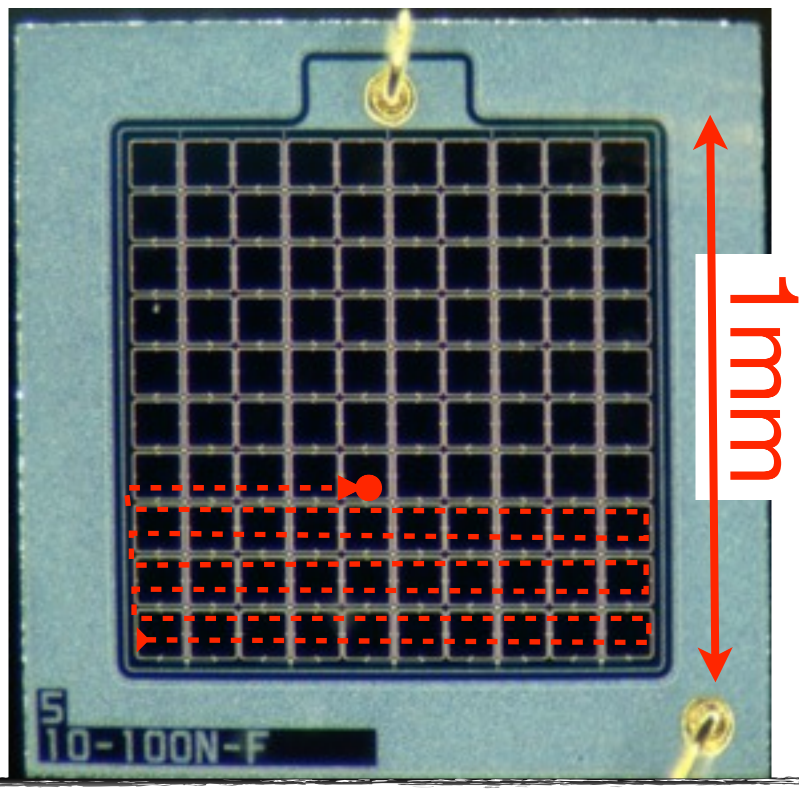
Uniformity Scans

Setup

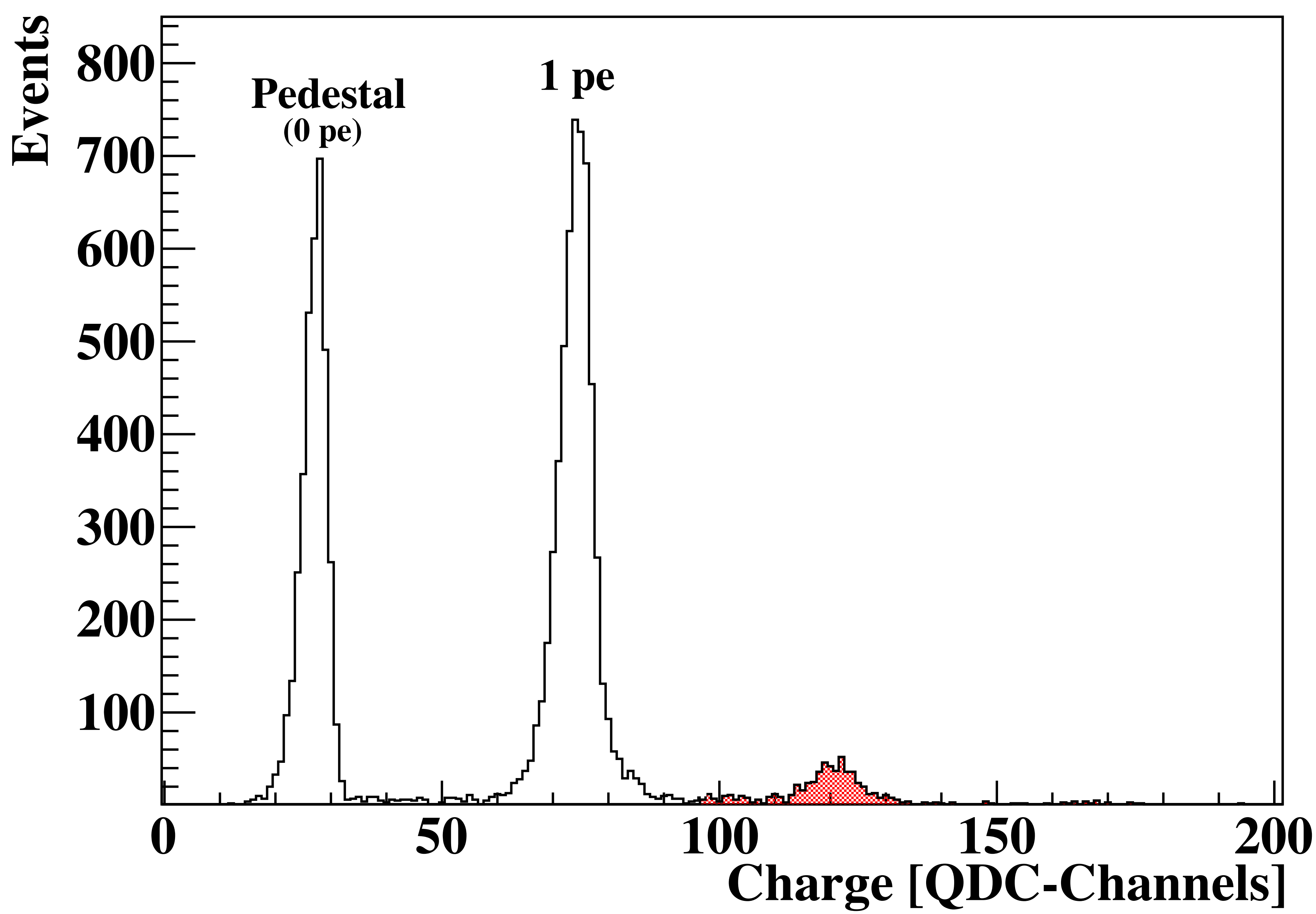


- Move spot over SiPM surface
- QDC readout *(30ns gate)*

  10,000 events per geom. position
- 3µm step size ⇒ 123,000 positions
- Total time ($1{\times}1\mathrm{mm}^2$): ≈100h



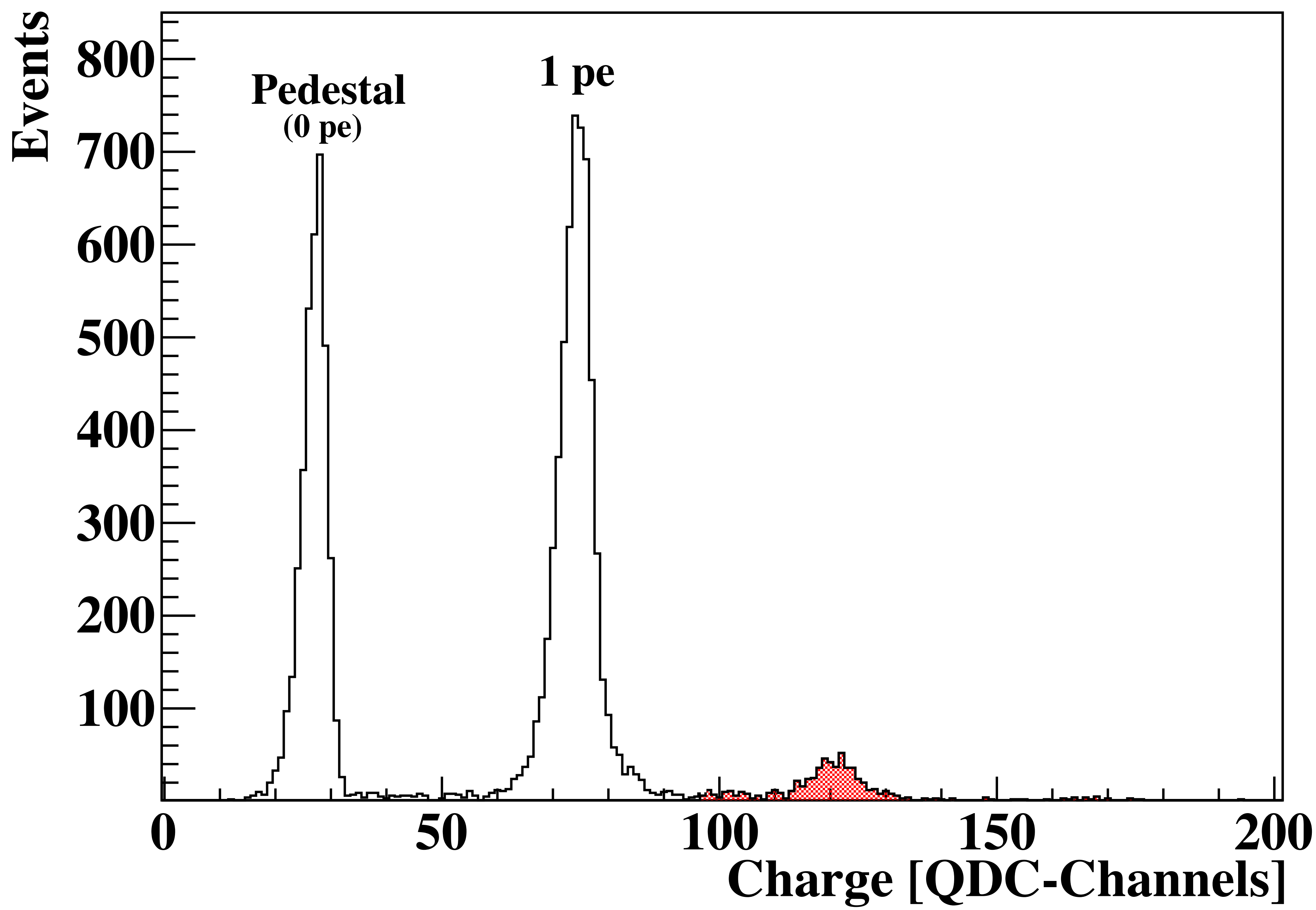
Single Pixel Spectrum



Single Pixel Spectrum

Sensitivity

$$N_{pe} = -\ln\left(\frac{N_{Ped.}}{N_{Tot.}}\right)$$



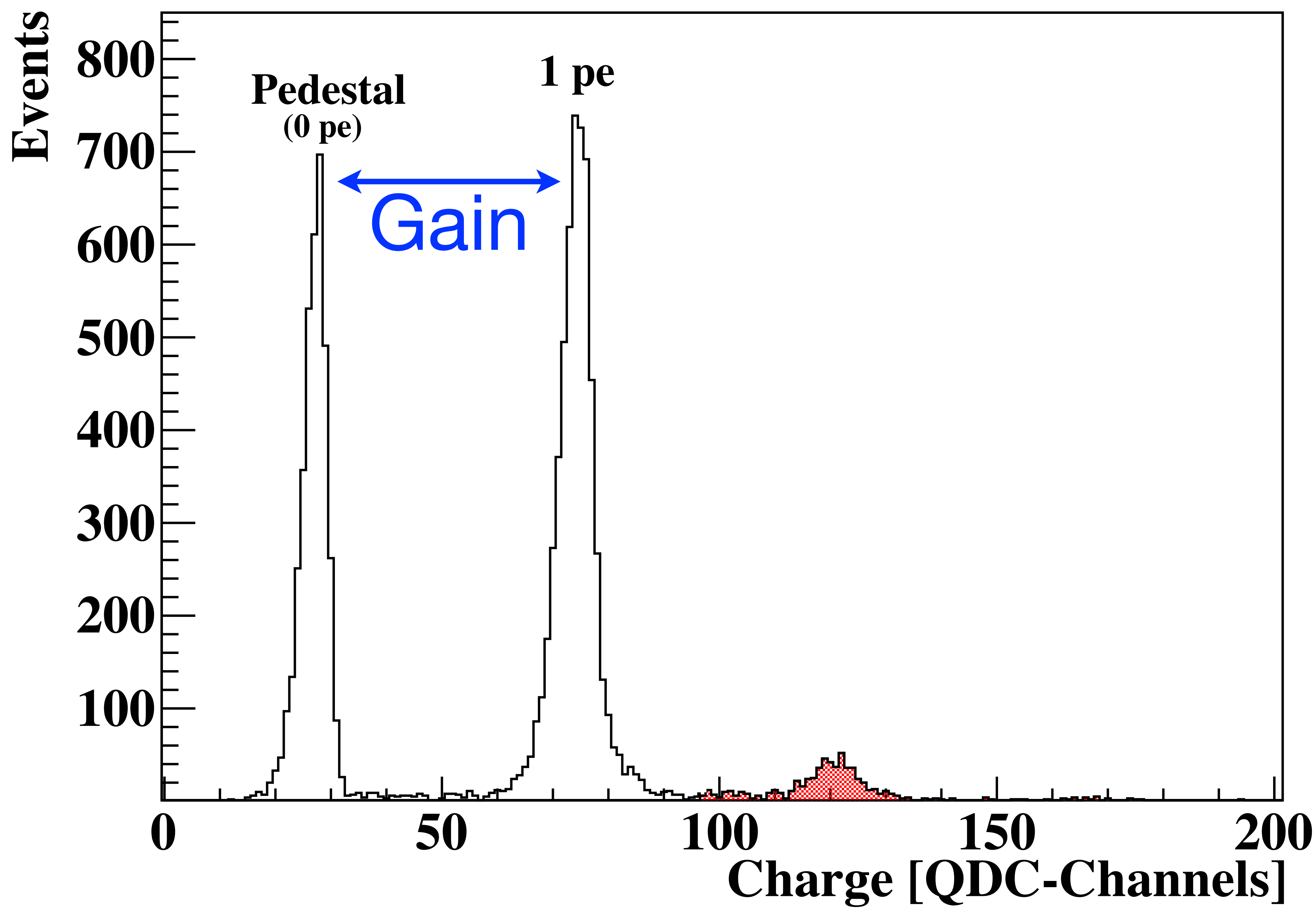
Single Pixel Spectrum

Sensitivity

$$N_{pe} = -\ln\left(\frac{N_{Ped.}}{N_{Tot.}}\right)$$

Gain

(peak distance)



Single Pixel Spectrum

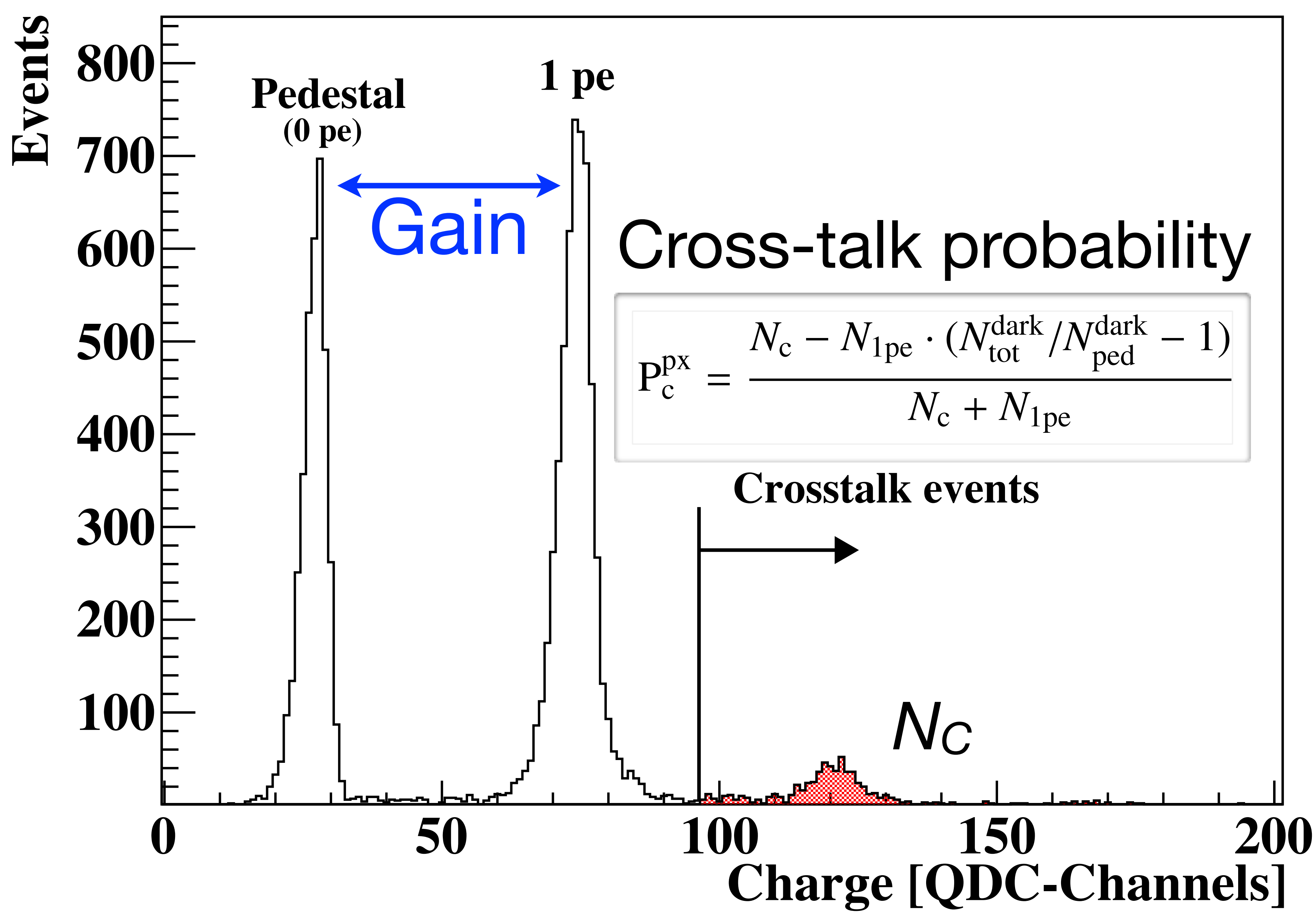
Sensitivity

$$N_{pe} = -\ln\left(\frac{N_{Ped.}}{N_{Tot.}}\right)$$

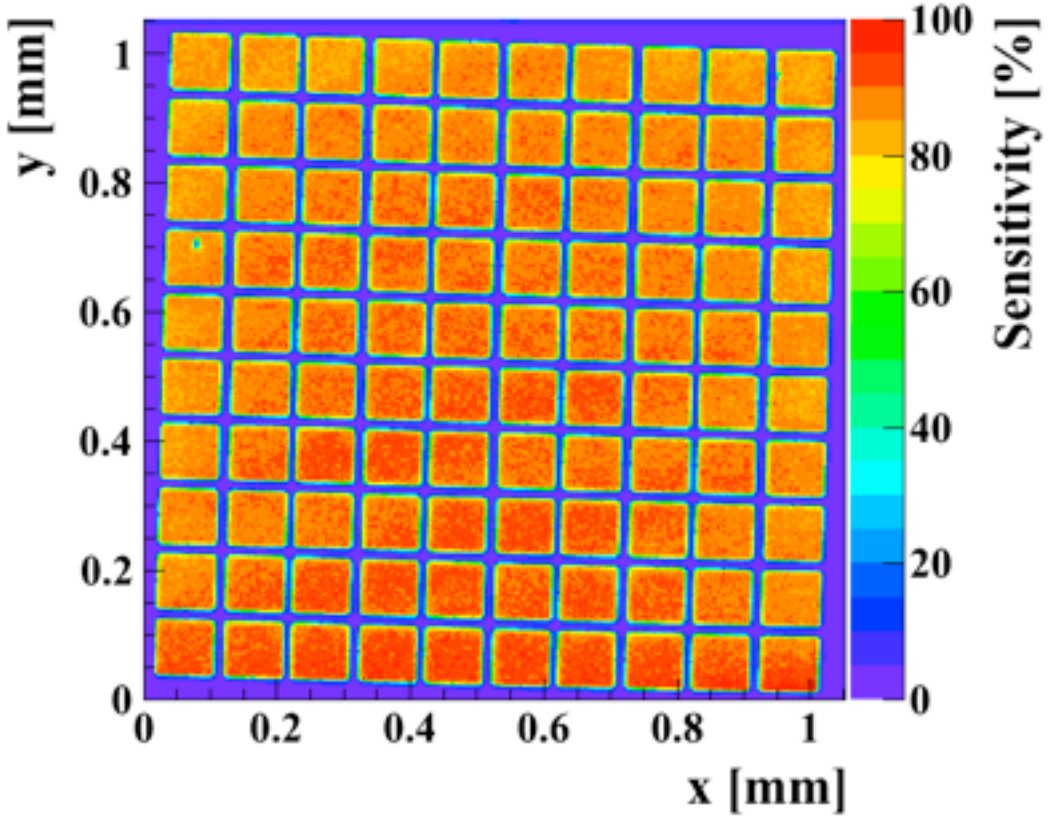
Gain
(peak distance)

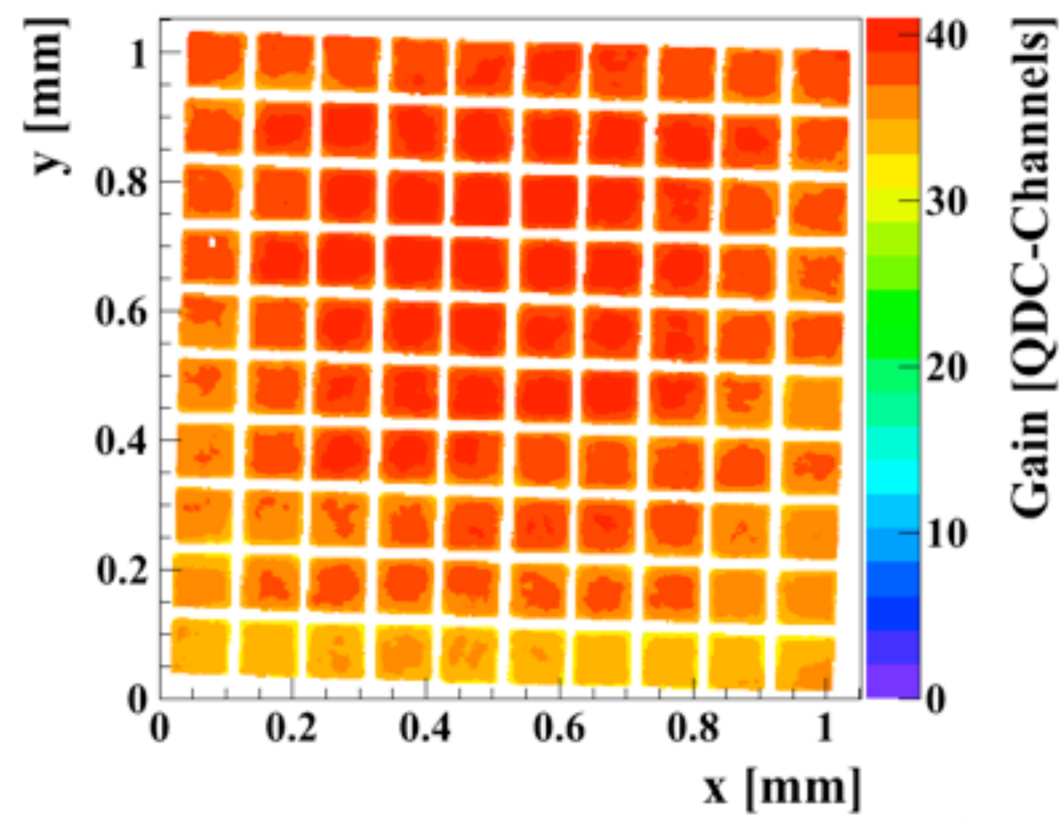
Optical cross-talk

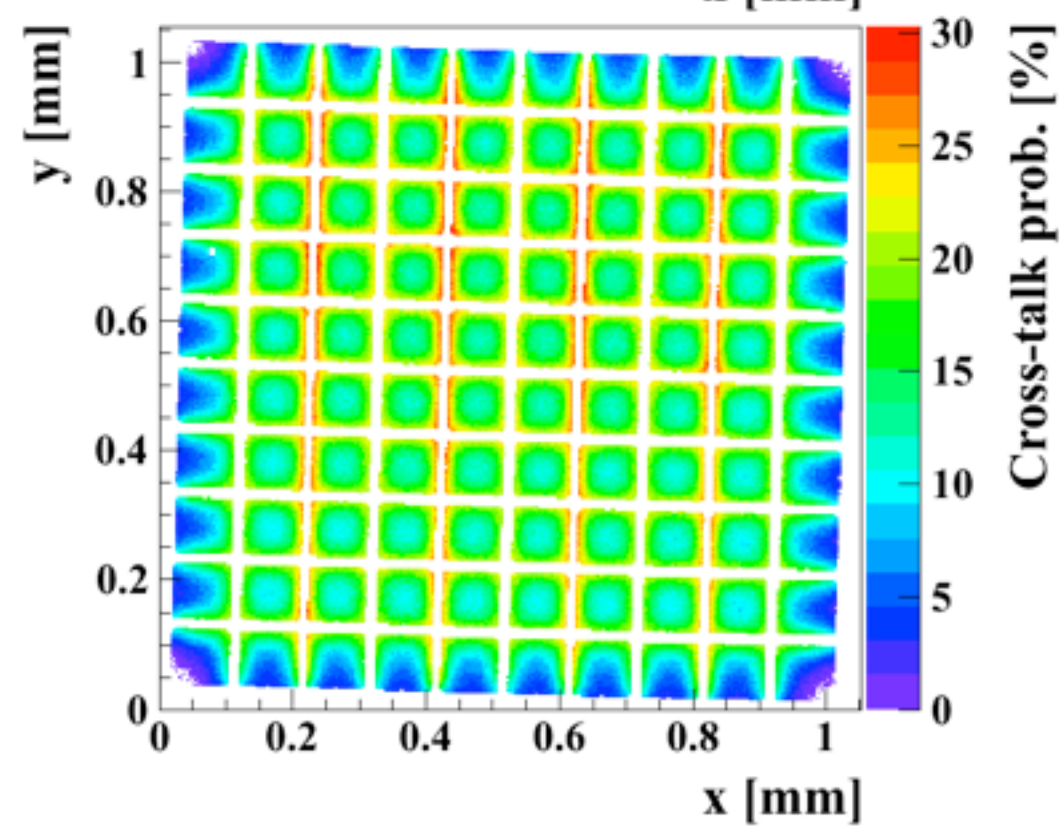
Only single pixel is illuminated, hence at most 1pe events are expected.
2pe events caused by cross-talk



MPPC 100 pixels

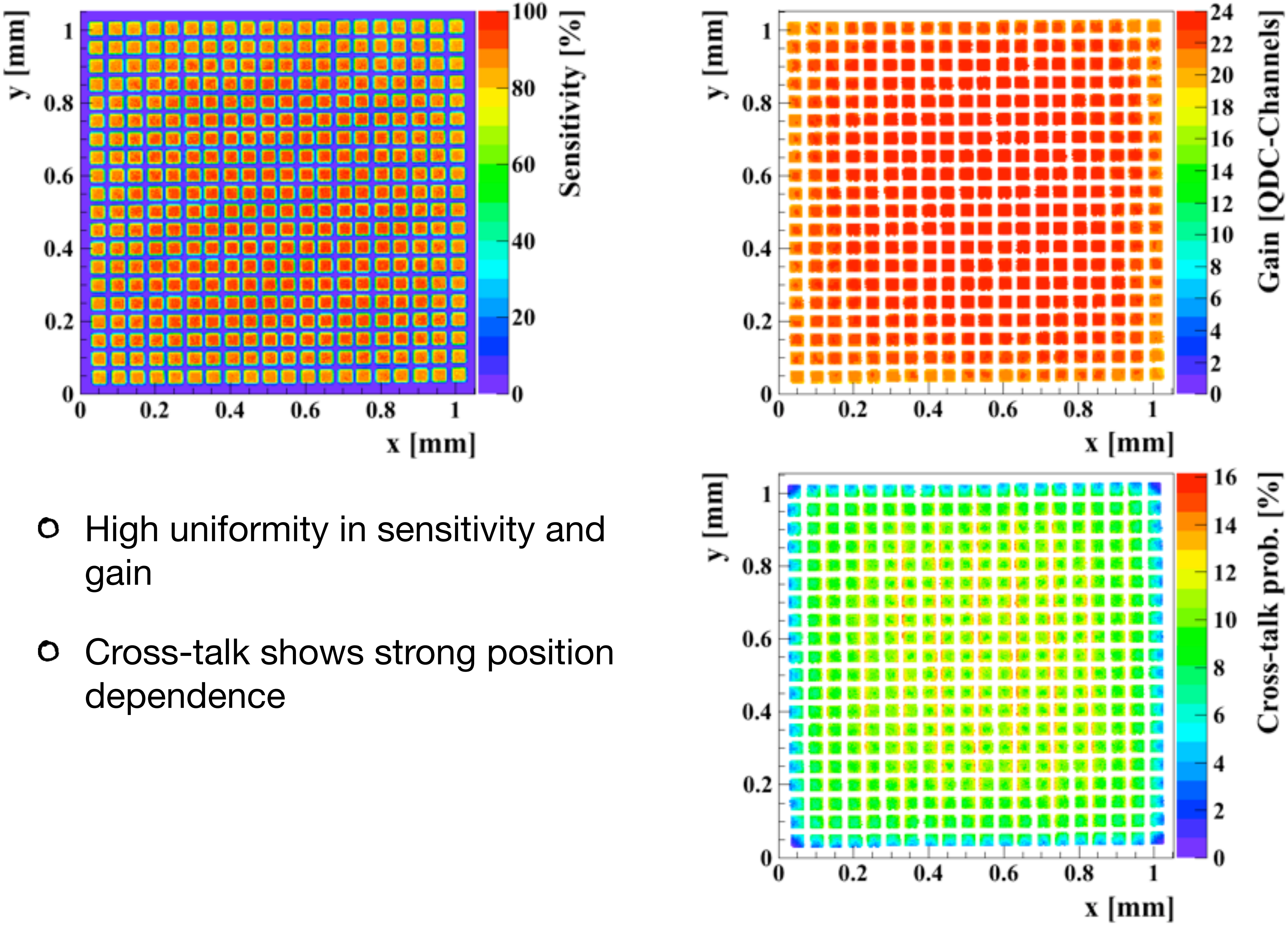






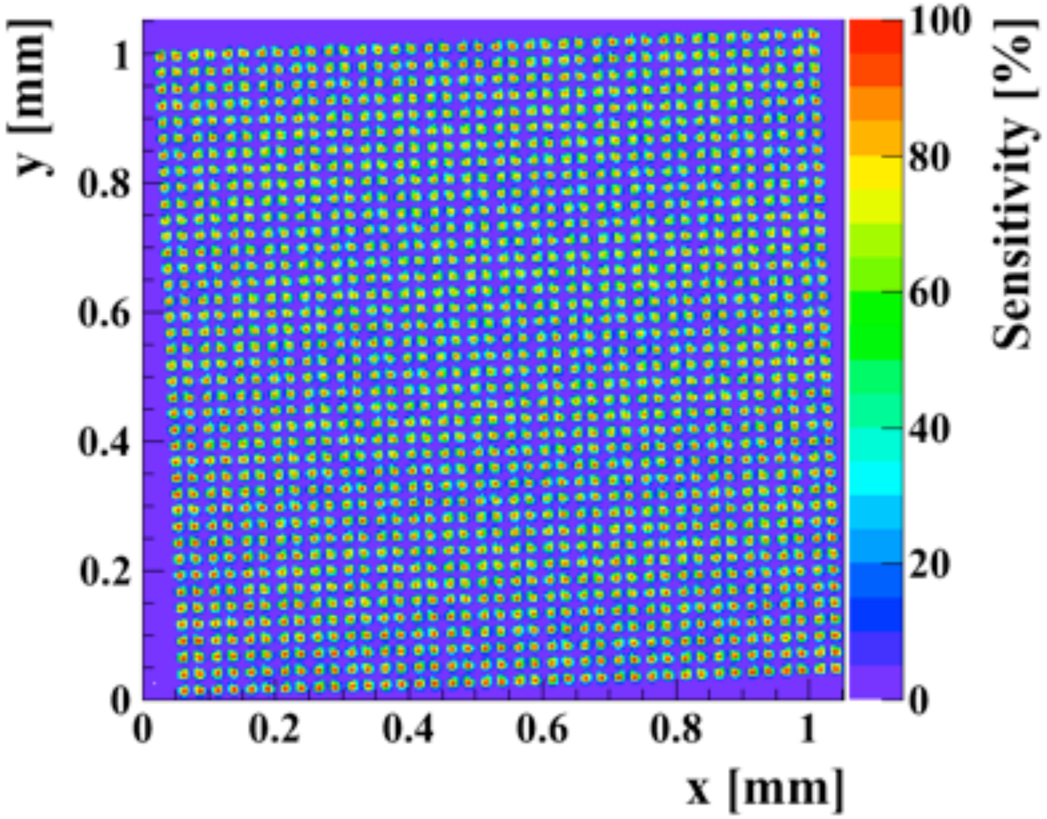
- High uniformity in sensitivity and gain
- Cross-talk shows strong position dependence

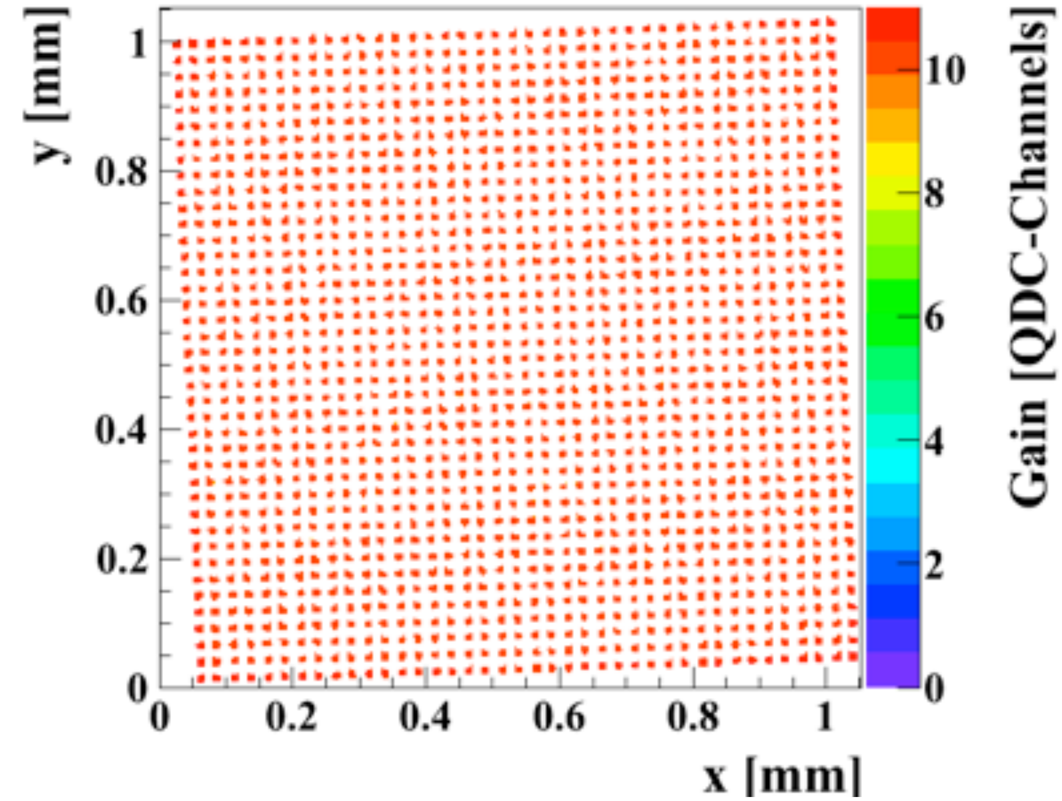
MPPC 400 pixels



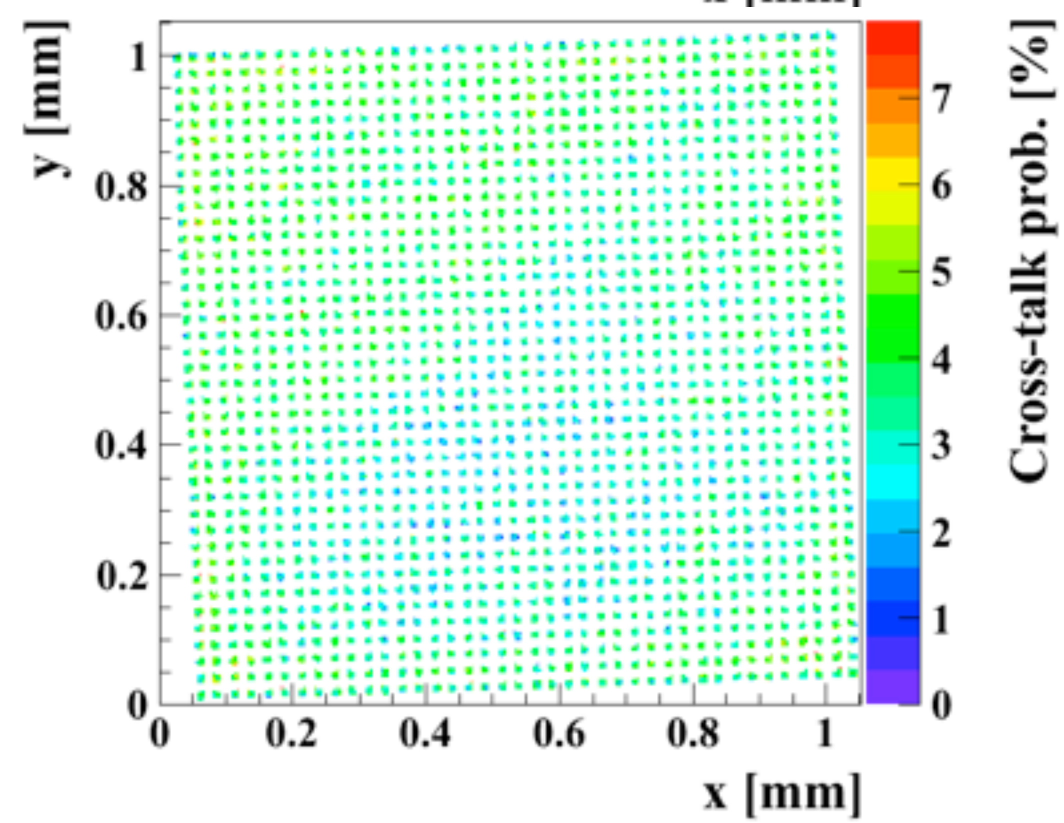
- High uniformity in sensitivity and gain
- Cross-talk shows strong position dependence

MPPC 1600 pixels





- High uniformity in sensitivity, gain and cross-talk probability



Enjoy the hands-on sessions!

References

"Characterisation studies of silicon photomultipliers", P. Eckert et al. / Nuclear Instruments and Methods in Physics Research A 620 (2010) 217–226

"Characterisation of Silicon Photomultipliers", Alexander Tadday, Diploma Thesis (2008)

"Advanced Silicon-Photomultiplier Characterization for Calorimetric Applications", Patrick Eckert, Diploma Thesis (2010)

"Advances in solid state photon detectors", D. Renker and E. Lorenz, 2009 JINST 4 P04004

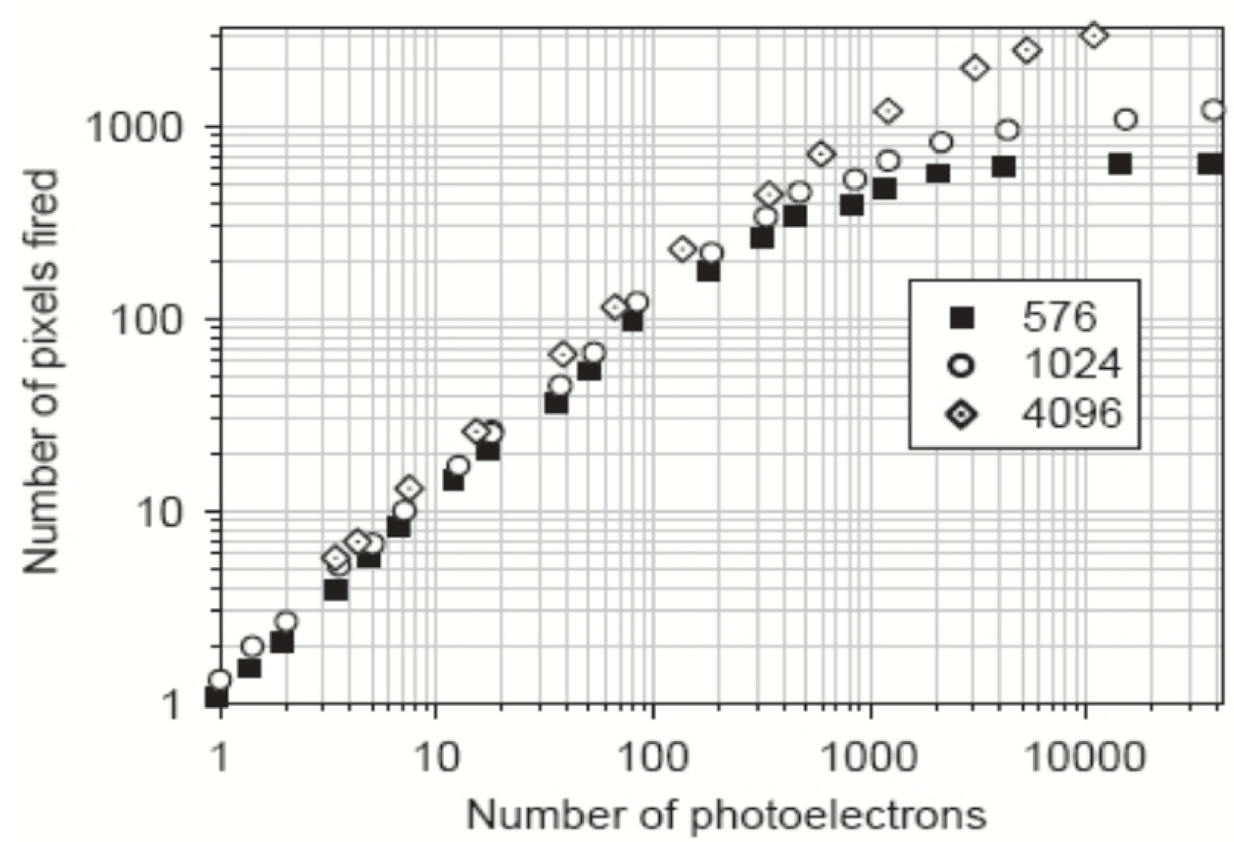
V. Andreev et. al., *"A high granularity scintillator hadronic-calorimeter with SiPM readout for a linear collider detector"*, Nucl. Instrum. Meth. A 540 (2005) 368

Backup Slides

Saturation function

- The maximum number of photons that can be detected is fundamentally limited by the total number of pixels N_{total}
- More pixels -> Higher dynamical range, but also smaller geometrical efficiency and smaller gain

$$N_{fired} = N_{total}\left(1 - e^{-\frac{N_\gamma PDE}{N_{total}}}\right)$$



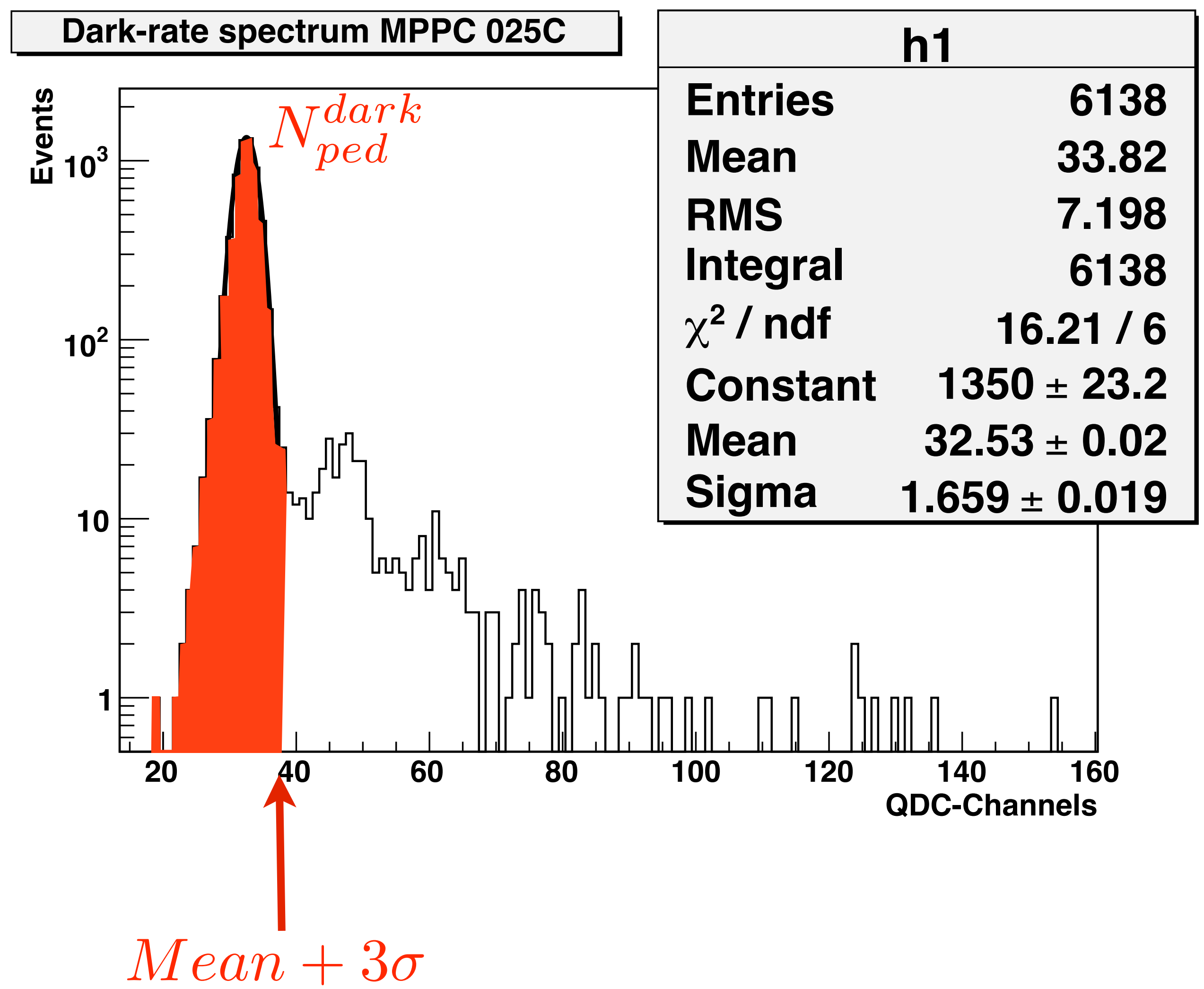
V. Andreev et. al., A high granularity scintillator hadronic-calorimeter with SiPM readout for a linear collider detector, Nucl. Instrum. Meth. A 540 (2005) 368

- If the recovery time of a cell is smaller than the width of the light pulse, pixels can fire multiple times which causes a larger number of "effective" pixels
  - Equation above not valid anymore (correction difficult)

Dark-rate Correction

The number of photoelectrons needs to be corrected for the dark-rate.
➔ Acquire dark-rate spectrum at each voltage value.
Correction factor α:

$$\alpha \cdot N_{ped}^{dark} = N_{ped}^{dark*} \stackrel{!}{=} N_{tot}^{dark}$$
$$\Rightarrow \alpha = \frac{N_{tot}^{dark}}{N_{ped}^{dark}}$$



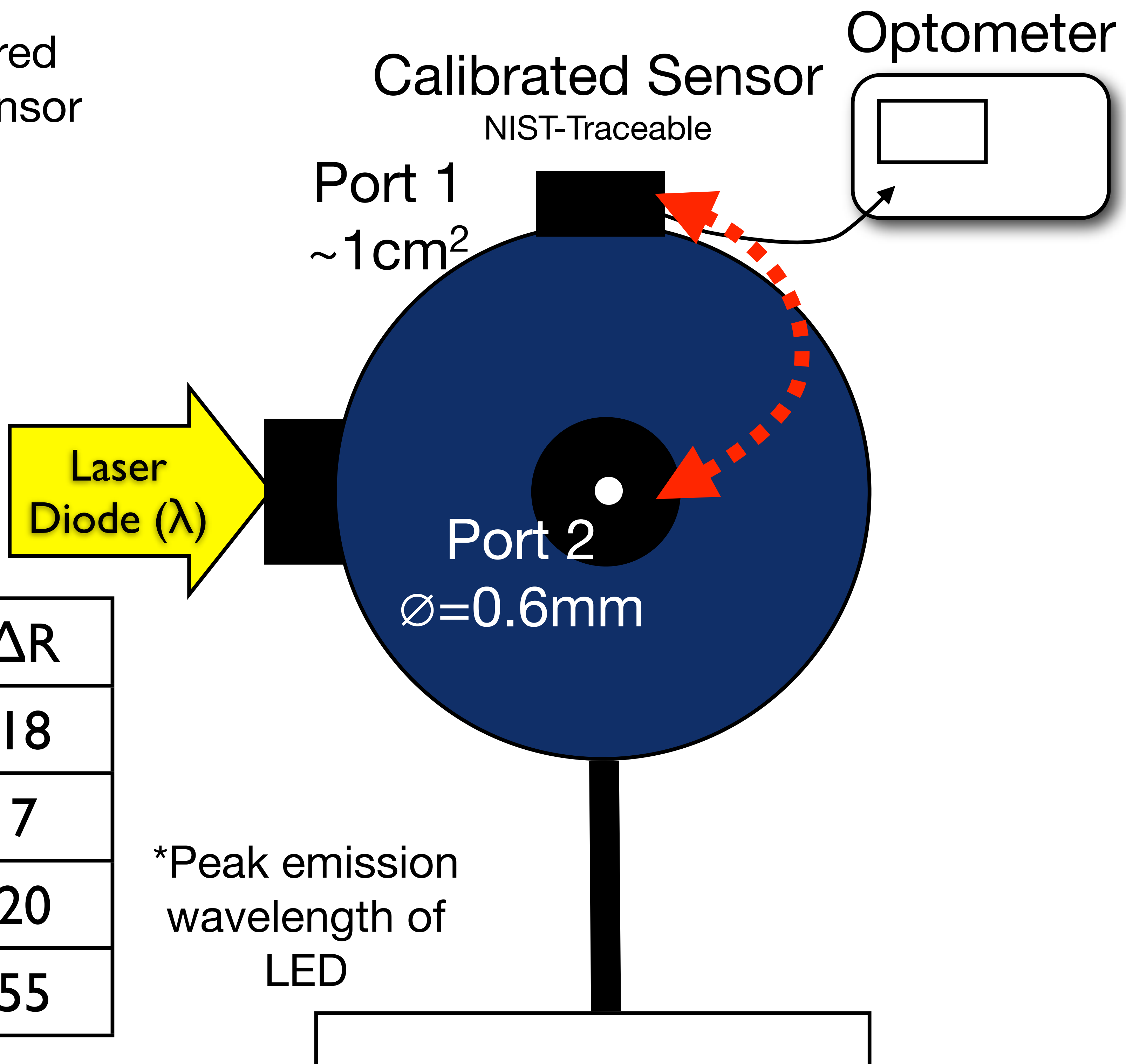
$$n_{pe} = -ln\left(\frac{\alpha \cdot N_{ped}}{N_{tot}}\right) = -ln\left(\frac{N_{ped}}{N_{tot}}\right) + ln\left(\frac{N_{tot}^{dark}}{N_{ped}^{dark}}\right)$$

Measurement of Power-ratio

The Power-ratio R is measured by moving the calibrated sensor from port 1 to port 2 and backwards

$$R = \frac{P_{\mathrm{Port1}}}{P_{\mathrm{Port2}}}$$

Type	λ [nm]	$R_{0.6mm}$	ΔR
Laserdiode	633	3852	18
Laserdiode	775	4328	7
LED	465*	4200	20
LED	870*	4625	55



*Peak emission wavelength of LED

SiPM Positioning

- All light should hit the active SiPM-Surface.
- ∅=0.6mm aperture was used for measurements with pulsed laser-diodes.
- Plateau on top allows reproducible positioning at maximum