Characterization of SiPMs

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Overview

- Complete test setup for SiPM measurements has been established
  - Dark-rate (T)
  - Cross-talk probability (T)
  - After-pulse probability (T)
  - PDE measurement
  - Uniformity scans
  - Photon counting resolution

Overview

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  - After-pulse probability (T)
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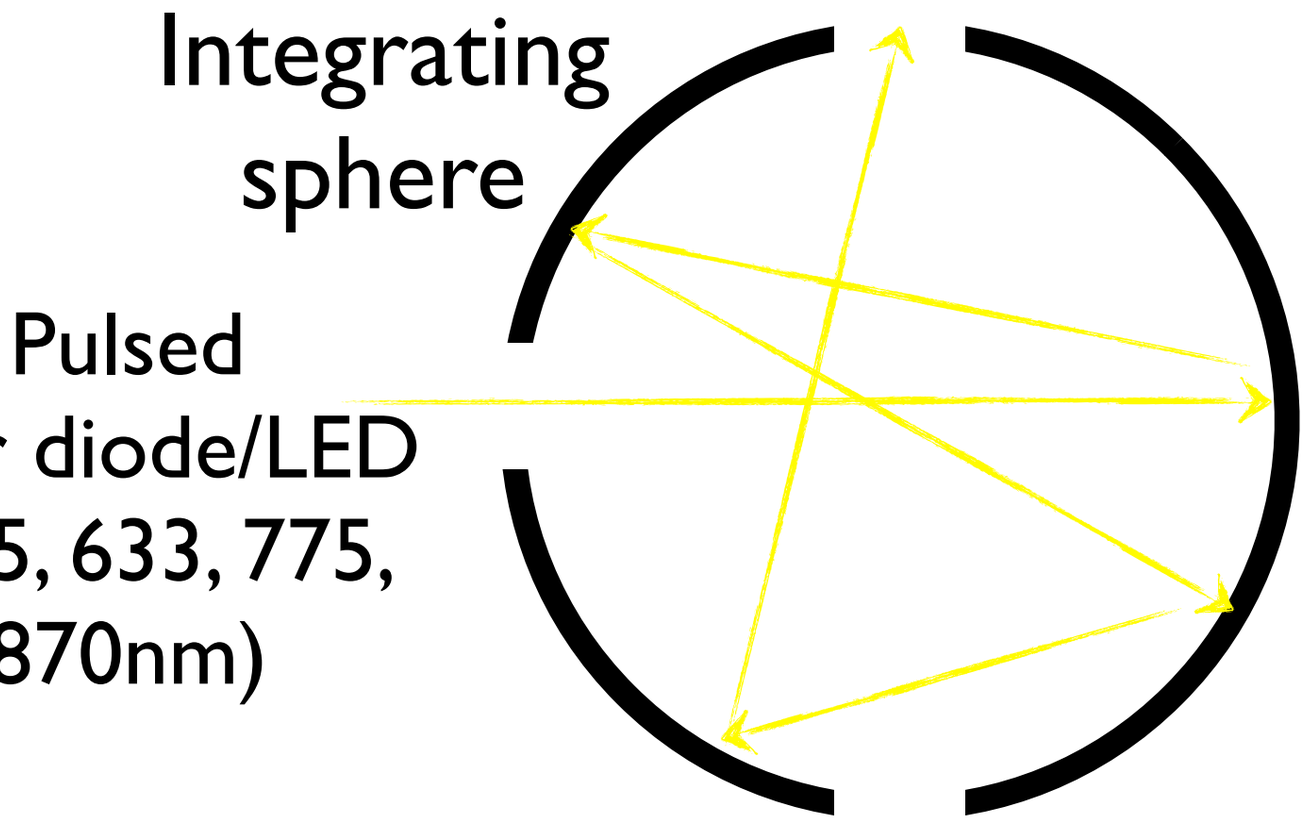
  - Photon counting resolution

Setup: Absolute PDE



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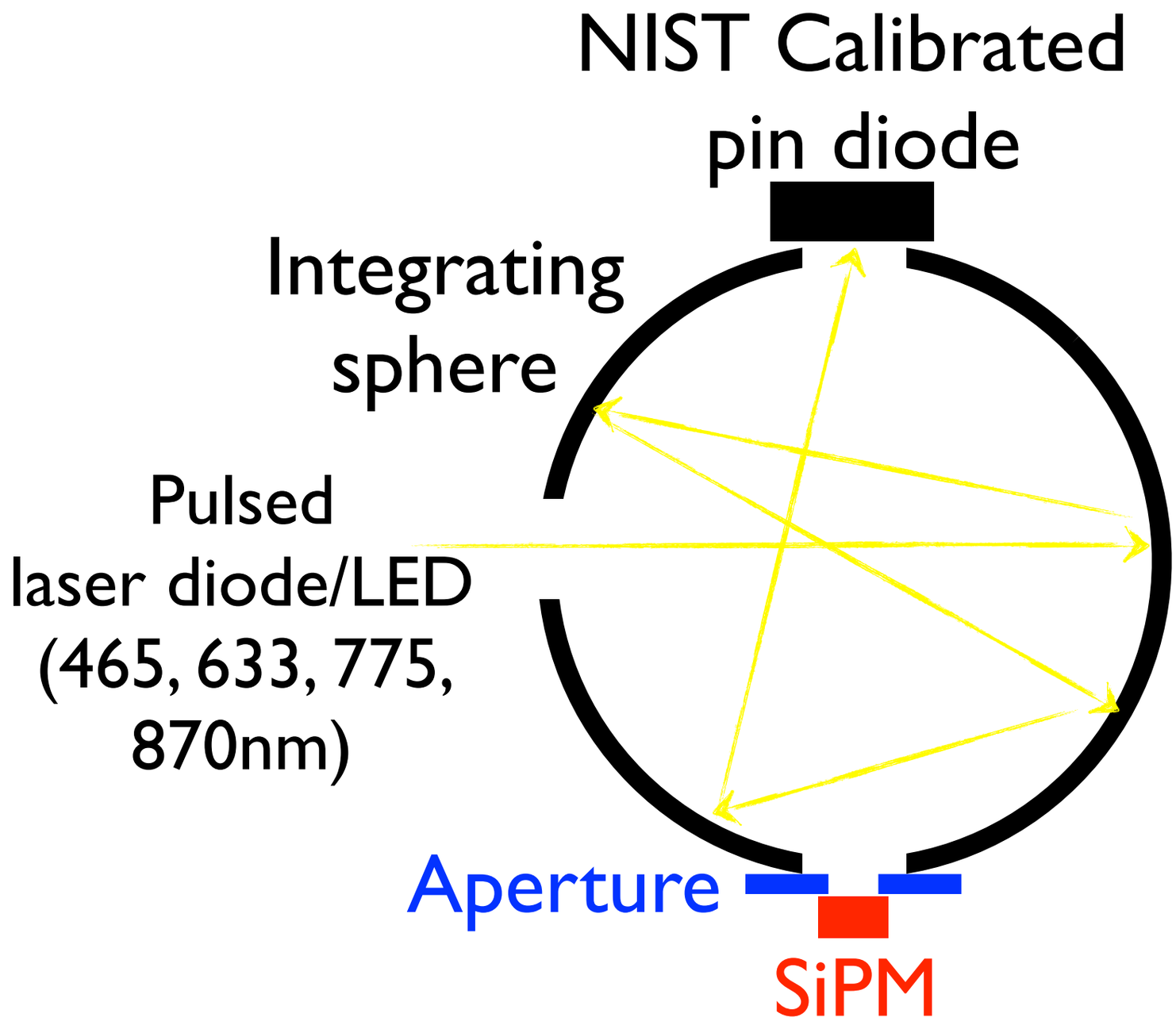
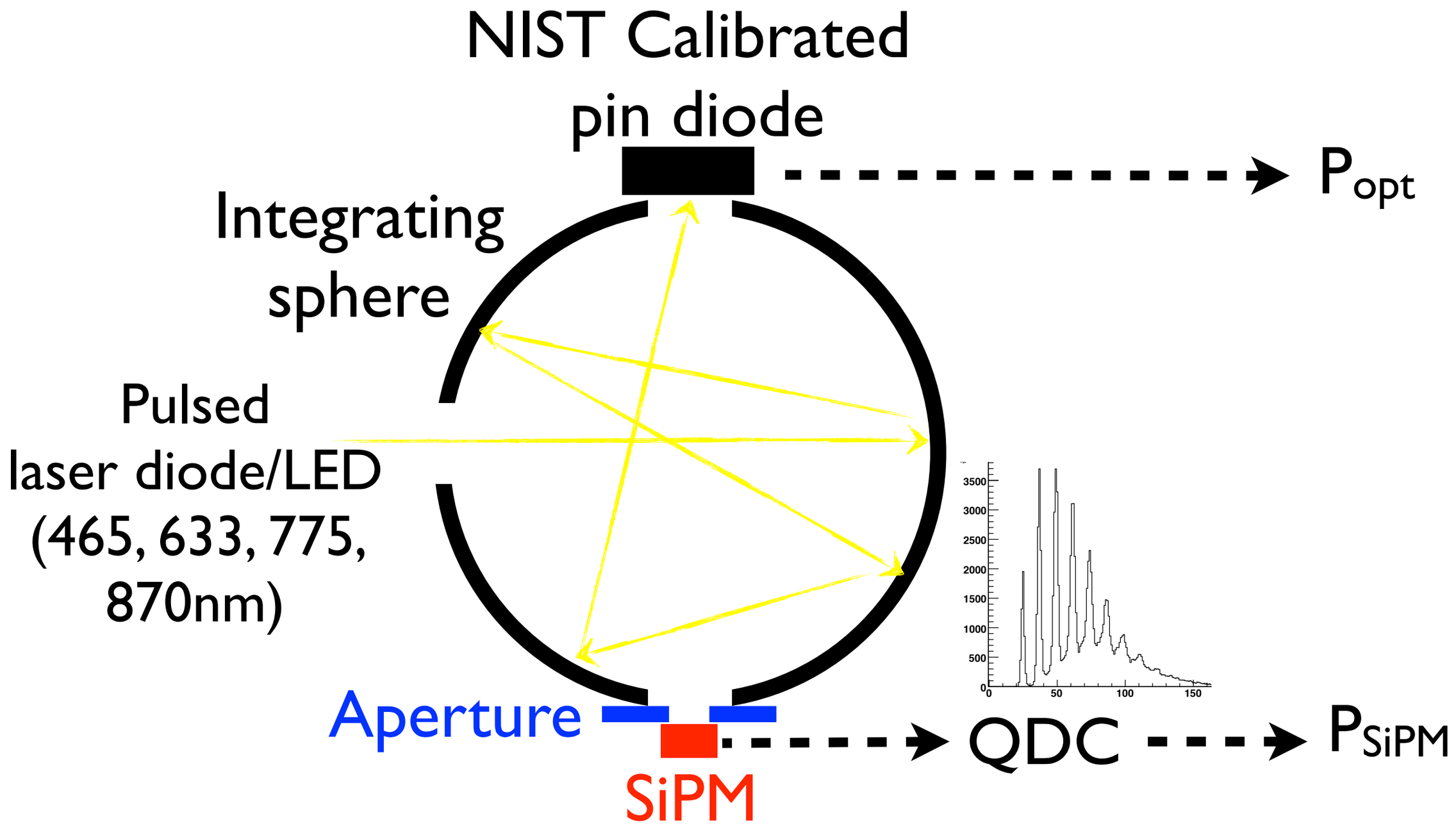


Setup: Absolute PDE



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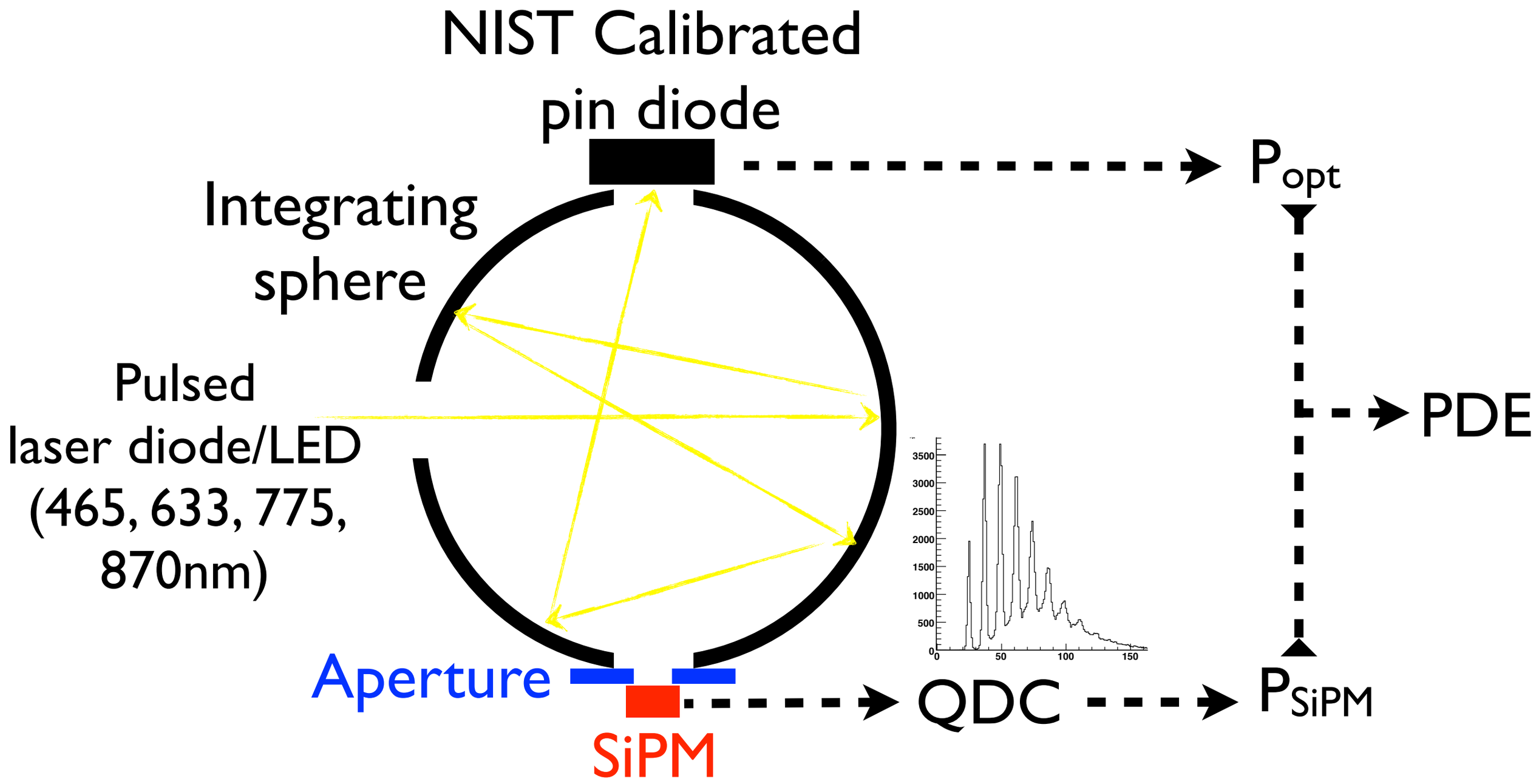
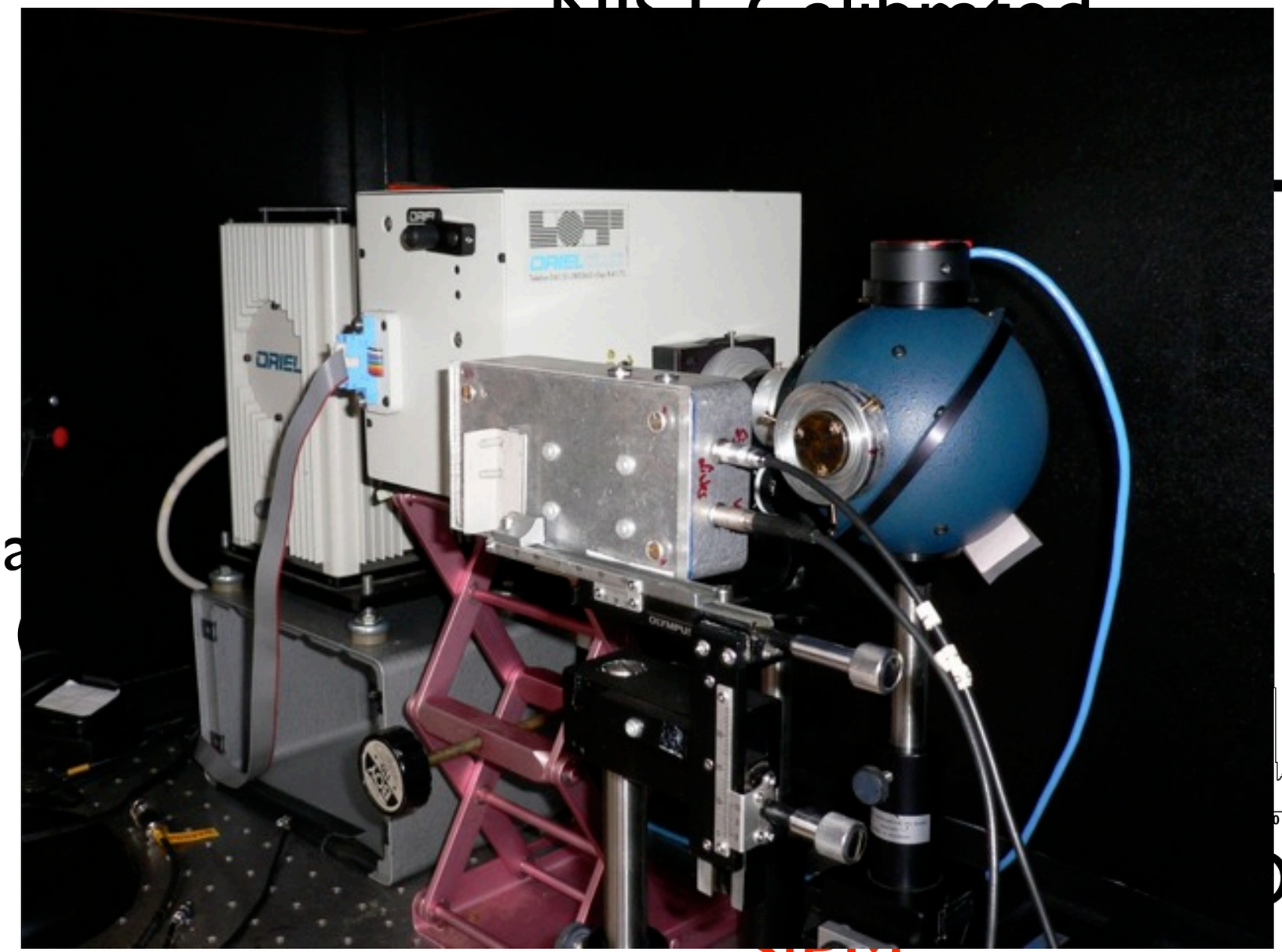


Setup: Absolute PDE

NIST Calibrated



la

(

SiPM

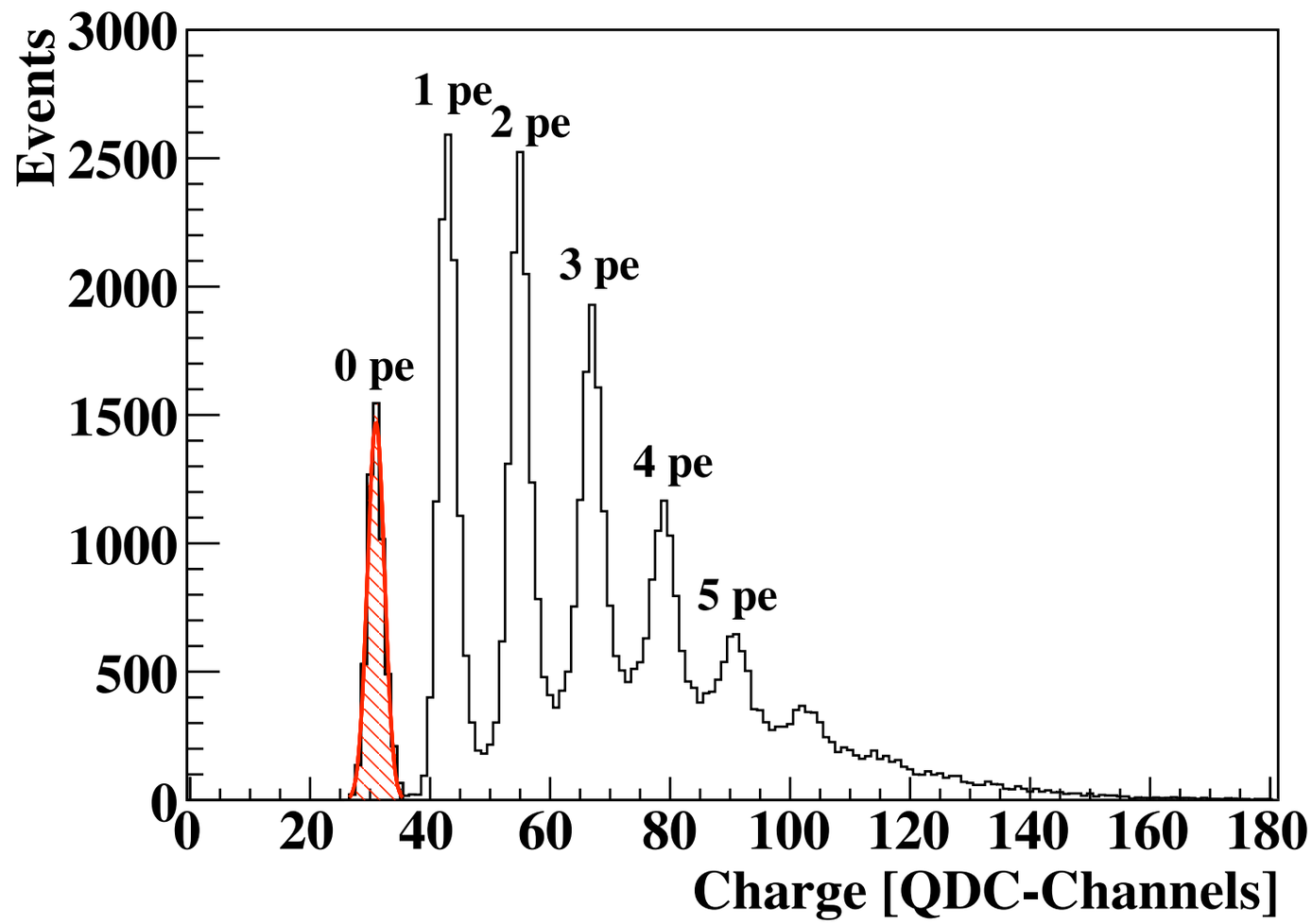
P_{opt}

PDE

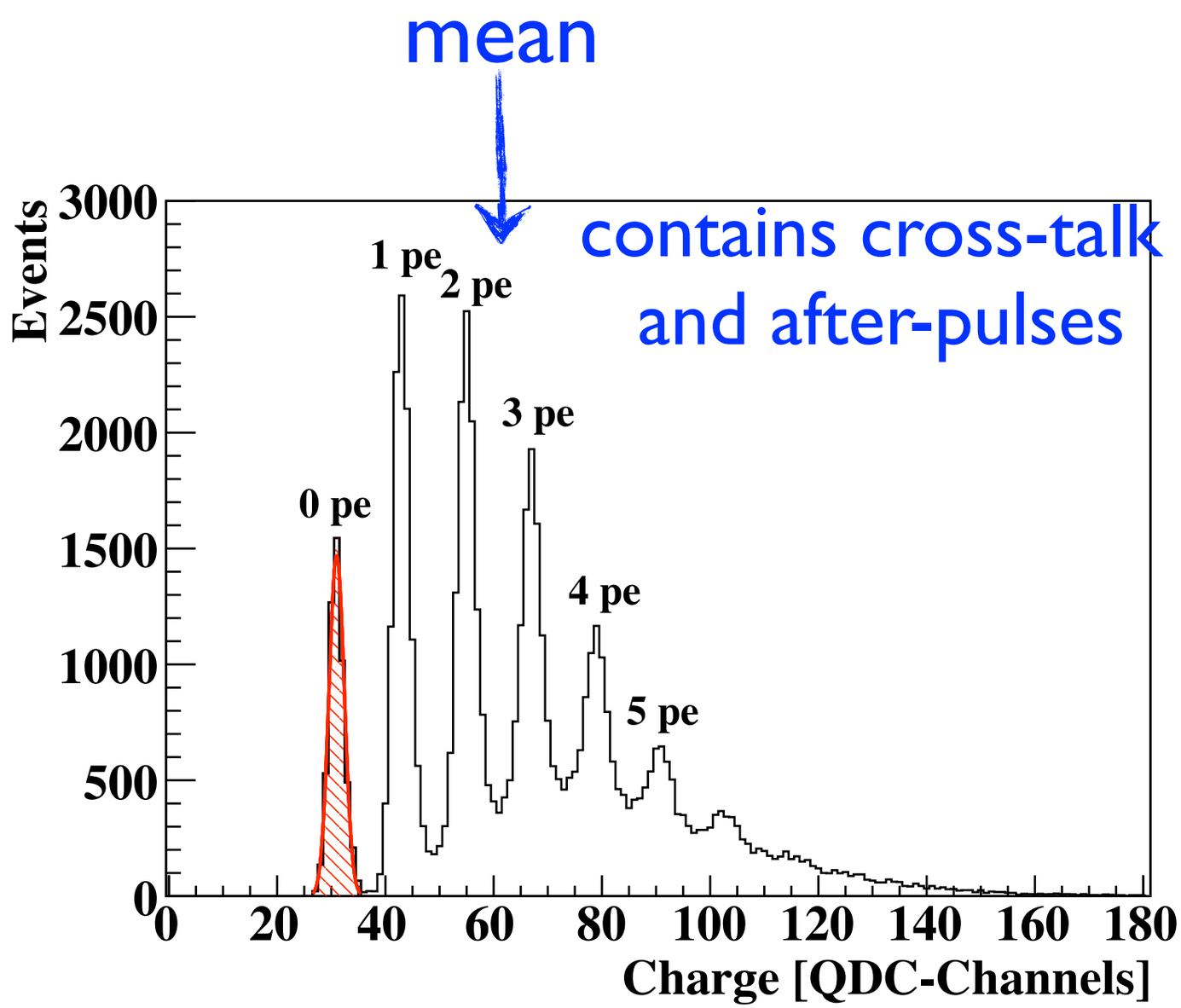
0 100 150

)C P_{SiPM}

Statistical Analysis

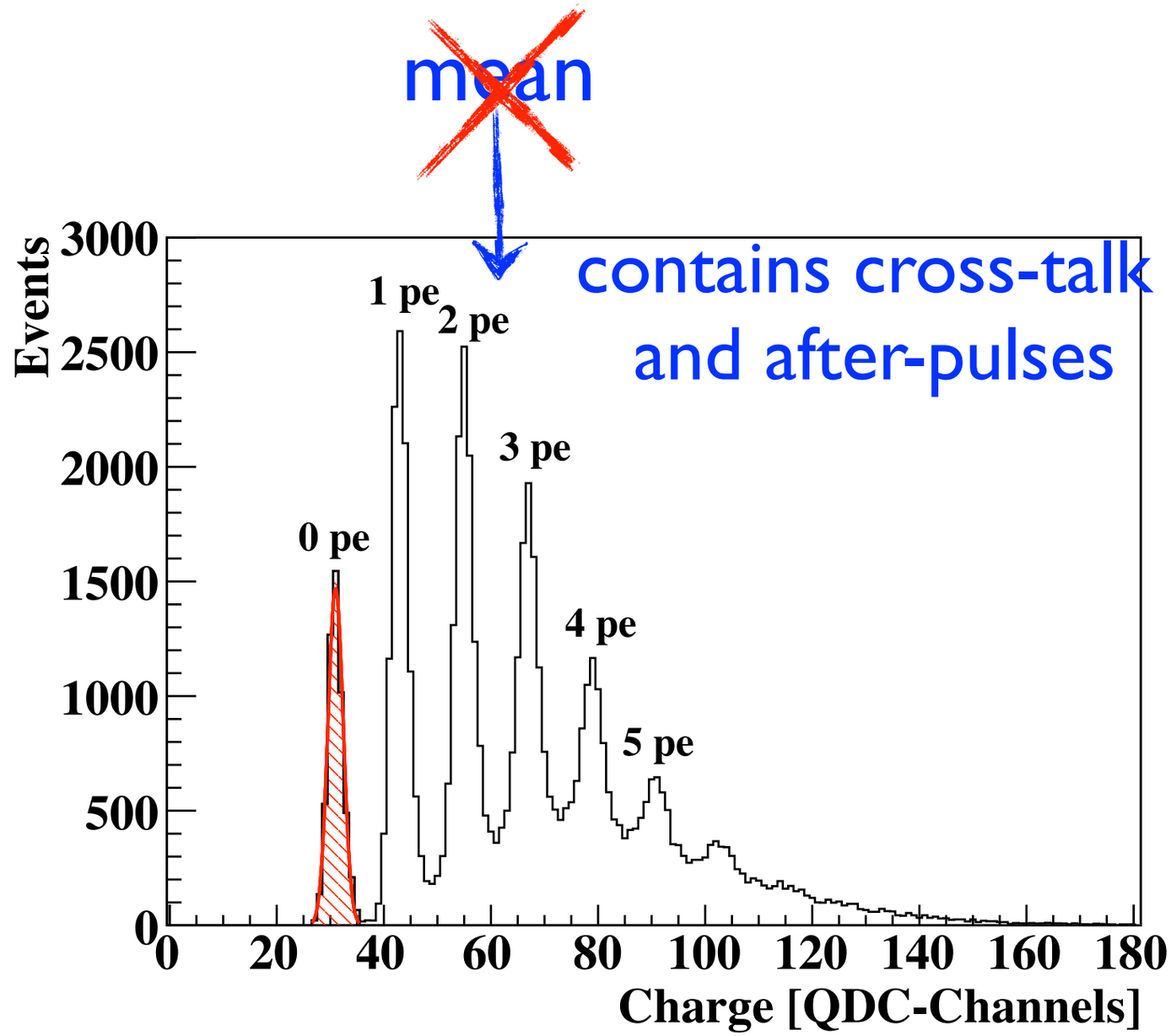


Statistical Analysis



Statistical Analysis

~~mean~~

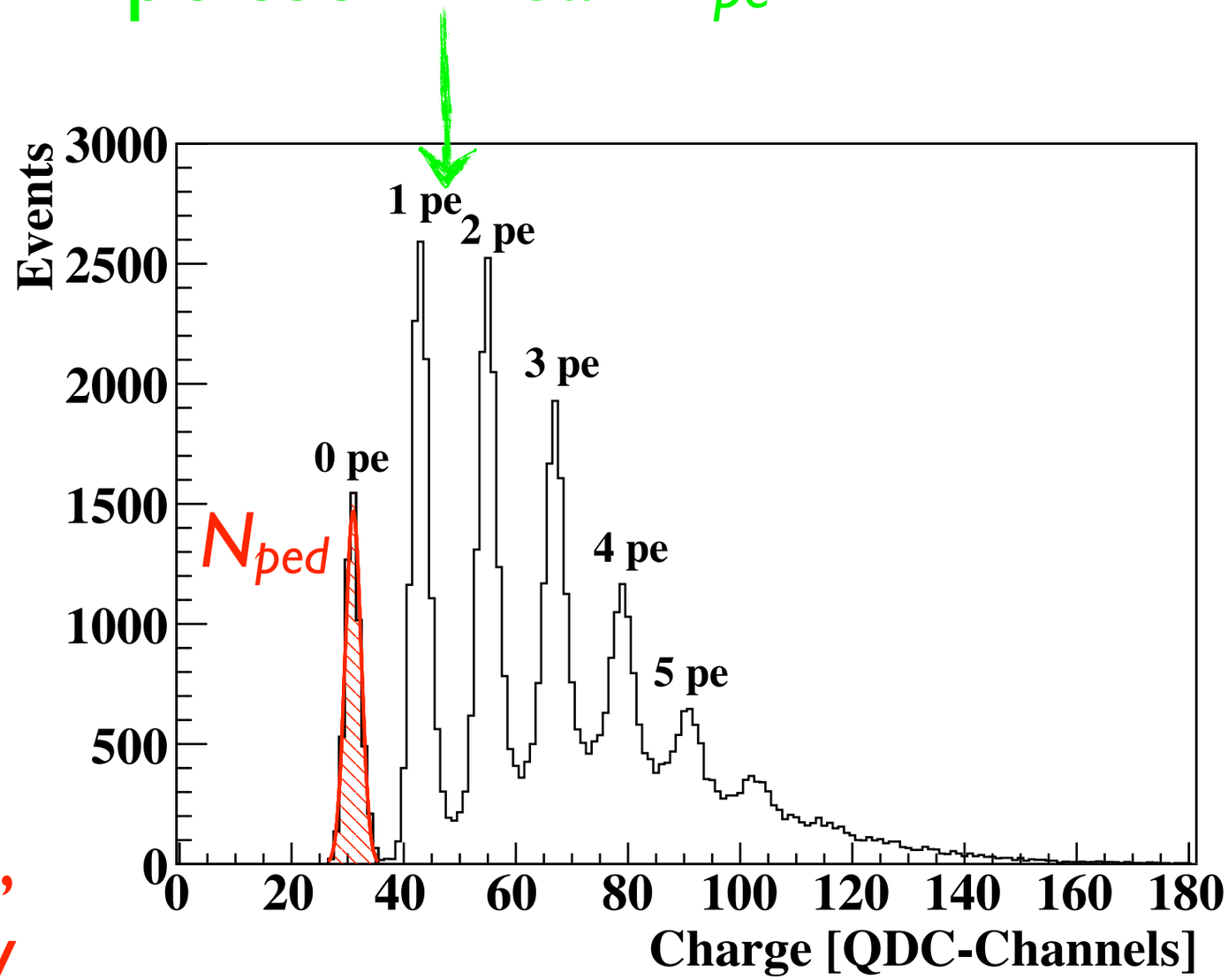


Statistical Analysis

Poisson:

$$
\begin{aligned}
P(0, n_{\mathrm{pe}}) &= e^{-n_{\mathrm{pe}}} \\
\rightarrow n_{\mathrm{pe}} &= -ln\left(P(0, n_{\mathrm{pe}})\right) \\
&= -ln\left(\frac{N_{\mathrm{ped}}}{N_{\mathrm{tot}}}\right) + ln\left(\frac{N_{\mathrm{ped}}^{\mathrm{dark}}}{N_{\mathrm{tot}}^{\mathrm{dark}}}\right)
\end{aligned}
$$

poisson mean n_{pe}



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

Statistical Analysis

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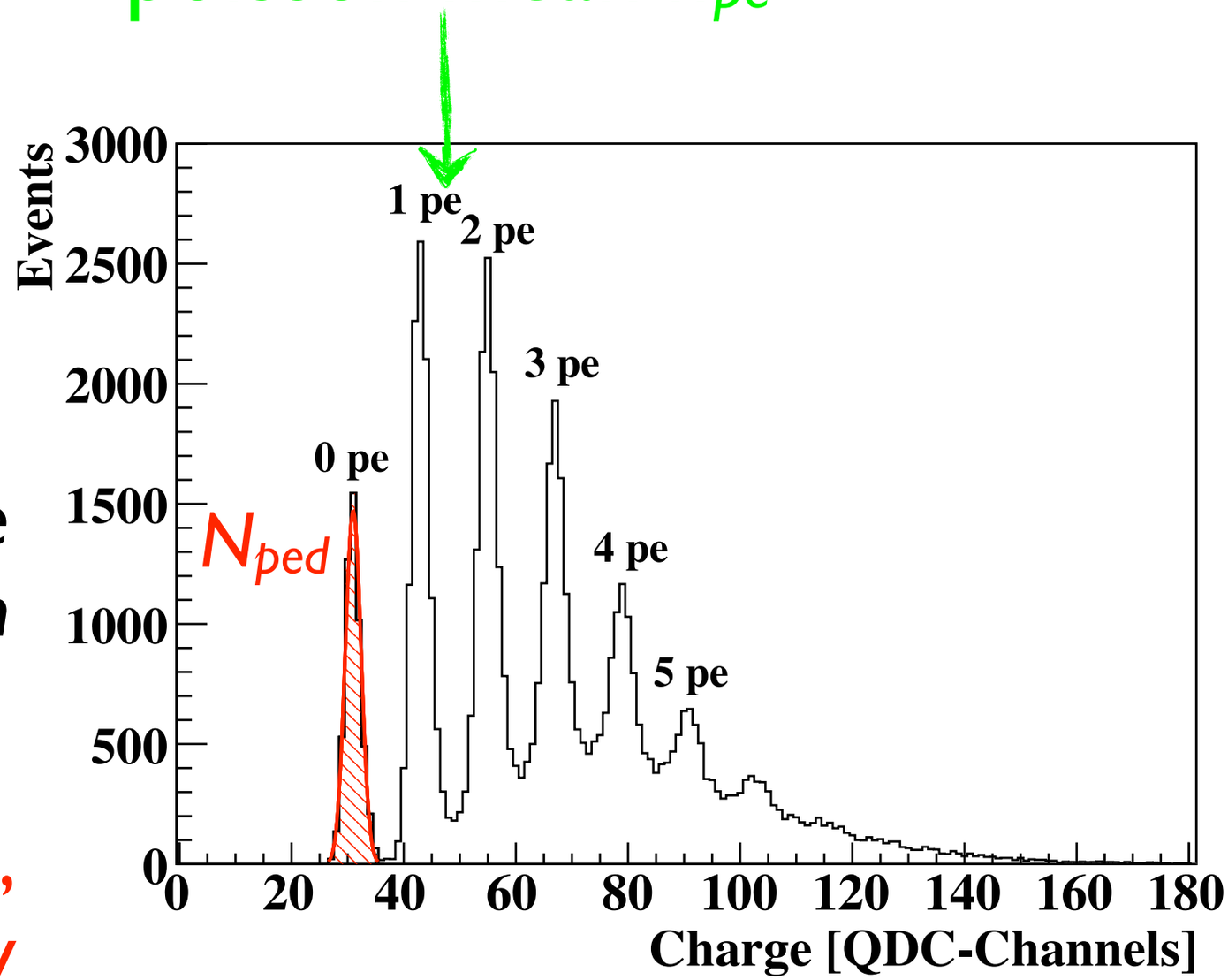
\end{aligned}
$$

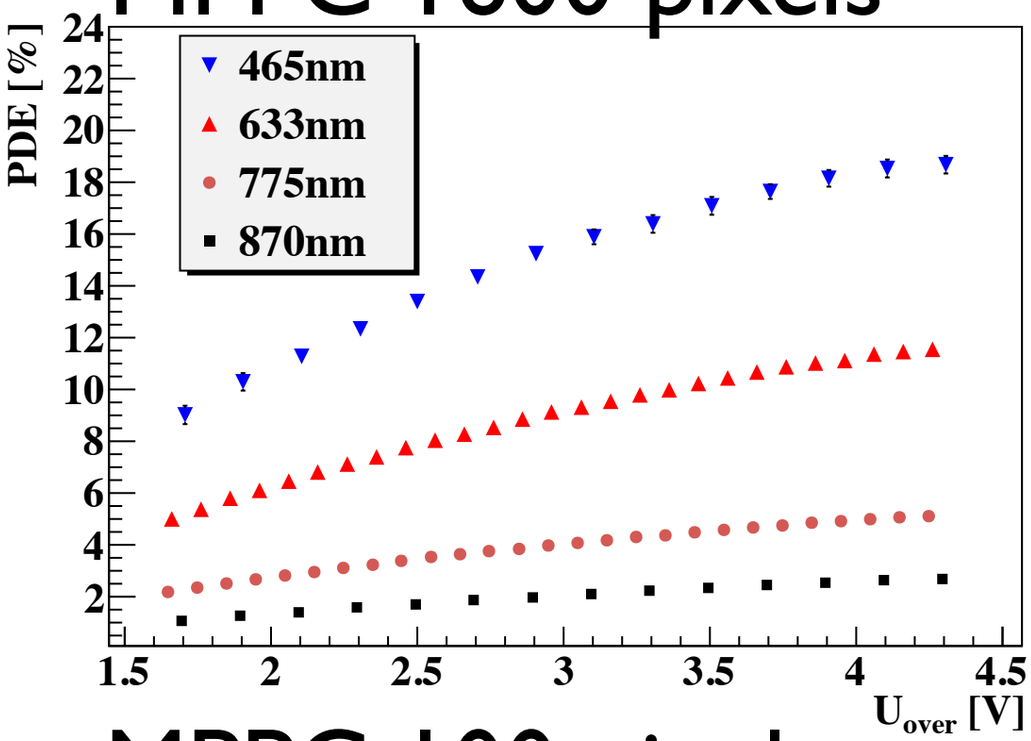
Dark-rate correction (small)

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

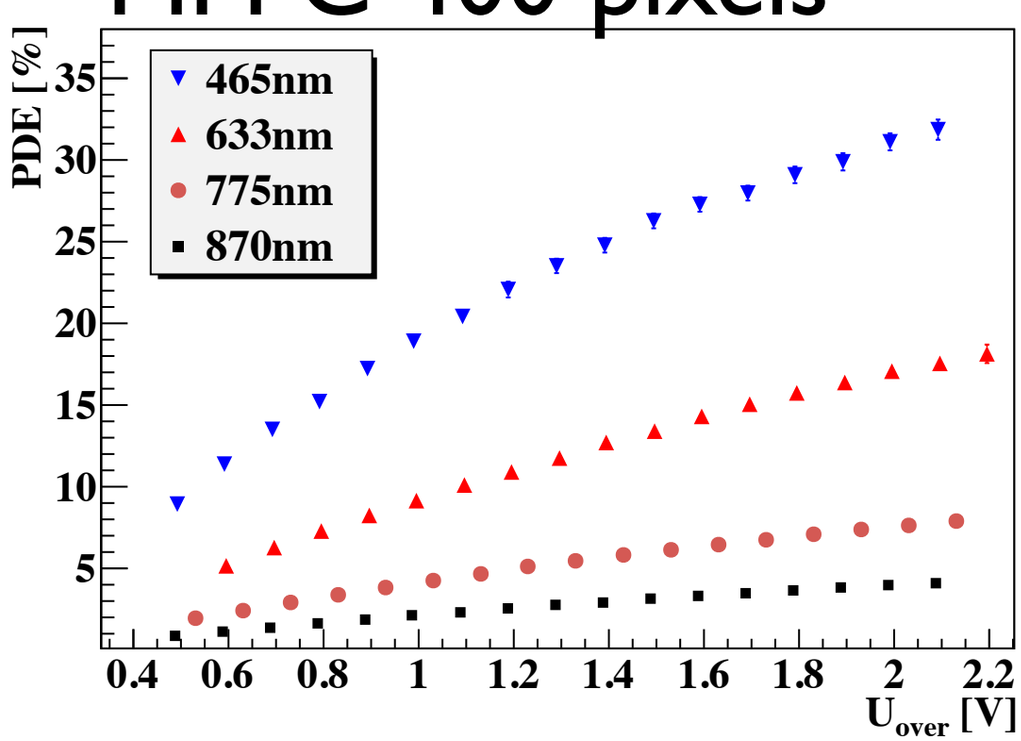


PDE vs. U_{over}

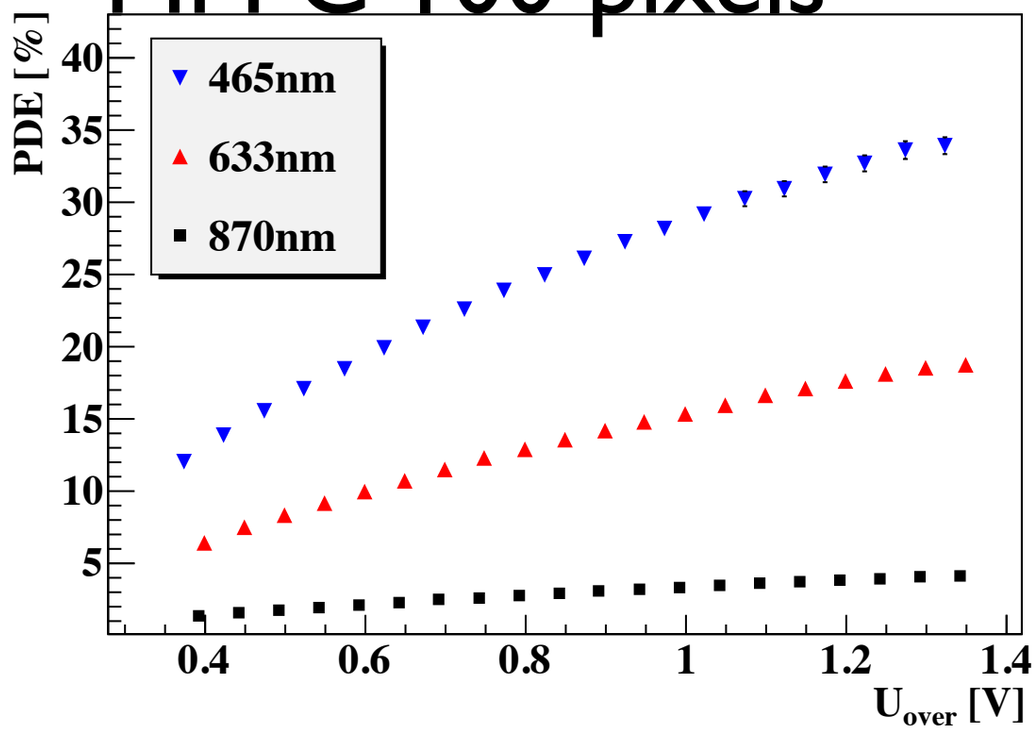
MPPC 1600 pixels



MPPC 400 pixels



MPPC 100 pixels



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

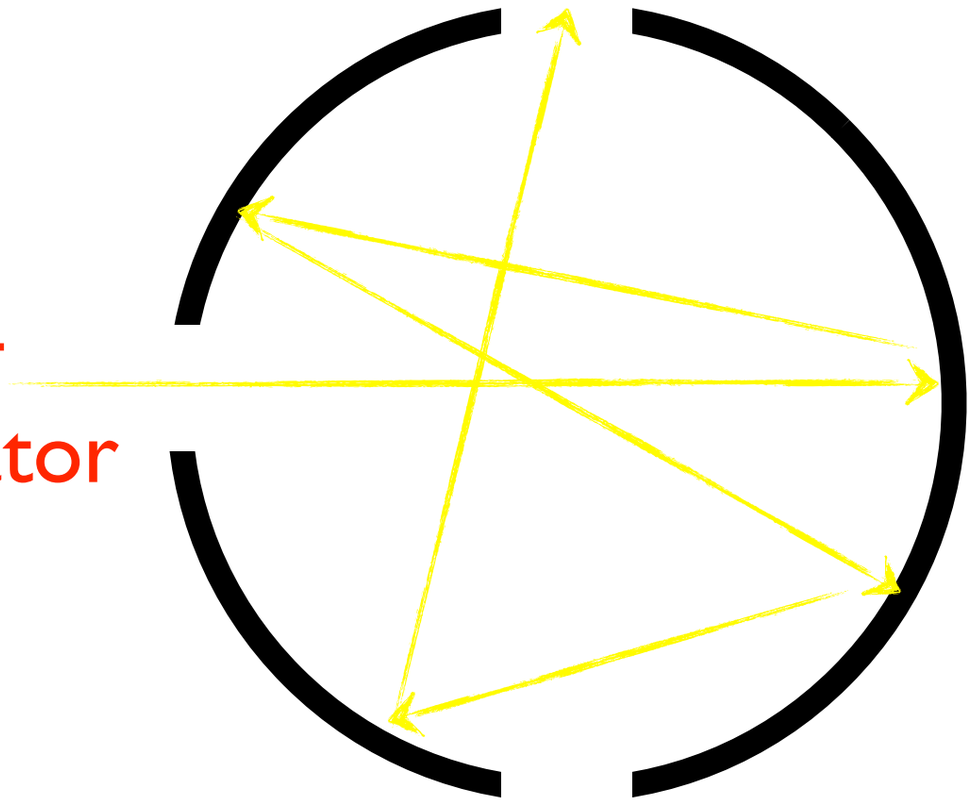
R: Power ratio

f: Pulsing frequency

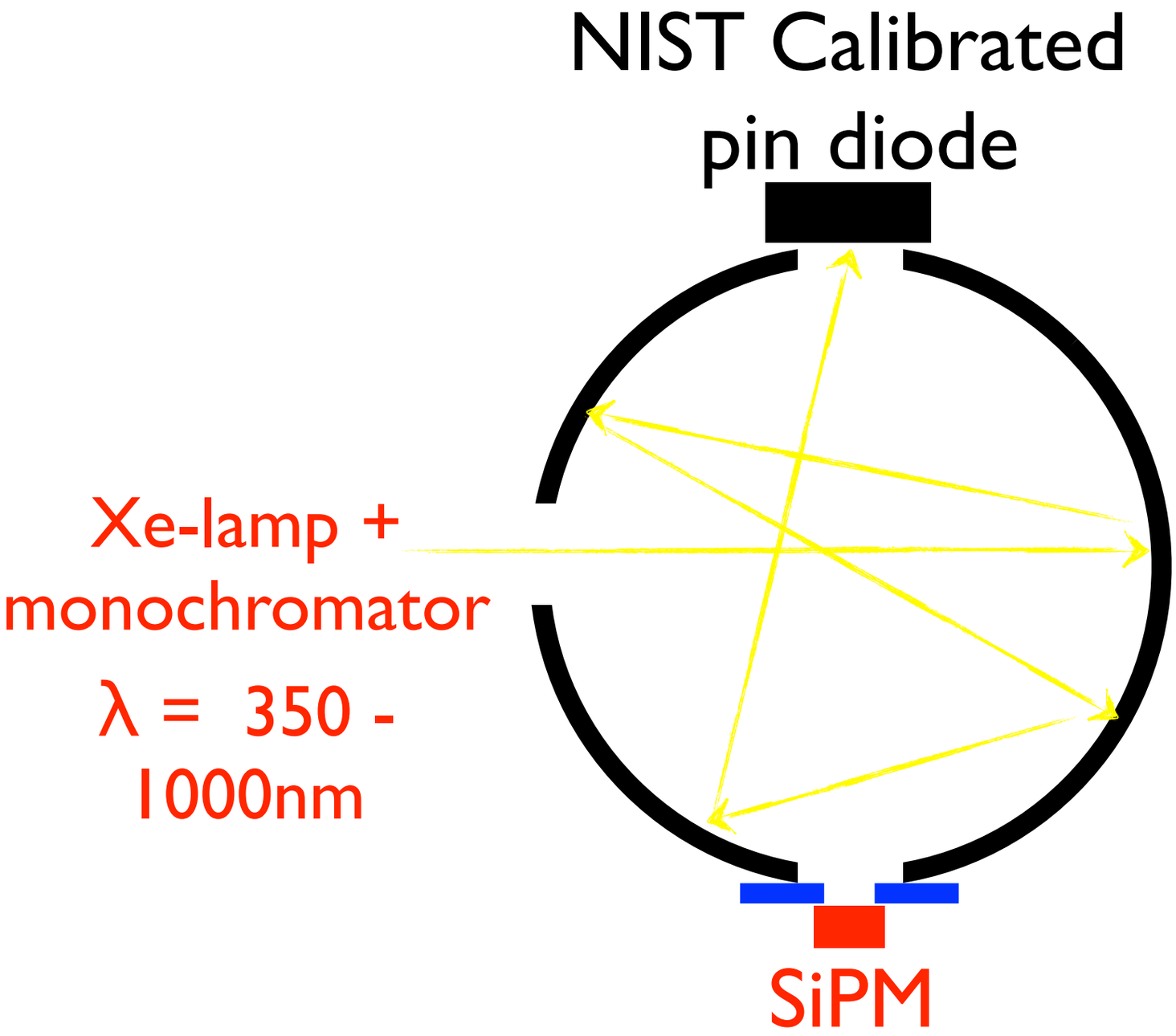
Setup: Spectral Sensitivity

Xe-lamp + monochromator

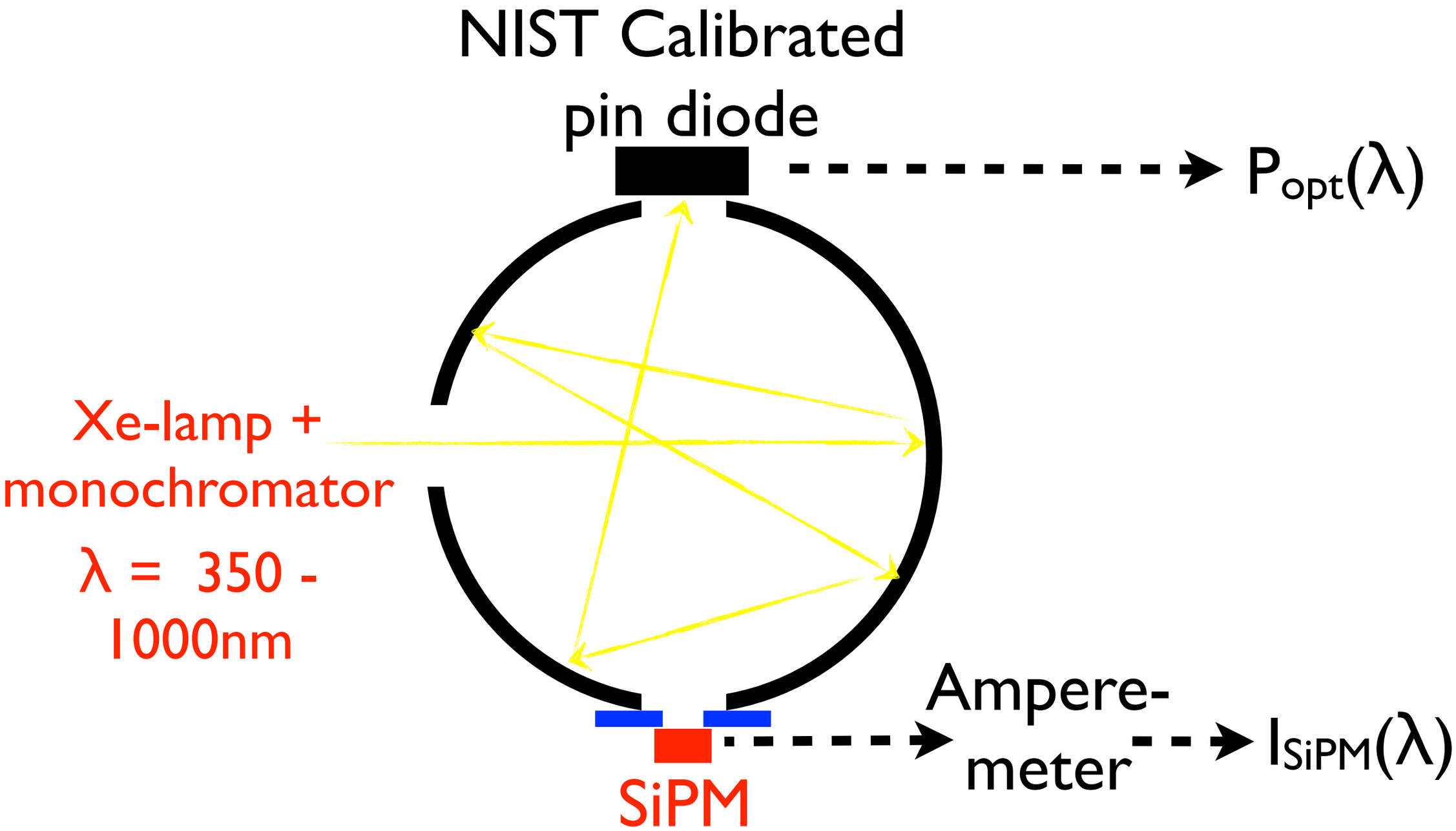
λ = 350 - 1000nm



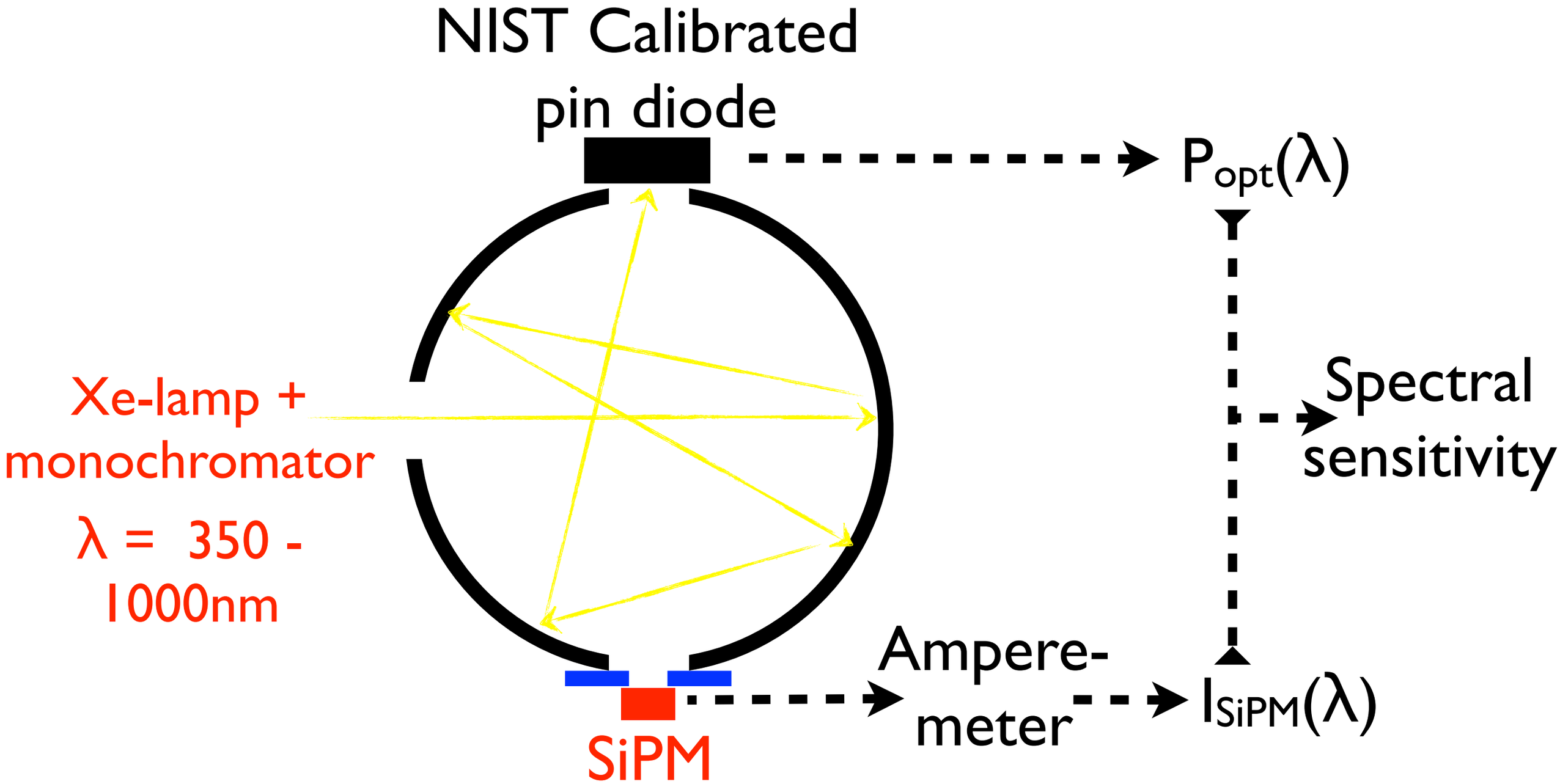
Setup: Spectral Sensitivity



Setup: Spectral Sensitivity

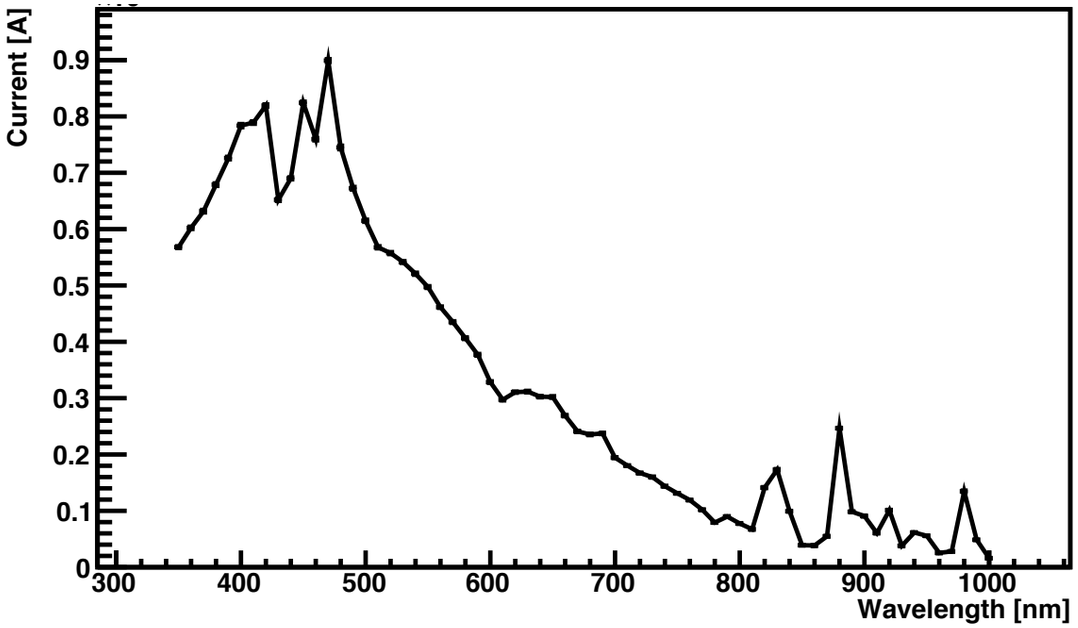


Setup: Spectral Sensitivity

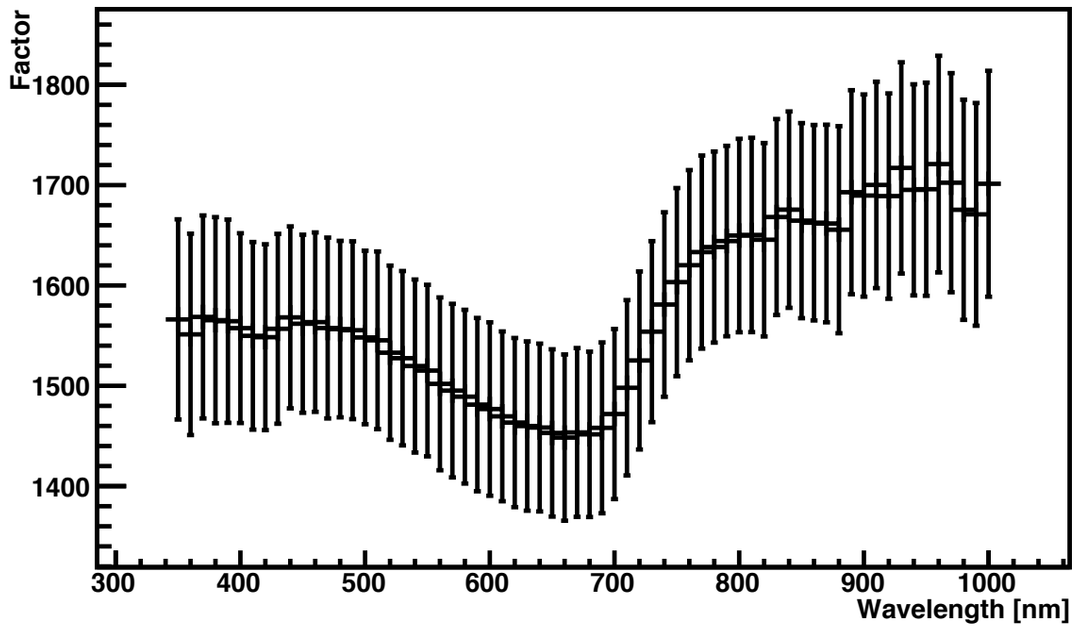


Spectral Sensitivity

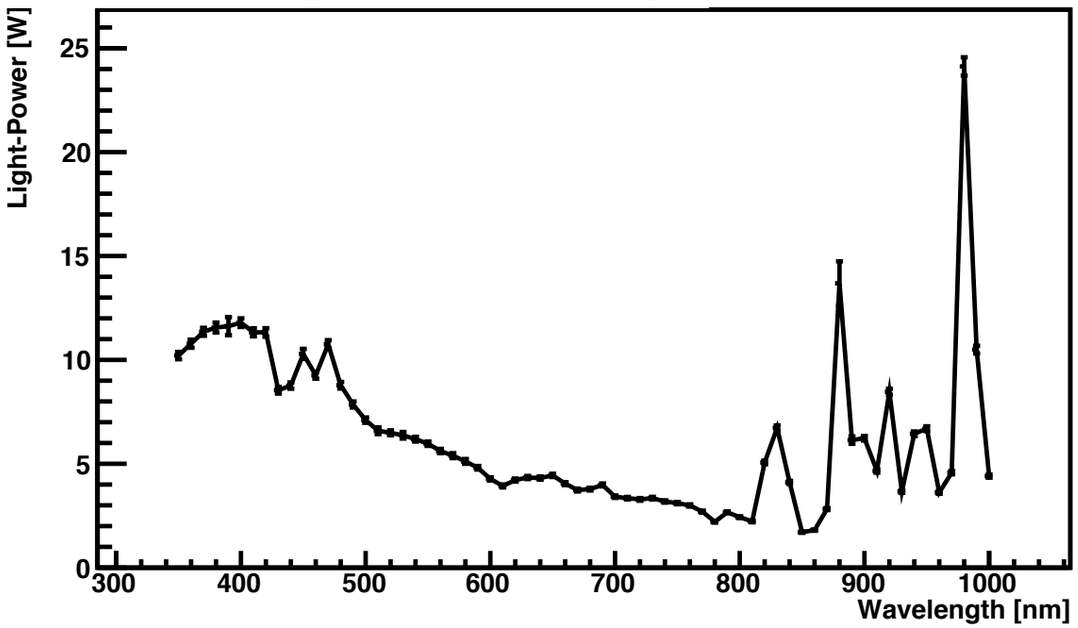
SiPM current, I_{SiPM} A



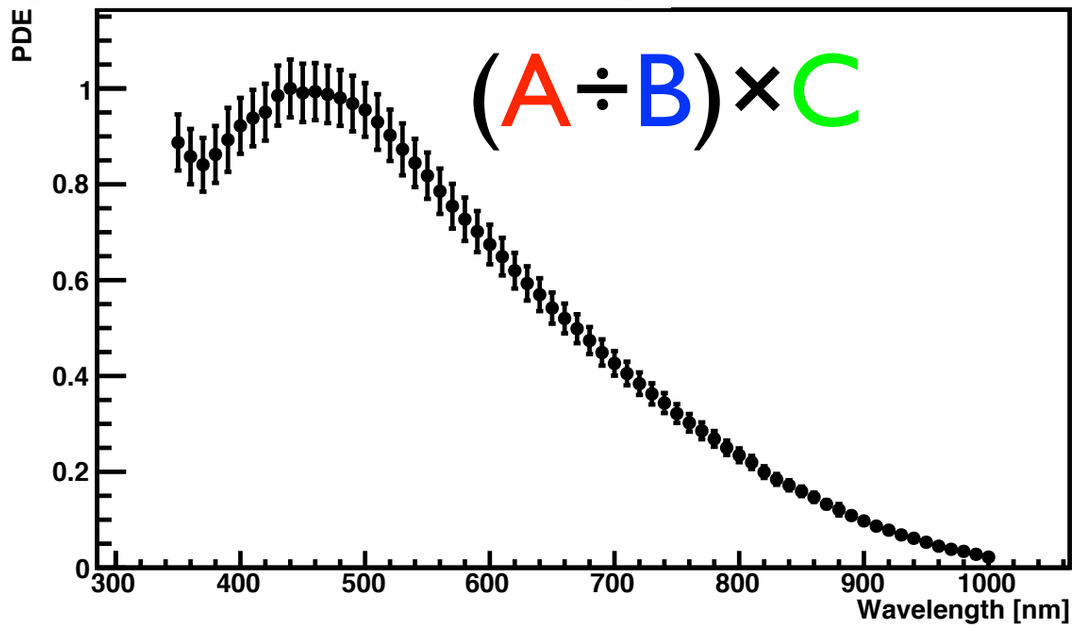
Power ratio C



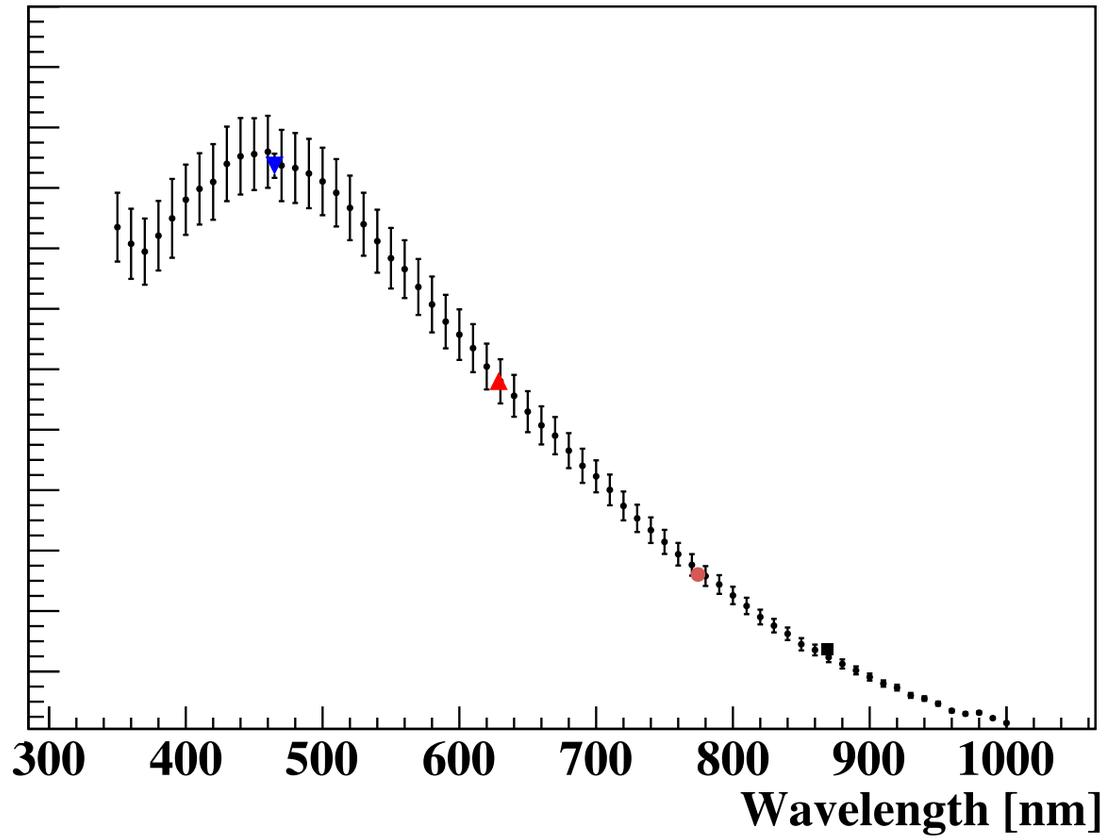
Optical power, P_{opt} B



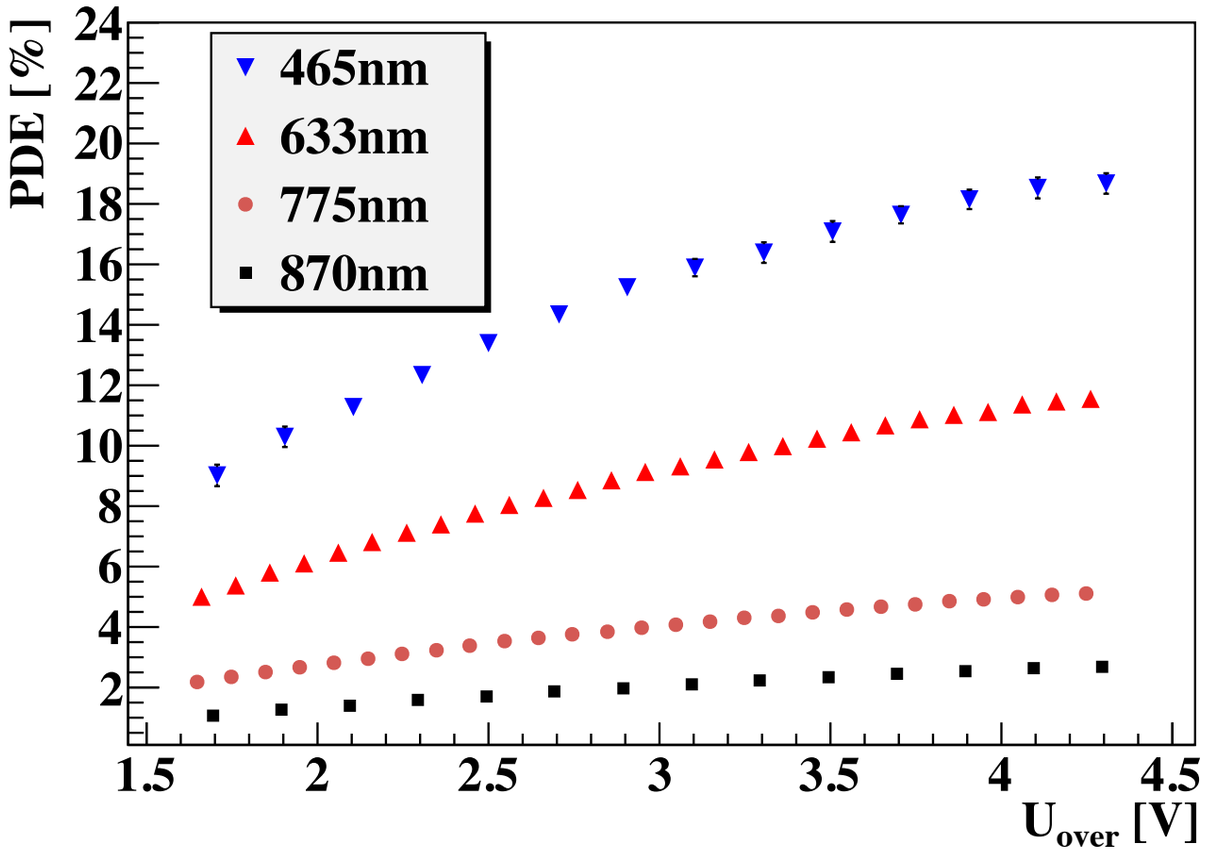
Spectral sensitivity

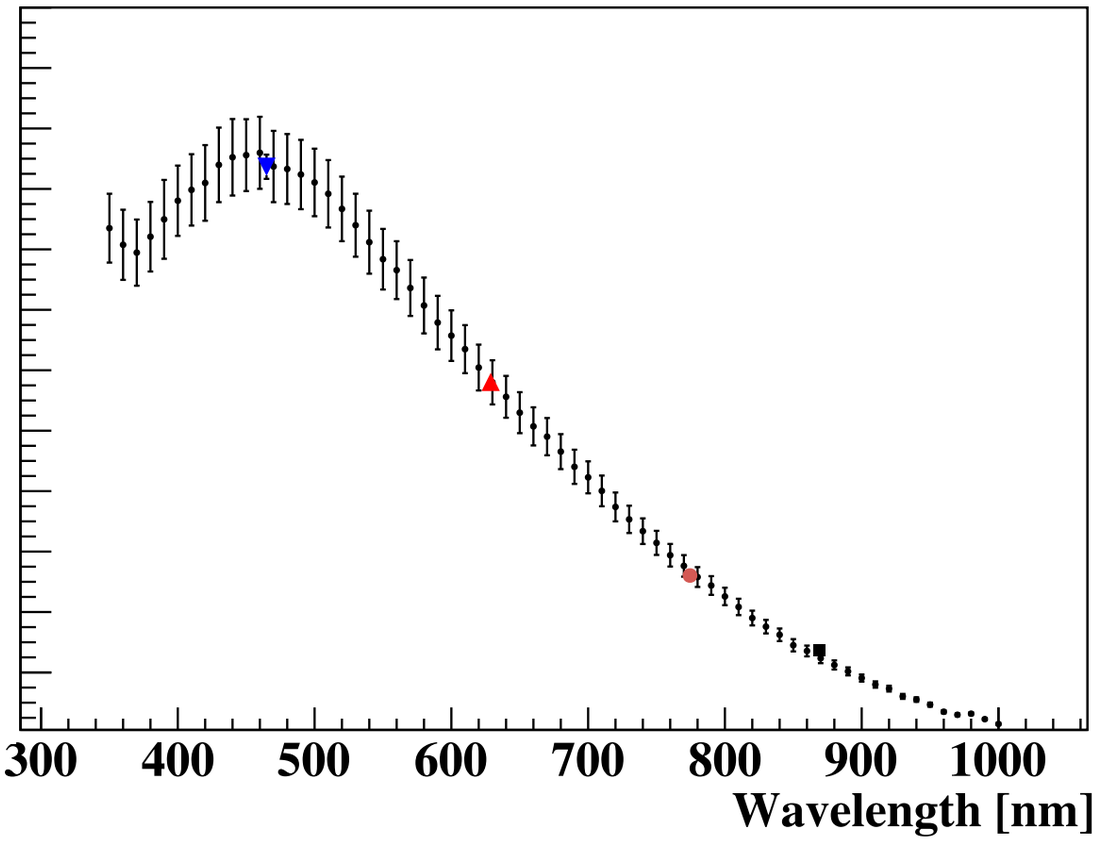


PDE Scaling

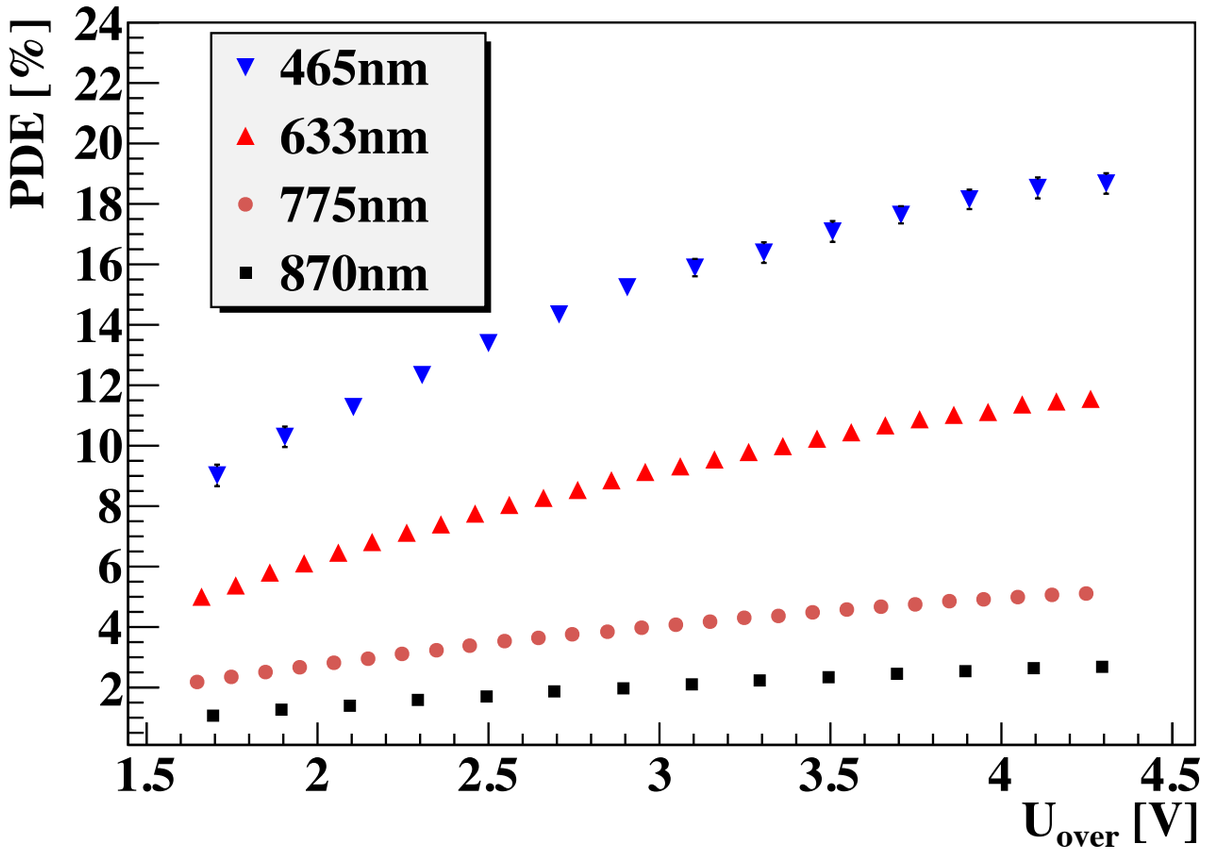


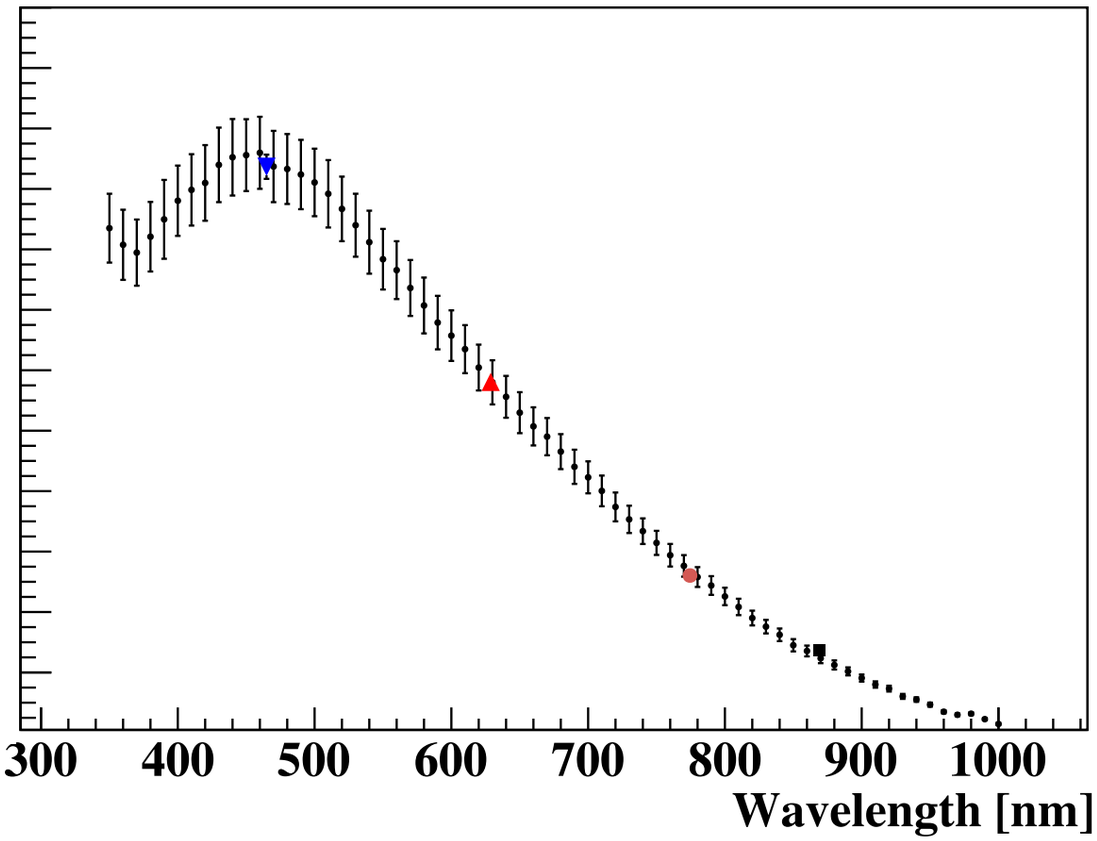
PDE Scaling


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]

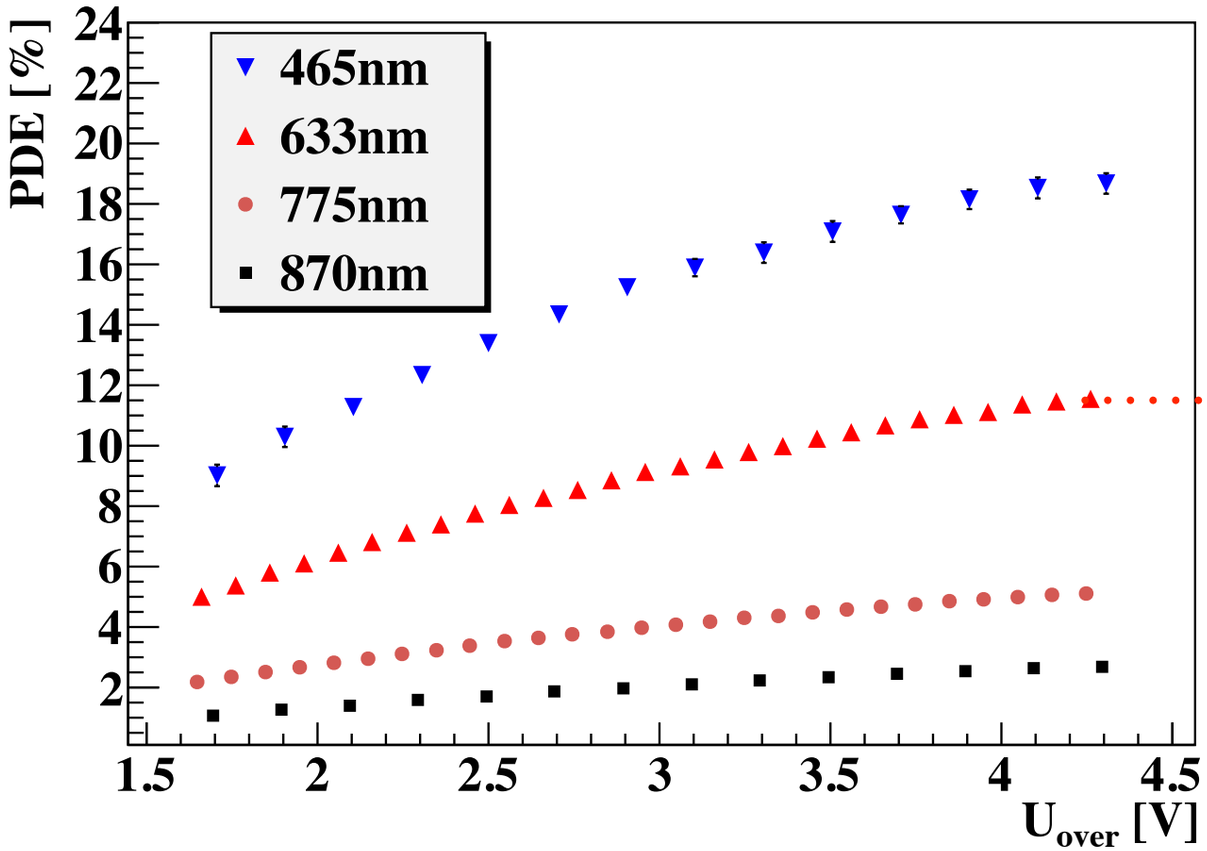
PDE Scaling

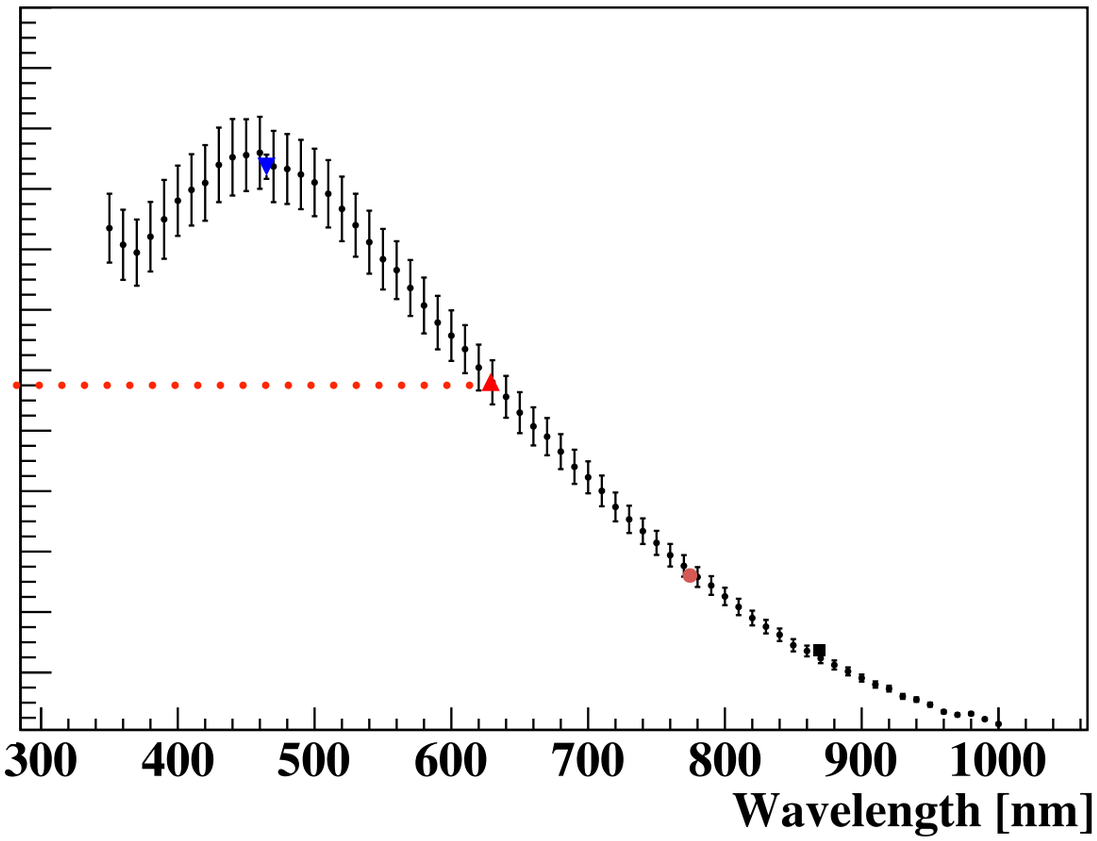




Scale to max. PDE value measured at 633nm

PDE Scaling





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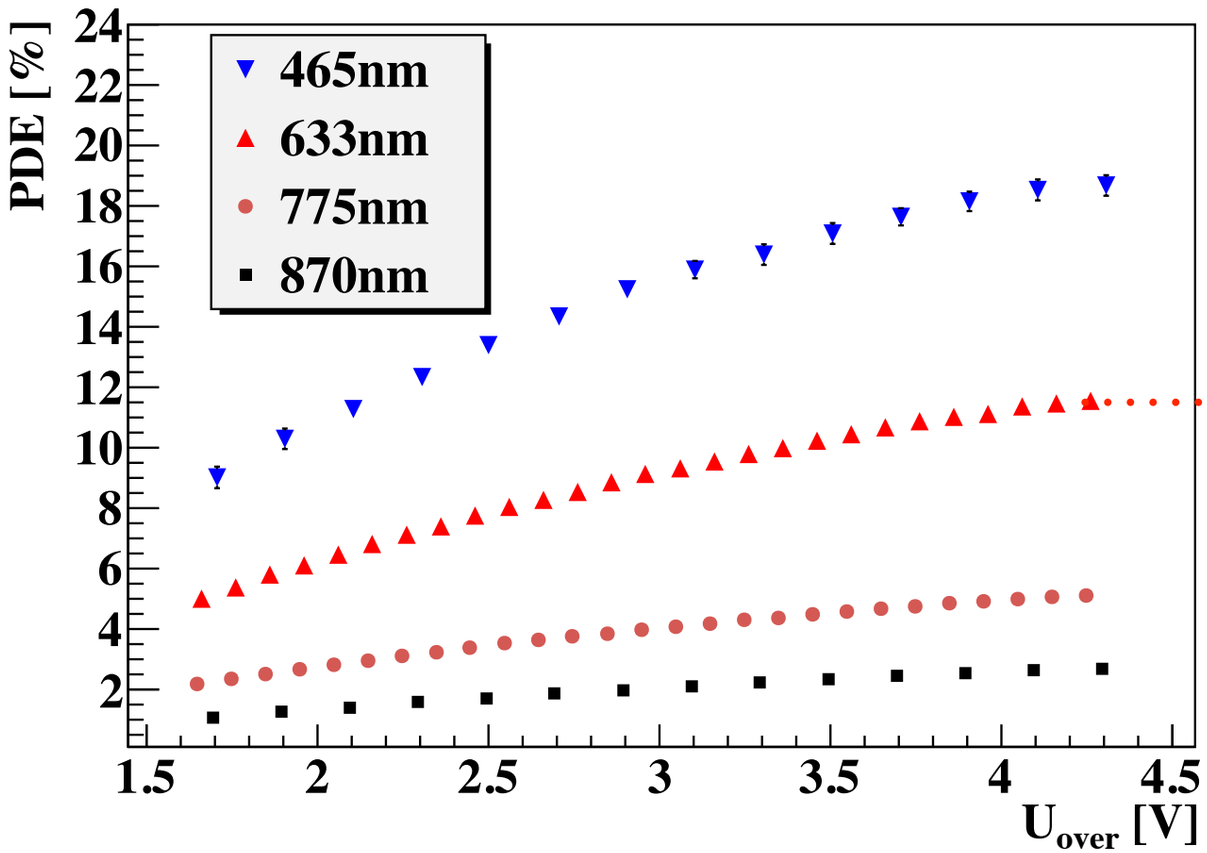
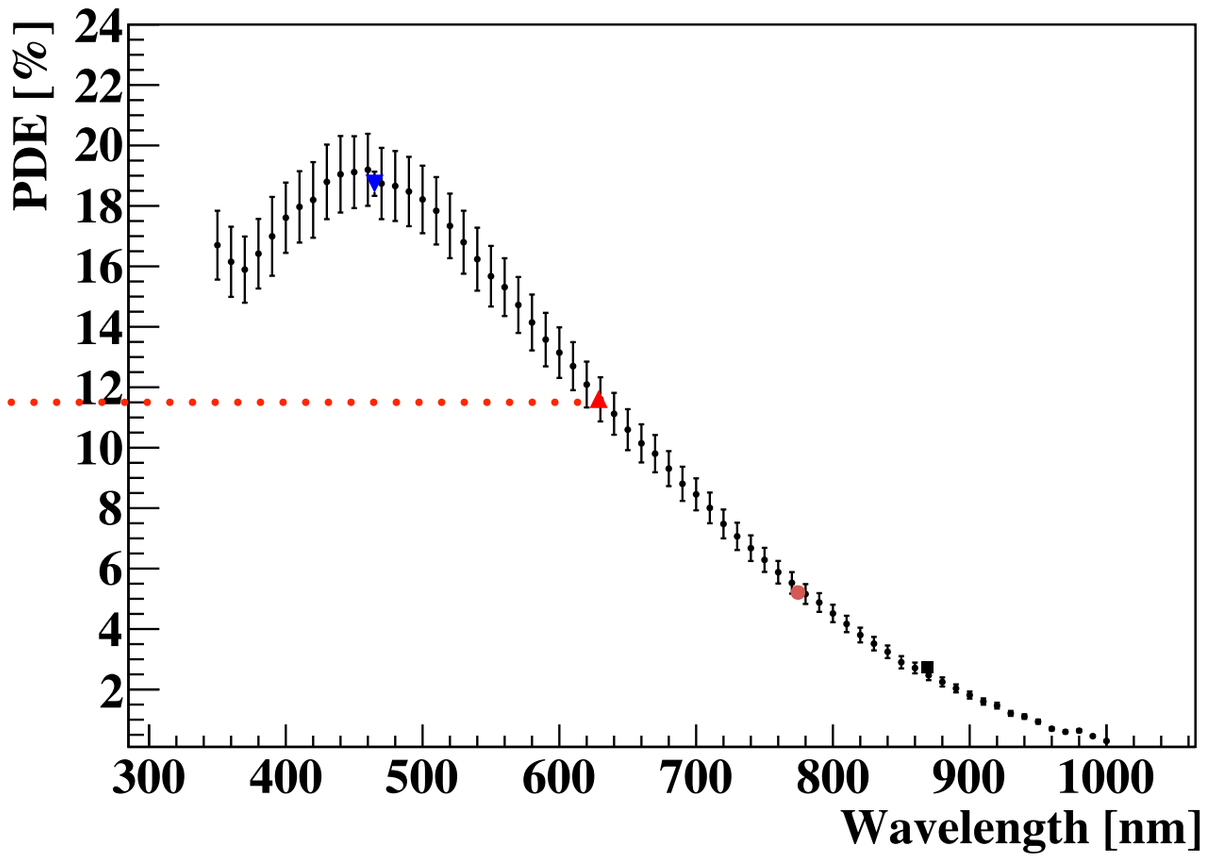
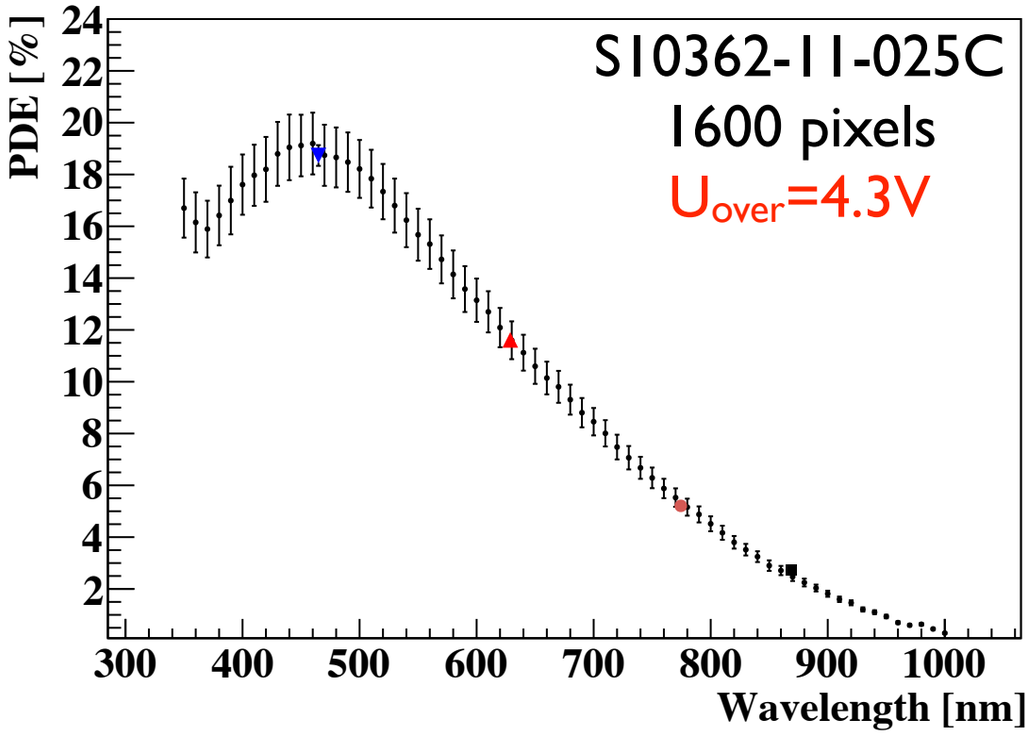
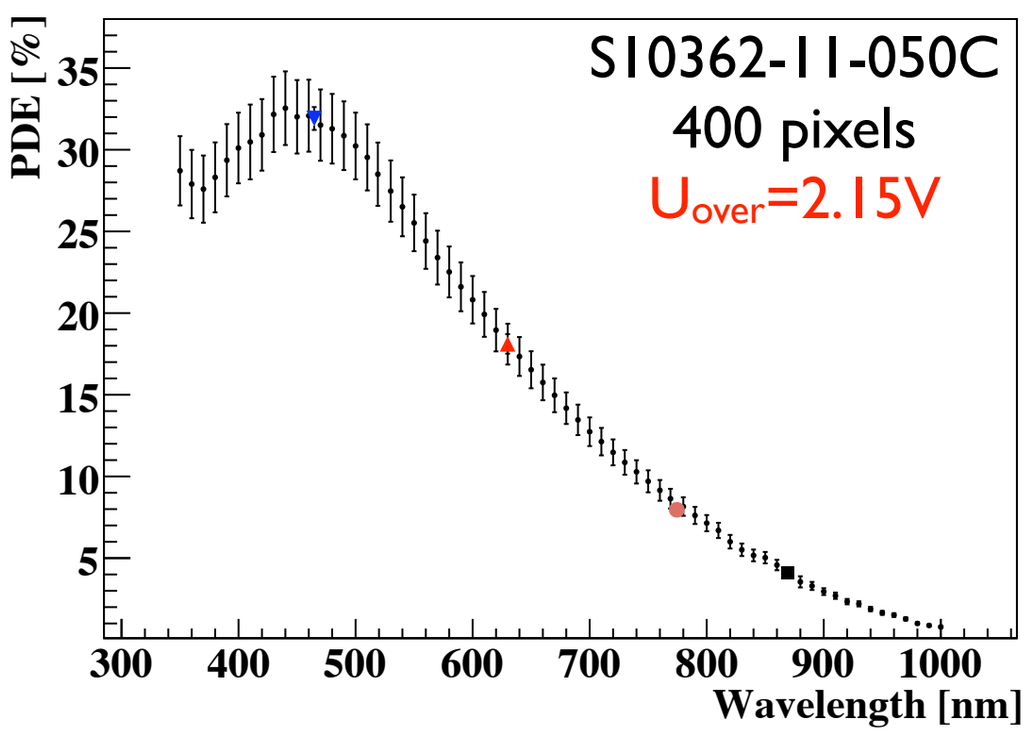


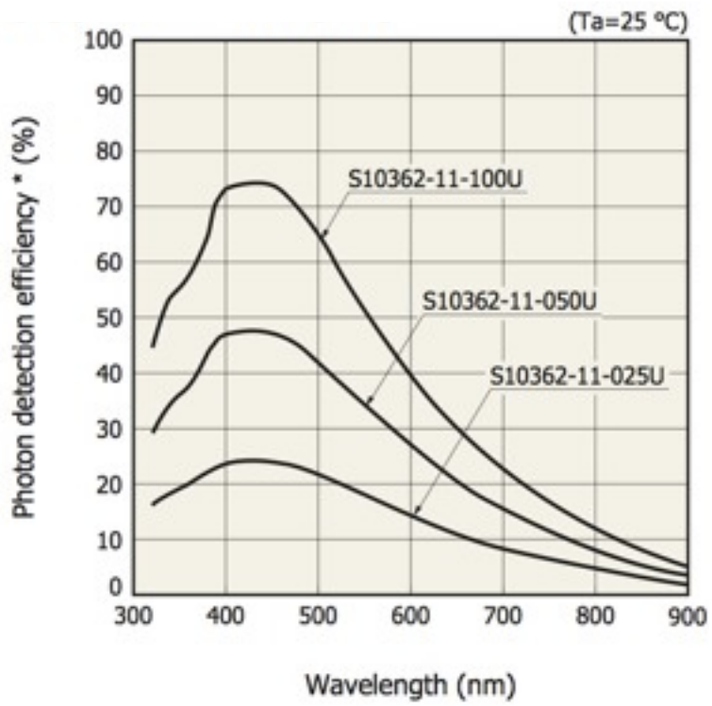


Scale to max. PDE value measured at 633nm

PDE Results: MPPC







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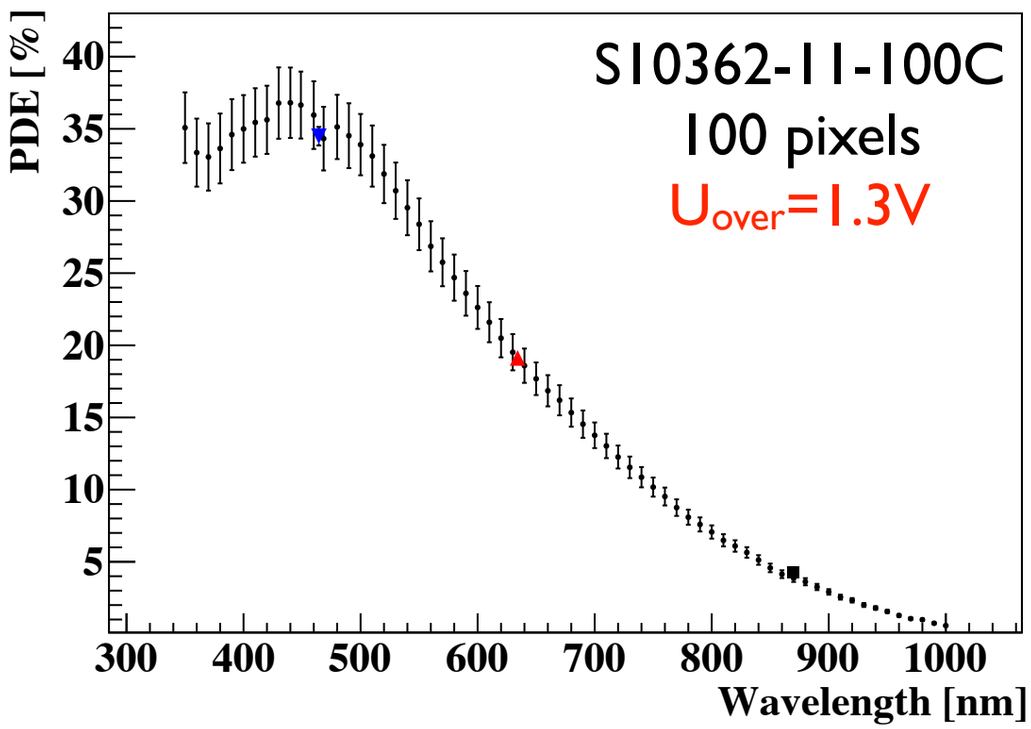

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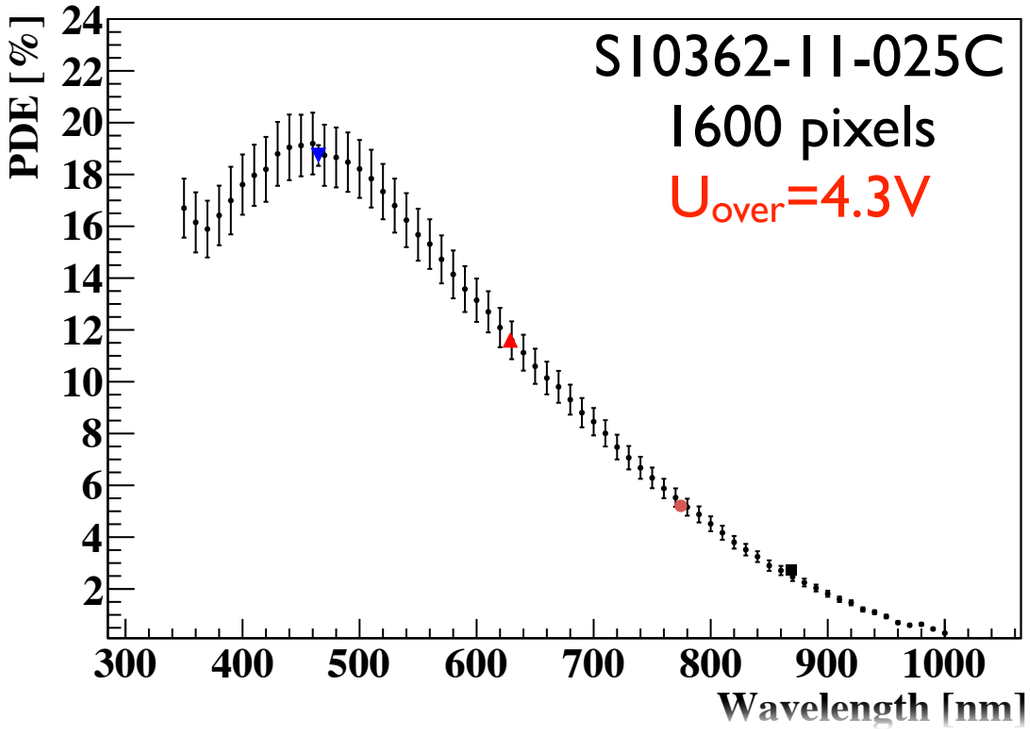
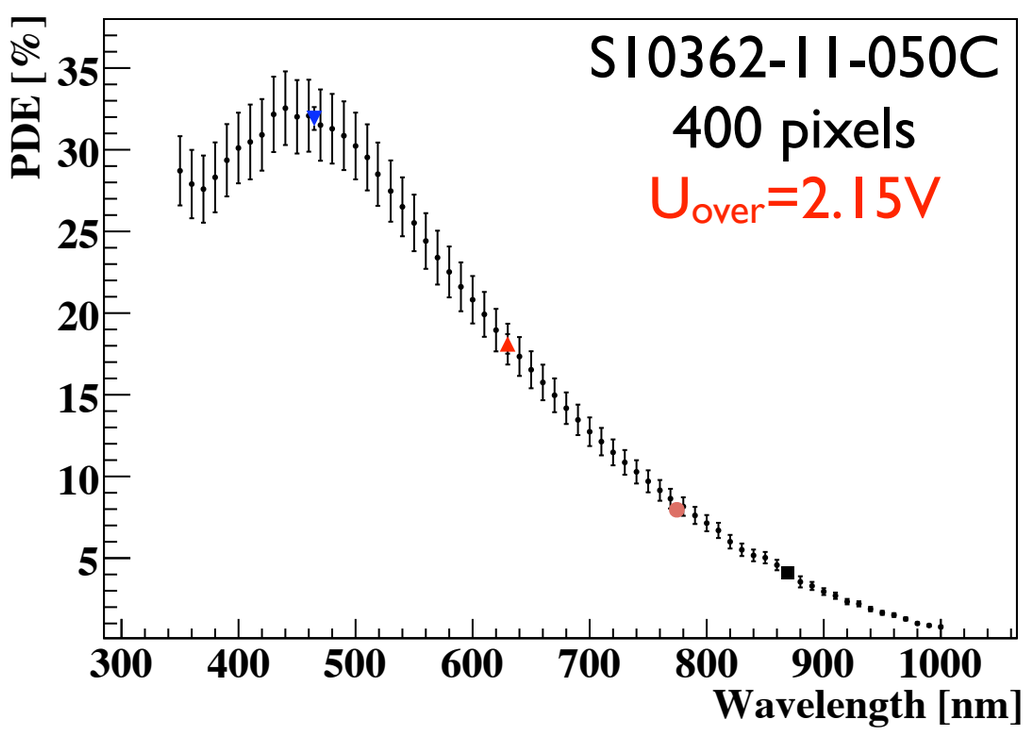
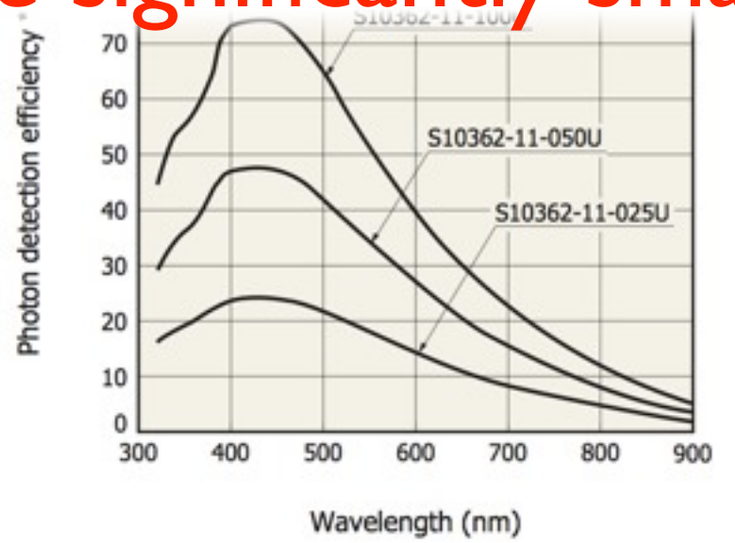


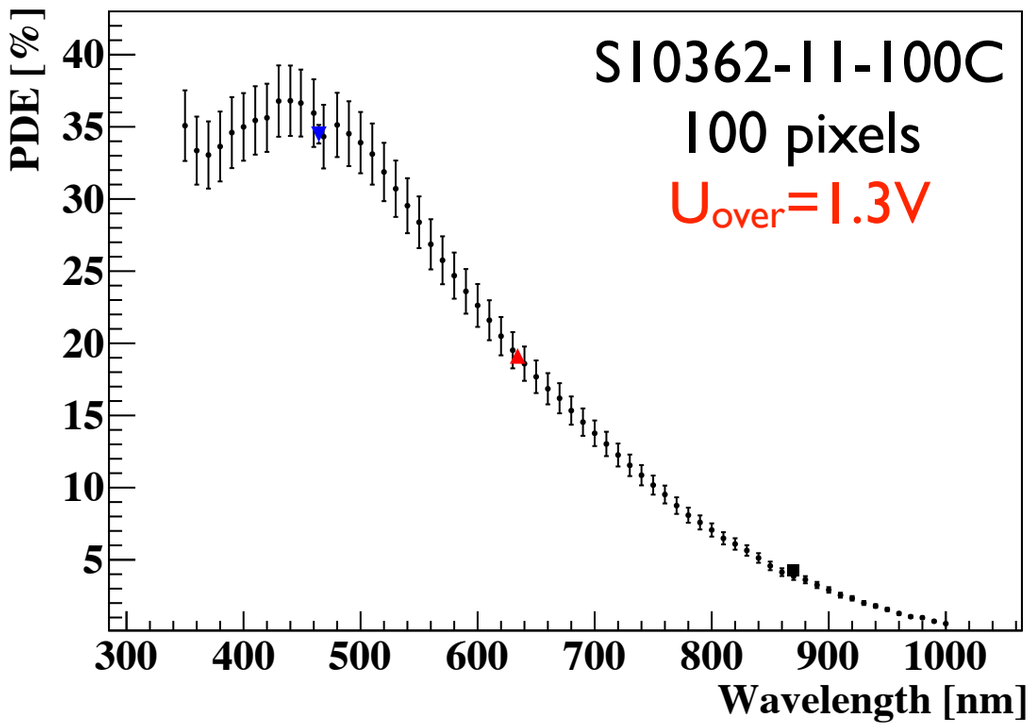


Measured PDE values are significantly smaller.

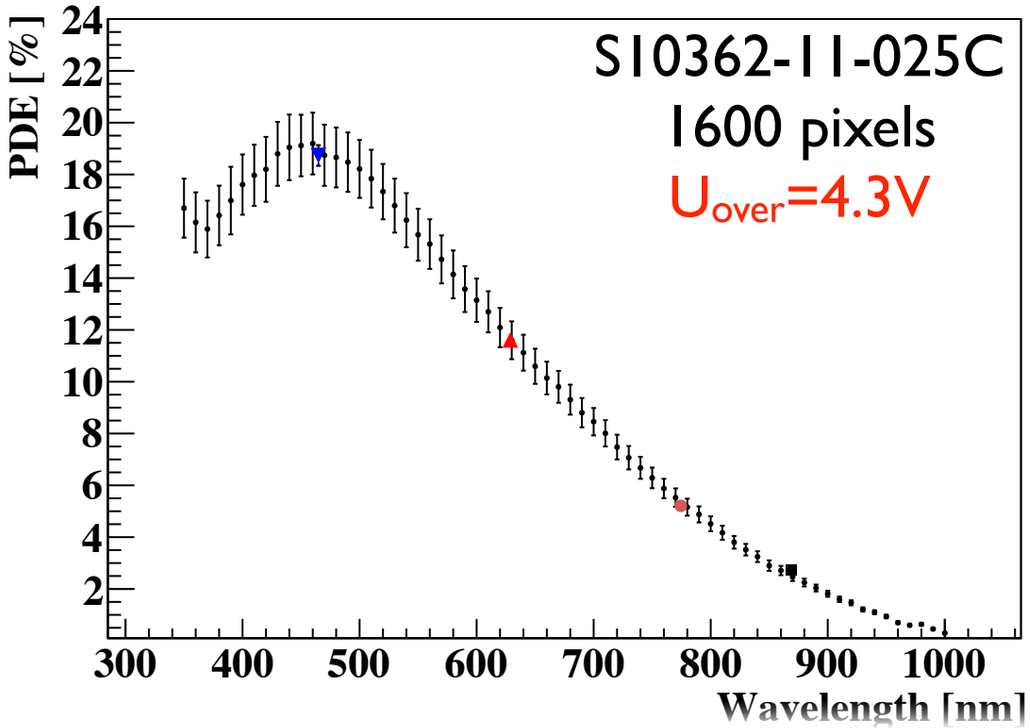


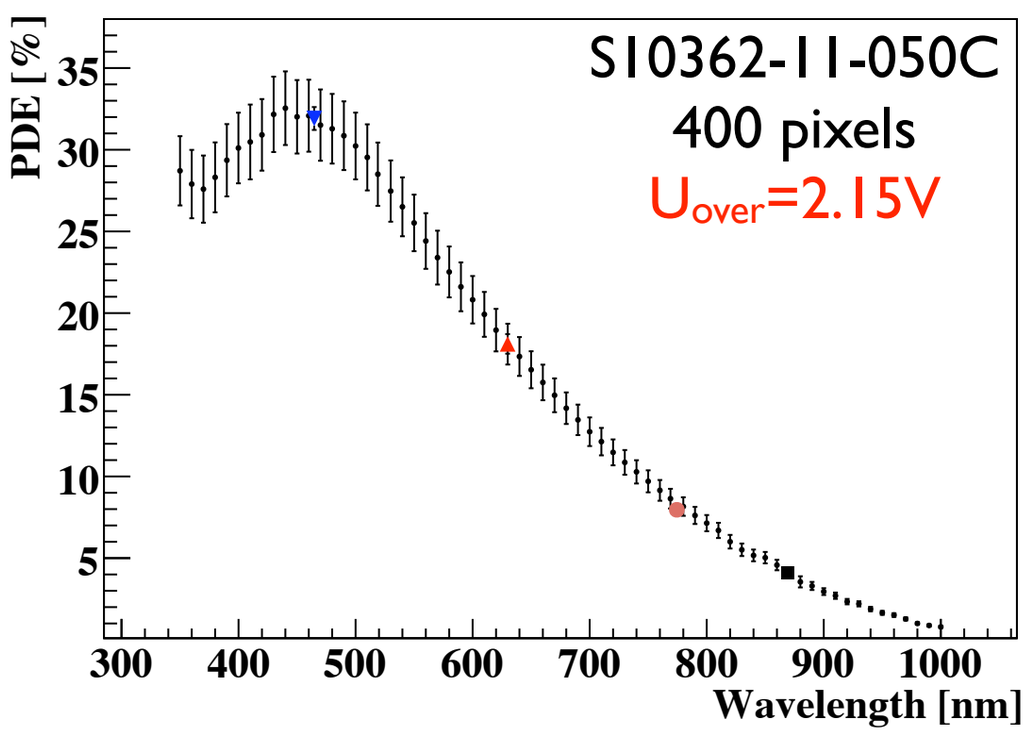
* Photon detection efficiency includes effects of crosstalk and afterpulses.

www.hamamatsu.com



PDE Results: MPPC





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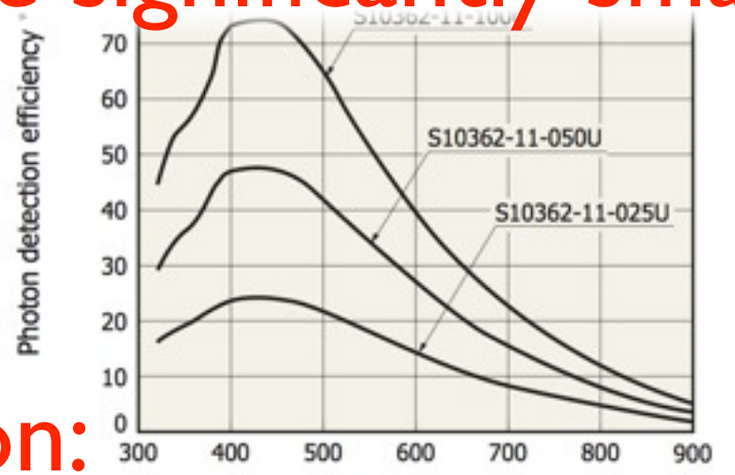
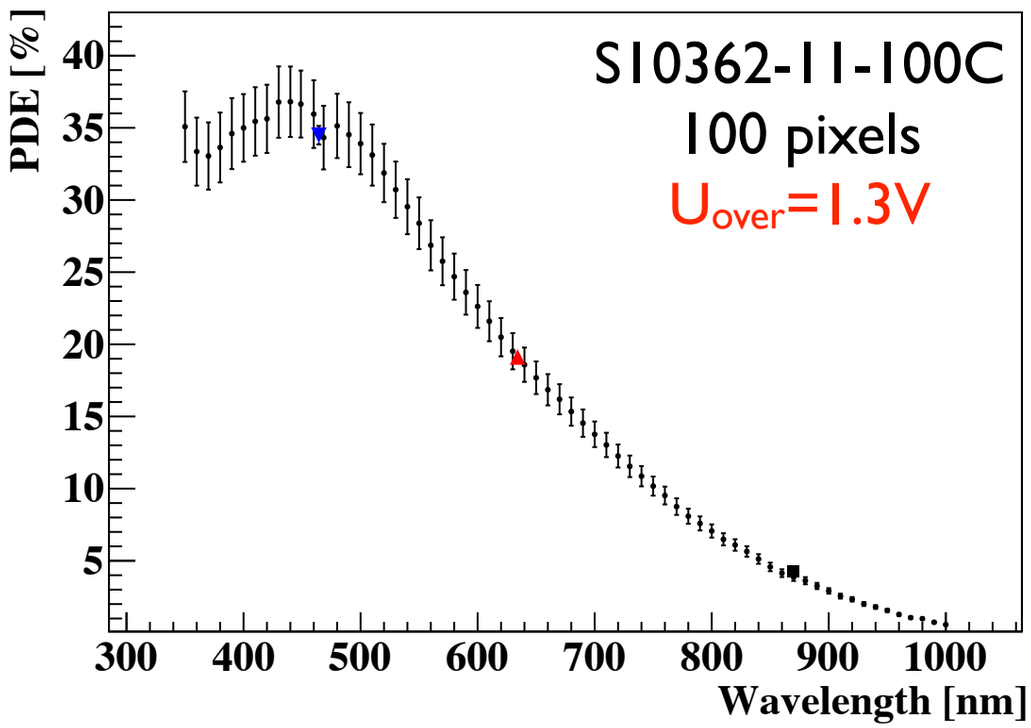
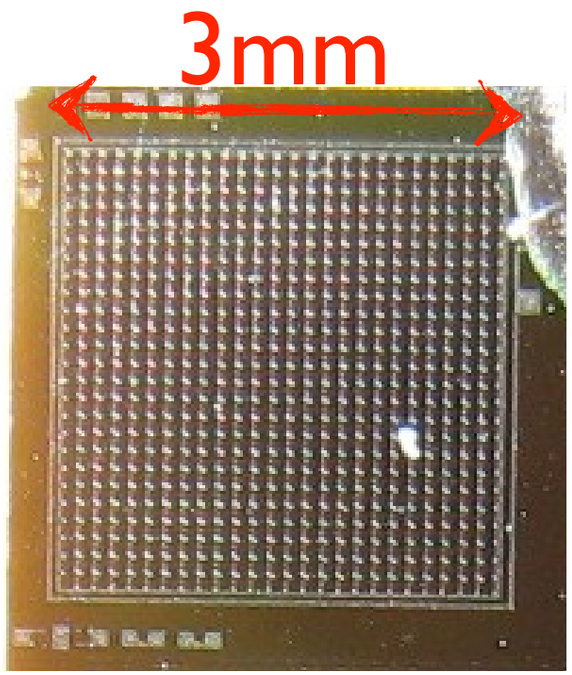




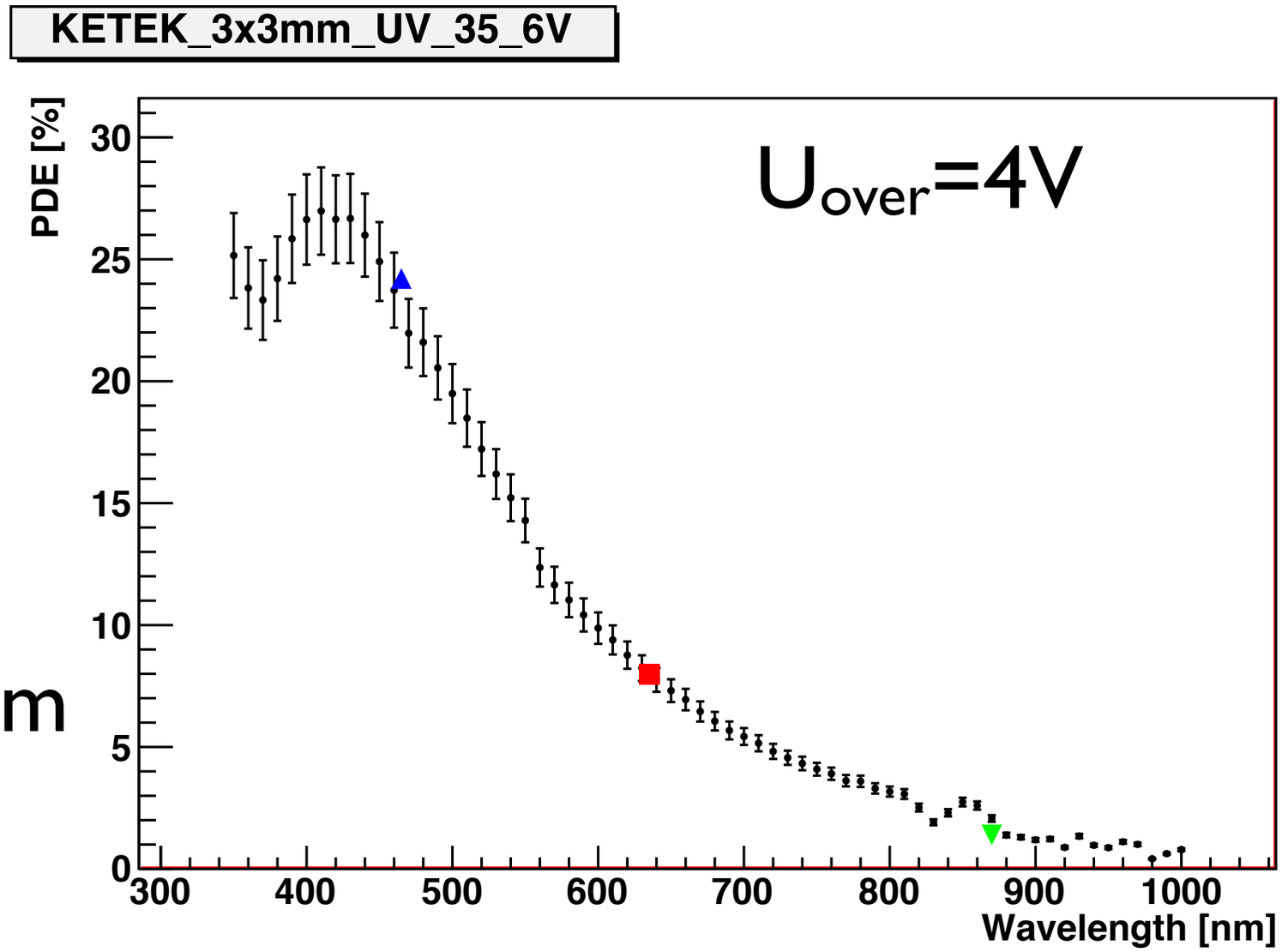
Reason:

* Photon detection efficiency includes effects of crosstalk and afterpulses.

PDE Results: KETEK

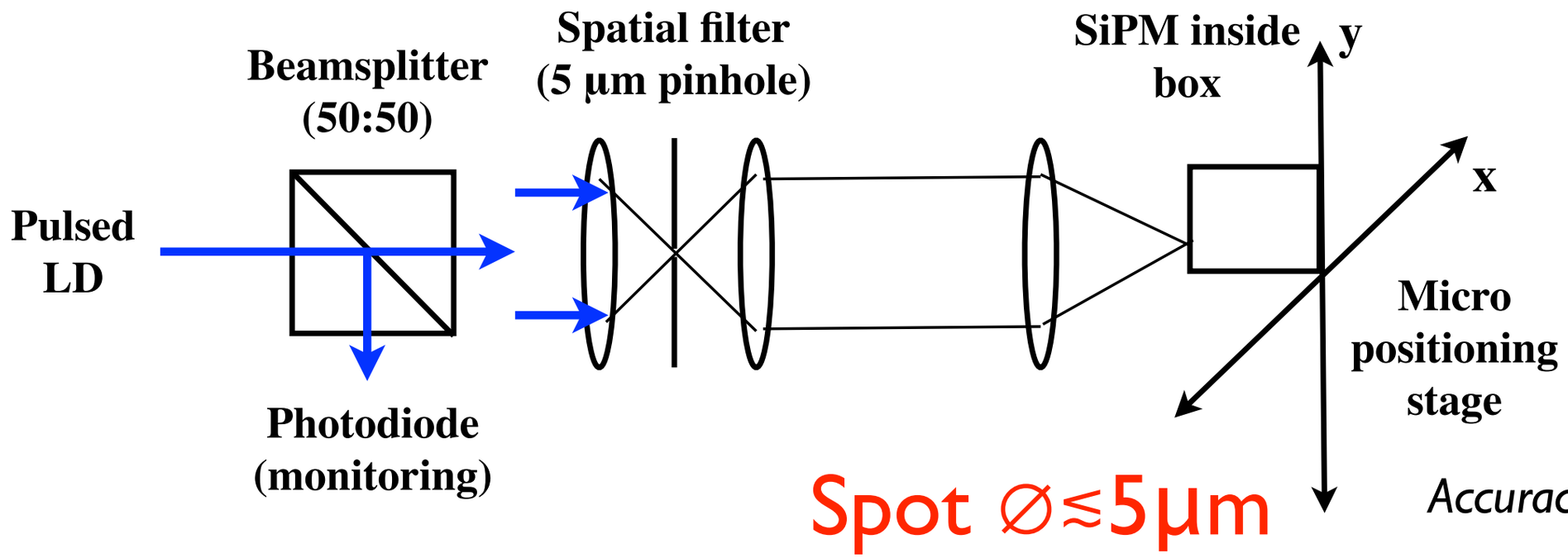


Highest PDE at ~420nm
blue/UV sensitive



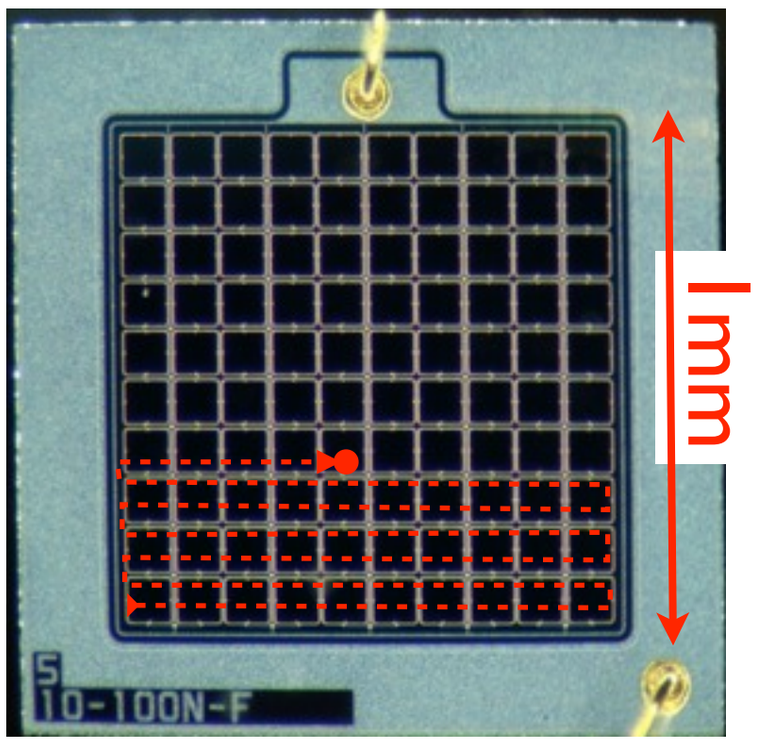
Uniformity Scans

Setup

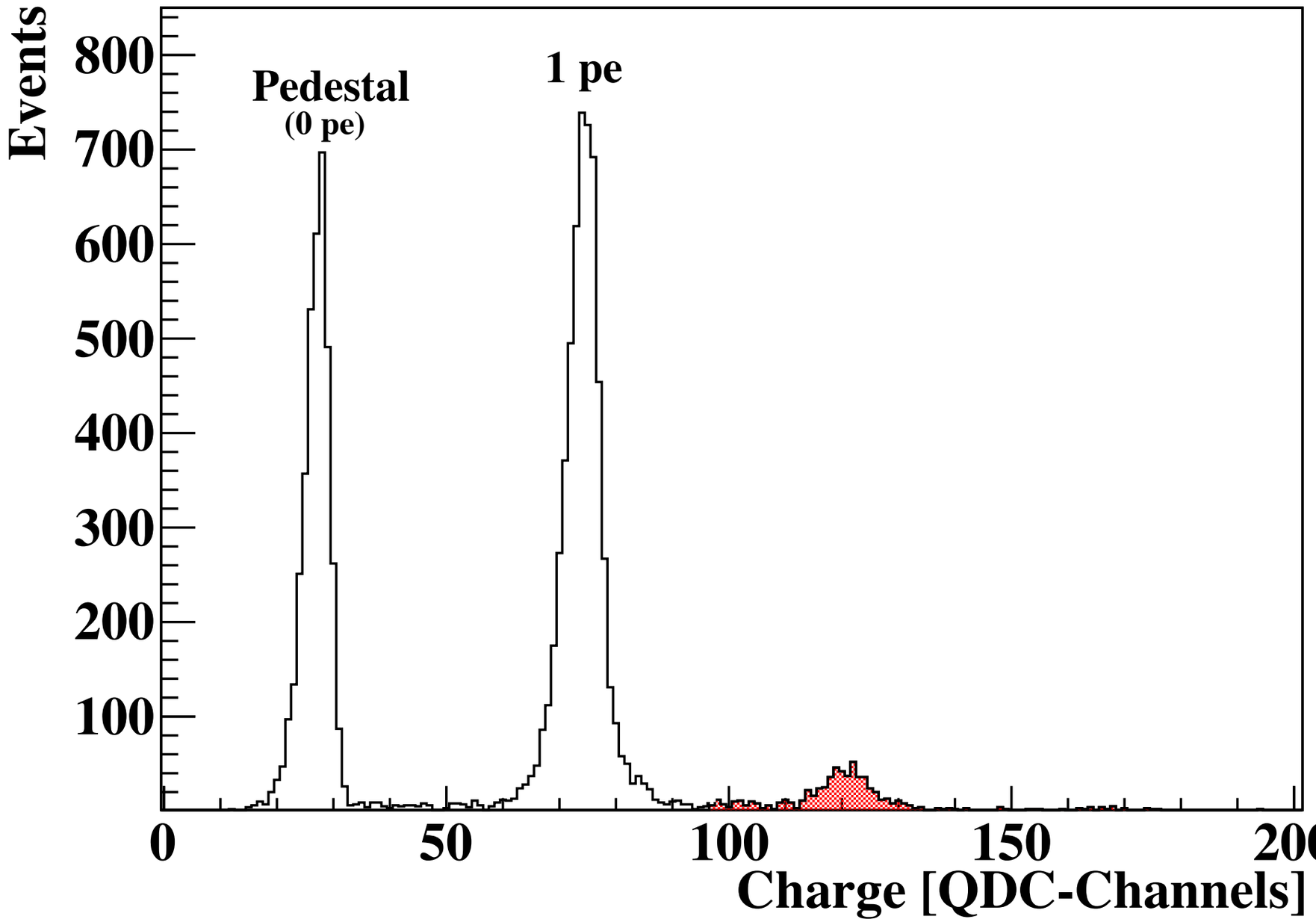


- Move spot over SiPM surface
- QDC readout *(30ns gate)*

  10,000 events per geom. position
- 3µm step size ⇒ 123,000 positions
- Total time ($1\times1\,mm^2$): ≈100h



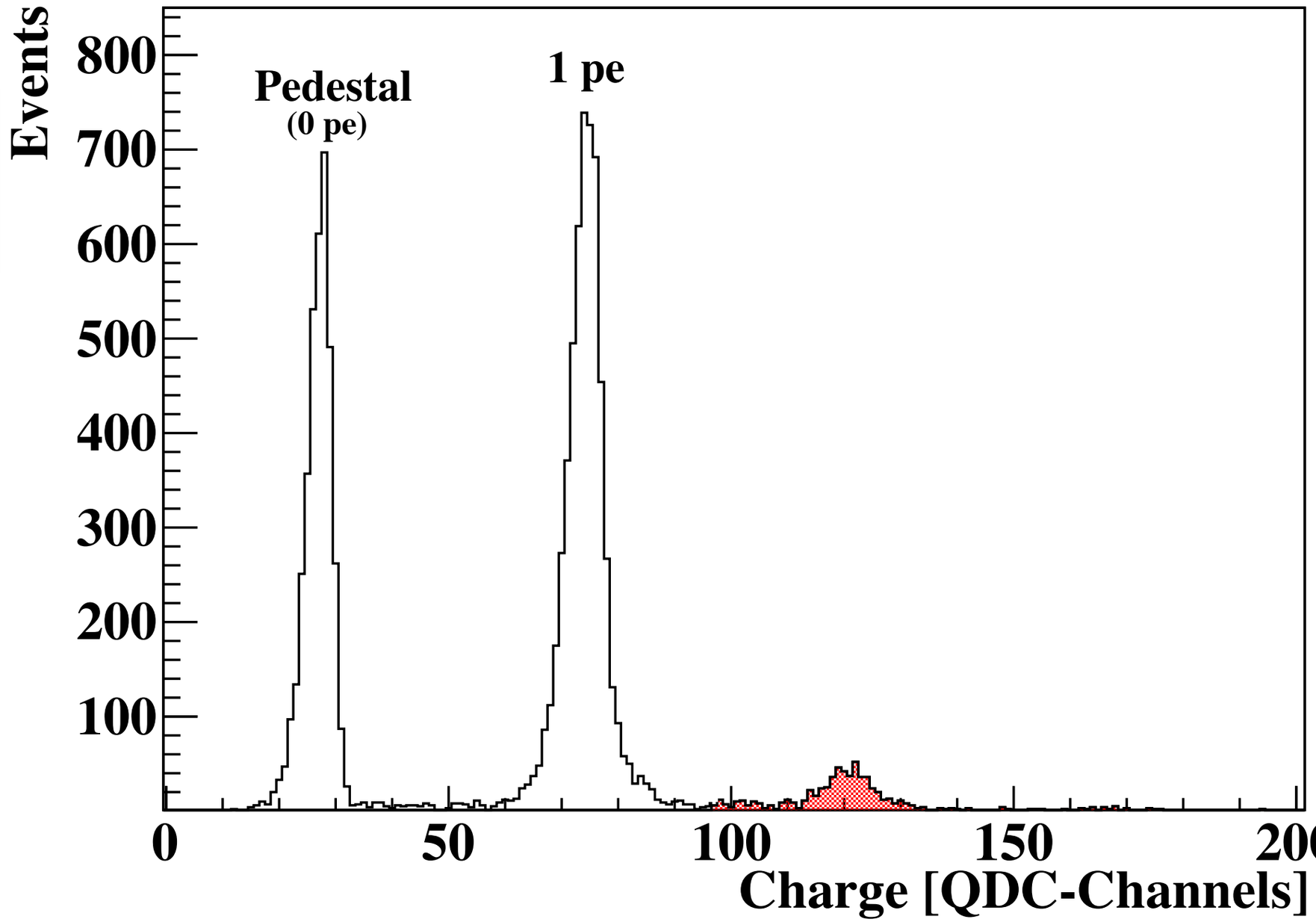
Single Pixel Spectrum



Single Pixel Spectrum

Sensitivity

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



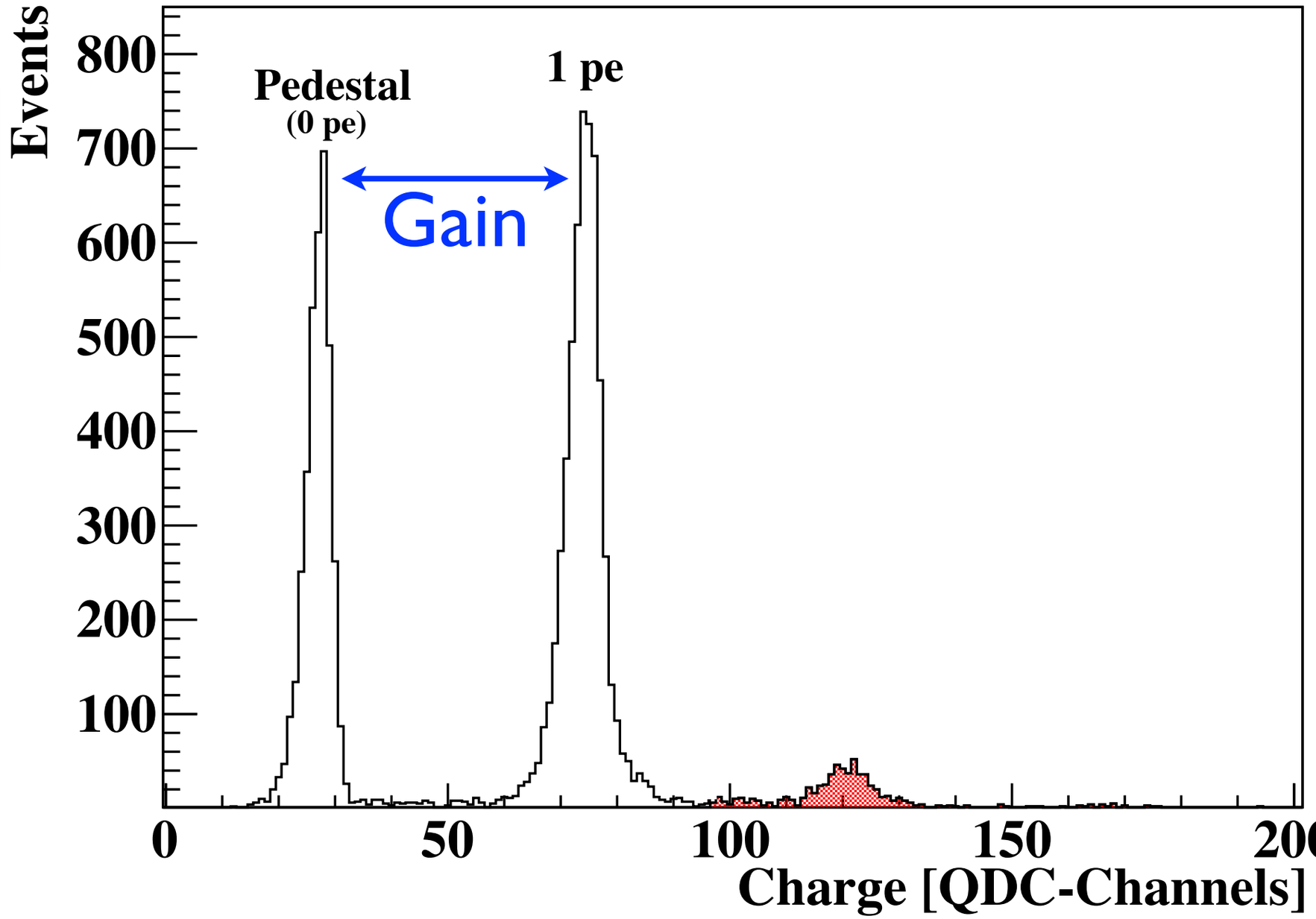
Single Pixel Spectrum

Sensitivity

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

Gain

(peak distance)



Single Pixel Spectrum

Sensitivity

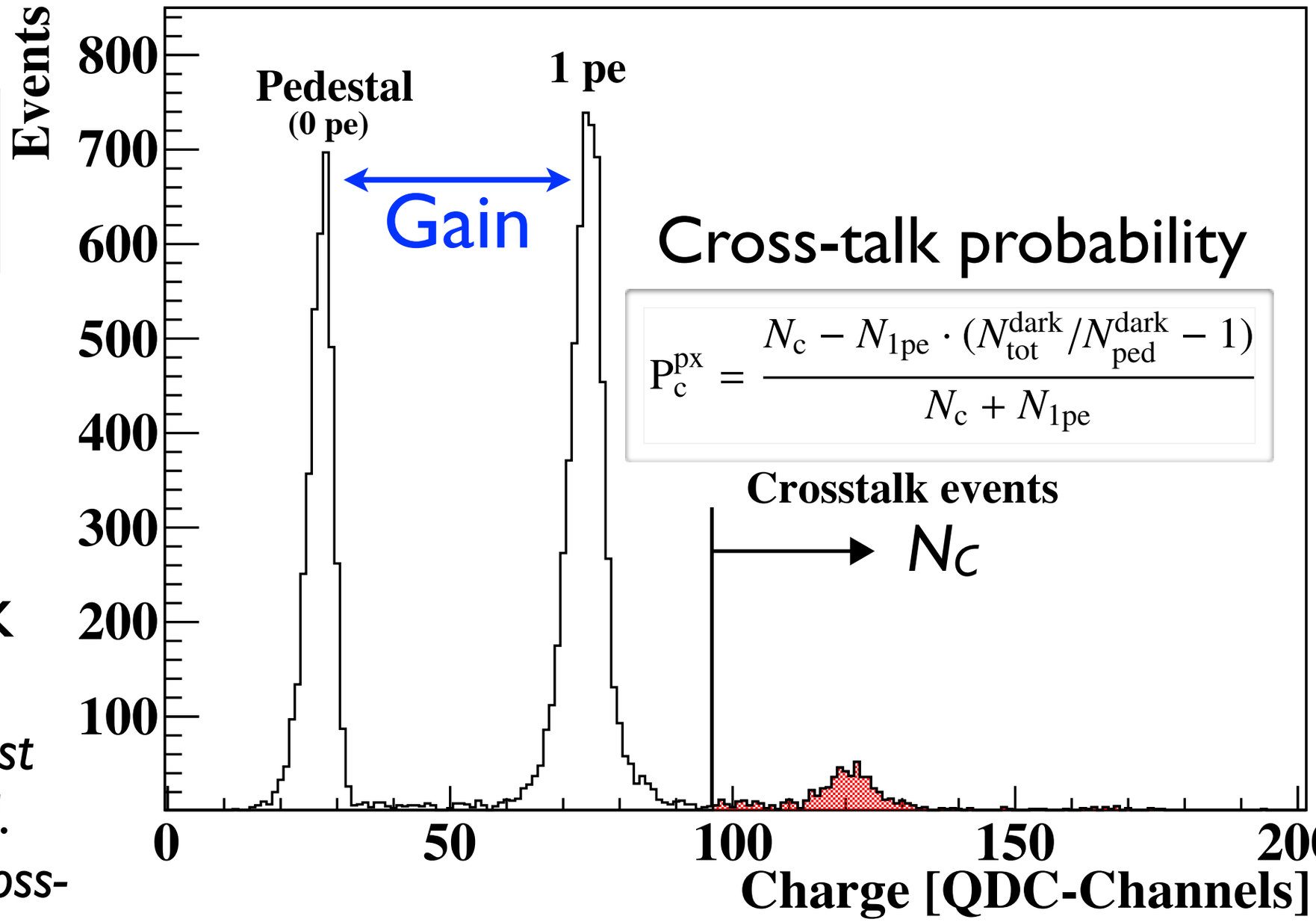
$$N_{pe} = -\ln\left(\frac{N_{Ped.}}{N_{Tot.}}\right)$$

Gain

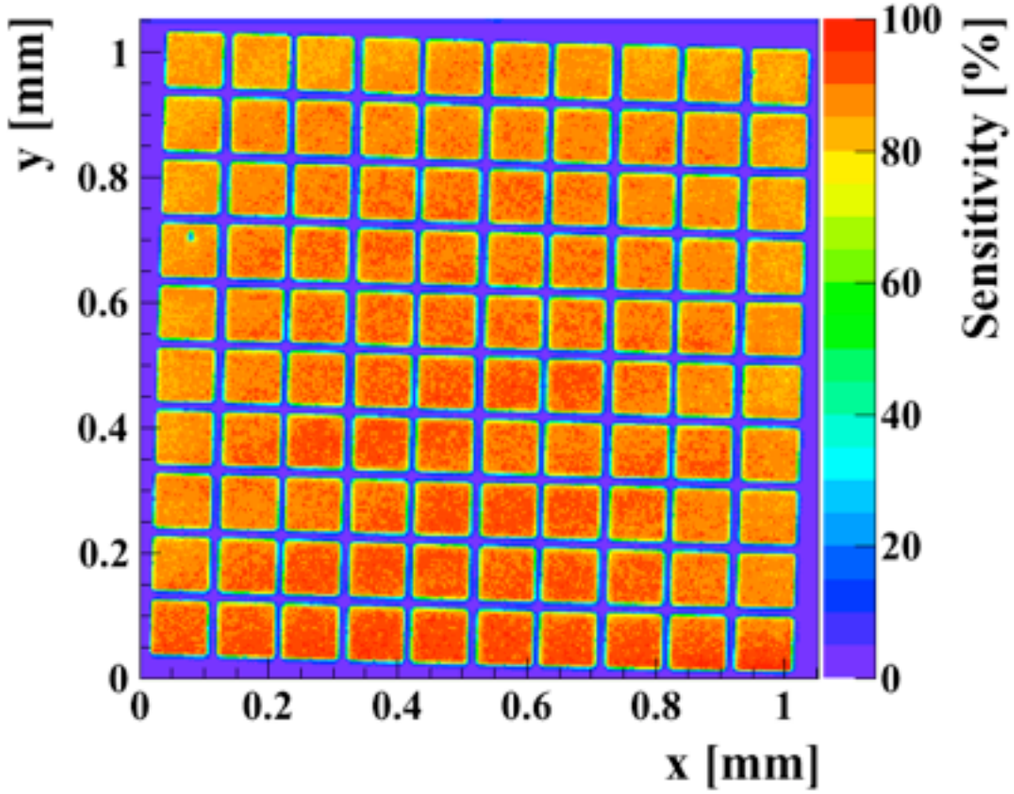
(peak distance)

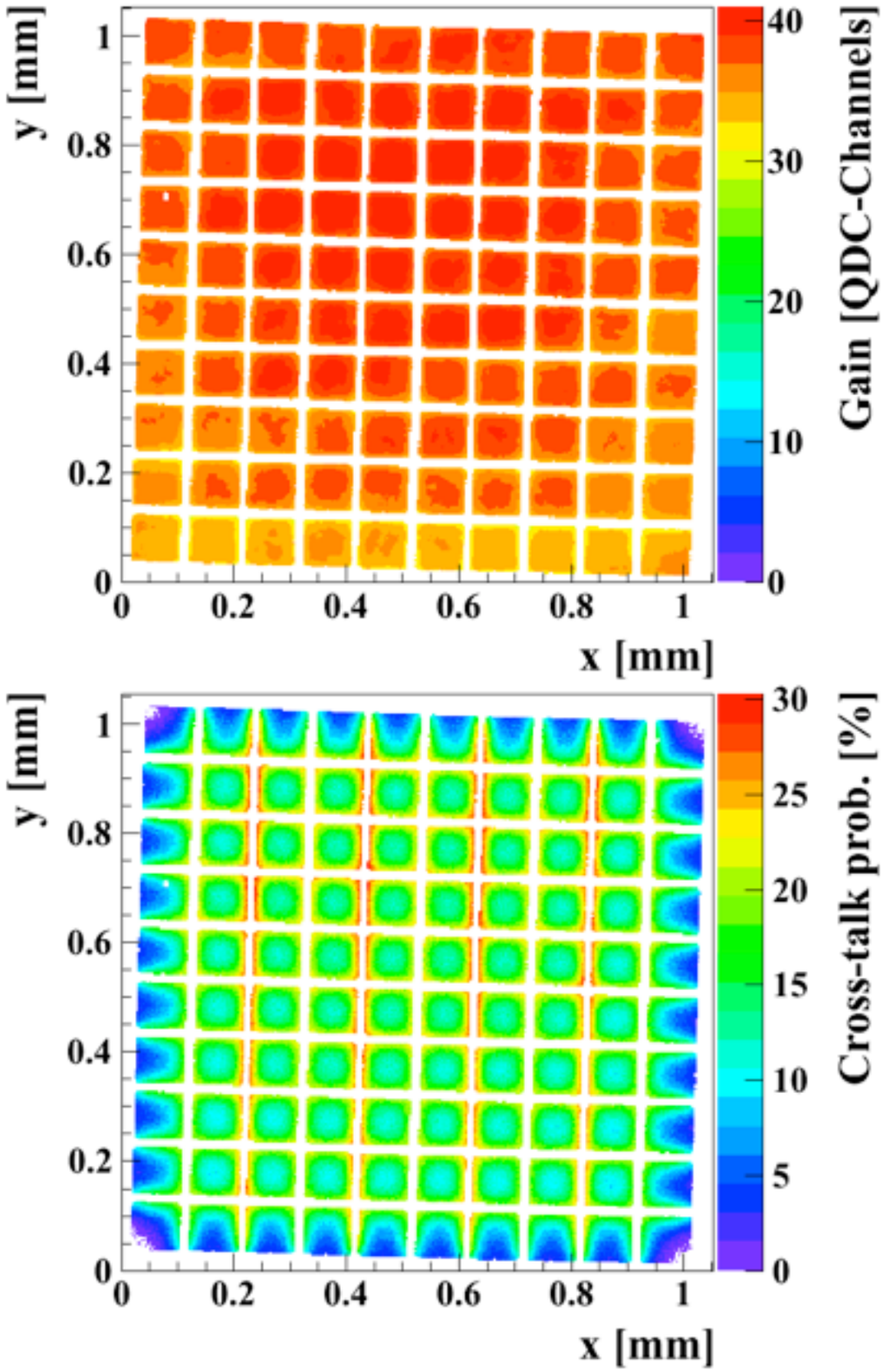
Optical cross-talk

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



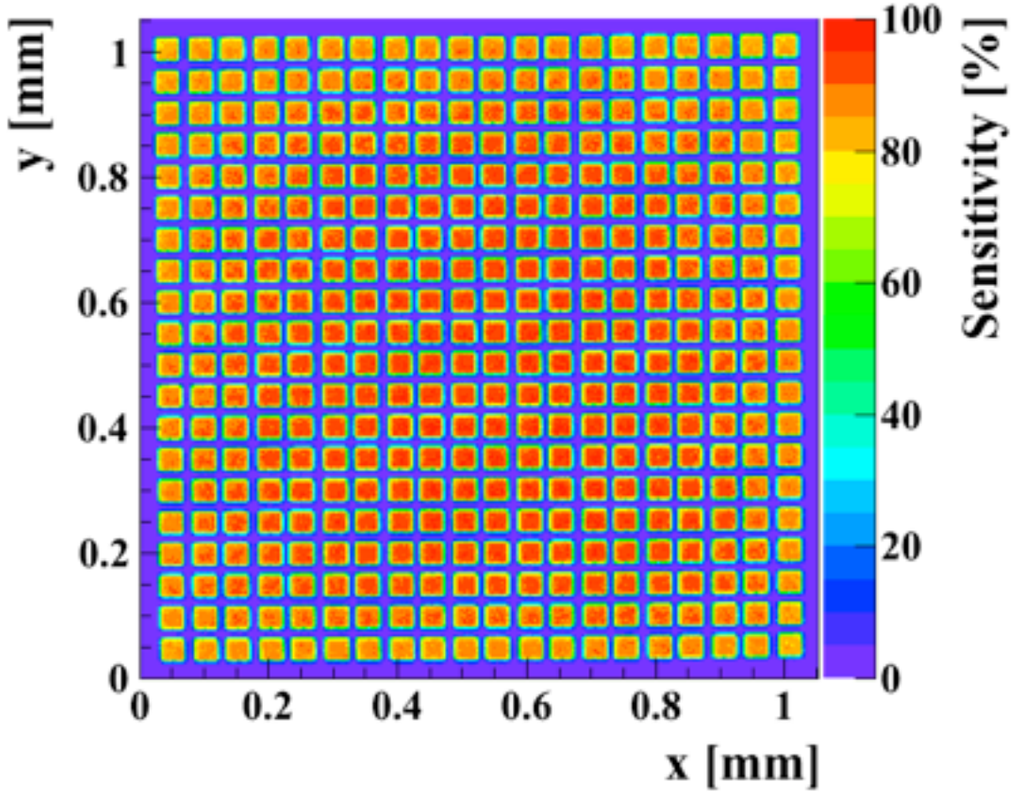
MPPC 100 pixels

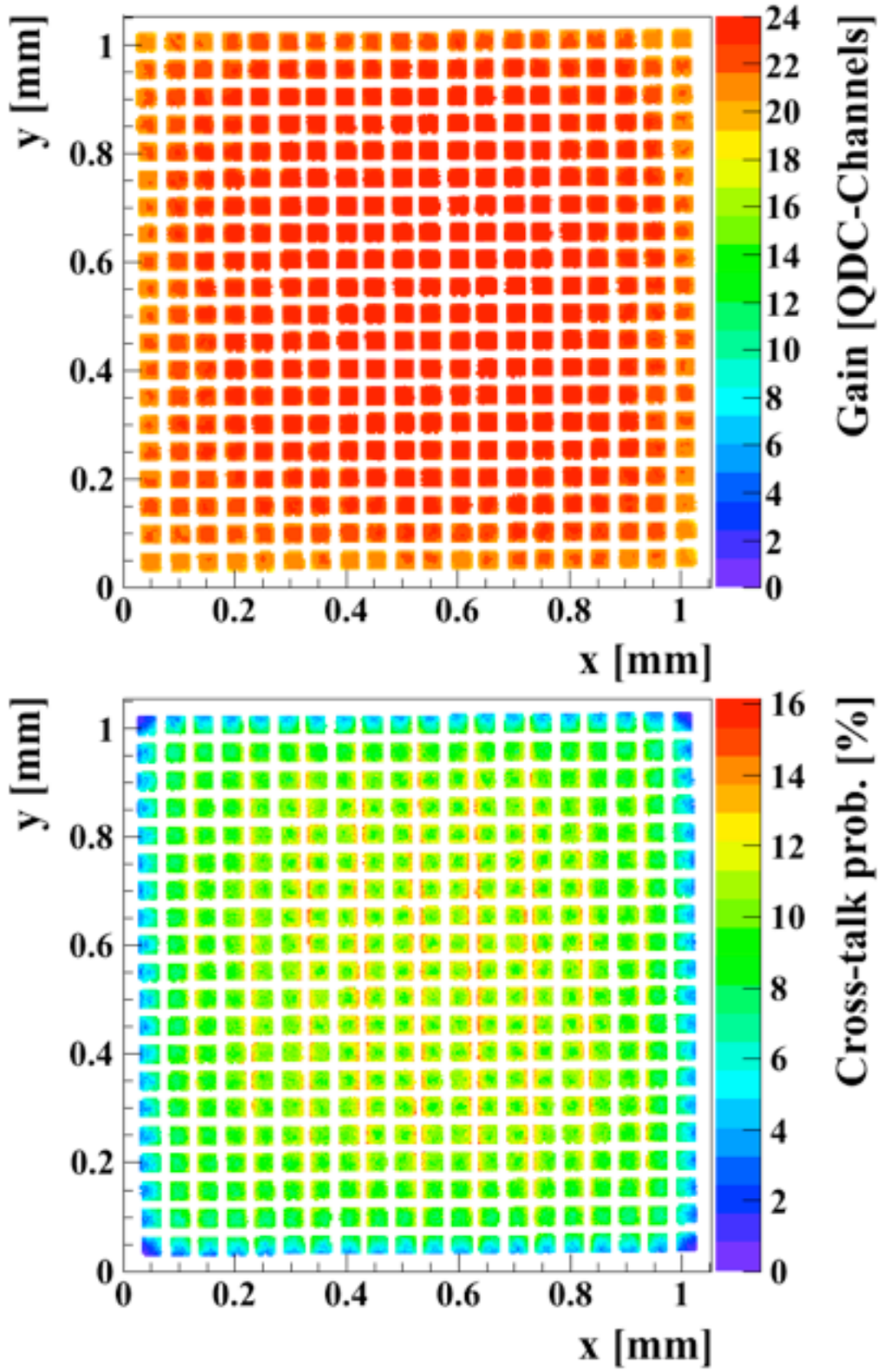




- High uniformity in sensitivity and gain
- Cross-talk shows strong position dependence

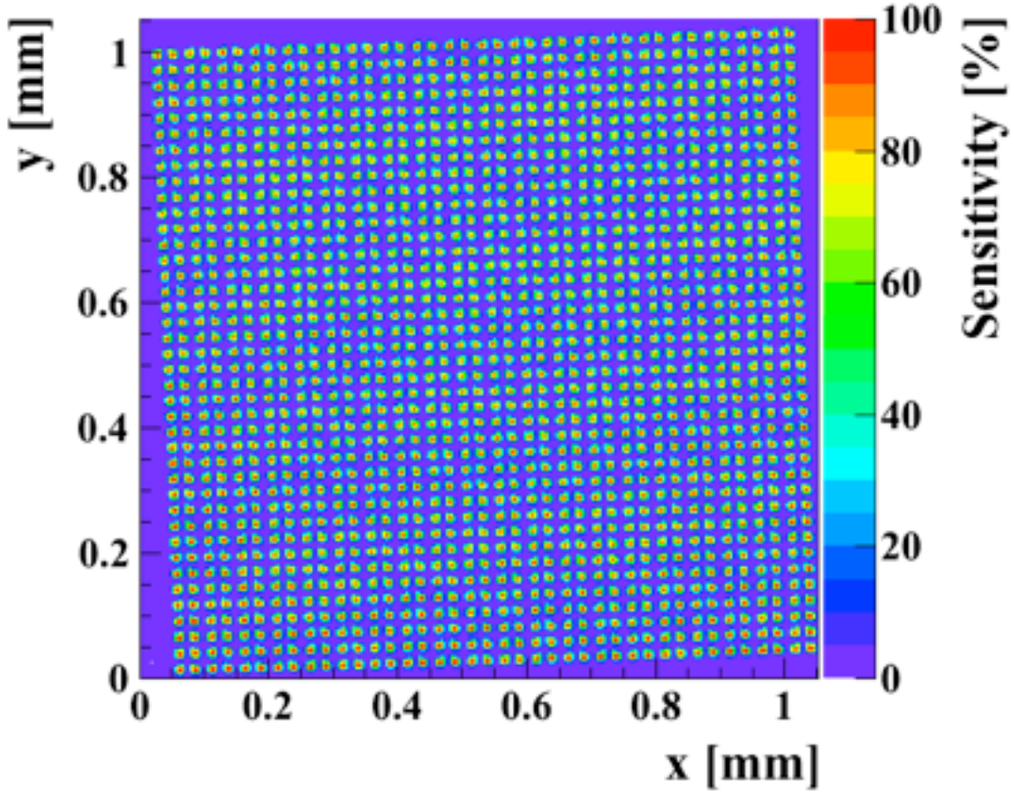
MPPC 400 pixels

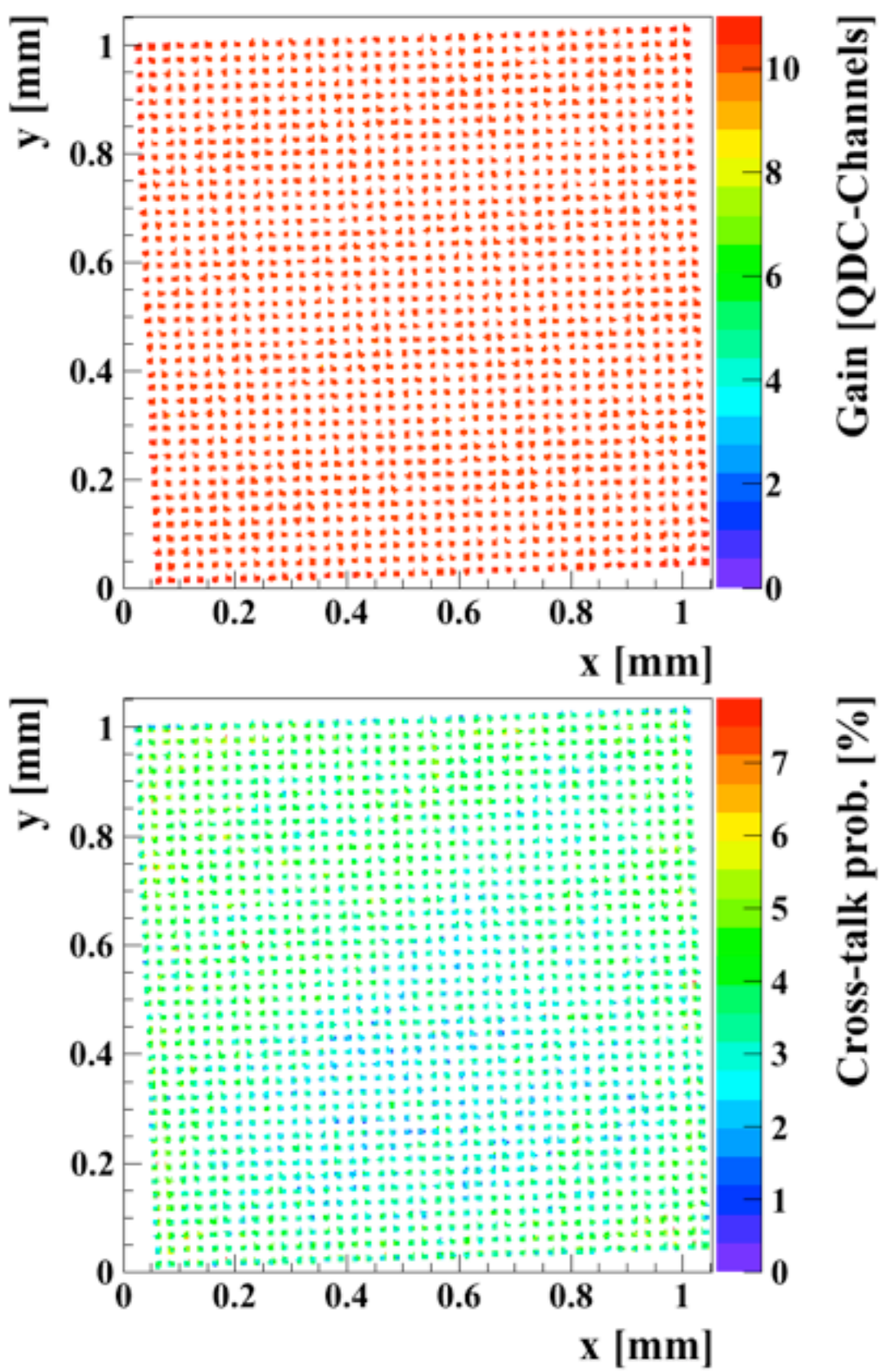




- High uniformity in sensitivity and gain
- Cross-talk shows strong position dependence

MPPC 1600 pixels





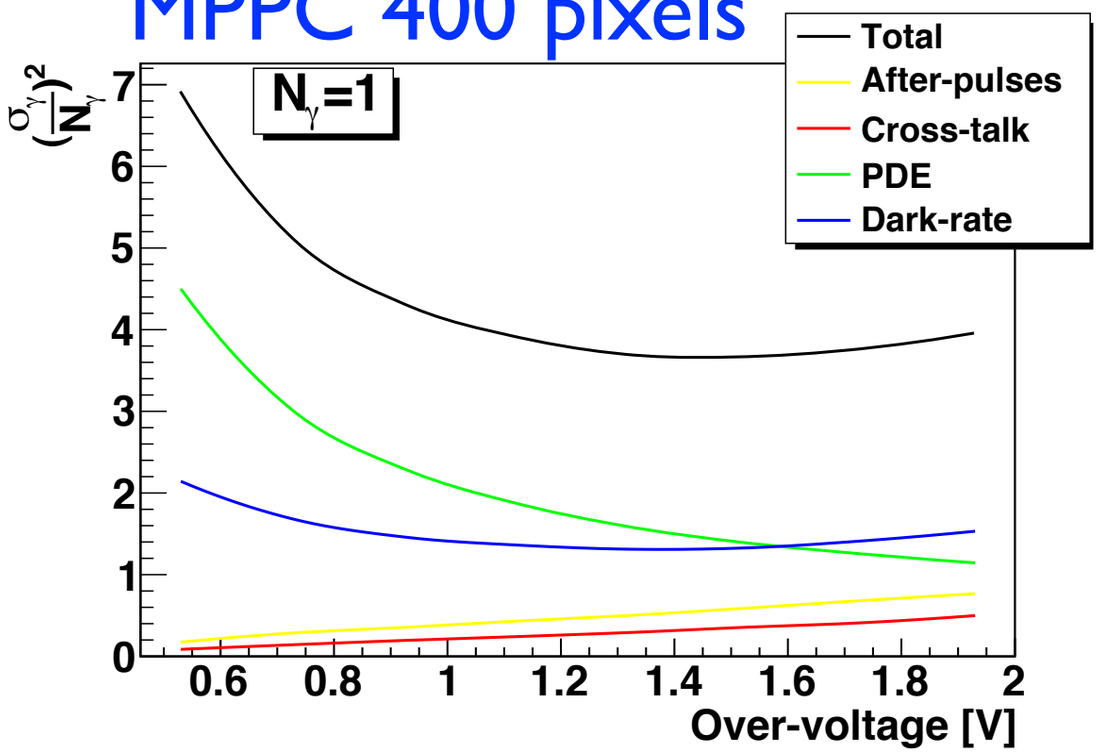
- High uniformity in sensitivity, gain and cross-talk probability

Photon Counting Resolution

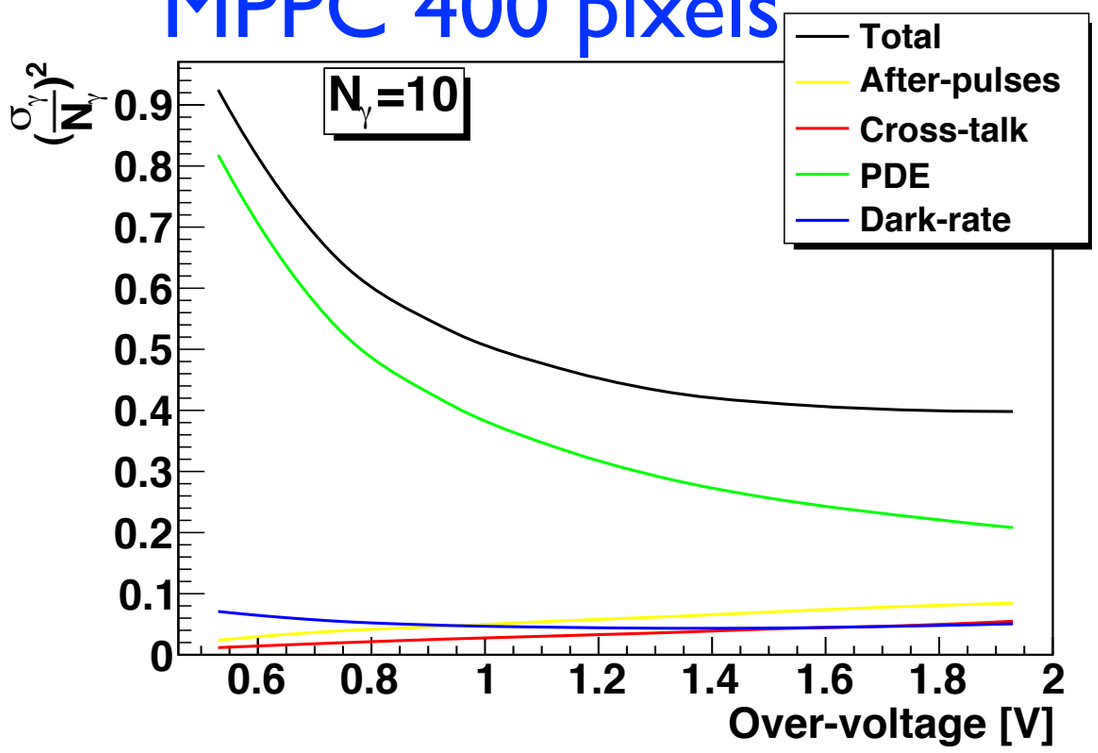
Combining the results of PDE, dark-rate, cross-talk and after-pulse measurements

Results

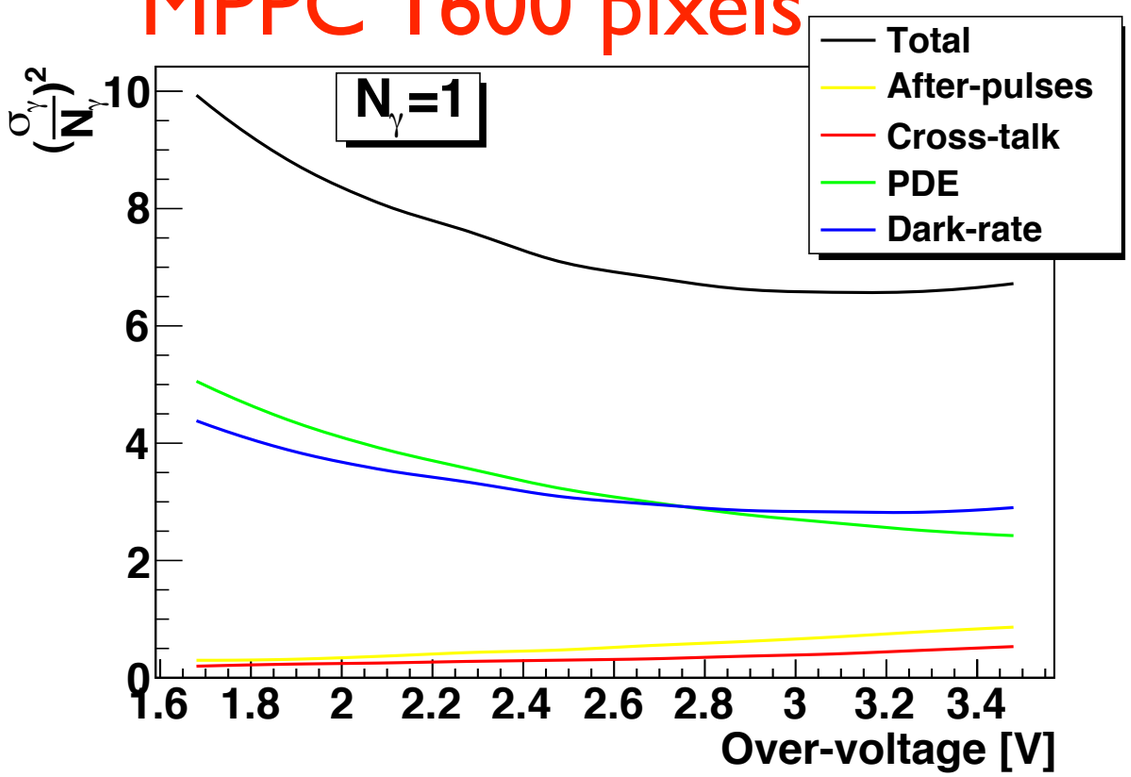
MPPC 400 pixels



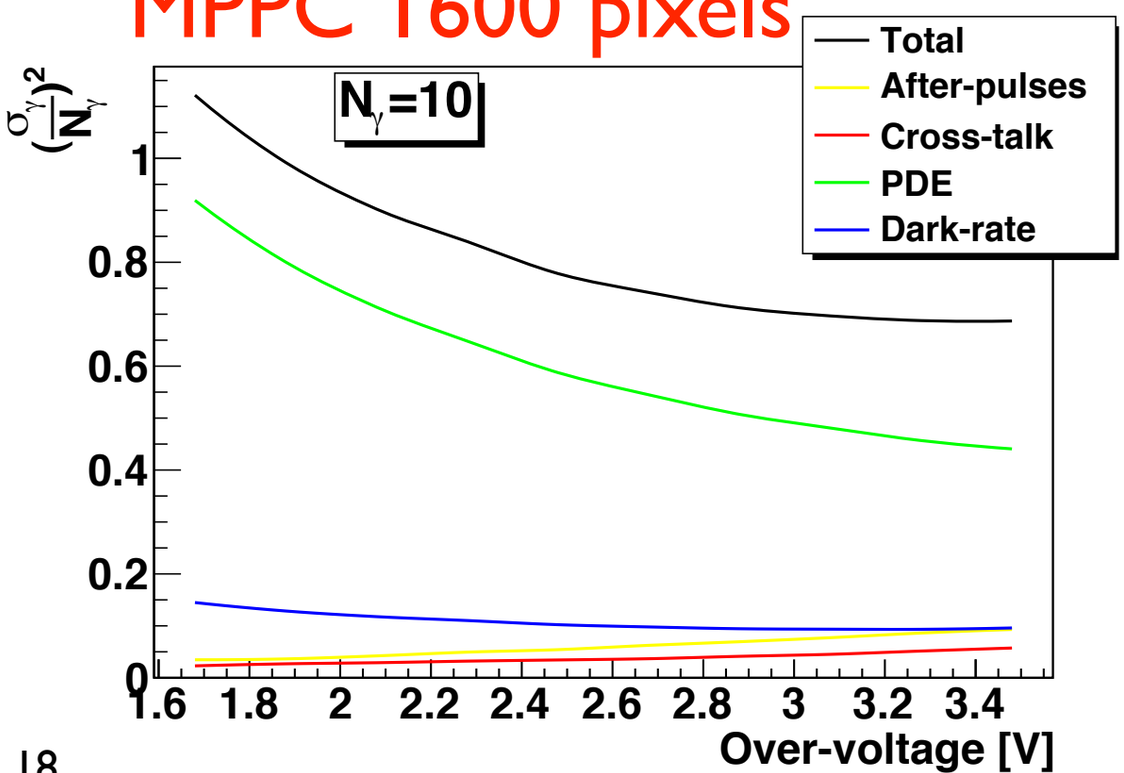
MPPC 400 pixels



MPPC 1600 pixels



MPPC 1600 pixels



Summary

- Test stand for SiPM measurements has been established
- Complete characterization
- Dark-rate, cross-talk, after-pulse prob.
- Temperature dependence
- Photon detection efficiency (350 - 1000nm)
- Photon counting resolution
- Uniformity scans

Backup

Photon Counting

PDE (binomial)

$$B_{PDE}(N_{PDE}) = \binom{N_\gamma}{N_{PDE}} PDE^{N_{PDE}} \cdot (1 - PDE)^{N_\gamma - N_{PDE}}$$

$$\langle N_{PDE} \rangle = N_\gamma \cdot PDE \qquad \sigma_{N_{PDE}} = \sqrt{N_\gamma \cdot PDE(1 - PDE)}$$

Cross-talk, after-pulses (binomial)

$$\sigma_{N_{CT}} = \sqrt{(\langle N_{PDE} \rangle + \langle N_{DR} \rangle) \cdot P_{CT}(1 - P_{CT})}$$

$$\sigma_{N_{AP}} = \sqrt{(\langle N_{PDE} \rangle + \langle N_{DR} \rangle) \cdot P_{AP}(1 - P_{AP})}$$

Dark-rate (Poisson)

$$\langle N_{DR} \rangle = DR \cdot \Delta t$$

$$\sigma_{N_{DR}} = \sqrt{DR \cdot \Delta t}$$

Δt=300ns

$$\frac{\sigma_{N_\gamma}}{N_\gamma} = \frac{\sigma_{N_{Signal}}}{N_\gamma \cdot PDE} = \frac{\sqrt{\sigma^2_{N_{PDE}} + \sigma^2_{N_{CT}} + \sigma^2_{N_{AP}} + \sigma^2_{N_{DR}}}}{N_\gamma \cdot PDE}$$

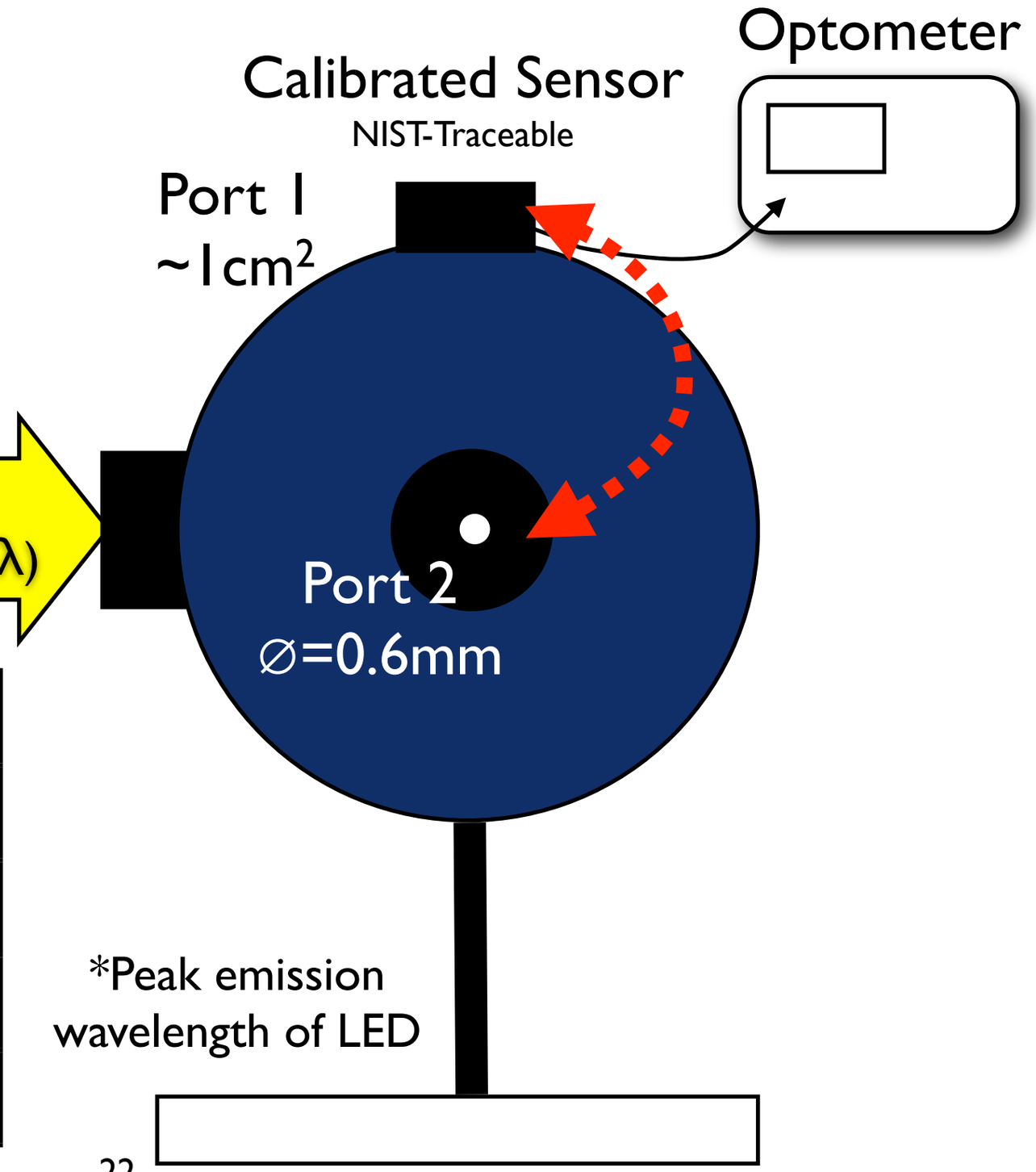
Measurement of Power-ratio R

(∅=0.6mm aperture)

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

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

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

Dark-rate Correction

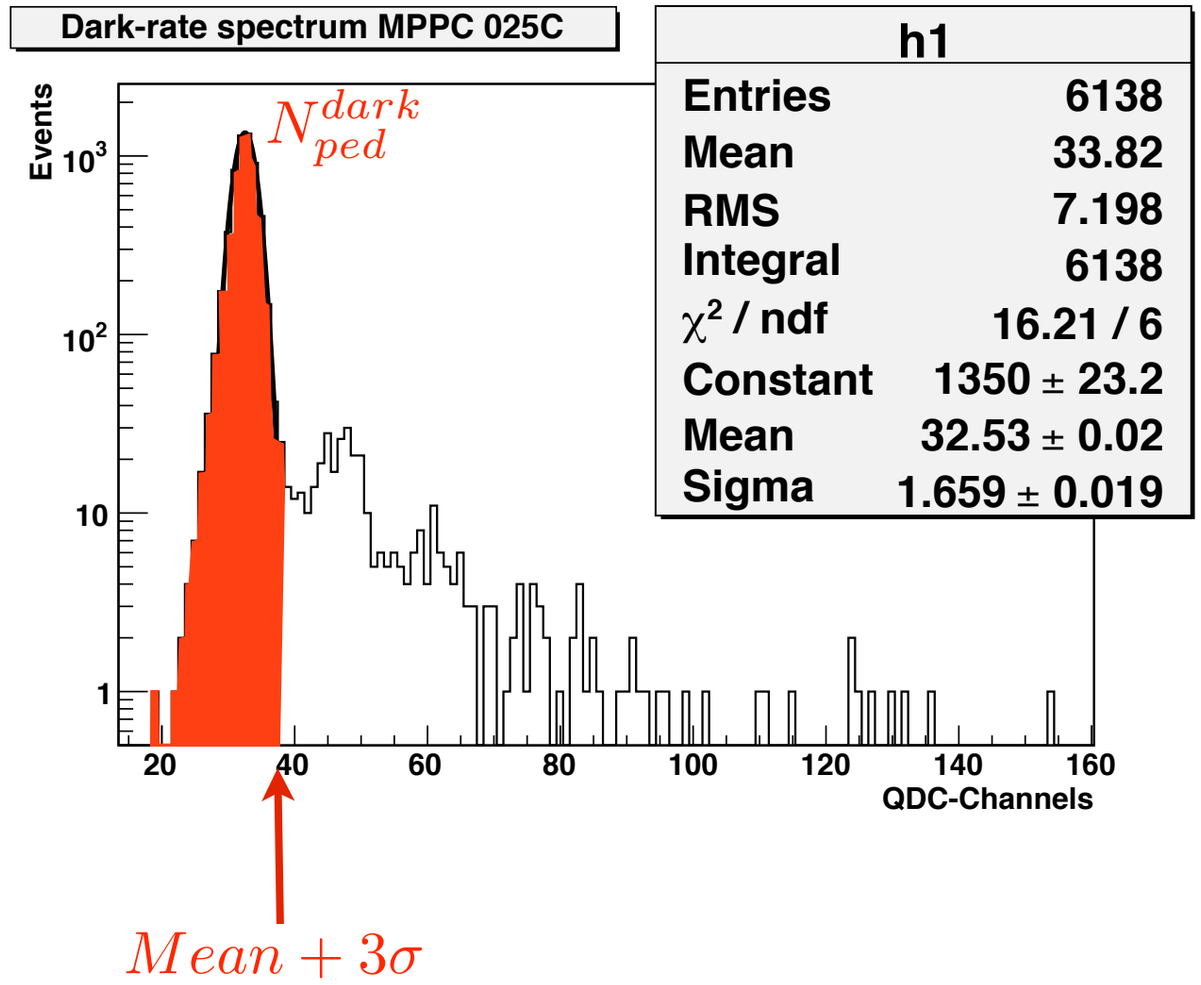
The number of photoelectrons needs to be corrected for the dark-rate.

➔ Acquire dark-rate spectrum at each voltage value.

Correction factor α:

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

$$\Rightarrow \alpha = \frac{N_{tot}^{dark}}{N_{ped}^{dark}}$$



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

SiPM Positioning

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