Understanding the nonlinear response of SiPMs

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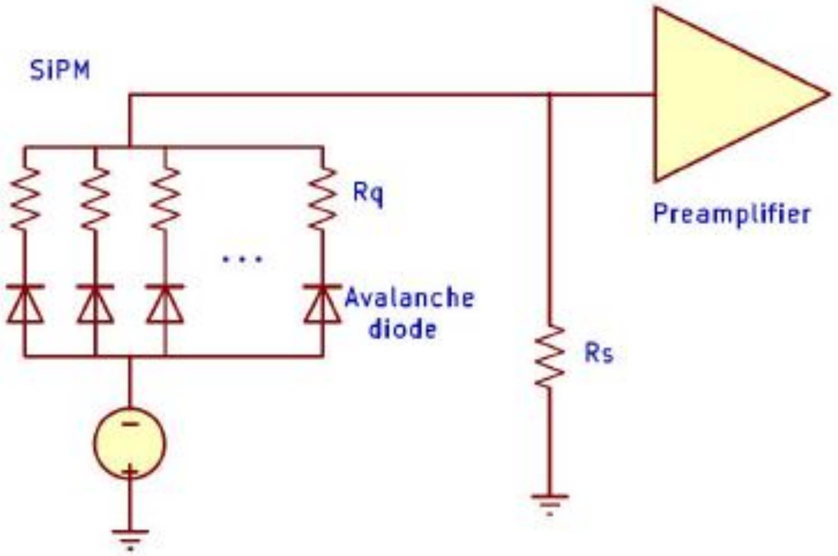
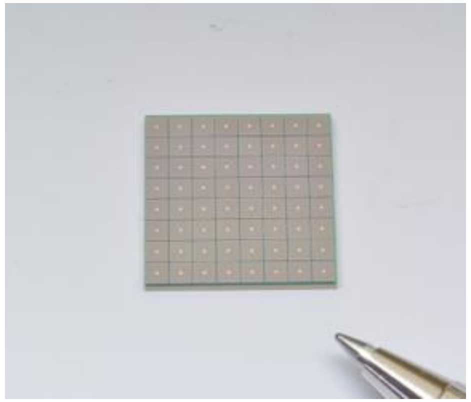
Silicon Photomultipliers (SiPMs)

- Photonsensor increasingly used in many applications, especially in scintillator detectors
- Array of reverse biased avalanche photodiodes (pixels) operating in "Geiger mode"
- Ideally, when any pixel is triggered by a photon, an avalanche of fixed charge is produced
- A pixel takes some time τ_{rec} to recover after an avalanche → If the number of photons of the light pulse is similar to the number of pixels, the SiPM response is nonlinear
- SiPMs also present:
  - ➢ Uncorrelated noise: "dark counts"
  - ➢ Correlated noise: crosstalk, afterpulsing, delayed crosstalk





Hamamatsu
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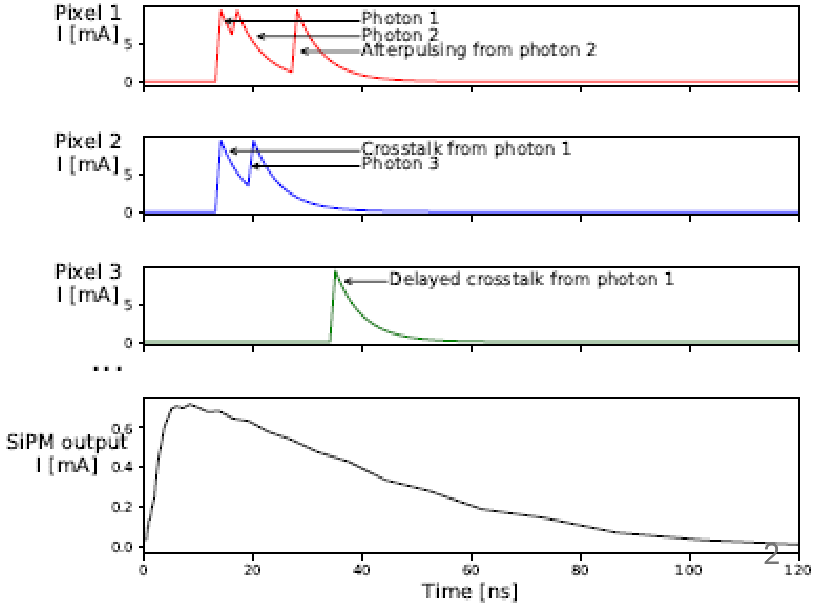
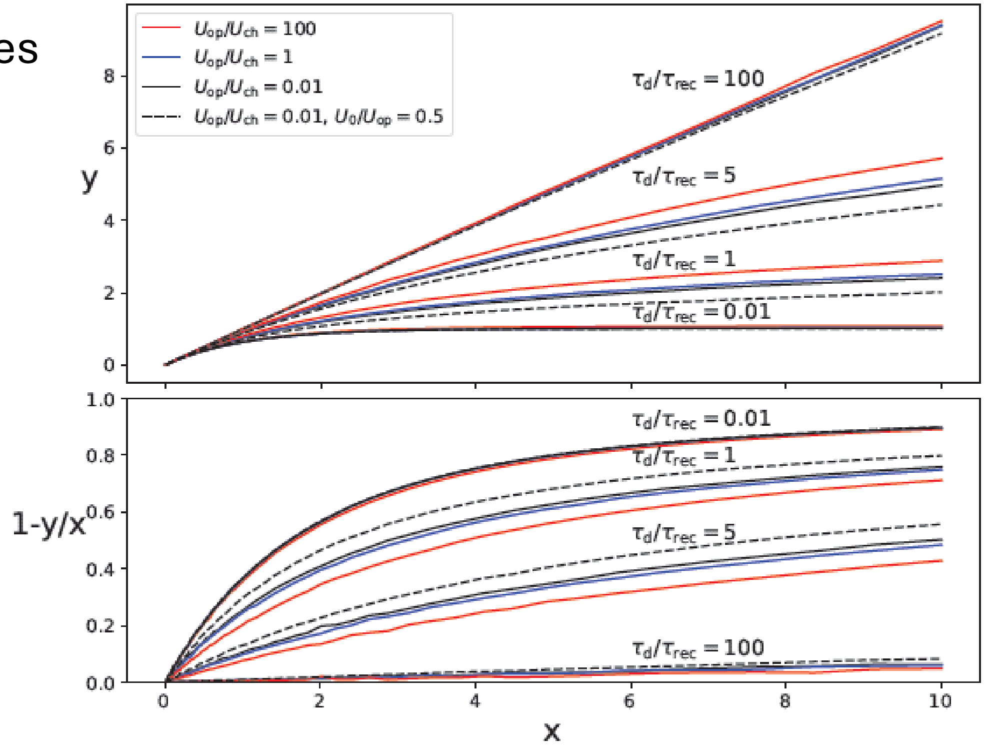


Nonlinear response

- Limitation to the dynamic range. Key factor in scintillator detectors
- Systematic analysis of the SiPM response through detailed MC simulations
- Response conveniently parameterized in terms of:
  - Effective number of full avalanches per pixel: $y = \frac{\langle Q \rangle}{q_{av} \cdot N_{pix}}$
  - Expected number of avalanches per pixel: $x = \frac{PDE \cdot N_{ph}}{N_{pix}}$

$\langle Q \rangle$: Mean output charge per pulse
q_{av}: Charge of a single full avalanche
N_{pix}: Number of pixels
PDE: Photon Detection Efficiency
N_{ph}: Number of photons per pulse

Direct comparison of y vs x curves for SiPMs with different bias voltage, N_{pix}, q_{av} (gain) and PDE



Simulation code: Jha, A.K. el al. IEEE TNS 2013, 60, 336–351

This work: Moya-Zamanillo, V.; Rosado, J. Sensors 2024, 24(8), 2648

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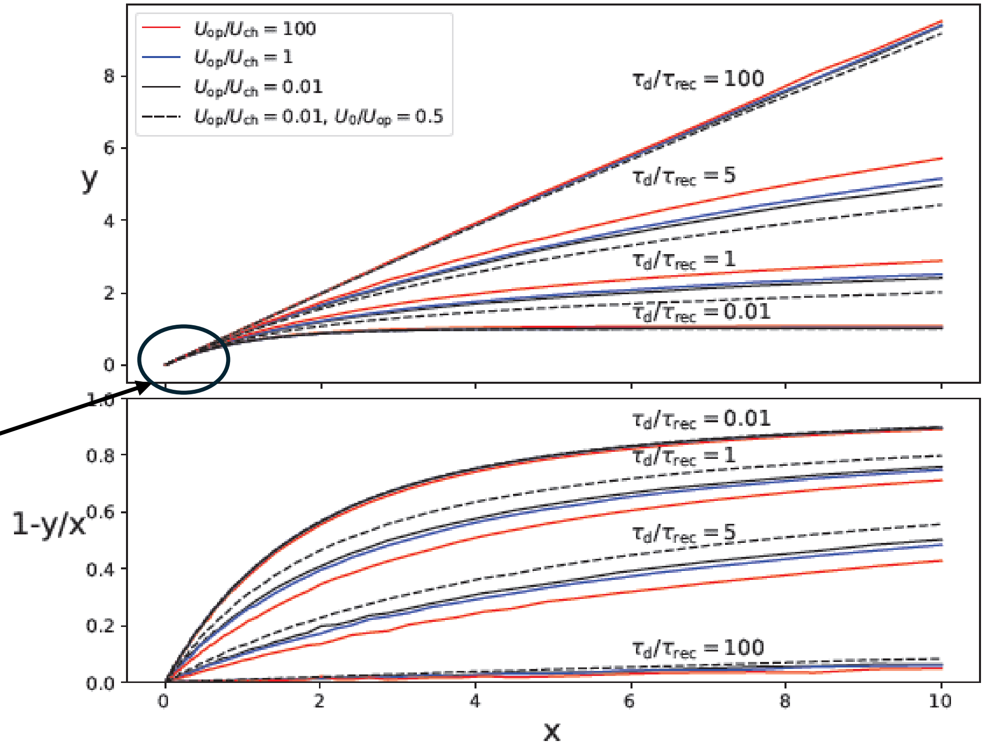
Ideally, $y = x$ in the linear region ($x < 0.1$) and in the absence of correlated noise



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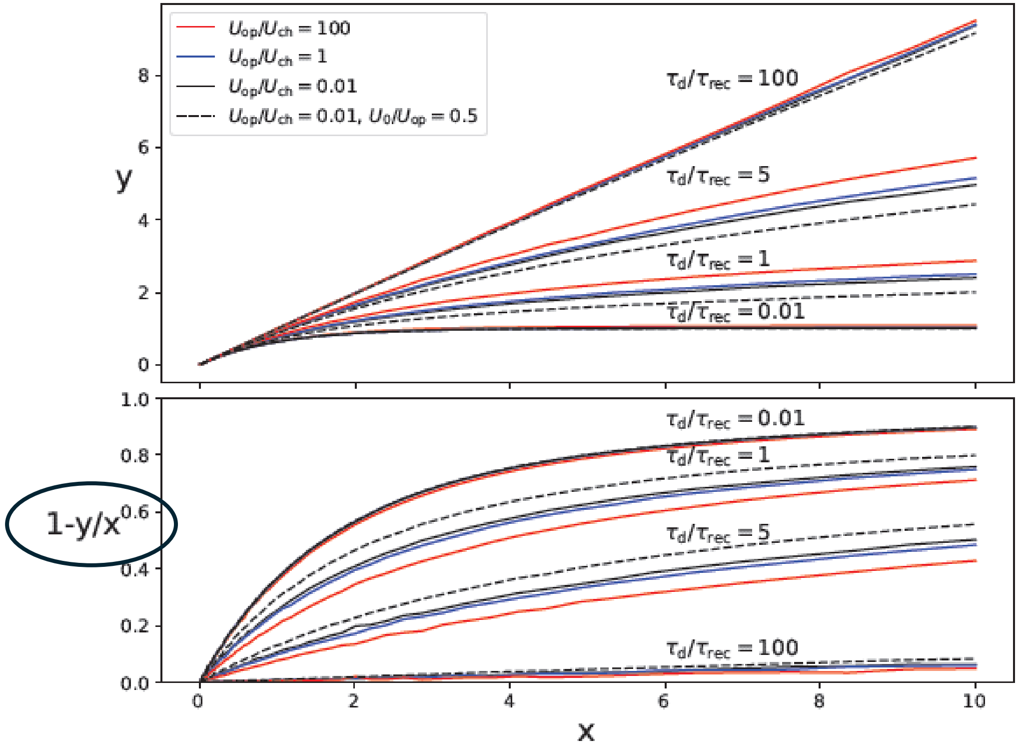
Nonlinearity parameter



Nonlinearity becomes stronger when the pulse length decreases relative to the recovery time

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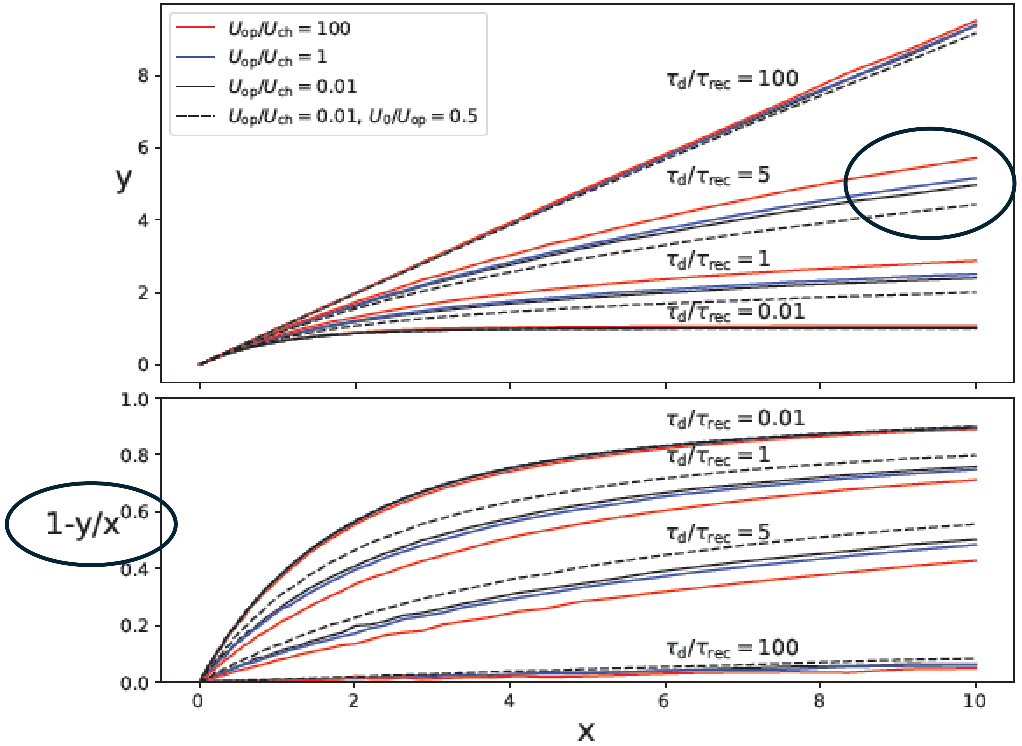

Nonlinearity also depends on the characteristics of the PDE vs voltage curve

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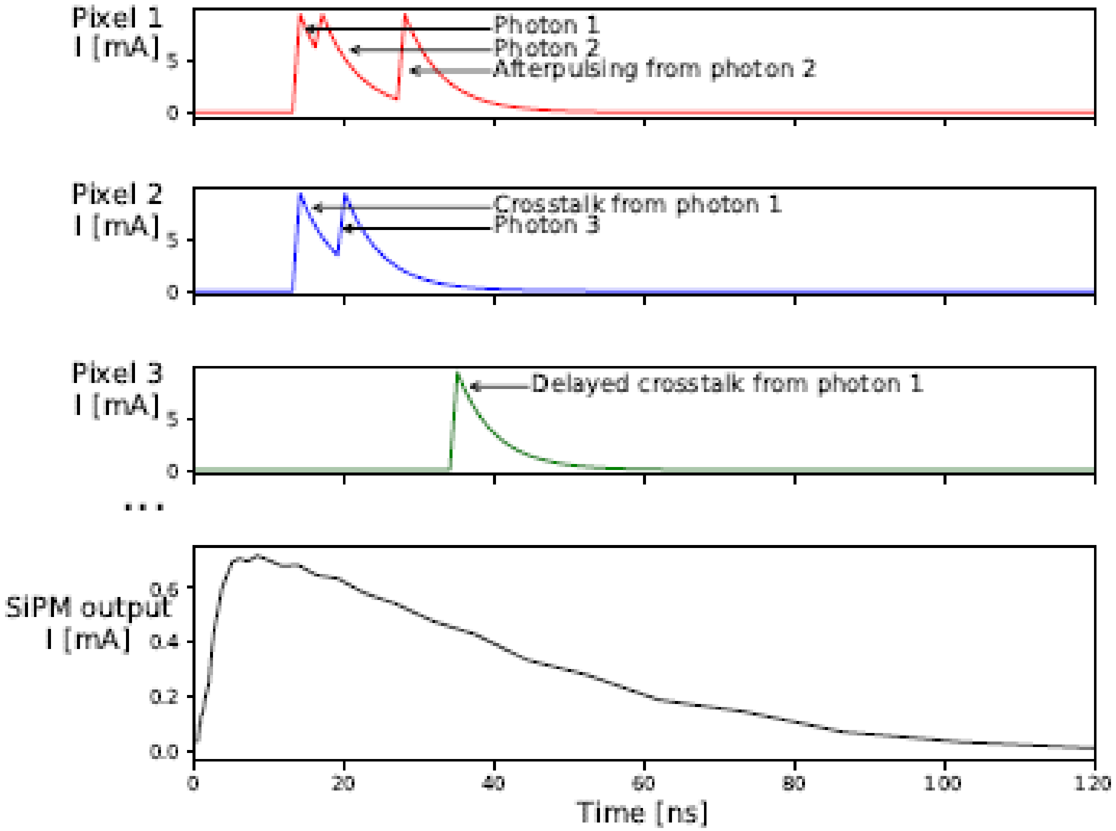
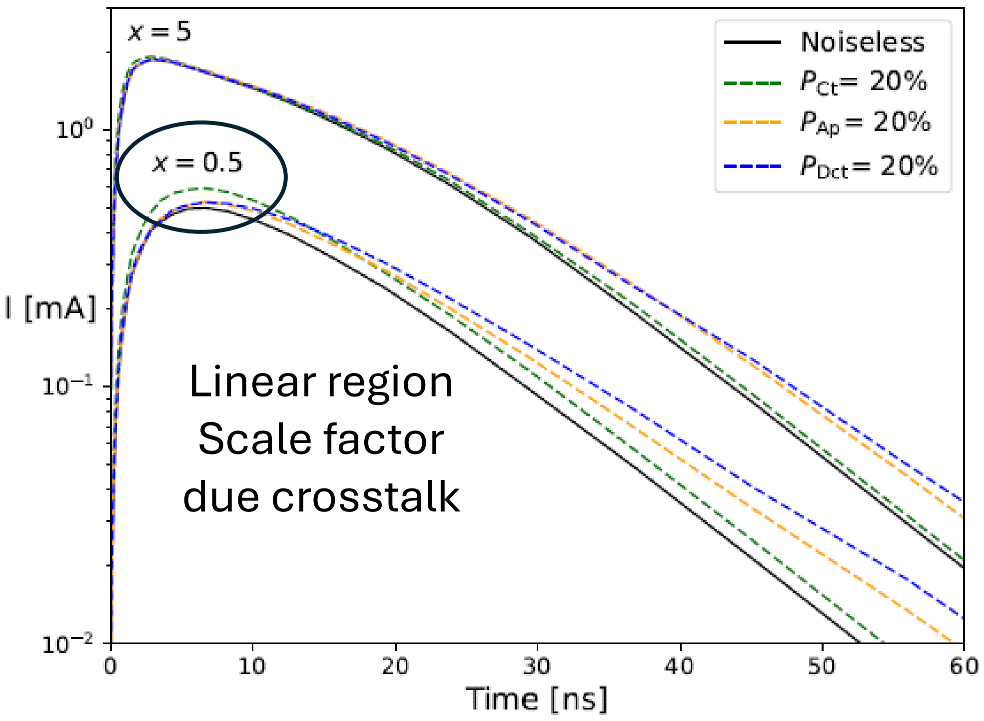
Correlated noise

- Correlated noise leads to an extra gain factor in the linear region
- Prompt crosstalk is strongly suppressed when nonlinearity becomes important
- Afterpulsing and delayed crosstalk less suppressed by nonlinearly and make the output signal longer





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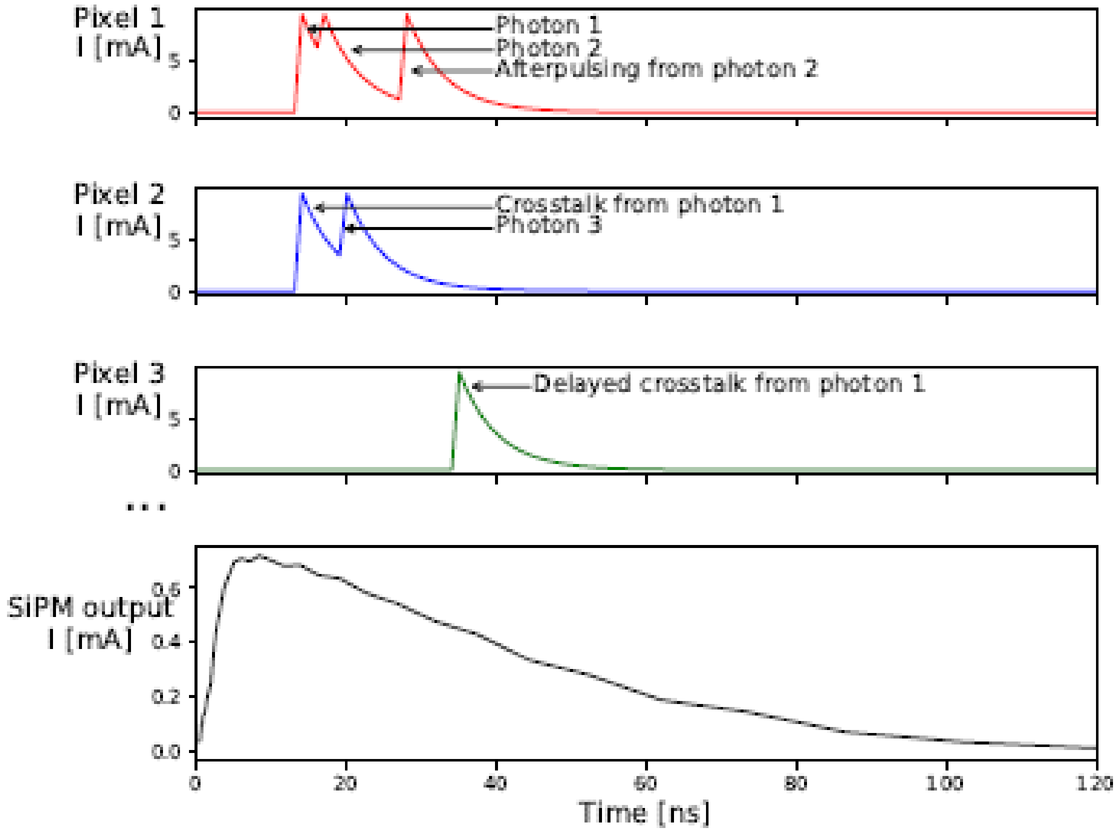
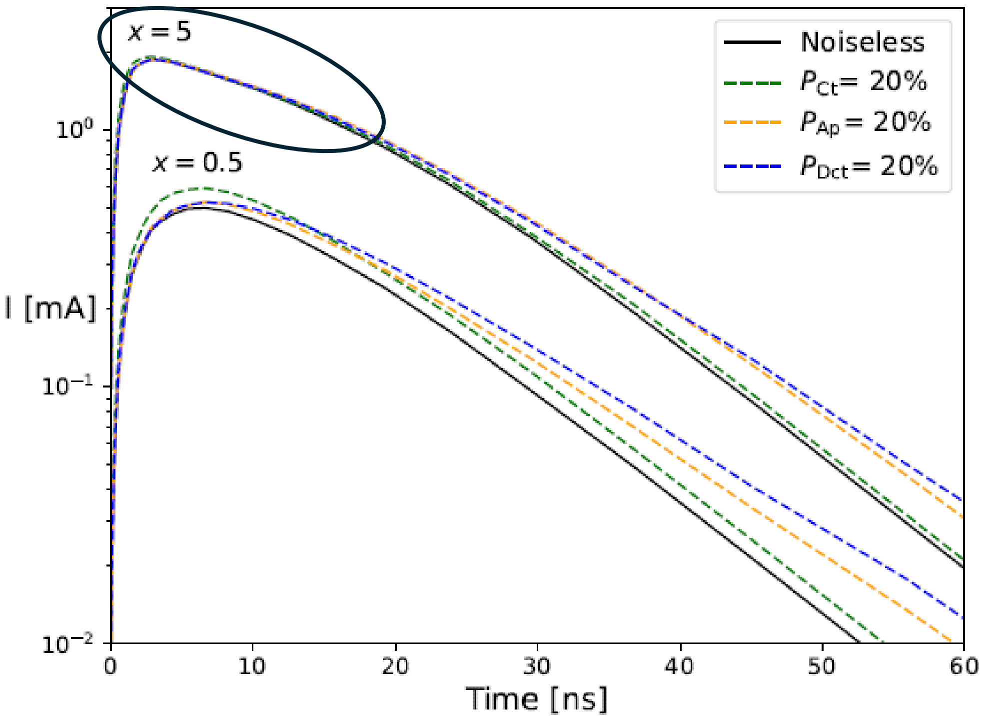


Nonlinear region
Crosstalk suppressed



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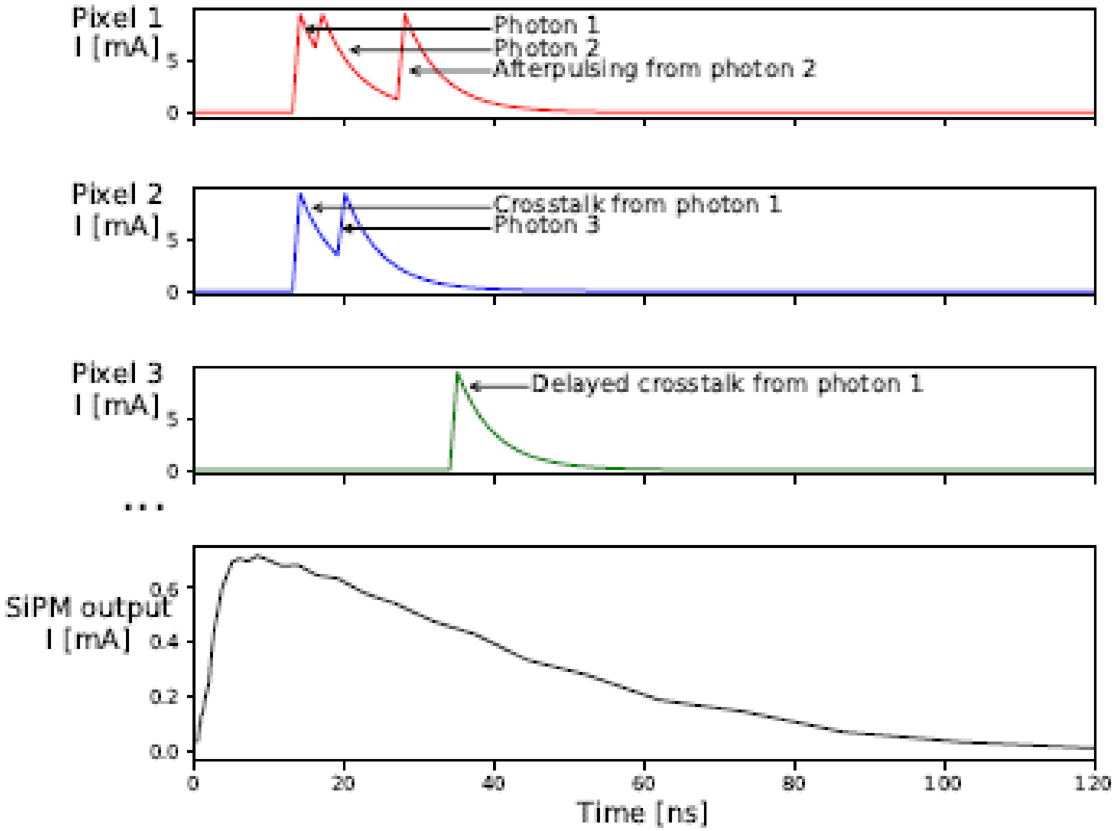
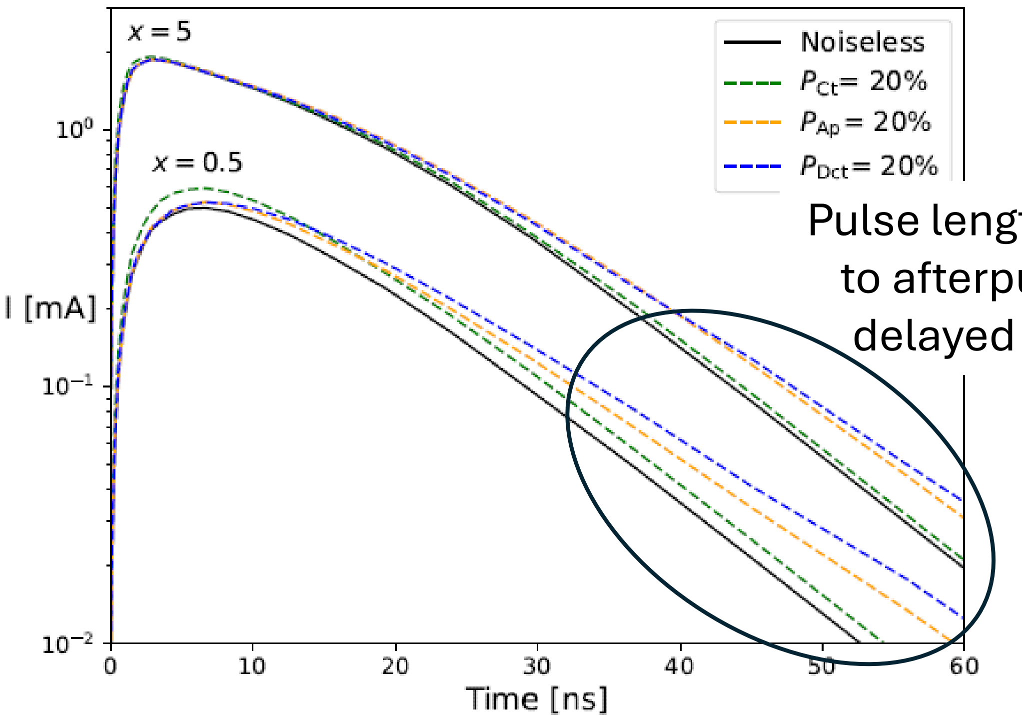
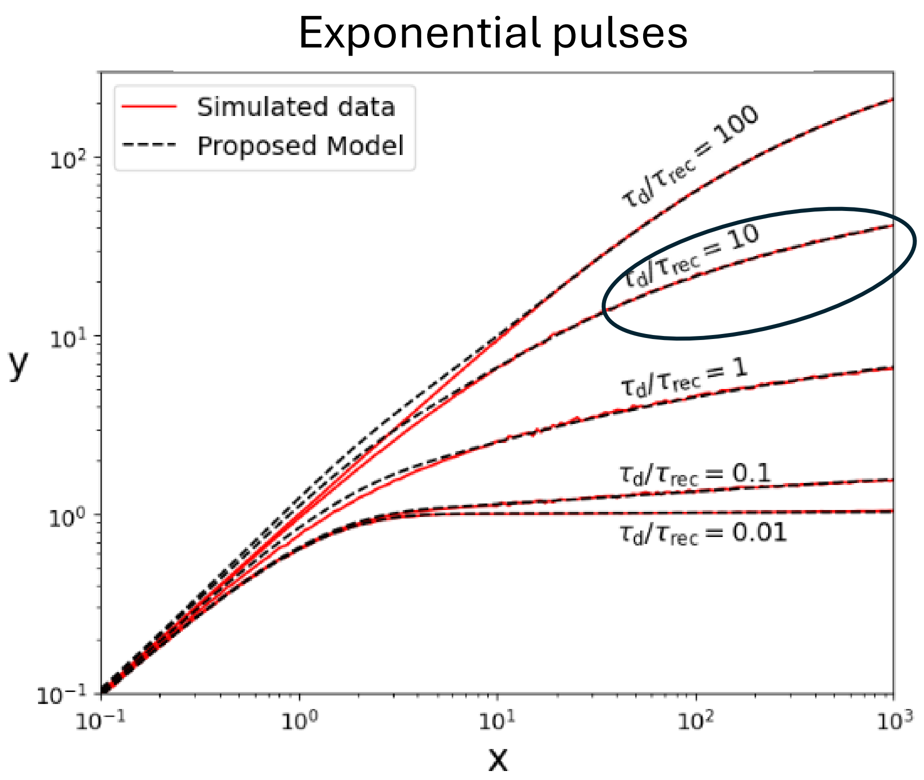


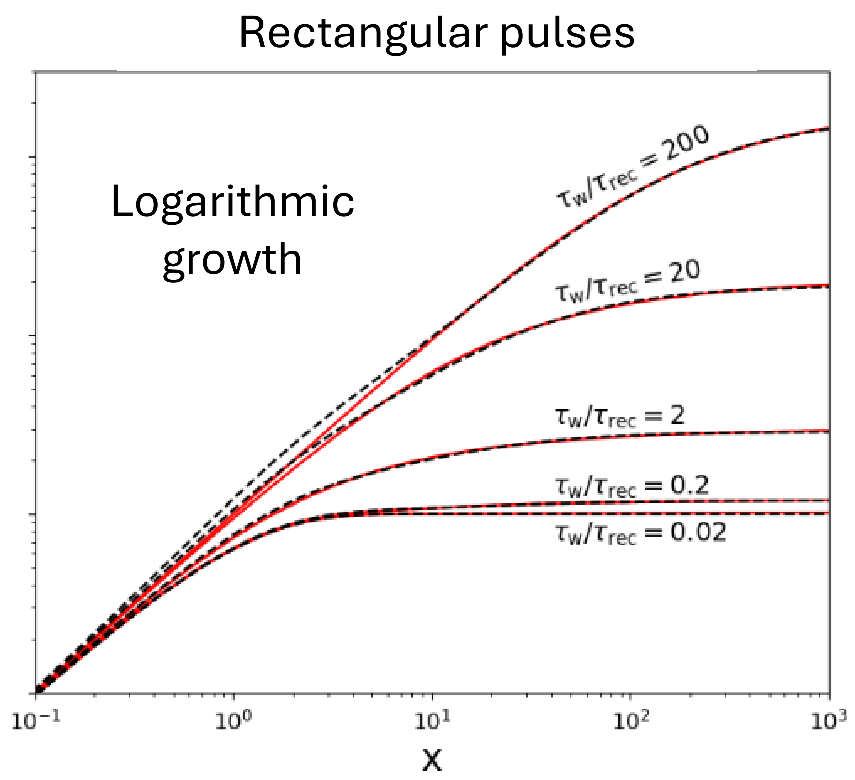


Pulse lengthening due to afterpulsing and delayed crosstalk

Response to different pulse shapes

- Apart from the photon rate, the SiPM response depends on the light pulse shape
- Long tailed pulses (e.g., scintillation pulses): logarithmic growth at large x values
- Finite pulses (e.g., rectangular pulses): saturation at large x values
- The flatter the pulse (the smaller variance of the photon rate), the stronger the nonlinearity





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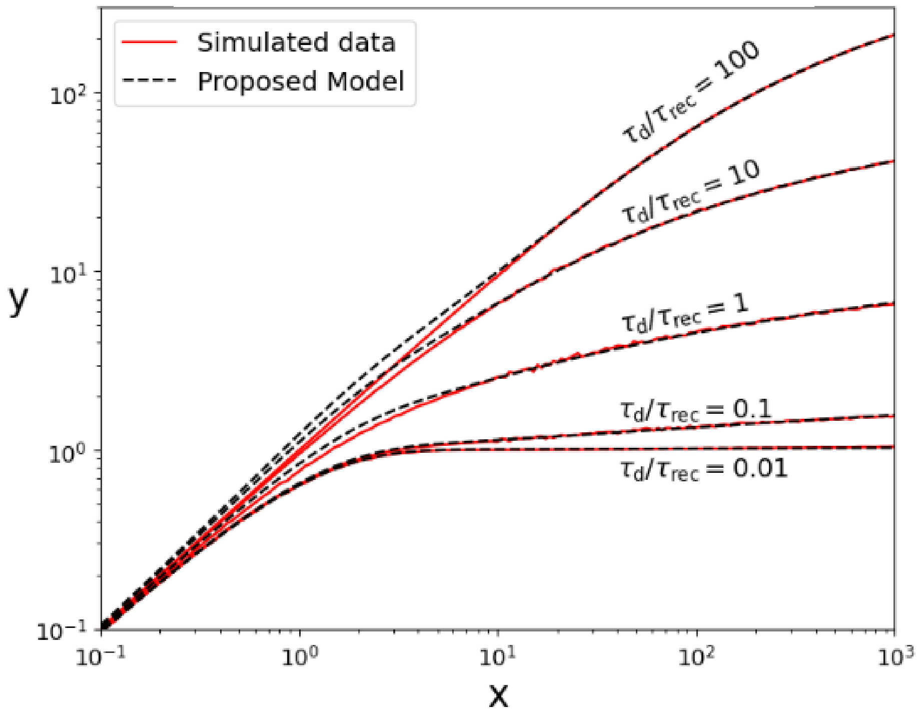
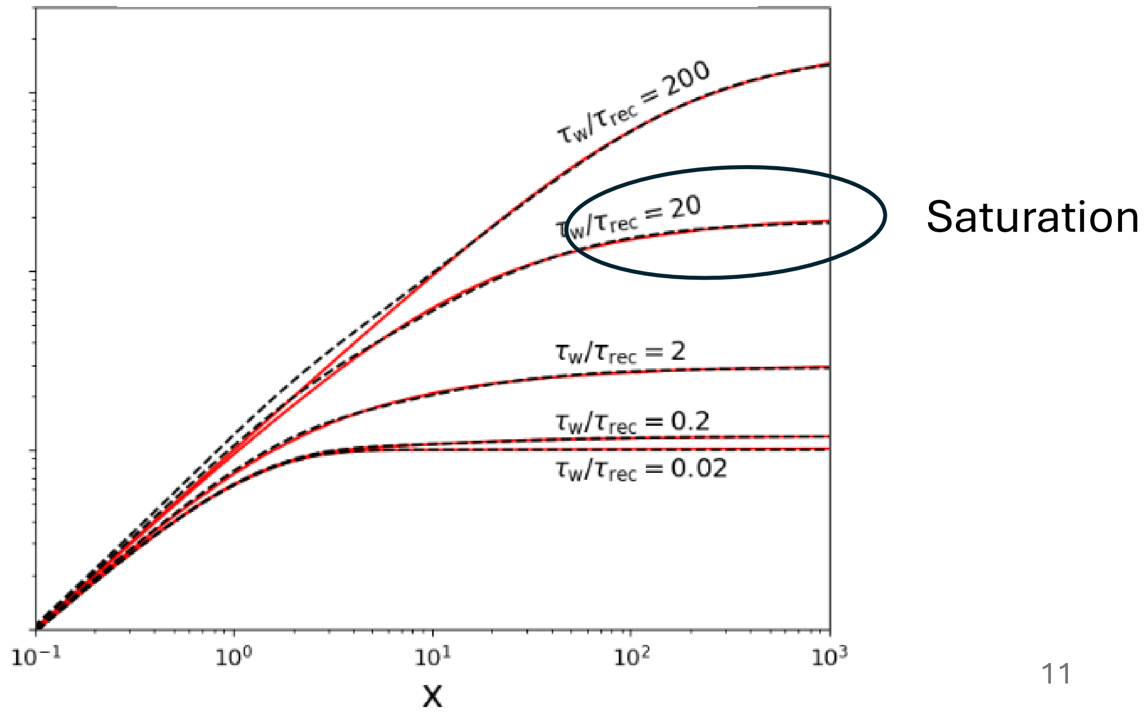
Exponential pulses



Rectangular pulses



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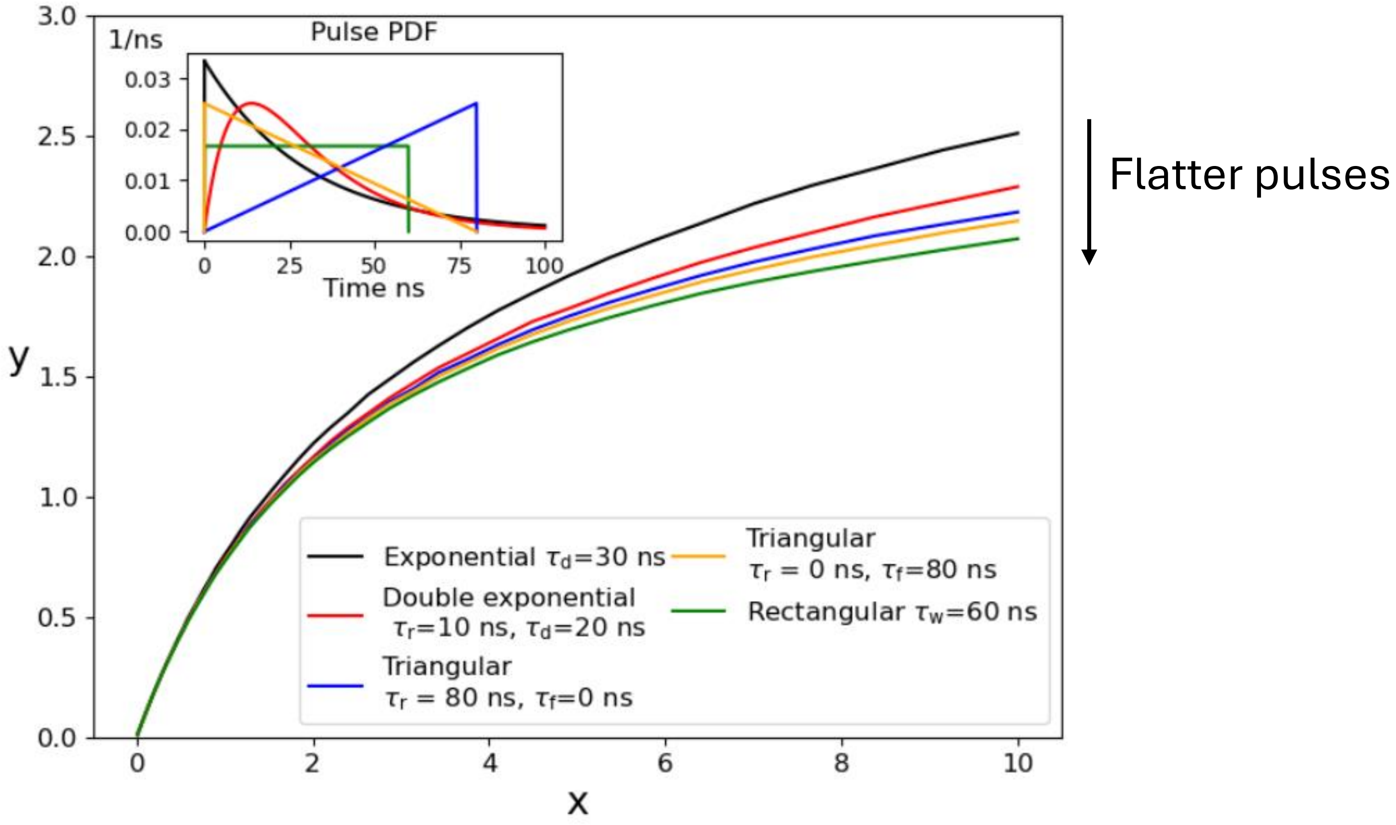


Fitting model

- Based on our simulation results, we modeled the SiPM nonlinear response as

$$y = (1 + N(x) + R(x)) \cdot (1 - e^{-x})$$

y: Number of full avalanches per pixel
x: Expected number of avalanches per pixel

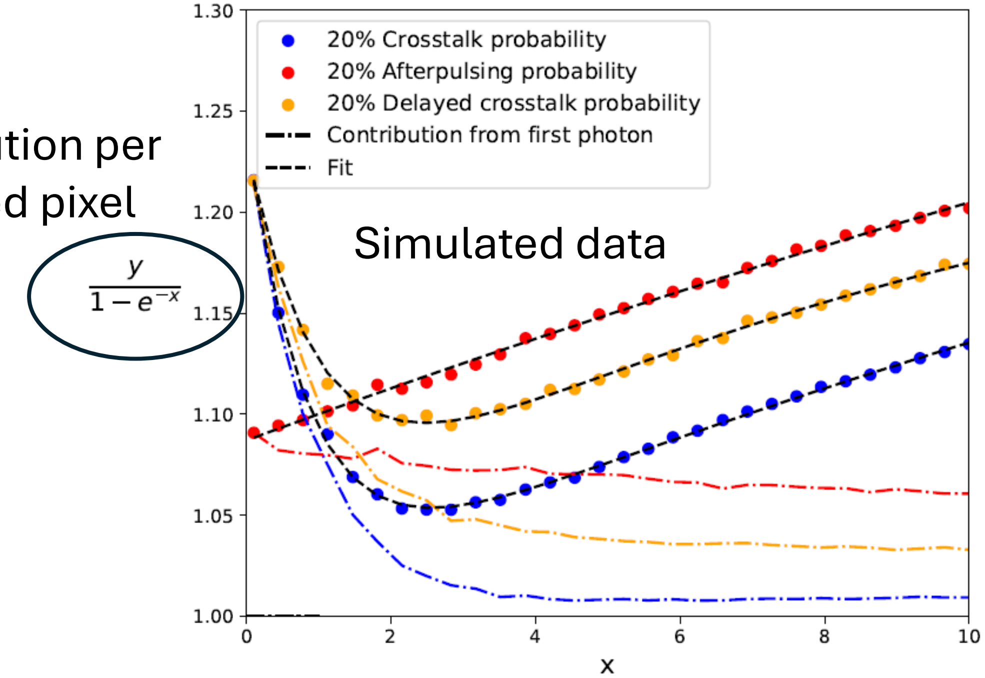
$1 - e^{-x}$: fraction of triggered pixels (from Poisson distribution of photons)

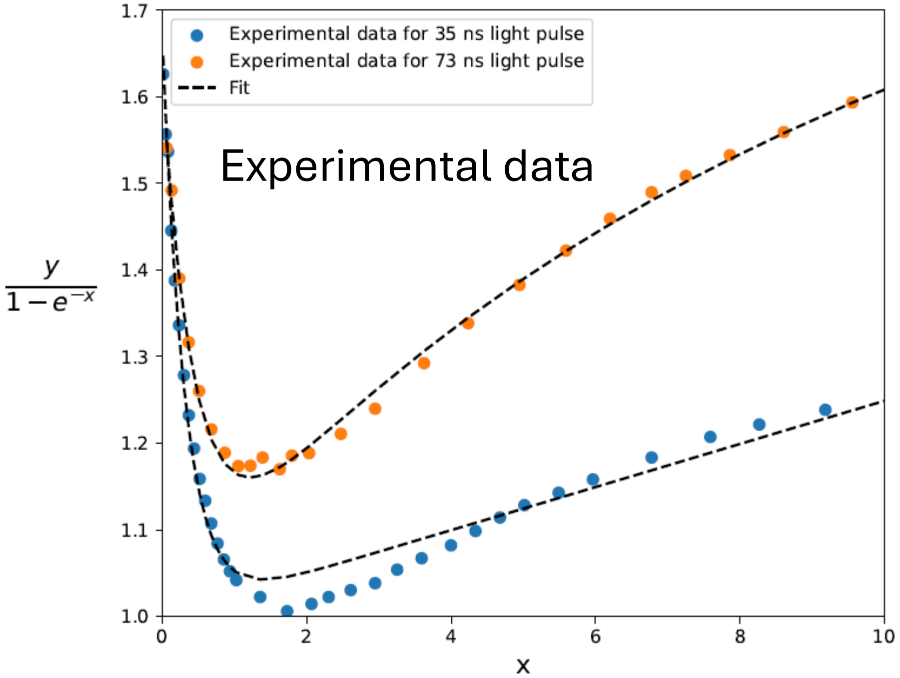
$1 + N(x) + R(x)$: average contribution per triggered pixel

$1 + N(x)$: First avalanche and correlated noise that it induces

$R(x)$: Avalanches produced during pixel recovery after first avalanche

Contribution per triggered pixel





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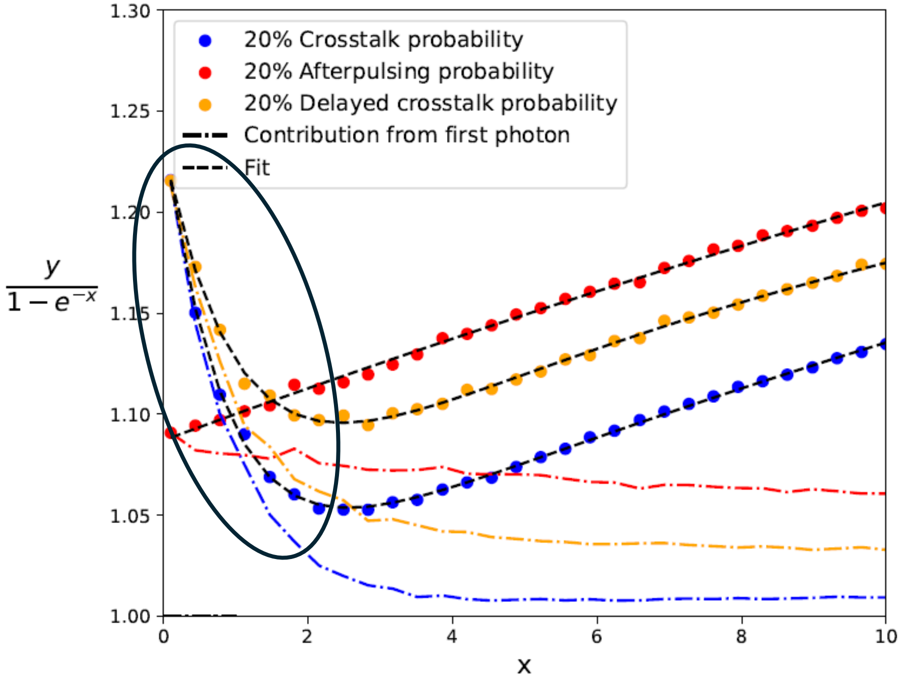
- Exponential suppression of correlated noise

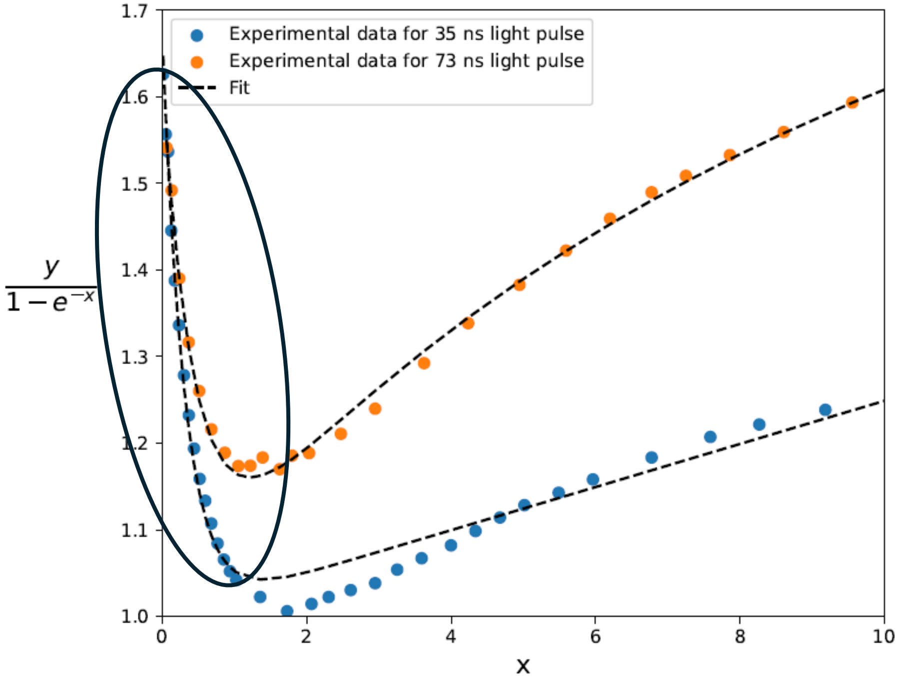
$$N(x) = c \cdot e^{-d \cdot x}$$

c and d are fitting parameters

Simulated data



Experimental data



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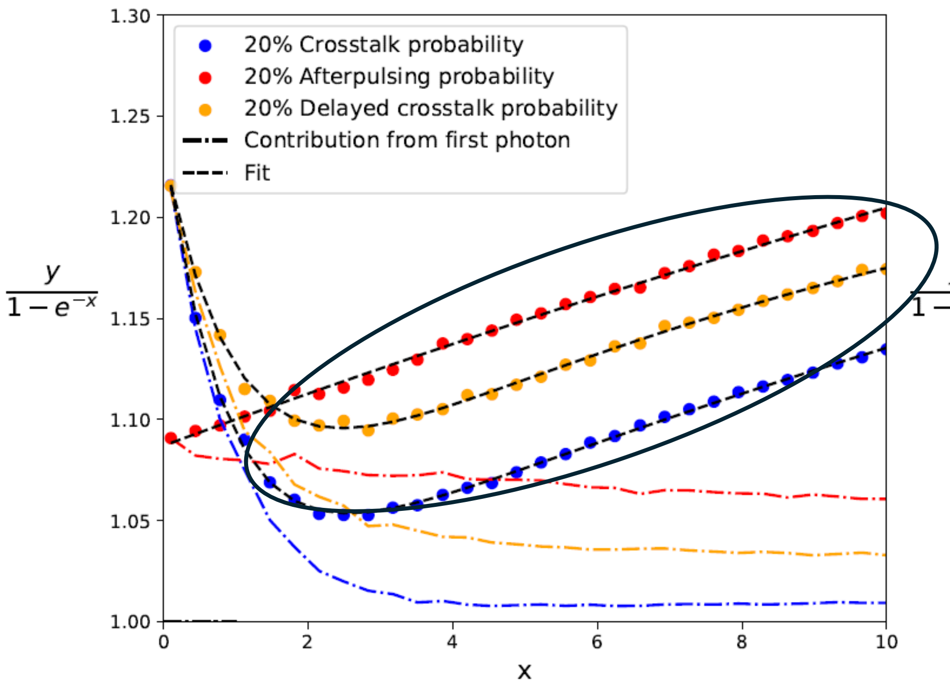
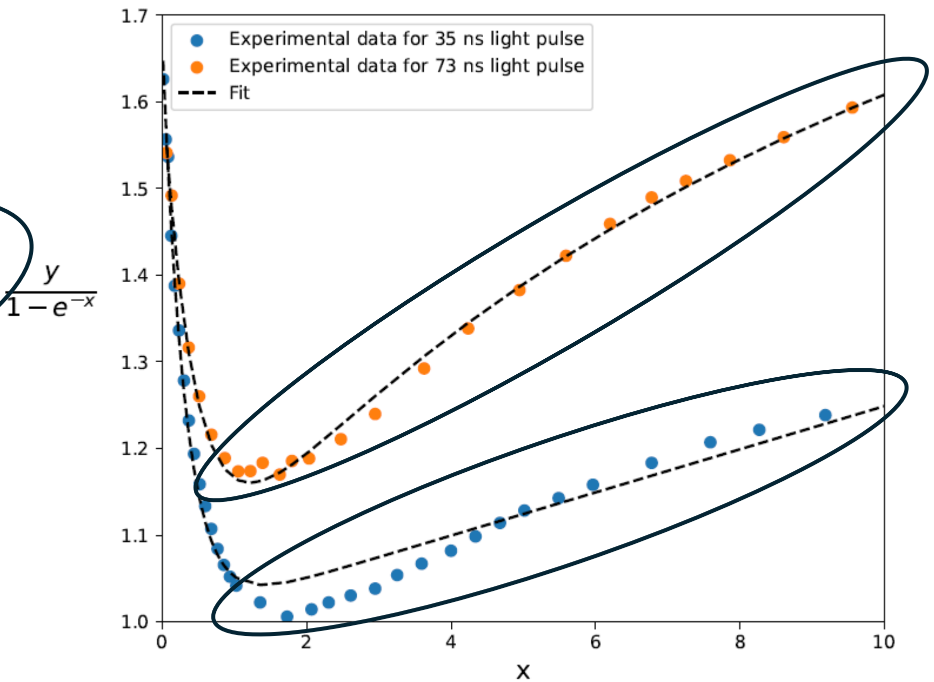
- Different response to different pulse shapes:
  - Long tailed pulses: $R(x) = a \cdot Ln(1 + b \cdot x)$
  - Finite pulses: $R(x) = \frac{a \cdot x}{1 + b \cdot x}$

Both models are equivalent for $x \lesssim 10$
$R(x) \propto x$

Results for rectangular LED pulses





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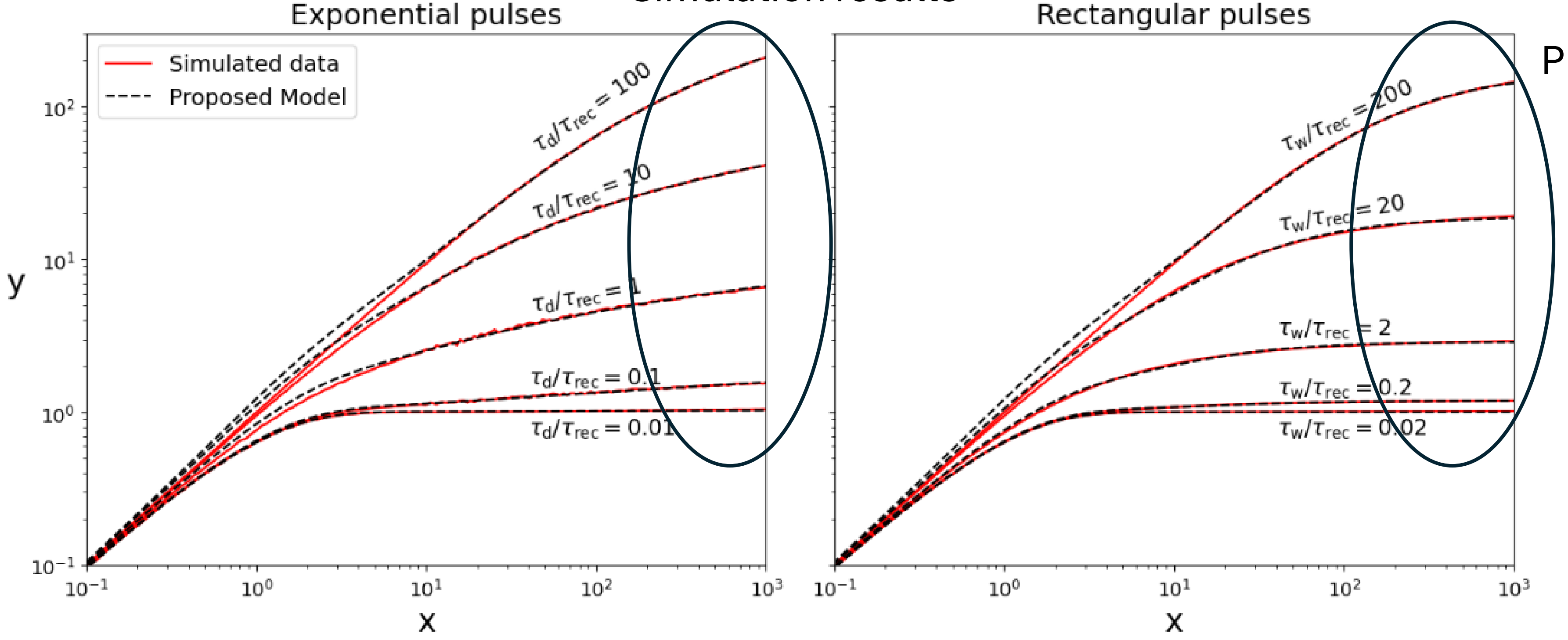
The models reproduce the asymptotic behavior at very large x
a and b are fitting parameters

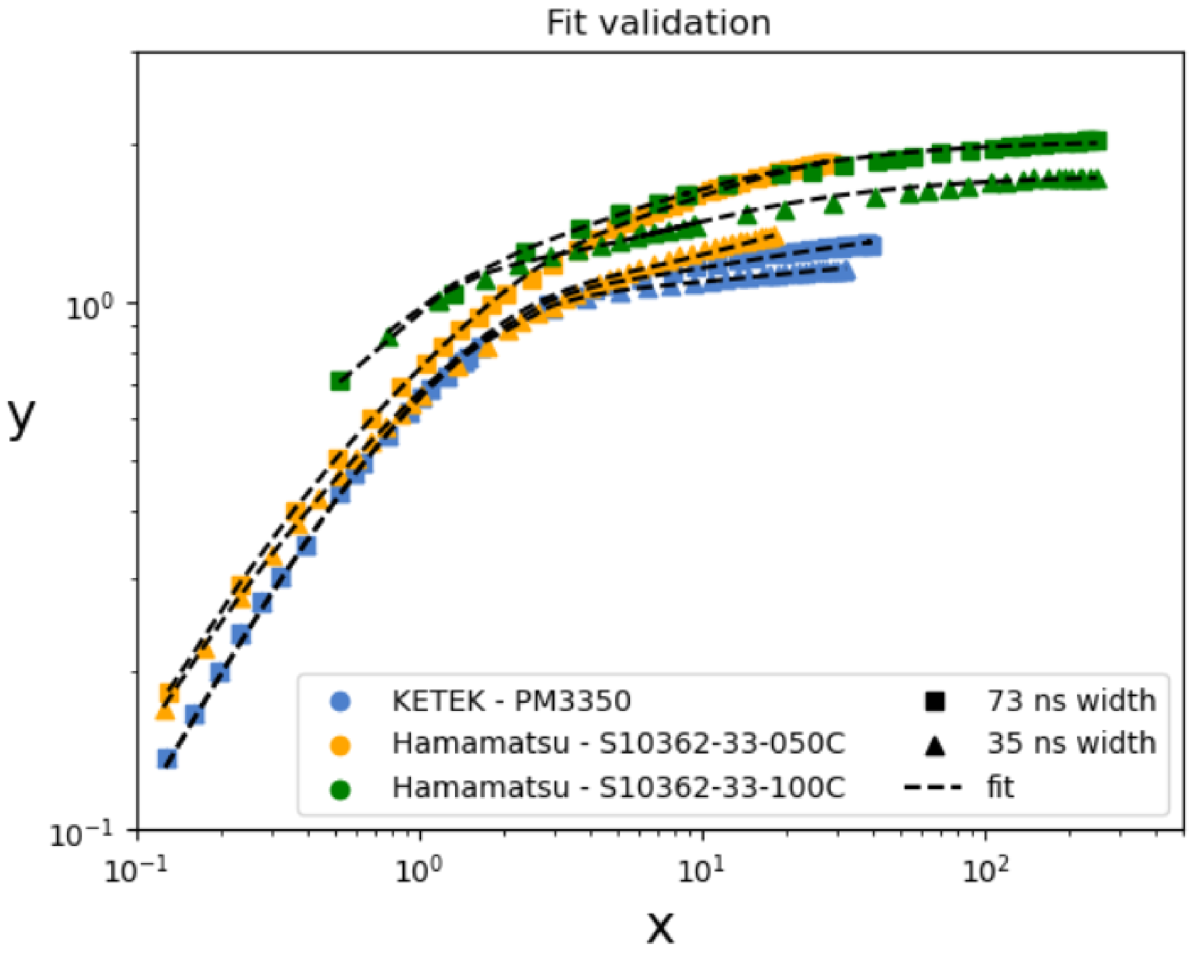
Simulation results



Previous models fail at large x

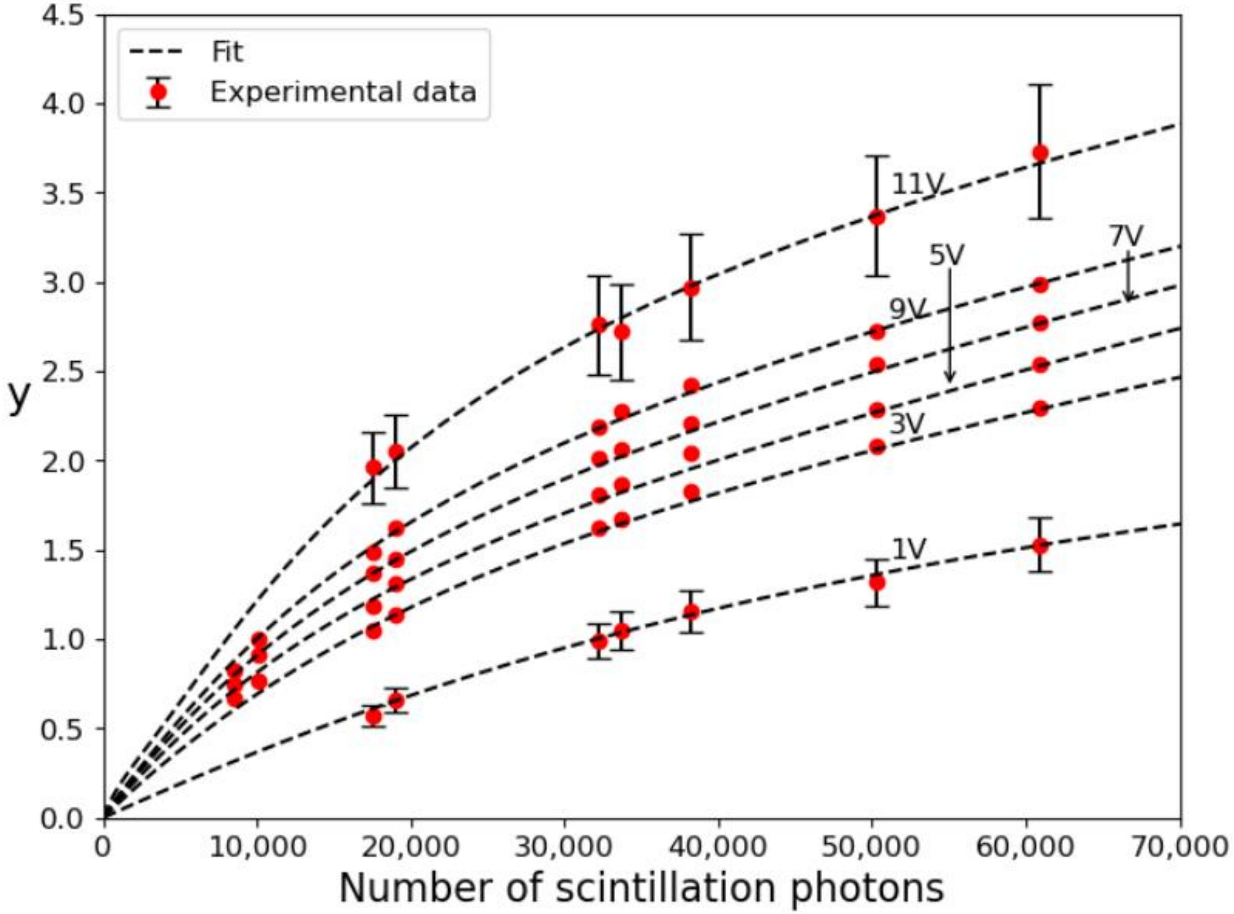
Model validation

- Model validated against experimental data for different SiPMs and pulse widths for from *Bretz, T et al. JINST 2016, 11, P03009*
- Residuals smaller than 5% in a very large range of light pulse intensities



Example of a scintillator detector

- LYSO(Ce)+Hamamatsu S13360-1350CS exposed to gamma rays from 300 to 2100 keV (^{22}Na, ^{60}Co, ^{137}Cs and ^{226}Ra)
- Residuals smaller than experimental errors (10%) in all the energy range



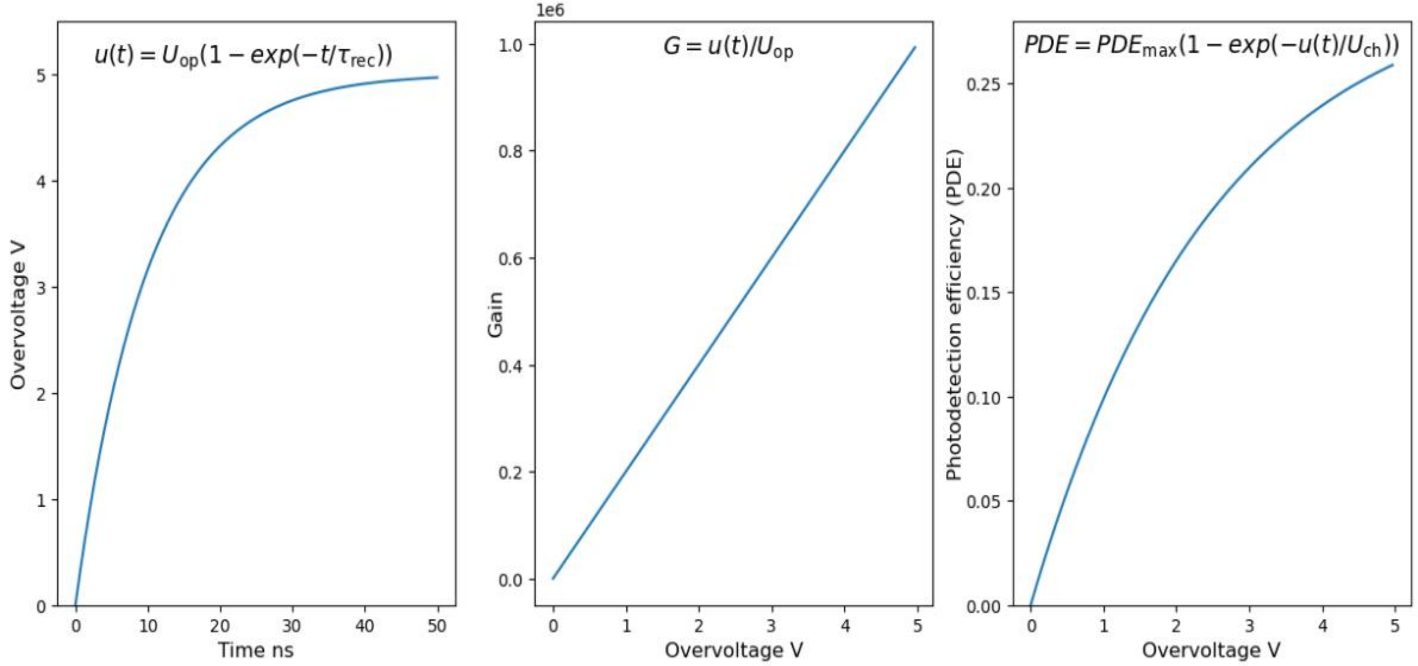
Conclusions and future plans

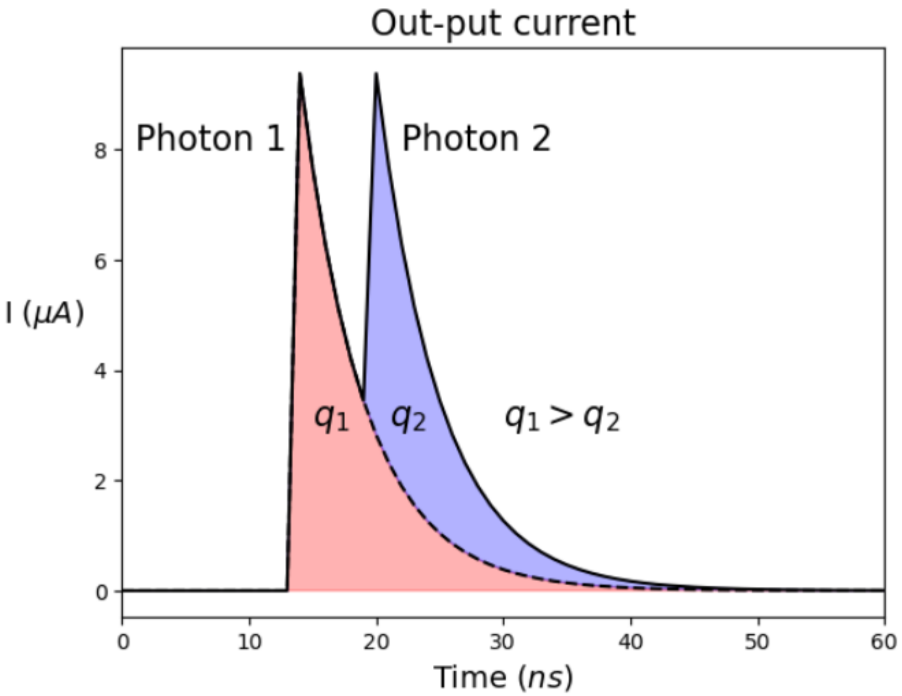
- SiPMs are photonsensors with excellent properties, but their use in scintillation detectors is limited by their nonlinear response
- A systematic study of the SiPM nonlinear response and its causes was performed by means of Monte Carlo simulations
- We propose a simple fitting model depending on 4 fitting parameters that reproduce both simulated and experimental data for light pulses of arbitrary shape and intensity
- Using our model may allow extending the dynamic range of scintillation detectors
- We plan to study in detail nonlinear effects on the output pulse signal as well as on the energy resolution

Back-up slides

SiPM recovery

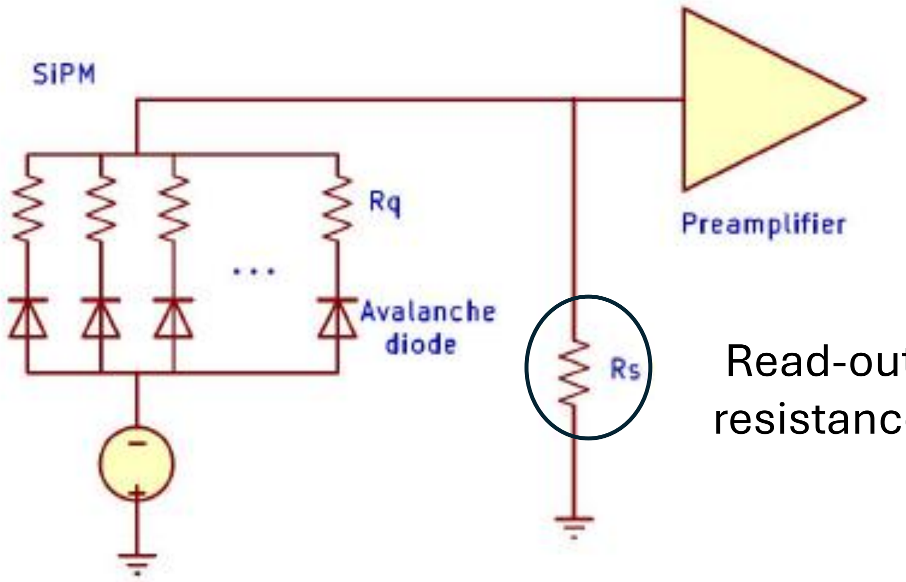
- After a charge avalanche in a microcell its overvoltage drops to 0 and starts recovering
- PDE and Gain also drop to 0.
- The charge created by a charge avalanche in a recovering pixel will be smaller
- If there is a significant number of unrecovered avalanches the response will not be linear





SiPM Read-out resistance effect

- Although the read-out resistance is usually small it has an important effect
- It adds a fast component to the SiPM response
- The net effect is to lower the output charge



Read-out resistance