Photon-based Characterization of Single Ion Geiger Mode Avalanche Detectors: Experiments and Simulations

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Quantum Information S&T

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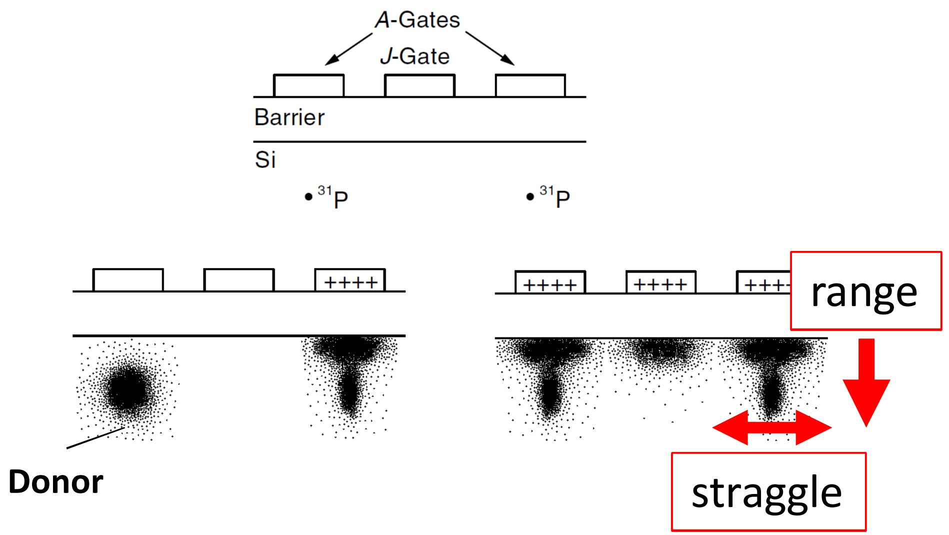
SAND:

Quantum computer as an array of donors



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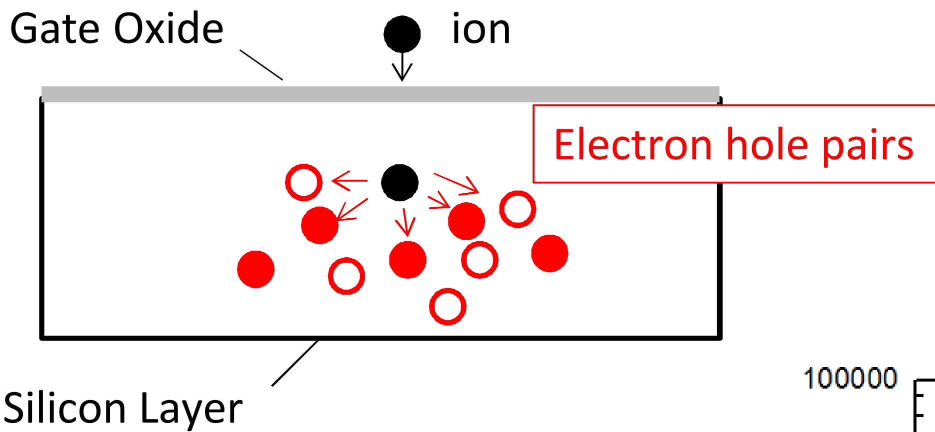
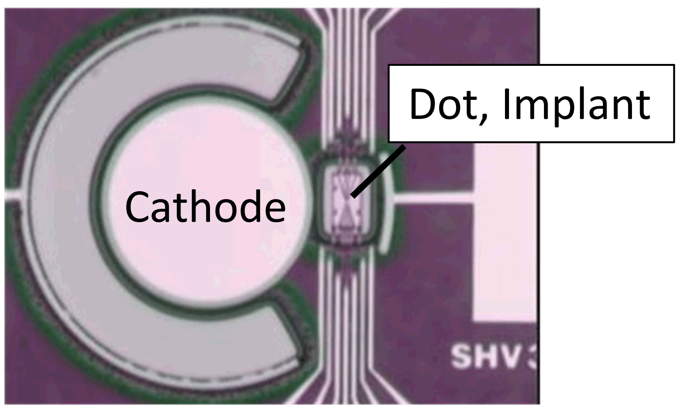
Range/Straggle must be small
Lower energy: smaller range, straggle

Fabrication of arrays of single donors can be achieved through ion implantation

<u>Challenge:</u> detect very low energy ion implants at shallow depths with minimal straggle

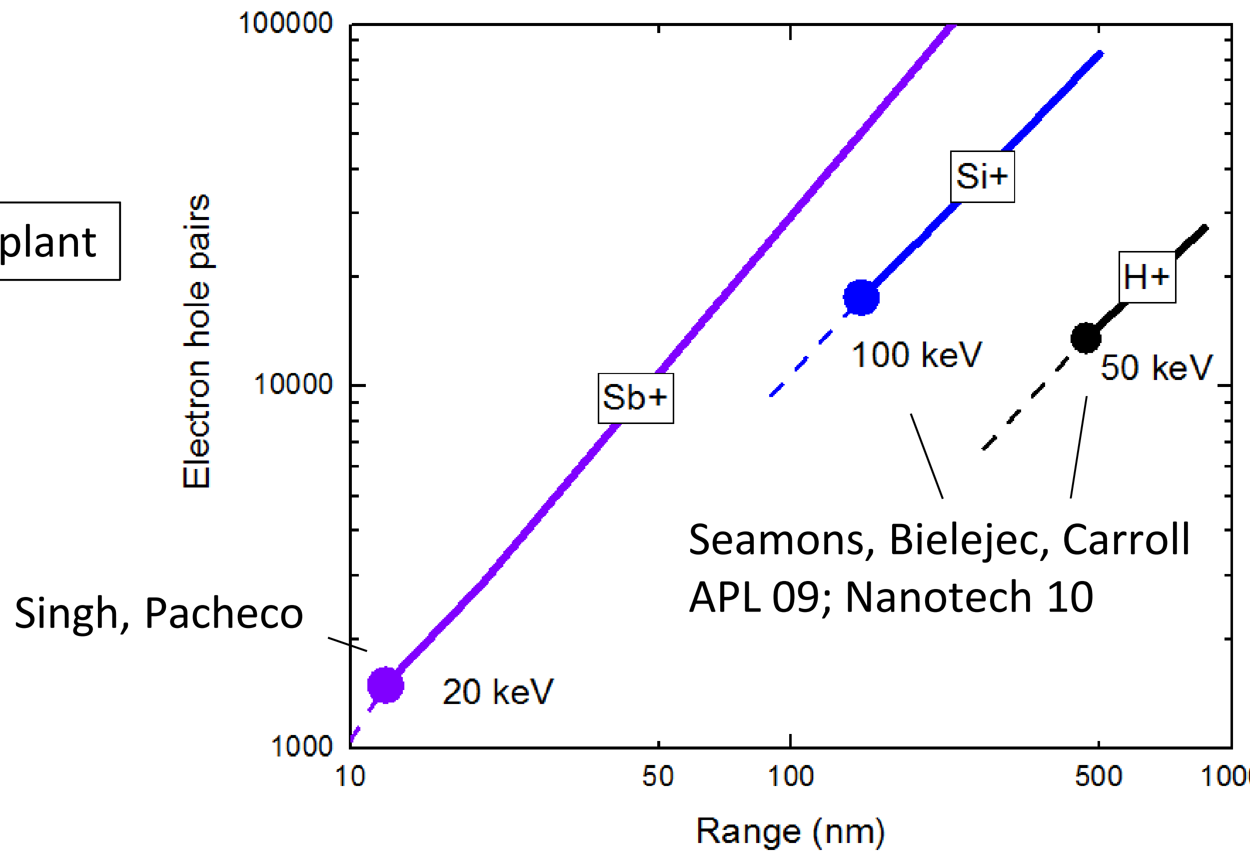
Shallow, low-straggle implants require detection of very small number of electron hole pairs





Detector + Dot

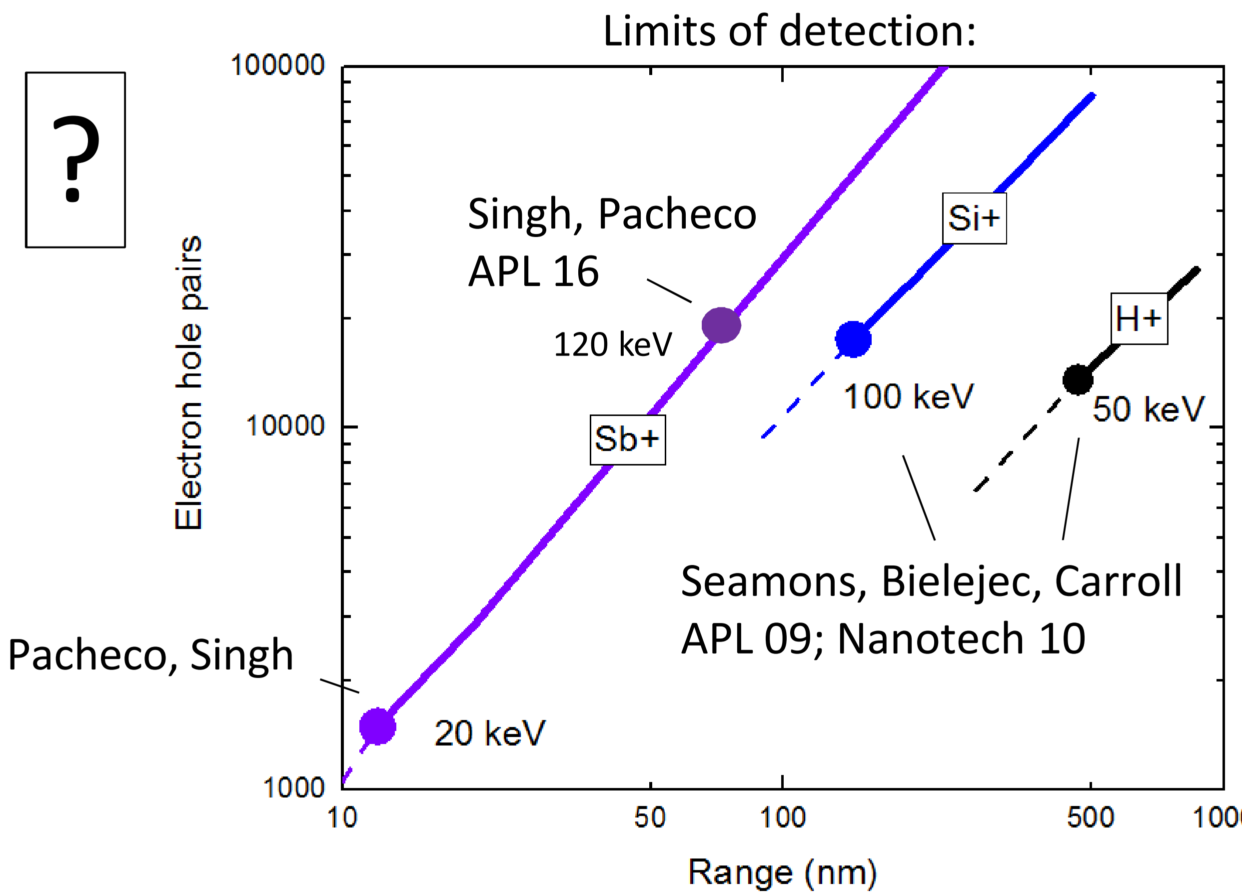
Detection in the few-ion limit



How do we improve detection?

Different species have different EH pair limits at different ranges

What are the limiting factors?



This work:

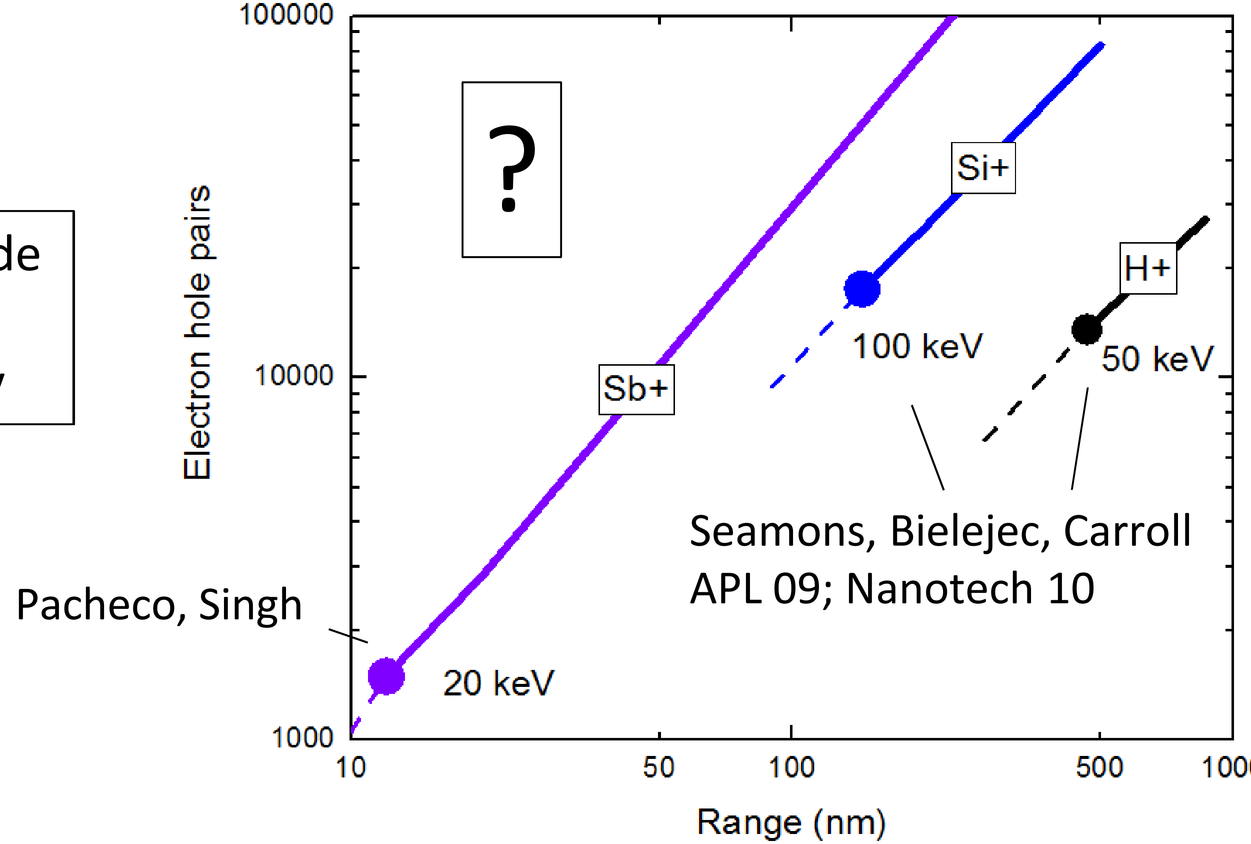
Understand Limiting factors for detection using Photons

1. Develop photon characterization methods

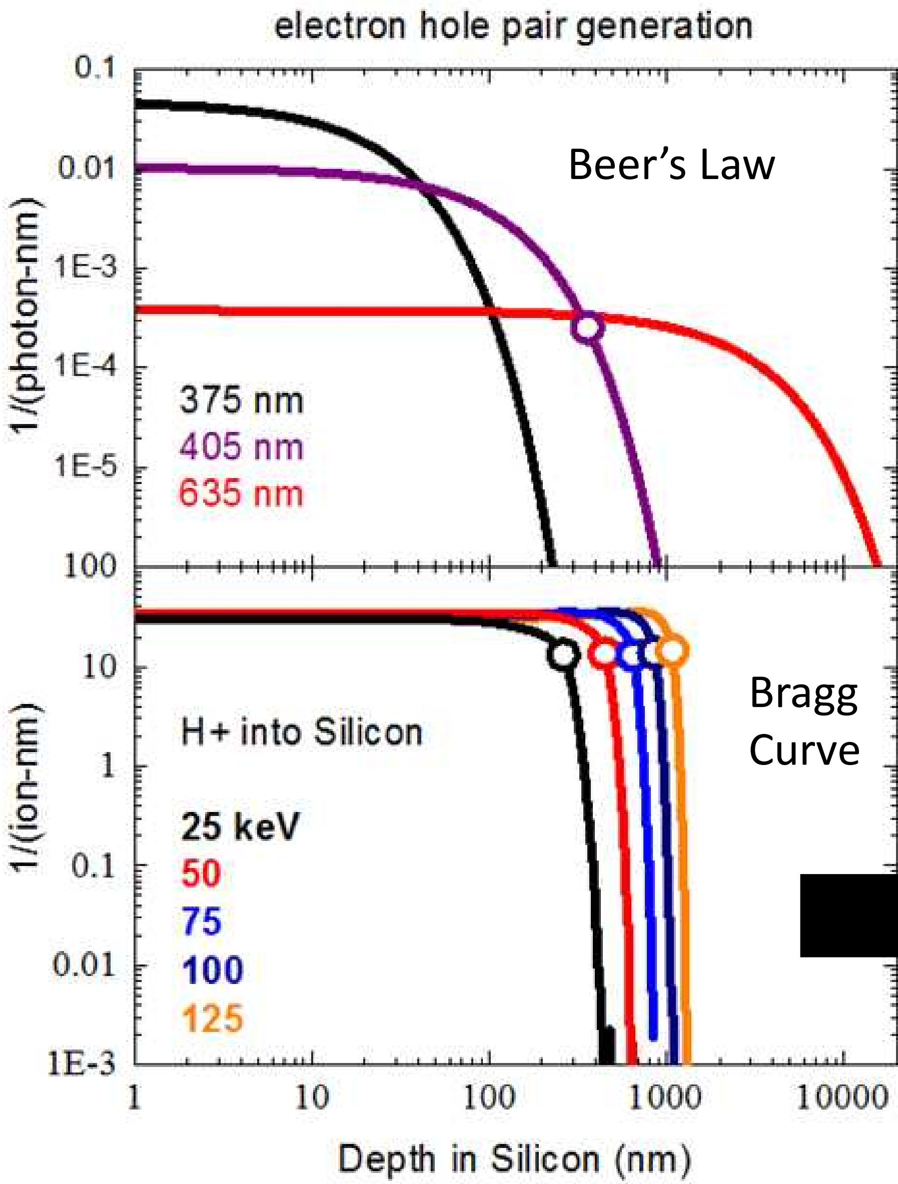
2. Physics-based simulation for detection

We focus on Geiger-mode detectors:
Single EH pair sensitivity

Limits of detection:



Photons are a damage-free proxy for Ions

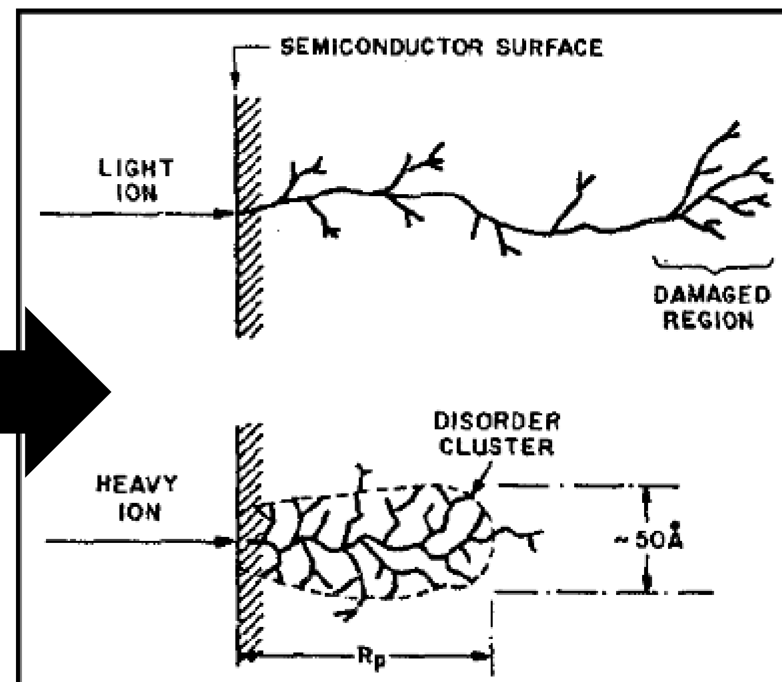


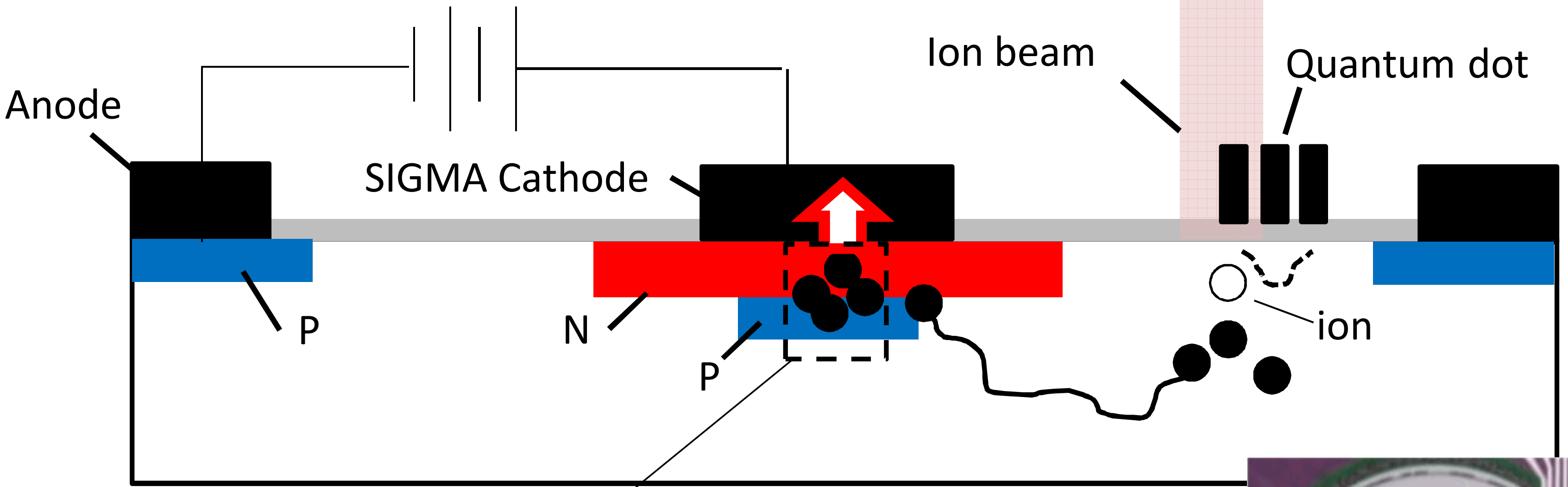
$$\mathrm{GR}(z) = F(1 - R)\alpha e^{-\alpha z}$$

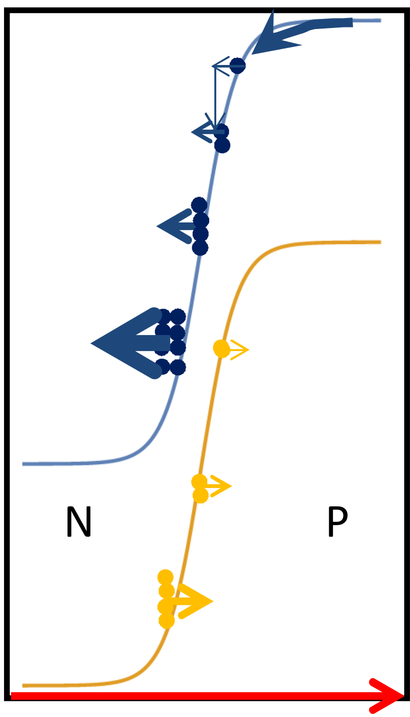
reflection

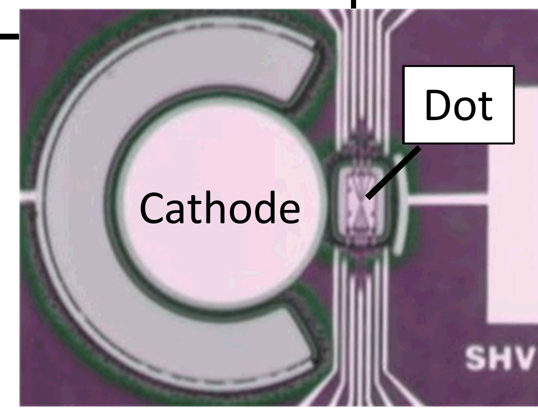
Photon flux

Absorption coefficient









SIGMA Detector

Physics of SIGMA detectors:

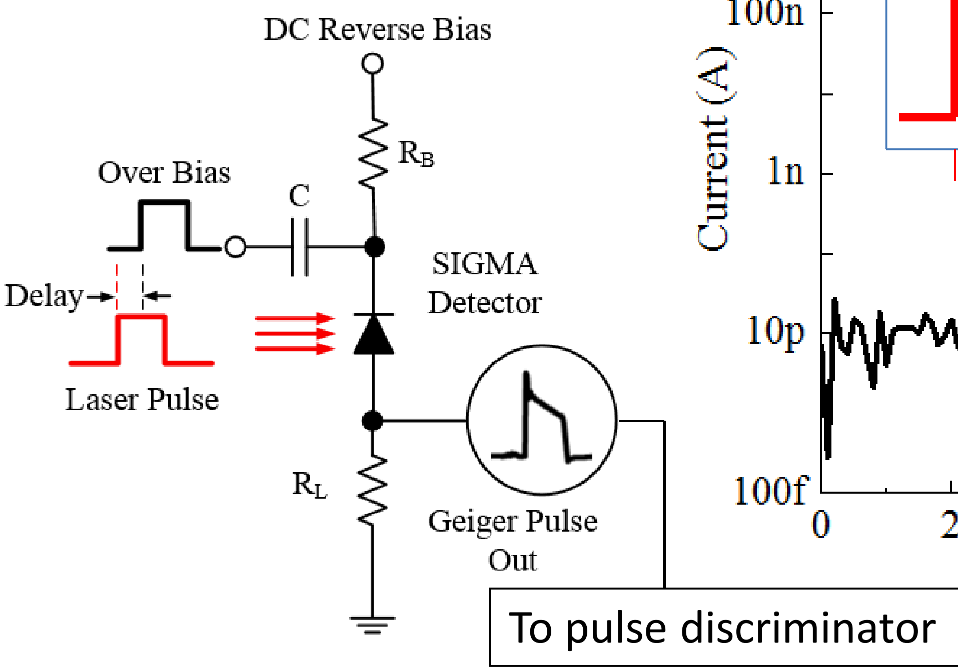
Probability of detection

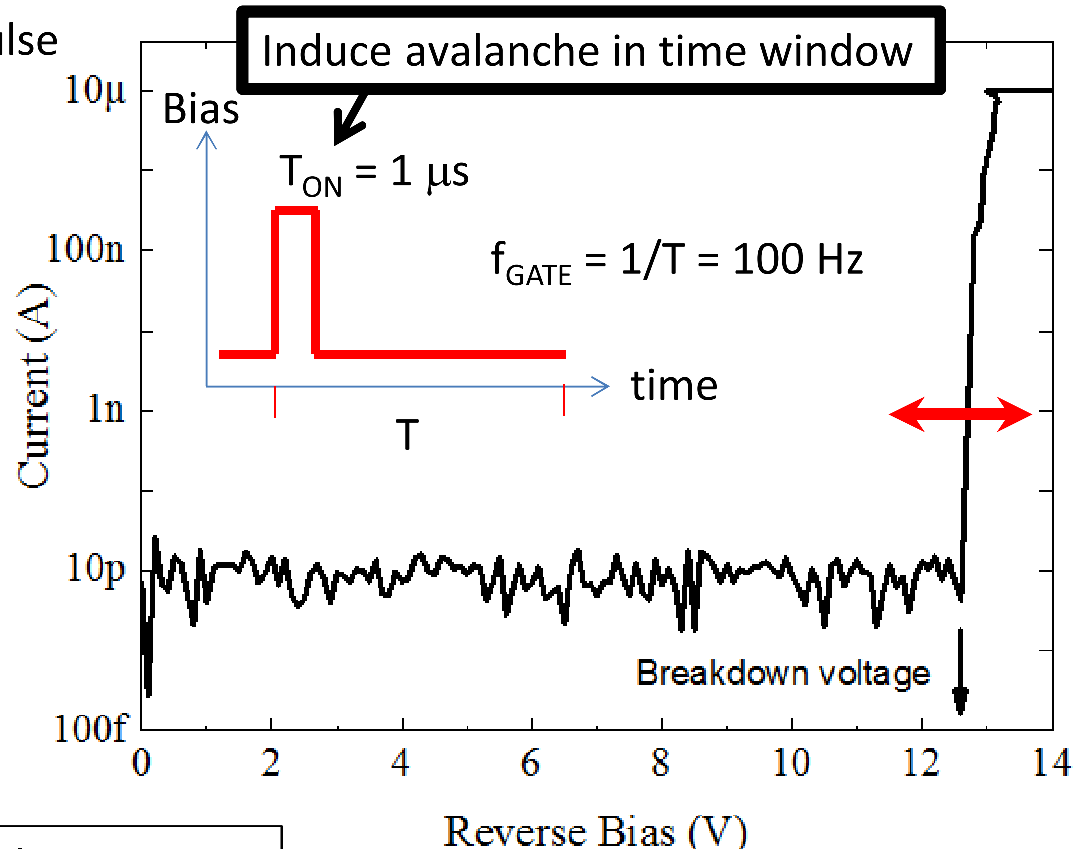
0. Probability of arrival (Poisson statistics)
1. Quantum yield
2. Probability of diffusion into the breakdown region
3. Breakdown probability

"Geiger Mode" Detection Efficiency using Photon Pulses

$$DE = \frac{\text{Counts/Second}}{\text{Gate Frequency}}$$

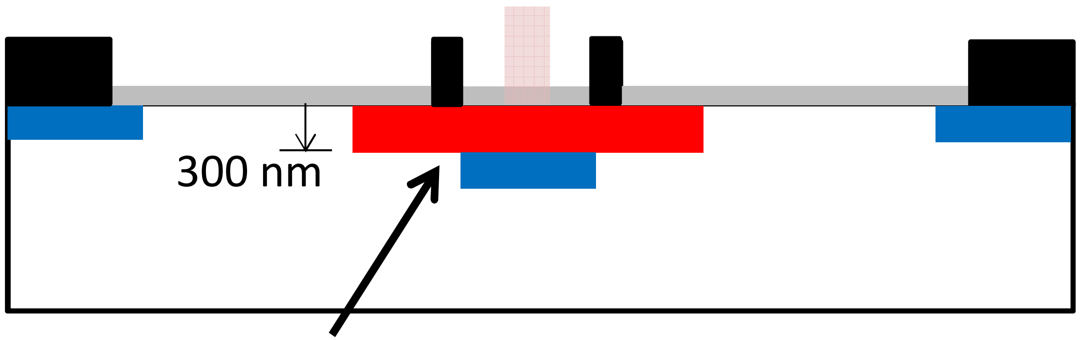
Detect: over-bias for T_{ON}, look for pulse
Turn off to "reset" the device
Count pulses for 1 second





Characterization of Detection Efficiency, Breakdown probability

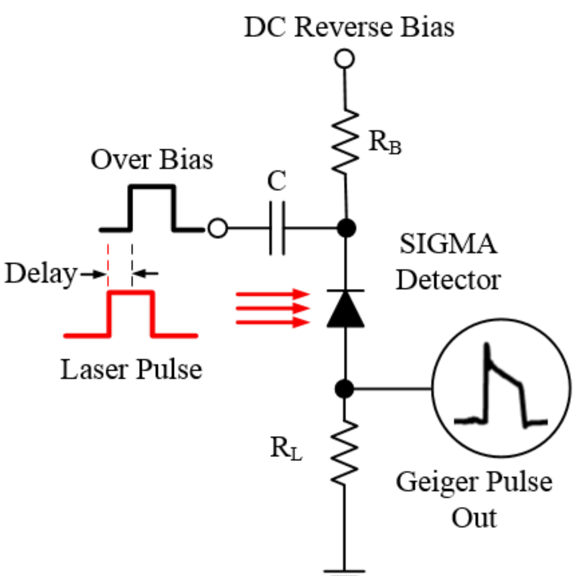
<N> photons per pulse, 405 nm

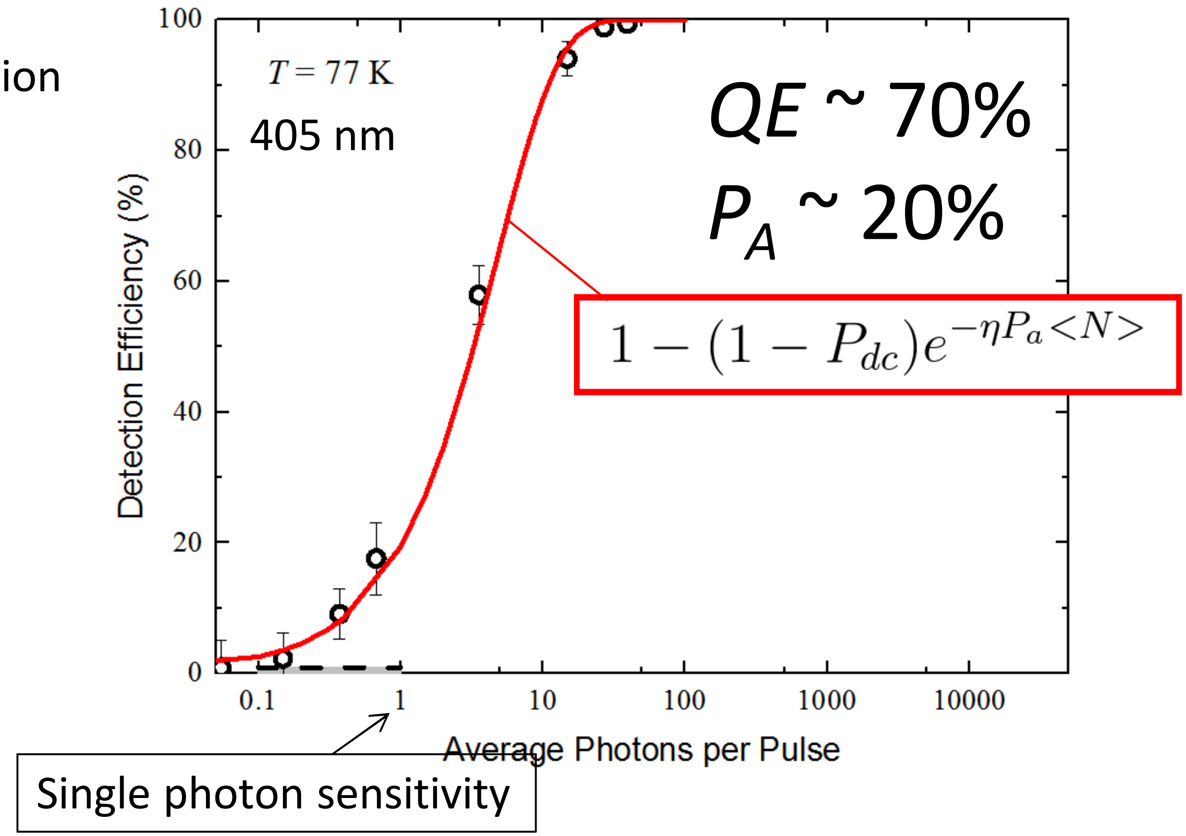


$$DE = \frac{\text{Counts/Second}}{\text{Gate Frequency}}$$

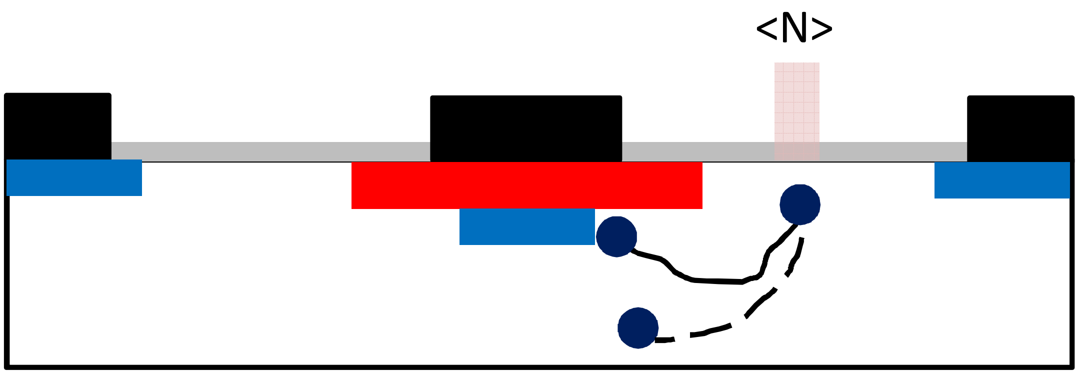
Photon-induced avalanche
Small contribution from diffusion

Delay = 0 ns





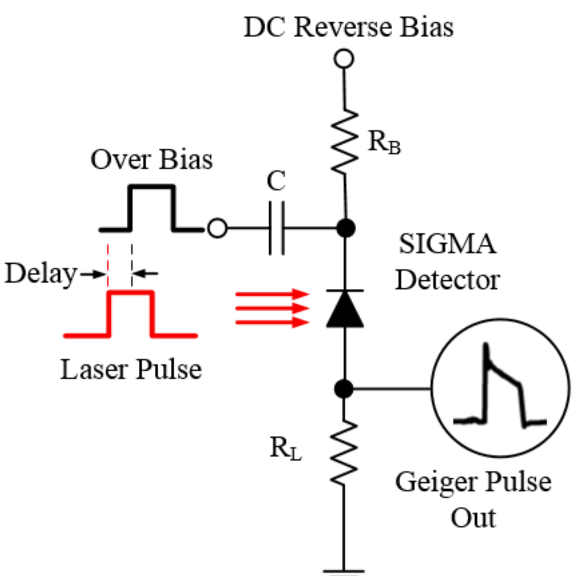
Detection Efficiency farther from the Avalanche region

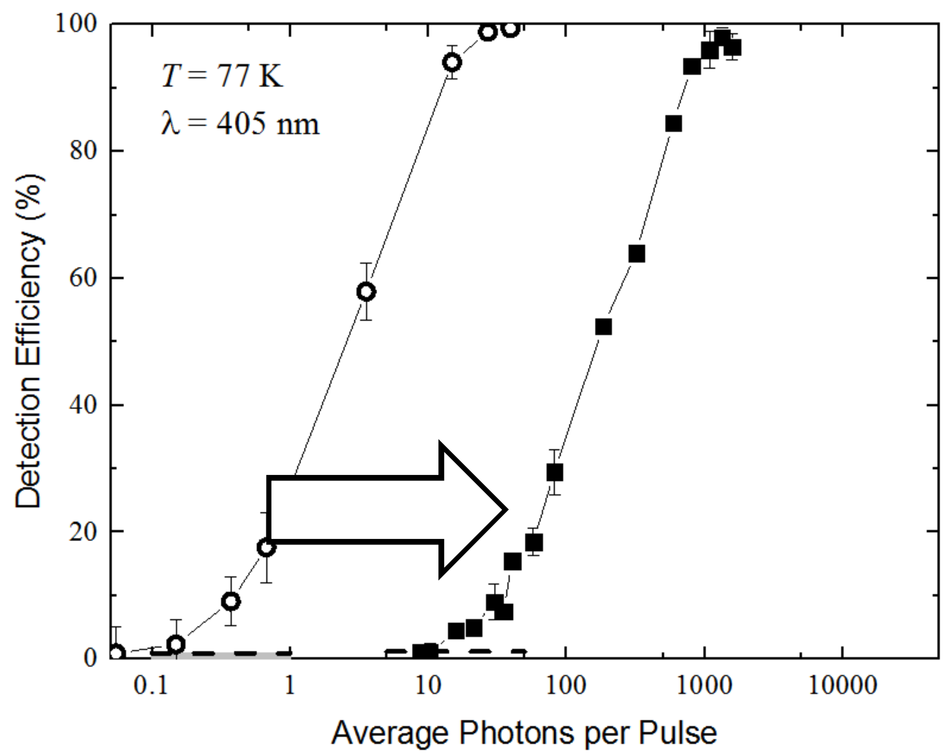


More photons/pulse needed to get same DE

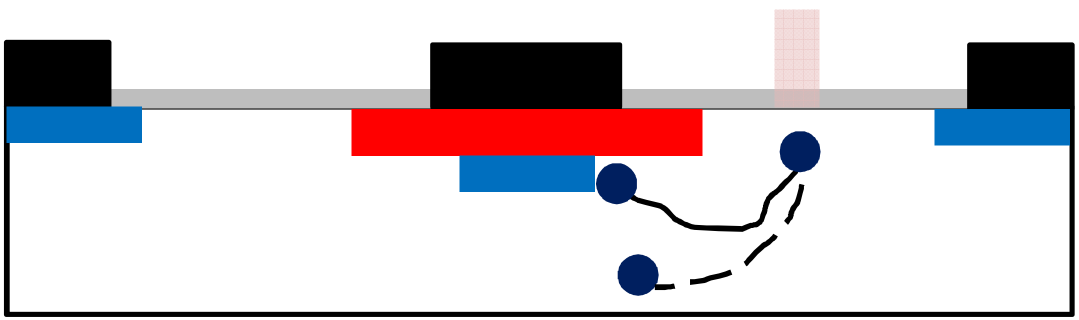
Minority carriers lost to recombination as they diffuse towards avalanche region

Delay = 250 ns



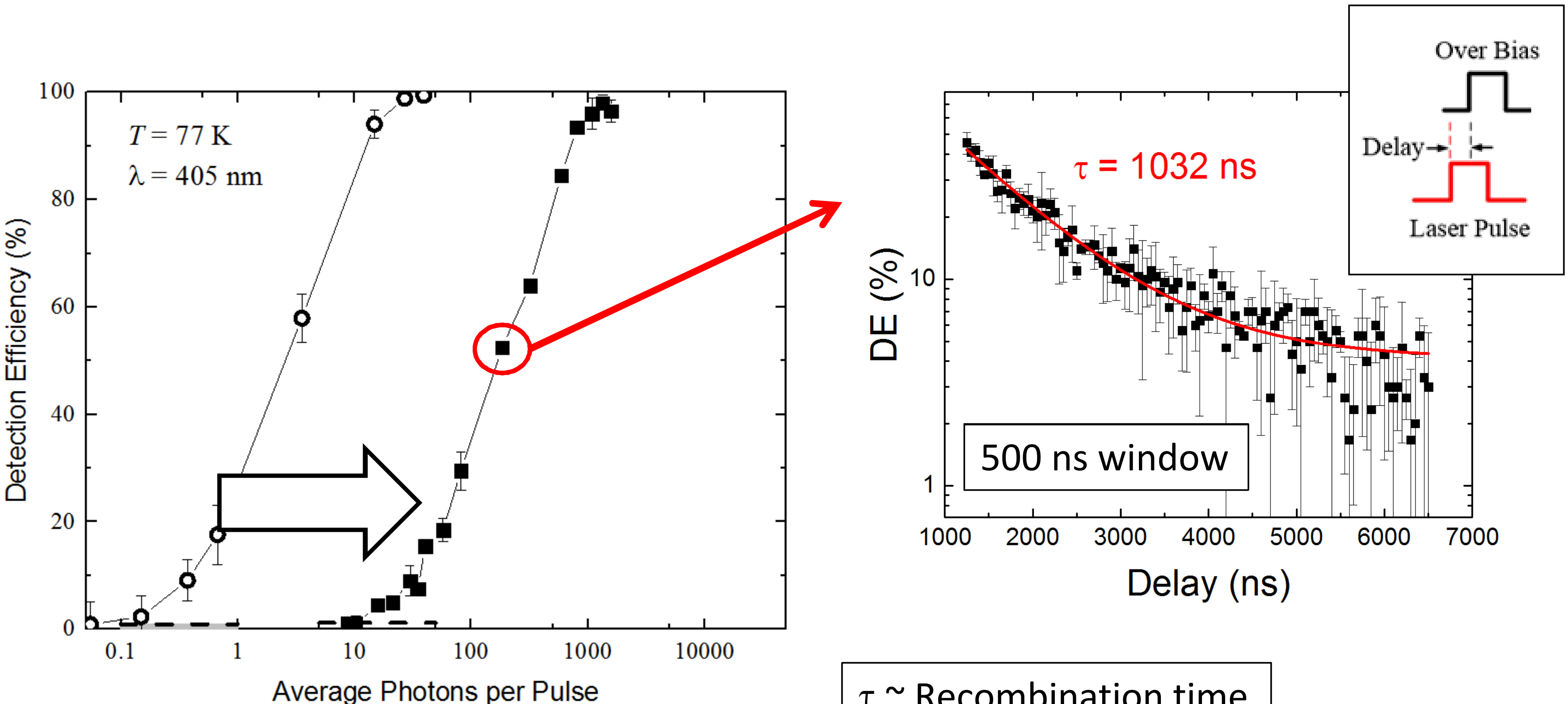


Detection Efficiency, characteristic time of arrival



Minority carriers lost to recombination as they diffuse towards avalanche region

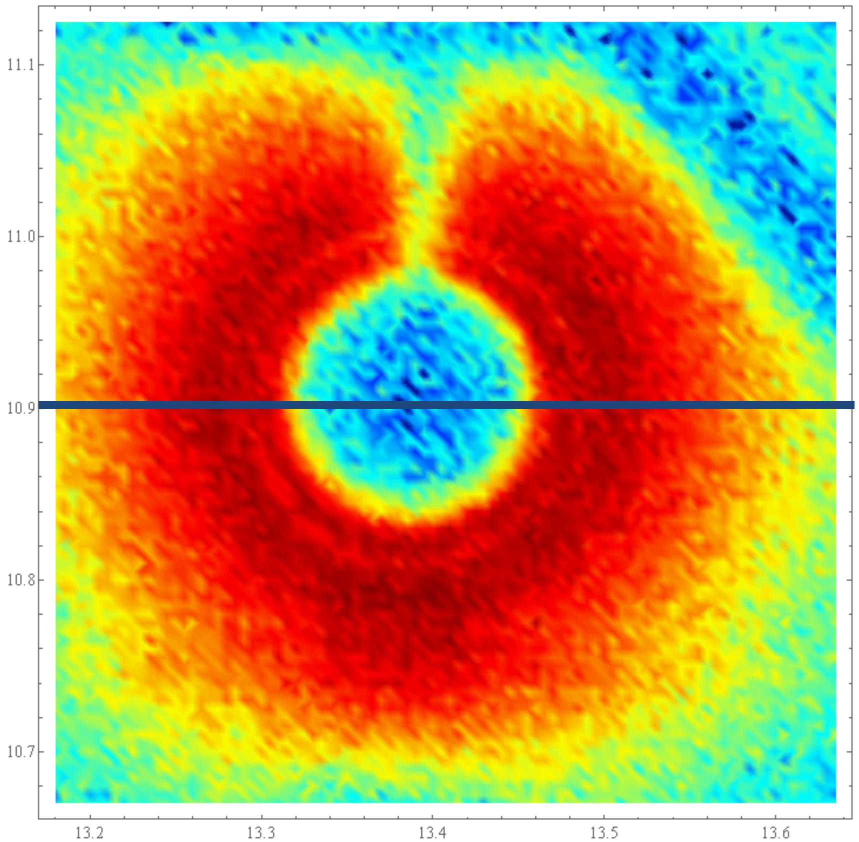
Carriers arrive at different times

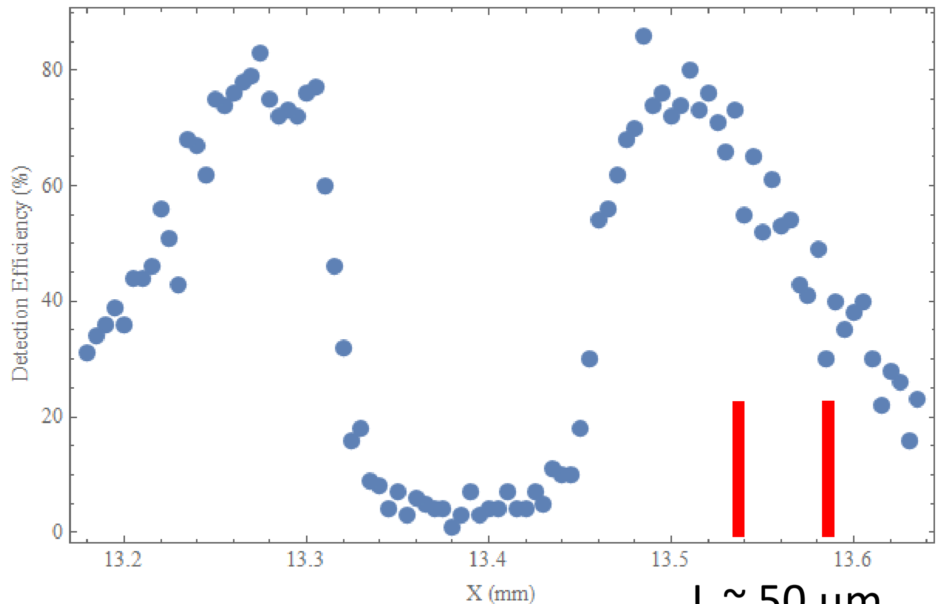


τ ~ Recombination time

Detection Efficiency in the XY plane: characteristic length for diffusion

<N>=320 Photons/pulse, 405 nm, 77 K, Delay = 0 ns, 1 μs pulse





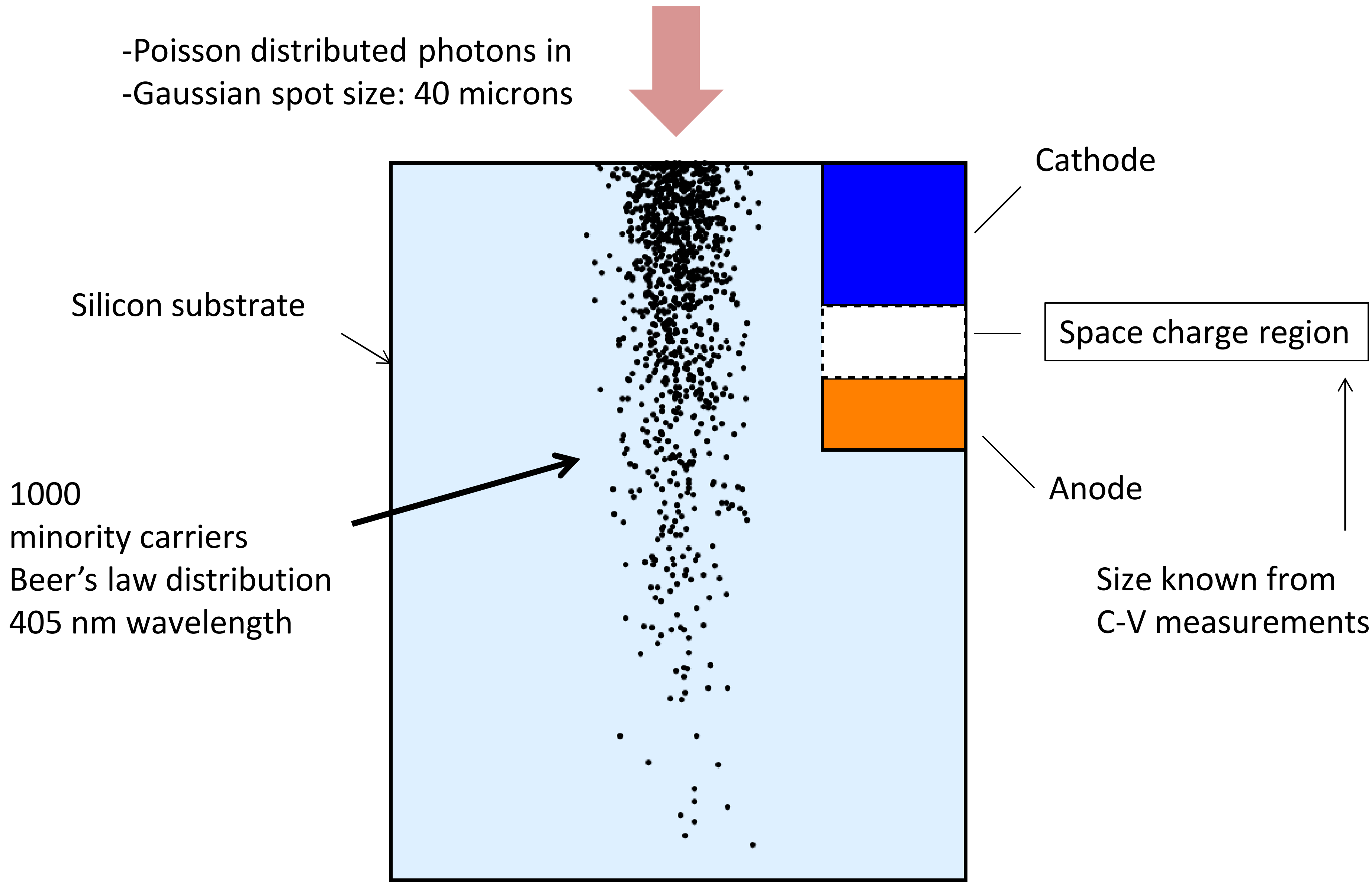
L ~ 50 μm

Decay of Detection Efficiency: minority carrier diffusion

$$D \sim 37\ \mathrm{cm}^2/\mathrm{s}$$
$$\tau \sim 1\ \mu\mathrm{s}$$

$$\Rightarrow \quad L \sim \sqrt{D\tau} \sim 60\ \mu\mathrm{m}$$

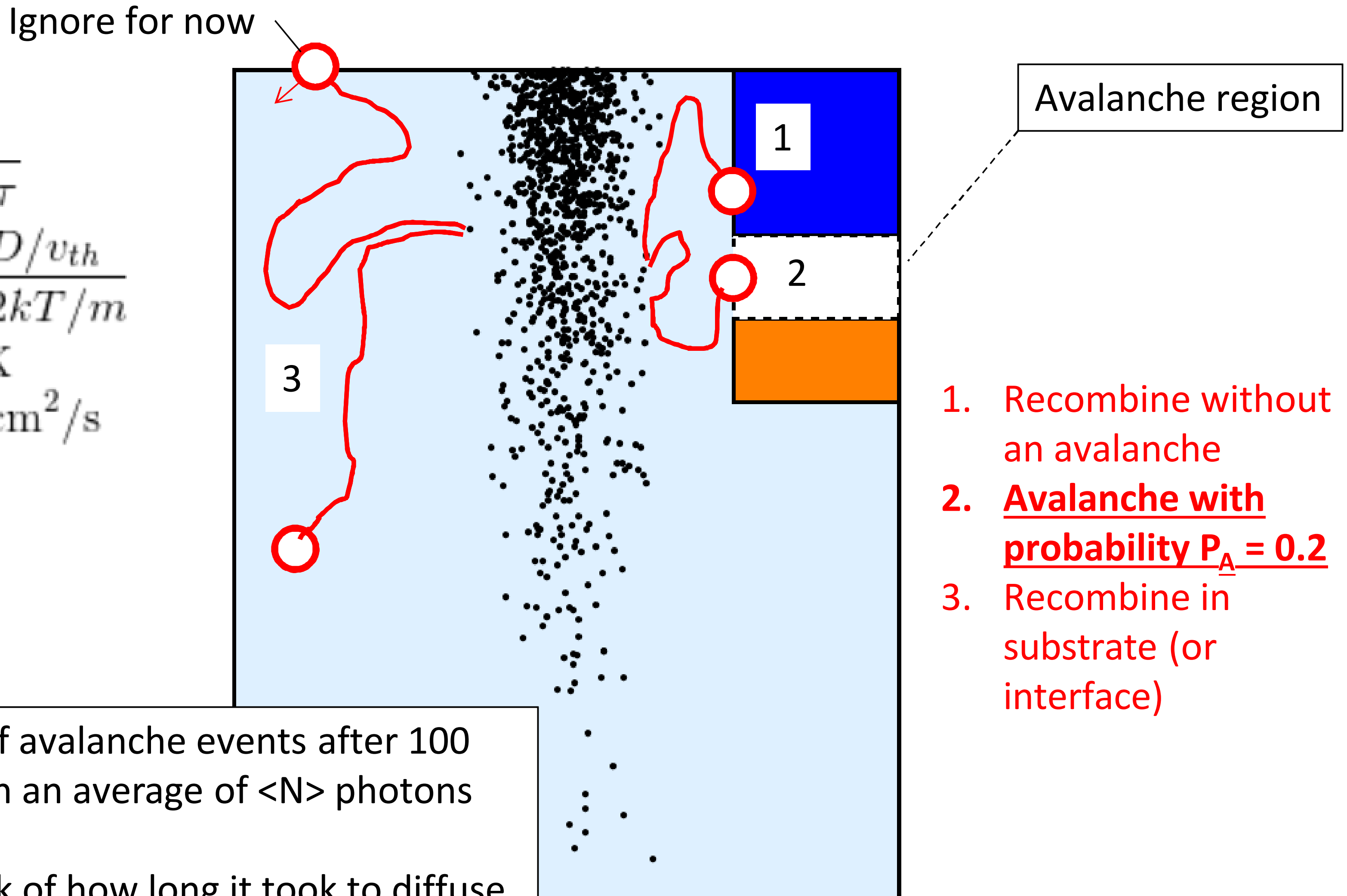
2D Simulations of the SIGMA detector, set up carrier distribution



Simulations of the SIGMA Detection Efficiency

Random walk of each carrier up to 3 diffusion lengths ($v_{th} >> v_D = \mu E$)

$$L = \sqrt{D\tau}$$
$$\text{mfp} \sim 2D/v_{th}$$
$$v_{th} = \sqrt{2kT/m}$$
$$T = 77 \text{ K}$$
$$D \sim 73 \text{ cm}^2/\text{s}$$
$$\tau \sim 1\ \mu\text{s}$$



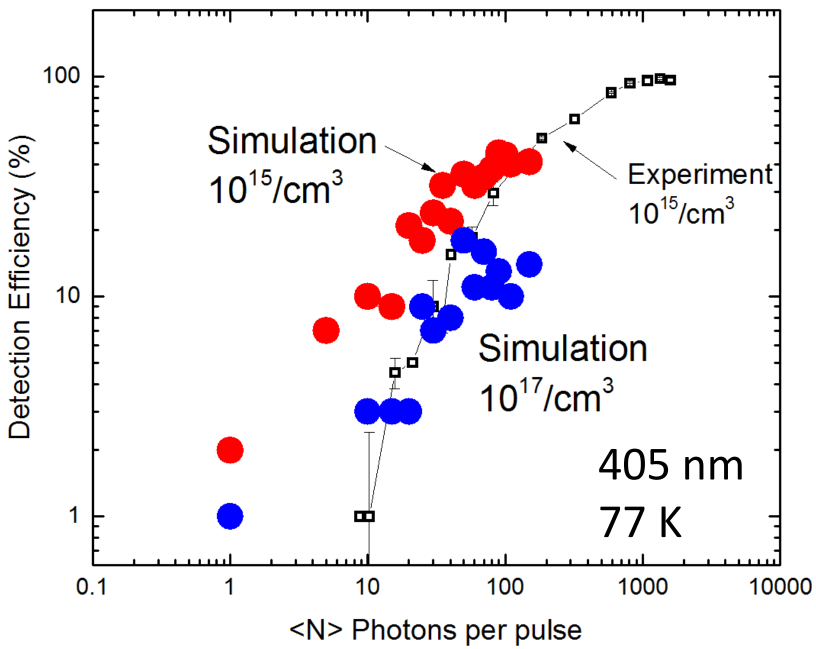
1. Recombine without an avalanche
2. **Avalanche with probability $P_A = 0.2$**
3. Recombine in substrate (or interface)

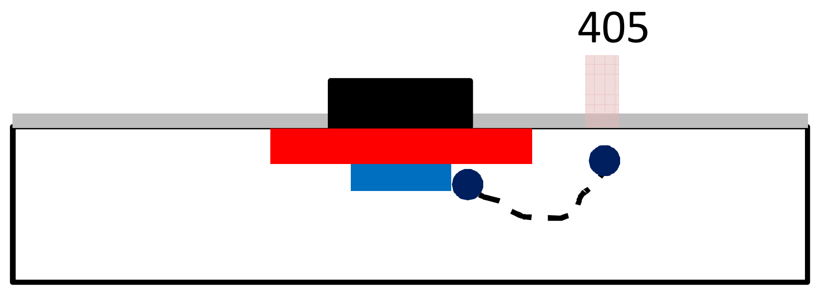
-Count # of avalanche events after 100 pulses with an average of <N> photons

-Keep track of how long it took to diffuse into avalanche region

Detection Efficiency versus <N> Photons per Pulse

Carriers arriving up to 1 μs

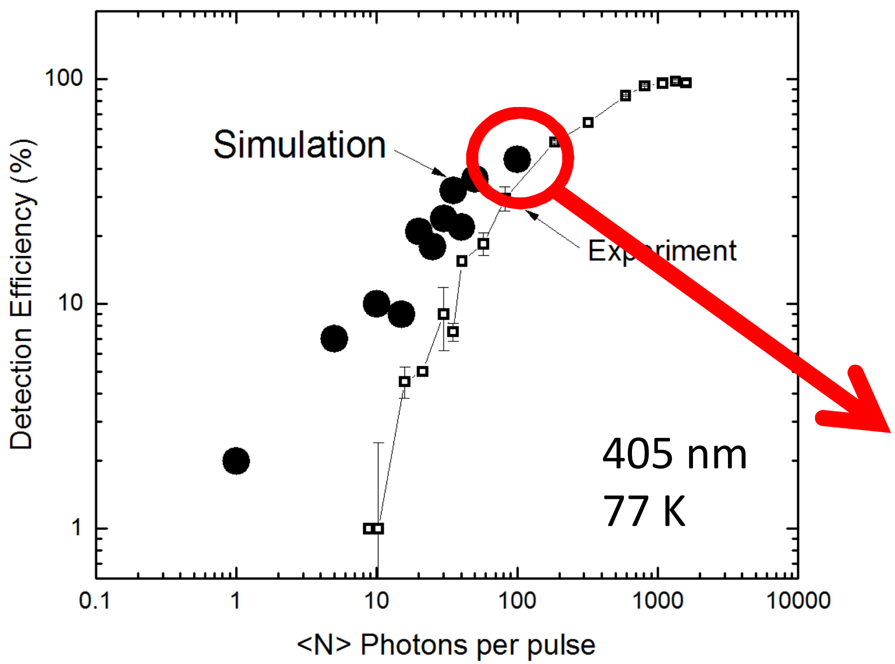


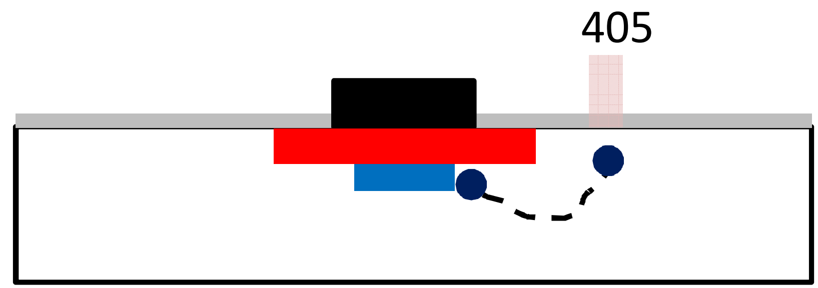


Increase background doping:
Decrease diffusion length

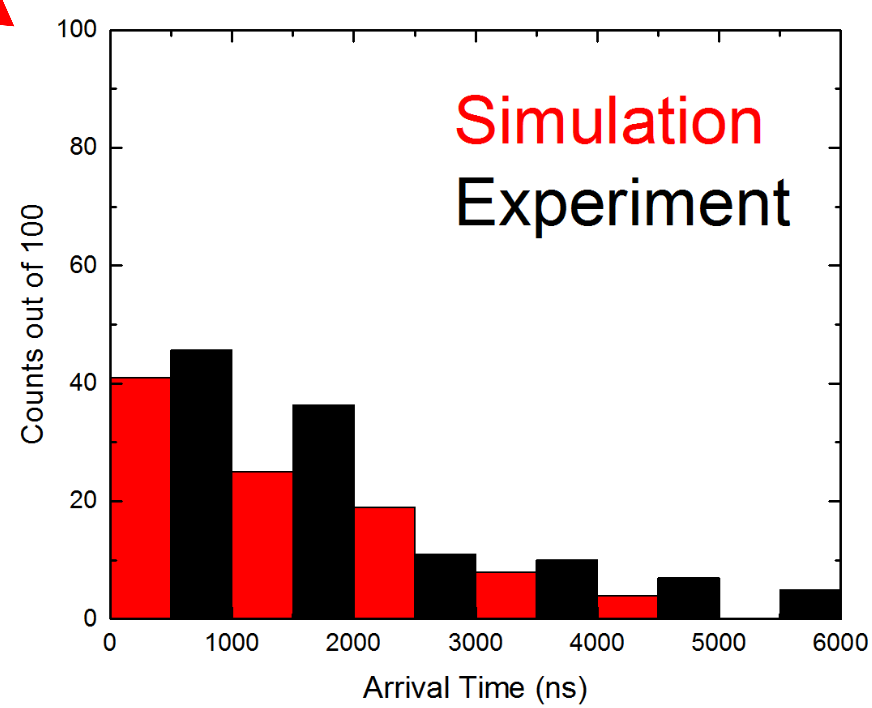
Diffusion/recombination of minority carriers into the detector

Carriers arriving up to 1 μs

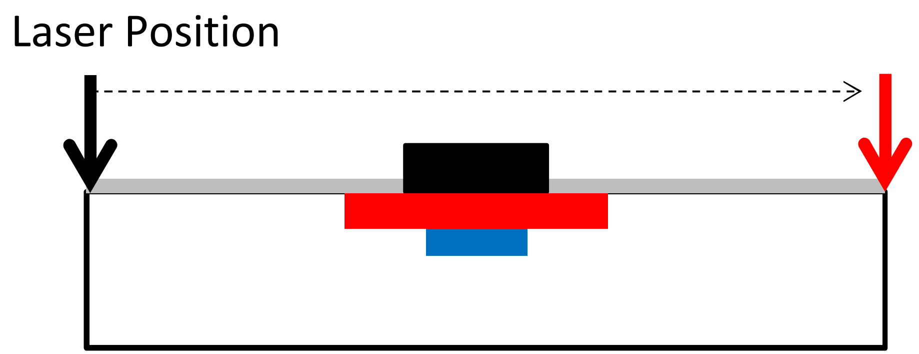




Distribution of arrival times

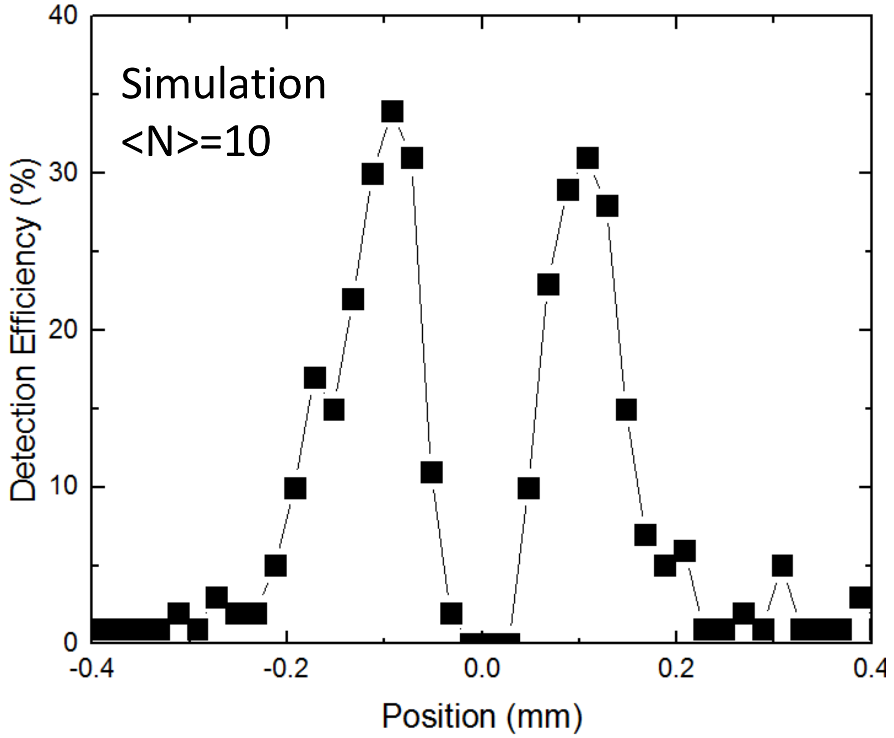


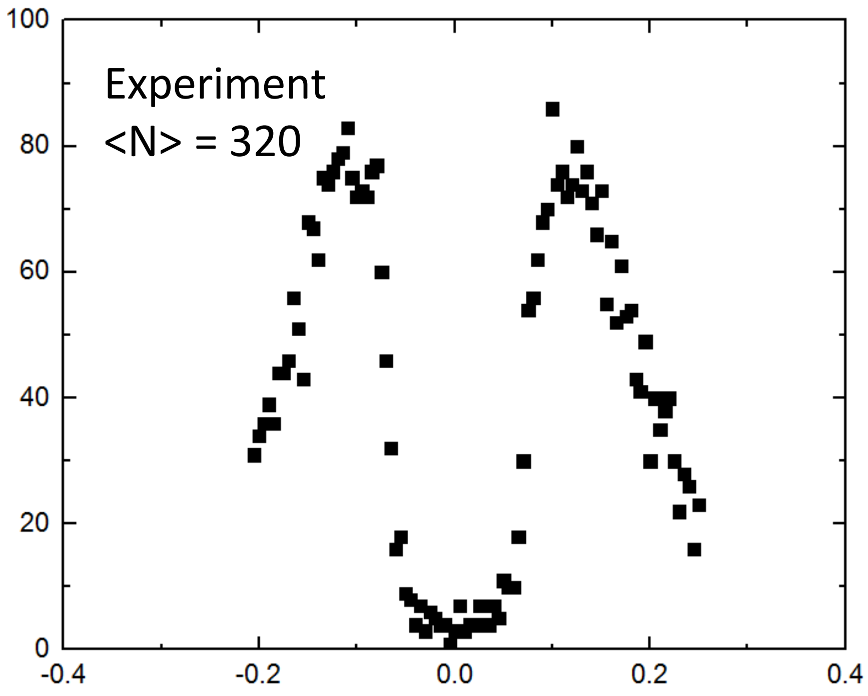
Length scale for position dependent Detection Efficiency



Fixed diffusivity and minority carrier recombination time

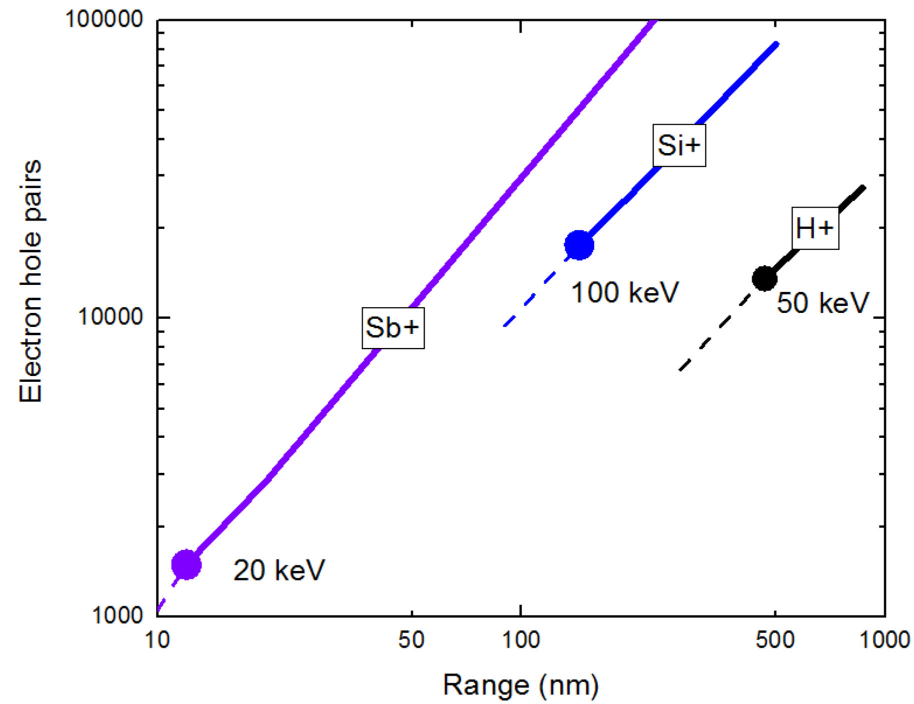
DE: count events for carriers arriving within 1 μs





Damage-free detector performance governed by diffusion and recombination

1. Developed photon-based characterization methods without damage
2. Diffusion-recombination based Simulations of detector performance agree with measurements



What have we learned?

1. Ensure high quality bulk/interface for device
    a. Deep level traps
    b. SiO_2/Si interface states
2. Move the detector closer < diffusion length
3. Use an electric field to ensure

transit time <recombination time