Developing a simulation for estimation of SiPM optical cross talk level

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On behalf of JADDE collaboration

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SiPMs

SiPMs are **photodetectors**.
They are arrays of APDs (semiconductor detectors), which are operating in Geiger mode outputting the sum of cell signal.

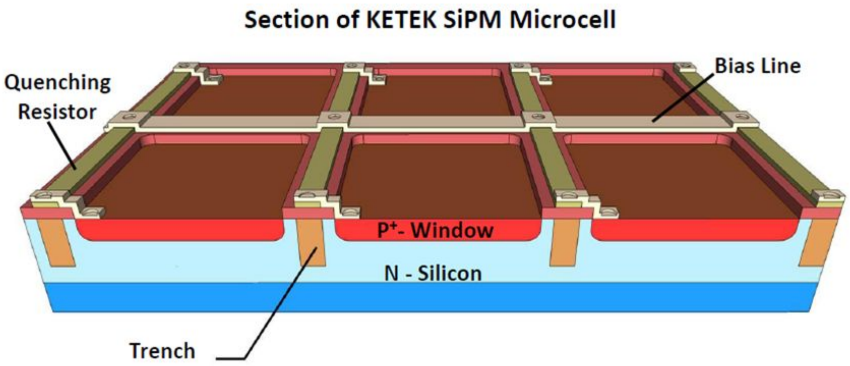


Figure: SiPM schematics

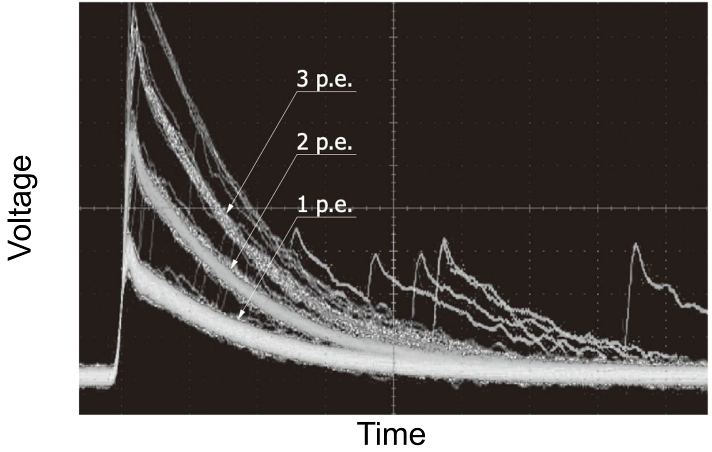
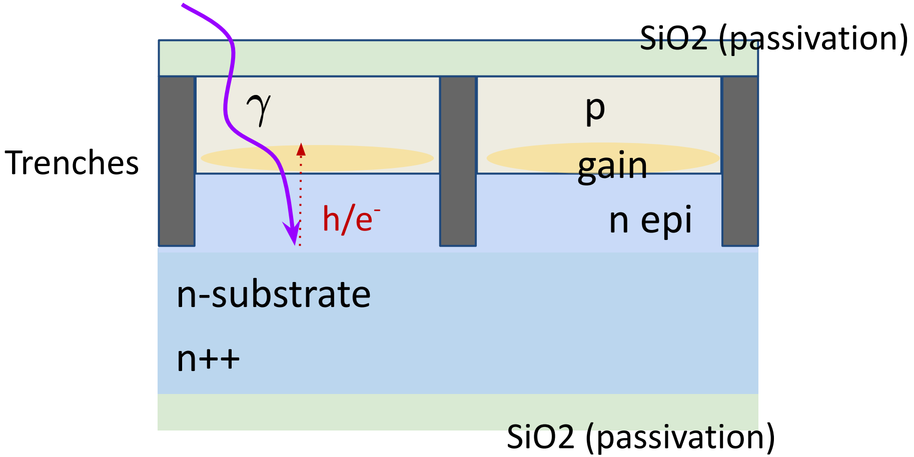


Figure: SiPM signal

Image taken from: https://www.appec.org/news/the-silicon-photomultiplier-sipm-concept-and-design-development

SiPMs

One photon - one photo electron (p.e.) height of the output signal.



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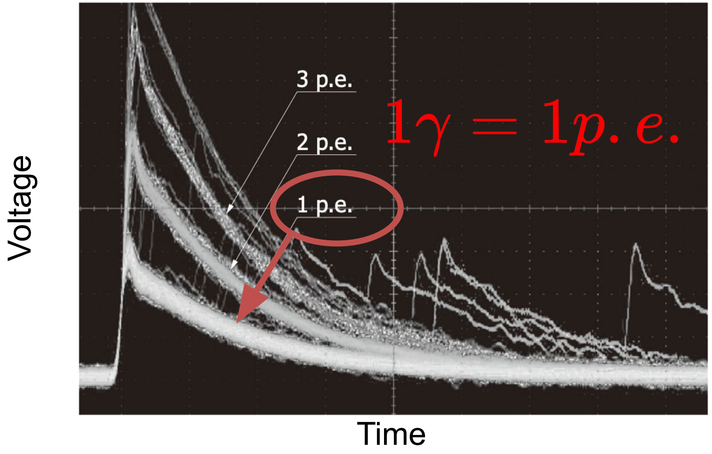
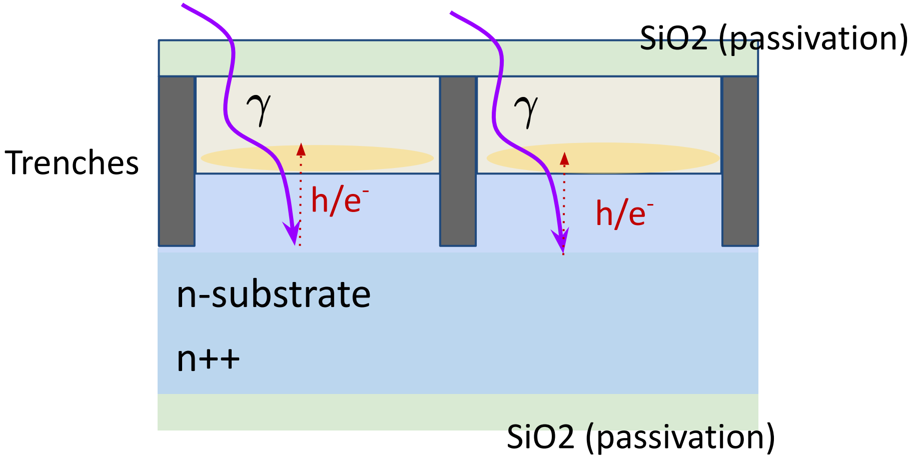


Figure: SiPM signal

Image taken from: https://www.appec.org/news/the-silicon-photomultiplier-sipm-concept-and-design-development

SiPMs

Two photons - two photo electron (p.e.) height of the output signal.



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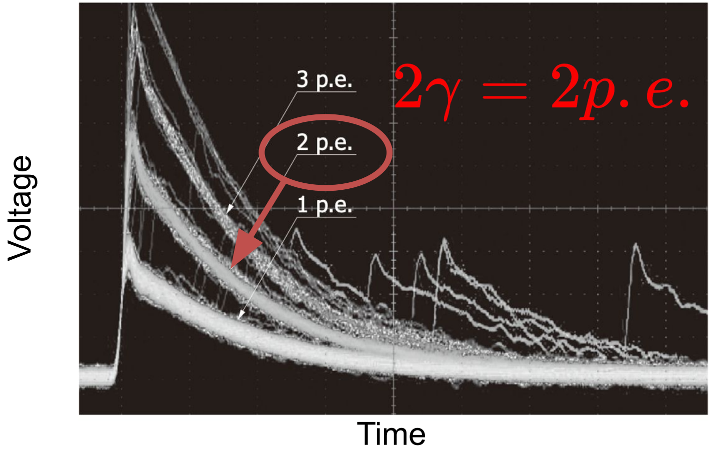

Figure: SiPM signal

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Optical crosstalk

- APD cells located close to each other (~µm)
- Photons produced in an avalanche can trigger neighbour cell.
- Create artificial increase in signal

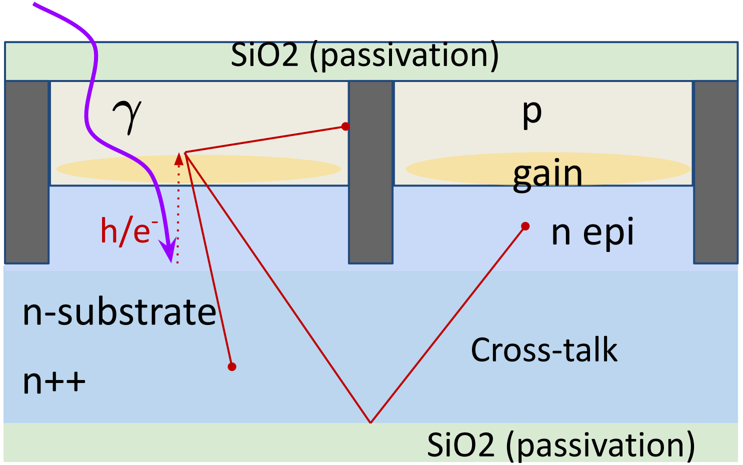

Figure: SiPM optical cross talk illustration

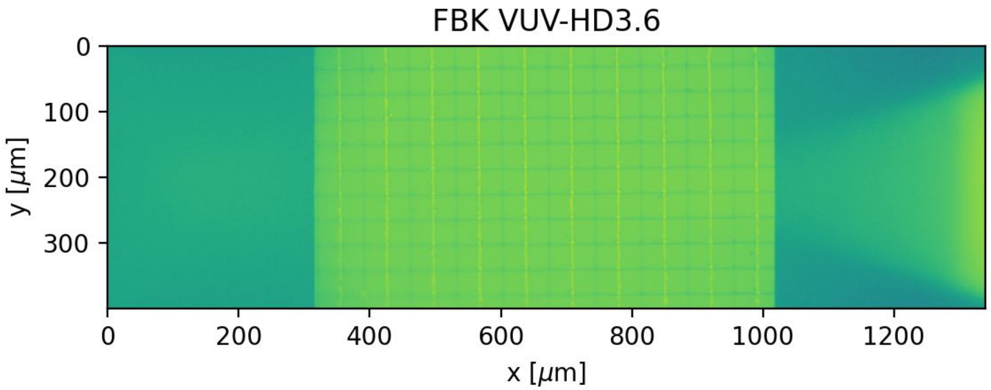

Figure: SiPM photo

Image credits: Juliette Martin CAP congress 2022 talk

Optical crosstalk

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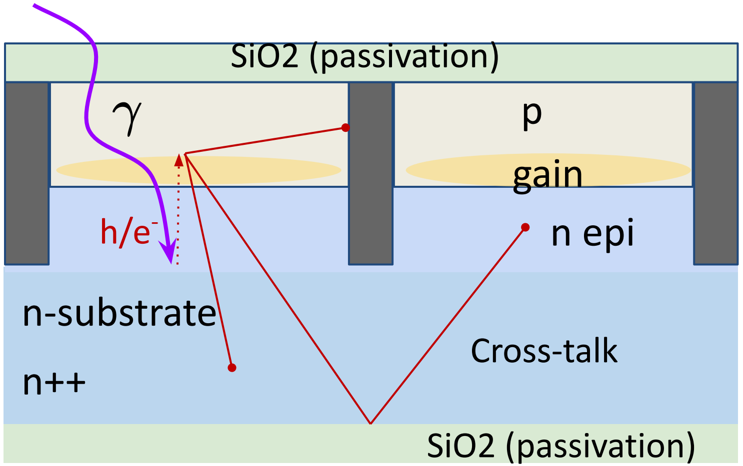

Figure: SiPM optical cross talk illustration

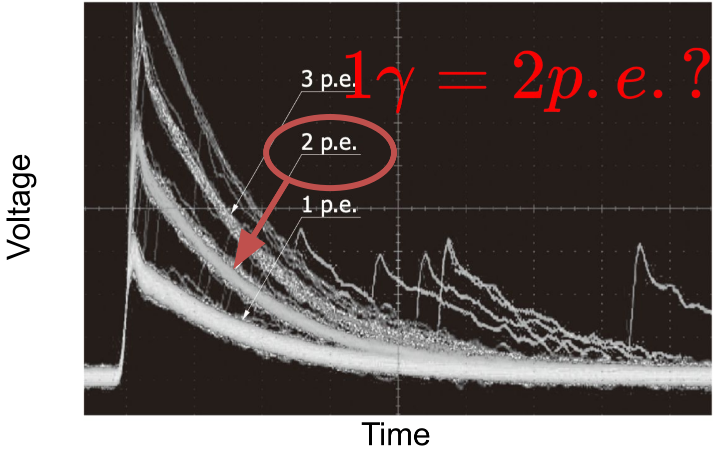

Figure: SiPM signal

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Image taken from: https://vertilon.com/products_sensor2/

Optical crosstalk

- Undesirable and unavoidable process
- Can be measured but requires a detector prototype, which is expensive to produce
- We would like to predict and minimize it in advance

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Optical crosstalk

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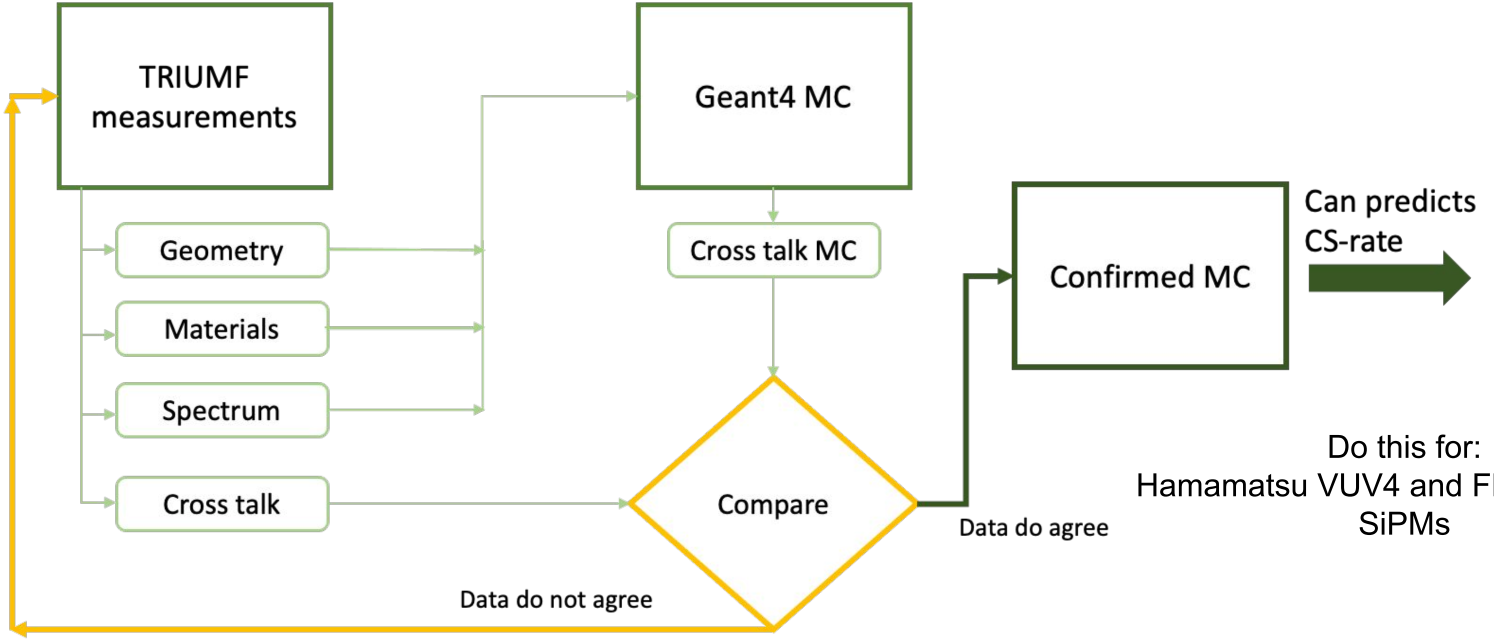
Create a simulation

SiPM crosstalk simulation



Do this for:
Hamamatsu VUV4 and FBK VUV-HD3 SiPMs

Diagram: SiPM crosstalk simulation steps

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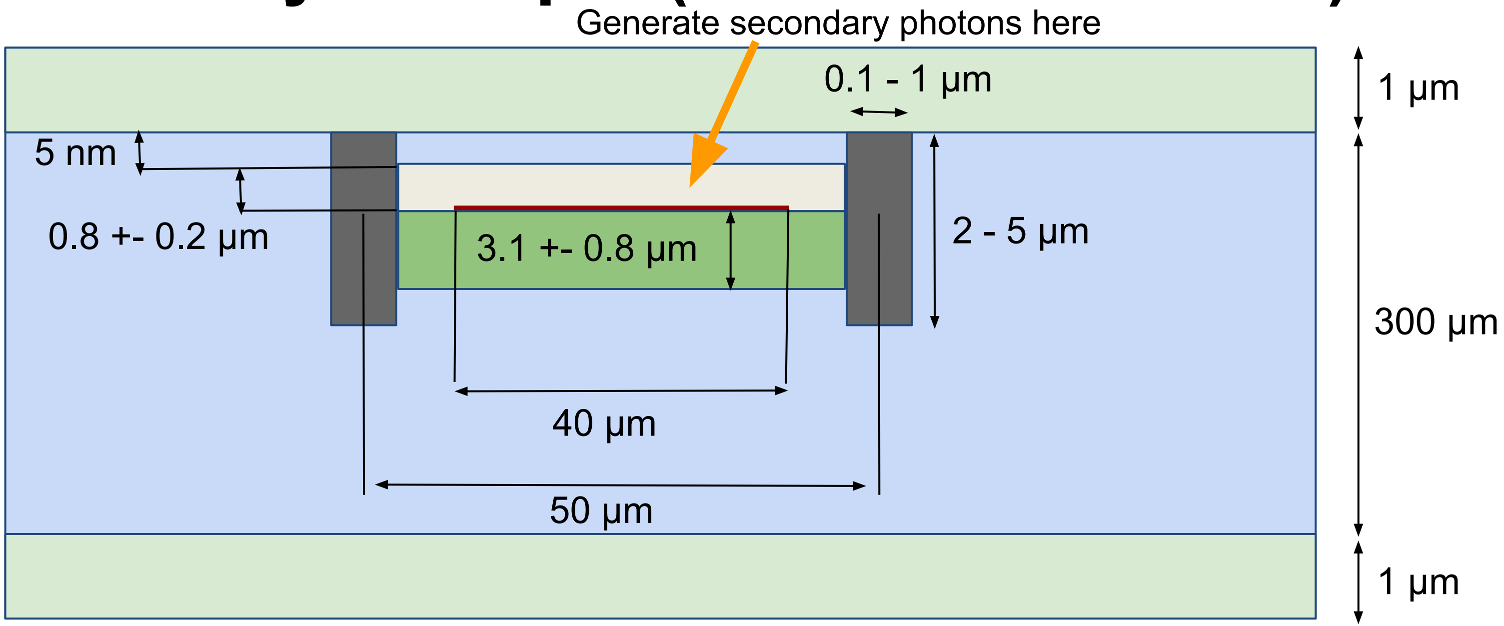
Geometry example (Hamamatsu VUV4)



- Initial photons position
- SiO2 layer
- Silicon
- Trenches
- Electron generating region
- Holes generating region

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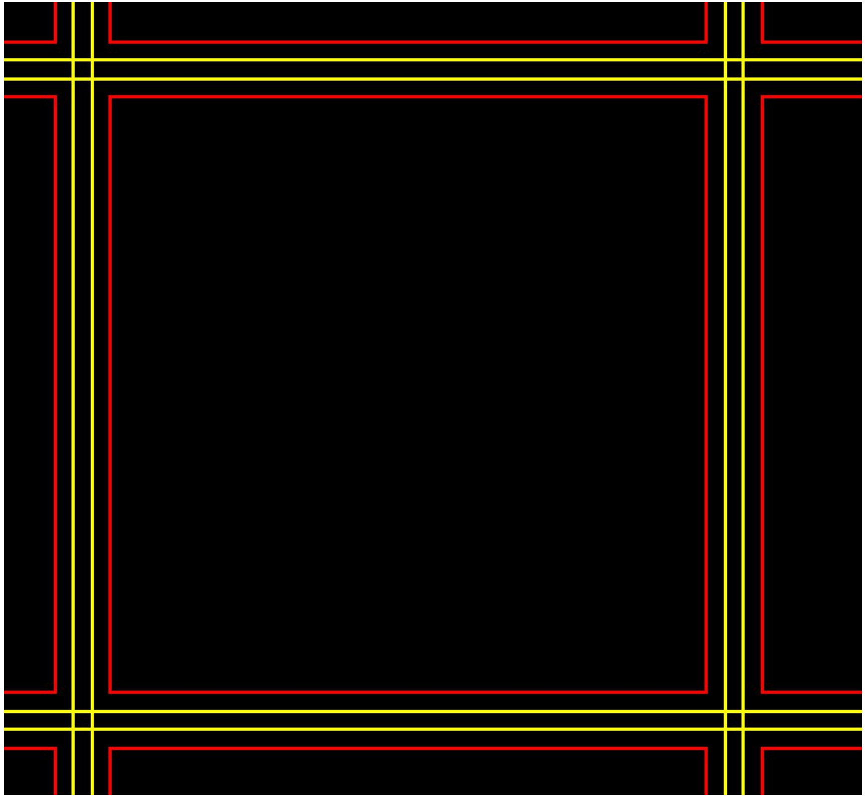
Geant4 geometry

Here you can see the top view of the cells. The trenches are yellow lines, the avalanche area is in red.



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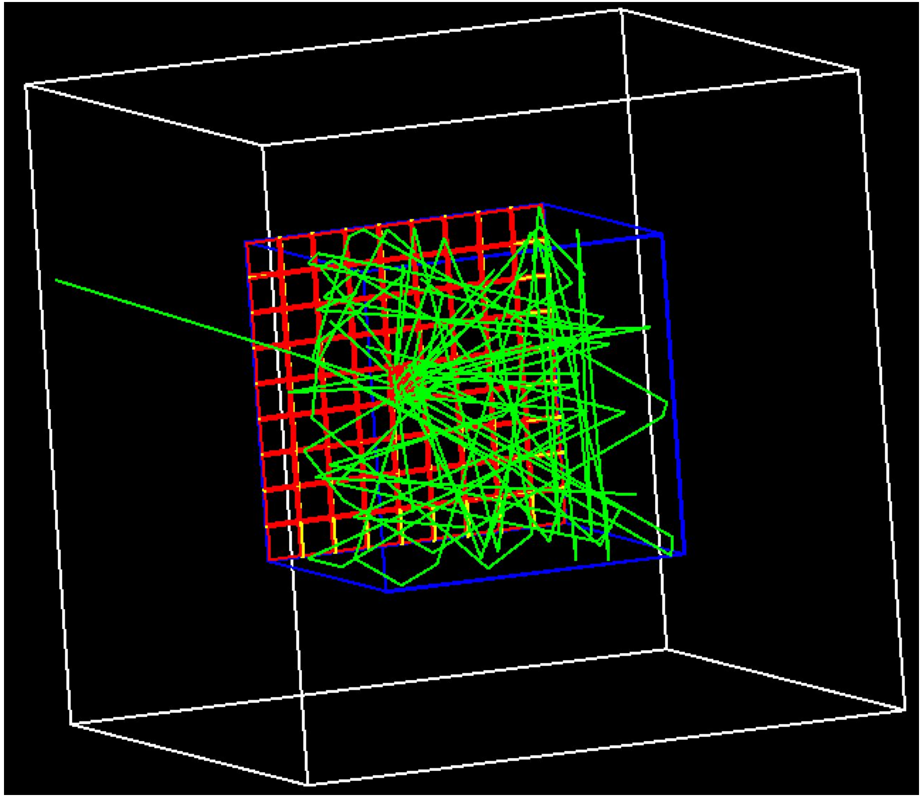
Geant4 geometry

- Photons with wavelength from 440 nm to 1000 nm are produced in the avalanche region.
- Final positions and properties of the photons are stored



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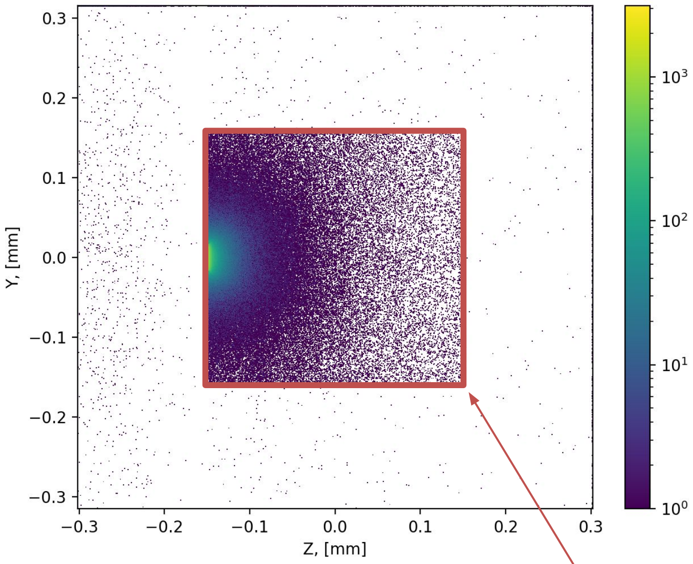
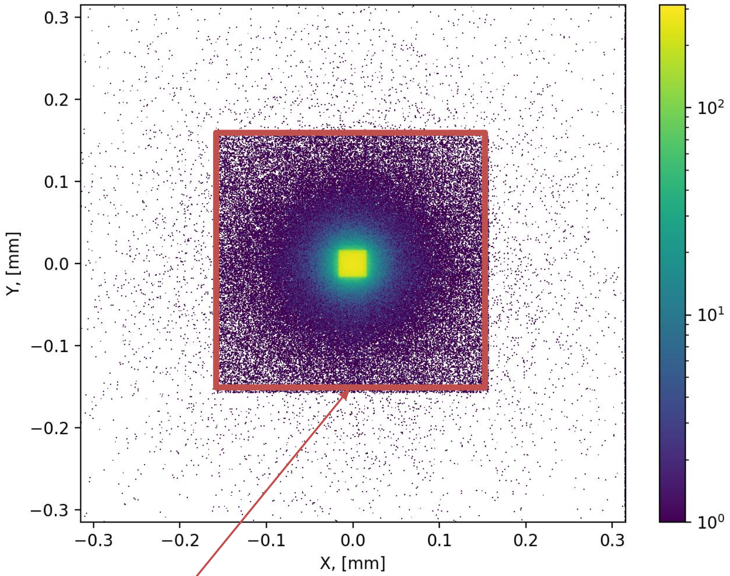
Analysis

Final positions of all secondary photons

FBK YZ plane

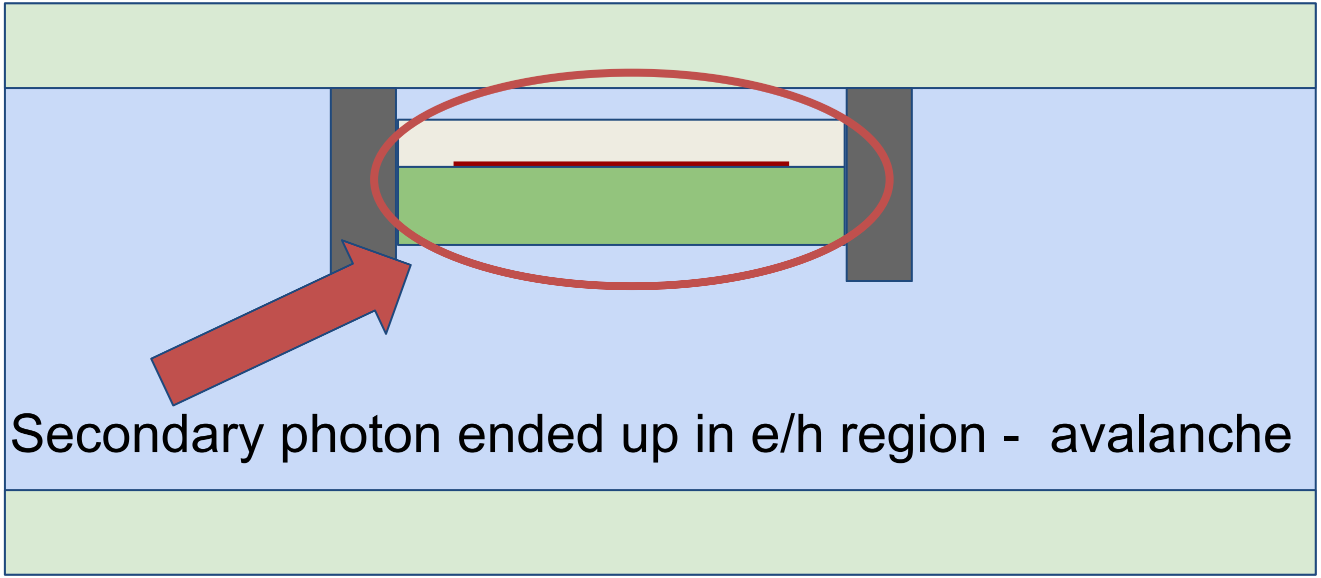


FBK XY plane



SiPM volume boundaries

What we count as a secondary avalanche



- Initial photons position
- SiO2 layer
- Silicon
- Trenches
- Electron generating region
- Holes generating region

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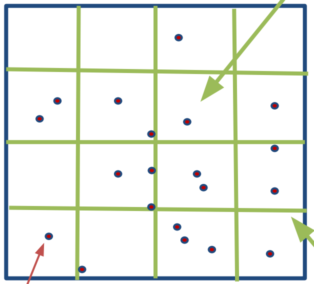
Analysis

A SiPM

A cell



Accepted photon coordinate

Trenches areas are excluded from bins

P_i - fraction of photons that ended up in the cell avalanche region

1%	2%	2%	0%
3%	13%	10%	4%
6%	14%	9%	3%
2%	8%	7%	2%

$$P_{CT} = \sum_i P_i \overbrace{G(V)\gamma}^{\text{Number of photons}} P_{av}$$

$G(V)$ - gain

γ - photon yield per a charge carrier

P_{av} - probability of an avalanche

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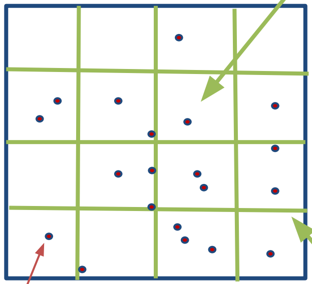
Analysis

A SiPM

A cell



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Measured in TRIUMF

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Crosstalk MC vs Measured

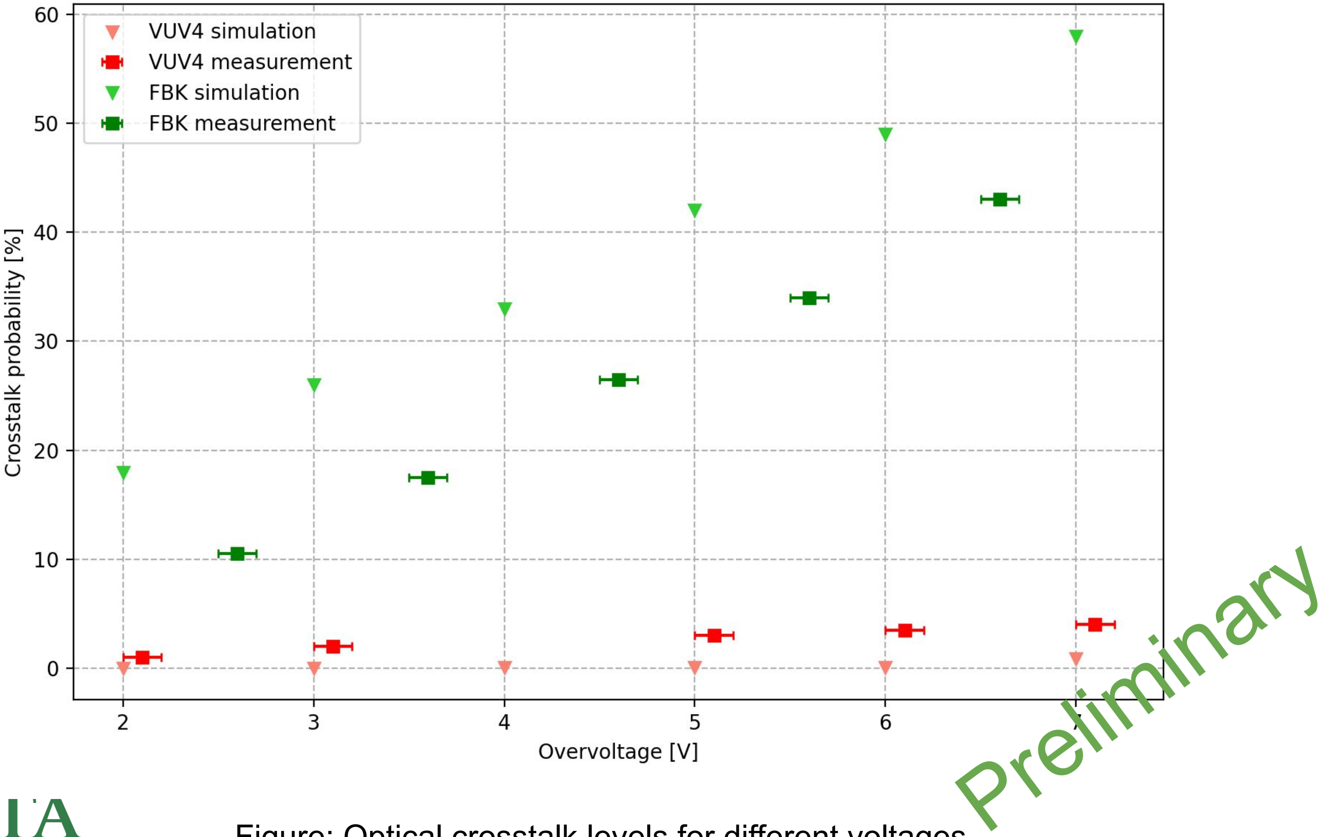
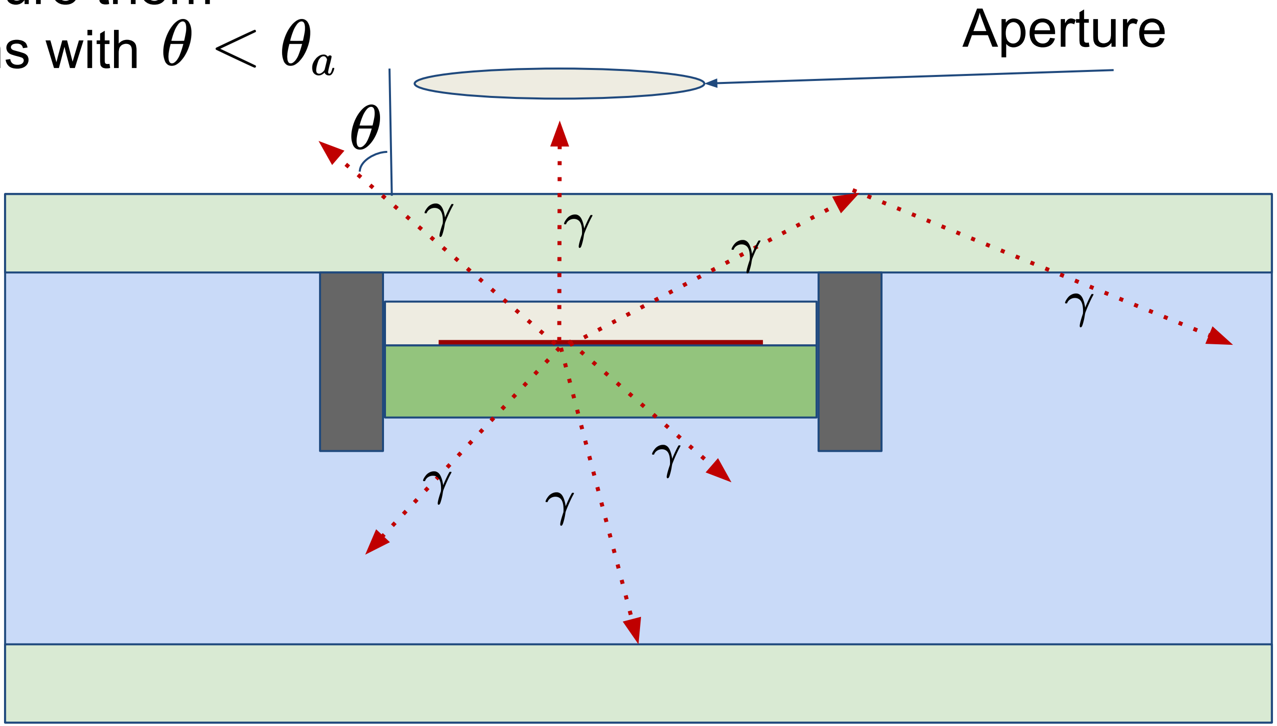


Figure: Optical crosstalk levels for different voltages

Emitted light

- Some of the secondary photons escape the SiPM
- We can measure them
- Select photons with $\theta < \theta_a$



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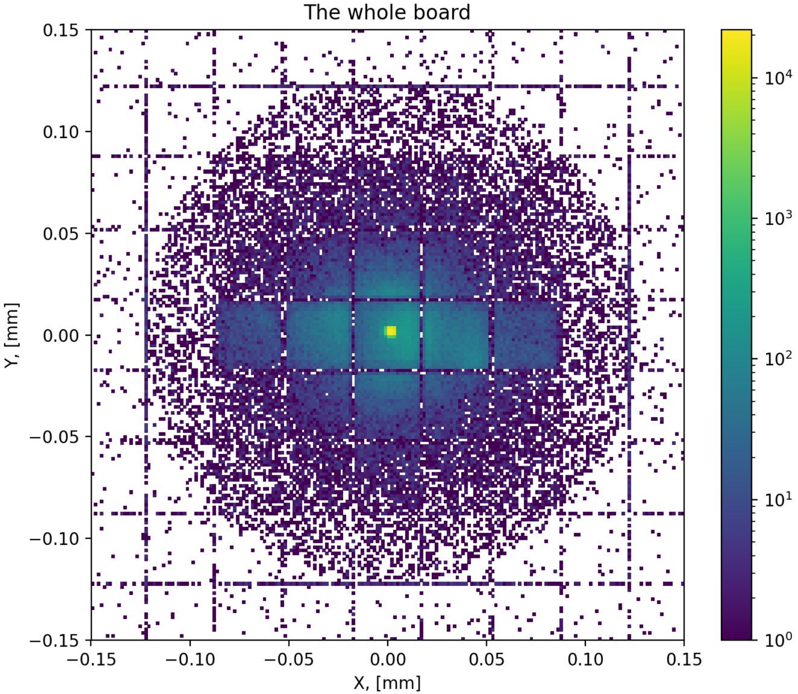
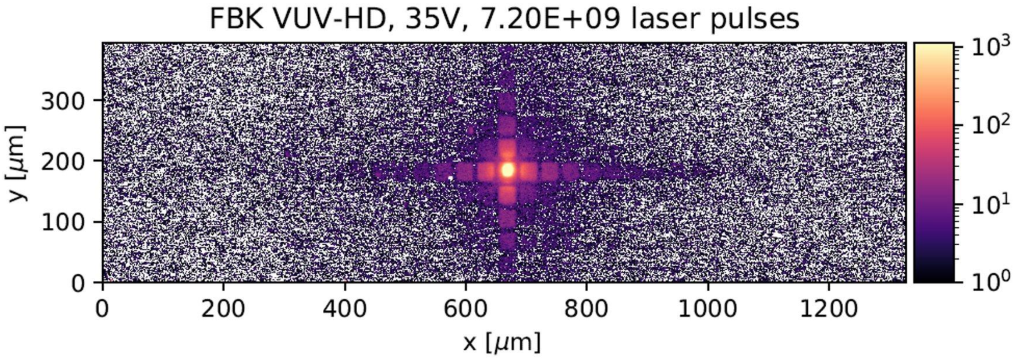
Emitted light FBK (poly-si trenches)

Simulated



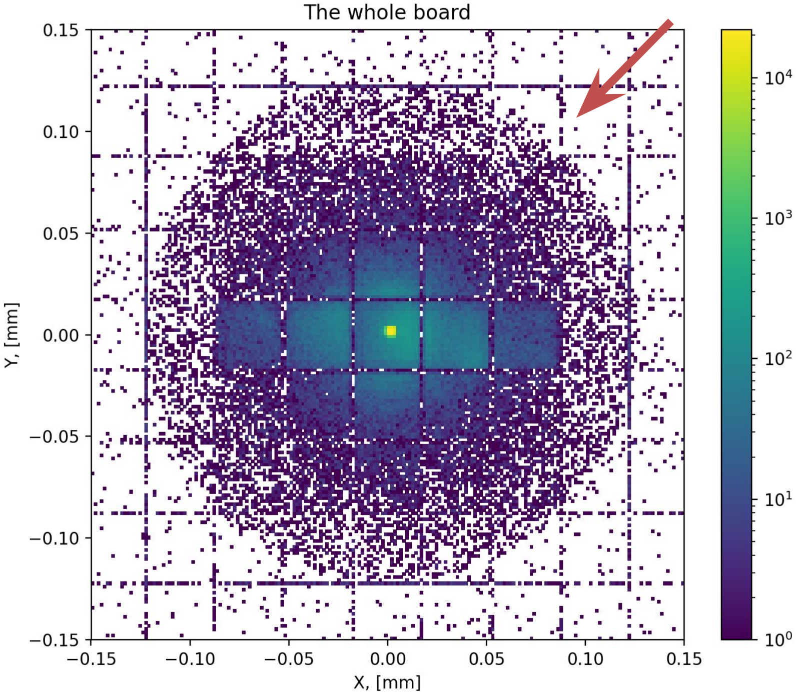
Data



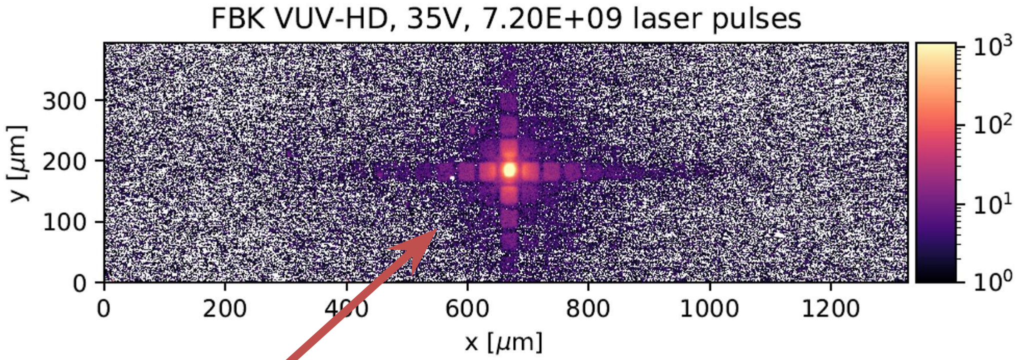
Data picture credits: TRIUMF and Juliette Martin CAP 2022 presentation

Emitted light FBK (poly-si trenches)

Simulated **5 x 5 cells SiPM**



Data



Thousands of cells

Data picture credits: TRIUMF and Juliette Martin CAP 2022 presentation

Conclusion and ongoing work

- We developed a MC simulation of optical cross talk
- We have preliminary results that give good qualitative agreement with the data
- Make the code work in parallel and get more quantitative data
- Fit data and MC
- Eventually will be able to predict cross talk levels of new possible designs of SiPMs including back side illuminated SiPMs

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Thank you for your attention!

Back Up

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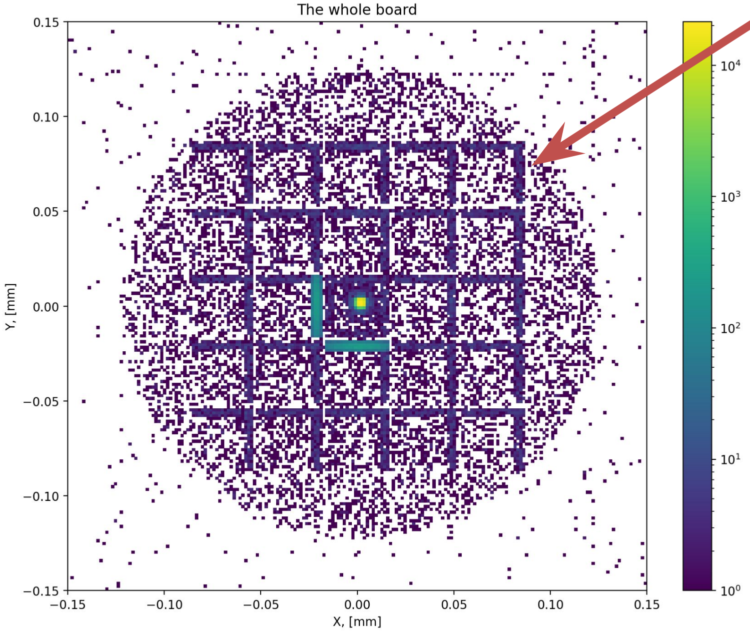
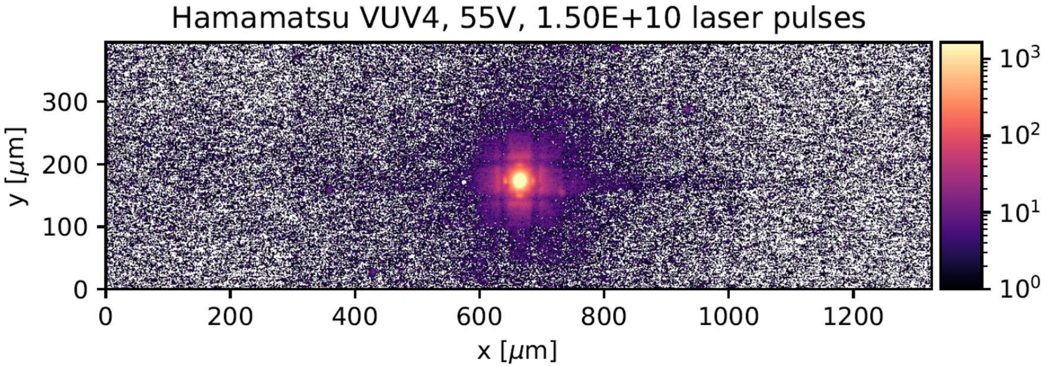
Emitted light Hamamatsu (Tungsten trenches)

Simulated

Weird artifacts when we change trenches material to tungsten





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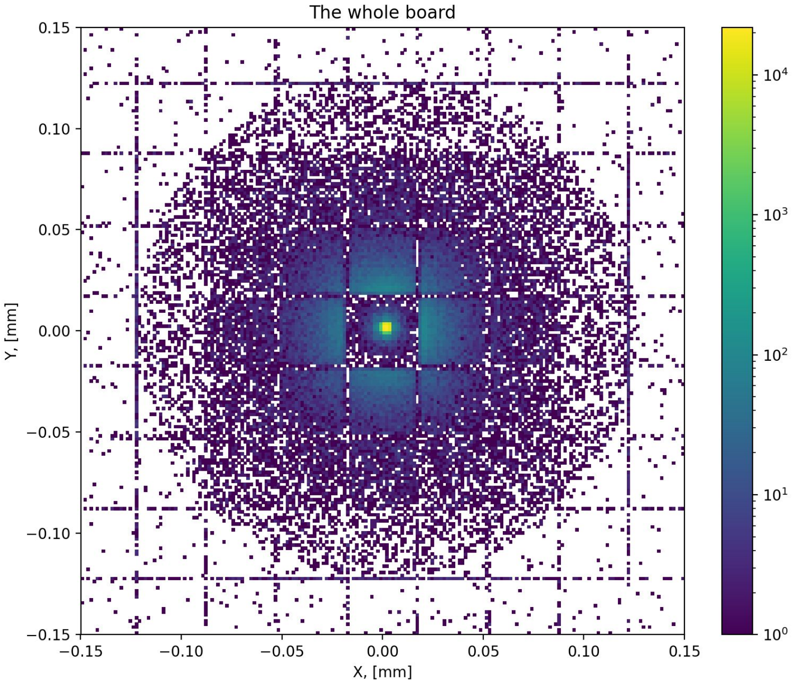
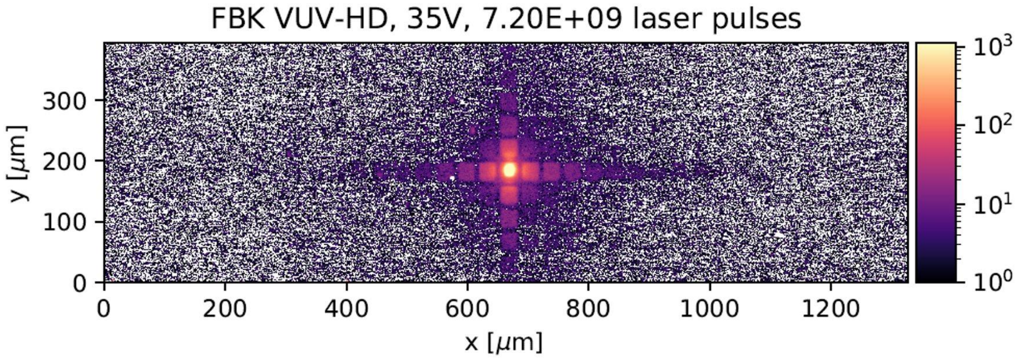
Emitted light FBK (poly-si trenches)

Simulated



Data



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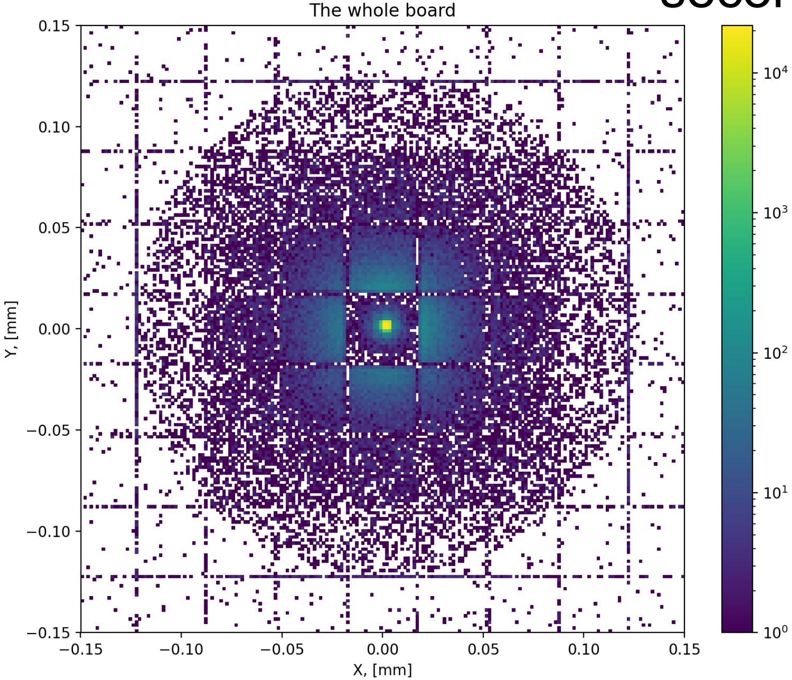
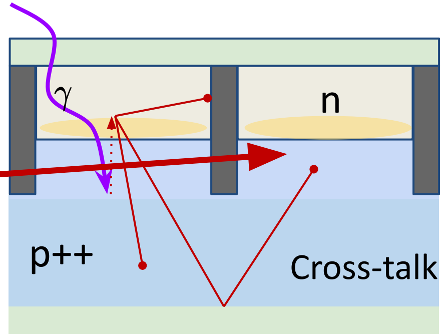
Emitted light FBK (poly-si trenches)

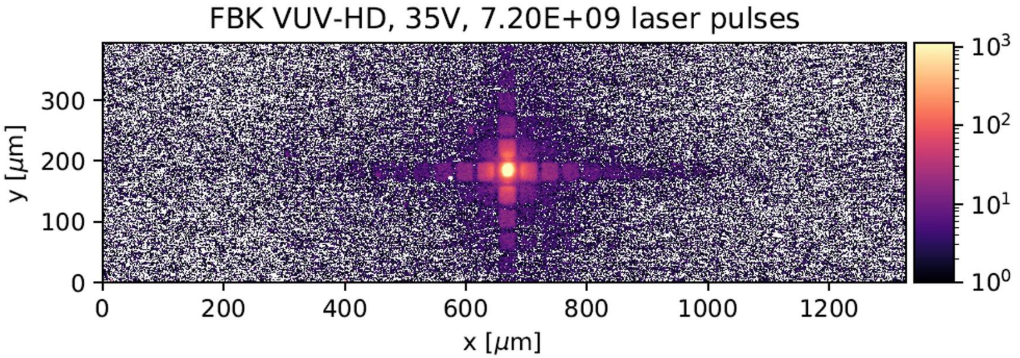
Can trigger another secondary CT

Simulated



Data





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Emitted light FBK (poly-si trenches)

Can trigger another secondary CT

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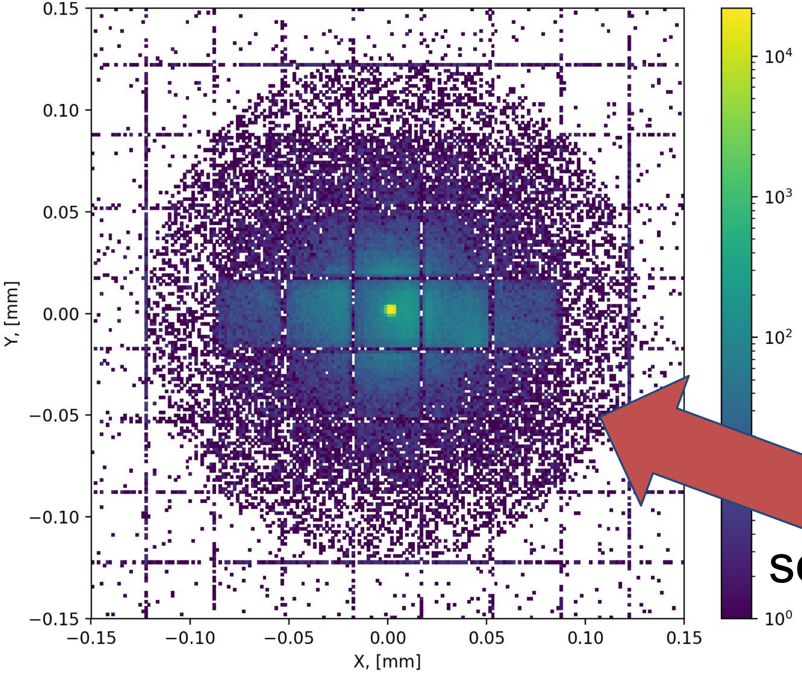
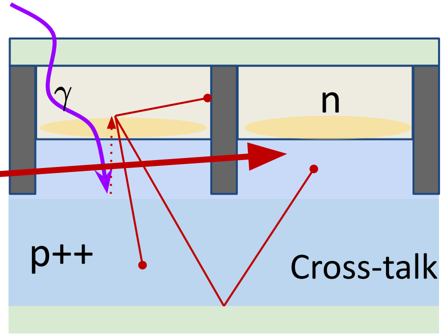
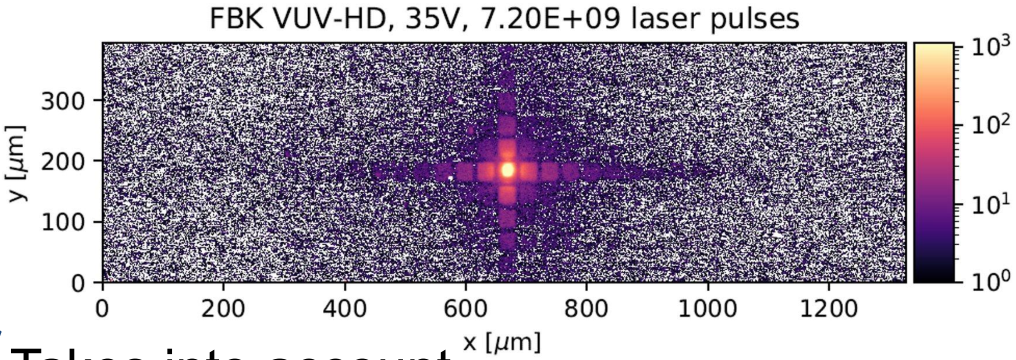


Data

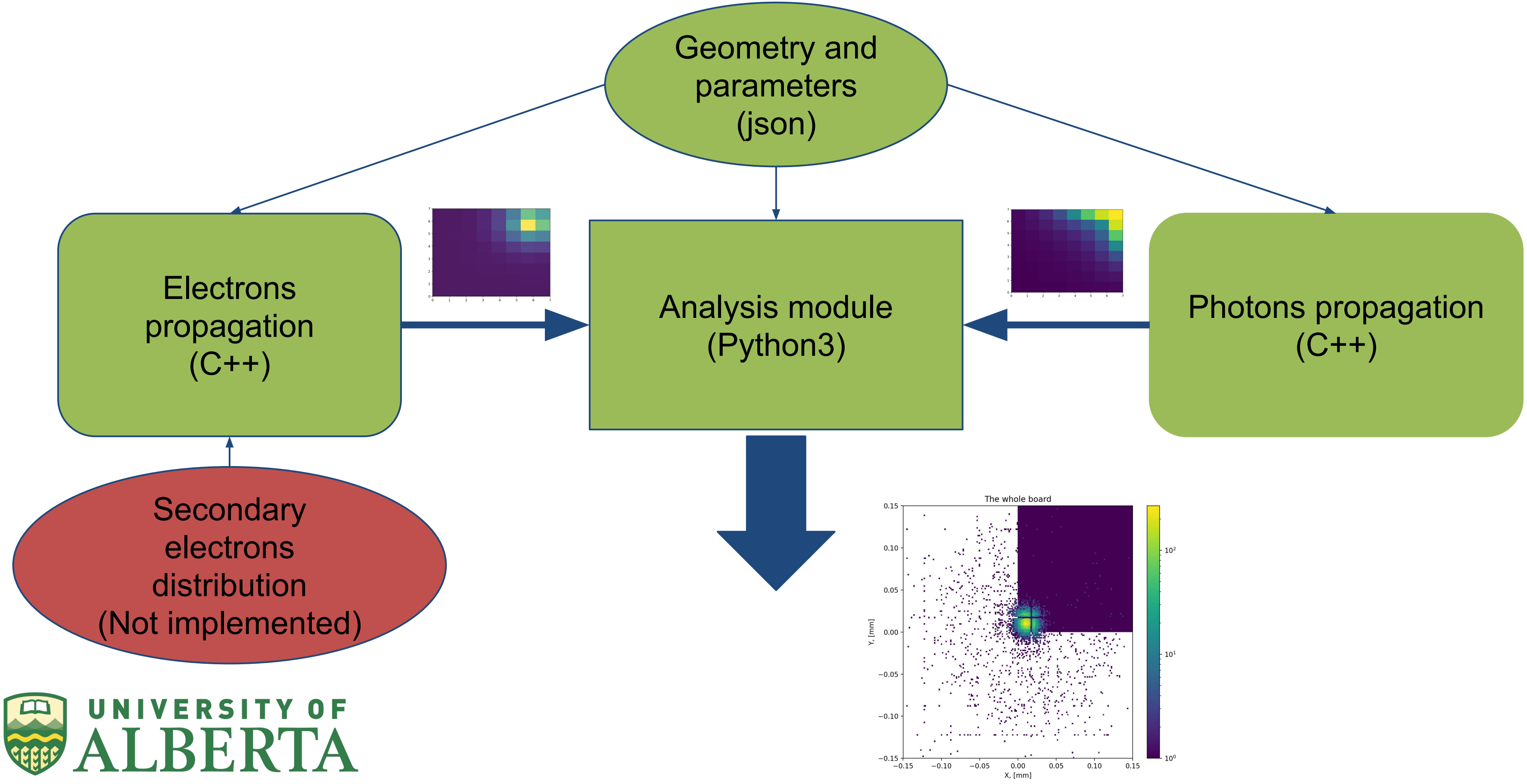




Takes into account secondary CT; ignores 3 order and higher

Data picture credits: TRIUMF and Juliette Martin CAP 2022 presentation

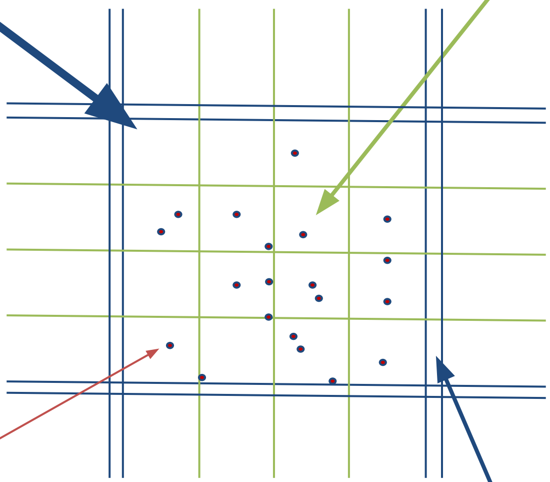
Current status of code



Photons map

A cell

A bin



Accepted avalanche coordinate

Trenches areas are excluded from bins

Fraction of photons that belongs to the bin

1%	2%	2%	0%
3%	13%	10%	4%
6%	14%	9%	3%
2%	8%	7%	2%

$$\Sigma \neq 100\%$$

Some photons hit trenches or do not trigger an avalanche

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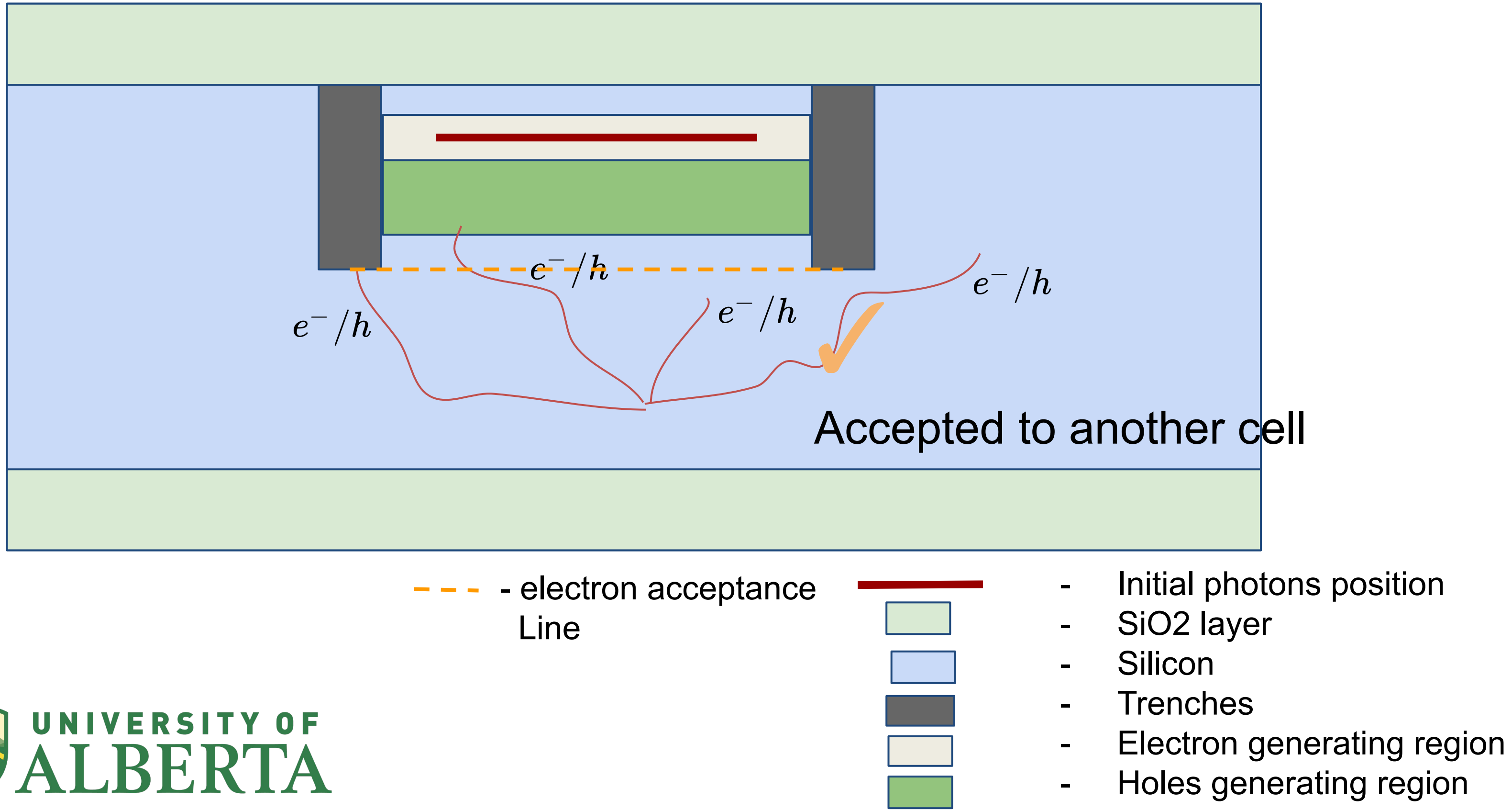
Electron propagation



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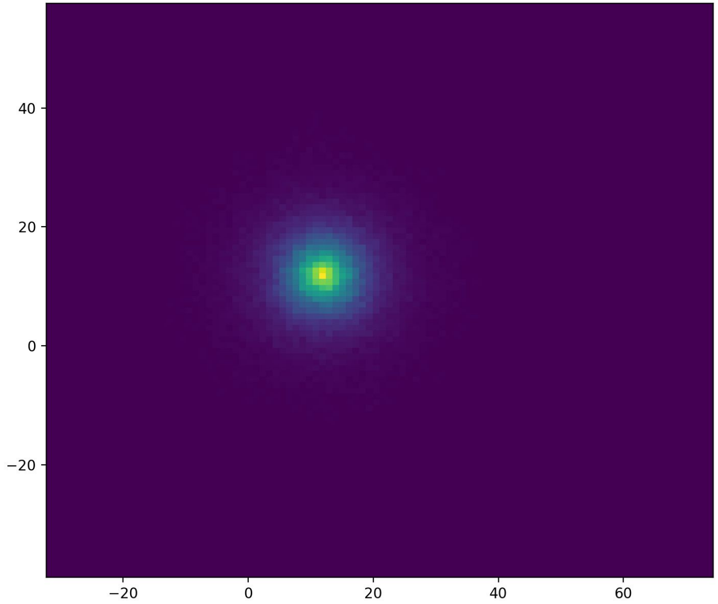
Example with HPK

100k electrons were injected at a random point in left top corner of central cell. The distance from trenches was set to 7µm.

Resulting distribution of the electrons that reached active region.



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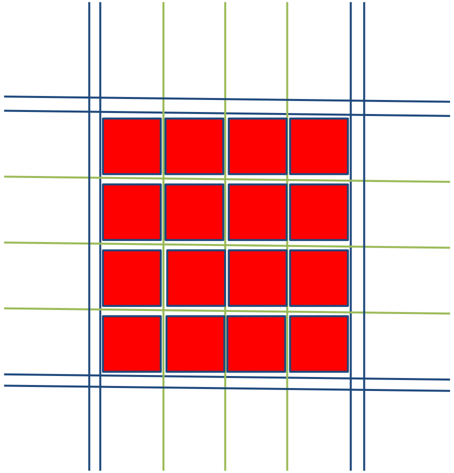
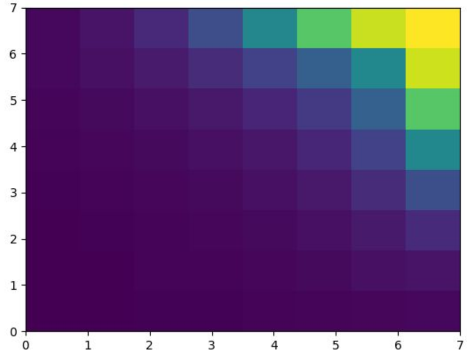
Analysis: building image

Weightening of injection map with the probabilities given by CT map

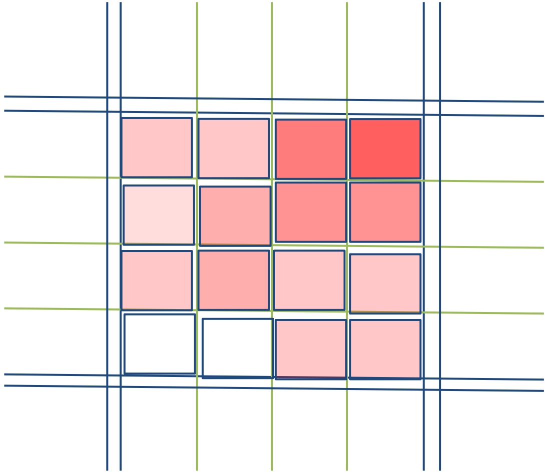
Binned photons injection map



Cross Talk map



Resulting combined CT data



Changes in geometry and simulation

HPK trenches are made of tungsten.
1 million photons in a wavelength range of 440-1000nm were created in the simulation for each geometry.

In new configurations the wavelength range was changed to 660-1200nm and absorption length was taken for doped silicon.

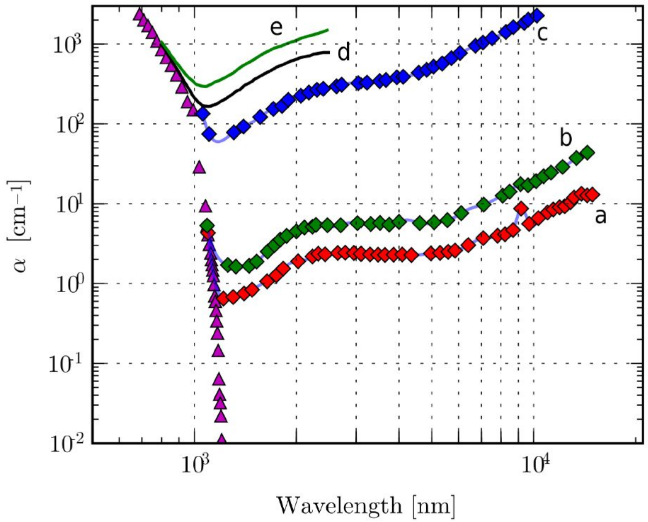
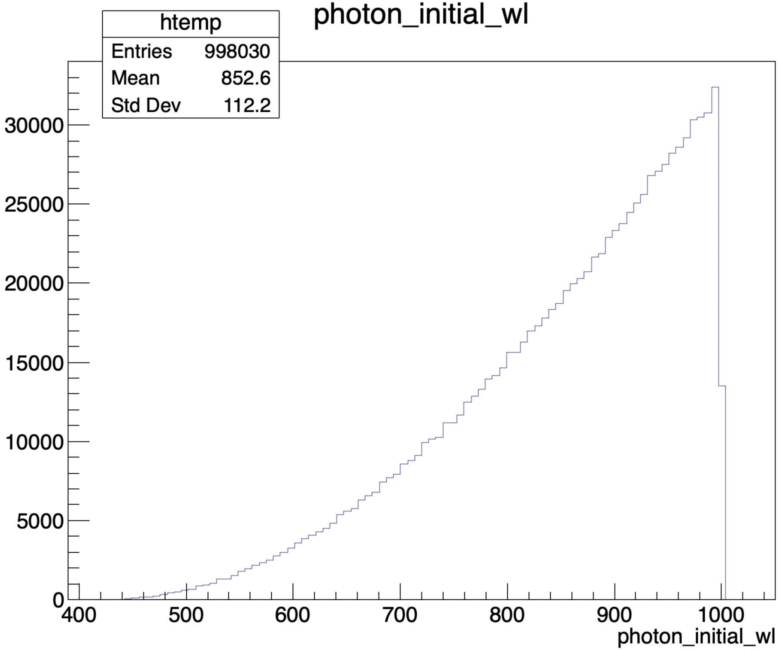


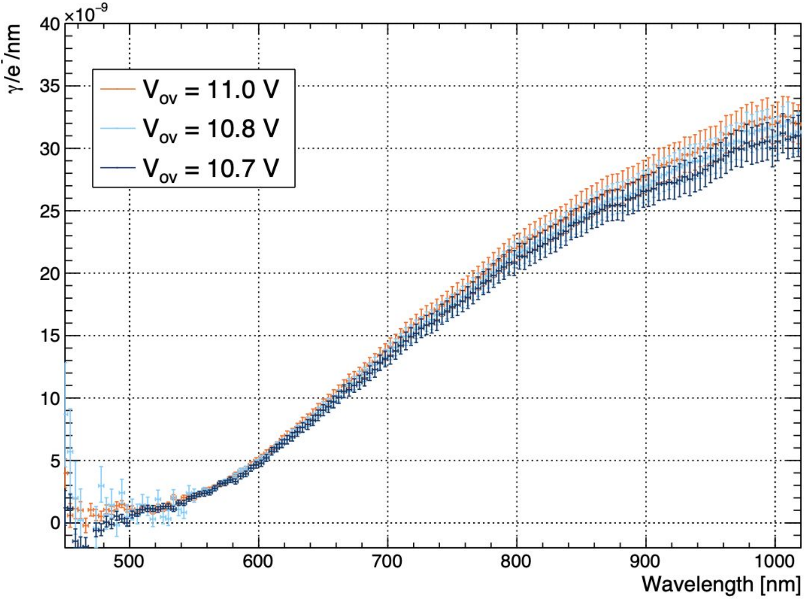
Figure: Absorption coefficient of silicon with different doping

Emission spectra HPK

Used in Geant4



Measured



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Analysis (gain and avalanche probability plots)

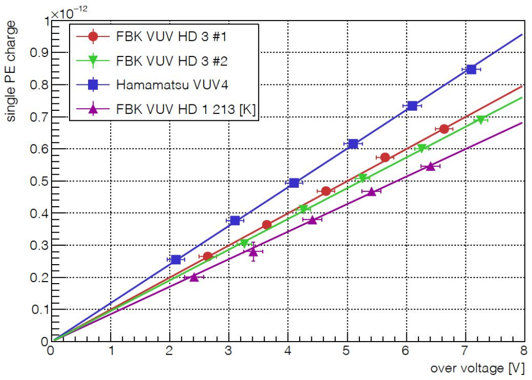

Figure 4.7: Measured single PE charge as a function of the over voltage for several devices tested for the nEXO experiment. The measurements of the FBK VUV HD 3 and Hamamatsu VUV4 were done at 163 K, while the one of the FBK VUV HD 1 was extrapolated from [59] and reported for a temperature of 213 K.

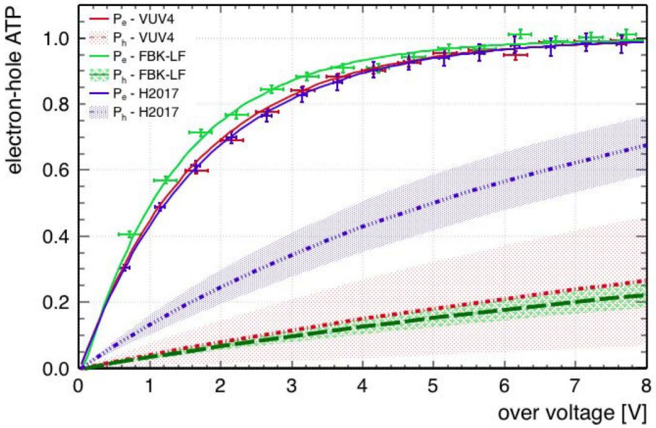

Fig. 6. Electron and hole Avalanche Triggering Probability (ATP), $P_e(d_P)$ and $P_h(d_W)$, for the three SiPMs analyzed in this article. For each $P_e(d_P)$ are also reported the data of Figs. 3 and 5 used to obtain the corresponding curve. Each $P_h(d_W)$ is derived using (12). The dashed regions represent the uncertainty on the hole probabilities $P_h(d_W)$ due to the uncertainty on the effective k values of Table I.

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