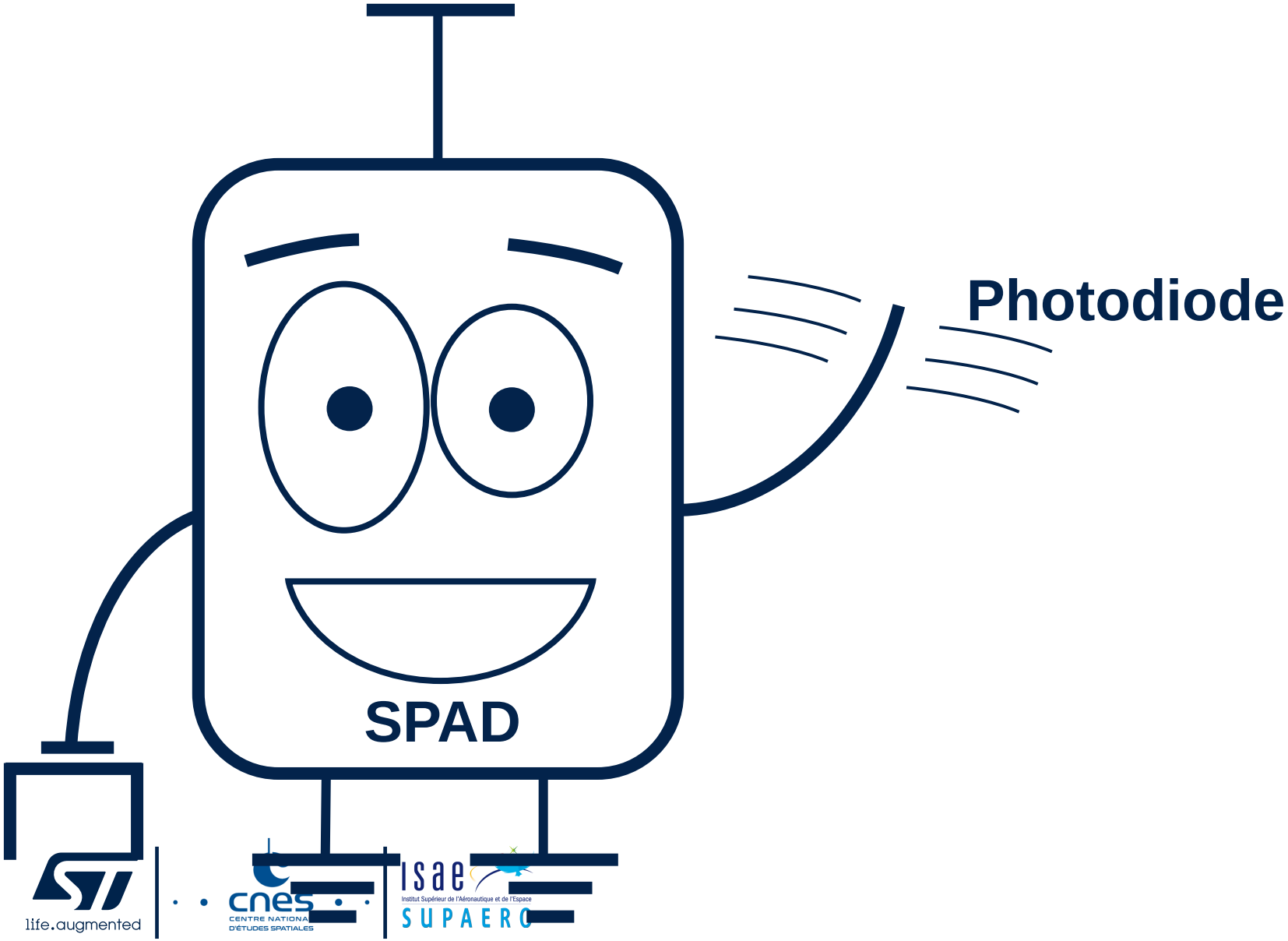
Effects of X-ray and γ-ray Irradiation on 2D and 3D CMOS SPADs

Ali Jouni[1,2,3], Valérian Lalucaa[1], Cedric Virmontois[1], Gilles Gasiot[2], and Vincent Goiffon[3]

[1]*CNES*
[2]*STMicroelectronics*
[3]*ISAE-SUPAERO*

Single Photon Avalanche Diode (SPAD) ?



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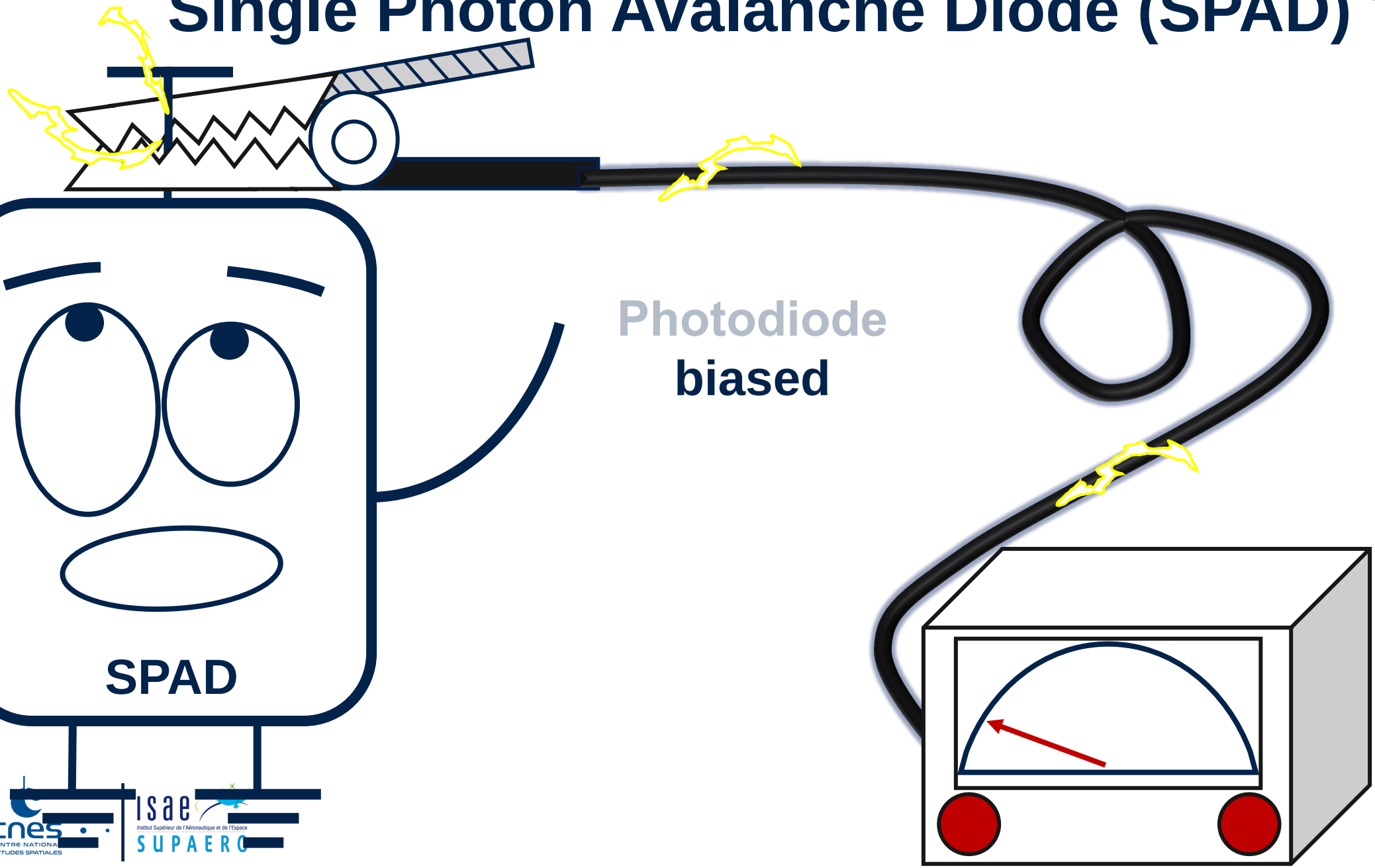

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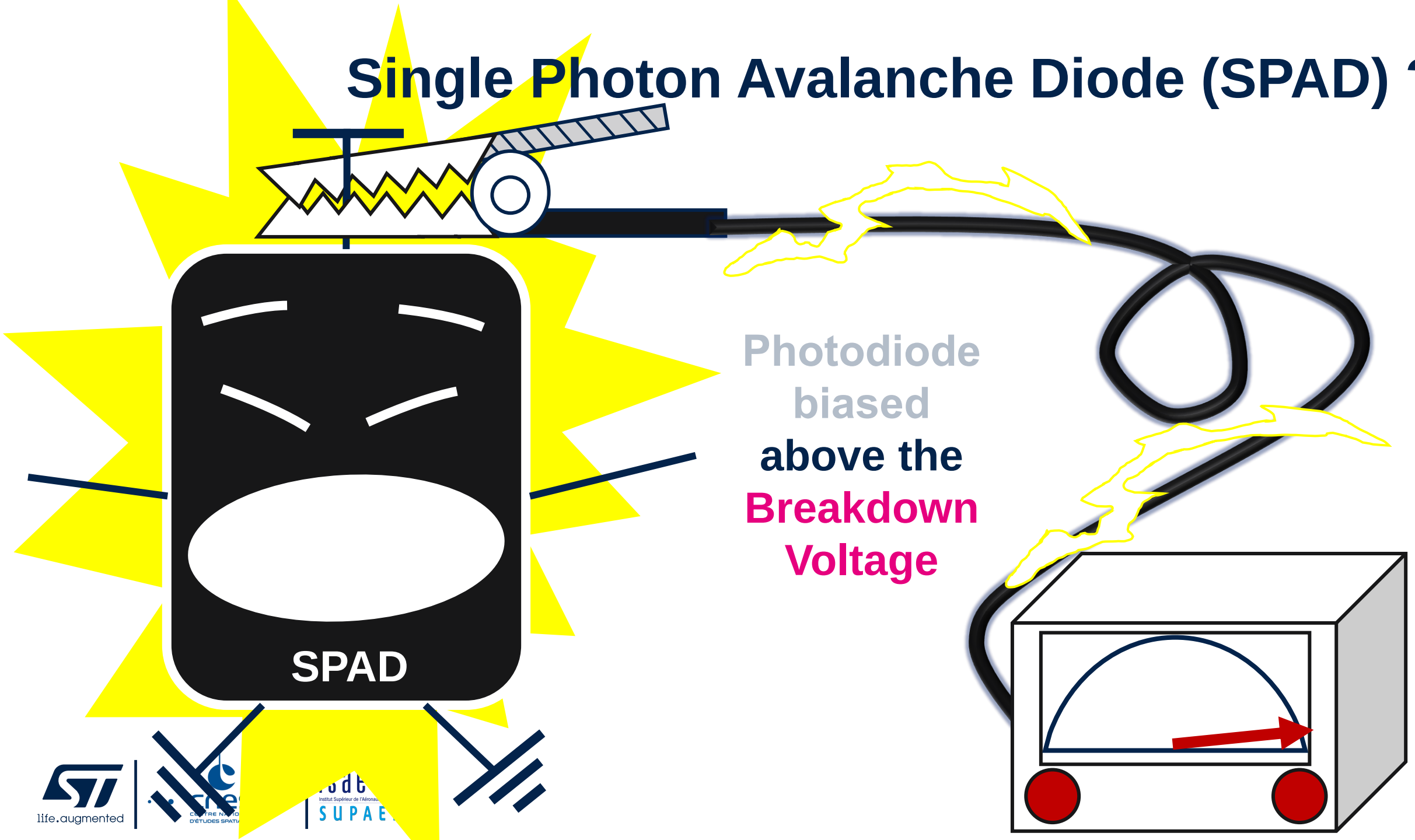
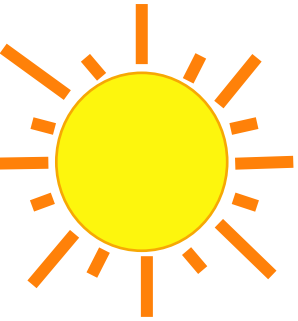
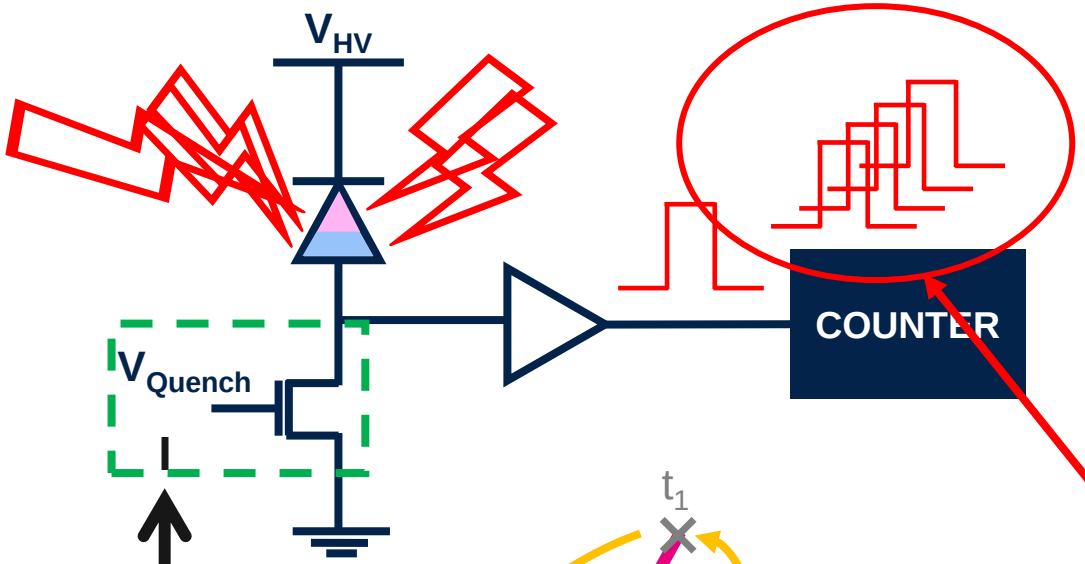


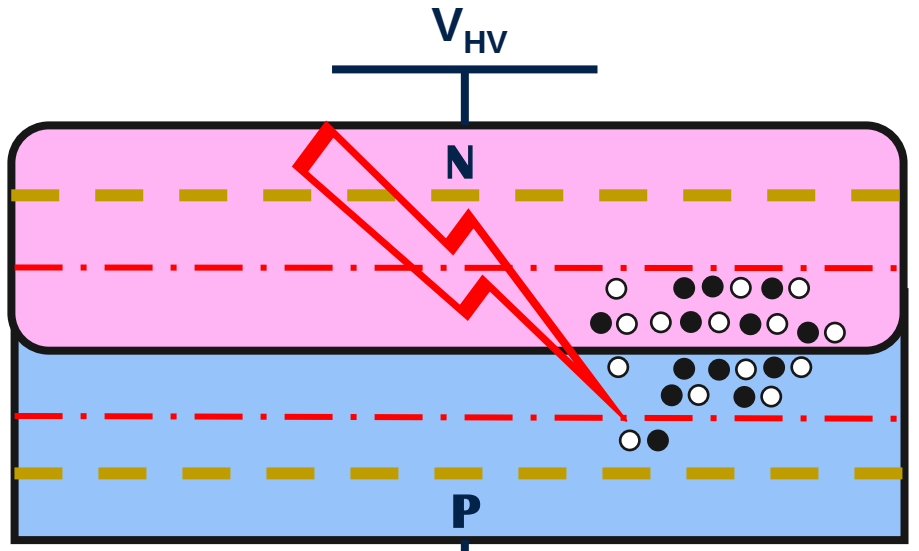
Photodiode biased above the **Breakdown Voltage**

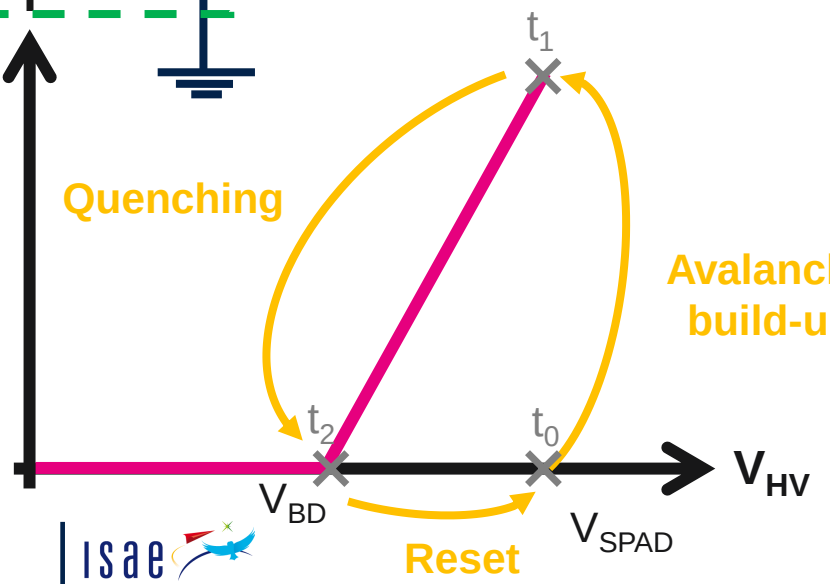
Single Photon Avalanche Diodes (SPADs)?

Photodiodes biased above breakdown:





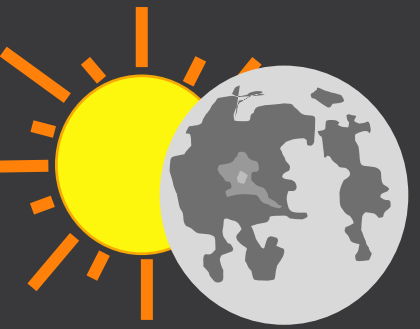


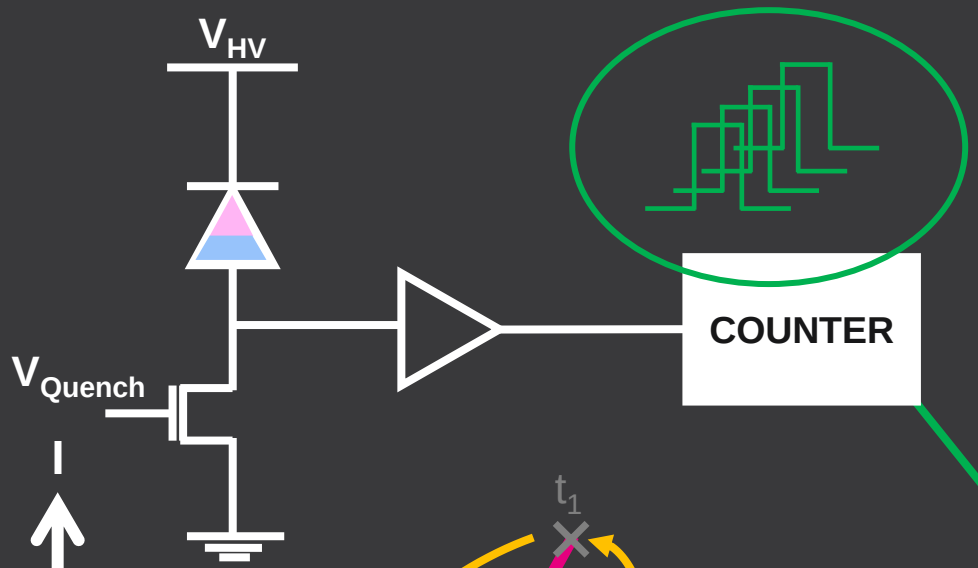


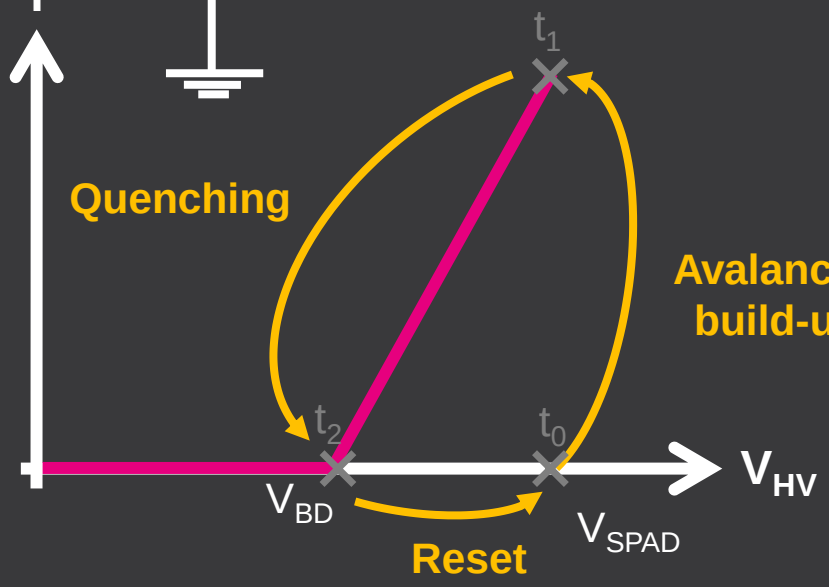
Counts per second (cps)

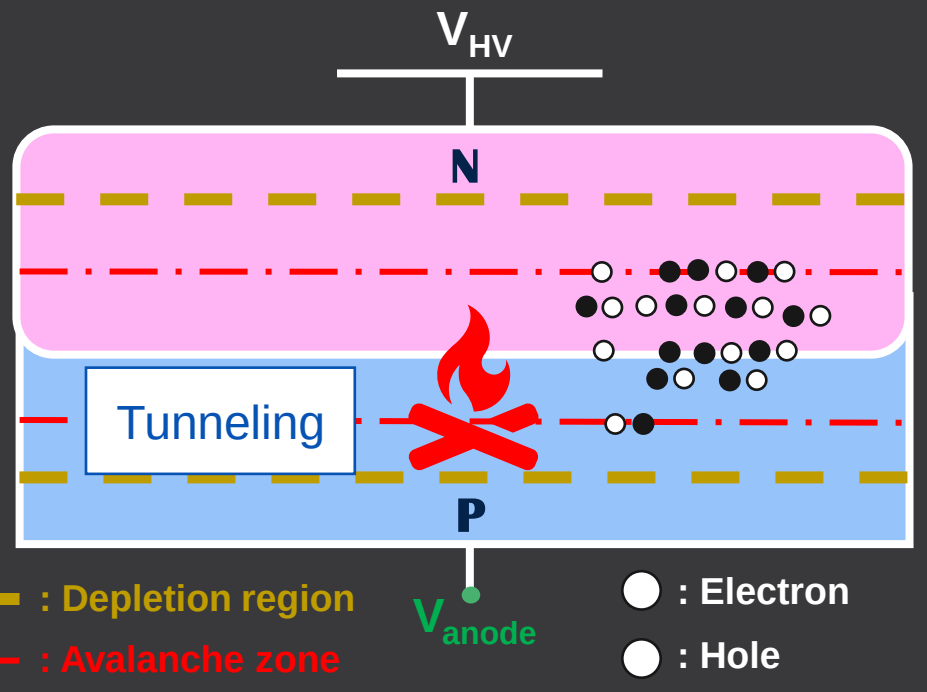
Single Photon Avalanche Diodes (SPADs)?

- **Photodiodes biased above breakdown:**









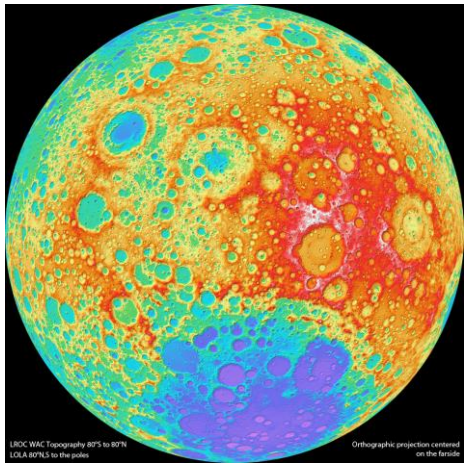
Dark Count Rate (DCR)

Use of SPADs in Space

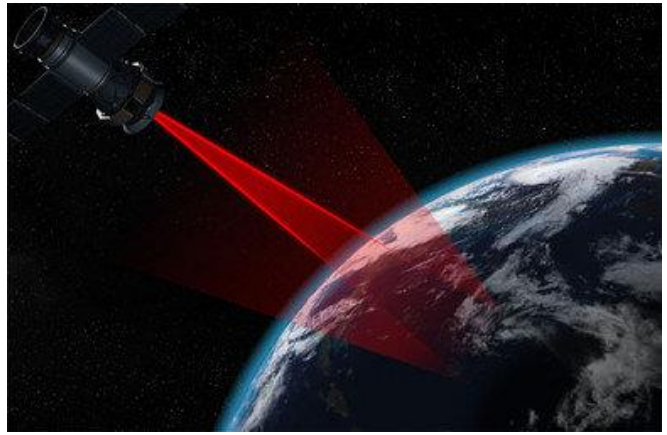
SPADs ➔ Low light sensitivity + high timing performances (hundreds of ps)

- Time of Flight
  - Space Rendezvous
  - Earth observation (LIDAR)
  - Altimetry/Topography
- 3D-Imaging

Space Rendezvous



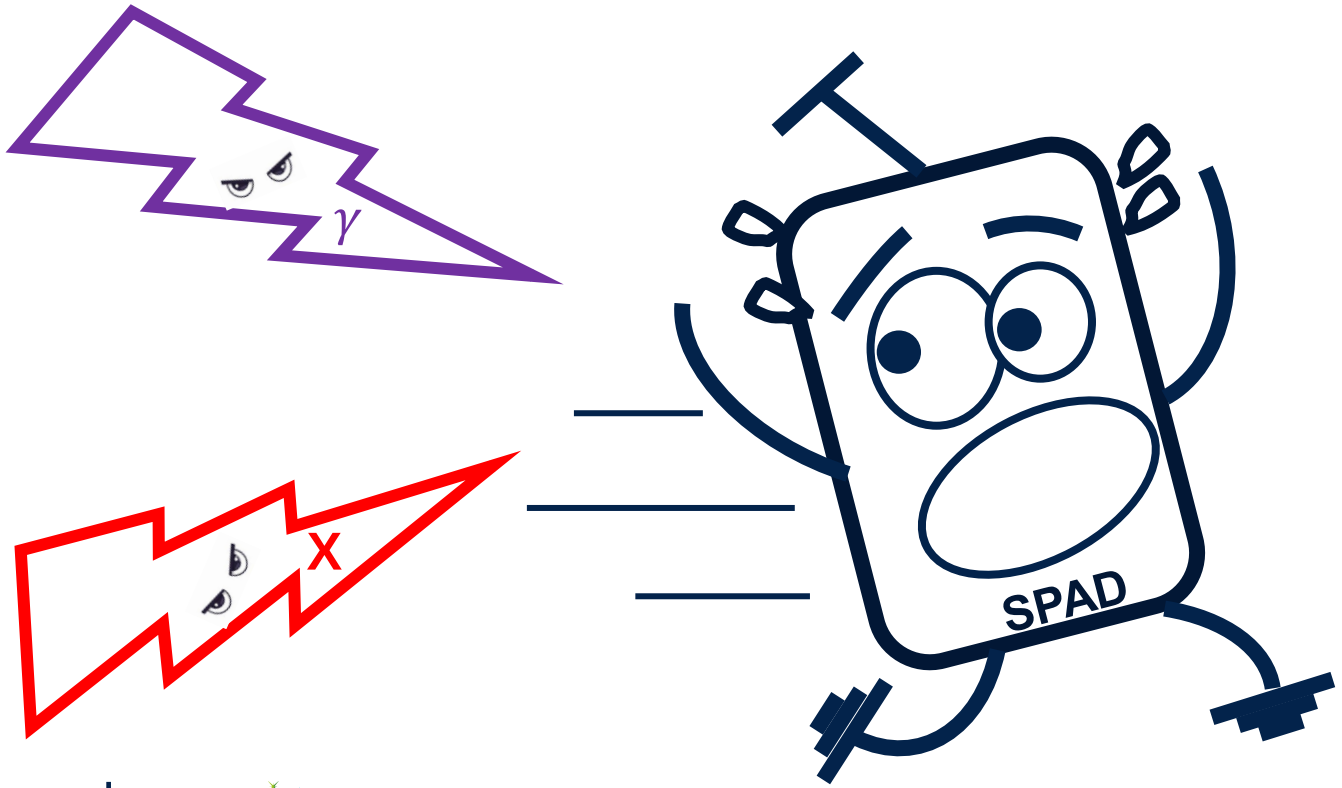
Lunar topography (LOLA instrument, credits: NASA GSFC)

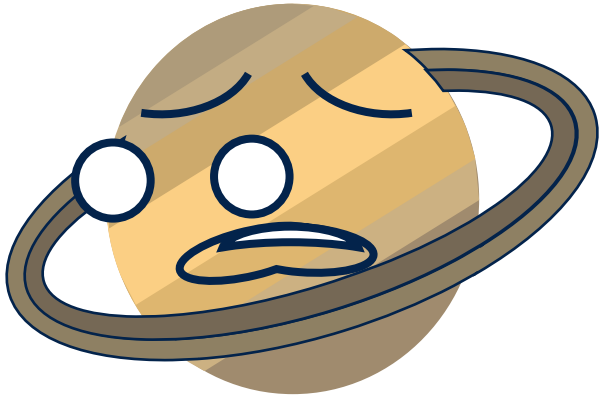


LiDAR

Motivations

- Study of Total Ionizing Dose (TID) effects with X-rays and γ-rays for two SPAD technologies up to 320 krad(SiO_2) (SPADs unbiased)





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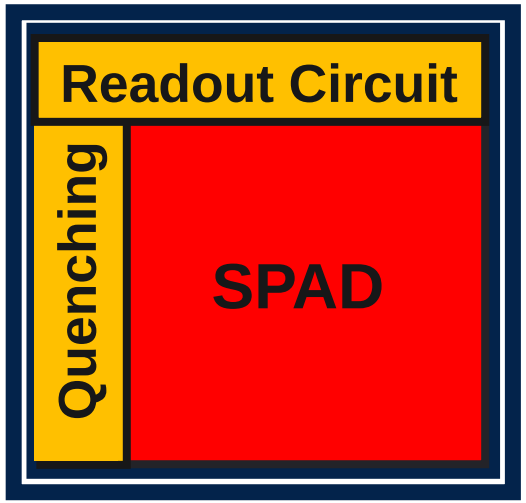
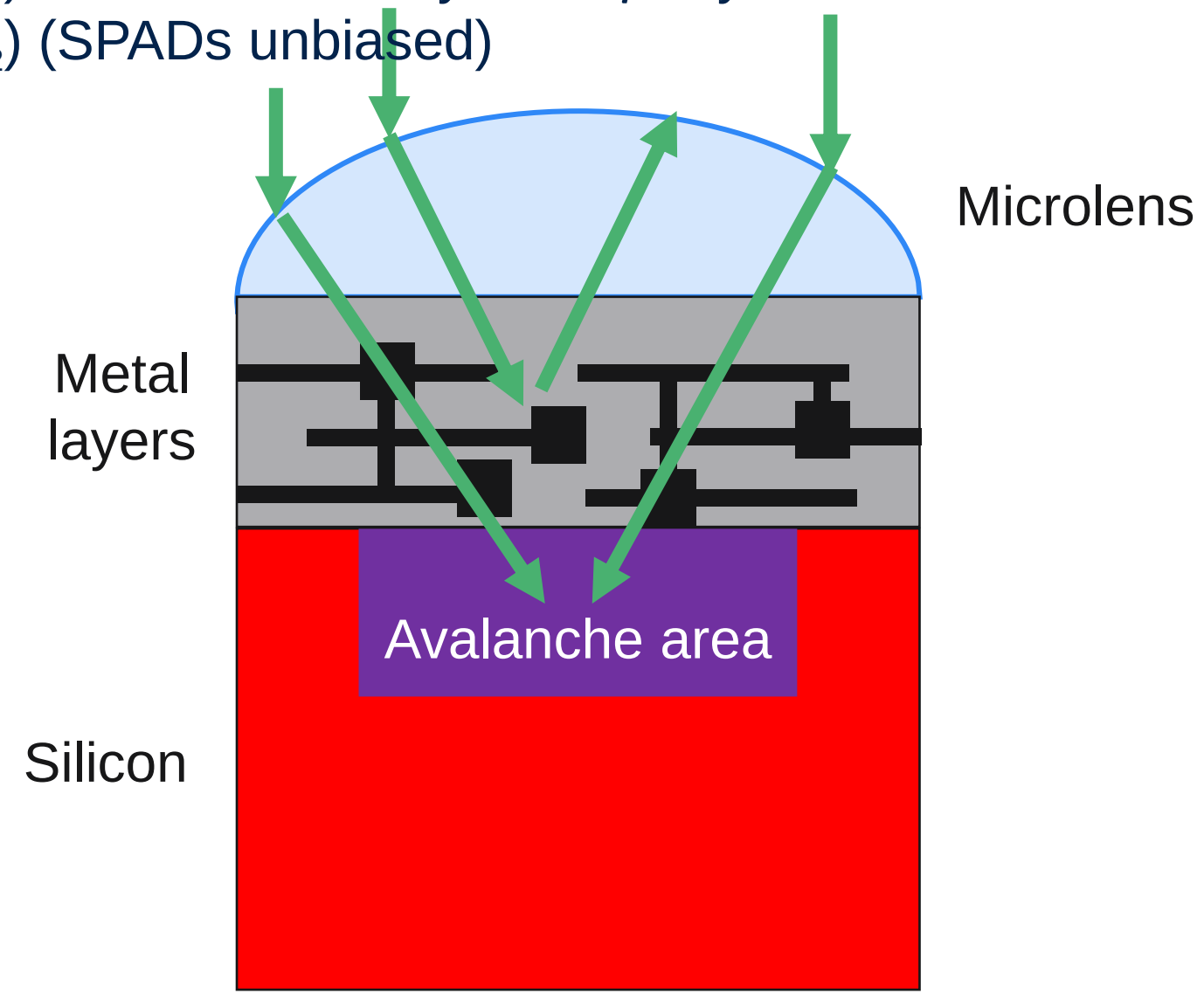
2D SPAD array



840 pixels
Frontside Illumination (FSI)



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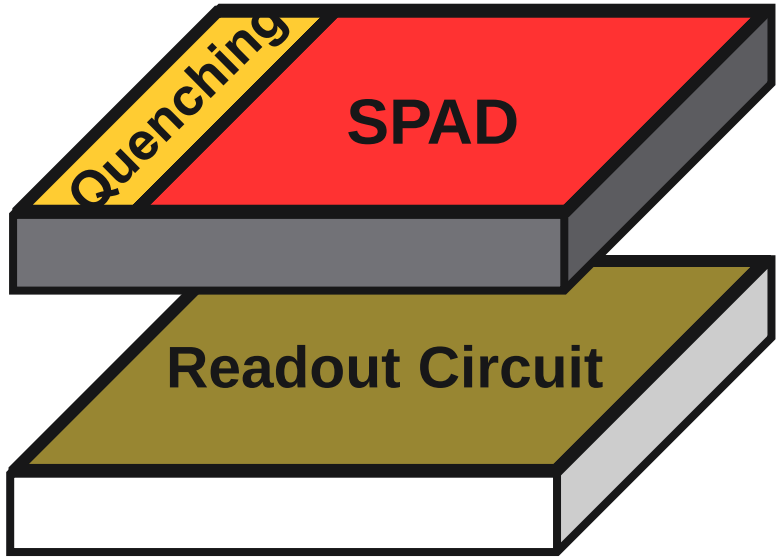
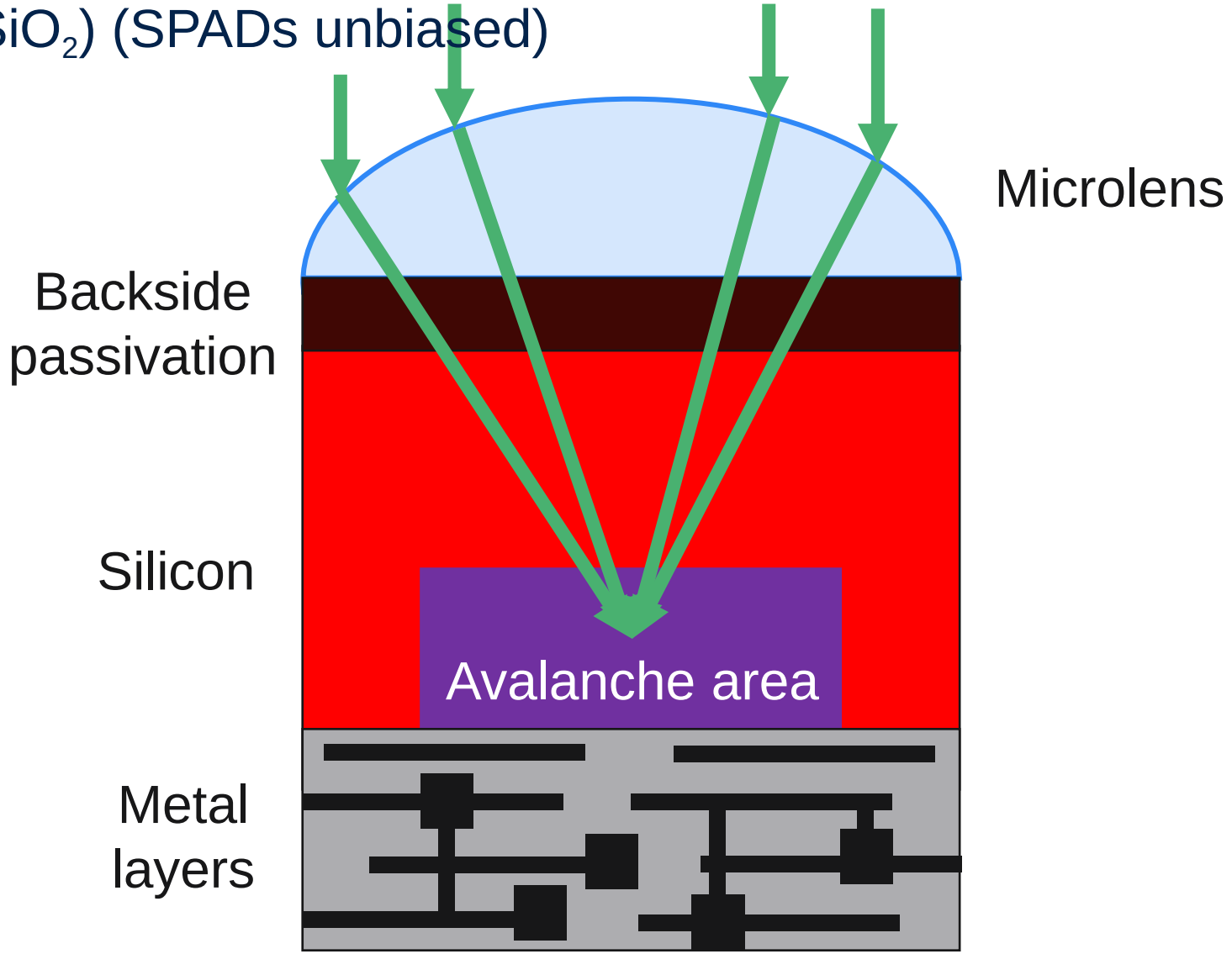
3D SPAD array

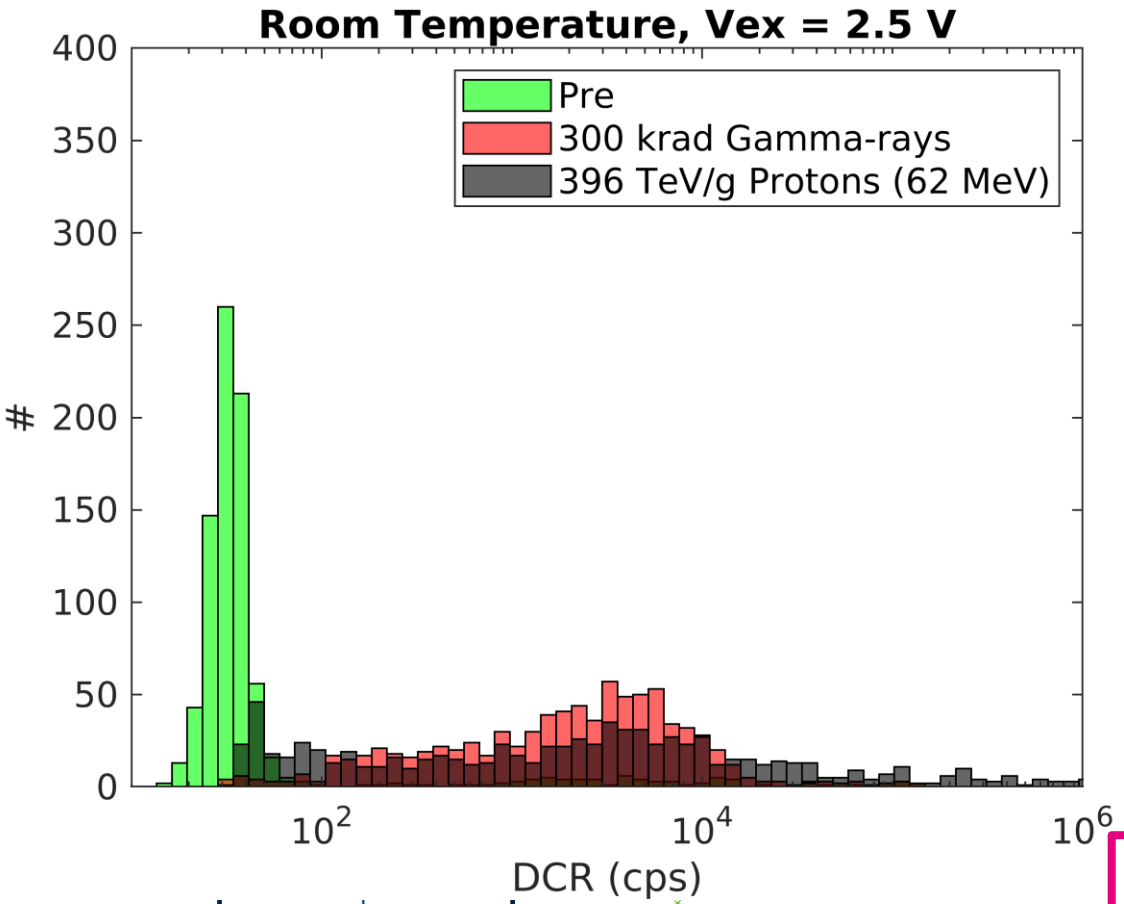


1024 pixels
Backside illumination (BSI)

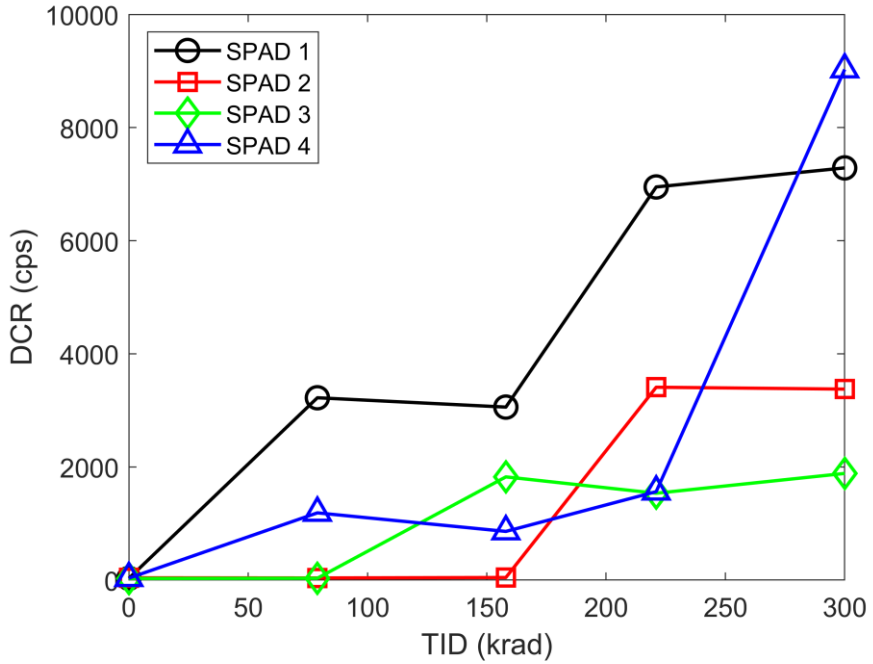


γ-rays on 2D-SPAD arrays: DCR distributions

γ-ray irradiation



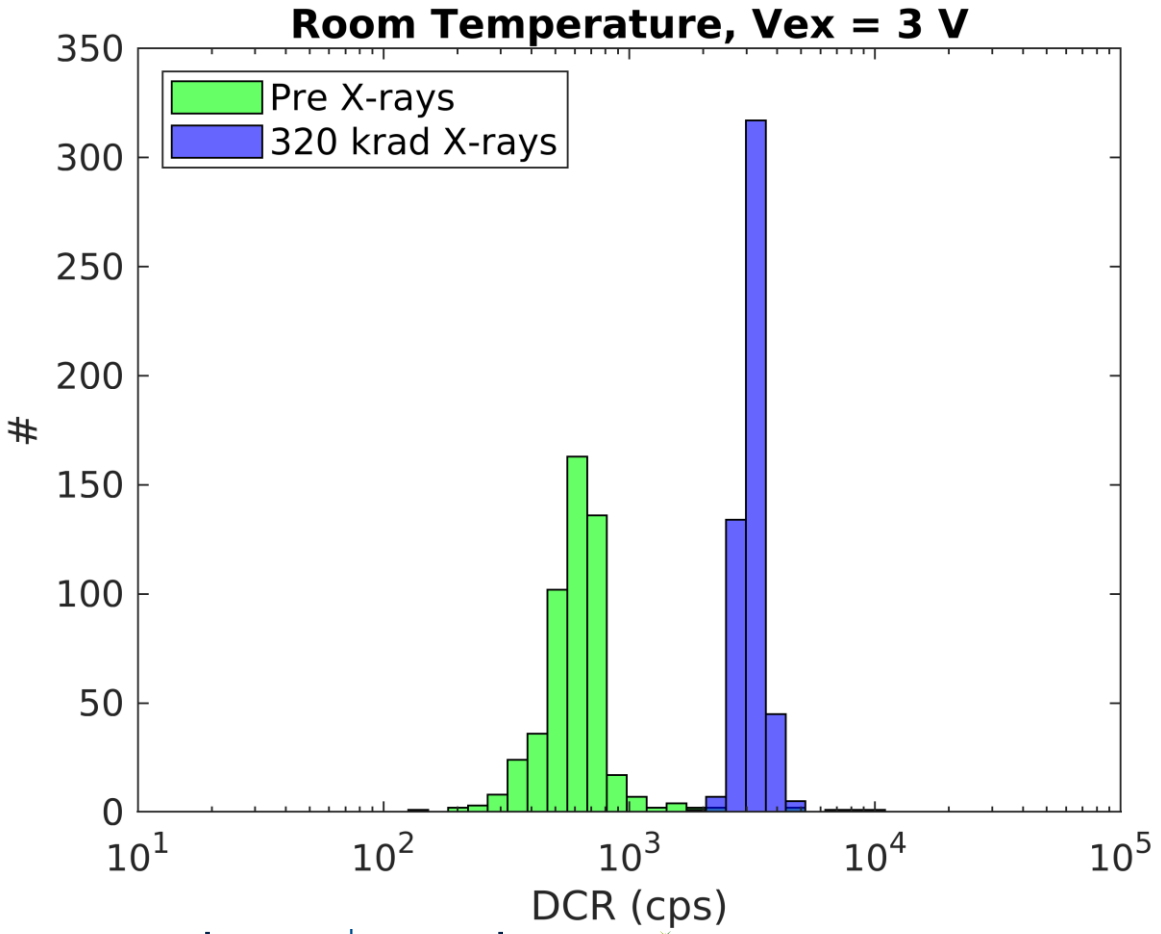
- **For approx. the same TID, different degradation**
- Large spread of DCR distribution = signature of **displacement damages induced by γ-rays**



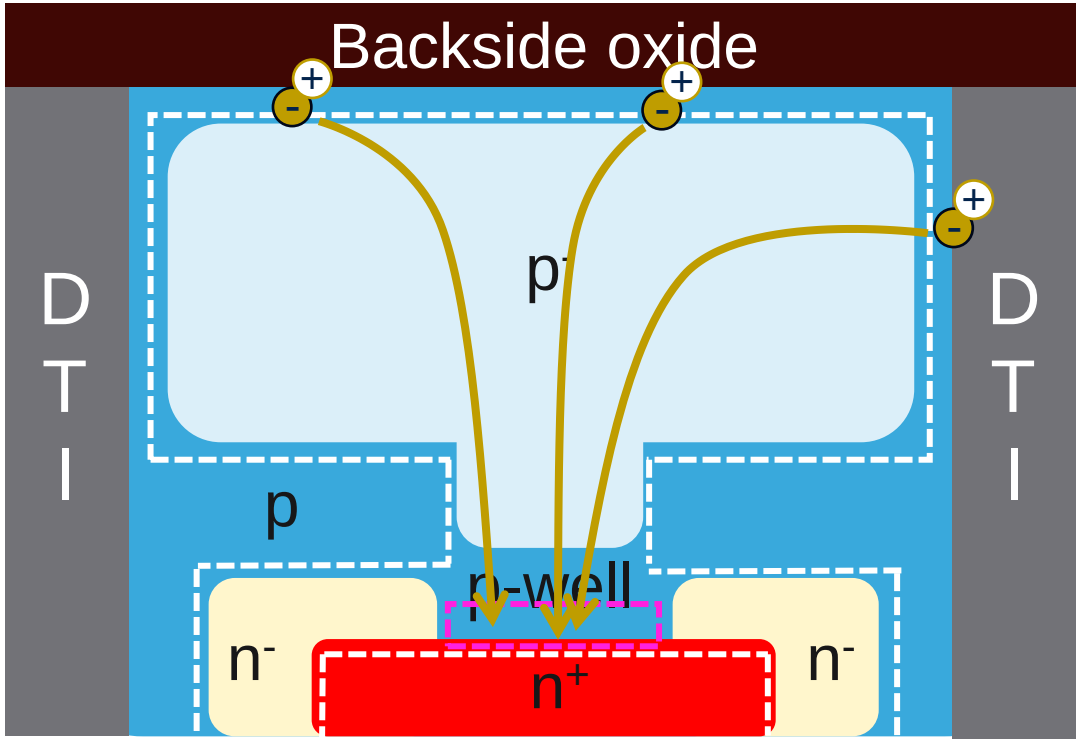
In 2D-SPADs: only the DDD contribution is seen after γ-rays ➔ mainly Point Defects

X-rays on 3D-SPAD arrays: DCR distributions

X-ray irradiation



- **Significant DCR increase after X-rays (> 1000 cps)**
  - ➔ more Si/SiO_2 interfaces due to DTIs + backside oxides
  - ➔ electric field engineering: an electron entering the depleted volume drifts toward the avalanche area



γ-rays on 3D-SPAD arrays: DCR distributions

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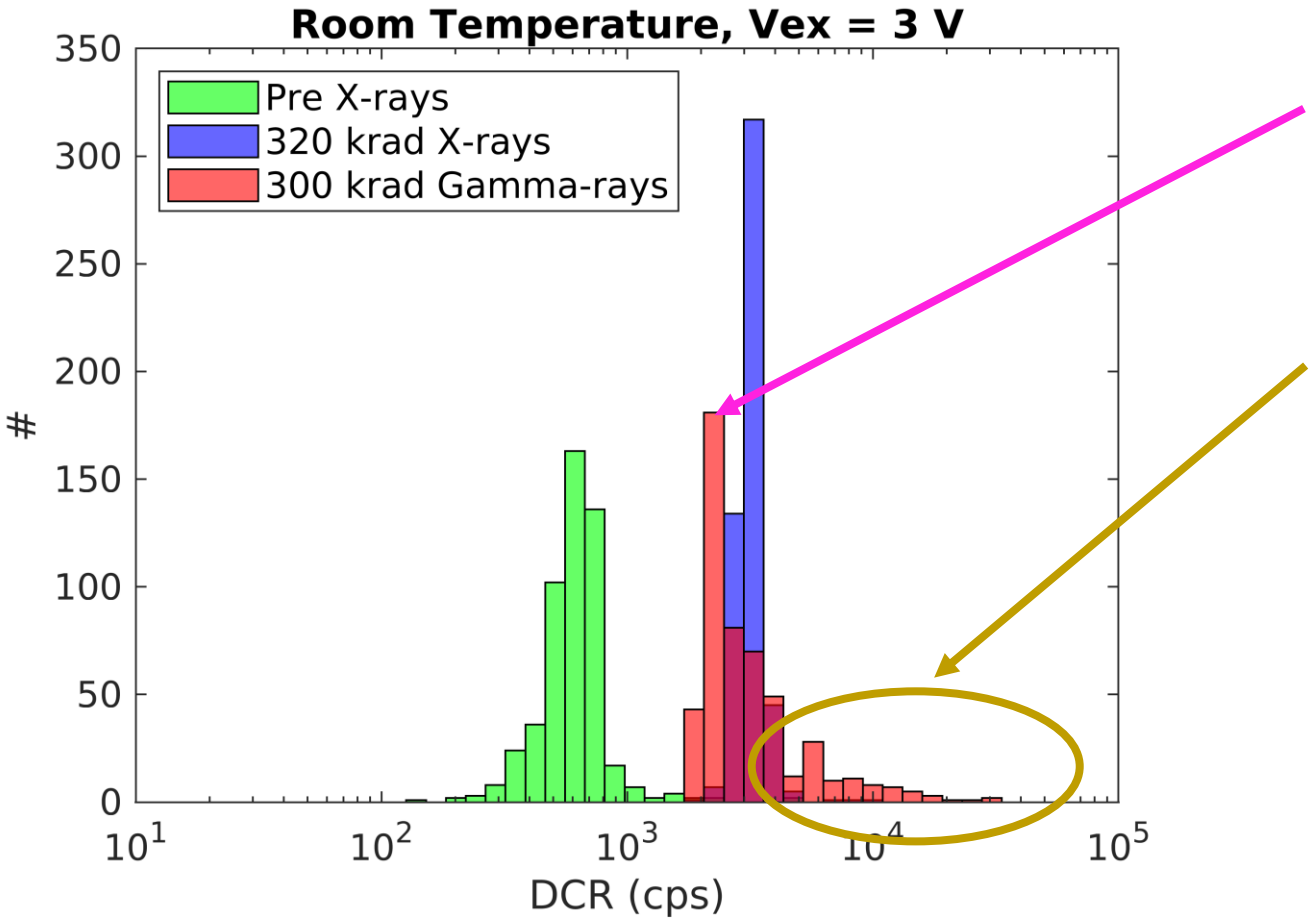


- Peaks due to **TID contribution**
  ➔ **3D-SPADs impacted by ionizing effects**

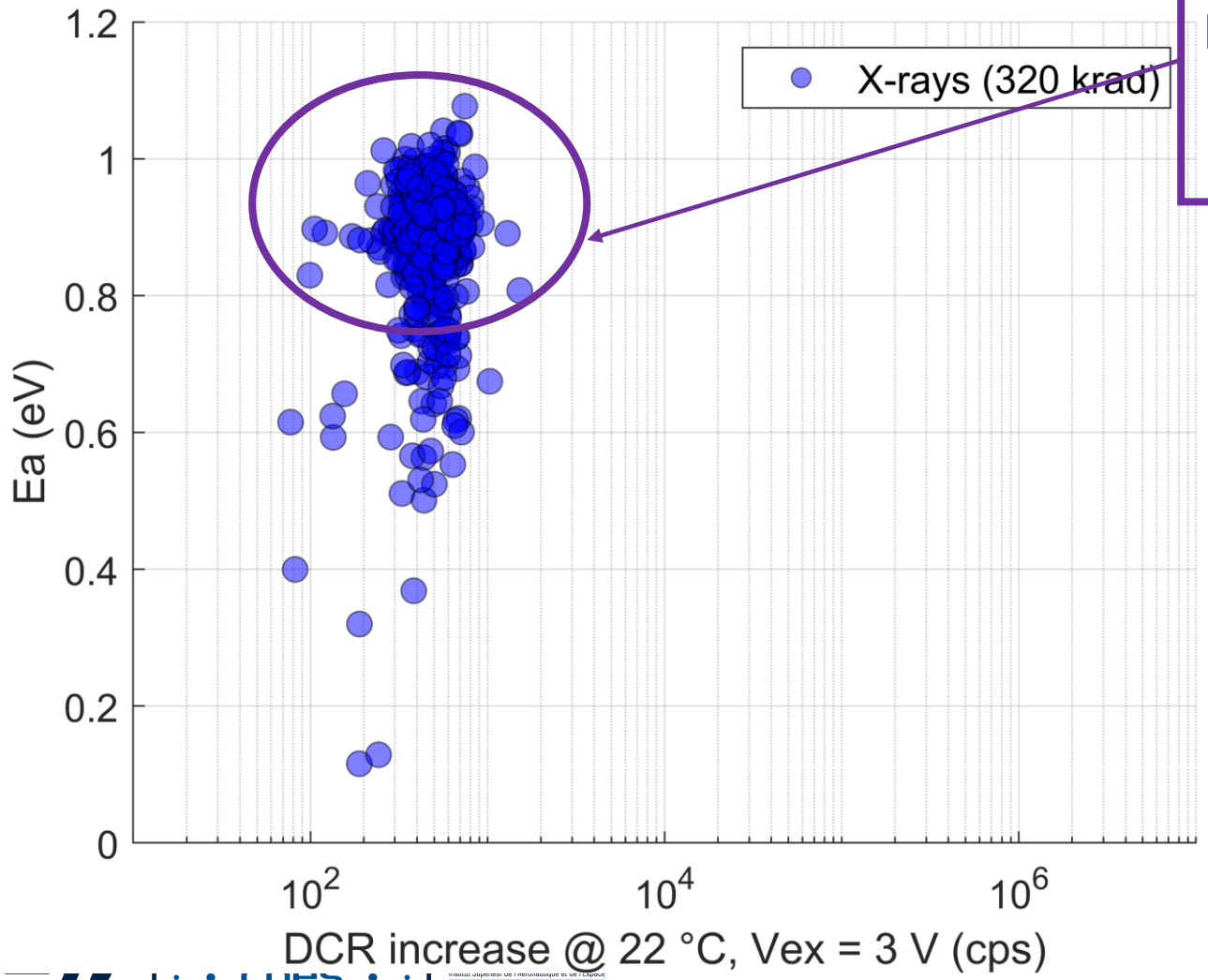
- Again, spread toward high DCR not present with X-rays:
  ➔ **Displacement damage contribution**

In 3D-SPADs: TID + DDD contributions are observed after γ-rays

$$DCR(T) \propto \exp(-\frac{E_a}{k_B.T})$$

Activation energies for 3D-SPAD arrays

- E_a extracted btw **–5 °C** and **22 °C**



High E_a (near Si bandgap)

➔ **Diffusion current, consistent with interface defects**

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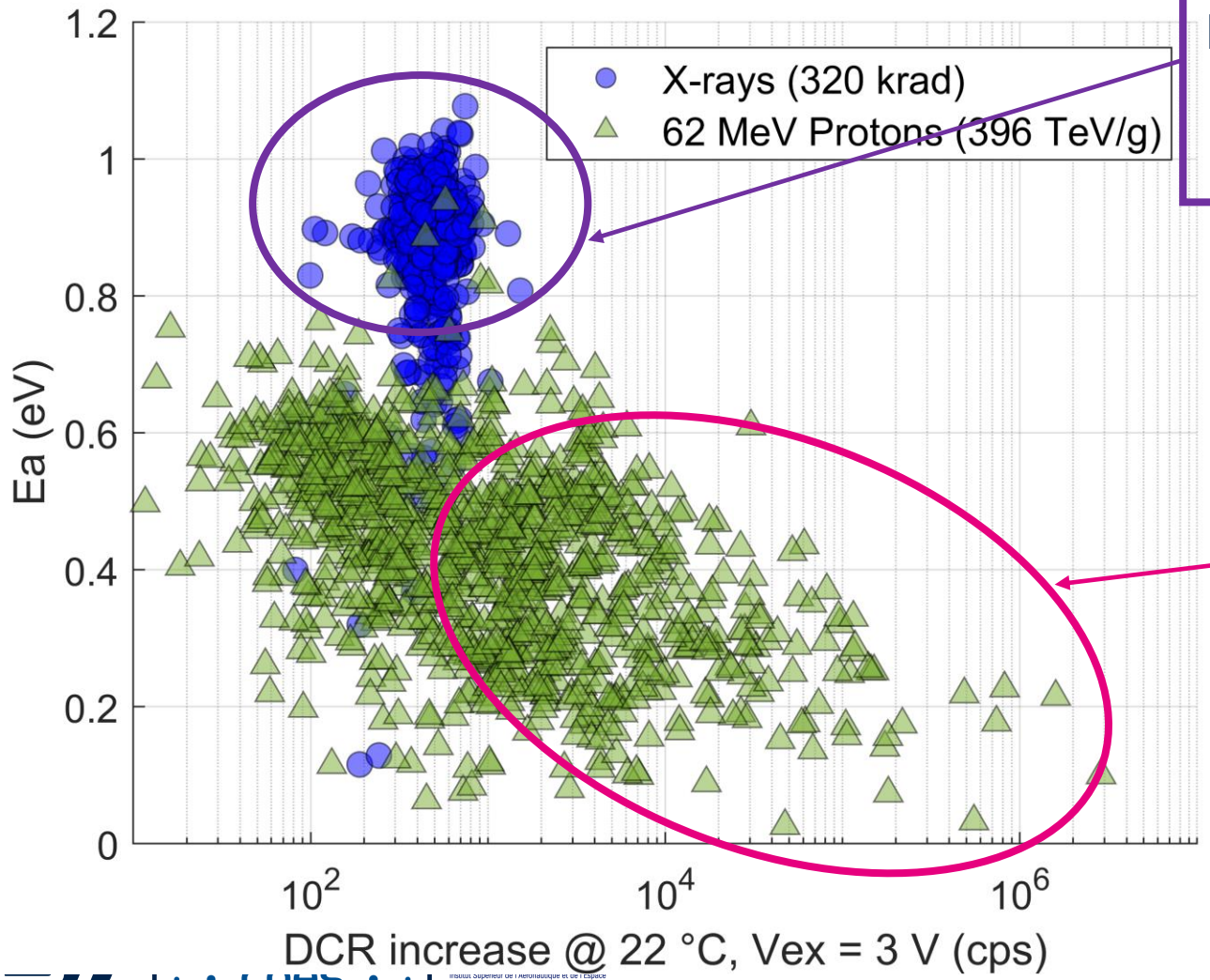

High E_a (near Si bandgap)
➔ **Diffusion current, consistent with interface defects**

E_a below midgap
➔ **Generation current in the avalanche volume, due to displacement damage defects**

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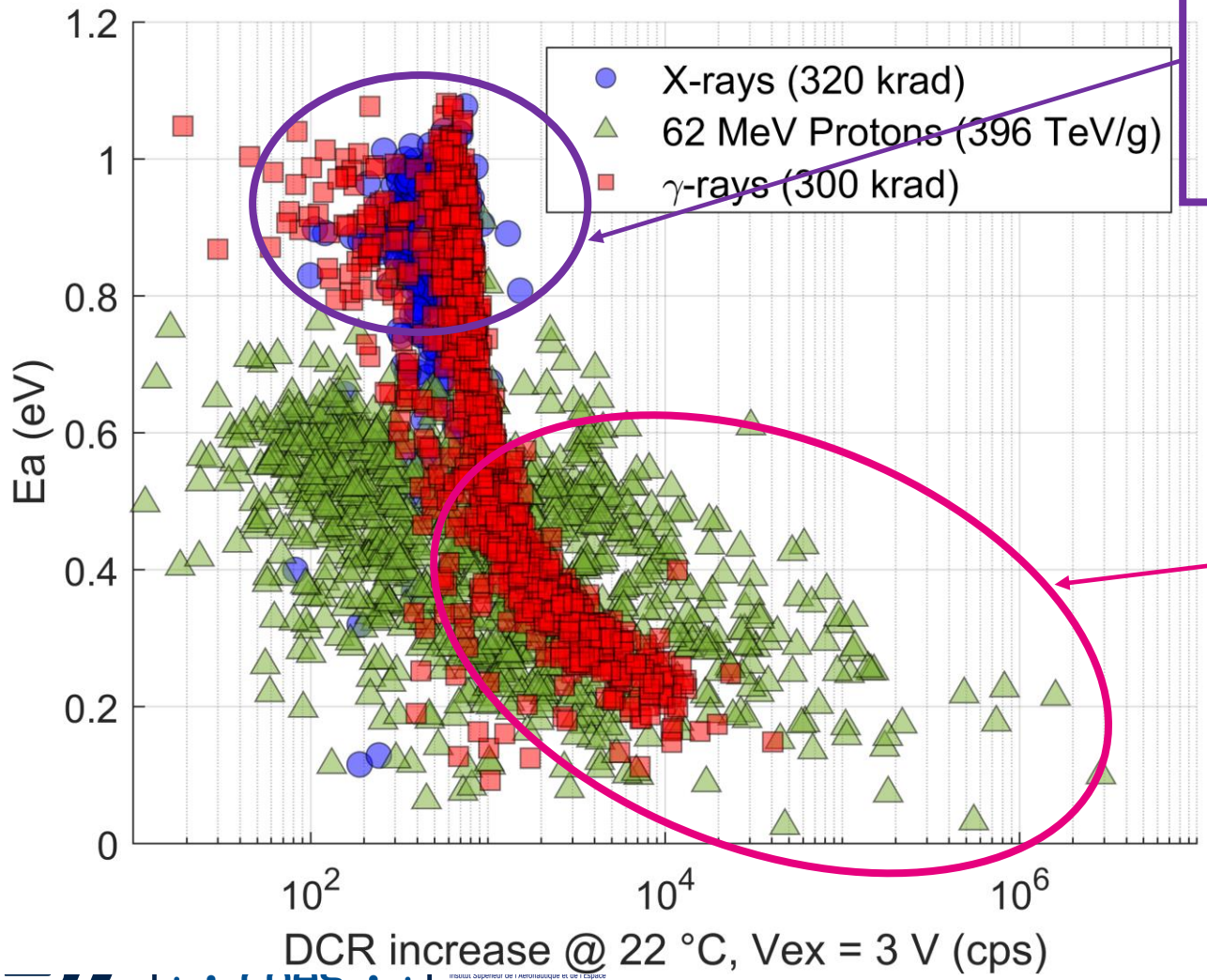


High E_a (near Si bandgap)

➔ **Diffusion current, consistent with interface defects**

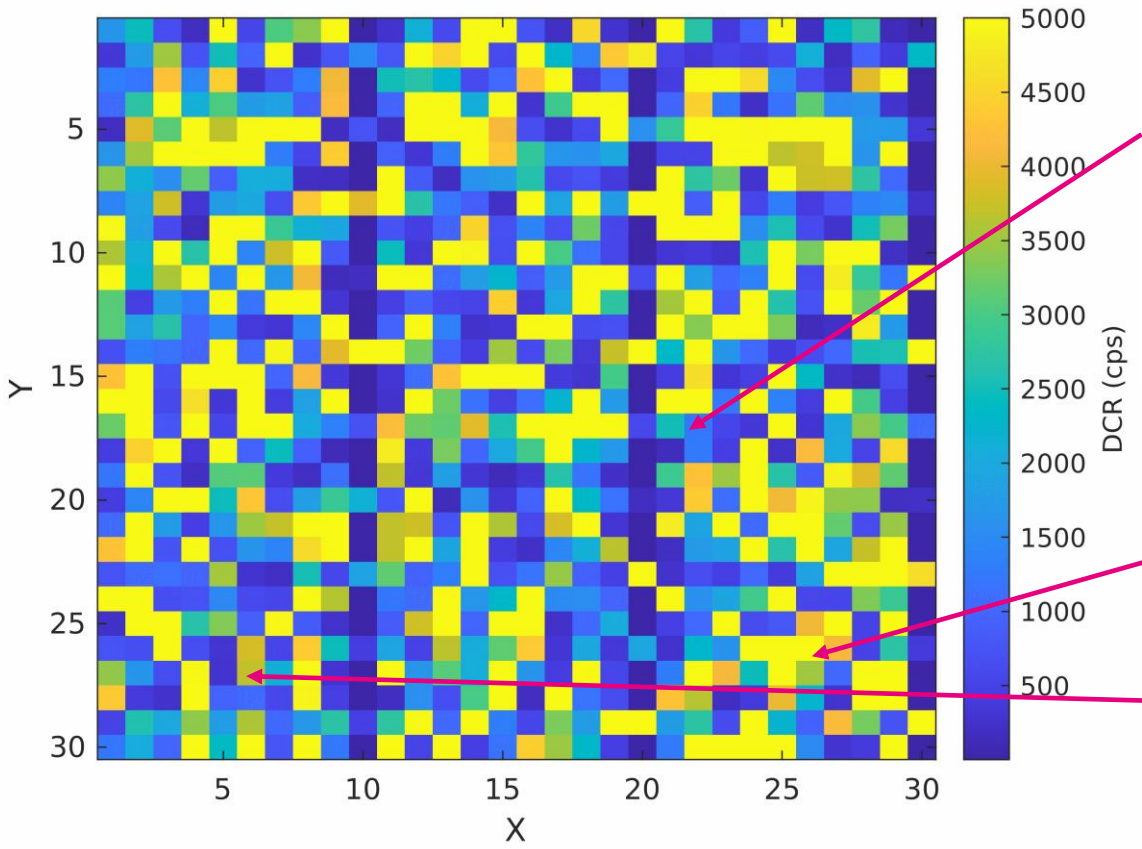
E_a below midgap

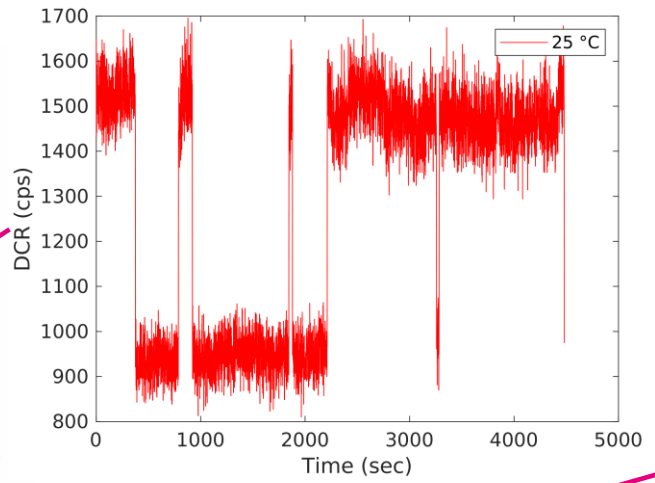
➔ **Generation current in the avalanche volume, due to displacement damage defects**

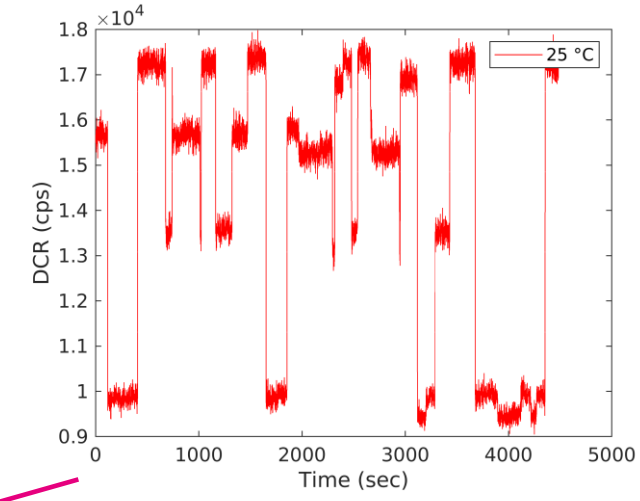
Induced Random Telegraph Signal (RTS)

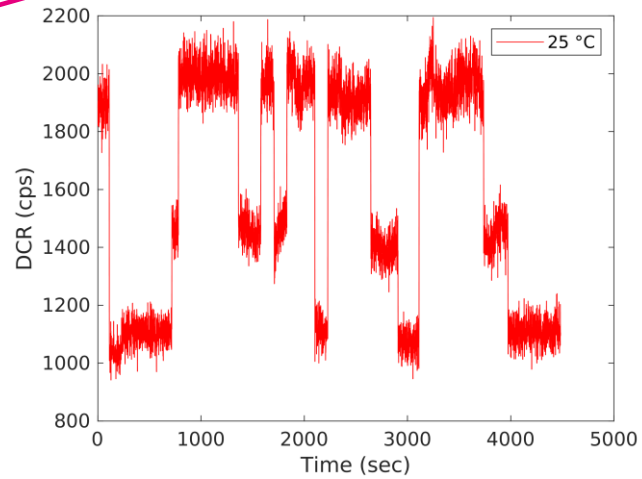
- RTS = variation with time of a signal (here the DCR) over two or more discrete levels due to meta-stable defects

2D-SPAD array after γ-rays









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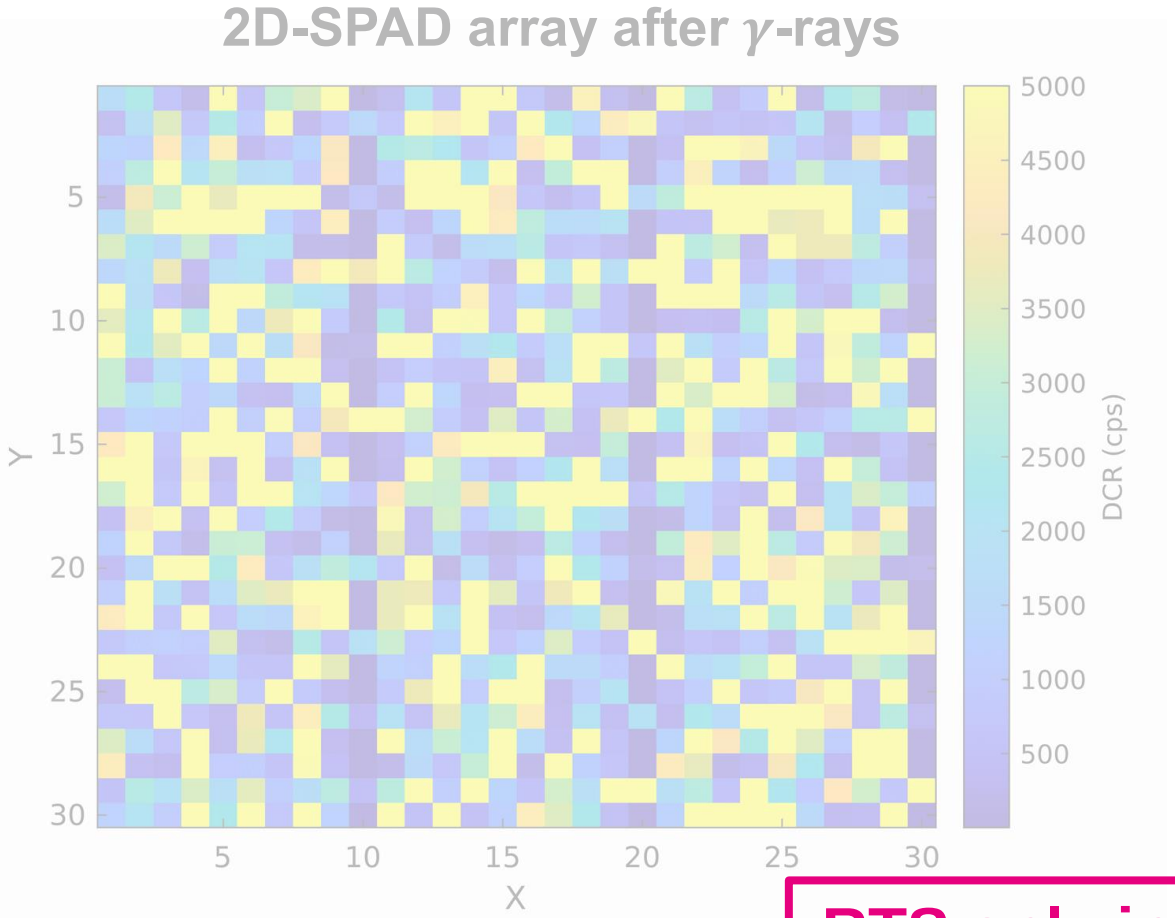
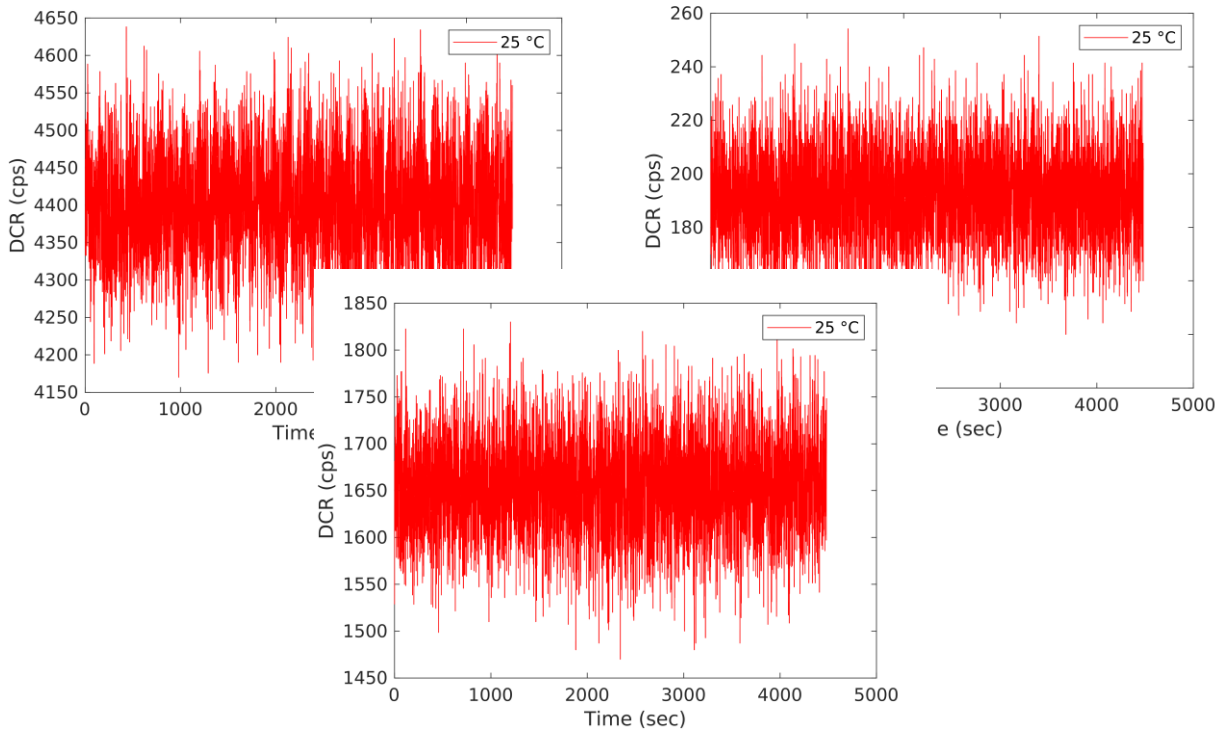


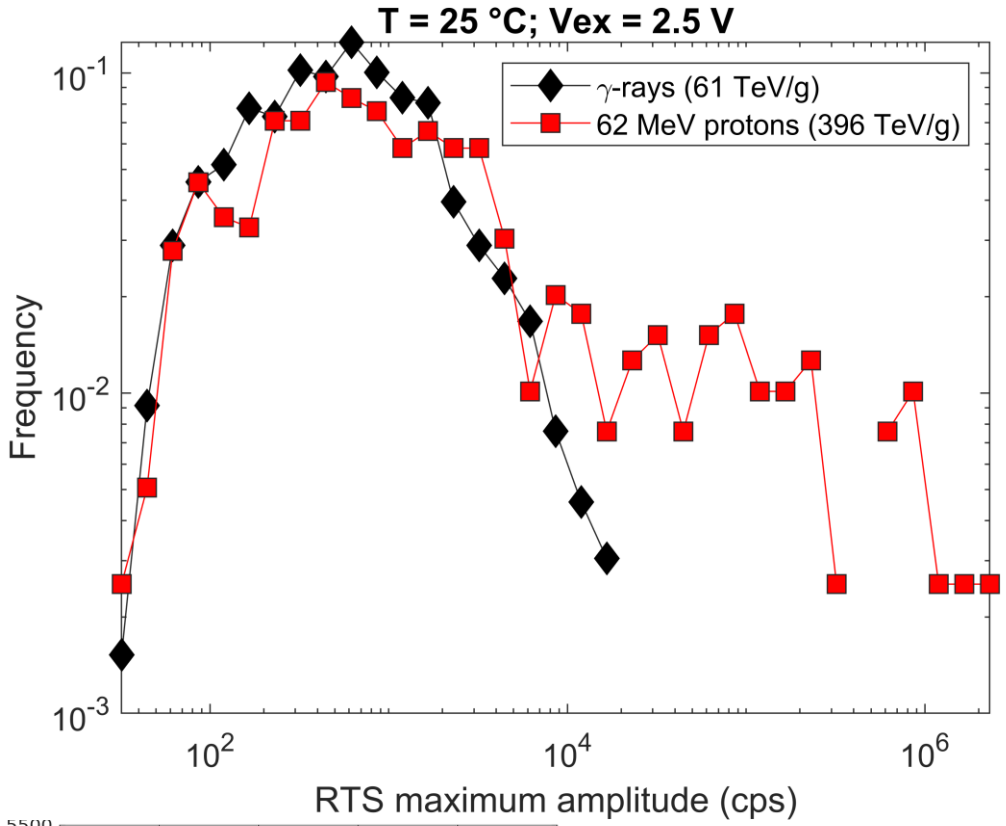
2D-SPAD + 3D-SPAD arrays after X-rays

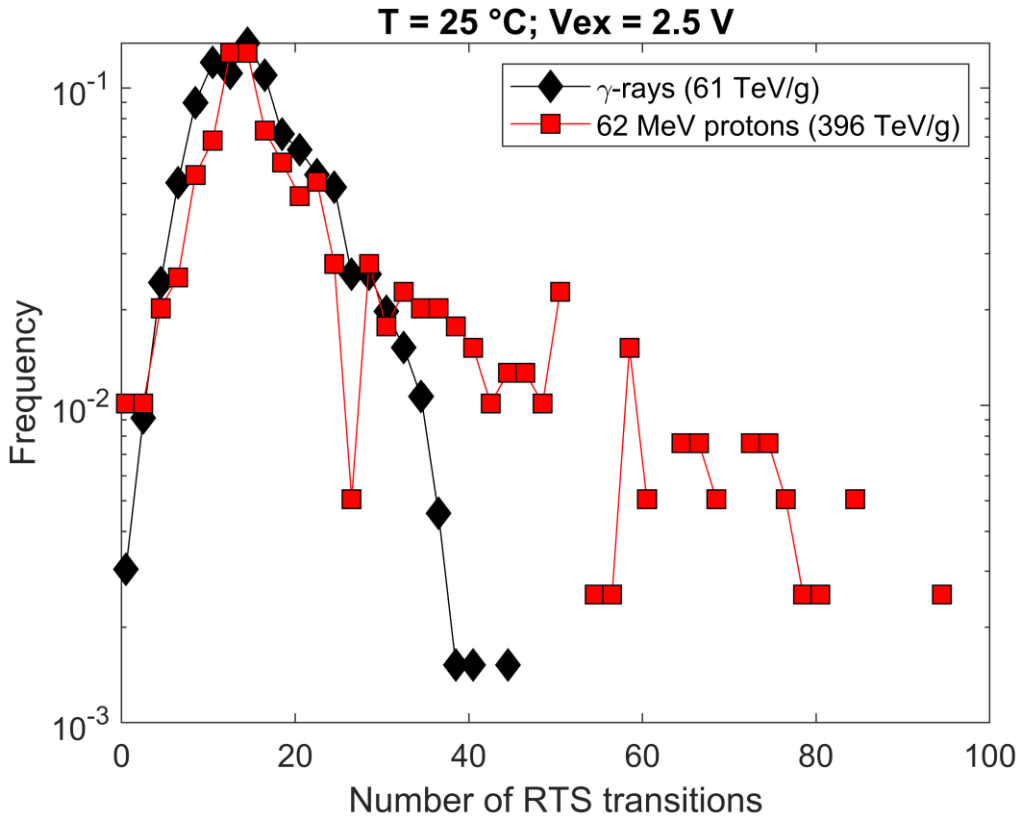


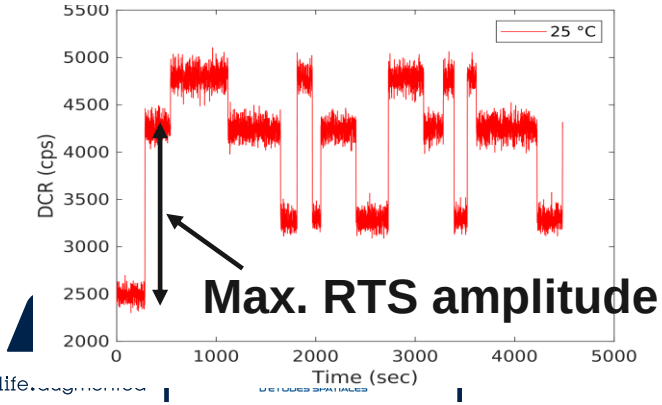
No TID-induced RTS visible

RTS only induced by displacement damages in silicon after γ-rays … so by point defects ?!

RTS induced by γ-rays and protons on 2D-SPADs







Consistent with two RTS origins: Point Defects + Clusters

Conclusion

- X-ray and γ-ray irradiation were performed on 2D- and 3D-SPAD technology up to 320 krad(SiO_2)
- 2D-SPADs slightly degraded after X-rays **due to interface traps generating charges that are swept out before reaching the avalanche volume**
- 3D-SPADs impacted by TID effects due to both **DTI + backside oxides + designed electric field**
- Measurable contribution of **the displacement damage contribution of γ-ray** in 2D- and 3D-SPADs
  - Confirmation with activation energy comparisons with proton irradiation data
- RTS SPADs **seen after γ-ray irradiation but not after x-rays**
  - **Point defects can be another origin of RTS** (with defect clusters)

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