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# Influence of gamma and proton radiation on COTS Silicon and InP based photodiodes and determination of EOL performance through modeling

**CNES / ESA Final Presentations Day**

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R037R006AET01

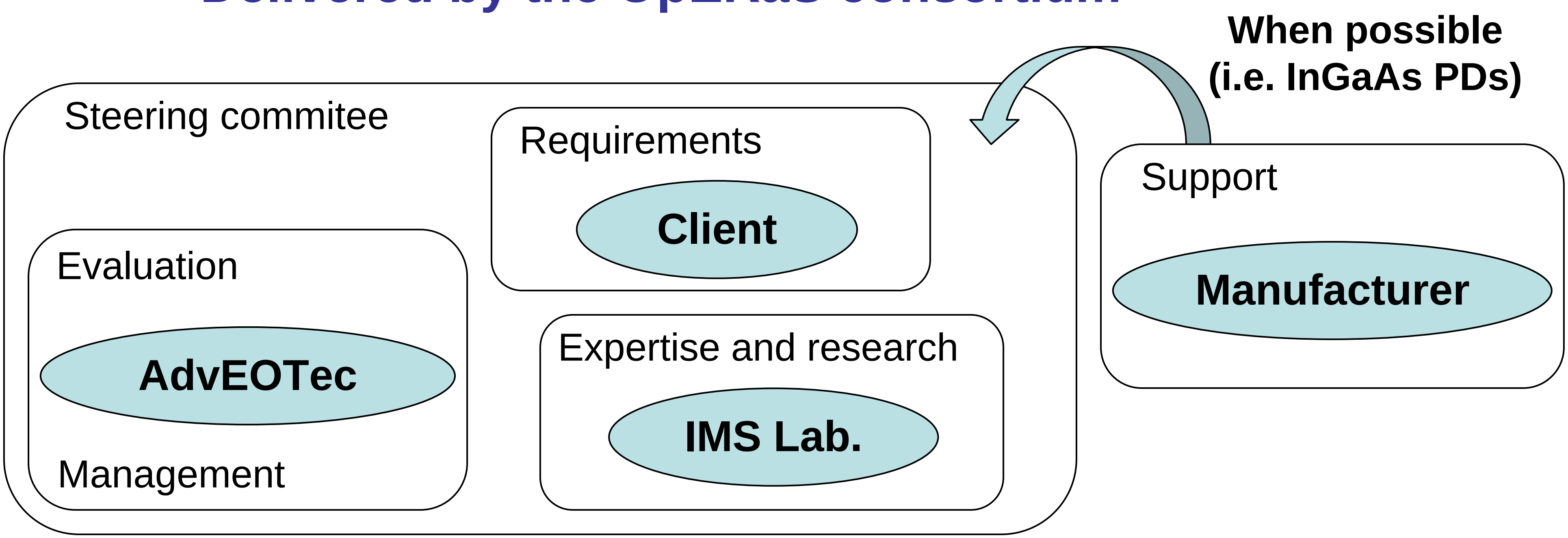
# Summary

- Project framework
- Components description
- Main experimental results
- Electro-optical modeling
- End Of Life performance prediction

# Project framework

- Two projects funded by CNES :
  - Reliability evaluation of Hamamatsu photodiodes for a potential use in the Galileo mission
  - Reliability evaluation of InGaAs photodiodes

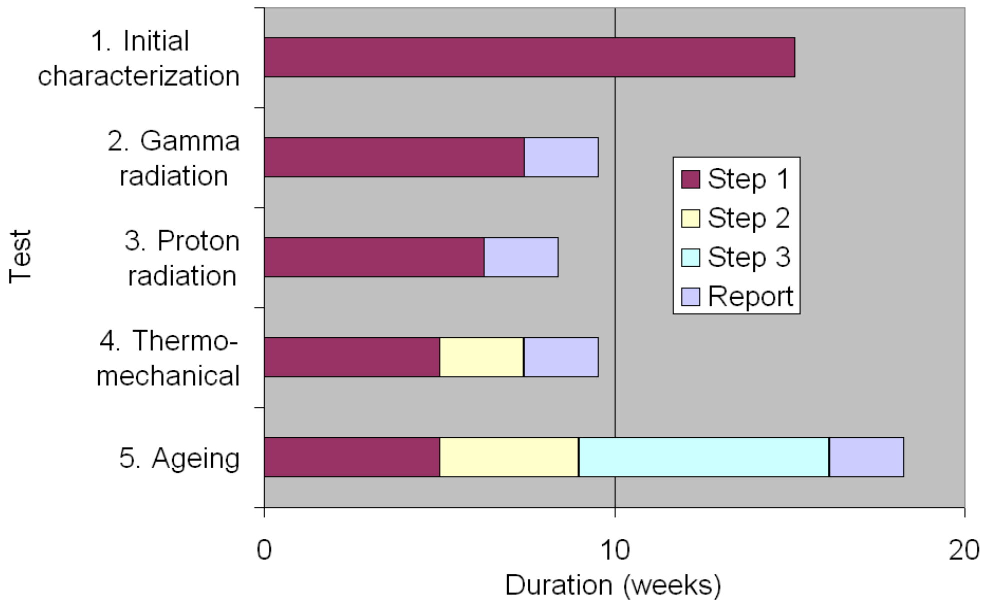
- Delivered by the OpERaS consortium



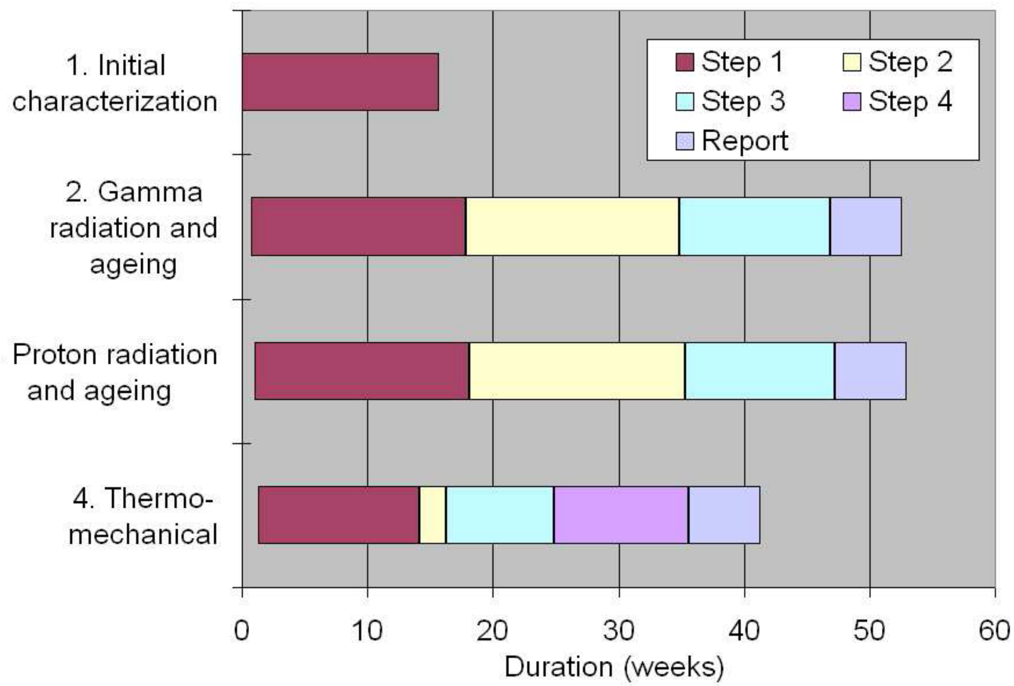
# Project flowchart

## Radiation tests : part of an evaluation program

### Si photodiodes



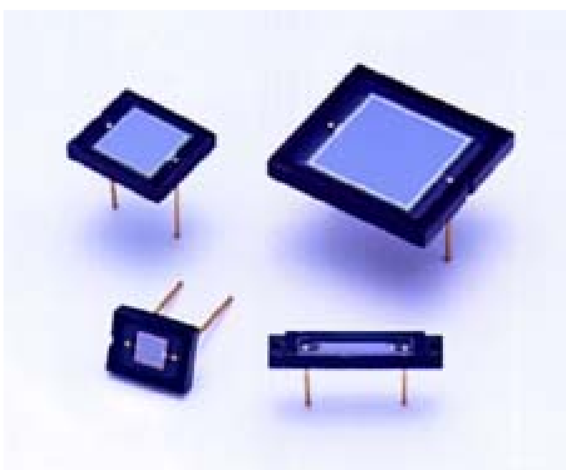

### InGaAs photodiodes

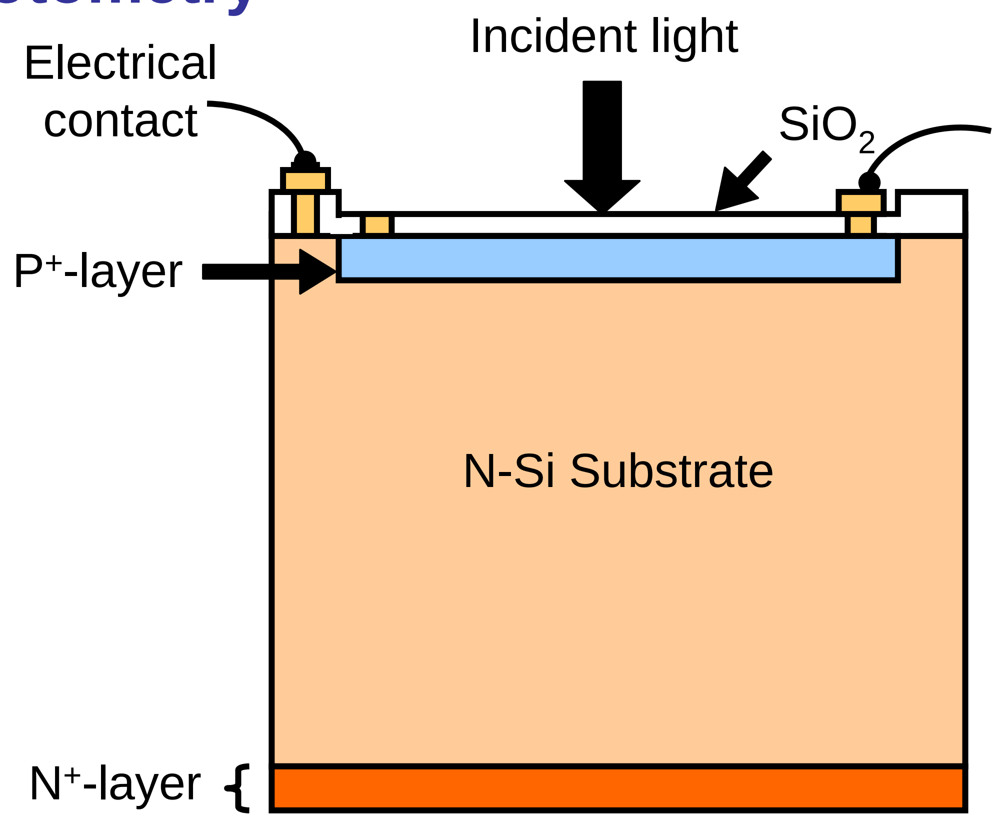



**Cumulated effects : radiation and ageing**

# Components description : Silicon

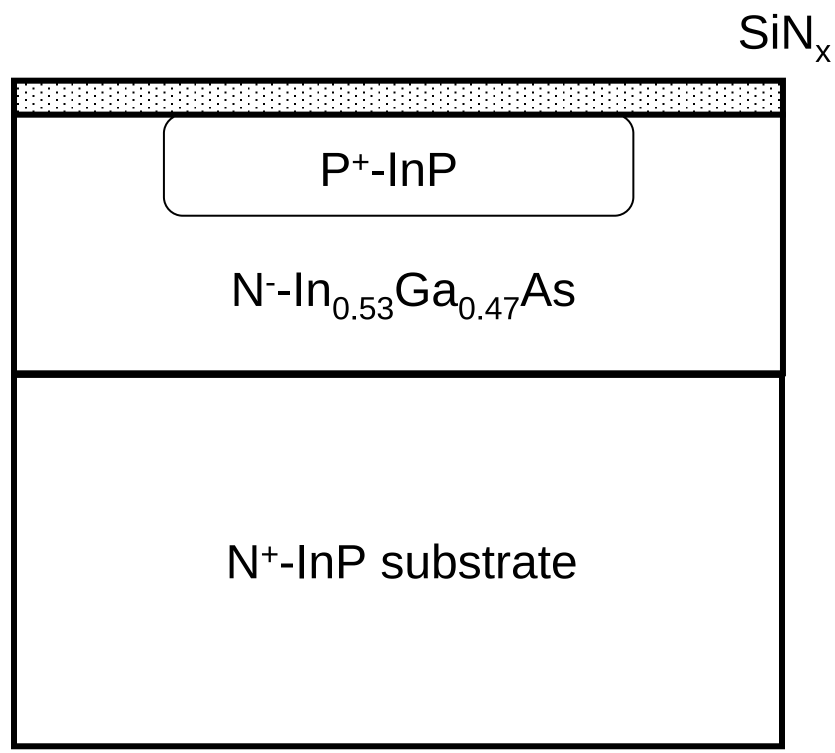
- COTS Silicon photodiode fabricated and qualified by Hamamatsu
- Designed for precision photometry
- Reference S1337-1010BQ
- Application : Galileo



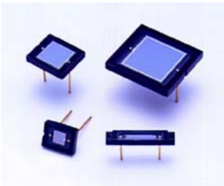


# Components description : InGaAs

- **COTS InP/InGaAs photodiode module fabricated by 3S Photonics (France)**
- **Designed for pump laser diode monitoring, qualified for undersea telecommunication applications (Telcordia)**
- **Reference 1931SGM**



# Radiation test plan : Silicon



**Gamma rays**

**2 DUTs ON, 2 OFF for each condition**

| Dose rate / Dose | 50 rad/h | 700 rad/h | 2 krad/h | 7,7 krad/h |
|---|---|---|---|---|
| 16 krad | | ✓ | | |
| 32 krad | ✓ | ✓ | | |
| 50 krad | ✓ | ✓ | ✓ | ✓ |

**Protons**

**+ multi-energy irradiation @ $5.4\times10^{10}$ p/cm²**

**(All DUTs OFF)**

| Energy / Fluence | 30 MeV | 60 MeV | 100 MeV | 150 MeV |
|---|---|---|---|---|
| $1{,}7\times10^{10}$ p/cm² | | ✓ | | |
| $5\times10^{10}$ p/cm² | | ✓ | | |
| $10^{11}$ p/cm² | ✓ | ✓ | ✓ | ✓ |

# Radiation test plan : InGaAs

**Gamma rays**

**1 DUT ON, 1 OFF for each condition**

| Dose rate \ Dose | 4 krad | 5 krad | 20 krad | 50 krad |
|---|---|---|---|---|
| 28 rad/h | ✓ | | ✓ | ✓ |
| 310 rad/h | | ✓ | ✓ | ✓ |

**Protons**

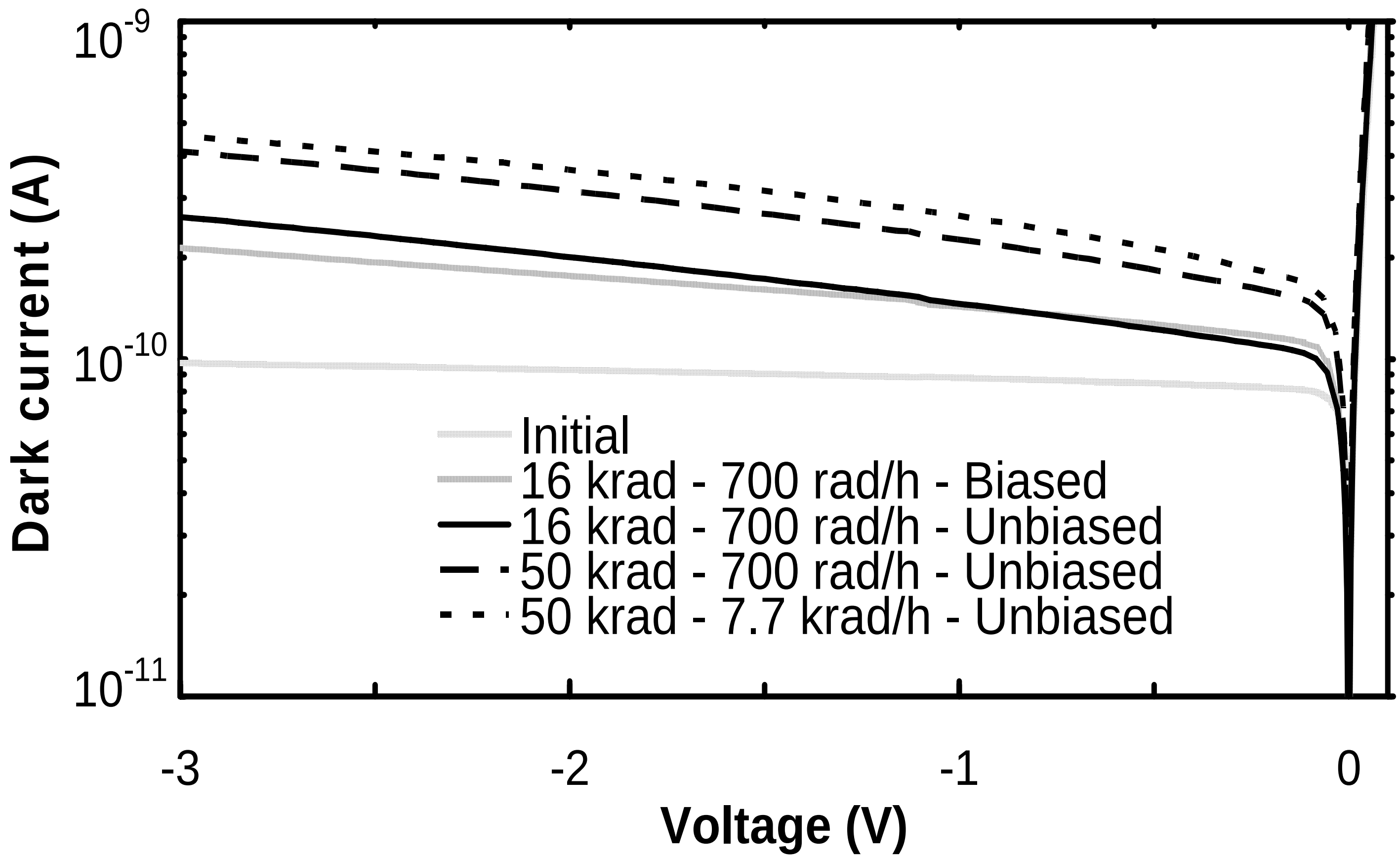
**+ multi-energy irradiation @ $5.4\times10^{10}$ p/cm²**

**(All DUTs OFF)**

| Energy \ Fluence | $5\times10^{10}$ p/cm² | $10^{11}$ p/cm² | $5\times10^{11}$ p/cm² | $10^{12}$ p/cm² |
|---|---|---|---|---|
| 30 MeV | ✓ | ✓ | ✓ | ✓ |
| 80 MeV | | | ✓ | |
| 190 MeV | | | ✓ | |

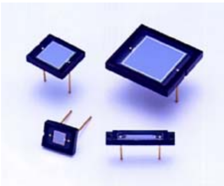
# Experimental results : Si and γ-rays

## Dark current increased by 100% at -0.1 V after γ-rays

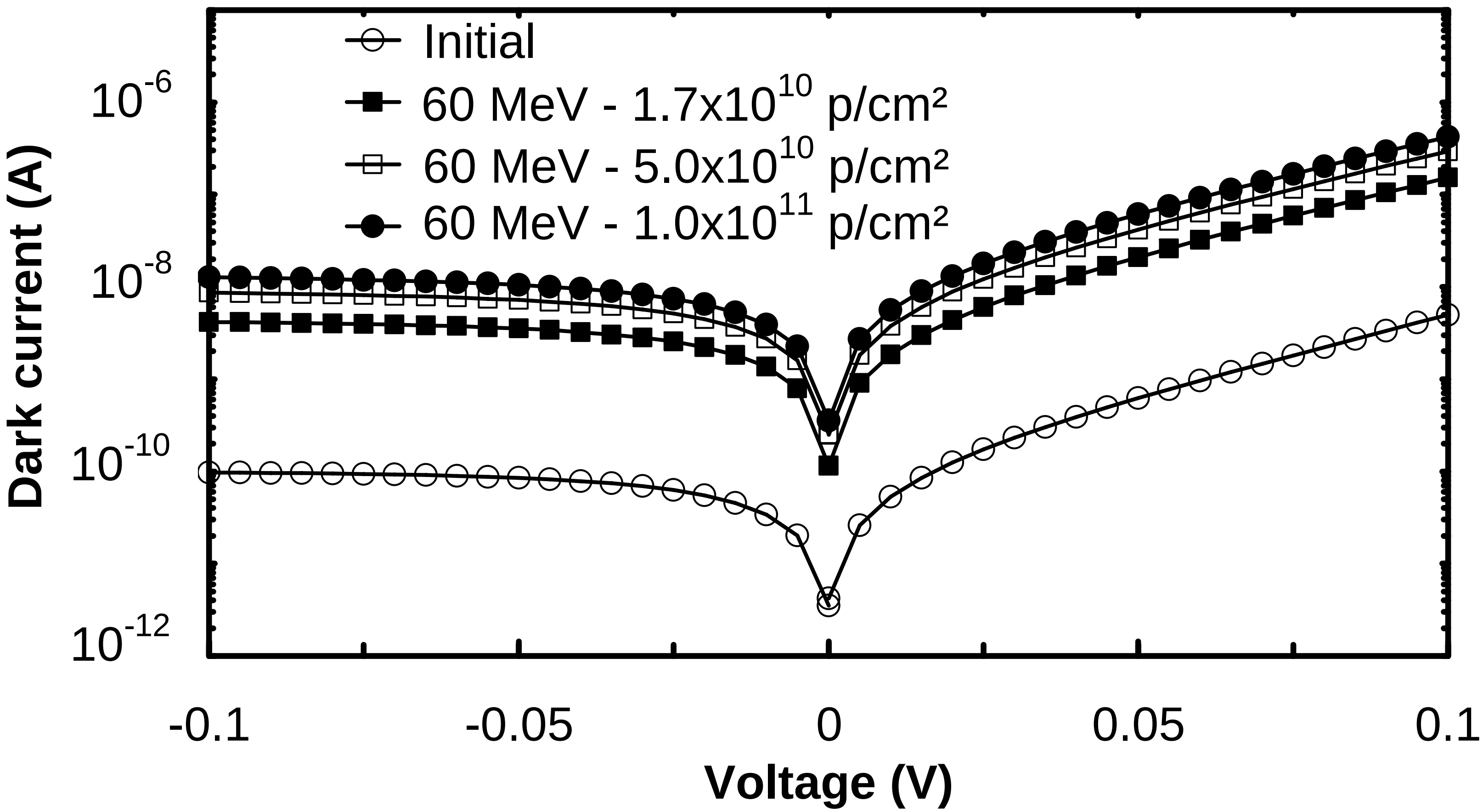



However, no responsivity drift

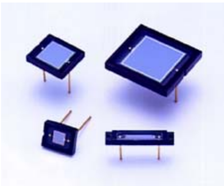
# Experimental results : Si and protons



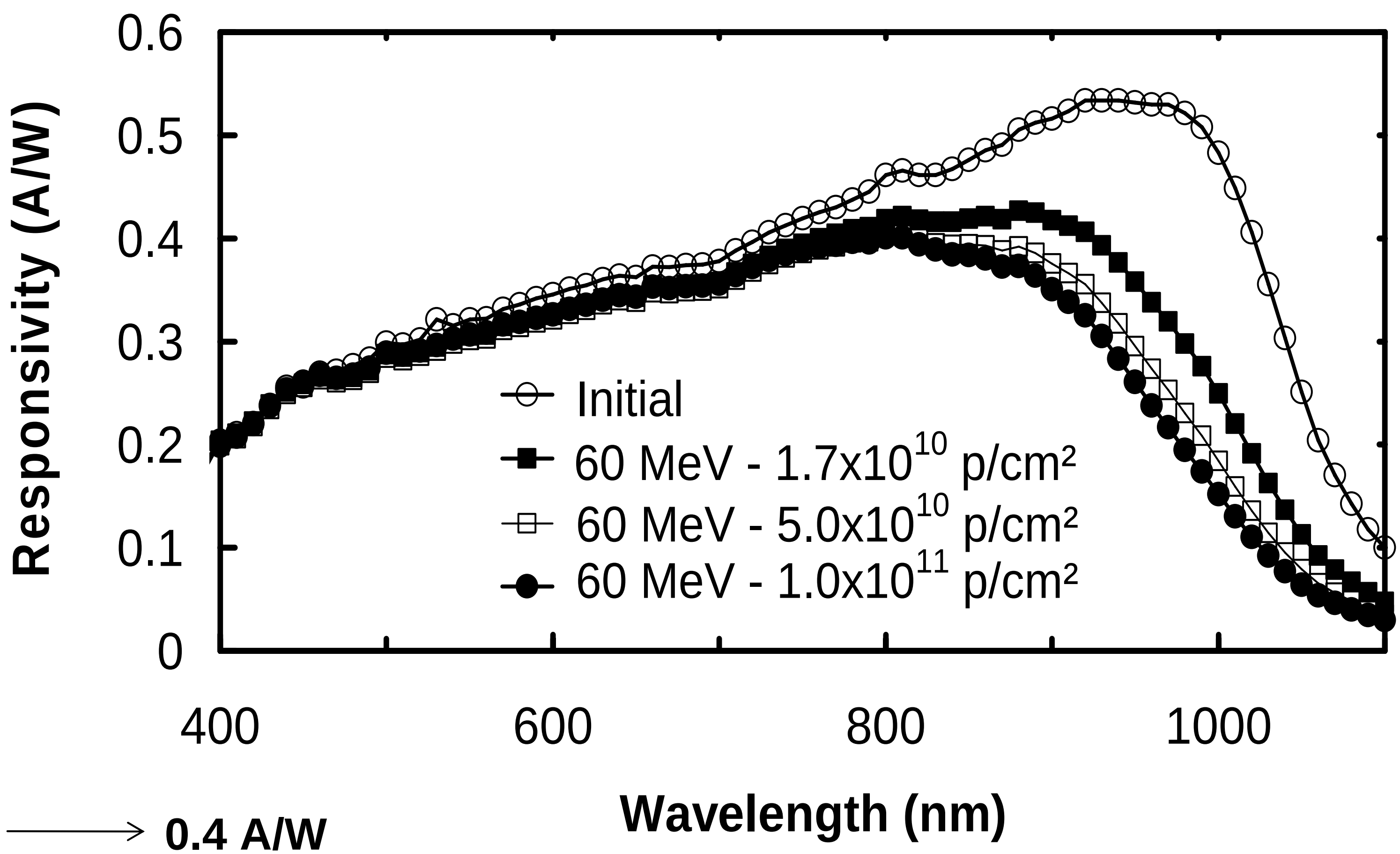
## Dark current increased by 2 decades at -0.1 V after protons



# Experimental results : Si and protons



## Responsivity decreased in IR region after protons

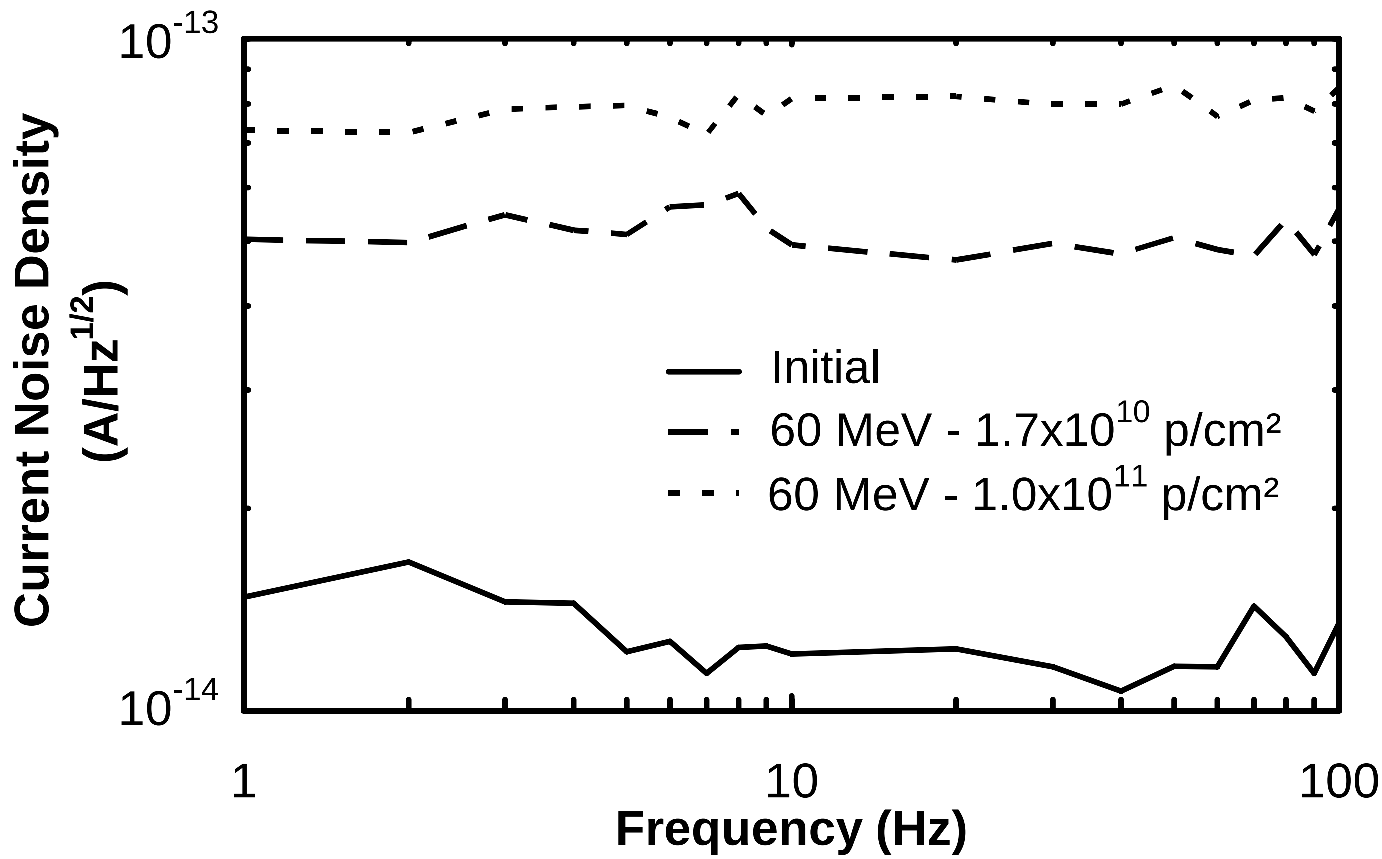



**0.54 A/W ⟶ 0.4 A/W**

**930 nm ⟶ 800 nm**

# Experimental results : Si and protons

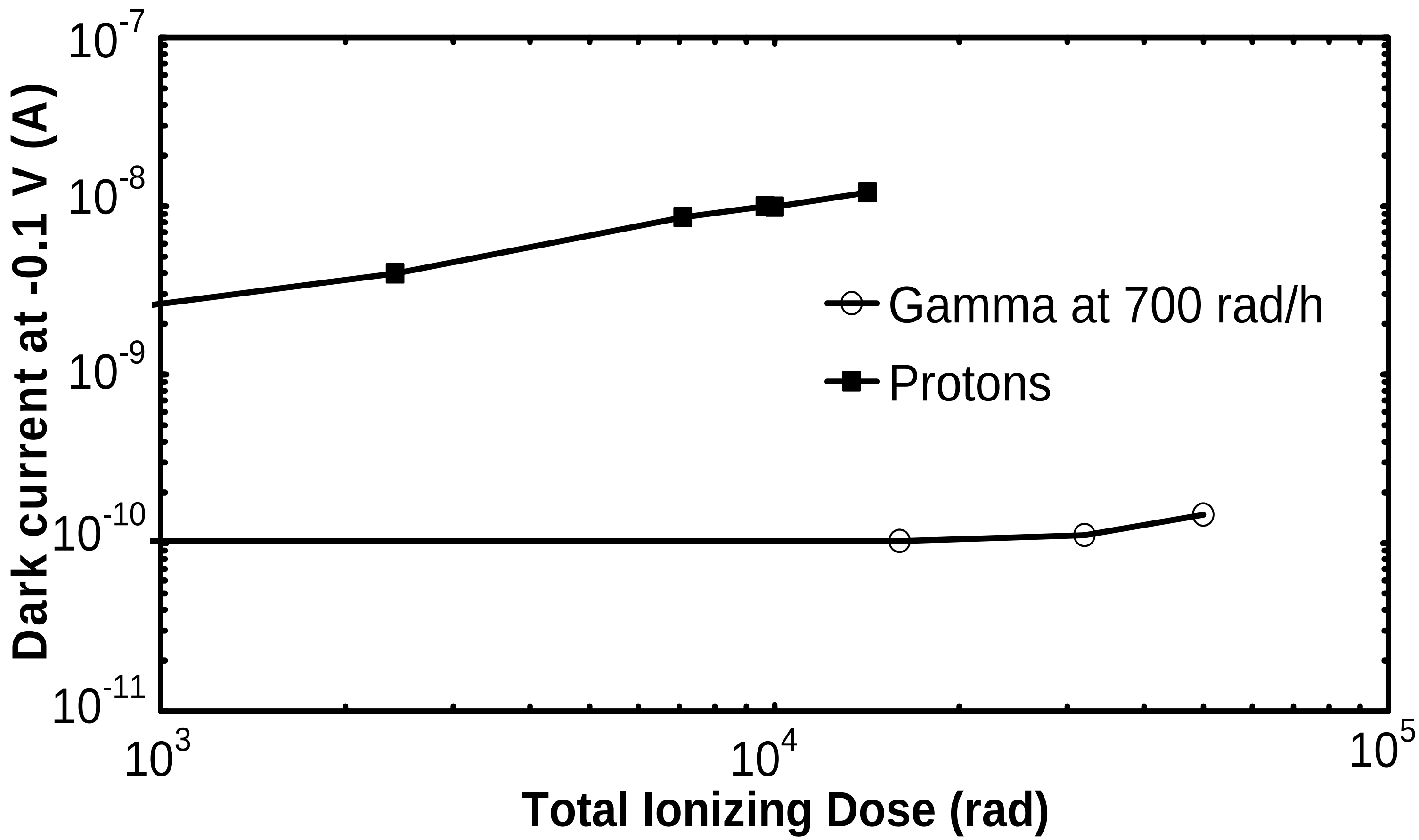
## Low-frequency current noise increased after protons
## No 1/f contribution



# Experimental results : Si $\gamma$-rays VS protons

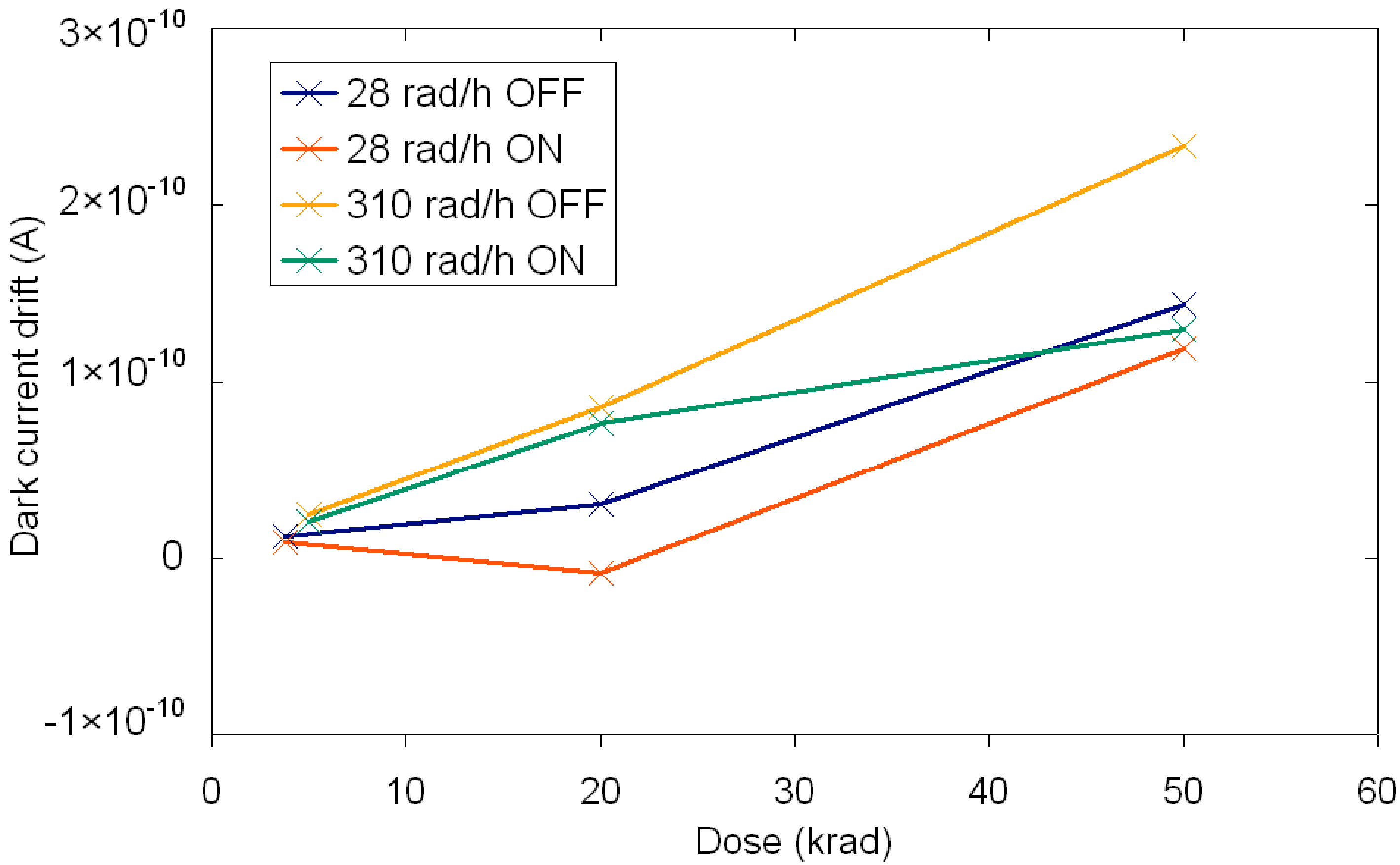
ADVEOTEC a step forward

**Gamma effects negligible compared to proton's**
**The photodiode is more affected by displacement damage effects**



# Experimental results : InGaAs and $\gamma$-rays

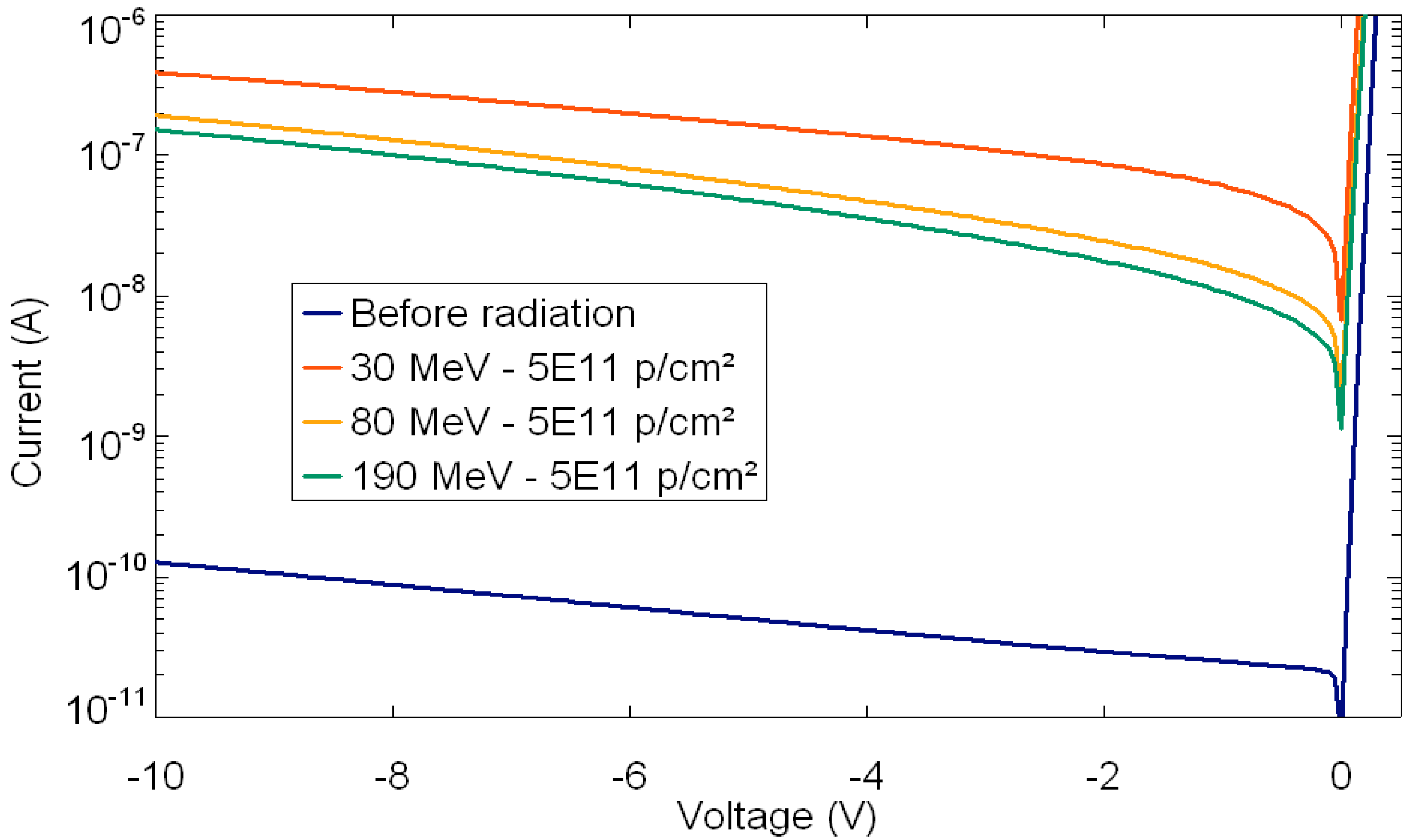
- Dark current increased with dose
- High dose rates are more destructive
- Higher degradation when unbiased




**No drifts observed on other electro-optical characteristics**

# Experimental results : InGaAs and protons

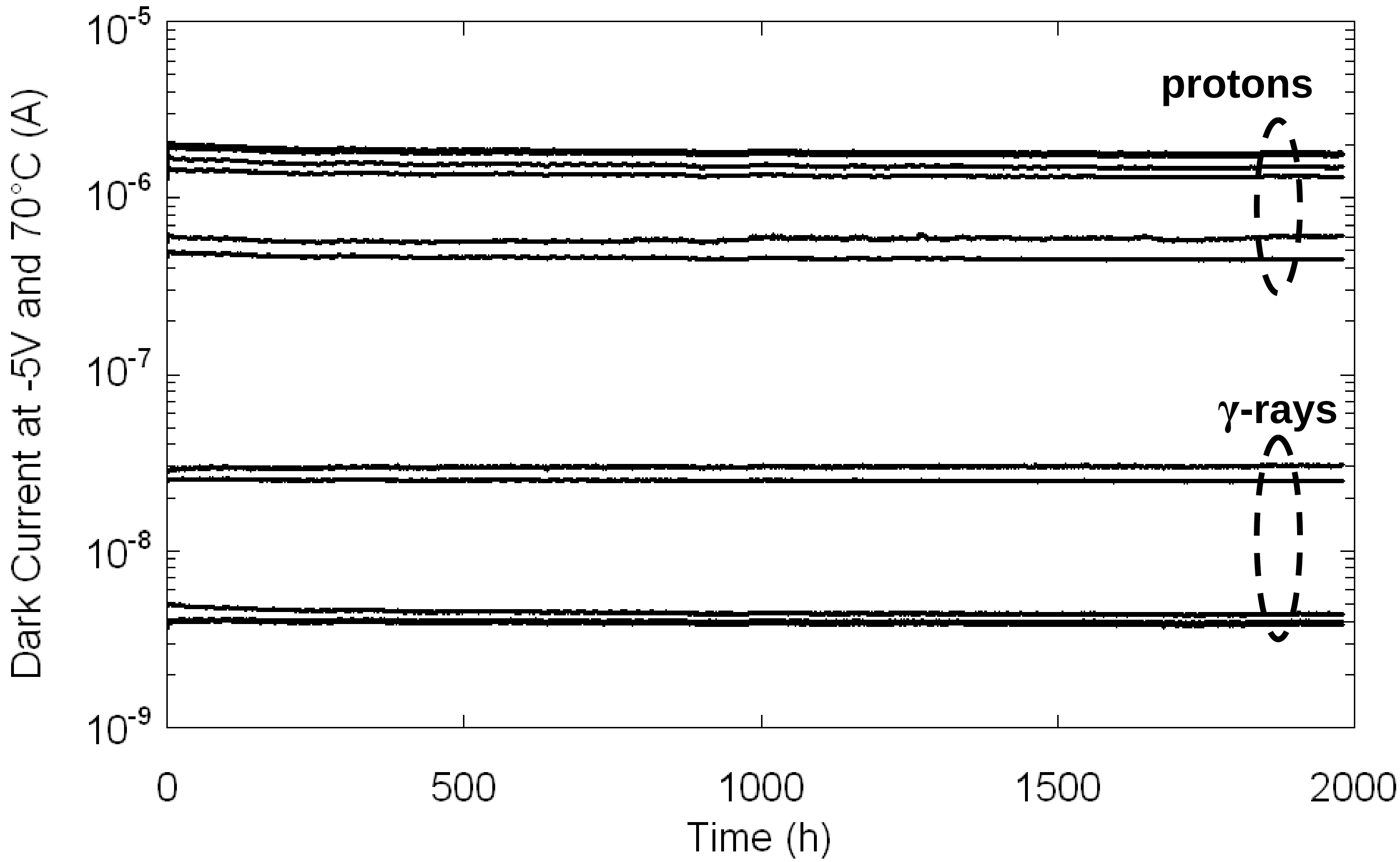
## Dark current increased by 3 decades after protons




## Dark current noise increased too (white noise only, no 1/f)

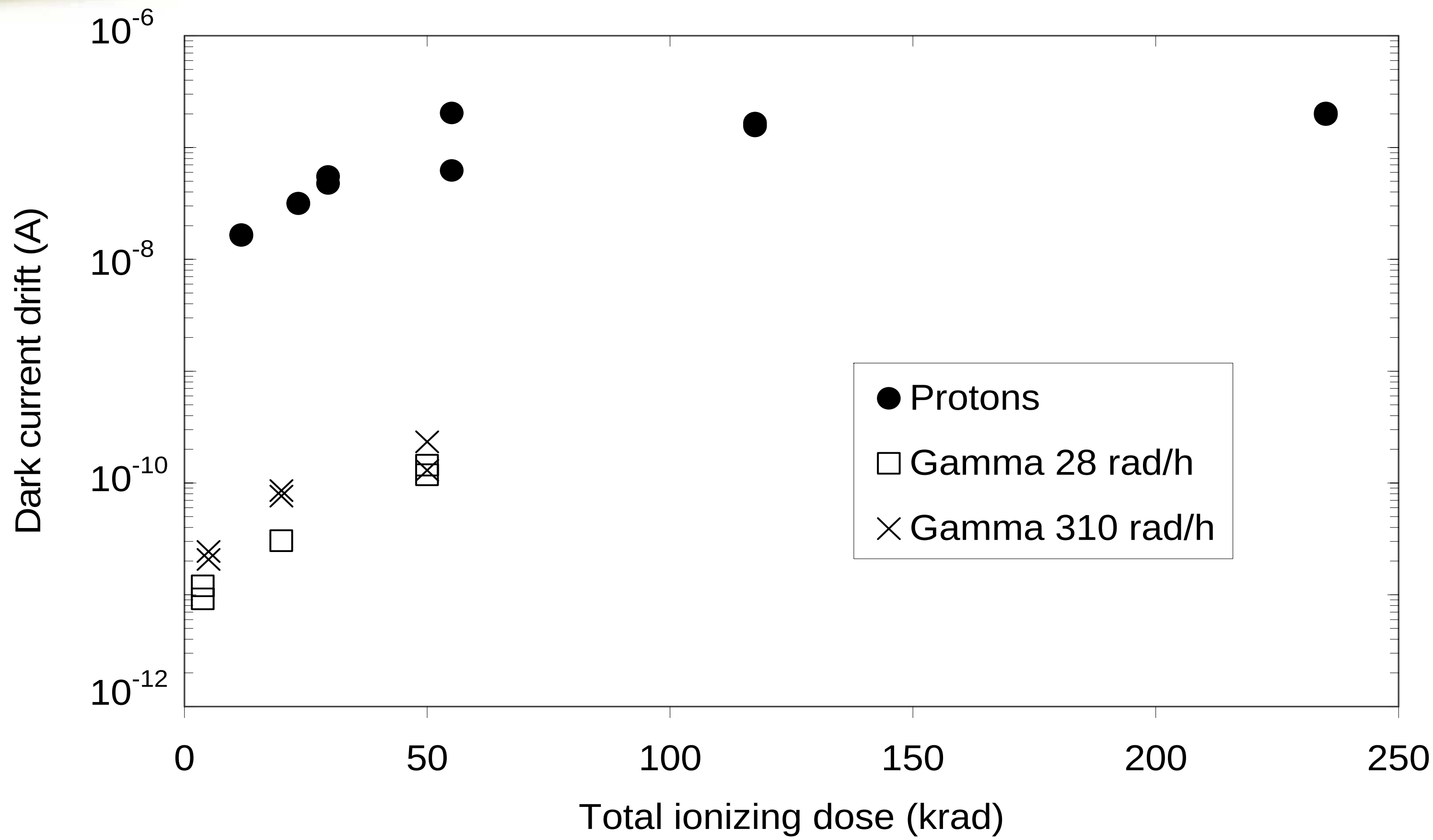
# Experimental results : InGaAs γ-rays and $H^+$

## Life test after radiation



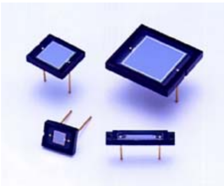

## Reliability not affected by radiation

# Experimental results : InGaAs $\gamma$-rays VS $H^+$




**As in Si photodiodes,**
**gamma effects negligible compared to proton's**

# EO modeling : Si before irradiation



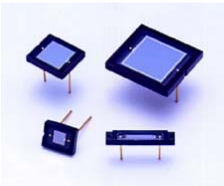
## Dark current

Low reverse bias (< 0.1 V) and $N_A >> N_D$ → Thin space charge region

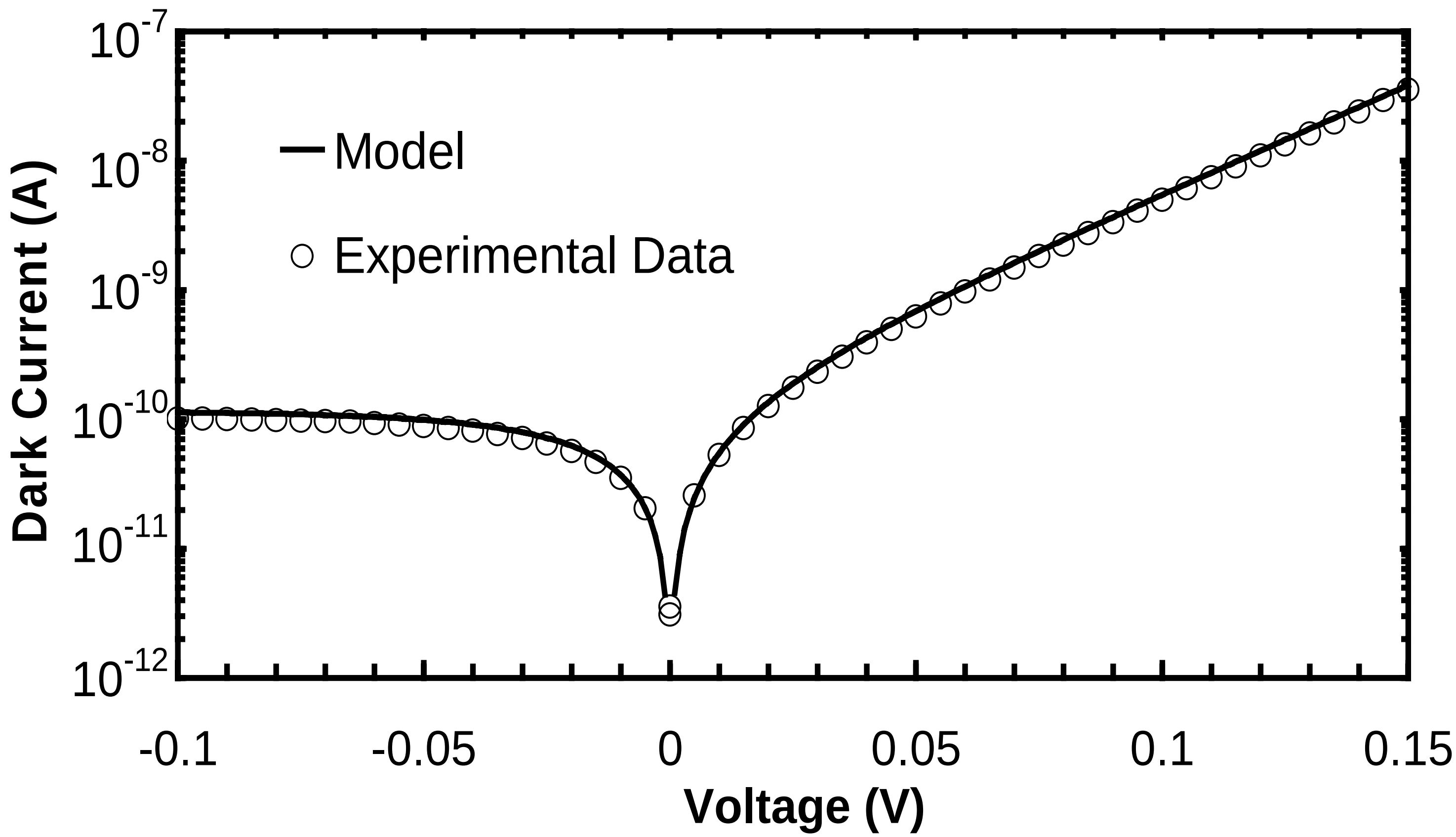
Thin $P^+$ layer → Diffusion of minority electrons negligible

Deep *n*-type bulk, and thick $N^+$ layer in the back side of the chip : Back Surface Field (BSF) → Diffusion of minority holes is the main transport phenomenon

# EO modeling : Si before irradiation

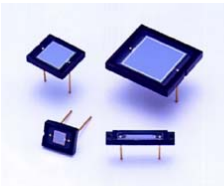


## Dark current before irradiation

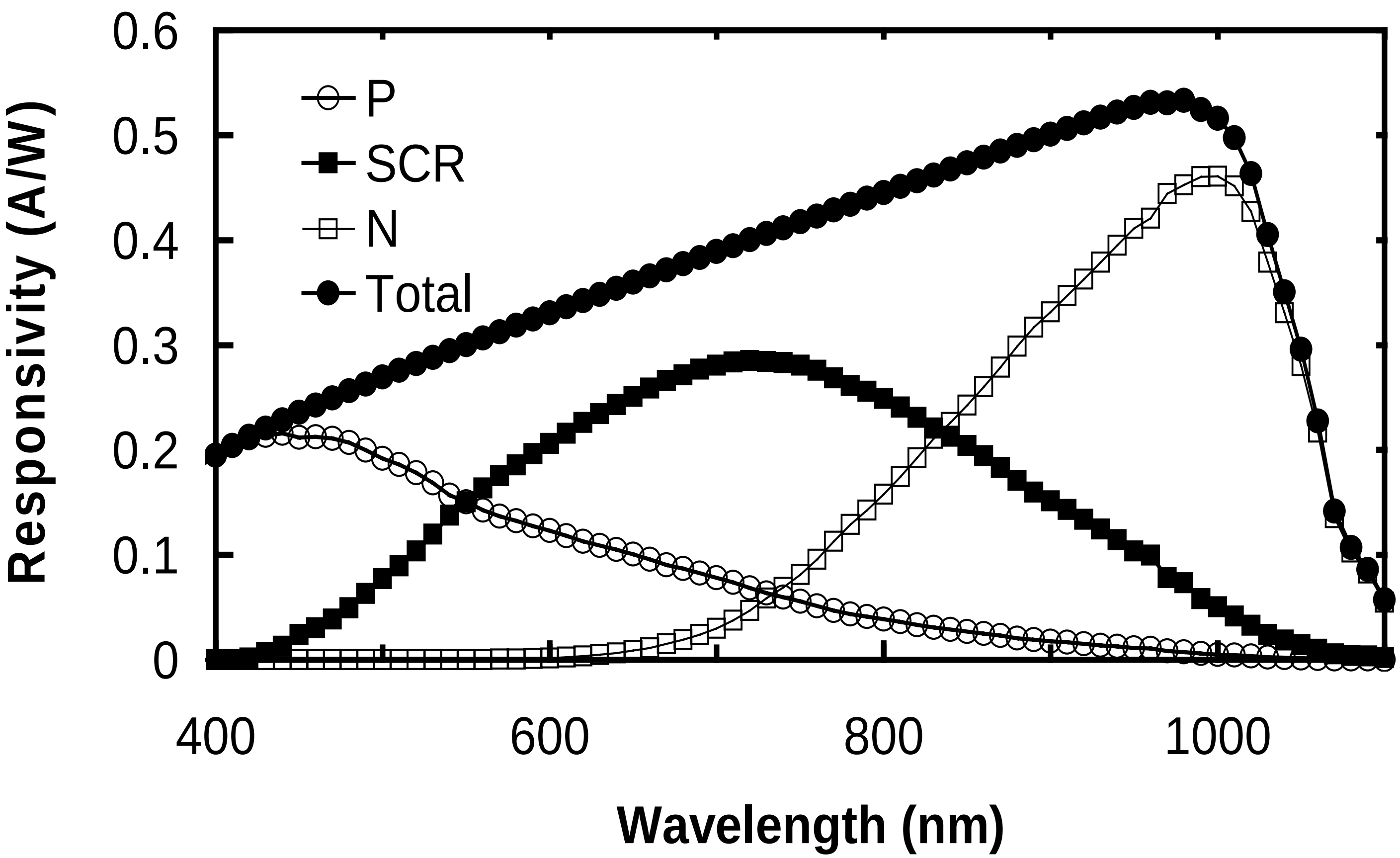



**Minority holes diffusion current in the substrate**
**Physical parameters found bibliographically and experimentally**

# EO modeling : Si before irradiation



## Responsivity before irradiation




**Total photocurrent = sum of the photocurrents generated in the three areas**

# EO modeling : InGaAs before irradiation

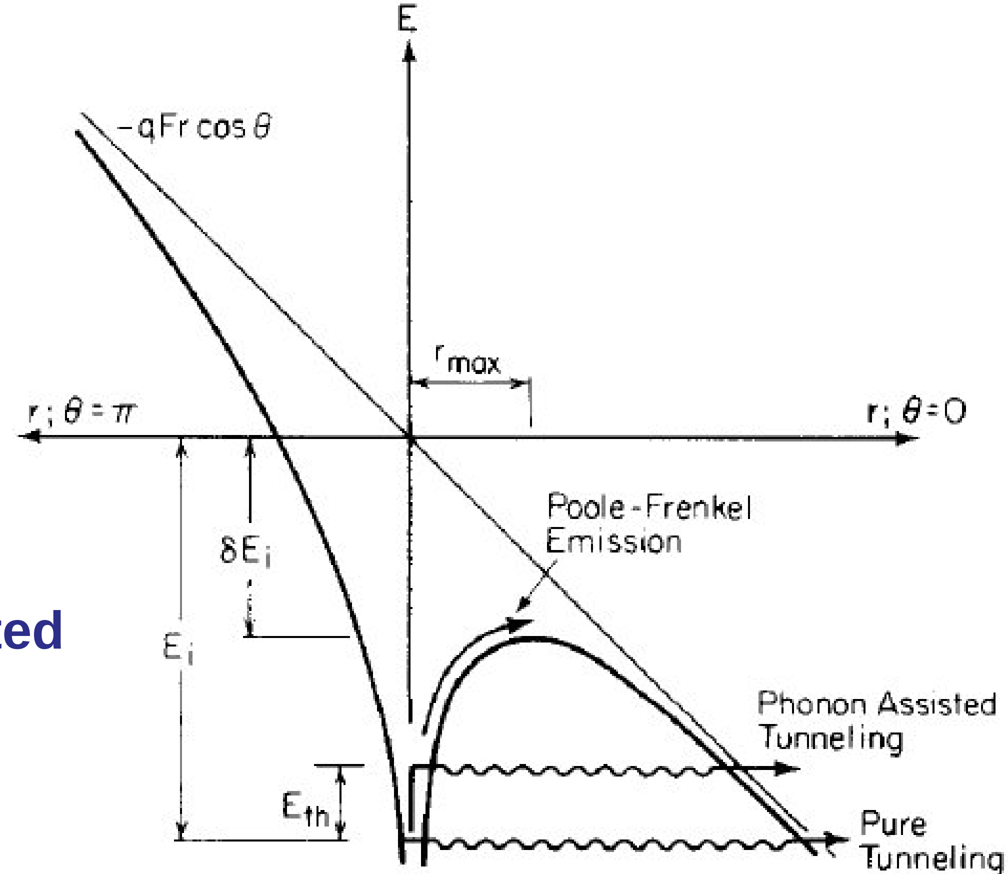
**Mid-gap traps**

↓

**Thermal emission**

**Electric field**

**Poole-Frenkel emission** | **Phonon assisted tunneling**




⟶ **Electric field enhanced generation**

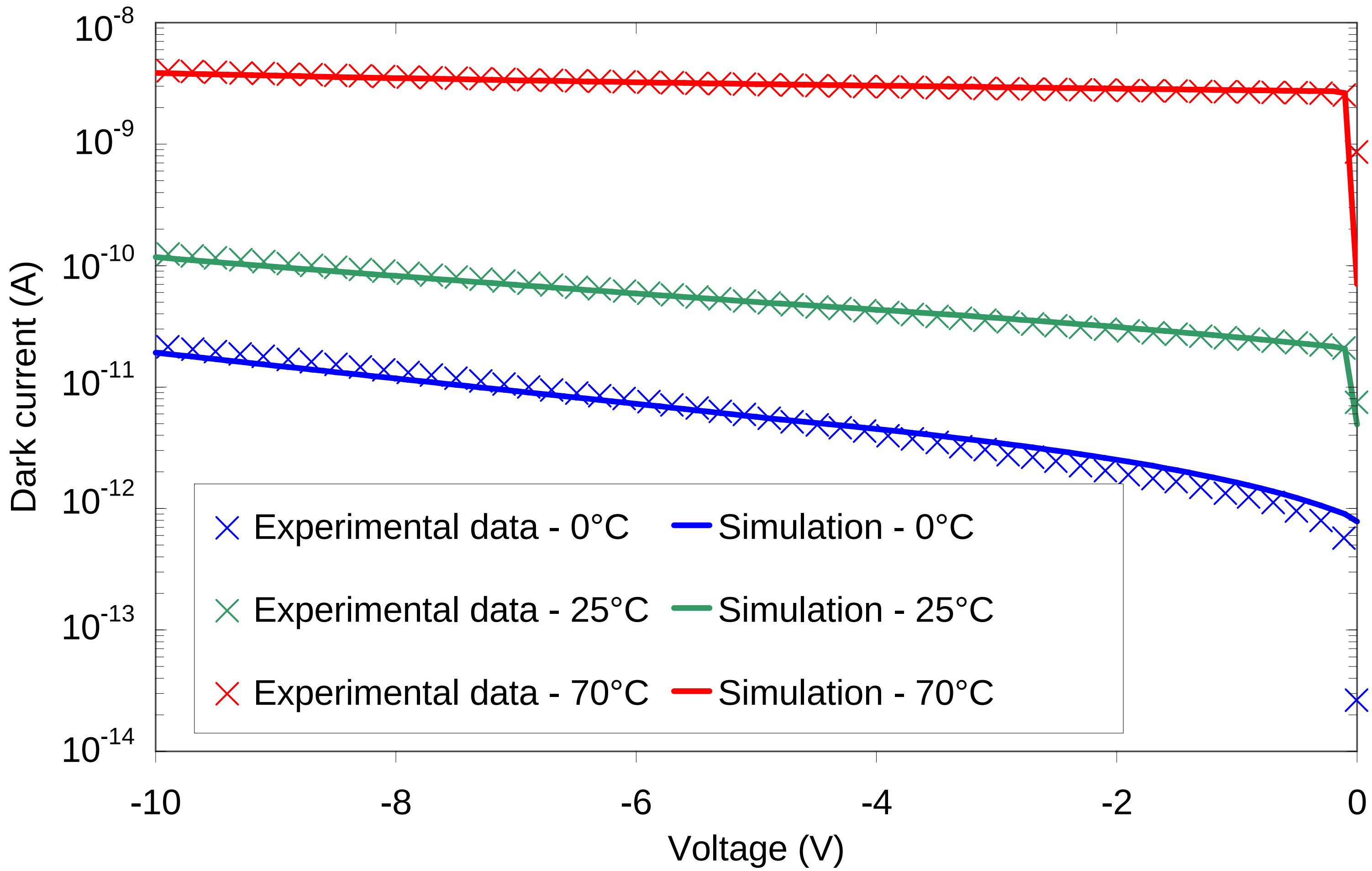
P.A. Martin *et al.*, J. Appl. Phys. **52**, 7409 (1981)

**+ diffusion at higher temperatures**

# EO modeling : InGaAs before irradiation

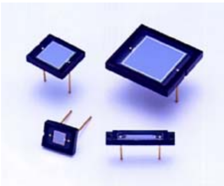
ADV EOTEC a step forward

## Dark current before irradiation




 R037R006AET01, 28 March 2011, CNES/ESA Final Presentation Days

# Proton effects on carrier lifetime in Si



**Displacement of atoms**

**Recombination centers : Shockley-Read-Hall**

**Decrease of the carriers lifetime (minority holes in our case)**

$$L_p = \sqrt{D_p \tau_p}$$

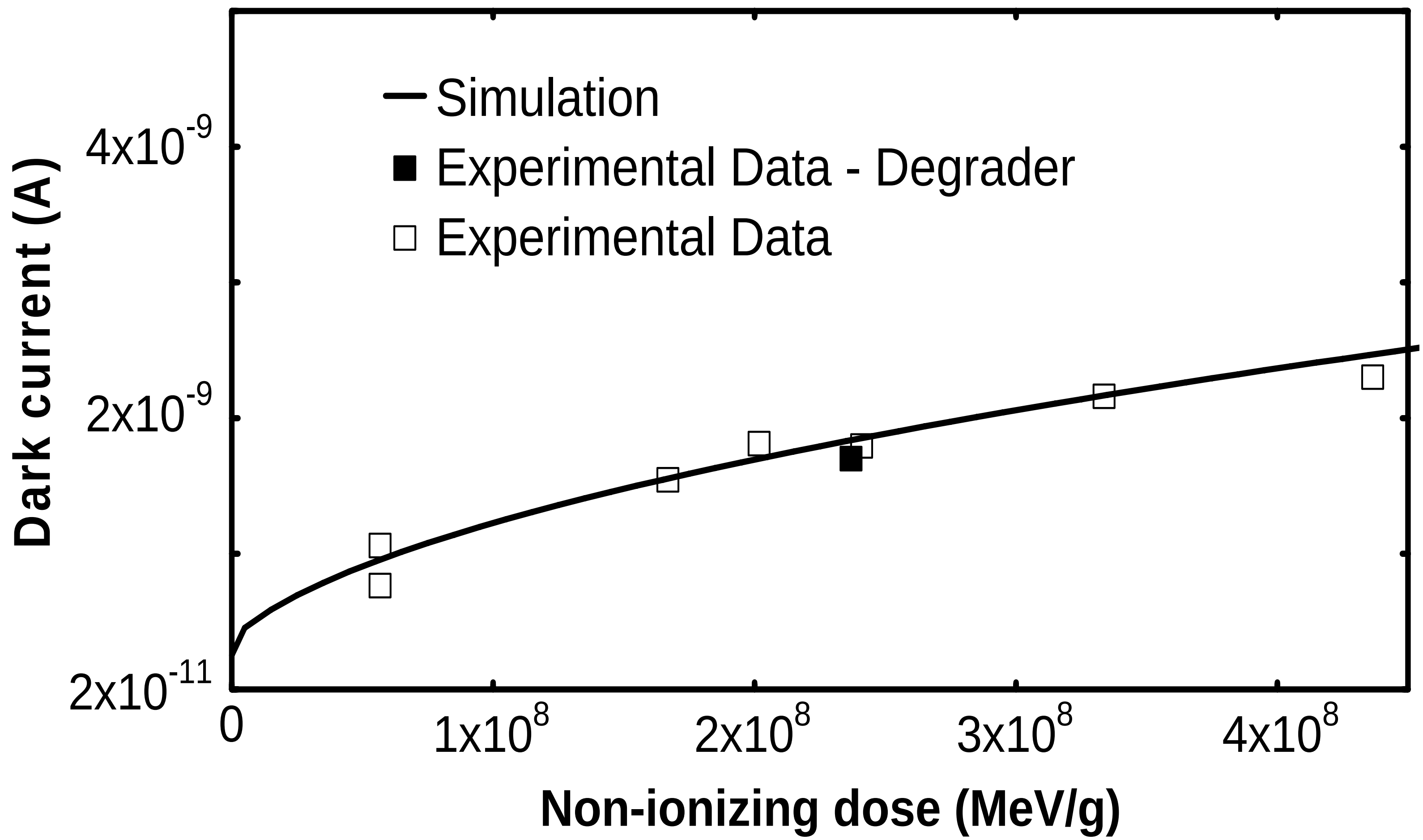
$$\frac{1}{\tau_p} = \frac{1}{\tau_{p,0}} + k.D_d$$

**where the displacement damage dose is**

$$D_d = NIEL.\Phi_P$$

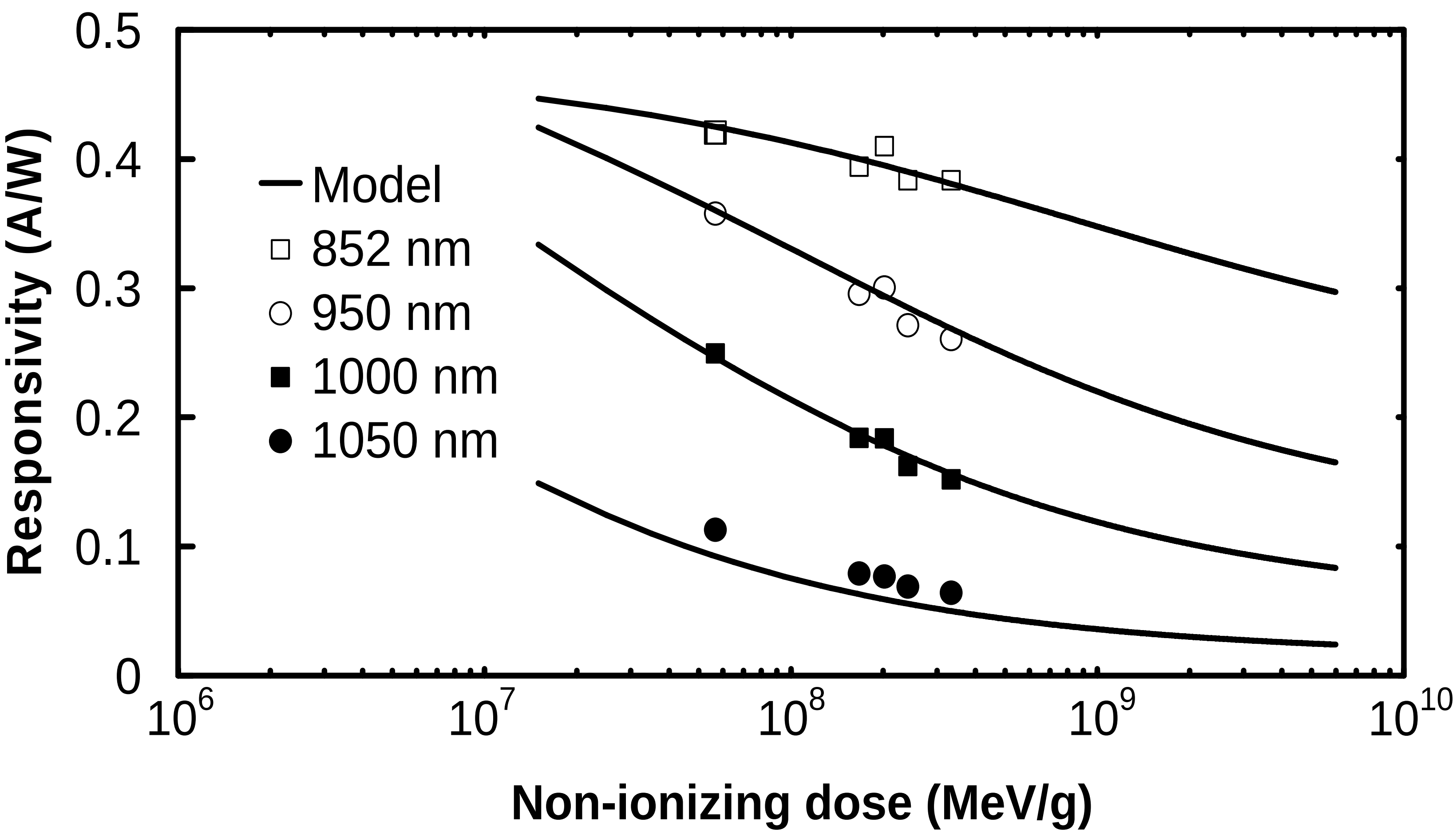
***k*** **: degradation factor**

# EO modeling : Si after irradiation




**Use of mono-energetic proton beam validated**

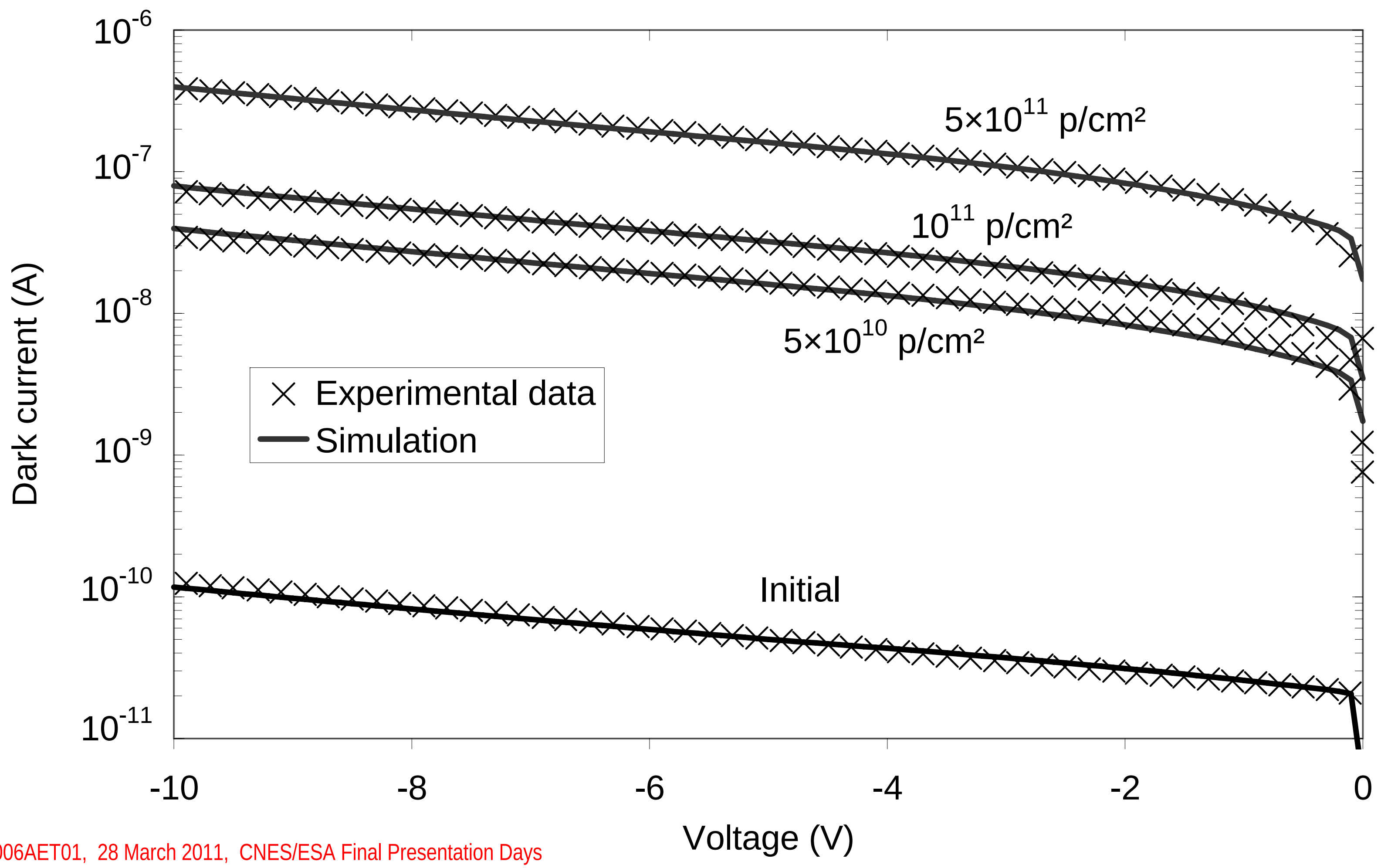
# EO modeling : Si after irradiation



# EO modeling : InGaAs after irradiation

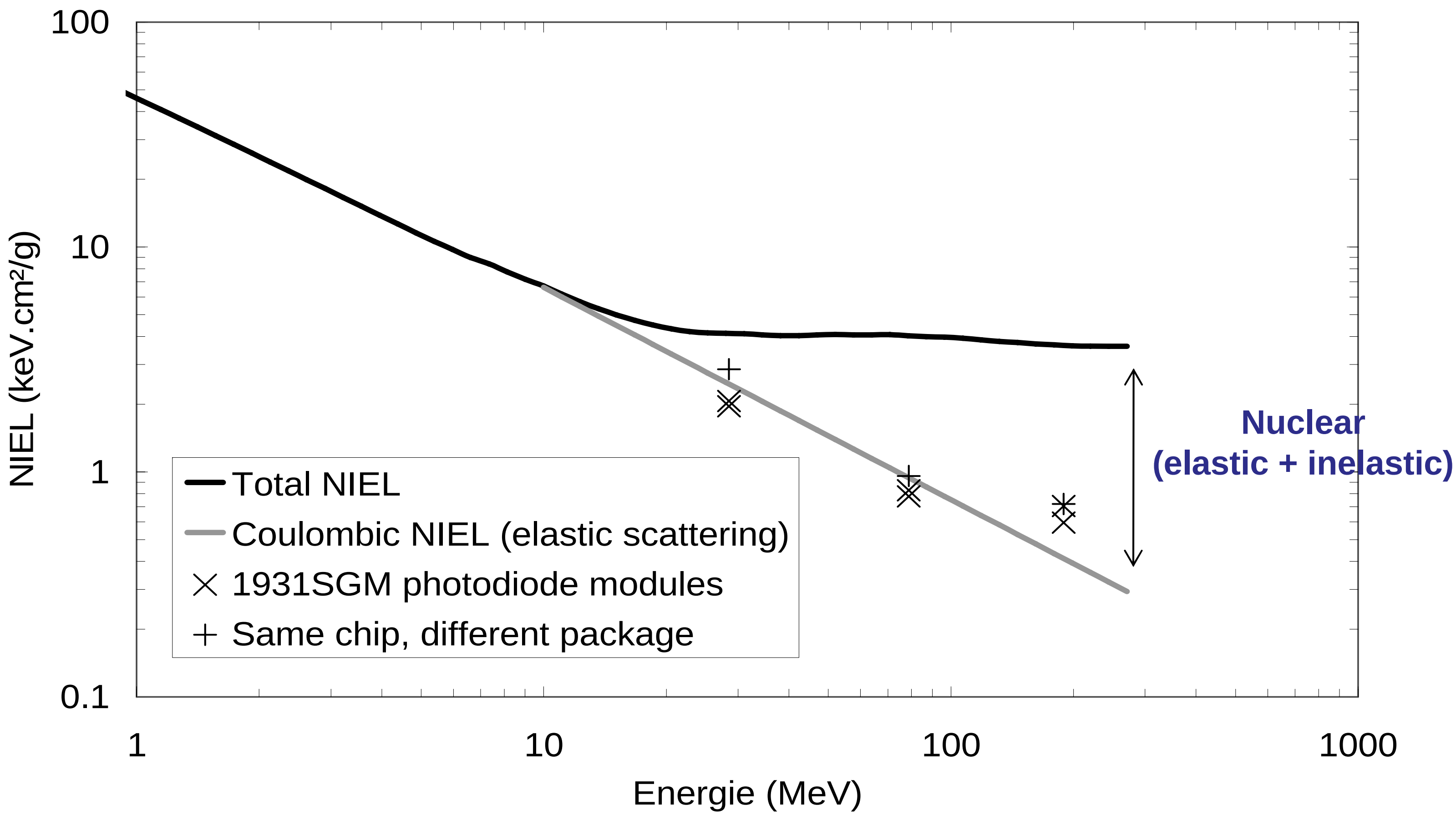
**Introduction of defects in SCR** $\longrightarrow$ $\frac{1}{\tau} = \sigma v_{th} N_t = k\Phi_P$

**Dark current versus fluence**



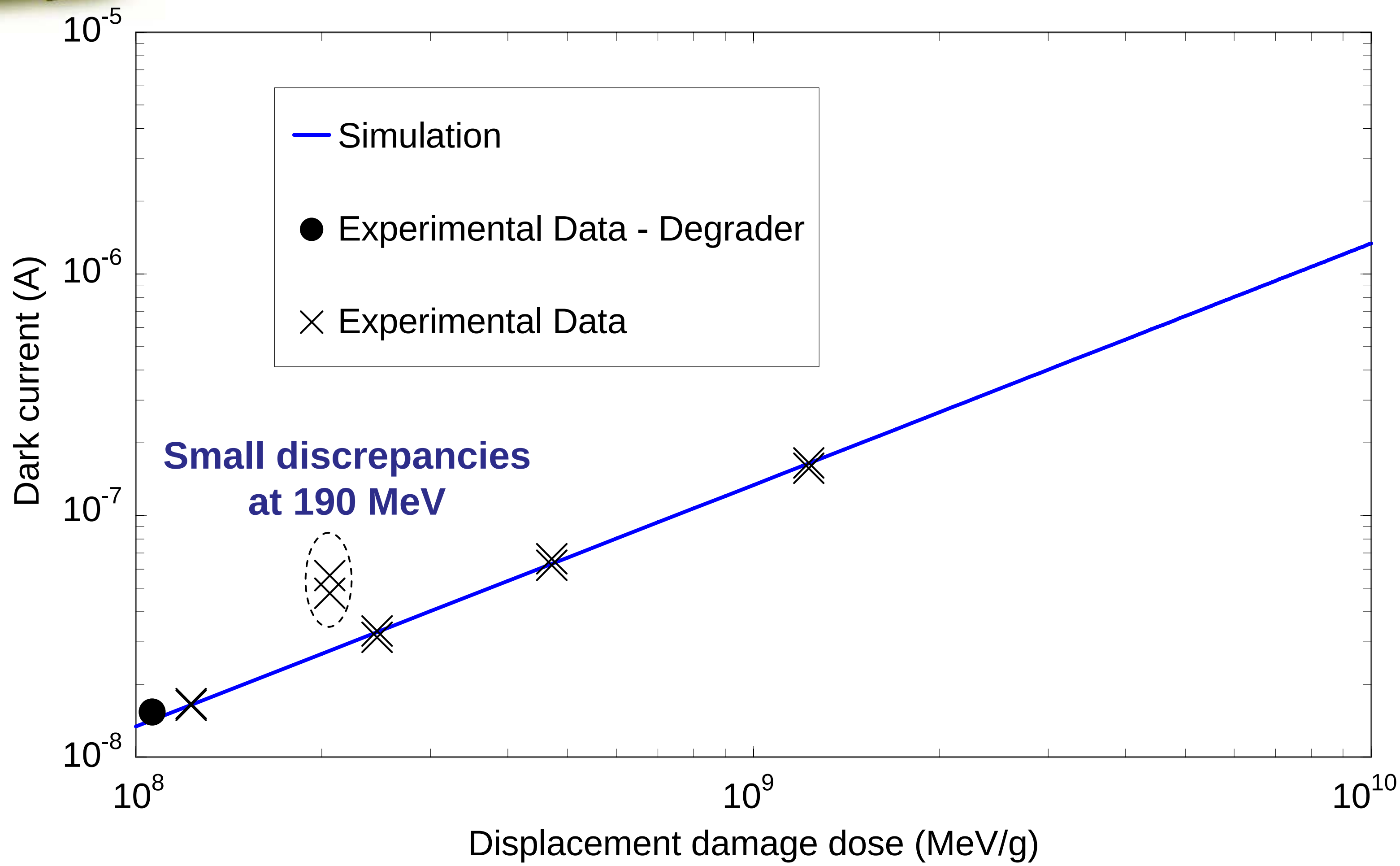
# EO modeling : InGaAs, $H^+$ & Energy

## As in GaAs, poor agreement with NIEL




**Some defects are not electrically active ?** ⟶ $D_d = NIEL_{Coulombic}.\Phi_P$

# EO modeling : InGaAs after irradiation




**As in Si, the use of mono-energetic proton beam is also validated**

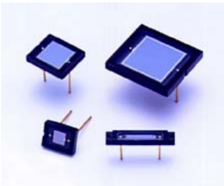
# EOL predictions

## Simulation of the space environment using OMERE software

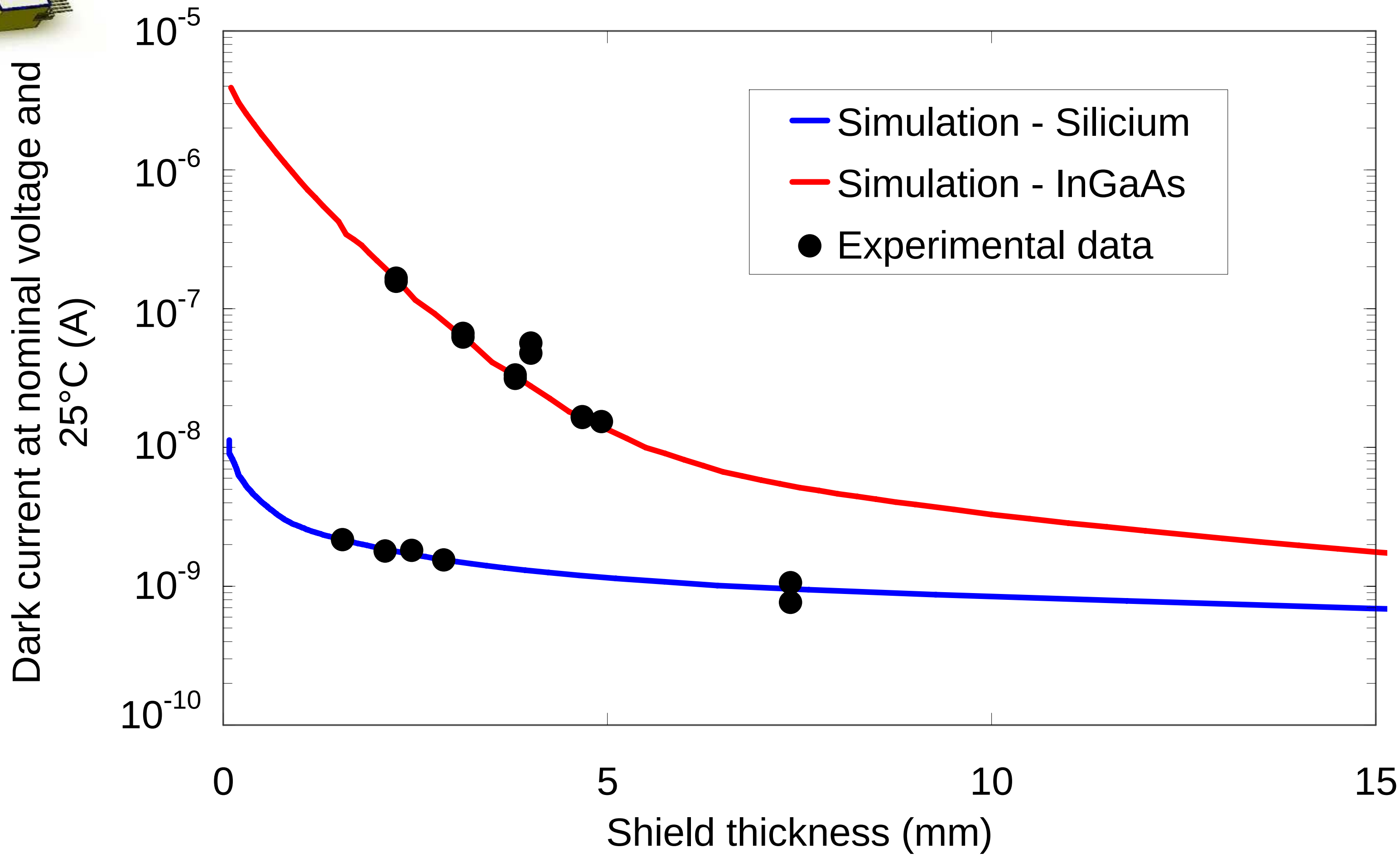
### Equivalent displacement damage dose for the Galileo mission

- **Distance to Earth : 23 222 km**
- **Inclination : 56 °**
- **Spacecraft lifetime : 12 years**
- **Radiation belt protons model : AP8 Min. standard**
- **Solar particles model : ESP (probability : 85 %)**

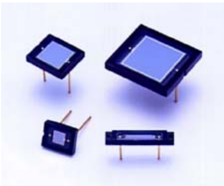
# EOL predictions : Si and InGaAs



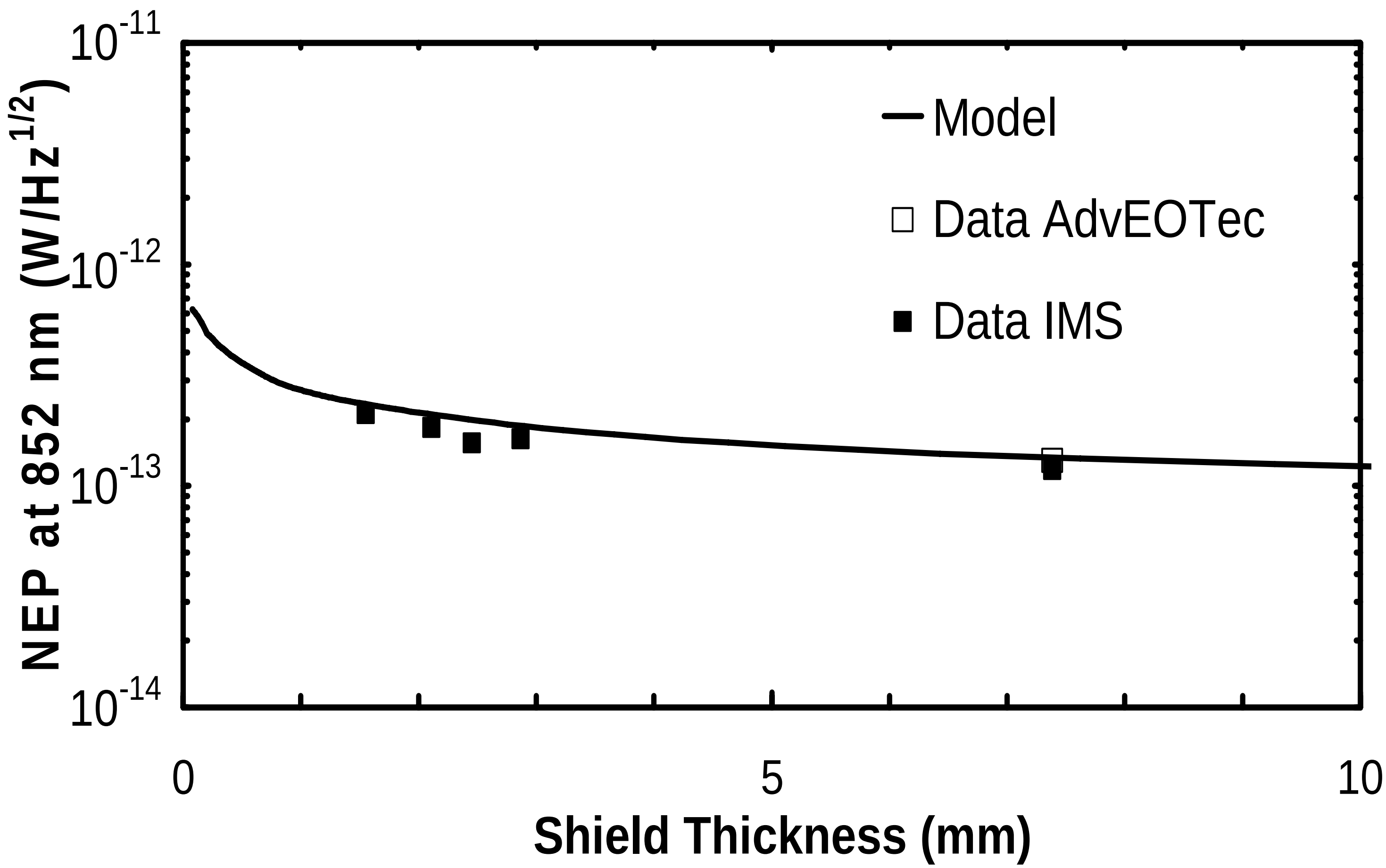
## Dark current estimation vs equiv. shield thickness



# EOL predictions : Si for Galileo

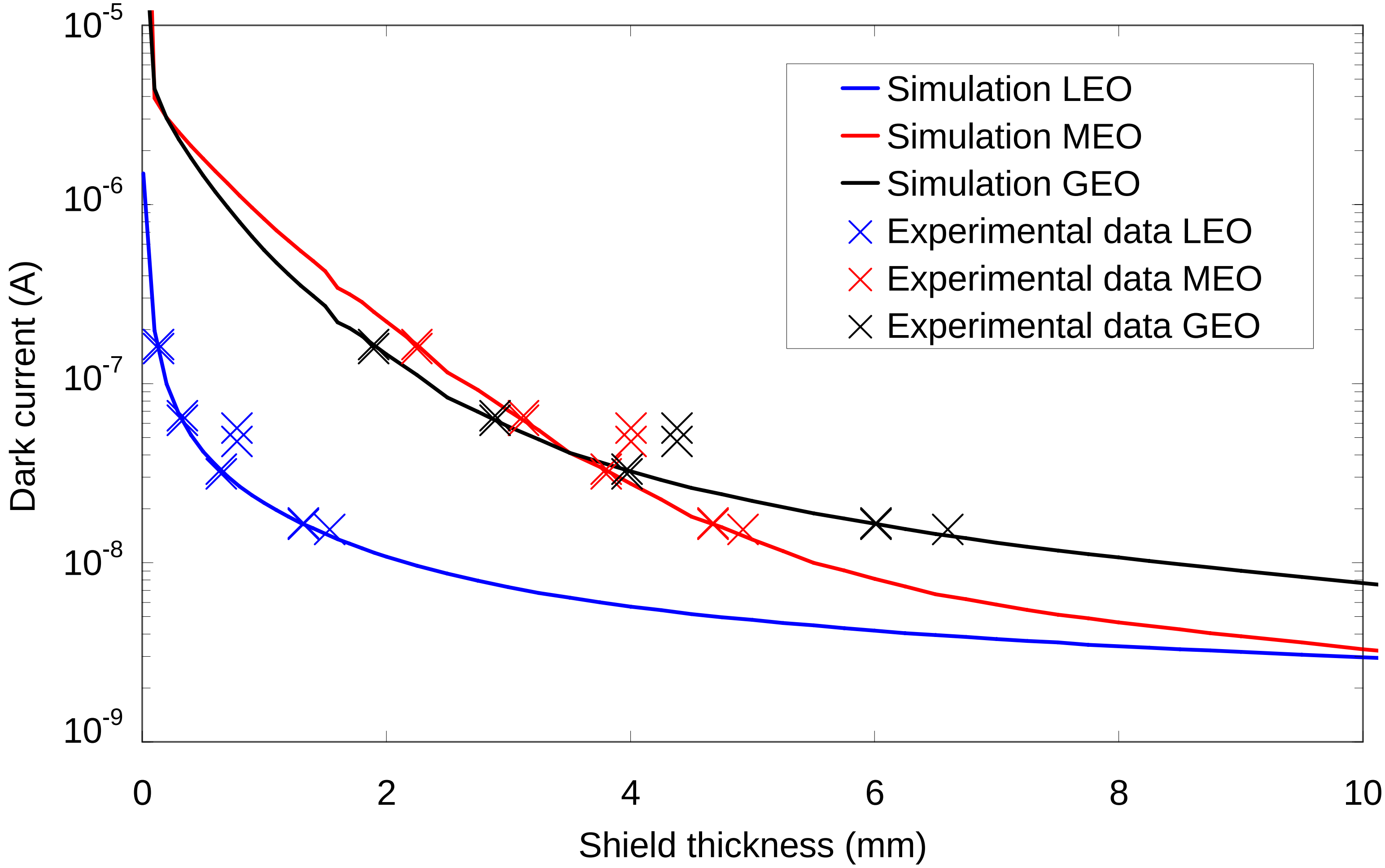


$$NEP = \frac{mean\ dark\ current\ noise}{responsivity}$$



# EOL predictions : InGaAs for 3 missions

## LEO (5 years), MEO (12 years), GEO (20 years)



# Conclusion

- Evaluation of silicon and InGaAs photodiodes' performances under radiation

- Cumulative tests demonstrate no effect of radiation on lifetest

- Successful modeling of electro-optical characteristics and effects of proton radiation through physical simulation and interpretation

  - High quality optoelectronic measurements (metrology) required for this modeling tool

  - Prediction of end of life performances for space applications is possible thanks to the model

# Acknowledgements

**All our appreciation goes to :**

**CNES for funding and support**

**3S Photonics for having provided photodiode modules and expertise**

**IMS Laboratory for physical analysis**

## Thank you for your attention