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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

SiPMs

in high radiation environment

Erika Garutti

Radiation hardness of SiPM

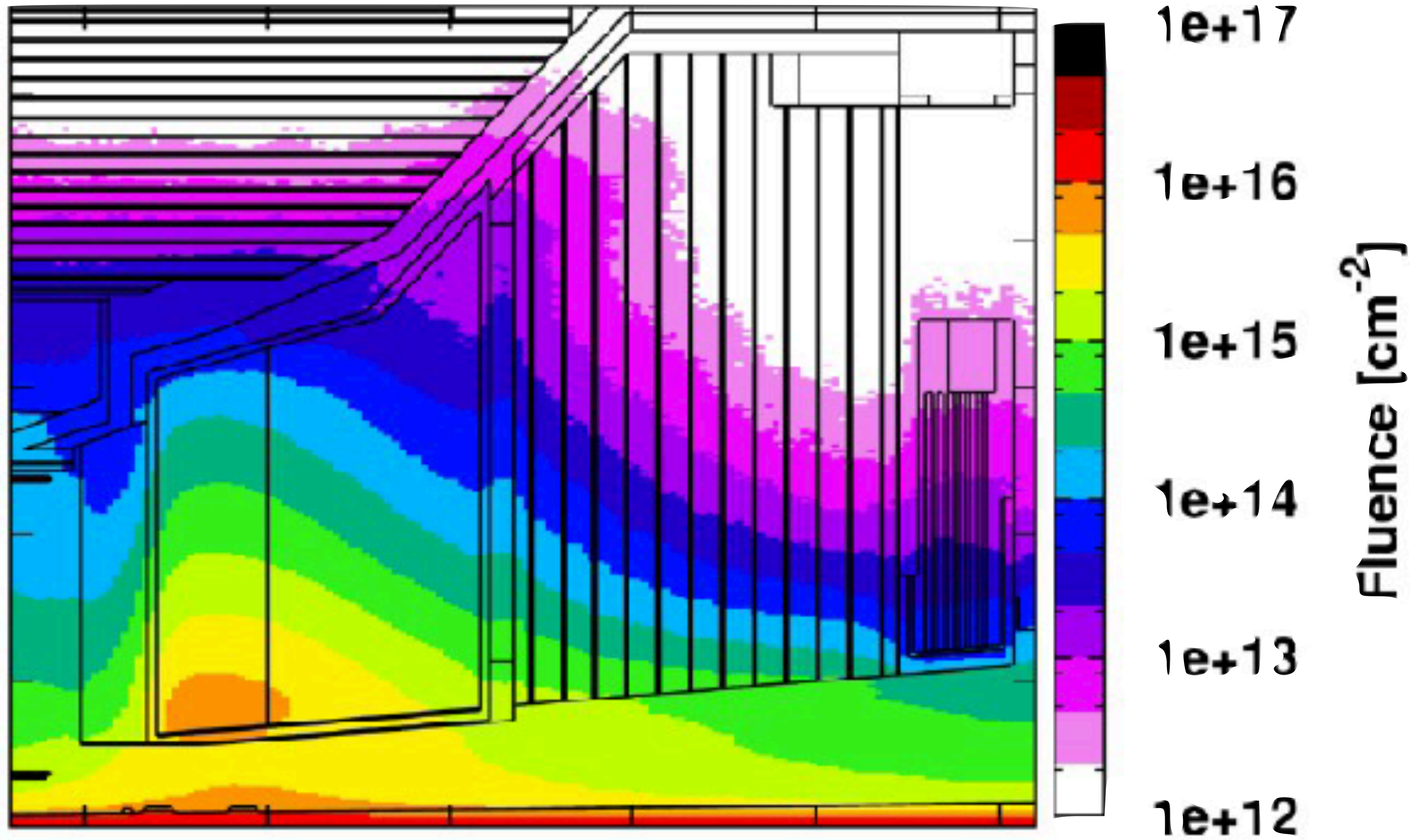
scientific relevance

- SiPMs is the photo-sensor of choice in many upcoming experiments often applied in radiation hard environment

Examples:

- Imaging calorimeters for collider experiments:
  - Hadronic calorimeter for ILC (CALICE)
    ➔ ϕ_{eq} ~10^{10} cm^{-2} after 500 fb^{-1}
  - Upgrade of CMS hadronic calorimeter (HGCAL)
    ➔ $\phi_{eq} = 6 \cdot 10^{13}$ cm^{-2} (after 300 fb^{-1})
  - New CMS MIP timing detector
    ➔ **$\phi_{eq} = 2 \cdot 10^{14}$ cm^{-2}** (after 300 fb^{-1})

CMS HGCAL



- Space experiments:
  - High radiation expected for detectors in space
    ➔ **$\phi_{eq} = 5 \cdot 10^{10}$ cm^{-2}**, AGILE gamma ray detector in geostationary orbit

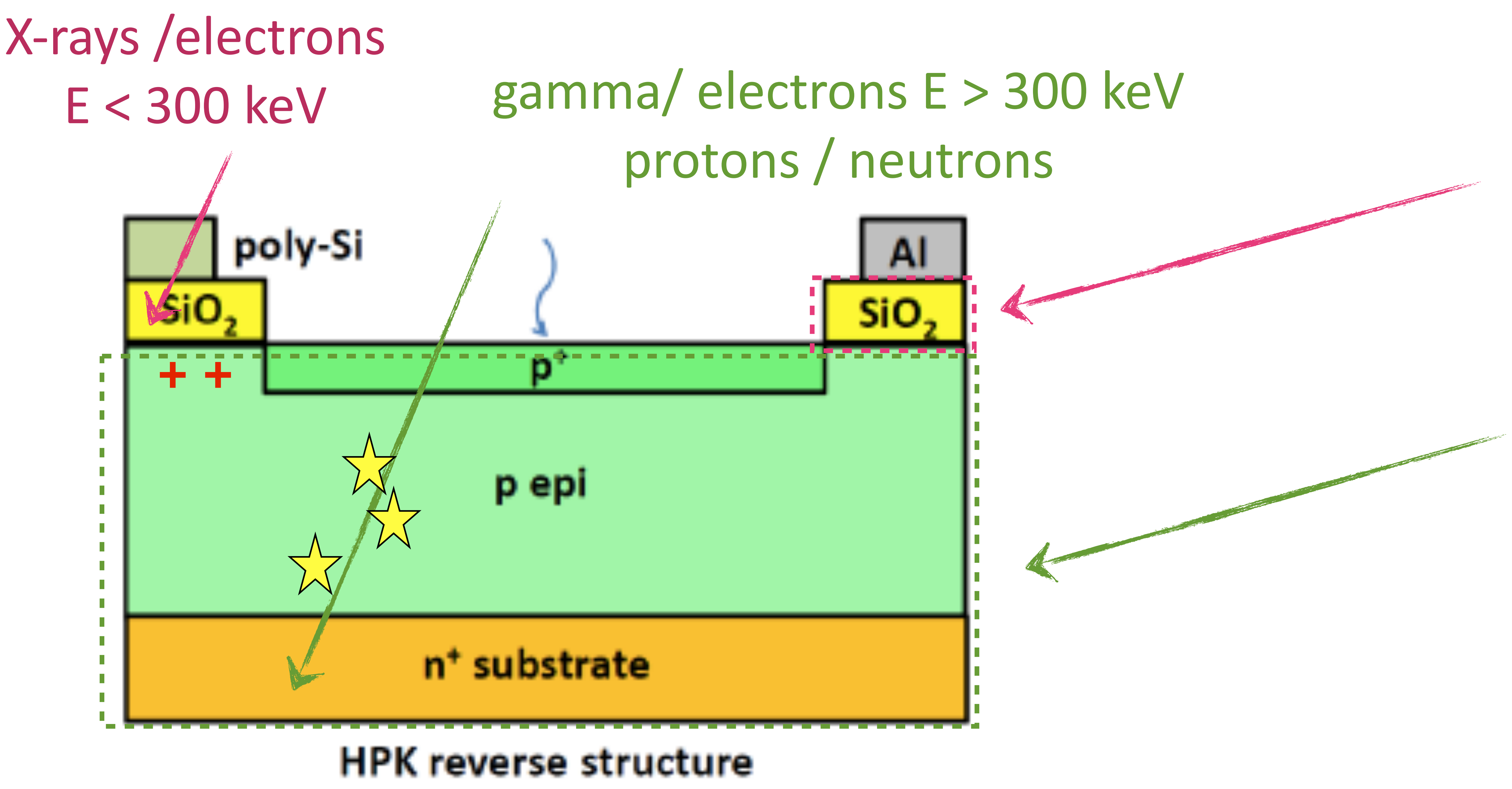
Radiation damage effects

a brief recap

Two types of radiation damage in silicon:

Bulk (Crystal) damage due to Non-Ionizing Energy Loss (NIEL)
displacement damage, built up of crystal defects

Surface damage due to Ionizing Energy Loss (IEL)
accumulation of charge in the oxide (SiO_2), traps at Si-SiO_2 interface



Surface damage:
Generate traps at the Si-SiO_2 interface
Fixed positive oxide charge (N_{ox}):
➔ Change in the electric field (V_{bd})
➔ Accumulation layers
➔ **Increase in leakage current** by additional surface current (J_{surf})

Bulk damage:
Locally distorted Si lattice with new energy states
➔ Add donor and acceptor levels
➔ **Increase DCR**
➔ **Increase after-pulsing**
➔ **Change in charge collection**

Radiation damage effects

for SiPMs

Radiation damage is a major concern when operating SiPMs in harsh radiation environment

Main effect:

Increase of dark current (I_{dark})/ dark count rate (DCR) proportionally to fluence that leads to:

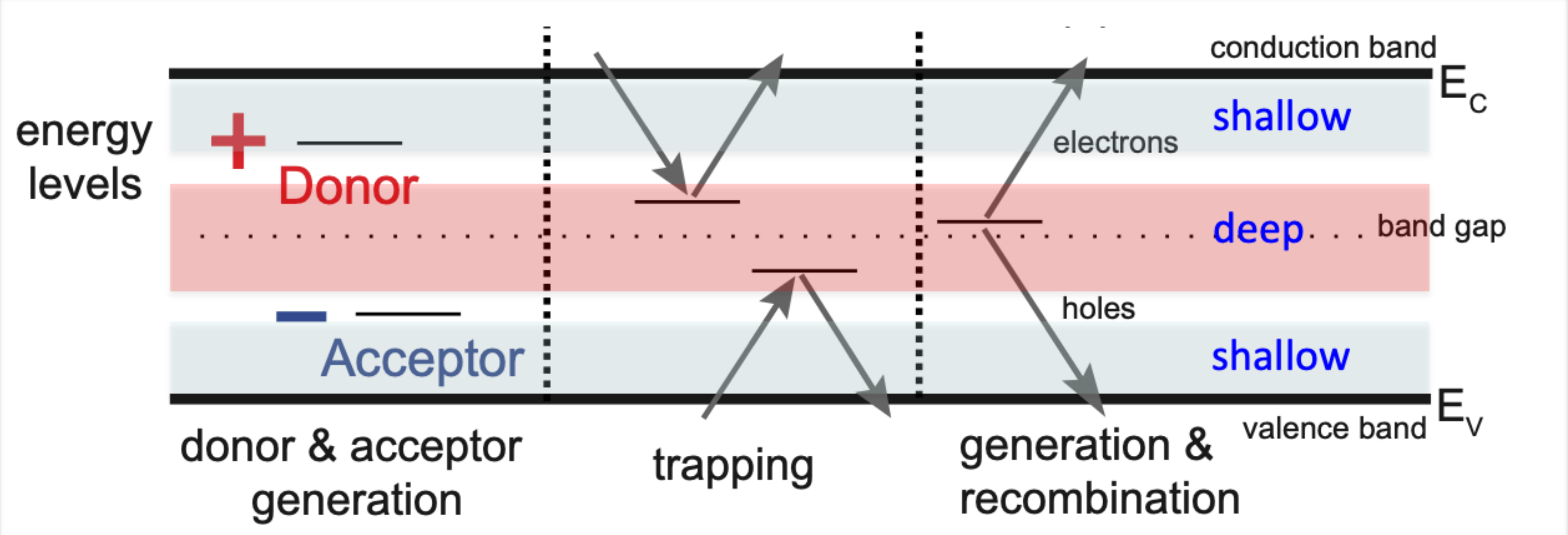
- loss of single photoelectron resolution
- decrease in response, which could be attributed to either: $I_{photo} = q_0 \cdot \mu \cdot G \cdot PDE \cdot (1 + CN)$ CN: Correlated Noise
  - decrease of gain (G)

    $$G = \frac{1}{q_0} C_{pix} \cdot (V_{bias} - V_{bd})$$
  - decrease of photon detection efficiency (PDE)

    $$PDE \propto (V_{bias} - V_{bd})$$
  - V_{bd} shift induced by change in E-field and self-heating effect due to high power dissipation (high I_{dark})

unclear which effect dominates or if all three are relevant

Determined by Shockley-Read-Hall statistics

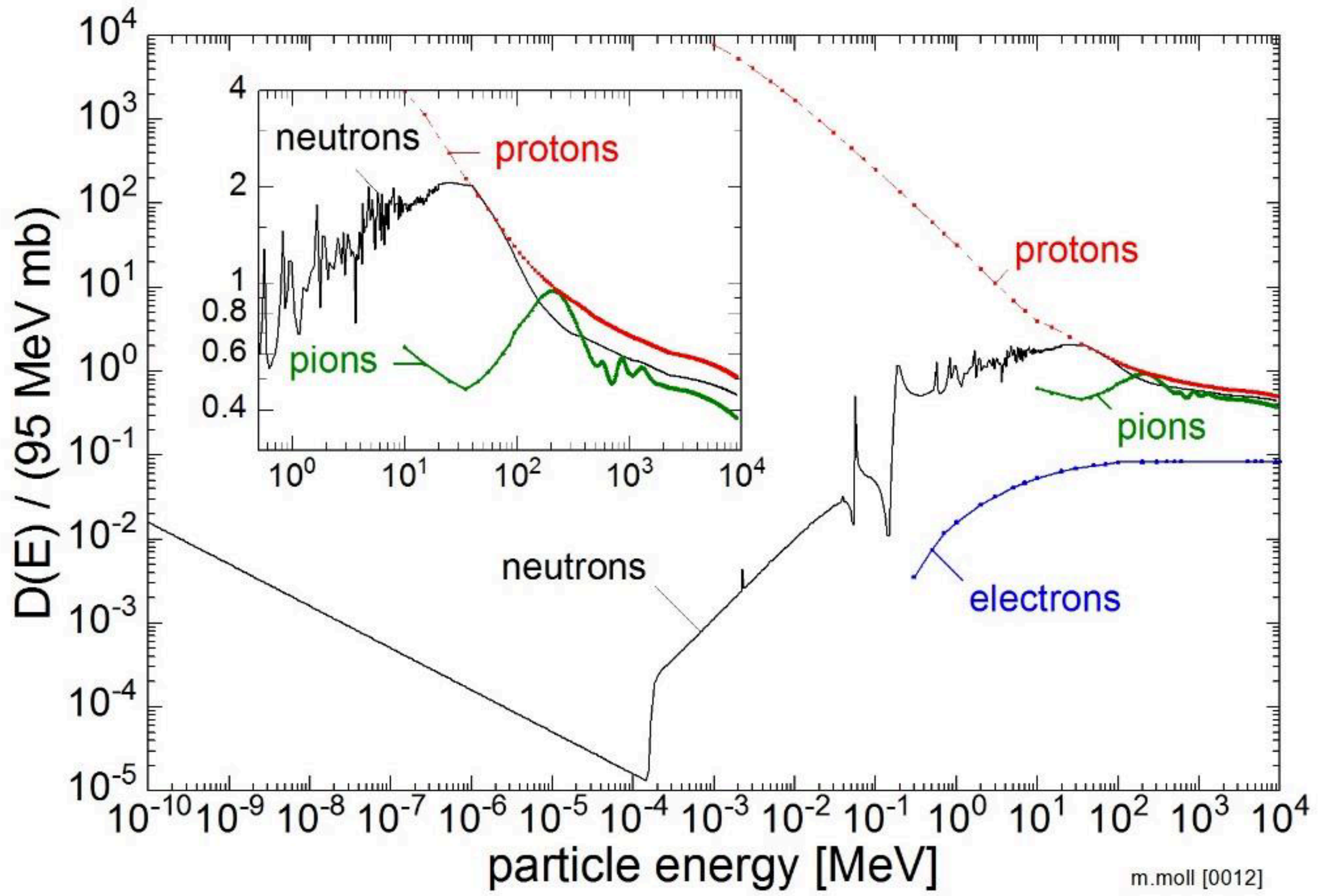


Charged defects (at RT)	Deep defects	Levels close to midgap
→ change of E-field, V_{dep} (Acceptors in the lower half and donors in the upper half of the band gap)	→ signal drop (Shallow defects do not contribute due to de-trapping)	→ current increase → Cooling during operation helps!

Radiation damage

NIEL scaling

- The Non-Ionizing Energy Loss (NIEL) concept is used for predicting radiation damage of silicon to radiation fields
- NIEL concept allows to scale a radiation field to an equivalent reference value
- **NIEL hypothesis:** The degradation of semiconductor devices in a radiation field can be linearly correlated to the NIEL deposited in the semiconductor material.
- Fluences often quoted in 1 MeV neutron equivalent / cm² using hardness factor to scale particles and energy

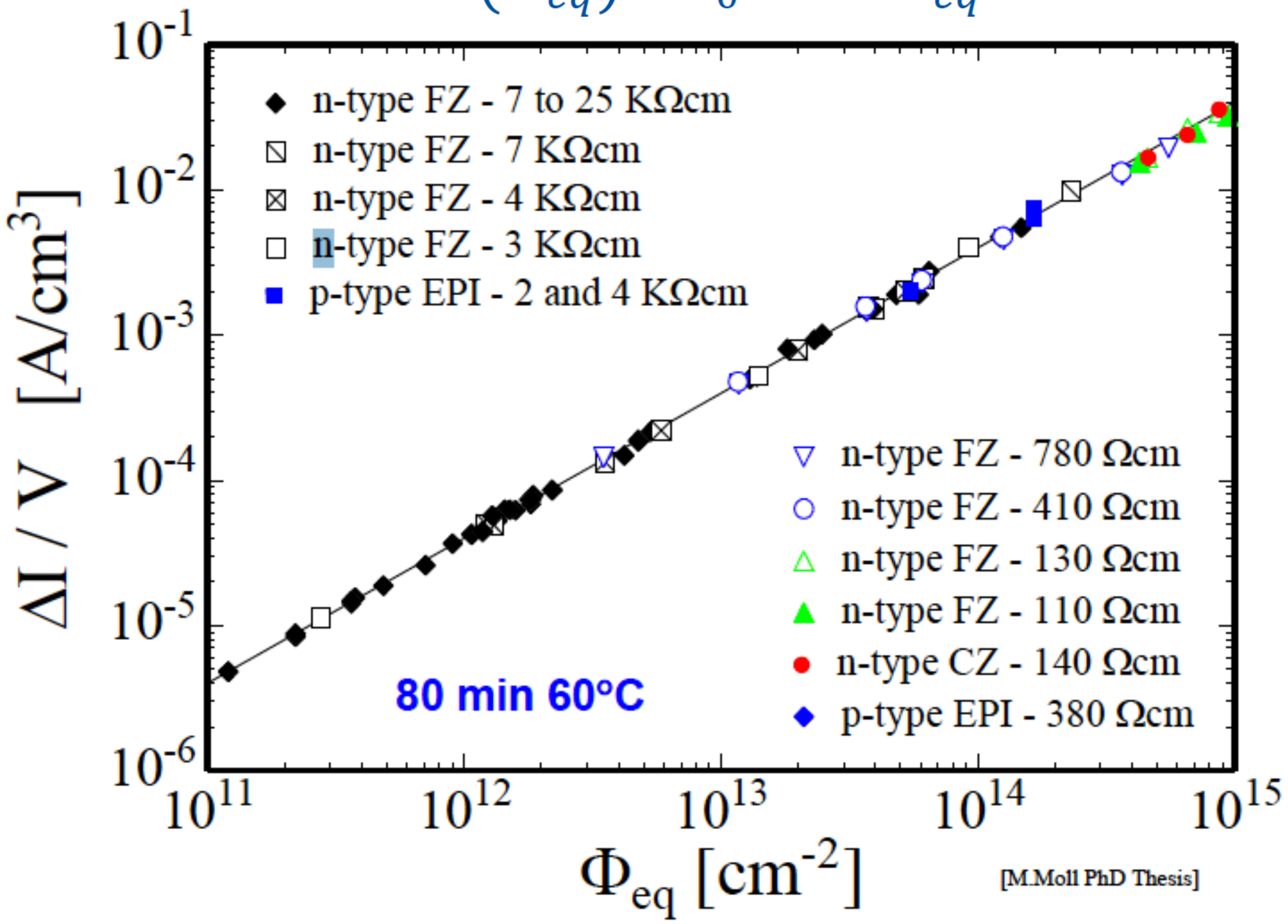


$$NIEL(E) = \frac{N_A}{A} \cdot D(E)$$

D(E): Displacement damage function

D(1 MeV neutron) = 95 MeV mb

$$I(\Phi_{eq}) = I_0 + \alpha \cdot \Phi_{eq}$$



Non-Ionizing Energy Loss (NIEL) processes are interactions in which the energy imparted by the incoming particle results in atomic displacements or in collisions where the knock-on atom does not move from its lattice location and the energy is dissipated in lattice vibrations (phonons), for instance.

Radiation damage

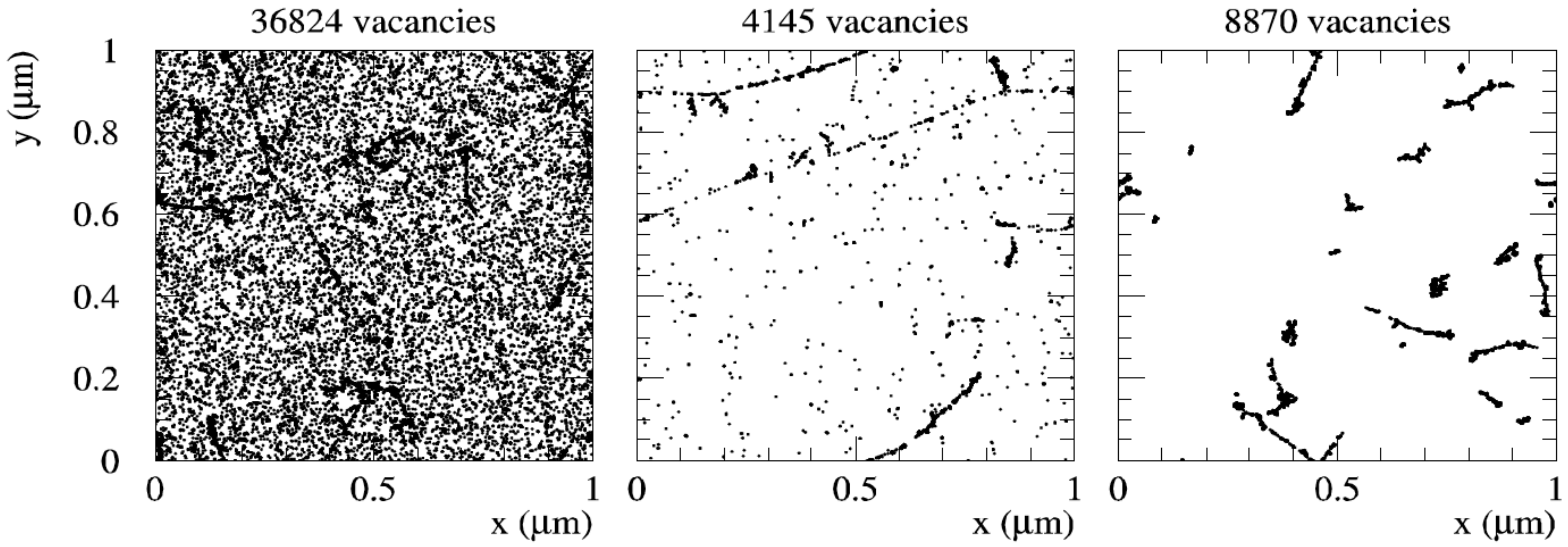
NIEL scaling violation

- NIEL hypothesis builds on the assumption that all damage scales with the displacement energy … but
- Different particles and particle energies cause different distribution of damage on the microscopic level!

- **NIEL scaling is violated**

- **Examples**:
  - Oxygen enrichment improves radiation hardness to proton / but not to neutrons
  - Acceptor (Boron) removal
    - in p-type epitaxial & FZ sensors
    - in HV-CMOS sensors
    - loss of gain in LGAD sensors

Simulation: Vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2



10 MeV protons | 23 GeV protons | 1 MeV neutrons

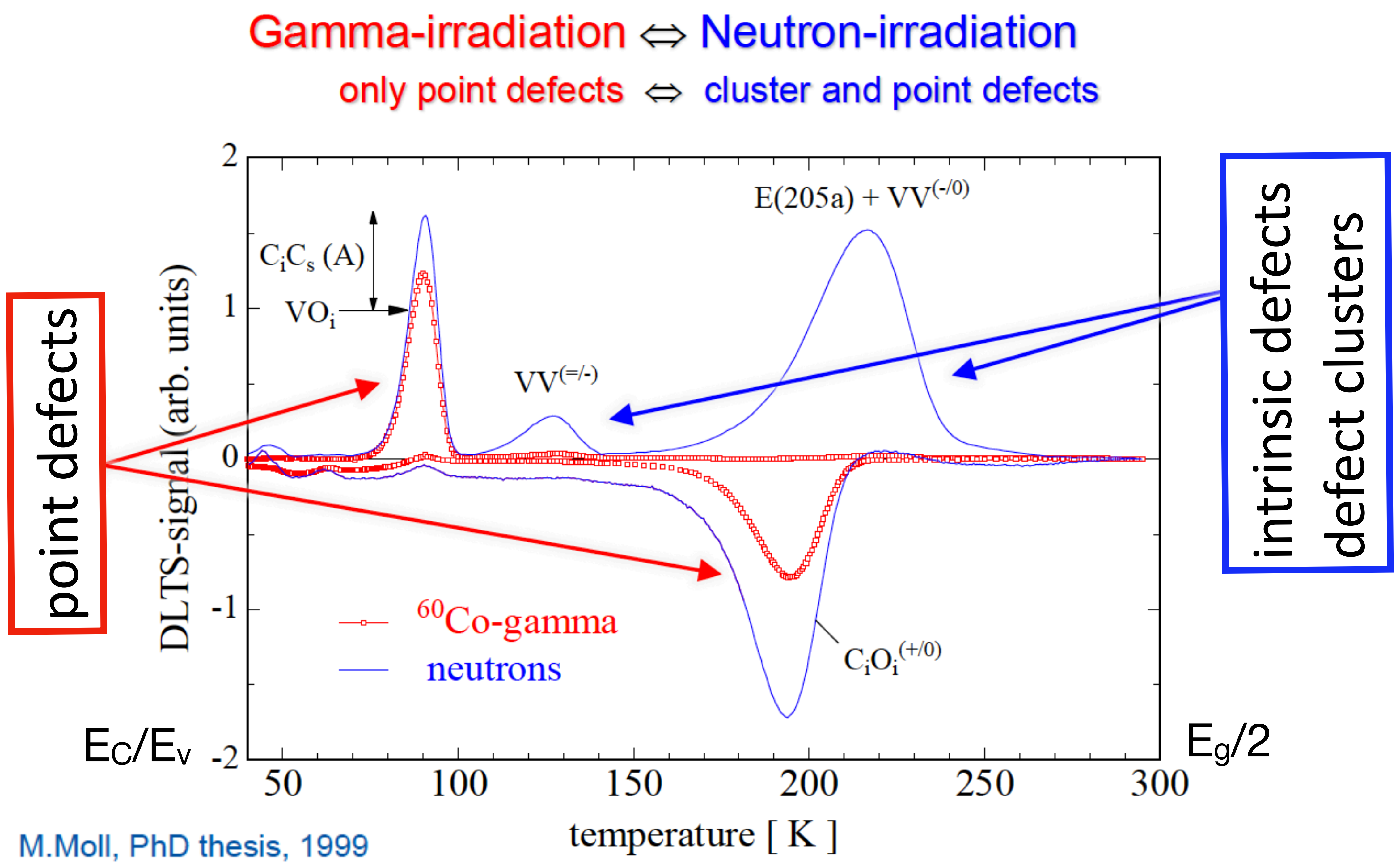
[M.Huhtinen, NIMA 491(2002), 194]

For SiPM no dedicated studies to distinguish between proton/neutron effects

Radiation damage

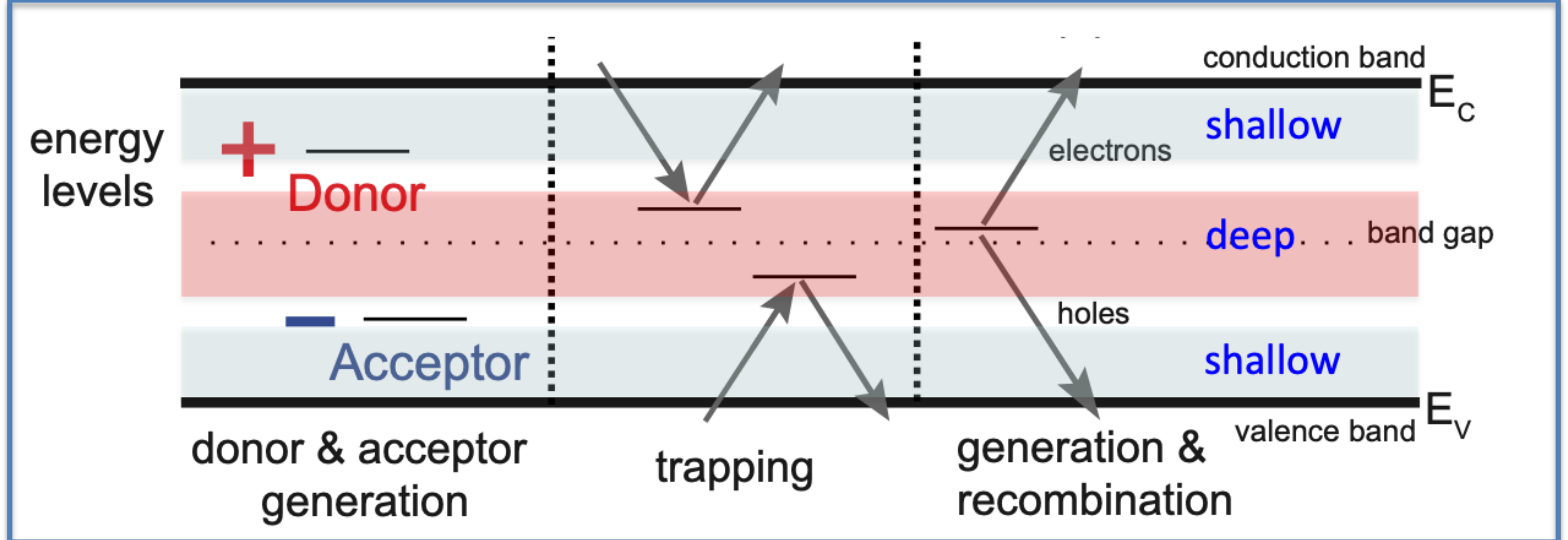
NIEL scaling violation

- Gamma induced damage effects are linked to the formation of point defects, do not follow NIEL scaling concept
- Damage effects scaling with the classical NIEL are usually originating from intrinsic defects, i.e. defects that contain only silicon vacancies and interstitials such as V_2I_2, ..cluster defects
- **Cluster defects** contribute to the increase of generation rate and therefore of **leakage current**



M.Moll, PhD thesis, 1999

Determined by Shockley-Read-Hall statistics

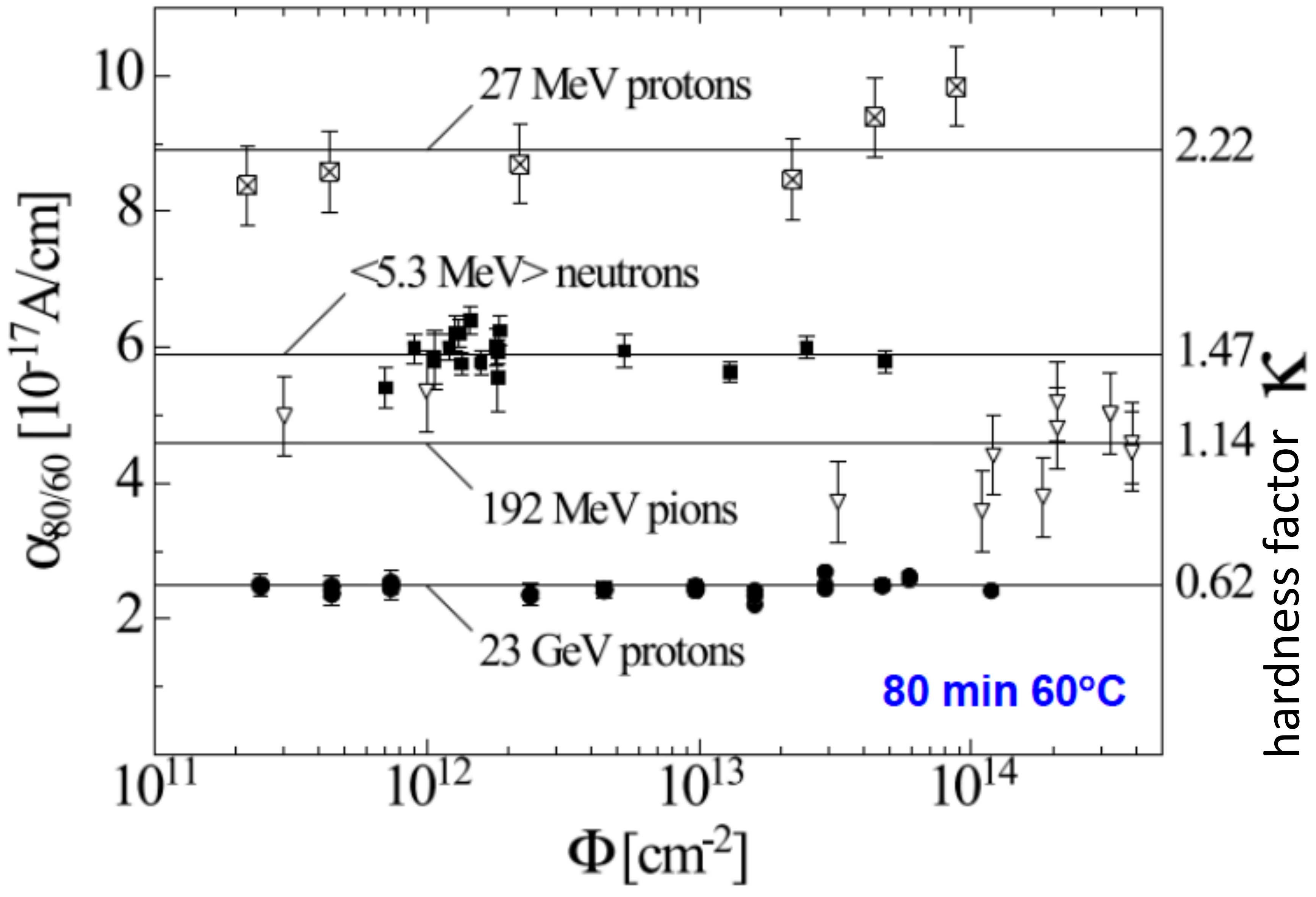


Charged defects (at RT) ➔ change of E-field, V_{dep} (Acceptors in the lower half and donors in the upper half of the band gap)	Deep defects ➔ signal drop (Shallow defects do not contribute due to de-trapping)	Levels close to midgap ➔ current increase ➔ Cooling during operation helps!

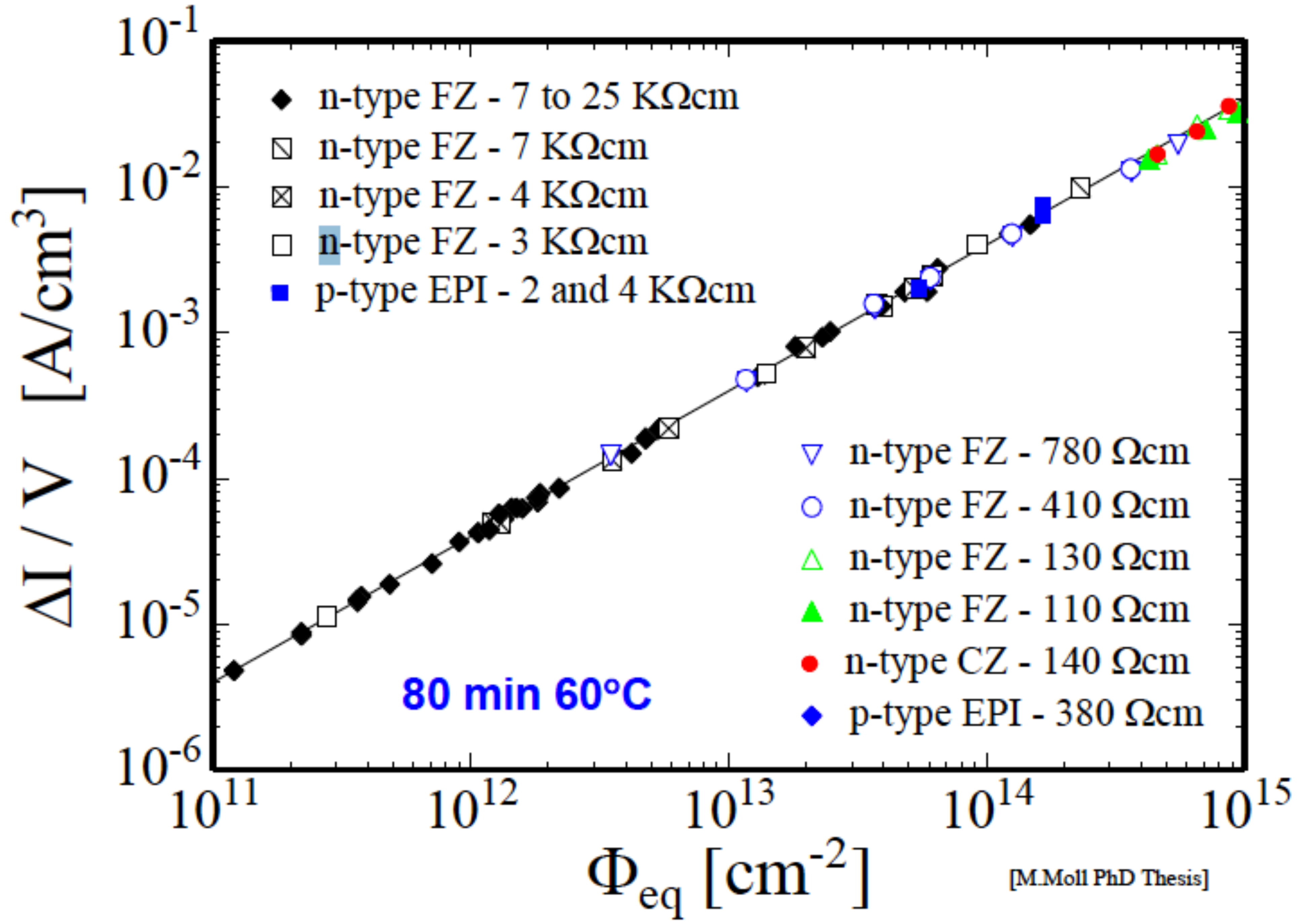
Radiation damage

NIEL scaling violation

- Bulk damage in silicon detectors without gain is related to the damage factor $\alpha = \frac{\Delta I}{Volume \cdot \Phi_{eq}}$



$I(\Phi_{eq}) = I_0 + \alpha \cdot \Phi_{eq}$



- α is used to determine the hardness factor $\Phi_{eq} = \kappa_x \Phi_x$

For devices with gain (SiPM) α is not constant with fluence, but depends on over voltage

instead α_G should be studies:

$$\alpha_G = \frac{\Delta I}{V \cdot \Phi_{eq} \cdot G \cdot ECF \;\; PDE}$$

ECF: excess charge factor

Radiation damage studies on SiPMs

an (incomplete) overview

Review of radiation damage effects on SiPM irradiated with

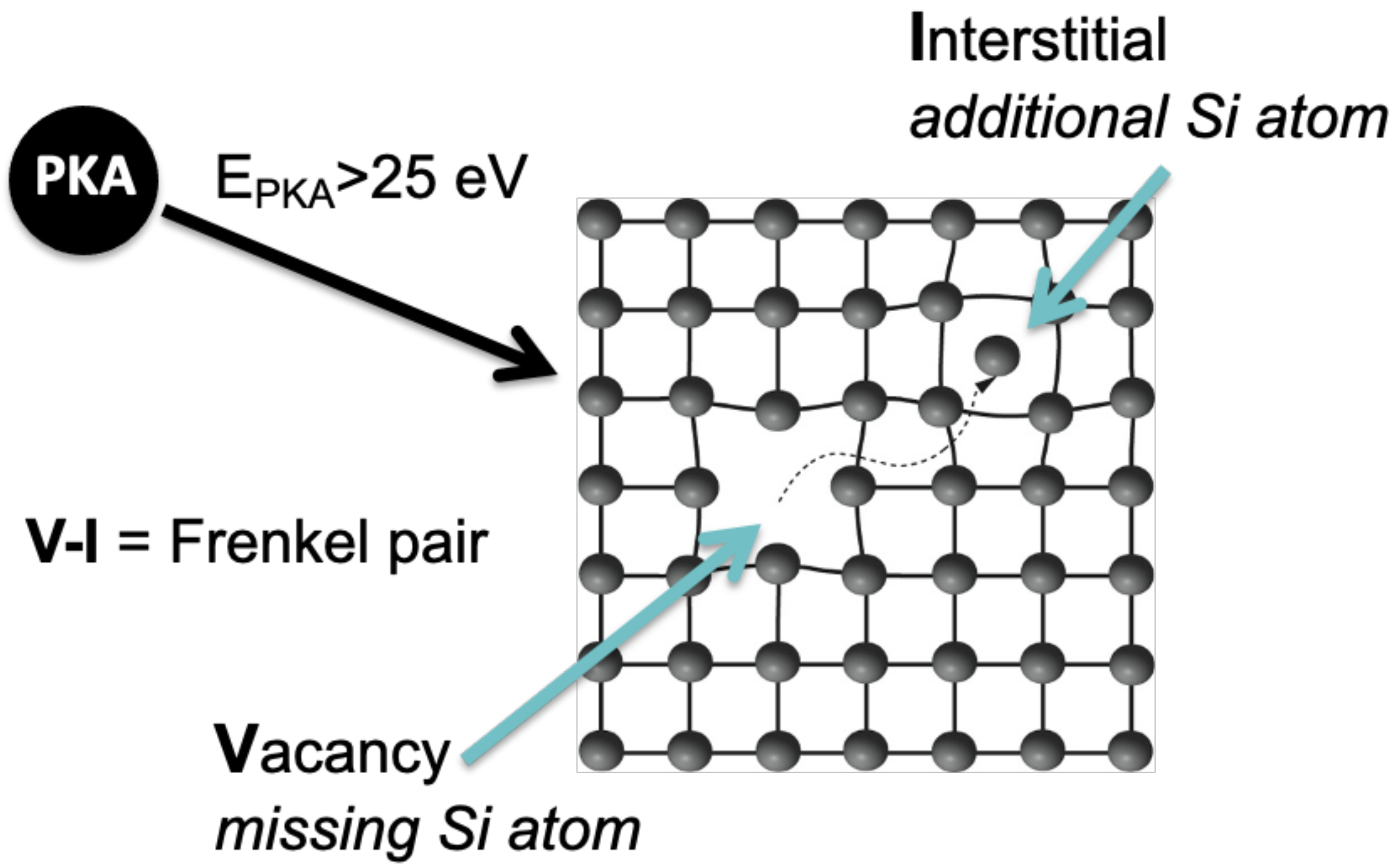
- X-ray (E < 300 keV)
- gamma / electron / positrons (E > 300 keV)
- hadrons (proton / neutrons):
  - medium-low fluences: $\phi_{eq} < 10^{12}$ cm^{-2}
  - high fluences: $\phi_{eq} > 10^{12}$ cm^{-2}

Surface damage

Bulk damage

Garutti, Musienko
”Radiation damage of SiPMs”
DOI:10.1016/j.nima.2018.10.191

Primary Knock on Atom (PKA)



Energy **threshold for bulk defects** generation:

Particle	Gamma/X-ray	Electron	Proton	Neutron
Frenkel pair	300 keV	255 keV	185 eV	185 eV
Cluster defects	-	8 MeV	35 keV	35 keV

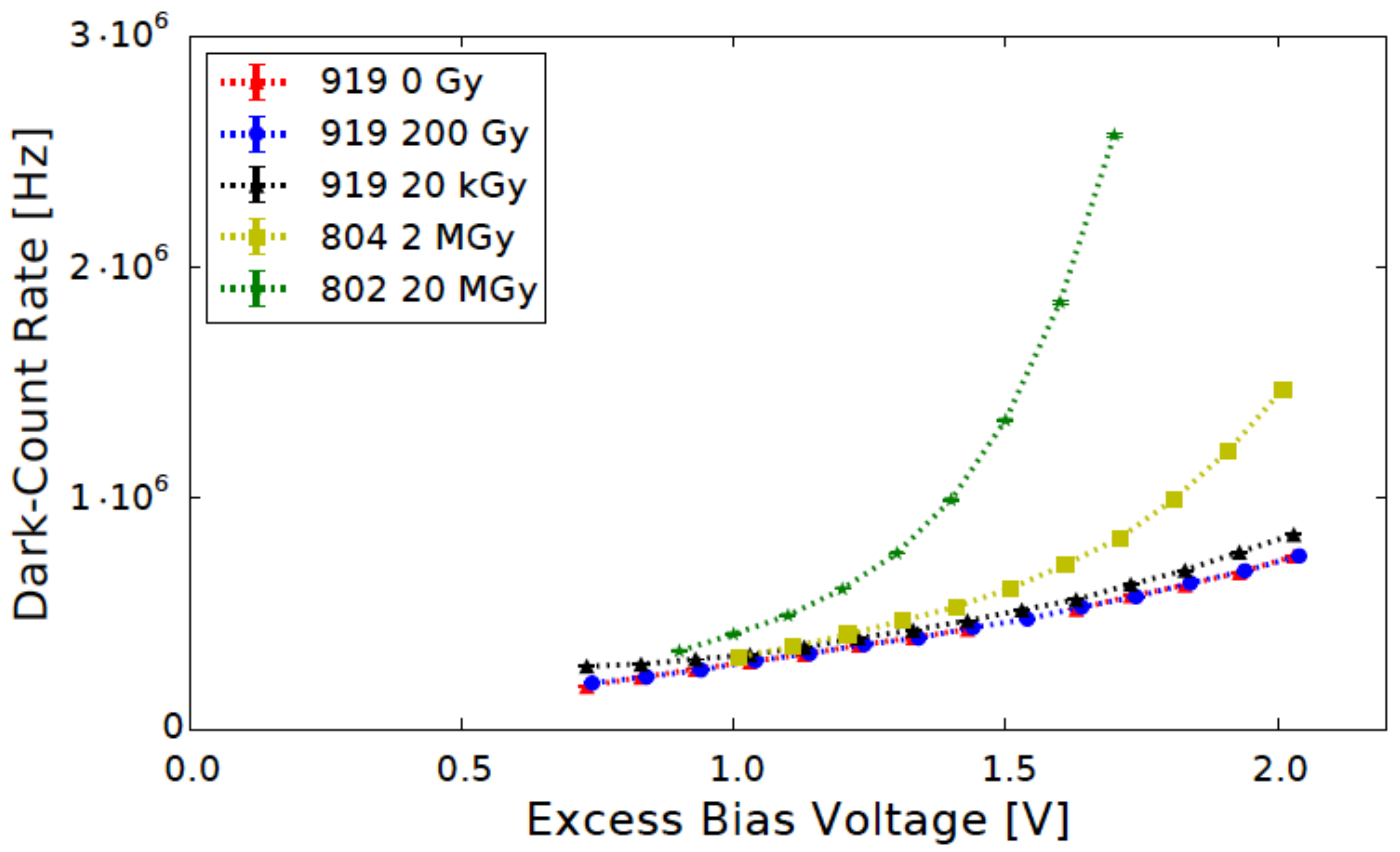
Irradiation with X-ray

surface damage

Main effects observed:

- all SiPM were operational after irradiation
- loss of single photoelectron resolution for dose > 1 kGy
- factor 1000 increase of DCR at 20 MGy explained as radiation-induced increase in surface current generated at the depleted Si-SiO_2 interface
- static parameters not affected

Dose	0 Gy	200 Gy	20 kGy	2 MGy	20 MGy
R_{par} [MΩ]	$2\,100 \pm 100$	$2\,000 \pm 100$	$1\,600 \pm 80$	275 ± 50	75 ± 20
R_q^{Cf} [kΩ]	125 ± 5	116 ± 5	112 ± 5	110 ± 5	108 ± 5
C_{pix}^{Cf} [fF]	94.0 ± 1.5	93.8 ± 1.5	93.5 ± 1.5	93.0 ± 1.5	93.5 ± 1.5
$R_q^{Cf} \cdot C_{pix}^{Cf}$ [ns]	11.8 ± 0.6	10.9 ± 0.6	10.5 ± 0.6	10.2 ± 0.6	10.1 ± 0.6



Photon irradiation is probably not the main worry

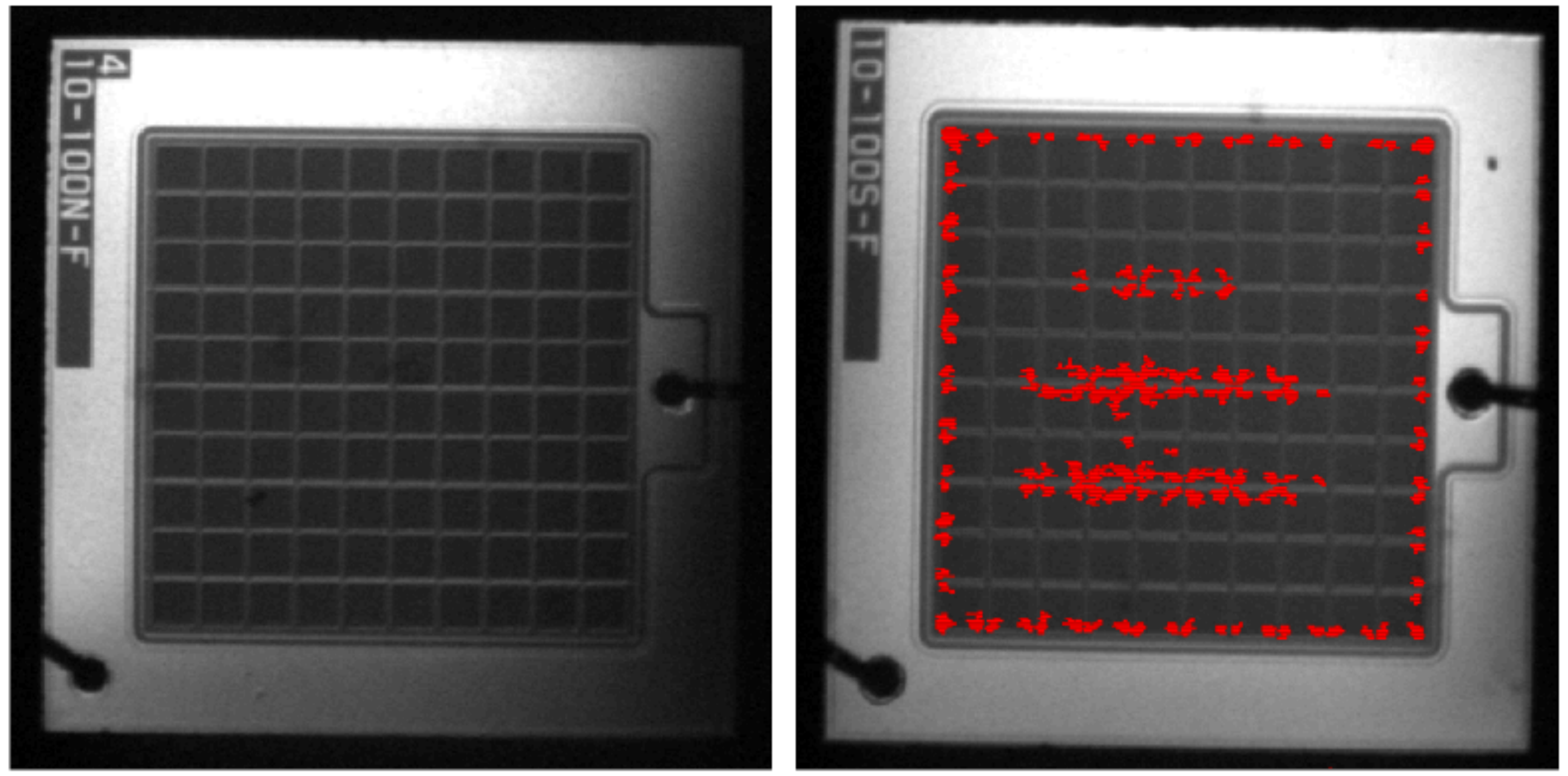
Xu, Klanner, Garutti, Hellweg,
"Influence of X-ray Irradiation on the Properties of the Hamamatsu Silicon Photomultiplier S10362-11-050C"
NIM A762, p149-161 (2014), doi:10.1016/j.nima.2014.05.112

Irradiation with gamma & electrons

surface & bulk damage

Main effects observed:

- all SiPM were operational after irradiation
- loss of single photoelectron resolution for dose > 1 kGy
- significant increase of dark count / current
- point-like defects along readout lines



Infrared pictures of a non-irradiation sample (left) and the irradiated sample (right).
Infrared light is emitted due to the Joule heat cause by passage of leakage current (red points).

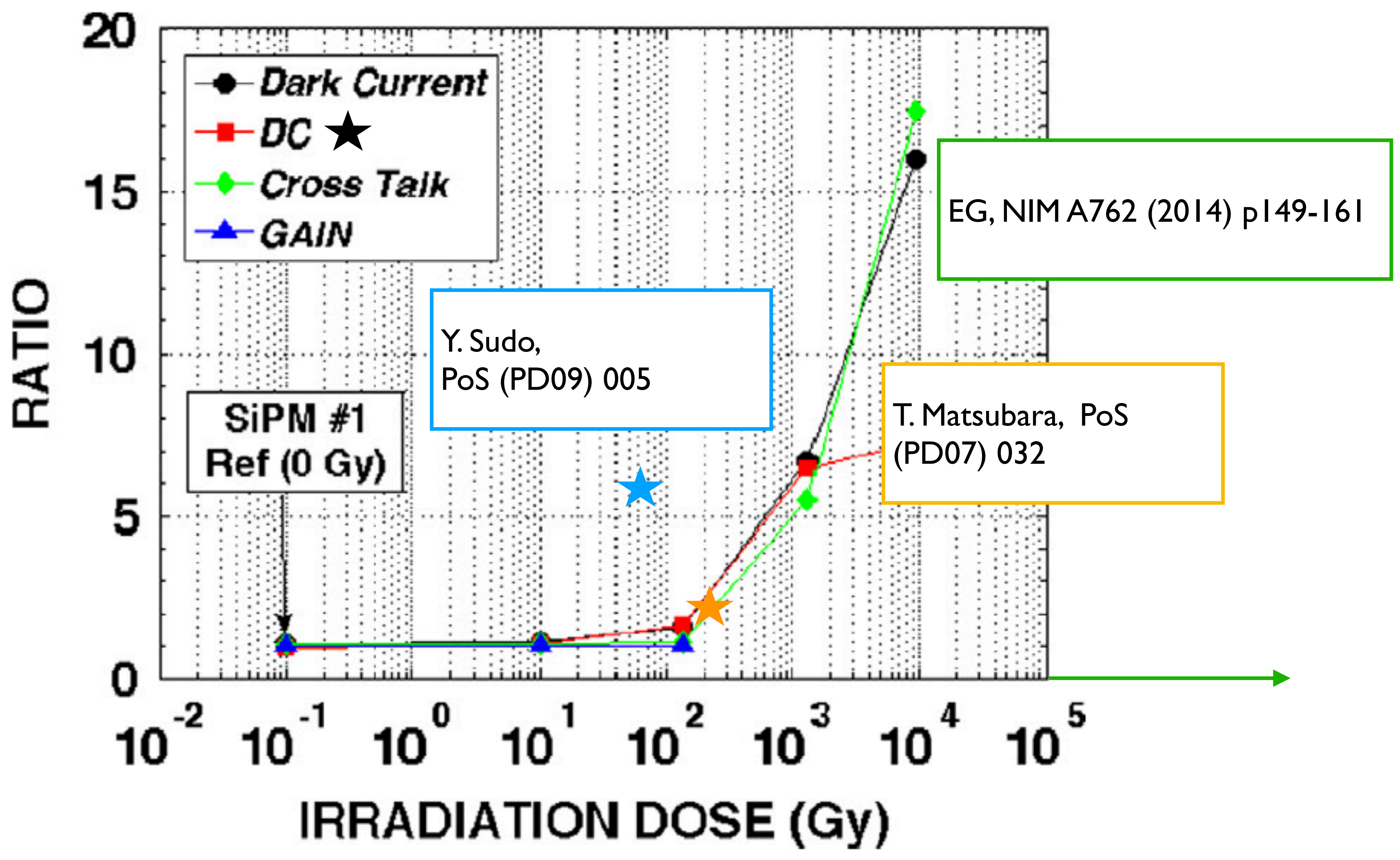


Fig. 7. Ratio of the measured quantities vs. irradiation dose at ΔV=3V (ΔV ≈ 11%).

Pagano, Lombardo, Palumbo, Sanfilippo, Valvo, Fallica, Libertino,
"Radiation hardness of silicon photomultipliers under ^{60}Co γ-ray irradiation",
NIM A767, p347-352 (2014) doi:10.1016/j.nima.2014.08.028

Matsubara, Tanaka, Nitta, Kuze,
"Radiation damage of MPPC by gamma-ray irradiation with Co-60"
PoS, PD07 p032 (2006)

Irradiation with hadrons

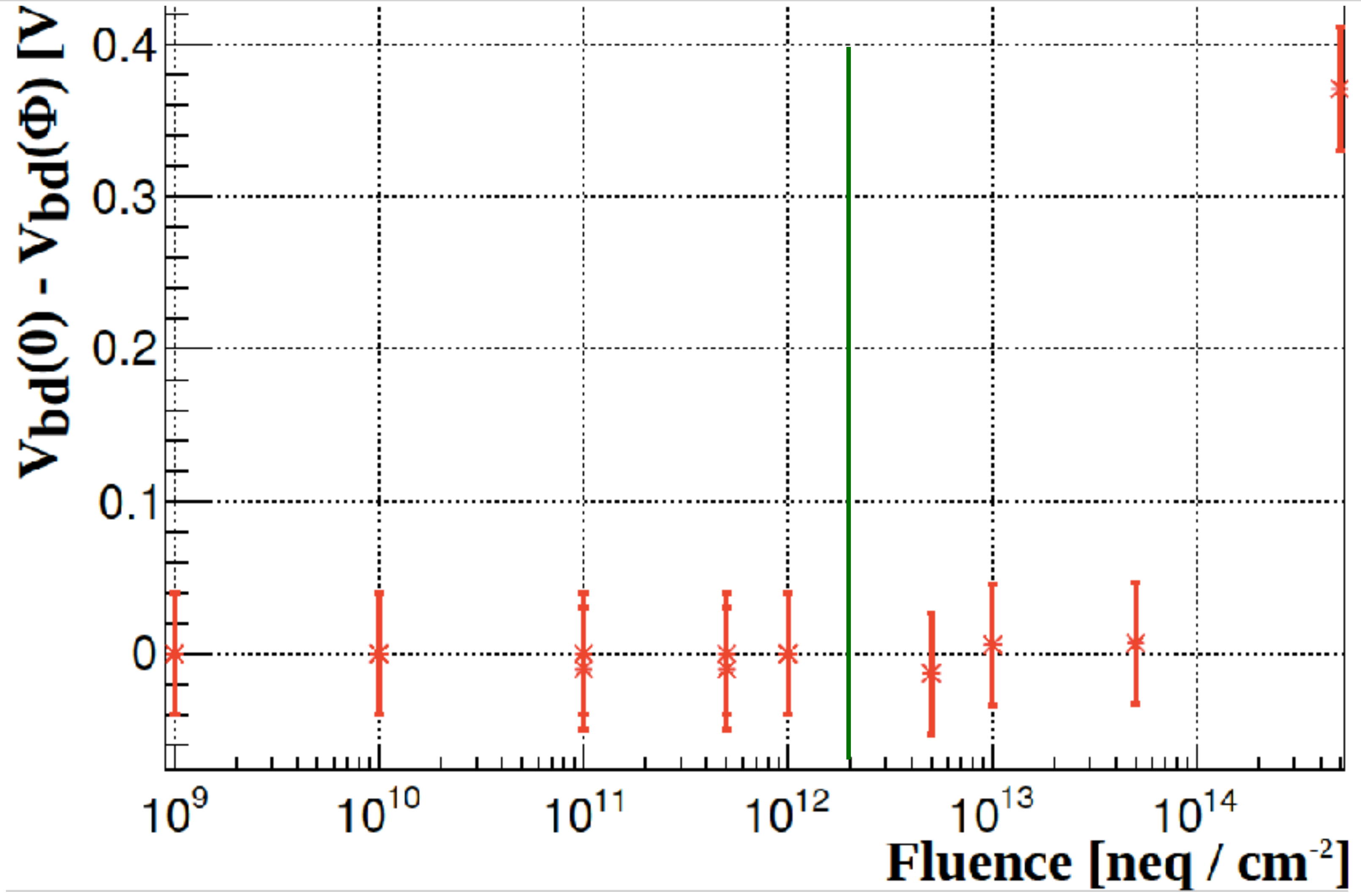
$\phi_{eq} < 10^{12}$ cm^{-2}

Centis Vignali, Garutti, Klanner, Lomidze, Schwandt
"Neutron irradiation effect on SiPMs up to $\phi_{eq} = 5 \cdot 10^{14}$ cm^{-2}"
https://doi.org/10.1016/j.nima.2017.11.003

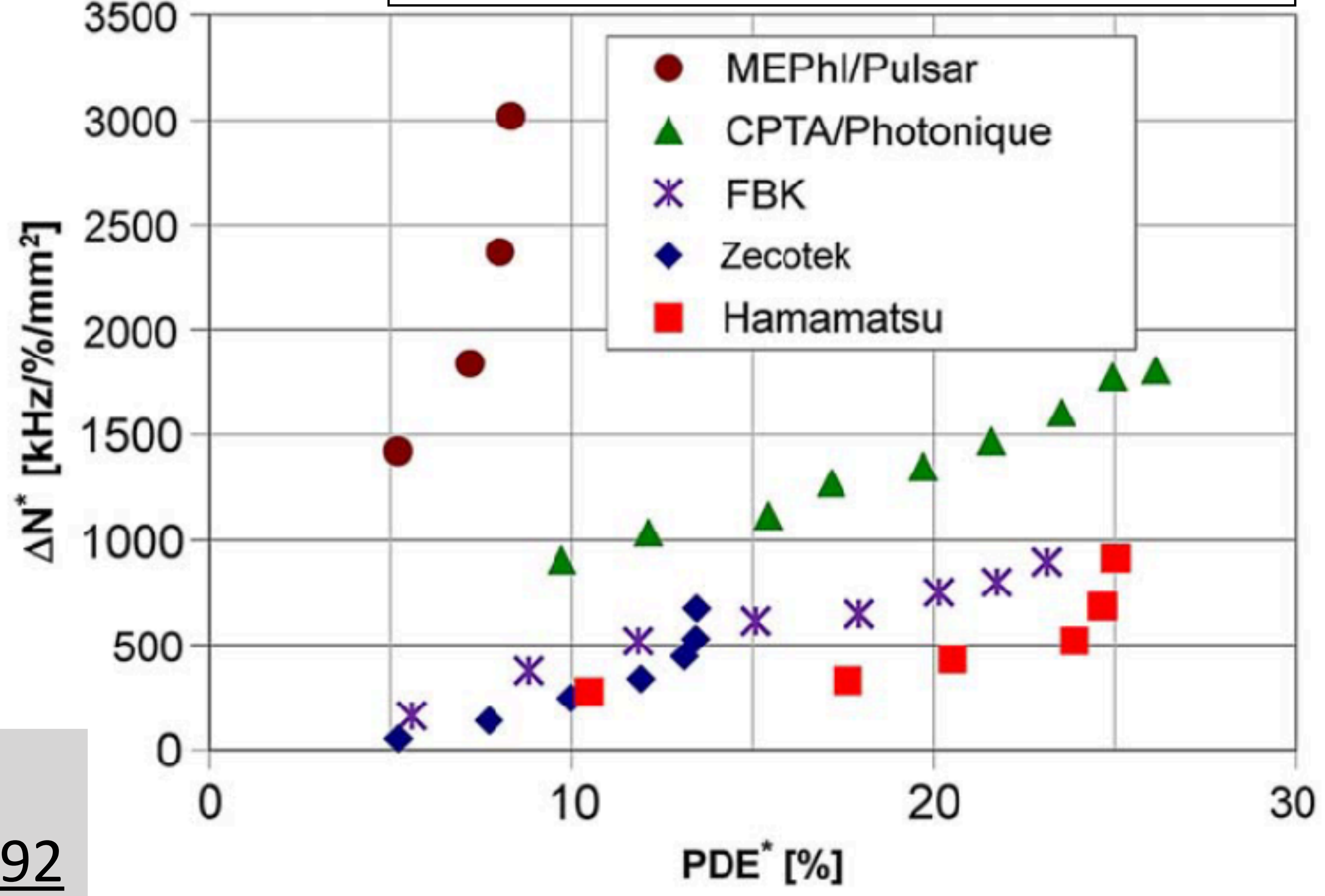
Main effects observed:

- all SiPM were operational after irradiation
- loss of single photoelectron resolution for $\phi_{eq} > 10^{10}$ cm^{-2} @ -30°C
- no change in static parameters (R_q, C_{pix}, V_{bd})
- small changes in G, PDE, CN (~10%)
- significant increase in DCR / DC

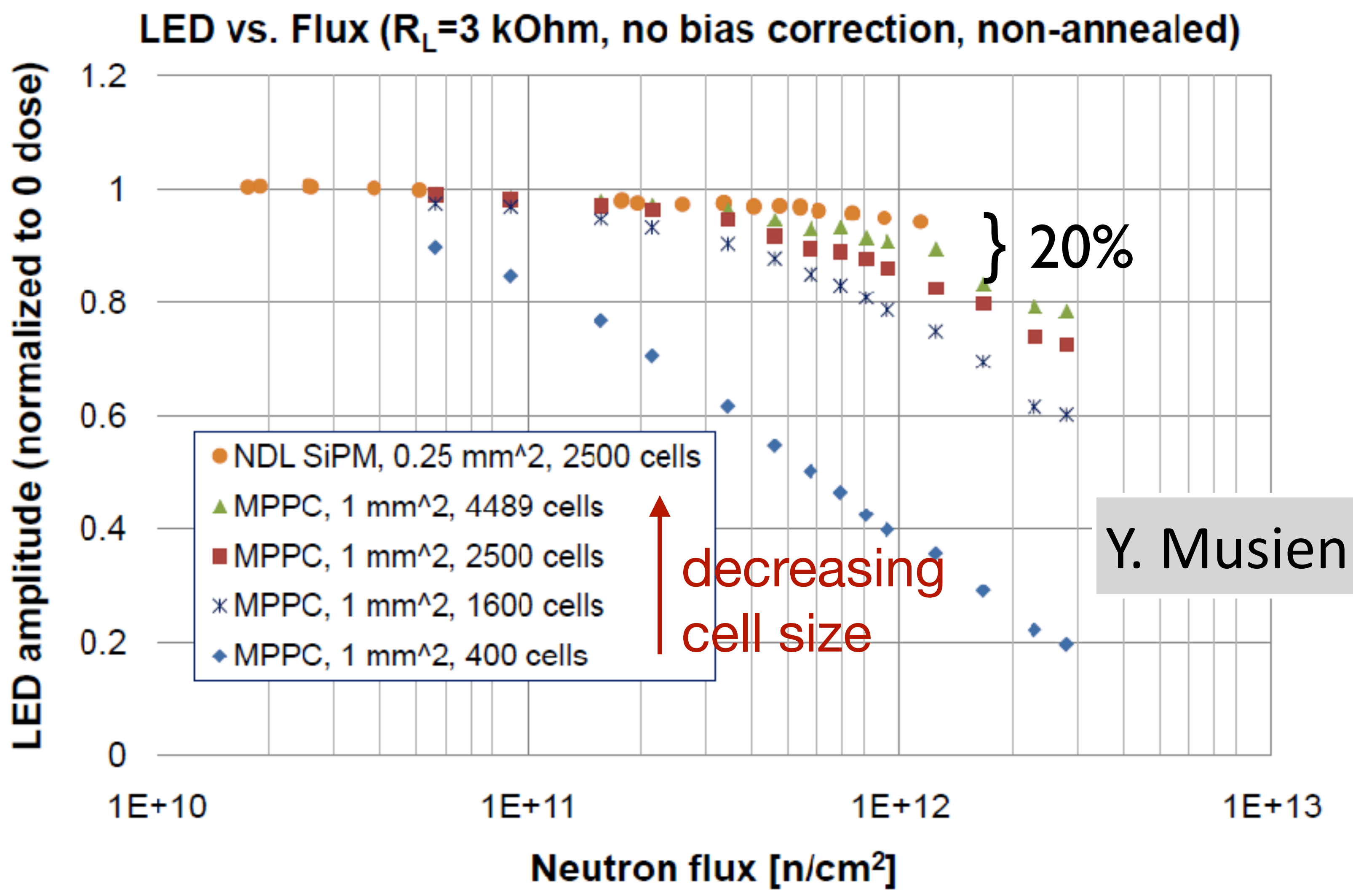
- small cells (small C_{pix} / fast recovery time / small G) are favourite



$$\Delta(N)_{norm}(U) = \frac{N_{after}(U) - N_{before}(U)}{A \cdot PDE_{515nm}(U)}$$



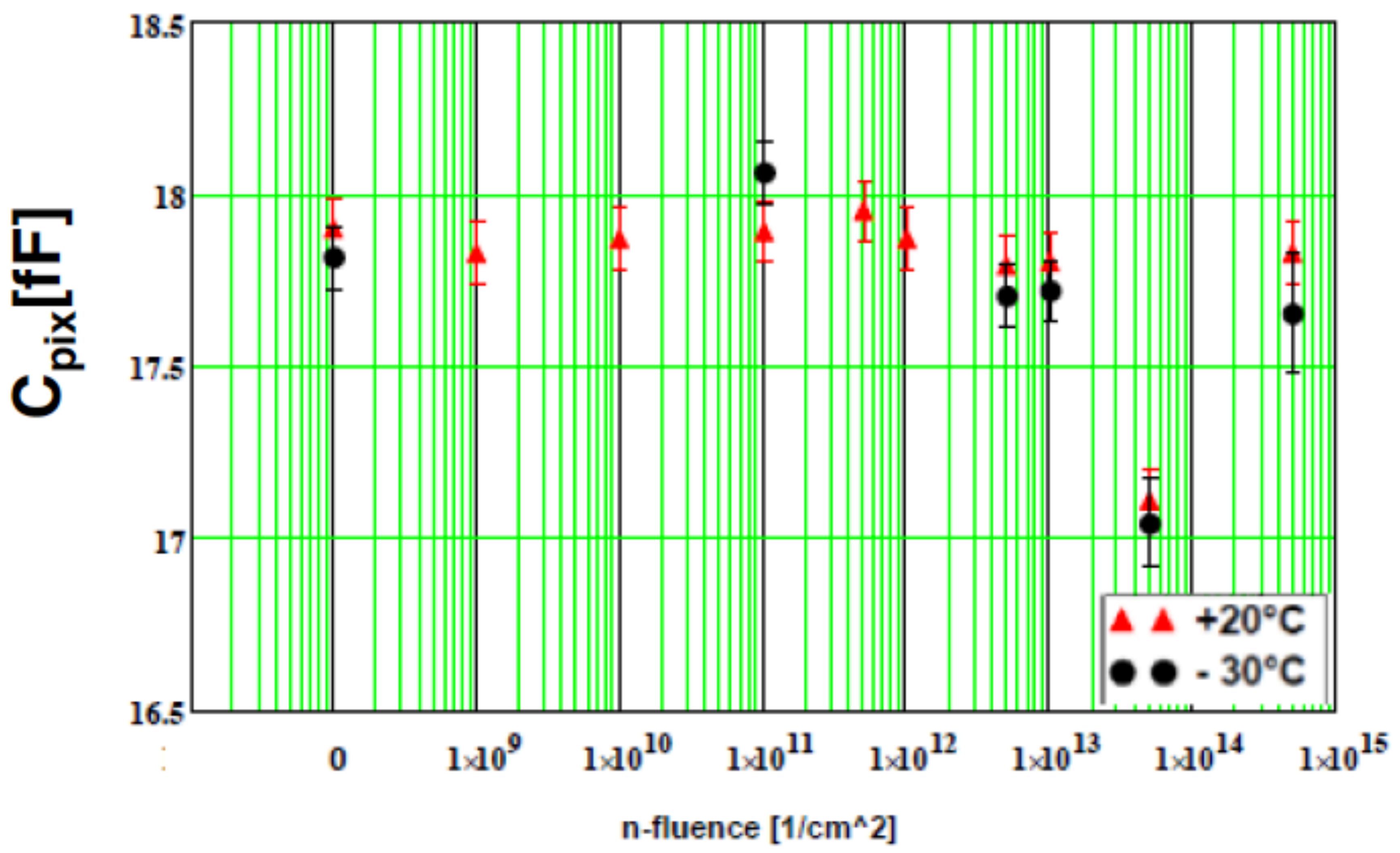
Musienko et al.
NIM A 610 (2009) 87–92



Y. Musienko

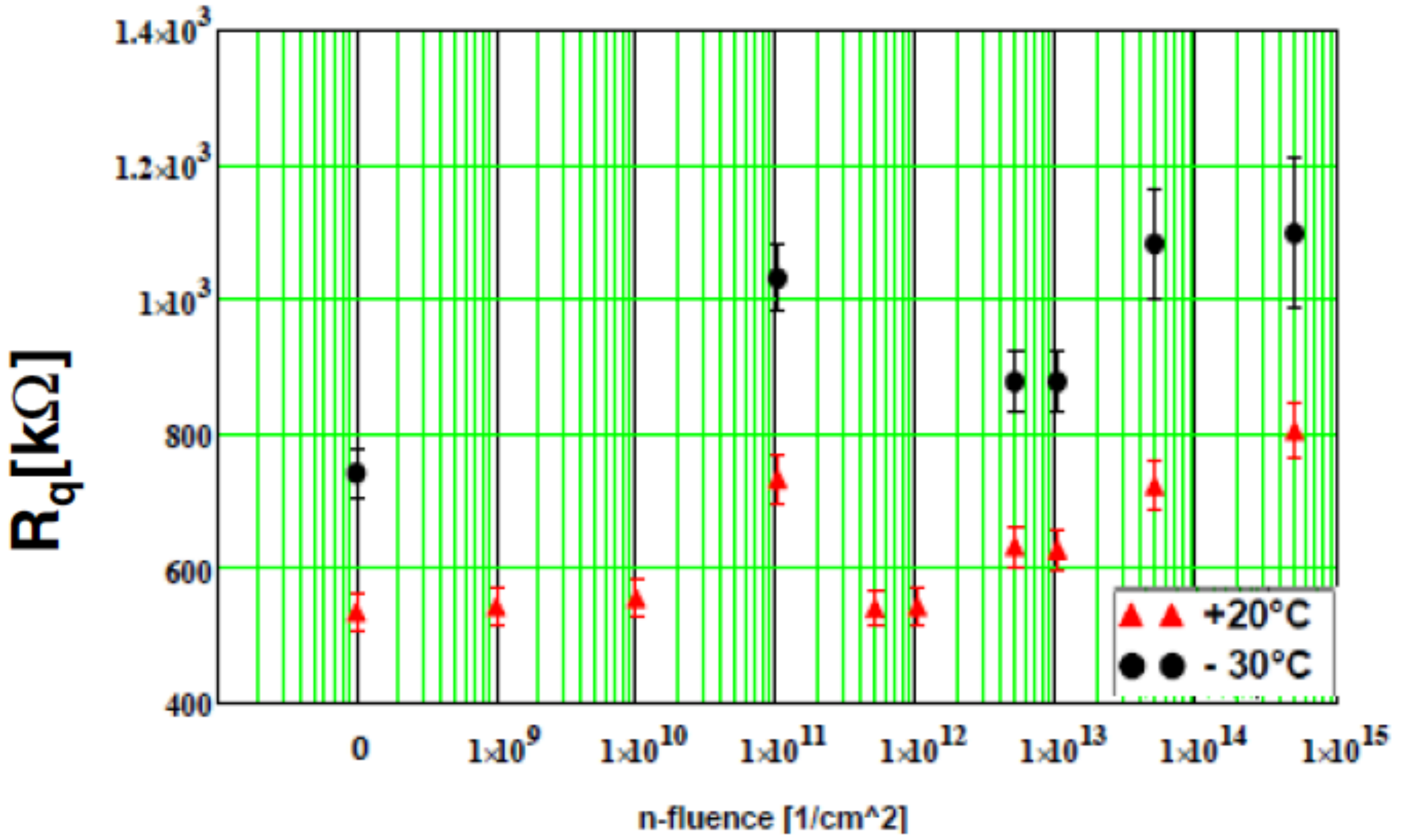
Irradiation with hadrons

ϕ_{eq} > 10^{12} cm^{-2}



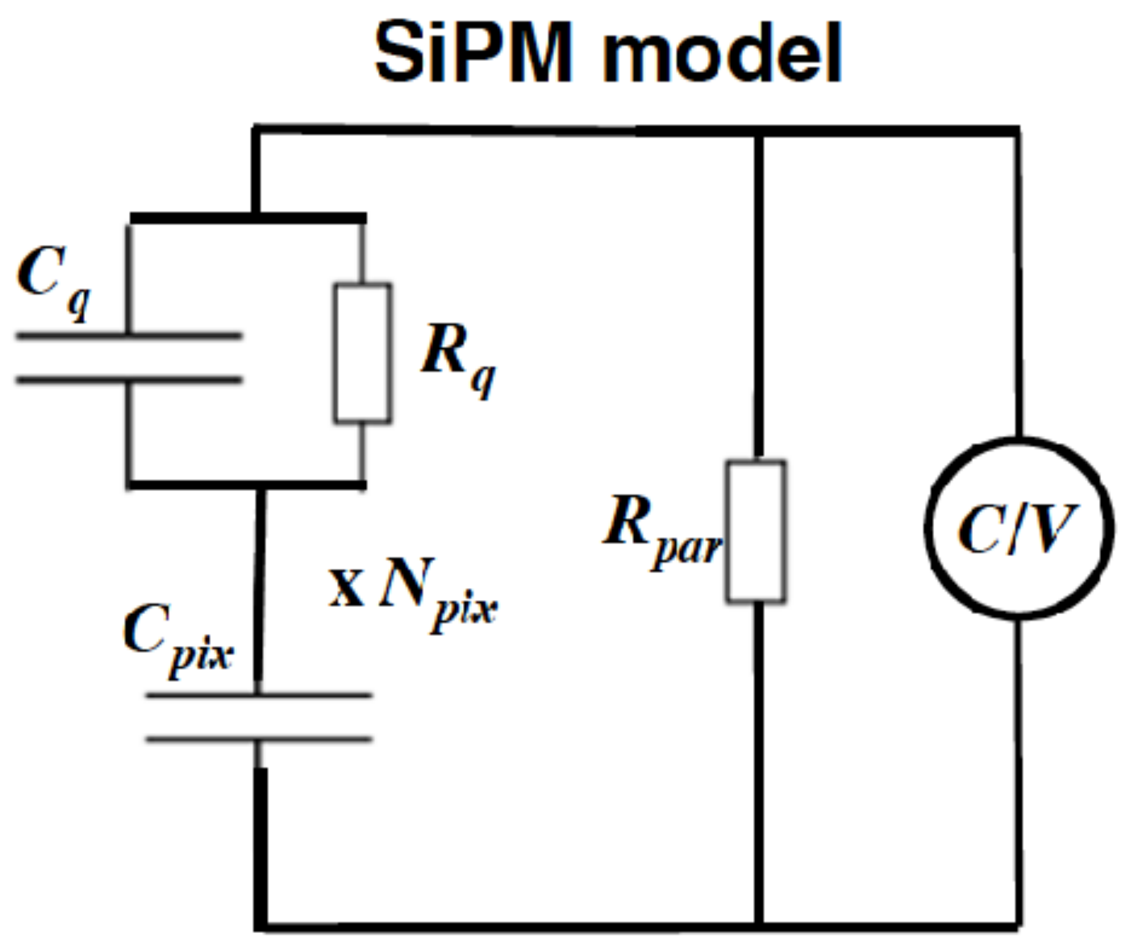
- Determine C_{pix} and R_q from C-V measurements
- Investigate temperature (T) and fluence (ϕ) dependence

- Upper limit C_q< 5 fF (~1 fF-pulse shape)
- Significant differences for SiPM samples



- R_q increases with decreasing T (poly-Si)
- R_q appears to increase for ϕ_{eq} >10^{13} cm^{-2}
- C_{pix} not influenced by T and ϕ
- No significant change in Gain expected:

$$G = \frac{1}{q_0}(C_{pix} + Cq) \cdot (V_{bias} - V_{bd})$$



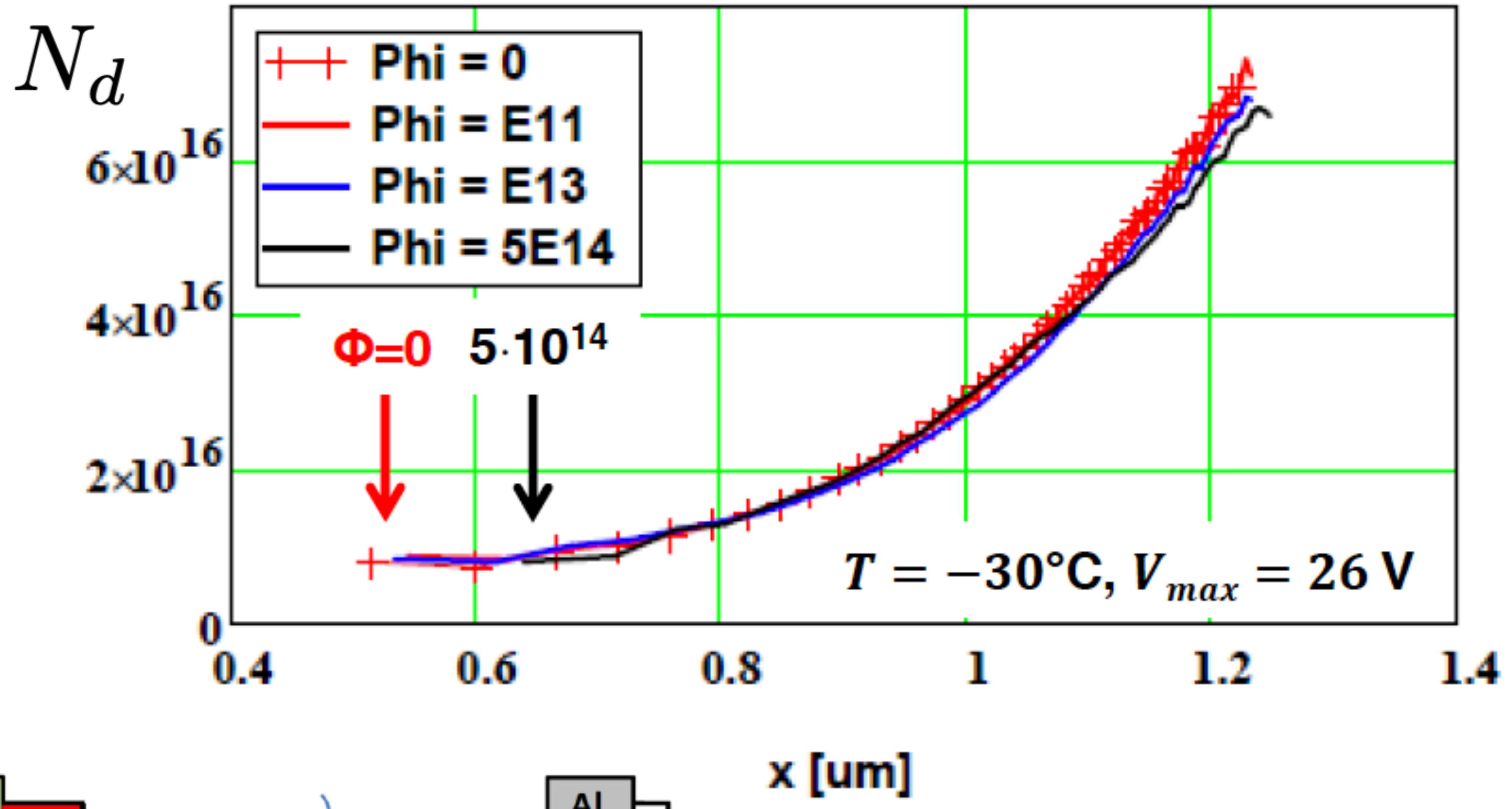
SiPM: KETEK MP15 with 4384 pixels 15x15 μm^2

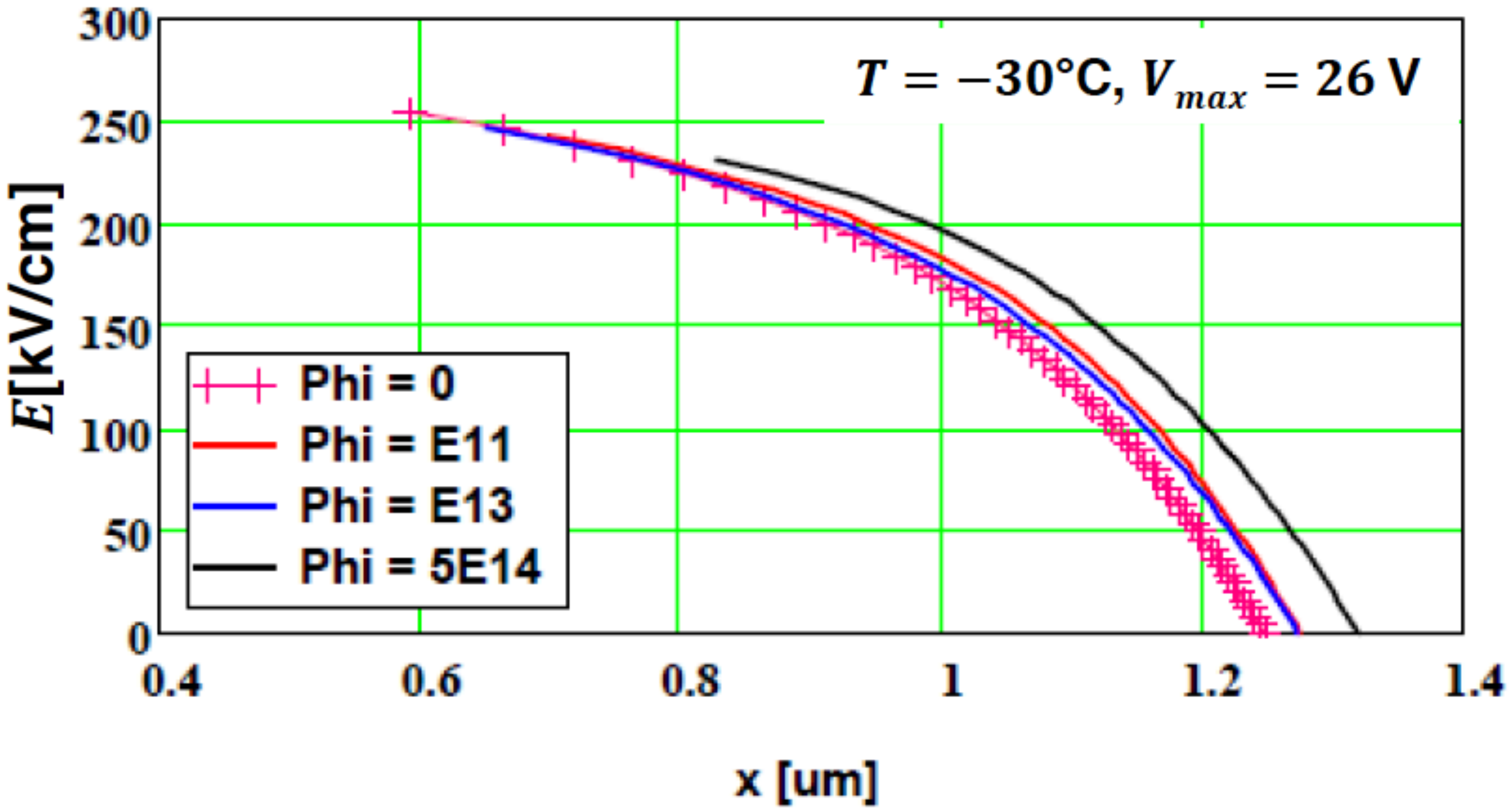
Irradiation with hadrons

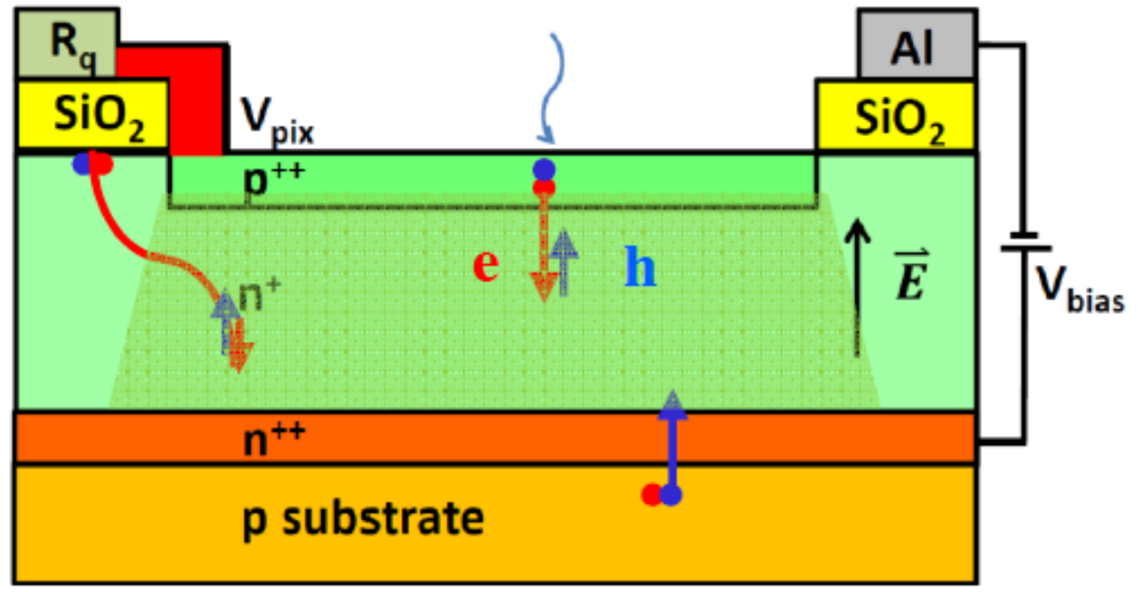
ϕ_{eq} > 10^{12} cm^{-2}

Determine doping concentration *$N_d(x)$* and electric field *$E(x)$* as function of ϕ

$$x(V) = \frac{\epsilon_0 \epsilon_{Si} A}{C(V)}, \quad N_d(x) = \frac{2}{q_0 \epsilon_0 \epsilon_{Si} A^2} \cdot \frac{1}{d(1/C^2)/dV}, \quad E(x) = \int_{x_{max}}^{x} \frac{q_0 N_d(x)}{\epsilon_0 \epsilon_{Si}} dx, \quad A = N_{pix} \cdot pitch^2$$







Minor decrease of for *$N_d(x)$* for ϕ_{eq} =5·10^{14} cm^{-2}
(expected from radiation-induced donor removal)

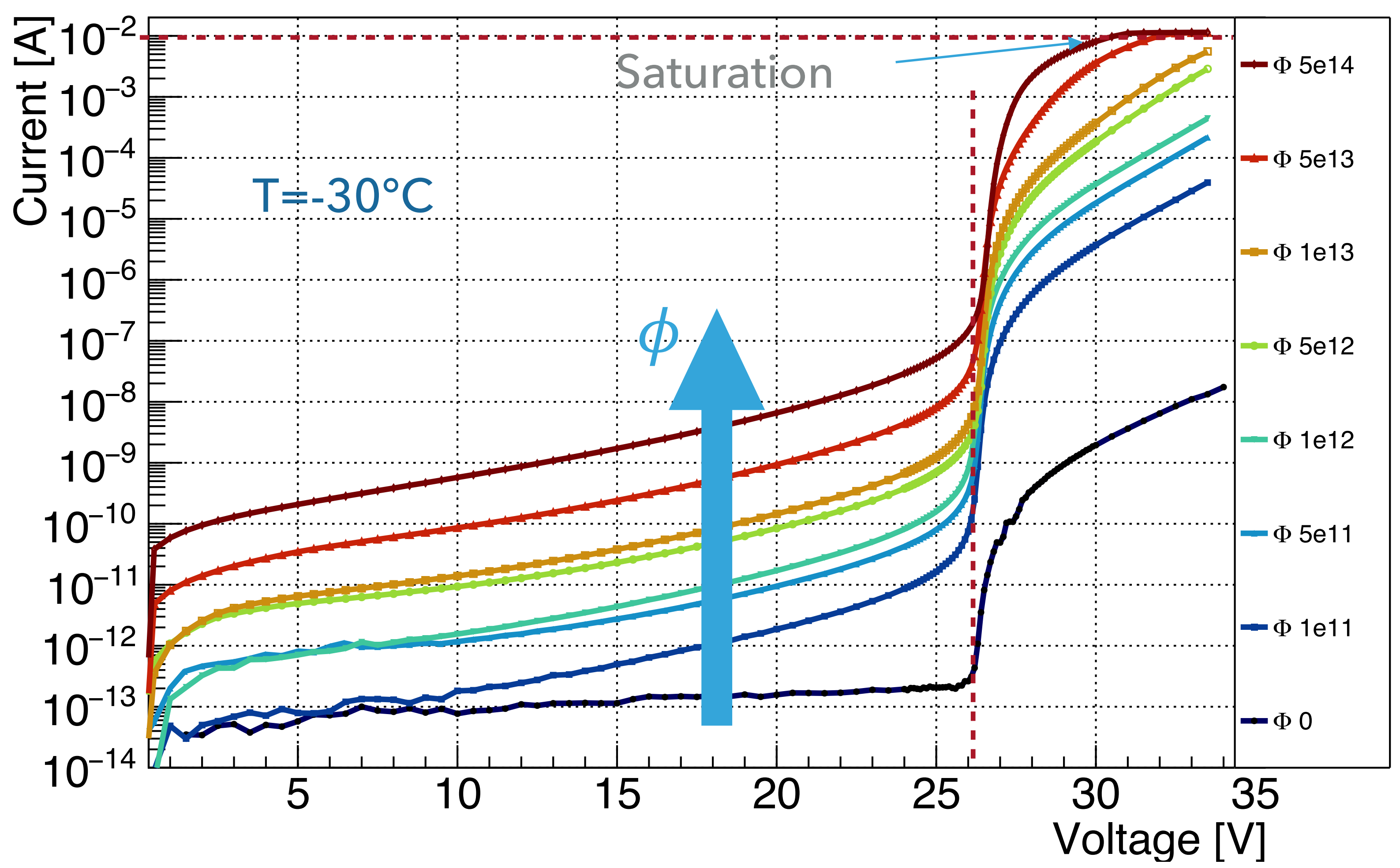
SiPM: KETEK MP15 with 4384 pixels 15x15 µm²

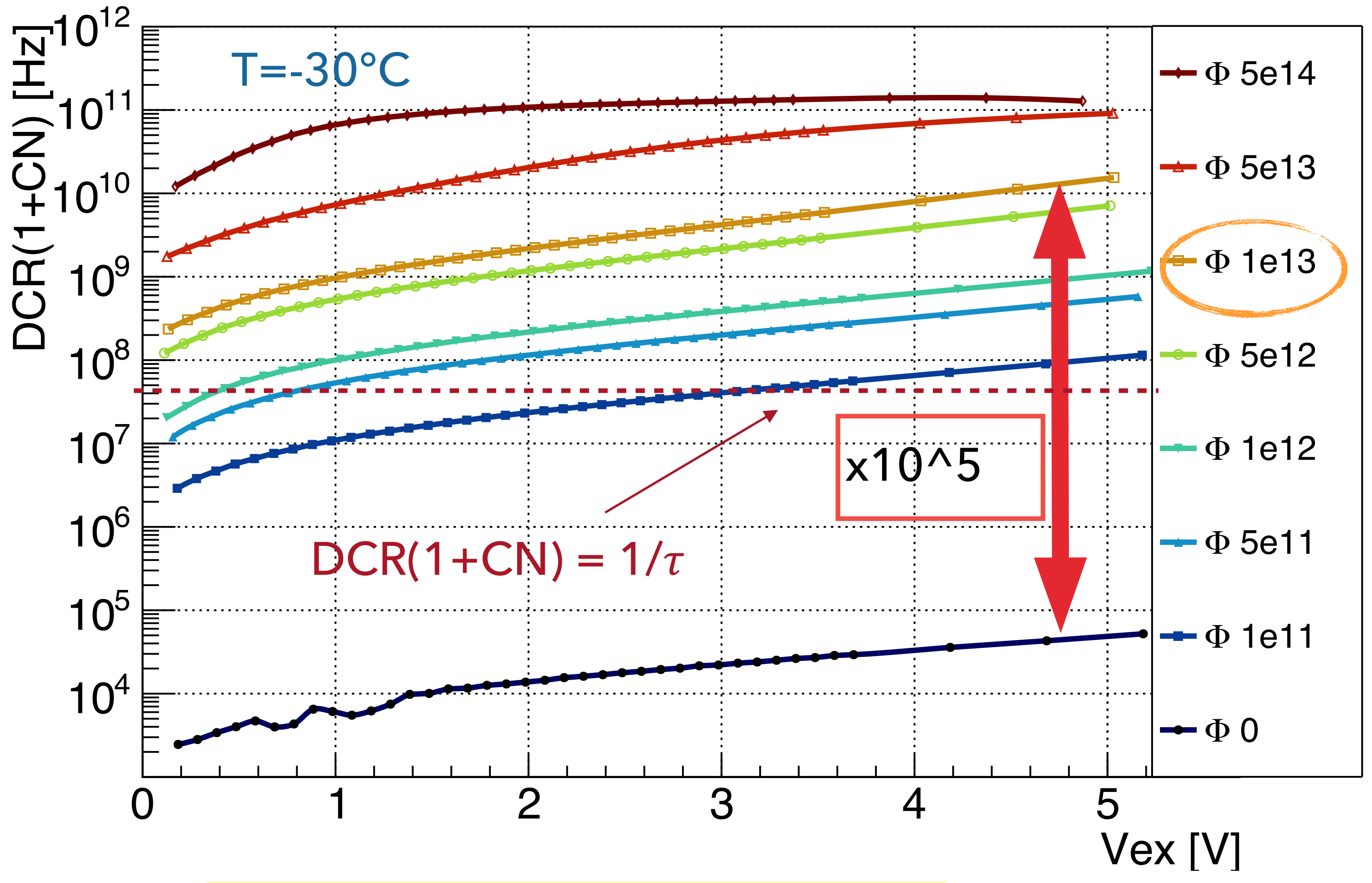
Irradiation with hadrons

$\phi_{eq} > 10^{12}$ cm^{-2}

$$\mathrm{DCR}\cdot(1+\mathrm{CN}) = \frac{I_{\mathrm{dark}}}{q_0 \cdot G}$$

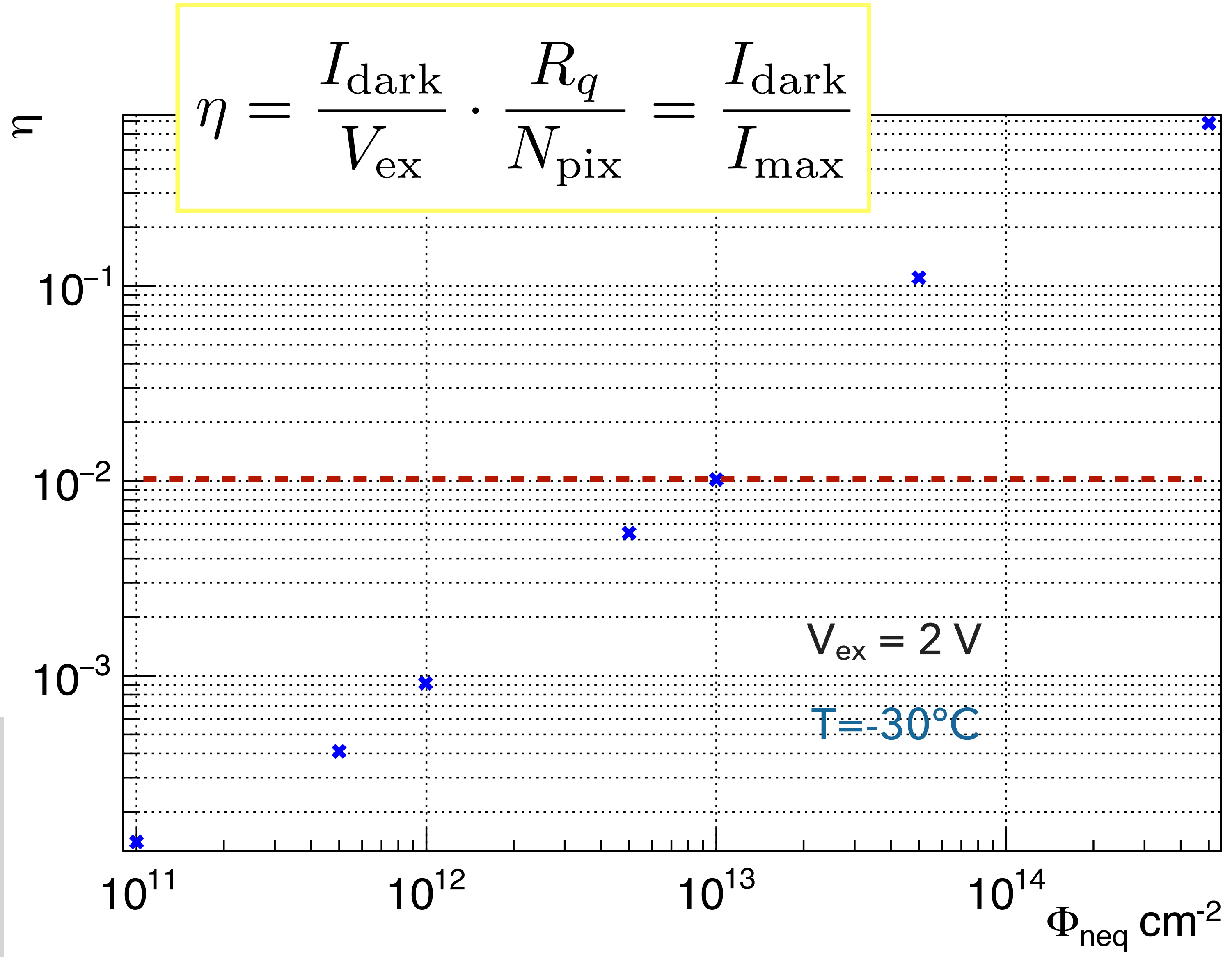
$$G = \frac{1}{q_0}(C_{pix} + Cq)\cdot(V_{bias} - V_{bd})$$





- Huge increase of dark current with irrad: 10 kHz before irrad, 2 GHz at $\phi_{eq} = 1\cdot 10^{13}$
- increase in pixel occupancy η > 1%
- self-heating effect = increase of V_{bd} = reduction of G at fix V_{op}

pixel occupancy due to dark rate



Centis Vignali, Garutti, Klanner, Lomidze, Schwandt
"Neutron irradiation effect on SiPMs up to $\phi_{eq} = 5\cdot 10^{14}$ cm^{-2}"
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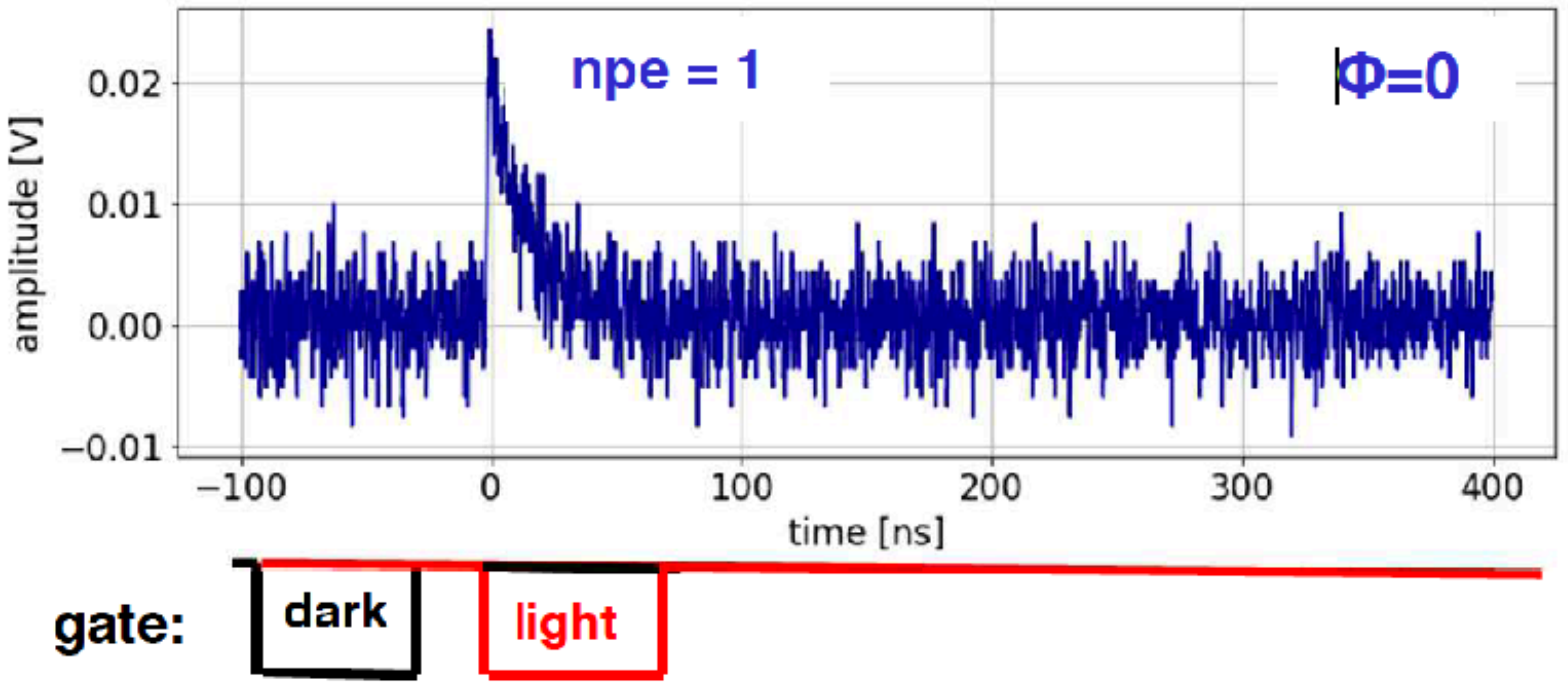
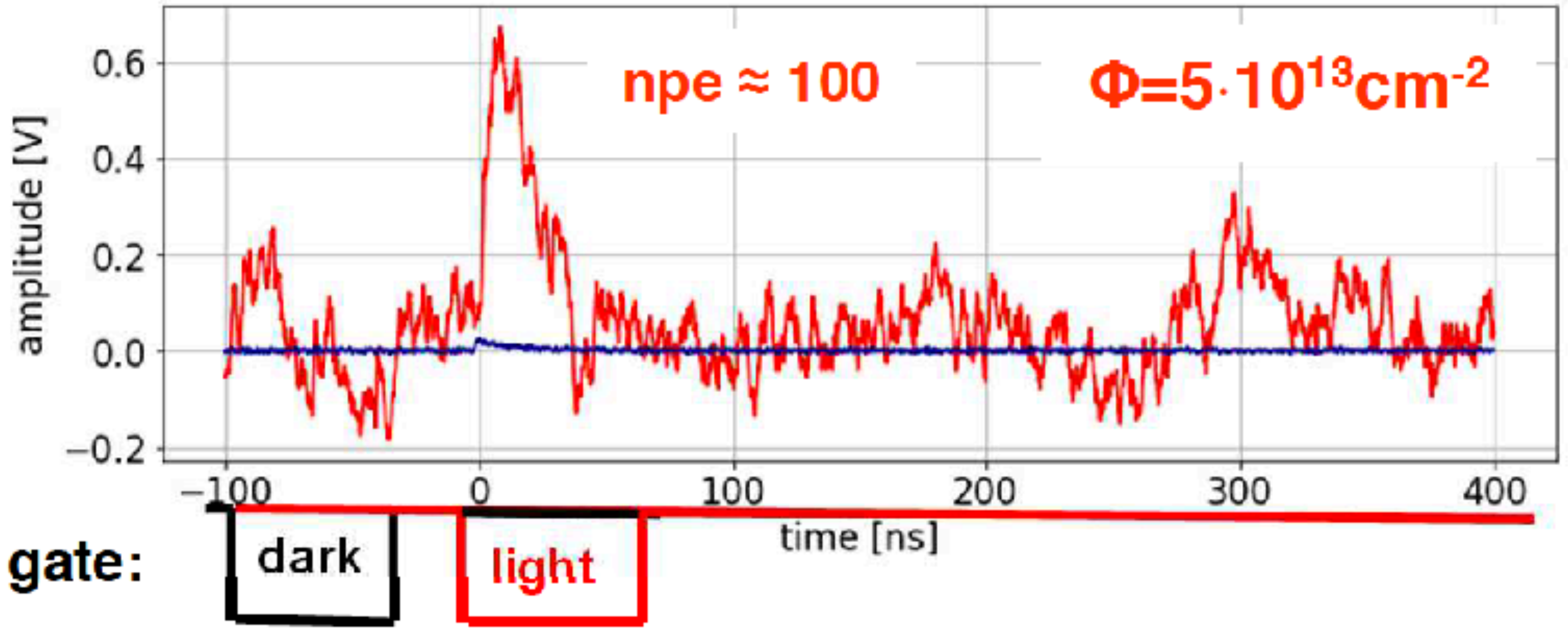
Irradiation with hadrons

$\phi_{eq} > 10^{12}$ cm^{-2}





N. of photons initiating a Geiger avalanche: $\mu = \frac{Mean}{G \cdot ESF} \propto PDE$

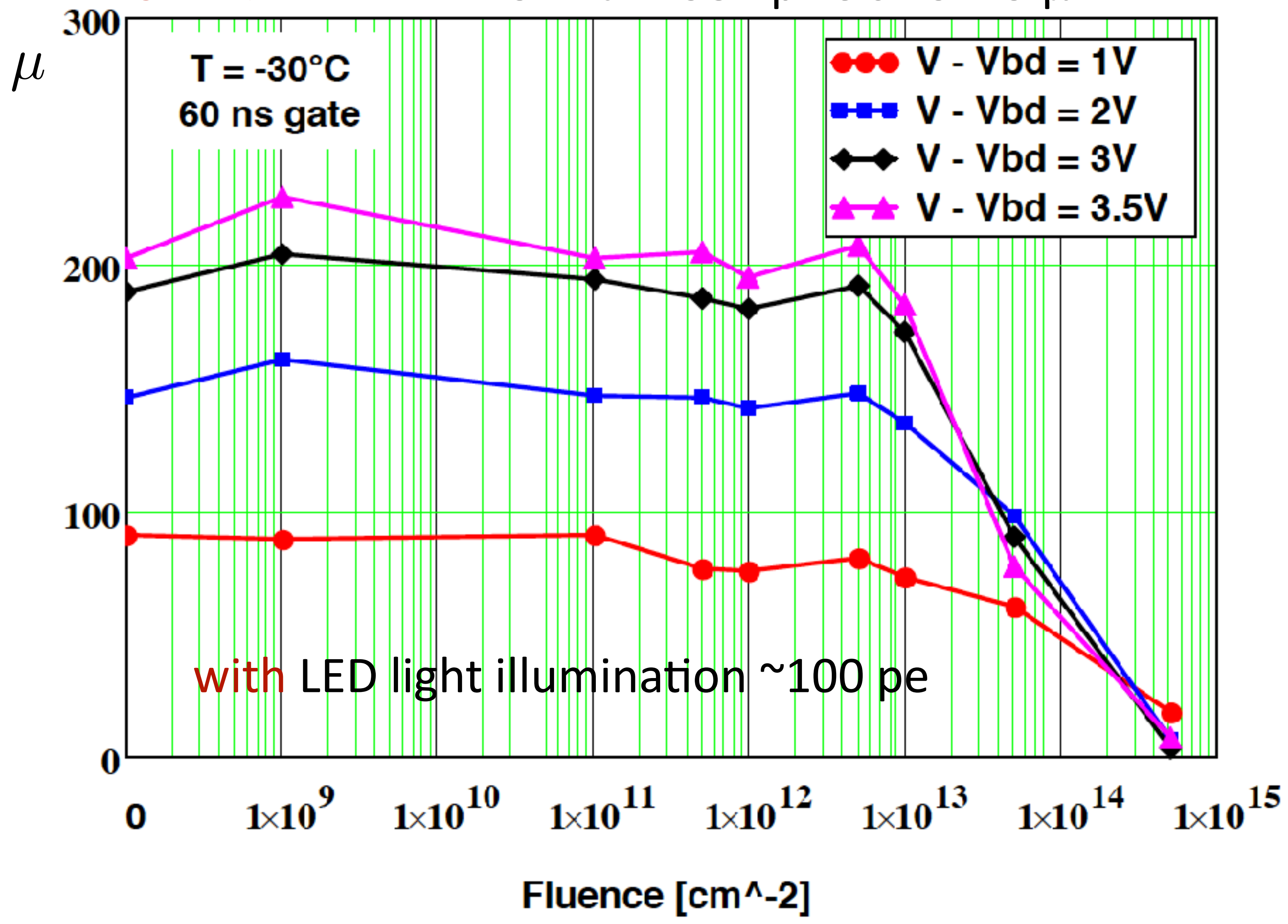
t_{gate} optimisation: short t_{gate} reduces DCR but also G

$$ESF = \frac{Mean}{Mean_{Poisson}}$$ Excess Signal Factor

$$G = \frac{1}{q_0}(C_{pix} + C_q) \cdot (V - V_{off}) \cdot \underbrace{f_{gate}}$$

fraction of signal inside the gate

SiPM: KETEK MP15 with 4384 pixels 15x15 μm²

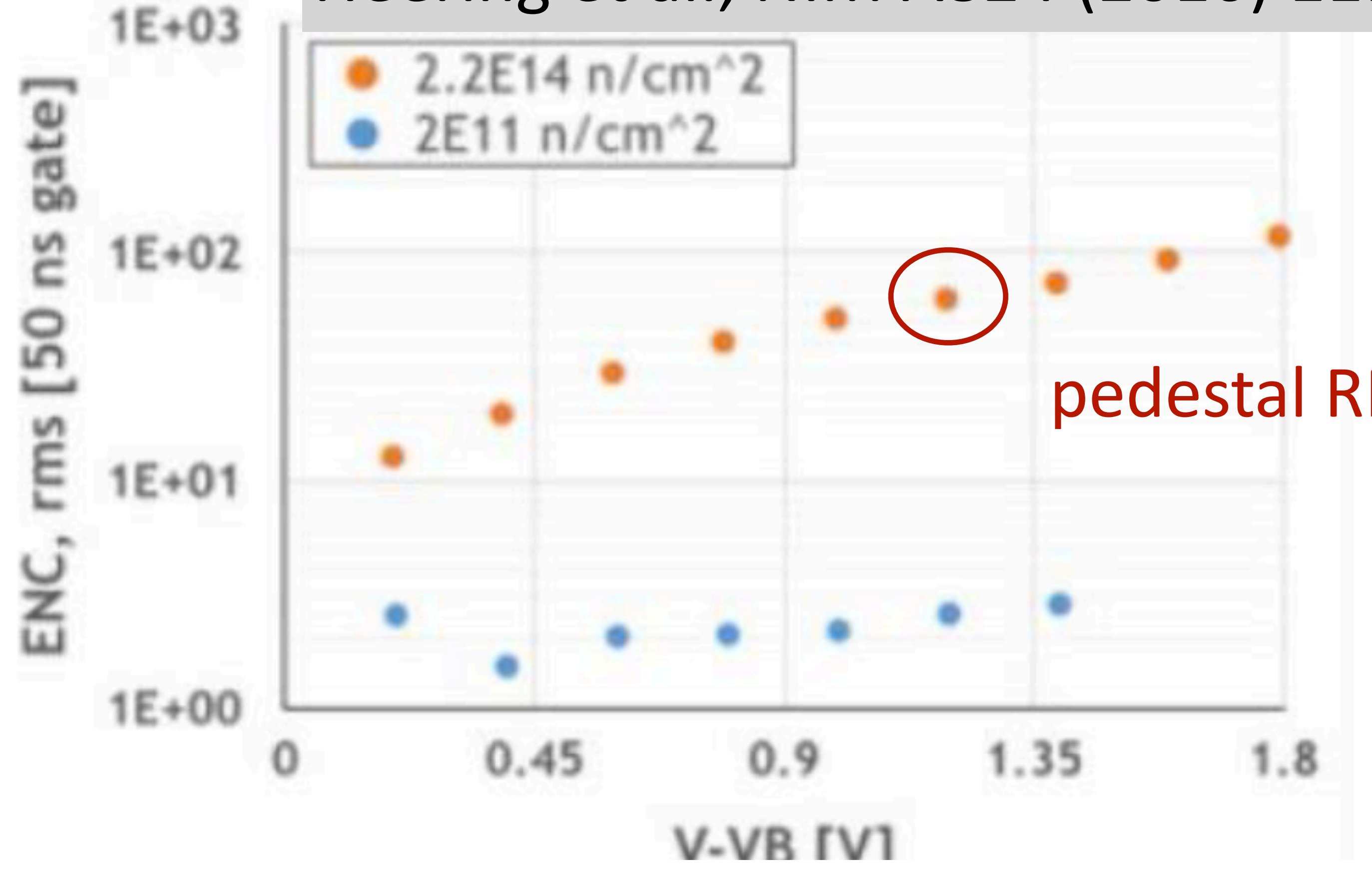


$\phi_{eq} < 10^{13}$ cm^{-2}:	PDE essentially unaffected by irradiation
$\phi_{eq} \sim 10^{13}$ - $5 \cdot 10^{13}$ cm^{-2}:	irradiation affects PDE (low V-V_{bd} still ok)
$\phi_{eq} = 5 \cdot 10^{14}$ cm^{-2}:	SiPM not a useful photo-detector

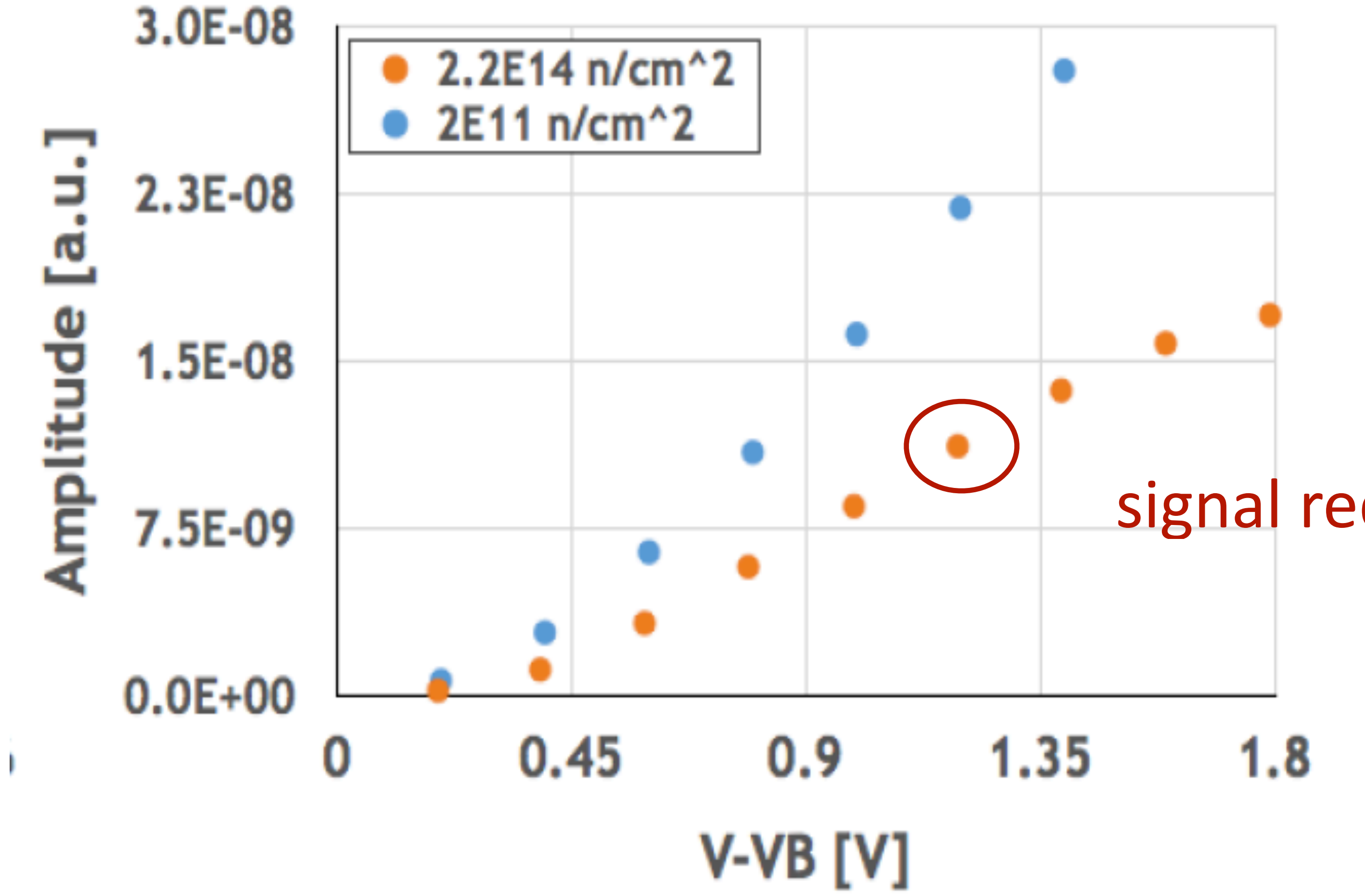
Irradiation with hadrons

$\phi_{eq} > 10^{12}\ cm^{-2}$

Heering et al., NIM A824 (2016) 111



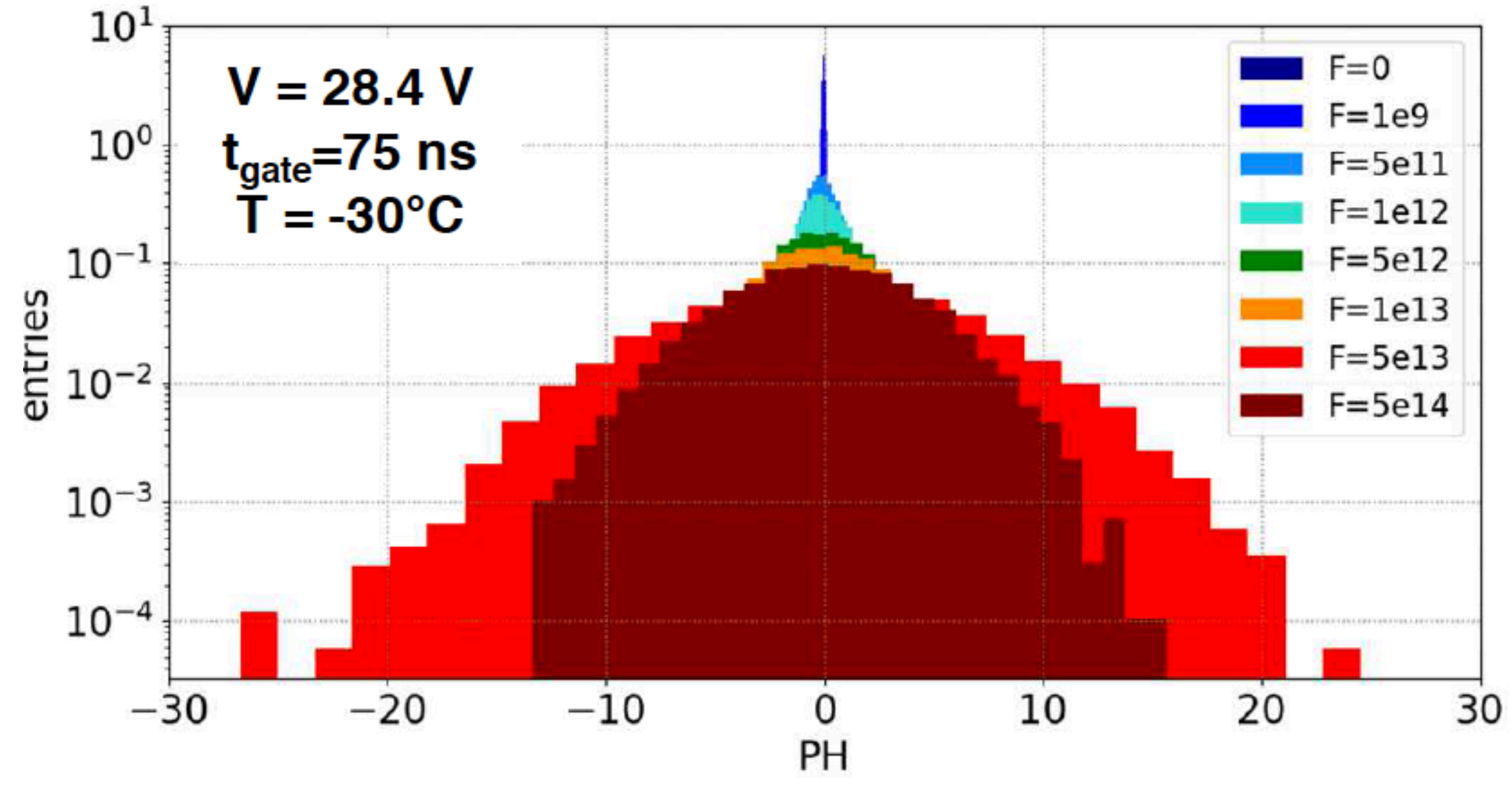
pedestal RMS ~ 70 pe



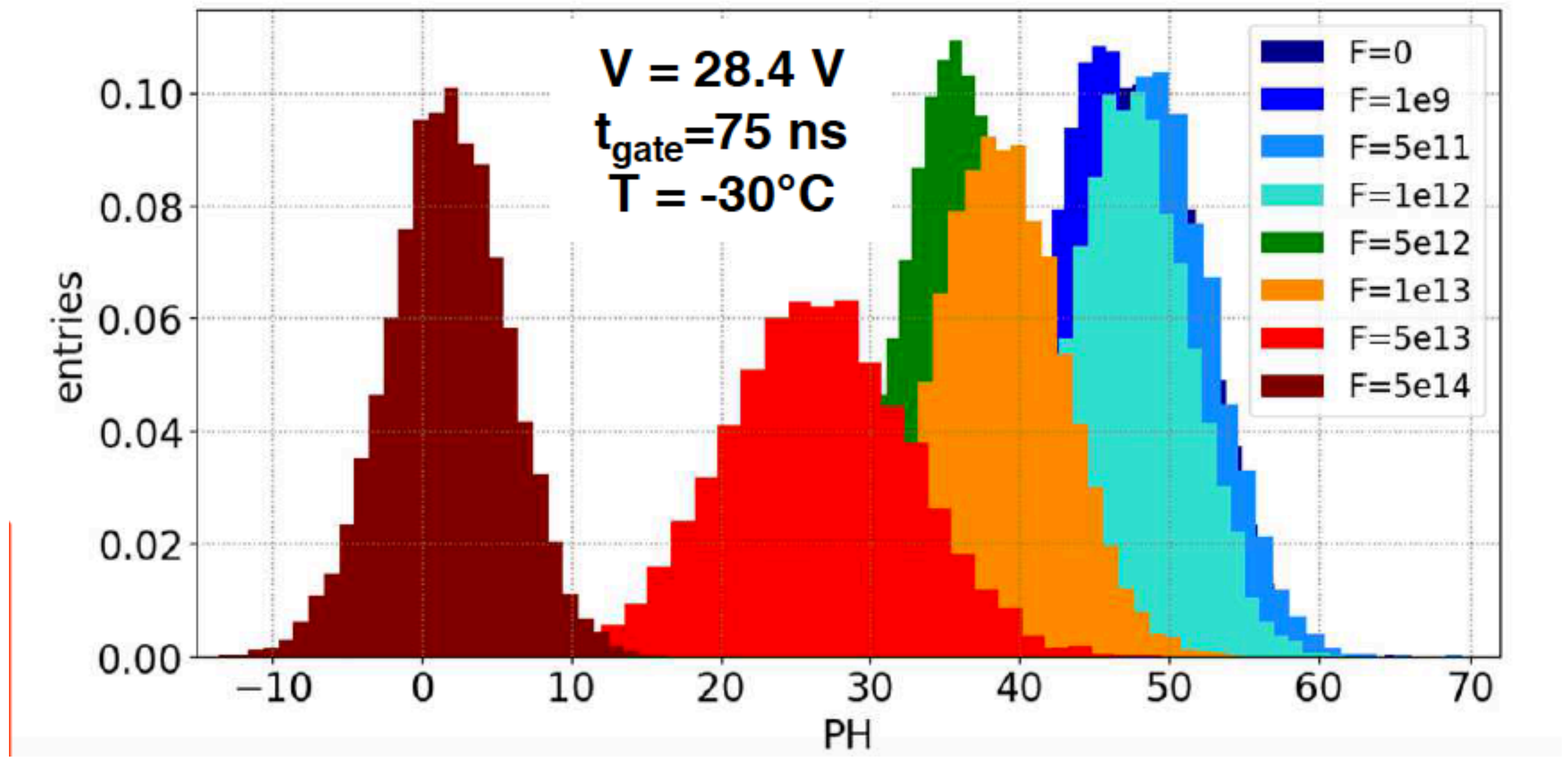
signal reduction by 60%

FBK SiPM, 12 µm pitch

dark



light

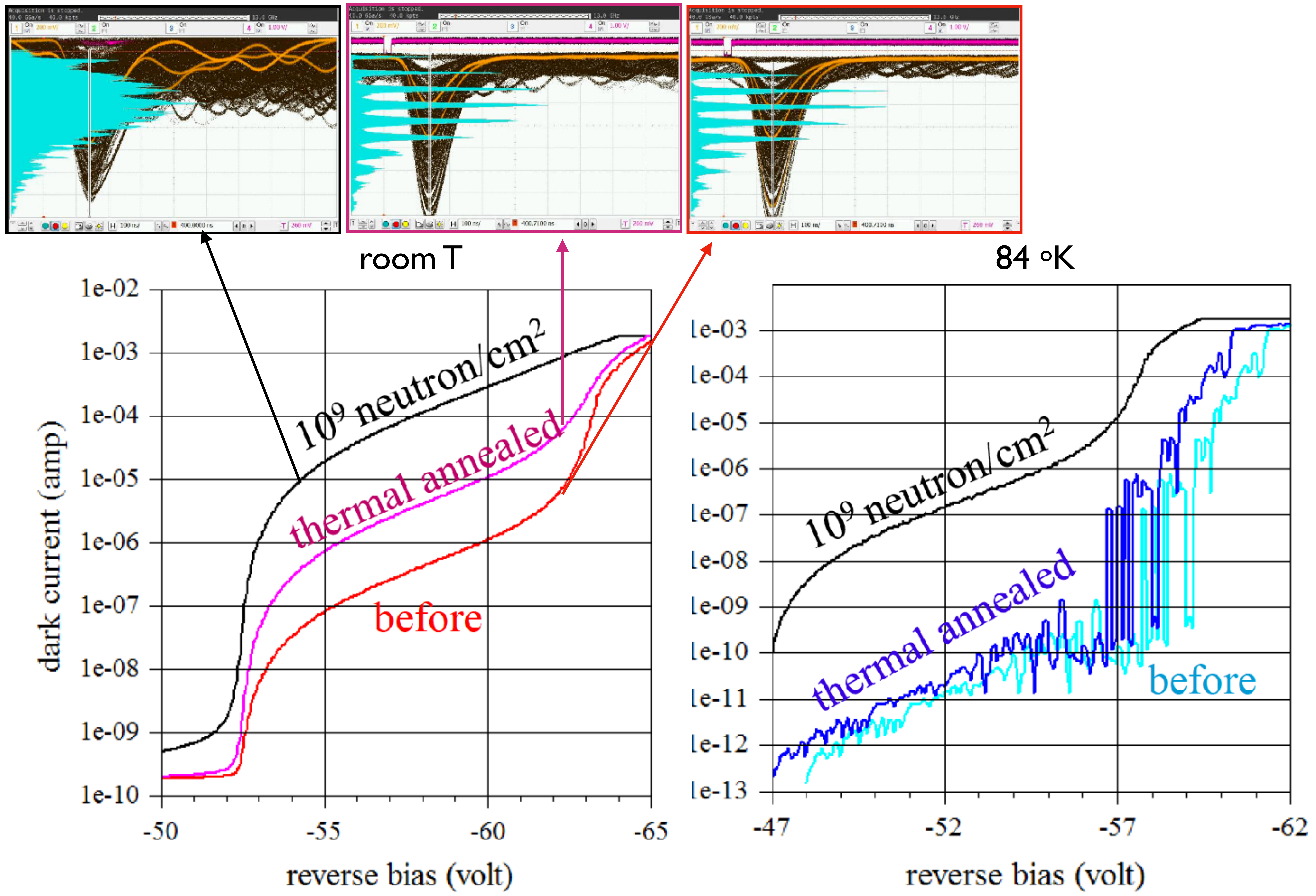


SiPM: KETEK MP15 with 4384 pixels 15x15 µm²

!! for $\phi_{eq} = 5 \cdot 10^{14}\ cm^{-2}$ pedestal RMS decreases = saturation !!

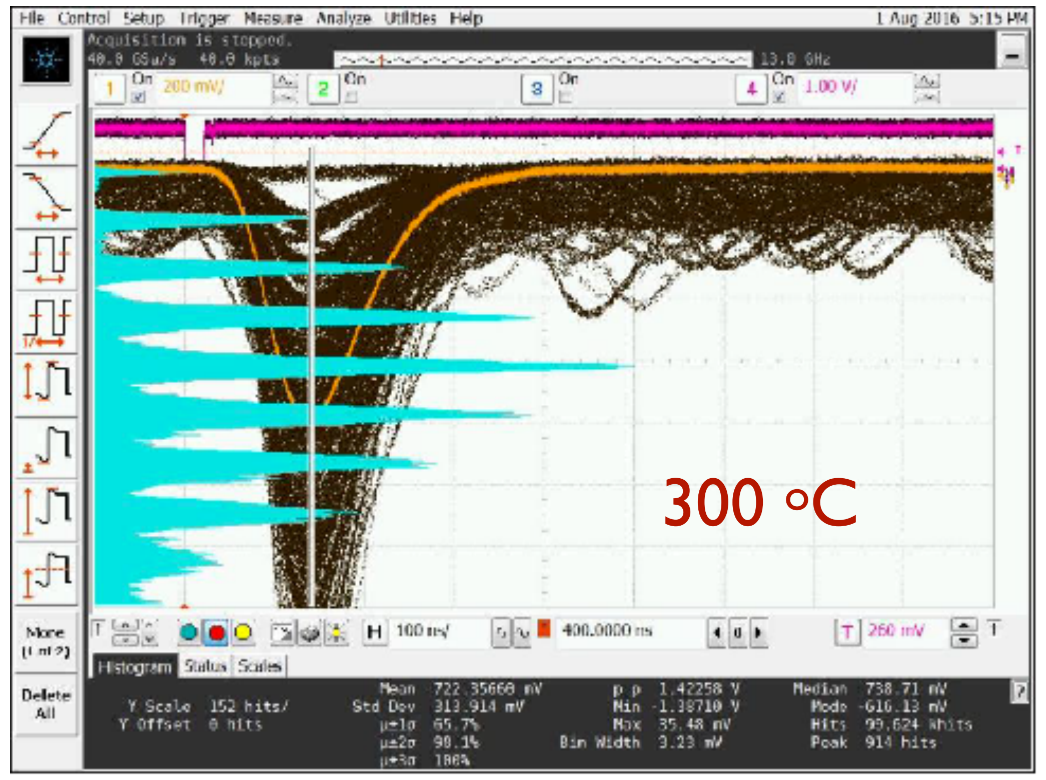
Need to look at combined effect of S/N to decide if an operable SiPM is still good for physics

Thermal annealing



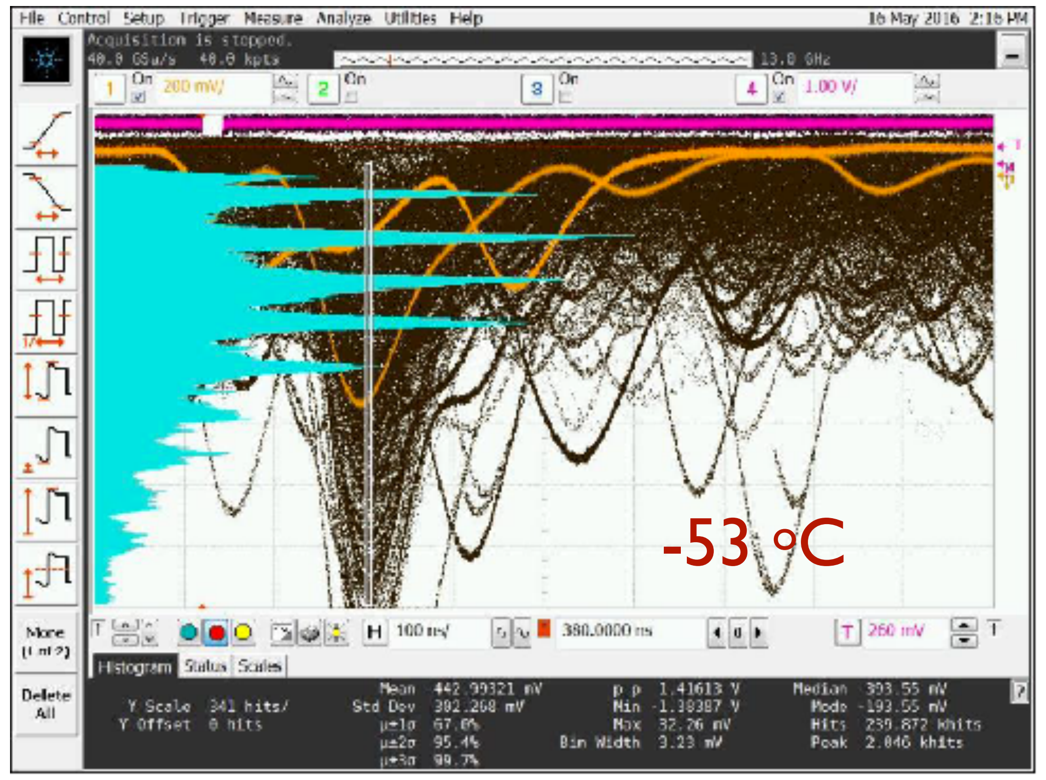
annealing at 250 °C
forward bias +10mA

$\phi_{eq} \sim 10^9$ cm^{-2}



T. Tsang (BNL),
ICASIPM workshop
Schwetzingen

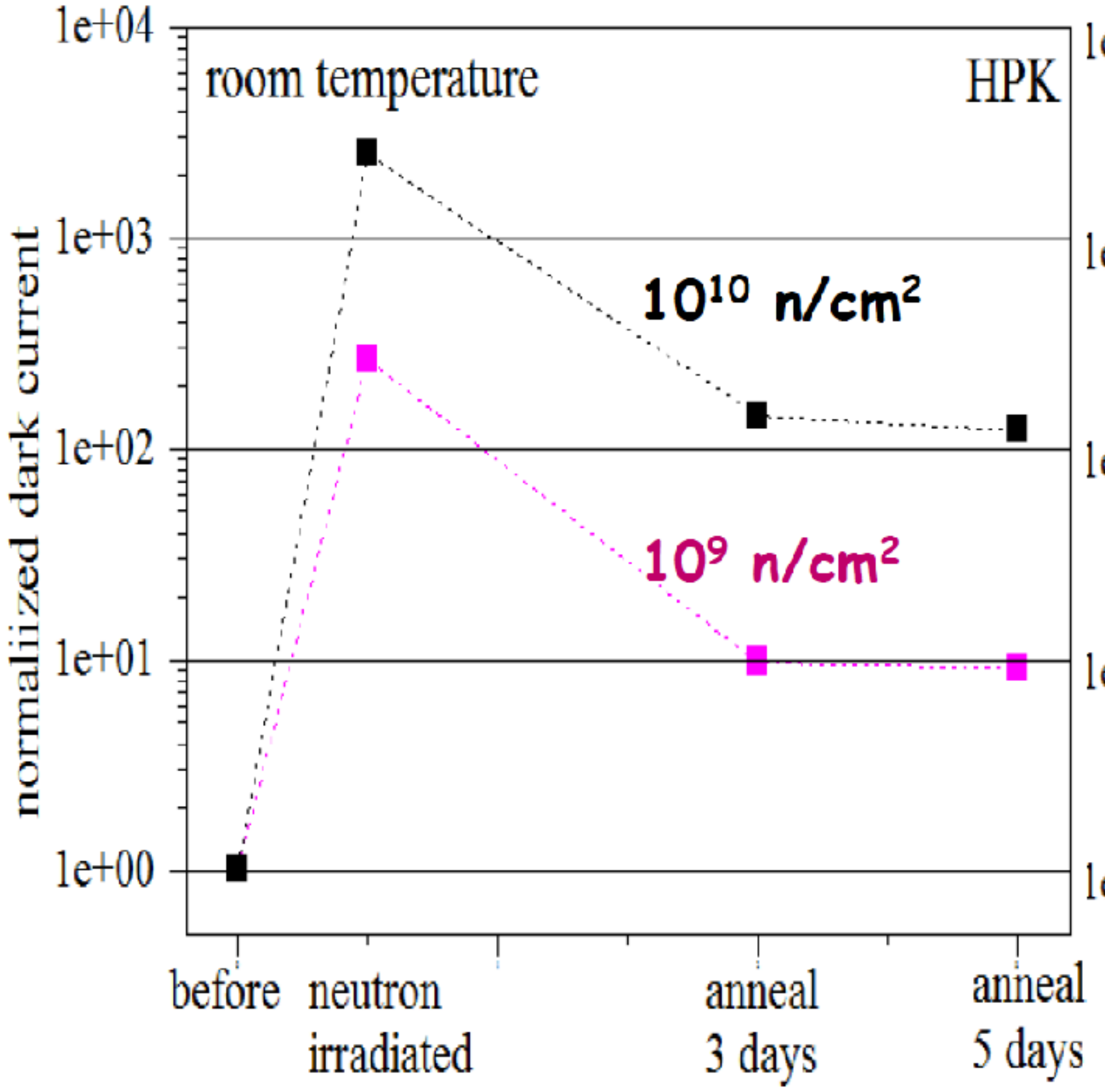
$\phi_{eq} \sim 10^{12}$ cm^{-2}



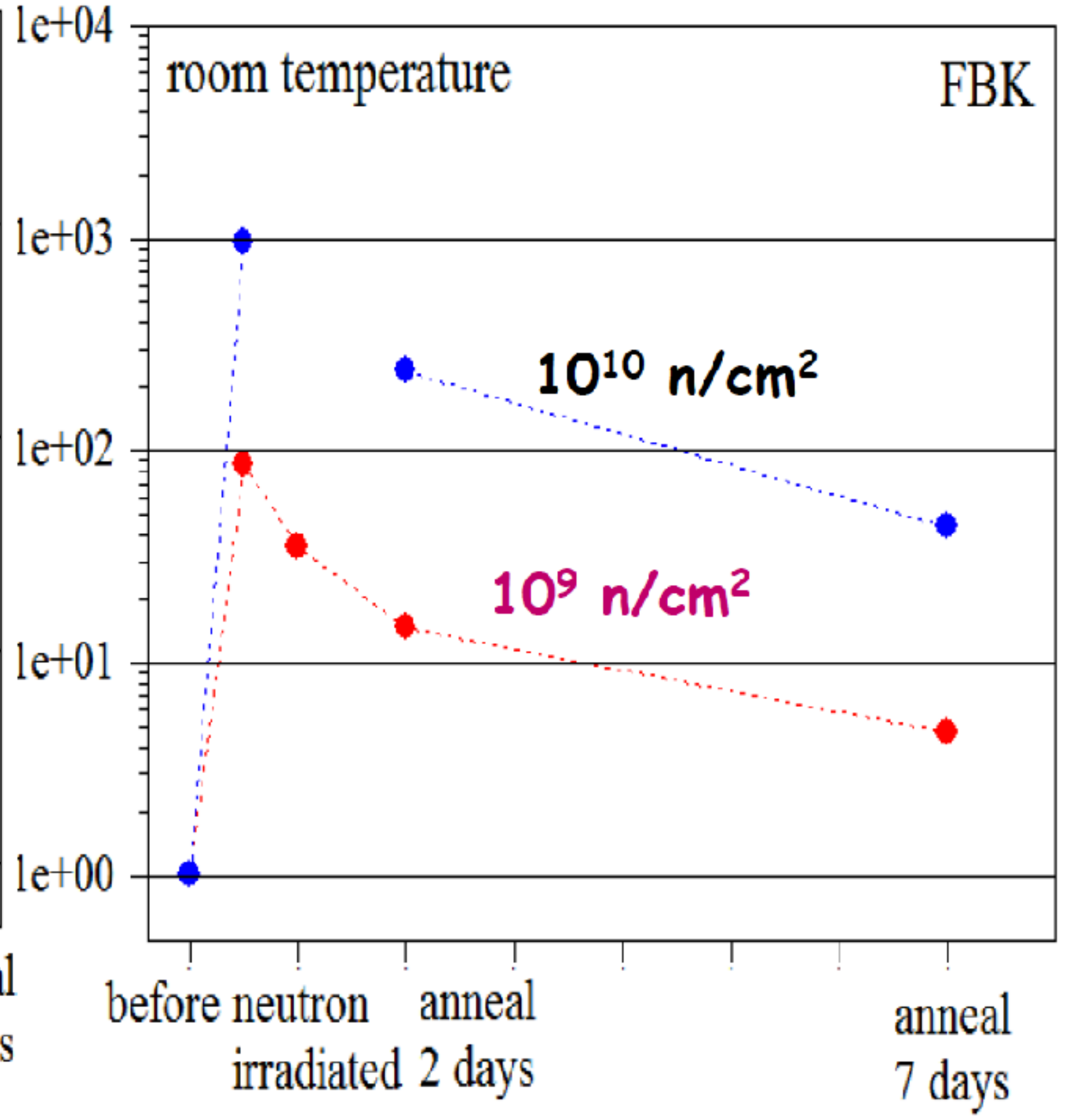
Remarkable effect of thermal annealing with forward bias
Single p.e. resolution possible after $\phi_{eq} \sim 10^{12}$ cm^{-2} with cooling

Thermal annealing

annealing: 250 °C, bias +8mA

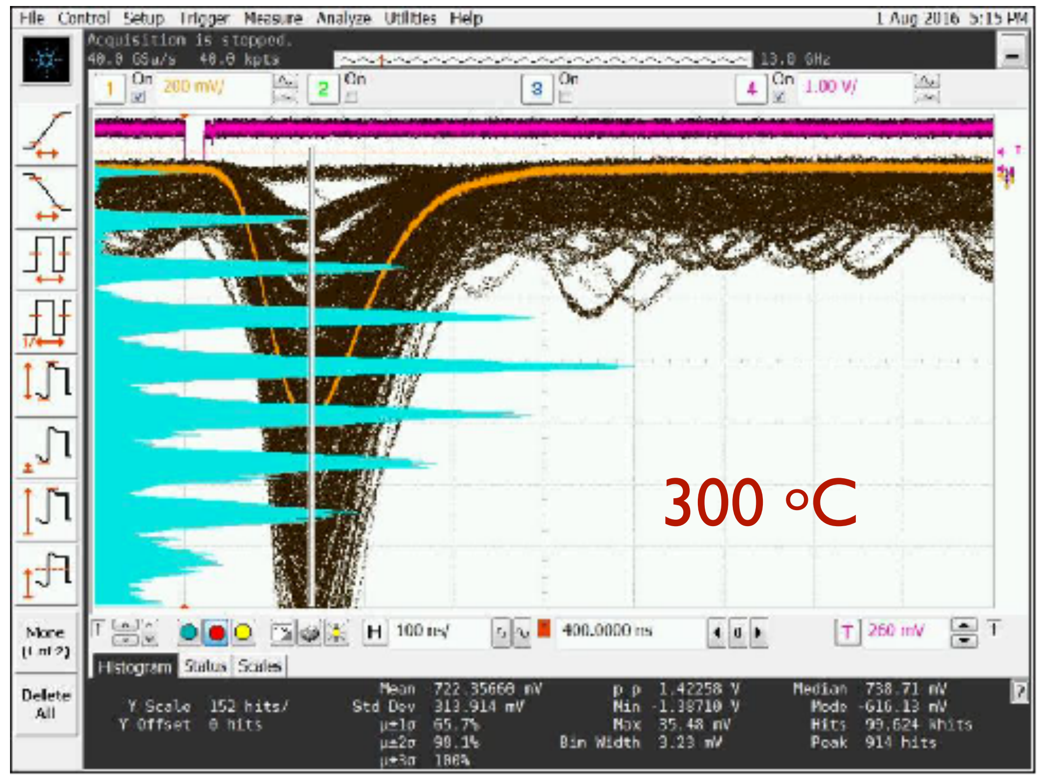


annealing: 230 °C, bias +10mA



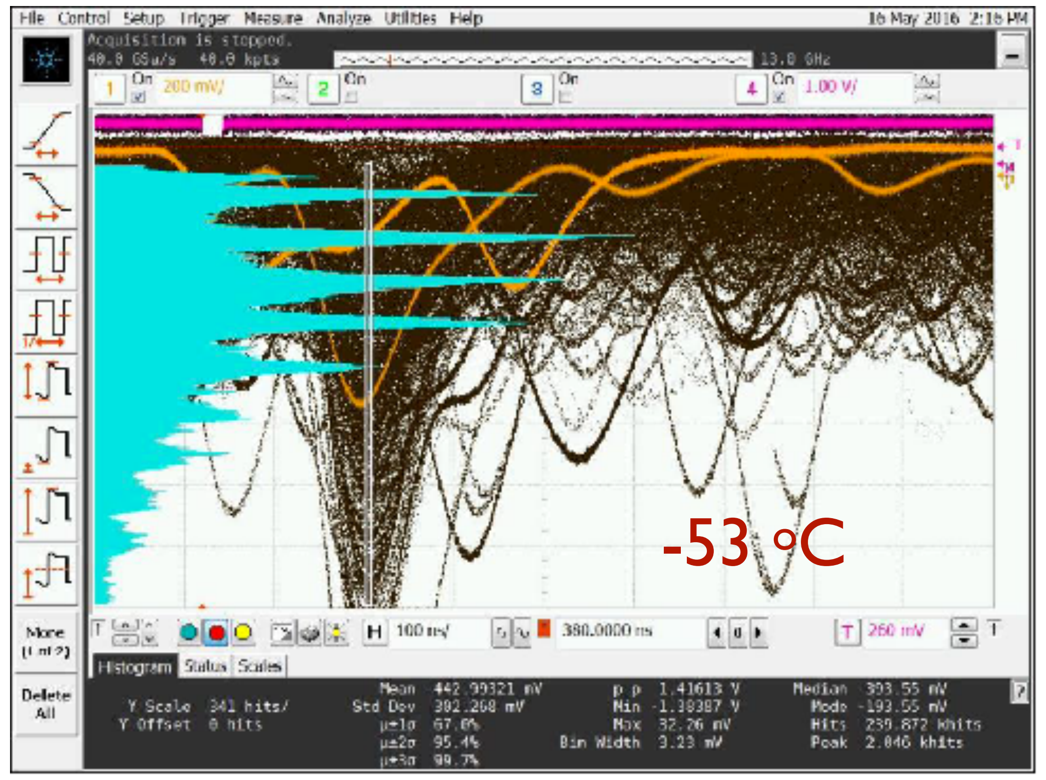
annealing at 250 °C
forward bias +10mA

$\phi_{eq} \sim 10^9$ cm^{-2}



T. Tsang (BNL),
ICASIPM workshop
Schwetzingen

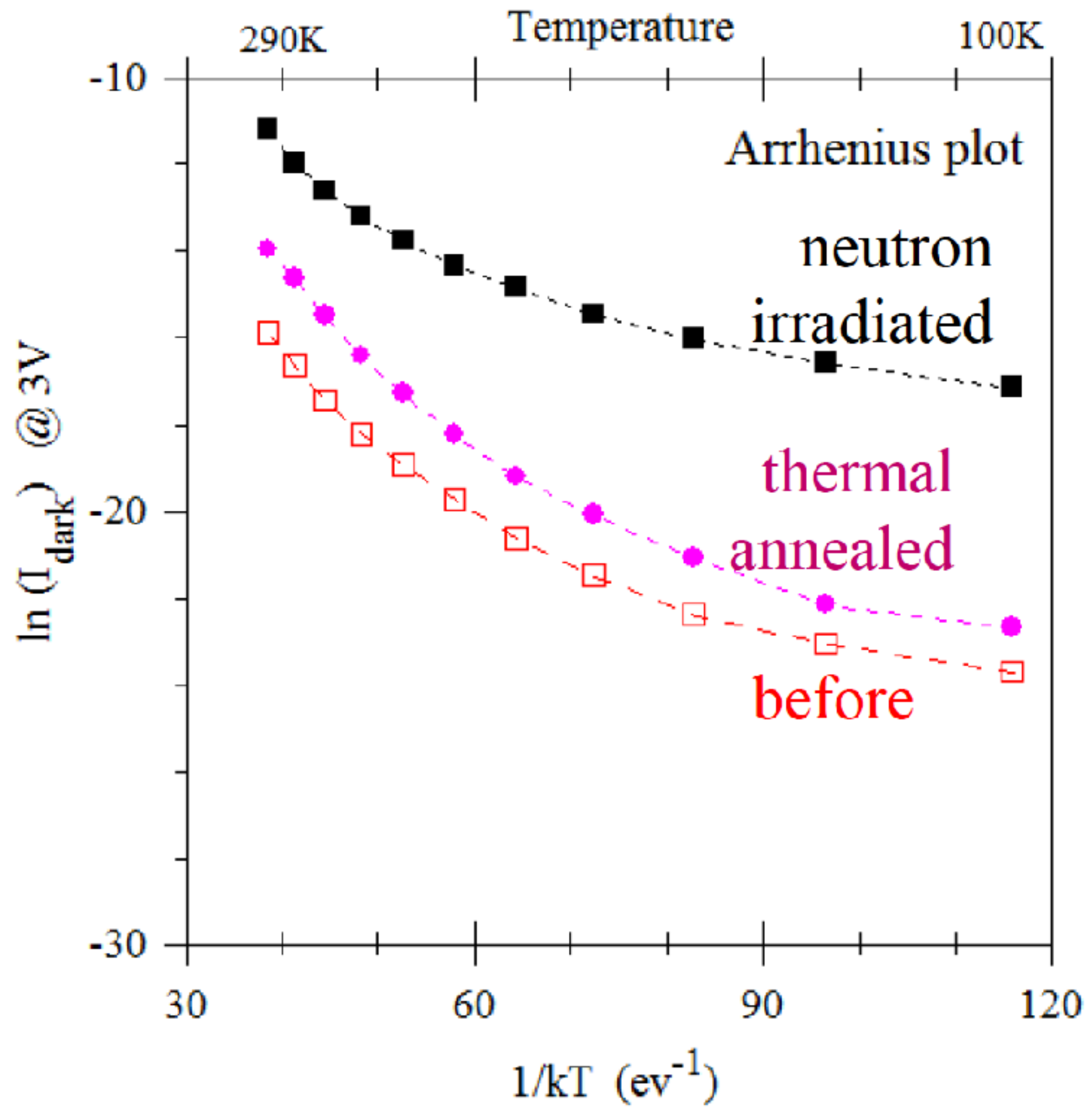
$\phi_{eq} \sim 10^{12}$ cm^{-2}



Thermal annealing takes time
Dark current partially recovered

Remarkable effect of thermal annealing with forward bias
Single p.e. resolution possible after $\phi_{eq} \sim 10^{12}$ cm^{-2} with cooling

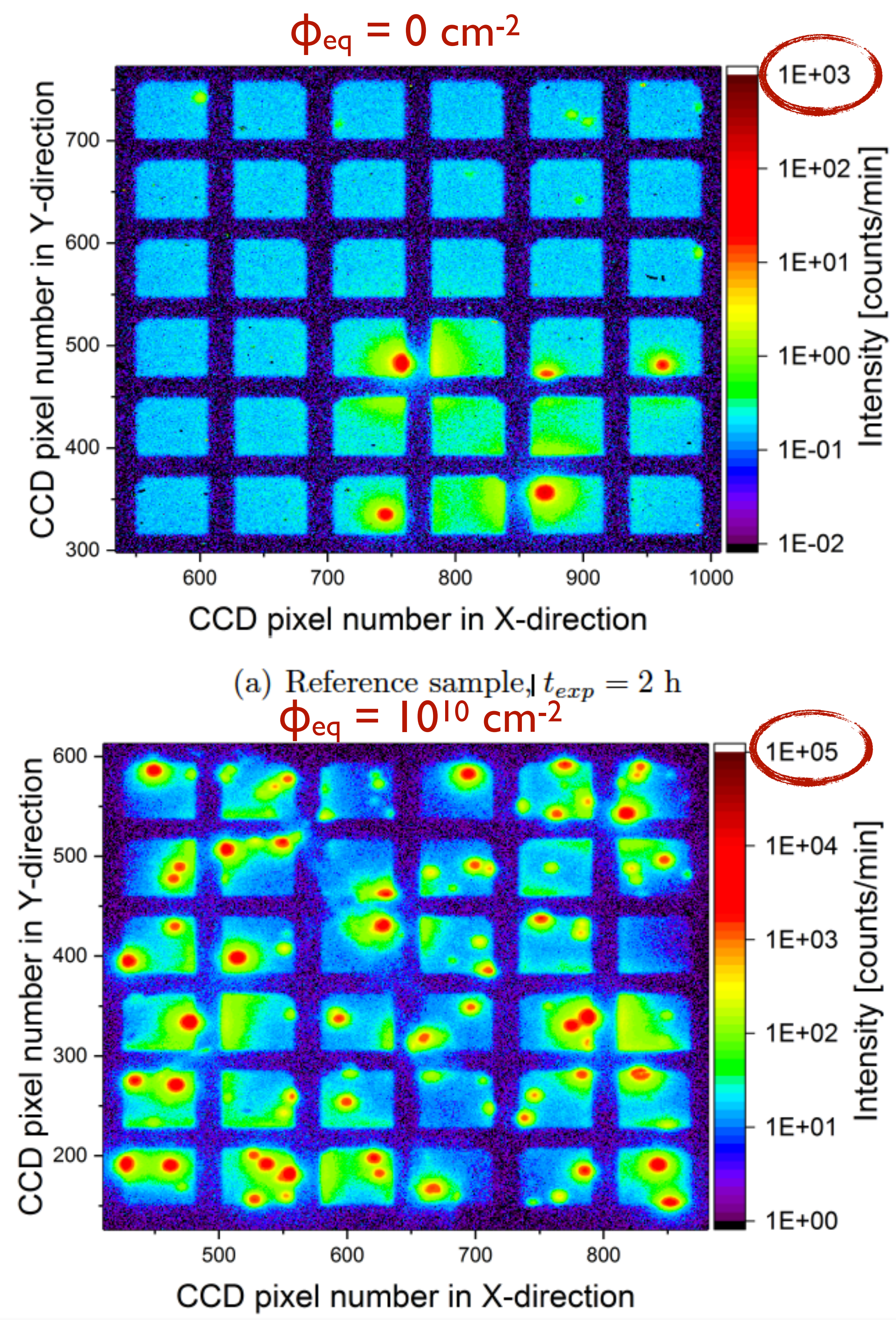
Temperature dependence of I_{dark}



I_{dark} (before) drops 1-decade / 80 °K
I_{dark} (neutron) drops 1-decade / 57 °K

I_{dark} (neutron) has a fundamentally different activation energy

E. Engelmann (KETEK), PhD thesis



(a) Reference sample, $t_{exp} = 2$ h

(b) Neutron irradiated sample, $t_{exp} = 2$ min

investigate activation energy of defects

Conclusion

Radiation damage effects on SiPMs

After irradiation SiPMs are mostly operable but:

- Significant increase of dark current (DCR)
- Loss of single photon resolving capability

- $\phi_{eq} < 10^{12}$ cm^{-2} generally no significant change in V_{bd}, Gain, PDE, C_{pix}, R_q
- $\phi_{eq} > 10^{12}$ cm^{-2}, increased occupancy, decrease of PDE, shift of V_{bd}

- Degradation of energy resolution
- Timing performance degraded mostly due to poor S/N
- High dark current ➔ self heating / increase of power consumption

Radiation damage in SiPM does not scale with NIEL:

- Require further investigation on scaling with fluence for different particle types and energies
- Requires detailed annealing studies

Radiation hard SiPM

a wish list

Dark noise reduction

1. start with low DCR before irradiation (pure material/low impurity process)
2. minimise thickness of the depleted region
3. reduce trap-assisted tunnelling by reducing peak electric field in the p-n-junction

   2. and 3. are contradicting ➔ find optimum between the two

Cell occupancy reduction

- reducing the cell active volume (small cell size) and cell recovery time
  - small cells = small C_{pix} / fast recovery time / small G
  - small cells = reduced PDE ➔ use very thin tranches and metal film resistors with high transparency to visible light

Breakdown voltage increase minimisation

- minimise thickness of the depleted region
- optimisation of initial doping concentration for the expected donor removal

Reduction of the damage in SiPM entrance window

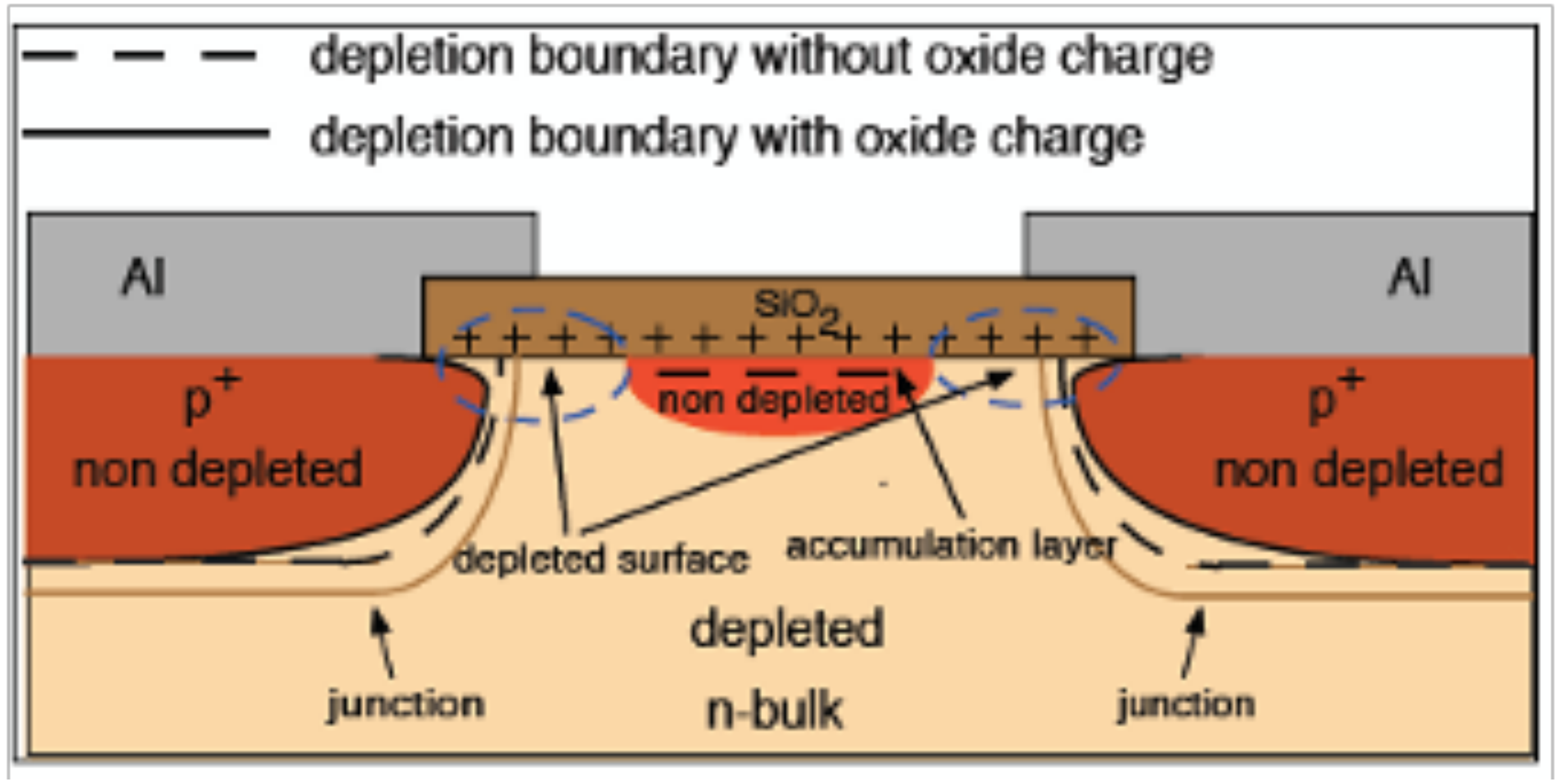
- use Si_3N_4 for the entrance window instead of SiO_2

BACKUP SLIDES

Surface damage effects

➡ Build-up of oxide charges and Si-SiO_2 interface traps

- Accumulation layers form (or increase)
- High field regions appear reducing the breakdown voltage
- Leakage currents increase due to interface states
- Depletion voltage and inter-pixel capacitances increase
- Charge losses close to the Si-SiO_2 interface occur (or increase)



Schematic picture of surface damage induced effects on a pixel detector