AIDA innova

INFN TORINO
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Sezione di Torino

UNIVERSITÀ DI TORINO

eXFlu

characterisation of thin silicon sensors for eXtreme Fluences

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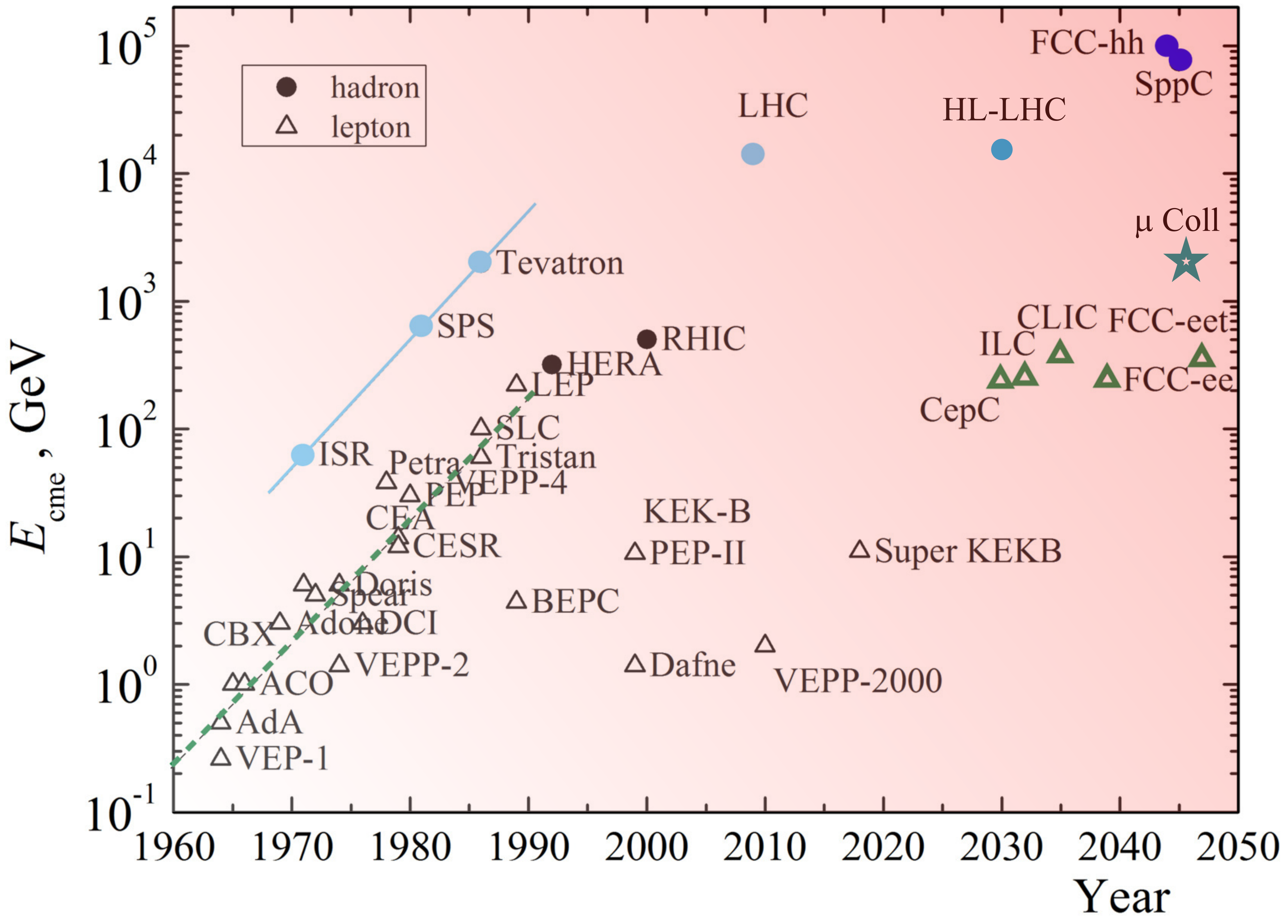
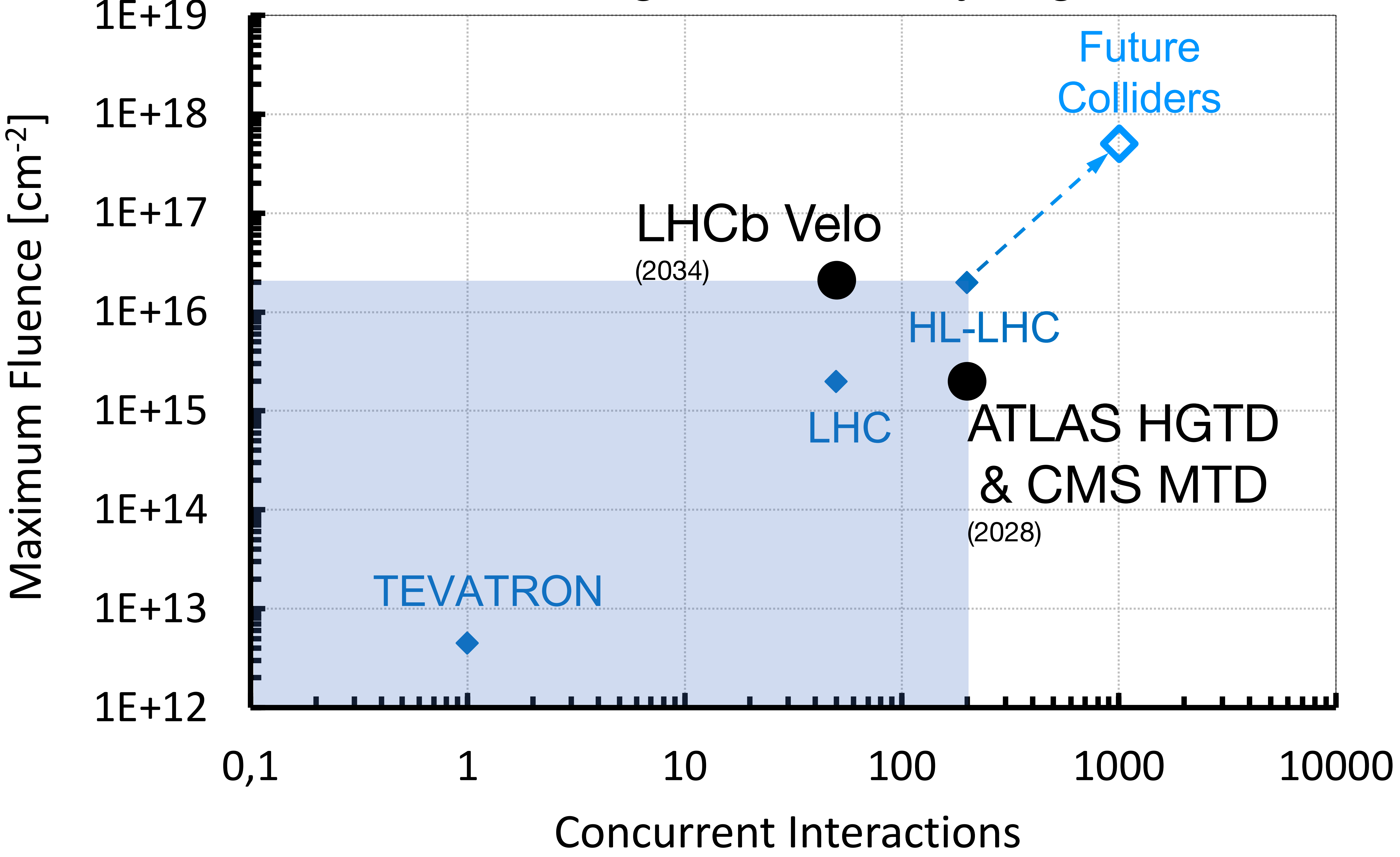
IPRD23 - 16th Topical Seminar on Innovative Particle and Radiation Detectors
25-29 September 2023 — Siena, Italy

The hurdles ahead: challenges in future HEP.

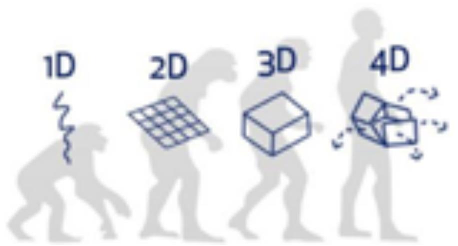
Push towards higher energies



Push towards higher luminosity, higher fluence



Strategies and necessities for the challenges ahead



MEASURE TIME

Timing information is crucial for enhancing the reconstruction efficiency in high pile-up events.

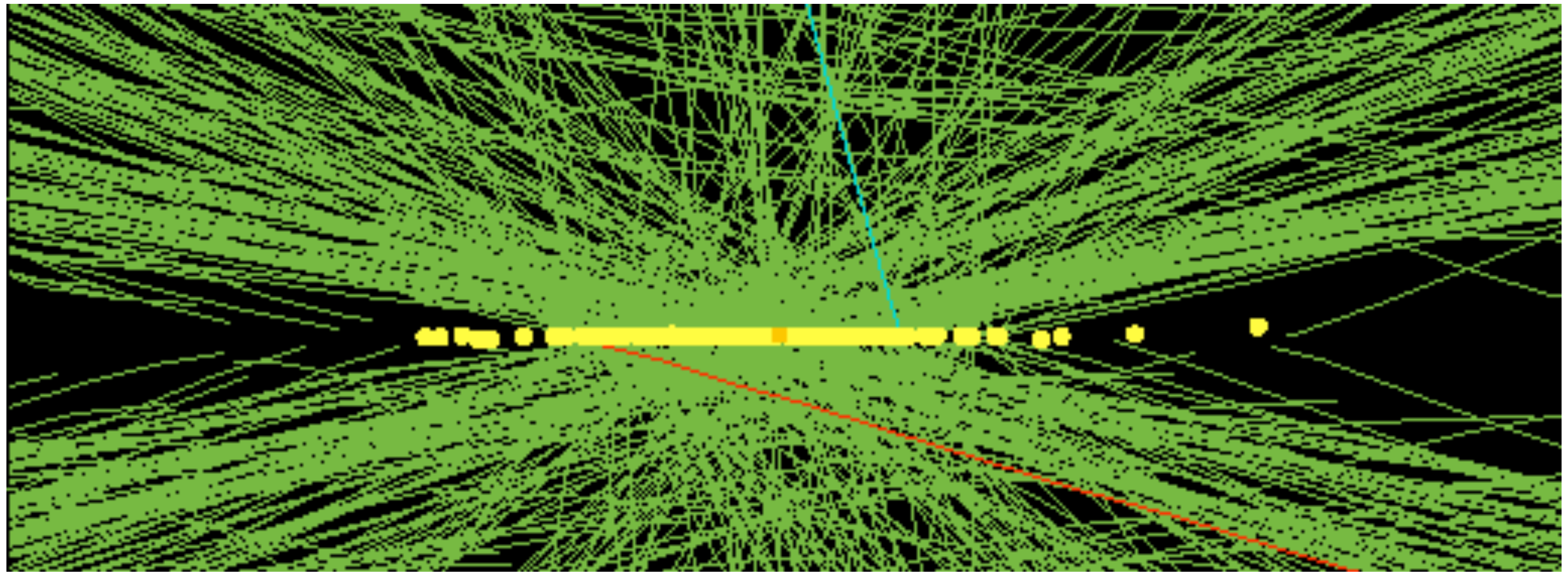
Track-Level timing
dedicated detector layers are used to provide time information in the event reconstruction.

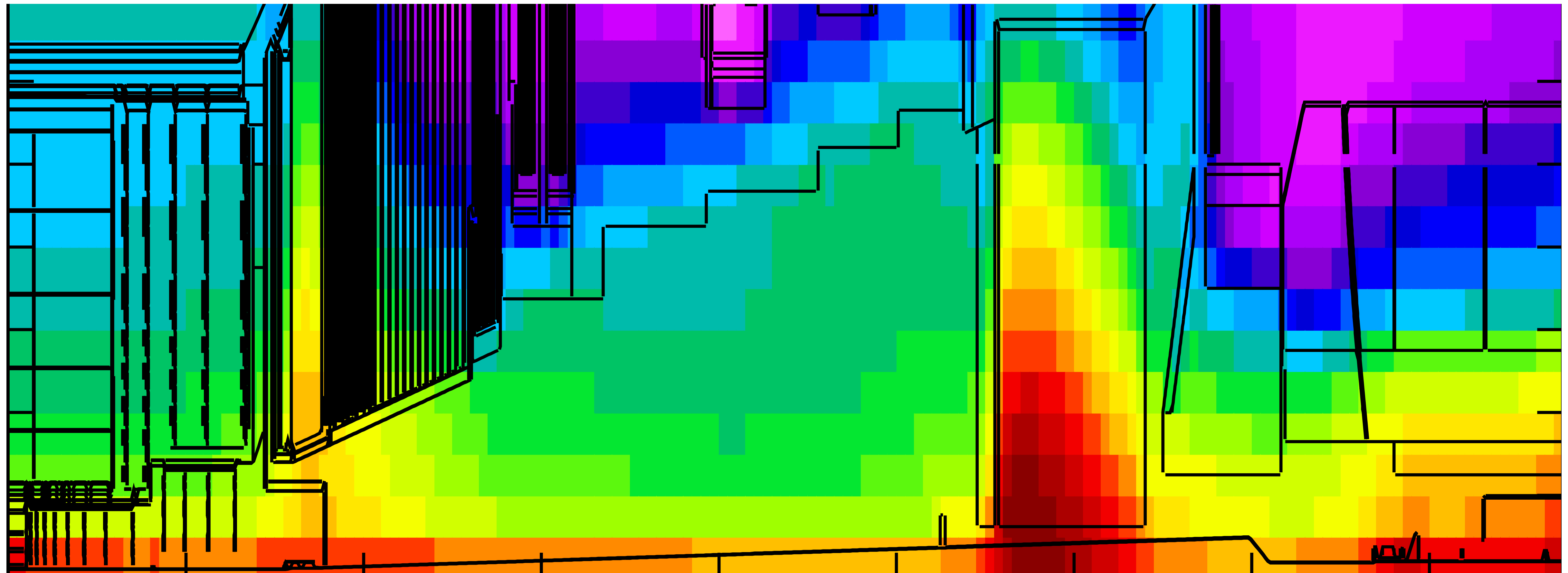
Hit-Level timing: 4D tracking
requires excellent both space and time resolutions

IMPROVE RADIATION RESISTANCE

Future sensors should retain an acceptable performance at $\Phi = 1\mathrm{e}17\,\mathrm{n}_{1\mathrm{MeV\,eq}}\,\mathrm{cm}^{-2}$ and beyond

Readout electronics requirements
~ 1 fC for tracking
≳ 5 fC and fast signals for timing





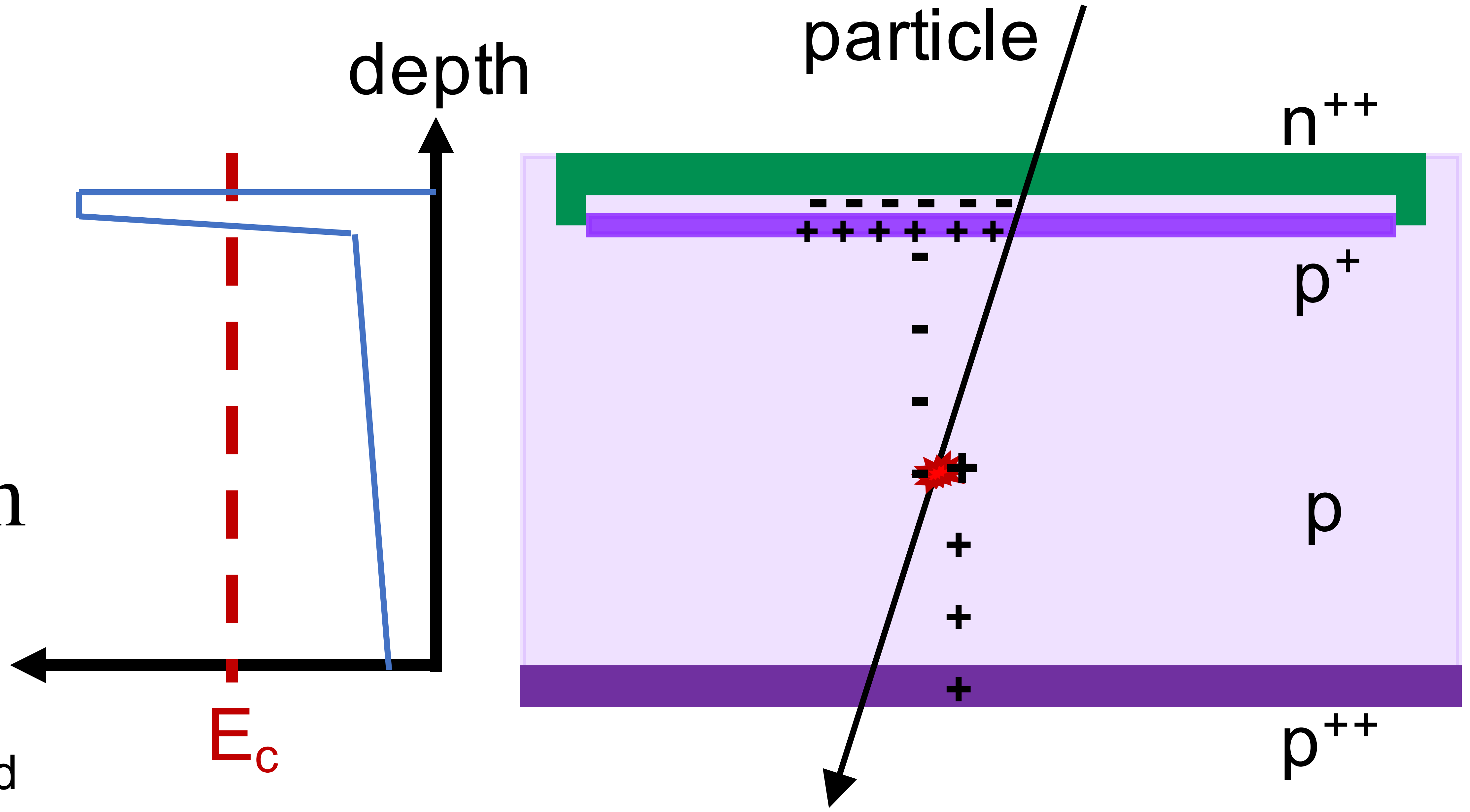
LGAD: evolving for the challenges ahead

Low-Gain Avalanche Diodes

n-in-p silicon sensors providing a controlled internal multiplication

gain p+ layer with $E_c > 30\,\mathrm{V}/\mu\mathrm{m}$

operated at GAIN ~ 30



MIP signal in silicon

$$\sim 65\ \mathrm{n}_{\mathrm{eh\ pairs}}\ \mu\mathrm{m}^{-1}$$

$$\sim 0.01\ \mathrm{fC}\ \mu\mathrm{m}^{-1}$$

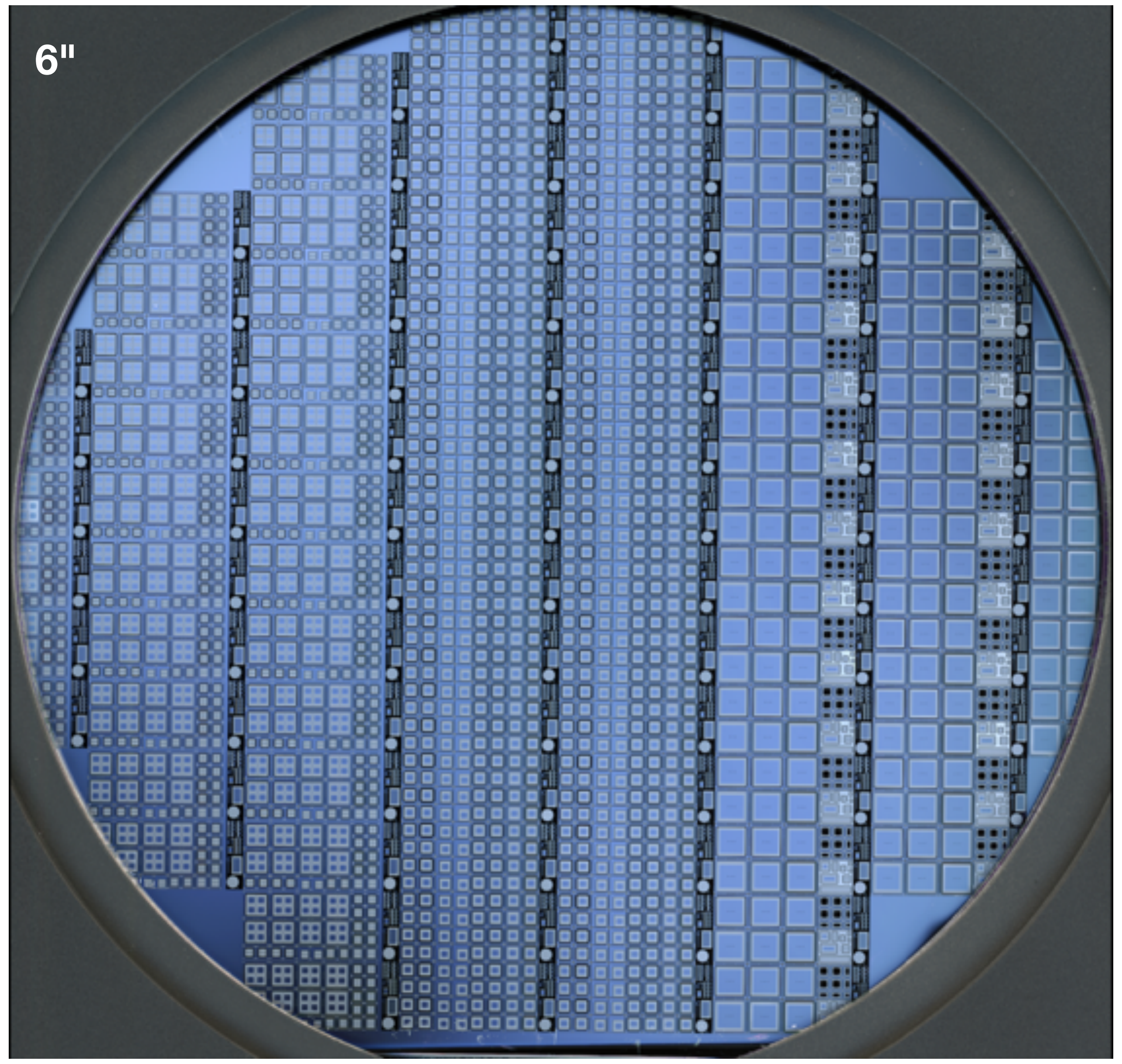
S. Meroli et al., doi:10.1088/1748-0221/6/06/P06013

Effects of extreme fluences in LGAD

- ✳ defects in the silicon lattice structure ➡ increase of the dark current
- ✳ trapping of the charge carriers ➡ decrease of the charge collection efficiency
- ✳ change in the bulk effective doping ➡ impossible to fully deplete the sensors
- ✳ gain removal mechanism ➡ $p^{+}(\Phi) = p^{+}(\Phi = 0)\ \exp(-c_A\Phi)$

[M. Ferrero et al.,doi:10.1201/9781003131946]

FBK EXFLU1: exploring LGAD innovation strategies

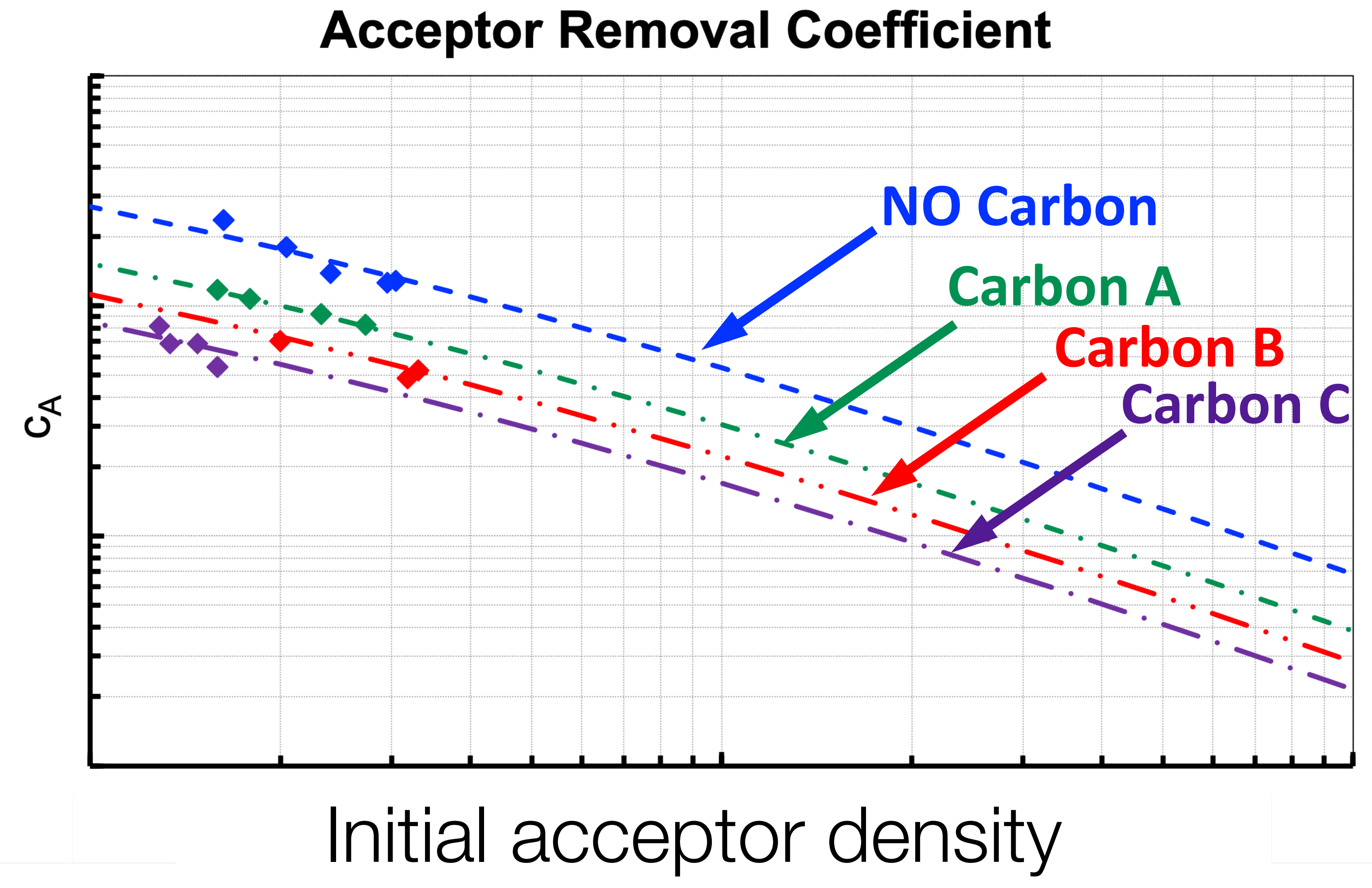


thin active substrates ($15 - 45\,\mu m$)
1.3 and $3.6\,\mathrm{mm}$ single pads,
LGAD-PiN, 2x2 arrays

For more details: l.infn.it/exflu

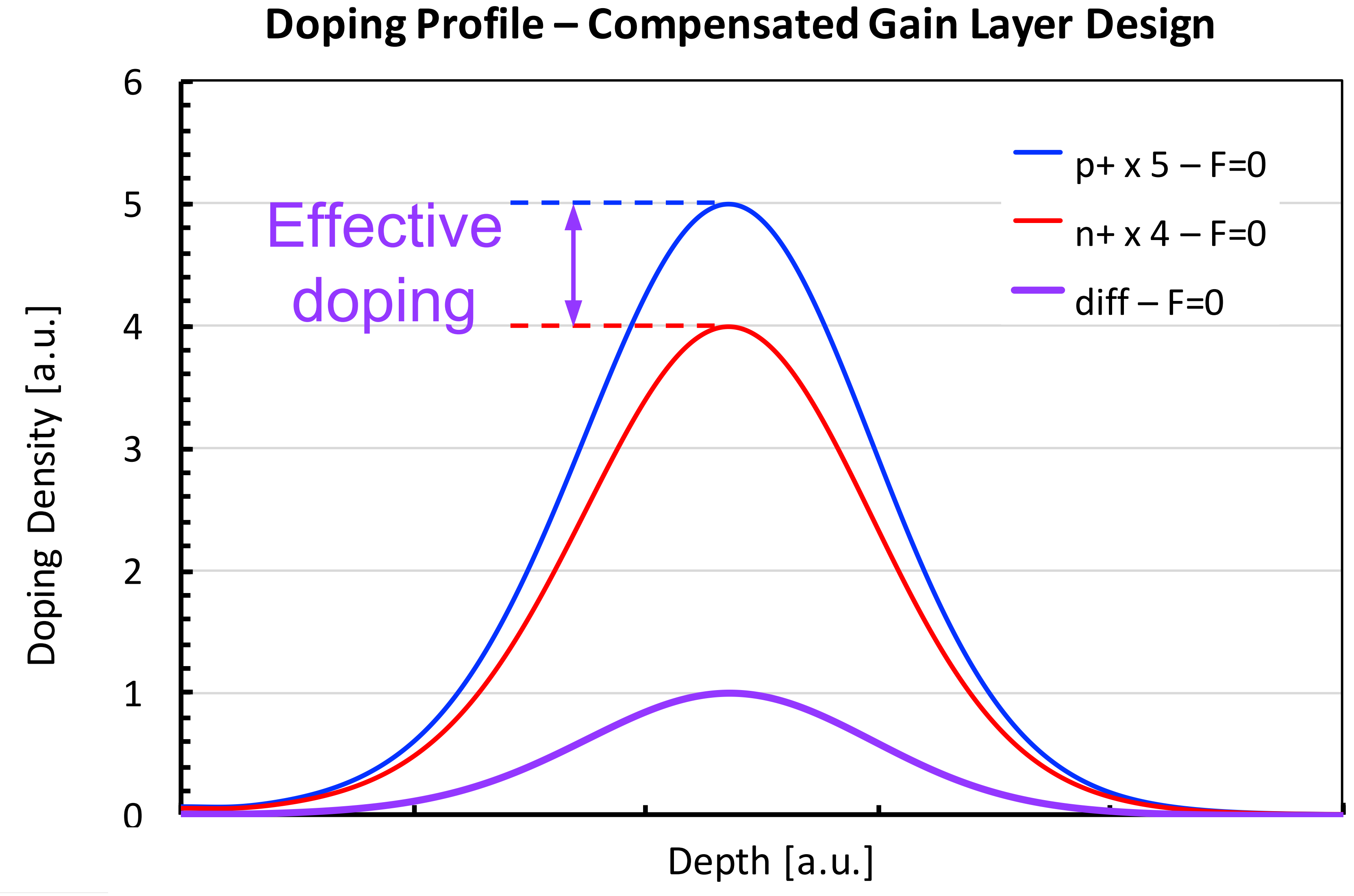
CARBON IMPLANT

Carbonated gain layer and carbon shield protect the gain layer implant from dopant removal due to radiation damage.
Goal: $\Phi = 5\mathrm{e}15\,\mathrm{n_{eq}}\,\mathrm{cm}^{-2}$



COMPENSATED GAIN LAYER

Use the interplay between acceptor and donor removal to keep a constant gain layer active doping density.
Technology under development.
Goal: $\Phi = 1\mathrm{e}17\,\mathrm{n_{eq}}\,\mathrm{cm}^{-2}$



Characterisation of irradiated EXFLU1 sensors

EXFLU1 sensors have been irradiated at Institut Jožef Stefan (JSI) Ljubljana to fluences Φ from $1e14$ to $5e15$ $n_{1Mev\,eq}\,cm^{-2}$.

Sensors arrived in Torino in mid September 2023. Annealing: 80 minutes at $60°C$

This presentation focuses on initial measurements on thin LGADs with carbonated gain layer, low carbon and boron diffusion.

Extensive characterisation is ongoing.

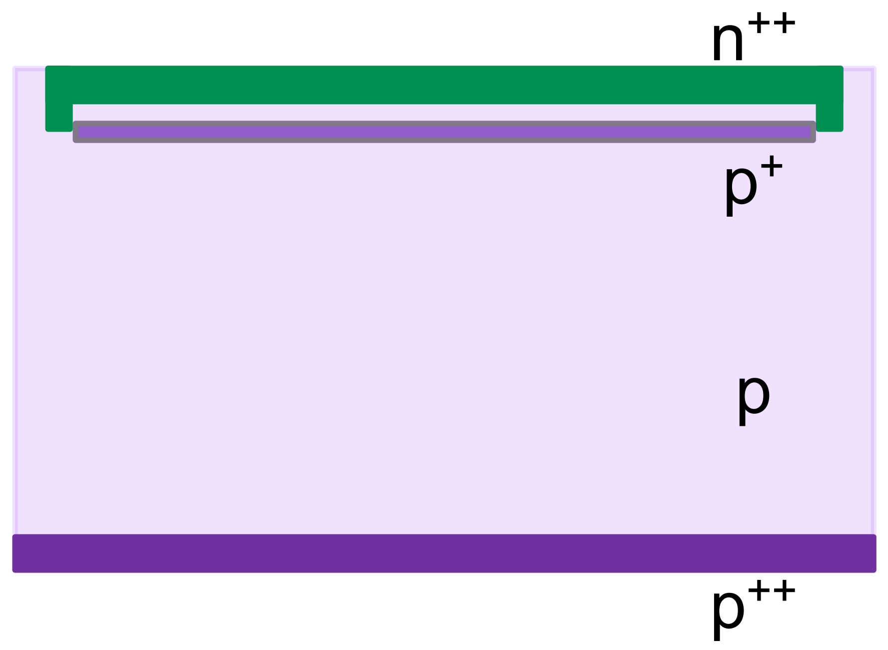
Split table

Wafer #	Thickness	p+ dose	C dose	Diffusion	Bulk
1	**45**	**1.14**	**1.0**	**CBL**	n-type
5	**30**	**1.12**	**1.0**	**CBL**	1.5E13/cm3
16	**20**	**0.80**	**1.0**	**CHBL**	1.5E14/cm3
17	**20**	**0.96**	**1.0**	**CBL**	
18	**15**	**0.94**	**1.0**	**CBL**	

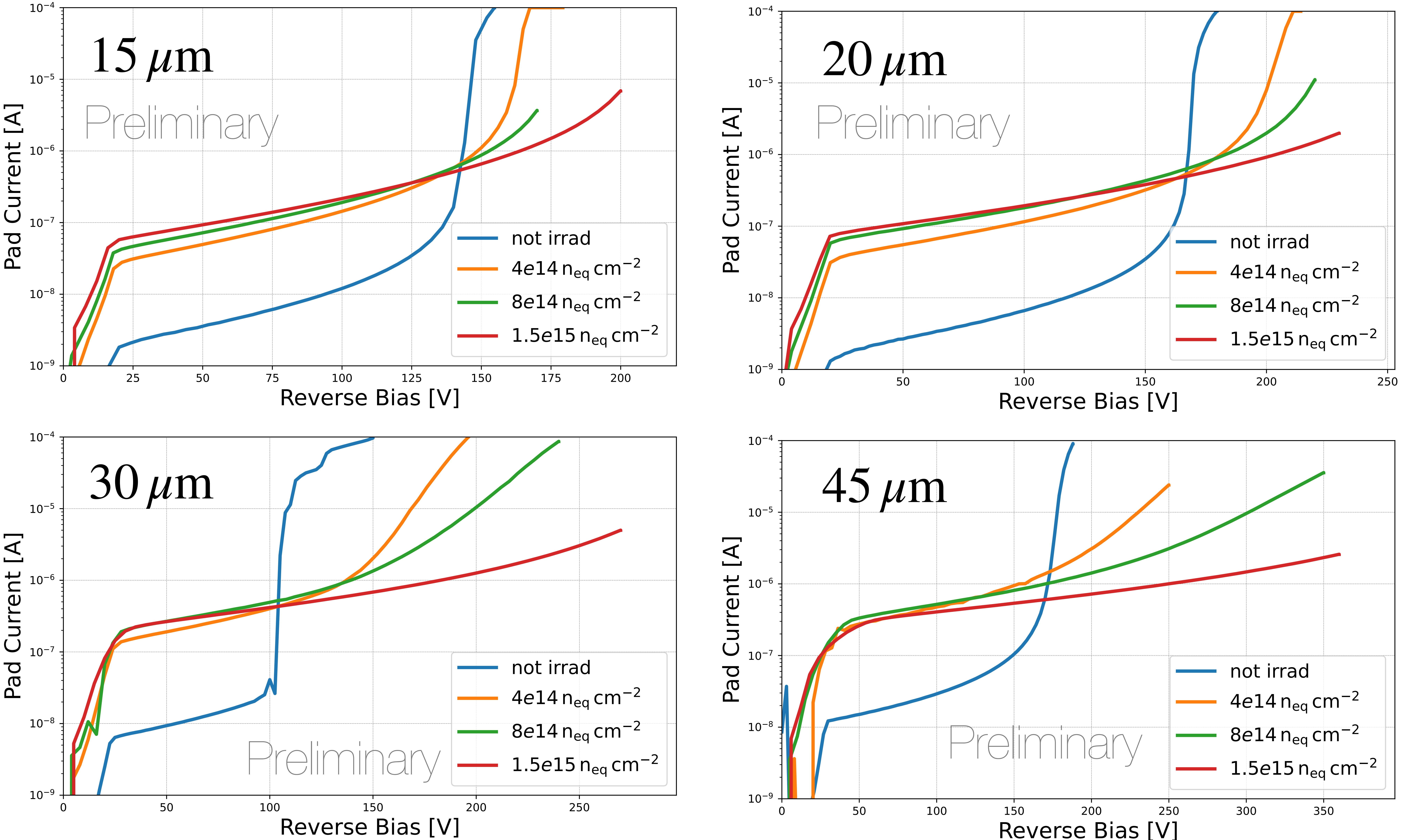
For more details: `l.infn.it/exflu`

CH: carbon high diffusion
BL: boron low diffusion

Carbonated GL



Thin carbonated EXFLU1 LGADs: IV



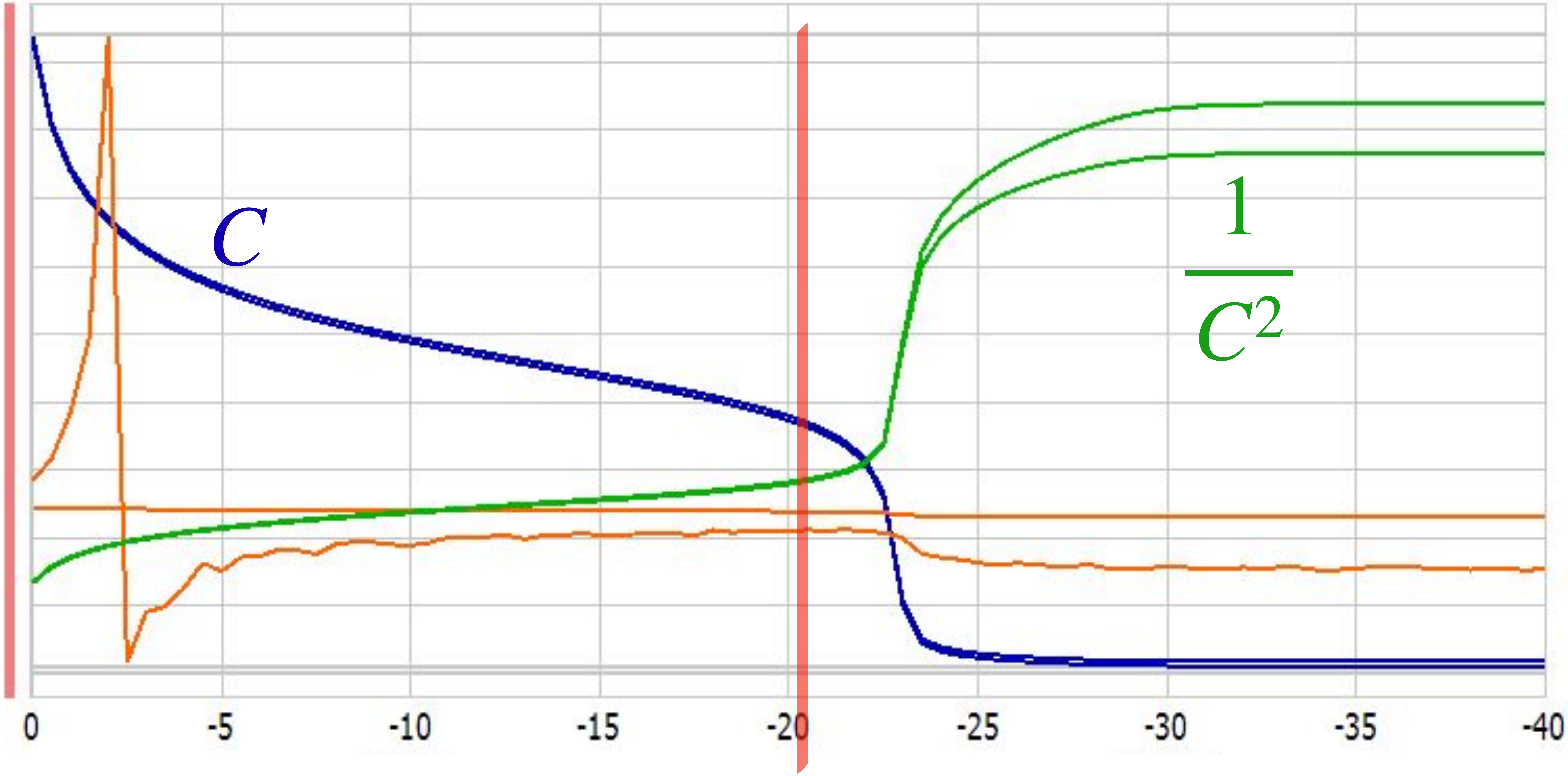
1.3 mm PAD
-20°C

Bulk and surface currents greatly increase with fluence.

Breakdown shifts at higher voltages as the fluence increases.

Indication of gain degradation

Thin carbonated EXFLU1 LGADs: CV



W5 $(30\,\mu\text{m})$

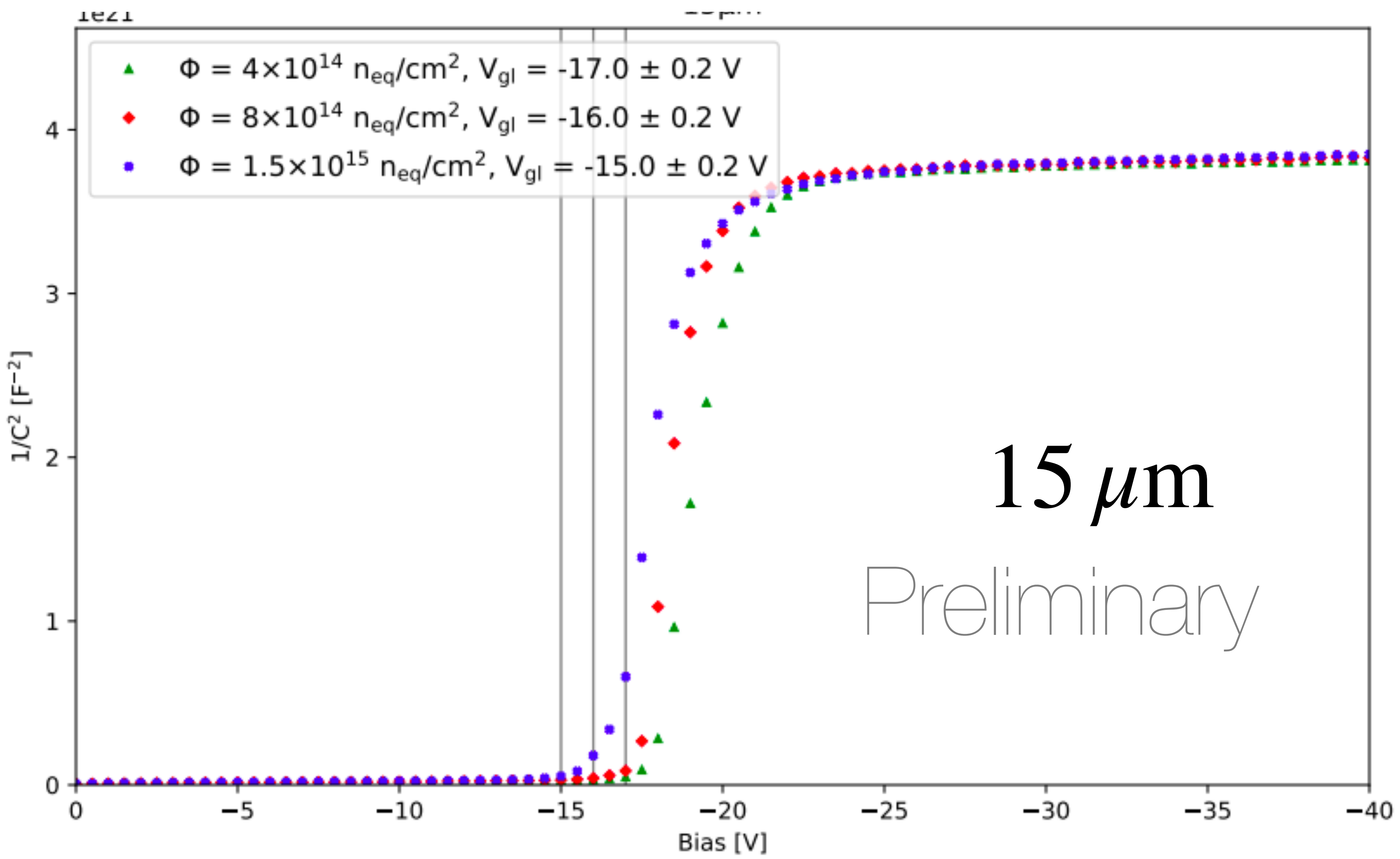
non irradiated
(as an example)

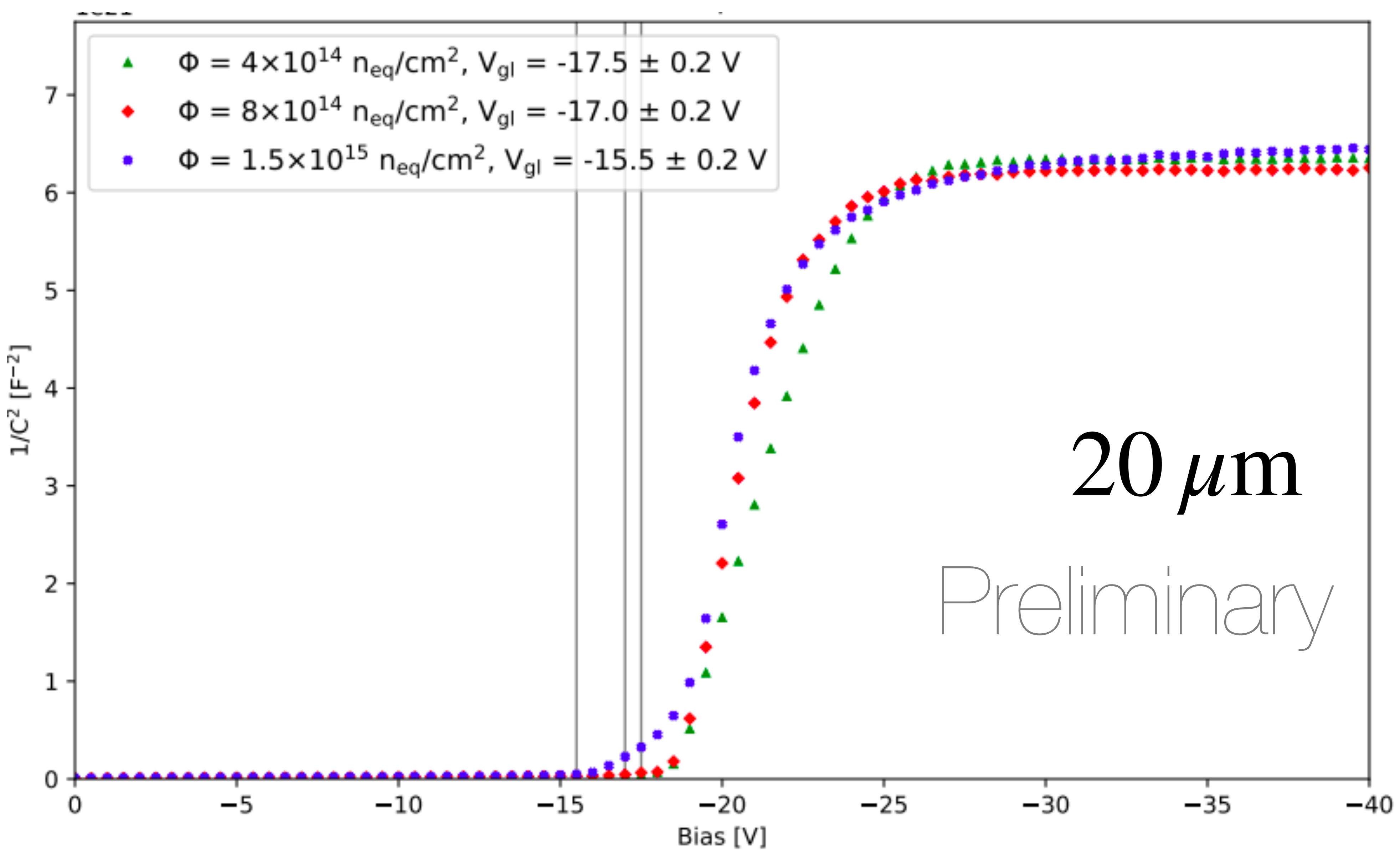
$1.3\,\text{mm}$ PAD
$+20^\circ\text{C}$

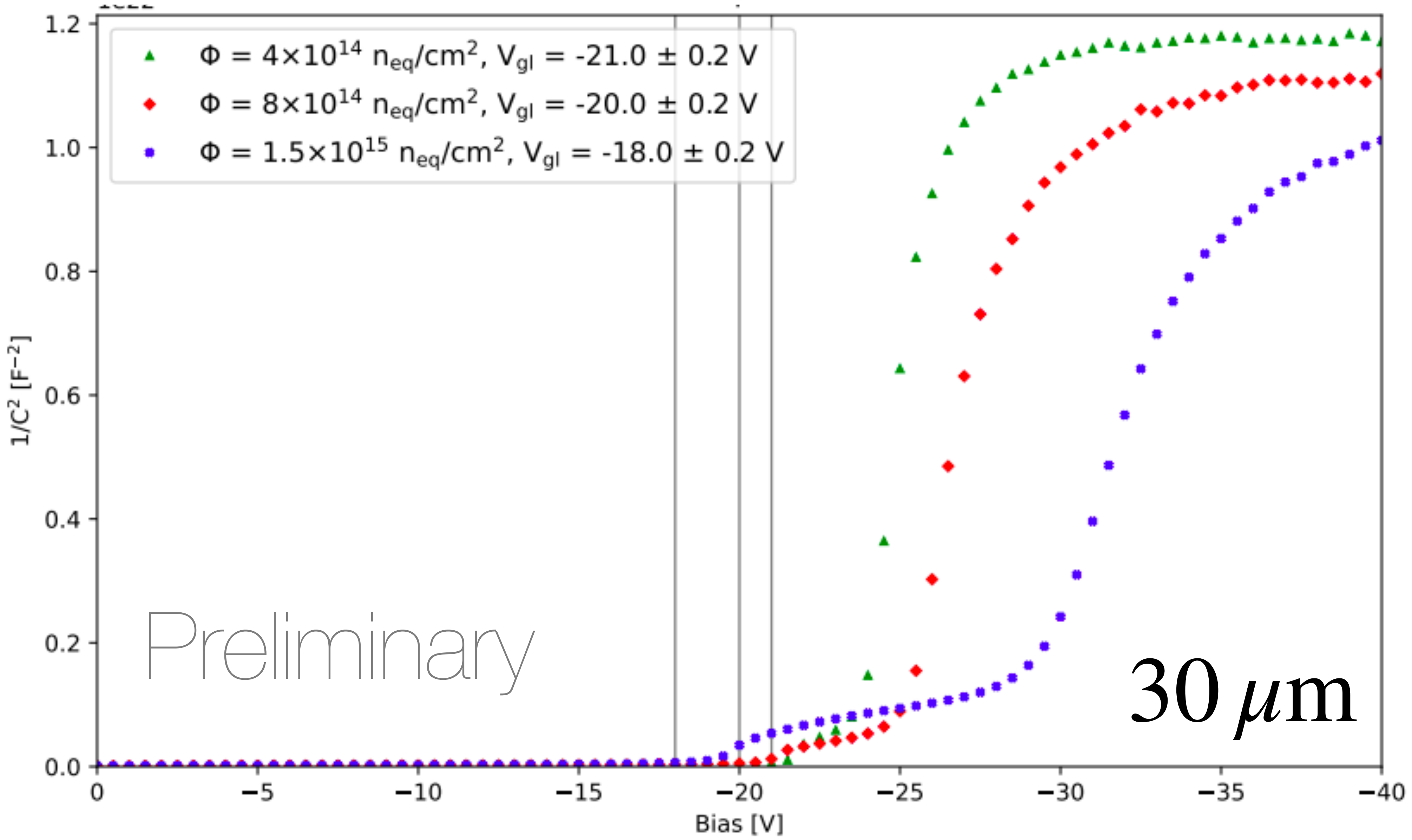
Gain layer depletion voltage V_{GL}

V_{GL} extracted from $1/C^2$ curves at first surge in gradient ($< -2\text{e}19\ \text{V}^{-1}\text{F}^{-2}$)

Thin carbonated EXFLU1 LGADs: $V_{GL}(\Phi)$



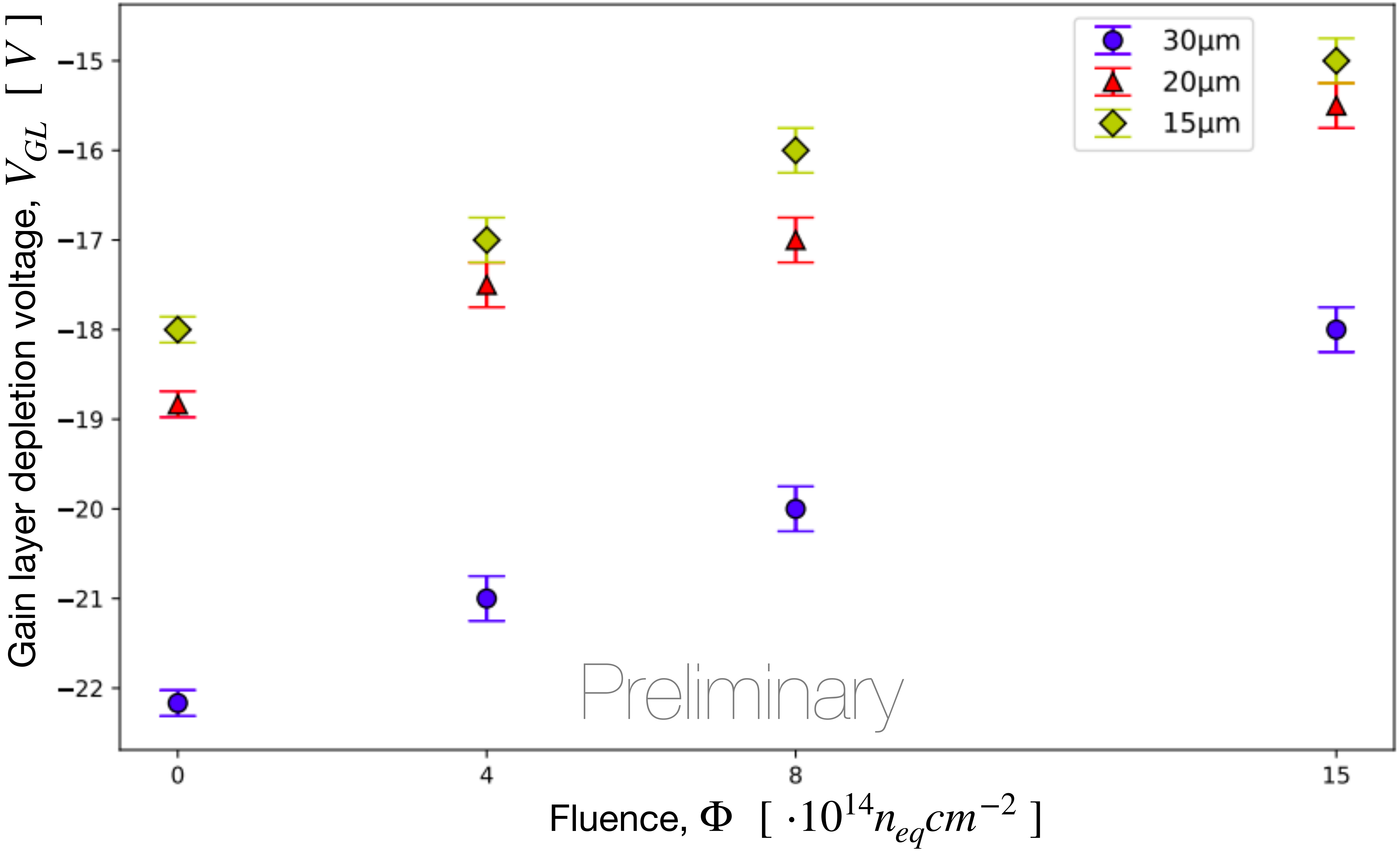




V_{GL} is related to the dopant concentration in the gain layer.

$V_{GL}(\Phi)$ enables the measurement of acceptor removal coefficient.

Thin carbonated EXFLU1 LGADs: $V_{GL}(\Phi)$

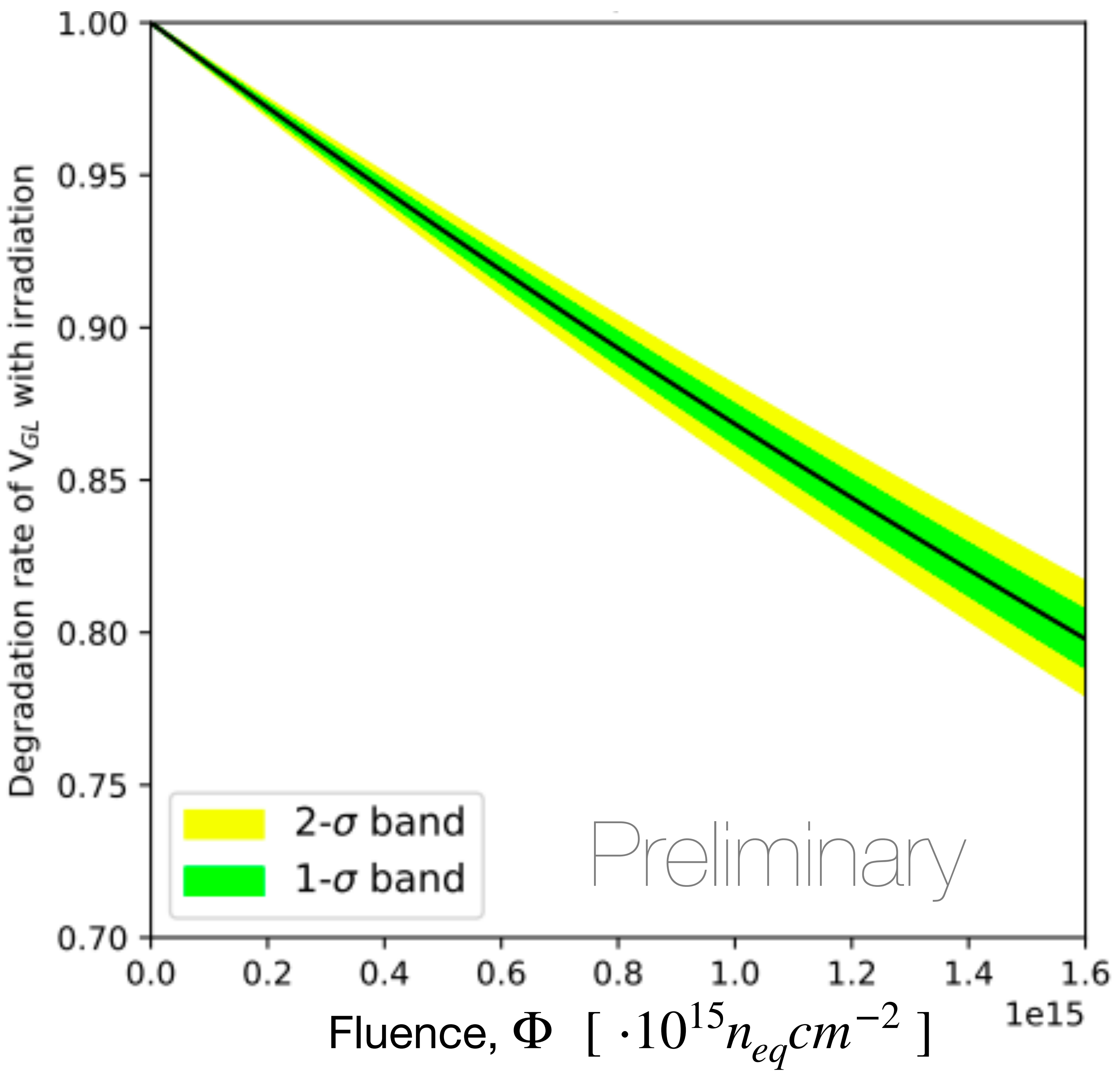


At high fluences, the gain layer is depleted for smaller $|V_{GL}|$ values

Thin carbonated EXFLU1 LGADs: gain removal

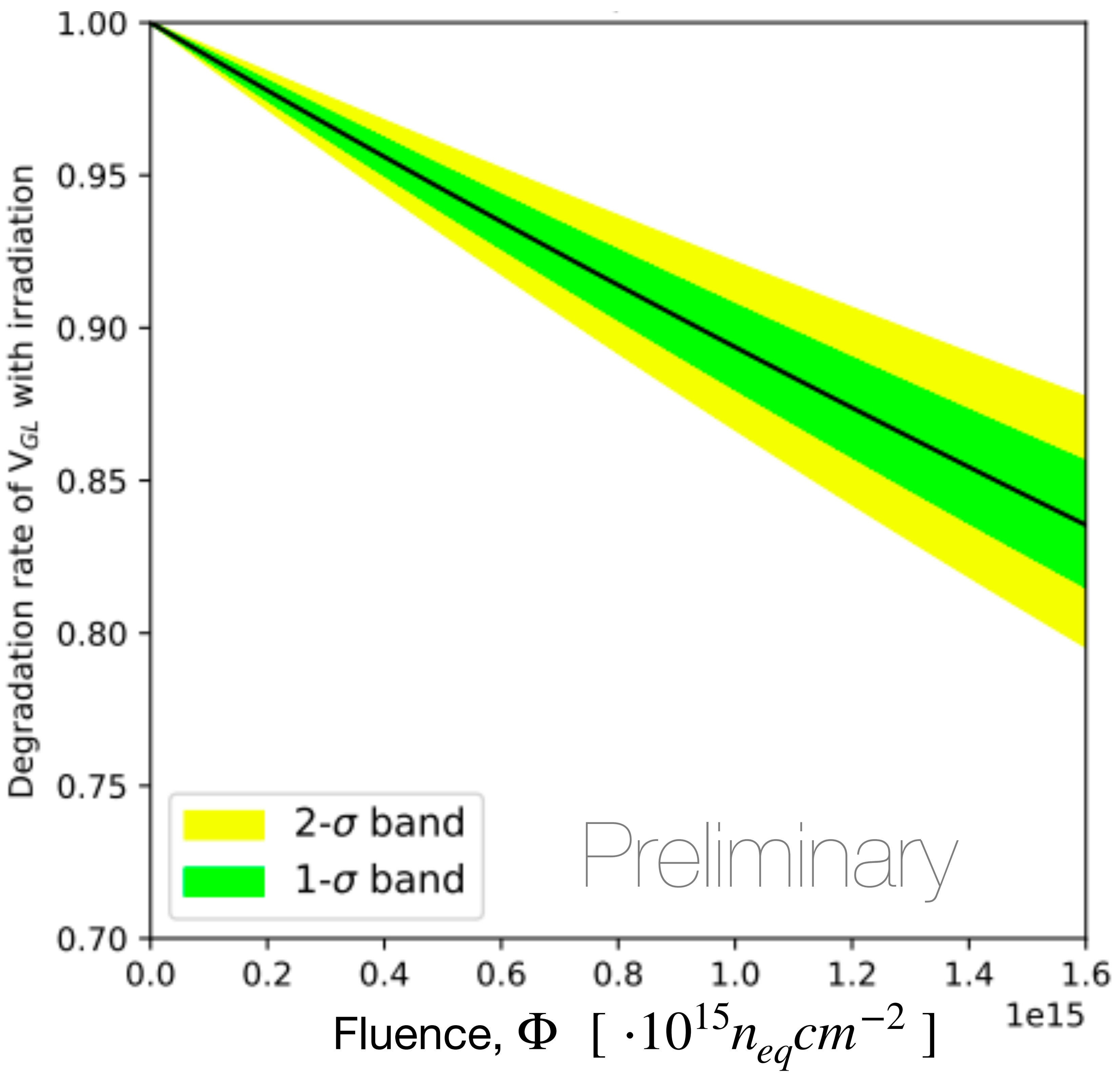
$30\,\mu m$

$$c_A = (1.4 \pm 0.1) \cdot 10^{-16}\,\mathrm{cm}^2\,\mathrm{n}_{\mathrm{eq}}^{-1}$$



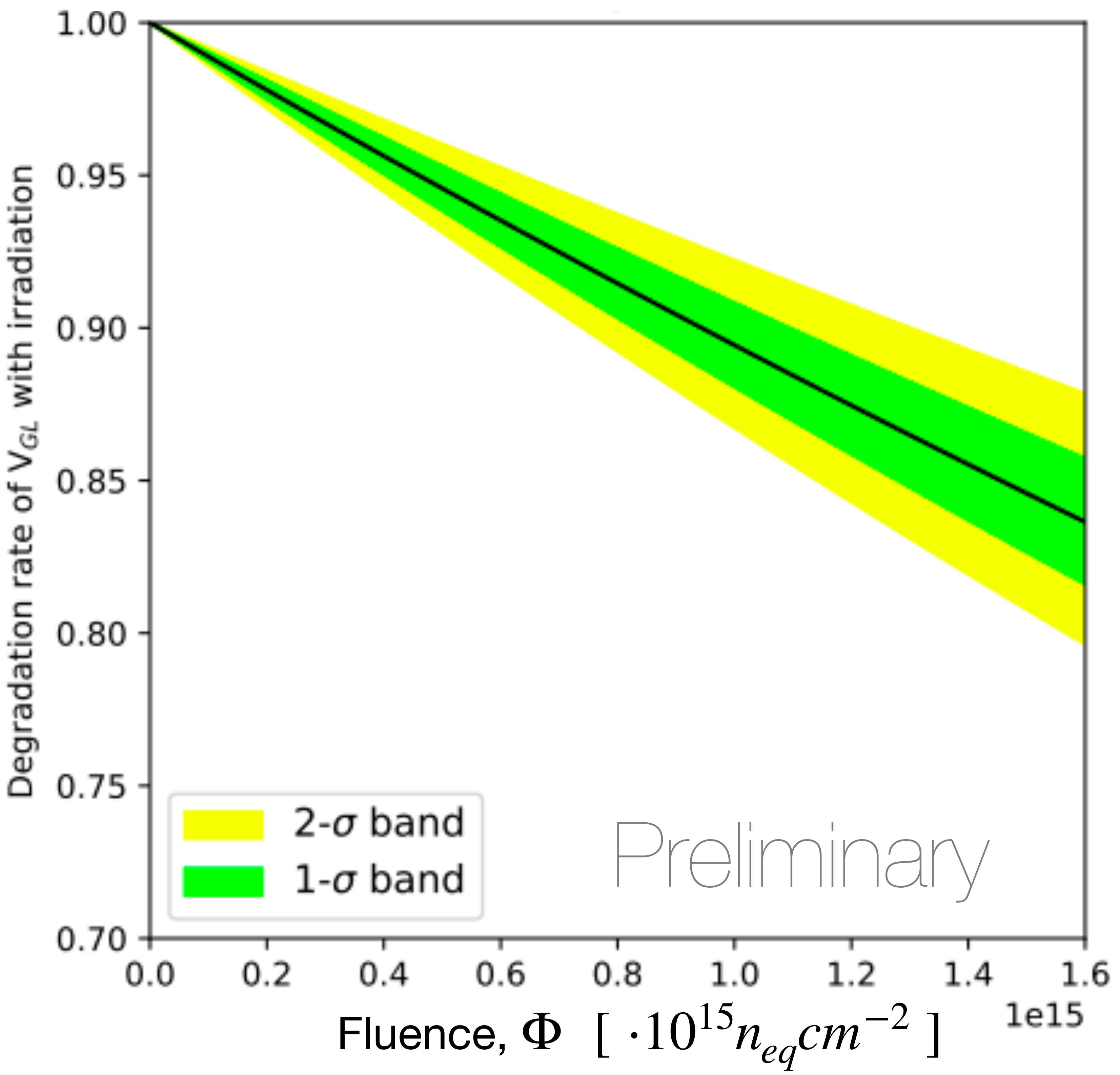
$20\,\mu m$

$$c_A = (1.1 \pm 0.2) \cdot 10^{-16}\,\mathrm{cm}^2\,\mathrm{n}_{\mathrm{eq}}^{-1}$$



$15\,\mu m$

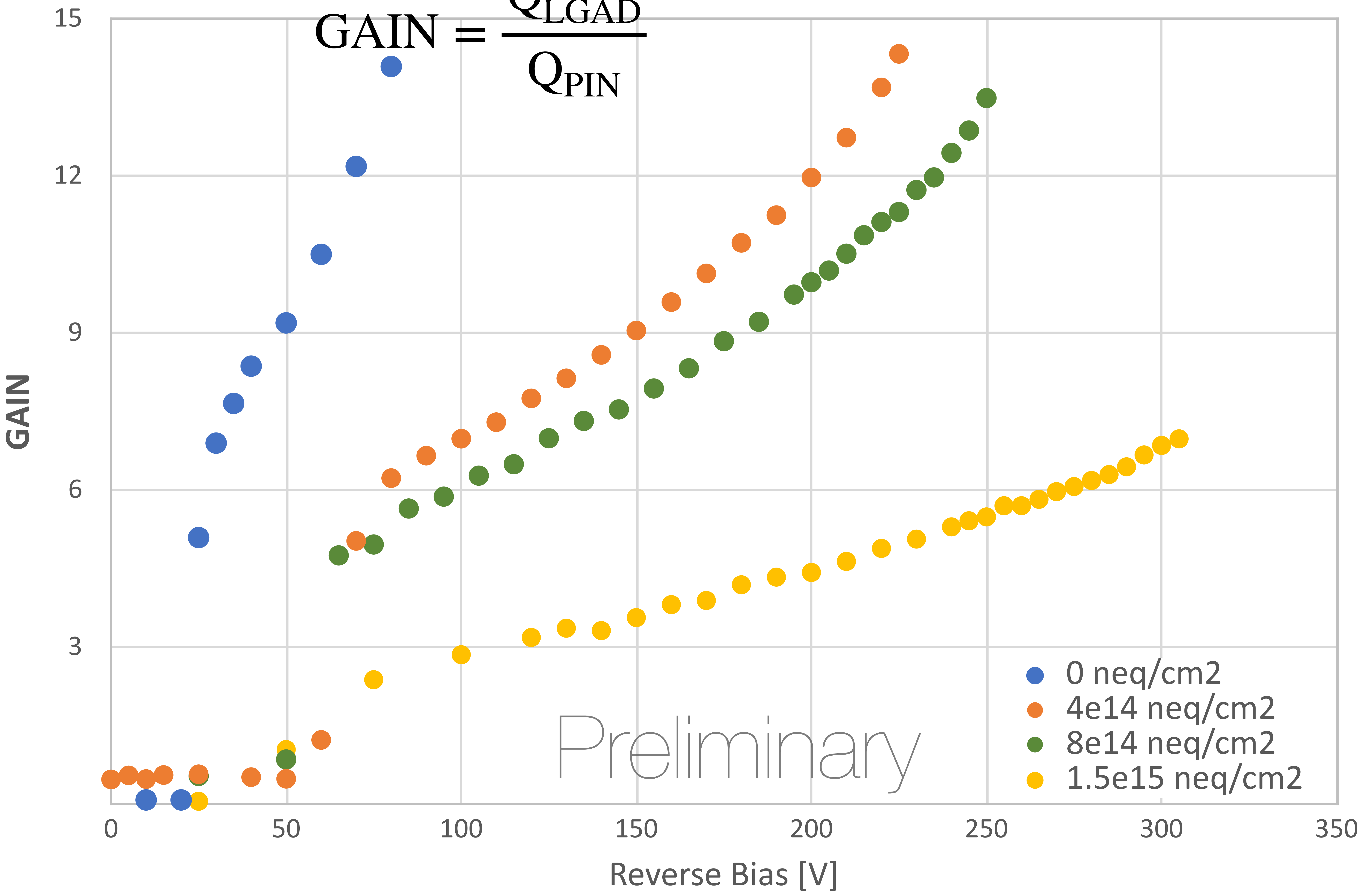
$$c_A = (1.1 \pm 0.2) \cdot 10^{-16}\,\mathrm{cm}^2\,\mathrm{n}_{\mathrm{eq}}^{-1}$$



GAIN DEGRADATION AT HIGHER FLUENCES

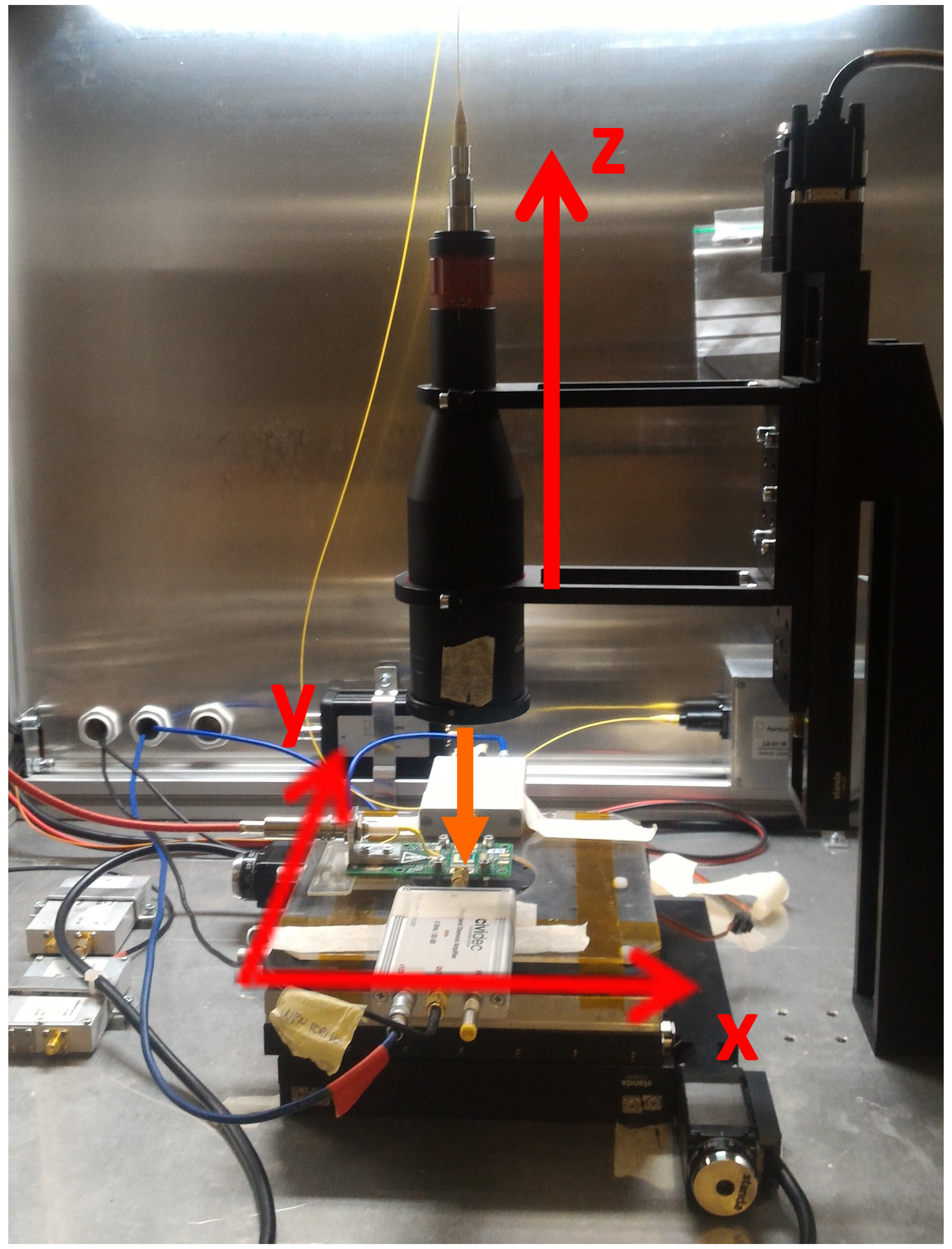
Thin carbonated EXFLU1 LGADs: laser measurement

$$\text{GAIN} = \frac{Q_{\text{LGAD}}}{Q_{\text{PIN}}}$$

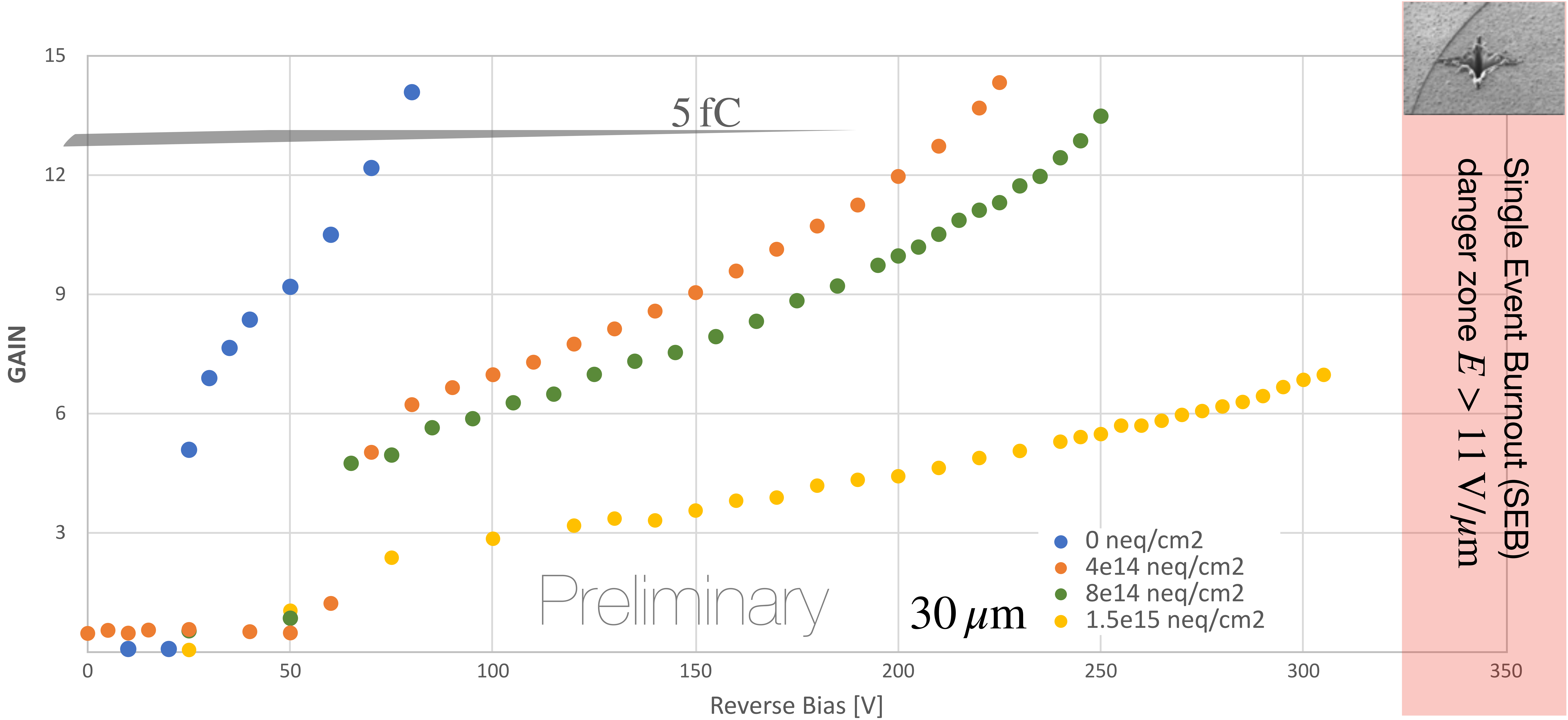


TCT Setup from Particulars

Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 μm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Room temperature



Thin carbonated EXFLU1 LGADs: laser measurement



5 fC

30 μm

Single Event Burnout (SEB) danger zone $E > 11$ V/μm

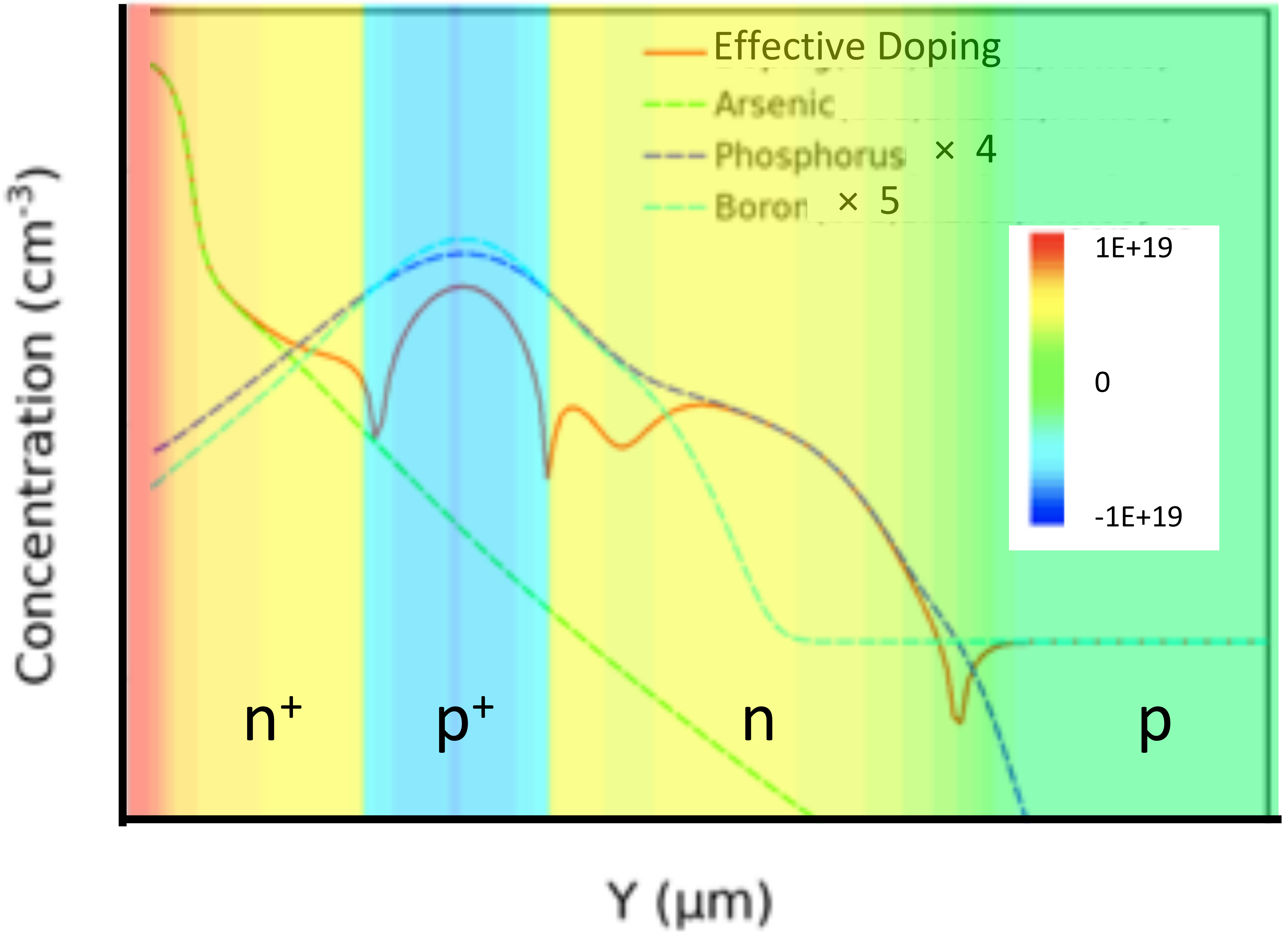
Compensated EXFLU1 LGADs

Gamble:
The acceptor and donor removal coefficients have approximately the same values.
Both p^+ and n^- decrease at the same rate with fluence.

Also: Best results if both dopants have same density profile.

Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

Doping Profiles from Process Simulation



Notation:

$2-1 \rightarrow p^+ = 2 \cdot k\,;\; n^+ = 1 \cdot k$

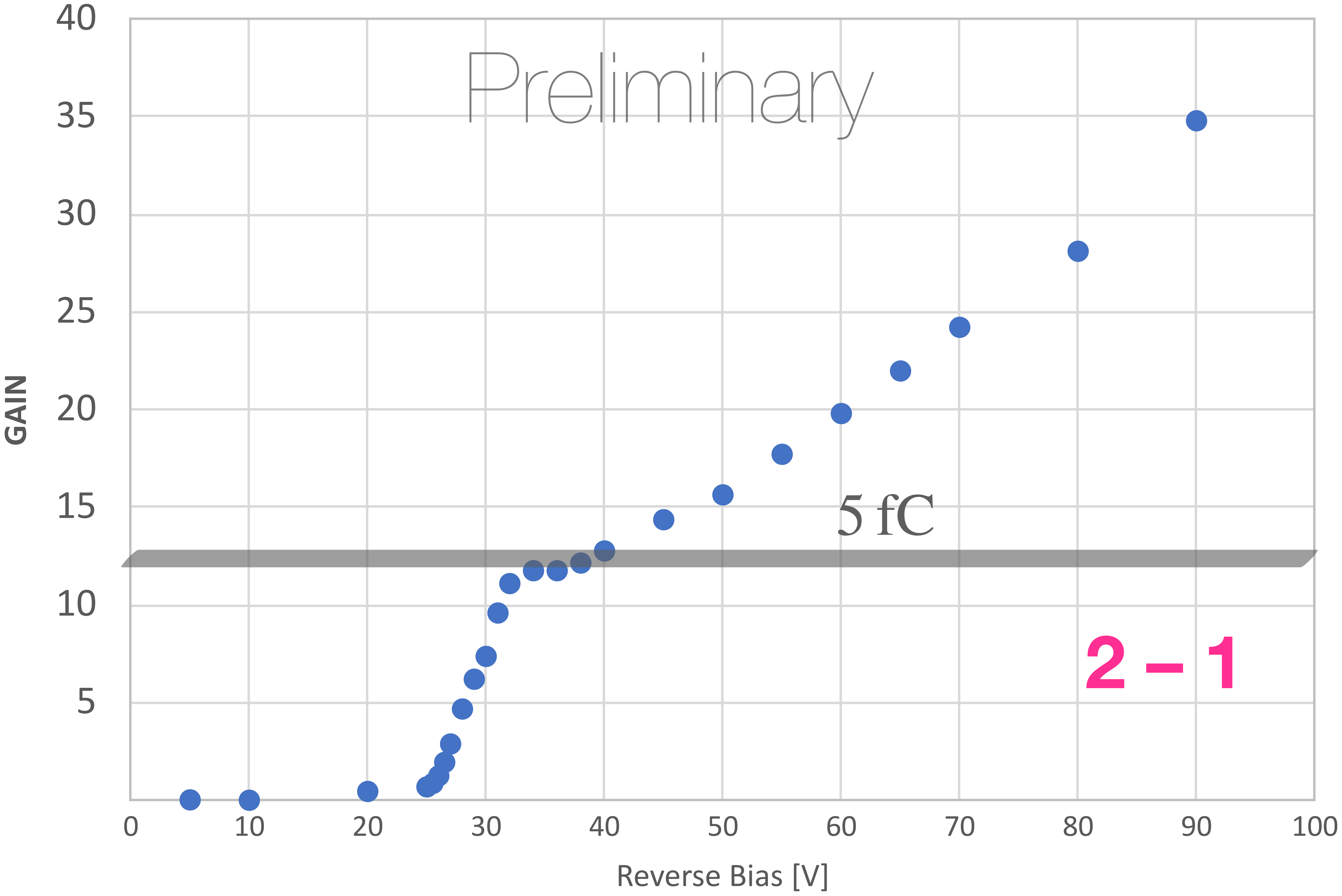
$3-2 \rightarrow p^+ = 3 \cdot k\,;\; n^+ = 2 \cdot k$

$5-4 \rightarrow p^+ = 5 \cdot k\,;\; n^+ = 4 \cdot k$

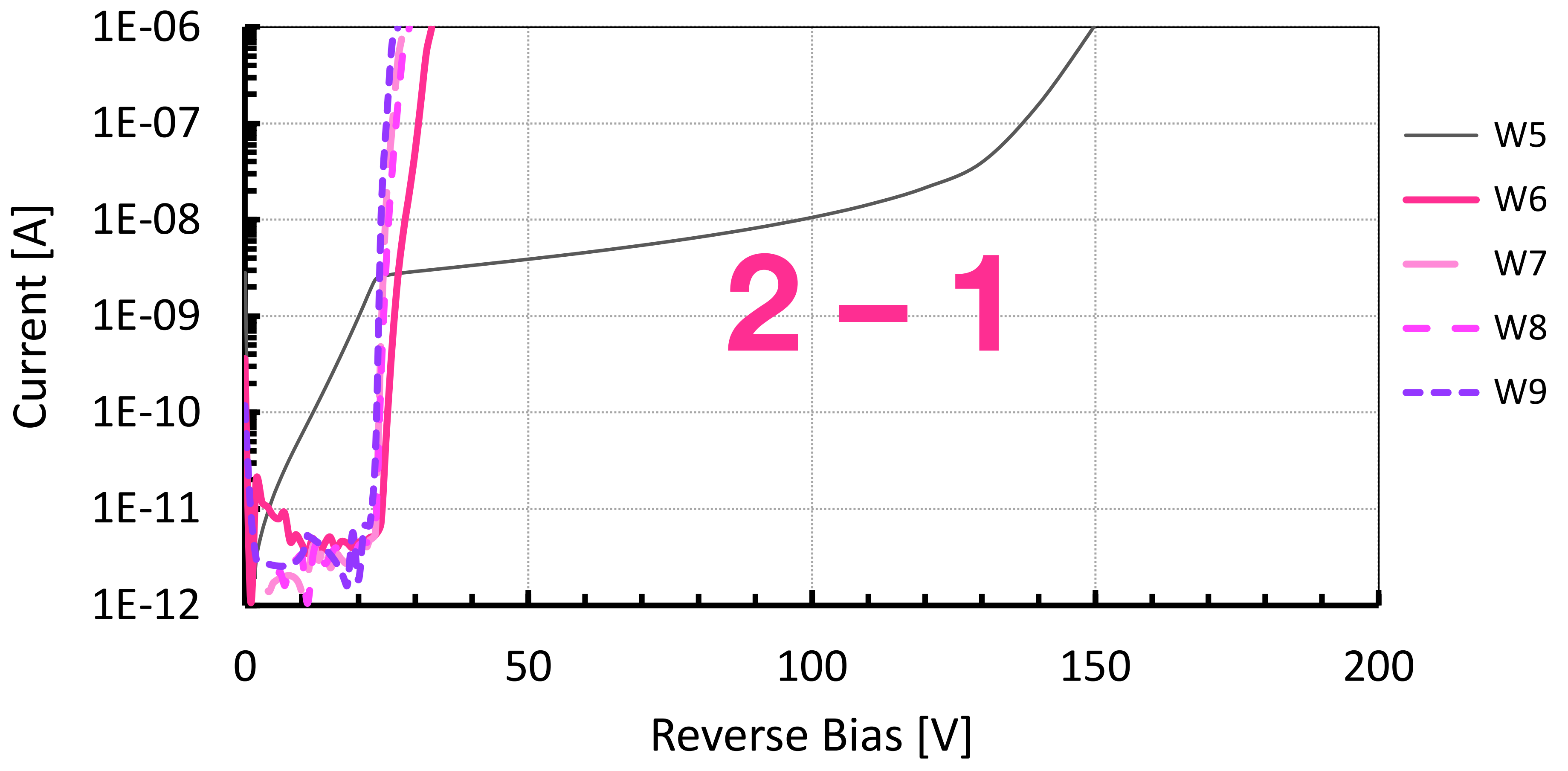
where $k = a, b, c$ with $a < b < c$

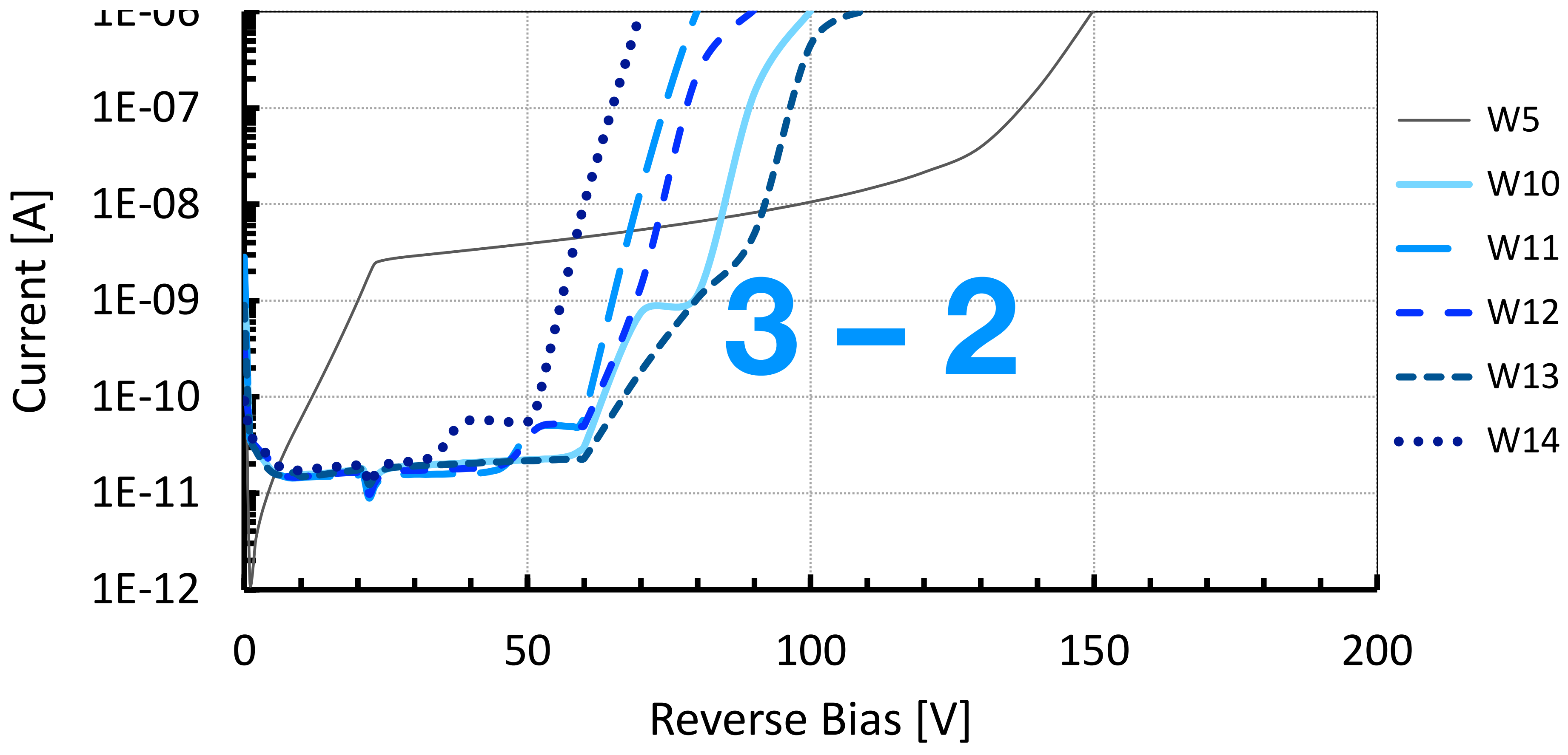
Compensated EXFLU1 LGADs

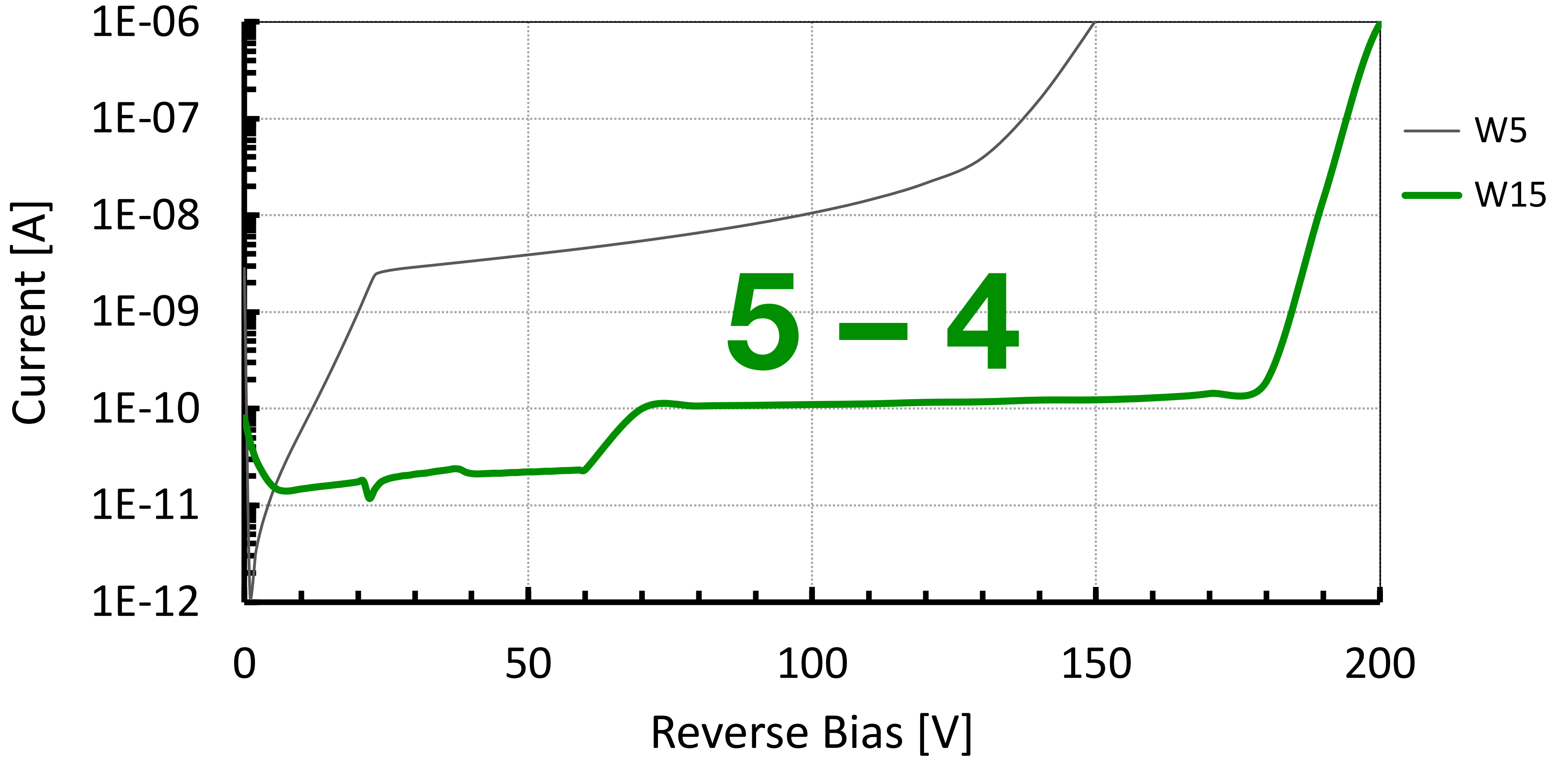
Pre irradiation laser measurements



30µm thick LGAD - TCT measurement with laser intensity ~ 4 MIPs







Summary and outlook

The LGAD technology continues its evolution in pursuit of unlocking the frontiers of future high-energy physics experiments.

EXFLU1, an R&D production, is dedicated to exploring promising strategies for delivering high-performance LGADs in extreme fluence environments at $\Phi = 10^{17}\,\mathrm{n_{eq}\,cm^{-2}}$, including:

- ➡ Investigating the timing performance of **thin** substrates
- ➡ Exploring gain survival in optimised **carbonated** gain layer implants and carbon shields
- ➡ Assessing the performance and radiation hardness of **compensated** gain layers.

Acknowledgements

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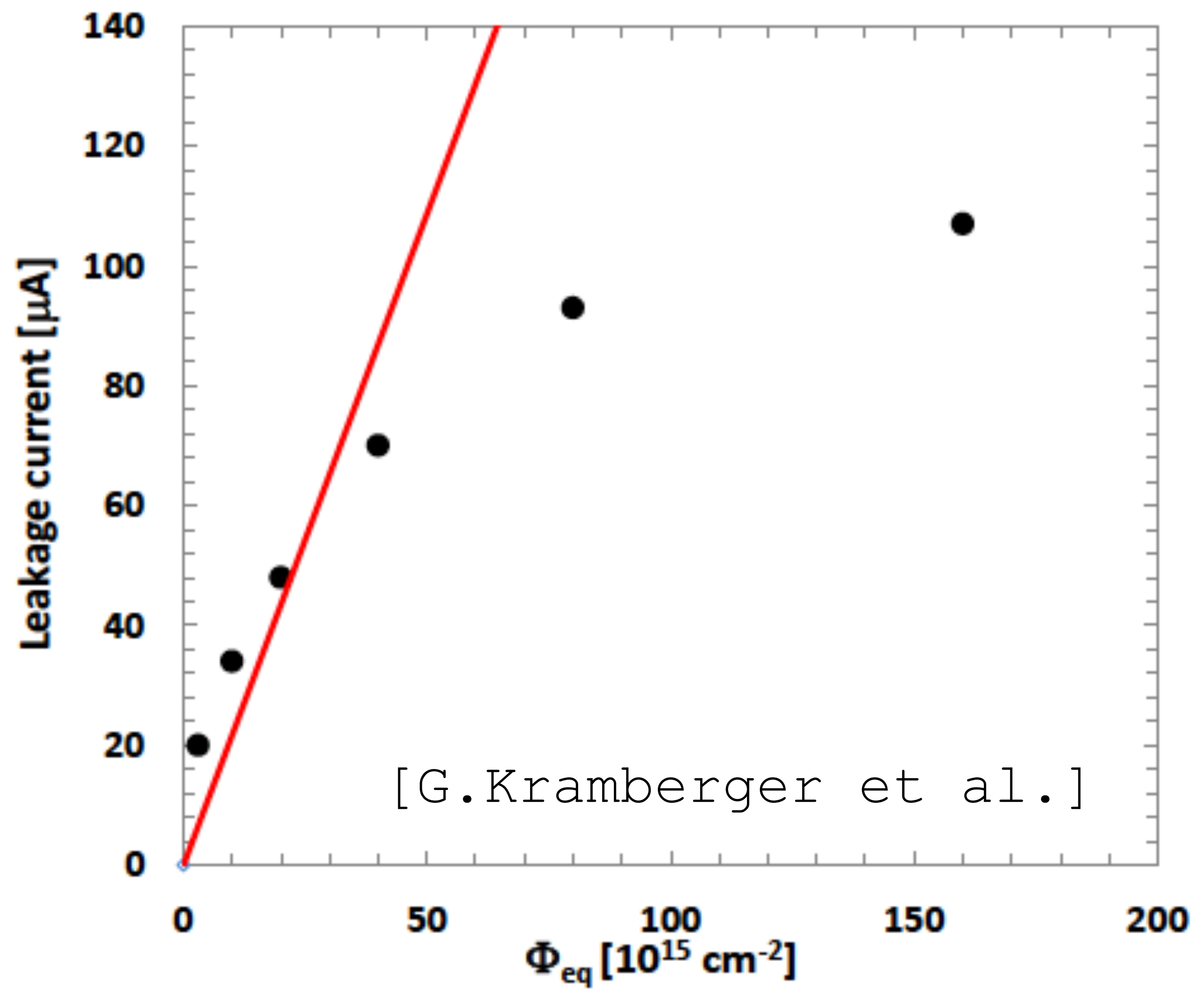
- INFN CSN5
- AIDAinnova, WP13
- Compagnia di San Paolo
- Ministero della Ricerca, Italia, FARE, R165xr8frt_fare
- Ministero della Ricerca, Italia, PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- Ministero della Ricerca, Italia, PRIN 2022, progetto 2022RK39RF – ComonSens
- European Union's Horizon 2020 Research and Innovation programme, Grant Agreement No. 101004761
- RD50, CERN

Back up

Saturation of radiation damage effect

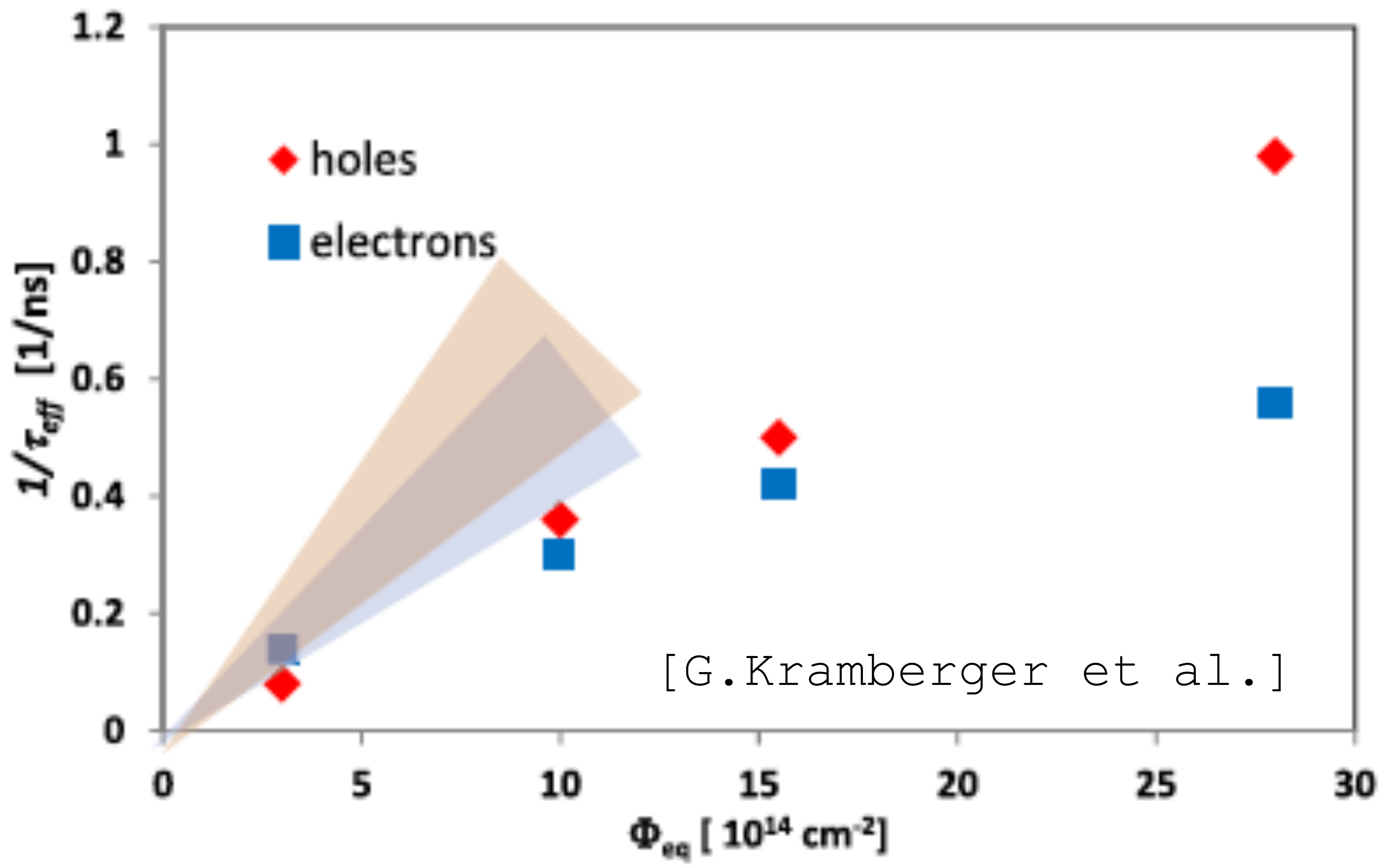
Luckily saturation of radiation effects is observed at fluences $> 5\mathrm{e}15\,\mathrm{n_{eq}\,cm^{-2}}$



Leakage current saturation

$I = \alpha V \Phi$

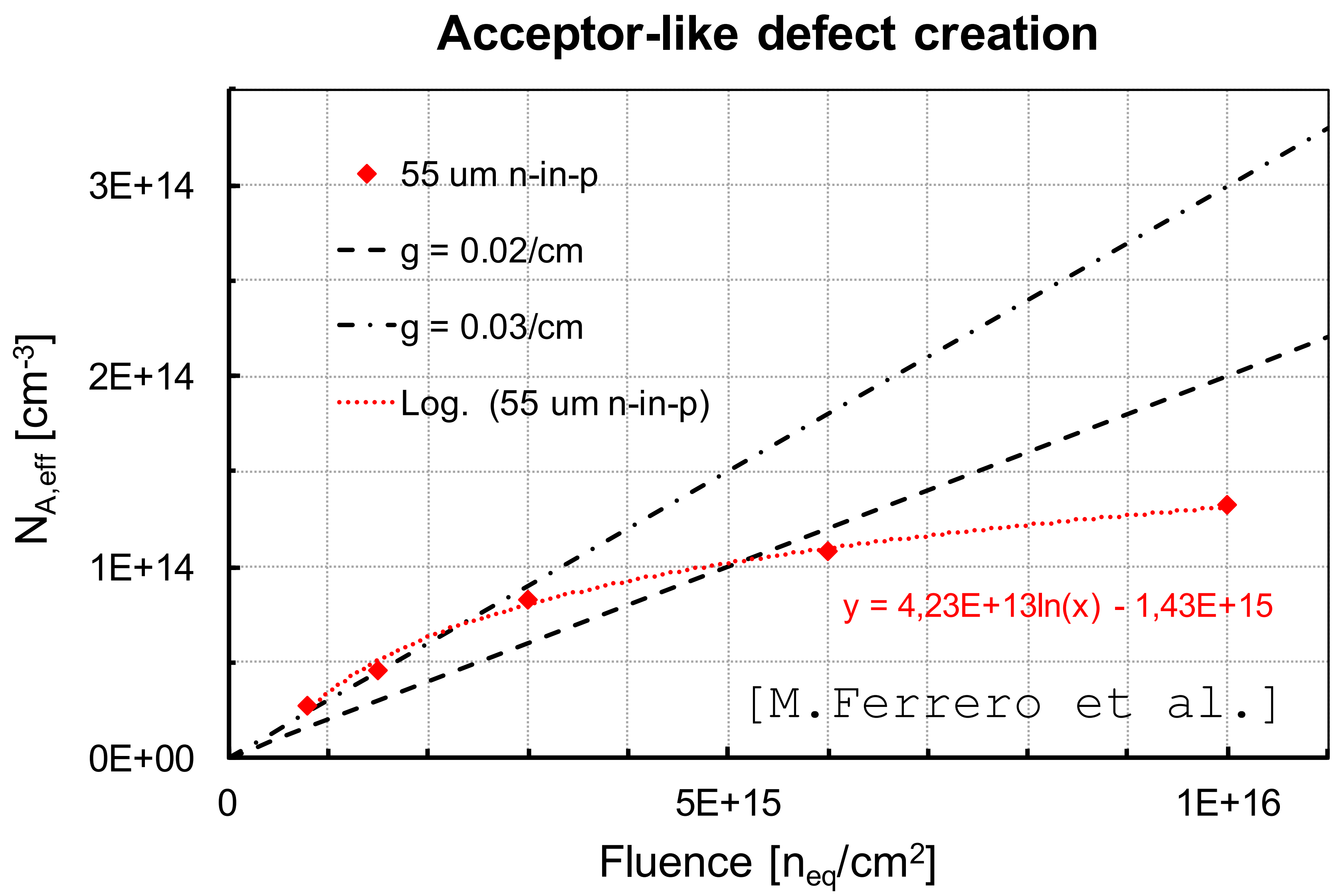
α from linear to logarithmic



Trapping probability saturation

$1/\tau_{eff} = \beta\Phi$

β from linear to logarithmic



Acceptor creation saturation

$N_{A,eff} = g_c\Phi$

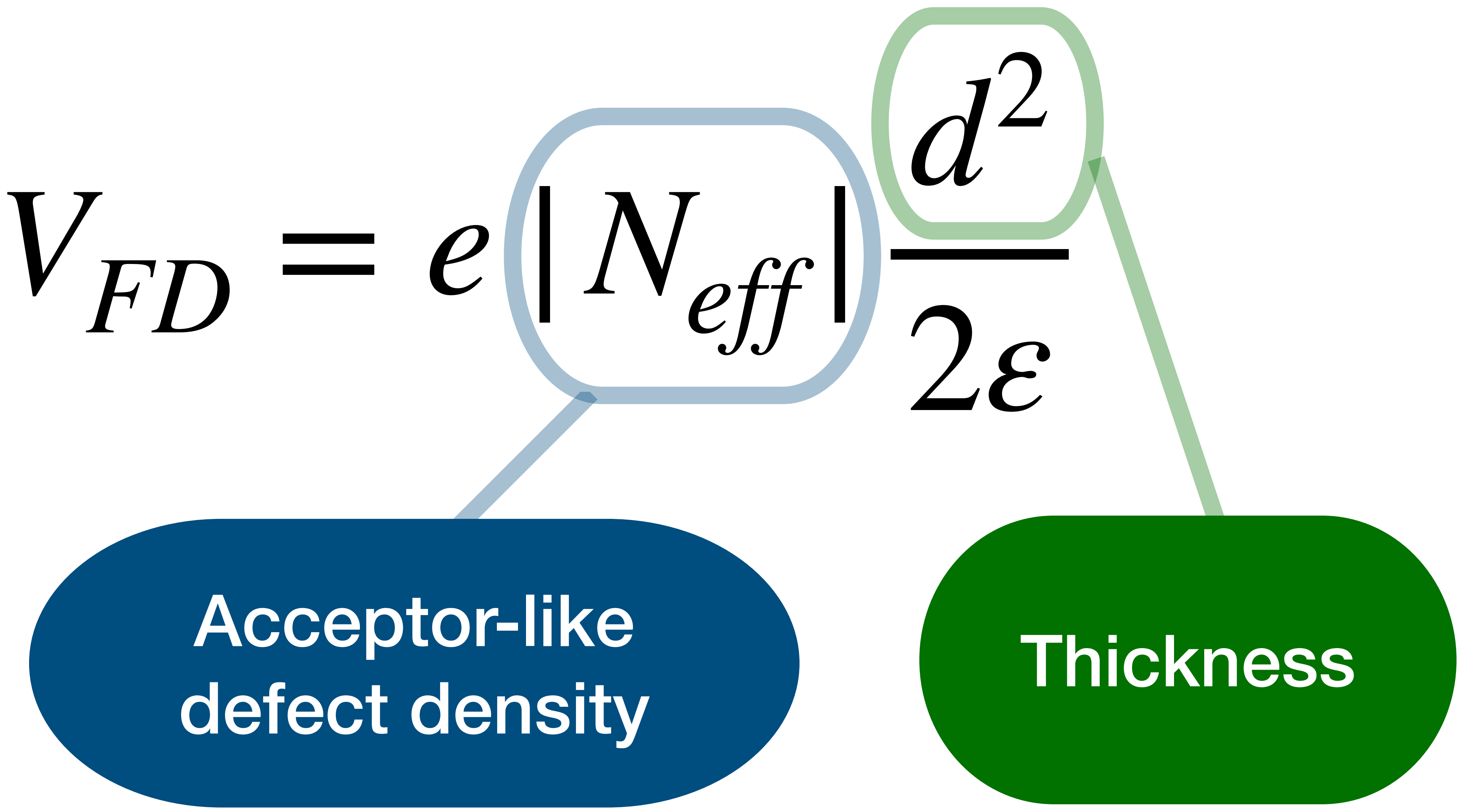
g_c from linear to logarithmic

Silicon detectors irradiated at fluences $1\mathrm{e}16 - 1\mathrm{e}17\,\mathrm{n_{eq}\,cm^{-2}}$ do not behave as expected

They behave better than expected

Reason for choosing thin LGAD

Sensor depletion voltage



$$V_{FD} = e\,|N_{eff}|\,\frac{d^2}{2\varepsilon}$$

At high fluences, only thin substrates can be fully depleted.

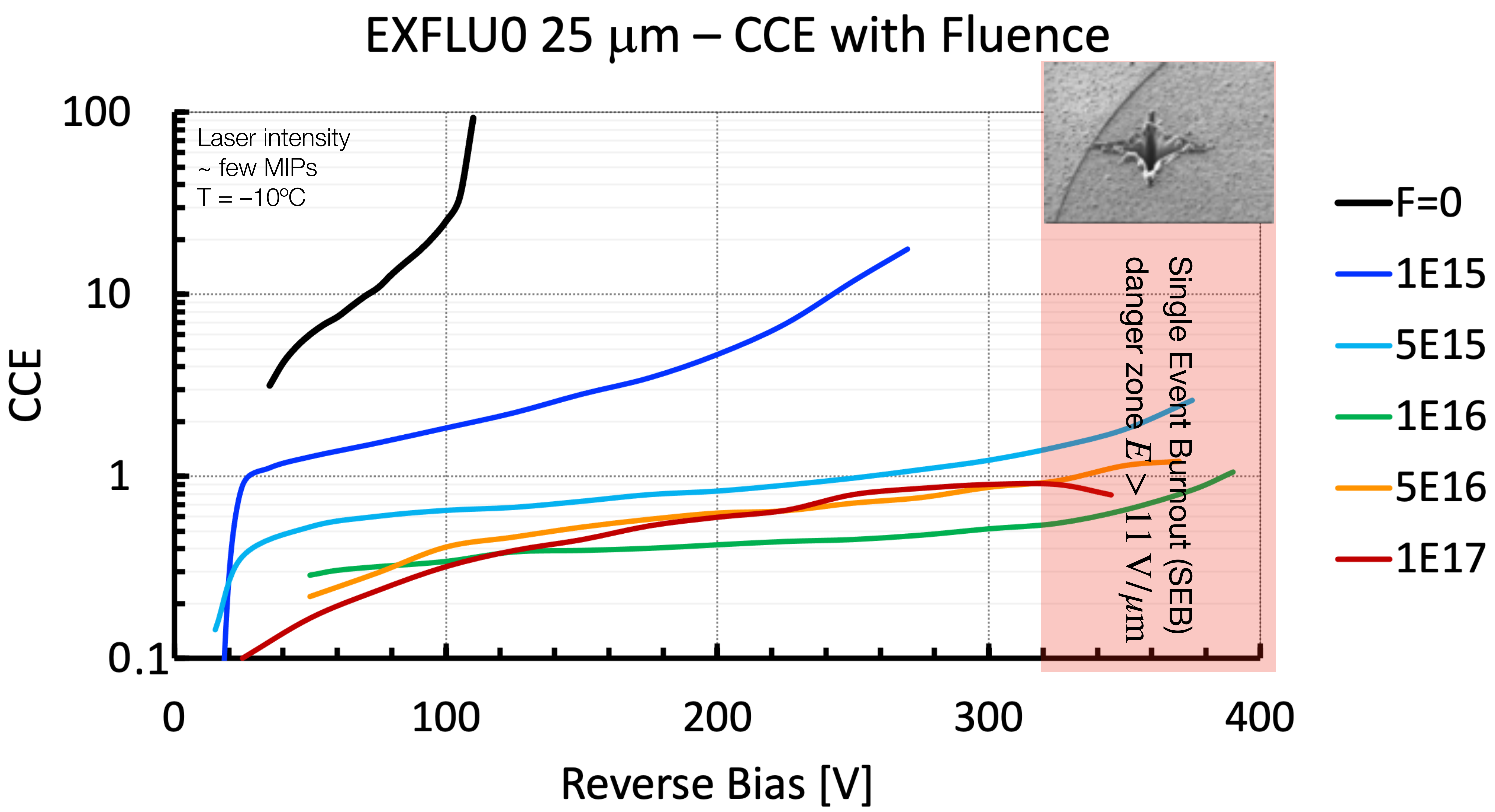
How does a $25\ \mu\mathrm{m}$ sensor perform after a fluence of $5\mathrm{e}16\ \mathrm{n}_{1\mathrm{Mev\,eq}}\,\mathrm{cm}^{-2}$?

▻ It can still be depleted
▻ Trapping is limited (small drift length)
▻ Dark current is low (small volume)

However: charge deposited by a MIP $\ll 5\ \mathrm{fC}$
→ This charge is lower than the minimum charge requested for timing by the electronics
→ Need a gain of at least ~ 5 in order to efficiently record a hit

Experience gained with EXFLU0

At the end of 2020, FBK released the first production of thin LGAD sensors: 25 and $35\ \mu\mathrm{m}$ thick. Some samples were irradiated to the fluences: $1\mathrm{e}15$, $5\mathrm{e}15$, $1\mathrm{e}16$, $5\mathrm{e}16$ and $1\mathrm{e}17\ \mathrm{n}_{1\mathrm{Mev\,eq}}\,\mathrm{cm}^{-2}$

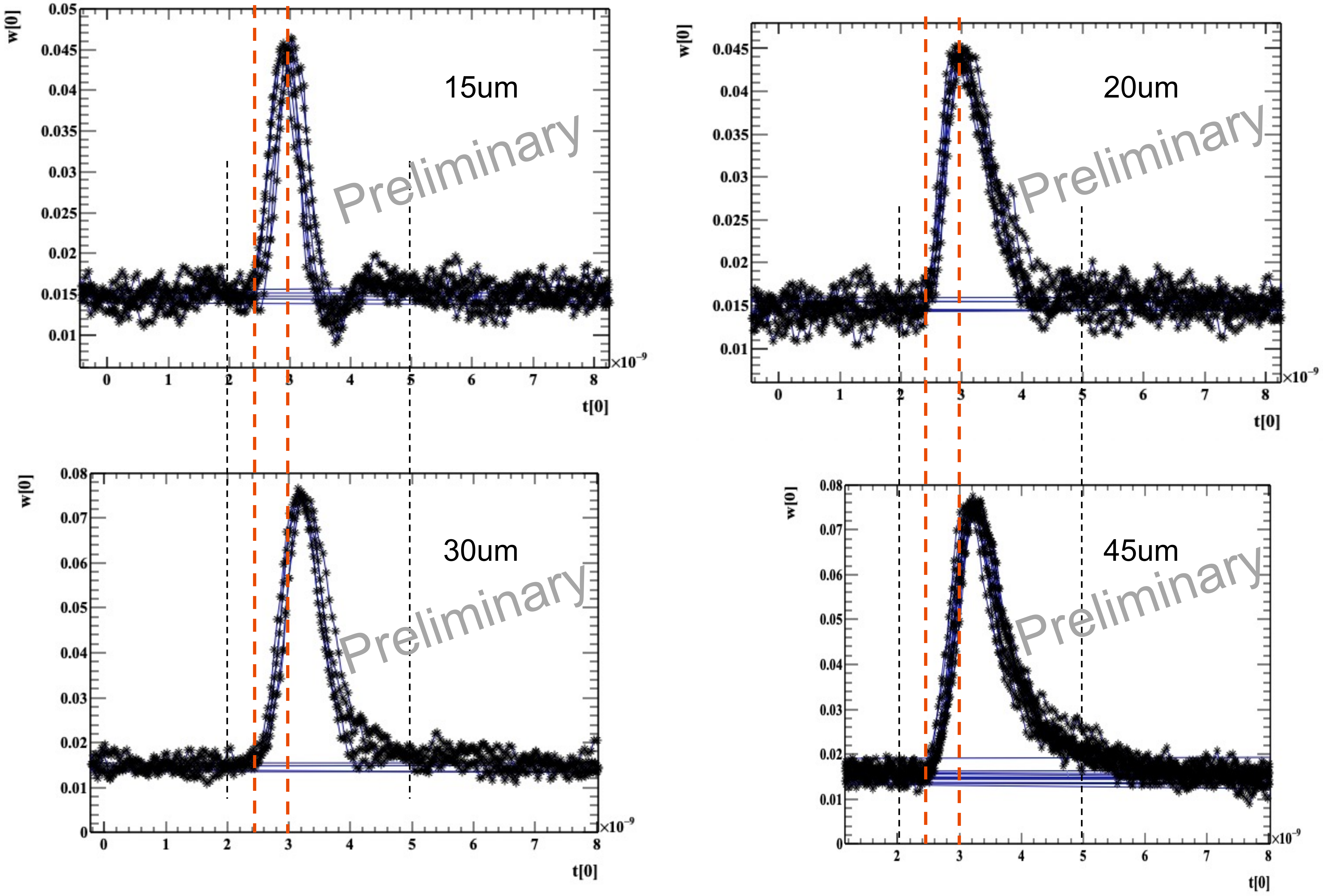


FINDINGS

- ➡ The LGAD multiplication mechanism ceases existing at $\sim 5\mathrm{e}15\ \mathrm{n}_{1\mathrm{Mev\,eq}}\,\mathrm{cm}^{-2}$
- ➡ From $1\mathrm{e}16$ to $1\mathrm{e}17\ \mathrm{n}_{1\mathrm{Mev\,eq}}\,\mathrm{cm}^{-2}$ the collected signal is roughly constant

- ➠ indico.cern.ch/event/896954/contributions/4106324
- ➠ indico.cern.ch/event/1074989/contributions/4601953

EXFLU1 β TEST



Markers on signal waveforms:

- - - Black dash: 2 – 5 ns range

- - - Red dash: 0 – 100% rise time of the $15\,\mu m$ sensor

The rise time does not decrease with the sensor thickness as much as the simulations predict. Maybe readout BW limit?

(2GHz BW BB amplifier board + 20dB Cividec BB amplifier)

Investigations in progress.

EXFLU1 BEAM TEST

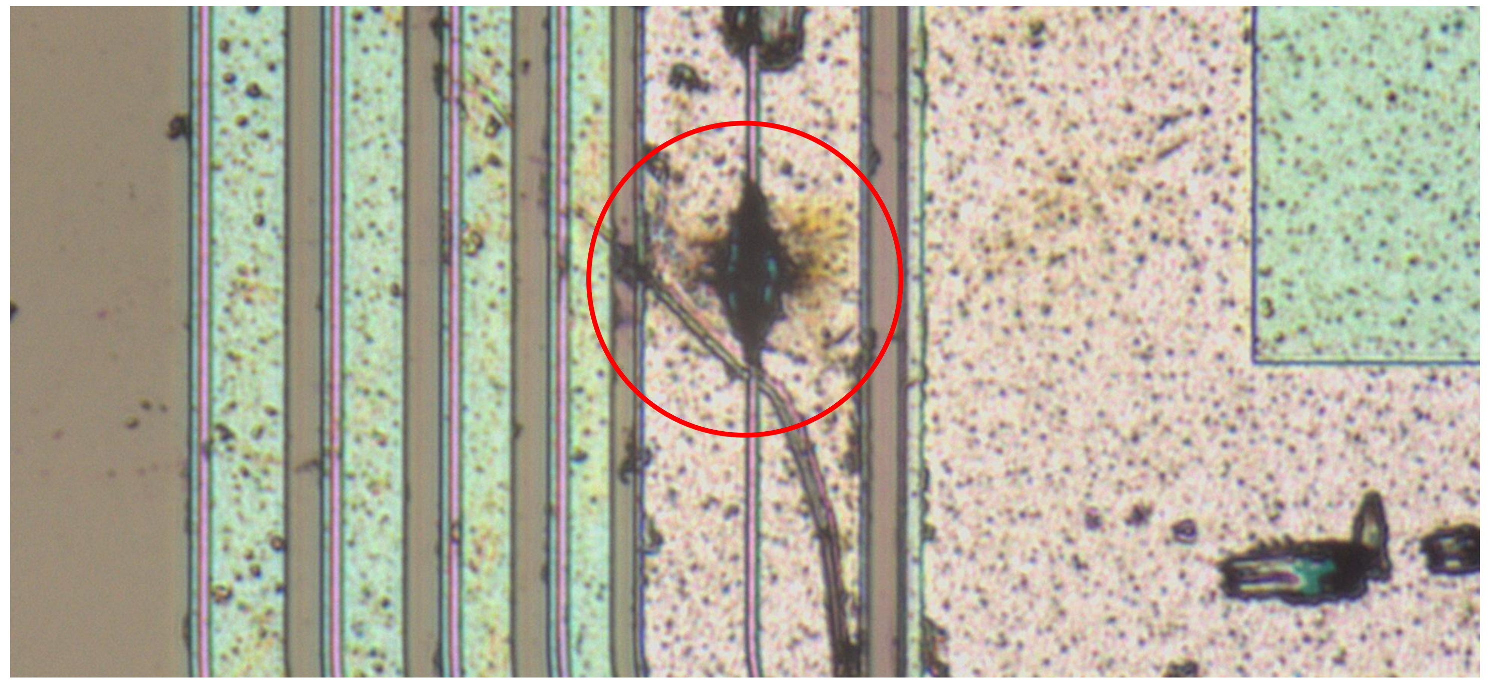
Beam test performed at SPS CERN in July 2023

1. Probing the Single Event Burnout (SEB) threshold on irradiated EXFLU0 LGADs and EXFLU1 PiNs.
2. Studying the signal amplitude and area (charge) of non irradiated EXFLU1 LGADs.
3. Studying the timing performance of non irradiated EXFLU1 LGADs.

1. SEB STUDIES ✅

Example: EXFLU0 35µm W6
PAD1.3mm PIN (1E15)

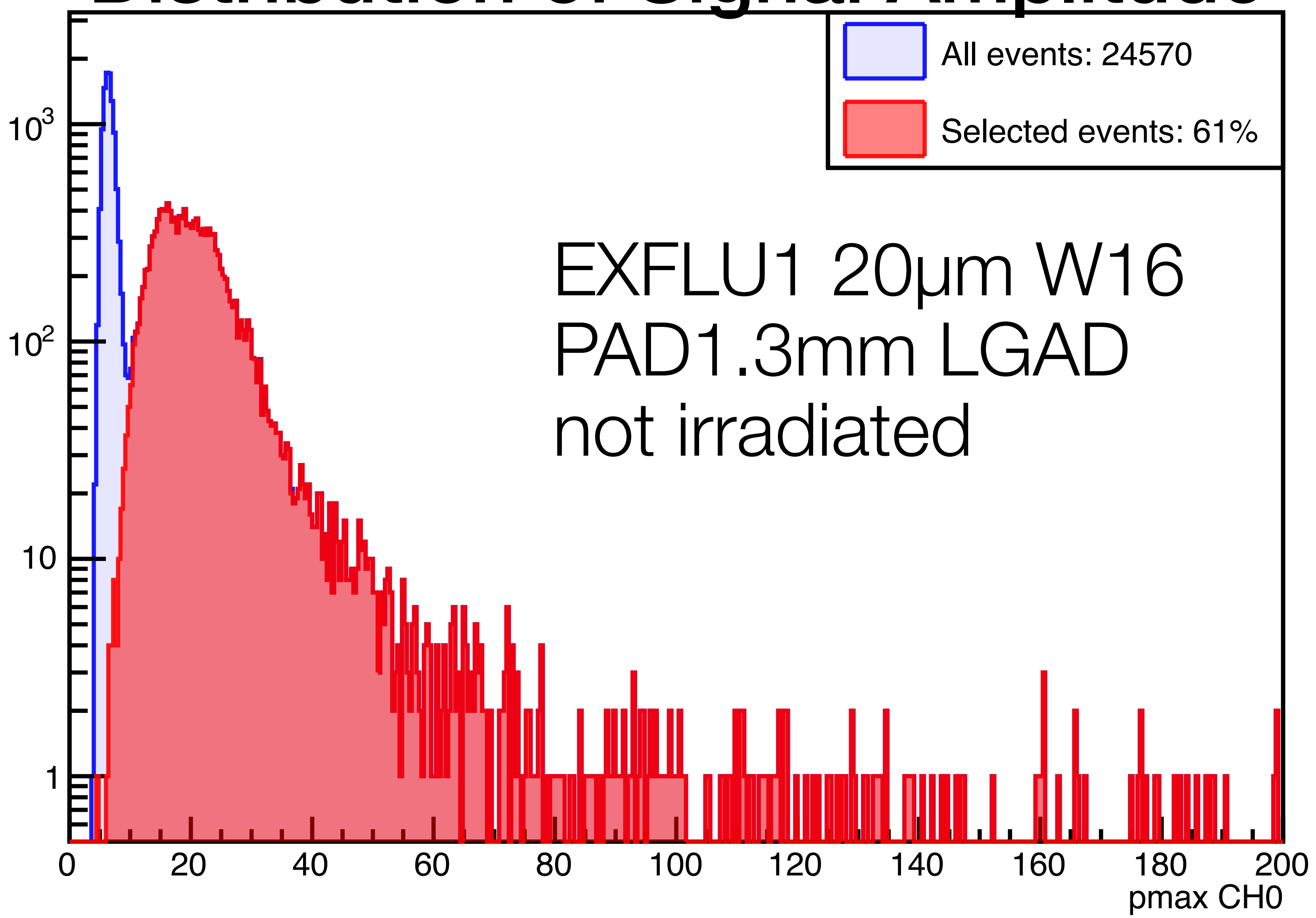
Bulk E_{field} [V/µm]		Exposure [# particles]
11	alive	2.7E+07
12	alive	1.3E+07
13.5	dead	3.8E+05



2. CHARGE STUDIES ✅

The amount of charge generated is small. However, the low noise level allow for a clean selection of signal vs background.

Distribution of Signal Amplitude



3. TIMING STUDIES 🚧

Same limitations of the β setup: perhaps the limited BW of out ReadOut is compromising the measurement of the time performance