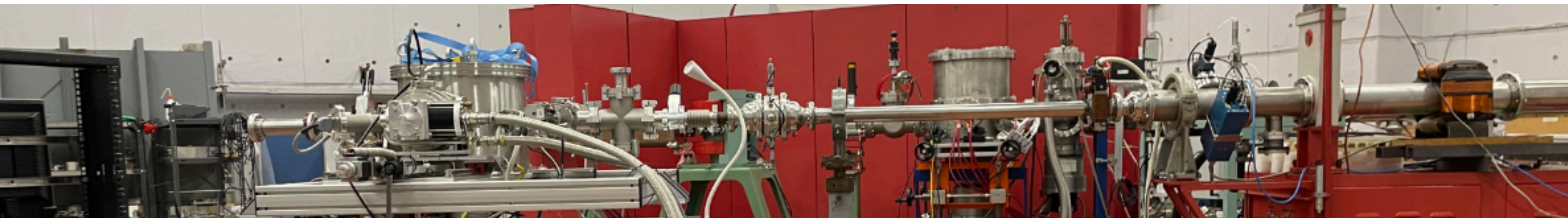


NUV-MT Silicon Photomultipliers

Performance characterisation and radiation hardness of
commercially available NUV-MT SiPMs

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NUV-MT SiPM technology

Measurement campaigns

Broadcom AFBR-S4N66P014M NUV-MT SiPMs

- Commercially available, off-the-shelf
- Sensitive area: $6 \times 6 \text{ mm}^2$, SPAD pitch: $40 \text{ }\mu\text{m}$
- Metal Trench (MT): between SPADs to reduce optical cross-talk
- Reduced DCR compared to Broadcom’s NUV-HD devices

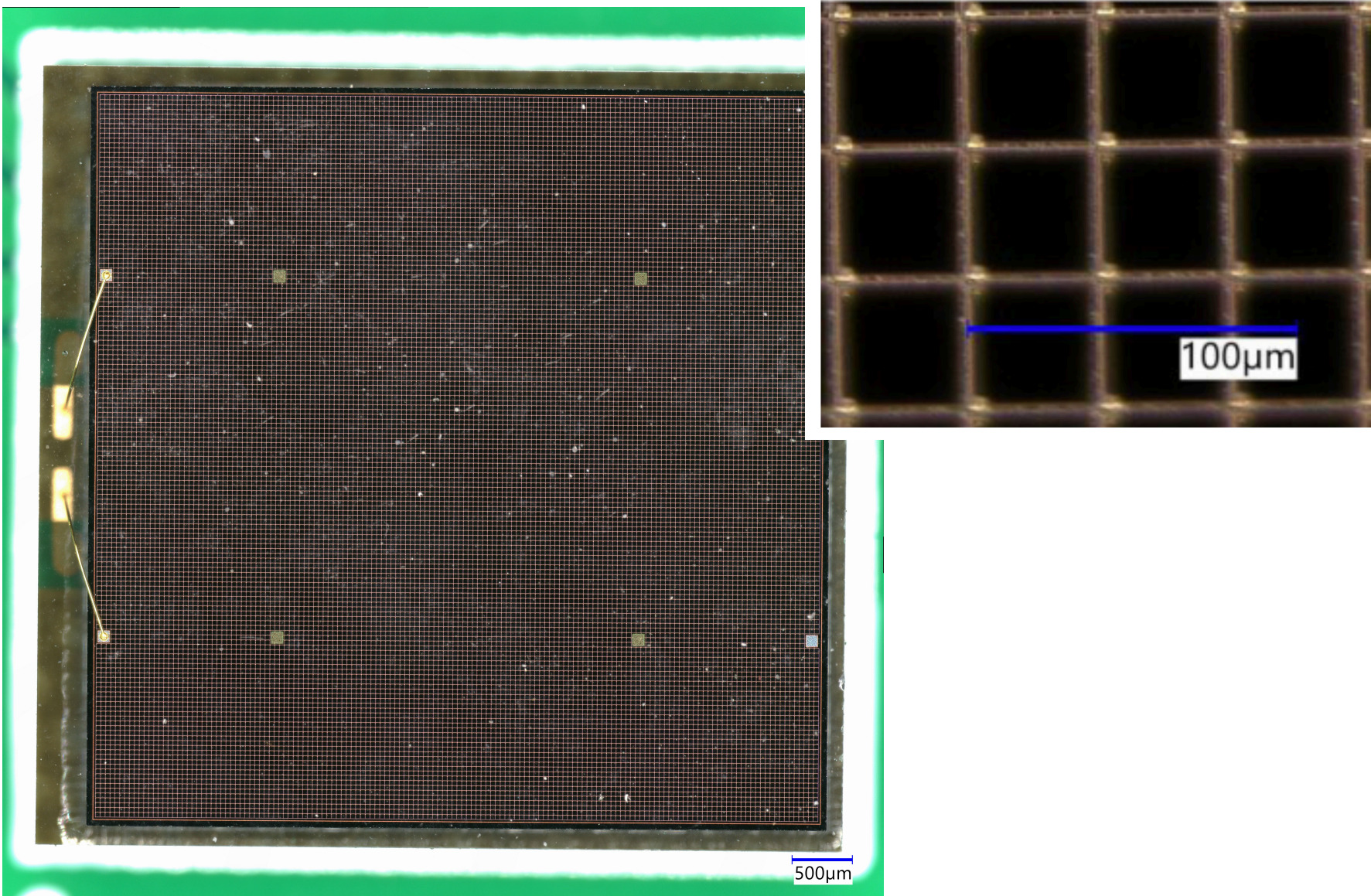
Two studies:

1. Baseline characterisation of NUV-MT SiPMs [arXiv:2608.19156]

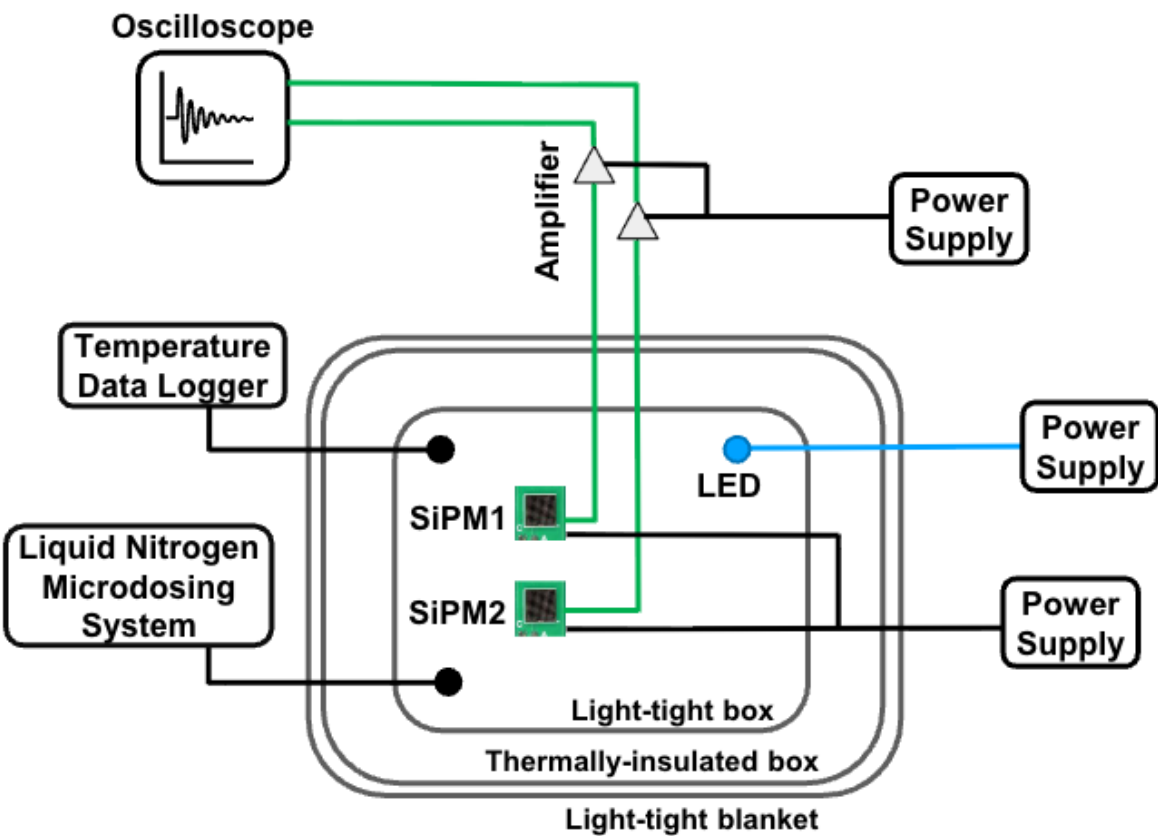
- Extended temperature range (-85°C - $+23^{\circ}\text{C}$) and operating voltages (10 - 16 Vov)

2. Radiation hardness of NUV-MT SiPMs [arXiv:2609.01809]

- 1 MeV neutron irradiation ($2.0 \times 10^9 - 1.1 \times 10^{10} \text{ n}_{eq}/\text{cm}^2$), thermal annealing cycles



Parameter	Value
Breakdown voltage, V_{bd}	32.5 V
Temperature coefficient of V_{bd}	30 mV/ $^{\circ}\text{C}$
Dark noise (R_{DN})	125 kcps/ mm^2
Gain	7.3×10^6
Optical crosstalk probability, p_{CT}	0.23
Afterpulse probability, p_{AP}	<0.01
Recharge time coefficient	55 ns

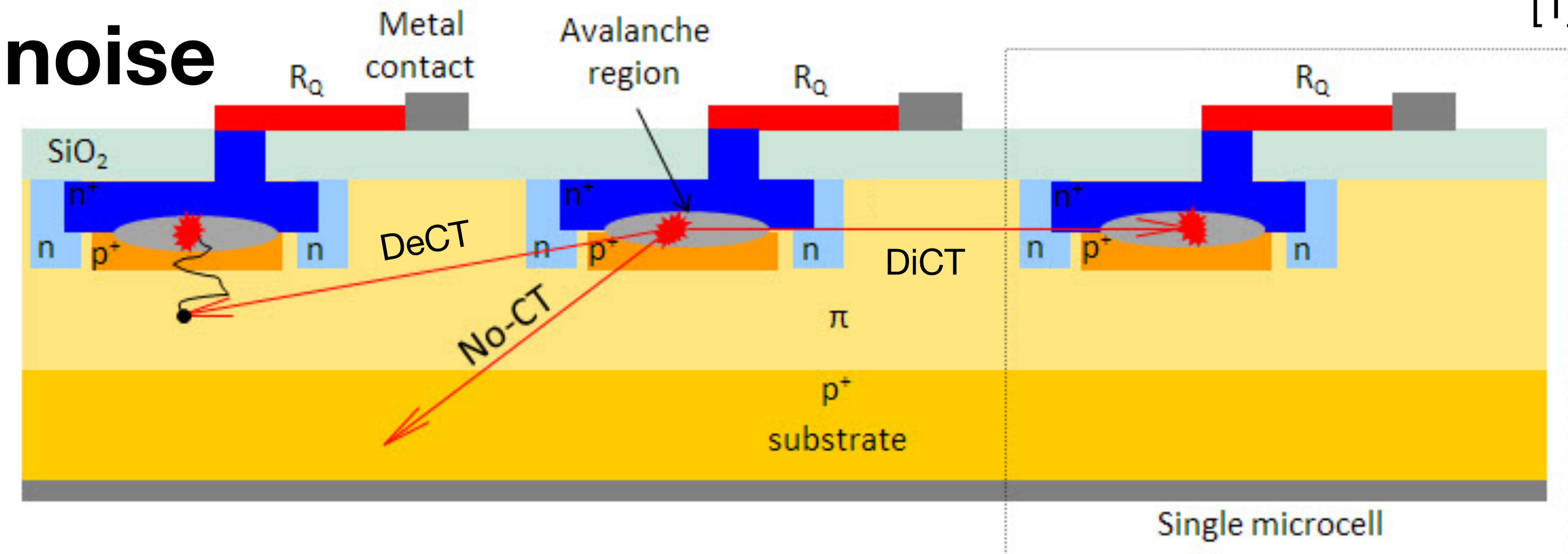


SiPM noise sources

Correlated and uncorrelated noise

Uncorrelated noise

DCR: thermally-generated carriers trigger avalanches, creating single photon signals



Correlated noise

Afterpulses: trapped carriers trigger avalanches within microcell during SiPM recharge
→ generate signal with reduced charge

Internal cross-talk - delayed and direct: photons generated in initial avalanche propagate to neighbouring microcells, triggering avalanche

External cross-talk: photons generated in initial avalanche propagate to neighbouring SiPM, triggering avalanche

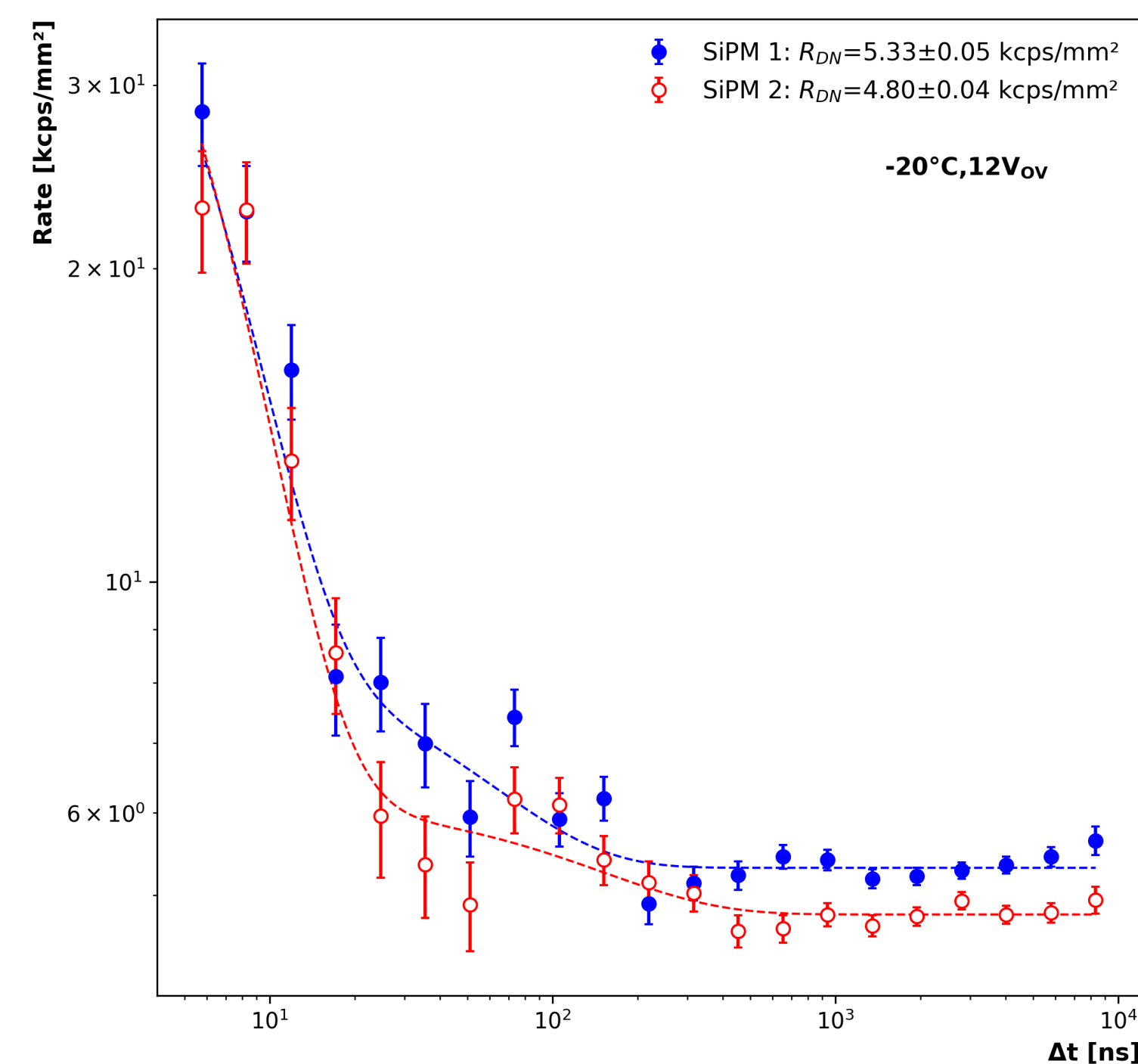
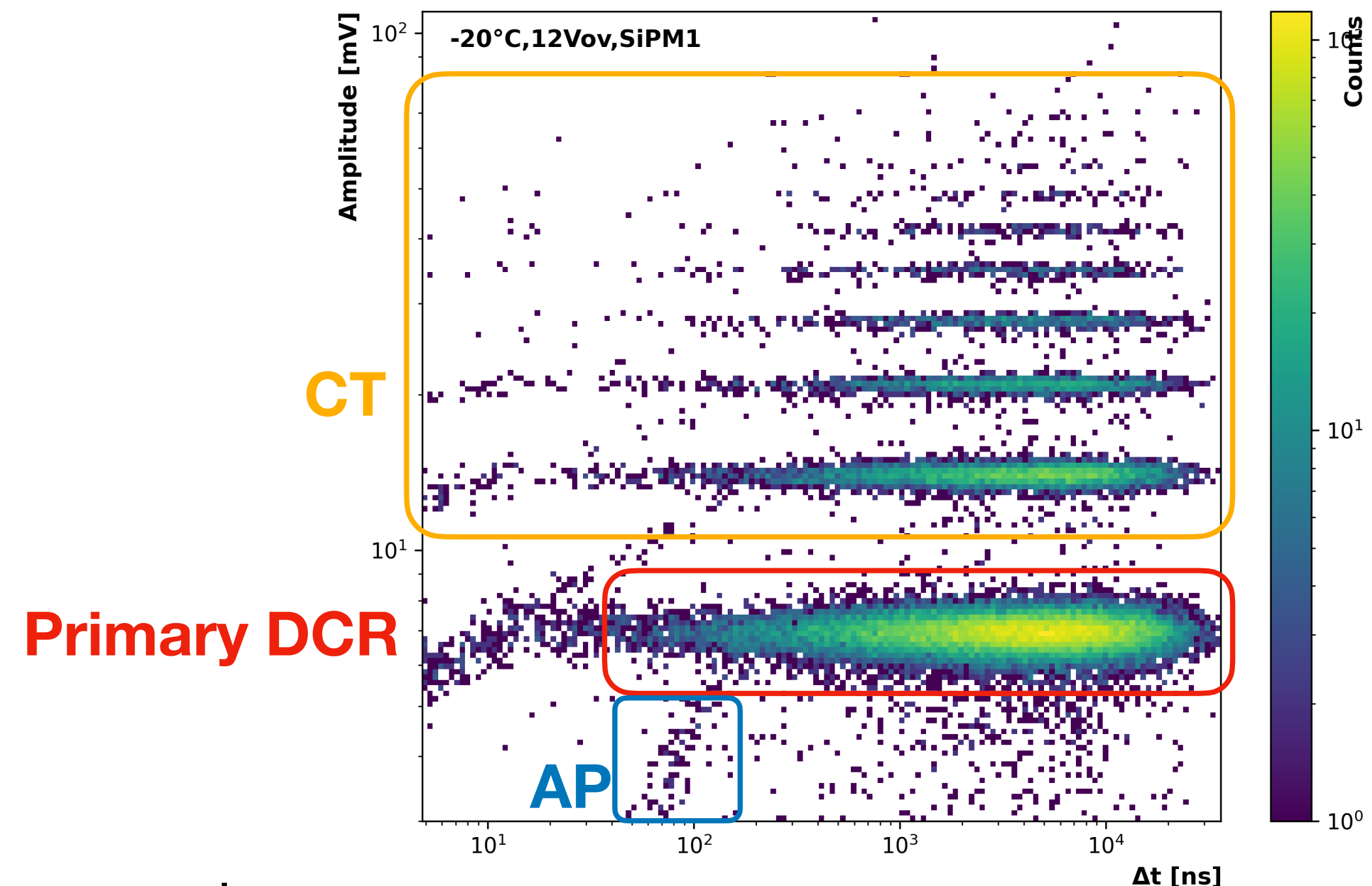
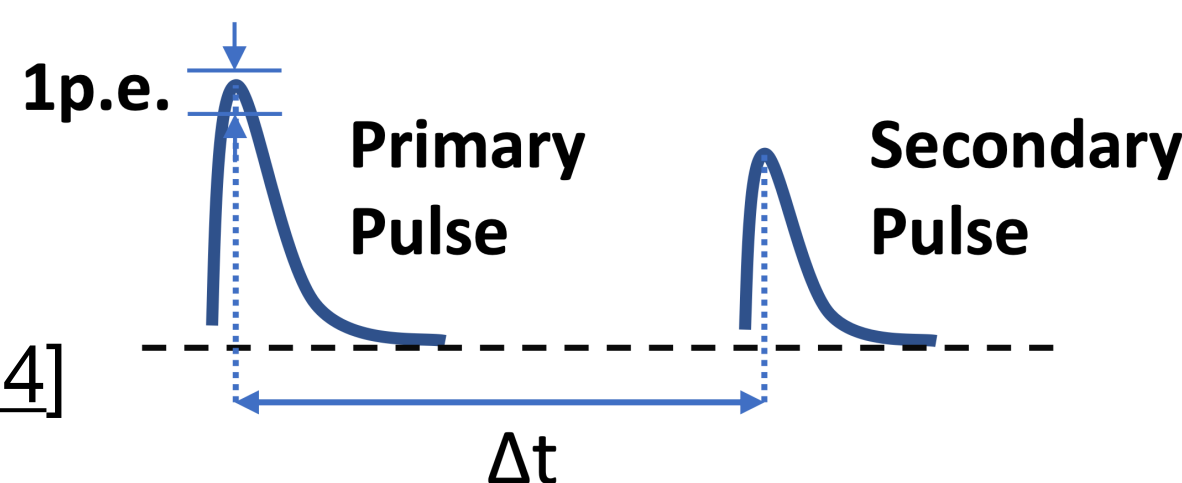
Noise characterisation

Analysis methodology

1. Counting method: $R_{DN} = \frac{N_{0.5PE}}{T}$

2. Time-distribution method:

- Select **primary pulse**: 1PE amplitude ($\mu_{1PE} \pm 3\sigma_{1PE}$), require no pulse in previous 300 ns
- Select **secondary pulse**: first pulse following a primary pulse
- Build ΔT distribution
- Unshadowing procedure [arXiv:1703.06204]
- Double exponential & constant fit $\rightarrow$ distinguish correlated and uncorrelated noise



Uncorrelated noise

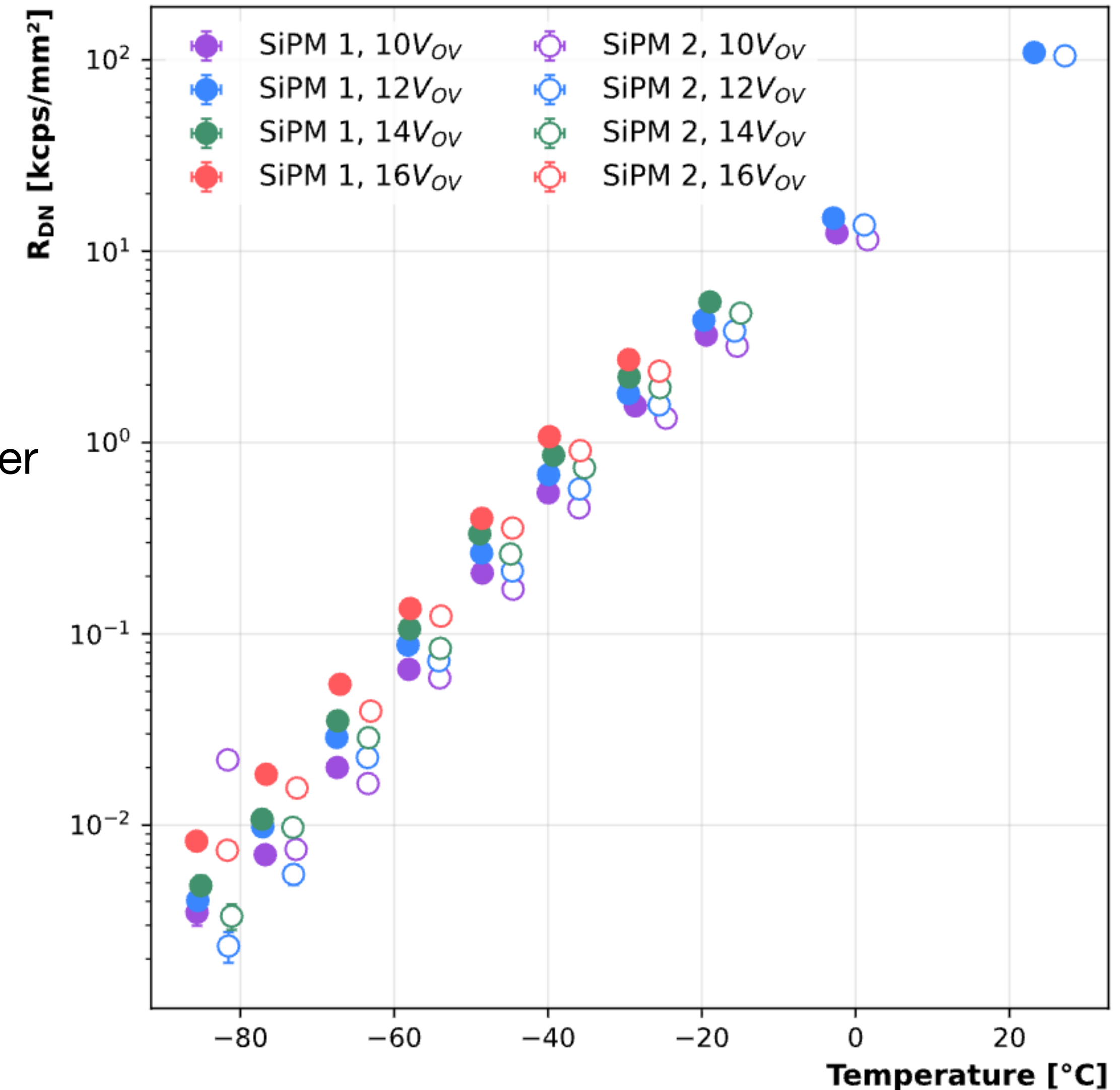
Dark noise

Expected behaviour:

- R_{DN} increases with increased temperature
 - Higher phonon interaction probability at higher temperatures → increased probability of charge carrier generation → higher dark noise rate
- R_{DN} increases with increased OV
 - Higher Geiger discharge probability at higher voltage

Results: (107.2 ± 2.1) kcps/mm² at $12 V_{OV}$ & 23°C

Arrhenius-type behaviour: factor 2 change every 8°C below -25°C (factor 2 every 6°C above -25°C)



SiPM 2 shifted along temperature axis for visual clarity

Correlated noise

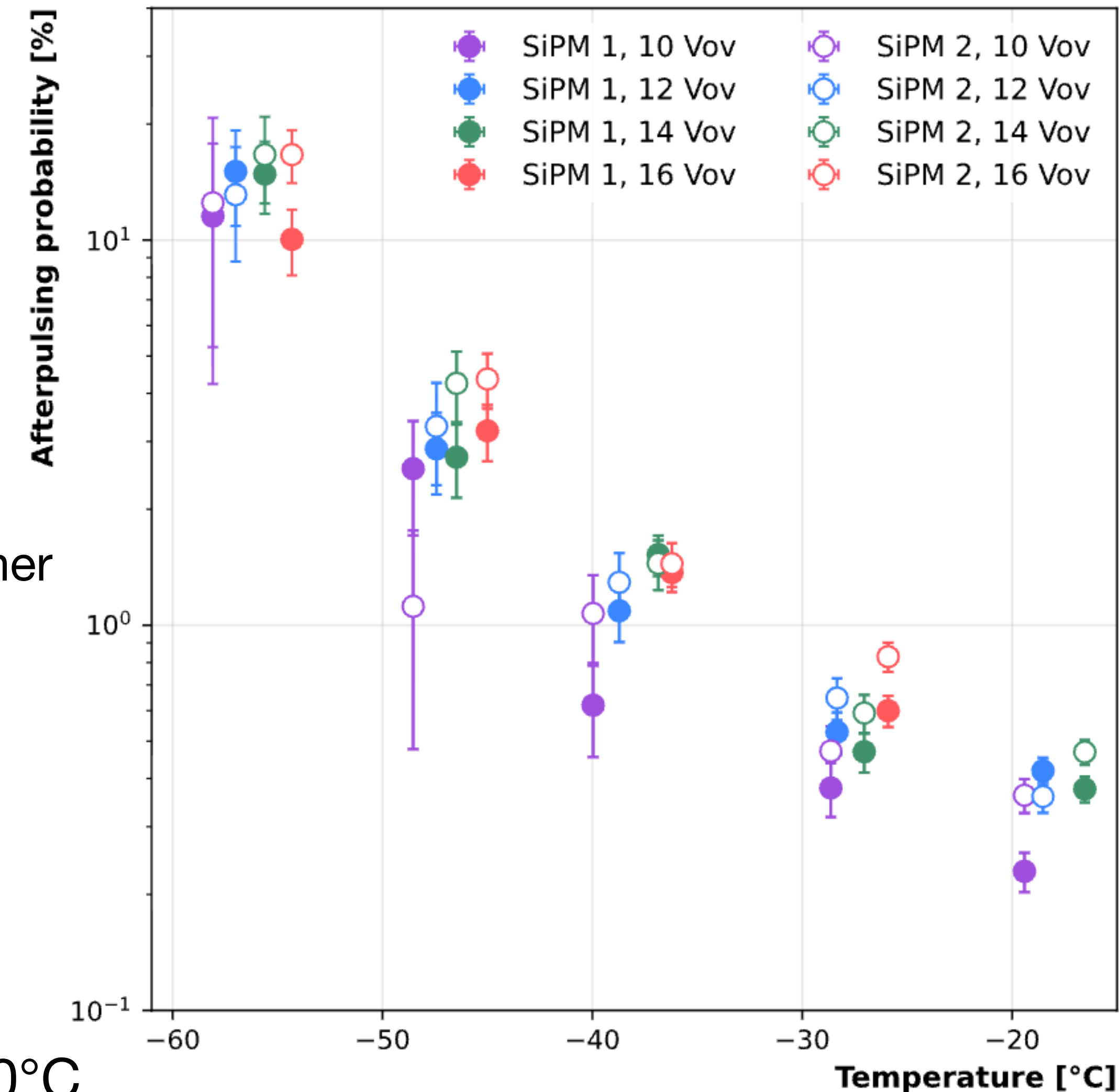
Afterpulses

Expected behaviour:

- p_{AP} increases with decreased temperature
 - Trap release time constant longer at lower temps $\rightarrow$ release time shifted into SiPM recharge window $\rightarrow$ higher p_{AP}
- p_{AP} increases with increased OV
 - Larger avalanche charge increases number of carriers available for trapping at defect sites $\rightarrow$ higher p_{AP}

Results: @ $12V_{OV}$, average p_{AP} : $(0.39 \pm 0.03) \%$ at -20°C
 $\rightarrow (14.1 \pm 3.0) \%$ at -58°C

@ -30°C , average p_{AP} : $(0.41 \pm 0.05) \%$ at $10V_{OV}$ $\rightarrow$ $(0.71 \pm 0.11) \%$ at $16V_{OV}$



Correlated noise

Direct & delayed Cross-talk

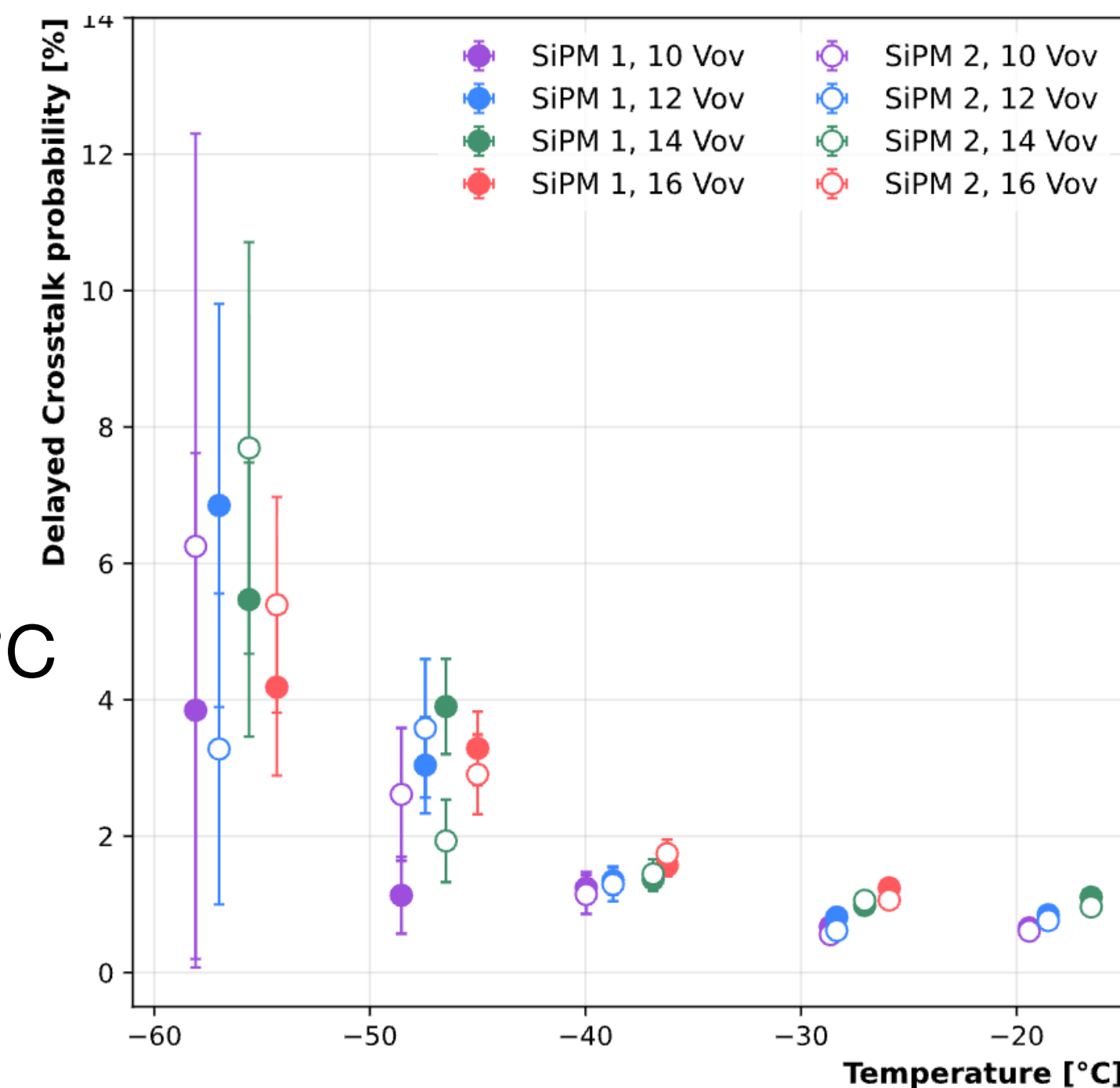
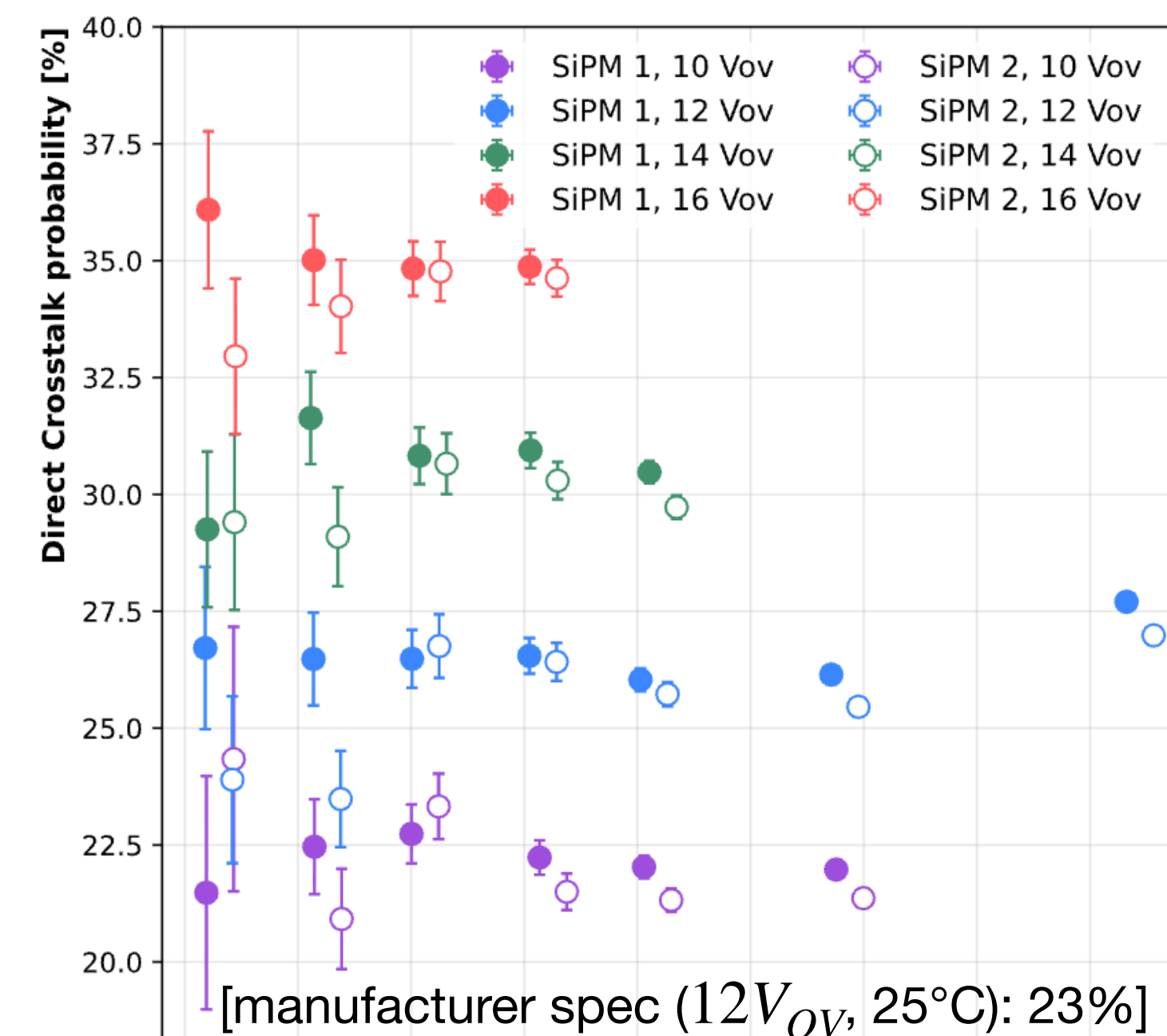
Expected behaviour:

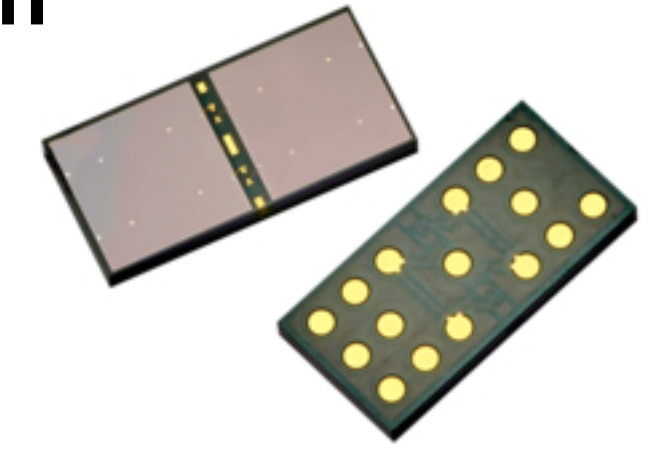
- p_{diCT} independent of temperature, increases with increased OV
 - Direct CT driven by avalanche charge not thermally generated carriers.
- p_{deCT} increases with decreased temperature, increases with increased OV
 - Reduced phonon scattering → higher probability of carriers diffusing into microcell active region at lower temps → higher p_{deCT} .
 - Larger avalanche charge at higher OV → higher probability of secondary photon emission → higher p_{diCT} / higher p_{deCT}

Results: @ $12V_{OV}$, average p_{deCT} $(0.80 \pm 0.04) \%$ at -20°C → $(4.6 \pm 1.8) \%$ at -58°C

@ -30°C , average p_{diCT} : $(21.9 \pm 0.4) \%$ at $10V_{OV}$ → $(34.8 \pm 0.3) \%$ at $16V_{OV}$

average p_{deCT} : $(0.61 \pm 0.06) \%$ at $10V_{OV}$ → $(1.15 \pm 0.09) \%$ at $16V_{OV}$





Correlated noise

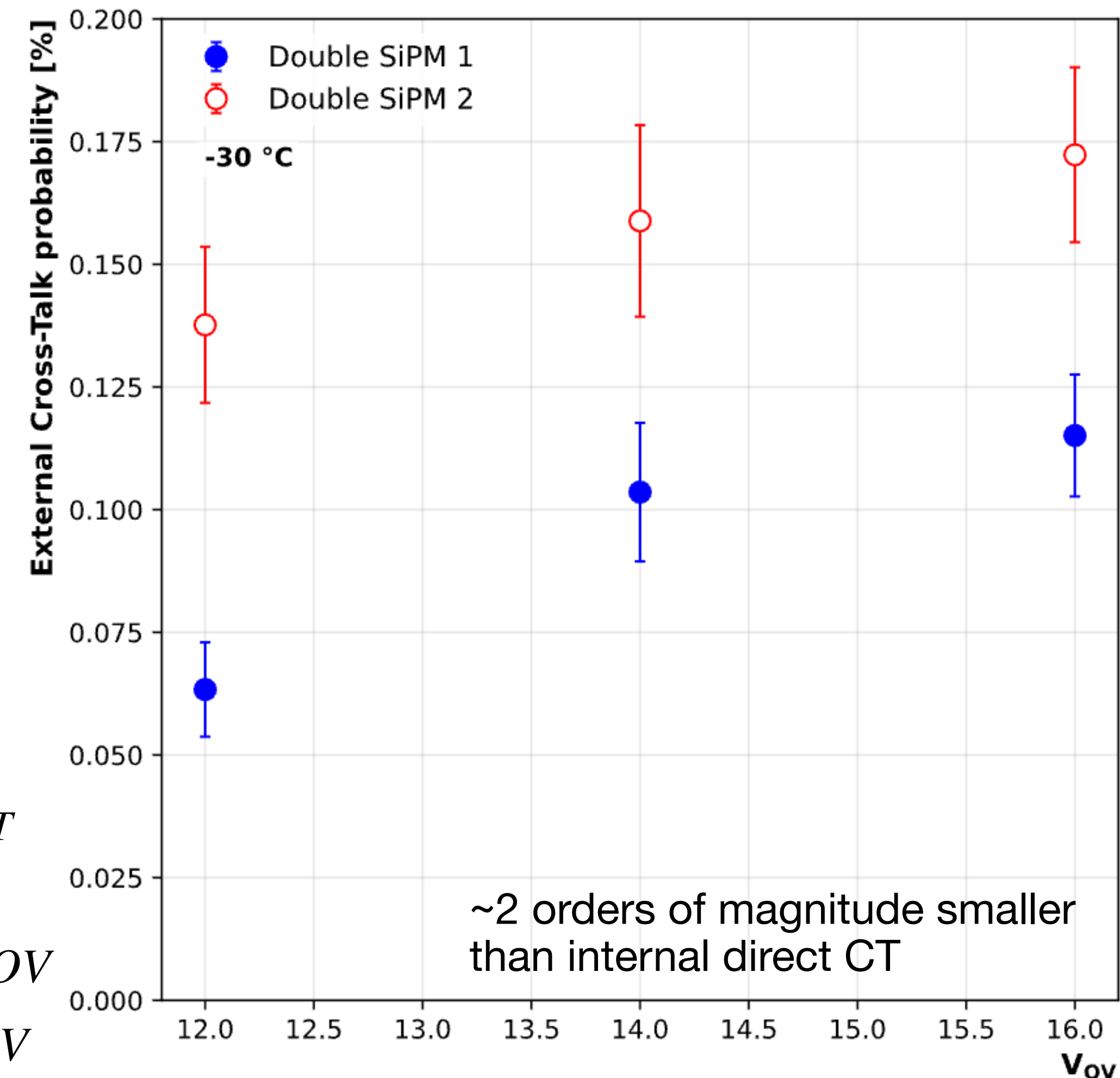
External Cross-talk

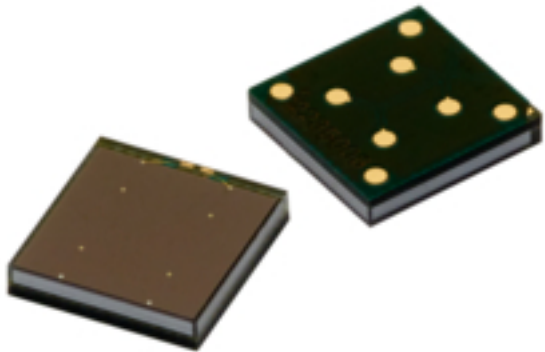
First measurement of fixed SiPM pitch external cross-talk **without** scintillator coupling.

Expected behaviour:

- p_{exCT} independent of temperature, increases with increased OV
- External CT driven by avalanche charge not thermally generated carriers.
- Larger avalanche charge at higher OV $\rightarrow$ higher probability of secondary photon emission and higher p_{exCT}

Results: @ -30°C, average p_{exCT} : $(0.10 \pm 0.04) \%$ at $12V_{OV}$
 $\rightarrow (0.14 \pm 0.03) \%$ at $16V_{OV}$





Radiation hardness

Irradiation campaign & annealing procedure

TANDEM accelerator at NCSR Demokritos, Athens

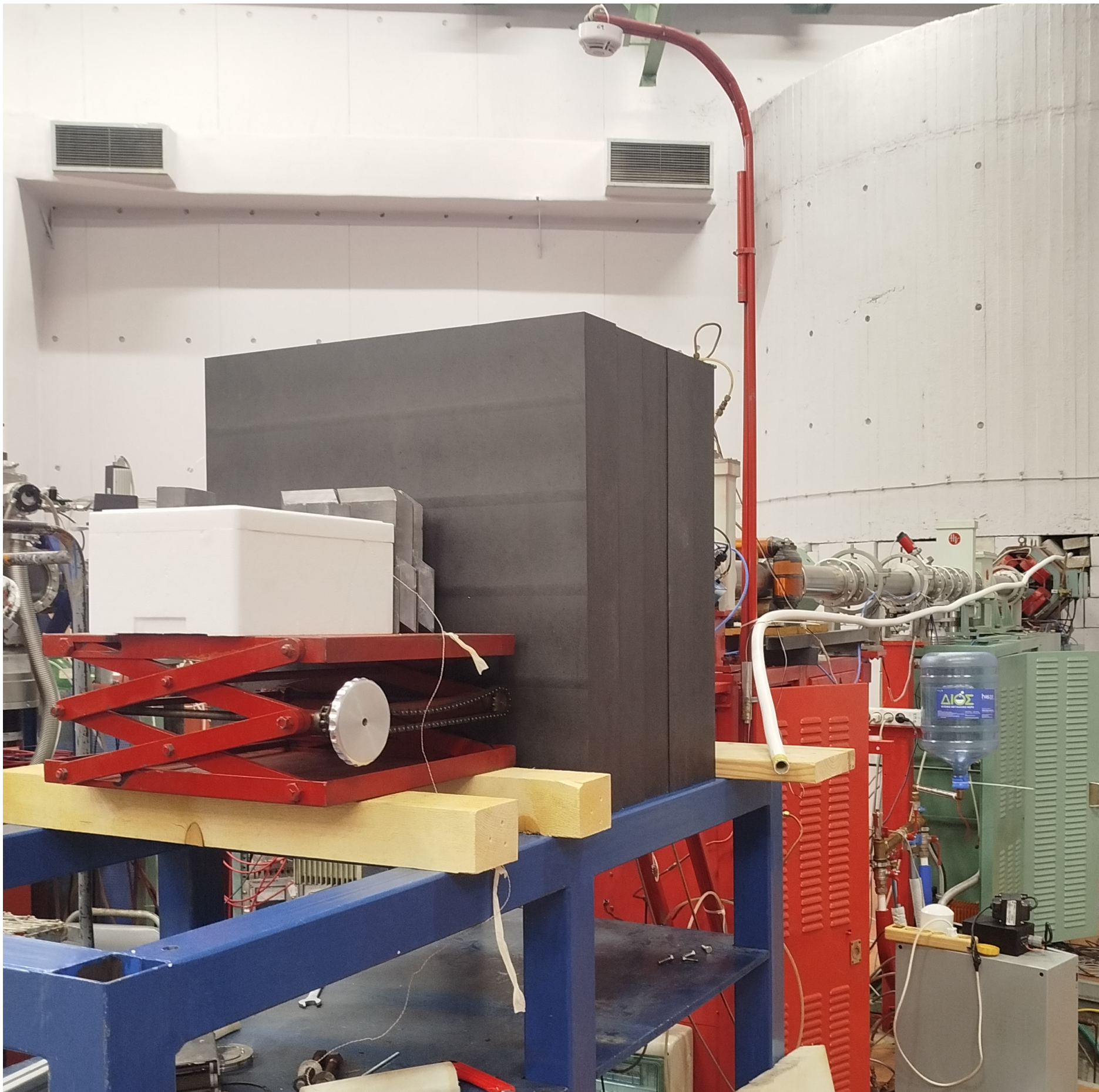
- ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction generates ~ 1 MeV neutrons with a mean flux $\sim 4 \times 10^5 n/cm^2/s$

Three SiPMs exposed to fluences between $2.0 \times 10^9 - 1.1 \times 10^{10} n_{eq}/cm^2$ with irradiation measured using indium foils.

- Fluences typical for space missions, low-Earth orbit satellites, detector R&D, cumulative exposure of long running ν /DM direct detection experiments

Radiation induced defects within Silicon lattice can be removed by thermal annealing: cycles of performance characterisation, followed by thermal annealing.

Annealing Cycle	Cumulative Duration [$\times 80$ min at 60°C]
A	0.89 ± 0.02
B	1.9 ± 0.1
C	4.9 ± 0.5
D	9.5 ± 1.0
E	23.5 ± 3.6



Radiation hardness

SPE resolution

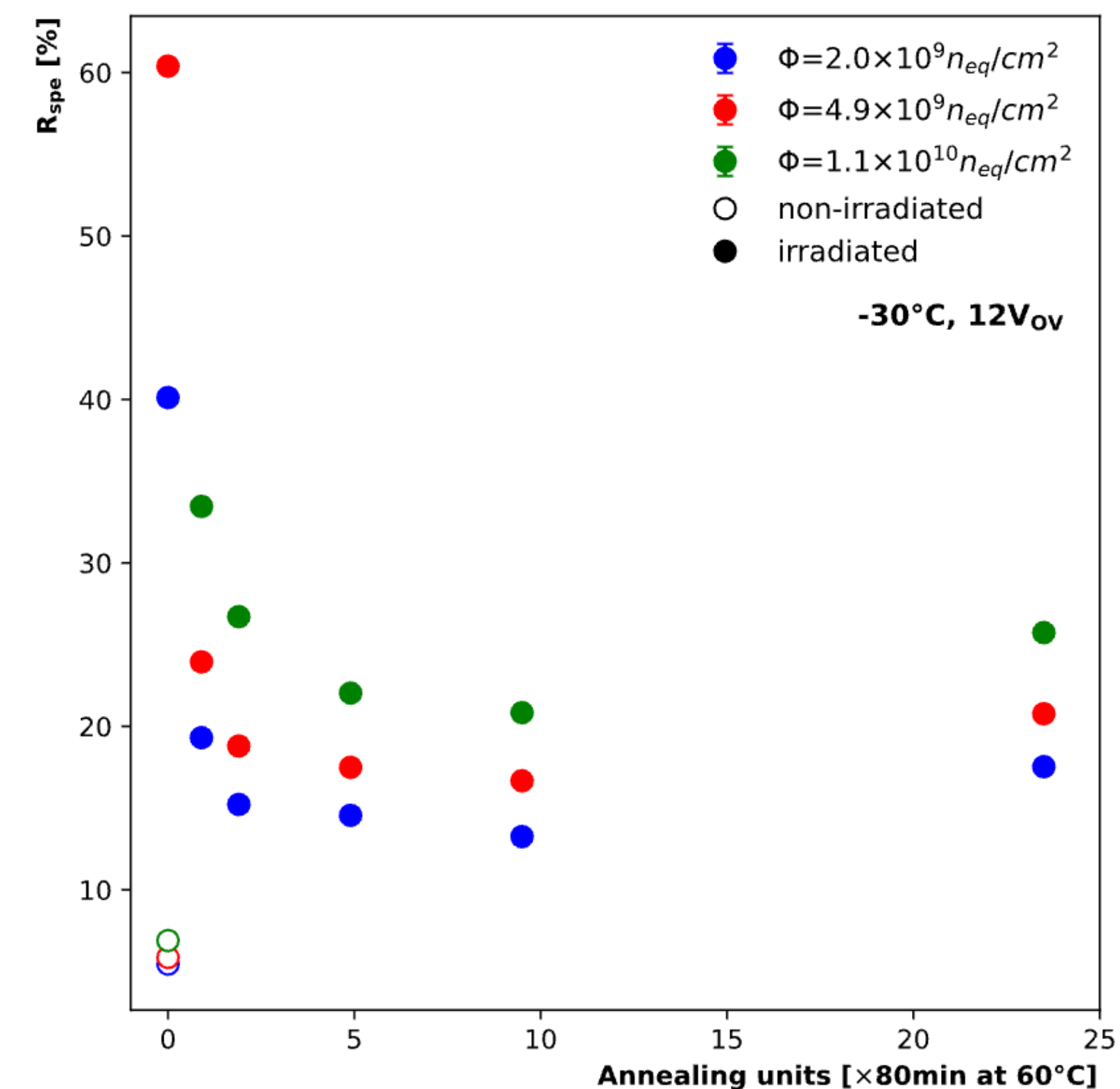
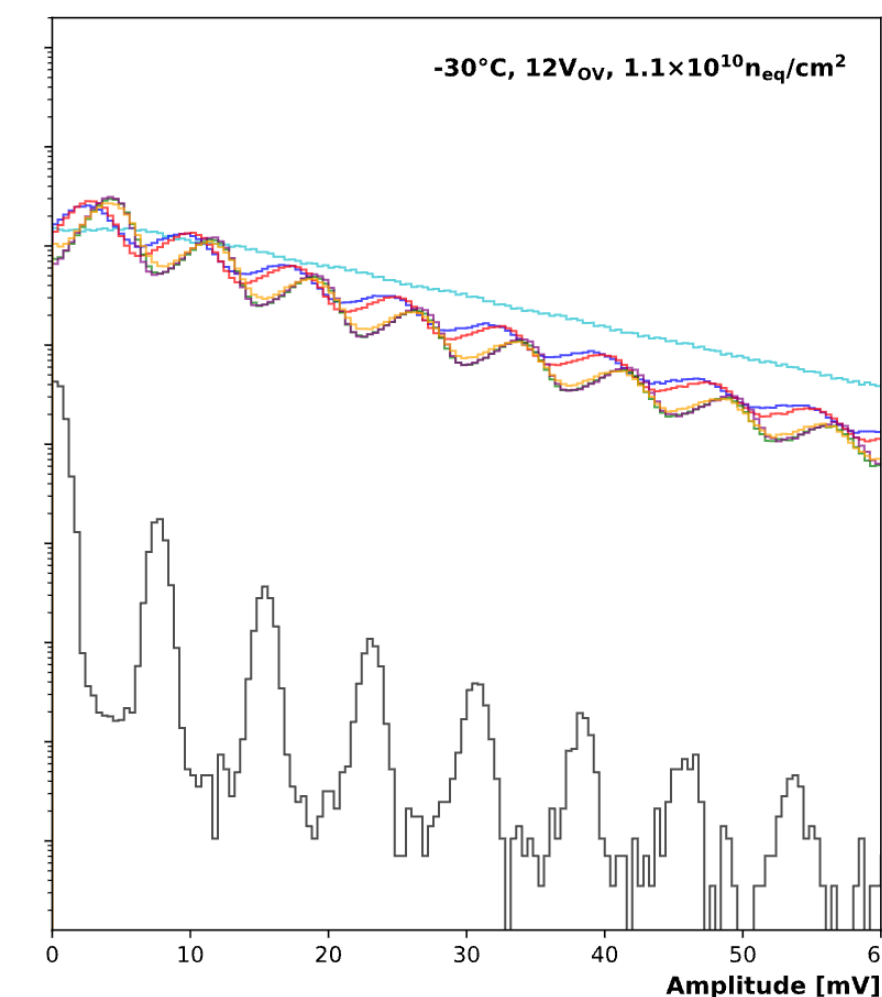
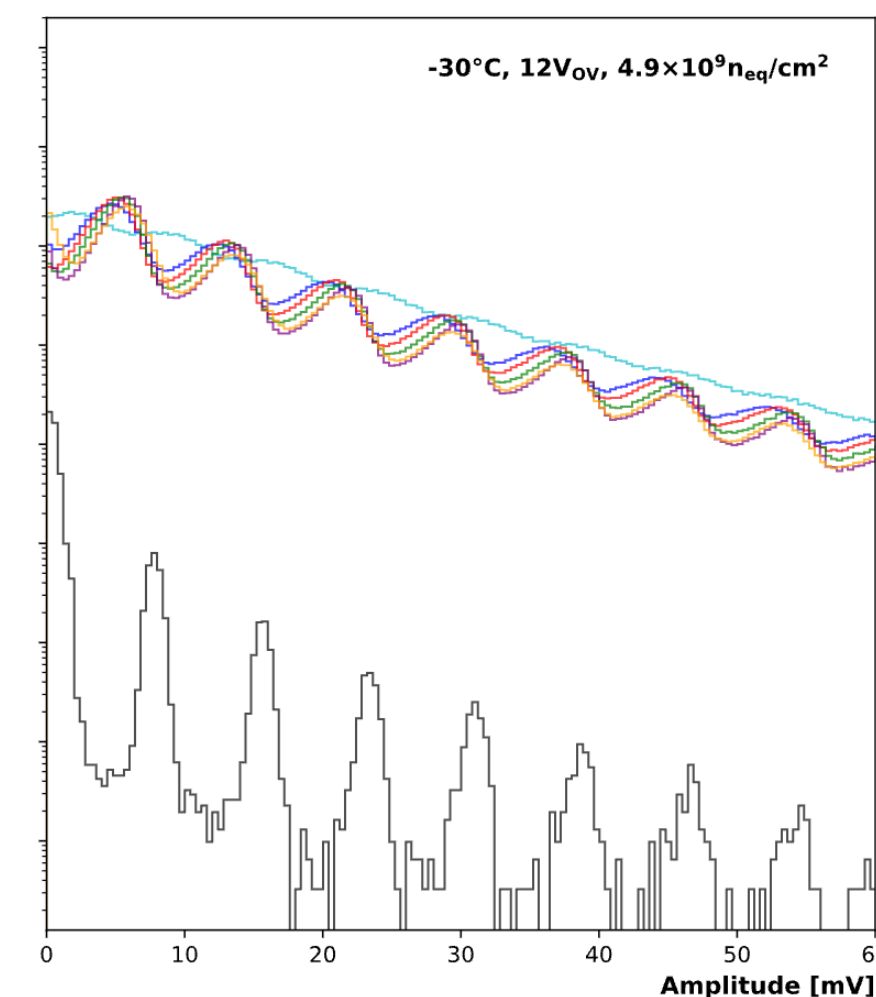
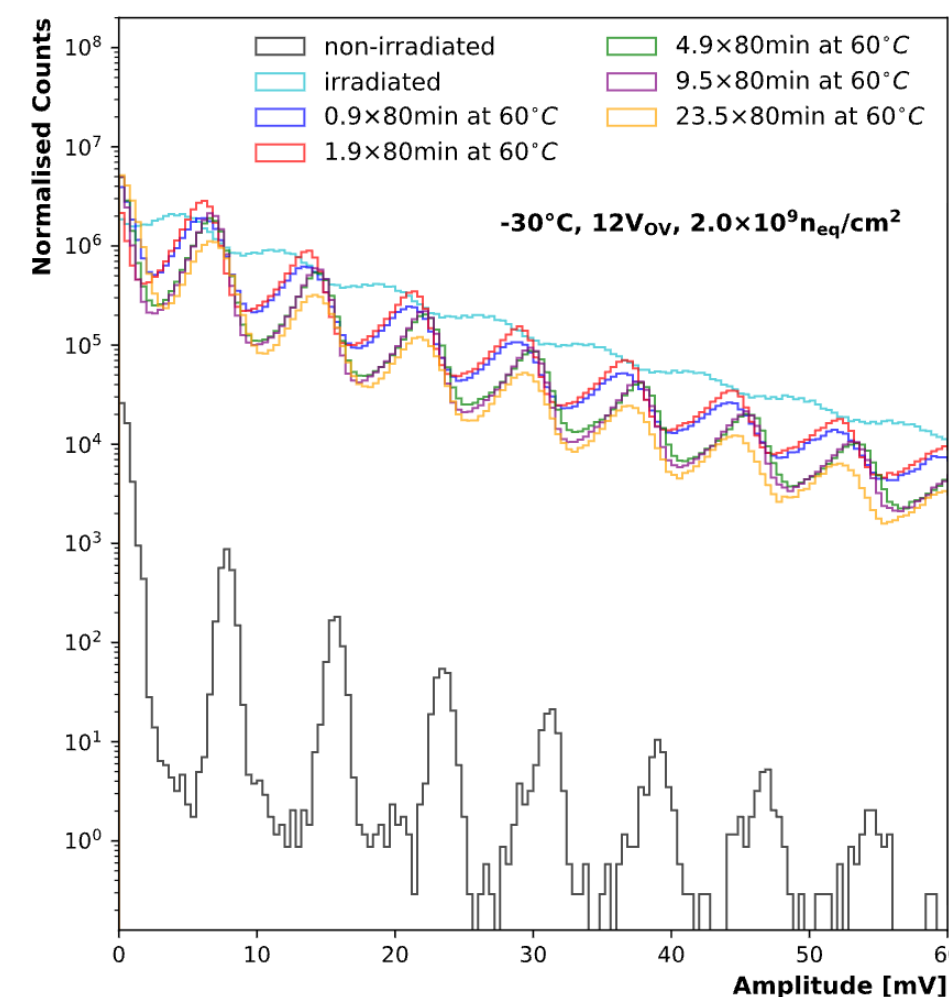
R_{SPE} degrades by

- factor 7.3 (fluence $2.0 \times 10^9 n_{eq}/cm^2$),
- factor 10.2 (fluence $4.9 \times 10^9 n_{eq}/cm^2$),
- single-photon ID lost entirely at $1.1 \times 10^{10} n_{eq}/cm^2$

Recovery: single-photon ID restored after just 1 thermal annealing cycle, improved by factor 3.0 - 3.6 after 10 cycles

Reverse annealing: slight degradation beyond 10 cycles

- high local defect density in clusters promotes the re-trapping and reformation of stable complexes $\rightarrow$ defects within cluster cores anneal less readily than isolated point



Radiation hardness

Dark noise

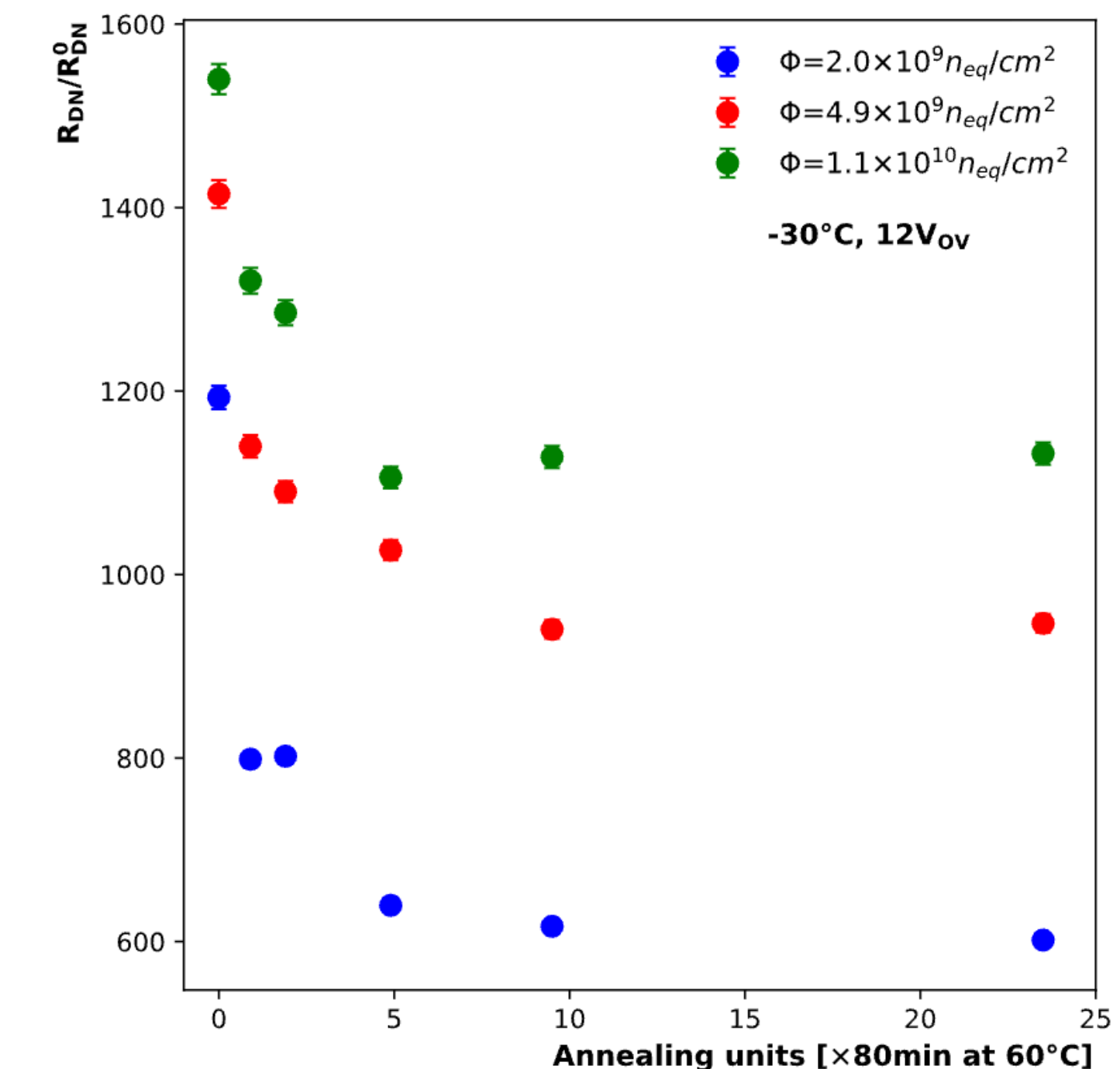
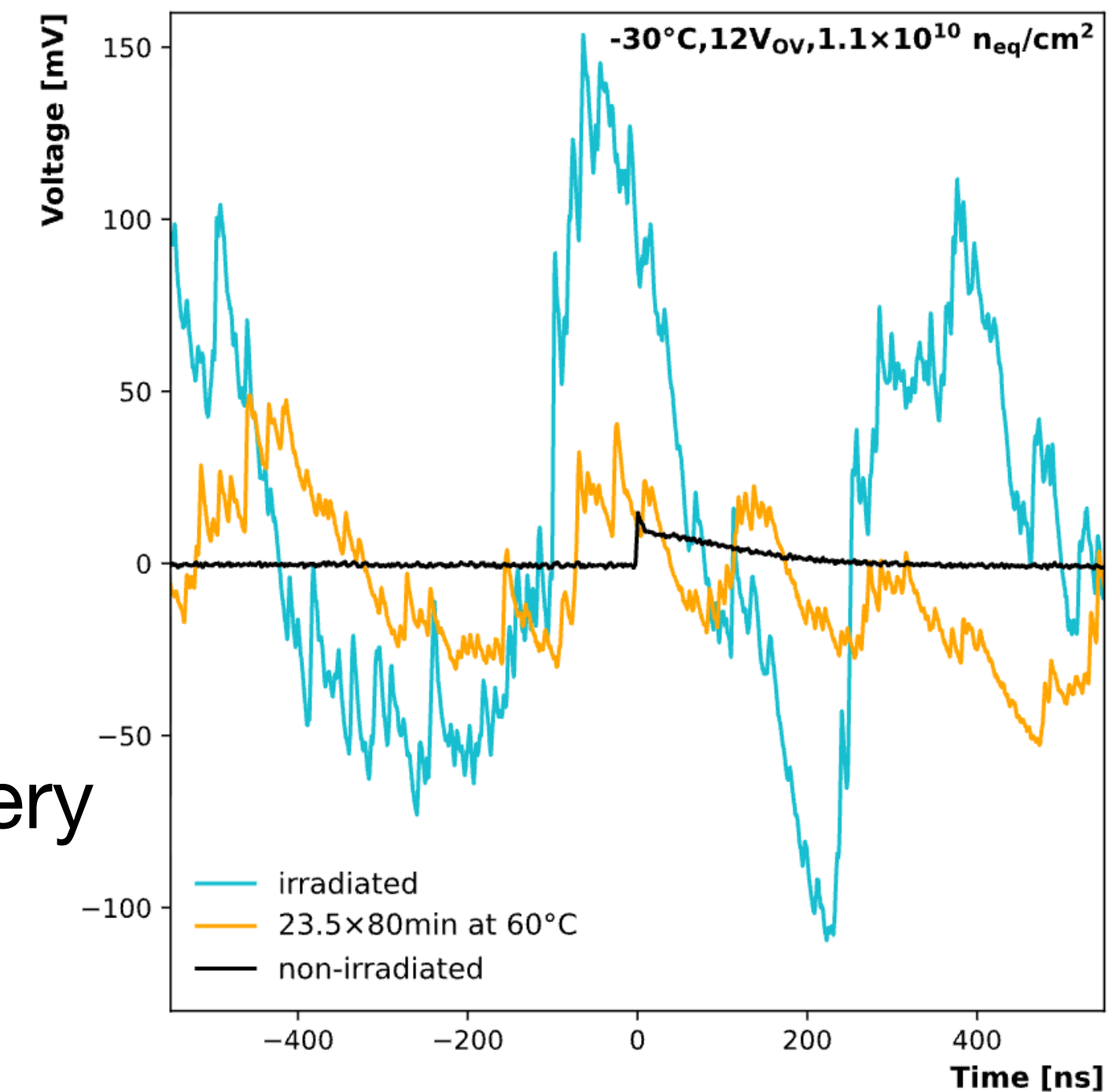
Observations:

- substantial increase in noise following irradiation, only partial recovery through 23.5 annealing cycles
- 3-orders-of-magnitude increase in DCR across all fluences

Recovery: noise recovery fraction decreases with fluence:

- $2.0 \times 10^9 n_{eq}/cm^2$: 50% recovered
- $4.9 \times 10^9 n_{eq}/cm^2$: 33% recovered
- $1.1 \times 10^{10} n_{eq}/cm^2$: 27% recovered

Higher fluence $\rightarrow$ more cluster defects in SiPMs $\rightarrow$ anneal less readily



Summary

SiPM characterisation & radiation hardness

Presented full characterisation of baseline SiPM performance for $-85^{\circ}\text{C} \rightarrow +23^{\circ}\text{C}$, for full range of overvoltages

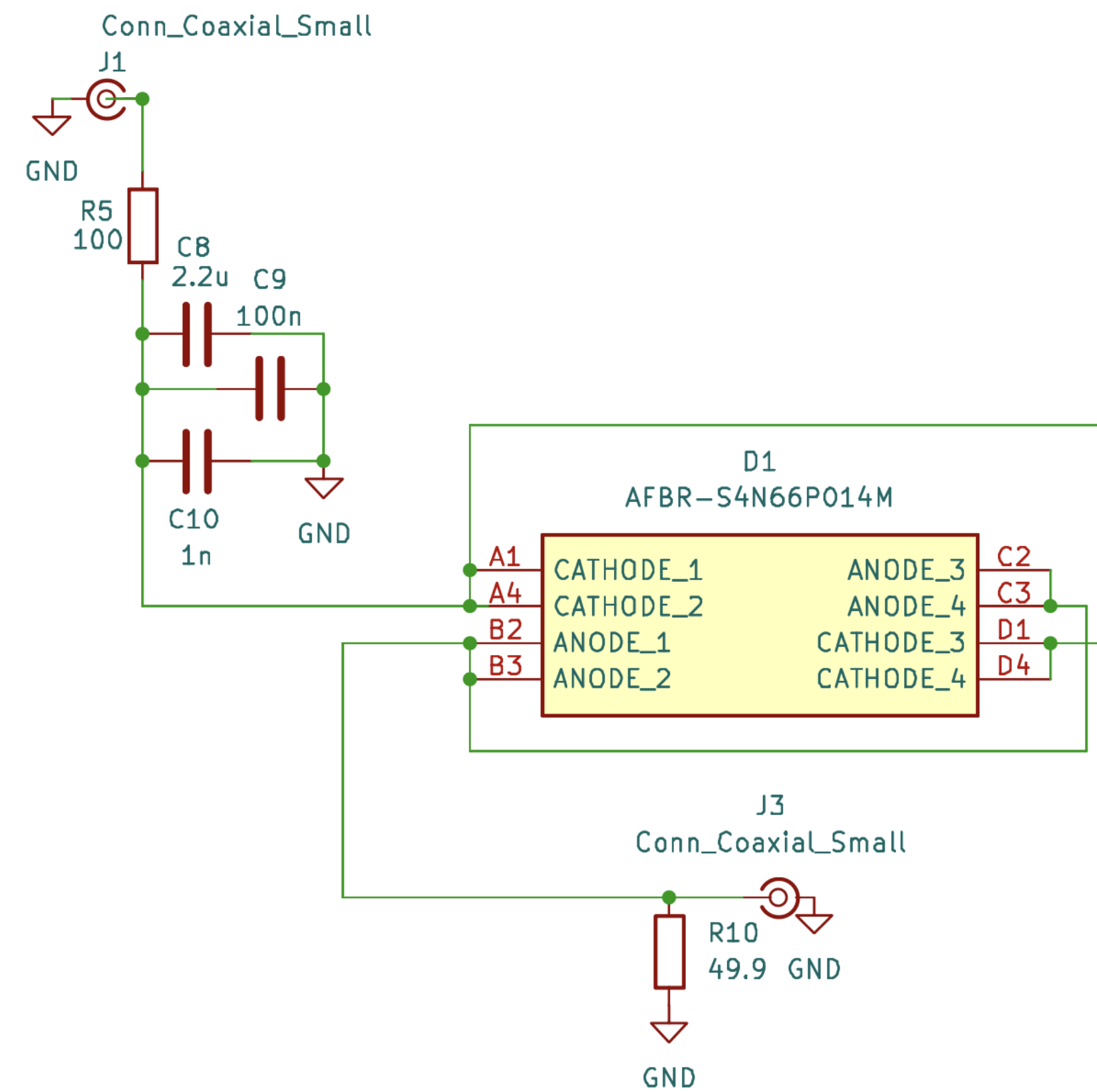
- V_{bd} , DCR, AP, CT in agreement with manufacturer specs
- First exCT results for SiPM-only setup

Presented study of SiPM performance following neutron irradiation at TANDEM accelerator at NCSR Demokritos

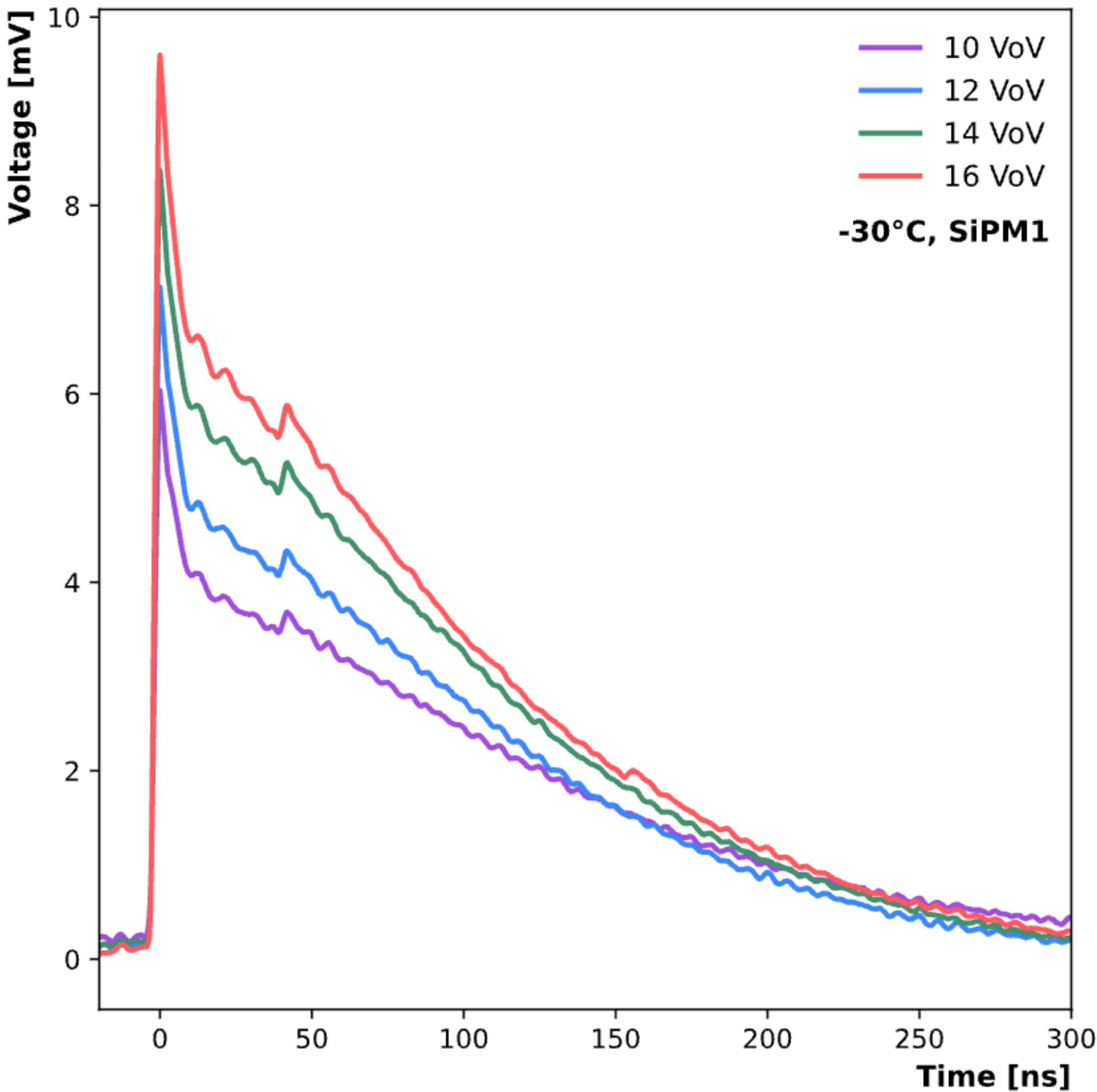
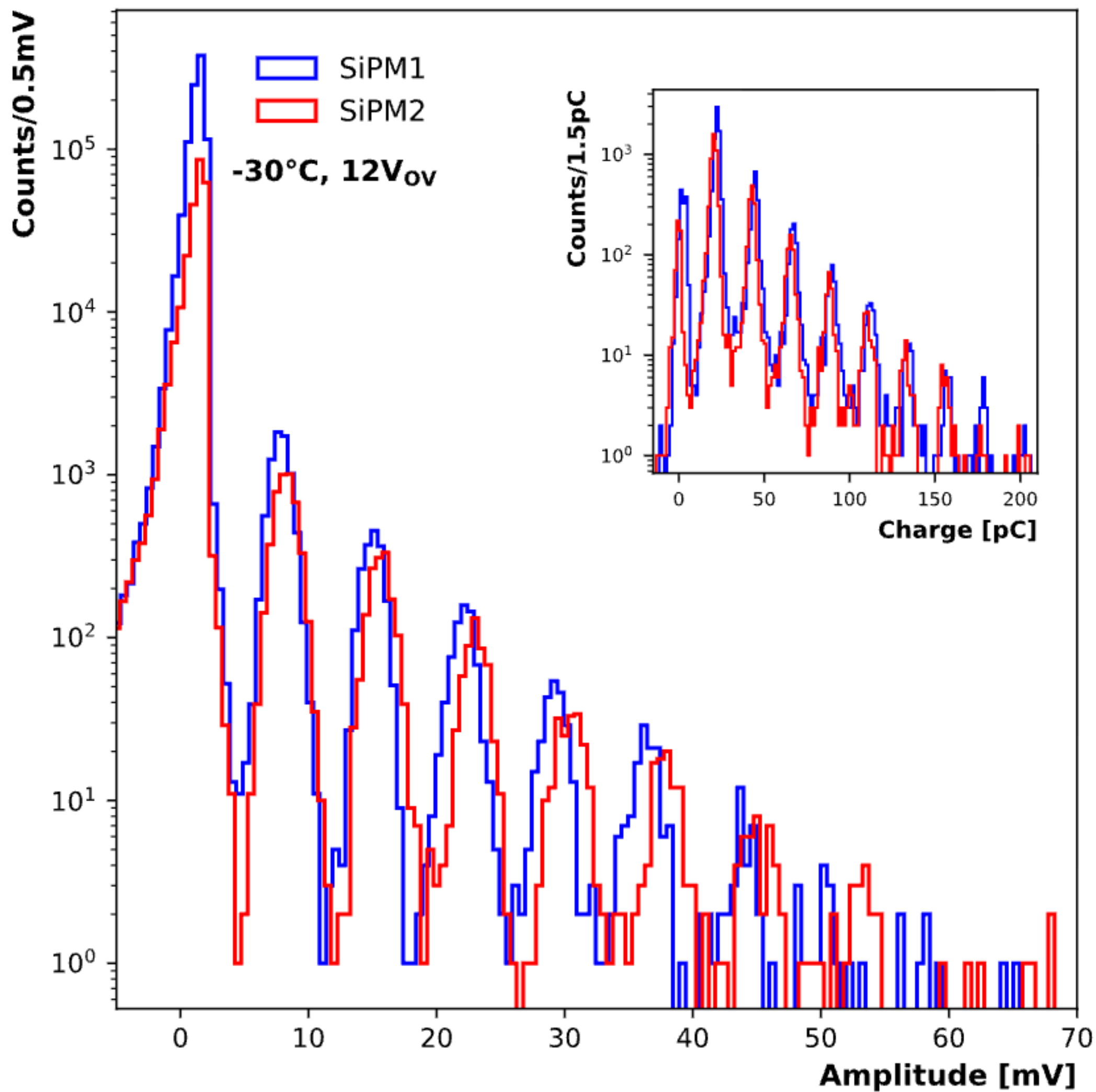
- V_{bd} stable to $1.1 \times 10^{10} n_{eq}/\text{cm}^2$ fluences
- DCR & R_{SPE} degraded significantly, partial recovery via thermal annealing,
- Residual damage attributed to stable cluster defects remaining within silicon lattice

Back-up

- SiPM signal amplified using Mini Circuits ZFL-1000LN+ low-noise amplifier

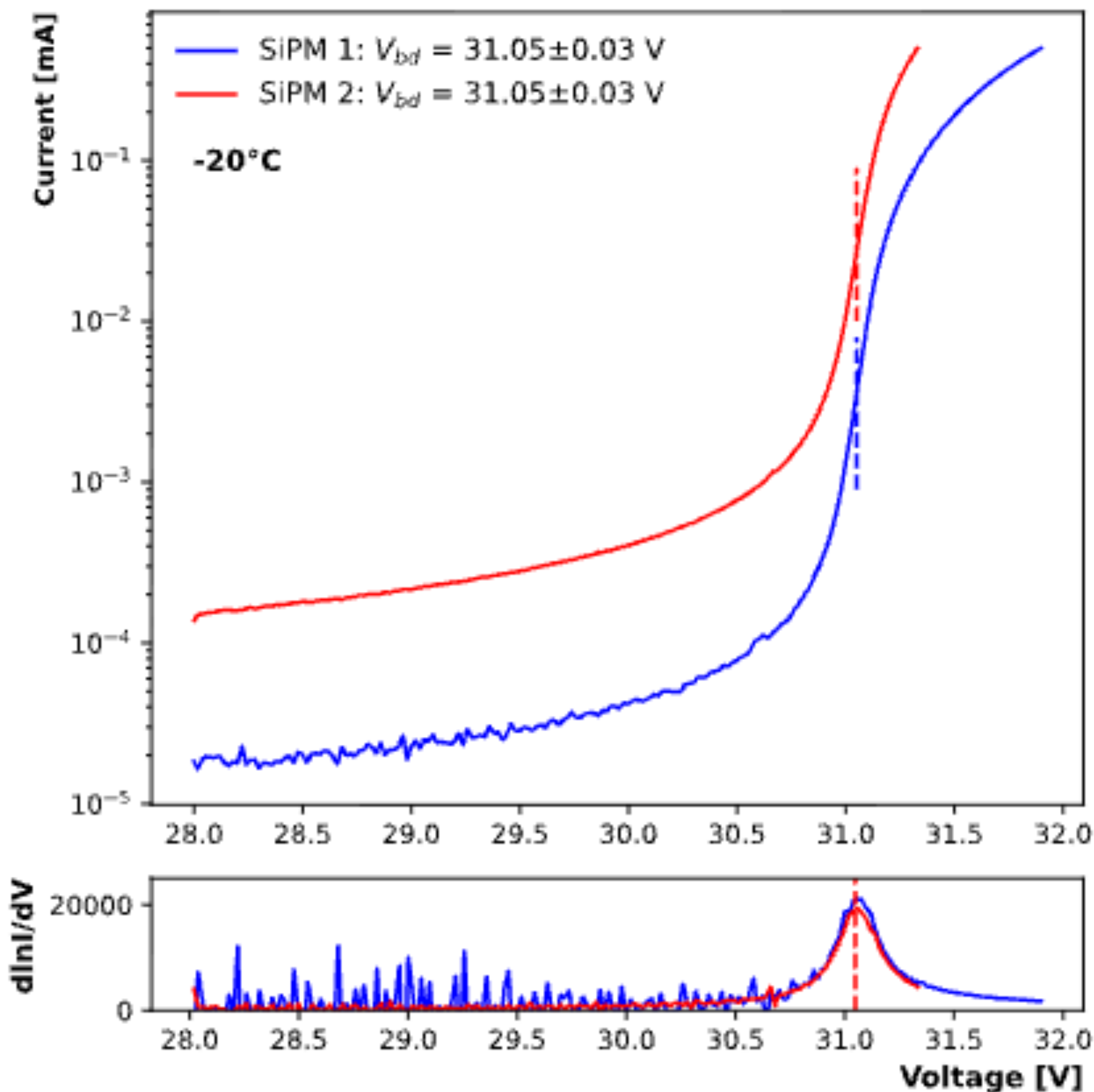


Single photon resolution



IV curves

Estimating breakdown voltage

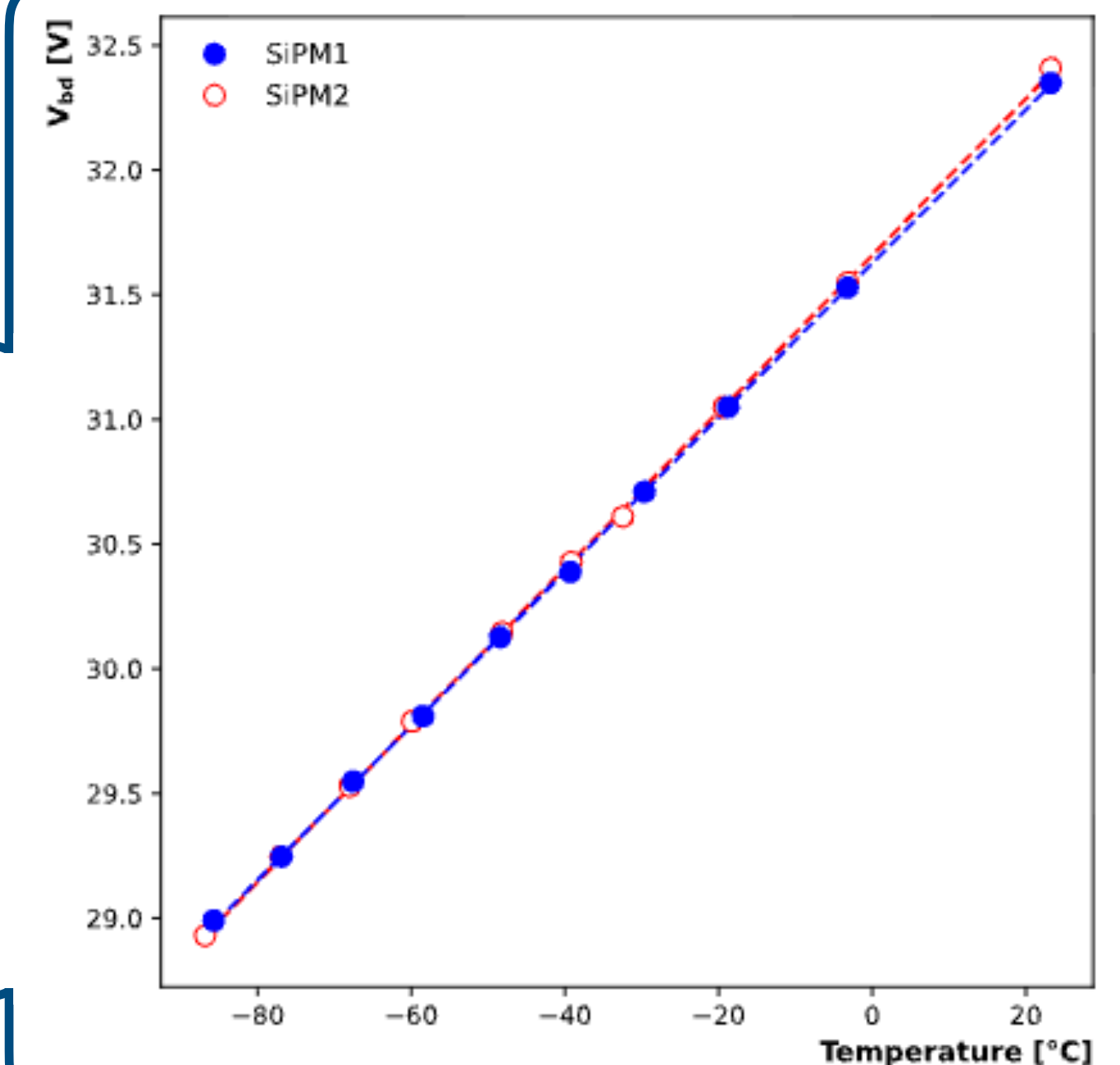
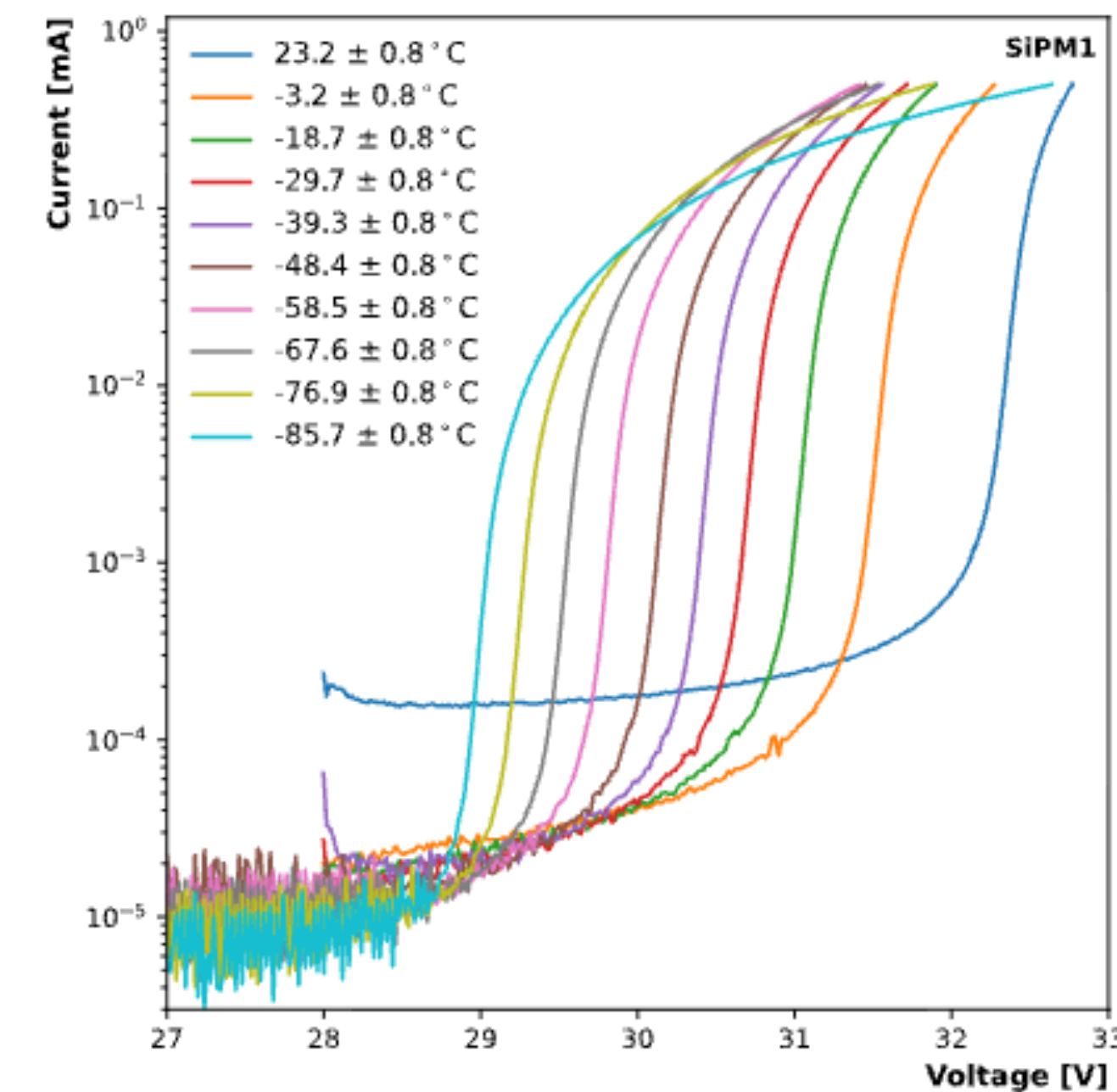


For each temperature:

- SiPM bias voltage incremented whilst current draw recorded
- Breakdown voltage (V_{bd}) estimated using maximum of $\frac{d\ln I}{dV}$

See expected behaviour: V_{bd} increases with temperature

- Temperature coefficient: $(31.2 \pm 0.3) \text{ mV}/^{\circ}\text{C}$ [manufacturer spec: $30 \text{ mV}/^{\circ}\text{C}$]



Radiation hardness

Leakage current & breakdown voltage

Observations:

- Leakage current increases substantially post-irradiation
 - $3 \times$ reduction at $8V_{OV}$ after 23.5 annealing cycles
- No change in SiPM breakdown voltage across fluence range
- Doping profile & junction geometry unaffected by radiation damage

