Studies of SiPM at Cryogenic Temperatures

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Overview
- Introduction
- Experimental methods
- Measurements and discussion
- Conclusions

Motivations

This talk: characterization of FBK SIPM in the range 50K<T<320K

1) junction forward and reverse (breakdown) characteristics
2) gain, dark current, after-pulses, cross-talk
3) photon detection efficiency (PDE)

Improved SiPM performances at low temperature:

1) lower dark noise by orders of magnitude
2) lower after-pulsing probability (down to ~100K)
3) higher PDE (down to ~100K, depending on λ)
4) higher timing resolution
5) better $V_{breakdown}$ stability (w.r.t. to variations of T)

→ SiPM is an excellent alternative to PMT at low T
even more than at room temperature !!!

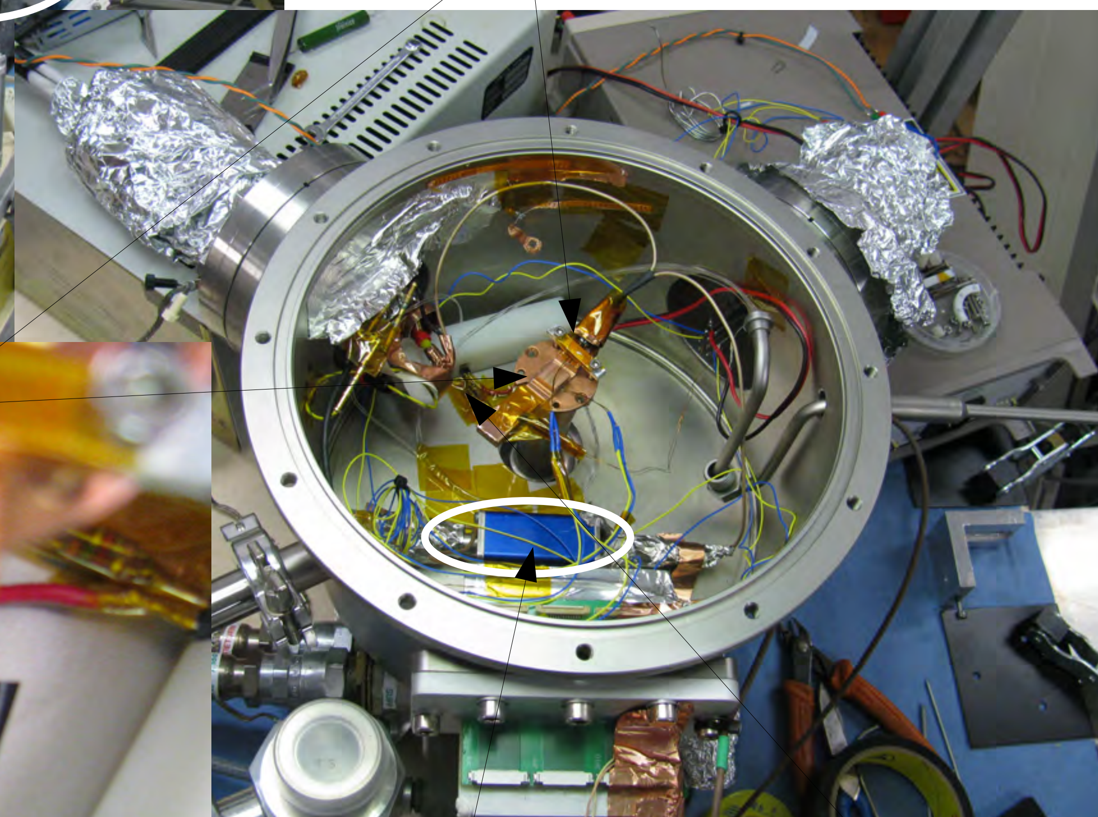
Experimental Setup

Vacuum vessel (P~10^{-3} mbar)

Alogen Lamp

Monocromator (200-900nm)

Quartz filers to
Calibrated Photodiode (outside)
and to **SiPM** (inside vessel)

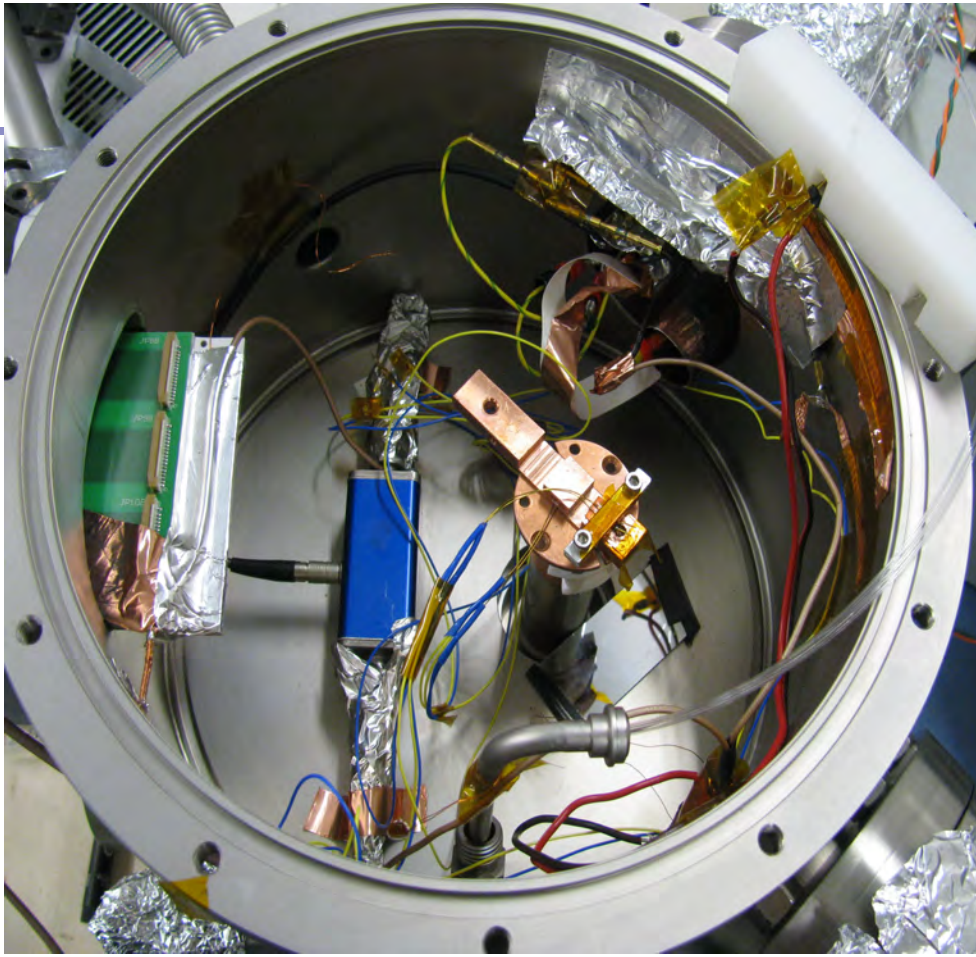


Cryocooler
(50K<T<300K)

Amplifier

UV LED (380nm)
+ fibers to SiPM

Experimental setup



Temperature control/measurement

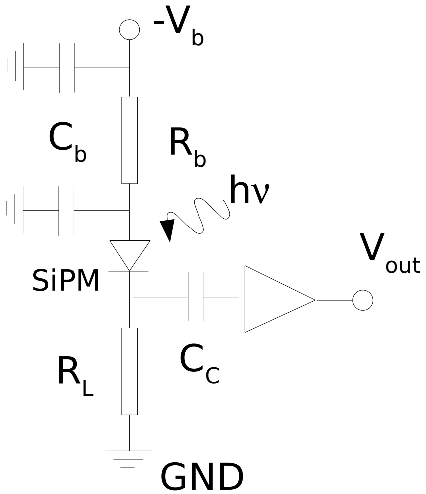
- Cryo-cooler + heating with low R resistor
- thermal contact (critical) with cryo-cooler head: SIPM within a copper rod
- T measurement with 3 pt100 probes
- Measurements on SiPM carried after thermalization (all probes at the same T)
- check junction T with forward characteristic

Voltage/Current bias/measurement

- Keytley 2148 for Voltage/Current bias/readout

Pulse measurement

- Care against HF noise → feed-throughts !!!
- Amplifier Photonique/CPTA (gain~30, BW~300MHz)

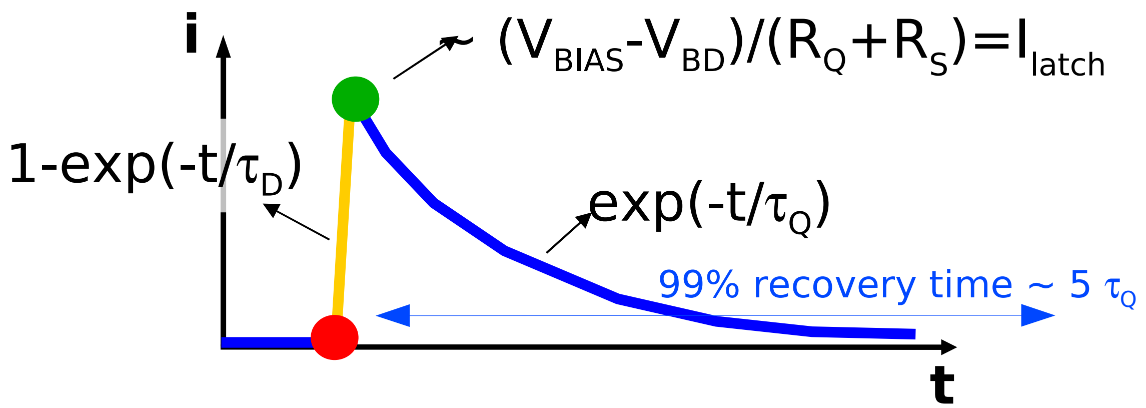


SiPM samples

- FBK SiPM runII – 1mm^2 (Vbr~33V, fill factor~20%)

Gain and pulse shape

If R_Q is high enough the internal current decreases at a level such that statistical fluctuations may quench the avalanche



The leading edge of the signal is much faster than trailing edge:

1. $\tau_D = R_S C_D << R_Q C_D = \tau_Q$
2. turn-off mean time is very short (if R_Q is sufficiently high, I_{latch} ~ 10μA)

Recovery time:

increases at low T due to polysilicon R_Q while C_D is independent of T

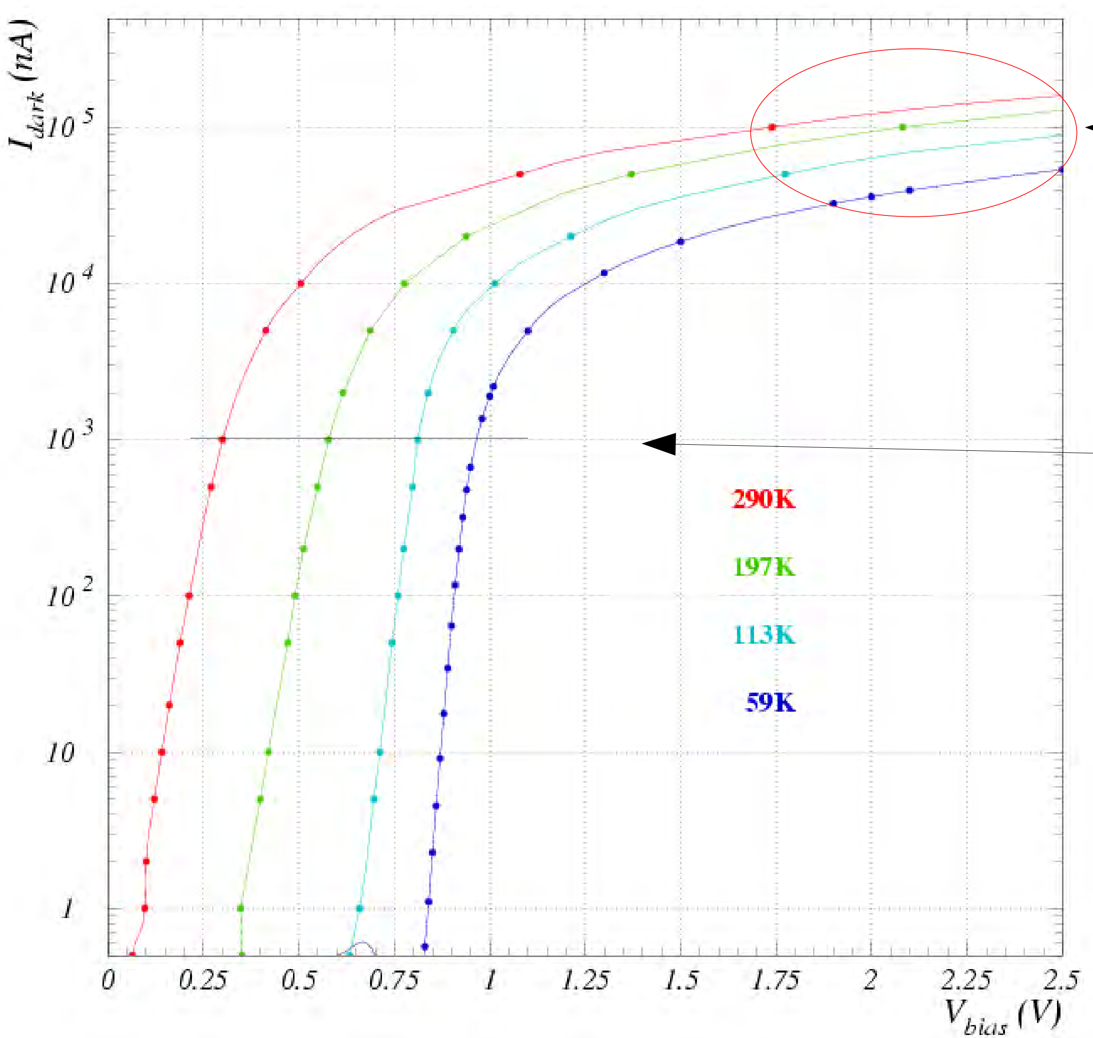
Gain~C_D ΔV → independent of T

at fixed Over-Voltage (ΔV)

I-V measurements: forward bias

1 **Forward current** $J_F \sim \exp(V_d \frac{q}{\eta k T})$

Diffusion dominating: η → 1
Recombination dominating: η → 2



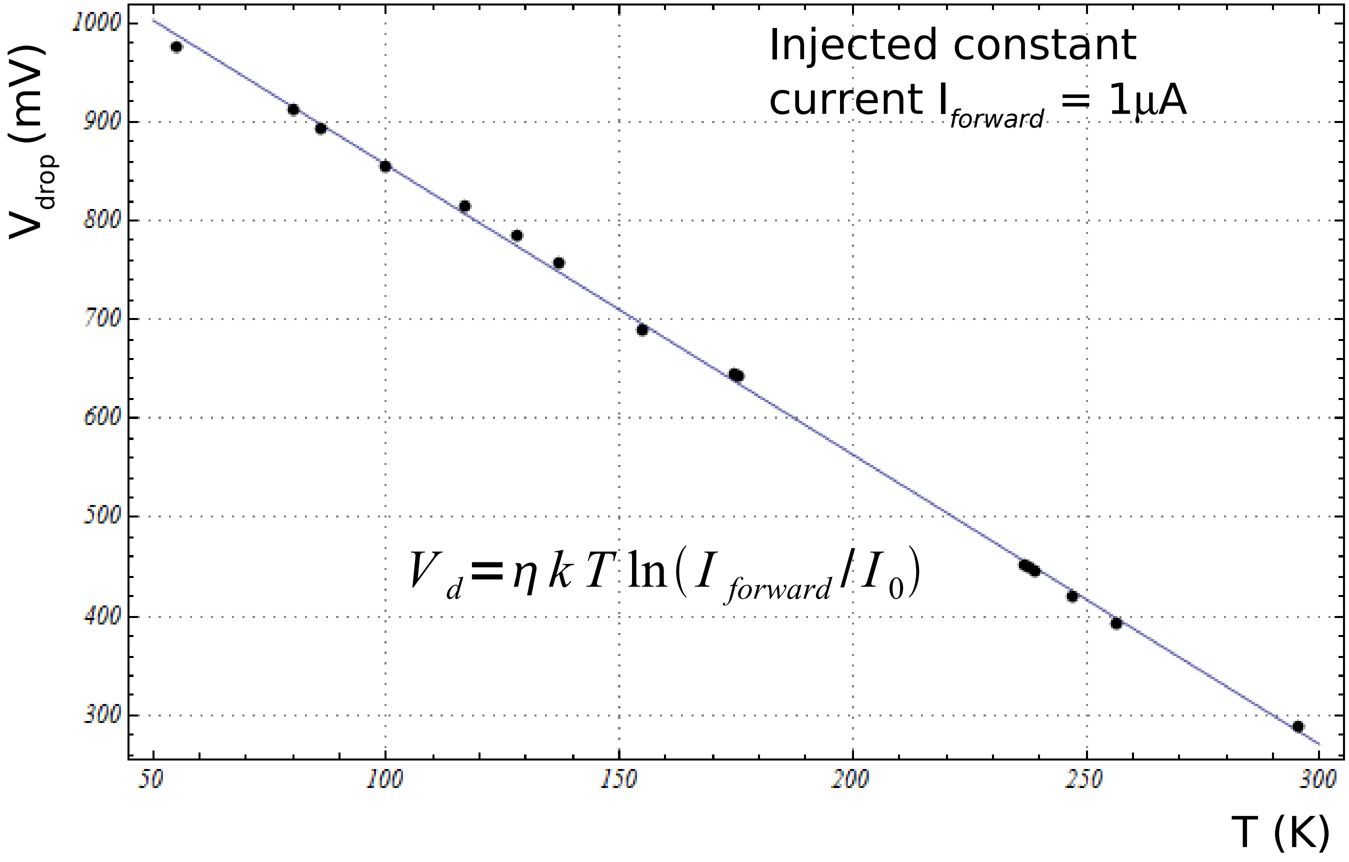
2 **Ohmic** behavior at high current

Linear fit → $R_{series} \sim R_Q / N_{cells}$

3 **Voltage drop** (V_d) increases with T decreasing (e.g. at 1μA)

I-V measurements: forward bias

Voltage drop at fixed forward current → precise **measurement of junction T**

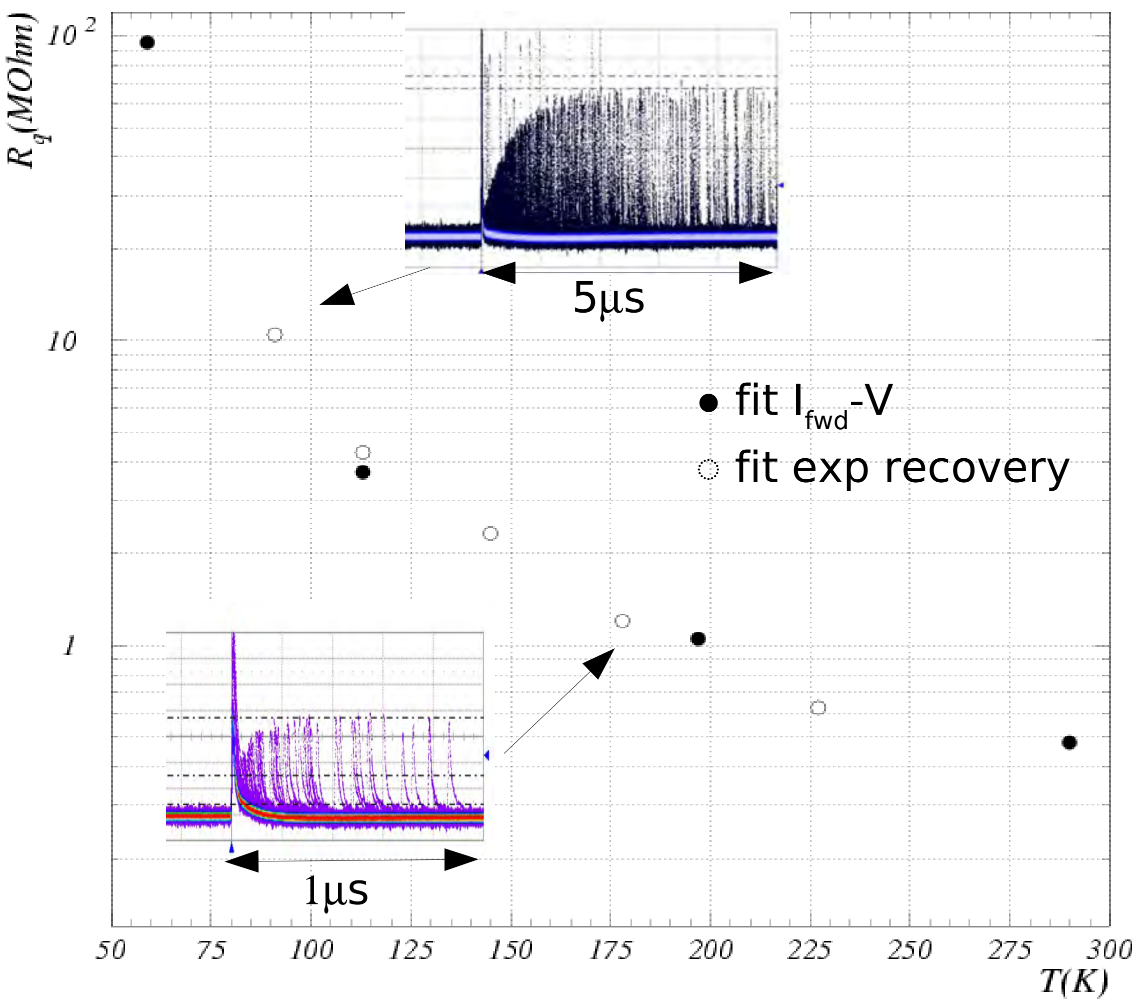


- linear dependence with slope $dV_{drop}/dT|_{1\mu A}$ ~ 3mV/K
- precise calibration/probe for junction Temperature

Series Resistance vs T

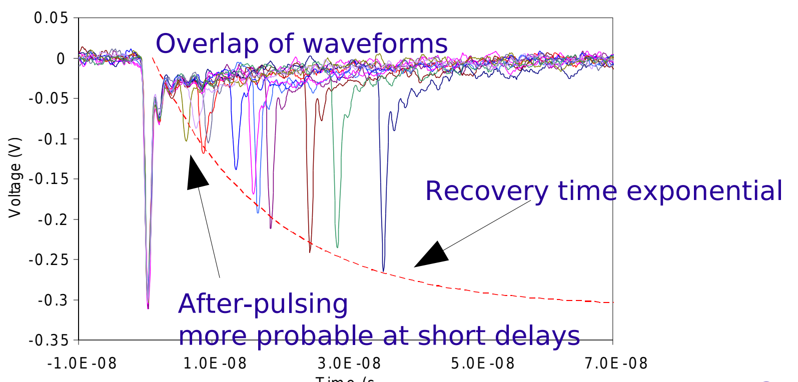
1) Fit at high V of forward characteristic → **measurement of series resistance R_s**

2) Exponential recovery time (afterpulses envelope) → **measurement of R_s**

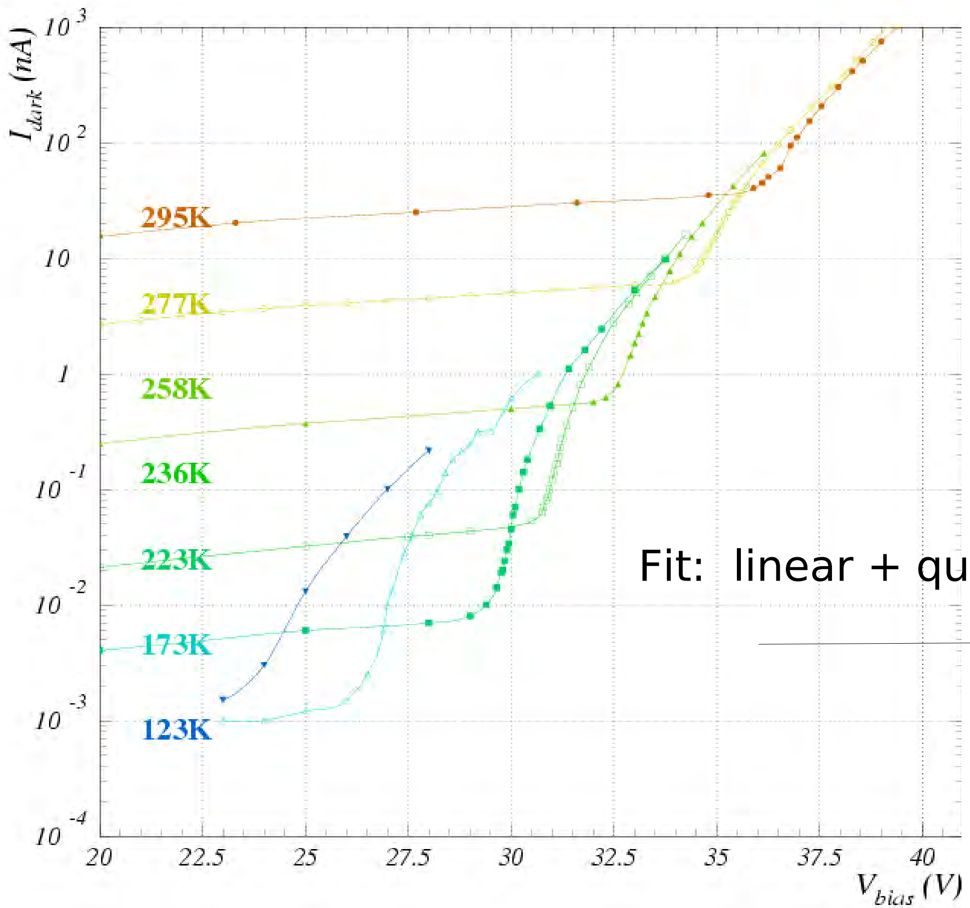


The two kinds of measurement are consistent
→ **dominant effect from quenching resistor R_Q**

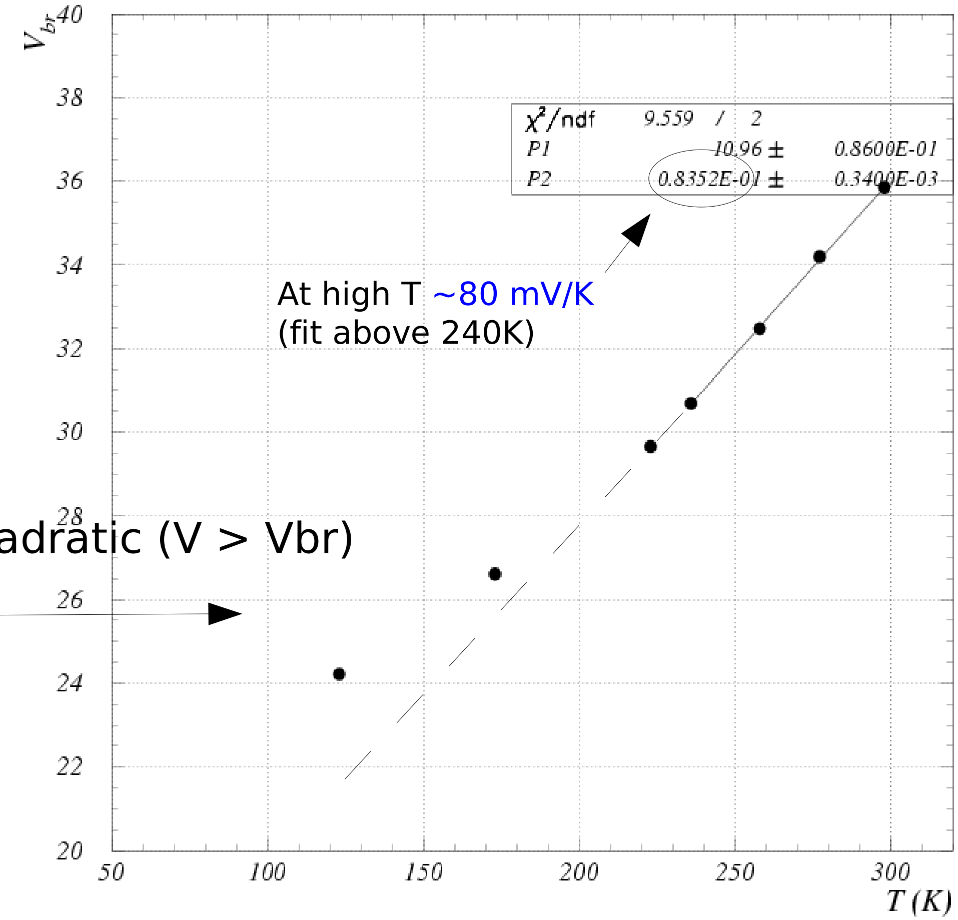
NOTE: afterpulses envelope



I-V measurements: reverse bias



$V_{breakdown}$ vs T

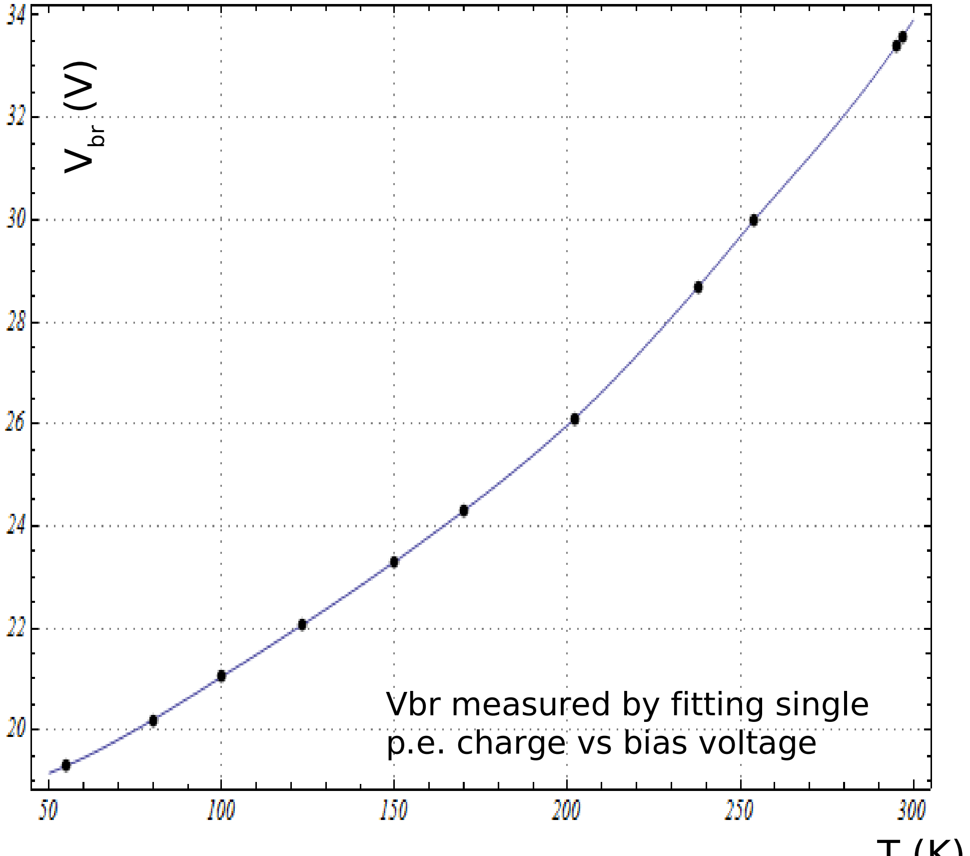


At high T ~80 mV/K
(fit above 240K)

Fit: linear + quadratic (V > Vbr)

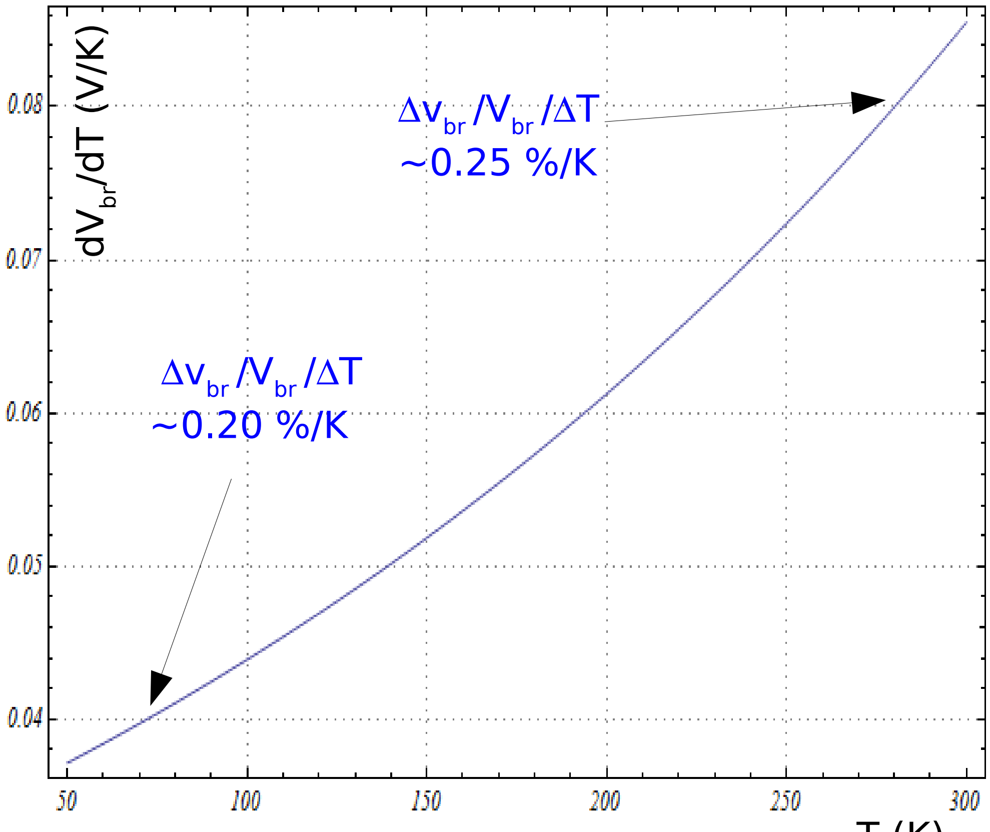
Avalanche breakdown voltage decreases due to increased carriers mobility at low T

V breakdown vs T



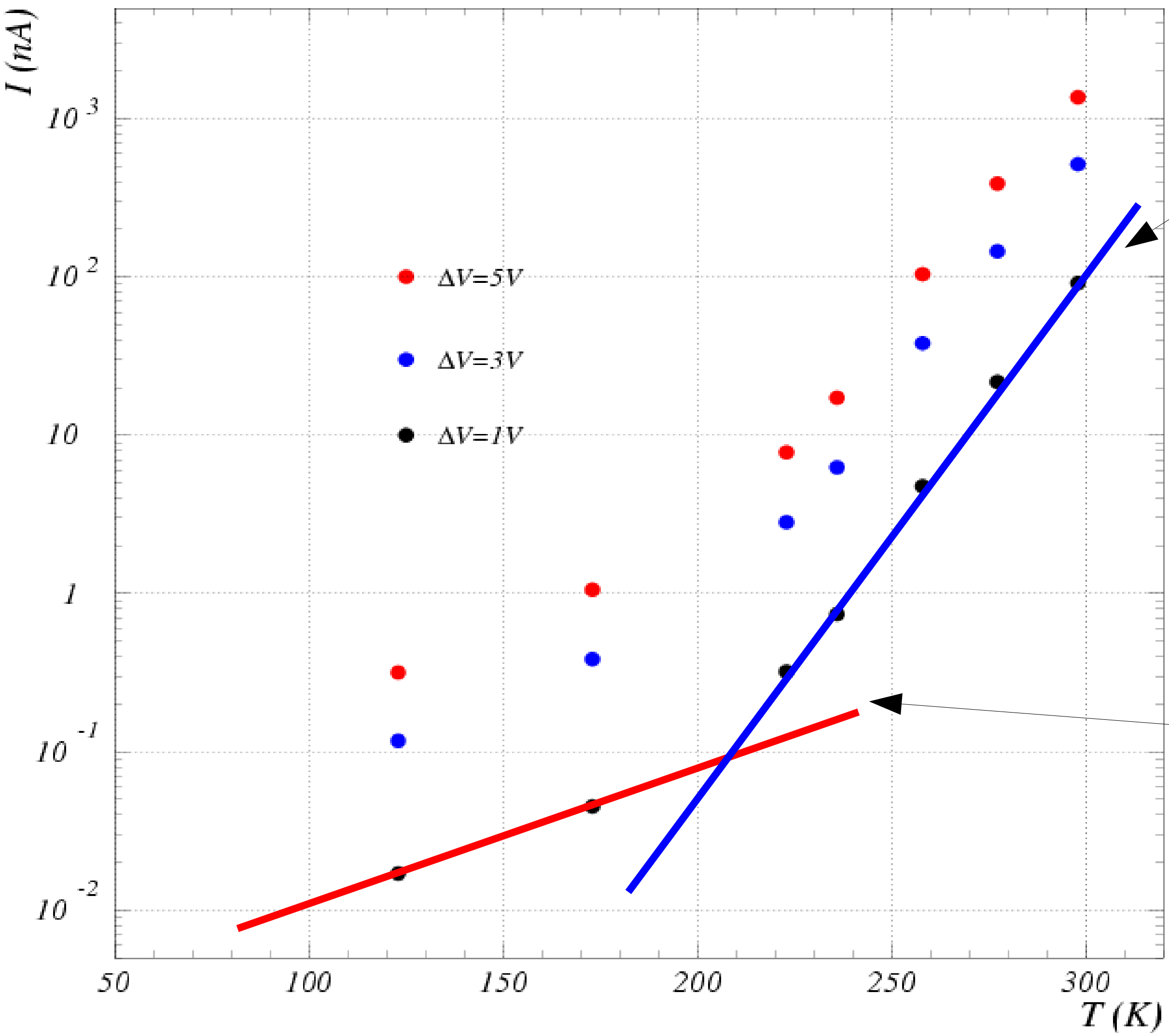
Consistent with Baraff model for doping profile of FKB SiPM

Temperature coefficient



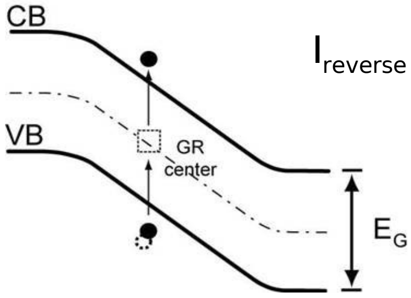
Improved stability at lower T

Dark current vs T at constant gain (i.e. fixed ΔV)



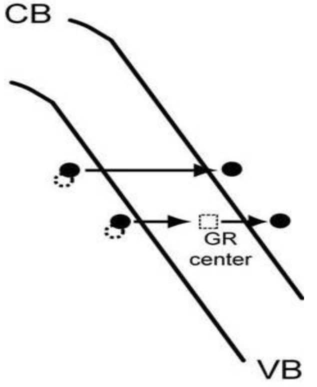
Main noise mechanisms:

1) Gereration/Recombination noise (SHR field enhanced)



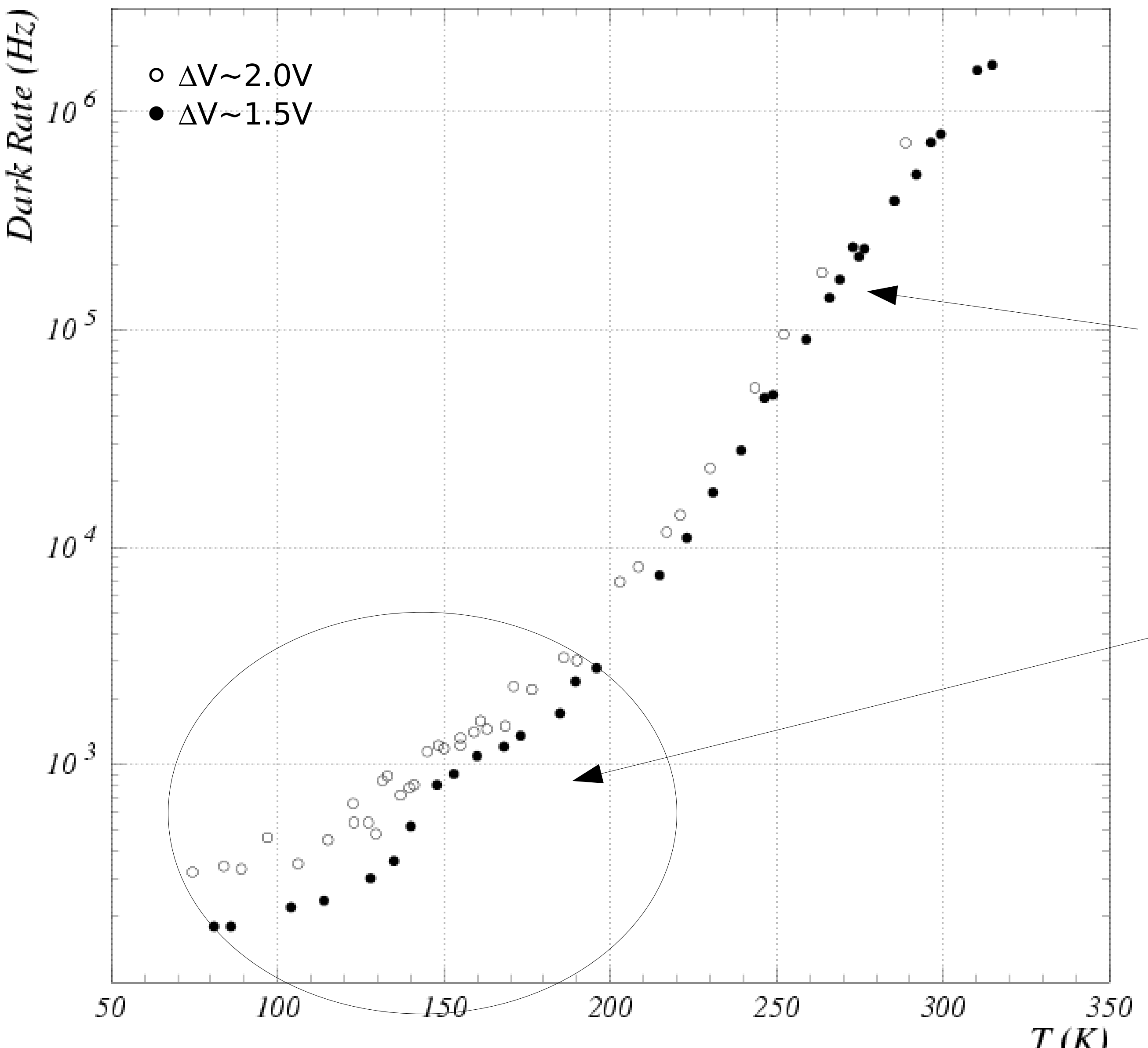
$$I_{reverse} \propto T^{1.5} \exp\frac{-E_g}{K_B T}$$

2) Band-to band Tunnel noise (strong dependence on the Electric field profile)



Tunnel noise dominating for T<200K (FBK devices)

Dark counts rate vs T at constant gain (i.e. fixed ΔV)

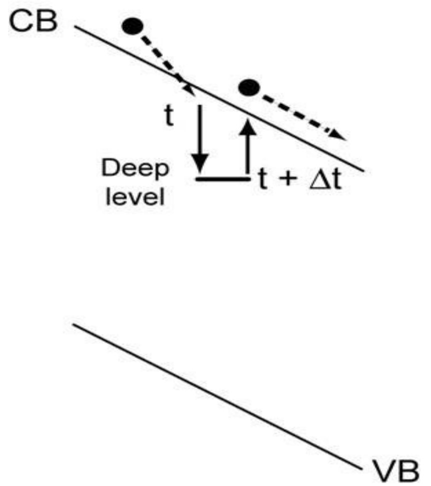


Measurement: **rate of ≥1p.e.** at fixed gain (i.e. ~fixed ΔV)

Activation energy
Eg~0.358eV

Two tunneling mechanisms ?
to be understood

After-pulsing



Carrier trapping and delayed release

$$P_{after-pulse}(t) = P_c \cdot \frac{\exp(-t/\tau)}{\tau} \cdot P_{01} \propto \Delta V^2$$

P_{01} : trigger probability
∝ ΔV(t) (over-voltage, recovery)

τ : trap lifetime
depends on trap level position

quadratic dependence on ΔV

P_c : trap capture probability
∝ carrier flux (current) during avalanche ∝ ΔV (over-voltage)
∝ N traps

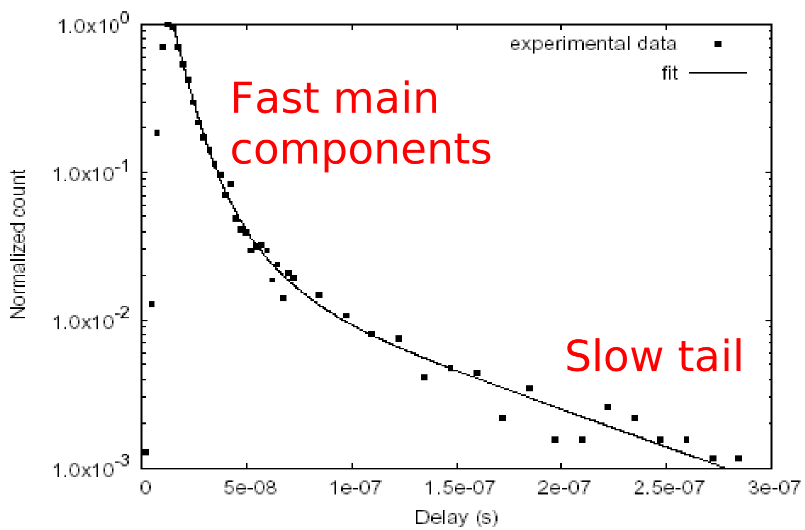
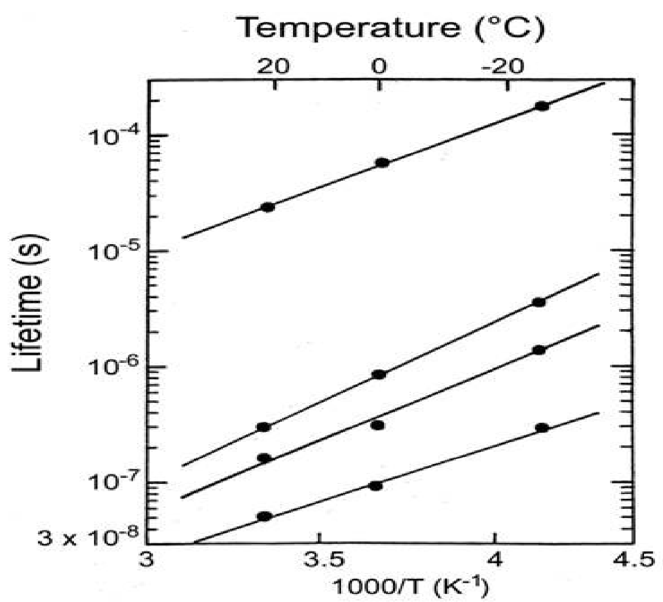


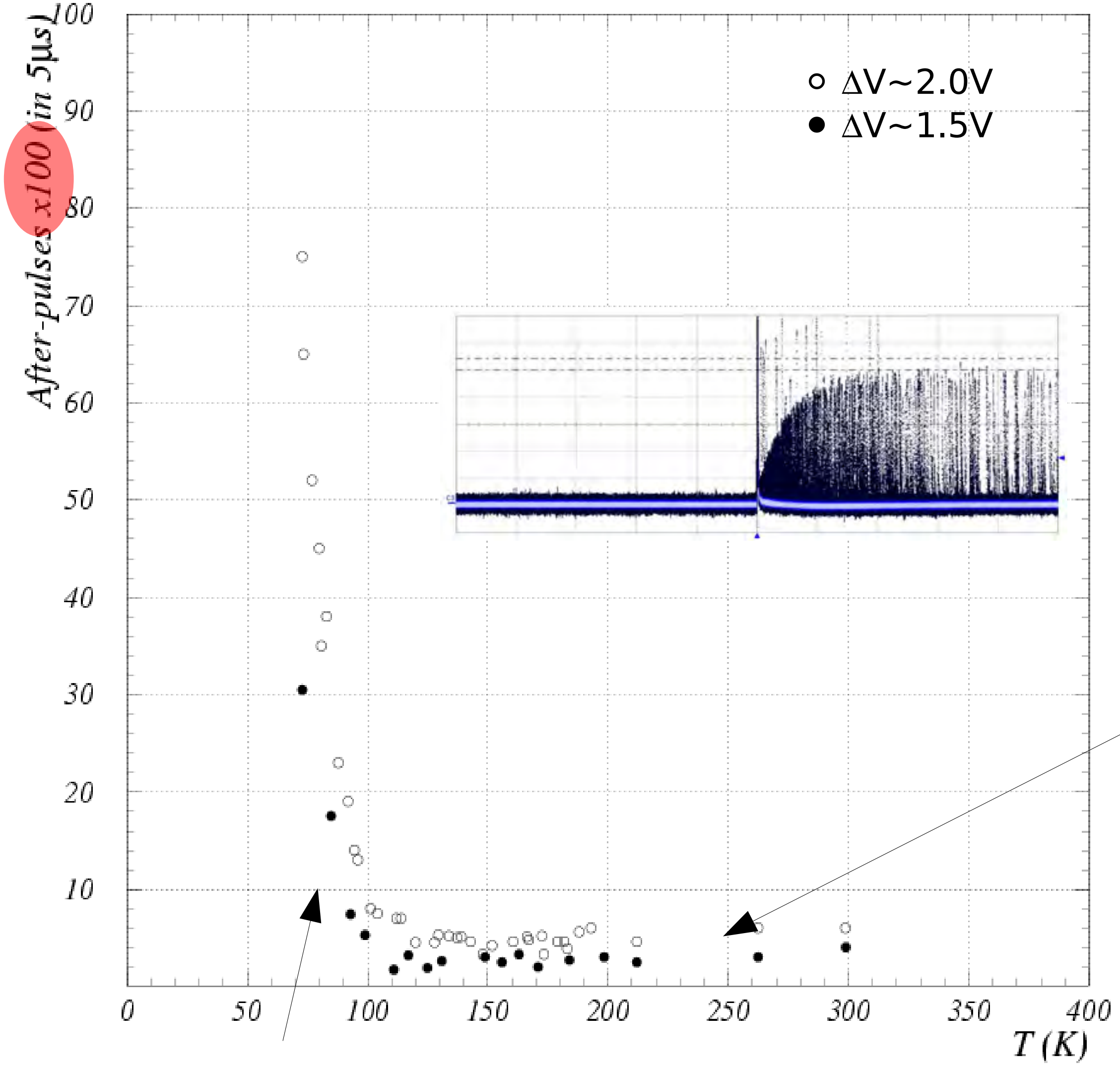
Fig. 10. Spectrum of the delay time from the primary pulse to the after-pulse.



S.Cova, A.Lacaita, G.Ripamonti, IEEE EDL (1991)

It can be reduced to % in a wide ΔV range... at 300K

After-pulses vs T (constant gain, ie ΔV)



Measurement:
of **average number of after-pulses** counted in the **5μs time window** following the trigger (1 p.e.) at fixed gain (i.e. ~fixed ΔV) (dark noise subtracted)

- Few % at room T
- quite constant down to ~120K

T decreasing: increase of characteristic time constants of traps (τ_{traps}) is compensated by increasing cell recovery time (R_Q)

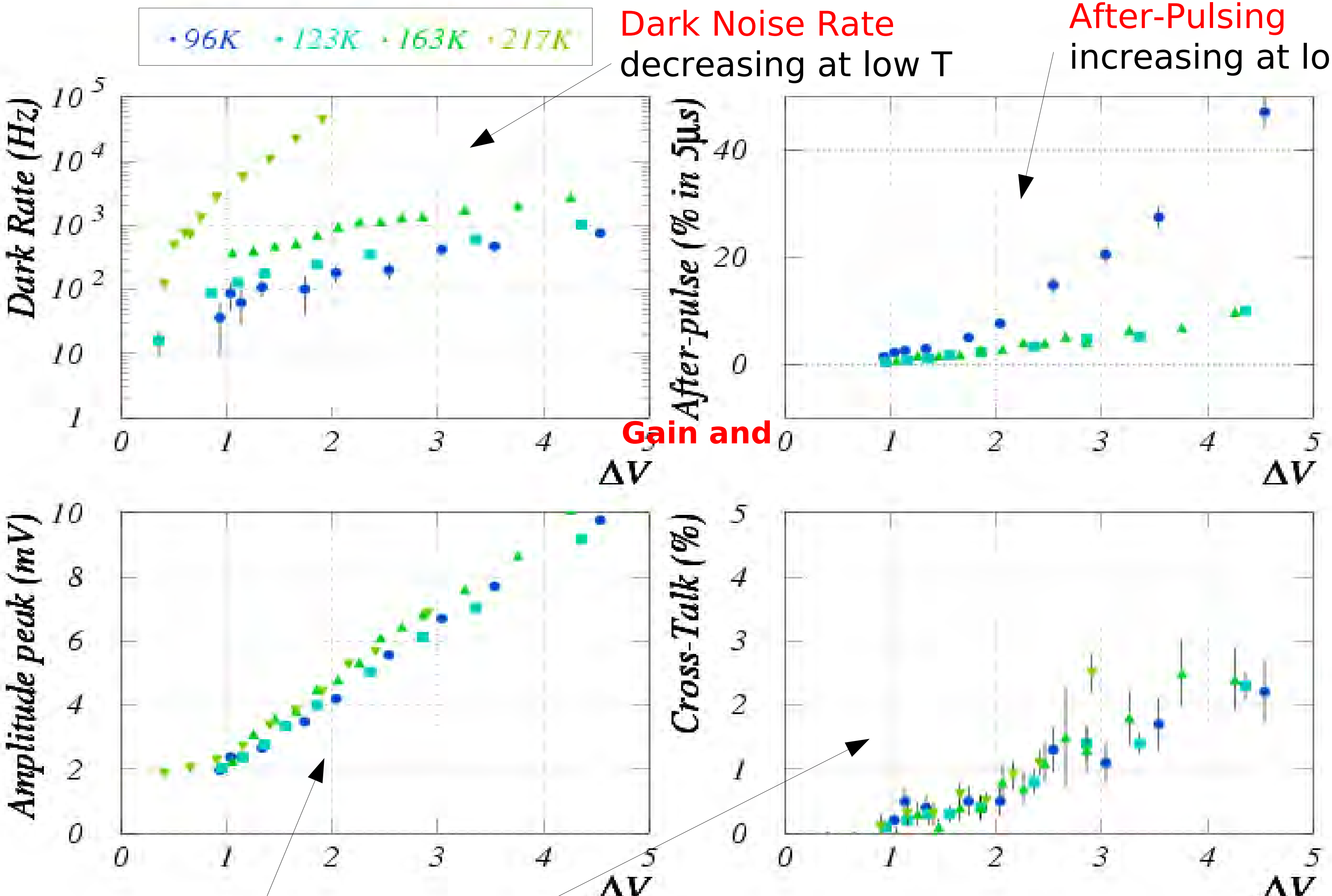
- Several % below 100K

T<100K: new traping centers active (to be studied in more detail)

ΔV scan (fixed T) – DR, AP, Gain, X-TALK

Dark Noise Rate decreasing at low T

After-Pulsing increasing at low T

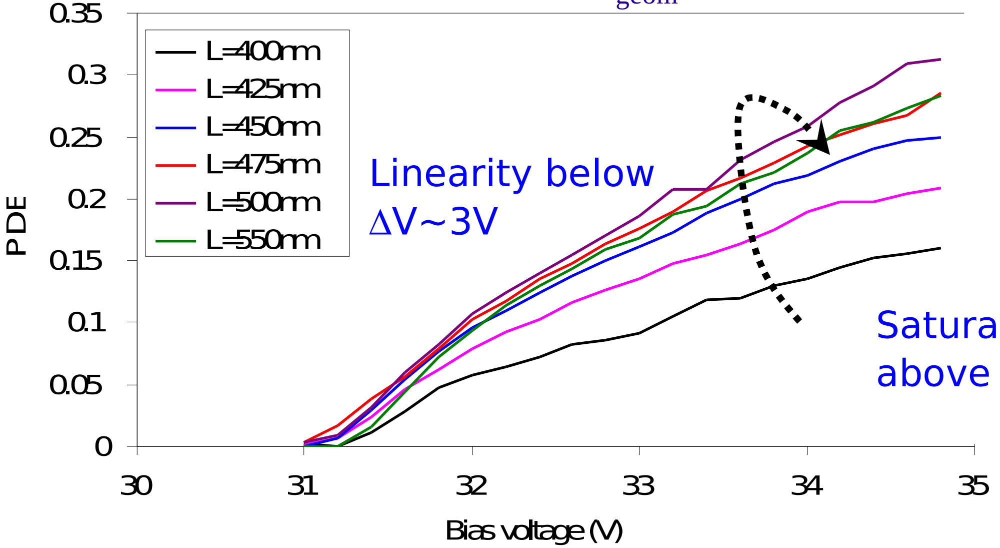


Gain and

Gain and Cross-Talk independent of Temperature

PDE vs ΔV and λ (room T)

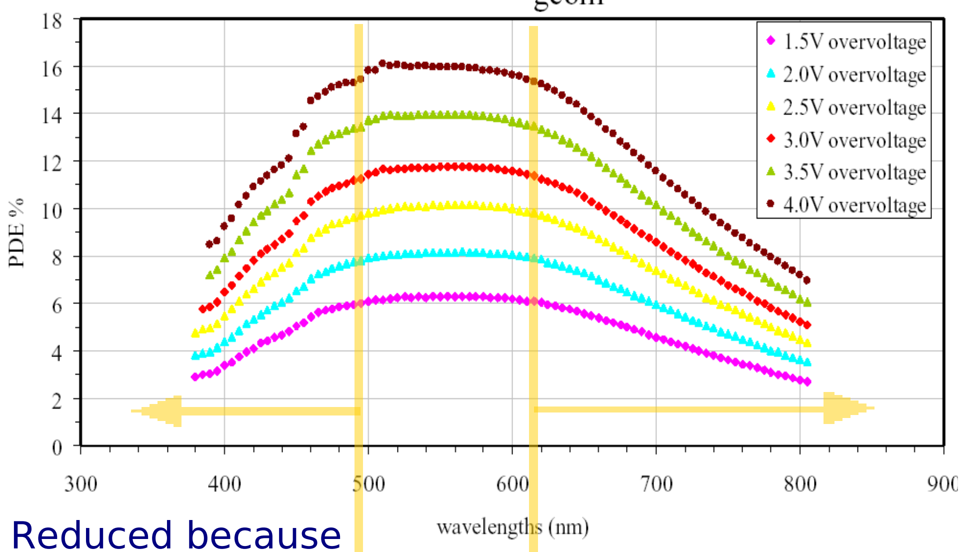
device with ε_{geom} ~50%



Saturation starts above ΔV~3V

PDE dependence on ΔV (at different λ)

device with ε_{geom} ~ 22%



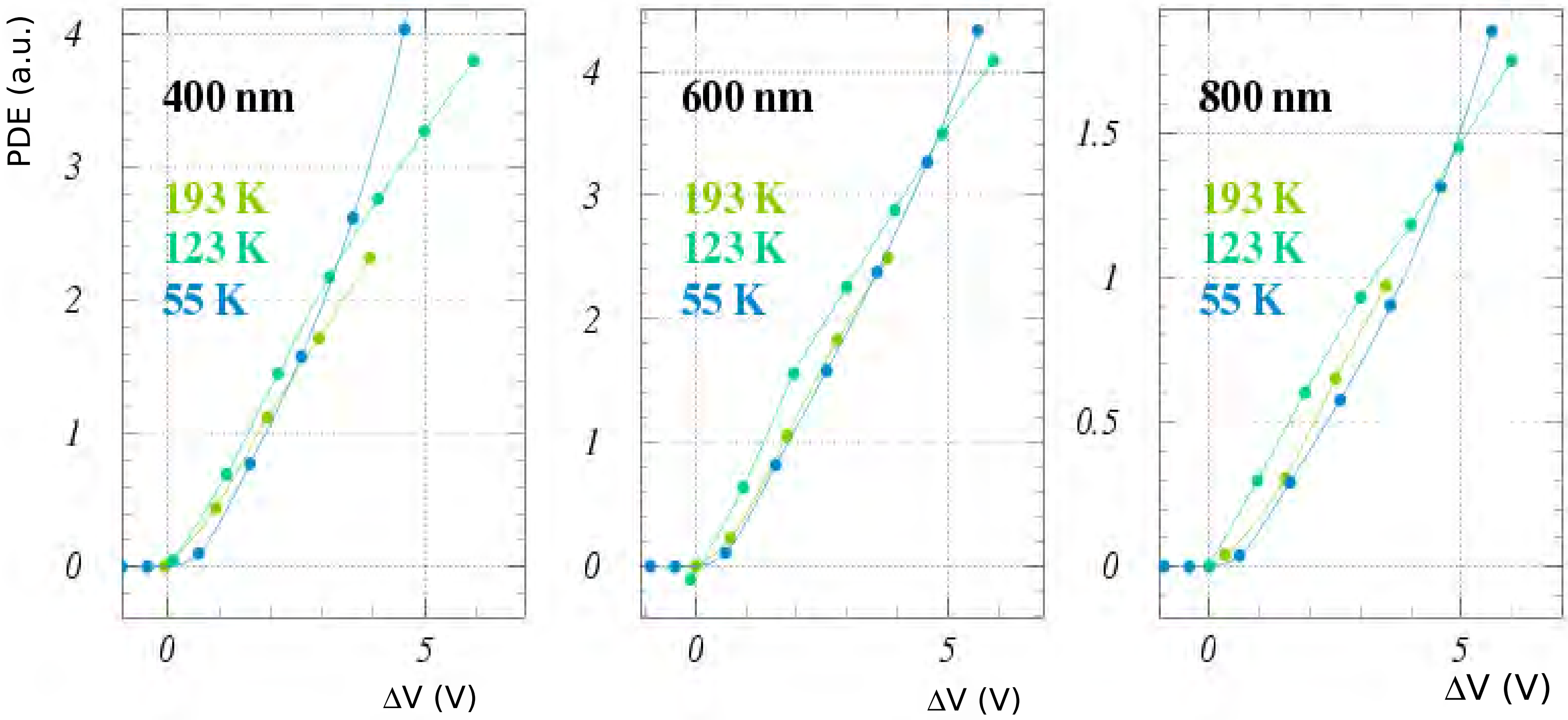
PDE dependence on λ (at different ΔV)

Reduced because avalanche triggered by holes (and ARC)

Reduced because low QE

PDE at various λ - ΔV scan (at constant T)

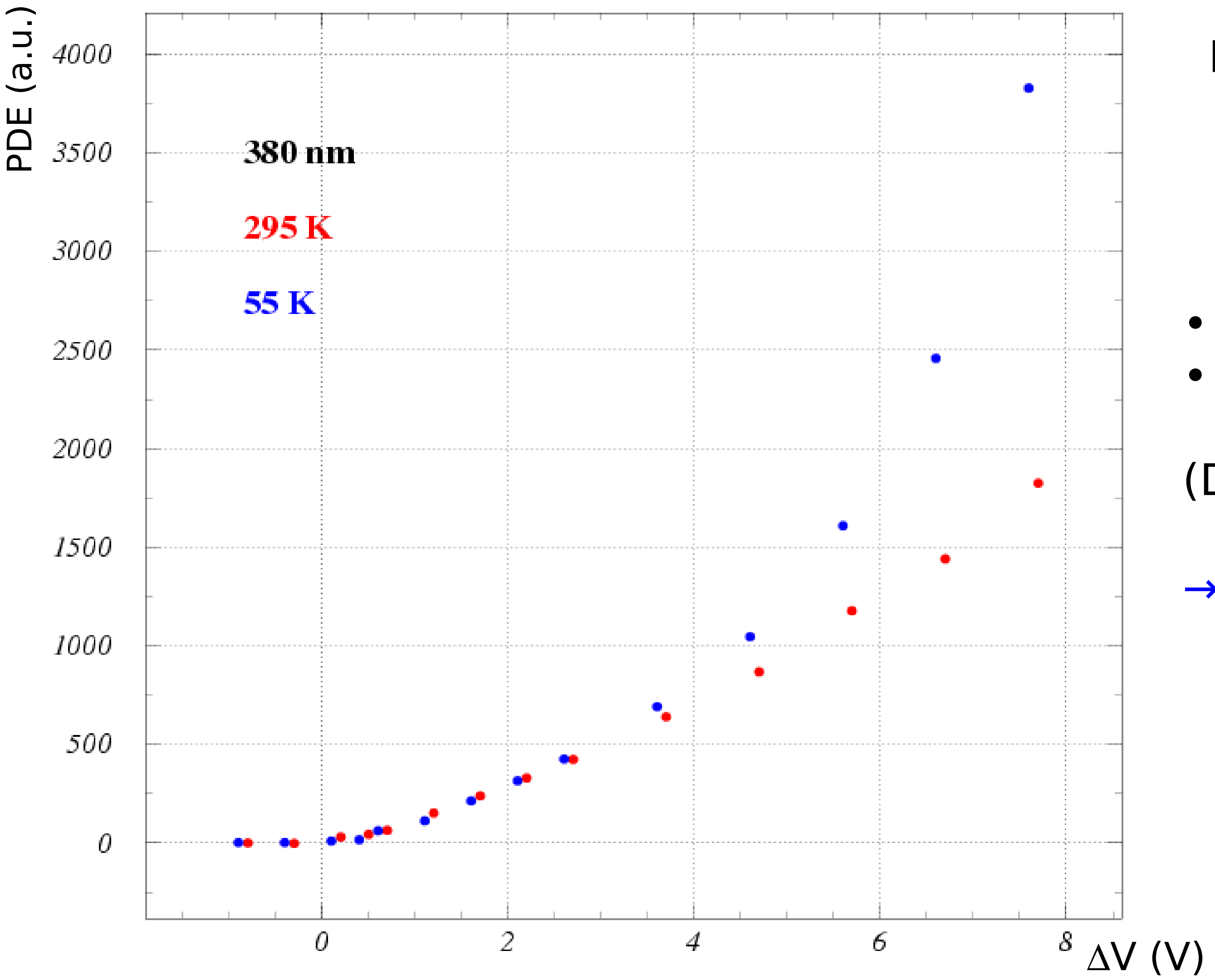
PDE vs ΔV measured as Current/Gain → PDE (a.u.) ≡ I_{SiPM} / I_{calib} / ΔV
Normalization to calibrated photo-diode current (not absolute # of photons)



- 193K and 123K measurements not affected by after-pulses → saturation visible
- 55K affetcted by after-pulses (not corrected; cross-talk is not subtracted too)

(Dark rate subtracted - small effect)

PDE with LED (380nm) - ΔV scan (const. T)



PDE (a.u.) $\equiv I_{SiPM} / I_{LED} / \Delta V$

- 55K affected by After-Pulses
- 295K less affected by A-P

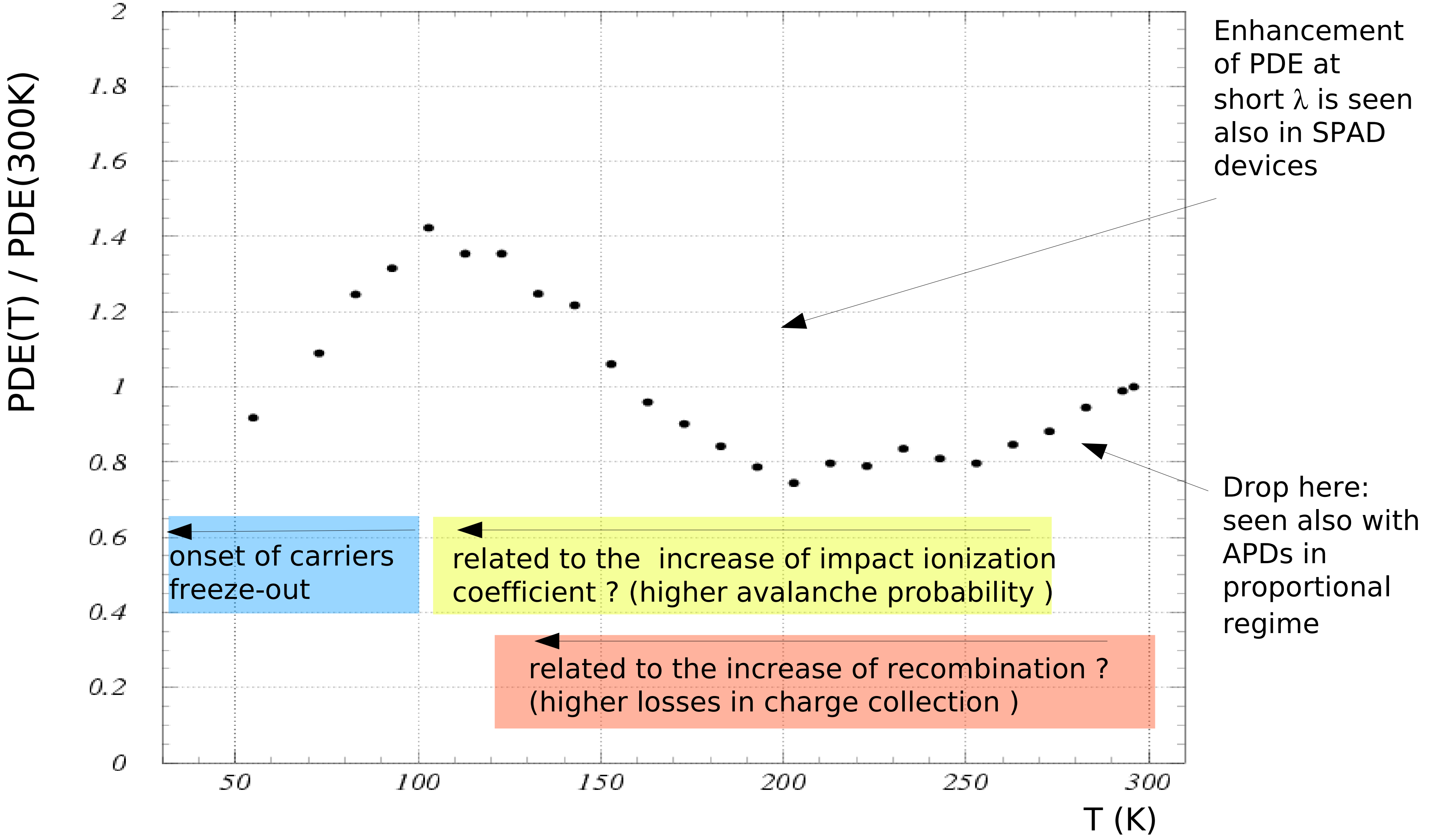
(Dark rate subtracted)

→ Slope PDE/ΔV (at small ΔV) independent of T

PDE with LED (380nm) - T scan ($\Delta V=2V$)

PDE dependence on T at fixed gain. Normalization with PDE at T=300K

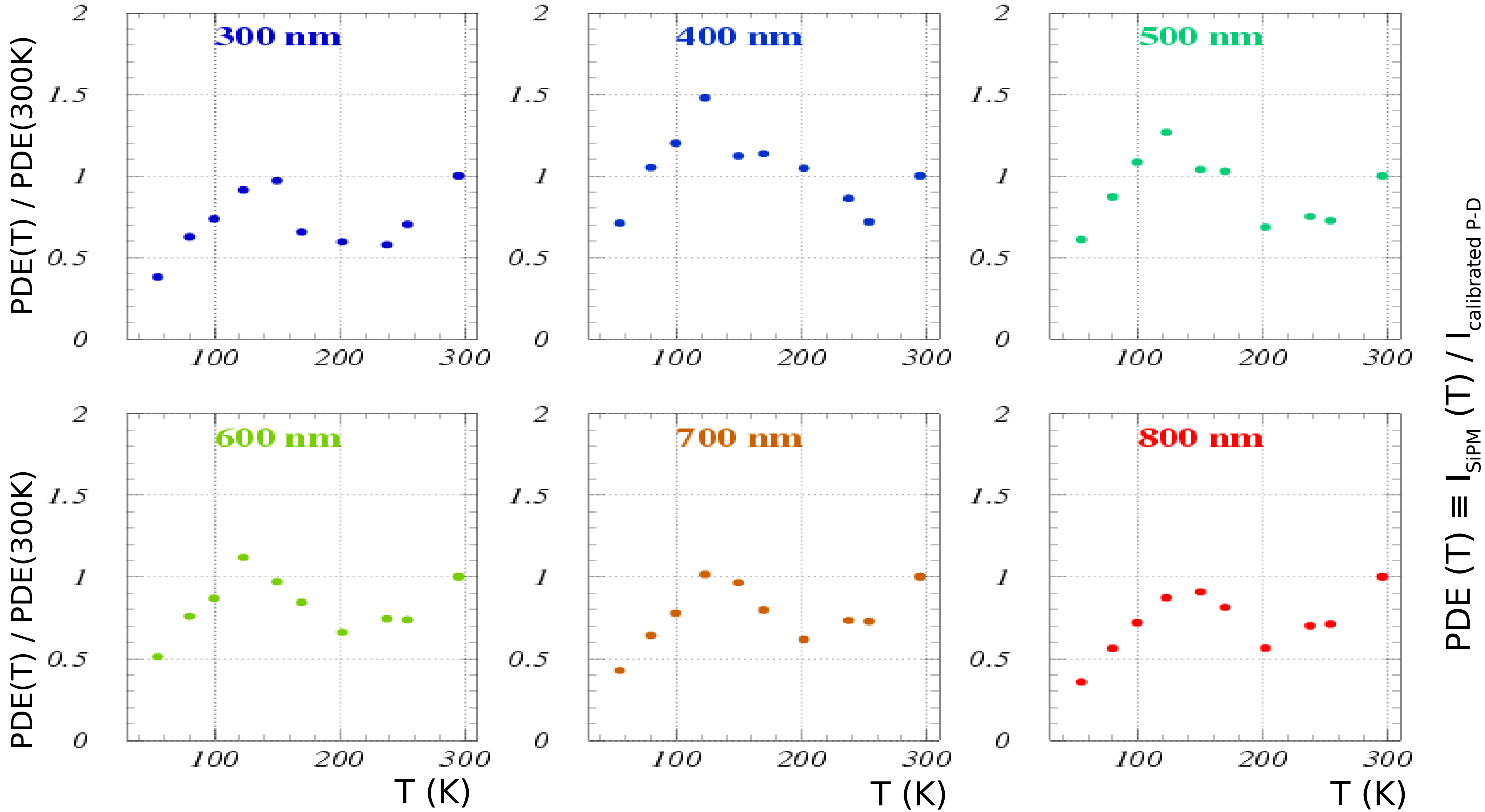
$PDE(T) \equiv I_{SiPM}(T) / I_{LED}$



Studies ongoing for better understanding this shape

PDE at various λ – T scan (ΔV =2V)

PDE dependence on T at fixed gain. Normalization with calibrated photo-diode current and with PDE at T=300K (double ratio)



- shape similar at different λ → related to properties of multiplication /recombination
- lower efficiency at low T for longer λ → due to absorption length ~ 1/T (with constant depletion width)

Conclusions

A few sets of measurements in DC and pulse mode show that SiPM behave quite well at low T:

- Breakdown V decreases non linearly with T
  → stability of devices wrt T is even better at low T
- Dark rate reduced by orders of magnitude
  → different (tunneling) mechanism below ~200K
- After-pulseing increases swiftly below 100K
- Cross-talk and Gain (detector capacity) are independent of T (at fixed Over-V.)
- PDE higher than at T room at low T for short λ

Additional measurements on-going with very short pulsed laser for

- accurately measuring after-pulsing characteristic time constant(s) vs T
- cross-checking PDE (with pulsed method)
- measuring timing resolution vs Temperature (expected to improve at low T)
- check gain resolution at low T

Studied on-going in modeling (for better understanding) After-Pulsing and PDE

In summary:
in the range 100K<T<200K SiPMs perform optimally (even better than at room T)
→ excellent alternatives to PMTs in cryogenic applications (eg Noble liquids)

Acknowledgments: E.Johnson, A.Baldini, A.Brez, G.Signorelli

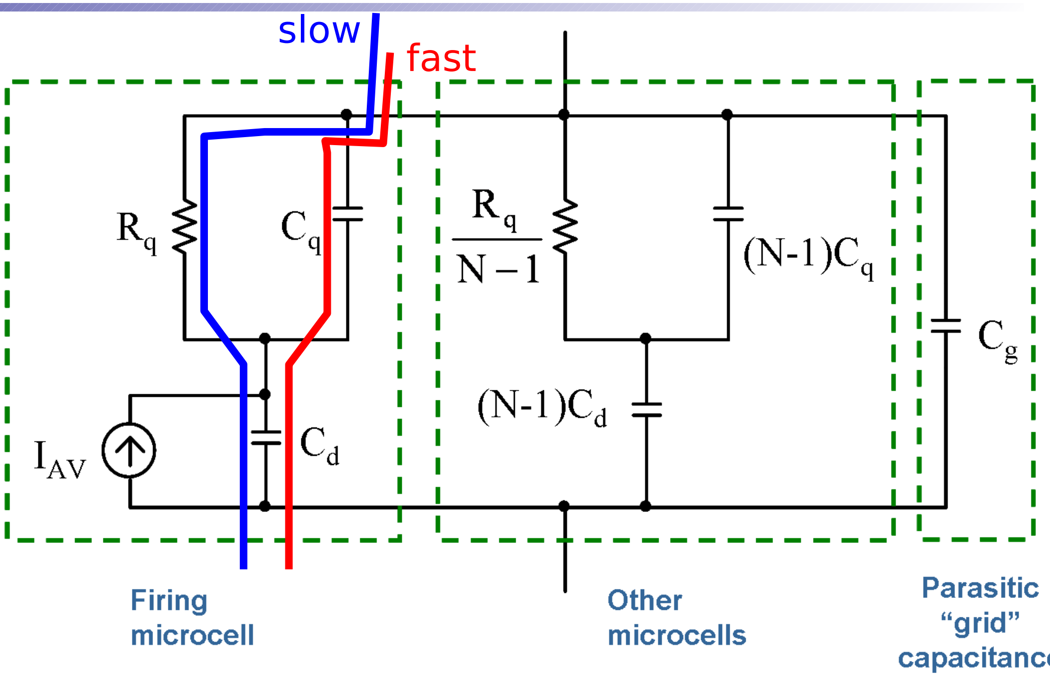
Additional material

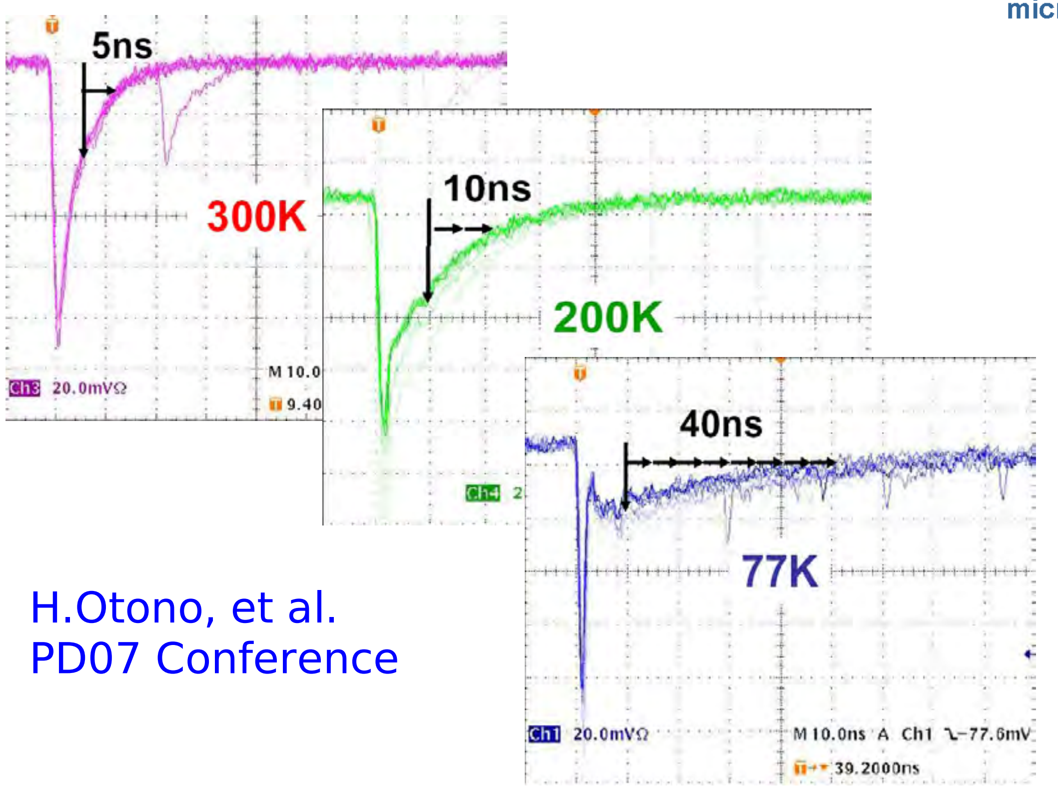
Gain and pulse shape

The SiPM equivalent circuit has two time constants:

- $\tau_F = R_{Load}\, C_{TOT}$ (fast)
- $\tau_Q = R_Q\,(C_D + C_Q)$ (slow)

F. Corsi, et al. NIMA 572(2007)





H.Otono, et al.
PD07 Conference

Waveform:

The two current components show different behavior with Temperature

(fast component is independent of T because stray C_Q couple with external R_{LOAD} independently of R_Q)

Silicon properties at low T: higher mobility

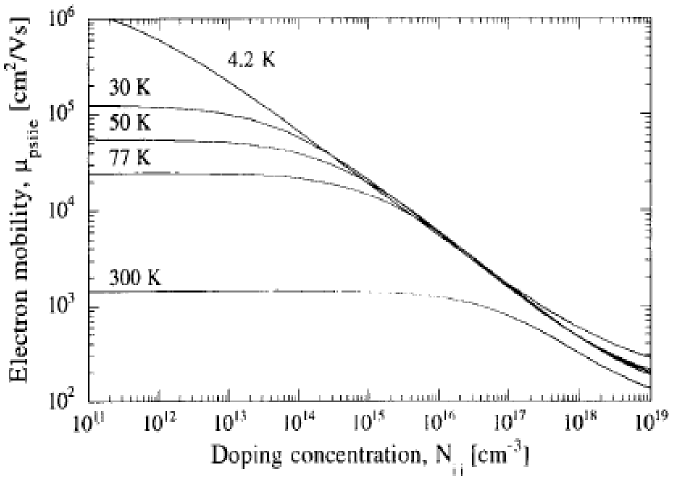


FIGURE 1.16. Calculated electron mobility due to phonon and ionized impurity scattering mechanisms. The five plots correspond to $T = 300, 77, 50, 30$, and 4.2 K.

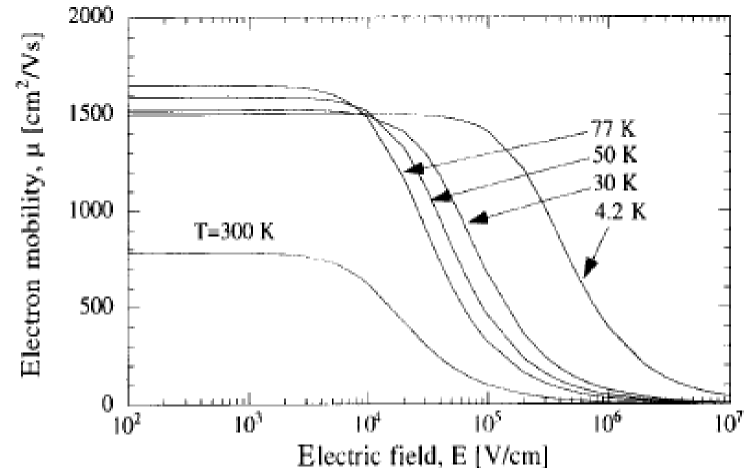


FIGURE 1.17. Calculated electron mobility, due to phonon, ionized impurities, and velocity saturation effects, as a function of the electric field for five temperatures; $N_{ii} = 10^{17}\,\mathrm{cm}^{-3}$.

Silicon propt's at low T: carriers freeze-out

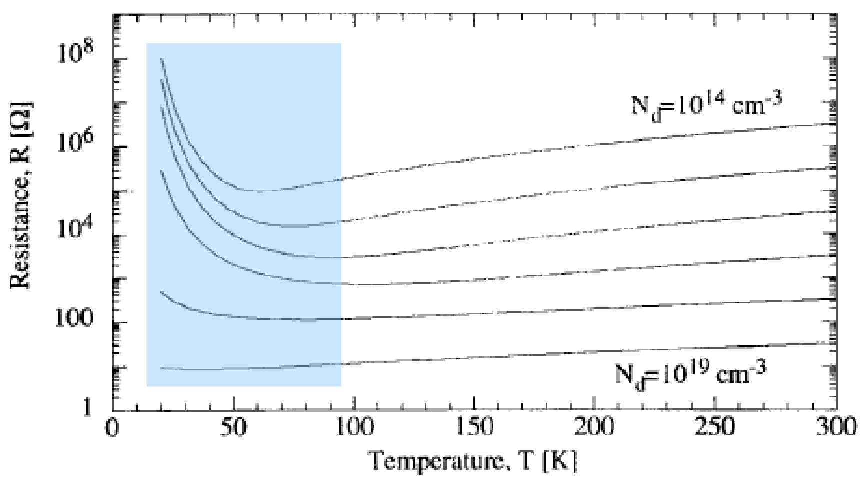


FIGURE 1.14. Calculated electrical resistance of a silicon slab of $(W/L) = 20/50\,\mu m$ and depth of $1\,\mu m$ for different doping concentration levels.

For T<100 K, the ionized impurities act as shallow traps (provided the impurity doping concentration below of 10^{18} atoms/cm^2) and carriers begin to occupy these shallow levels.

For T<30 K, practically no carriers remain in the bands

Plots from Guiterrez, Dean, Claeys - "Low Temperature Electronics: Physics, Devices, Circuits and Applications", Academic Press 2001

Silicon propt's at low T: impact ionization

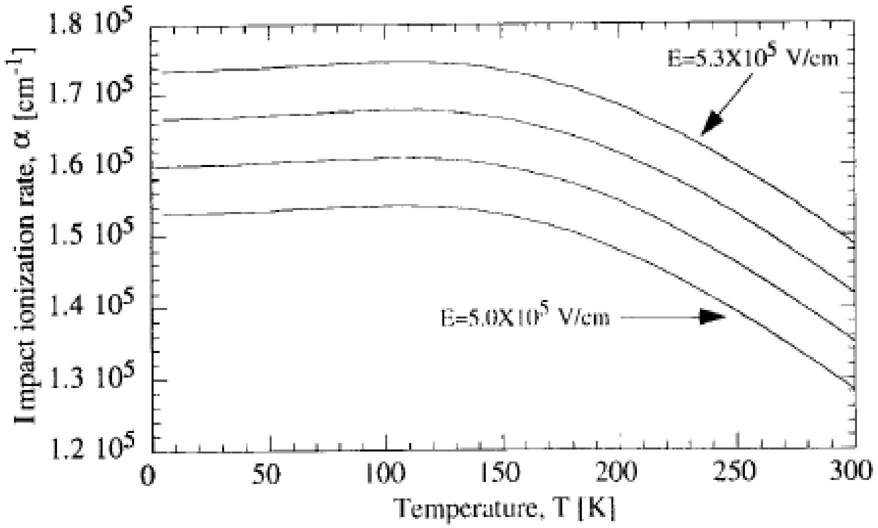


FIGURE 1.43. The impact ionization rate α as a function of temperature T_A with the electric field E as a parameter calculated from Okuto and Crowell's (*85*) model.

For T<77K no data are available → modeling is quite difficult...

Silicon propt's at low T: absorption length

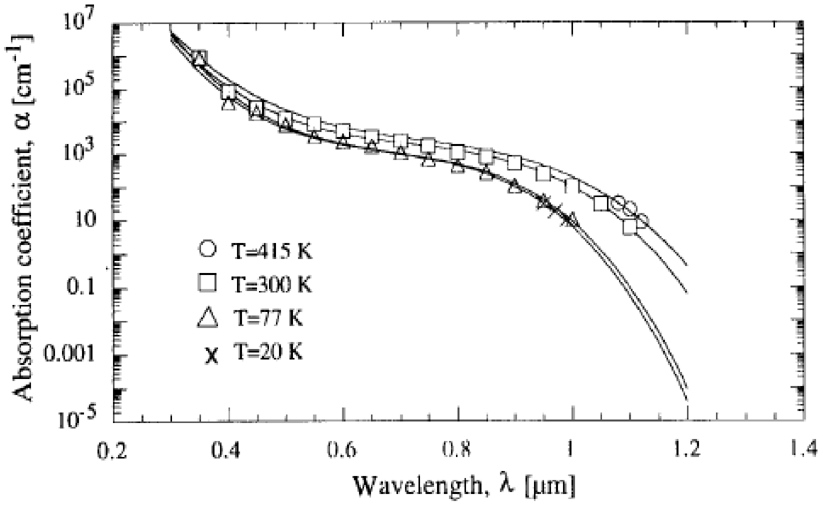


FIGURE 1.53. Experimental (symbols) and fitted (lines) absorption coefficient α of silicon at T = 415, 300, 77, and 20 K [replotted from Rajkanan *et al.* (*109*)].

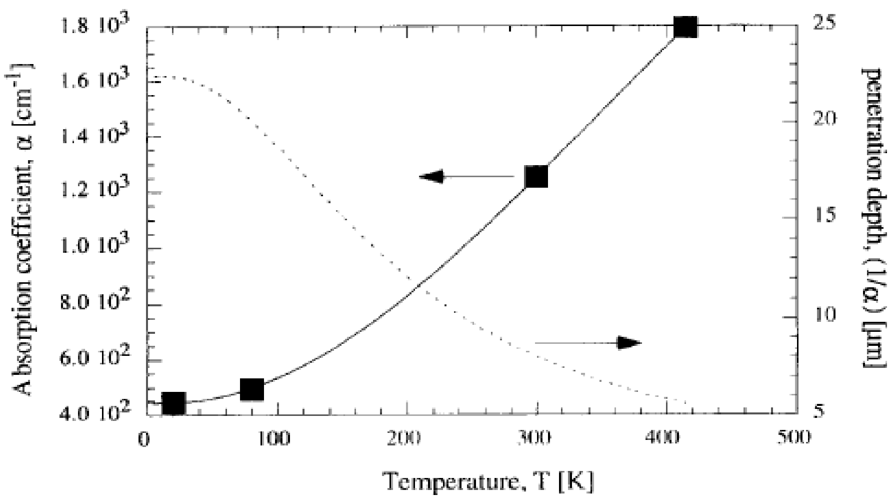


FIGURE 1.54. Measured absorption coefficient α (■) (*101*) and fitted α (solid line) versus temperature T. On the right axis the fitted penetration depth (1/α) is also shown.

Avalanche breakdown vs T

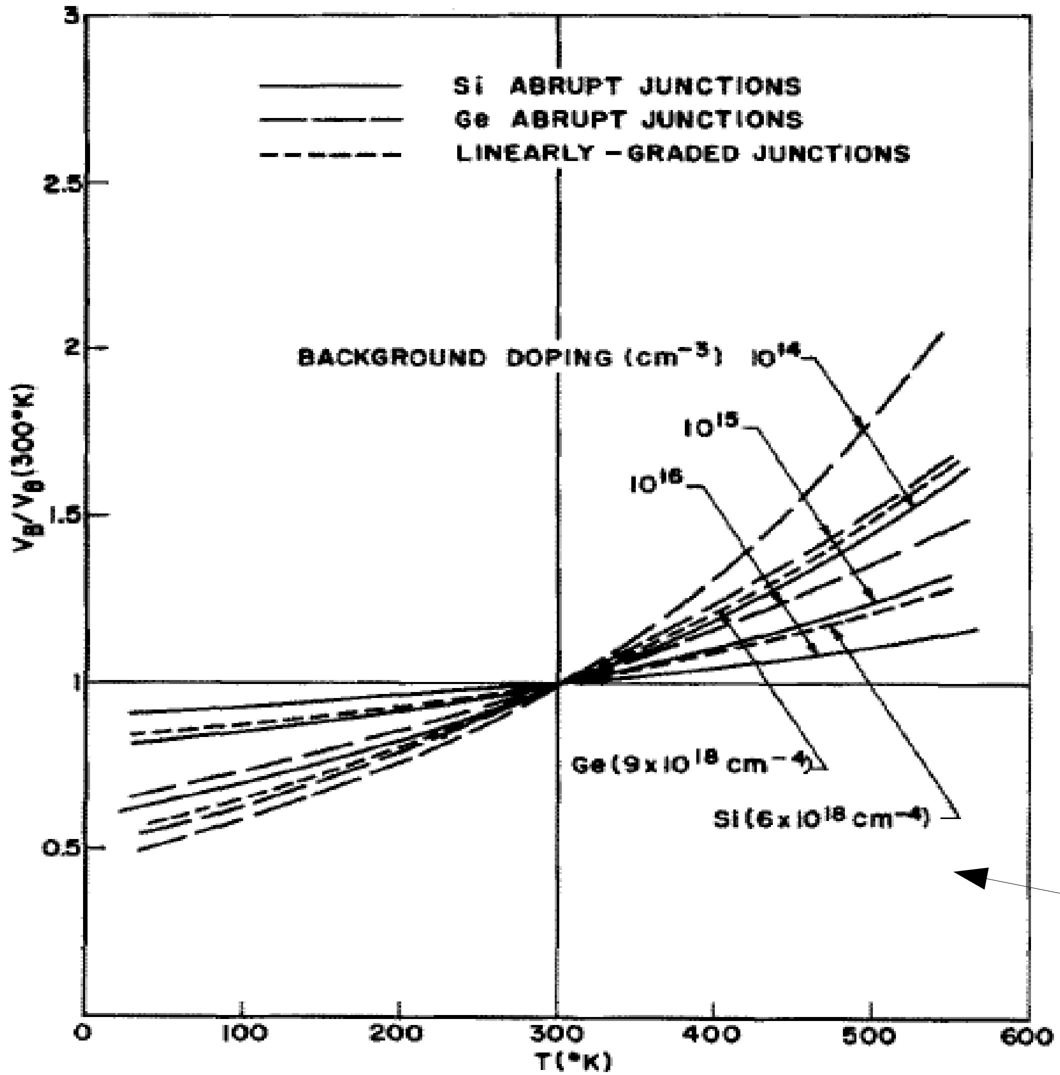


Fig. 4. Breakdown voltage vs temperature for Si and Ge p-n junctions. $V_B(300°K)$ is 2000, 330, and 60 V for Si and 950, 150, and 25 V for Ge for dopings of 10^{14}, 10^{15}, and 10^{16} cm^{-3} respectively. The linear-graded junctions have $V_B(300°K)$ the same as those for doping of 10^{15} cm^{-3}.

Avalanche breakdown V is expected to show a **non linear dependence on T** (depending of the junction type and doping concentration)

Breakdown V decreasing with T due to increasing mobility

NOTE: in freeze-out regime Zener (tunnel) breakdown could be relevant.
→ negative Temperature coefficient (increasing with decreasing T)

Crowell and Sze

More recent model by Crowell and Okuto after Shockley, Wolff, Baraff, Sze and Ridley.

p-n junction characteristics: forward bias

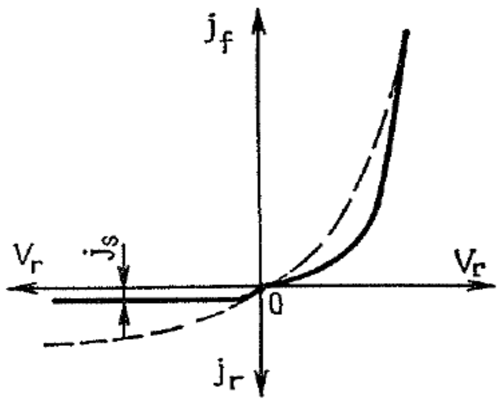
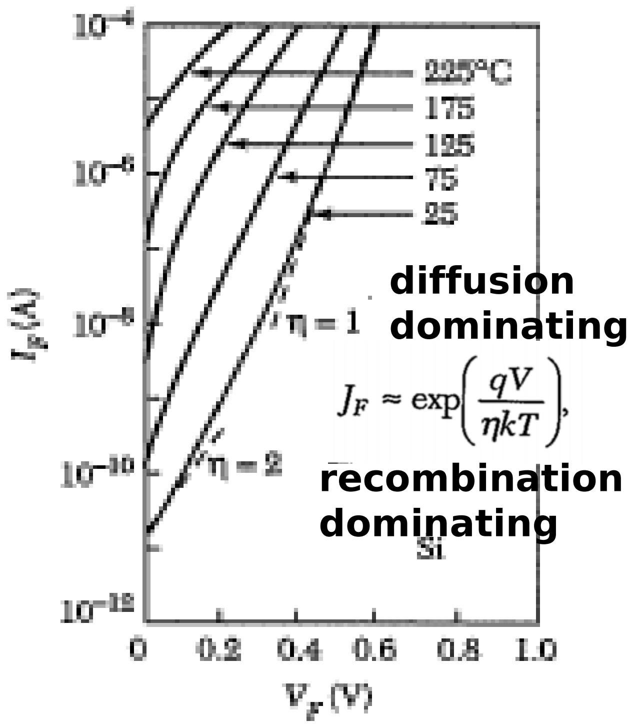
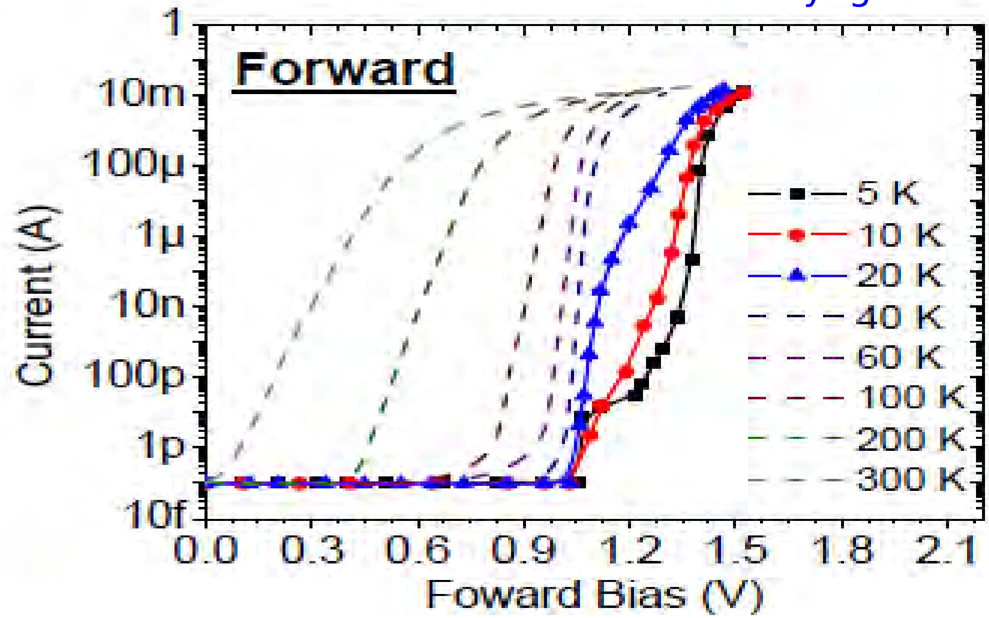


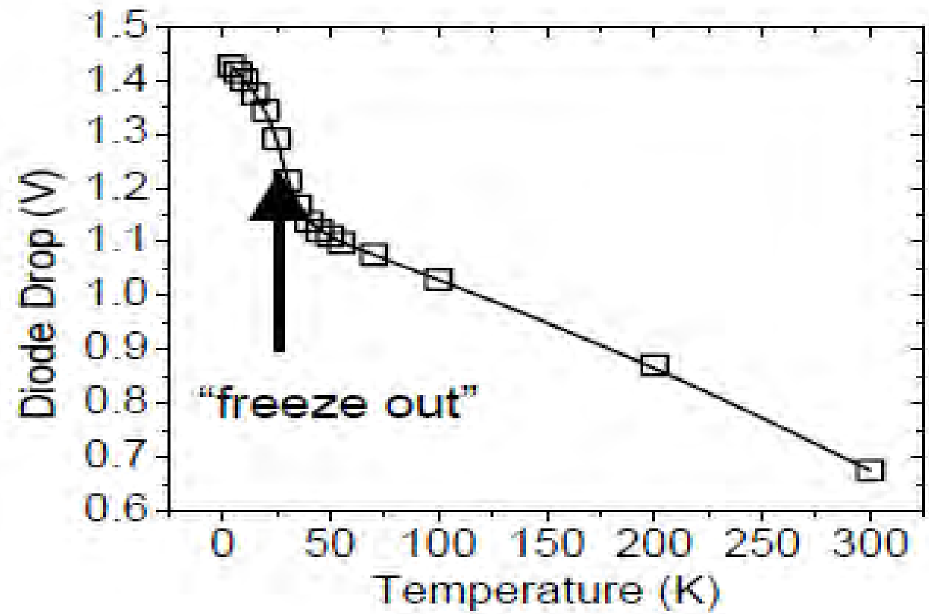
Fig. 8.16. The current-voltage characteristic of a *pn* junction



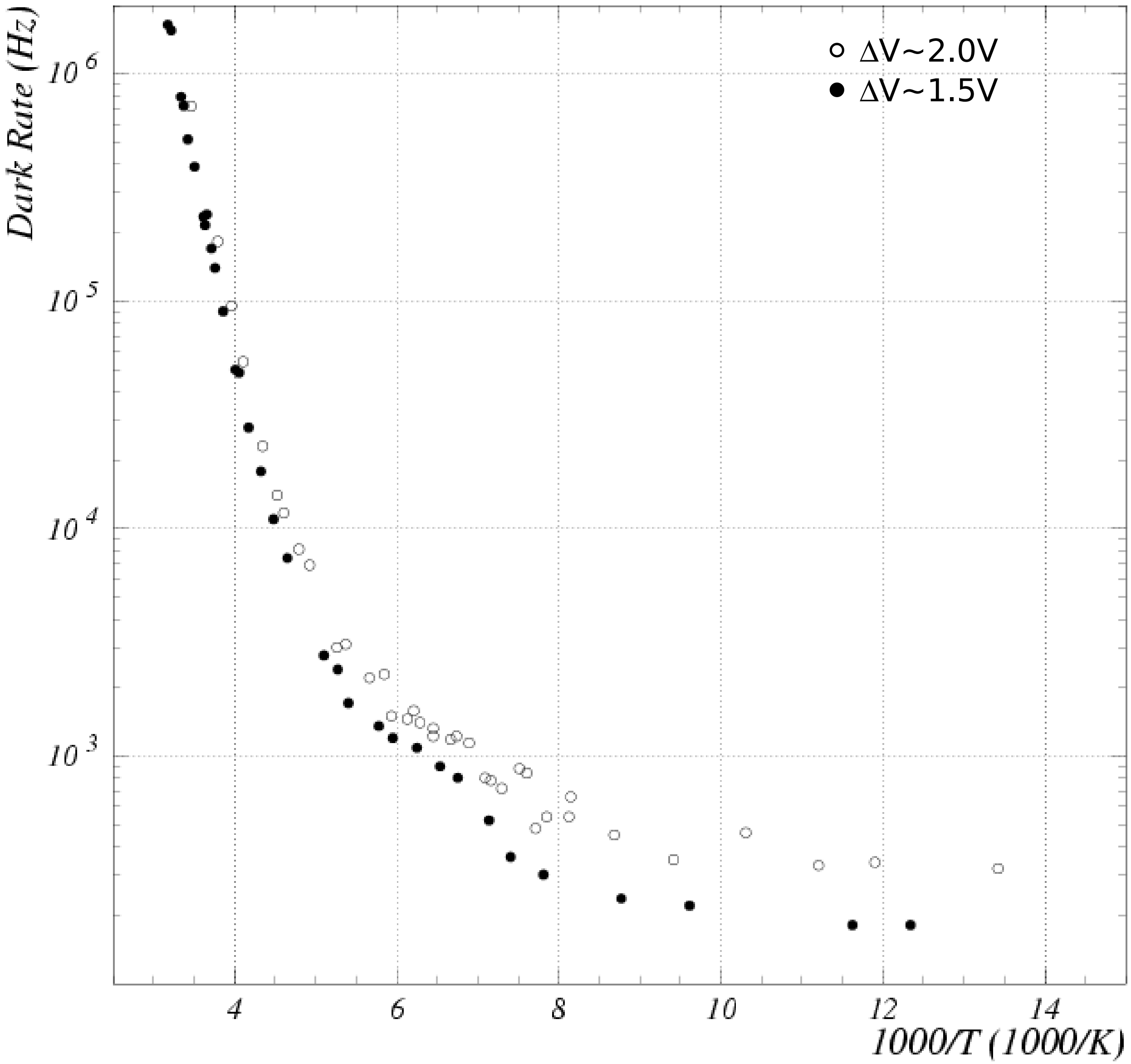
Sze - "Semiconductor devices"

E.Johnson (RMD) at IEEE 2009
"Characterization of CMOS APD at cryogenic T"



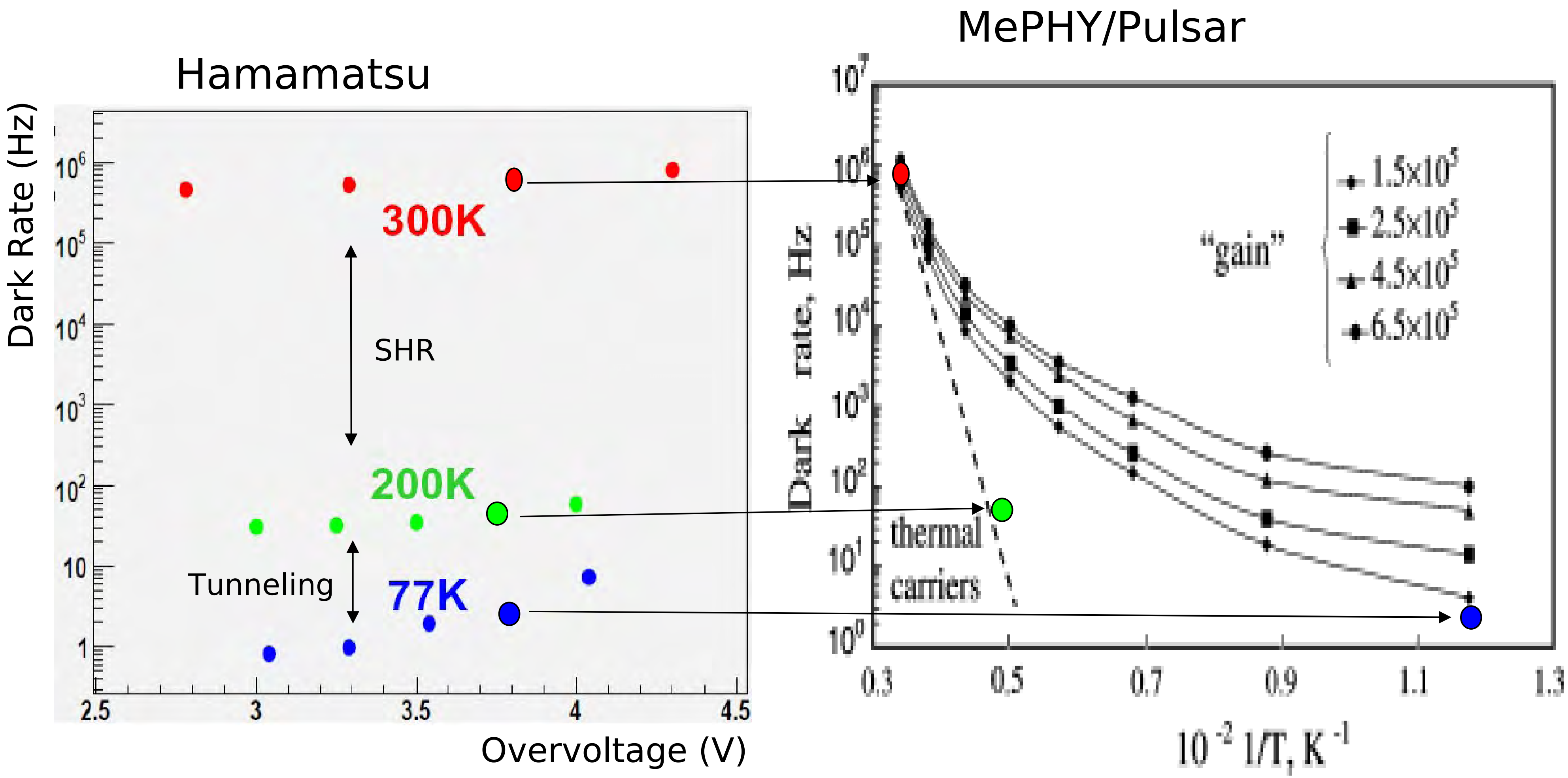


Dark count rate vs T (at fixed gain)



Measurement: **rate of ≥1p.e.** at fixed gain (i.e. ~fixed ΔV)

T dependence: Dark Rate



H.Otono – PD07

Dolgoshein et al, NIM A 442 (2000)

Electric field engineering and silicon quality
make huge differences in dark noise as a function of T

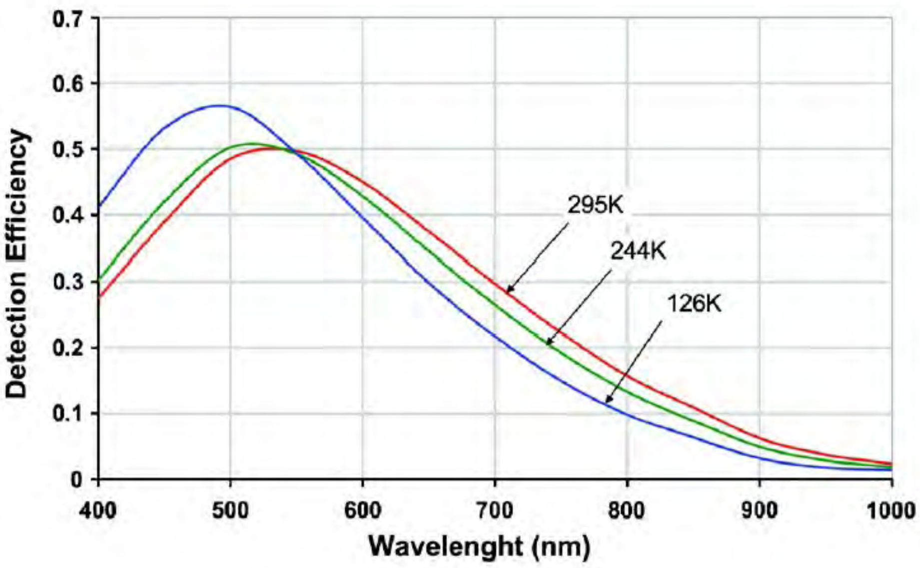
T dependence: PDE (SPAD/APD devices)

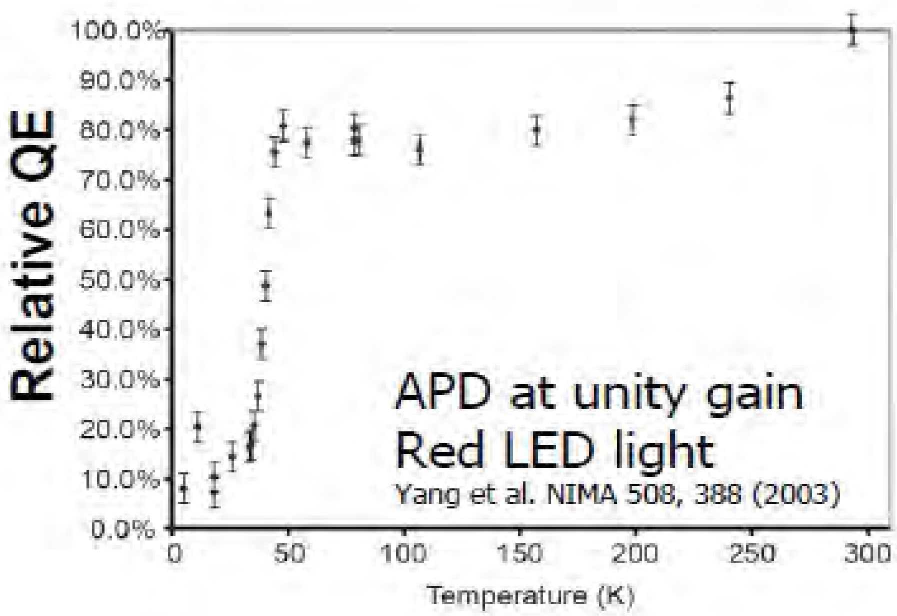
PDE dependence on T
(Over-voltage fixed)

Combination of various effects:
- P_{01} increases at low T because of increased impact ionizazion
- Optical attenuation length increased (Energy gap increases) at low T
- Depletion region widening in APDs, but not in SiPM which are fully depleted

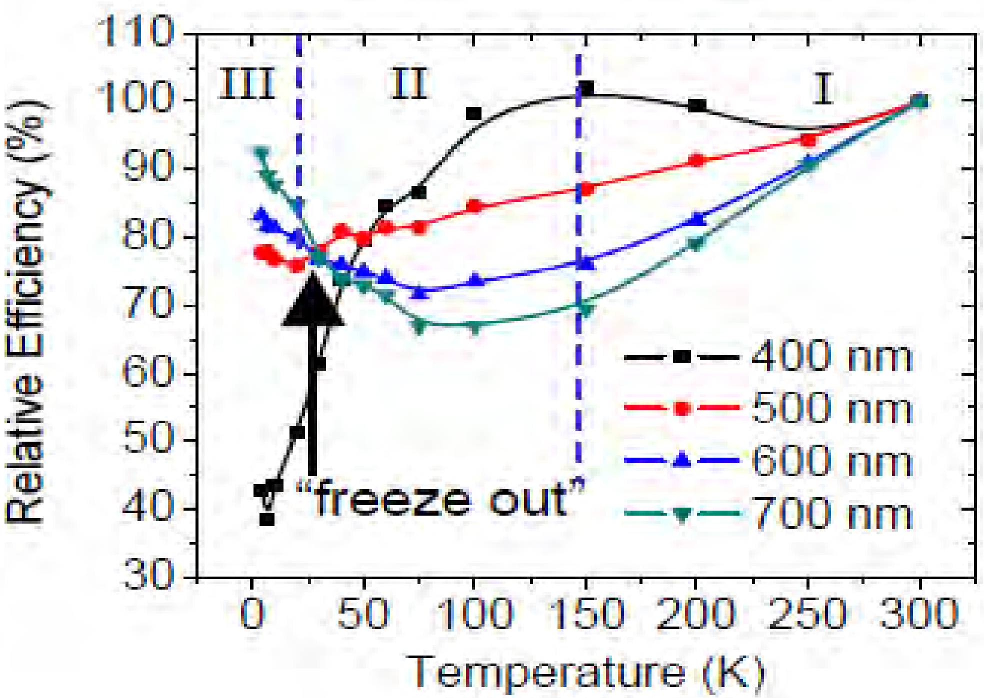
Similar effect expected also for SiPM

SPAD: Cova el al, Rev.Sci.Instr. 7 (2007)





APD: Johnson et al (RMD) IEEE 2009

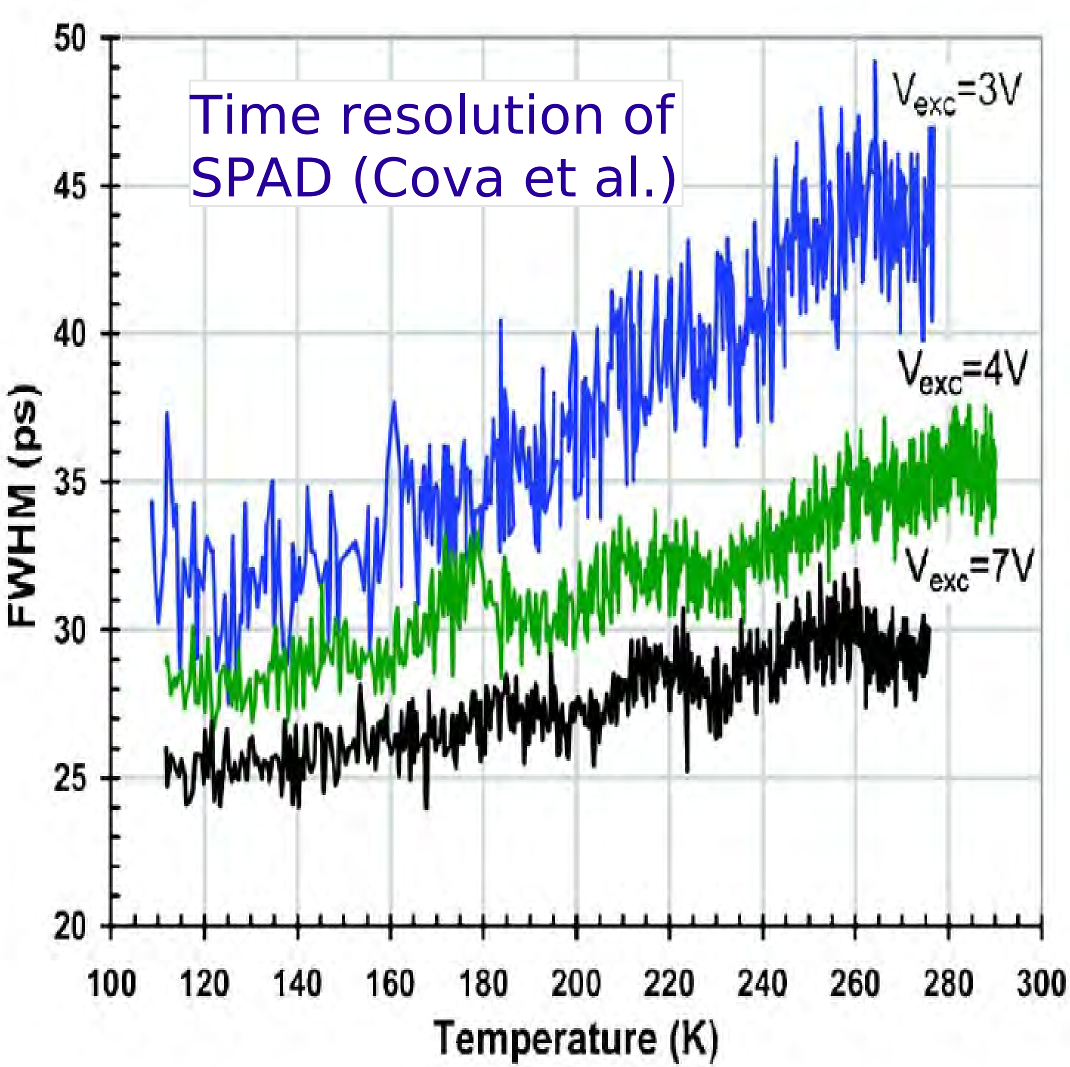


Timing vs T (SPAD devices)

Timing: better at low T

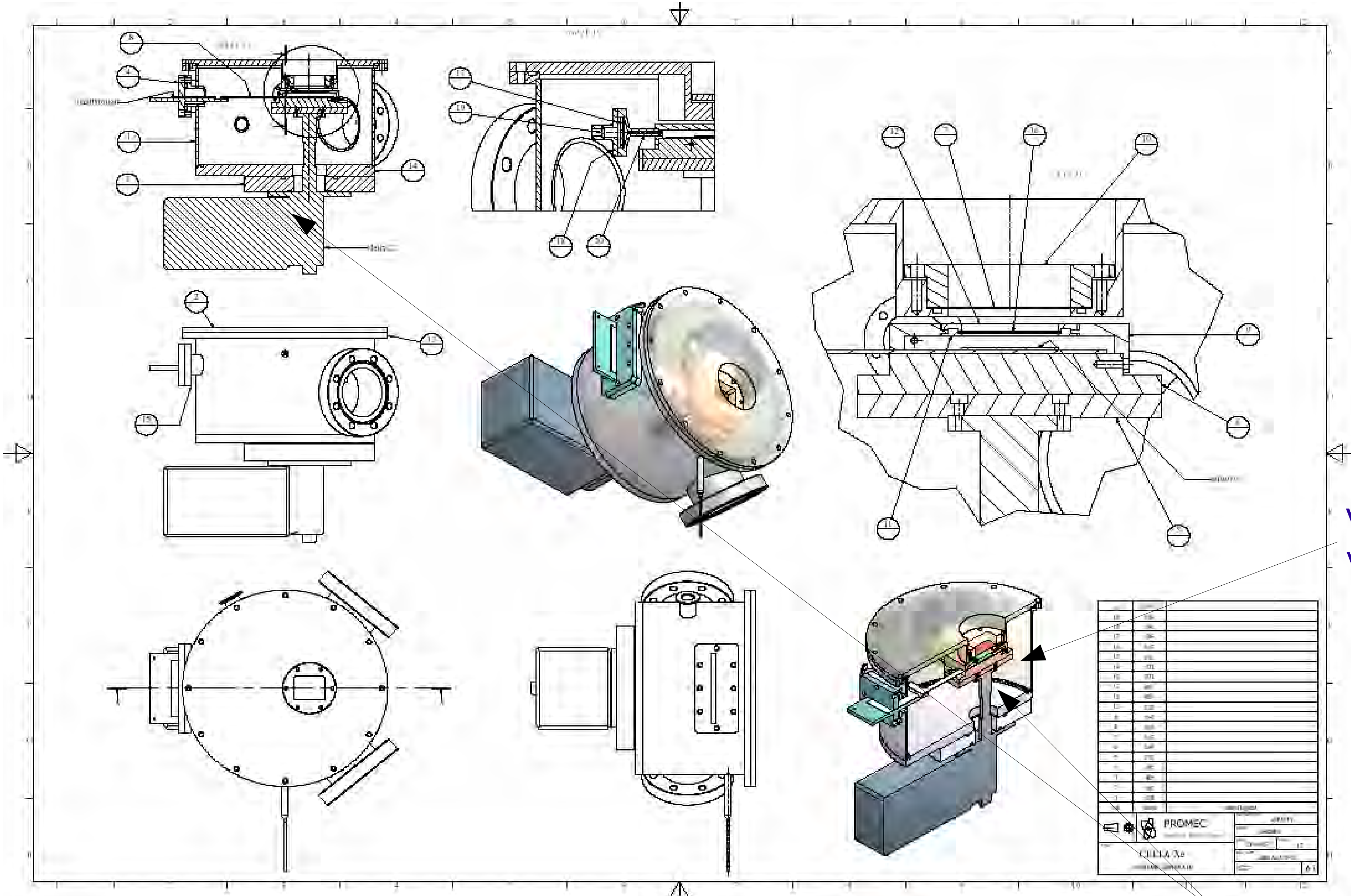
Lower jiitter at low T due to higher mobility

(Over-voltage fixed)



I.Rech el al, Rev.Sci.Instr. 78 (2007)

Setup: vacuum vessel + cryo-cooler



Acknowledgments: A.Brez, A. Baldini, G.Signorelli (Pisa)

SiPM's are in thermal contact with a cooled Cu rod