A GUIDE TO CRYOGENIC APPLICATIONS OF SIPMS

- Relatively young field
  - One running experiment (GERDA, LAr veto shield)
  - One experiment under commissioning (MEG II)
  - Few experiments in the preparation phase (DUNE, DarkSide, nEXO,…)
- Liquid Noble Gases experiment, new requirements and emphasis (very large area detectors, radiopurity, VUV sensitivity, low noise electronics and massive ganging, infrared sensitivity?? ..)
- Not much to standardize, yet, but rather share experience and guide the developments

MENU

- Review of the existing/planned experiments (Fabrice Retiere)
- Physics of SiPMs at cryogenic temperatures (Gianmaria Collazuol)
- Review of the readout electronics approaches (Wataru Ootani)
- Testing setups at cryogenic temperatures (Andrii Nagai)
- Reliability issues for large scale applications (Vishnu Zutshi)
- Interesting new contributions

PHYSICS OF SIPMS AT CRYOGENIC TEMPERATURES

AND IMPLICATIONS FOR THEIR PERFORMANCE AND CHARACTERISTICS

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ICASiPM 2018, Schwetzingen

SUMMARY

- Cryogenic experiments (LXe/LAR) use SiPMs in the regime where the fundamental physics of silicon changes considerably (source of the figures: Gutierrez, Dean, Claeys "Low Temperature Electronics: Physics, Devices, Circuits and Applications")
- (Some) SiPMs characteristics may vary significantly from room temperature to the operating conditions
- Cold/warm temperature variation may depend on the specific device design (room for the device optimization)

FREE CARRIERS IN DOPED SILICON

LAr LXe Room temperature

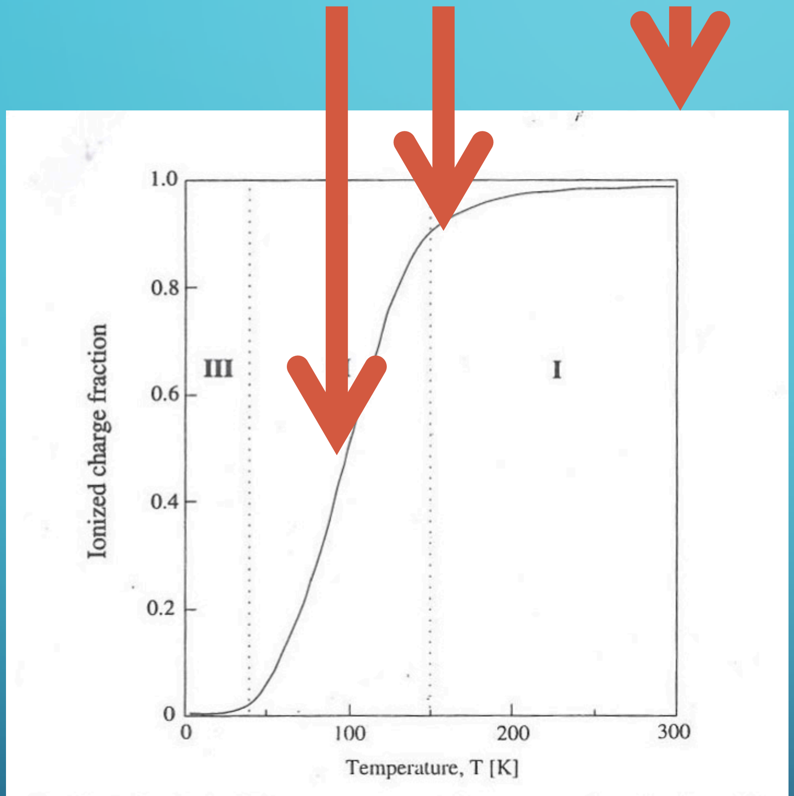


FIGURE 1.32. Ionized charge concentration versus temperature for silicon (73).

Donors/acceptors fully ionized by **thermal excitations**. Silicon is a semiconductor.

Free carriers produced by a temperature-dependent combination of

- Thermal excitations
- ‘field-assisted’ excitations
- tunneling

Donors/acceptors levels filled up. Insulator.

SILICON PROPERTIES AT LOW T: HIGHER CARRIER MOBILITY

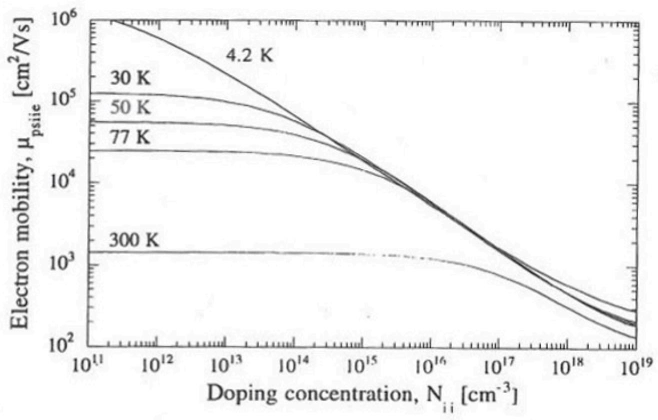


FIGURE 1.16. Calculated electron mobility due to phonon and ionized impurity scattering mechanisms. The five plots correspond to $T = 300$, 77, 50, 30, and 4.2 K.

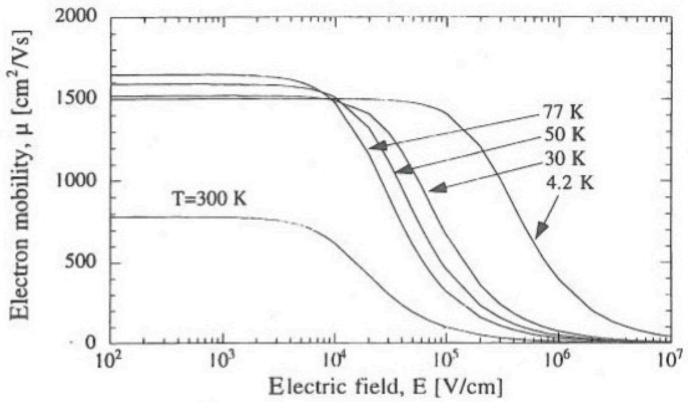


FIGURE 1.17. Calculated electron mobility, due to phonon, ionized impurities, and velocity saturation effects, as a function of the electric field for five temperatures; $N_{ii} = 10^{17}\ \mathrm{cm}^{-3}$.

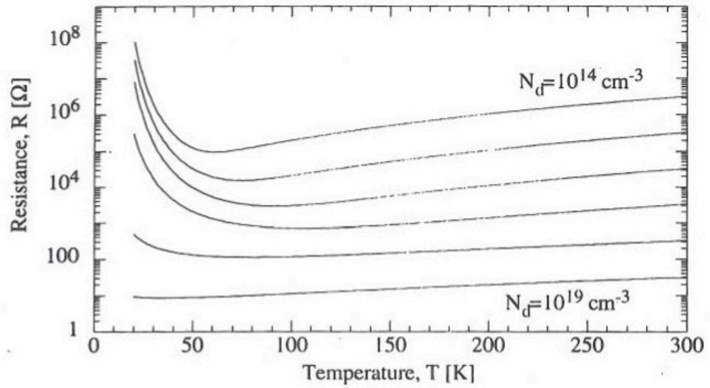


FIGURE 1.14. Calculated electrical resistance of a silicon slab of $(W/L) = 20/50\ \mu m$ and depth of $1\ \mu m$ for different doping concentration levels.

- Carrier mobility → avalanche development, time development
- Temperature variation depends on doping profiles and electric fields → effect onSiPM performance may depend on the details of the SiPM design

SILICON PROPERTIES AT LOW T: IONIZATION COEFFICIENTS

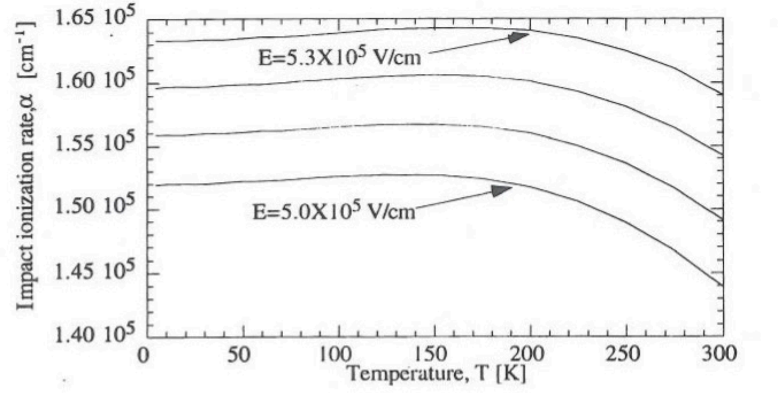


FIGURE 1.42. The impact ionization rate α for electrons as a function of the temperature *T*, with the electric field *E* as a parameter, calculated from Sutherland's (*82*) model.

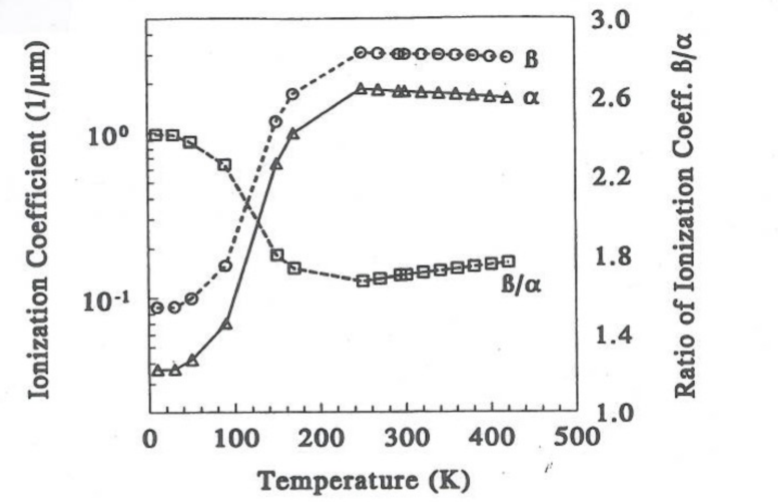


FIGURE 6.73. The ionization coefficients for electrons and holes and their ratio under the condition of breakdown as a function of temperature [after (*249*) Bandyopadhyay et al.].

- Impact ionization coefficient ➔ avalanche development, time development, breakdown voltage
- Electron/hole variation ➔ Wavelength dependence of PDE
- Temperature variation depends on doping profiles and electric fields ➔ effect onSiPM performance may depend on the detais of the SiPM design

AVALANCHE BREAKDOWN: TEMPERATURE VARIATION

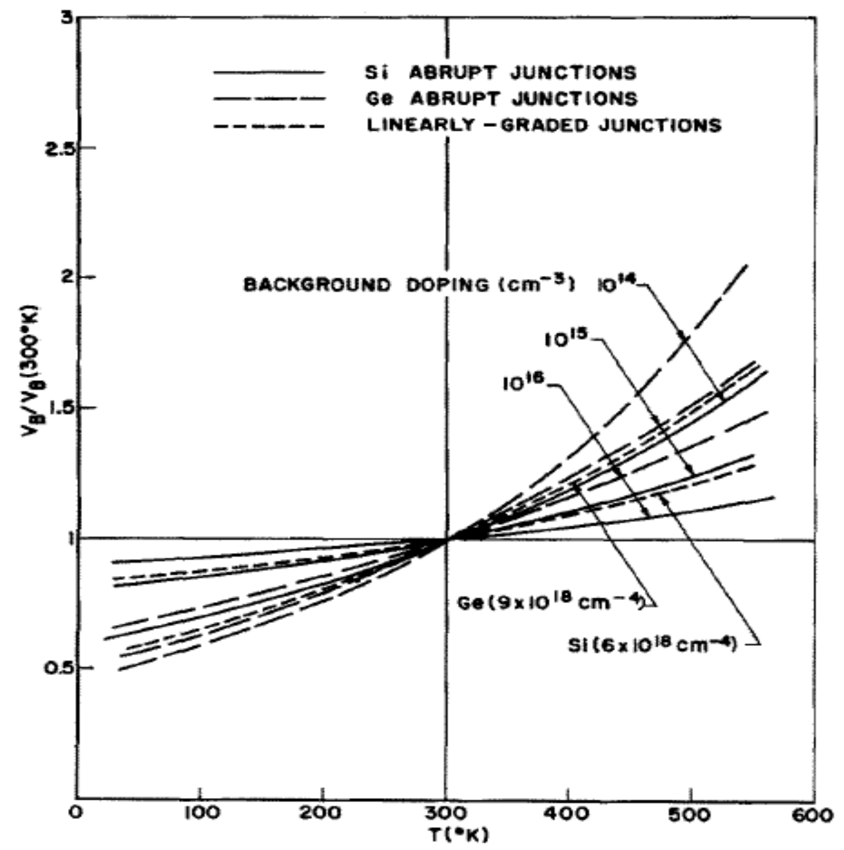


Fig. 4. Breakdown voltage vs temperature for Si and Ge p-n junctions. V_B(300°K) is 2000, 330, and 60 V for Si and 950, 150, and 25 V for Ge for dopings of 10^{14}, 10^{15}, and 10^{16} cm^{-3} respectively. The linear-graded junctions have V_B(300°K) the same as those for doping of 10^{15} cm^{-3}.

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.

SILICON ABSORPTION LENGTH AT LOW TEMPERATURES

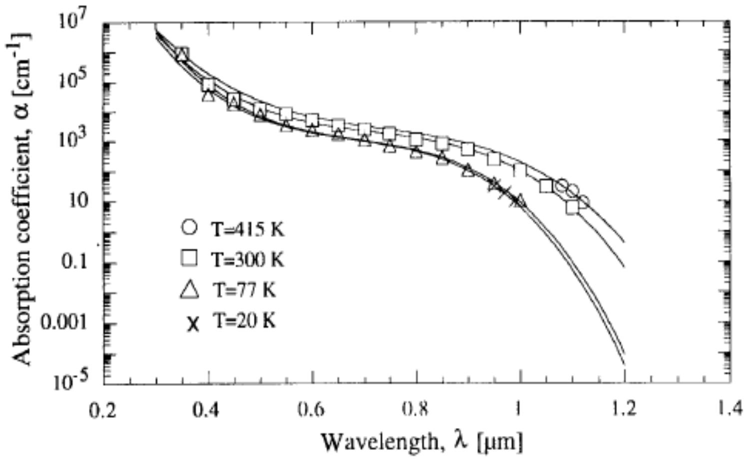


FIGURE 1.53. Experimental (symbols) and fitted (lines) absorption coefficient α of silicon at $T = 415$, 300, 77, and 20 K [replotted from Rajkanan *et al.* (109)].

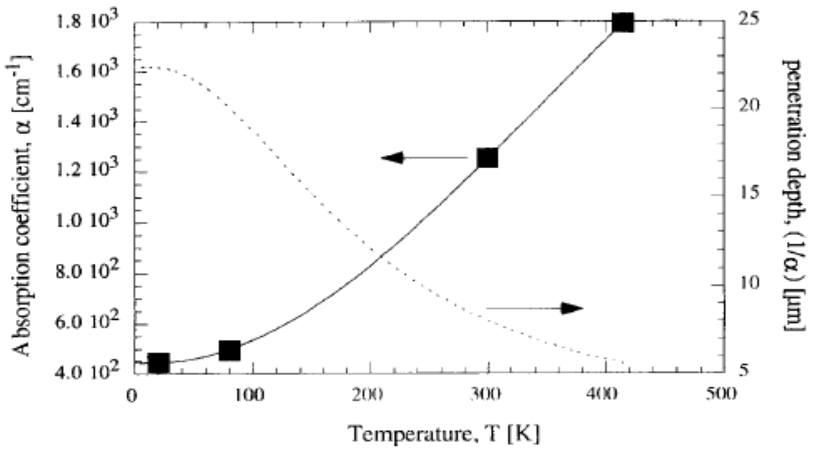
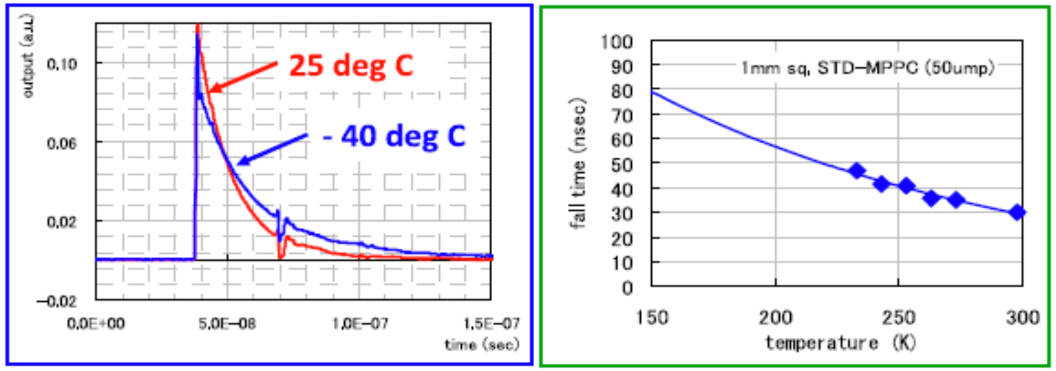


FIGURE 1.54. Measured absorption coefficient α (■) (*101*) and fitted α (solid line) versus temperature T. On the right axis the fitted penetration depth ($1/\alpha$) is also shown.

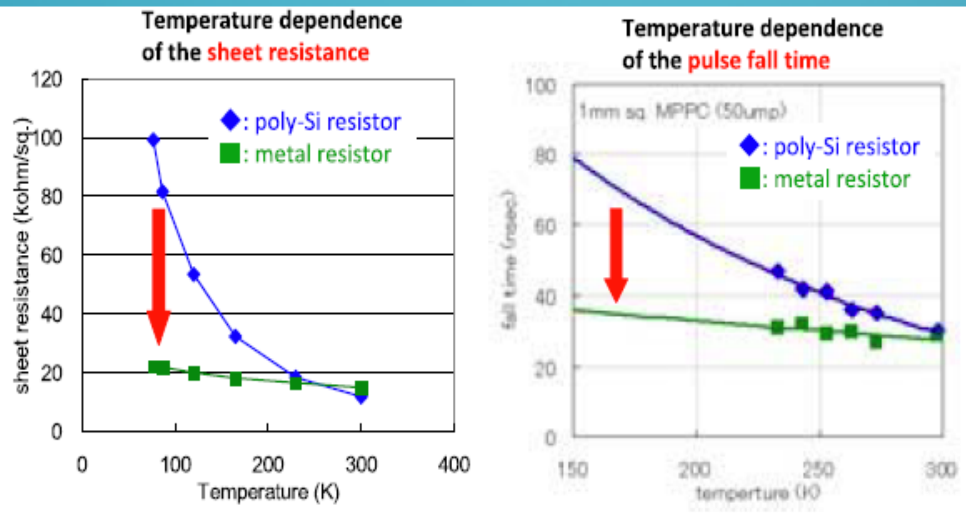
- Variation of the wavelength-dependence of PDE with temperature

IN ADDITION: QUENCHING RESISTOR



The quenching resistor value increases as environmental temperature decreases. The larger resistor makes the pulse amplitude lower and the tail longer.

Adopting metal quenching resistor



Metal quenching resistor achieved 1/5 temperature dependence

Improved temperature stability

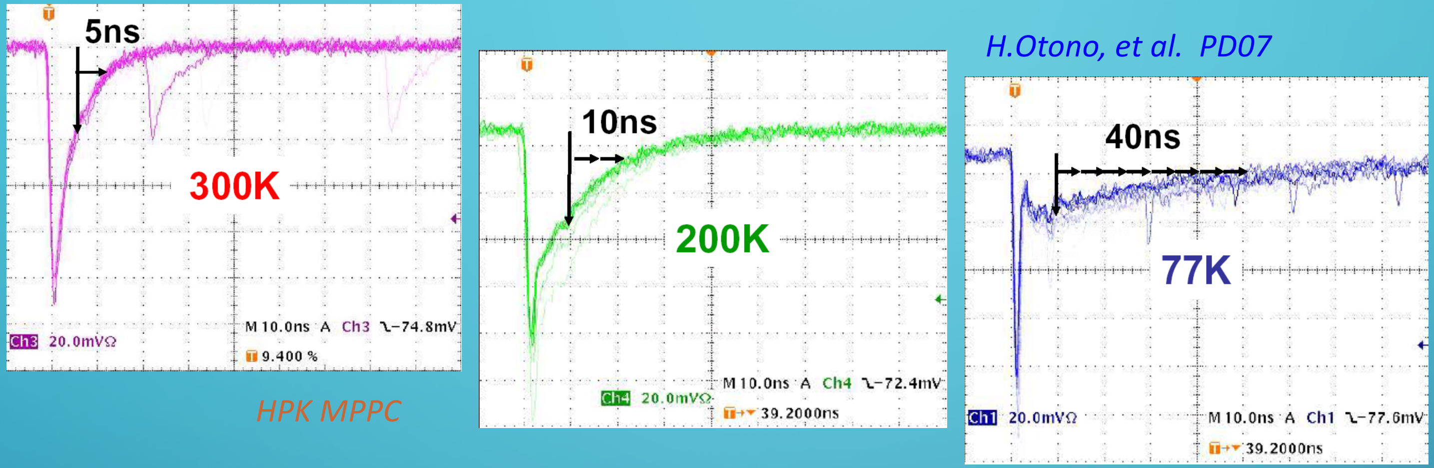
PULSE SHAPE: DEPENDENCE ON TEMPERATURE

The two current components behave differently with Temperature

→ fast component is independent of T because C_{tot} couples to external R_{load}

→ slow component is dependent on T because $C_{d,q}$ couple to $R_q(T)$

H.Otono, et al. PD07



HPK MPPC

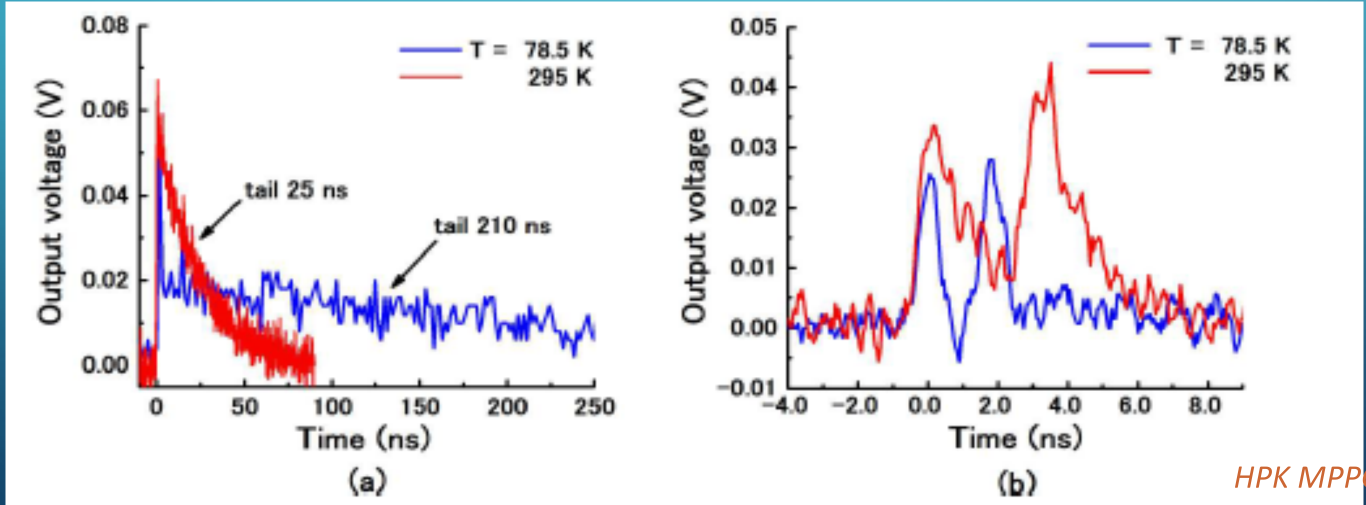


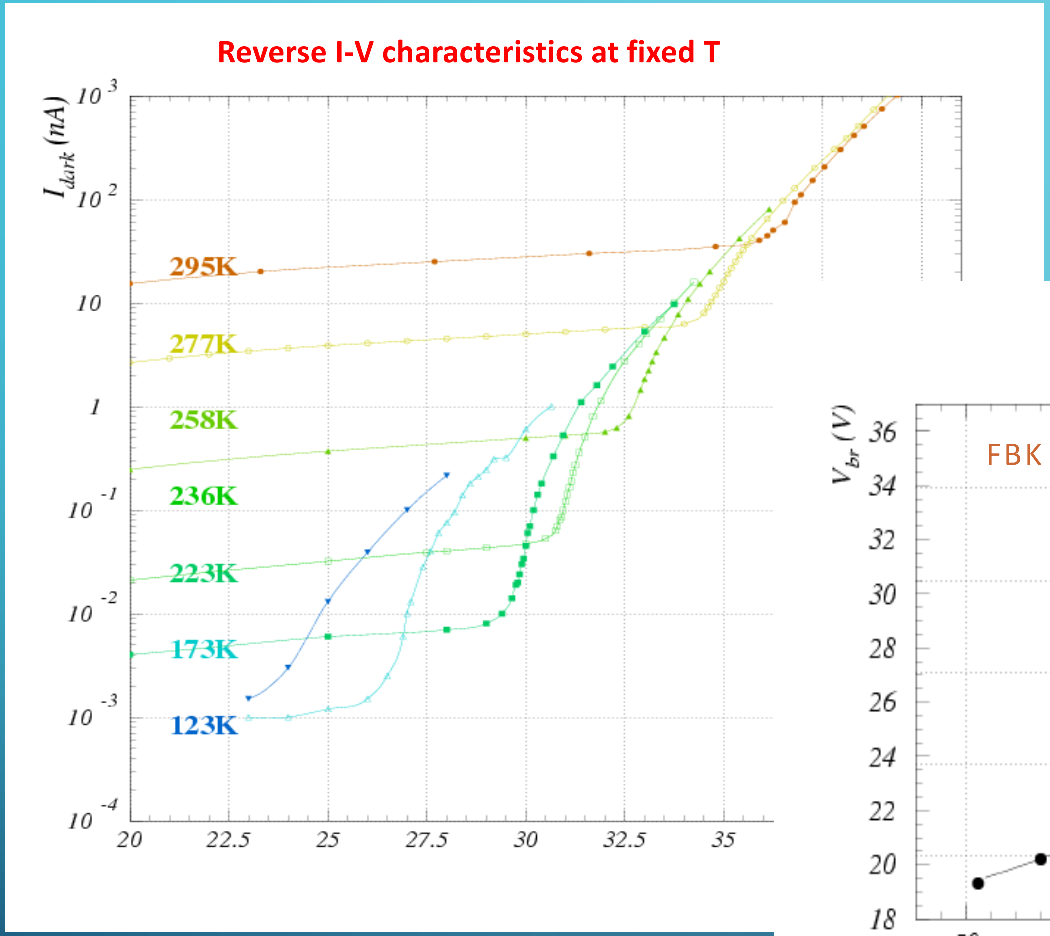
Fig. 2. (a) Output signals from the MPPC when no high-pass filter is used, and (b) output signals from the high-pass filter when two pulses were generated successively.

HPK MPPC

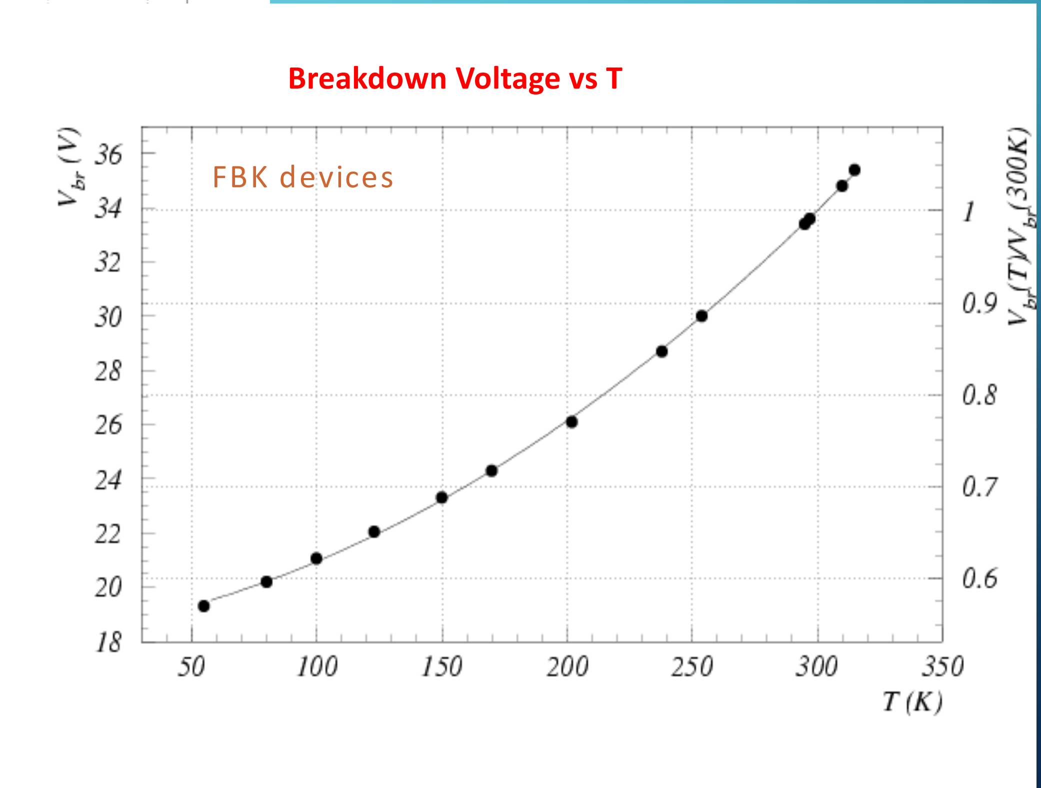
high pass filter / shaping
→ recover fast signals

Akiba et al Optics Express 17 (2009) 16885

REVERSE BIAS I-V CURVES → DARK CURRENT AND V_{BD}



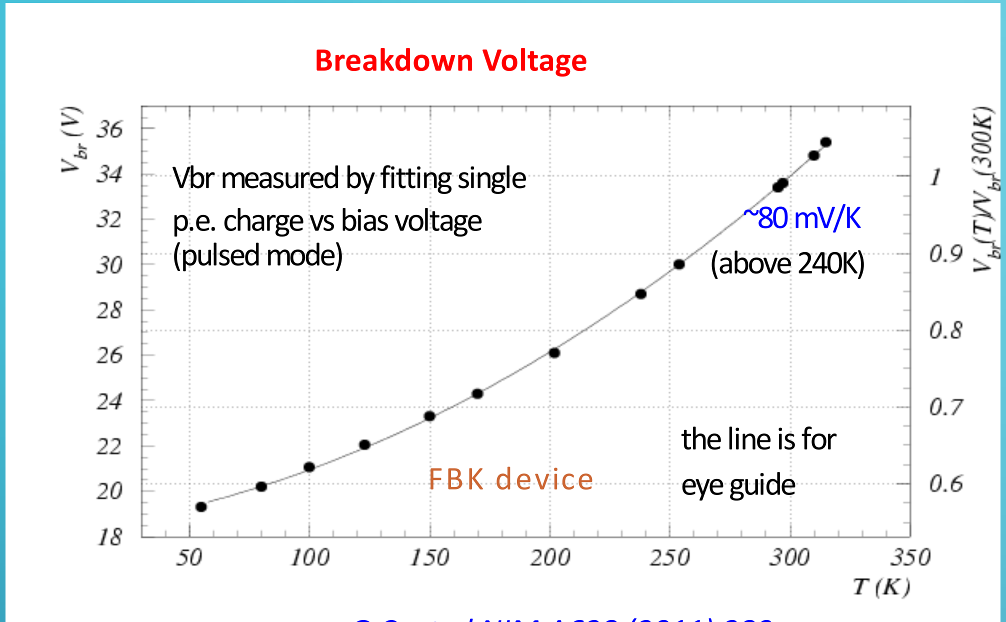
Dark current decreases rapidly with T at rate ~ x2 / 10K



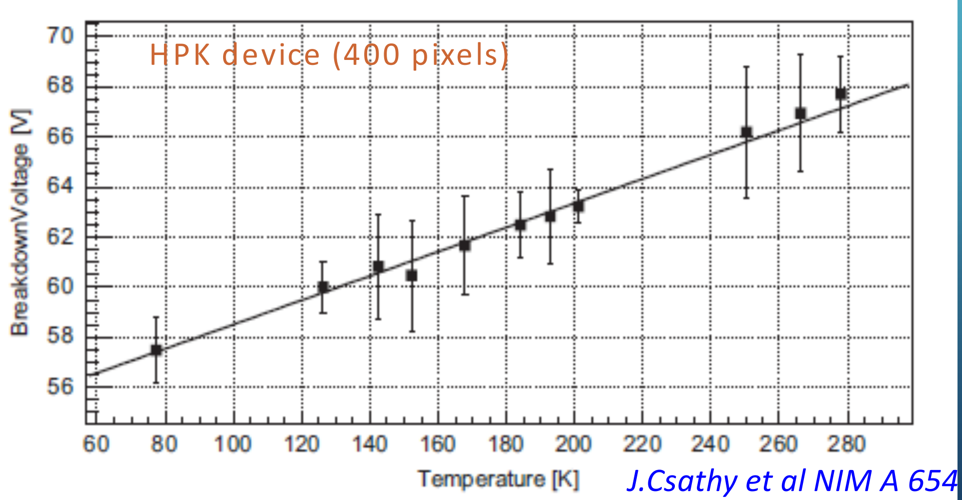
Breakdown voltage decreases
at low T due to larger carriers mobility
→ larger ionization rate (electric E field fixed)

G.C. et al NIM A628 (2011) 389

V_{BD} VS T → TEMPERAURE COEFFICIENT (ΔV STABILITY)



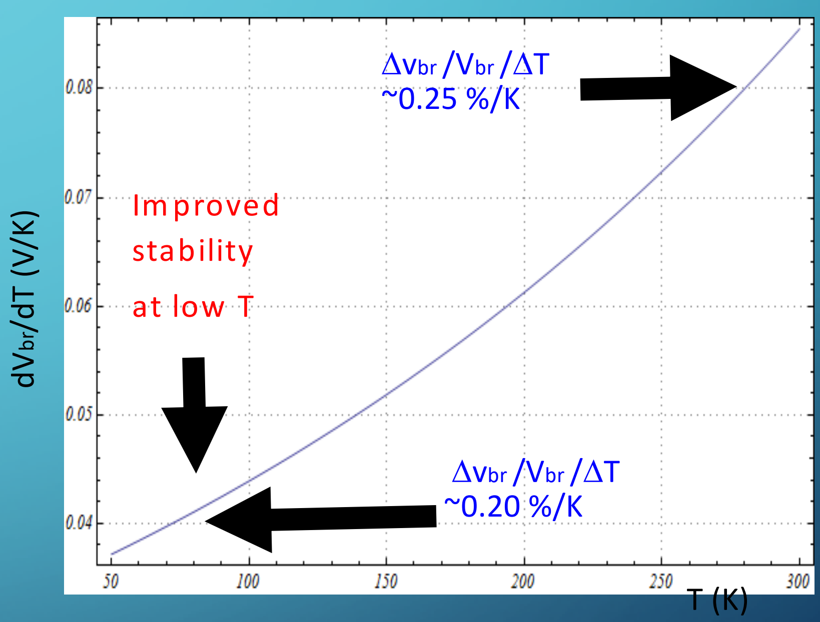
G.C. et al NIM A628 (2011) 389



J.Csathy et al NIM A 654 (2011) 225

Fig. 6. Breakdown voltage as a function of temperature of the MPPC with 400 pixels.

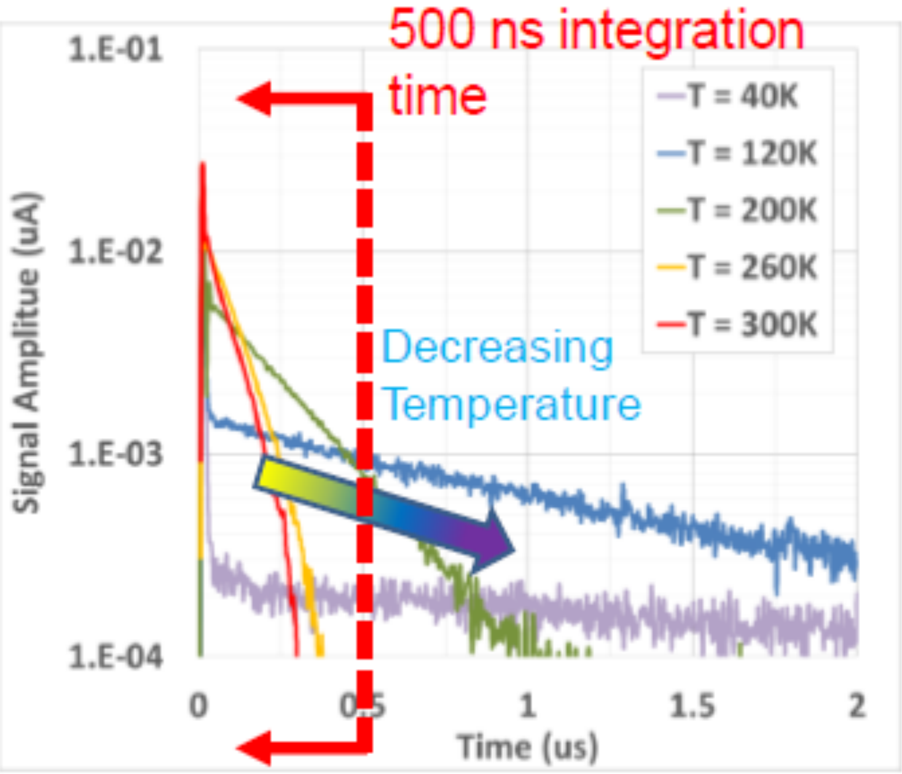
Temperature coefficient



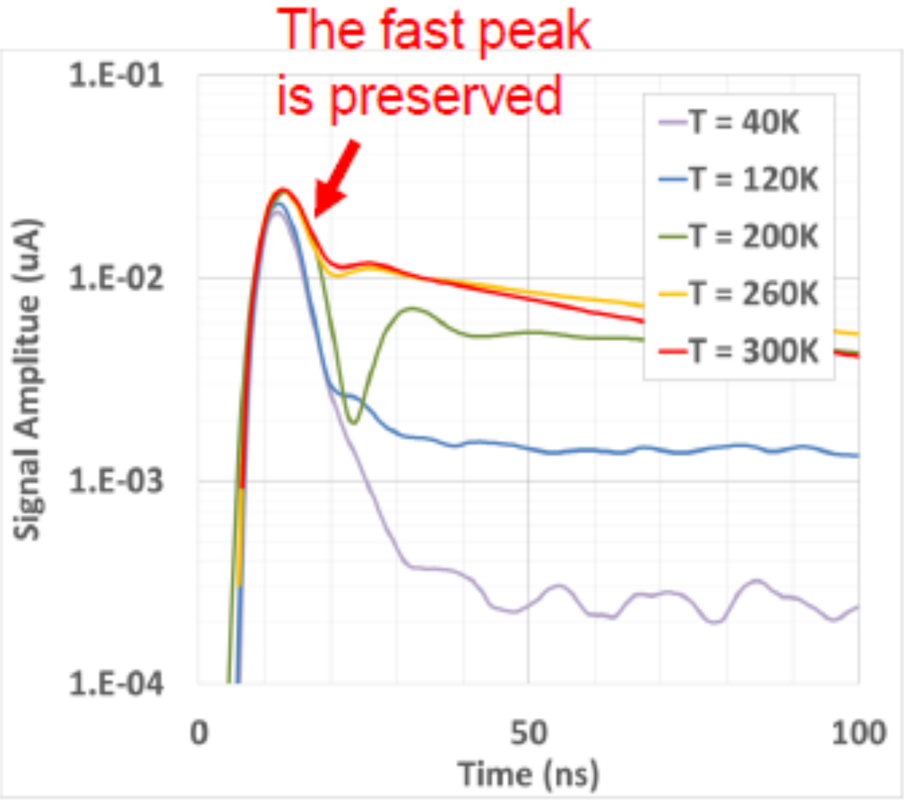
PULSE SHAPE VS T

Alberto Gola – IEEE NSS-MIC 2015

The exponential tail of the single cell response (SCR) becomes almost negligible at cryogenic temperature.



Average SCR

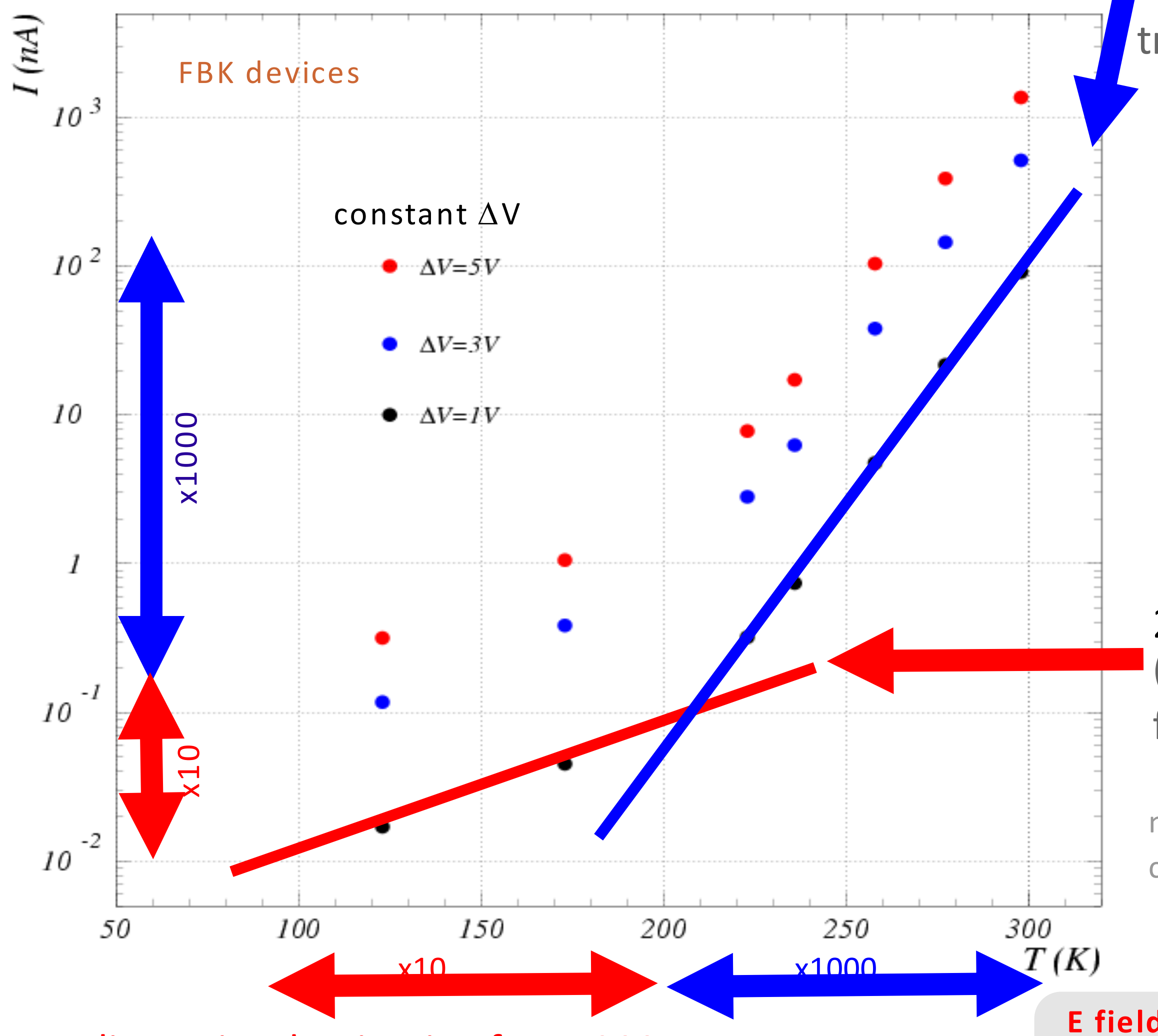


Zoom of the first part of the SCR

DARK CURRENT VS T sources of DCR

contribution to DCR from diffusion of minority carriers negligible below 350K

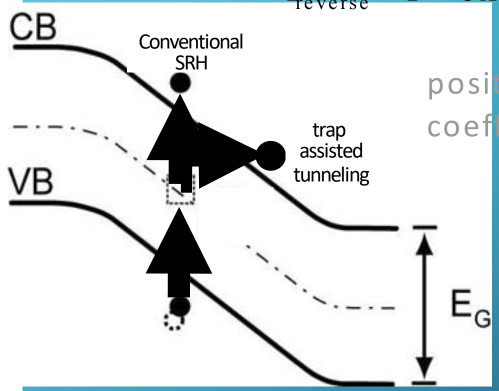
Noise mainly comes from the high E Field region (no whole depletion region)



Tunneling noise dominating for T<200K (sharp high E field region → higher noise)

1) Generation/Recombination SRH noise (enhanced by trap assisted tunneling)

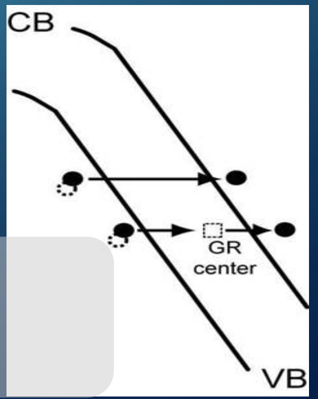
$$I_{reverse} \sim T^{1.5} \exp \frac{-E_{act}}{K_B T}$$



positive T coefficient

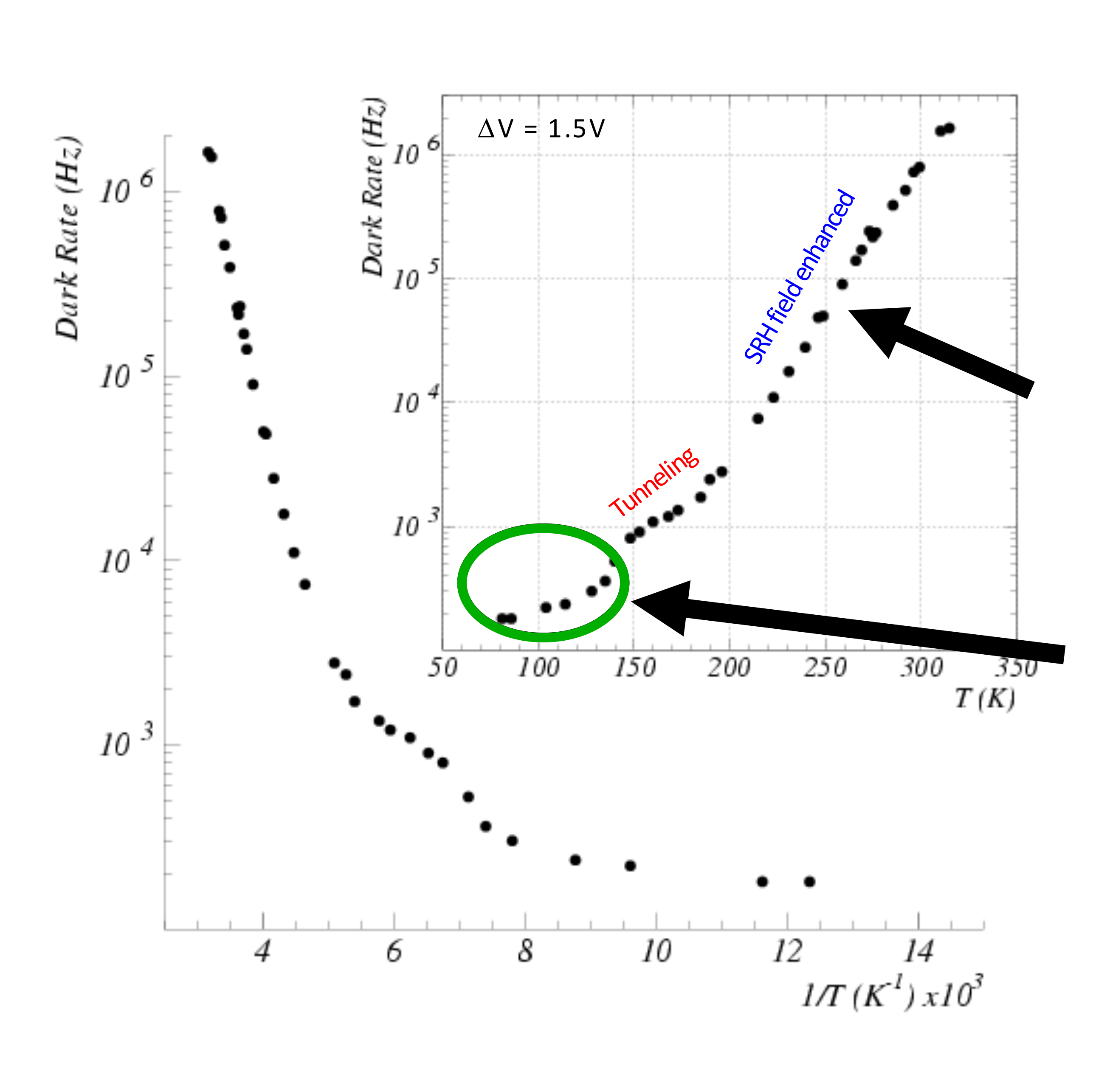
2) Band-to-band Tunneling noise (strong dependence on the Electric field profile)

negative T coefficient



E field engineering is crucial for min. DCR (esp. at low T)

DARK COUNT RATE VS TEMPERATURE (CONSTANT ΔV)



Measurement of
counting rate of ≥1p.e.
at fixed ΔV=1.5V
(→ constant gain)

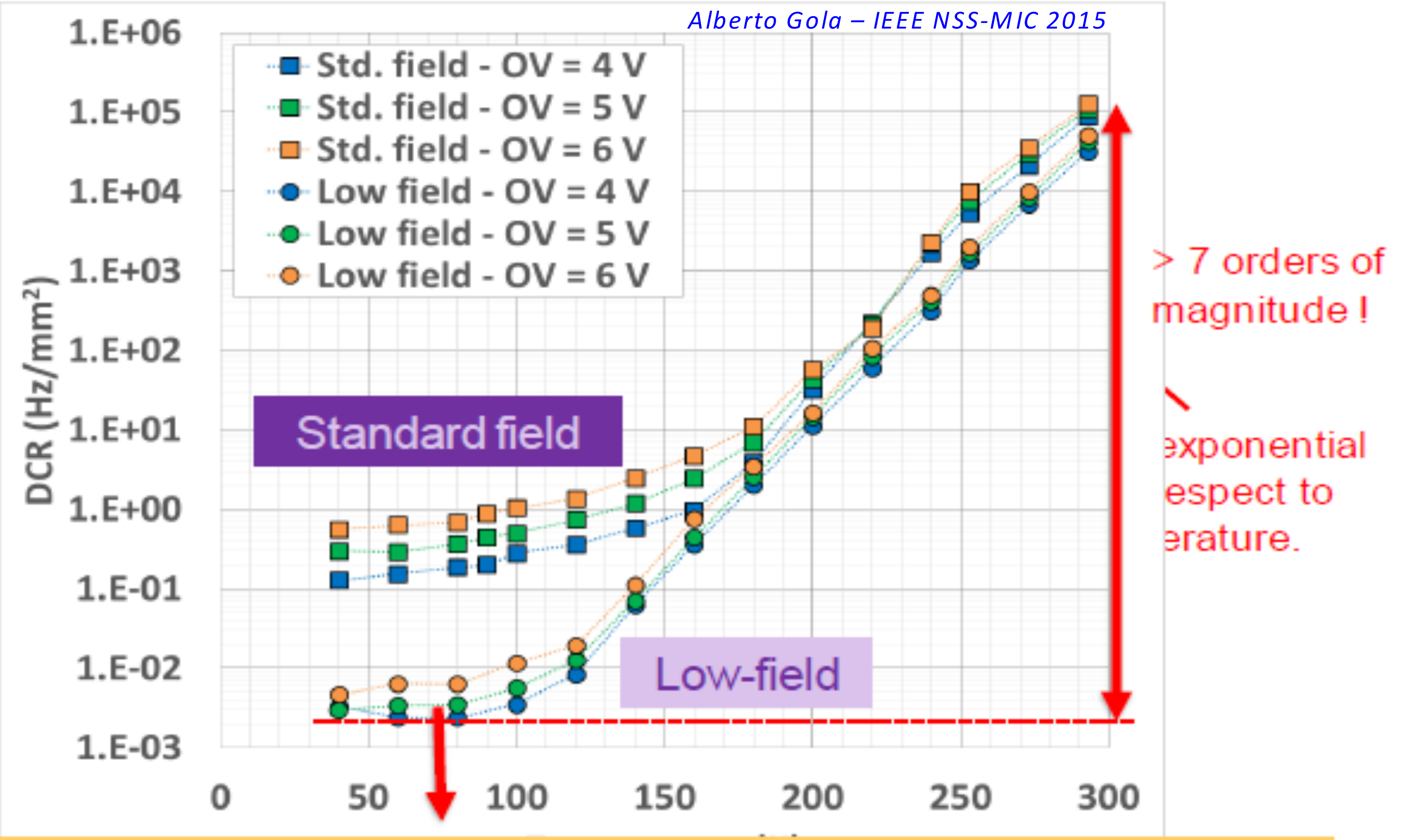
$$DCR \sim T^{1.5} \exp \frac{-E_{act}}{K_B T}$$

Activation energy E_{act}~0.36eV

??? onset of carriers freeze-out

(carrier losses at very low T
due to ionized impurities acting
as shallow traps)
Under investigation

OPTIMIZE SIPM FOR CRYOGENIC OPERATION: FBK



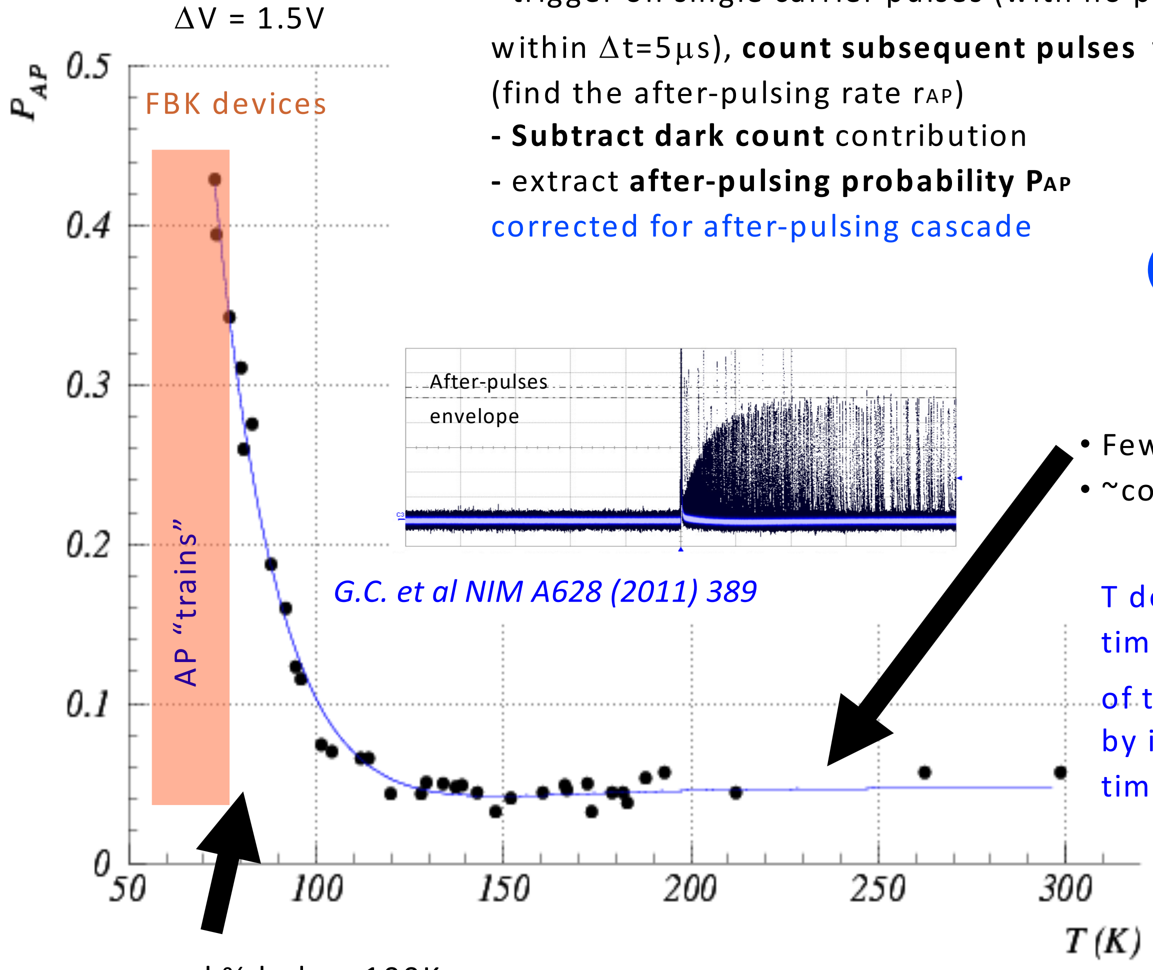
A 10x10 cm² SiPM array would have a total DCR < 100 Hz!

AFTER-PULSES VS T (CONSTANT DV)

Measurement by waveform analysis:

- trigger on single carrier pulses (with no preceding pulses within Δt=5μs), **count subsequent pulses** within Δt=5μs (find the after-pulsing rate r_{AP})
- **Subtract dark count** contribution
- extract **after-pulsing probability P_{AP}** corrected for after-pulsing cascade

$$P_{AP} = \frac{r_{AP}}{1+r_{AP}}$$



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

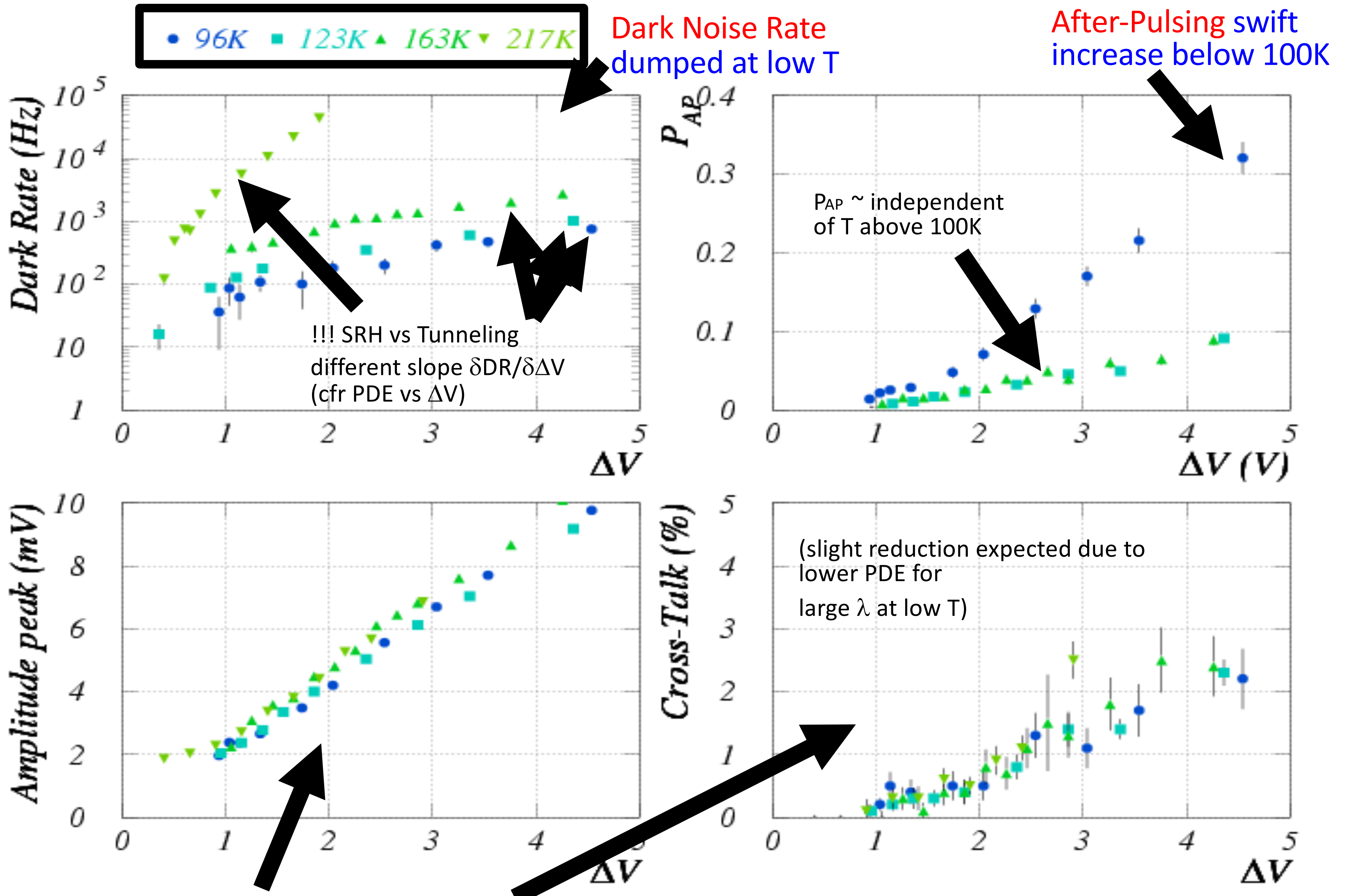
T decreasing: increase of characteristic time constants of traps (τ_{traps}) compensated by increasing cell recovery time (R_q)

- several % below 100K

T<100K: additional trapping centers activated possibly related to onset of carriers freeze-out

The growth of micro-cell recharge time help reducing the after-pulsing at low T

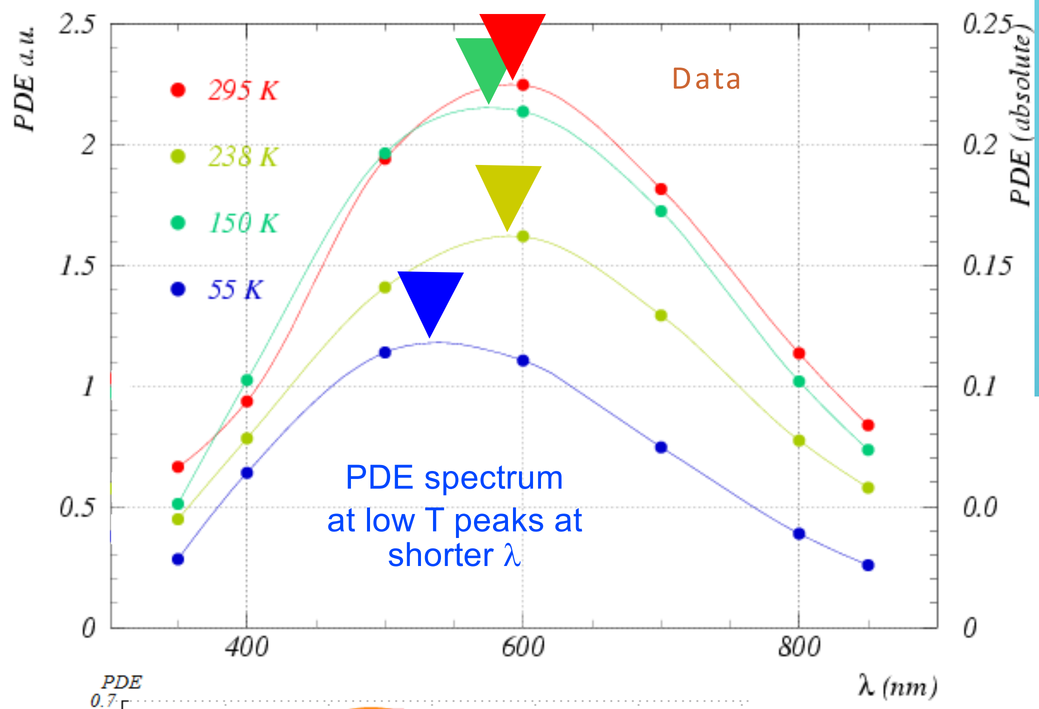
QUICK GUIDE: DARK RATE, AFTERPULSES, CROSS TALK

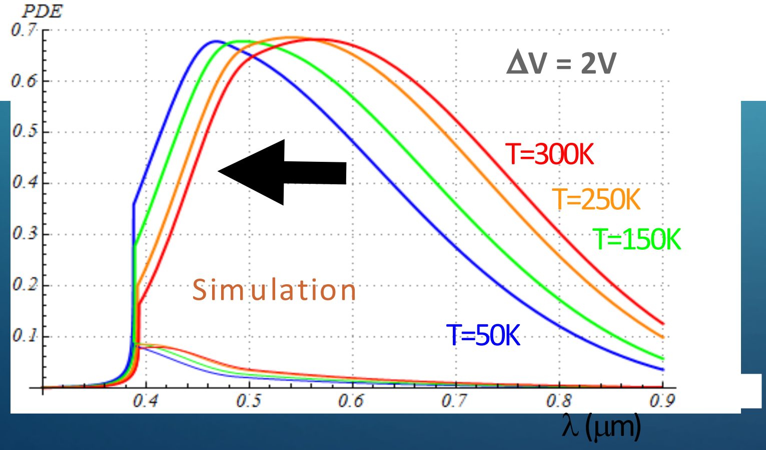


Gain and Cross-Talk are independent of T

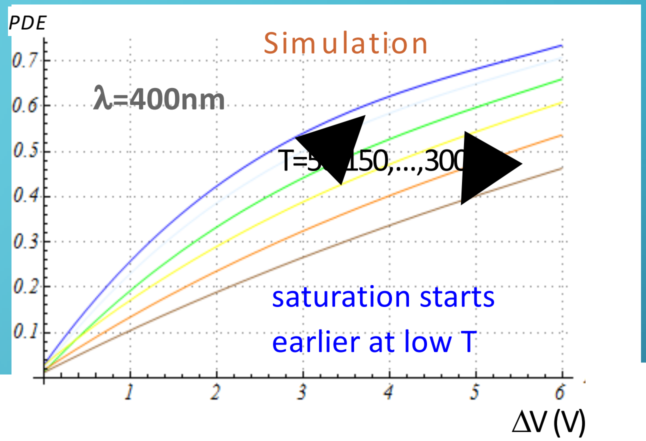
SPECTRAL SENSITIVITY

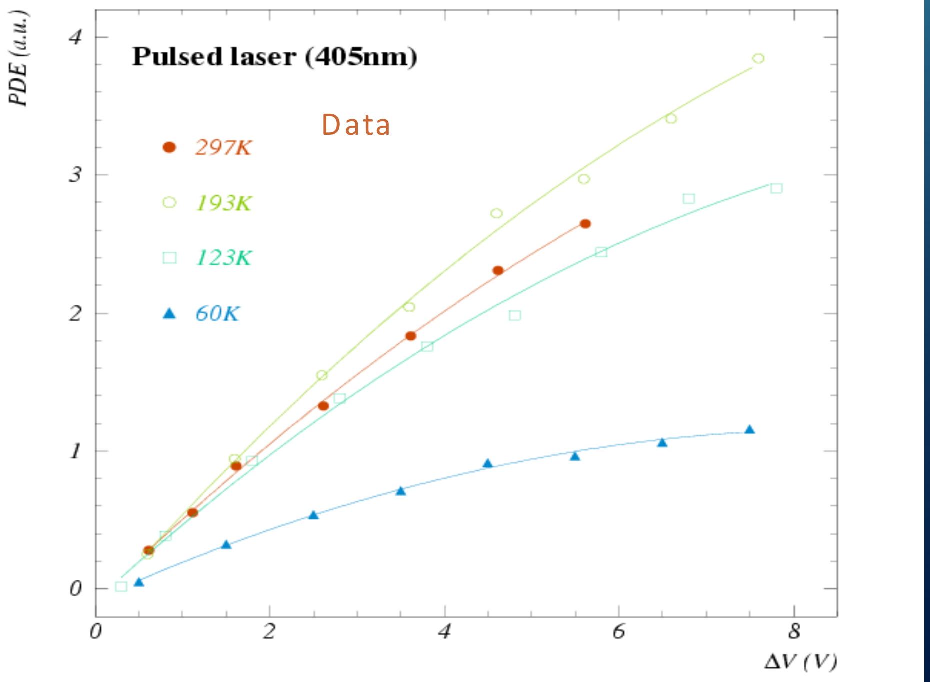
PDE vs λ (ΔV constant)





PDE ΔV vs (λ constant)



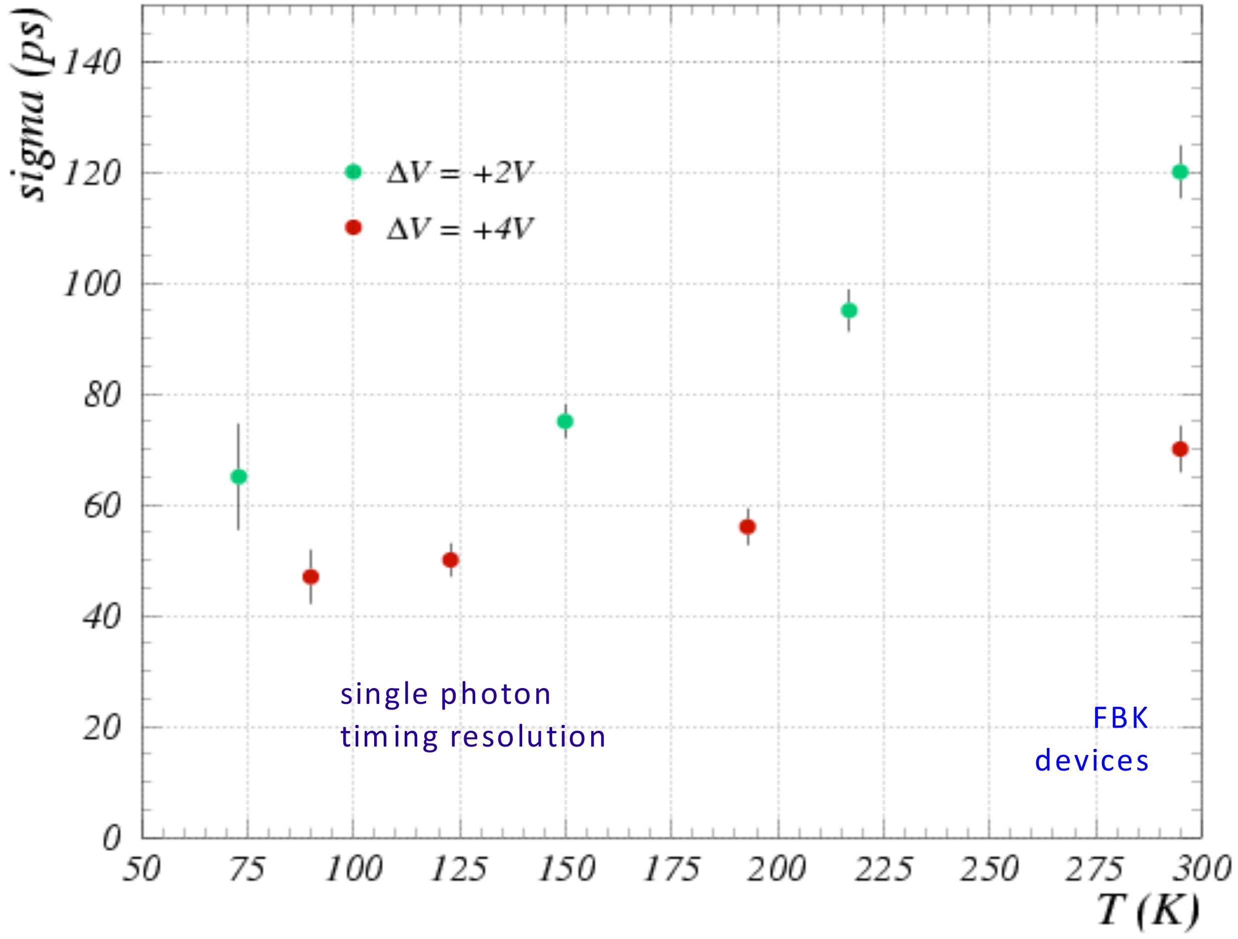


TIMING AT LOW TEMPERATURE

- Timing resolution improves with decreasing T
- Lower jitter at low T due to higher mobility:
  - a) avalanche process is faster
  - b) reduced fluctuations

NOTE:

- Ultimate timing resolution not likely to be a major factor for LXe/LAr experiments



G.C. (2011, unpublished)

SUMMARY

- Area of intensive research. Large body of results (very selected examples shown for the illustration) confirming the 'standard model' of SiPMs (no physics beyond the standard model, yet)
- Useful guide for the developments of specialized SIPMs (large area/low noise, VUV,..)
- Useful guide for development of testing and characterization techniques and strategies. For example: different physics processes dominate at different temperatures hence some of the characteristics measured at cryogenic temperatures may not be well correlated with the same characteristics measured at room temperatures → need for dedicated cryogenic testing setups.