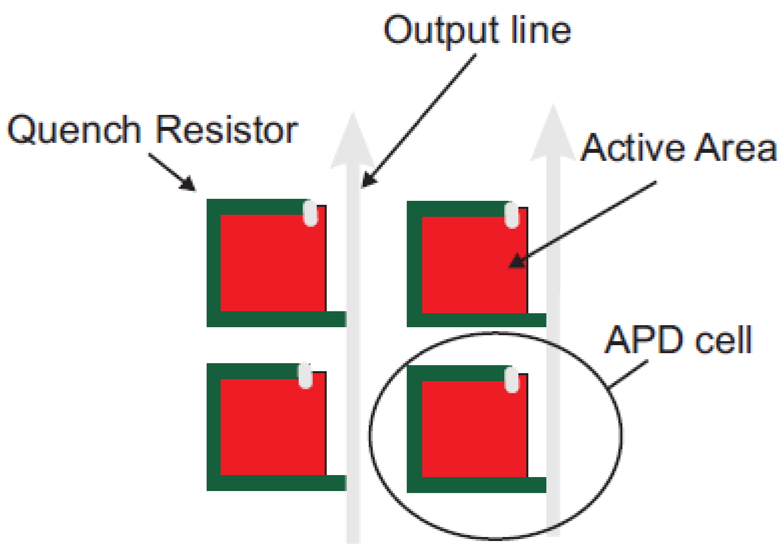
Silicon Photomultiplier

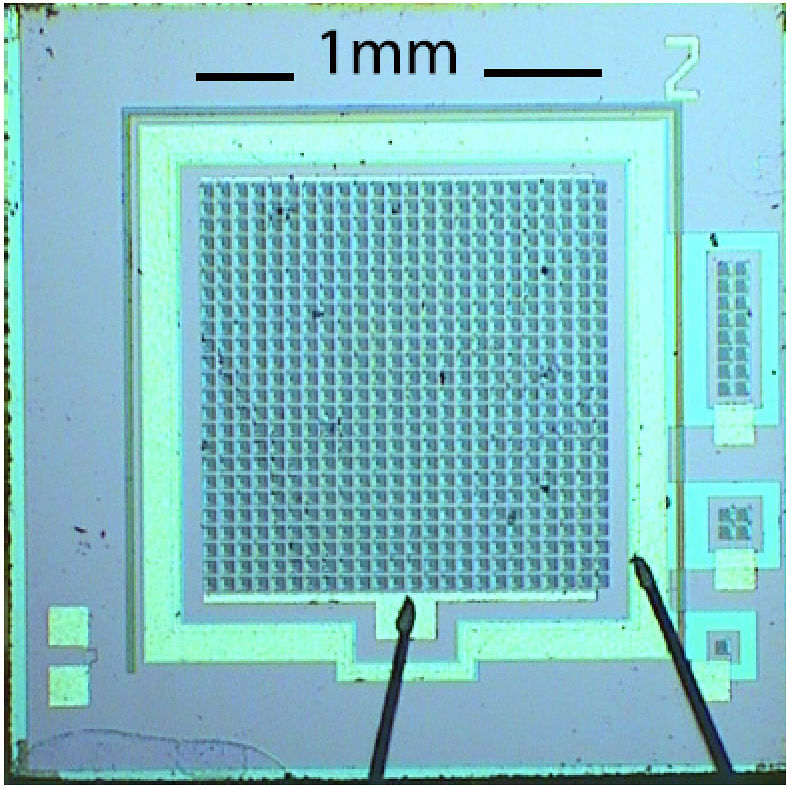
How they work and their application in indirect and direct DM searches

Nepomuk Otte

The Basics



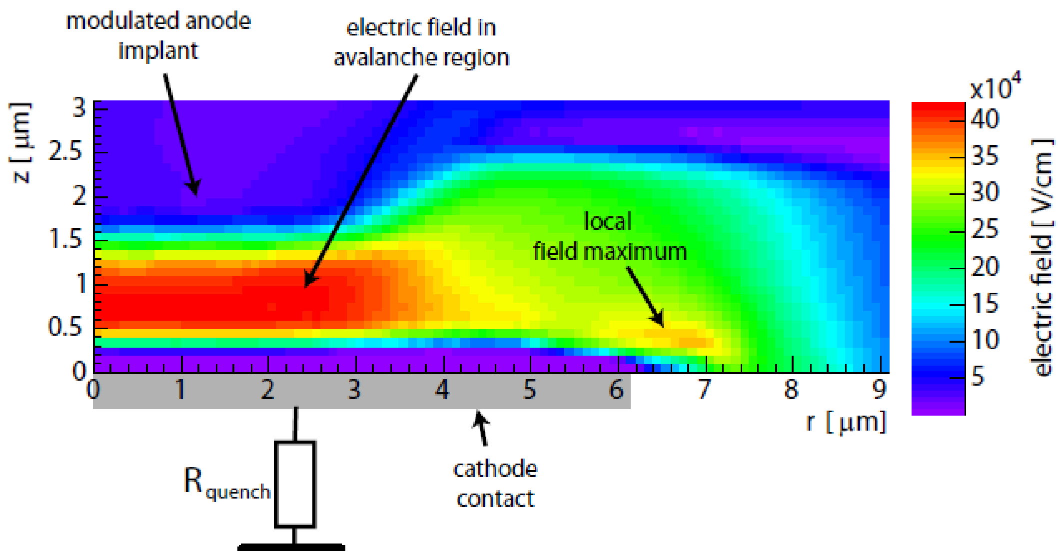
(a) Sketch of four cells of a SiPM

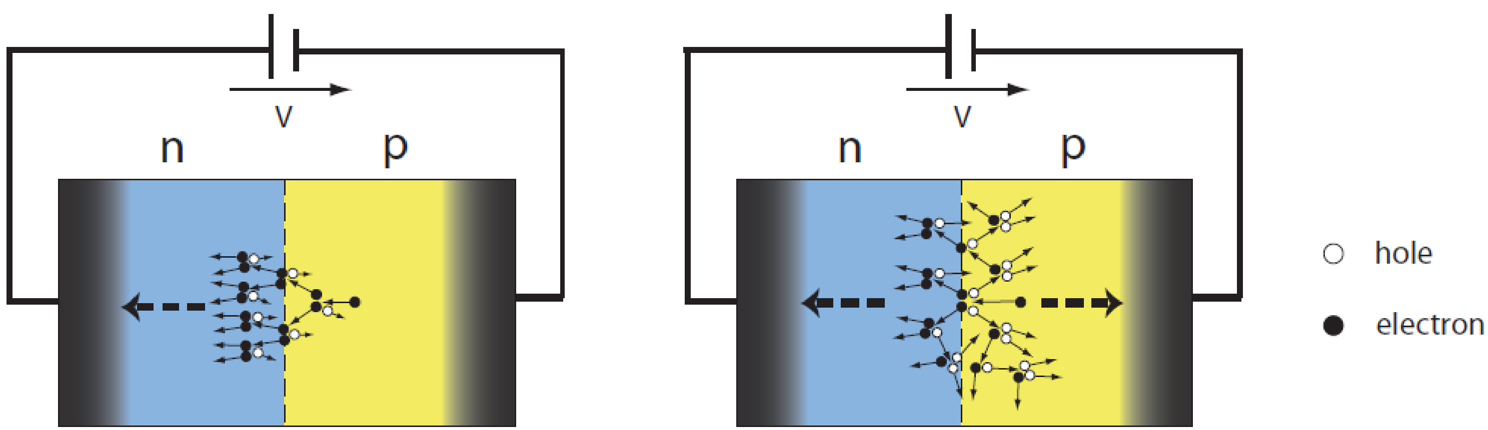


(b) Photograph of a SiPM

Device is not dead if one cell is fired
Cell recovers after breakdown -> reduction of overall efficiency

Dissecting one cell



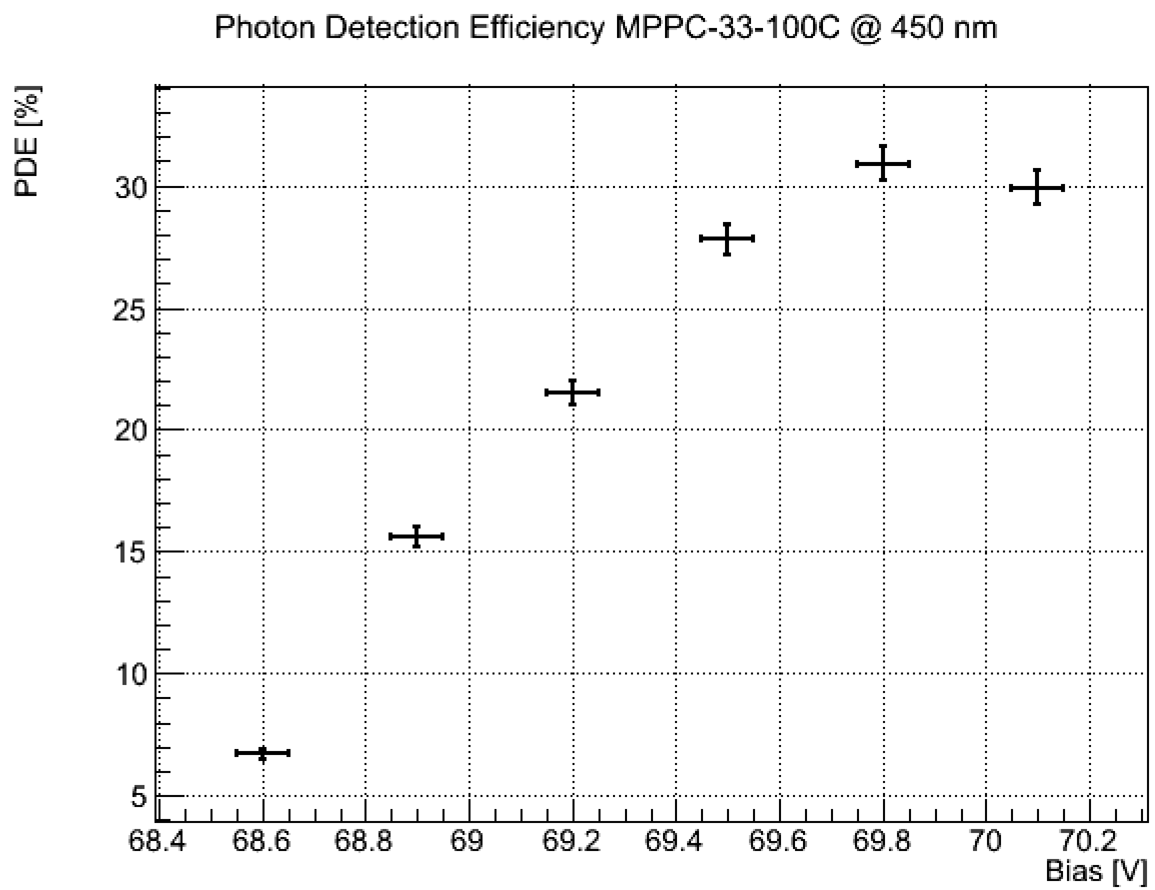


Proportional mode

Geiger mode

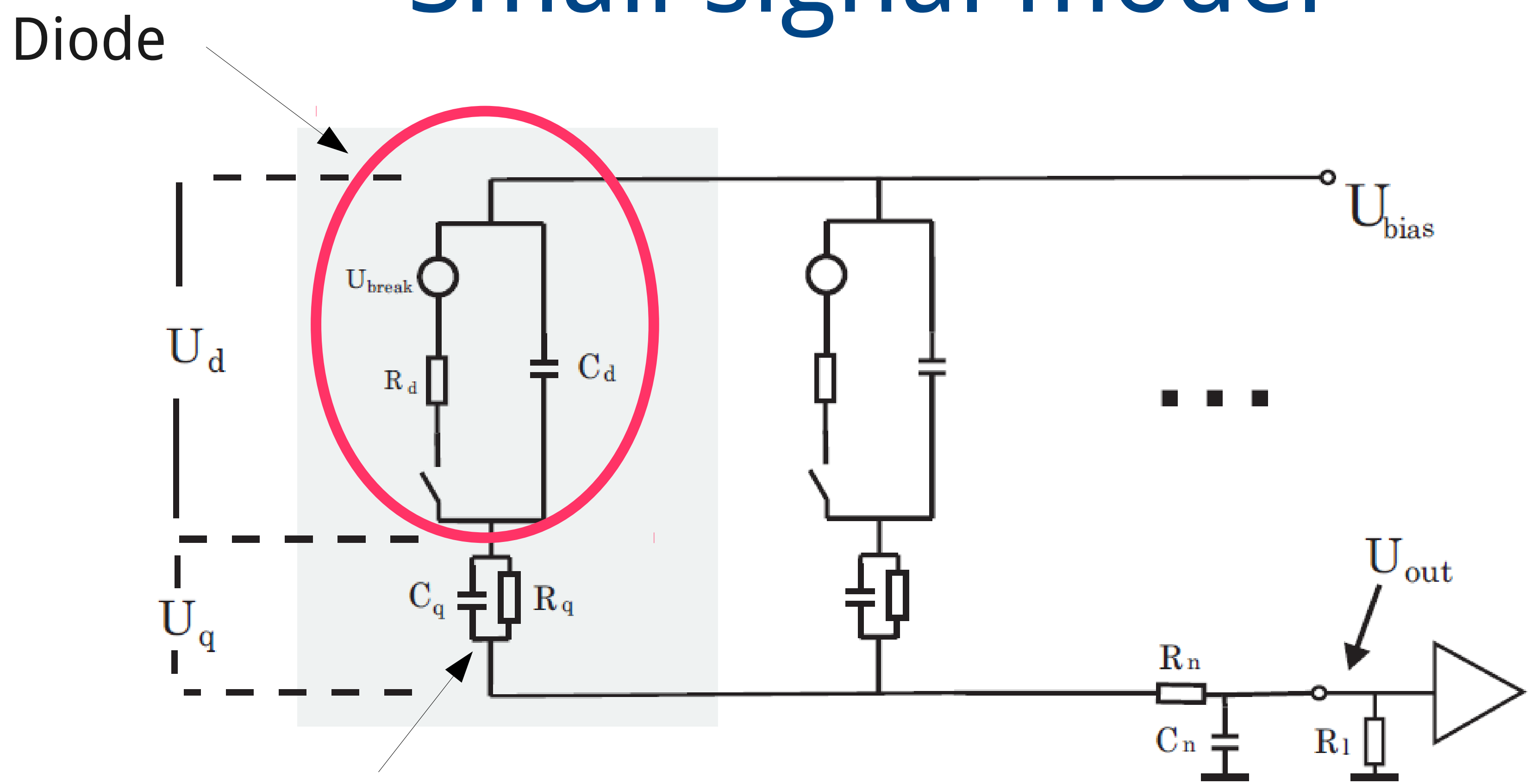
Purpose of quenching resistor is to limit current to < 10...20 uA
If bias is too high -> current is not limited enough anymore

Breakdown Probability: Field Dependence



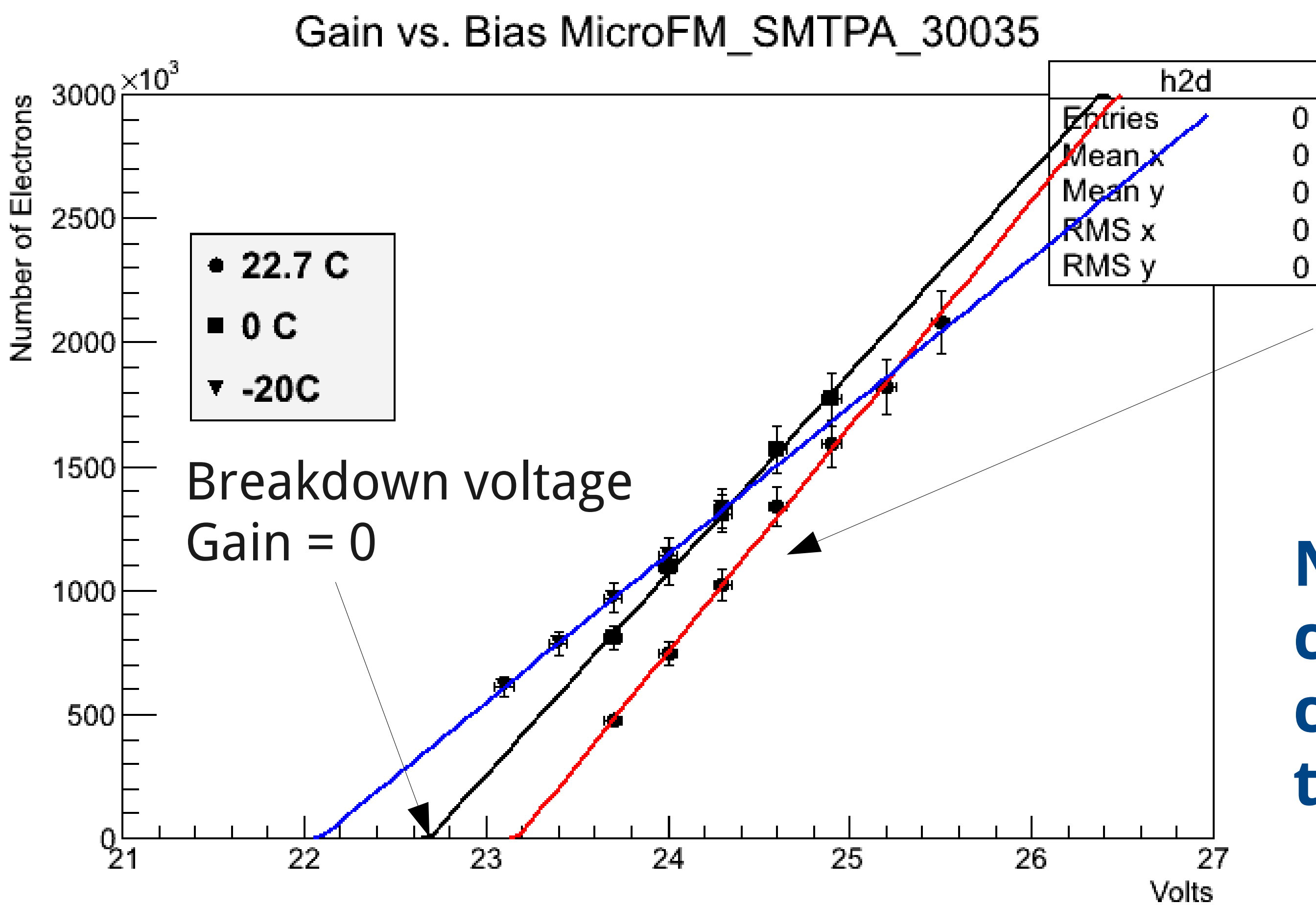
Breakdown probability increases with increasing electric field

Small signal model



Capacitances and resistances determine gain / signal shape

Gain (not in the usual sense)



Slope of gain vs. bias gives net capacitance that is charged/discharged

Note that capacitance can change with temperature

Gain is the discharge of a capacitance (linear dependence on over voltage)
-> knowledge about number of photoelectrons in cell is lost

Photon Emission during Breakdown

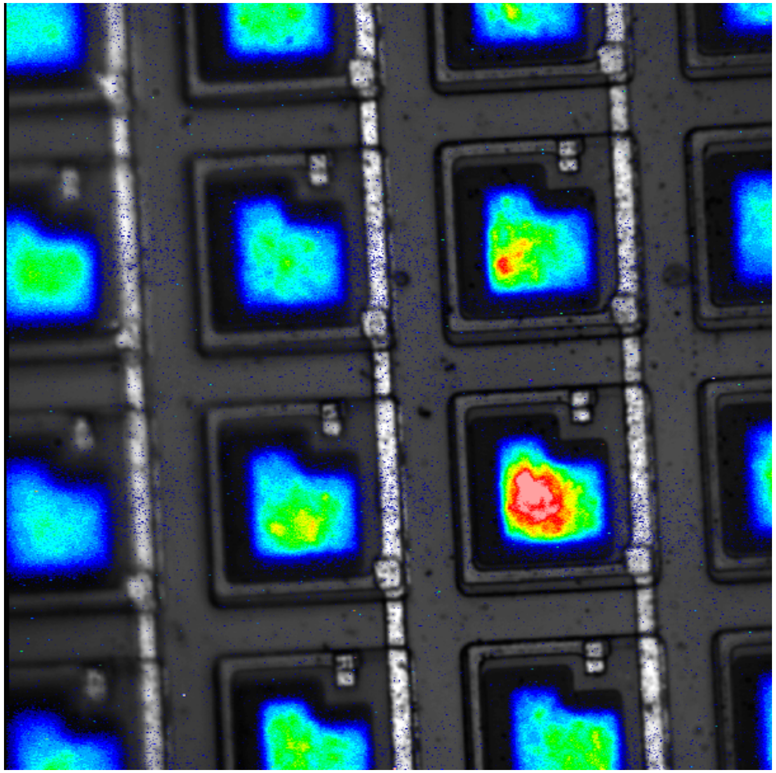
Avalanches produce a lot of photons, emission processes are being debated

Photons in a very narrow energy range propagate out of their originating cell

Photon energies: from 1.1 eV to 1.4 eV

Photon intensity: $3x10^{-5}$ photons per avalanche electron

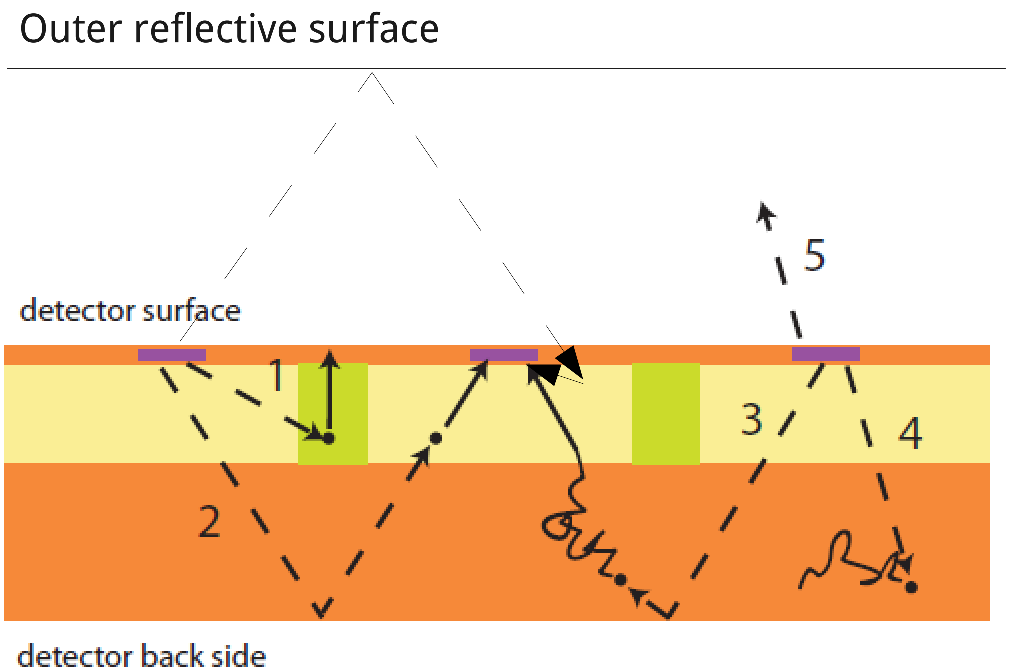
Intensity is direct proportional with gain

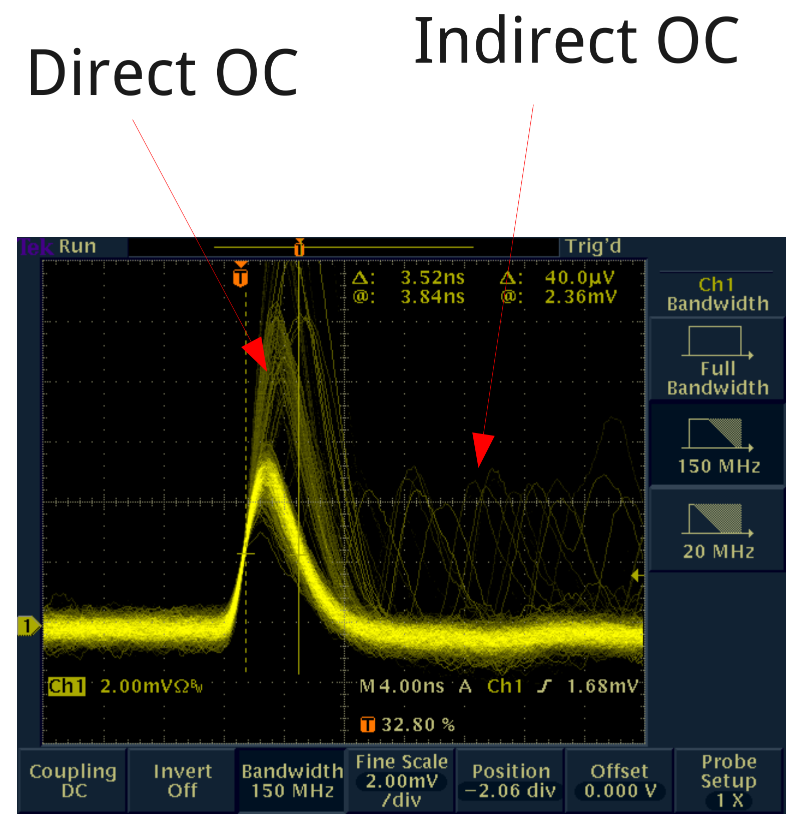


Picture taken by C. Merck

ANO NIM A (610) 2009, 105–109

Optical Crosstalk (OC)





Hamamatsu 3x3mm^2 MPPC, shaped signal

OC is determined by geometry and gain

Trenches and lower gain / capacitance help

It is equivalent to PMT afterpulsing

Temperature Dependencies

- Dark rates
- Breakdown probability
  - PDE, Gain, Optical Crosstalk
- Cell capacitance
  - Gain, Optical Crosstalk

No time to go into details

Factors limiting the Photon Detection Efficiency

- Geometrical occupancy of the Geiger diodes ~50% (aimed at 70%)
- Reflection losses on the SiPM surface (<10% possible)
  - Can be tuned by coating
- λ_{min} determined by thickness of surface implantation
- λ_{max} determined by thickness of active volume
- Breakdown Initiation Probability (~90%)
  - Function of the electric field in the avalanche region

→ Currently achieved PDE 20-40%

Comparison G-APD / PMT

PMTs	G-APD
Large areas	Small <6x6 mm^2
Large gain	Large gain ~10^5- ~10^6
Single photoelectron resolution	Single photoelectron resolution
Well established technology	**Commercially available and lots of room for improvements**
Fast signals (~ns)	Signals ~ns to several 100 ns
Sensitive to magnetic fields	Not sensitive to magnetic fields
Damaged in daylight/sunlight	Not Damaged in daylight/sunlight
Afterpulsing	No Afterpulsing but optical crosstalk
<1 kHz dark count rate per mm^2	100 kHz Dark count rate per mm^2 @ room temperature
Use of high voltage	Bias < 100 V
Bulky and fragile	Electrical and mechanical robust / light weight
Average QE ~25%	**Average QE >20%, possible > 50%**
Temperature stability <0.5%/C	Temperature stability <3%/C
	Low power consumption (μW)

The short List of Requirements

- **Price:** SiPM are presently about as expensive as PMT (often depends on the situation)
  want to be cheaper than PMTs
  (not a matter of production costs)

- **PDE 300nm-600nm:** 100% is the limit but we would even be happy with 60% in the blue
  seems possible in the future **Biggest challenges**

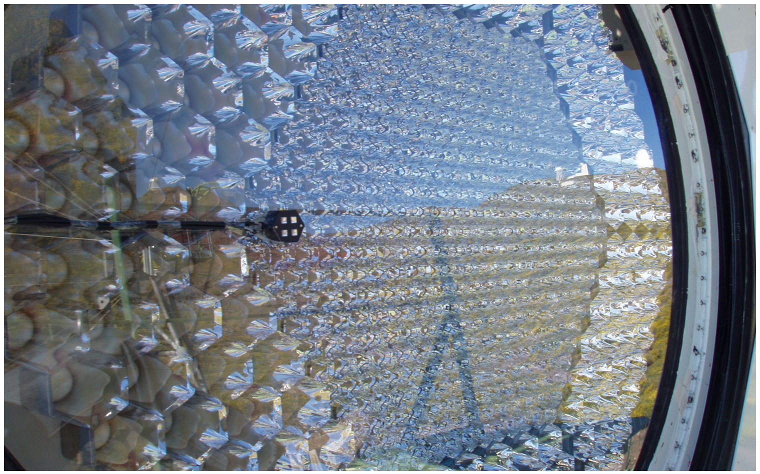
- **Size:** 5x5 mm^2 to 10x10 mm^2

- **Dark count rate:** < 100 kHz/mm^2 needed
  Thermal generated Charge carriers, afterpulsing, optical crosstalk
  achieved by some devices at room temperature otherwise
  moderate cooling necessary

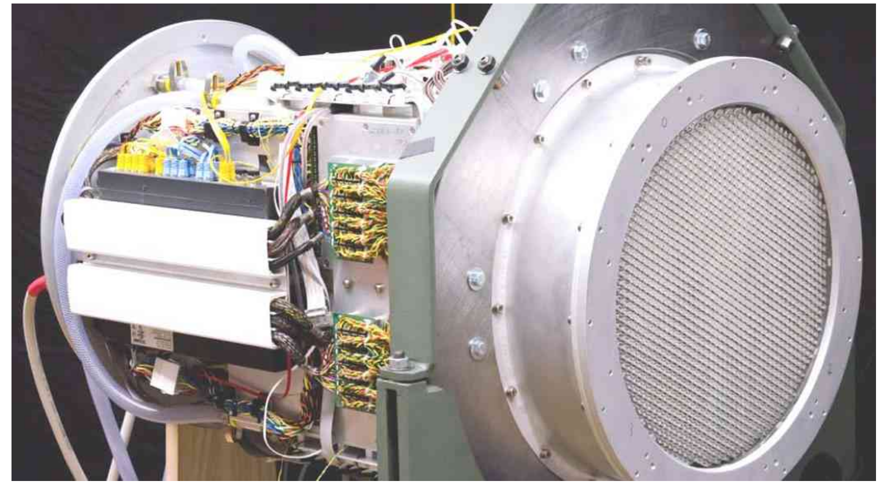
- **Temperature Dependence of Gain:** varies between ~5%/K and 0.3%/K; 0.3%/K is ok
  Requires large breakdown voltages, small cell capacitances, high overvoltages

- **Optical Crosstalk:** can be several 10%, needed are less than a few %
  Trenches between cells -> now pursued by most producers but not standard

SiPM in Astroparticle Experiments



From first tests (2004-2007)



To the first SiPM camera in operation (FACT) 2011

To the first array of IACT with SiPM
The SC-MST and SST component of CTA

Direct Dark Matter Detection

Example:
liquid Xe ->scintillation light at 178 nm operating temperature –100 C

Advantage of SiPM: no radioactivity
low mass,
no power
Excellent single phe resolution
Low bias voltage

Problem: PDE @ 178 nm
Operating temperature at -100 C

NEXT collaboration: coating of SiPM with tetraphenyl butadienne (TPB) to enhance VUV sens.

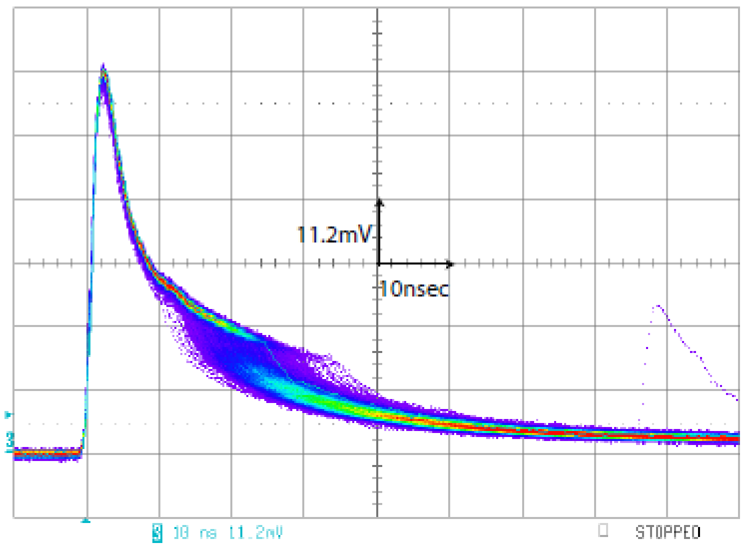
A huge Advantage: Different Vendors

- Hamamatsu
- Excelitas
- ST-Microelectronics
- KETEK
- ...

Conclusions

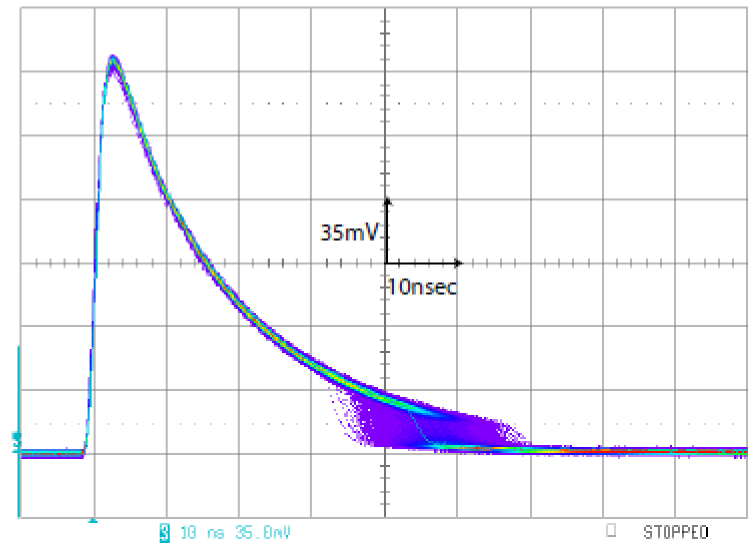
- SiPM have matured enough to be considered baseline photon detectors in many HEP and AP experiments, e.g. SC-MST and SST part of CTA
- Not much activity in researching SiPM for direct DM experiments
- Still relatively young device with lots of room for improvements. For example why Si? Other compound semiconductors can be more attractive and better suited for some applications.

100 fF



(c) 2 MΩ 100 fF

200fF



(d) 2 MΩ 200 fF

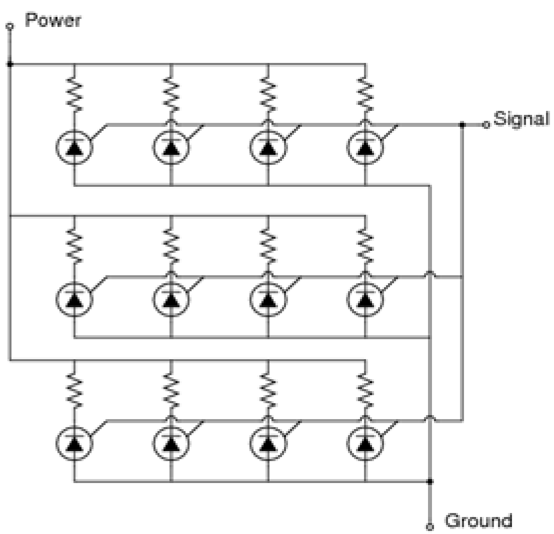
In general larger capacitance mean longer decay times

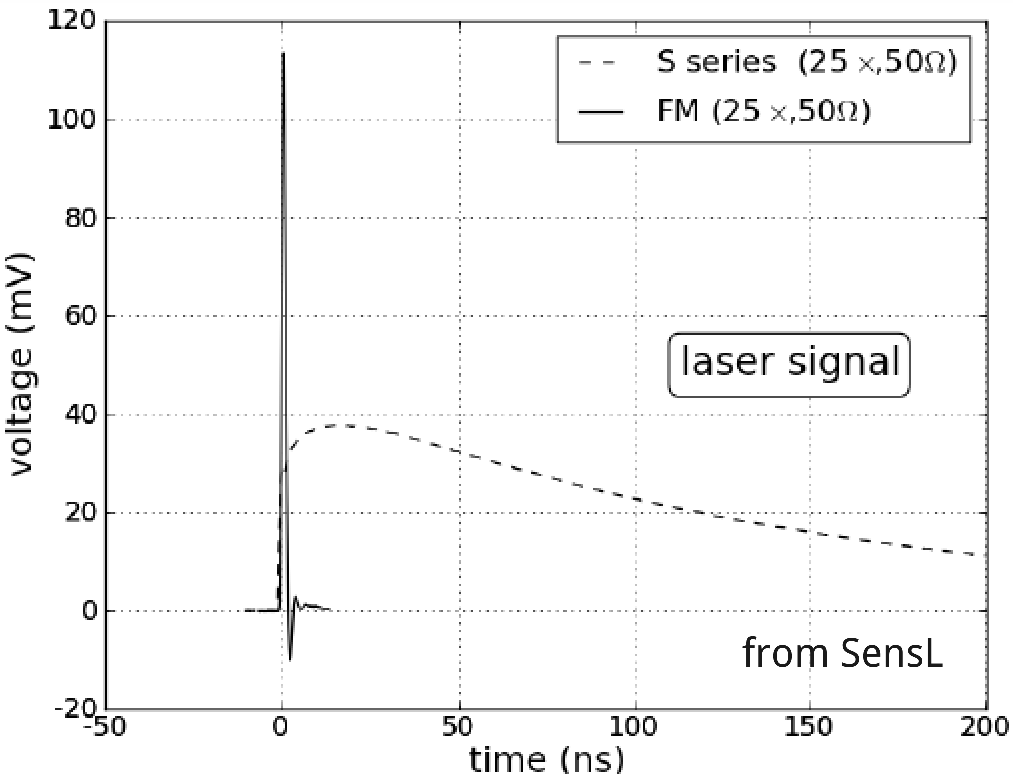
Note that normally you cannot infer from signal shape when quenching occured
The above is not the norm. Also the recharge of the cell is mostly not visible. In the above case the recovery times are >400 ns

Faster output pulses

What we want are signals that are a 5 ns wide

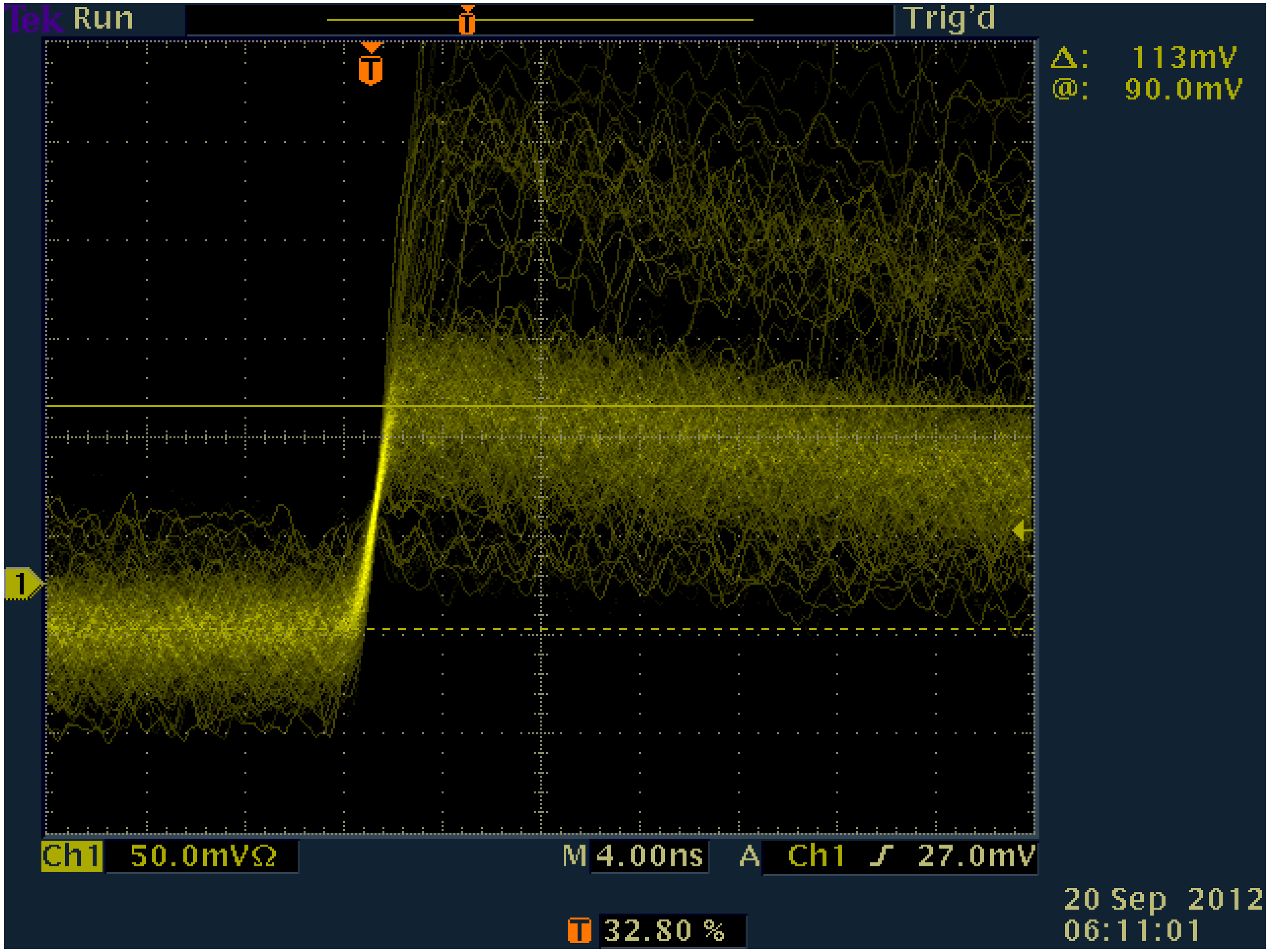
SensL: get signal by capacitive coupling between diode and resistor





pulse widths ~ ns

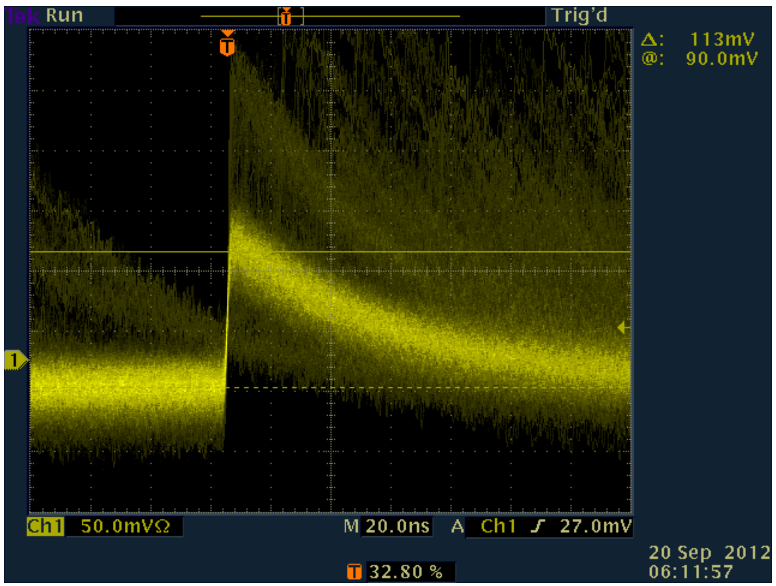
Signal shaping



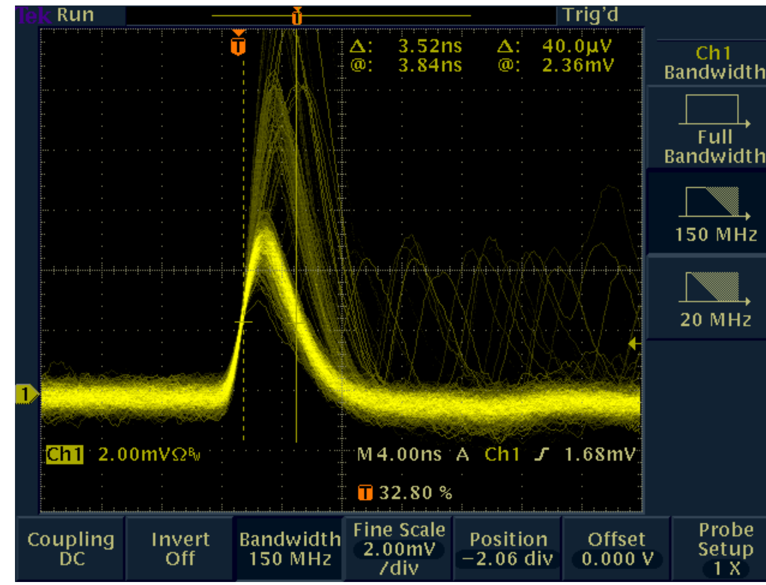
Differentiate signal: Works if rise time is small and decay time is long

Hamamatsu 3x3 mm^2 MPPC

before

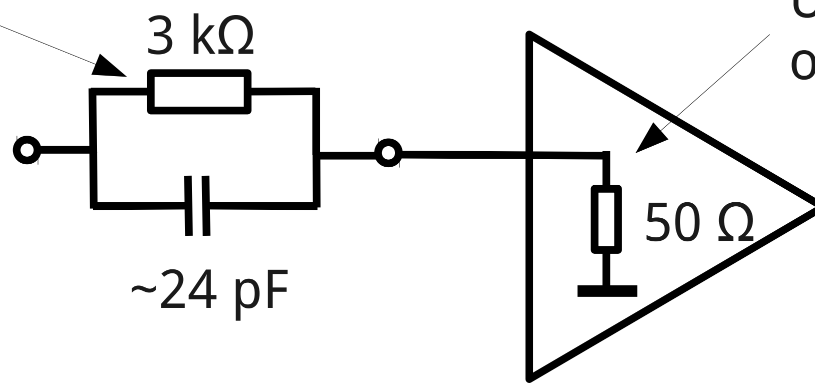


after
(note 150 MHz bandwidth)



Pole zero cancellation
not really needed

Use input impedance
of next stage



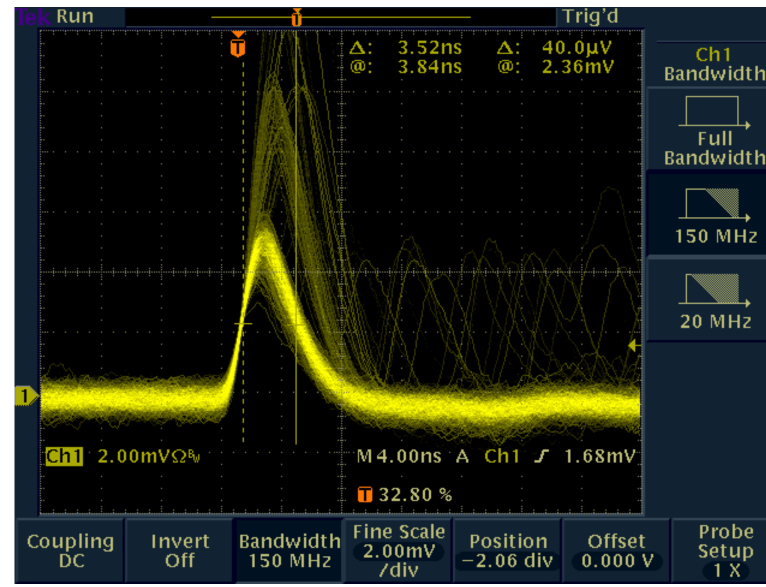
How much Optical Crosstalk is bearable?

Requirement: Want that accidental rate at optimal discriminator threshold is dominated by random pile up of NSB signals and not direct OC. Otherwise the threshold goes up.

Example:

- 30 MHz NSB per pixel
- Summing 4 pixel in trigger
- 4 phe threshold in discriminator
- Coincidence window 4ns

Summed pixel trigger rate ~ 200kHz



OC probability < $(200\text{kHz}/120\text{MHz})^{1/4}$ = 20%

Higher OC -> clipping

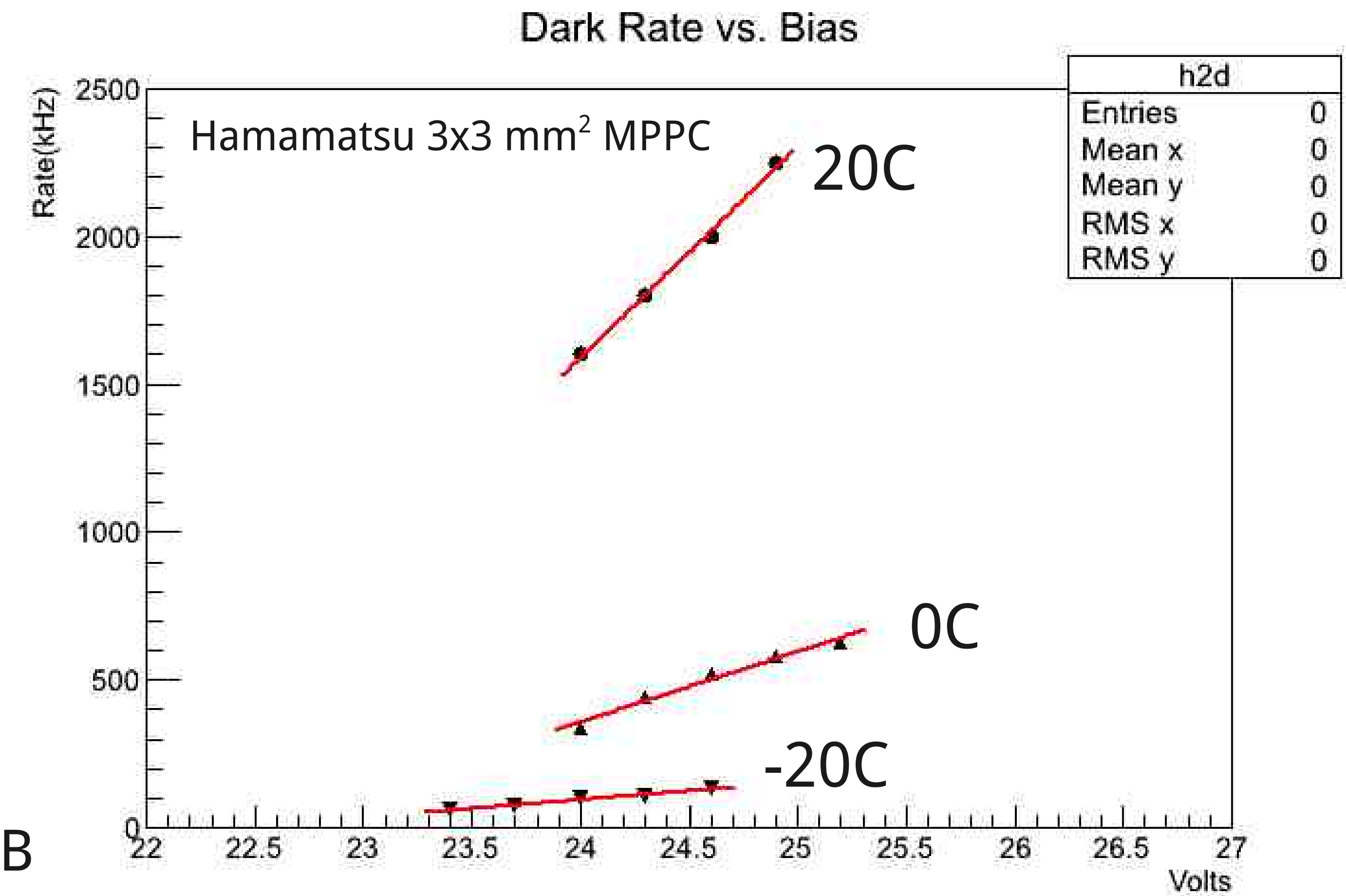
More precise OC requirements depend on trigger details -> simulations

Dark Rates

Rule of thumb:
dark rates drops by a factor of 2 every 8-10 C change in temperature

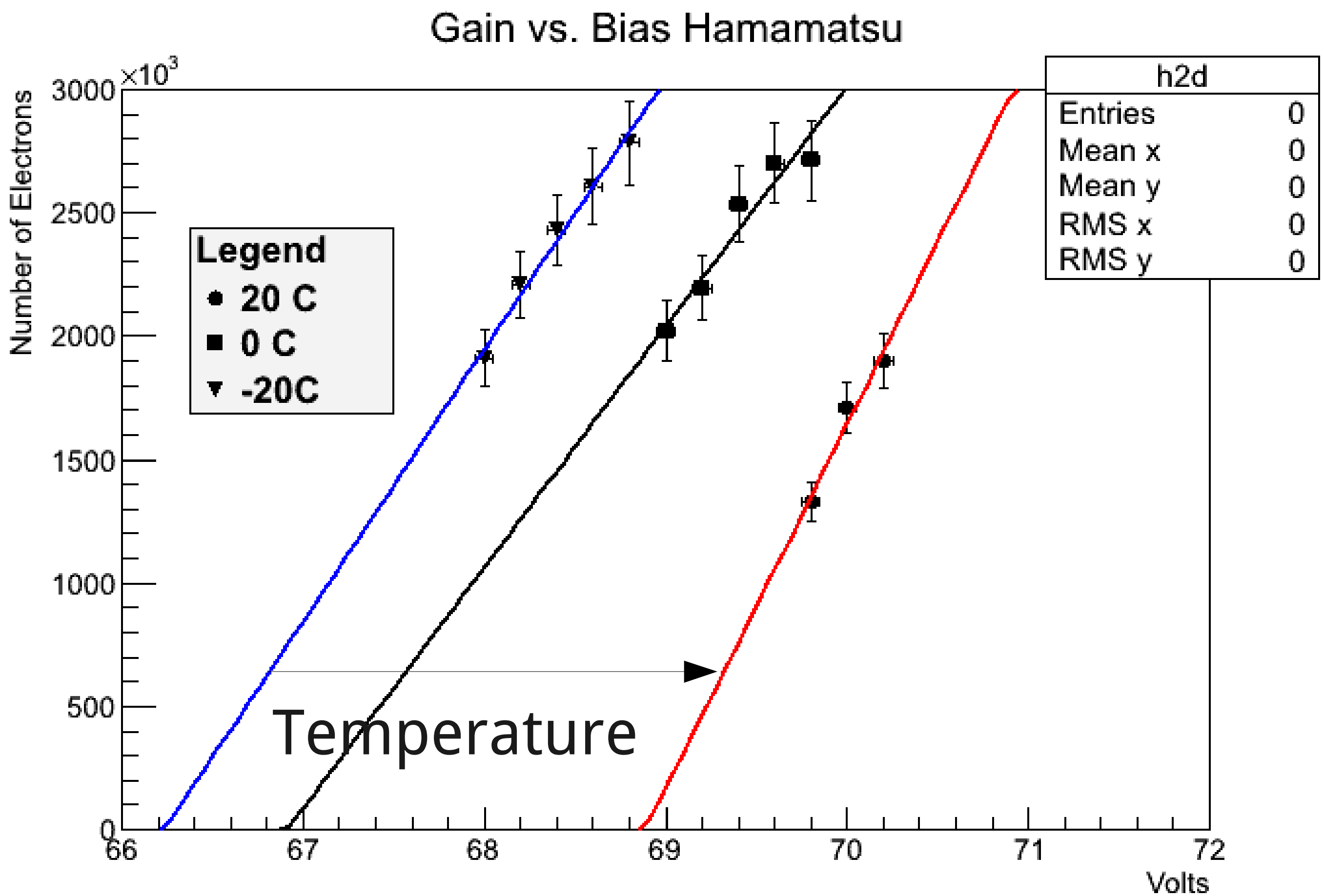
Absolute rates depend on technology

We expect 300 - 600 kHz per mm^2 from NSB



We do not worry about dark rates as long as they are about the same as the NSB or less

Breakdown voltage



Breakdown E-field depends on temperature

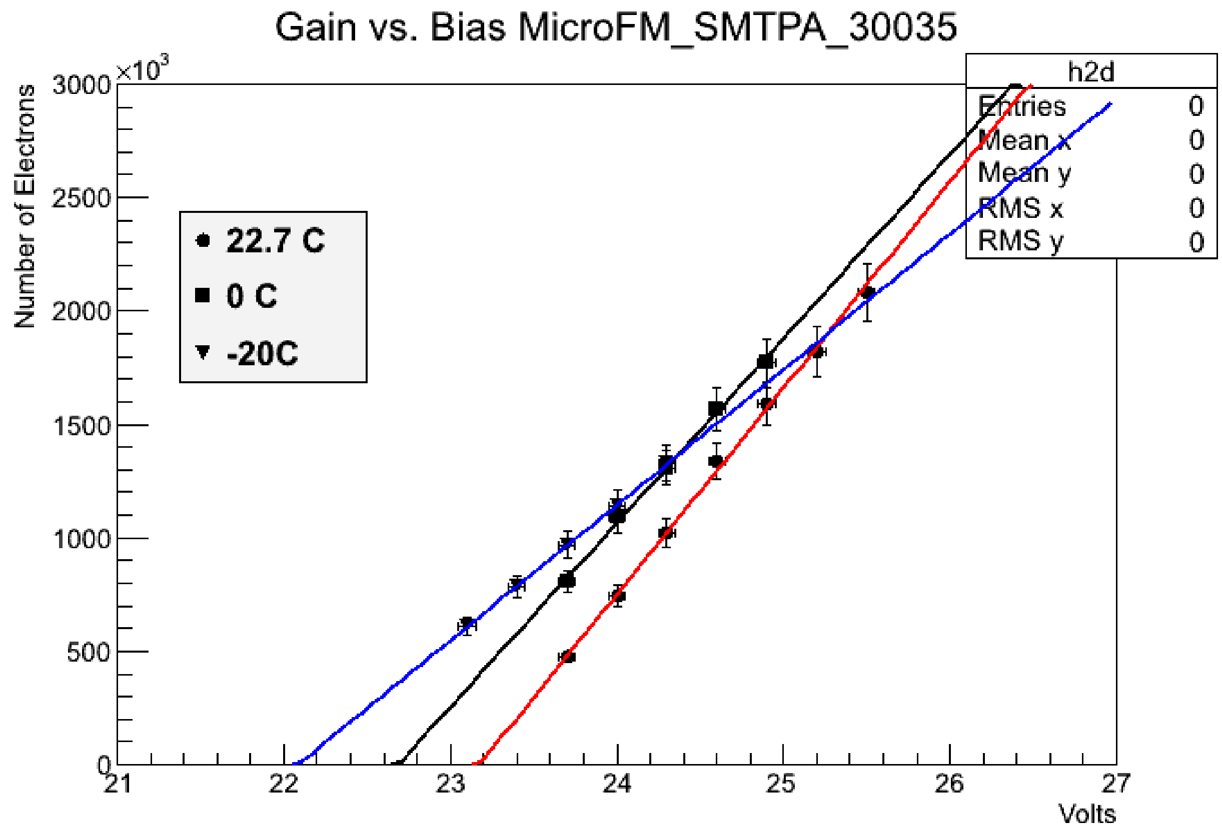
-> gain changes with temperature ~2-3 % / degree

The smaller the capacitance the smaller the temp. dependency

Dependency of cell capacitance on temperature

Slope = capacitance

-> changes with temperature



Operate at same gain => not the same E-field

=> not the same breakdown probability

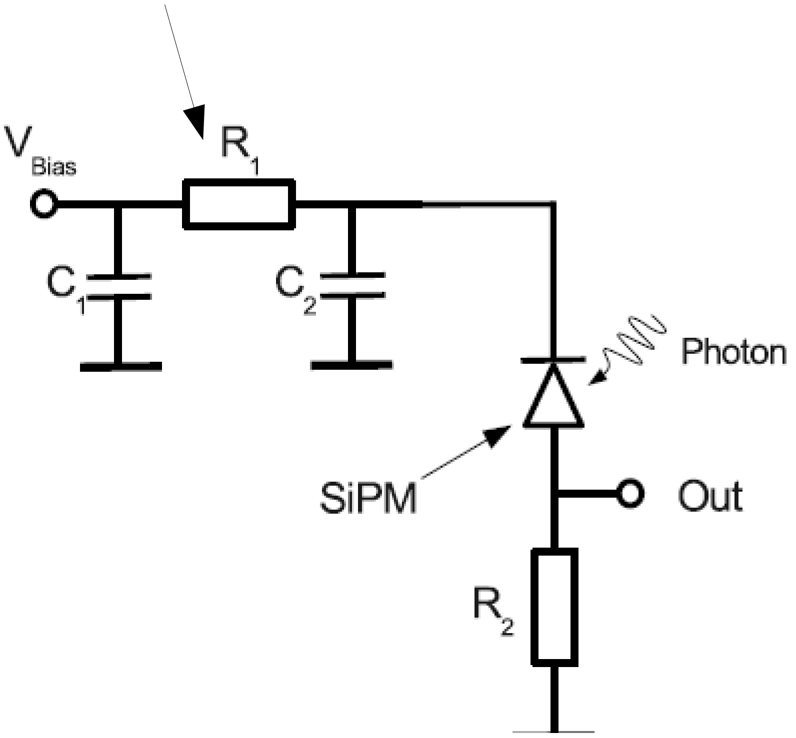
=> not the same PDE

Peace of mind: Operate at stable temperature +/- 0.5 C or better

Dependency of gain on NSB rate

Replace with inductor

Larger NSB -> larger current
-> larger voltage drop over R1
-> lower bias on SiPM
-> lower gain / PDE



Example Hamamatsu:
Change in NSB rate by 100 MHz
-> 25% change in gain

Again, lower capacitance would help

Possible solution use inductor instead of resistor