Photodetectors

Lecture at EDIT 2018

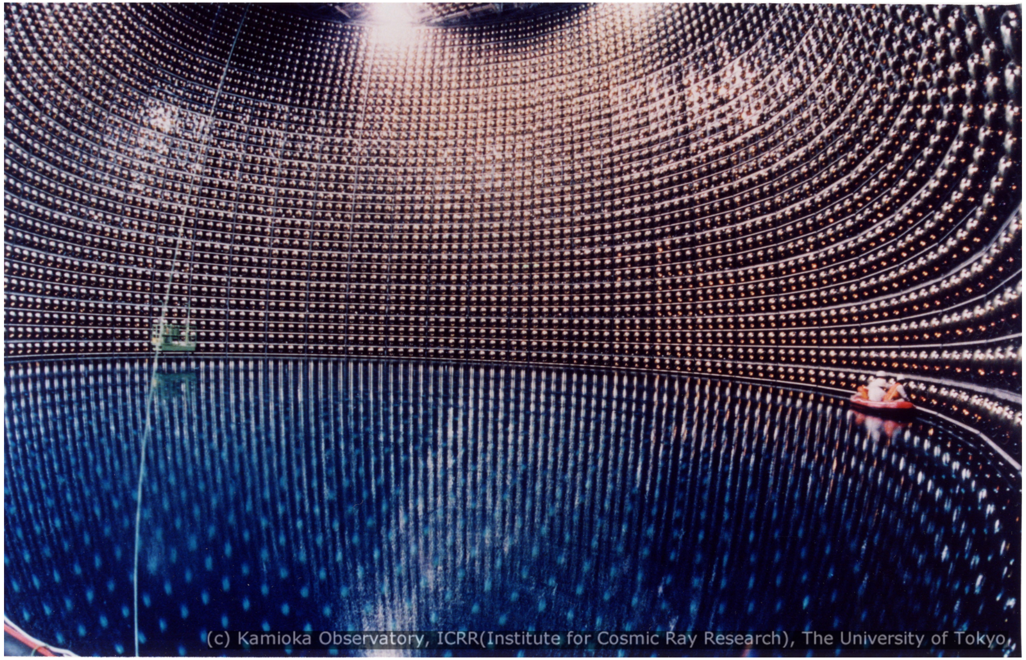
Nepomuk Otte

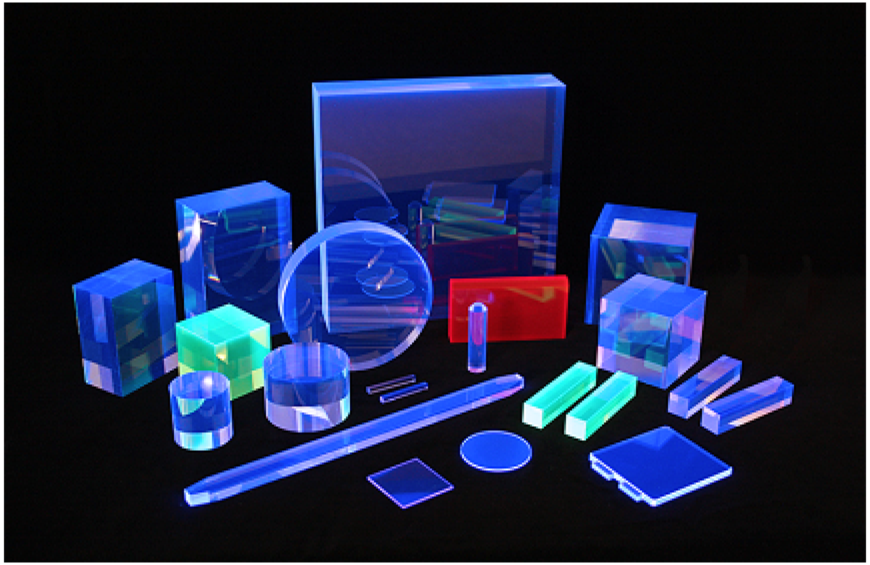
School of Physics
&
Center for Relativistic Astrophysics

Georgia Tech Physics College of Sciences

Photodetector Applications in Physics

- Used to detect:
  - Scintillation
  - Cherenkov
  - Fluorescence





Photoelectric Effect

- Discovered in 1887 by Hertz when exposing negative electrode to UV light.
- Explained by Einstein in 1905 → Nobel Prize

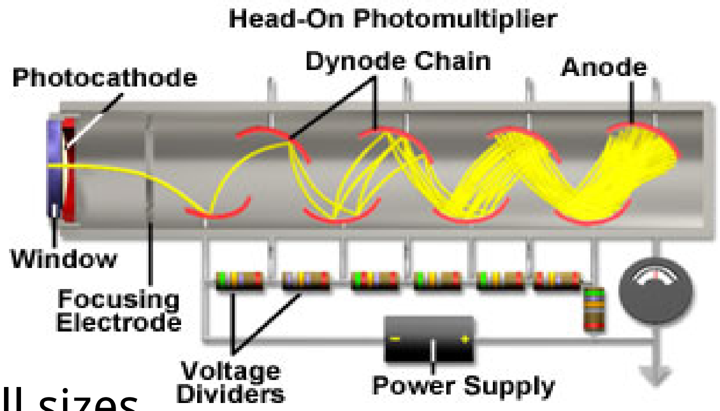
Light is quantized

$$E = h\nu = \frac{hc}{\lambda} = \frac{1240}{\lambda[nm]} eV$$

→ in order to create a free charge carrier a photon must have more energy than the binding energy of the charge carrier

Photomultipliers

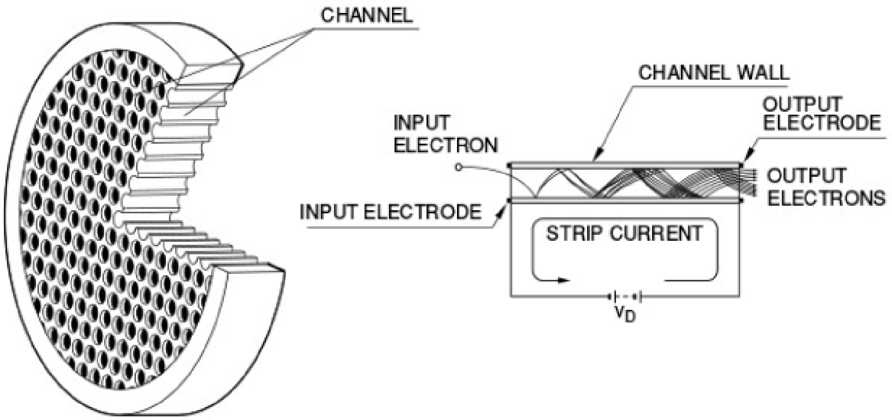
- Most often used photon detector in HEP
  - High efficiency
  - Single photon response

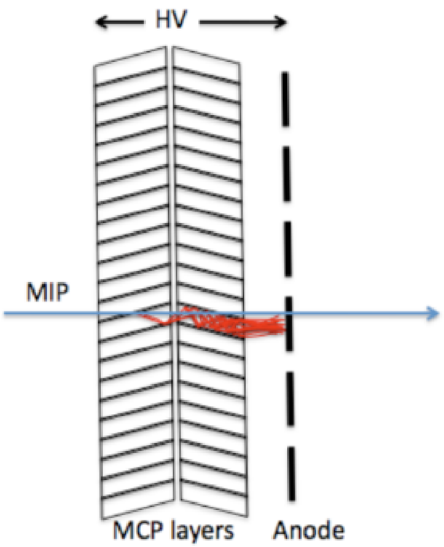


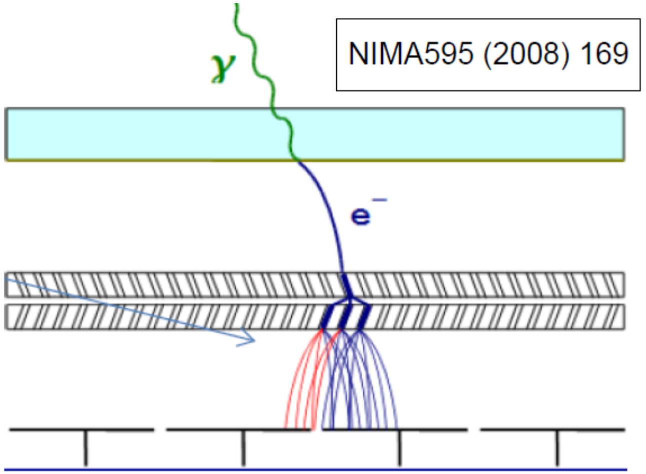
But:
- Labor intensive production
- Glass → can break
- Bulky → difficult to scale to small sizes
- Needs high voltage
- Sensitive to magnetic fields

For an excellent resource on PMTs:
http://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf

Micro Channel Plates



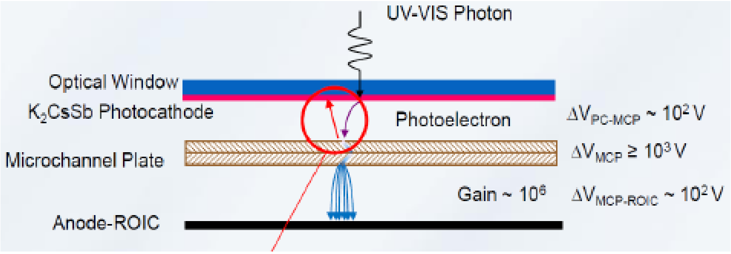


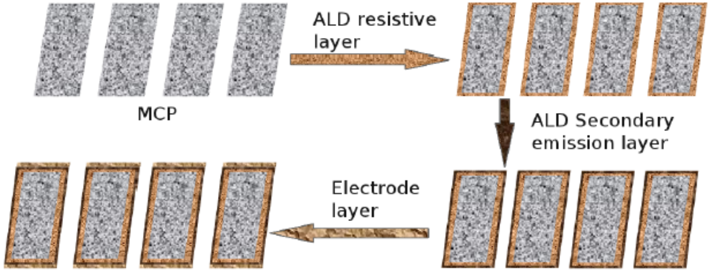


- Fast timing <30ps for single photoelectrons
- Channel diameters 5-26 um
- Thickness 0.4 – 1 mm
- Gain >1000
- Rate capability ~1MHz/cm^2
- Used as charged particle detector
- Or photon detector when combined with photocathode

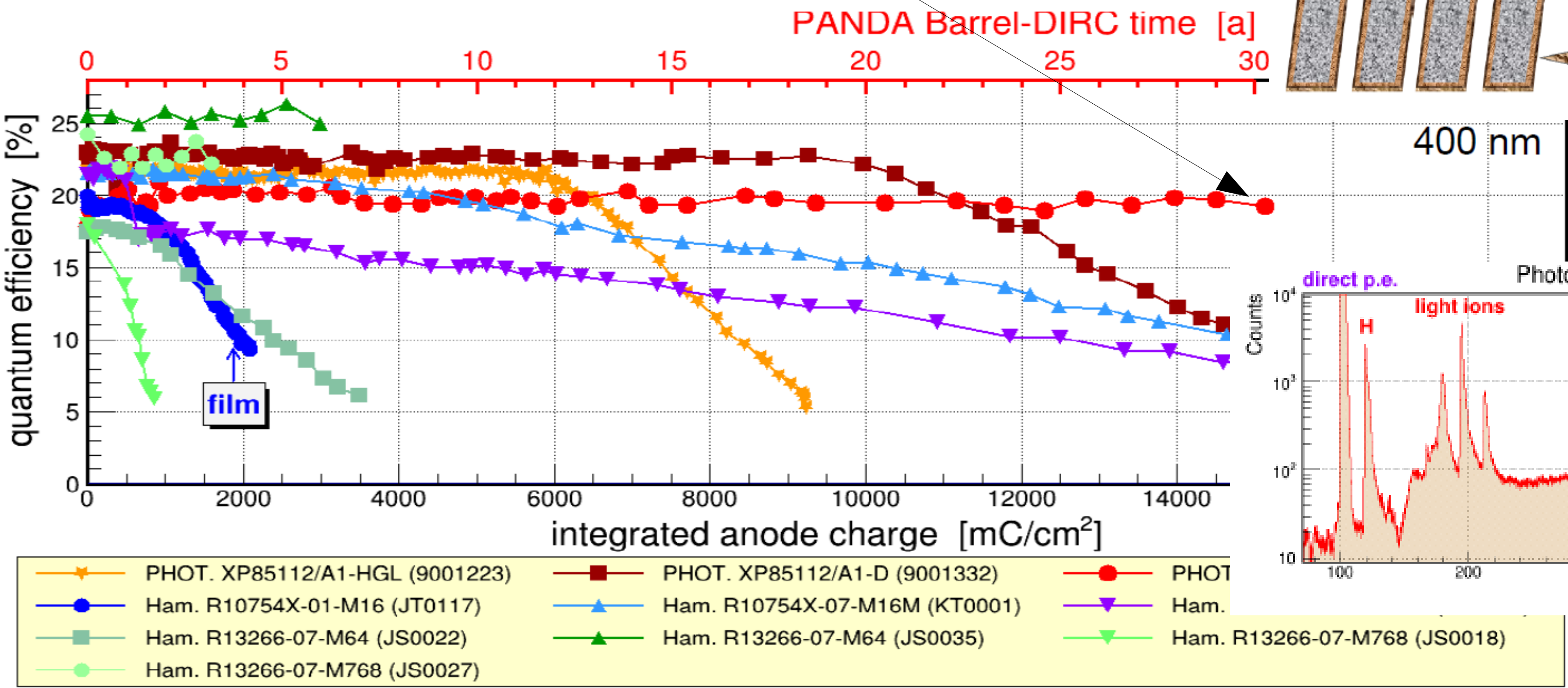
Aging (A. Lehmann)

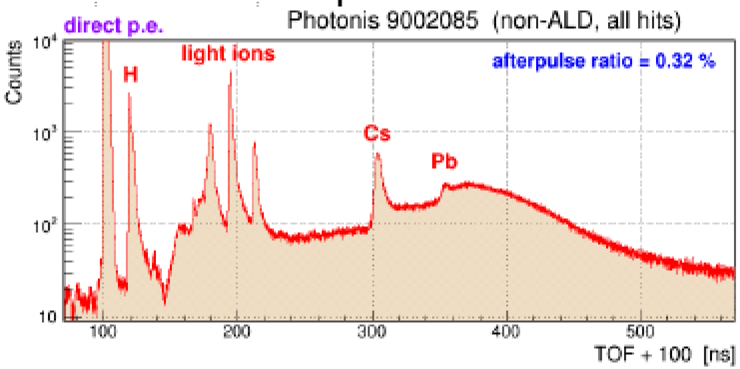
- Atomic Layer Deposition was key to reduce aging





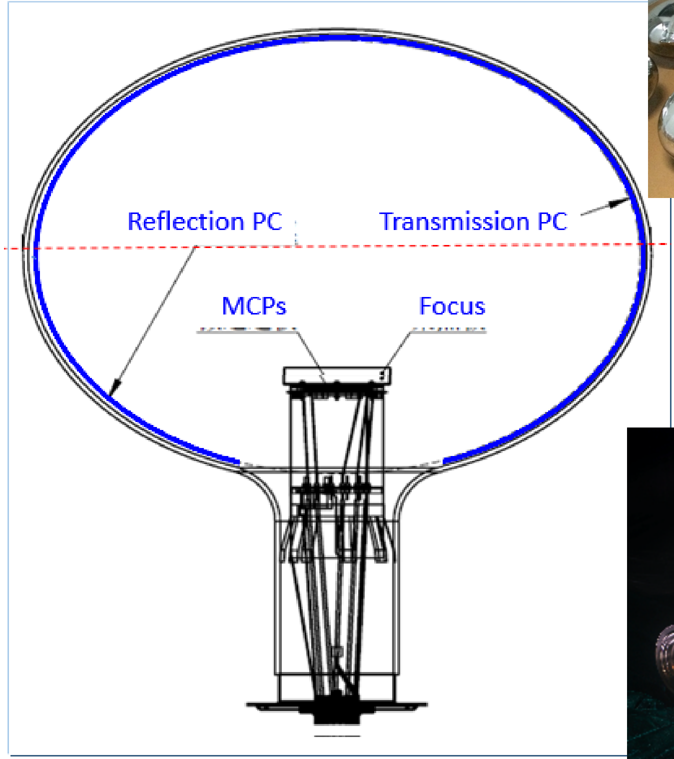
No sign of degradation after 15C/cm^2





MCP PMTs for JUNO

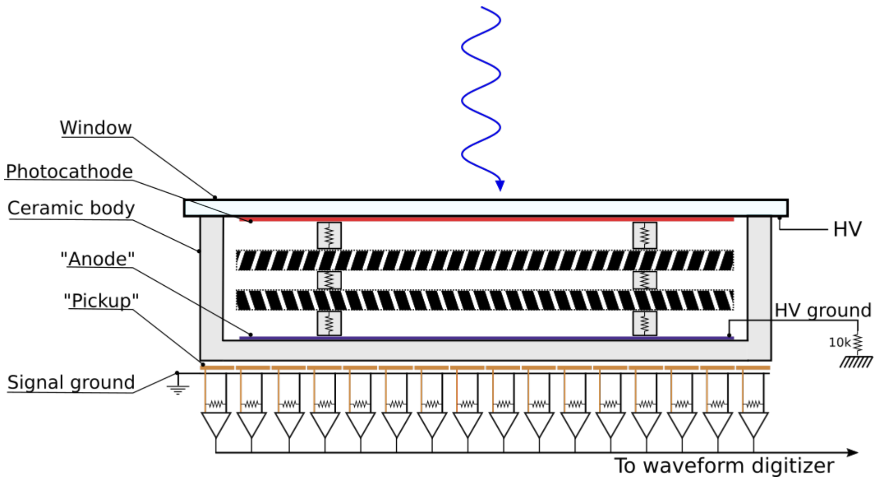
S. Qian

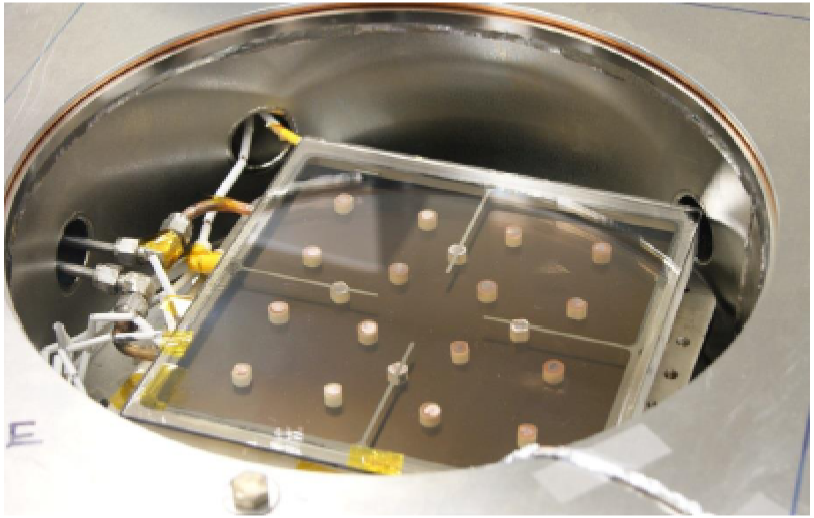


PMT Parmaeters	data in Contract	Prototype	2687 mass production
单波长 QE@410nm	≥ 26.5%	~ 26%	29.2%
均匀性 （ QE Uniformity ）	≤ 10%	≤ 10%	7.7%
单光子探测 （ SPE-P/V ）	≥ 2.8	~ 5.6	6.9
能量分辨率 （ SPE-ER ）	≤ 40%	~ 41%	33.4%
高压 （ HV ）	≤ 2800V	~ 1780V	1747V
探测效率 （ DE ）	≥ 24%	~ 26%	29.2%
暗计数率 （ DR ）	≤ 30KHz	~ 30KHz	40.0 KHz
渡越时间涨落 （ TTS ）	≤ 15ns	~12ns	20.6ns
后脉冲率 （ APR ）	≤ 5%	~ 2.5%	0.7%
非线性 （ Linearity ） <10%	≥ 1000pe	~ 1000pe	1293pe
信号波形 （ RT ）	≤ 2ns	~ 1.2ns	1.4 ns
信号波形 （ FT ）	≤ 12ns	~10.2ns	25 ns

Large Area Picosecond Photodetector

H. Frisch, A. Lyashenko, V. Fisher, B. Wagner



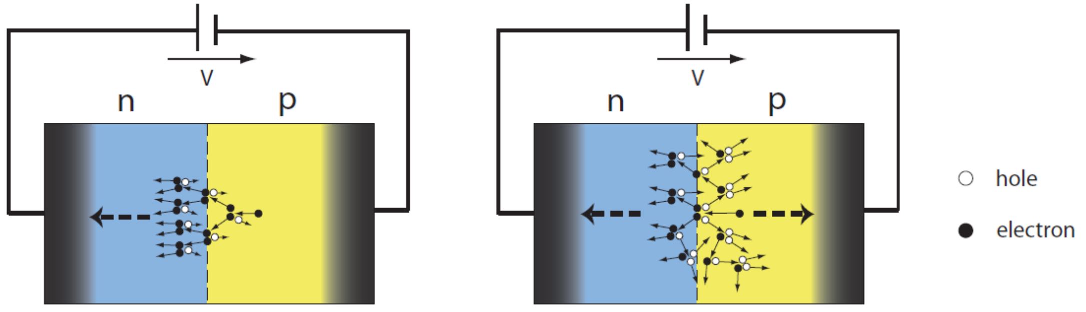


U. of Chicago

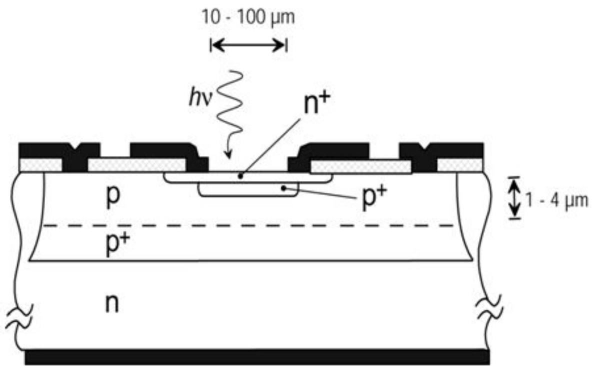
Make use of ps-timing:

- Optical Time Projection Chamber
- Collider proton/ch vertexing and track quark content

SPADs: P-N Junctions biased in Geiger Mode



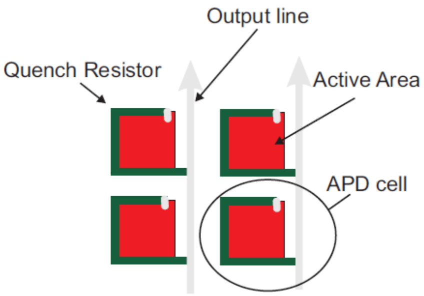
Proportional mode　　Geiger mode

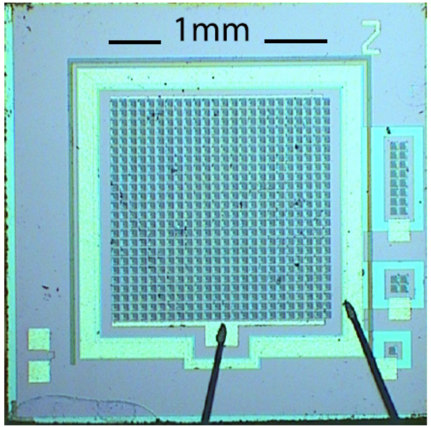


- Extensively studied in 60s, early 70s by Haitz, McIntyre, Oldham,...
  in the 90's by Cova, Lacaita, ...
- Did the majority of the groundwork:
  - PDE, Optical crosstalk, afterpulsing, avalanche micro physics, quenching mechanisms, ...

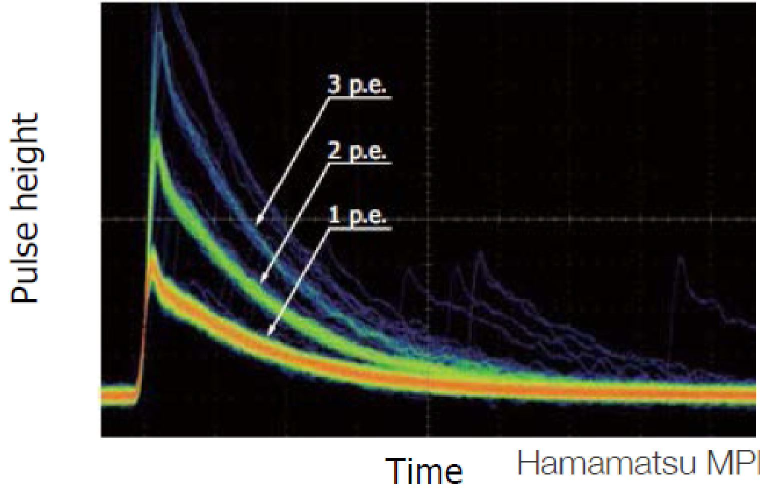
The Geiger mode provides
excellent signal to noise ratio (high "*Gain*") and
sub-nanosecond timing

The SiPM





MEPhI/Pulsar SiPM 2004



Hamamatsu MPPC techinfo

The SiPM concept provides multi-photon resolution:

Many passively quenched SPADs are connected in parallel

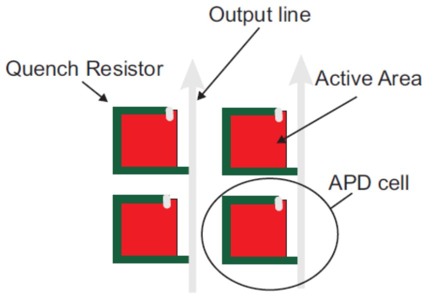
Recover information about number of photons
if photons per cell per recovery time <1

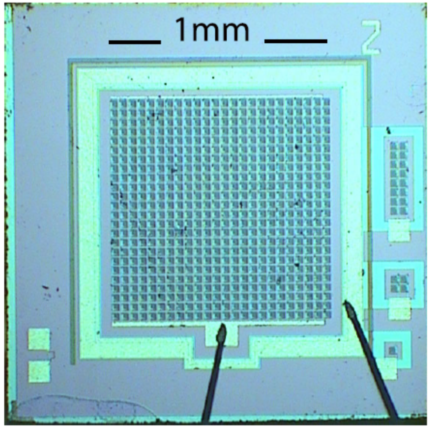
Pioneered in the 90's
Key persons: Dolgoshein, Golovin, and Sadykov

For an extensive review on the history of solid state photon detectors see D. Renker and E. Lorentz (2009)

The Silicon Photomultiplier

- Compact
- Optical and electrical robust
- Low intrinsic radioactivity
- Plus all the advantages of photomultiplier tubes
- Ideal where small photon detectors are needed



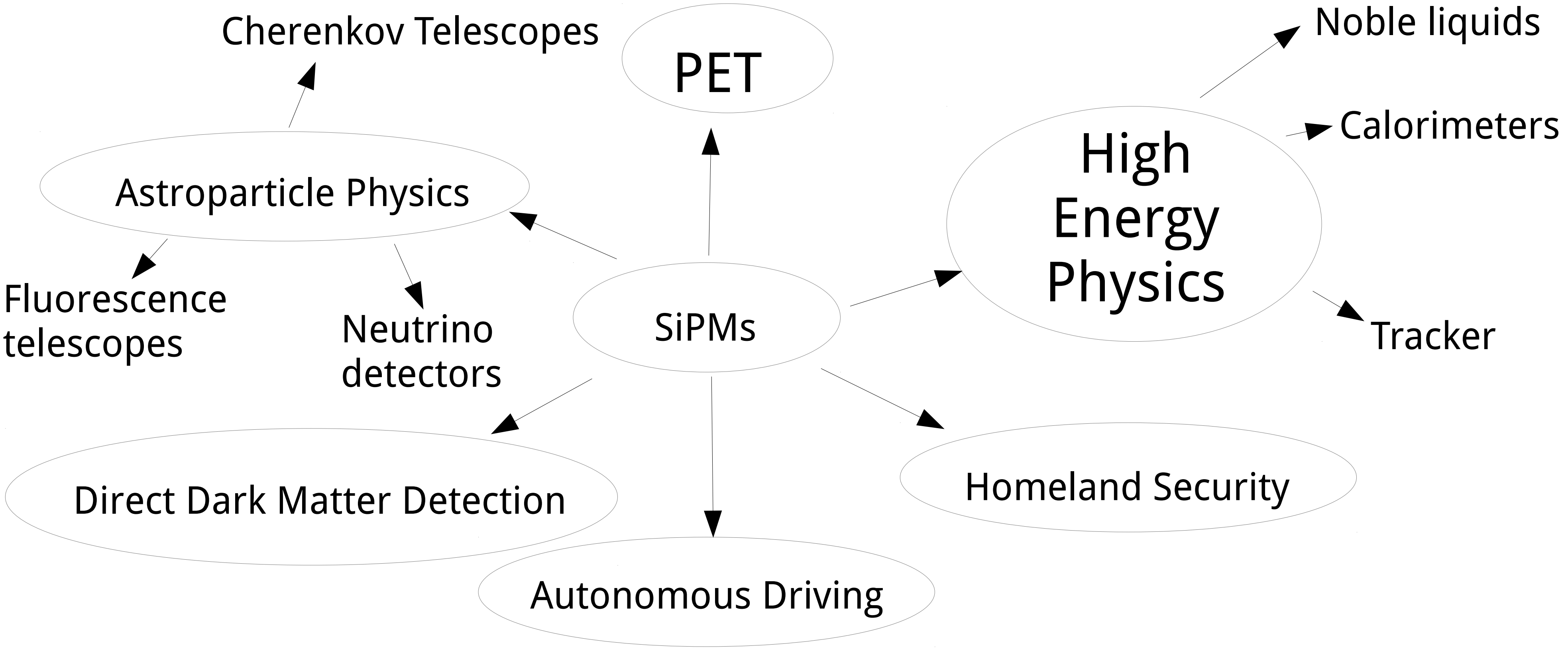


History of Key SiPM Parameters

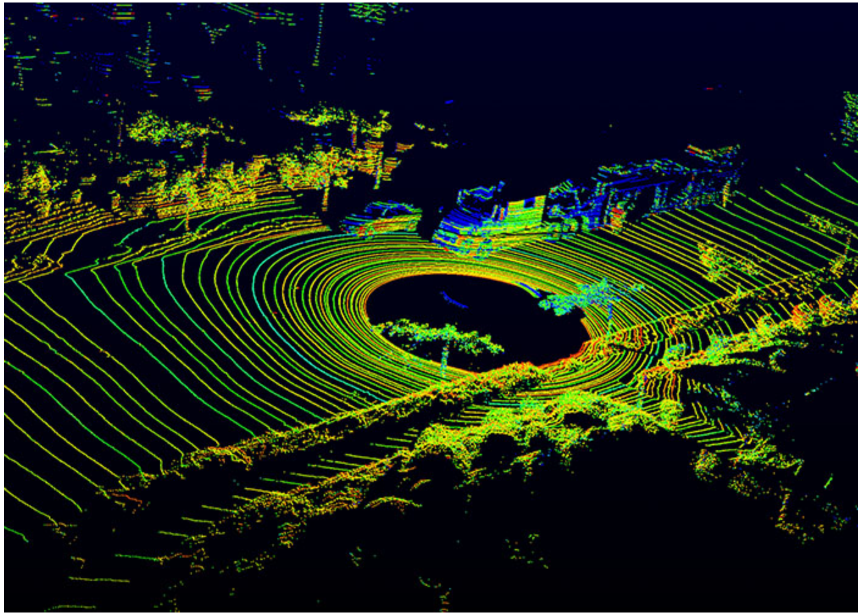
Parameter	2004	2013	2017	Wish List
Spectral Response	Green Sensitive **n-on-p structure**	Blue and Green **p-on-n structure**	Blue and Green Enhanced below 350 nm	Tailored to application
Photon Detection Efficiency	~10%	~45%	~55%	>70%
Dark Noise At room temperature	1MHz/mm^2	~100kHz/mm^2	50 kHz/mm^2	As low as possible
Optical Crosstalk	>20%	<10%	1%	As low as possible
Afterpulsing	>20%	<1%	<1%	As low as possible
Temperature dependency of gain	5-10 %/°C	5-10 %/°C	1 %/°C	
Sensor Size	1mm^2	1mm^2-36mm^2	1mm^2-36mm^2	

SiPMs are (fully?) mature devices
Due to rapid improvements in the past 17 years

SiPM Applications



SiPM Developments are driven by Multi-Billion Dollar Markets



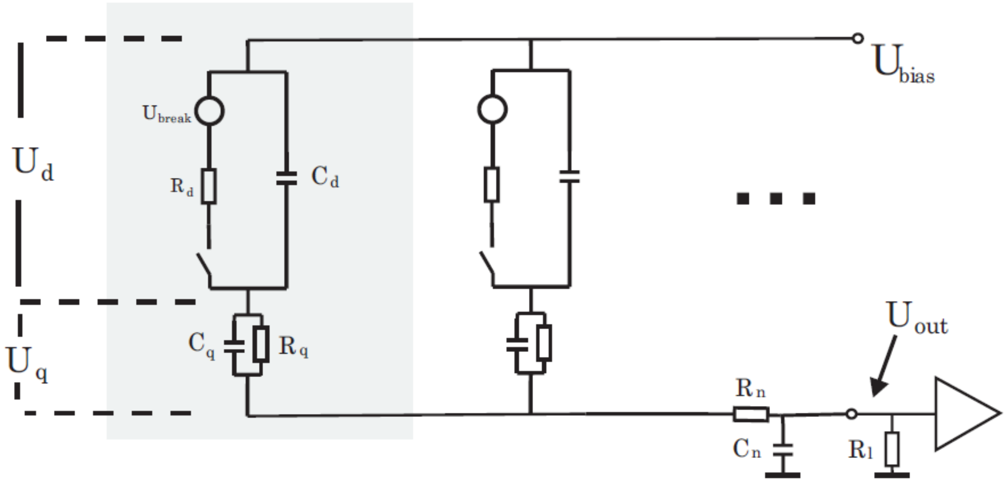
LIDAR

PET

SiPM Signals

- Breakdown is quenched within 1 nanosecond
  - Produces fast current pulse
  - Dispersed by capacitance of network connecting cells
  - Signal proportional to overvoltage times effective cell capacitance

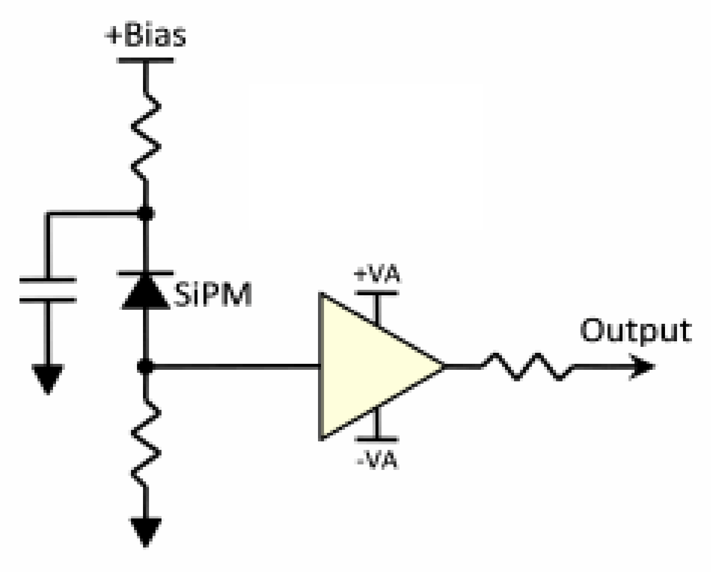
- Cell recharges after breakdown
  - Time constant determined by
    - Quench resistor
    - Effective cell capacitance



Otte (2007)

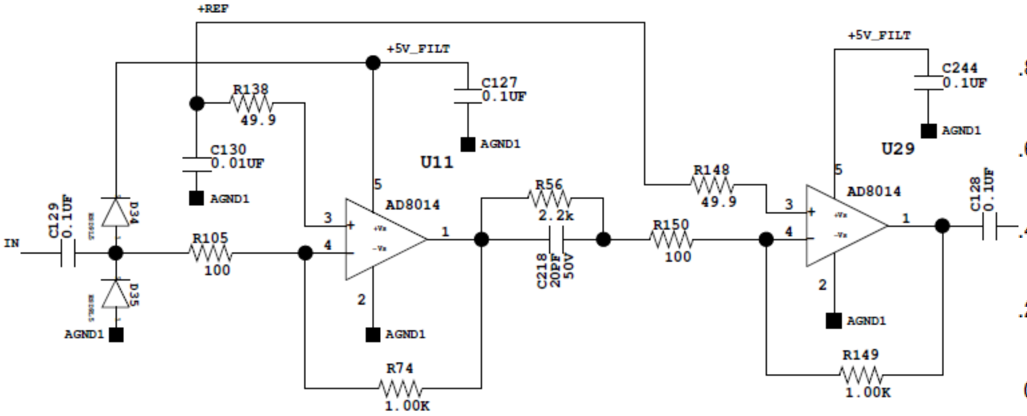
Hooking up SiPMs

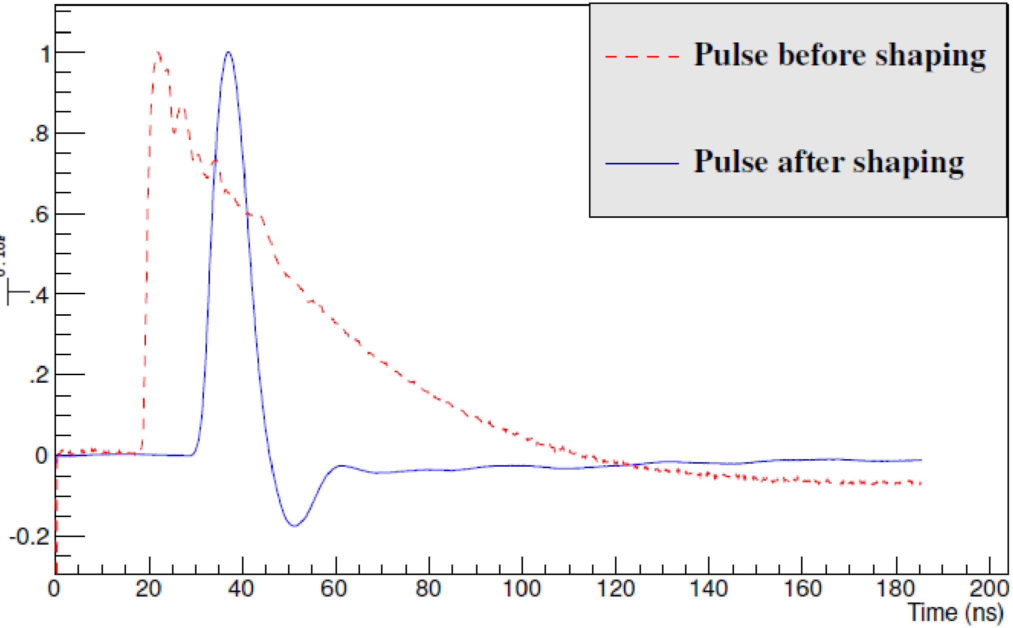
- Typical bias: ~30 V



Signal Shaping

- Large SiPM capacitance requires low input impedance amplifiers
- And/Or shaping: Differentiation with pole-zero cancellation

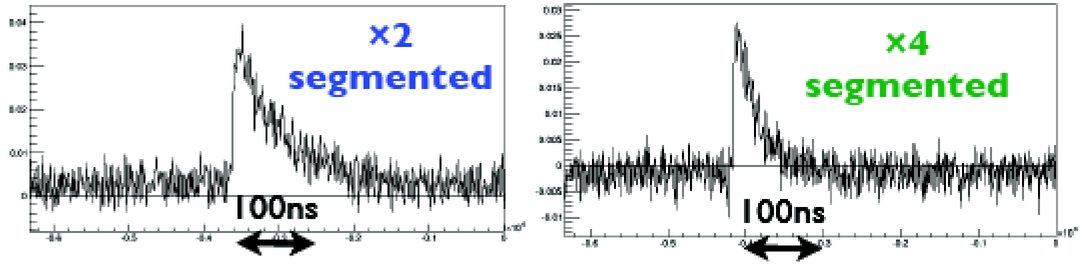




Otte, et al. (2015), DOI: 10.1016/j.nima.2014.11.026

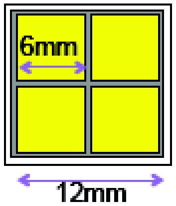
Series Connection reduces effective Capacitance

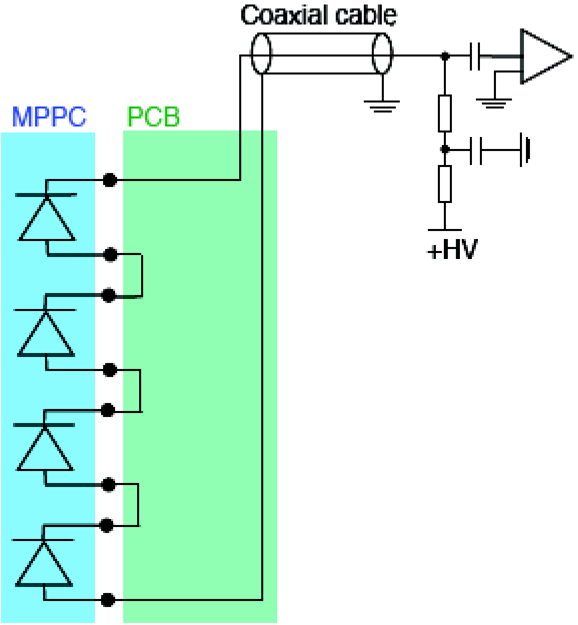
Single photoelectron signal



	Non-segmented	×2 segmented	×4 segmented
Fall time	200ns	45ns	25ns

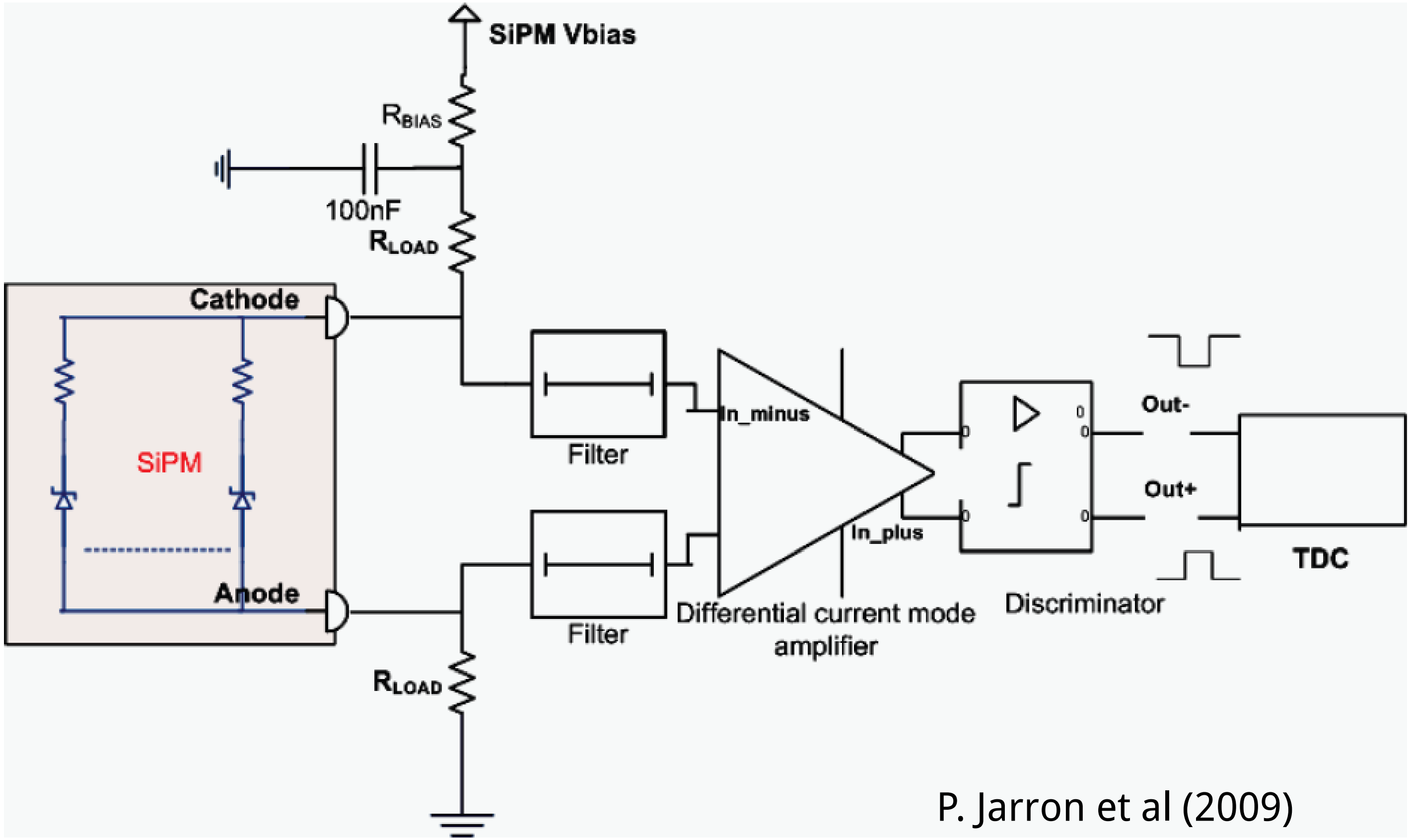
Sensor segmentation (×4)





W. Ootani for the MEG Collaboration (2013)

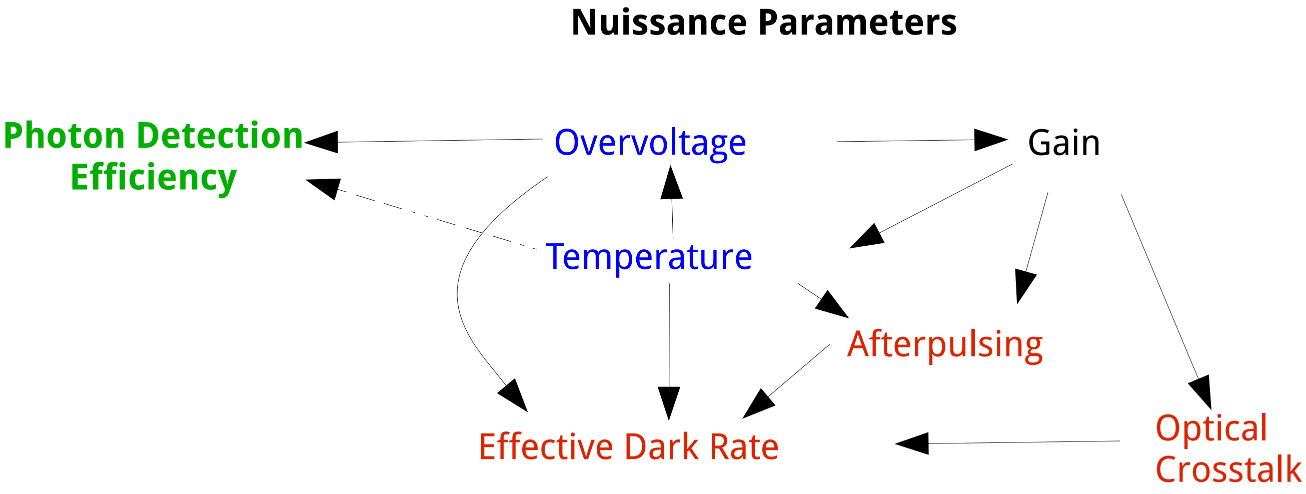
Differential Readout

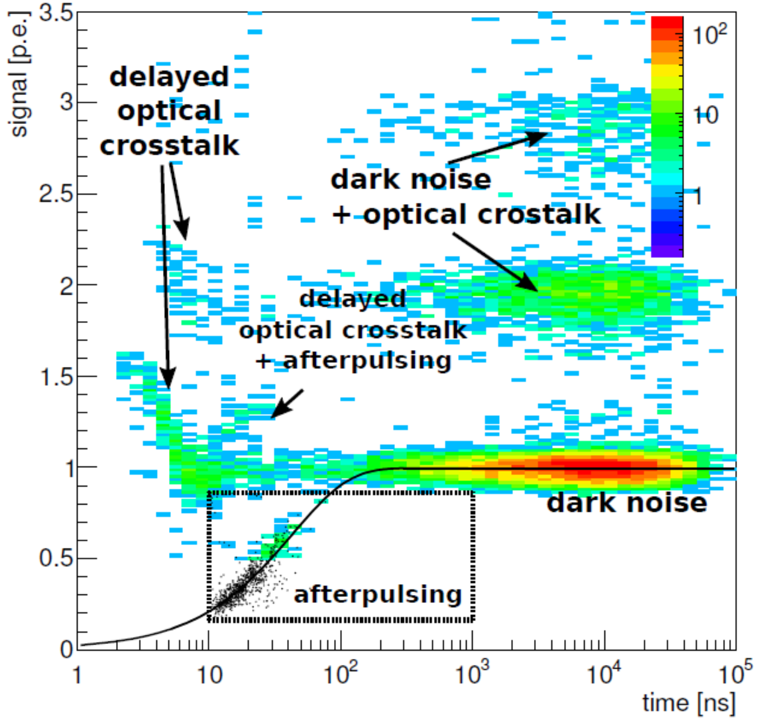


P. Jarron et al (2009)

SiPM Parameters

User's perspective





Otte et al. (2017)

Choice of bias has profound impact on SiPM performance in application

Photon Detection Efficiency

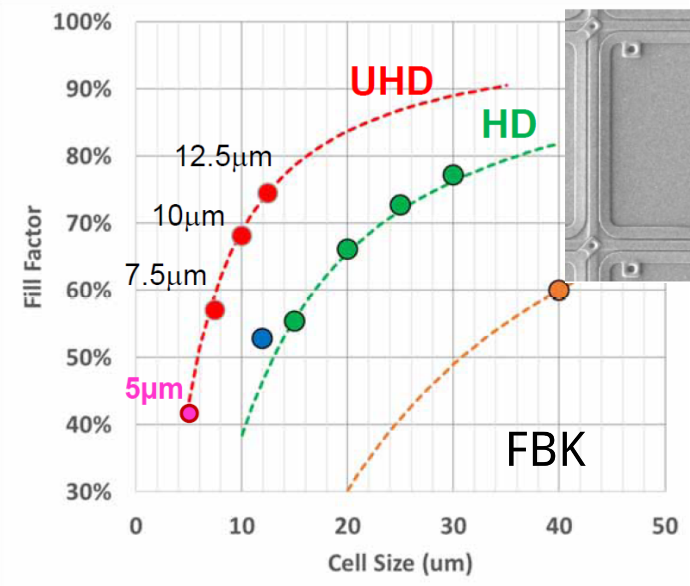
geometrical efficiency * transmission * effective QE * breakdown probability

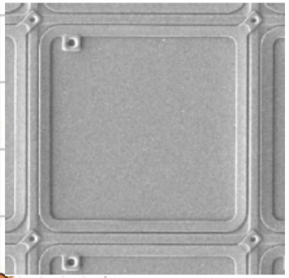
>80%
For >50µm cells

>90% >90%

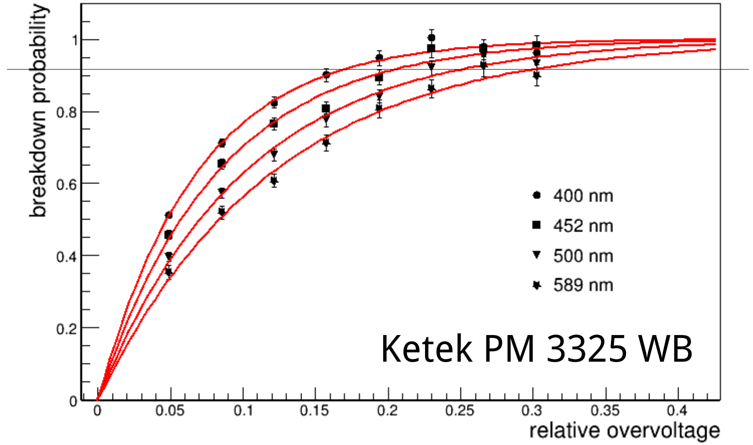
Values are quoted for peak response

90%





Hamamatsu



Otte 2017

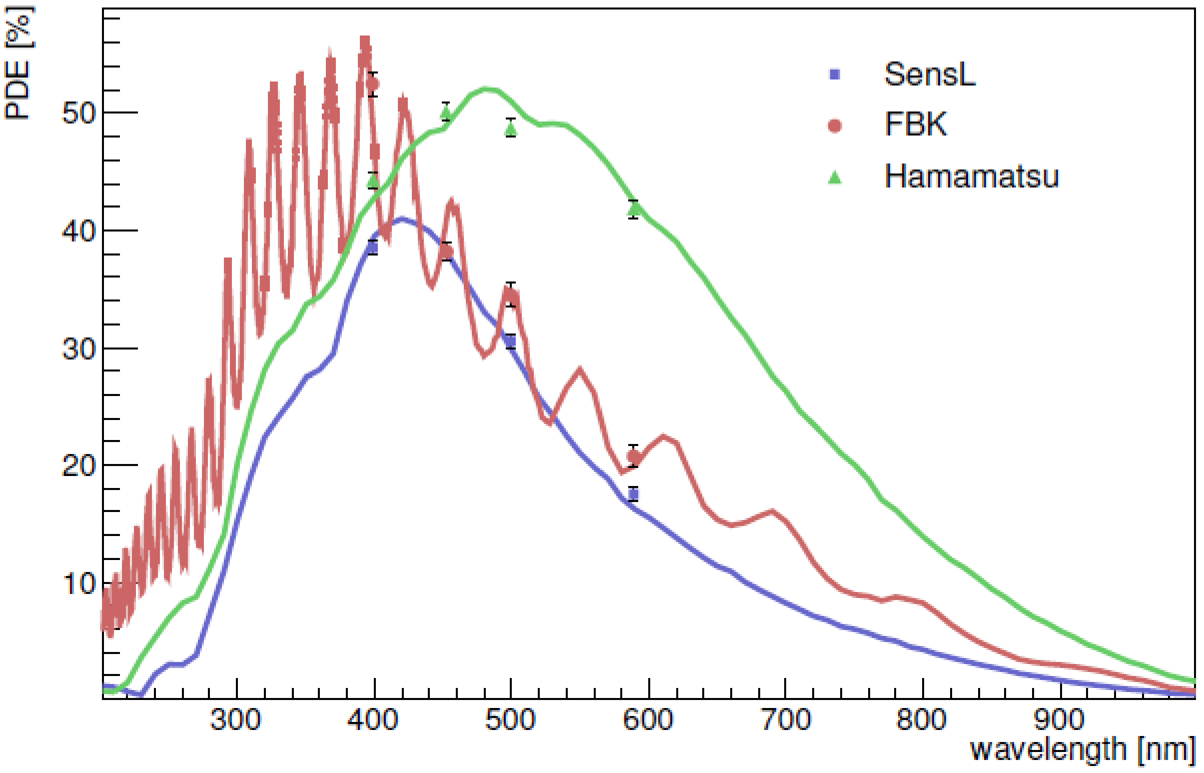
DOI:10.1016/j.nima.2016.09.053

Photon Detection Efficiency

DOI:10.1016/j.nima.2016.09.053

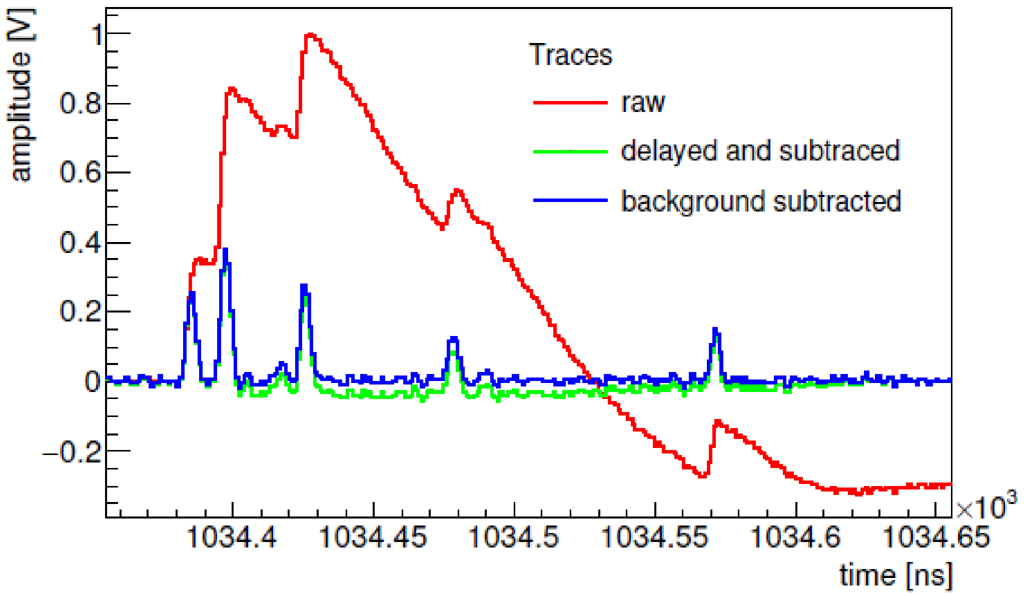
Otte et al. (2017)

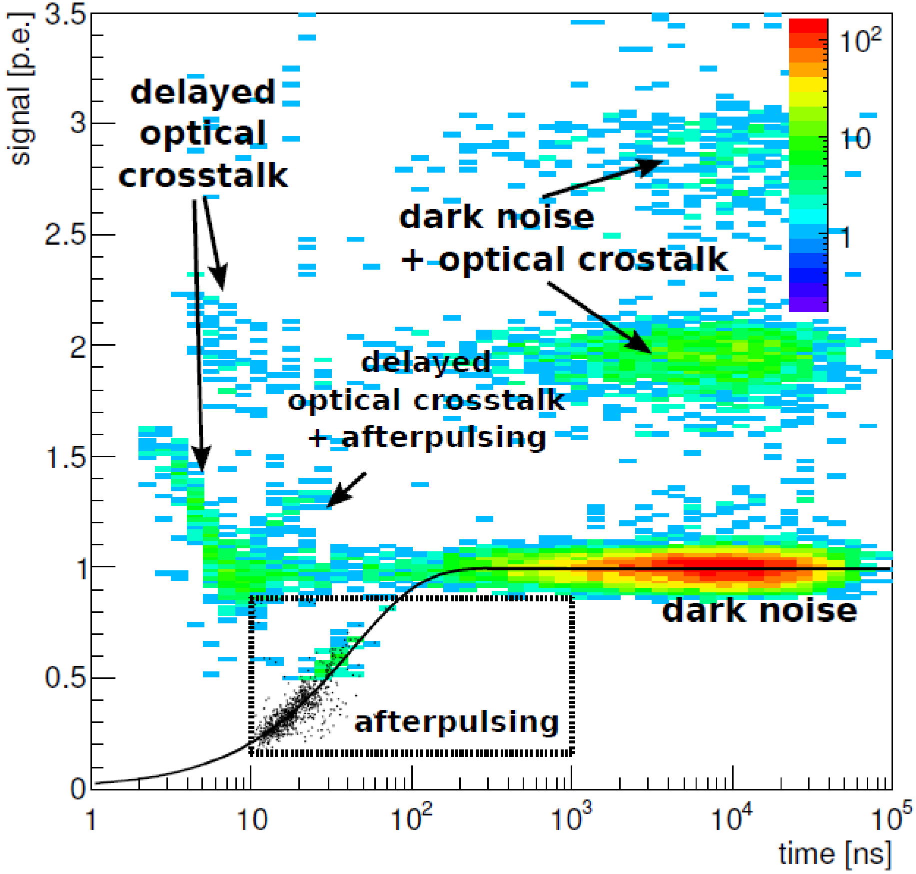
SiPMs biased to achieve 90% breakdown probability @ 400nm



Have we reached the maximum possible peak PDE?

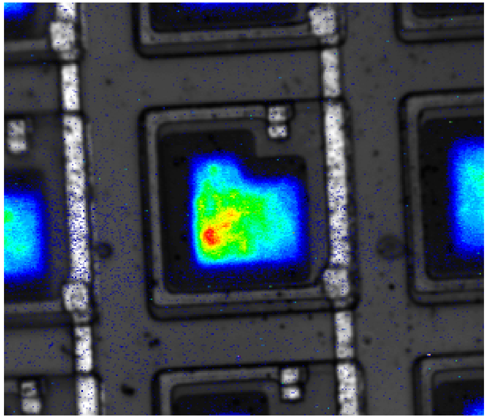
Maybe some more improvement possible but not much





DOI:10.1016/j.nima.2016.09.053

Optical Crosstalk



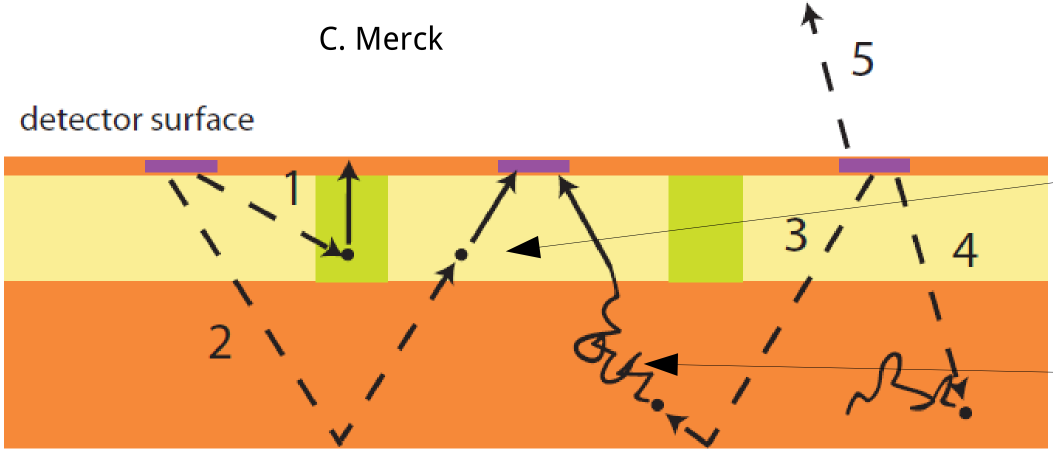
C. Merck

Photons are emitted during breakdown

Photon emission mechanism not well understood

Photons with λ = 900nm – 1100nm have the right absorption length to produce optical crosstalk

~3·10^{-5} photons per charge carrier in the breakdown

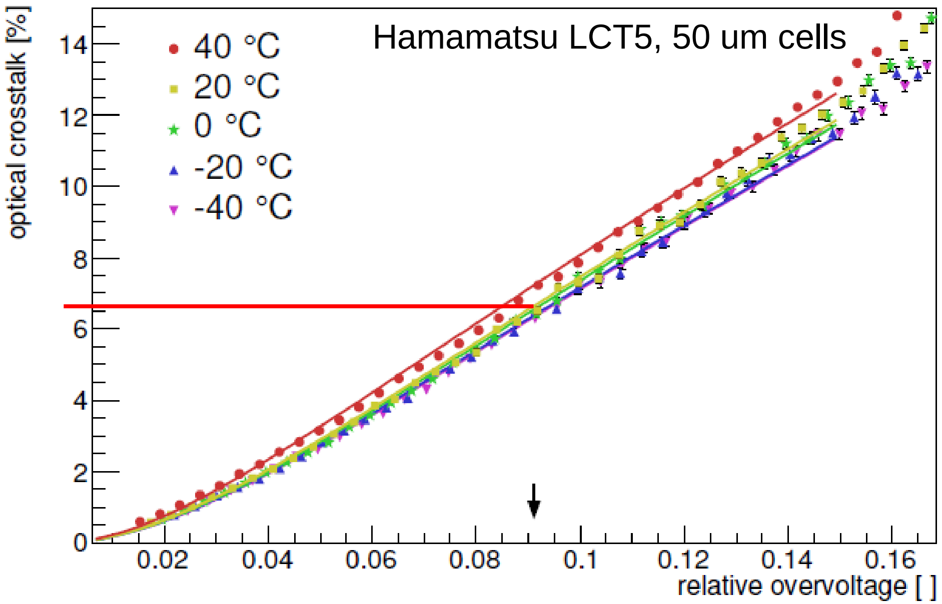


Direct/prompt optical crosstalk
Instantaneous <<1ns
→ pile up of signals

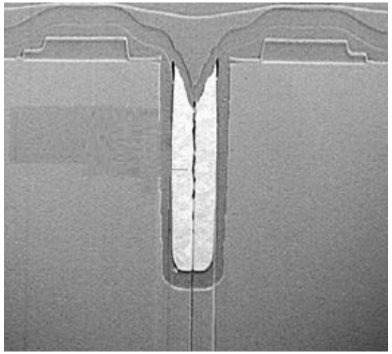
Indirect/delayed optical crosstalk
Delayed up to 100s of nanoseconds
→ contribution to afterpulsing and effective dark rate

Direct Optical Crosstalk

DOI:10.1016/j.nima.2016.09.053

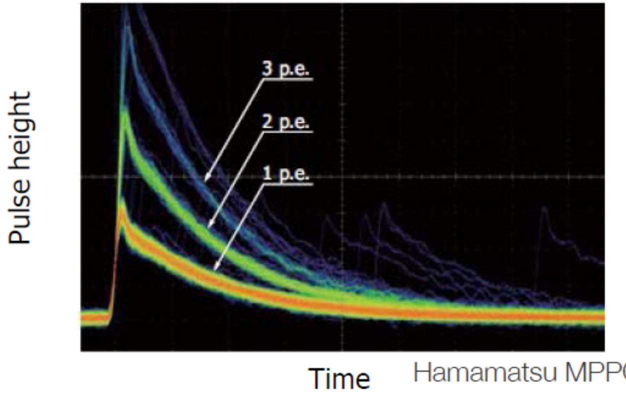


→ increase of accidental trigger rate
  → increase in trigger threshold
→ increase in variance of detected signal
  → worse energy resolution



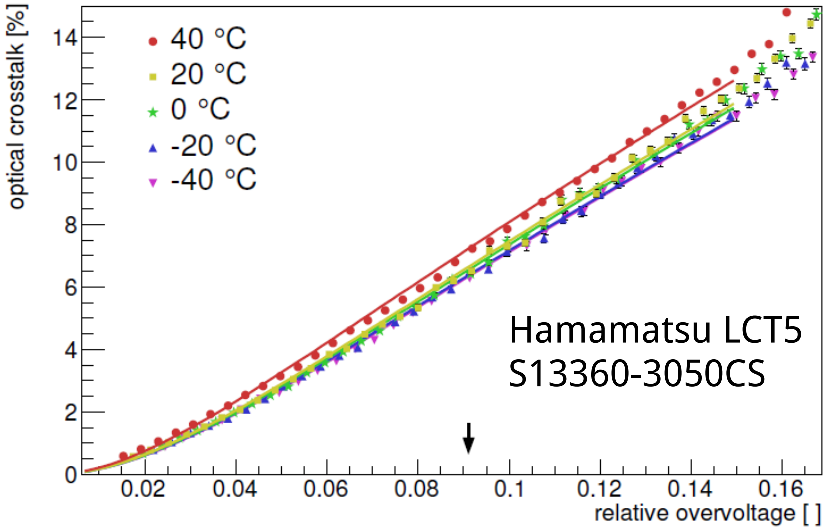
Hamamatsu

Optical isolation is key

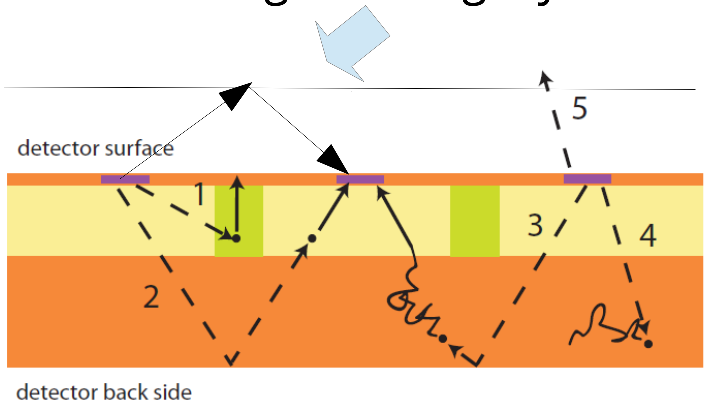


Hamamatsu MPPC techinfo

Direct (Prompt) Optical Crosstalk (OC)



Dominant process: Xtalk photons bounce through coating layer



Gain*ε * $OC_{transmission}$ * $1-e^{\frac{-U_{rel.OV}}{\alpha}}$

Photons produced during breakdown

Optical crosstalk transmission factor

Breakdown probability

ε=3*10^{-5} photons/charge carrier

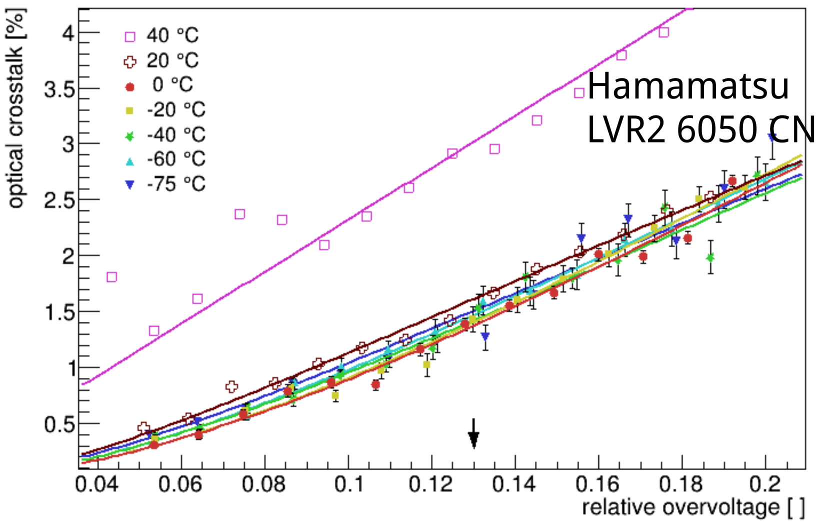
$OC_{transmission}$=0.076

α=0.040±0.001

Pure electron injected

Nepomuk Otte

Prompt OC in latest Hamamatsu LVR2



LVR2 with very thin coating

From Fit:

$OC_{transmission}$=0.014

LVR structure (coating) suppresses OC five times better than LCT5

α=0.10±0.03

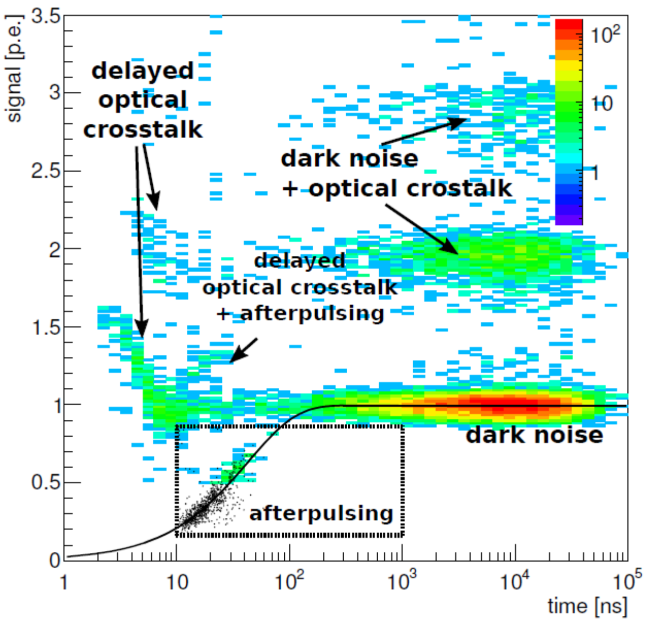
Remaining OC due to photons entering cell below avalanche structure

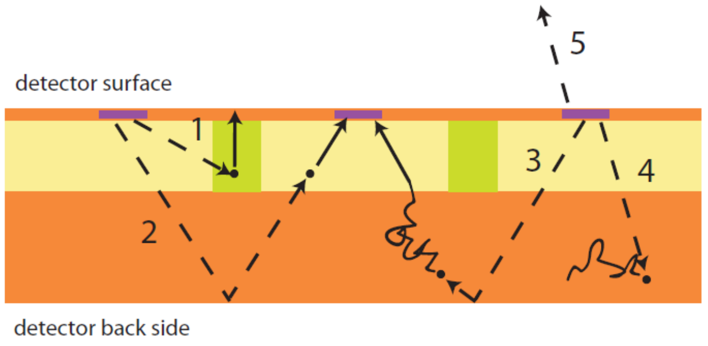
Prompt OC vs. afterpulsing in PMTs

The OC probability to get >4 pe pulses is $3x10^{-6}$

→ lower than the probability to get >4pe pulses from afterpulsing in good PMTs (1e-4)

Delayed Optical Crosstalk





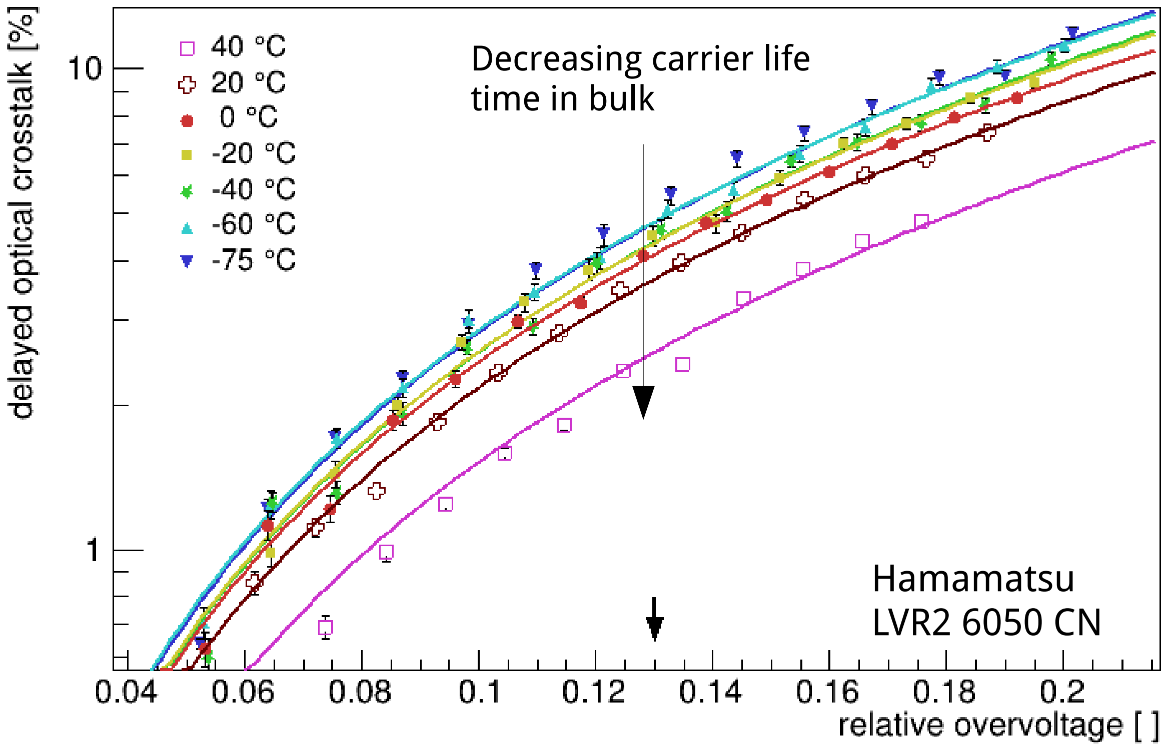
Measurement depends on how well two pulses can be separated

In our setup the minimum resolving time is 2 ns

All delayed OC signals with shorter delay are reconstructed as prompt OC signals

A late delayed OC signal comes from deeper inside the bulk → expect temperature dependency

Delayed Optical Crosstalk



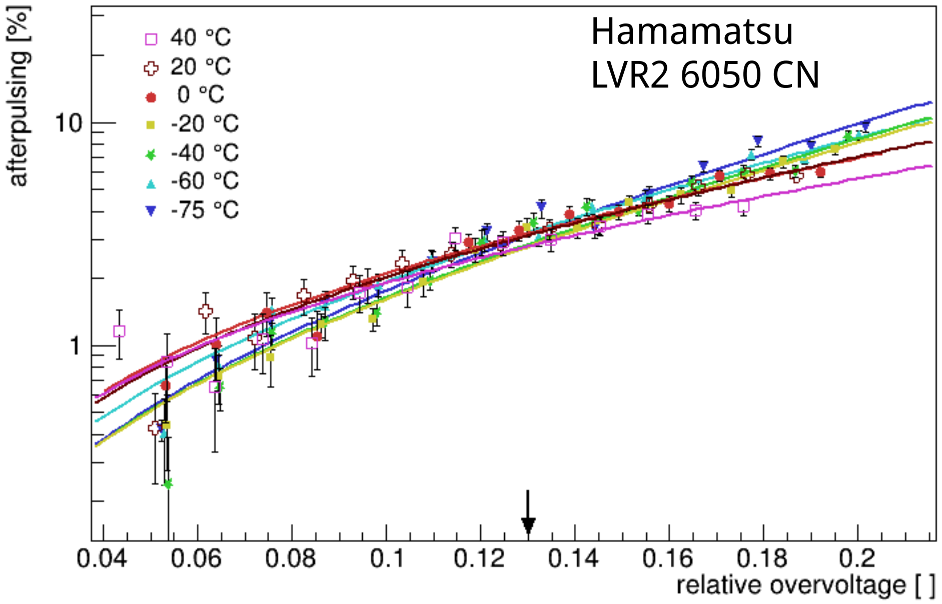
Same model to fit data as for prompt OC (does not include time dependence)

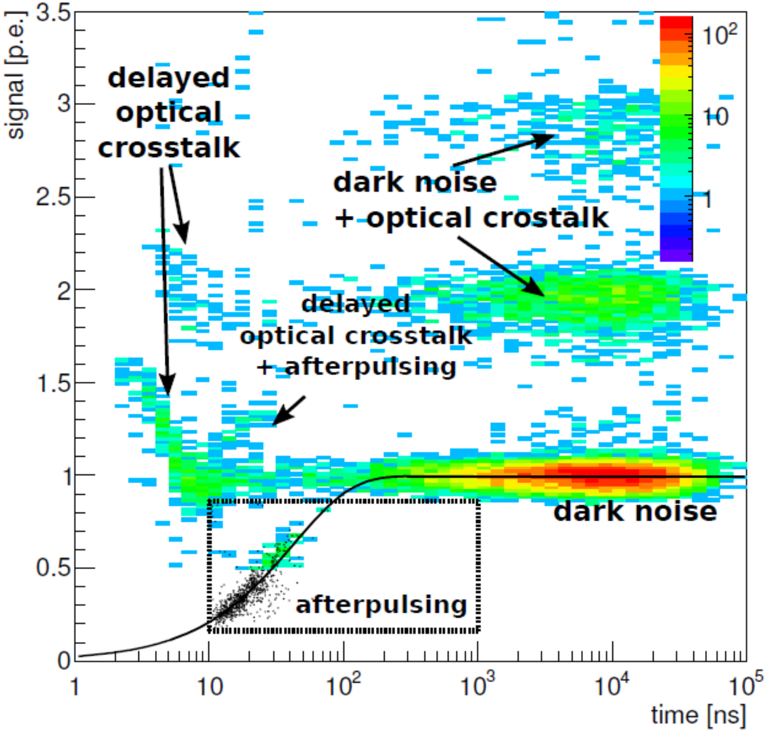
Uncertainties on fit too large to extract useful information

The temperature (and time) dependence has encoded the information about the carrier lifetime in non-depleted bulk

Delayed OC is 3 times higher than prompt OC in LVR2

Afterpulsing





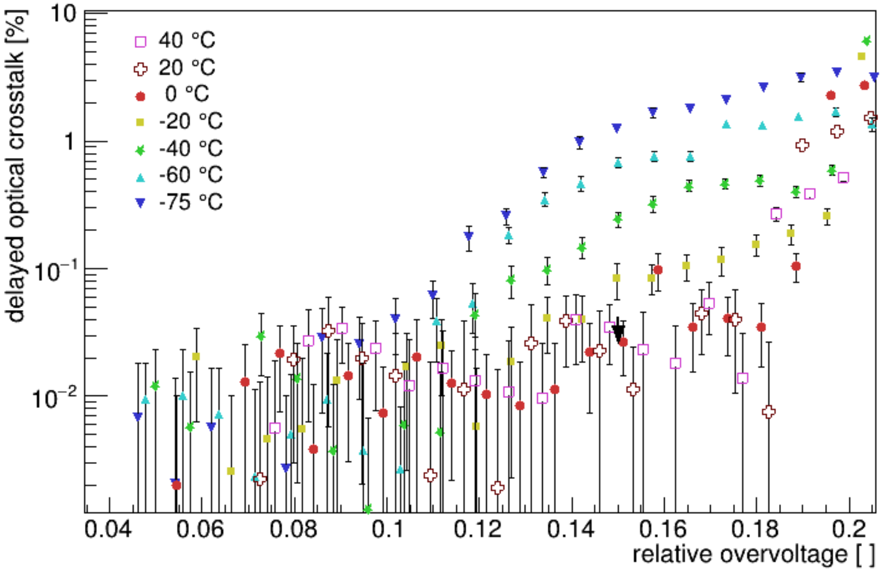
Fitfunction: $AP(U_{\mathrm{rel}}) = A \cdot e^{(U_{\mathrm{rel}}/\delta)} \cdot \left[1 - e^{(-U_{\mathrm{rel}}/\alpha)}\right]$

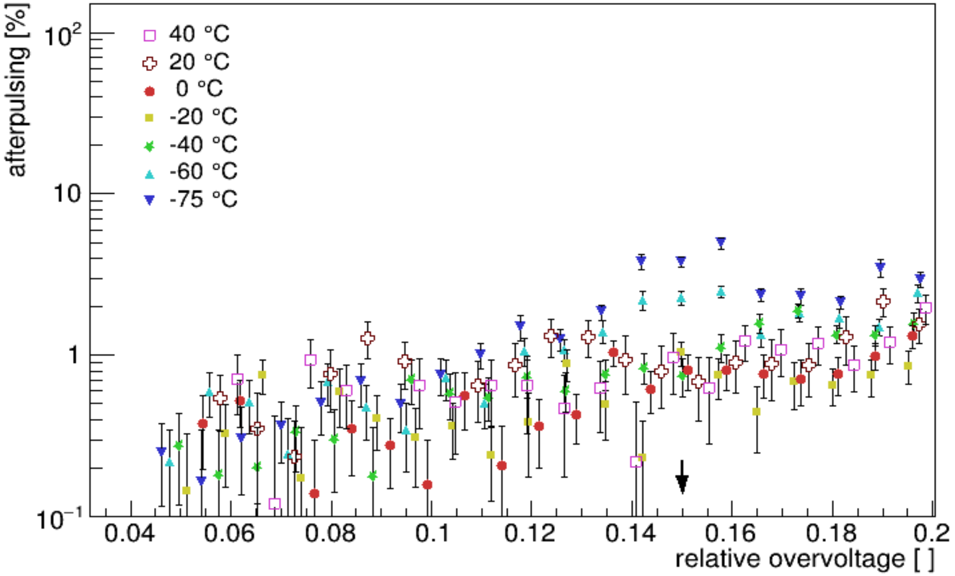
Notes:

Contamination from delayed OC and

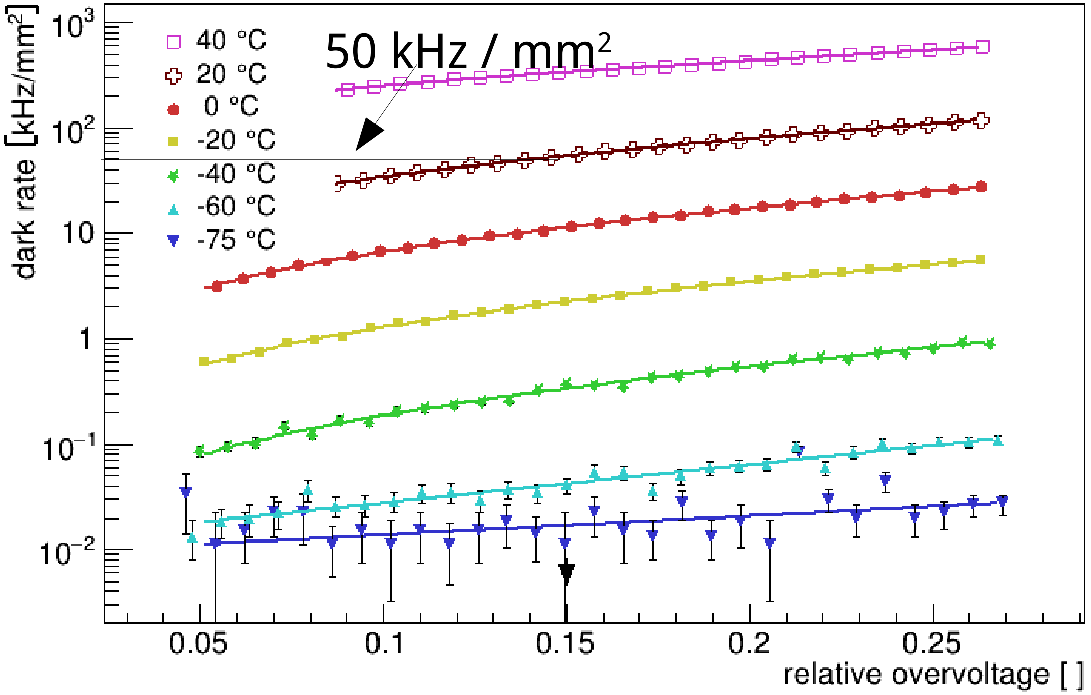
Minimum pulse height 0.5 pe

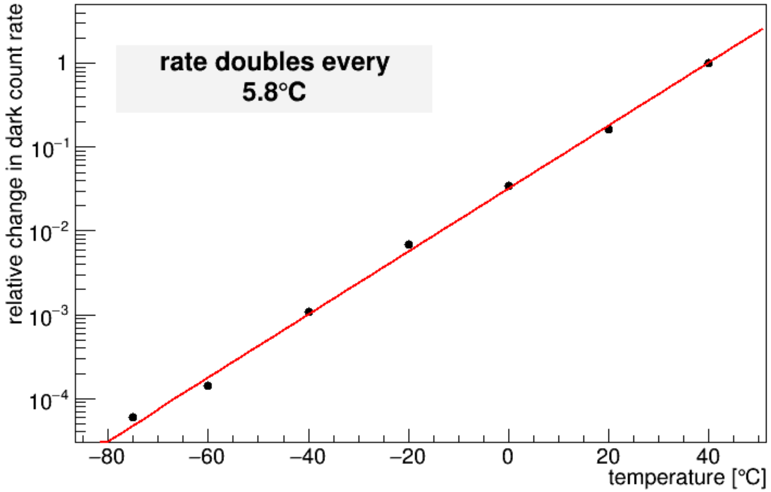
Afterpulsing and delayed OC in KETEK PM3325 WB





Dark-Count Rates



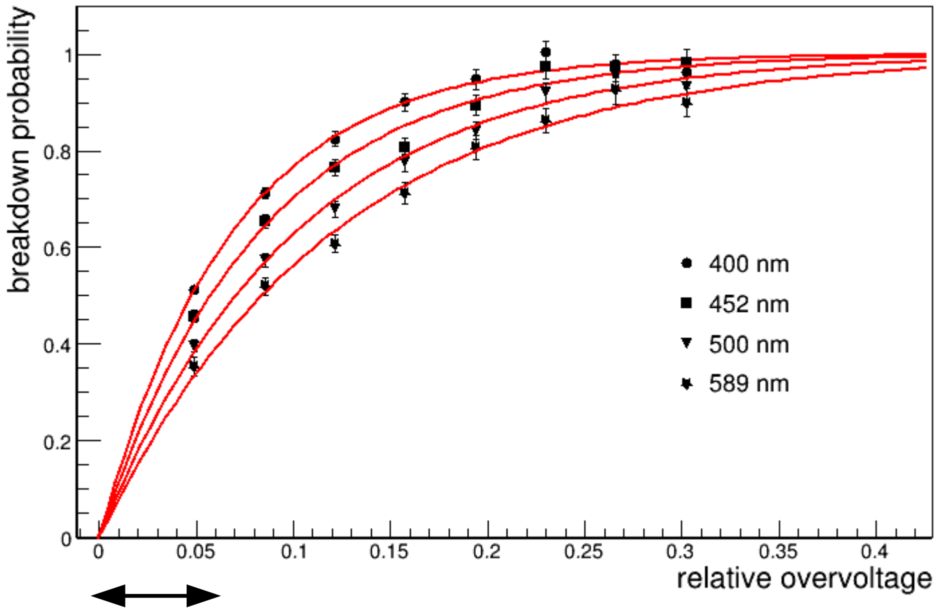


Ketek PM 3325 WB

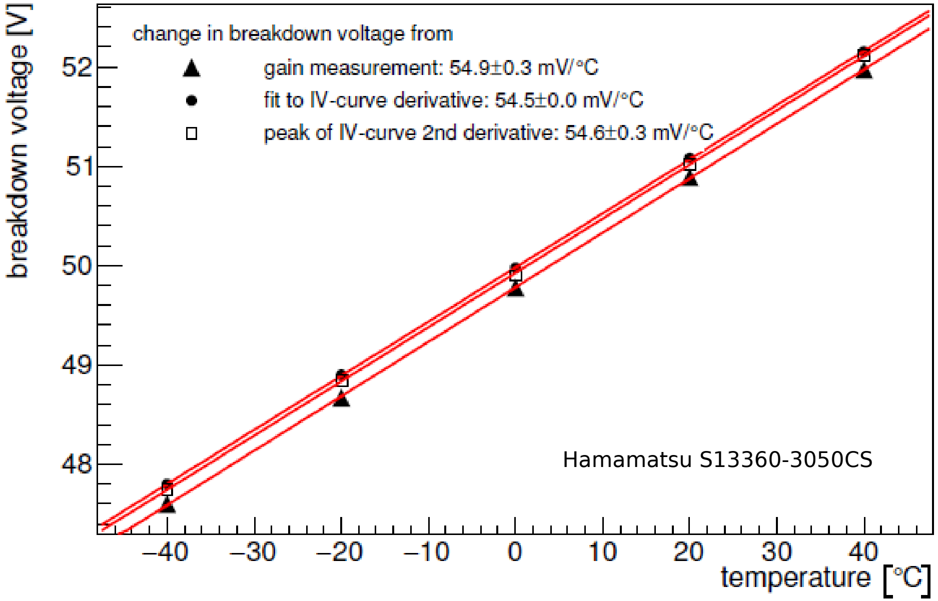
Temperature Dependence of PDE and Gain

arXiv:1606.05186

New devices operate at 10 – 20 % overvoltage
→ significantly reduces temperature dependence



Operating range of early devices



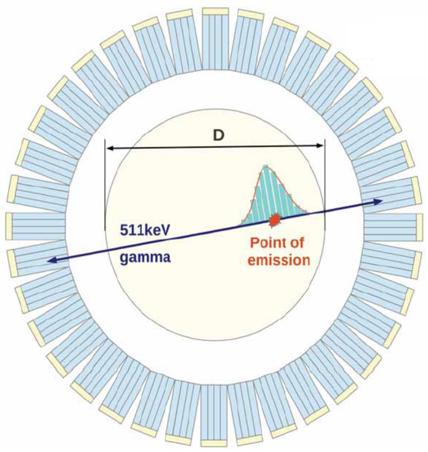
Gain changes: 0.5-1%/°C

PDE changes: 0.2-0.3%/°C

→ modest temperature control to several °C is sufficient to keep PDE within +/- 2%
→ changes in gain can be calibrated out

Timing

- Main driver is 10 ps FWHM timing resolution for TOF-PET
  - corresponds to range of positron before annihilation
- Allow shorter bunch crossing times in future collider experiments



*SiPM + **LSO:Ce codoped with Ca** coupled with Meltmount (n=1.68)*	*CTR [ps] 2x2x3mm^3*	*CTR [ps] 2x2x20mm^3*	*PDE [%] @ 410nm*	*SPTR [ps] FWHM*
HPK S13360 3x3mm² (50µm)	**85 ± 3**	**128 ± 5**	62 ± 3	157 ± 7
HPK S13360 3x3mm² (75µm)	**80 ± 4**	**121 ± 4**	67 ± 3	148 ± 7
Ketek PM 3350 3x3mm² (50µm)	**94 ± 5**	**150 ± 5**	45 ± 3	223 ± 7
Sensl FJ 30035 3x3mm² (35µm)	**89 ± 3**	**140 ± 5**	54 ± 3	277 ± 12
FBK NUV-HD 4x4mm² (25µm) **no resin**	**73 ± 2**	**117 ± 3**	55 ± 3	193 ± 12
FBK NUV-HD 4x4mm² (40µm) **no resin**	**70 ± 3**	**112 ± 3**	60 ± 3	129 ± 9

Individual SPADs achieve ~ 22 ps FWHM SPTR

M. V. Nemallapudi et al. (2016)

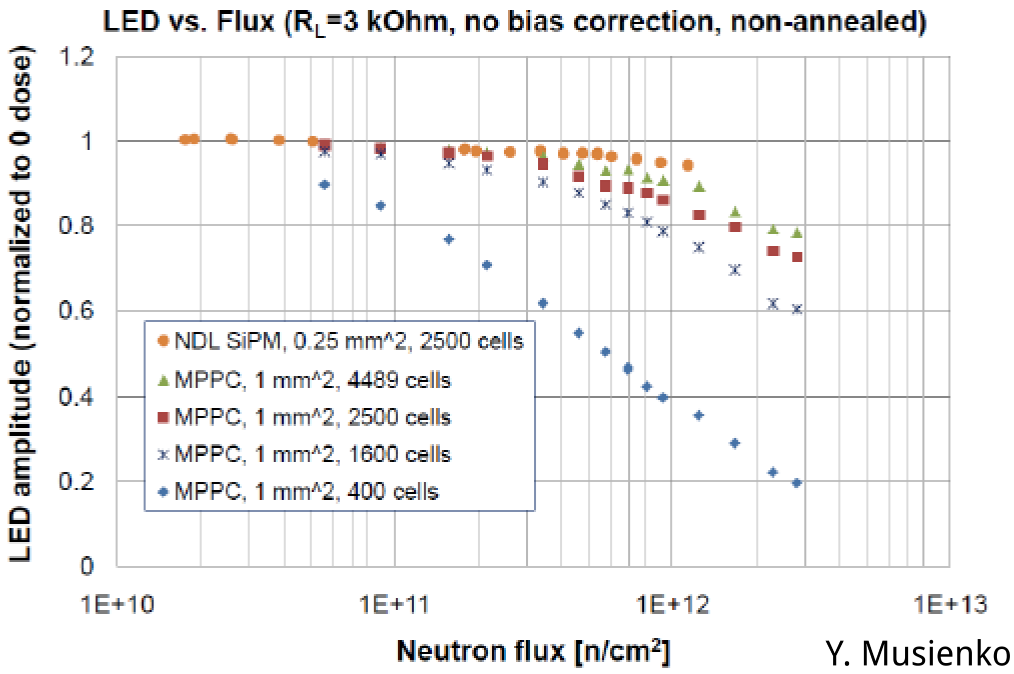
S. Gundacker (NDIP 2017)

Radiation Hardness

Radiation damage increases number of generation centers
→ higher dark count rates

Need:

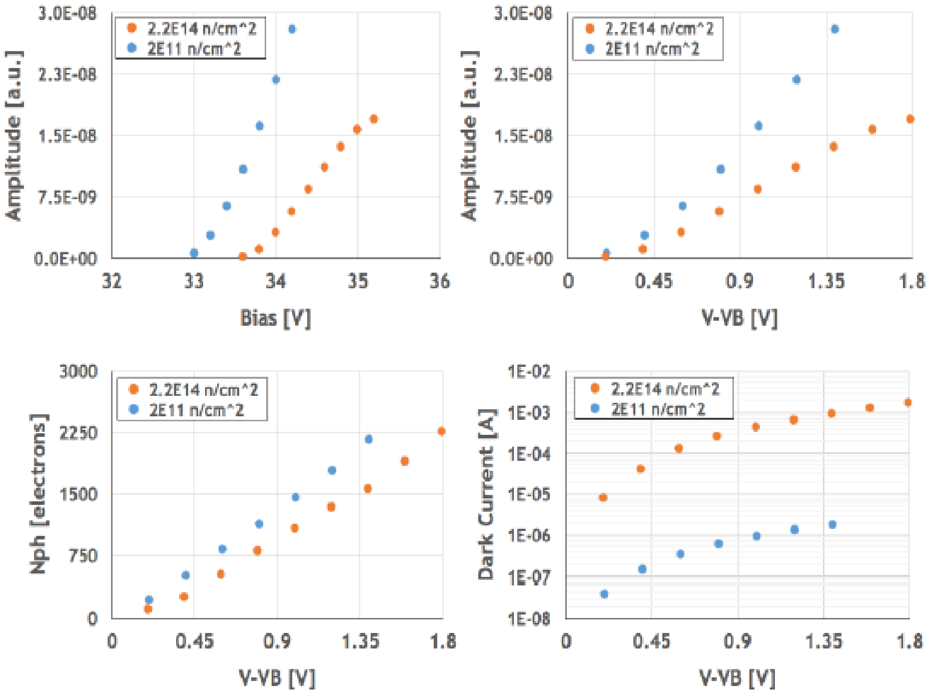
- High cell densities
- Fast recovery times

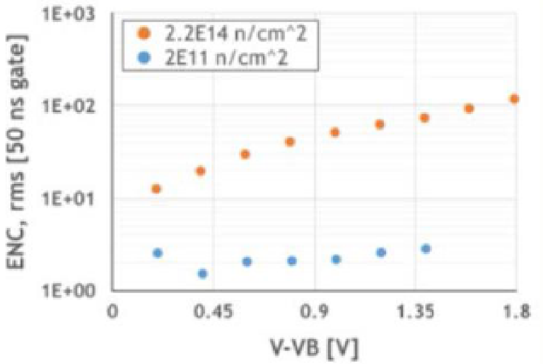


Y. Musienko (2015)

SiPM irradiated up to $2.2*10^{14}$ n /cm^2

Can SiPM survive very high neutron fluences expected at high luminosity LHC? Yes they can! FBK SiPM (1 mm^2, 12 μm cell pitch was irradiated with 62 MeV protons up to $2.2*10^{14}$ n /cm^2 (1 MeV equivalent).





We found:

- Increase of VB: ~0.5 V
- Drop of the amplitude (~2 times)
- Reduction of PDE (from 10% to 7.5 %)
- Increase of the current (up to ~1mA at dVB=1.5 V
- ENC(50 ns gate, dVB=1.5V)~80 e, rms

The main result is that SiPM survived this dose of irradiation and can be used as photon detector!

(A.Heering et al., NIM A824 (2016) 111)

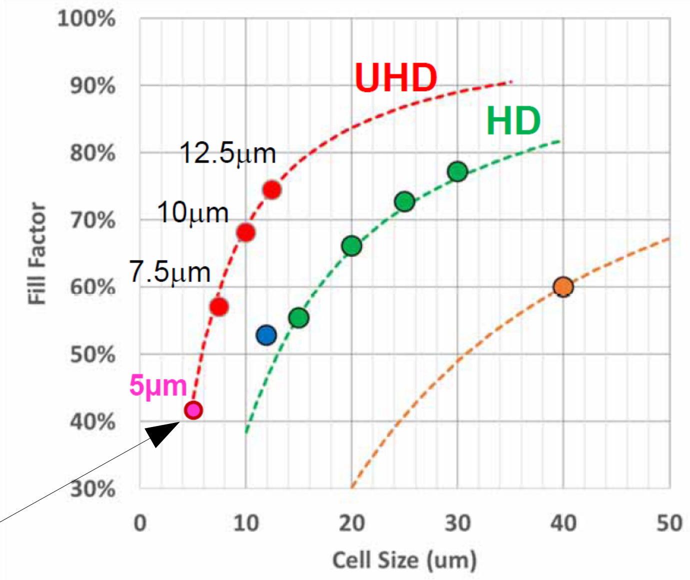
Backup

Dynamic Range

- Important for calorimeter applications
- Radiation hardness

Dynamic range depends on:
- cell density
- recovery time

5 µm cell sizes are in reach
Recovery times of 3-5 ns?



46,000 cells / mm^2

Summary

SiPMs are mature devices:

- Enormous push in development by industry to serve mass market (PET, LIDARs)
- Further developments tailored to HEP/astrophysics applications must be funded by our own funding agencies
- SiPMs with prompt OC, delayed OC, and afterpulsing of less than 1% are possible
  - Expect devices with such features in the next 1-2 years
- SPTR of 10 ps are in reach?
- Reaching device performance limits determined by physics rather than technology

Blue sky developments:

Evolutionary:

- Push sensitivity in the VUV up → uncertain outcome, limited potential for improvement?

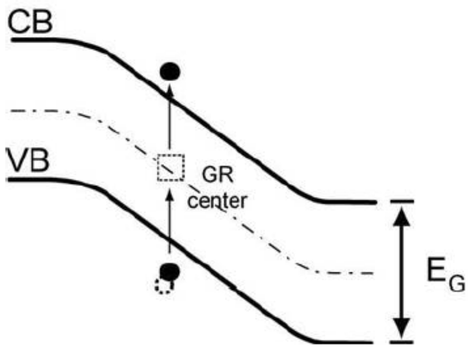
Revolutionary:

- Go for compound semiconductors → bypass physics limitations of silicon , face technological challenge instead

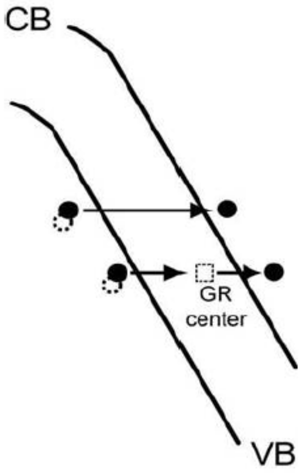
Effective Dark Rates

Contributions

1. thermal generated
2. tunneling
3. afterpulsing



Generation - Recombination Centers

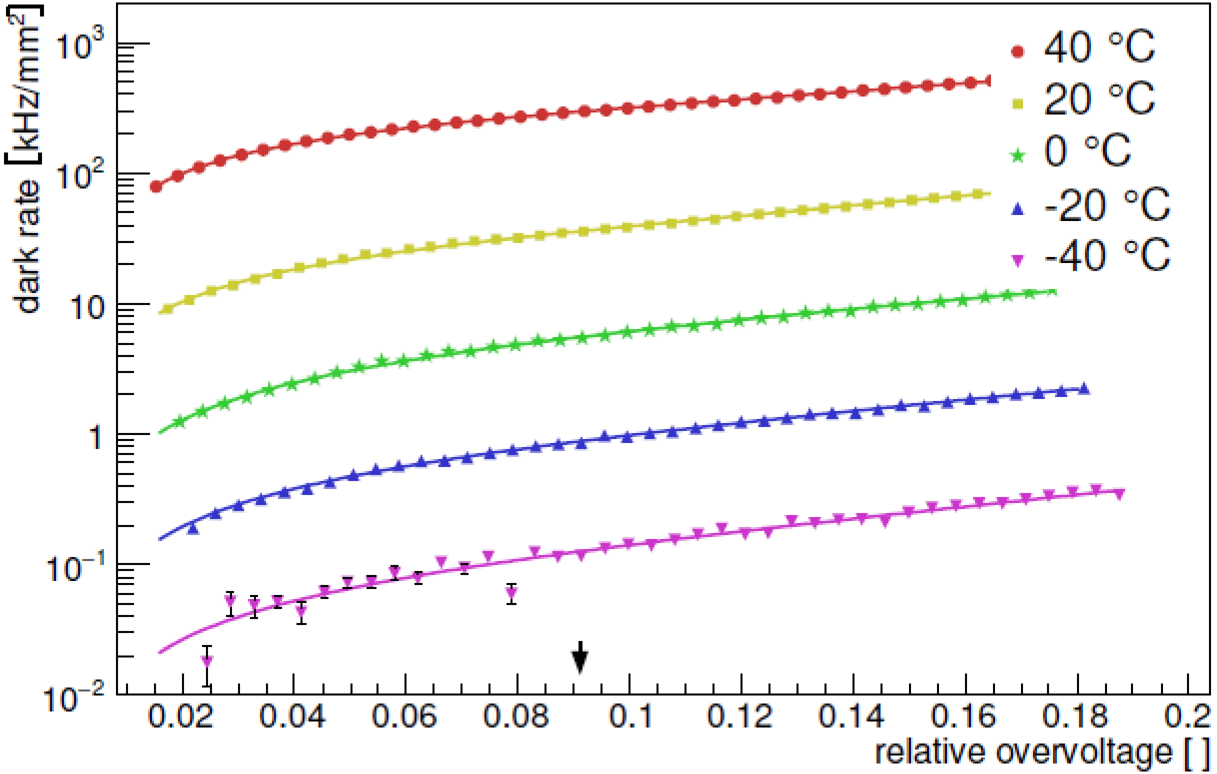


Field-Assisted Generation

Dark Rates

<50 kHz at room temperature is standard

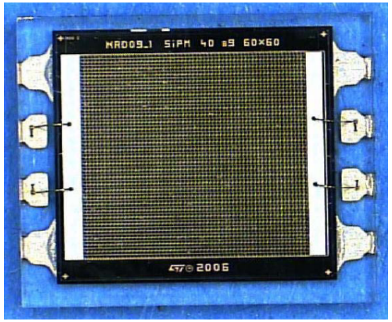
Can be cooled away



(b) Hamamatsu S13360-3050CS

SiPMs to detect steady Very-Low-Light Levels

Adamo et al. (2013)

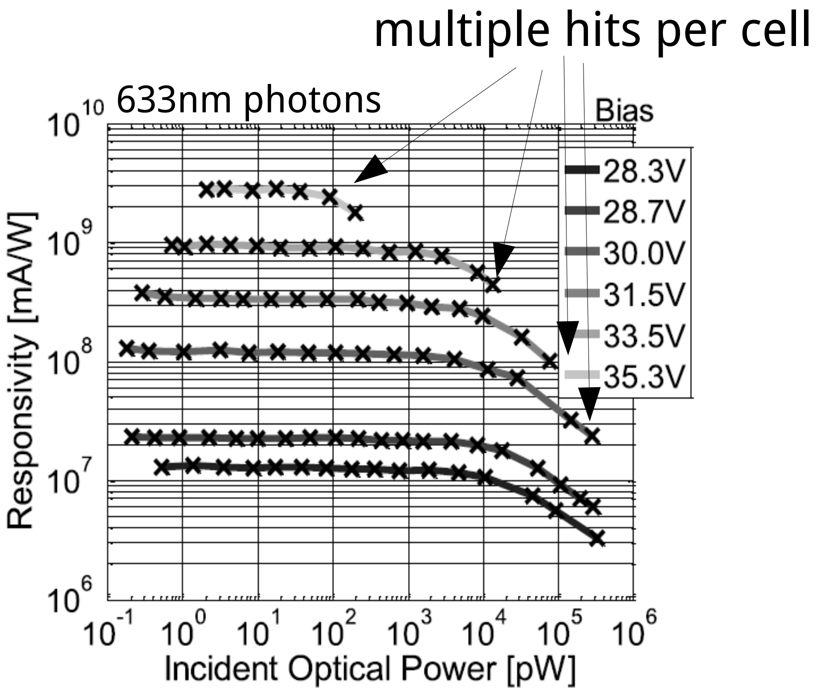


ST Microelectronics
3.5 x 3.5 mm²

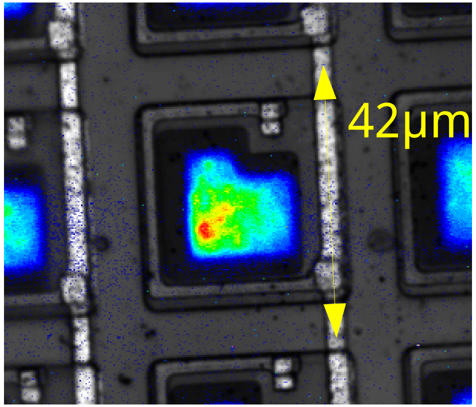
Sensitive to photocurrents of ~10^{-15} A

Linear regime:

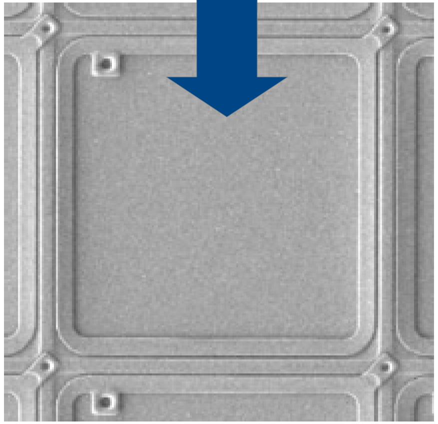
Acceptable photon rate for linear response
<< 1 photon / cell / recharge time



Geometrical Efficiency: intra-cell spacing

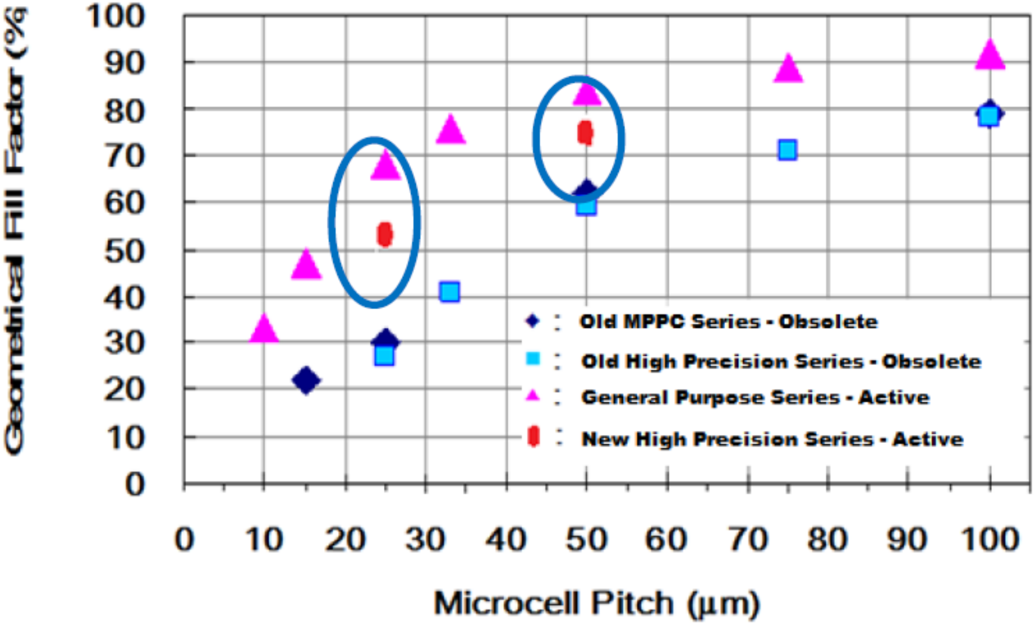


2004 MEPhI



50µm

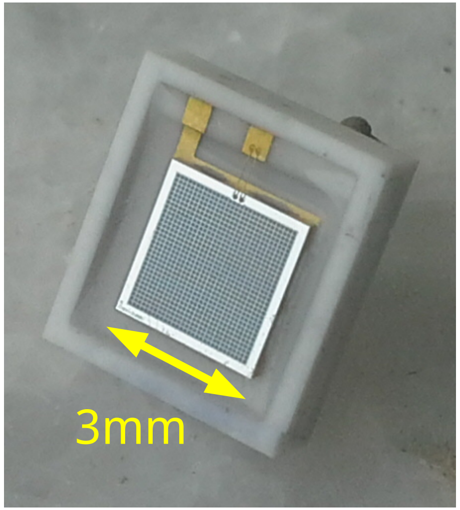
2014 Hamamatsu



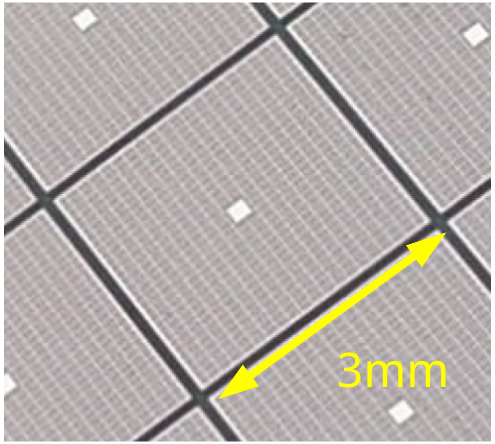
Hamamatsu

50% to 100% improvements depending on cell size

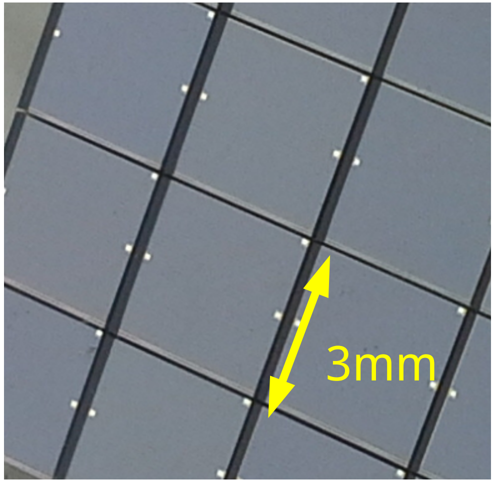
SiPMs Sizes



Hamamatsu 2008



Hamamatsu



SensL

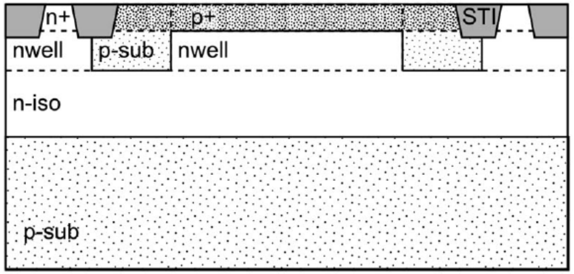
Elimination of bond wires with through silicon vias

thinner guard ring around device

Chip packaging with much reduced gaps between chips
0.1 to 0.2 mm gap possible between chips → **>90% efficiency**

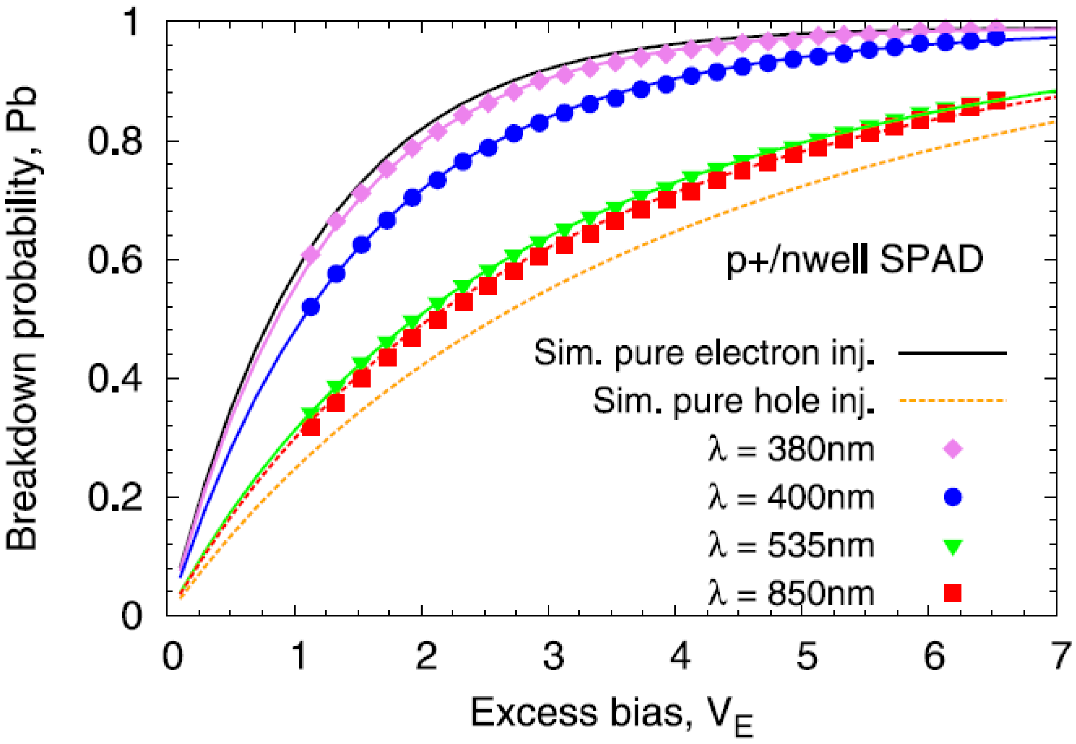
The pragmatic and cost-effective approach to arrive at large sensor sizes
Single SiPMs are typically < 6 x 6 mm^2

Breakdown Probability vs. Bias

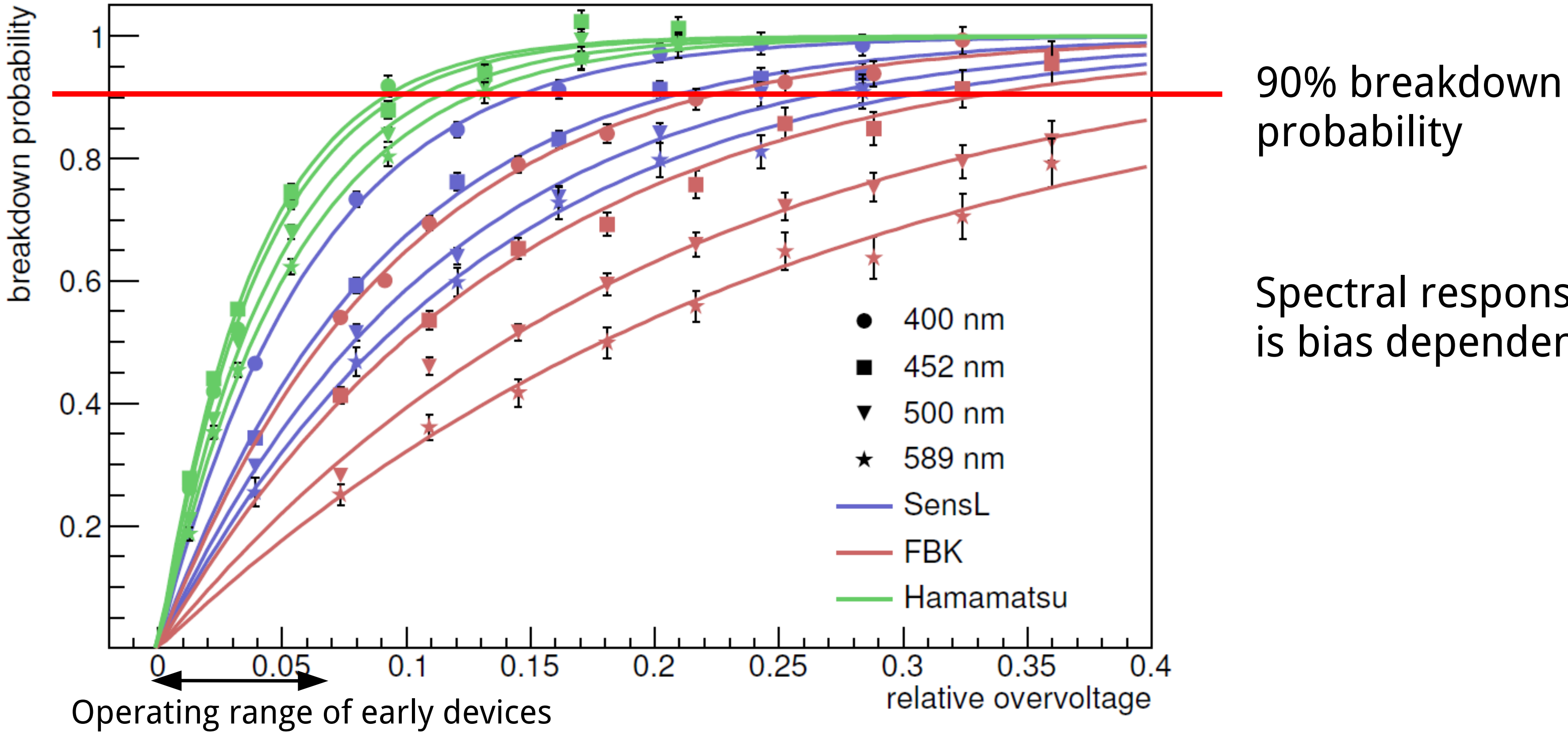


p-on-n structue

Pancheri et al (2014)



Breakdown Probability

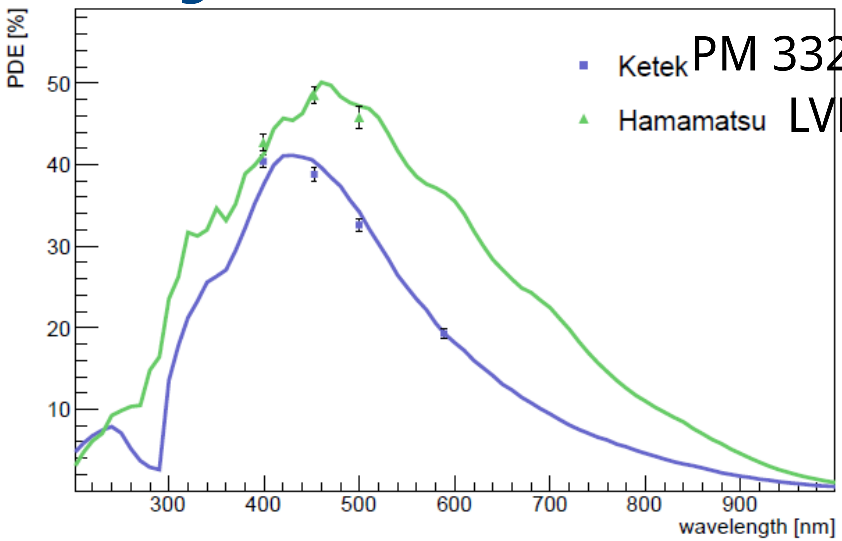


Spectral response is bias dependent

Pathways towards better UV/VUV sensitivity

Spectral response matches emission spectrum of most anorganic & organic scintillators

But below 400 nm ...



PM 3325WB
LVR2

For Cherenkov light detection want better NUV sensitivity

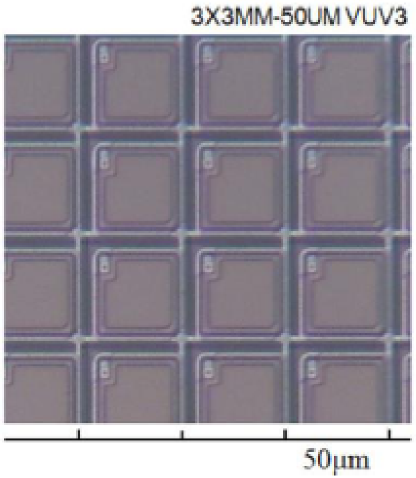
UV transparent coating
thinner passivation layer
anti reflective coating

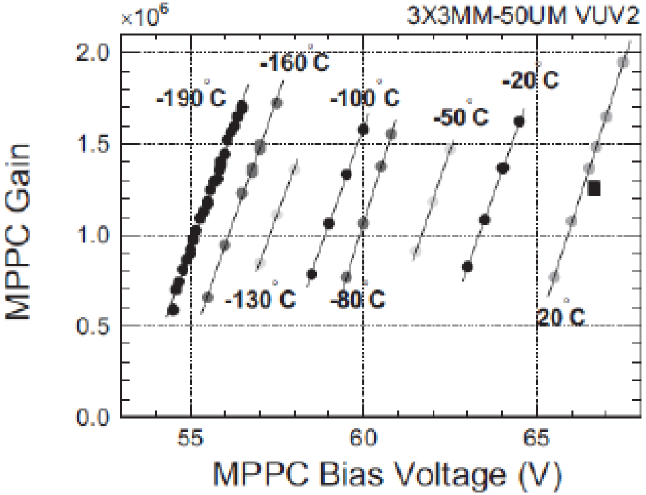
→ room for improvement 30% - 50%

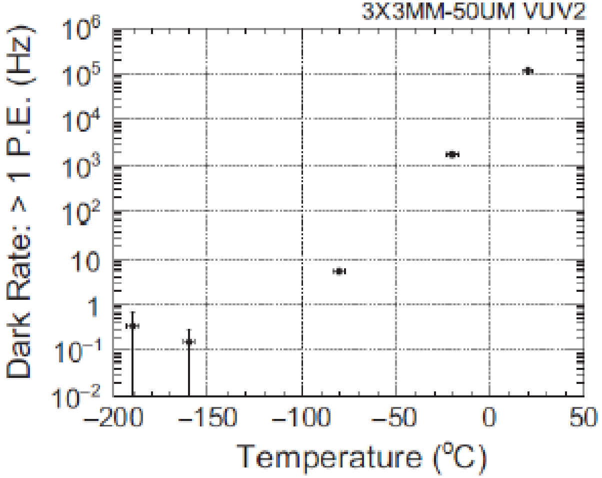
Otte (2017) to be submitte

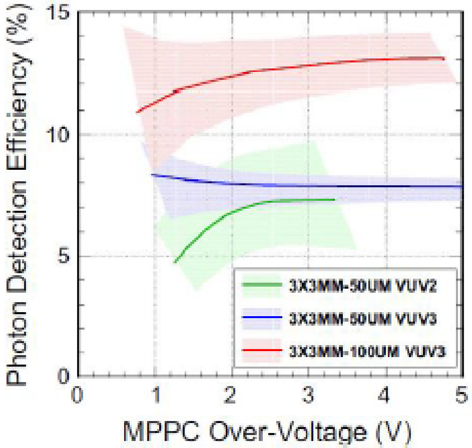
Ultimate goal is to have response curves tailored for different applications

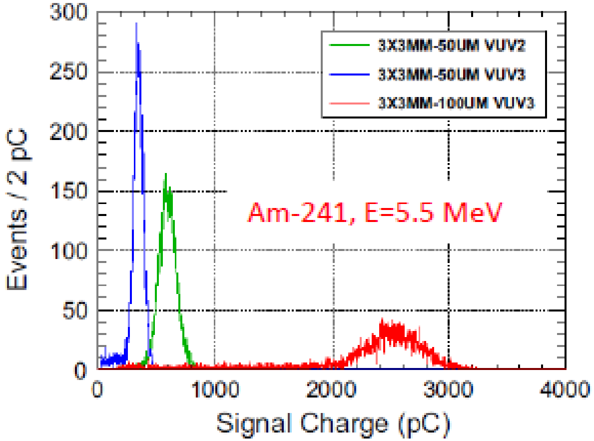
Another important development: SiPMs sensitive to VUV light (<150 nm) were recently developed by HPK for detection LAr (T=-186 °C) scintillation light (λ = 128 nm).









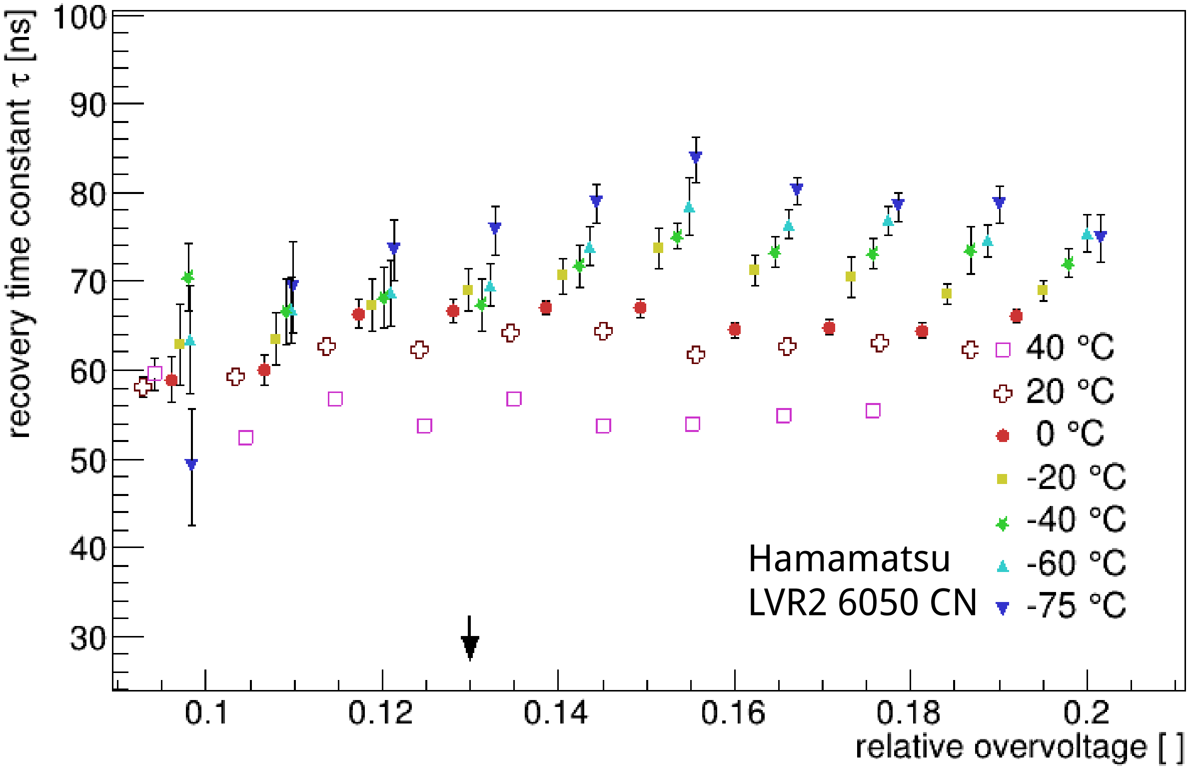


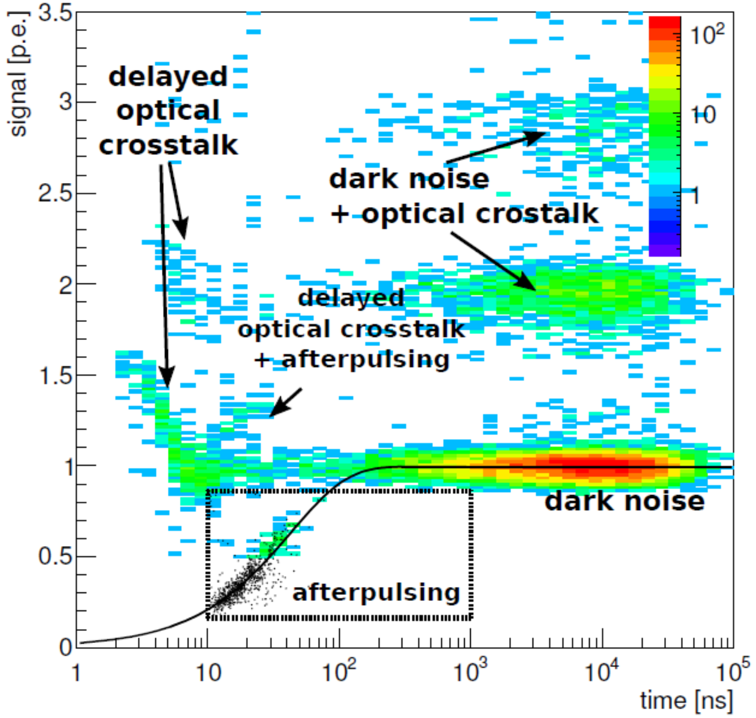
The PDE(128 nm) was measured ~8% for 50 μm pitch SiPMs and ~13% for 100 μm pitch SiPM at dVB=3 V

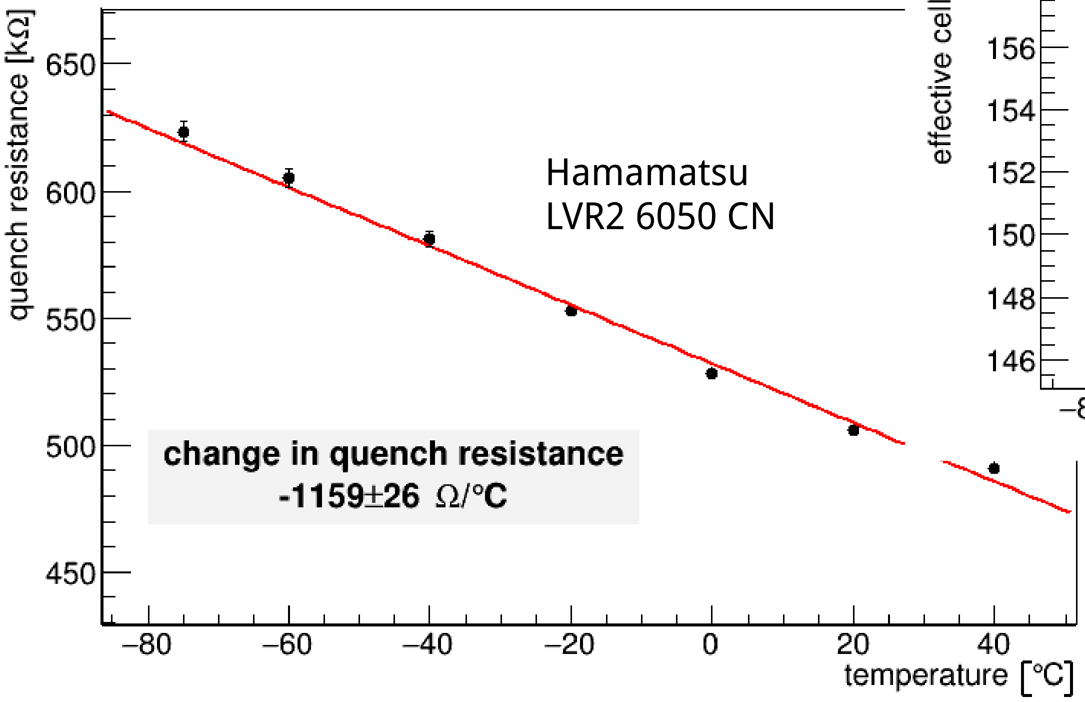
(NIM A833 (2016) 239–244)

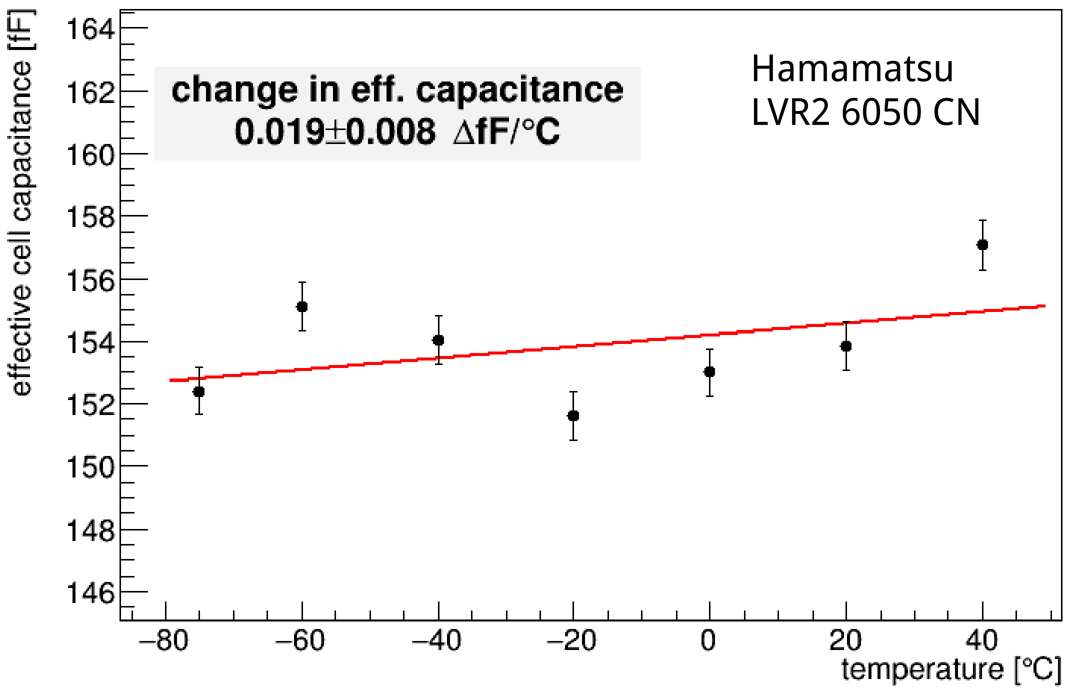
Cell Recovery Time Constants

Cell recovery time $\tau = RC$





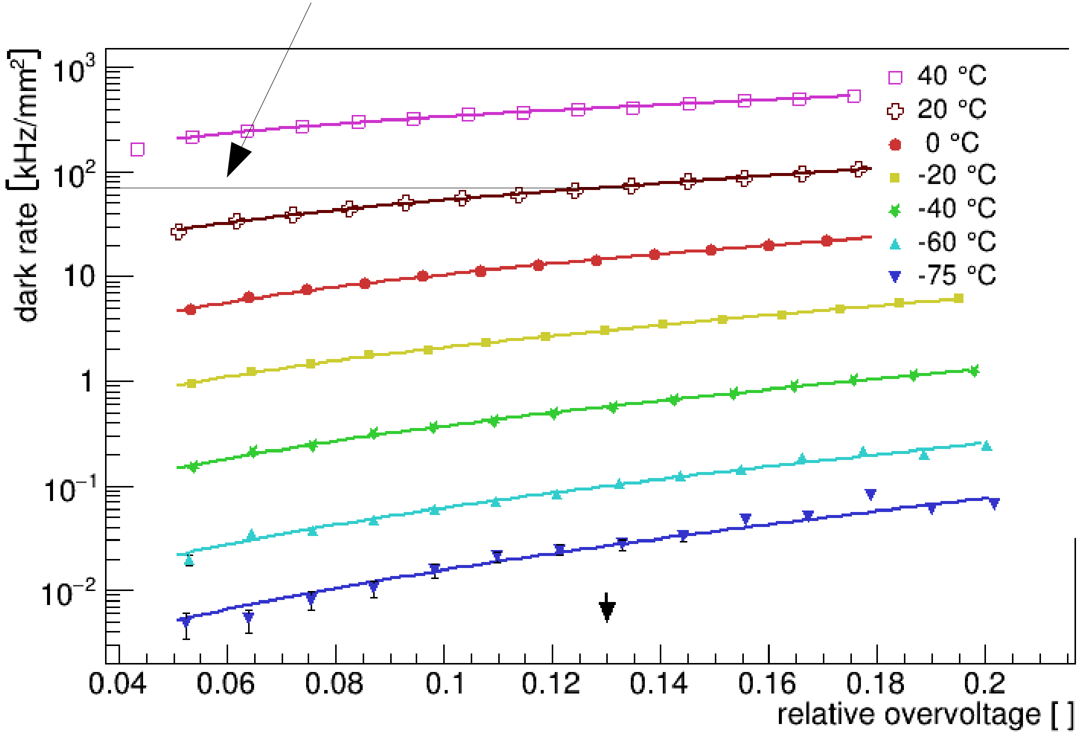


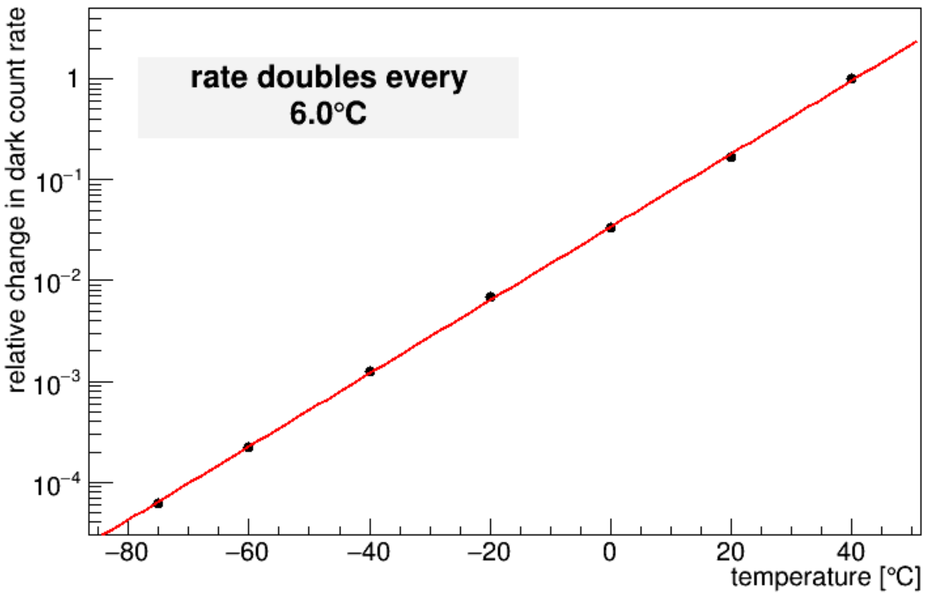


R x C_eff ~ recovery time constant

Dark Count Rates

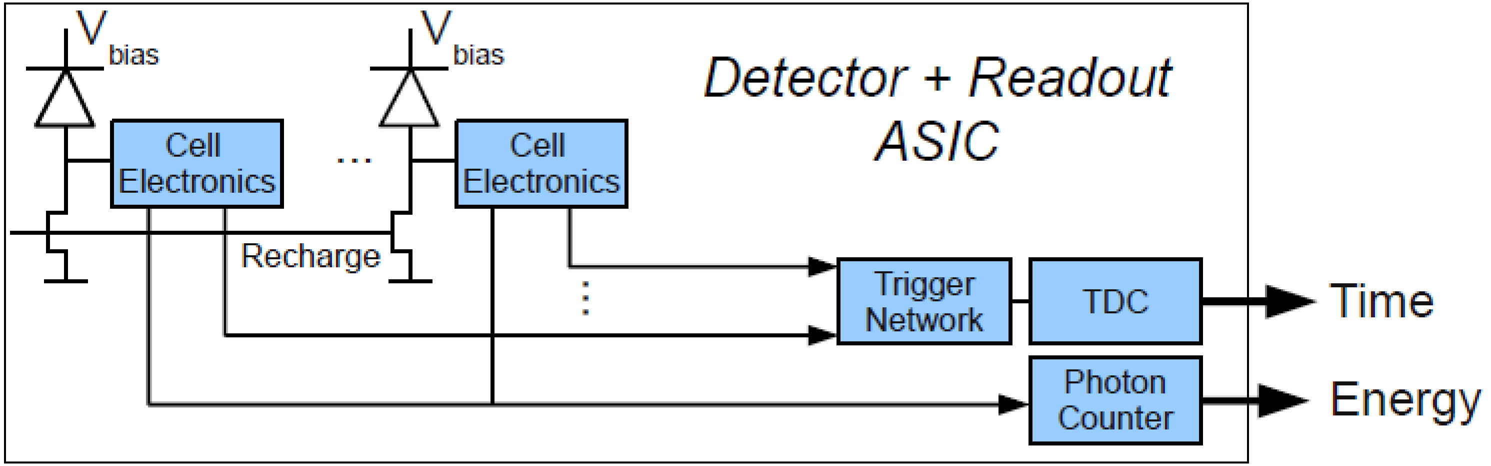
70 kHz/mm²





Hamamatsu LVR2

SiPM with Active Quenching: dSiPM

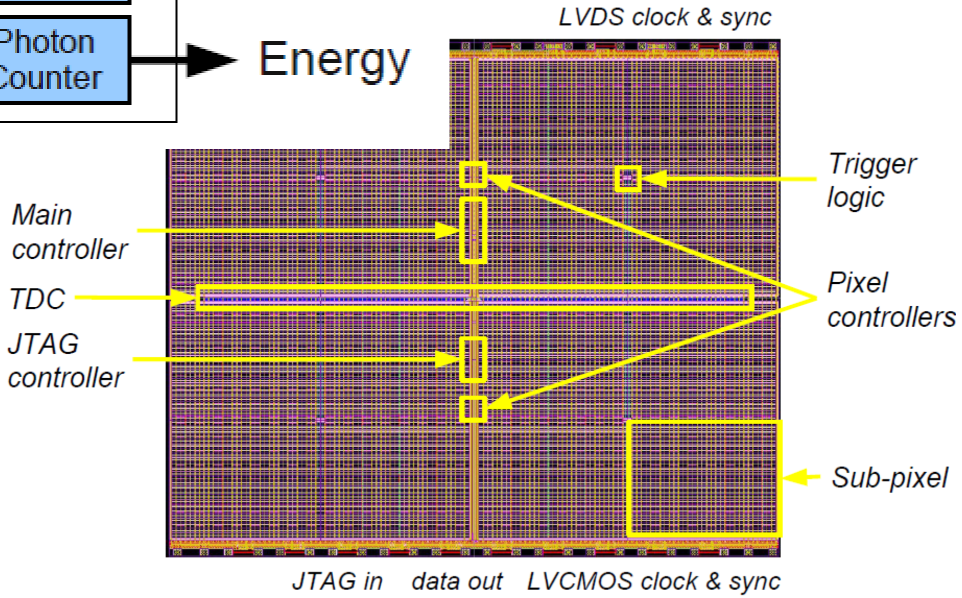


First commercial dSiPM from Philips

Individual pixels can be turned on/off

Excellent timing

Reduced geometrical efficiency → lower PDE (for now...)



SiPM Advantages and *Nuisances*

- Mechanical robust
- Compact
- Operating voltages < 100V
- Not damaged in bright light
- No aging
- Insensitive to magnetic fields
- Excellent SNR
- Excellent single photon timing (<100 ps)
- Very high photon detection efficiency
- Low radioactivity

What's being worked on

- Radiation hardness
- Better UV/VUV sensitivity
- Lower optical crosstalk
- Lower dark rates
- Size

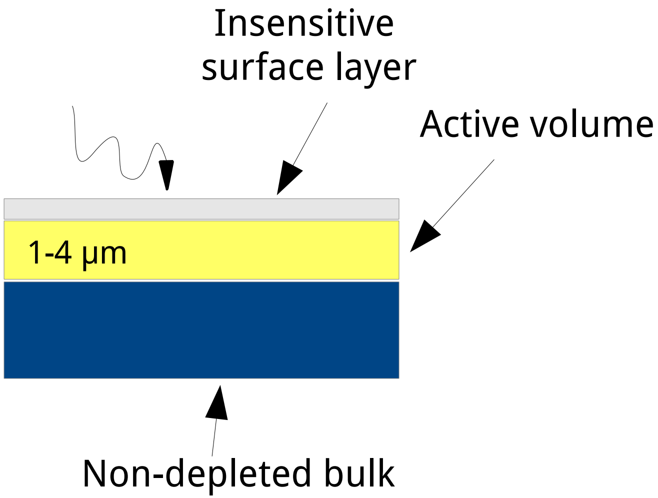
A near perfect device for many applications

You have Choices

from W. Ootani

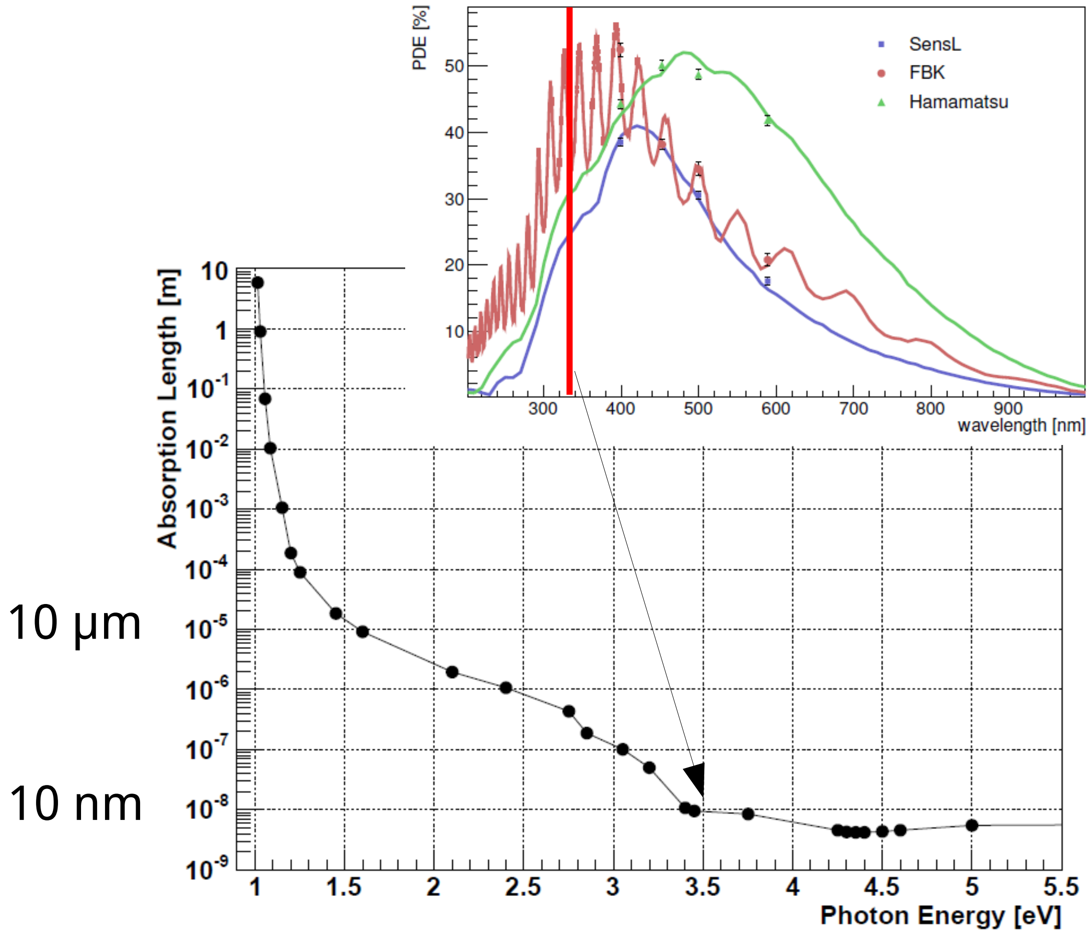
Interactions between producers and users are very productive!

Spectral Response



Spectral response determined by:
- photon absorption length
- Surface reflectivity

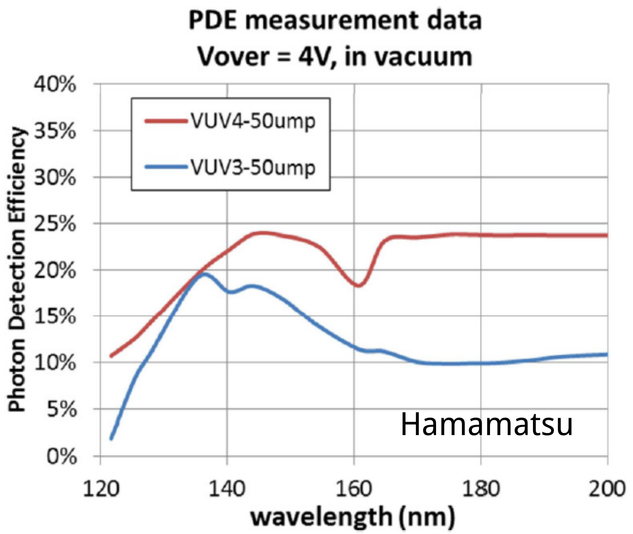
→ For UV/VUV need:
- thin passivation layer
- anti reflective coating
- Wavelength shifter



Response in the VUV

Liquid Nobels are the dominating detection media in HEP/DM in the foreseeable future

→ Need photon detectors that are sensitive between 100 nm and 200 nm



30% PDE seems possible

Efforts will ultimately be limited by silicon properties

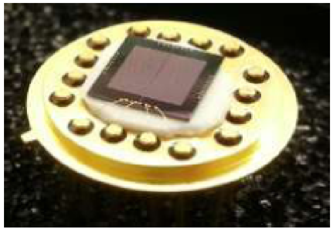
See talk by F. Retiere

Solid State Photomultipliers: SiC GaInP, GaAs,…

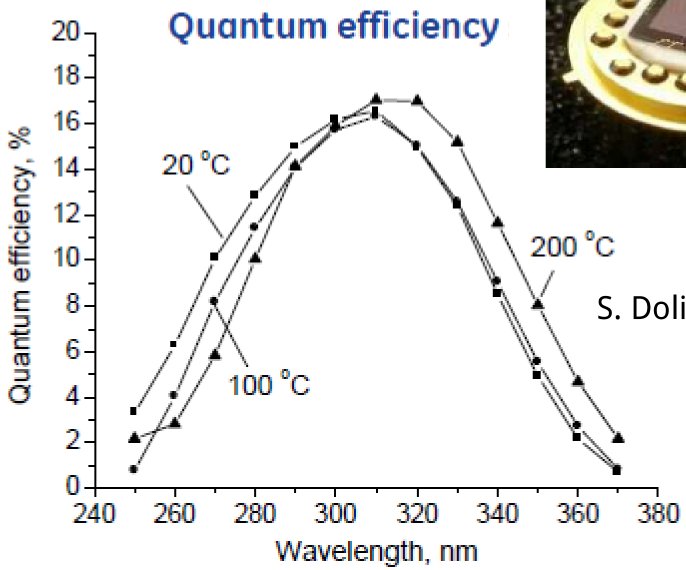
- Bandgap can be adjusted → spectral response can be tuned
- Potentially better radiation hardness
- Used on industrial scale → infrastructure exists

It is a technological challenge very much like in the early days of SiPMs

Packaged SiC SSPM

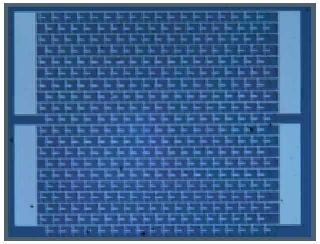


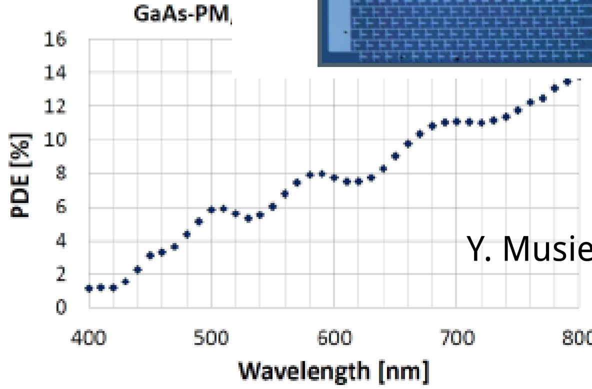
Active area: 4x4 mm²
Pixel size: 60 um
16 sub arrays
Area of sub-array:
1x1 mm²



S. Dolinsky NDIP 2014

LightSpin Photomultiplier Chip™





Y. Musienko