Radiation Tolerance Issues with Implementation of Silicon Photomultipliers

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Tech Transfer Workshop
Opportunities with Detector Technologies in Nuclear Physics
Catholic University of America
Washington, DC
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OUTLINE

Introduction to SiPM tech (user view)

Go over some of the key aspects of SiPM operational characteristics

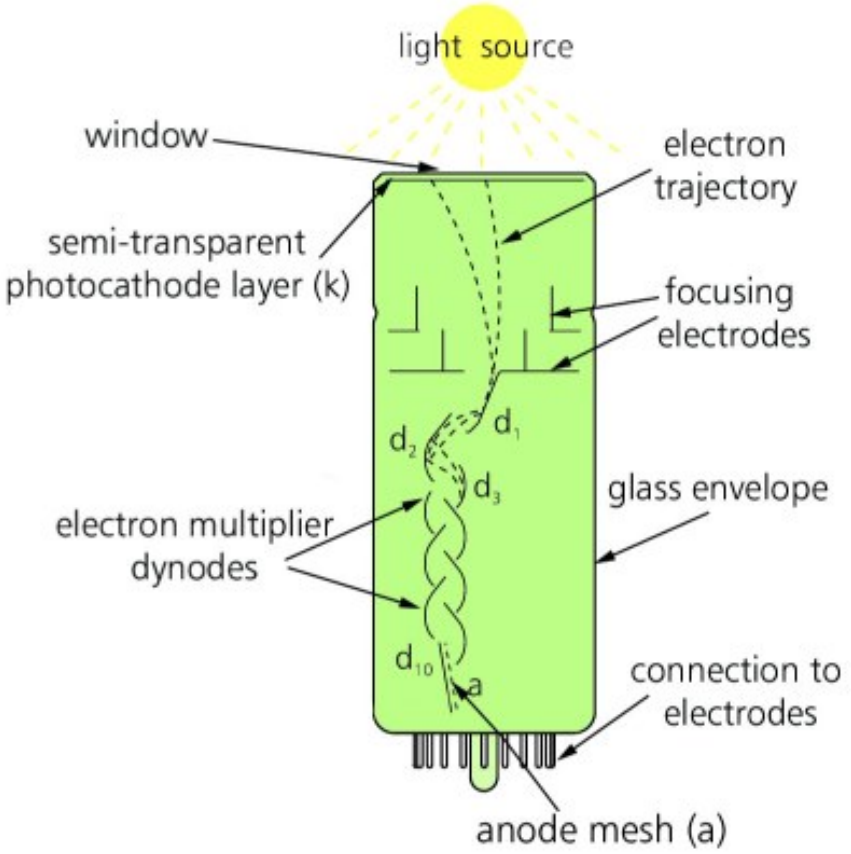
Radiation damage to SiPM (user view)

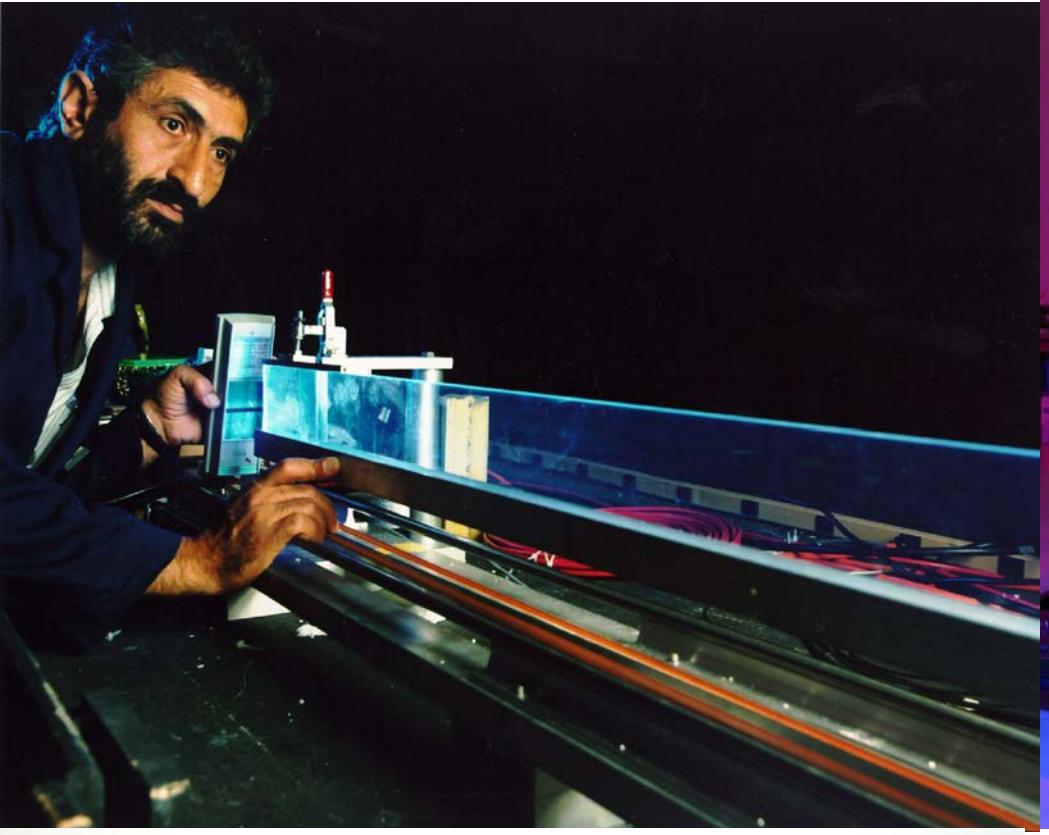
Go over the key phenomena

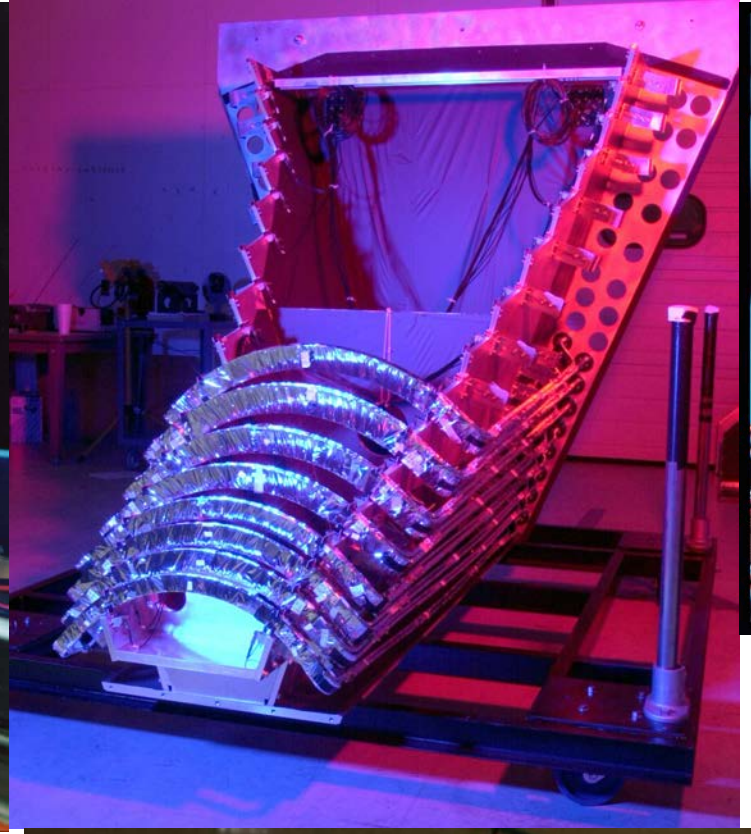
More importantly, go over some ways to abate the damage

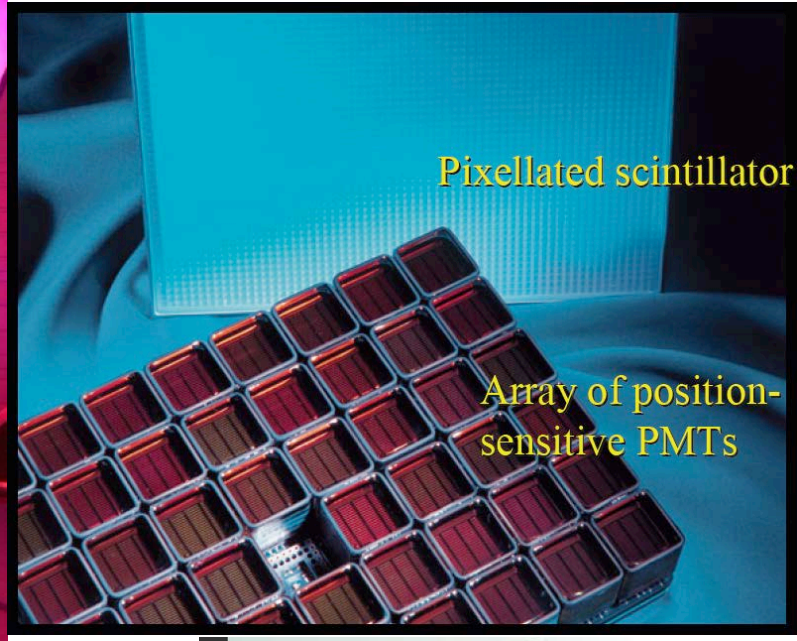
Suggestions for future work

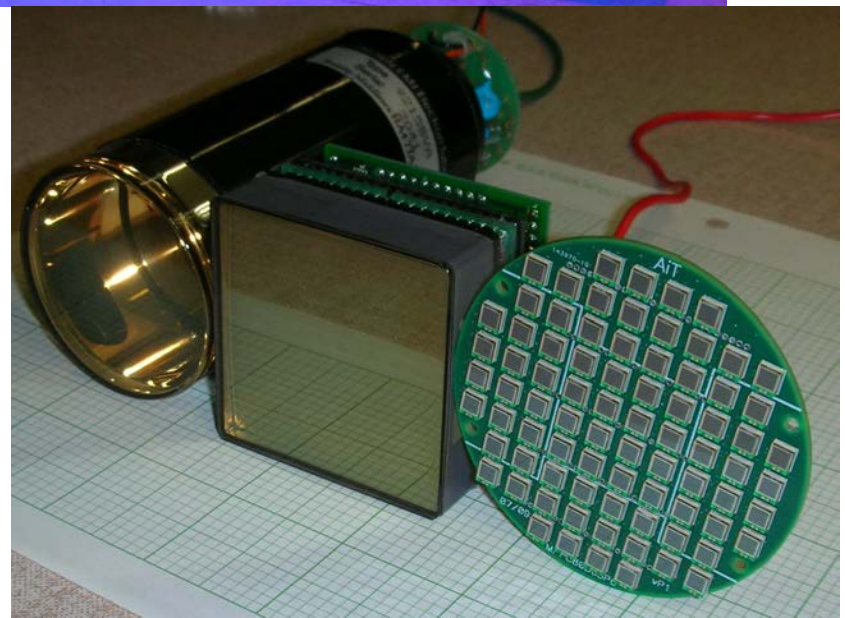
Traditional Photodetector "Workhorse": *Vacuum Photomultipliers*





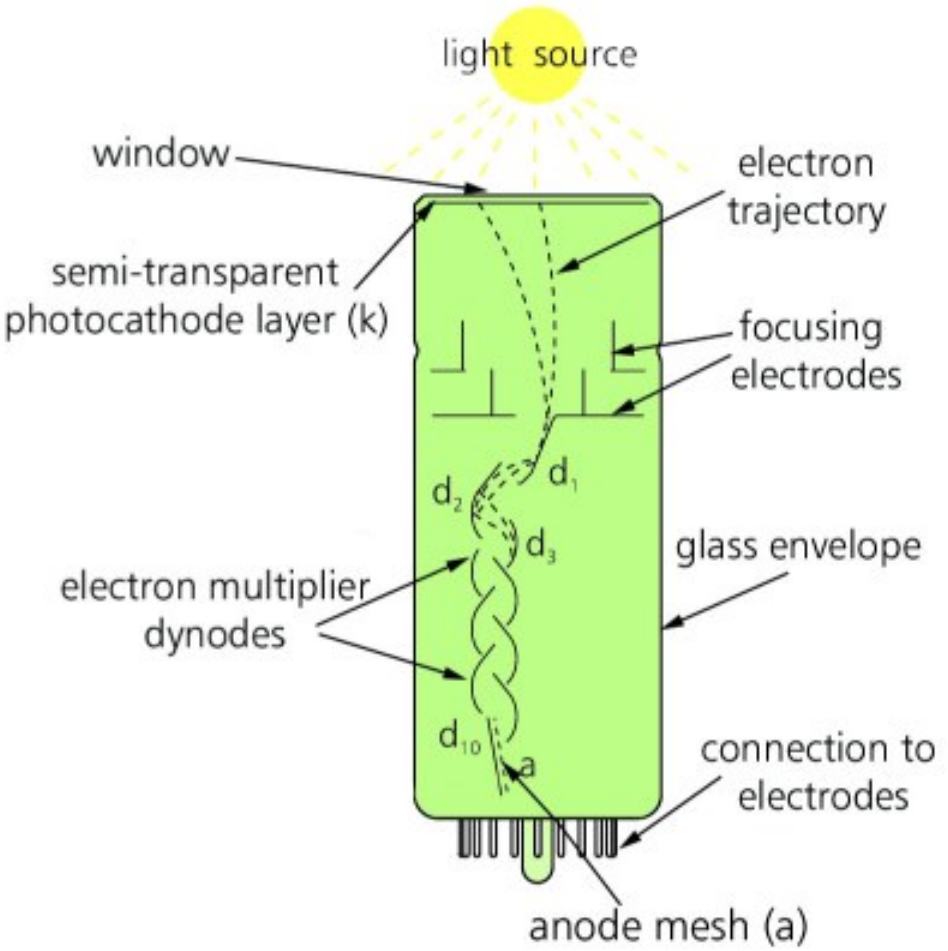



Pixellated scintillator
Array of position-sensitive PMTs

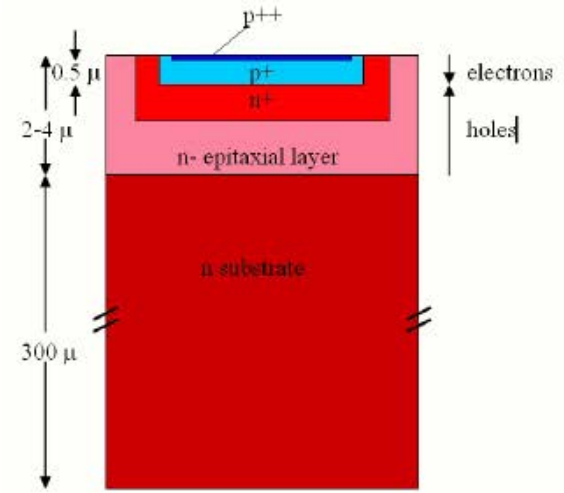


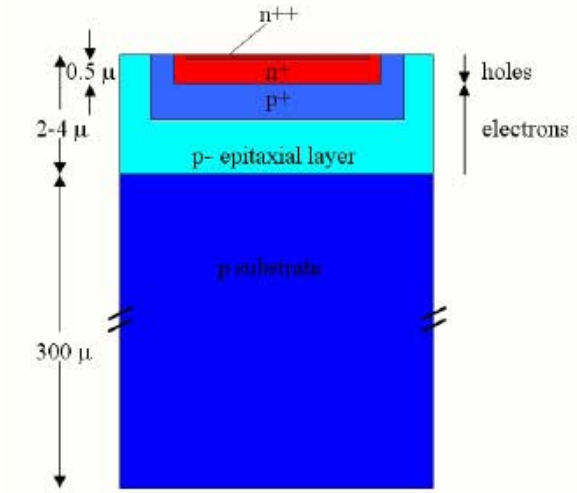
Photomultipliers

PMT



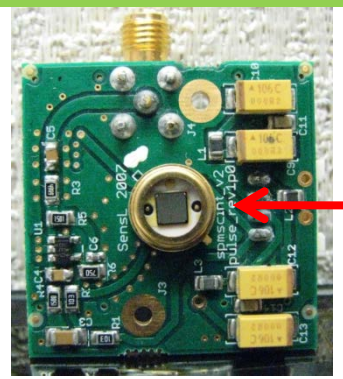
SiPM





"p on n"
Higher breakdown voltage (70V)
Blue-peaked sensitivity
Less dark noise

"n on p"
Lower breakdown voltage (30V)
Green-red sensitivity
More dark noise



3x3 mm^2

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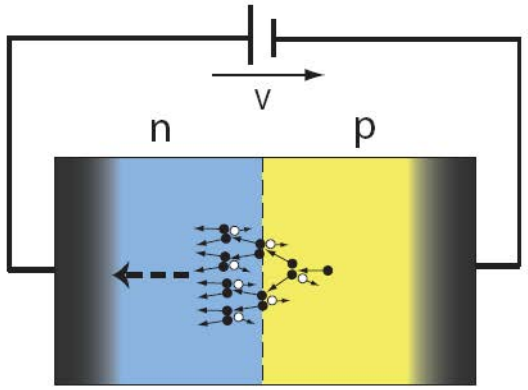
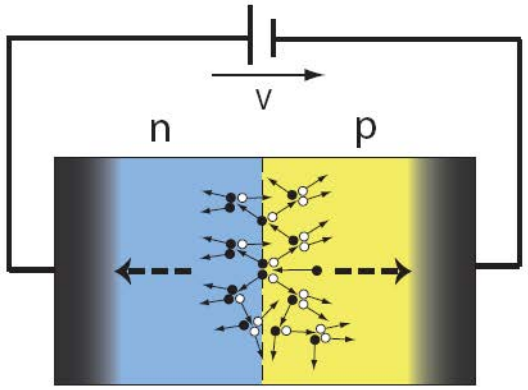
Avalanche Photodiode (APD)



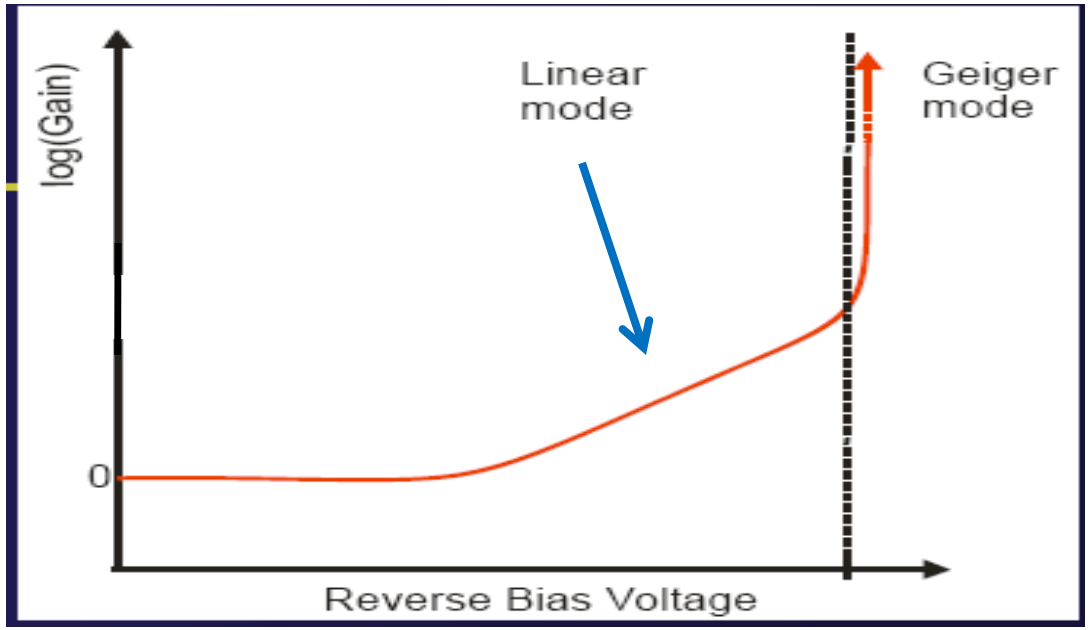
Linear Mode



Geiger Mode

hole

electron



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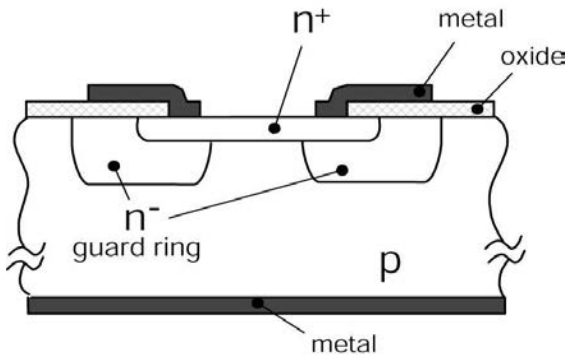
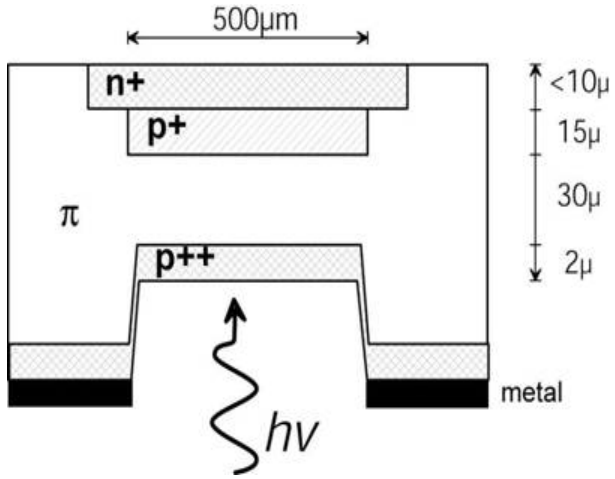
A Bit of History



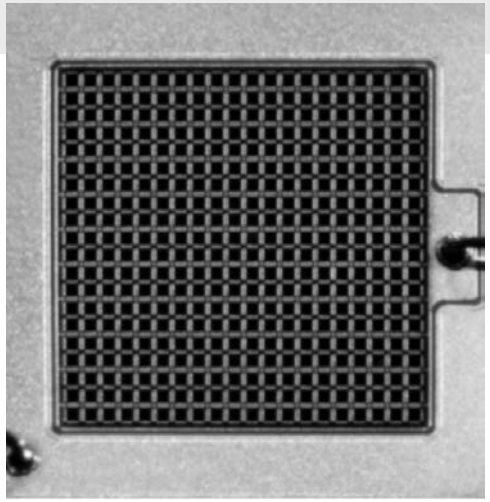


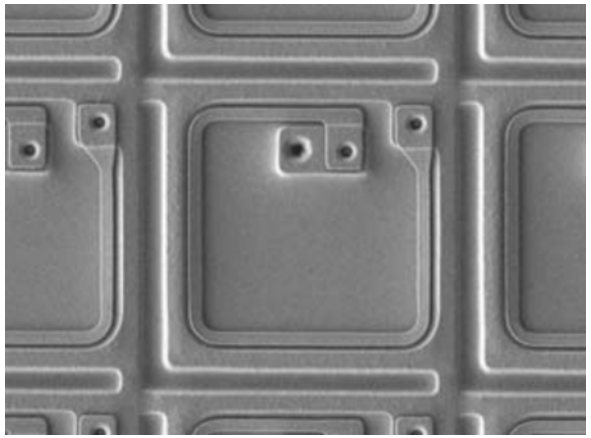
First geiger-mode APDs made in 60/70s could only be used as single photon counters.

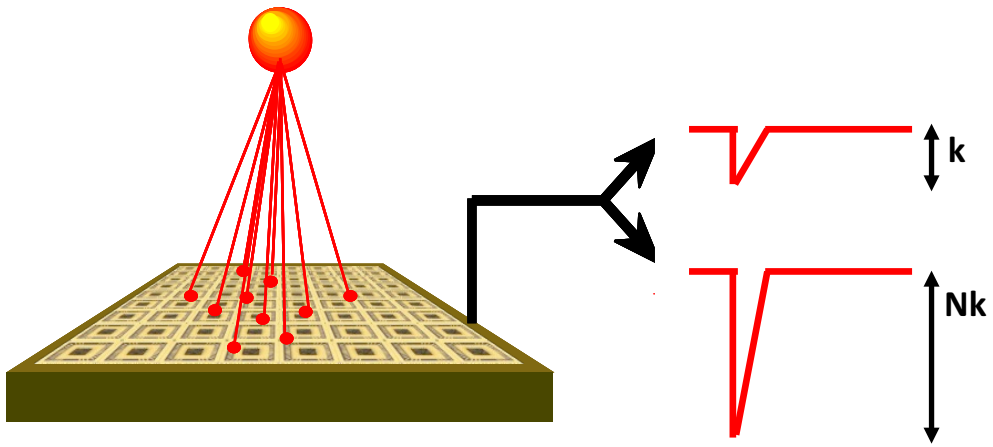
Still available today – commonly used in biomolecular work

SiPM ➔ Geiger mode SPAD array

- Array of several micro-cells, connected in parallel
- Each cell is a Single Photon Avalanche Diode (SPAD)
- The device is biased above its breakdown voltage
- Each cell is sensitive to one photon (digital response)
- The whole array is an analogue device

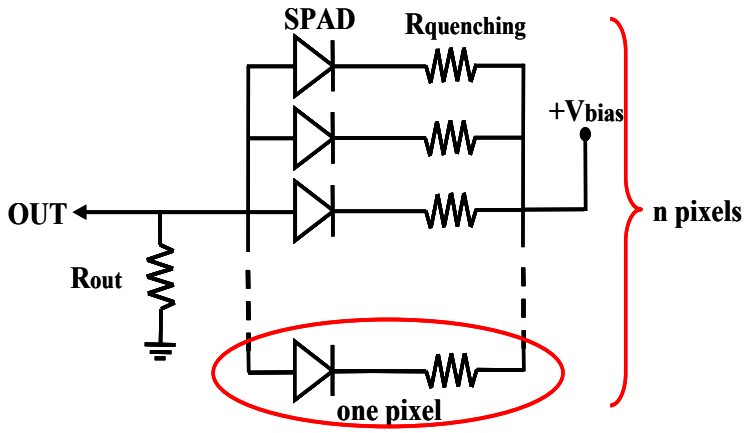






N activated pixels

SiPM equivalent circuit



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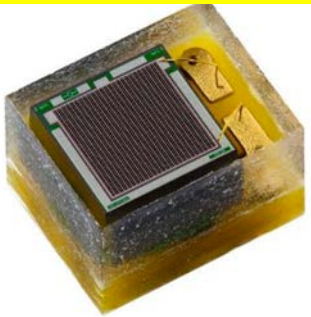
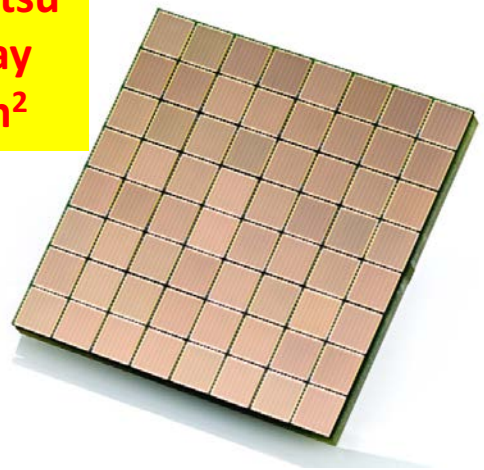
Pics of SiPMs

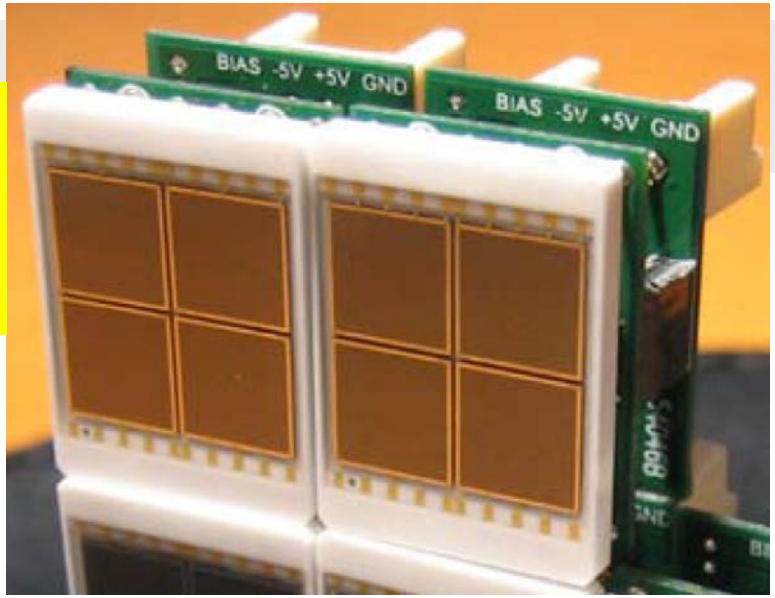
1x1 mm^2 Ketek

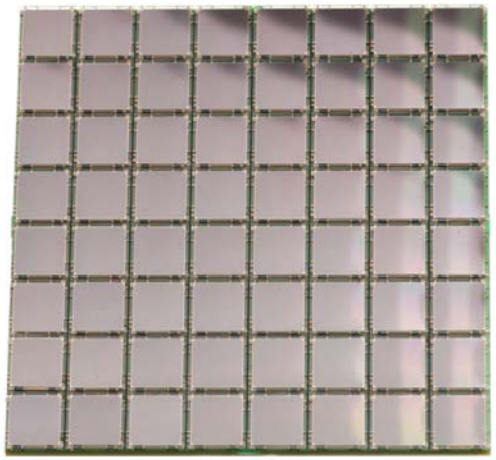


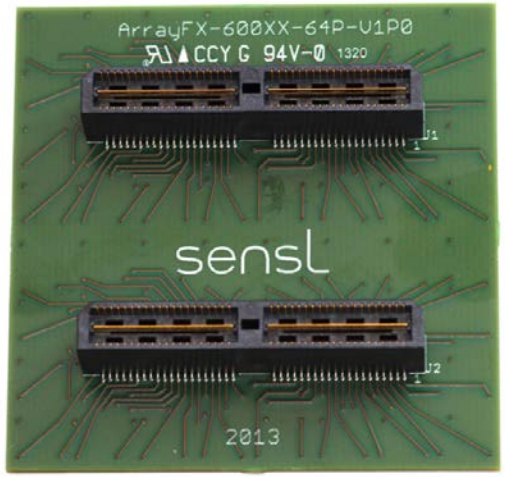
Hamamatsu
8x8 array
3x3 mm^2



Hamamatsu
Hall D array
4x4 array
3x3 mm^2







SensL
8x8 array
3x3 mm^2

16x16 array
3x3 mm^2
SiPM replacement
for 5x5 cm^2 PSPMT

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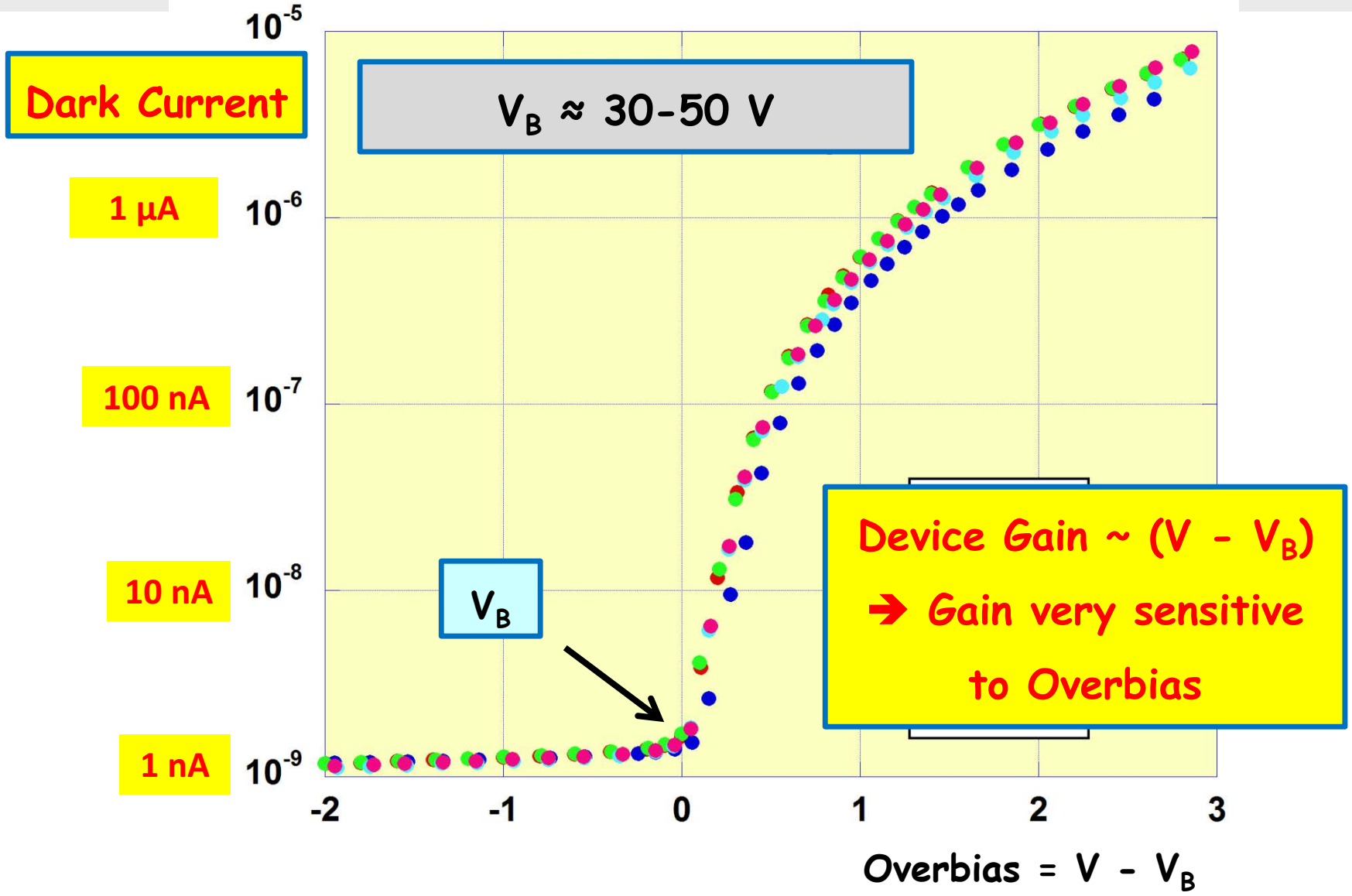
Turning on a SiPM (in the *Dark*)



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Signal Gain

PMT

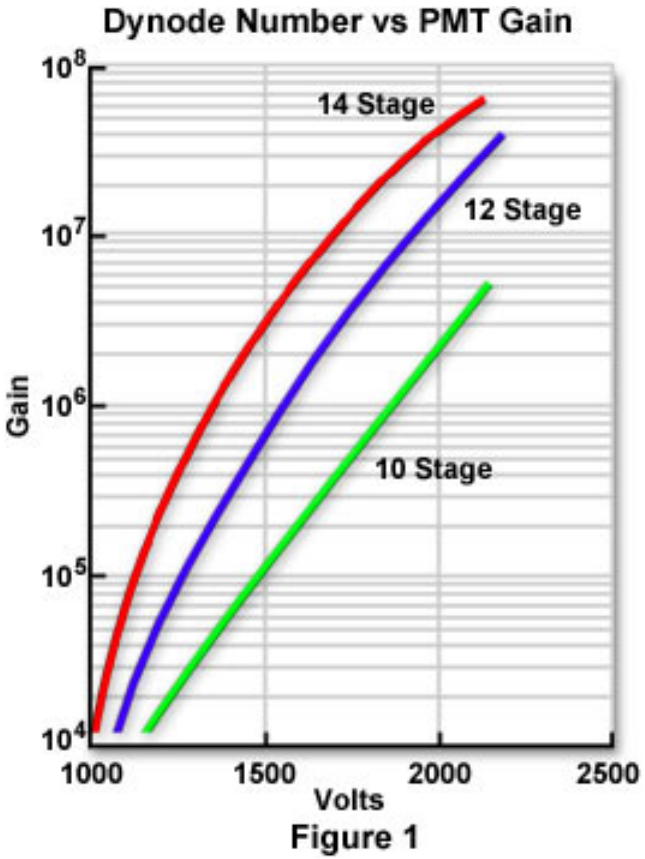
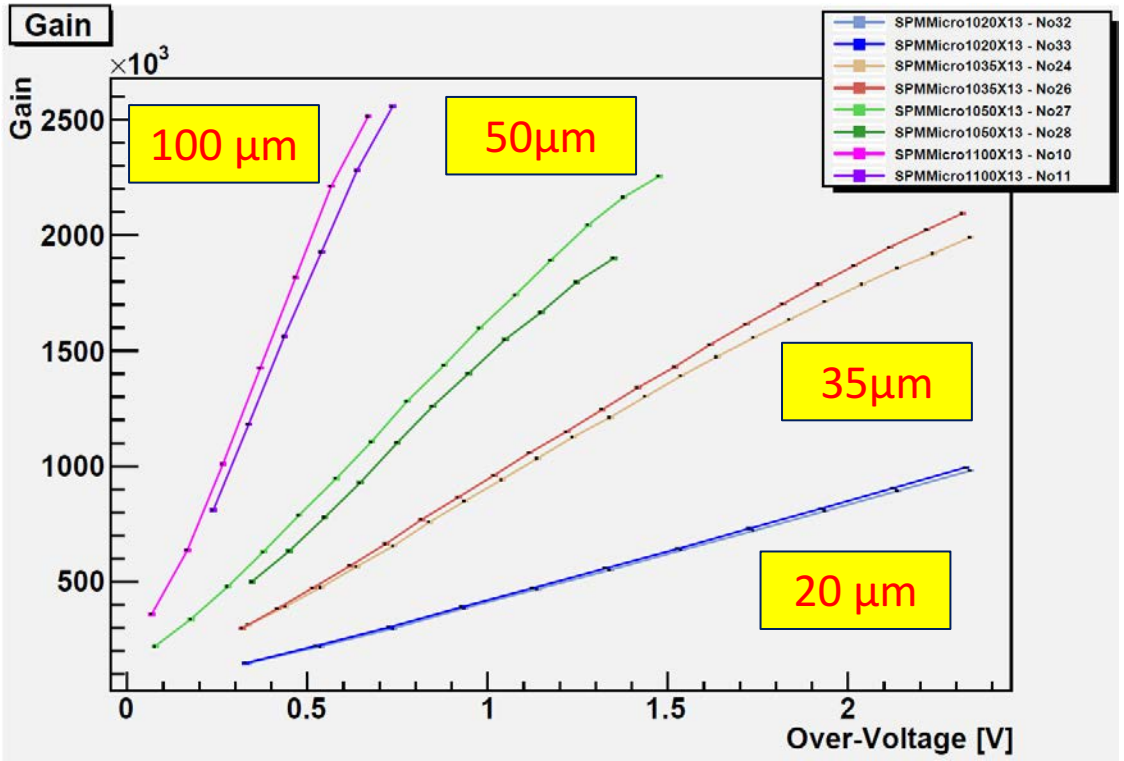


Figure 1

SiPM*



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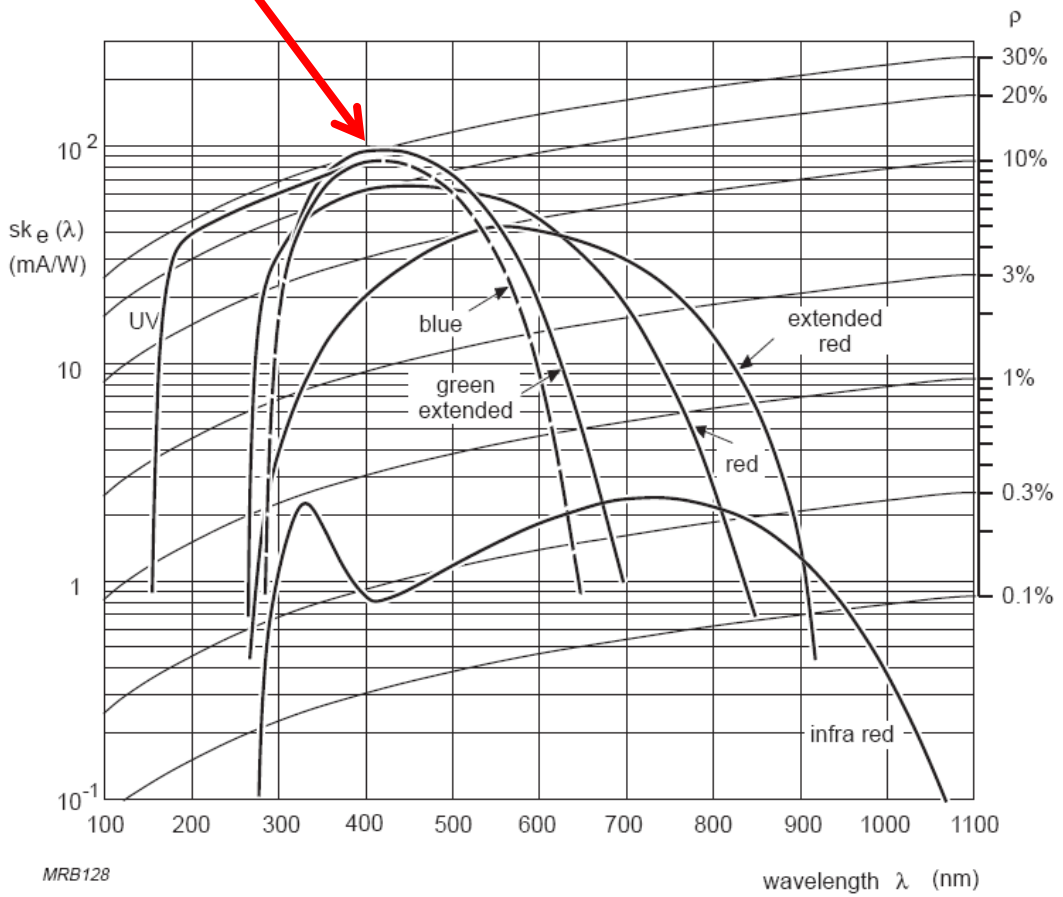
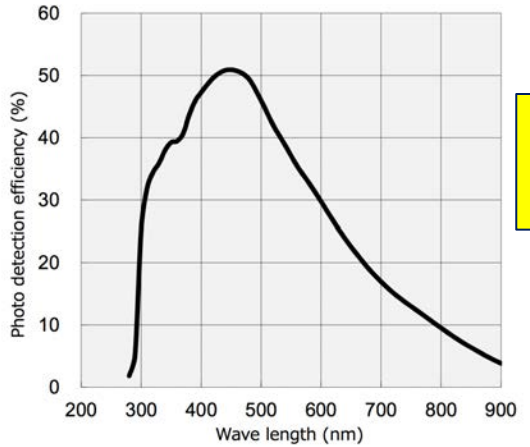
Quantum Efficiency vs Wavelength

PMT

20-30% peak is typical

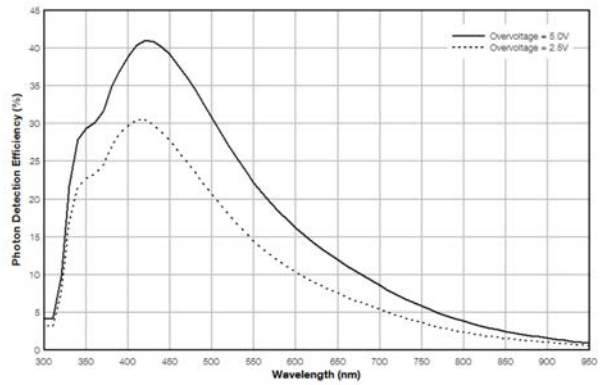


SiPM



Hamamatsu
14160 series

~40-50% peak is typical now



SensL
C series

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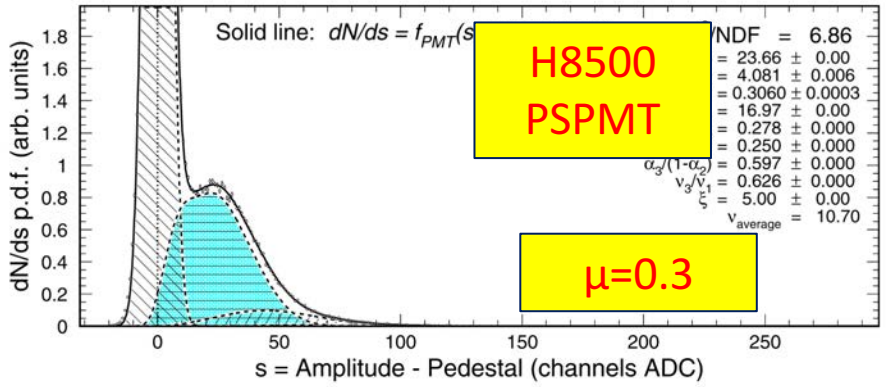
PMT

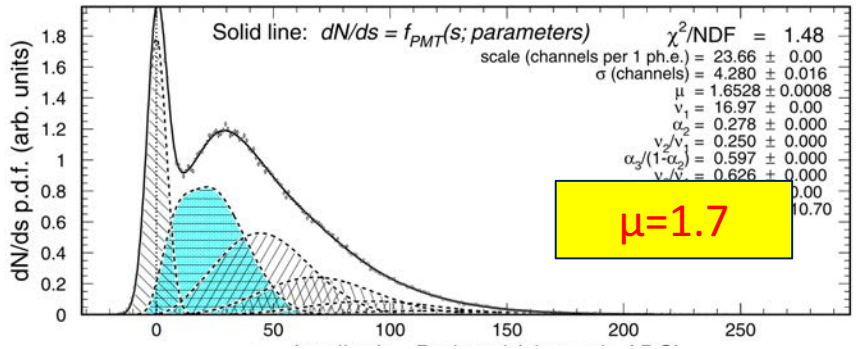
Photoelectron Resolution

SiPM

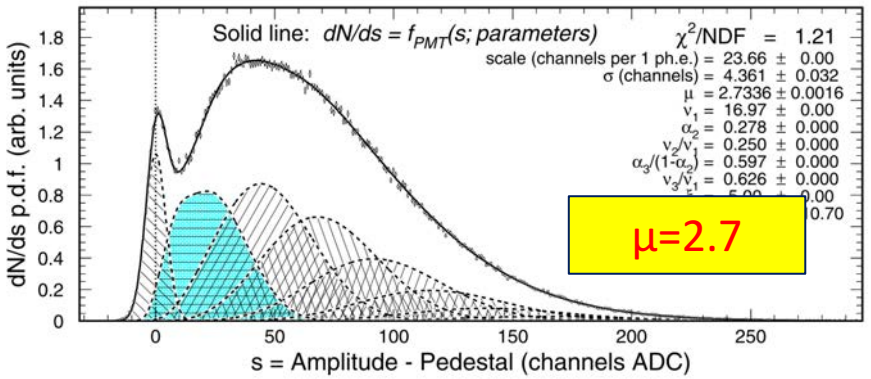


H8500 PSPMT

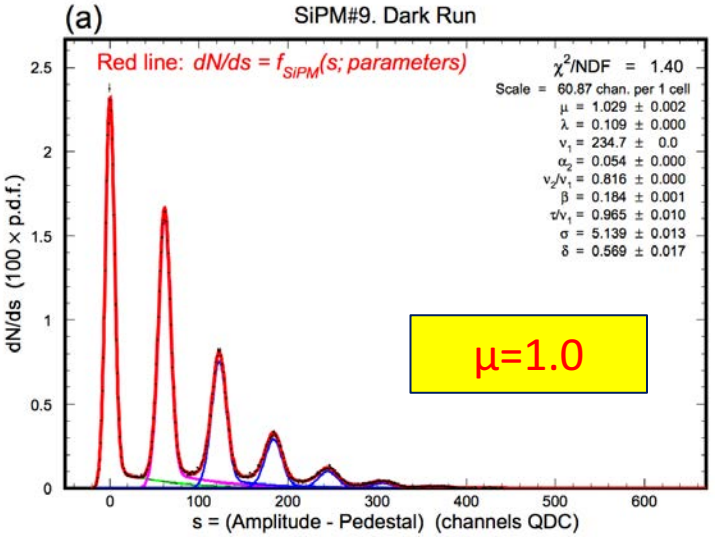
μ=0.3



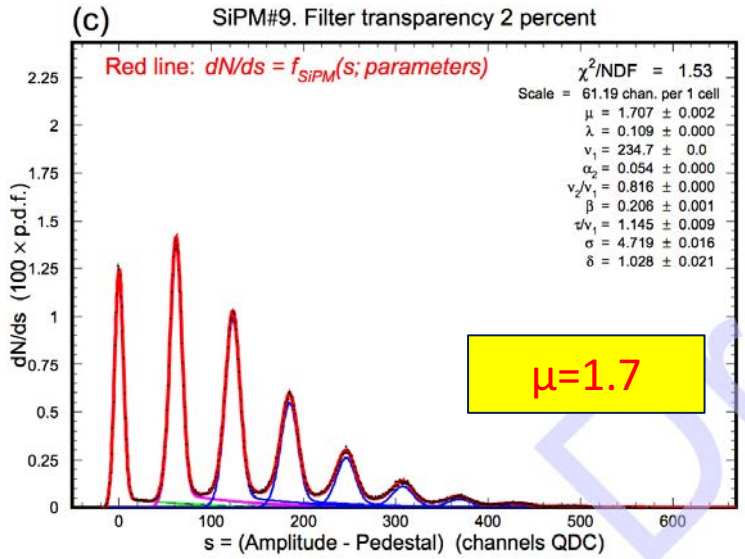
μ=1.7



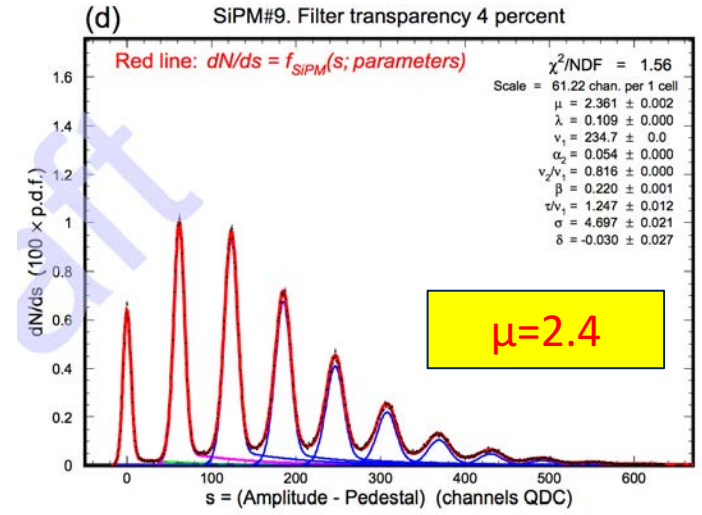
μ=2.7



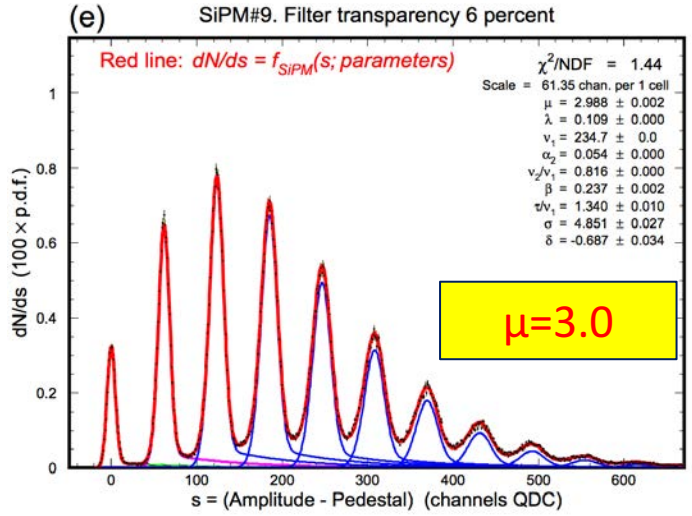
μ=1.0



μ=1.7



μ=2.4



μ=3.0

P.Degtiarenko, NIM A 872 (2017) 1-15

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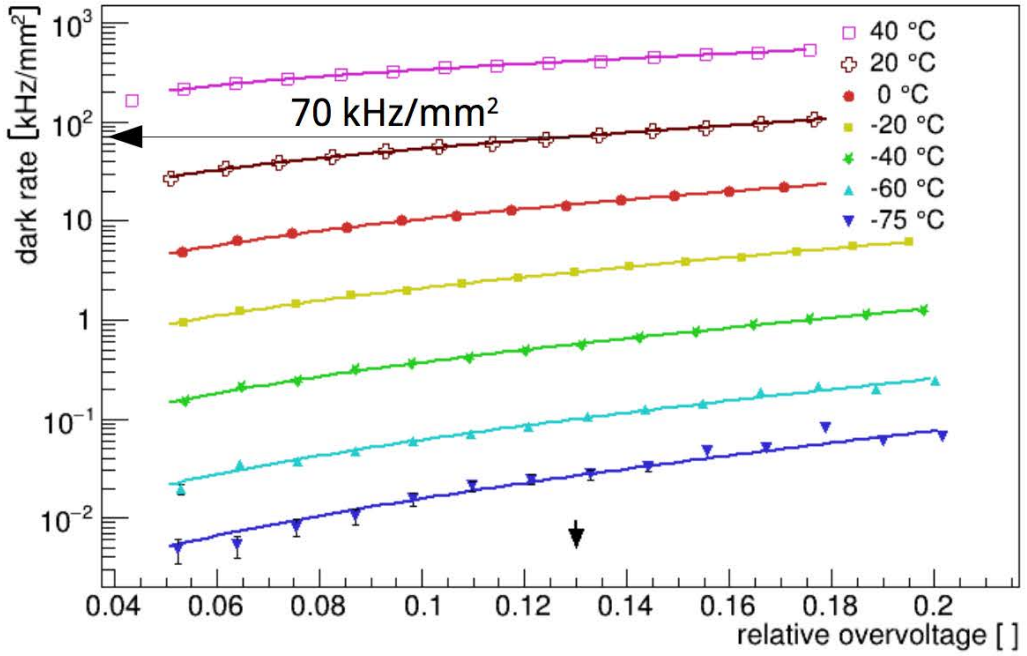
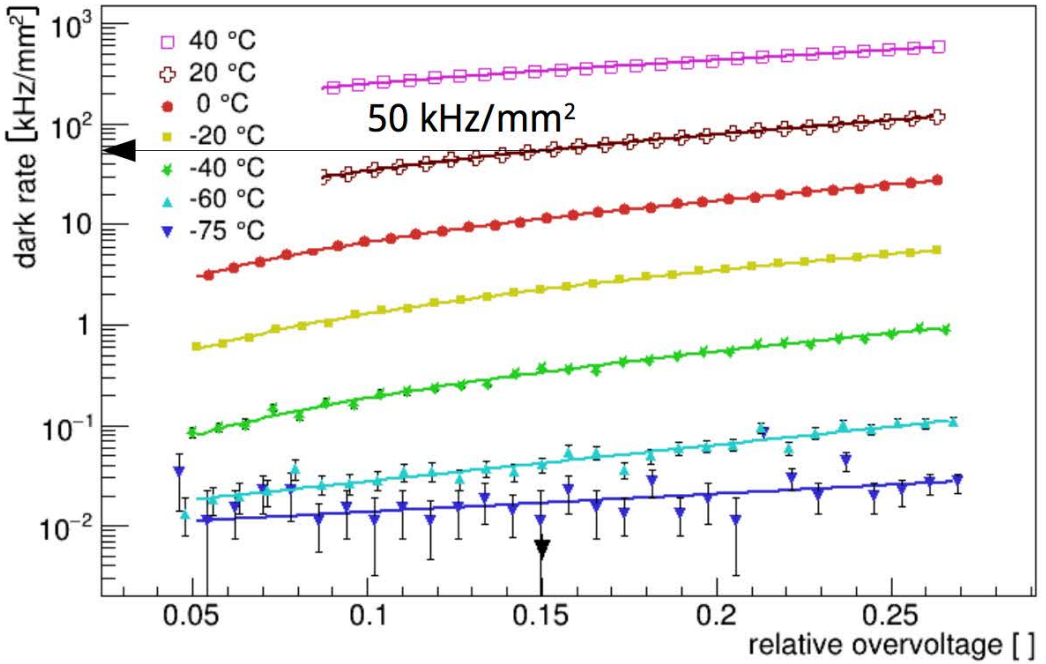
Dark Rate vs Temperature

Hamamatsu LVR2 6050 CN



KETEK PM 3325 WB



Otte et al. NIM A 846 (2017) 106-125

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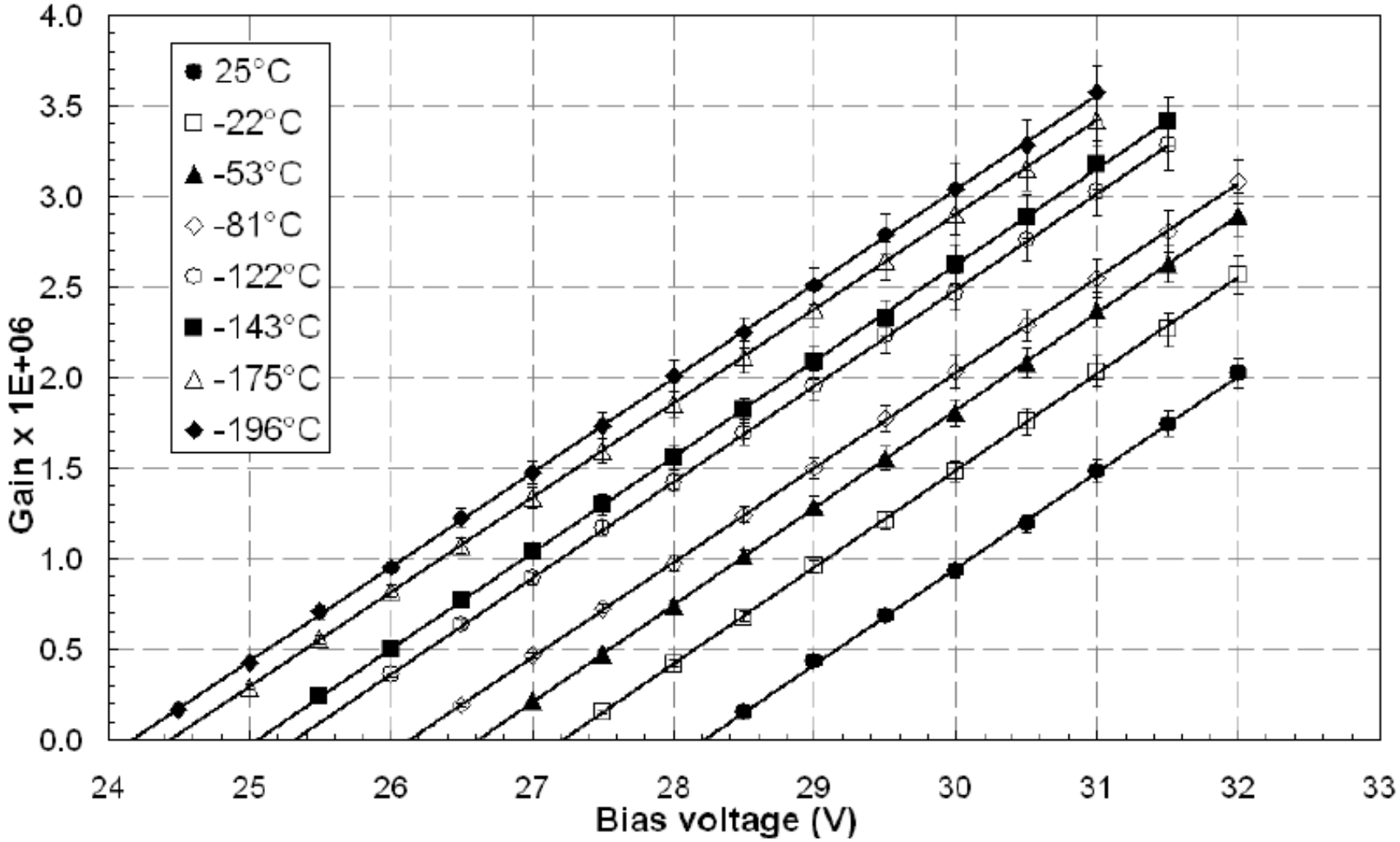
Gain vs Temperature



V_B as temp. decreases

Ref: Lightfoot *et al.*, **J. Inst.,** Oct. 2008

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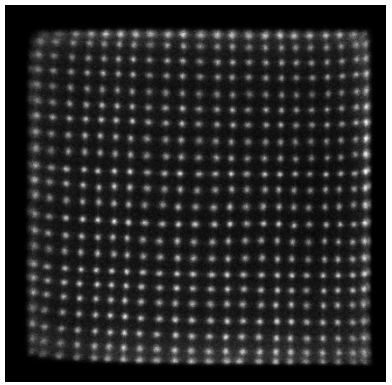
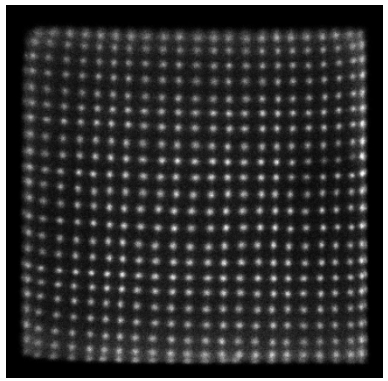
Effect of transverse field on Burle PMT

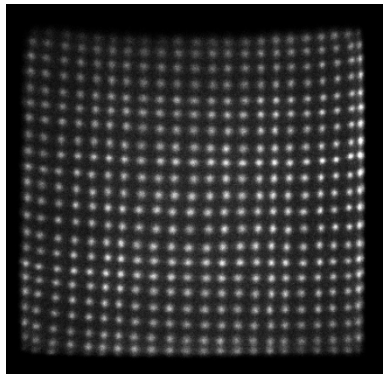
43 gauss



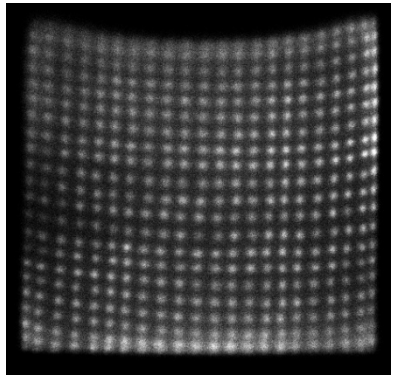
75 gauss



100 gauss



133 gauss



B field

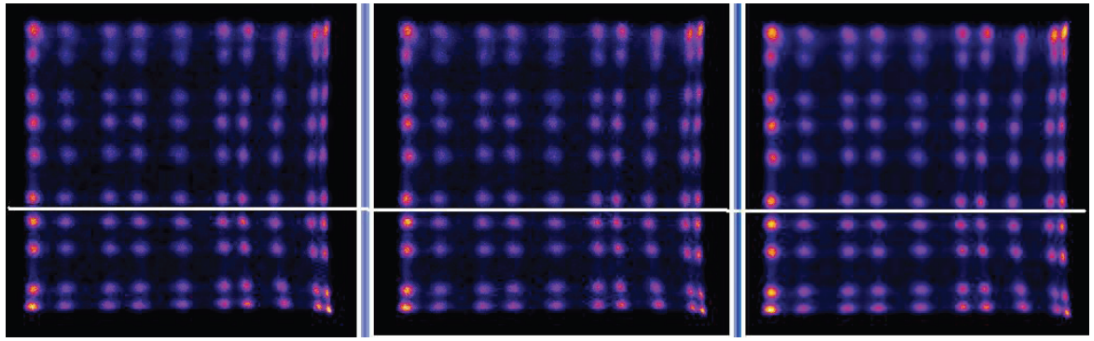
Top View

Burle

Planacon

v x B gives downward force

Effect of MRI fields on SiPM

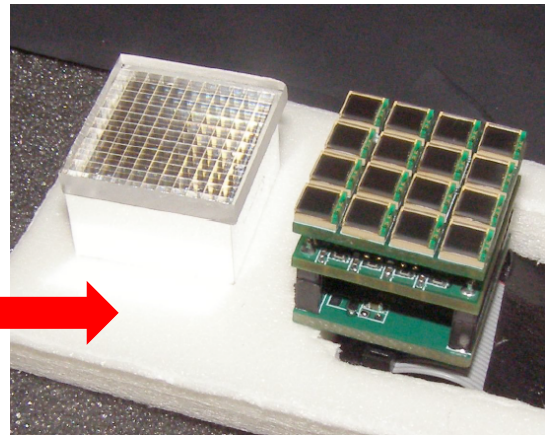


0 Tesla

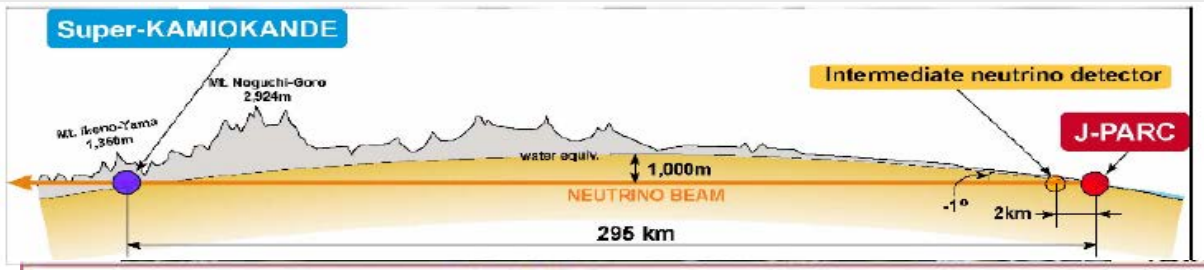
3 Tesla ||

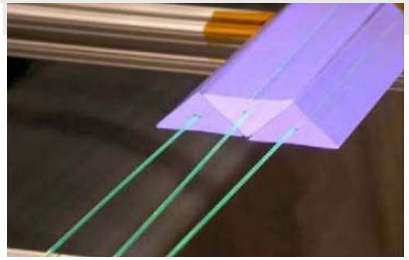
3 Tesla ⊥

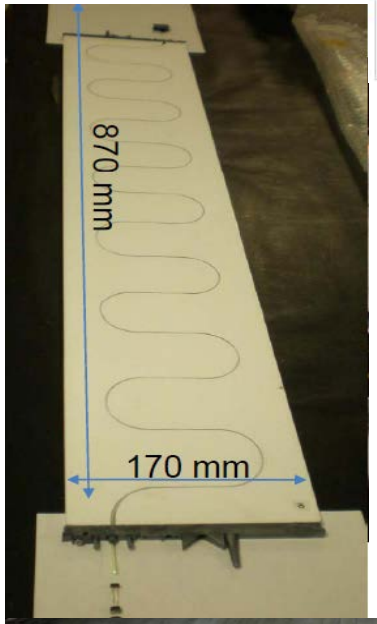
Array of SiPMs + scintillating crystal array

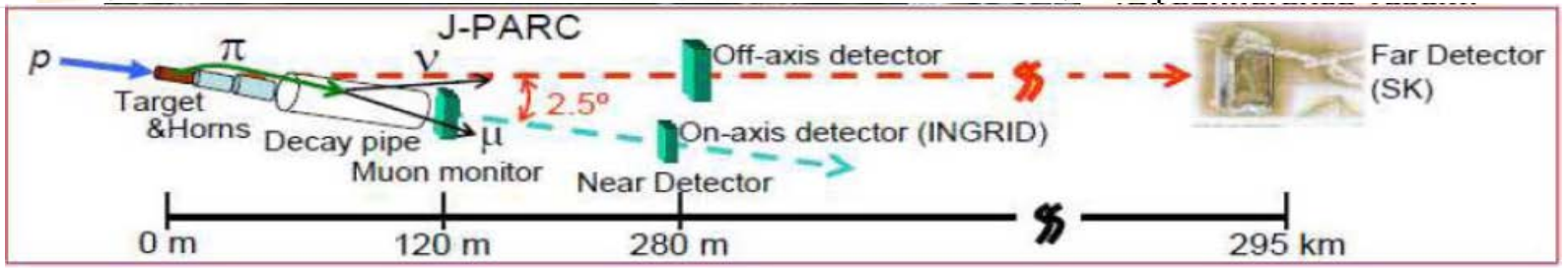


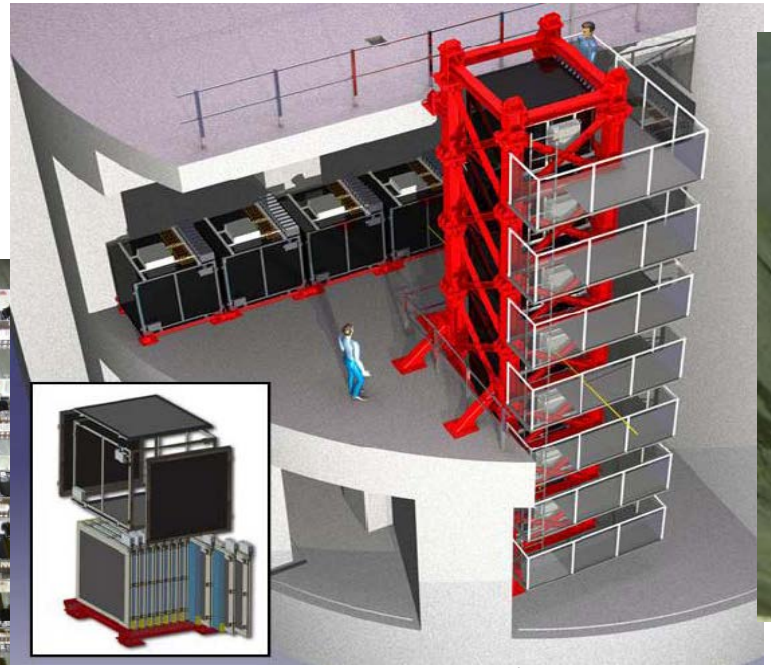
First High Volume Use of SiPMs – T2K neutrino experiment - Japan

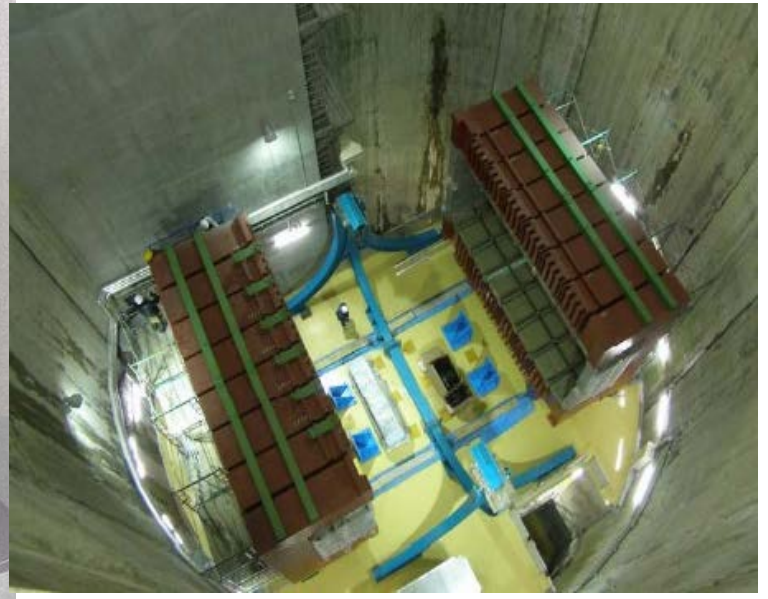


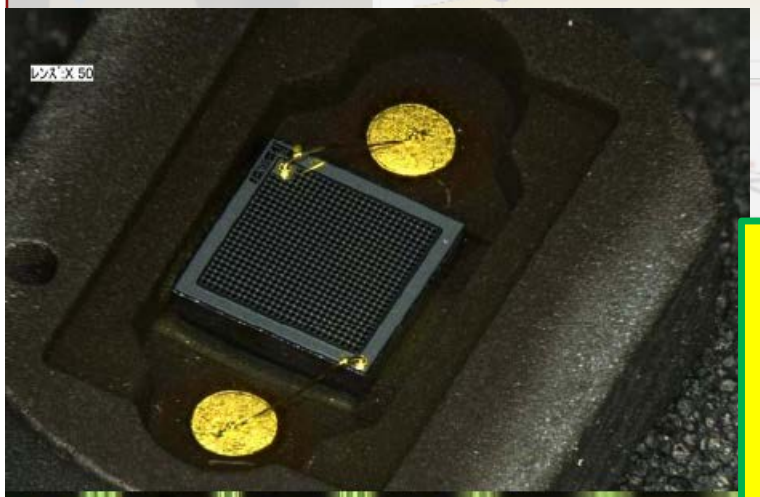


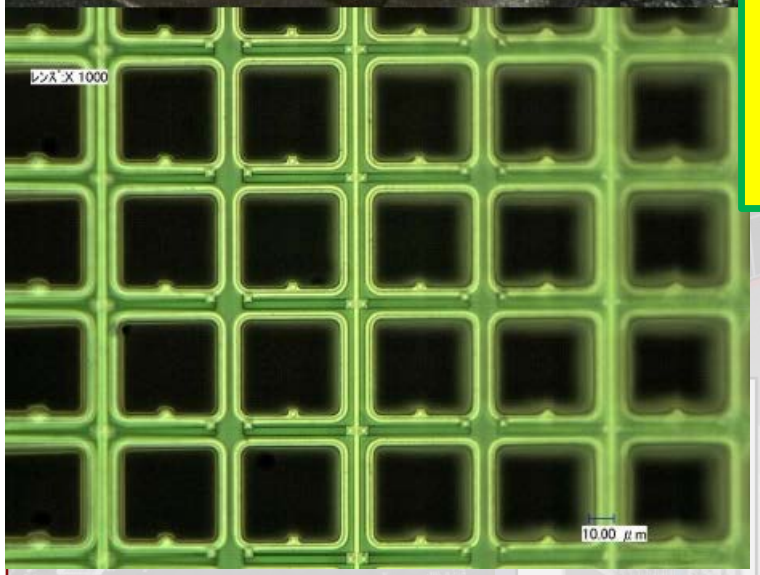












- > 60,000 delivered by Hamamatsu (~0.1 m^2)
- 1.3x1.3 mm^2 specifically designed for T2K
  - Well suited for 1 mm diameter fiber
  - 667 pixels
  - 26x26 array of 50 μm pixels
- Dark noise < 1.2 MHz at nominal voltage (~700 kHz/mm^2)
  (7.5x10^5 gain at 25°C)

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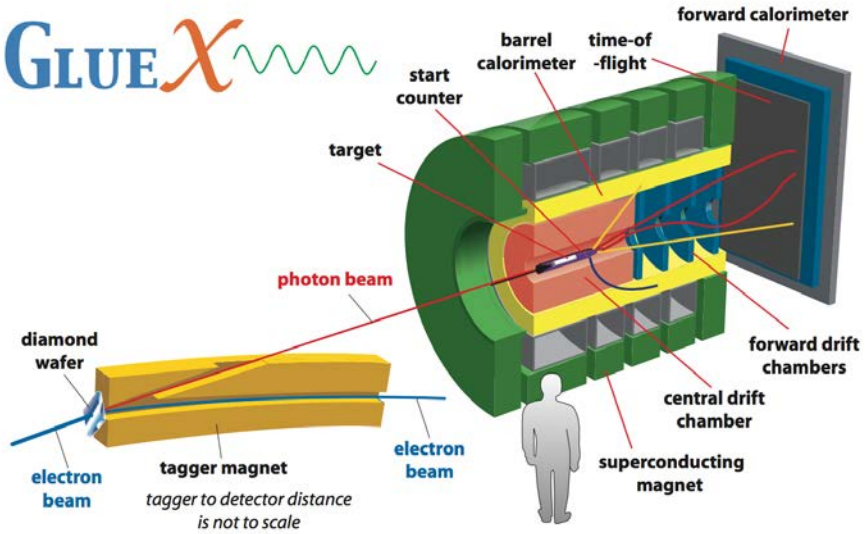
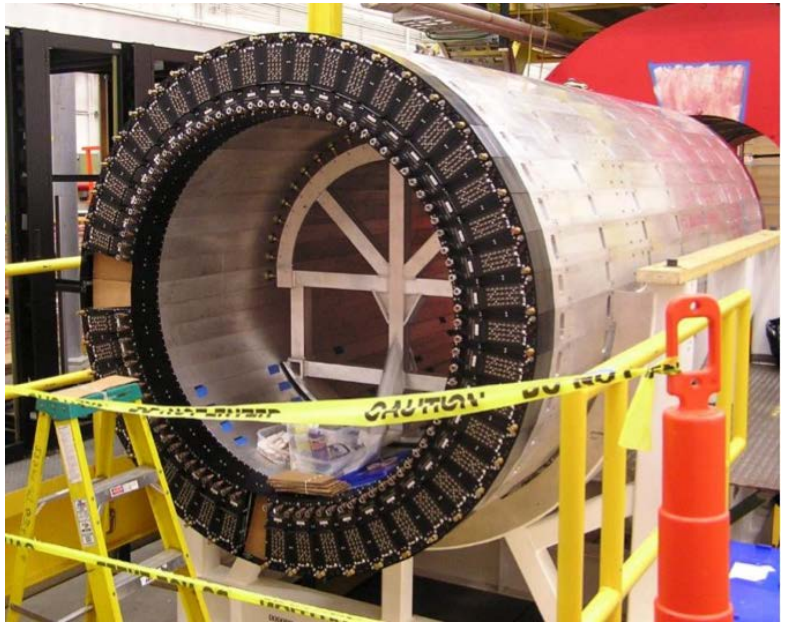
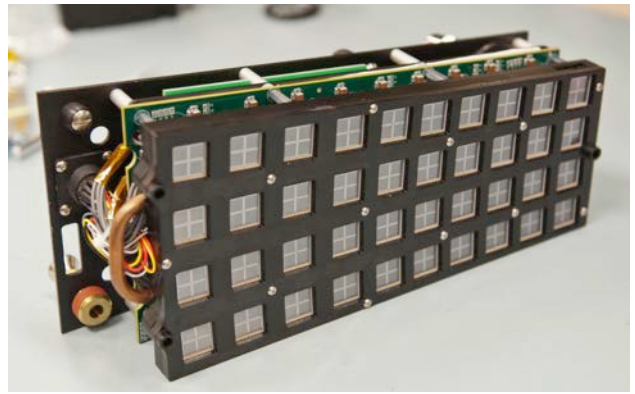
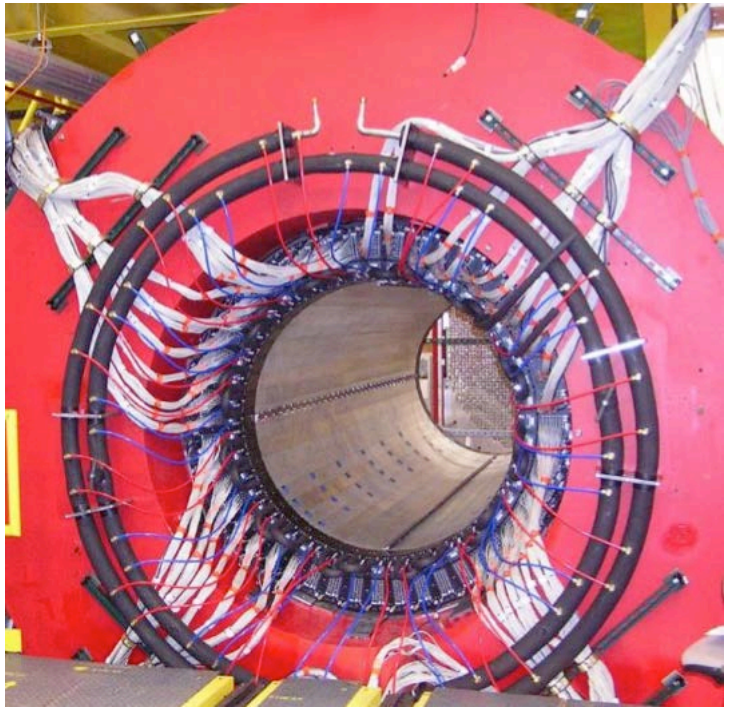
Hall D – First Large Scale Use of SiPMs at JLAB





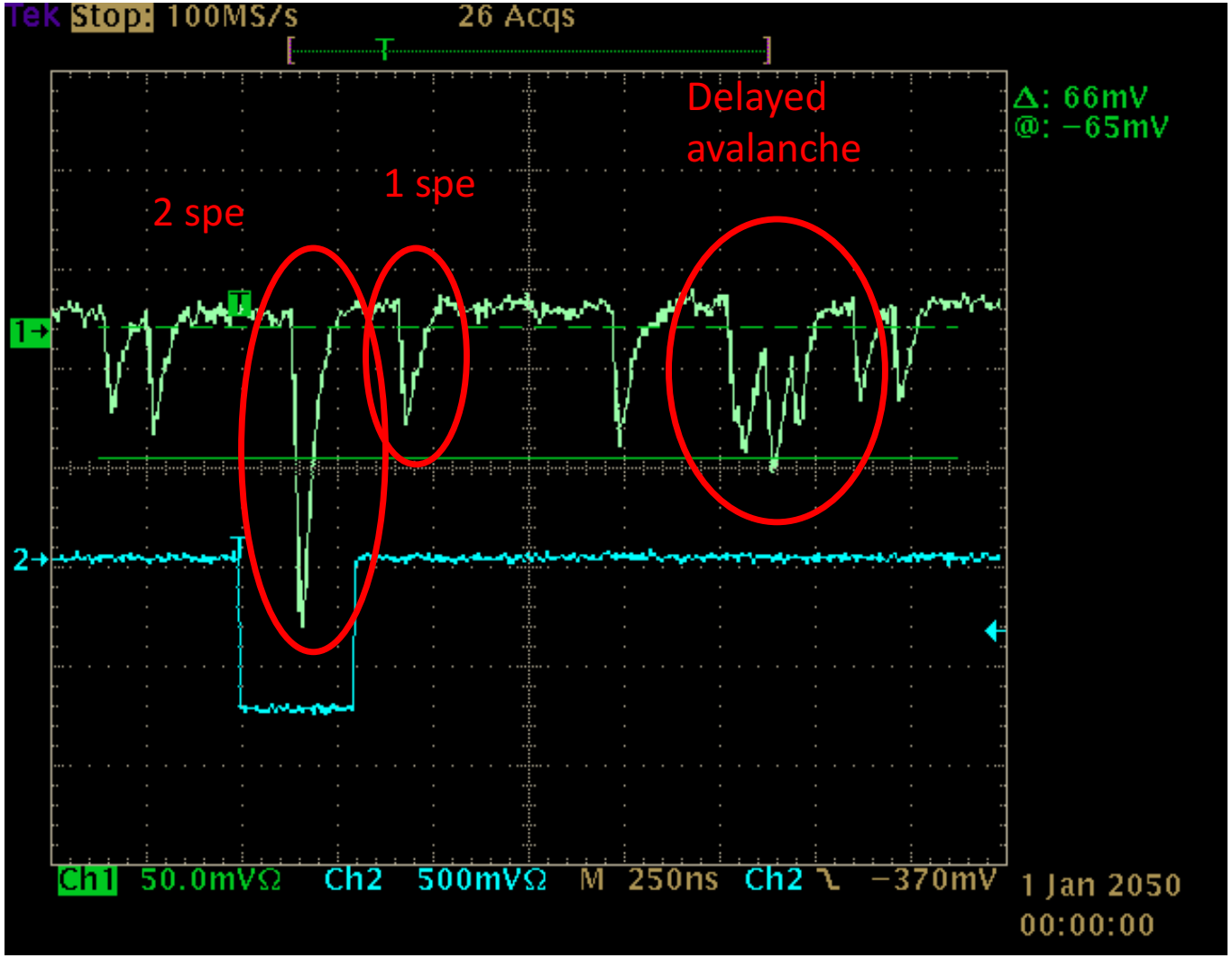




Total of 0.55 m² of SiPMs

Barrel Calorimeter
3840 SiPM arrays
4x4 array of 3x3 mm² 50 μm microcell (Hamamatsu)
PDE~20%, DCR=110 kHz/mm²

Noise in SiPMs: Dark current, crosstalk, afterpulses



- Noise derived from defects in lattice that create intermediate energy levels between valence and conduction band
- Radiation can increase number of such defects leading to increased noise - **dark current**
- Internal avalanche emits near-IR light – this can trigger avalanches in nearby pixels – **crosstalk**
- Also possible to have delayed avalanches – **afterpulses**
- These are also affected by radiation
- **The suppression of this radiation induced noise is the key to future SiPM implementation**

Particle interactions with SiPMs

X-rays (~ 10s keV)

Limited penetration depth leads to increased noise from surface interactions

High energy electrons and gammas (~ MeV)

Volumetric penetration – leads to defect buildup throughout SiPM via ionization processes

High energy neutrons (~MeV)

Principal source of defect buildup – neutron can displace atom from lattice site leading to interstitial vacancy – primary knock-on atom can continue to create other defects in material – essentially a non-ionizing source of noise buildup

Thermal neutrons (meV)

Nuclear transmutation ($^{30}Si + n \rightarrow {}^{31}Si \rightarrow {}^{31}P + \beta$-)

High energy charged hadrons (i.e., protons)

Essentially combination of ionization and non-ionizing effects

Overall effects have to judged by experimental conditions of background radiation sources

Gamma Irradiation – Co-60 - 1 MeV

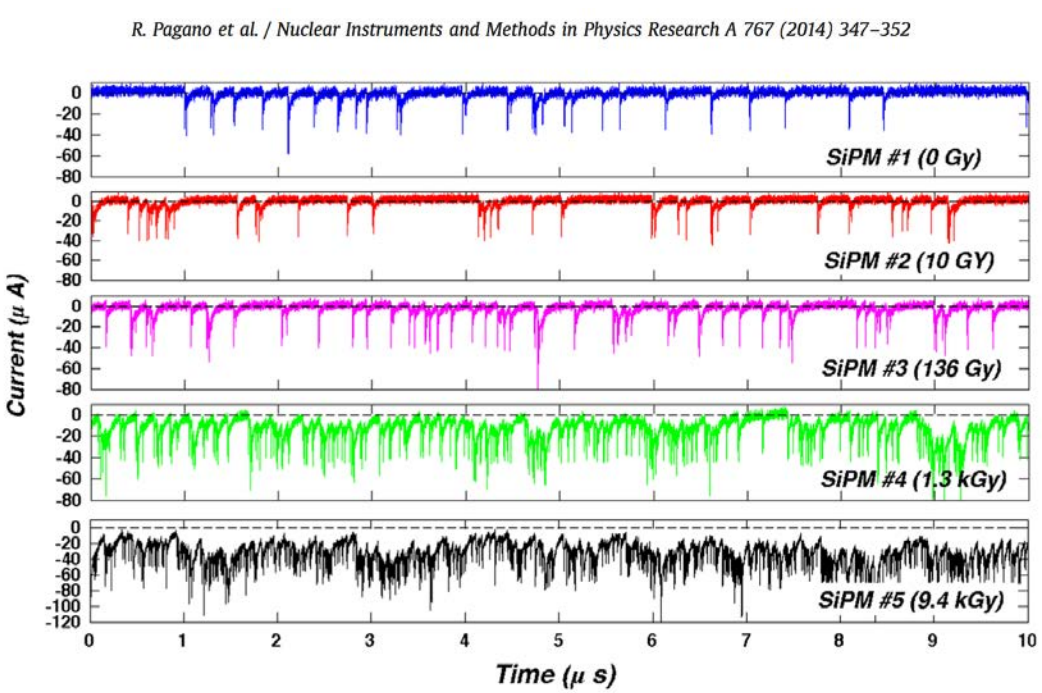


Fig. 2. Dark current traces at RT (21° ± 3 °C) for a ΔV=3 V for the SiPM before and after irradiation at different doses.

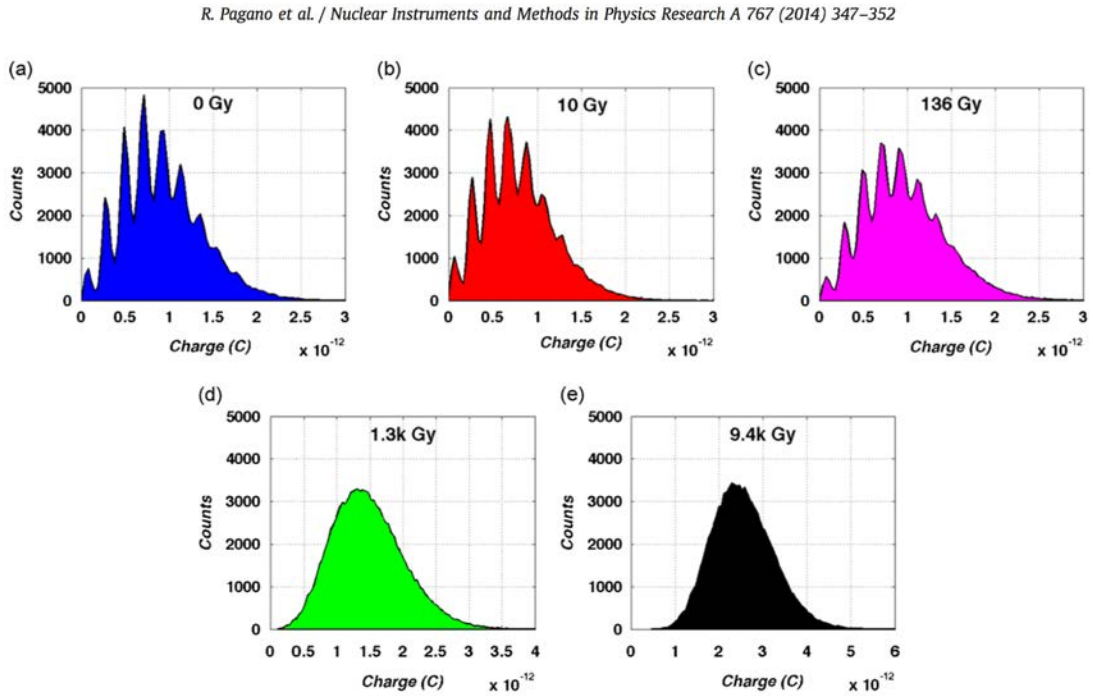
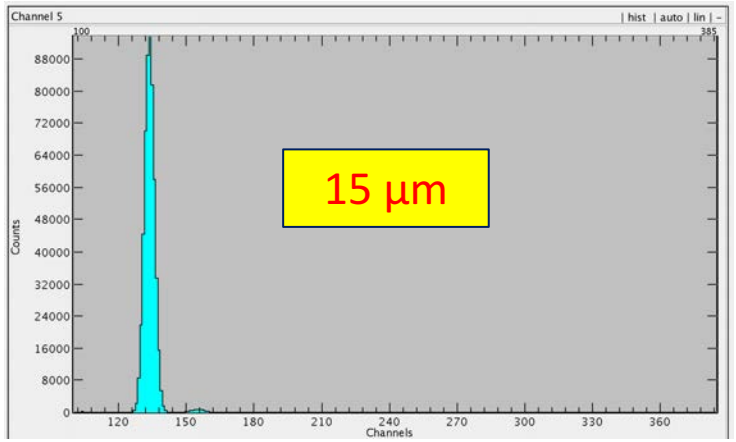


Fig. 5. SPS at ΔV=3 V and at RT (21° ± 3 °C) before and after γ–rays irradiation.

Pagano et al. NIM A 767 (2014) 347-352

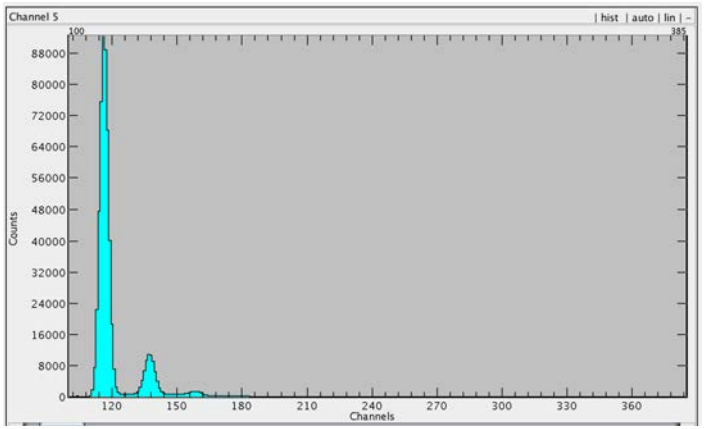
Annealed at room temperature

Dark Rate increase with irradiation by high energy neutrons (Am/Be source) (post-irradiation annealed at 60°C for 24 hrs)

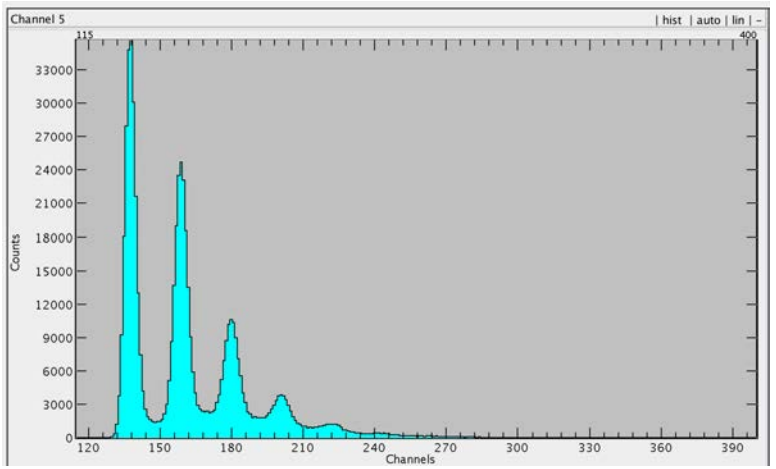


15 µm

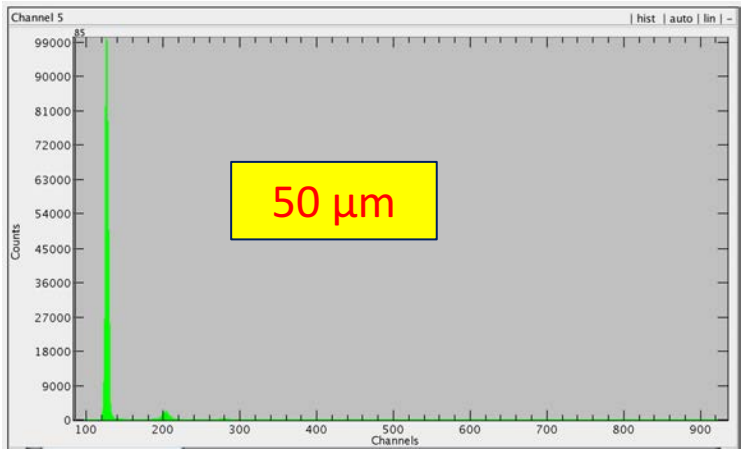
Pre-irradiation



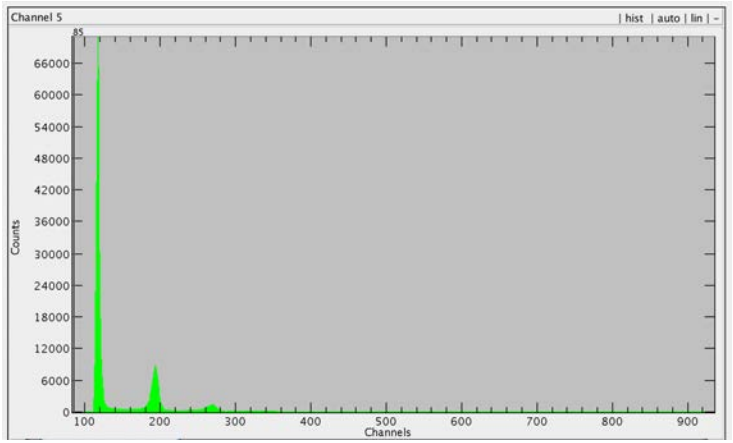
10^9 n/cm2

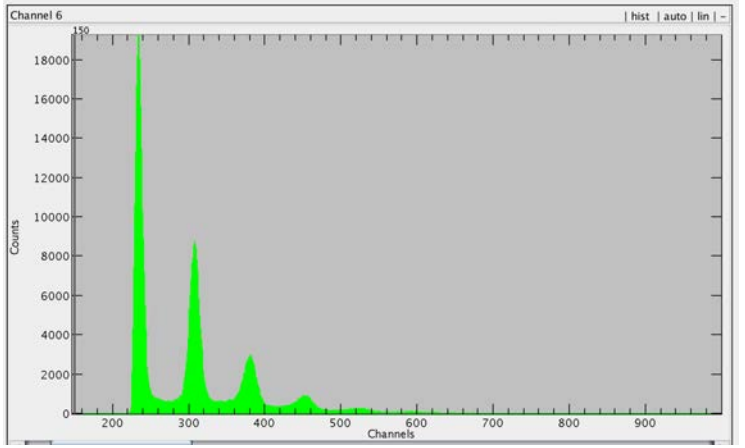


5 x 10^9 n/cm2



50 µm





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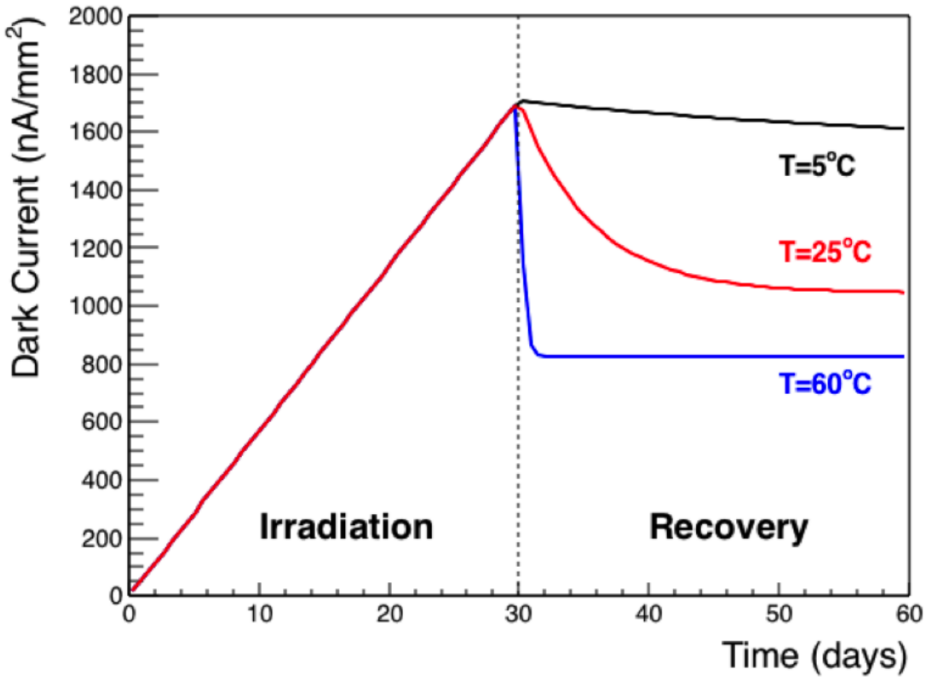
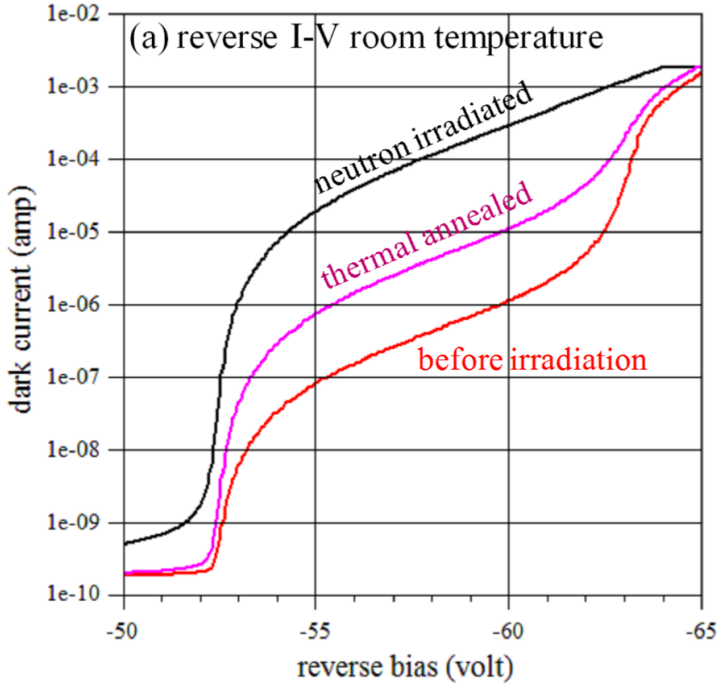
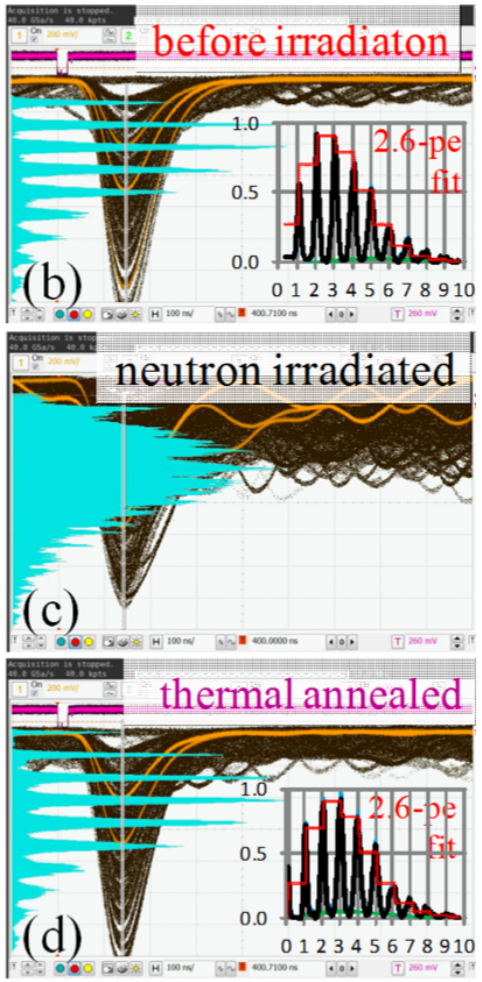
Radiation Damage – Annealing of Prompt effects

JLAB SiPM raddam study
Qiang et al., NIM A 698 (2013) 234-241



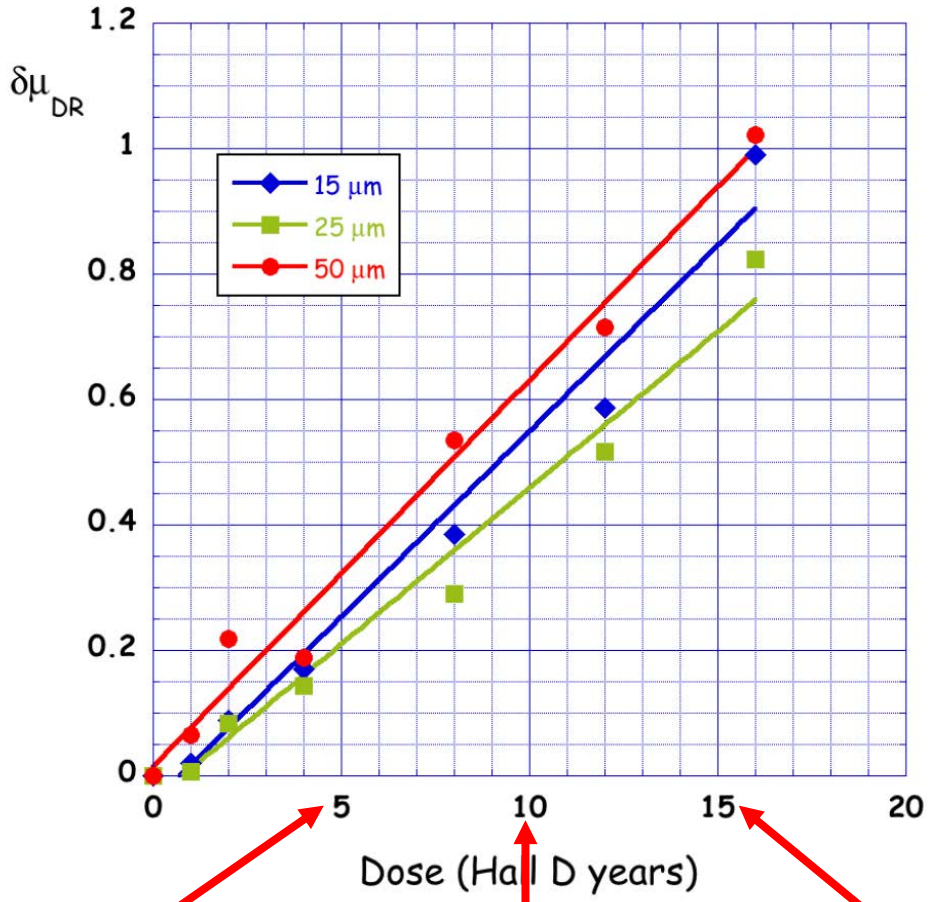
BNL study - 10^9 n/cm^2
Thermal anneal – 250°C
+ 8 mA forward bias





Tsang et al., 2016 JINST 11 12002

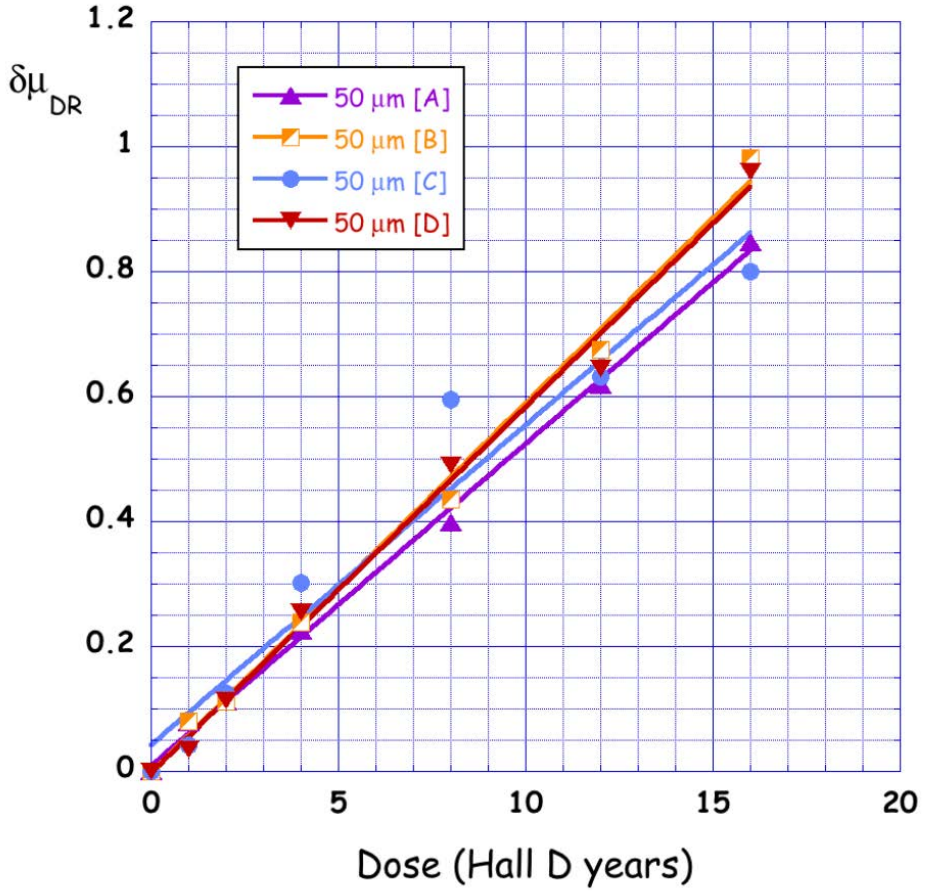
Dark Noise increase with dose - Hamamatsu SiPMs (MPPCs)



1.5 x10^9 n/cm^2

3 x10^9 n/cm^2

4.5 x10^9 n/cm^2



Irradiation of 3x3 mm^2 SiPMs with Am/Be source

Barbosa et al., 2012 IEEE proceedings

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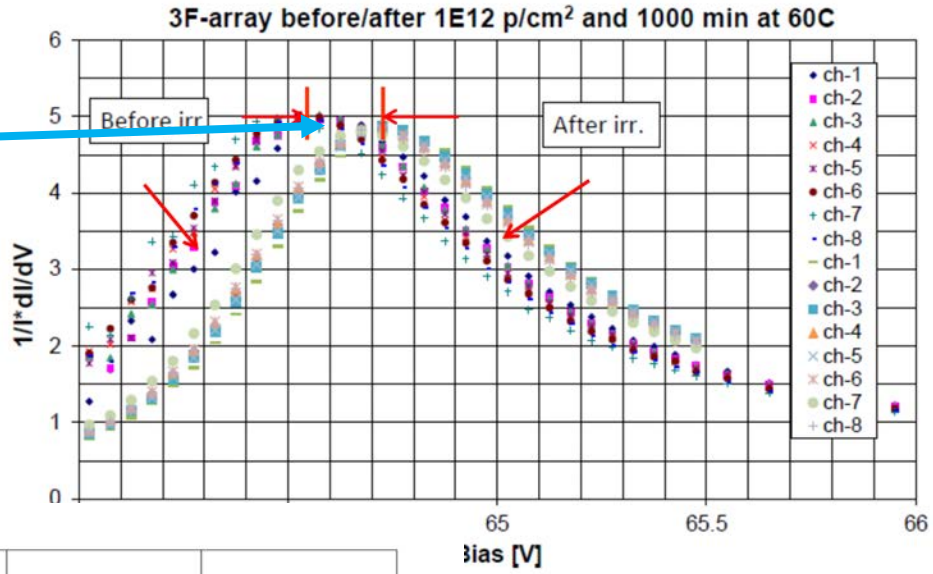
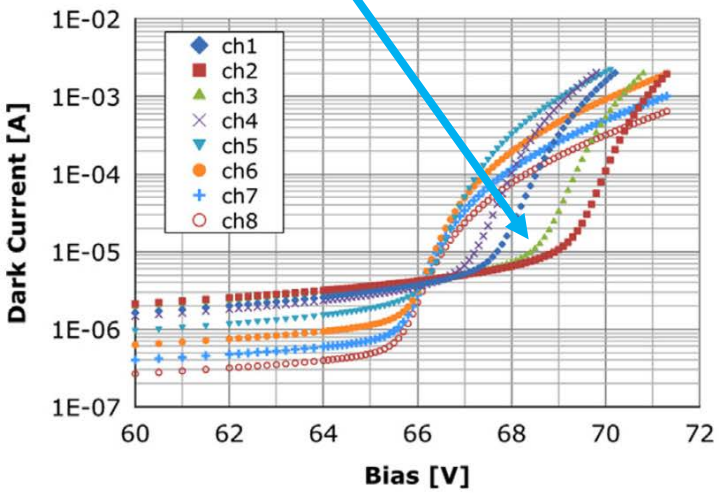
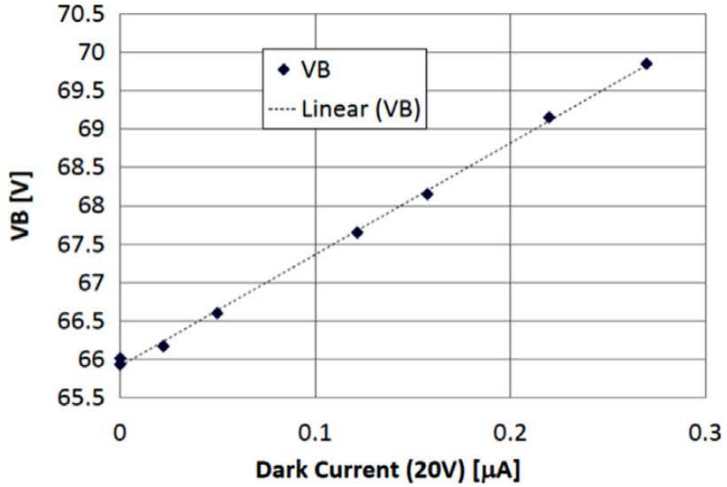
Effects of Very High Doses – Shift in V_B – affects Gain and PDE

175 mV increase in breakdown voltage $2x10^{12}$ n/cm^2

Maximum dose 2.2×10^{14} n/cm^2







Heering et al. NIM A 824 (2016) 111-114

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Rundown of Effects of Radiation on SiPMs

Increased dark current

- → leads to smearing of photoelectron resolution
- → threshold 10^8 n/cm^2 or 1 kGy
- → above 10^{11} n/cm^2, dark noise can be so high as to saturate device response
- → longer recovery time of larger pixels is relevant parameter – smaller pixels recover faster

Change in Breakdown Voltage

- → VB increases slightly – example: +175 mV for > 10^{12} n/cm^2
- → threshold > 10^{10} n/cm^2
- → creates a gain and PDE decrease – will need to shift the bias voltage

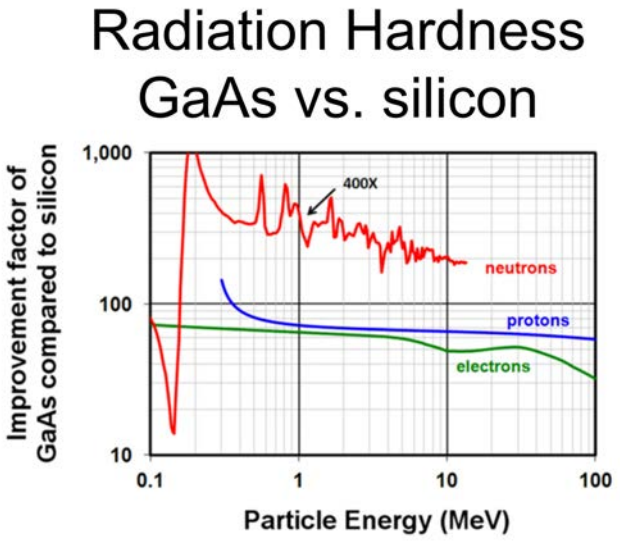
Thermal Neutron Contribution to Dark Noise

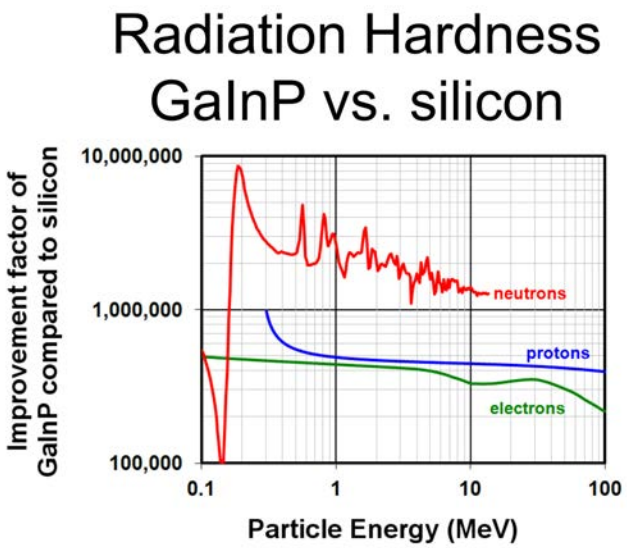
- → seems to be significant only > 10^{11} n/cm^2

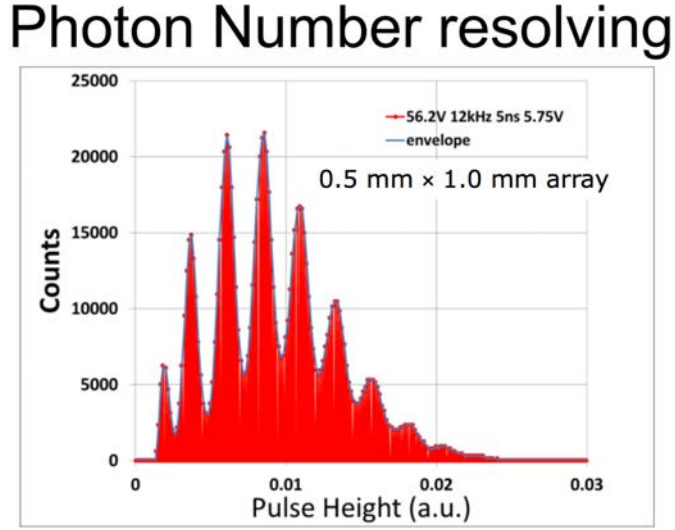
Transmission window of SiPM may yellow with irradiation

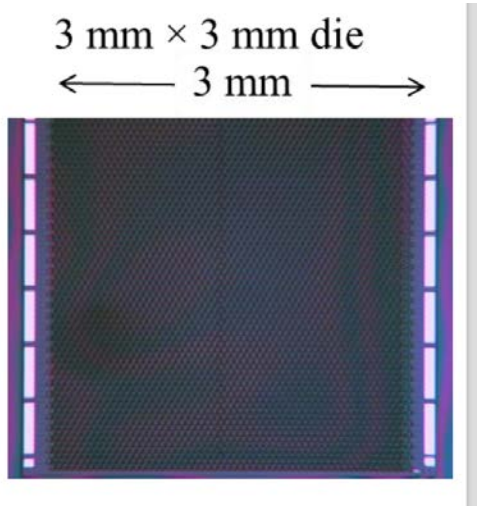
- → neutrons have almost no effect
- → > 10 kGy to see any effect from gammas

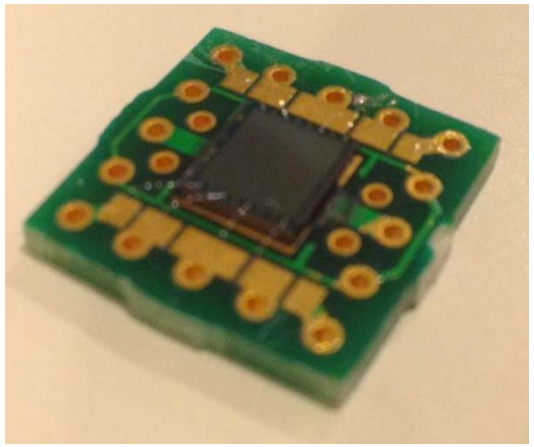
Farther down the Line – new tech – *LightSpin Technologies (NY)* – GaAs/GaInP "SiPM"





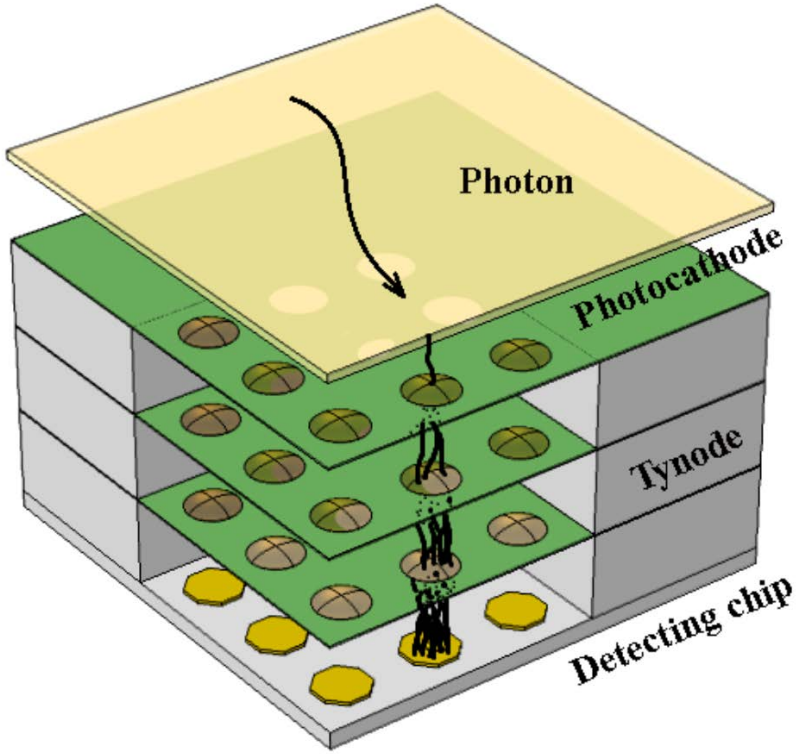






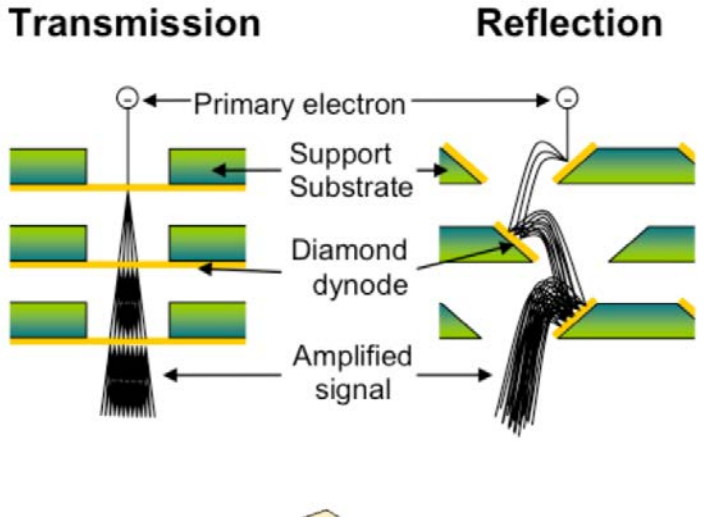
LightSpin Technologies, Inc.

Another example of possible Future Tech – TiPC – Harry van der Graaf



Timed Photon Counter

Trynode – transmission dynode



PHOTONIS

TU Delft

BROOKHAVEN NATIONAL LABORATORY

Argonne NATIONAL LABORATORY

NIKHEF

➔ Expect very low noise compared to SiPM

➔ And very high timing resolutions (< 10 ps)

In Conclusion…

Present knowledge base is effort of many people dealing with their own experimental priorities

Time to pool knowledge and craft a R&D path with the goal of creating a certified community accepted knowledge base

Industry is interested in our feedback to them – raddam especially

Needed to successfully take advantage of this remarkable device