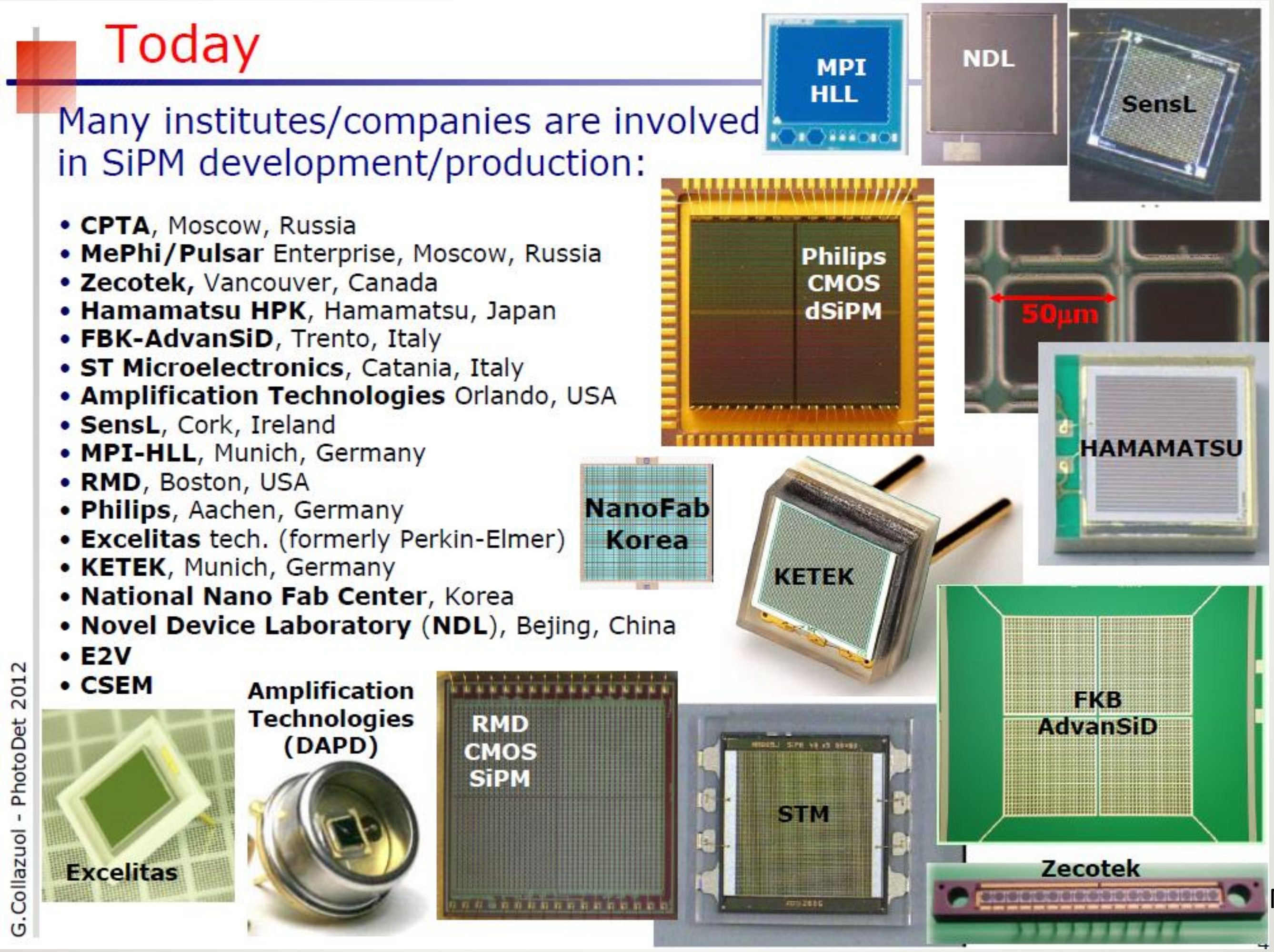
Progress on Geiger-type avalanche photodiodes

Vitaly Chepel
University of Coimbra

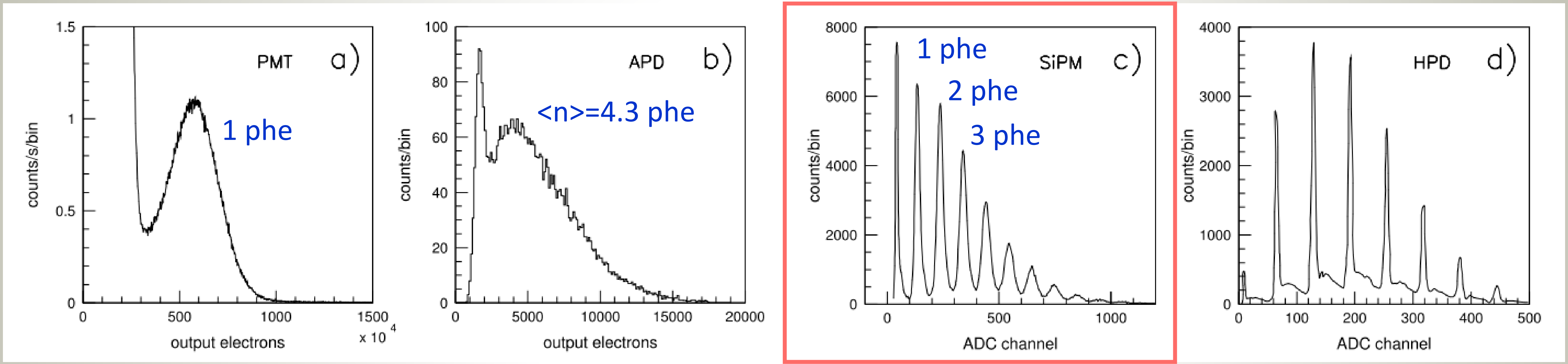
Terminology:
G-APD = SiPM = MPPC = …



Musienko, 2014

What's special about SiPMs?

Single electron response



2'' Hamamatsu R7724Q-MOD

Advanced Photonix LAAPD, 5 mm

Hamamatsu 1 x 1 mm2 MPPC S10362-11-100U

Hybrid photodiode (Delft Electronic Products, PP0270K)

Expensive, very HV

Other attractive features of SiPM:

- Compact
- Low voltage
- Low radioactive background compared with PMTs
- High granularity can be achieved
- Cheap ?

(from Chepel and Araújo, 2013 JINST_8_R04001)

Good for LXe/LAr ?

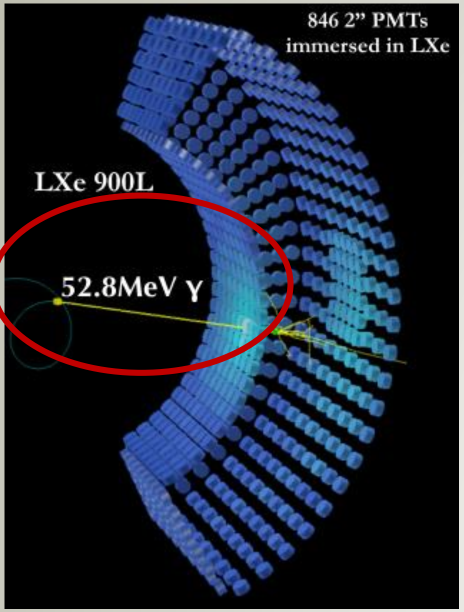
Commercial devices are not sensitive in VUV
Have other problems, too (e.g. afterpulses, crosstalk, large noise), but progress is being made

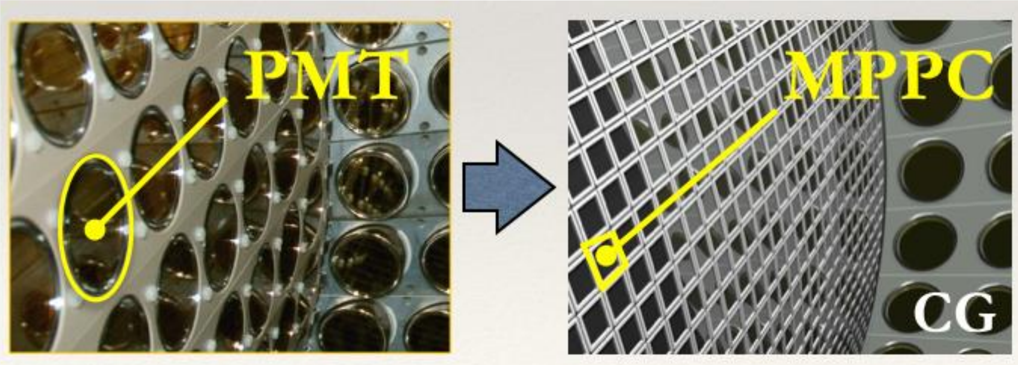
There is also some progress in the VUV region – MEG LXe experiment is the driving force (special SiPMs (MPPCs) are being developed by Hamamatsu Photonics for them)

In general, the technology is becoming sufficiently mature
For LXe/LAr still needs to be proven…

For LAr, use of a wavelength shifter is the only prospect, for now (LXe may need it, too)

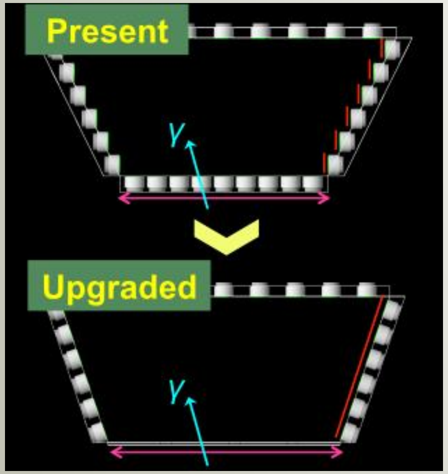
MEG upgrade





2’’ HPK R9288, QE~15%

Incident face 216 2” PMT → 4092 12x12mm2 SiPM



Expected:

- Better imaging power ← higher granularity
- Better energy, position resolutions ← better uniformity close to the entrance
- Better detection efficiency
  - smaller sensors, 63→69% ← better coverage

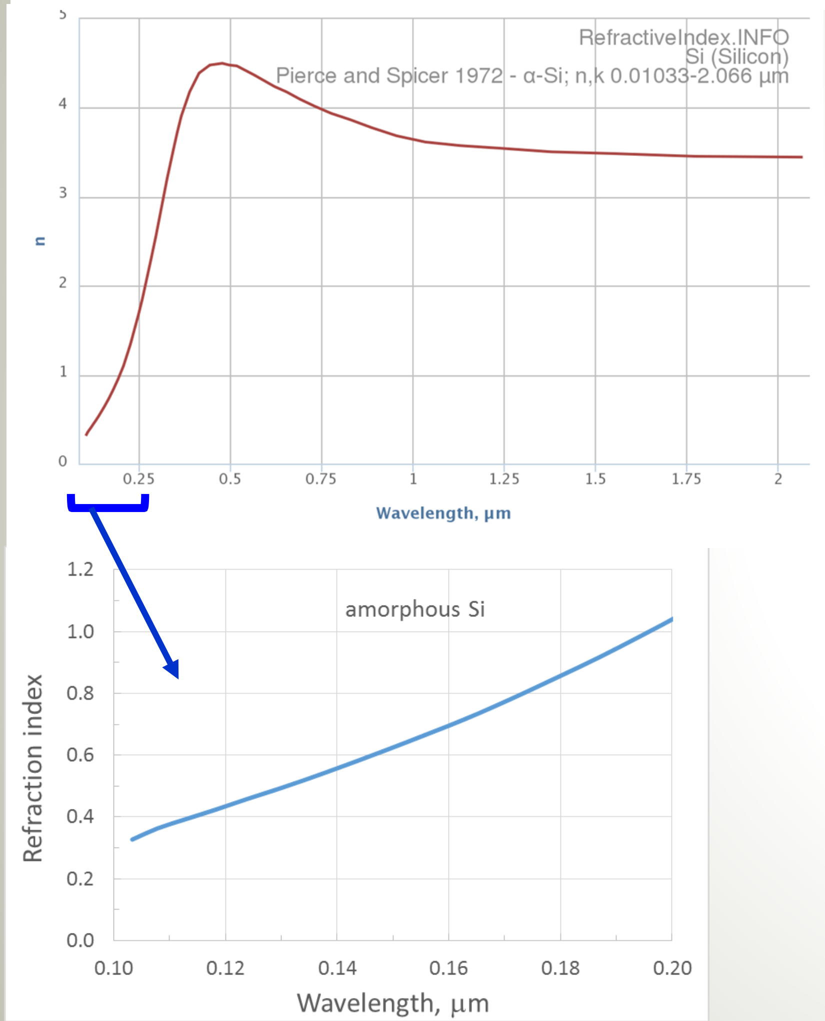
(From: T. Iwamoto, IEEE NSS&MIC Workshop on large area, low background, VUV sensitive photo-detectors, 2014)

How to make a photodiode (an amateur view)

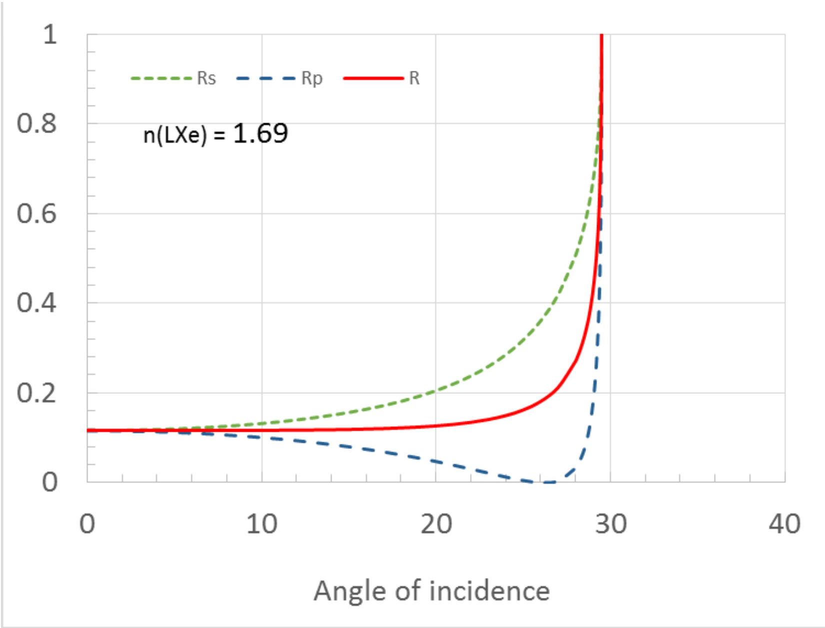
1. Let photon in to the detector (minimize reflections and absorption in the window)
2. Let it produce e-h pair in the right place
3. Do not let them recombine at the surface (diffusion against surface recombination)
4. Make sure that the carriers live enough time to reach the multiplication region
5. Multiply avoiding uncontrollable positive feedback
6. After you succeed, fight noise (uncorrelated and correlated)
7. Control traps, defects, and impurities

Optical properties of LXe/Si interface

Refraction index of Si (amorphous)



Fresnel reflections at the LXe/Si interface



n(Si for 177 nm) = 0.832

n(LXe for 178 nm) = 1.69

(Solovov e.a., NIMA516(2004)462; Hitachi, e.a. JCP133(2005)234508)

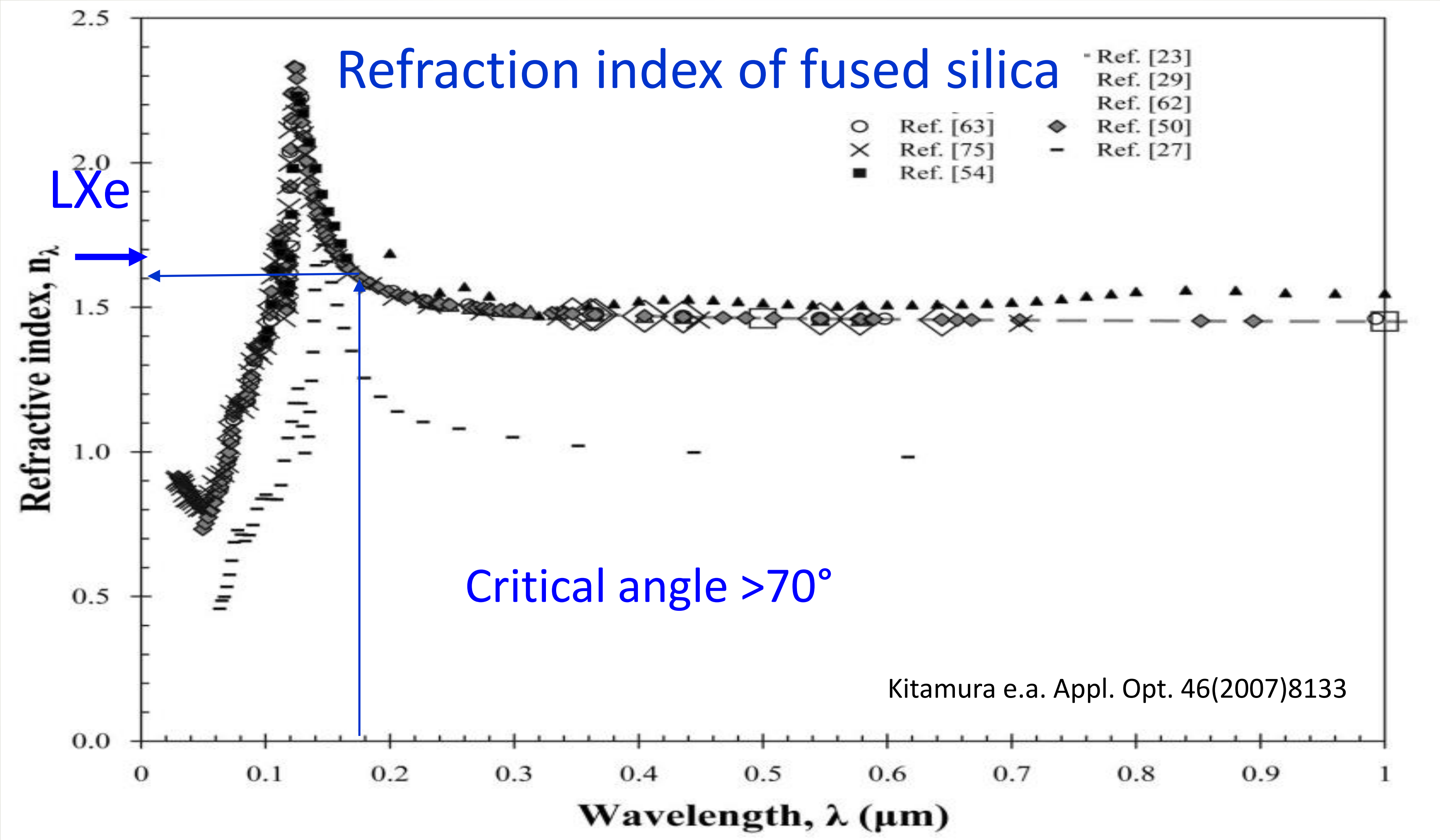
Strong refraction index mismatch

Critical angle 29.5°

Integrated solid angle 0.13$\times 2\pi$

Adding 12% reflection → 11% of isotropic light can enter Si

Why fused silica (PMT) is OK?



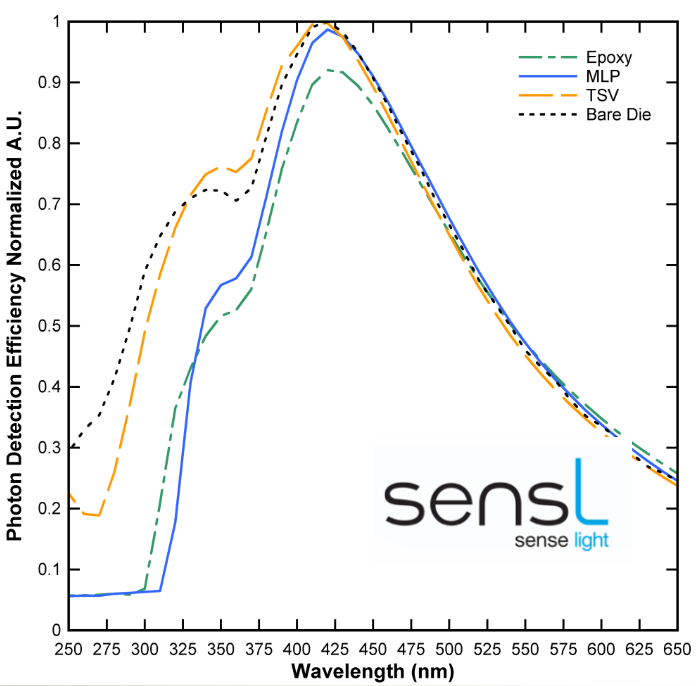
Reducing reflection and absorption in window

Effect of the window and package type

PDE

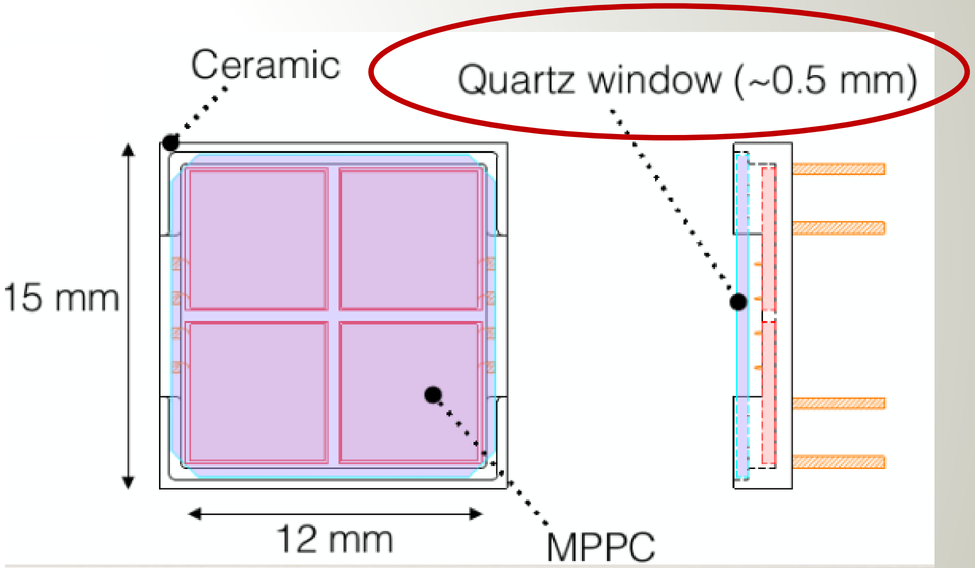
Bare Si die

TSV technology



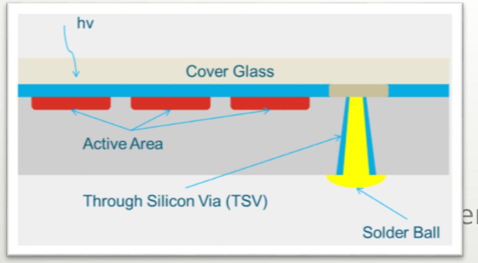
J.Murphy, NSS/MIC 2014

MEG/Hamamatsu solution for LXe

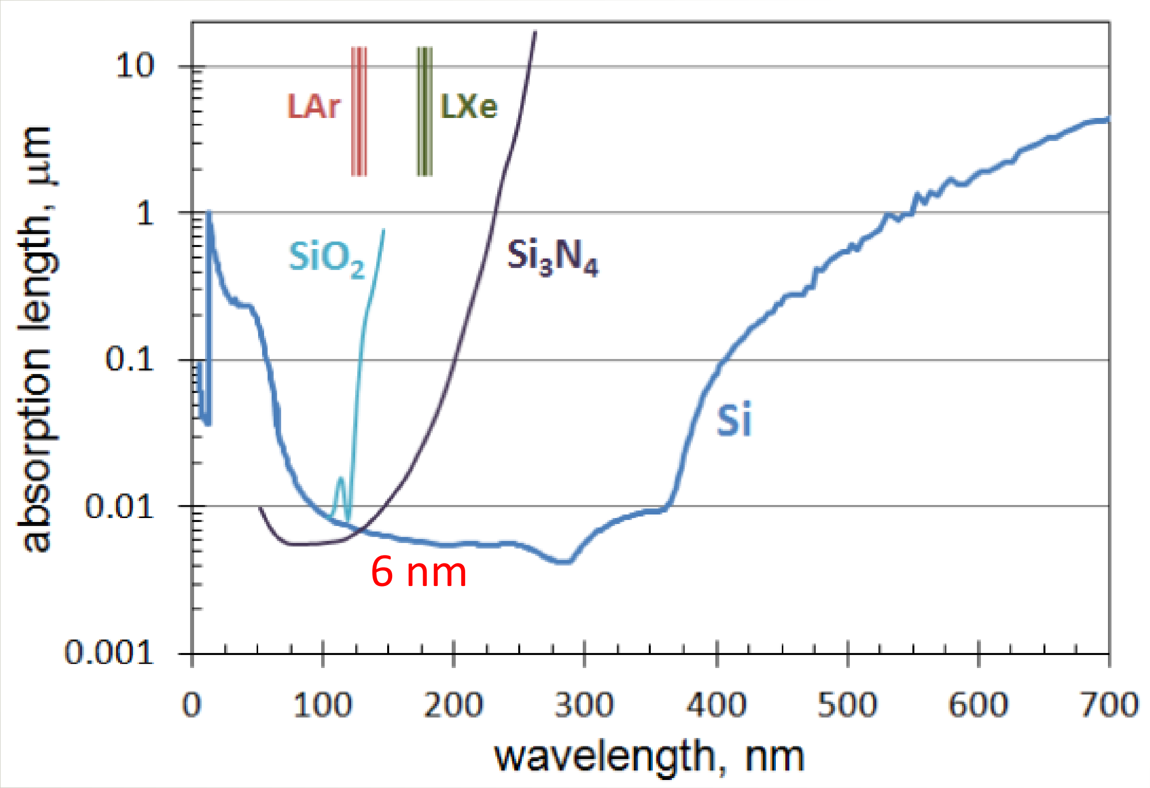


Iwamoto, NSS/MIC 2014

MLP – Moldless Leaded Package
TSV – Through Silicon Via – new technology



Photon absorption length in Si – "ultraviolet catastrophe"



(Chepel and Araújo, 2013 JINST_8_R04001)

Calculated with extinction coefficients from [275] and [276].

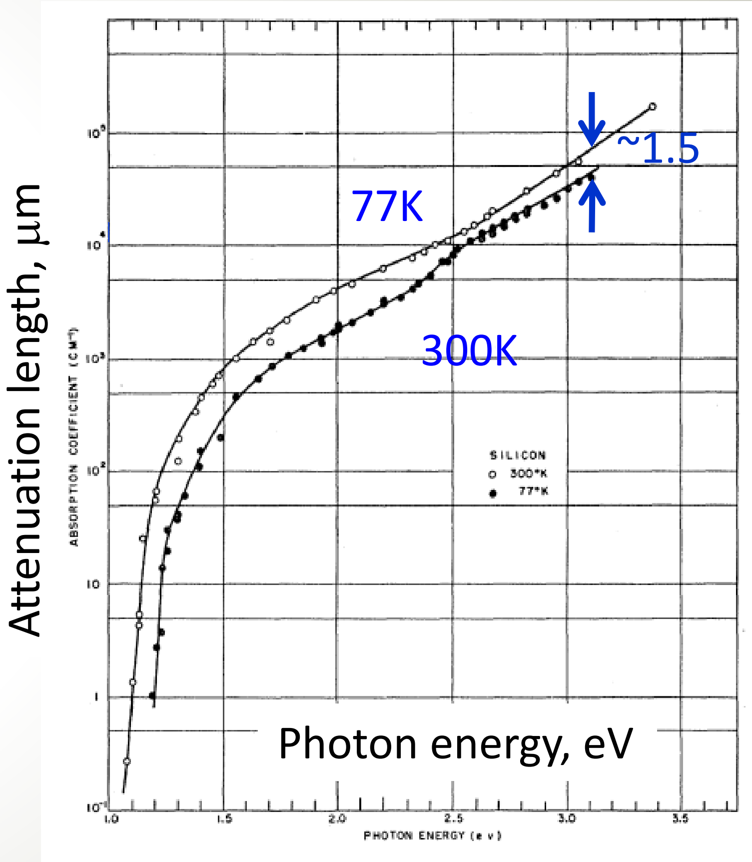
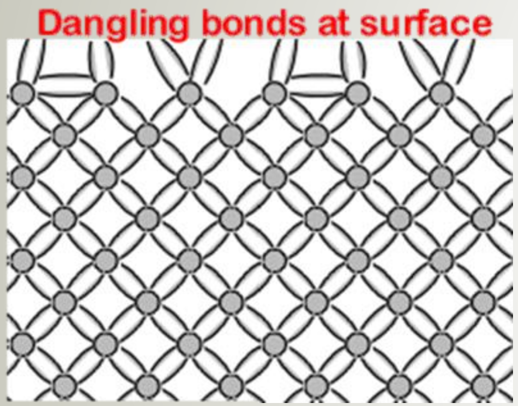


FIG. 4. Absorption spectra of single-crystal silicon at 77°K and 300°K.

(Dash and Newman, PhysRev 99(1955)1151

Diffusion and surface recombination

UV photons are absorbed very near the surface (~10 atomic layers!) → high recombination probability at the surface



Passivation aims to close the dangling bonds at surface

Any defects or impurities within or at the surface of the semiconductor promote recombination.

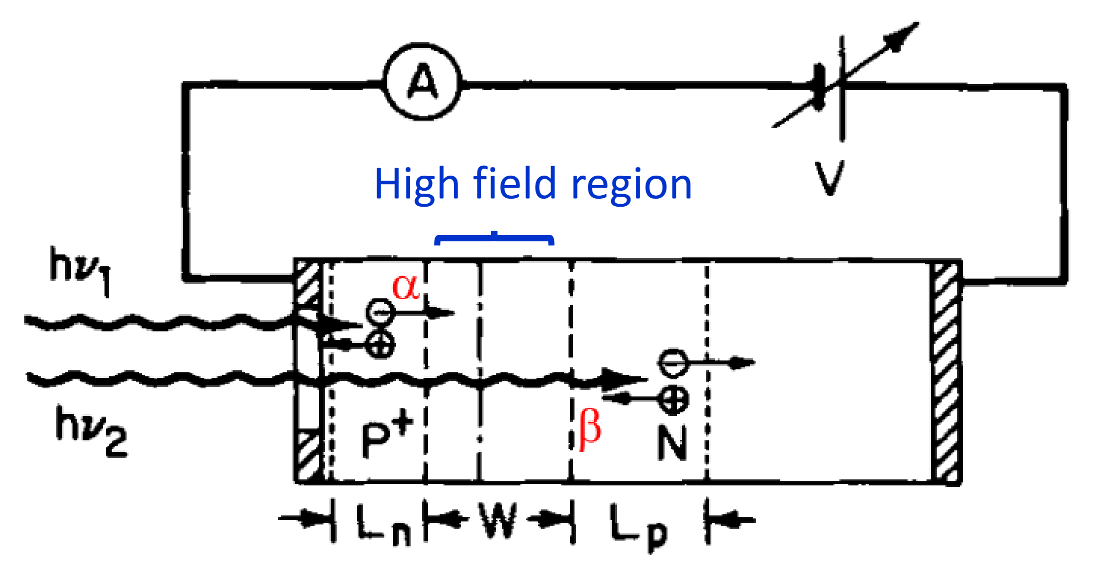
S – surface recombination rate
D – diffusion coefficient for minoritary carriers
τ – carrier life time
$L = \sqrt{D\tau}$ - diffusion length (should be > than detector thickness)
S/D should be low

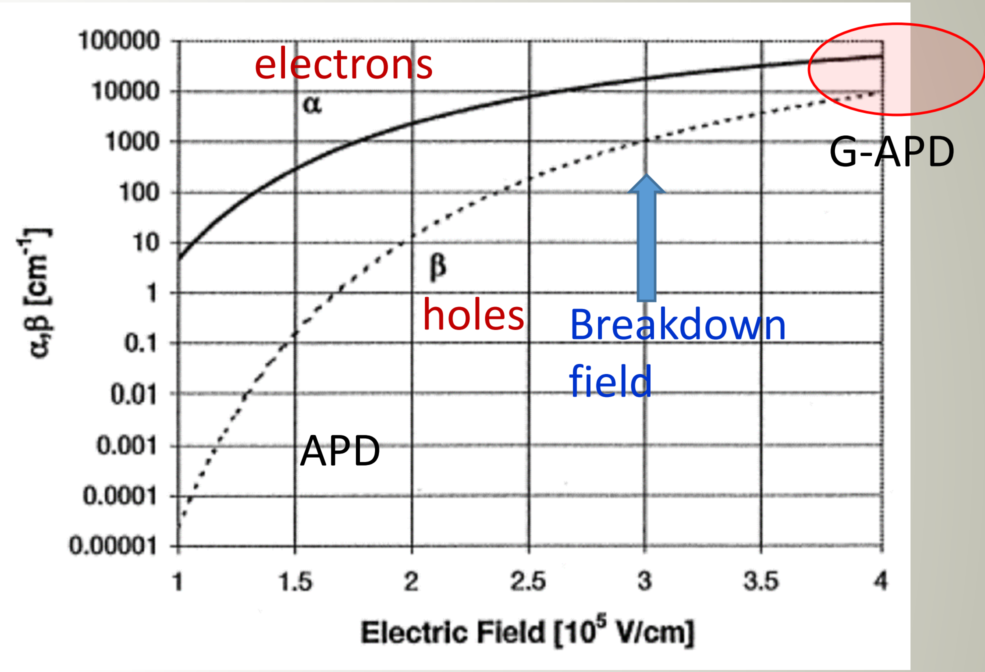
Surface recombination
Surface recombination rate depends on treatment of Si surface and lies in the range between $10^2 \div (6\text{-}8) \cdot 10^4$ cm/s.
Surface recombination rate on the Si-SiO_2 interface can be as small as ≤ 0.5 cm/s.

Multiplication in the depleted p-n junction

short wavelengths

long wavelengths





In this configuration ("P on N"),
short wavelength photons trigger electron avalanche (good!);
Long wavelength photons can trigger both (bad)

In semiconductors, both electrons and holes can ionize, however with different probability

Breakdown triggering probability (for Geiger regime APD):

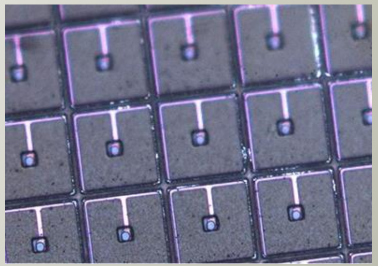
high for electrons

low for holes

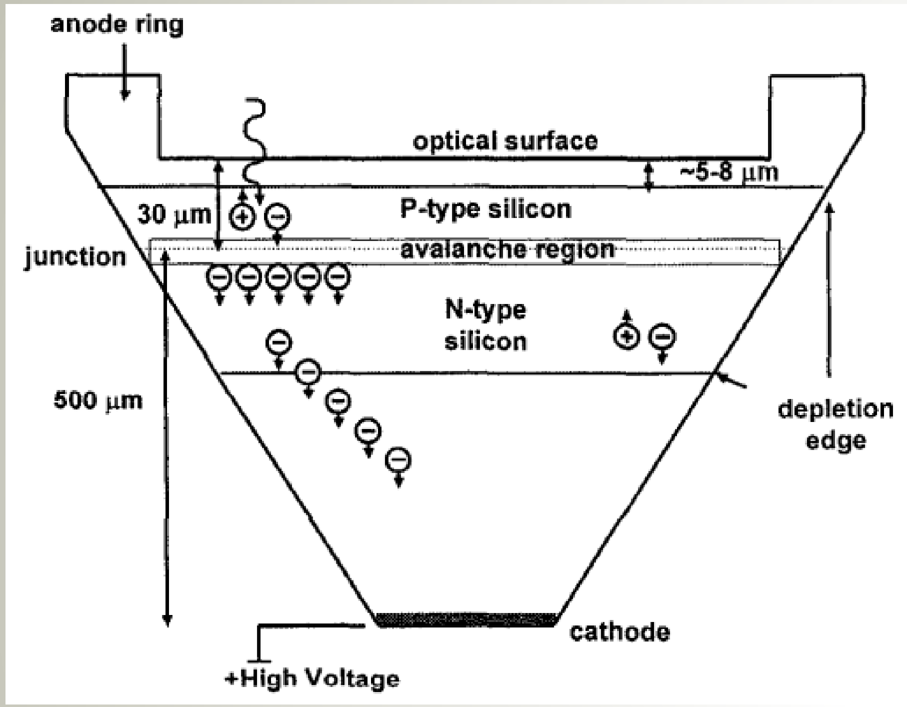
Geiger APD vs linear APD

APD	G-APD
Sub-breakdown bias voltage	Over-breakdown voltage
Avalanche develops in one direction (mostly due to electrons)	Both electrons and holes (as well as photons) participate in the avalanche
Positive feedback should be suppressed	Positive feedback is essential
Avalanche extinguishes by itself	External quenching is necessary
Large continuous areas are possible	Can be kept without spontaneous discharges for a sufficient time <u>only in very small volumes</u>
Signal amplitude is proportional to the number of incident photons	The amplitude <u>does not depend on the number of photons</u> (it is defined by the charge accumulated in a capacitor)

Pixelization is essential



Linear APD



Boisvert e.a., Conf.Rec. NSS/MIC 1992, p.16

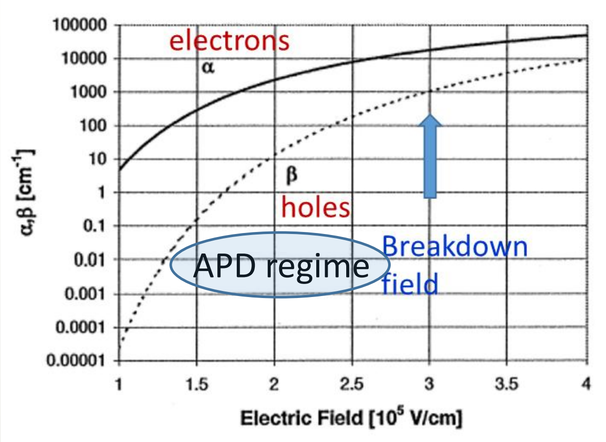
P on N structure → the avalanche is due to electrons

Holes created in the avalanche region also can ionize but with a small probability → **source of noise, not signal**

$$\frac{\beta}{\alpha} = k \sim 10^{-2} - 10^{-3}$$ Excess noise factor (describes fluctuations due to the multiplication process; the lower the better)

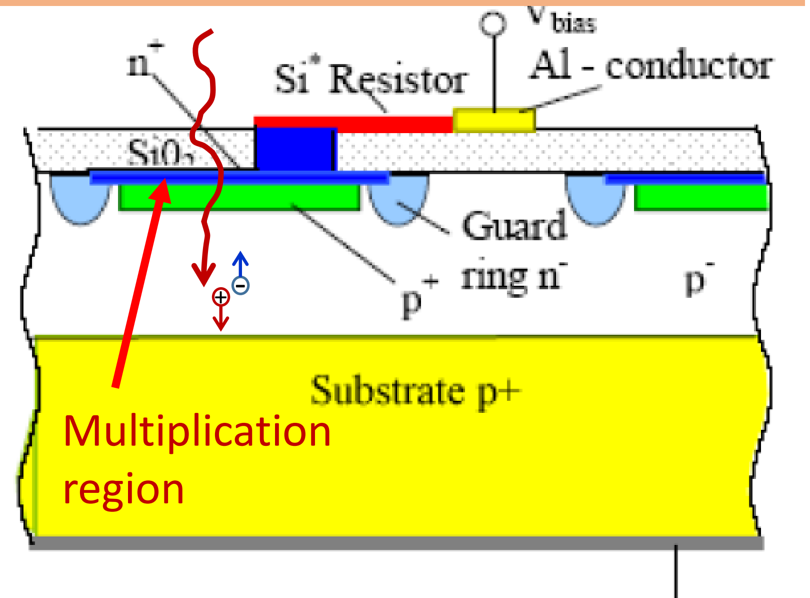
Large Area APD from Advanced Photonix (**up to 15 mm dia**)

RMD produces LAAPDs up to 14 x 14 mm^2



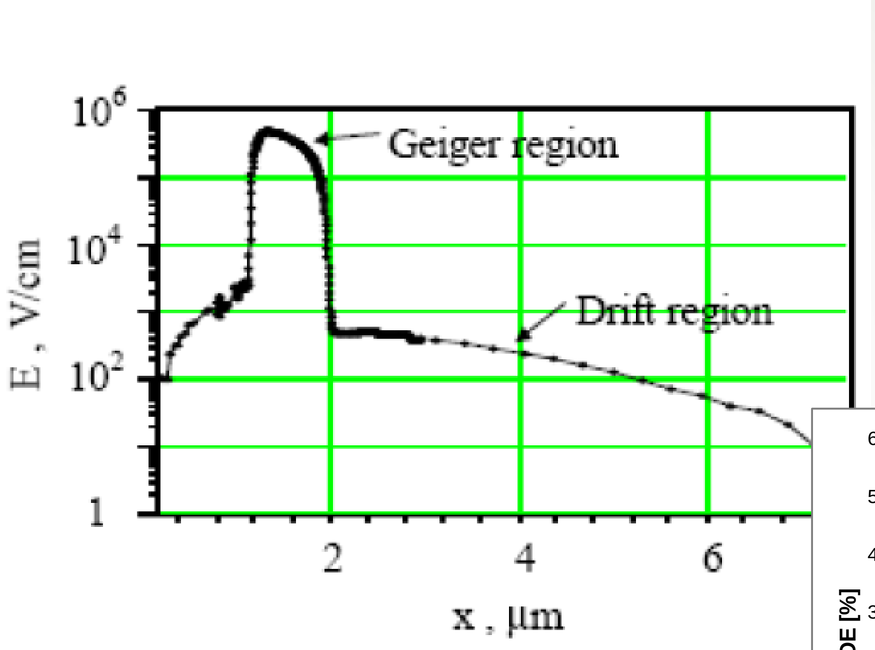
“Original” SiPMs : *N on P* structure

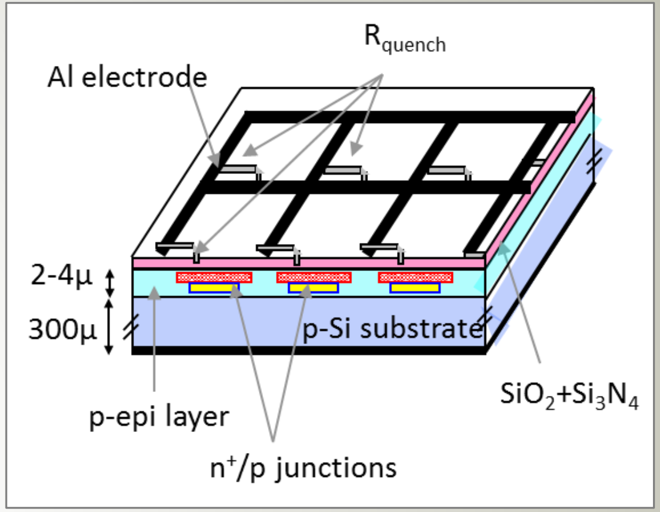
N on P structure – good for visible and IR

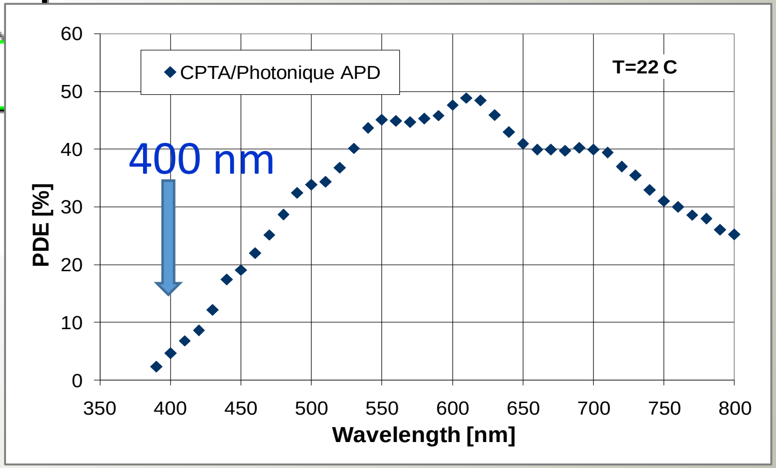


B. Dolgoshein et. al., “An advanced study of silicon photomultiplier”, ICFA-2001

MEPhI/PULSAR APD



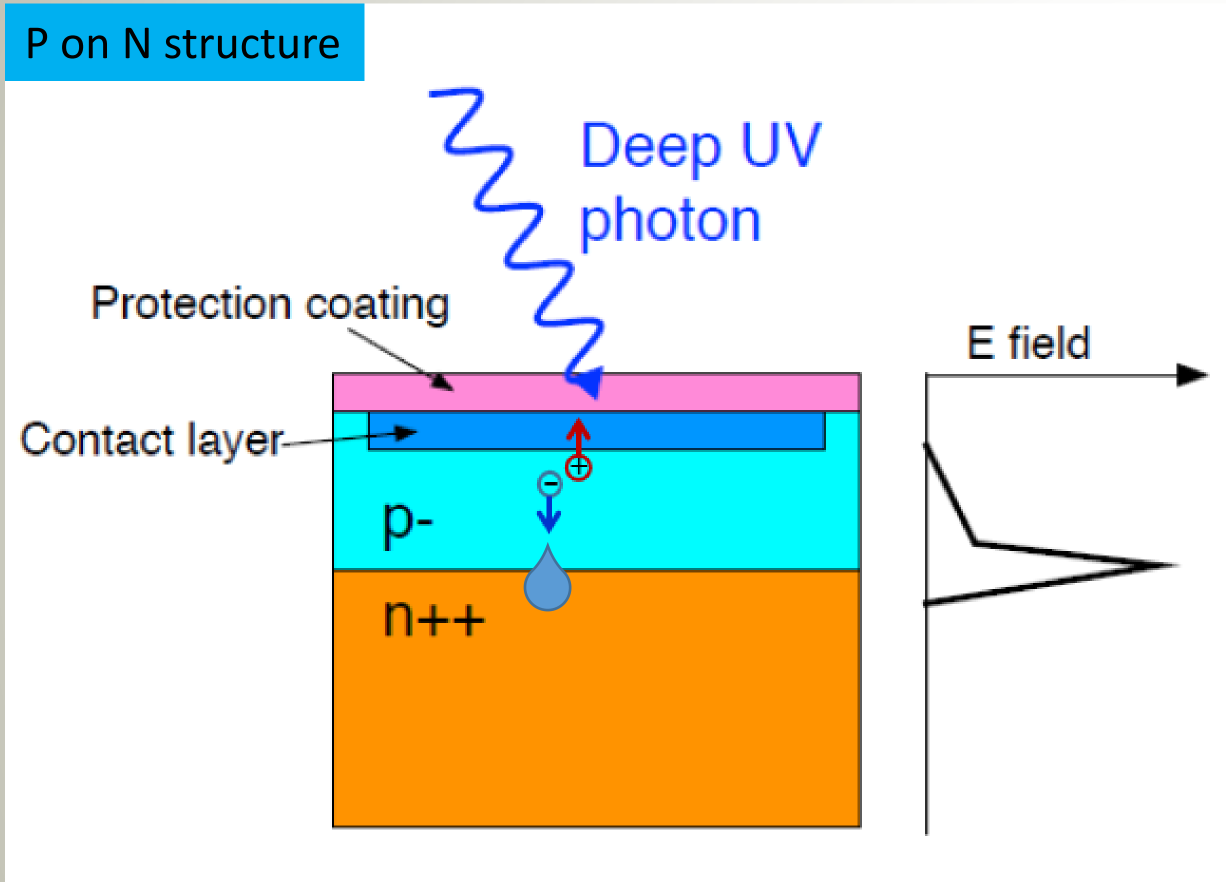




From Yu.Musienko, 2nd CHIPP Workshop on Detector R&D, 12 September 2013

N on P structure – good for visible and IR (the avalanche is triggered by electrons)
Short wavelengths are absorbed close to the surface → holes trigger (but mostly not) avalanche

UV SiPMs: *P on N* structure



Hamamatsu for MEG

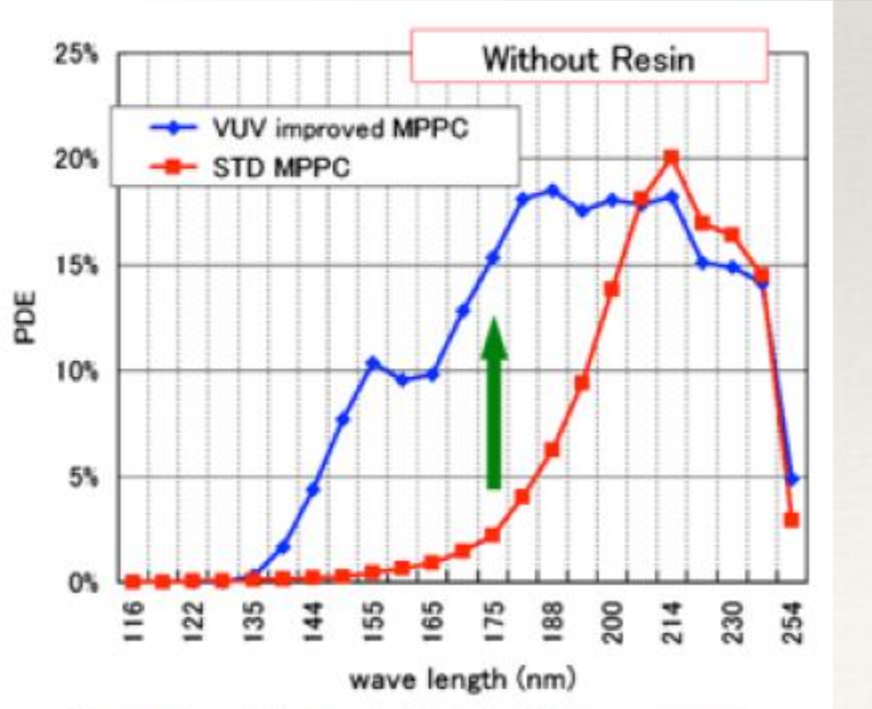


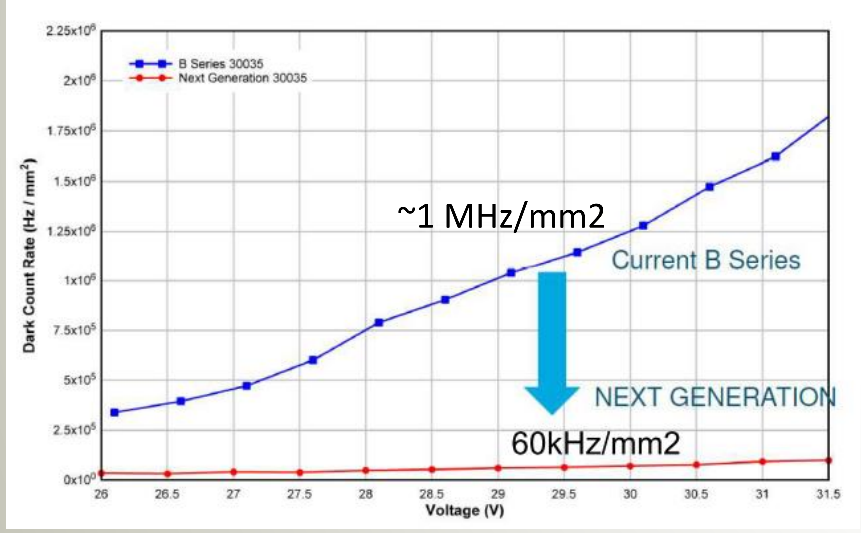
Fig. 5. VUV sensitivity of standard MPPC and VUV improved MPPC.

NIM A 732(2013)427-430

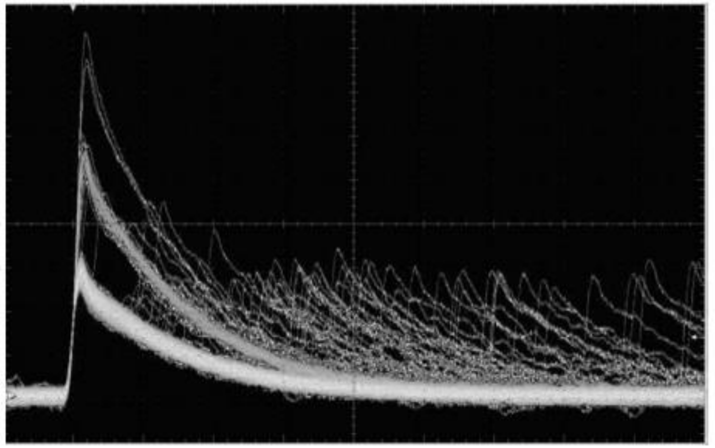
P on N structure – better for short wavelengths (the avalanche is triggered by electrons)

Common problems

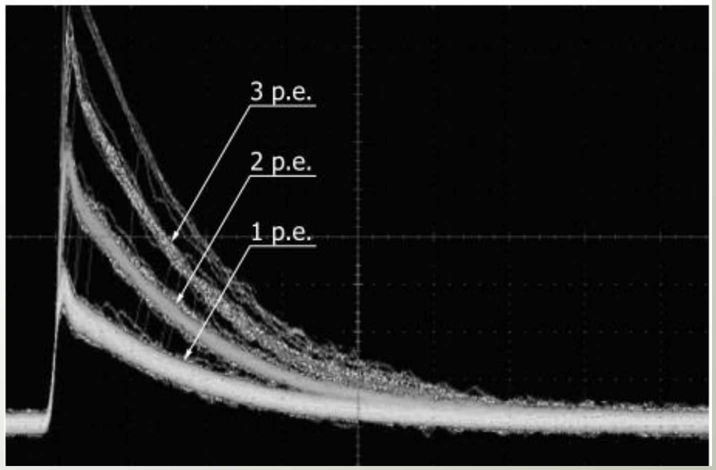
High single electron noise
(spontaneous discharges)



Afterpulsing
(delayed pulses)



Cross talk
(few electrons where only one is expected)



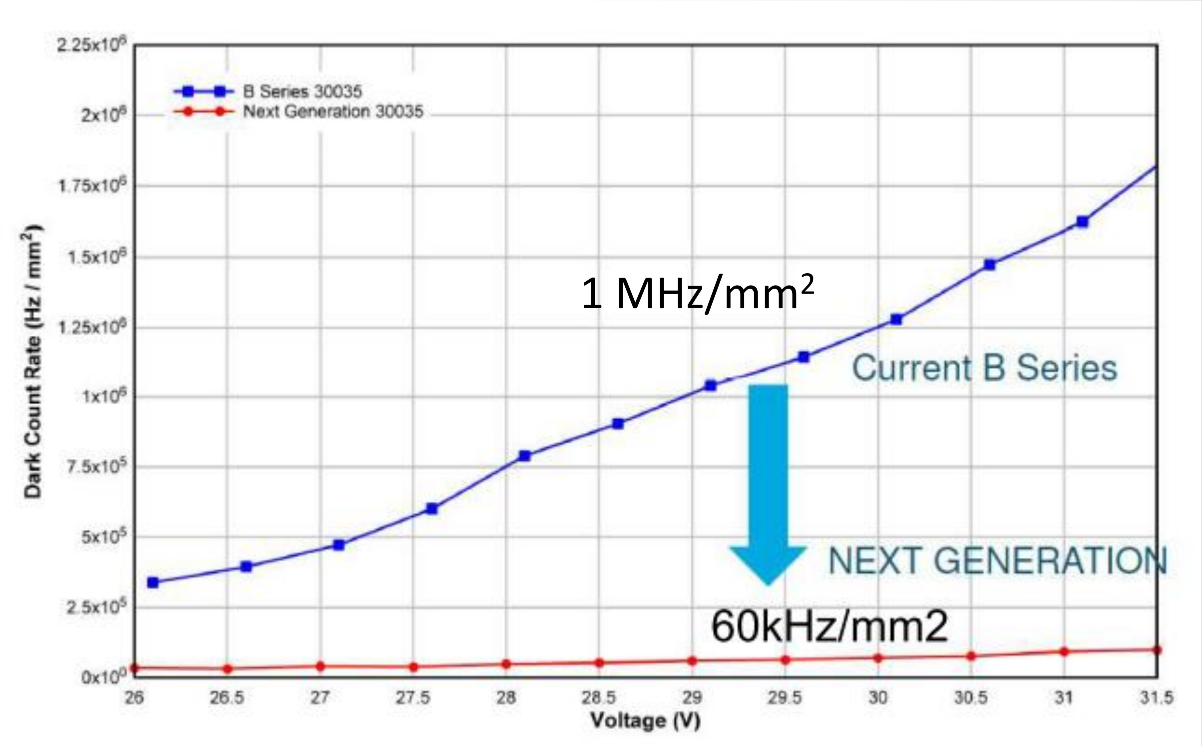
Dark counts

Spontaneous discharges – difficult to keep a semiconductor above the breakdown voltage (this is why SiPMs are pixelized) – significant improvement

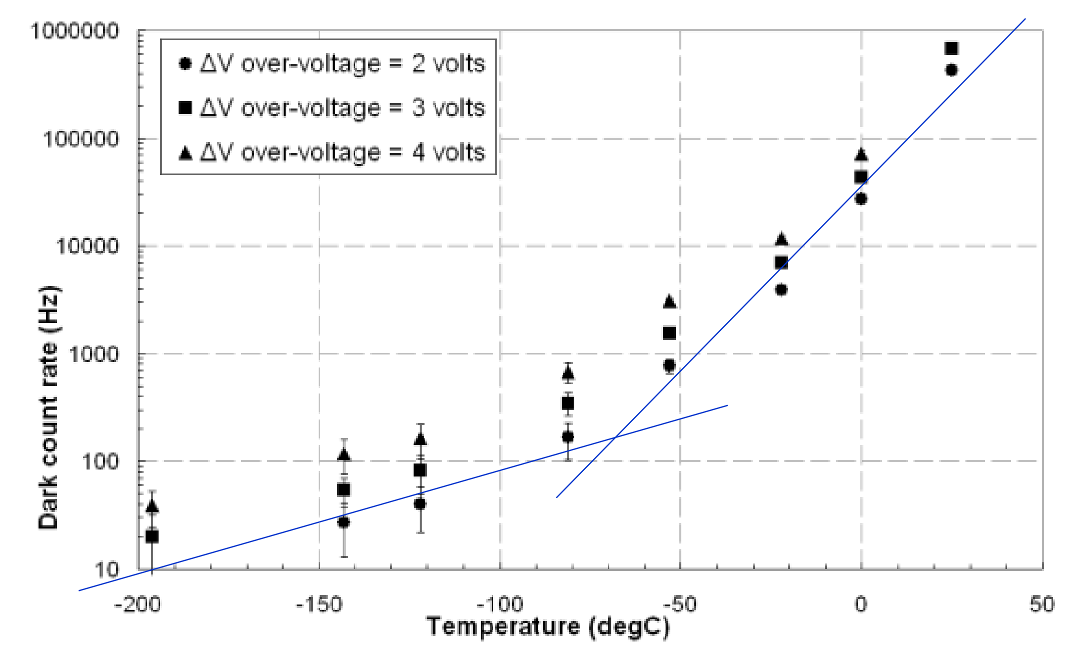
Various devices show room T DCR at level of ~50kHz/mm^2 in extended over-voltage range

e.g.

sensL

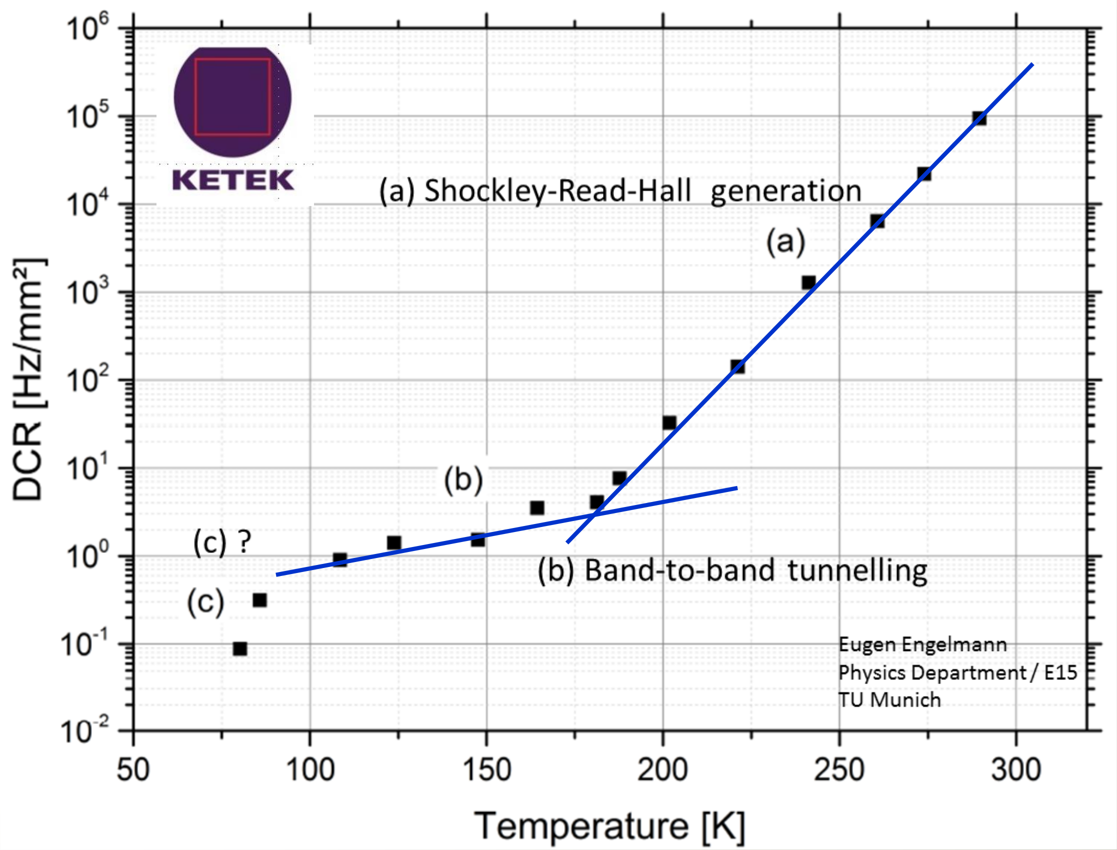


Dark count rate is lower at low T



Lightfoot e.a., JINST 2009, 3 P10001

First use of a SiPM in LNG (LAr)



W.Hartinger, NSS/MIC 2014

SiPM tests by nEXO

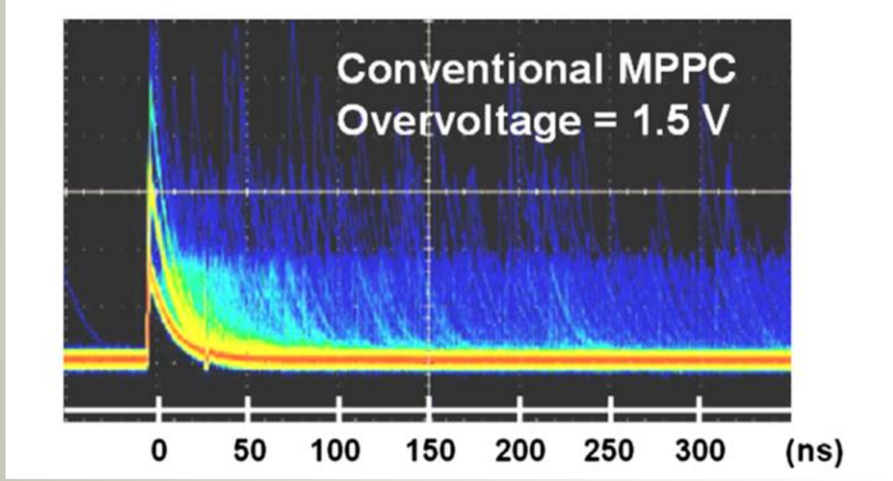
Parameters	Spec.	FBK-2010	HPK	KETEK	SensL
Over-voltage	N/A	5V	2.5V	2.5V	
PDE at 175nm (%)	>15%	10	17-19	0	0
Dark noise rate at -100C (Hz/mm^2)	<50	10^3	0.5	4	?
Cross-talk probability		0.06[S]	0.34[T]	0.1[T]	?
Total after-pulsing rate at -100C		?	0.16[T]	0.25[T]	?
Xt+AP within 10 μs at -100C	<0.2	?	0.38[T]	0.15[T]	?
Recovery time		?	25ns[T]	900ns[T]	?
Pulse rise time (Gaussian σ)		?	1.6ns[T]	0.5ns[T]	?
Pulse fall time(s) (exp. constant)		?	30ns[T]	6/300ns[T]	?
Capacitance (pF/mm^2)	<50	330	35	100	80 / 3.2
Thorium content (μBq/kg)	< 43	<13 [A]	?	?	$<2\ 10^6$ [N]
Uranium content (μBq/kg)	< 9	$<2.5\ 10^2$ [A]	?	?	$<94\ 10^6$ [N]
Potassium content (μBq/kg)	?	$<1.4\ 10^2$ [A]	?	?	$<4.7\ 10^6$ [N]

[S] Measured at Stanford, [T] Measured at TRIUMF, [A] measured at U.Alabama with neutron activation
[M] Measured by the MEG collaboration, [N] measured by the NEXT collaboration by Ge counting

Afterpulsing

Origin – carrier trapping and delayed release

Delay can be very large (some authors observed afterpulses even in the microsecond scale)



K.Sato e.a., NIMA732(2013)427

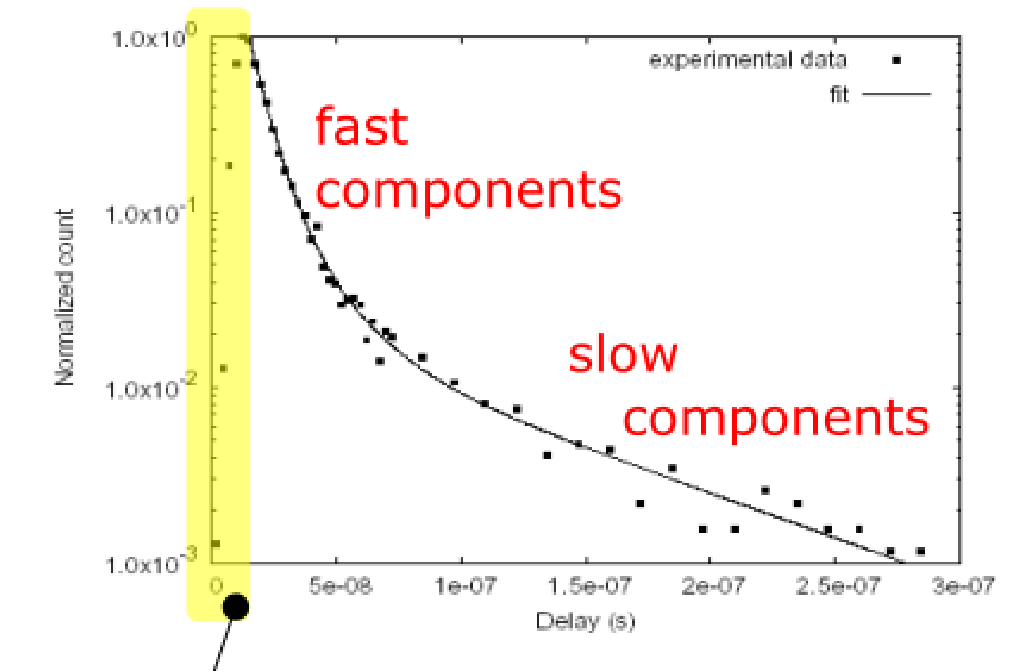


Fig. 10. Spectrum of the delay time from the primary pulse to the after-pulse.

From G. Collazuol, MEDAMI 2014

Progress in afterpulsing reduction

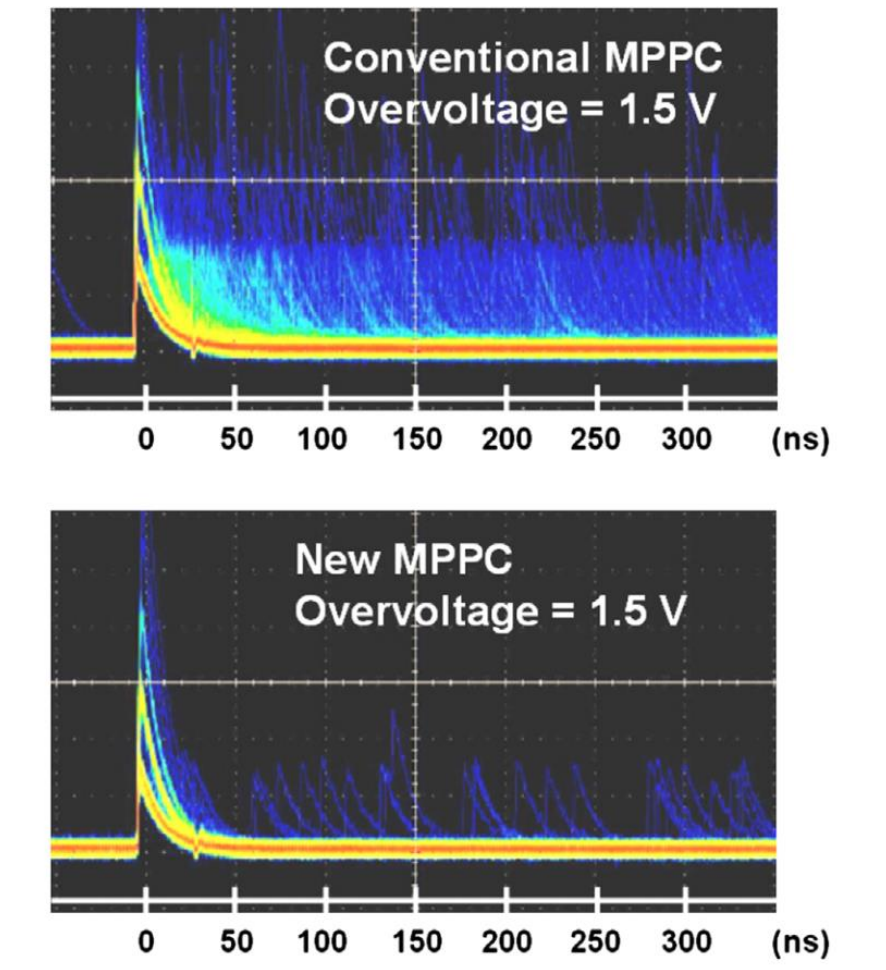


Fig. 6. Waveform of the traditional and afterpulse-reduced MPPC.

Hamamatsu MPPC

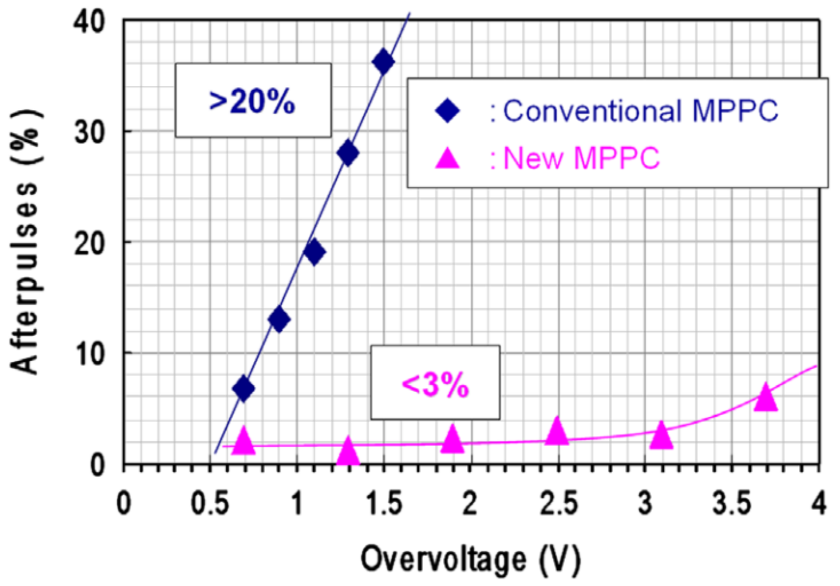
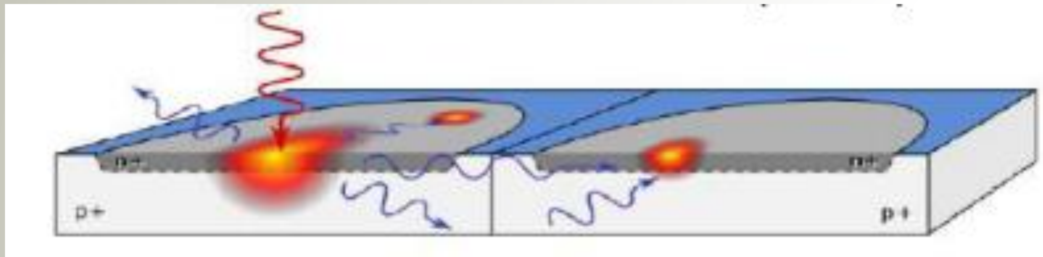


Fig. 7. Afterpulse ratio of the traditional and afterpulse-reduced MPPC.

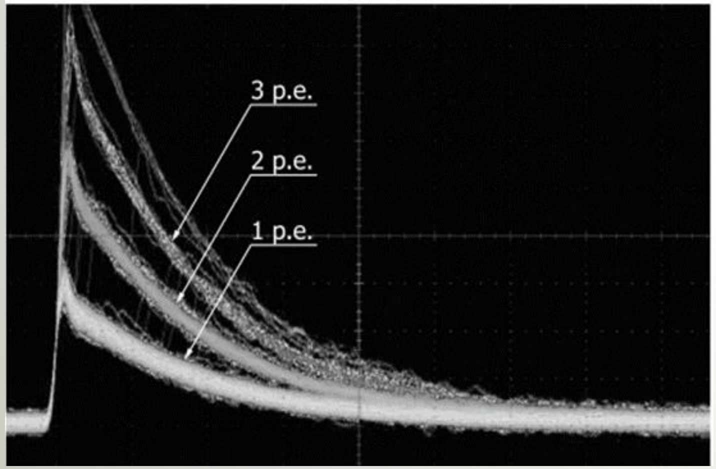
K.Sato e.a., NIMA732(2013)427

Optical crosstalk

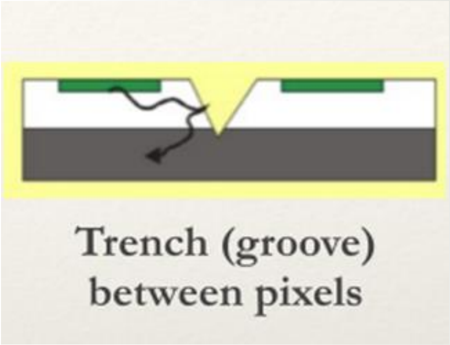
Photons generated in an avalanche can hit a neighbour cell
→ 2 (or more) cells can be triggered by one incident photon

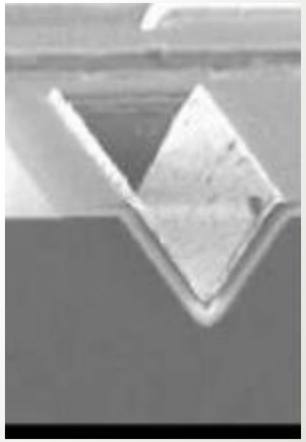


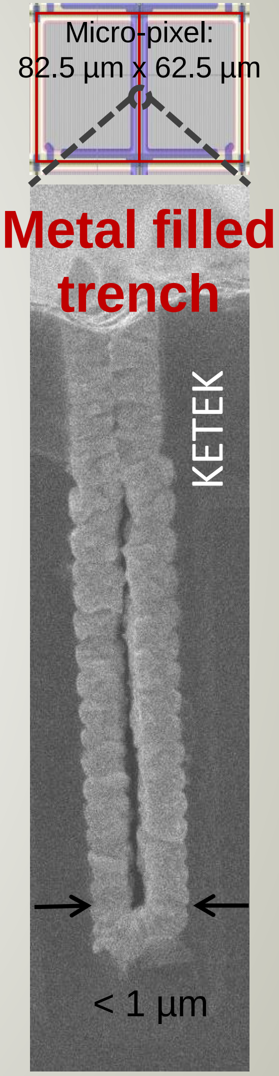
Crosstalk: prompt and delayed ~1ns (about 50/50)



Fighting crosstalk:







Crosstalk reduction

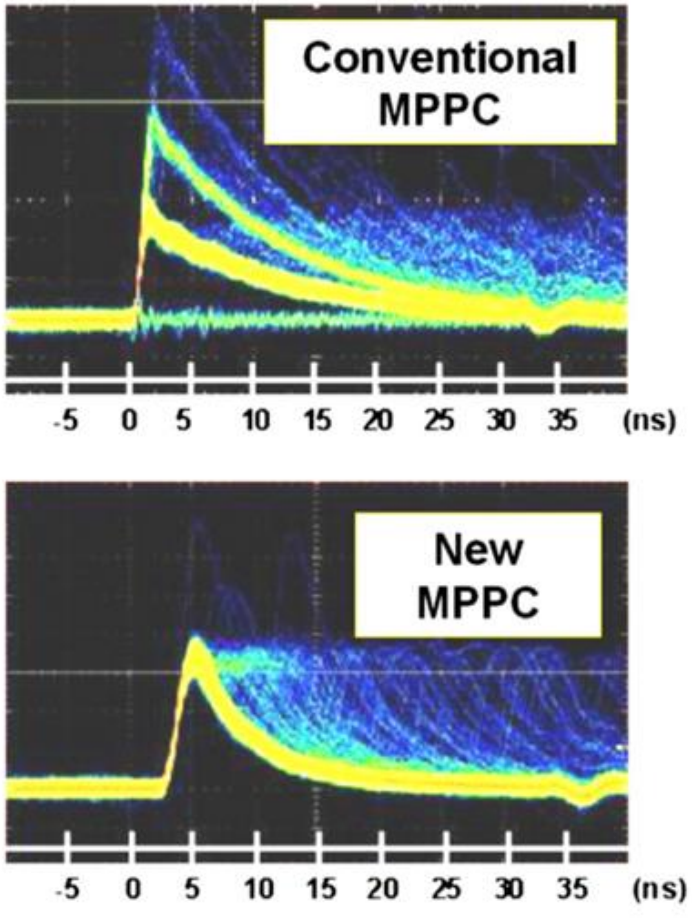


Fig. 8. Waveform of the traditional and crosstalk-reduced MPPC.

Hamamatsu MPPC

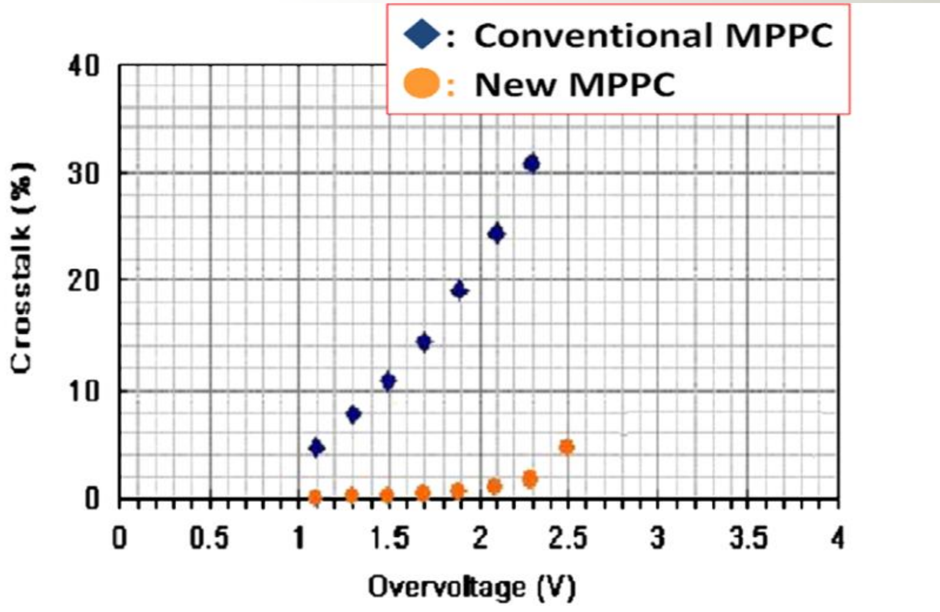
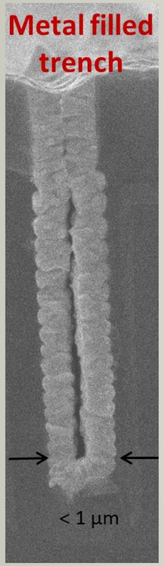


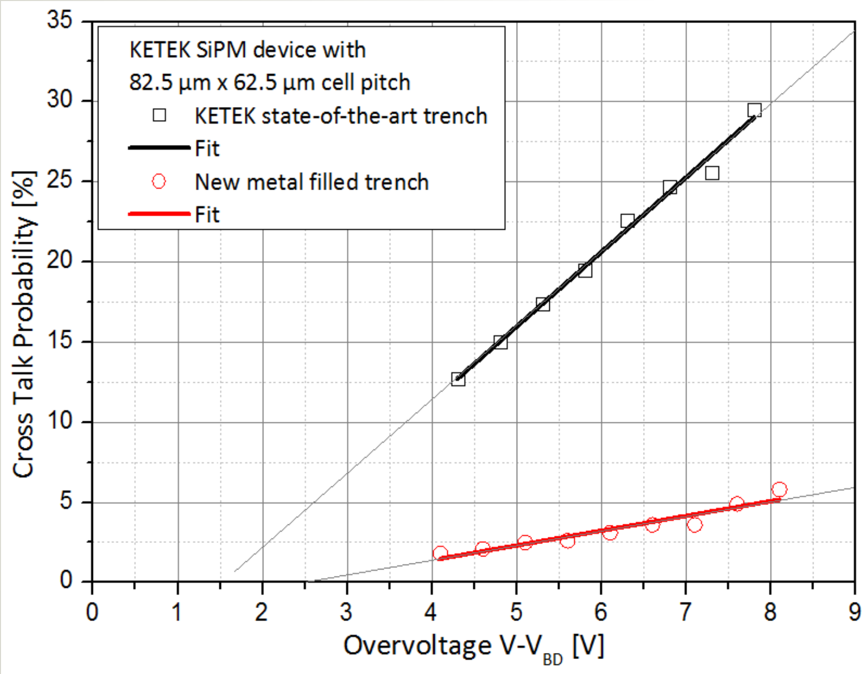
Fig. 9. Crosstalk ratio of the traditional and crosstalk-reduced MPPC.

K.Sato e.a., NIMA732(2013)427

Crosstalk reduction (examples)

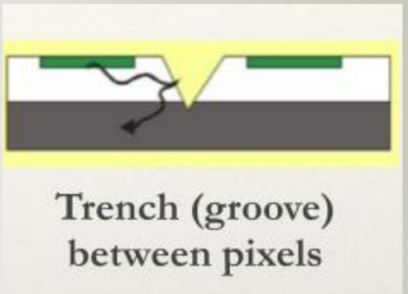


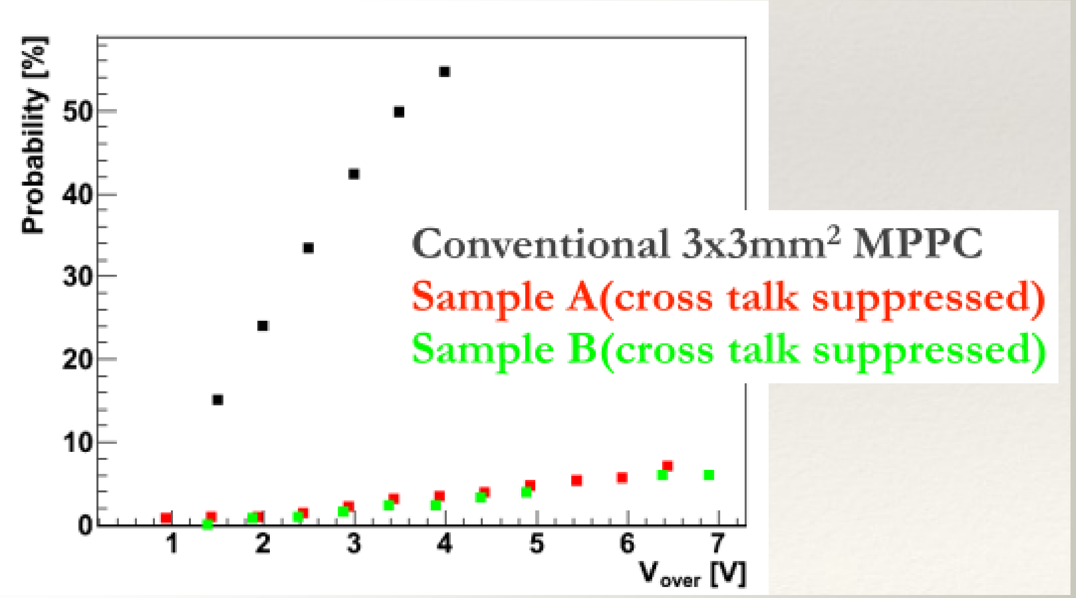
KETEK



Hamamatsu/MEG

VUV SiPM for LXe

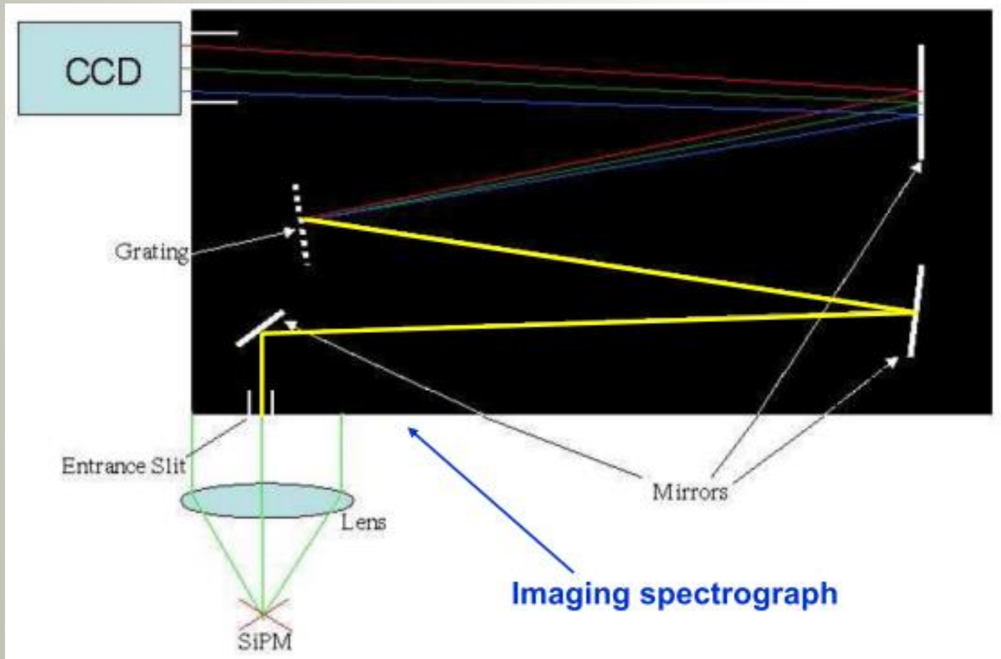




(From: T. Iwamoto, IEEE 2014)

SiPM emission spectrum

1 mm x 1 mm Hamamatsu MPPC
Gain 1.56×10^6
operated in continuous mode (i.e. no quenching)
Short laser pulse excitation



Mirzoyan e.a., NDIP08, NIMA610(2009)98

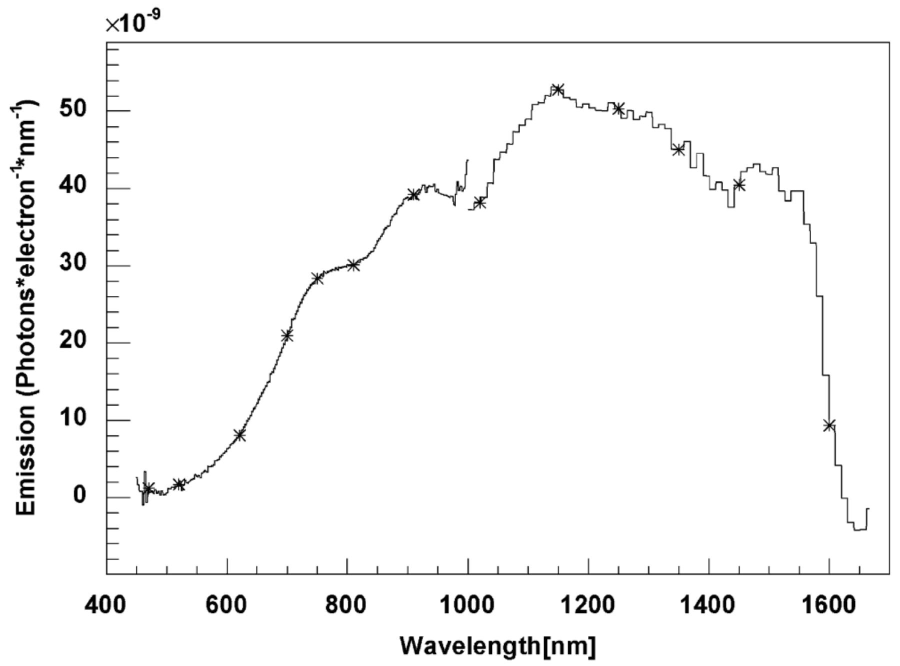


Fig. 2. Measured differential light emission spectrum from Si avalanche. The stars mark the peak wavelengths of the LEDs used for the calibration. The largest error for any point in the spectrum is $\leq$24.8%.

Intensity:
2.6×10^{-5} ph/e in λ= 500 – 1600 μm
1.2×10^{-5} ph/e in λ= 500 – 1117 μm → ~20 ph/avalanche
(3×10^{-5} ph/e from other authors)

Crosstalk between SiPMs

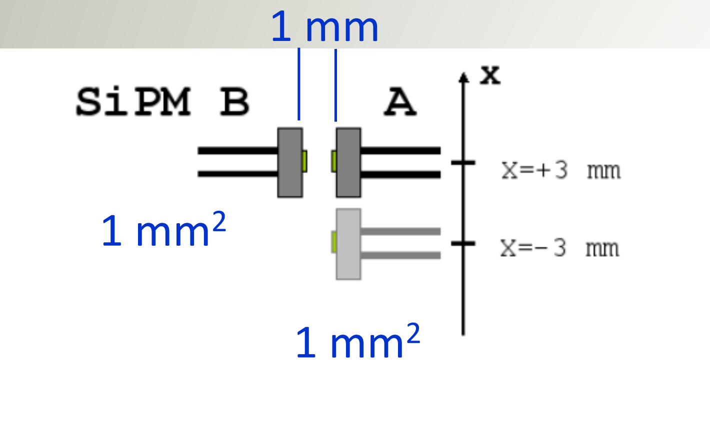


Figure 5. Experimental set-up to measure the optical crosstalk between a Hamamatsu S10362-11-100C SiPM (SiPM A) and a Hamamatsu S10362-11-050C SiPM (SiPM B).

Korpar e.a., NuclPhysB197(2009)283

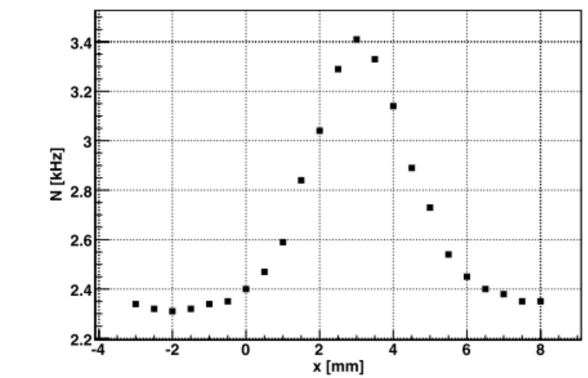
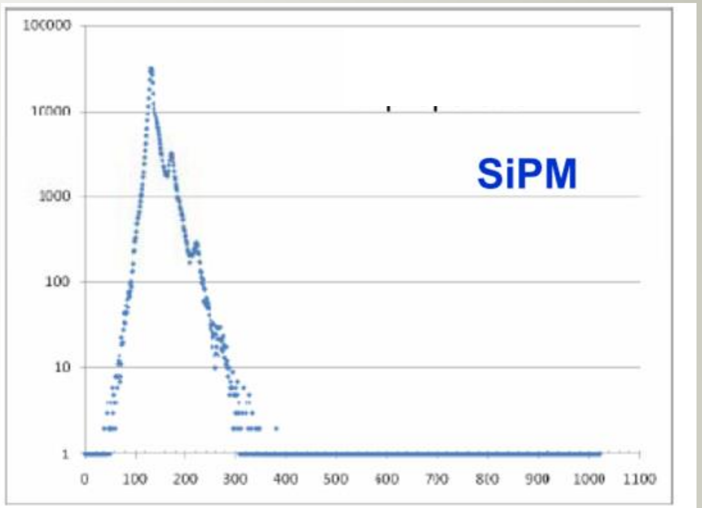
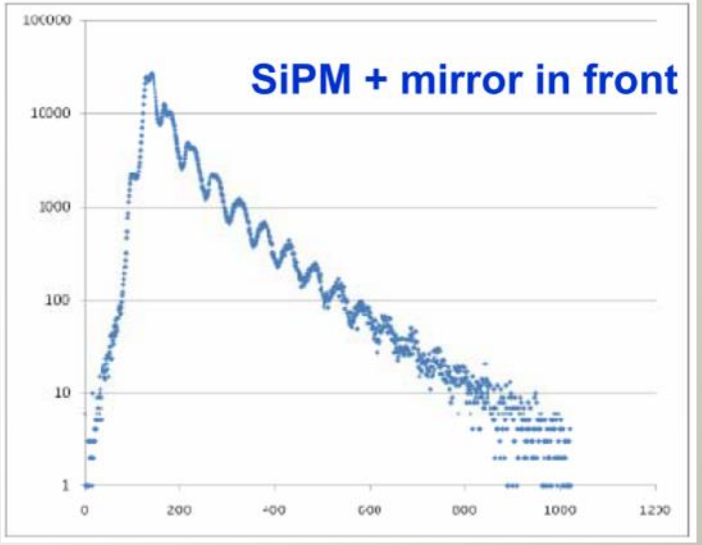


Figure 6. False coincidence rate as a function of distance x. The two SiPMs overlap when x = 3 mm.



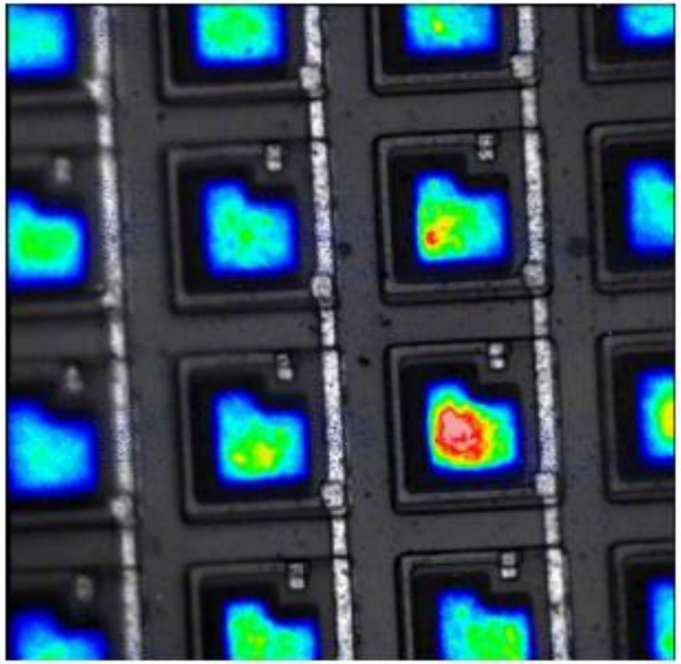


Mirzoyan e.a., NDIP08, NIMA610(2009)98

The noise of each SiPM increases from 200 kHz to 250 kHz in front of the other

SiPM as a light source

Avalanche luminescence (NIR)



N.Otte, SNIC 2006

From G.Gollazuol, MEDAMI 2014

Carriers' luminescence (spontaneous direct relaxation in the conduction band) during the avalanche: probability 3.10^{-5} per carrier to emit photons with E> 1.14 eV

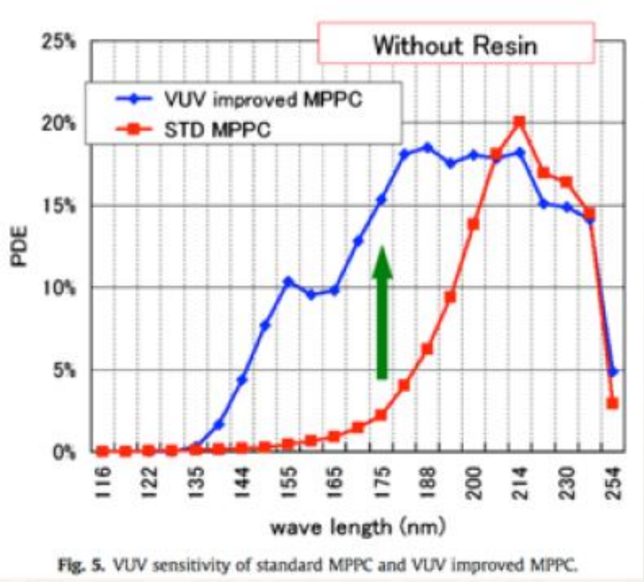
A.Lacaita et al. IEEE TED (1993)

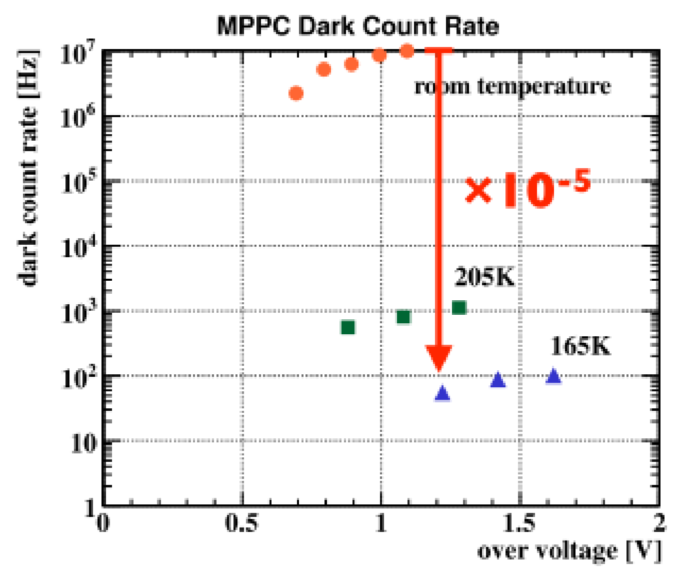
For a detector in a single photon counting mode (as DM detectors) with ~4π SiPM coverage this may be a problem

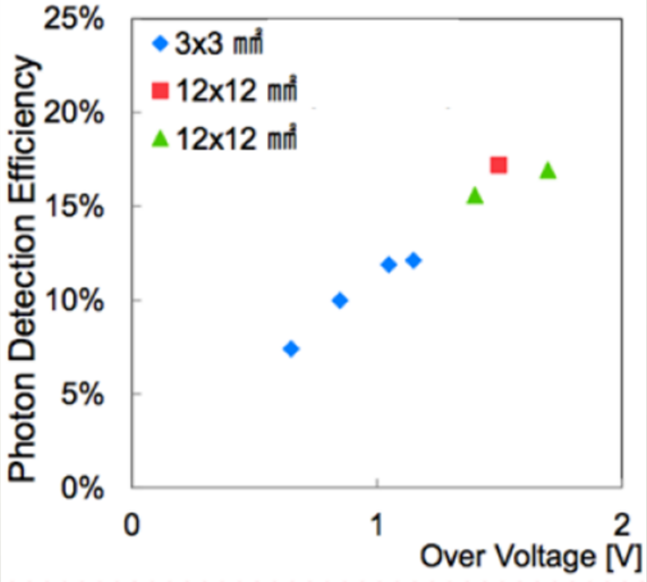
MEG/Hamamatsu SiPMs for LXe

(Based on presentation by T.Iwamoto, TNS/MIC 2014)

VUV-sensitive MPPCs developed with Hamamatsu Photonics:
- protection layer removed,
- insensitive layer made thinner,
- anti-reflection coating optimized,
- best matching of refractive index to LXe found,
- metal quench resistors suitable for low temperature is used.

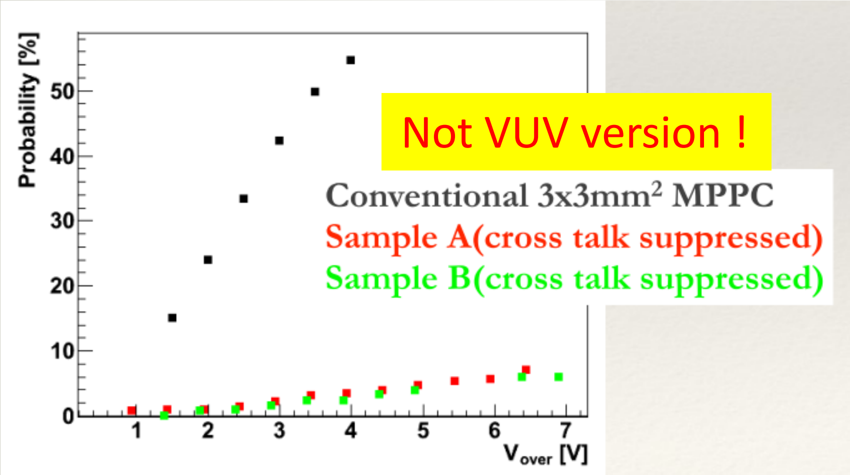




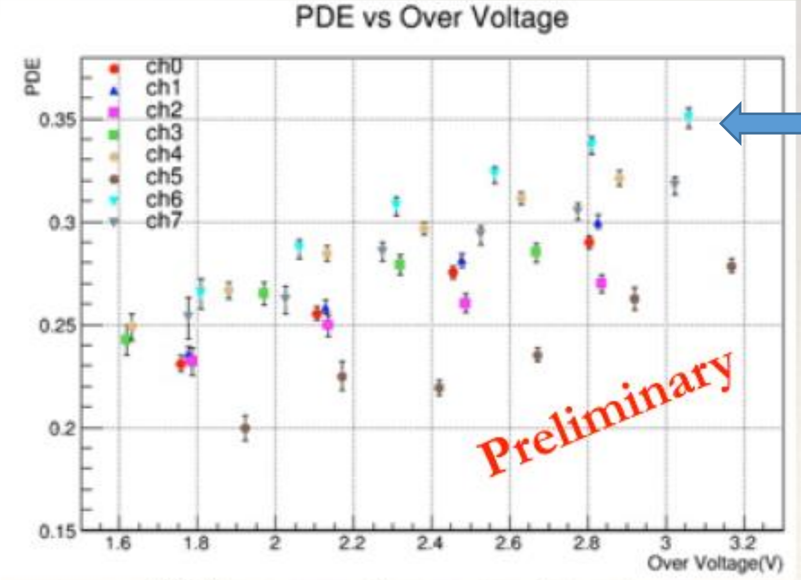


MEG/Hamamatsu SiPMs for LXe

Crosstalk suppression



Not VUV version !



±12% systematics not written here

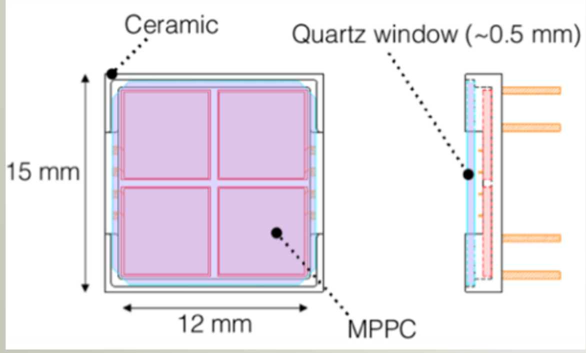
Wph(eV) = 19.6±2.0, α energy etc.

PDE 35%

λ = ?

(LED was mentioned…)

Active area 14 x 14 mm^2



600 delivered in March 2014

8 MPPCs are measured at LXe temp. using the test facility at PSI

With Xe light?
In LXe?

Max PDE in visible is about 60%

An exercise: is dark count rate of 100 Hz/SiPM low enough?

Assume time window of 100 ns (for LXe) and 2000 SiPMs , dark count rate of 100 Hz.
Setting S1 threshold to 2, 3 or 4 phe one gets random coincidence rate

$$n_k = n_1^k (\Delta\tau)^{k-1} \binom{k}{N}$$

$n_1 = 100s^{-1}$, $\Delta\tau = 100ns$, and $N = 2000$ detectors:

$$n_2 \approx 2000s^{-1}$$

$$n_3 \approx 13s^{-1}$$

$$n_4 \approx 7 \times 10^{-2} s^{-1}$$

Conclusion

A significant progress in performance improvement of Geiger APDs is made

One can say that the technology has reached sufficient maturity

VUV/LXe:

Close but not there yet

Careful with optical feedback and noise

Fear for surprises…