ISMART-2018, Minsk, Belarus

State of Art in development of Silicon photomultipliers

Nikolay Anfimov
Joint Institute for Nuclear Research, Dubna.

Vendors

W.Ootani, "SiPM, Status and Perspectives", Special Workshop on Photon Detection with MPGDs, June 10-11, 2015 CERN

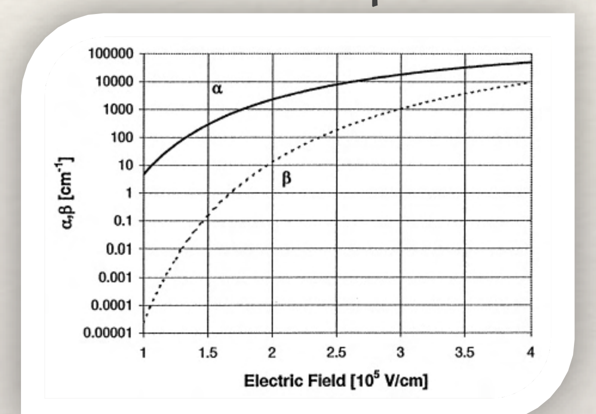
Different names - one meaning

- **SiPM - Silicon Photomultiplier**
- MAPD - Micropixel Avalanche PhotoDiode
- MPPC - MultiPixel Photon Counter
- SSPM - Solid-State Photomultiplier.
- MRS APD - Metal - Resistance - Semiconductor APD.
- Other…

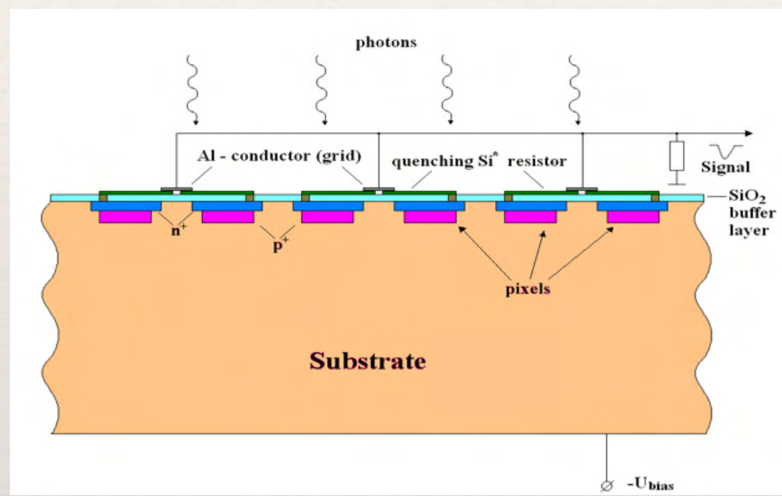
Operation Principle

- Many binary (yes/no) pixels give proportional response.

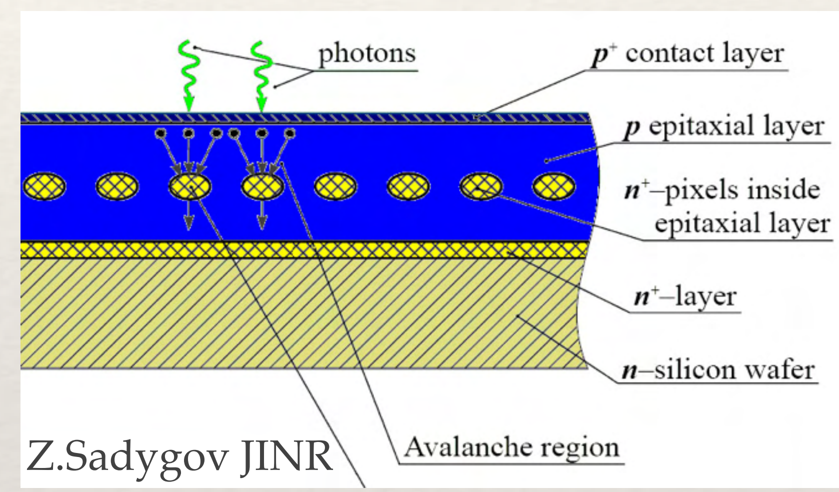
Impact ionization
α - electrons, β - holes

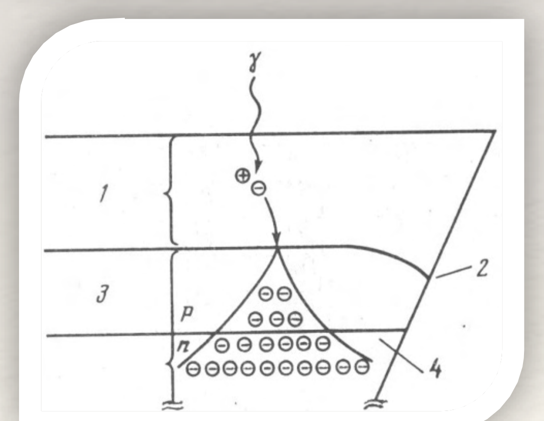


Pixels on surface

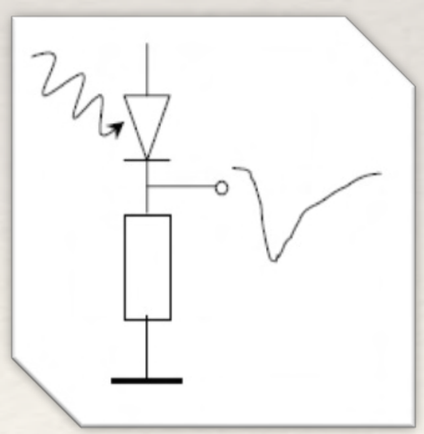


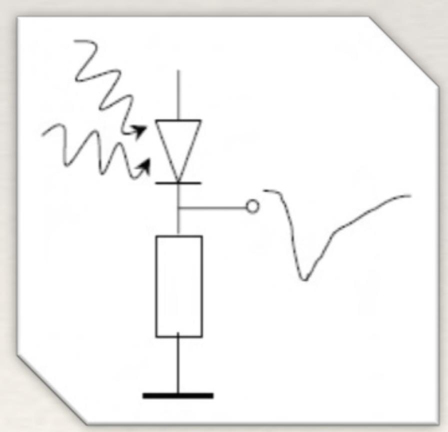
Deeply buried pixels (DMW-SiPM)



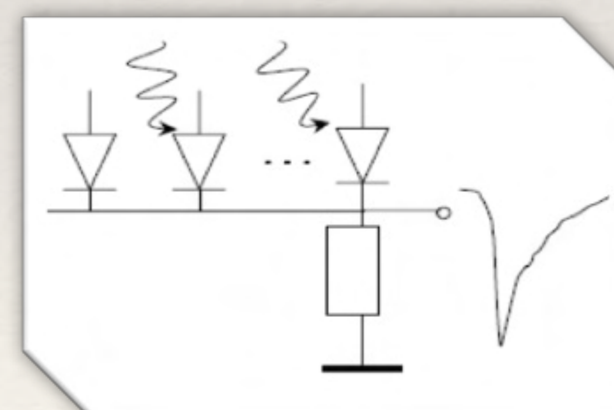


α>>β APD
Linear Signal





α≈β Geiger APD (SPAD) - Digital Signal
(Yes/No Counter)



Many APDg = SiPM
Quasi linear
Number of pixels ~ linearity

Dynamic range and nonlinearity

Dynamic range is defined by total number of pixels, but response is not linear!

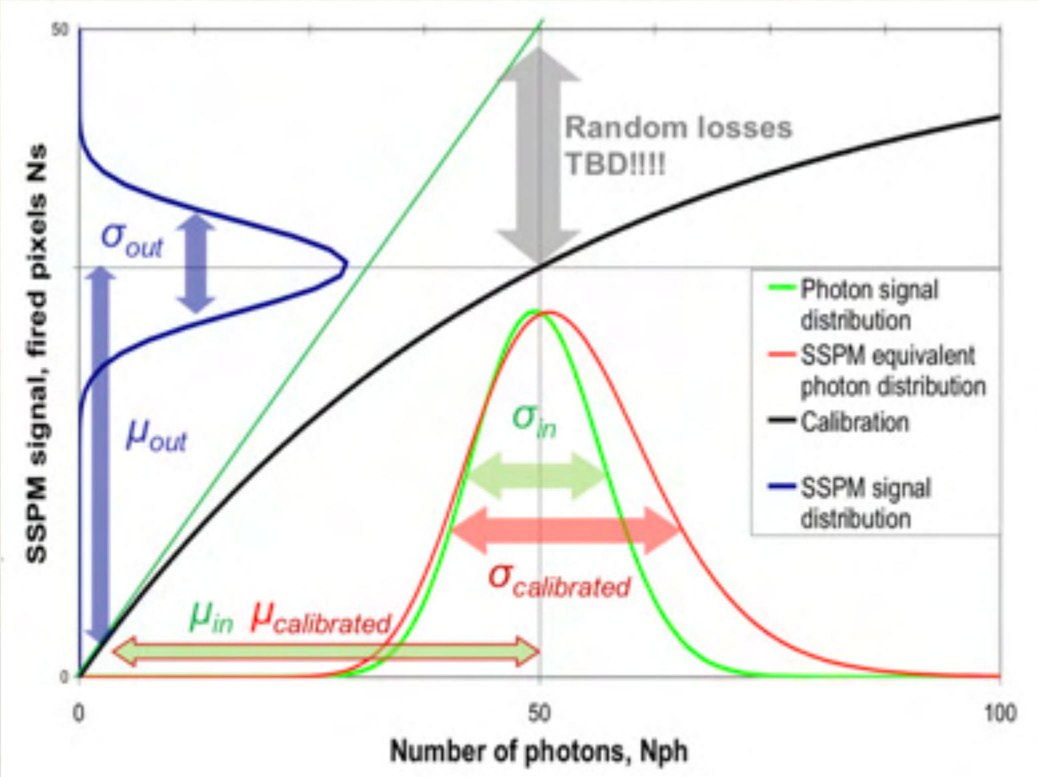
Simple approach:

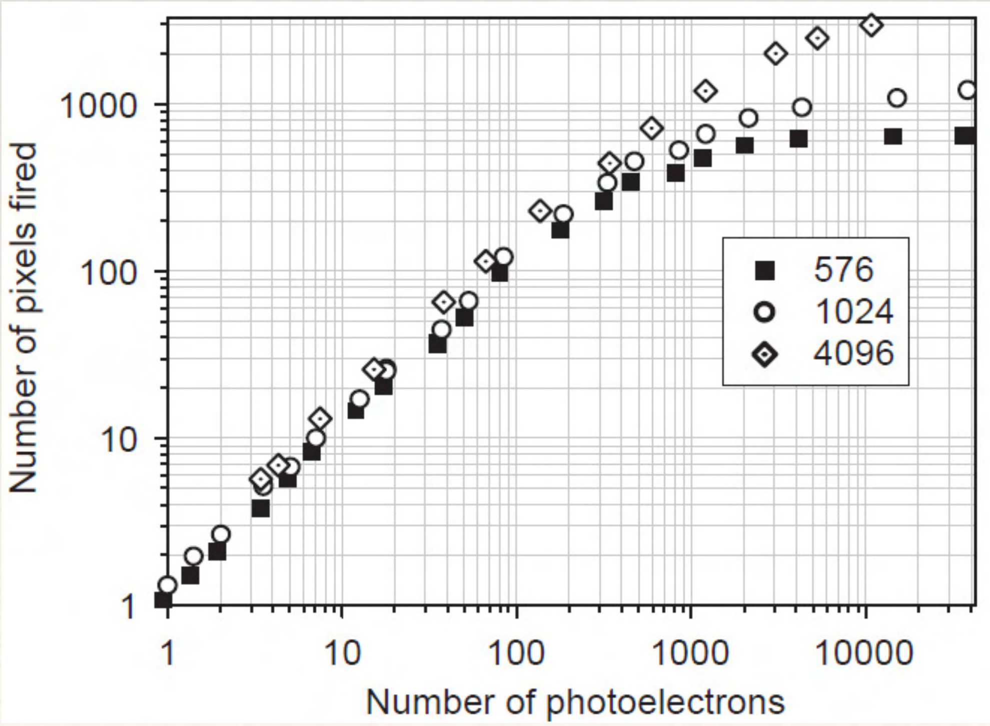
$$N_{det} = N_{pix}\left(1 - \mathrm{e}^{-\frac{N_{pe}}{N_{pix}}}\right)$$

- Excess noise of nonlinearity

$$ENF = \frac{Res^2_{calib}}{Res^2_{in}} = \frac{\sigma^2_{calib}}{\sigma^2_{in}} = \frac{1}{\sigma^2_{in}} \cdot \frac{\sigma^2_{out}}{\left(\frac{d\mu_{out}}{d\mu_{in}}\right)^2}$$

S. Vinogradov. Statistics and models of SiPM nonlinearity and saturation





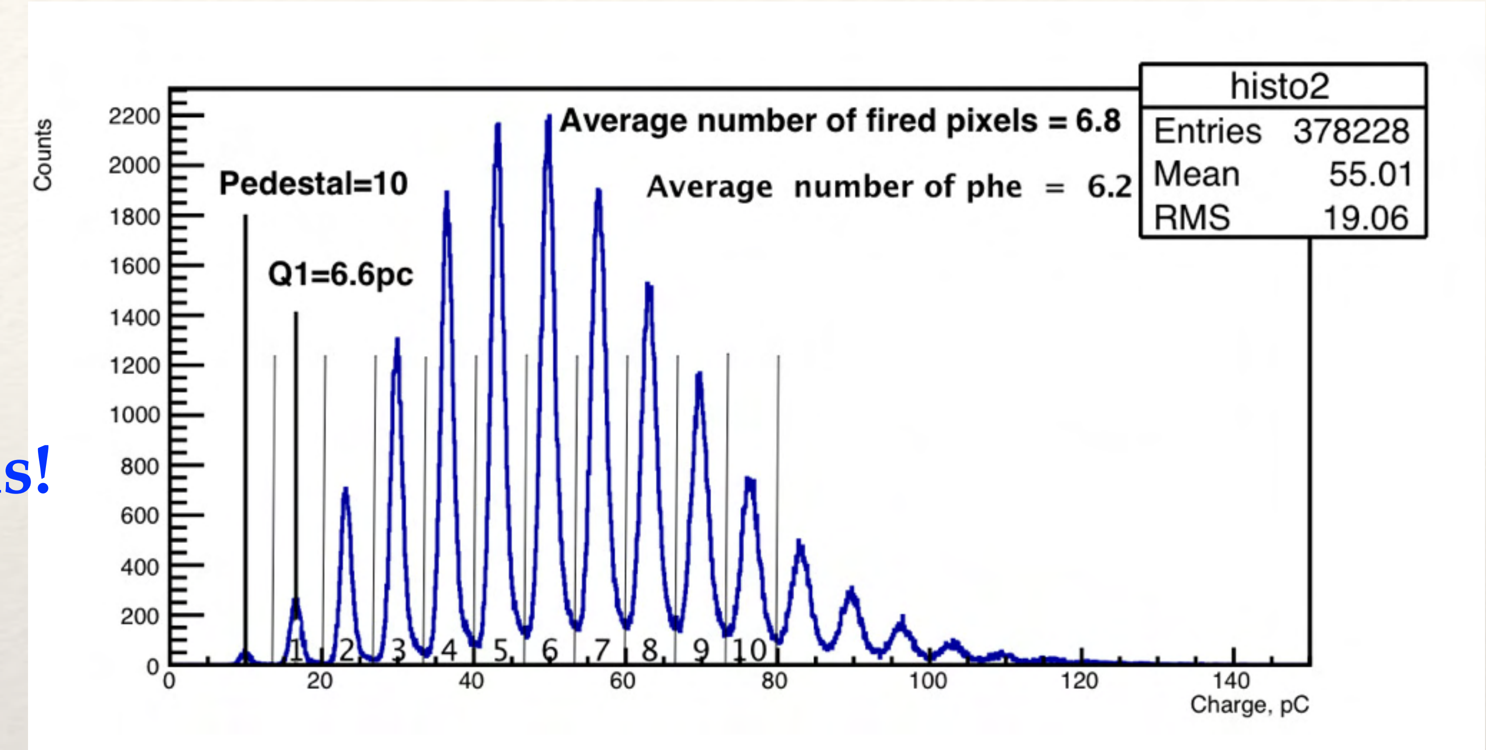
V. Andreev et al, NIM A, 540(2-3) (2005)

Cross-talk decreases linearity!

Single photon resolution

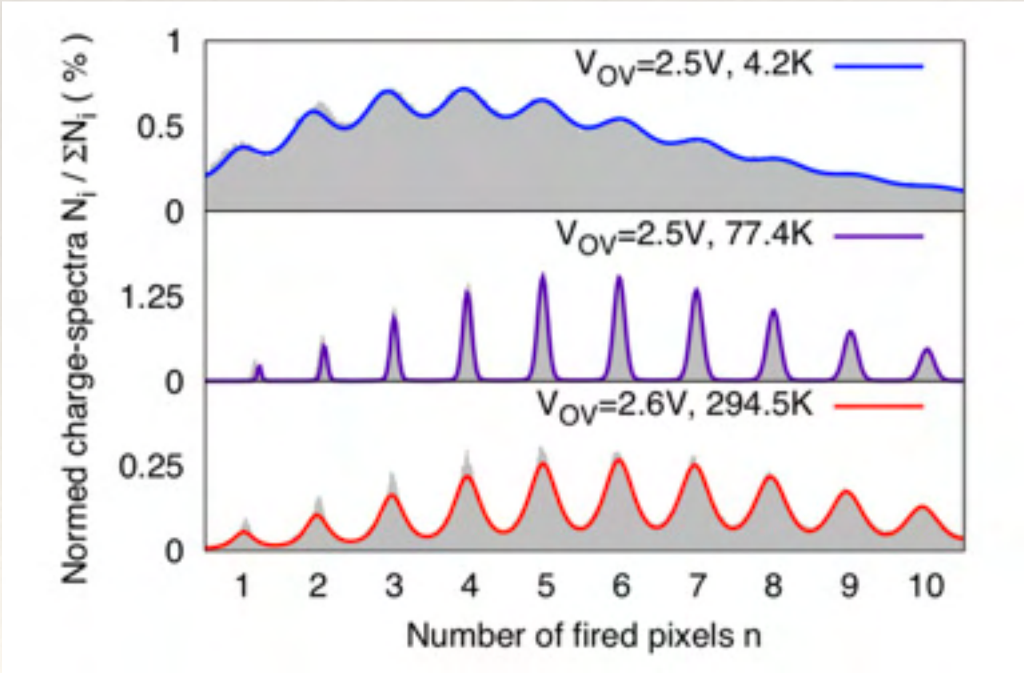
SiPM can detect single photons!

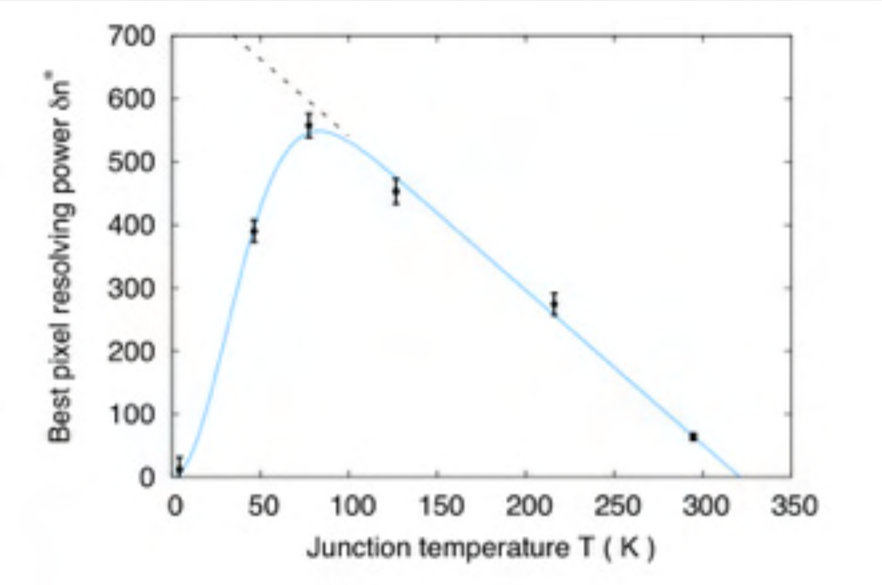
And distinguish number of photons!



Hamamatsu MPPC S12572-010C(X).
3x3 mm2, 90 000 pixels

N. Anfimov et al., Measuring of the time resolution parameters of silicon photomultiplier



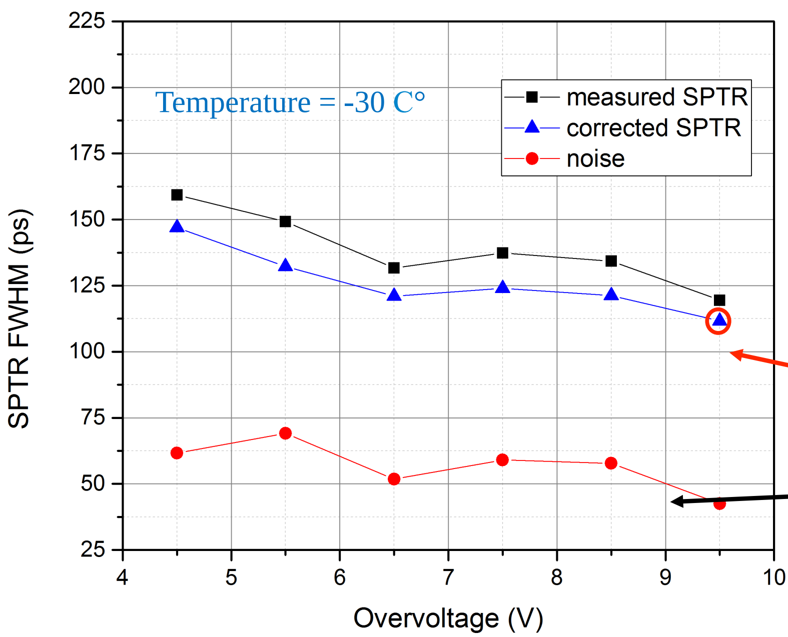


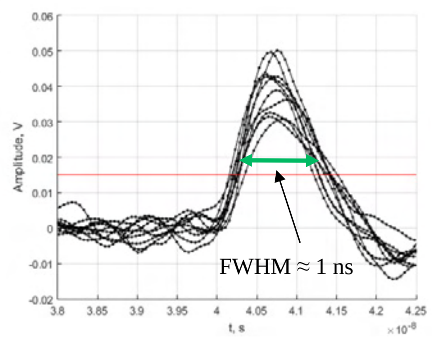
Resolution depends on Temperature! Best @ LiN Temp!

M. Biroth. An analytical approach to predict fundamental properties of SiPM.

Single Pixel Time Resolution - SPTR

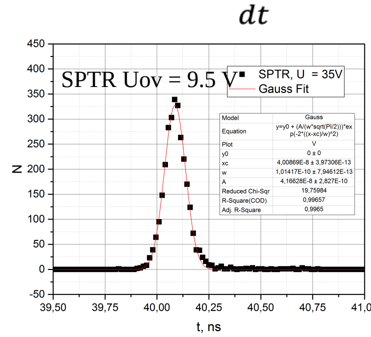
SPTR measurements





1_phe pulse shape, Uov = 4.5 V

$$\bar{\sigma}_{t,noise} = \frac{\bar{\sigma}_{A,noise}}{\frac{dU}{dt}}$$



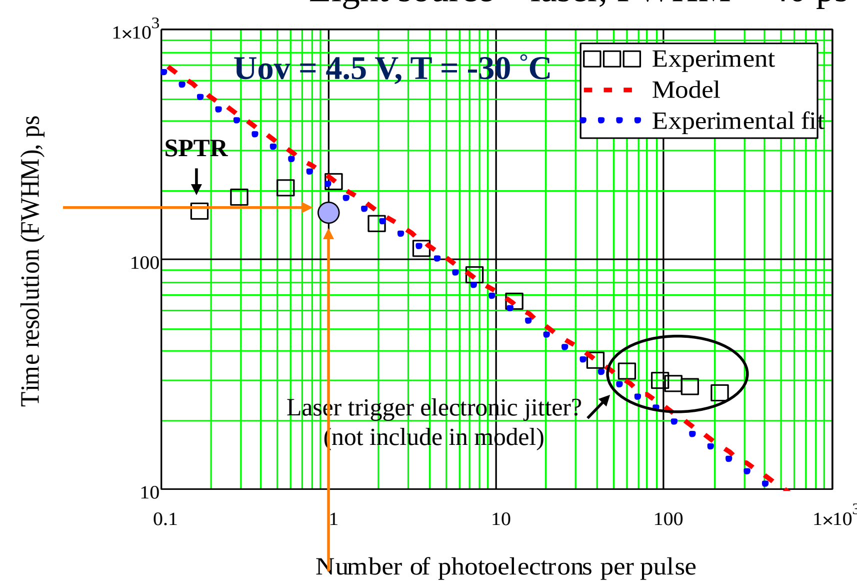
13 June 2018 ICASIPM E.Popova

TR vs Light intensity for short laser pulse

(T = -30°C, Uov = 4.5V, SPTR (true SPTR without noise contribution)= 147 ps

Pct=0.13, ENFct=1.16, no Dark rate)

Light source – laser, FWHM = 40 ps



$$FWHM_t(N_{pe}) \approx \frac{SPTR}{\sqrt{N_{pe}}} \cdot 1.5$$

Analytical model:
Tr = 0.5 ns, Tf = 1 ns

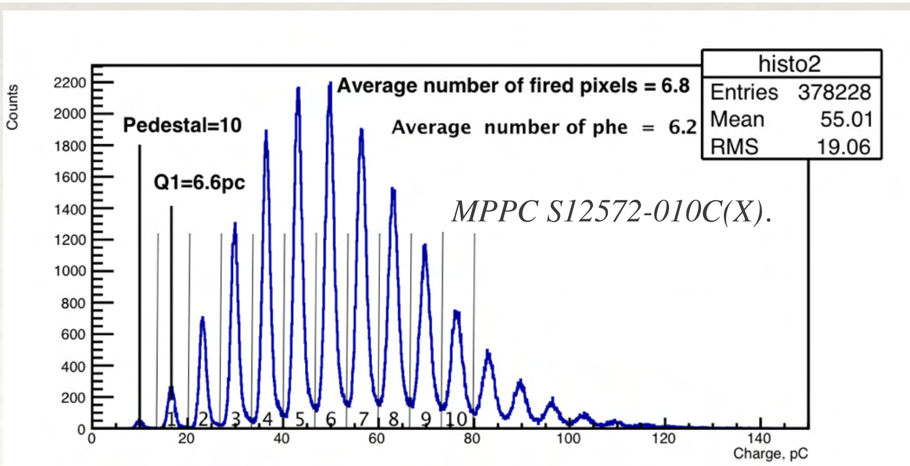
$$FWHM_t(N_{pe}) \approx \frac{210\,ps}{\sqrt{N_{pe}}}$$

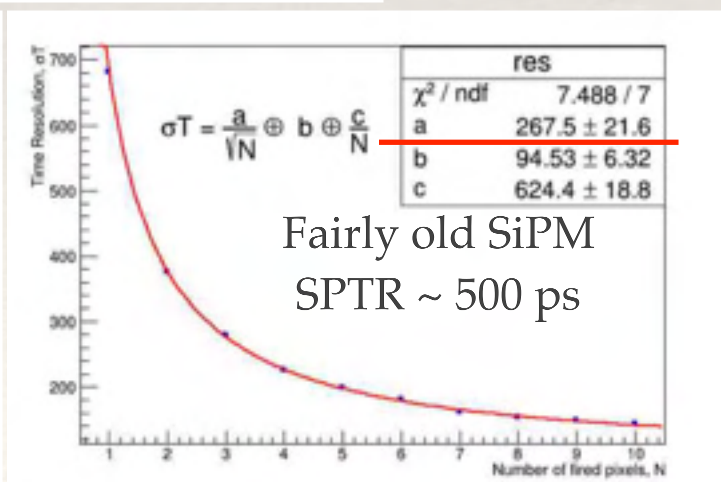
Experimental Fit

$$\frac{210}{1{,}5} = 140 \approx SPTR_{corr}$$

Extracted SPTR

13 June 2018 ICASIPM E.Popova



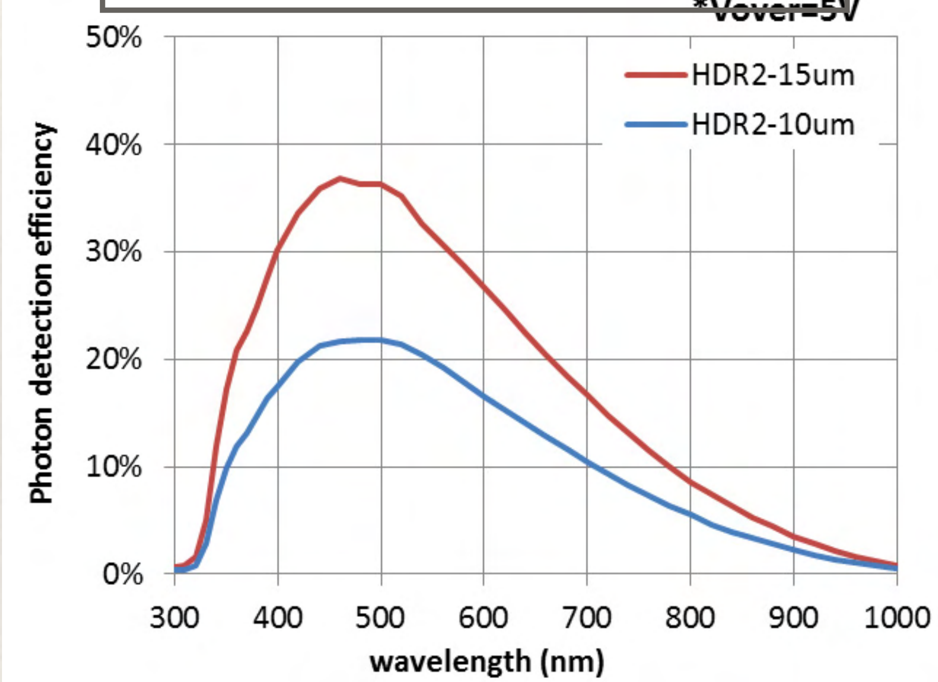


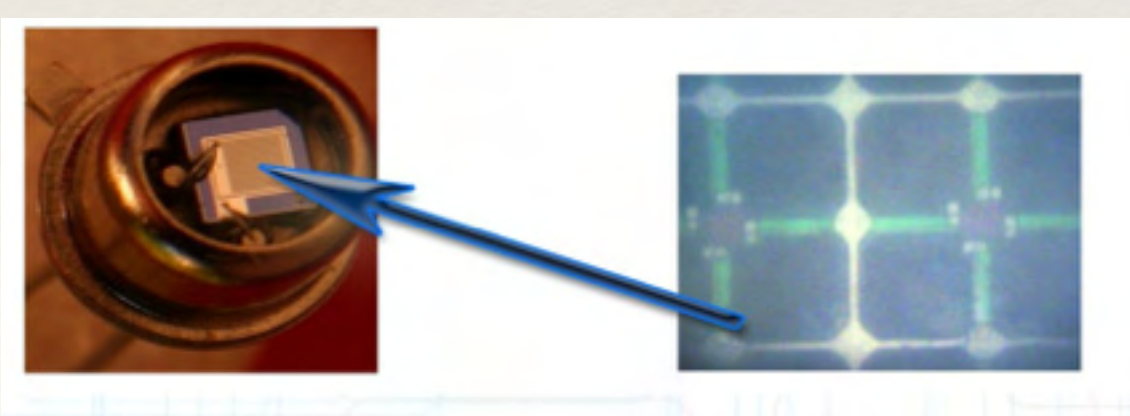
For new SiPMs

SPTR (FWHM) ~ 100 ps
for new SiPMs

Photon Detection Efficiency

ε_g **- Geometrical filling factor**
ε_g = Active/Total
ε_g**>50% is Achievable**
Depends on pixel density,
but new technologies!

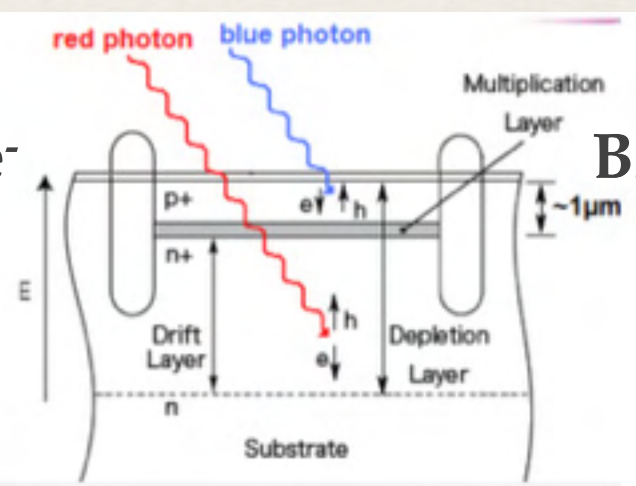




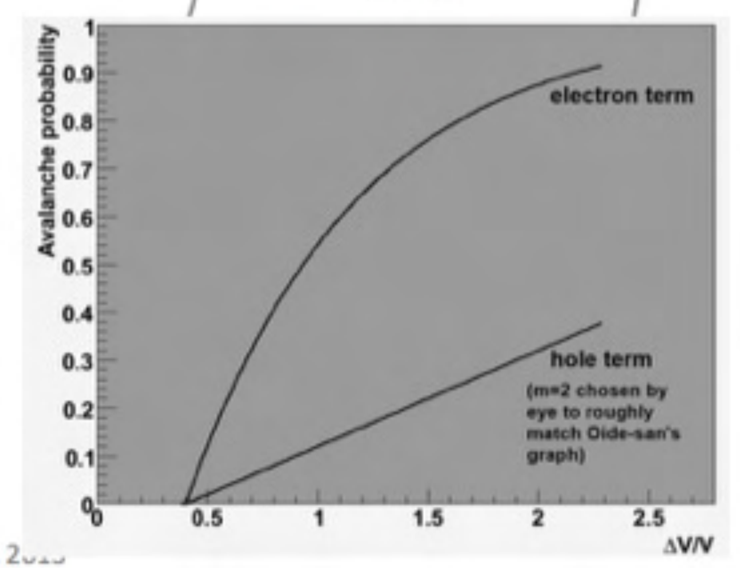
$$PDE = QE \cdot \varepsilon_g \cdot P_{tr}$$

QE - Quantum Efficiency of material
(+ Fresnel reflection)

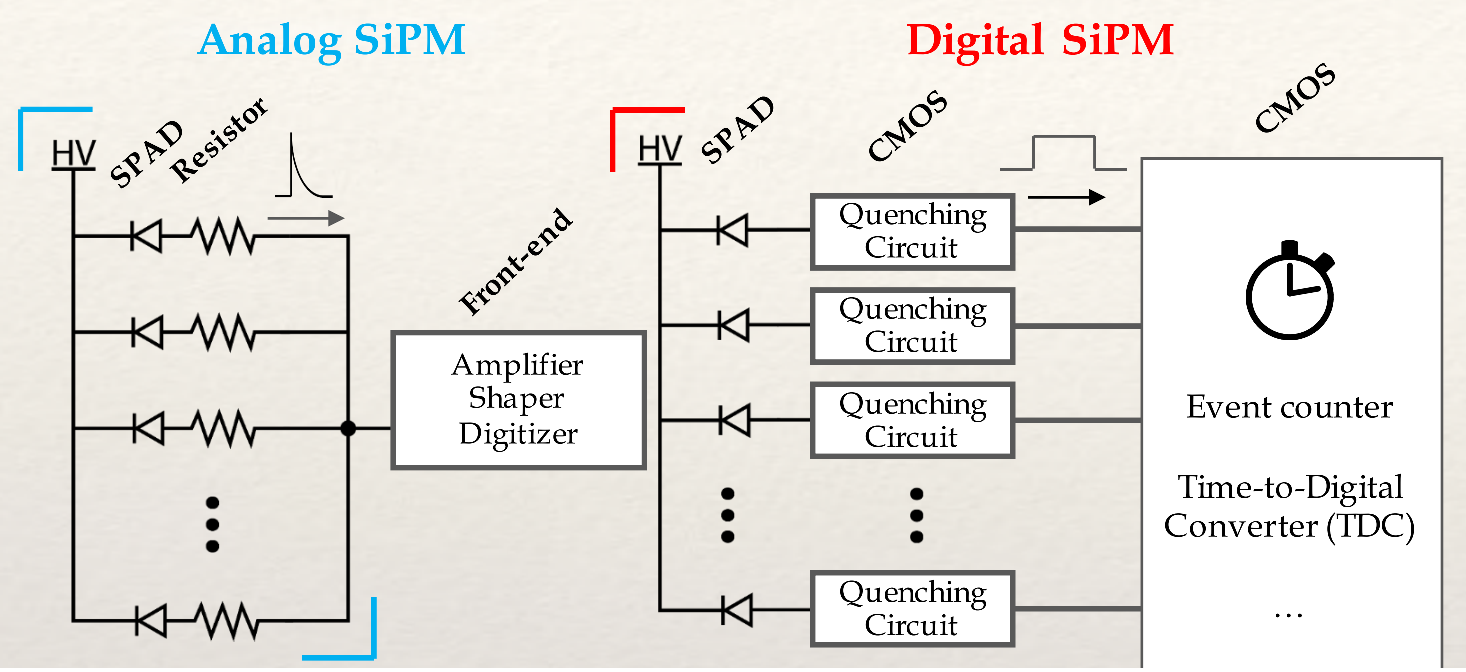
p-substrate:
Blue - h$^+$, Red - e$^-$



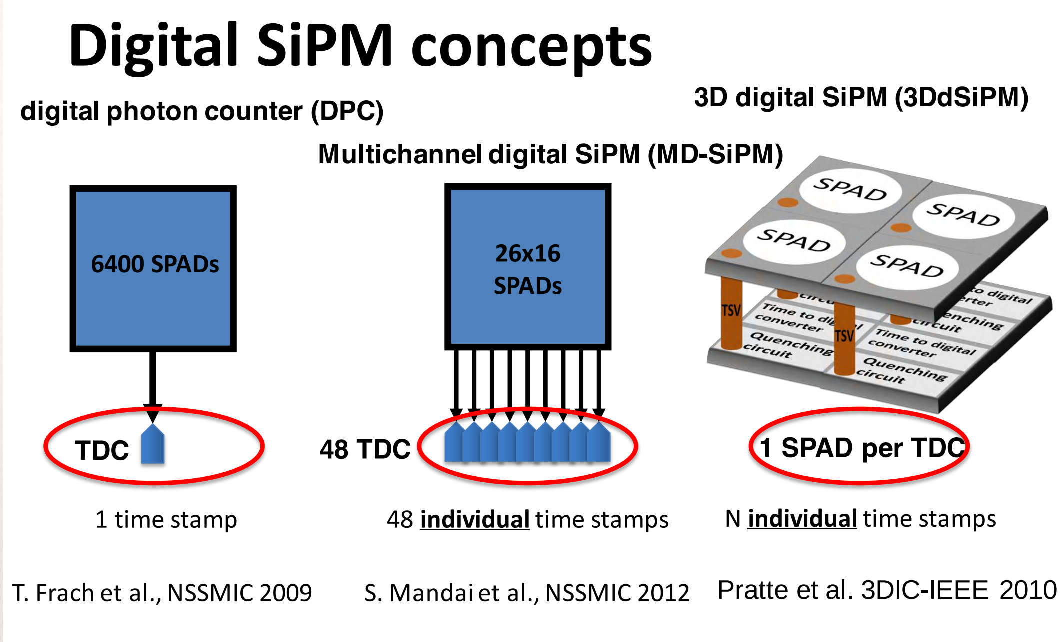
n-substrate:
Blue - e$^-$, Red - h$^+$



Digital SiPM



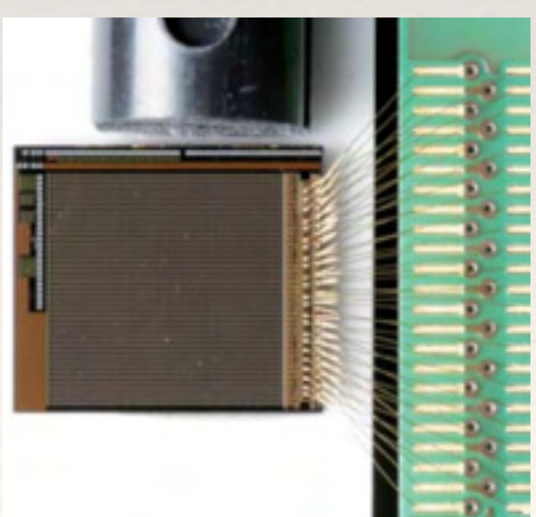
F. Vachon. PDE Measurement for Digital SiPMs: Comparison Between Pulsed And Continuous Light Methods



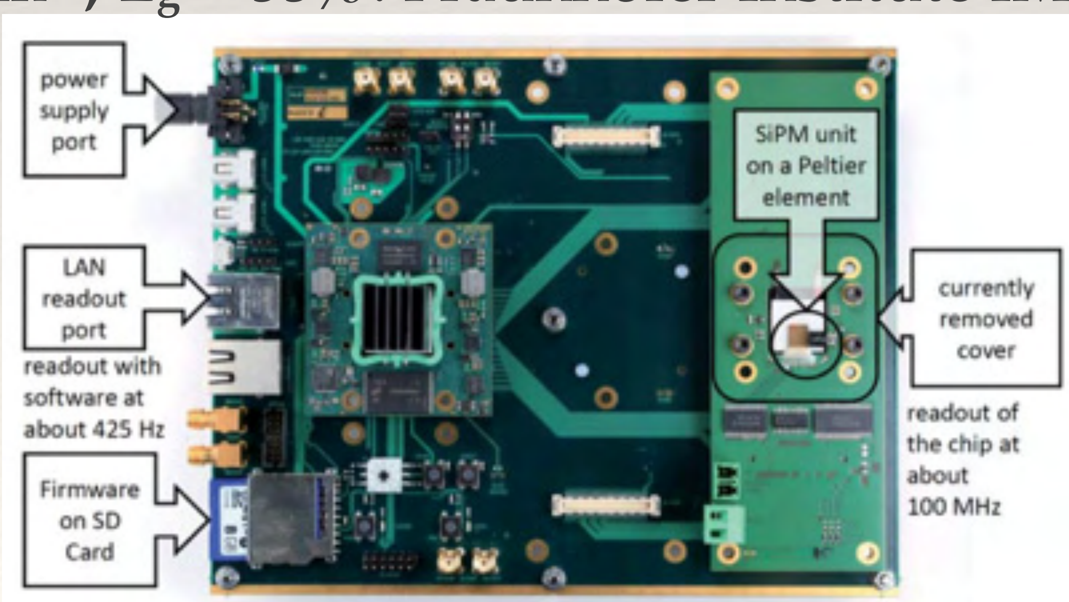
E. Venialgo. Single-Photon Timing Resolution in Digital Silicon Photomultipliers

16

88x88 pixels, 5x5 mm^2 , E_g = 55%. Fraunhofer Institute IMS DSiPM



R. Joppe. Preparation and first applications of a digital SiPM



DSiPM

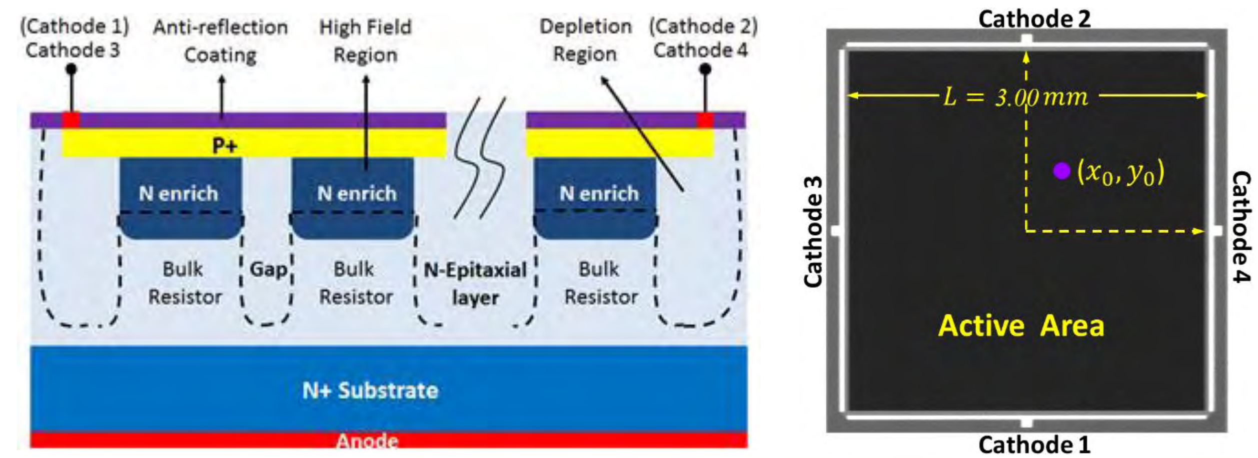
Expensive, complex

Very promising technology

Pixel position?

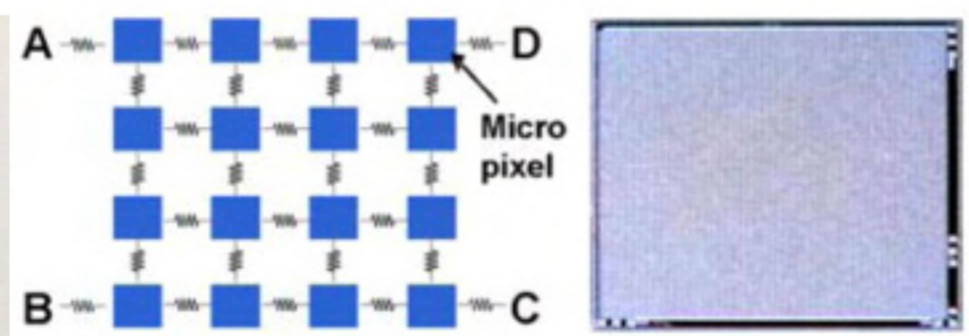
Position-sensitive SiPM

SeSP Uni. of Aachen, Germany
ISiPM Univ. of Heidelberg, Germany
PS-SSPM RMD, USA
LG-SiPM FBK, Italy
NDL EQR-SiPM→CRL-SiPM



NDL PS-SiPM

Based on Charge sharing (Gravity Center) principle!

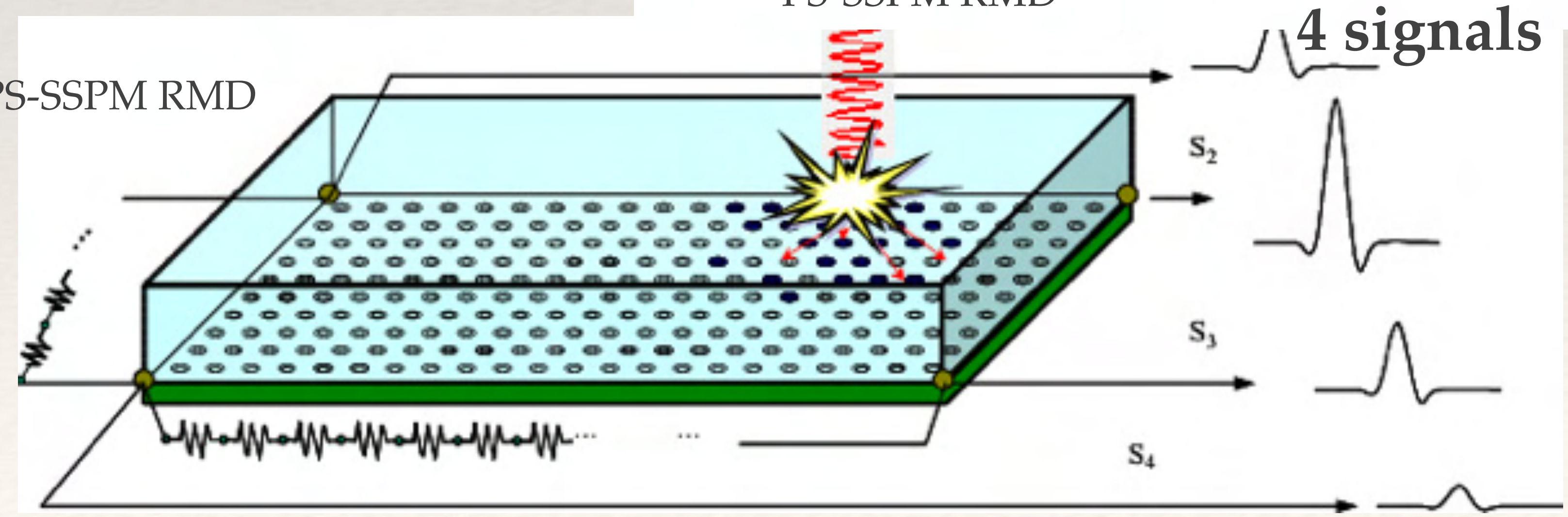


PS-SSPM RMD

Suitable to read out an array of small crystals
8x8 1x1x20 mm^3 by 4 channels!

Active area	10mm x 10mm
Total Number of micropixels	40000
Micro-pixel area	30µm x 30µm
Micro-pixel pitch	44.3µm x 44.3µm
Geometrical Fill Factor	36%
Quench Resistors O	144k
Network resistors O	90
PDE @ 420 nm	7 - 10%
Dark Count Rate MHz	700 (V_x =2V)
Capacitance fF/pixel	220
Operating voltage	27.5V to 32V

PS-SSPM RMD

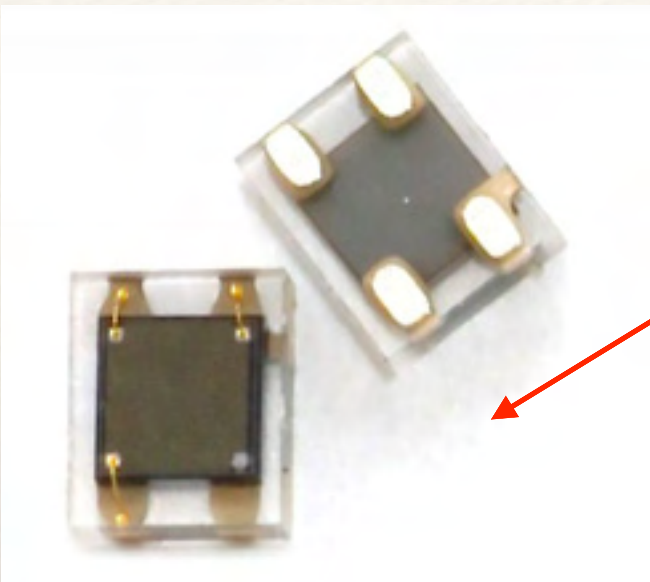


Applications outline

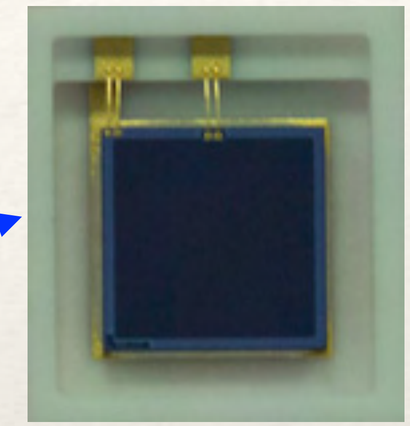
- Light detection: Visible, UV, IR
- Fiber optics (clean, WLS, etc)
- Small Scintillators, compact detectors.
- Cherenkov light detectors
- High Energy Physics
- Cryogenics
- Timing TOF (TOF-PET, Particle Identification, Ranging).
- LiDAR, SmartCars, …
- Photon counting applications (Quantum entanglement, cryptography, medicine, military, …)
- others…

IR, Visible, UV

SensL R-series



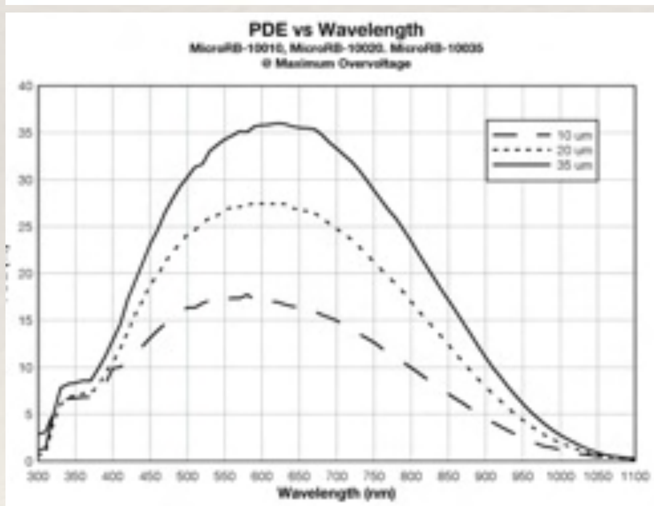
3 × 3 mm2 S13370-3050CN MPPCs



All SiPMs can detect visible light

p-substrate shifted to Red (IR)

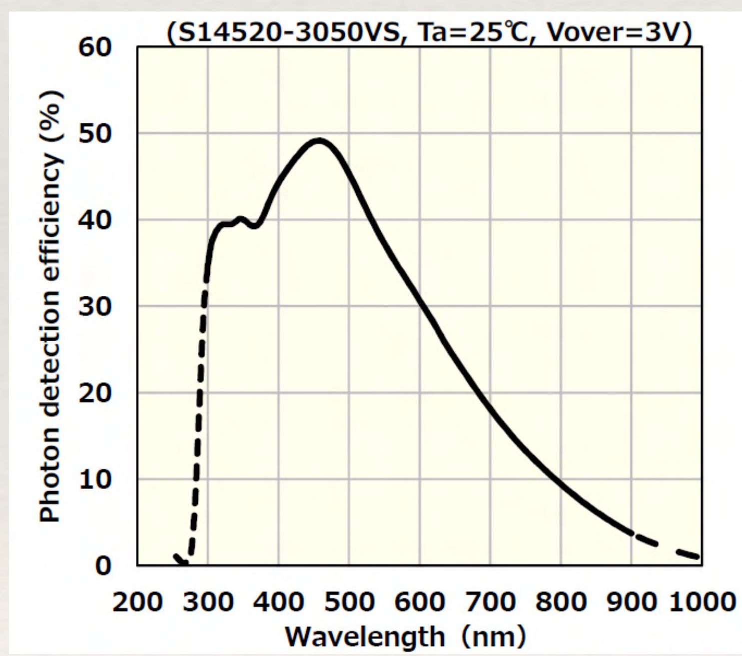
n-substrate to Violet (UV)



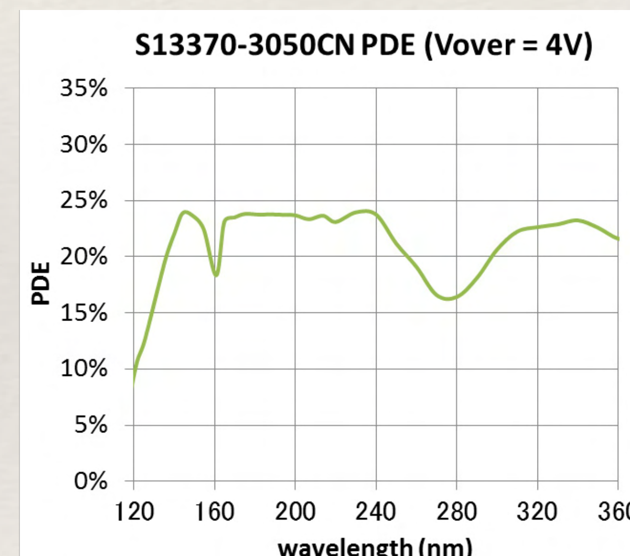
PDE (900 nm) ~ 10%
LiDAR applications, NV

PDE(600-650) ~ 35%

Red Scintillators???



PDEmax ~ 50%

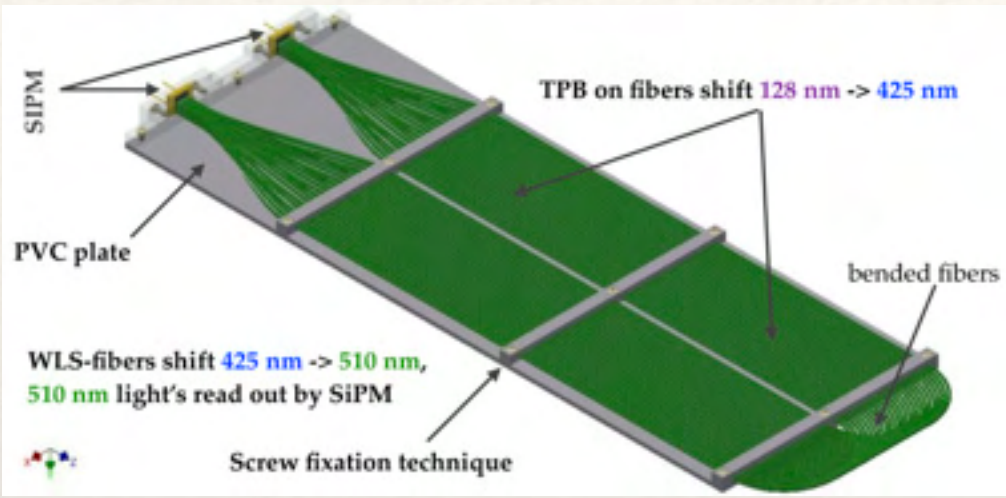


No protection covering - Naked!
PDE (178 nm) ~ 25%
May operate in liquid Xe, Ar
10.1088/1748-0221/13/03/C03026

For liquid gases Efficiency < 15%
(refraction mismatch)

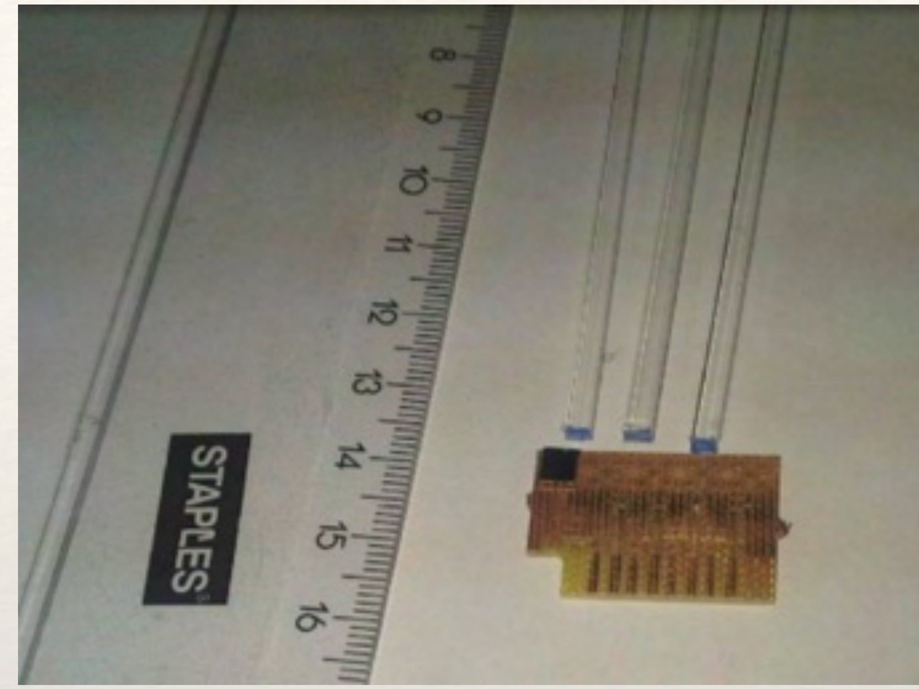
Small Size -> Fibers!

Fibers are coated with TPB



Tests @ UniBe

Light Collection module for Liquid Argon TPC (Design @ JINR)

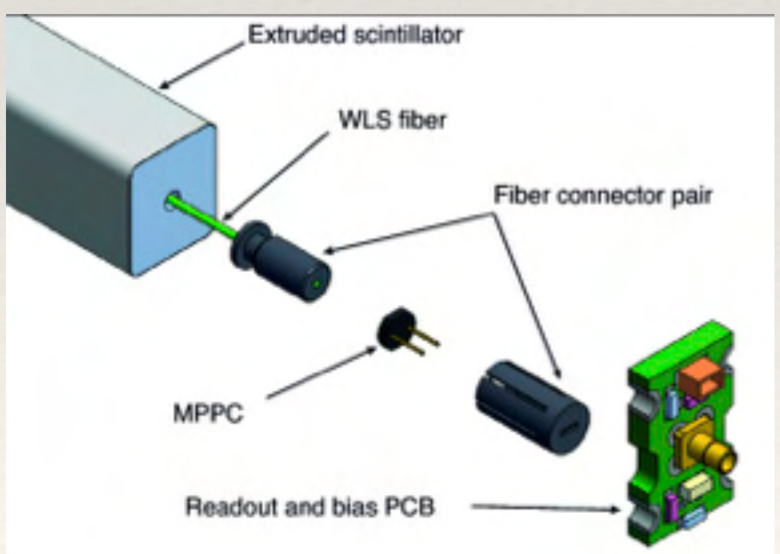


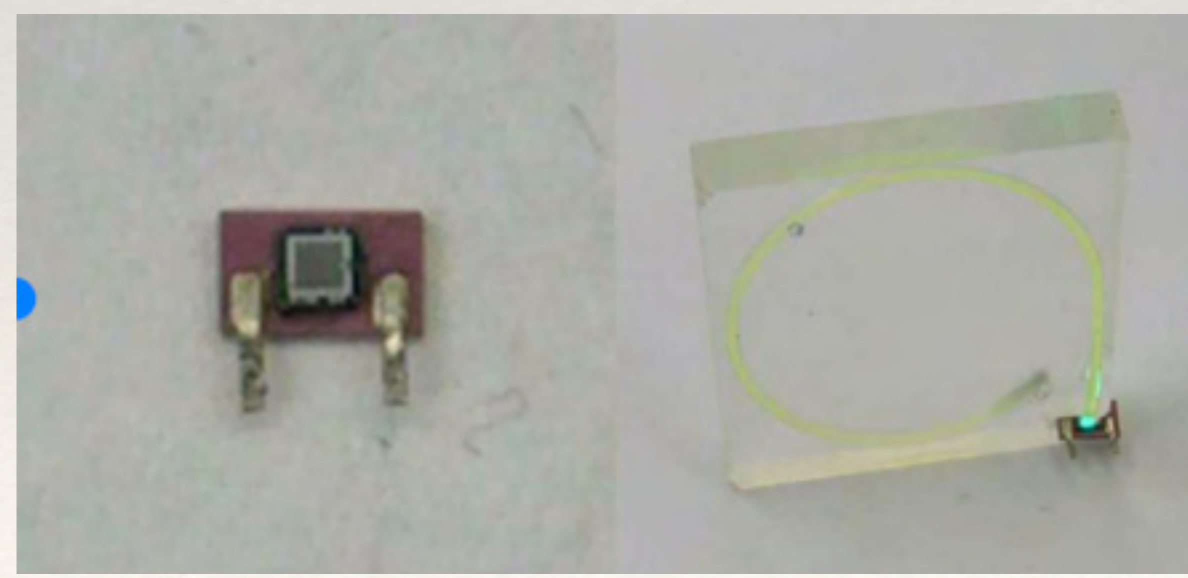
SiPM for Square Fibers

DOI: 10.15161/oar.it/1446116818.88

Relatively high noise
@Room Temperature
~ 100 kHz/mm^2

Scintillator + Fibers

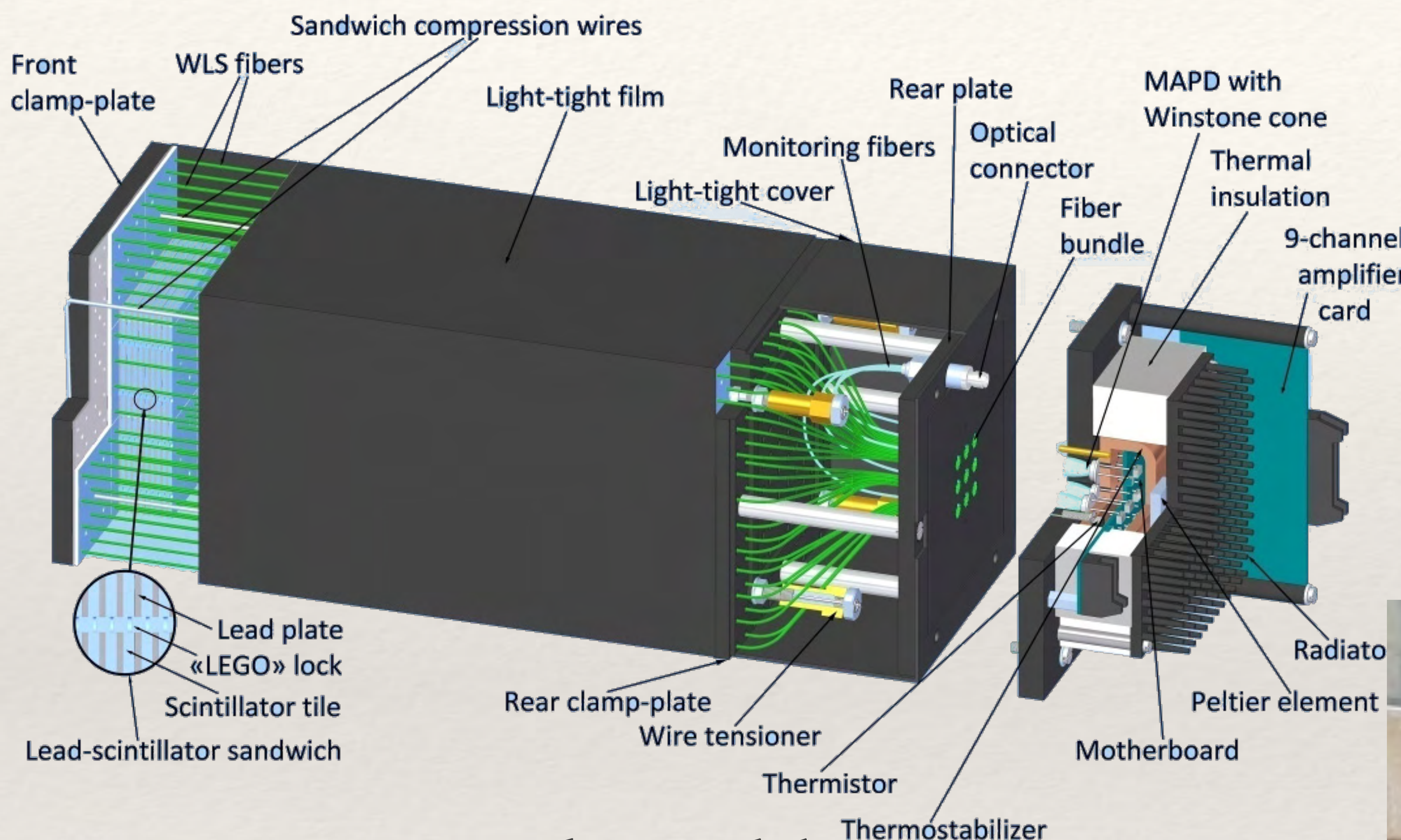


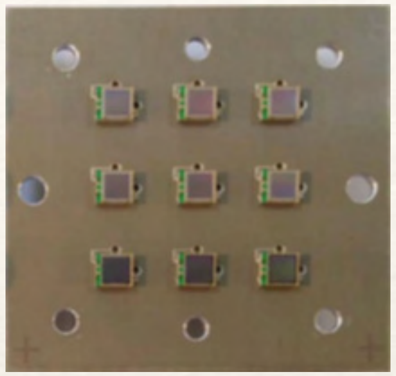


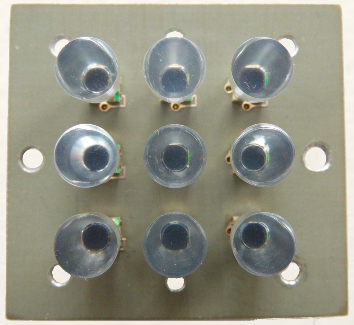
DOI: 10.1063/1.4863648

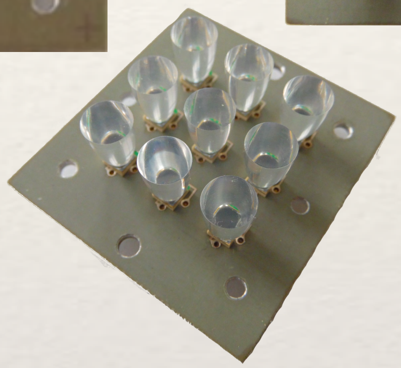
The SiPM sensor mated with a 1mm WLS fiber and embedded in a 3cm x 3cm tile.
Proposal to DOE/NSF for ILC Detector R&D, Beznosko et al.

Shashlik ECAL for COMPASS-II









Developed by

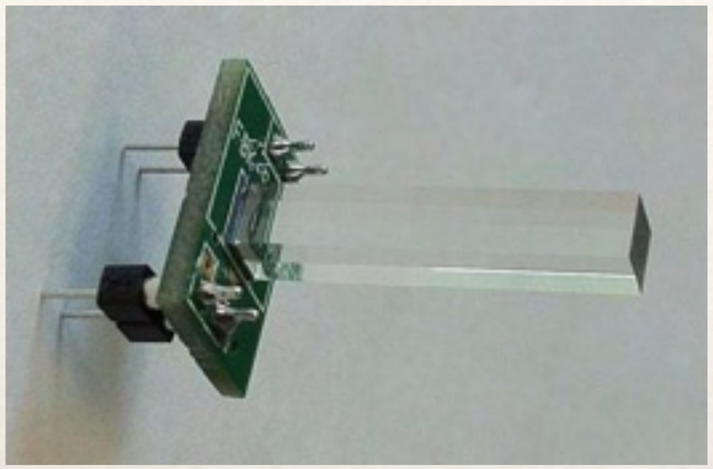
JINR (Dubna) & ISMA (Kharkov)

+ CERN, WTU (Warsaw), TUM (Munich)

Successful operation for 2 years

This is Me!

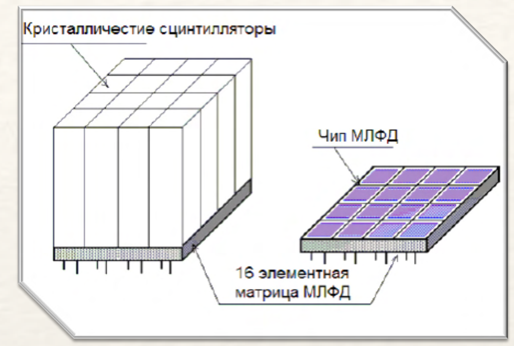
Small scintillators -> Compact Solutions



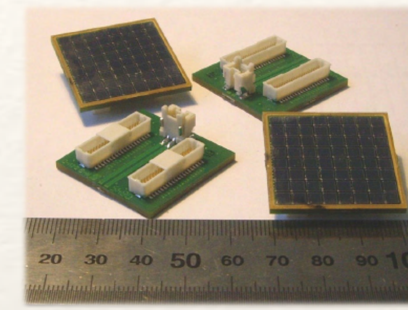
SiPM with LYSO

SiPM with BGO

http://physicsopenlab.org/

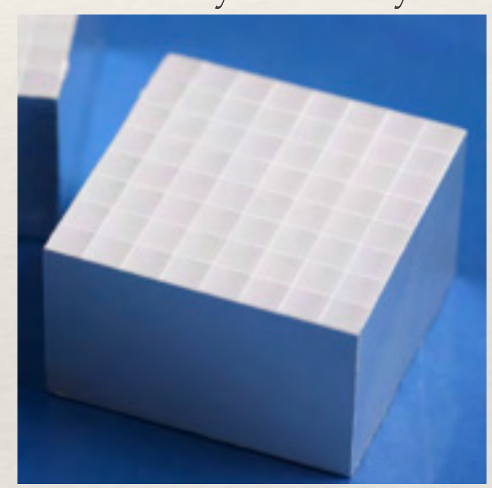


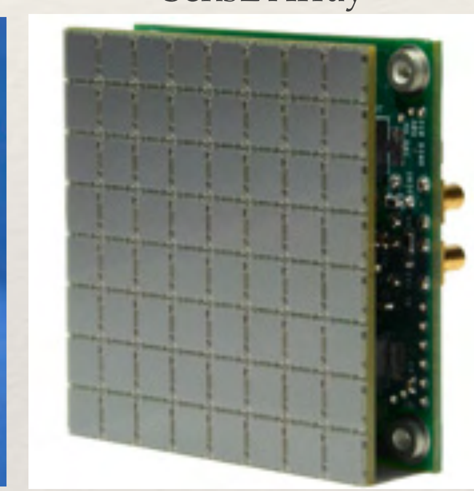
Zecotek/JINR Array



LSO Crystals Array

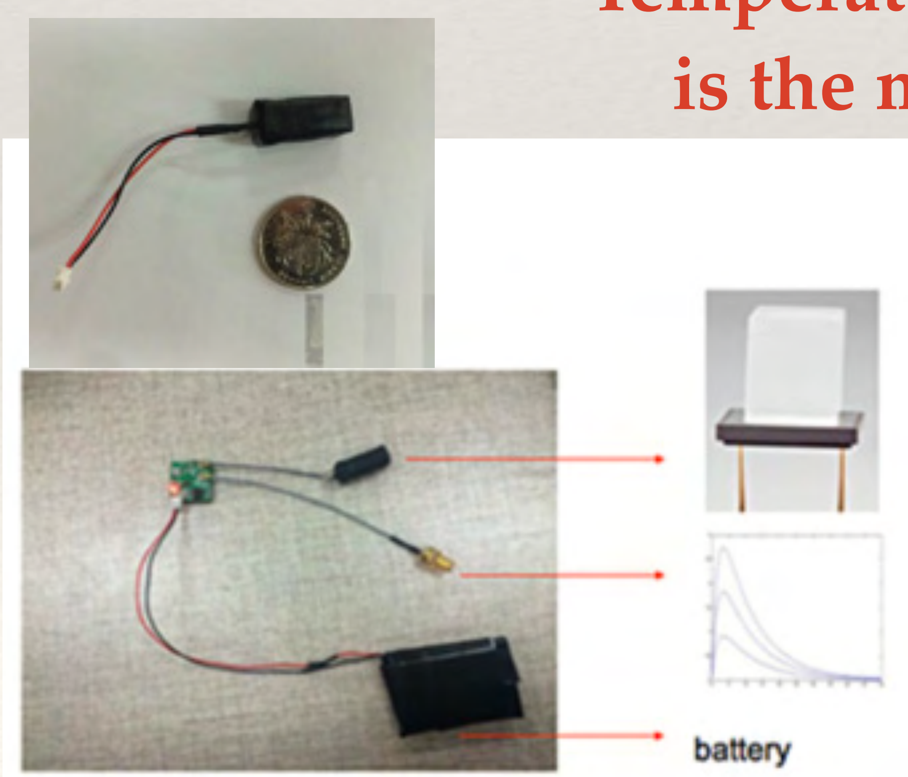
SensL Array





The main concept for PET (PET/MRI)

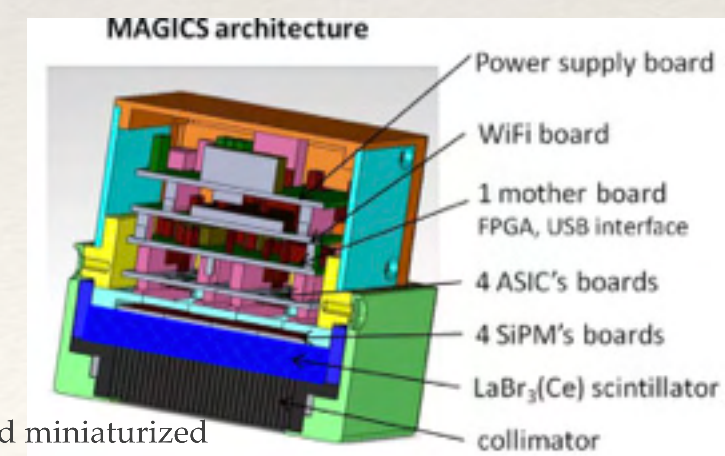
Temperature variation is the main issue!



Compact Radiation detection module (X-Z lab)

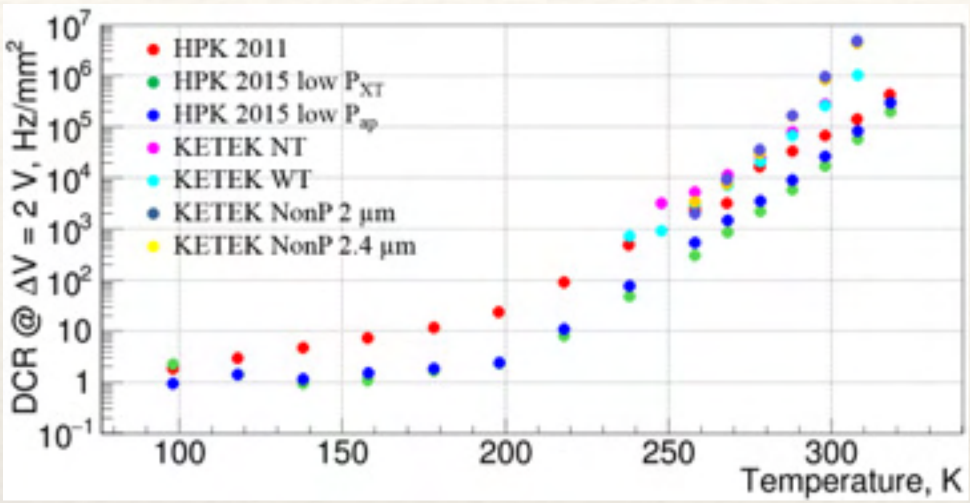
Array Size ~ 5 x 5 cm^2

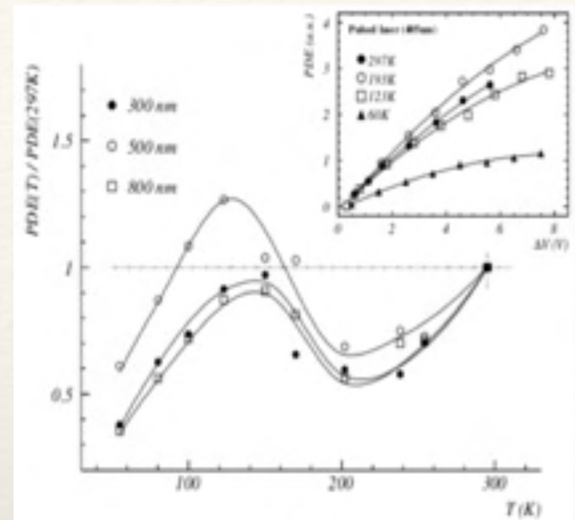
Compact Gamma Camera



N. Dinu, et al. SiPM arrays and miniaturized readout electronics for compact gamma camera

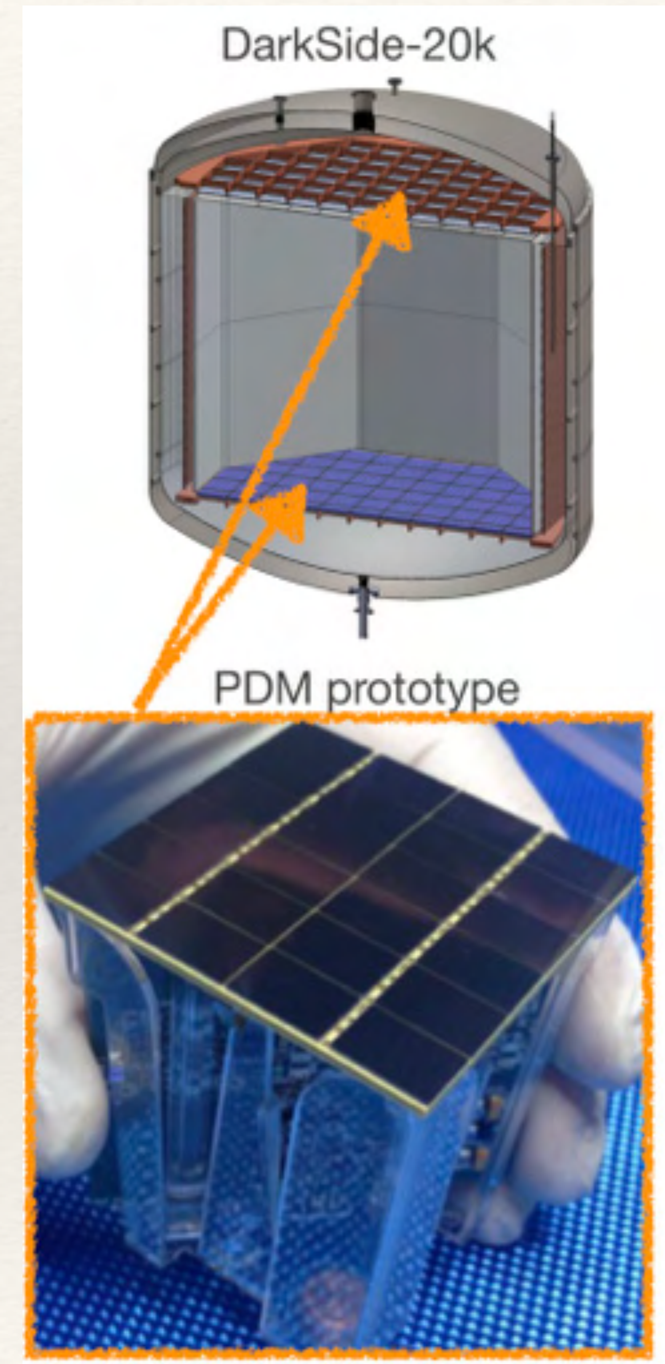
SiPM can operate @ cryo Temp

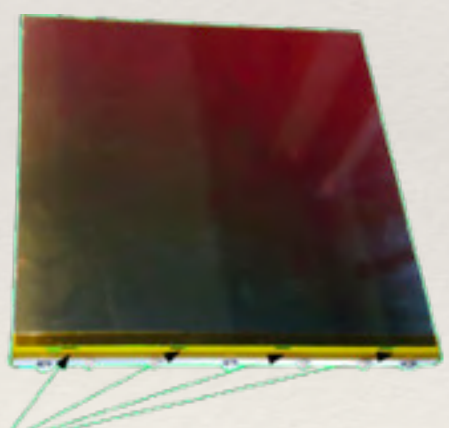




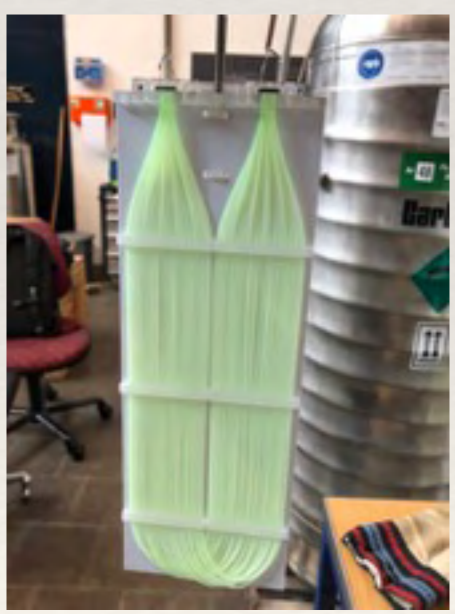
Very low noise ~ Hz/mm² Still efficient to detect light

A. Nagaii. Overview on Experimental Setups to Study SiPM Parameters Cryogenic Temperature





SiPMs



ArcLight and Fiber-LCM
for Dune (ArgonCube)

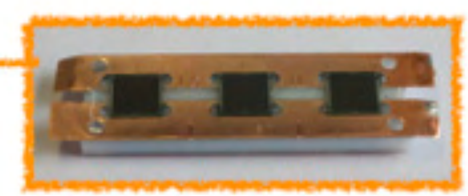


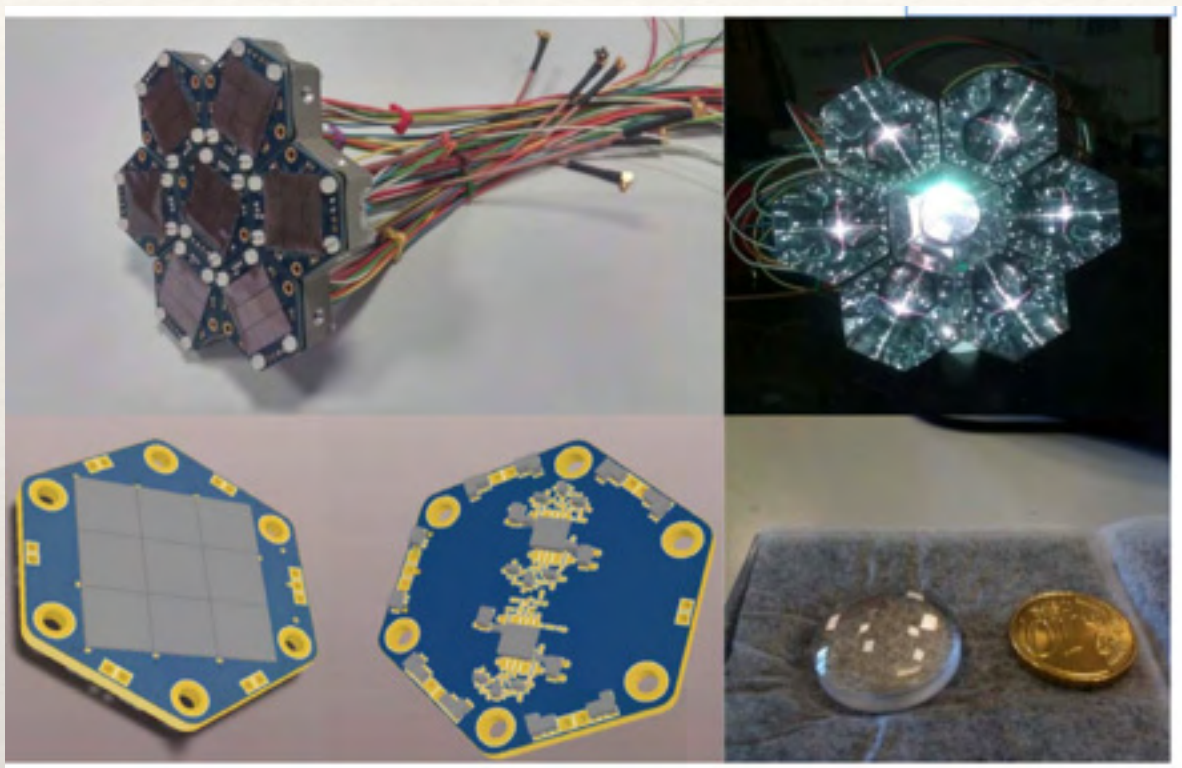
Fig. 14 The fiber curtain: height ~ 1 m, diameter ~ 0.5 m; 405 fibers read out on both ends by 90 SiPMs

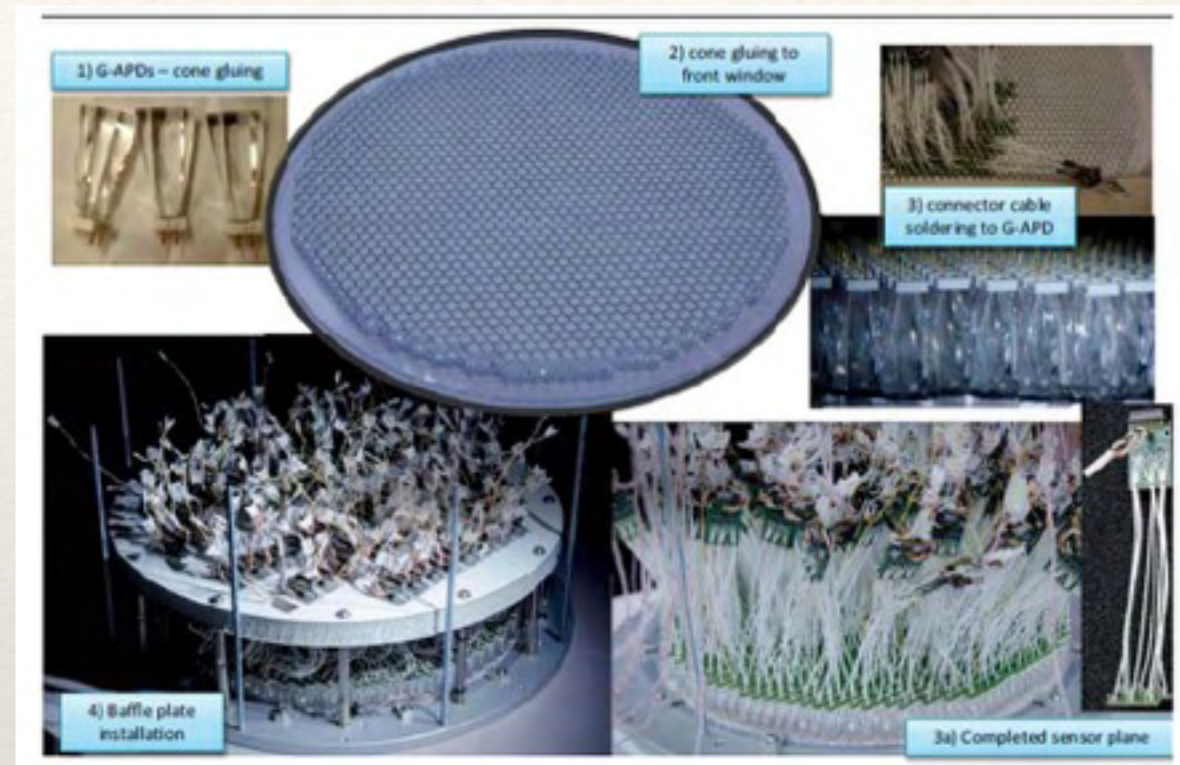
GERDA
(Phase-II)

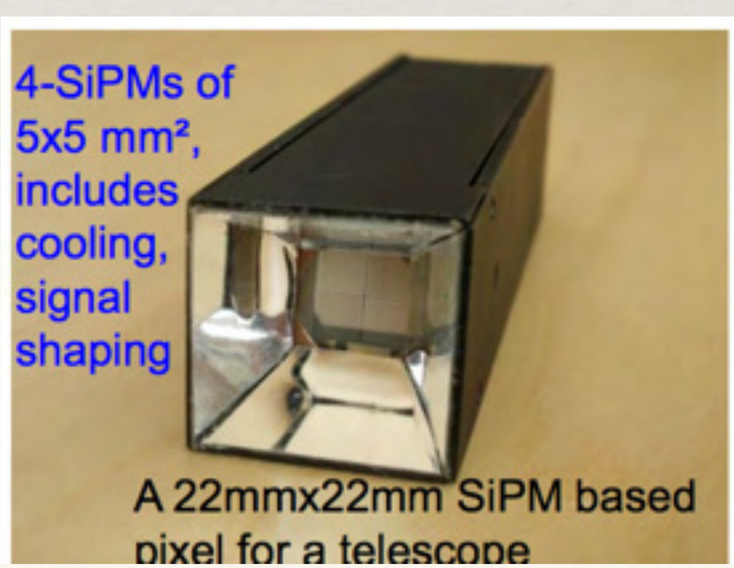
And many others…

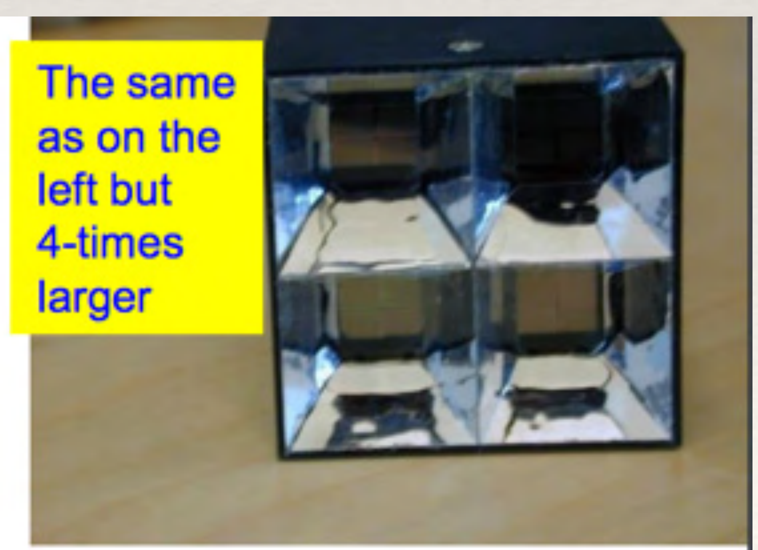
Cherenkov light detection

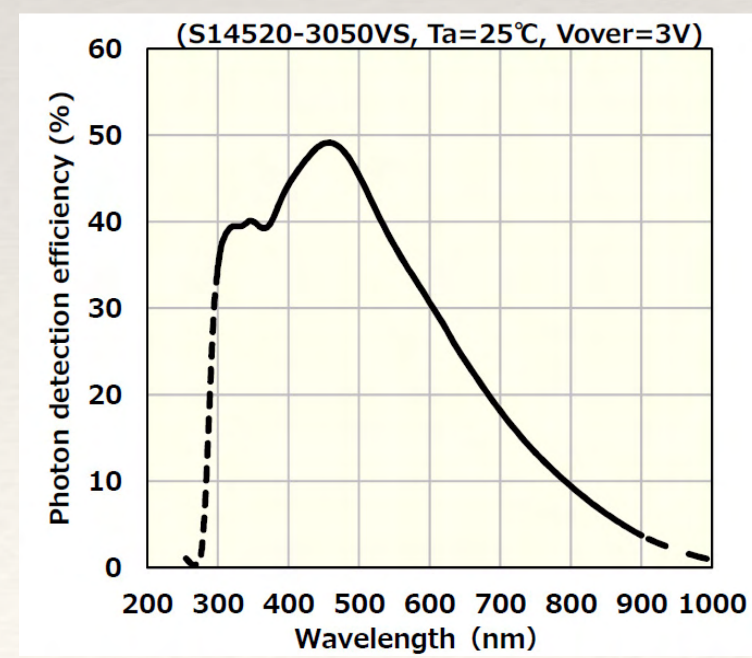
Huge number of SiPMs







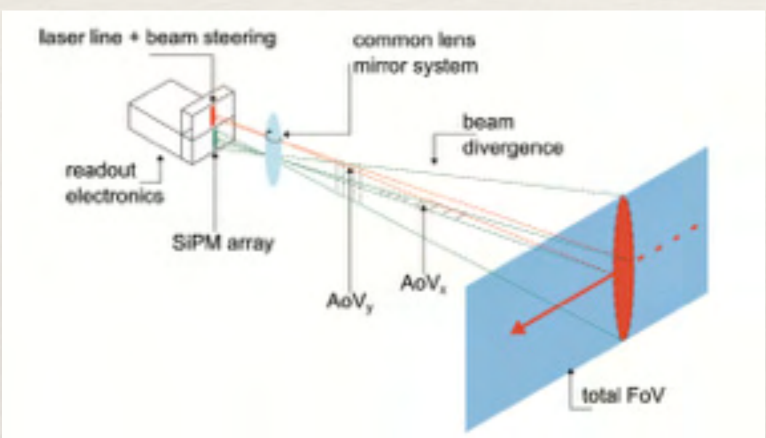




LIDARs, Smart Cars

LIDAR - Light Identification Detection and Ranging

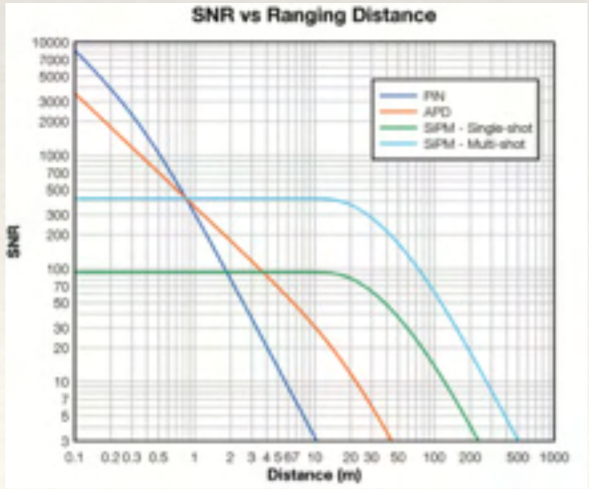
1x16 IR SiPM Array (SenseL)

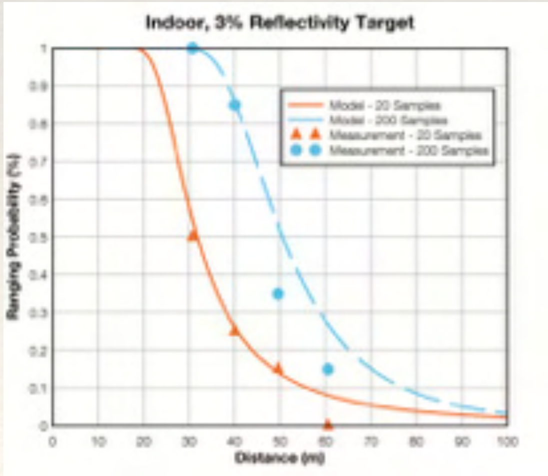


Youtube. SensL - 100m Imaging Demonstration

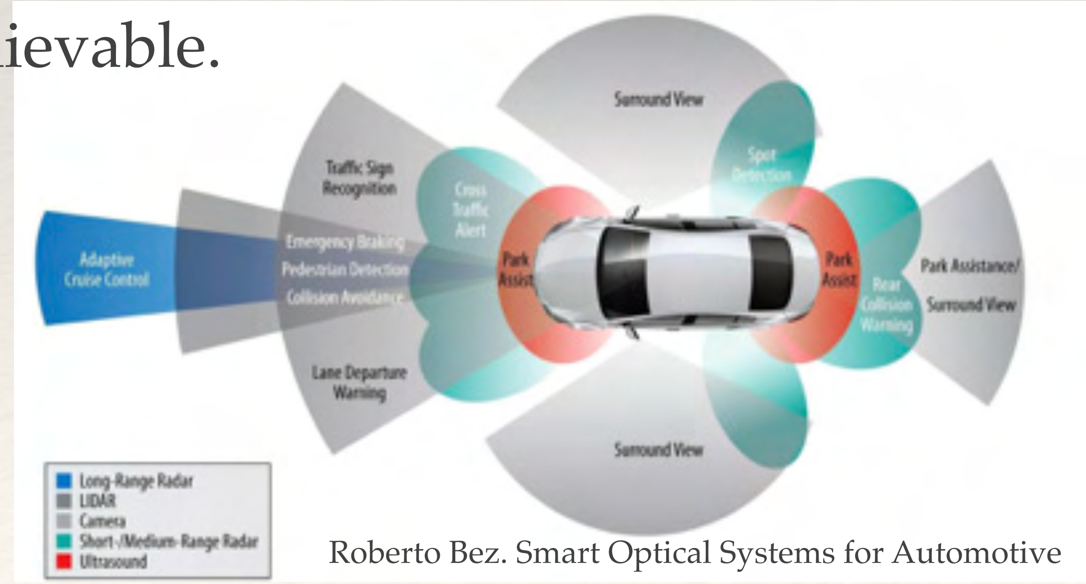
1 mm ~ 6 ps.

~cm (~100 ps) is achievable.



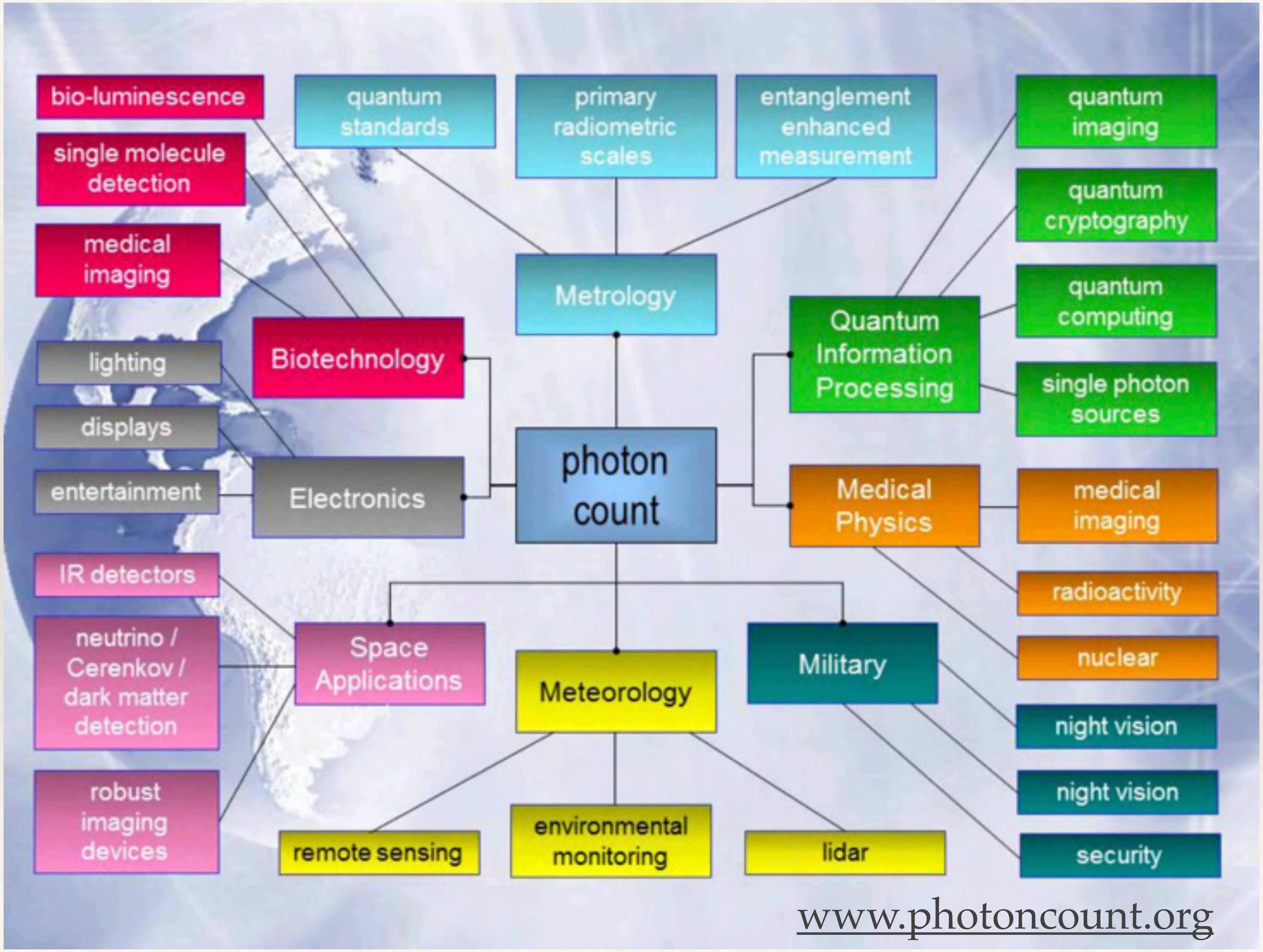


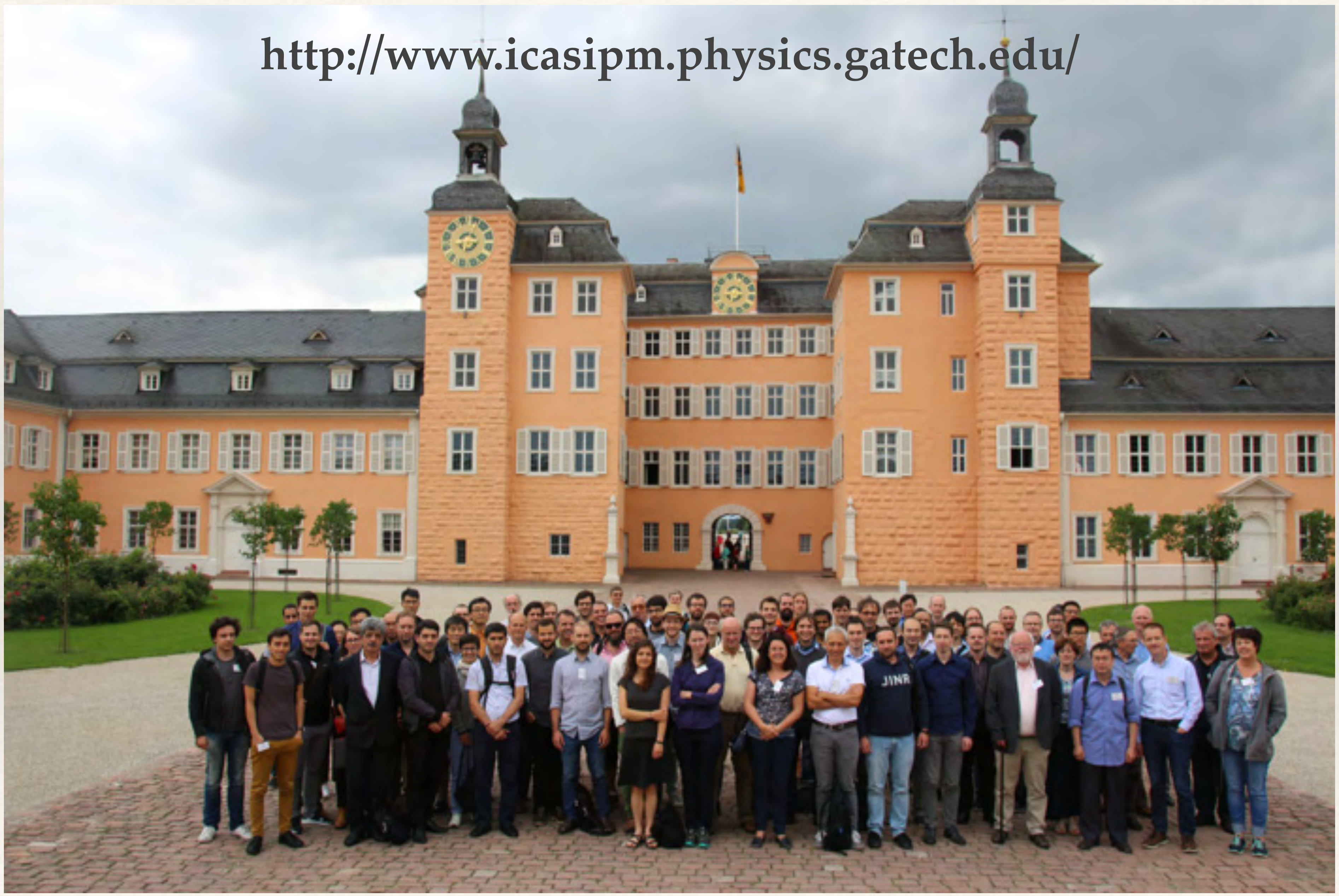
Distance ~ hundred meters



Roberto Bez. Smart Optical Systems for Automotive

Photon Counting





Publication of proceedings as a HandBook is coming soon…