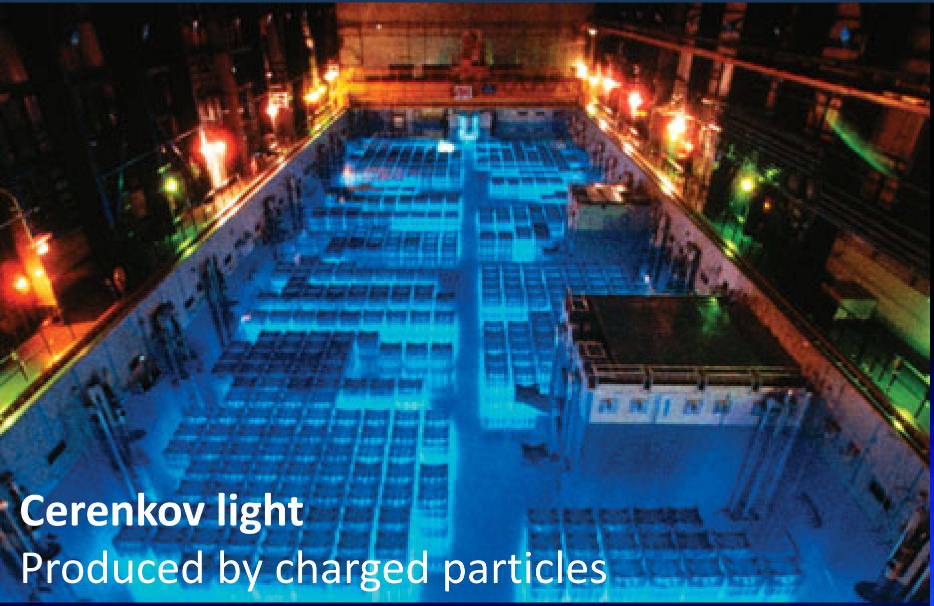
Photo-detection with SiPMs in particle physics and material science

Fabrice Retière

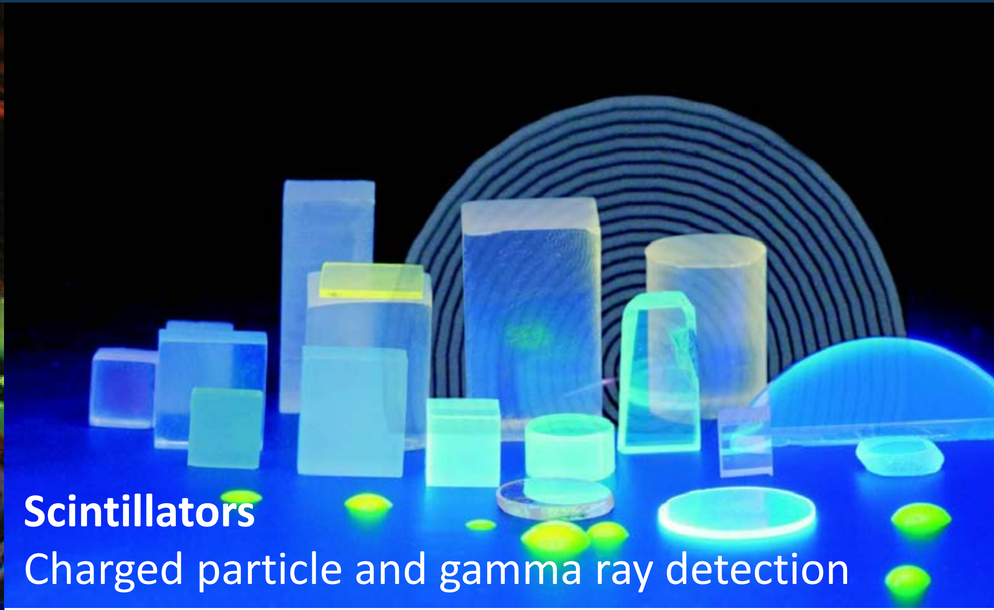
TRIUMF

Motivation: ionizing radiation detection



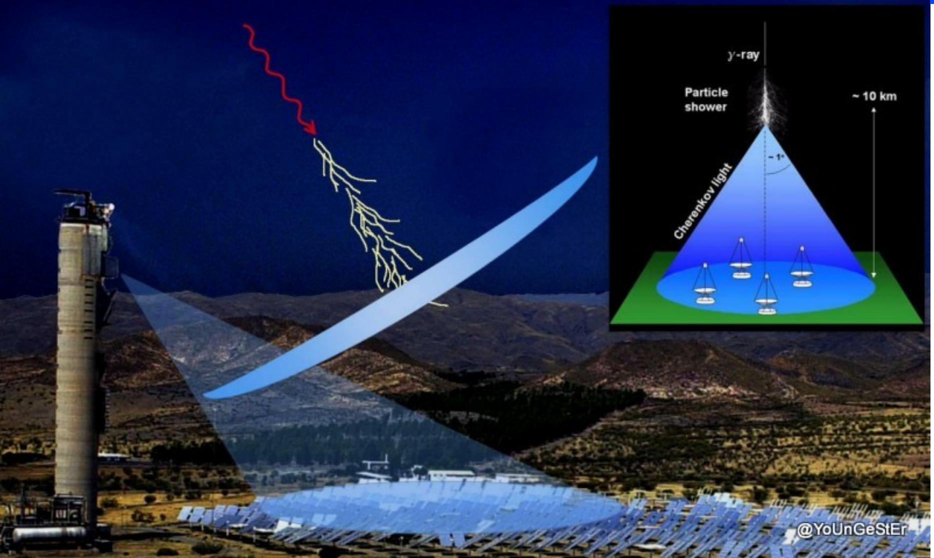
Cerenkov light

Produced by charged particles



Scintillators

Charged particle and gamma ray detection



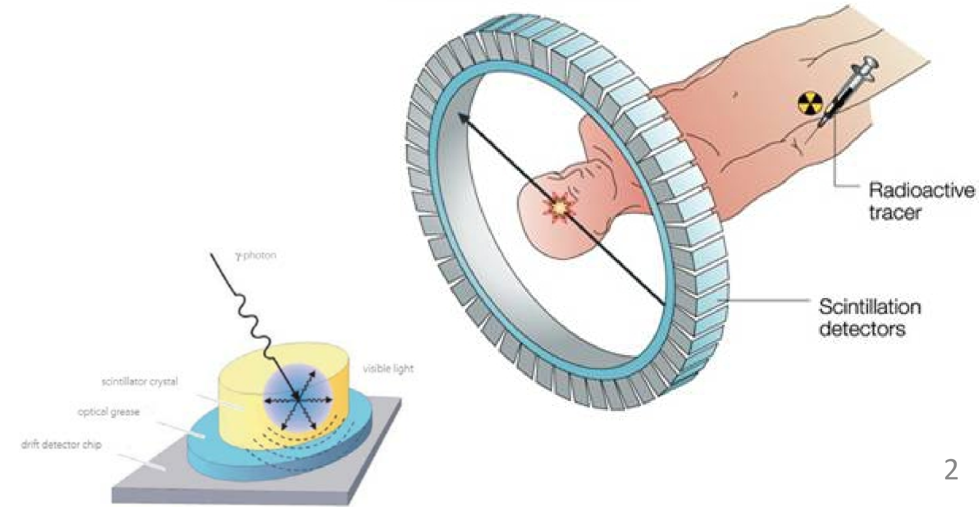
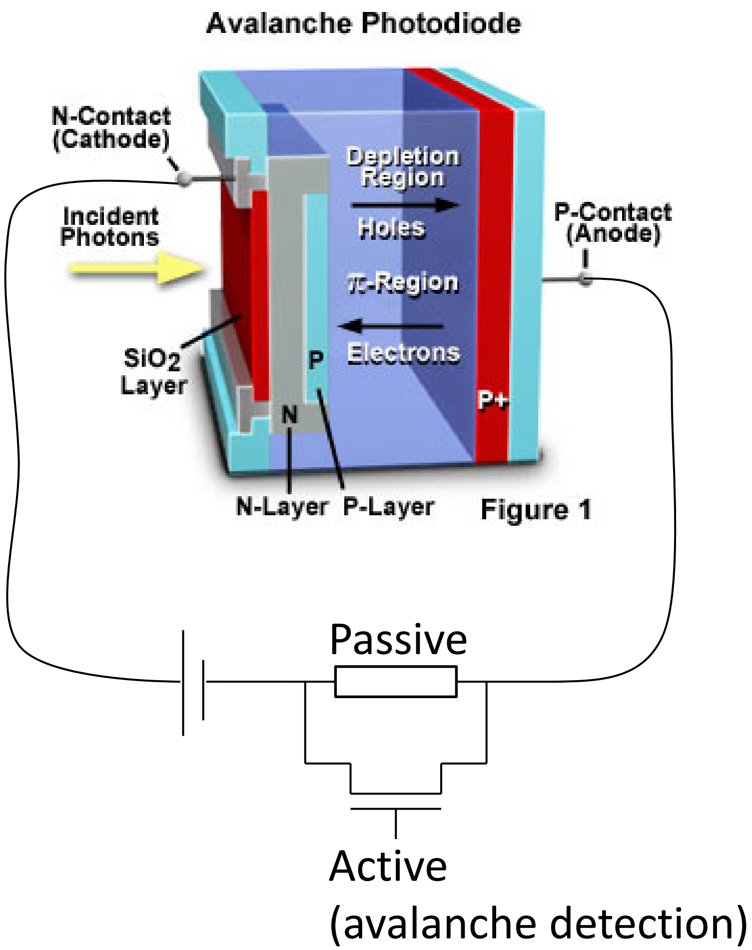


Photo-detector specifications for radiation detection

- Fast:
  - pulse width<100ns
  - single photon timing resolution<100ps
- High gain for single photon detection
- Multi-photon counting capabilities (up to few 1,000s)
- Efficiency > 20%
- For some applications, no sensitivity to magnetic field

Typical light sources	Wavelength	Time constant	Photons per keV	Applications
Cerenkov	Power law from EUV to red	Prompt	N/A <1	Particle and astro-particle physics
Plastic scint. (BC408)	425nm	2.1ns	11	Physics, dosimetry,...
Xenon scint.	175+-5nm	2.2 (5%)/34ns	~40	Astro-particle physics
LaBr3	380nm	16ns	63	Gamma Ray (PET)
LSO	420nm	41ns	32	Gamma Ray (PET)
BGO	480nm	300ns	8	Low cost Gamma ray

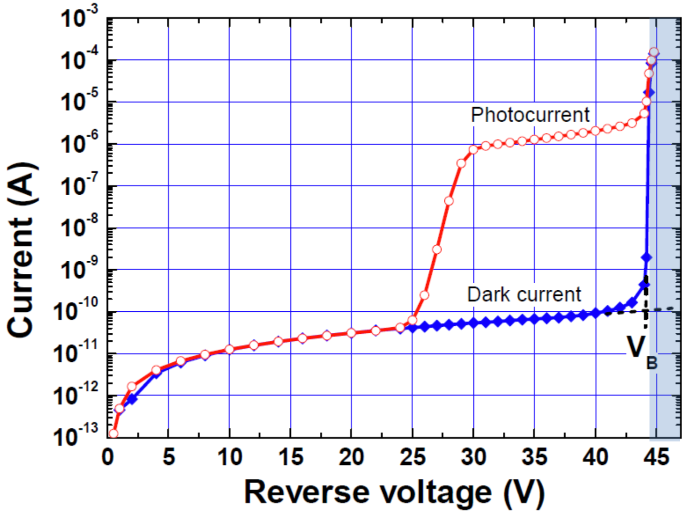
Single Photon Avalanche Detector



Passive

Active
(avalanche detection)

- Avalanche photo-diode operated above breakdown
  - Runaway avalanche due to impact ionization
- with quenching circuit
  - Passive (resistor)
  - Active (transistor + quenching detection)

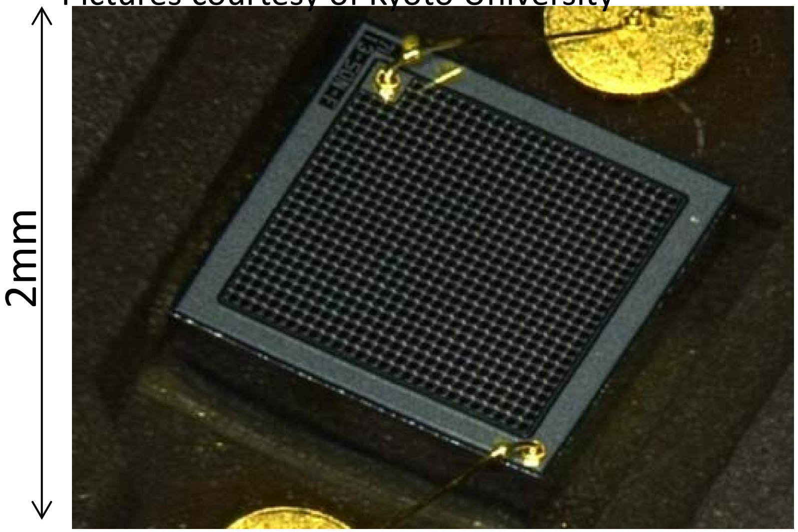


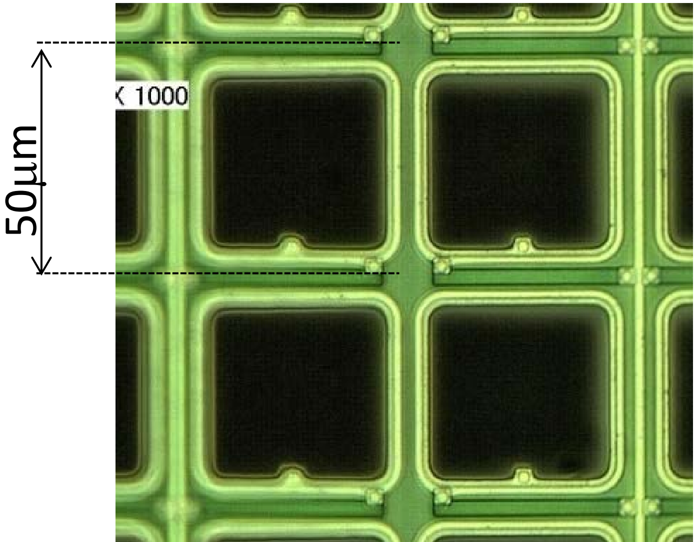
Geiger-Mode Pixelated Photon Detector, aka Silicon Photo-multipliers

- Array of SPADs
  - Passive quenching: Each micro-cell with individual quenching resistor
  - Active quenching: transistors on each micro-cell
  - Photon counting by counting micro-cells
    - 25 to 100 μm pitch micro-cells
    - Typical device sizes 1×1mm^2, 1.3×1.3mm^2, 3×3mm^2

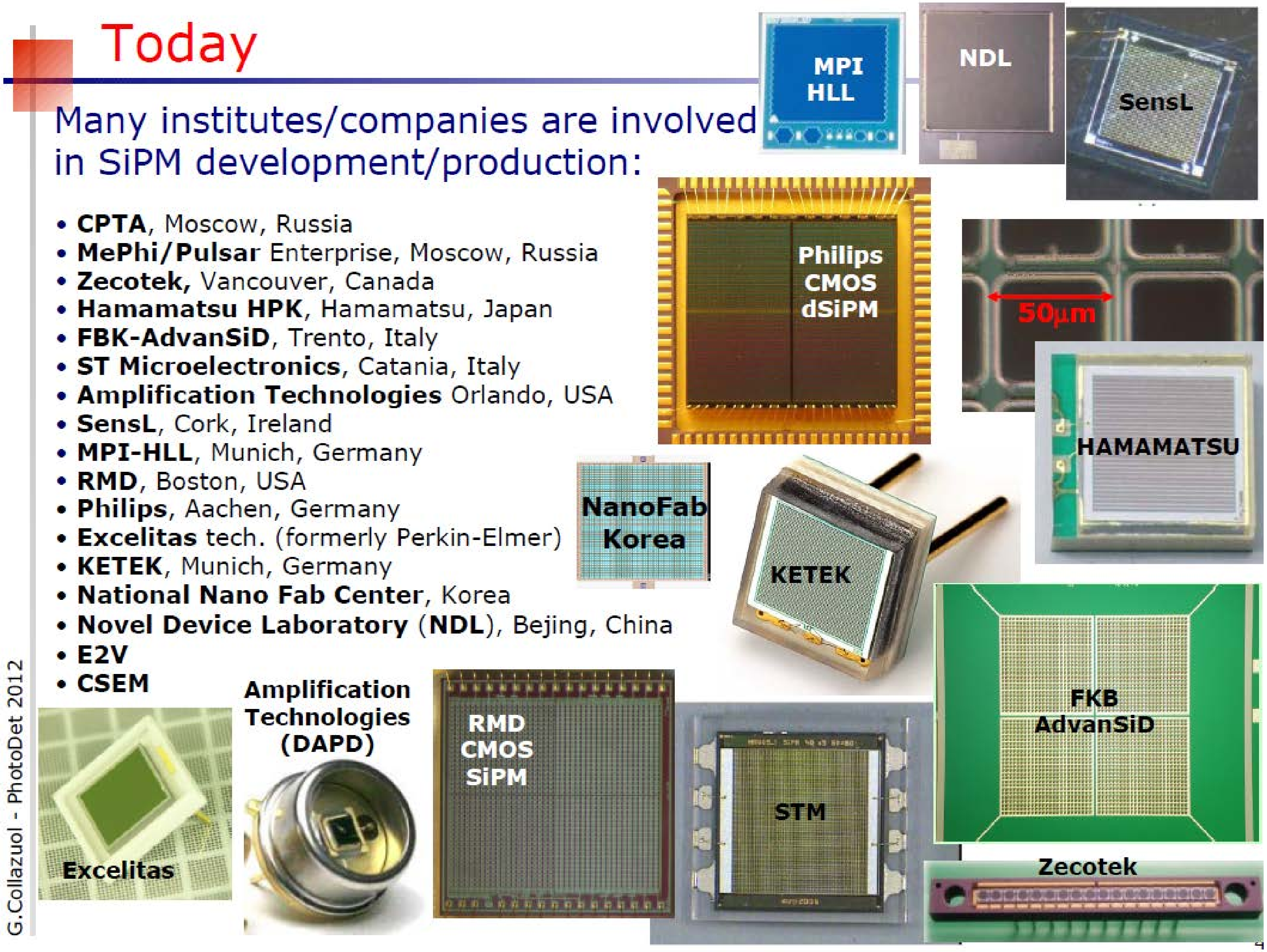
1.3x1.3 mm^2 T2K Multi-Pixel Photon counter

Pictures courtesy of Kyoto University





The analog SiPM family



Today

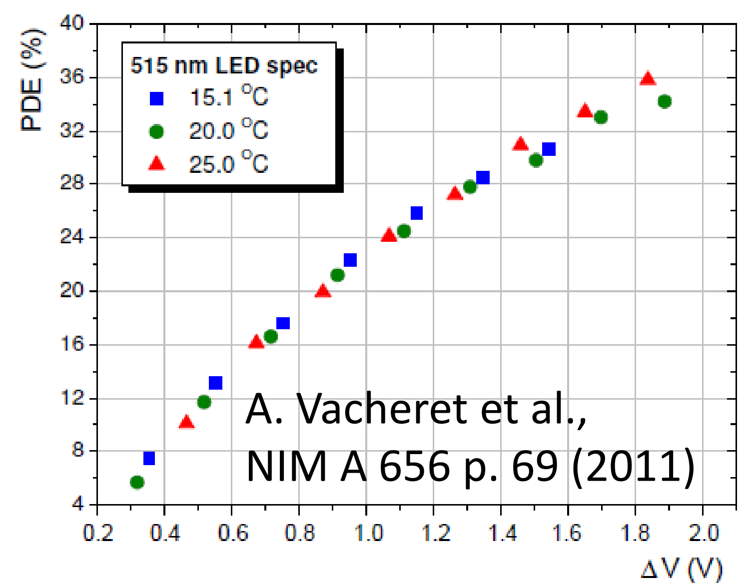
Many institutes/companies are involved in SiPM development/production:

- **CPTA**, Moscow, Russia
- **MePhi/Pulsar** Enterprise, Moscow, Russia
- **Zecotek,** Vancouver, Canada
- **Hamamatsu HPK**, Hamamatsu, Japan
- **FBK-AdvanSiD**, Trento, Italy
- **ST Microelectronics**, Catania, Italy
- **Amplification Technologies** Orlando, USA
- **SensL**, Cork, Ireland
- **MPI-HLL**, Munich, Germany
- **RMD**, Boston, USA
- **Philips**, Aachen, Germany
- **Excelitas** tech. (formerly Perkin-Elmer)
- **KETEK**, Munich, Germany
- **National Nano Fab Center**, Korea
- **Novel Device Laboratory** (**NDL**), Bejing, China
- **E2V**
- **CSEM**

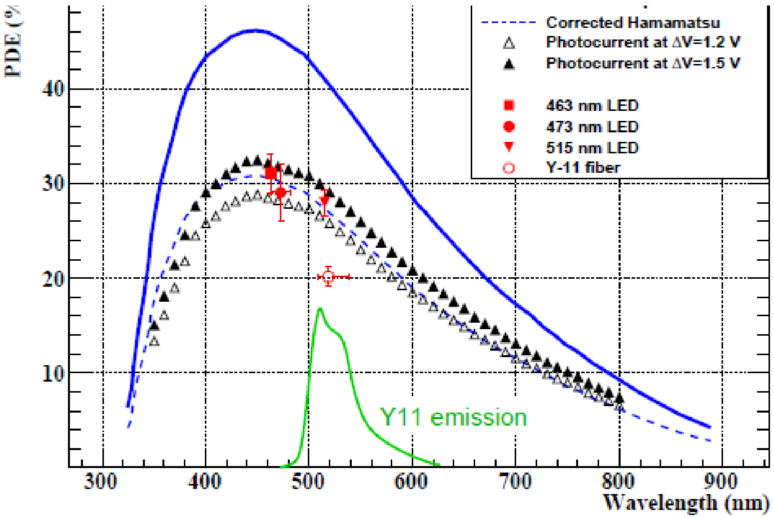
G.Collazuol - PhotoDet 2012

4

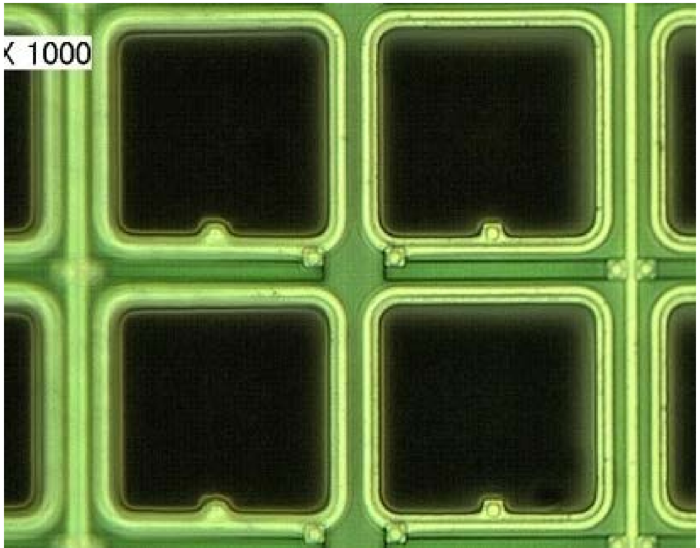
Photo-detection efficiency



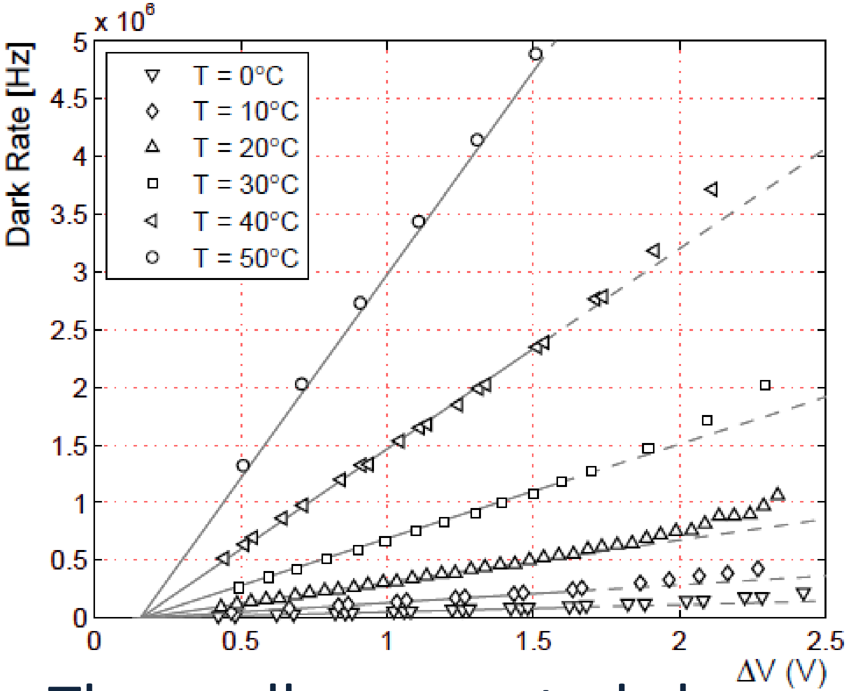
A. Vacheret et al.,
NIM A 656 p. 69 (2011)



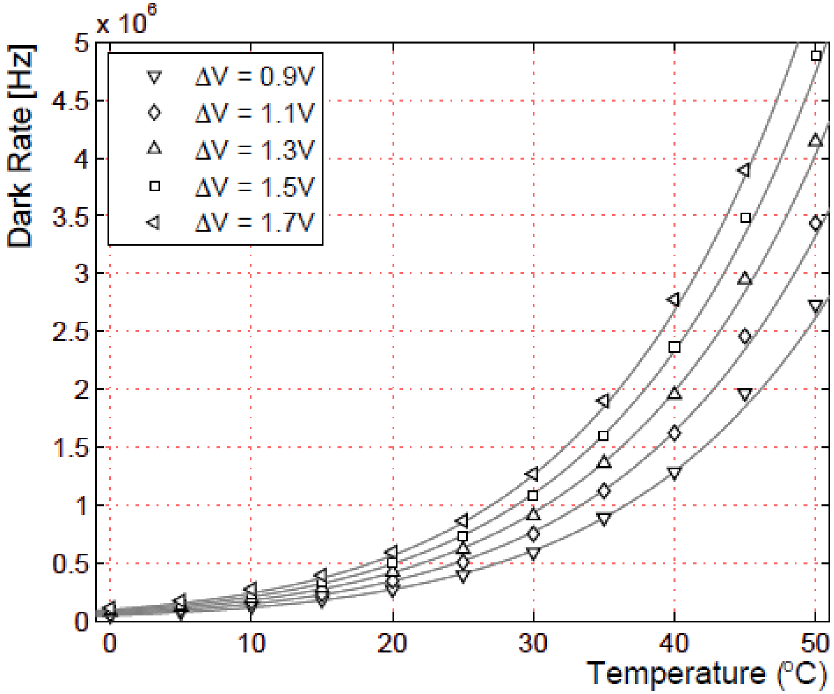
- Peak at ~30% at 420nm
  - Fill factor ~60%
    - Depend directly on pixel size
  - Probability of starting an avalanche ~50%
    - Being improved
- Strong dependence on operating voltage



Nuisance 1: dark noise



- Thermally generated charge carriers trigger avalanches
  - From depleted region, surface or bulk + diffusion
- Rate of single micro-cell avalanche



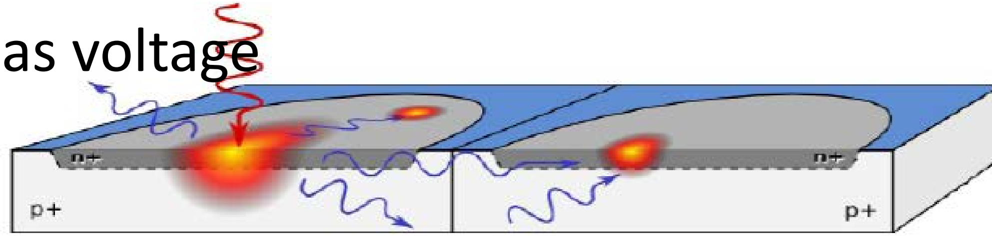
A. Vacheret et al., NIM A 656 p. 69 (2011)

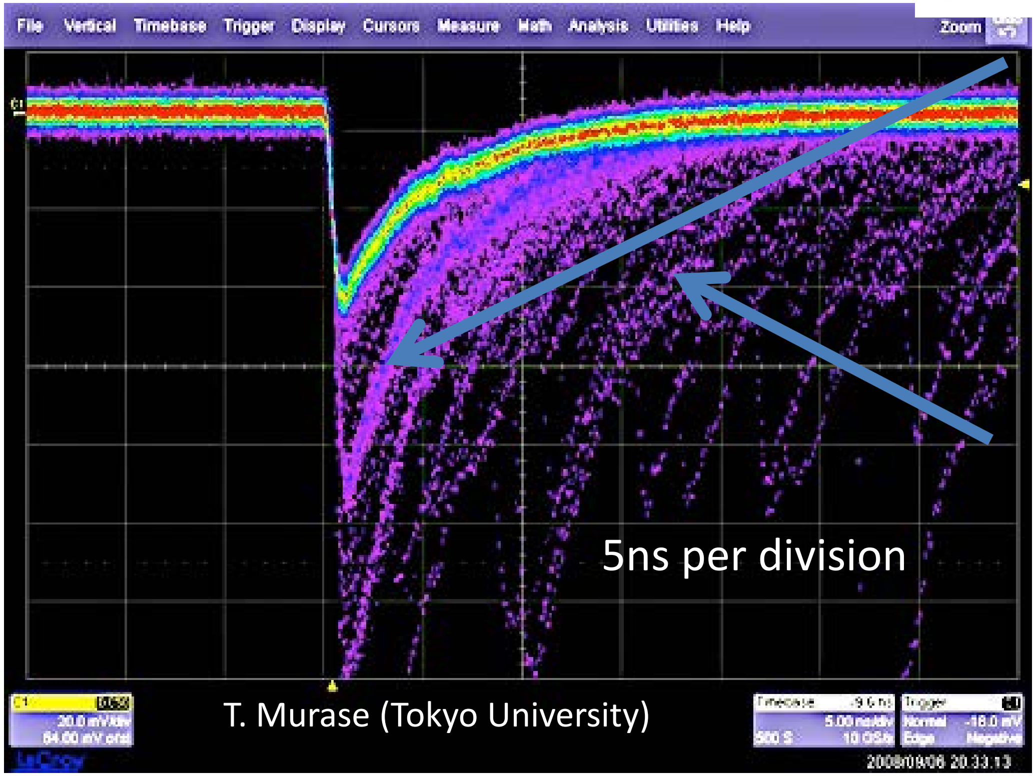
- Expected temperature dependence with E=1.1eV:

$$R_{\mathrm{DN}}(\Delta V, T) = A \cdot (\Delta V - V_0) \cdot \left(\frac{T}{298}\right)^{3/2} \cdot e^{-\left(\frac{E}{2kT} - \frac{E}{2k \cdot 298}\right)}$$

Nuisance 2: correlated avalanches

Big worry at first because at high bias voltage one gets large (>10 PE) dark pulses





5ns per division

T. Murase (Tokyo University)

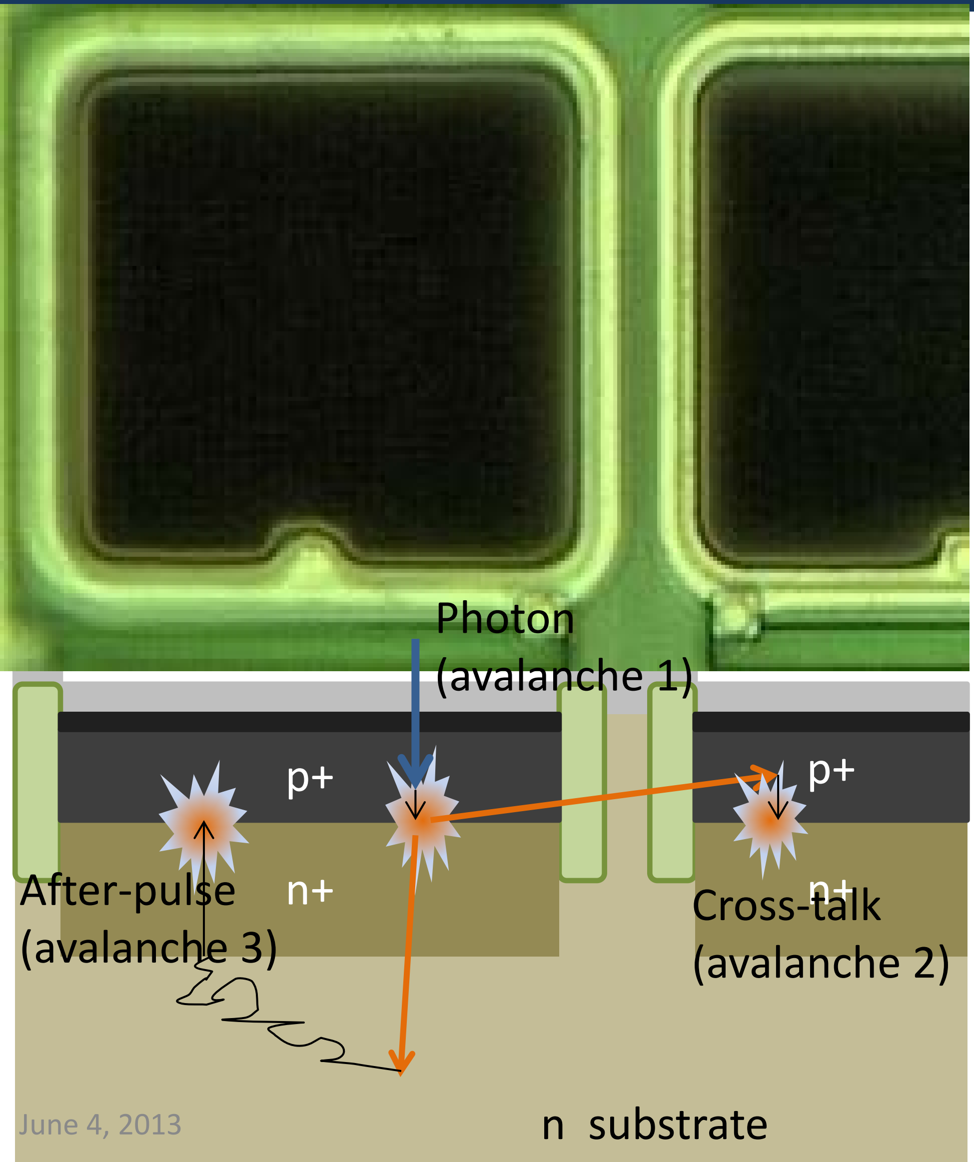
Cross-talk

- Photons emitted during 1 avalanche trigger an avalanche in neighboring cell(s)

After-pulse

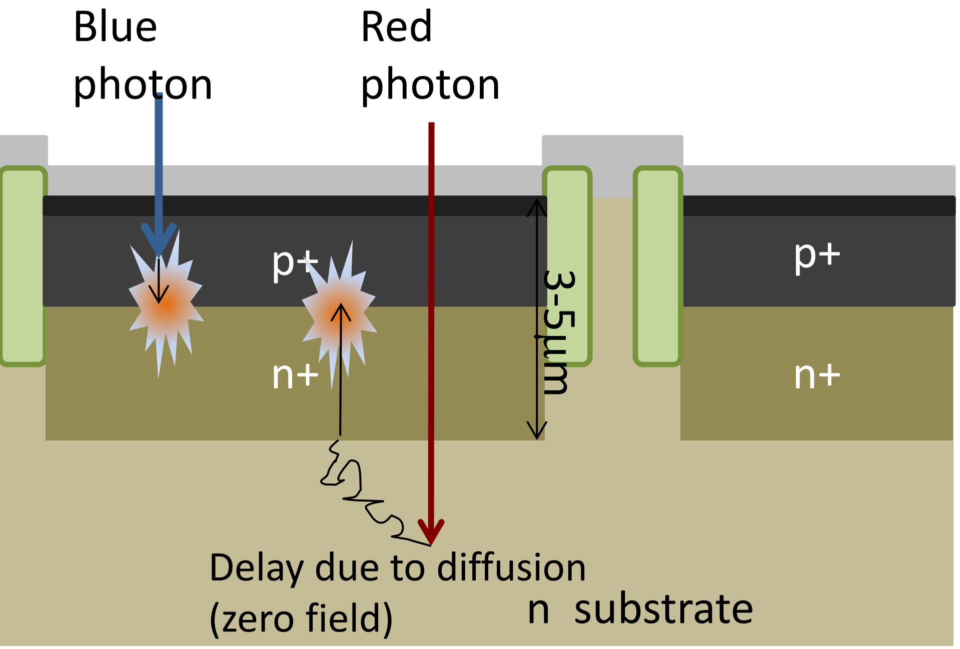
- Expected to be due to trapping of carriers produced in the avalanche and released at a later time

Origin(s) of cross-talk and after-pulsing



- Cross-talk
  - Prompt = by definition
  - Origin: photons produced in the avalanche absorbed in neighboring high field region
- After-pulse
  - Delayed = by definition
  - “Usual” origin: carrier produced in the avalanche trapped on impurities
  - Alternative origin: photons absorbed in bulk
    - Delay due to diffusion
    - Lets test this hypothesis

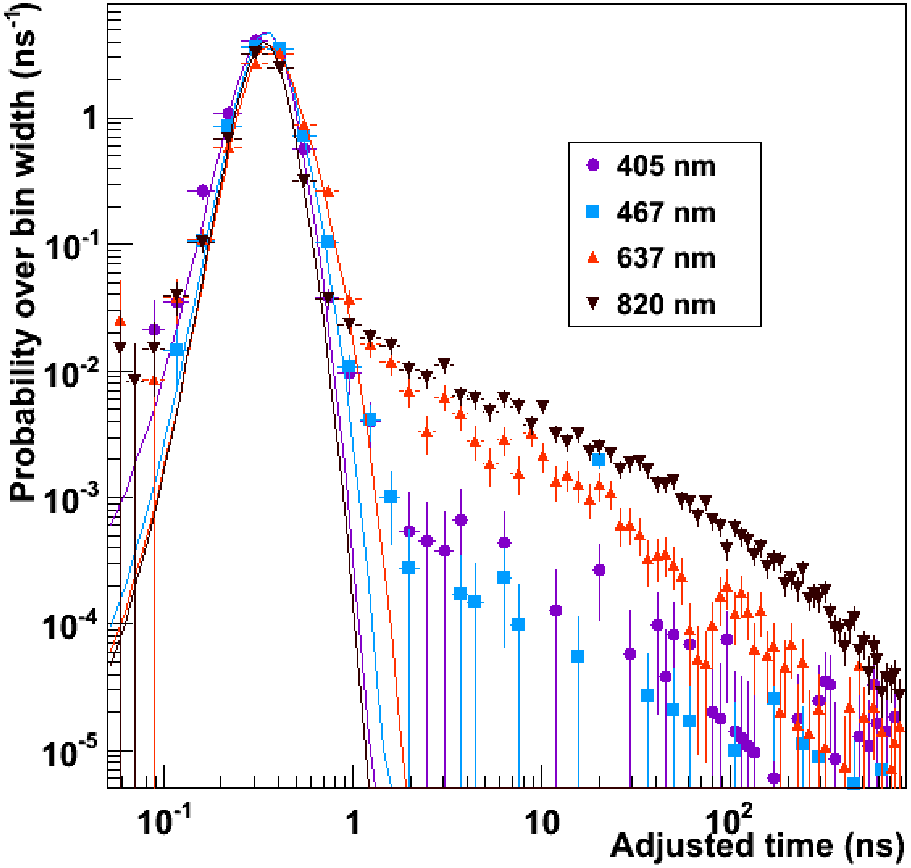
Probing the source of after-pulsing



Blue photon

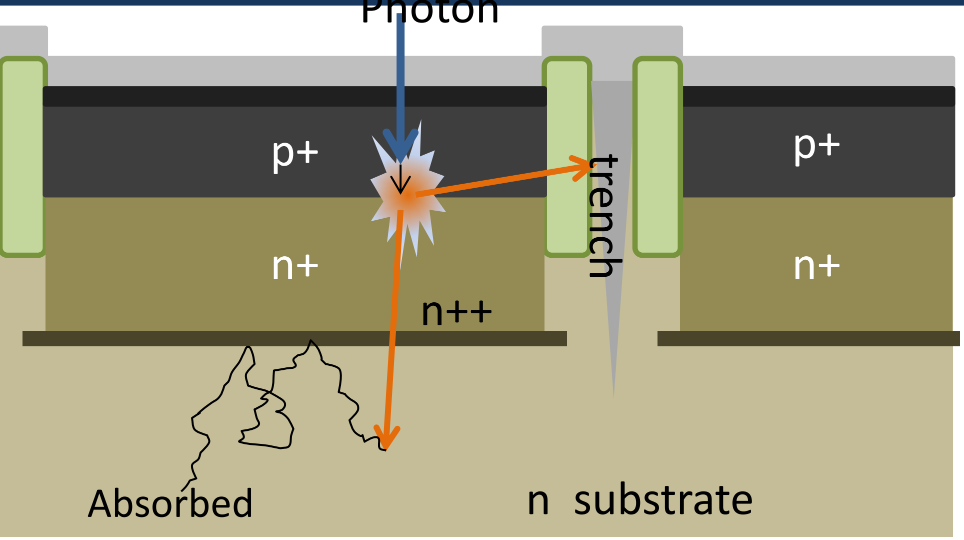
Red photon

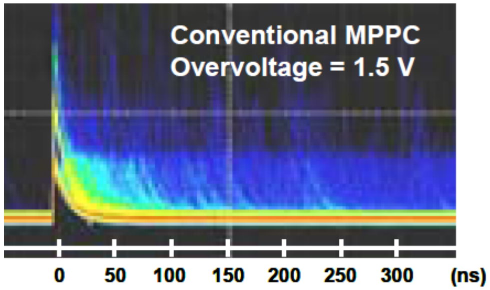
Delay due to diffusion (zero field)

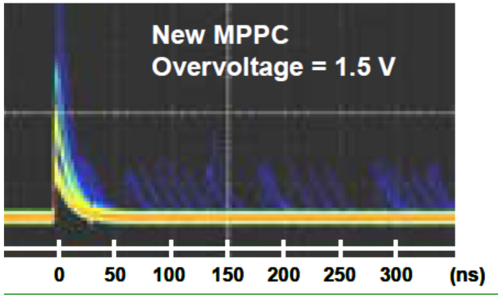


Demonstrating contribution of holes from the n substrate

Dealing with correlated avalanches



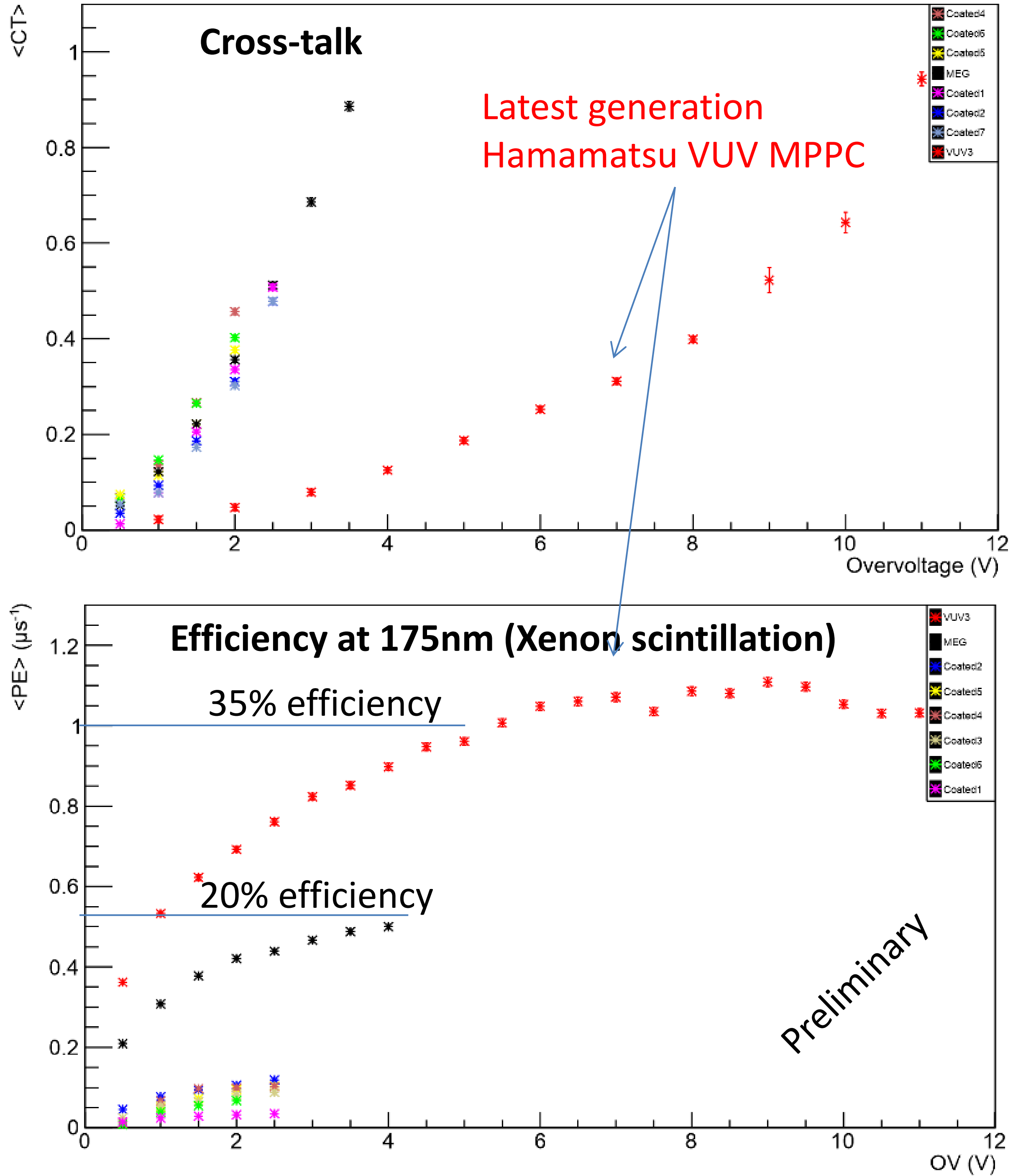




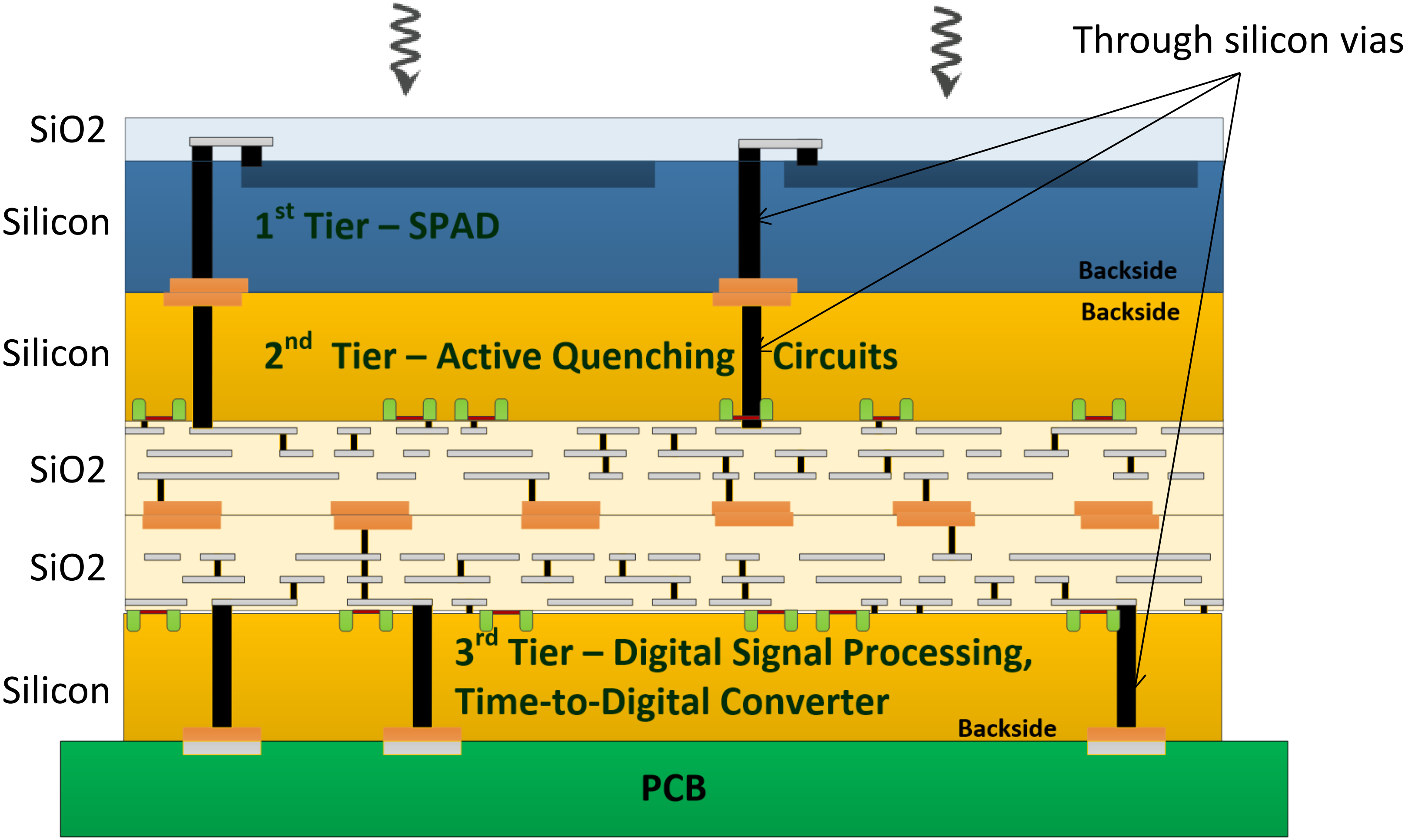
- Hamamatsu corrected the issues:
  - Add trench to prevent cross-talk
  - Add n++ layer (?) to prevent diffusion from substrate
- Claim to drastically suppress correlated avalanches
  - Very good news to be confirmed

Application

- SiPM for detecting liquid Xenon scintillation light
    - Motivation: nEXO



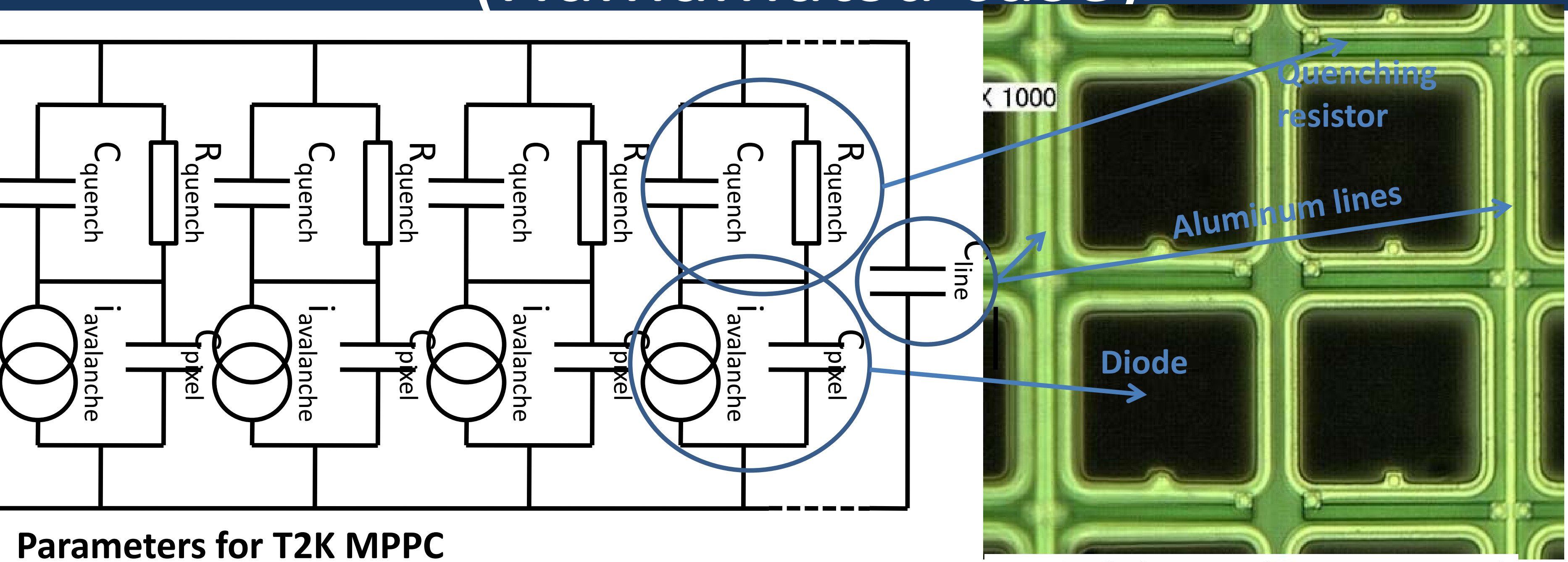
The future: 3D integration



jean-francois.pratte@usherbrooke.ca

Merci

Corresponding electrical circuit (Hamamatsu case)

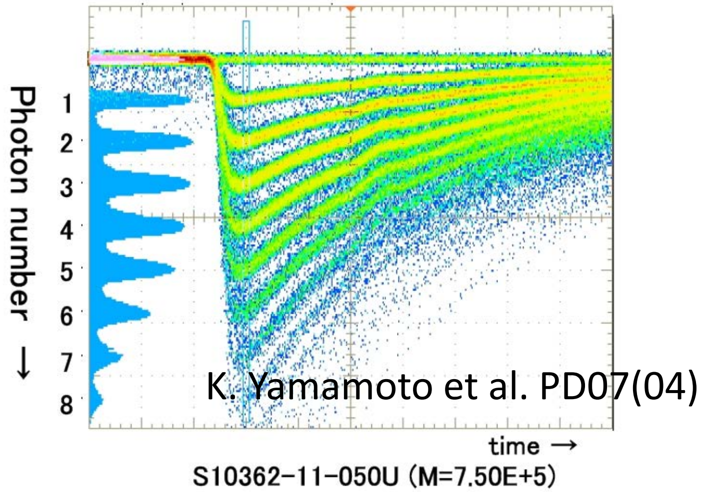


Parameters for T2K MPPC

C_{pixel} = 90 fF, R_{quench} = 150 kΩ
Parasitic C_{quench} ~ 4 fF, C_{line} ~ 10 pF (parasitic)

Peak current: $I = (V_{op} - V_{breakdown}) / R_{quench}$ ~ 5-10 μA
Only 0.5mV on 50Ω. Hard to see directly on a scope

Charge per photon $Q = (V_{op} - V_{breakdown})\ C_{pixel}$ ~ 90-160 fC
Gain for 1 e-h pair created up to 1 million



K. Yamamoto et al. PD07(04)

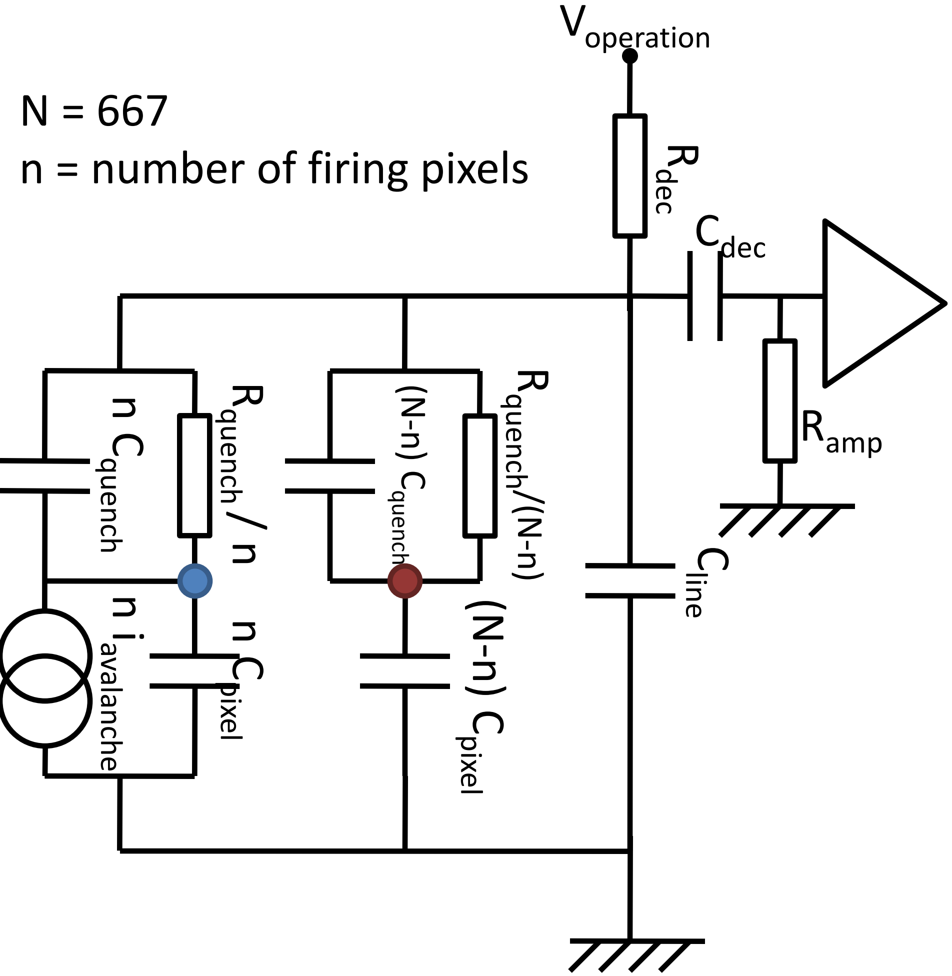
SiPMs vs PMTs

Parameters	PMT	SiPM
Photo-detection efficiency	15-35%	**15-35% ↗**
Gain	**10^6-10^7**	10^5-10^6
Gain fluctuations	50%	**1%**
Dark noise pulse at 20°C (Hz/mm^2)	**<1**	10^5-10^6
Correlated avalanche (after-pulse)	10-20%	5-30%
Leakage current	µA-mA (base)	100nA/mm^2
Bias voltage (V)	1000-2500	**25-75**
Capacitance	**1-50pF**	35pF/mm^2
Single Photon timing resolution (ps, FWHM)	300-3,000	**150-500**
Sensitivity to magnetic field	Strong	**None**
Compactness	Poor	**Excellent**
Ruggedness	Decent	**Good**
Price ($/cm2)	~250	~250↘

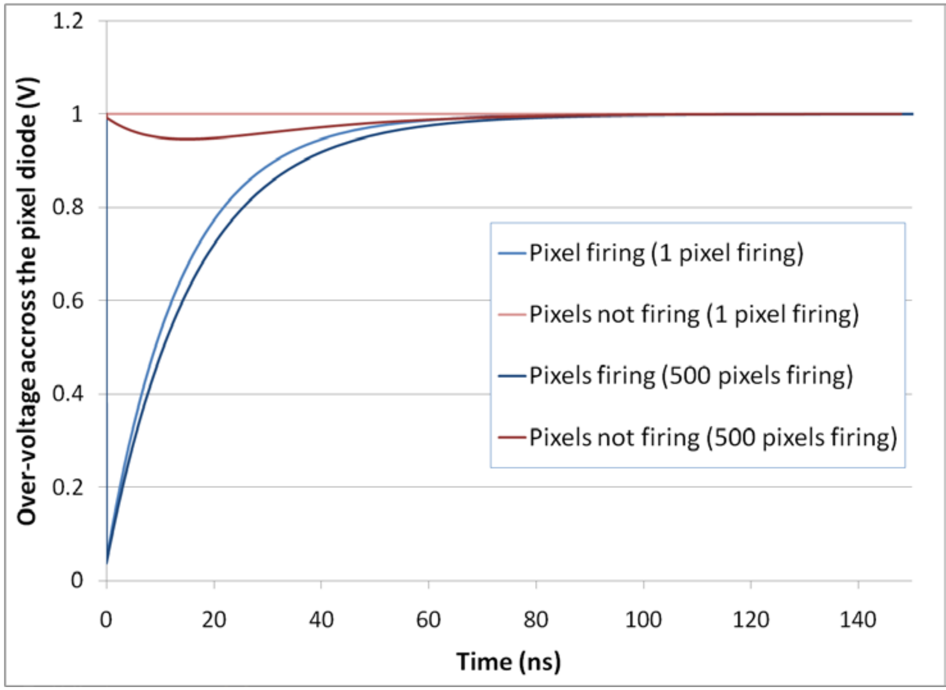
Quenching and recovery

N = 667

n = number of firing pixels



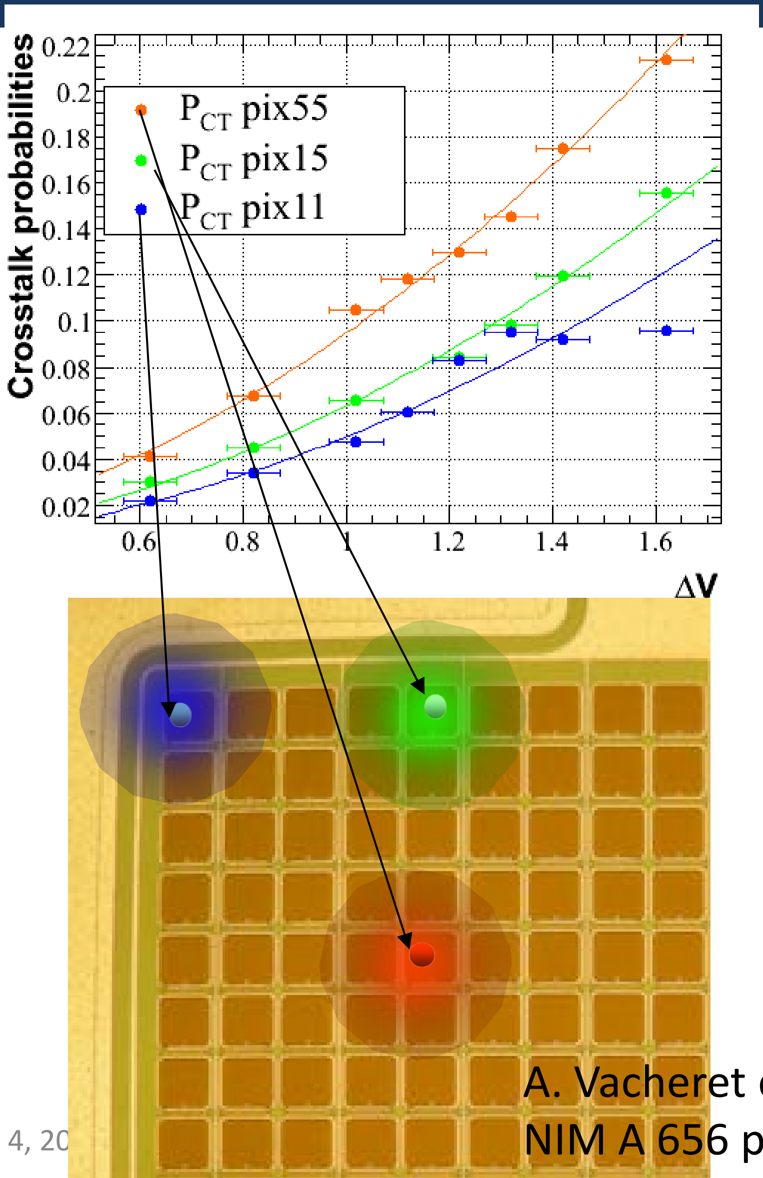
Calculation for $C_{dec} = 1\mu F$ and $R_{amp} = 50\Omega$



What if not all the pixels fire at the same time?

Need Monte Carlo simulations

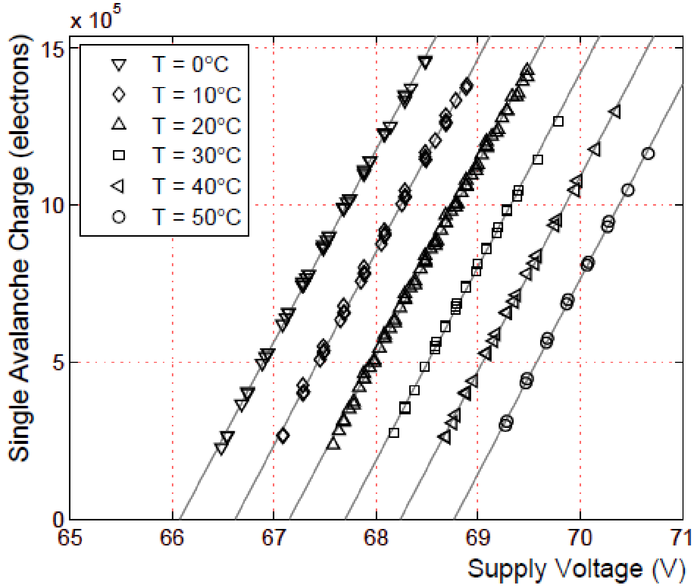
Cross-talk

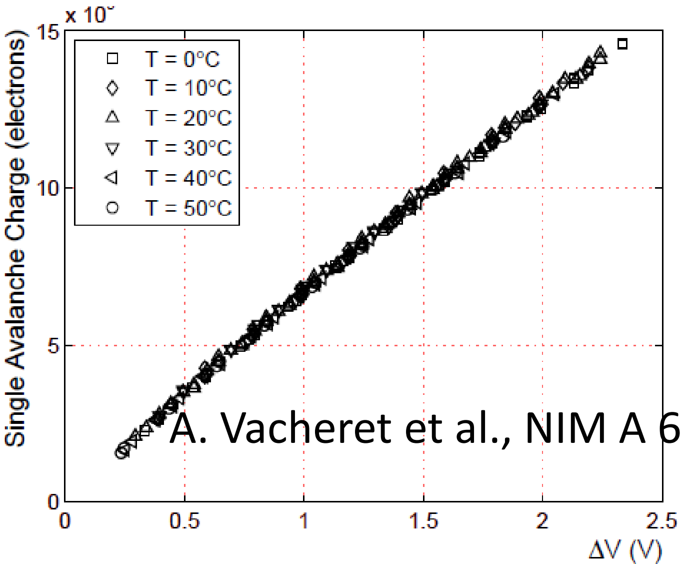


A. Vacheret et al.,
NIM A 656 p. 69 (2011)

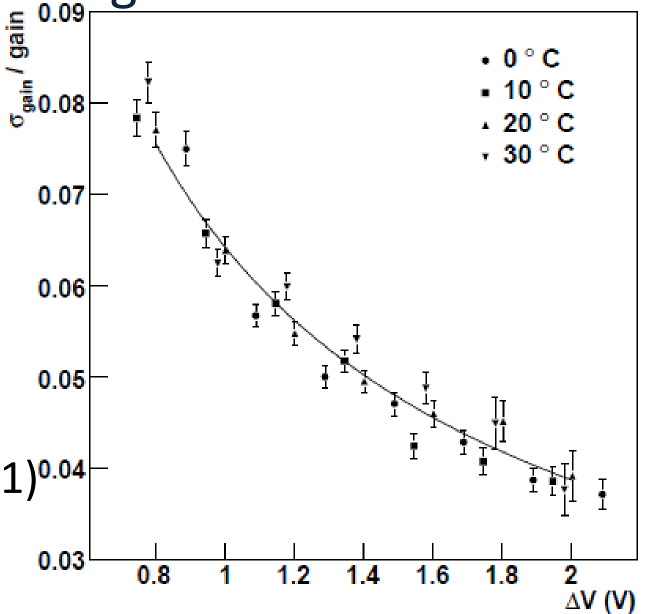
- Measurement
  - Take data at low light
  - Histogram prompt (with few ns) pulse charge
  - Poisson parameters measured from probability of measuring 0
  - Cross-talk = measured number of avalanche / Poisson expectation
- Expected sensitivity to micro-cell location
  - Scaling is not straightforward however

Gain



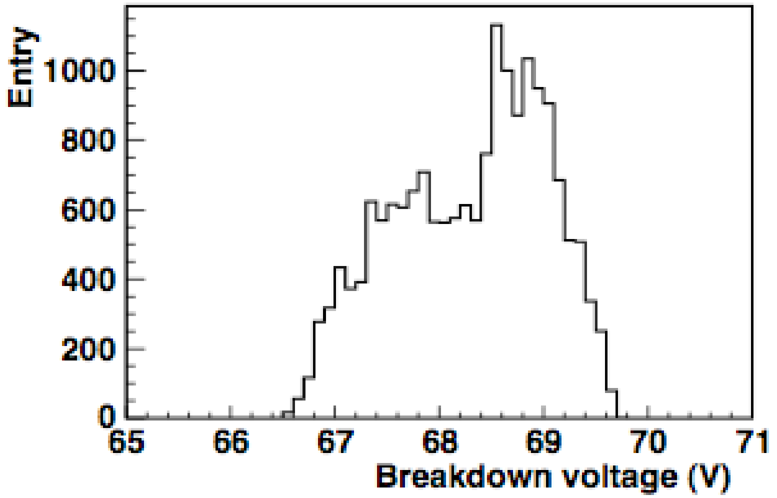


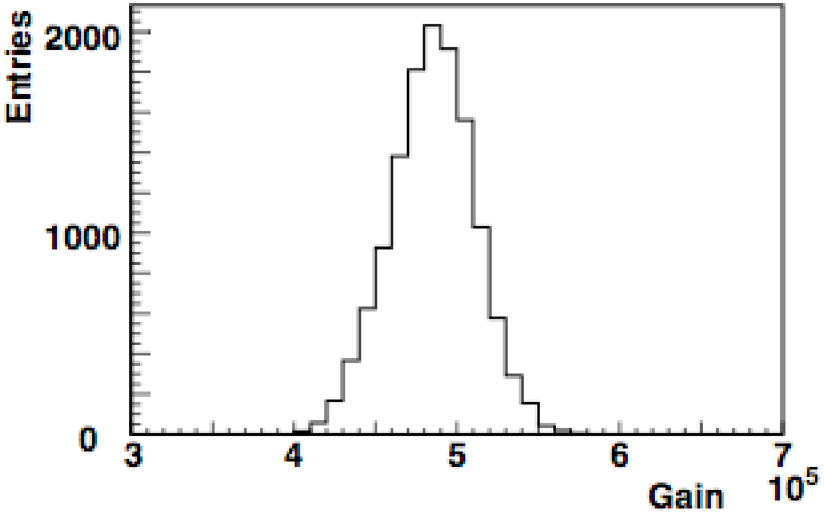
- Gain = C_{pixel} ΔV
  - Linearity may not be perfect
- ΔV = $V_{op} - V_{BD}$
- V_{BD} breakdown voltage
  - Temperature variation 54±3 mV/°C
  - This number is surprisingly hard to measure better than 10%
- Low gain fluctuations



A. Vacheret et al., NIM A 656 p. 69 (2011)

Gain and breakdown voltage variation across 17,686 MPPCs





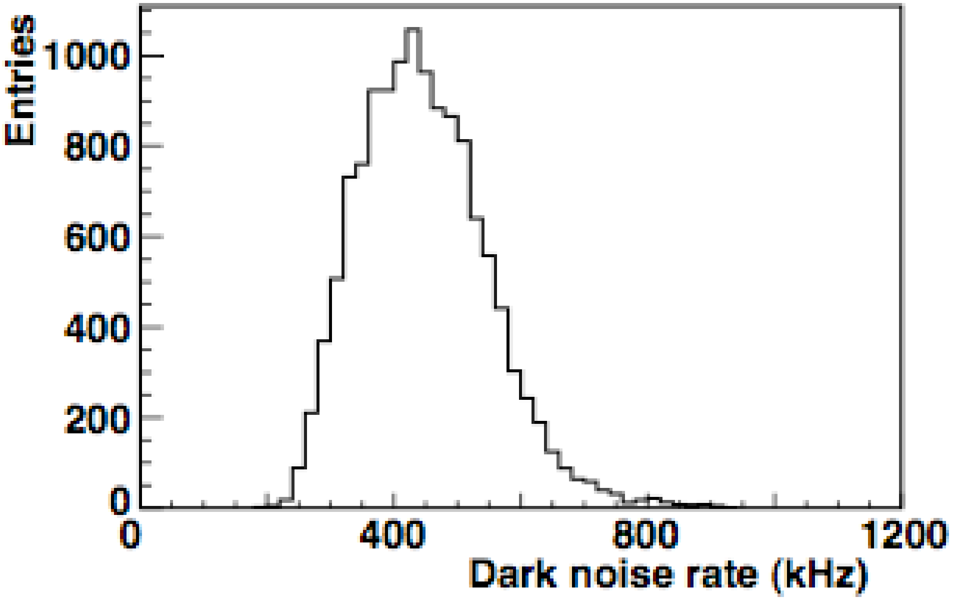
- Large variation of breakdown voltage
  - Require operating MPPCs at different operating voltage
- Small gain variations between MPPCs
  - 5.3% variation

Yokoyama et al., Nucl. Inst. Meth. A 622, 567 (2010))

Dark noise variations between MPPCs

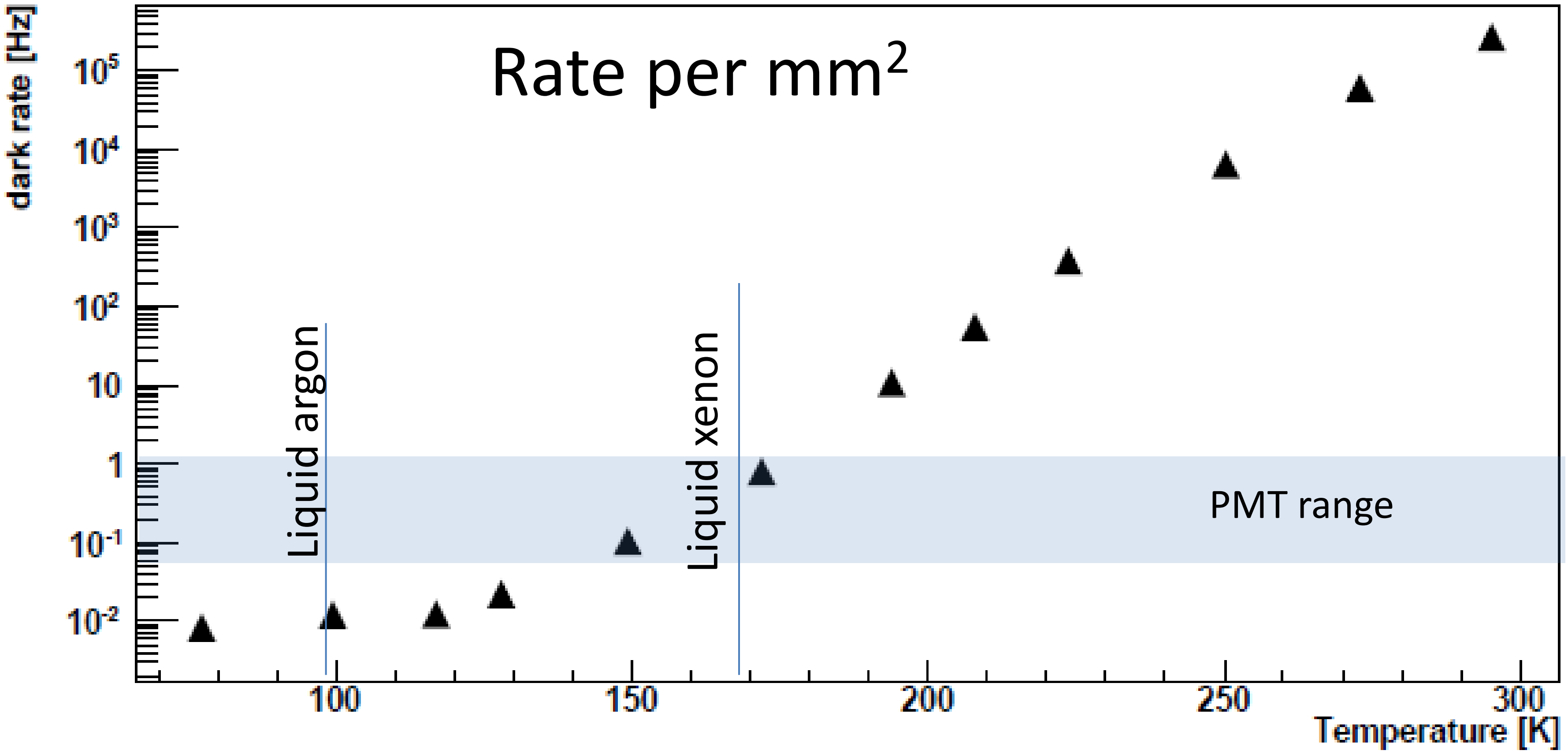
- Significant variation between MPPCs
  - Hot pixels?
- Significantly lower dark noise than specified

Data at over-voltage = 1V, T = 20°C



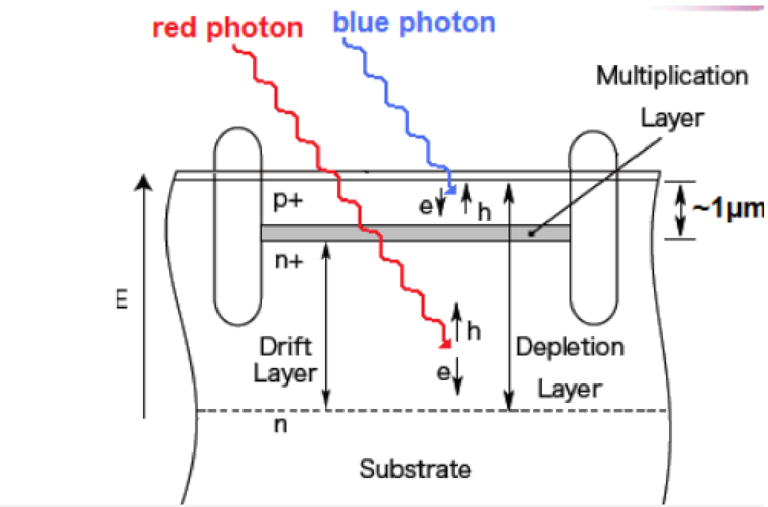
Yokoyama et al., Nucl. Inst. Meth. A 622, 567 (2010))

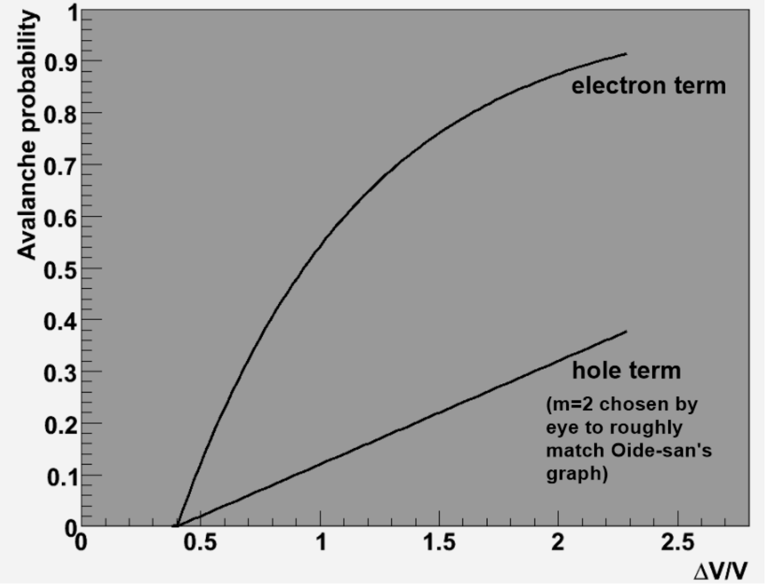
Side comment outside T2K
Cryogenic dark noise for MPPCs



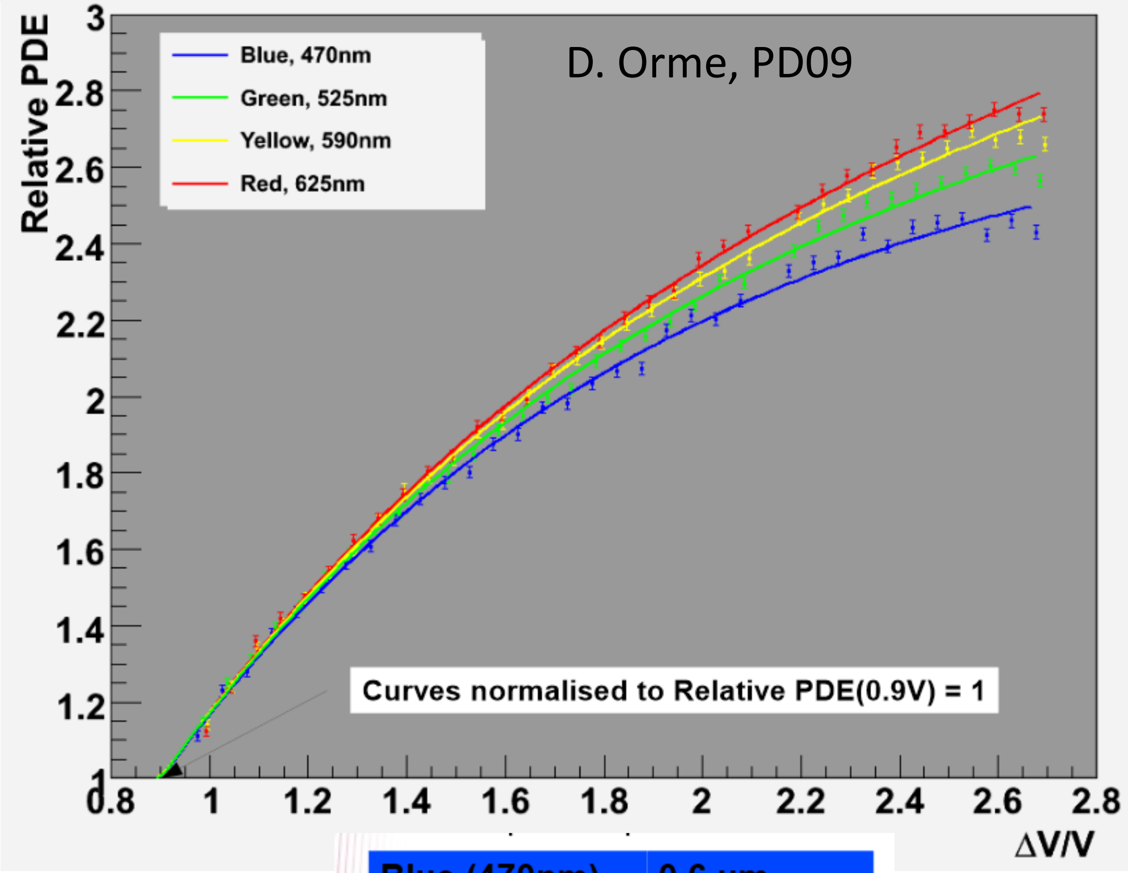
J. Csathy et al. NIM A 654 (2011) 225

Electron vs hole triggered avalanches





(m=2 chosen by eye to roughly match Oide-san's graph)



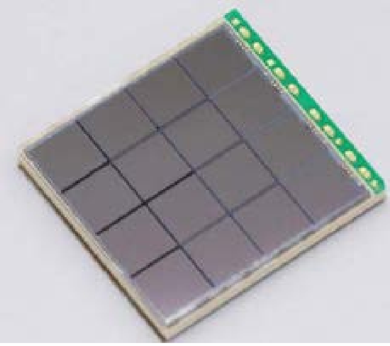
D. Orme, PD09

Curves normalised to Relative PDE(0.9V) = 1

Blue (470nm)	0.6 μm
Green (525nm)	1.2 μm
Yellow (590nm)	2.2 μm
Red (625nm)	2.9 μm

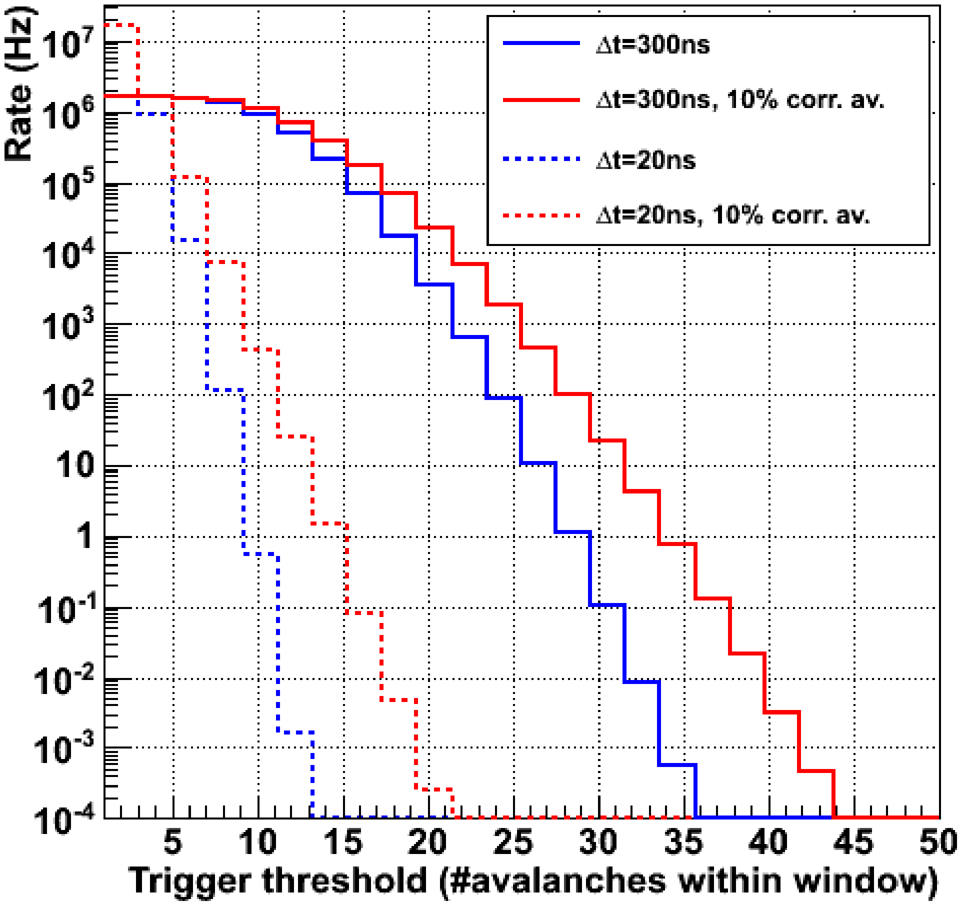
Deep junction not needed for blue/UV

Dark noise



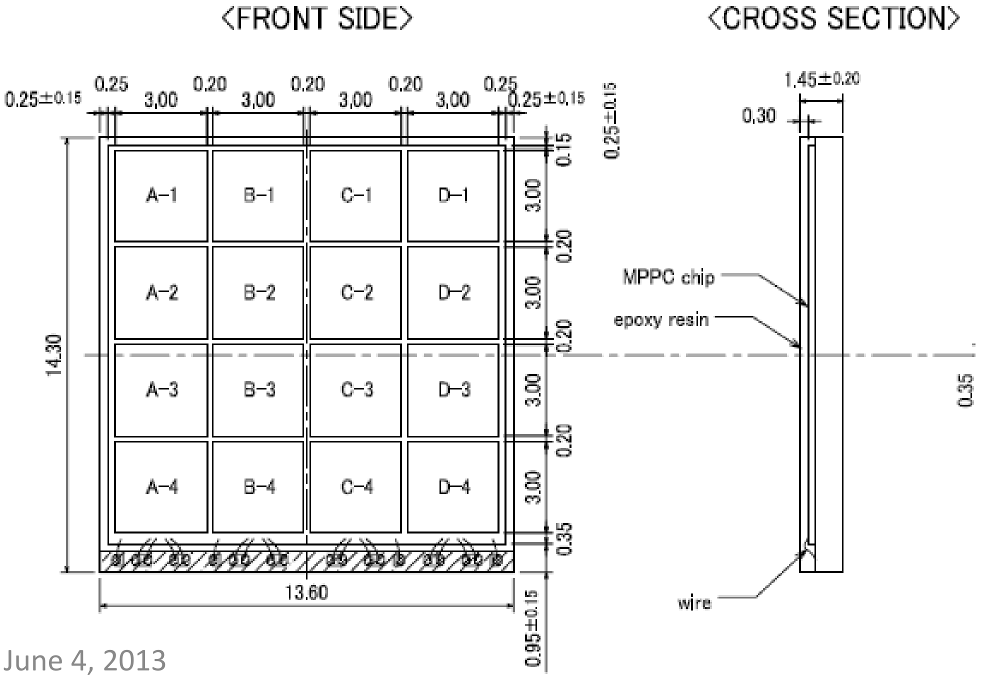
- Dark noise rate 100-500 kHz/mm^2
  - MHz for 10 mm^2!
  - Single avalanche rate
    - Poisson statistics for multi-avalanche
  - Correlated avalanches make things worse
    - 1 avalanche may trigger another one
- Need lots of light or/and narrow timing window
  - Border line for BGO: slow (300 ns time constant) and not very bright
  - Investigating for nuclear physics experiments at TRIUMF
- Or need to cool below -100°C

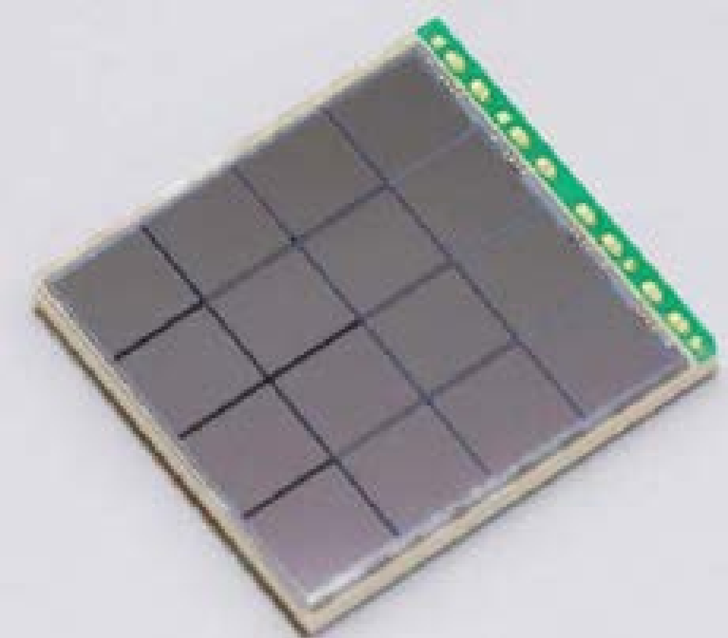
Self trigger rate due to dark noise
For 200kHz/mm^2 and 1.44 cm^2 active area



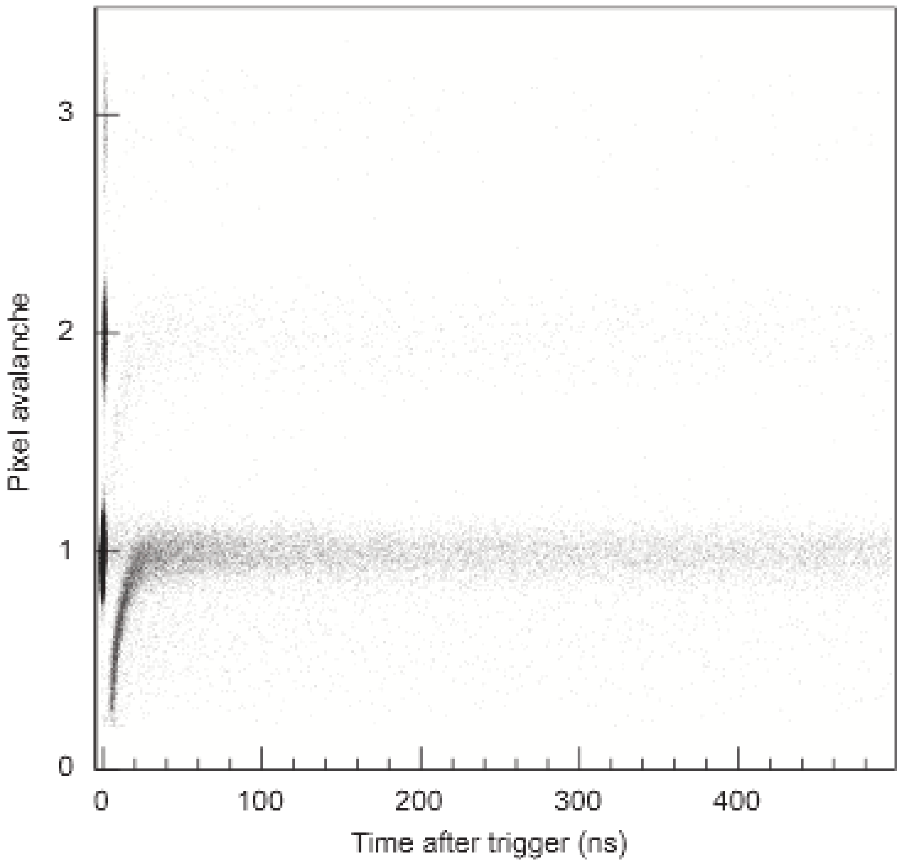
SiPM moving to larger area applications

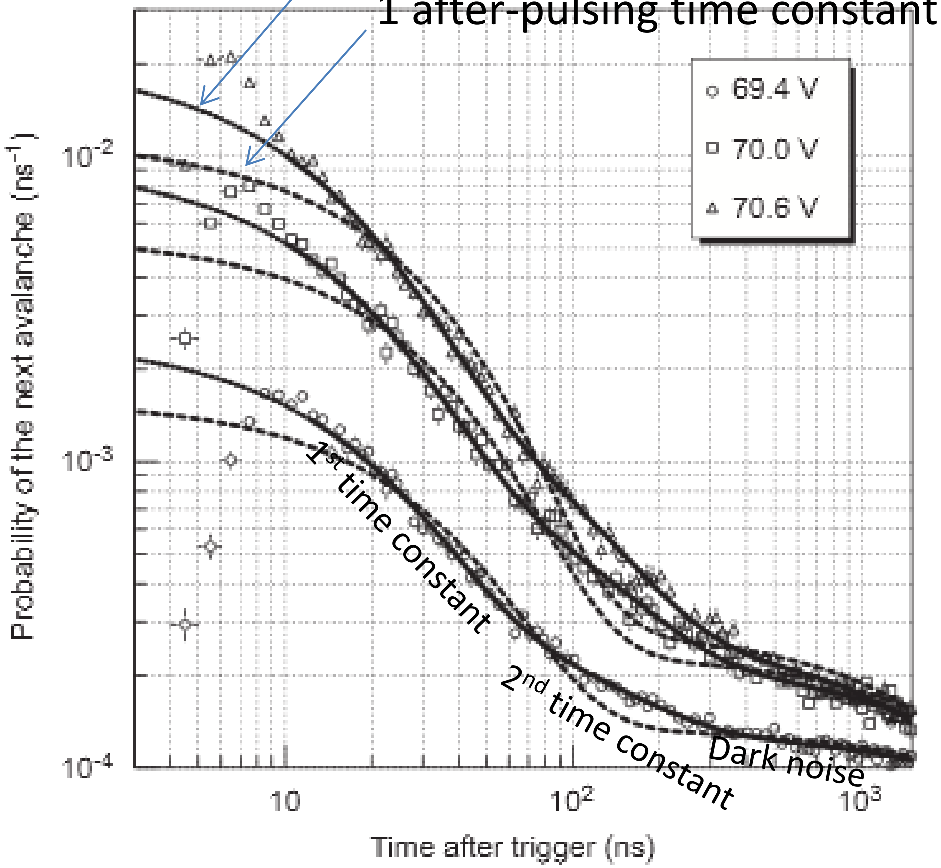
- Successful application of SiPMs up to 3×3 mm^2
  - Matrices routinely used for PET: 4x4 pixels ~ 1.5 cm^2 total
- Can we join all the 16 SiPMs together?
  - Cheap because of economy of scale
    - PET = big user





Now looking at delayed correlated avalanches





2 after-pulsing time constants

1 after-pulsing time constant

1st time constant

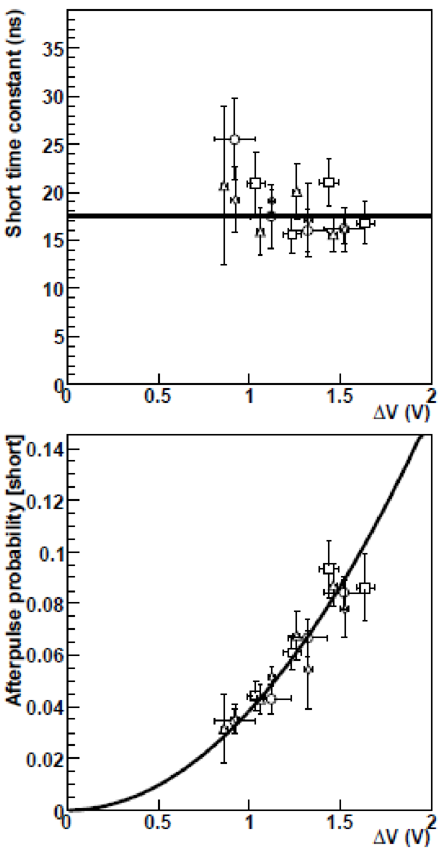
2nd time constant

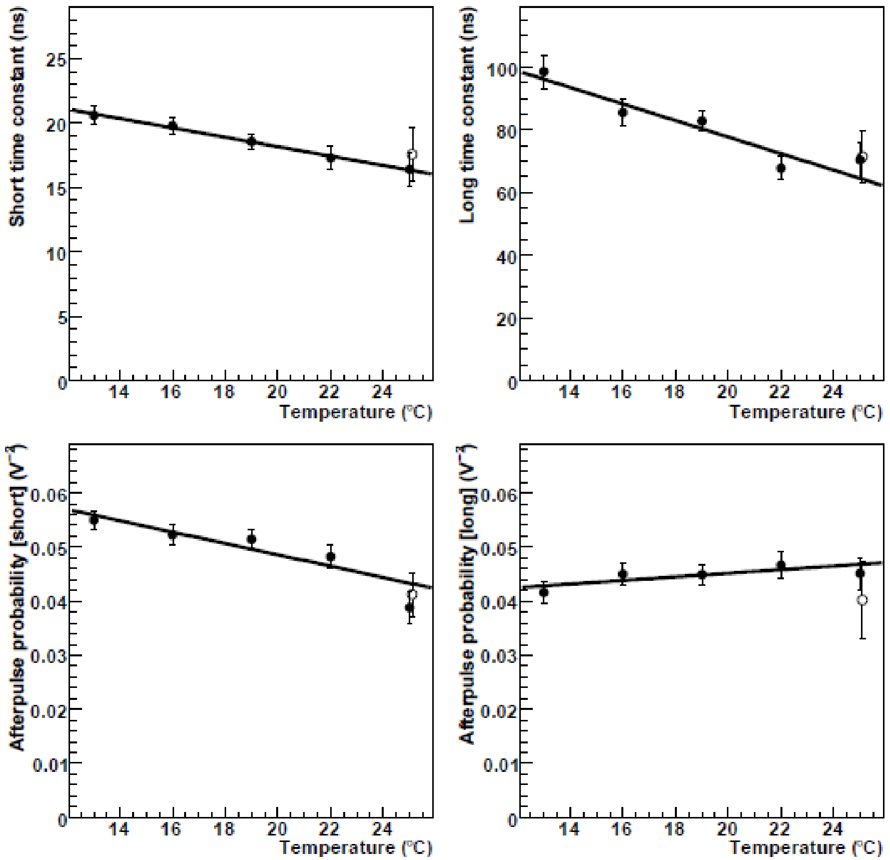
Dark noise

Y. Du and FR, NIM A 596 (2008) p. 396

After-pulsing quantitative estimate

At 20C



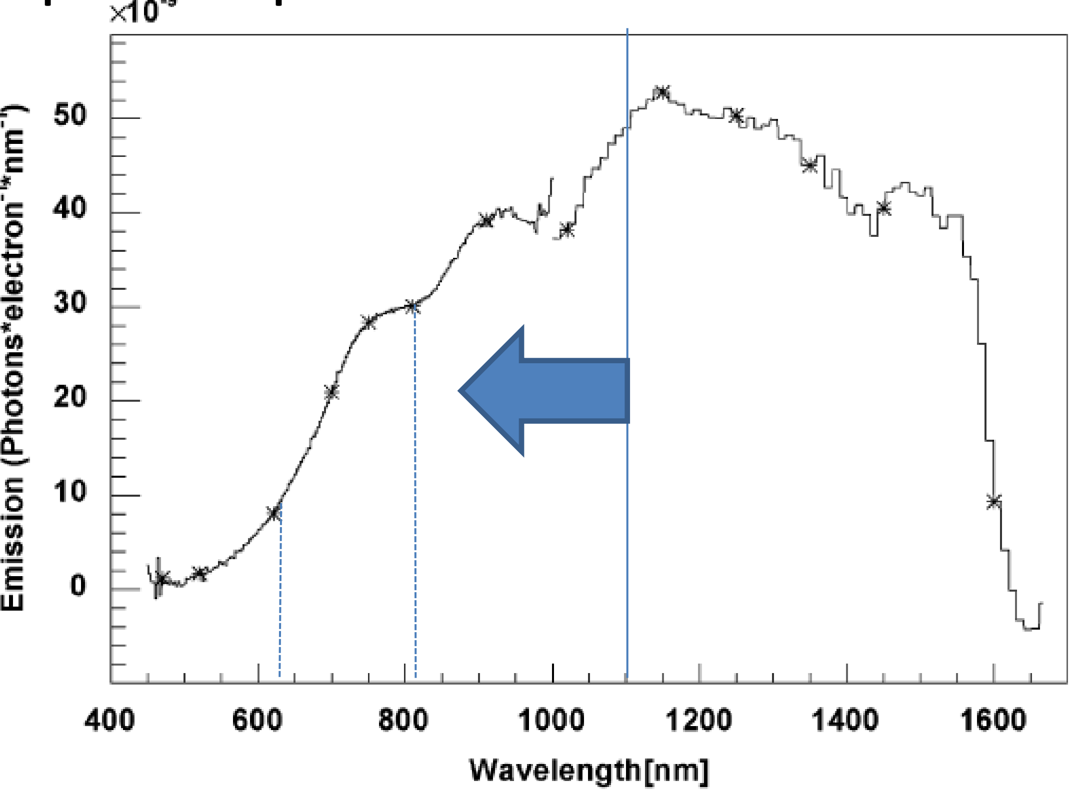


A. Vacheret et al.,
NIM A 656 p. 69 (2011)

Use external light source mimicking internal light source

- Internal light source

Spectrum of photons emitted in MPPC avalanches



R. Mirzoyan , R.Kosyra H.-G.Moser ,
NIMA 610 (2009) 98–100

- External light source
  - Hamamatsu PLP-10
  - Pulse width and jitter <80ps

Wavelength	Att. Length in Si
404 nm	0.12 µm
467 nm	0.55 µm
637 nm	3.2 µm
820 nm*	14.1 µm

* Laser system lent to us by Hamamatsu thanks to Y. Iwai