# Geiger-mode APDs
(2)

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**I Seminario Nazionale Rivelatori Innovativi**
Nov.30-Dec.4, 2009, INFN/LNF

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# Plan for today

1. Basic performance (cont.)
   - Dark noise, cross-talk, afterpulsing
2. Radiation damage

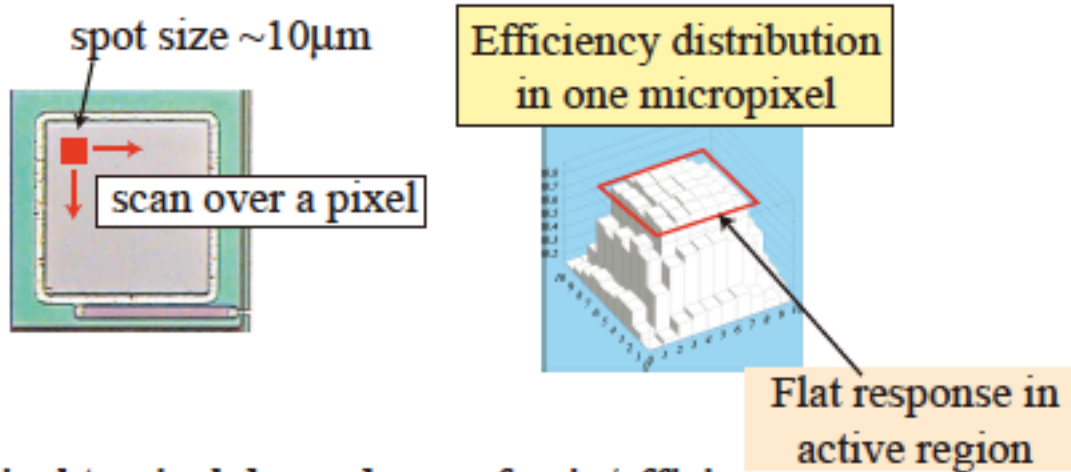
# Parameters and performance (cont.)

# 4. Test with spot laser system

Injected p.e.

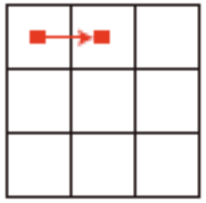
Inject pulsed laser (859nm, 50ps) onto a 100 pixel MPPC

### 3.1 Position dependence of efficiency in a micro-pixel




### 3.2 Pixel to pixel dependence of gain/efficiency

Inject light on center of each pixel



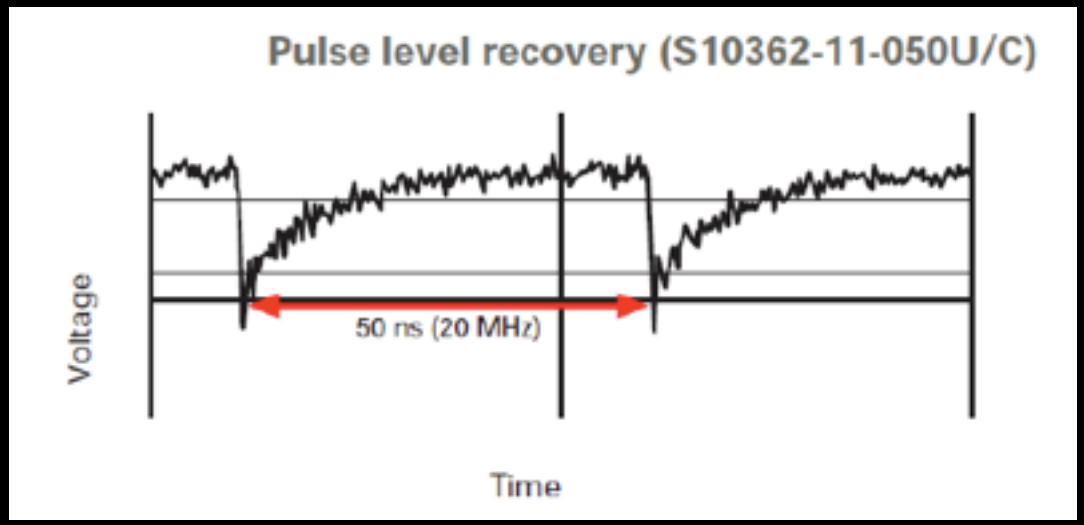
Distributions for 10x10 pixels


**Excellent uniformity!**

M. Yokoyama,
poster at SNIC06 (Apr. 06)
arXiv: physics/0605241

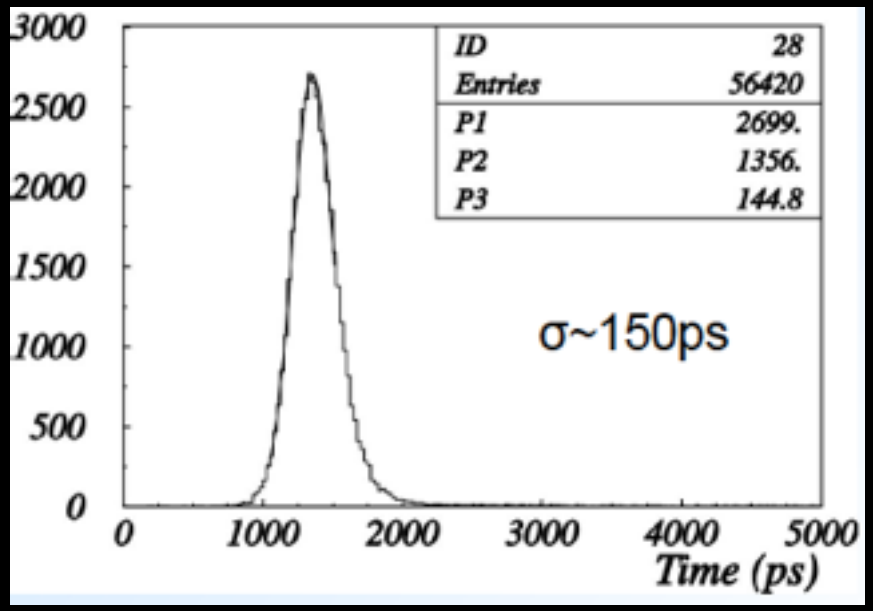
# Pulse shape and recovery

- Signal 'rise time' usually very fast (~a few ns).
- Fall time / pixel recovery time determined by recharging through RC.
  - Larger pixel size = large C, longer recovery



# Timing resolution

- Fast breakdown process in thin (a few μm) multiplication layer.
  - Timing resolution expected to be good even with single photon.

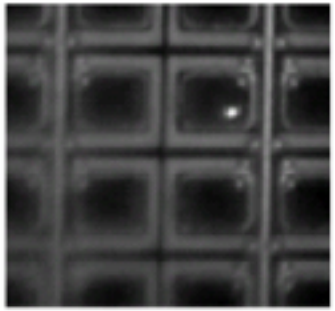


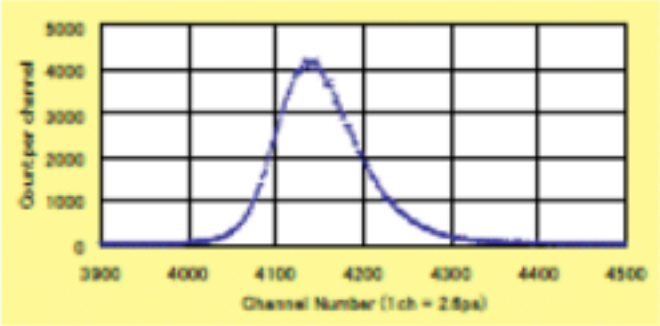

S.Korpar, PD09

K.Yamamato (Hamamatsu) @ PD07

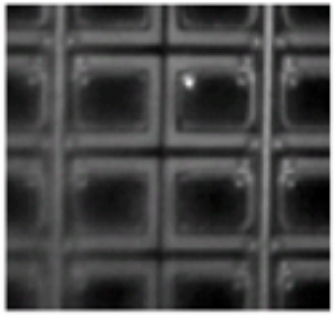
# Time resolution in one pixel

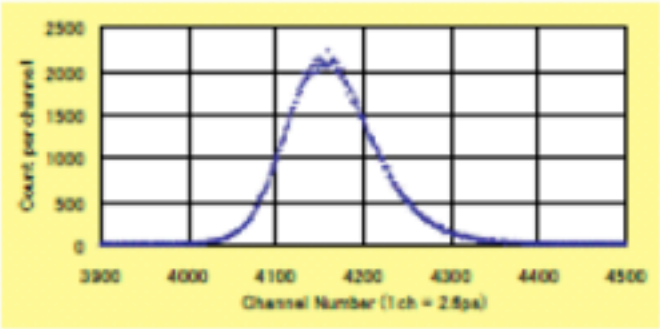
MPPC:1mm2 50 $\mu$ m pitch



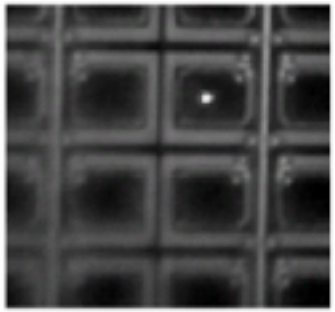


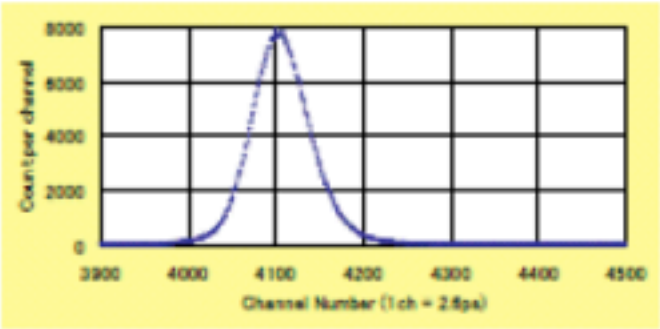

FWHM = 263 ps






FWHM = 294 ps






FWHM = 192 ps

# Performance

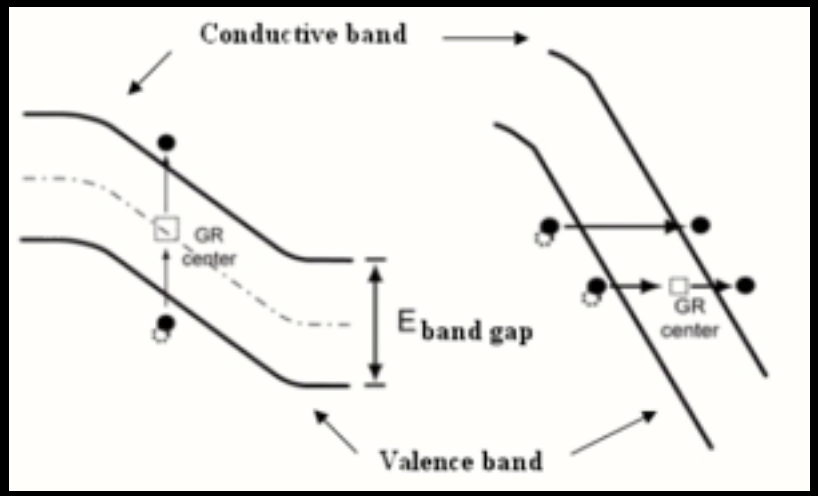
- Discussed yesterday: signal generation
  - Gain, PDE, timing, recovery
- Today: other effects
  - Dark noise, cross-talk, afterpulse
  - Temperature dependence of parameters
  - Radiation damage


Talking about the dark side of device...

# Dark noise

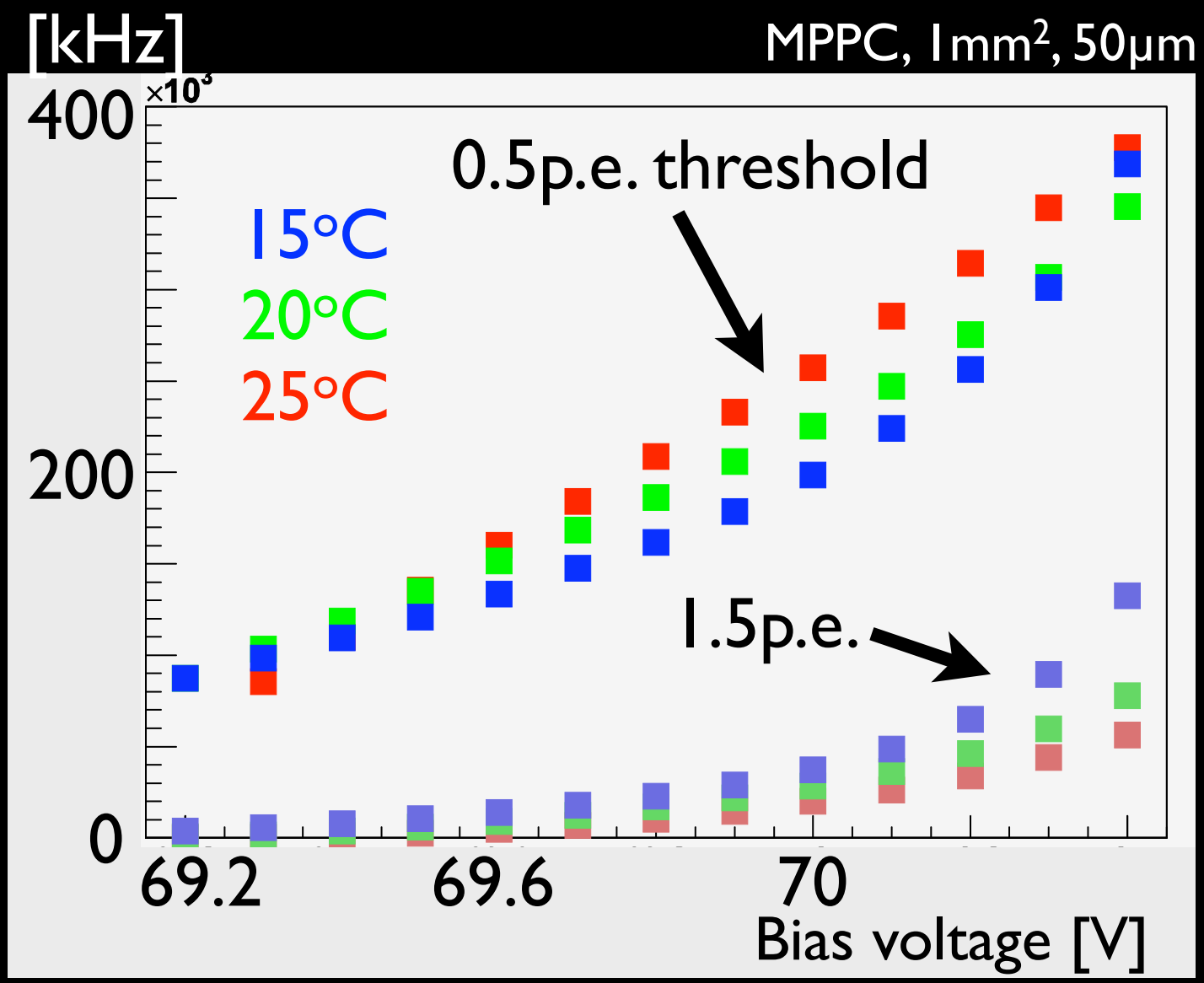
# Dark noise

- Avalanche can be triggered by *any* generation of free carriers, not only by photon injection.
  - Thermally generated carriers gives a dominant contribution to the dark rate at room temperature.
  - Dark noise gives signal identical to the photon-triggered avalanche.
- Typical rate:
  ~100kHz-1MHz/mm$^2$
  at 25°C with 0.5 'pe' threshold.



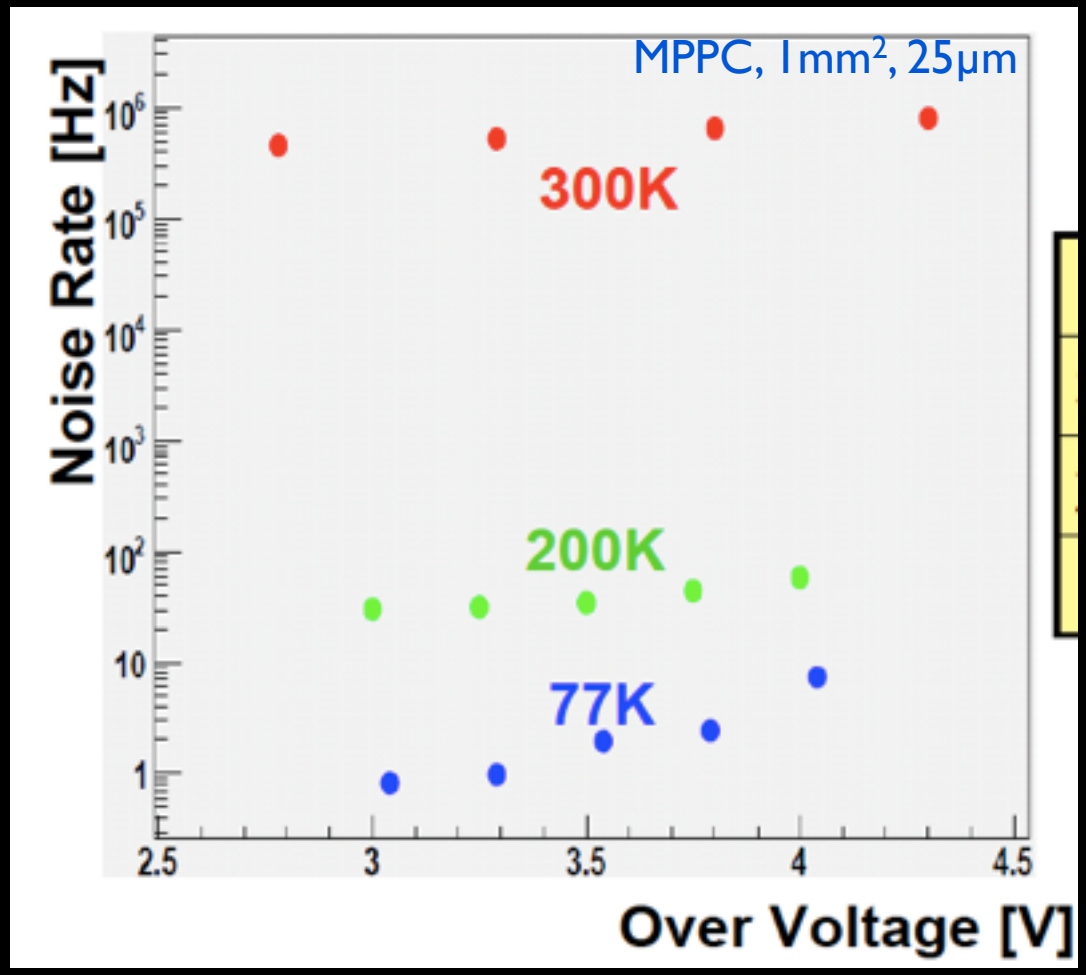
# Dark noise rate

- Measured with scaler
- 1p.e. noise dominates
- Dark noise more than 1p.e. created with cross-talk



# Dark noise

- Dark noise rate can be reduced by lowering temperature: ~1/2 every -8°C.



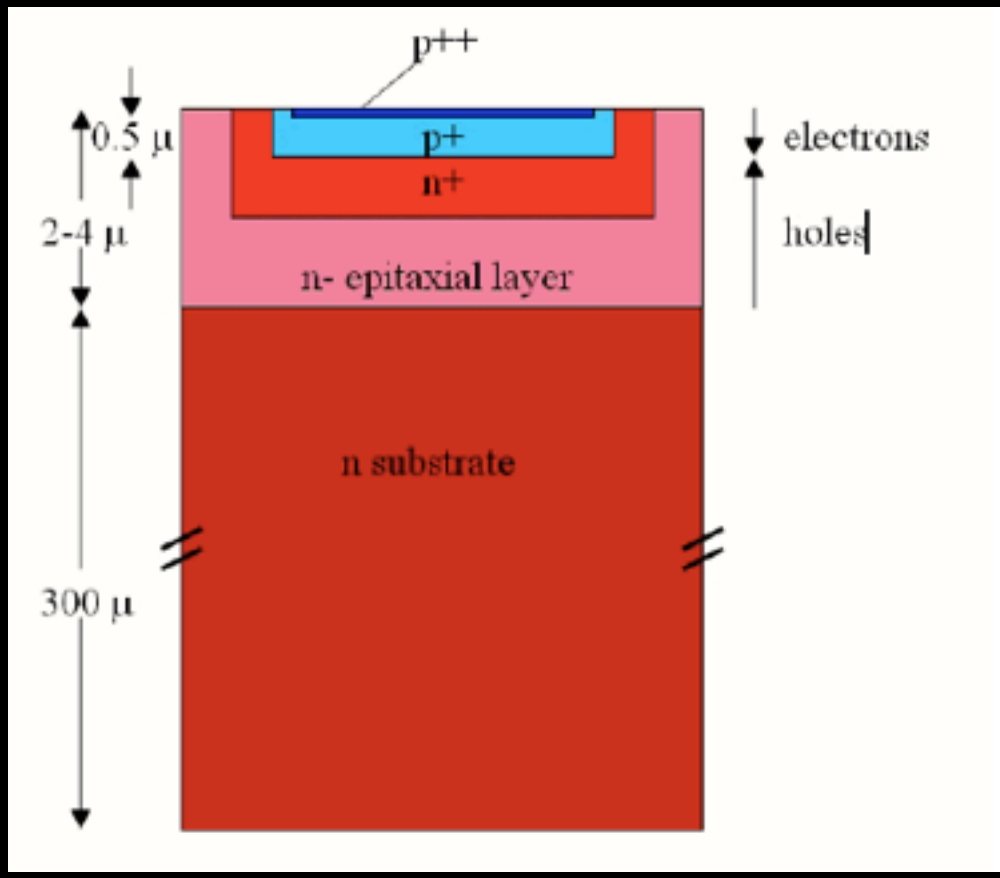

H. Otono, PD07

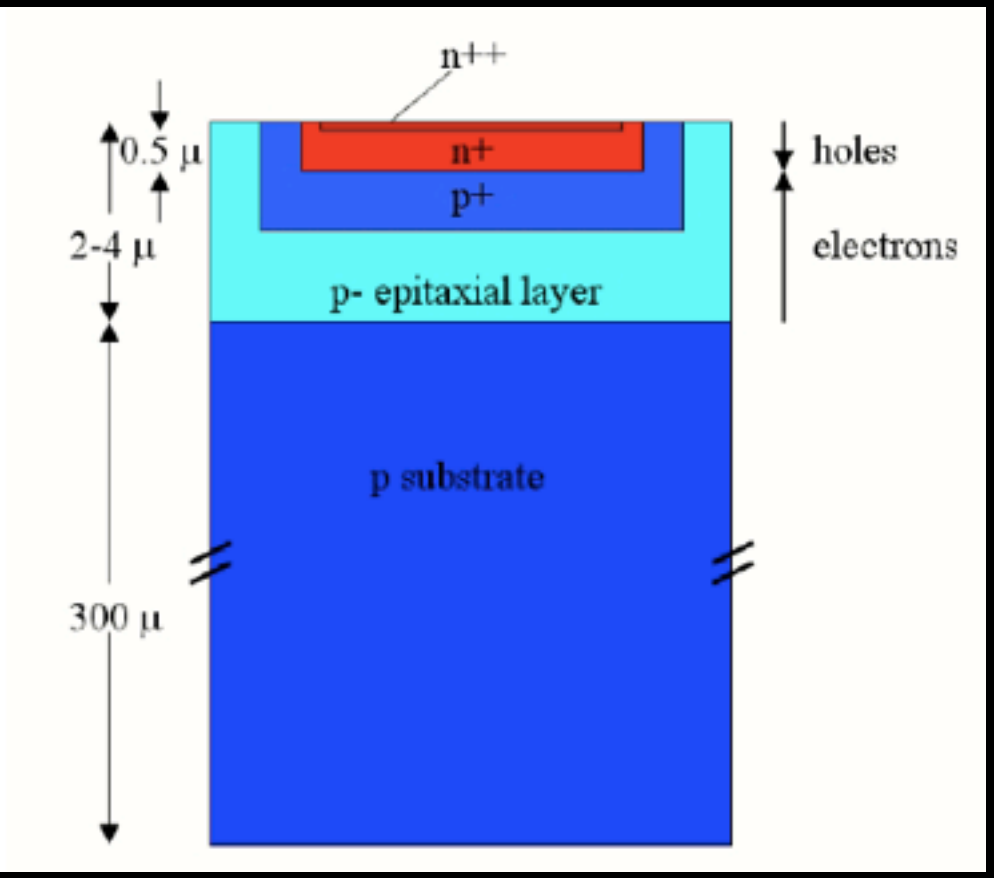
# Dark noise rate

- Thermal generation of carriers
  $\propto$ volume of depleted region
- Electrons more efficient to avalanche than holes
  - p-type: electron drifts to high field region
  - n-type: hole drifts

➡ Smaller p-type volume results in smaller dark noise rate

# Structure revisited




p-on-n

n-on-p

Shallow p region
⇒ smaller noise rate possible

# Dark noise rate: prospects

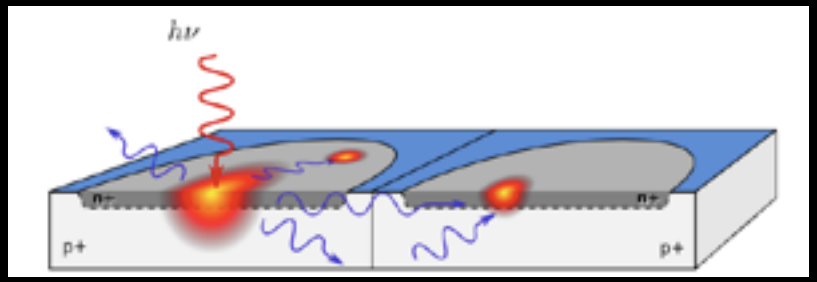
- Dark noise rate suppression needs minimization of impurities/crystal defects.
  - Hard to control beyond some level.
- One of major limitations to realize large area device.
  - Some innovation necessary for dramatic suppression of the rates.

# Optical cross-talk

# Optical photon generation in avalanche breakdown

- Avalanche makes 3photons / $10^5$ carriers*
  - They can trigger a breakdown when entering neighboring pixel →optical cross-talk
  - A stochastic process, increases excess noise factor.

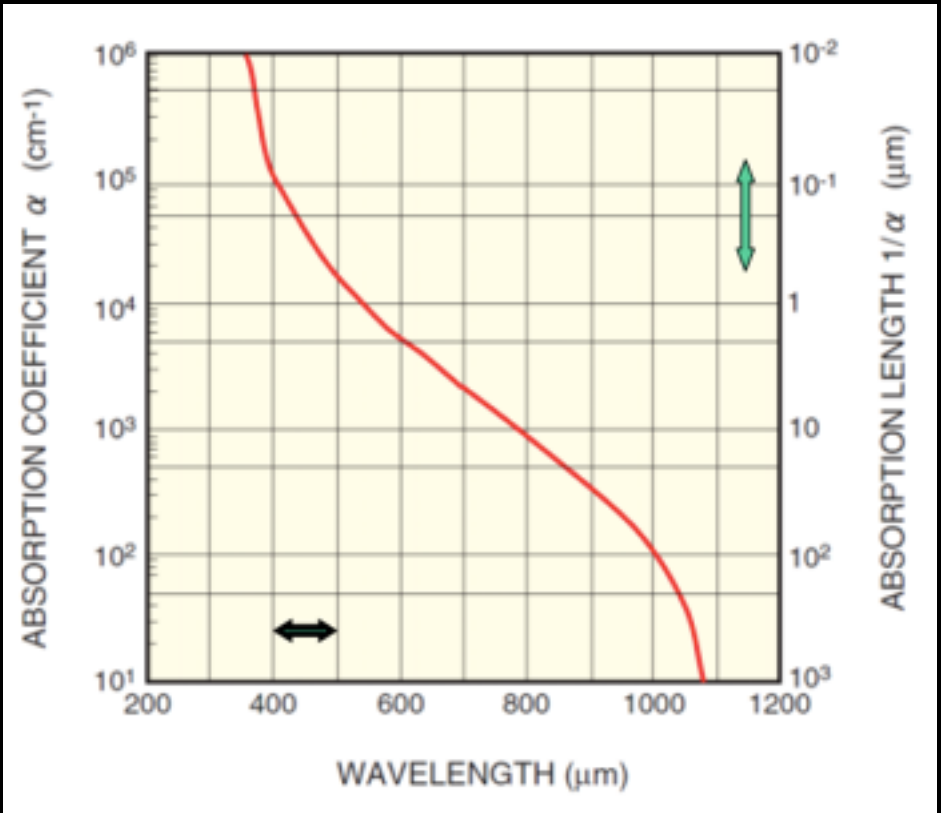
* A. Lacaita et al., IEEE Trans. Electron. Dev. **40**, 577 (1993).




S. Cova et al., J. Modern Opt. **51**, 1267 (2004)
A. Ingargiola, NDIP08

# Optical cross-talk

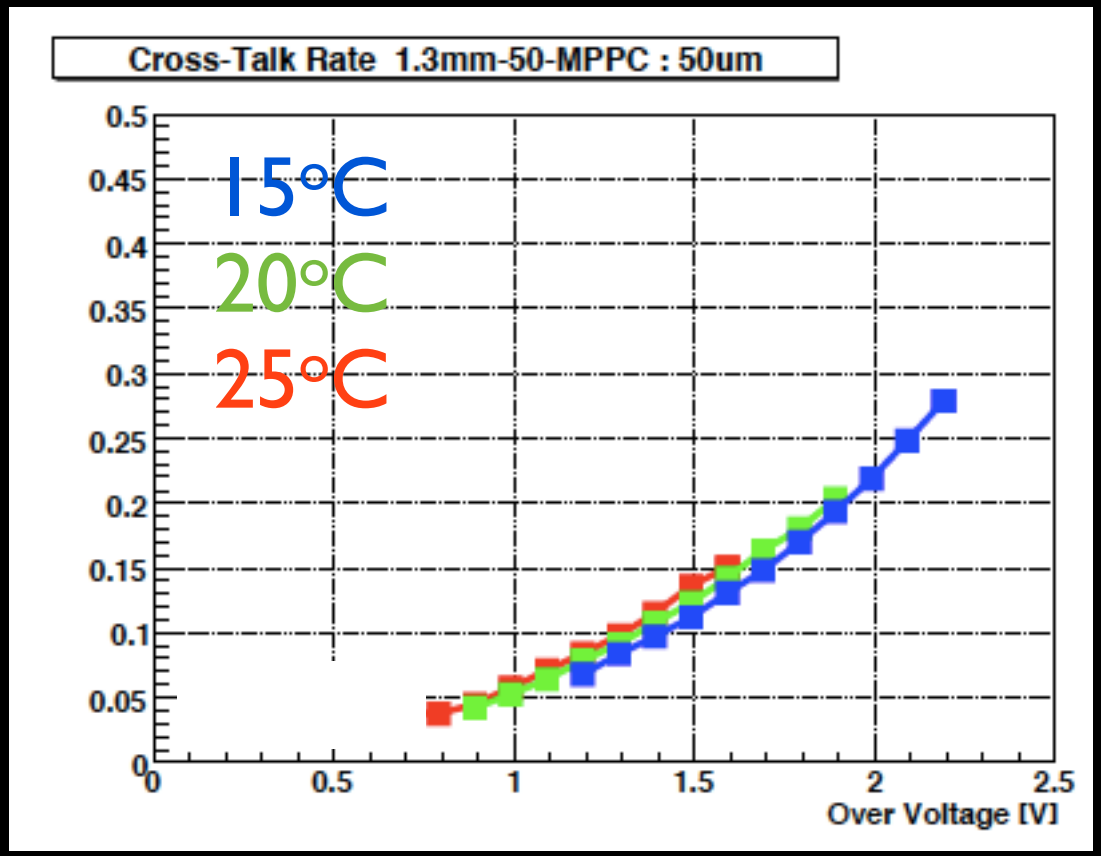
- ~850-1100nm is critical wavelength (N. Otte, NDIP08)
  - Shorter wavelength: absorbed in the same pixel
  - Longer wavelength: not absorbed



# Voltage dependence

- With higher voltage,
  - High gain → more photon created
  - High PDE → more probability of breakdown
  - Both depends on $\Delta V$
    → quadratic function of $\Delta V$

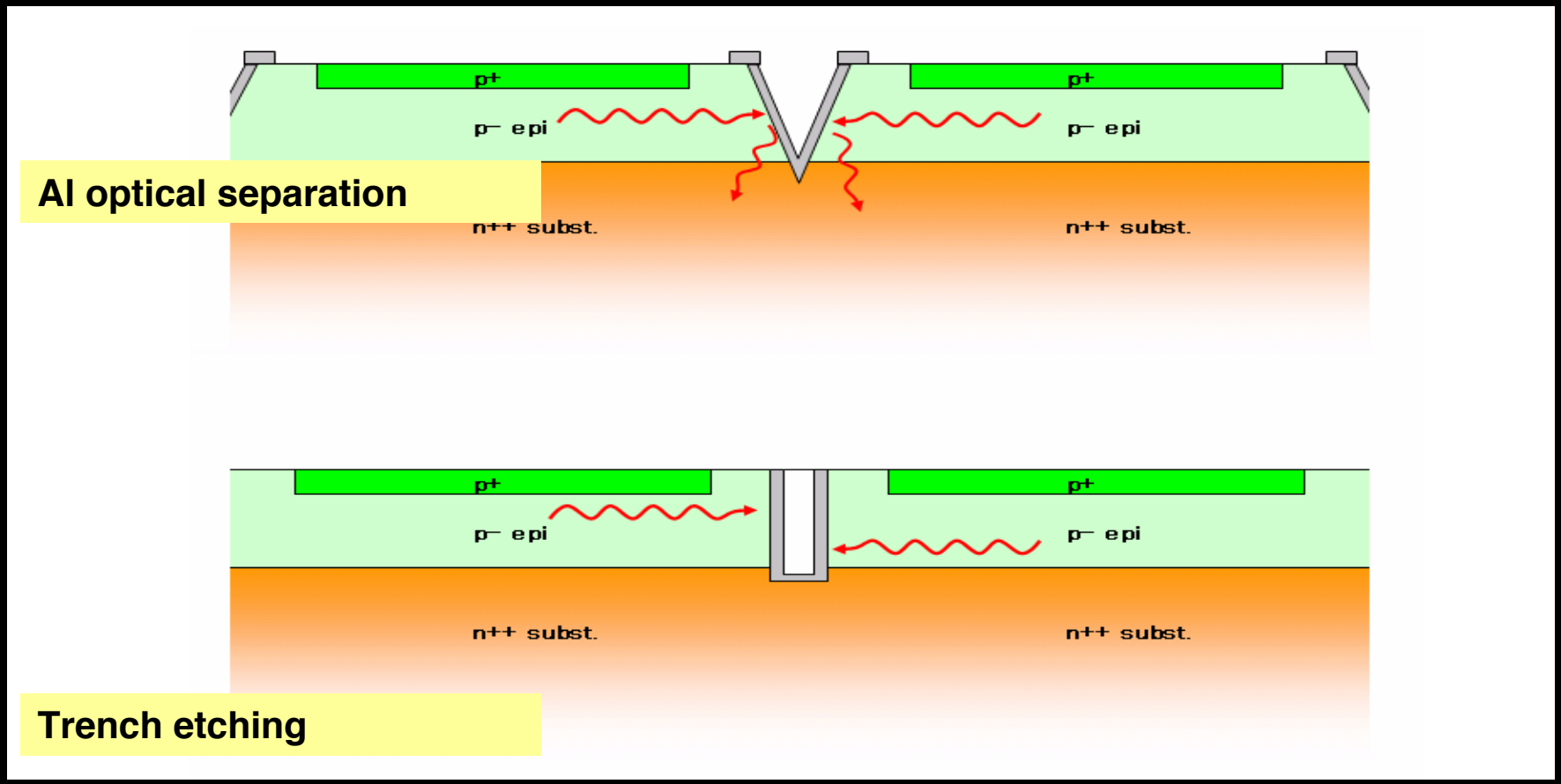
# Optical cross-talk




S. Gomi,
master's thesis
Kyoto U (2008)

Cross-talk of MPPC, measured with scaler

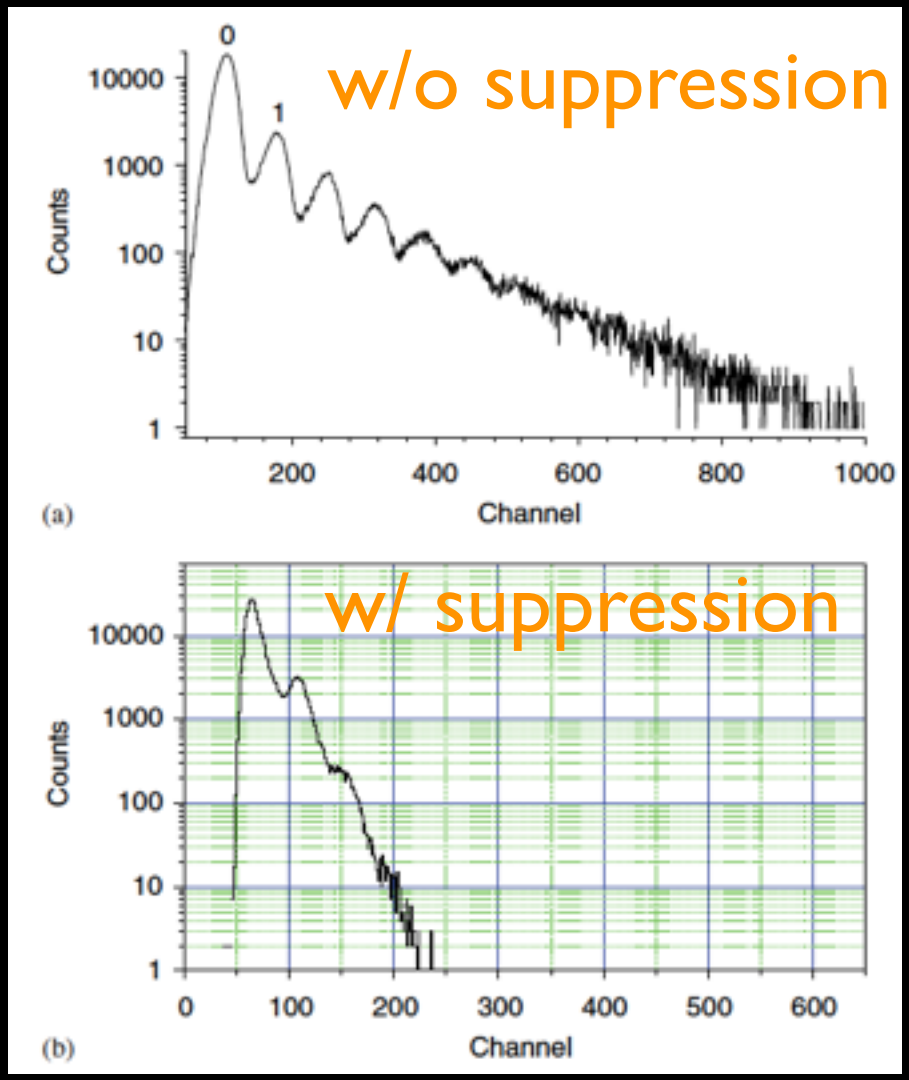
# Possibility of cross-talk suppression




K.Yamamoto @ PD07

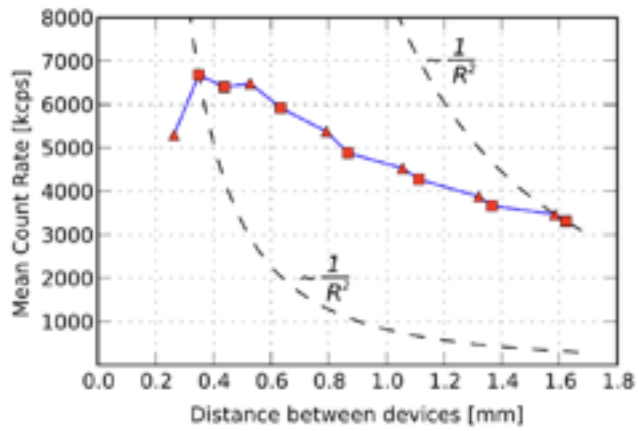
# Cross-talk suppression

- Promising result reported from MEPhI/Pulser/MPI group with optical isolation.
- Isolation requires additional dead area -- needs optimization




P.Buzhan et al., NIM A567 78 (2006)

# Another study

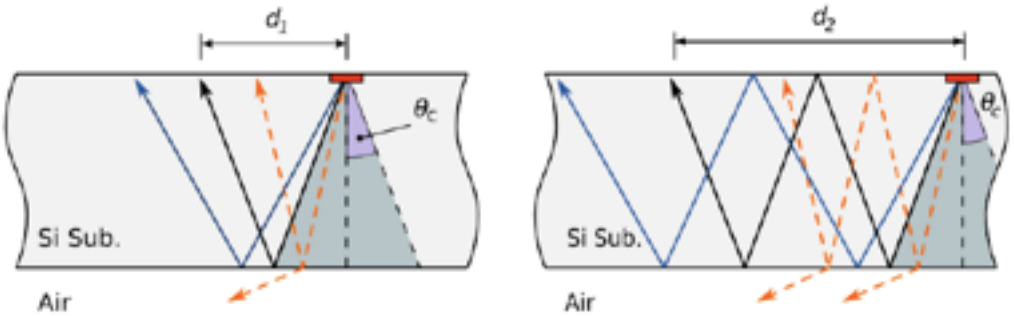



- Does not follow an $1/R^2$ behavior
- Is not either monotonous

**Direct optical paths are not able to explain the phenomenon**

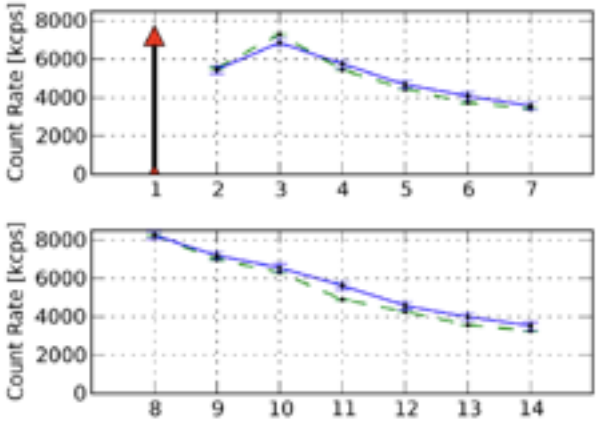
A. Ingargiola, NDPI08

*Due to total internal reflection ...*




- Single reflection → peak at distance $d_1$
- Double reflection → peak at distance $d_2$

***We observe a non monotonous dependence !***




- The $x$ axis indicates the SPAD position
- The arrow marks the detector position (1)
- *Continuous line: measured crosstalk*
- *Dashed line: simulated crosstalk*

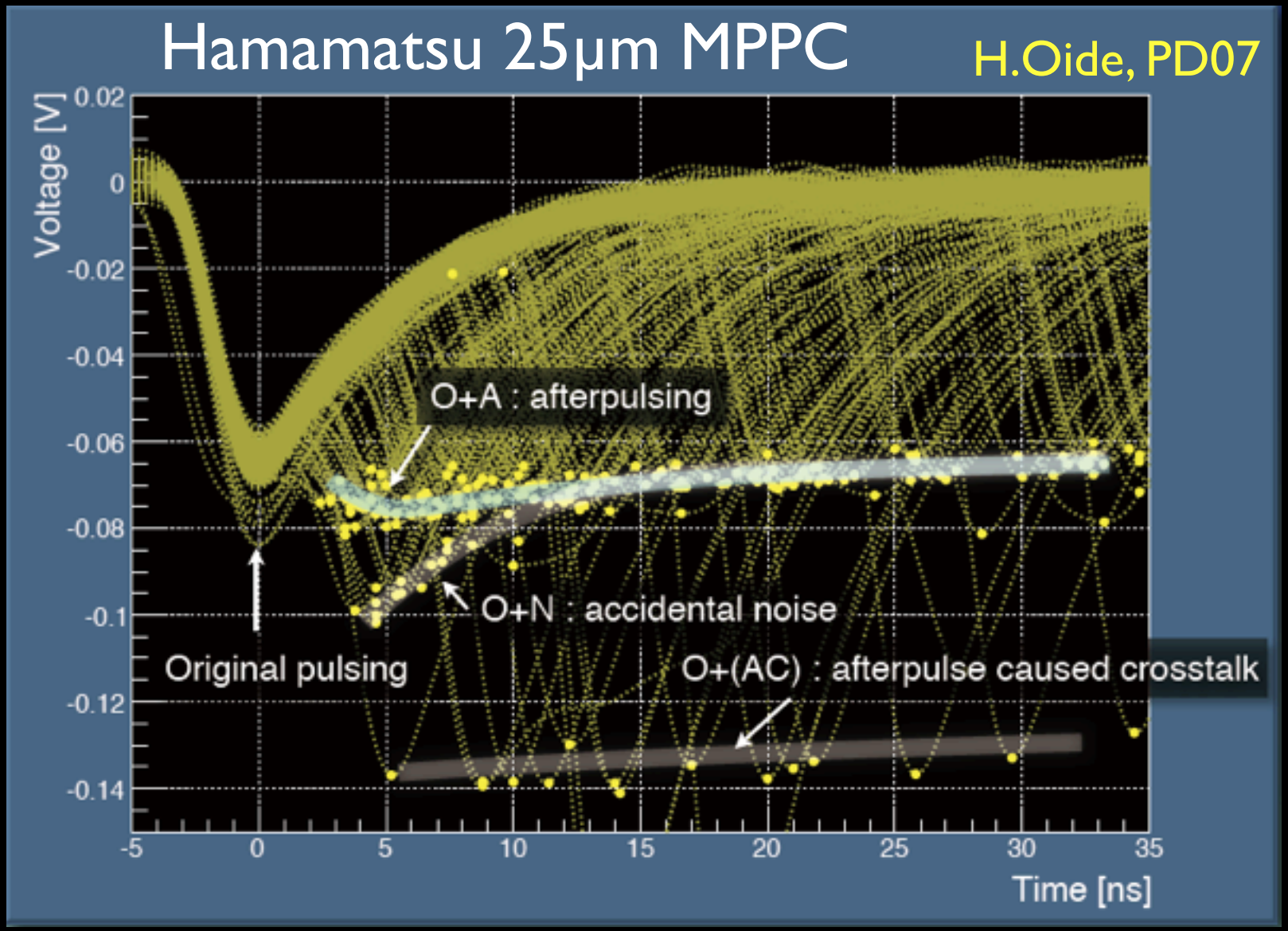
***Excellent agreement with experimental data***

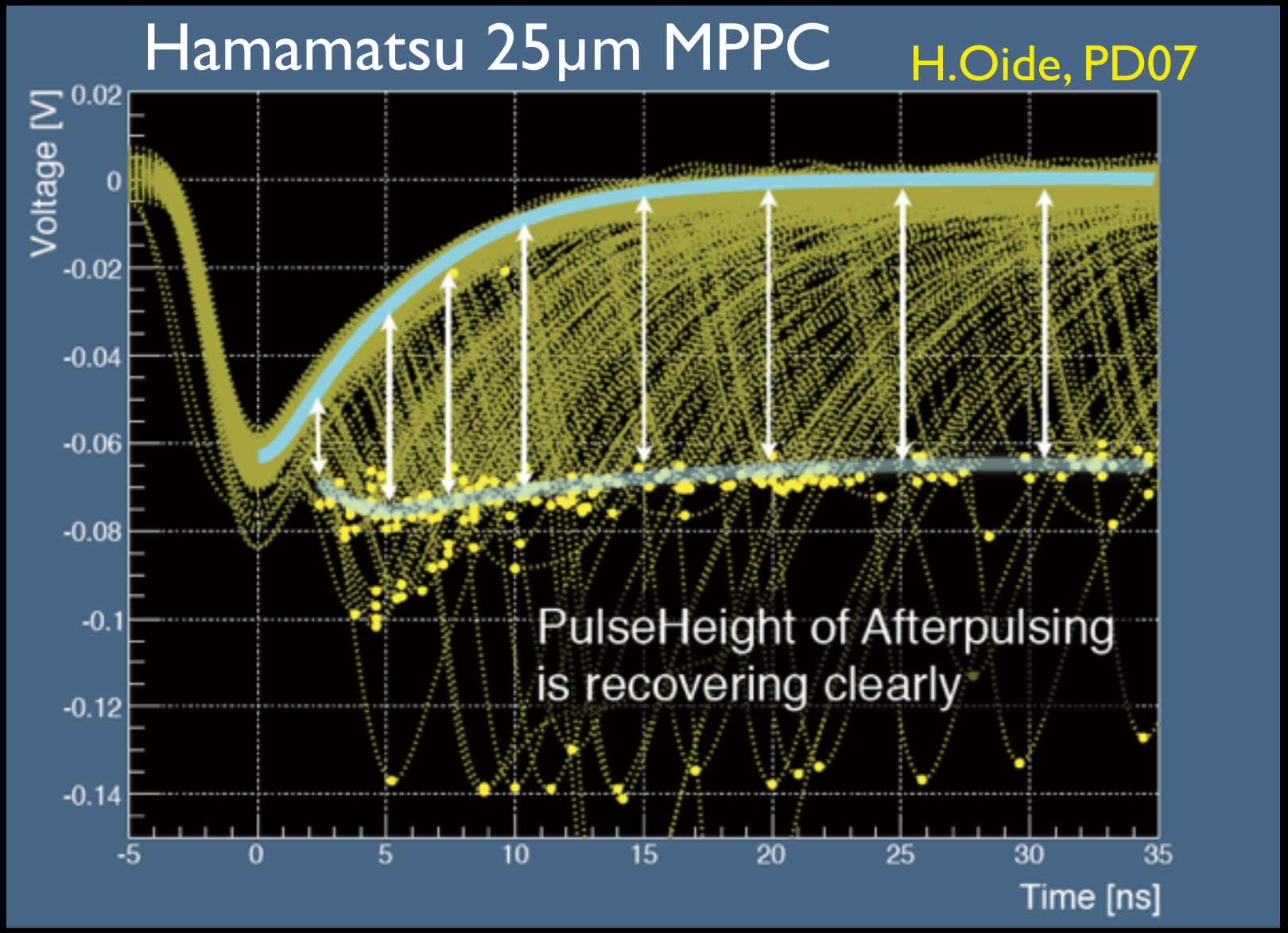
# Afterpulsing

# After-pulse

- Carrier trapped in impurity state may be released after certain time and cause delayed avalanche in the same pixel, or after-pulse
- Typical timescale in room temp: 100ns
- Also increases excess noise factor

# Afterpulse


Hamamatsu 25μm MPPC
H.Oide, PD07
Voltage [V]
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
-5
0
5
10
15
20
25
30
35
Time [ns]
O+A : afterpulsing
O+N : accidental noise
Original pulsing
O+(AC) : afterpulse caused crosstalk

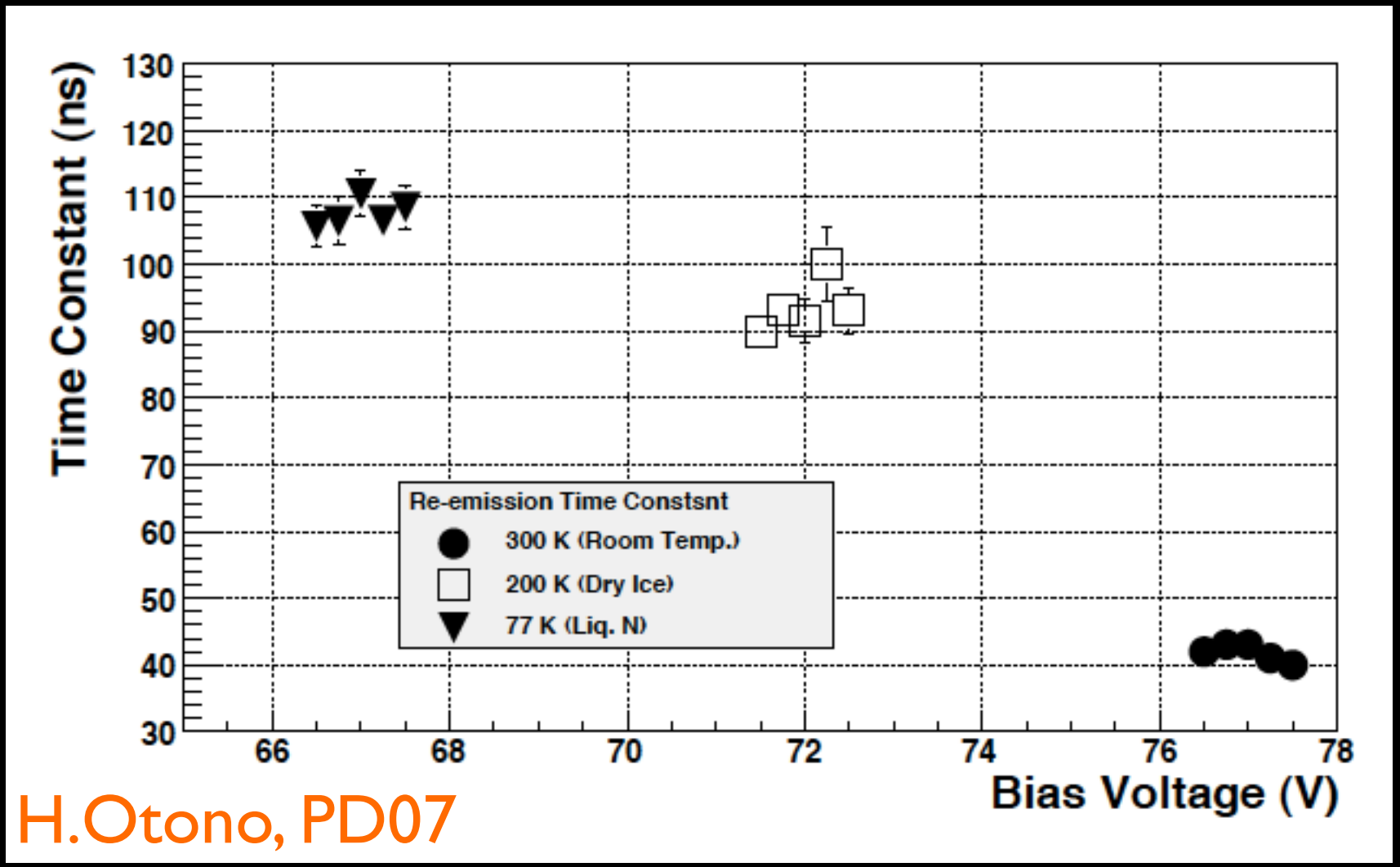



You can also see the effect of recovery.

# T/V dependence

- Probability of afterpulsing depends on $\Delta V$.
  - Higher field results in more carrier (gain).
- Temperature also affects the release time of the trap.
  - Lower temperature makes the trap release time longer.

# Temp. dependence




H.Otono, PD07

# After-pulse suppression

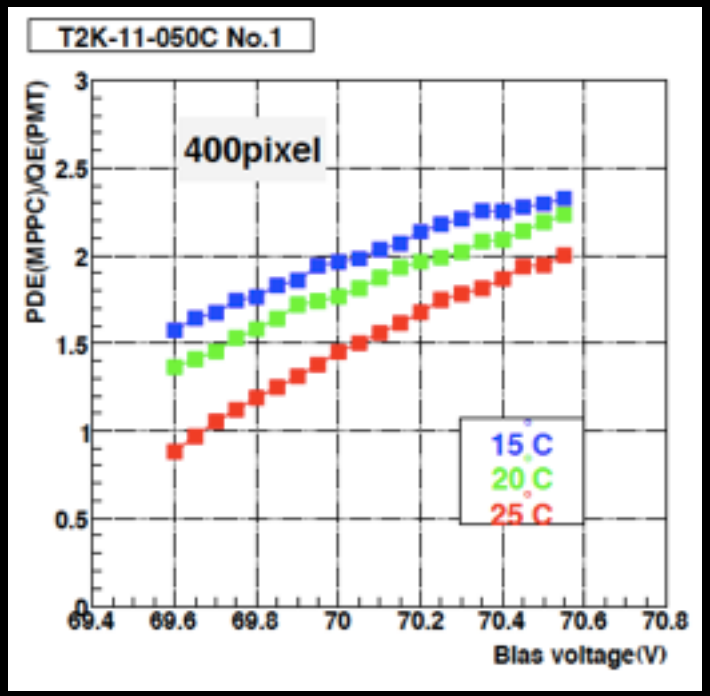
- One possibility is to make recovery time longer with e.g. larger quenching register. (no afterpulsing before recovery)
  - Confirmed with test sample.
  - Dead time also increases.
- Again, control of impurity gets difficult beyond certain level.
- Innovation?

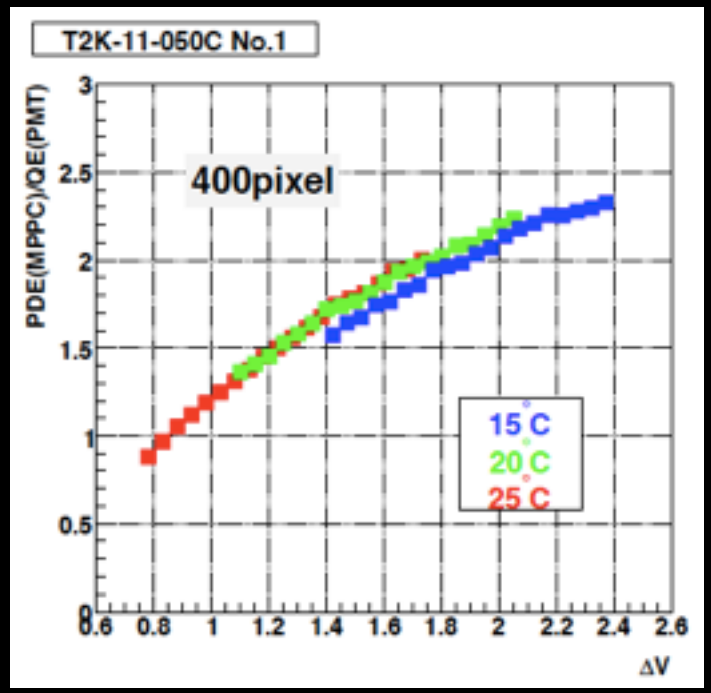
# Temperature dependence

- Already mentioned temperature / voltage dependence in several points.
- As this is one of major issue in operation, summarizing the situation here.
- NB: Discussion here is for MPPC. Other devices may have different dependence. (some will be shown later)

# T/V dependence

- Gain, PDE, cross-talk, afterpulsing known to (to the first order) dependent only with ΔV.

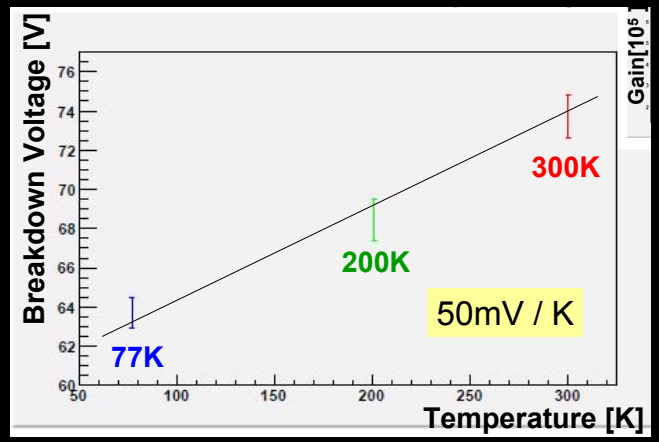



PDE measurement
as a function of V (left) and ΔV (right)

M. Taguchi (Kyoto)
master's thesis (Feb. 2007)

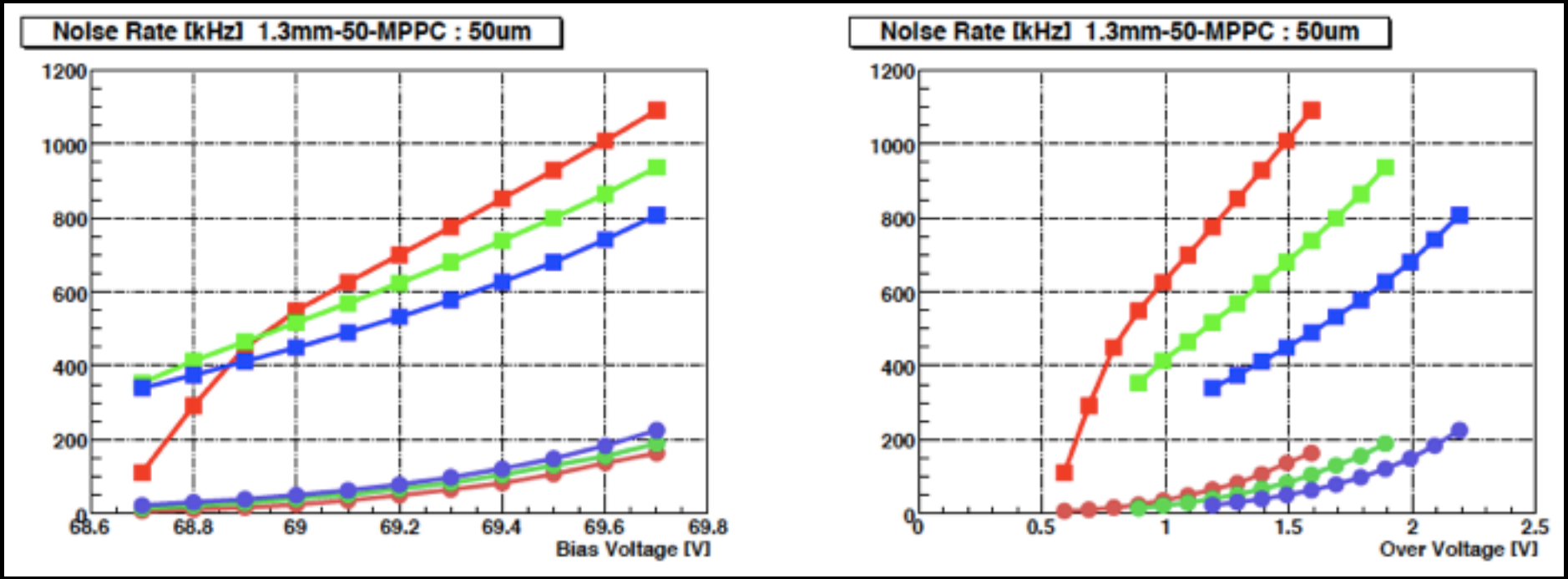
# T/V dependence




- $V_{bd}$ depends on temperature (~50mV/K for MPPC).
  →ΔV changes if V is constant.
- Around ΔV=1V (typical operation V in T2K), 1°C corresponds to 5% change in ΔV(= thus gain).
  - Note PDE, cross-talk also changes
    → output charge for same light changes more!
  - Main issue of calibration in real use.

# Dark noise rate

- Dark noise rate is known not to follow ΔV dependence.




Dark noise rate as a function of V (left) and ΔV (right)

By S. Gomi (Kyoto)

# Radiation effects

# Radiation damage of Si

- Two major effects:
  - Si bulk defects
    - Change effective doping density
    - Increase charge traps
  - Si-$SiO_2$ interface damage
    - Increase impurity states at interface
- May change $V_{bd}$, leak current, gain, noise, PDE, ..

# Radiation effects study

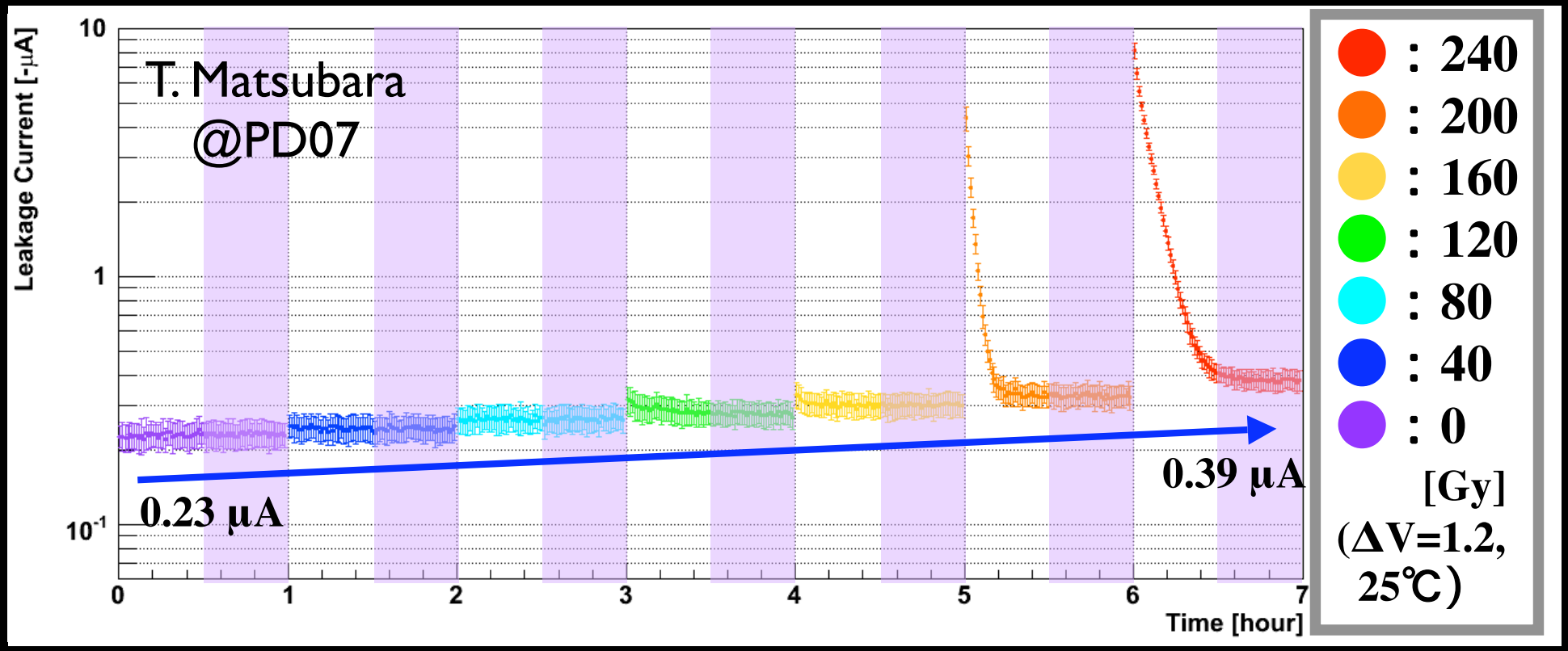
- Studied with irradiation of
  - γ-ray
  - electron
  - proton / neutron
  - heavy ion

Mainly interface damage

Bulk damage

# γ-ray irradiation

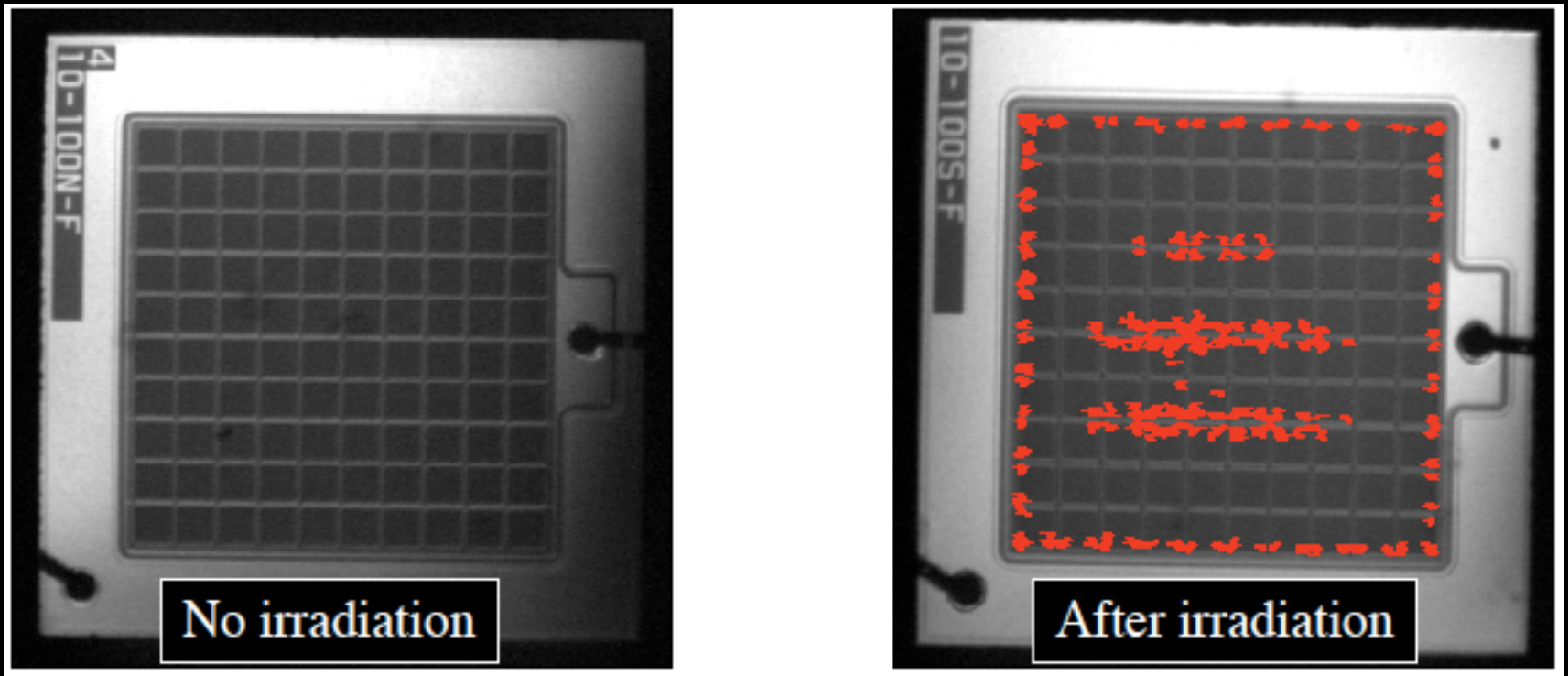
$^{60}Co$




- Leakage current after every 40Gy irradiation cycle
- Annealing observed

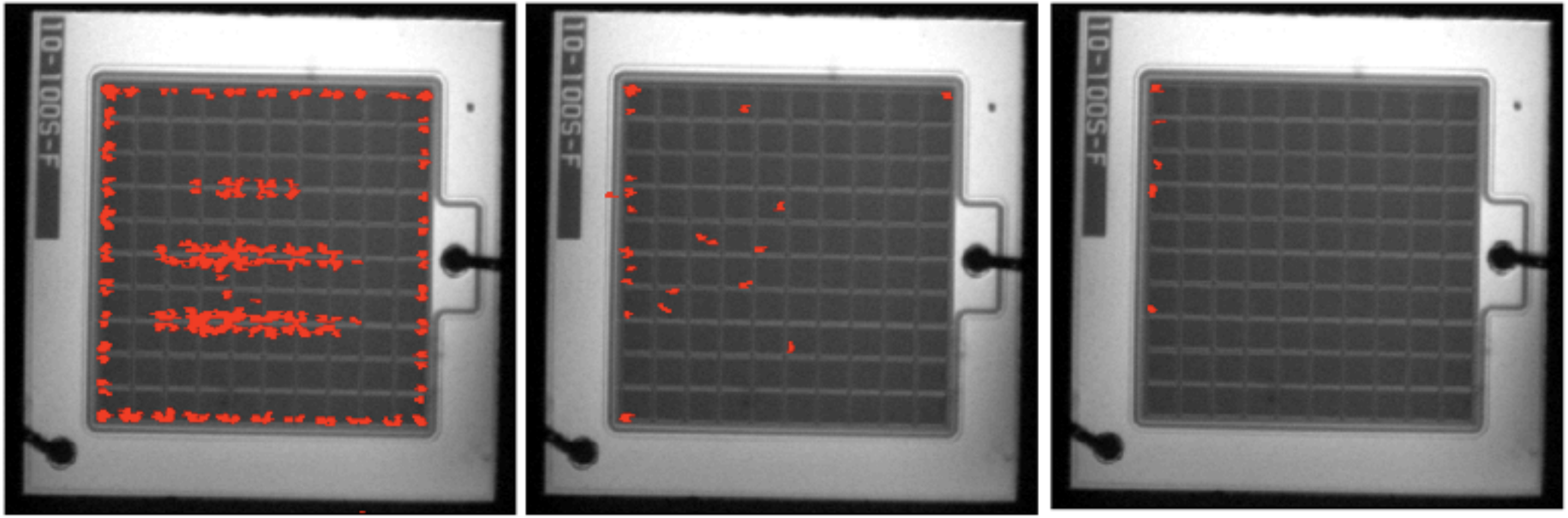
# γ-ray irradiation

- Tested upto 240Gy ($^{60}$Co).
- Effect on Si/$SiO_2$ interface. (small bulk effect)




T. Matsubara
@PD07

Picture with infrared camera



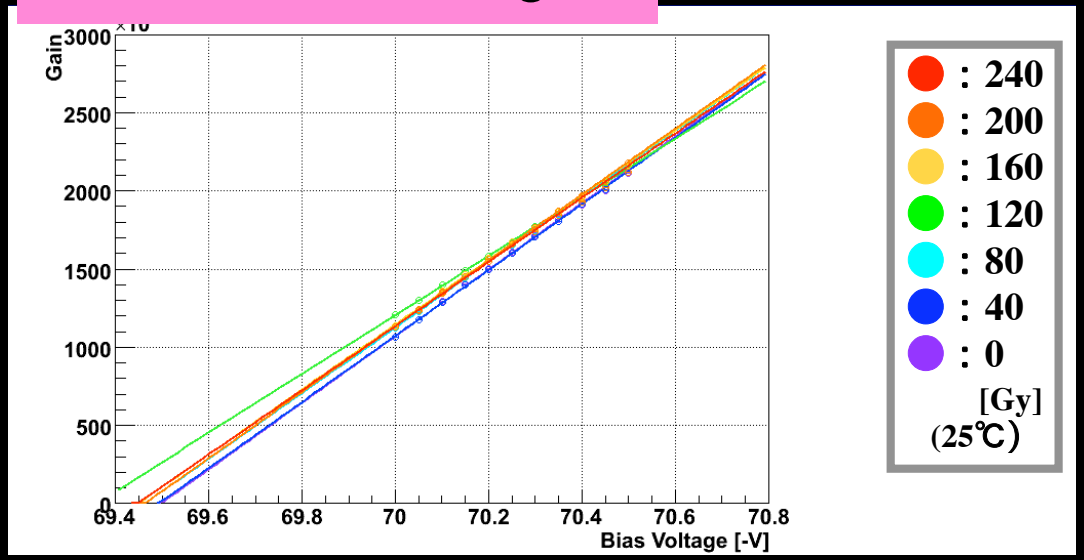

Just after voltage supplied | After 5 min. | After 10 min.

T. Matsubara
@PD07

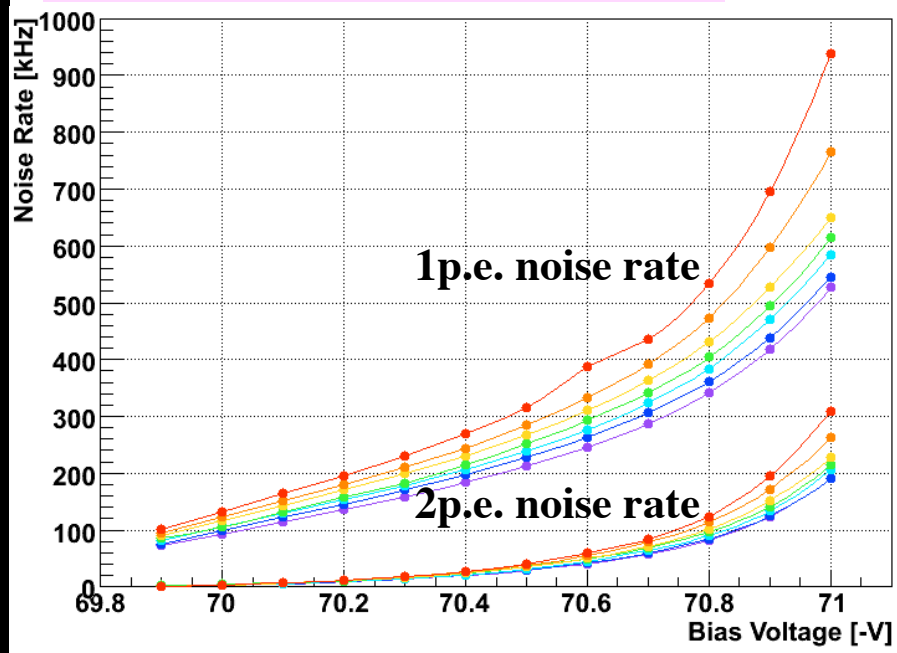
# γ-ray irradiation

T. Matsubara
@PD07

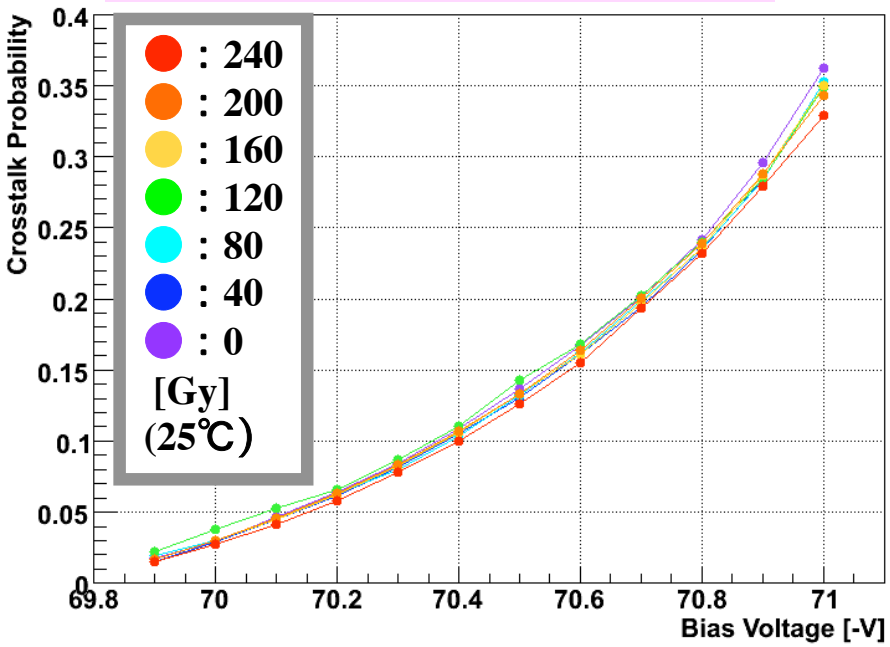
## Gain vs Bias voltage



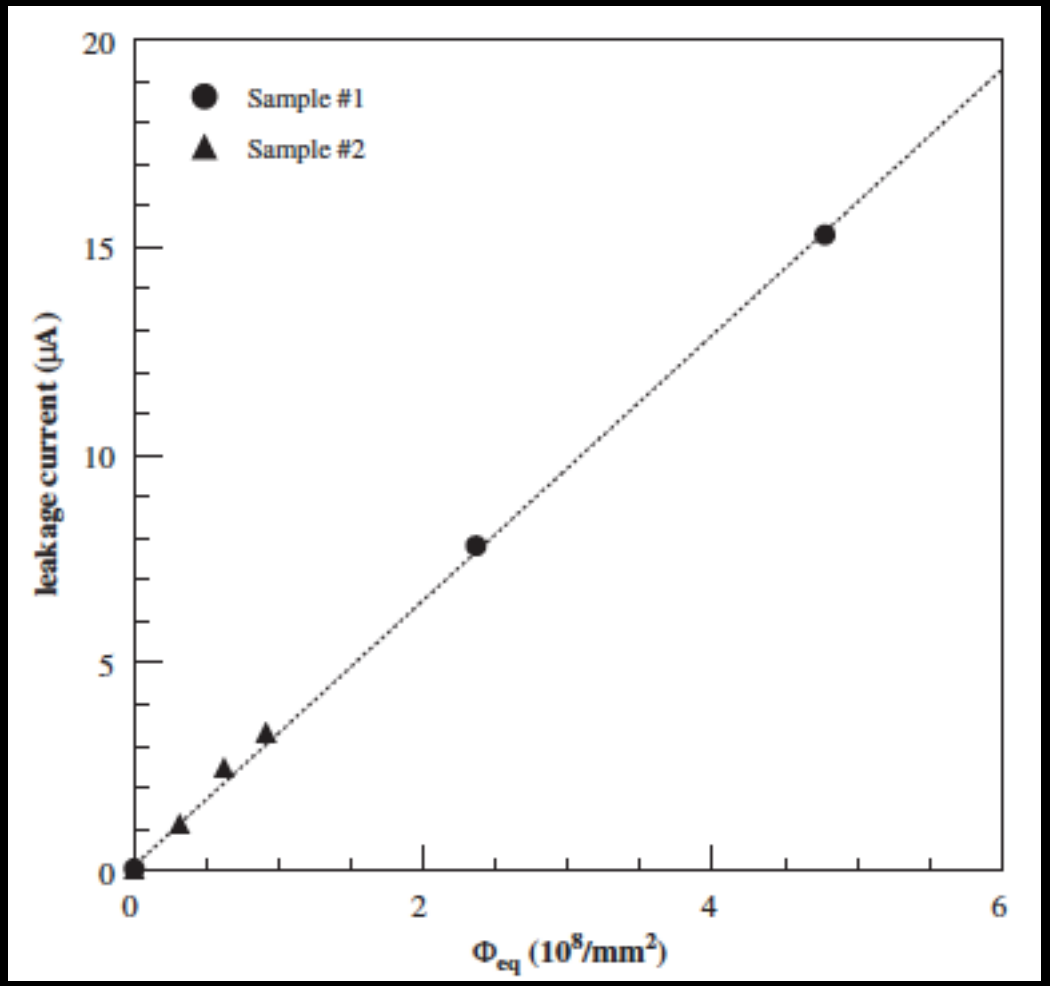

## Noise rate vs Bias voltage




## Crosstalk vs Bias voltage



# Proton irradiation



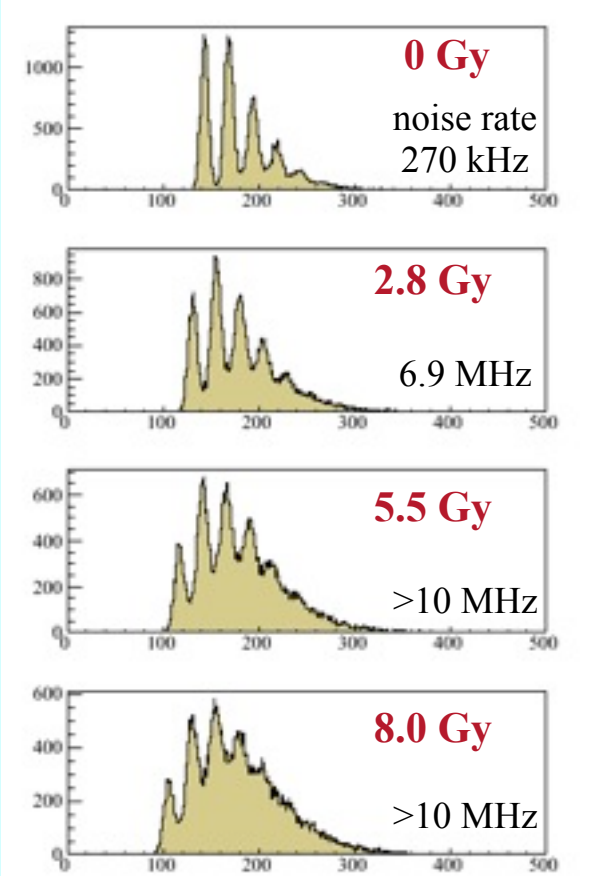

T. Matsumura et al.,
NIM A 603, 301 (2009)

1MeV n equivalent flux

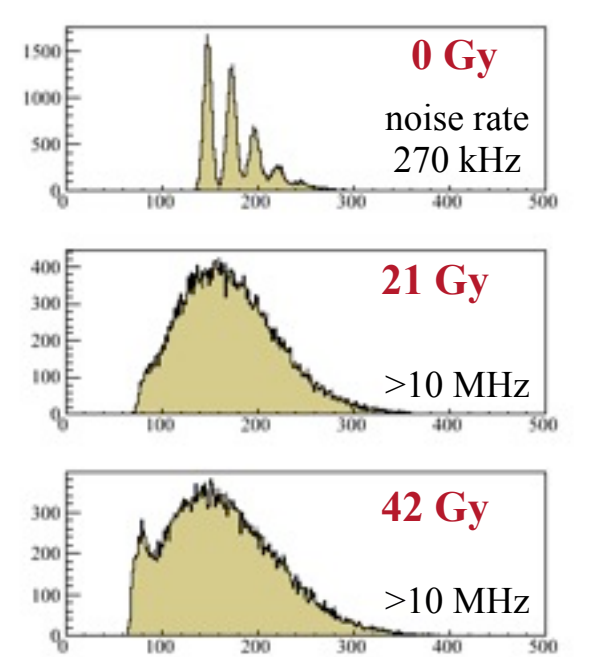
- Bulk damage → defect→ dark current

# Proton irradiation

**Sample #21** (16 Gy/h)




**Sample #20** (130 Gy/h)




gate width : 55 ns

Noise-rate measurements were limited due to scaler performance

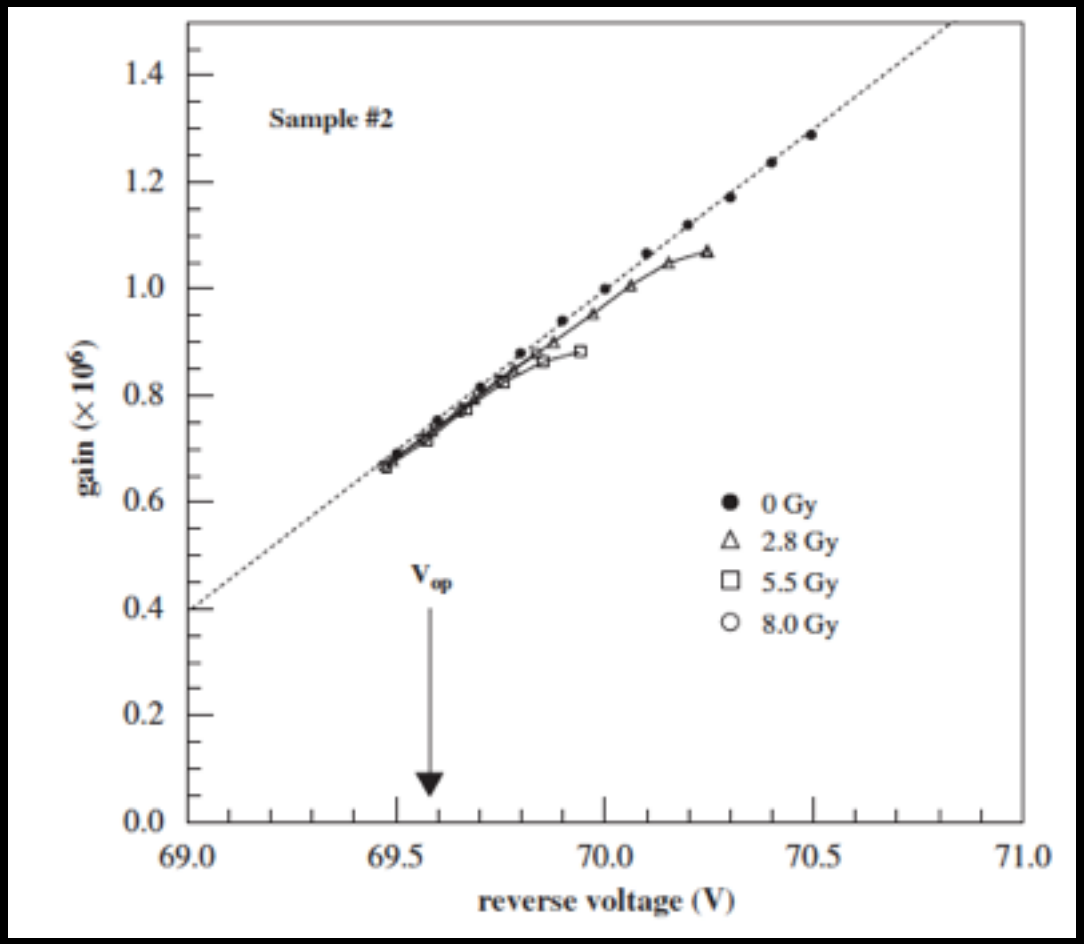
T. Matsumura @PD07

- Photon-counting capability is lost due to baseline shifts and noise pile-up after 21 Gy irradiation.

# Gain after proton irrad.

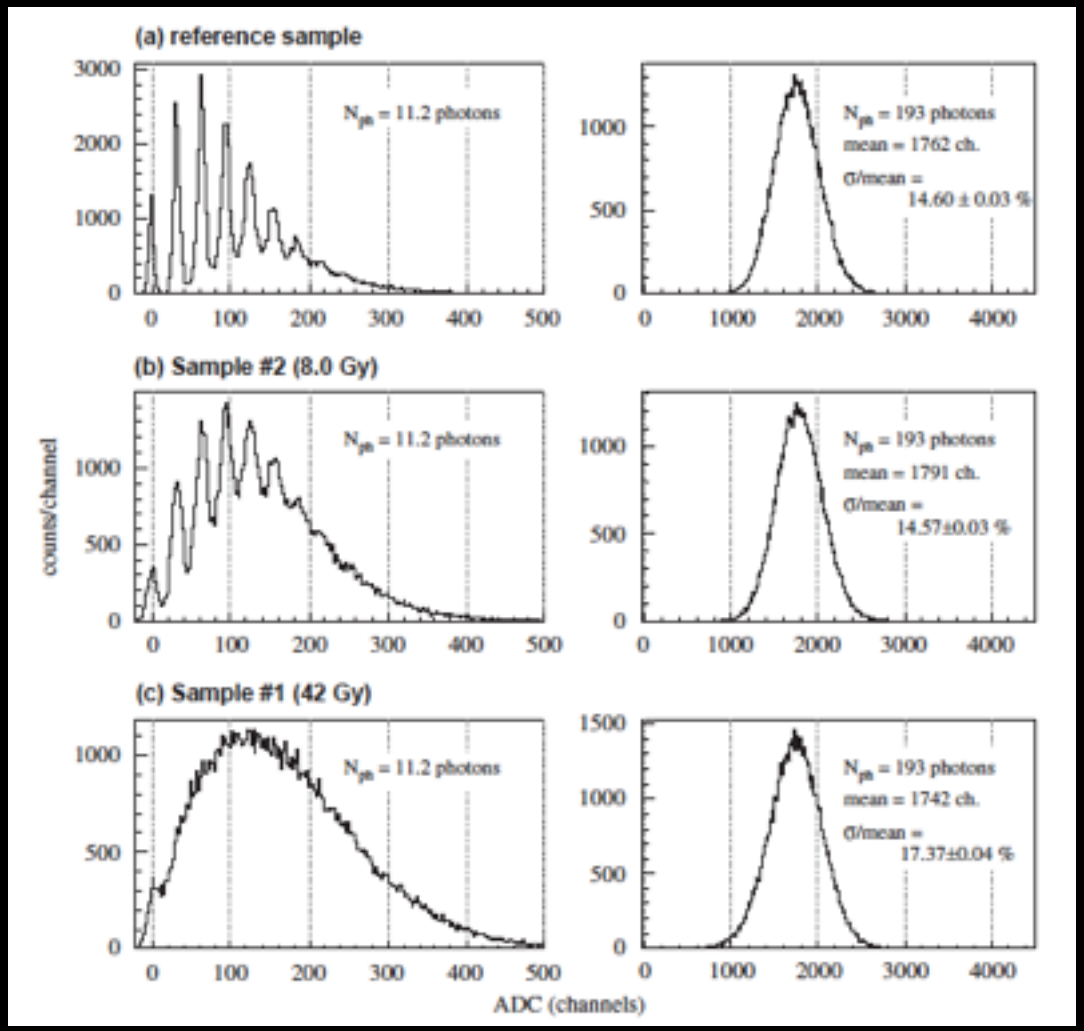
- No significant change (<3%) at normal operation point after 8Gy.
- Difficult to evaluate at higher V due to large noise.

T. Matsumura et al., NIM A 603, 301 (2009)



# Proton irradiation: after 1 year

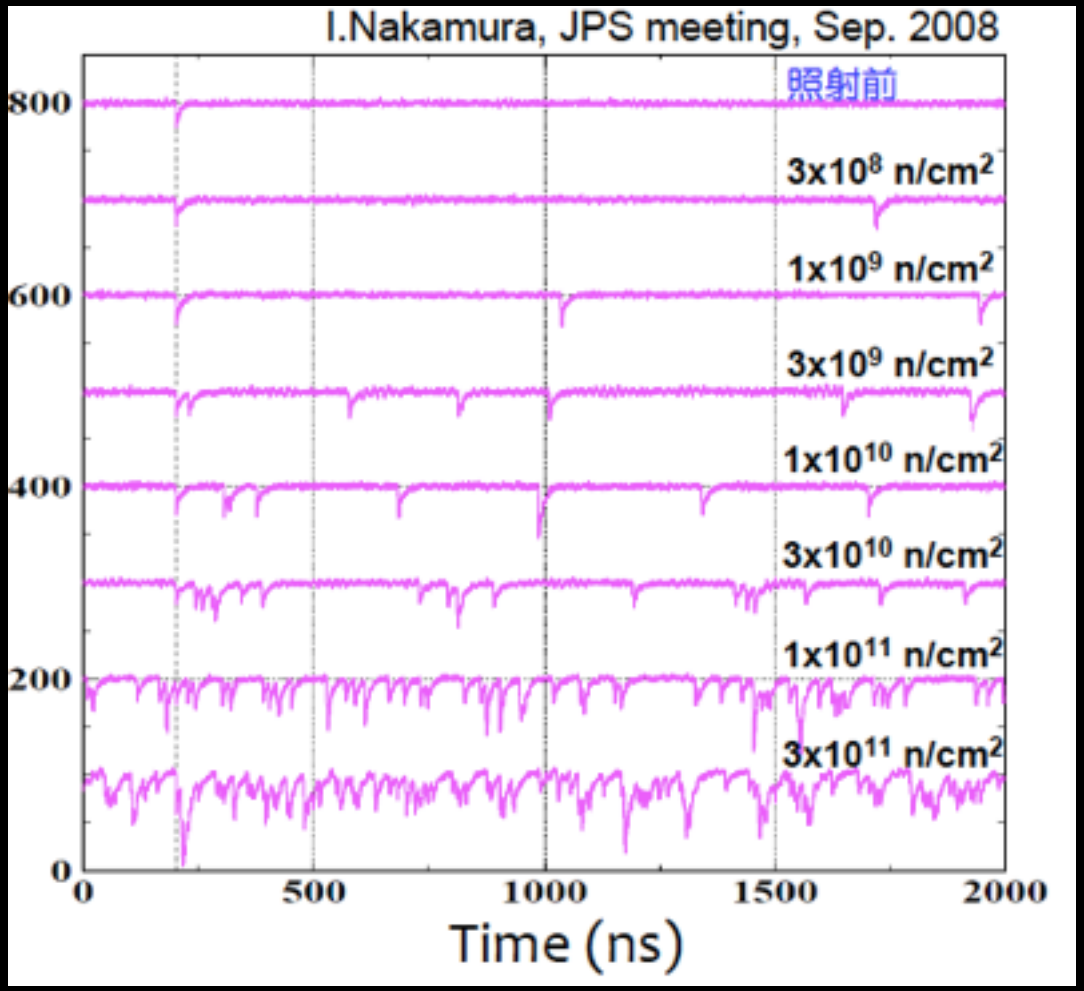
- Measurement 430 days after irradiation.
- Gain/PDE look the same as the non-irradiated reference.




T. Matsumura et al., NIM A 603, 301 (2009)

# Neutron irradiation

- Consistent result with proton irradiation.
- Bulk damage with non-ionization energy loss.



# Bulk damage

- Peak structure lost ~$10^{10}$ 1MeV n equiv /cm$^2$.
- Gain/PDE look the same upto $10^{11}$ n/cm$^2$.
- So far, no clear answer to how to improve it (as far as I know)
  - Study needed for use in high radiation environment (e.g. Super-B).
  - cf. 2-20x$10^{11}$ n/cm$^2$ expected for Belle-II PID.

# Long term stability

- MPPCs tested with acceleration by heat (~80°C)
- Study in Russia (INR): heated for ~1 month, no change in performance
  - Same for MRS-APD

O. Mineev et al., NIMA **557**, 540 (2007)

- Another study in US (LSU)
  - Heat cycle (80°C/20°C) every ~12 hr, no change after more than 1 year

# Robustness

- Among >60,000 MPPCs produced for T2K, O(0.1)% is broken after shipment (mostly by mishandling by students and professors)
- Tested against strong light (direct exposure to sunshine made no damage)

# Summary and next

- Today's topics
  - Dark noise, cross-talk, afterpulse
  - Radiation damage
- Tomorrow: practical issues
  - Example of major application: T2K
    - Testing large number of devices
    - Operation experience
  - Other applications
  - Device variation on the market
  - Future developments