Geiger-mode APDs
(3)

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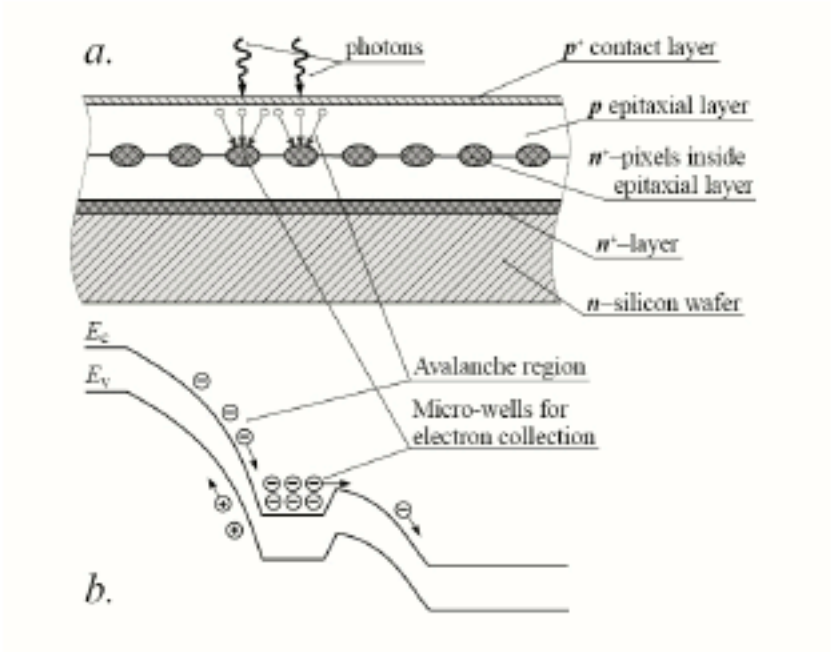
Plan for today

- Variation of device on market
- Example of application: T2K
  - Testing large number of devices
  - Some operation experience
- Other applications
- Future developments

Variation of device

Introduction of devices with special features

Devices with almost no saturation

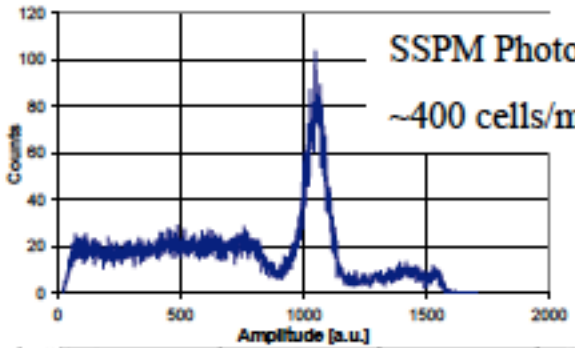


Taken from Z. Sadygov's contribution to NDIP08

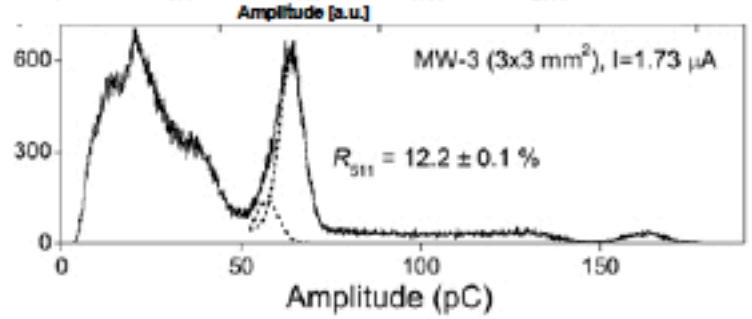
Zecotek produces 3x3 mm^2 G-APD's based on ideas of Z. Sadygov (JINR, Dubna).

The devices have a very high density of cells: 15,000 and 40,000 cells/mm^2.

The gain of 10^4 to 10^5 is relative low.



^{22}Na spectra measured with G-APDs and LYSO crystals



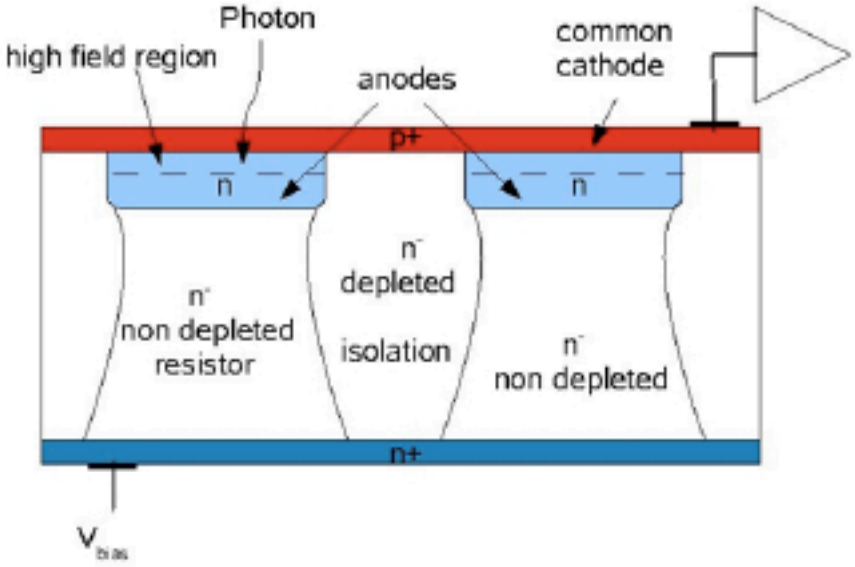
Zecotek

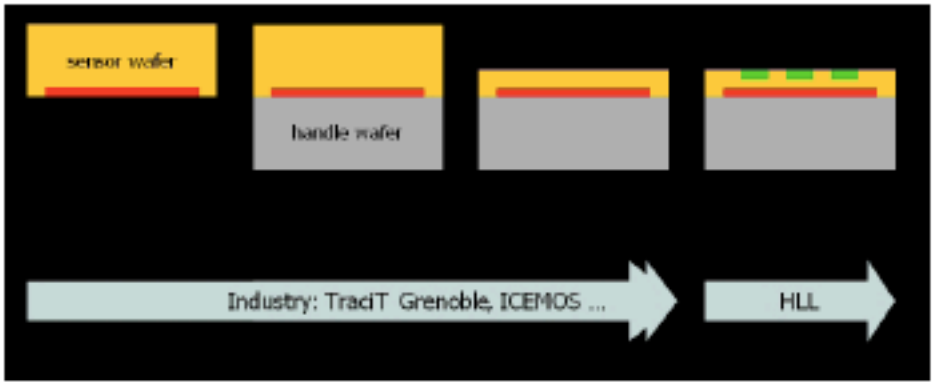
15000 cells/mm^2

D. Renker, PD09

SiMPI: G-APD with bulk integrated quench resistors from MPI-HLL

- geometric factor ~75 % - no resistor on the surface → PDE ~ 60 %
- free entrance window for light, no metal necessary within the array
- allows engineering of the entrance window
- improved radiation hardness – no lateral high field regions on the surface

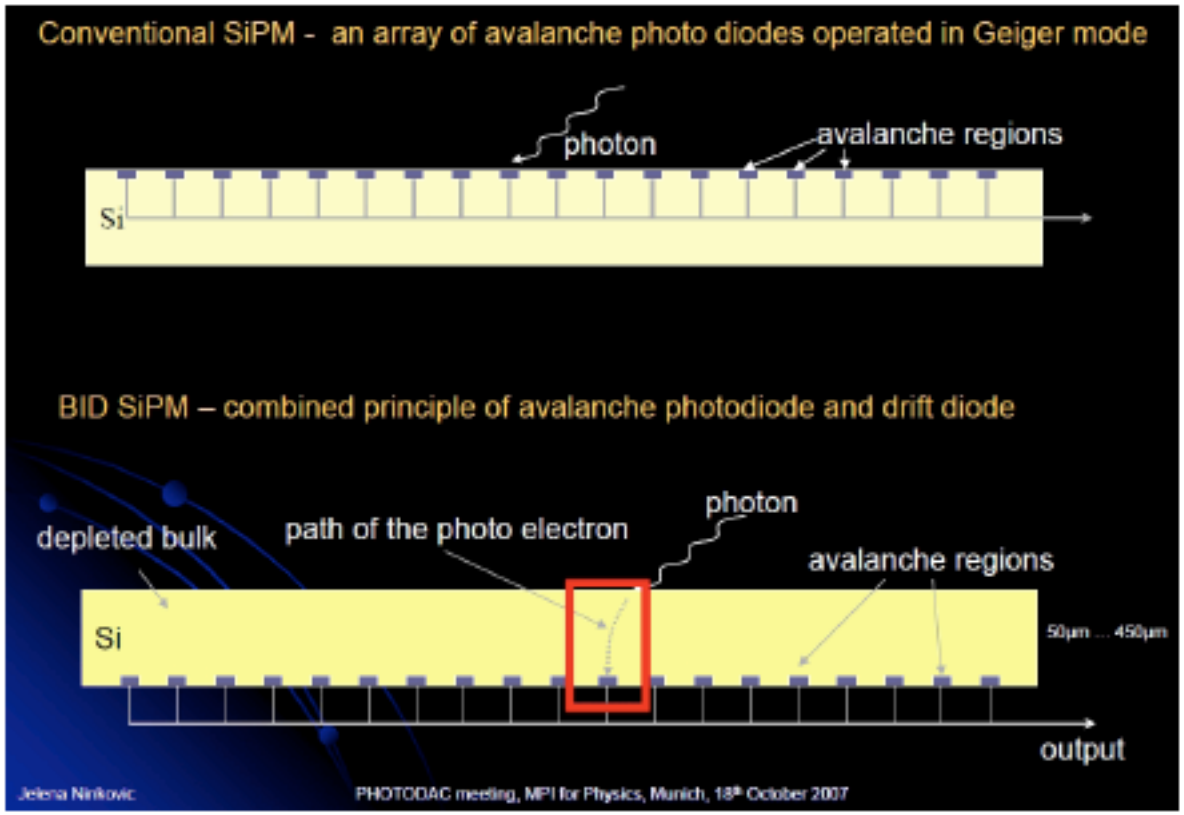


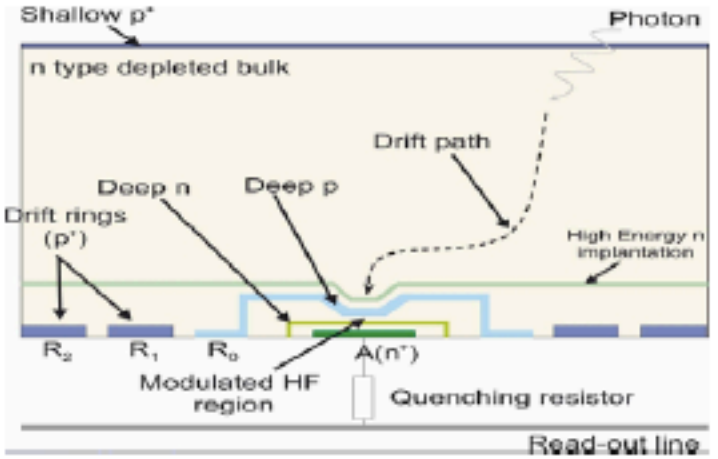


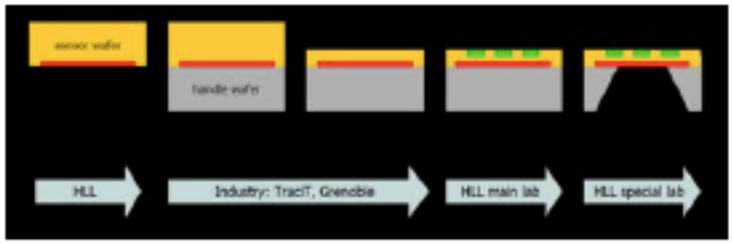
D. Renker, PD09

BID-SiPM: Back illuminated G-APD from MPI-HLL

- combination of drift diode and G-APD – geometric factor 100% → QE > 80%
- direct coupling of entrance window to scintillator (no wire bonds)
- bump bonding to a readout chip possible – signal detection for each cell





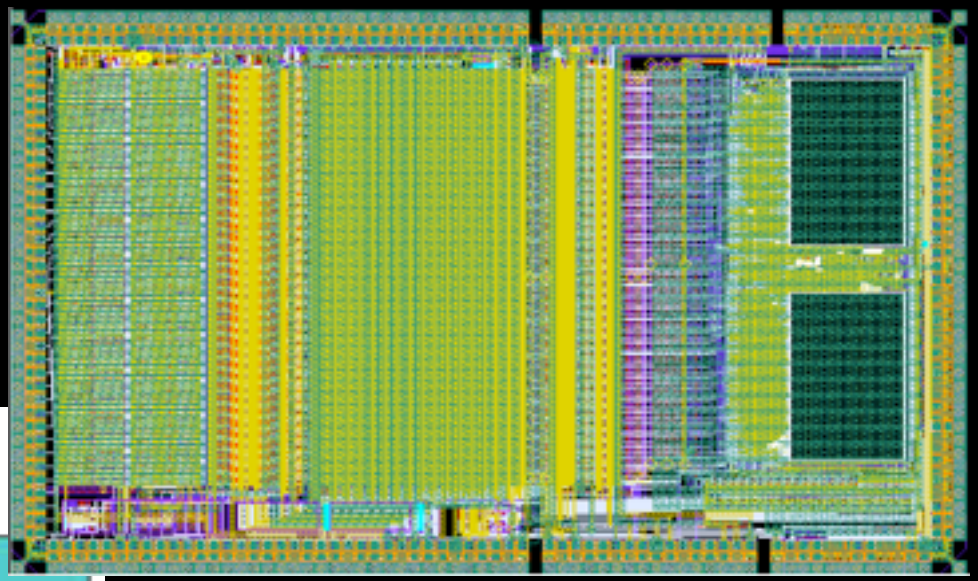


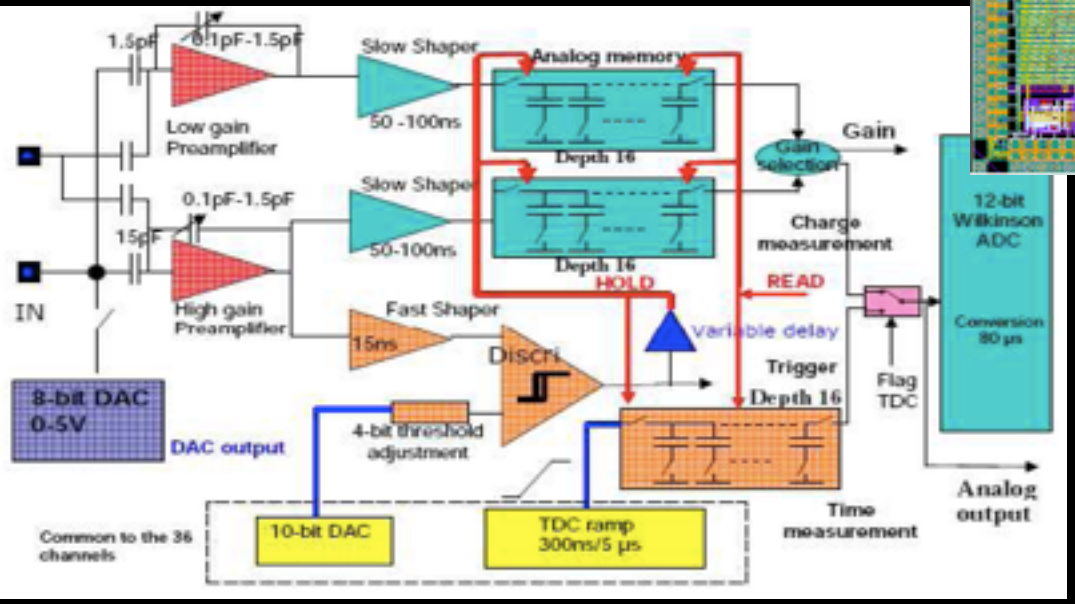
D. Renker, PD09

Readout

- Integrated readout is another place of intense R&D.

Example: SPIROC chip
by OMEGA/Orsay





arXiv:0911.1566
[physics.ins-det]

Application 1:
T2K neutrino experiment

First large scale (>10,000) application
in real experiment

T2K Experiment

- Long baseline neutrino experiment in Japan
  - Search for ν_e appearance from ν_μ beam
  - Precision measurements of ν_μ disappearance
- Start from April 2009

The T2K Collaboration

~500 members, 62 institutes, 12 countries

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
U. Aachen

Italy
INFN, U. Roma
INFN, U. Napoli
INFN, U. Padova
INFN, U. Bari

Japan
Hiroshima U.
ICRR Kamioka
ICRR RCCN
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
U. Tokyo

Poland
A. Soltan, Warsaw
H.Niewodniczanski, Cracow
T. U. Warsaw
U. Silesia, Katowice
U. Warsaw
U. Wroklaw

Russia
INR

S. Korea
N. U. Chonnam
U. Dongshin
U. Sejong
N. U. Seoul
U. Sungkyunkwan

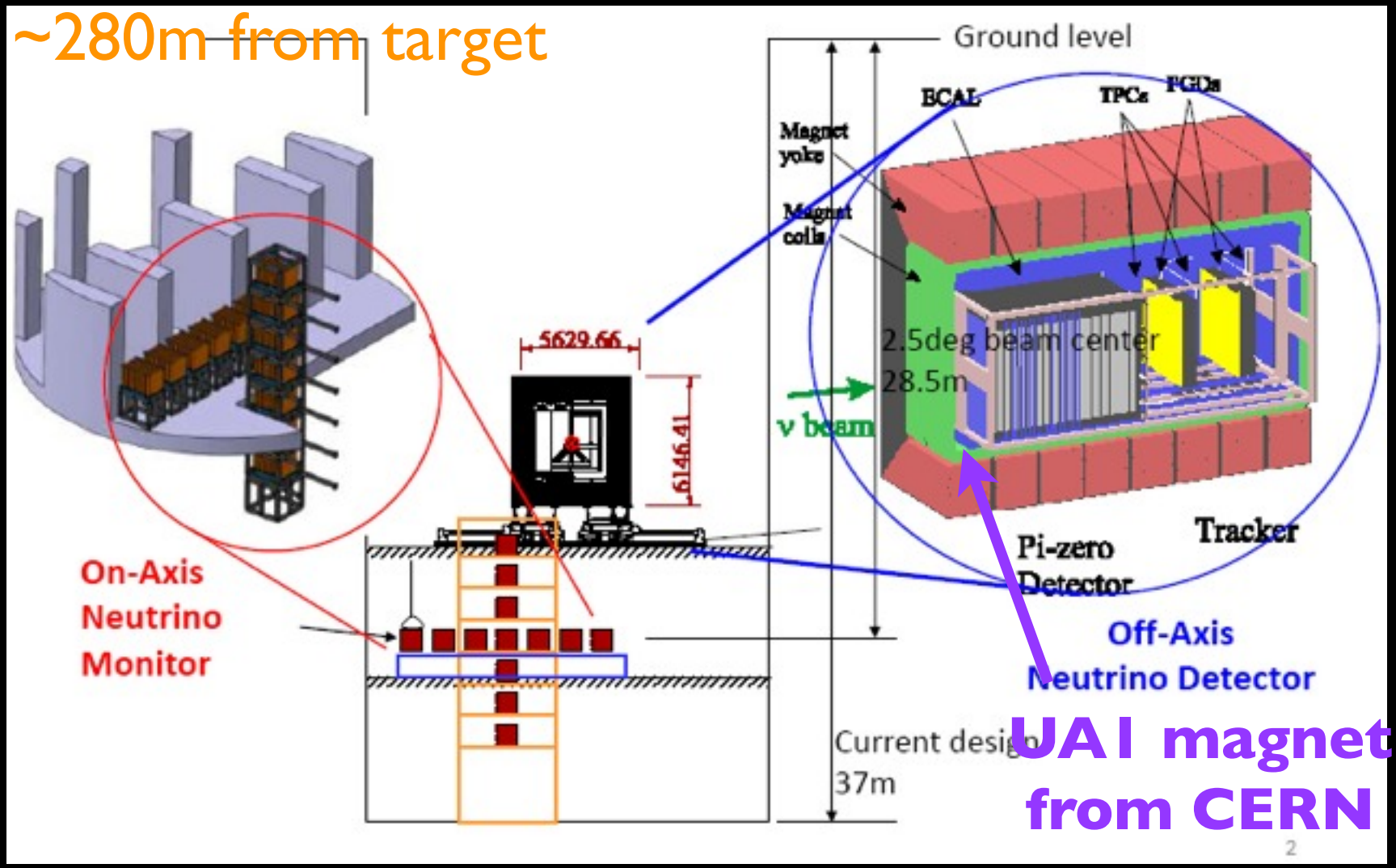
Spain
IFIC, Valencia
U. A. Barcelona

Switzerland
U. Bern
U. Geneva
ETH Zurich

United Kingdom
Imperial C. London
Queen Mary U. L.
Lancaster U.
Liverpool U.
Oxford U.
Sheffield U.
Warwick U.
STFC/RAL
STFC/Daresbury

USA
Boston U.
B.N.L.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

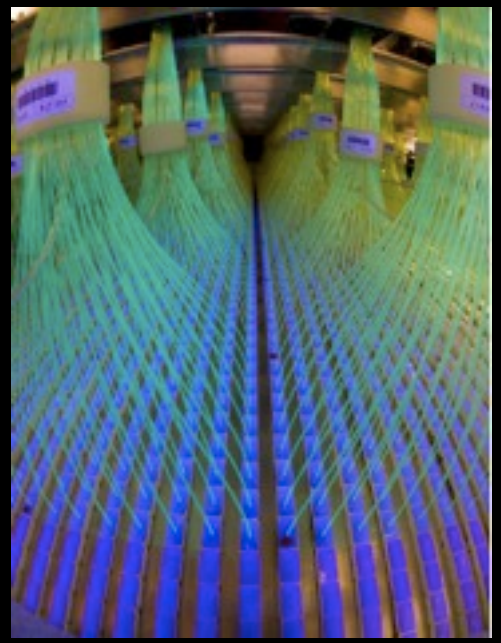
T2K Near Detectors



Several complimentary sub-detectors to fully characterize neutrino beam at production.

Common elements: WLS fiber readout + MPPC

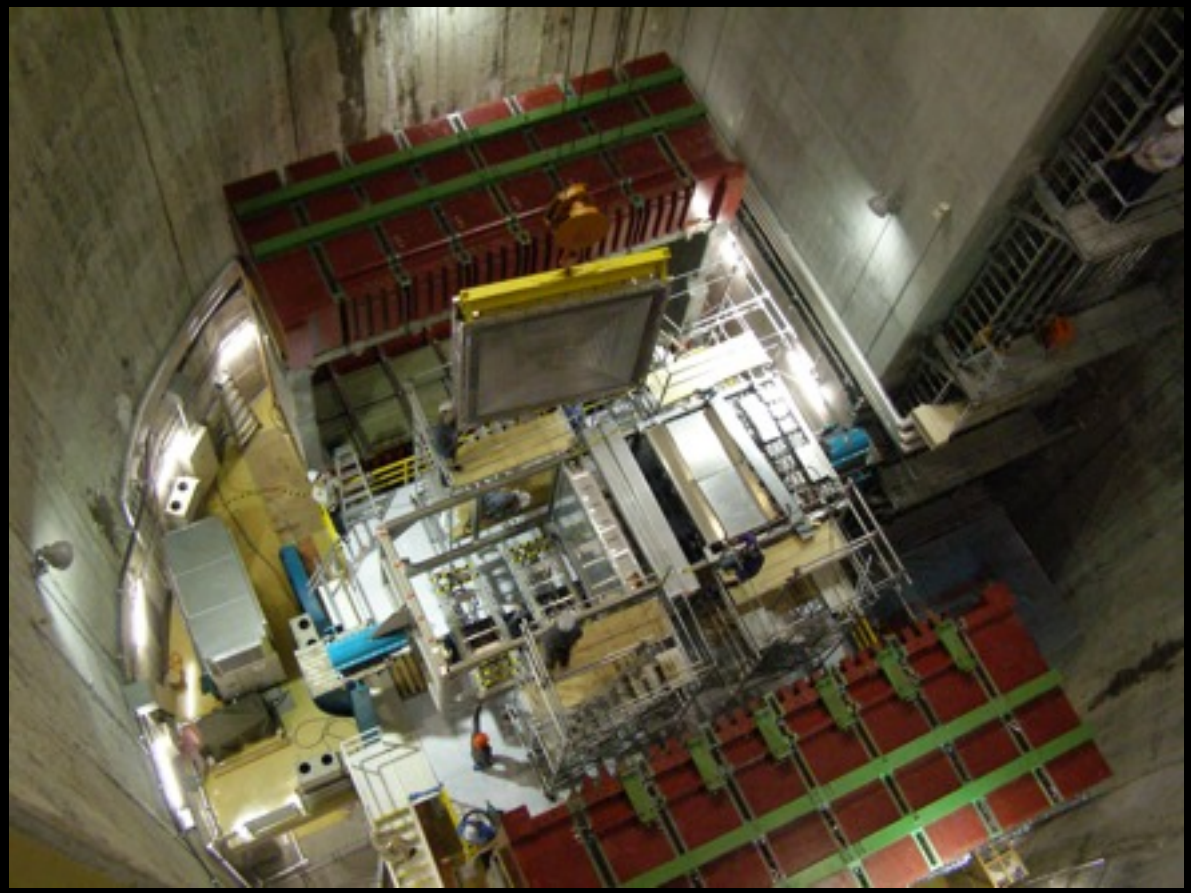
- All but TPC use plastic scintillator + wavelength shifting fiber + photosensor
  - Successful in recent neutrino detectors (K2K-SciBar, MINOS, MINERvA, SciBooNE, ...) with MA-PMT
- Photosensor matched with fiber readout needed (+operational in B-field, compact) ⇒selected MPPC in Aug. 2005



and worked with Hamamatsu and KEK-DTP (KEK detector technology project, lead by J. Haba)

Detector built, installed and under commissioning...

'INGRID' on-axis detector

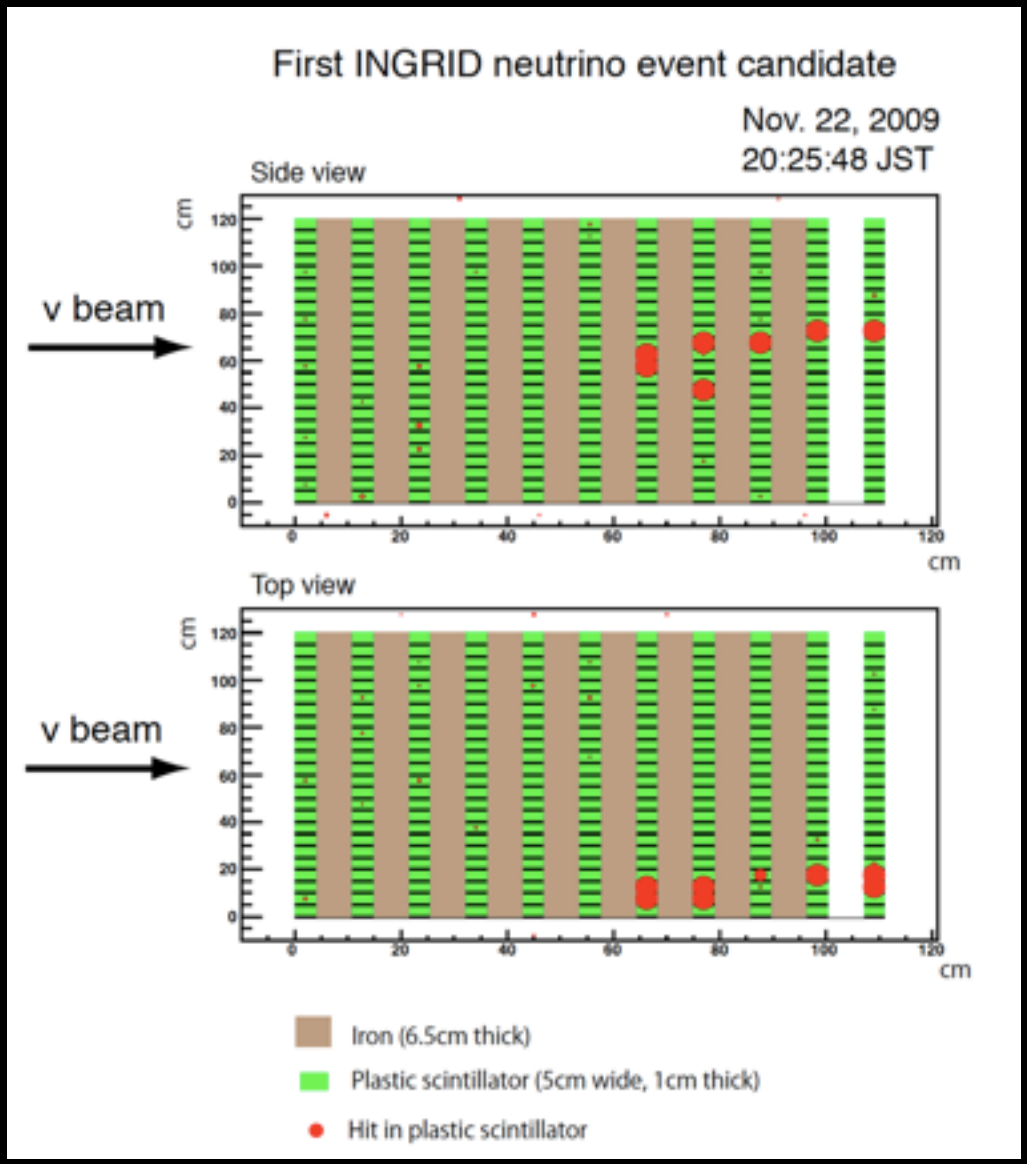


Off-axis detector complex installation in October

Just saw the neutrino!

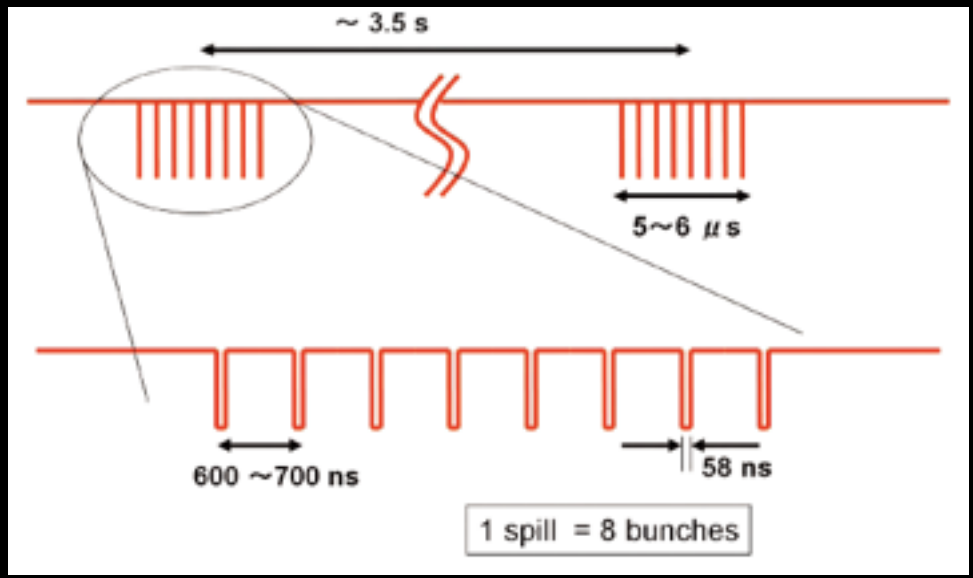
22 Nov. 2009
(one day before LHC first collision)

First neutrino interaction detected with SiPM technology!



Using MPPC for T2K

- Magnetic field (0.2T) by UA1 magnet.
  - Space very limited inside magnet.
- Timing from accelerator available
  - Can largely suppress random noise
- Signal large (MIP), not 1pe level
- Rare interaction (signal) probability = no high rate issue
- Calibration triggers b/w beam spills

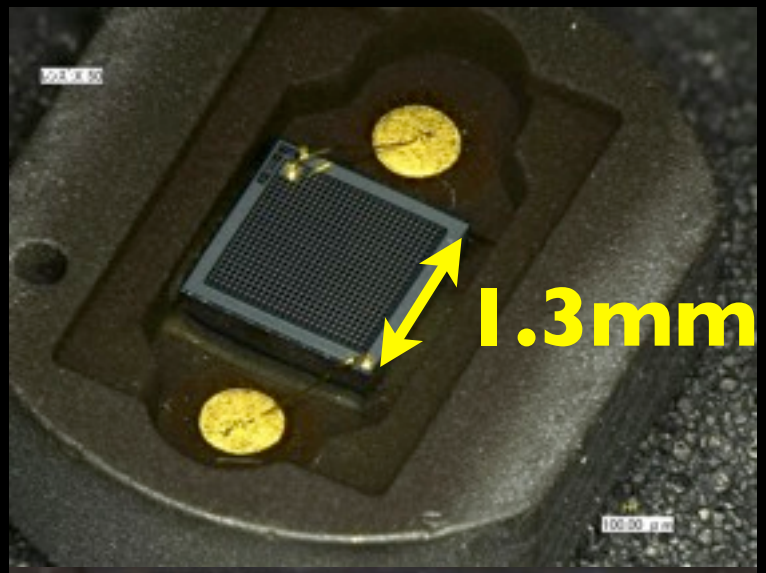


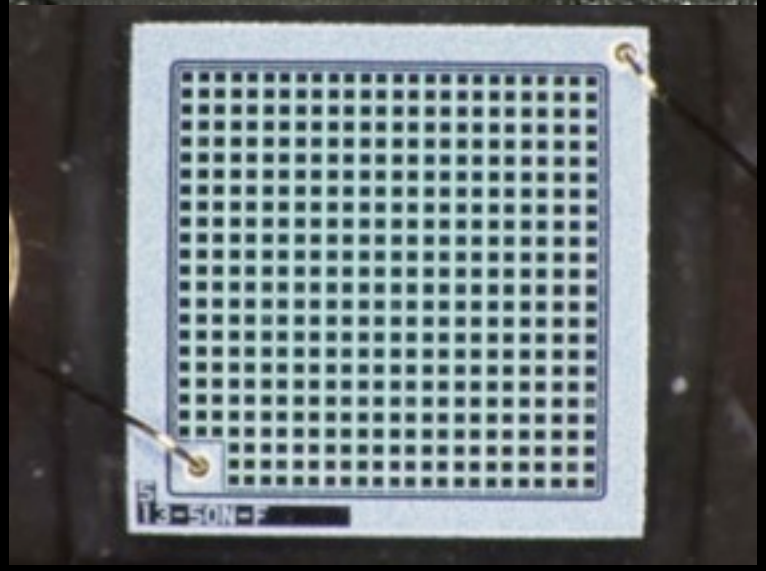
MPPC Spec for T2K

Item	Spec
Active area	1.3×1.3mm^2
Pixel size	50×50μm^2
Number of pixels	667
Operation voltage	70V (typ.)
Photon detection eff. @ 550nm	>15%
Dark count (gain=7.5×10^5)	<1.35Mcps(0.5pe) <0.135Mcps(1.5pe)
Number of device	**~60,000**
Price (with 60 kpcs order @ Dec. 2007)	1,900 JPY

S10362-13-050C

Specially developed for T2K





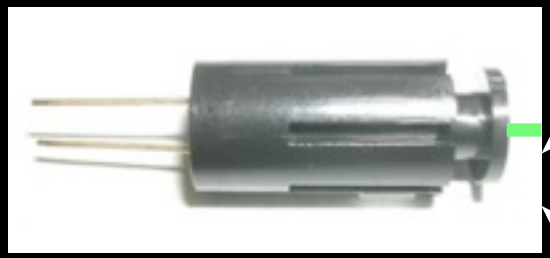
Coupling to fiber

- Connector developed at Kyoto U.

H.Kawamuko et al.,
PoS PD07:043,2006

MPPC holder Fiber ferrule

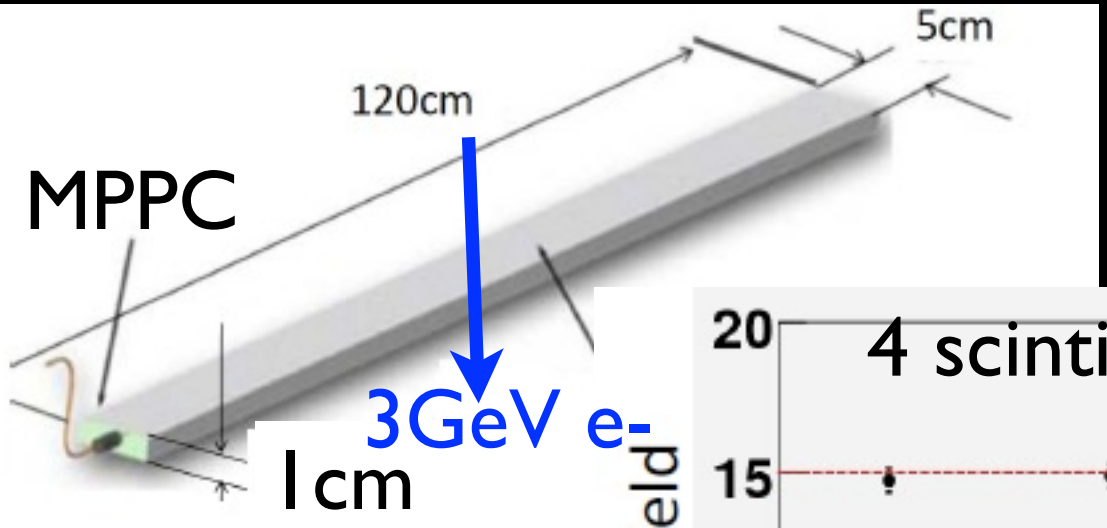
Black polyacetal



(* several types developed for T2K.)

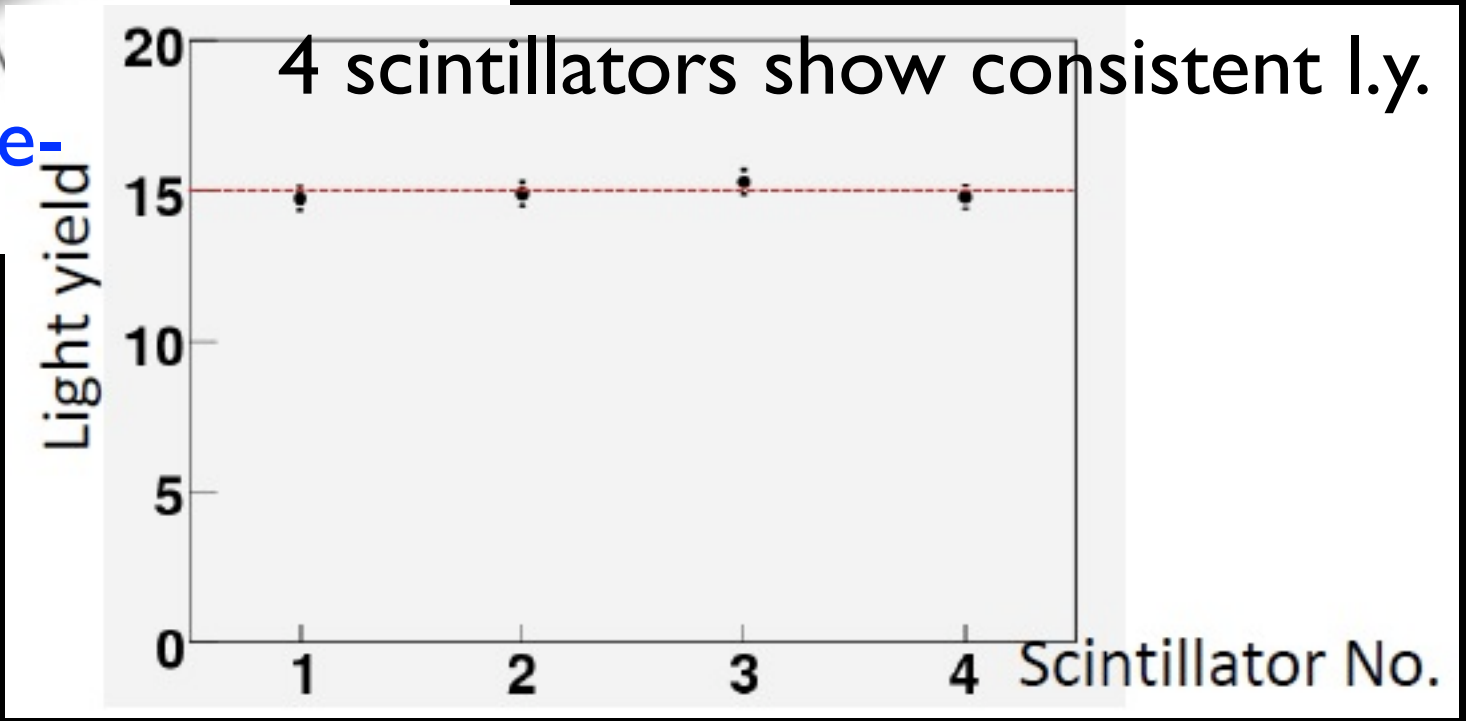
- Easy reattachment with good reproducibility.
- Fiber is glued with optical cement after polishing.
- Air gap b/w fiber and MPPC.
- Light loss at contact: 13% with 1x1mm^2 MPPC.

Light yield with scintillator



~25°C
ΔV=1.5V

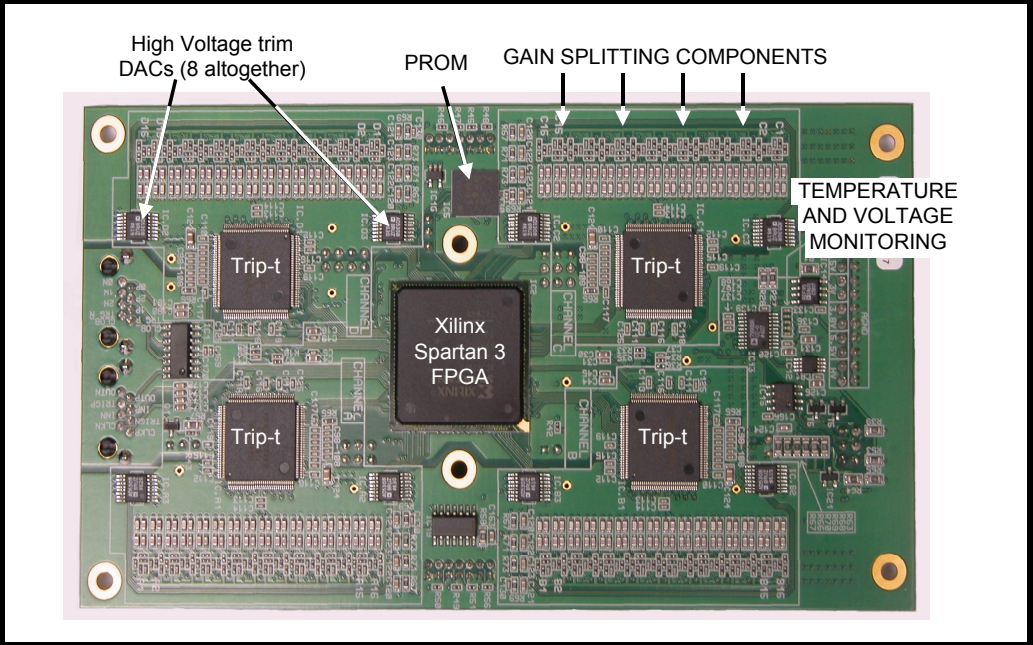
Scintillator for on-axis detector



- ~15p.e. with WLS fiber (Y11, 1mm dia.) and real scintillator (produced at Fermilab).

Readout electronics

- Two options of readout ASIC
  - Trip-t AISC (developed at Fermilab)
  - AFTER ASIC (Saclay)



Trip-t frontend board developed in UK

AFTER electronics by Saclay

Trip-t based electronics

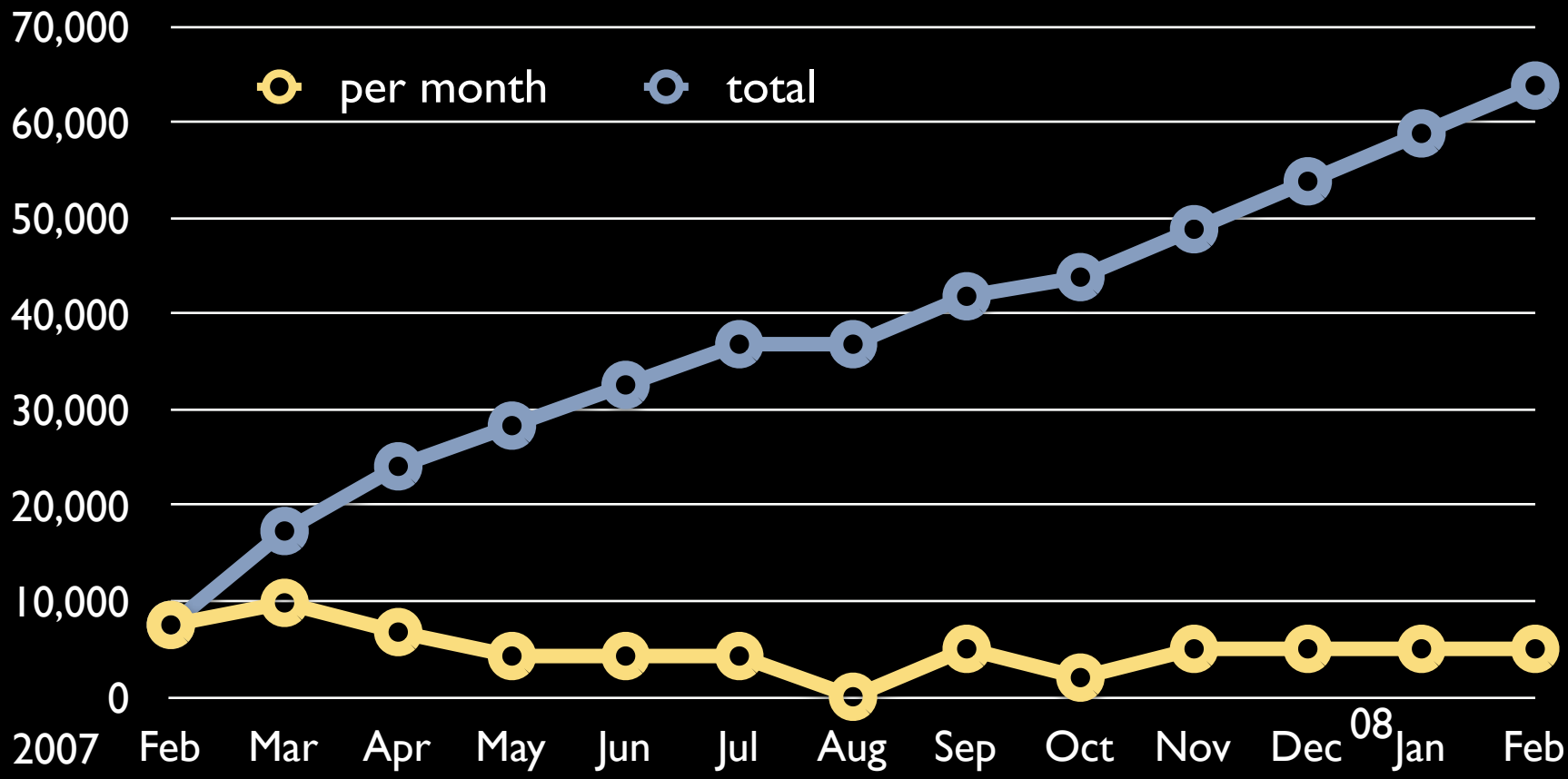
- ASIC originally developed for D0 tracker (VLPC)
- RAL/UK group designed/produced FE/BE boards
  - ADC w/ integration amp
    - with 48 cell analog pipeline
    - Use 2 channels for 1 MPPC (high/low gain)
  - TDC timestamp
  - Fast discriminator timing for triggering
  - HV trim for each channel (5V range)
  - Monitoring of temperature onboard & external

Production and testing of MPPCs

Production

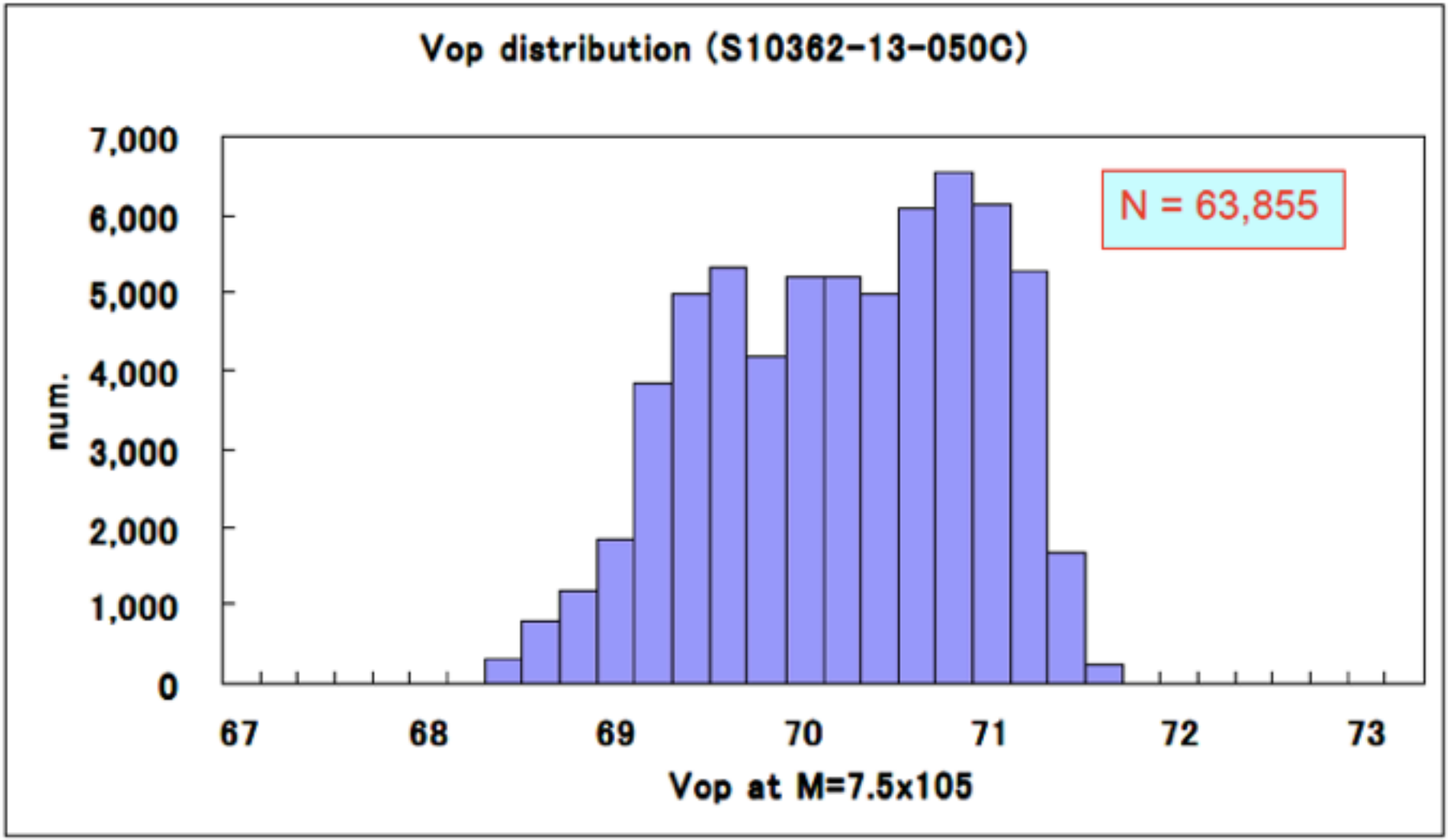
- Went quite well! (relief to MY as project leader)
  - Excellent work by Hamamatsu.
- 63,855 pcs delivered in ~1 year.
- Typical delivery rate ~5,000 pcs / month
  - Limited mainly by testing capability before shipment.

Progress chart

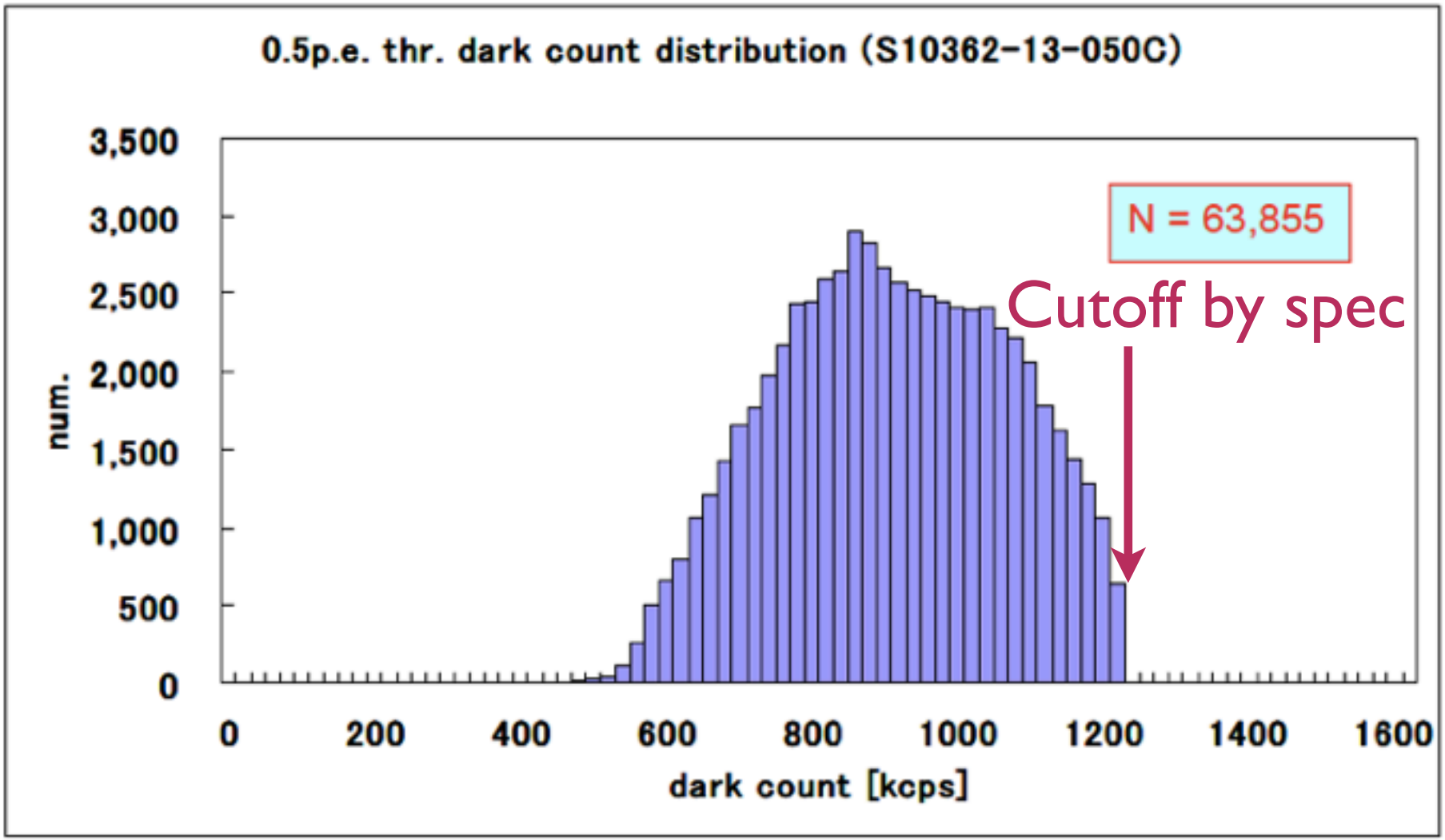


63,855 pcs delivered in one year.

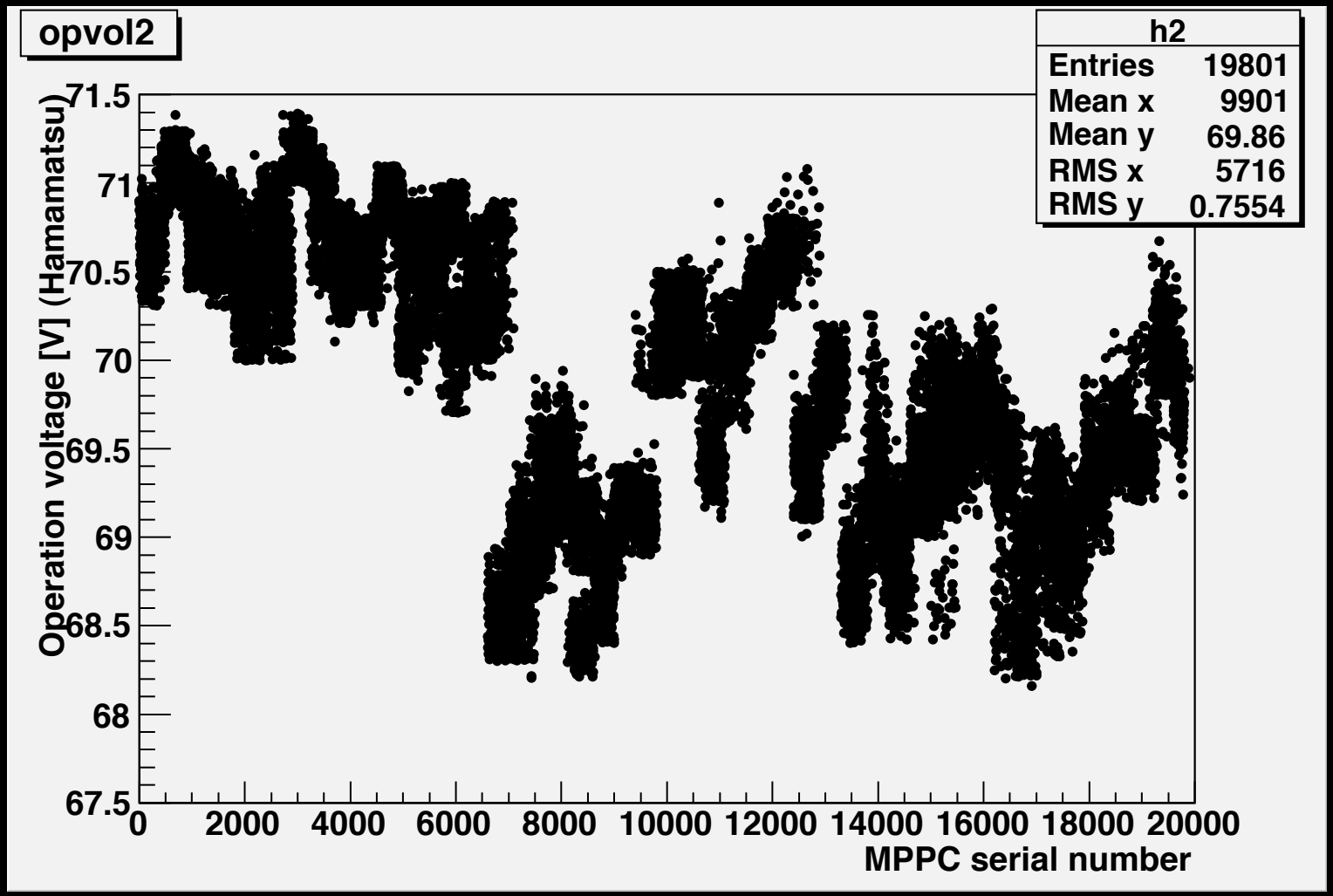
Distribution of operation bias voltage (Vop)



Distribution of dark count (0.5p.e. threshold)



Voltage at gain=7.5x10^5, 25°C (V_{op})



Data from Hamamatsu

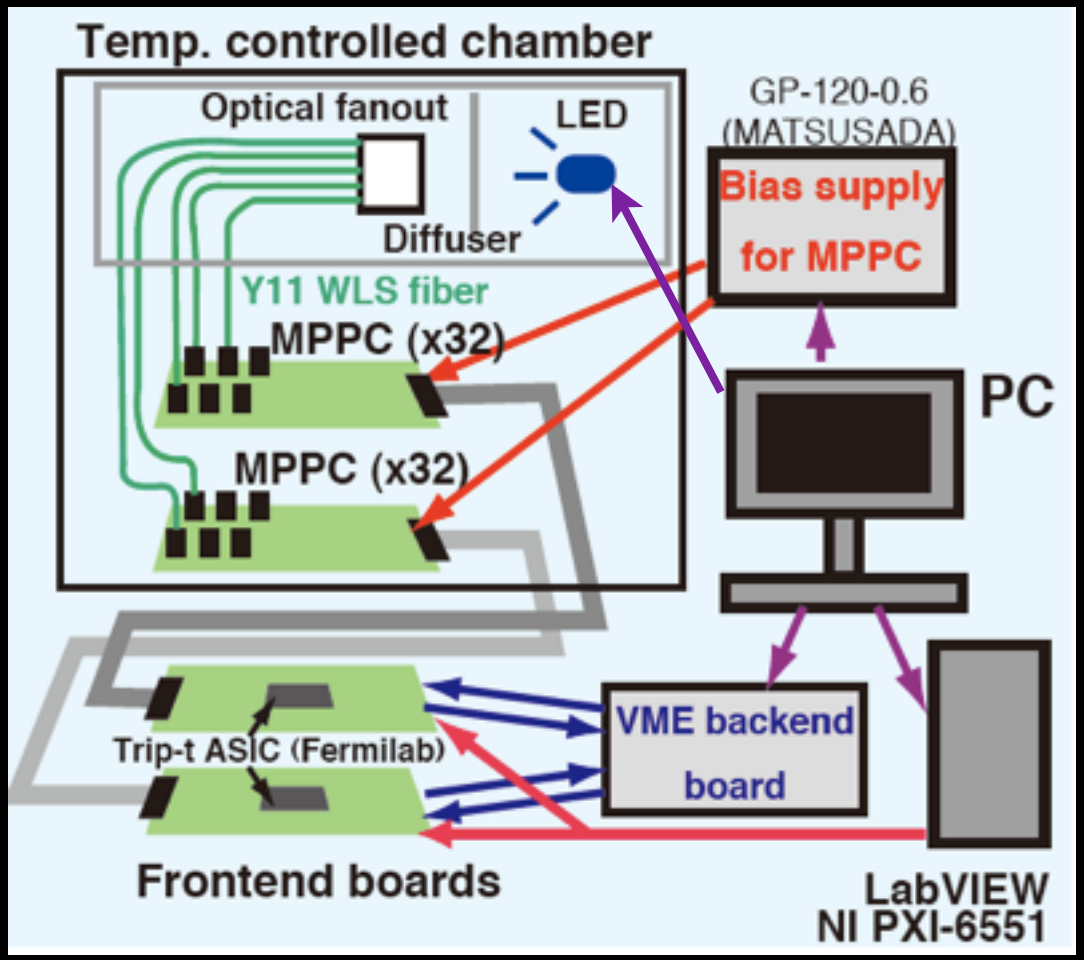
Testing MPPCs

- To characterize each MPPC.
  - Gain, V_{bd}, PDE, noise, cross-talk/afterpulse
  - Need to know voltage/temperature dependence.
- Need to measure many MPPCs at once.
- QA rather than detail calibration.
  - Real calibration done *in situ*.

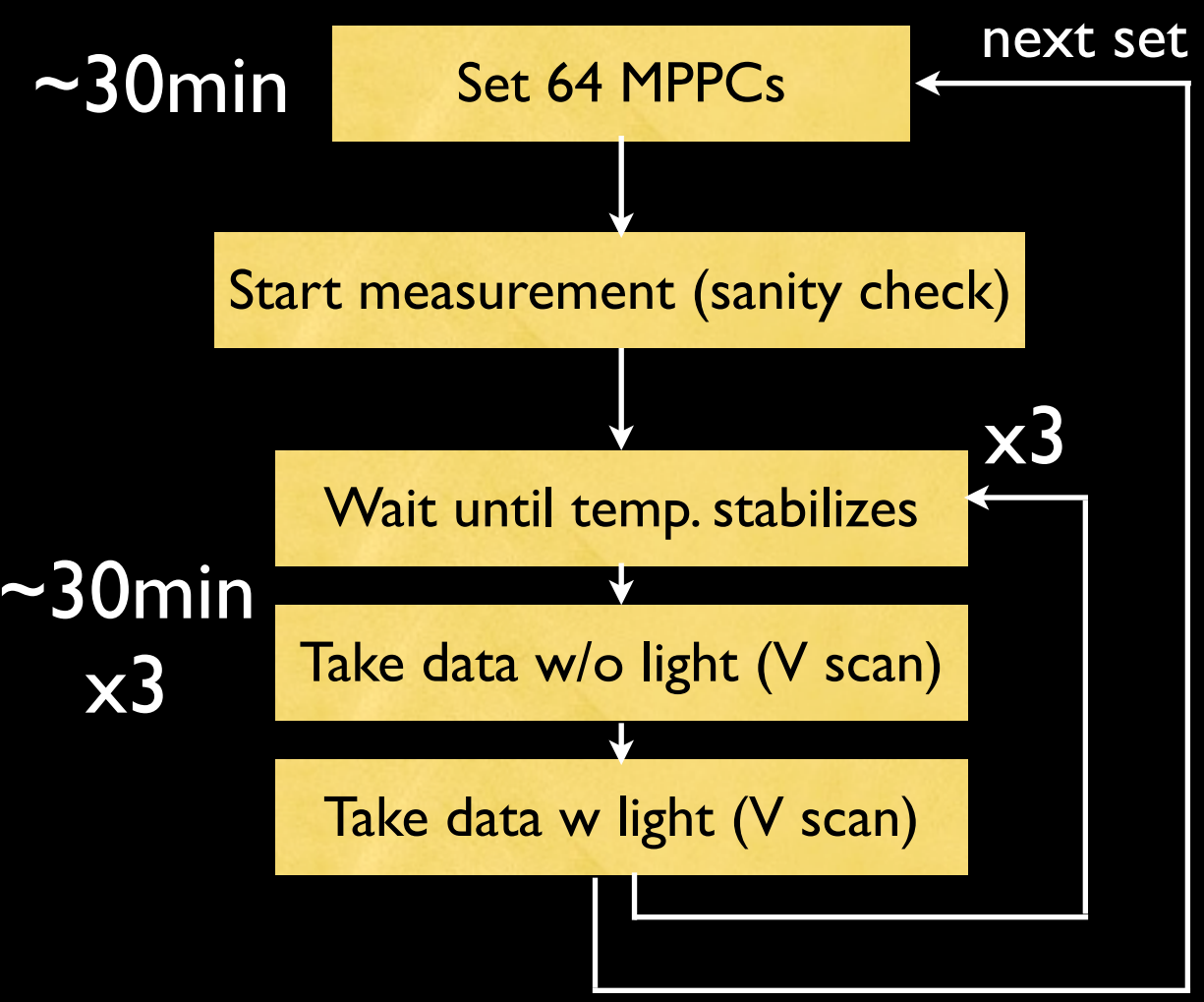
M. Yokoyama @ NDIP08,
paper in preparation

MPPC test system

- Developed automatic data acquisition system.
  - 64 MPPCs at once
  - with and without light input
  - 0.1V step scan, ~0.8-2.0V above breakdown
  - at 15, 20, 25 °C

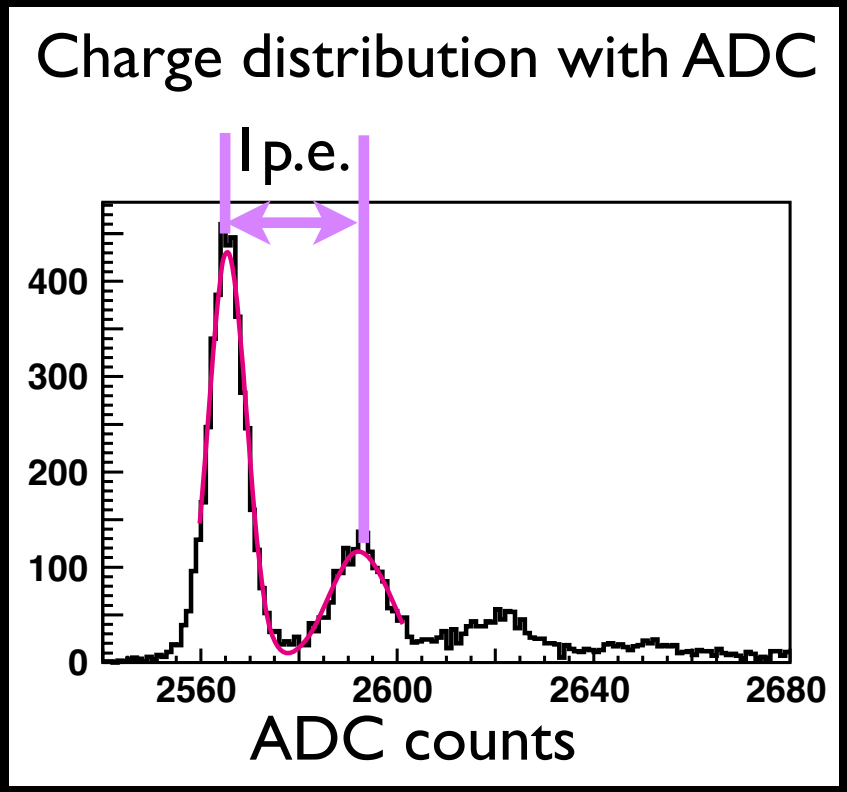


Measurement

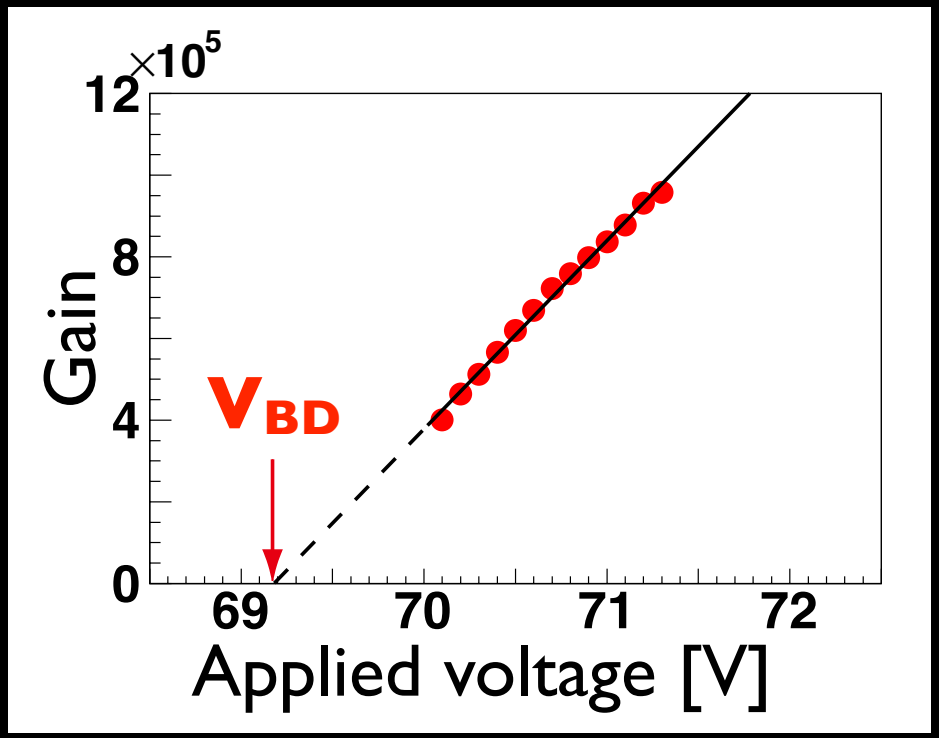


- Measure 64 MPPCs in 2hours.
- Upto 6 cycles/day
  →384 MPPCs/day

Gain and breakdown voltage



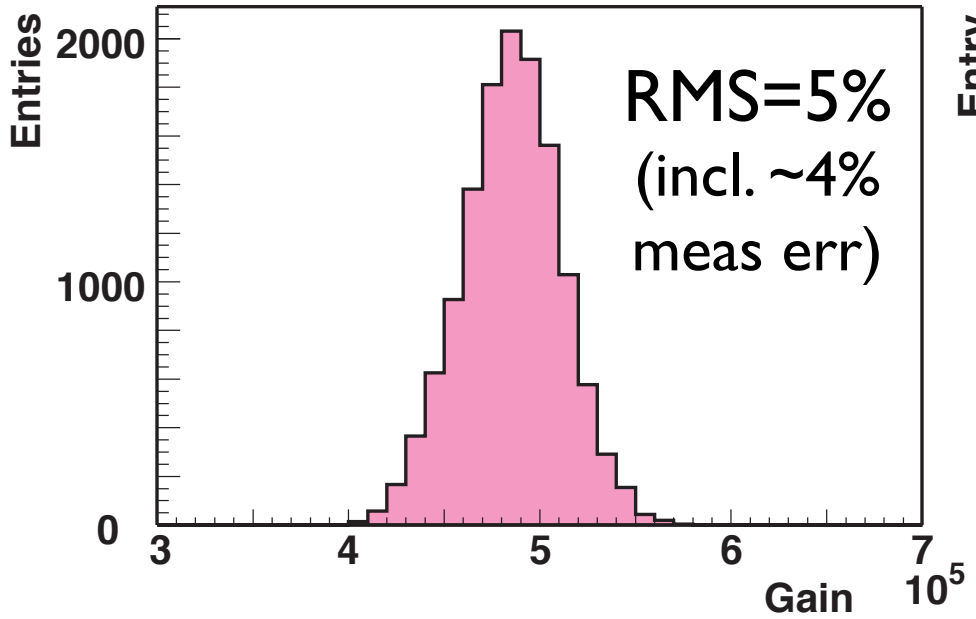
Gain easily measured with p.e. peaks in ADC distribution

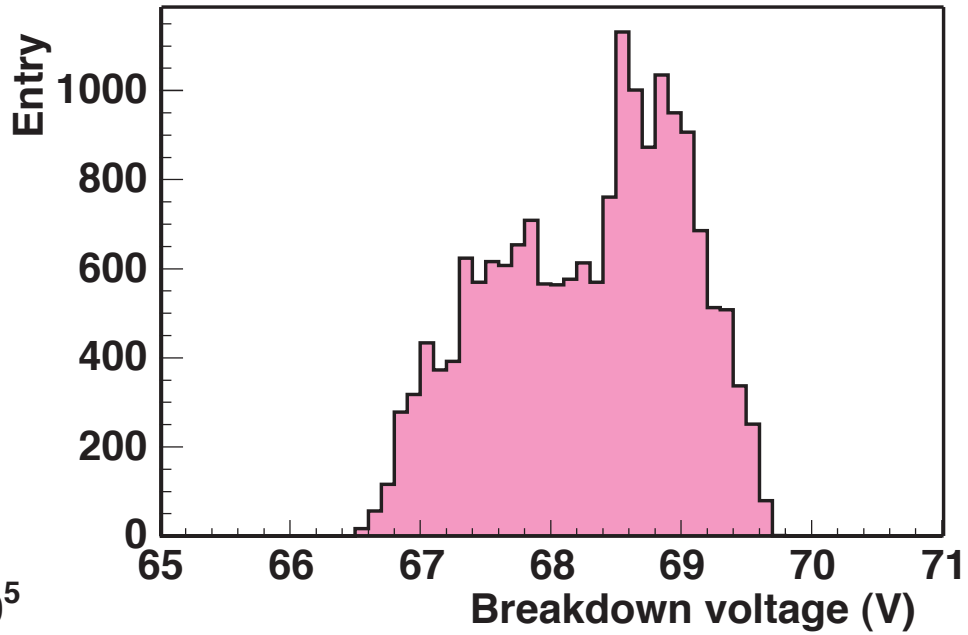


With linear extrapolation of V-gain, 'Breakdown voltage' (V_{BD}) defined as the point where gain=0

Gain/V_{BD} for T2K-MPPC

For 17,686 MPPCs 20°C





ΔV=1.0V

Good device uniformity.

Estimating number of avalanche

- Number of "no hit" events, N_0, not affected by cross-talk and afterpulsing.
  - Assuming Poisson distribution, fraction of N_0 in total events ≡ P_0 gives the true mean

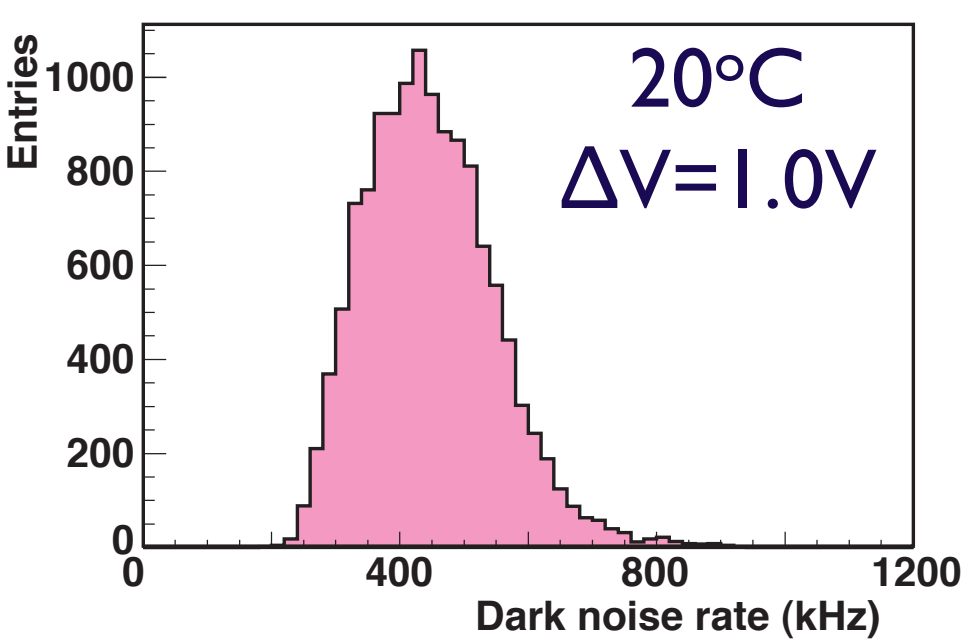
$$\mu = -\ln (P_0)$$

  - This definition will be used in the following.

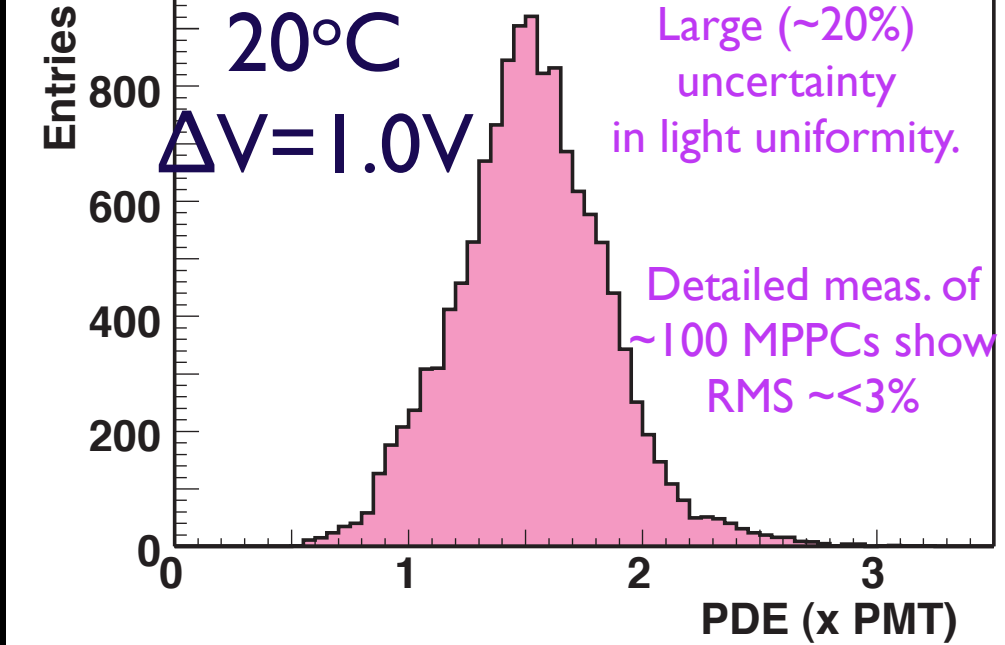
Commonly used technique to estimate number of 'signal' removing cross-talk/afterpulse effects.

Results

Dark noise rate defined by
(Number of avalanche)/(trigger time)



PDE measured relative to
bialcali reference PMT (~15% QE)



17,686 MPPCs

Average performance

S10362-13-050C

	ΔV=1.0V	ΔV=1.4V
Gain	5×10^5	7×10^5
Dark noise	450kHz	600kHz
Cross-talk +afterpulse	0.07	0.16
PDE (relative)	1.5	2.0

at 20°C

Operation

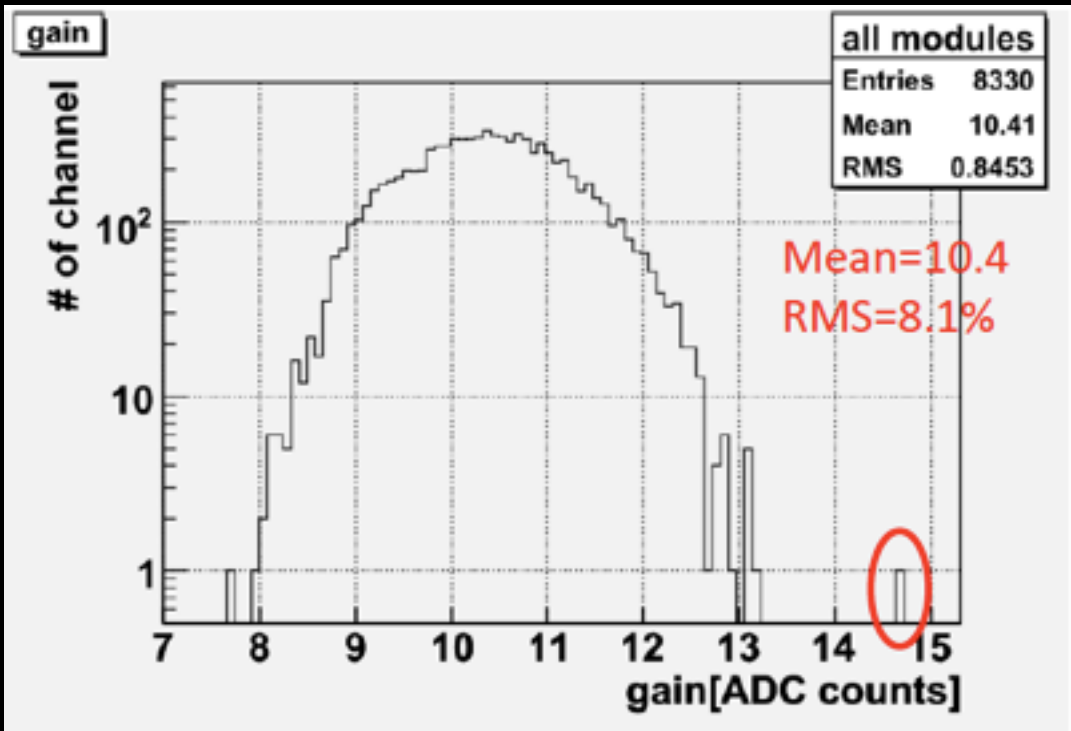
Operation voltage

- Choosing ΔV in T2K:
  - Enough light yield,electronics gain
  - Want to reduce unnecessary effects
- ΔV~1V (minor variation by subsystem)

Setting voltage..

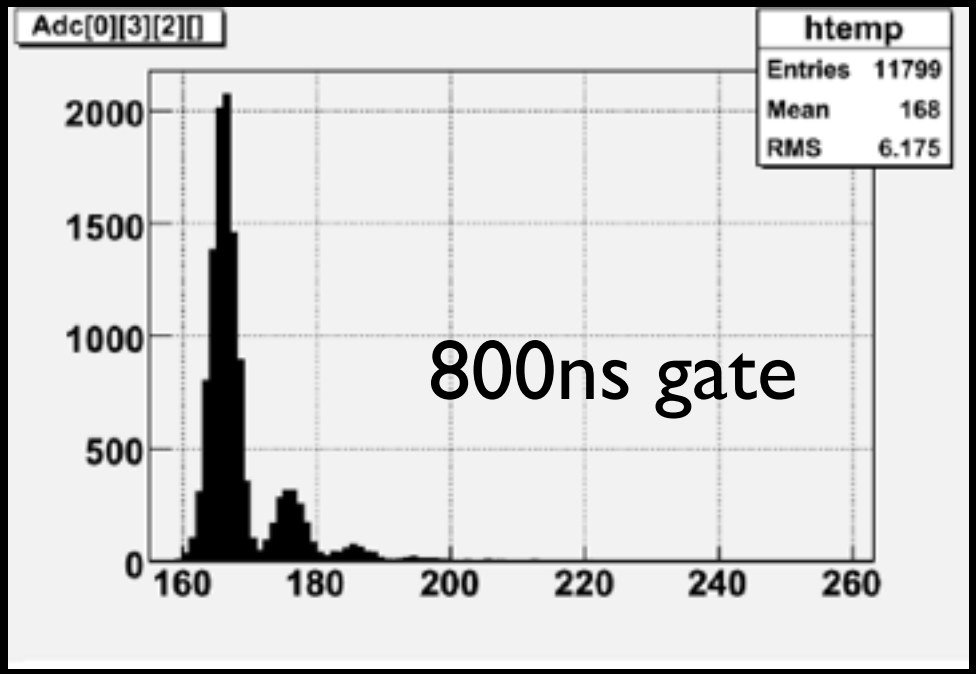
~8,000 channels for
'INGRID' subdetector

- Set V according to pre-measurement at Kyoto
- No fine tuning of V



in situ calibration

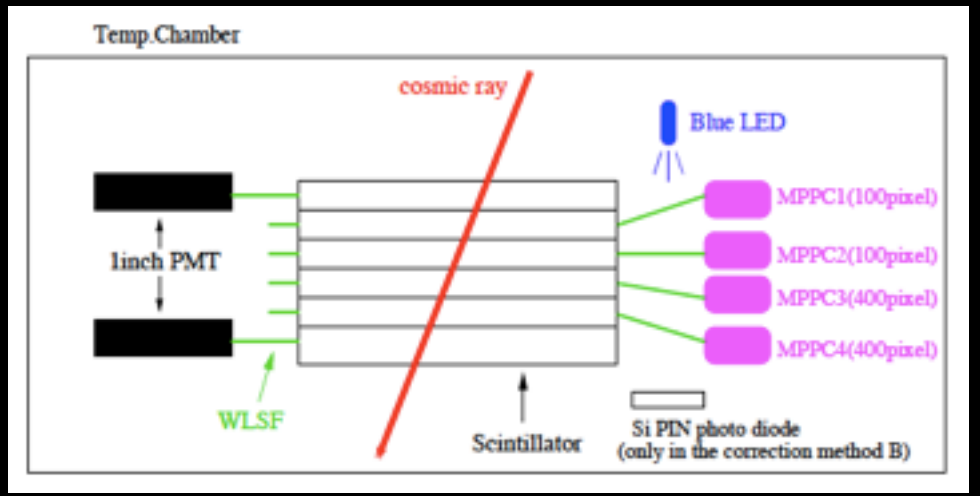
- MPPC gain can be monitored by dark noise
  - Gain measurement → derive ΔV
- Some subsystem also equipped with light injection system (LED+fibers)
  - Response to large number of photons (linearity, etc.)



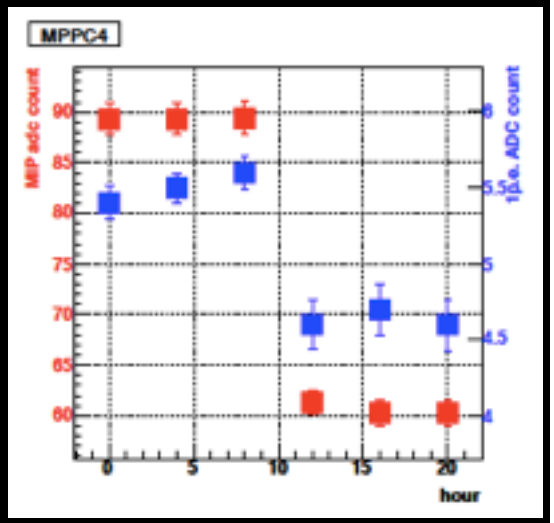
Proof of principle

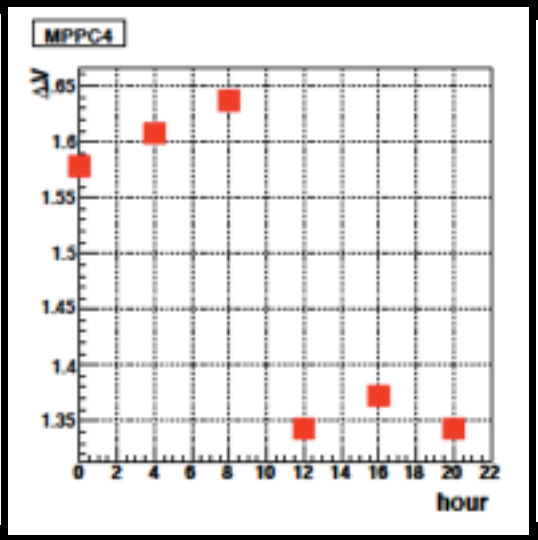
M. Taguchi, masters thesis, Kyoto U Feb. 2007

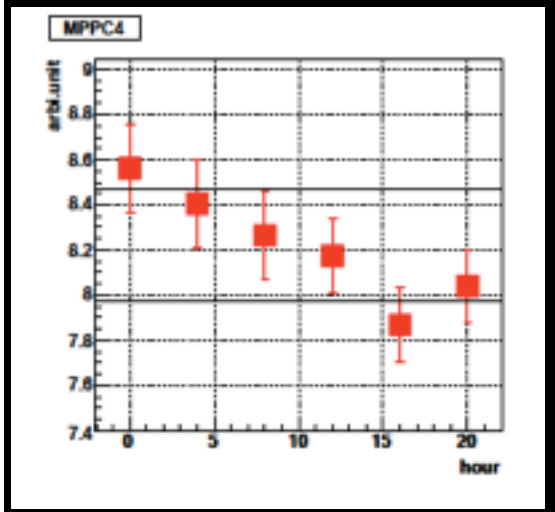
Intentionally changing temperature by 5°C, derive ΔV from 1pe and correct cosmic ray signal for gain, PDE, cross-talk



~±20%







+3%

-3%

cosmic and 1pe derived ΔV calibrated MIP

Temperature

- We are still in process of commissioning of detector system, including air conditioner.
- Early data suggests T variation in a day is within 1°C.
  - Not critical problem so far
  - Longer term variation to be monitored.

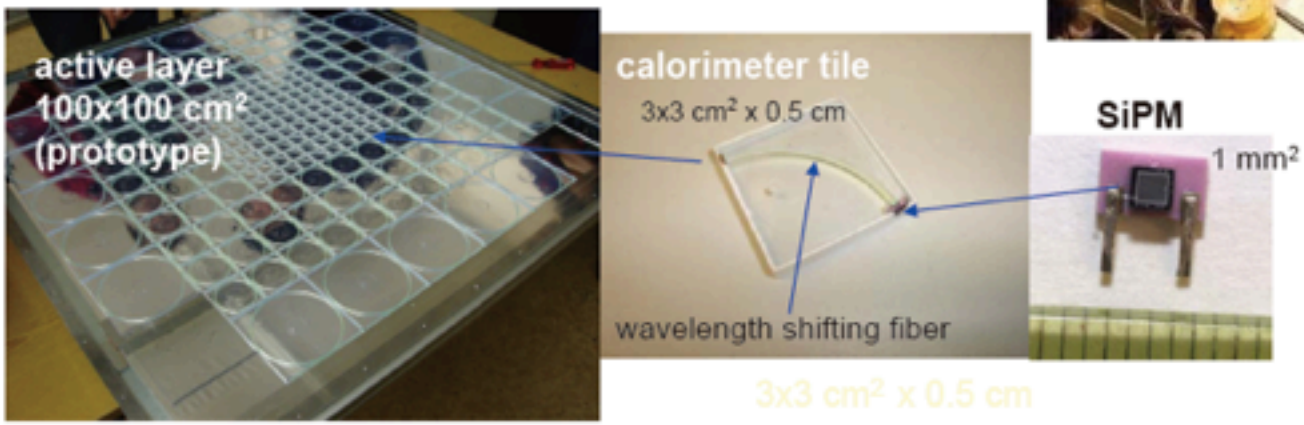
More applications

Calorimeter

Calorimeter Application

A. Taddy, PD09

- r/o of plastic scintillators with SiPMs
- highly granular electromagnetic and hadronic calorimeters for high precision measurements at the ILC (imaging calorimeter, particle flow approach)
- CALICE analogue HCAL
- plastic-scintillator-steel sandwich calorimeter
- prototype with about 8000 tiles



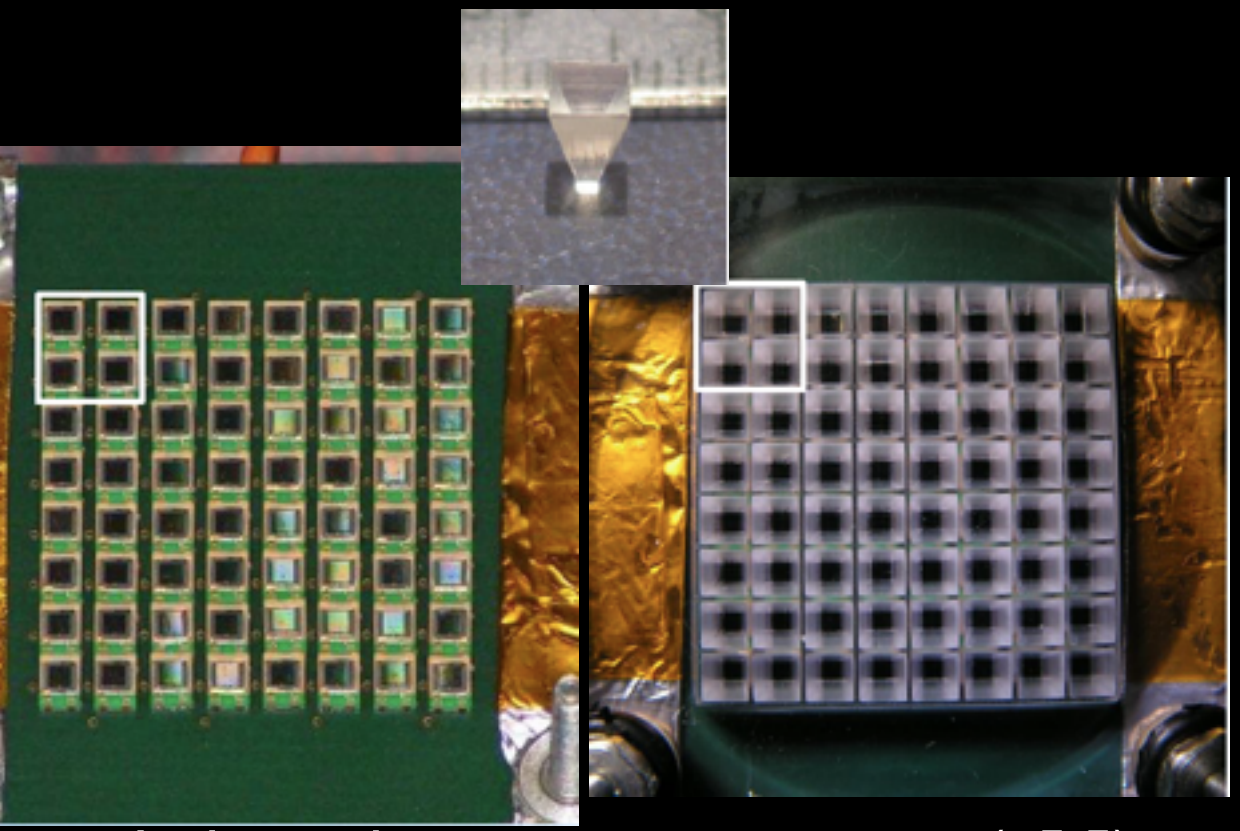
3

RICH

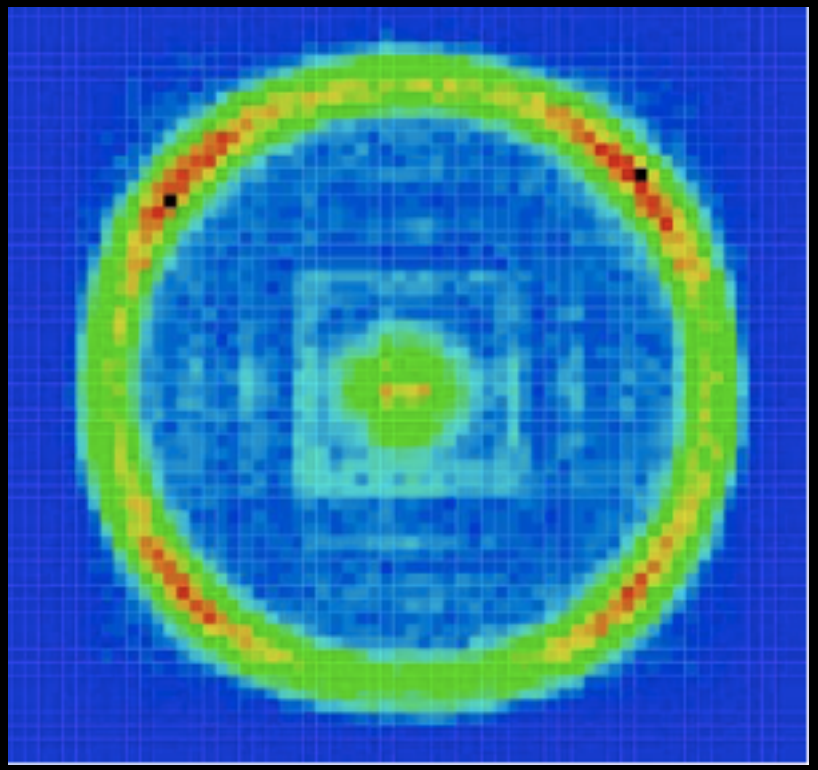
(S.Korpar, TIPP09)

R&D for Japanese
Super B-factory (Belle-2)

Clear Cherenlov ring
seen in beam test

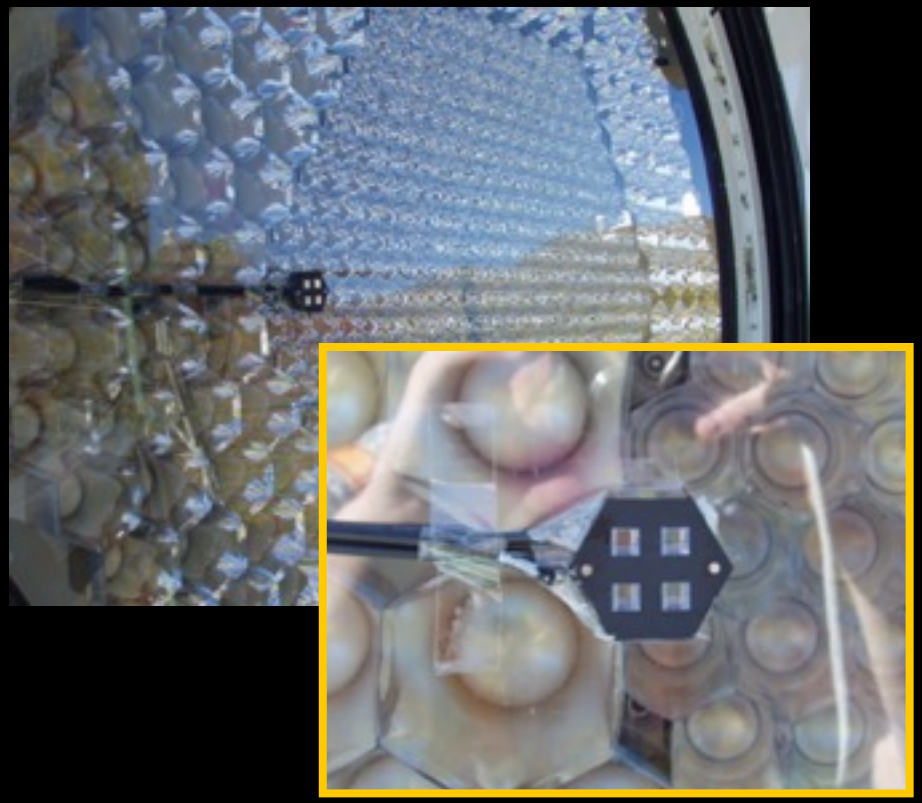


Light guide to increase coverage (x5.5)
Increase of light x2.3

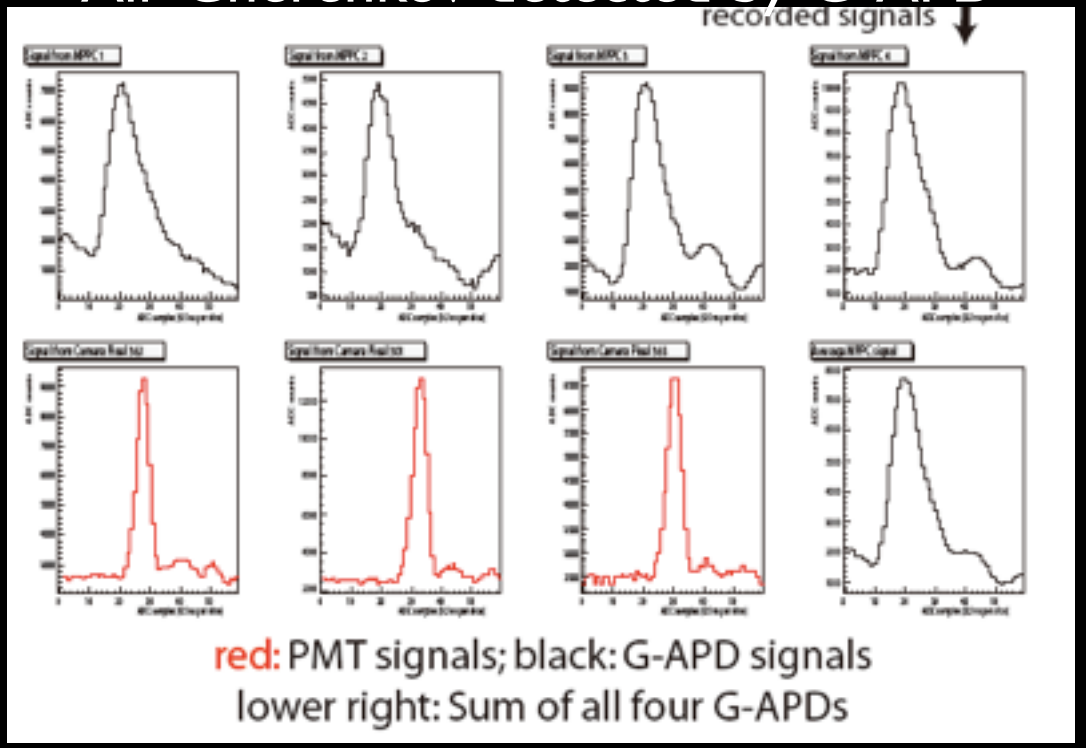


Cherenkov telescope

Intense R&D by MAGIC group
Other group also interested



Air Cherenkov detected by G-APD



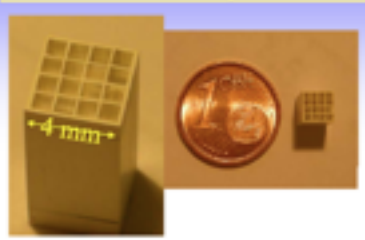
N. Otte, NDIP08

PET

- Many groups interested and studying.

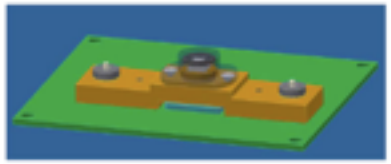
G.Llosa, NDIP08

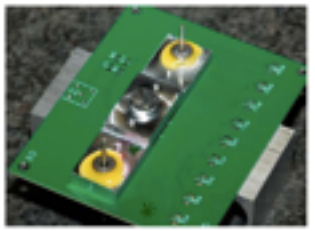
Results with pixellated crystals



LYSO crystal array: 16 (4x4) crystals of 0.96 mm x 0.96 mm x 10 mm separated by 100 μm of white epoxy resin.
Perfect match to the SiPM matrix

Holder for precise positioning:
Error < 50 μm.

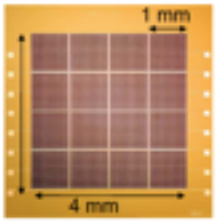


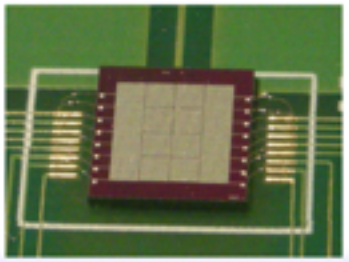


SiPM matrices from FBK-irst

Composed of 16 pixel elements in a common substrate
1 mm pixels in 1.06 mm pitch

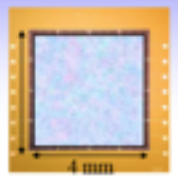
- Structure: n^+-p-π -p^+ optimized for blue light: Shallow n^+ layer + specific antireflective coating.
- 625 (25 x 25) microcells, 40 μm x 40 μm size.
- Polysilicon quenching resistance.
- Fill factor (GF) 30 – 35%.
- PDE 8 % at ΔV=3.5V for λ = 420 nm.



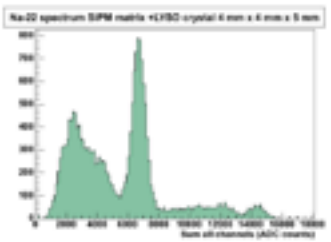


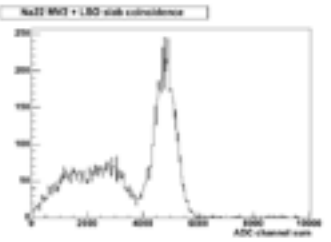
Results with continuous crystals

- Crystal 4 mm x 4 mm x 5 mm covering the whole matrix.
- Na-22 spectrum summing signals from all channels.



4 V overvoltage





And more?

- Space, industry, ...
- Can be used for charged particle detection?
  - Digital pixel detector with high gain?
  - HAPD?
- You can add your idea...

Future developments

Where we stand

- After a few years of intense study, 'SiPM' device has reached to the level of real application.
- However, many people, including myself, think it has still large room for improvements.
  - Parameters can be further optimized for applications
  - Basic parameters may be further improved
  - New structure/principle to be tested

Random thought list of R&D items (incomplete)

- Reduction of noise/cross-talk
  - Large area device
- Less temperature dependence
- Timing resolution
- Wider wavelength
  - UV sensitivity (carbon nanotube?)
  - Red/IR?
- Radiation hardness
- Larger array (digital imaging?)
- Readout integration
- Device with other material than silicon?
- Better understanding of fundamental process and development of better model/simulation

Summary and comments

- Reviewed current 'SiPM' device
- Already useful device, still has more potential
- With more development, wider application promising
  ⇔ Necessity is the mother of invention.

  Consider if 'SiPM' can be used for your application. If not, what needs to be improved?
- YOUR innovative idea may open the new world!

References

- Workshops for photon detectors
  - PD07 http://www-conf.kek.jp/PD07/
  - NDIP08 http://ndip.in2p3.fr/ndip08/
  - PD09 http://www-conf.kek.jp/PD09/
- KEK-DTP http://rd.kek.jp/index_e.html
- Also many presentation at IEEE-NSS, TIPP09