Upgrade of the CsI calorimeter for the KOTO experiment

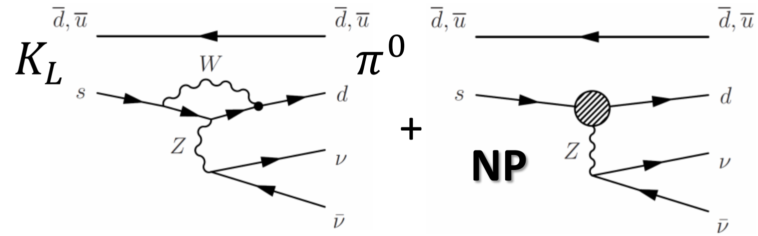
Osaka University for the KOTO collaboration

PD 2018, Tokyo, Japan 27th Nov.

New outer wear of the calorimeter

Summer **Now**

KOTO experiment

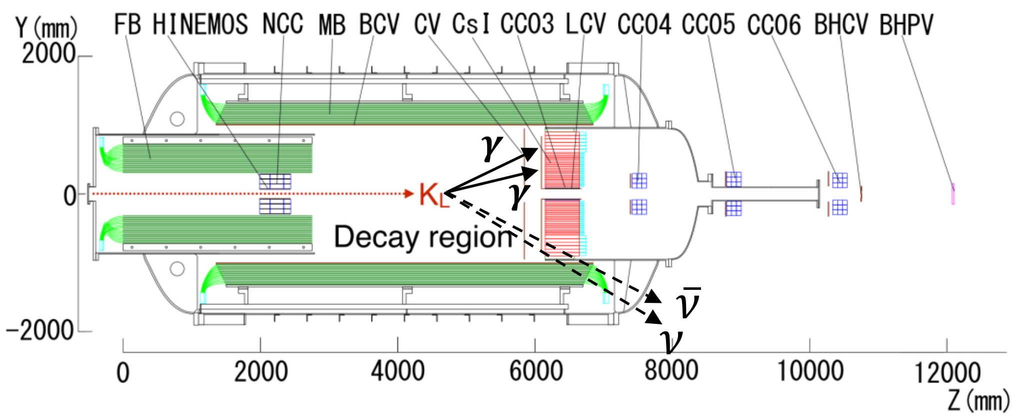


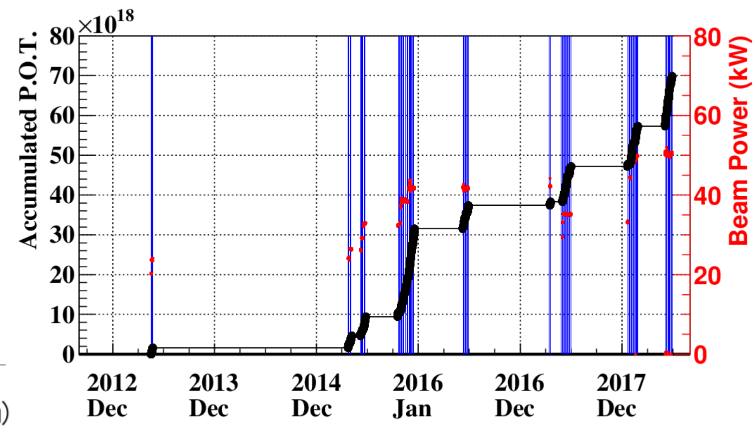
- $K_L \to \pi^0 \nu \bar{\nu}$

  $\mathcal{B}_{\mathrm{SM}}(K_L \to \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$ JHEP **11** 033 (2015)

  $\mathcal{B}_{\mathrm{EXP}}(K_L \to \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8}$ (90% C.L.) by E391a

- Detector





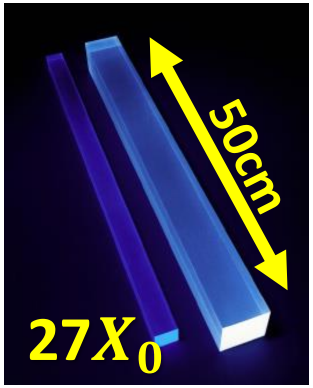
Signal: $2\gamma + \text{nothing}$

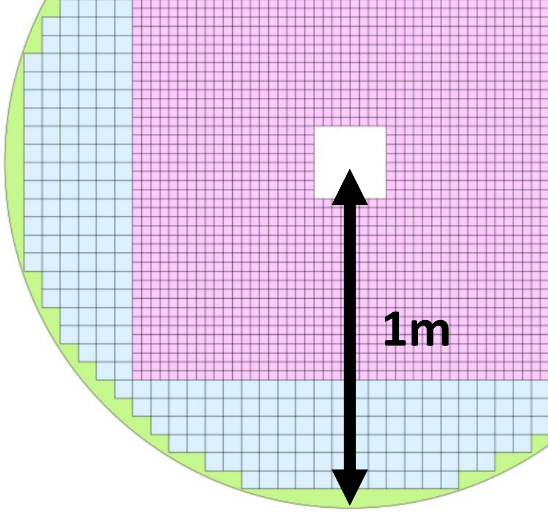
Two electromagnetic showers in CsI and no signal in the hermetic veto counters

Key: avoid missing photons and exclude neutron-induced BG

→ Upgrade CsI calorimeter to reject neutrons

CsI calorimeter of the KOTO detector





- CsI crystal
  - undoped CsI

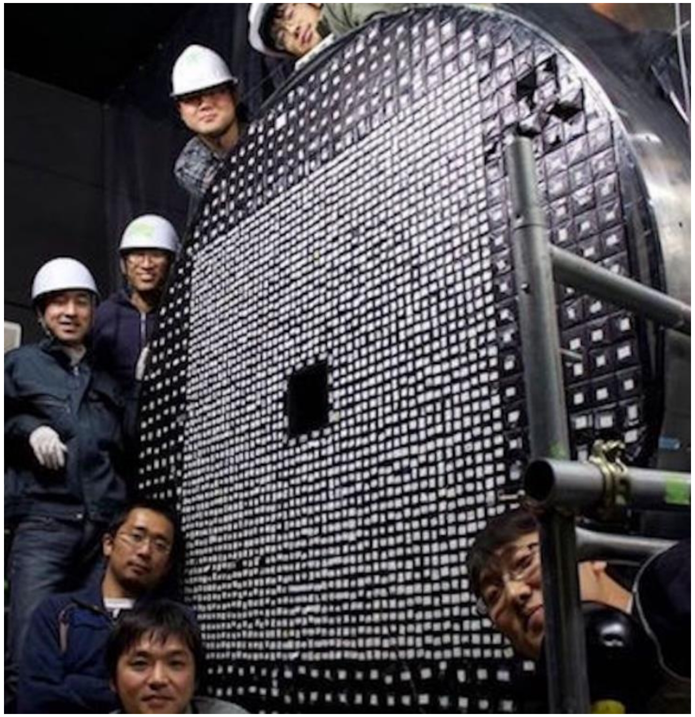
    #crystal = 2716

    2240 *small* ($25 \times 25\ \mathrm{mm}^2$)

    476 *large* ($50 \times 50\ \mathrm{mm}^2$)

- Good performance of resolution
  - $\sigma_E/E = 0.99\% \oplus 1.74\%/\sqrt{E[\mathrm{GeV}]}$

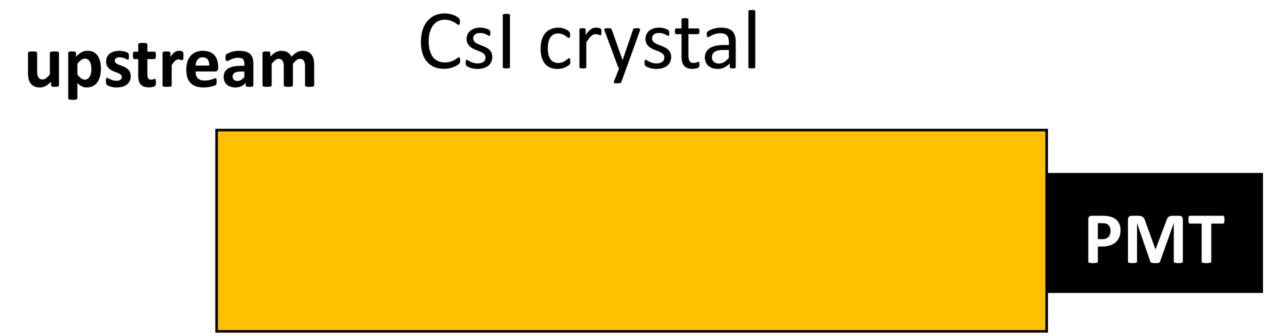
JPS Conf. Proc. 8, 024007 (2015)



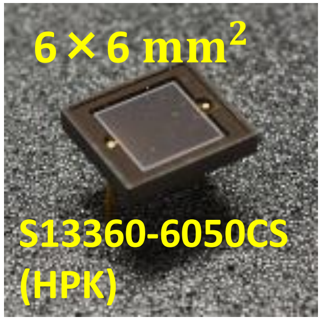
- PMT signals are digitized by flash ADC
  - 14 bit 125 MHz sampling
  - 512 ns timing window (64 samples)
  - Timing resolution $\sigma_t \sim 1\mathrm{ns}$

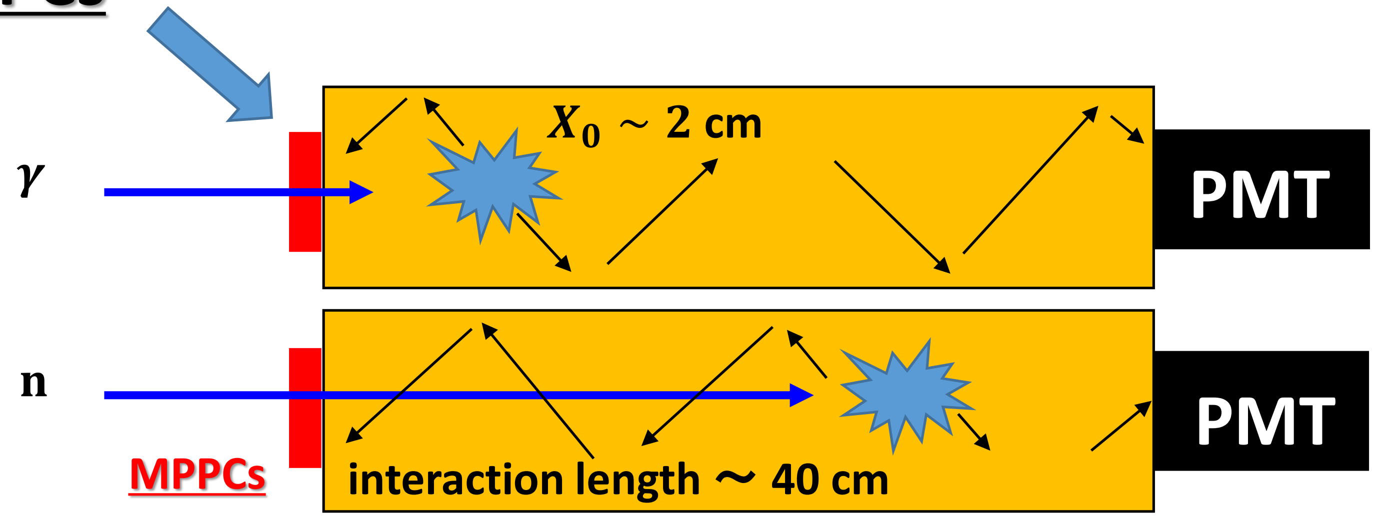
Idea of the CsI calorimeter upgrade

Previous



Attach MPPCs

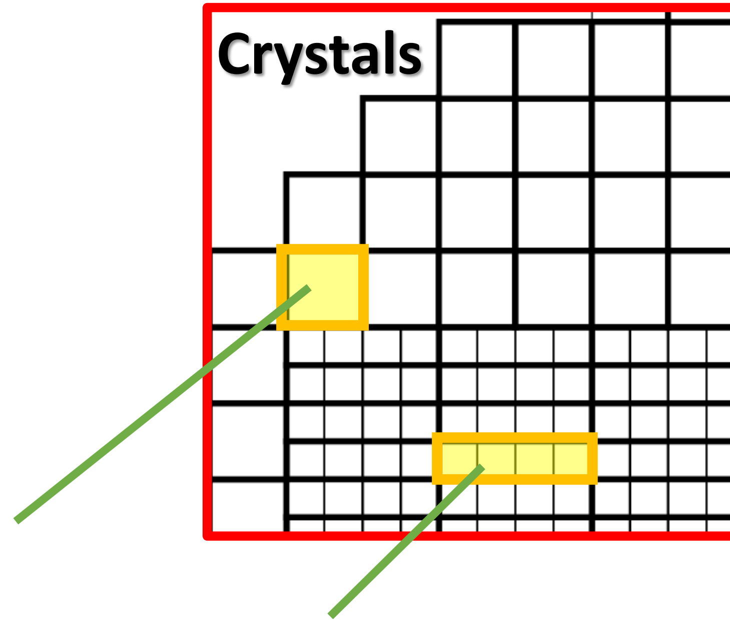




Measure the depth as $\Delta t \equiv T_{MPPC} - T_{PMT}$

→ **Small Δt** implies γ

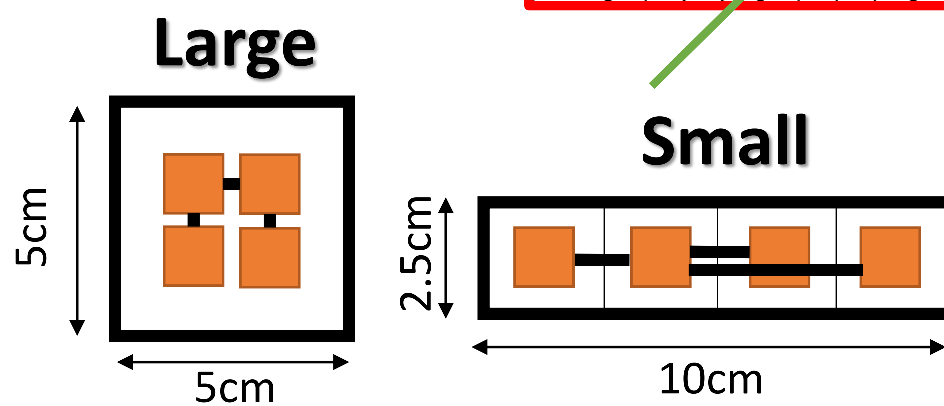
New front-end readout



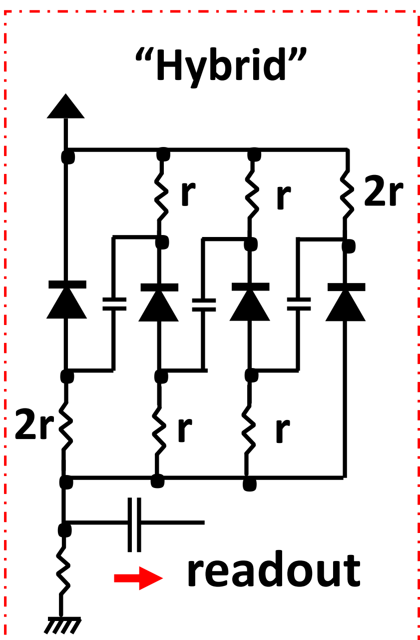
☐ MPPC readout

of MPPCs: **4096 (>#PMT=#CsI)**

To reduce # of channels..
4 MPPCs are connected



☐ Bias connection

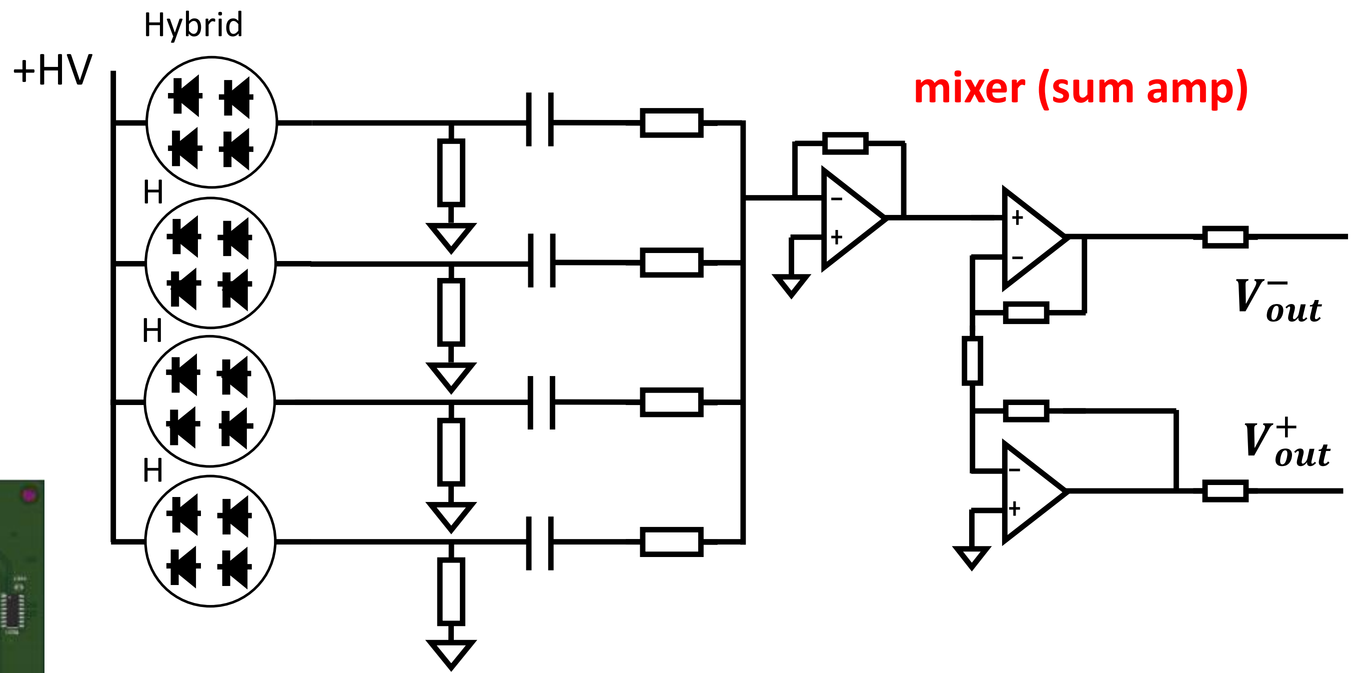


"Hybrid" bias connection

- adopted by MEG II upgrade
- AC line: series
- DC line: parallel

Development of front-end: amplifier

See N. Hara's poster (27th)



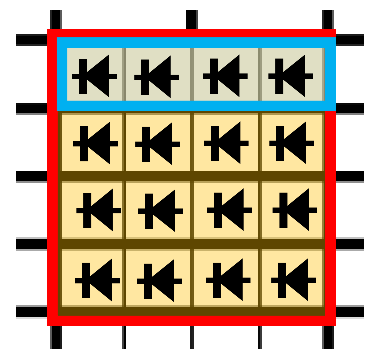
4096 MPPCs

4 MPPCs are connected ×1/4

1024

4 readout is summed × 1/4

256 channels

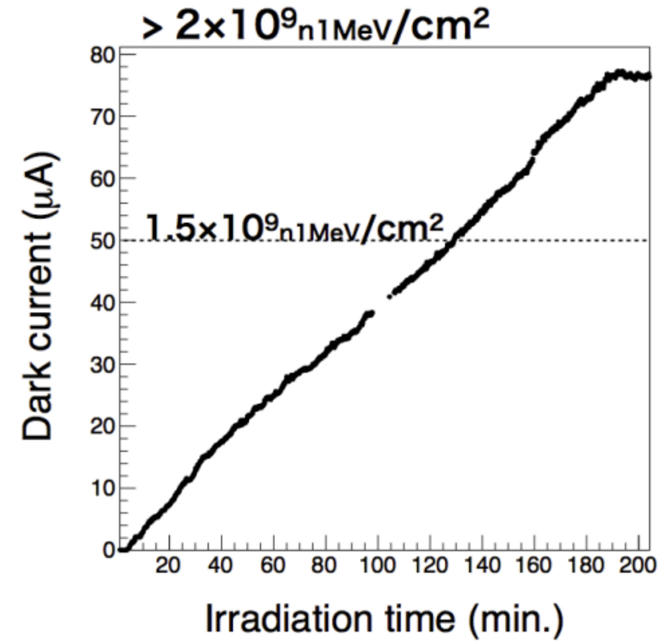


→Manageable number of channels

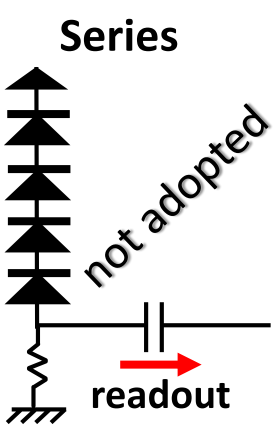
Effect of the Irradiation

Dark current

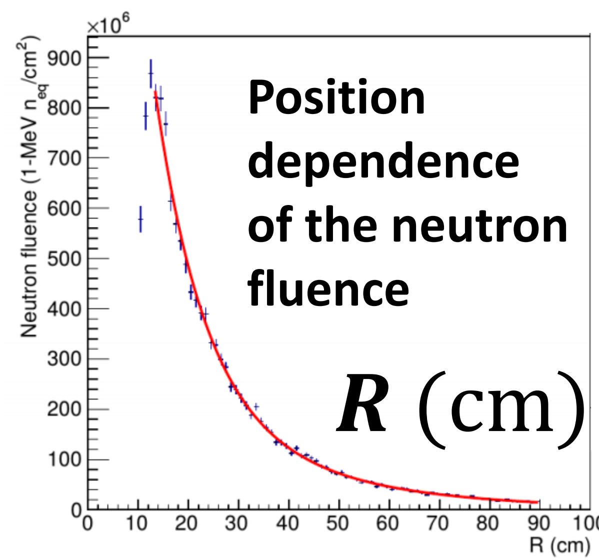
- increases $\times 100$ for
  $\sim 1 \times 10^9$ 1MeV- n/cm^2 (3-years operation)
- Prepare irradiated sample of MPPCs



Instability of bias voltage



Position dependence of different $I(V)$ causes instability of bias for the series connection.



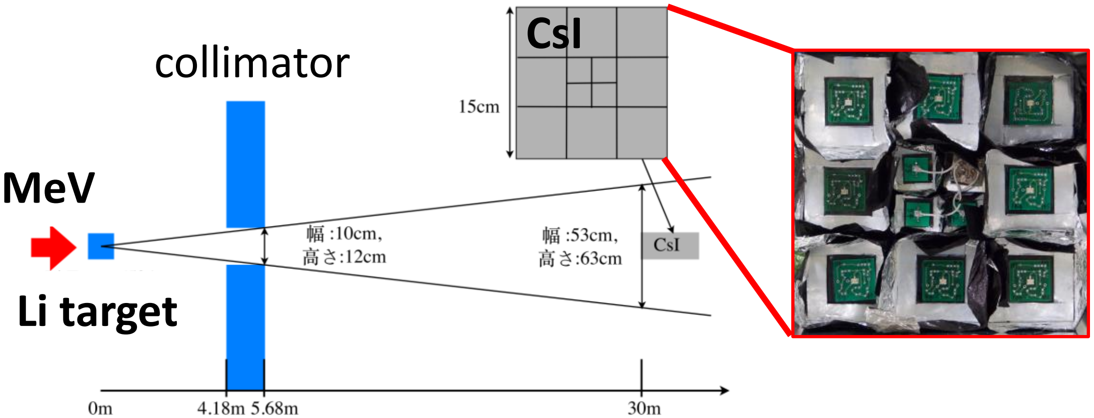
→ Solved by adopting the Hybrid connection

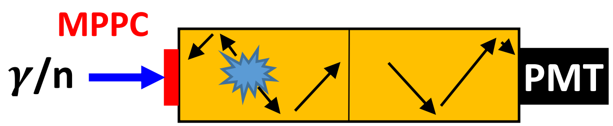
Performance tests (γ/n separation)

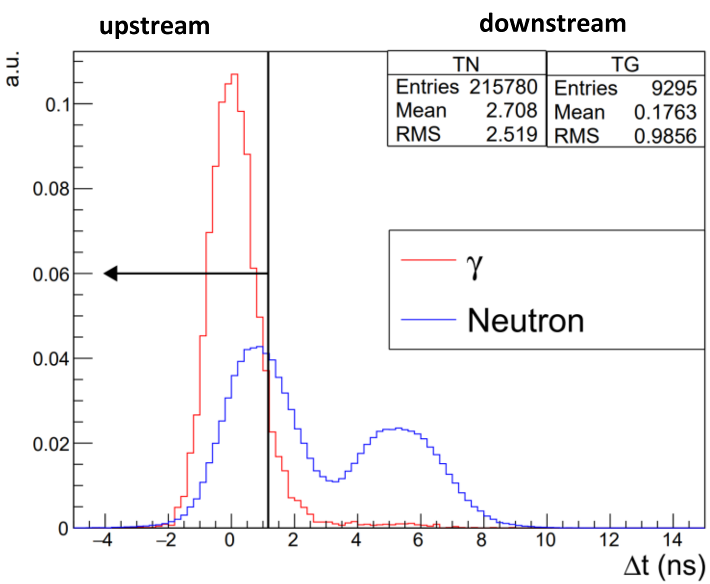
- Beam test at RCNP-Osaka cyclotron
  - γ/n beam from Li target

γ: continuous beam up to 392 MeV

n: 392 MeV







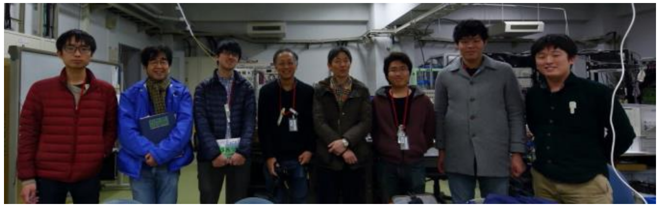
Distribution

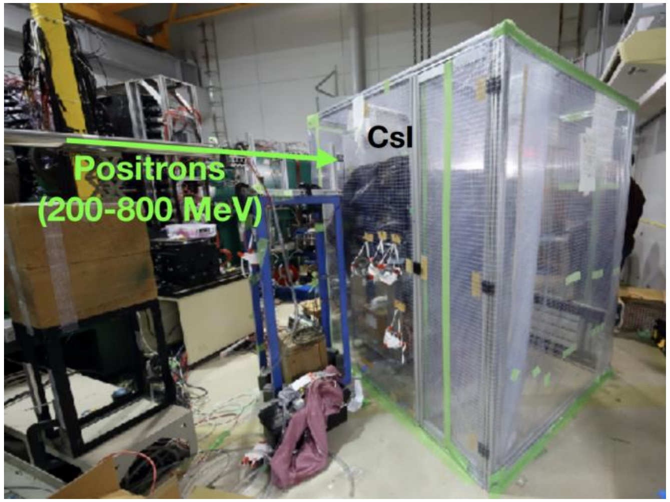
$$\Delta t \equiv T_{MPPC} - T_{PMT}$$

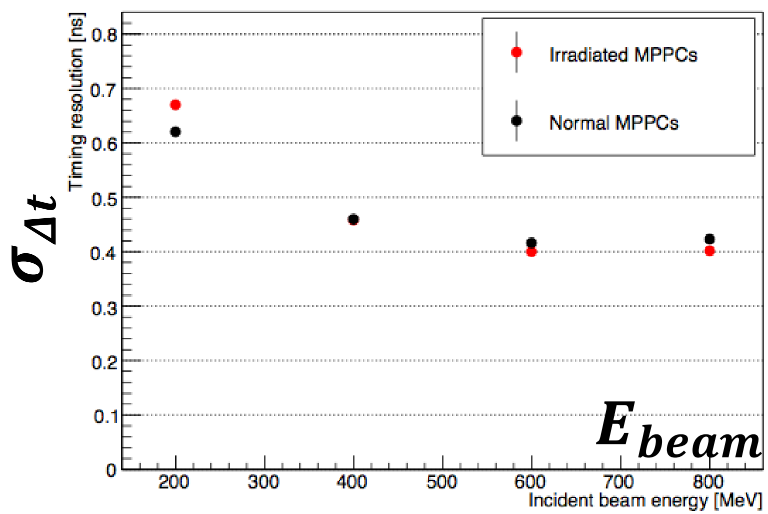
Retain 90% of γ while suppressing n to 34%

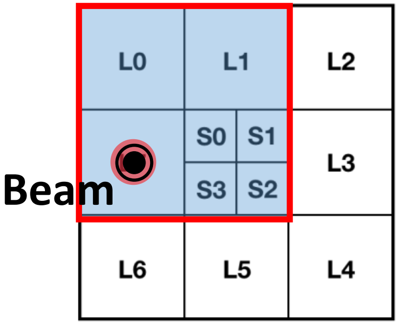
Performance tests ($\sigma_{\Delta t}$)

- Beam test at the ELPH (Tohoku, Japan) electron synchrotron
  - evaluate $\sigma_{\Delta t}$ (as a func. of E)
    - Monochromatic 200, 400, 600, 800 MeV e^+ beams
  - Used setup as realistic as possible
  - Confirmed MPPC functionality after dose
    →Irradiated MPPCs were used







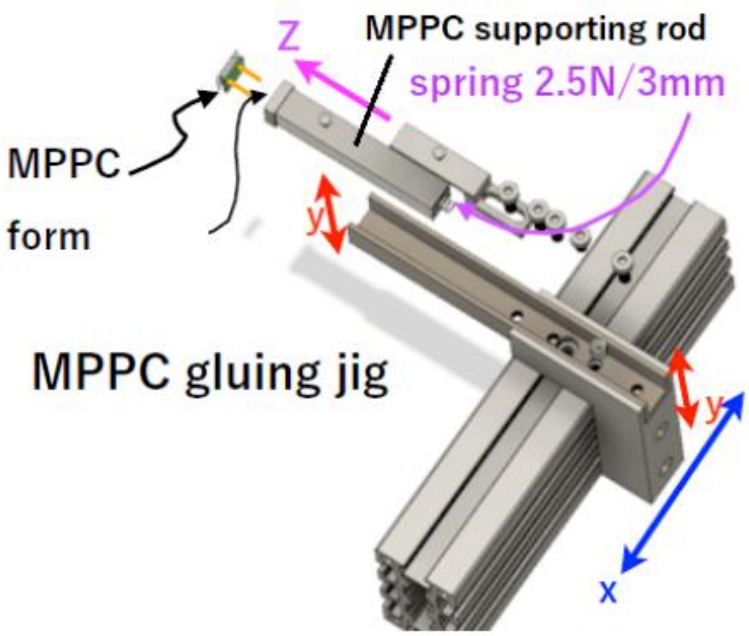


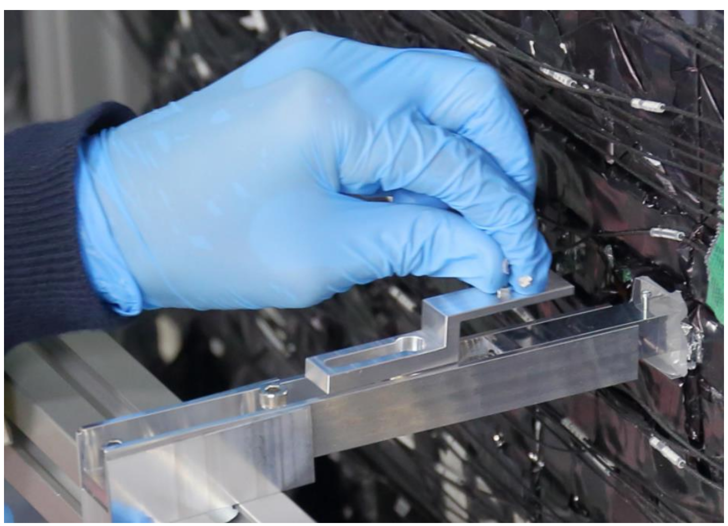
summed $100 \times 100\ \mathrm{mm}^2$ region

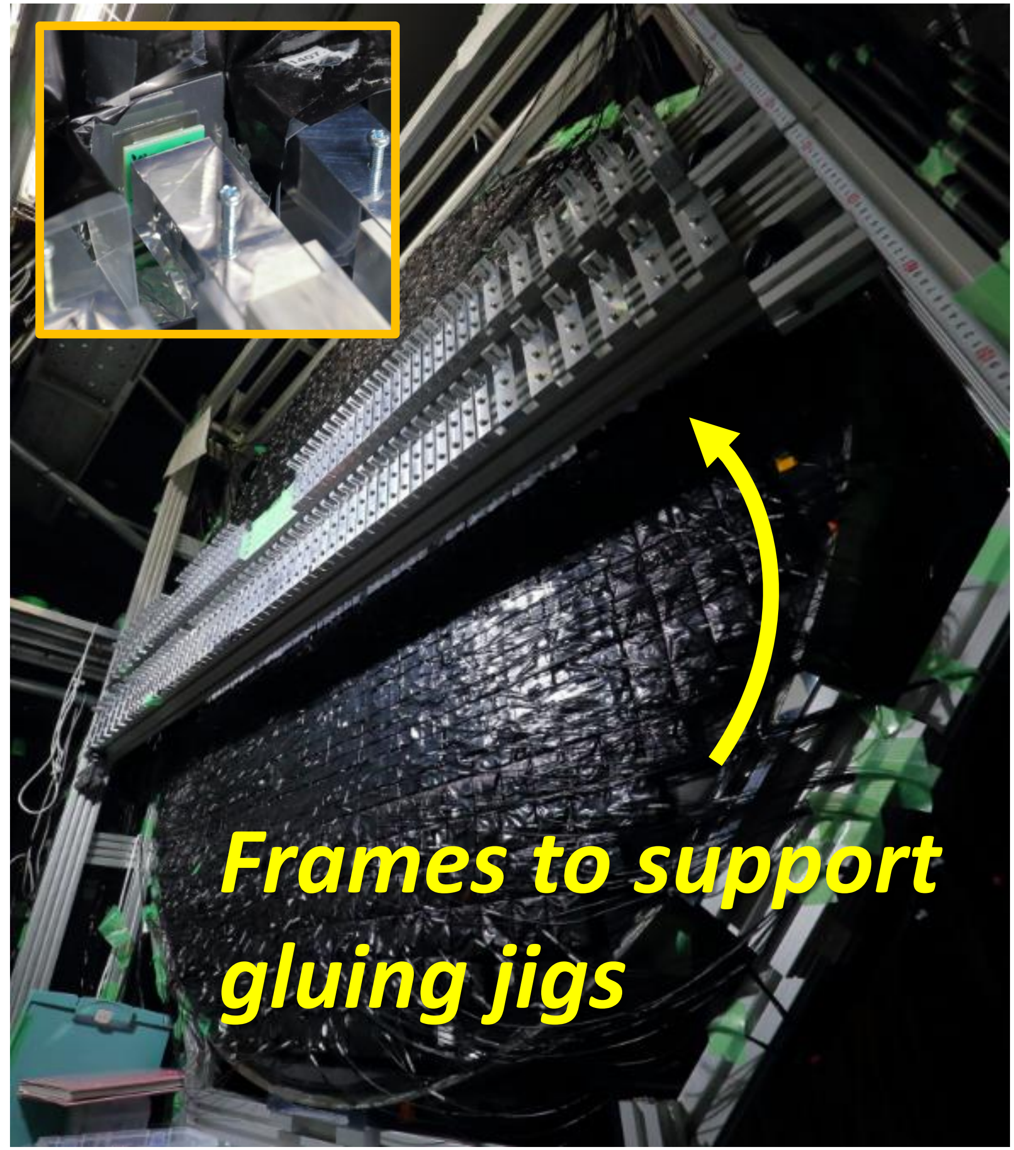
✓ **Irradiated MPPCs worked enough**
✓ **Readout worked well**

MPPC installation

MPPC instrumentation

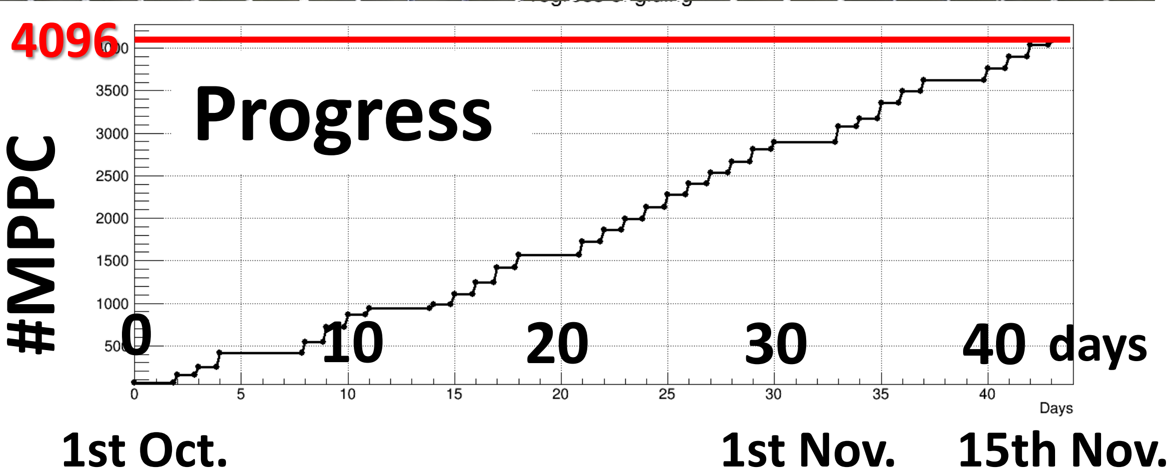






MPPC instrumentation

- Glue MPPCs on two rows in a day
- Start from 1st Oct. and 45 days to finish all
- No serious problem occurred



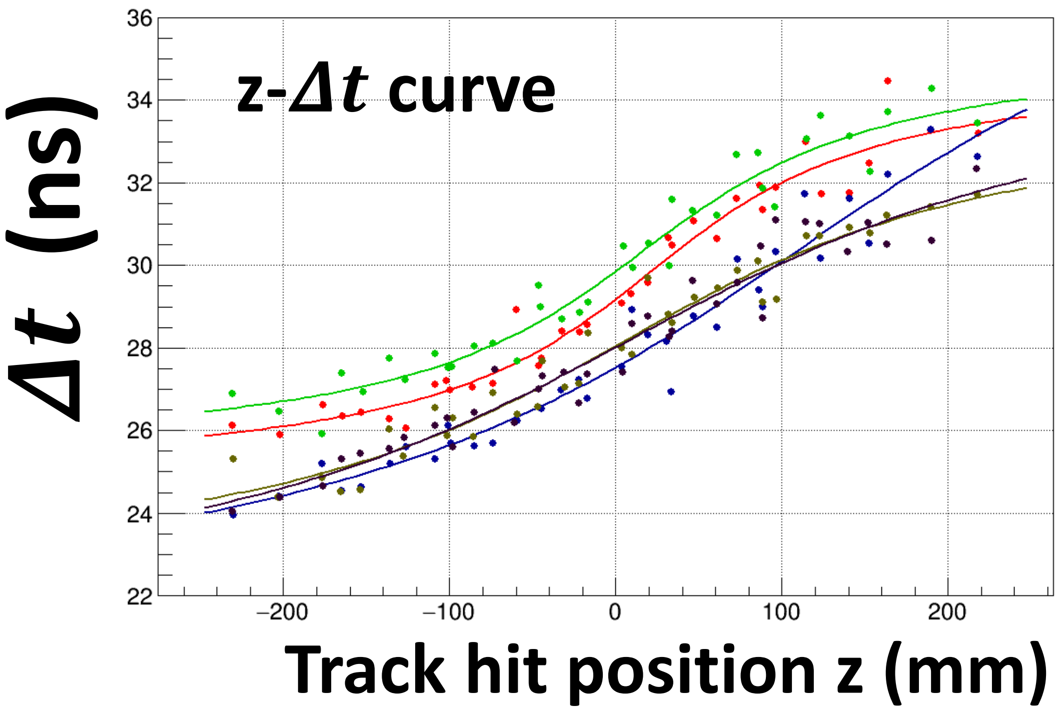
Time lapse movie

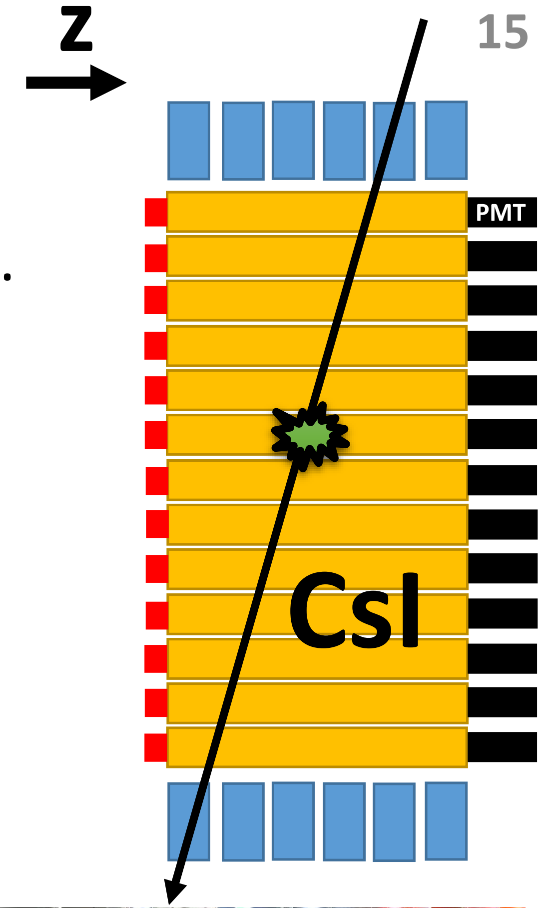

Finished!!!

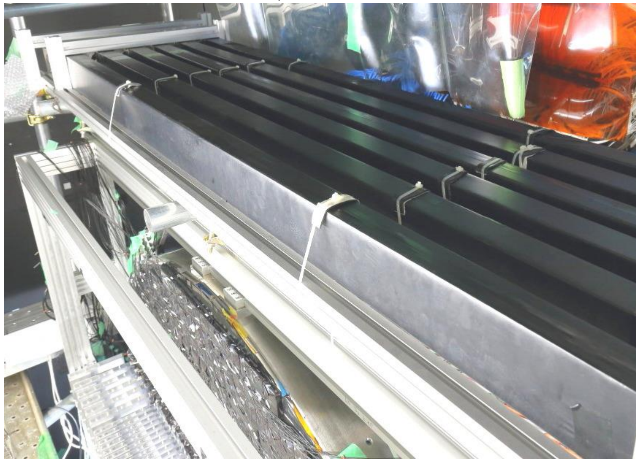
Cosmic ray test

☐ Construct 12 plastic scintillators to…

- evaluate z-Δt dependence using cosmic rays.
- find dead channels







✔ **Functionality of measurement of depth**

✔ **Understand individualities of crystals**

Summary and plan

- KOTO collaboration aims to search for New Physics via very rare decay $K_L \to \pi^0 \nu \bar{\nu}$, $\mathcal{B}_{\mathrm{SM}} = (3.0 \pm 0.3) \times 10^{-11}$.

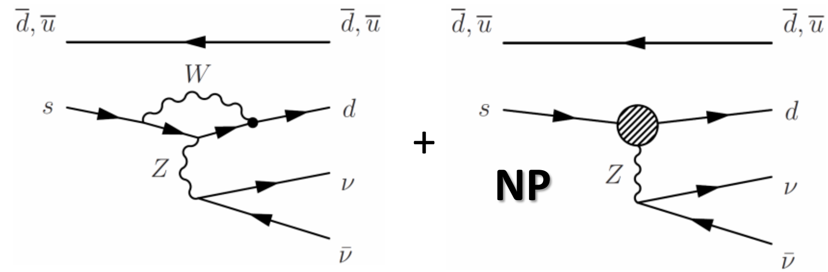
- In the last autumn, we attached >4000 MPPCs on the front surface of CsI crystal to improve $\boldsymbol{\gamma}$**/n** separation power:

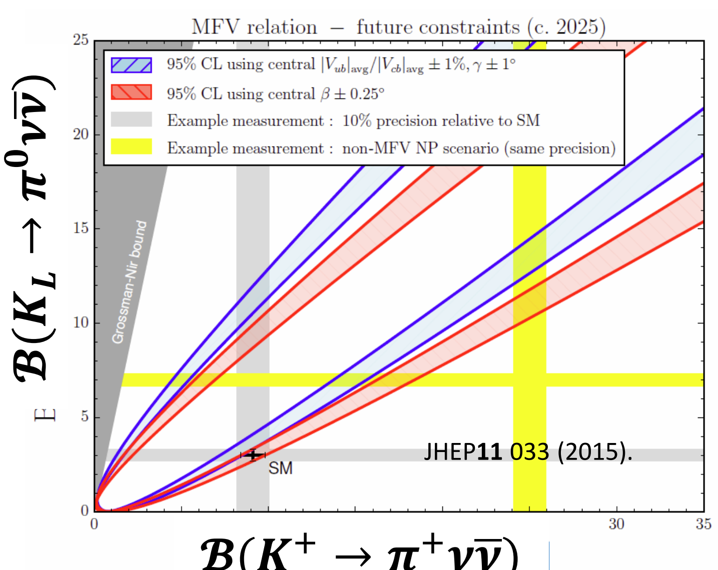
- In the next March, we will start physics data taking and
  - obtain calibration data ($K_L \to 3\pi^0$ and neutron rich sample),
  - develop new discriminator to reject neutrons

That's all

$K \to \pi\nu\bar{\nu}$ decay

- Suppressed by FCNC in the SM
- Small QCD uncertainty
  - useful prove to the New Physics
- Two compatible processes
  - $K^+ \to \pi^+\nu\bar{\nu}$: $\mathcal{A} \propto |V_{td}|$
  - $K_L \to \pi^0\nu\bar{\nu}$: $\mathcal{A} \propto \mathrm{Im}V_{td}$





EXP

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 2.6 \times 10^{-8}$ (90% C.L.) E391a

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = 17.3^{+11.5}_{-10.5} \times 10^{-9}$ E949

SM prediction

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$

JHEP**11** 033 (2015).

Rejection of neutron BG

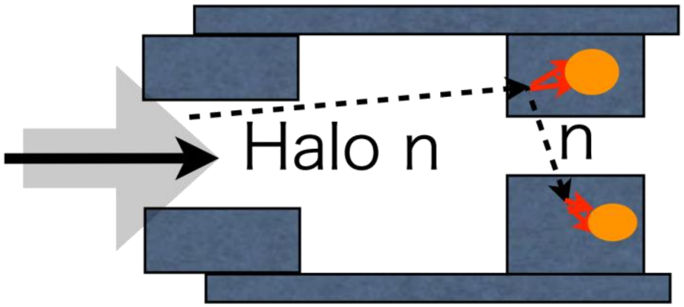
☐ Halo-neutron BG

* Prog. Theor. Exp. Phys. (2017) 021C01

Result of 4 days run: $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) < 5.1 \times 10^{-8}$ (90% C.L.)*

Background source	Number of events
$K_L \to 2\pi^0$	0.047 ± 0.033
$K_L \to \pi^+\pi^-\pi^0$	0.002 ± 0.002
$K_L \to 2\gamma$	0.030 ± 0.018
Pileup of accidental hits	0.014 ± 0.014
Other K_L background	0.010 ± 0.005
Halo neutrons hitting NCC	0.056 ± 0.056
Halo neutrons hitting the calorimeter	0.18 ± 0.15
Total	0.34 ± 0.16

The largest contribution from BG



- We need 3 more magnitudes of suppression

two-dimensional shower envelope → 1/10 ✓done

Pulse shape likelihood → 1/10 ✓done

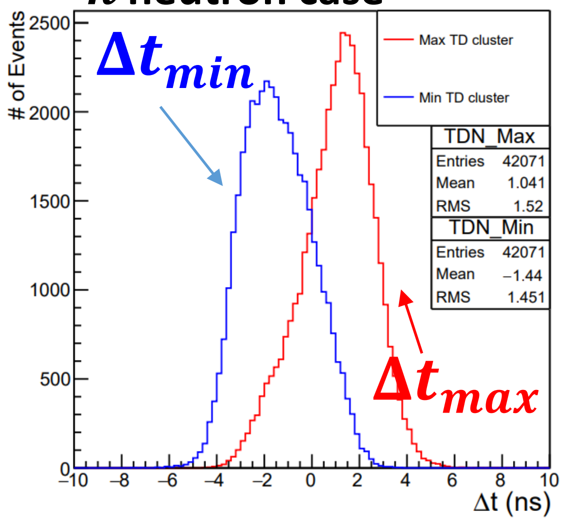
measure shower development (in z)

in the calorimeter → O(1/10)

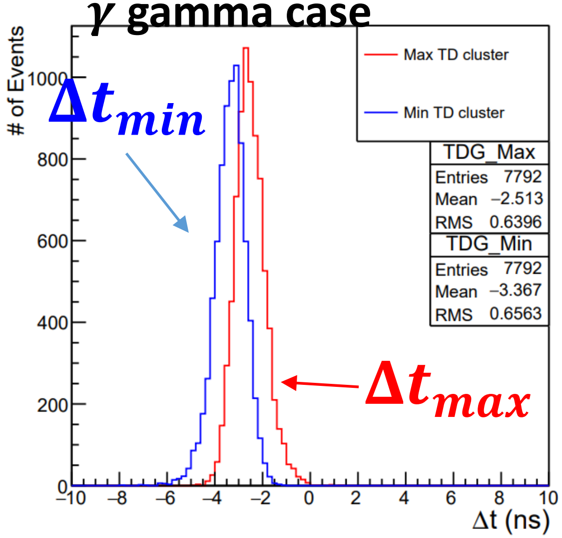
Performance tests (γ/n separation)

MC evaluation of performance for halo neutron events, based on the result of beam test

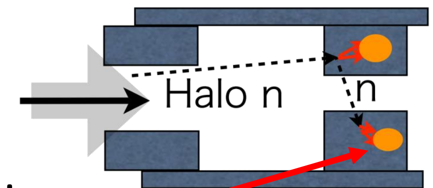
n neutron case



γ gamma case



Taking into account…



① Correlation of two cluster position:

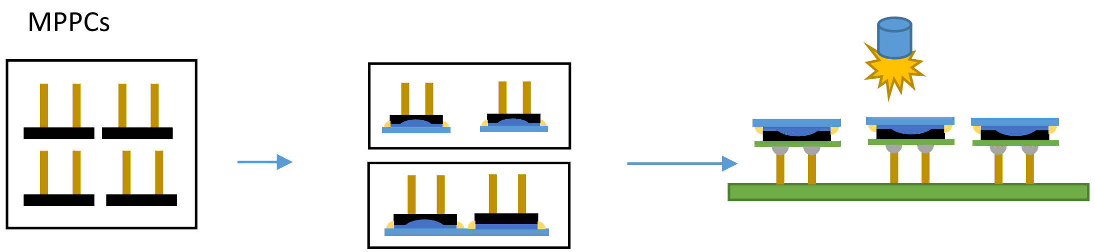
- the second cluster is deeper

The larger one → Δt_{max}
The smaller one → Δt_{min}

② Other neutron cuts

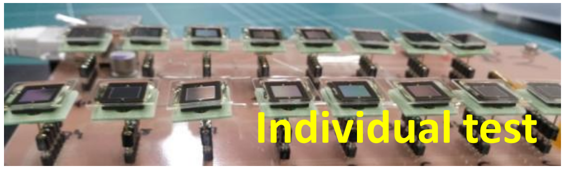
→ suppresses halo neutron BG to 10% while retaining 90% efficiency of two γ signal events!

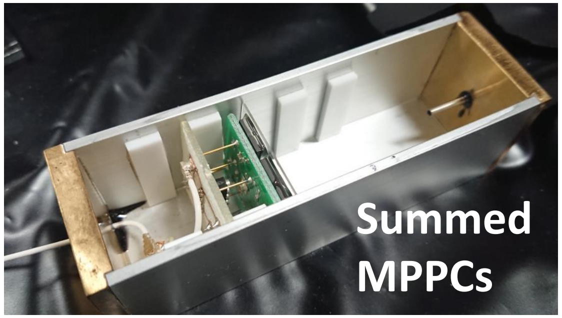
Quality assurance of MPPCs

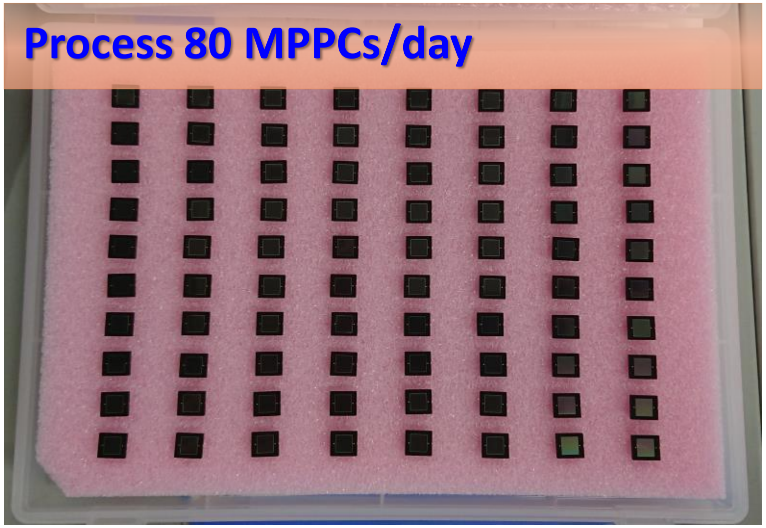


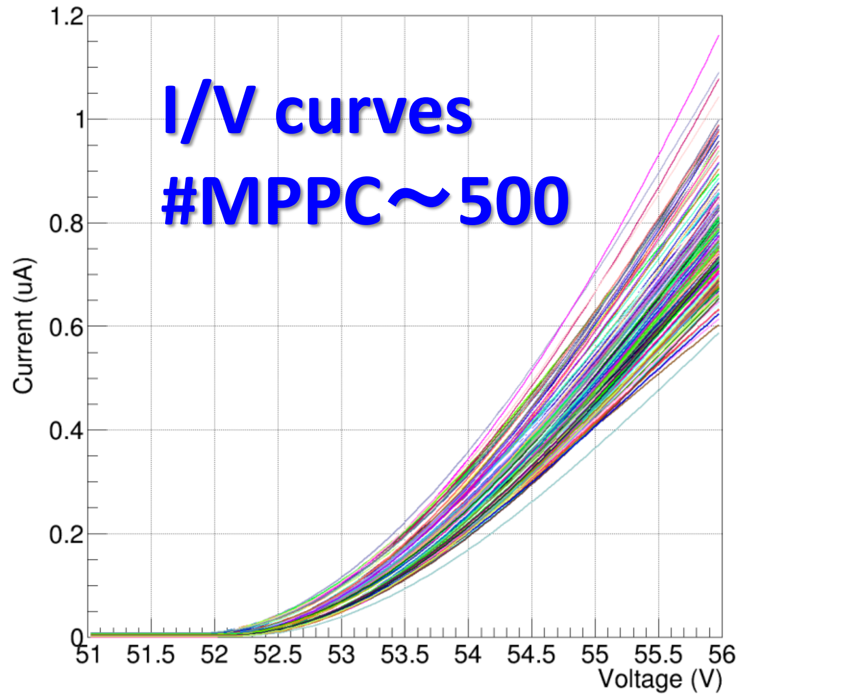
Quartz gluing
Soldering
temperature test

I/V inspection
LED test



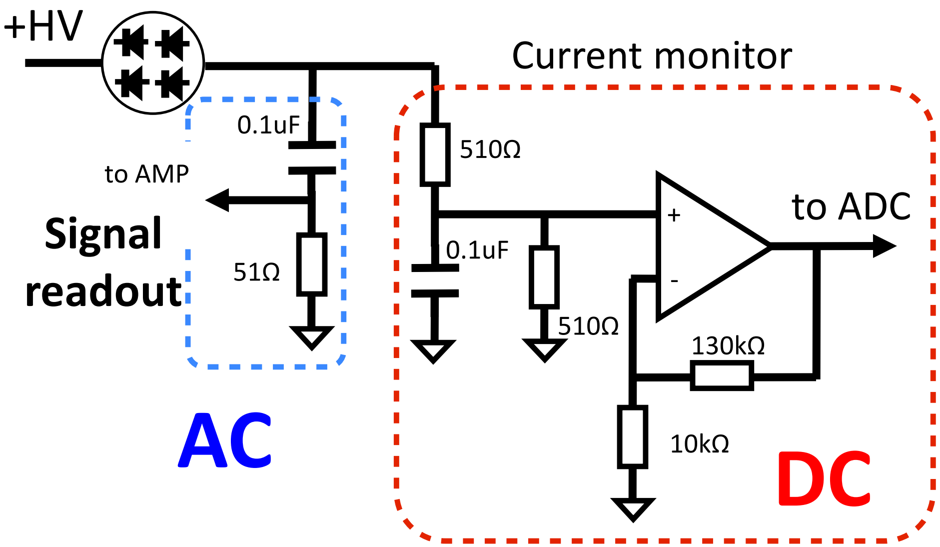






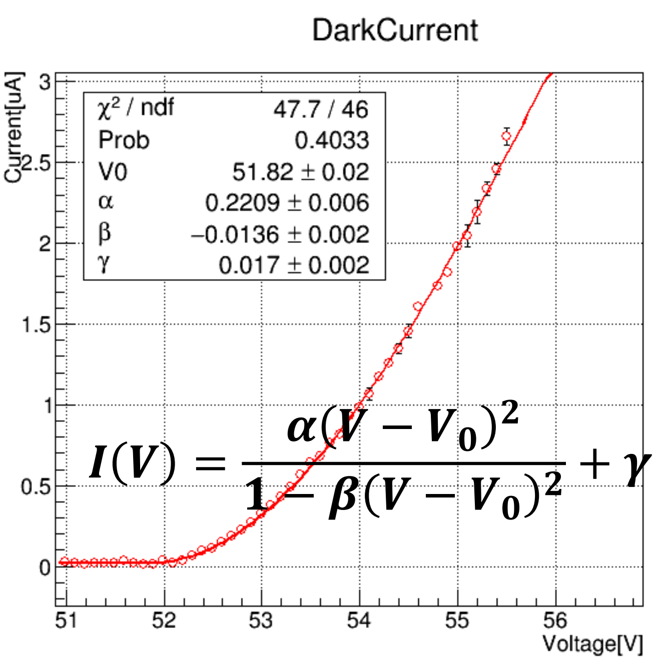
Inspect all of MPPCs (#~4000) before installation
→ Start gluing on CsI in this summer

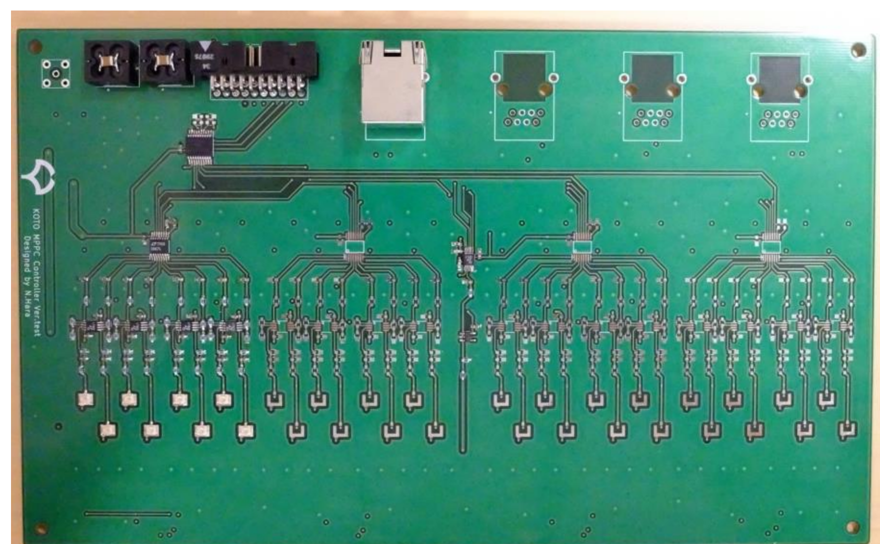
Development of front-end: monitor



DC dark current is continuously monitored to confirm the functionality and level of radiation damage.

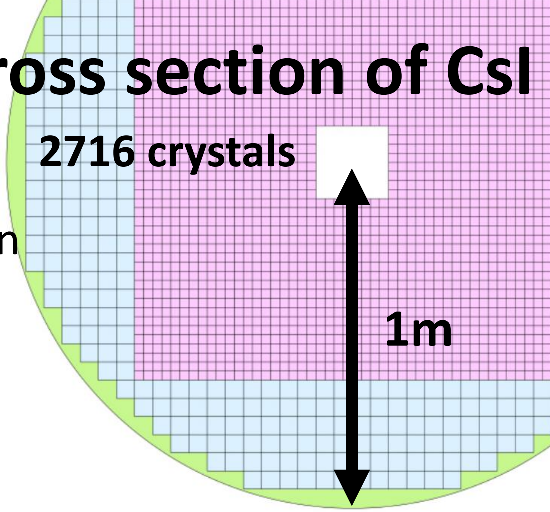
Operation current increases by a factor of 100 in three snowmass year: $\boldsymbol{I_{op}} = 0.5\mu\mathrm{A} \rightarrow 50\mu\mathrm{A}$





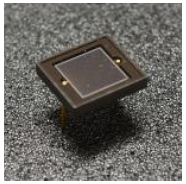
Development of front-end

Cross section of CsI



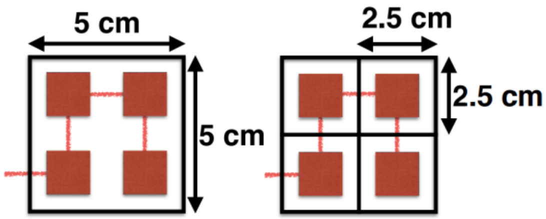
□ MPPC readout

S13360-6050CS (HPK)



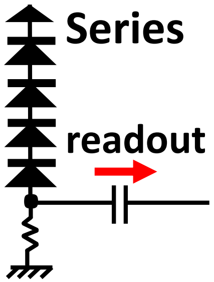
$6 \times 6\ \mathrm{mm}^2$ sensitive region
Si-window

Two types of crystals

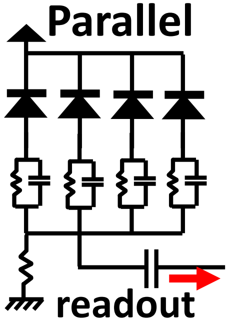


4 MPPCs are simultaneously read out

□ Bias connection

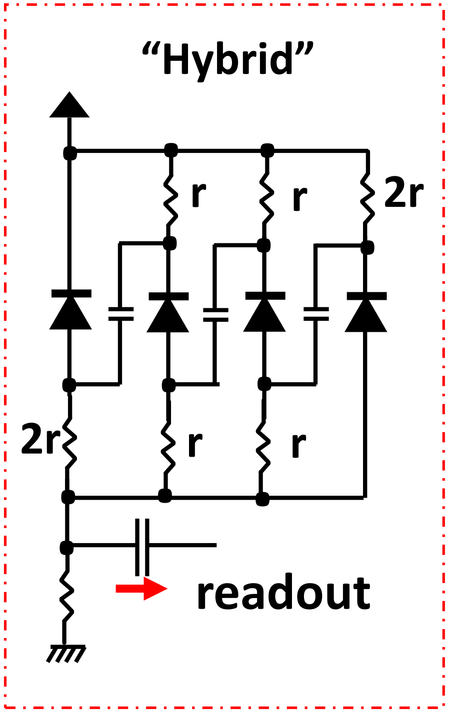


☺ small time constant (~200ns)
☹ high bias voltage (220V)
☹ unstable individual operation voltage toward irradiation



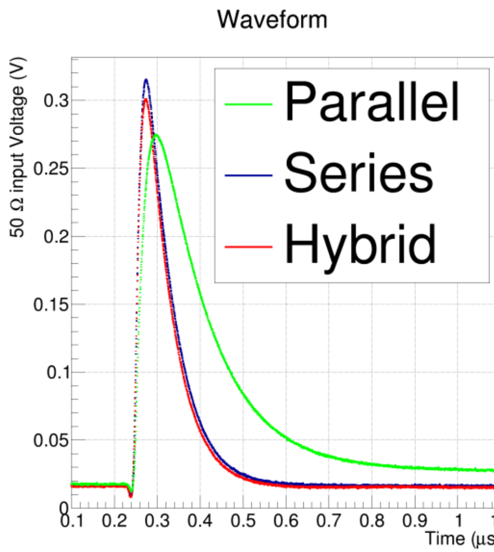
☹ large time constant (~0.5us)
☺ low bias voltage (55V)
☺ stable breakdown voltage toward irradiation

adopted!



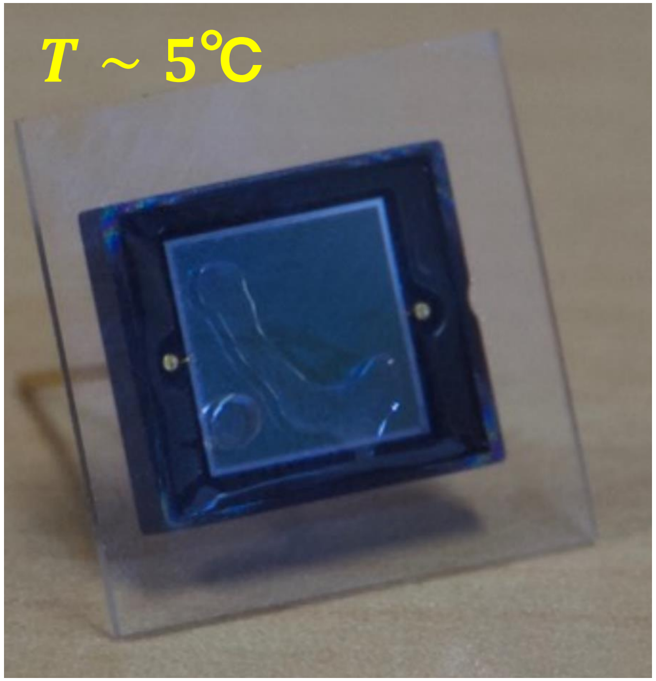
"Hybrid"-connection

- adopted by Meg2 upgrade
- AC line: series
- DC line: parallel
- have both pros

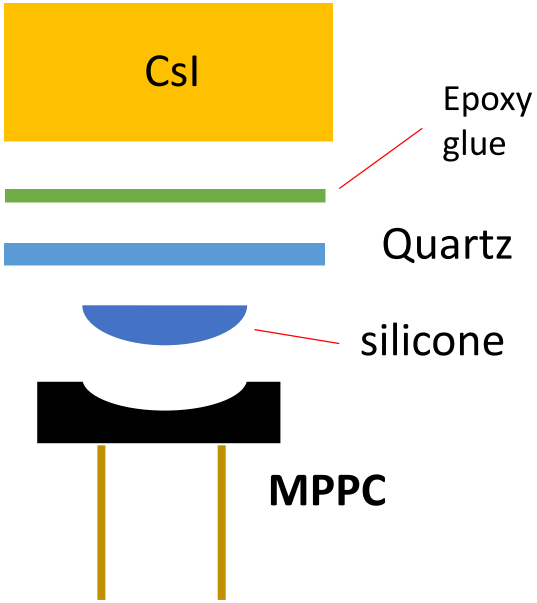


Gluing of MPPC on the CsI surface

- Difficulties to glue MPPC
  - Concave shape of MPPC
  - Epoxy glue does not cure well on CsI surface
  - bubbles appear at low temperature

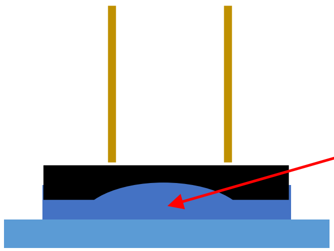


Quartz plate to assure the flatness and transparency in advance



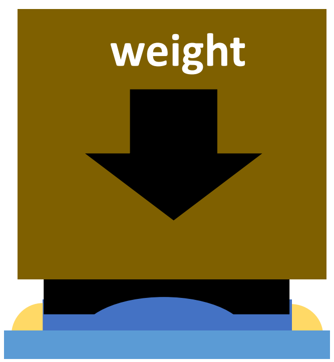
Fabrication of MPPCs

①

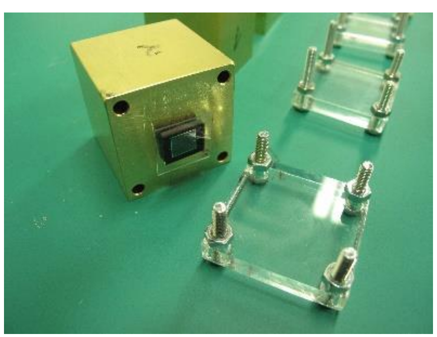


To keep the internal pressure high…

②



after silicone is cured, **apply pressure and dispense epoxy glue along edges**



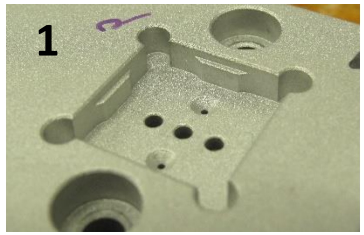
→Strong tolerance to low temperature

For more detail, see the backup.

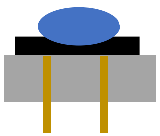
Fabrication of MPPCs

1

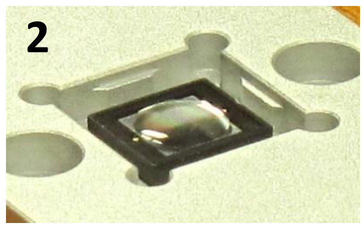
Insert MPPC on jig



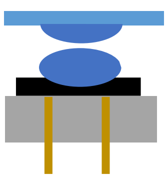
2



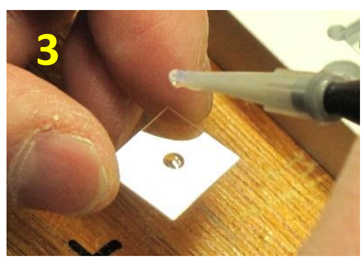
Drop glue



3



Drop glue on quartz



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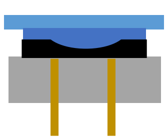
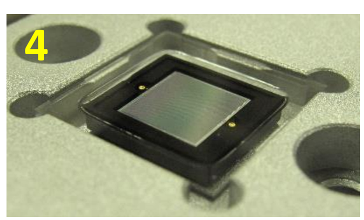
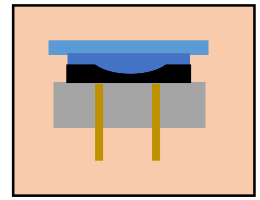


wait for cure keeping the quartz floated

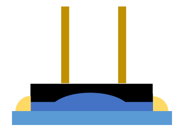


5

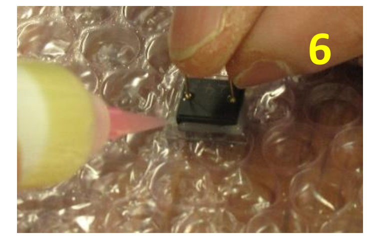


Put MPPCs into oven and wait 24 h (keeping 45 deg)

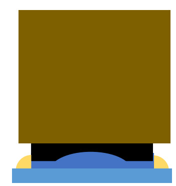
6



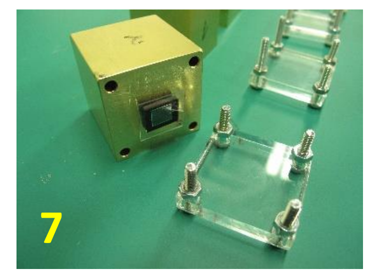
dispense epoxy glue (araldite 2011)



7

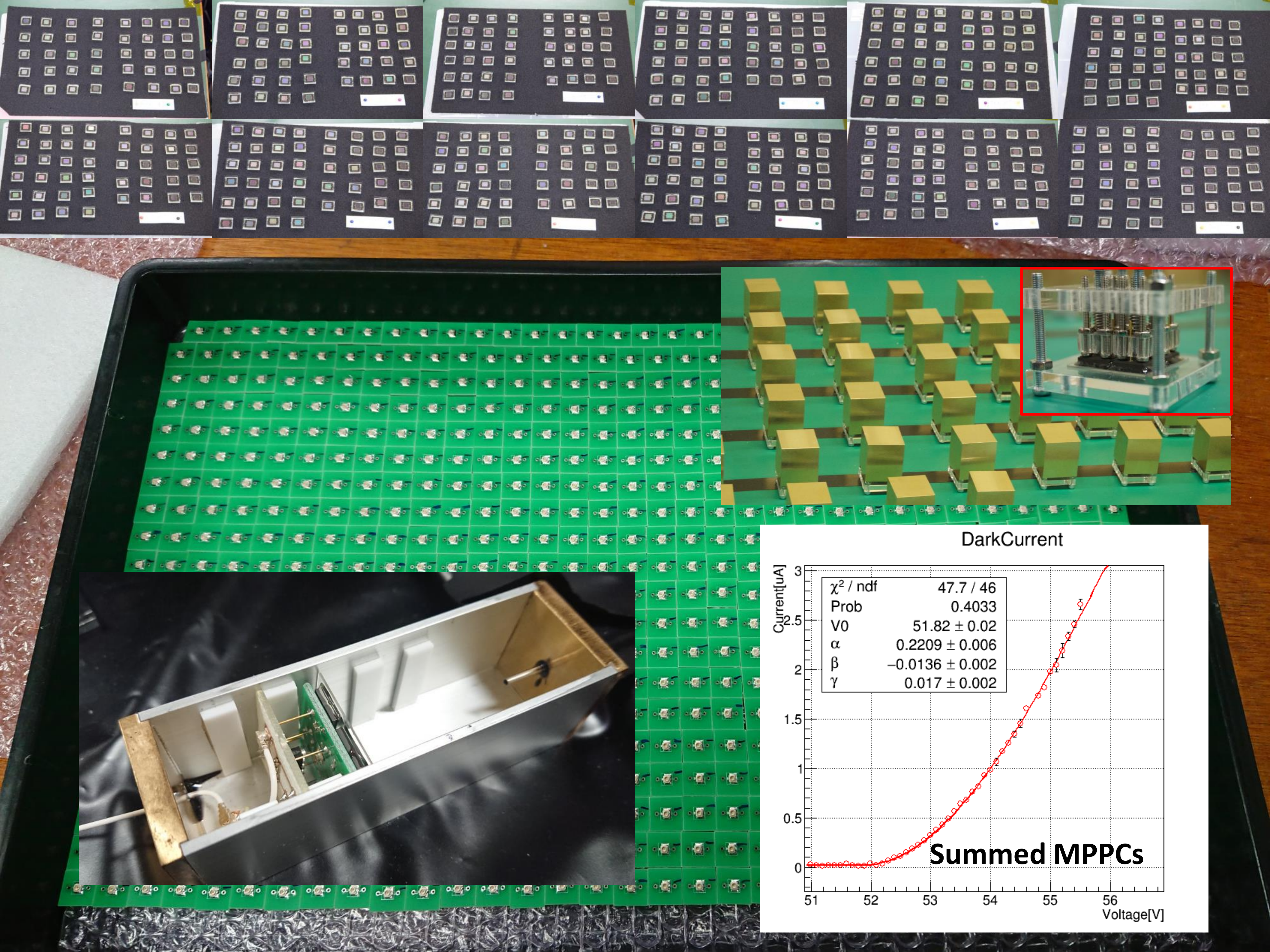


apply weight



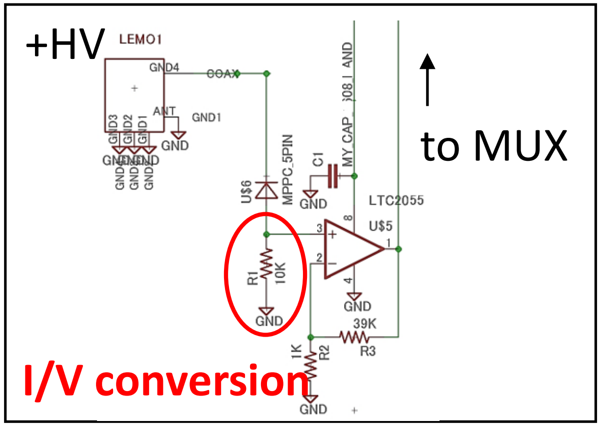
8

wait 24 h for cure

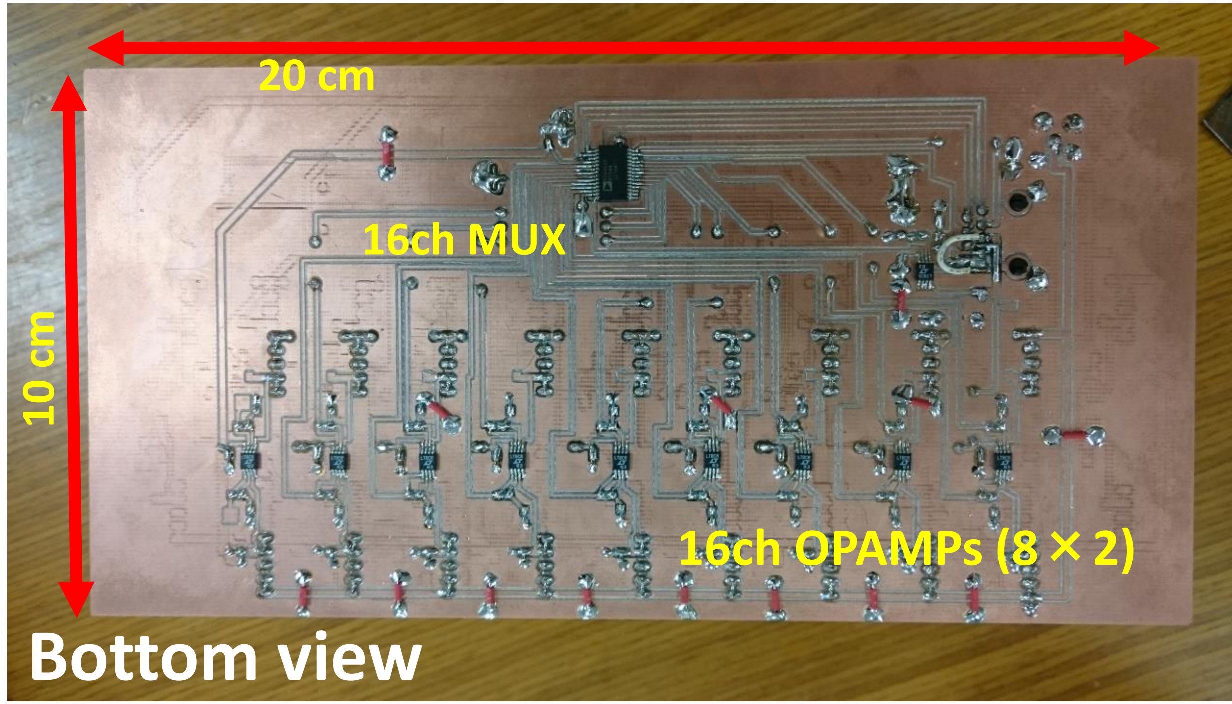

DarkCurrent
Current[uA]
Voltage[V]
χ^2 / ndf 47.7 / 46
Prob 0.4033
V0 51.82 ± 0.02
α 0.2209 ± 0.006
β −0.0136 ± 0.002
γ 0.017 ± 0.002
0
0.5
1
1.5
2
2.5
3
51
52
53
54
55
56
Summed MPPCs

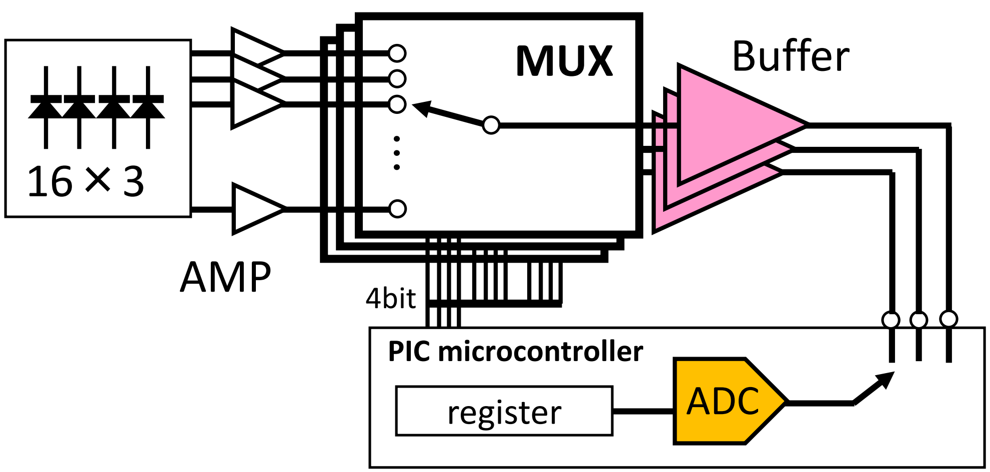
I/V inspection of MPPCs

I/V inspection front end



OPAMP
→FET input（high impedance）
Gain 100

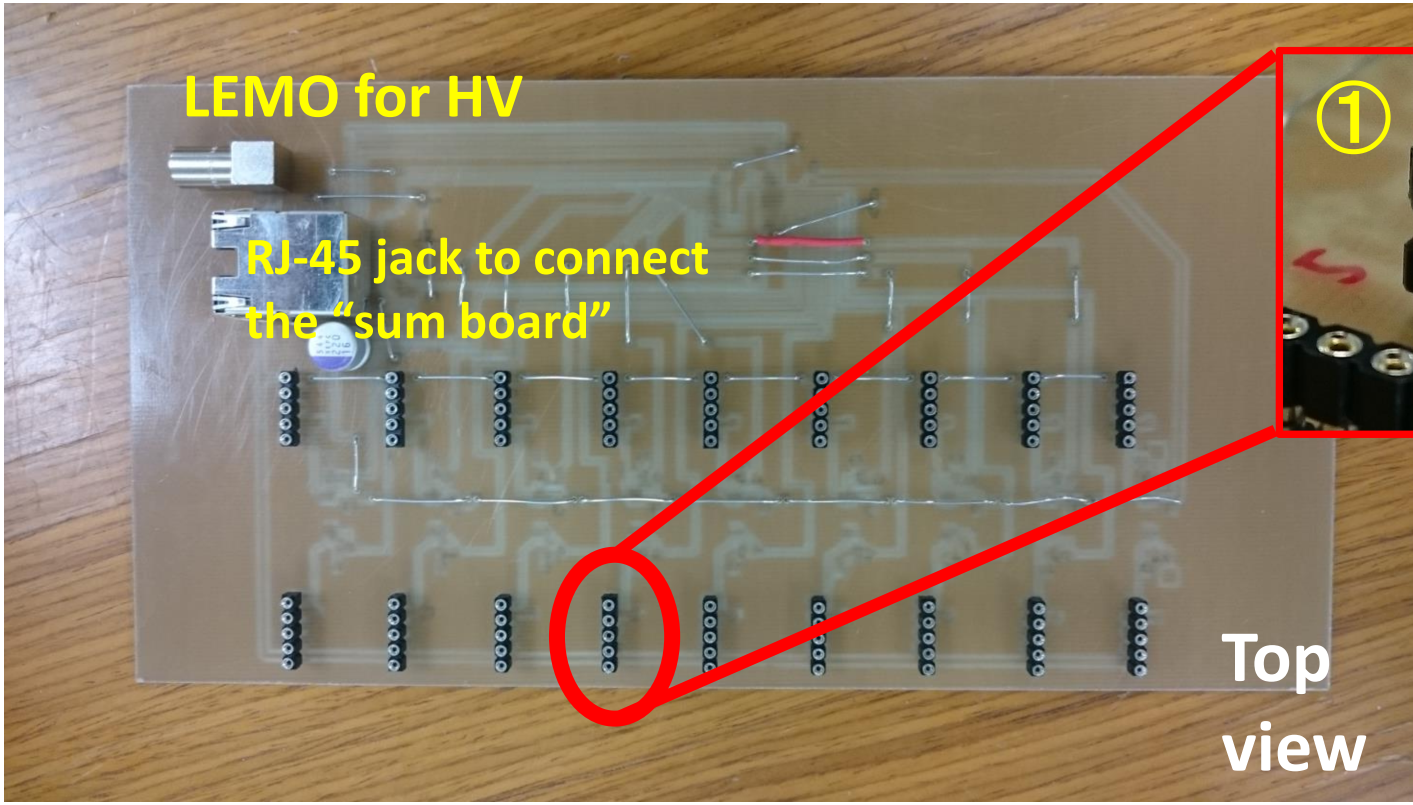


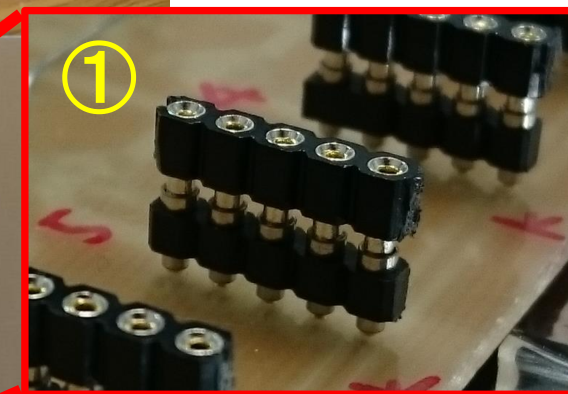


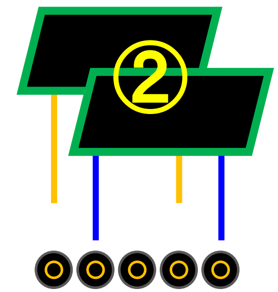
Basic design

- 16ch are chosen by MUX
- DC voltage is buffered by voltage follower after the MUX

Front-end board 1/3 (top)







IC socket

IC socket is used as a connector