July 28th 2020

Construction and performance of 4-D CsI Calorimeter for the $K_L \to \pi^0 \nu\bar{\nu}$ search of KOTO experiment

K. Kotera Osaka U
on behalf of KOTO collaboration

@ICHEP 2020

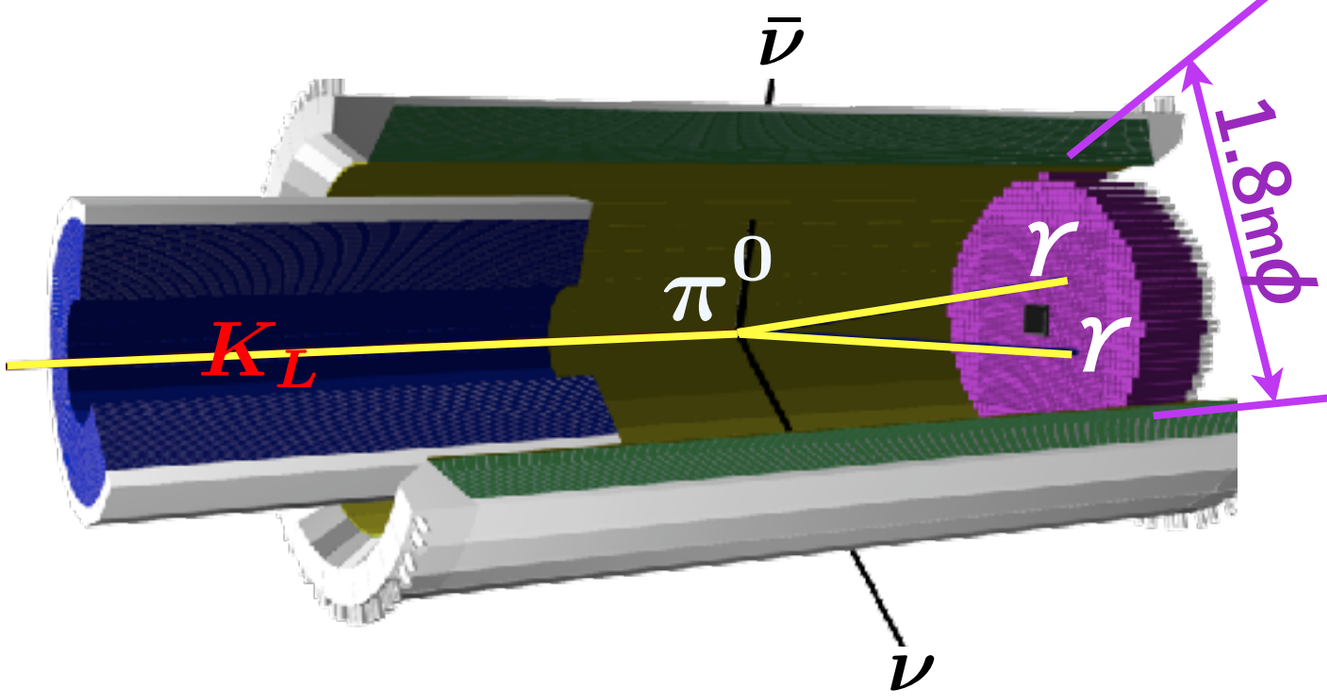
KOTO ➡ Study of $K_L \to \pi^0 \nu\bar{\nu}$

direct ~~CP~~ : the Standard Model - Bf: 3×10^{-11}

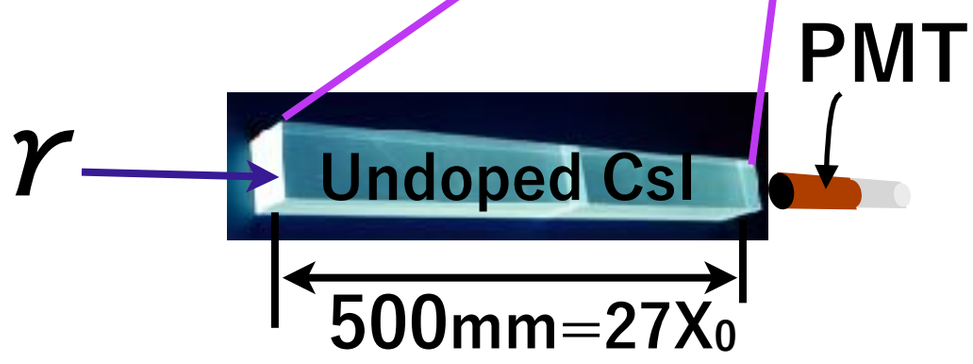
sensitive to BSM

a golden needle in a haystack

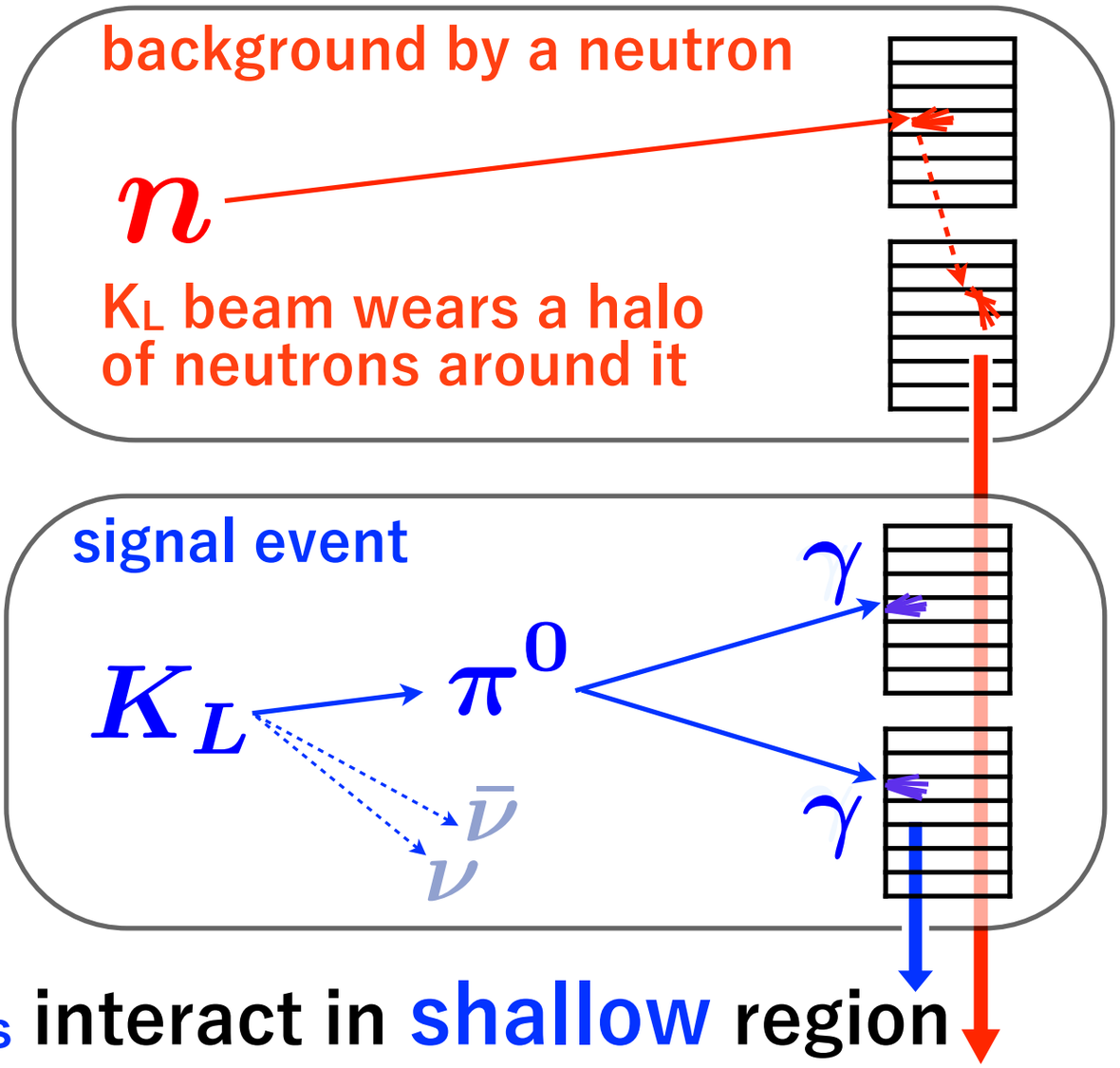
J-PARC Tokai
in Japan



hermetic veto counters



Neutron BG: a neutron fakes two showers in the calorimeter



γ_s interact in shallow region

neutrons reach deeper

from 2019 PRL (2015Data)

1.3×10^{-9} Single event sensitivity

background source	#events
Halo neutron hitting CSI	0.24 ± 0.17
Halo neutron hitting upstream detectors	0.04 ± 0.04
η background	0.03 ± 0.02
$K_L \to \pi^+ \pi^- \pi^0$	0.05 ± 0.02
$K_L \to 2\pi^0$	0.02 ± 0.02
other KL decays	0.02 ± 0.02
Sum	0.42 ± 0.18

neutron BG : $K_L \to \pi^0 \nu\bar{\nu}$ SM prediction = 10:1

3×10^{-11}

GOAL: reduce at least factor 10

Idea of the both-side readout

Measure energy position in Z adding to position x and y.

this study

Existing setup

Only rear-end readout with PMT

t_{MPPC} t_{PMT}

$t_{\mathrm{MPPC}} - t_{\mathrm{PMT}}$

$= \Delta T \propto z_{\mathrm{cluster}}$

SiPM: Hamamatsu MPPC

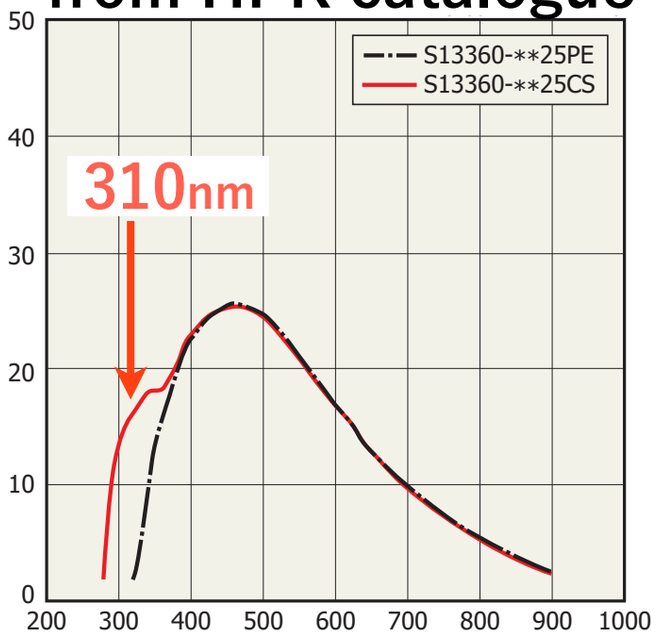
50 μm pitch in 6 × 6mm^2 =14400 pixel

Gain: 1.7 × 10^6 @ V_{break} + 3V

UV transparent silicone window

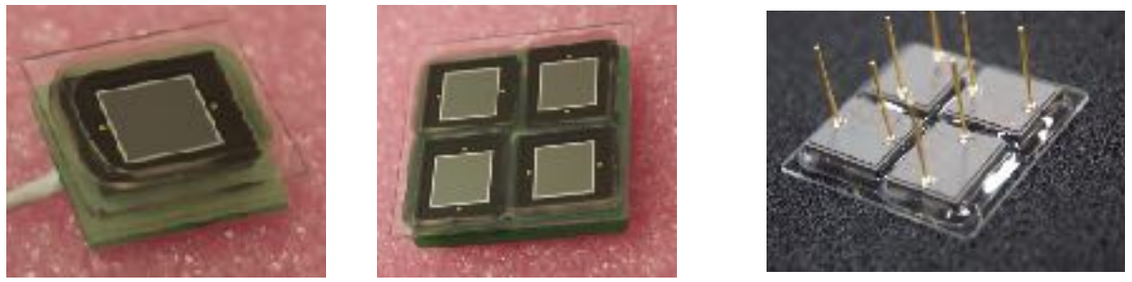
0.01X_0 × 1cm^2/6.25cm^2 crystal surface

from HPK catalogue

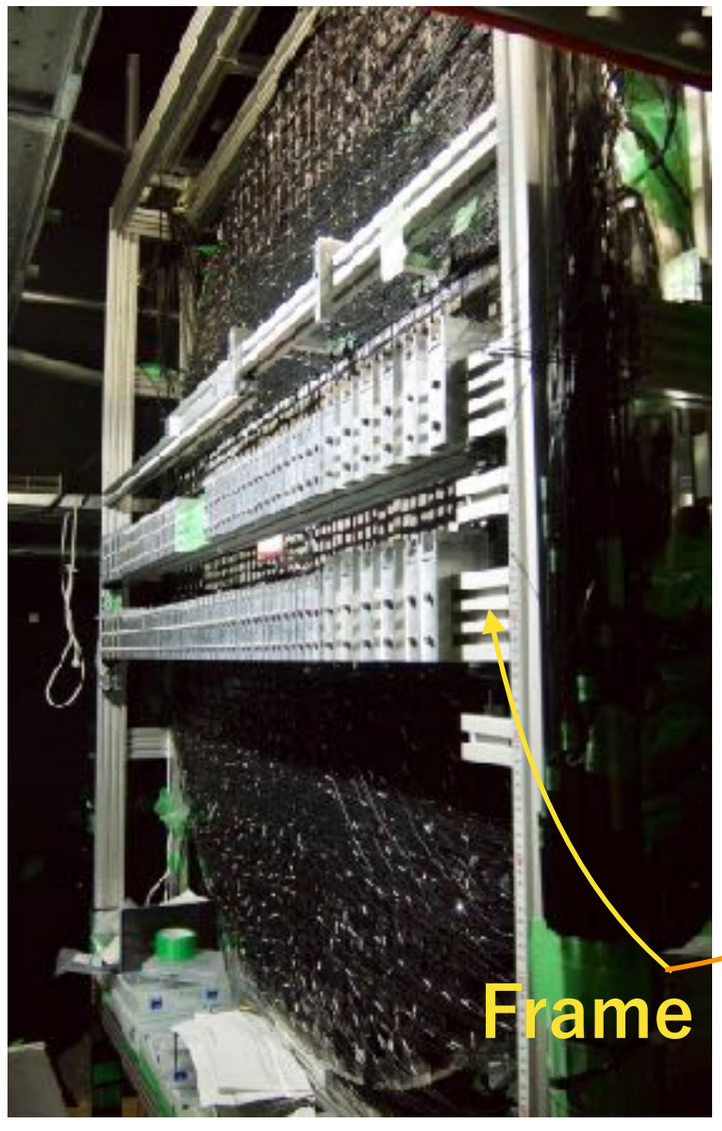


Construction onsite (avoid disassembly)

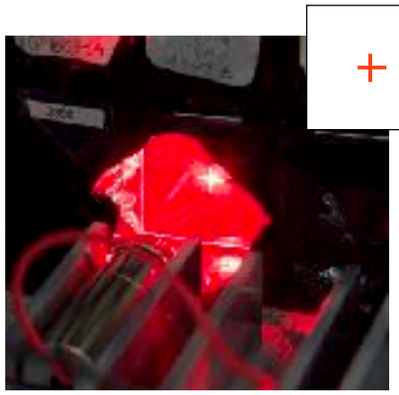
- Large crystal: 4MPPCs
- Small crystal: one MPPC



0n 0.5mmT quartz plate

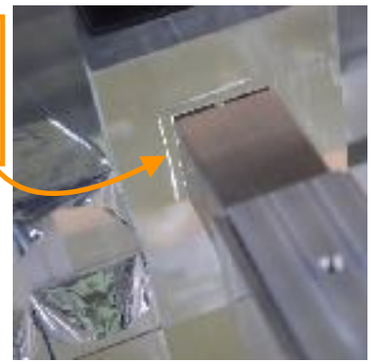


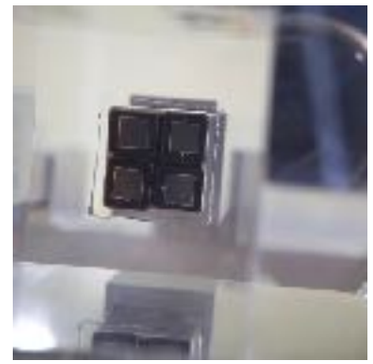
two lines/day



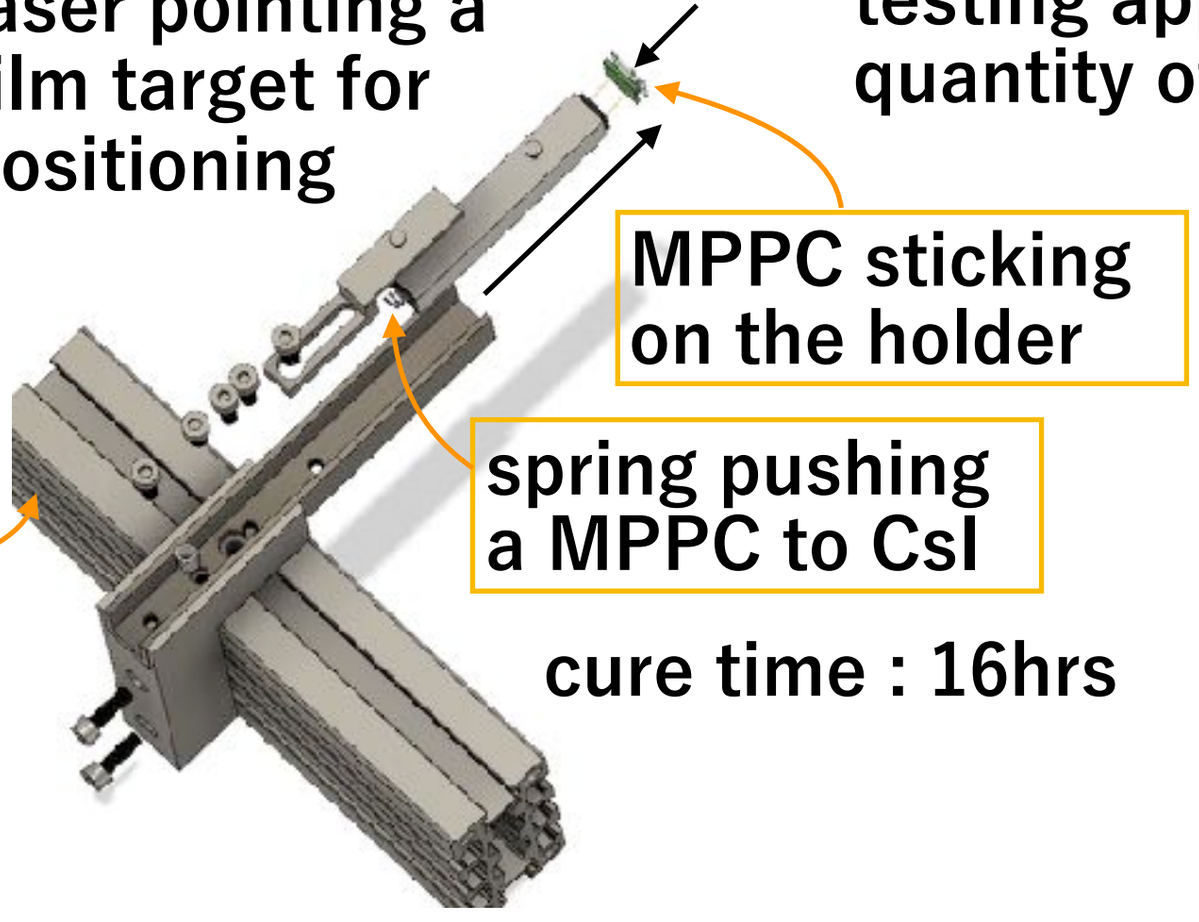
laser pointing a film target for positioning

good overflow





testing appropriate quantity of glue



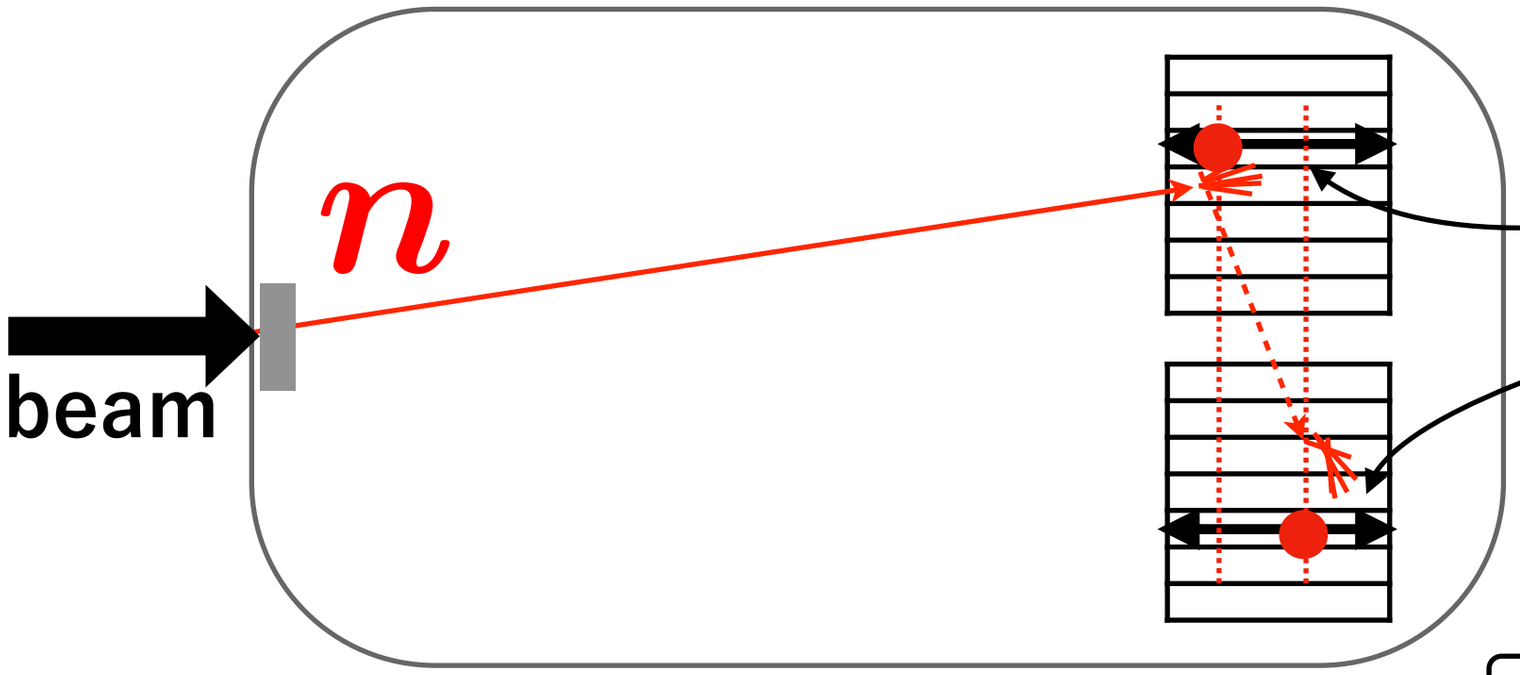
MPPC sticking on the holder

spring pushing a MPPC to CsI

cure time : 16hrs

γ and neutron samples for ΔT_{study}

Aluminum target in beam (3mmT)



$$\Delta T = t_{\mathrm{MPPC}} - t_{\mathrm{PMT}}$$

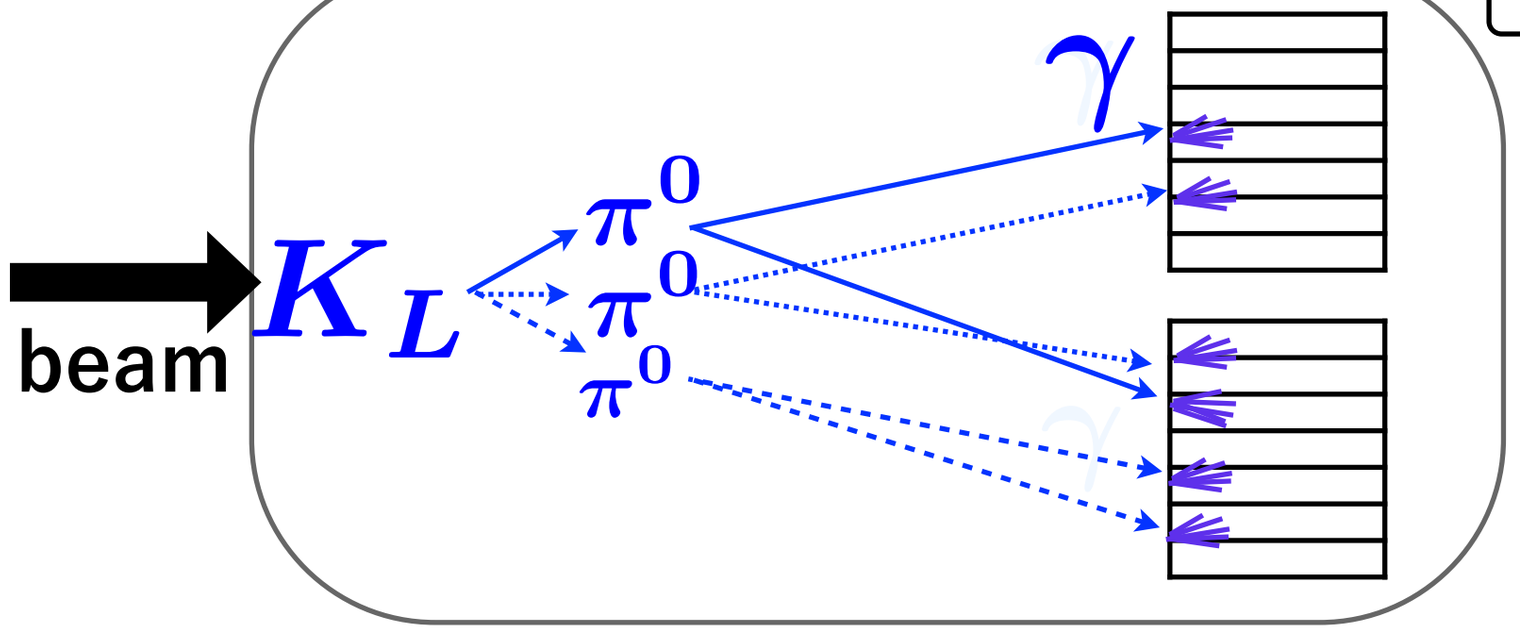
small ΔT= ΔT^{min}

Large ΔT= ΔT^{max}

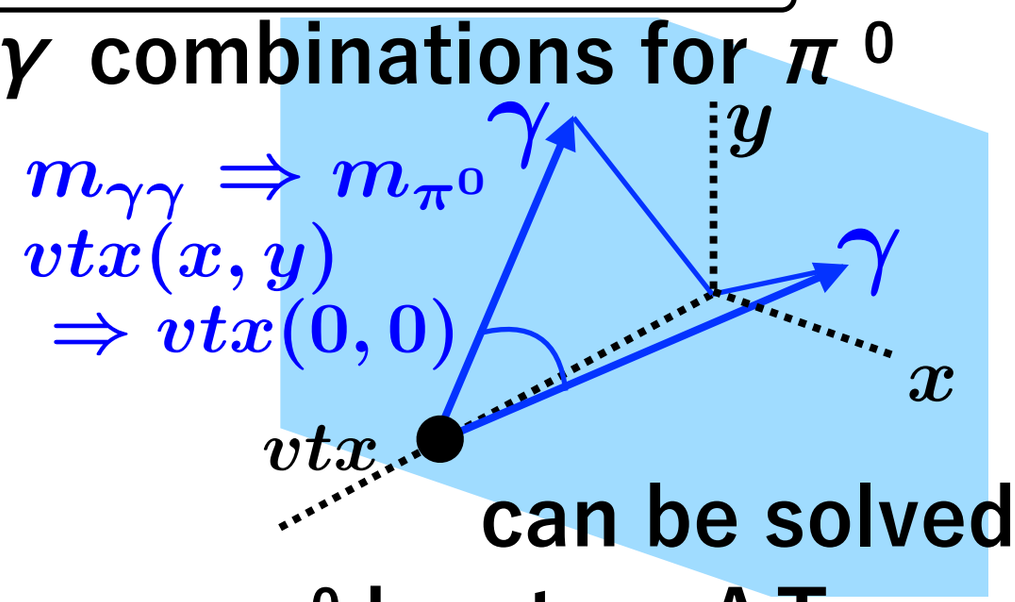
one event has two ΔT

Use $K_L \to 3\pi^0$ events

Large Br(19.52%)
less contamination



γ combinations for π^0

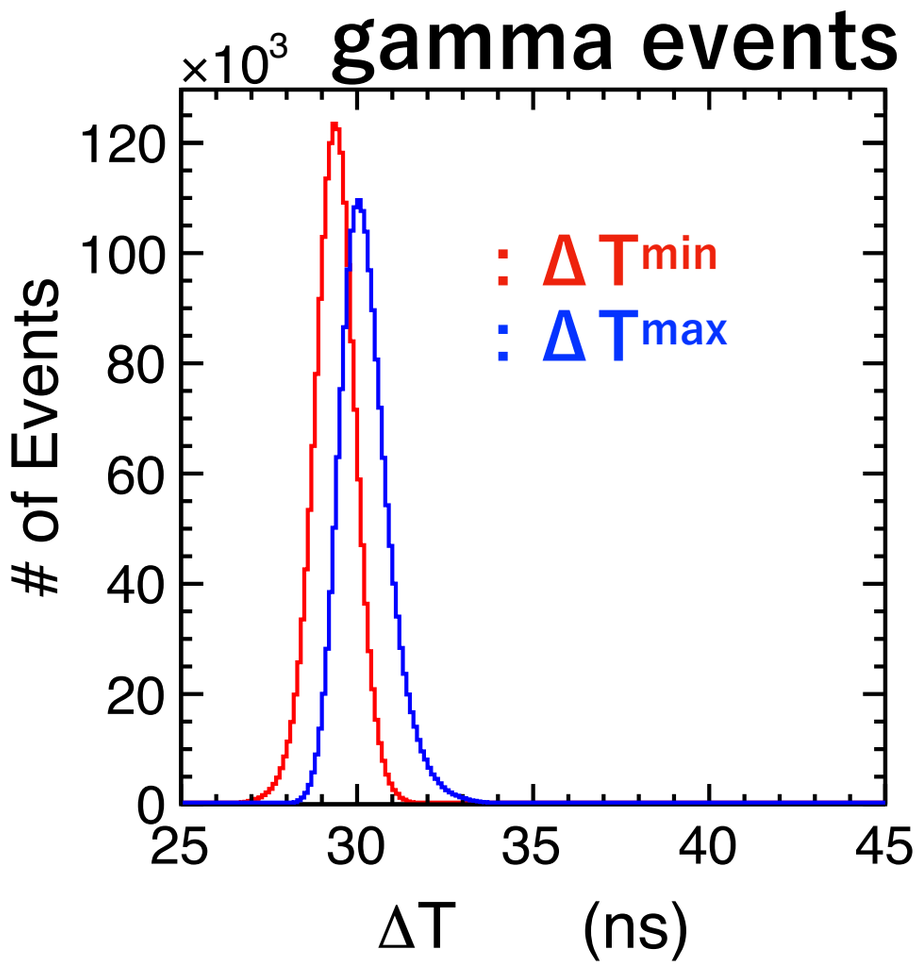


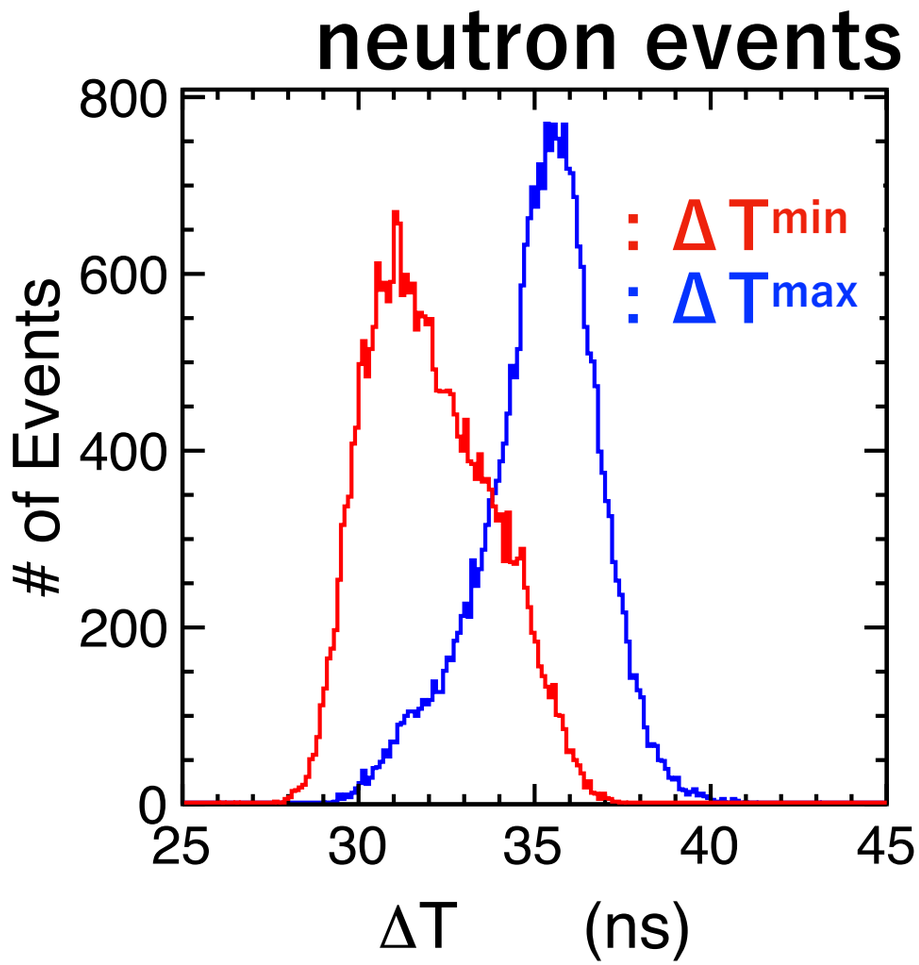
can be solved

one π^0 has two ΔT

ΔT of gamma/neutron events

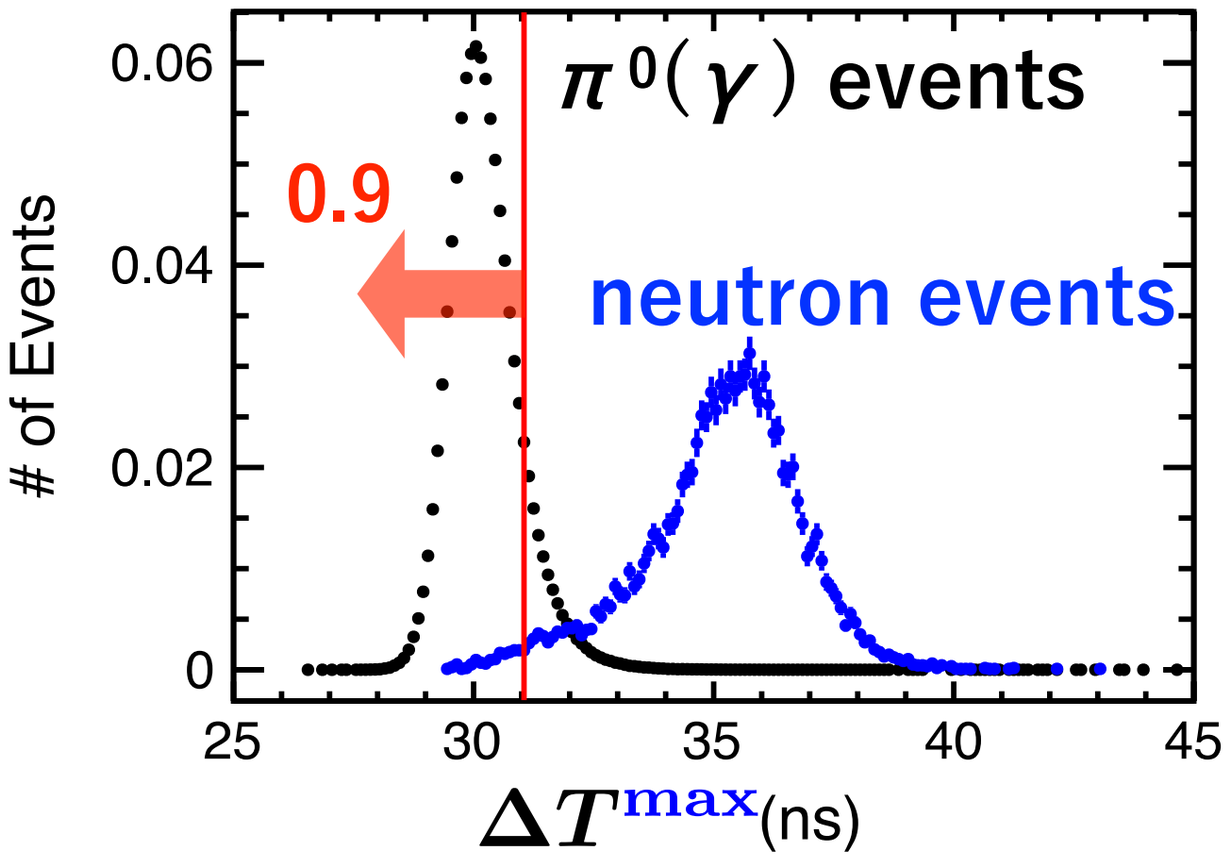
- γ events are pairs of γs reconstructing π^0





- ΔT^{max} has better selection ability

γ/n separation by ΔT^max

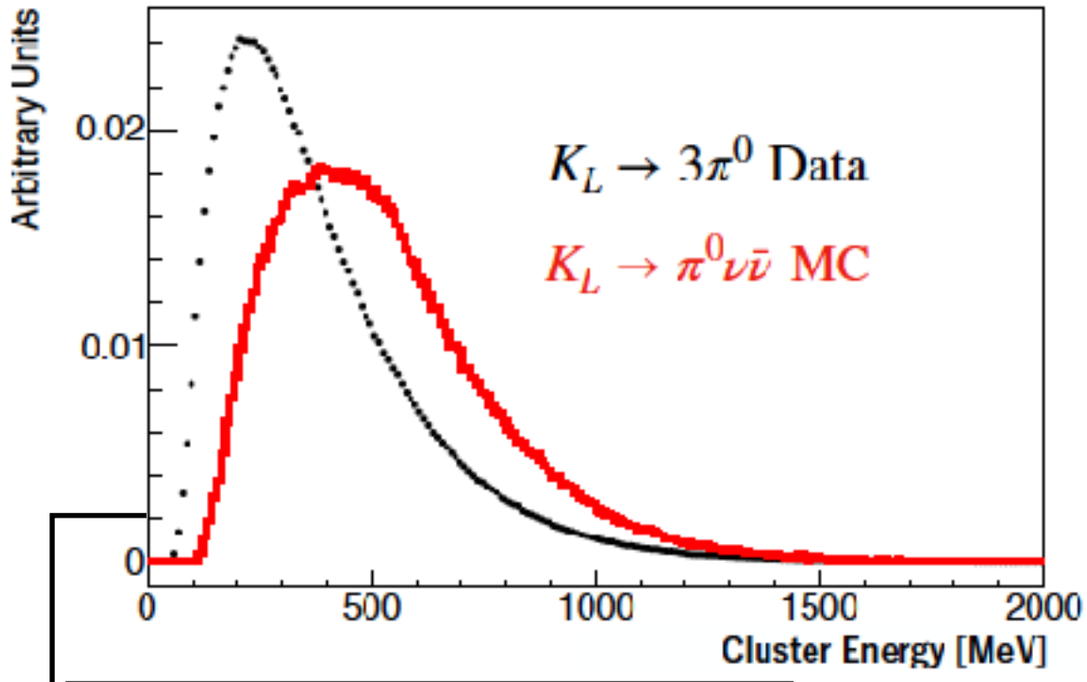


remaining neutron event

(2.1 ±0.1) ×10⁻²

(1.6 ±0.1) ×10⁻²

ΔT^max:
large ΔT
t_{MPPC} was weight by energy



correction energy dependence

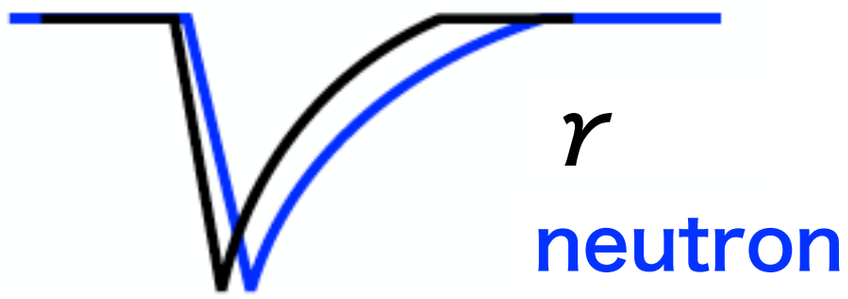
$K_L \to 3\pi^0 \Rightarrow K_L \to \pi^0\nu\bar{\nu}$

Beyond the first goal (reduction factor 10)

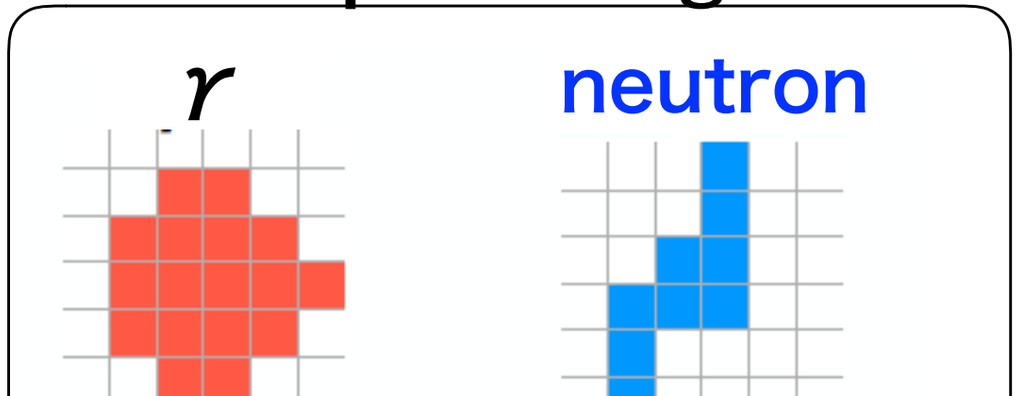
Remaining neutron BG for KOTO

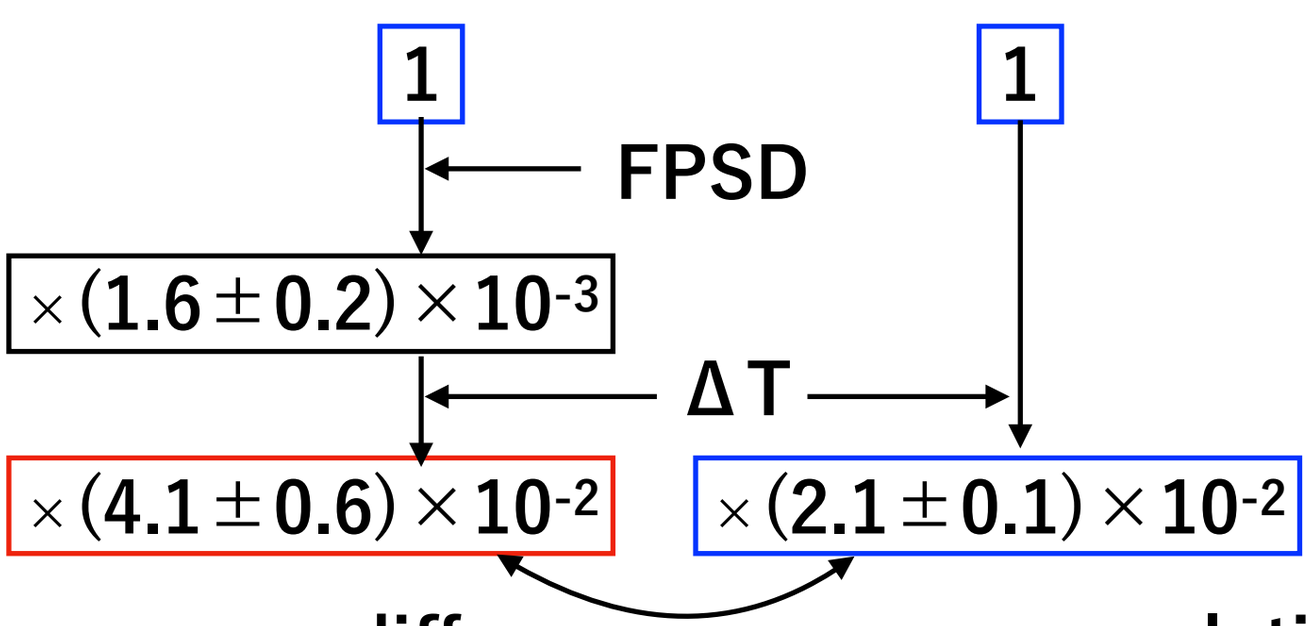
Two other cut methods were developed

Fourier Pulse Shape Discriminator

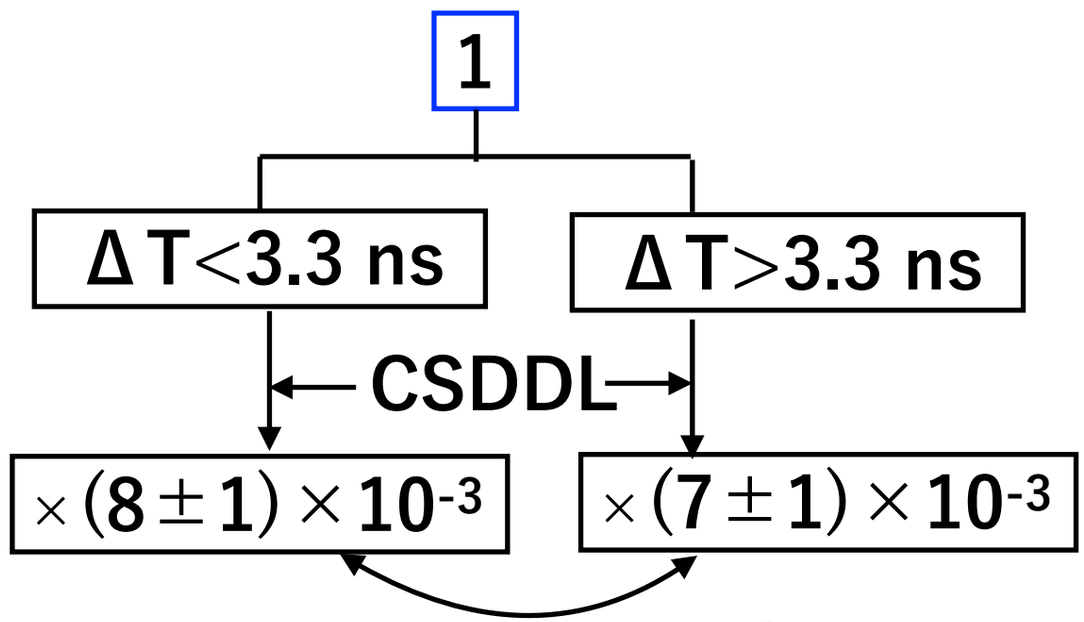


Cluster Shape Discriminator with Deep Leaning





difference means a correlation:
$(4.1 \pm 0.6) \times 10^{-2}$ still enough



no correlation between
ΔTcut : CSDDL

with 3 cuts

Estimated remaining n events are 0.5 ± 0.5 in 1 SM events(3×10^{-11})

Invariant time → 4D calorimetry

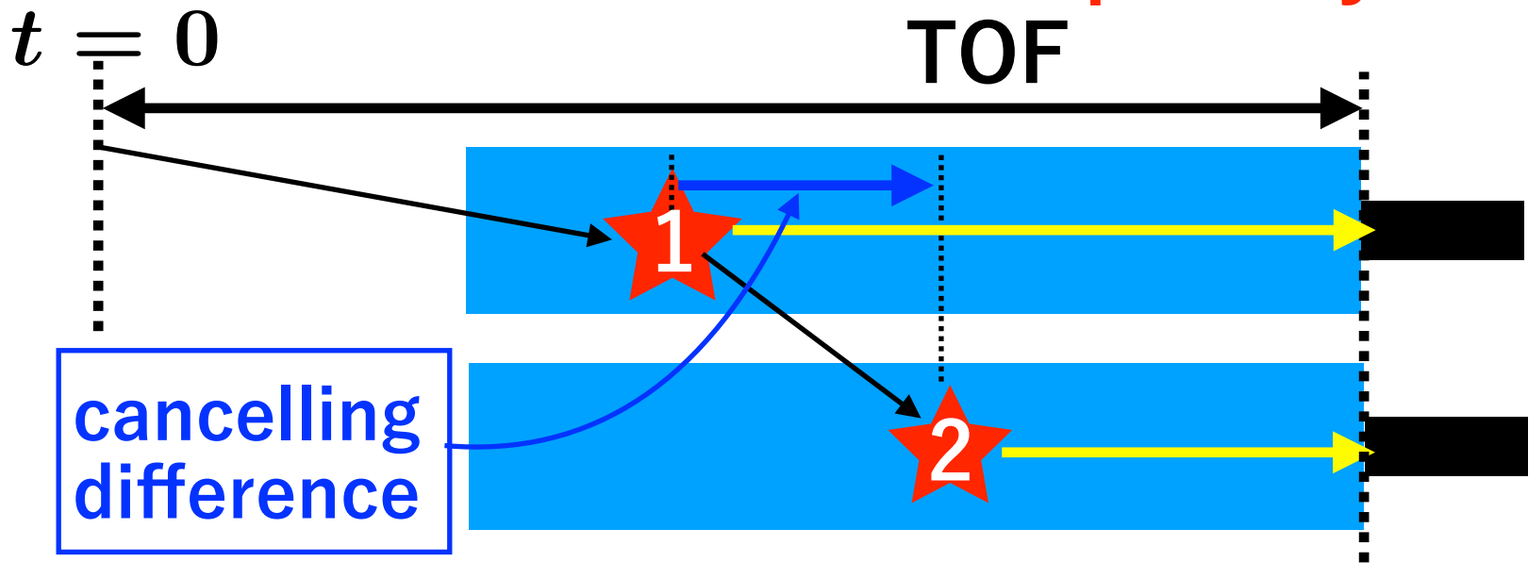
$$T_{\mathrm{inv}} = (T_{\mathrm{MPPC}} + T_{\mathrm{PMT}})/2$$

independent of the cluster depth (intrinsic)

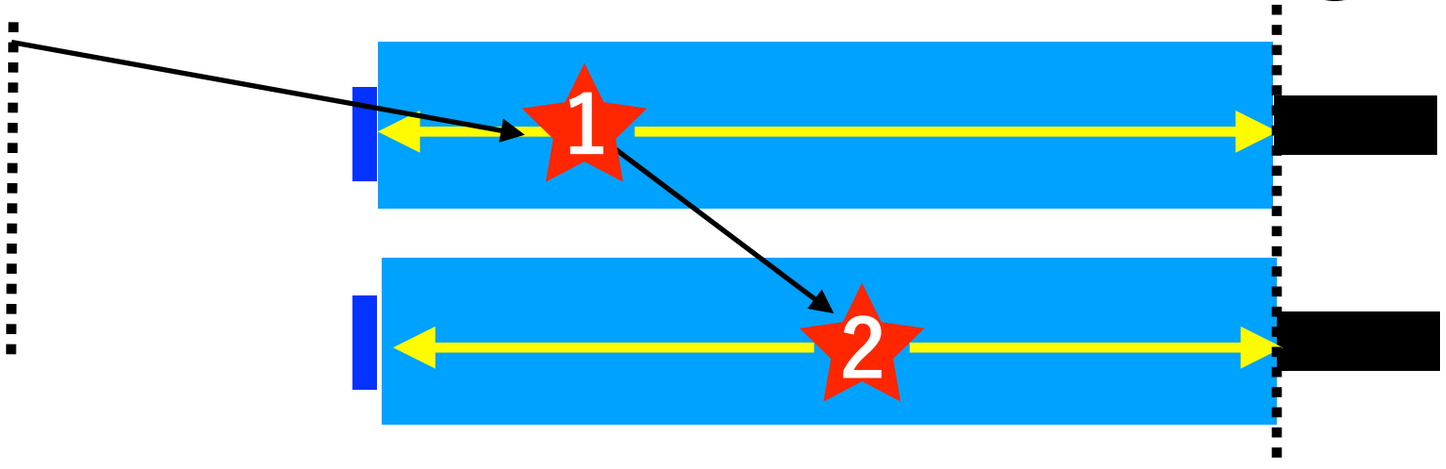
Merit of T_{inv}

Conventional TOF w/o both-side readout

cannot discriminate primary and secondary



ΔT_{inv} no cancelation occurs on the average of $T_{\mathrm{MPPC}}, T_{\mathrm{PMT}}$

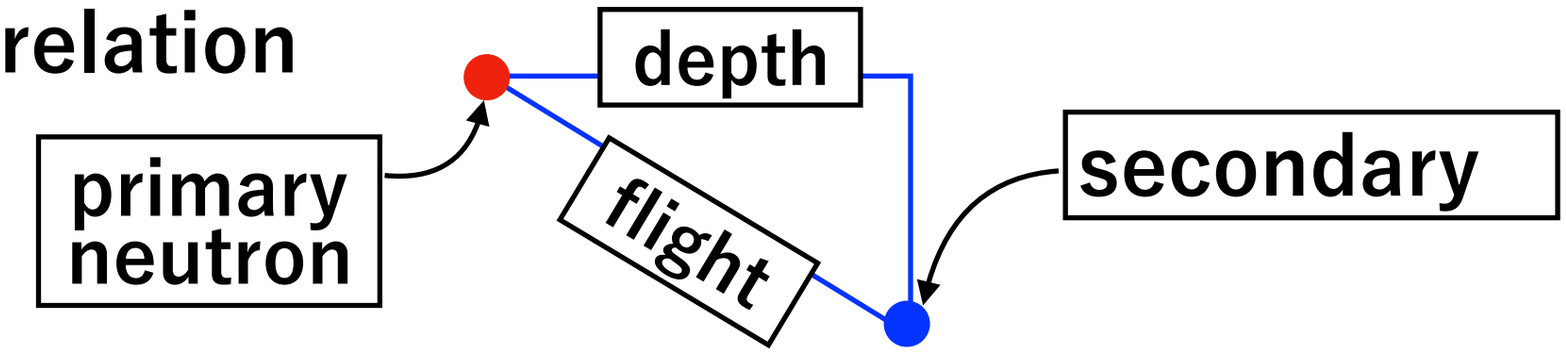


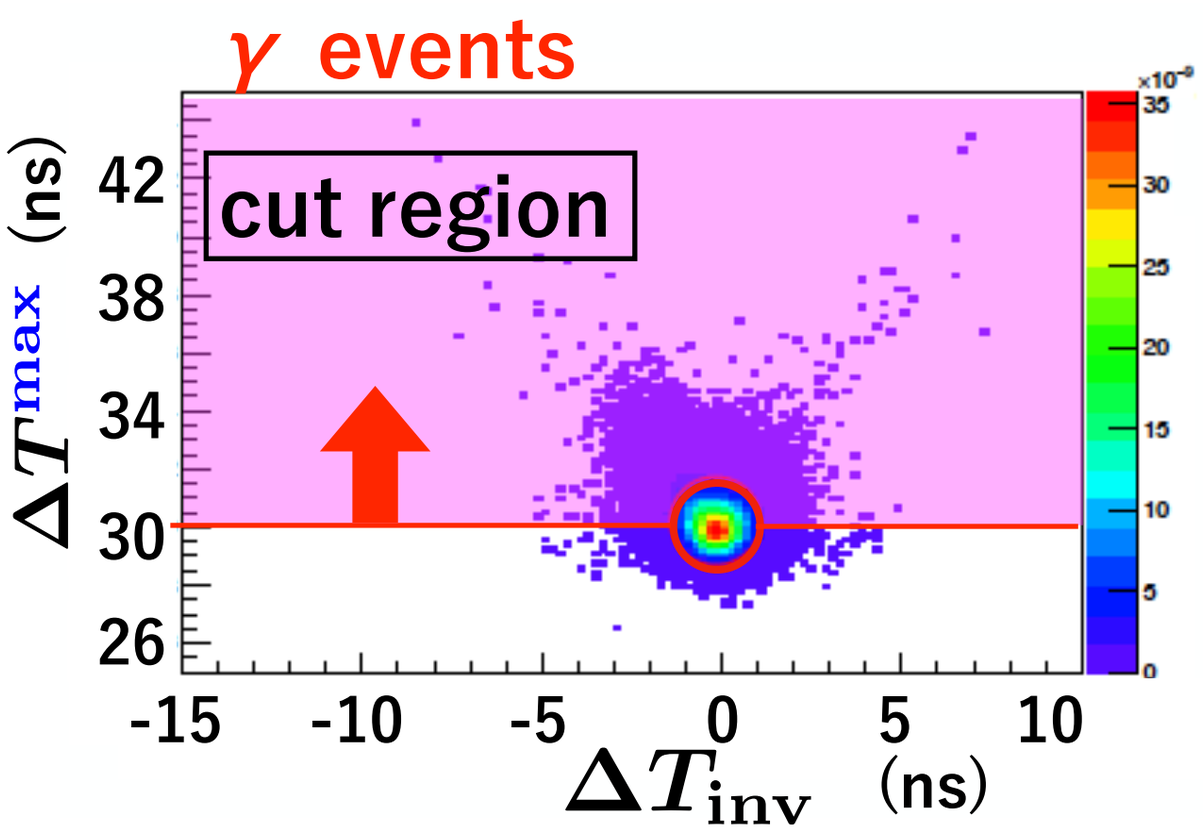
Applying invariant time info.

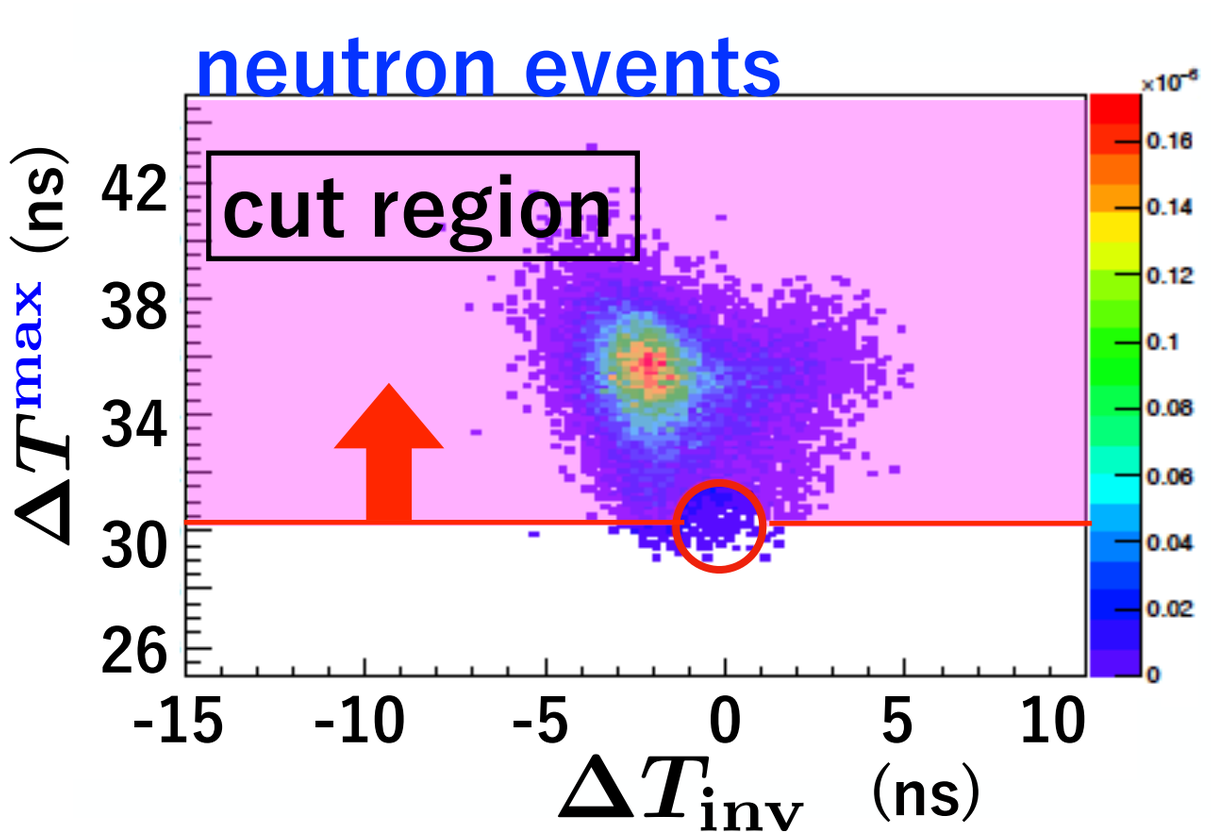
$\Delta T_{\mathrm{inv}} \propto$ flight length of the secondary particle

$\Delta T^{\mathrm{max}} = T_{\mathrm{MPPC}} - T_{\mathrm{PMT}} \propto$ depth of secondary particle

Flight time (ΔT_{inv}) and depth (ΔT^{max}) of the secondary particle have a correlation







when 90% of γ events remain, $(0.96 \pm 0.06) \times 10^{-2}$ of n events remain

Summary

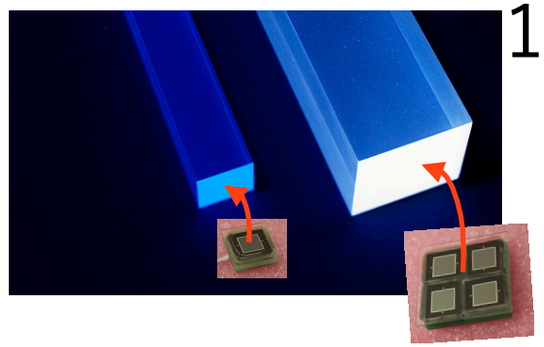
- We developed a both-side readout method for KOTO CsI calorimeter to reject neutron events
- Successfully installed 4080 MPPCs,

When 90% of signal remains
(99.04 ± 0.06)% of neutrons are rejected with both-side readout method 4-D calorimeter.

Estimated remaining neutron events are 0.5 ± 0.5 with one SM signal with $\Delta T^{\max}$ and other two cuts.

Backup slides

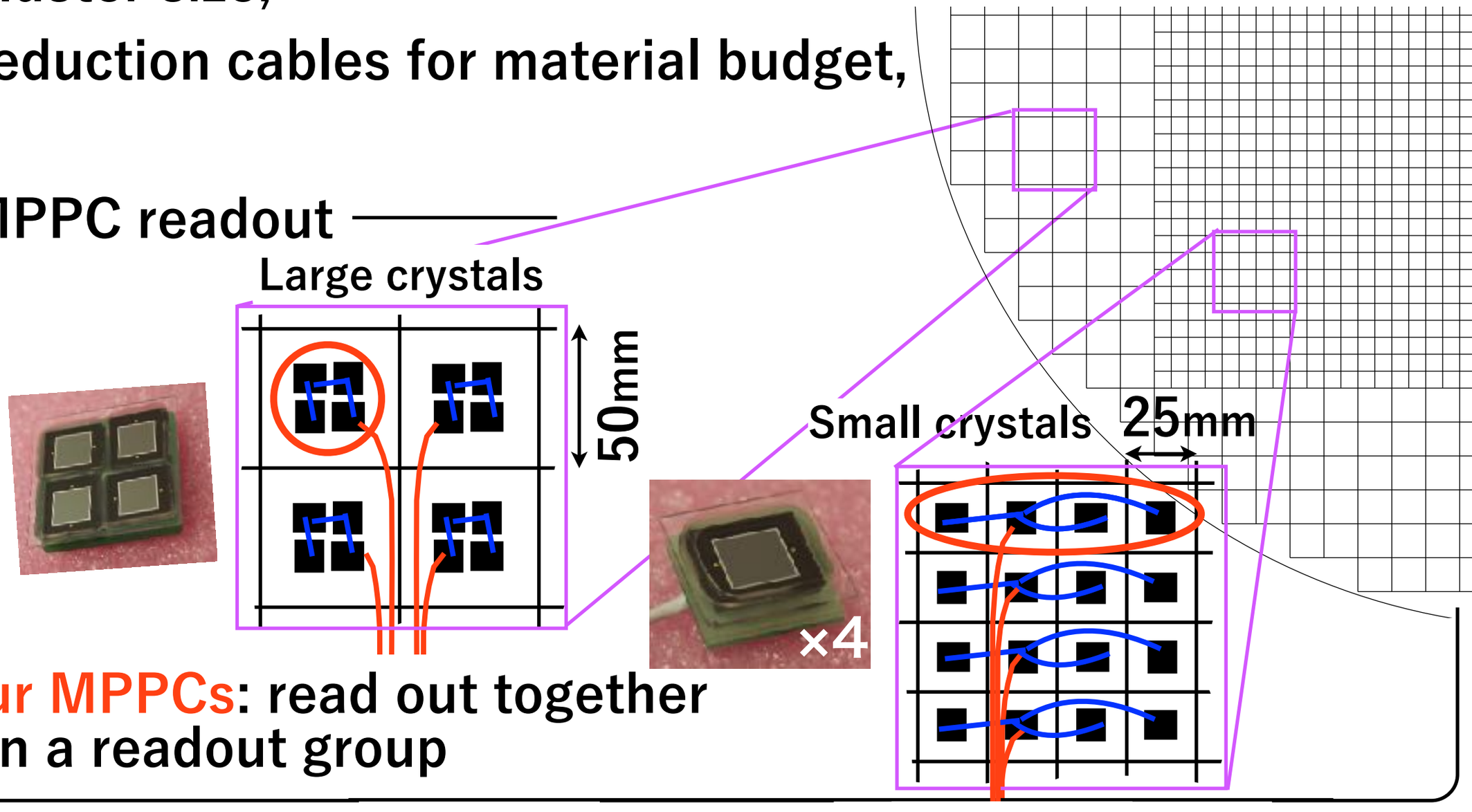
Construction Readout



Optimized readout group size is 100×100mm²

- cluster size,
- reduction cables for material budget,

4-MPPC readout



Four MPPCs: read out together in a readout group

[4-MPPC] ×4 ➡ 100×100mm²/channel;
4080➡ 256 channels total

Idea of the both-side readout

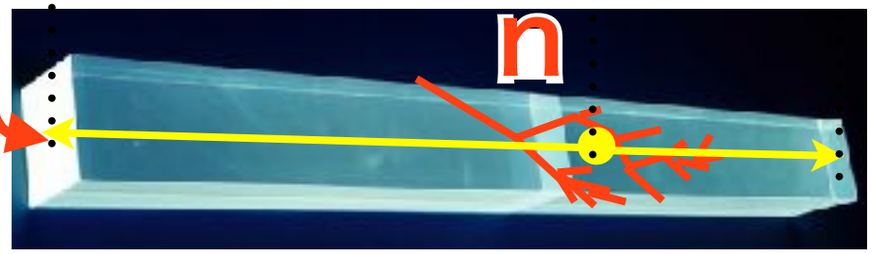
Measure energy position in Z and invariant cluster time T_{inv} adding to position x and y.

this study

Existing setup

Only rear-end readout with PMT

$$t_F - t_R = \Delta_t \propto z_{\mathrm{cluster}}$$



SiPM: Hamamatsu MPPC

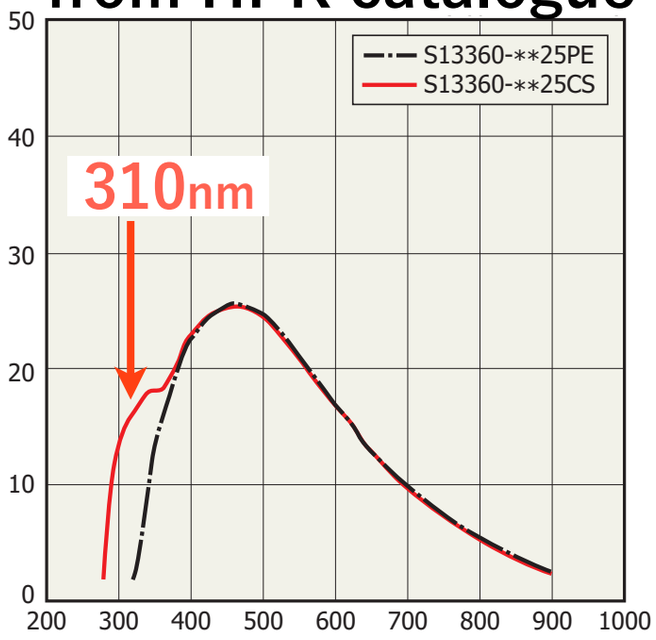
50 μm pitch in 6 × 6mm^2 =14400 pixel

Gain: 1.7 × 10^6 @ V_{break} + 3V

UV transparent silicone window

0.01X_0 × 1cm^2/6.25cm^2 crystal surface

from HPK catalogue

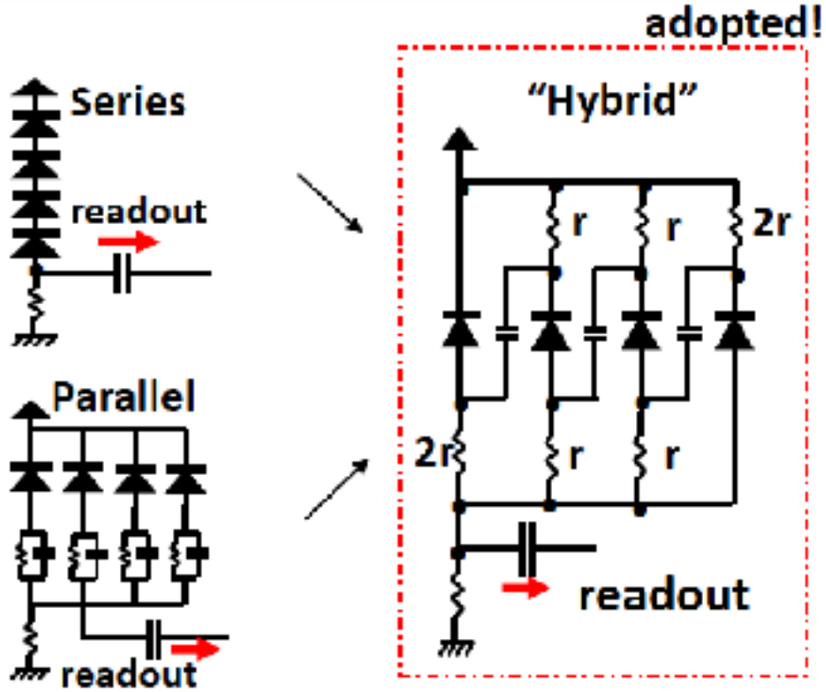


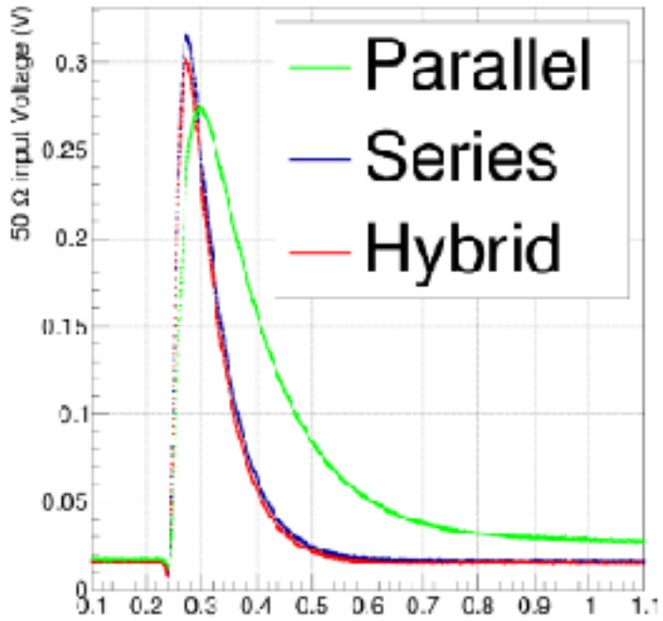
Circuit boards for 16-MPPCs

4-MPPCs

Serial connection
fast pulse,
bias depends on current

Parallel connection
slow pulse
bias not depend
on current





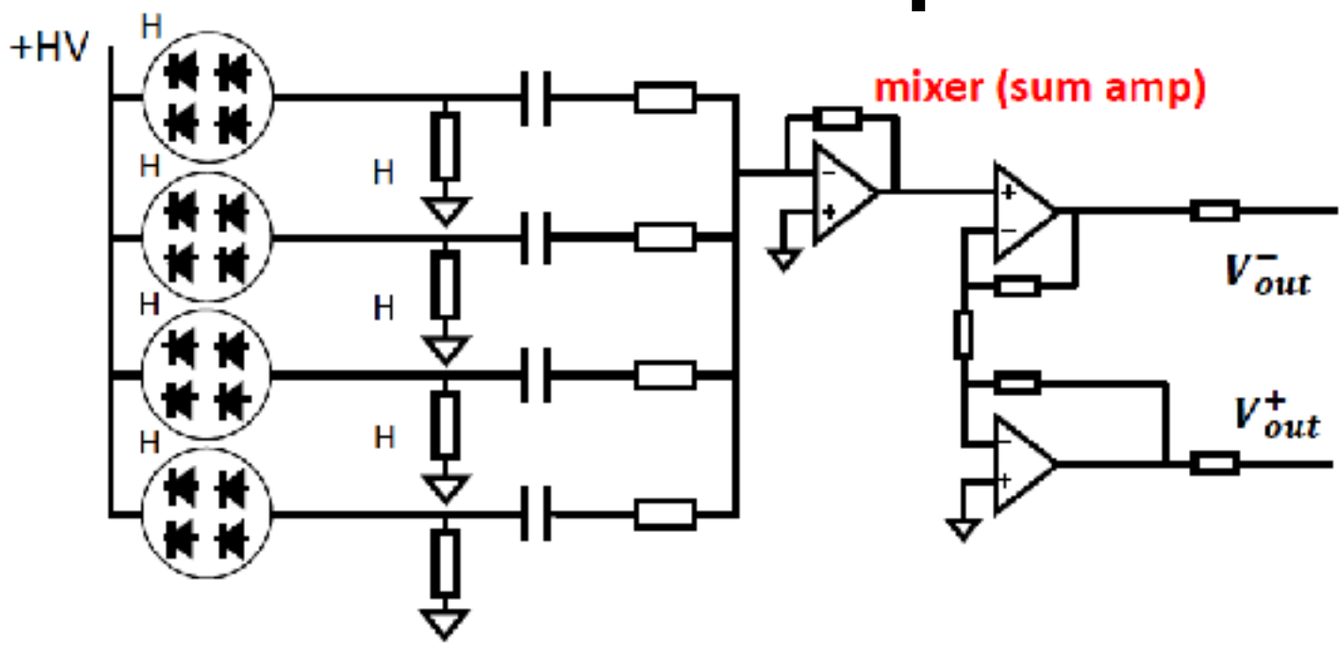
signal➡serial
bias ➡parallel

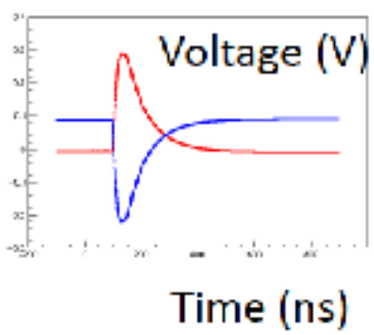
developed for MEGII

still fast pulse of hybrid case

bias not depend on current

4-MPPCs ×4 in an Amplifier

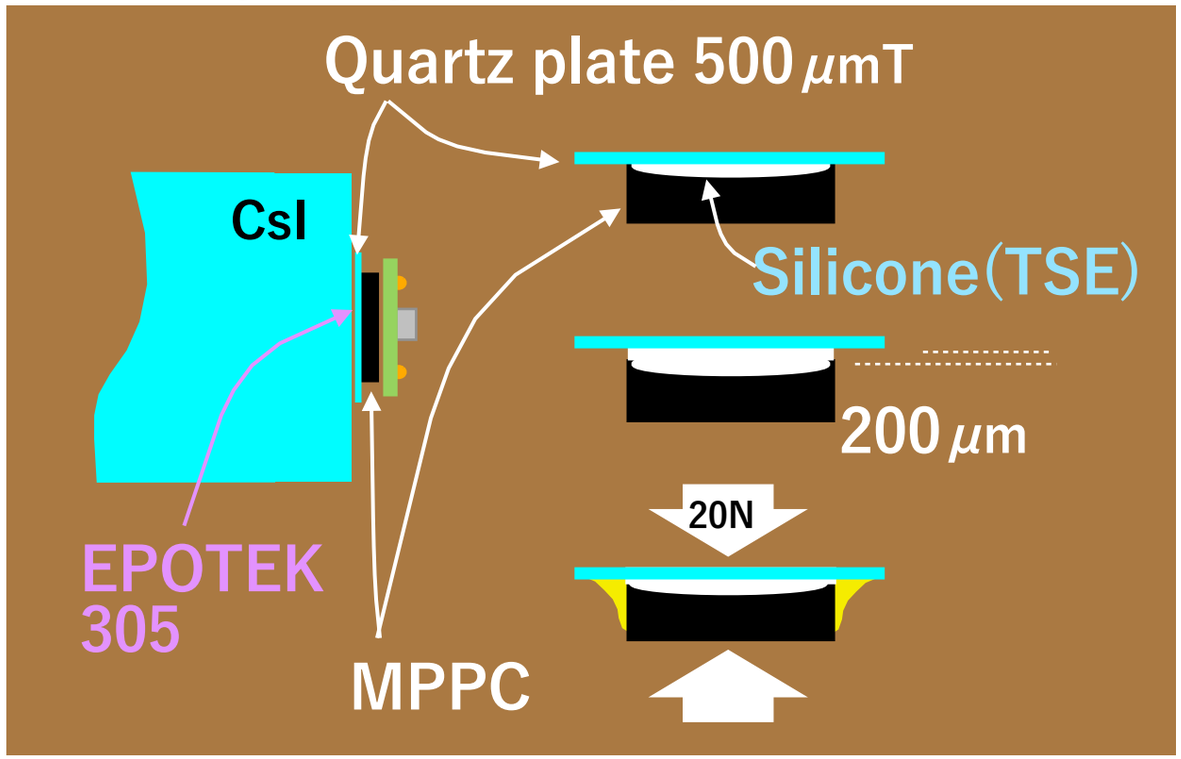




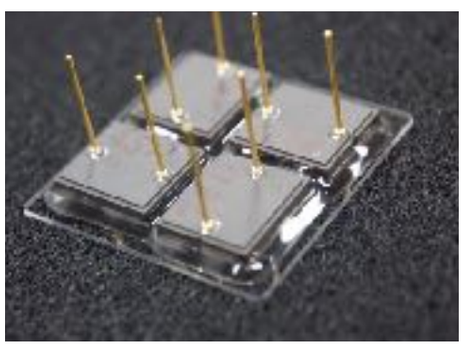
4096 MPPCs

Gluing

Design-glueing

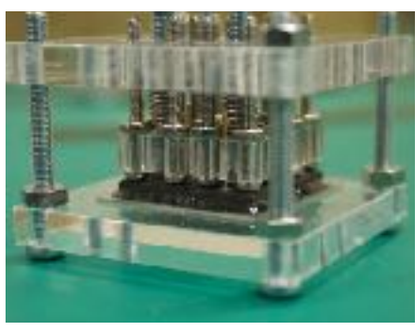


EPOTEK305:UV transparent glue
TSE3034:UV transparent silicone



Araldite

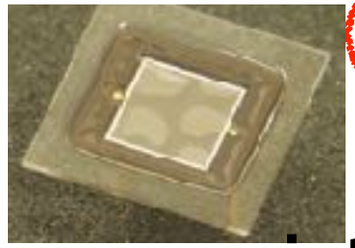
quartz plate



curing with 20N press.

fill silicone in the concave of MPPC surface and sealed with a quartz plate

babbles



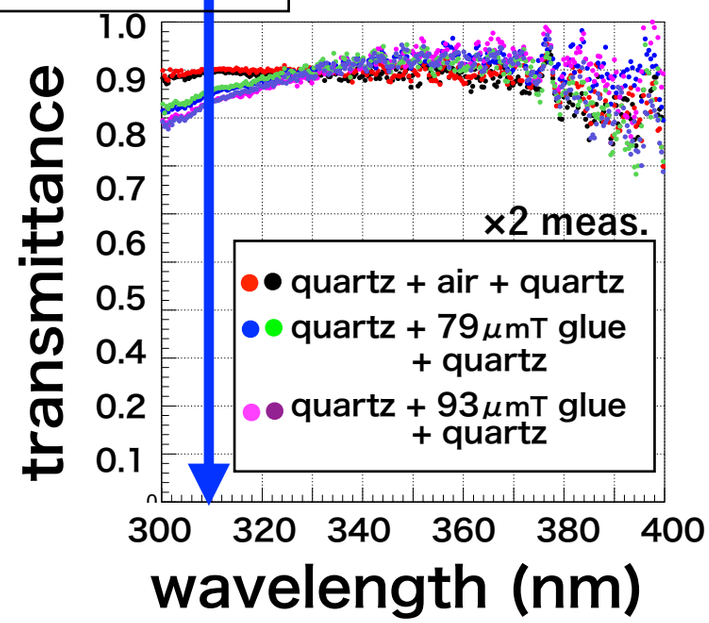
temp.variation

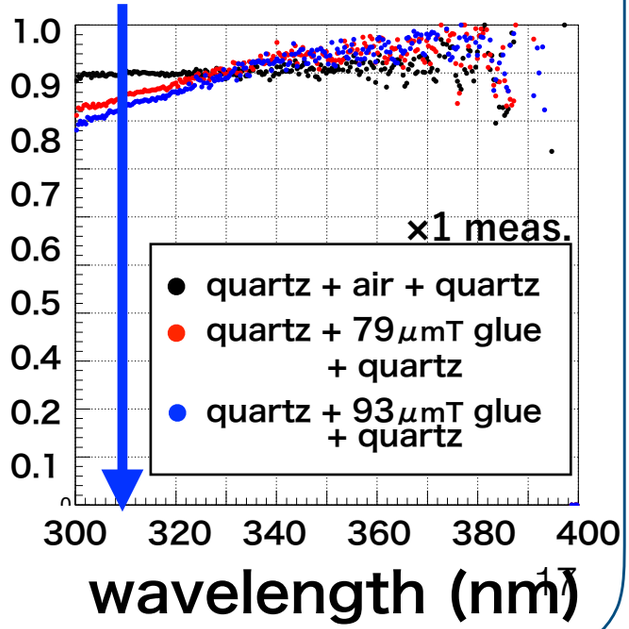
overfill silicone with 200 μm gap
press and fix with cement (Araldite)
leaving an inner pressure.

tolerance of temp: -10 —45℃

310nm CsI scint.

Before $\xrightarrow{8\times10^{8}\ \mathrm{n1MeV/cm^2}}$ After





Radiation hardness

Start from ~2 μA for 4 combined MPPCs

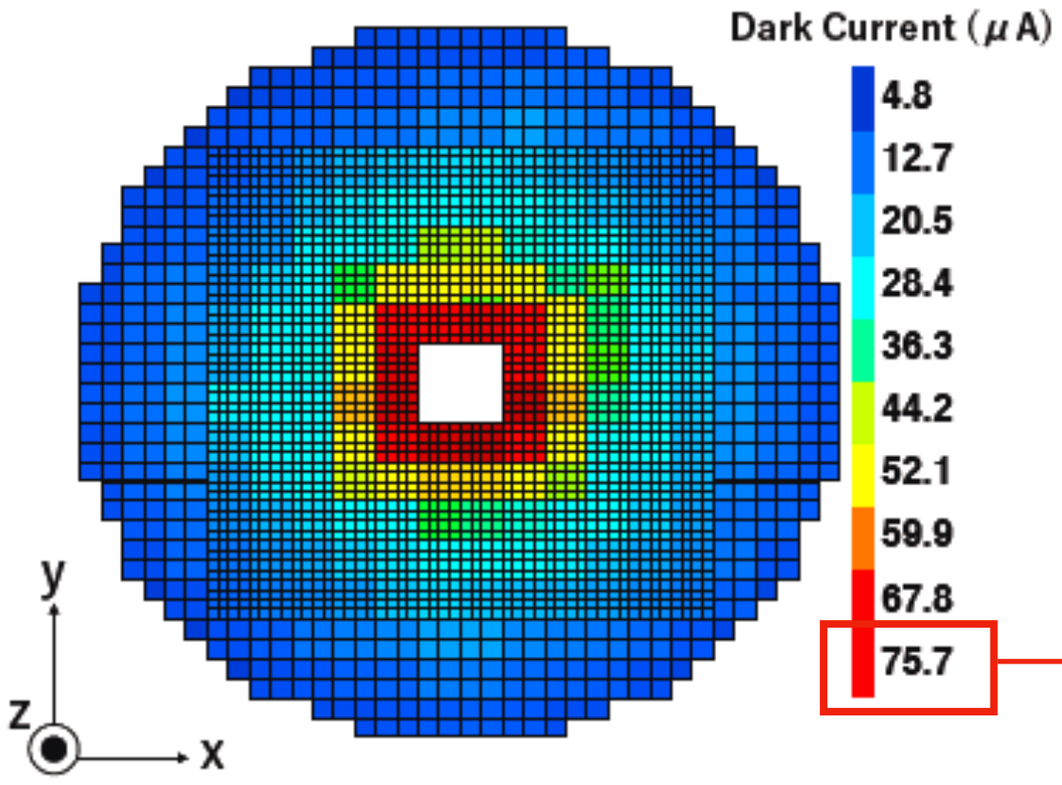
After 2.2×10^{19} proton on target (2019)

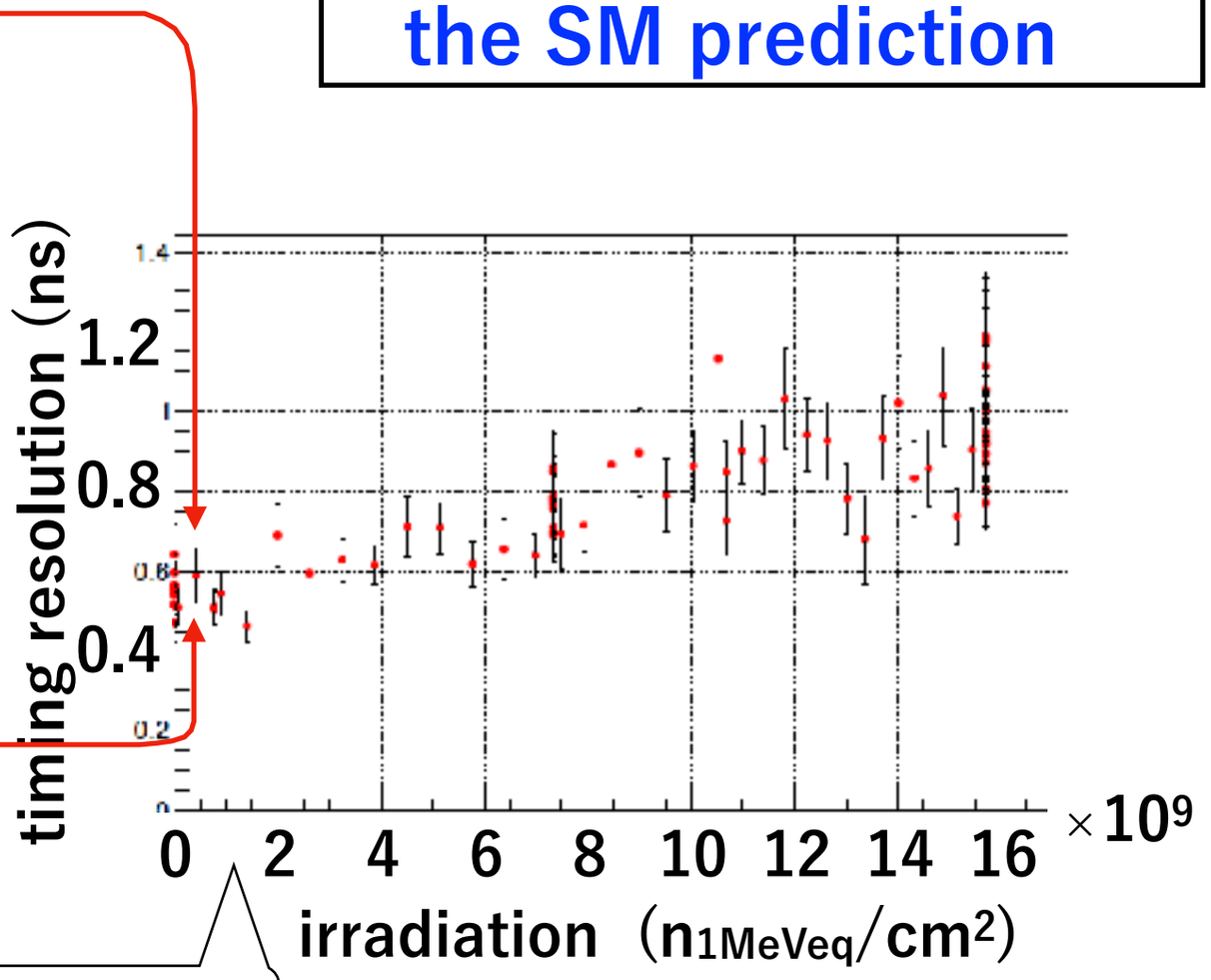
~10^{-9} sensitivity of $K_L \to \pi^0\nu\bar{\nu}$

very roughly estimation

➡corresponds 3×10^{8}n/cm^2

➡enough tolerable to the SM prediction





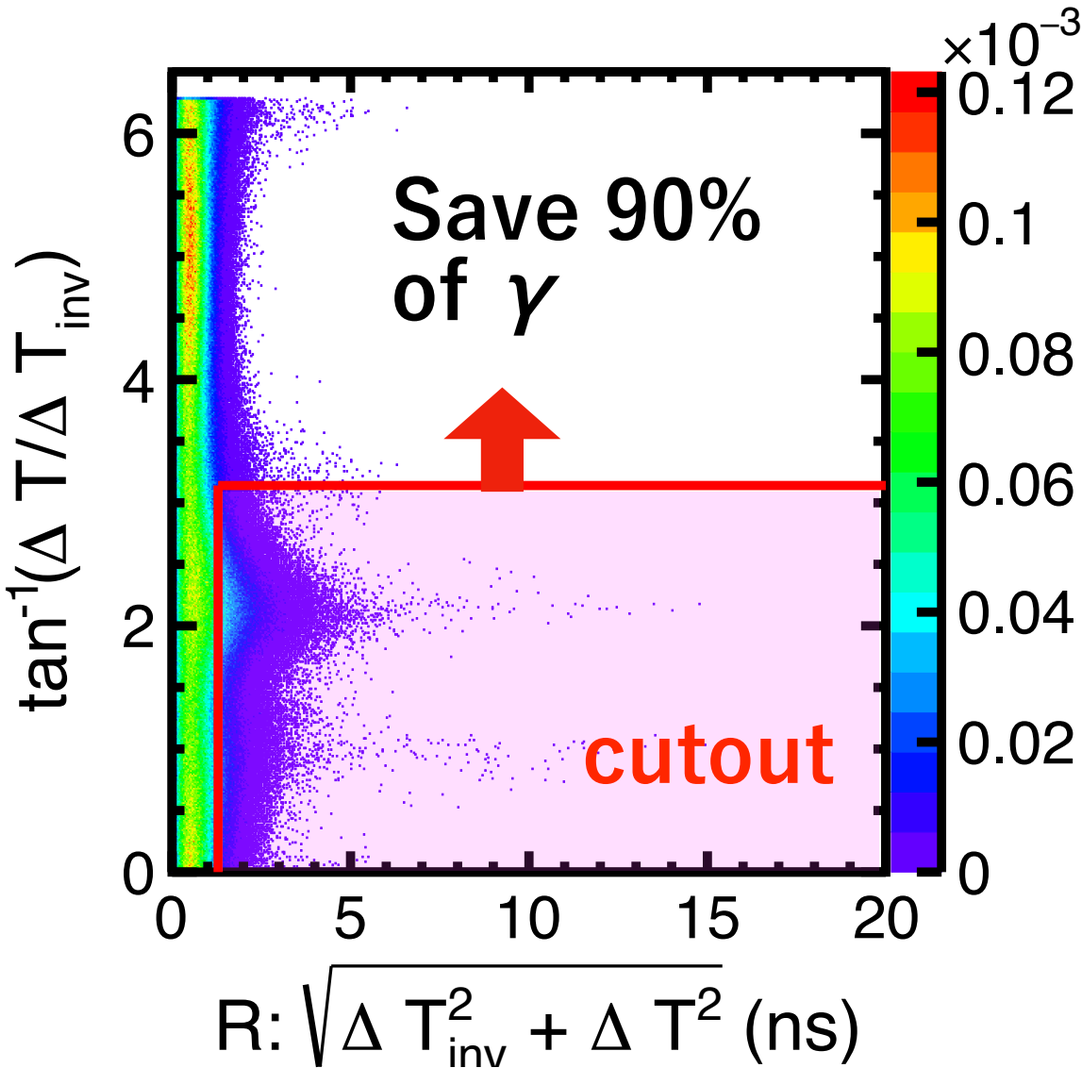
Relation (Dark current)-(neutron dose)-(timing resolution; σ_t) was measured with a special exp. @KOBE U Tandem Electron Accelerator

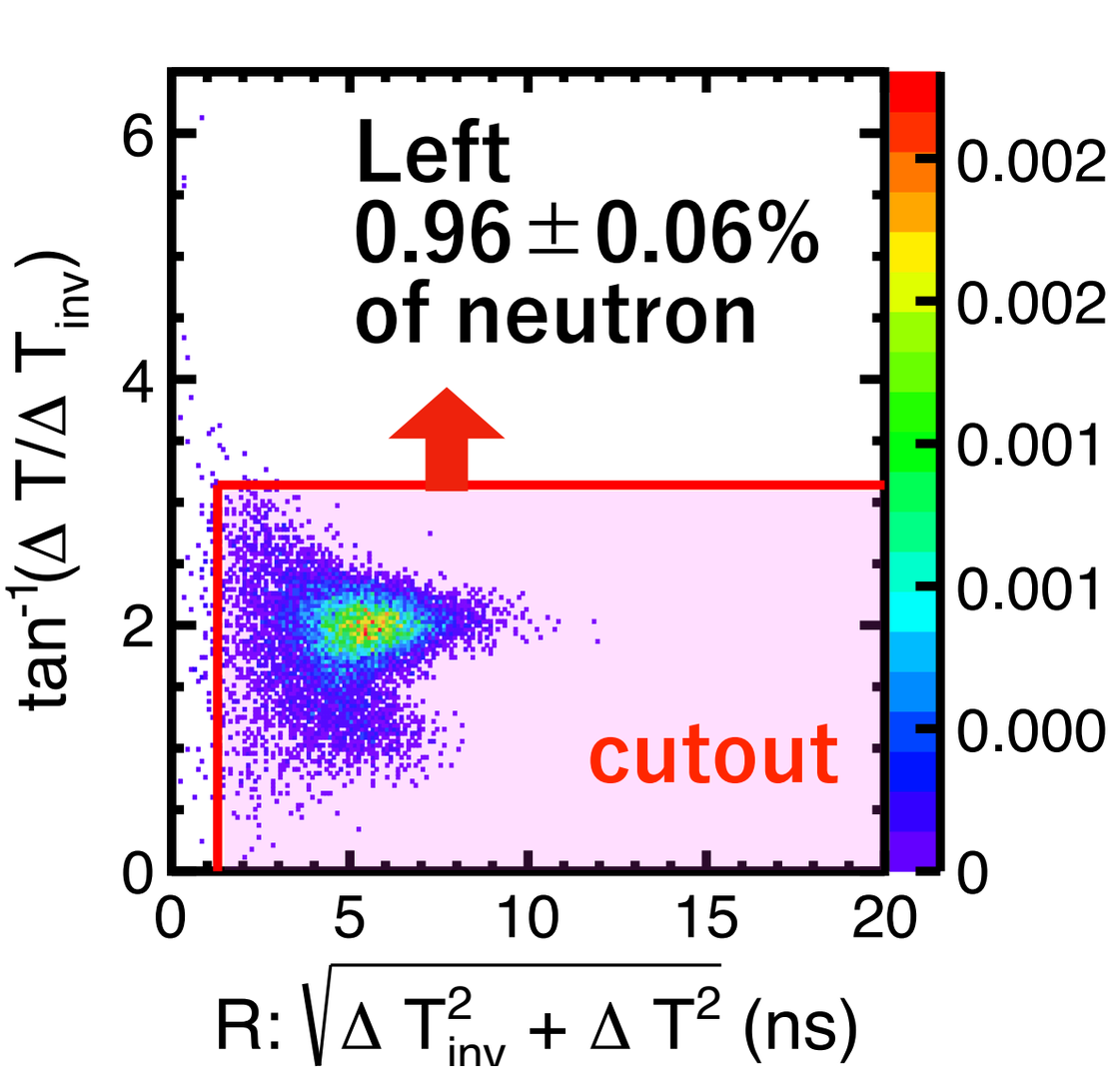
$\sigma_t \sim 1$ ns is enough to separate n - γ

Coordinate transformation

$$(\Delta T_{\mathrm{inv}}, \Delta T_{\mathrm{E.W.}}^{\mathrm{max}}) \rightarrow (\sqrt{\Delta T_{\mathrm{inv}}'^2 + \Delta T_{\mathrm{E.W.}}^{\mathrm{max}\,\prime 2}}), \tan^{-1}(\Delta T_{\mathrm{E.W.}}^{\mathrm{max}\prime}/\Delta T_{\mathrm{inv}}')$$

$\Delta T_a \rightarrow \Delta T_a'$: scaled by $\sigma_{\Delta T_a}$





$(0.96 \pm 0.0.06) \times 10^{-2}$

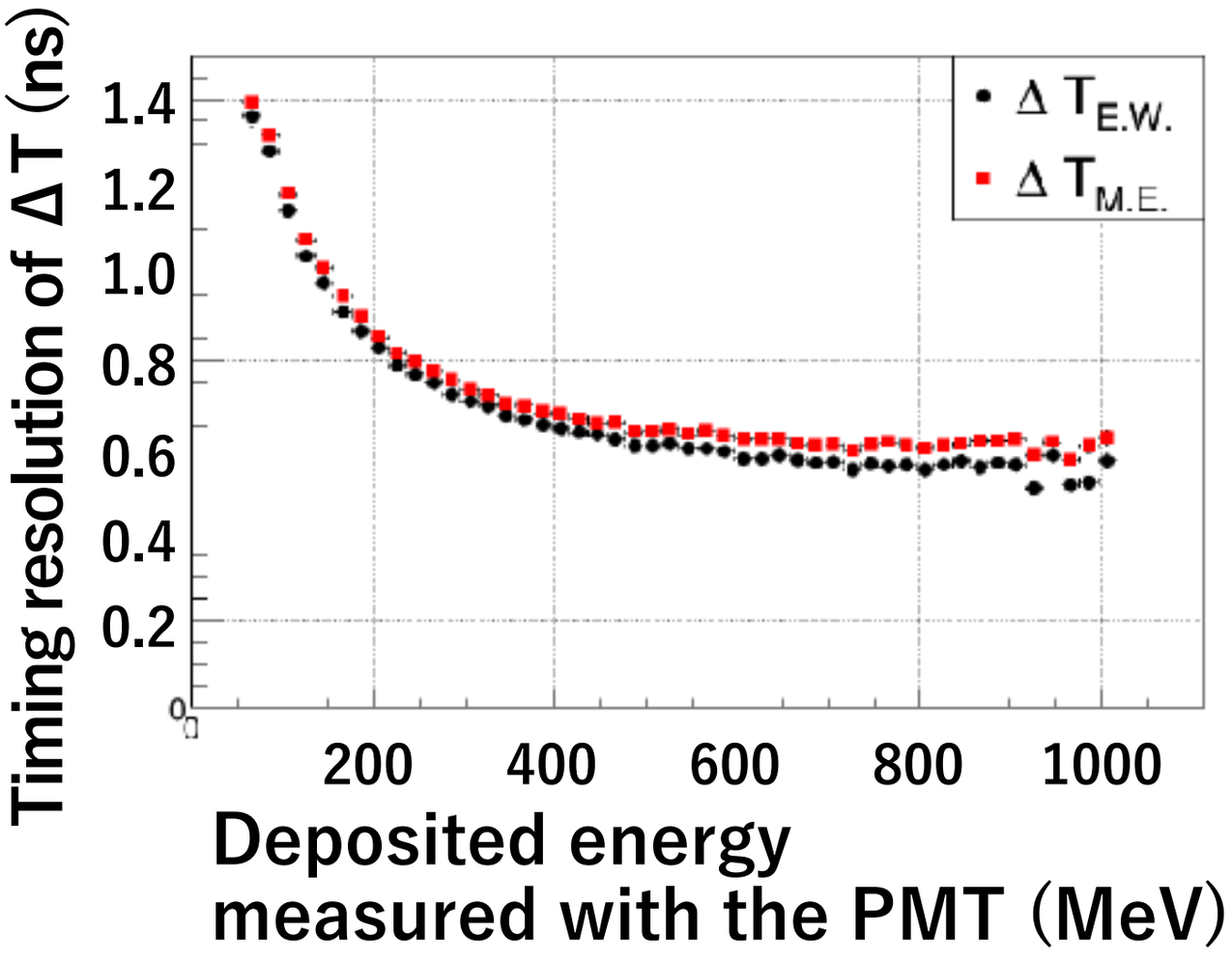
Timing resolution

= the σ of ΔT distribution of γ events

Comparison between two ΔT: T_{MPPC} - T_{PMT}

$\Delta T_{E.W.}$; T_{MPPC}: energy weight in clusters

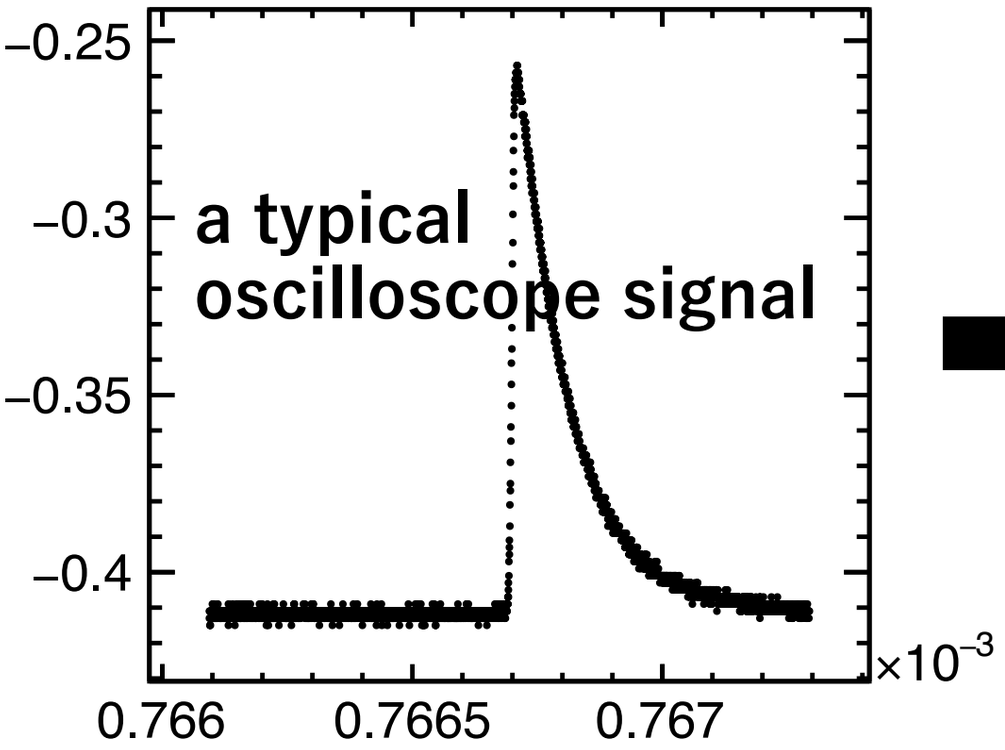
$\Delta T_{M.E.}$; T_{MPPC}: use T_{MPPC} of maximum energy

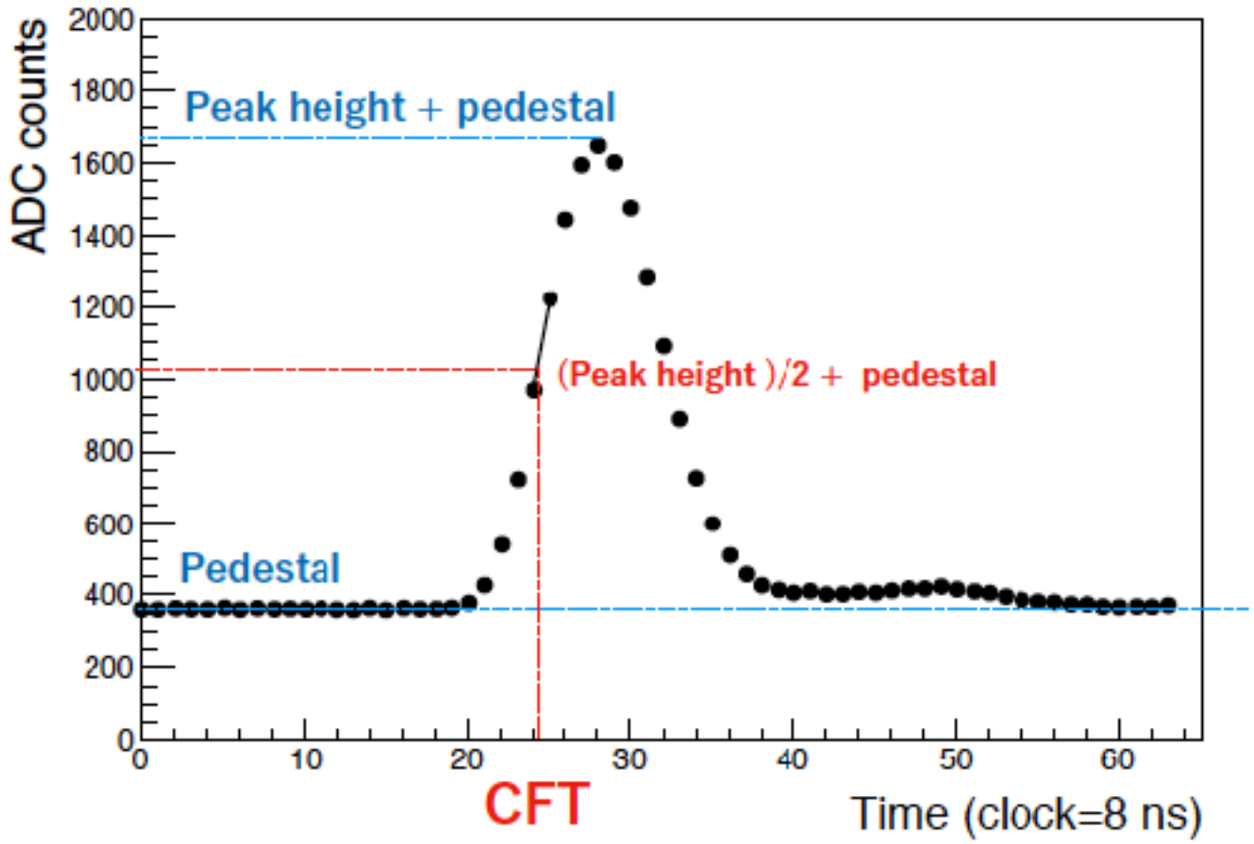


We use $\Delta T_{E.W.}$

Waveform treatment

125MHz FADC signal → 10 pole Bessel filter





- Raw signals are too fast for 125MHz FADC.
- Peak was determined as the peak of parabola function matching on the three highest data.