2025 Nov 27th

KOTO 4-D calorimeter for the $K_L \to \pi^0 \nu \bar{\nu}$ Search

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the University of Osaka

@ Future Tau Charm Facility 2025

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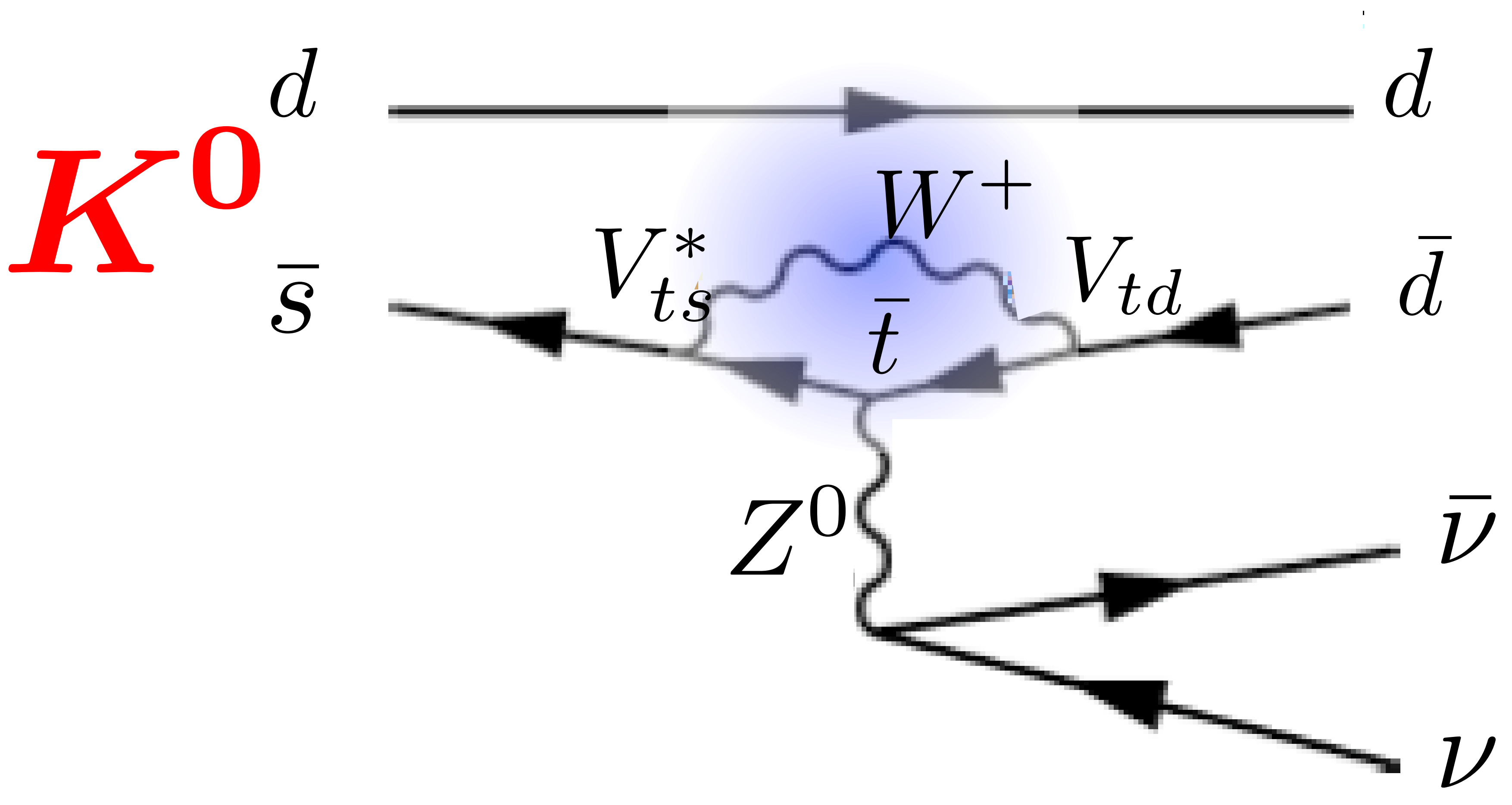
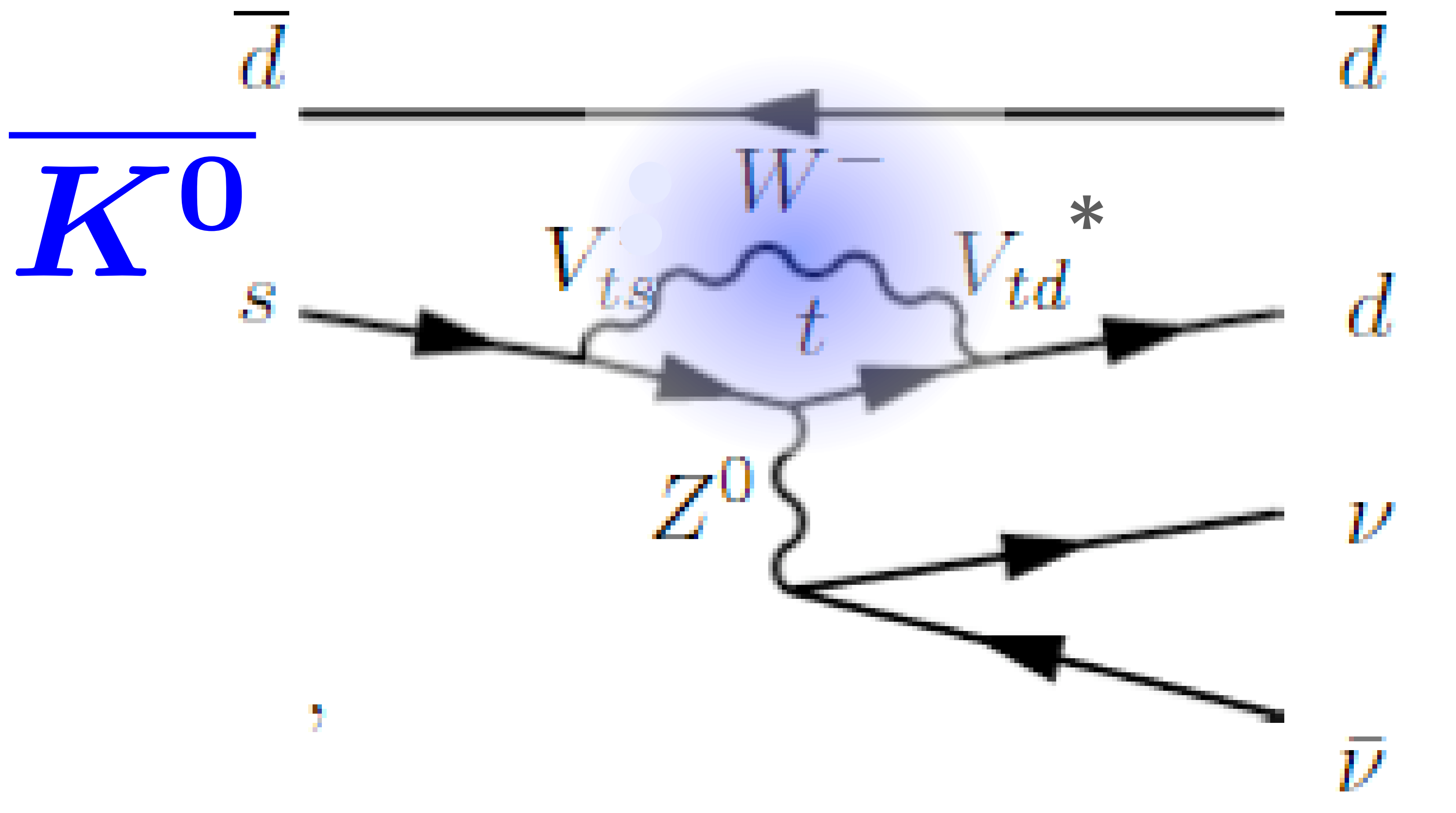
5. Summary

1. $\boldsymbol{K_L \to \pi^0 \nu \overline{\nu}}$

Advantage in the SM (search for NP)

Pure direct CP violation





$$K_L \sim (K^0 - \overline{K^0})/\sqrt{2}$$

Only imaginary part Remains

Negligible long distance QCD

Calculable

Pure direct ~~CP~~

The current theoretical uncertainty on Br($K_L \to \pi^0 \nu\bar{\nu}$) is ~ 2%.

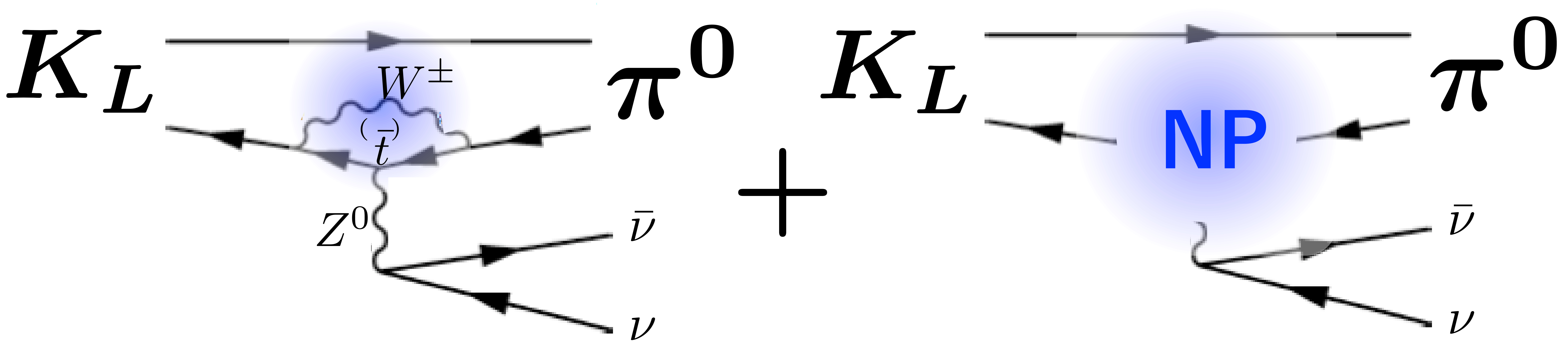
As a Probe of New Physics (NP)

Br($K_L \to \pi^0 \nu\bar{\nu}$) is strongly suppressed by FCNC dynamics and its purely CP-violating nature.

SM prediction: 3×10^{-11}

Current world record by KOTO: $< 2.2 \times 10^{-9}$ (90% C.L.)

Phys. Rev. Lett. 134, 081802



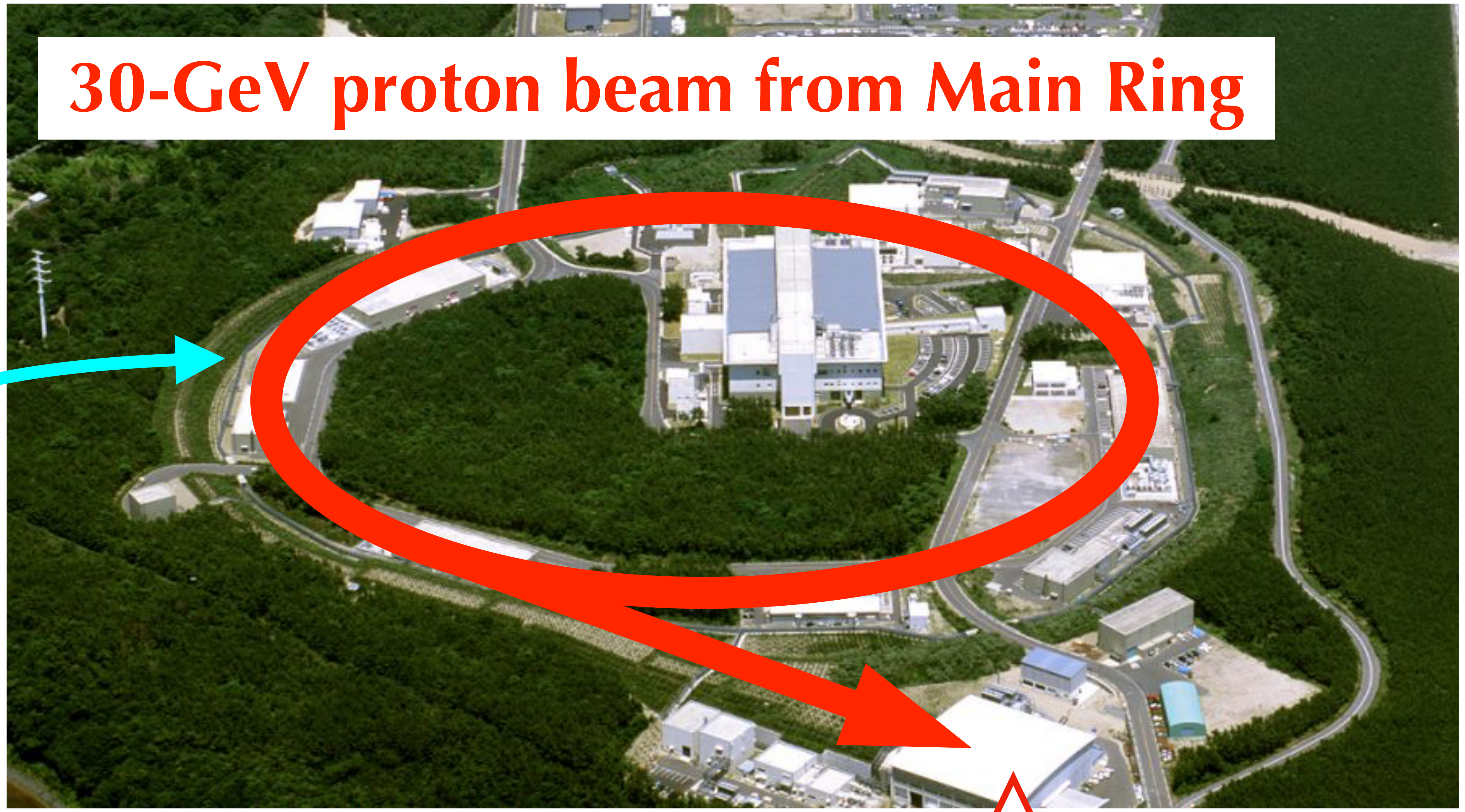
The small SM amplitude makes the process highly sensitive to NP

2. Experiment

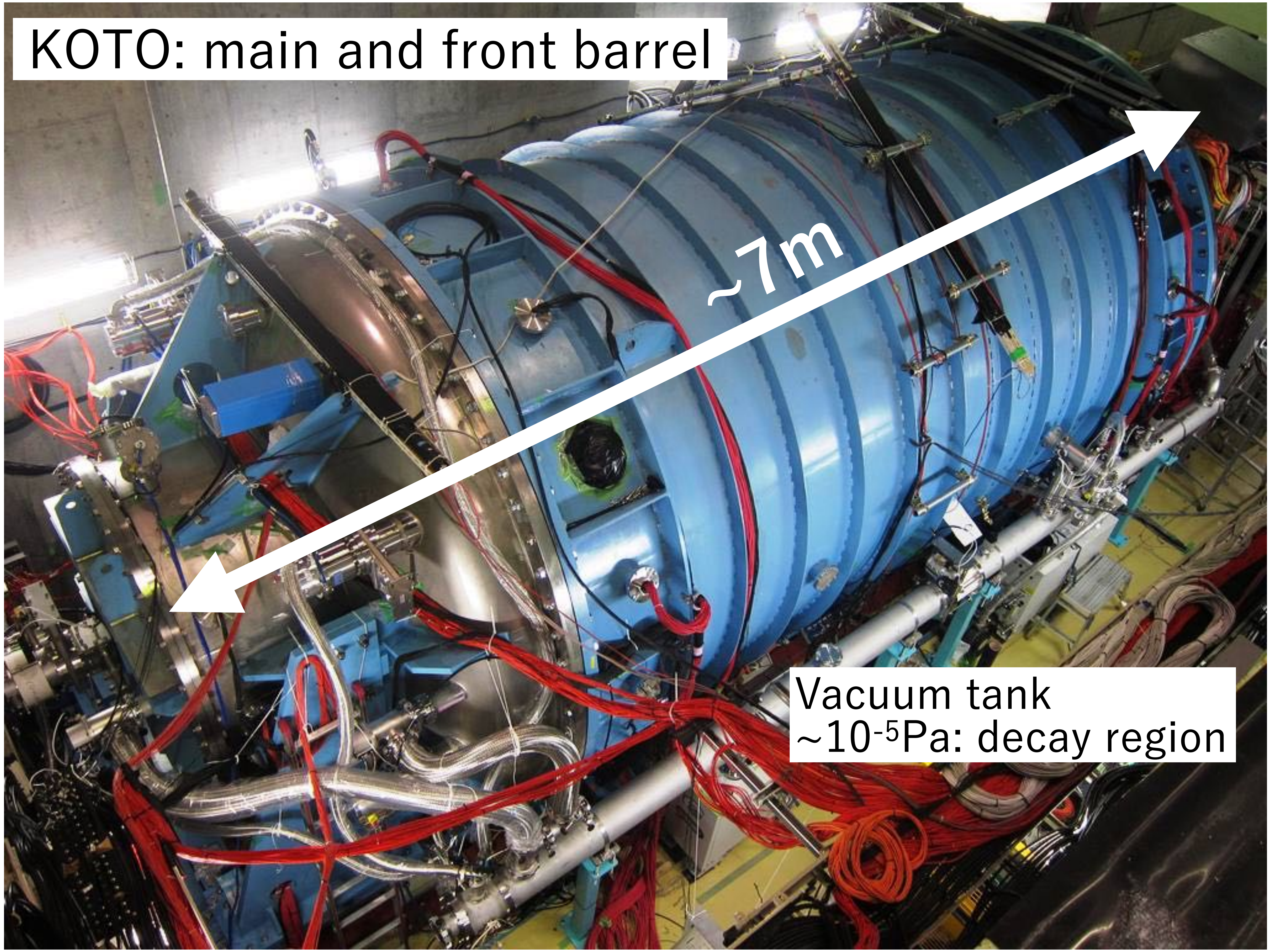
J-PARC KOTO experiment

- KOTO (= **K⁰** at **TO**kai) searching for new physics via $K_L \to \pi^0 \nu \bar{\nu}$
- KOTO collaboration: ~40 members: Japan, Korea, Taiwan, US

J-PARC:



Hadron Experimental Facility


KOTO: main and front barrel
~7m
Vacuum tank
~10-5Pa: decay region

Experimental concept

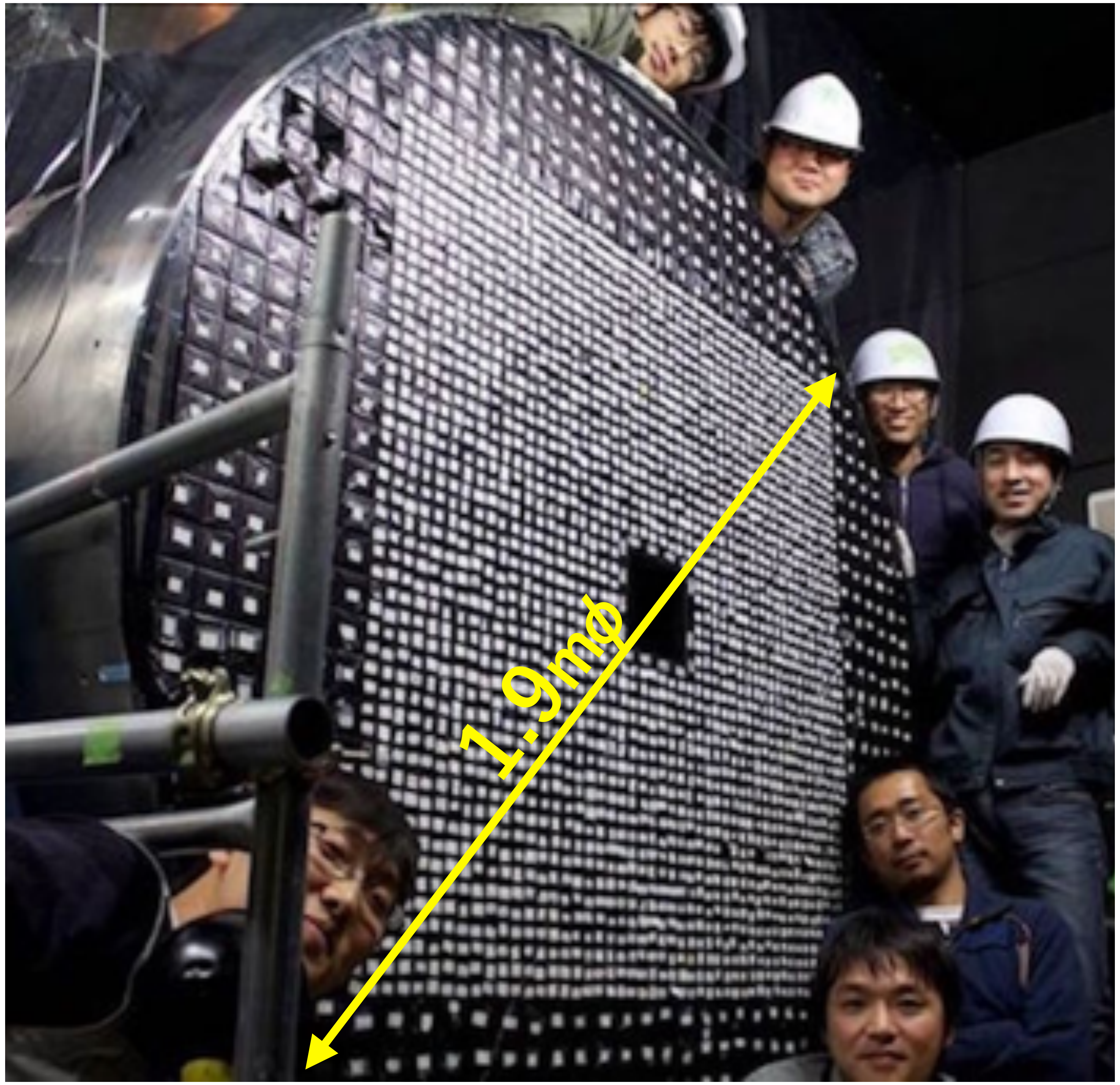
Signal identification

$(\pi^0 \to)\ 2\gamma$ + nothing else

Calorimeter

Veto

CSI calorimeter

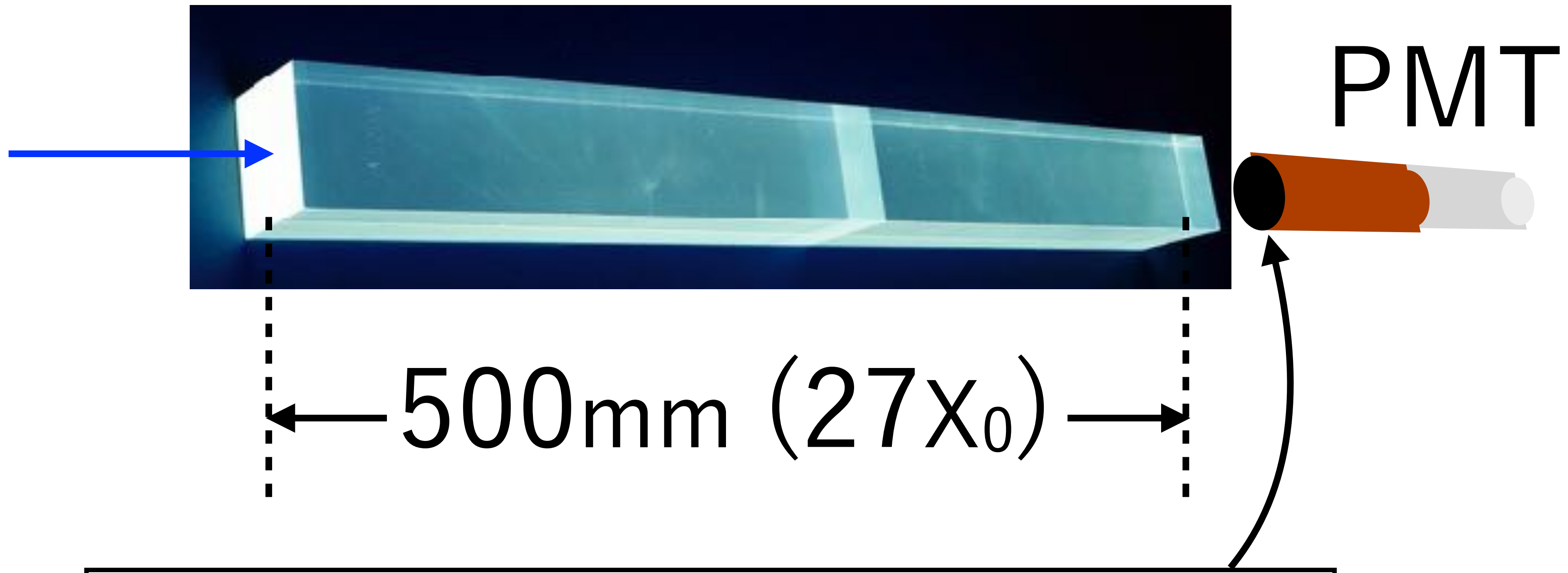


2716 un-doped CsI crystal

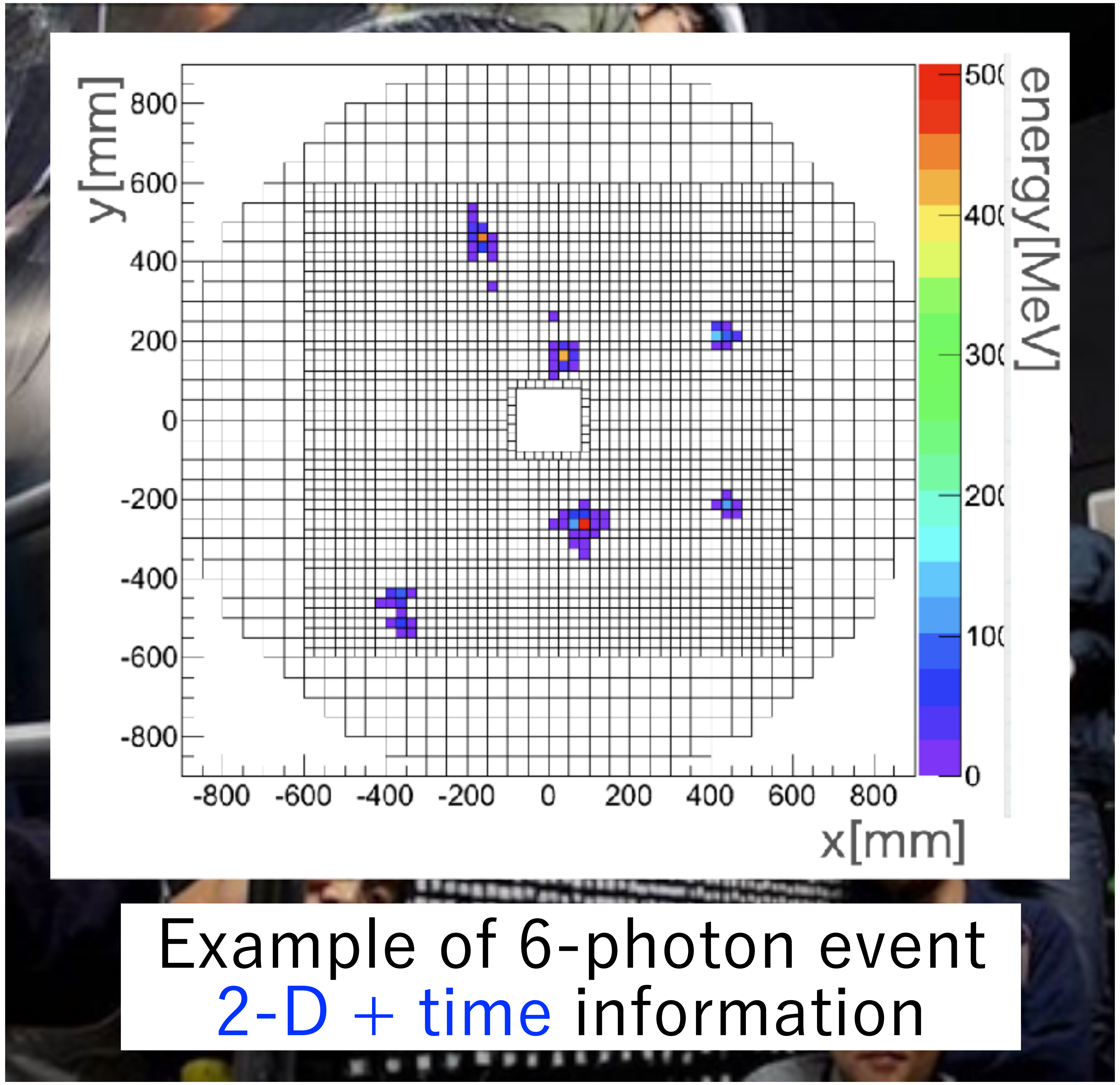
Lateral segmentation

Inner region: 25 × 25mm^2

Outer region: 50 × 50mm^2



The CSI calorimeter



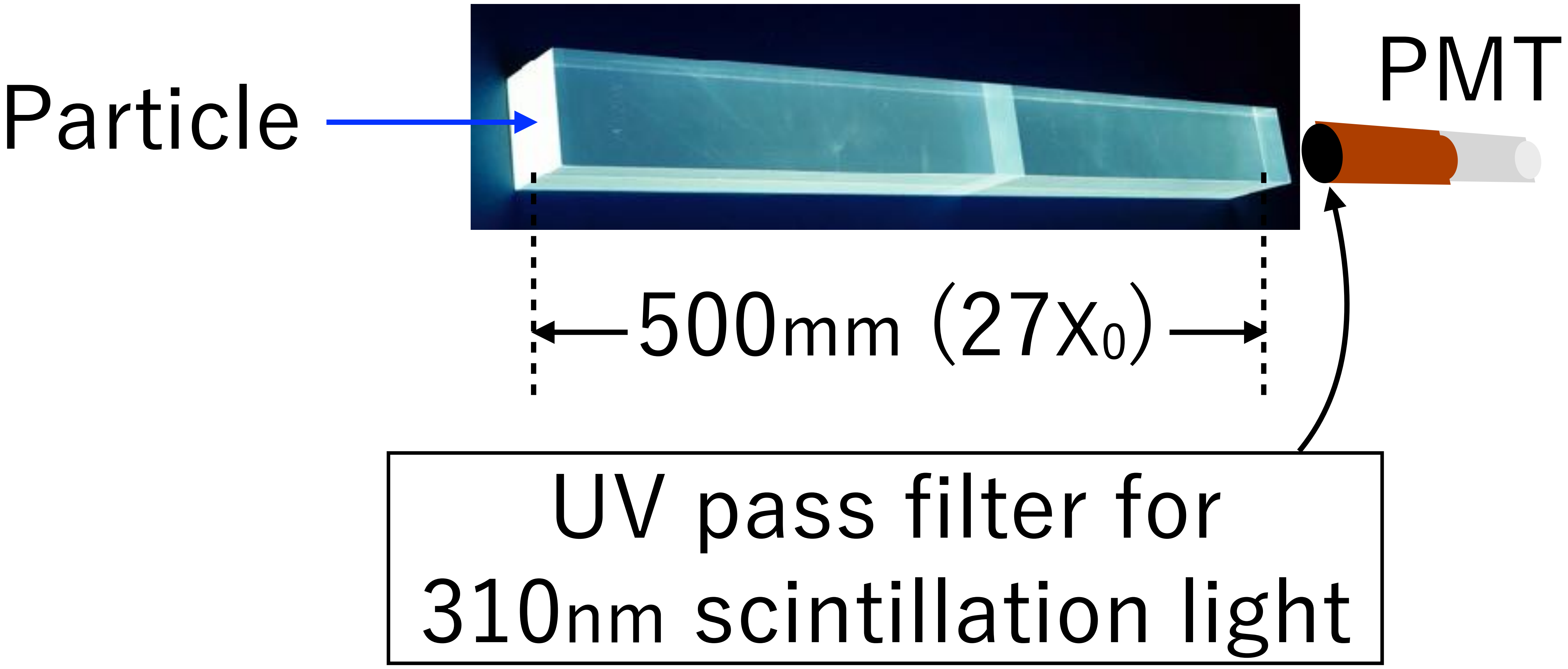
Example of 6-photon event
2-D + time information

2716 un-doped CsI crystal

Lateral segmentation

Inner region: 25×25mm²

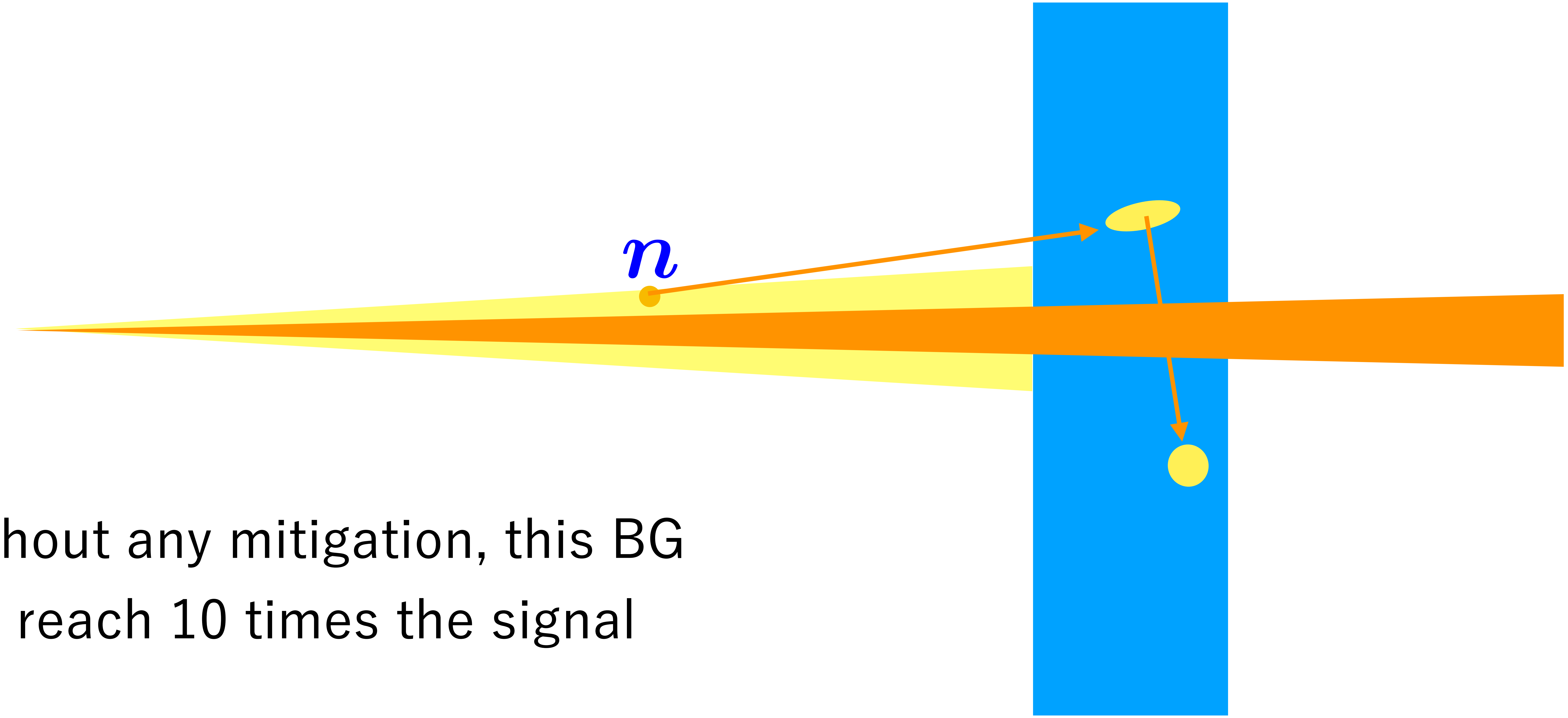
Outer region: 50×50mm²



3. Halo-neutron background and the 4D calorimeter.

A serious background from neutron($\boldsymbol{n}$)s

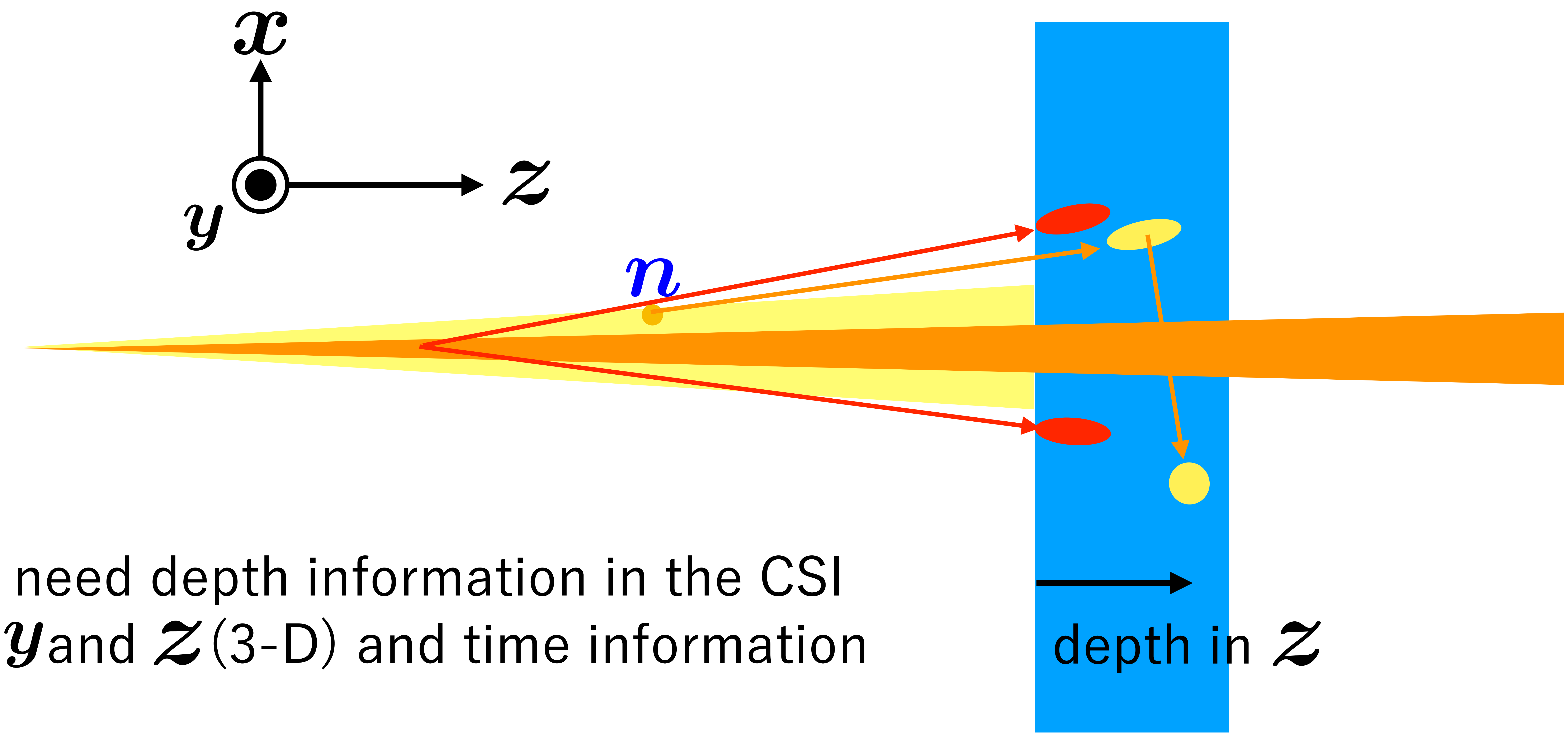
Neutrons in the beam but outside the nominal beam solid angle; halo neutron.



Without any mitigation, this BG
will reach 10 times the signal

Using shower depth to separate γ's and neutrons

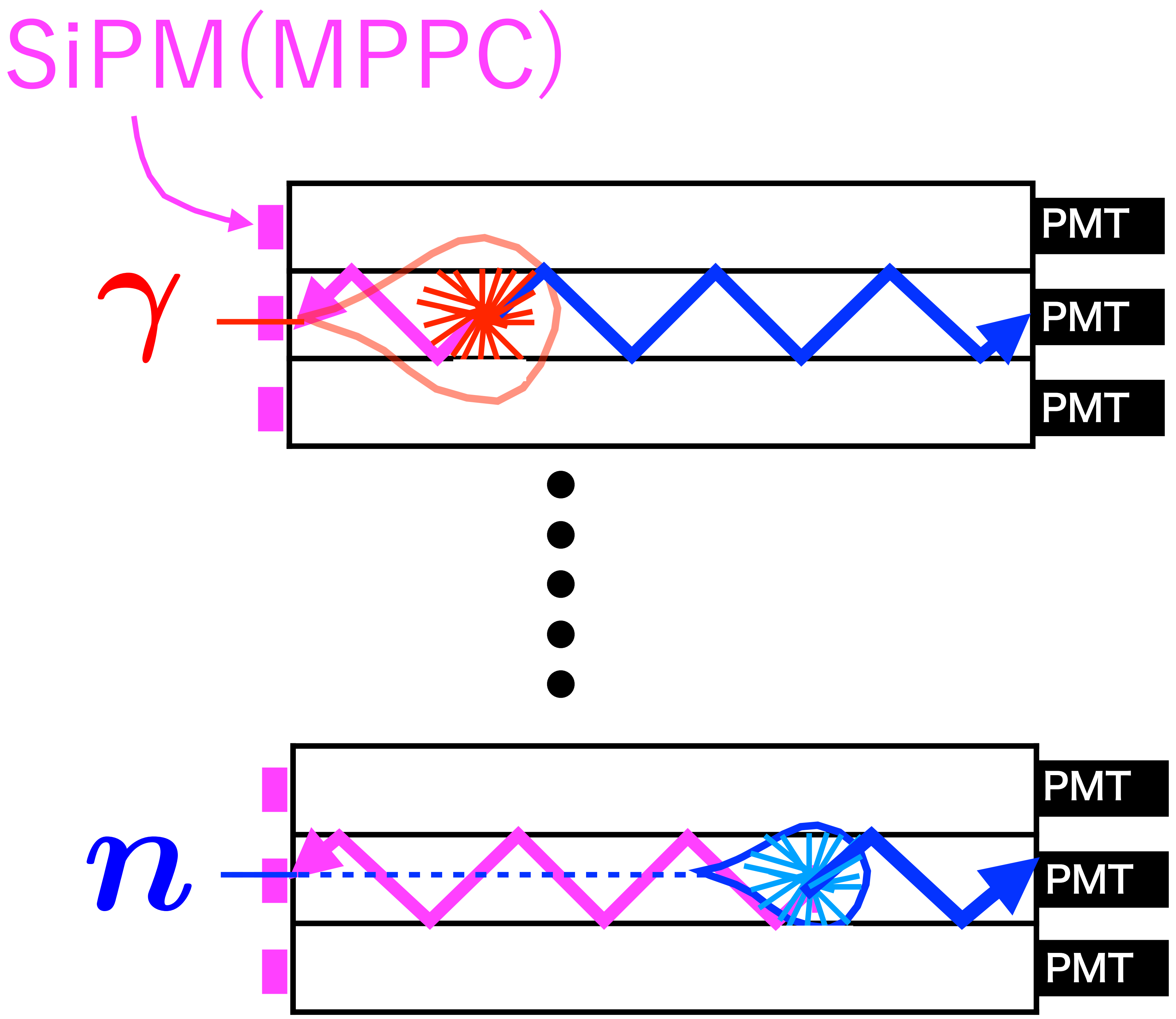
γ's produce showers at shallower depths, while neutrons do so at various depths.



We need depth information in the CSI
x, y and z (3-D) and time information

To make the Calorimeter having 3-D + timing information

Both-side readout method can determine the shower position.



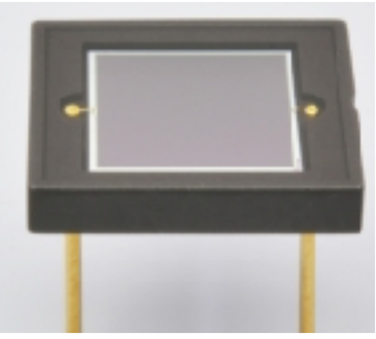
$$\Delta_t = t_{\mathrm{MPPC}} - t_{\mathrm{PMT}}$$

Both-side readout calorimeter separates n/γ by timing

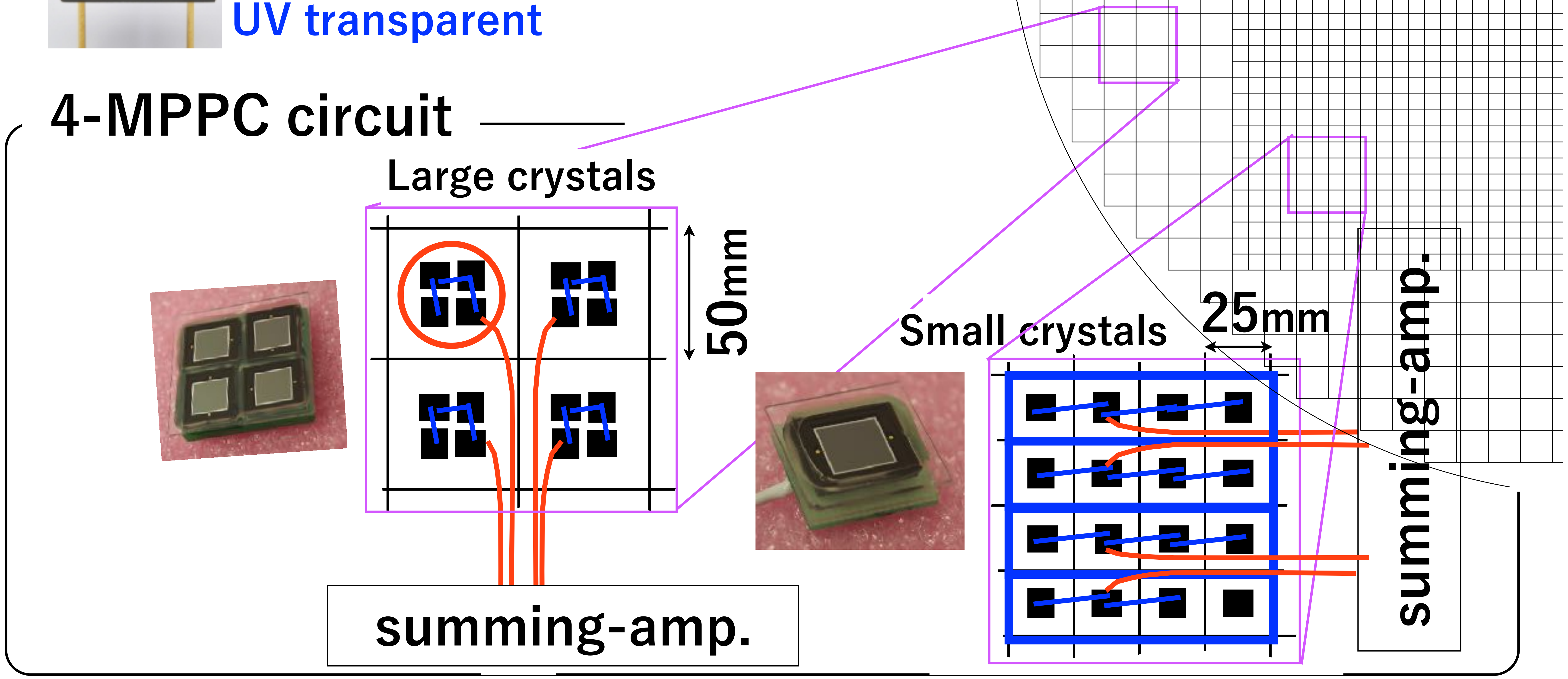
Configurations

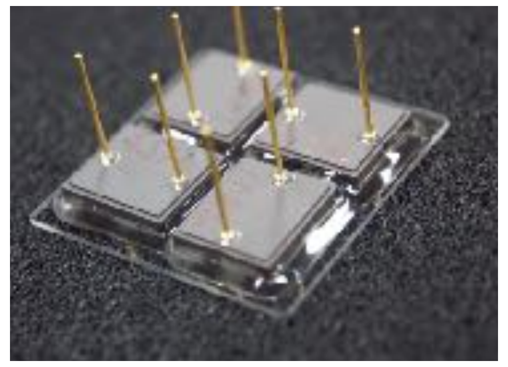
2018 winter

- Total 4080 MPPCs were glued onto CsI crystals using a specially developed method.



S13360-6050-SC
6×6mm², 50 μm pitch
UV transparent

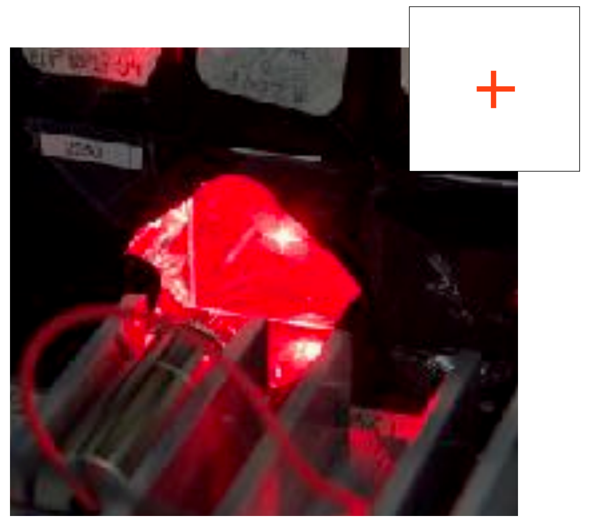




MPPCs were glued onto 0.5-mm-thick quartz plate.

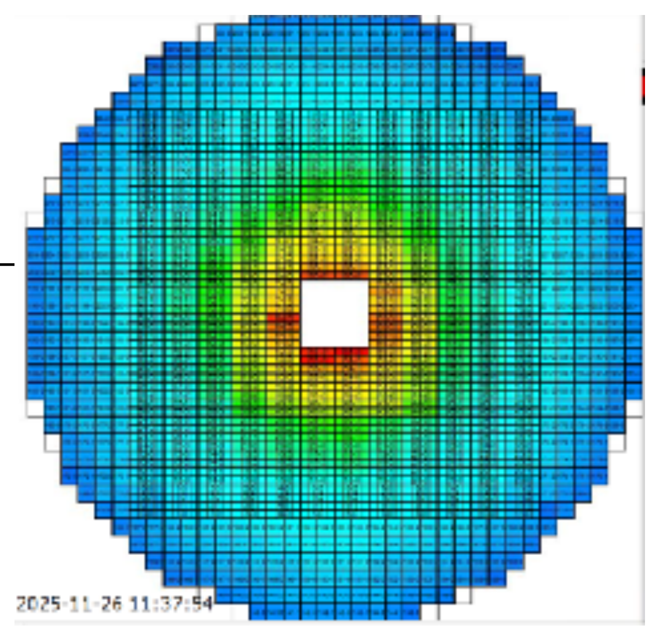
Photo for a large crystal.

Jig for pressing and holding the quartz plate with MPPCs against the CsI crystal



2020 J. Phys.: Conf. Ser. 1526 012036

Circuit boards for 16-MPPCs



High dark current
near the beam hole

4-MPPCs : note that irradiation changes the dark current of MPPCs

Serial connection

fast pulse,

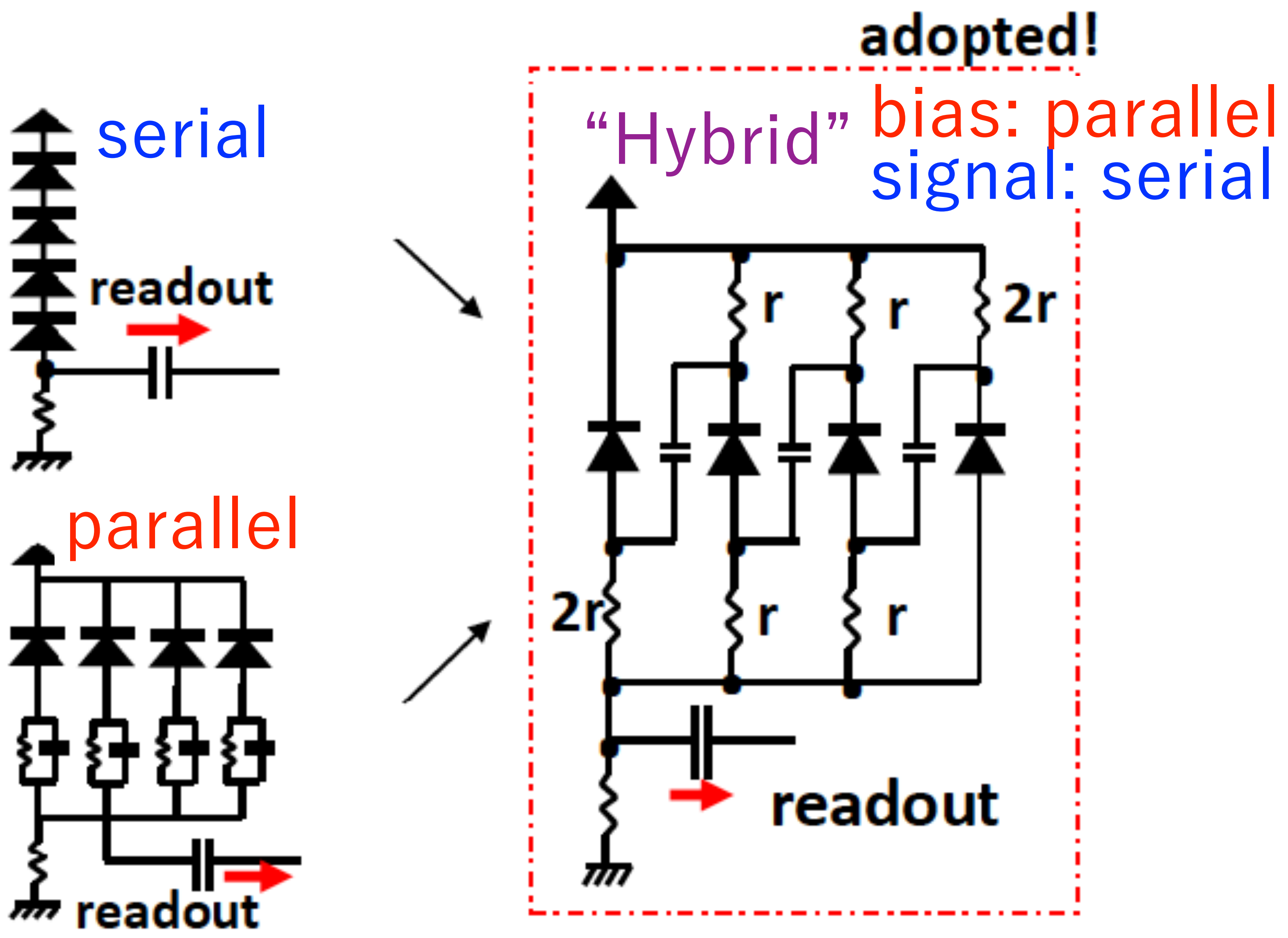
bias depends on current

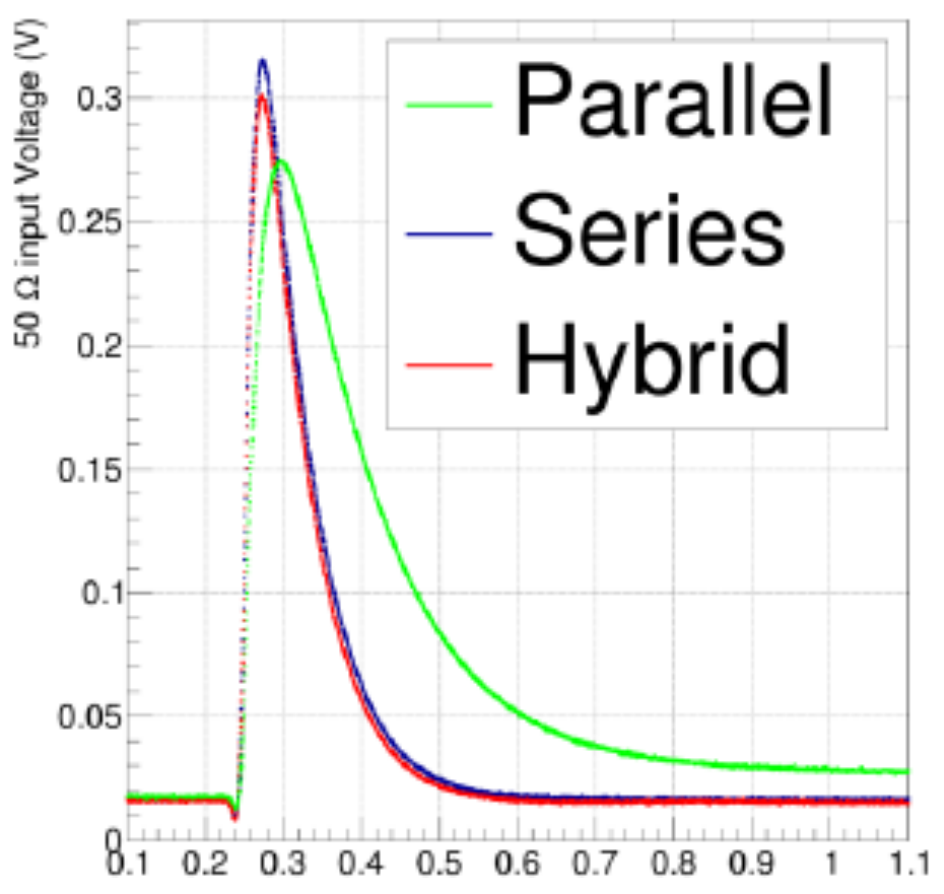
Parallel connection

slow pulse

bias not depend

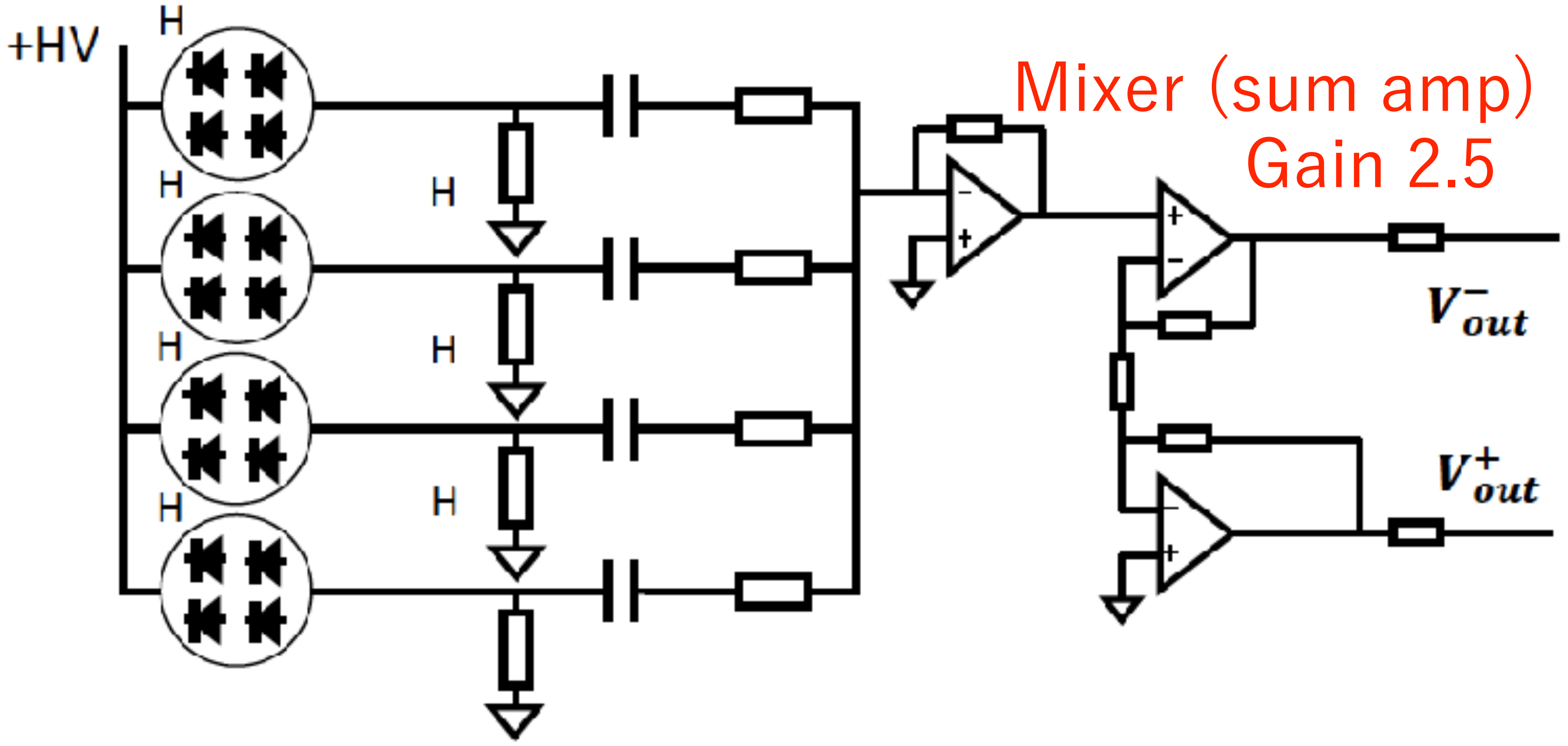
on current

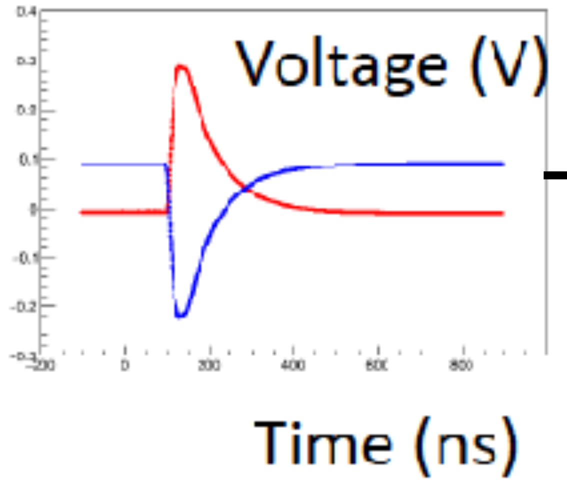




still fast pulse of
"Hybrid" case
bias not depend on current

4-MPPCs ×4 in an Amplifier

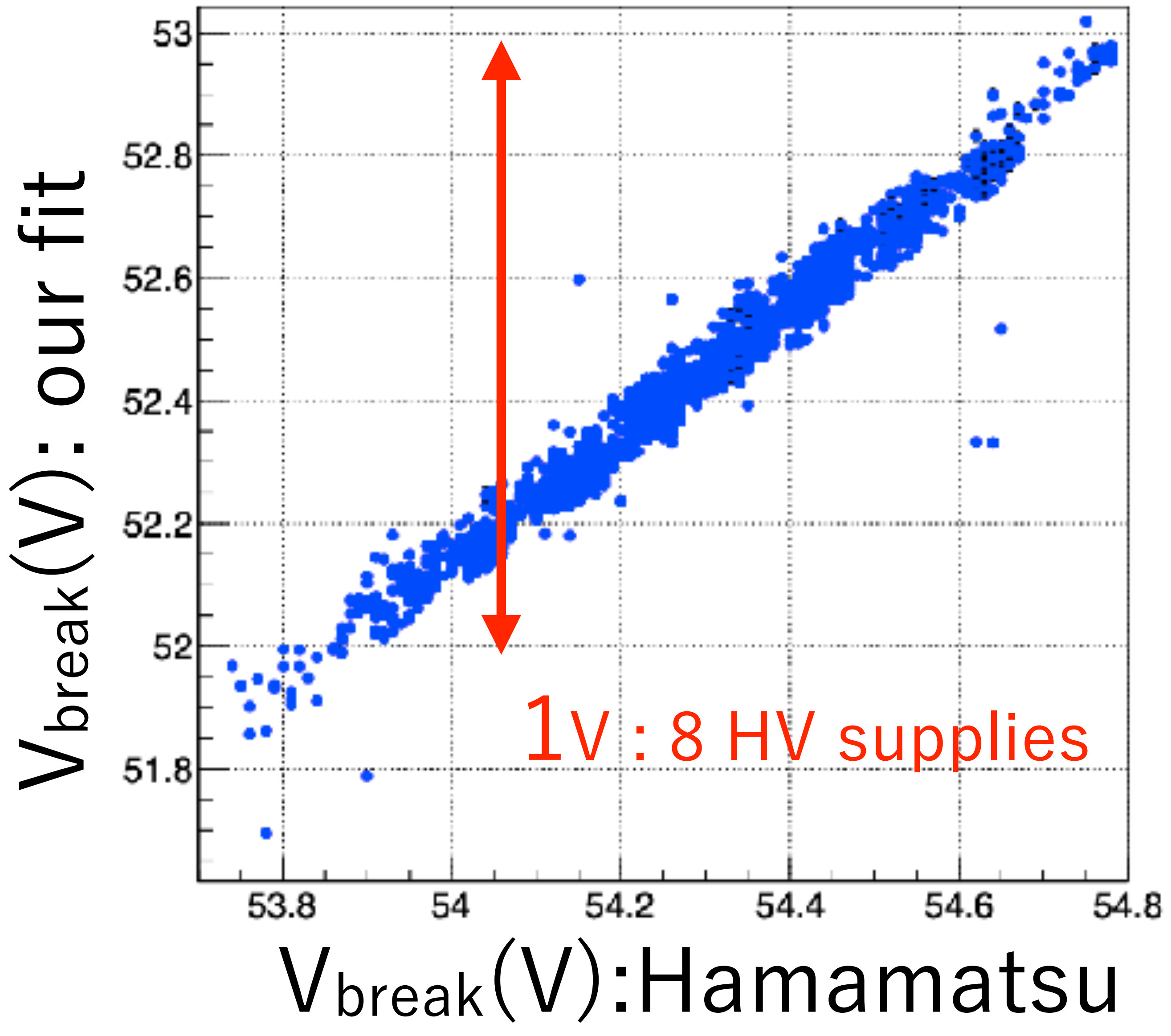




→ 10-pole Bessel filter → 125MHz ADC

Conditions and operational status

HV for MPPCs

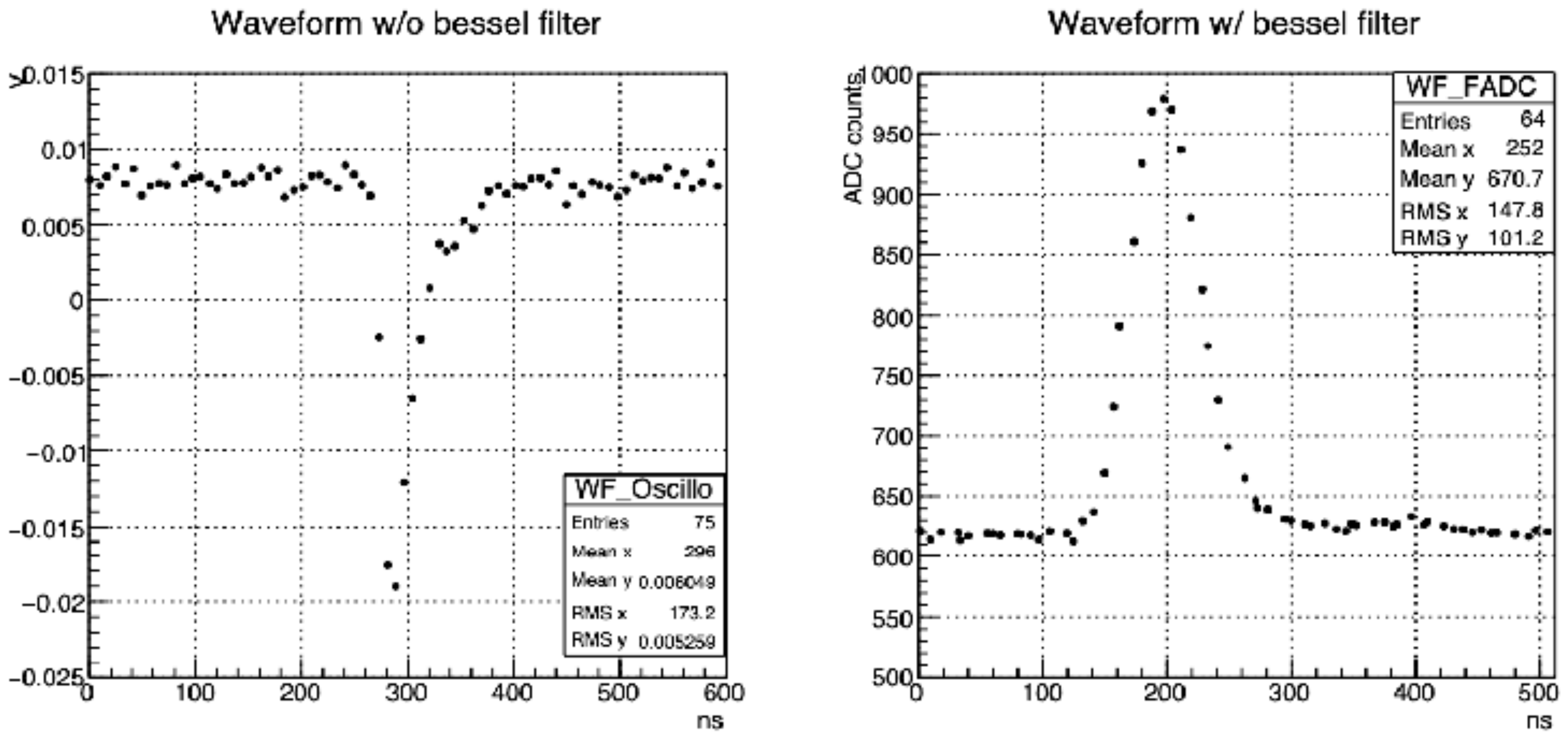


The range of V_{break} is ~1V.

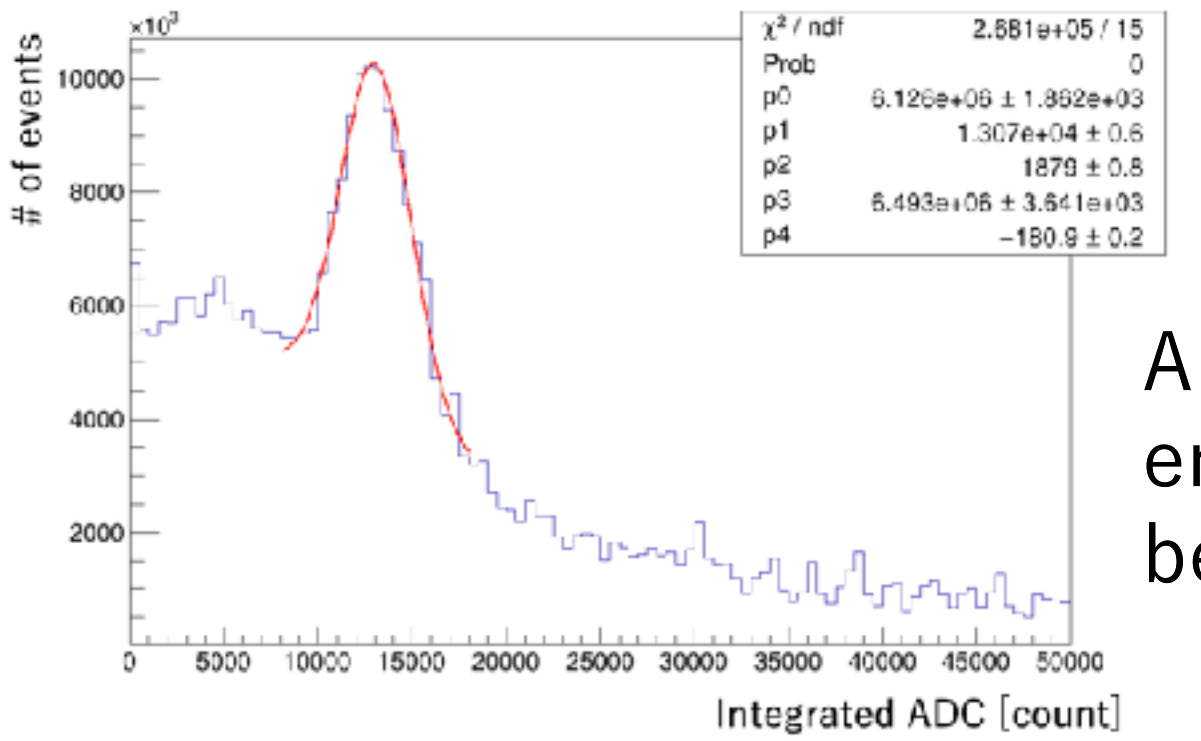
Eight HV supplies provide ~3 V V_{over} at 25°C to eight groups of MPPCs with close V_{over}, with a typical gain of 1.7×10^6

During the run, the calorimeter surface temperature stable at 29-30°C

Pulse shape



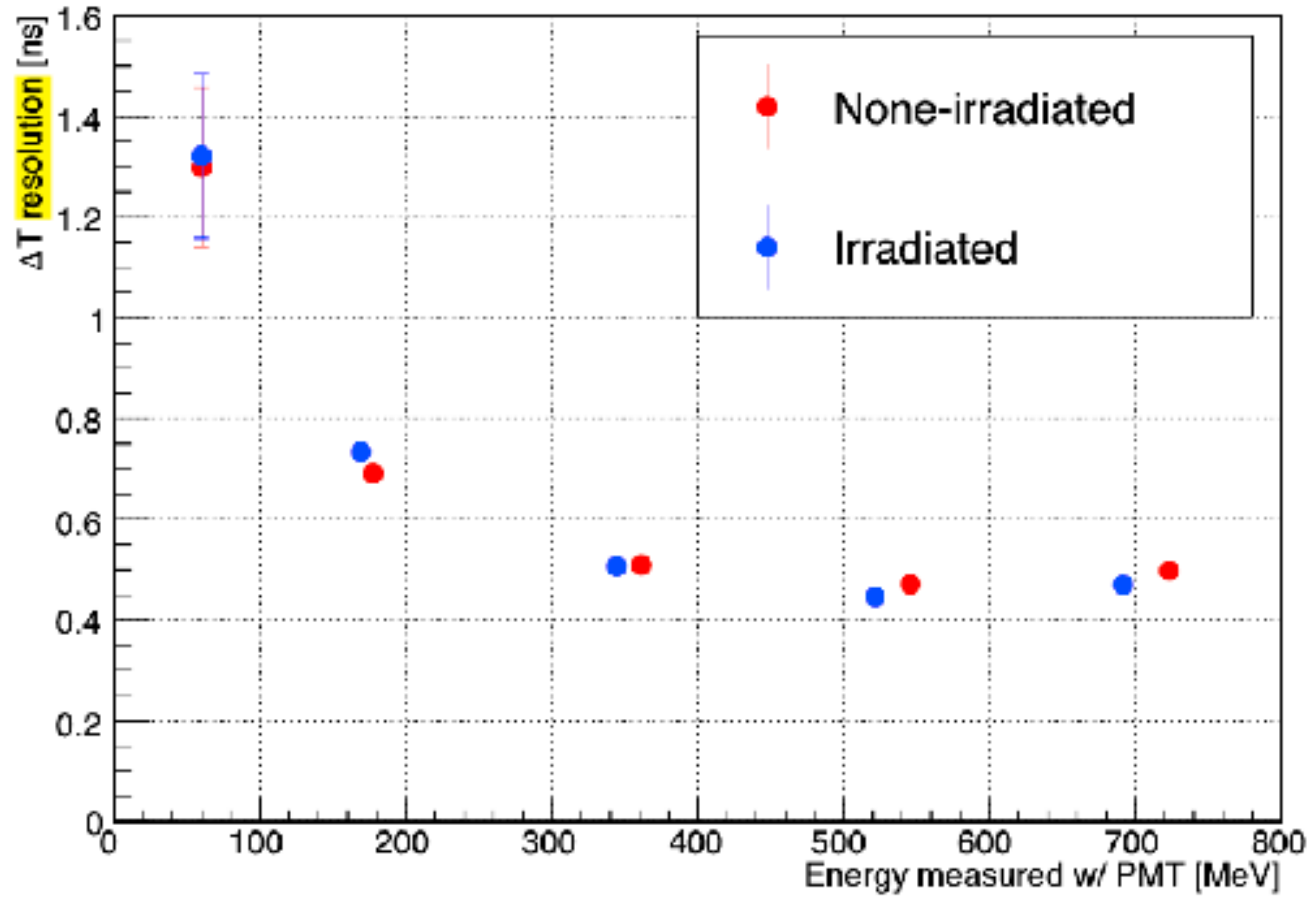
Raw waveform of a channel (left) and the waveform after the 10-pole Bessel filter (right), which preserves the timing resolution despite the 8 ns sampling interval.



MIP peak

A typical deposited energy of MIP like beam event.

Timing resolution



Timing resolution of MPPC as a function of deposited energy on a crystal measured by PMT, comparing between non irradiated MPPC and with irradiation ($1.5 \times 10^9 n_{1MeV}/cm^2$)

There is no deterioration of the timing resolution.

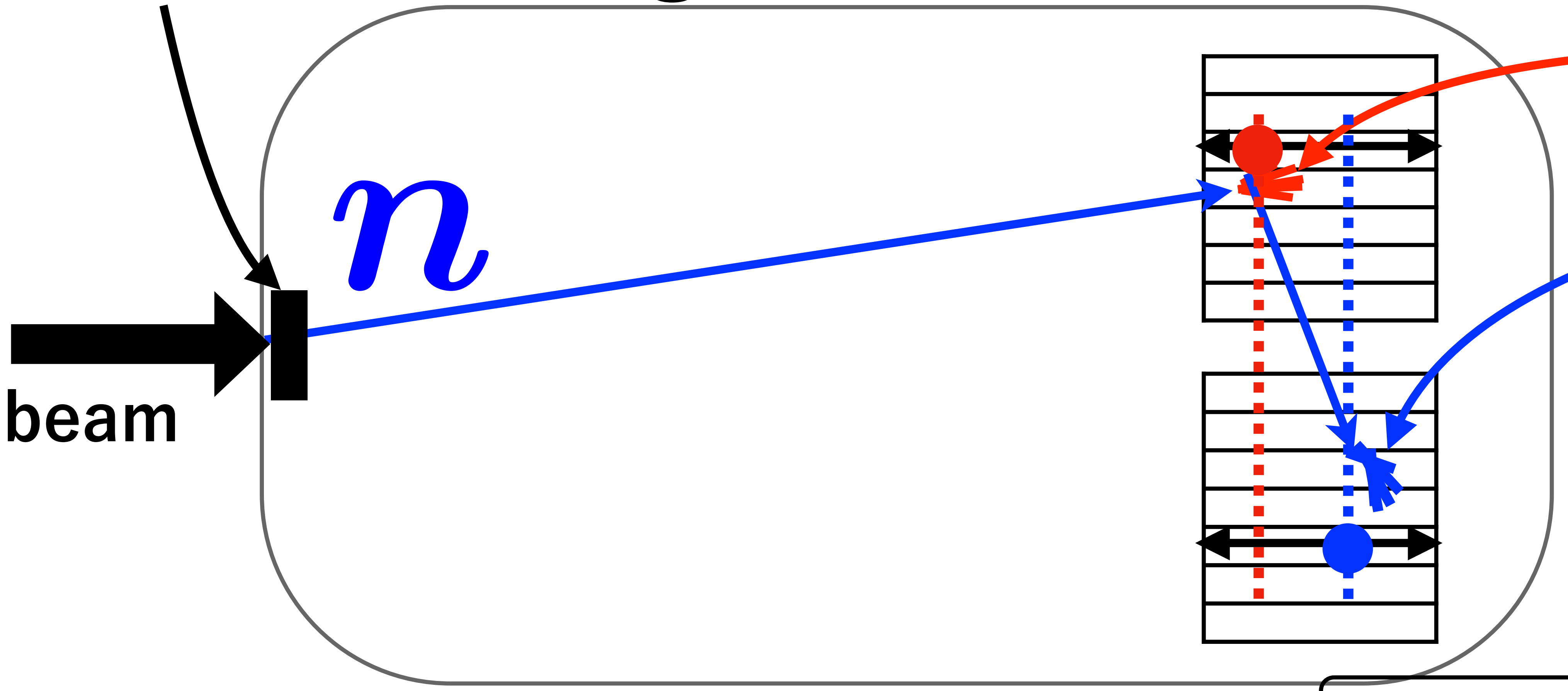
4. Performance of the 4D calorimeter.

γ and neutron samples for ΔT study

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

For neutron sample

Aluminum target in beam (3mmT)



Small ΔT= ΔT^{min}

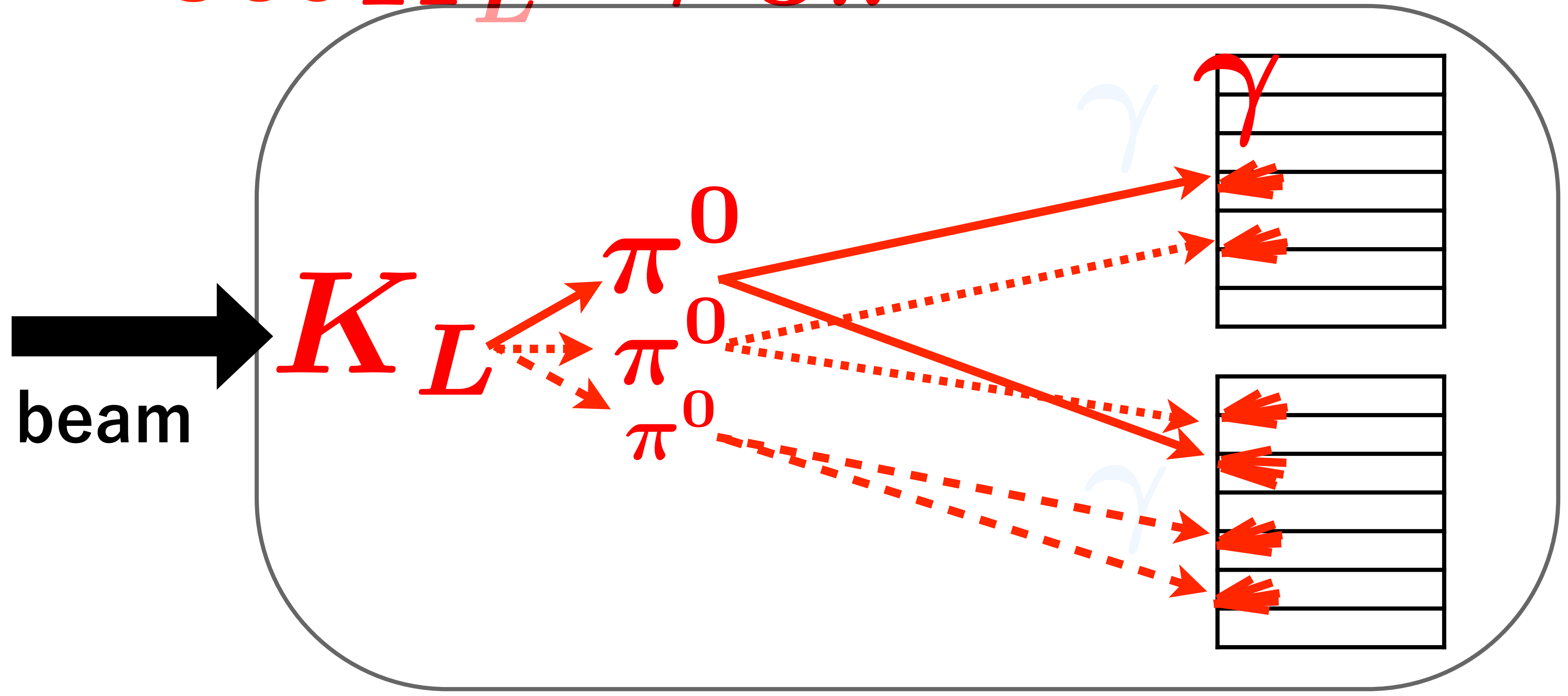
Large ΔT= ΔT^{max}

One event has two ΔT

For γ sample

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

Large Br(19.52%)
less contamination

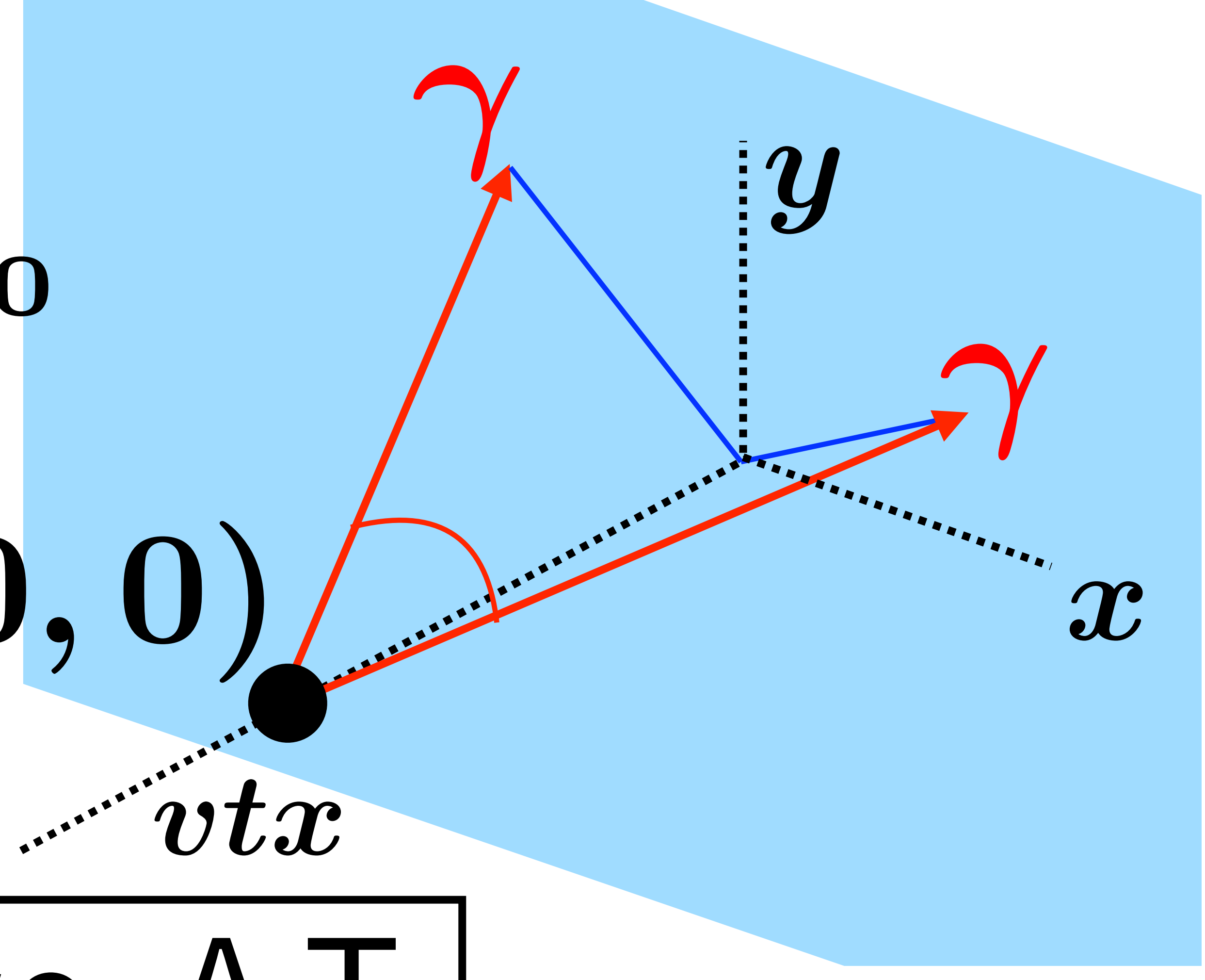


The reconstruction resolves the γ-combination ambiguity

$m_{\gamma\gamma} \Rightarrow m_{\pi^0}$

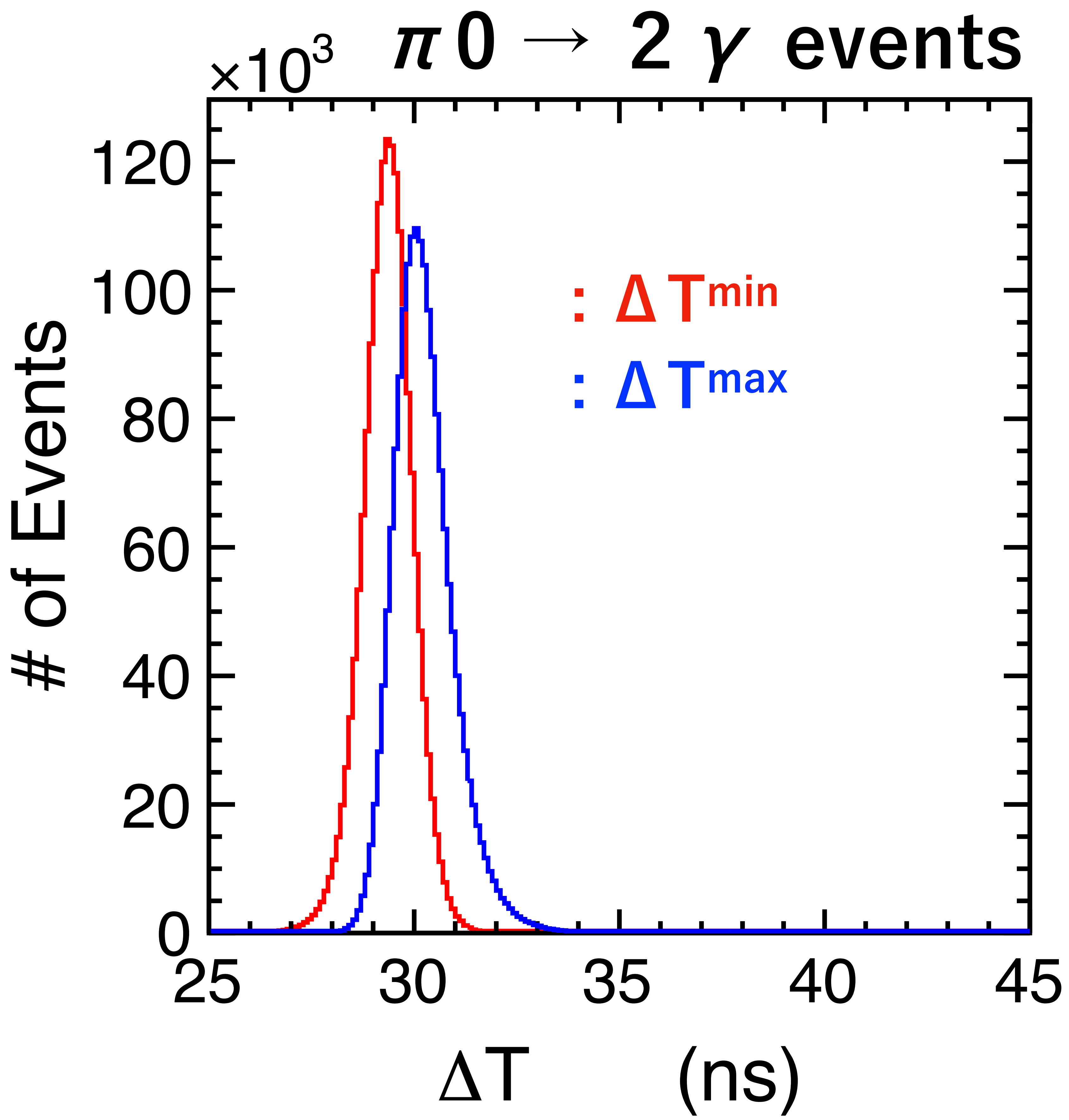
$vtx(x, y)$

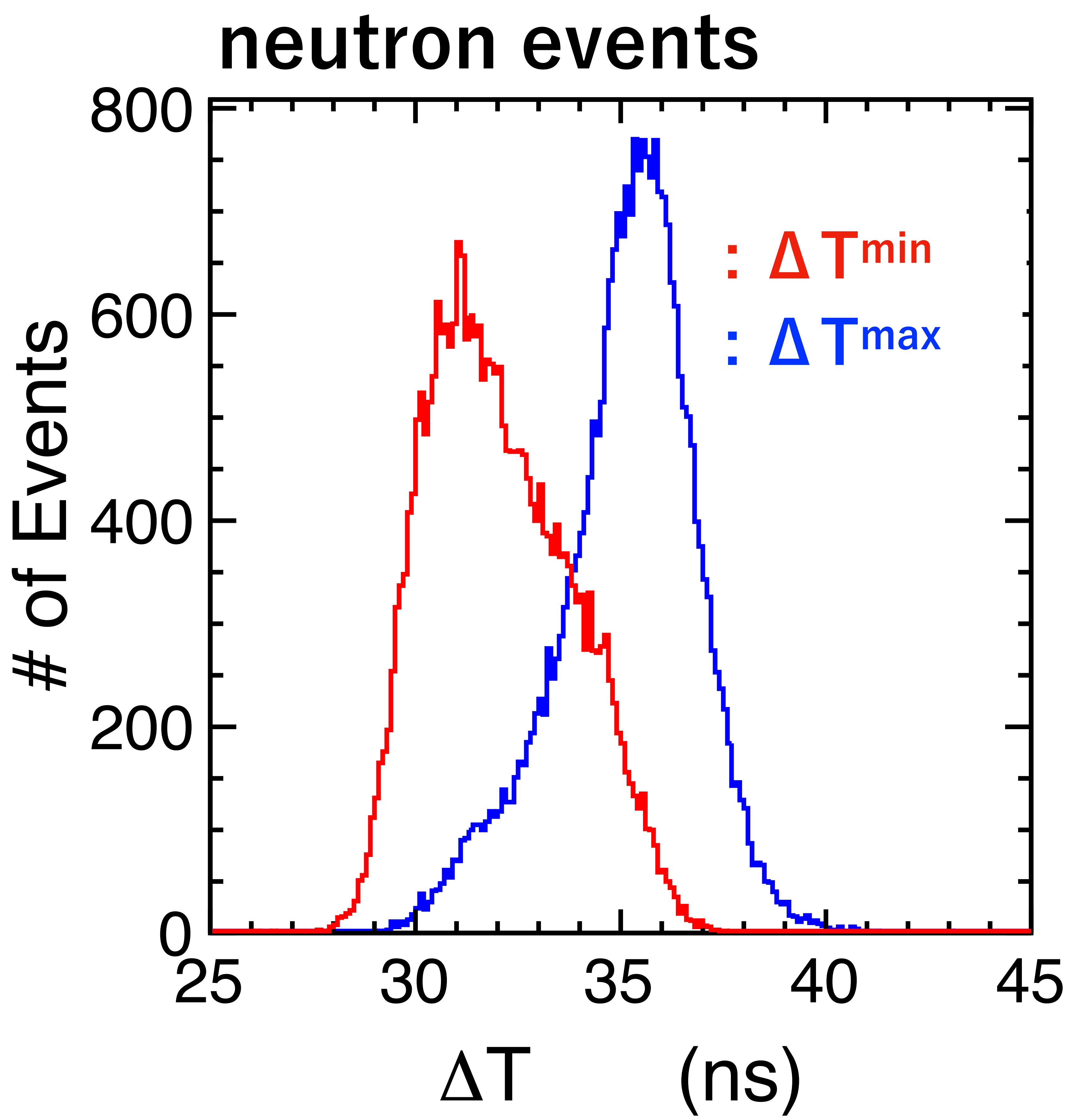
$\Rightarrow vtx(0, 0)$



One π^0 has two ΔT

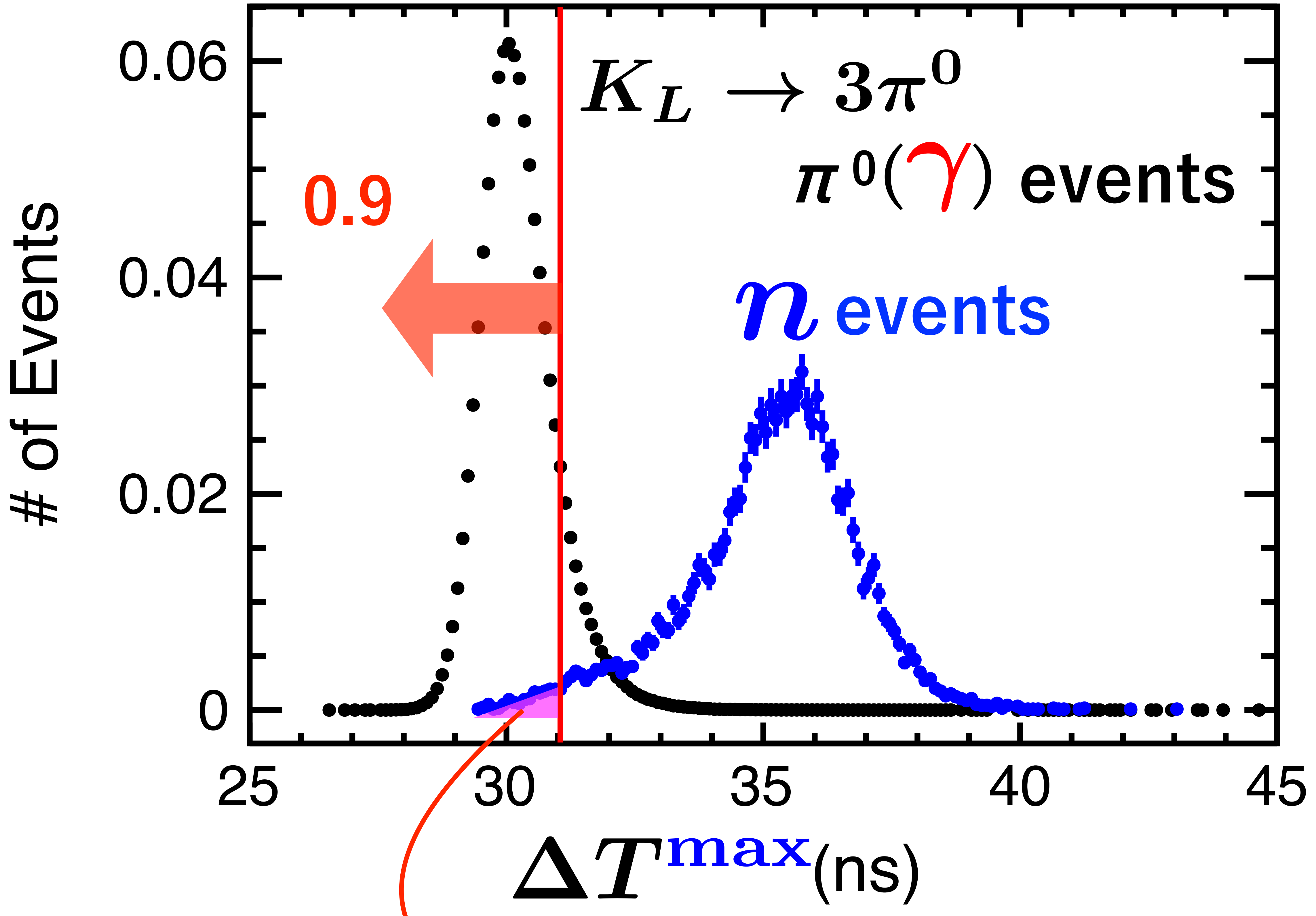
Comparison between $\Delta T^{\mathbf{min}}$ and $\Delta T^{\mathbf{max}}$

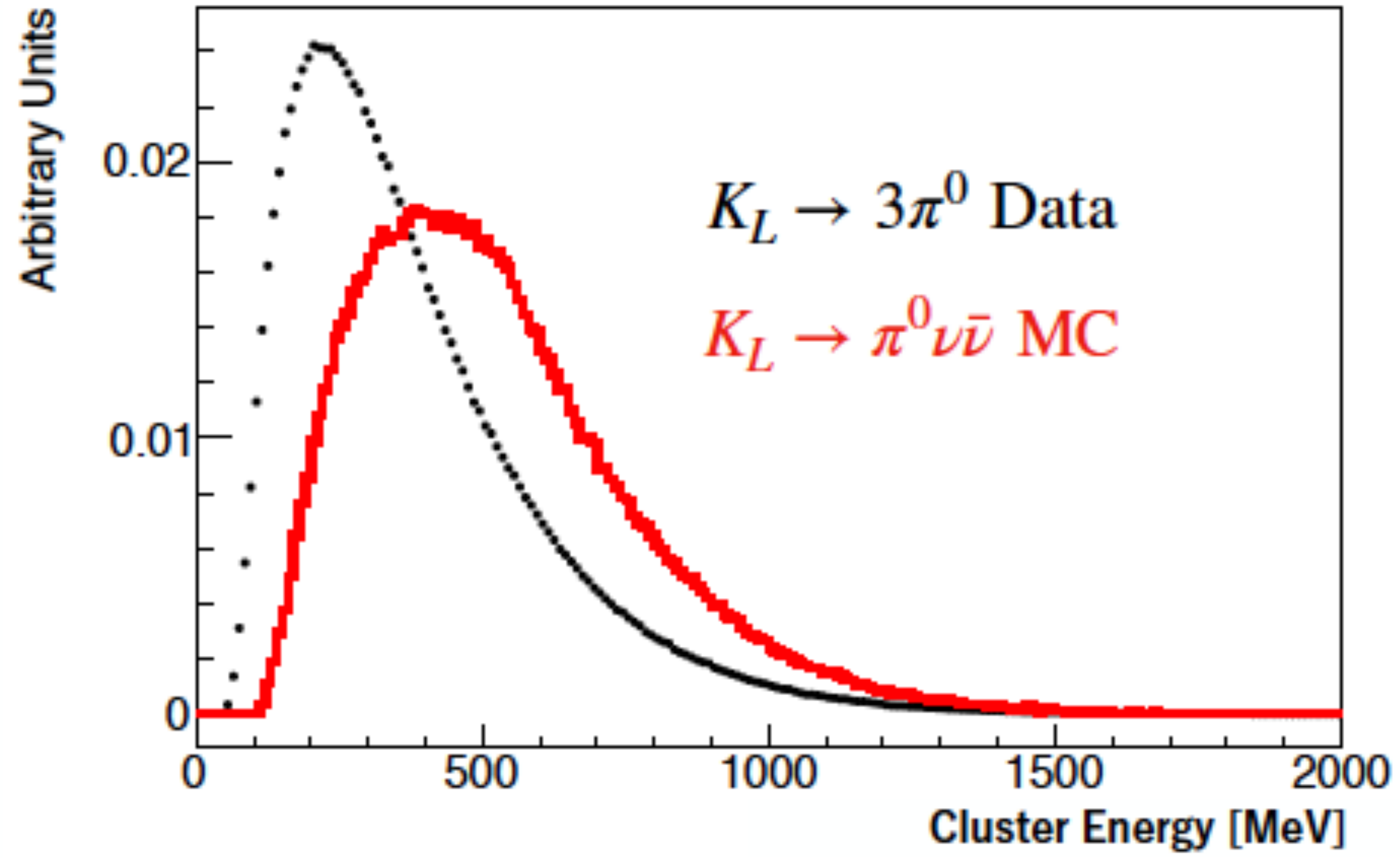




$\boldsymbol{\Delta T^{\mathbf{max}}}$ has better selection ability

γ/n separation by ΔT^{max}





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

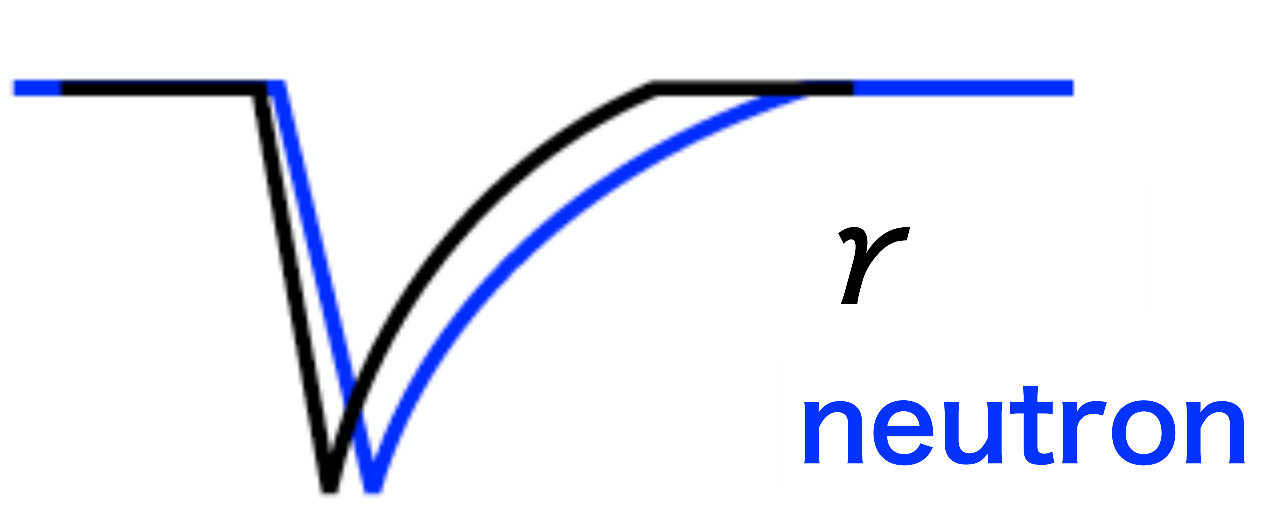
$(2.1 \pm 0.1) \times 10^{-2}$

ΔT was weight by energy

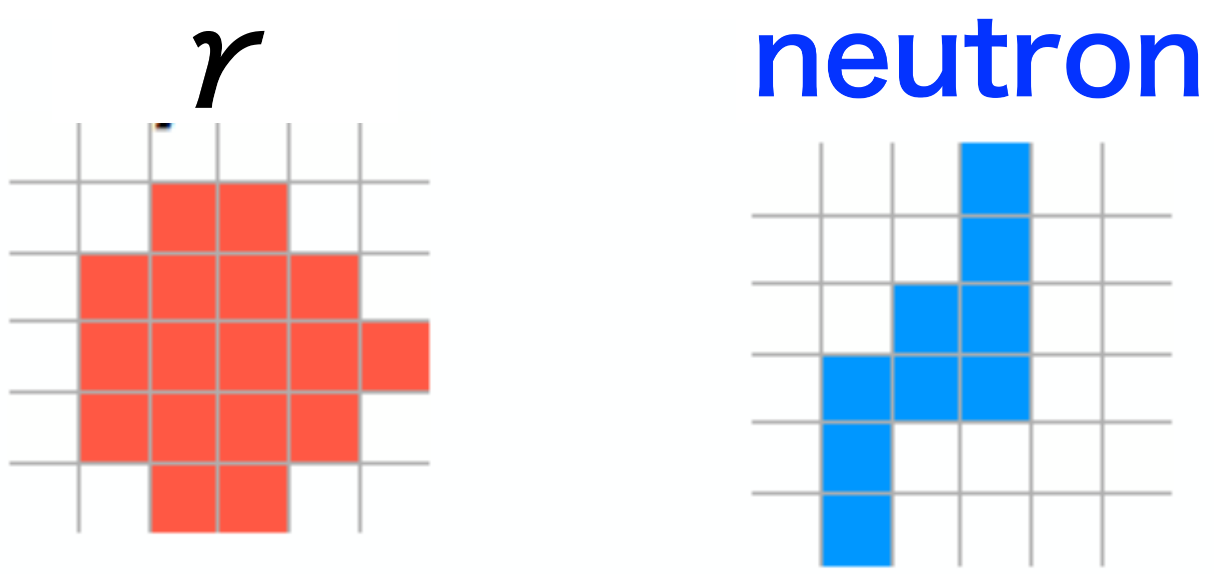
$(1.6 \pm 0.1) \times 10^{-2}$

Other two cut methods for the neutron events

Fourier Pulse Shape Discriminator



Cluster Shape Discriminator with Deep Leaning



With FPSD, CSDDL and ΔT cuts

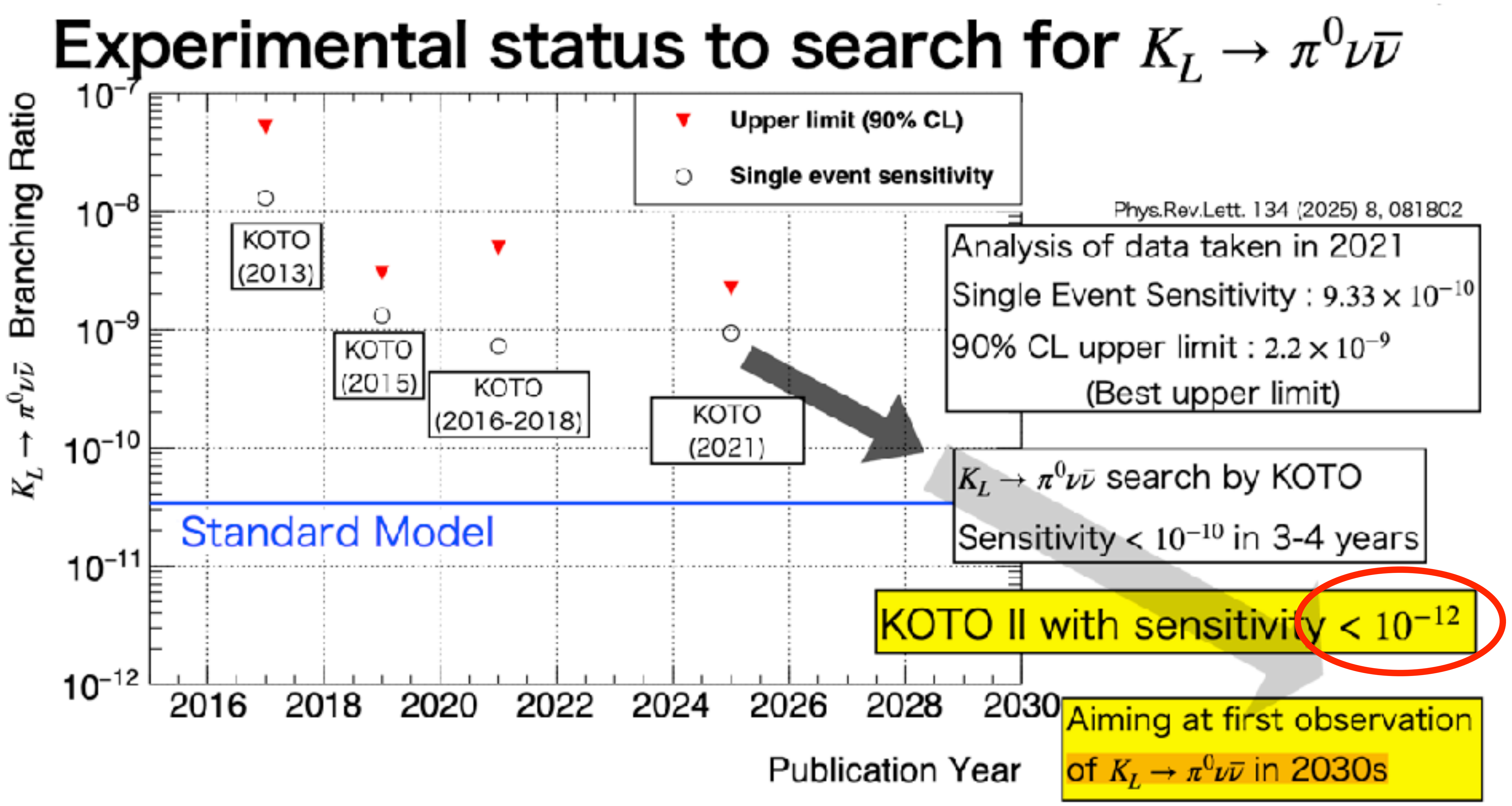
- the estimated number of neutron background events 0.024 ± 0.006
- with the single event sensitivity of $(9.33 \pm 0.06 \pm 0.84) \times 10^{-10}$

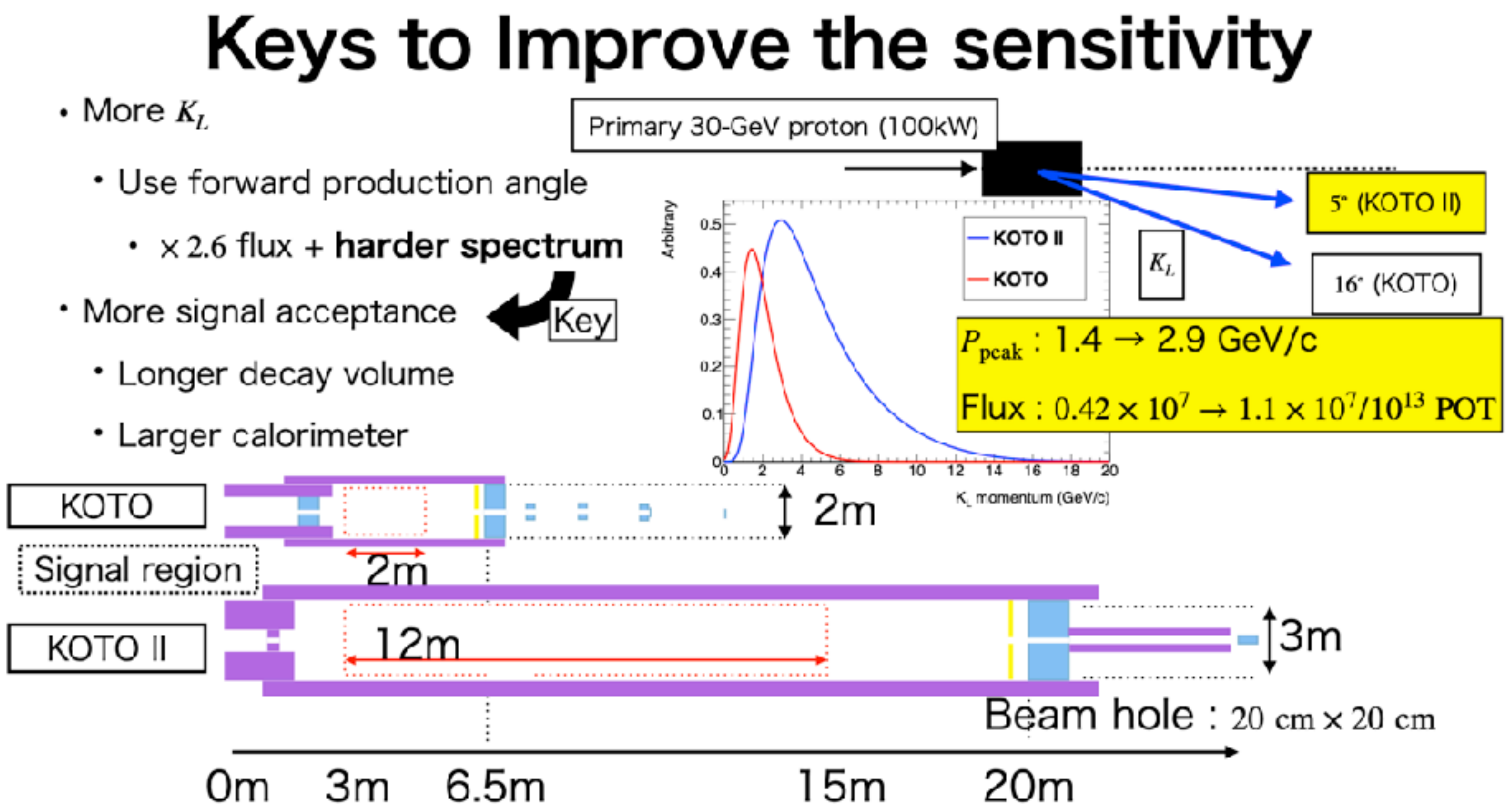
in data where the latest published KOTO

$$Br(K_L \to \pi^0 \nu \bar{\nu}) : < 2.2 \times 10^{-9} \text{ (90\% C.L.)}$$

Phys. Rev. Lett. 134, 081802

KOTO → KOTO II experiment





Welcome!

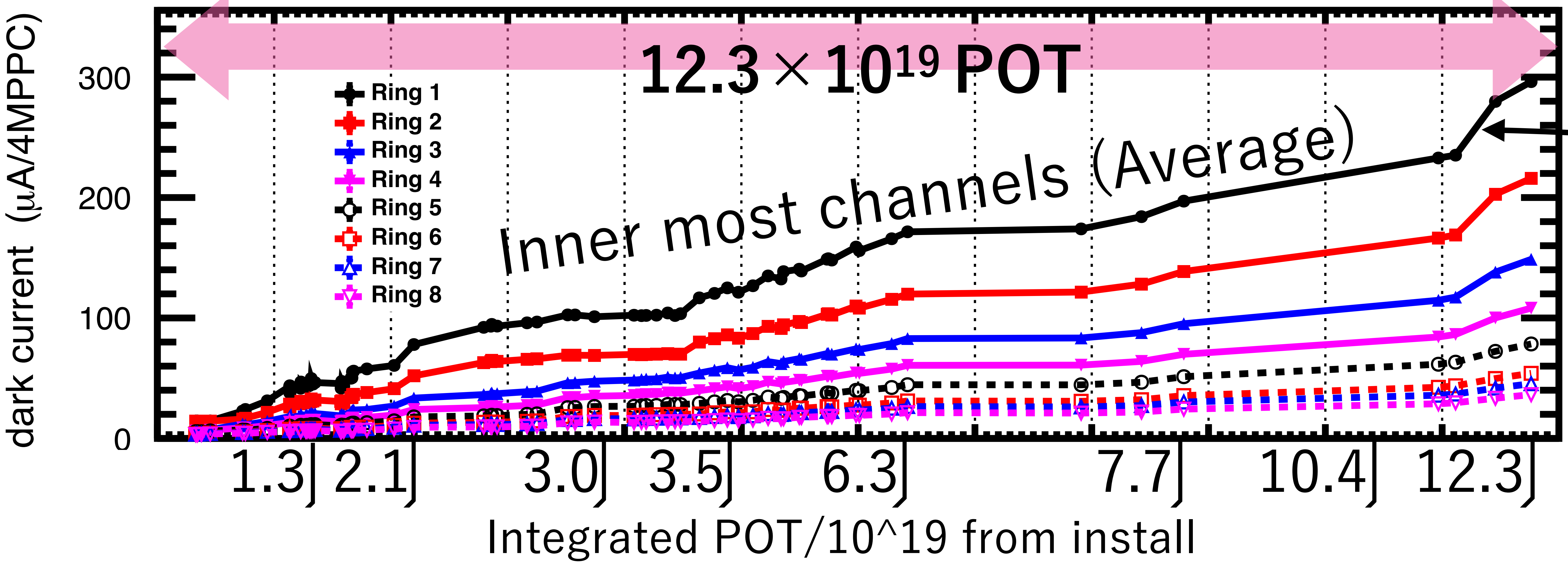
Summary

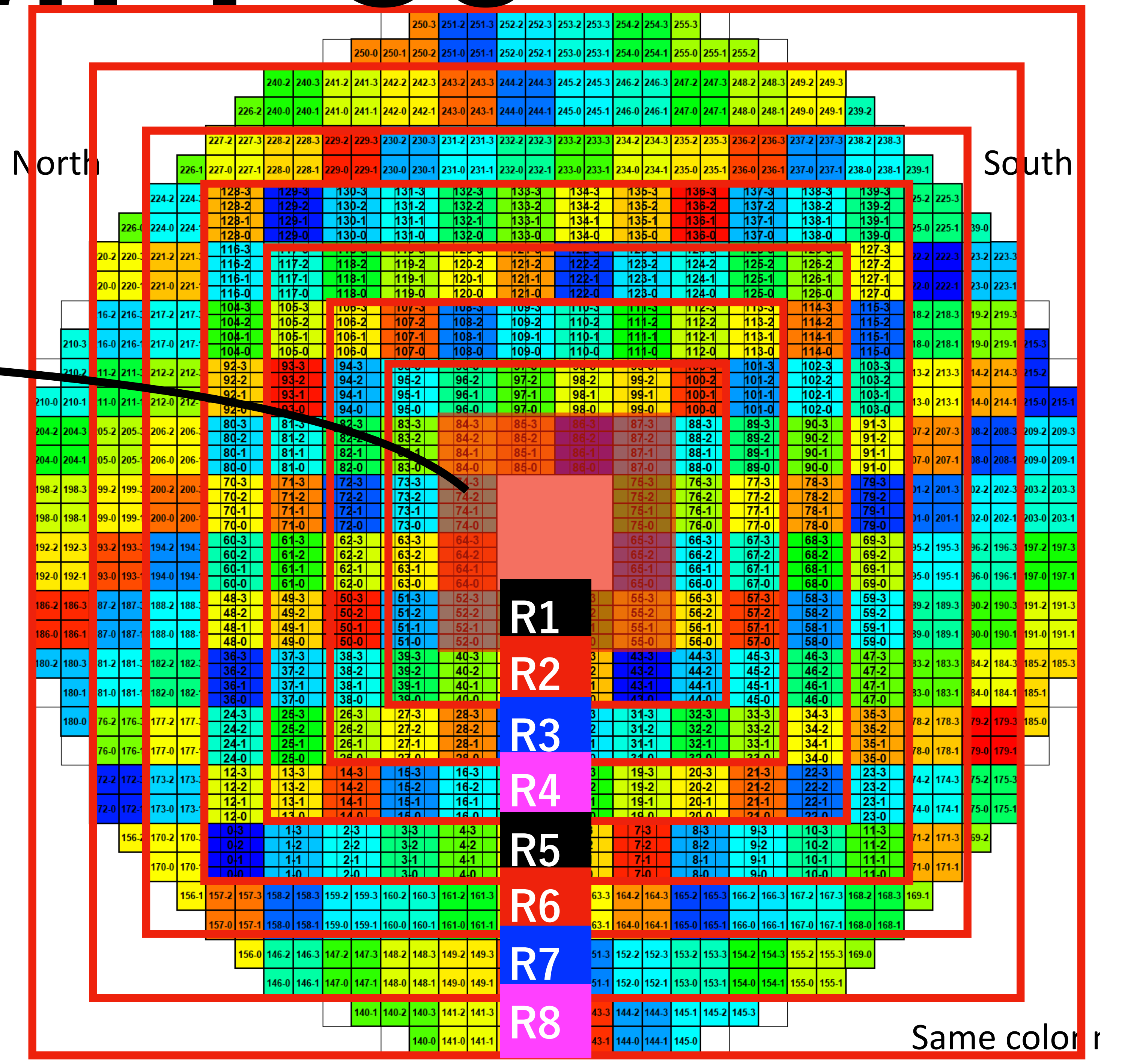
- KOTO is searching for the $K_L \to \pi^0 \nu \bar{\nu}$ decay.
- Halo neutrons (n) make one of the major background.
- A 4D calorimeter (3D+timing) was developed for γ/n separation.
- 4080 MPPCs were glued onto the front of the CsI calorimeter.
- Shower depth is determined from the timing difference between MPPCs (front) and originally installed PMTs (rear).
- n background is reduced to $< 2\%$ with 90% γ efficiency.

backup

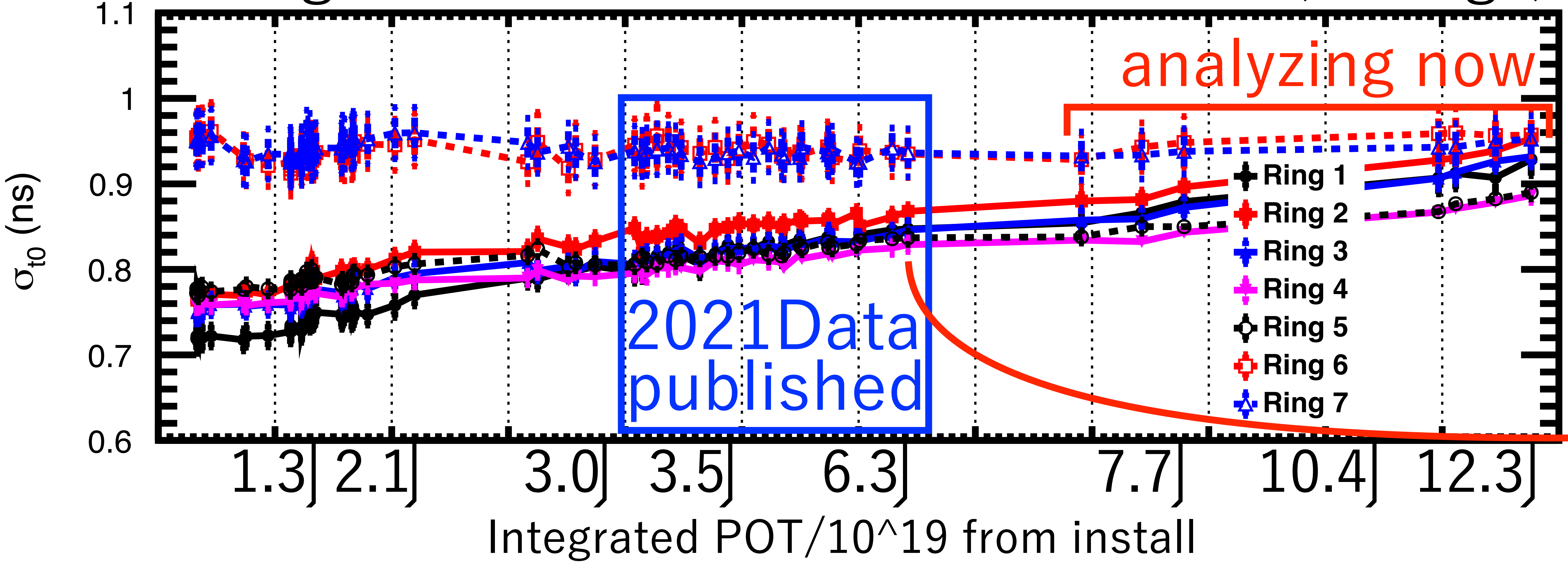
Neutron radiation hardness of MPPCs

Dark current of 4-MPPC circuit increased x 150





timing resolution of 16-MPPCs readout (average)



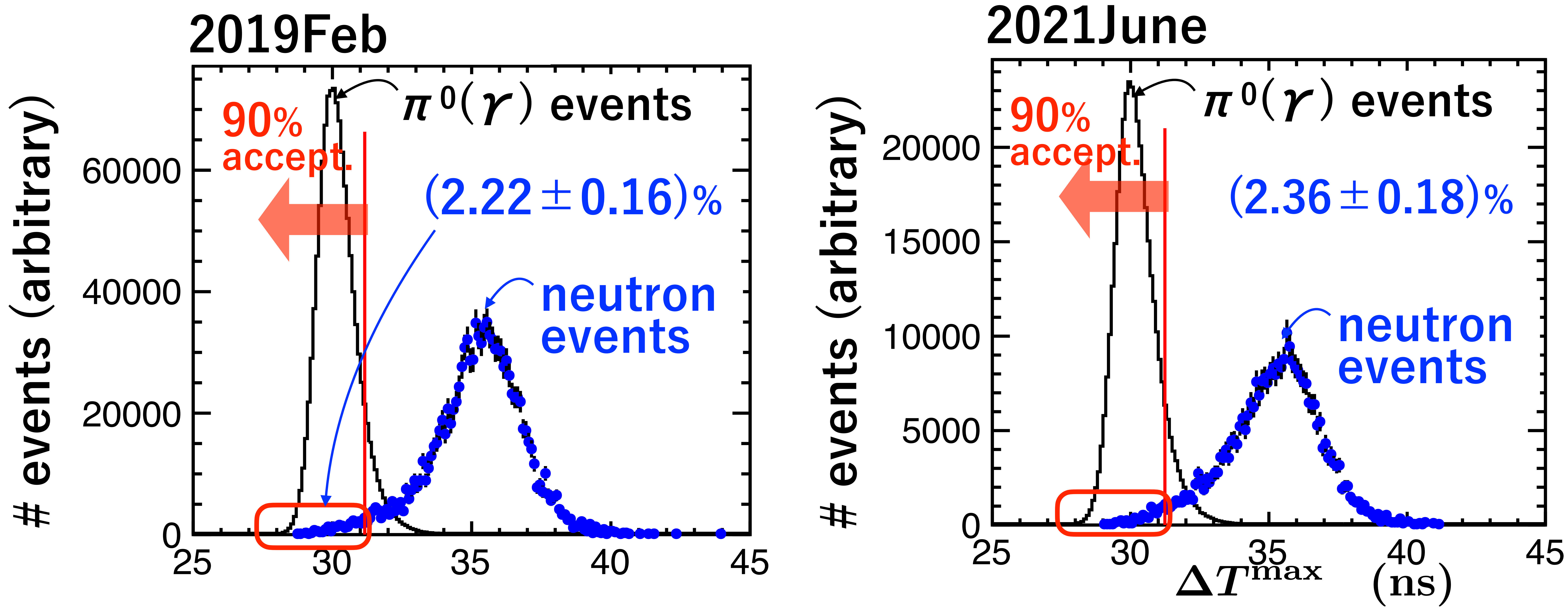
Center region

σ_t: 0.7ns → 0.9ns

Aℓ target data shown in the next page

γ / n separation ability in 2021 data

Right after installation 2019 ➡ after 6×10^{19} POT



(2.2 ± 0.2)% ➡ (2.4 ± 0.2)%

no significant deterioration

Invariant time → 4D calorimetry

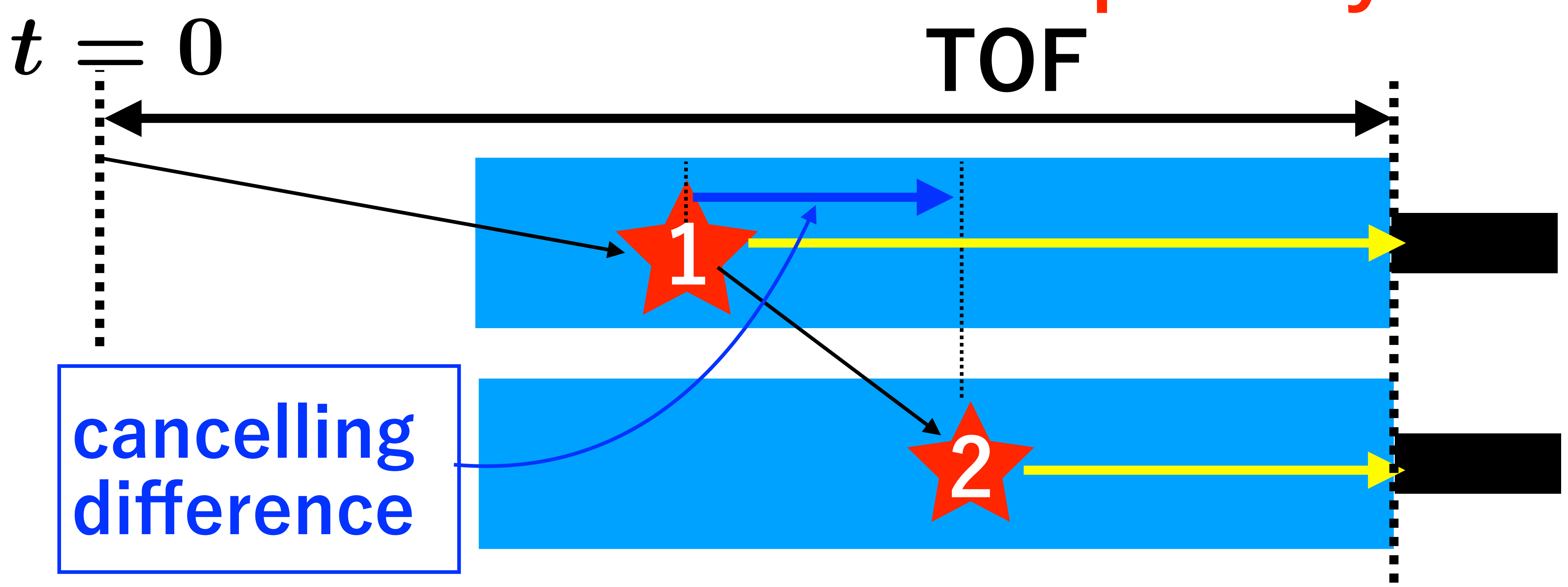
$$T_{\mathrm{inv}} = (T_{\mathrm{MPPC}} + T_{\mathrm{PMT}})/2$$

independent of the cluster depth (intrinsic)

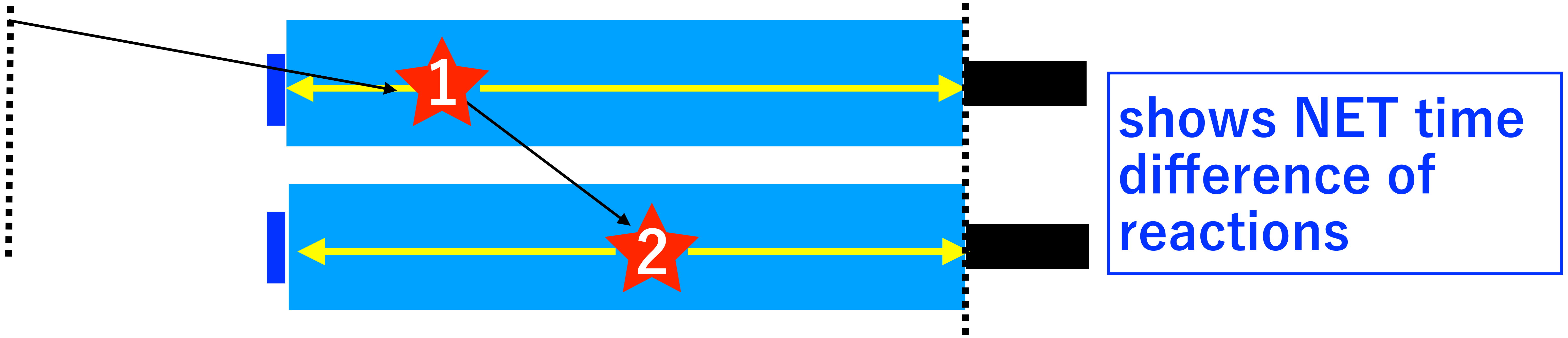
Merit of T_{inv}

Conventional TOF w/o both-side readout

cannot discriminate primary and secondary



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

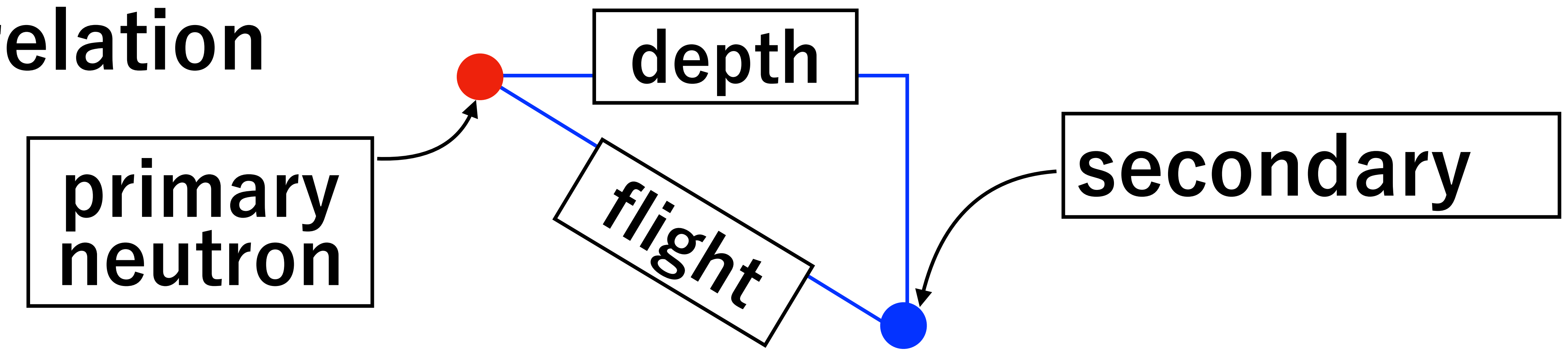


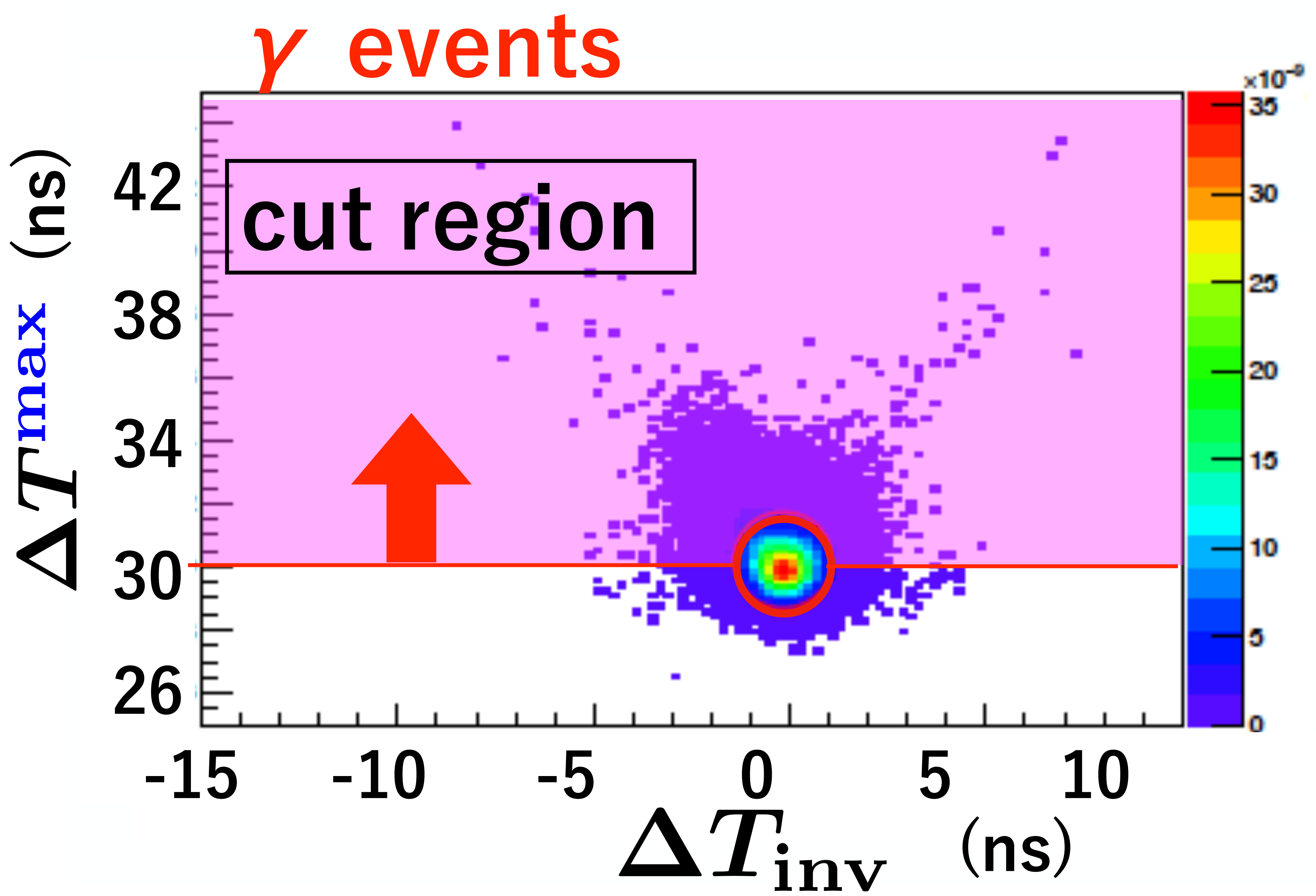
Applying invariant time info.

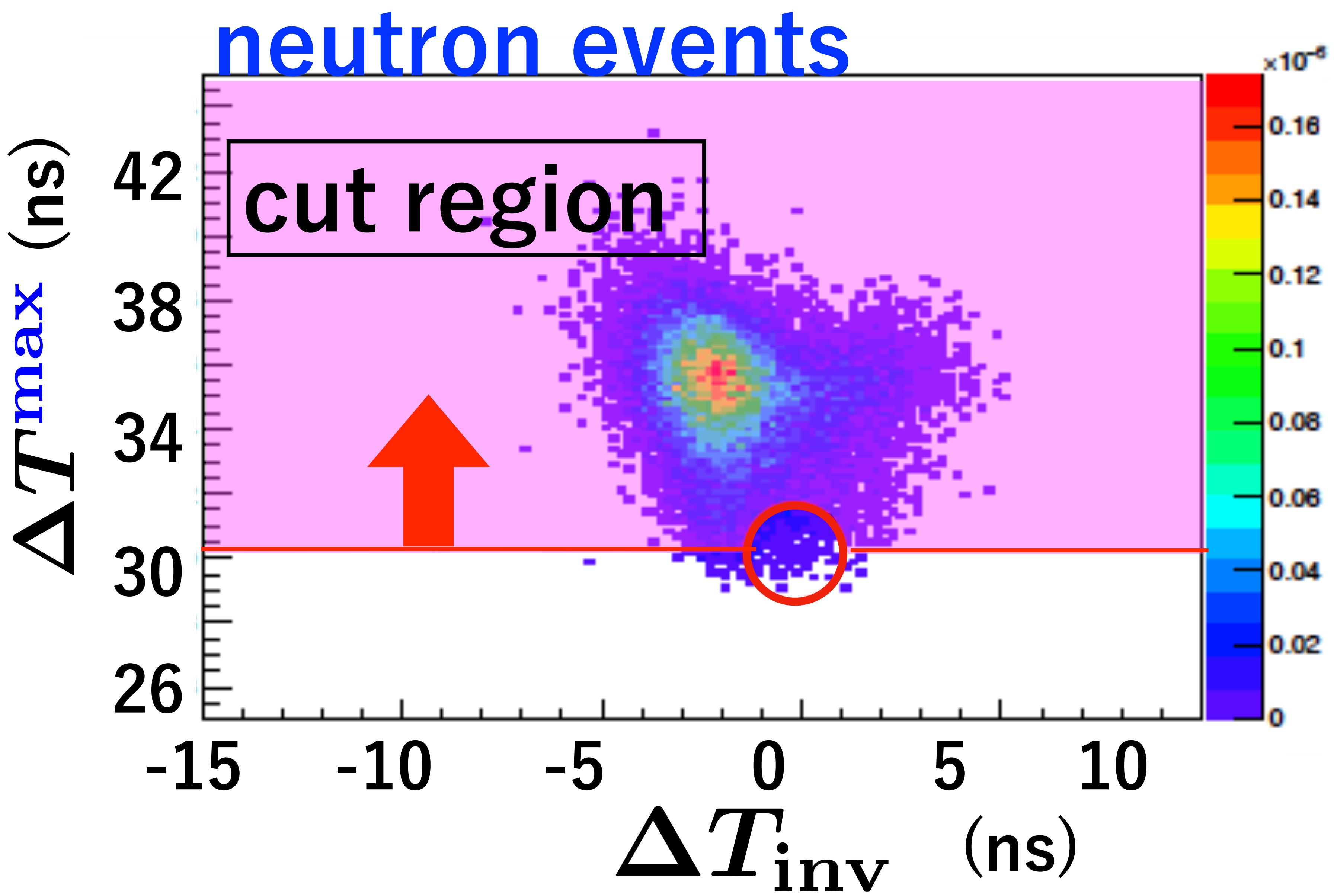
$\Delta T_{\mathrm{inv}} \propto$ flight length of the secondary particle

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

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



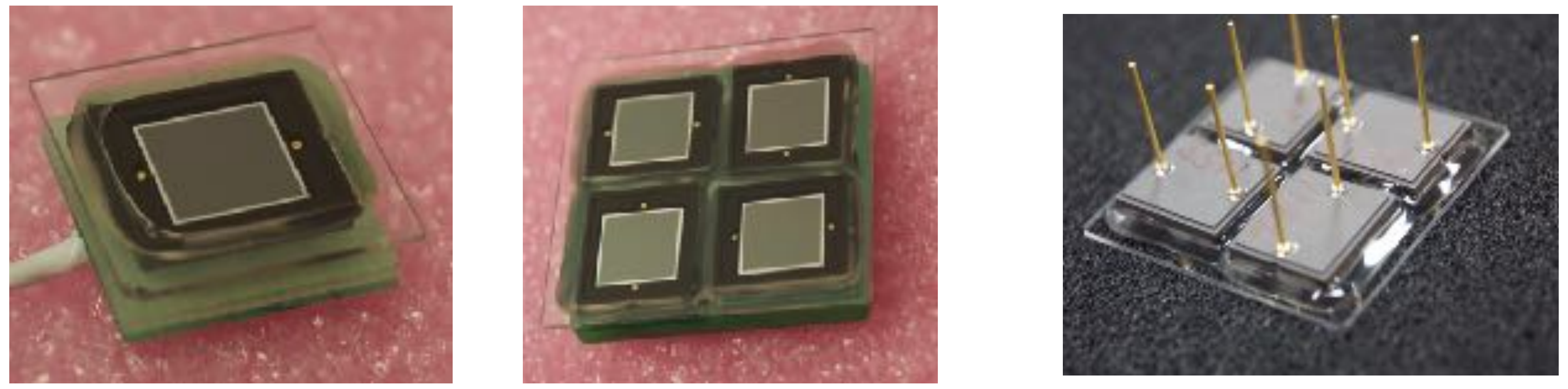




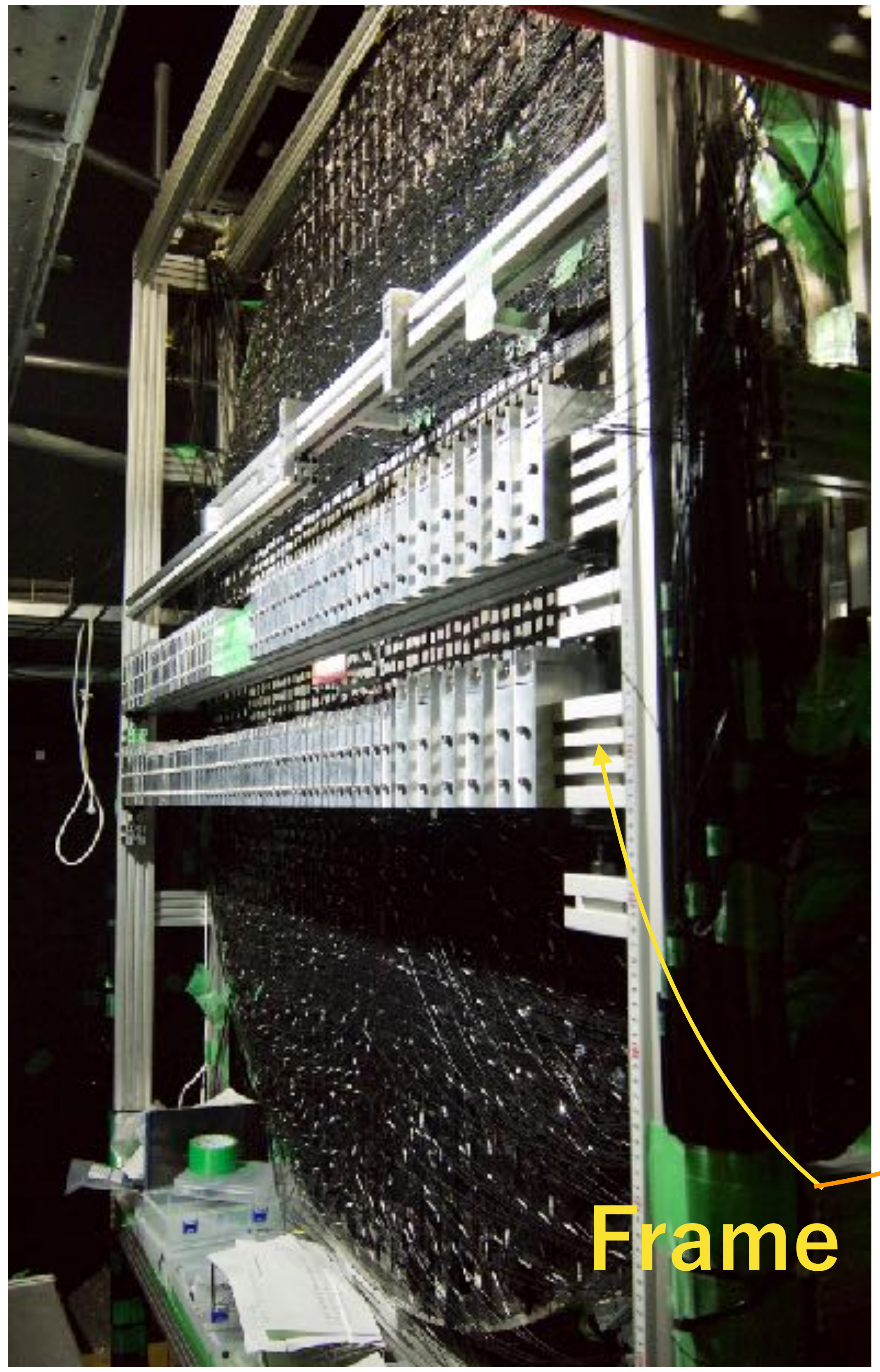
when 90% of γ events remain, $(0.96 \pm 0.06) \times 10^{-2}$ of n events remain

Construction onsite (avoid disassembly)

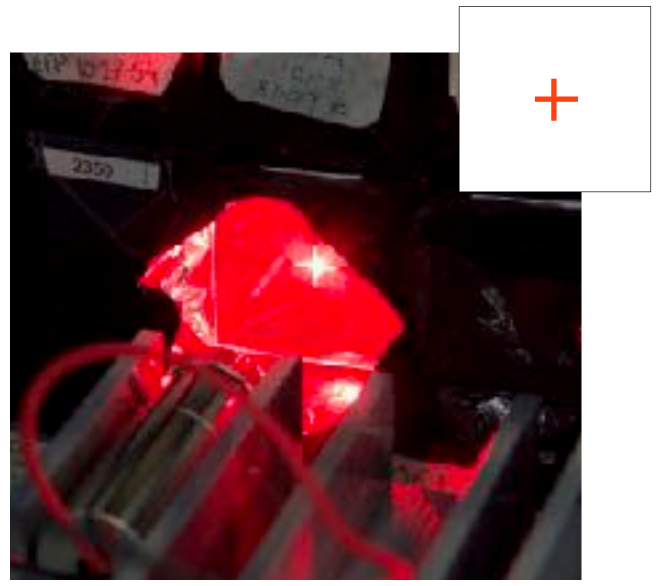
- Large crystal: 4MPPCs
- Small crystal: one MPPC



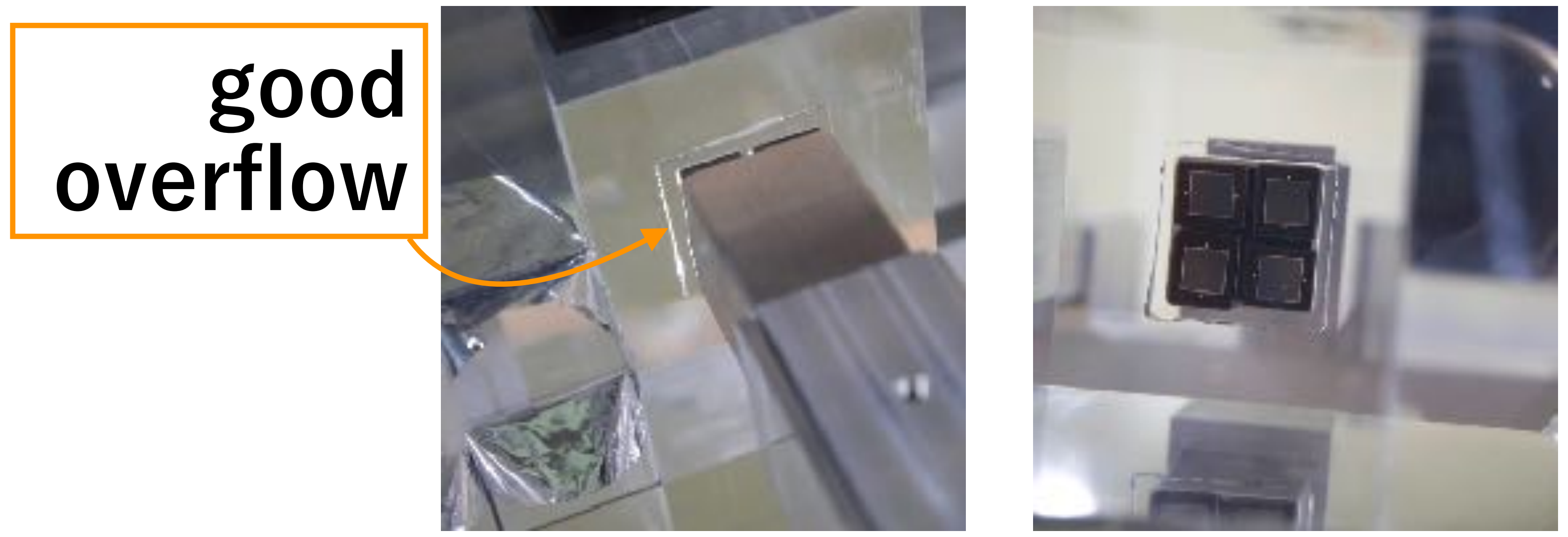
On 0.5mmT quartz plate



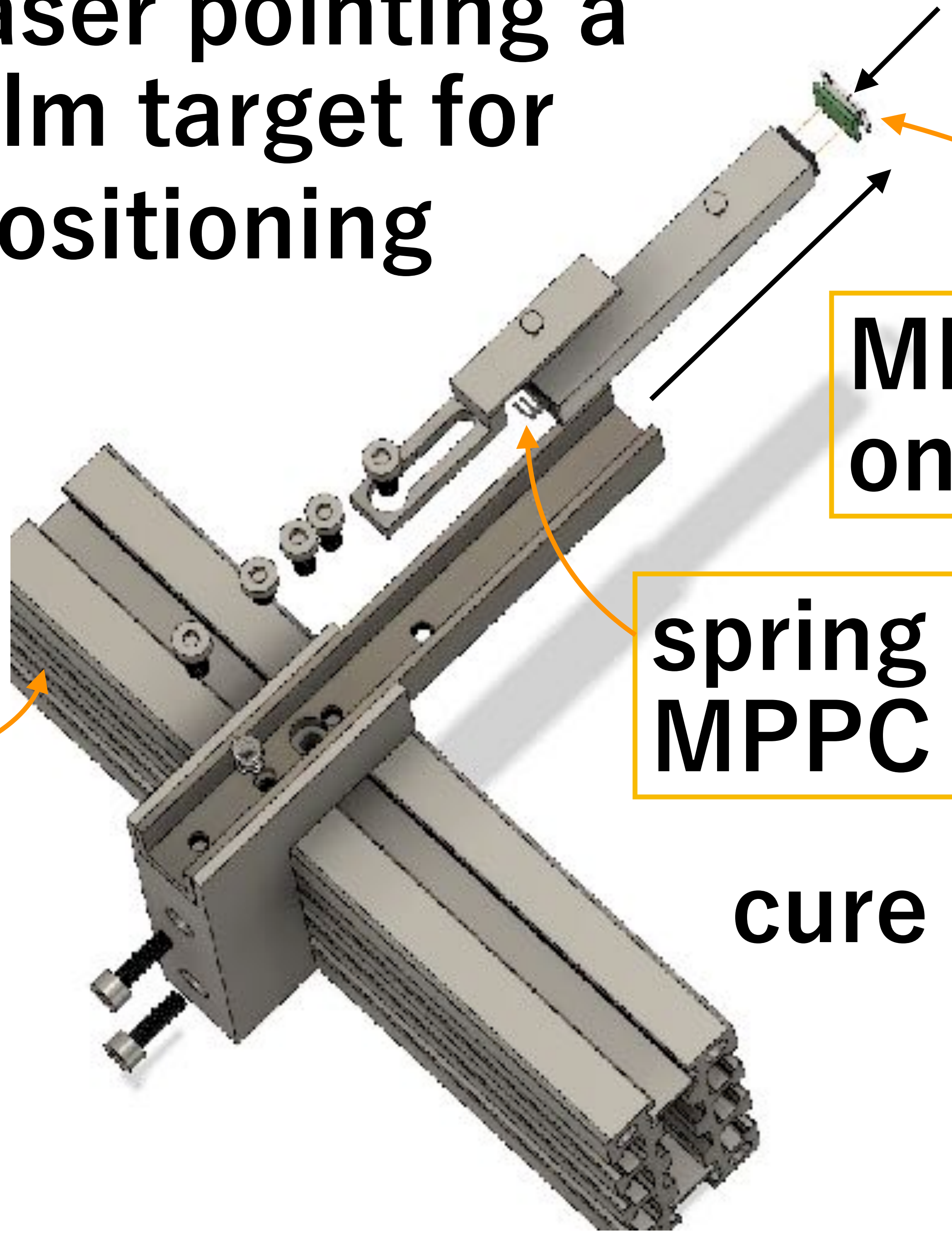
two lines/day



laser pointing a film target for positioning



testing appropriate quantity of glue



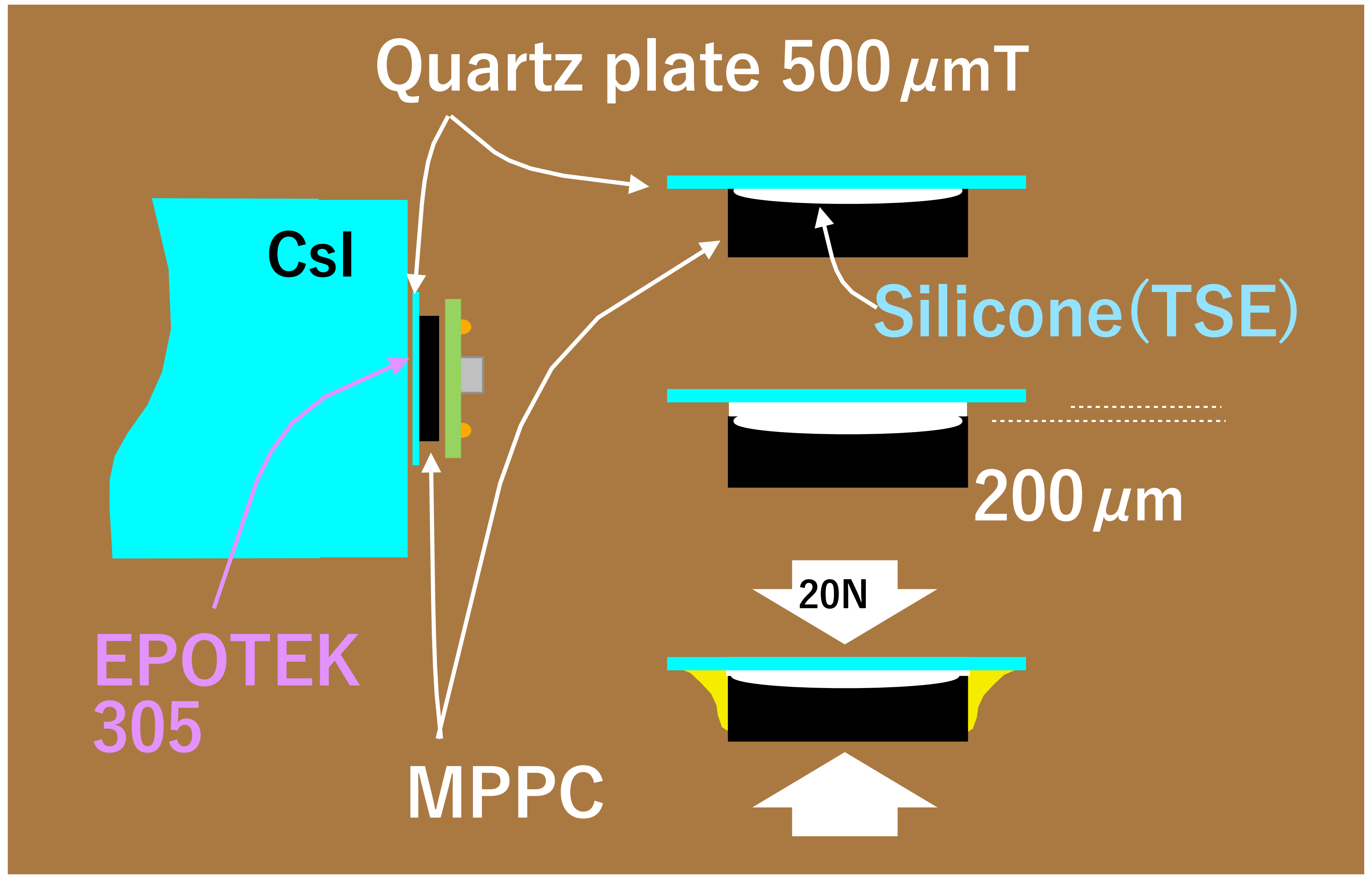
MPPC sticking on the holder

spring pushing a MPPC to CsI

cure time : 16hrs

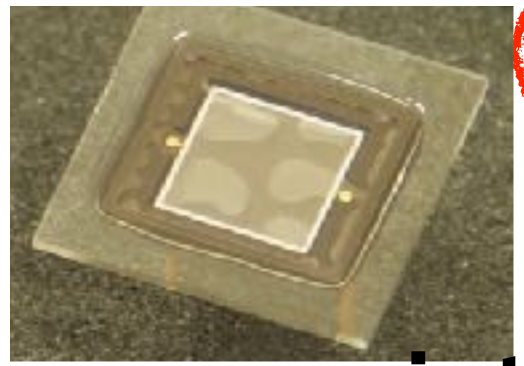
Gluing

Design-glueing



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

babbles

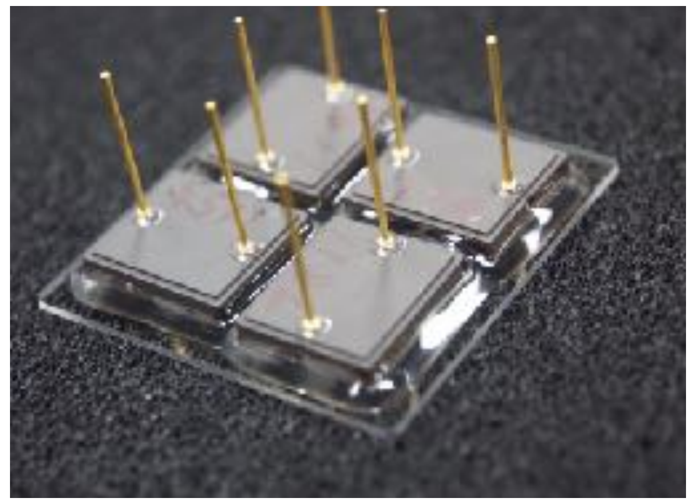


temp.variation

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

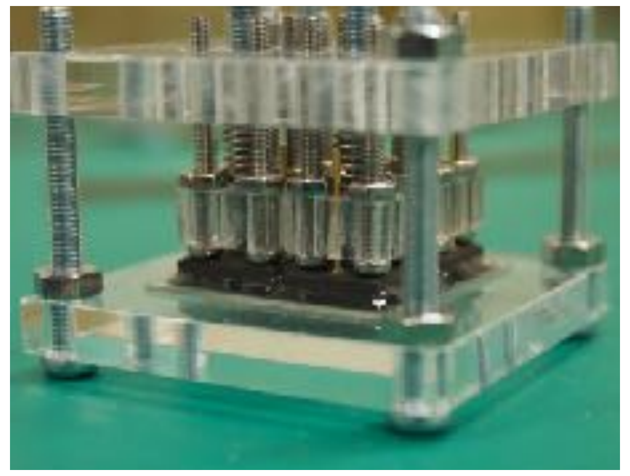
tolerance of temp: -10 —45℃

EPOTEK305:UV transparent glue
TSE3034:UV transparent silicone



Araldite

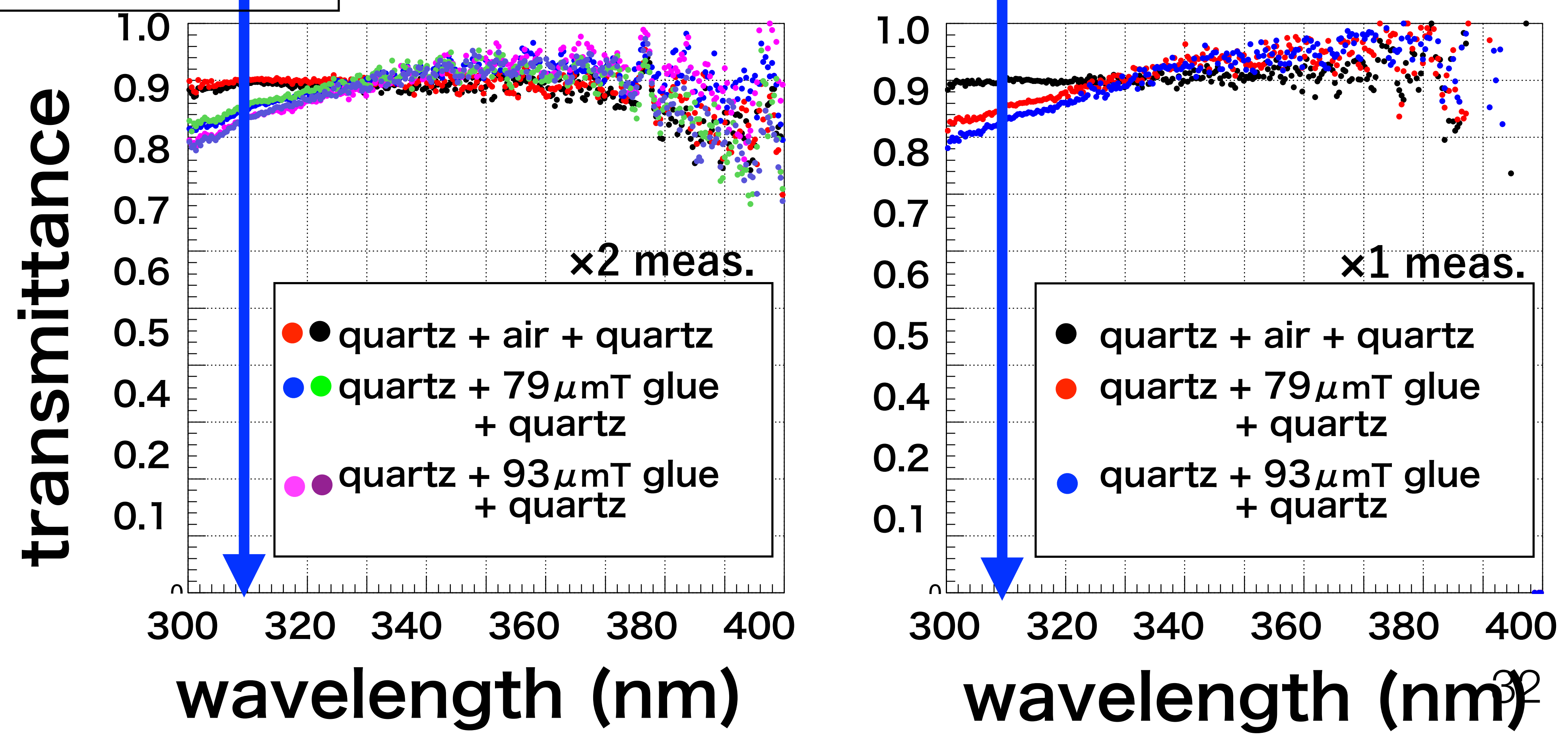
quartz plate



curing with 20N press.

310nm CsI scint.

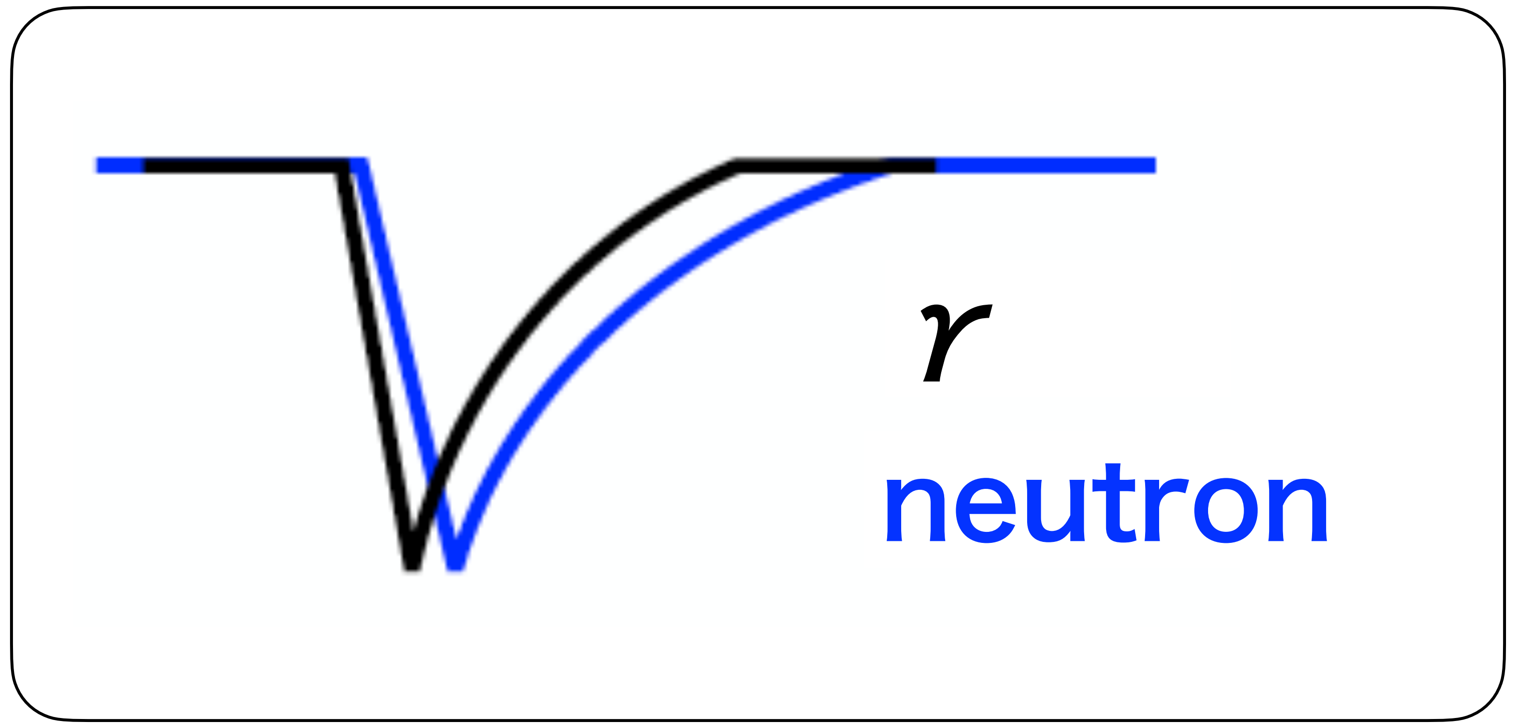
Before $\xrightarrow{8\times10^{8}\,_{n1MeV}/cm^{2}}$ After



Remaining neutron BG for KOTO

Two other cut methods were developed

Fourier Pulse Shape Discriminator



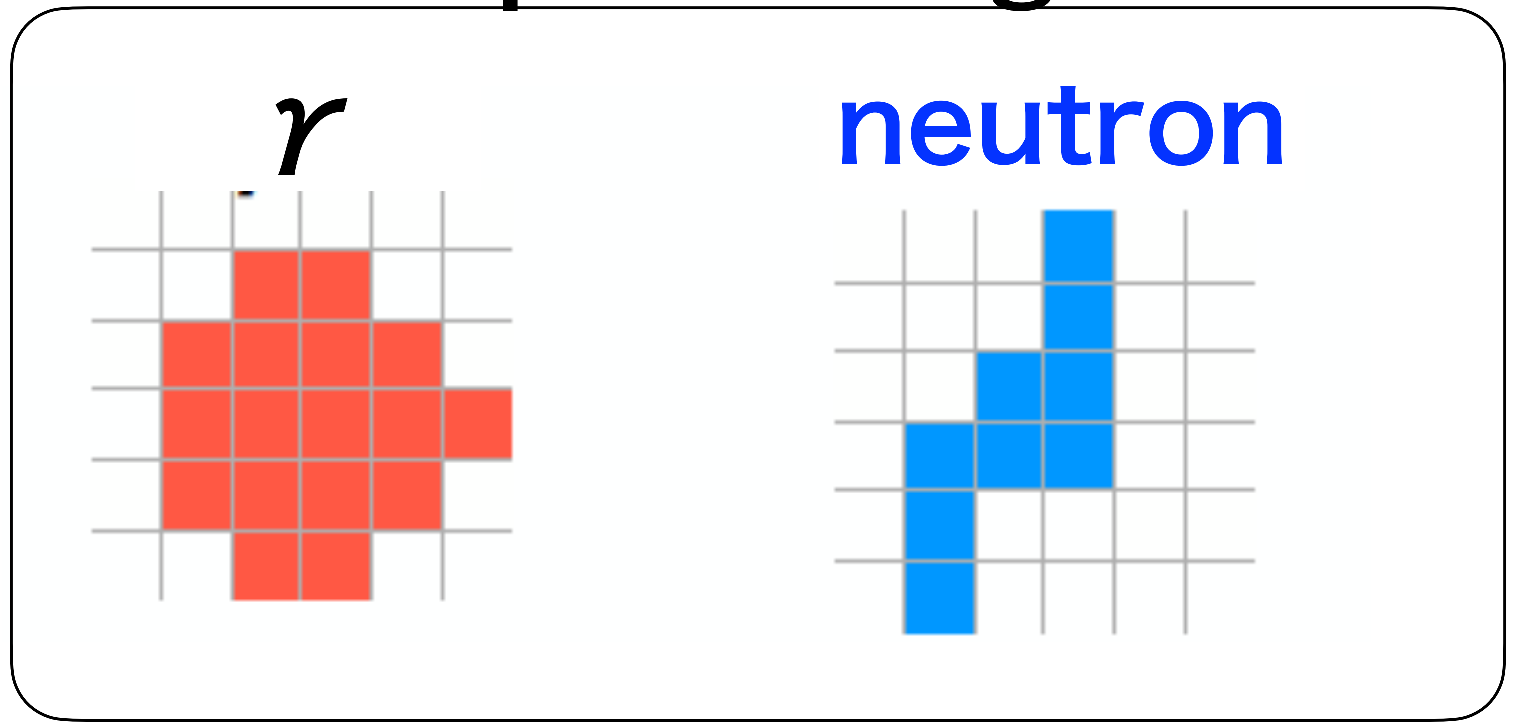
1 → FPSD → ×(1.6±0.2)×10^{-3} → ΔT → ×(4.1±0.6)×10^{-2}

1 → ΔT → ×(2.1±0.1)×10^{-2}

difference means a correlation:
(4.1±0.6)×10^{-2} still enough

with 3 cuts

Cluster Shape Discriminator with Deep Leaning



1

ΔT<33 ns → CSDDL → ×(8±1)×10^{-3}

ΔT>33 ns → CSDDL → ×(7±1)×10^{-3}

no correlation between
ΔTcut : CSDDL

Estimated remaining n events are 0.5±0.5 in 1 SM events(3x10^{-11})

Latest published results

- Single Event Sensitivity (SES)
  - $\mathrm{SES} = (9.33 \pm 0.06 \pm 0.84) \times 10^{-10}$
- Expected number of background events
  - $0.252 \pm 0.055^{+0.052}_{-0.067}$
- No events observed in the signal region

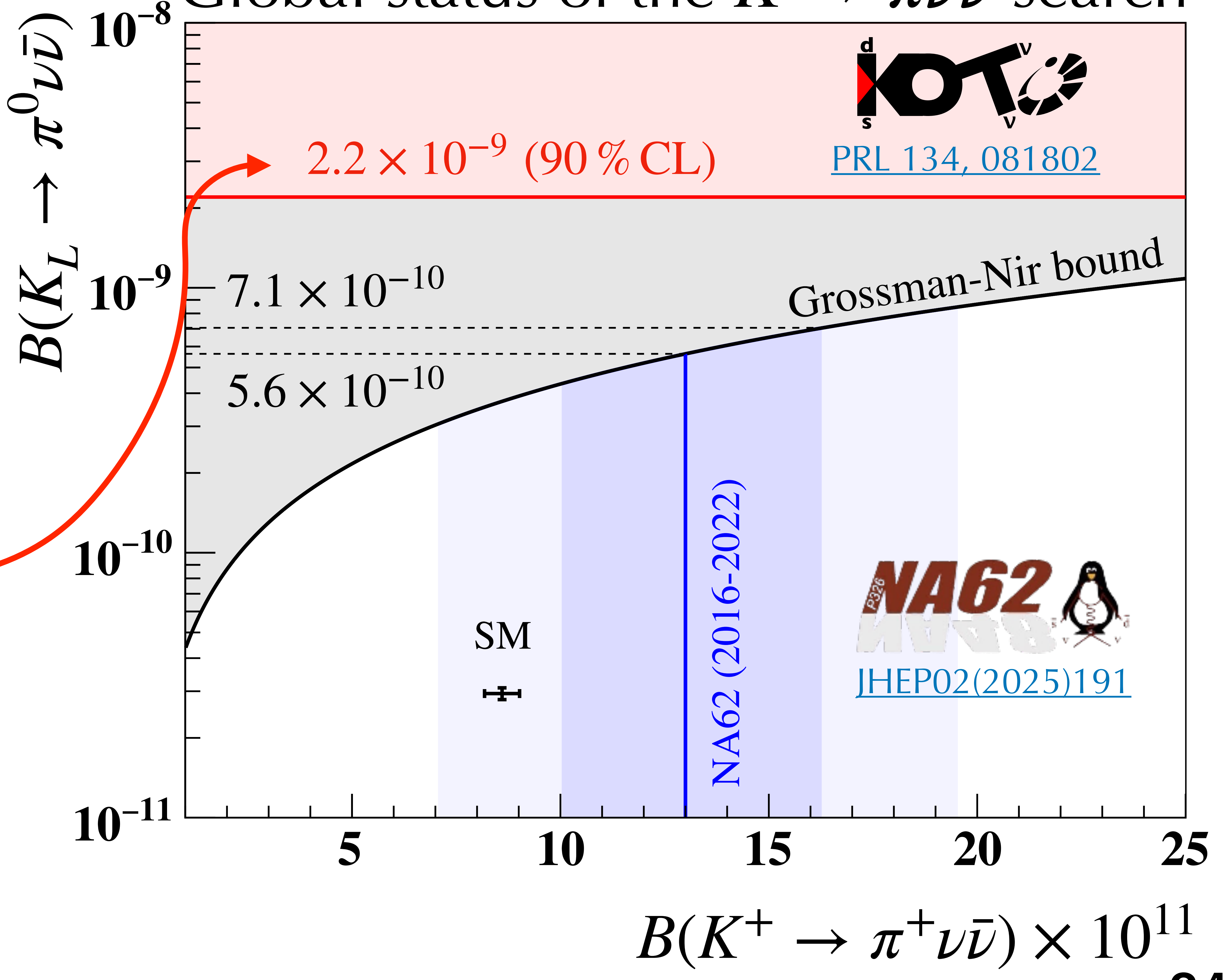
$\Rightarrow B(K_L \to \pi^0 \nu \bar{\nu}) < 2.2 \times 10^{-9}$ (90% C.L.)

(current World record)

[Phys. Rev. Lett. 134, 081802]

A violation of the $K^+ \to \pi^+ \nu \bar{\nu}$ constraint reveals the CPV nature of NP (approaching).

Global status of the $K \to \pi \nu \bar{\nu}$ search



Conditions of MPPCs