Pulse Shape Discrimination Measurement of CsI(Tl) Scintillator with Green-Extended Photocathode PMTs

Sedong Park

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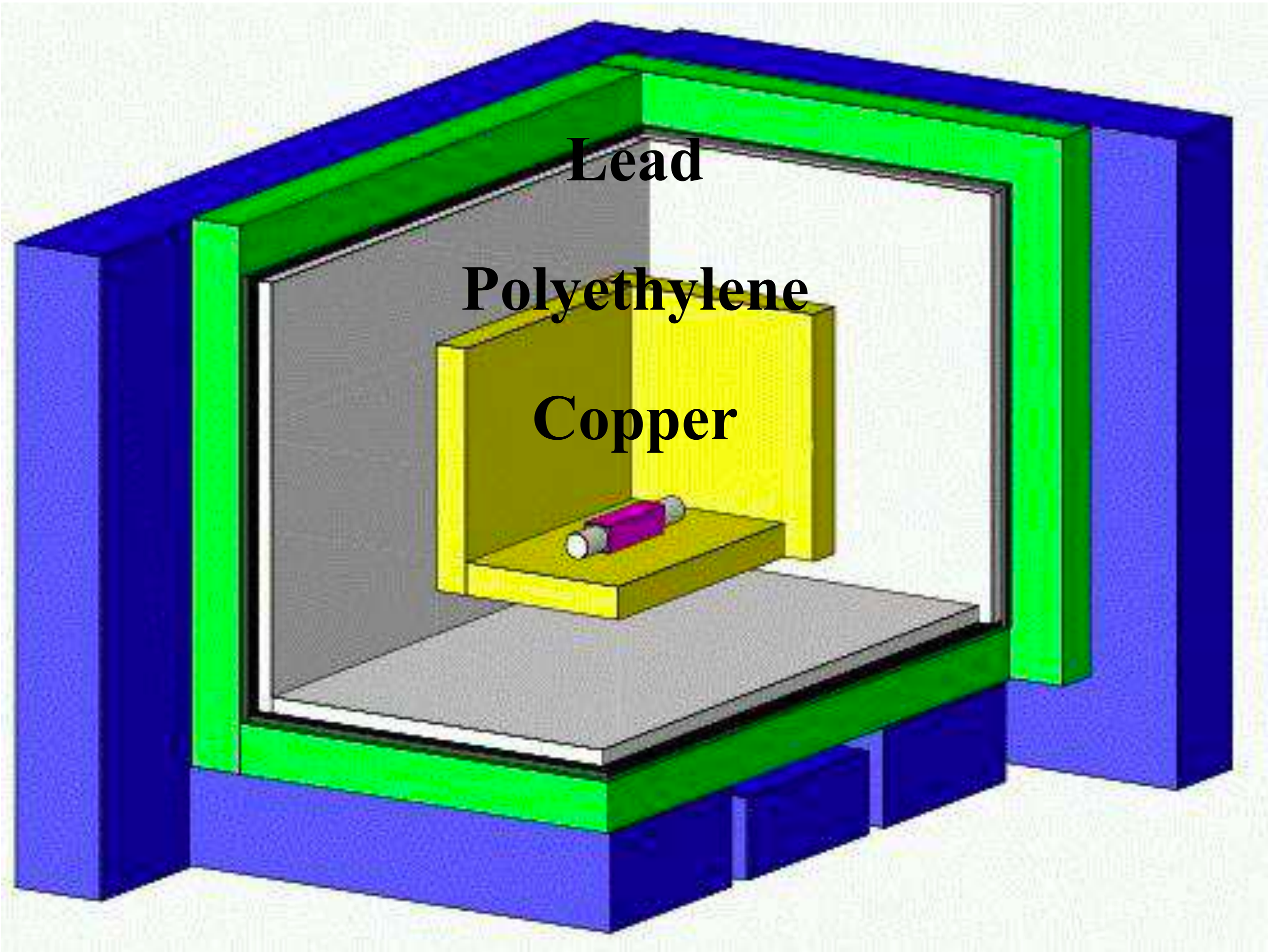
Department of Physics, Kyungpook National University

Properties of CsI(Tl)

Property	CsI(Tl)	NaI(Tl)
Density (g/cm^3)	4.53	3.67
Decay time(ns)	1000	250
Peak emission (nm)	550	415
Hygroscopic	Slight	Yes

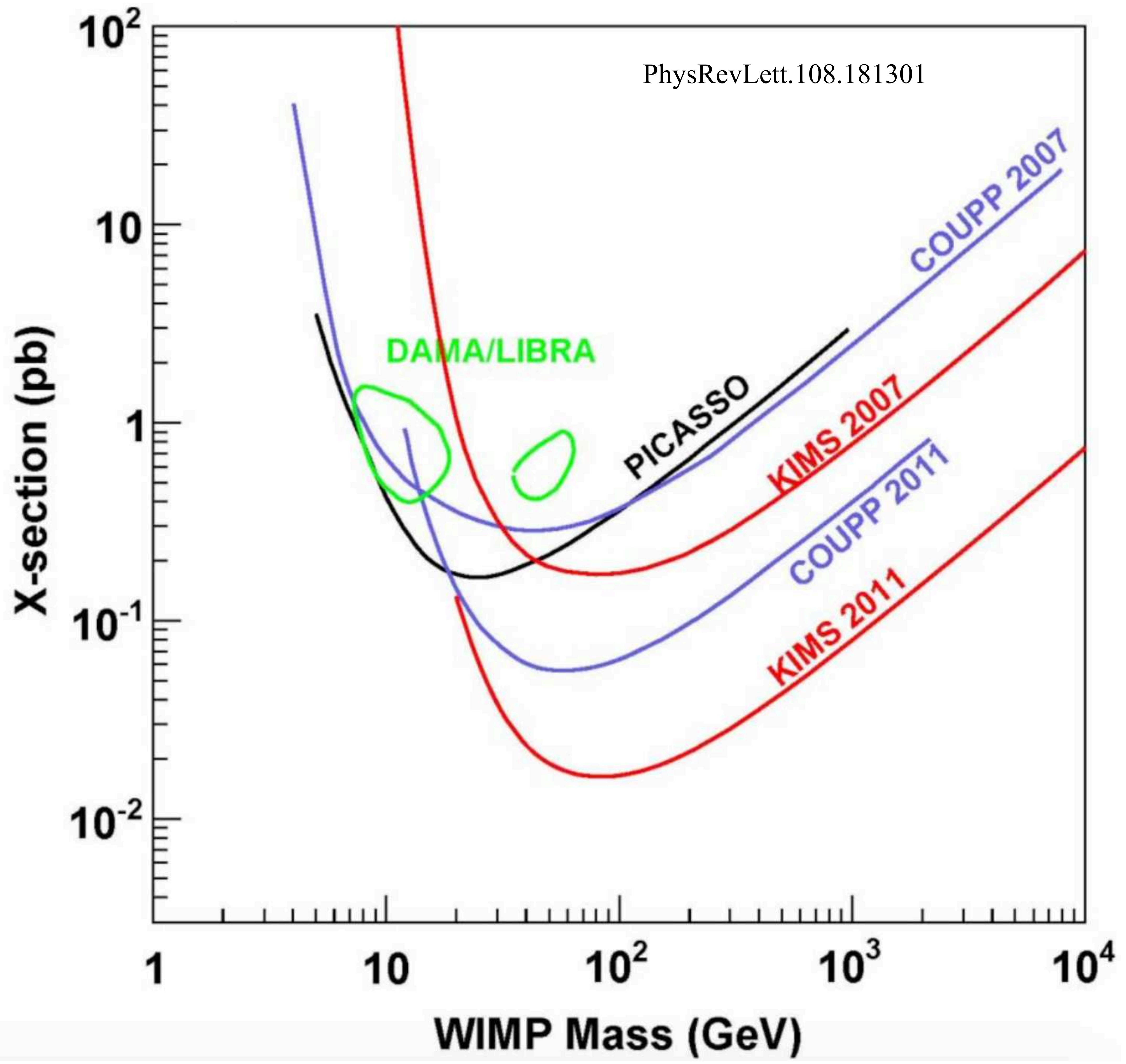
- It is less hygroscopic than NaI(Tl), making it easier to handle.
- Long decay time.
- Has good Pulse shape discrimination (PSD).
- Emission spectrum is not matched with typical PMT.
- The KIMS experiment used CsI(Tl) as a detector.

KIMS experiment



- Yangyang Underground Laboratory (Y2L)
- 12 CsI(Tl) crystals (total 104 kg)
- Data were taken from 2009 to 2012.
- Background: 2 ~ 3 counts/kg/day/keV

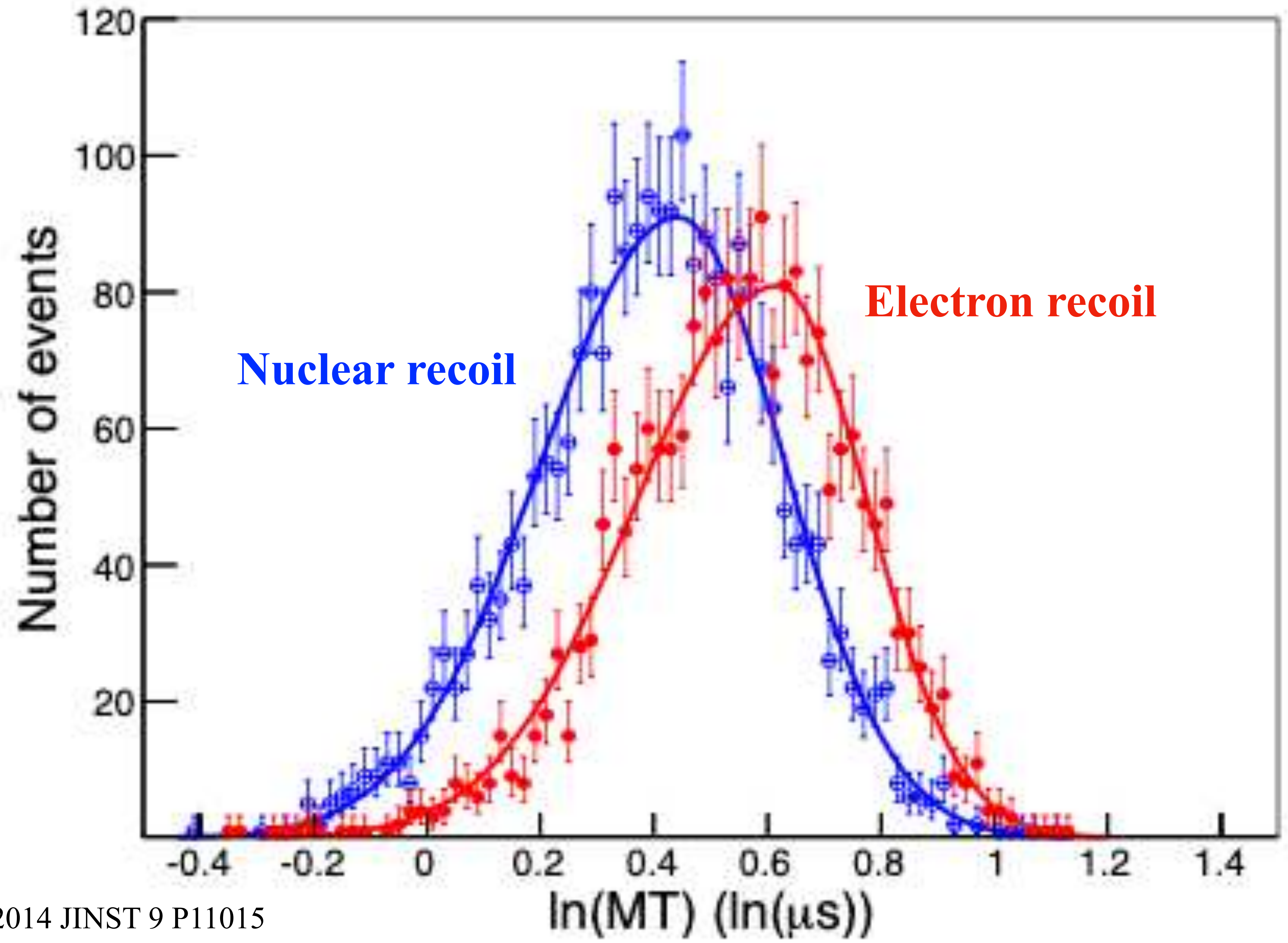
KIMS experiment result in 2012



Spin dependent cross section limit

- Achieved a world-leading upper limit on spin dependent WIMP-proton interactions in the high-mass region in 2012.
- Limit setting was constrained by the pulse shape discrimination (PSD) threshold.
- Improving light yield can lower the threshold and lead to improved upper limits.

Pulse shape discrimination



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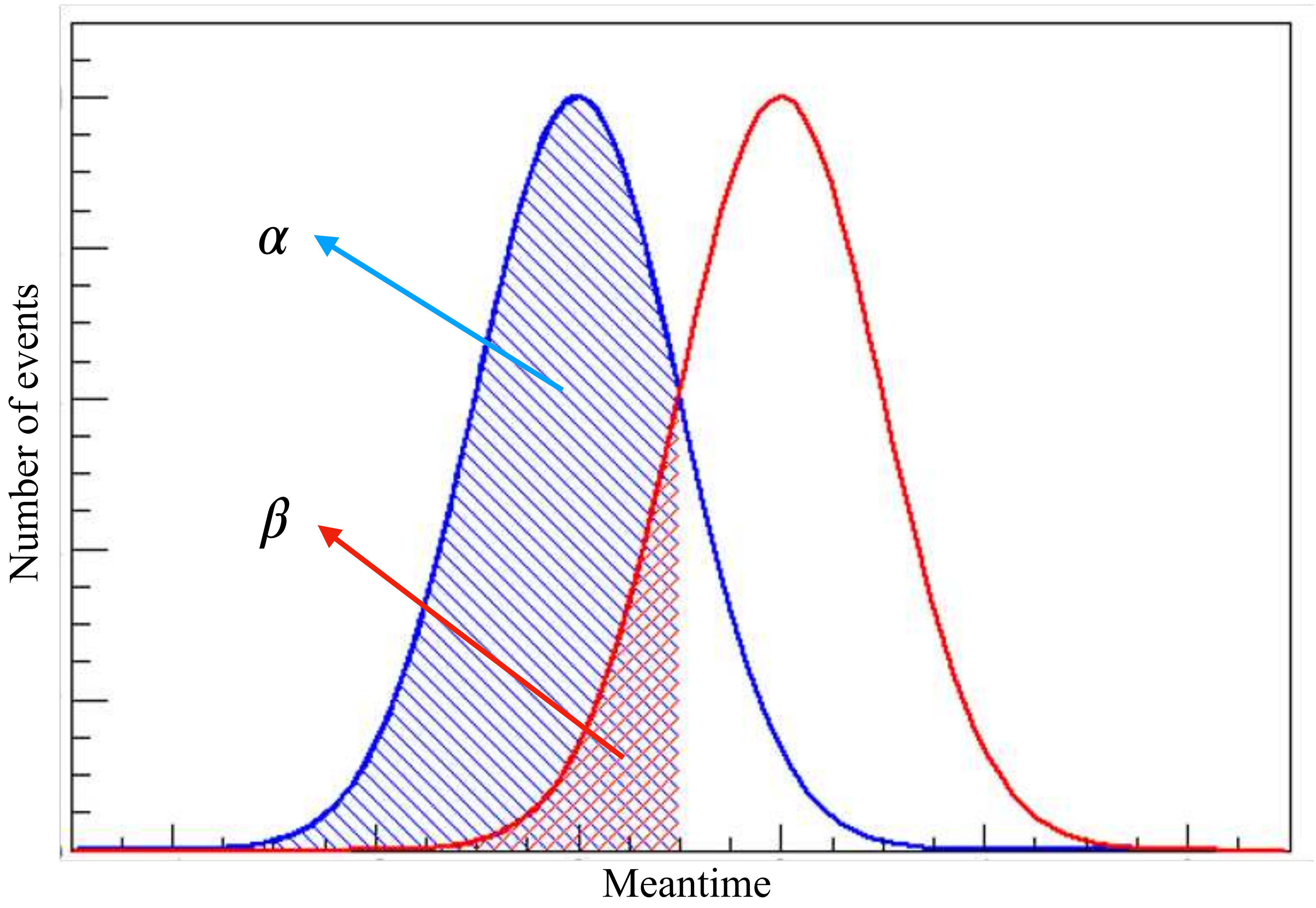
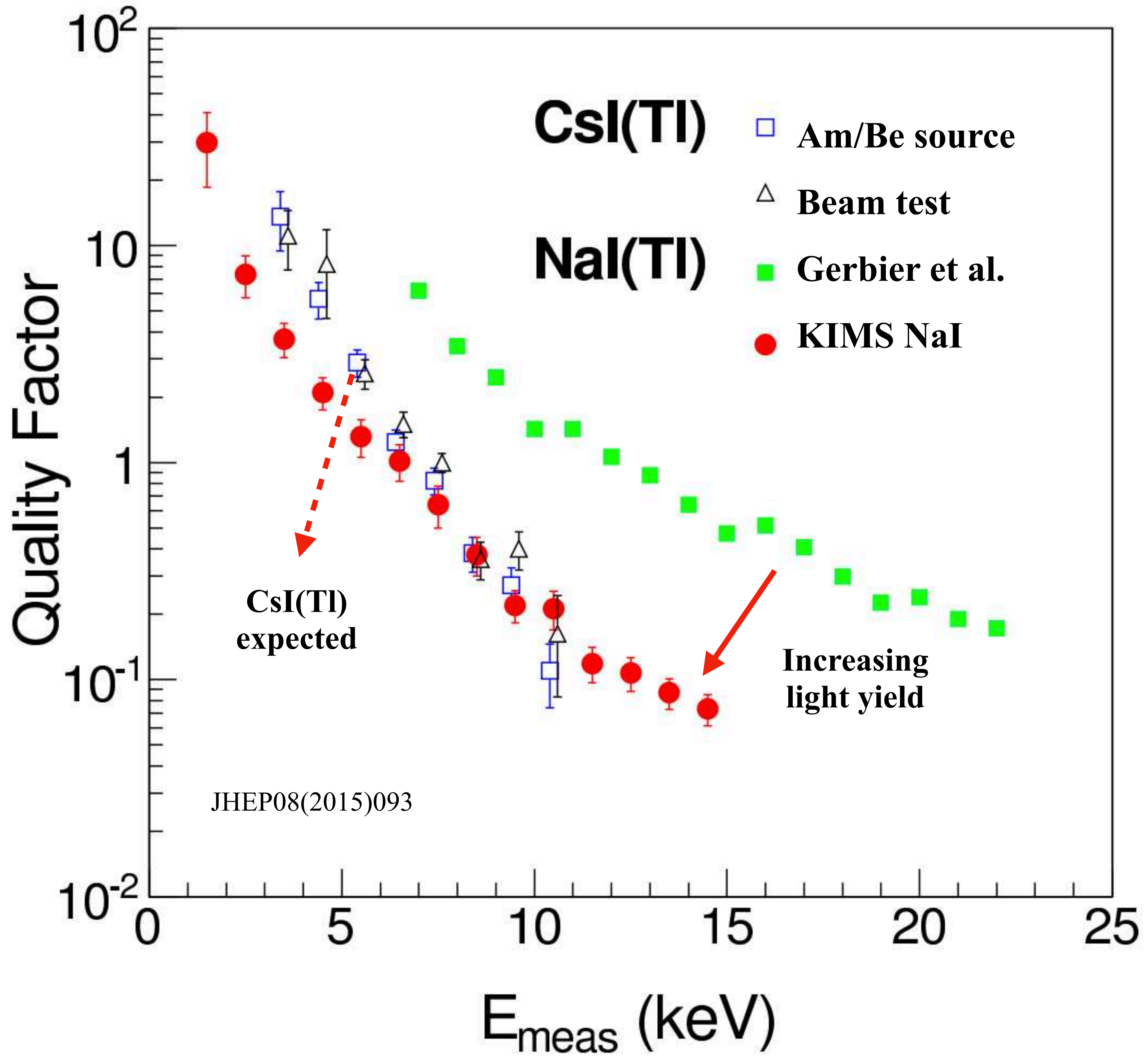


- Nuclear recoil events are distinguished from electron recoil events using a pulse shape discrimination (PSD).
- Quality factor (QF) is defined as

$$K = \frac{\beta(1-\beta)}{(\alpha-\beta)^2}$$

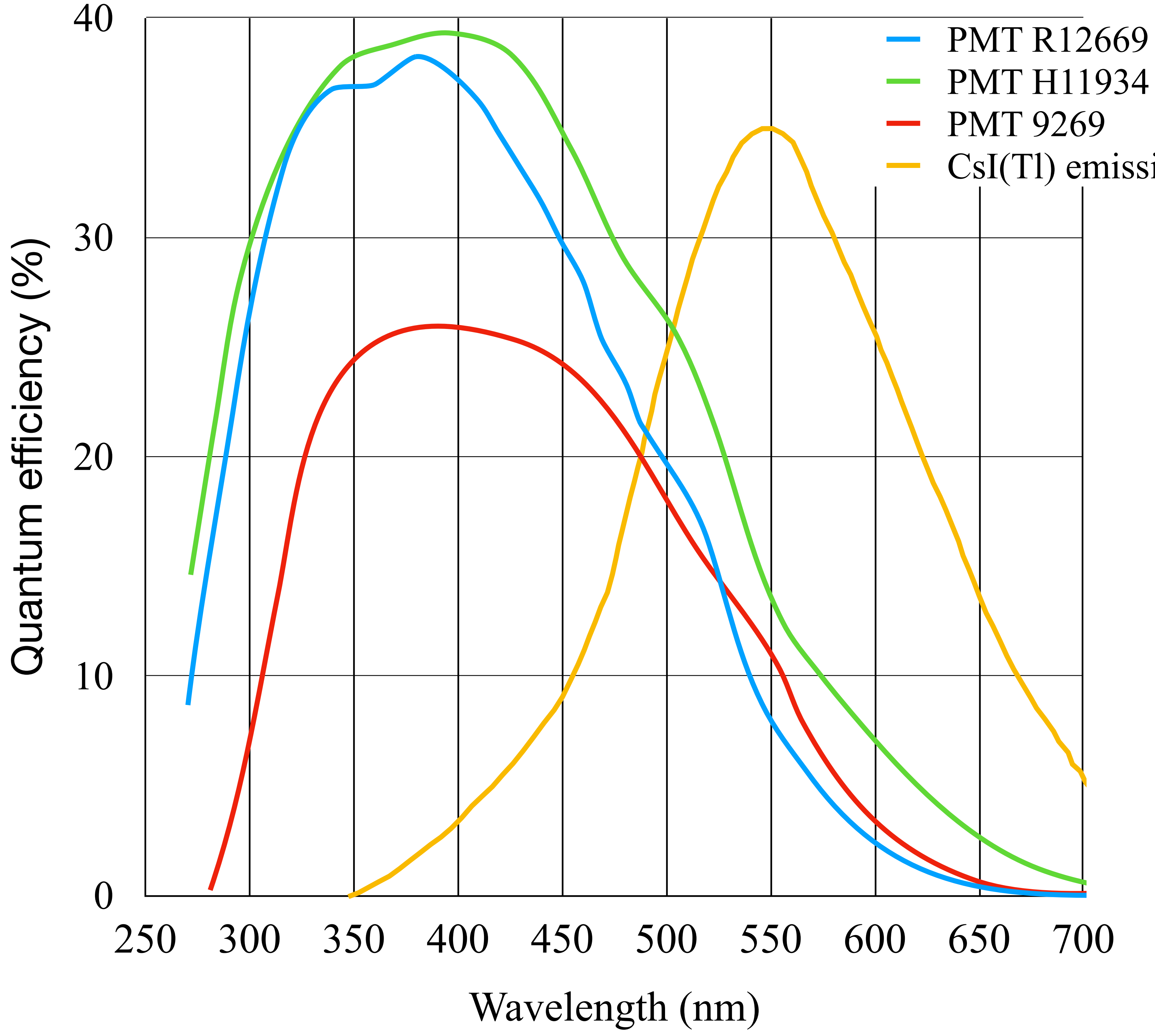
- α and β are fraction of signal (nuclear recoil) and background (electron recoil) passed the event selection.

Quality factor and light yield



- In NaI(Tl), QF improved as the light yield increased.
- When compared at similar light yield, CsI(Tl) shows better QF performance than NaI(Tl)
- Similar to NaI(Tl), a significant improvement is expected for CsI(Tl) with higher light yield.

PMT for light yield improvement

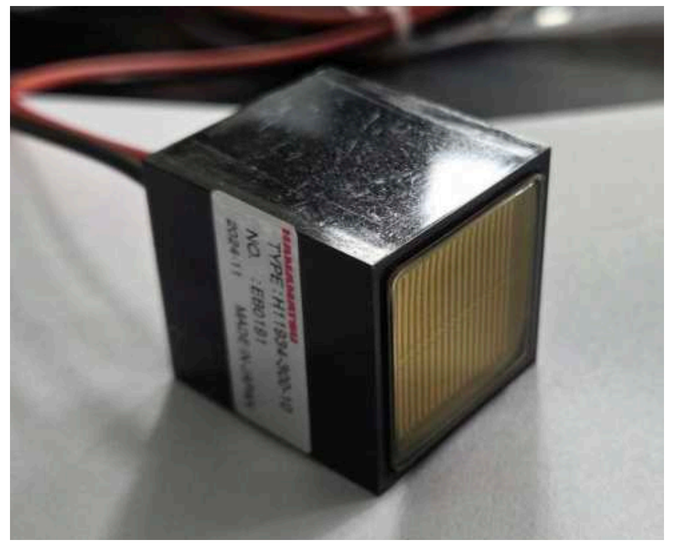


PMT	PMT A	PMT B	PMT C
Manufacturer	Eletrontube	Hamamatsu	Hamamatsu
Cathode	RbCs	SBA	EGBA
Window	Quartz	Borosilicate	Borosilicate
Body	Quartz+Borosilicate	Borosilicate	
Effective area (cm^2)	45.4	38.5	5.3
QE (%) at 500 nm	18	20	25

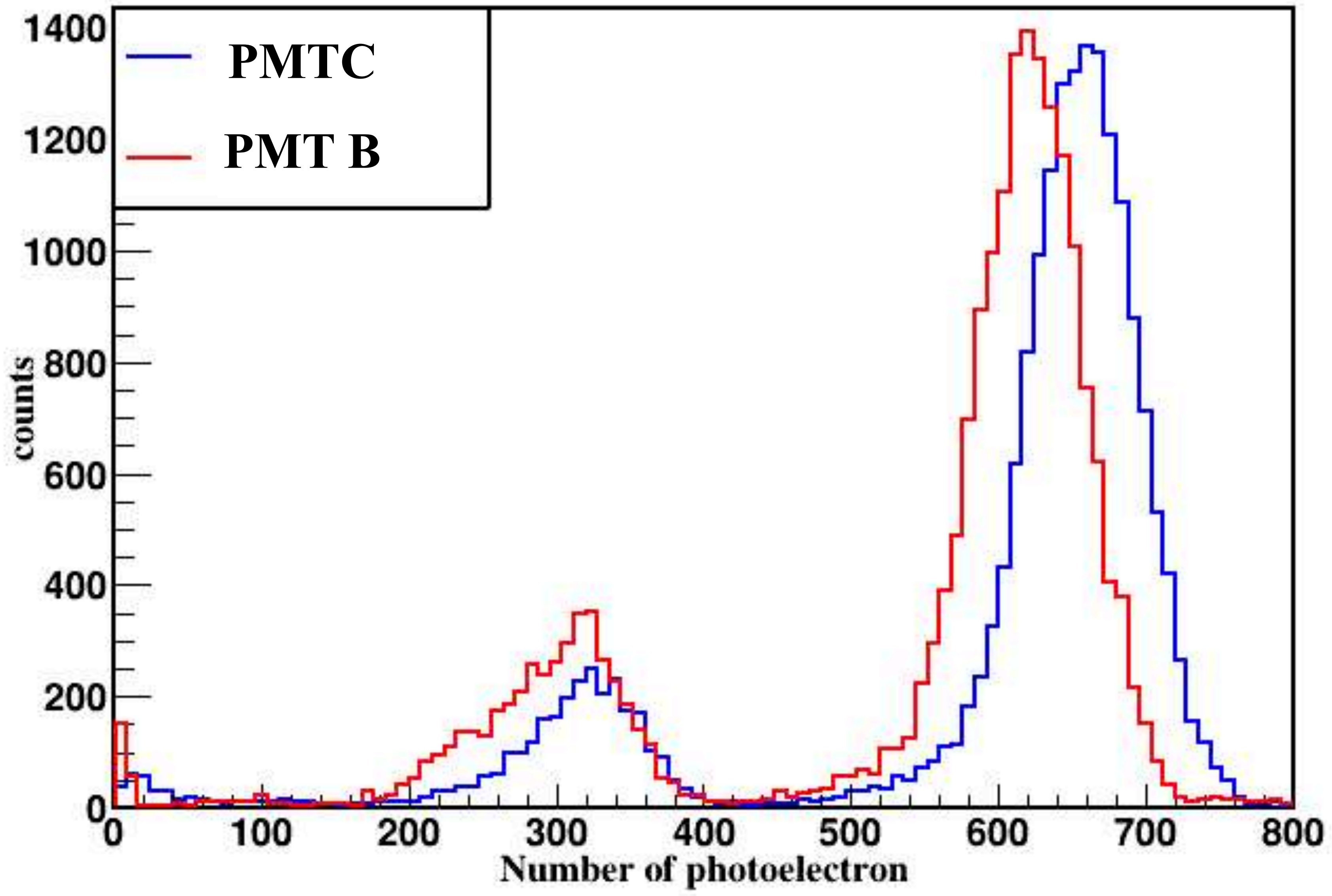
- KMS used enhanced green bialkali PMT, 9269 (PMT A).
- Hamastsu developed super bialkali (SBA) PMT, R12669 (PMT B).
- Extended green bialkali (EGBA) PMT H11934 (PMT C) is developed.
- Since the EGBA PMT show highest quantum efficiency, it is expected to provide highest light yield.

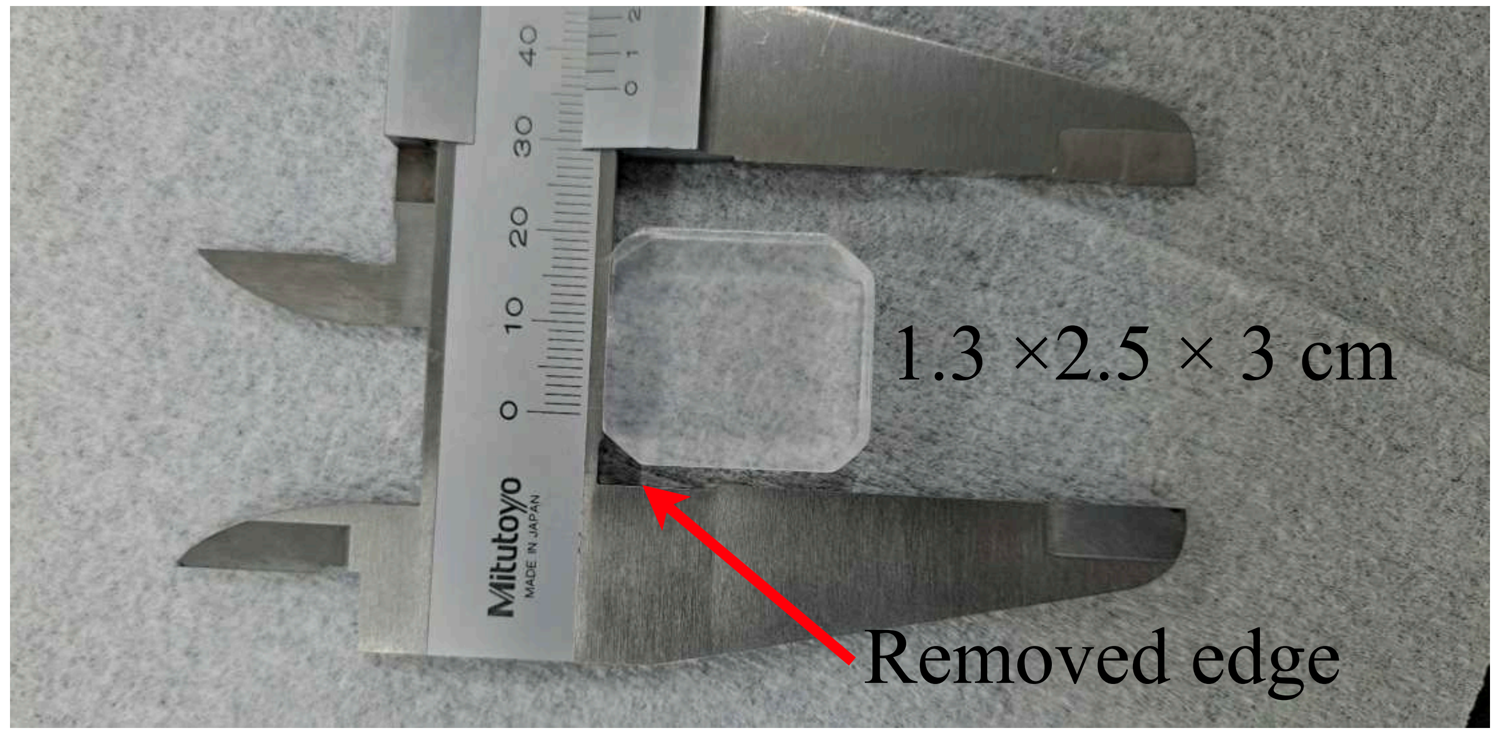

9269, PMT A

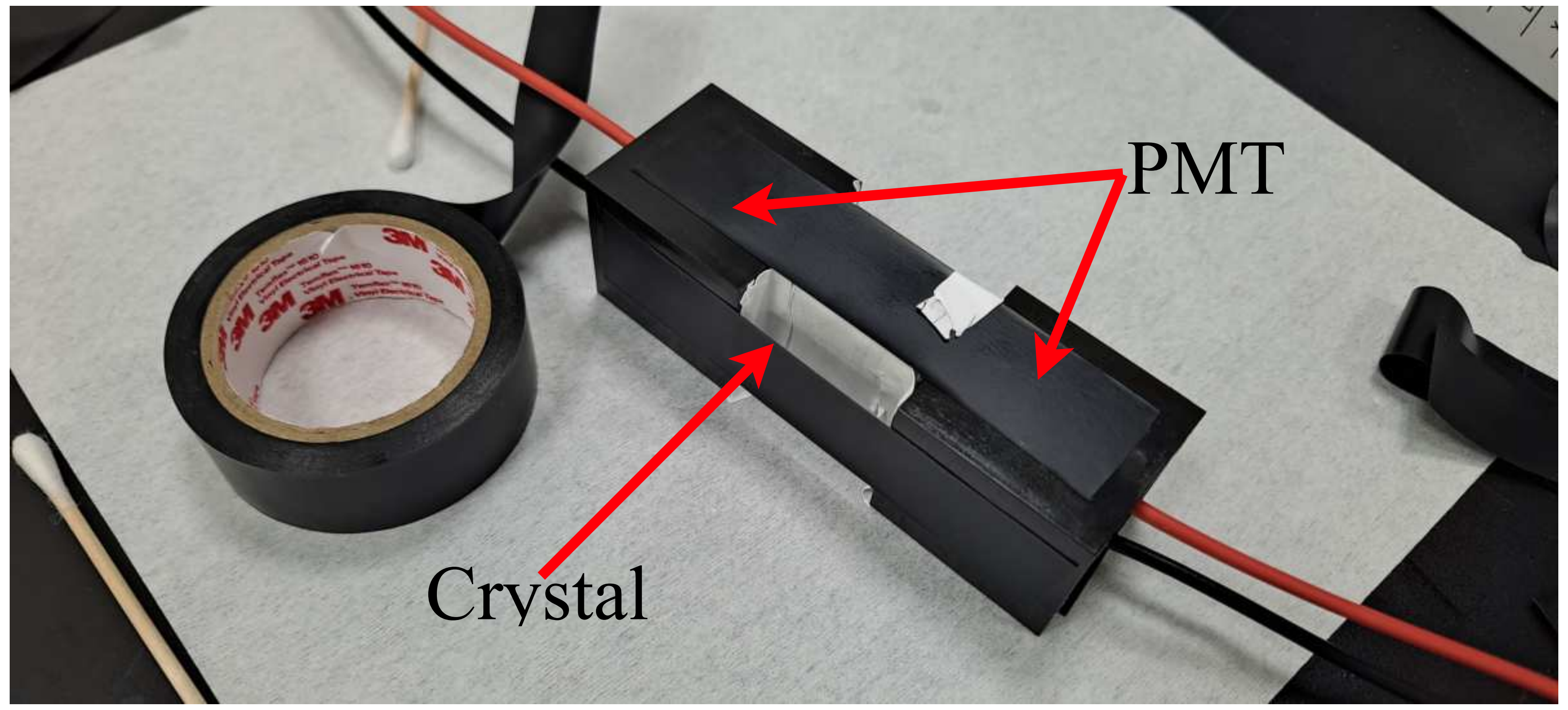

R12669, PMT B


H11934, PMT C

Light yield





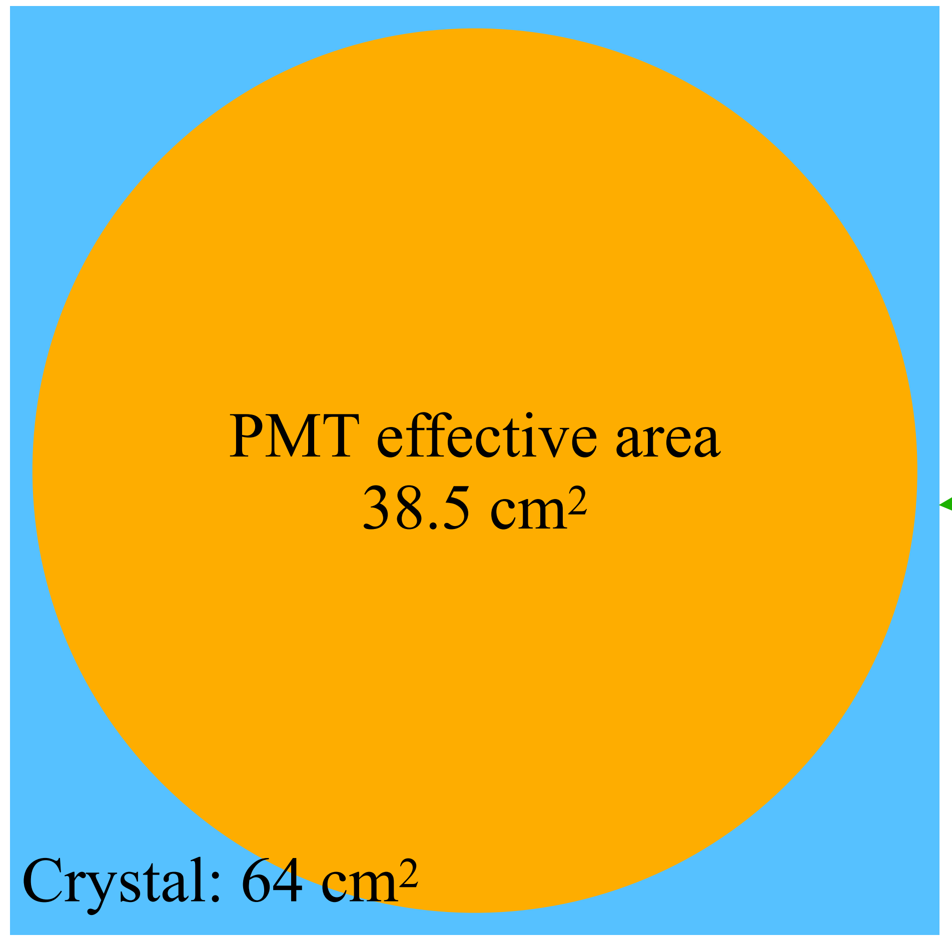


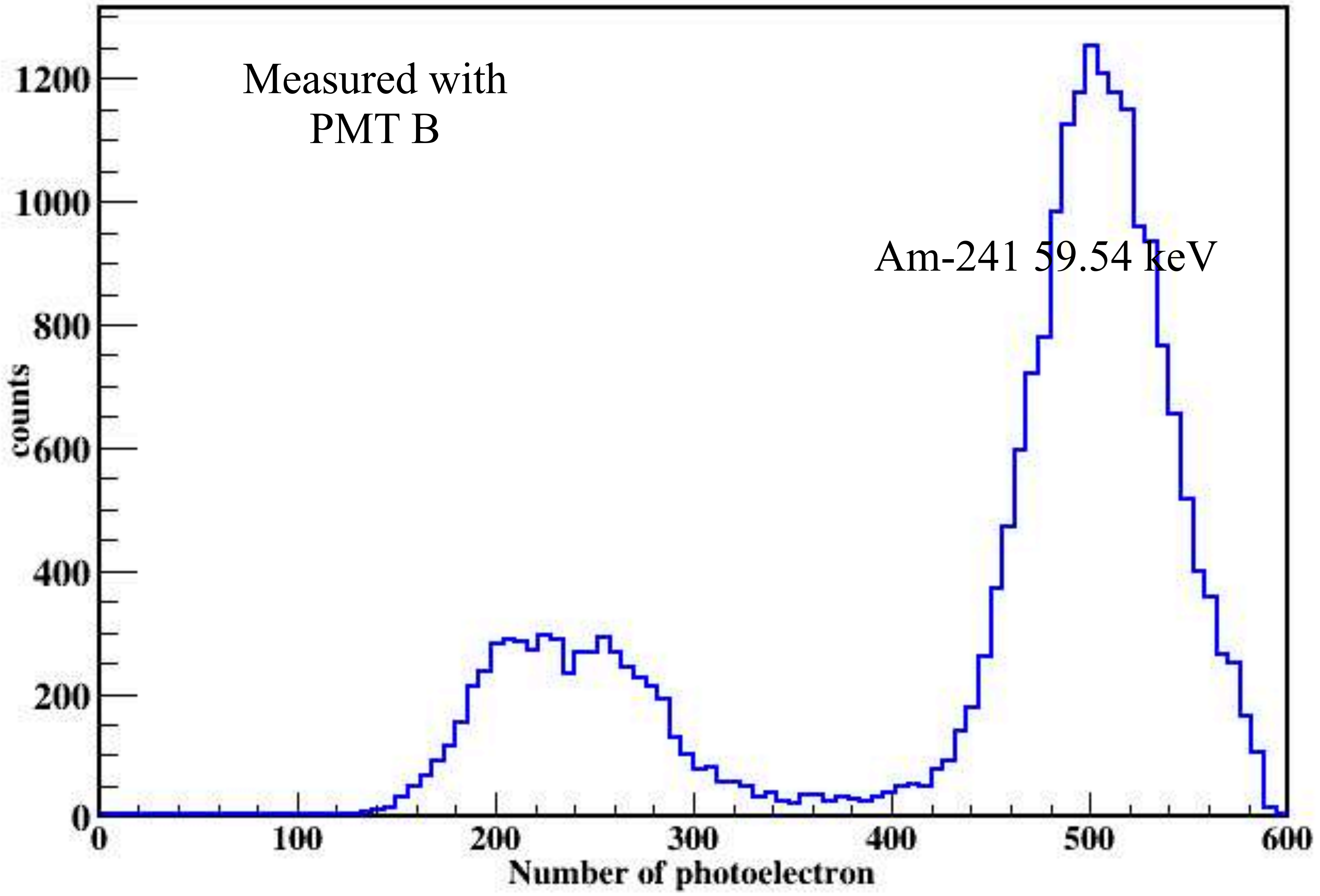
PMT	PE	ER (%)
PMT A*	6.9	7.1
PMT B	10.2±0.3	5.8±1.5
PMT C	11.2±0.3	5.6±1.3

*Measured in different setup.

- CsI(Tl) crystal was assembled with PMT B and PMT C.
- Am-241 source is used.
- Since the crystal surface was larger than the PMT's effective area, the edges were trimmed to minimize light loss.
- Light yield: 10.2 (PMT B), 11.2 (PMT C)
- Compare to the PMT A, the light yield is improved more than 35%.

Light yield



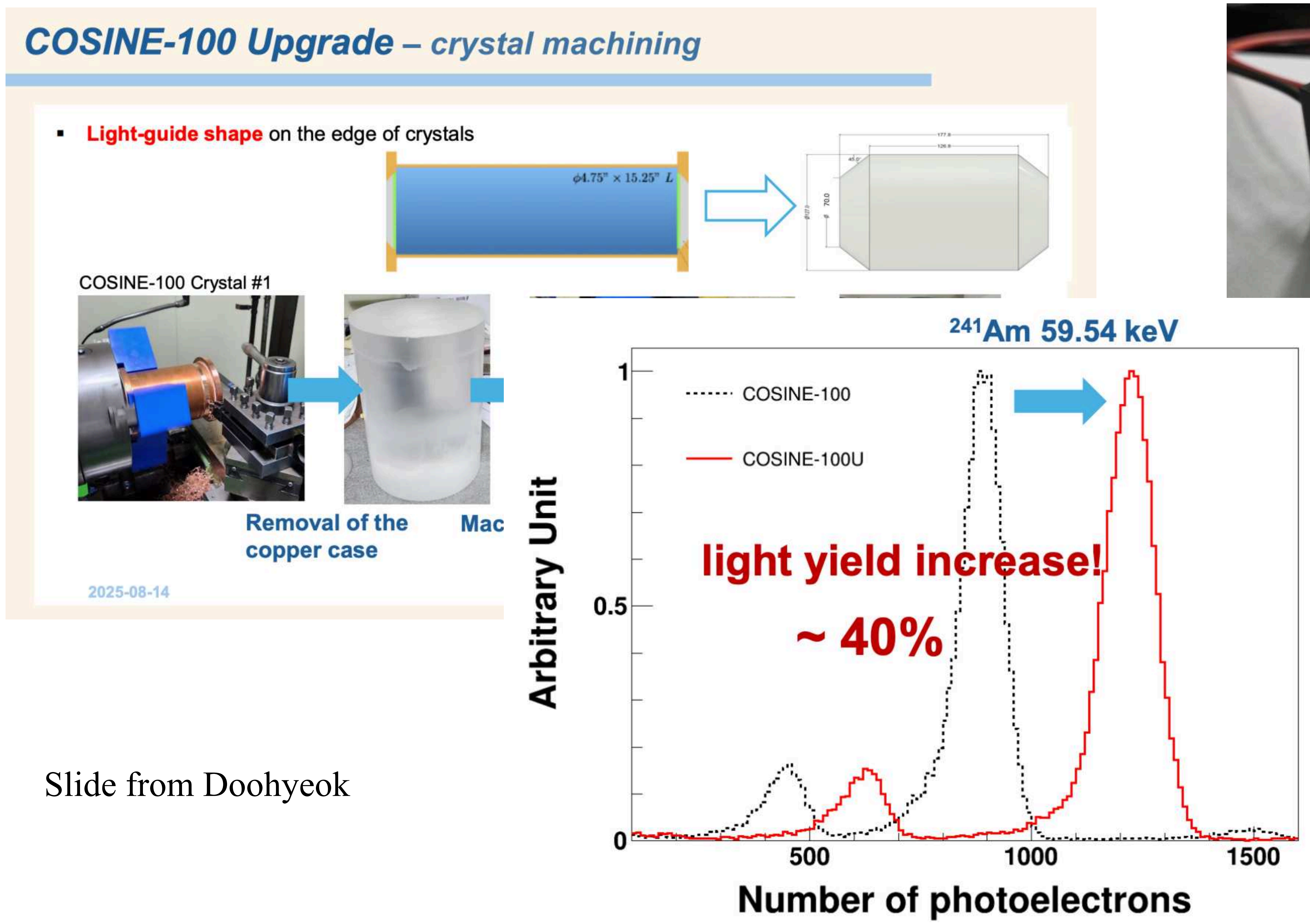


PMT	PMT A*	PMT B
LY	5	8.5

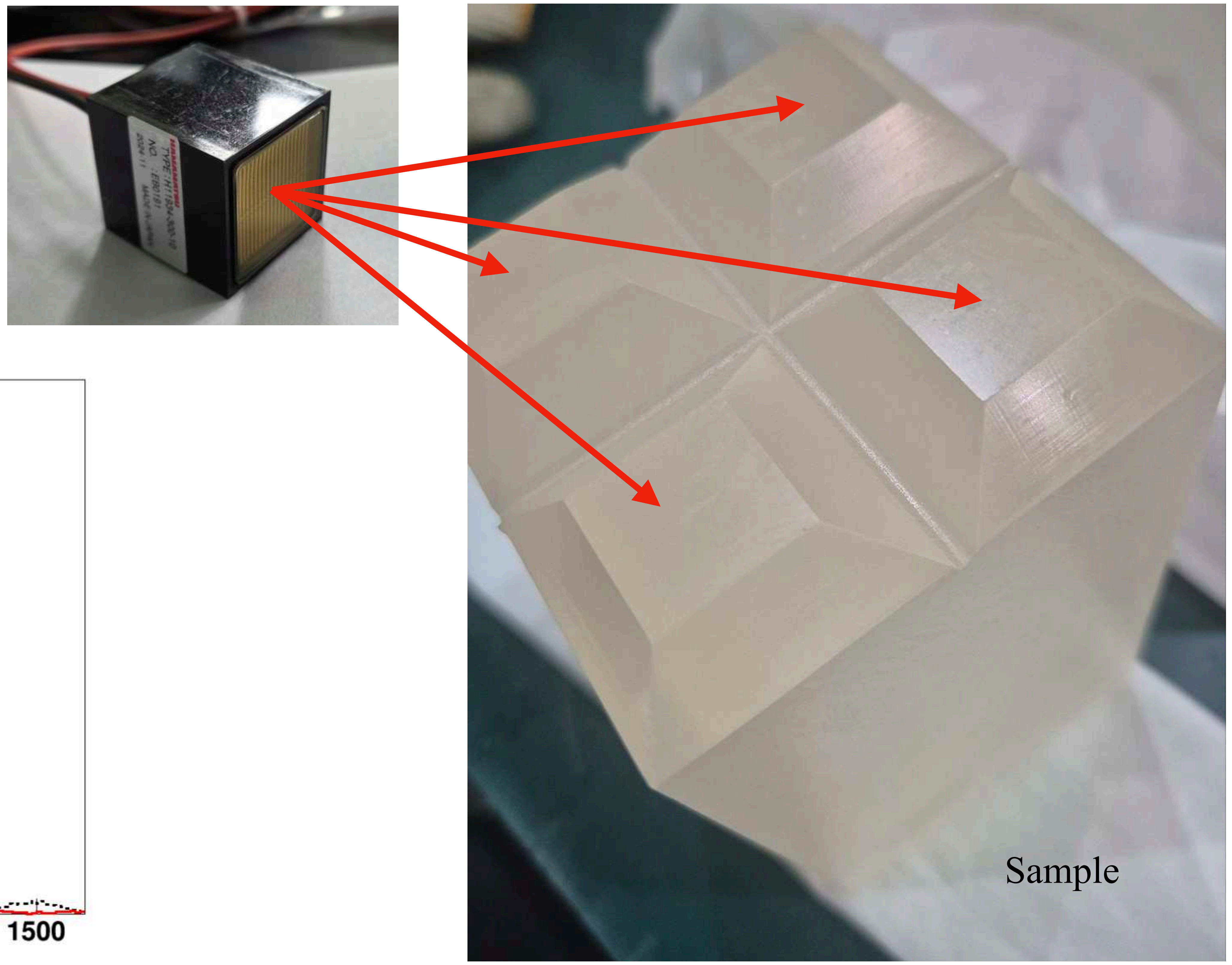
*Measured in different setup.

- Bring one CsI(Tl) crystal used in KIMS for test. 2 PMT B are assembled.
- Compare with the PMT A result, PMT B light yield increased about 40 %.
- PMT effective area covered about 60% of crystal surface, which may cause light loss.

Crystal machining



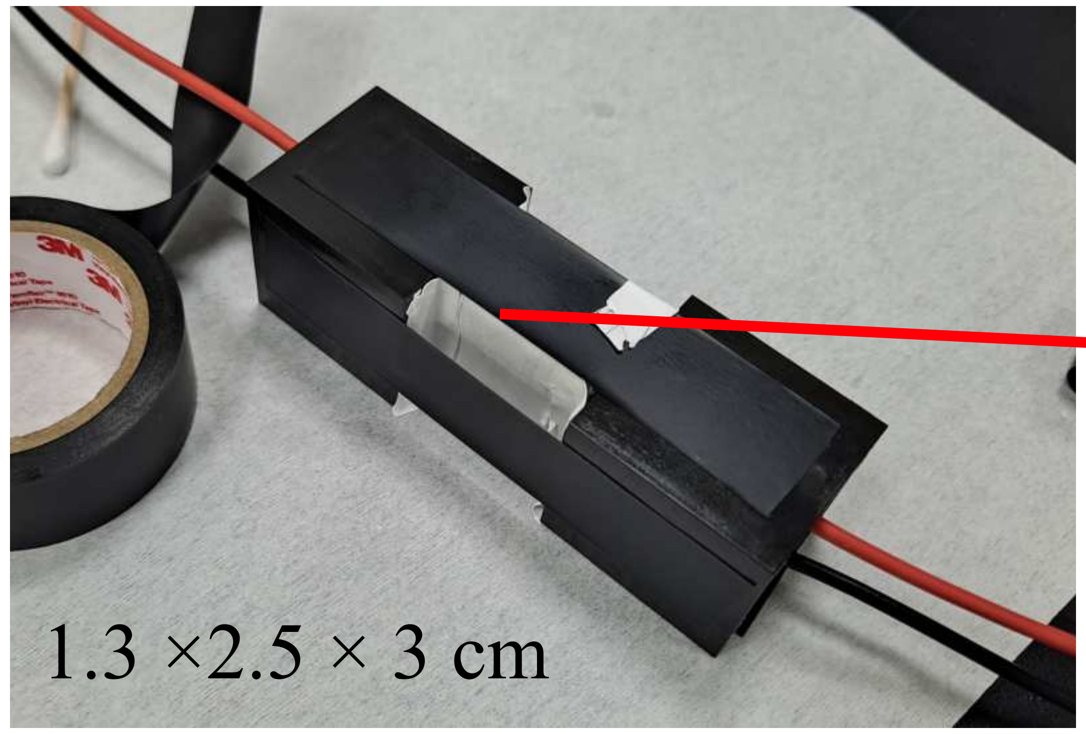
Slide from Doohyeok



Sample

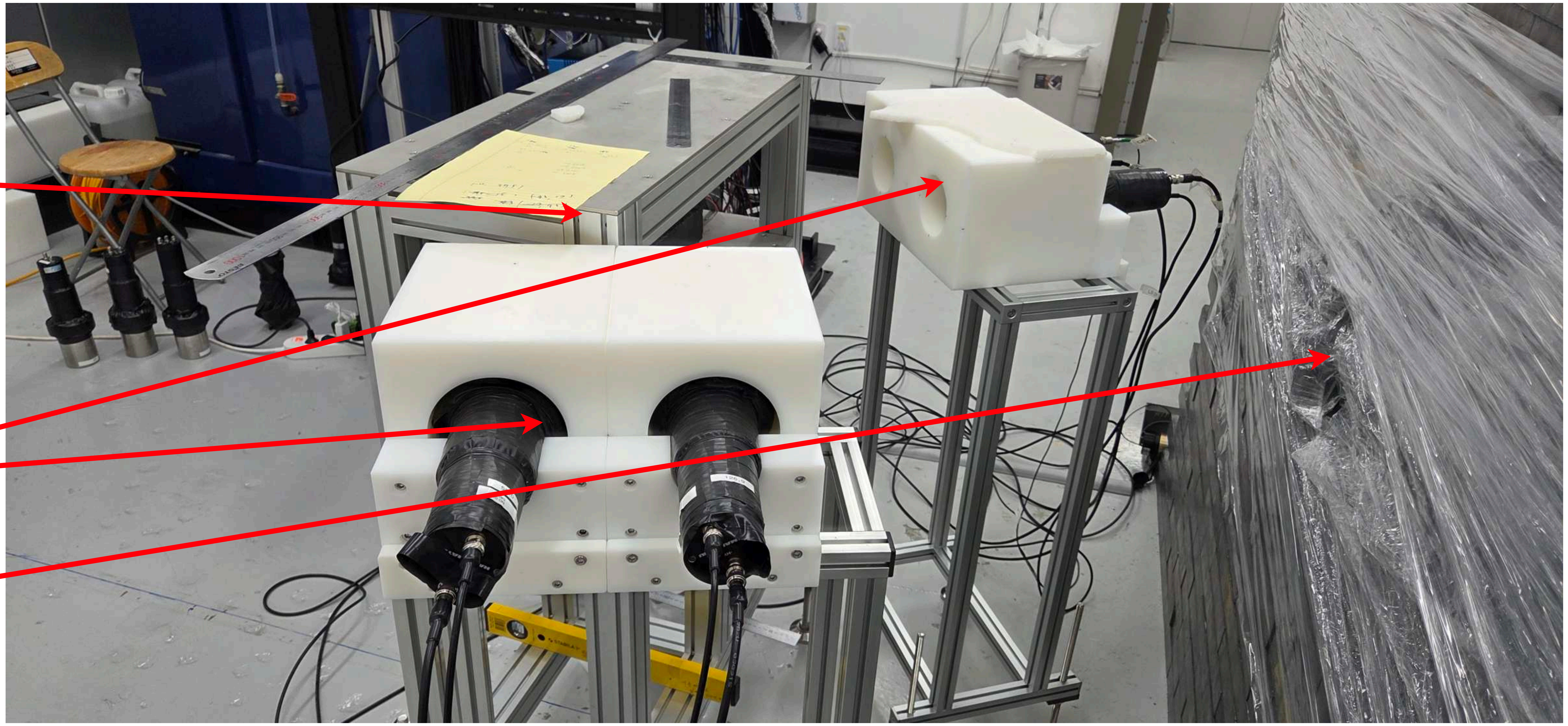
- Total 8 PMT C will be assembled to the CsI(Tl) crystal.
- Since the PMT effective area is smaller than the crystal surface, the CsI(Tl) crystal will be machined so that its edges act as a light guide.
- A similar method was applied in COSINE-100U, where an increase in light yield was reported after the processing.

PSD measurement with Neutron generator



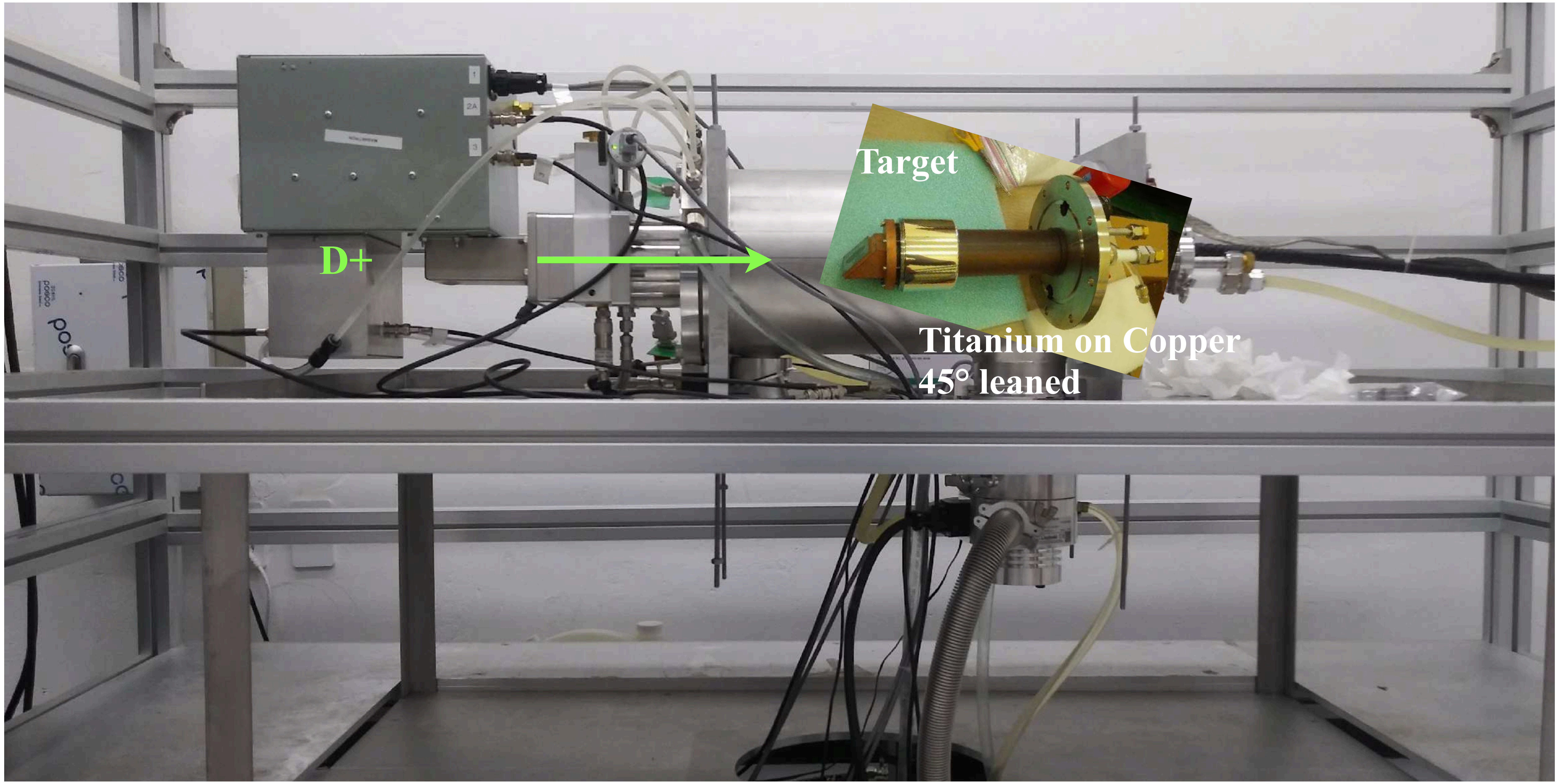
Neutron detector

Neutron generator



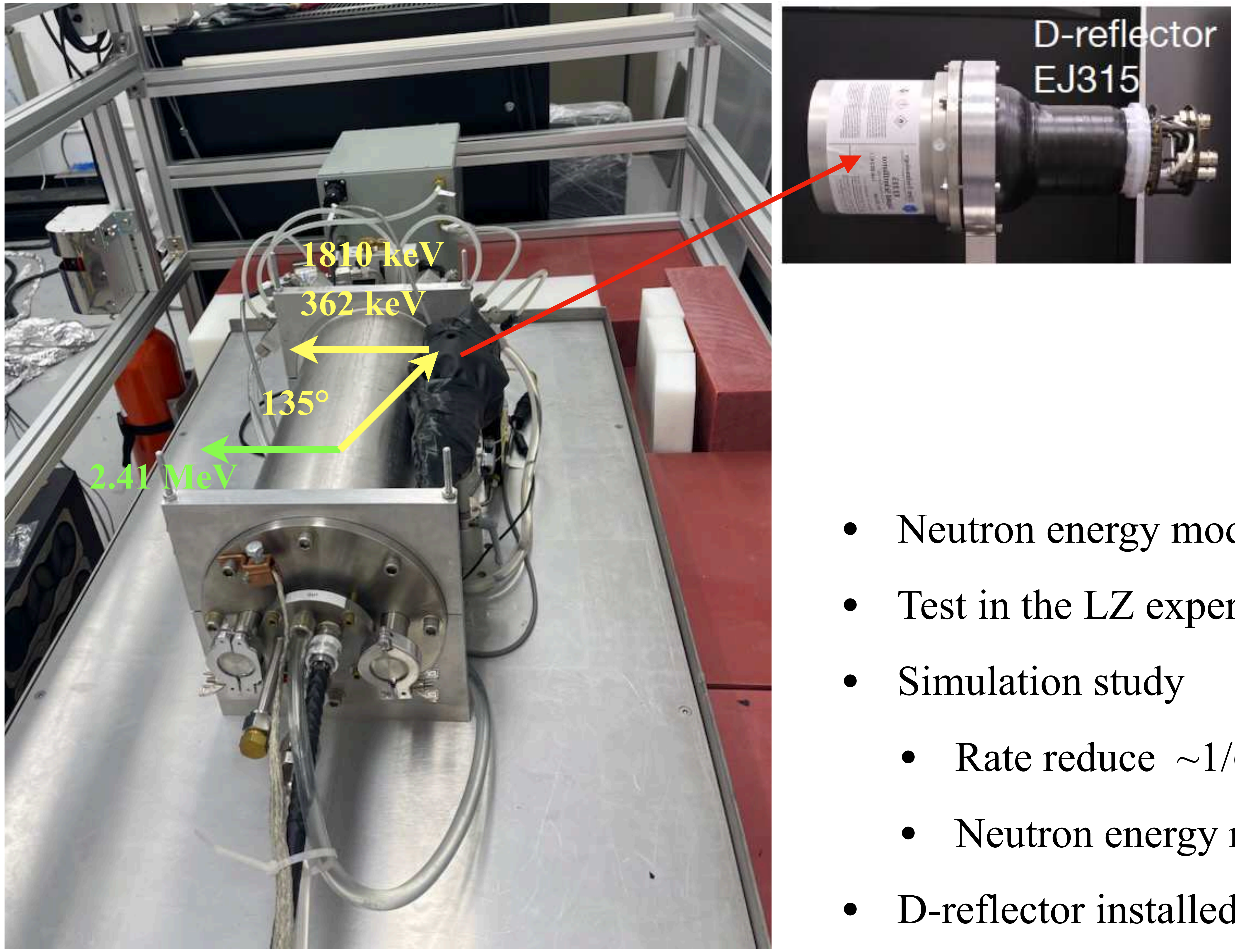
- To evaluate PSD performance, nuclear recoil (NR) events must be measured.
- A neutron generator setup is being prepared to measure NR events.
- Four liquid scintillator (LS) detectors are arranged around the CsI(Tl) crystal to tag scattered neutrons.

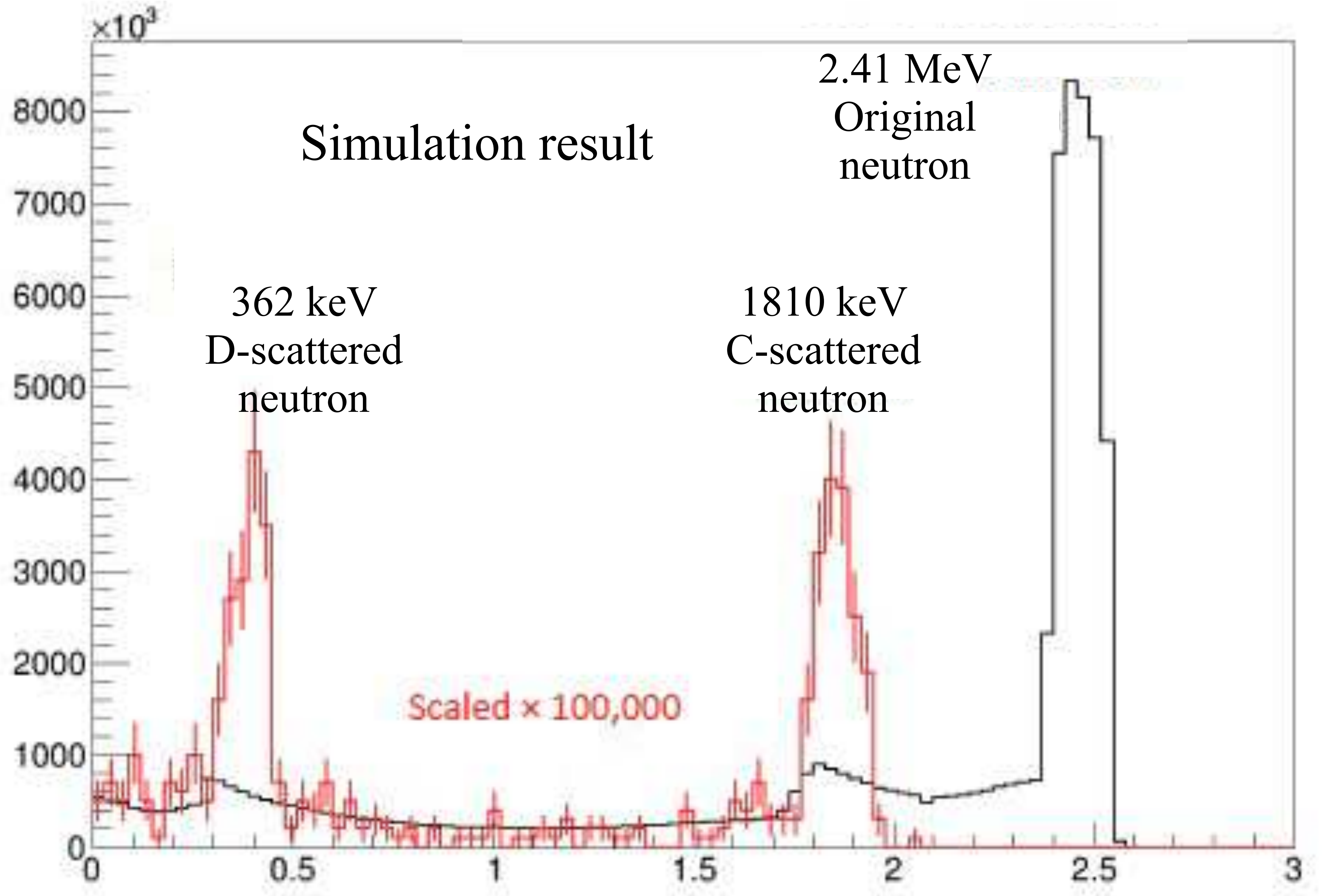
Neutron Generator



- Model: Adelphi technology DD-109.
- D + D → He-3 + n. Neutron energy 2.41 MeV monoenergetic neutrons.
- Neutron rate: up to 10^{10} n/s → reduction is required to measure a scintillator has long decay time.

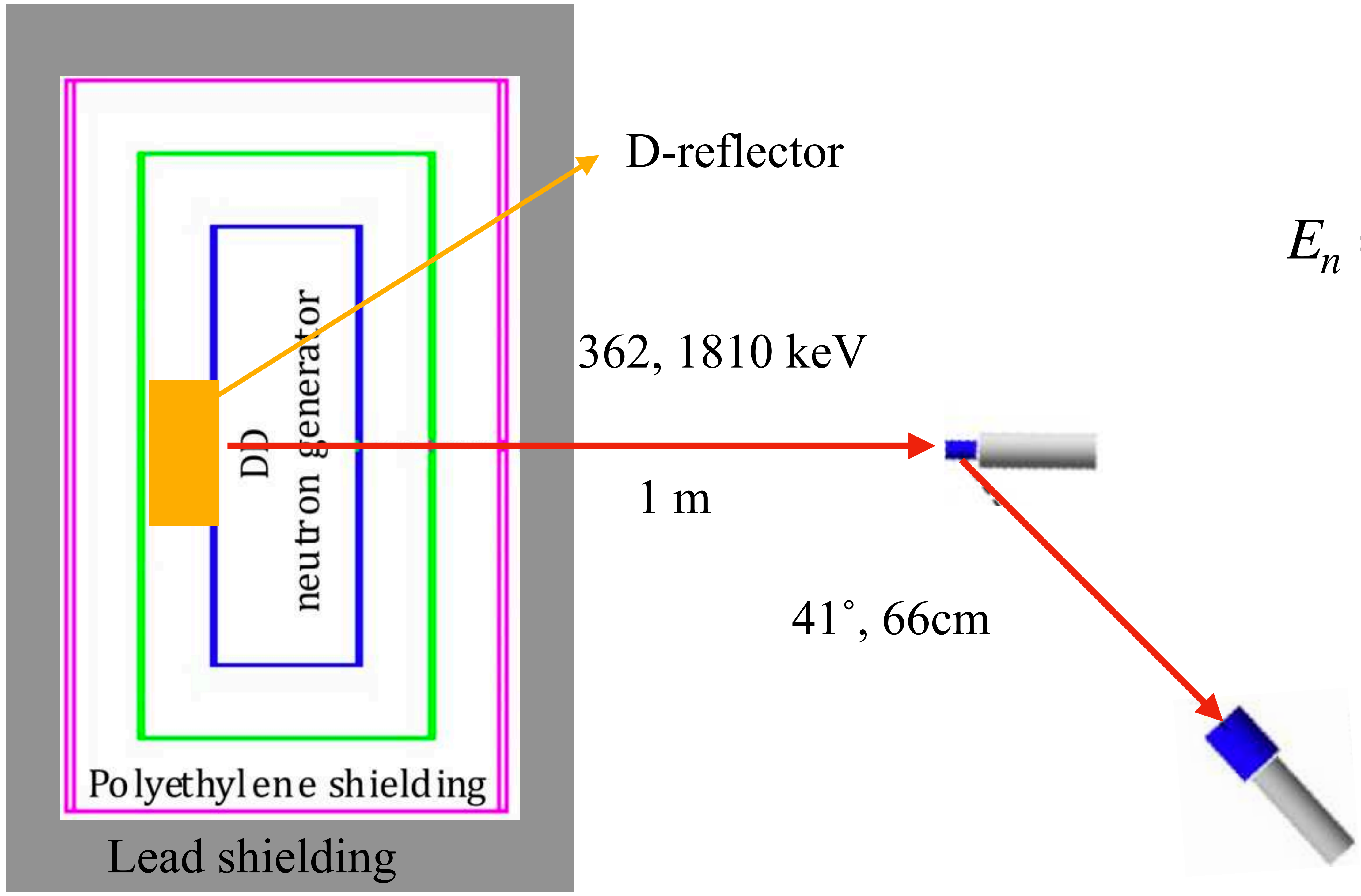
D-reflector



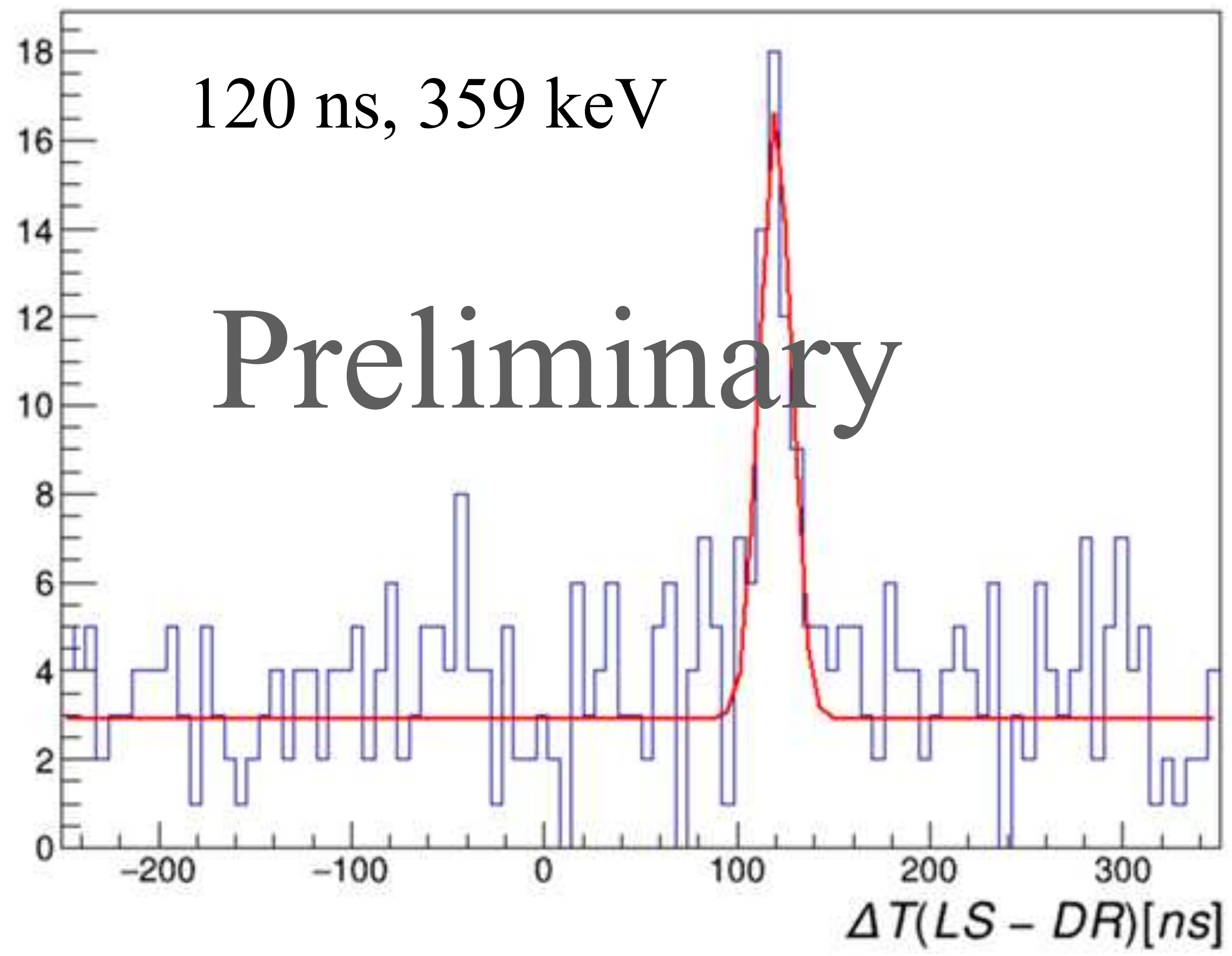


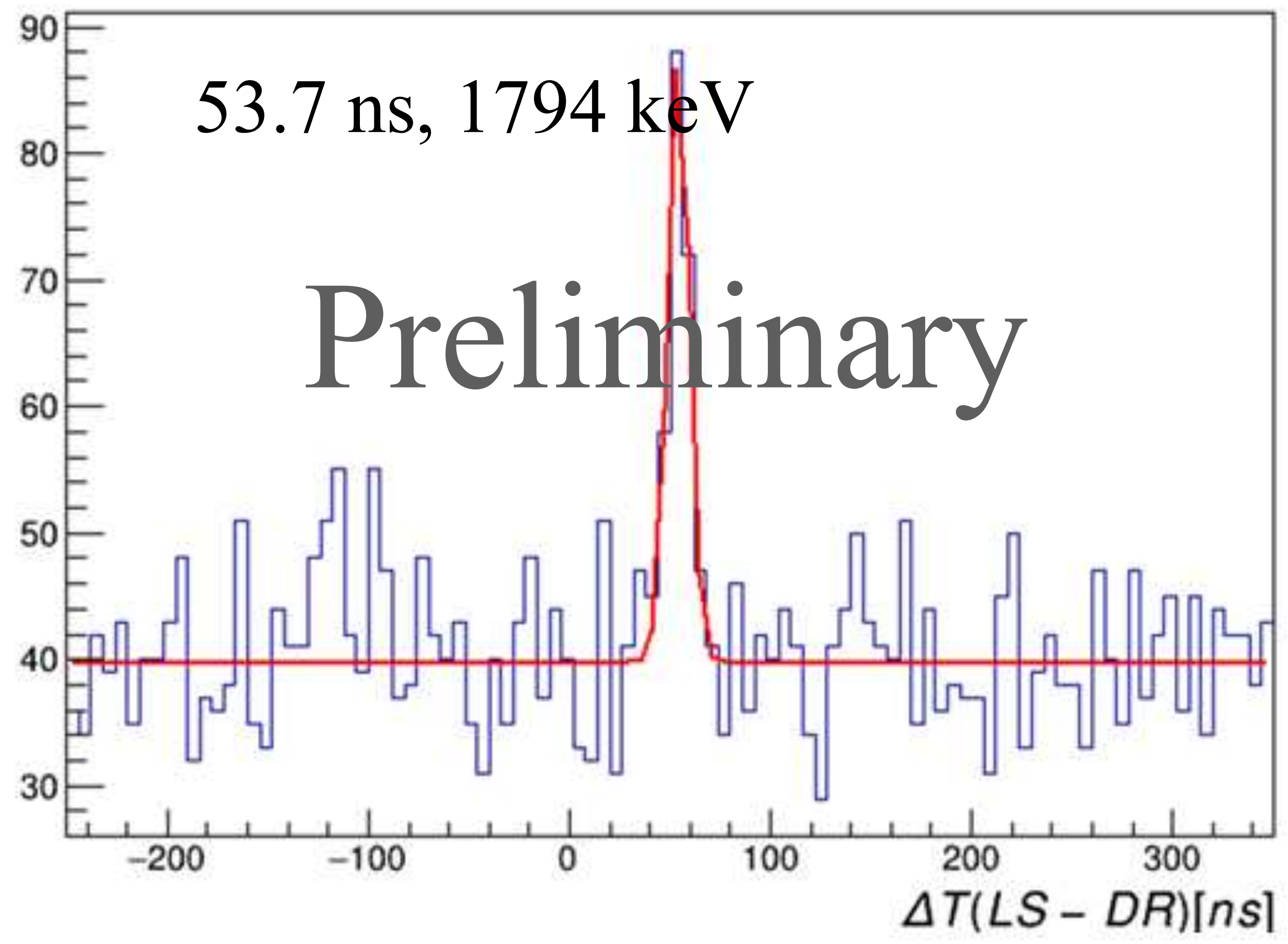
- Neutron energy moderated through liquid scintillator (deuterated benzene).
- Test in the LZ experiment: Deuterium reflector (D-reflector).
- Simulation study
    - Rate reduce ~1/60
    - Neutron energy reduce about 362, 1810 keV
- D-reflector installed near the generator.

low energy neutron



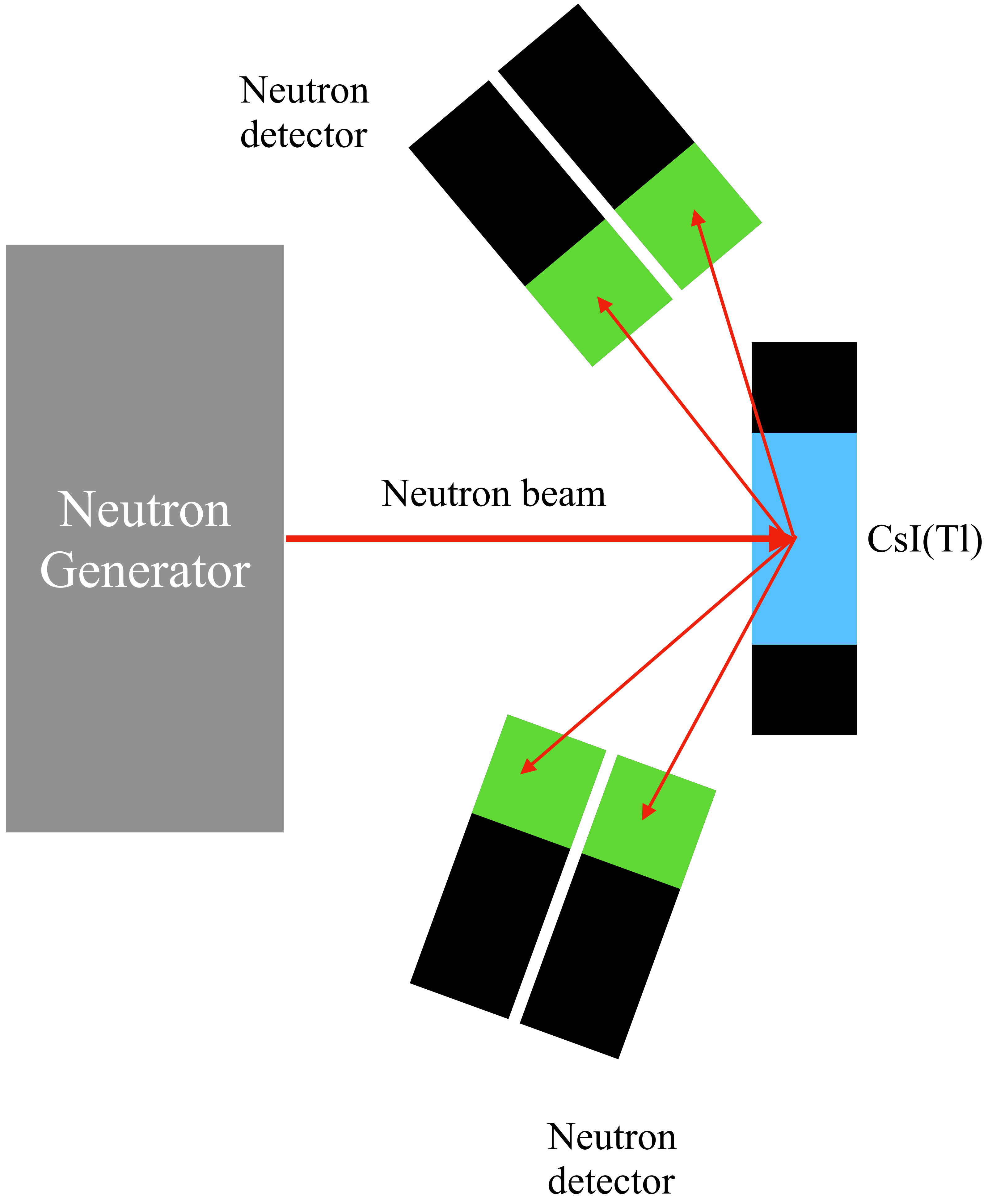
$$E_n = \frac{M_n}{2}\left(\frac{d}{\Delta t}\right)^2$$





- Neutron energy was measured using the time-of-flight (TOF) between the D-reflector and LS1.
- Time of flight measurement agreed with the expected reduced neutron energy.
- Low energy neutron can be measured by using D-reflector.

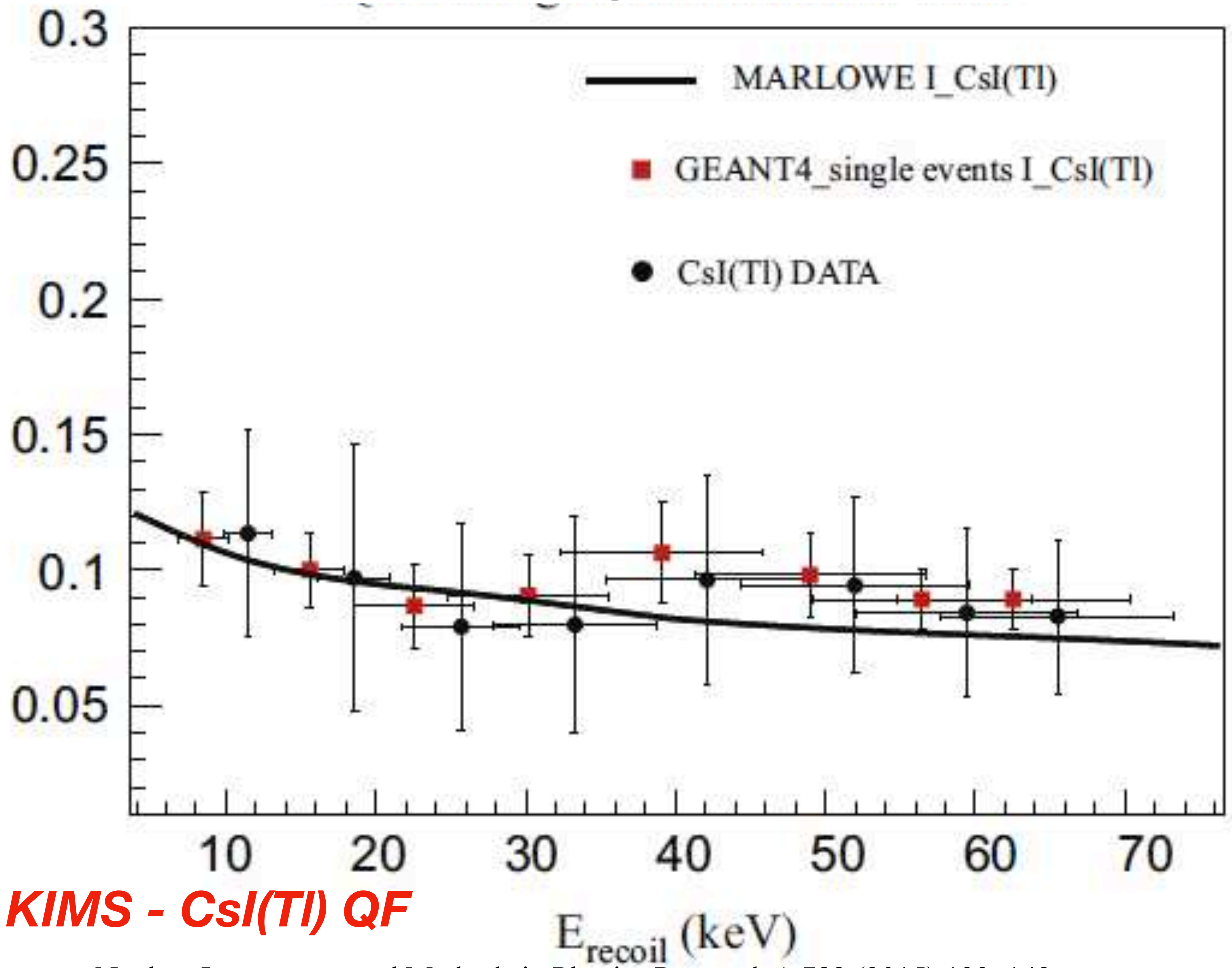
Expected neutron energy



	1810 keV		2410 keV	
	keVnr	keVee	KeVnr	keVee
80	23.09	2.31	30.75	3.07
90	27.91	2.79	37.16	3.72
100	32.71	3.27	43.55	4.35
120	41.70	4.17	55.52	5.55
135	47.38	4.74	63.08	6.31
150	51.72	5.17	68.87	6.89
160	53.74	5.37	71.55	7.15
170	54.97	5.50	73.19	7.32

- Assuming quenching factor of 0.1, PSD can be measured at 2 keV.
- Using D-reflector, lower neutron energy can be reached.

Quenching factor



KIMS - CsI(Tl) QF

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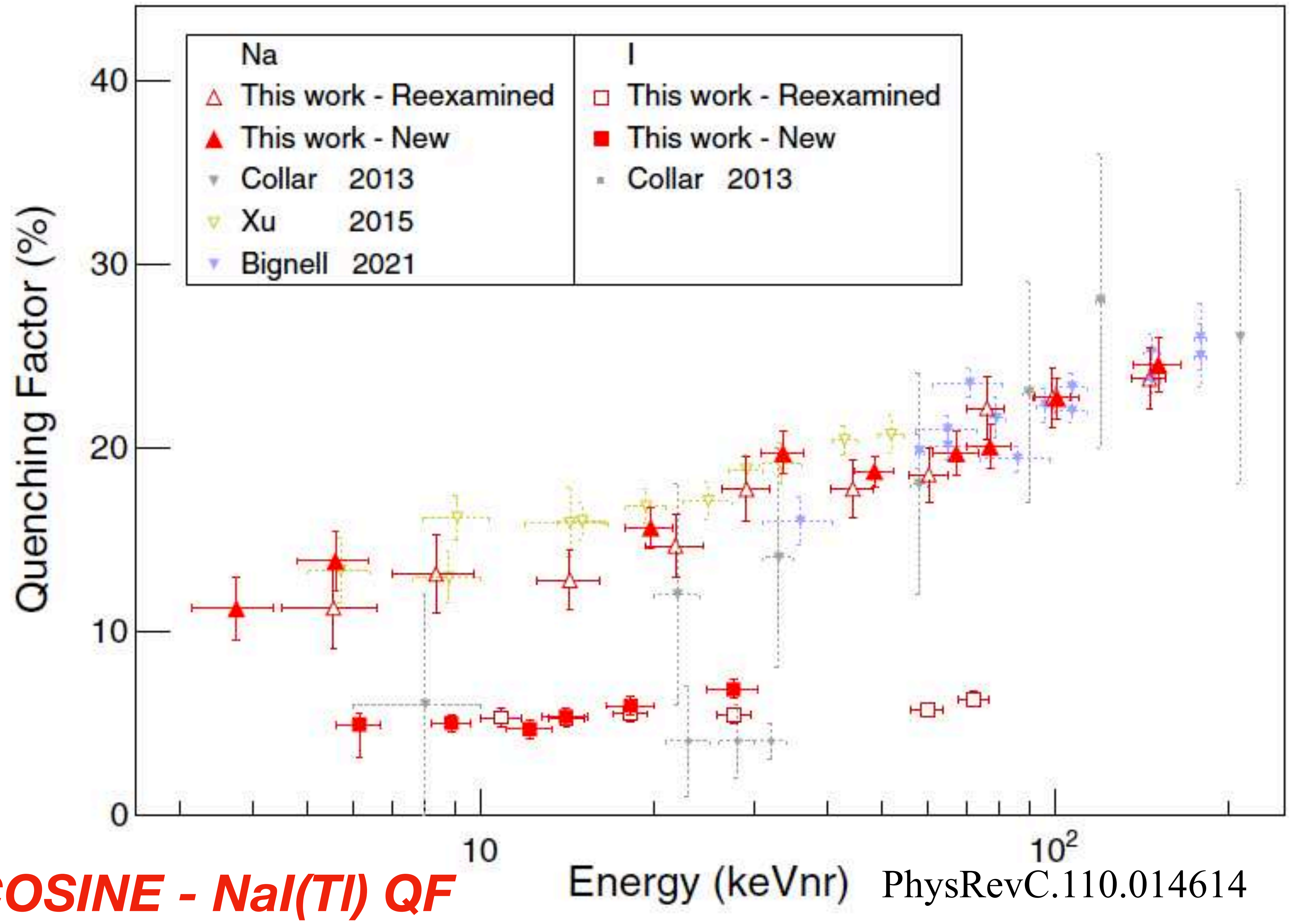

COSINE - NaI(Tl) QF

PhysRevC.110.014614

$$Q = \frac{E_{ER}}{E_{NR}}$$

- CsI(Tl) quenching factor had been measured only above 10 keV.
- In this setup, the iodine quenching factor was measured at ~6 keV.
- The setup is expected to enable CsI(Tl) quenching factor measurement at even lower energies.

Summary

- ✓ Extended green bialkali PMT shows the highest light yield when assembled with CsI(Tl).

- ✓ Neutron generator setup preparation is in progress, which will allow studies PSD performance in the low energy region and may also enable quenching factor measurement.