Scintillation Characteristics of an Undoped CsI Crystal with SiPM Readout for Dark Matter Detection

Won Kyung Kim[1,2], Hyeyoung Lee[3], Kyungwon Kim[2], Hongjoo Kim[4] and Hyunsu Lee [2,1]

[1]IBS School, University of Science and Technology (UST), Daejeon, Republic of Korea
[2]Center for Underground Physics, Institute for Basic Science (IBS), Daejeon, Republic of Korea
[3]Center for Exotic Nuclear Studies, Institute for Basic Science (IBS), Daejeon, Republic of Korea
[4]Kyungpook National University, Daegu, Republic of Korea

Motivation

- NaI and CsI crystals are being used with photomultiplier tube (PMT) in dark matter search experiment. Absolute light yield of **COSINE-100 (NaI(Tl))** is 15 photoelectron(PE)/keV and **KIMS (CsI(Tl))** is 5-6 PE/keV.

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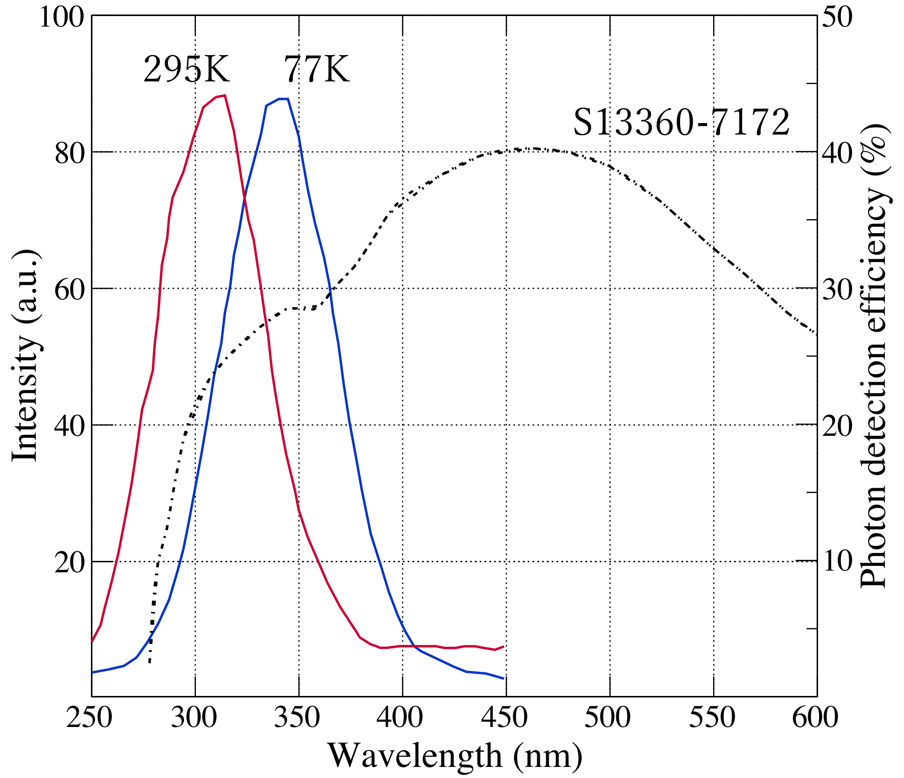
- It has been reported that the high absolute light yields of CsI crystals at liquid nitrogen temperature (77 K) are above 80,000 photons/MeV.
- There are some results about operation of **pure CsI with SiPM at 77 K**. One of the results got light yield of **43.0 PE/keV** without considering cross-talk and the other results is **30.1 PE/keV** using wavelength shifter.
  Liu et al. Eur. Phys. J. C (2022) 82:344, Wang et al. Eur. Phys. J. C (2024) 84:440

Silicon Photomultipliers

➢ **Emission spectrum of pure CsI and PDE of SiPM**

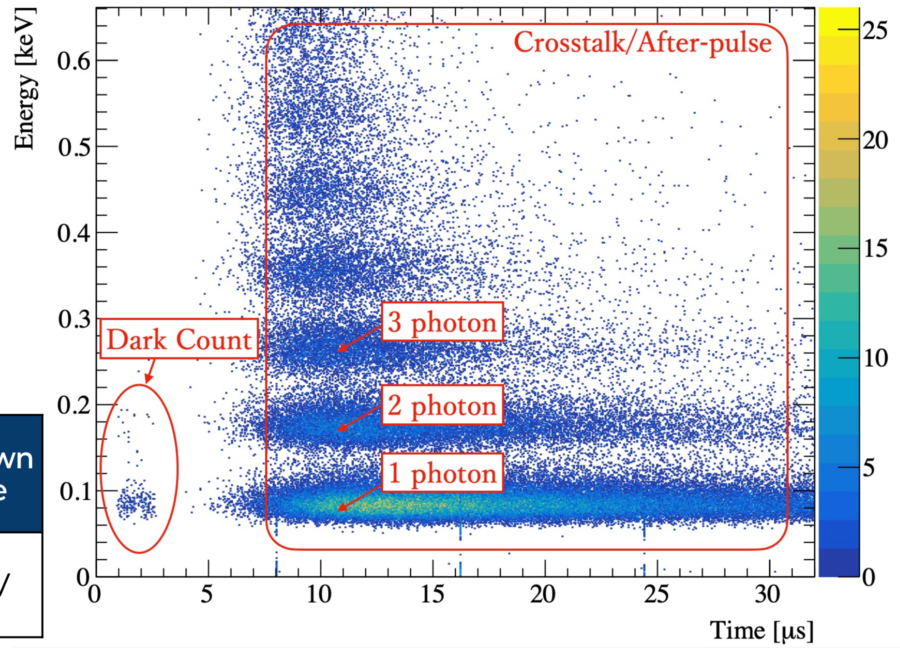


Main Features :

- Signals are countable
- Silicon is radiopure
- High gain
- Compact size

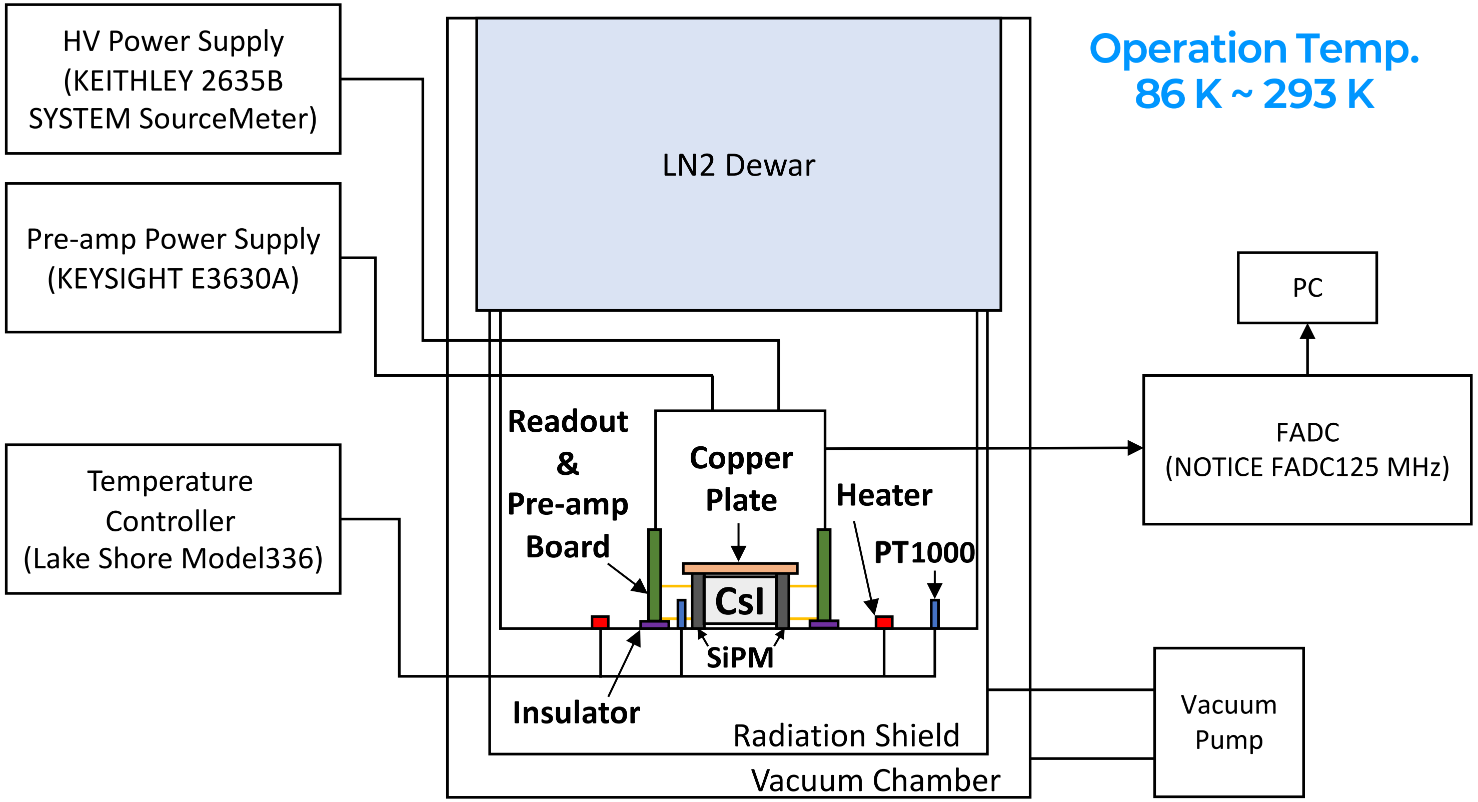
Noise source :

- Dark Count Rate
- Optical cross-talk
- After-pulse

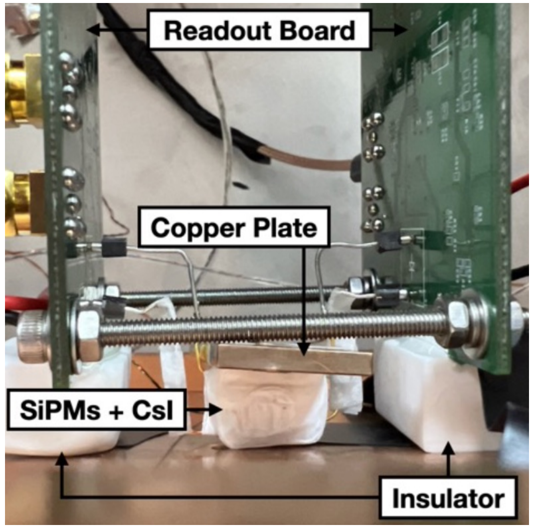


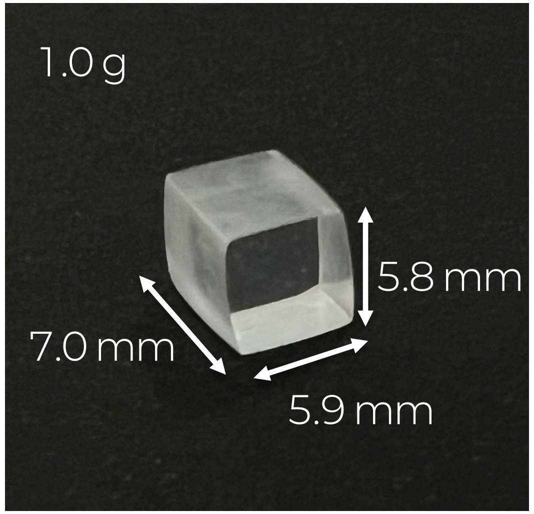
Type no.	Pixel pitch	Window material	Light sensitive area	Number of pixels	Gain	Photon Detection Efficiency	Dark Count @ 25 ℃	Breakdown Voltage
S13360-7172	50 μm	Quartz	6 × 6 mm^2	120 × 120	1.7 × 10^6	40%	500 kHz	54.27 V

Experimental Setup



Operation Temp.
86 K ~ 293 K





- Turbo pump maintained the vacuum inside the chamber.
- We fill up the tank with liquid nitrogen to cool down.
- Two temperature sensors (PT1000) and heaters were used for monitoring and controlling the temperature.

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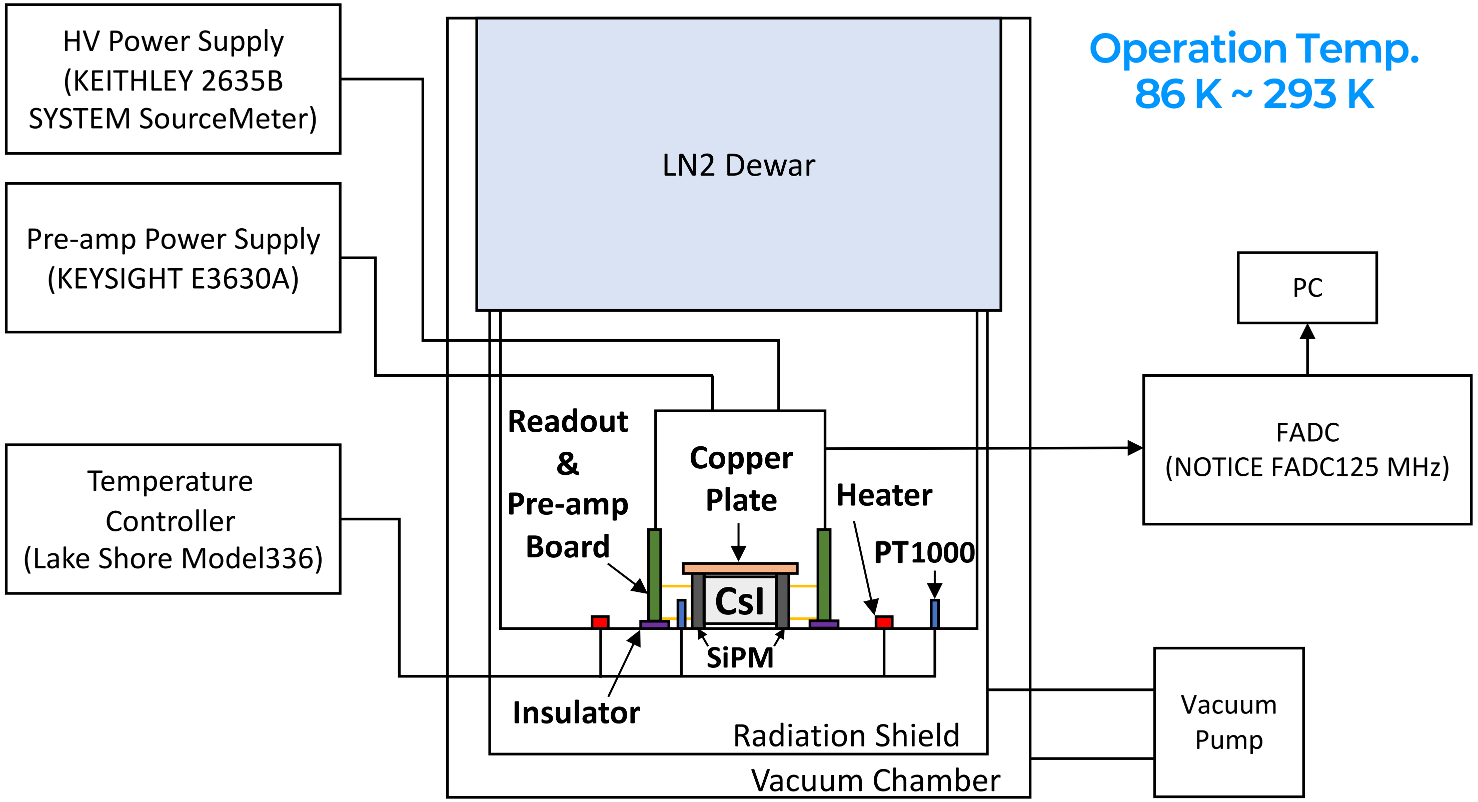

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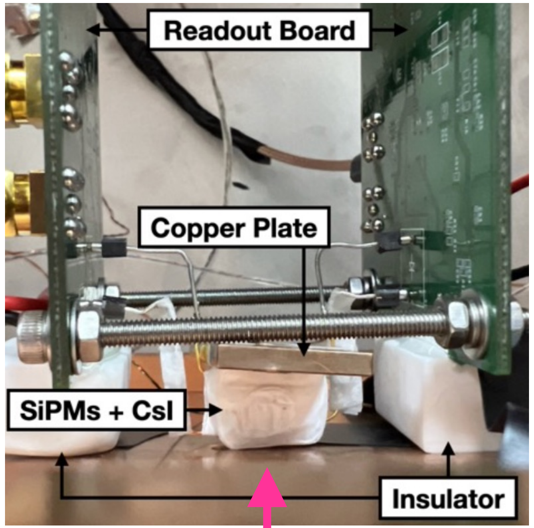

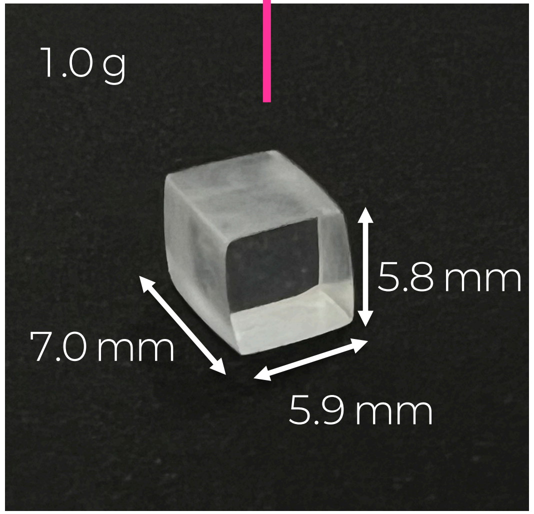

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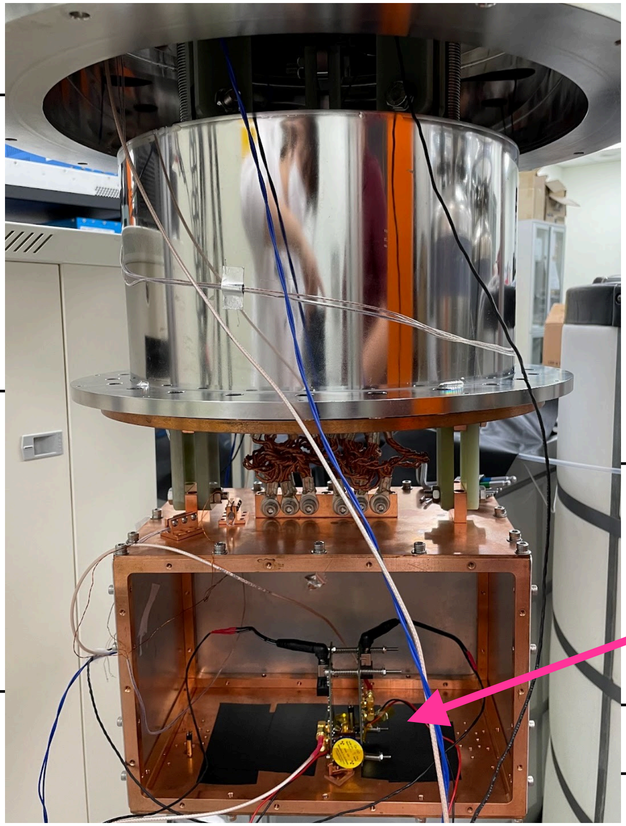
Experimental Setup

HV Power Supply (KEITHLEY 2635B SYSTEM SourceMeter)

Pre-amp Power Supply (KEYSIGHT E3630A)

Temperature Controller (Lake Shore Model336)

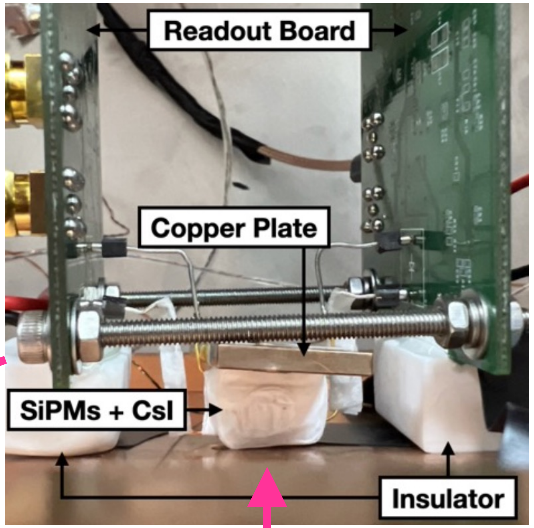


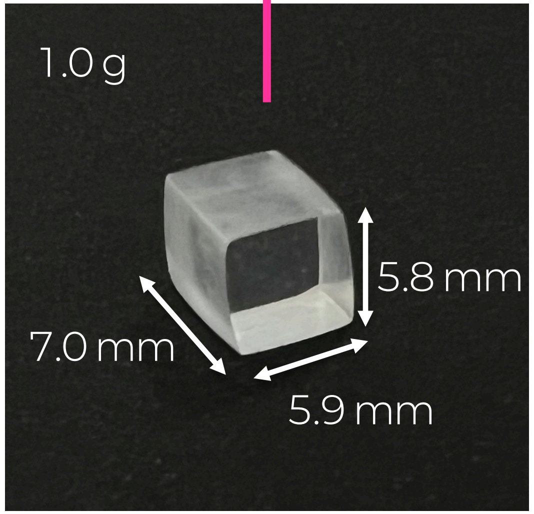
Operation Temp.
86 K ~ 293 K

PC

FADC (NOTICE FADC125 MHz)

Vacuum Pump





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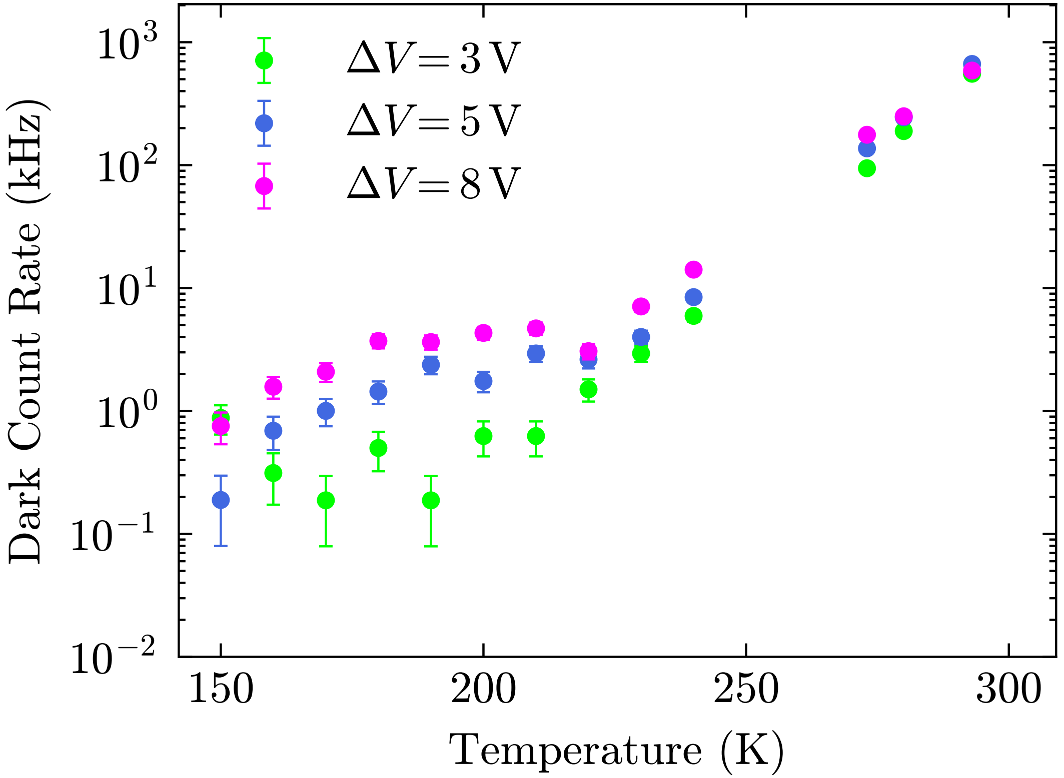
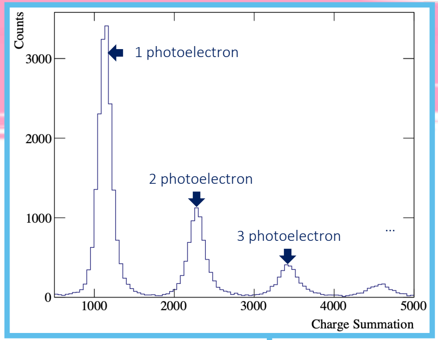
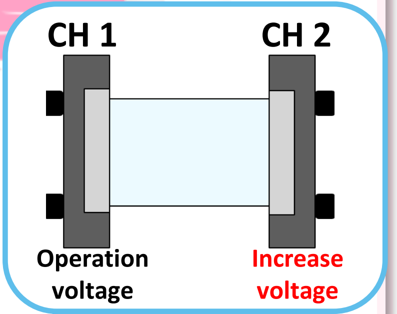
Measurements & Results

➢ Dark Count Rate (DCR)







➢ Cross-talk probability

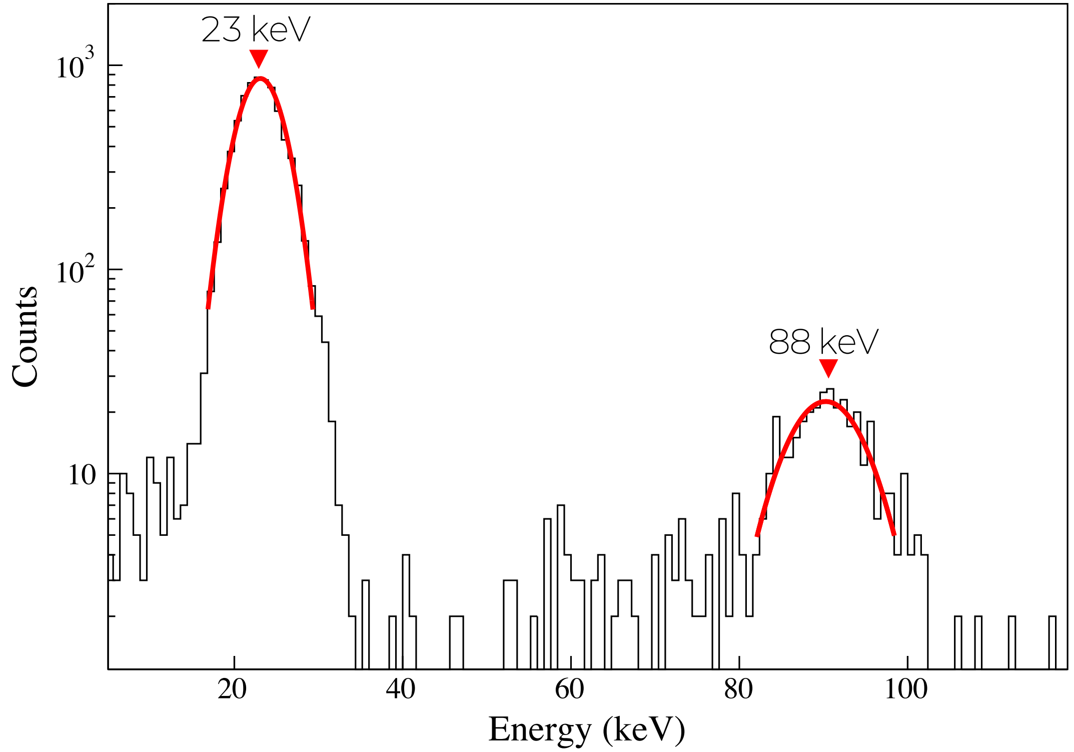
Over-voltage (V)	Internal Cross-talk (%)	External Cross-talk (%)
3	11.9 ± 0.3	7.6 ± 0.4
4	13.9 ± 0.3	8.8 ± 0.2
5	27.3 ± 0.3	8.1 ± 0.2
6	54.5 ± 0.4	10.6 ± 0.2
7	71.2 ± 2.2	14.2 ± 0.3
8	90.8 ± 7.8	33.6 ± 0.3

* Cross-talk : Electrons in a cell enter and fire a neighboring cell.

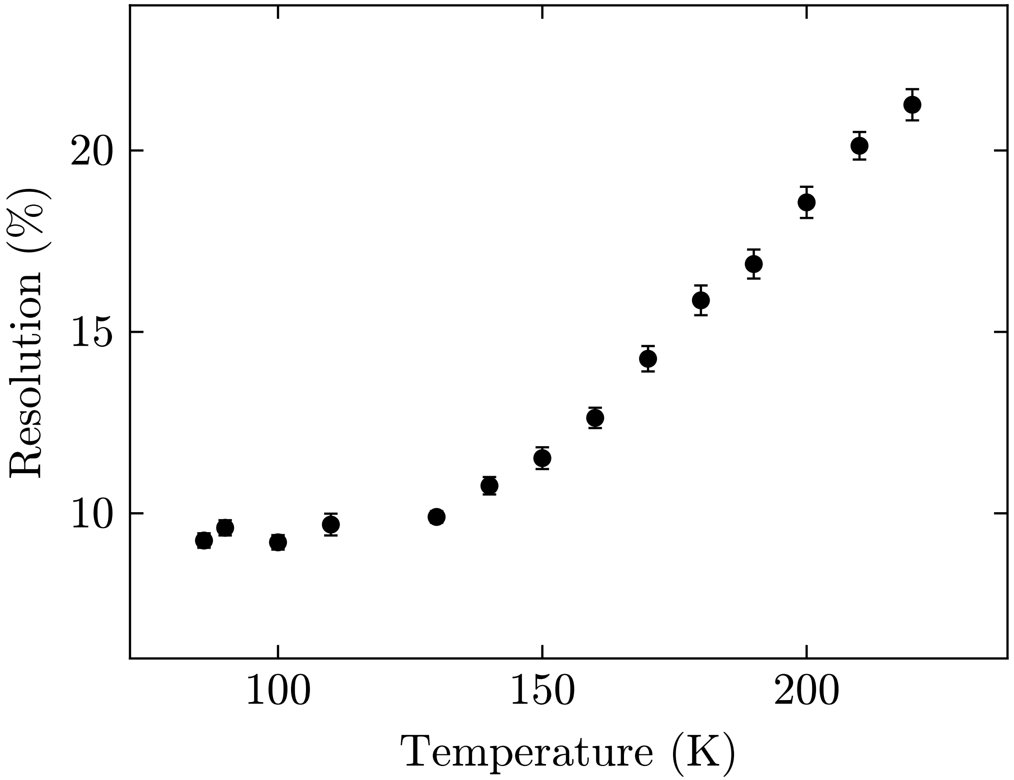
- Data was taken with 6 different bias voltages. Over-voltage ($\Delta V = V_{bias} - V_{breakdown}$) from 3 V to 8 V for each temperature points. That means 6 different gains (we defined gain is the height of single photoelectron (SPE)).
- The highest DCR is **700 kHz at 293 K**. However, DCR is dramatically decreases as the temperature decreases and reached to **0.2 kHz**.
- Cross-talk probability is known to be independent of the temperature at the same ΔV. We measured at room temperature (293 K).

Measurements & Results

➢ **Energy spectrum of ^{109}Cd**



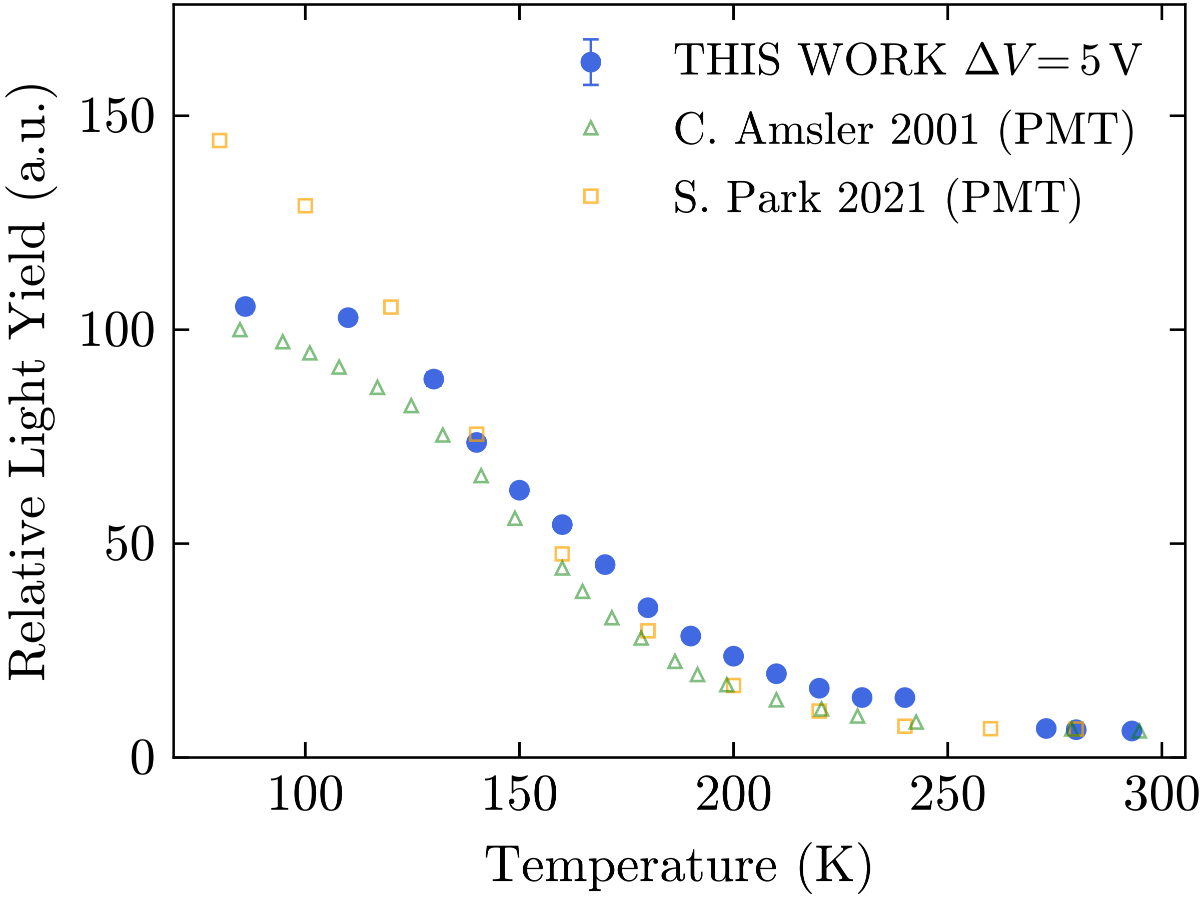
➢ **Energy Resolution for 23 keV peak (ΔV = 5)**



- Temperature > 220 K : 88 keV γ-ray peak
  Temperature < 220 K : 23 keV X-ray peak for calibration.
- Energy resolution (σ/m) of 23 keV peak was obtained as **9.3 ± 0.2 % at 86 K** and **20.7 ± 1.0 % at 220 K**.

Measurements & Results

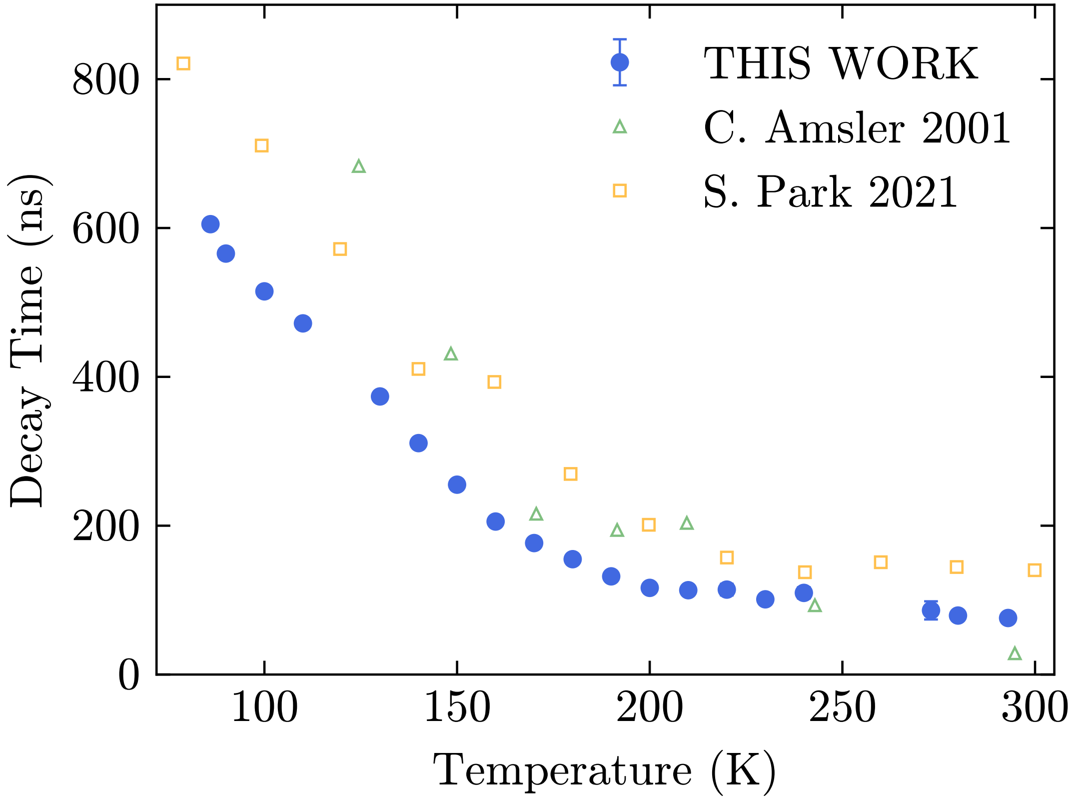
➢ Light Yield of pure CsI

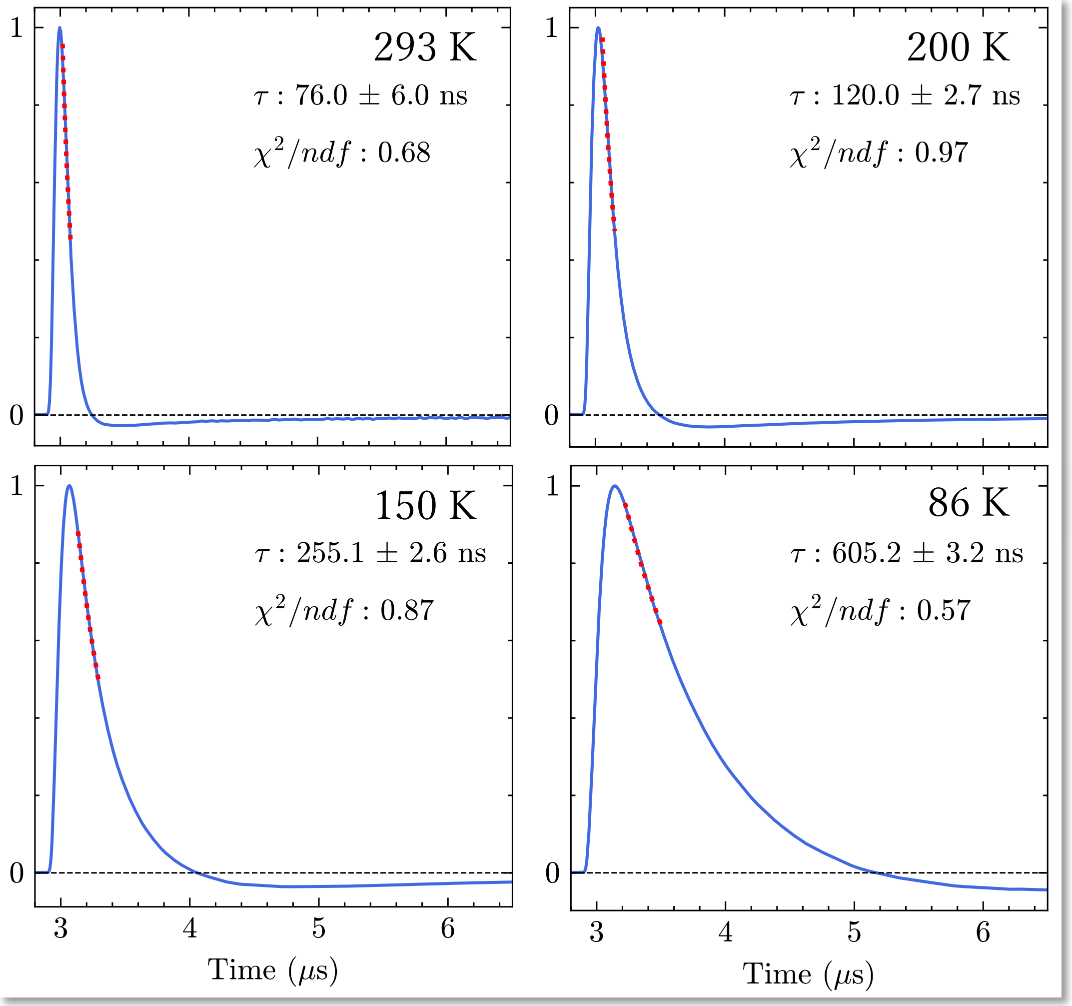


- At 86K, we obtained **22.9 ± 0.8 PE/keV** in ΔV = 5V. Furthermore, **26.2 ± 1.3 PE/keV** in ΔV = 8V.
- The trend of light yield increasement is consistent with other pure CsI-PMT measurements.
- Relative light yield of CsI were normalized to have the same value at 280 K.

Measurements & Results

➢ **Decay Time of pure CsI**

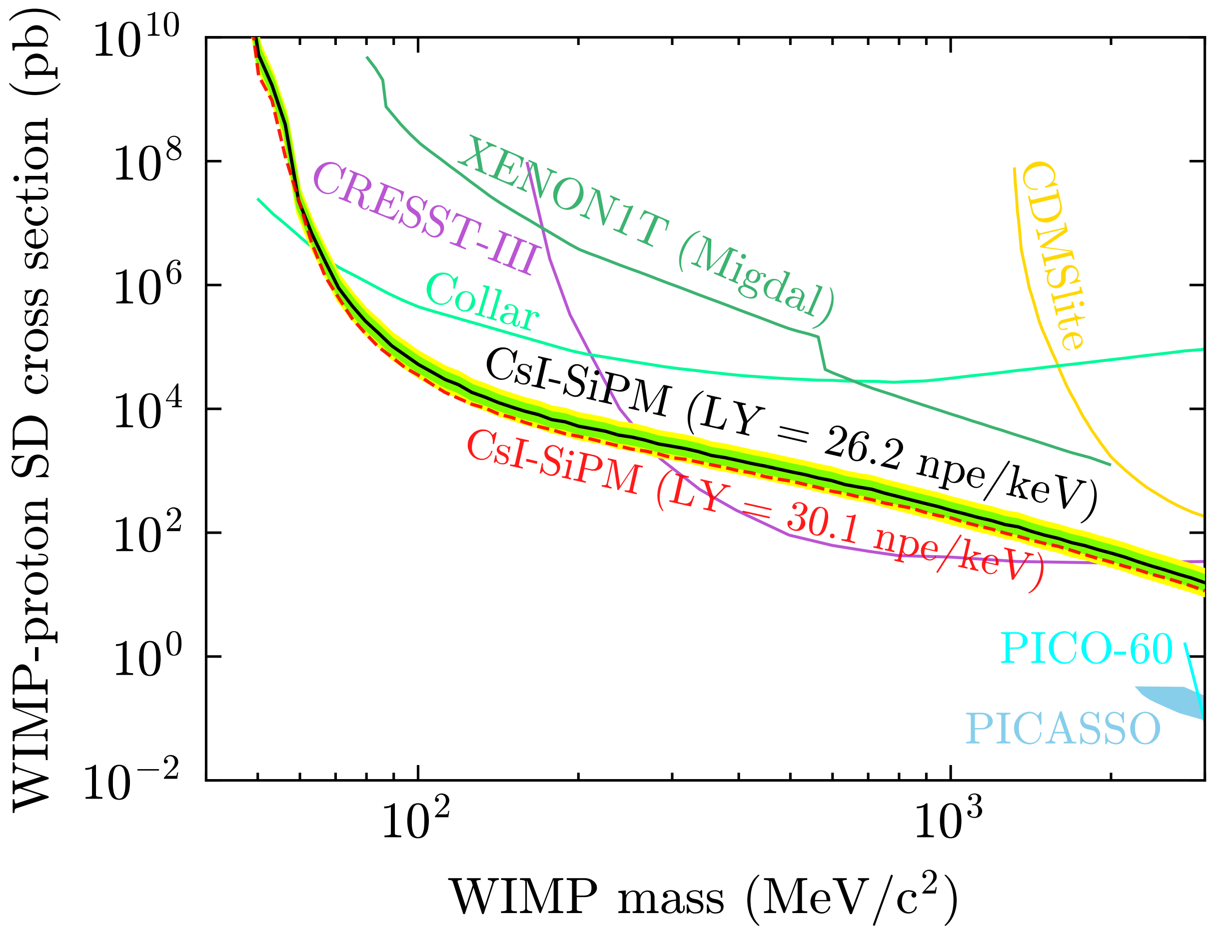




- Because of undershoot of the signal, we used a single exponential function for the waveform fitting.
- At the low temperature, decay time likewise increases. From 293 K to 86 K, the decay time increases by roughly 8 times, increasing from **76.0 ns to 605.2 ns**.

Measurements & Results

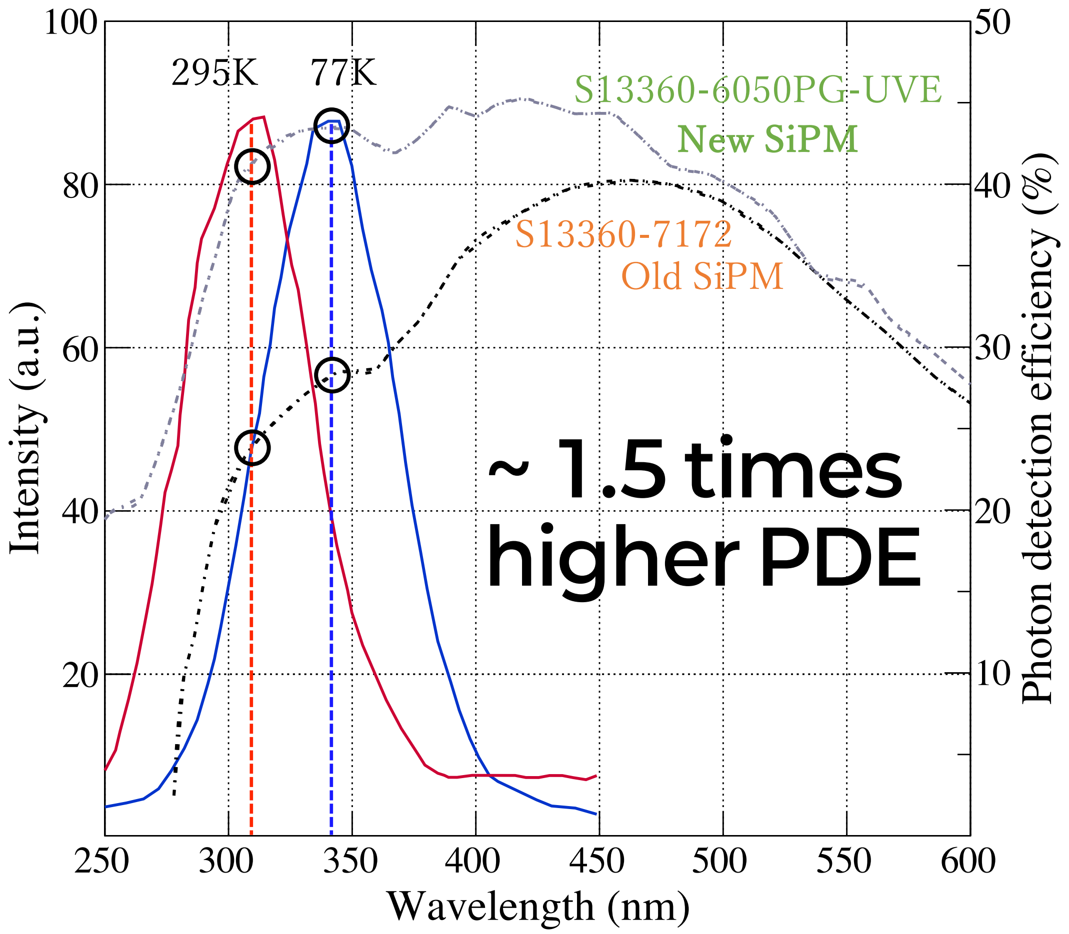
➢ **Limits on the WIMP-proton Spin-Dependent interaction with the Migdal effect**



- The expected 90% confidence level limits for CsI 200kg, 1-year exposure using the Migdal effect on the WIMP-proton spin-dependent cross-section.
- Simulated spectrum based on a background-only hypothesis,
  1 count/kg/keV/day background rate, and a 5 NPE energy threshold.
- Furthermore, light yield of 30 PE/keV were assumed (red dotted line). *Wang et al. Eur. Phys. J. C (2024) 84:440*
- The undoped CsI crystal have potential to explore low-mass dark matter between 60 MeV/c^2 and 2 GeV/c^2 with the world's best sensitivities.

New SiPM Test

➢ **Emission spectrum of pure CsI and PDE of SiPM**



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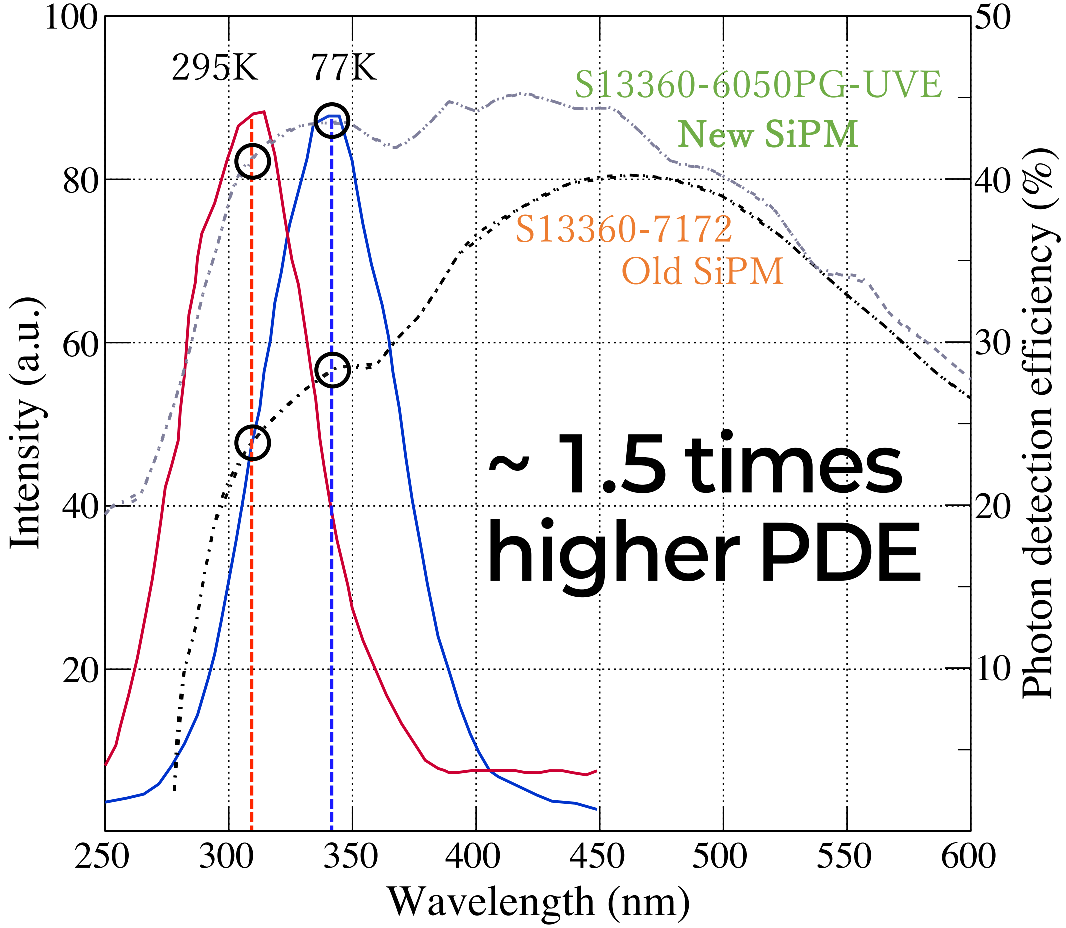
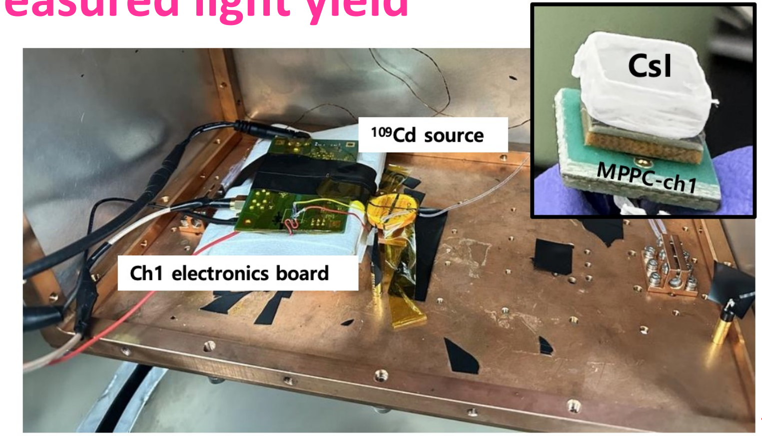


➢ Measured light yield



One Channel
Smaller Crystal
Not directly comparable to the former measurement

Old SiPM

Temperature (K)	89			293		
Overvoltage (V)	2	3	4	2	3	4
Light Yield (PE/keV)	11.76	14.79	16.33	0.39	0.41	0.46

New SiPM

Temperature (K)	87			293		
Overvoltage (V)	2	3	4	2	3	4
Light Yield (PE/keV)	21.04	27.16	27.39	0.53	0.65	0.69

- **The new SiPM** recorded the light yield about **27 PE/keV @ 87 K.** Showing **improvement of about 1.7 times**.

Summary

- Detector of **pure CsI-SiPMs** characteristics were investigated at various temperature points from **293 K to 86 K**.
- The light yield increases from 293 K to 86 K. We obtained maximum light yield of **26.2 ± 1.3 PE/keV at 86 K**.
- The temperature decreases also result in an improvement in energy resolution and dark count rate.
- This detector **can achieve world-competitive sensitivity** for low-mass dark matter detection, particularly in the context of **dark matter-proton spin-dependent** interactions.
- New Hamamatsu SiPM with 1.5 times higher photon detection efficiency is currently being tested at IBS.

Scan for our publication!

Astroparticle Physics (2025) 173:103150

Thank you
for
your attention!

Reference

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[3] S. Park et al, New Physics: Sae Mulli 72, 469-475 (2021)

[4] Liu et al. EPJC (2022) 82:344

[5] Wang et al. EPJC (2024) 84:440

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[7] Hamamatsu Photonics K.K., MPPC S13360 series, http: //www.hamamatsu.com/