Cryogenic CsI and SiPM-Based Detector with Ultra-High Light Yield for CEνNS Experiments

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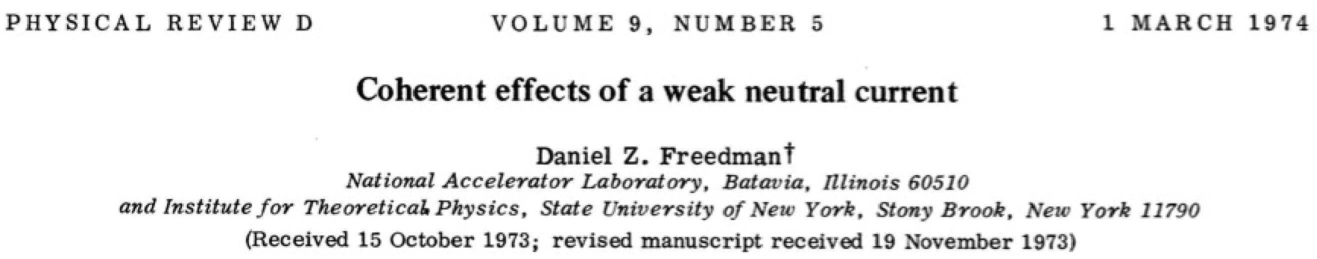
Outline

- Introduction
- The Low-Threshold Challenge
- The CsI+SiPM Detector Solution
- Characterization of SiPMs at Cryogenic Temperatures
- Prototype Detector Performance
- Sensitivity Projections for CEvNS
- Summary

CEvNS (coherent elastic neutrino-nucleus scattering)

- **Theoretically predicted about 50 years ago**
- **Experimentally confirmed in 2017 (Akimov et al., Science)**


PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

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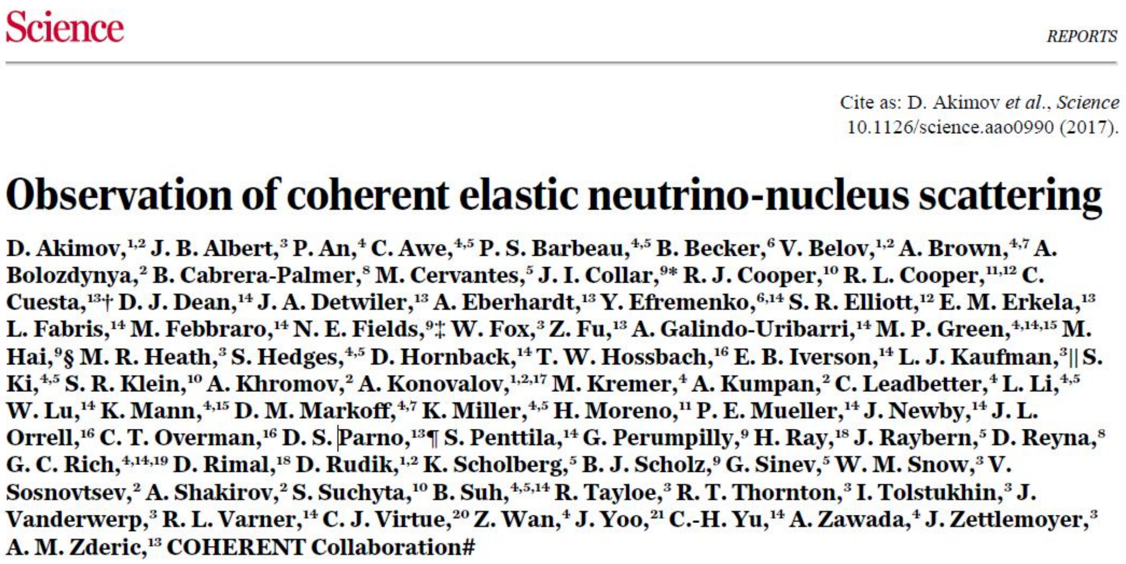
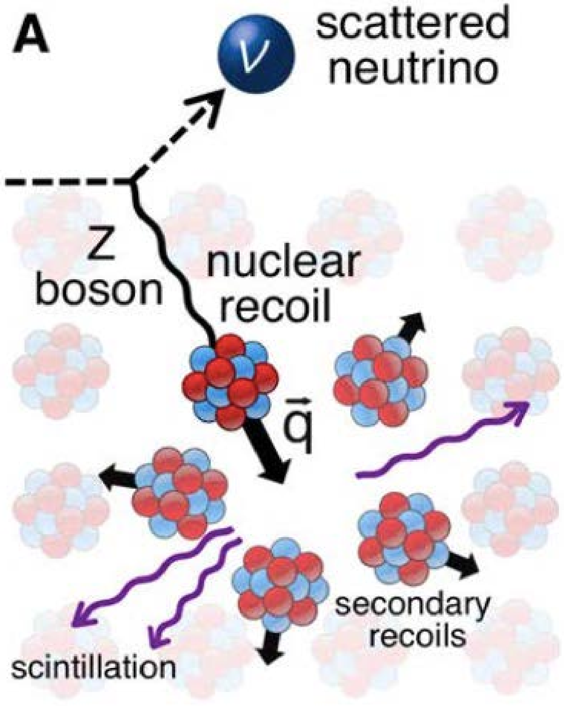
(Received 15 October 1973; revised manuscript received 19 November 1973)


Science REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9]* R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13]† D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9]‡ W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9]§ M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3]‖ S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13]¶ S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

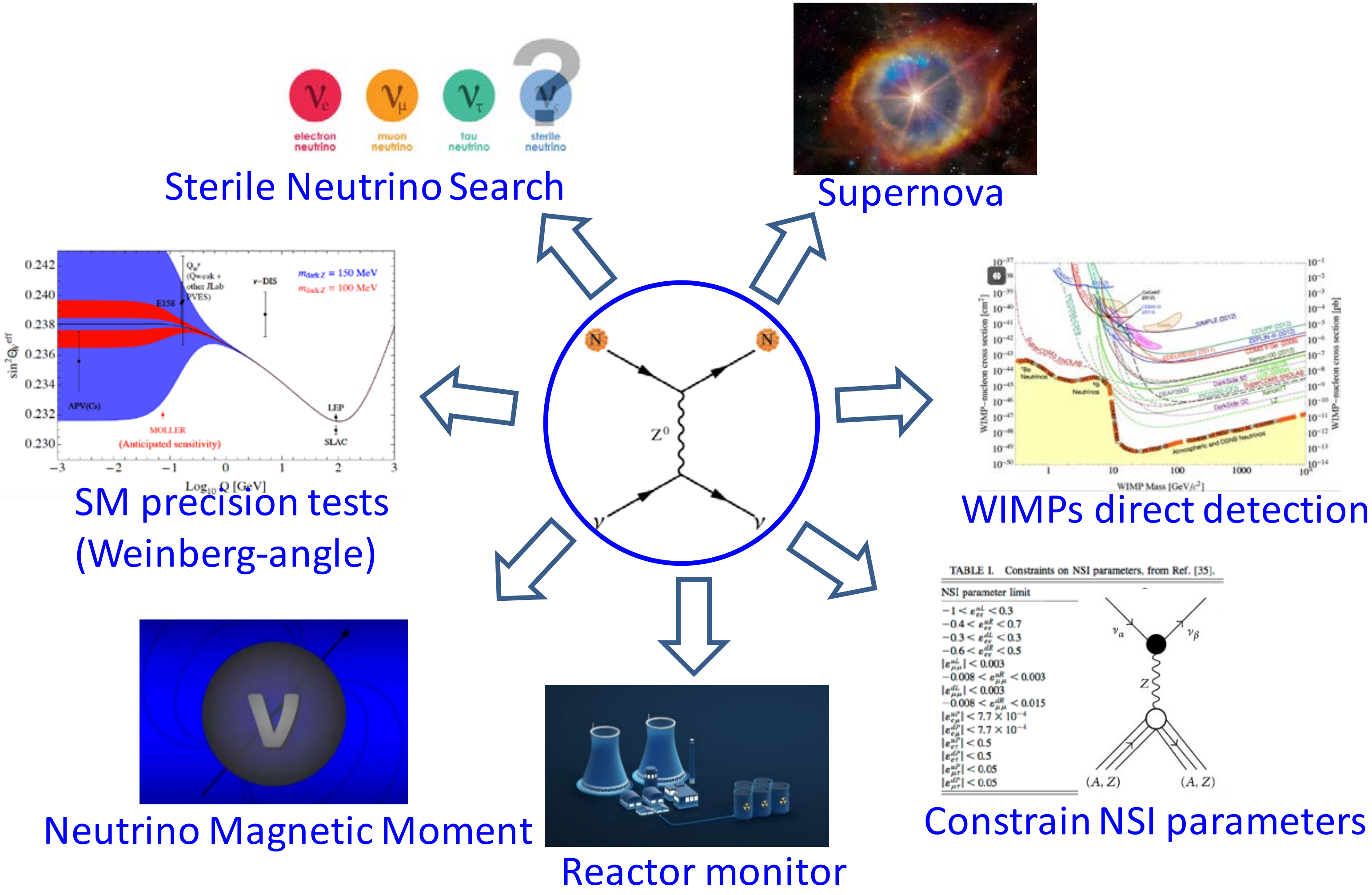


Akimovet al.,Science357, 1123–1126 (2017)

The CEvNS Physics

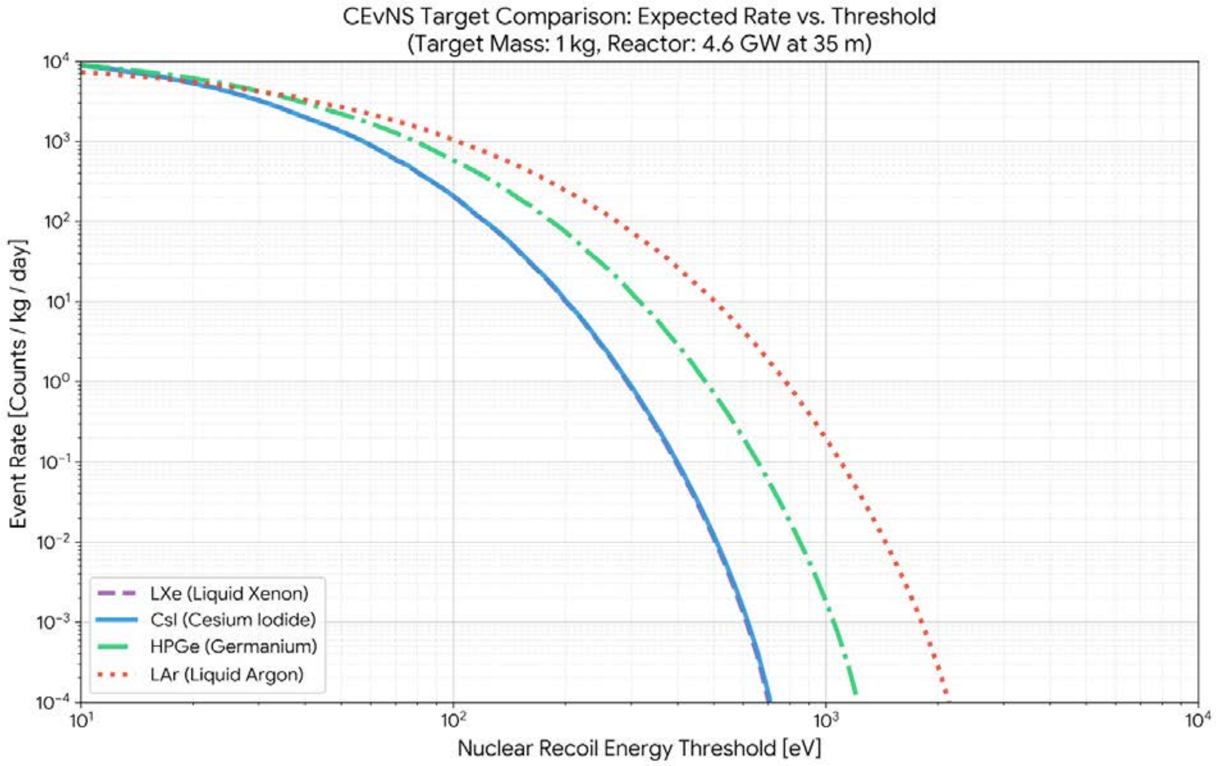
Compelling Physics at Eν <50 MeV

- 探测中微子磁矩
- 超新星中微子探测
- 标准模型的精密检验，例如 Weinberg 角
- 寻找惰性中微子，并约束非标准相互作用参数
- 反应堆监测应用
- WIMP 暗物质的直接探测



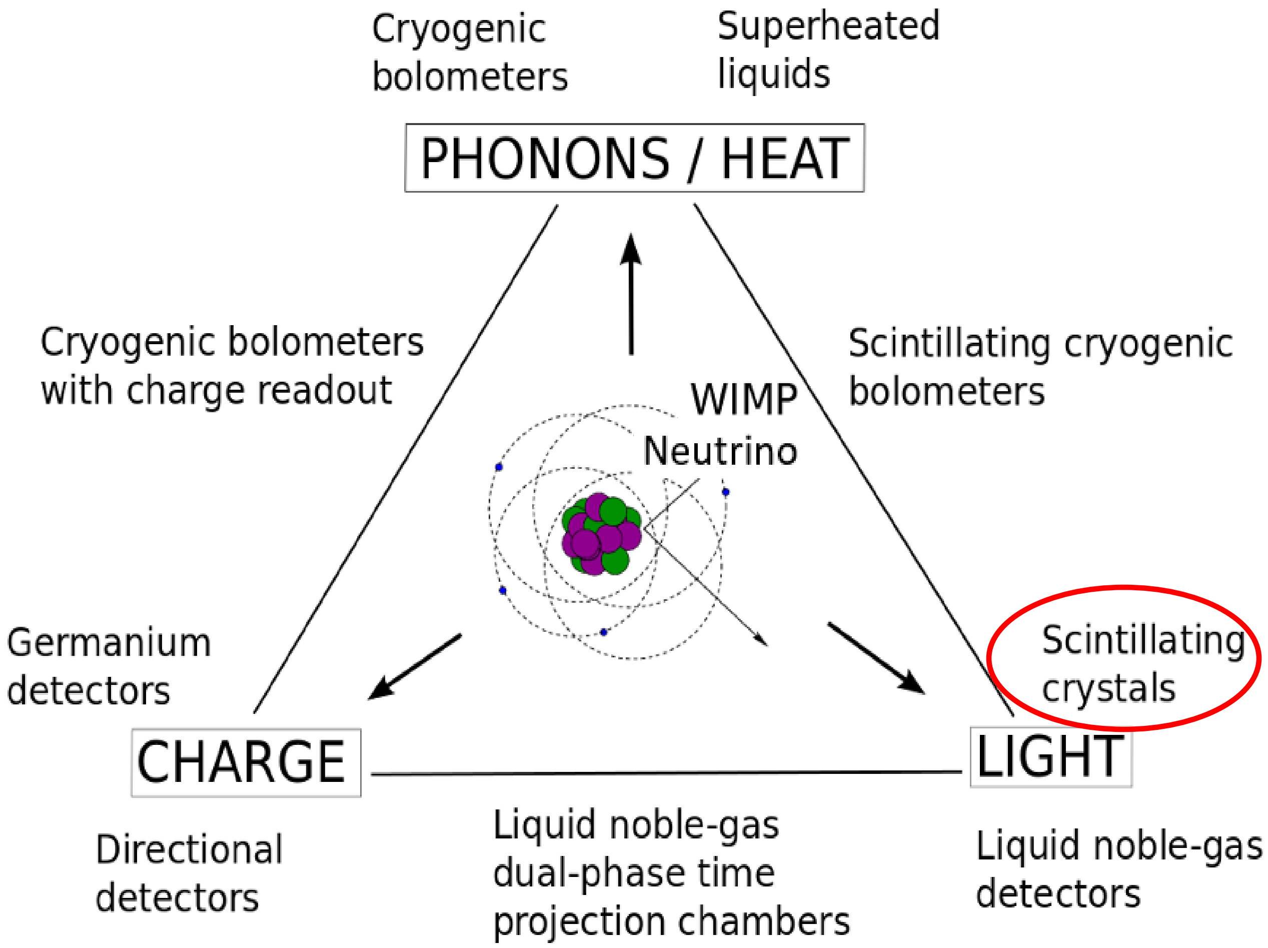
The Low-Threshold Challenge

- In CEνNS experiments, detector sensitivity is fundamentally bound to the energy threshold
- The exponential gain: A mere 0.1 keV reduction in the nuclear recoil threshold can increase the expected event rate by a full order of magnitude



Detection technology of CEvNS

- **Primary Signal Channels: Photons (Scintillation), Phonons (Heat), and Electrons (Ionization)**



ar5iv.labs.arxiv.org/html/1509.08767

The First Scintillator CEvNS detector

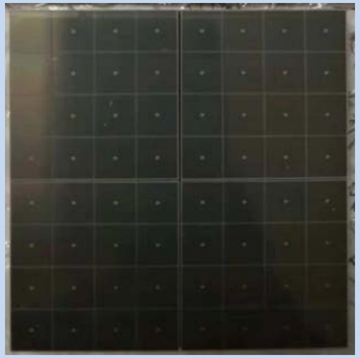
- Utilized a CsI(Na) + PMT configuration at room temperature
- Dimensions: 11 cm diameter, 34 cm length, yielding a 14.57 kg mass
- Light Yield (LY): ~40,000 photons/MeV at 420 nm
- QE ~33%, resulting in ~13 p.e./keVee
- QF ~8.8%, yielding an effective~1 p.e./keVnr
- Next-generation neutrino detectors:
  - require higher light yield
  - and lower threshold.

Ultra-High Light Yield Solutions

- **Proposed Architecture: Low temperature CsI+SiPM+TPB**
- **Undoped CsI: LY ~100 photons/keV at cryogenic temperatures**
- **SiPM Readout: Peak PDE of 50%-60%, averaging ~ 40% across the emission spectrum**
- **Expected light yield of 30–40 p.e./keVee**

CsI

+



SiPM

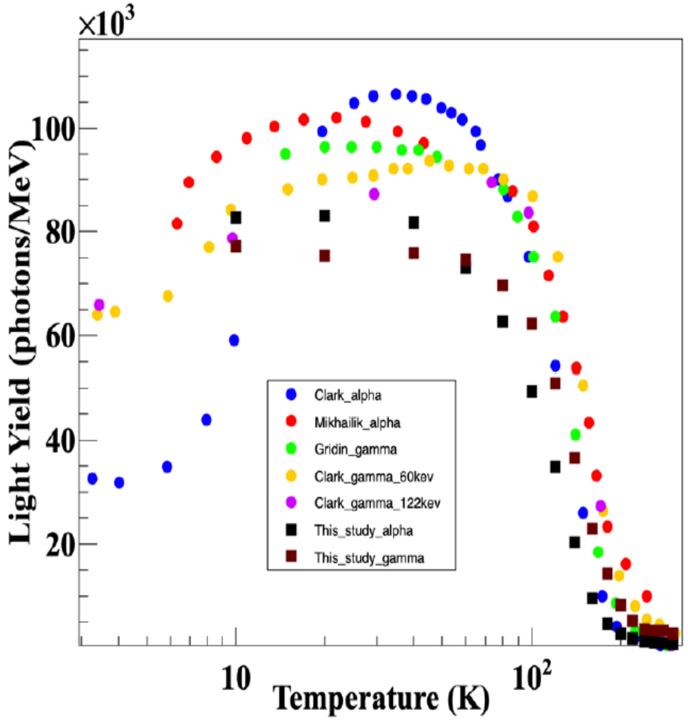
+

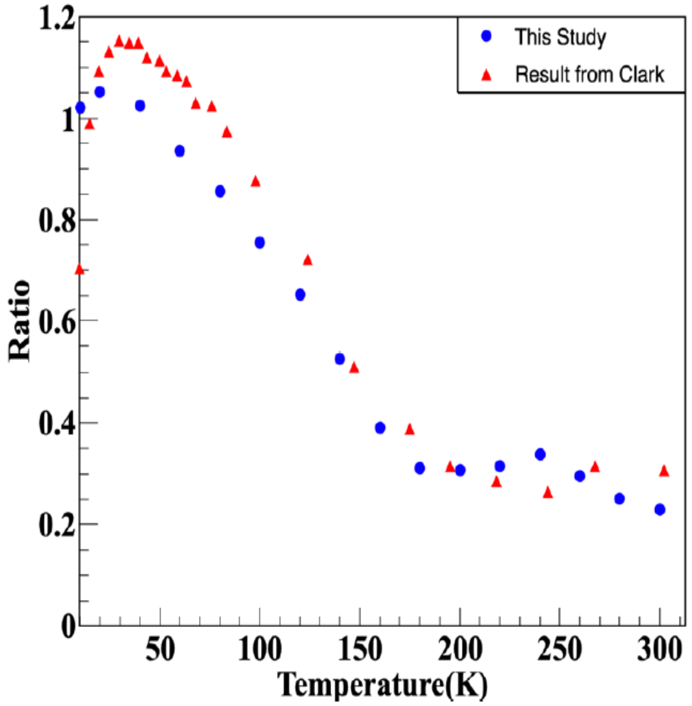
TPB (WLS)

Low temperature

CsI Crystal Properties

- **Recognized as the brightest known scintillator at cryogenic temperatures (LY > 70,000 photons/MeV at 10–80 K)**
- **QF>100% for alpha/gamma, QF for nuclear recoil maybe >10% (Requires further precise measurement)**

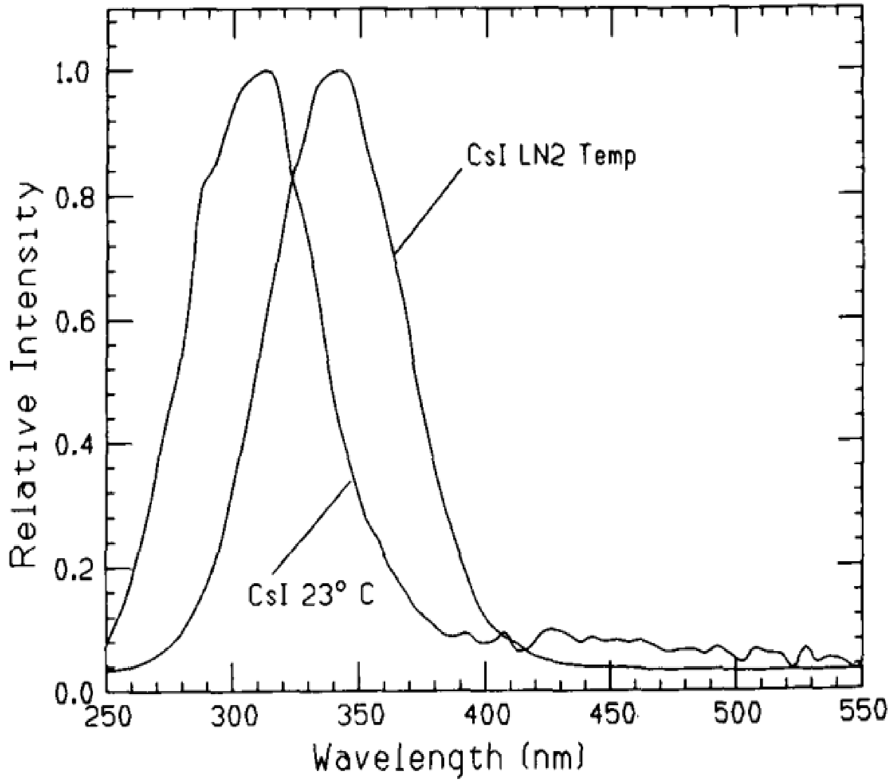




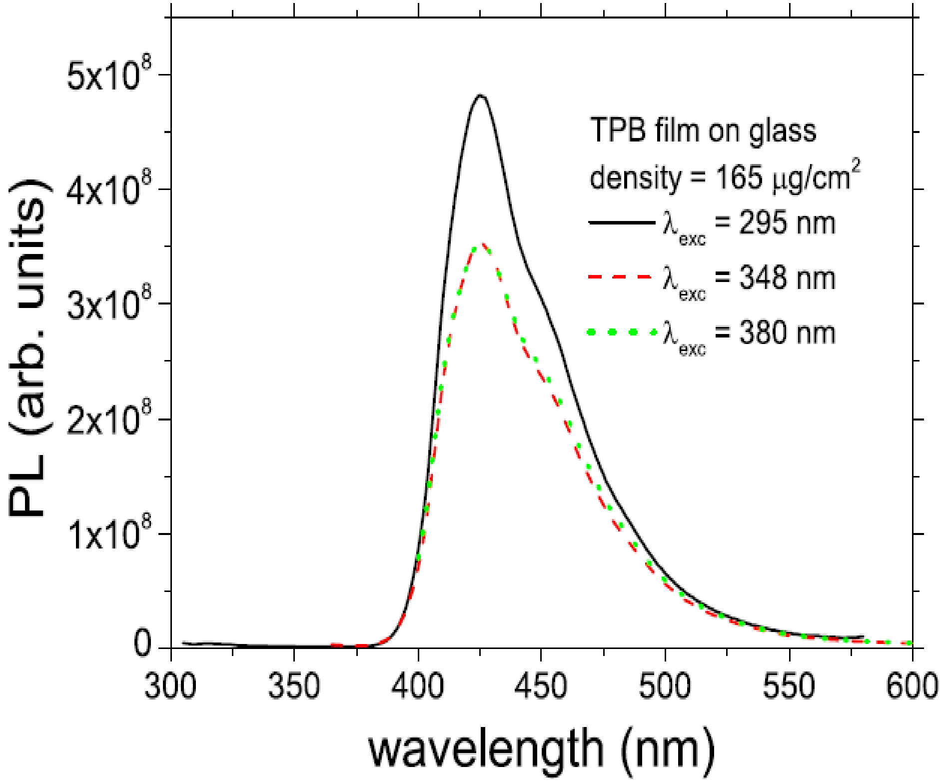
New Physics: Sae Mulli, Vol. 71, No. 5, May 2021, pp. 469475

TPB wavelength shifter

- **Function: Shifts the 340 nm UV emission of pure CsI to 420 nm.**
- **Purpose: Perfectly matches the peak spectral sensitivity of the coupled SiPMs.**



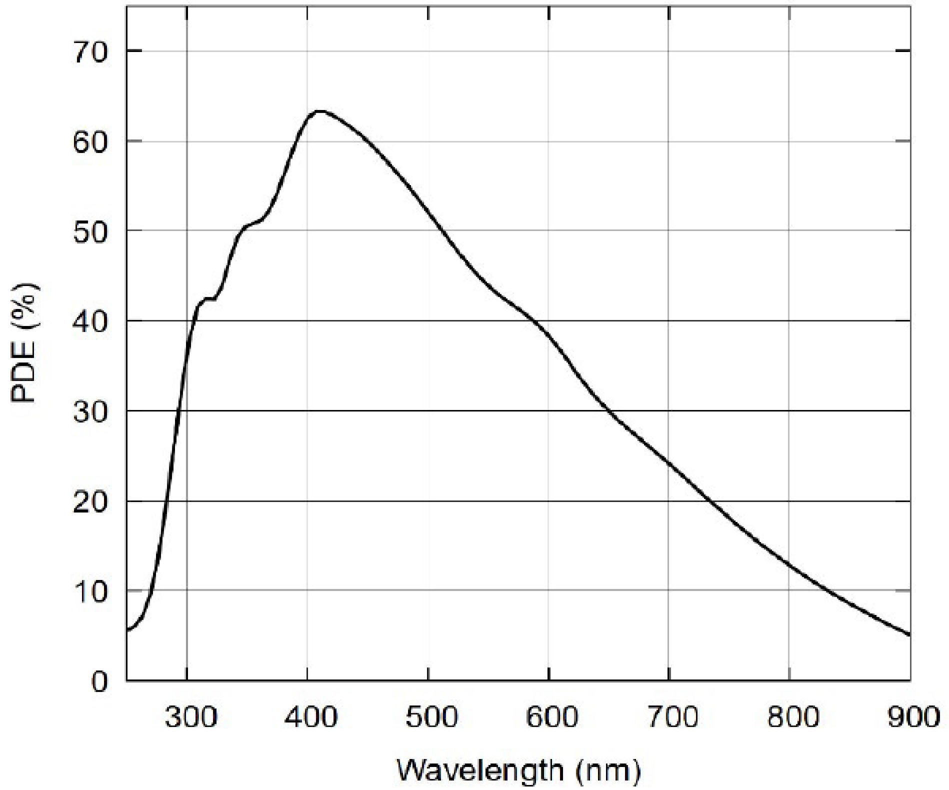
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 37, NO. 2, APRIL 1990



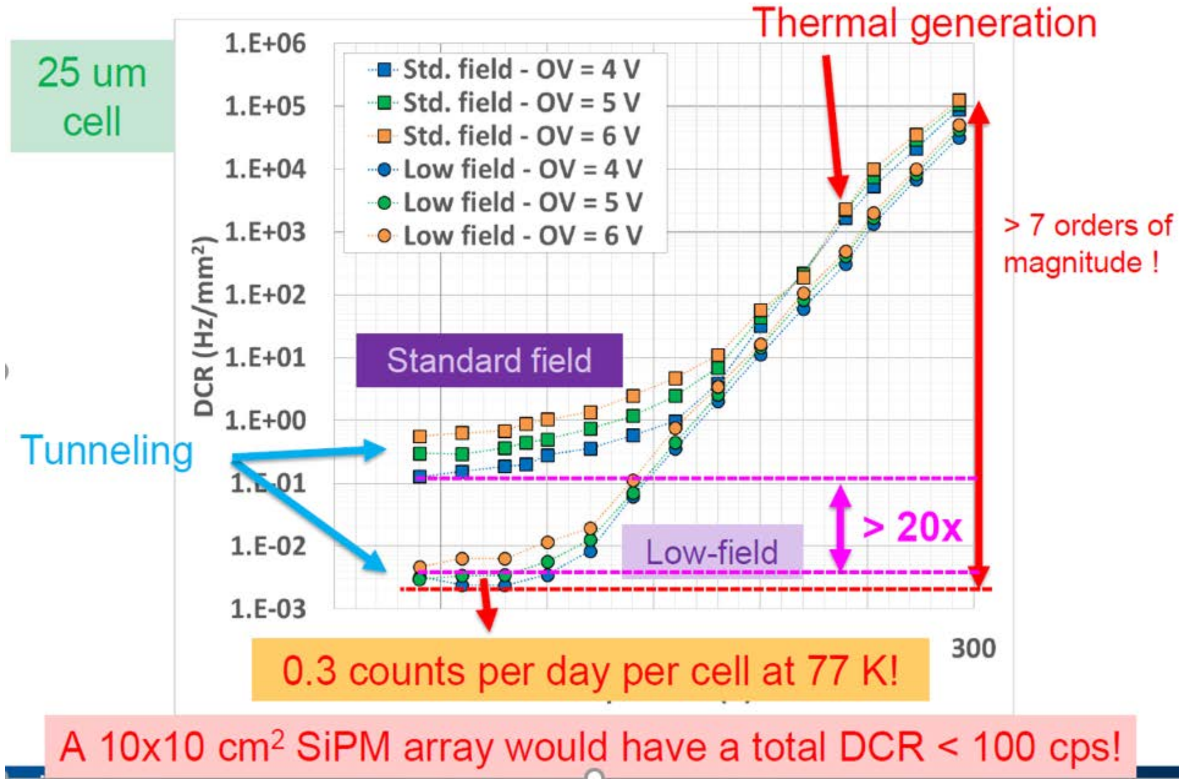
R Francini et al 2013 JINST 8 P09006

SiPMs properties

- **PDE 50-60% at 420 nm**
- **DCR reduced by 7 orders, reaching 0.01-0.1 CPS/mm² at 77K**



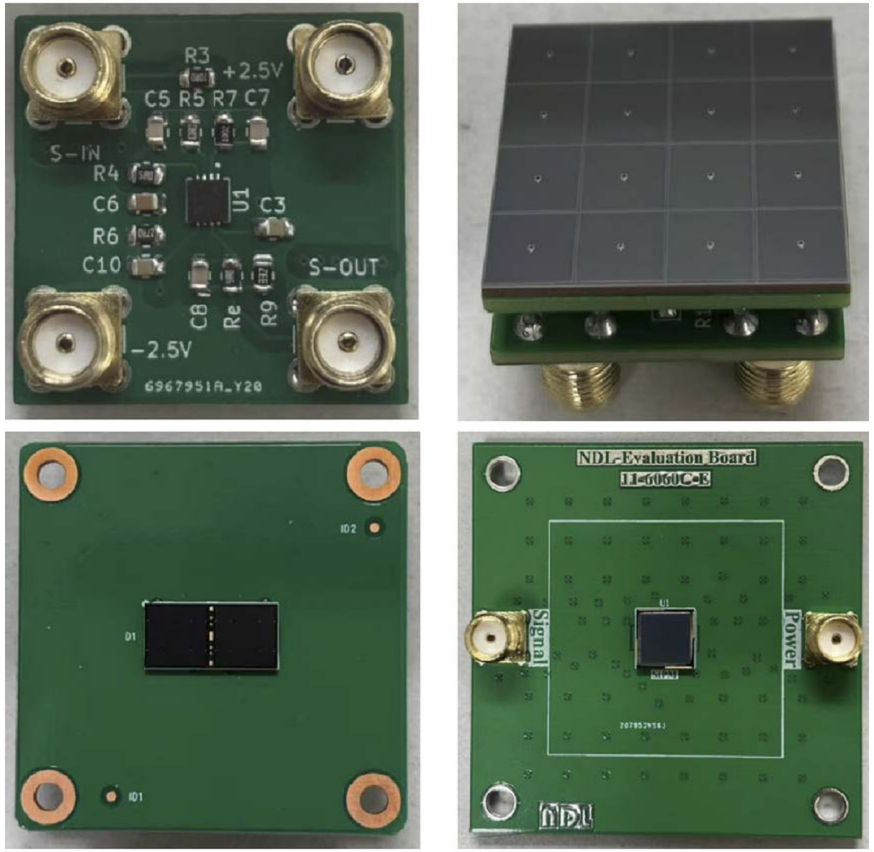
AFBR-S4N66P014M NUV-MT Silicon Photomultiplier

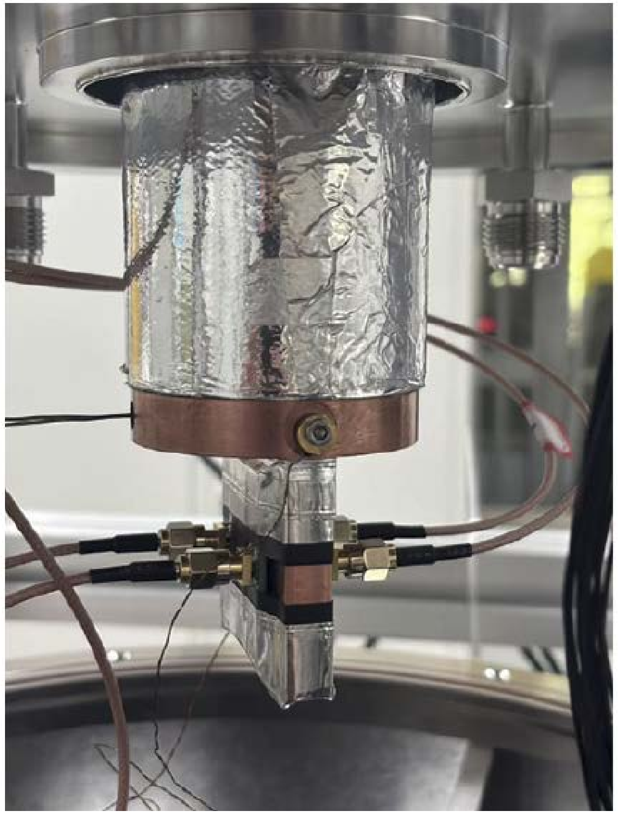


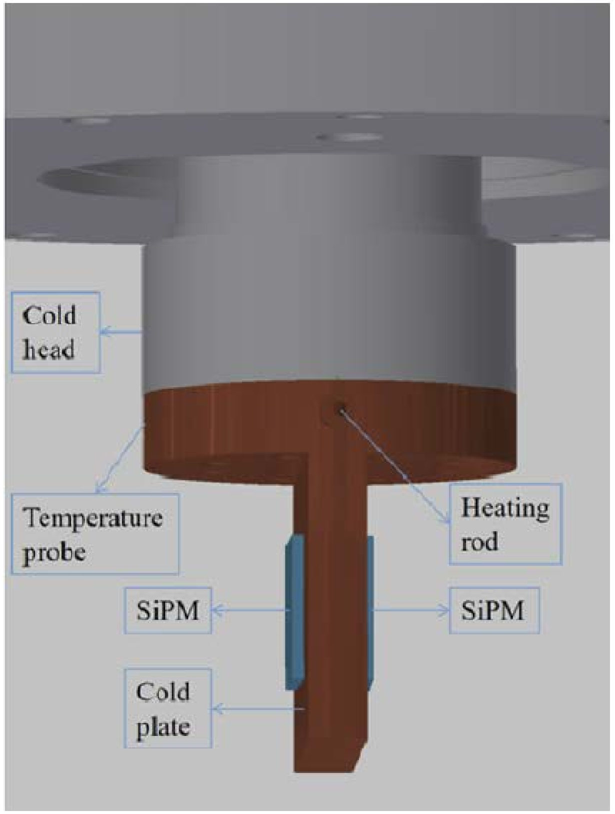
Alberto Gola FBK

Characterization of SiPMs

- **Testing Apparatus: Custom 30–240 K low-temperature testing device utilized to characterize models from NDL, Broadcom, and Hamamatsu**



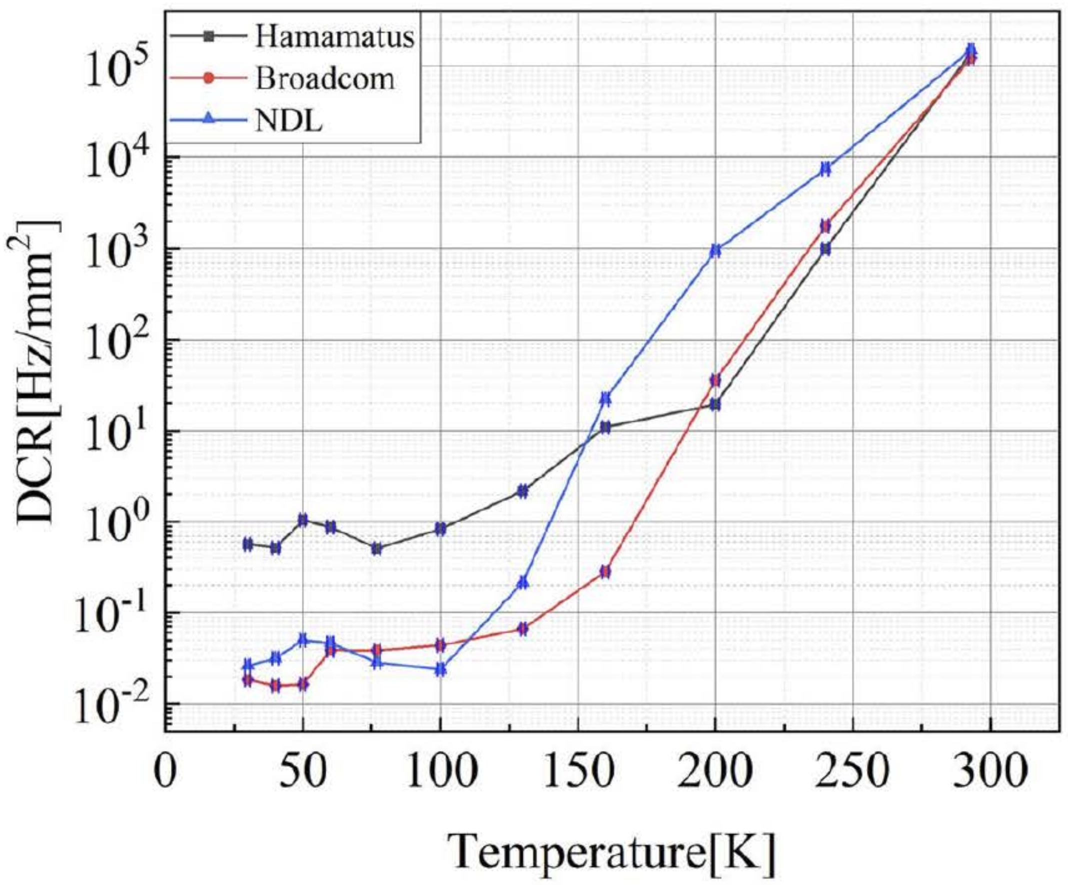


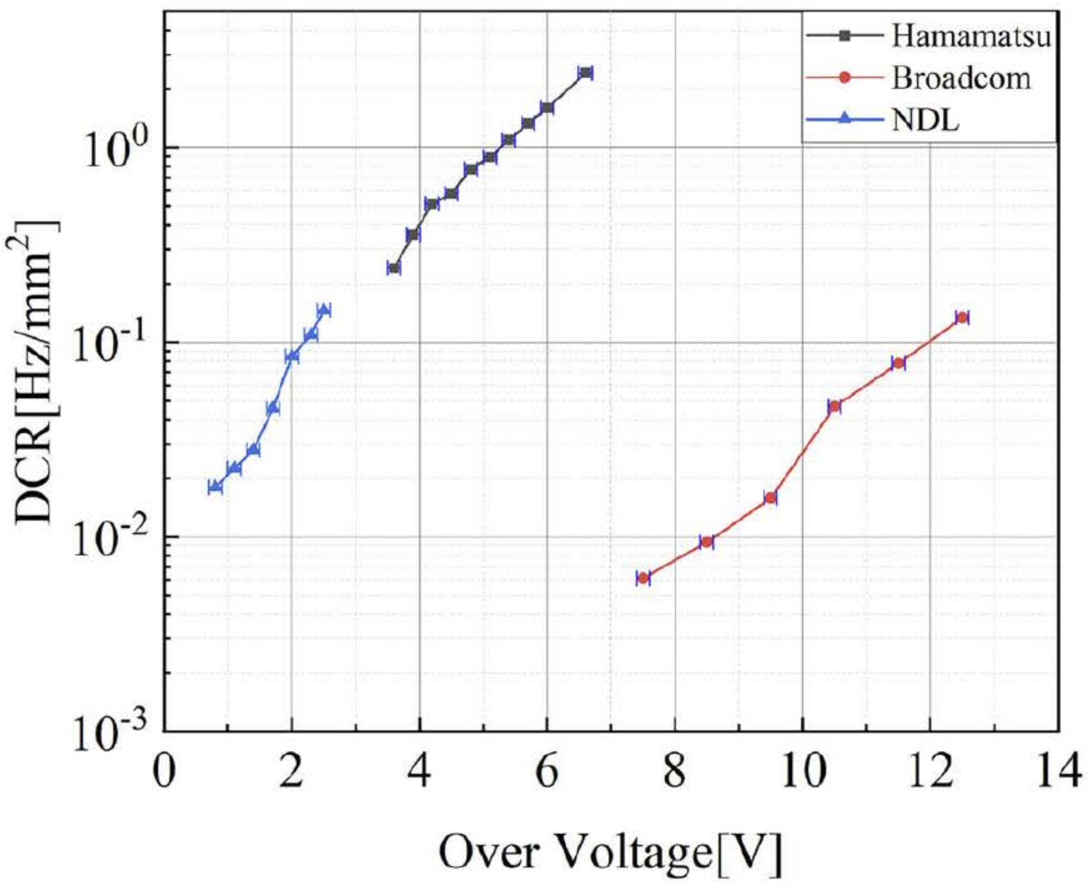


Liu, T., Sun, X., Luo, F. *et al. Radiat Detect Technol Methods* **10**, 253–262 (2026).

Characterization of SiPMs

- **Dark count rate, can reach 0.01-0.1 Hz/mm²**

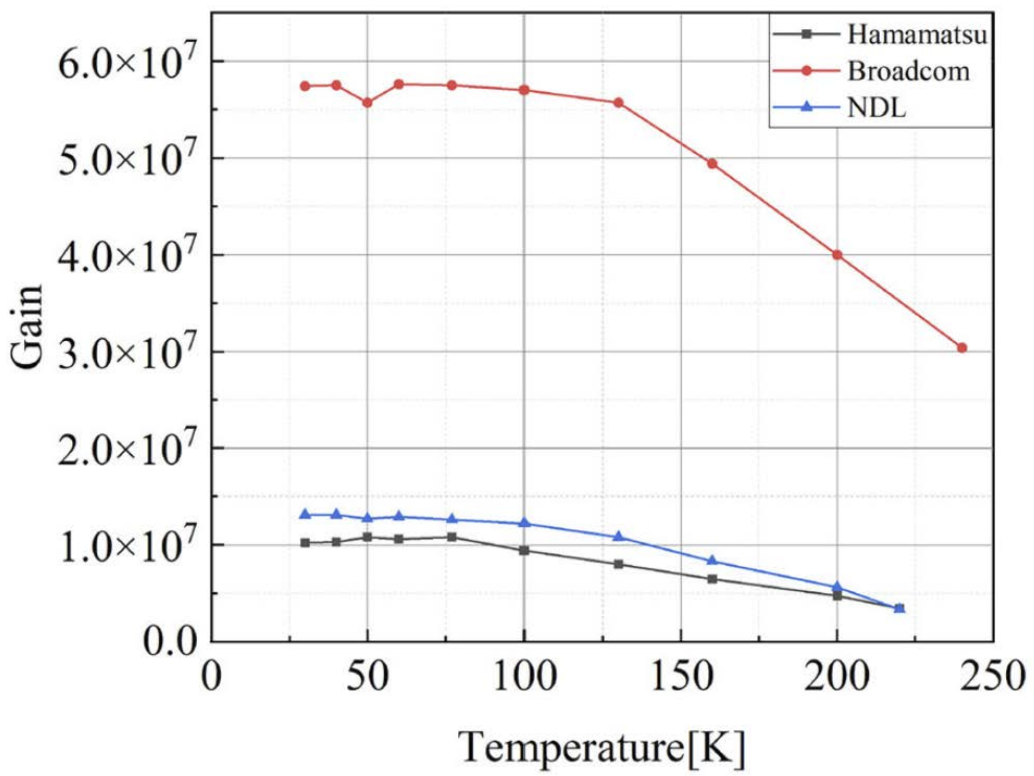


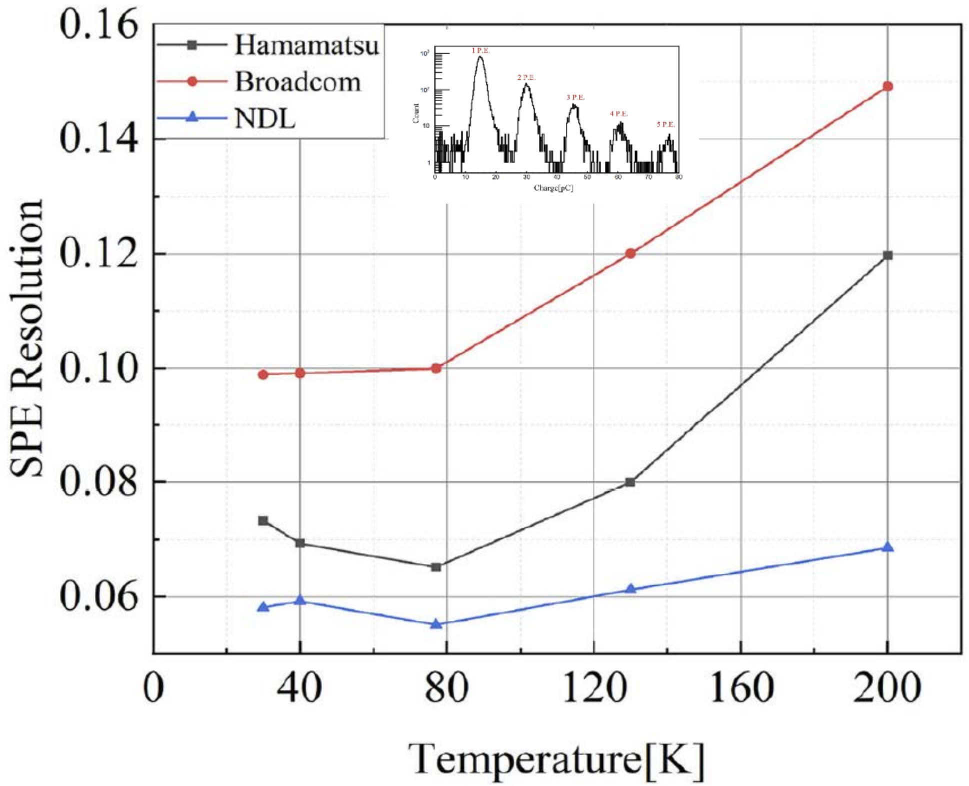


Liu, T., Sun, X., Luo, F. *et al. Radiat Detect Technol Methods* **10**, 253–262 (2026).

Characterization of SiPMs

- **Single-photon electron resolution is good, with a resolution better than 10% at LT**
- **The gain can reach 10^7**

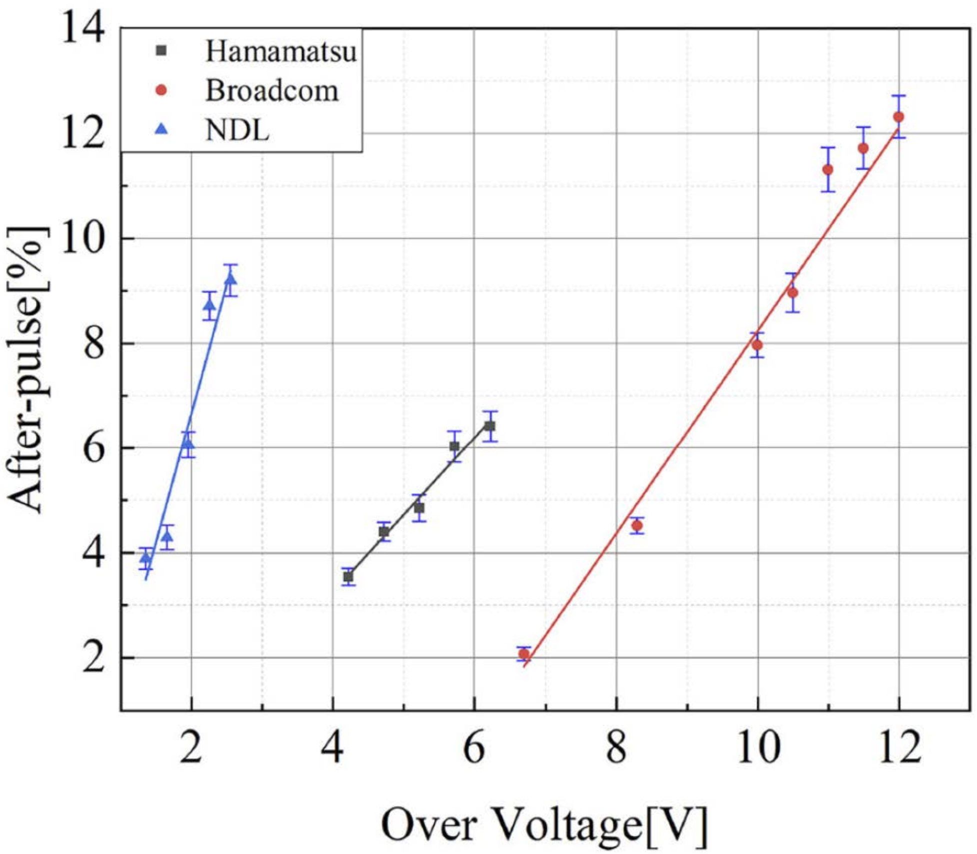


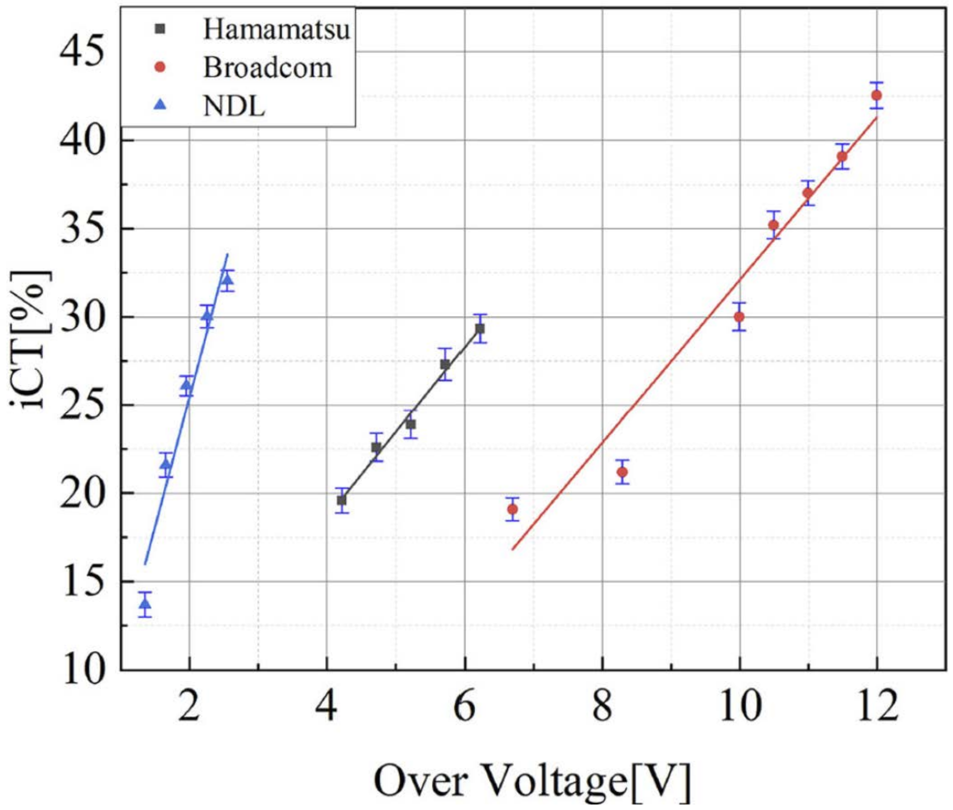


Liu, T., Sun, X., Luo, F. *et al. Radiat Detect Technol Methods* **10**, 253–262 (2026).

Characterization of SiPMs

- **After pulse, < 12%**
- **internal Cross talk, 20-40%**

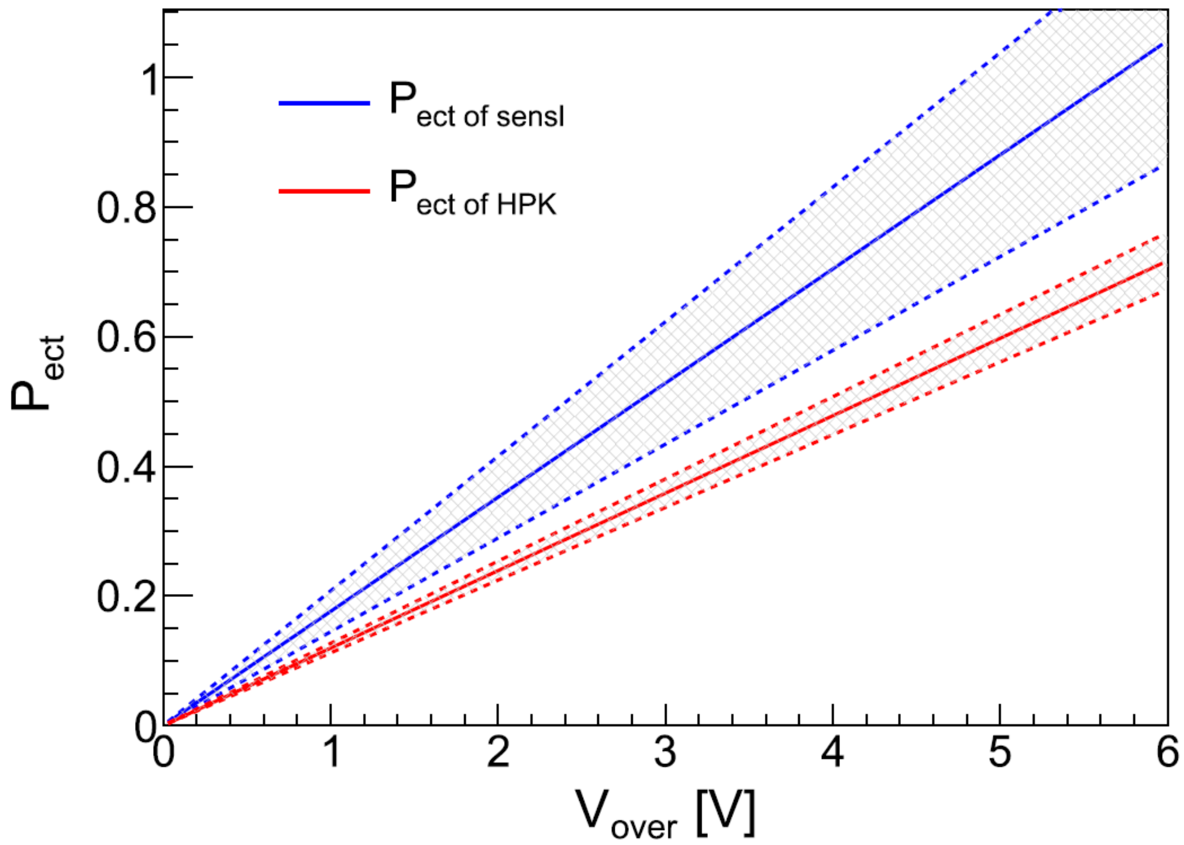




Liu, T., Sun, X., Luo, F. *et al. Radiat Detect Technol Methods* **10**, 253–262 (2026).

Characterization of SiPMs

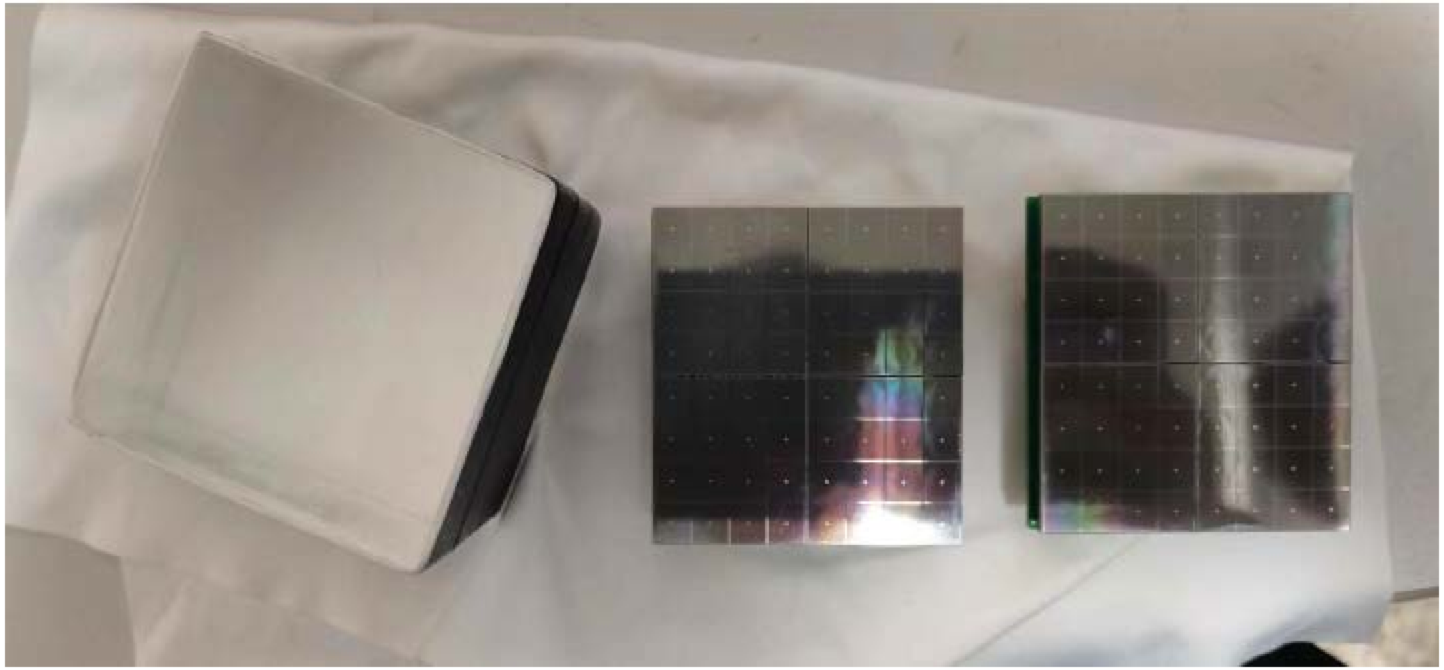
- **external Cross talk, the probability is directly proportional to the overvoltage**

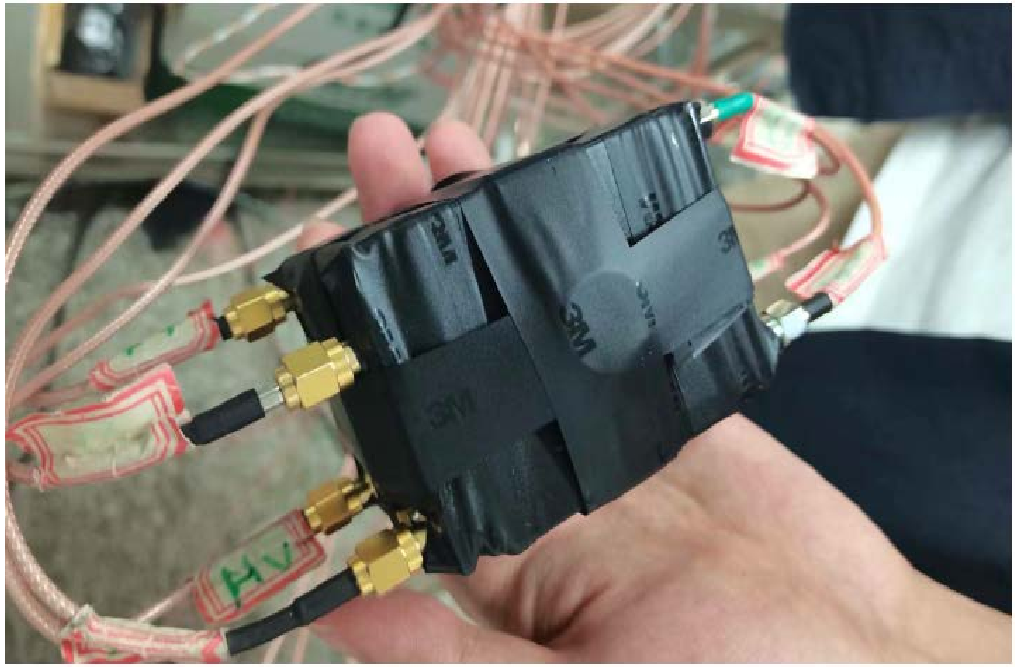


Guanda Li et al. IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 71, NO. 7, JULY 2024

2-Inch Prototype Detector Performance at 77K

- **CsI crystal 5x5x5 cm, 0.56 kg, polished**
- **Wrapped in Teflon reflective film (without TPB coating)**
- **Readout: Dual-ended 5x5 cm SiPM arrays (with TPB coating), cooled to 77 K via liquid nitrogen.**

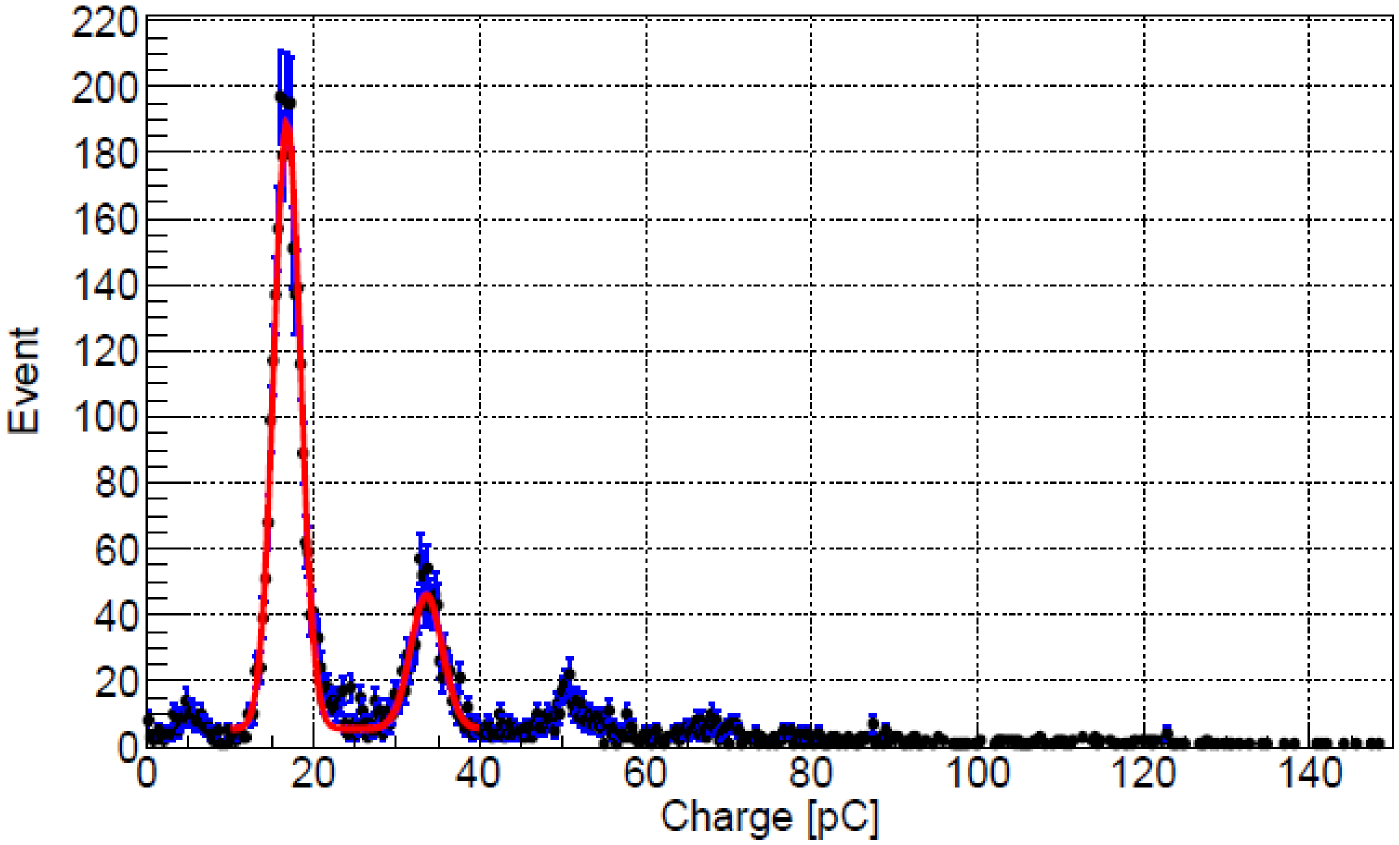




Lei Wang *et al.* Eur. Phys. J. C (2024) 84:440

2 inch SiPMs array performance at 77K

- **Single photoelectron resolution is good**
- **DCR ~0.1 Hz/mm^2 @35V bias**



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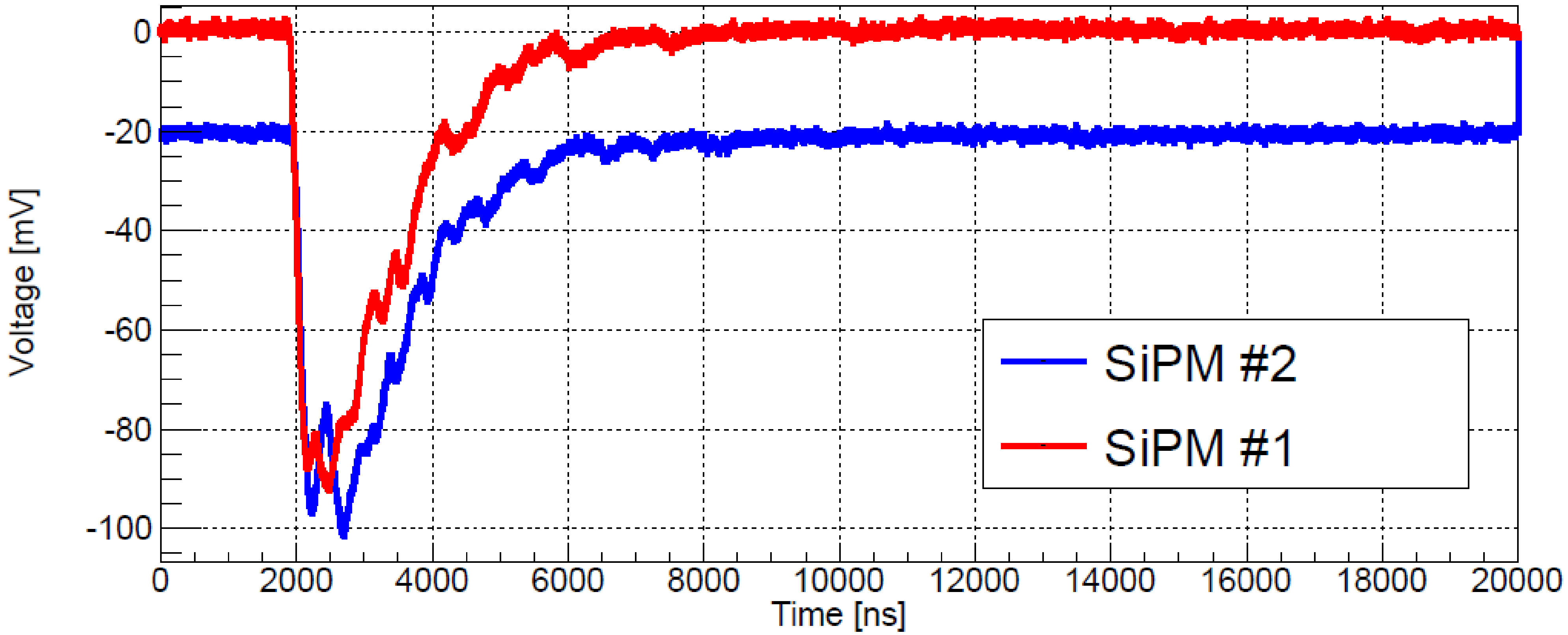
2 inch Prototype Waveform performance at 77K

- **Decay time ~1 μs, Pulse Width ~6 μs**



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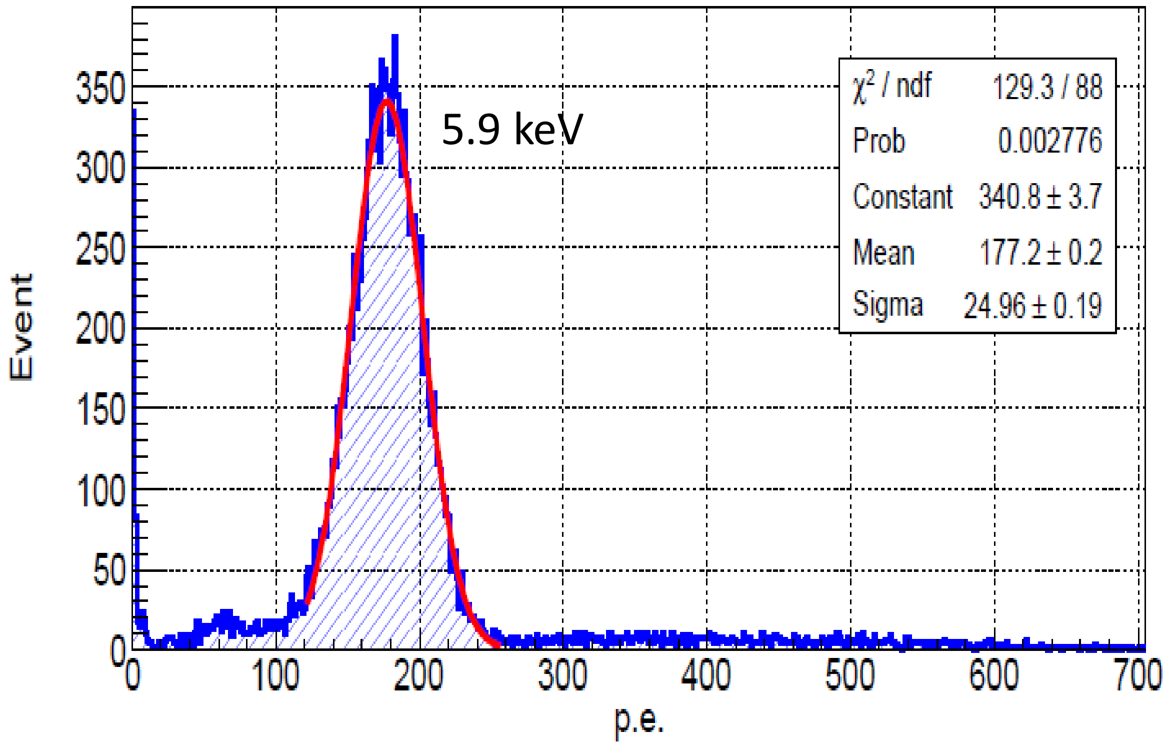
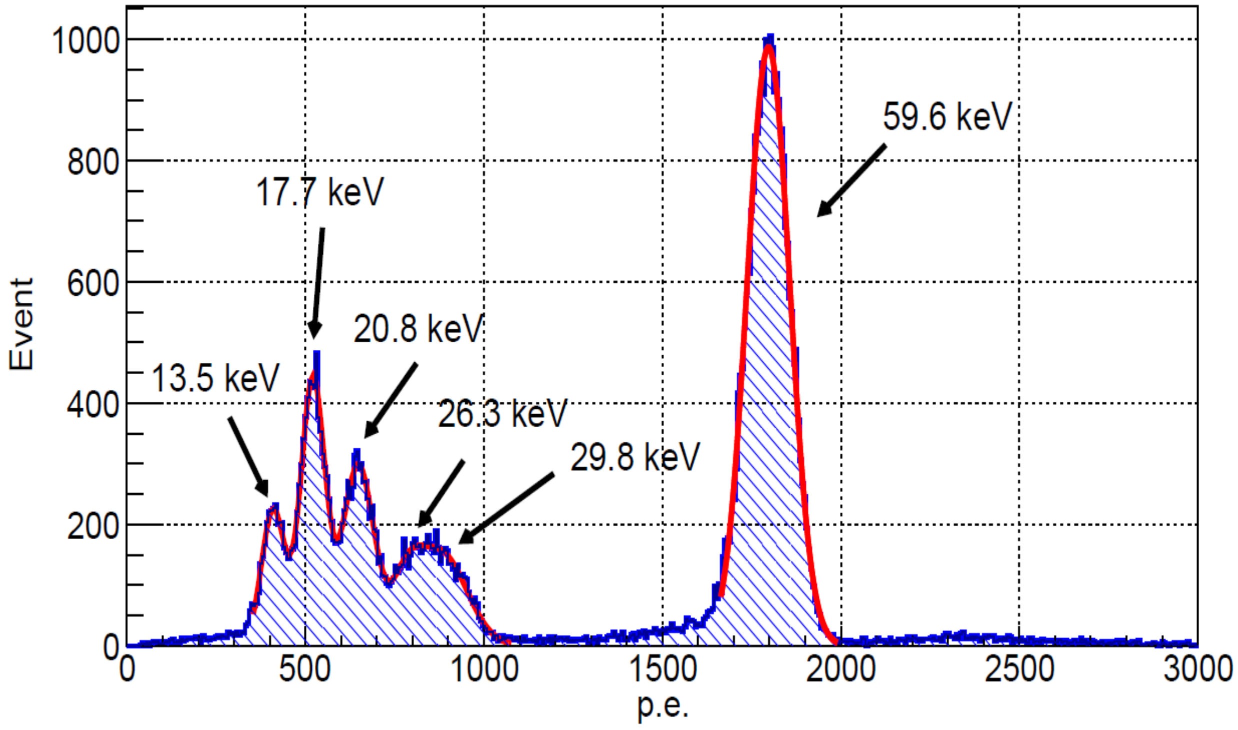
2 inch Prototype Energy spectrum at 77K

- **Good energy resolution, fine structures are clear**
- **7.8%(FWHM), at 59.6 keV**





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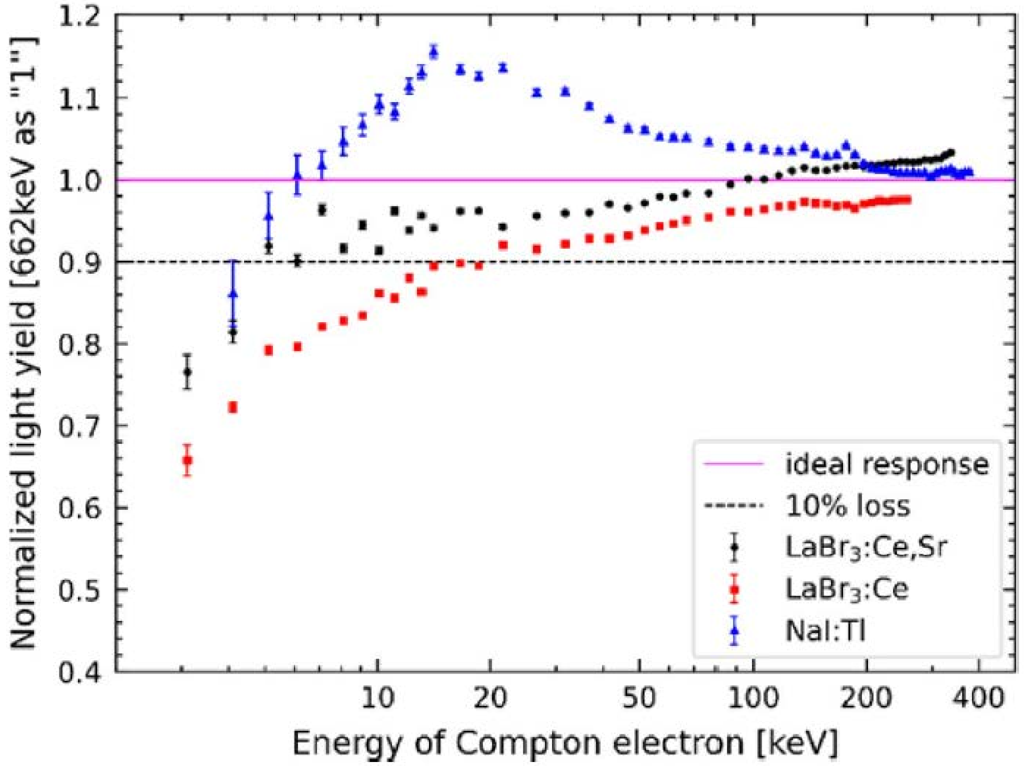
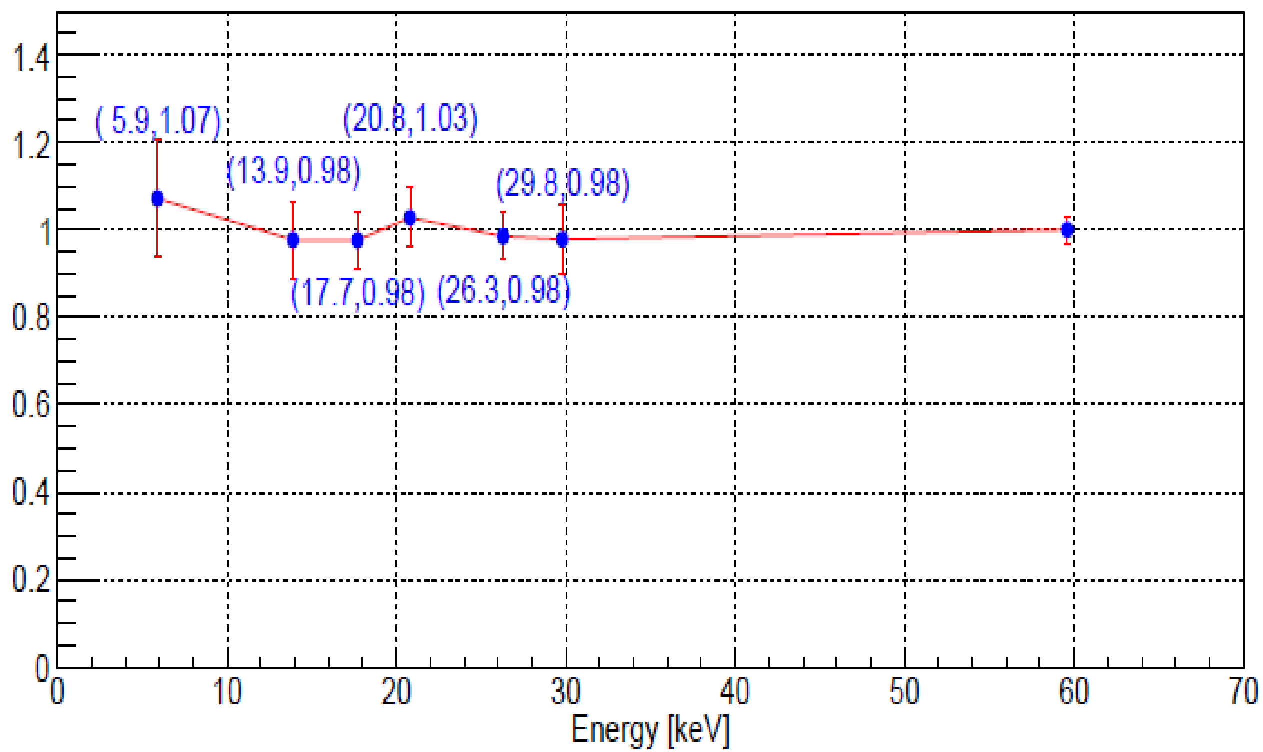
2 inch Prototype Linearity at 77K

- **Excellent LY linearity, showing a highly favorable upward trend at energies below 10 keV**
- **Better than $LaBr_3$, NaI:Tl in the low-energy regime**



Peiyi Feng *et al.* Nuclear Science and Techniques (2024) 35:23



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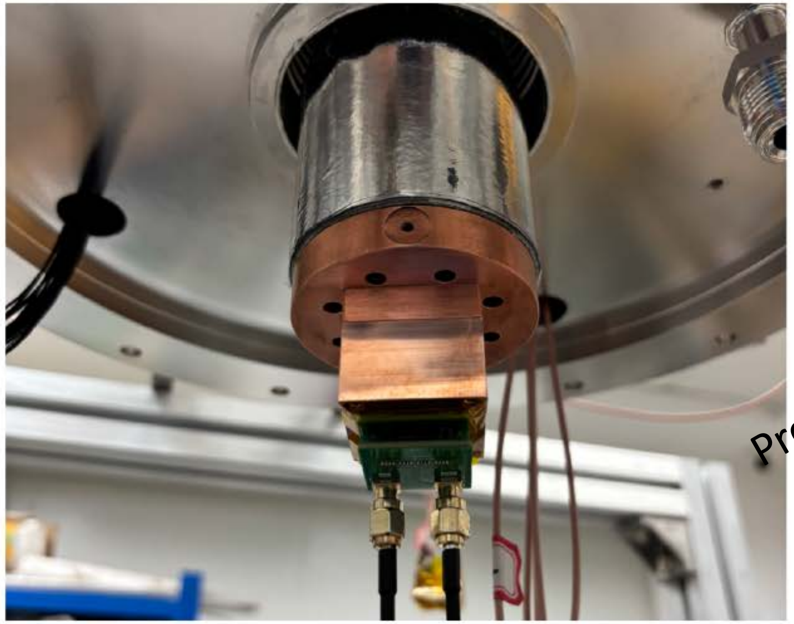
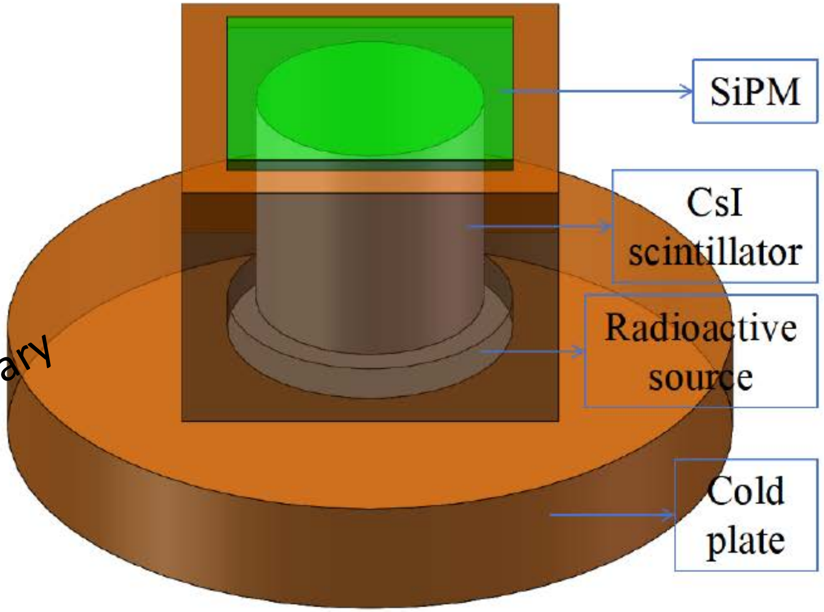
1-Inch Prototype Performance at 40 K

- CsI crystal ϕ2.5x2.5 cm, polished
- Packaging with Teflon reflective film, without TPB coating
- Single-end readout, SiPMs array, 2.5x2.5 cm, without TPB coating
- Cooling to 35 K with cooling machine

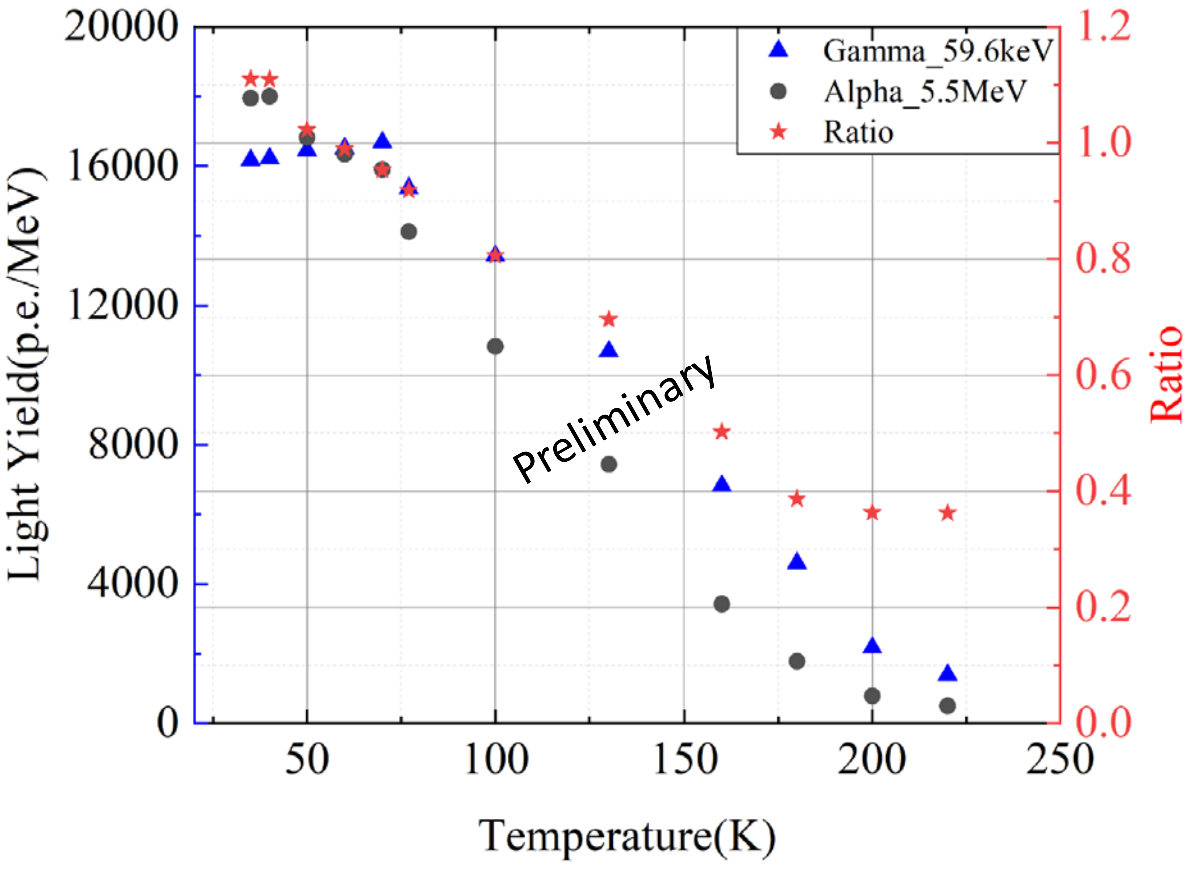


Preliminary



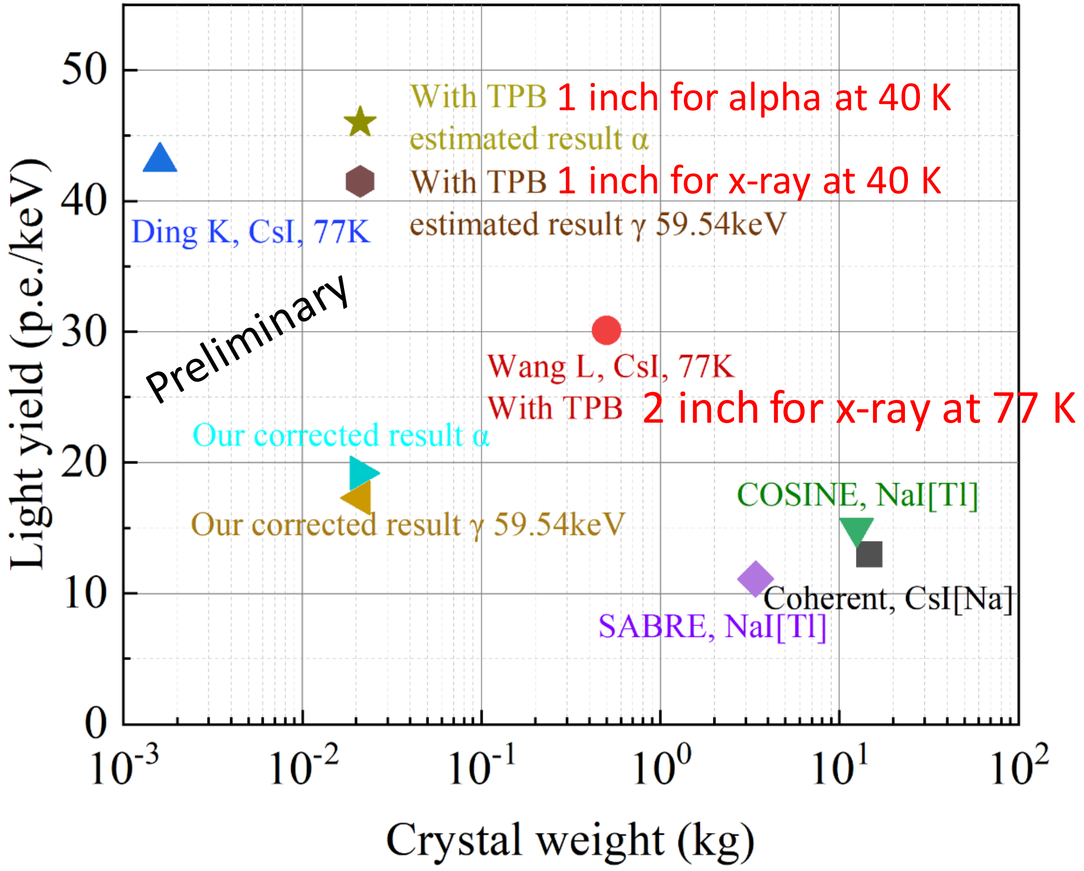
1-Inch Prototype Performance at 40 K

- **~16 p.e./keVee for 59.6 keV gamma, at 35.0 V bias, without TPB**
- **~18 p.e./keVα for 5.5 MeV alpha, at 35.0 V bias, without TPB**



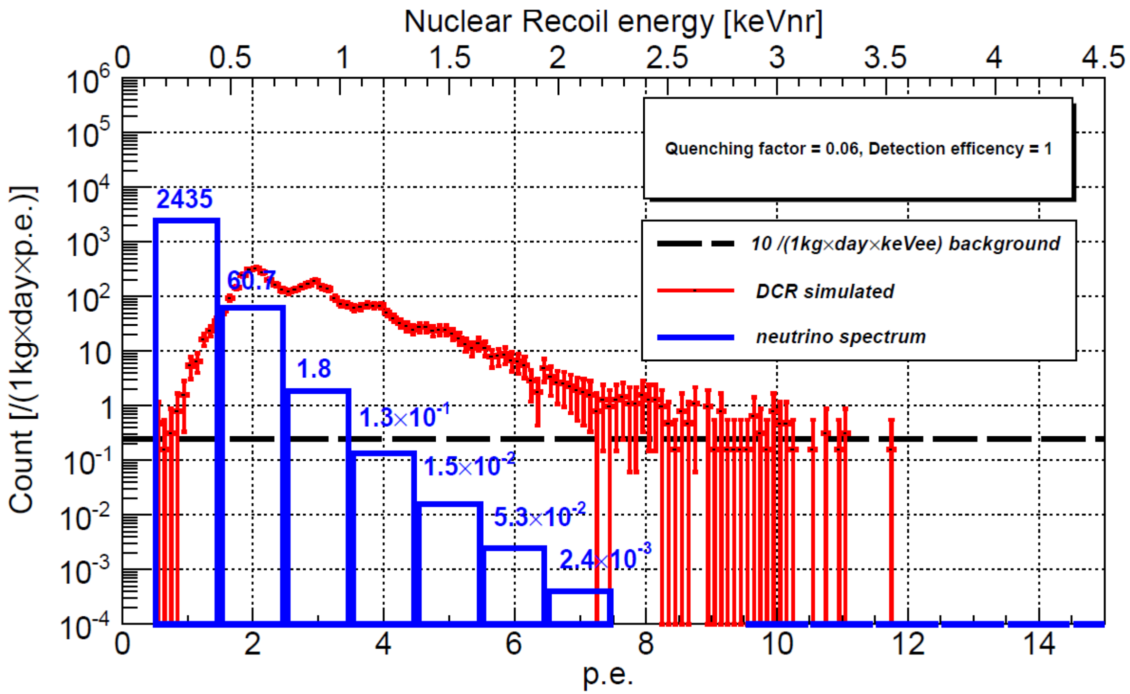
Light Yield Performance (With TPB)

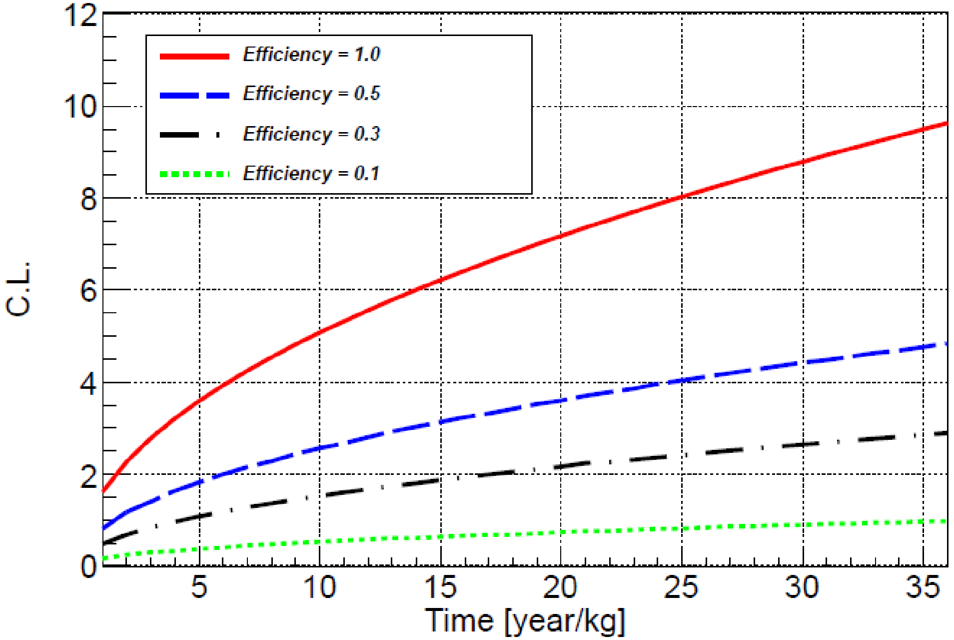
- **2-inch (77 K): ~30 p.e./keVee at 37.0 V bias,**
- **1-inch (40 K): ~37 p.e./keVee and ~42 p.e./keVα, at 37.0 V bias**



Sensitivity Projections for reactor neutrino

- 35 m distance to a 4.6 GWth reactor
- Assuming 40 p.e./keVee, QF=0.06, DCR= 0.1 CPS/mm^2
- 10 kg, requires 1 year to reach 5σ confidence level





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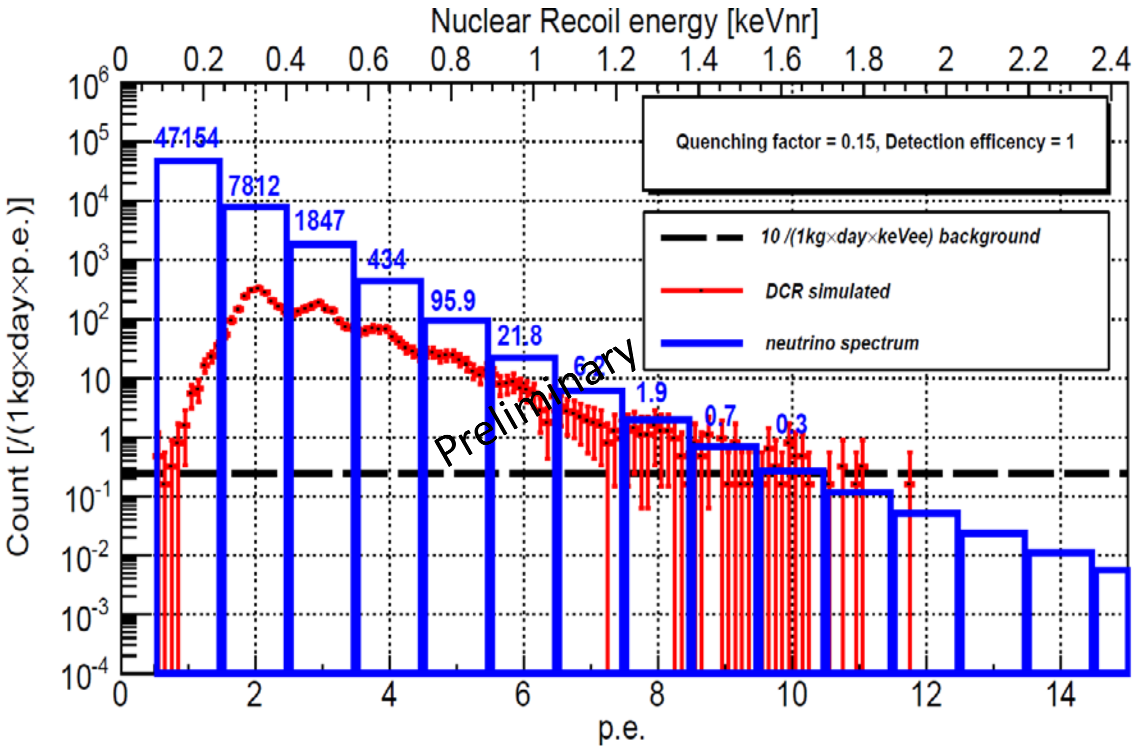
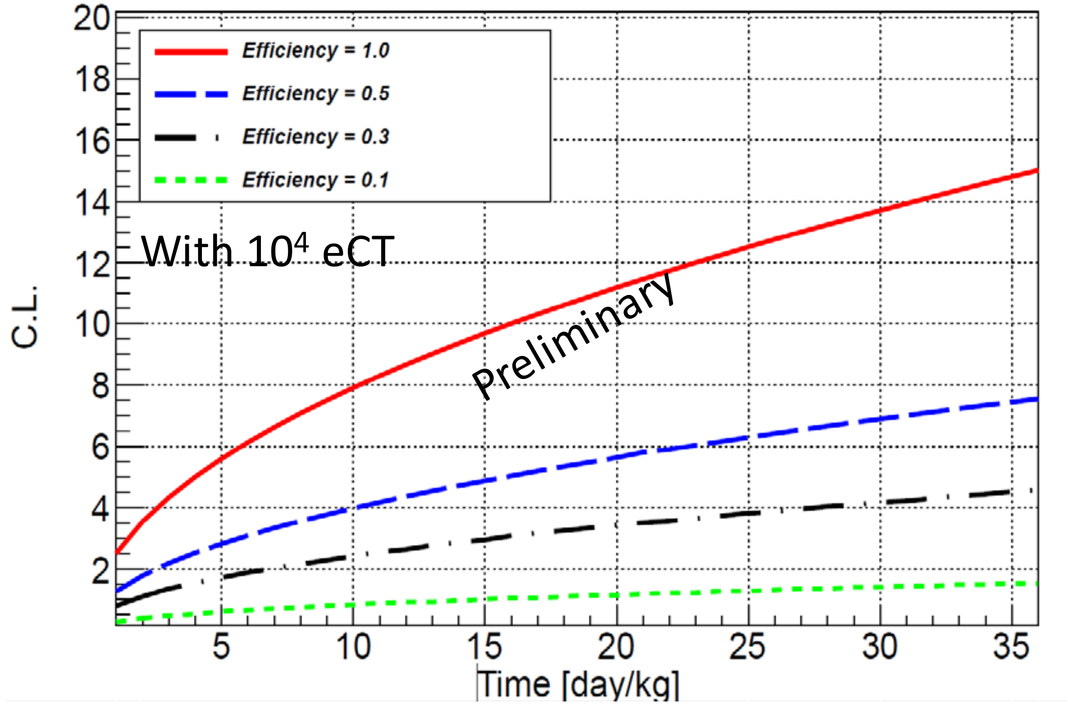
Sensitivity Projections for reactor neutrino

- **35 m distance to a 4.6 GWth reactor**
- **40 p.e./keVee, QF=0.15, DCR= 0.01 CPS/mm^2, optimistic estimate**
- **A 10 kg detector could achieve a 5σ confidence level in just 1 day**





Summary

- Overcoming the ultra-low energy threshold is the primary challenge for the next generation of CEvNS experiments
- Our proposed architecture (CsI + SiPM + TPB at 40 K) preliminary achieves a light yield of ~40 p.e./keVα
- QF is a key parameter and requires further measurement
- Kilogram-day scale detector is expected to be realized


Thank you for your attention!

backup

2 inch Prototype Light yield

- **~123 p.e./keVee, with CT AP**
- **~30 p.e./keVee, without CT AP**

V_{bias} (V)	p.e.	resolution	measured LY	corrected LY
34.0	176.8	14.3%	30.0±4.3	20.9±3.1
34.5	206.4	14.4%	35.0±5.0	23.4±3.6
35.0	241.4	14.4%	40.9±5.9	25.8±4.0
35.5	286.7	15.4%	48.6±7.5	26.7±4.3
36.0	359.4	16.2%	60.9±9.9	28.2±4.8
36.5	473.5	19.7%	80.2±15.8	29.0±5.9
37.0	723.8	26.0%	122.7±32.2	30.1±8.1

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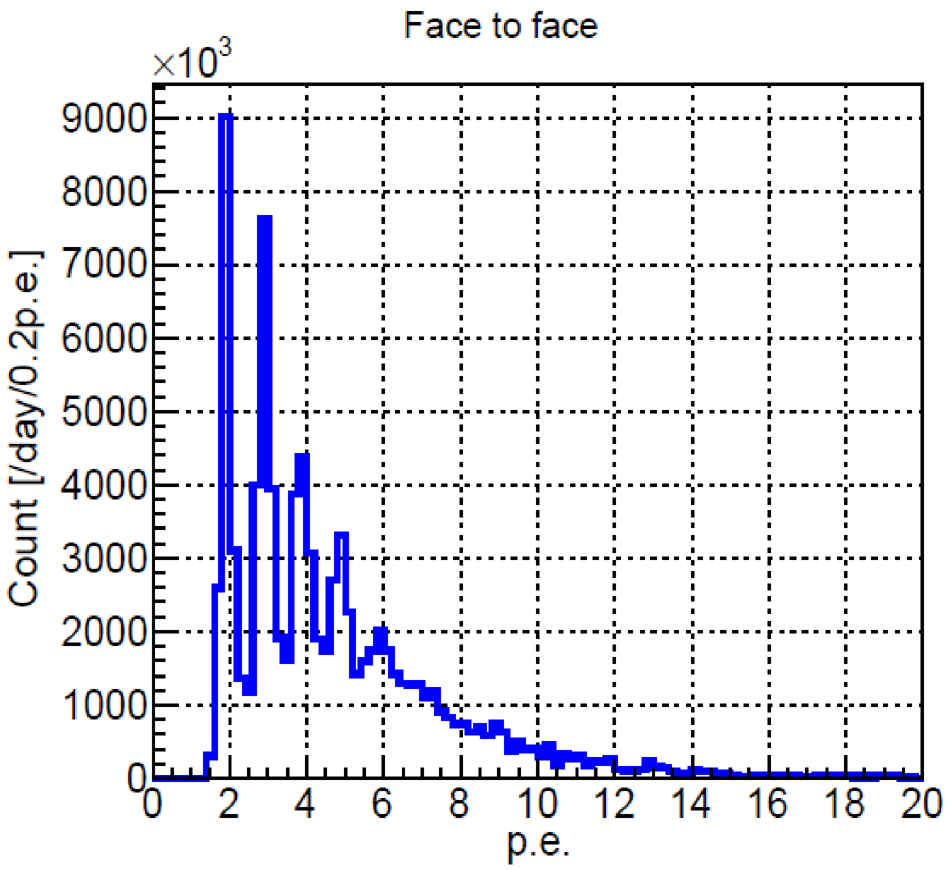
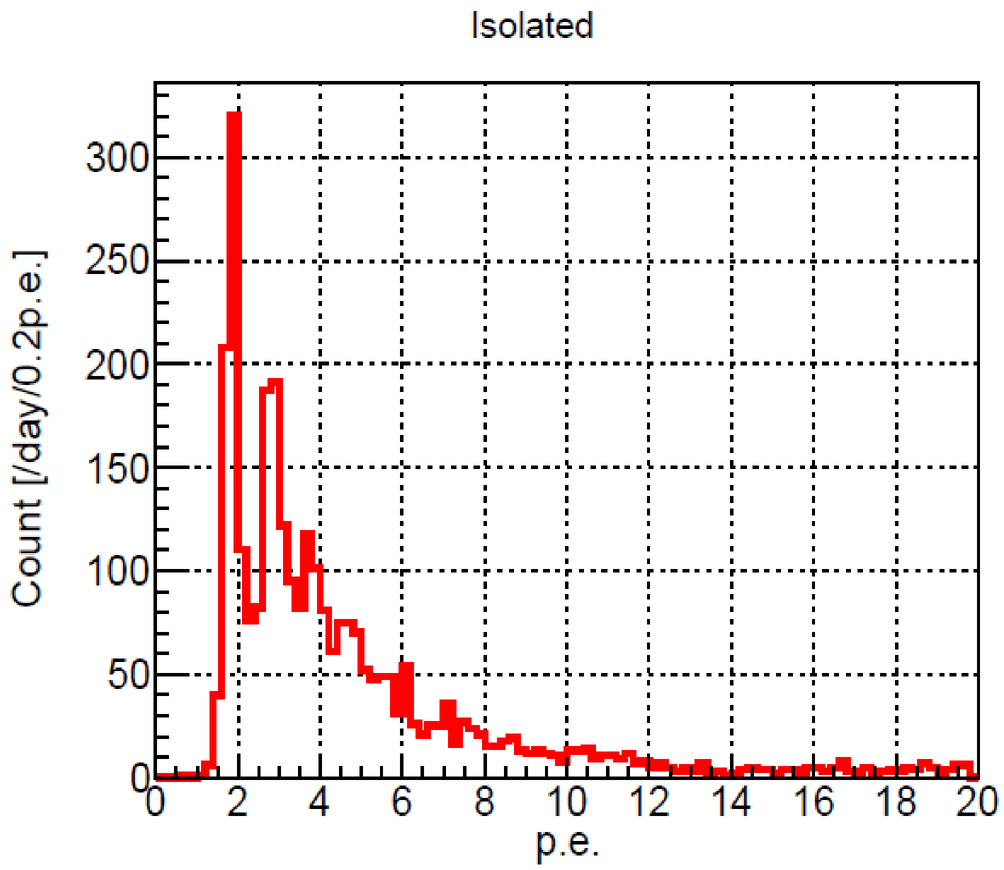
Issue of SiPMs eCT coincidence events

- **Events rate of eCT coincidence is very high**
- **5 orders larger than accidental coincidence of DCR**





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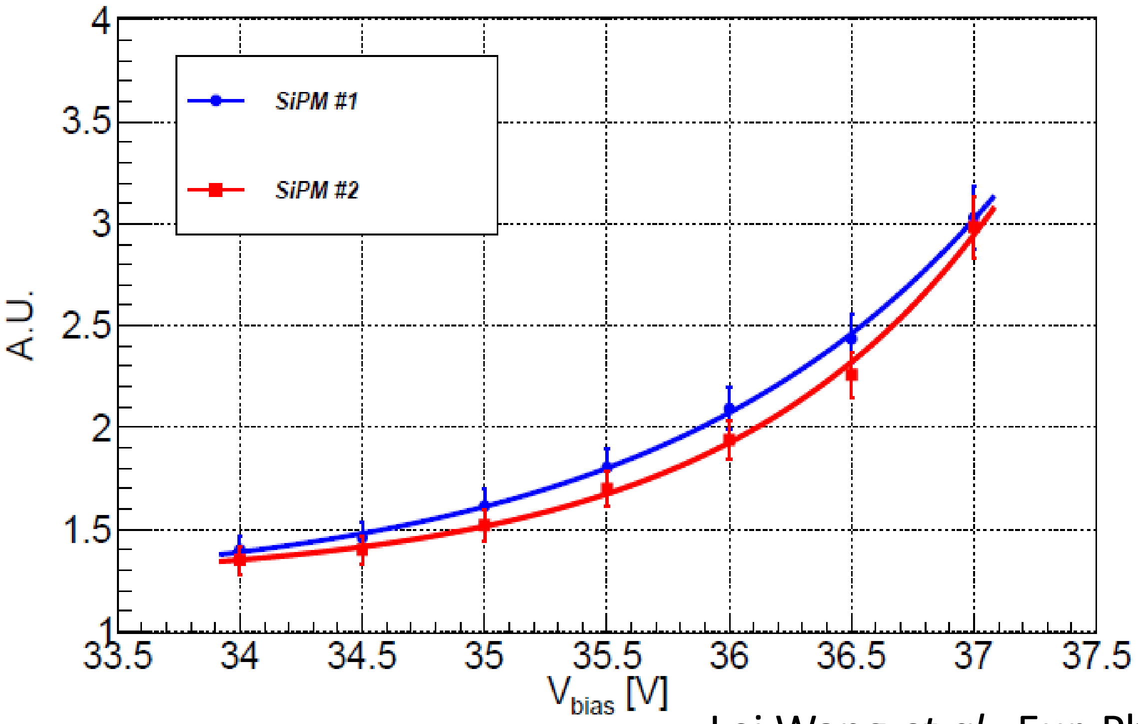
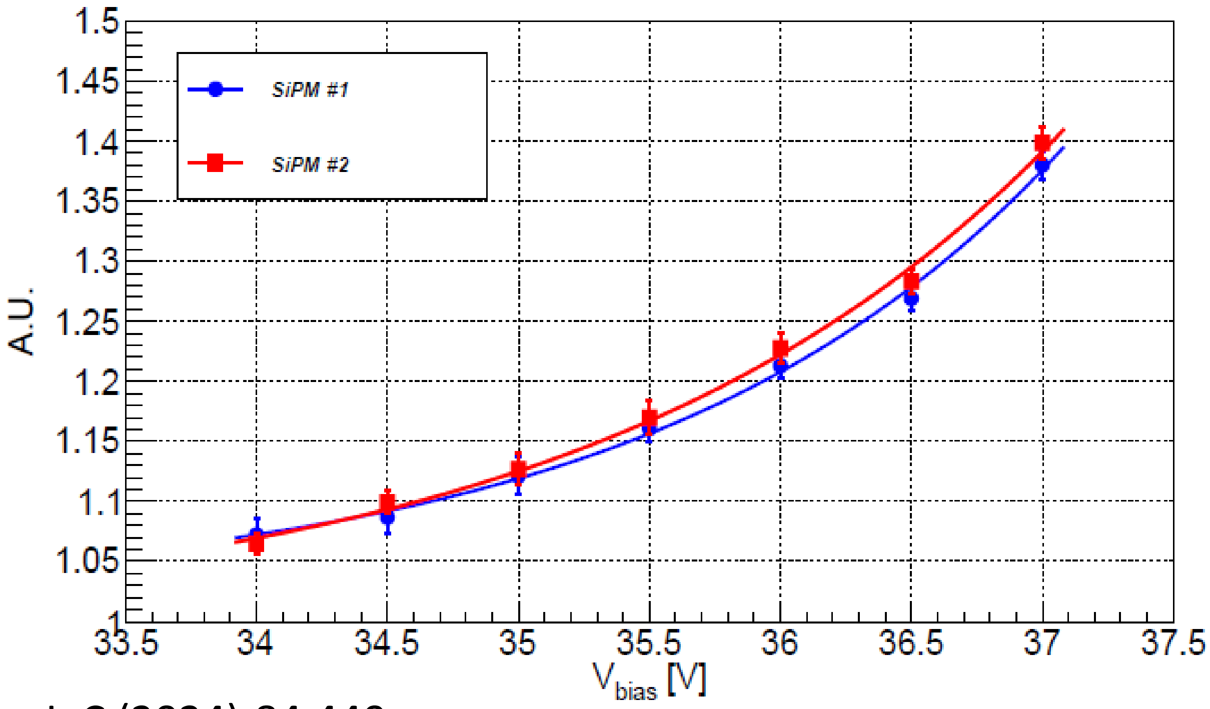
Influence of SiPMs Cross Talk and After Pulse

- **CT, AP significantly increasing the measured p.e. number**
- **Internal CT, AP triples the number of p.e. at 37 V_{bias}**
- **External CT 1.4 times the number of p.e. at 37 V_{bias}**





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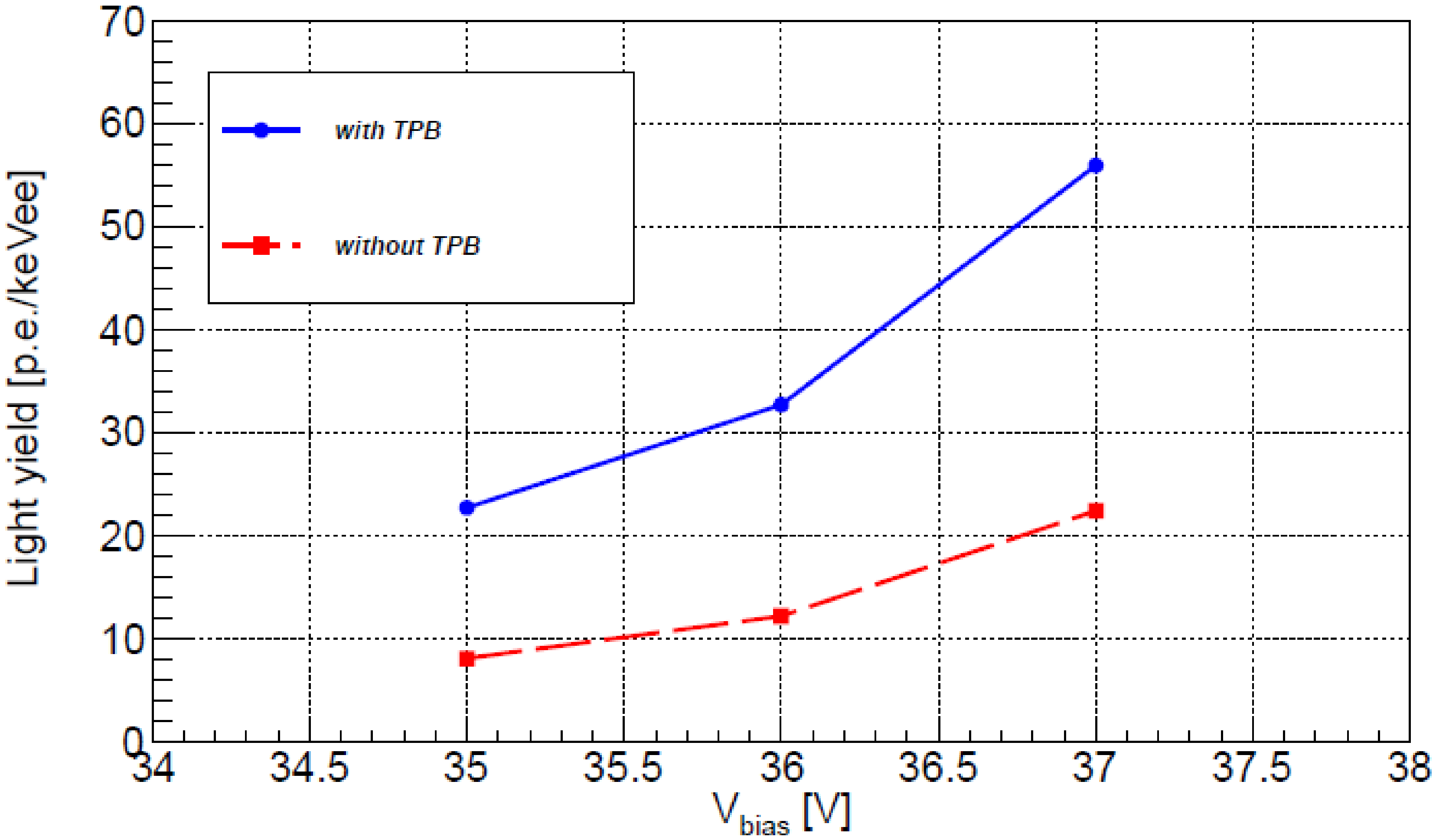
Influence of TPB

- Photoelectrons number is doubled with TPB



Lei Wang *et al.* Eur. Phys. J. C (2024) 84:440

Performance indicators	NaI:Tl[28]	SrI_2:Eu[29]	$LaBr_3$:Ce[3a]	$Cs_3Cu_2I_5$:Tl[6]	$Cs_3Cu_2I_5$:Mn This work
Light yield (^{137}Cs, Photons/MeV)	38,000	>90,000	70,000	87,000	95,772
Scintillation decay time (^{137}Cs)	230 ns	1200 ns	~16 ns	690 ns (88%)	3 ns (81.5%)
Energy resolution (^{137}Cs)	6%	2.6%	2.6%	3.4%	3.7%
Emission wavelength	415 nm	435 nm	390 nm	550 nm	445 nm
Density (g/cm^3)	~3.67	~4.55	~5.29	~4.51	~4.56

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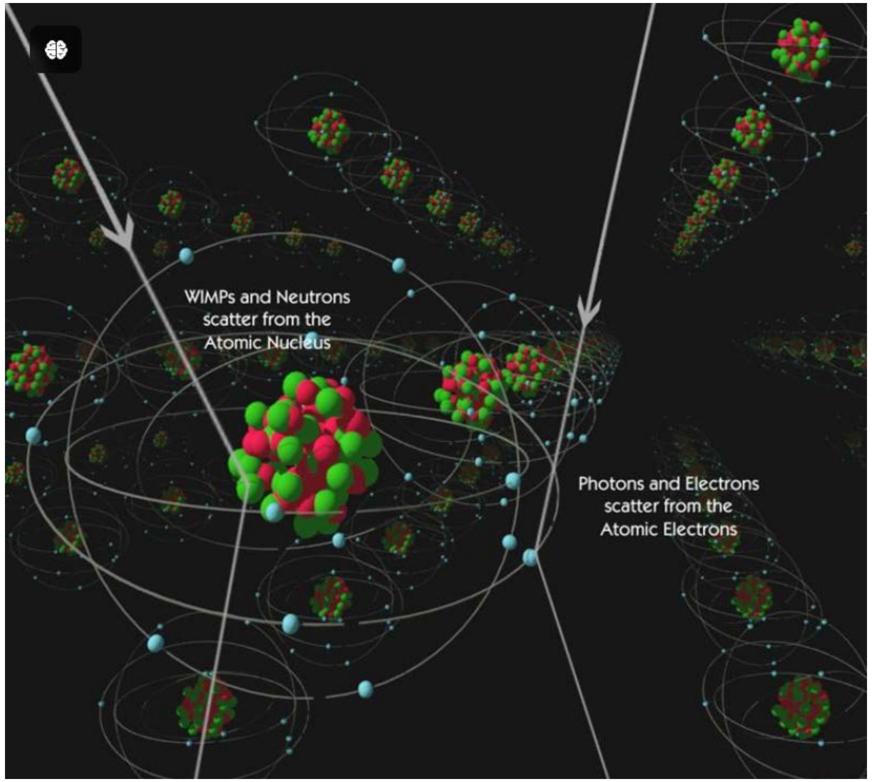
Other Potential Applications

- **Dark matter searches, better than RT NaI(Tl), CsI(Tl)**
- **Gamma ray spectrometer, no intrinsic BKG like $LaBr_3$**



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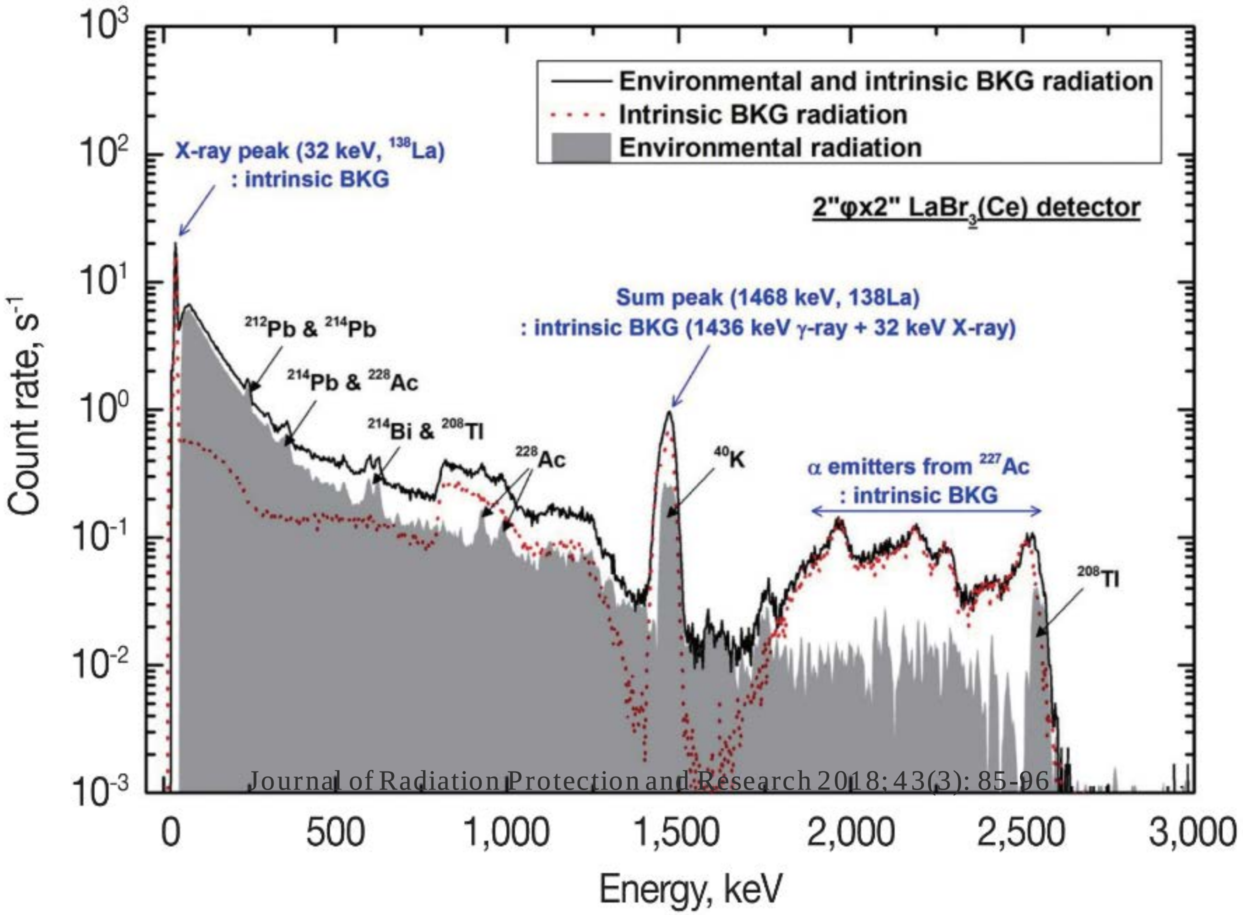

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