Brookhaven National Laboratory

U.S. DEPARTMENT of ENERGY

Characterization of Germanium Charge-coupled Devices toward Infrared Detectors for Spec-S5

E. Tamura, J. Estrada, P. Mukim, G. Pinaroli (Brookhaven National Laboratory)

S. E. Perez (University of Chicago)

C. Leitz, I. Prigozhin, K. Donlon (MIT Lincoln Laboratory)

S. Herrmann (Cornell University)

@BrookhavenLab

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MKI MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Brookhaven National Laboratory

Outline

- ✓ Scientific objective
- ✓ Germanium charge-coupled device
  - ✓ Device
  - ✓ Experimental setup
- ✓ Characterization results
  - ✓ Dark current
  - ✓ Optical characterization
  - ✓ X-ray characterization
- ✓ Summary and future development

Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MKI MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Outline

- ✓ Scientific objective
- ✓ Germanium charge-coupled device
  - ✓ Device
  - ✓ Experimental setup
- ✓ Characterization results
  - ✓ Dark current
  - ✓ Optical characterization
  - ✓ X-ray characterization
- ✓ Summary and future development

Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MKI MIT Kavli Institute for Astrophysics and Space Research

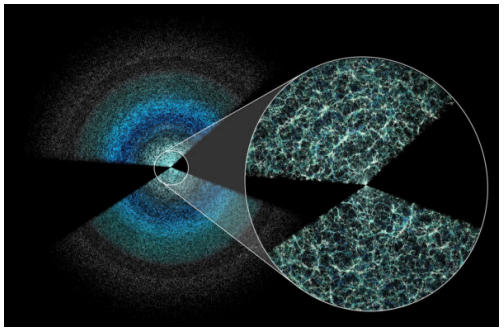
THE UNIVERSITY OF CHICAGO

Scientific Objective (I): DESI to Spec-S5

DESI (Dark Energy Spectroscopic Instrument)

- State-of-the-art spectroscopic sky survey
- Dark energy and the expansion history of the cosmos
- 5000 robotic fiber positioners
- Create the largest 3D map of the universe ever made
- Galaxies to $z \approx 1.6$ ([O II])

Limited by Si CCD cutoff (~1.1 μm) due to Eg=1.15 eV **Si wall**

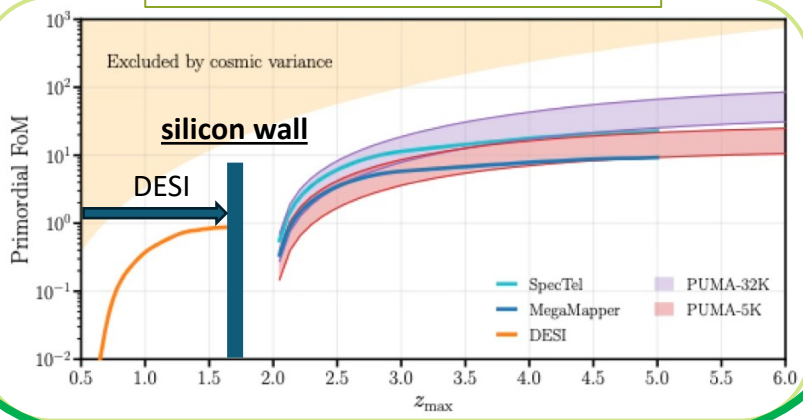


Claire Lamman /DESI collaboration

Spec-S5 (Spectroscopic Stage-V Experiment)

- Next-generation cosmological survey
- Use ~26,000 robotic fibers
- Map the high-redshift universe (z>1.6)
- Increase ×10~100 primordial FoM to study the physics of inflation and the early universe

Scientific power in measuring the initial conditions of the universe



Brookhaven National Laboratory

LINCOLN LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

DESI Collaboration 2025, DR2 Results II (arXiv:2503.14738)

Schlegel et al. (2022) arXiv:2209.03585

Scientific Objective (II): Why Germanium CCD

Why germanium?

- Comparison between silicon and germanium

	Bandgap (eV)	Cutoff wavelength (μm)	z_{max} ([O II])
Silicon	1.15 (at 170 K)	1.1	1.6
Germanium	0.73 (at 77K)	1.7	3.0–3.5

Germanium can break the silicon wall to reach z=3.0–3.5

Why germanium CCD?

1. CCD readout: low noise (CDS/skipper), large format
2. Monolithic: no hybridization, low cost
3. Similar fabrication technology: nearly the same VLSI tools*
4. Same infrastructure: electronics, cooling, data processing

Brookhaven National Laboratory

LINCOLN LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MKI MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

*Leitz et al. (2020) SPIE Proc. 11454 114541B

Outline

- ✓ Scientific objective
- ✓ Germanium charge-coupled device
  - ✓ Device
  - ✓ Experimental setup
- ✓ Characterization results
  - ✓ Dark current
  - ✓ Optical characterization
  - ✓ X-ray characterization
- ✓ Summary and future development

Brookhaven National Laboratory

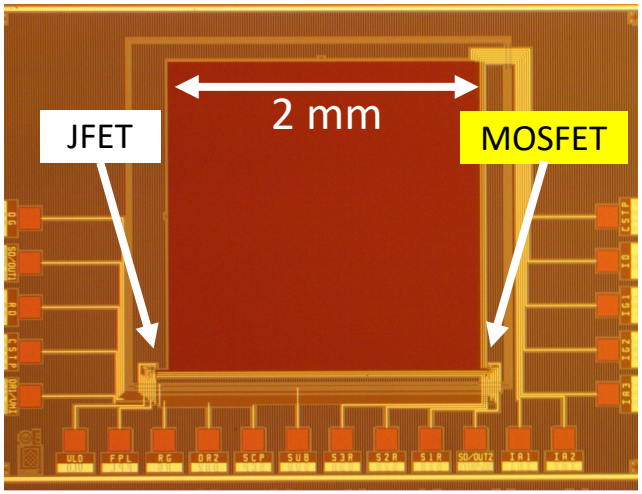
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MKI MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Ge-CCD: Device GEDI7 -1 0

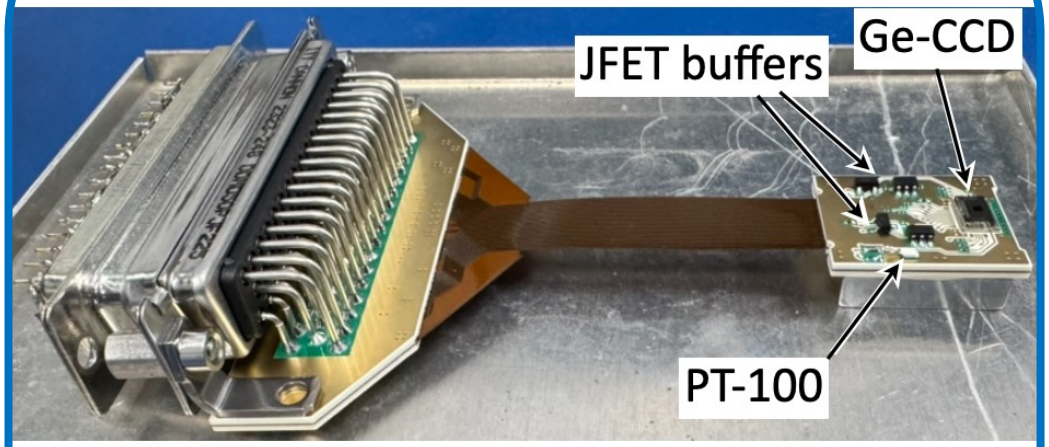
Microscope image



- Fabricated by MIT LL
- Front-illuminated
- Full-frame transfer, three phase
- P-ch (carrier: hole)
- 256×256 pixels
- 8.1 µm×8.1 µm
- Charge injection gate
- Two output nodes (MOSFET & JFET)

Packaged CCD

GEDI7 -1 0



- Custom interposer for cryogenic cooling
- Die-bonded and wire-bonded on the custom interposer
- Temperature monitor with PT-100
- DB50 for signal interfacing

Tamura et al. (2026) arXiv:2610.22785

Brookhaven National Laboratory

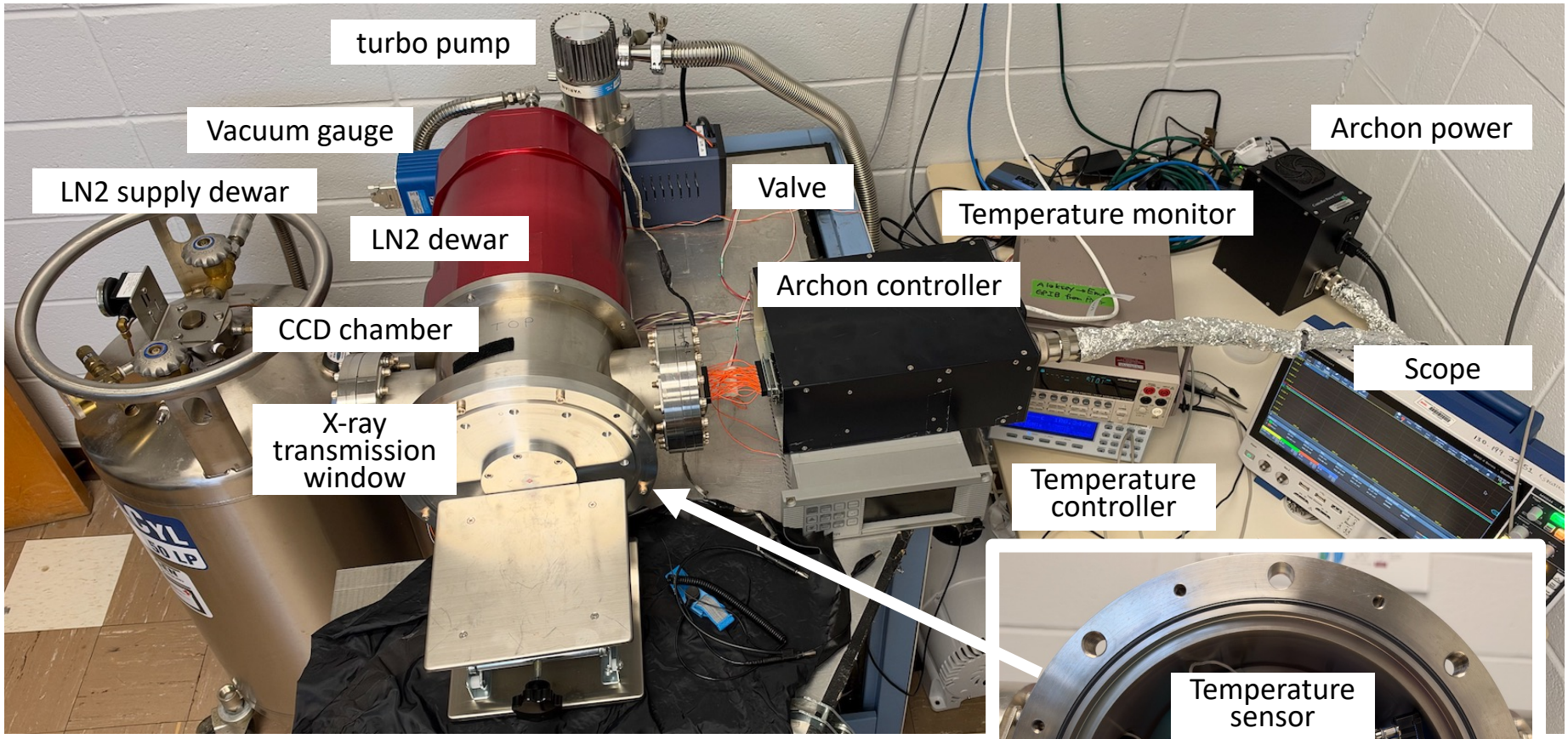
LINCOLN LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY

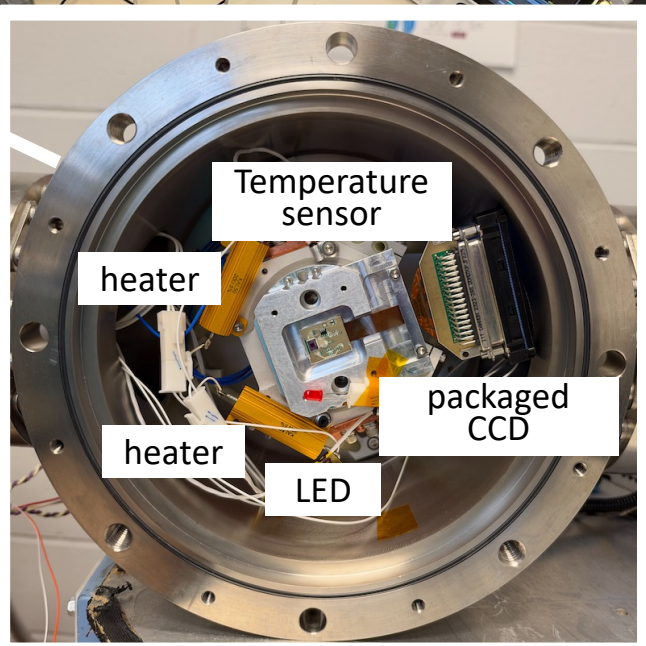
MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Donlon et al. (2025) SPIE Proc. 3625, 136251S

Ge-CCD: Experimental Setup at BNL





Rapidly completed using LSST heritage

Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MKI MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Tamura et al. (2026) arXiv:2610.22785

Ge-CCD: Operating conditions

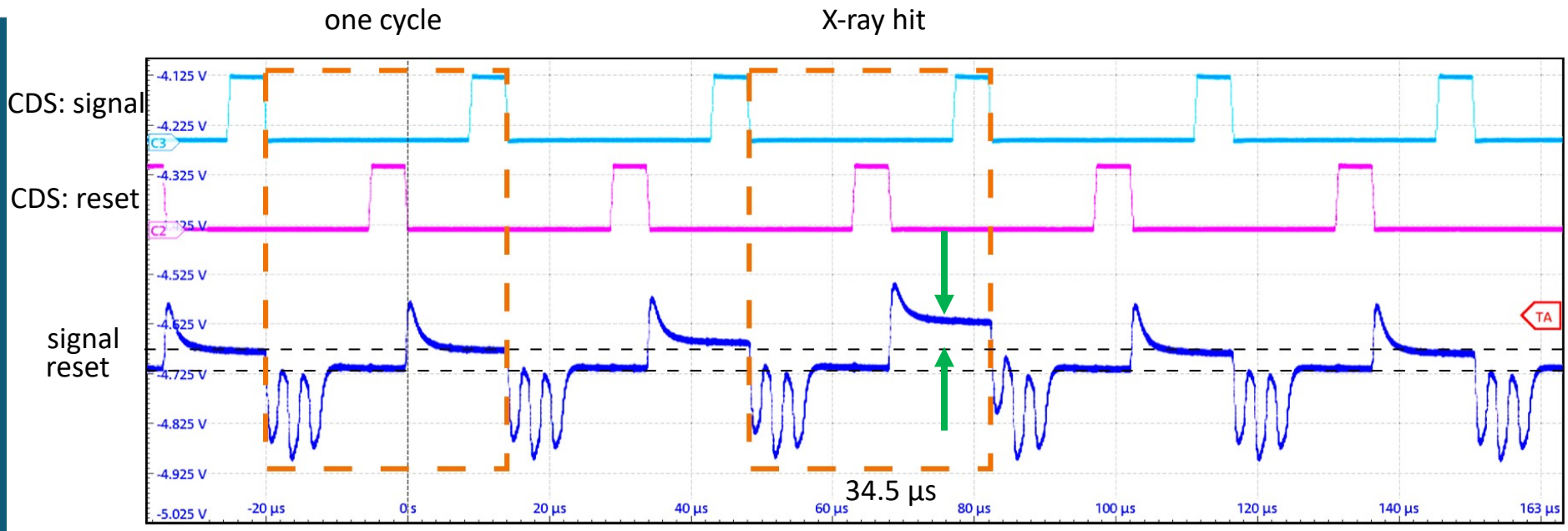
- Operating temperature: 95–97 K
- Operation mode
  - Unbinned mode (1×1) <30 keV
    - 256×256 (active) 300×300 (readout) 8.1 μm square
    - pixel rate: 29 kHz, frame readout: 3.25 s
  - On-chip 2×2 binning mode >30 keV
    - 128×128 (active) 150×150 (readout) 16.2 μm square
    - pixel rate: 23 kHz, frame readout: 1.14 s
- Exposure time: 60 s for optical, 51 ms for X-rays
- Parallel clock voltage: +1/-2 V (nominal) 0/-2 V (exposure)
- Serial transfer clock voltage: +1/-2 V
- Reset voltage: +2/-0.5 V
- |Maximum bias voltage|: 10 V

Voltage ranges are basically the same or even lower than those of silicon CCDs

Brookhaven National Laboratory
LINCOLN LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MKI MIT Kavli Institute for Astrophysics and Space Research
THE UNIVERSITY OF CHICAGO

Ge-CCD: CCD waveform with CDS

Unbinned mode



CDS: correlated double sampling
sampling window = 5.12 µs
averaged over 512 samples

Silicon-CCD-like waveforms obtained!

Tamura et al. (2026) arXiv:2610.22785

Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Outline

- ✓ Scientific objective
- ✓ Germanium charge-coupled device
  - ✓ Device
  - ✓ Experimental setup
- ✓ Characterization results
  - ✓ Dark current
  - ✓ Optical characterization
  - ✓ X-ray characterization
- ✓ Summary and future development

Brookhaven National Laboratory

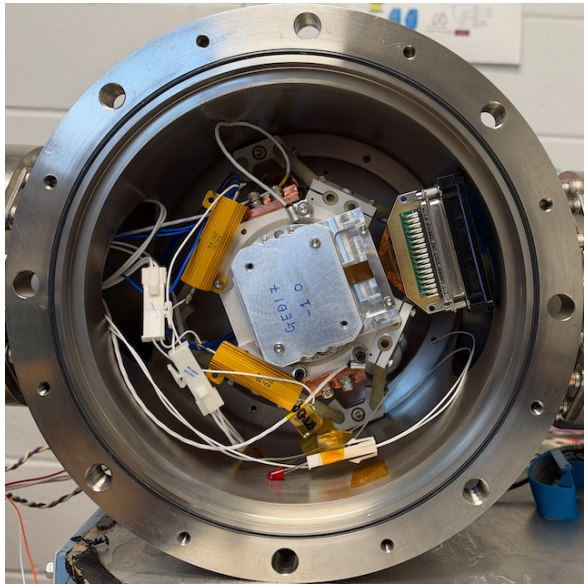
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

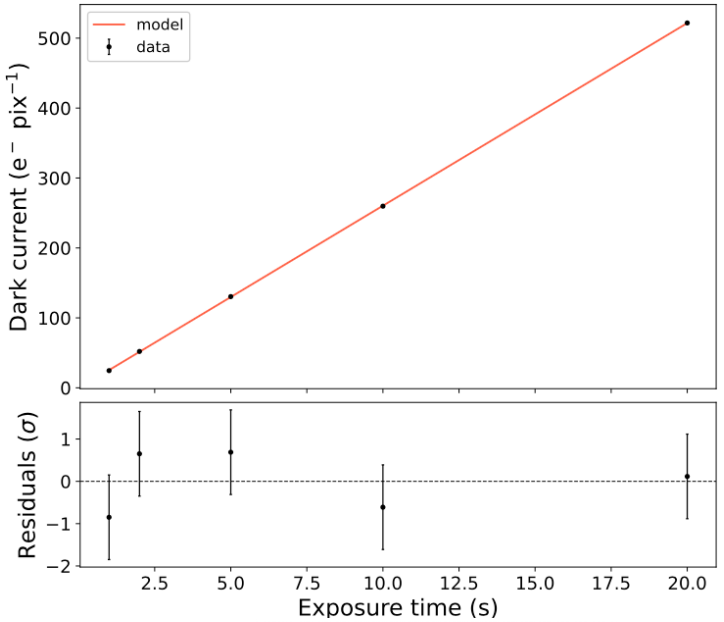
MKI MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Ge-CCD: Dark current

- Calculated by
  (average of active area)-(average of vertical over-clocked area)
  with conversion gain measured by X-ray characterization
  after excluding hot pixels (~2% of total pixels).
- Measured for exposure times between 1 and 20 s
- Dark current: 26.12 $\pm$ 0.08 e^- pix^{-1} s^{-1} at 94.69 $\pm$ 0.04 K





Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

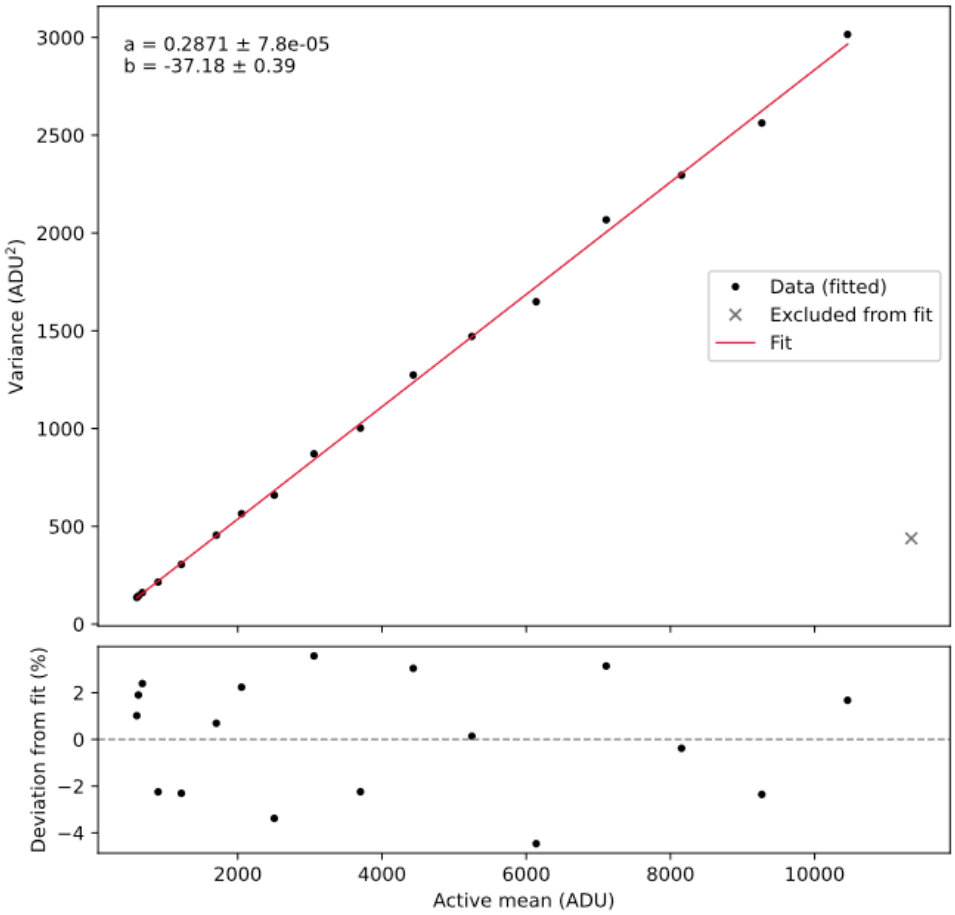
MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Tamura et al. (2026) arXiv:2610.22785

Ge-CCD: Optical Characterization

- Photon transfer curve using a simple LED irradiation.
  - Well fitted with linear function
  - Conversion gain: 3.48 e^- ADU^{-1}
  - Full well: 36.4 ke^-
- Will use an integrating sphere to take a precise measurement



Brookhaven National Laboratory

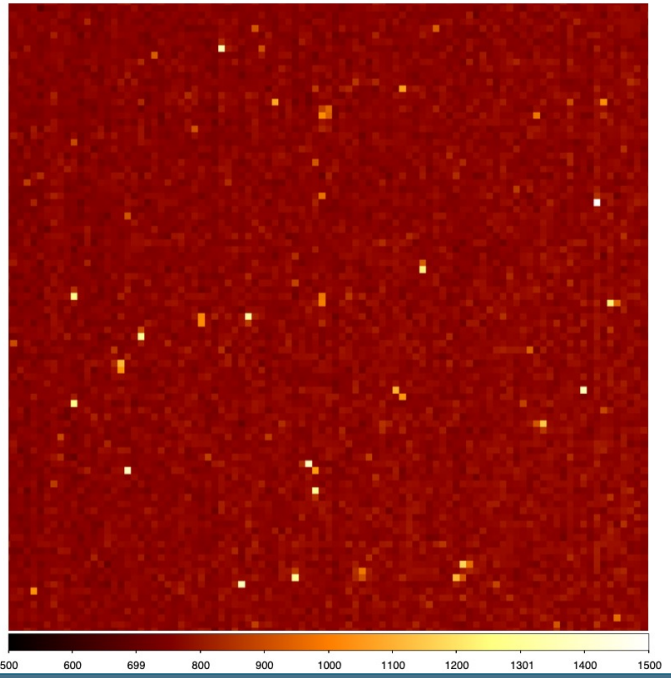
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

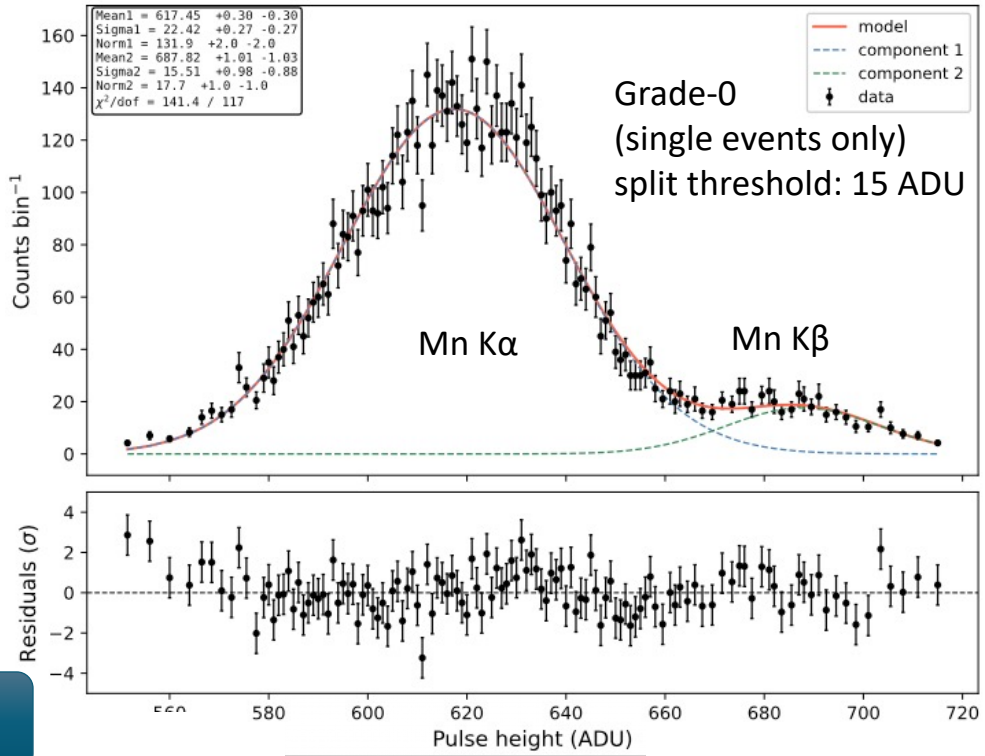
MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Ge-CCD: X-ray Characterization (I)

- ^{55}Fe irradiation
- Operated with unbinned (1×1) mode
- X-ray charge confined within 2×2 pixels
- Mn Kα and Kβ can be resolved
- 8.5±0.1% FWHM @ 5.9 keV for single-pixel events





Silicon-CCD-like image obtained!

Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

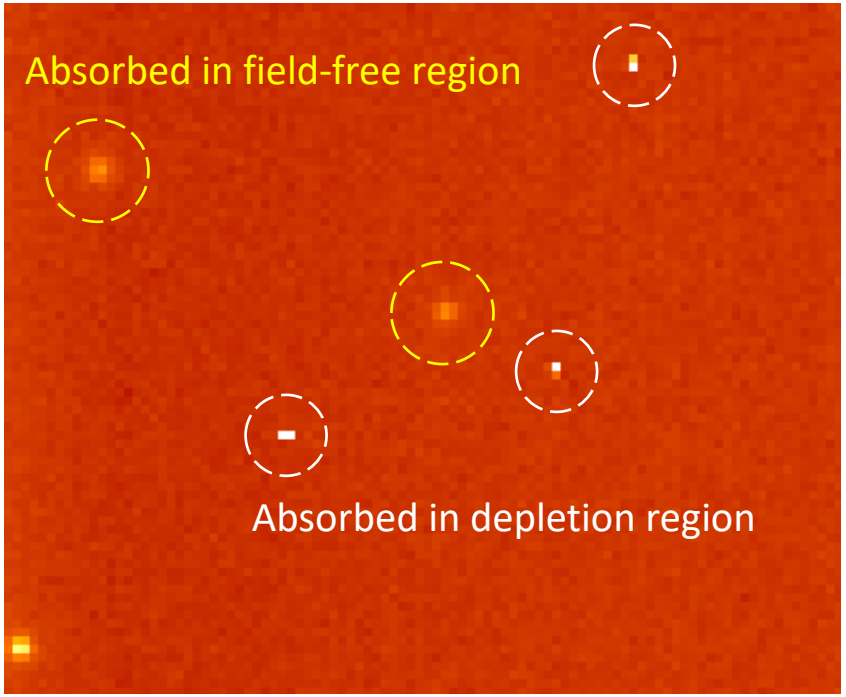
MKI MIT Kavli Institute for Astrophysics and Space Research

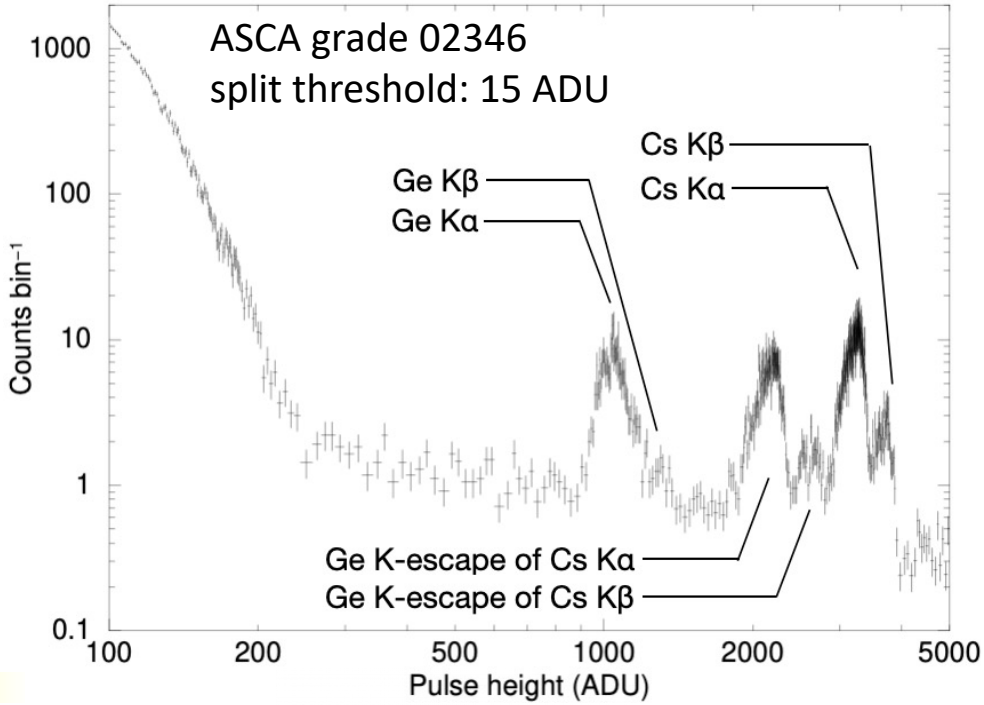
THE UNIVERSITY OF CHICAGO

Tamura et al. (2026) arXiv:2610.22785

Ge-CCD: X-ray Characterization (II)

- ^{133}Ba irradiation
- Operated with on-chip 2×2 binning mode
- Cs Kα, Kβ, and their Ge K-escape can be clearly resolved
- 8.4±0.4% FWHM @ 30.9 keV for ASCA grade 02346 (2×2) events





Brookhaven National Laboratory

LINCOLN LABORATORY, Massachusetts Institute of Technology

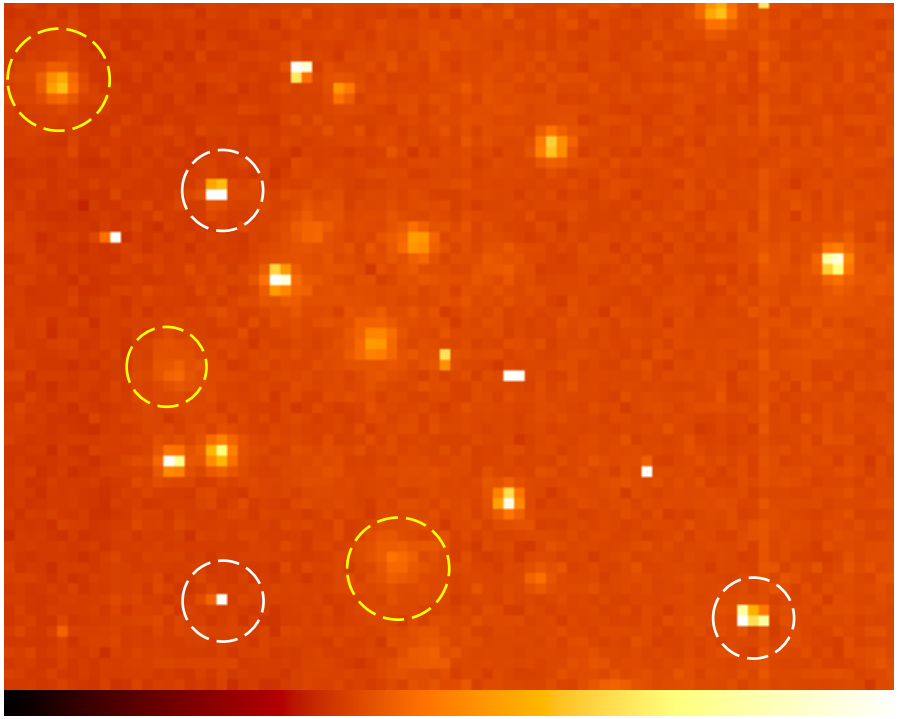
MKI MIT Kavli Institute for Astrophysics and Space Research

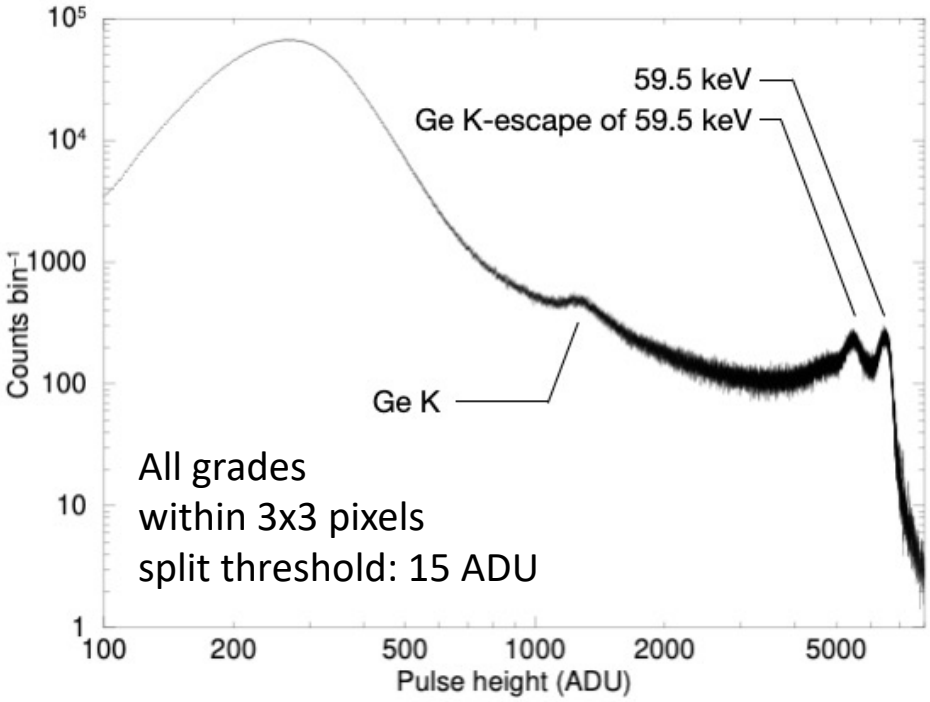
THE UNIVERSITY OF CHICAGO

Tamura et al. (2026) arXiv:2610.22785

Ge-CCD: X-ray Characterization (III)

- ^{241}Am irradiation
- Operated with on-chip 2×2 binning mode
- 7.45 ± 0.45% FWHM @ 59.5 keV for all-grade (3×3) events





Brookhaven National Laboratory

LINCOLN LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY

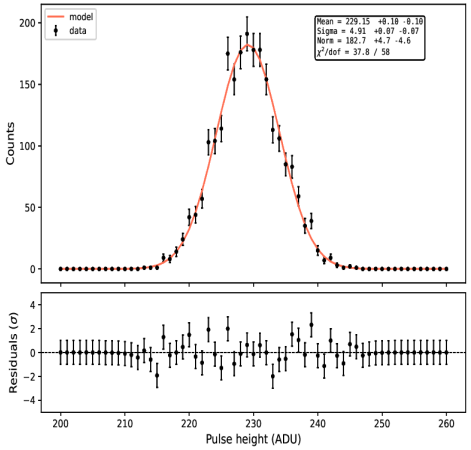
MIT Kavli Institute for Astrophysics and Space Research

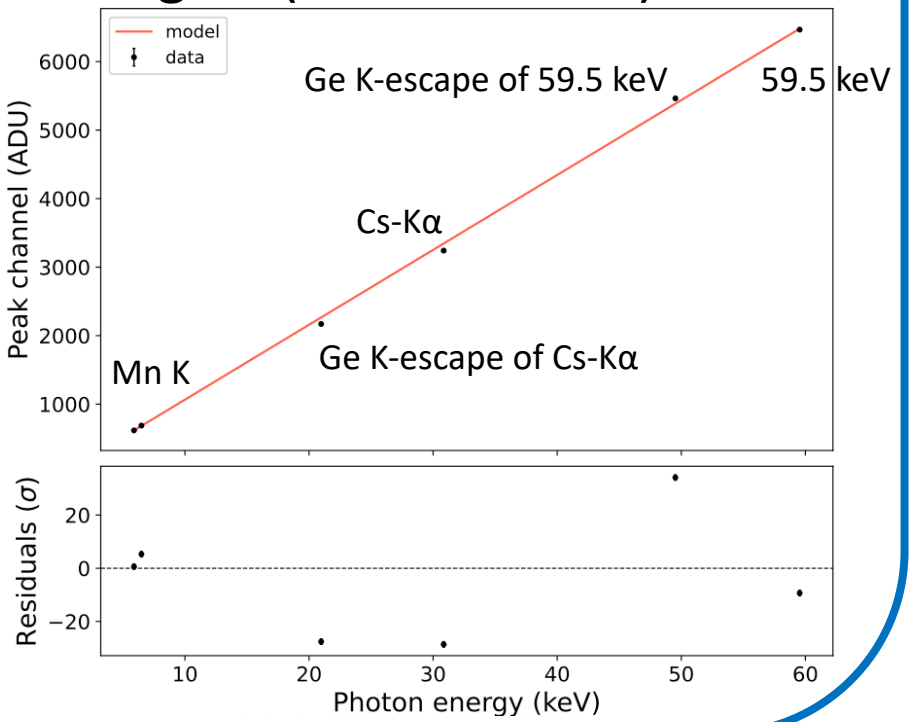
THE UNIVERSITY OF CHICAGO

Tamura et al. (2026) arXiv:2610.22785

Ge-CCD: X-ray Characterization (IV)

- Photon energy and pulse height relationship
- Linear fitting gives us gain of 9.13 eV ADU^{-1}
- Using w=2.97 eV $(e^-)^{-1}$(Antman), conversion gain=3.08 e^- ADU^{-1}
  - Reasonable agreement with PTC gain (3.48 e^- ADU^{-1})
- σ of horizontal overclock
  = 5.02 ADU rms
- Readout noise: 15.4 e^- rms





Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Tamura et al. (2026) arXiv:2610.22785

Outline

- ✓ Scientific objective
- ✓ Germanium charge-coupled device
  - ✓ Device
  - ✓ Experimental setup
- ✓ Characterization results
  - ✓ Dark current
  - ✓ Optical characterization
  - ✓ X-ray characterization
- ✓ Summary and future development

Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MKI MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Summary and Future Development

- ✓ We set up the measurements for the germanium charge-coupled devices (Ge-CCDs) by MIT LL under cryogenic conditions (95 K).
  - ✓ Same infrastructure and software as Si-CCDs
  - ✓ Dark current of 26.12 ± 0.08 $e^- pix^{-1} s^{-1}$ at 94.69 ± 0.04 K
  - ✓ Photon transfer curve to determine the conversion gain (3.48 $e^- ADU^{-1}$) and the full well at 36 ke^-
  - ✓ First detailed X-ray characterization of a Ge-CCD, from 5.9 to 59.5 keV to evaluate the gain (3.08 $e^- ADU^{-1}$), noise, and linearity
  - ✓ Readout noise of 15.4 e^- rms

Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Ge-CCD: Comparison with other IR detectors



Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Tamura et al. (2026) arXiv:2610.22785

Ge-CCD: Comparison with other IR detectors



Brookhaven National Laboratory

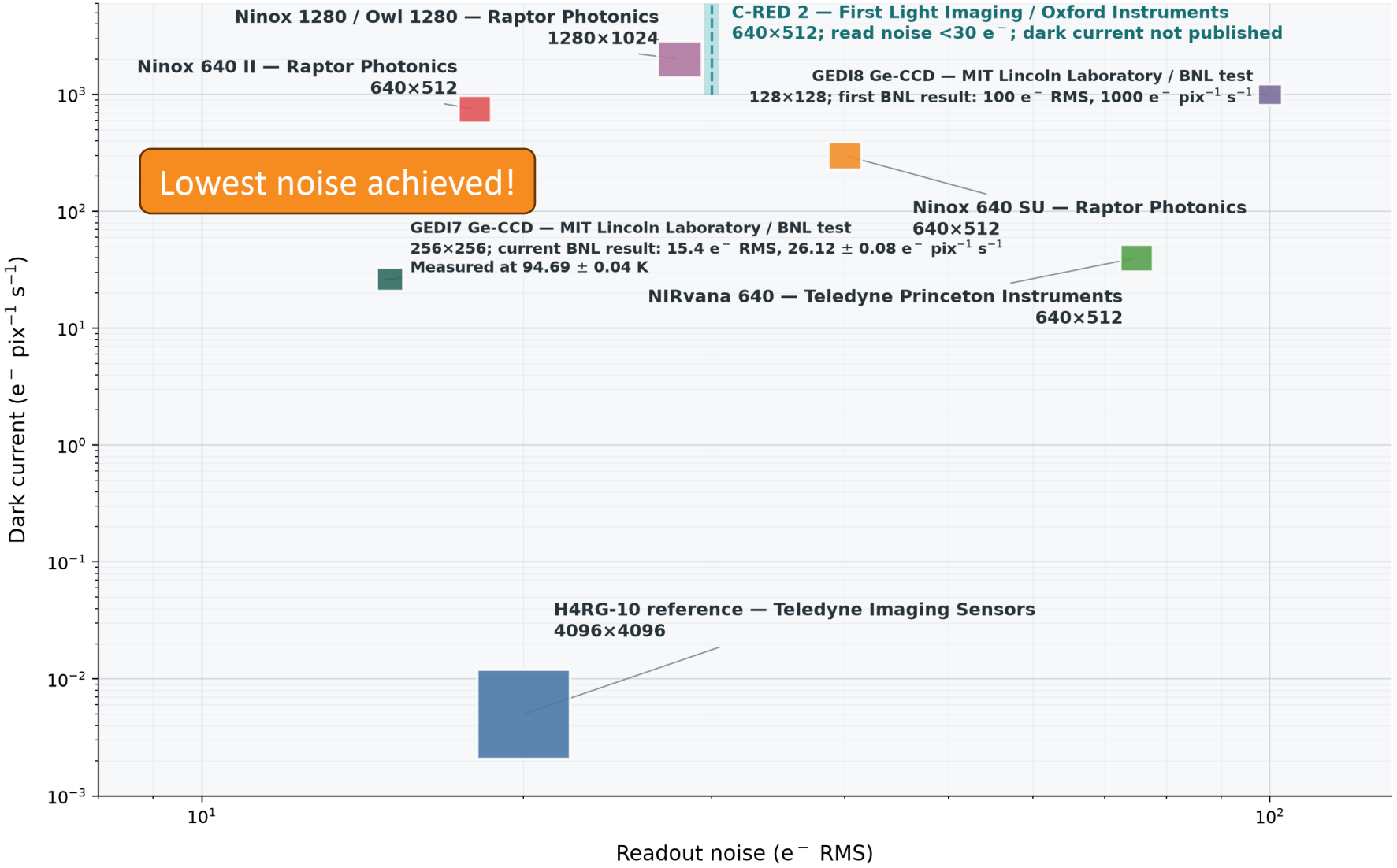
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Tamura et al. (2026) arXiv:2610.22785

Ge-CCD: Comparison with other IR detectors



Brookhaven National Laboratory

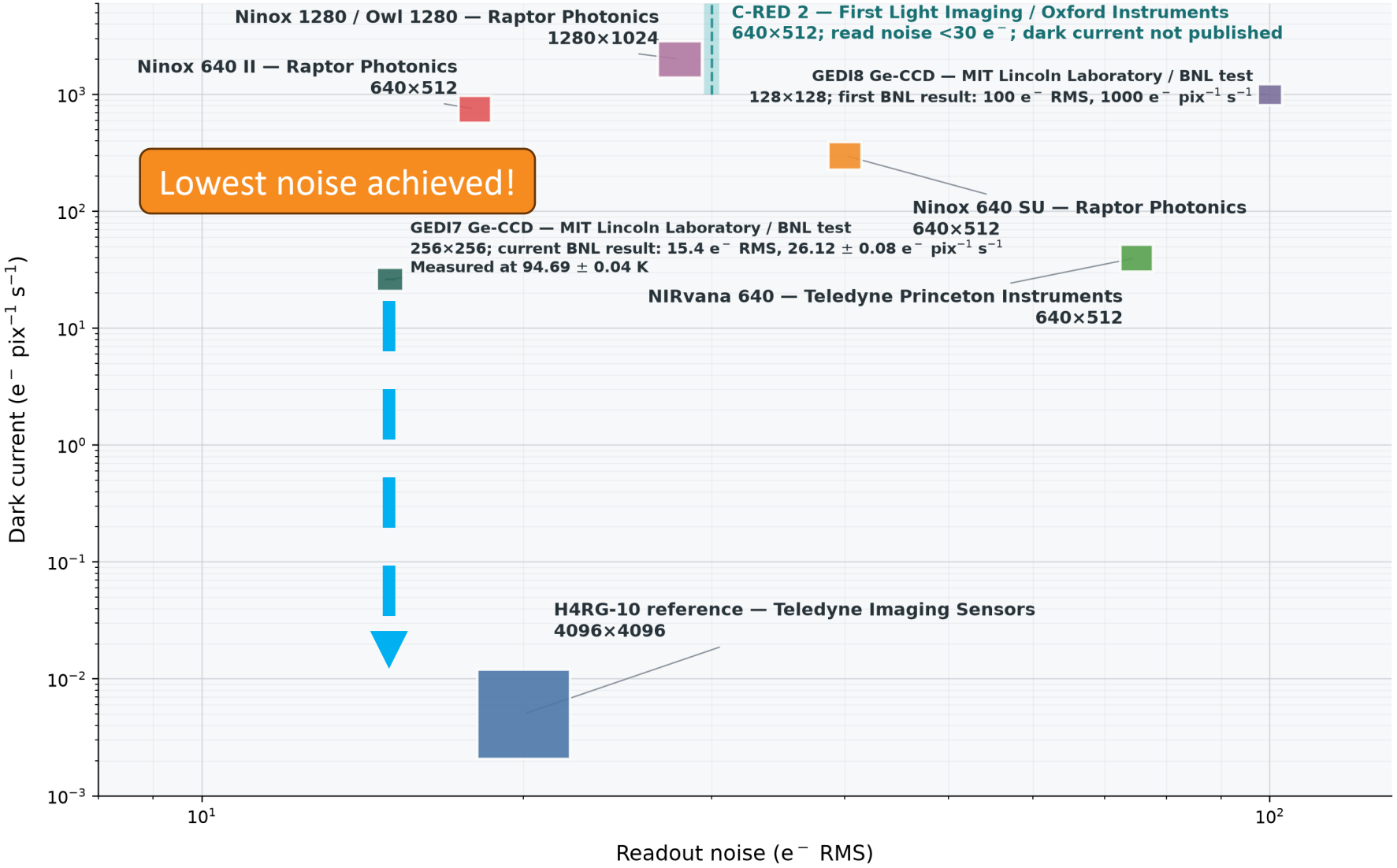
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MKI MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Tamura et al. (2026) arXiv:2610.22785

Ge-CCD: Comparison with other IR detectors



Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

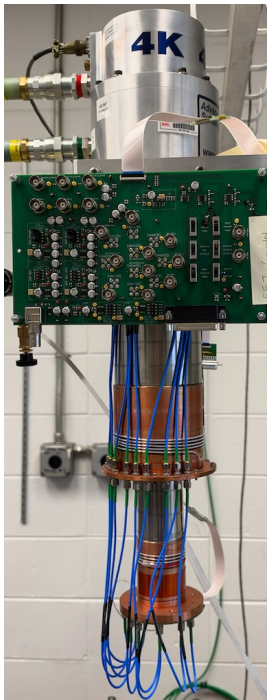
MKI MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Tamura et al. (2026) arXiv:2610.22785

Summary and Future Development

- ✓ We set up the measurements for the germanium charge-coupled devices (Ge-CCDs) under cryogenic conditions (95 K).
  - ✓ Same infrastructure and software as Si-CCDs
  - ✓ Dark current of 26.12 ± 0.08 e^- pix^{-1} s^{-1} at 94.69 ± 0.04 K
  - ✓ Photon transfer curve to determine the conversion gain (3.48 e^- ADU^{-1}) and the full well at 36 ke^-
  - ✓ First detailed X-ray characterization of a Ge-CCD, from 5.9 to 59.5 keV to evaluate the gain (3.08 e^- ADU^{-1}), noise, and linearity
  - ✓ Readout noise of 15.4 e^- rms
- Reduce noise by adding a preamp inside the chamber
- Test devices below 50 K
  - Reduce dark current
- Take precise measurements of the PTC using an integrating sphere.
- Measure NIR quantum efficiency
- Agentic optimization by Mukim et al.



Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO

Acknowledgement

This work is supported by the Brookhaven National Laboratory Program Development fund (PD26-006).
We gratefully acknowledge support for this device fabrication from NASA's Astrophysics Division through Astrophysics Research and Analysis Award 80HQTR19T0048.

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited. This material is based upon work supported by the National Aeronautics and Space Administration under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration

Brookhaven National Laboratory

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MKI MIT Kavli Institute for Astrophysics and Space Research

THE UNIVERSITY OF CHICAGO