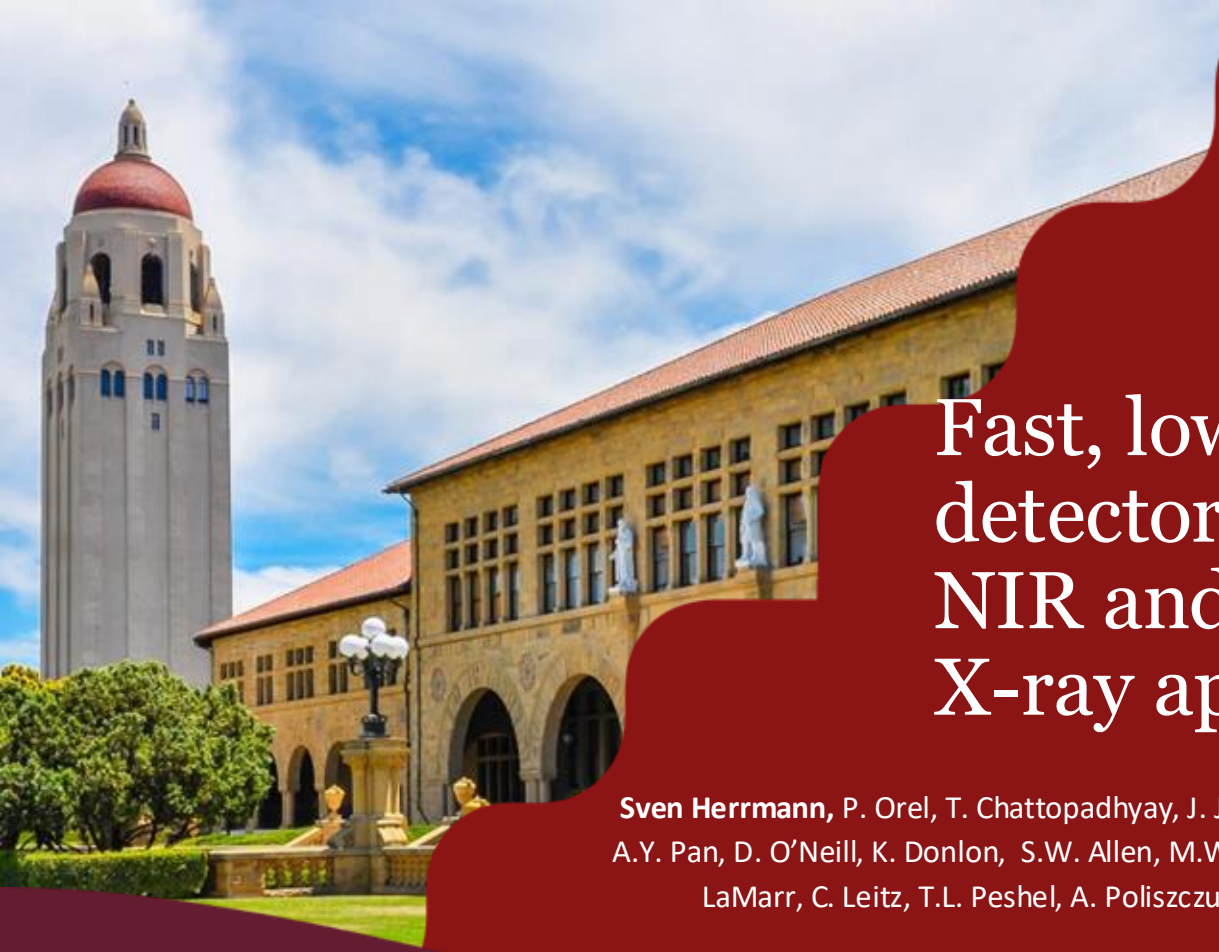


Stanford KIPAC

KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY

Fast, low noise SiSeRO detectors for NUV-VIS-NIR and X-ray applications

Sven Herrmann, P. Orel, T. Chattopadhyay, J. Juneau, E.D. Miller, R.G. Morris, H.R. Stueber, A.Y. Pan, D. O'Neill, K. Donlon, S.W. Allen, M.W. Bautz, M. Cooper, C.E. Grant, M. Heine, B.J. LaMarr, C. Leitz, T.L. Peshel, A. Poliszczuk, G.Y. Prigozhin, K. Warner, D. Wilkins

Massachusetts Institute of Technology

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2nd , 2026, ASTRA workshop, Pasadena

Outline

- Motivation and Development Approach
- Current State of the Art
  - multi-output CCDs
  - integrated readout electronics (ASICs)
- When the standard CCD is not enough
  - SiSeRO CCDs (1st gen)
  - SiSeRO CCDs (2nd gen, future)

Successors to Chandra: flagships and flaglets

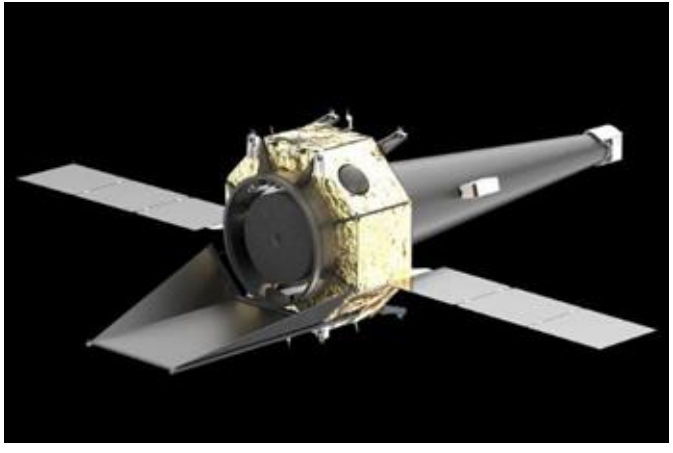
The Astro2020 Decadal Survey recommended a phased, technology-first development approach for the next generation of NASA flagship observatories, with the Habitable World's Observatory going first, followed by a "high-resolution" X-ray observatory and a far infrared (FIR) mission.

Astro2020 also recommended that NASA establish a new $1B "Probe" class of astrophysics missions with the joint top priorities being a FIR mission and an X-ray Probe "to complement Athena".

The X-ray concept selected to enter Phase A study in 2025 was AXIS.

AXIS Primary Characteristics:

Mirror collecting area: 0.42m^2 at 1keV
Angular resolution <1.5" (HEW) FOV average
Fast X-ray CCD detectors (5-20 fps)
FOV 24x24 arcmin^2, 0.3-10 keV energy band



Unfortunately, in early 2026 the AXIS team learned that the mission would not advance as the first probe selection (for 2032 launch)

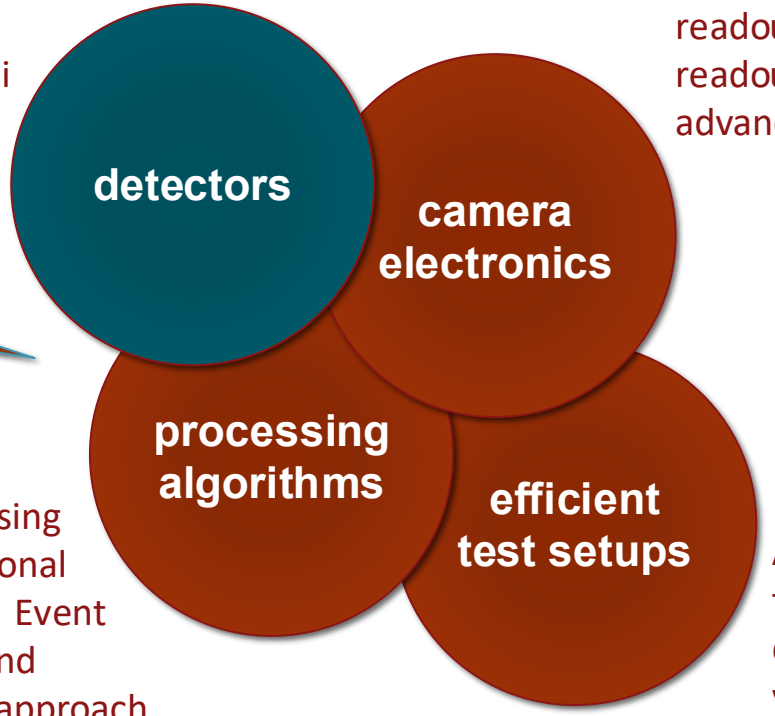
Development approach

State-of-the-art X-ray CCDs are close to being able to deliver all key performance figures for future strategic X-ray missions except for the required readout rates

Detectors with MIT-LL and MIT Kavli

Mission specific front end readout ASICs. Camera readout electronics with advanced features.

"Software" defined instrumentation



Digital waveform processing replacing more conventional analog signal processing. Event extraction and background suppression with AI/ML approach.

Automatized high throughput test setup to characterize the detector output stages and verify designs efficiently.

Leveraging mature industrial scale foundries for science instrumentation

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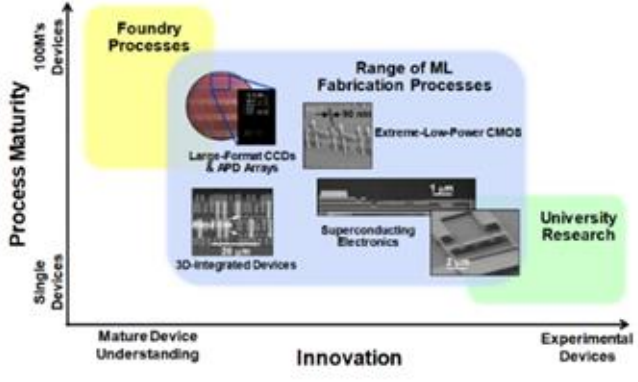
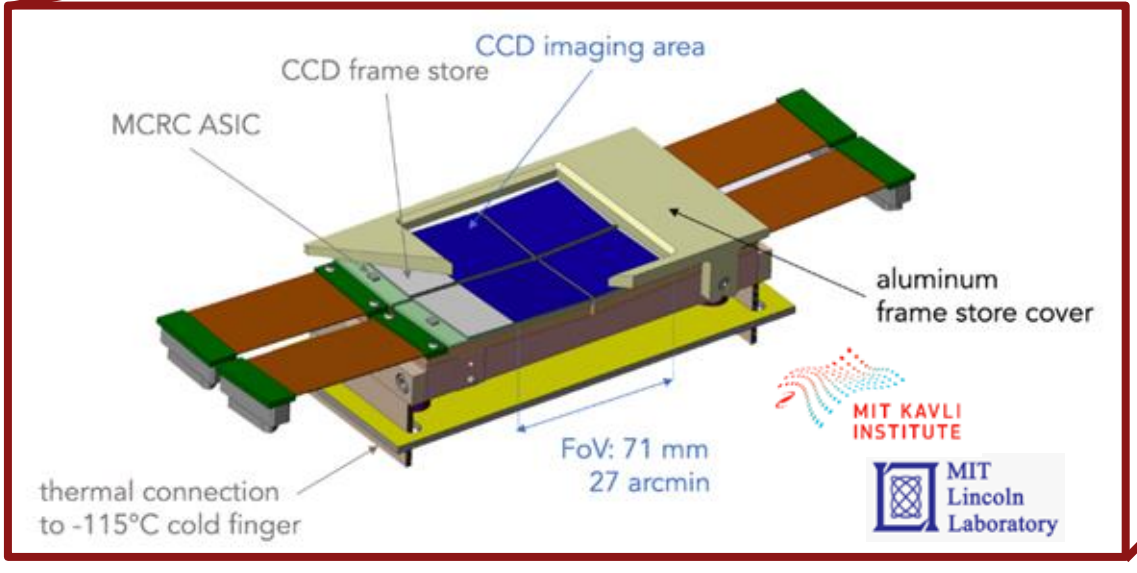
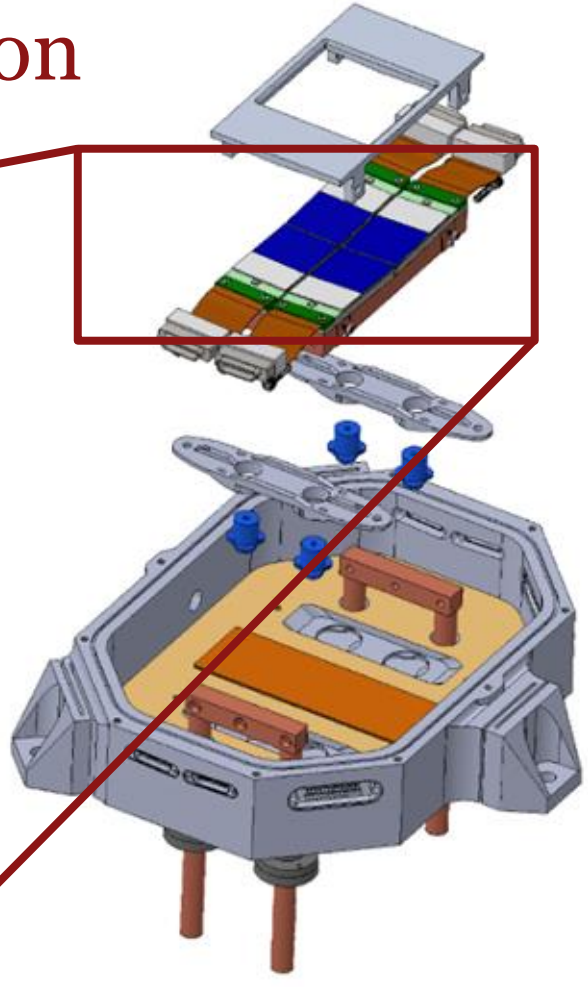


Fast, Low-Noise X-ray Imaging Spectrometers for next generation X-ray space telescopes

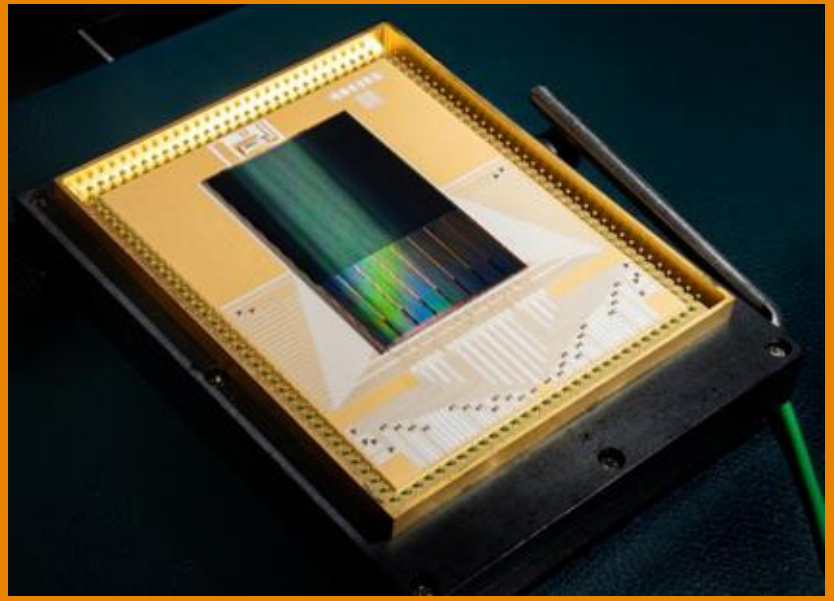




Current state of the Art:

Multi-output CCDs

More channels, more speed



16 channel 2.1Mpixel X-ray CCD

- **MIT Lincoln Laboratory single poly imager process**
  - CMOS like process technology with NMOS, PMOS and JFET's
  - stitched stepper lithography process for large devices
  - low clock voltages -> low power
  - supports large number of outputs
- **1440 x 1440, 24µm pixel, 16-channel CCD** developed for the AXIS probe concept
  - "CCID-100"
  - 90 pixels short serial registers
- Front-illuminated prototype versions fabricated and tested at Stanford University and MIT Kavli Institute
- Back-illuminated versions will be available later this year

Designed to deliver AXIS baseline performance of
> 5 frames/sec readout at 3e- noise levels with a target of 20 frames /sec

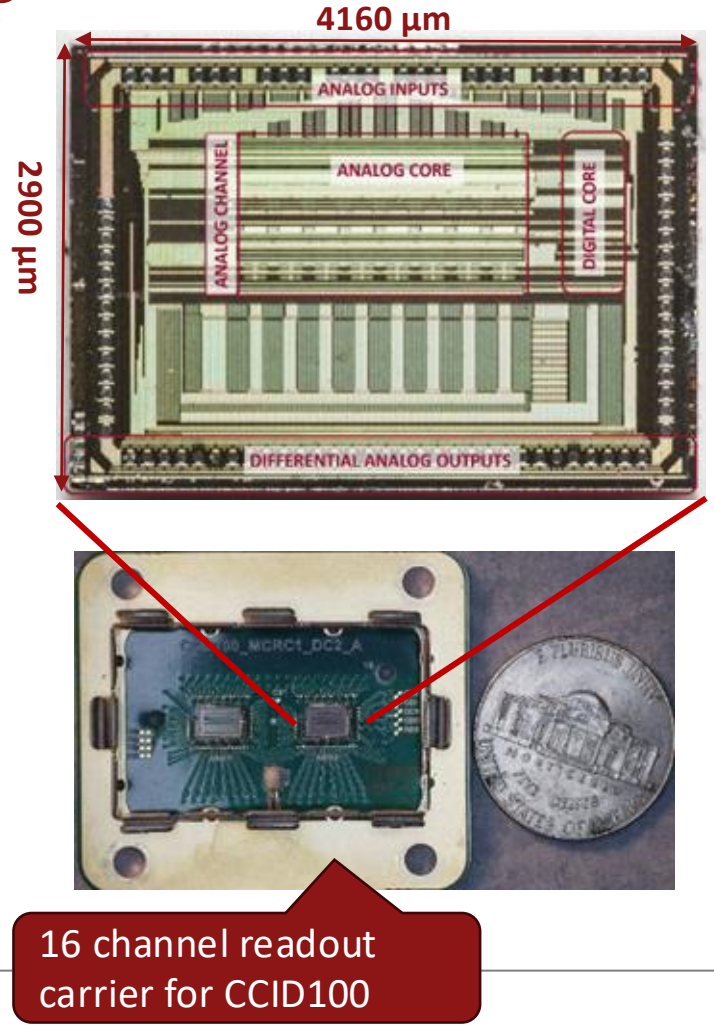
Proven performance of X-ray CCDs with much higher frame rates !

Complemented by an integrated readout ASIC: *MCRC*

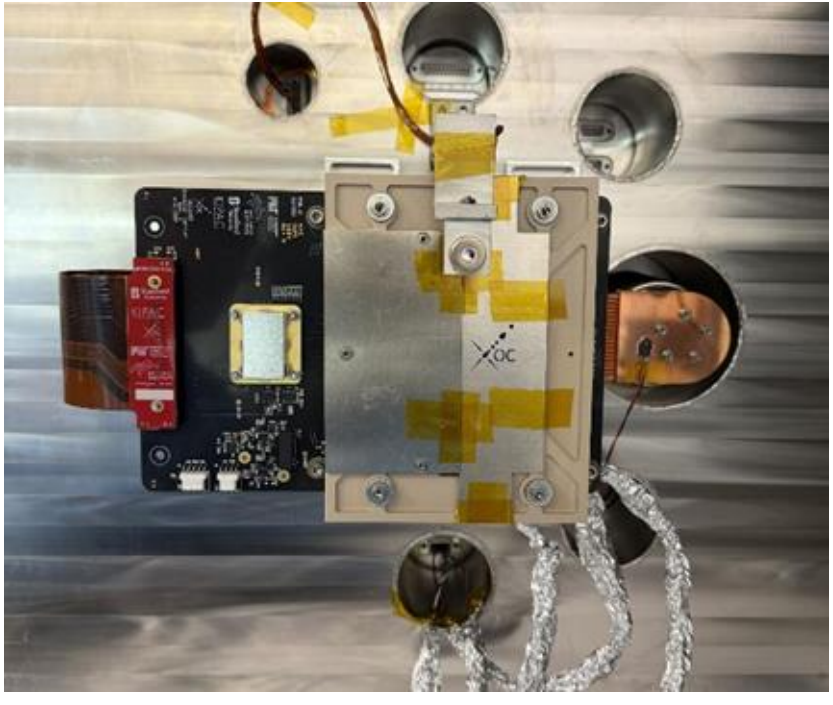
The MCRC-V1 readout chip

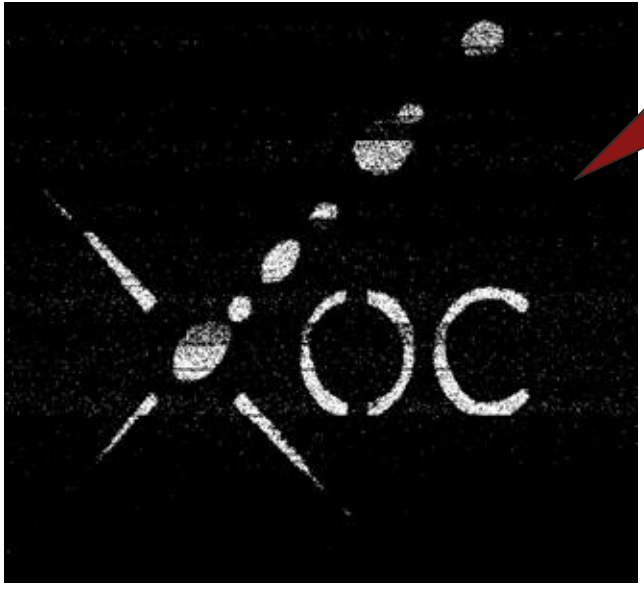
MCRC V1.0

- **M**ultichannel **C**CD **R**eadout **C**hip
- 0.35um (HV) CMOS process
- 8 analog readout channels per chip
- Low input capacitance -> fast
  - up to 5 MPIX/sec per input
- ASIC noise contribution with JFET CCD
  - < 1e- rms (2MPIX/sec)
- Low power consumption (35mW/ch)
- Integrated current source to bias the CCD output (10V capable) -> minimum external components
- Fully differential output buffers
- SPI interface for configuration with LVDS
- Tested to ~50krad TID



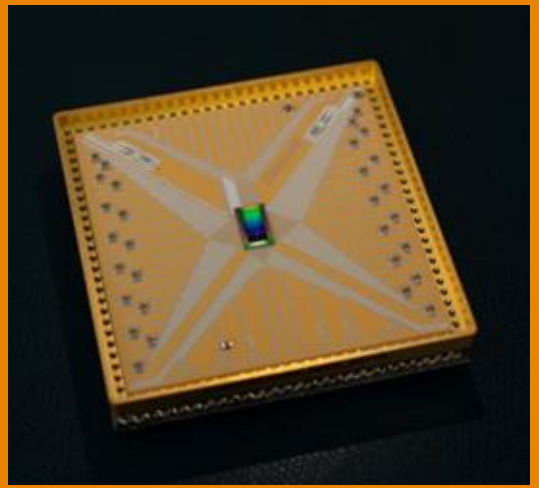
CCID-100 2.1Mpixel X-ray CCD results



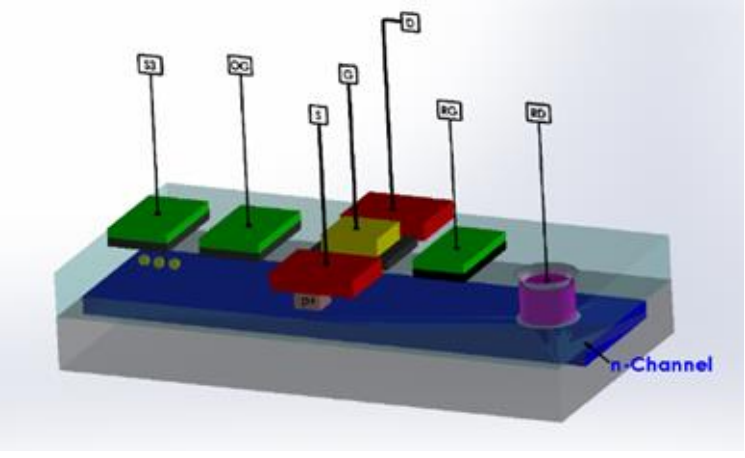


- 20fps; 4.3MPIX/sec per output
- readout noise: 4-5 e_{rms}
- FWHM: ~160eV for 5.9keV
- frame transfer speed limits the out of time fraction

When the standard CCD is not enough - SiSeRO



Single-electron Sensitive Readout (SiSeRO)



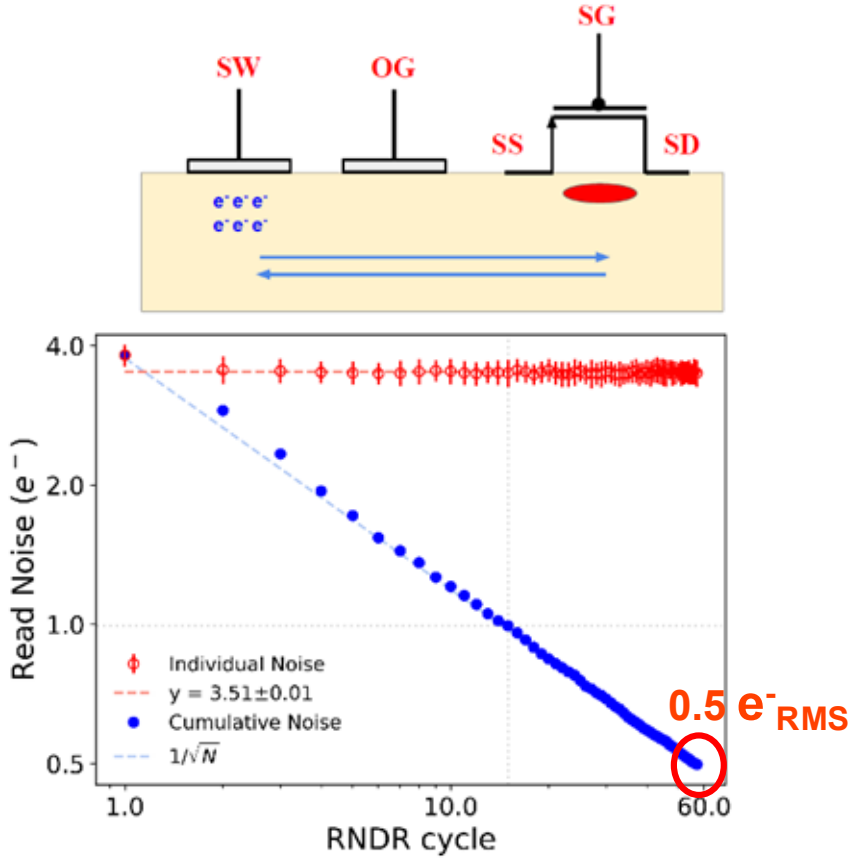
p-MOSFET with internal gate transistor channel similar to NewAthena's DEPFET

- **Higher conversion gain and lower noise**
- **No reset / KTC noise**
- **Repetitive Non-destructive Readout (RNDR) → noise ≈ 1 / √N**

SiSeRO devices are an evolution within the established MIT-LL CCD process technology

- can be used as direct replacement for the conventional MOSFET or JFET output stage
- compatible with established MIT-LL CCD process
  - thick depletion
  - backside illumination
  - **X-ray or optical entrance windows**
- Pathway for SiSeRO devices to evolve into active pixel sensors

First generation SiSeRO results: RNDR



First demonstration of RNDR in SiSeROs

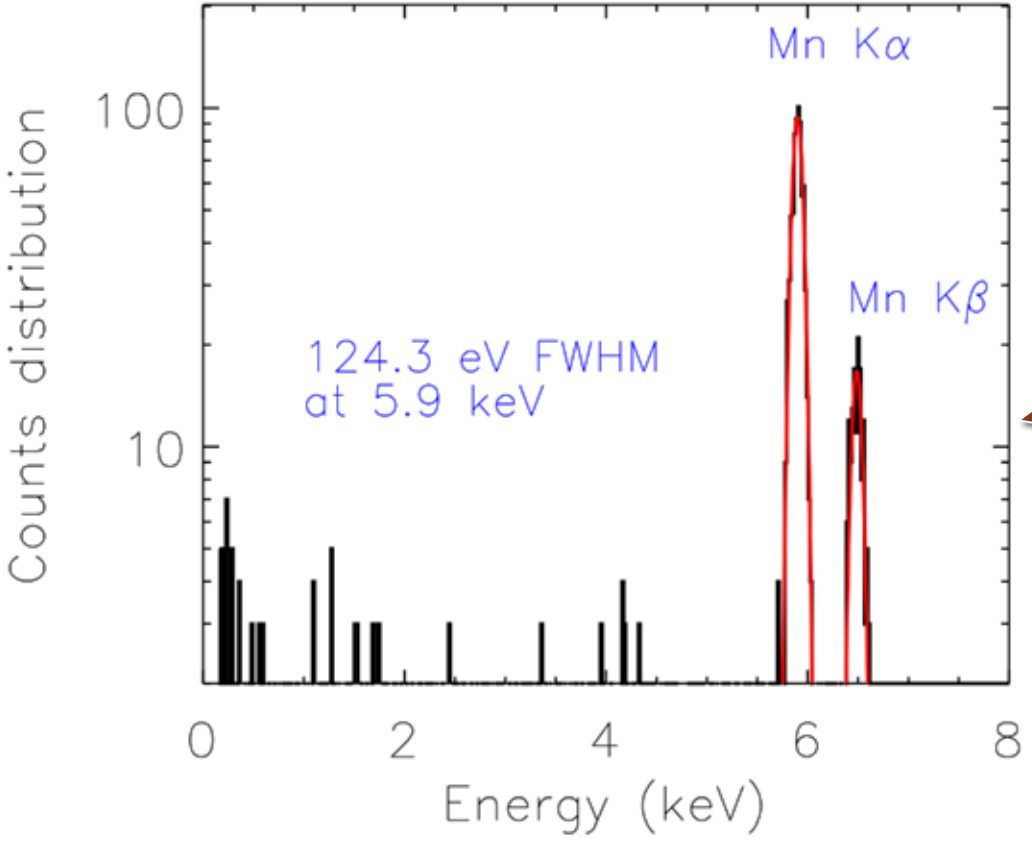
- Repetitive Non-Destructive Readout
- Charge is shuffled in and out of the amplifier and measured multiple times
- → noise ≈ 1 / √N

1 e^-_{RMS} read noise is achieved in **13 cycles** effective **50 KHz** readout rate

After **57 cycles** (effective **10 KHz**), read noise is **0.5 e^-_{RMS}**
→ sub-electron regime!

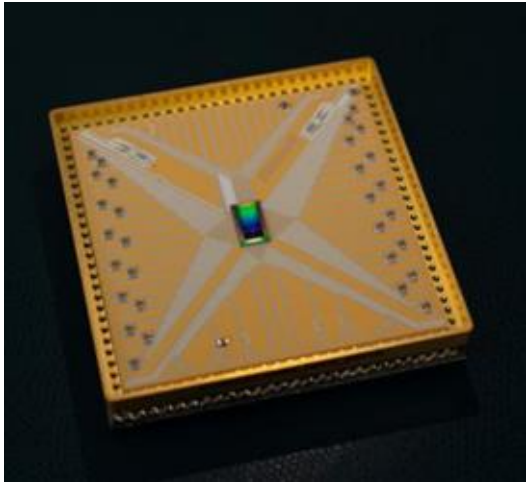
low read noise will substantially improve the soft X-ray (< 1keV) performance

First generation SiSeRO X-ray performance

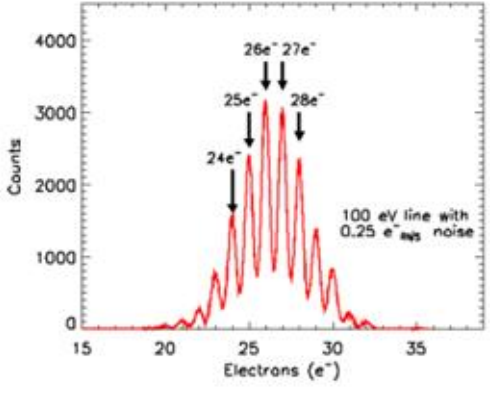


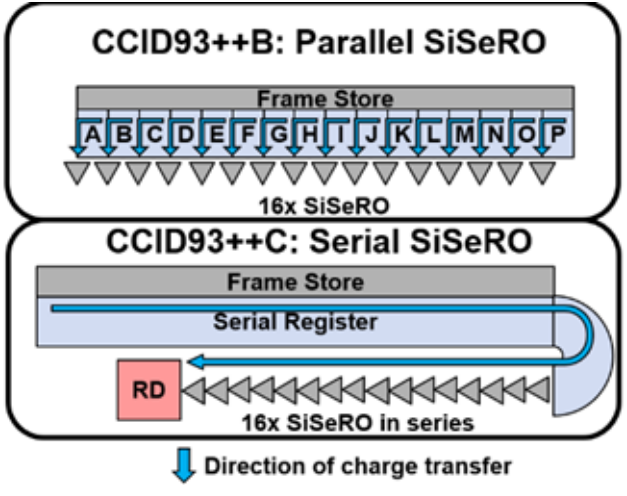
1st generation SiSeRO CCDs demonstrate excellent performance

Second generation SiSeRO devices



512 x 512 8um pixels + frame store



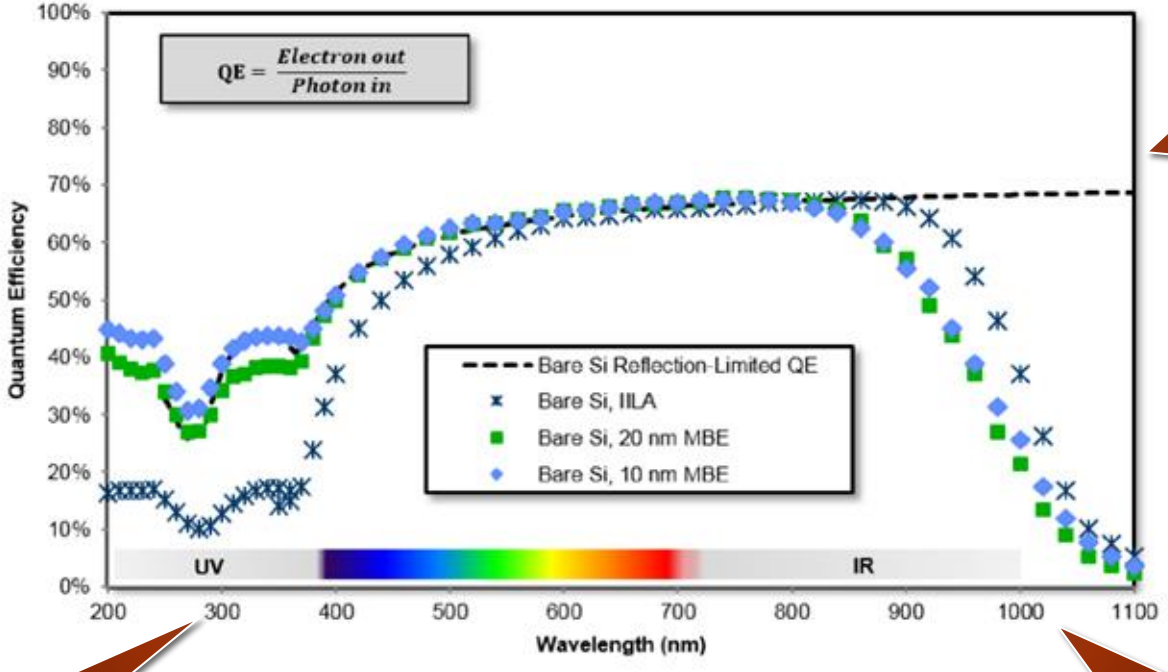


- 16 channels
  -> 16x faster readout compared to first gen. devices
- short serial registers
- ~ 250um output pitch
- a total of 32 different SiSeRO variants for evaluation

- MAS output with 16 SiSeRO
- long serial register (512 pix)
- -> 4x lower readout noise
- 27um pitch SiSeROs

we are planning to process some of these devices with an optical entrance window (in addition to the X-ray window)

Deep depletion Silicon is reasonably matched to the NUV / Vis / NIR waveband



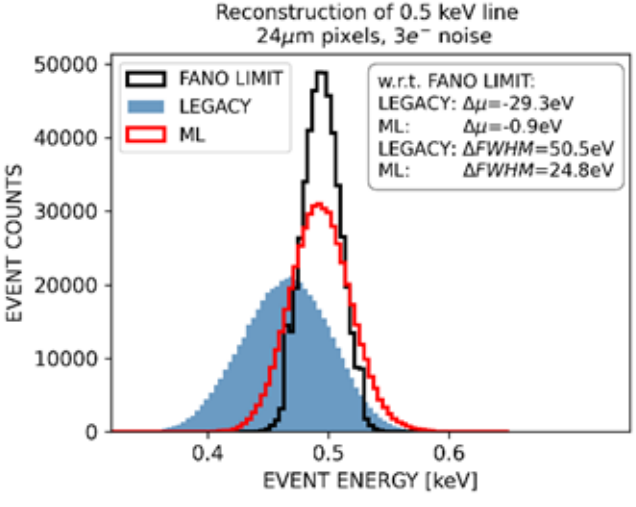
without AR coating !

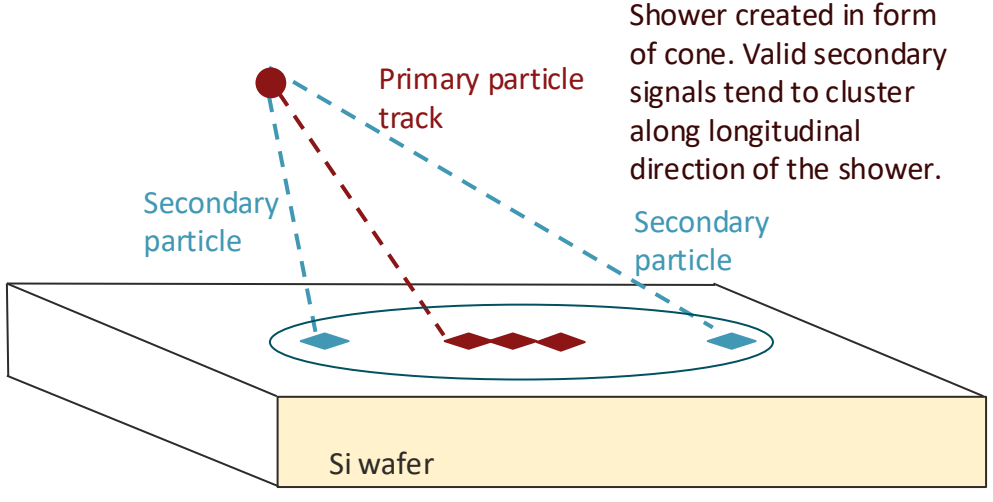
thin entrance windows for UV response

deep depletion for extended NIR response

AI / ML algorithms

Recent efforts in AI (Artificial Intelligence) and ML (Machine Learning) have demonstrated substantial improvements over legacy algorithms in both particle background rejection (>40% reduction in residual background) and event reconstruction (improved energy resolution, and pileup and CTI mitigation). Modern FPGA's like the one used in our development hardware can support these algorithms in flight.





One stop shop for space telescope cameras

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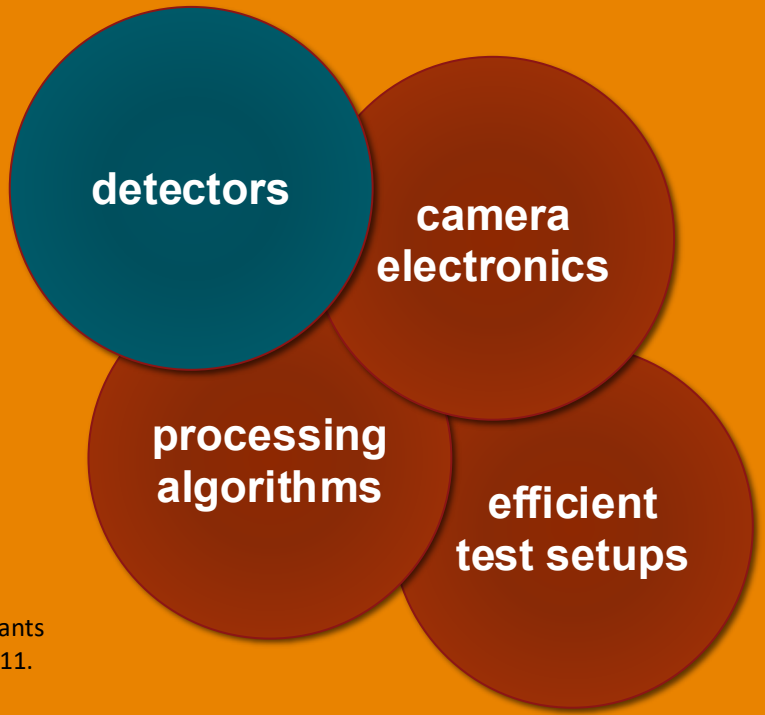

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