New Directions in Detector Development at MIT Lincoln Laboratory

Christopher Leitz

christopher.leitz@ll.mit.edu

9 November 2019

MIT-LL Silicon Charge-Coupled Devices (CCDs)

Space Surveillance

Directed Energy (AFRL SOR)

Astronomy & Astrophysics

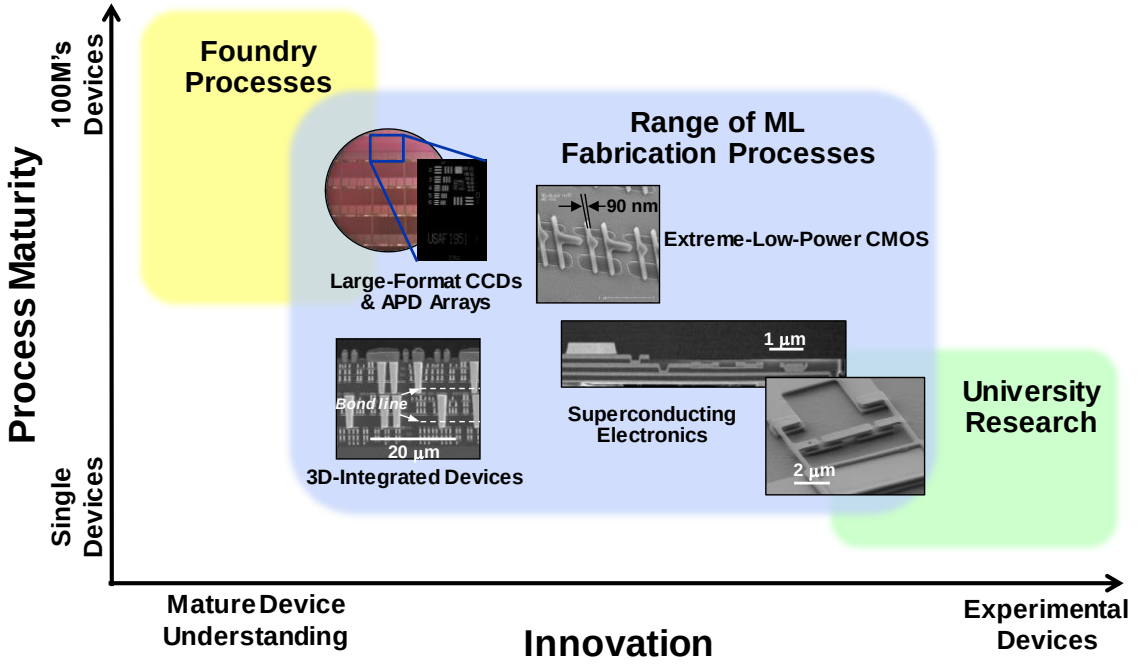
Nuclear Stockpile Stewardship (LANL)

Astronomy & NEO Detection

- **Exquisite sensitivity and dynamic range**
- **High spatial uniformity enables large-format imagers**
- **Noiseless, efficient charge transfer enables time delay integration (TDI) operation, pixel binning**
- **Orthogonal transfer for motion compensation**

MIT-LL Microelectronics Laboratory

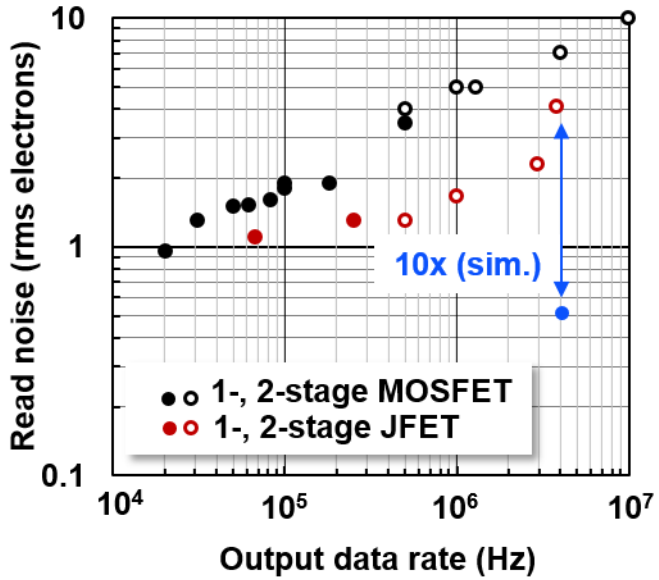
An Enabling Resource for Advanced CCD Fabrication



- Production-class 90-nm toolset on 200-mm diameter wafers
- Lithography capabilities from i-line to e-beam, reticle stitching for very large formats
- ISO 9001 certification, DoD trusted foundry
- R&D through flight deliverables

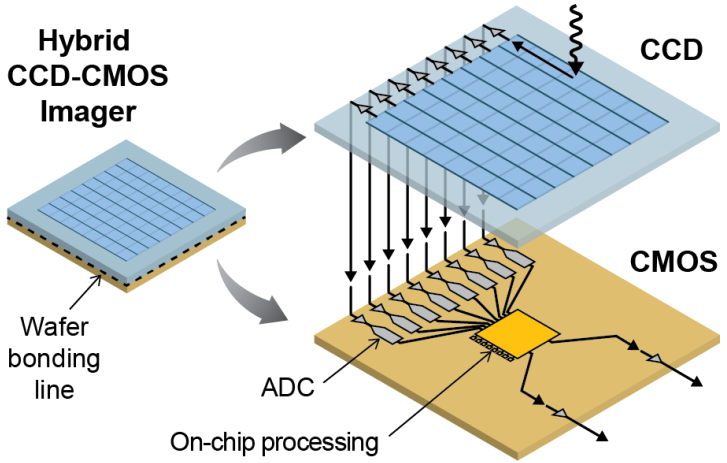
Roadmap for Next-Generation Silicon CCD Capabilities

Novel Low-Noise Amplifiers



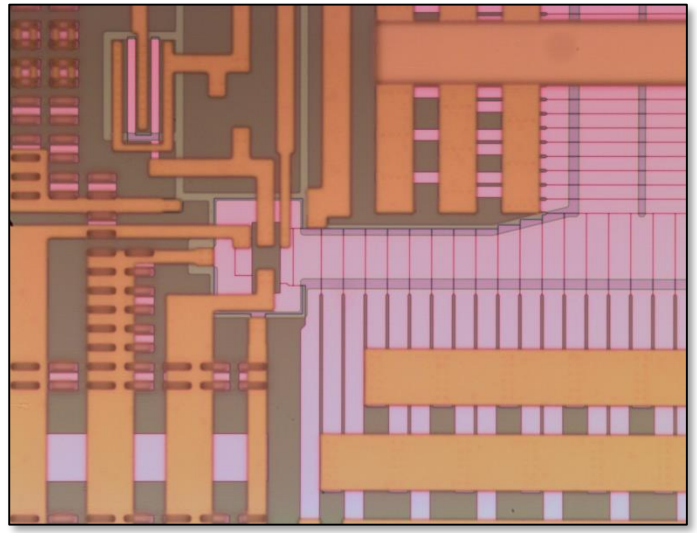
- New sub-electron read noise, non-destructive amplifier under development

High-Speed Focal Planes



- Tight coupling of focal plane to ADCs via 3D integration for high-speed continuous imaging

Multi-Project Wafer Runs



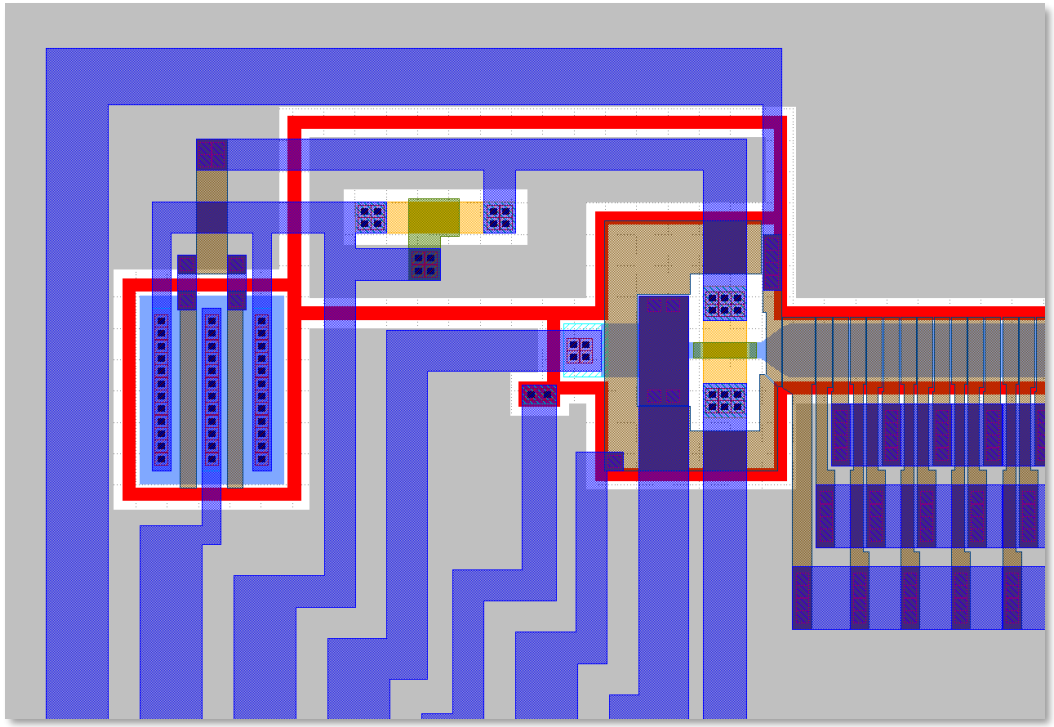
- Streamlined, standardized single-poly process with flexible floor plans for low cost of entry

Outline

- **Background**
- **Germanium image sensors**
- **Superconducting detectors**

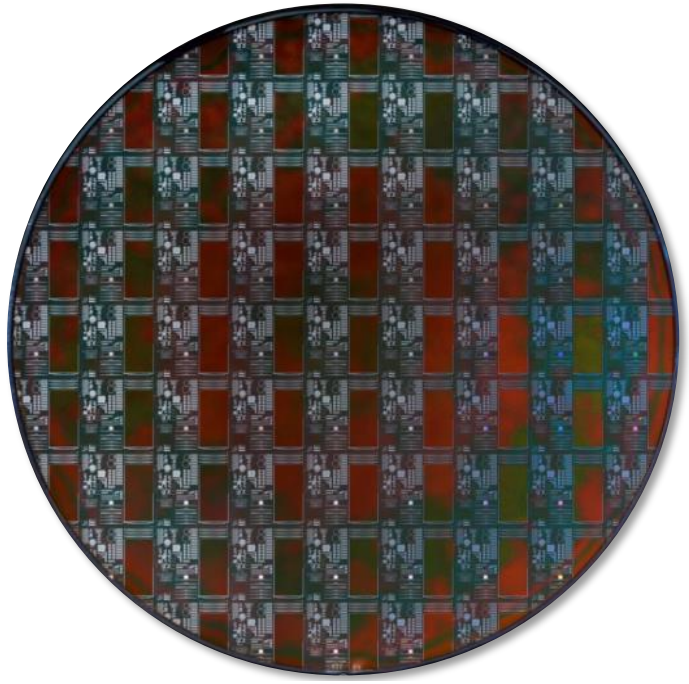
Opportunity Presented by Germanium CCDs

Low noise & broadband sensitivity



- CCDs on high-z material → maintain the low noise of silicon CCDs (< few e^-) with covering a broader spectral / mass / energy range

…in a large format



- Utilize mature 200-mm wafer processing tool set to build large-format devices
- Monolithic detectors → no bump bonding required

Germanium CCD Development at MIT Lincoln Laboratory

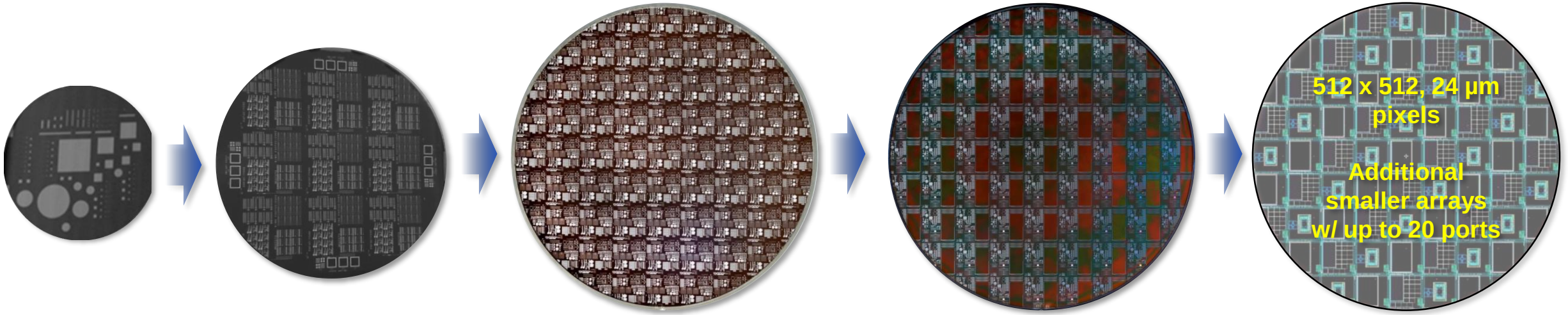
2013 2015 2017 2019

100-mm Wafers
MOS Capacitors

150-mm Wafers
Diodes, Capacitors

200-mm Wafers
Diodes, Capacitors, MOSFETs

200-mm Wafers
Imagers



0 mask levels
CD = 100 µm

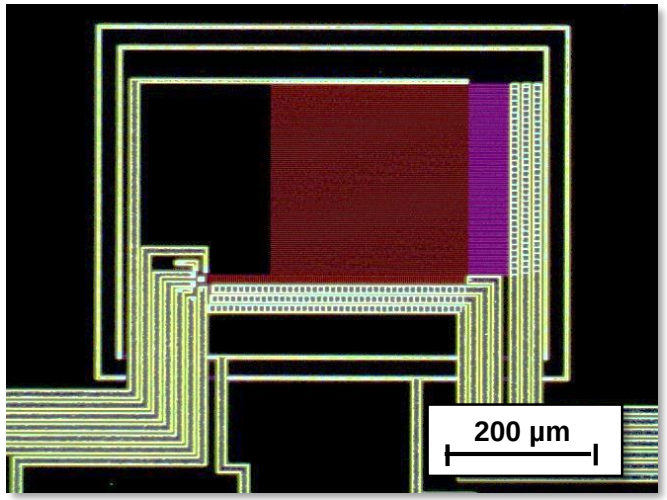
5 mask levels
CD = 2 µm

7 mask levels
CD = 1 µm

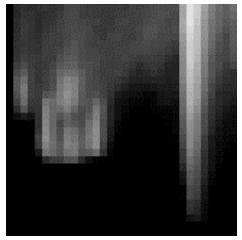
11+ mask levels
CD = 0.2 µm

Recent Progress in Germanium CCDs

Steadily Improving Pixel Arrays



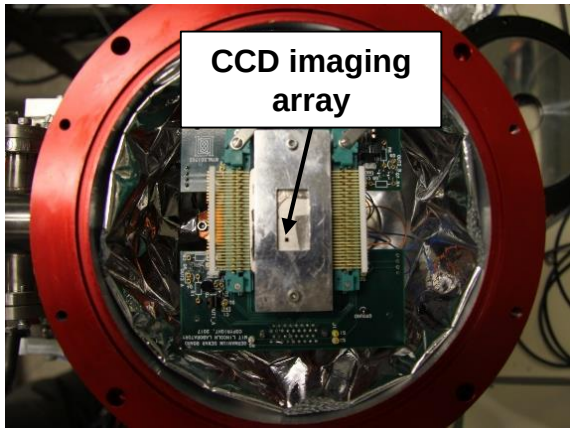
Initial Result

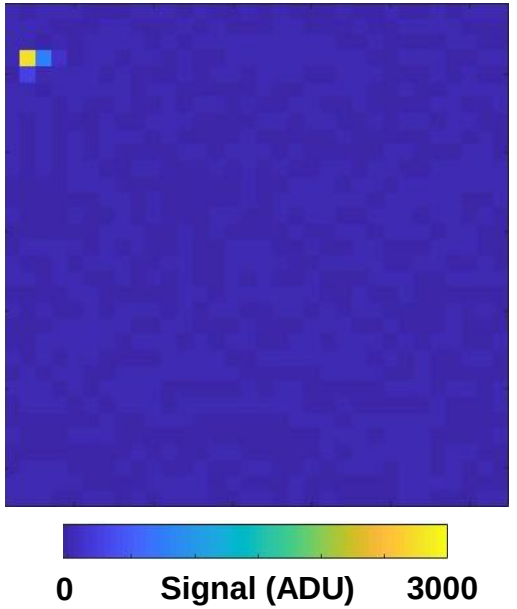


Recent Result

- Demonstrated pixel arrays with improved charge-transfer efficiency, formats up to 128 × 128 pixels

Back-Illuminated Detectors





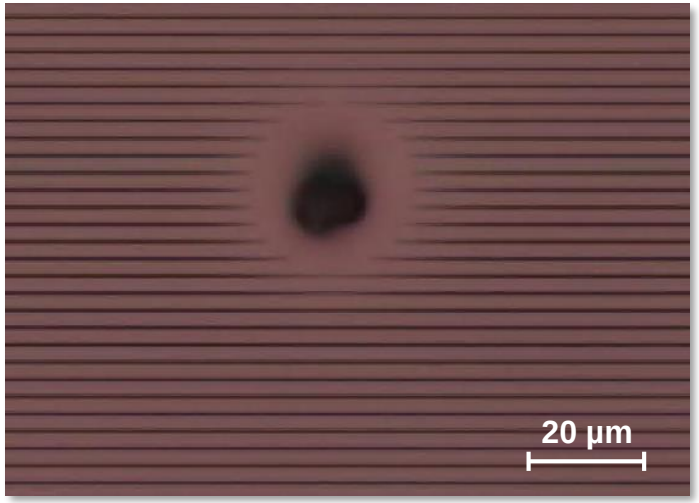
- Back-illuminated CCD shows expected sensitivity to ^{241}Am X-rays

Steady progress in device understanding, building towards science-grade devices

Yield Enhancement

Through partitioning, we have identified particles as our major yield limiter

"Killer defect" causing shorts in CCD imaging array



- **Large Al_2O_3 particles lead to shorts in adjacent metal lines**

Static Yields vs. Process Technology

Process	1 Mpixel CCD Yield
Silicon monitor, no Al_2O_3	82%
Silicon monitor, no Al_2O_3, plasma-free interlayer dielectric	77%
Silicon monitor with Al_2O_3	0%
Best Germanium CCD	<< 0.1%

- **Partitioned testing clearly indicates impact of particles on yield**

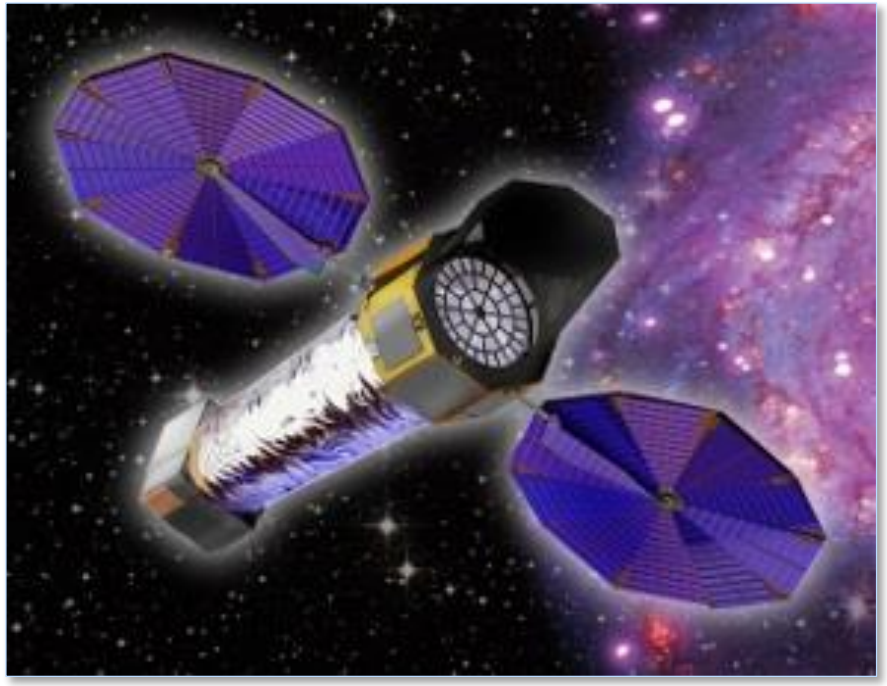
New Al_2O_3 deposition system will enable step-function yield improvements

Outline

- **Background**
- **Germanium image sensors**
- **Superconducting detectors**

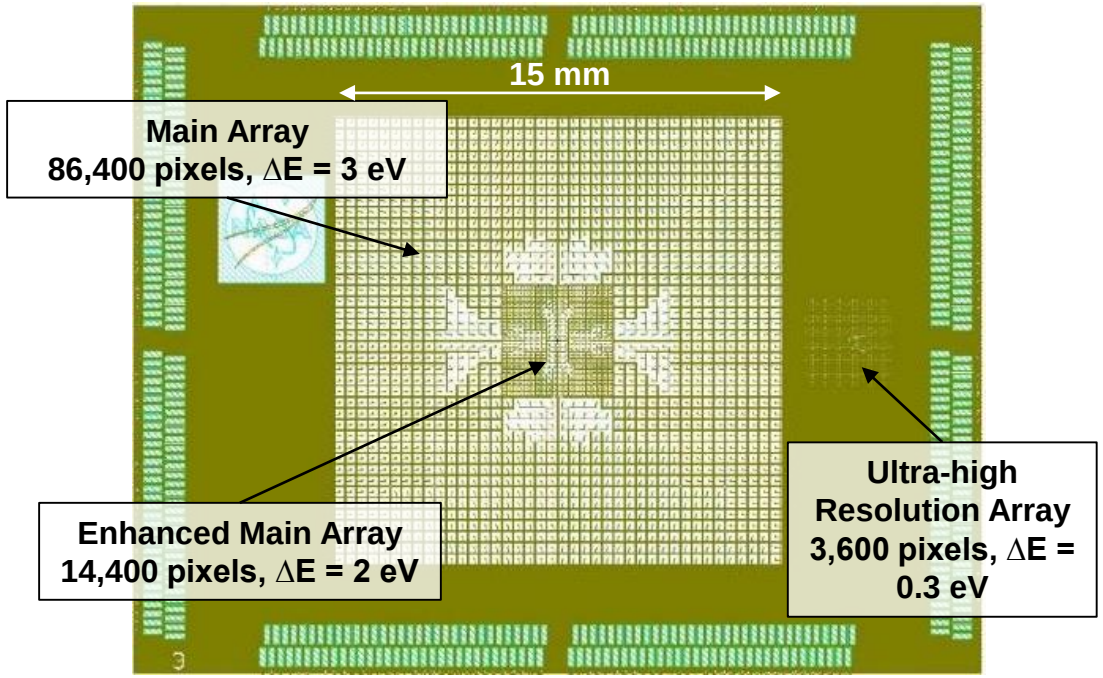
Lynx X-Ray Microcalorimeter (LXM)

Lynx Mission Concept



- Flagship mission candidate for X-ray astrophysics with instruments including microcalorimeter

LXM Detail

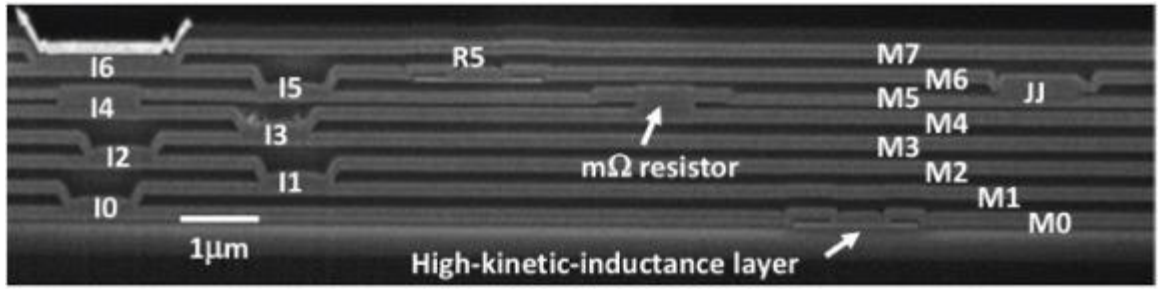


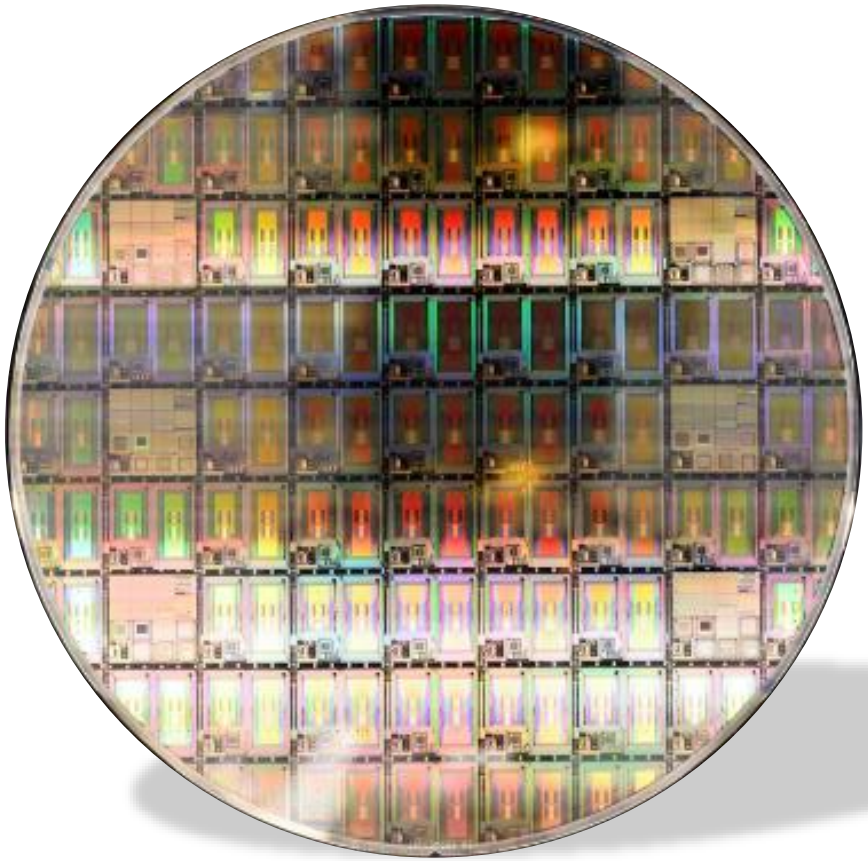
- Very large format microcalorimeter array with each pixel requiring superconducting wiring to SQUID amplifiers

Desired LXM pixel count is ~1000x higher than largest arrays flown to date

Superconducting Integrated Circuit Fabrication

Superconducting Integrated Circuit Cross-Section



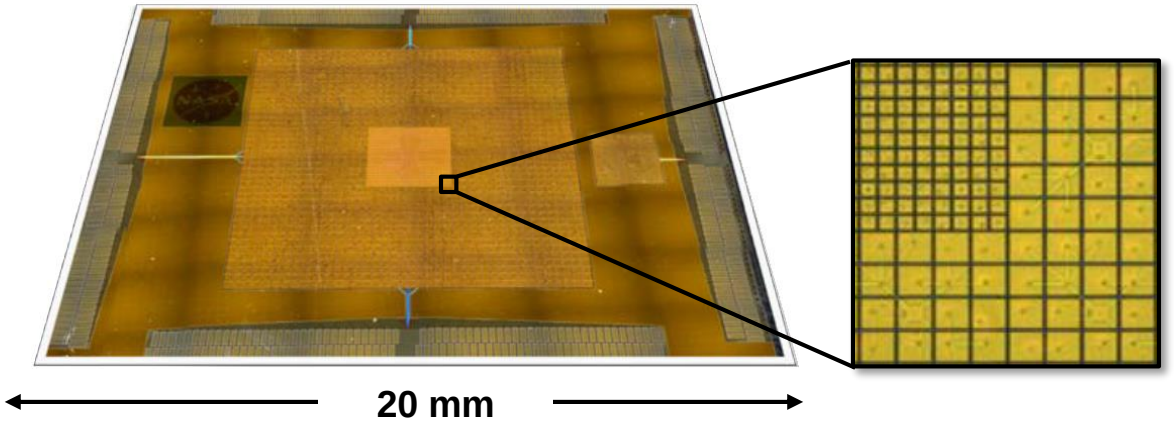


- **MITLL has established a multi-layer superconducting wiring technology**
  - **8-inch wafers**
  - **Fully planar process**
  - **High-yield**

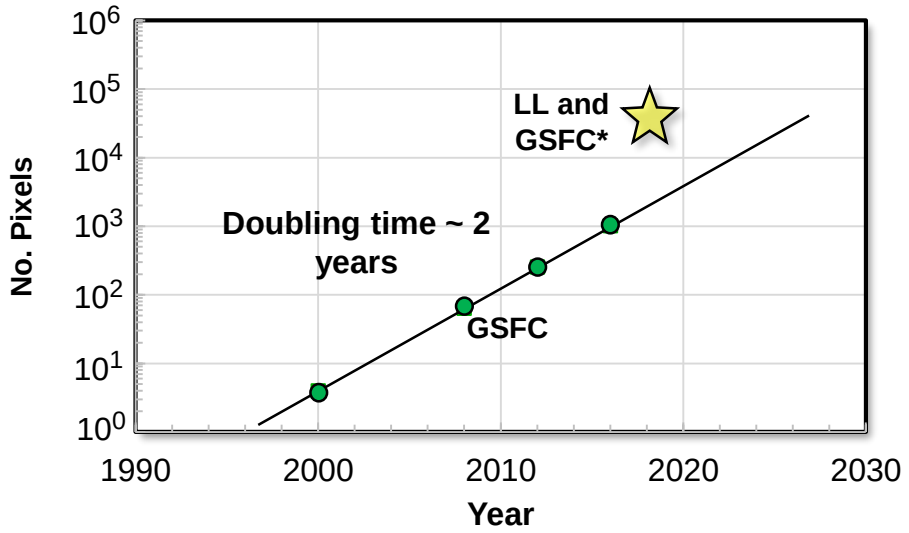
Leverage existing advanced superconducting electronics process at Lincoln Laboratory to enable large-format microcalorimeters

Large-Format X-Ray Microcalorimeter Arrays Demonstrated with MITLL Superconducting Wiring

Prototype LXM arrays with 49,100 pixels



Microcalorimeter "Moore's Law"



- **Half the size of the full Lynx X-ray Microcalorimeter array (49.1 kpix), 3 types of array on single focal plane**
- **Close to meeting challenging noise requirements for Lynx on first iteration**

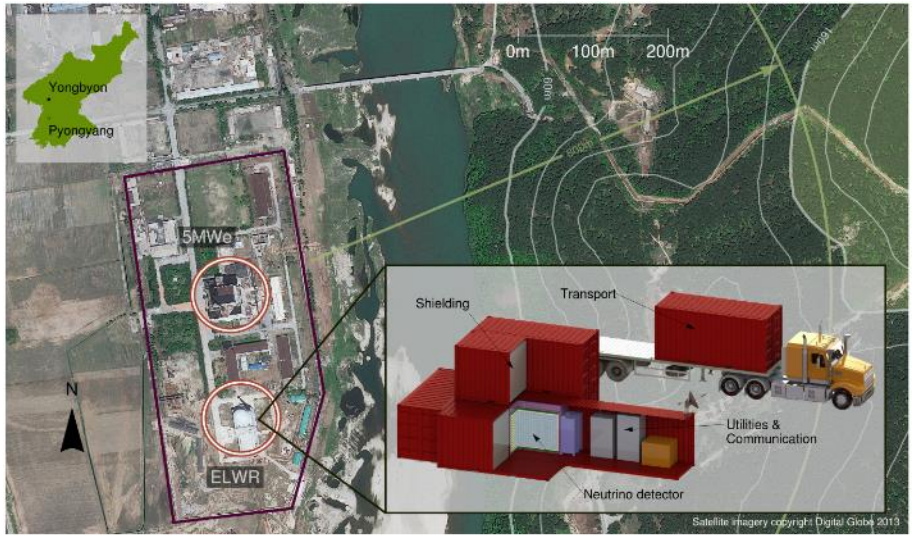
* ***Wiring is complete, but bond pads are only available to connect a limited number of pixels in this prototype***

Successful demonstration of prototype Lynx X-ray microcalorimeter using high density, multi-layer Nb superconducting wiring

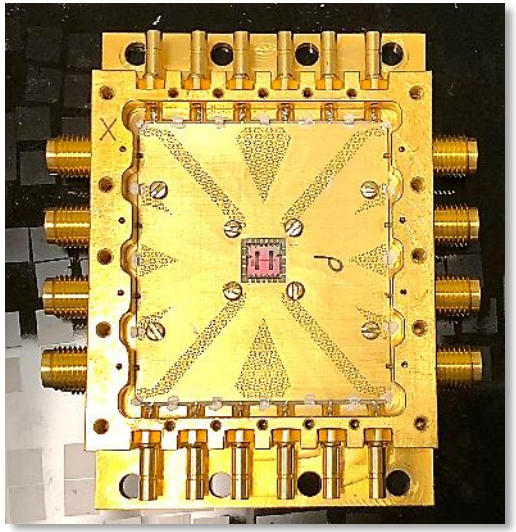
SQUID Preamplifiers for Ricochet Experiment

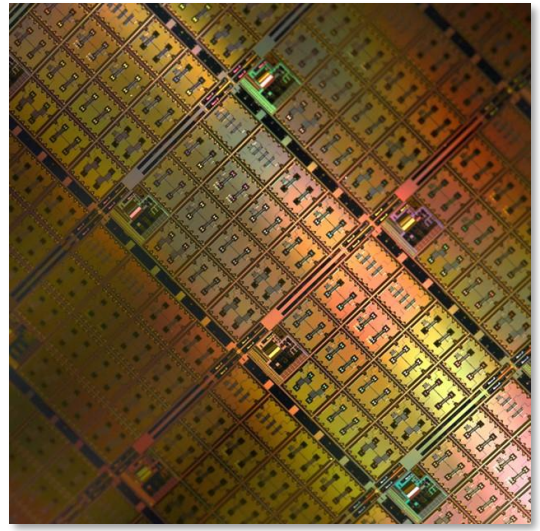
Massachusetts Institute of Technology

Nuclear monitoring concept [1]



Images of fabricated readout chips





- **Ricochet experiment: PI Joseph Formaggio (MIT); goal is to detect neutrinos emitted from a nuclear reactor using coherent elastic neutrino-nucleus scattering**
- **Prototype detector uses a transition edge sensor (30g Zn absorber) and SQUID preamplifiers, the latter fabricated at MITLL**

For more details, see Steve Weber's talk Monday at 11:30

[1] Carr, R., et al., "Neutrino-Based Tools for Nuclear Verification and Diplomacy in North Korea," *Science & Global Security* **27**(1) (2019) 15.

Summary

- **MITLL seeks to continue to improve the capabilities of CCDs through development of low-noise and high-speed readouts, fabricated in a streamlined single-poly process**
- **We are also maturing germanium CCDs to exploit the unique properties of this material for low-noise detectors**
- **We have begun to leverage our mature superconducting electronics fabrication processes to fabricate microcalorimeters for scientific and national security applications**