Fully depleted Charge-Coupled Devices (CCDs) for scientific applications including single-electron detection

Steve Holland

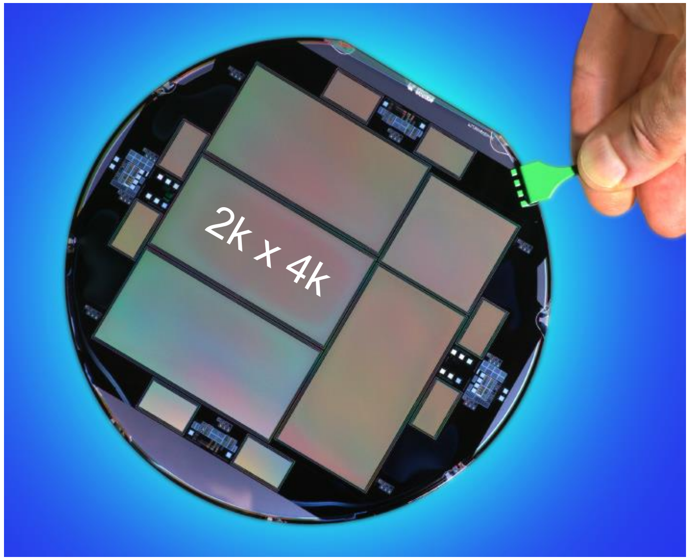
Lawrence Berkeley National Laboratory

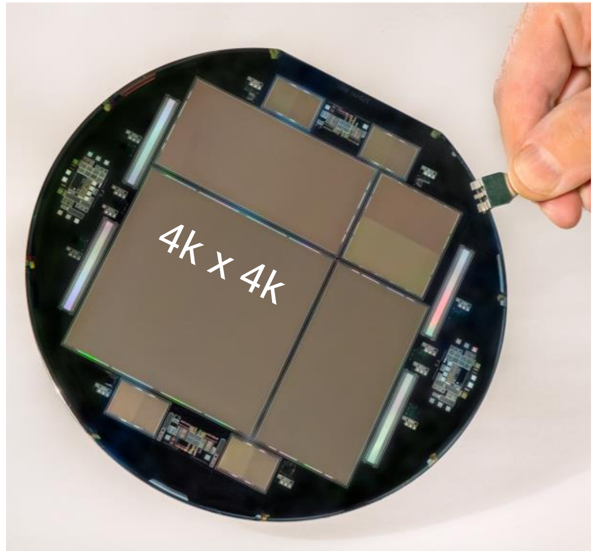
September 28th, 2022

- Lawrence Berkeley National Laboratory
  - U.S. Department of Energy National Laboratory
    - Office of Science
- LBNL CCD development
  - Support DOE High-Energy Physics projects, e.g. detectors for Dark Energy and Dark Matter, Quantum Information Science (QIS)
  - Collaborators include Teledyne DALSA Semiconductor (150-mm CCD fabrication), DOE Labs FermiLab / PNNL, Lincoln Laboratory
  - <u>New:</u> 200 mm CCD fabrication
    - Microchip Technology and Lincoln Laboratory

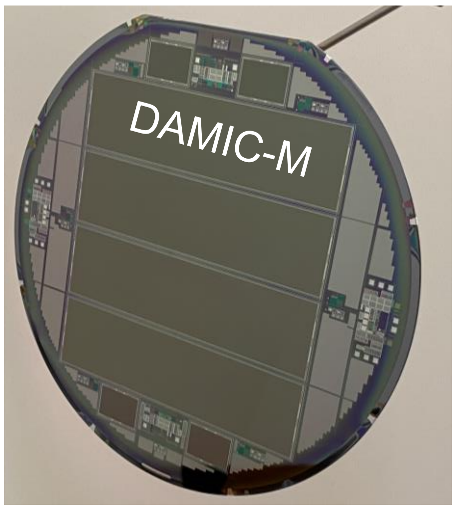
Fully depleted CCDs: 150-mm wafers

U.S. DOE Dark Energy →

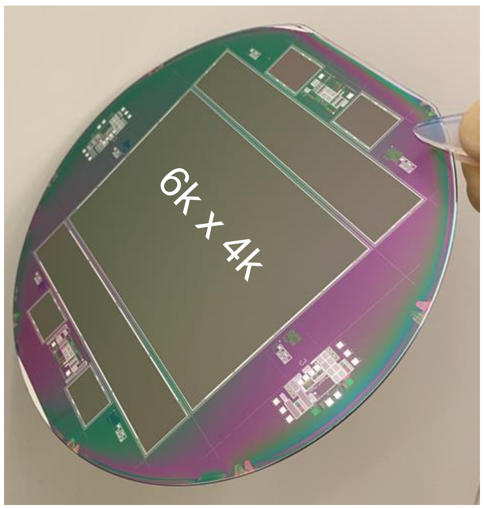




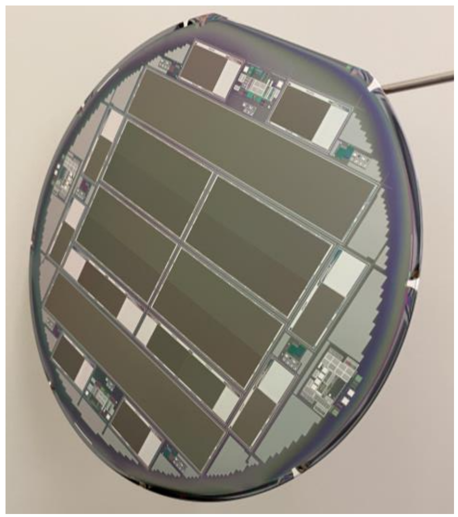
- Astronomy and QIS: Back illuminated / 250 um thick
- Dark Matter: 650 um thick
- Radiation detection: 580 um thick and back illuminated



Dark Matter



Radiation detection
Dark Matter



Quantum Information Science

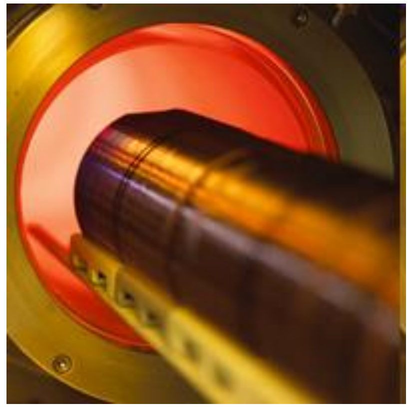
Pixel sizes:

$(15\ \mathrm{um})^2$ typical

Also $(10.5\ \mathrm{um})^2$

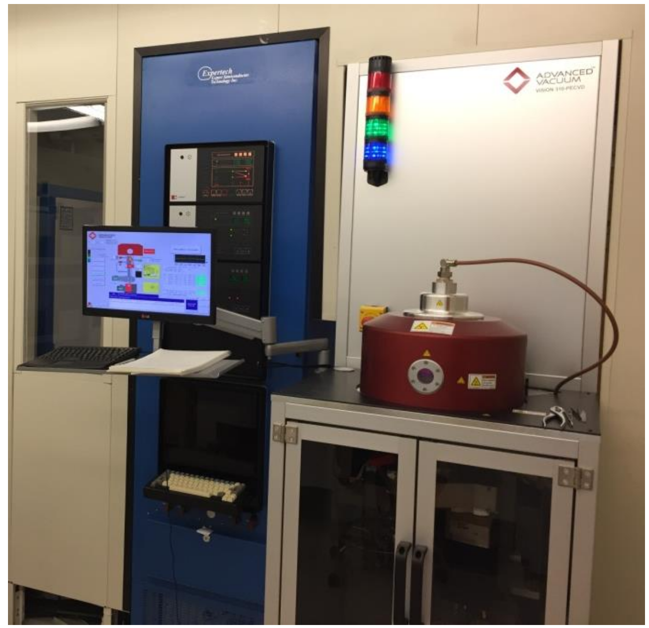
CCD fabrication

- Industrial fabrication at Teledyne DALSA
  — Commercial CCD foundry located in Bromont, Quebec, Canada / 150 mm silicon wafers

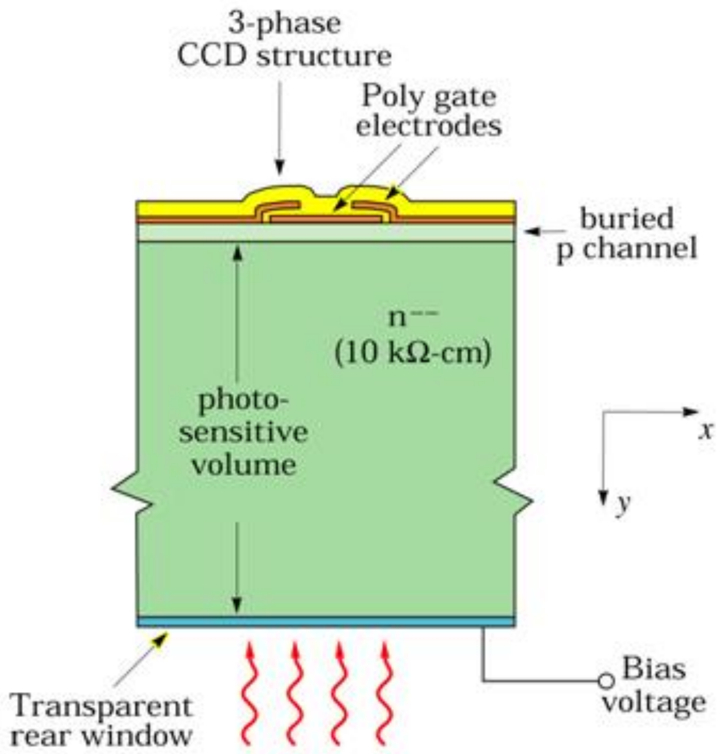

- Dark Matter detection: Full fabrication at DALSA
- For back illuminated CCDs, the wafers are partially processed at DALSA with the steps needed for back illumination done at the LBNL MicroSystems Lab

LBNL MicroSystems Laboratory



- Class 10 clean room
  - —150 mm wafer processing
  - — DECam / DESI CCDs with DALSA
  - — QIS / radiation detecting CCDs

"Fully depleted CCDs" 101

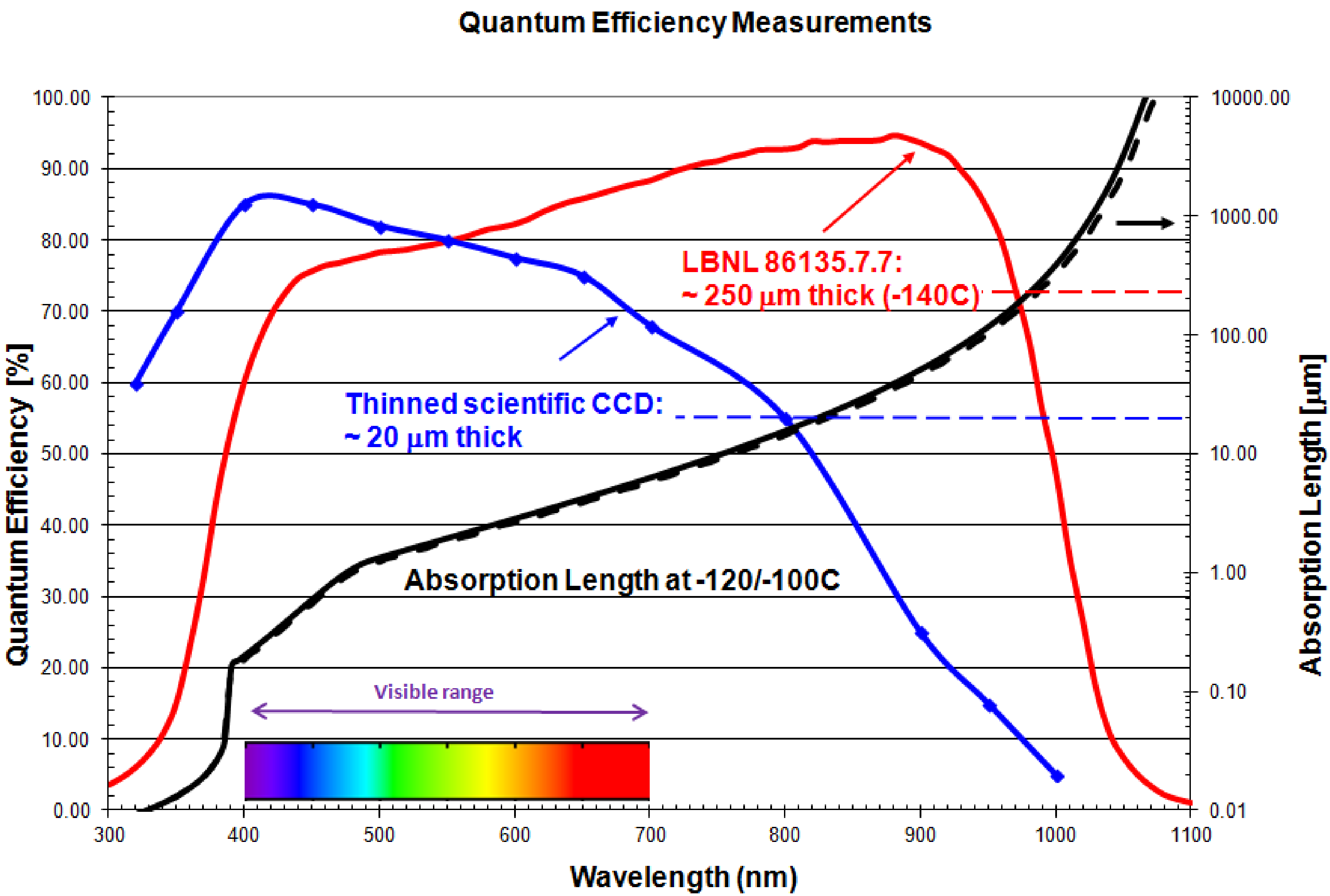


Not to scale

CCD fabricated on a <u>high-resistivity</u> silicon substrate that is <u>fully depleted</u> by the application of a <u>substrate bias</u>

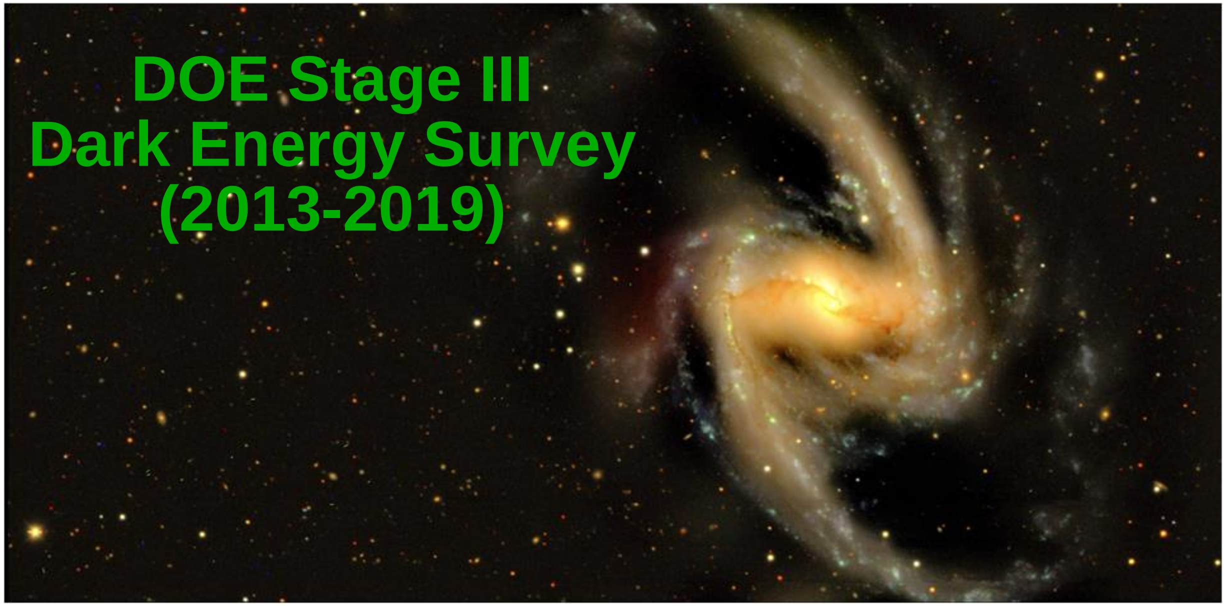
- Merging of CCD / p-i-n detector
- Typical thickness for astronomy is 200 – 250 µm
- Thick device results in high near-infrared response
- Main advantage for astronomy
  - Detect high redshift objects

Quantum efficiency



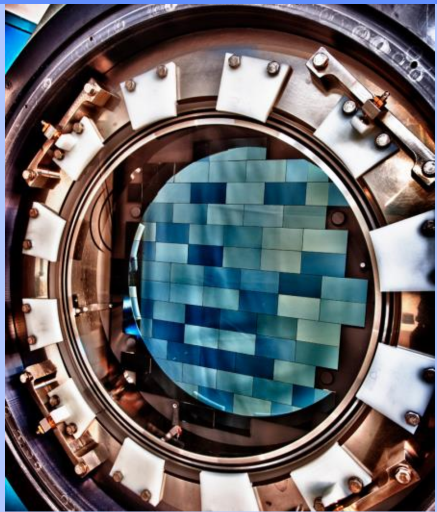
Near IR – Silicon becoming transparent, E_{ph}< Si bandgap (~ 1.1 eV)

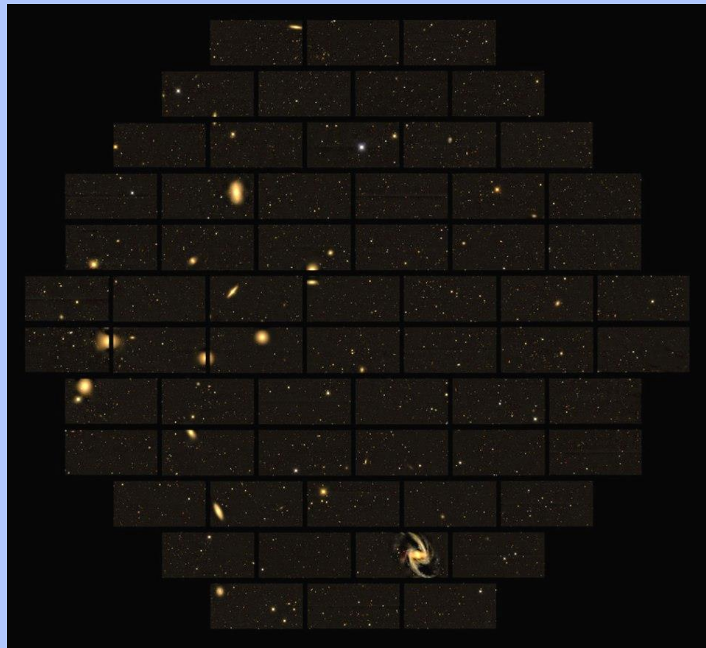
Blue end – Strong absorption in dead layers (n^+ of p-i-n structure)



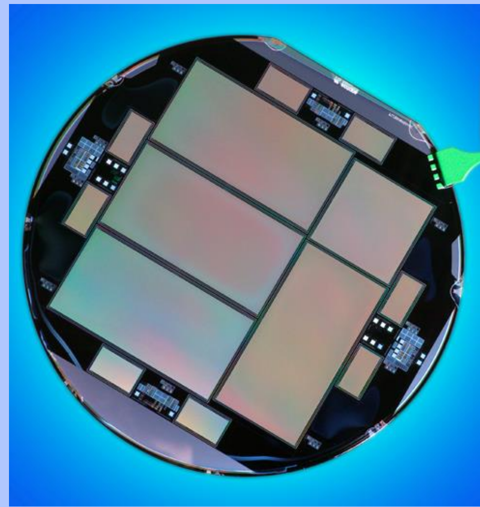
- Dark Energy Camera: CTIO Blanco 4-m telescope
  - FermiLab was the lead institution
  - DALSA/LBNL fully depleted CCDs
    - 1st light in September 2012
    - Over 1.1 million images to date

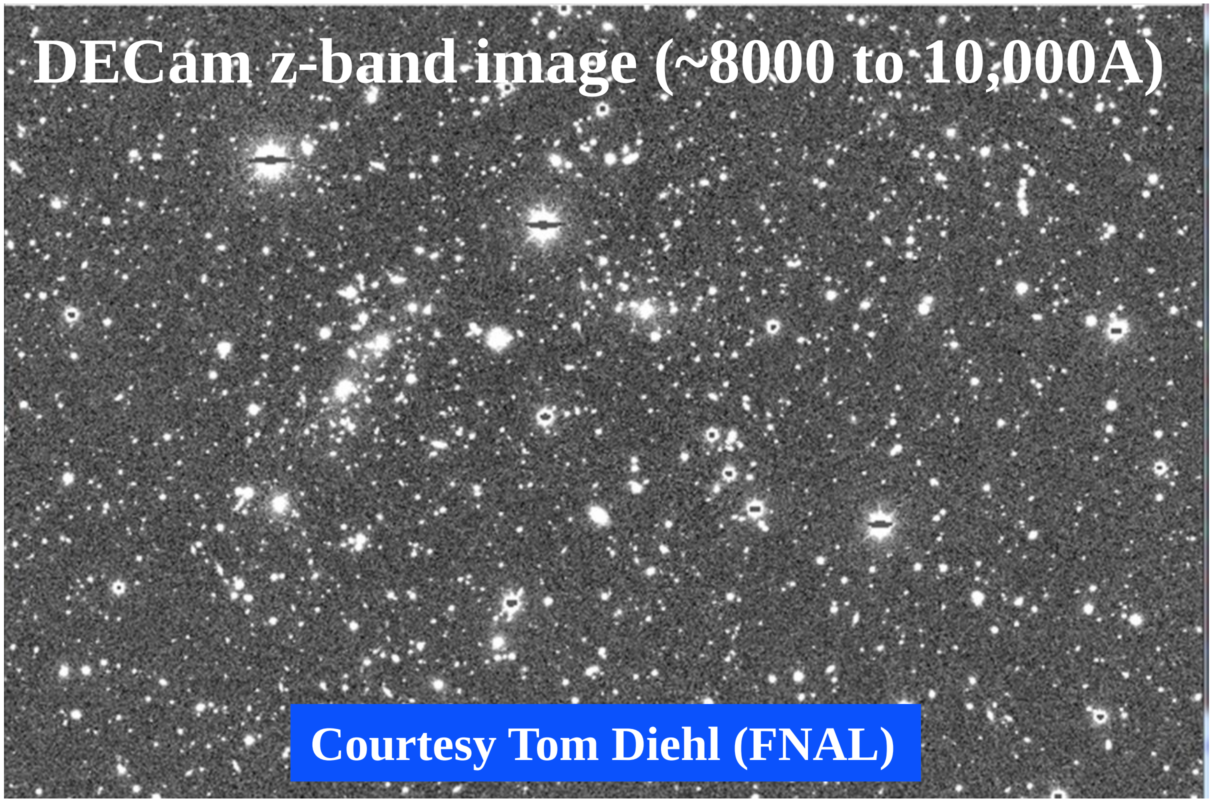
520 Mpixels
250 um thick, fully depleted CCDs

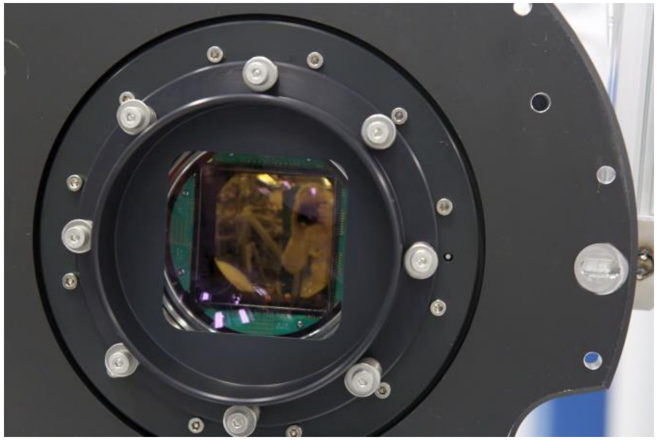


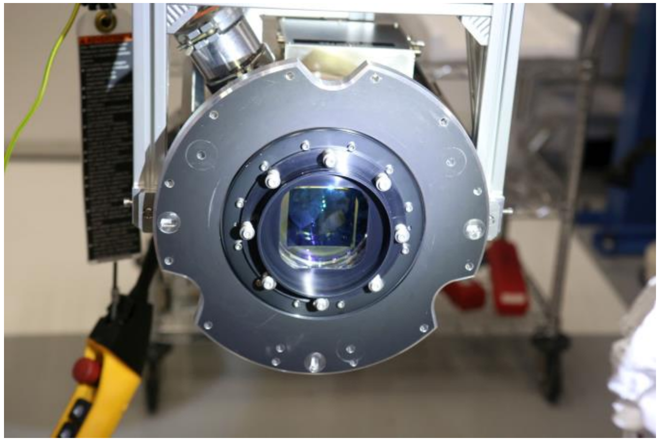


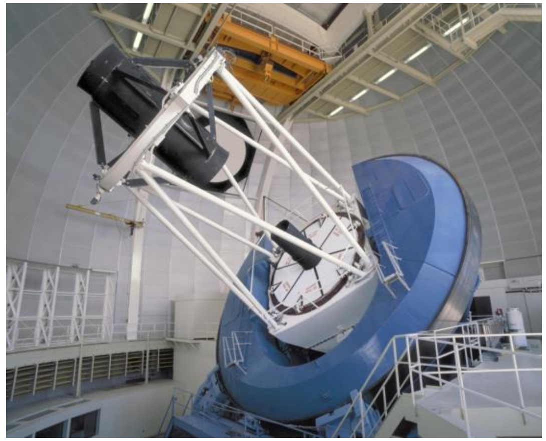
150 mm diameter Si wafer
8 Mpixels (15 um pixels)







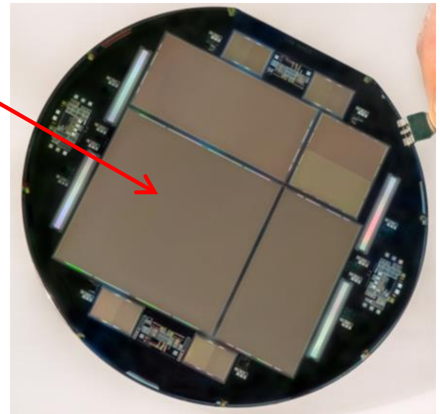




Blue-sensitive CCDs (10):
360 < λ ≤ 555 nm
20 um thick, 4k x 4k
DALSA / Semiconductor Technology Associates, Inc / University of Arizona Imaging Technology Laboratory

Red-sensitive CCDs (10):
555 < λ ≤ 656 nm
Near-infrared CCDs (10):
656 < λ ≤ 980 nm
250 um thick, 4k x 4k
DALSA / LBNL

Focal plane:
5000 robotic fiber positioners
Mayal 4-m telescope



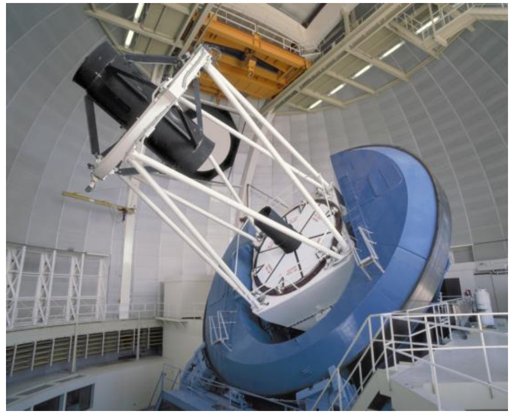
Dark Energy Spectroscopic Instrument

DOE Stage IV Dark Energy experiment

- Measure ~ 30 million redshifts using 4 classes of objects (LRGs, ELGs, QSOs, Lyman-α forest)
- 10 spectrographs each with 3 4k x 4k, 15 µm pixel CCDs
- First light October 22nd, 2019

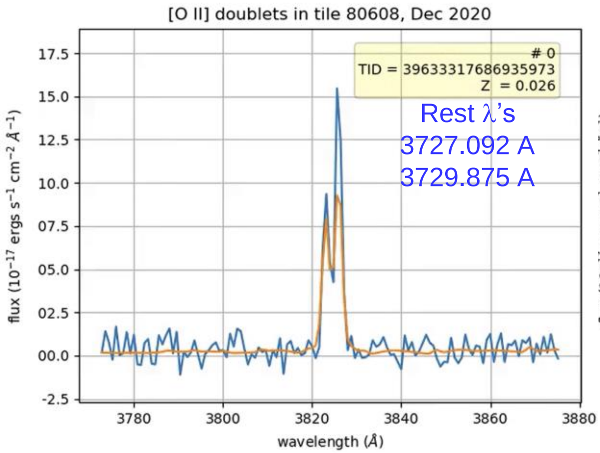
Dark Energy Spectroscopic Instrument

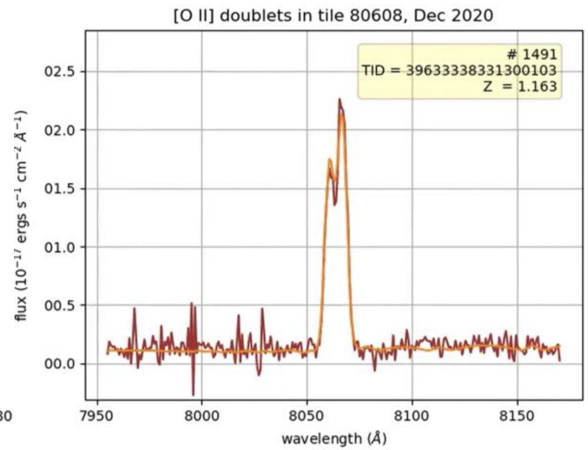
- [O II] doublet: Marker for Emission Line Galaxies
  - — Results from December 2020

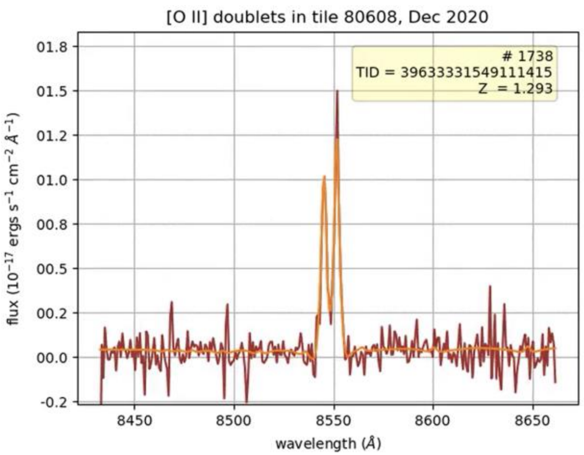


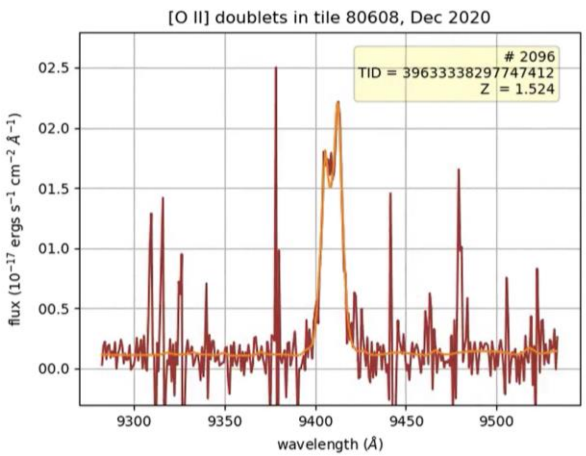
DESI Blue CCD: ~ Rest wavelength

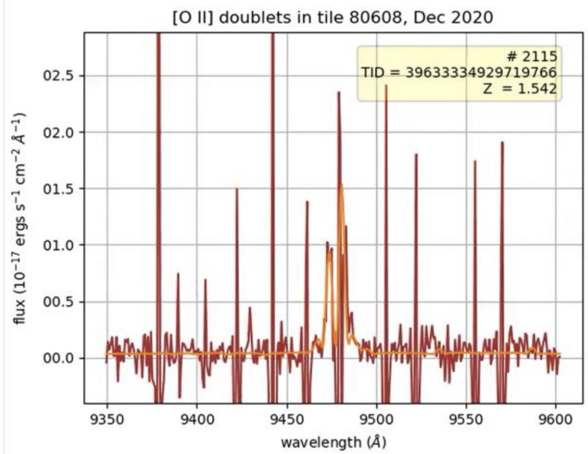
DESI near-IR CCDs (red shift z)



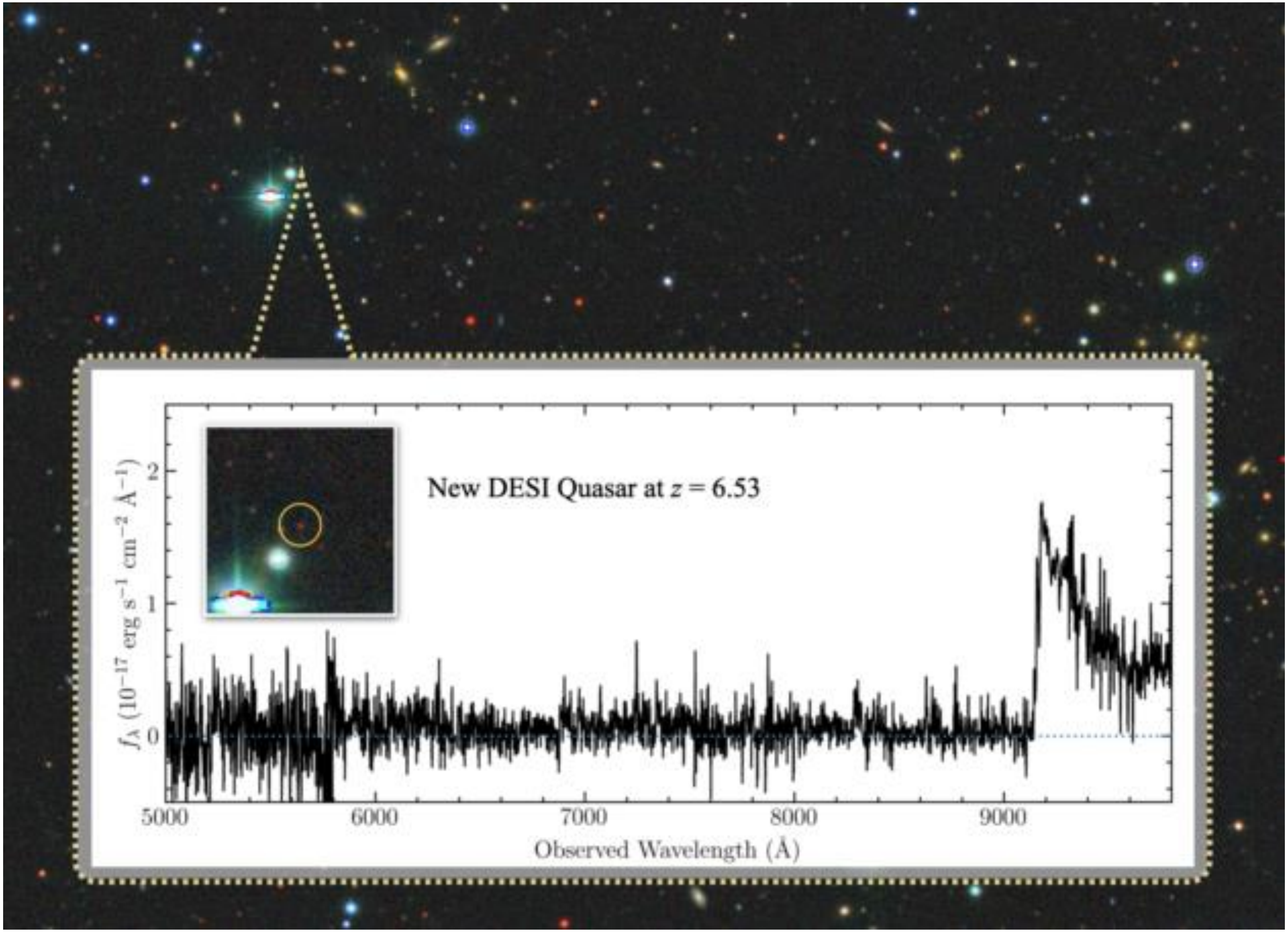






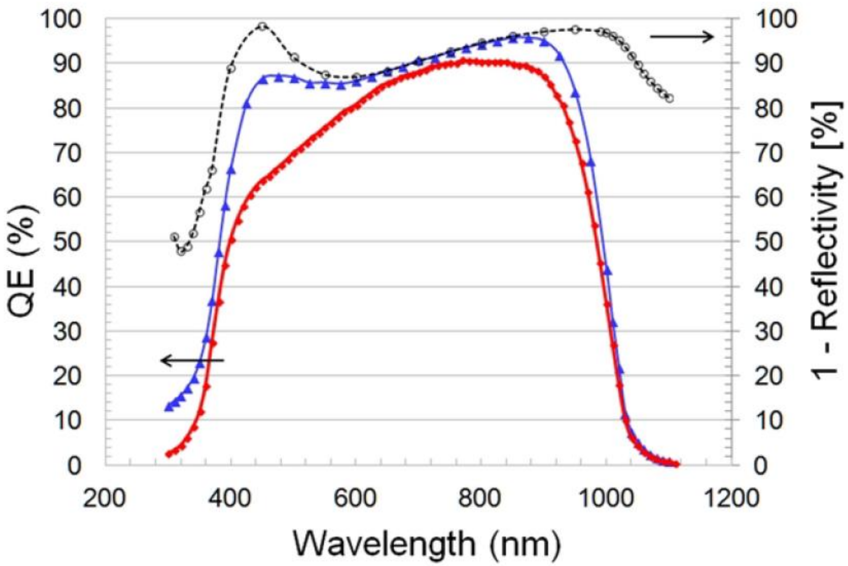


Dark Energy Spectroscopic Instrument



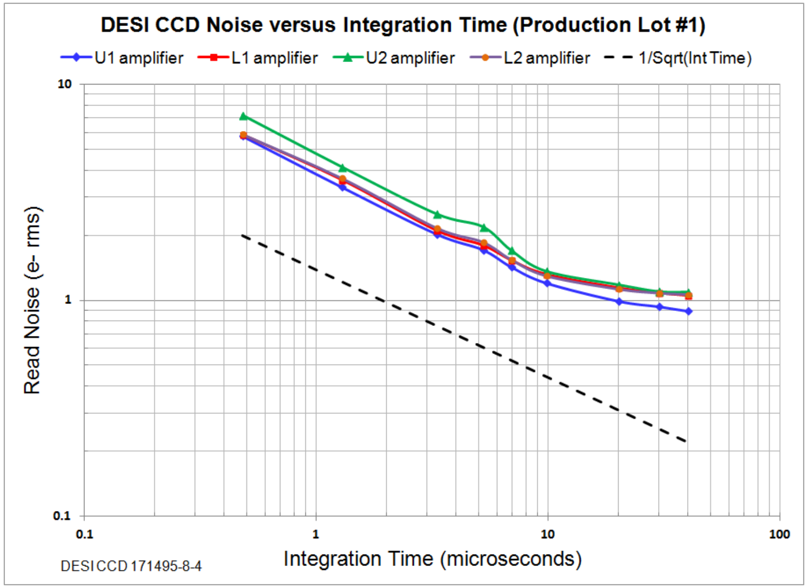
R&D for improved DESI CCDs

- New anti-reflection coating design (D. Groom)
- Lower readout noise



Improved DESI QE (blue) versus
Dark Energy Camera CCDs (red)

doi:10.1088/1748-0221/12/04/C04018
http://dx.doi.org/10.1088/1748-0221/10/05/C05026

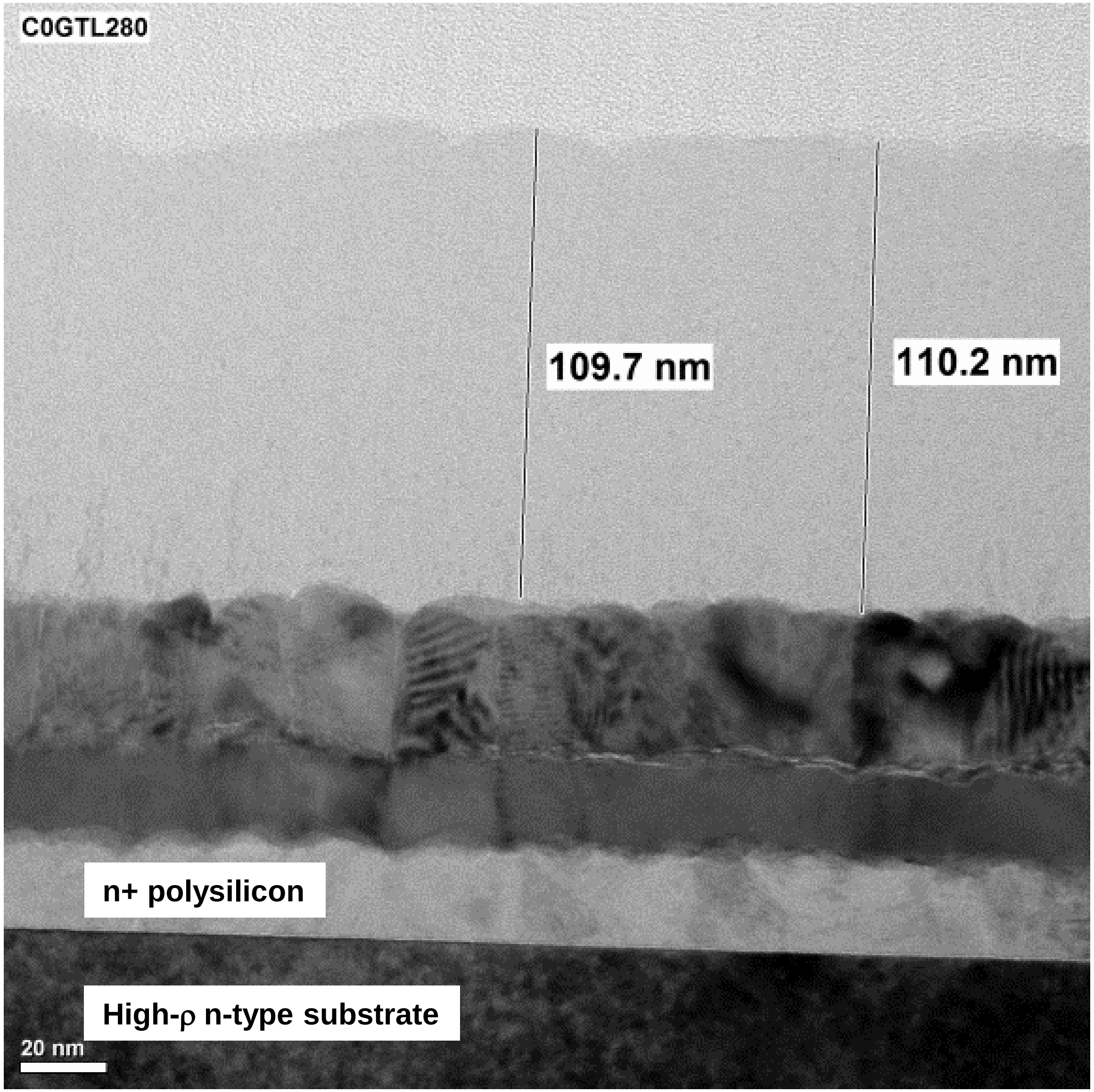


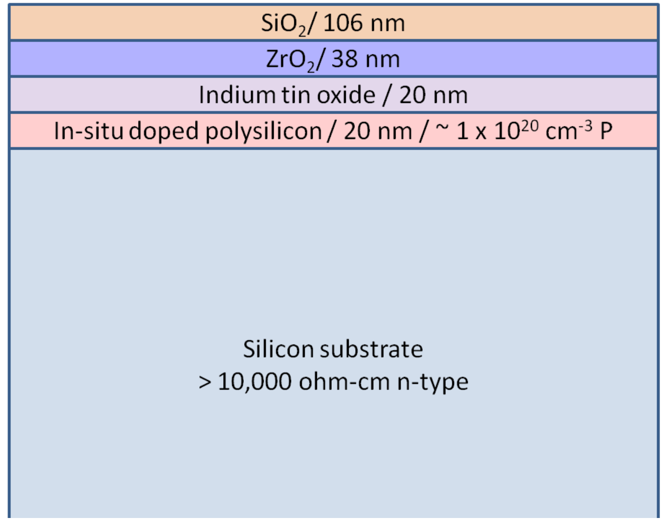
	STA	LBNL	LBNL
SPEC	BLUE	RED	NIR
0	3.62	2.61	2.49
1	3.82	2.77	2.82
2	3.21	3.02	2.38
3	3.24	2.6	2.91
4	3.37	2.73	2.5
5	3.64	2.95	2.45
6	3.37	2.63	2.32
7	3.03	2.4	2.49
8	3.2	2.52	2.48
9	3.14	2.47	2.44

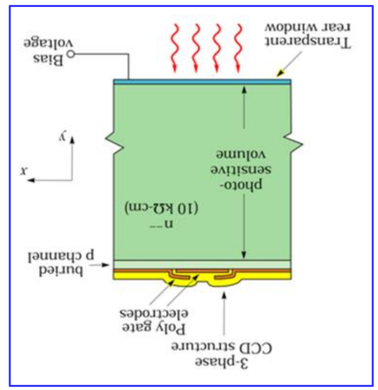
June 2022
Ave of 4 amps

Backside layers: LBNL CCDs

- TEM cross-sectional image







SiO_2

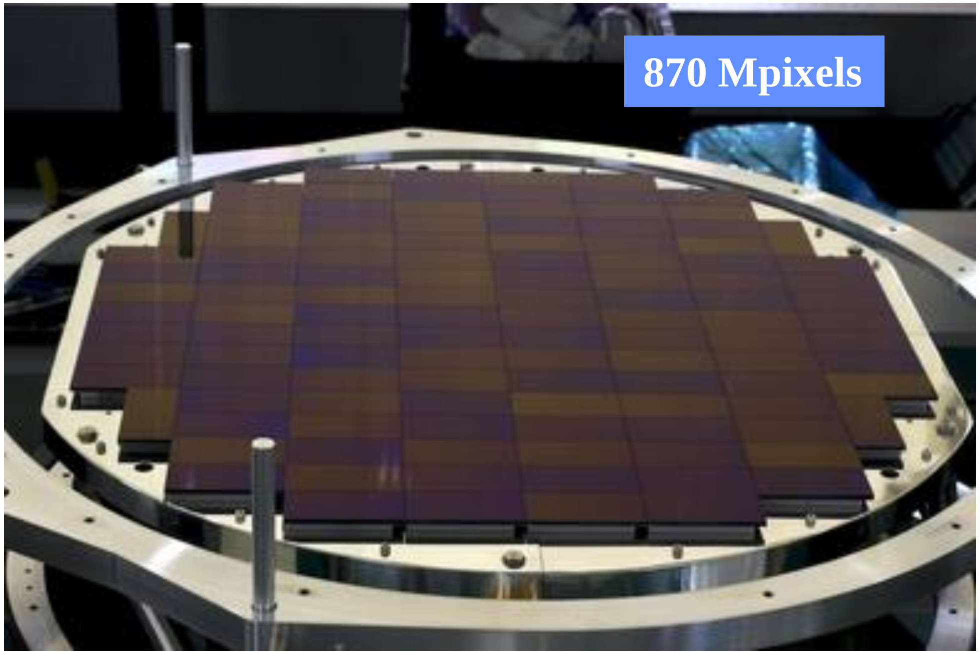
ZrO_2

ITO

In-situ doped polysilicon

Silicon substrate

Astronomical cameras with fully depleted CCDs

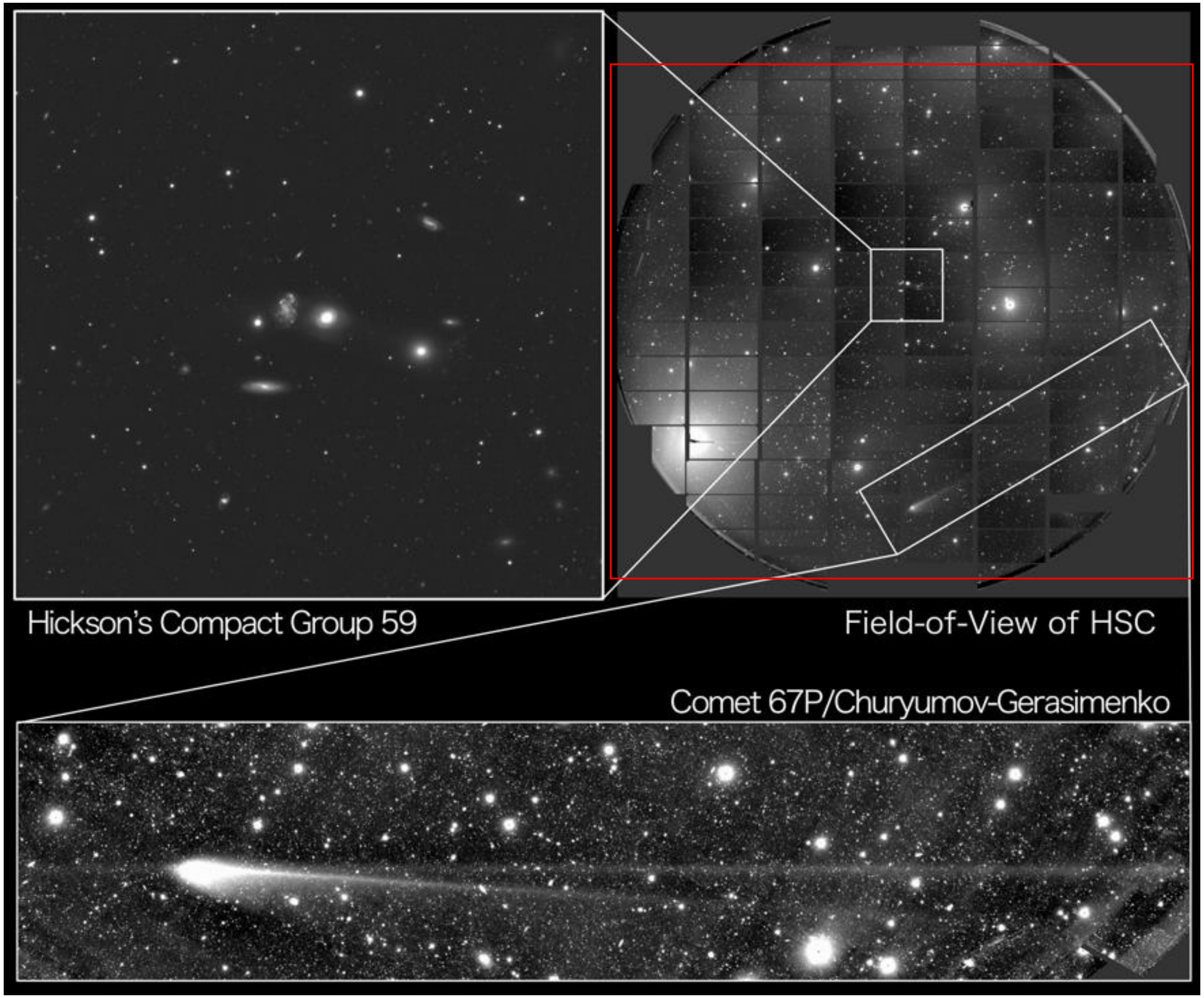


HyperSuprimeCam – 116 2k x 4k, (15 μm)^2-pixel CCDs
200 um thick fully depleted CCDs from Hamamatsu Corporation
Subaru 8-m Telescope

Satoshi Miyazaki (PI) and Yukiko Kamata (CCD testing)

Also PAN-STARRS (Lincoln Labs) and Vera Rubin Observatory (e2V and DALSA/STA/University of Arizona CCDs)

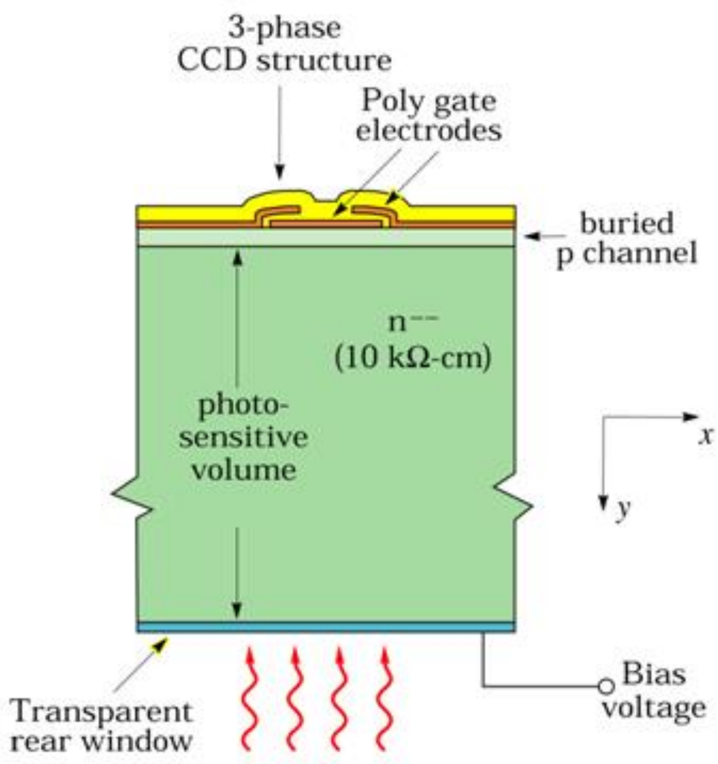
Astronomical cameras with fully depleted CCDs



Full moon
for scale

HyperSuprimeCam – 116 2k x 4k, (15 μm)^2-pixel CCDs (870 Mpixels)
CCDs from Hamamatsu Corporation / Subaru 8-m Telescope

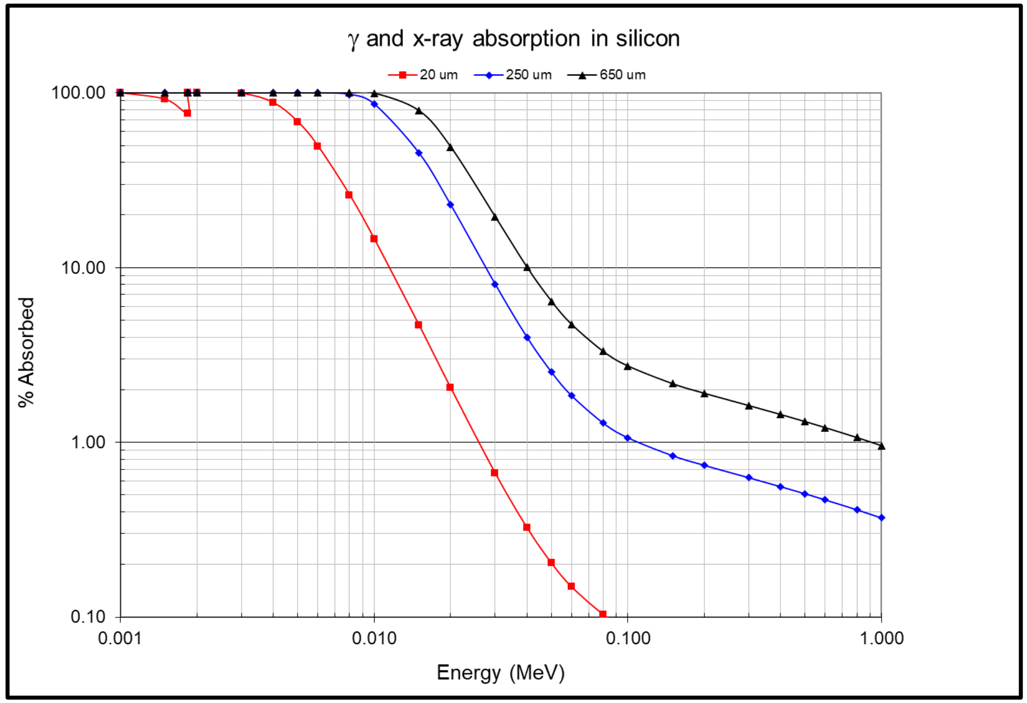
"Fully depleted CCDs" 101



Not to scale

CCD fabricated on a high-resistivity silicon substrate that is fully depleted by the application of a substrate bias

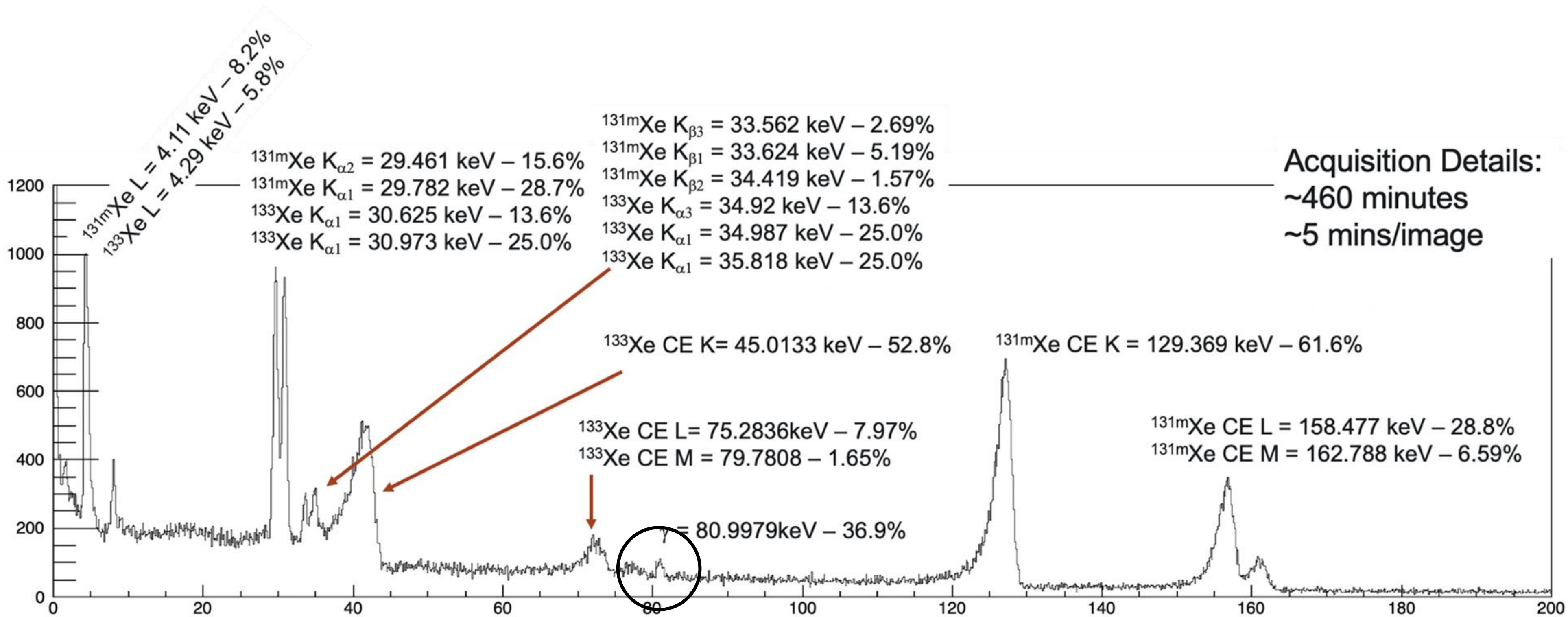
- Thick CCDs for radiation detection
  - Charged particles, x and γ rays



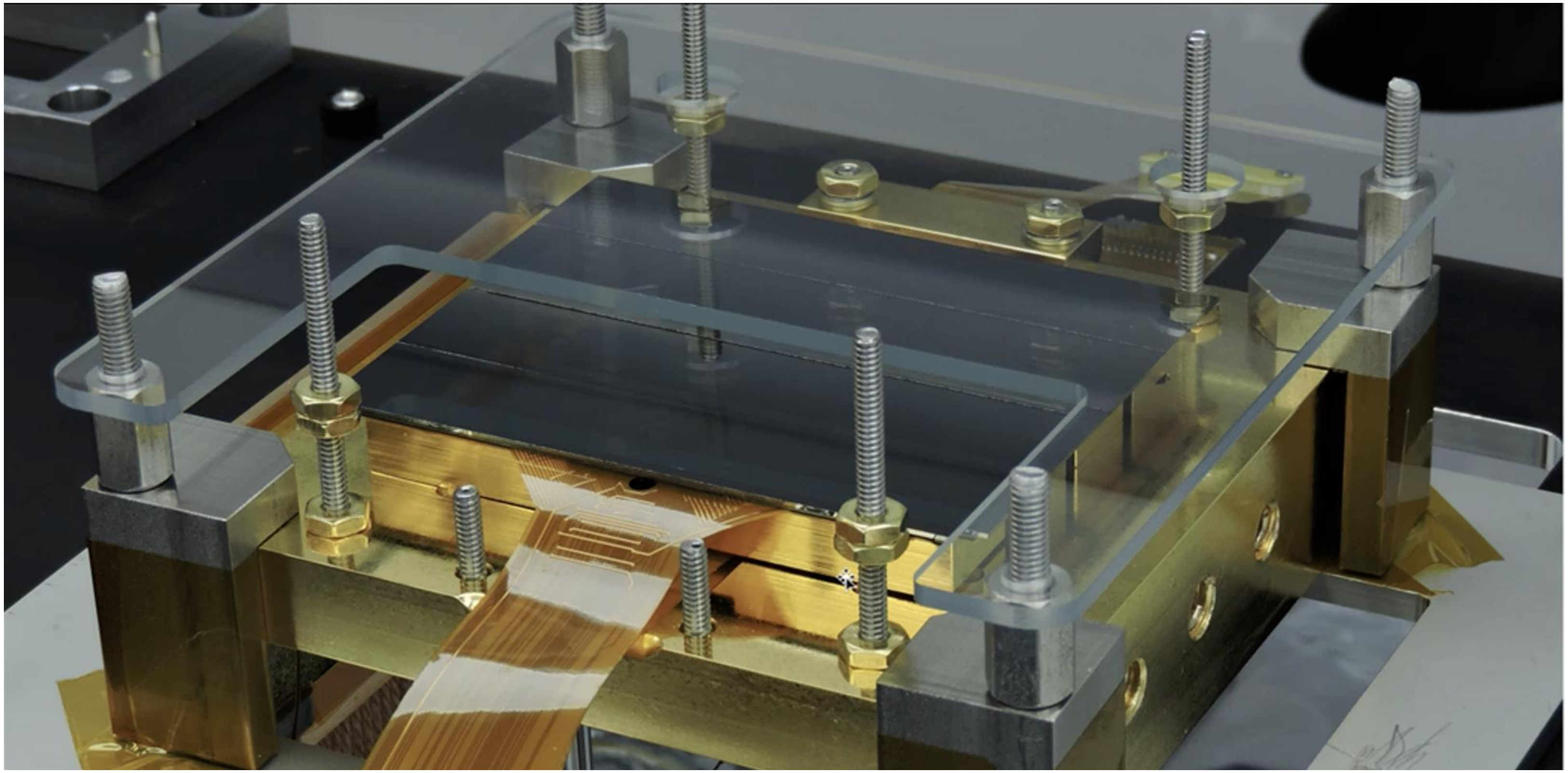
Radiation detection with thick, FD CCDs

CCD-based ionizing radiation detectors with low-energy (<100 keV) gamma-ray sensitivity / 650 um thick and fully depleted

Todd Hossbach: Pacific Northwest National Lab



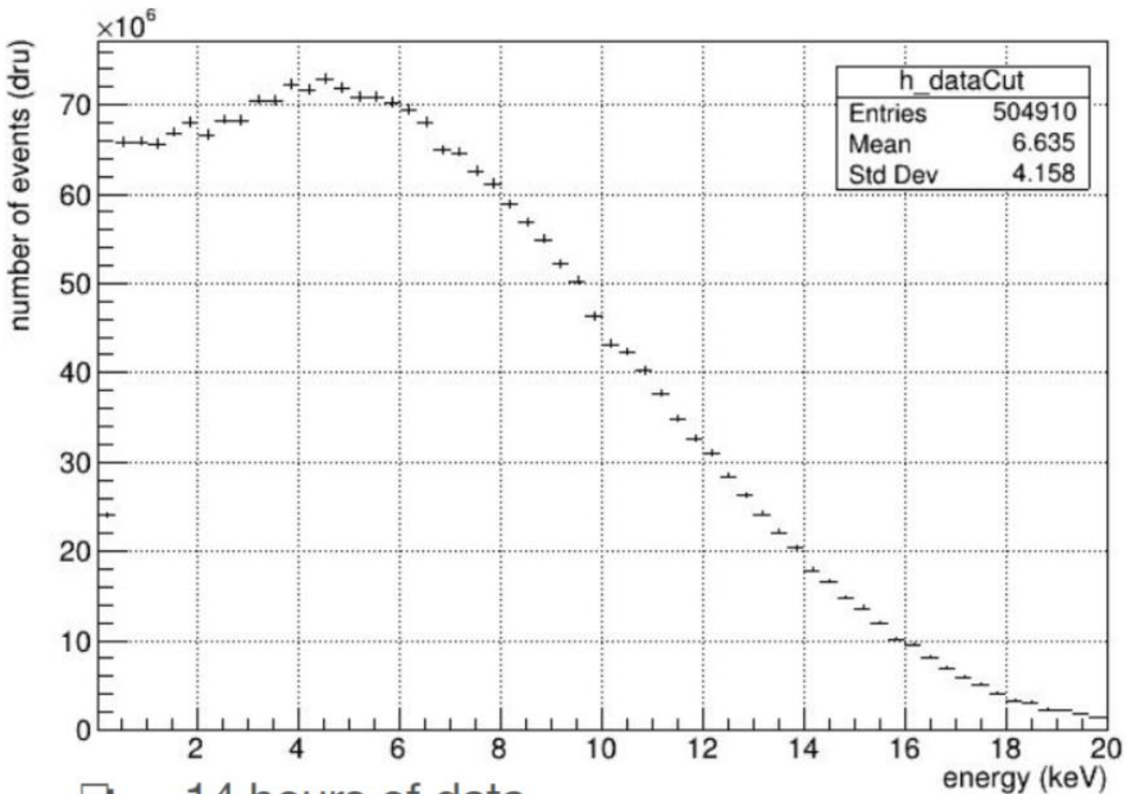
^3H detection with thick, BI, FD CCDs



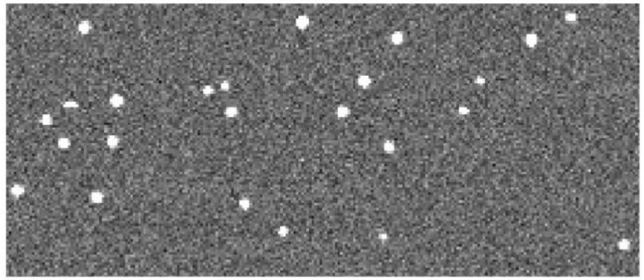
- GRAIL focal plane for radiation detection
  - 4 1k x 6k, 580-um thick back-illuminated CCDs
  - Mix of finishing at LBNL and Lincoln Laboratory
    - Lincoln Labs molecular-beam epitaxy backside

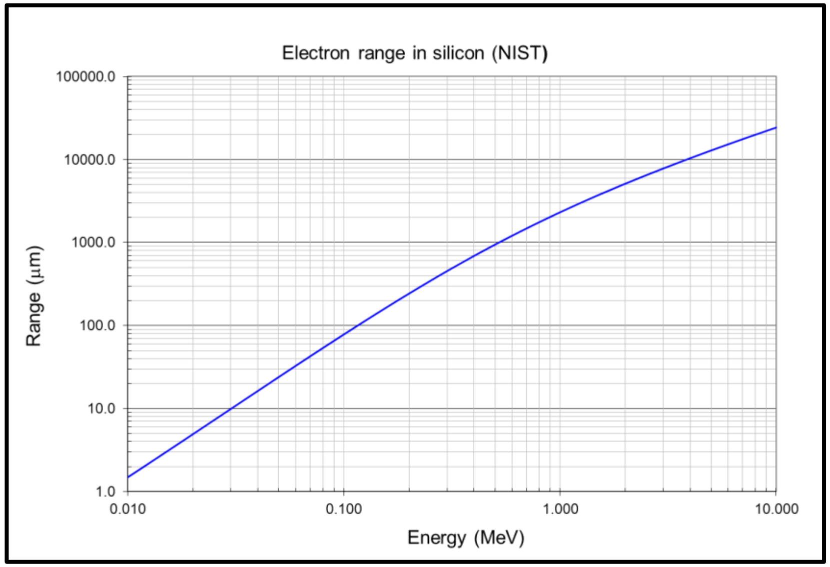
^{3}H detection with thick, BI, FD CCDs

Measured tritium spectrum using G2-CCD



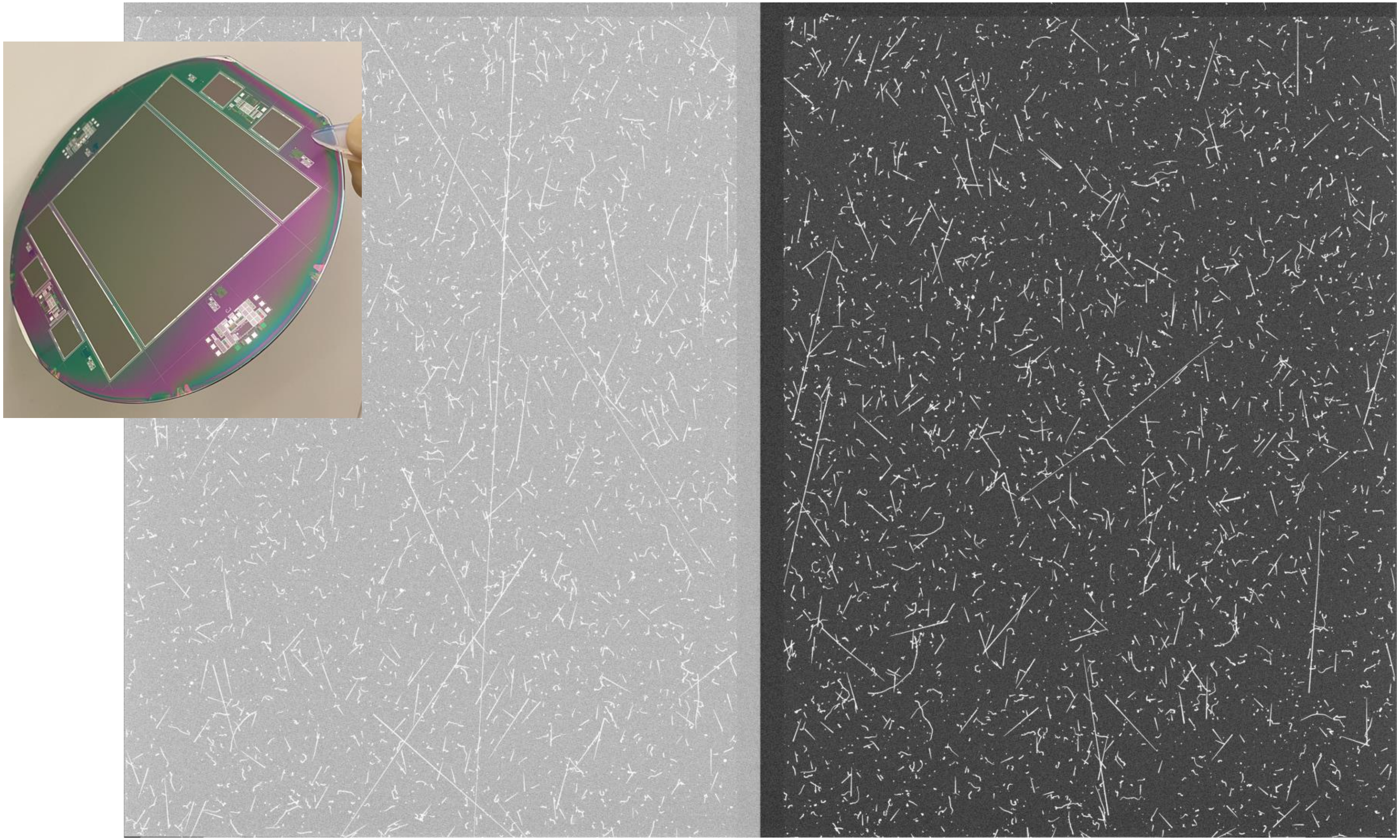
❑ ~14 hours of data





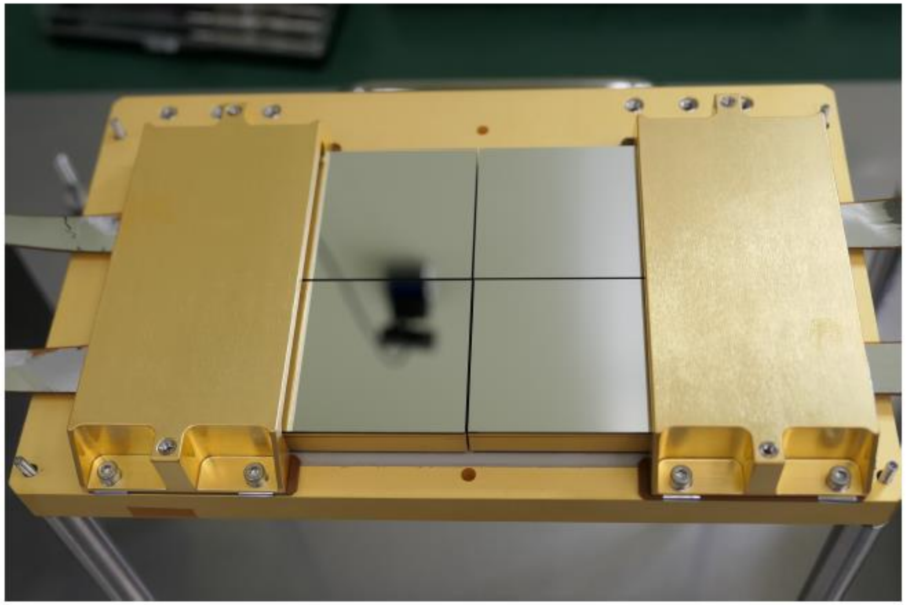
- GRAIL project with PNNL, LBNL, FermiLab, Lincoln Laboratory
    - ~ 2 keV β-electron detection

580 um thick, back-illuminated CCD



LBNL-processed 6k x 4k CCD: Thin n+ backside contact / no AR
1 hour dark / 60V / 120K
University of Chicago

Xtend CCDs on XRISM space mission



https://doi.org/10.1117/12.2626894
https://doi.org/10.1117/12.2560348
https://doi.org/10.1016/j.nima.2020.164676

Table 1. Specifications and nominal operation parameters of the SXI CCD

CCD Specification	Architecture	Frame transfer
	Imaging area size	30.720 mm $\times$ 30.720 mm
	Pixel format (physical/logical)	1280 $\times$ 1280 / 640 $\times$ 640
	Pixel size (physical/logical)	24μm $\times$ 24μm / 48μm $\times$ 48μm
	Depletion layer thickness	200 μm
	Incident surface layer (back side)	100 nm + 100 nm thick Aluminum coat
	Readout nodes (equipped/used)	4 / 2
Operation parameters	Frame cycle	4 seconds
	On-chip binning	2$\times$2
	Charge injection	every 160 physical rows

Xtend soft x-ray imaging telescope (Launch 9/6/2023)

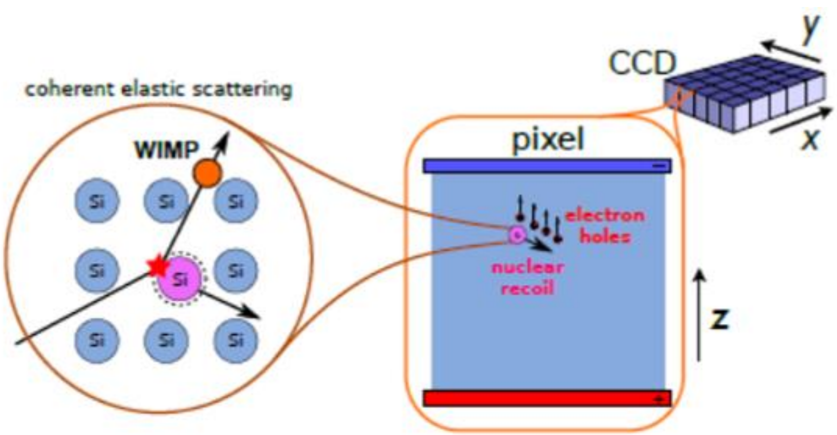
CCDs from Hamamatsu Corporation / Testing at Osaka University

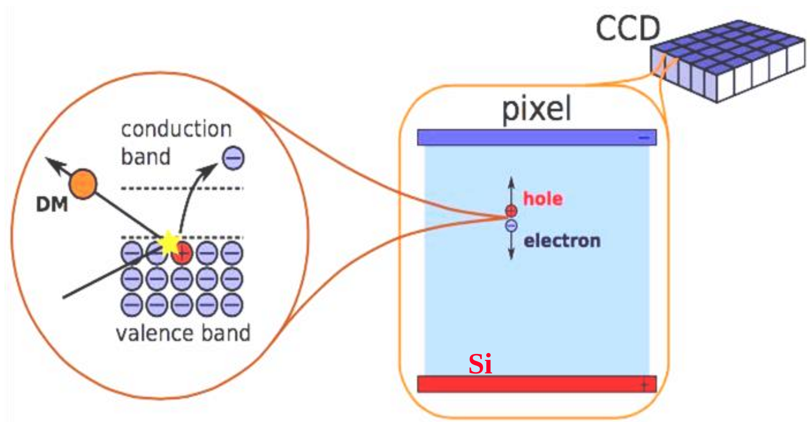
Dark Matter detection with CCDs

Proposed by Juan Estrada et al of FermiLab (2008)

- https://doi.org/10.48550/arXiv.1105.5191

- Low noise / improves low-energy detection threshold
  - Si bandgap ~ 1.1 eV
- Thick CCDs for larger volume
- Expected dark-matter particle interactions
  - Nuclear recoil (silicon nucleus)
  - Scattering off electrons





Dark Matter detection with CCDs

1st underground engineering run / one 4 Mpixel DECam CCD

- https://doi.org/10.1016/j.physletb.2012.04.006

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ELSEVIER

Direct search for low mass dark matter particles with CCDs

J. Barreto [a], H. Cease [b], H.T. Diehl [b], J. Estrada [b,*], B. Flaugher [b], N. Harrison [b], J. Jones [b], B. Kilminster [b], J. Molina [c], J. Smith [b], T. Schwarz [d], A. Sonnenschein [b]

[a] Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
[b] Fermi National Accelerator Laboratory, Batavia, IL, USA
[c] Facultad de Ingenieria, Universidad Nacional de Asuncion (FIUNA), Asuncion, Paraguay
[d] University of California at Davis, CA, USA

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ABSTRACT

A direct dark matter search is performed using fully-depleted high-resistivity CCD detectors. Due to their low electronic readout noise (R.M.S. ~7 eV) these devices operate with a very low detection threshold of 40 eV, making the search for dark matter particles with low masses (~5 GeV) possible. The results of an engineering run performed in a shallow underground site are presented, demonstrating the potential of this technology in the low mass region.

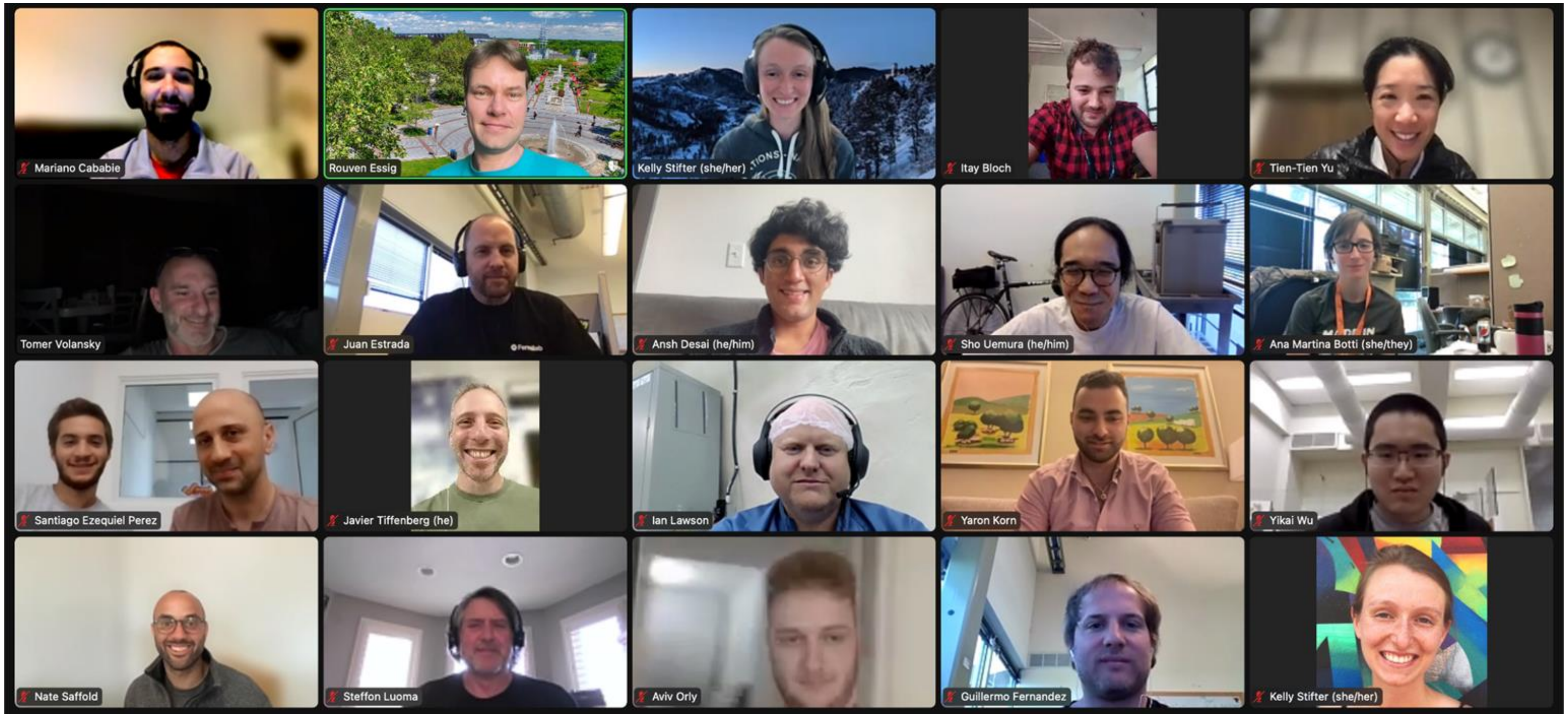
- SENSEI / DAMIC-M / OSCURA are 0.1/1/10 kg scale
  - 2 e- noise (2012) ⟹ now deep sub-electron (Skipper CCDs)
  - 250 um (2012) ⟹ now 650-725 um
  - Dark current orders of magnitude less than astronomy CCDs

Dark Matter detection with CCDs

SENSEI

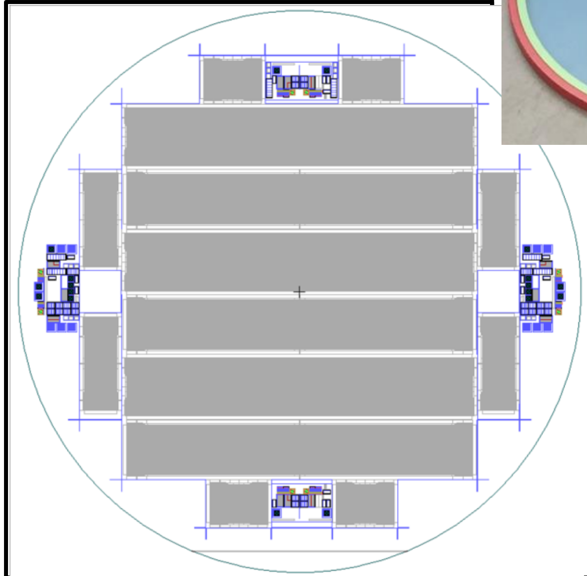
Sub-Electron-Noise Skipper-CCD Experimental Instrument

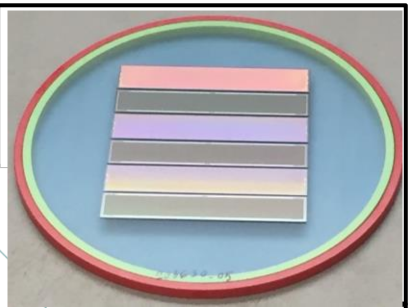
100 g scale (1 Teledyne DALSA Semiconductor lot of 25 wafers)



SENSEI collaboration at unblinding meeting

LBNL Dark Matter CCD development





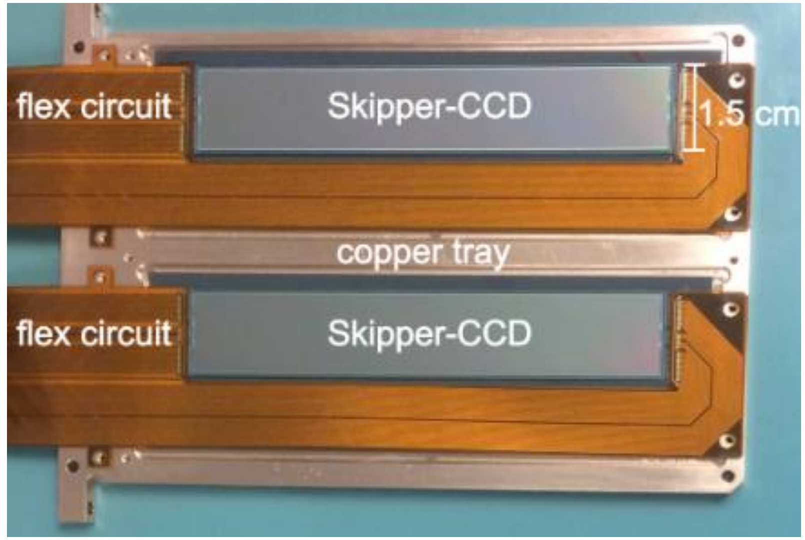
SENSEI

CCD fabrication complete March 2019

650 um thick, fully depleted CCDs
150-mm wafers
Full fabrication at DALSA Semiconductor

6 6k x 1k CCDs installed now (13 g)
2 km underground at SNOLAB
1st science run was 9/2022 – 4/2023
100-g scale experiment

SENSEI@SNOLAB

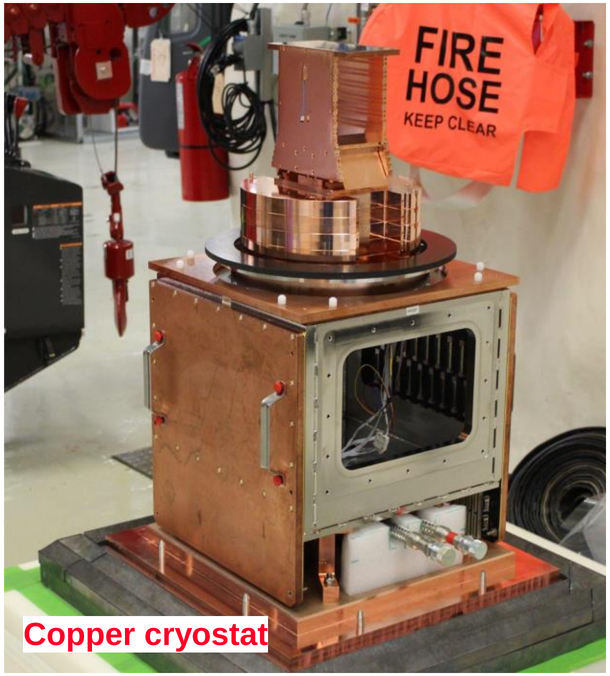


SENSEI publications

- 2017 Skipper CCD
  - PRL 119.131802
- 2018 Surface run prototype CCD
  - PRL 121.061803
- 2019 Underground prototype CCD
  - PRL 122.161801
- 2020 Underground science CCD
  - PRL 125.171802

LBNL Dark Matter CCD development

SENSEI@SNOLAB



Results presented at
APS April Meeting 2023
2023 Phenomenology Symposium

Paper in preparation

Presently installing more CCDs

SNOLAB underground laboratory

SNOLAB

SNOLAB is Canada's deep underground research laboratory, located in Vale's Creighton mine near Sudbury, Ontario Canada.

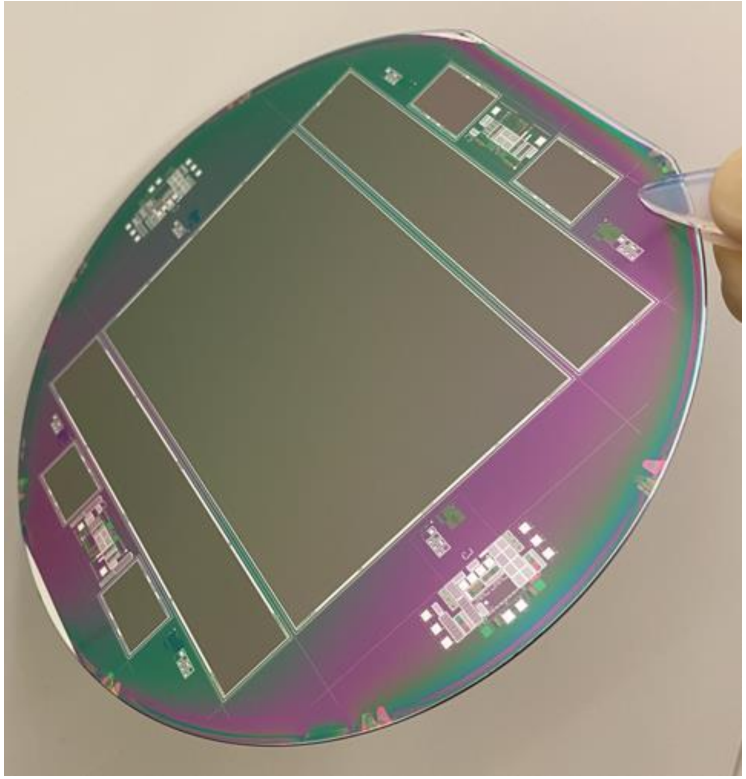
It provides an ideal low background environment for the study of extremely rare physical interactions. SNOLAB's science program focuses on astroparticle physics, specifically neutrino and dark matter studies, though its unique location is also well-suited to biology and geology experiments. SNOLAB facilitates world-class research, trains highly qualified personnel, and inspires the next generation of scientists.

At 2km, SNOLAB is the deepest cleanest lab in the world. It is an expansion of the facilities constructed for the Sudbury Neutrino Observatory (SNO) solar neutrino experiment and has 5,000 m^2 of clean space underground for experiments and supporting infrastructure. A staff of over 100 support the science, providing business processes, engineering design, construction, installation, technical support, and operations. SNOLAB research scientists provide expert and local support to the experiments and undertake research in their own right as members of experimental collaborations.

DAMIC-M
Dark Matter in CCDs at Modane

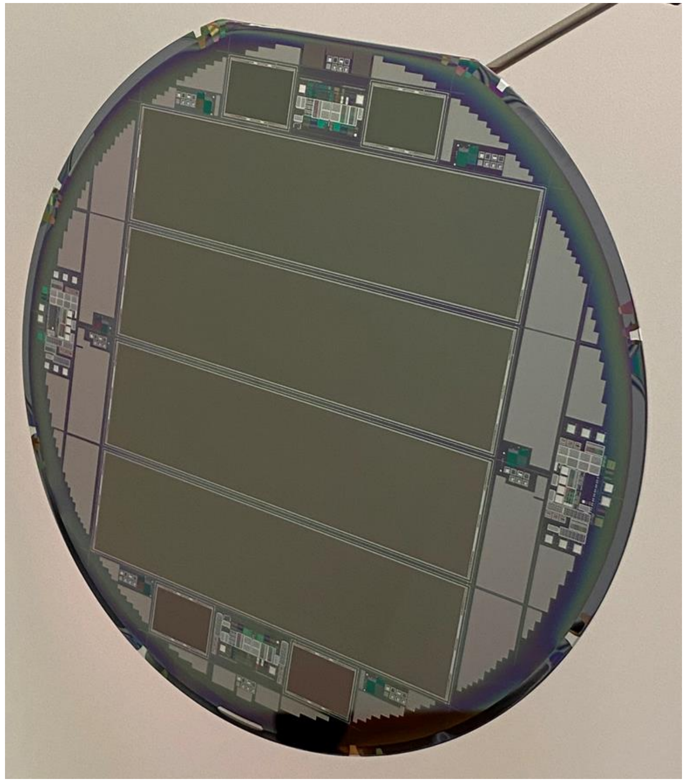
1 kg scale (~10 Teledyne DALSA Semiconductor lots of 25 wafers)

LBNL Dark Matter CCD development



DAMIC-M R&D CCDs
650 um thick, fully depleted CCDs
150-mm wafers

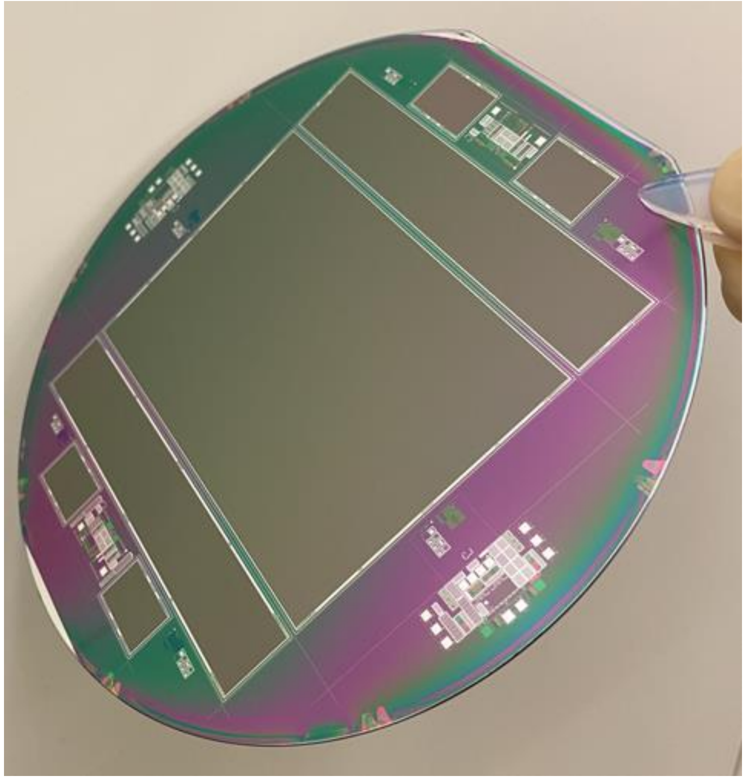
See DAMIC-M web site
https://damic.uchicago.edu/



DAMIC-M production CCDs
1 kg scale dark matter
Fabrication started March 2021
9-10 lots for 1 kg

Full fabrication at DALSA Semiconductor

LBNL Dark Matter CCD development



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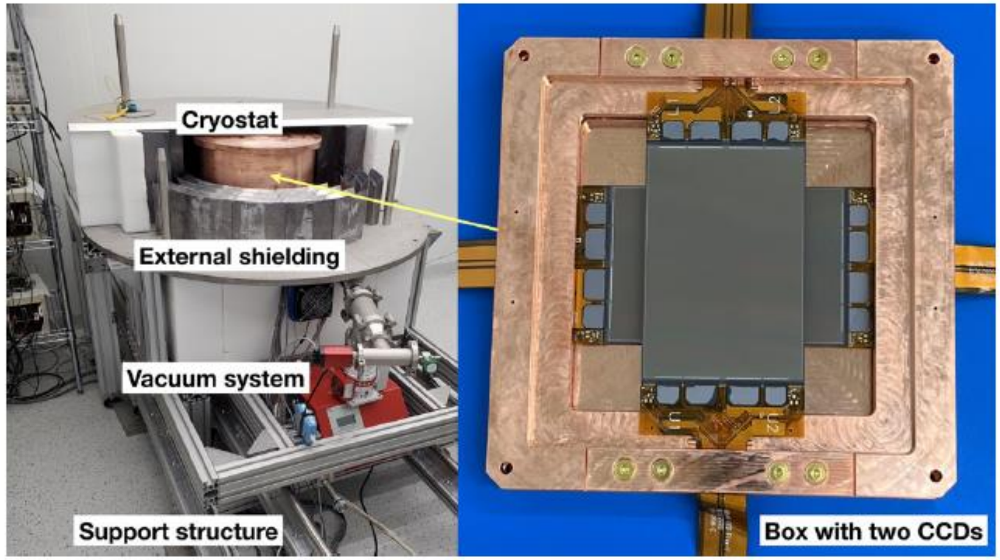
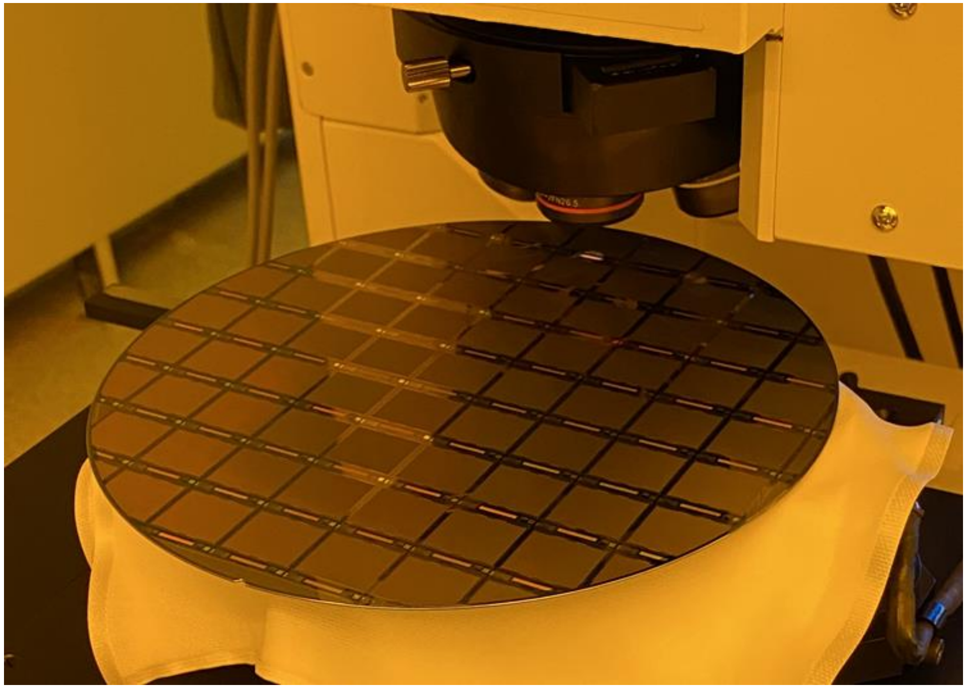


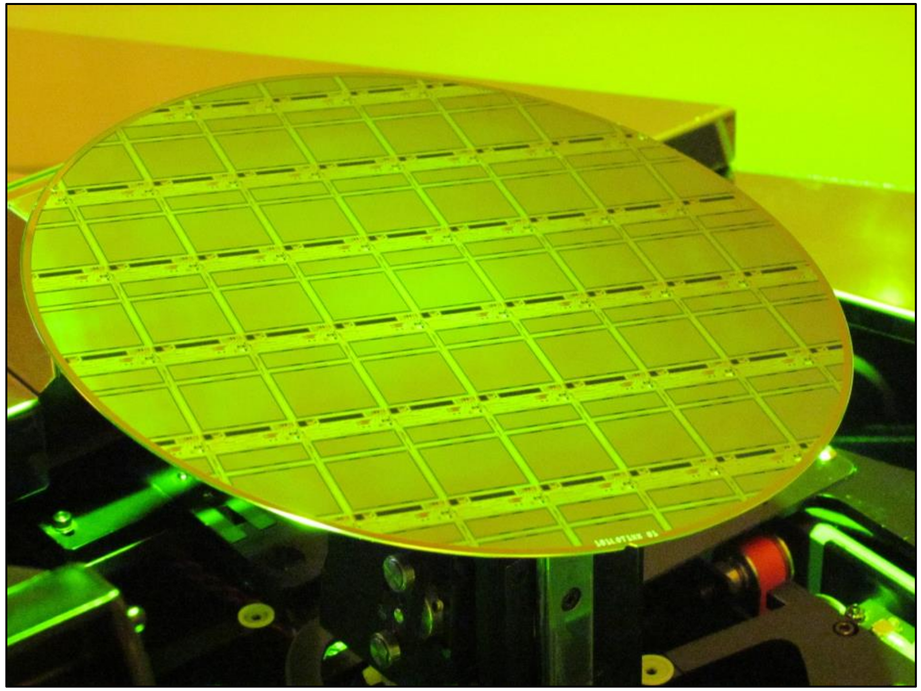
- 2022 DAMIC-M run at Modane
  - PRL 130.171003
  - Low background chamber (LBC)
  - Laboratoire Souterrain de Modane
  - 2 6k x 4k CCDs, 650 um thick
- 2022-2023 DAMIC-M at SNOLAB
  - arXiv:2306.01717
  - 2 6k x 4k CCDs, 650 um thick
  - Feb 2022 – Jan 2023
  - Excess signal noted

LBNL Dark Matter CCD development

OSCURA

Observatory of Skipper CCDs Unveiling Recoiling Atoms





- Technology transfer of the LBNL p-channel fully depleted technology to Microchip Technology (above left) and Lincoln Laboratory (above right)
  - 200 mm wafers with step-and-repeat photolithography
  - 10 kg scale (~20k 1Mpix CCDs, 10x more pixels than LSST/Rubin)

First results from a multiplexed and massive instrument with sub-electron noise Skipper-CCDs

F. Chierchie,[a,b,1] C.R. Chavez,[c,b,d] M. Sofo Haro,[e] G. Fernandez Moroni,[c] B.A. Cervantes-Vergara,[c,f] S. Perez,[g,c] J. Estrada,[c] J. Tiffenberg,[c] S. Uemura[c] and A. Botti,[c]

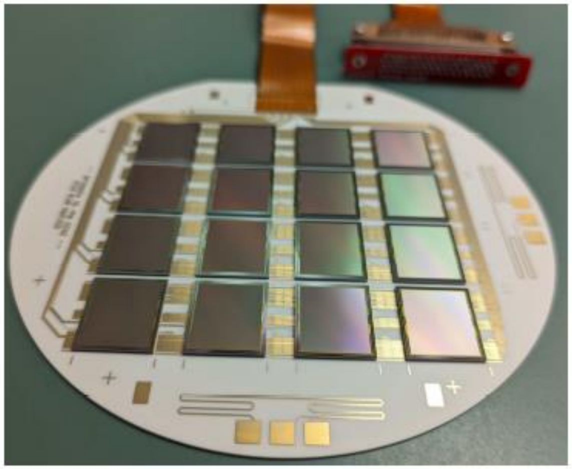


Figure 3: Photograph of a Multi-Chip Module (MCM): single layer ceramic substrate with 16 glued single-electron resolution Skipper-CCDs.

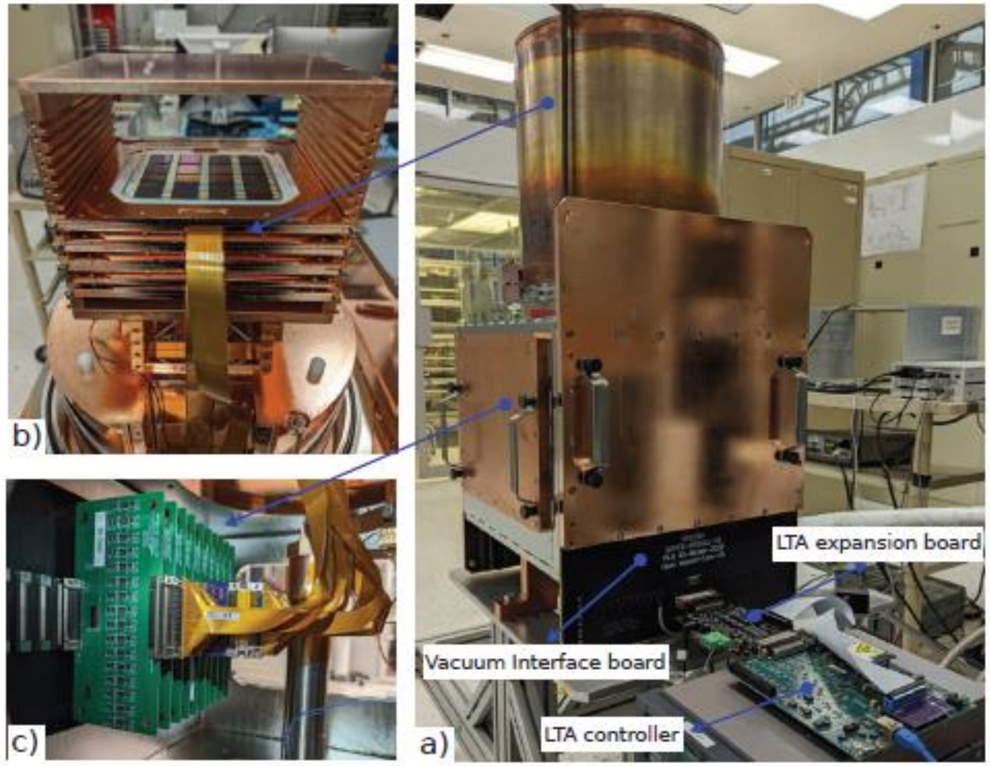


Figure 2: a) Photograph of the exterior of the instrument: cylinder in the top holds the sensors, box in the bottom houses the frontend electronics; b) Copper box and copper trays holding the sensors and flex cables; c) frontend electronics connected to the vacuum interface board.

https://doi.org/10.1088/1748-0221/18/01/P01040

DESI (astronomy) vs SENSEI (DM)

Parameter	DESI	SENSEI[1]
CCD format Thickness	4k x 4k (15 um)^2 250 um	6k x 1k (15 um)^2 650 um
Read noise	2.5 – 3.0 e- rms	0.1 e- rms See note 1
Dark current	~ 1 e-/pixel-hour (133K)	~ 2 x 10^{-4} e/pix-day (135-155K) See note 2
Exposure time	15 minutes	20 hours
Readout time	1 minute	7.3 hours

Note 1: Skipper CCD with 300 samples / pixel
Note 2: Cold Cu, some shielding / 100 m underground
Number quoted is the single-electron event rate

1 **Sub-GeV dark matter searches with SENSEI**

Nate Saffold, for the SENSEI collaboration
APS April Meeting
4/15/2023

Dark Matter detection with CCDs

Fully depleted CCD advantages for dark matter detection

- Low noise / few e- and deep sub electron (Skipper CCDs)
- Thick depleted regions / larger mass
- Background suppression / spatial and energy resolution
- Extremely low dark current for DM experiments

- Main disadvantage is the lack of timing information

Skipper CCDs / 1990

Two SPIE papers in 1990 / sub e- noise CCDs

New advancements in charge-coupled device technology - sub-electron noise and 4096x4096 pixel CCDs

James Janesick, Tom Elliott, Arsham Dingizian,

Jet Propulsion Laboratory, 4800 Oak Grove Dr, Pasadena, CA. 91109

Richard Bredthauer, Charles Chandler

Ford Aerospace Corporation, Ford Road, Newport Beach, CA. 92658

James Westphal

California Institute of Technology, Pasadena, CA. 91125

James Gunn

Princeton University, Princeton, NJ. 08544

https://doi.org/10.1117/12.19452

Sub-electron noise charge coupled devices

Charles E. Chandler, Richard A. Bredthauer

Ford Aerospace Corporation
Ford Road, Newport Beach, California 92658

James R. Janesick

Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena, California 91109

James A. Westphal

California Institute of Technology
Pasadena, California 91125

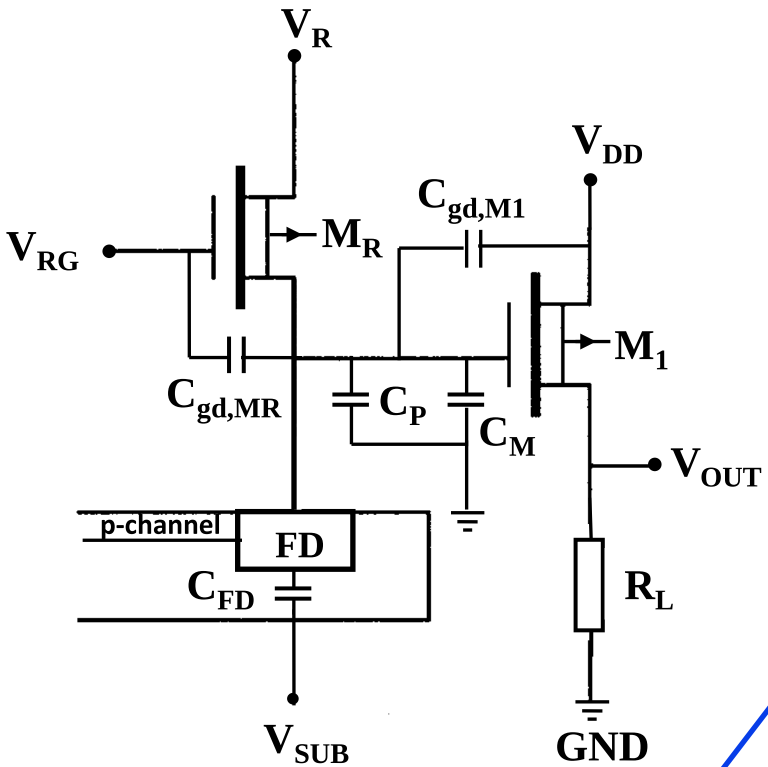
James E. Gunn

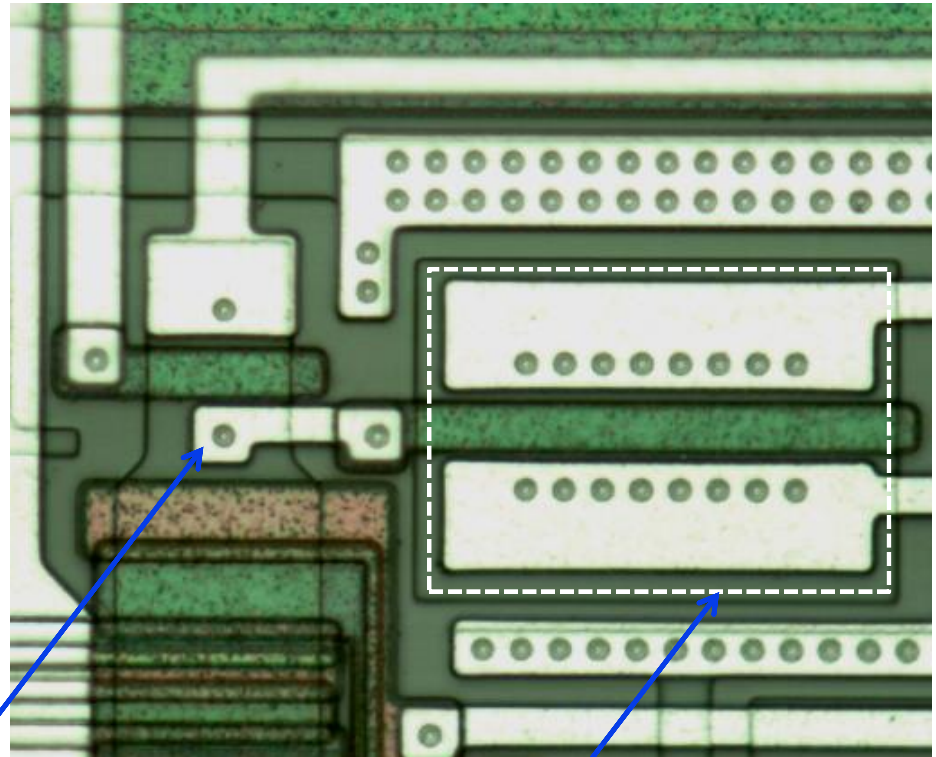
Princeton University
Princeton, New Jersey, 08544

https://doi.org/10.1117/12.19457

- Invented by Jim Janesick
  - U.S. patent 5250824 (1993)
- Based on the floating-gate amplifier first reported by Fairchild in the early 1970's
- Conventional CCDs use floating-diffusion amplifiers

Floating-diffusion amplifier





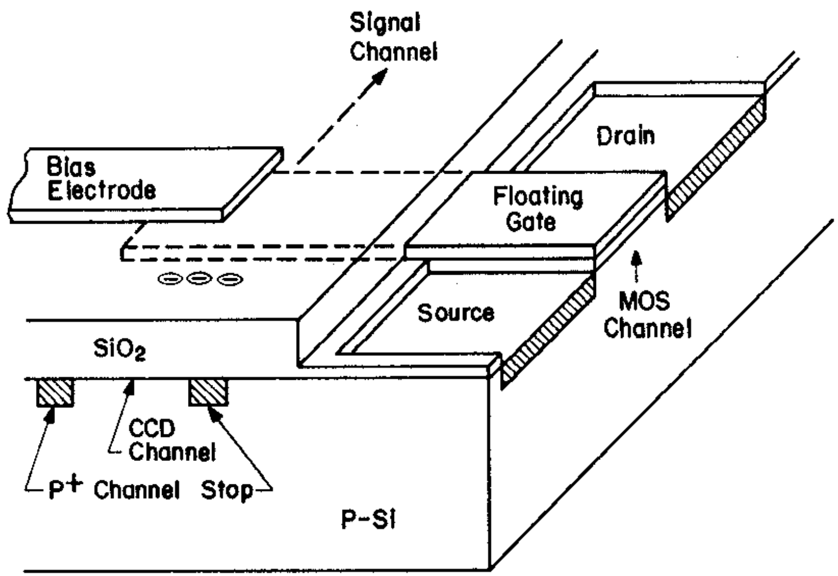
Floating diffusion

Output transistor M1

Floating-gate amplifier

- Floating-gate amplifier paper (1974 Fairchild)

WEN: FLOATING GATE AMPLIFIER



Design and Operation of a Floating Gate Amplifier

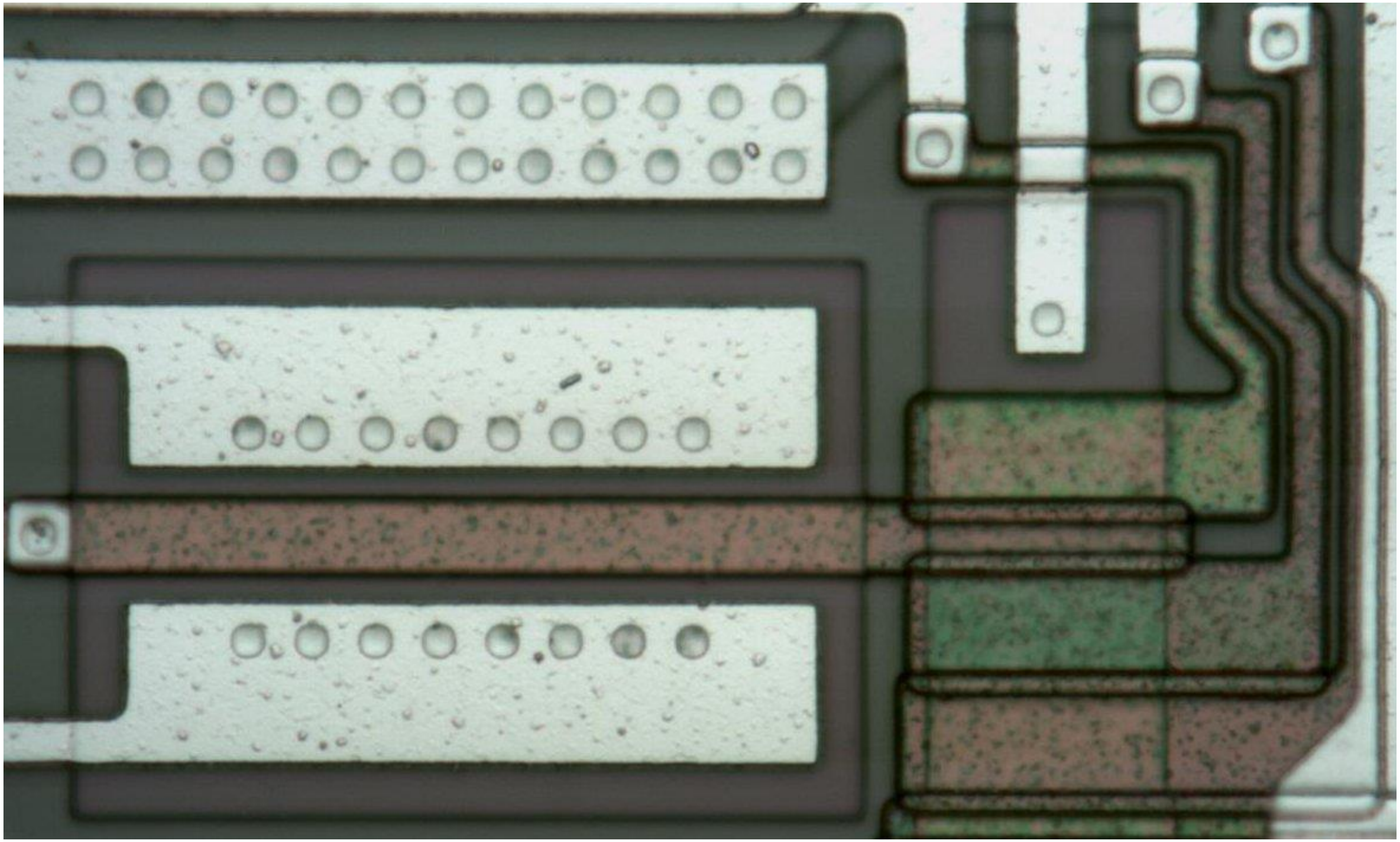
DAVID D. WEN, MEMBER, IEEE

IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. SC-9, NO. 6, DECEMBER 1974

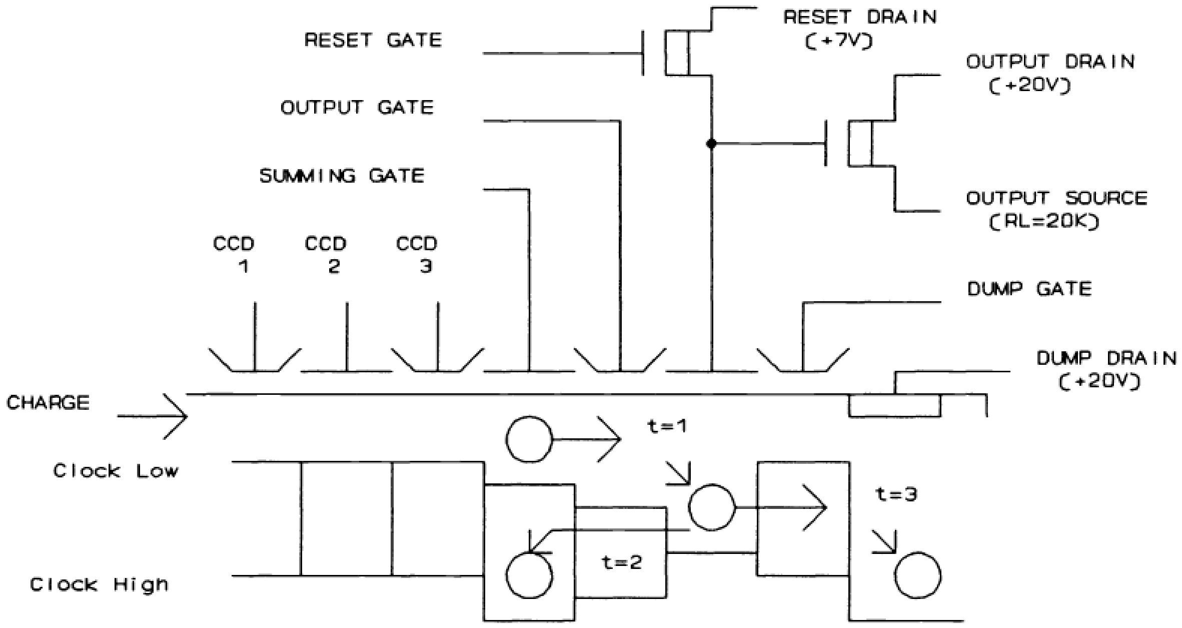
DOI: 10.1109/JSSC.1974.1050535

Floating-gate amplifier

- LBNL implementation (floating-gate amplifier)



Skipper CCD operation



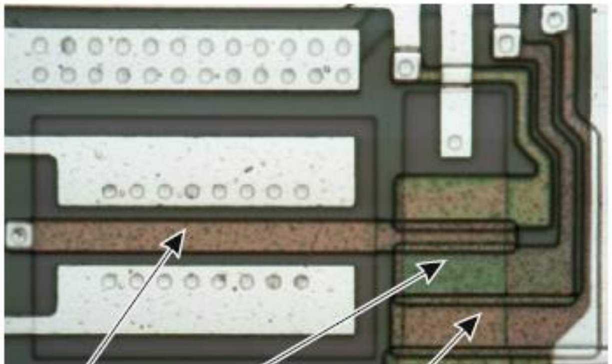
240 / *SPIE Vol. 1242 Charge-Coupled Devices and Solid State Optical Sensors (1990)*

- Multiple, nondestructive reads of the charge (floating-gate)
- Noise ∝ Inverse square root of the number of samples
  —1990 results
    - 0.5 e- noise but no improvement after 256 samples

Version 1 Skipper CCD tested at FermiLab

- 1022 x 1024 (15 um pixel)^2 CCD (LDRD 2009)
  - 0.2 e- after 1227 samples (2012)

Fig. 4 L2 amplifier layout. The floating gate, the output gate and the summing well gate are shown



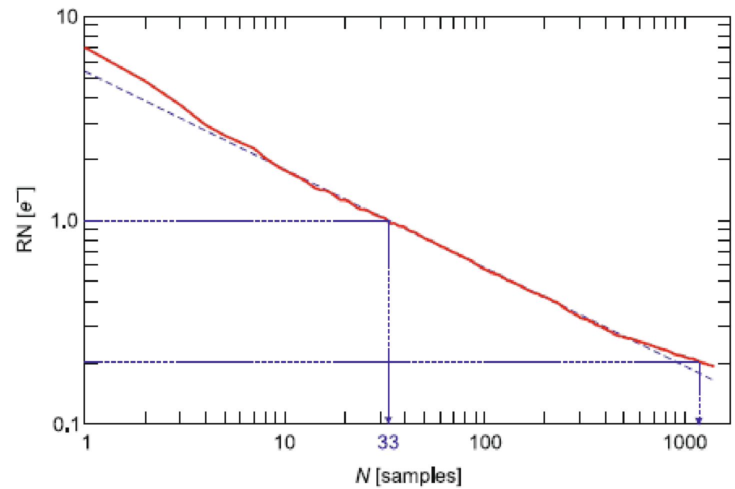


Fig. 10 Skipper CCD RN in the overscan region as a function of the number of averaged samples *N*. *Continuous line* RN measured from images. *Dashed line* theoretical RN reduction fit for white or $1/f^2$ noise

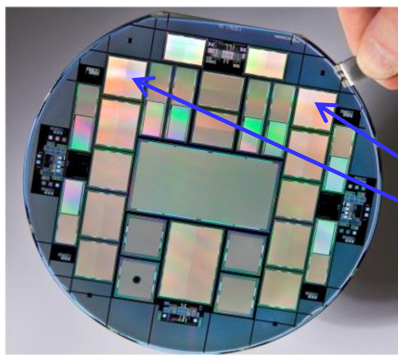
https://doi.org/10.1007/s10686-012-9298-x

Exp Astron (2012) 34:43–64
DOI 10.1007/s10686-012-9298-x

ORIGINAL ARTICLE

Sub-electron readout noise in a Skipper CCD fabricated on high resistivity silicon

Guillermo Fernández Moroni · Juan Estrada · Gustavo Cancelo · Stephen E. Holland · Eduardo E. Paolini · H. Thomas Diehl



Factor of 2.5 better than 1990's work

FG amplifier CCDs

Version 2 Skipper CCD tested at FermiLab

- 2nd version (LDRD 2013)
  - 0.068 e⁻ after 4k samples (2017)

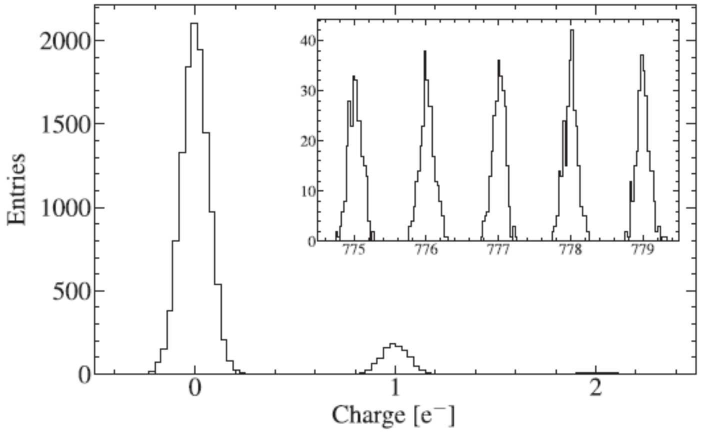


FIG. 1. Single-electron charge resolution using a Skipper CCD with 4000 samples per pixel (bin width of 0.03 e^-). The measured charge per pixel is shown for low (main) and high (inset) illumination levels. Integer electron peaks can be distinctly resolved in both regimes contemporaneously. The 0 e^- peak has rms noise of 0.068 e^- rms/pixel while the 777 e^- peak has 0.086 e^- rms/pixel, demonstrating single-electron sensitivity over a large dynamical range. The Gaussian fits have $\chi^2 = 22.6/22$ and $\chi^2 = 19.5/21$, respectively.

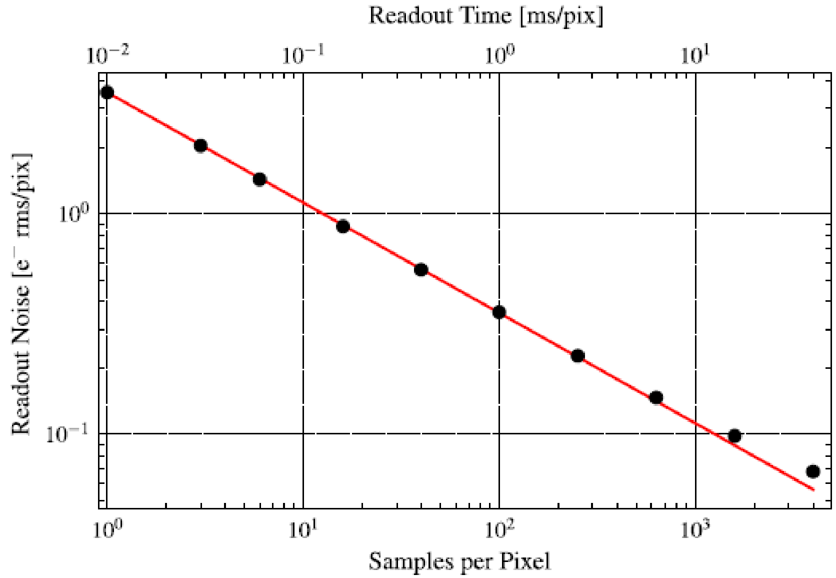


FIG. 3. Readout noise as a function of the number of nondestructive readout samples per pixel for the Skipper CCD. Black points show the rms of the empty-pixel distribution as a function of the number of averaged samples. The red line is the theoretical expectation assuming independent, uncorrelated samples [Eq. (1)].

PRL **119,** 131802 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

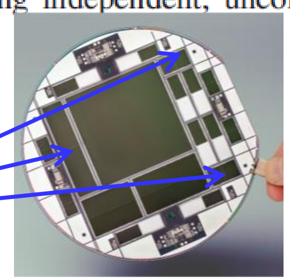
Single-Electron and Single-Photon Sensitivity with a Silicon Skipper CCD

Javier Tiffenberg,[1,*] Miguel Sofo-Haro,[2,1] Alex Drlica-Wagner,[1] Rouven Essig,[3] Yann Guardincerri,[1,†] Steve Holland,[4] Tomer Volansky,[5] and Tien-Tien Yu[6]

[1]*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA*
[2]*Centro Atómico Bariloche, CNEA/CONICET/IB, Bariloche R8402AGP, Argentina*
[3]*C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*
[4]*Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, California 94720, USA*
[5]*Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel*
[6]*Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*

(Received 4 June 2017; published 26 September 2017)

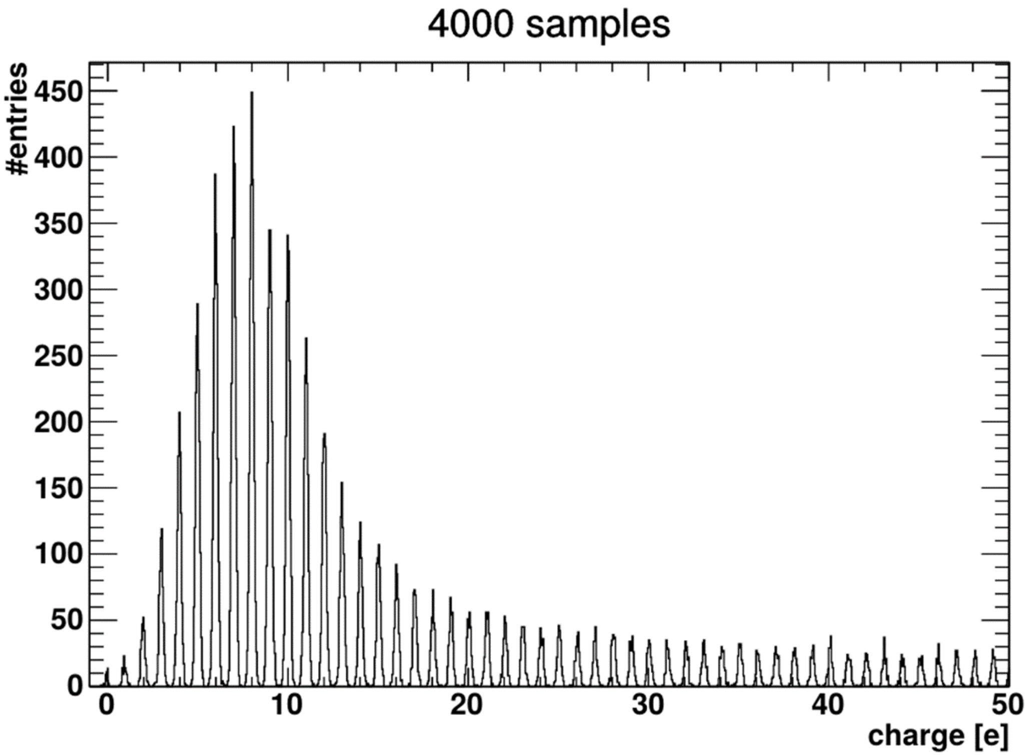
FG amplifier CCDs



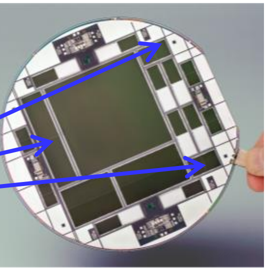
https://doi.org/10.1103/PhysRevLett.119.131802

Version 2 Skipper CCD tested at FermiLab

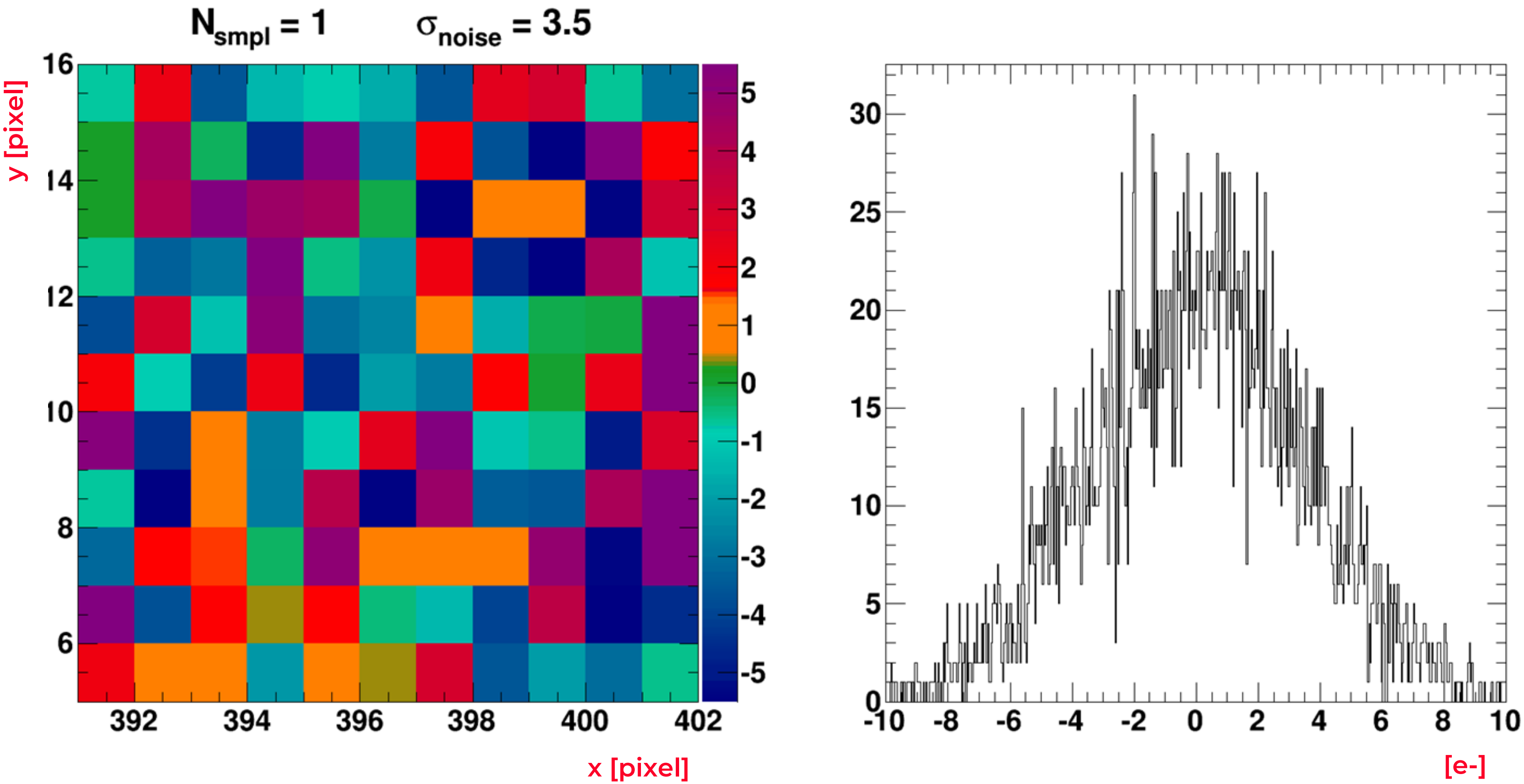
- 2nd version (LDRD 2013)
  - Low-level light charge histogram (FermiLab)



FG amplifier CCDs

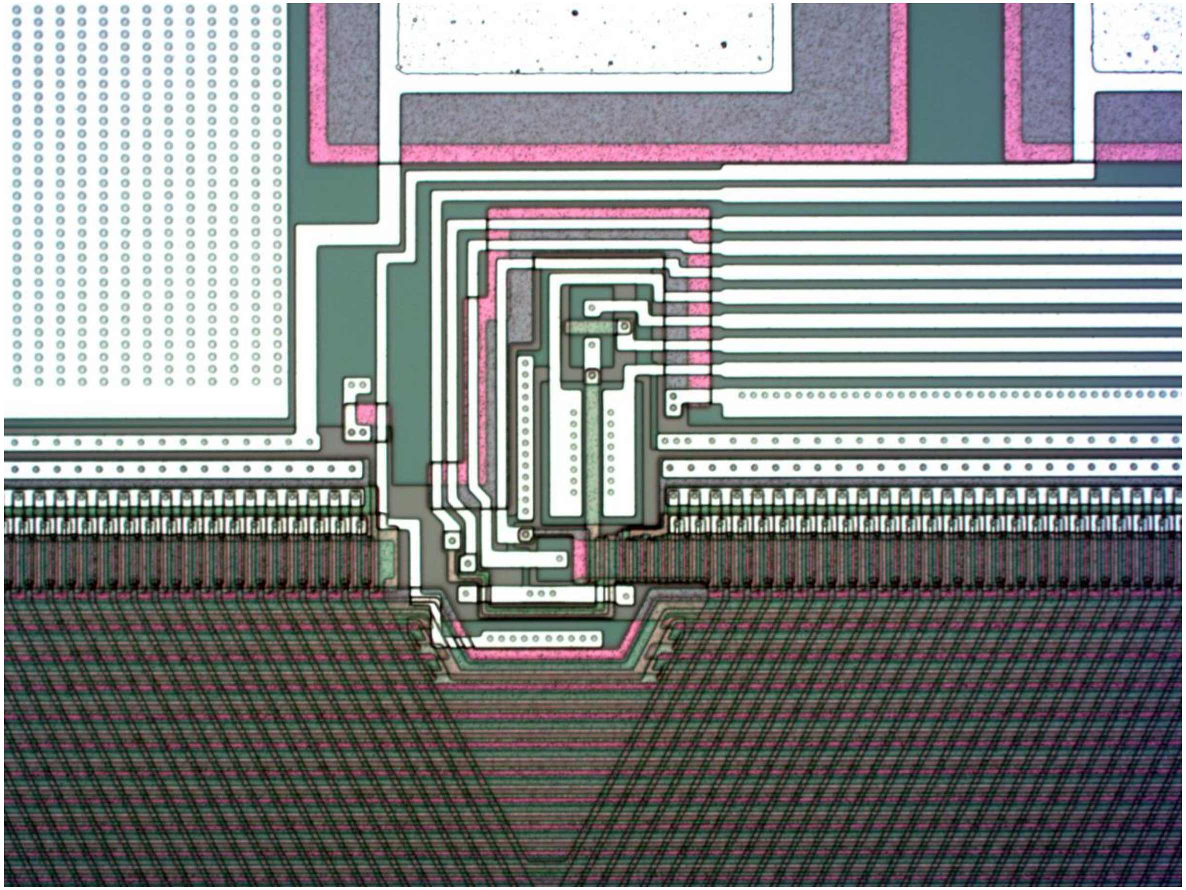


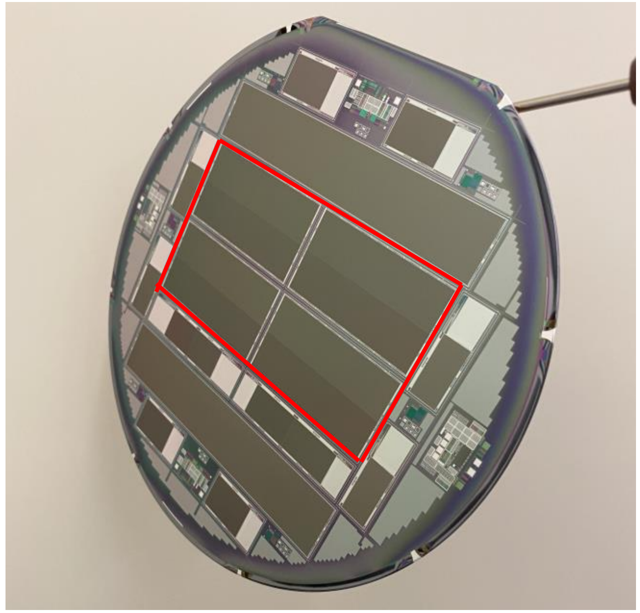
Skipper-CCD basics

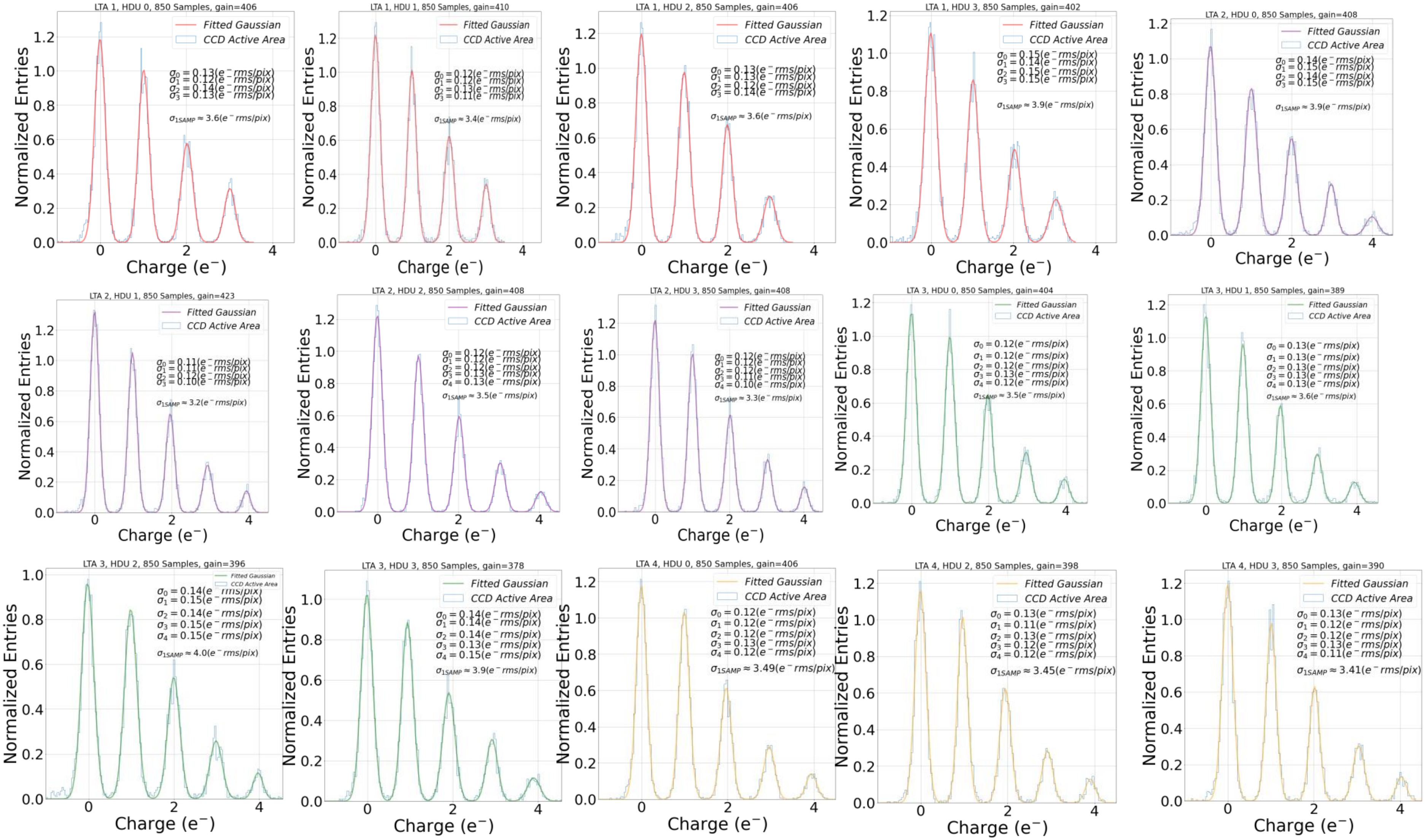


Faster readout for Skipper CCDs

- #1: Amplifiers every 512 columns (LSST type CCD)
  - 4k x 2k, $(10.5\ \mu m)^2$ pixel CCDs with 16 amplifiers
  - Tapered columns to 10.2 µm serial registers







16-channel Skipper CCD results

Measurements at FermiLab (850 samples)

E. Marrufo Villapando (U Chicago)

Faster readout for Skipper CCDs

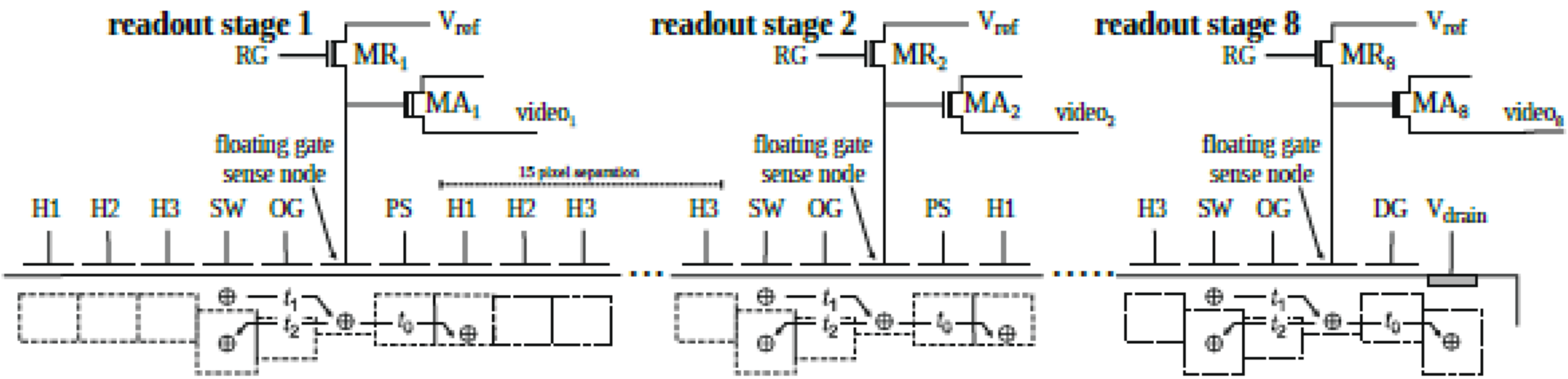
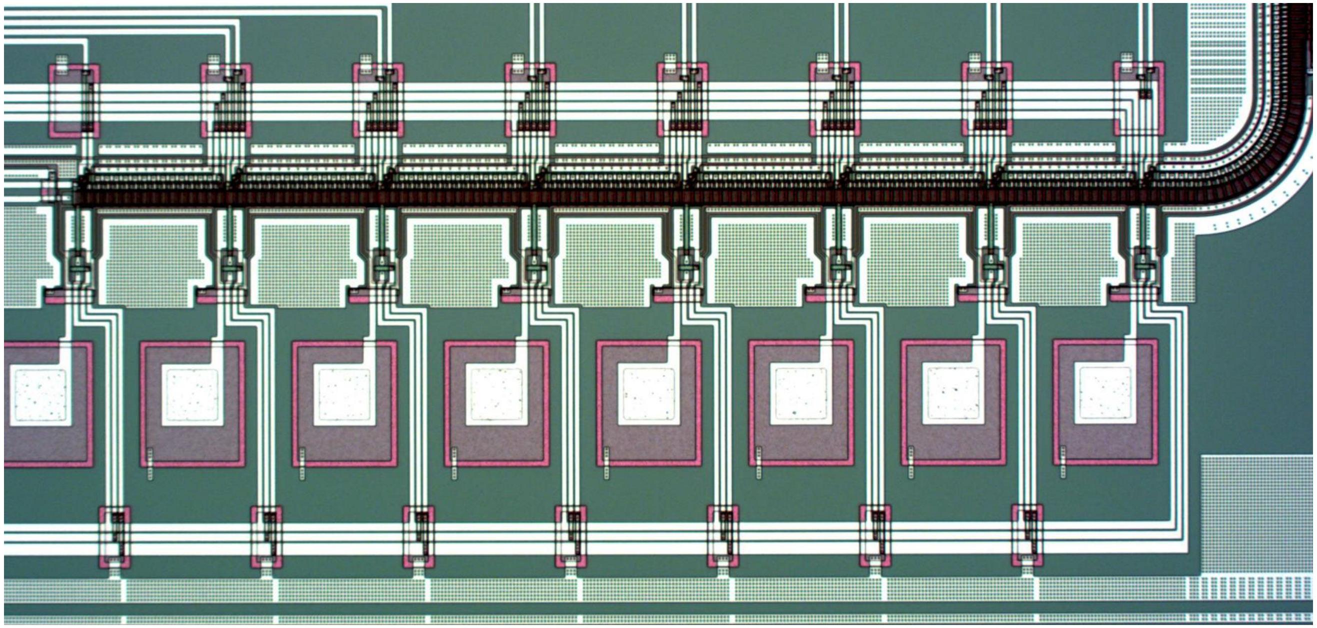


FIG. 1: Architecture of the eight inline amplifiers at the end of the serial register of the MAS-CCD.

- Multiple-amplifier sensing
  - When the first pixel is read out of the Mth amplifier, the next pixel has been sampled by M-1 amplifiers
    - ~ Conventional readout once the initial overhead to get to amp M
  - Can average over the # of amplifiers if statistically independent
  - Interest for astronomy
    - Read once per amp with ~ 1 e- after averaging (16 amplifiers)

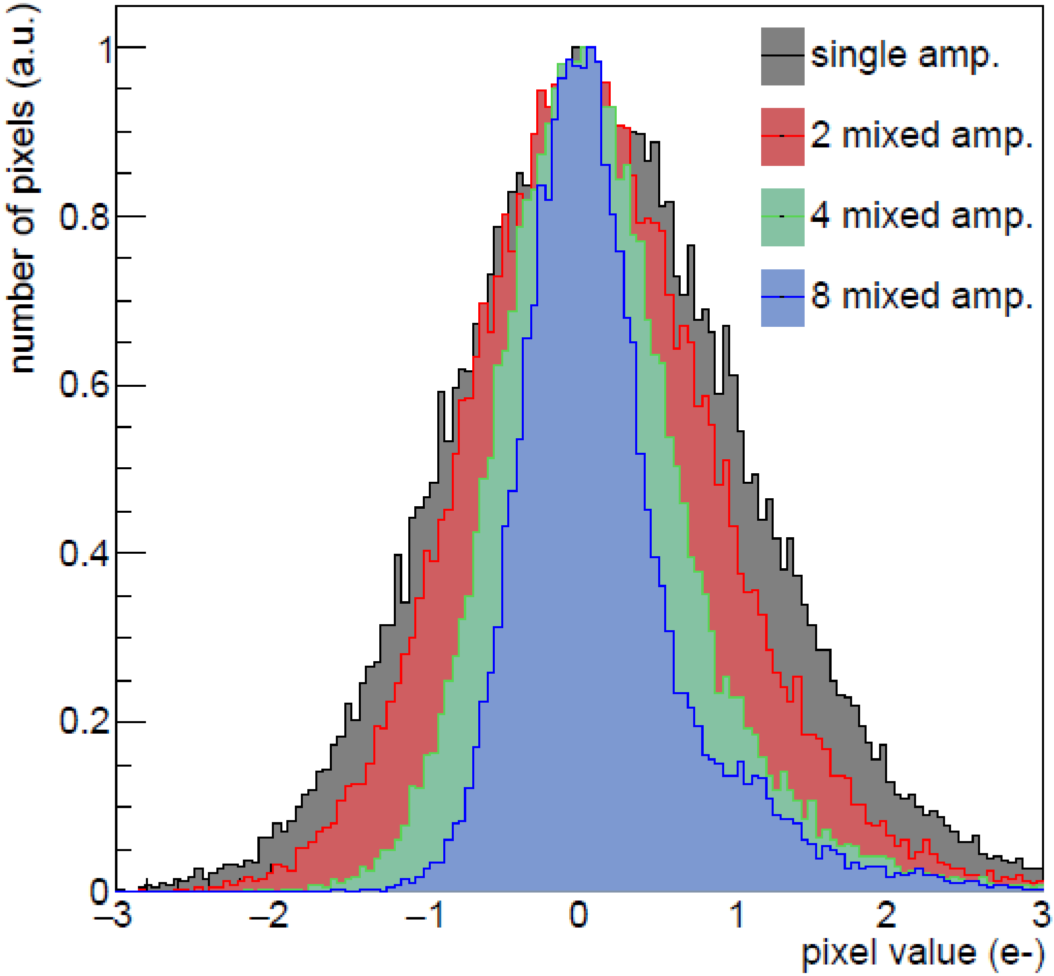
Faster readout for Skipper CCDs



- Multiple-amplifier sensing
  - When the first pixel is read out of the M^{th} amplifier, the next pixel has been sampled by M-1 amplifiers
    - ~ Conventional readout once the initial overhead to get to amp M
  - Can average over the # of amplifiers if statistically independent
  - Interest for astronomy
    - Read once per amp with ~ 1 e- after averaging (16 amplifiers)

Faster readout for Skipper CCDs

- 8-amplifier version (testing at FermiLab)

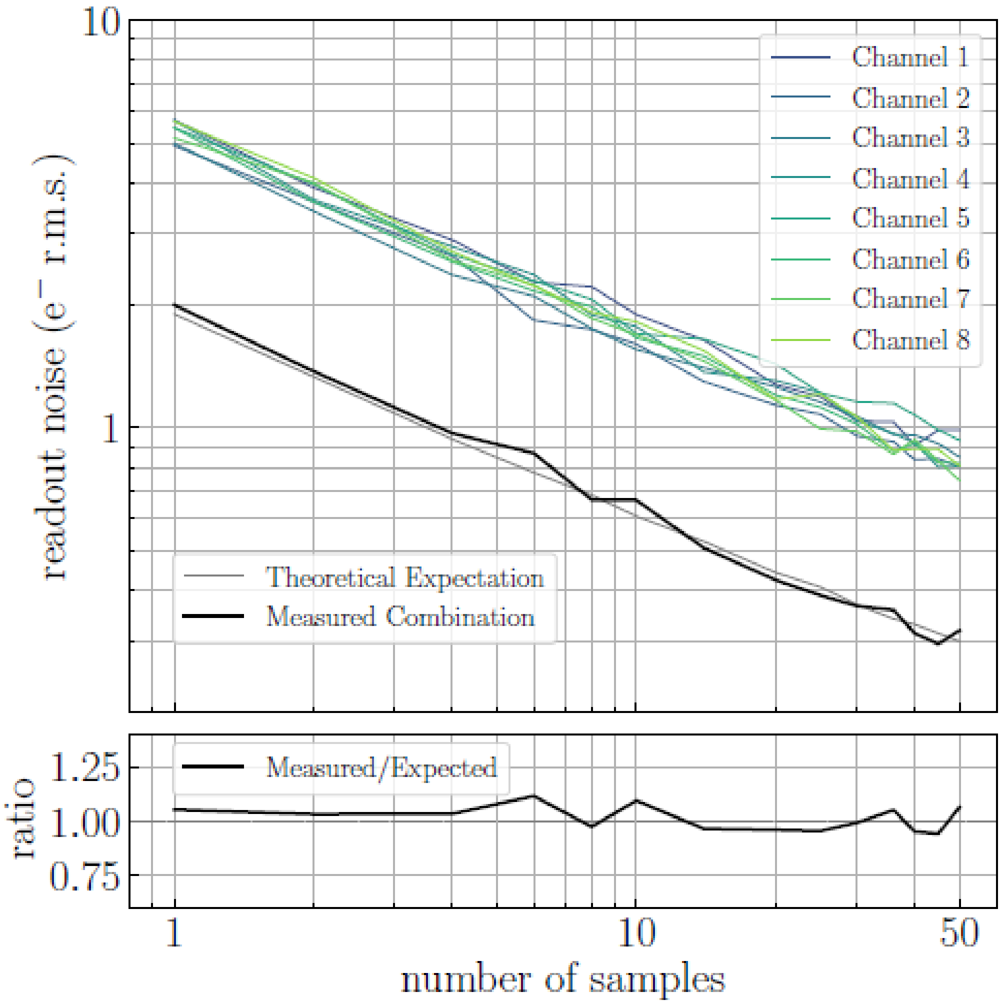


50 samples / amplifier

https://doi.org/10.48550/arXiv.2308.09822

Faster readout for Skipper CCDs

- 8-amplifier version (testing at FermiLab)



https://doi.org/10.48550/arXiv.2308.09822

Dark Matter detection with CCDs

Fully depleted CCD advantages for dark matter detection

- Low noise / few e- and deep sub electron (Skipper CCDs)
- Thick depleted regions / larger mass
- Background suppression / spatial and energy resolution
- Extremely low dark current for DM experiments

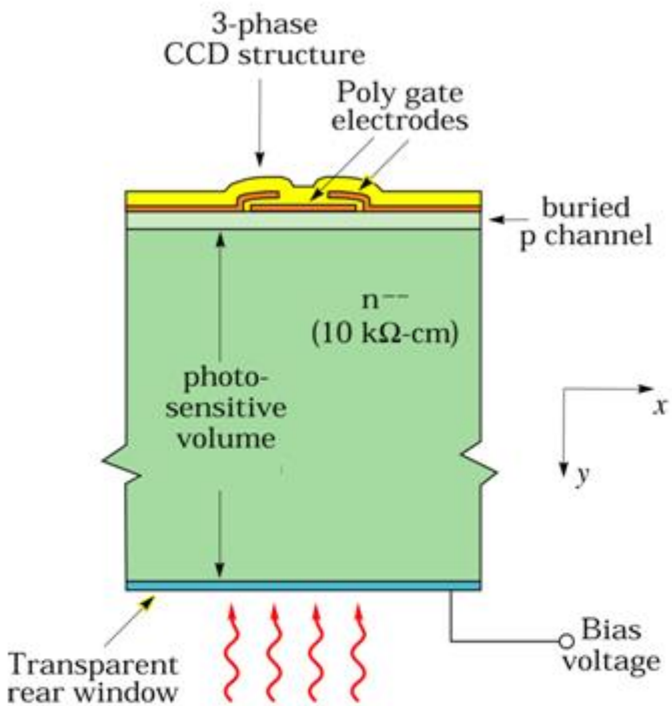
- Main disadvantage is the lack of timing information

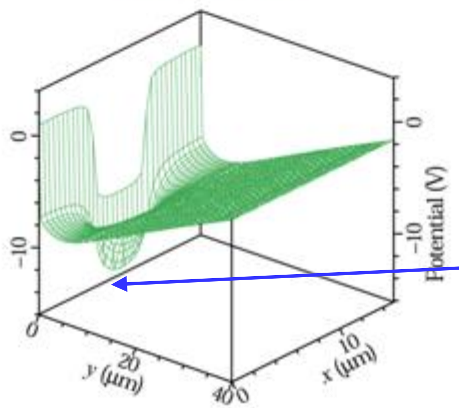
Dark Matter detection with CCDs

- Dark Matter CCDs require as large as practical volume limited by the standard wafer thickness
  - Semiconductor industry standards (SEMI/JEIDA)
    - 150 mm / 200 mm Ø corresponds to 650 µm / 725 µm
- Depletion voltage goes as $(\text{thickness})^2$ and $(\text{resistivity})^{-1}$
  - LBNL high-voltage compatible CCD designs
    - **DOI:** 10.1109/TED.2009.2030631 and https://doi.org/10.1117/12.672393
  - Improvements in the production of float-zone silicon
    - Higher resistivity / lower depletion voltage

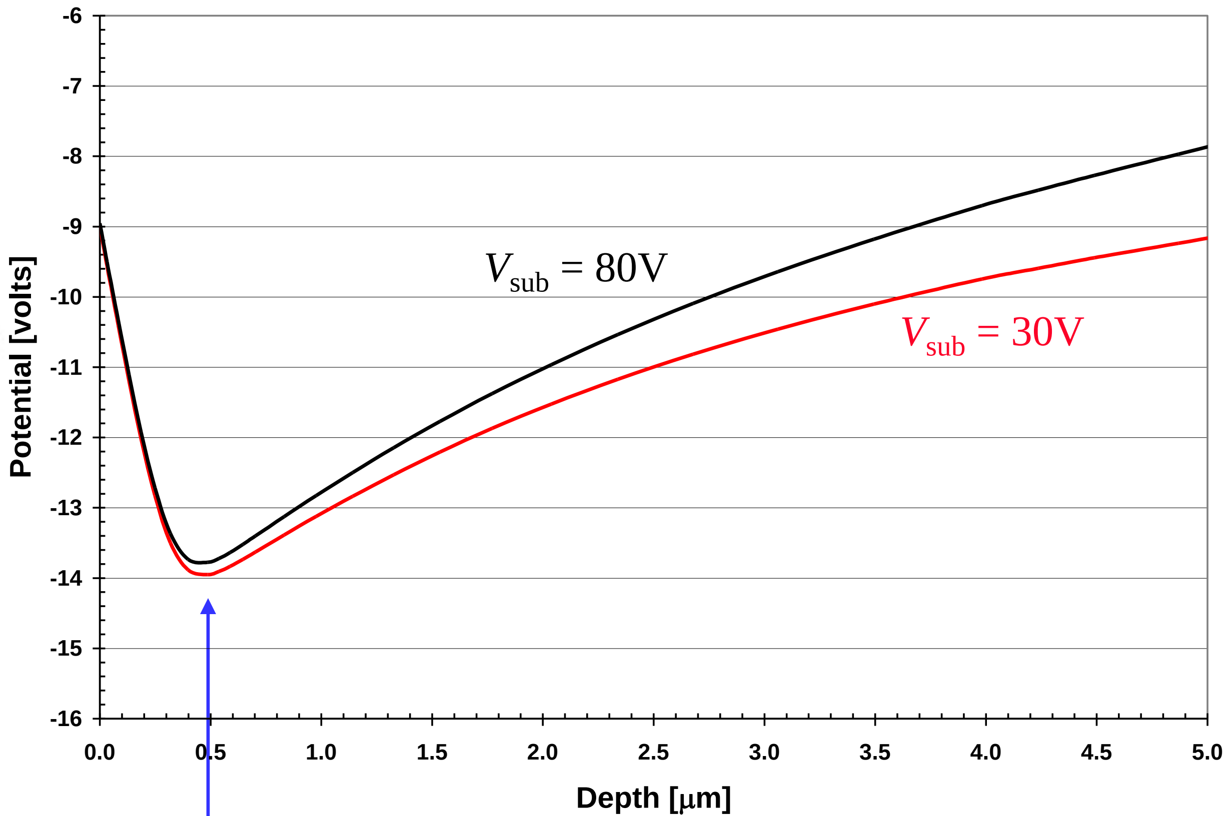
$$V_{\mathrm{depl}} = \frac{qN_D}{2\varepsilon_{Si}} x_D^2 \quad \rho = \frac{1}{q\mu_n N_D}$$

Fully depleted CCDs / 2D simulations





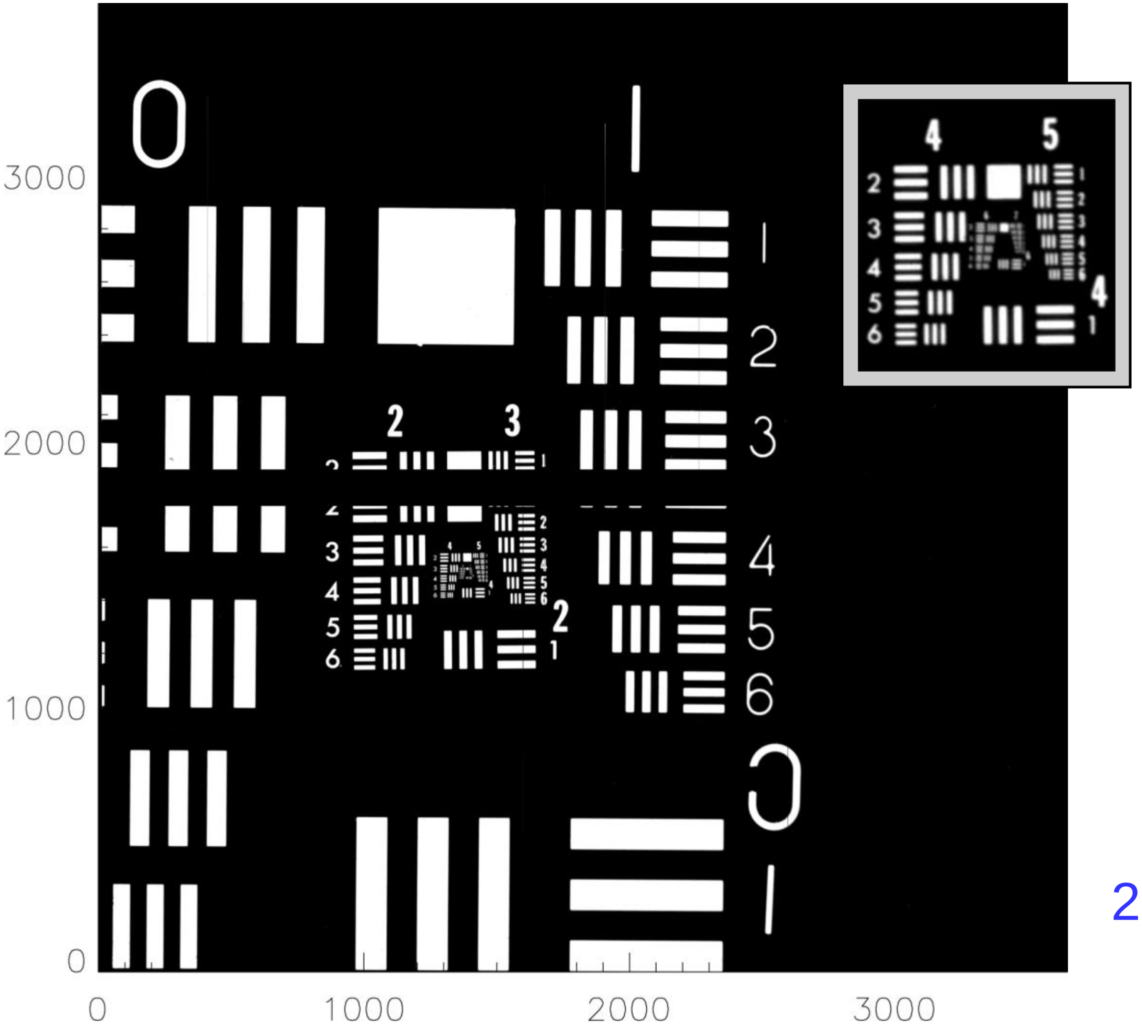
MEDICI 2-D simulation



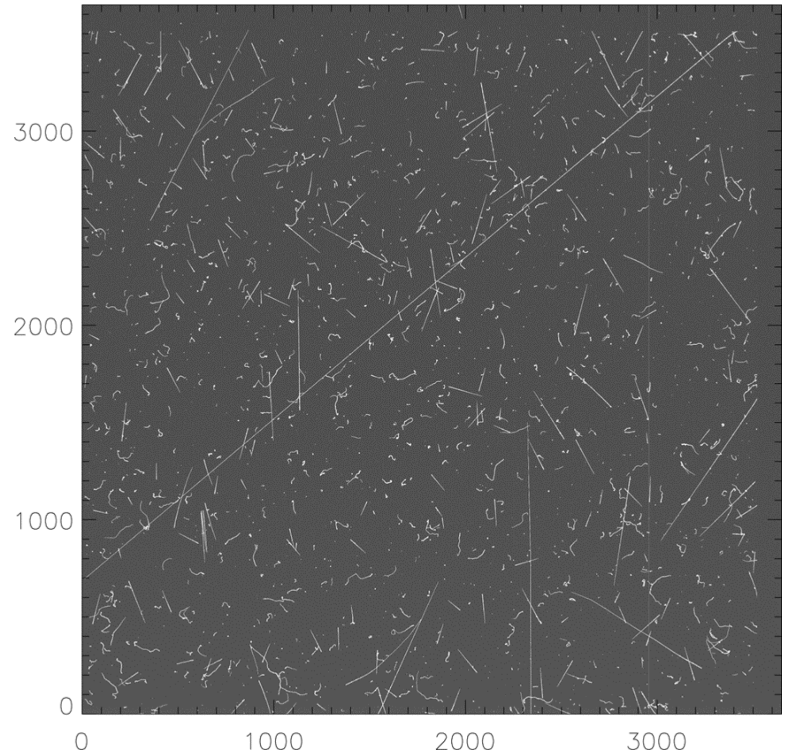
MEDICI simulations

Potential minimum (collecting phase)
- Relatively insensitive to Vsub
- Wide range of V_{sub} possible
- Capacitor voltage divider effect

HV-compatible CCD design (SNAP)

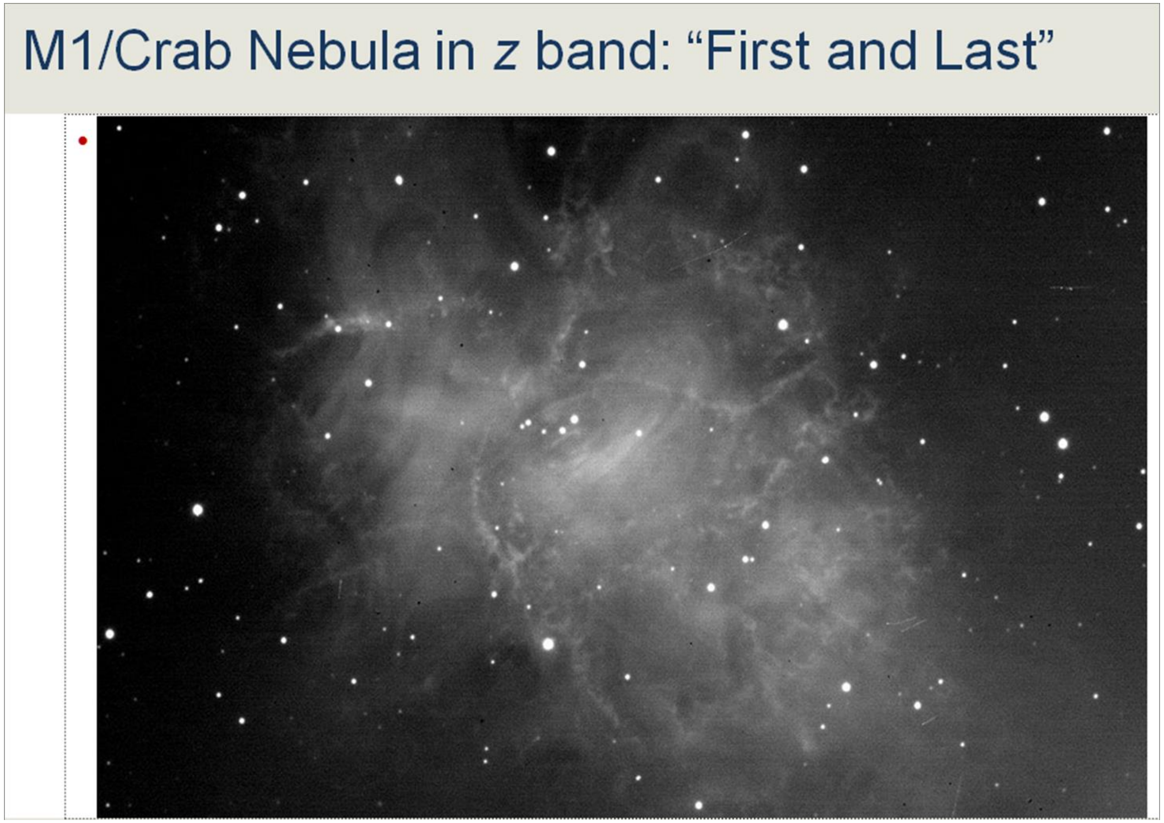


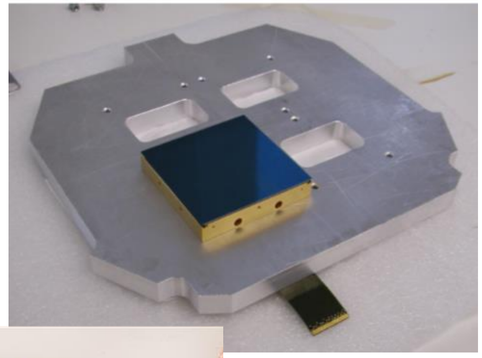
30 minute dark exposure

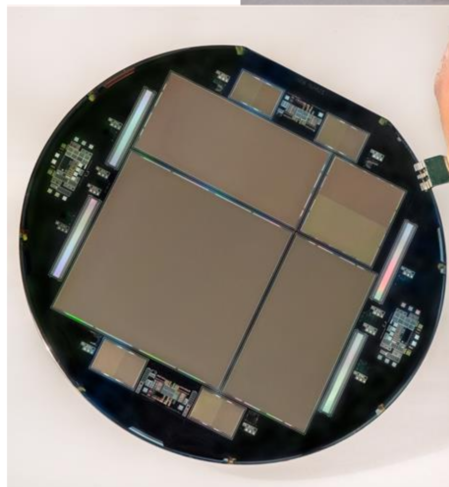


200V Vsub
-140C

$$V_{\text{depl}} = \frac{qN_D}{2\varepsilon_{Si}} x_D^2 \qquad \rho = \frac{1}{q\mu_n N_D}$$

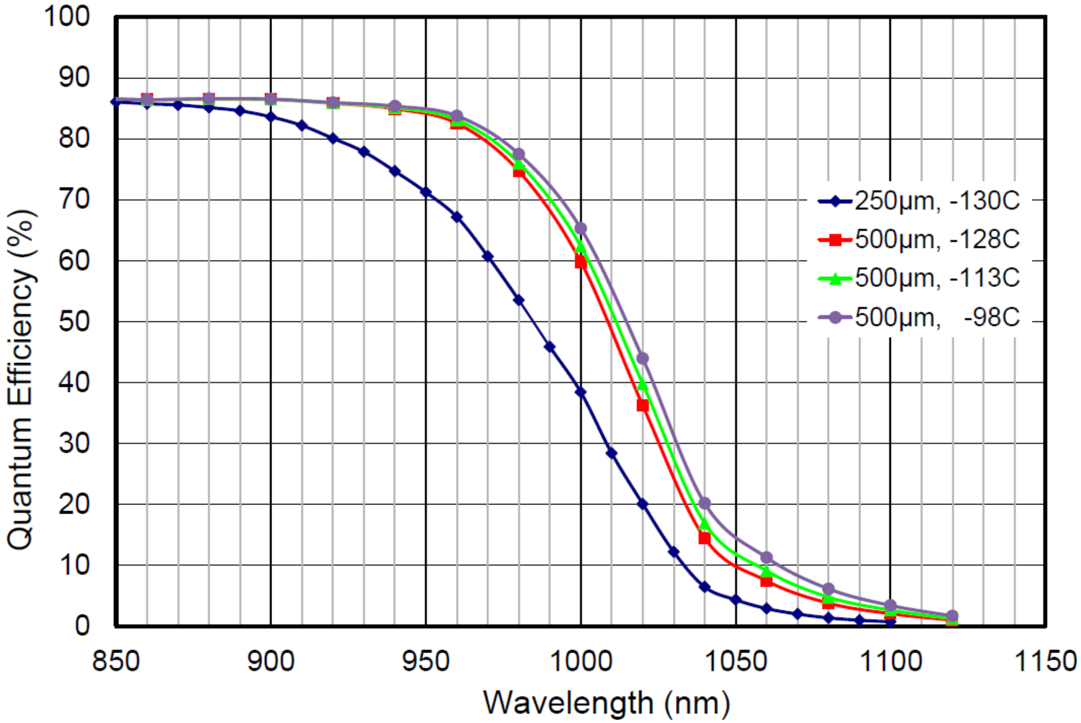


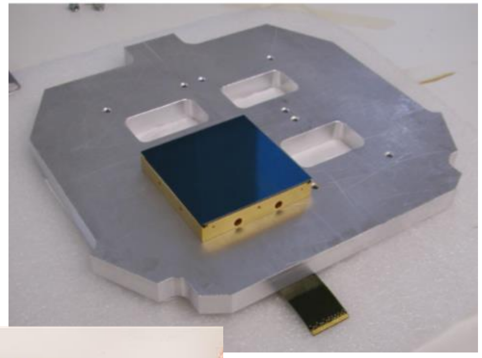


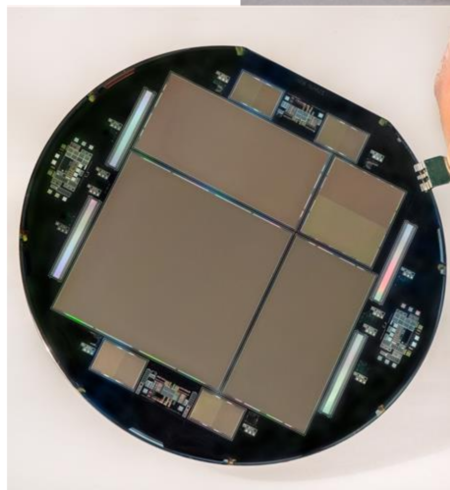


- 500 um thick, fully depleted CCD (DESI R&D)
  - MOSAIC3 was an 8k x 8k imager (2x2, 4k x 4k CCDs)
    - Lead institution was Yale University
  - One CCD now installed in the Keck LRIS instrument

A. Dey et al, “Mosaic3: A red-sensitive upgrade for the prime focus camera at the Mayall 4m telescope”, Ground-based and Airborne Instrumentation for Astronomy VI, edited by Christopher J. Evans, Luc Simard, Hideki Takami Proc. of SPIE Vol. 9908, 99082C,2016







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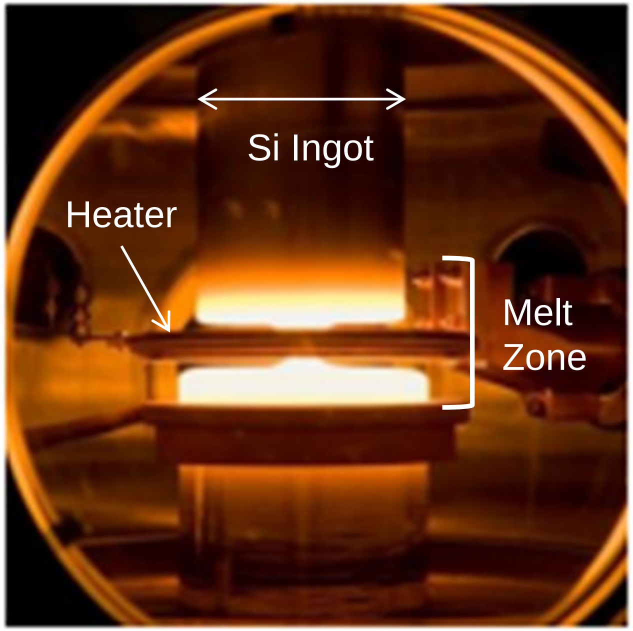

Link to Topsil Float-Zone silicon

Year Acquired	Topsil Crystal #	Resistivity ρ (kΩ-cm)	Lifetime τ (ms)
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2020	33-1751-30	> 10.0	18.9
2020	32-1345-20	18.0 – 20.0	23.5
2020	34-1802-10	17.7 – 22.4	18.4

Blue table entries are 150-mm diameter
Red are 200-mm diameter wafers

$$V_{\mathrm{depl}} = \frac{qN_D}{2\varepsilon_{Si}} x_D^2 \quad \rho = \frac{1}{q\mu_n N_D}$$

Dark Matter detection with CCDs

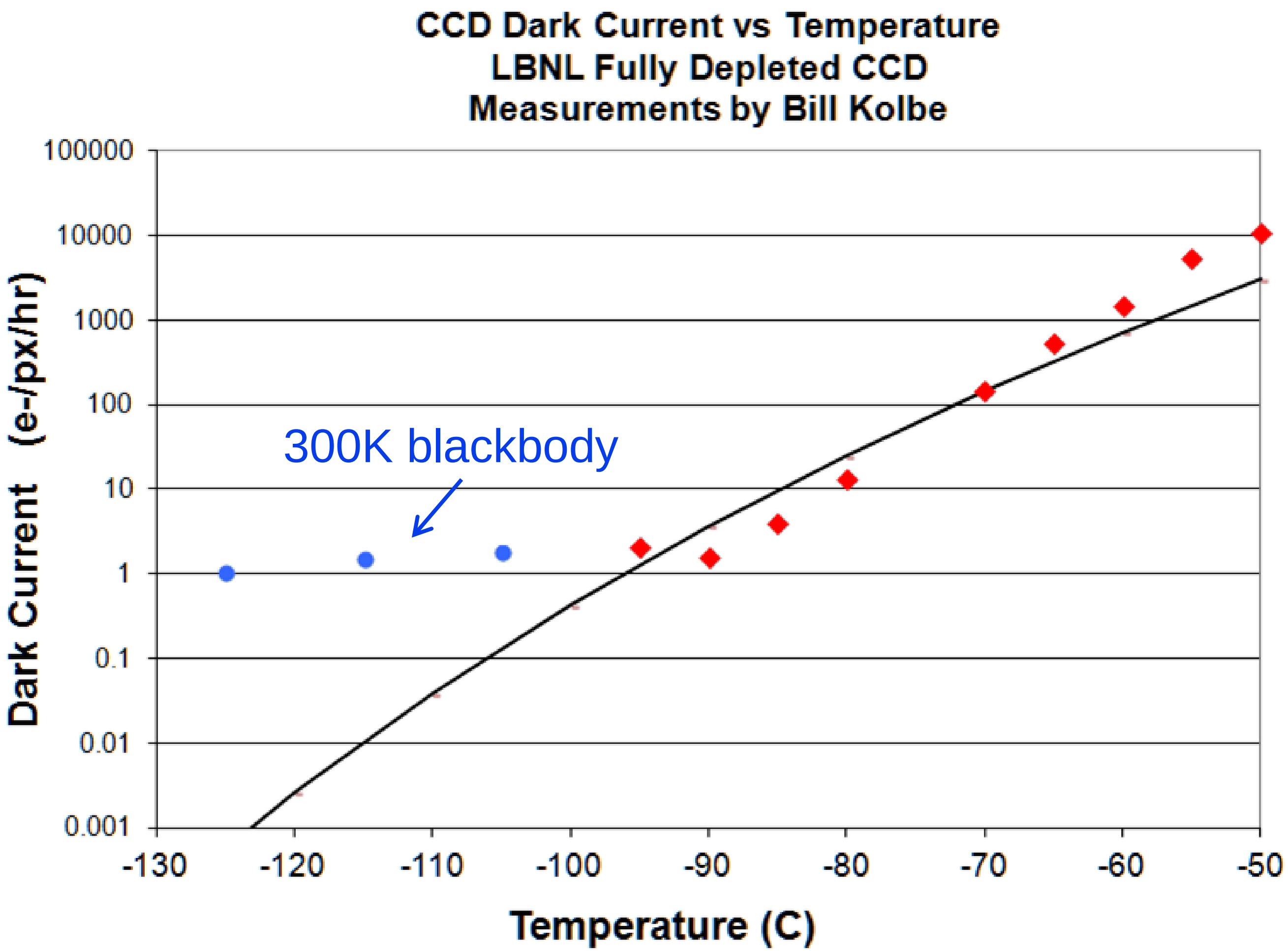
Fully depleted CCD advantages for dark matter detection

- Low noise / few e- and deep sub electron (Skipper CCDs)
- Thick depleted regions / larger mass
- Background suppression / spatial and energy resolution
- Extremely low dark current for DM experiments

- Main disadvantage is the lack of timing information

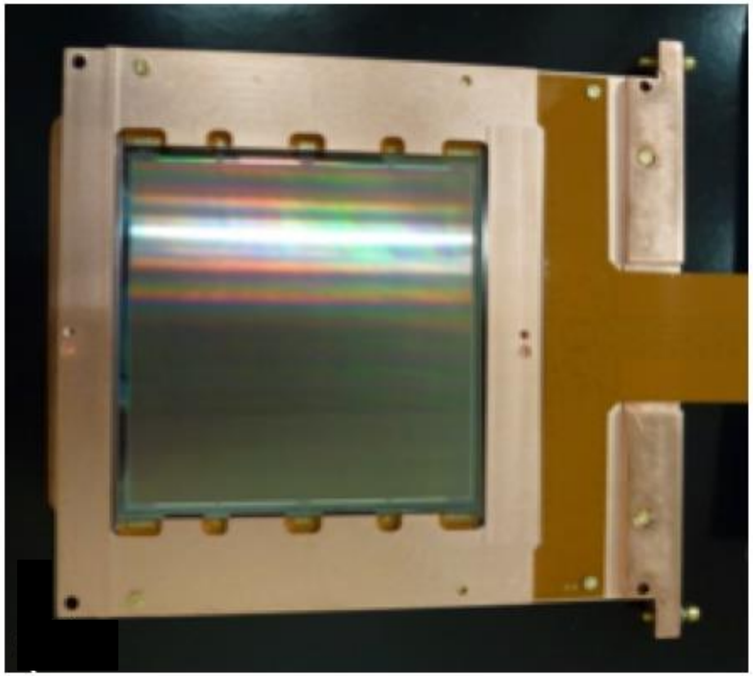
Dark Current

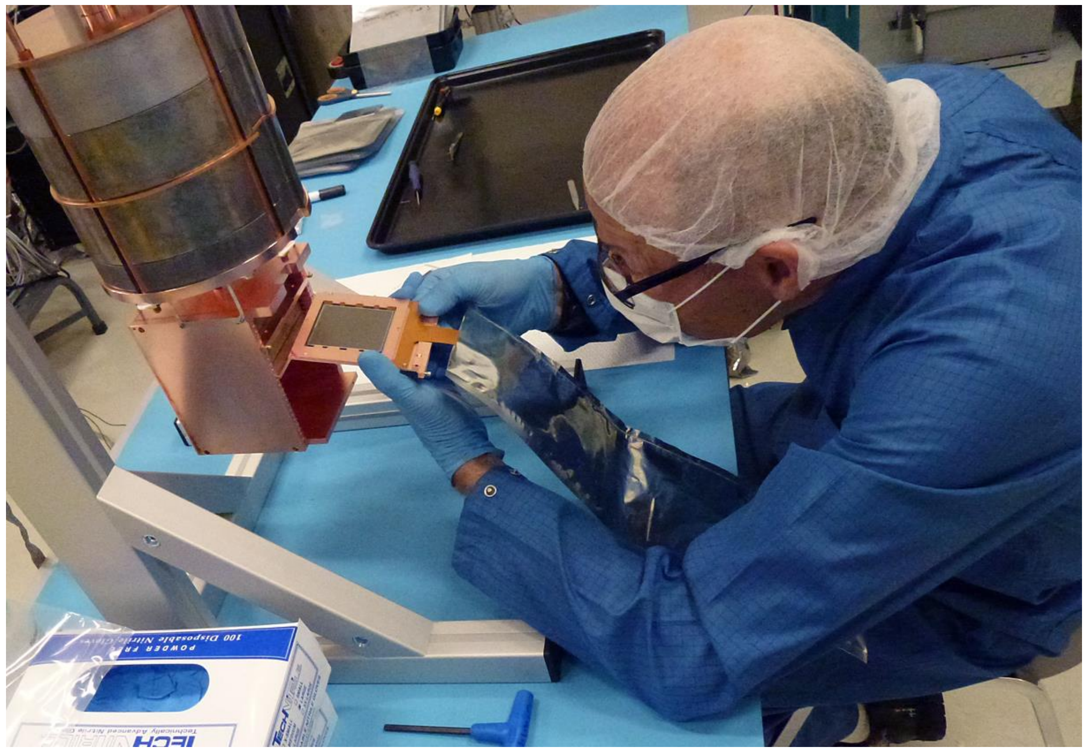
- Dark current measurements on a fully depleted LBNL CCD / line is the Shockley-Read-Hall model



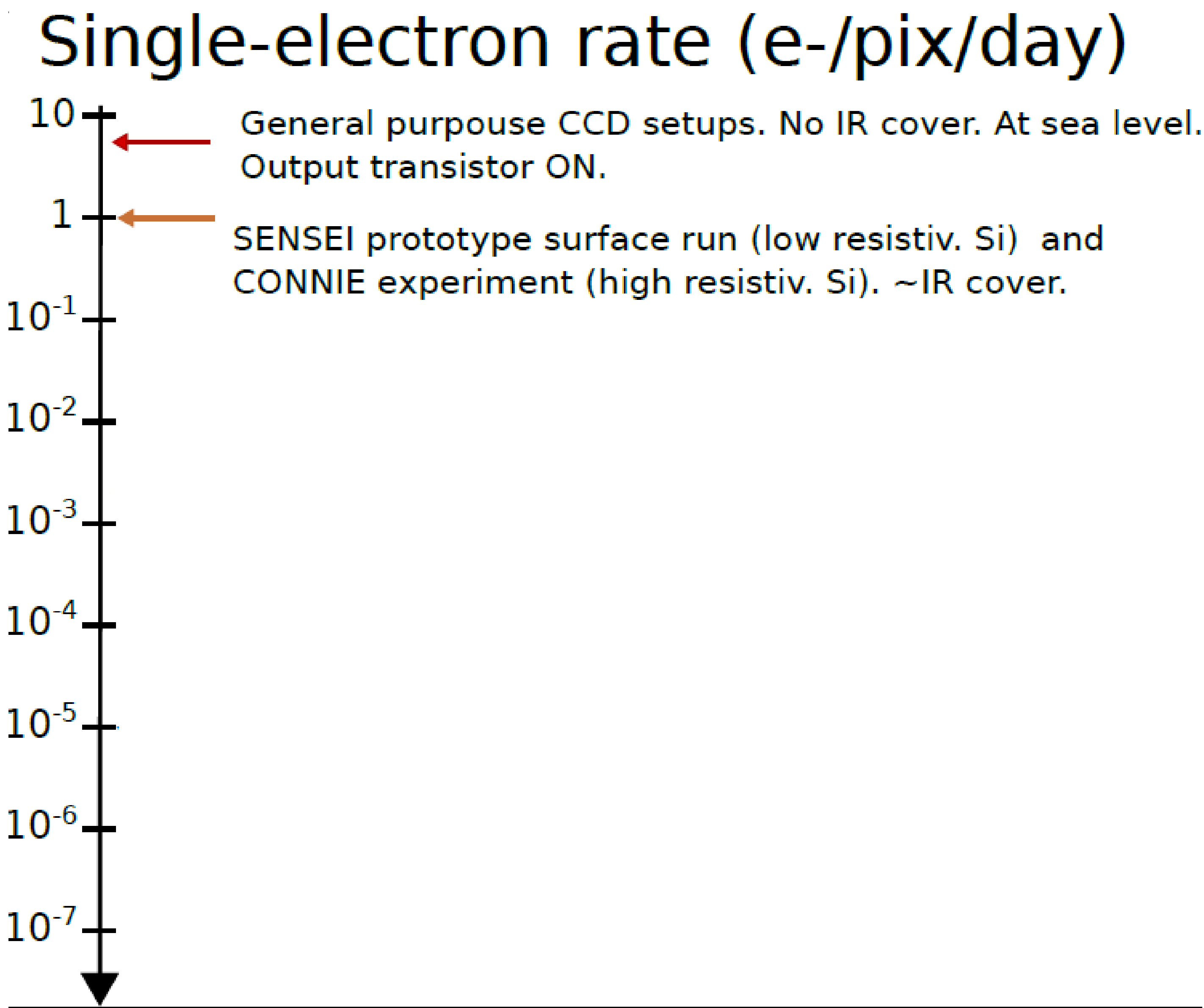
Dark Current

- Dark Matter CCDs surrounded by cold Cu to suppress 300K blackbody radiation
  - — https://doi.org/10.1016/j.physletb.2012.04.006





“Dark Current” / SEE



Dark Current

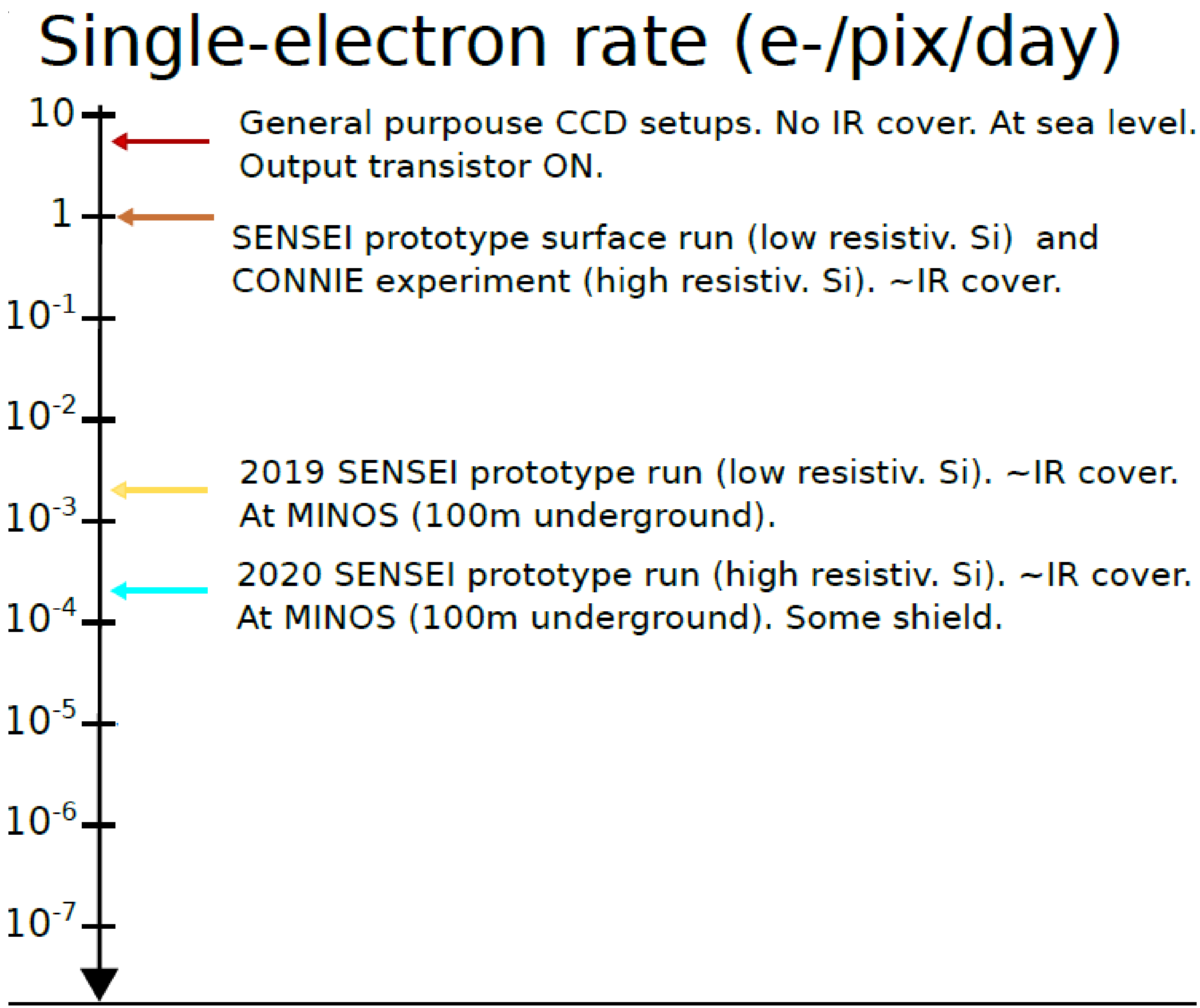
- Deep underground to reduce photon generation from high-energy particles e.g. cosmic-ray muons
  - Photons from e- hole recombination in P-doped layers
    - Low probability but a problem for DM detection
  - High-energy particles produce Cherenkov radiation
    - Photon background
    - 10.1103/PhysRevX.12.011009

PHYSICAL REVIEW X **12,** 011009 (2022)

Sources of Low-Energy Events in Low-Threshold Dark-Matter and Neutrino Detectors

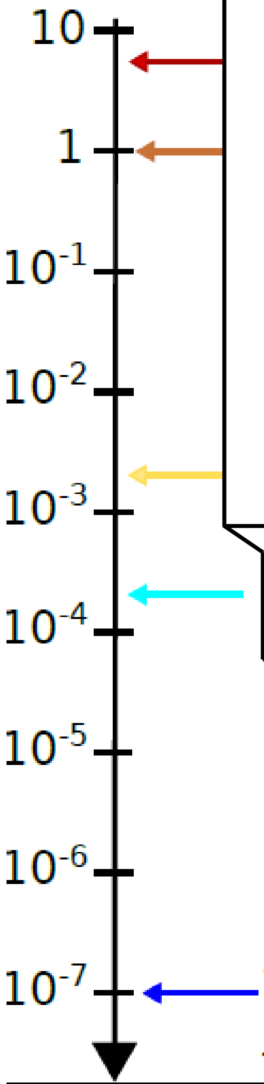
Peizhi Du,[1] Daniel Egana-Ugrinovic,[2] Rouven Essig,[1] and Mukul Sholapurkar[1]
[1]*C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*
[2]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*

“Dark Current” / SEE



“Dark Current” / SEE

Single-electron rate (e-/pix/day)



PHYSICAL REVIEW LETTERS **125,** 171802 (2020)

Editors' Suggestion | Featured in Physics

SENSEI: Direct-Detection Results on sub-GeV Dark Matter from a New Skipper CCD

Liron Barak,[1] Itay M. Bloch,[1] Mariano Cababie,[2,3] Gustavo Cancelo,[3] Luke Chaplinsky,[4,5] Fernando Chierchie,[3] Michael Crisler,[6] Alex Drlica-Wagner,[6,7,8] Rouven Essig,[4] Juan Estrada,[3] Erez Etzion,[1] Guillermo Fernandez Moroni,[3] Daniel Gift,[4,5] Sravan Munagavalasa,[4,5] Aviv Orly,[1] Dario Rodrigues,[2,3] Aman Singal,[5] Miguel Sofo Haro,[3,9] Leandro Stefanazzi,[3] Javier Tiffenberg,[3] Sho Uemura,[1] Tomer Volansky,[1] and Tien-Tien Yu[10]

Single-electron event rate: (1.594 +/- 0.160) x 10^{-4} e/pix/day (135K)

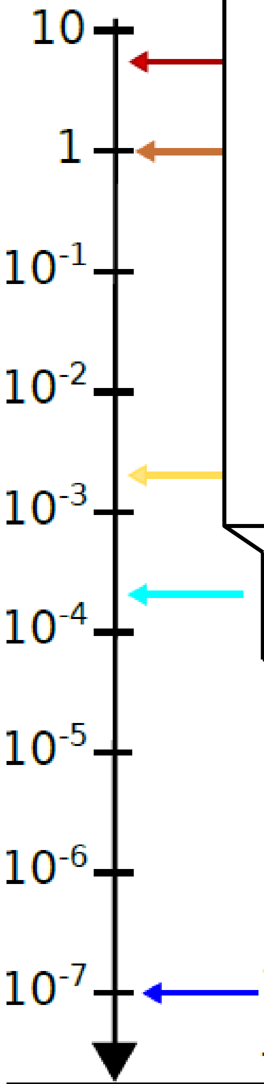
10.1103/PhysRevLett.125.171802

2020 SENSEI prototype run (high resistiv. Si). ~IR cover.
At MINOS (100m underground). Some shield.

Theoretical expectation for thermal fluctuations.
Janesick, SPIE press, 2001.

“Dark Current” / SEE

Single-electron rate (e-/pix/day)



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[10.1103/PhysRevLett.125.171802]

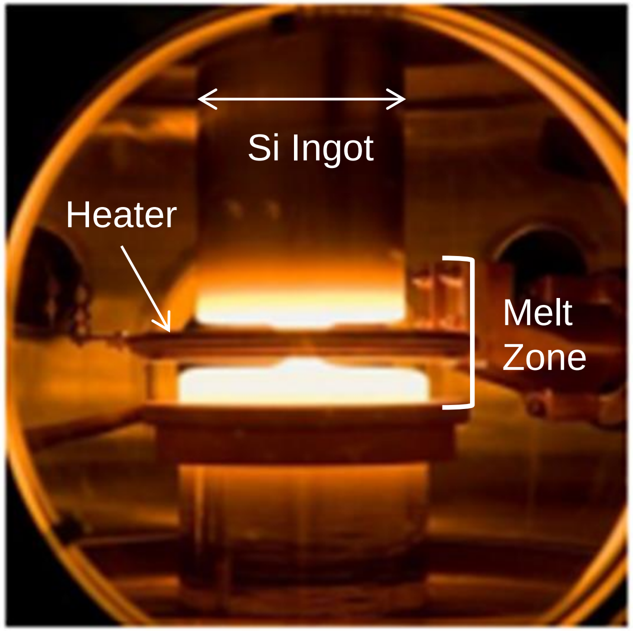
2020 SENSEI prototype run (high resistiv. Si). ~IR cover.
At MINOS (100m underground). Some shield.

Other sources of SEE’s

- Output transistor light emission
- Clock-induced (spurious) charge

Not covered: Technology development for low dark current / gettering method

Theoretical expectation for thermal fluctuations.
Janesick, SPIE press, 2001.



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2020	34-1802-10	17.7 – 22.4	18.4

Blue table entries are 150 mm Ø diameter
Red are 200 mm Ø diameter wafers

Bulk dark current ~ x_D/τ (x_D = Depletion depth)

Effective “gettering” method used to maintain low dark current
LBNL/DALSA method is backside in-situ doped polysilicon

Dark Matter detection with CCDs

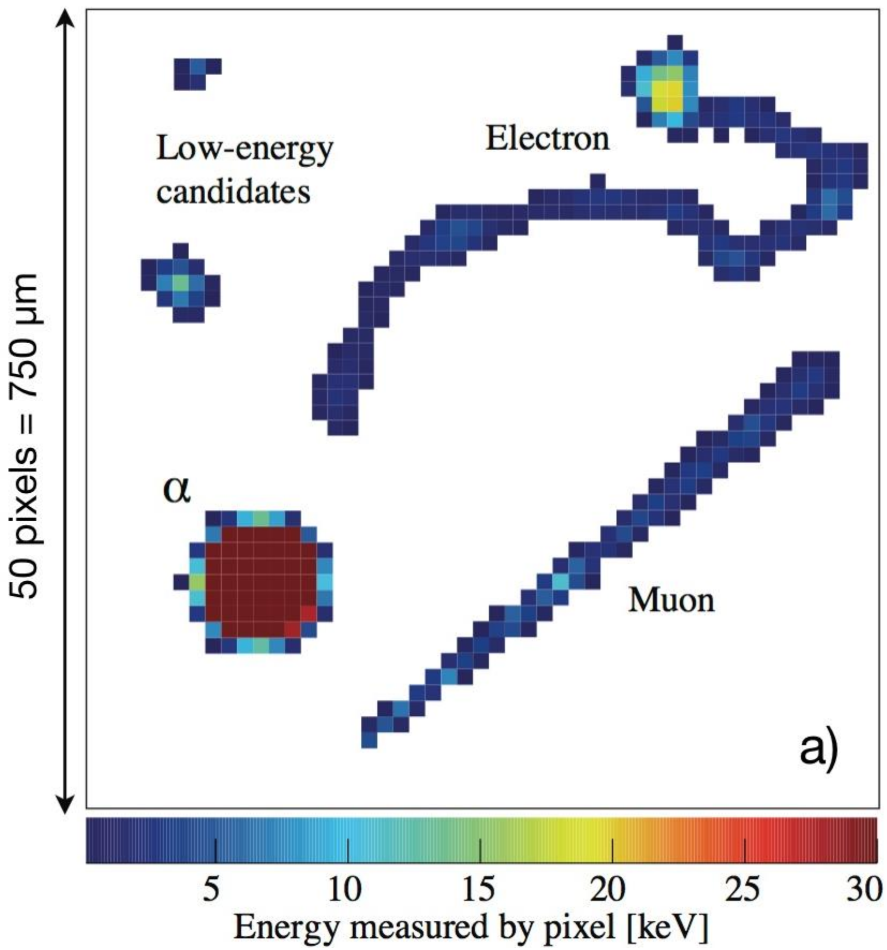
Fully depleted CCD advantages for dark matter detection

- Low noise / few e- and deep sub electron (Skipper CCDs)
- Thick depleted regions / larger mass
- Background suppression / spatial and energy resolution
- Extremely low dark current for DM experiments

- Main disadvantage is the lack of timing information

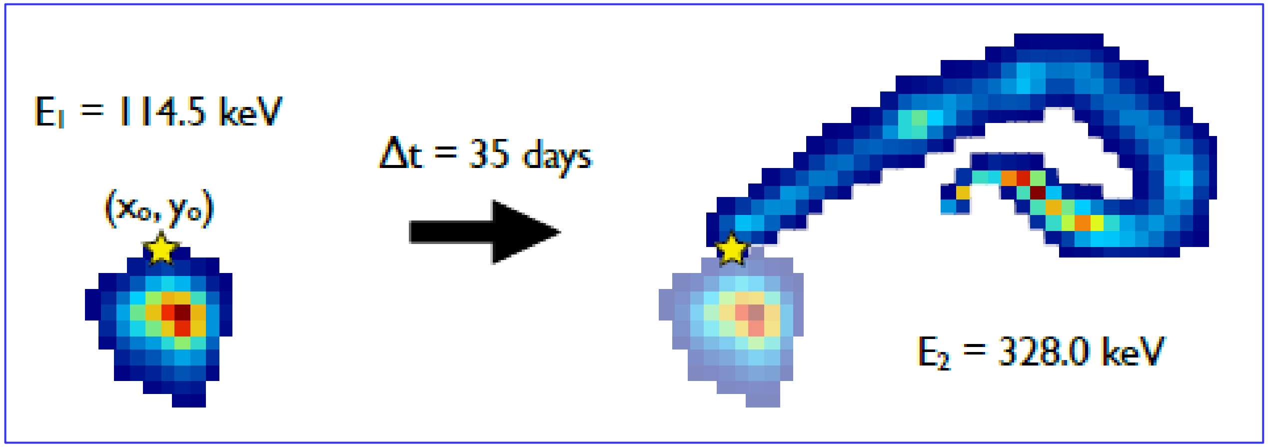
Dark Matter detection with CCDs

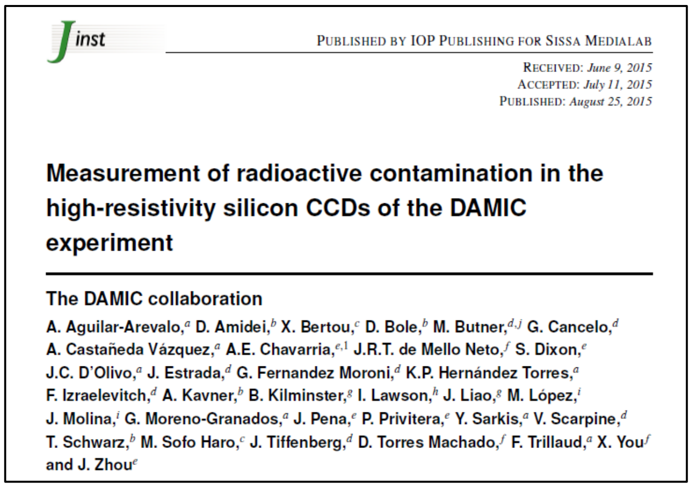
- Fully depleted CCDs for dark-matter detection cont'
  - Particle identification for background suppression
    - Spatial correlation and energy measurement



Dark Matter detection with CCDs

- Fully depleted CCDs for dark-matter detection cont’
  - Radioactive contamination in the silicon substrate
    - Decay chain products spatially correlated (double β event below)

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Published by IOP Publishing for Sissa Medialab

Received: *June 9, 2015*
Accepted: *July 11, 2015*
Published: *August 25, 2015*

Measurement of radioactive contamination in the high-resistivity silicon CCDs of the DAMIC experiment

The DAMIC collaboration

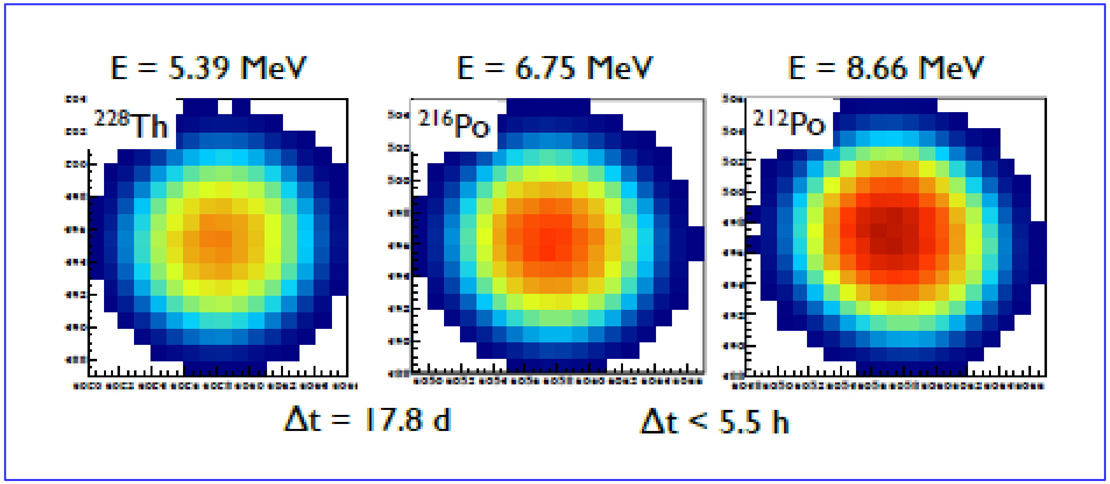
A. Aguilar-Arevalo,[a] D. Amidei,[b] X. Bertou,[c] D. Bole,[b] M. Butner,[d,j] G. Cancelo,[d] A. Castañeda Vázquez,[a] A.E. Chavarria,[e,1] J.R.T. de Mello Neto,[f] S. Dixon,[e] J.C. D’Olivo,[a] J. Estrada,[d] G. Fernandez Moroni,[d] K.P. Hernández Torres,[a] F. Izraelevitch,[d] A. Kavner,[b] B. Kilminster,[g] I. Lawson,[h] J. Liao,[g] M. López,[i] J. Molina,[i] G. Moreno-Granados,[a] J. Pena,[c] P. Privitera,[e] Y. Sarkis,[a] V. Scarpine,[d] T. Schwarz,[b] M. Sofo Haro,[c] J. Tiffenberg,[d] D. Torres Machado,[f] F. Trillaud,[a] X. You[f] and J. Zhou[e]

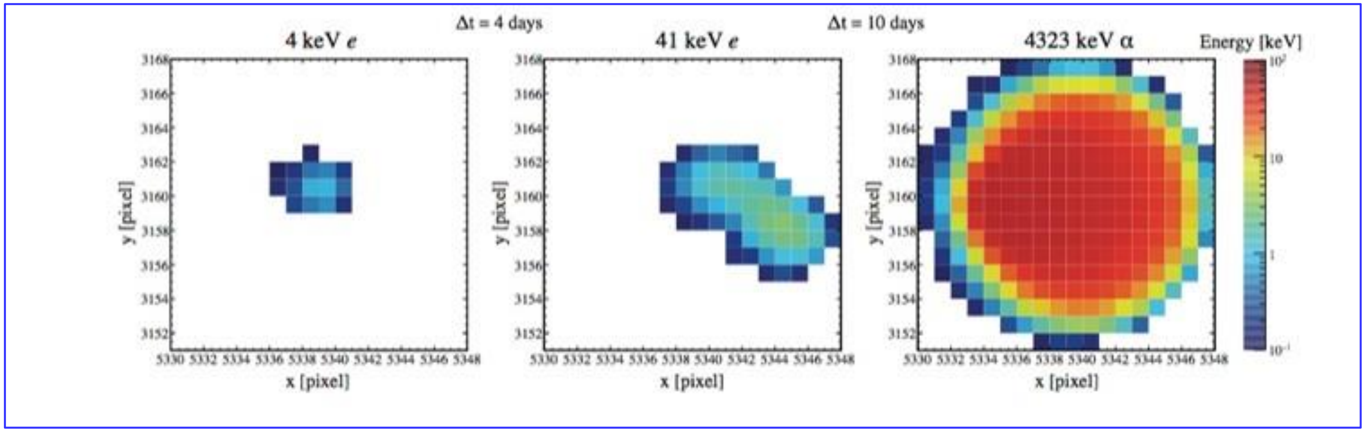
- Candidate ^{32}Si – ^{32}P event
- Cosmogenic activation of silicon
- Rejected by spatial / energy / decay time correlation

10.1088/1748-0221/10/08/P08014

Dark Matter detection with CCDs

- Fully depleted CCDs for dark-matter detection cont’





Future work

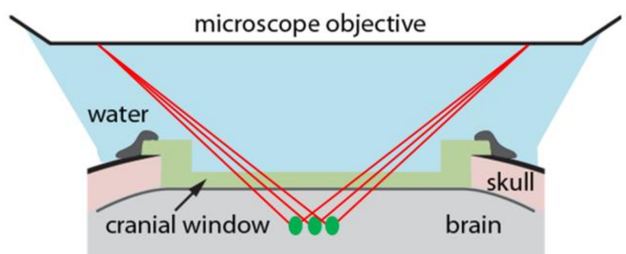
- Large-format CCD development with 16 x 4 amplifiers
  - U Chicago lead institution
- Challenge: Large format CCDs on 200-mm wafers
  - Stitching with wafer-stepper lithography
  - Requires new backside n+ technology
- Possible new application
  - Imaging of biological tissue

In the brain, hemoglobin absorbs blue and green light strongly, but not red or NIR light (this is why blood appears red to our eye). At the other end, for wavelengths beyond 1 μm, water becomes the dominant absorber. Within this "optical window" (650–1,200 nm), where the light used for two-photon excitation falls, the major source of its attenuation in brain tissue is not absorption, but scattering.

The Practical and Fundamental Limits of Optical Imaging in Mammalian Brains

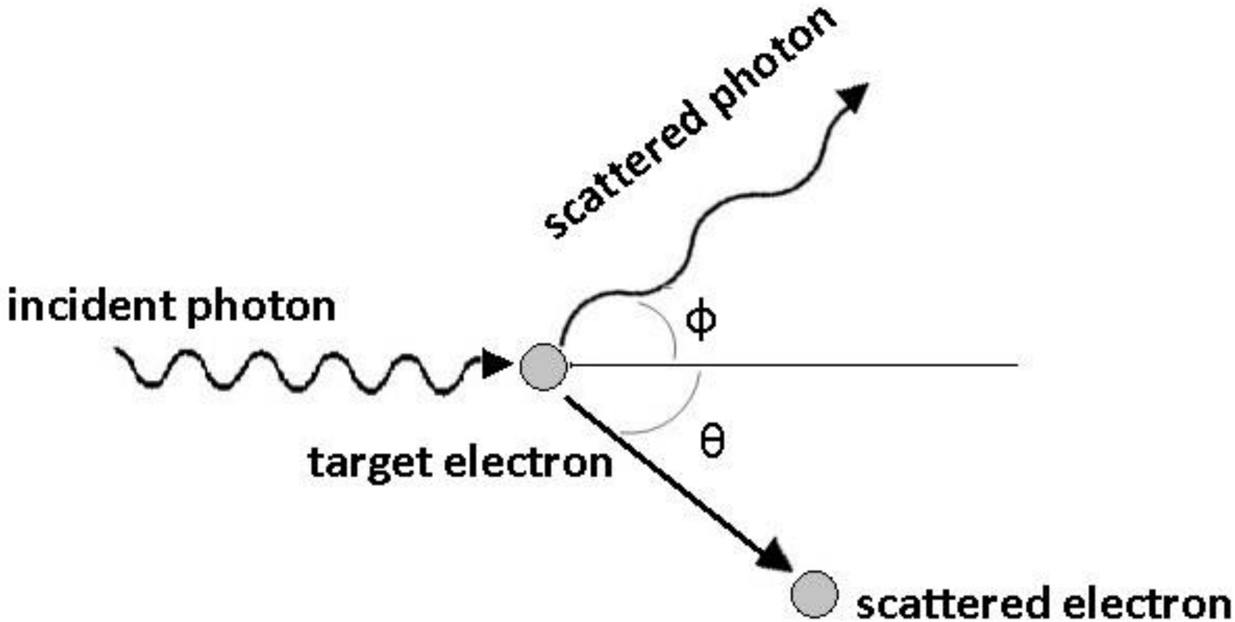
UC-Berkeley Physics

Na Ji[1,*]
[1]Howard Hughes Medical Institute, Janelia Farm Research Campus, Ashburn, Virginia 20148, USA
*Correspondence: jin@janelia.hhmi.org
http://dx.doi.org/10.1016/j.neuron.2014.08.009



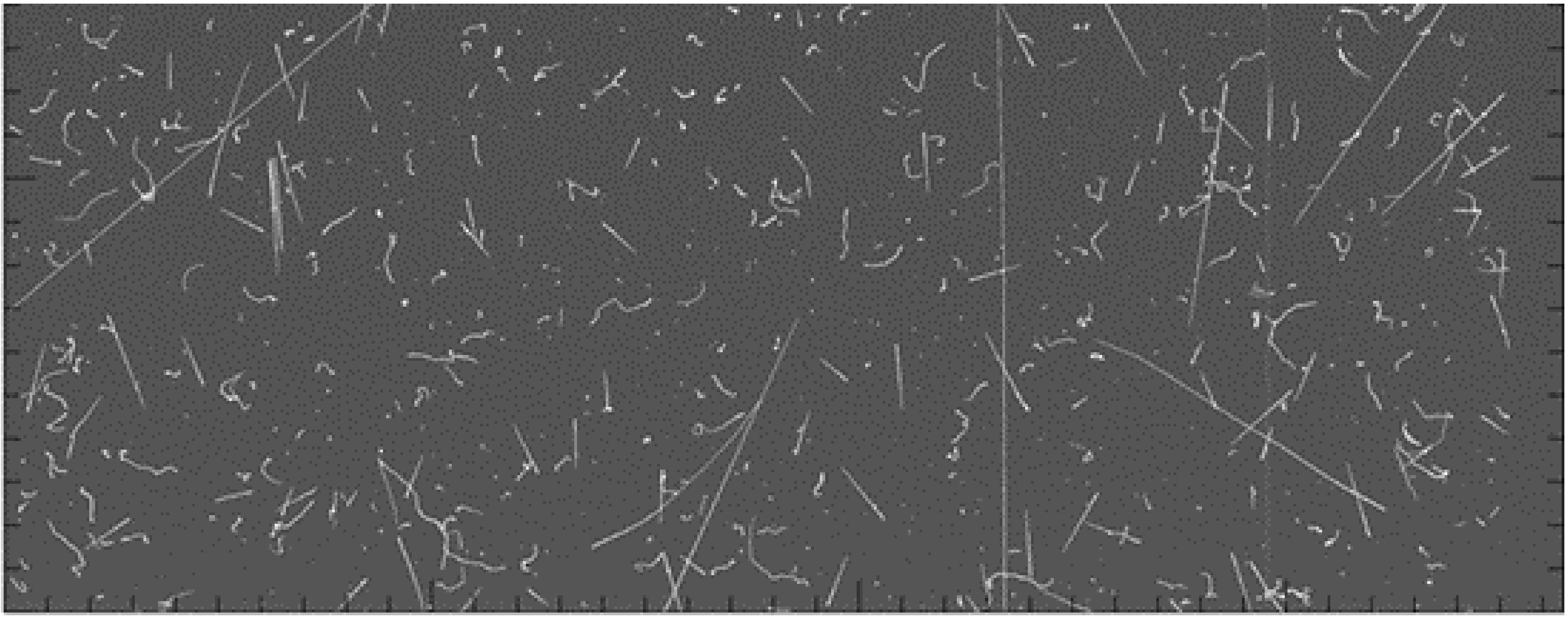
Compton spectrum / Skipper CCDs

- Fundamental Si studies with Skipper CCDs
  - Silicon response to low-energy particles is needed for DM studies
  - Compton effect / low-energy Compton electrons generated in the bulk of the silicon can mimic dark-matter particles



Compton spectrum / Skipper CCDs

- Fundamental Si studies with Skipper CCDs
  - 650 um thick LBNL CCD sub-image / 30 minute dark at -150C
    - Sea-level (LBNL CCD lab)
  - Highly curved tracks are (mostly) Compton electrons
  - Low-energy, point-like events are problematic for DM detection



  - Don Groom (retired LBNL) terminology: Worms and spots

Compton spectrum / Skipper CCDs

- Fundamental Si studies with Skipper CCD

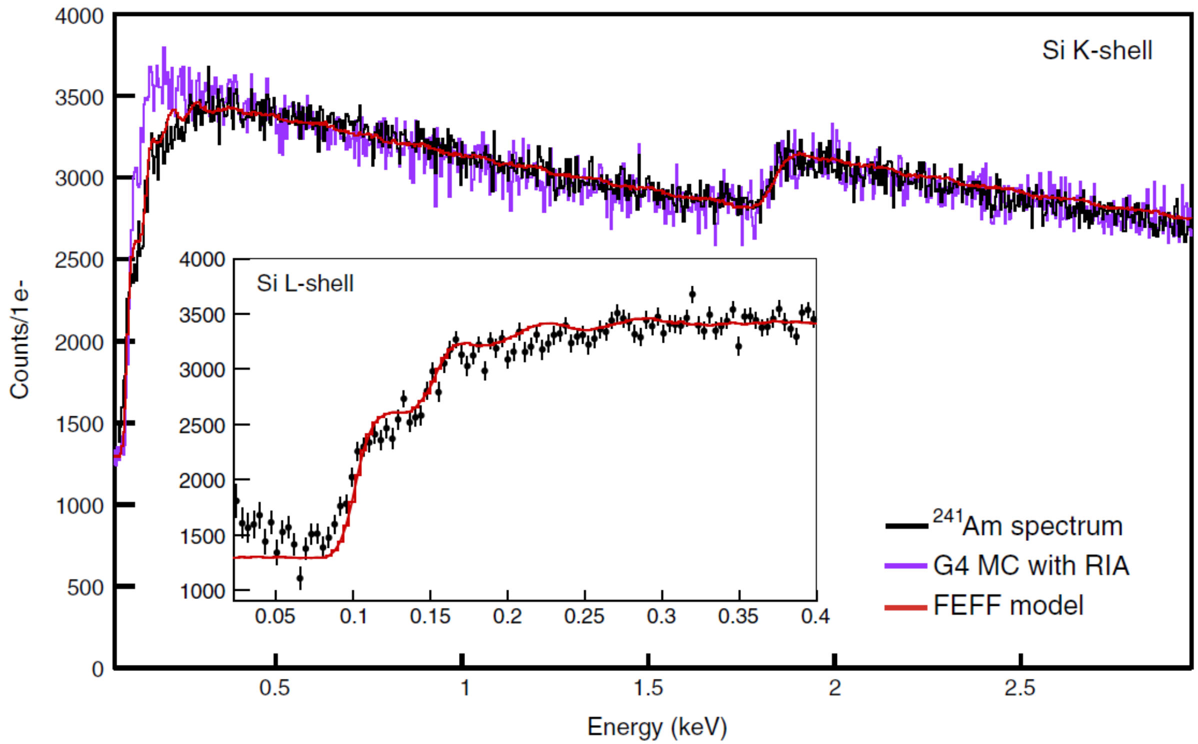


FIG. 10. The measured ^{241}Am Compton spectrum (black) from the 23 eV detection threshold to 2.1 keV. The K-step is observed at 1.8 keV. The GEANT4 simulated spectrum (purple) that is based on the relativistic impulse approximation is also shown. In red is the *ab initio* calculation from the FEFF code, with detector response taken into account. The inset shows the data comparison to the FEFF prediction in the L-shell energy range.

- e- counting to 550 e-
- Exposure in days
  - 106 with ^{241}Am
    - 224k images
  - 48 no source
    - 103k images
- 23 eV lower limit

10.1103/PhysRevD.106.092001

DAMIC-M

Abstract

The Oscura experiment will lead the search for low-mass dark matter particles using a very large array of novel silicon Charge Coupled Devices (CCDs) with a threshold of two electrons and with a total exposure of 30 kg-yr. The R&D effort, which began in FY20, is currently entering the design phase with the goal of being ready to start construction in late 2024. Oscura will have unprecedented sensitivity to sub-GeV dark matter particles that interact with electrons, probing dark matter-electron scattering for masses down to ∼500 keV and dark matter being absorbed by electrons for masses down to ∼1 eV. The Oscura R&D effort has made some significant progress on the main technical challenges of the experiment, of which the most significant are engaging new foundries for the fabrication of the CCD sensors, developing a cold readout solution, and understanding the experimental backgrounds.

(i) The small silicon band gap allows us to probe DM masses an order of magnitude lower in mass (for both scattering and absorption) than noble-liquid targets, which have an ionization energy of $\mathcal{O}(10\text{ eV})$.

(ii) Due to the small silicon band gap, the electron recoil-energy needed to promote additional electrons from the valence to the conduction band is lower in silicon (∼3.8 eV) than in many other target materials, so that DM-electron scattering events will often contain two or more electrons.

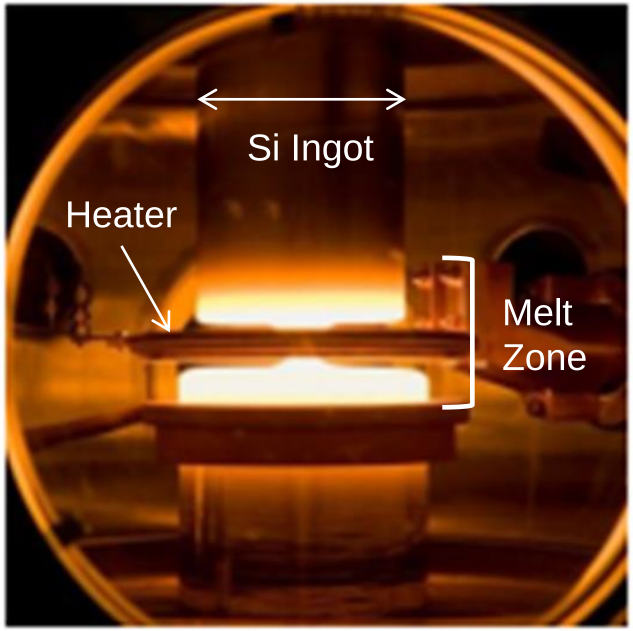
(iii) The small mass of the silicon nucleus ensures that solar neutrinos that scatter coherently off nuclei are not a limiting background for the proposed experiment with a 30 kg-year exposure [51].

(iv) The skipper-CCD technology has already been demonstrated and provides an unprecedented charge resolution, extremely low leakage currents, exquisite spatial resolution and three-dimensional reconstruction, and background identification and rejection capabilities. Indeed, the strongest constraints on low-mass DM scattering off electrons and absorption by electrons (down to ∼500 keV and ∼1 eV, respectively) are currently obtained with skipper-CCDs [16].

(v) Rapid progress is being been made in understanding the origin and the mitigation strategies of single- and few-electron backgrounds [52–55].

The Oscura Experiment

Enabling technology: Float-zone silicon



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2020	33-1751-30	> 10.0	18.9

- Float-zone refining: Favorable impurity segregation into the liquid phase, and localized melting with repeated passes results in extremely pure silicon
- 10 kΩ-cm n-type doping level is ~ 4 x 10^{11} cm^{-3}, or a purity level of about 1 part in 10^{11}
- The depletion voltage ~ x_{Depl}^2/ρ, and bulk dark current ~ x_{Depl}/τ (x_{Depl} = Depletion depth)

- Standard Czochralski silicon limited to a resistivity ρ of about 50 ohm-cm (O_2 donors)
  - Conventional CCDs and CMOS image sensors limited to depletion depths of a few to ~ 20 um

Dark Current

- One final topic related to Skipper CCDs
  - —Dark current
- We use gettering methods during the CCD fabrication to maintain low dark current
  - —Backside in-situ doped (P) polysilicon (ISDP)

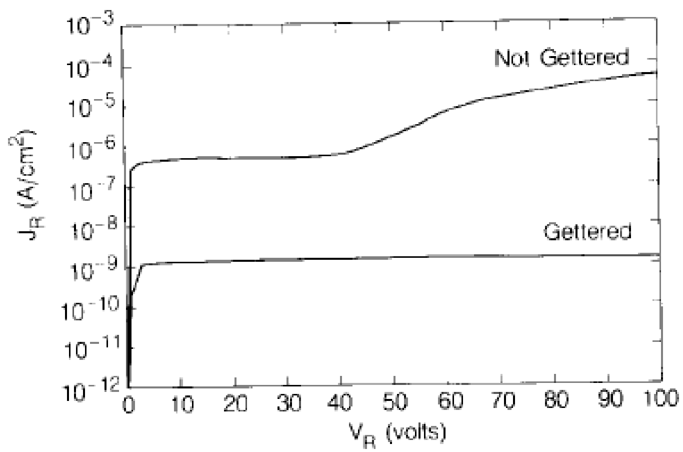


Fig. 2. The detector diode reverse-leakage current for a device with backside gettering compared to one without. The devices were fabricated on 10 kΩ cm ⟨100⟩ substrates, and both devices are from the same wafer.

Nuclear Instruments and Methods in Physics Research A275 (1989) 537–541 537
North-Holland, Amsterdam

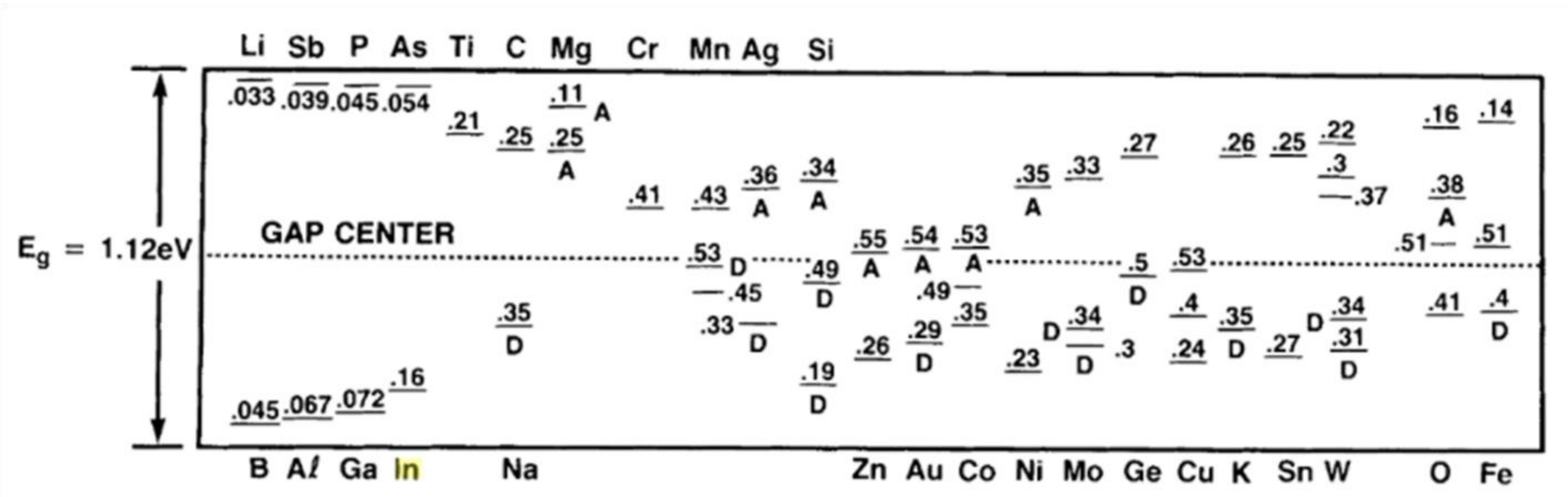
FABRICATION OF DETECTORS AND TRANSISTORS ON HIGH-RESISTIVITY SILICON

Steve HOLLAND
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA

Especially important for thick, fully depleted devices

Dark Current

- Dark current from the substrate is determined by extremely low levels of unwanted impurities (metals) that have energy states near the bandgap center



- In the early semiconductor days metals in Si were referred to as “Deathnium” (William Shockley)

The Gettering Process for High-ρ silicon

- A significant and collaborative effort was needed to optimize the "gettering" process to achieve low dark current
  - Backside layer traps "lifetime killing" impurities (metals)
  - Looks simple, but a high yield, robust process was not trivial to realize
  - Close collaboration and willingness on Mitel / DALSA's part was critical
  - https://www.sciencedirect.com/science/article/pii/0168900289907419

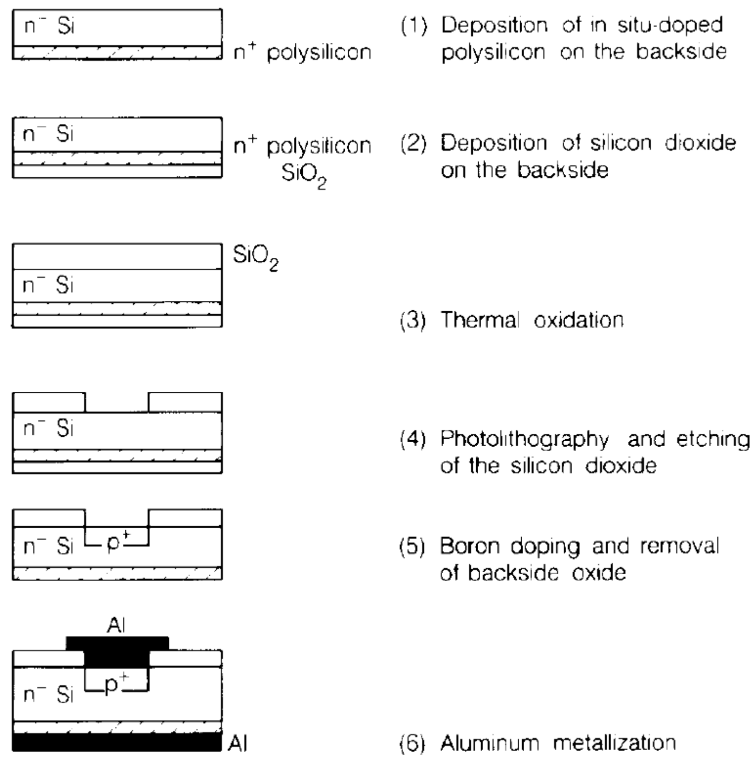


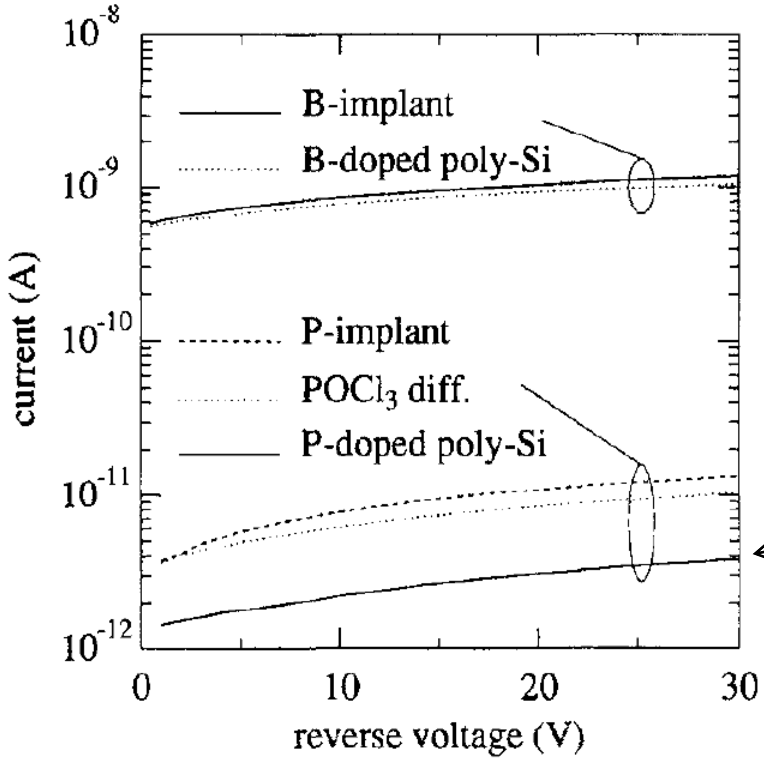
Fig. 1. The fabrication process used in this work.

FABRICATION OF DETECTORS AND TRANSISTORS ON HIGH-RESISTIVITY SILICON

Steve HOLLAND
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA

The Gettering Process for High-ρ silicon

- Dark current for high-ρ silicon pin diodes



- Comparison study of various gettering methods (1997)
- https://www.sciencedirect.com/science/article/pii/S0168900297006128

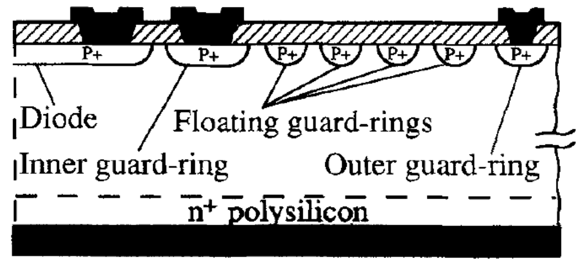


Fig. 2. Schematic cross-section (half device) of a PIN detector on n-type substrate.

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 395 (1997) 344–348

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

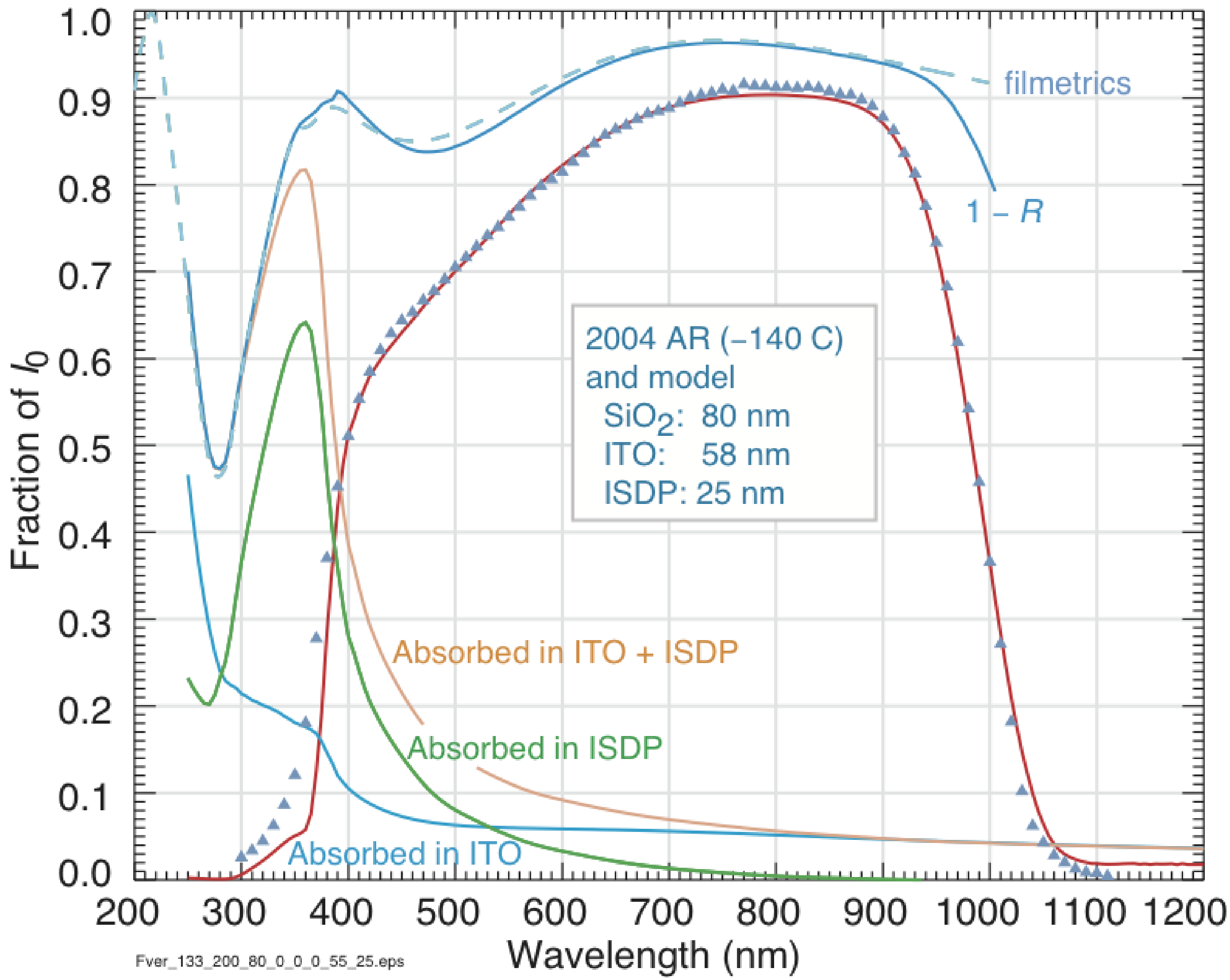
Si-PIN X-ray detector technology

G.F. Dalla Betta[a], G.U. Pignatel[a,*], G. Verzellesi[a], M. Boscardin[b]

[a] Dipartimento di Ingegneria dei Materiali, Università di Trento, I-38050 Mesiano (TN), Italy
[b] IRST-Microelectronics, 38050 Povo (TN), Italy

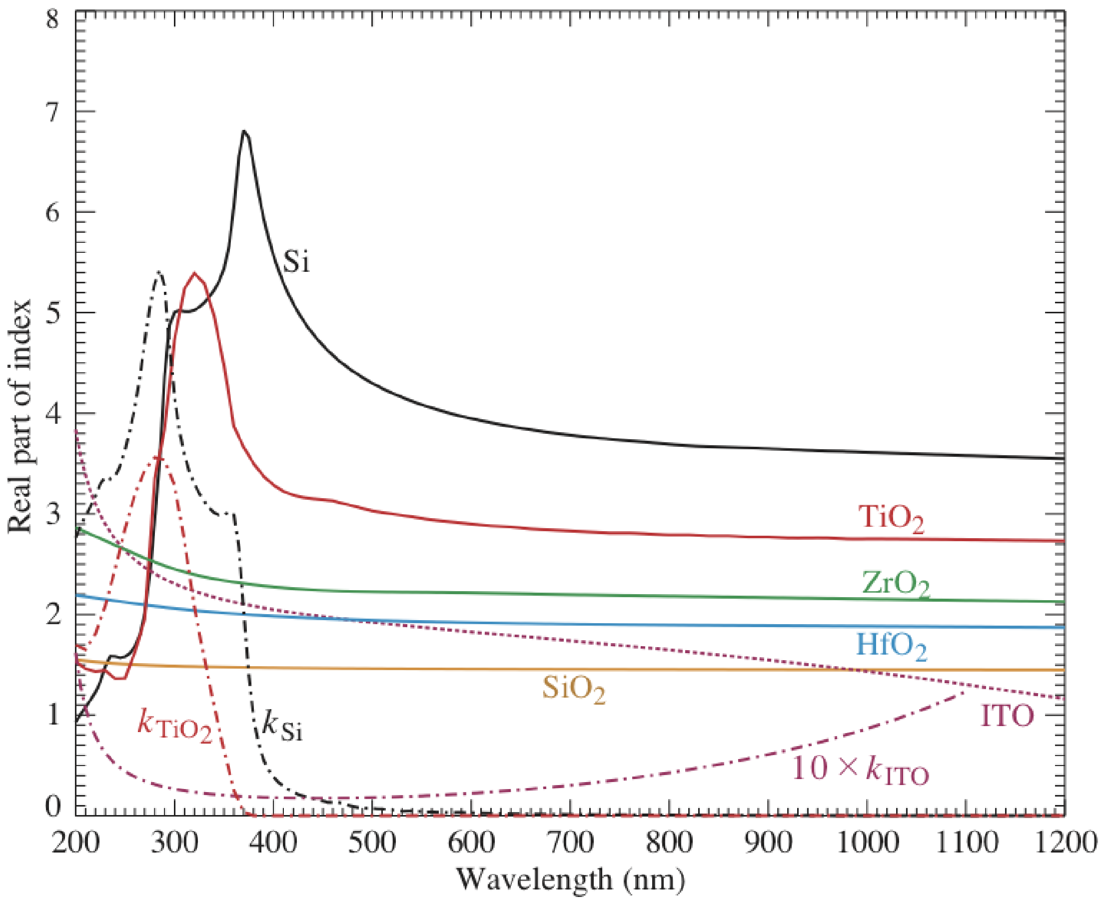
Quantum Efficiency

- QE results DECam ITO SiO_2 AR coating



Quantum Efficiency

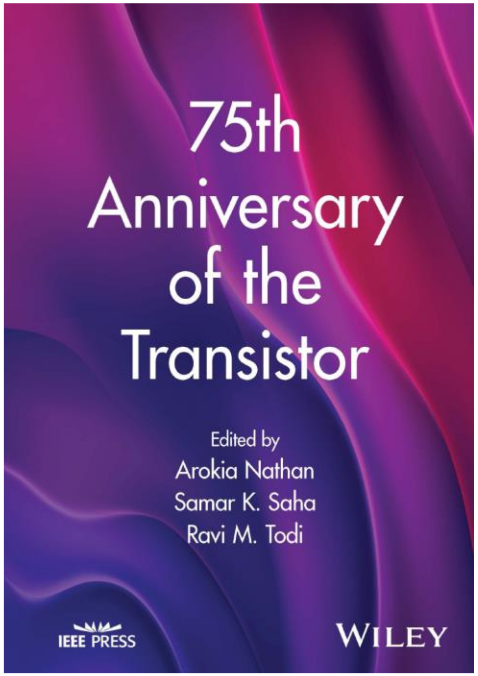
- New anti-reflection coating material used in the DESI CCDs to address ITO performance



- ITO index decreasing with λ
- Looks like single AR coating at long λ when used with SiO_2 ǂ
- Replace most of the ITO with ZrO_2

ǂ Pointed out originally by Don Groom

CCDs and CMOS image sensors



Chapter 22

Imaging Inventions

Charge-Coupled Devices

Michael F. Tompsett

Chapter 23

The Invention and Development of CMOS Image Sensors

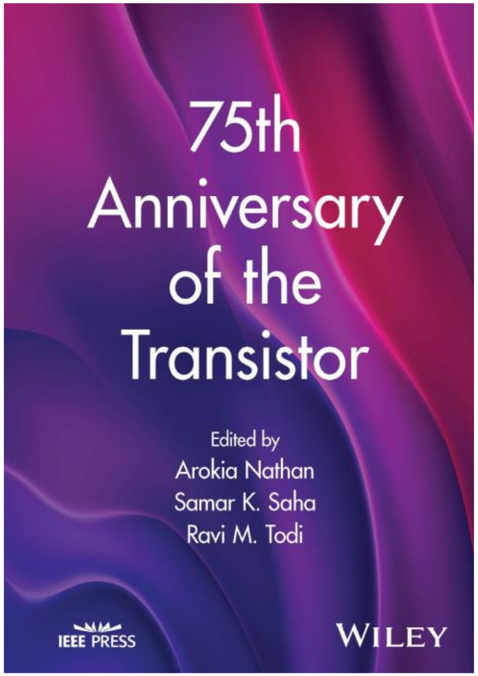
A Camera in Every Pocket

Eric R. Fossum

Thayer School of Engineering, Dartmouth College, Hanover, NH, USA

The invention of CCD imagers was actually preceded by work on a thin-film-transistor array in 1963 by Paul Weimer at RCA Labs, and simultaneous proposals for *x*–*y* addressed MOS imagers in 1967 by Peter Noble at Plessey in England and Gene Weckler at Fairchild in California. However MOS technology was too primitive at the time and 25 years of MOS technology development were required before these proposals were picked up again by Eric Fossum and yielded viable devices. Today's CMOS imagers are made with incredible quality and yield and have replaced CCD imagers for other than space and astronomical work.

CCDs and CMOS image sensors



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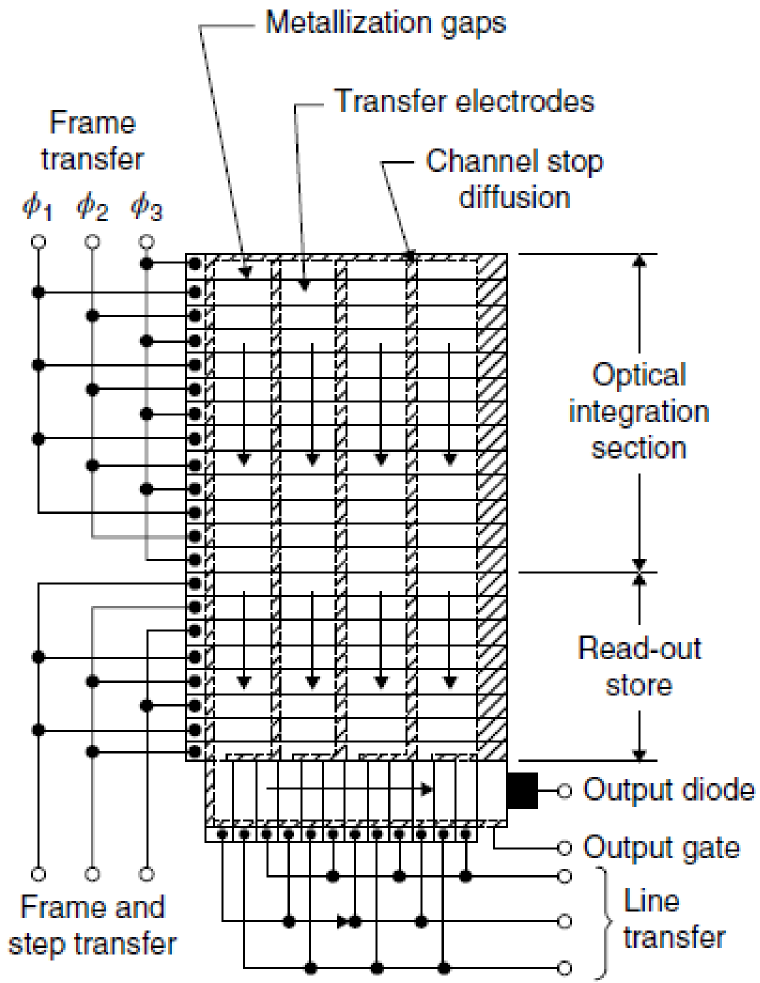
, dark matter and fundamental radiation detection.

CCDs and CMOS image sensors

75th Anniversary of the Transistor



Chapter 22

Imaging Inventions

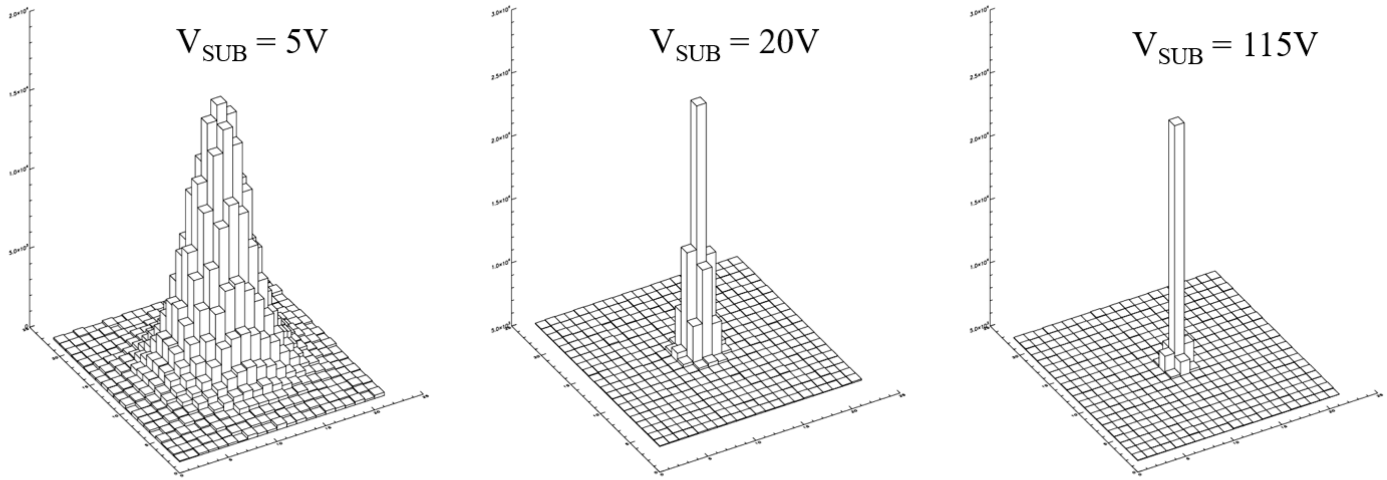
Charge-Coupled Devices

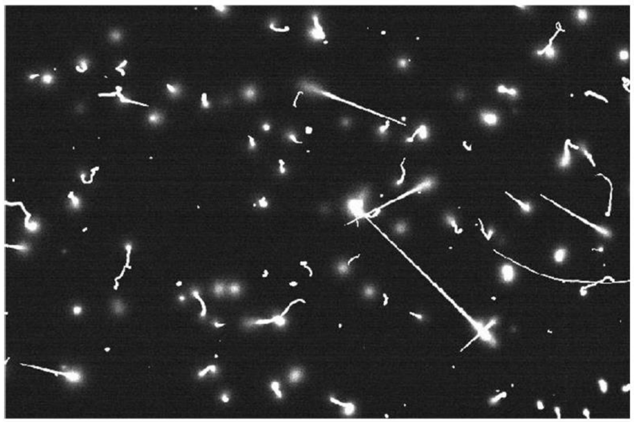
Michael F. Tompsett

Figure 22.3 Readout principle of "Frame-Transfer" CCD imaging array.

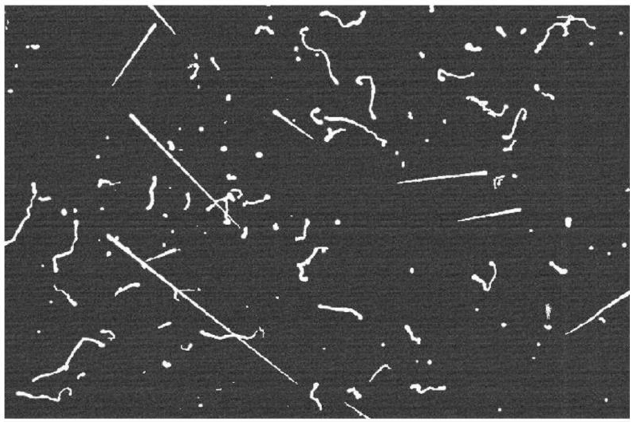
High-voltage compatible CCDs

- Spatial resolution in fully depleted CCDs goes as ~ $1/(V_{sub})^{-1/2}$
  - Carrier transit time (holes)





a)



b)

Figure 4. Sub-images of 30 minute dark exposures taken at −140° C on a 500 μm-thick, 4k × 2k, $(15\ \mu m)^2$-pixel CCD fabricated on ~20,000 Ω-cm silicon. The size of the sub-image is approximately 650 rows by 770 columns. a) V_{sub}=30V b) V_{sub}=60V.