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U.S. DEPARTMENT OF ENERGY
Office of Science

Photon-counting CCDs for Future Spectroscopic Surveys

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11/08/2023

RDC2: Photodetectors, CPAD 2023 @ SLAC

CCDs for cosmological physics

Long legacy in astronomy with excellent **linearity**, **uniformity**, **quantum efficiency**

What's next for spectroscopic surveys?

– Upgrade to Dark Energy Spectroscopic Instrument (DESI)

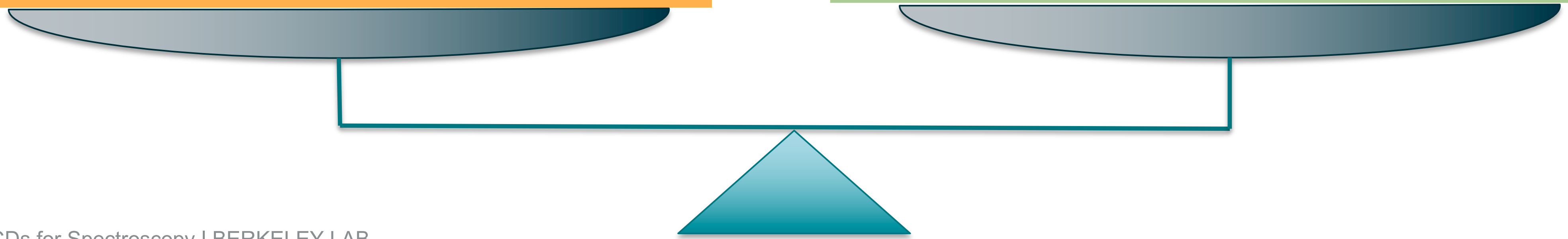
– Mapping 0 < z < 6: Stage-V spectroscopy

Readout noise

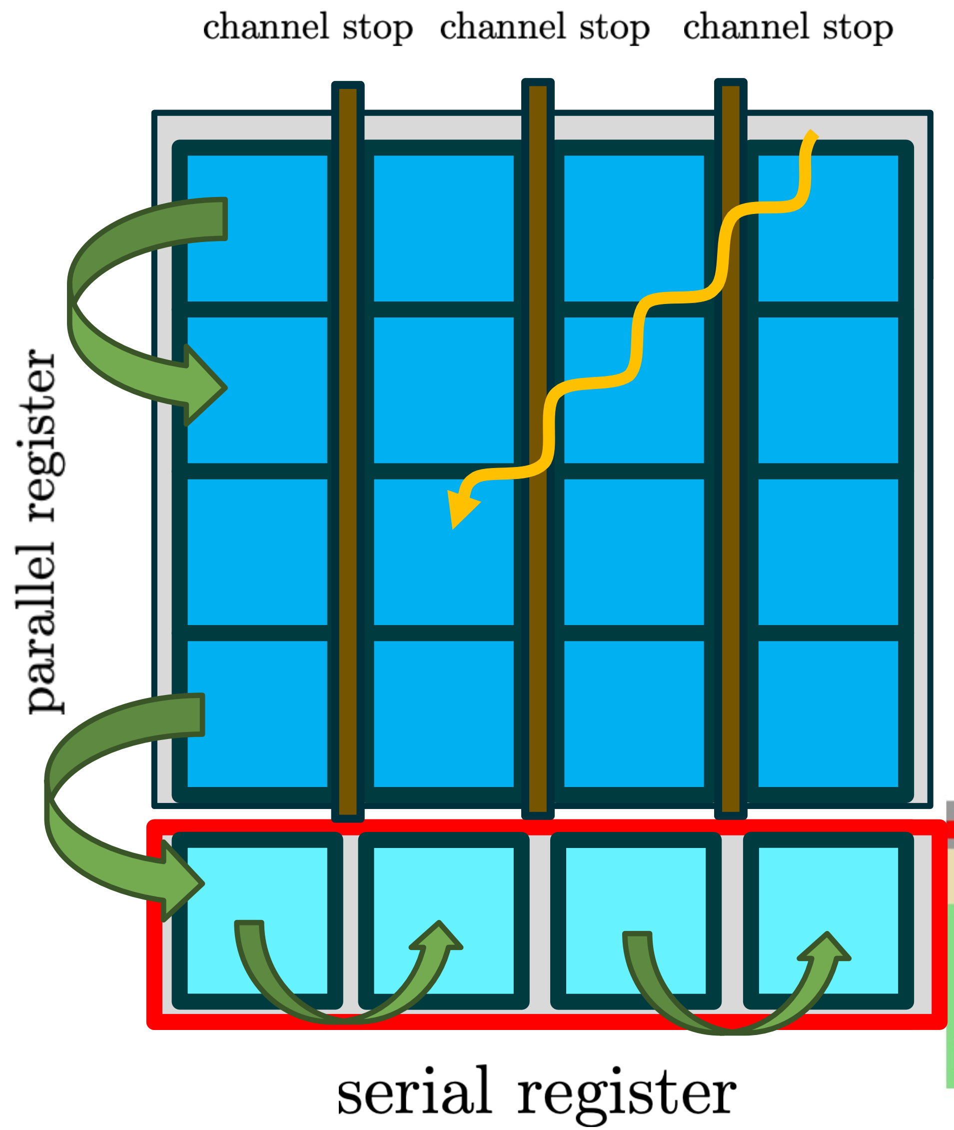
- Dominates in low-signal, low-background regime
- Dispersed light from faint sources have low SNR/pixel

Readout rate

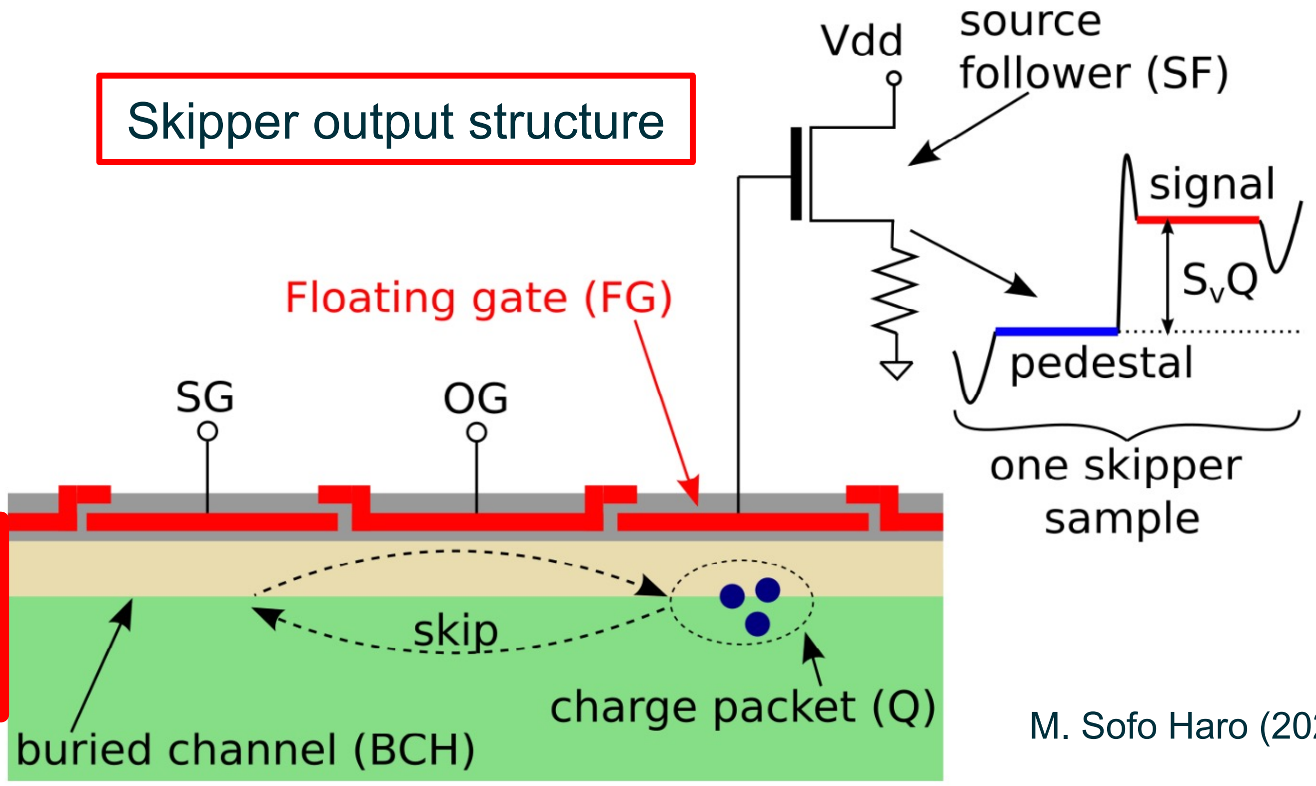
- Read time overhead between exposures impacts survey efficiency and cost
- Capability for probing transient targets, follow-ups with complementary facilities



Sub-electron noise with Skipper CCDs



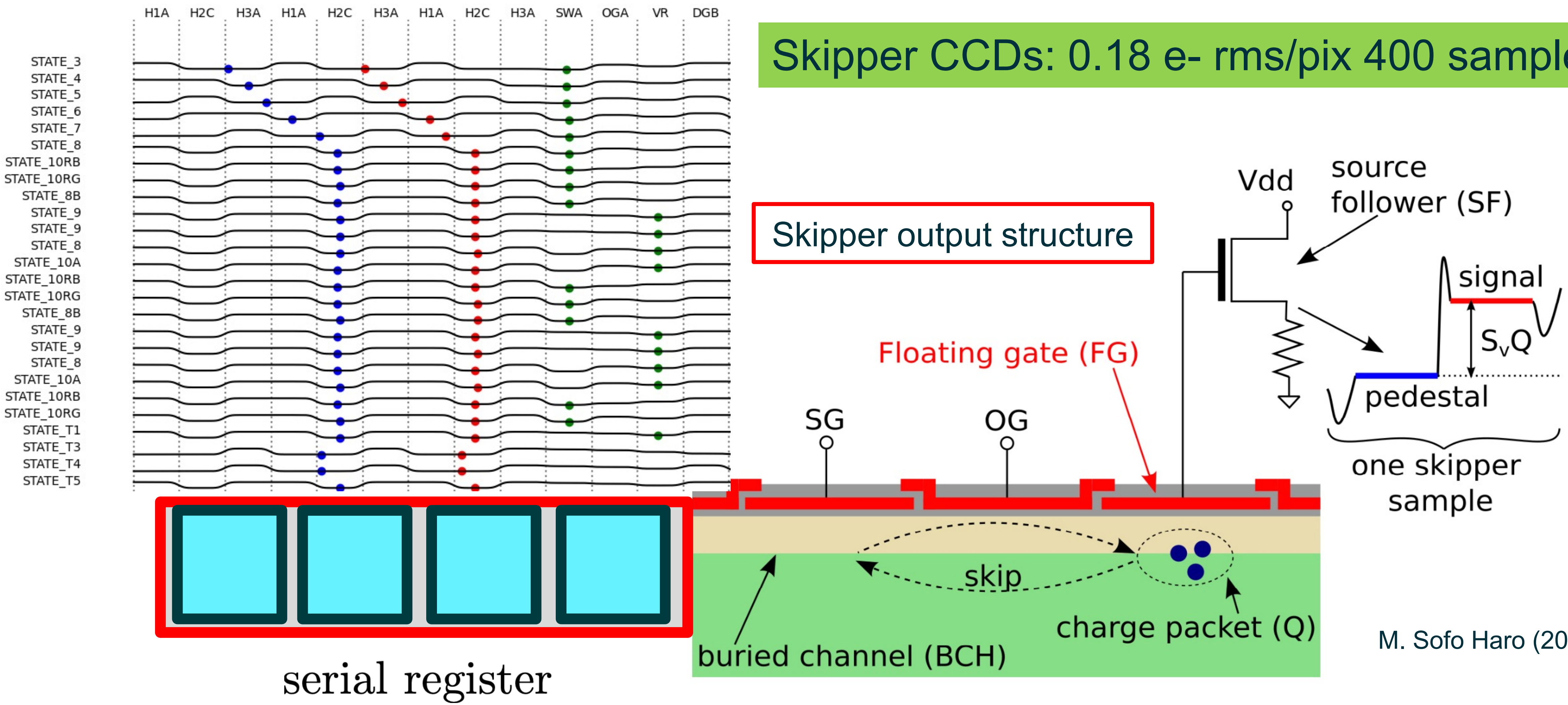
Skipper CCDs: 0.18 e- rms/pix 400 samples



M. Sofo Haro (2021)

Sub-electron noise with Skipper CCDs

Skipper CCDs: 0.18 e- rms/pix 400 samples



M. Sofo Haro (2021)

Readout time challenge with Skipper CCDs

$$\sigma_N = \frac{\sigma_1}{\sqrt{N}}$$

Noise proportional to inverse square root of number of samples *N* ("skips")

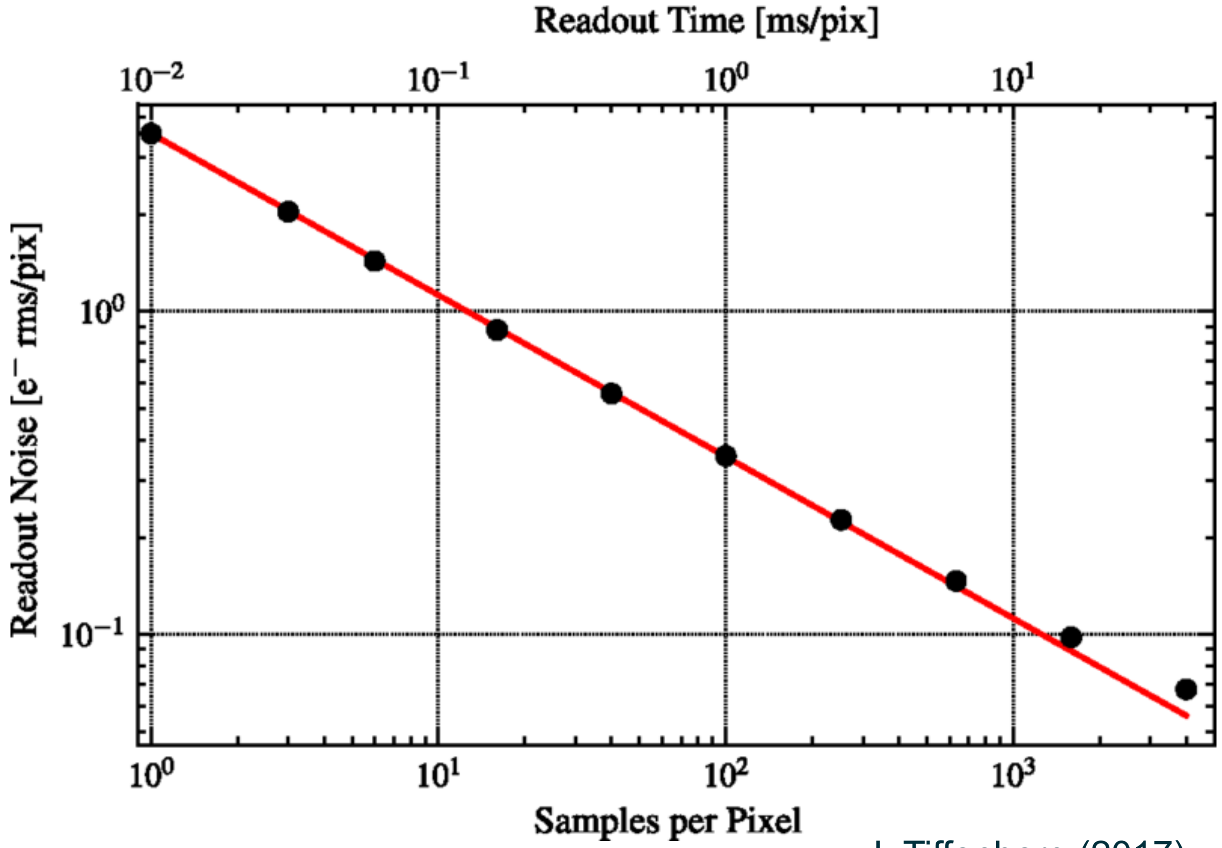
Solutions being explored:

- Single sample noise reduction
- Region of interest selection
- Frame-transfer

This work:
Parallelized readout structure with Multi-Amplifier Sensing CCD

For 4M pixels/channel (e.g., DESI)

40 s **7 min** **70 min** **11 hrs**



J. Tiffenberg (2017)

Multi-Amplifier Sensing (MAS) CCD

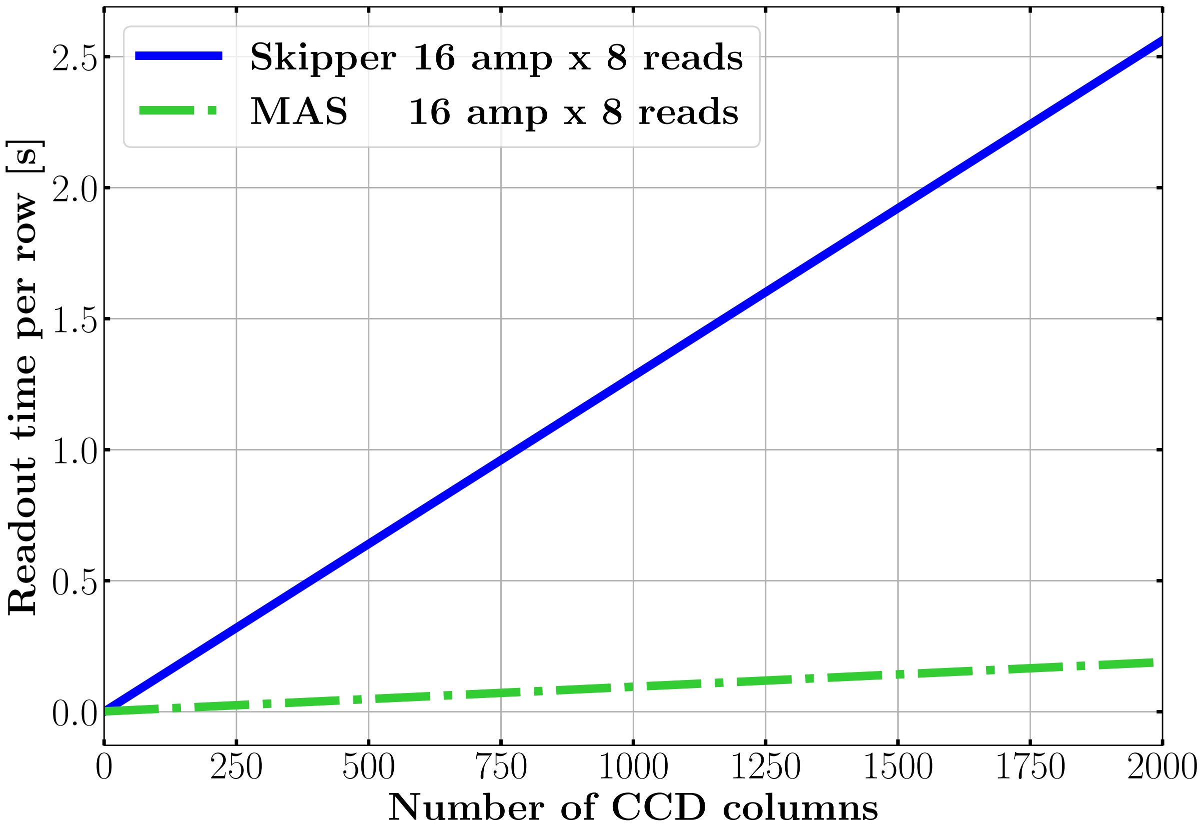
$$\sigma_N = \frac{\sigma_1}{\sqrt{N}\sqrt{M}}$$

Noise proportional to inverse square root of number of samples *N* and number of amplifiers *M*

Solutions being explored:

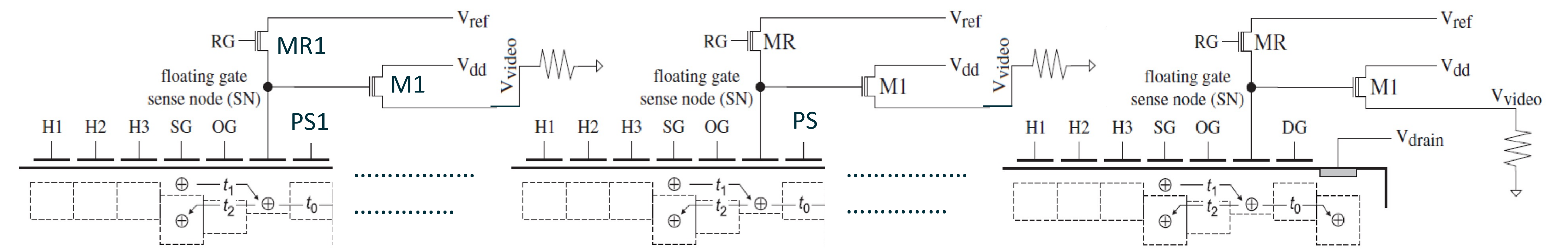
- Single sample noise reduction
- Region of interest selection
- Frame-transfer

This work:
Parallelized readout structure with Multi-Amplifier Sensing CCD

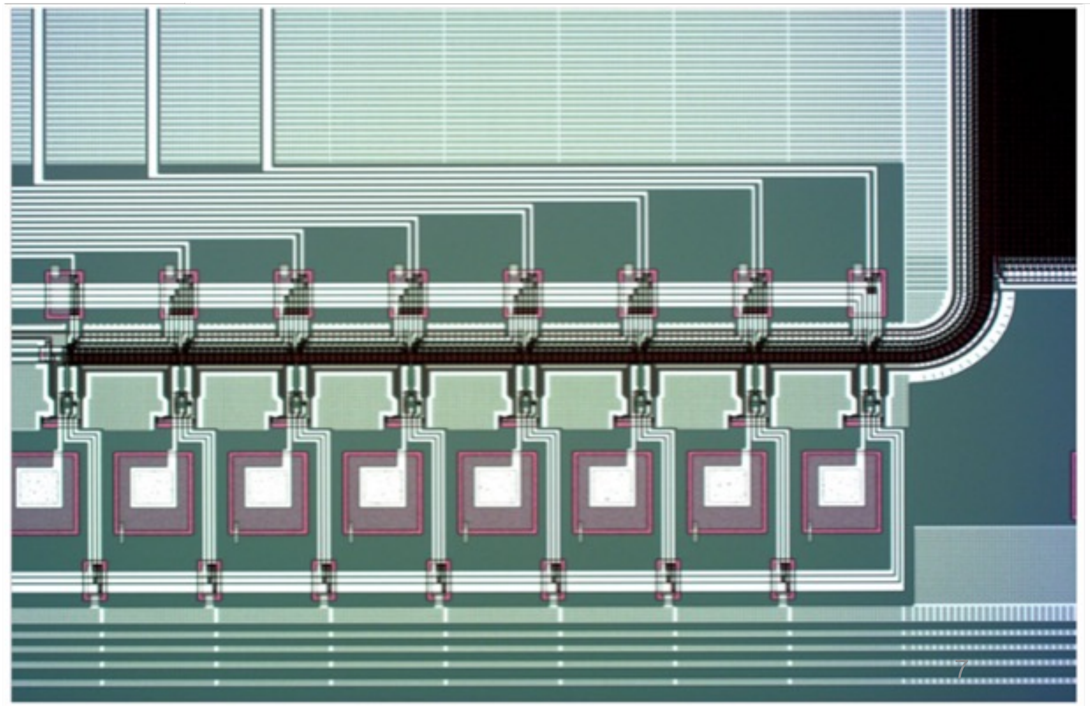


$$\frac{t_{\mathrm{MAS}}}{t_{\mathrm{Skipper}}} \propto M^{-1}$$

Multi-Amplifier Sensing (MAS) Architecture

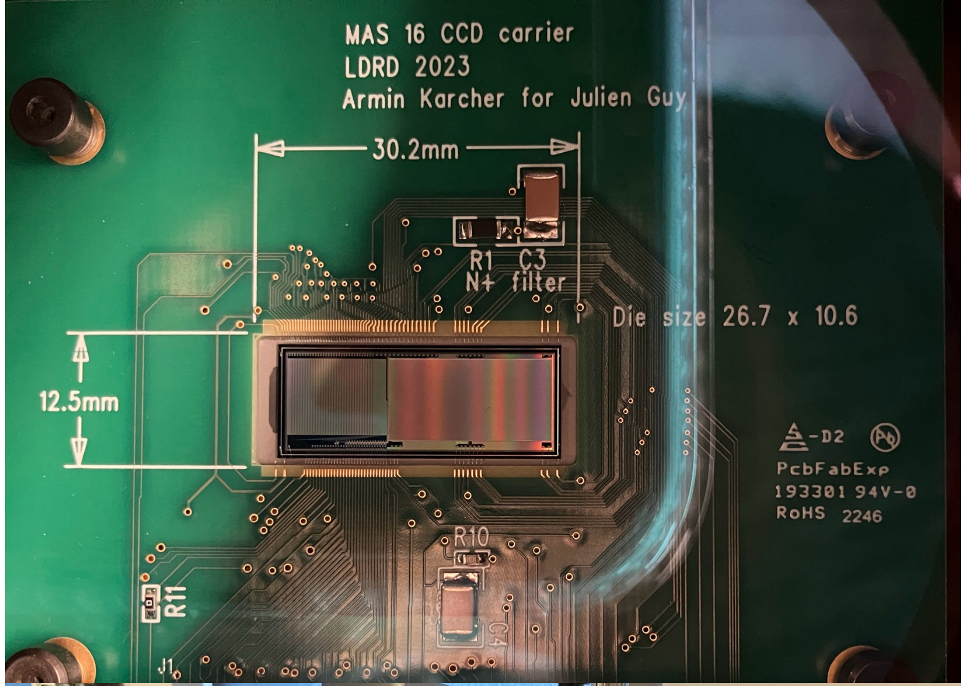


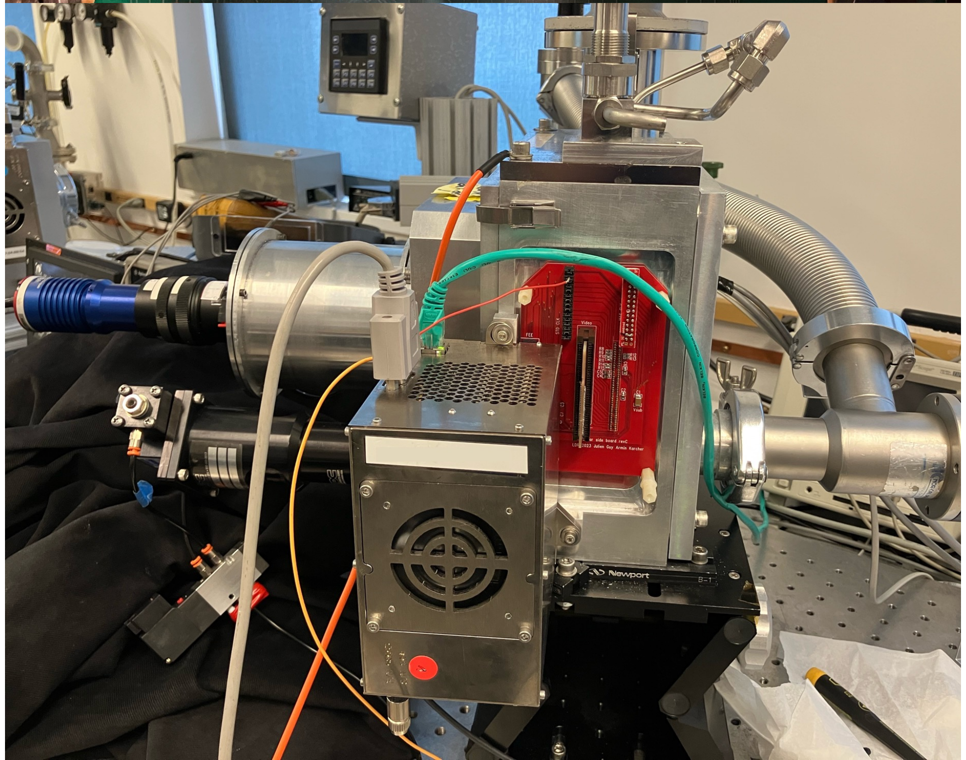
- Design at Lawrence Berkeley National Laboratory (Steve Holland)
- Developed as part of DOE quantum information science initiative and an outgrowth of Skipper CCD
- Fabrication at Teledyne DALSA Semiconductor and LBNL MicroSystems Laboratory (back-illumination)



MAS-CCD testing at LBNL

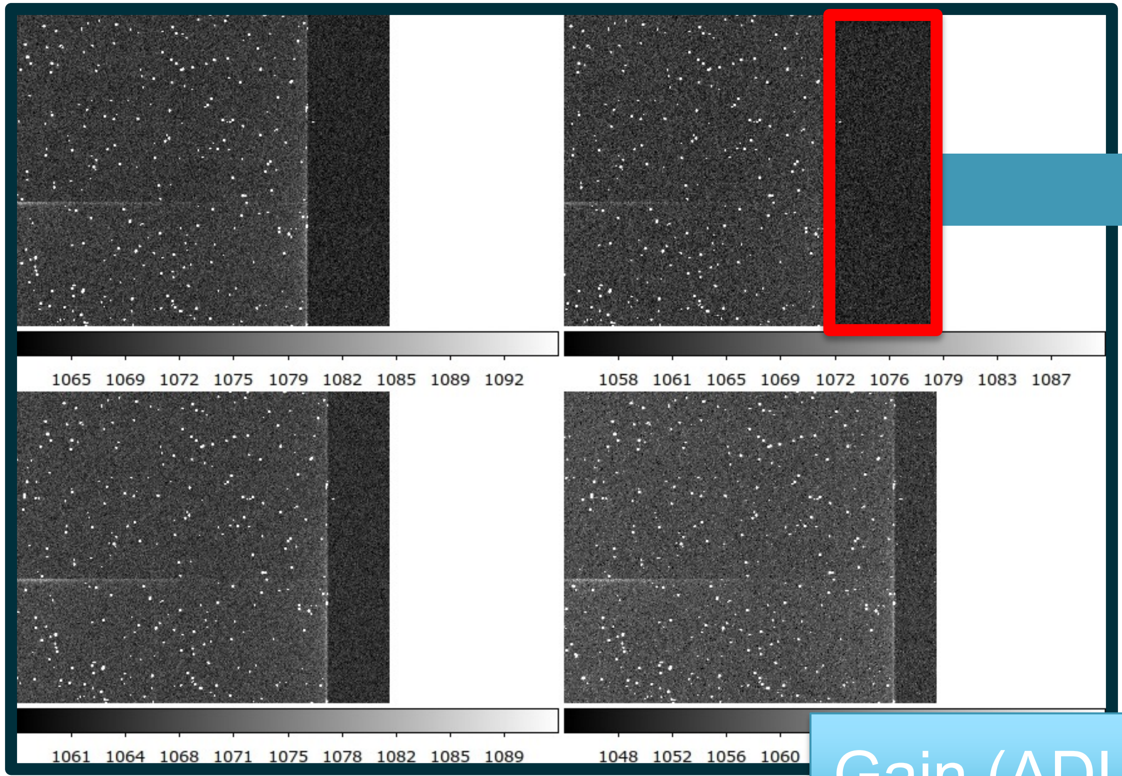
Type	p-channel on high-resistivity n-type substrate
Format	1024 x 512
Pixel size	15 µm
Pitch	15 µm
Thickness	650 µm
Illumination	Frontside
Operating temperature	~140-170 K
Fabrication	Teledyne DALSA / LBNL
Readout	DESI Front-end Electronics





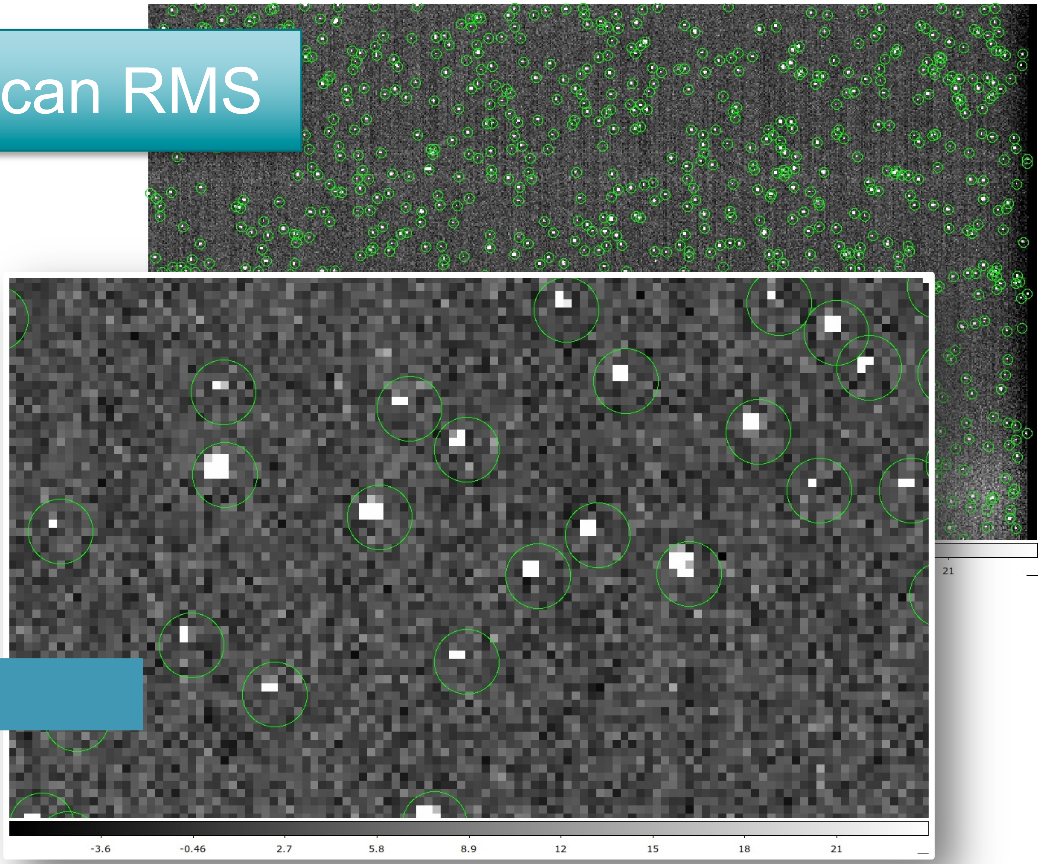
Read noise performance – 4 channels

🎯 **Read time = 40 kHz** or **25 µs/pixel**



Overscan RMS

Gain (ADU/e-)

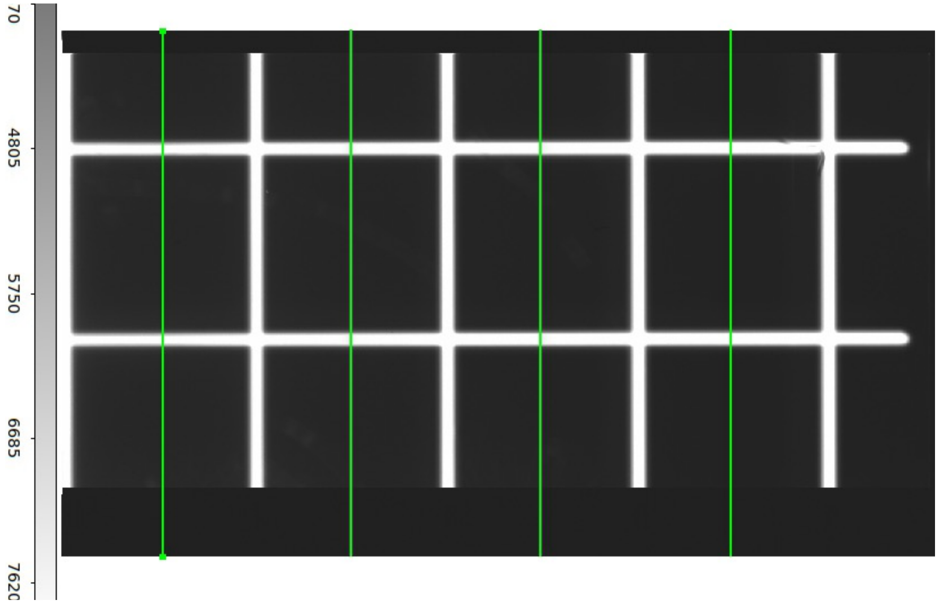


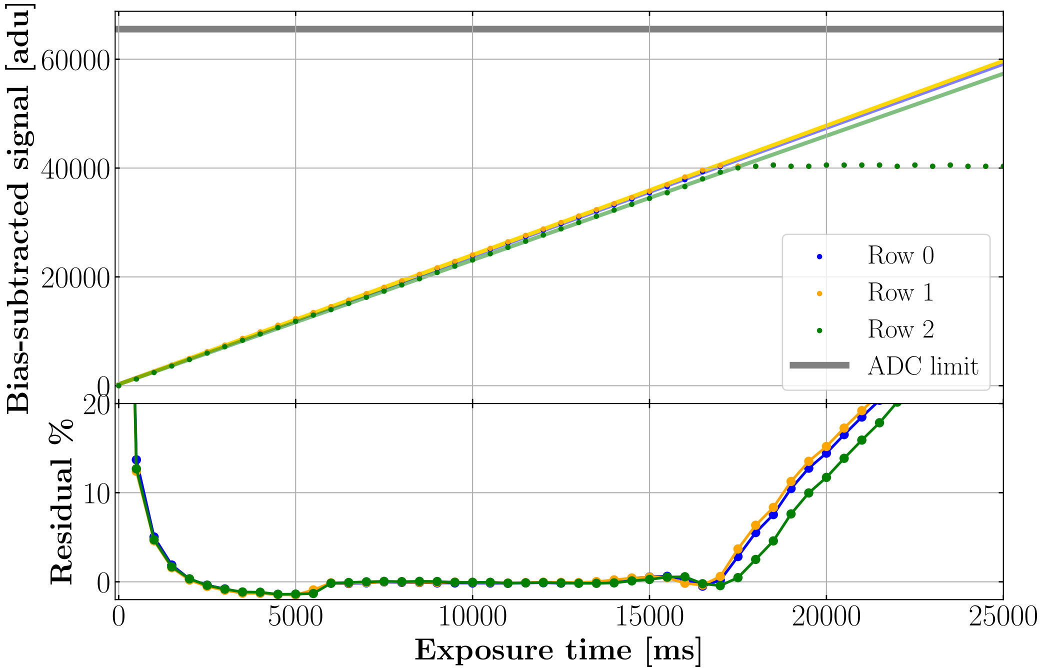
$$\sigma_N = \frac{\sigma_1}{\sqrt{N}\sqrt{M}}$$ **~ 2.5 e- rms/pixel for 4-channels**

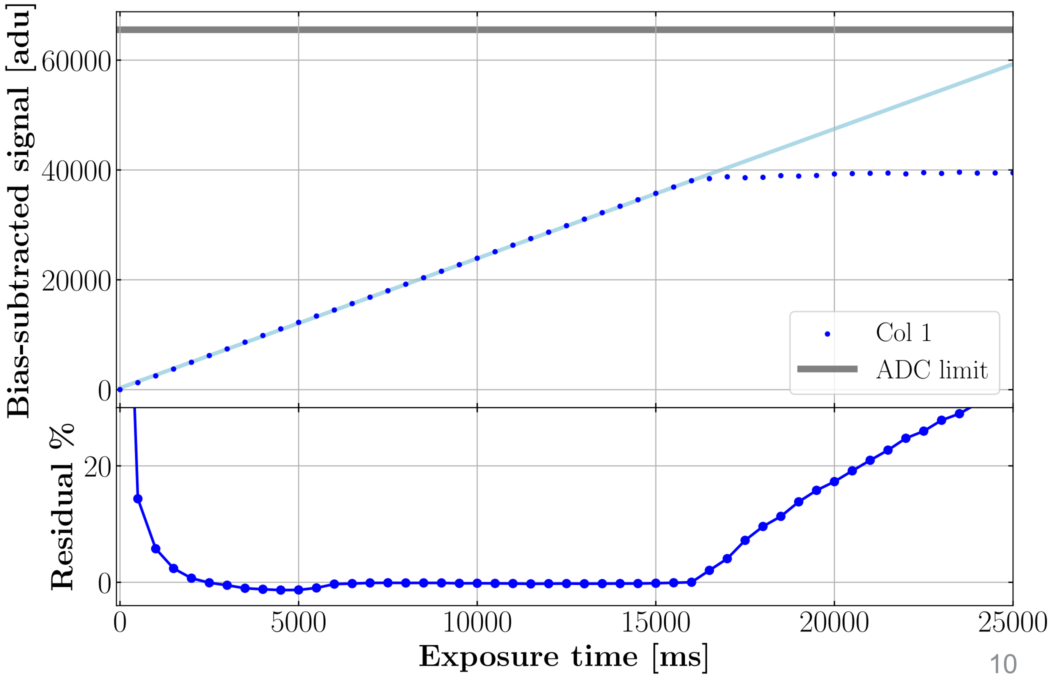
~ 5 electrons rms/pixel per channel using Mn Kα X-ray peak

Full well

- Synergy with astrophysics community to maximize full well capacity + low-signal capabilities
- Reduce gain ~ 0.4 ADU/e- for ADC dynamic range
- Pixel full well ~ 89,000 electrons
- Low-signal nonlinearity needs to be understood

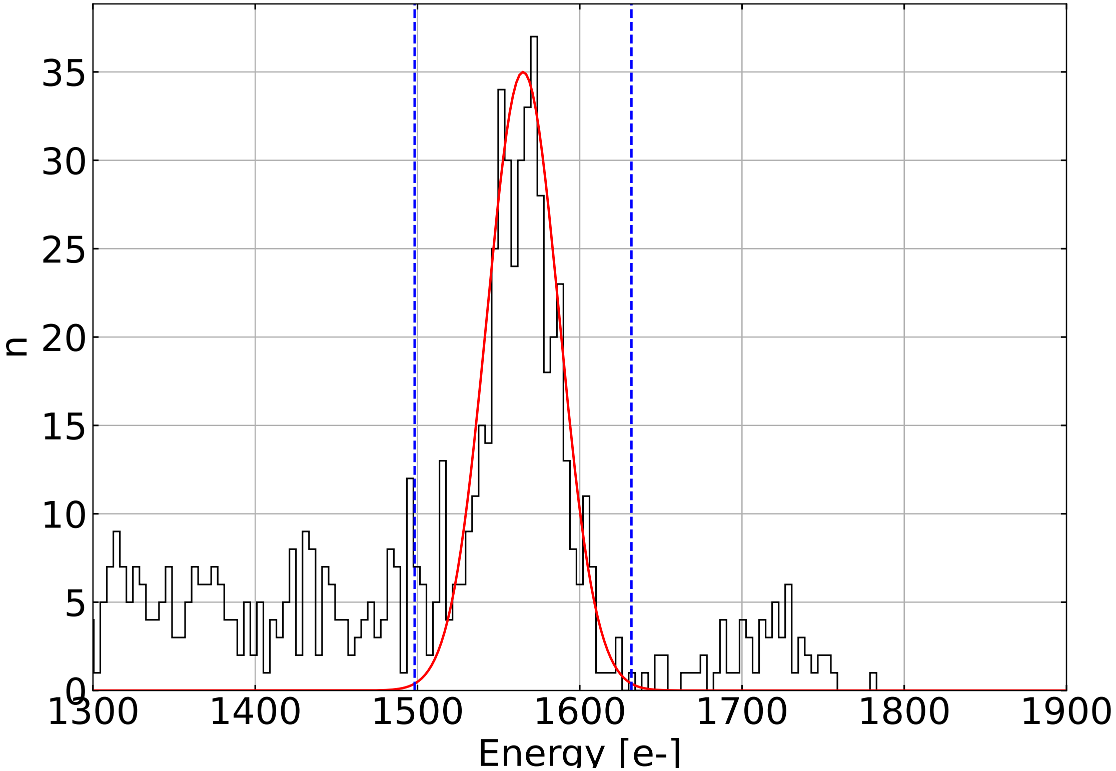




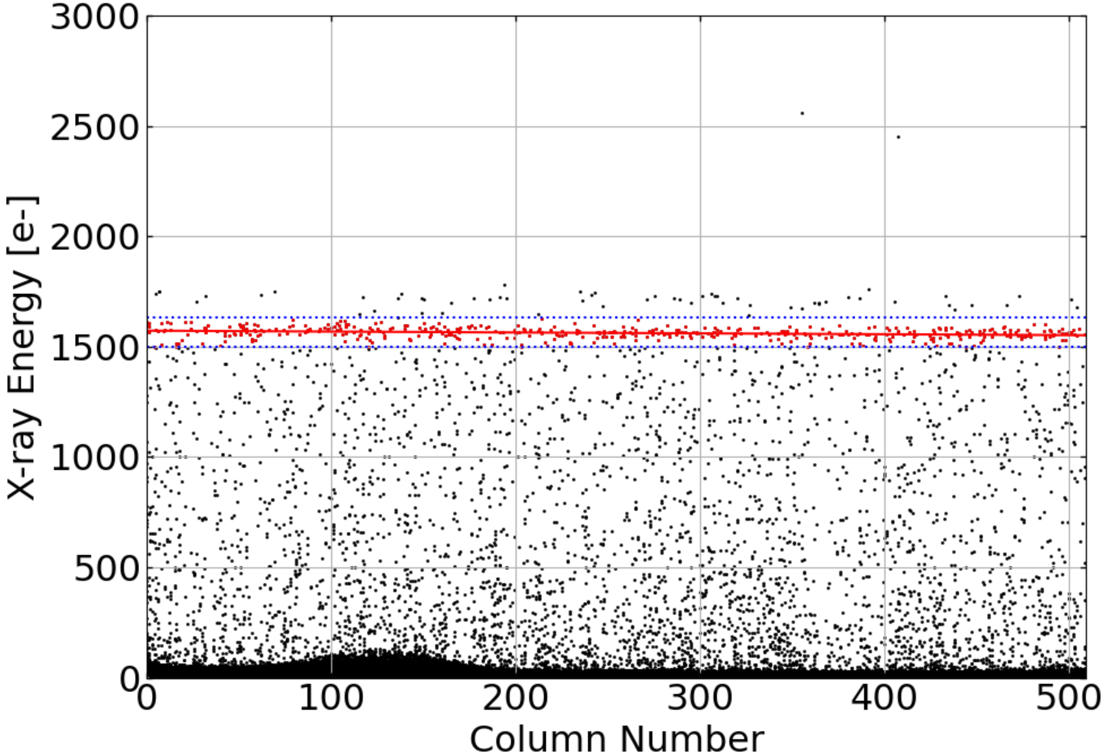


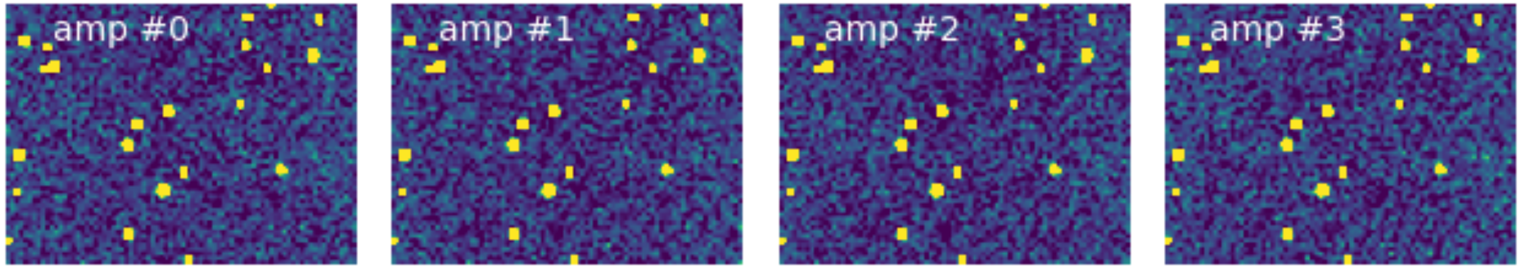
Charge transfer efficiency

^{55}Fe Kα 5.9 keV peak

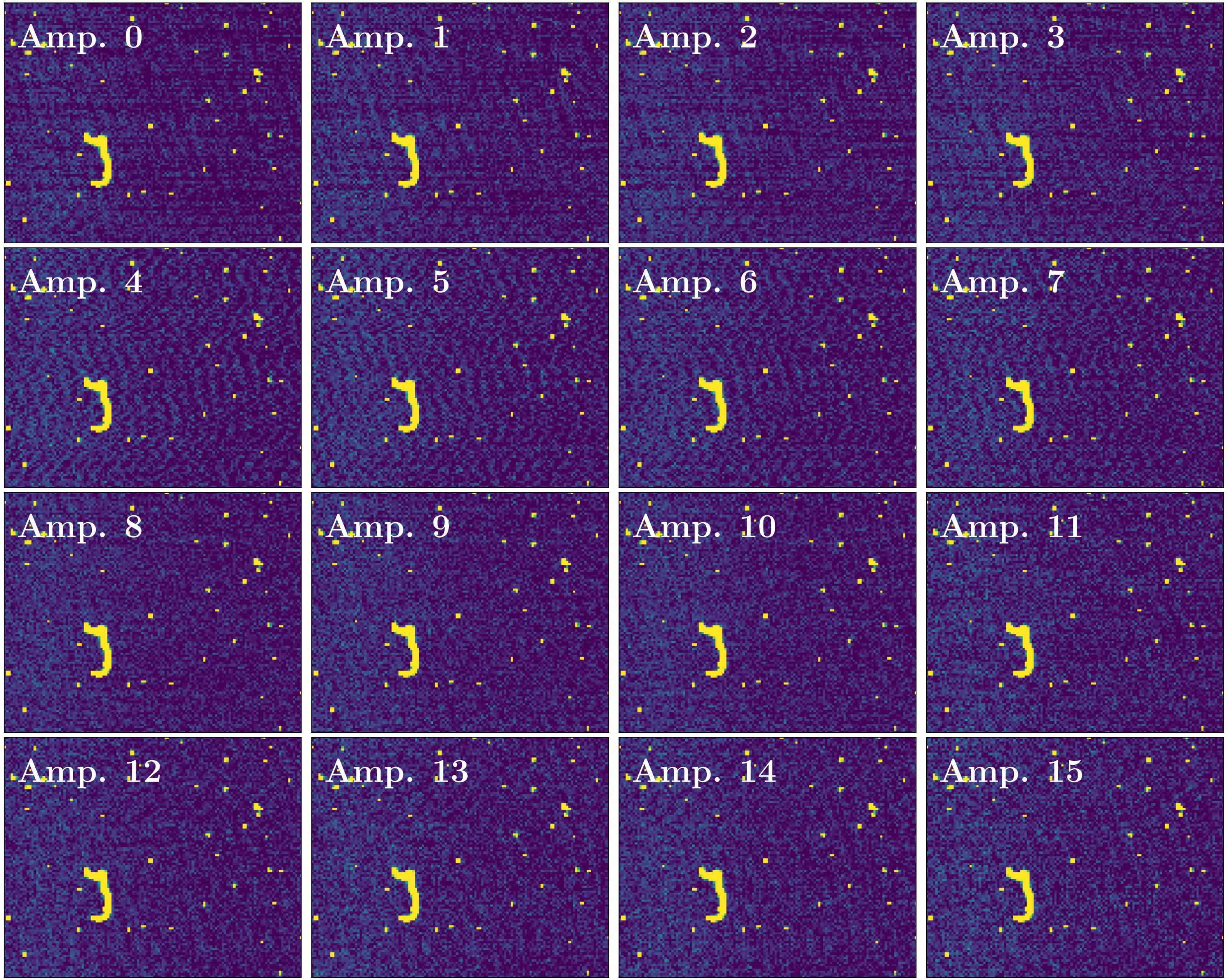


X-ray stacking plot

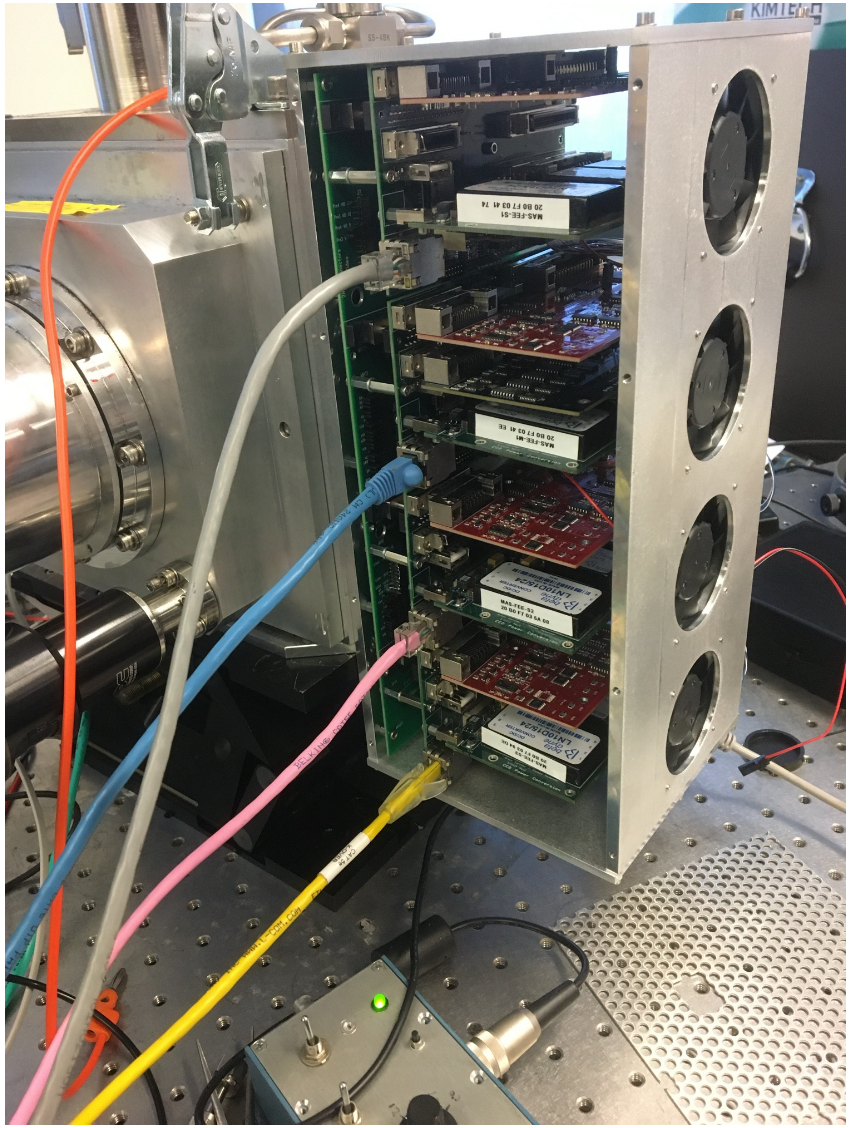




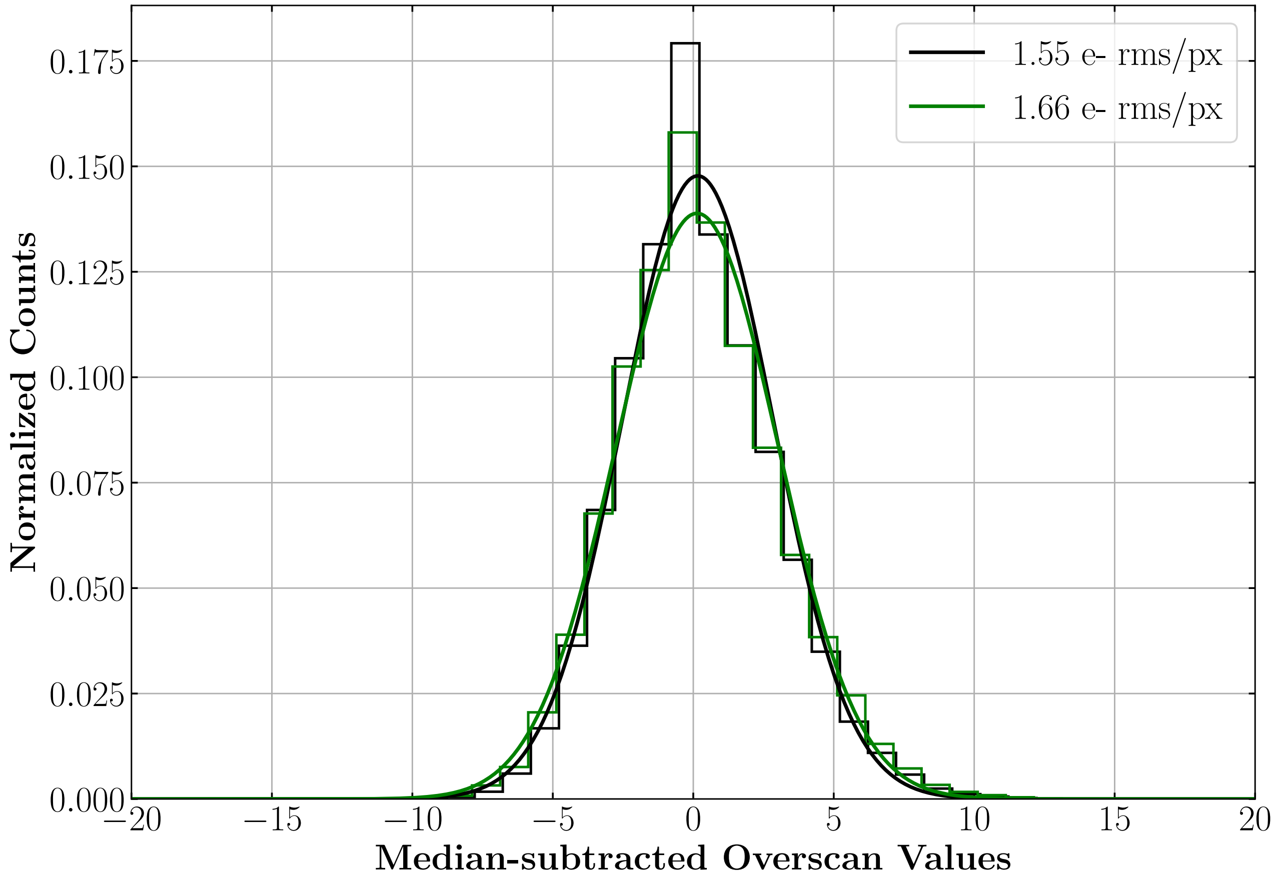
99.998% serial CTE
Errors dominated by fit

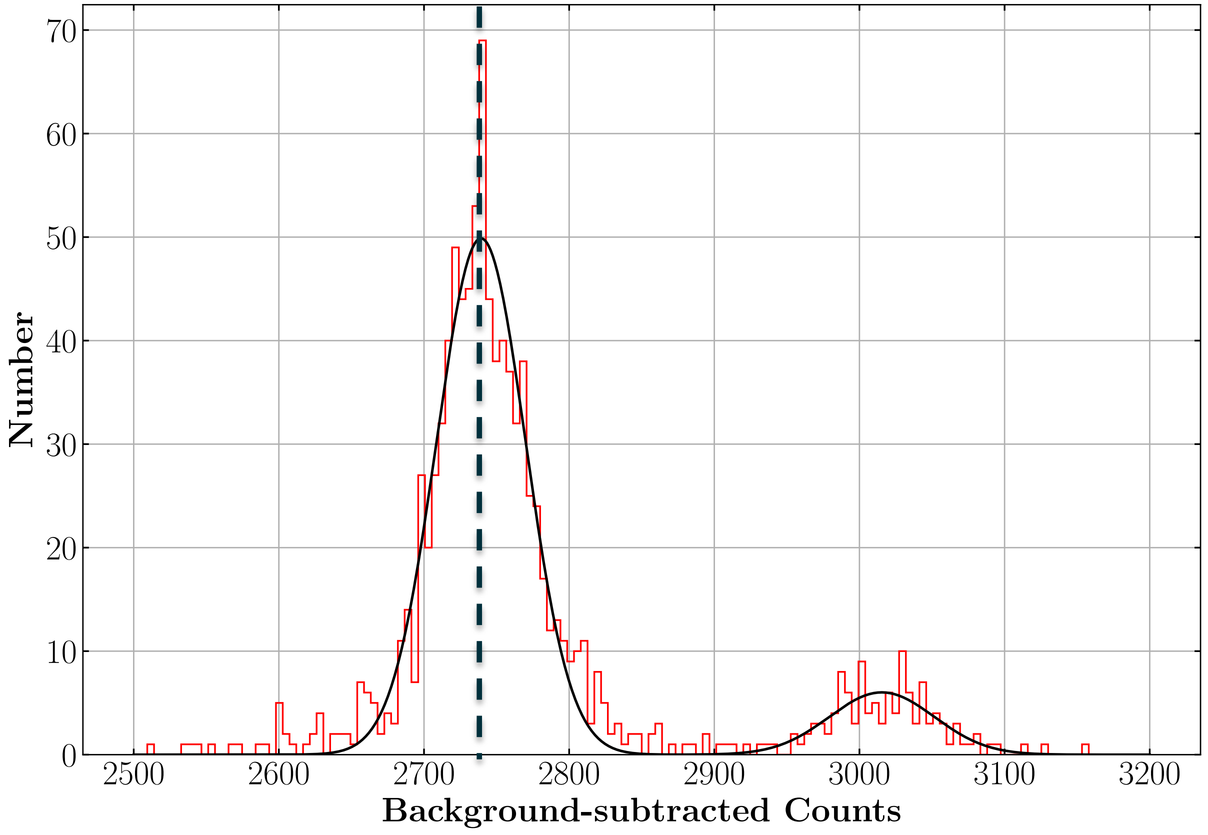


First light for 16-ch with “Hydra”



Read noise performance – 16 channels



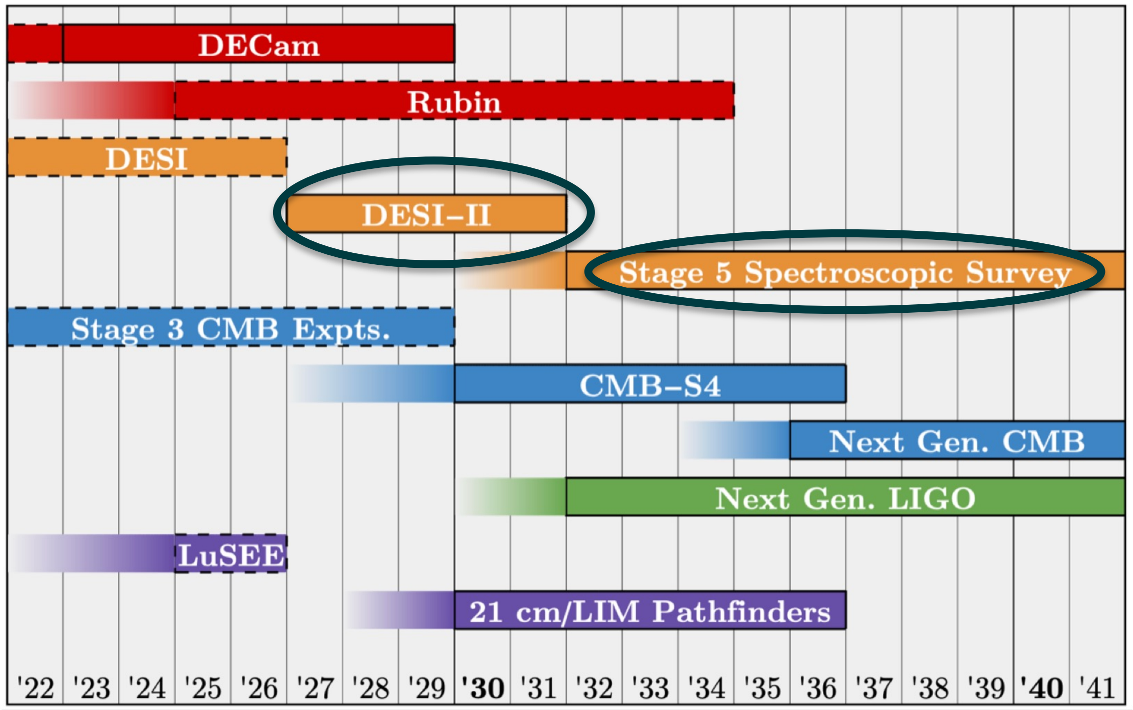


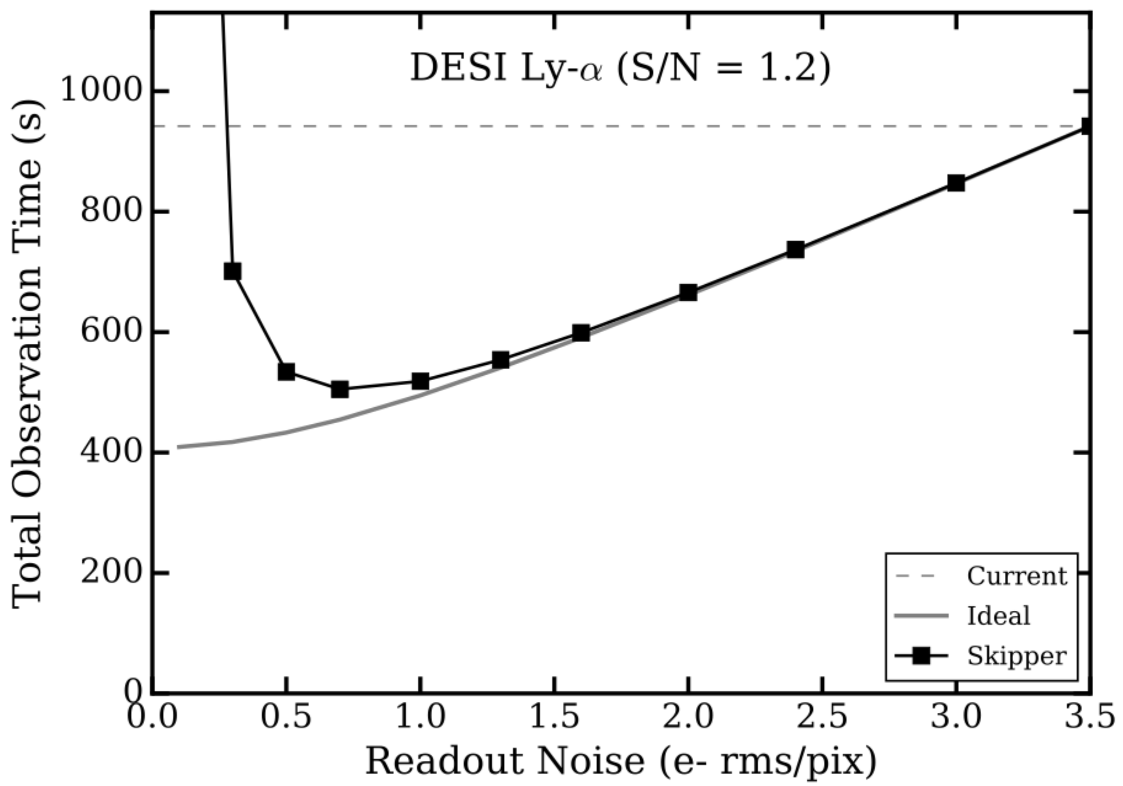
First results: 1.55 electrons rms/pixel

Now optimizing voltages and timing!

MAS-CCD for astrophysics

- Identified as a candidate detector for DESI-II, Spec-5 survey, ~10^8 extragalactic redshifts
- Pilot of Skipper CCDs for cosmology on CTIO SOAR integral field spectrograph early 2024 [arXiv:2311.00813]



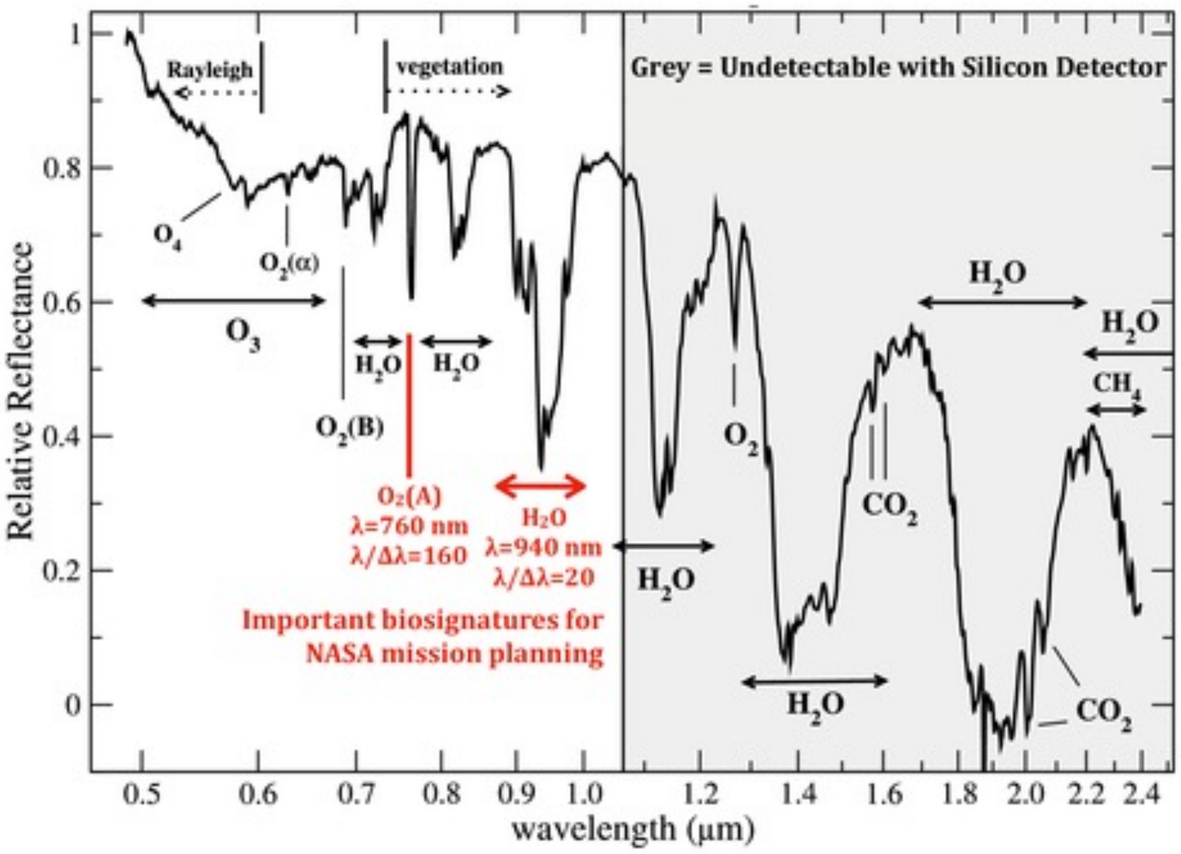


arXiv:2103.07527

Snowmass 2021 CF6 Report

MAS-CCD for astrophysics

Earth's reflectance spectrum model



B. Rauscher (NASA)

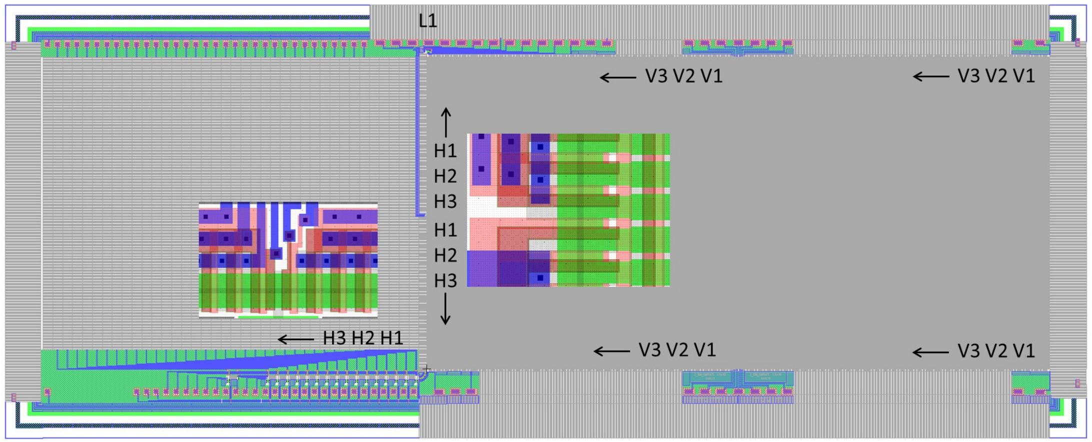
Candidate for next NASA flagship mission as endorsed by *Astro 2020 Decadal Survey*:

HABITABLE WORLDS OBSERVATORY

– Passive cooling: no requirement for cryocooler
– p-channel CCD radiation tolerance
– Excellent QE extending into near-IR for key biosignature markers in exoplanet atmospheres

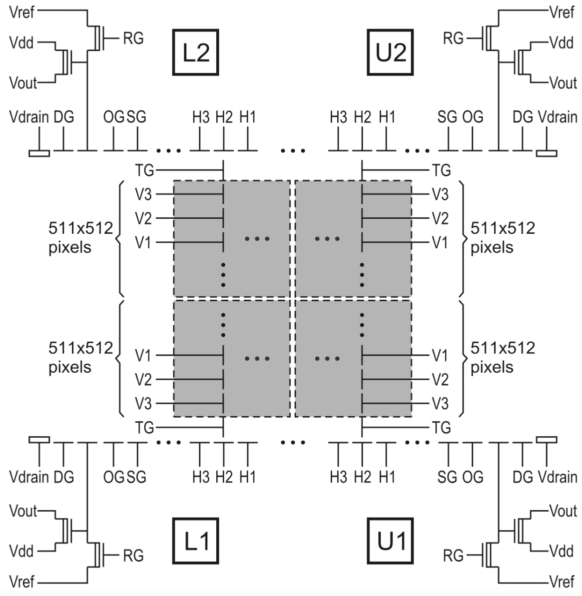
Future MAS-CCD development

- Goal: 4k x 4k with $\sigma_M \lesssim$ 1e-/pixel at < 15 μs/pixel
- Planned and under development
  - 4 corner readout structure
    Supported by Heising-Simons Foundation
    (PI Alex Drlica-Wagner)
  - Large-format active area with 64-channel readout electronics
    Supported by LBNL LDRD
  - Fast readout electronics for massive multiplexing
    Supported by DOE/Fermilab & LBNL LDRD



QIS MAS CCD layout

Steve Holland (2023)



Skipper 4-corner readout

Figure from Fernández Moroni (2011)

BERKELEY LAB Fermilab Berkeley UNIVERSITY OF CALIFORNIA HEISING-SIMONS FOUNDATION

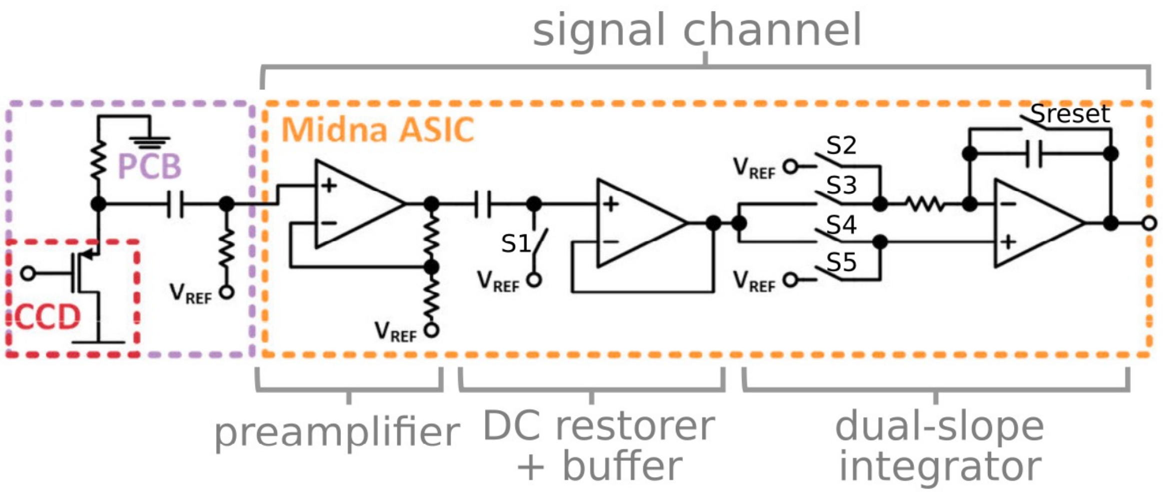
Summary & outlook

- Results for 4-channel tests are extremely promising
  - Promising sub-electron readout noise sensor for future spectroscopic surveys, astronomical instrumentation, space telescopes
- Optimization: reducing noise per amplifier with Hydra (16-ch) readout system
- Another complementary effort at Fermilab
  - Optical characterization of thinned (250 μm), back-illuminated, AR-coated devices
  - Testing the MIDNA ASIC readout solution
  - Package development
- Progress underway for compact 4-corner MAS CCD layout with 4k x 4k format at LBNL
- Planning for future radiation tolerance testing
- See talk tomorrow by Blas Irigoyen (Session RDC1+2+7) for more on our joint efforts

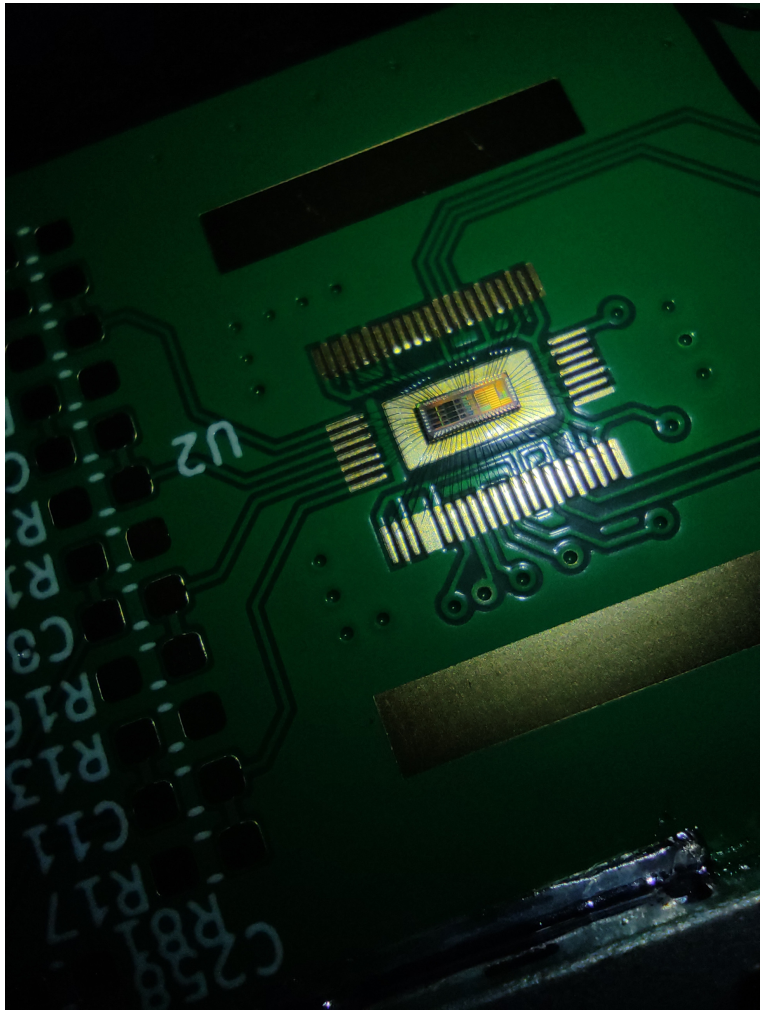
Extra slides

MIDNA as a scalable readout solution

- ASIC readout chip for Skipper CCDs based on TSMC 65 nm CMOS process
- Dimensions: 2 mm x 1 mm
- Operational under cryogenic conditions
- 4 channels each with: low-noise preamp, DC restorer, dual-slope integrator

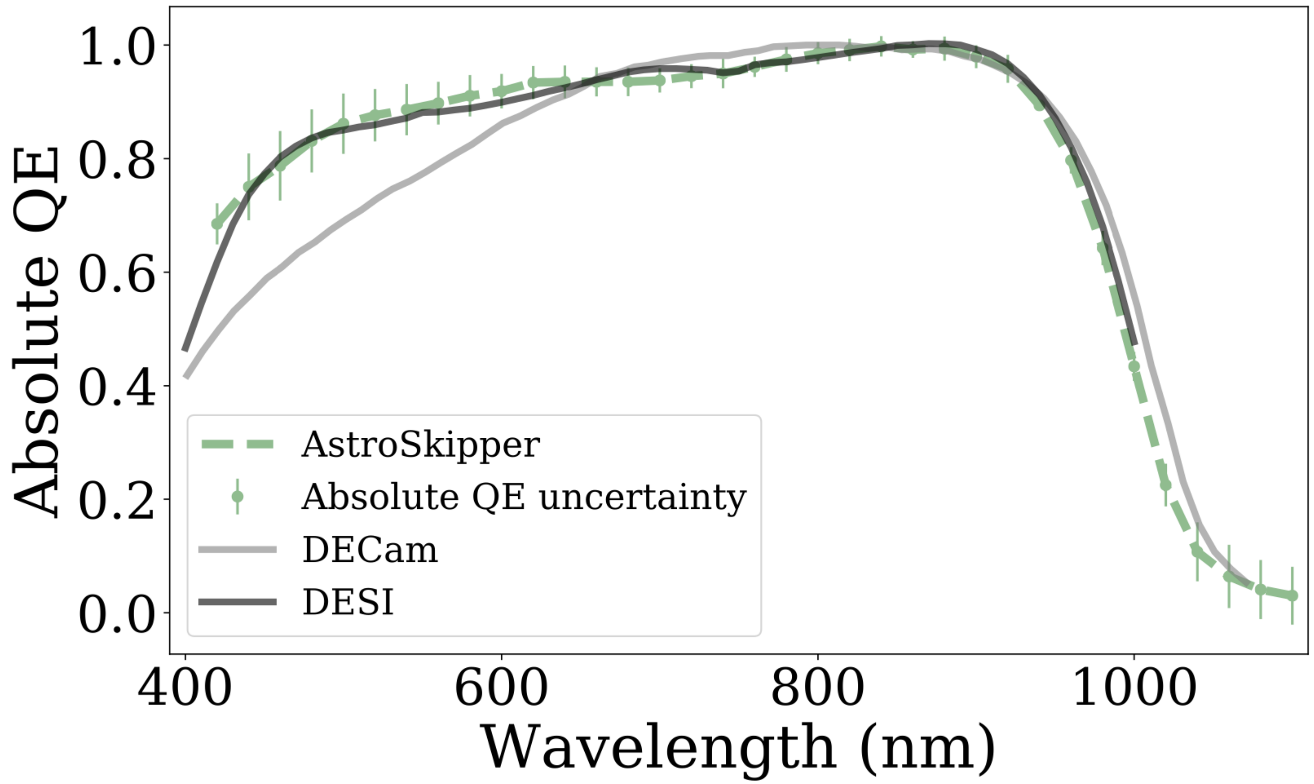


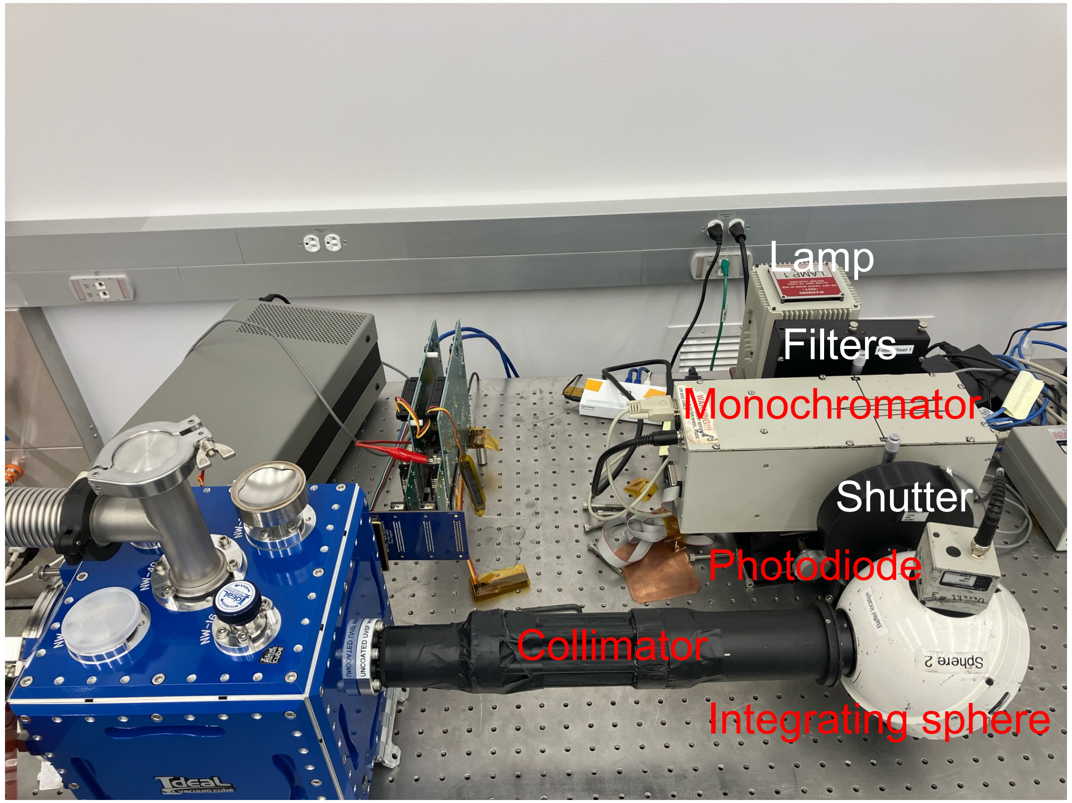
F. Bessia (FNAL/CONICET)



C. Chavez (FNAL)

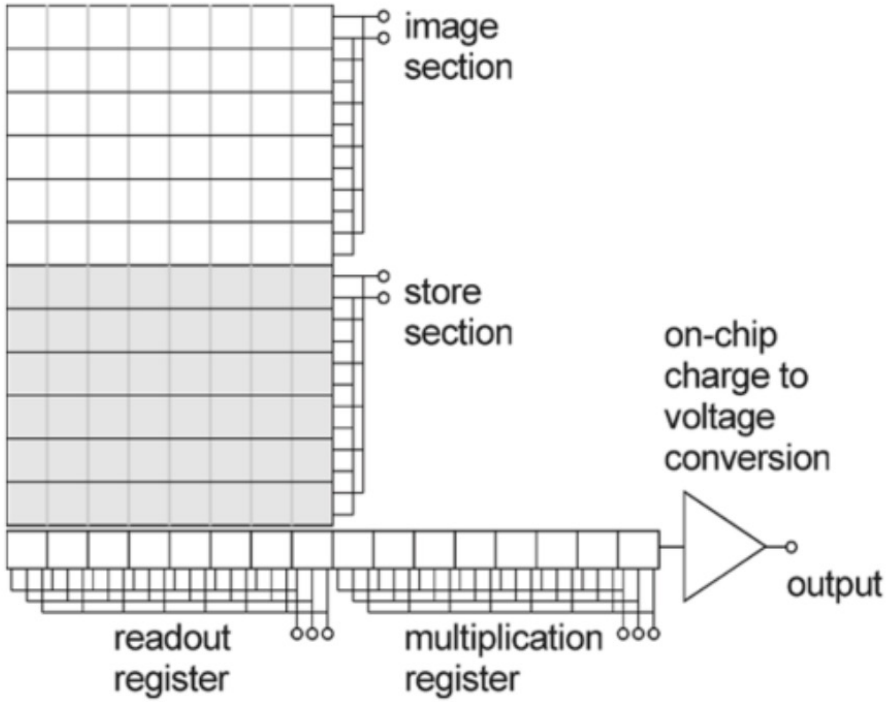
Quantum efficiency of Astro Skipper





arXiv:2311.00813

MAS CCD vs. EM-CCD



Tutt et al. (2011)

- Multiplication gain increases all signal levels – cannot tell between electrons generated from photon detection and clock-induced charge (spurious charge)
- Magnitude of multiplication gain highly sensitive to temperature (Tutt et al. 2011)
- Energy resolution degradation from stochastic nature of multiplication gain