FERMILAB-SLIDES-24-0128-V

Astronomical Spectroscopy with Skipper CCDs: First Results from a Skipper CCD Focal Plane Prototype at SIFS

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Fermilab

THE UNIVERSITY OF CHICAGO

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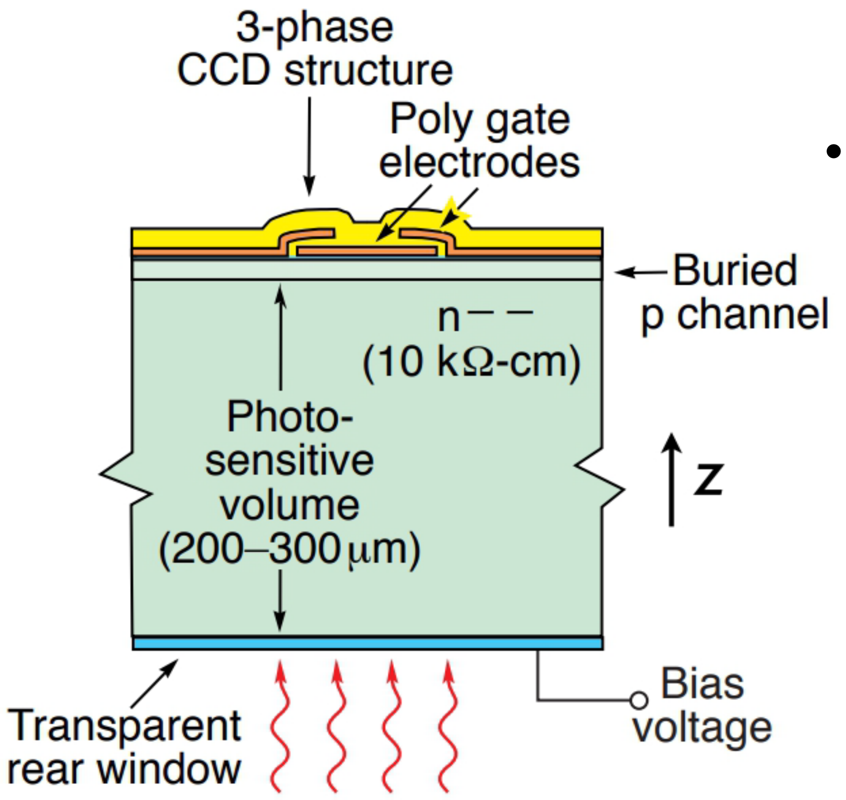
- Skipper CCDs

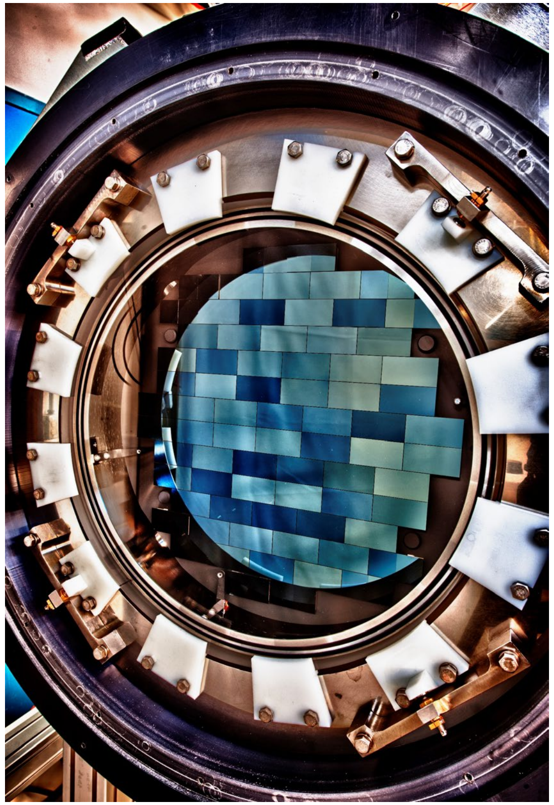
Charge-Coupled Devices (CCDs)

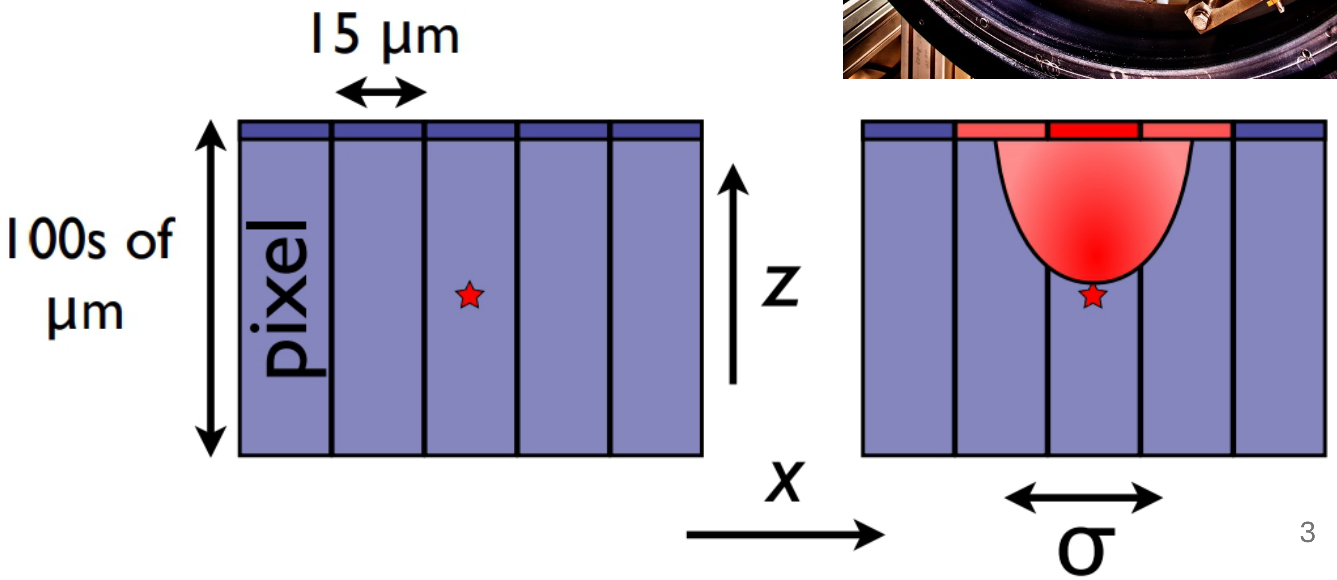
CCDs: Metal-Oxide-Semiconductor capacitors.



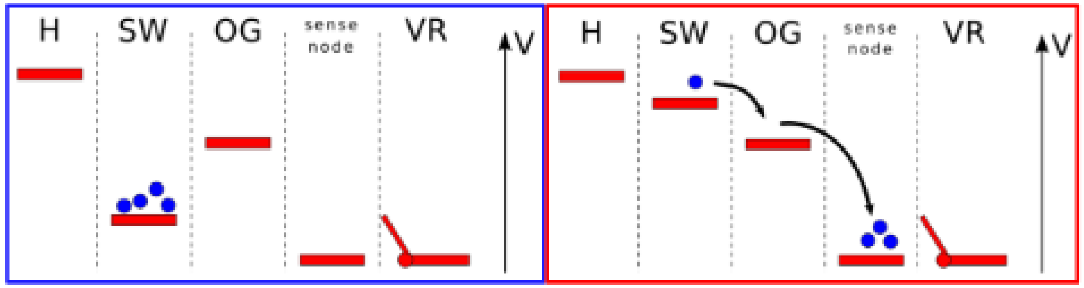
- Radiation interacting in the Si substrate (photoelectric effect) produces electron-hole pairs

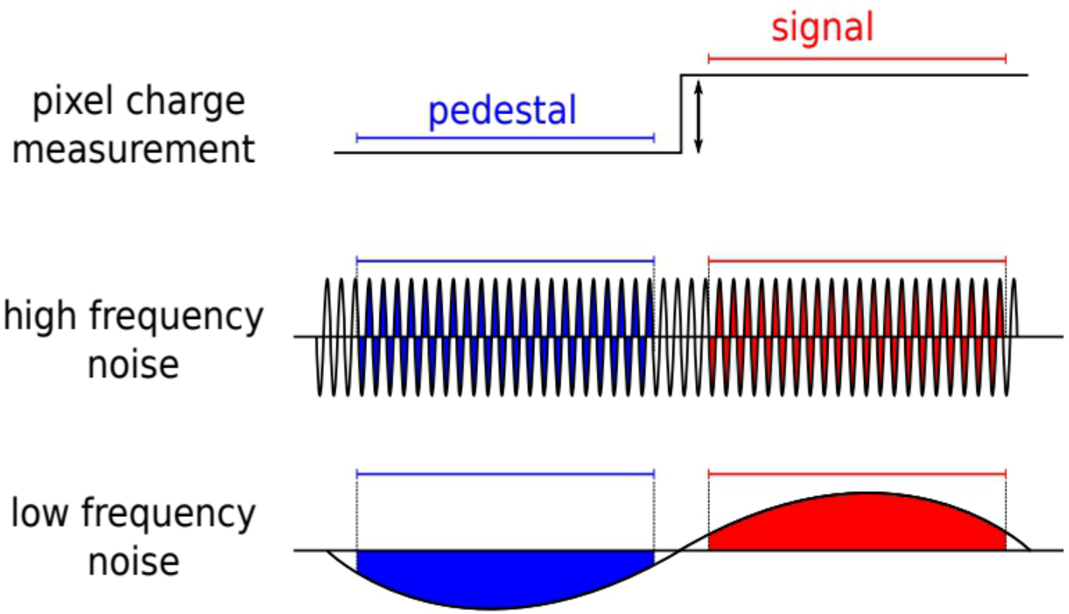
- Charge is collected near the surface by applying V_{Sub}





CCD Readout





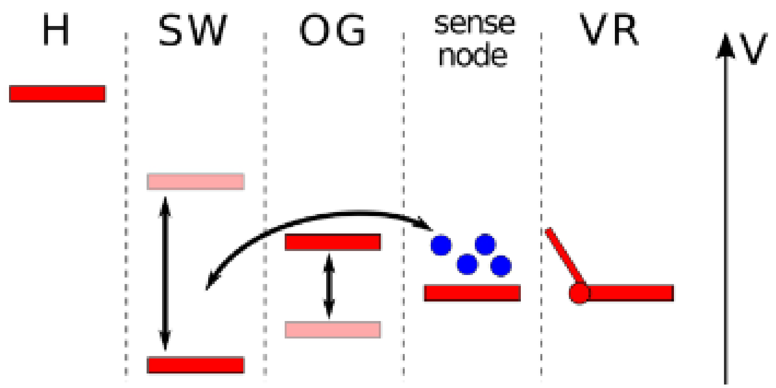
Correlated Double Sampling:

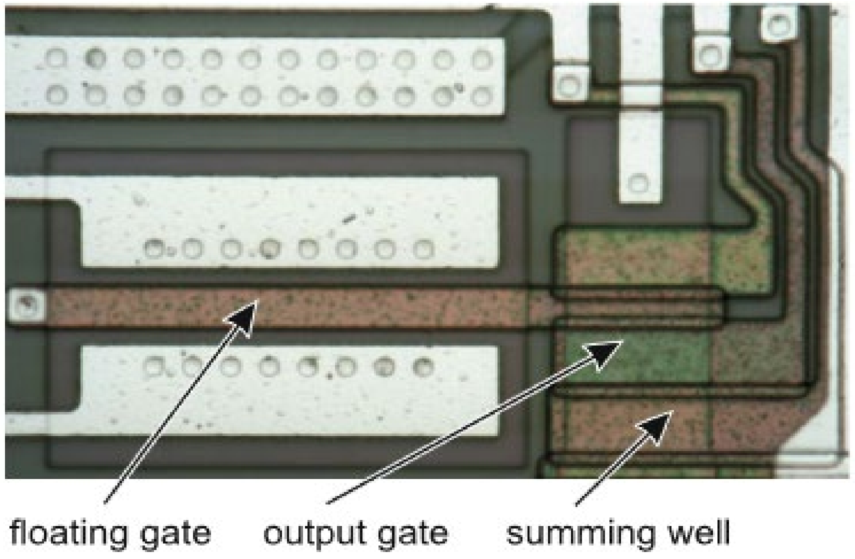
1. Pedestal integration
2. Signal integration
3. Charge = Signal-Pedestal

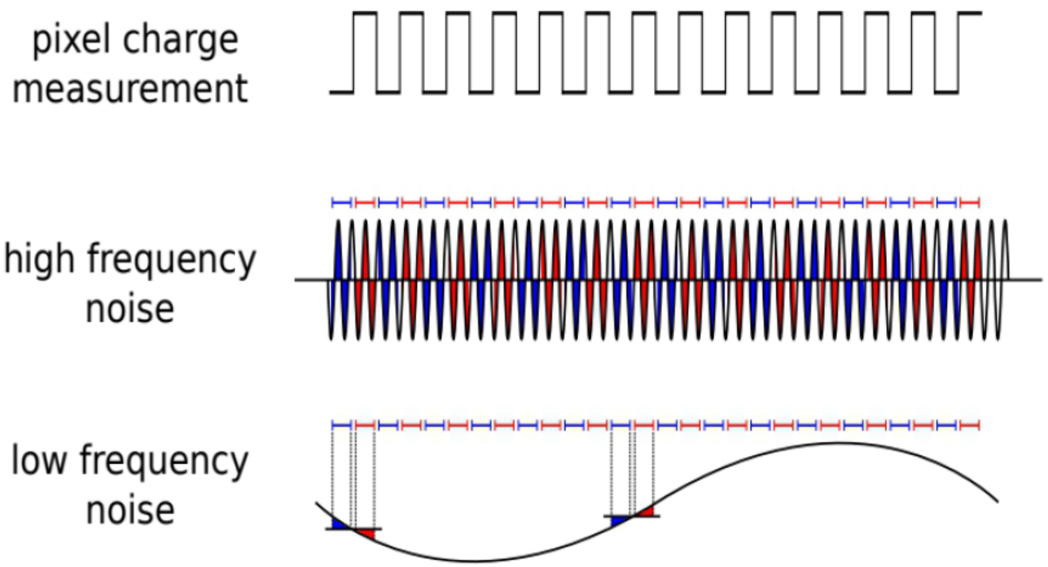
$$P_i = \frac{1}{t_i}\left(\int_{t_i+\tau}^{2t_i+\tau} x(t)dt - \int_0^{t_i} x(t)dt\right)$$

Still sensitive to low frequency noise

Skipper CCD Readout



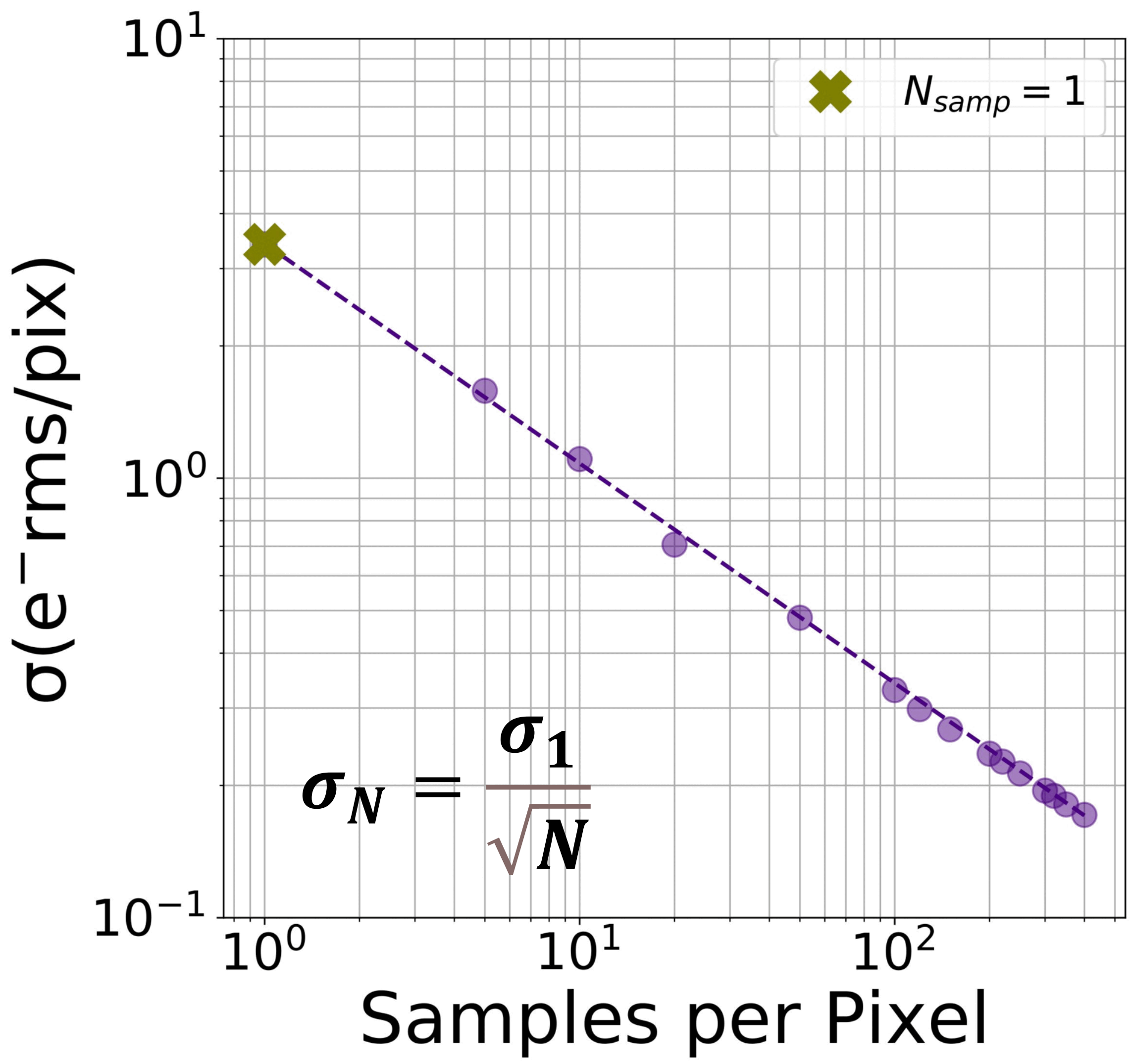


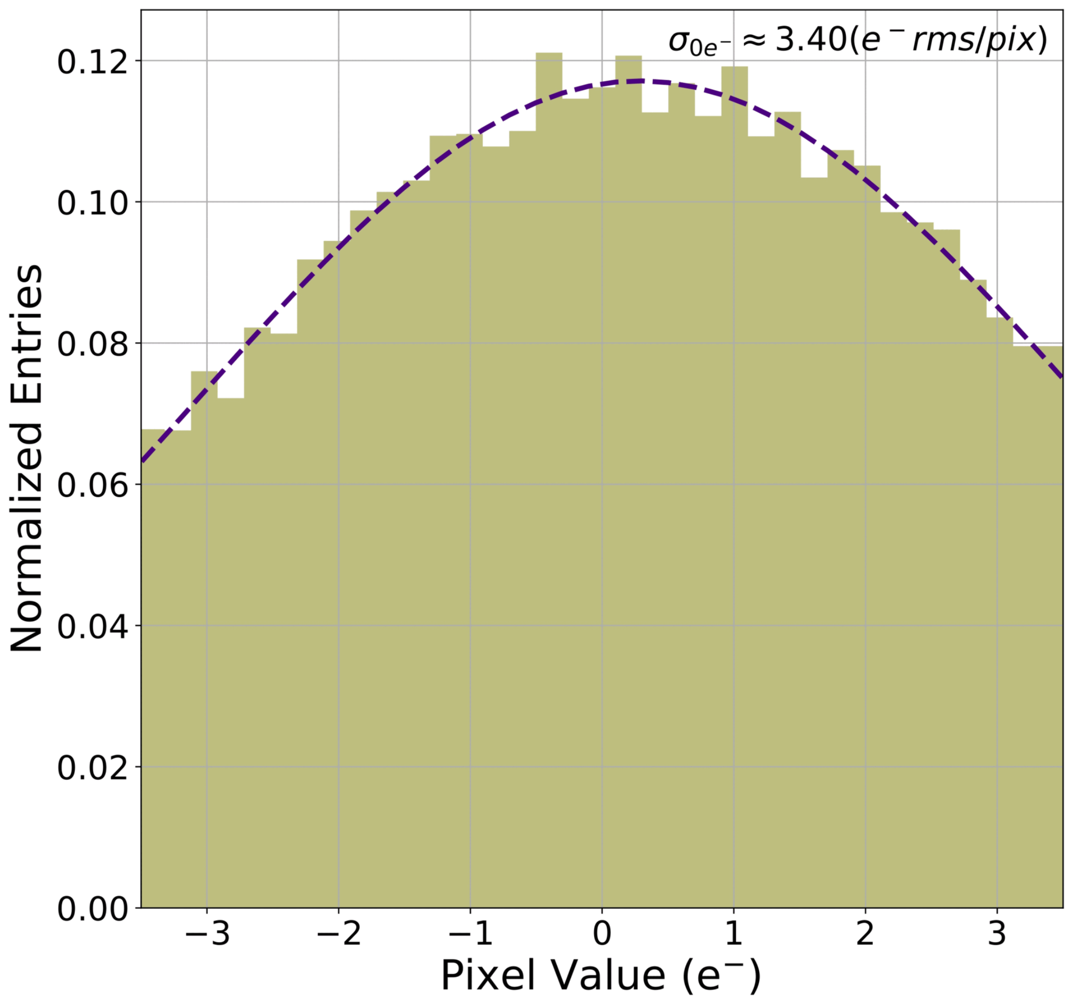


1. Pedestal integration
2. Signal integration
3. Charge = Signal-Pedestal
4. Repeat N times
5. Pixel Value = average of all N samples

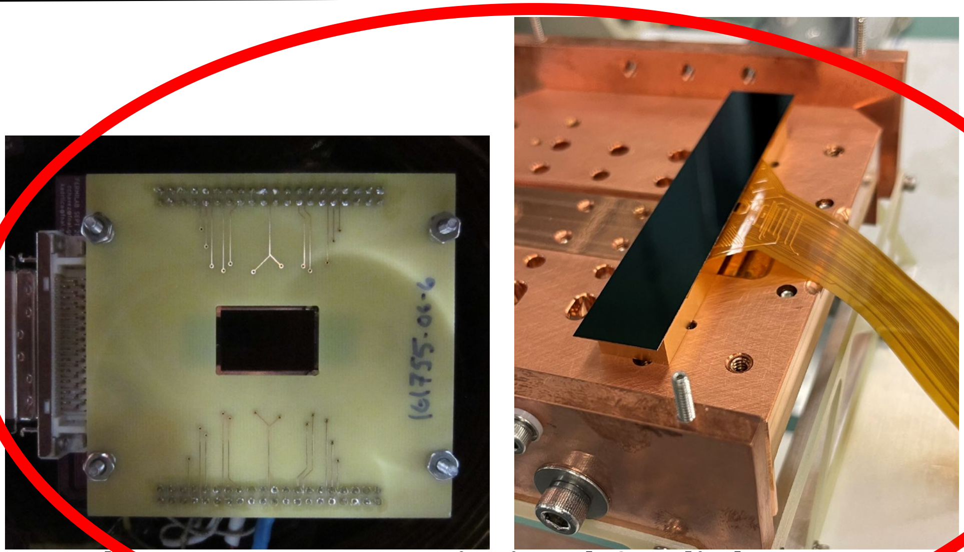
Low frequency noise is reduced by the averaging of samples

Skipper CCD Readout

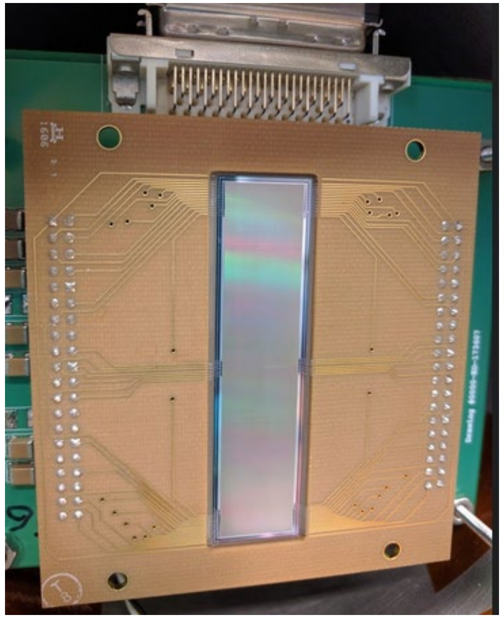


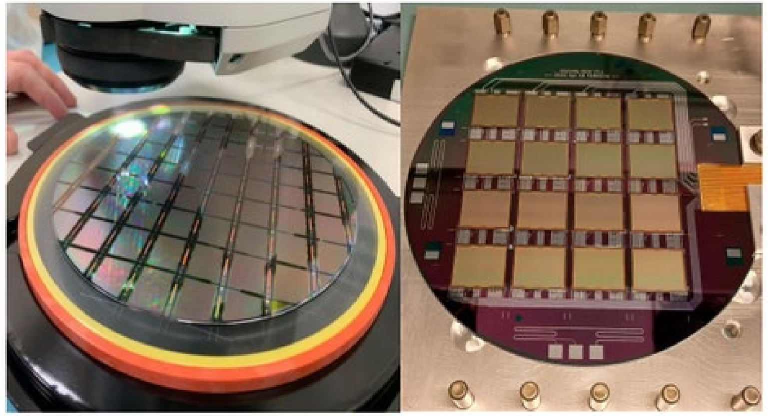


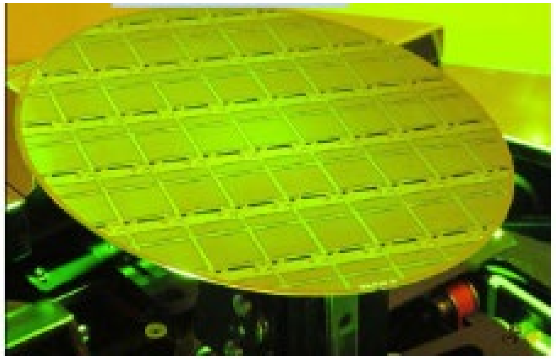
Skipper CCDs



Skipper CCDs optimized for light detection (Astronomy-NUV/O/NIR)

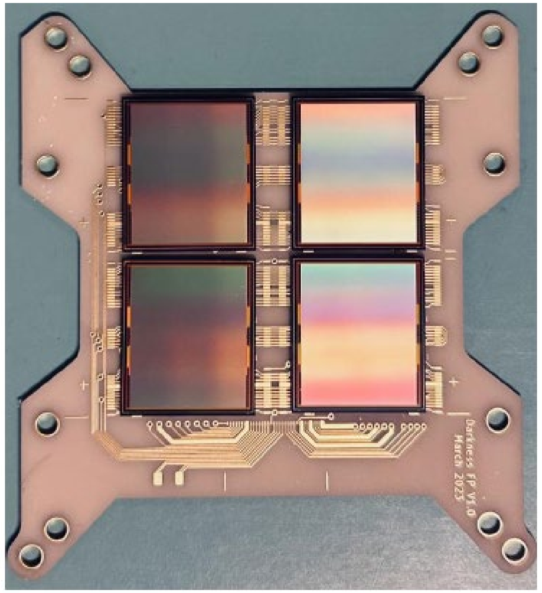






Skipper CCDs for rare particle searches (dark matter detection)

Leveraging Skipper CCD technology to enable scientific breakthroughs

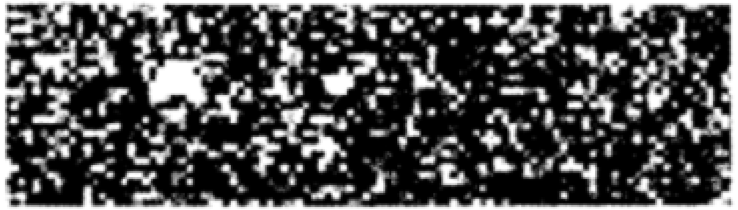


Skipper CCDs as X-ray detectors in space (CubeSat)

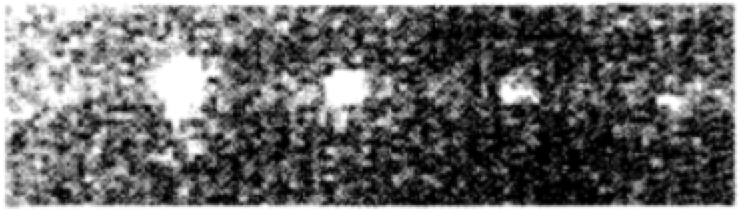
Skipper CCDs for Astronomy: History

Skipper CCD Development

The ultimate test for the Skipper CCD, yet to be achieved, is to detect the single photo-electron. Skipper cameras have been constructed which employ ultra high gain, in excess of 100 ADC counts per electron. Assuming that the noise can be lowered to 0.2 e- rms using multiple sampling, there is no fundamental reason why the photo-electron can't be detected. It will be interesting to see if the CCD can accomplish this feat in the near future.



READ NOISE = 7.6 e⁻ rms

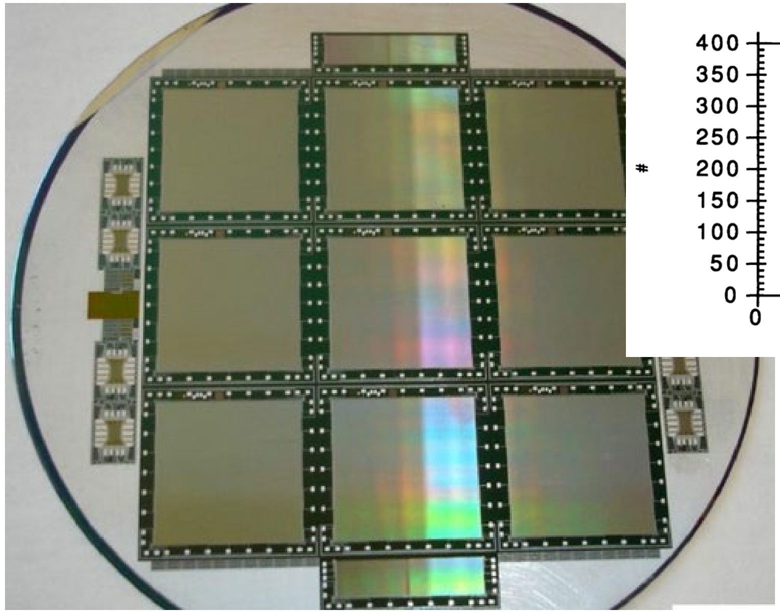


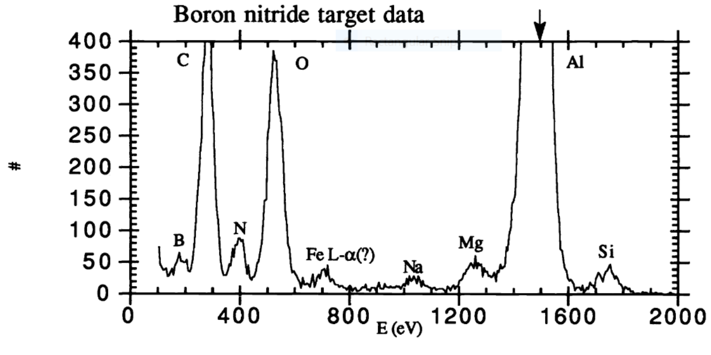
READ NOISE = 0.97 e⁻ rms

N_s = 64

[1990ASPC....8...18J]

Cosmic Unresolved X-ray Background Instrument Using CCDs (CUBIC) (NSA-CUBIC: 1994)





https://doi.org/10.1117/12.162838

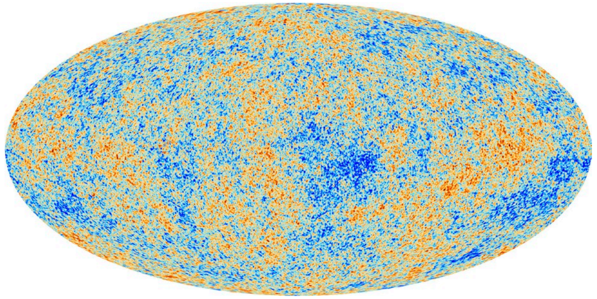
Each CCD has four amplifiers; two standard floating diffusion amplifiers, and two floating gate amplifiers ("skipper" amplifiers). As *CUBIC* will not use the floating gate amplifiers, we have concentrated our testing on the diffusion amplifiers.

- Applications in Cosmology

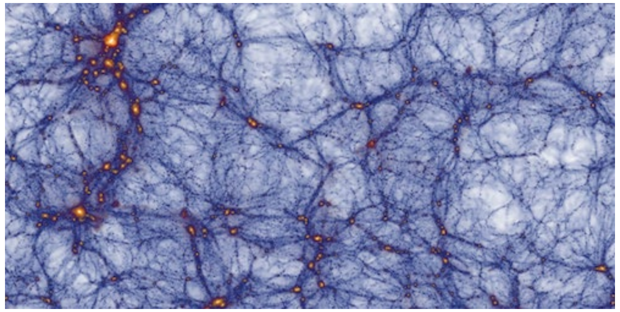
Dark Matter Measurements: A Cosmological Perspective

Dark Matter

Observable Universe

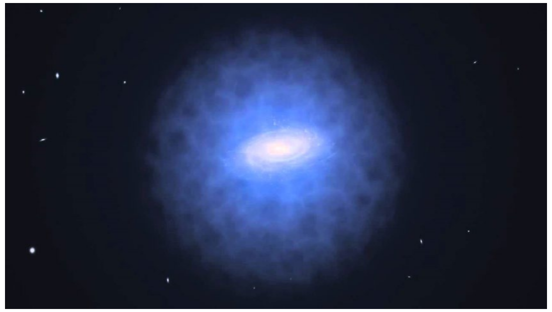


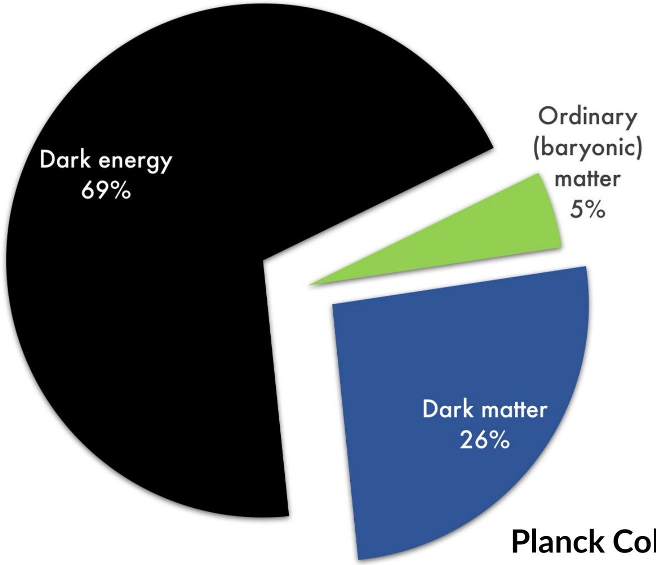
Large Scale Structure



Galaxy Clusters

Galaxy

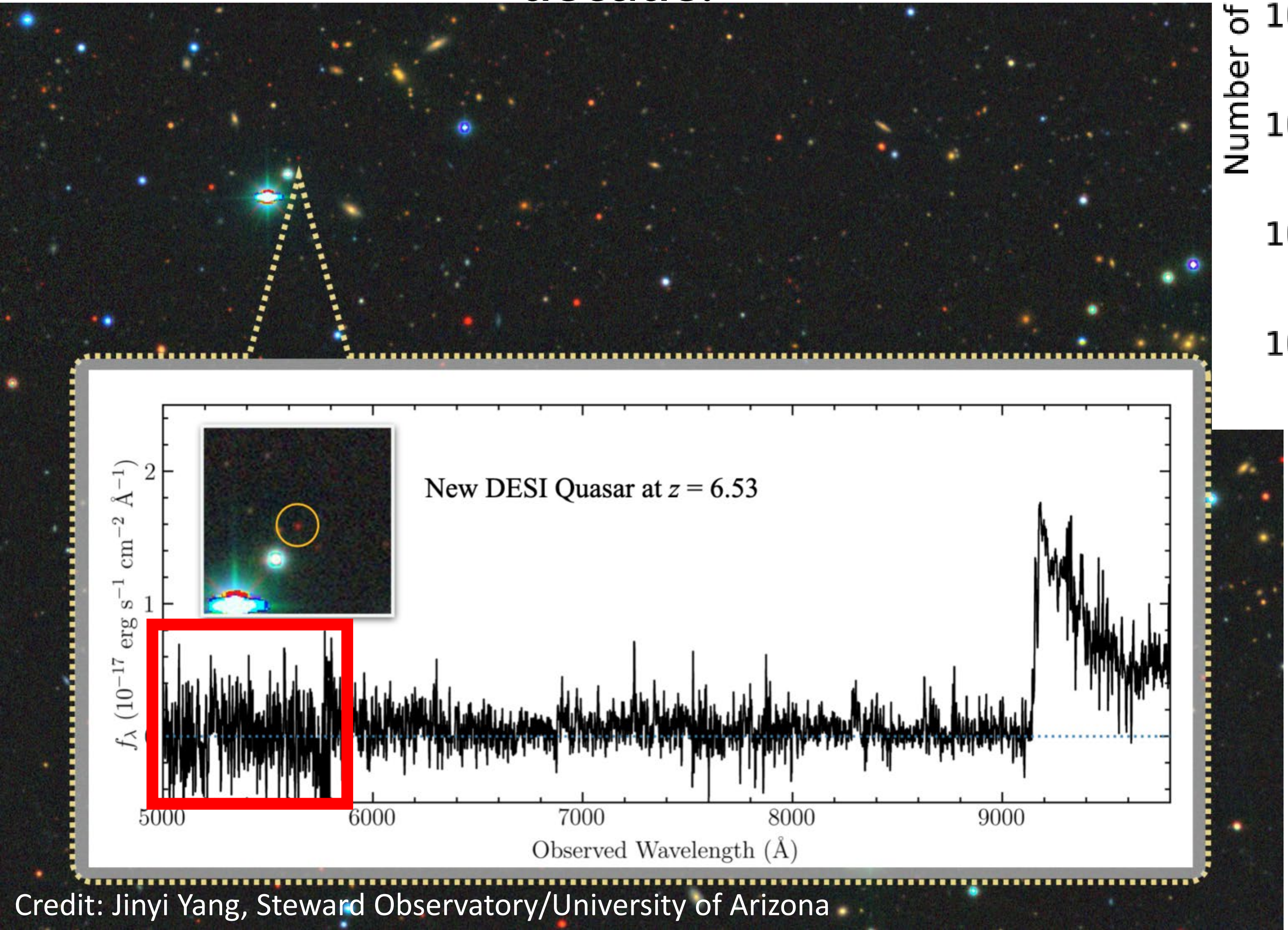




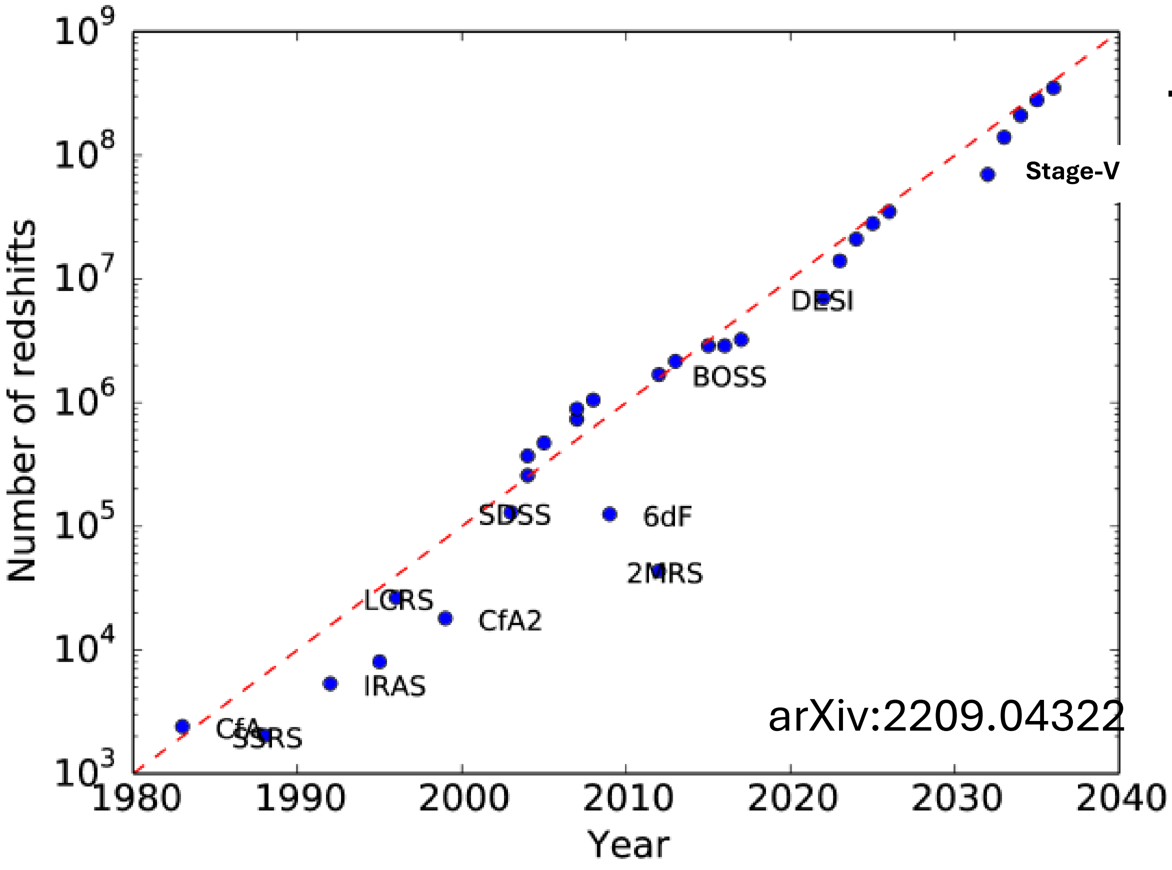
Planck Collaboration 2008

Improved Detector Technology for Cosmic Surveys

Spectroscopic survey speed has increased by a factor of 10 each decade.



Credit: Jinyi Yang, Steward Observatory/University of Arizona



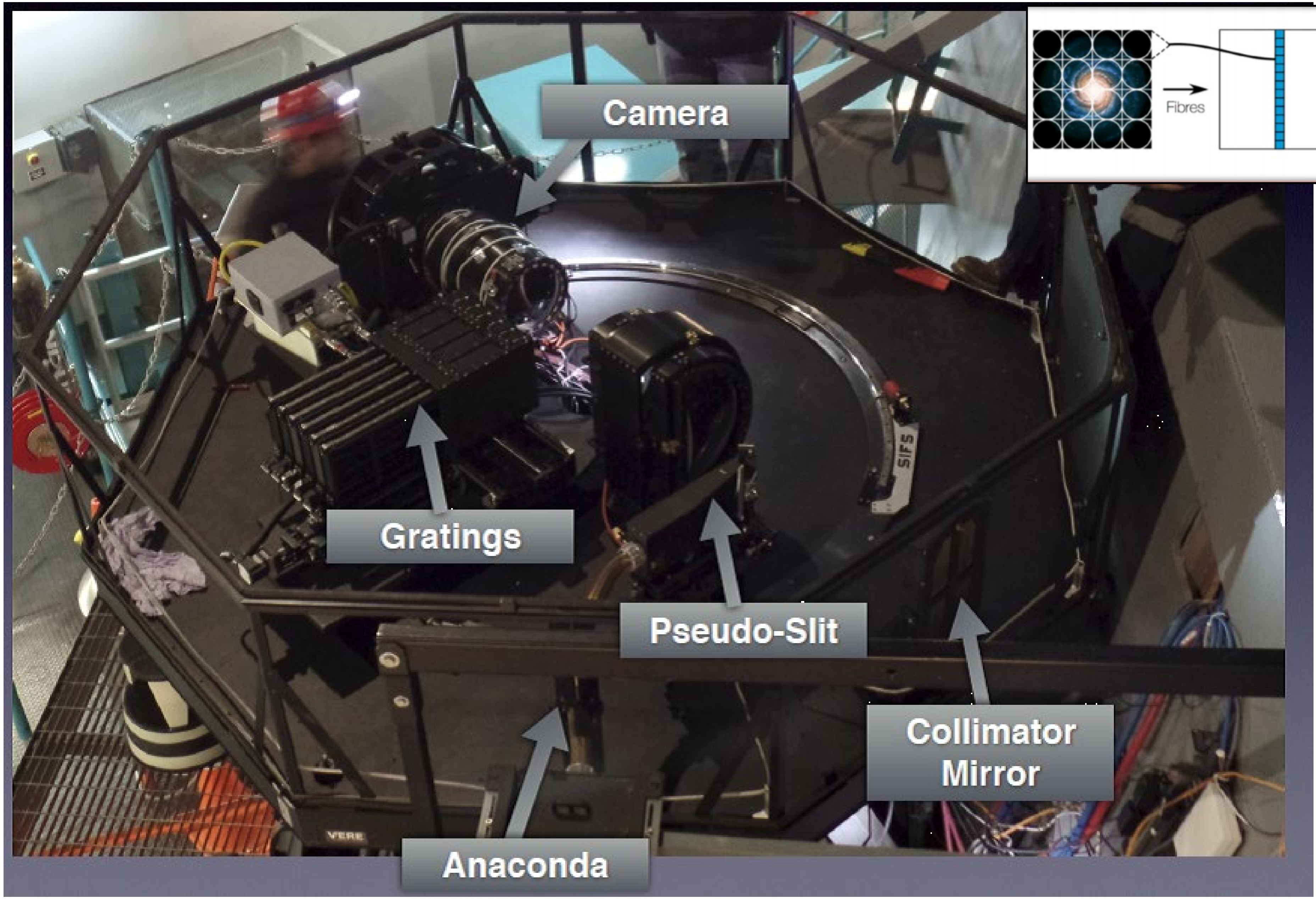
Future spectroscopic surveys (e.g., DESI-2 and a Stage-5 Spectroscopic Survey) need to be sensitive to fainter objects, particularly at blue wavelengths (Lyman-break galaxies and Lyman-alpha emitters at redshift 2 < z < 5).

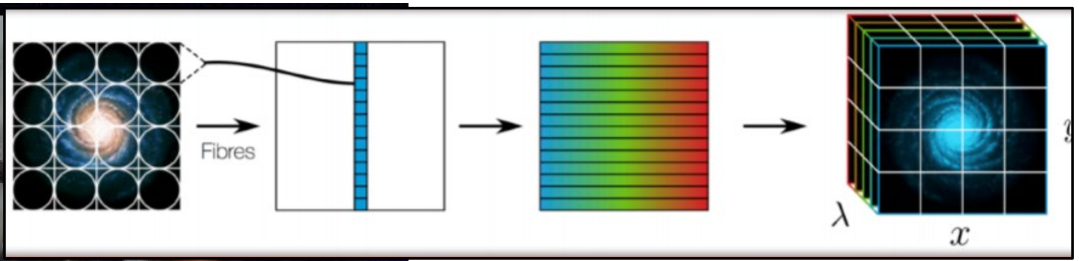
- Astronomy-optimized Skipper CCDs

A Skipper CCD Prototype for SOAR

- Demonstrate the performance of the Skipper CCD in real observing scenarios.
- Verify that Skipper CCDs retain the desirable characteristics of thick, p-channel, fully depleted astronomy-grade CCDs.
- Develop tools for optimizing signal-to-noise and readout time for the Skipper CCD.
- Develop analysis tools for astronomical data collected with Skipper CCDs.
- Demonstrate the ability to do astronomy with Skipper CCDs in the low-signal, low-background regime.

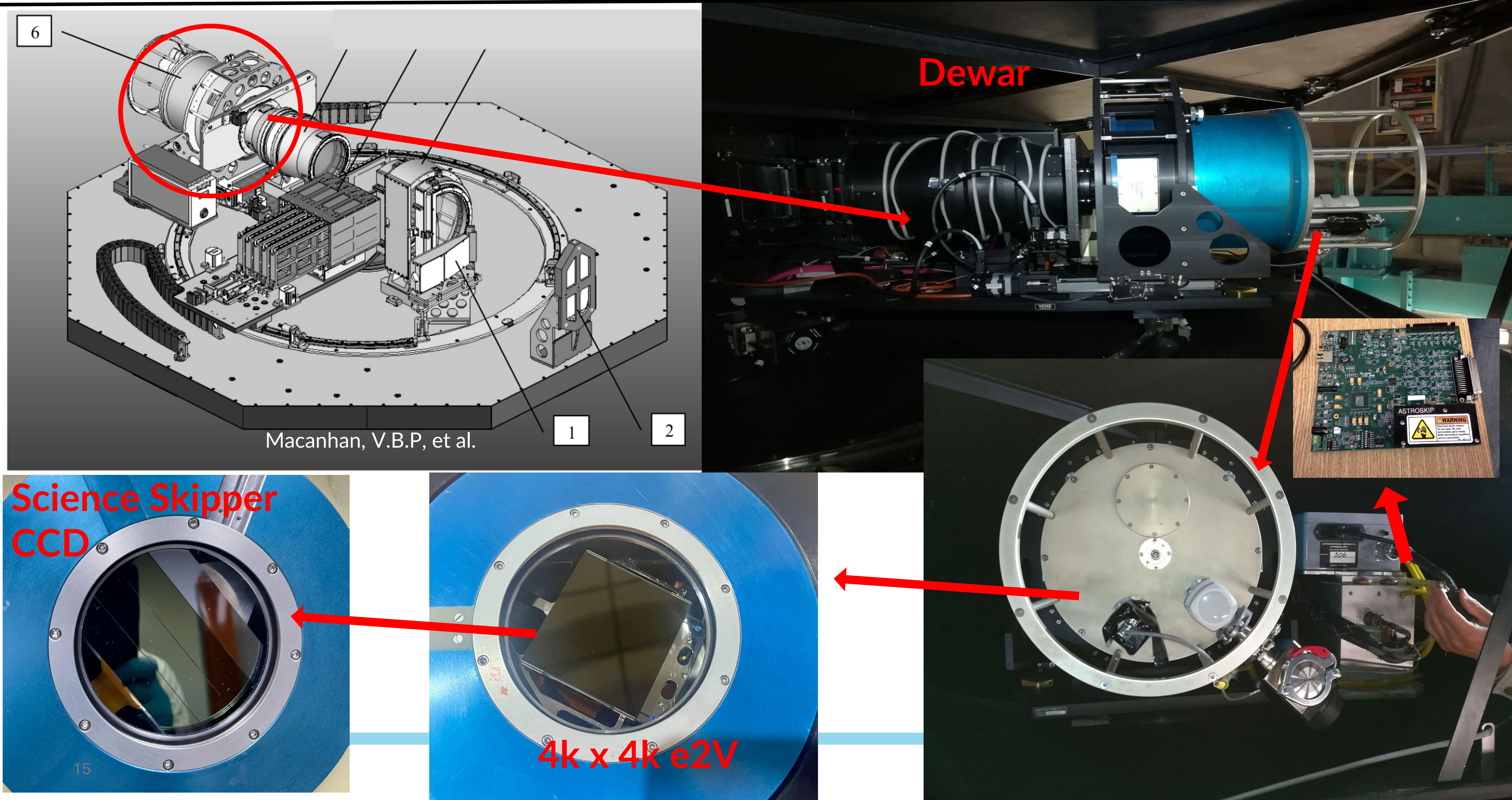
The SOAR Integral Field Spectrograph (SIFS)





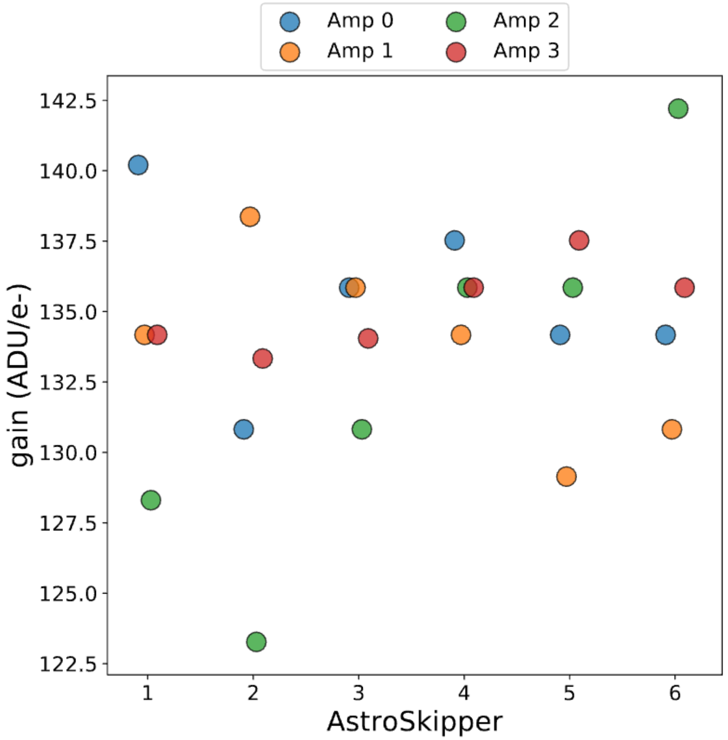
- 2D array of 1300 fiber lenslets subtending a 15”x7.8” field of view
- Fibers re-arranged into a pseudo slit at the spectrograph entrance
- Modular instrument design; only need to replace the dewar holding the detector
- Chosen primarily due to availability and convenience

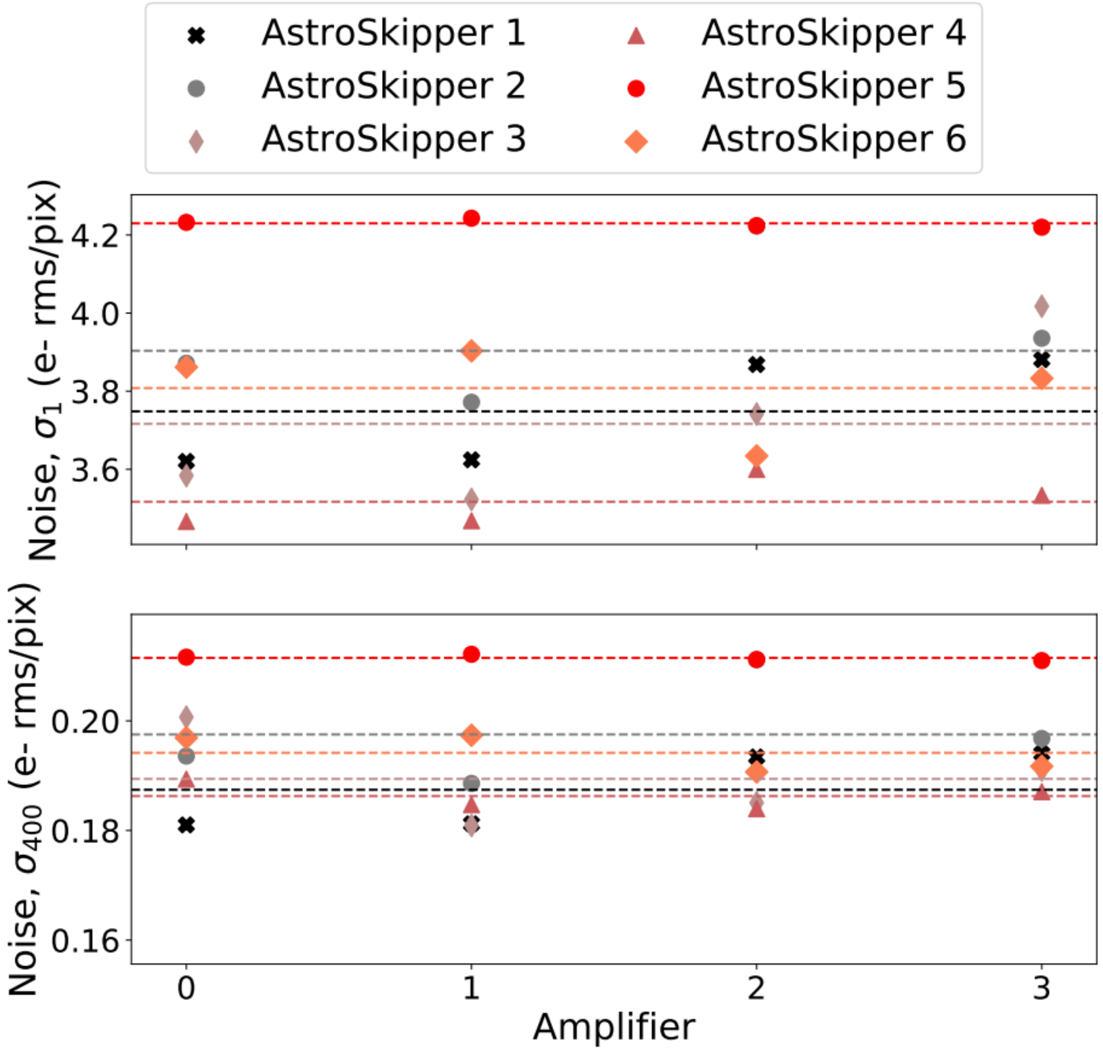
Skipper CCD Focal Plane for SIFS



Skipper CCDs: Noise Characteristics

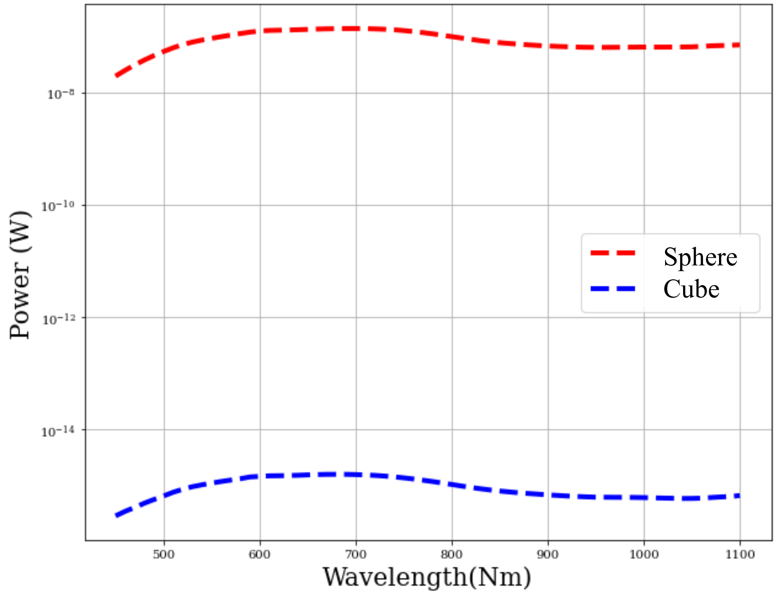
- Amplifier yield of 97%; detector yield of 75%.
- Performance is fairly stable across detectors and amplifiers.

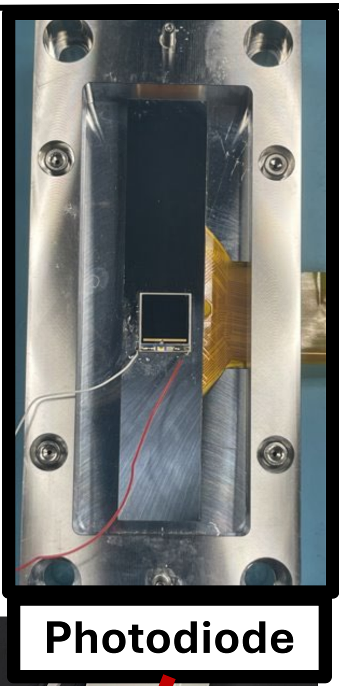


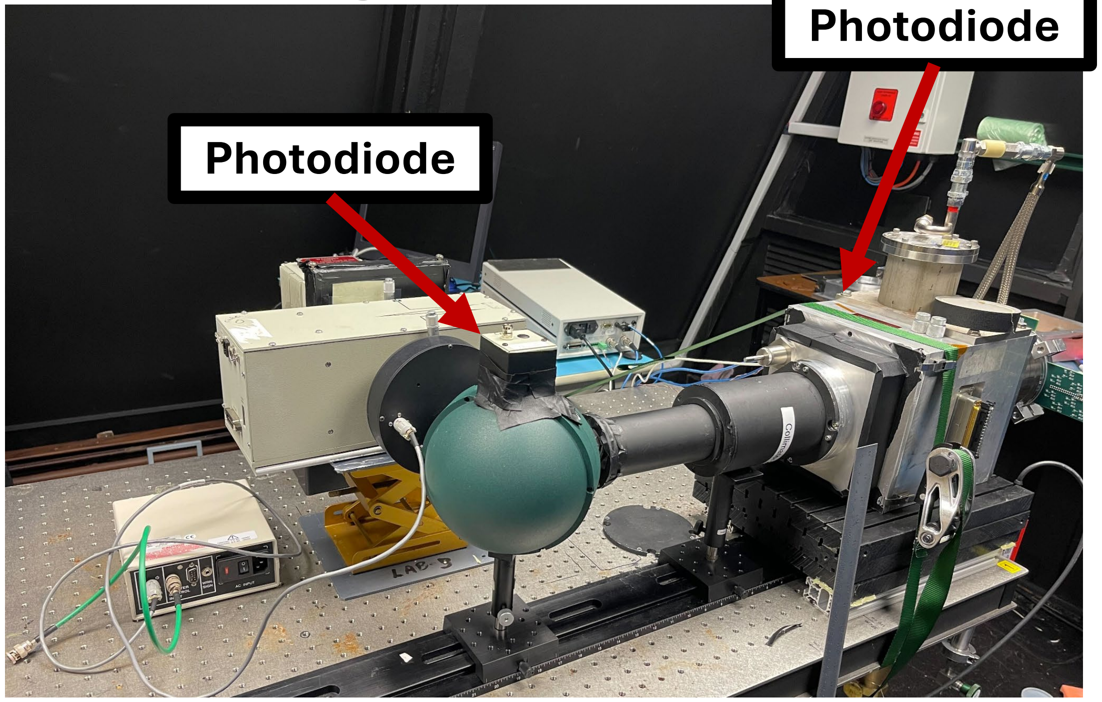


Skipper CCDs: Absolute Quantum Efficiency

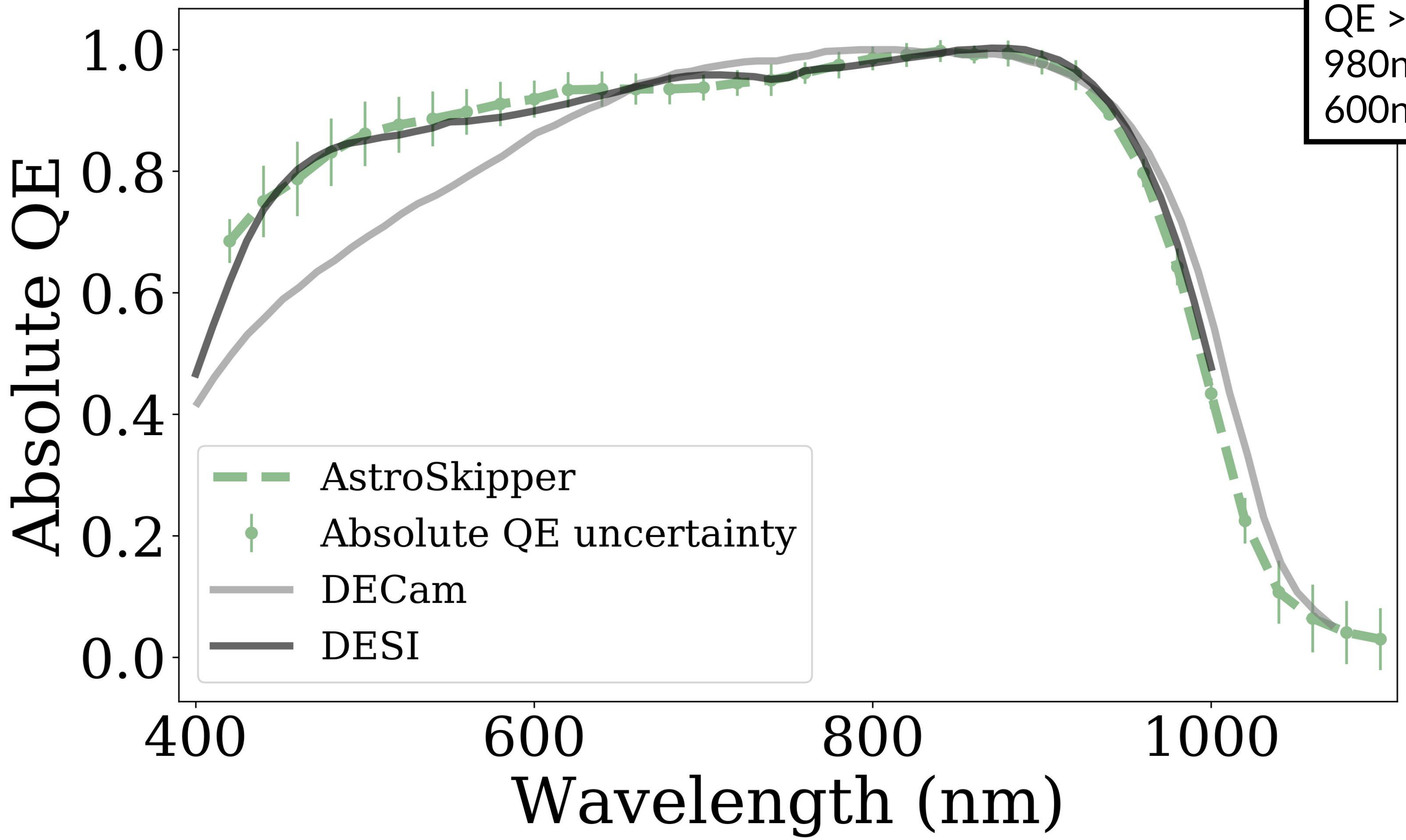
- Absolute QE measurements depend on a precise calibration of the incident power at the CCD (non-trivial).
- Instrumented testing system with two NIST-traceable photodiodes:
  - Mounted on integrating sphere
  - Mounted on an AstroSkipper package and put inside the vacuum chamber
- Cross-calibrate power measurement between both photodiodes:
  - Absolute calibration for “scaling” integrating sphere readings
  - Measurement repeatability







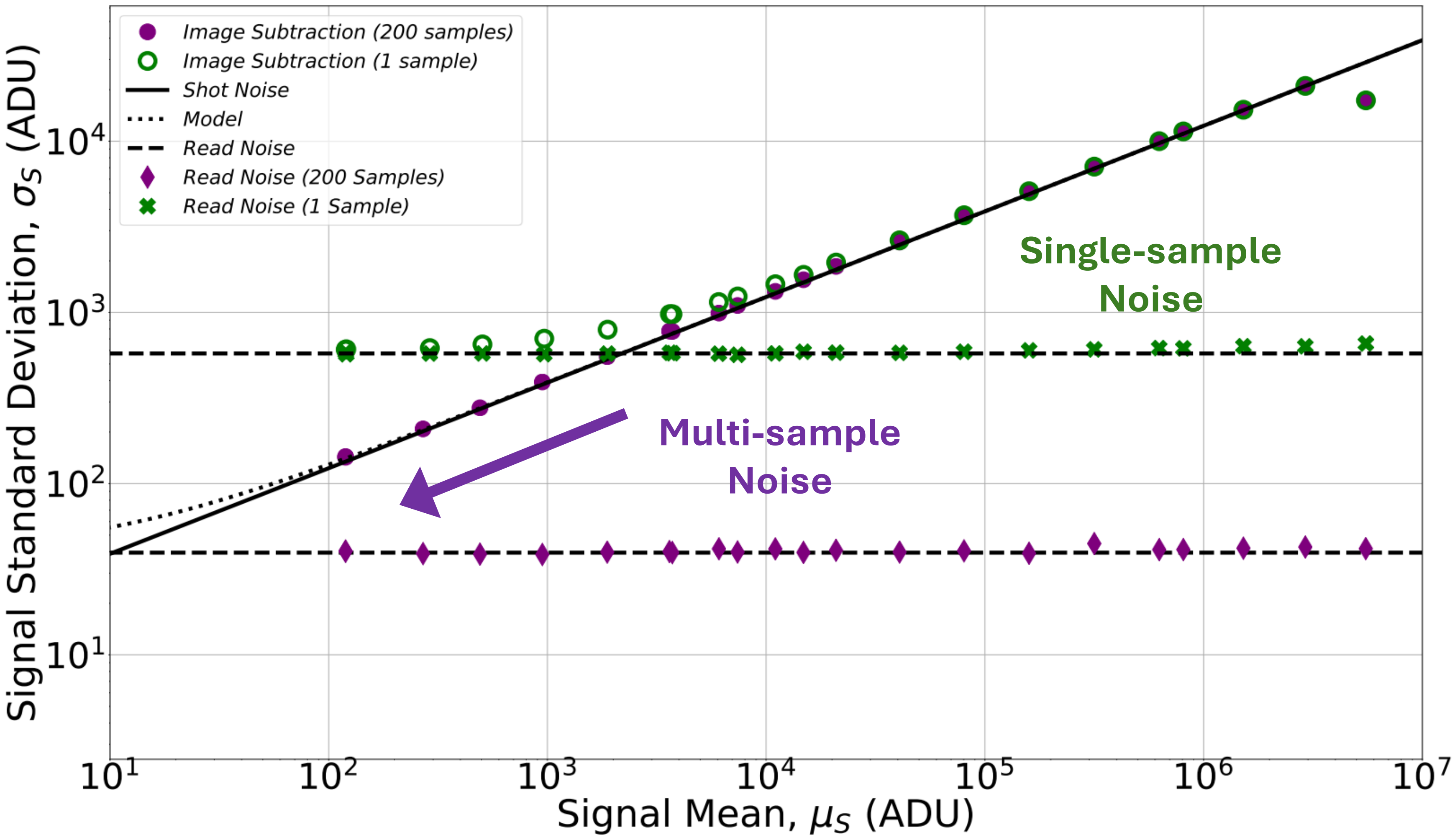
Skipper CCDs: Absolute Quantum Efficiency



QE > 80% for 450nm and 980nm, QE > 90% from 600nm to 900nm.

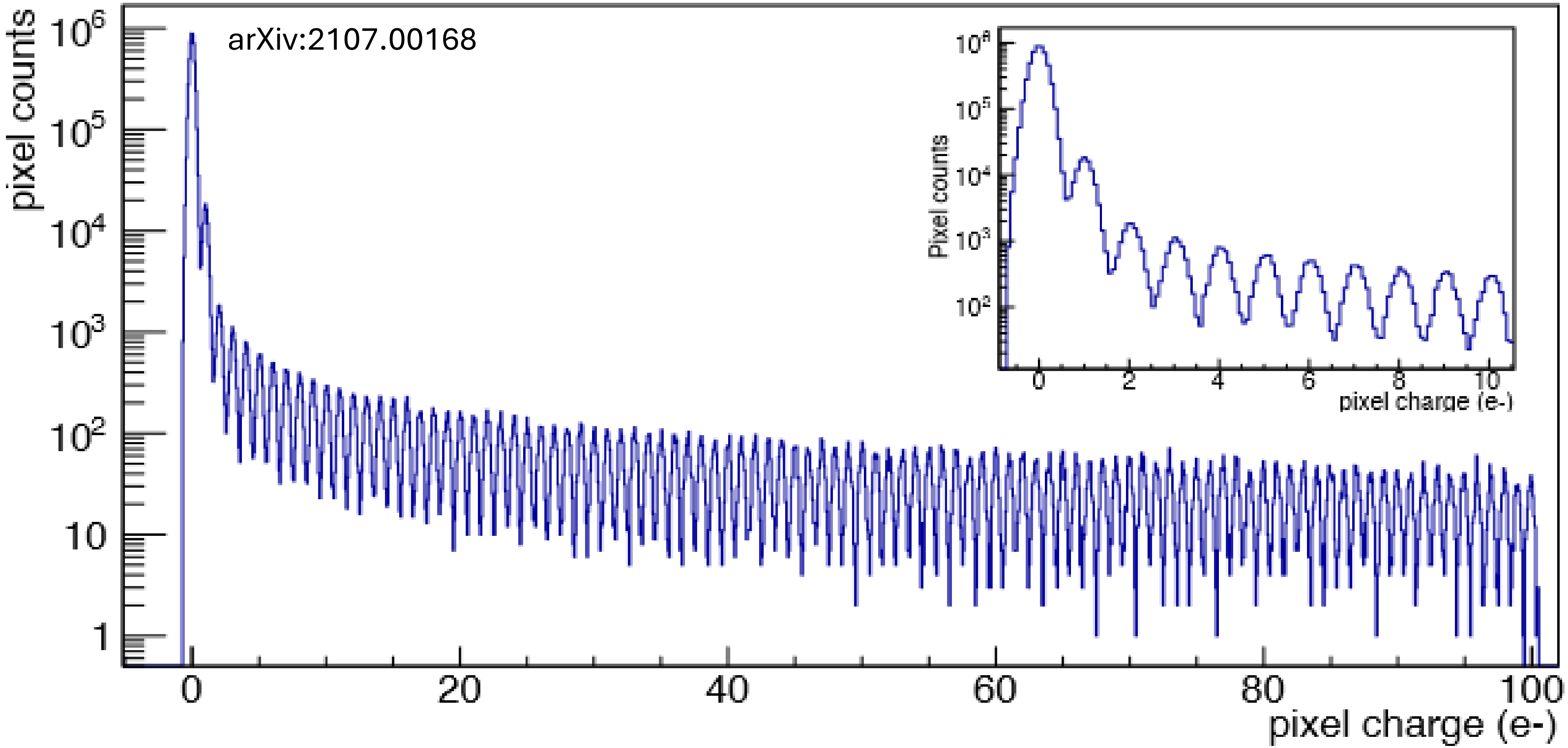
AstroSkippers retain the high QE of the thick, fully depleted DESI detectors from LBNL

Skipper CCDs: Photon Transfer Curves



AstroSkippers have linear behavior and allow you to dive below the noise floor.

Skipper CCDs: Direct Gain Measurements

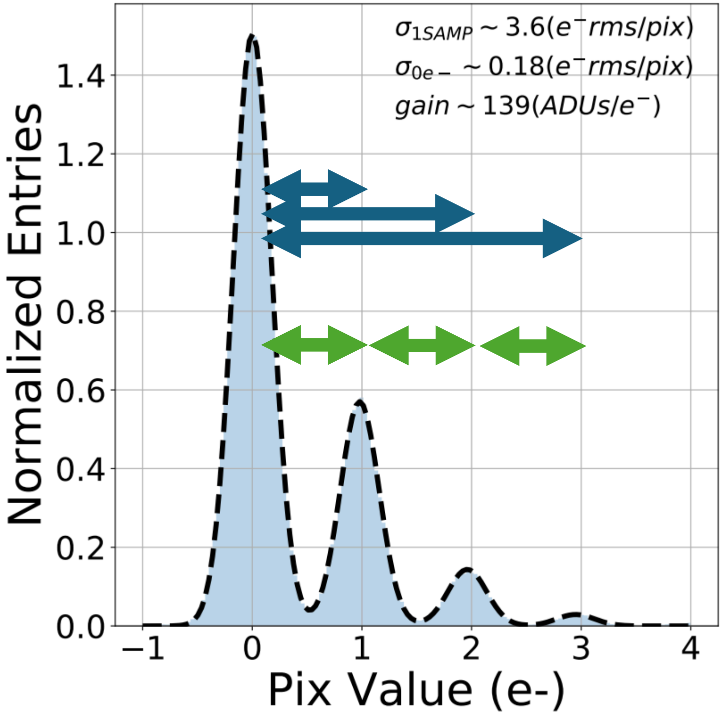


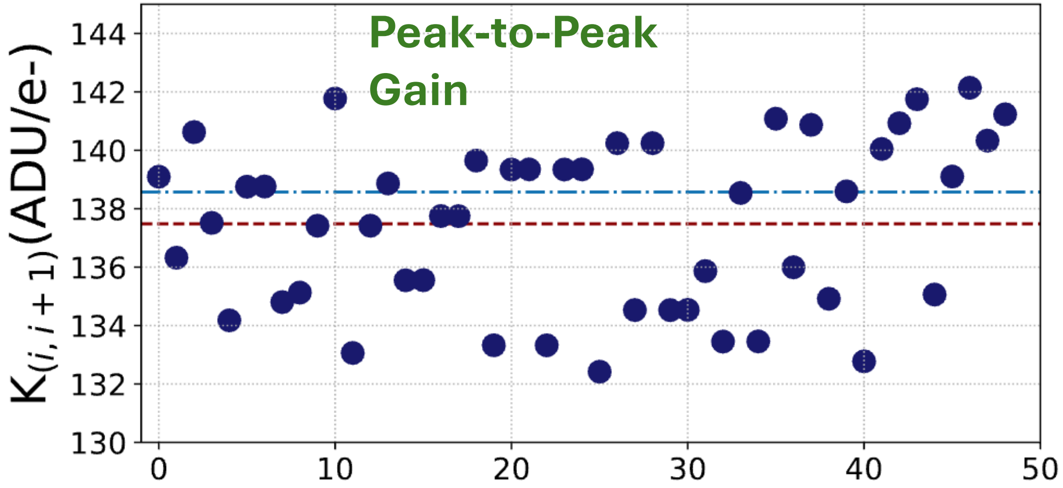
Photon counting allows direct gain measurements at low and high signal levels

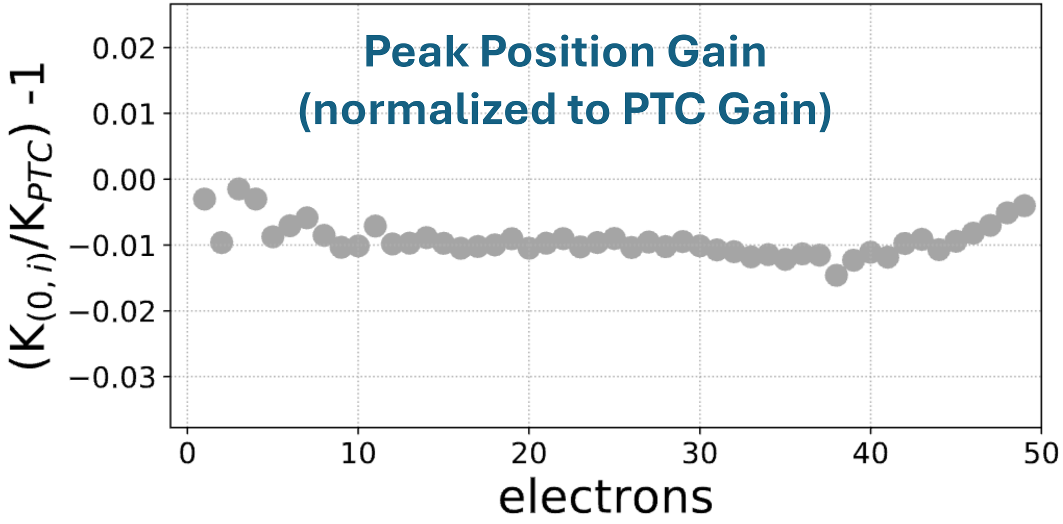
Skipper CCDs: Photon Counting and Low-Signal Linearity

- We can measure the gain from the peak-to-peak spacing $([\mu_i - \mu_{i-1}])$ or the position of the i^{th} peak $([\mu_i - \mu_0]/i)$.

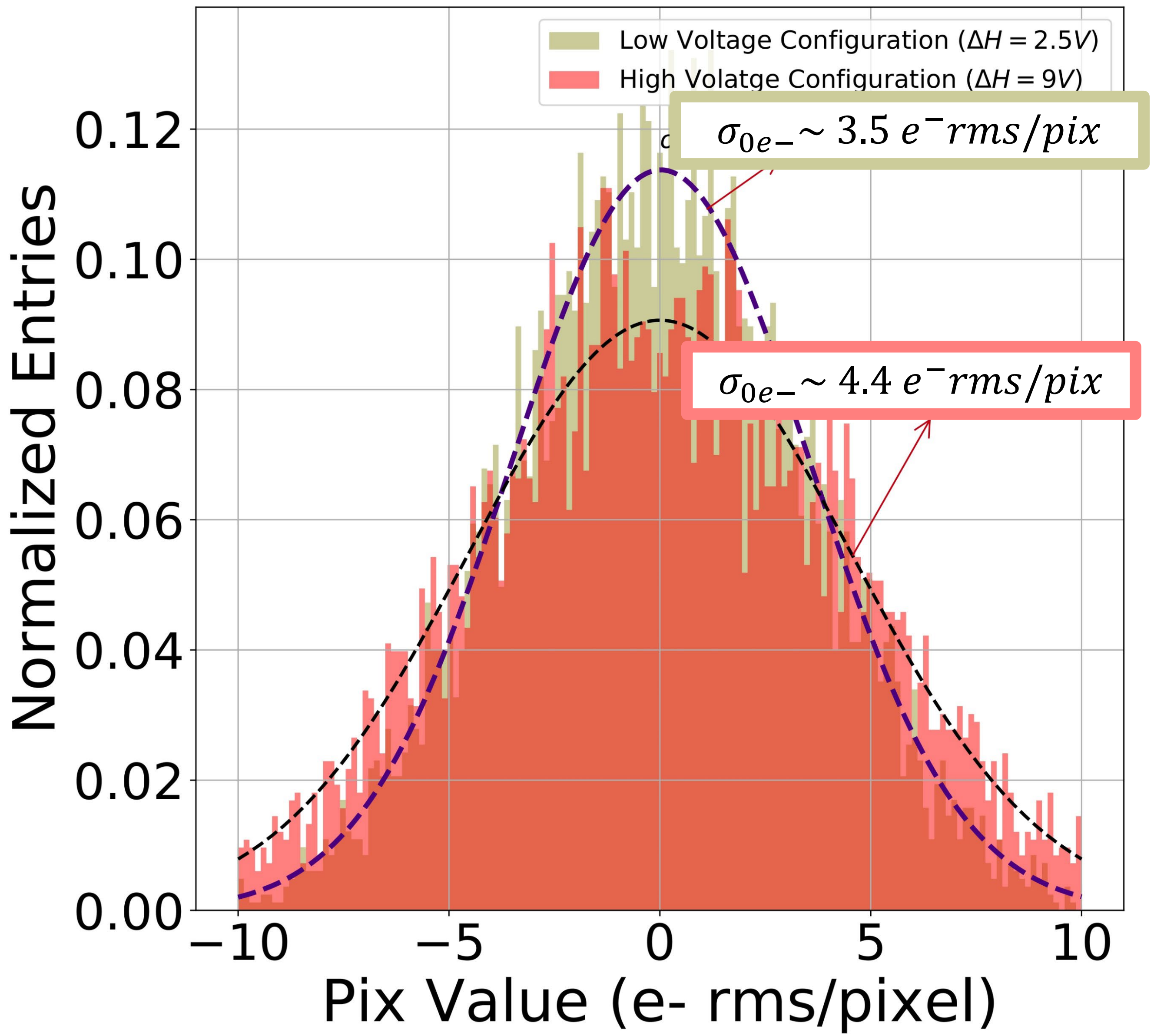
- Gain calculated from the PTC agrees with the gain measured from electron peaks to within ~1%.

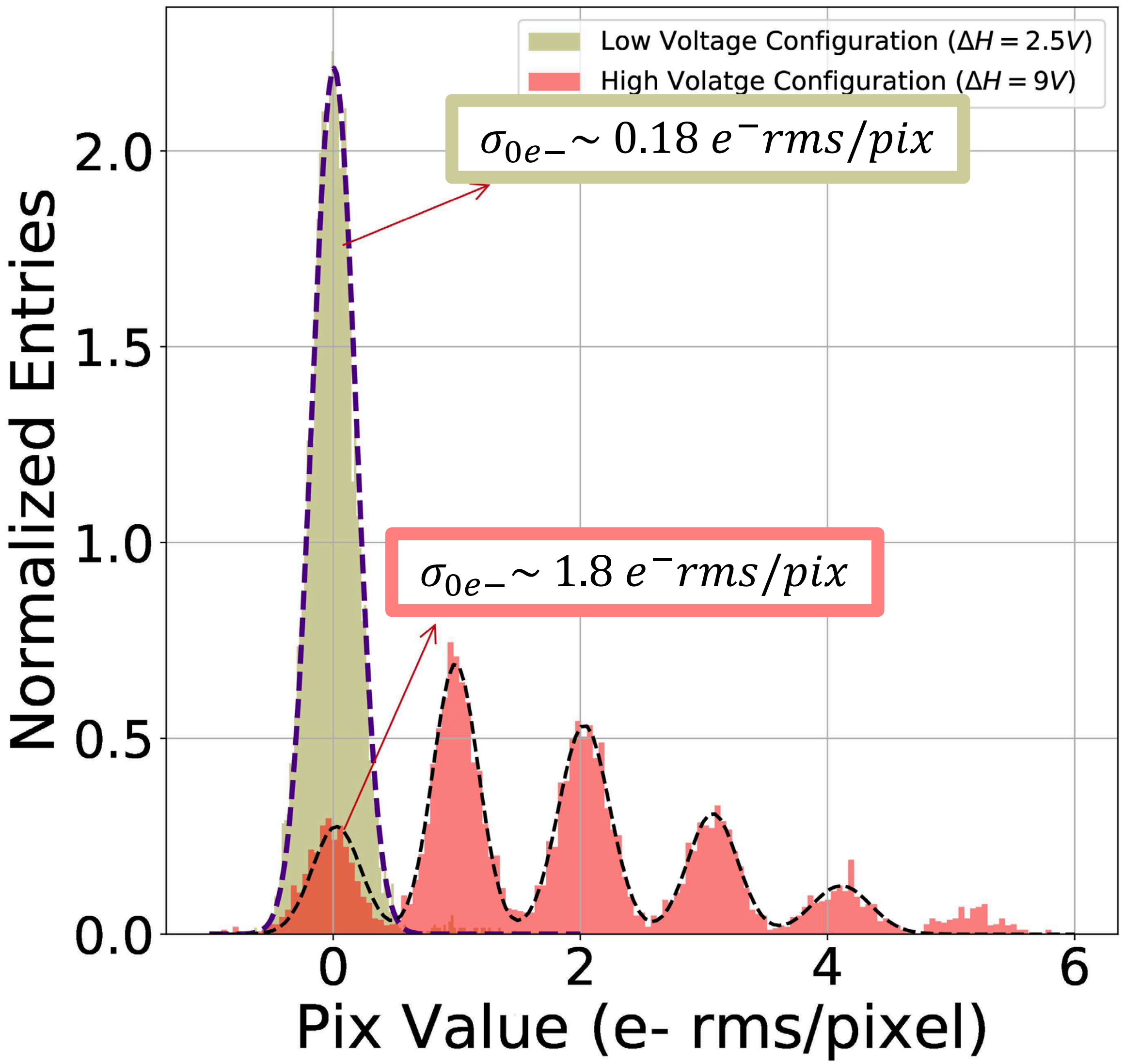






Skipper CCDs: Clock Induced Charge Modeling and Measurements



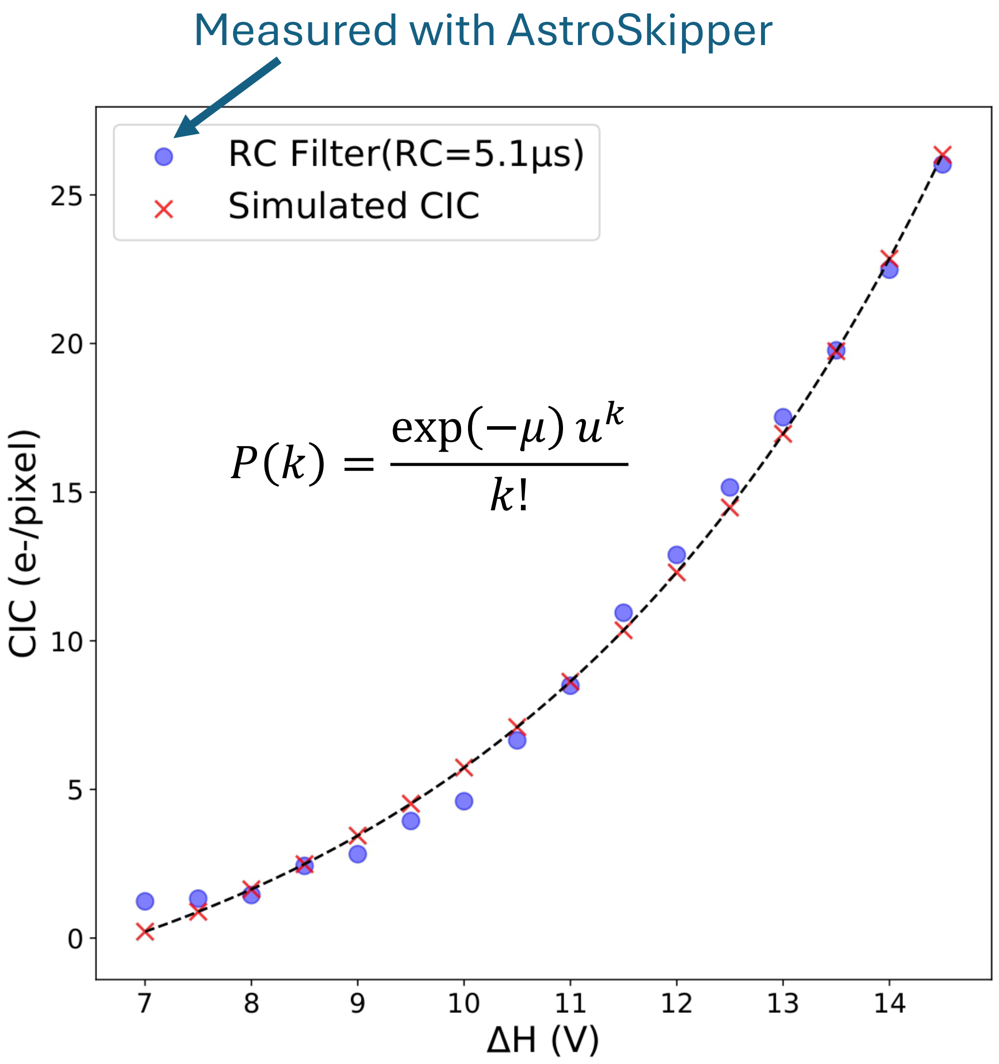


Skipper CCDs: Clock Induced Charge Modeling and Measurements

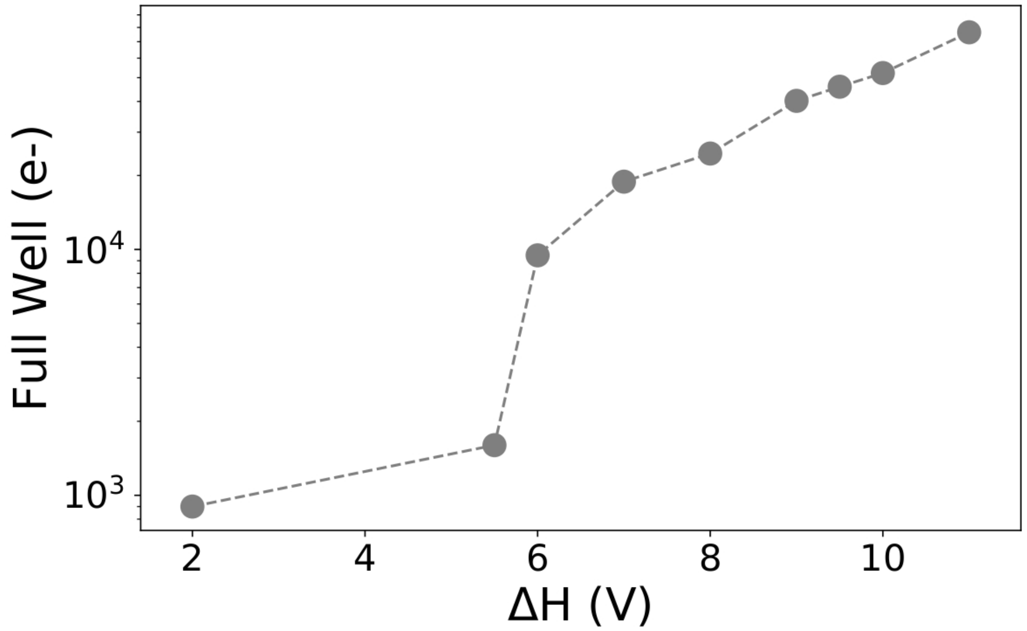
CIC is generated when switching clocks between high- and low-voltage states. CIC can be an appreciable background for measurements in the single-photon regime.

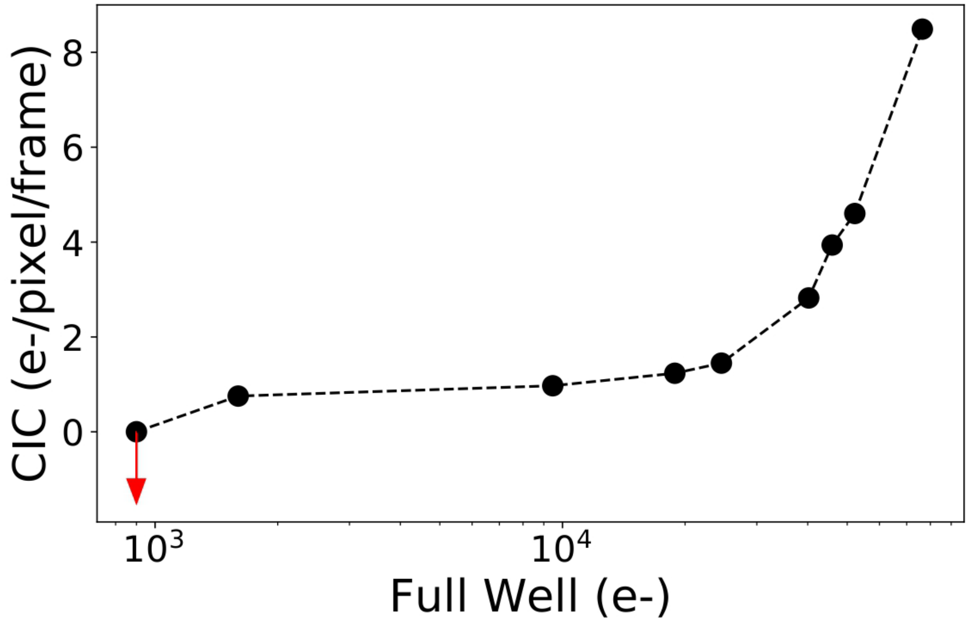
Dark matter experiments with Skipper CCDs use low clock voltages to reduce CIC.

For SIFS, we need higher voltages to increase full-well capacity (~1,000 e- for science images and >40,000 e- for calibration products).



Skipper CCDs: Clock Induced Charge vs Full Well Capacity





Simultaneous optimization of full-well and CIC.

- Low voltages ($\Delta H \sim 2V$; e.g., SENSEI)
  - Full-well capacity ~900 e-
  - CIC < 1.45×10^{-3} e-/pixel/frame (upper limit on CIC from this measurement technique)

- Intermediate voltages ($\Delta H \sim 6V$)
  - Full-well capacity ~10,000 e-
  - CIC $\sim$ 1 e-/pixel/frame

- High voltages ($\Delta H \sim 9V$)
  - Full-well capacity >40,000 e-
  - CIC $\sim$ 3 e-/pixel/frame

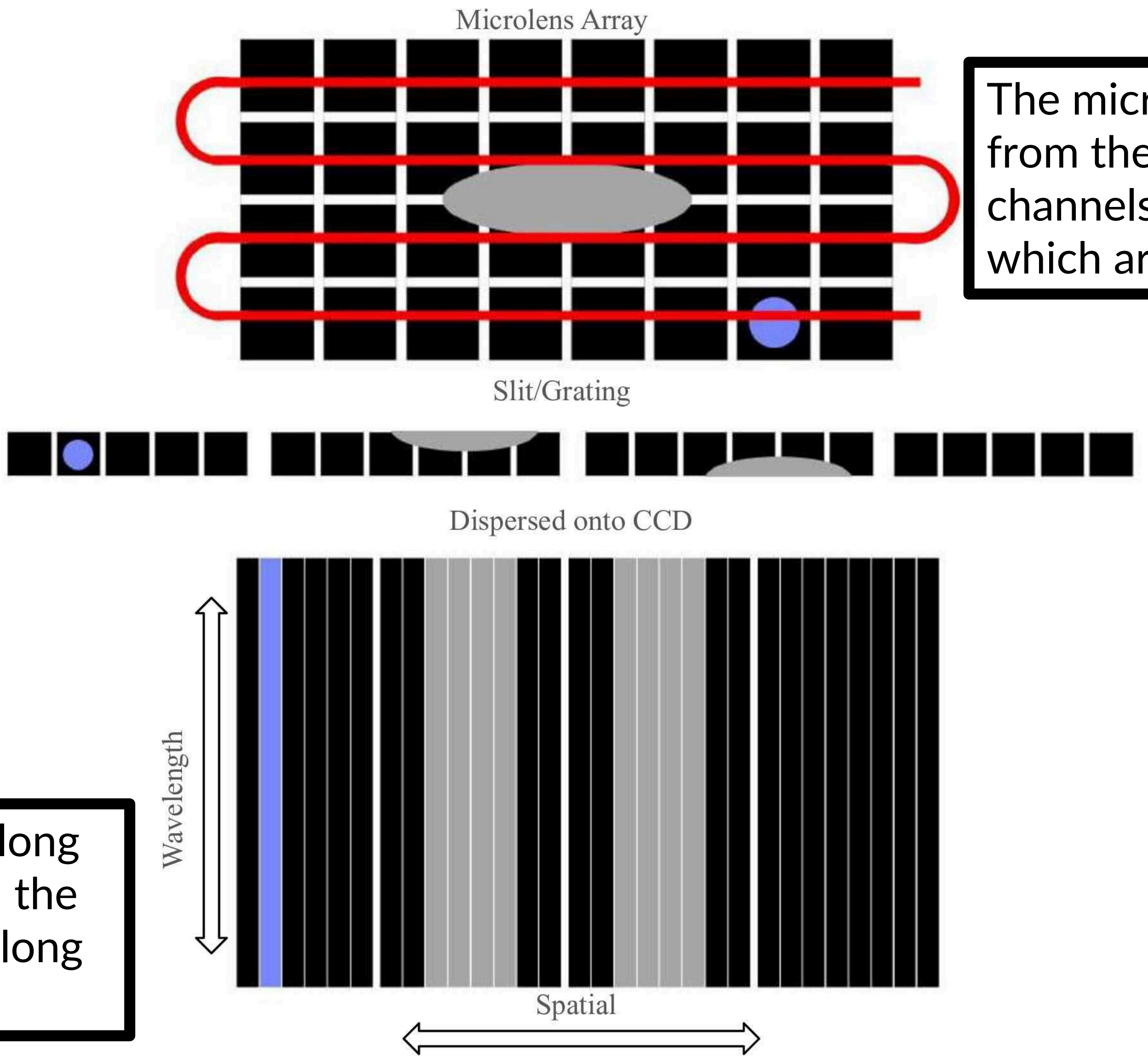
AstroSkipper Characterization Measurements

Parameter	Goal	Measured	Units
Single-Sample Readout Noise ($N_{\text{samp}} = 1$)	3.5	< 4.3	e^- rms/pixel
Multi-Sample Readout Noise ($N_{\text{samp}} = 400$)	0.18	0.18	e^- rms/pixel
Cosmetic Defects	10%	$< 0.45\%$	...
Dark Current	$< 8 \times 10^{-3}$	2×10^{-4}	e^-/pixel/s
Clock Induced Charge	1.52×10^{-4}	3	e^-/pixel/frame
Full-Well Capacity	$> 40,000$	$\sim 40,000 - 60,000$	e^-
Non-linearity	$< 1.5\%$	$< 0.05\%$ and $< 1.5\%$ (low signals)	...
Charge Transfer Inefficiency	$< 1 \times 10^{-5}$	3.44×10^{-7}	...
Charge Diffusion (PSF)	< 15	< 7.5	μm
Absolute Quantum Efficiency	$> 80\%$	$\gtrsim 80\%$ (450nm to 980nm); $\gtrsim 90\%$(600nm to 900nm)	...

AstroSkipper characterization results meet target goals based on DECam and red DESI detector requirements

- Observation Optimization

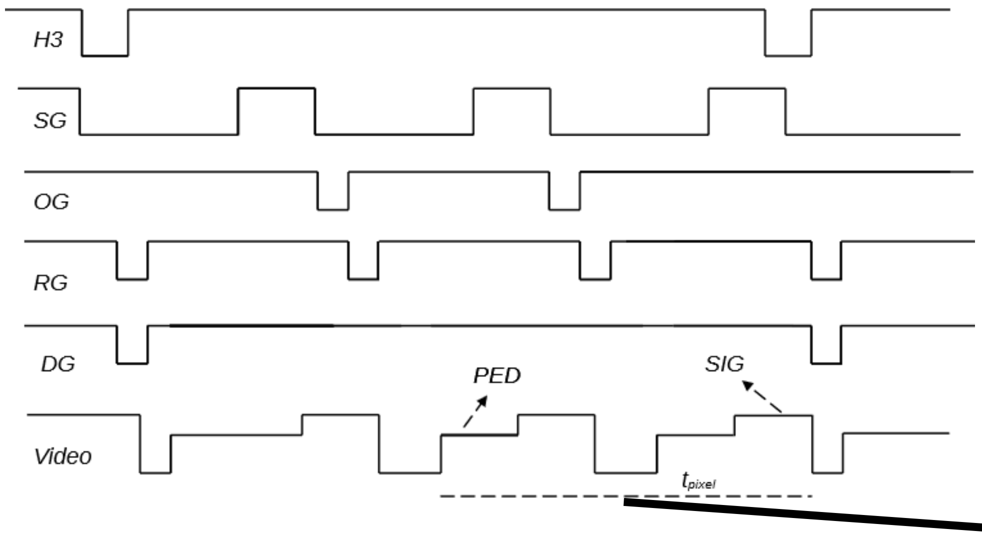
SIFS Signal Mapping onto FoV

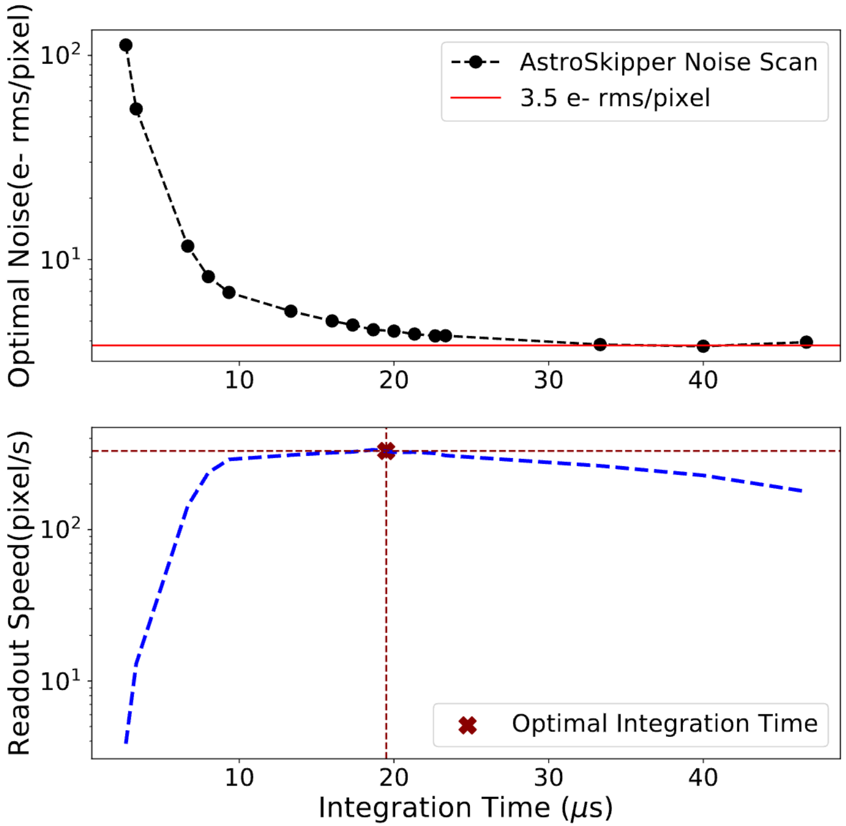


The microlens array collects light from the astronomical target and channels the light into the fibers, which are arranged into a pseudo-slit.

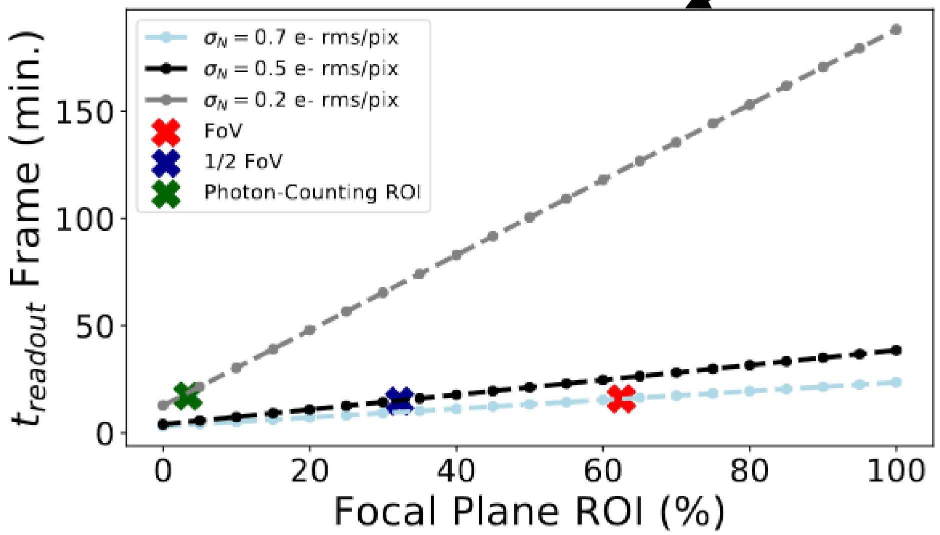
Wavelength direction runs along the Skipper CCDs' rows and the fibers' spatial position runs along the detectors' columns.

Skipper CCDs: Observation Optimization (Readout Time)



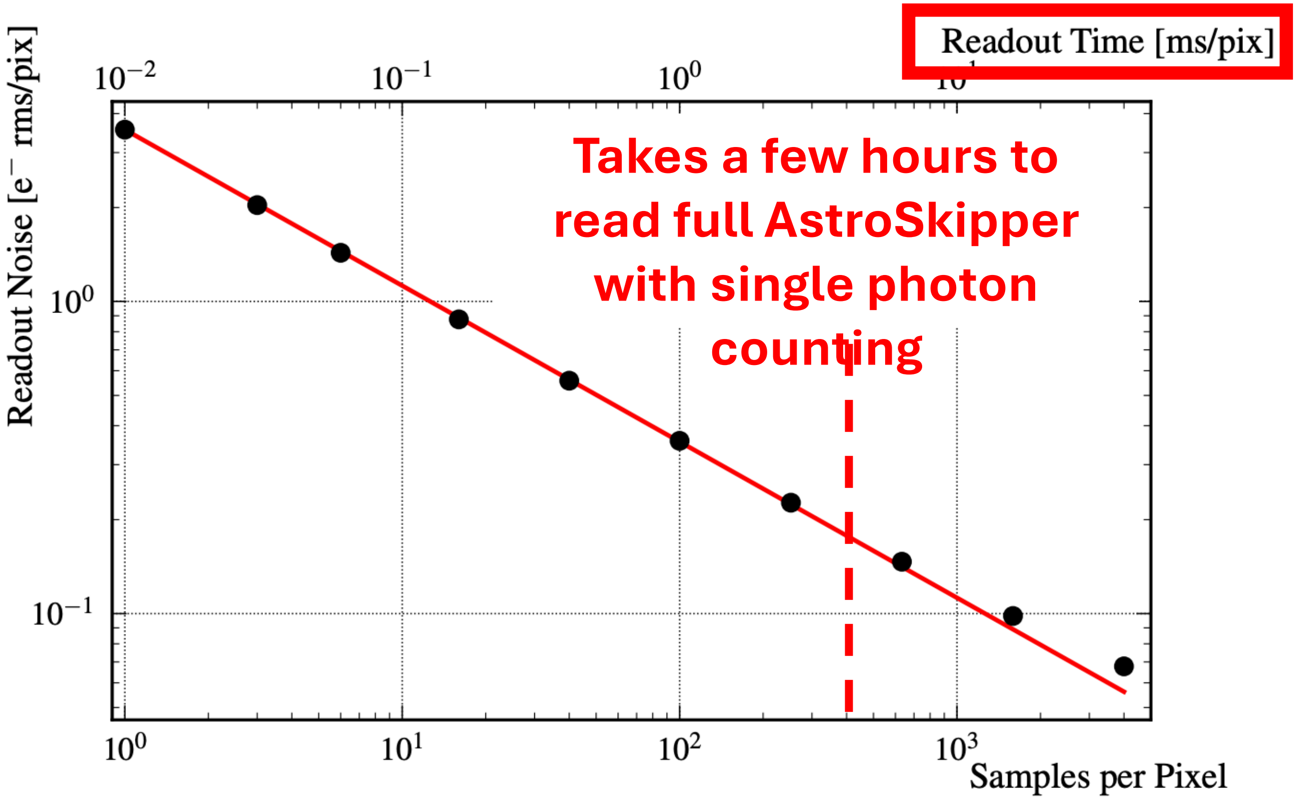


Optimize for detector readout with sub-electron noise

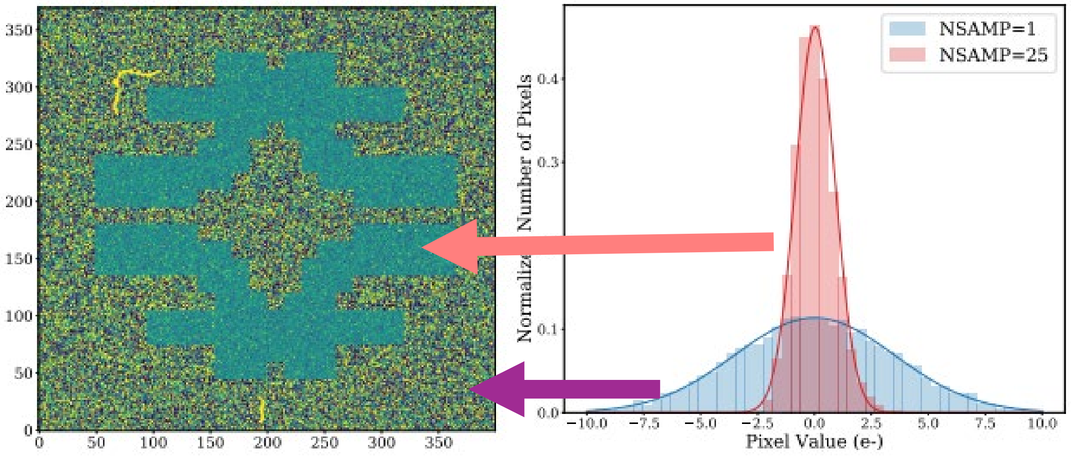


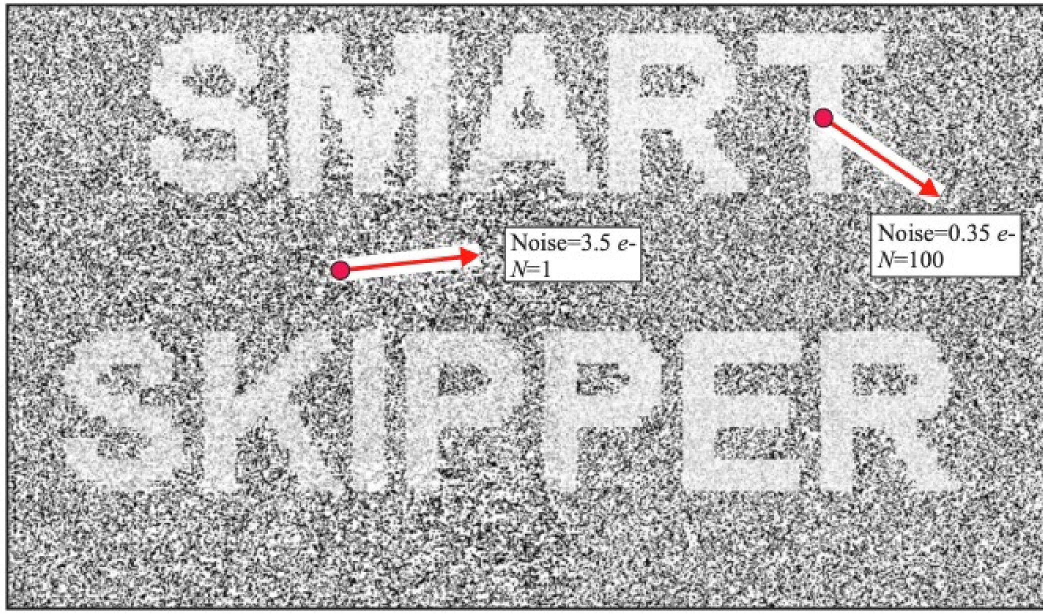
Optimize for pixel integration time and number of samples per pixel to reach target noise the fastest

Skipper CCDs: Observation Optimization (Regions of Interest)



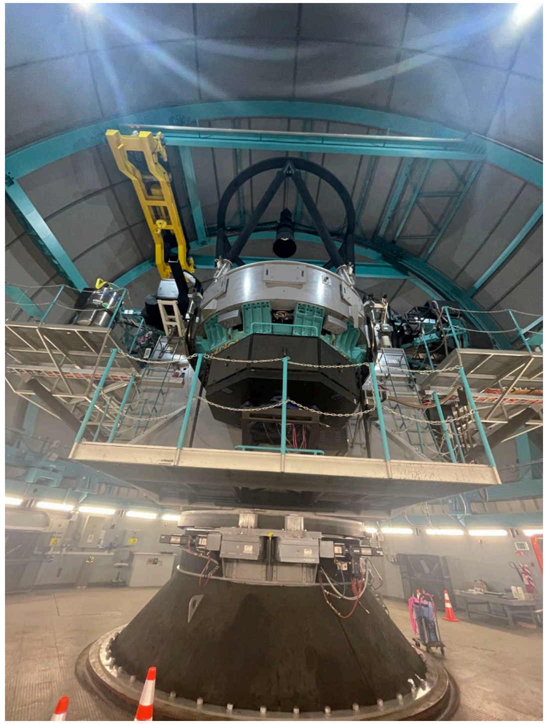
arXiv:1706.00028

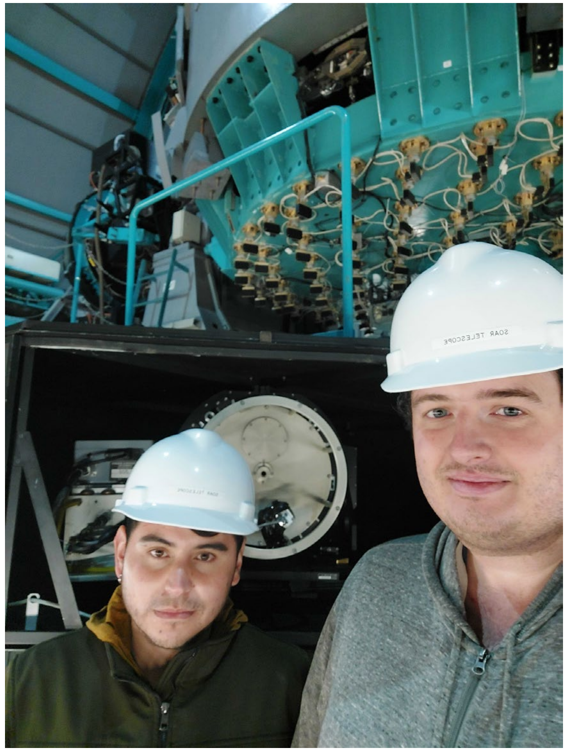


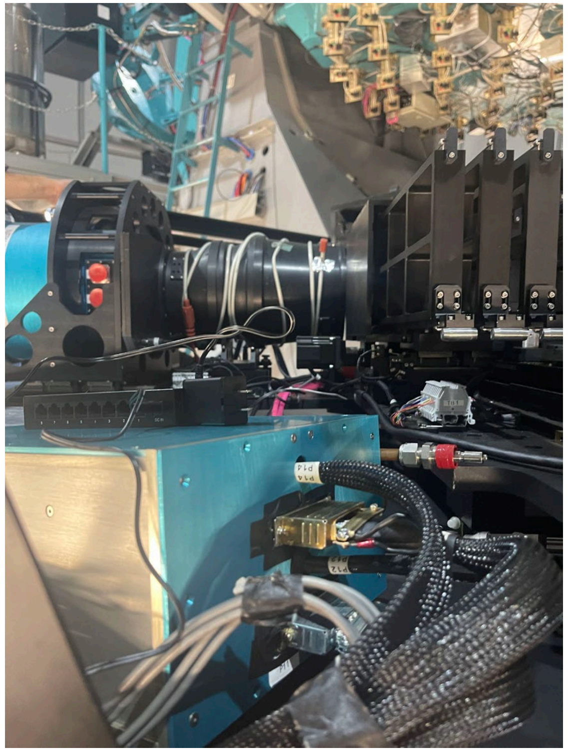


arXiv:2012.10414

Skipper CCD Focal Plane Prototype: Commissioning





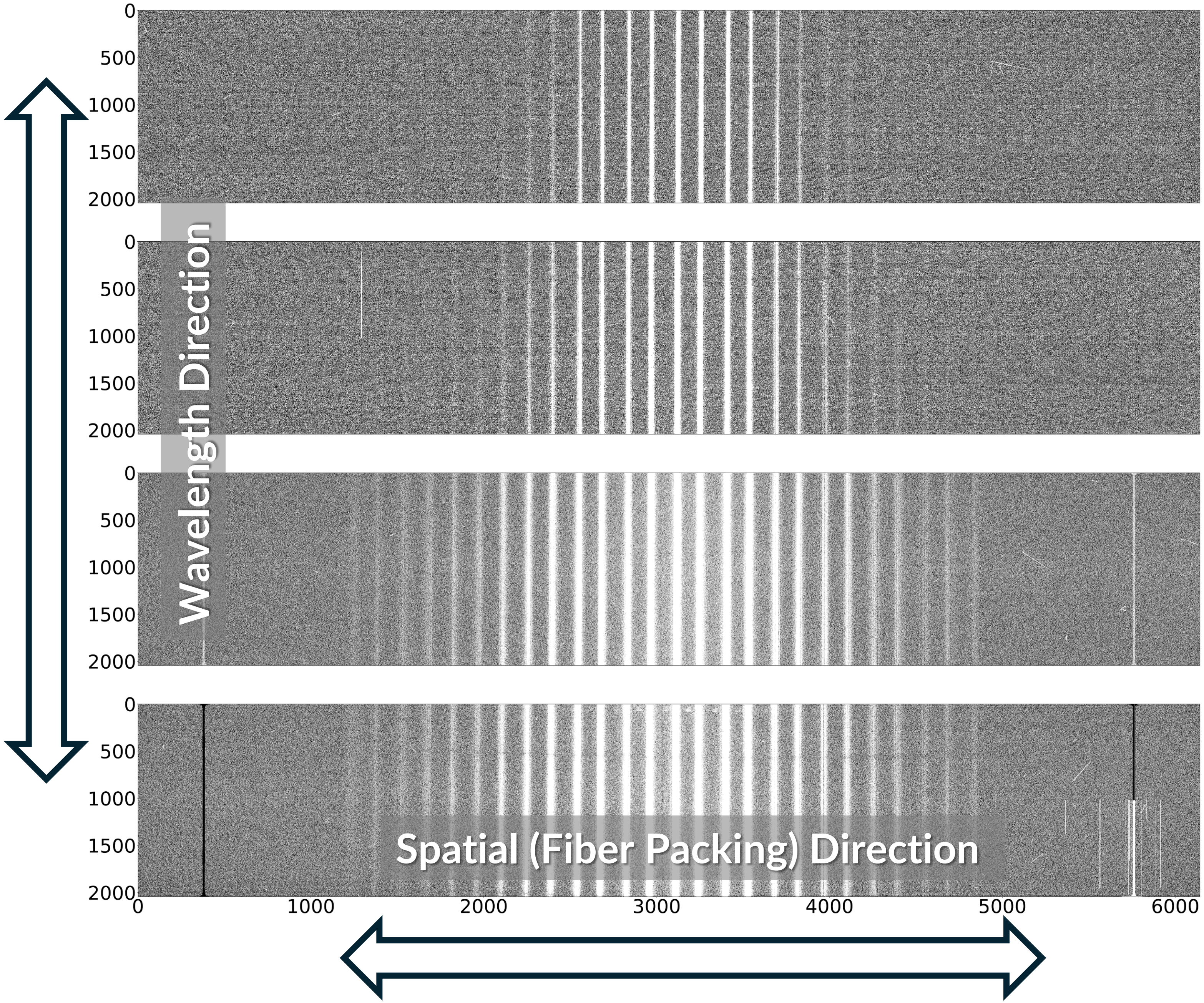


More on Commissioning:

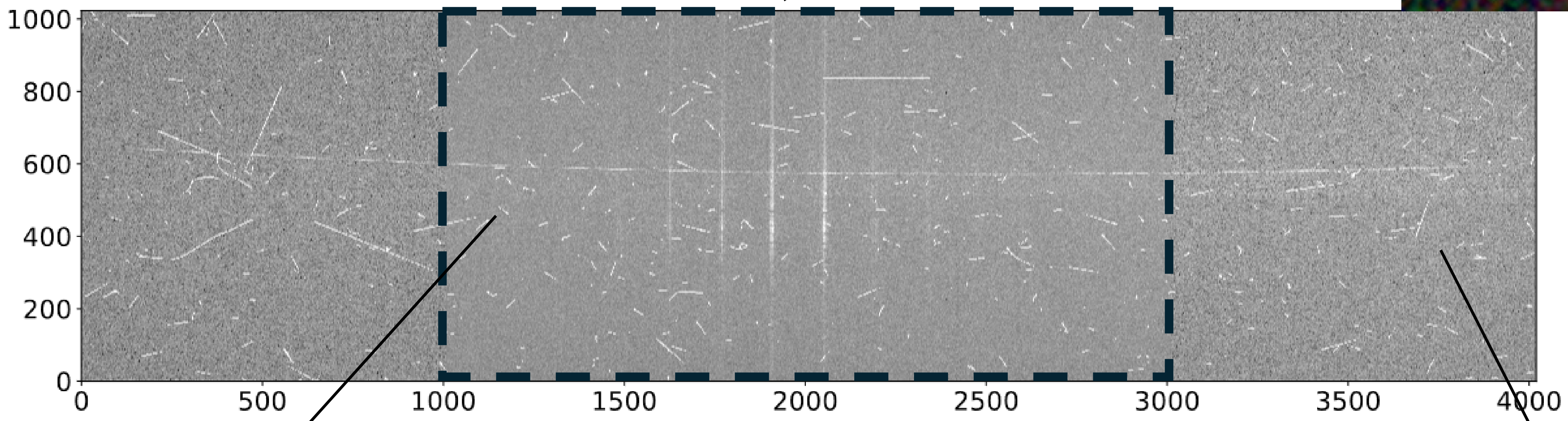
- ***Skipper CCD mosaic on the SOAR integral field spectrograph (Presenter: Braulio Cancino)***
  20 June 2024 • 17:30 - 19:00 Room G5, North - 1F

- Results

Skipper CCDs: First On-Sky Demonstration

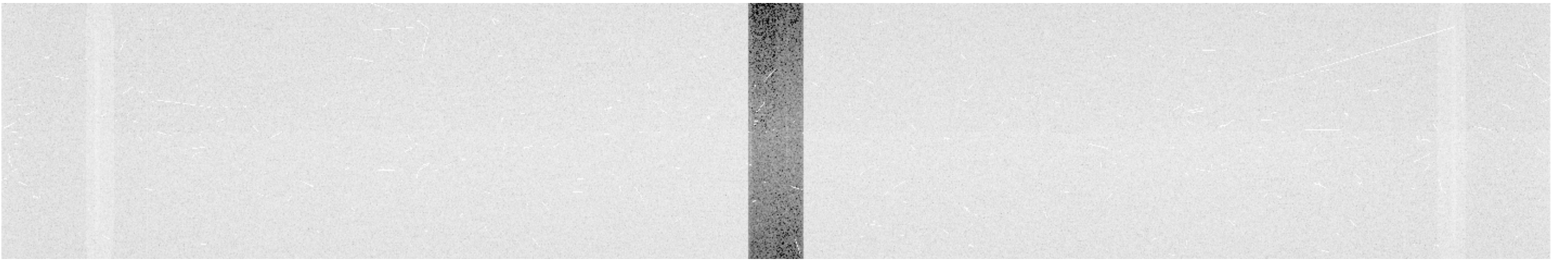


Skipper CCDs: First On-Sky Demonstration (Sub-electron Noise)

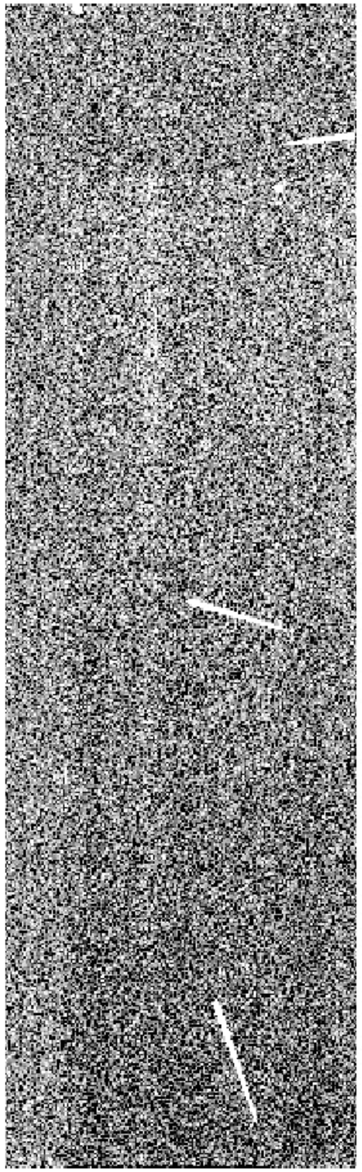


Achieved sub-electron readout noise (0.5 e- rms/pixel) in science frames for an area 2k x 4k pixels. ROI minimizes readout time from ~55 min to ~15 min.

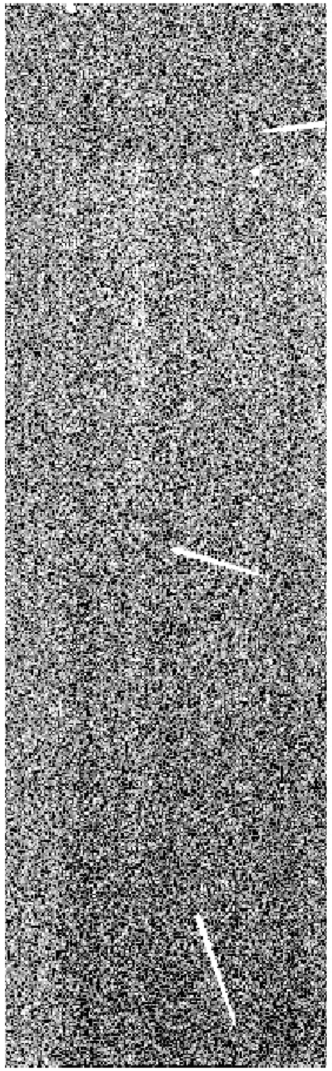
Skipper CCDs: First On-Sky Demonstration (Photon-Counting)

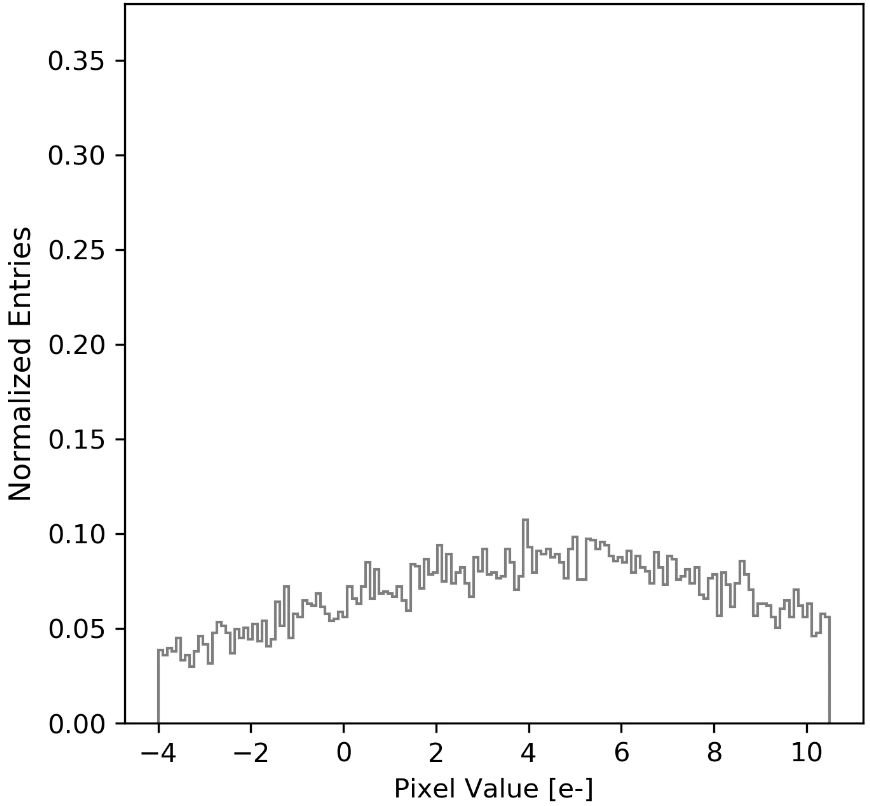


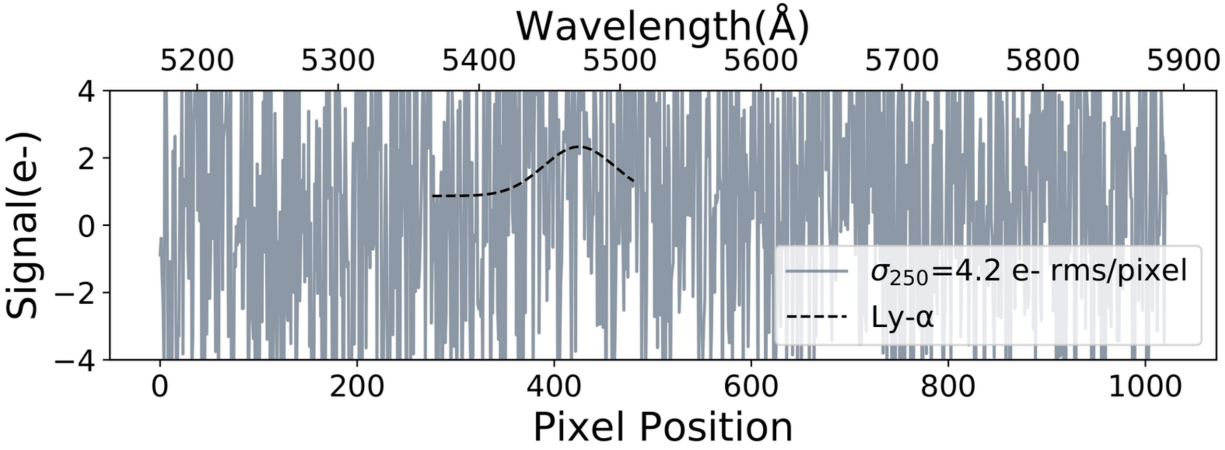
Photon-counting was achieved for the first time for astronomical observations with a Skipper CCD (charge quantizing read out noise on a CCD).



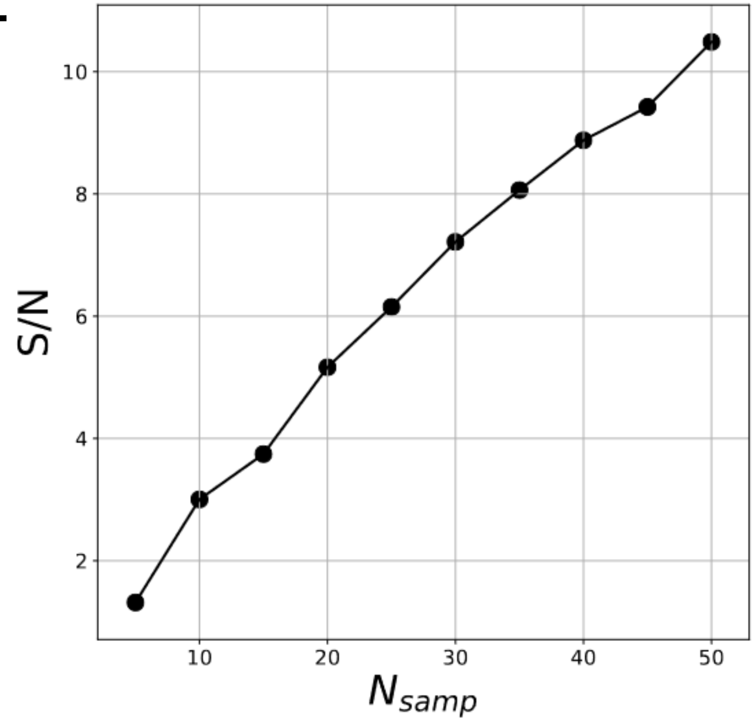
Skipper CCDs: First On-Sky Demonstration (Photon-Counting)







Signal-to-Noise (Read Noise Dominated Regime)

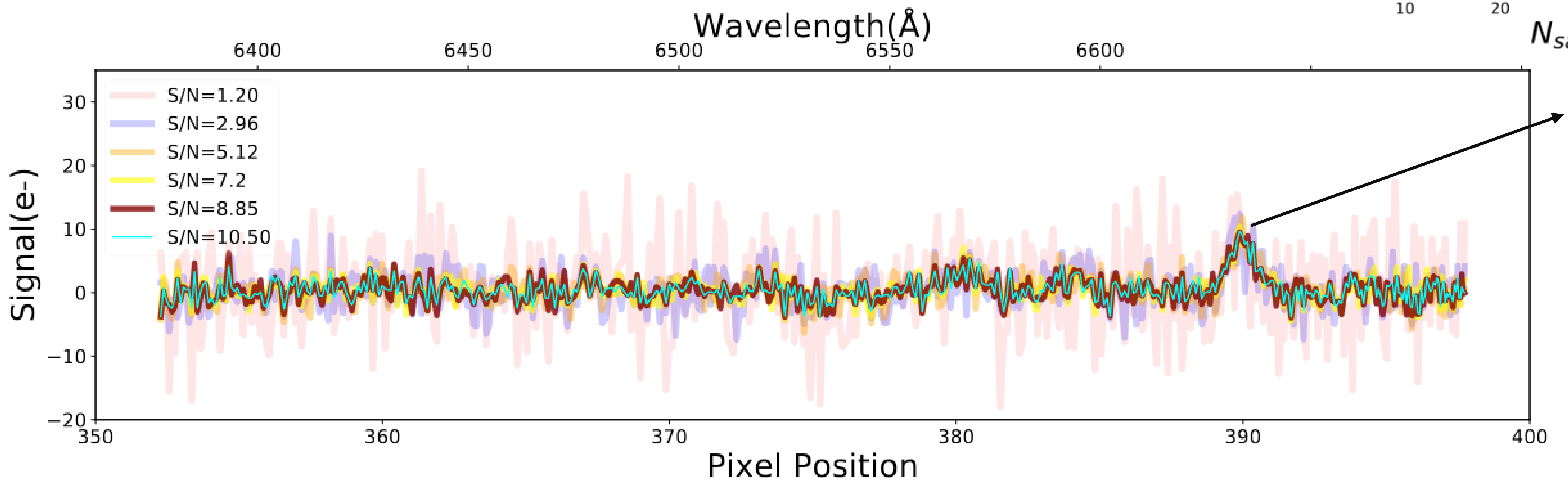


Region of interest N_{samp} is optimized to minimize backgrounds and demonstrate S/N improvements for SIFS.

$$\frac{S}{N} = \frac{R_{src} t_{exp}}{\sqrt{(R_{src} + R_{bkg} + R_{dark}) t_{exp} + N\sigma^2}}$$

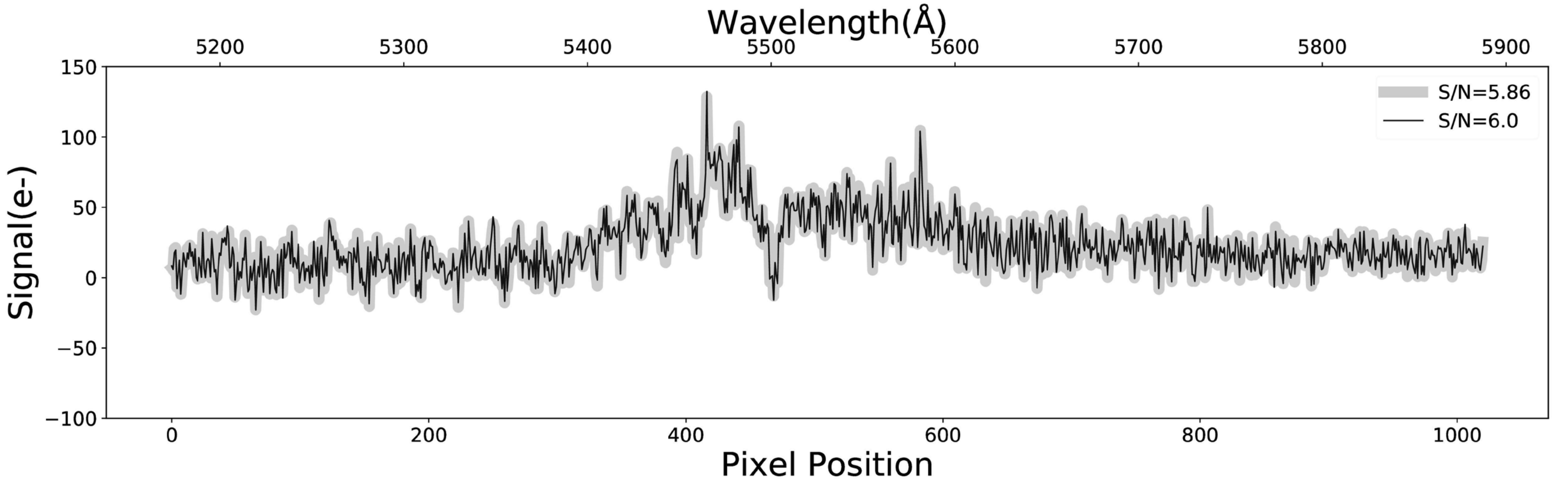
$$N\sigma^2 \geq (R_{src} + R_{bkg} + R_{dark}) t_{exp}$$

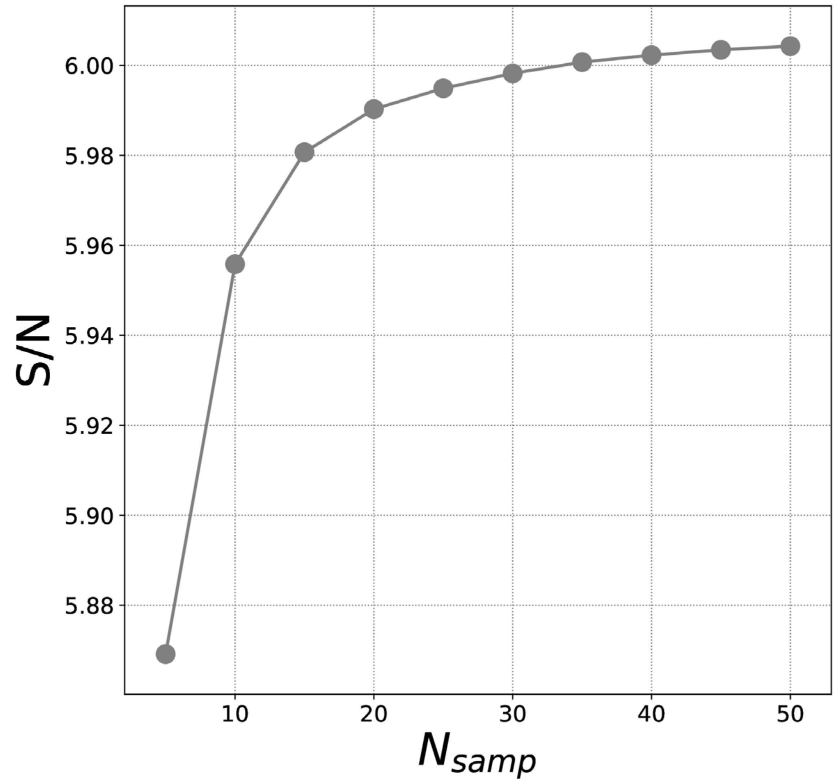
$$R_{src} < R_{bkg}$$

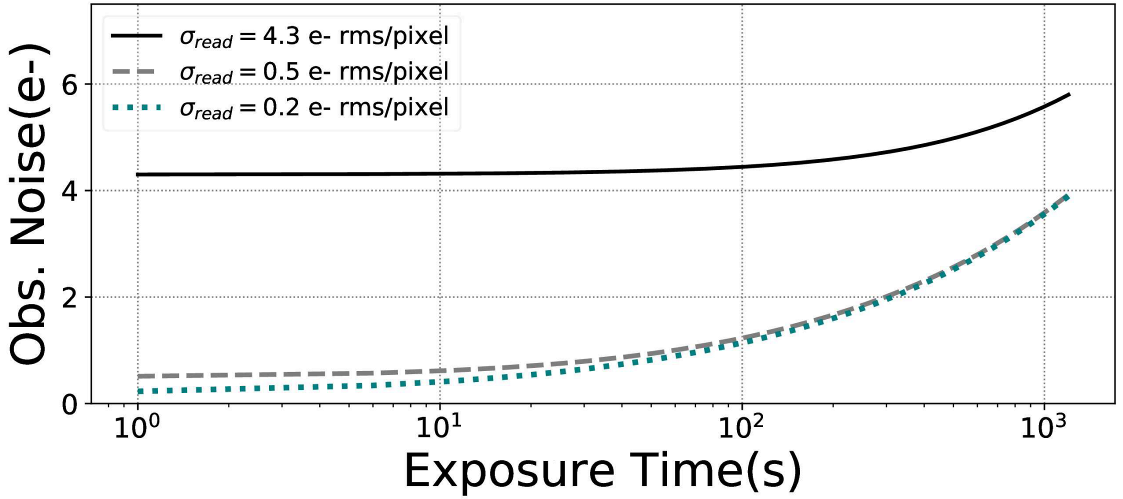


O III

Signal-to-Noise (Shot Noise Dominated Regime)







Skipper CCDs retain the performance of conventional CCDs at high signal-levels. Improvements to the signa-to-noise only in the readout noise dominated regime.

- Planned Science

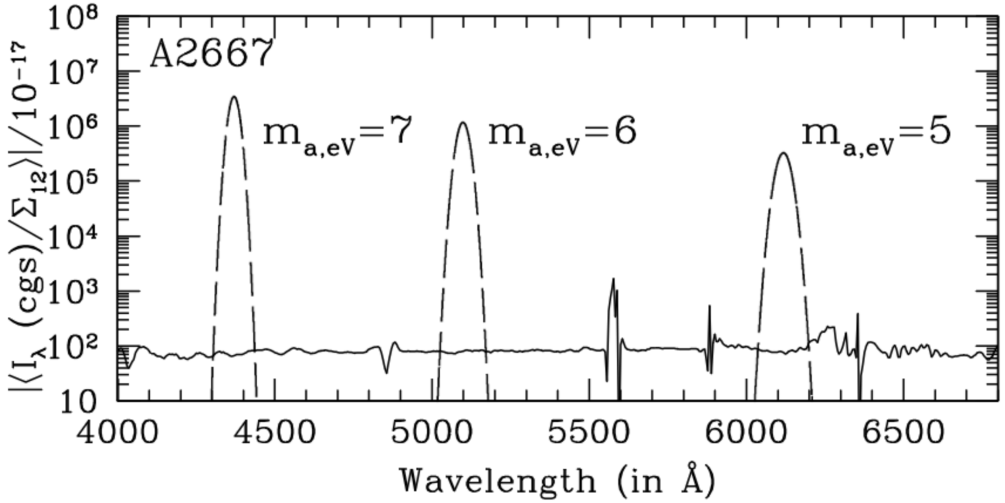
Axion-like-Particle Dark Matter in Galaxy Clusters

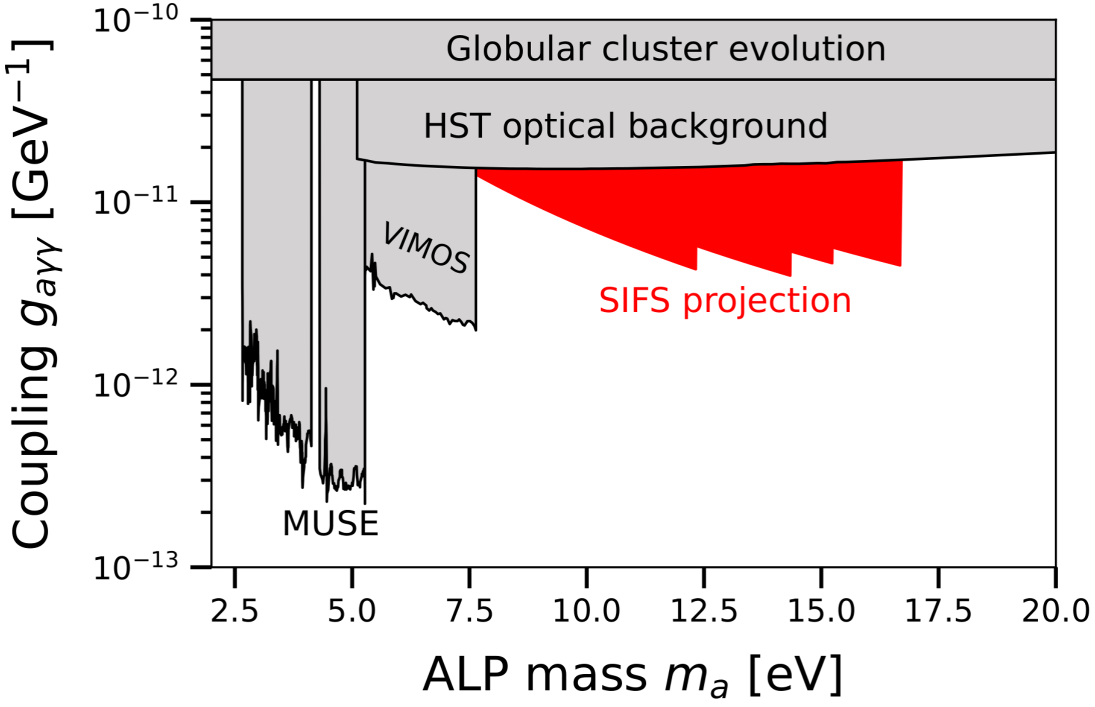
ALPs or other eV-scale DM may decay into mono-energetic photons, producing a spectral line.

For two-photon decays, each photon has observed wavelength λ = 2480 Å * (10 eV) * (1+z).

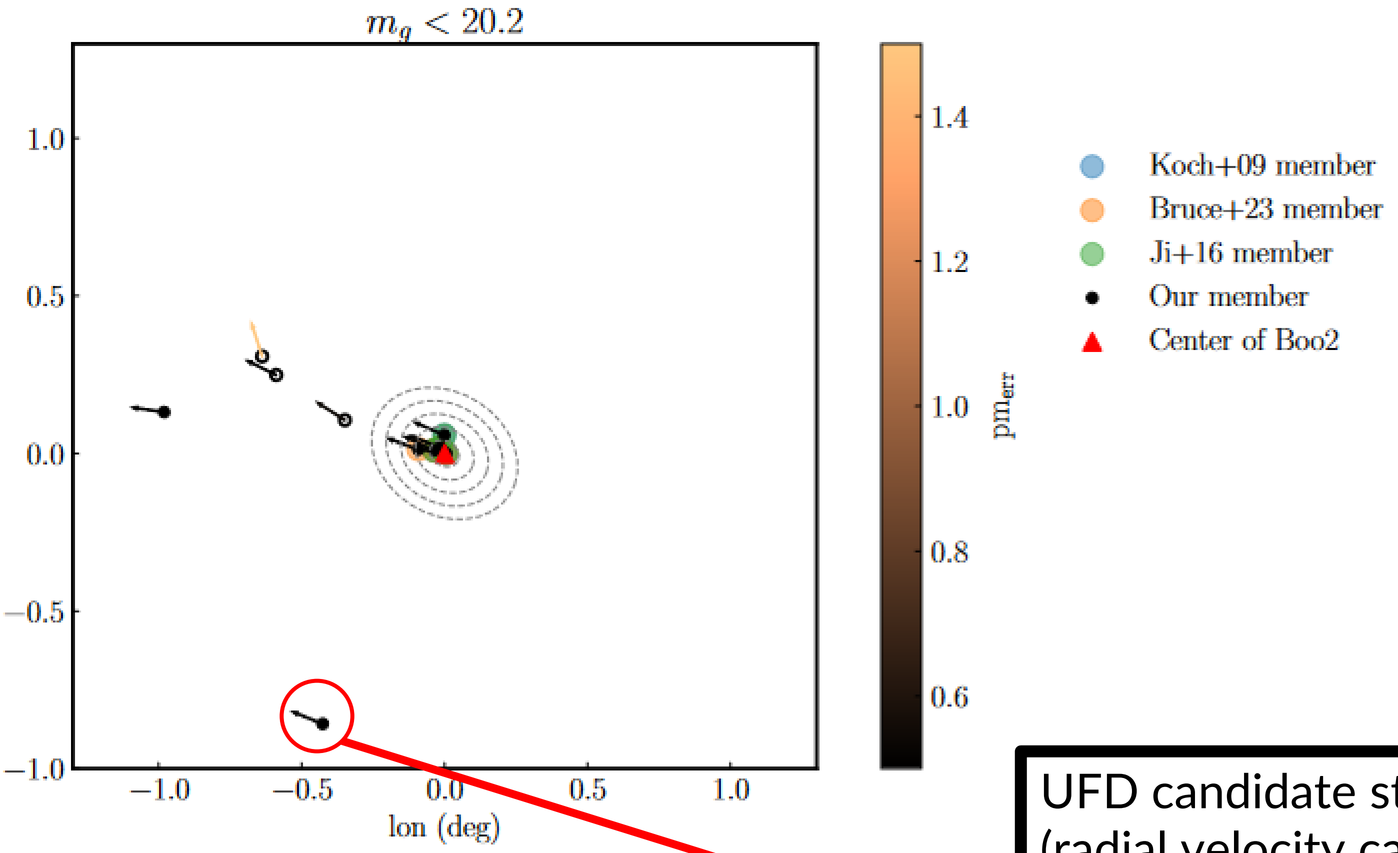
Moderate-redshift (z ~ 1–2) galaxy clusters have several advantages for ALP searches:

- Large DM masses constrained by SZ observations (e.g., ACT or SPT)
- Increases ALP mass reach for a given wavelength bandpass by a factor (1+z).





Ultra-faint-Dwarf Galaxy Candidate Member Star



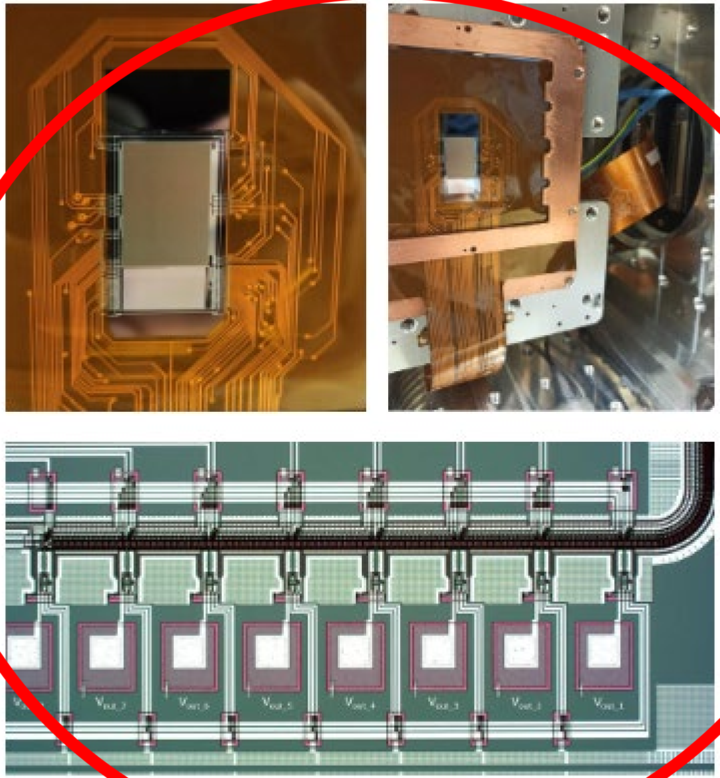
UFD candidate star member confirmation (radial velocity calculations).

Extend the mapping of stellar population of UFDs to larger distances (galaxy evolution and their small dark matter halos).

- Outlook

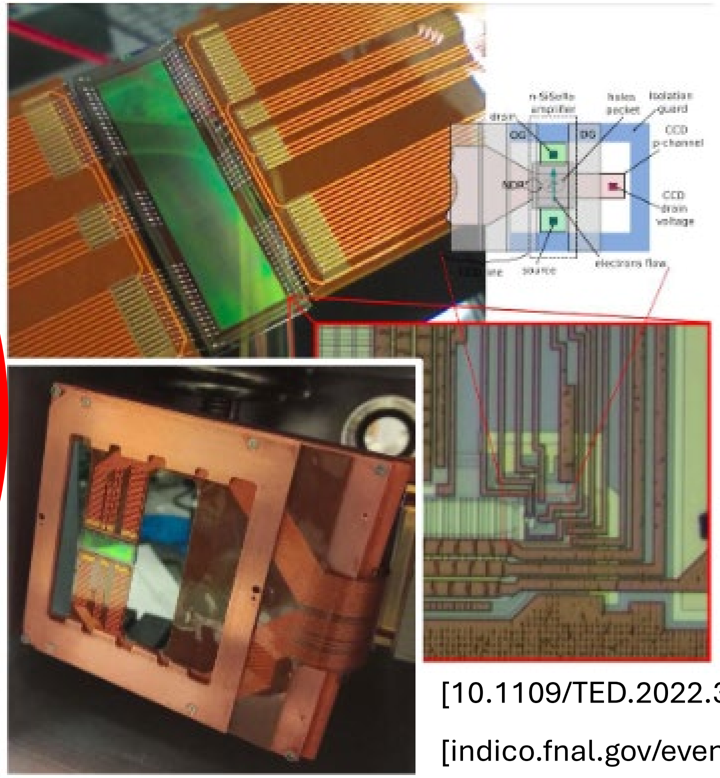
Outlook

Multi-Amplifier Sensing (MAS) CCDs



[10.1002/asna.20230072]

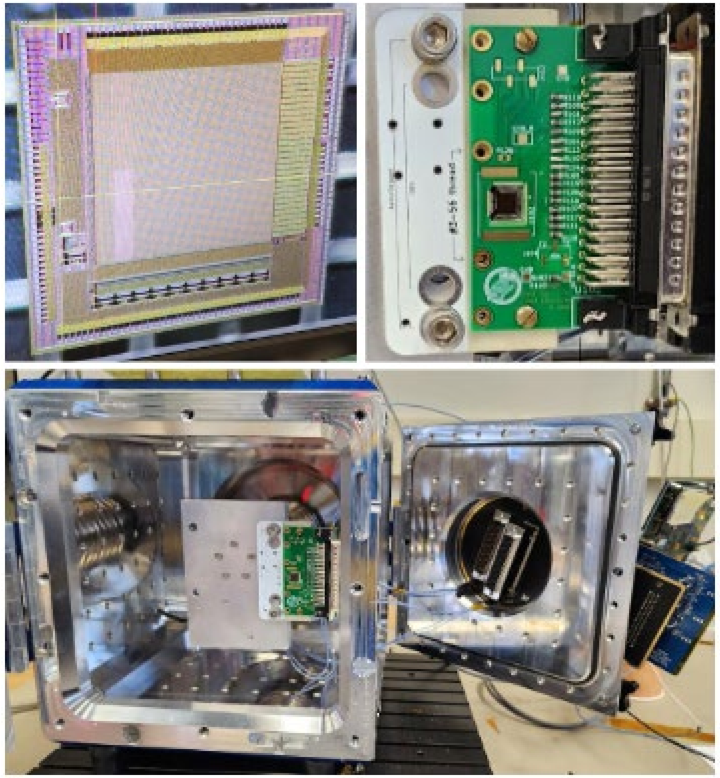
CCDs with n-Sisero Stages



[10.1109/TED.2022.3233288]

[indico.fnal.gov/event/58707]

Skipper-in-CMOS



[B. Parpillon @ CPAD 2022]

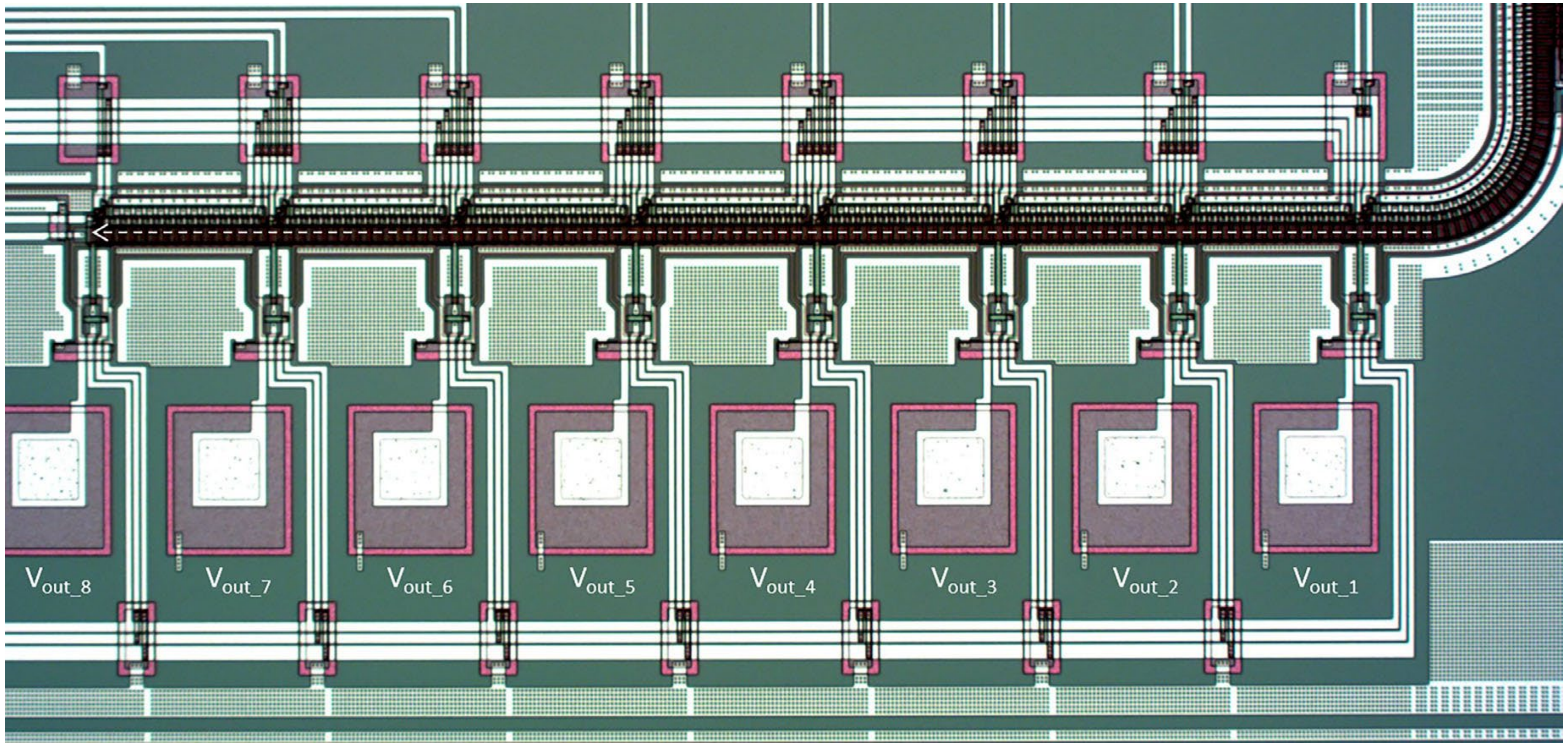
See Guillermo Fernandez Moroni’s presentation (19 June 2024 • 11:10 - 11:30 Room G312/313)

Fast-readout technologies with single-electron resolution. Testing of first prototypes is ongoing.

[10.1002/asna.20230072]

Multi-amplifier-sensing (MAS) Skipper CCD. Charge is transferred along a serial register with M amplifiers. Readout is performed in parallel with each amplifier.

We plan to test 4k x 4k MAS devices on SIFS.

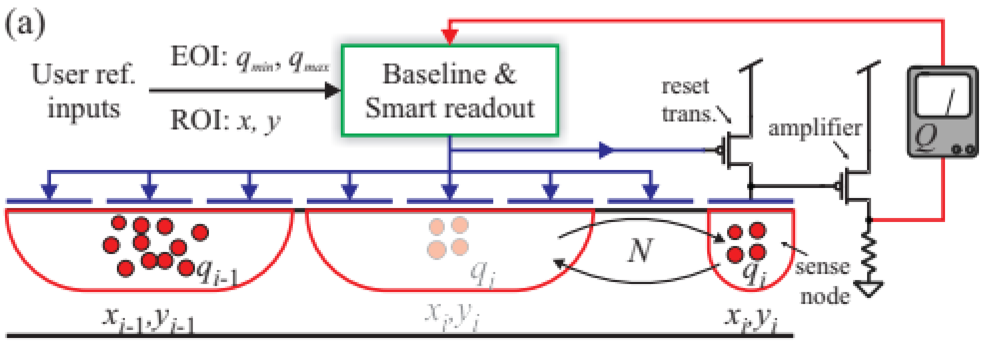


Please check these presentations to learn more about MAS:

- ***Sub-electron noise Multi-Amplifier Sensing CCDs for spectroscopy (Kenneth Lin, et al.)***
  19 June 2024 • 10:30 - 10:50 Room G312/313
- ***First Demonstration of Single-Quantum Measurements with a Multi-Amplifier Sensing Charge-Coupled Device (Guillermo Fernandez Moroni, et al.)***
  19 June 2024 • 10:50 - 11:10 Room G312/313

- Extra Slides

Skipper CCD: smart readout



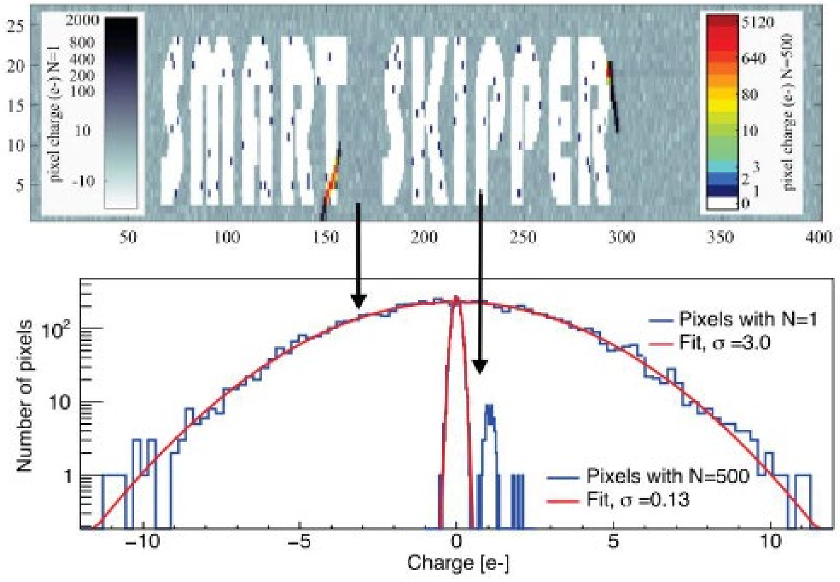


FIG. 3. Measurement using ROI technique. Pixels in the words have $N = 500$ (right scale); pixels outside the words have $N = 1$ (left scale). s_f was zero in most pixels, with some pixels having $s_f = 1, 2, 3$ or very large values for the two muon tracks that are observed.

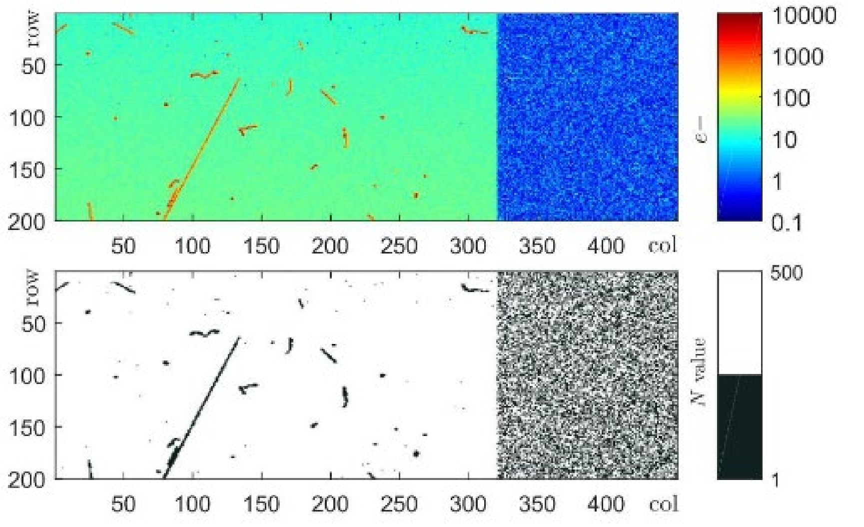
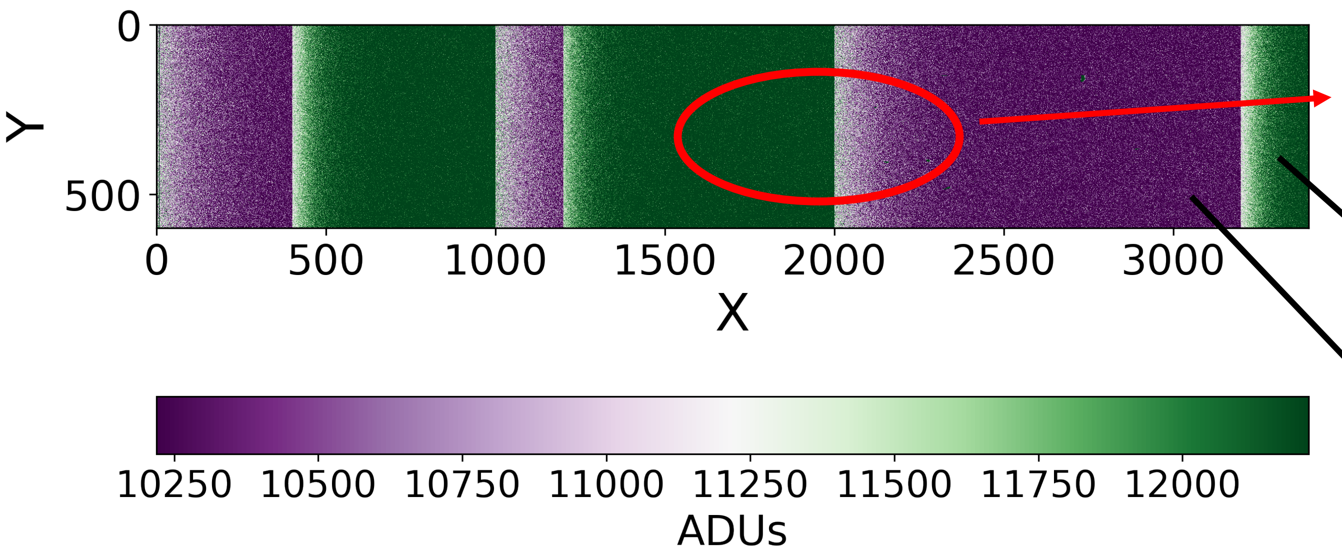


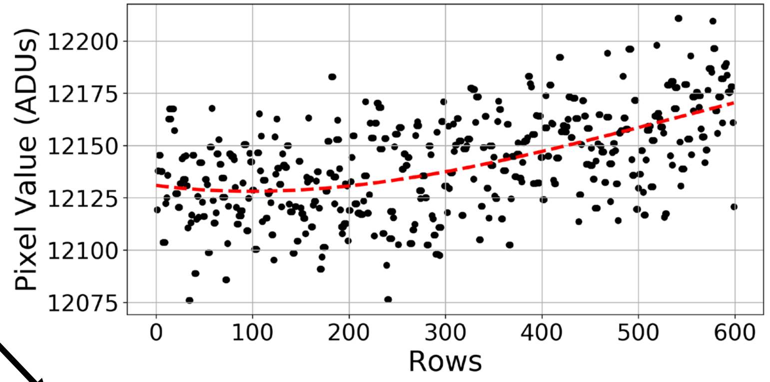
FIG. 4. (Top) Image using EOI technique. (Bottom) N for each pixel.

Two approaches during DAQ: Region-of-interest (ROI) and Energy-of-interest (EOI).
Decreases overall sensor readout time.

Skipper CCDs: Data Pipeline



Bias shifts between single-sample and multi-sample regions



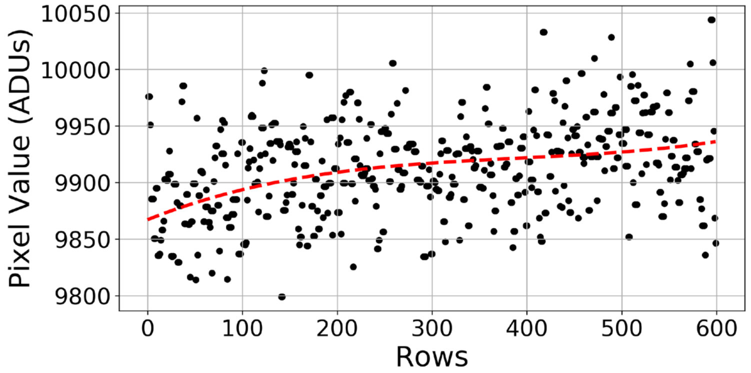
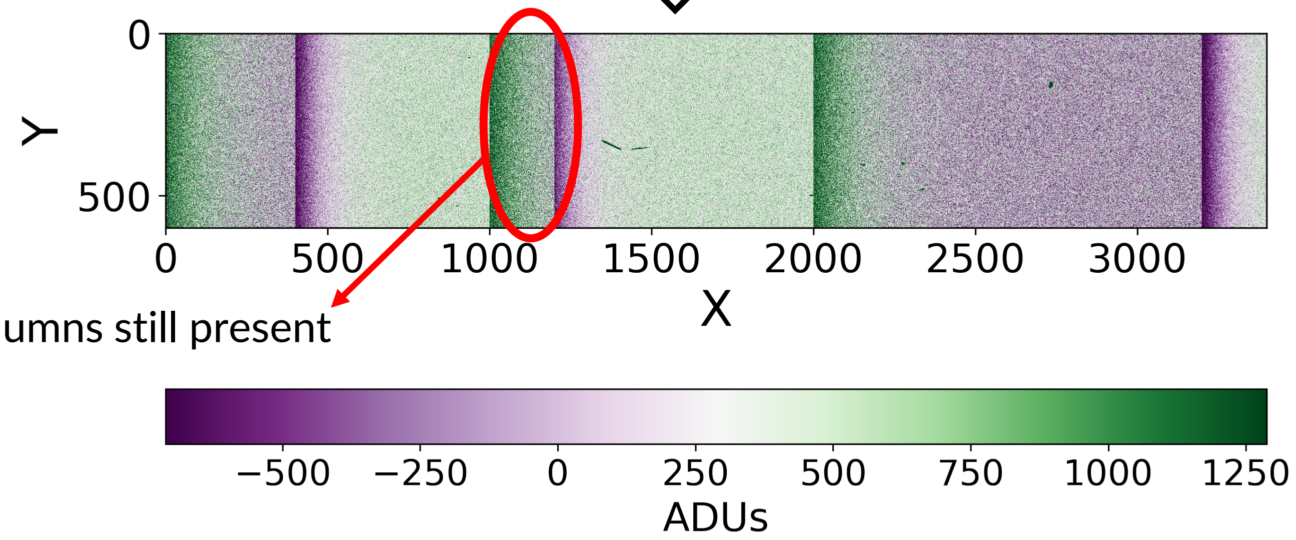


Image processing pipeline

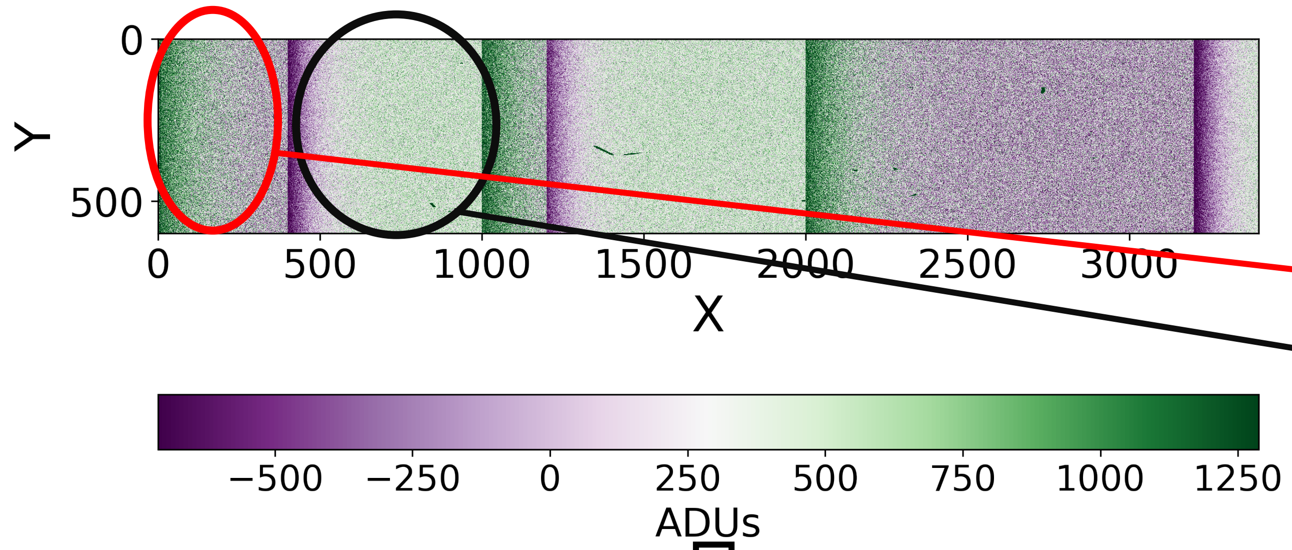
Serial OS subtraction by row

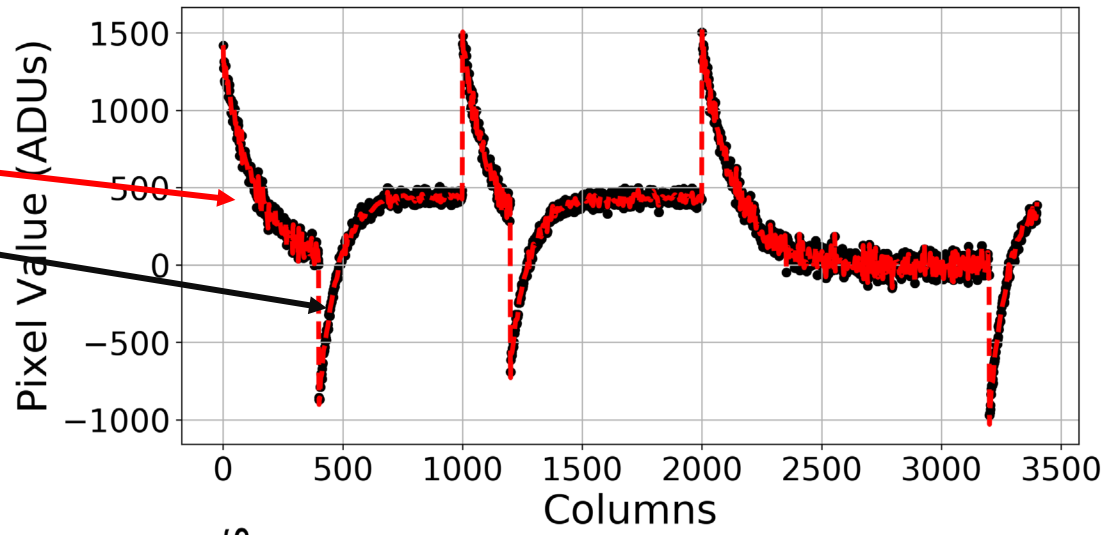


Transients in columns still present

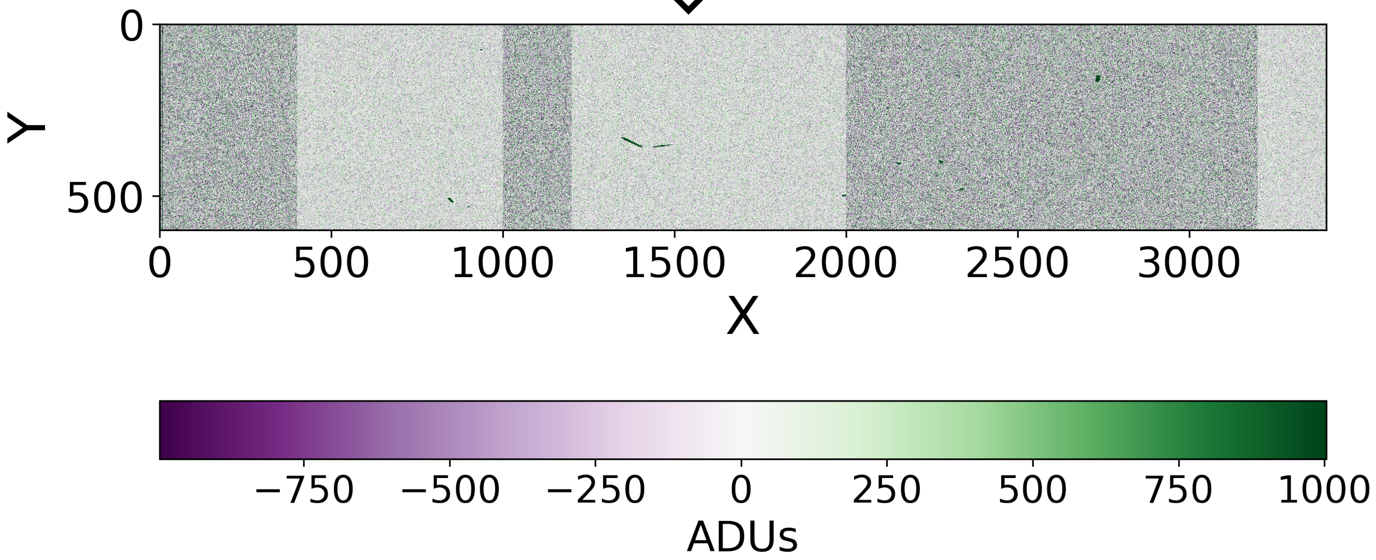
Median filter and spline fit row-by-row in single- and multi-sample serial overscan regions

Skipper CCDs: Data Pipeline





Parallel OS subtraction by row



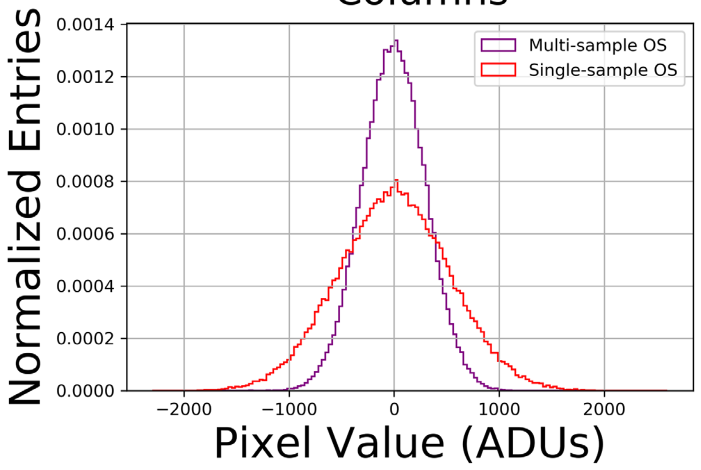
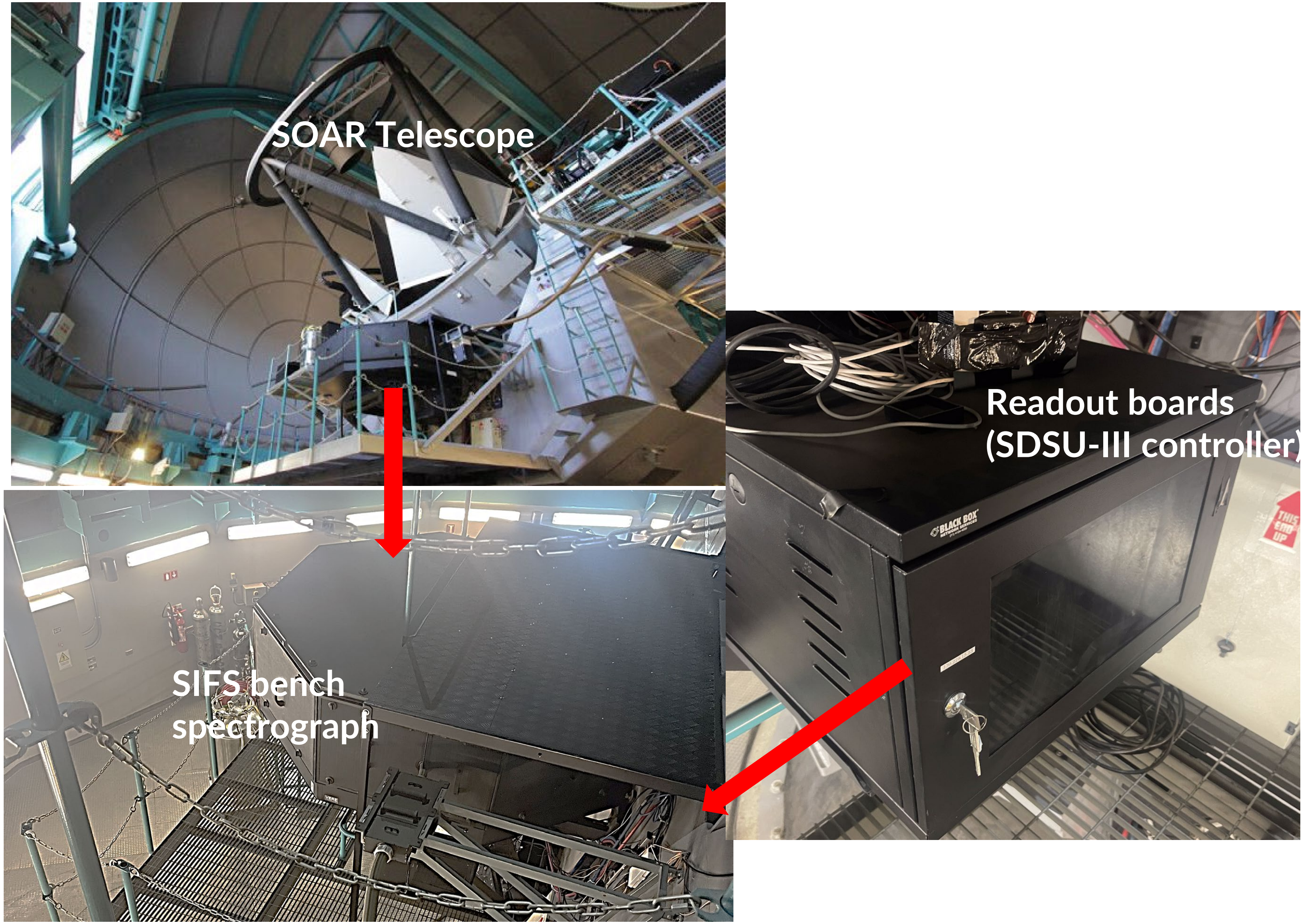


Image correction algorithms remove transients

SIFS


SOAR Telescope
Readout boards
(SDSU-III controller)
SIFS bench
spectrograph