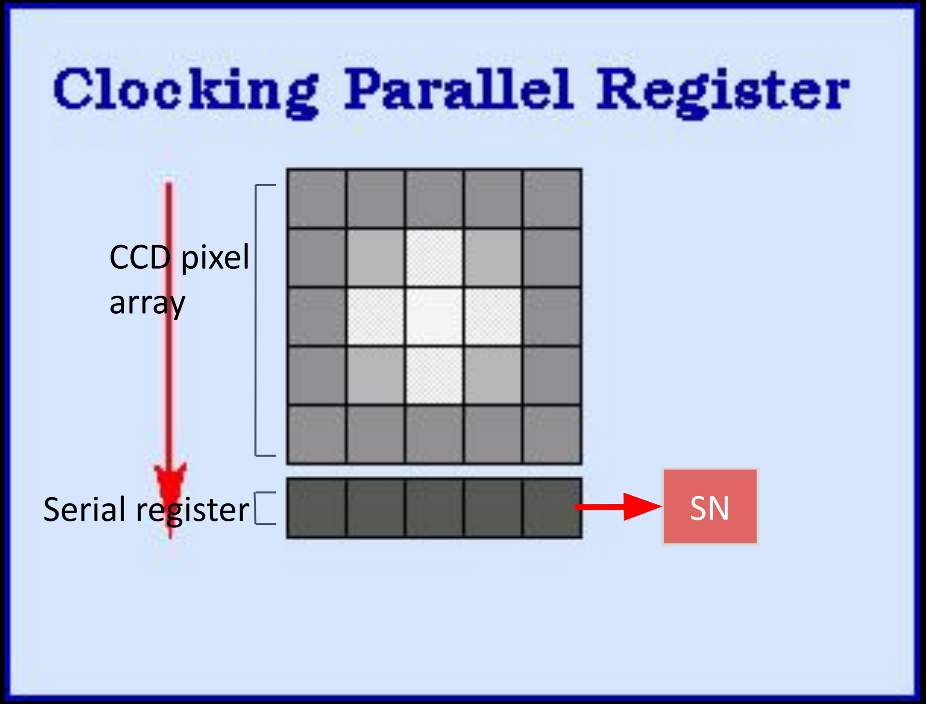
Regional Selection with Skipper CCDs for Astronomical Applications

SOAR Telescope

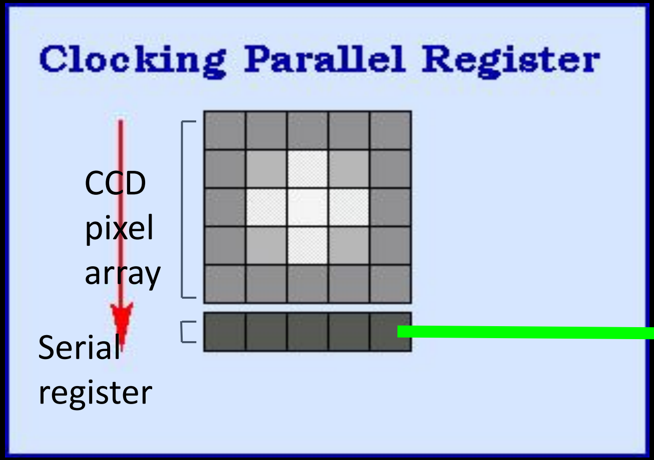
Rachel Hur

Advisor: Alex Drlica-Wagner

Charged Coupled Device

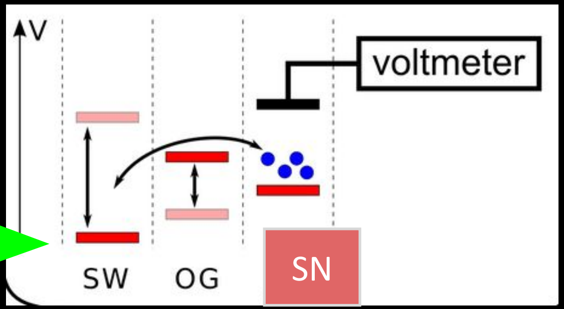


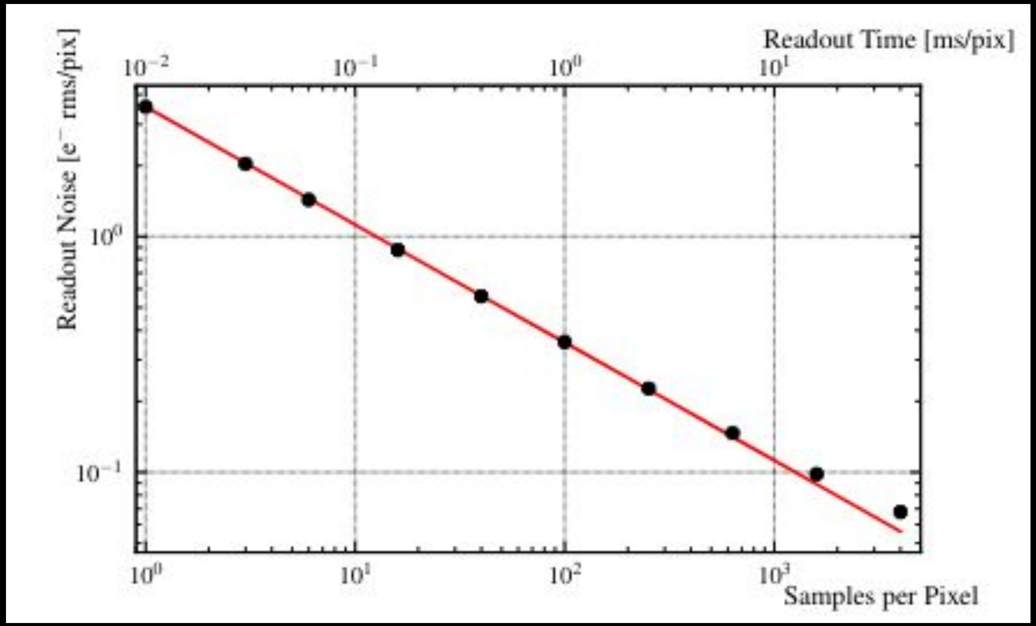
Skipper Charged Coupled Device



$$\sigma_N = \frac{\sigma_1}{\sqrt{N_{\rm samp}}}$$

Output stage modified





Tiffenberg et al. 2017, Figure 3

Motivation for Skippers in Astronomy and Cosmology

- Observations of faint objects in the low-signal, low-background regime are currently limited by readout noise
  - Exoplanets of nearby stars (.1e- rms/pixel)
  - High cadence searches for short duration transient signals; ie. fast radio bursts
  - Multi-object spectroscopy of faint stars and galaxies (.5e- rms/pixel)

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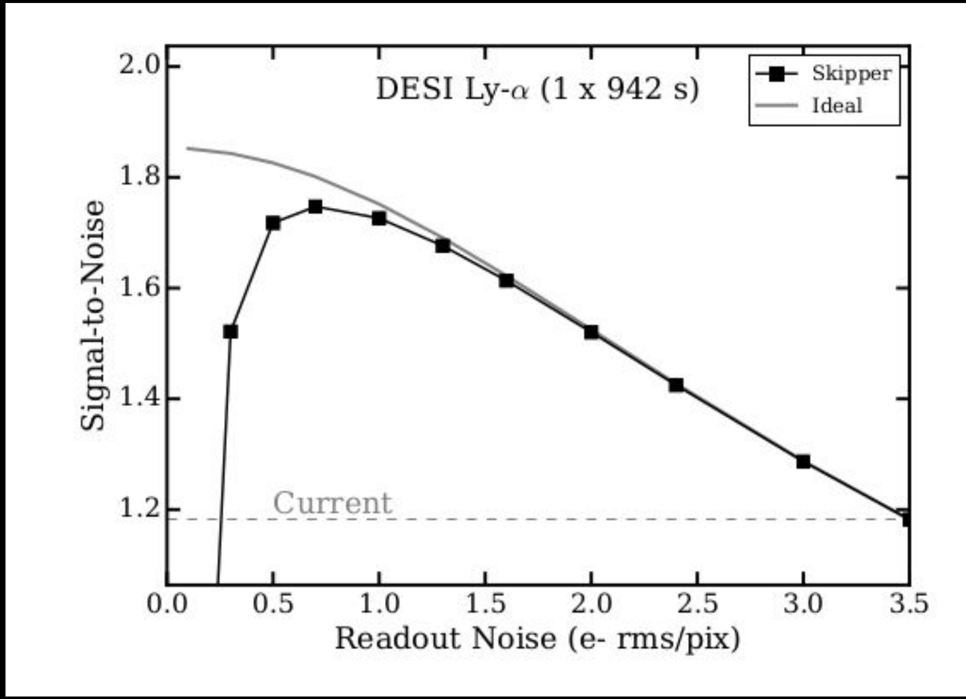
As a first proof-of-concept, Skipper CCDs will be used at the SOAR Integral Field Spectrograph (SIFS) to observe spectra of strong gravitational lensing systems

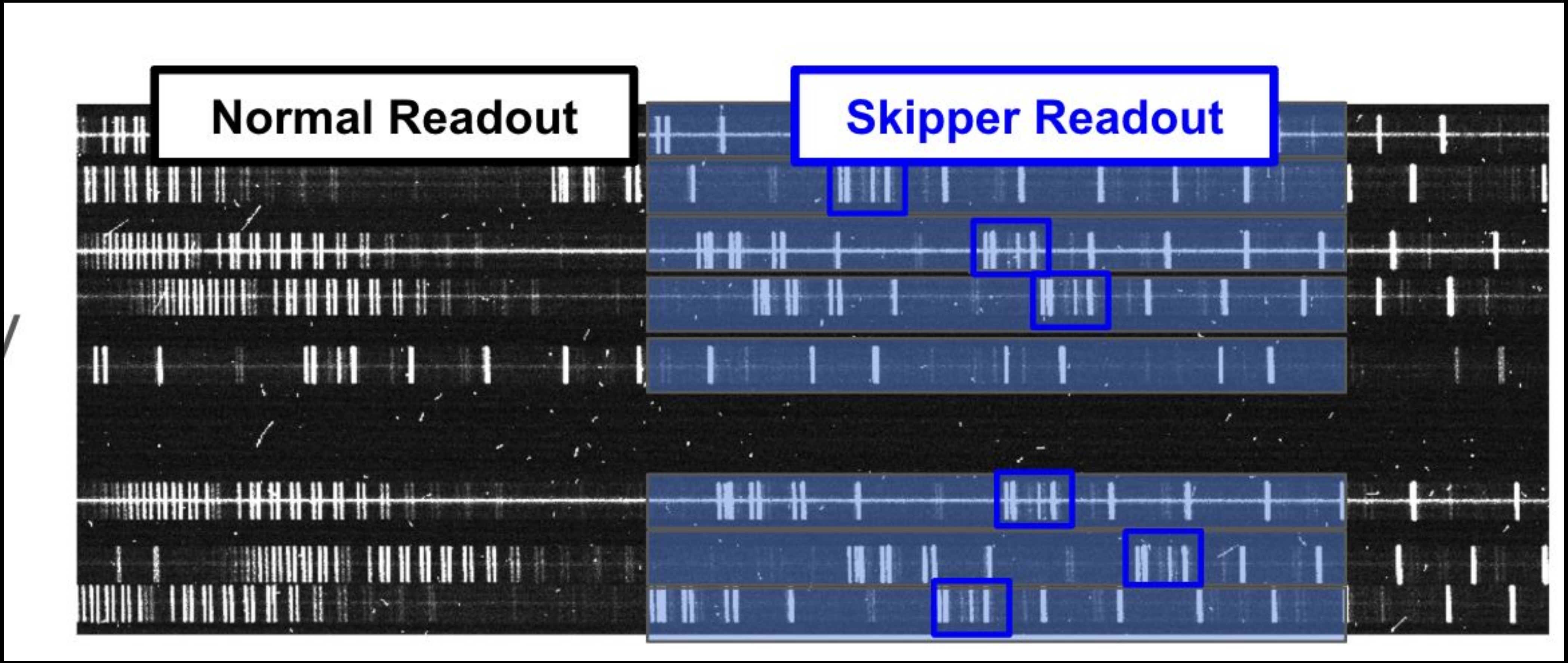
Optimizing S/N with Skippers at SIFS

- Observation time = exposure time + readout time
- Readout time scales with number of samples
- **Optimizing signal-to-noise ratio requires reduction in readout time**

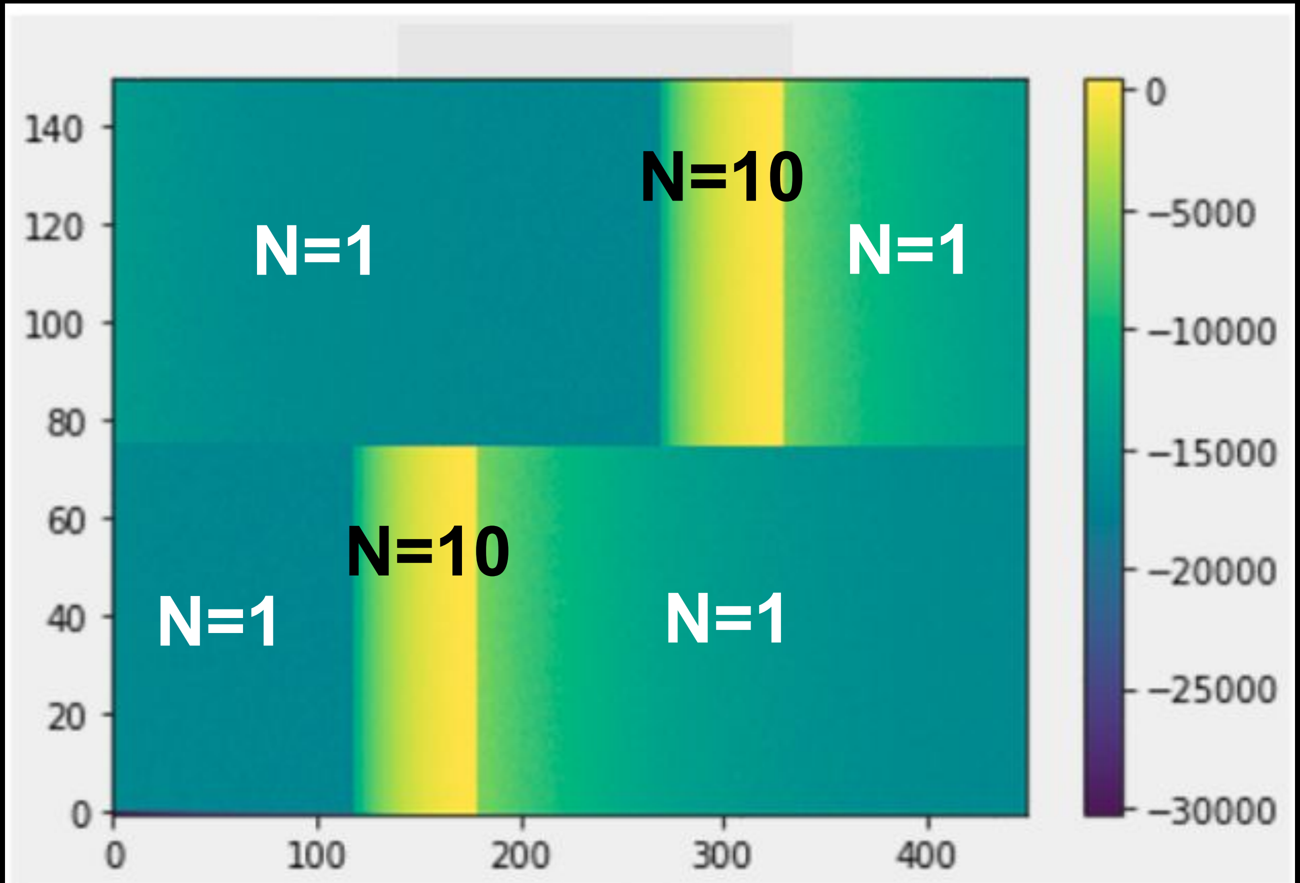
$$\mathrm{S/N} = \frac{\mathrm{R_{src}t_{exp}}}{\Sigma_{\mathrm{tot}}} = \frac{\mathrm{R_{src}t_{exp}}}{\sqrt{(\mathrm{R_{src}} + \mathrm{R_{bkg}} + \mathrm{R_{dark}})\mathrm{t_{exp}} + \mathrm{N}\sigma^2_{\mathrm{read}}}}.$$



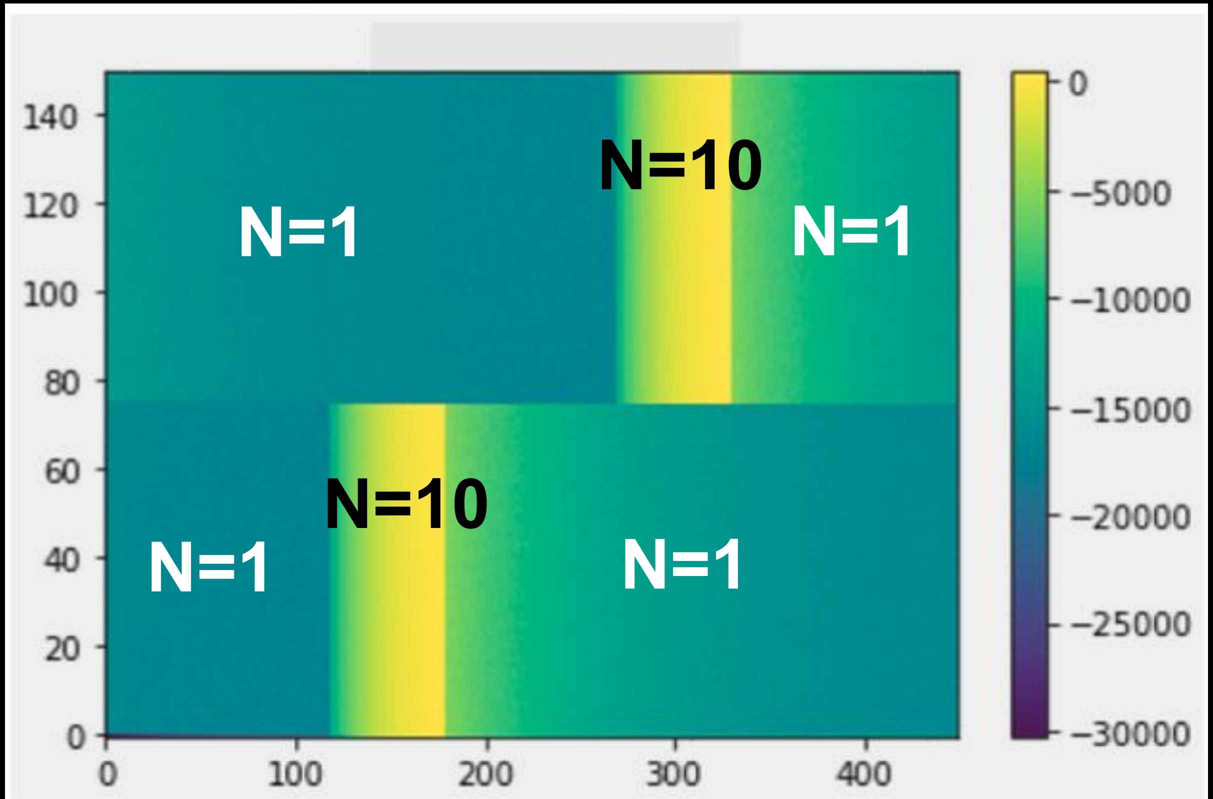
Regional selection

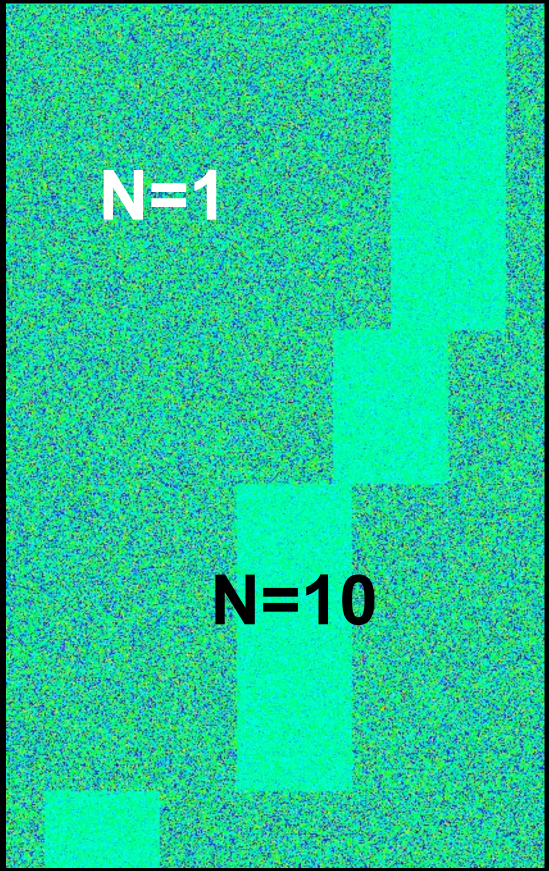


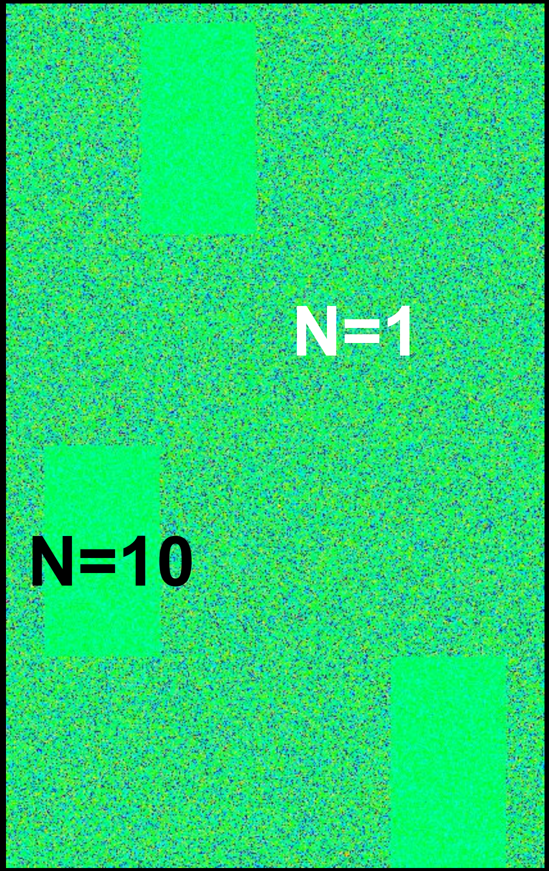
Regional Selection



Regional Selection

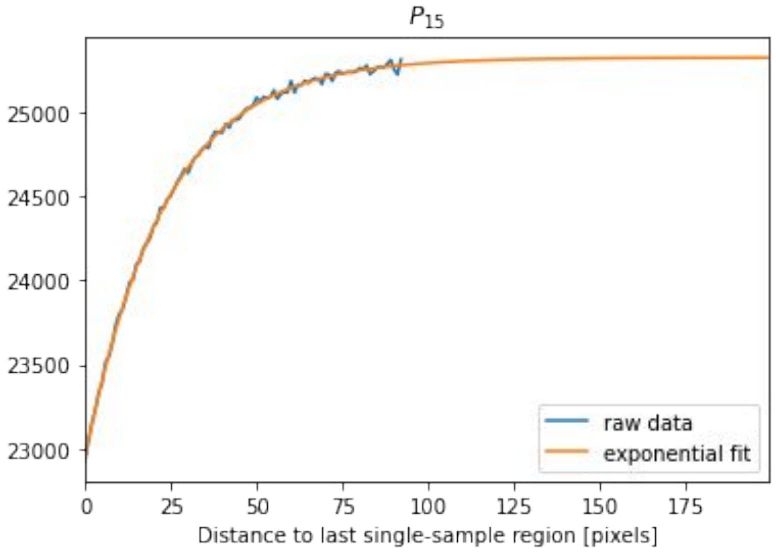


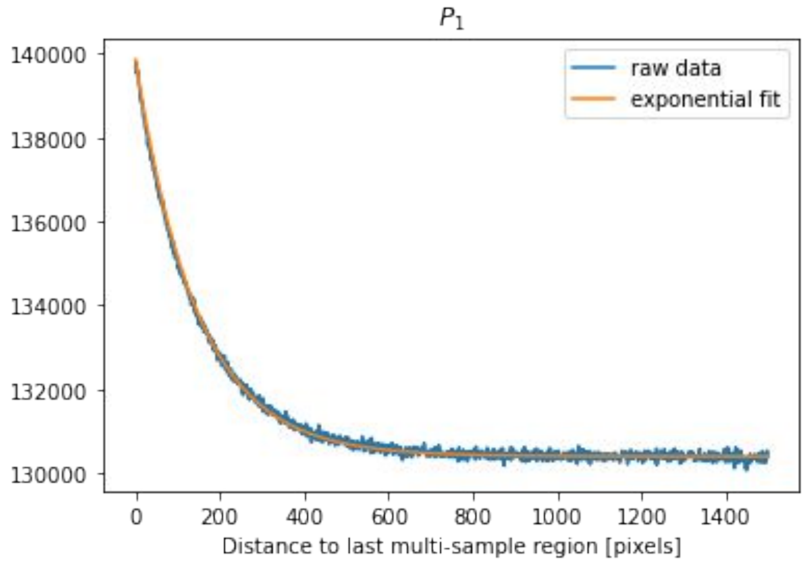




Predictive baseline model

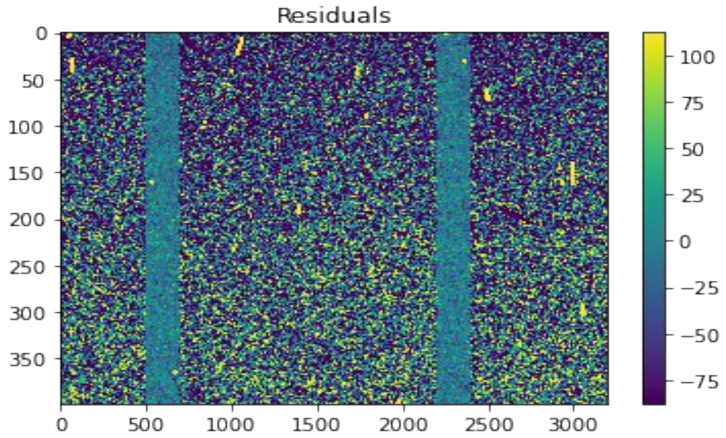
- Transients are exponentially decaying over time
- Transients are independent - bias shifts are simply additive
- Lookup tables for each noise source are generated from only one set of calibration images
- Predicts baseline shifts for any set of regions of interest

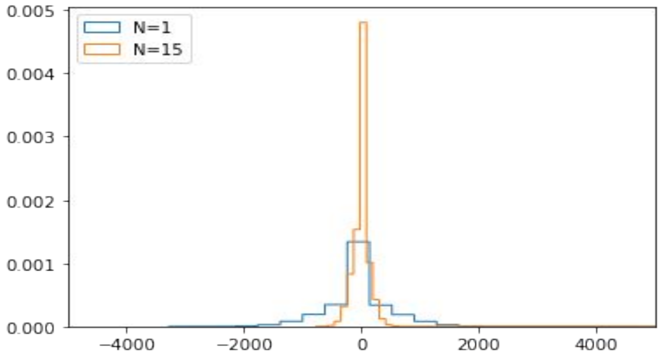




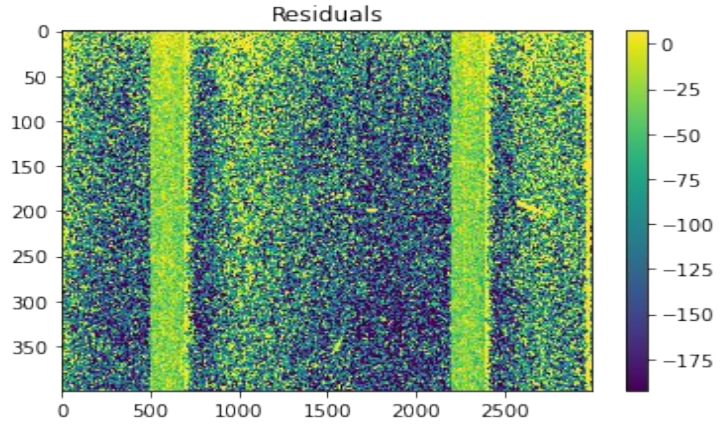
Preliminary Results

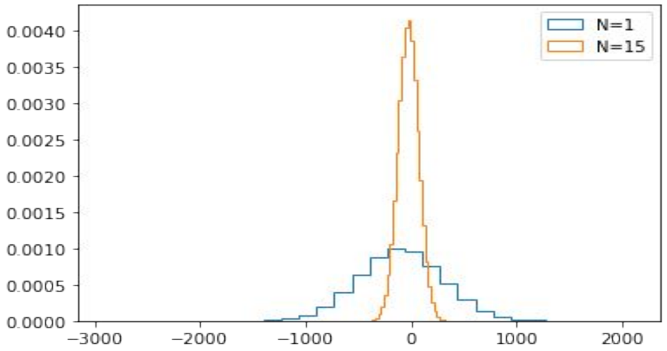
(1) Master bias image subtraction method





(2) Predictive exponential fitting model

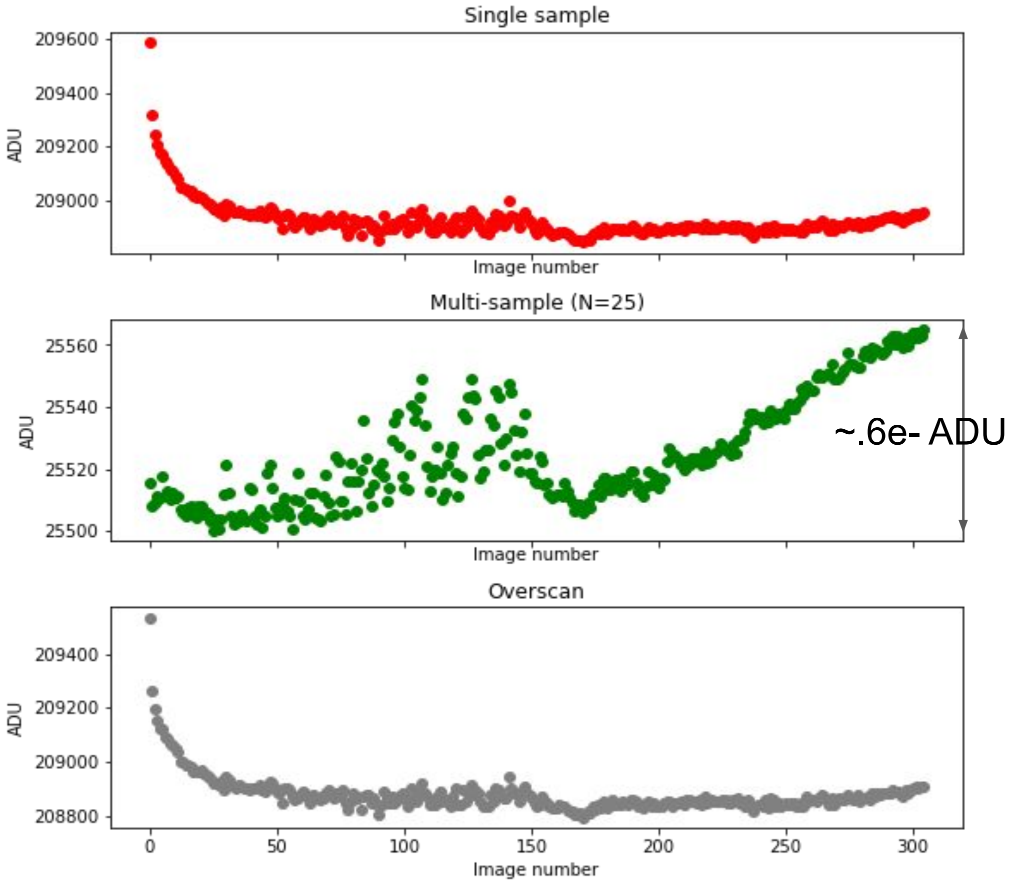




Summary

- Skipper CCDs can significantly decrease readout noise levels by taking multiple, non-destructive samples per pixel
- Skipper CCDs could improve on current astronomical observations with conventional CCDs
- A Skipper CCD composed focal plane will be used at SIFS as a first, proof-of-concept application of Skippers to astronomy
- Regional selection can significantly reduce readout time and aid in optimizing signal-to-noise ratio
- Regional selection will be implemented for the first time in a real observing scenario at SIFS

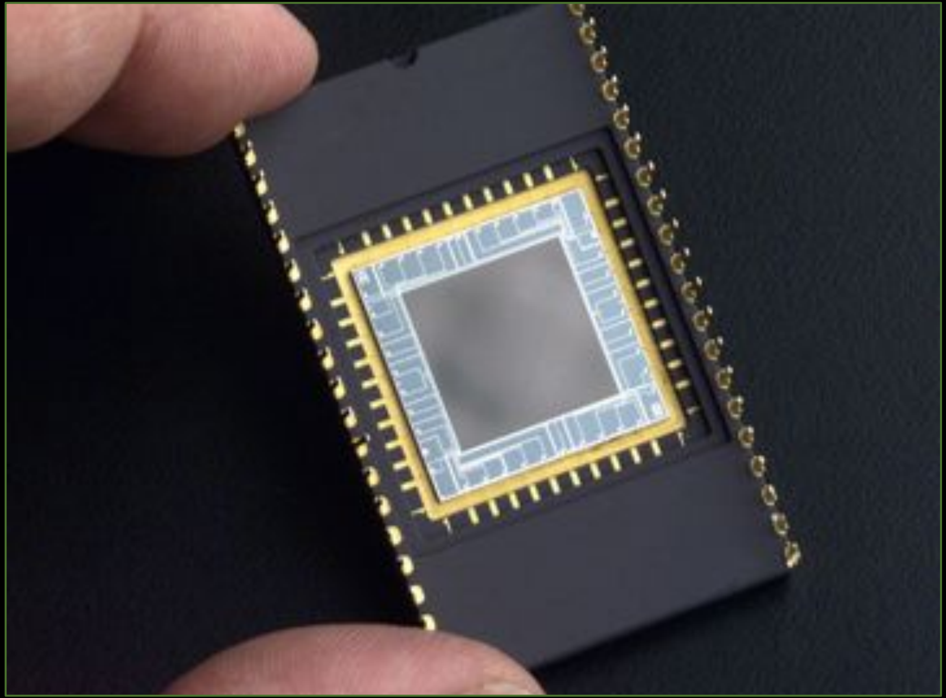
300 pixel multisample region width

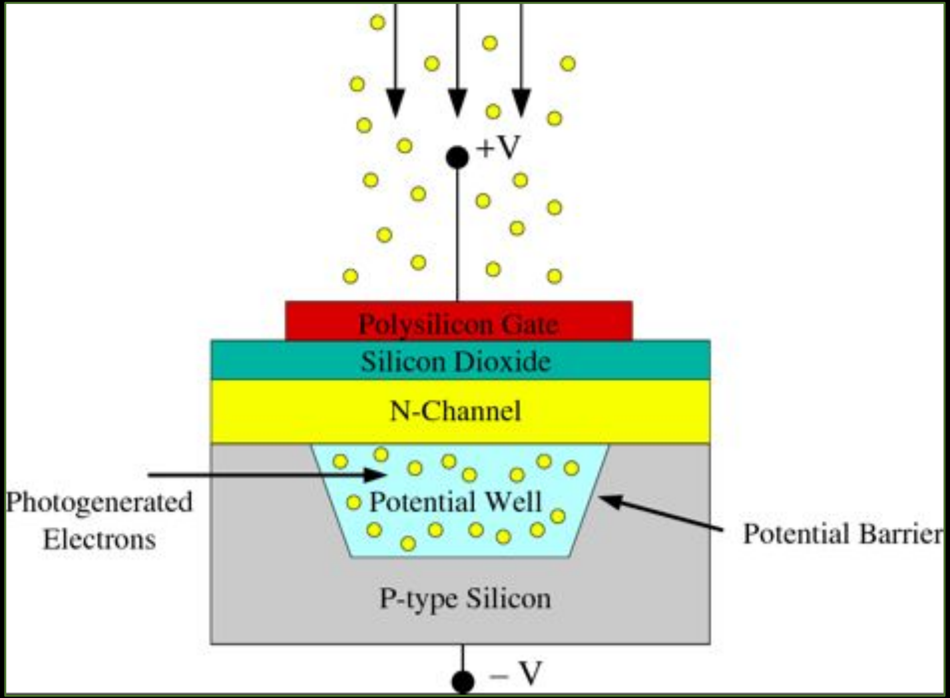


$$\mathrm{S/N} = \frac{\mathrm{R_{src}t_{exp}}}{\Sigma_{\mathrm{tot}}} = \frac{\mathrm{R_{src}t_{exp}}}{\sqrt{(\mathrm{R_{src}} + \mathrm{R_{bkg}} + \mathrm{R_{dark}})\mathrm{t_{exp}} + \mathrm{N}\sigma^2_{\mathrm{read}}}}.$$

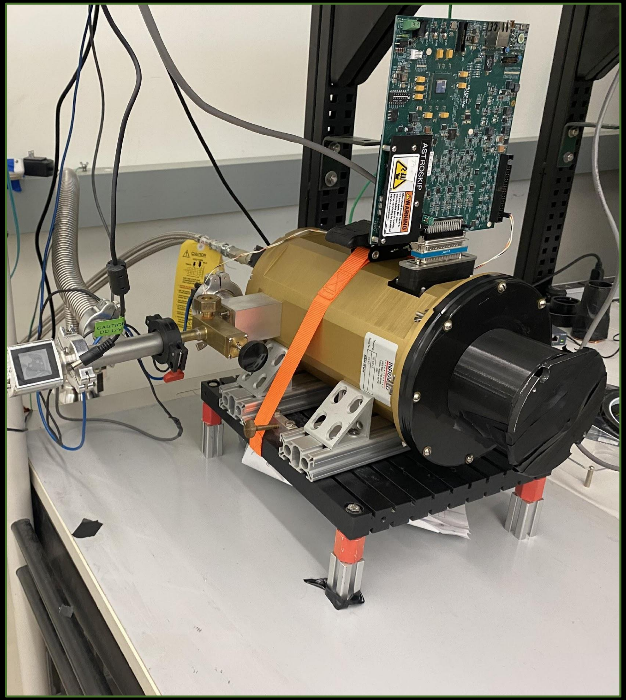
Outline

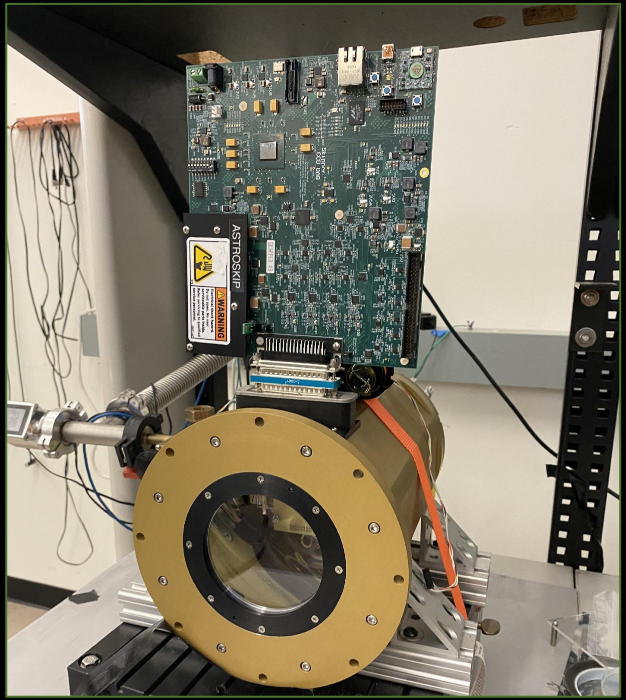
1) What are CCDs?
2) How do Skipper CCDs reduce readout noise?
3) Benefits of regional selection
4) Mitigating transient noise effects in regional selection

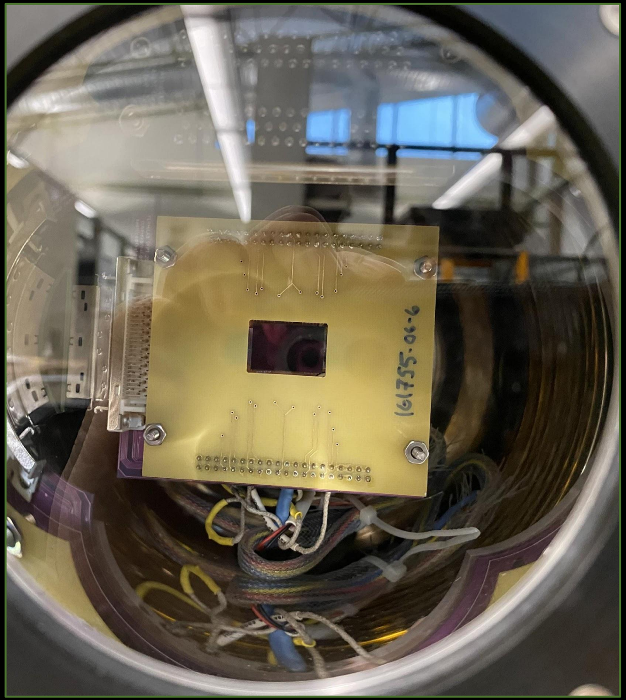




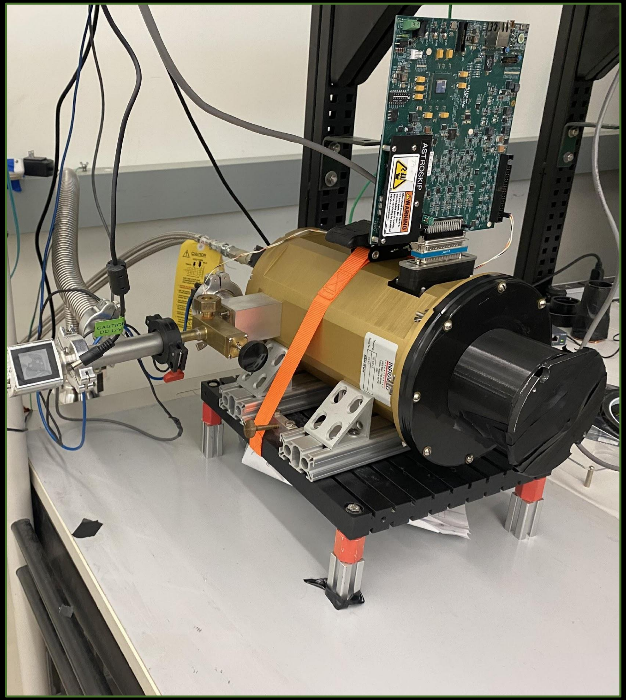
Charged Coupled Device

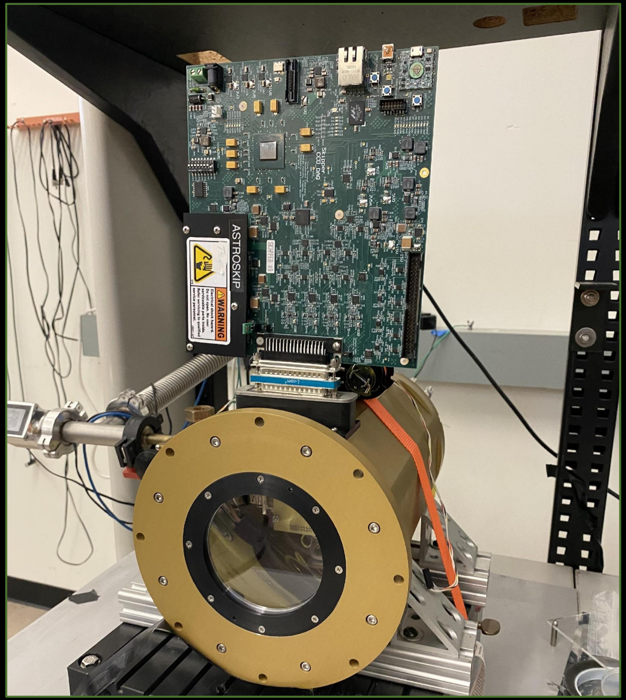


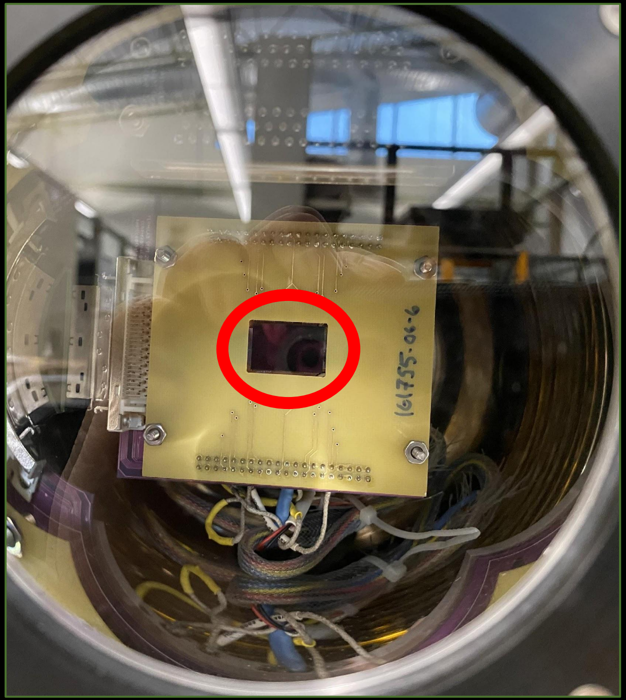




Testing setup at Fermilab







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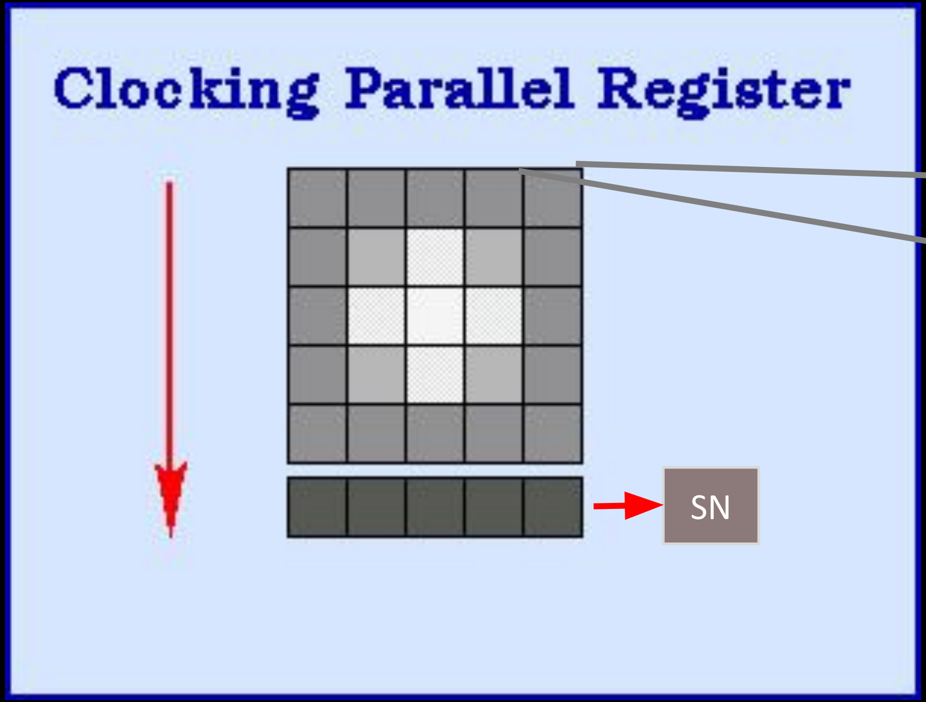

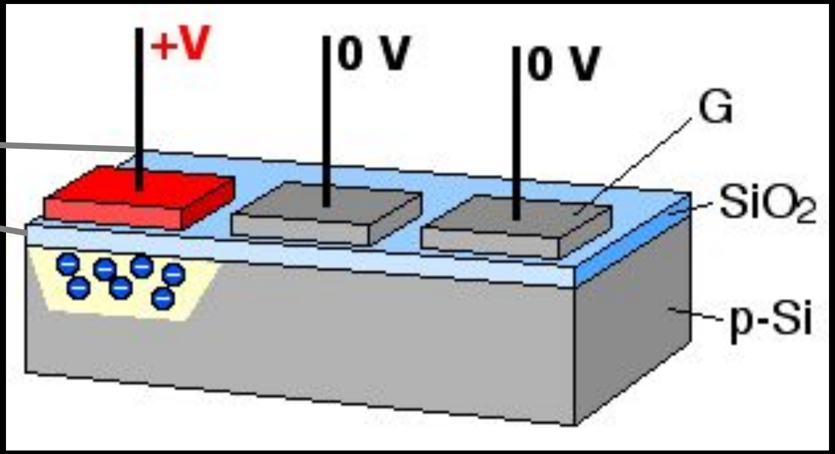

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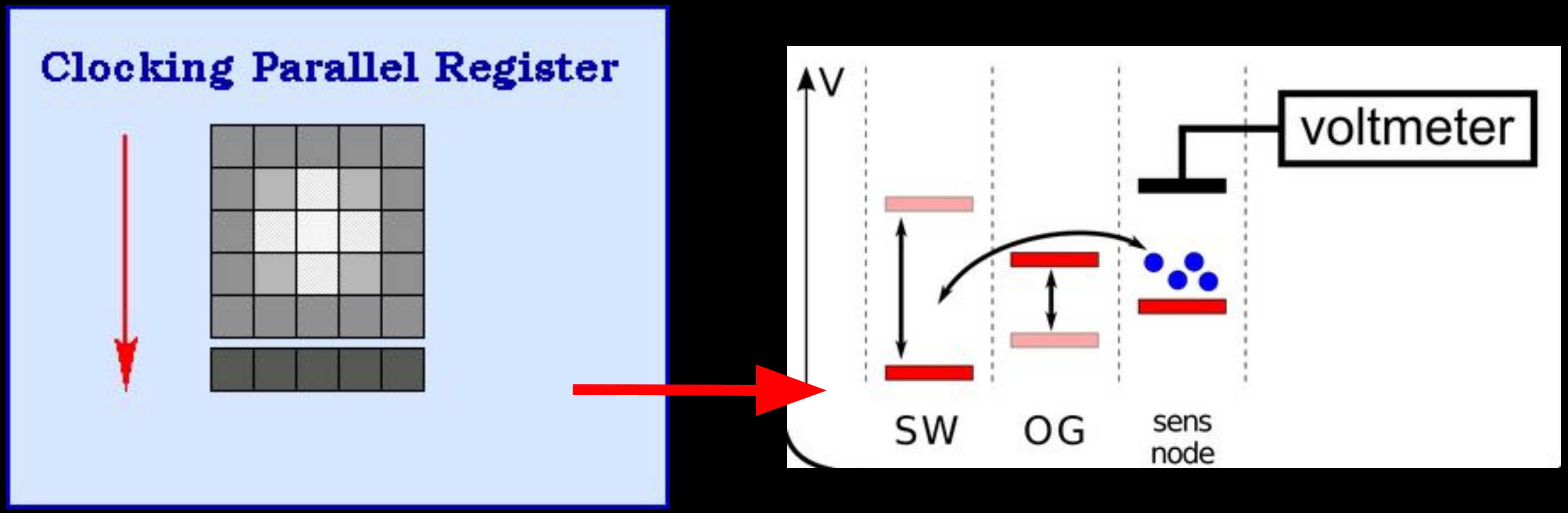
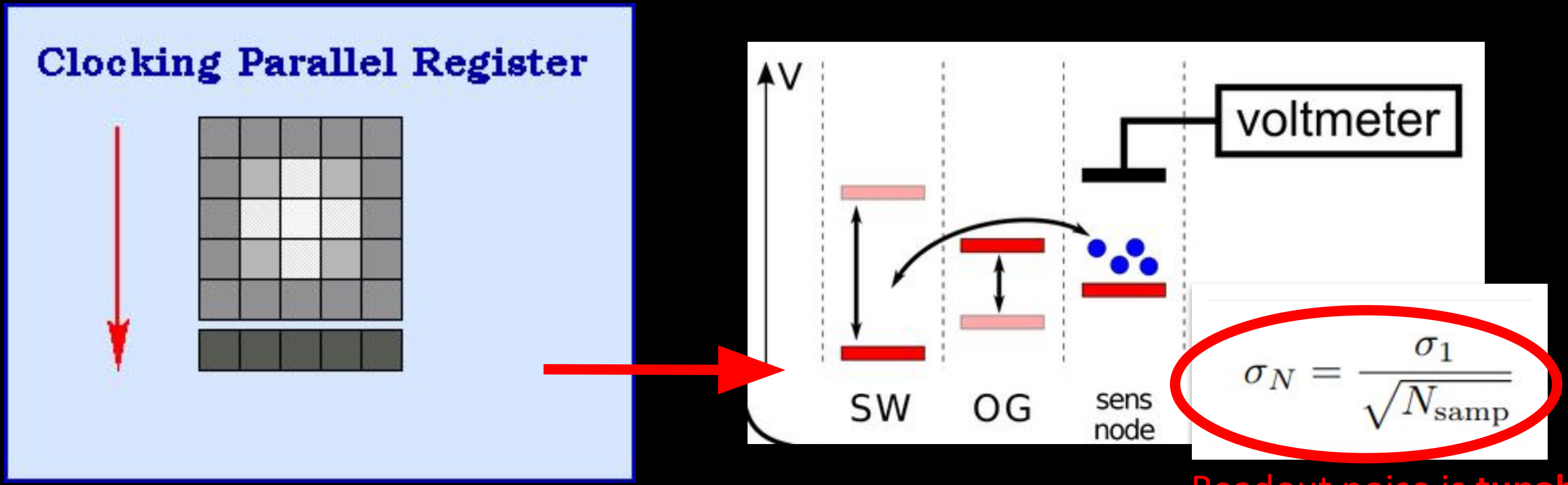


Only output stage modified

Skipper Charged Coupled Device



Readout noise is **tunable**

Only output stage modified

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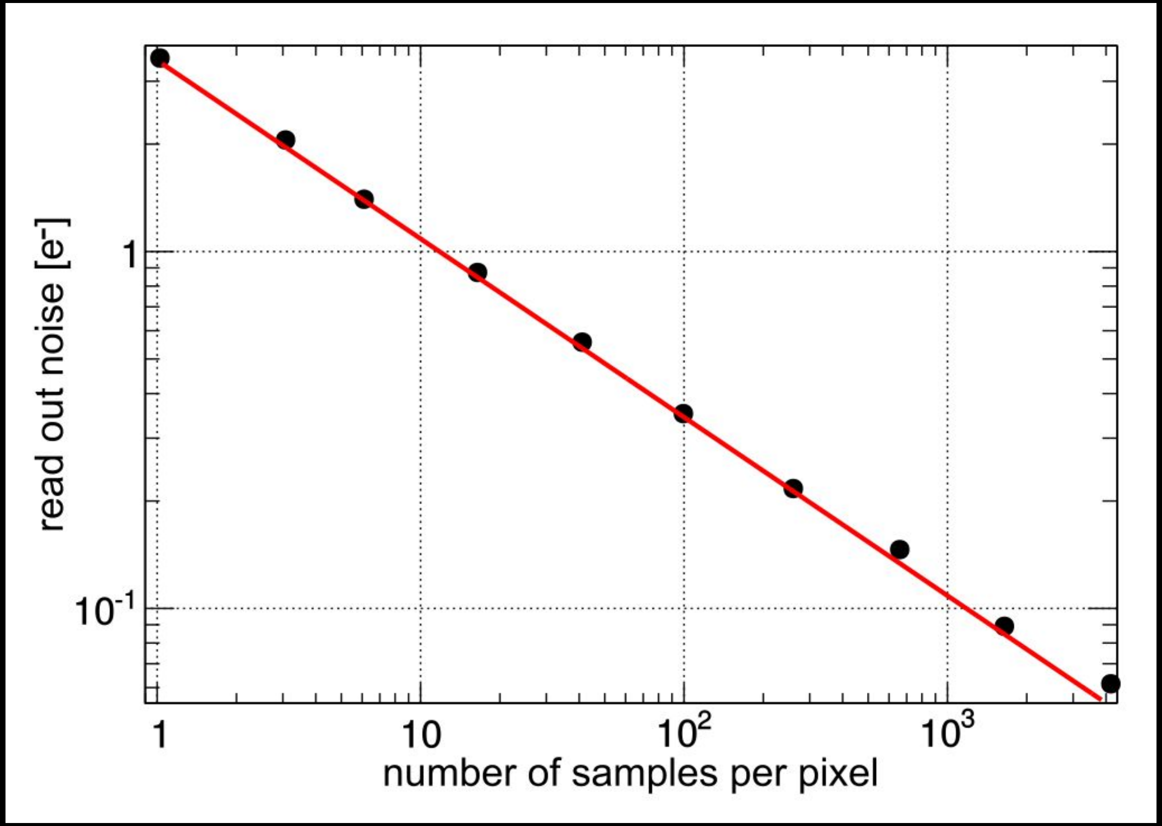
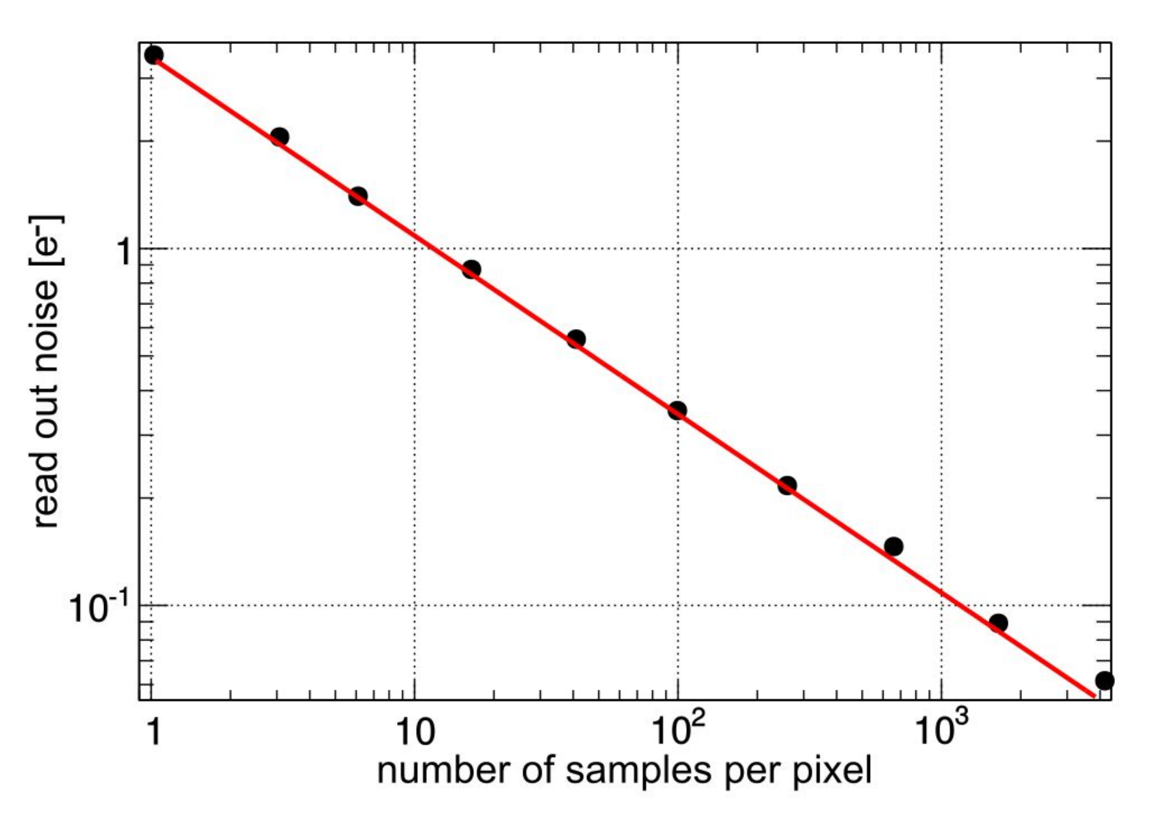


$$\sigma_N = \frac{\sigma_1}{\sqrt{N_{\mathrm{samp}}}}$$

Readout noise is **tunable**

Skipper Charged Coupled Device



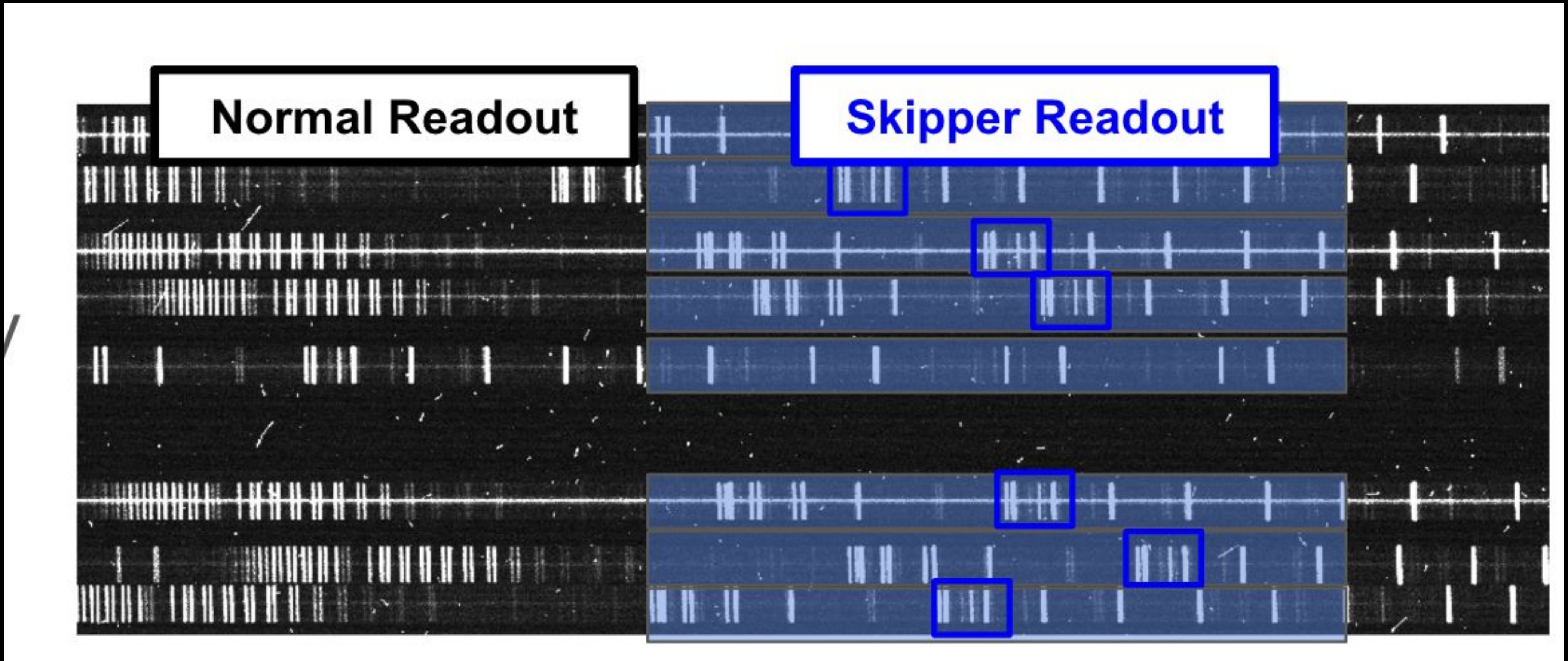
$$\sigma_N = \frac{\sigma_1}{\sqrt{N_{\rm samp}}}$$

Readout noise is **tunable**

Cost: readout time

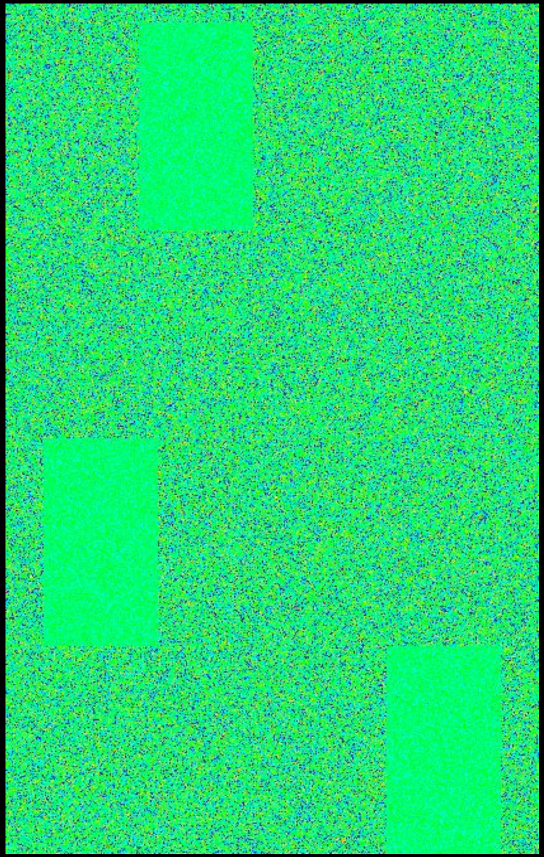
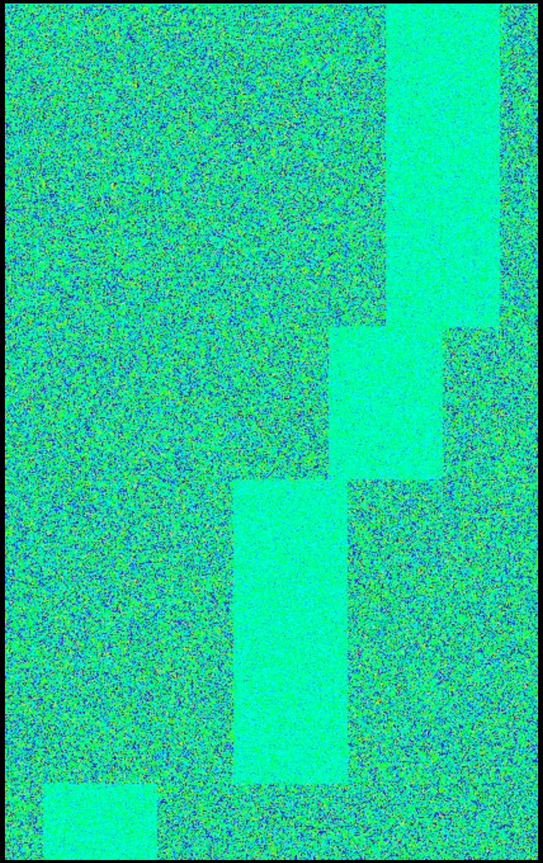
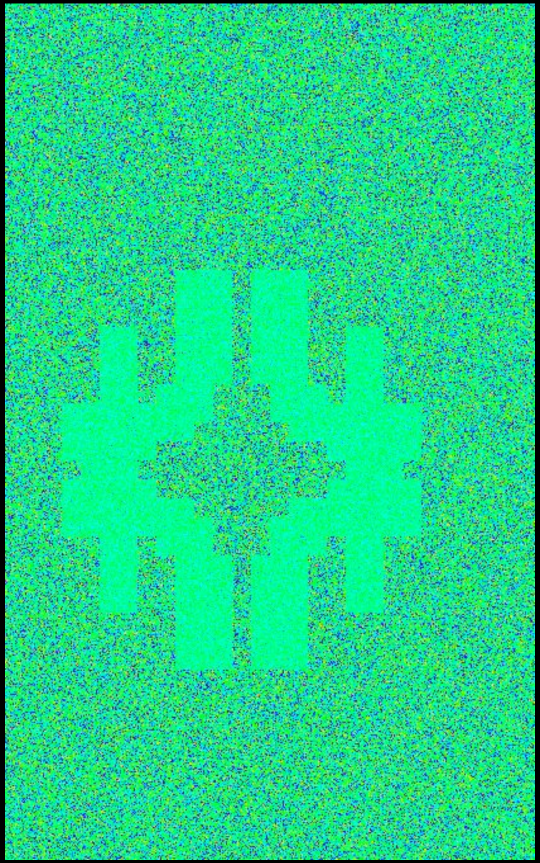
$$t_{\rm obs} = t_{\rm exp} + (1-f)t_{\rm read} + fN_{\rm samp}t_{\rm read}.$$

Skipper Charged Coupled Device

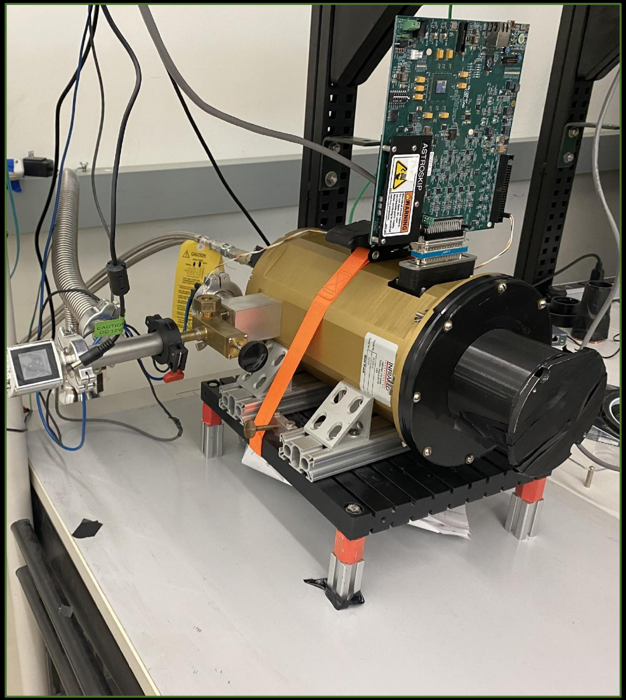


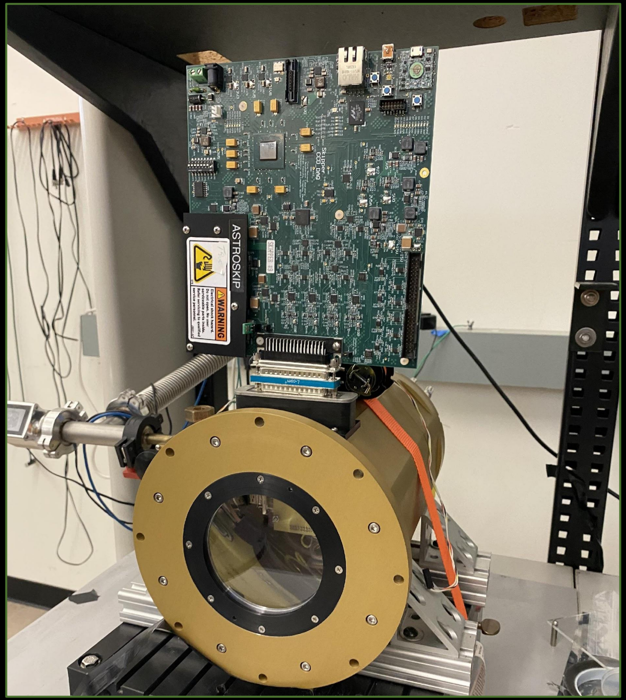
$$t_{\rm obs} = t_{\rm exp} + (1 - f)t_{\rm read} + fN_{\rm samp}t_{\rm read}.$$

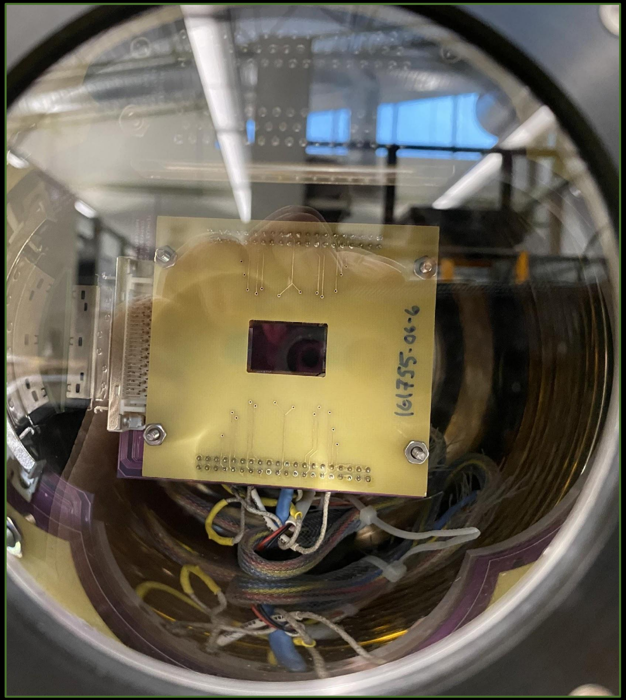
Benefits of Regional Selection

Regional selection

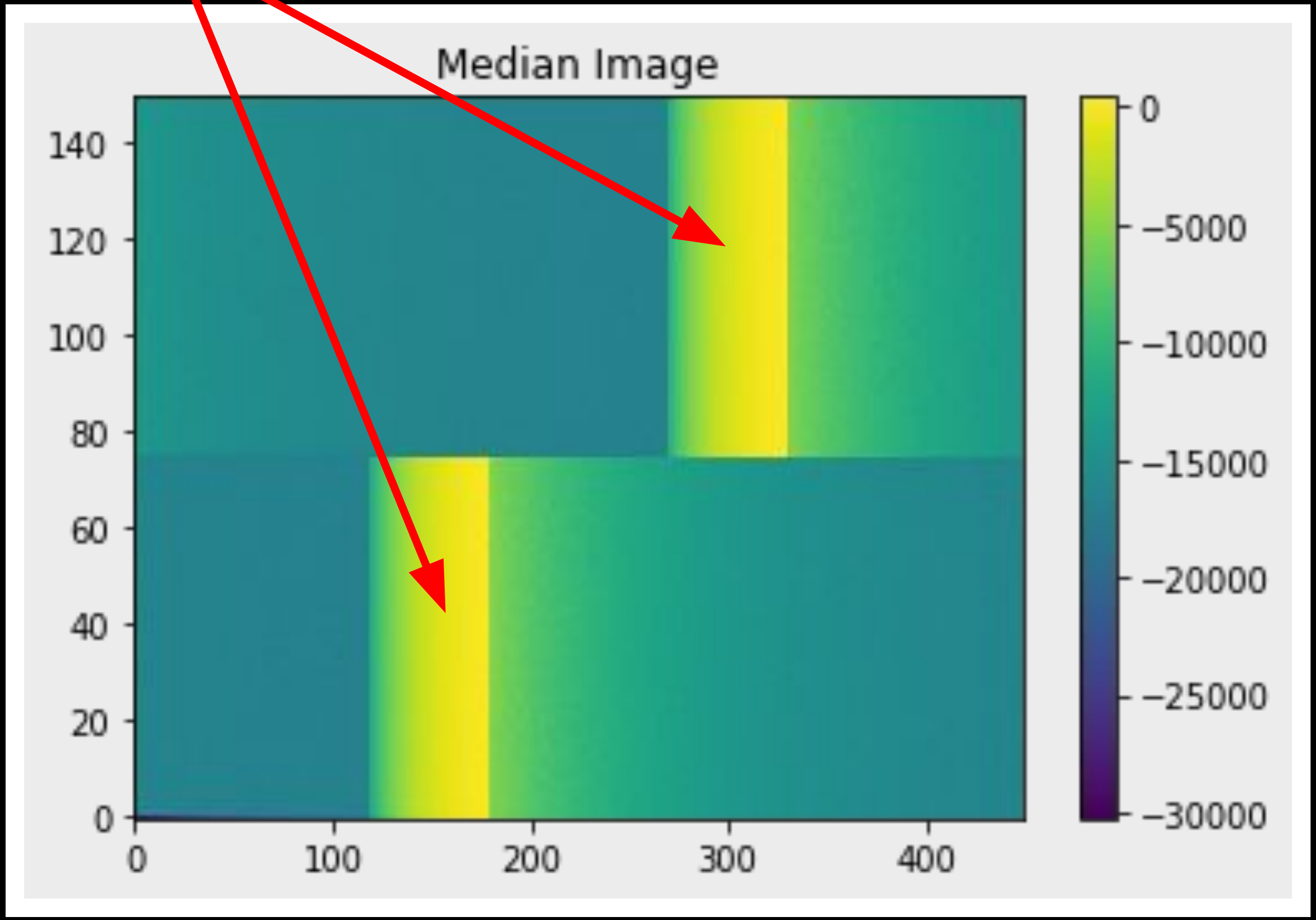






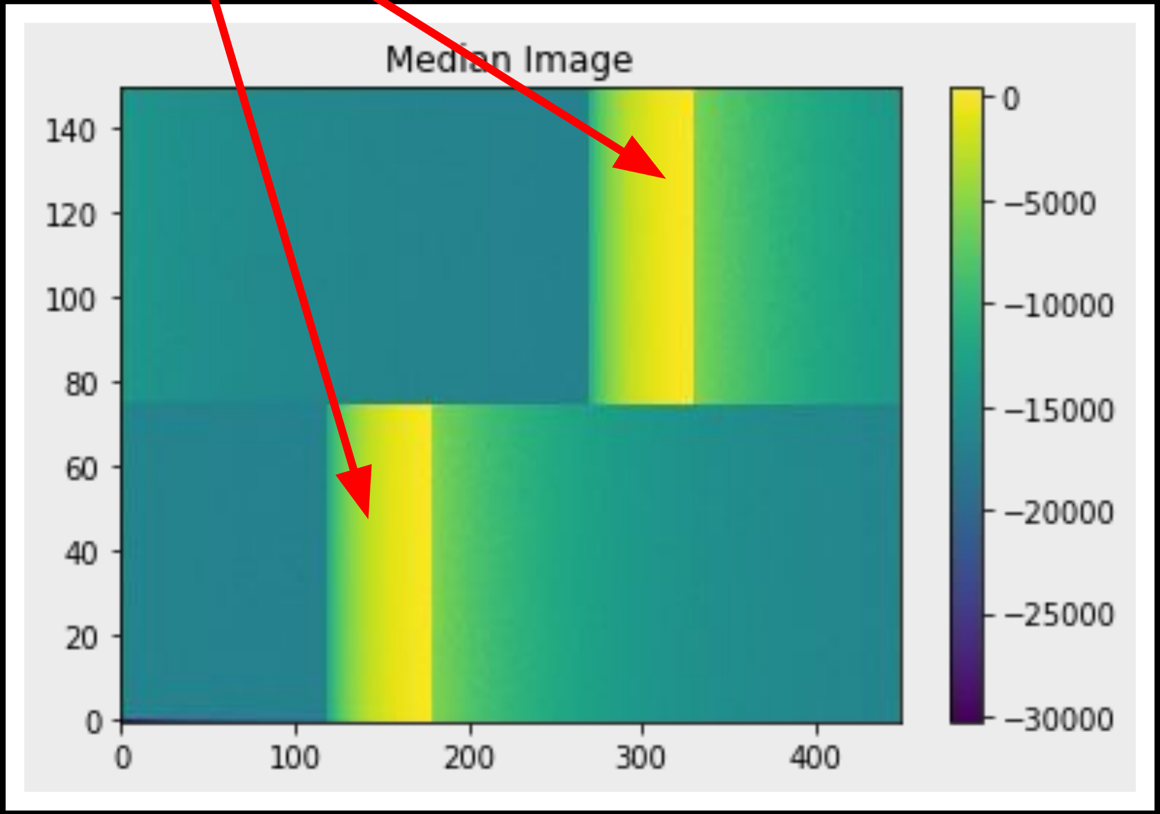
Testing setup at Fermilab

N=10



Median Image
140
120
100
80
60
40
20
0
0
100
200
300
400
0
−5000
−10000
−15000
−20000
−25000
−30000

N=10


Median Image
140
120
100
80
60
40
20
0
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−5000
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−20000
−25000
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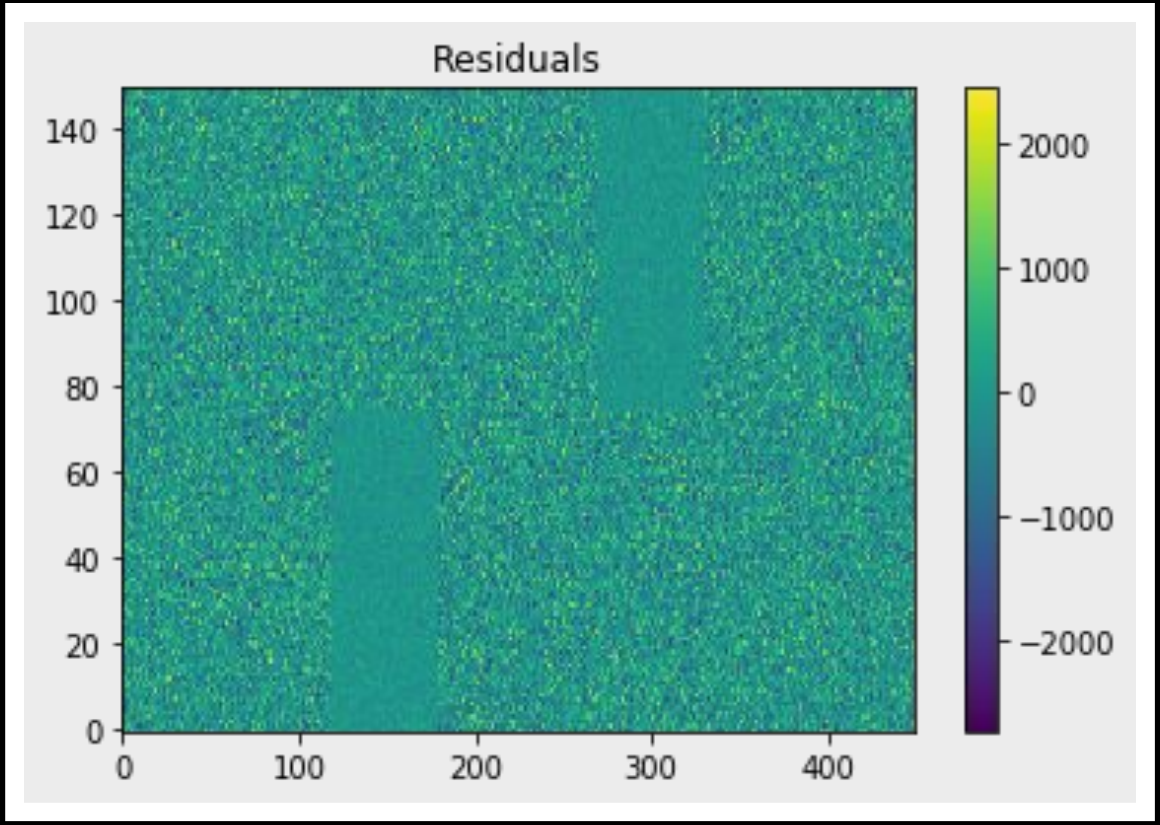
Residuals
140
120
100
80
60
40
20
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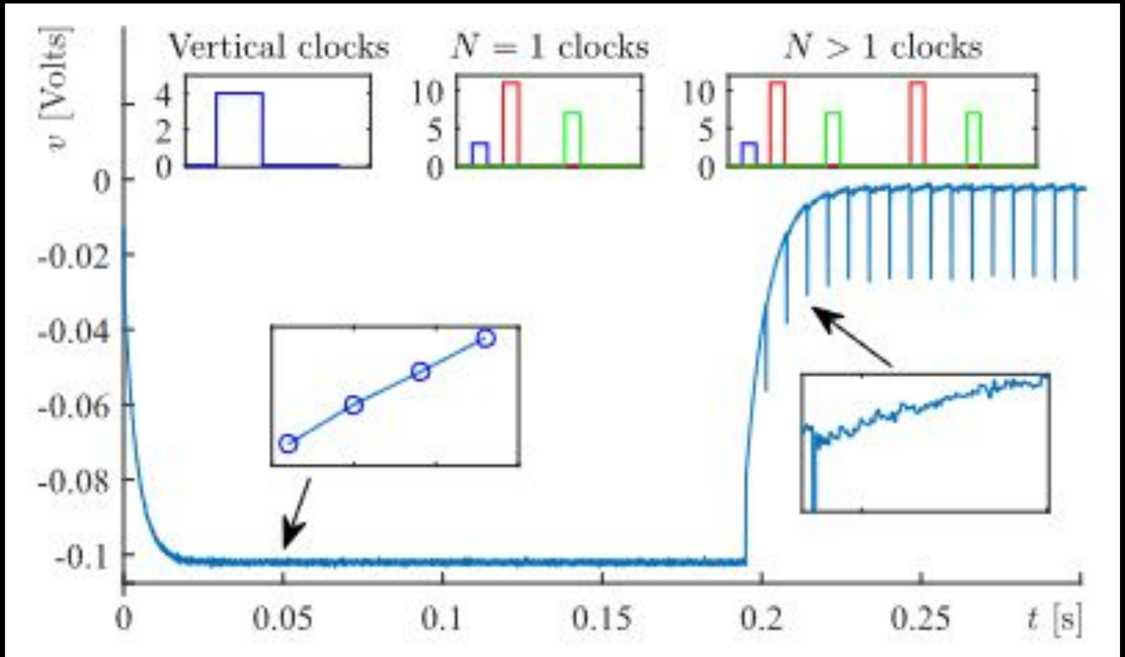
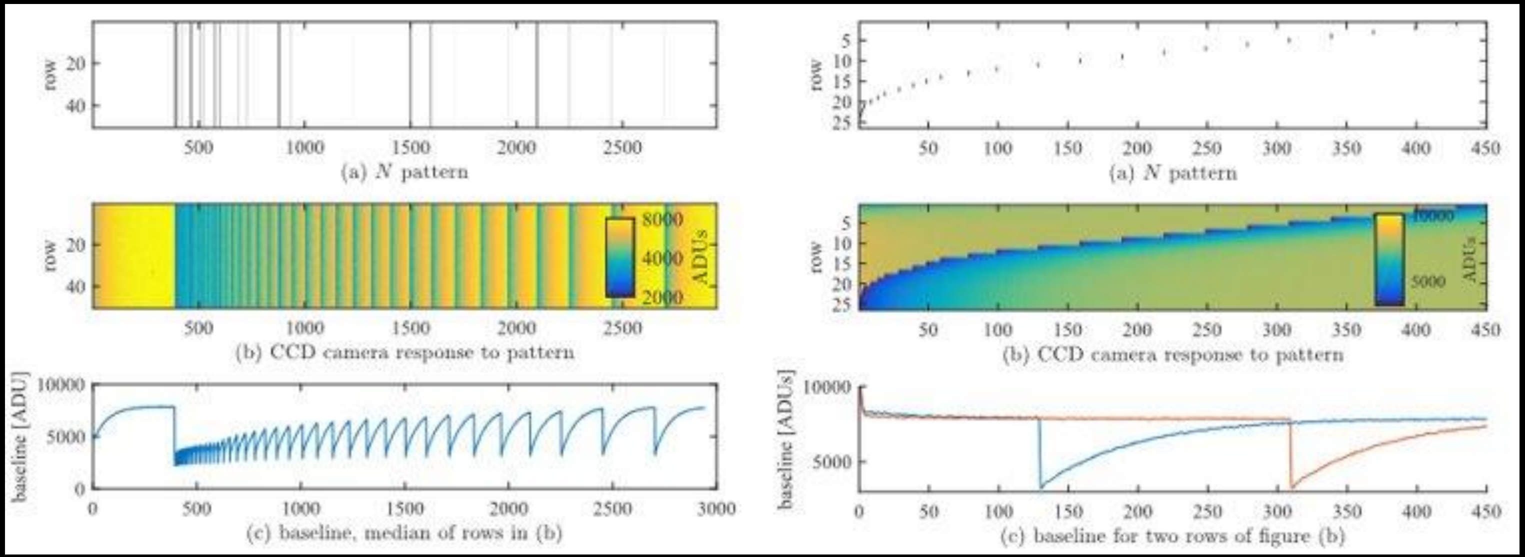
0
100
200
300
400
2000
1000
0
−1000
−2000

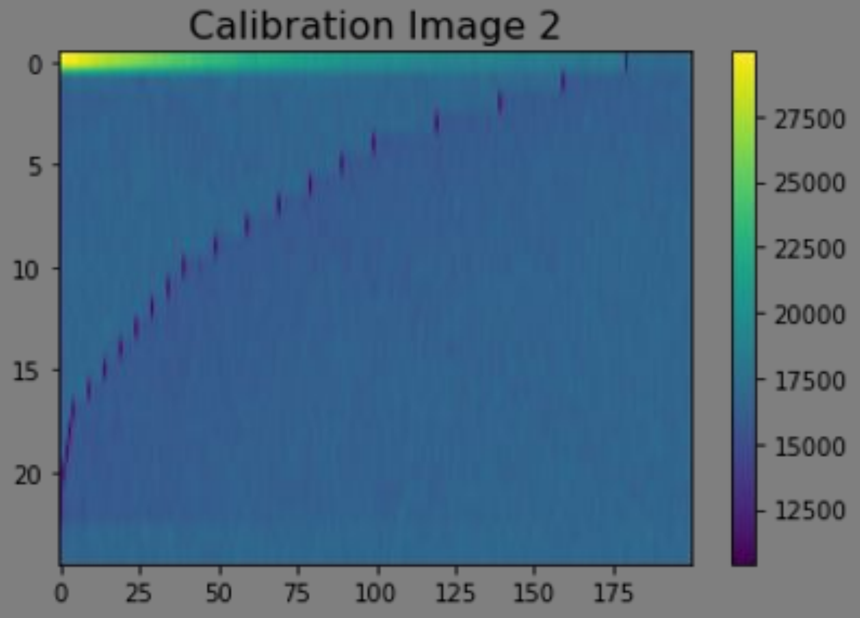
Looking forward: Mitigating transient noise

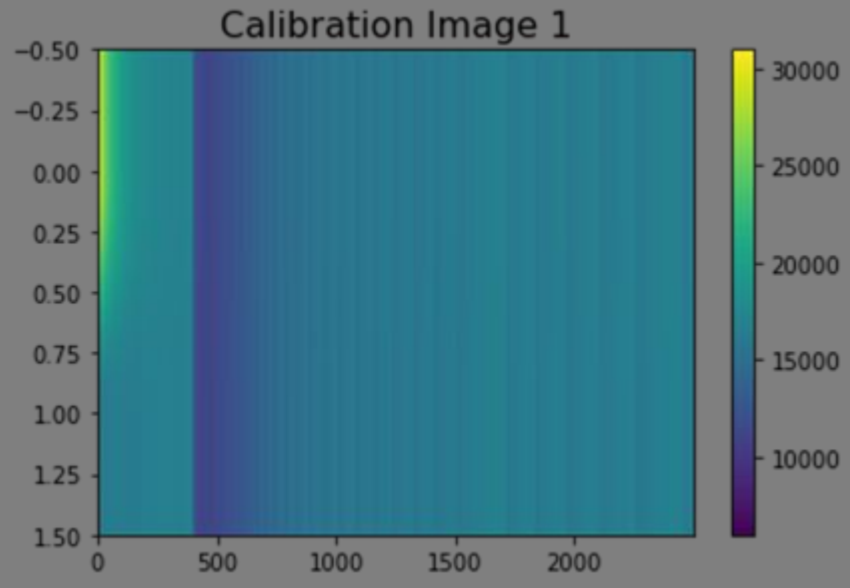


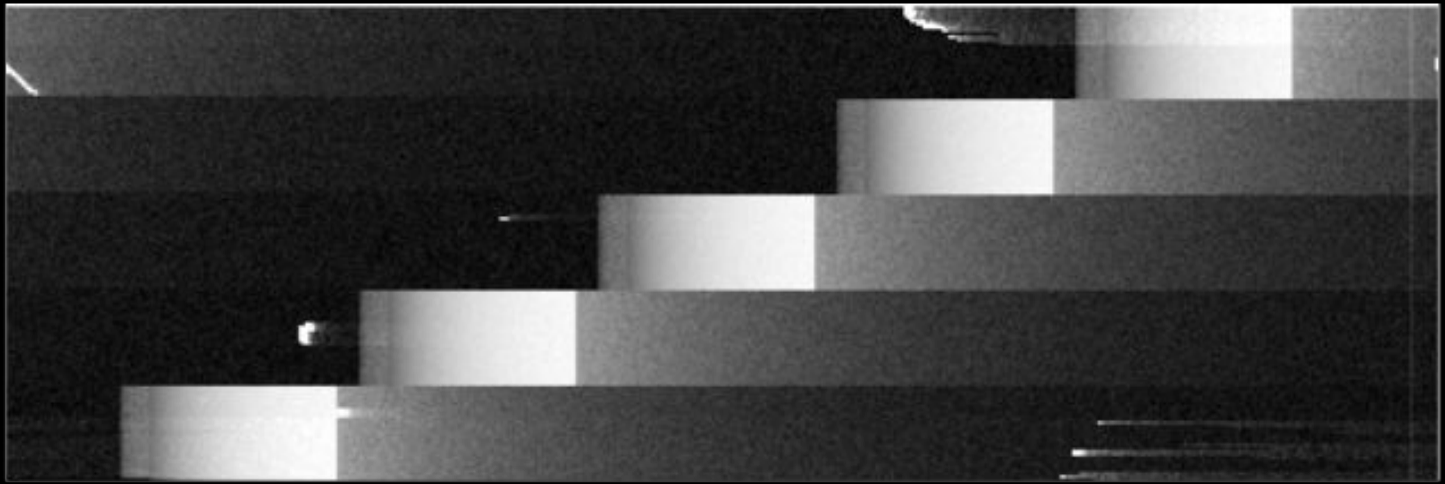
Looking forward: Mitigating transient noise

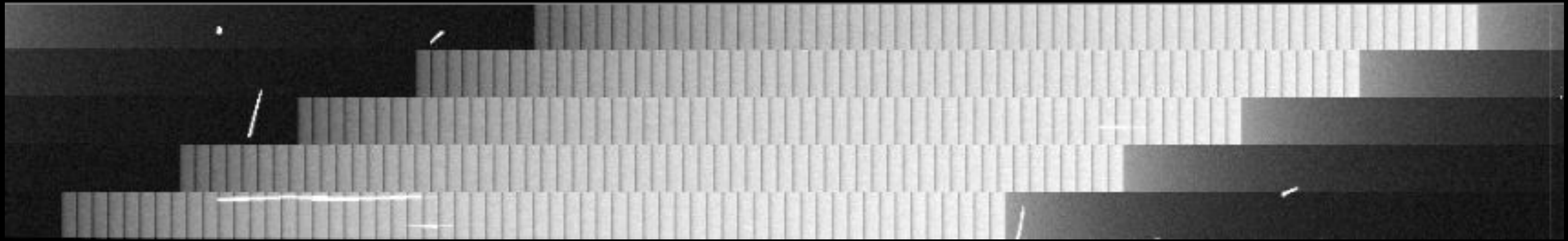


Calibration images



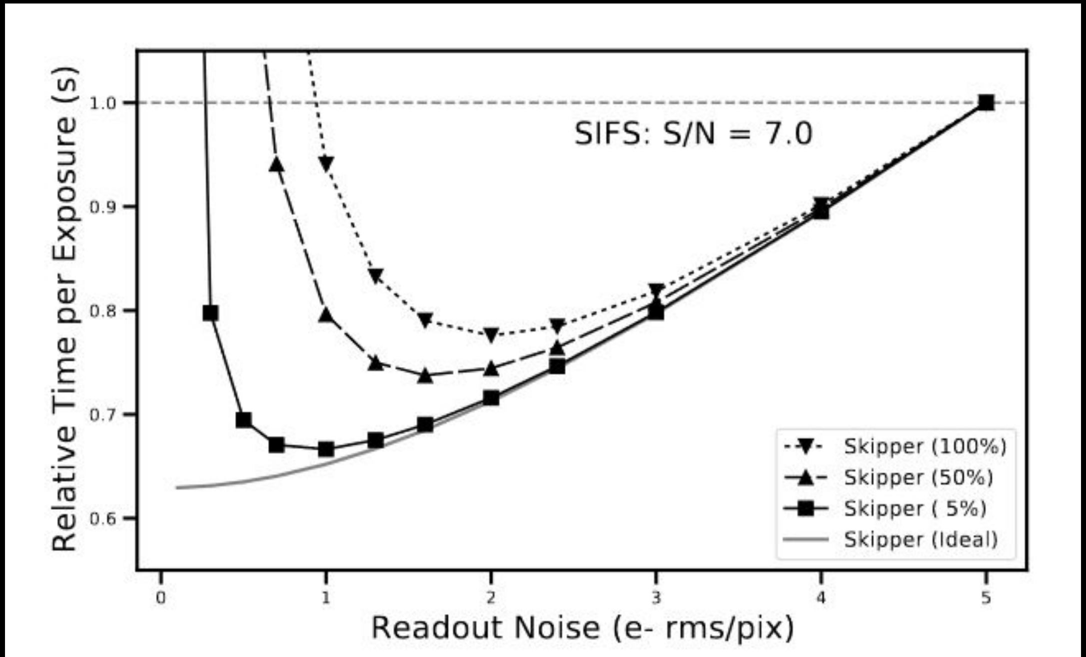






N=10

Skipper CCDs



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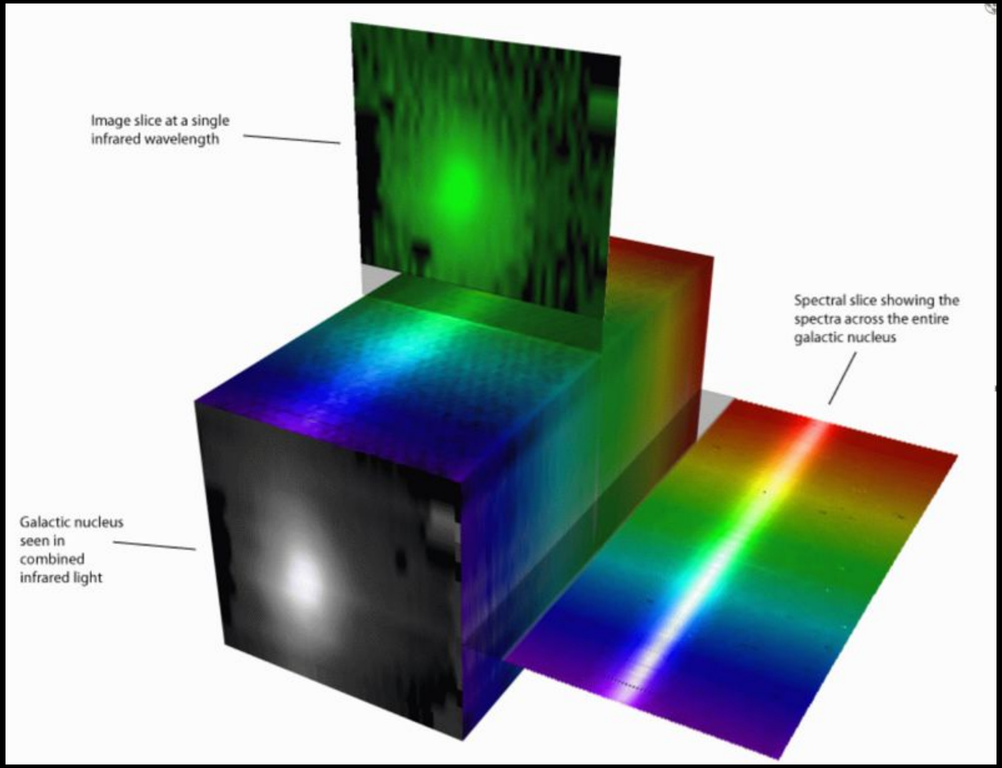
$$\Sigma_{\mathrm{tot}} = \sqrt{(R_{\mathrm{src}} + R_{\mathrm{bkg}} + R_{\mathrm{dark}})t_{\mathrm{exp}} + N_{\mathrm{samp}}\sigma_N^2}$$

Integral Field Unit Datacube



Readout noise

- Electrical noise added to the CCD video signal
- Main source: CCD output amplifier
- Other sources: voltage biases and clock signals used for charge collection and transfer

Cosmic rays!