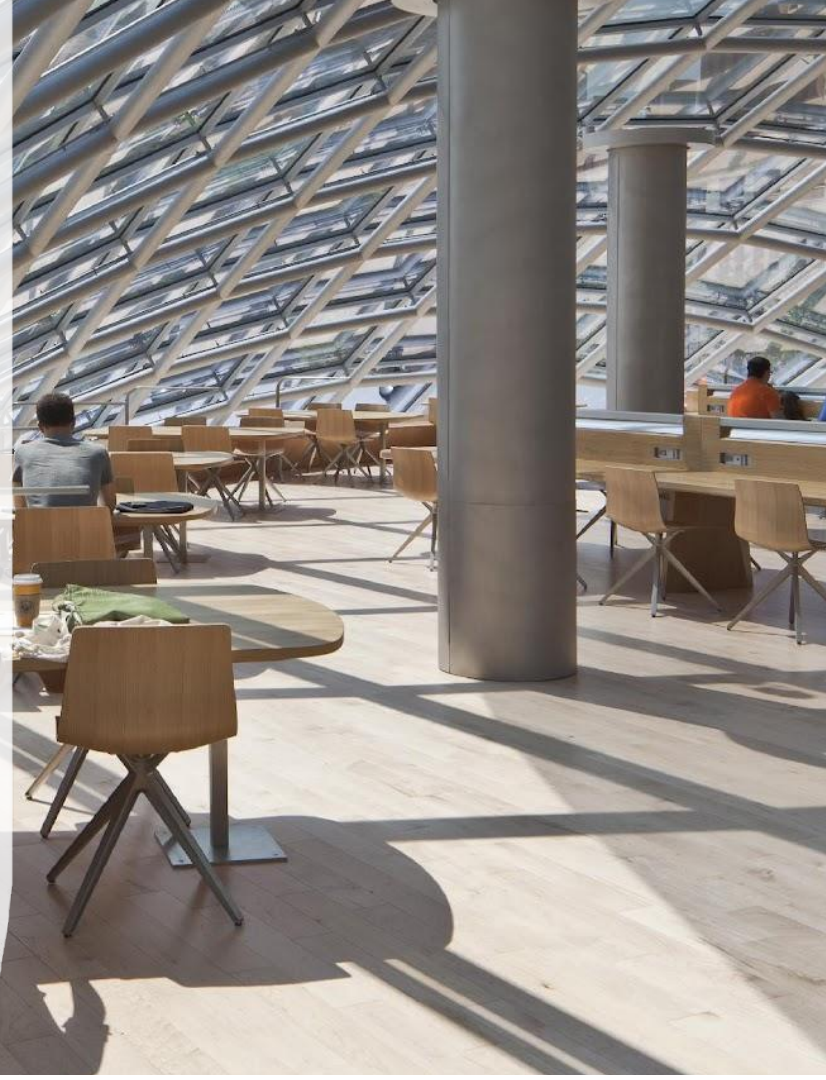


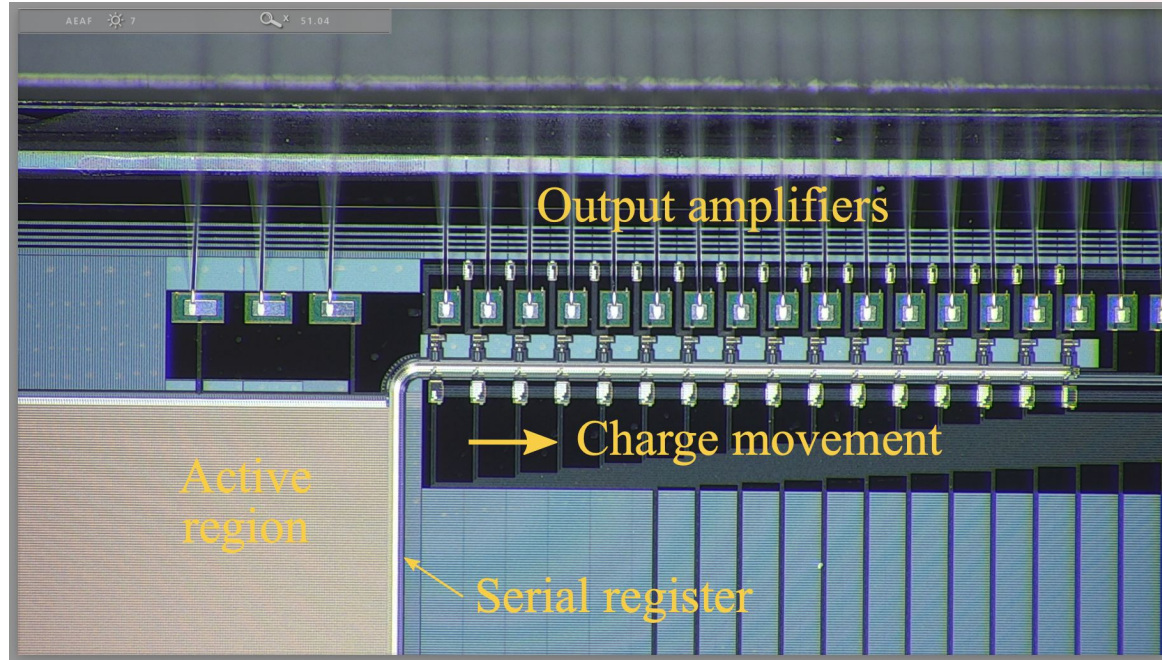
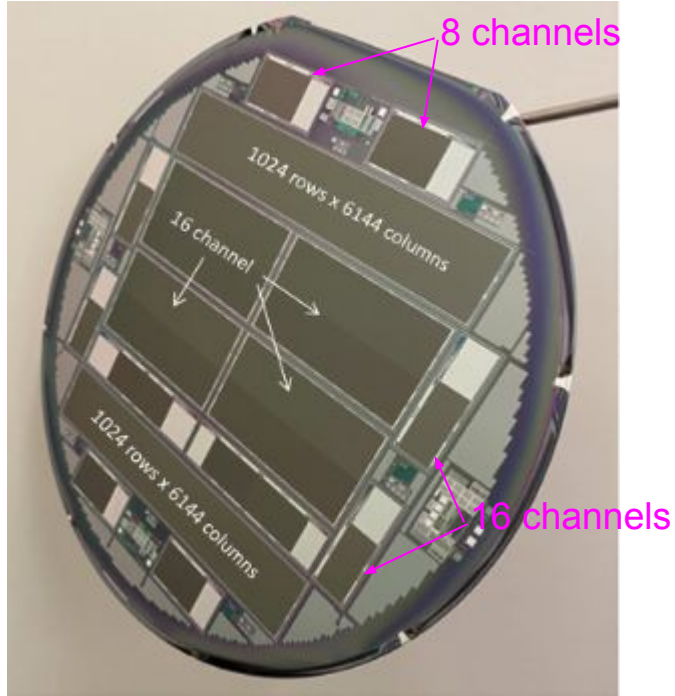
p-channel MAS-CCD characterization results and instrumentation efforts

Agustin Lapi – University of Chicago – ajlapi@uchicago.edu

Authors: Agustin Lapi, Guillermo Fernandez-Moroni, Fernando Chierchie, Blas Irigoyen Gimenez, Miqueas Gamero, Juan Estrada, Marco Bonatti, Christopher Montalban, Braulio Cancino, Claudio Chavez, Fabricio Alcalde, Alex Drlica-Wagner, Stephen Holland, Gustavo Cancelo, Sho Uemura, Javier Tiffenberg, Marcelo Jaque Arancibia, José Luis Nilo Castello, Rodrigo Hinojosa, Guillermo Damke

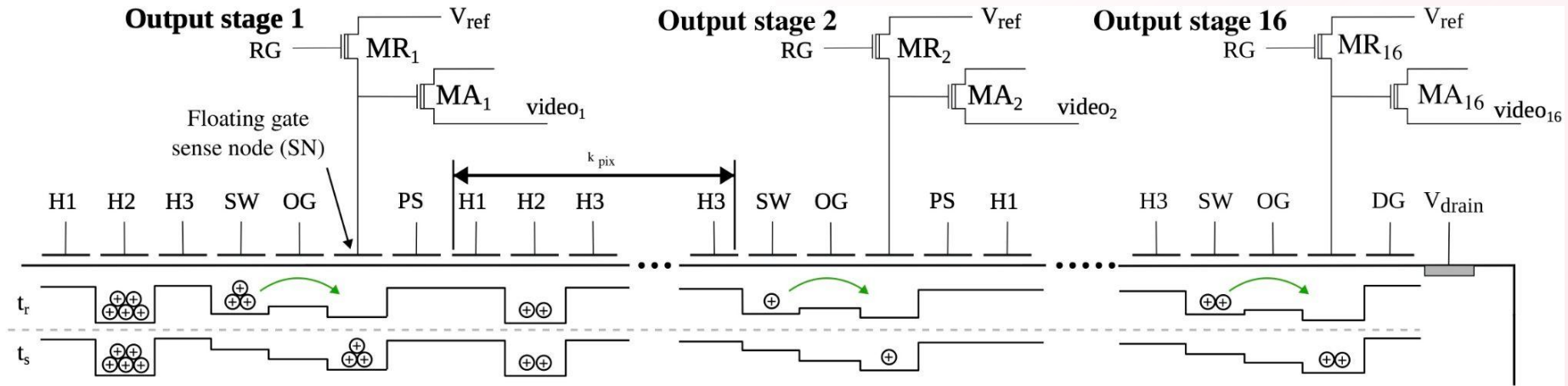


MAS-CCD



Multiple Amplifier Sensing Charge Coupled Device (MAS-CCD) was fabricated under the auspices of the U.S. Department Of Energy (DOE) Quantum Information Science initiative. Designed at LBNL by Steve Holland and fabricated at Teledyne DALSA Semiconductor. The device has $15 \times 15 \mu\text{m}$ pixels. These are p-channel devices. MAS-CCD through a microscope, 16 channel device format. [1, 2].

MAS-CCD

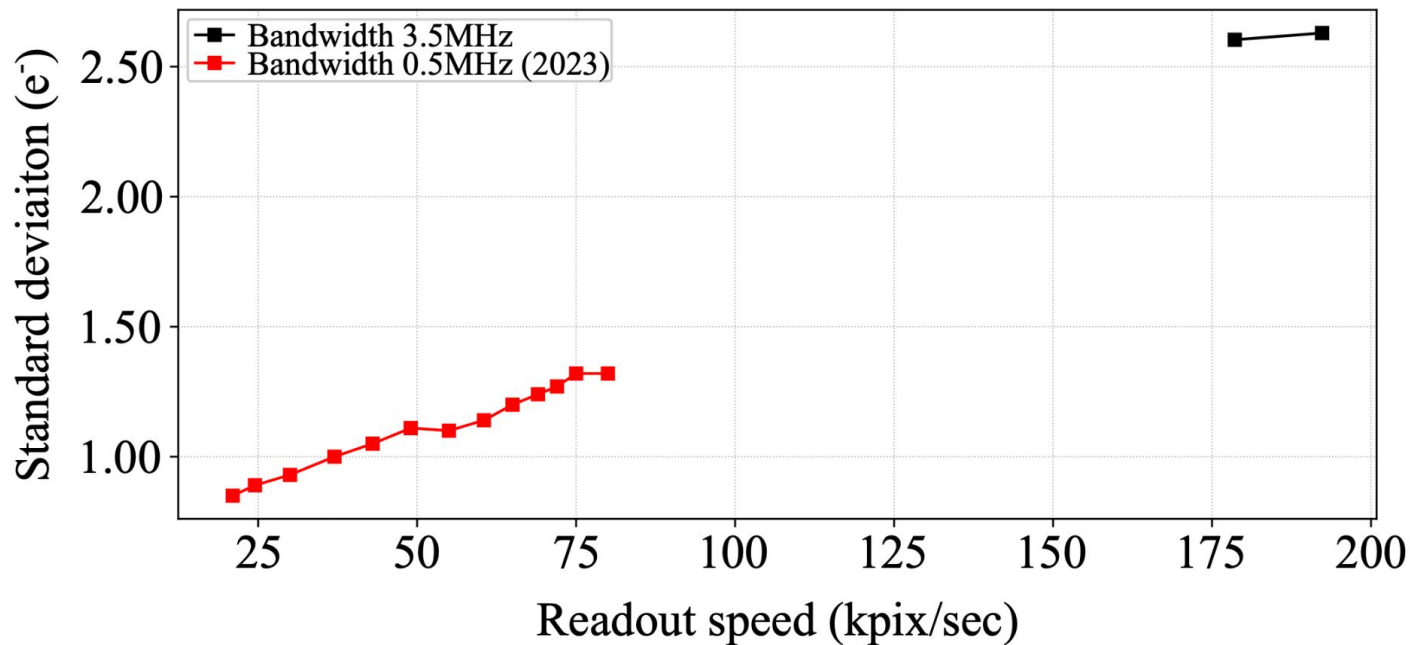


Schematic structure of the MAS-CCD device. Pixel Separation (PS) is a new gate allowing to reinsert the charge packet into the serial register.

The skipper output stages are separated k_{pix} pixels from each other.

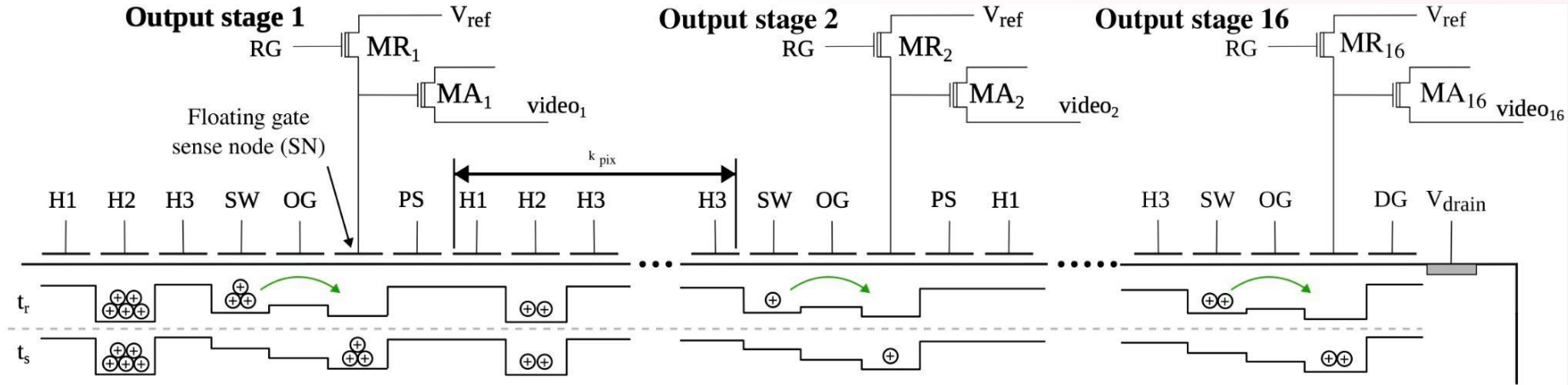


MAS-CCD readout speed vs noise performance



Achieved $1.2e^-$ @ 70 kpix/s with Low Threshold Acquisition (LTA) controller (2024), red curve. Black line acquired with tProc firmware. Both curves are mixing all the 16 channels using $N_s=1$. Red curve BW limited to 500KHz, black curve BW limited to 3.5MHz.

Node Removal Inefficiency (NRI)



Problem arises when the charge is not completely reinserted into the serial register → Node Removal Inefficiency. The first amplifier measures the charge packet without NRI-related issues because in the first sense node, no charge was lost yet. This recursive effect has been modeled and is reported in [7].

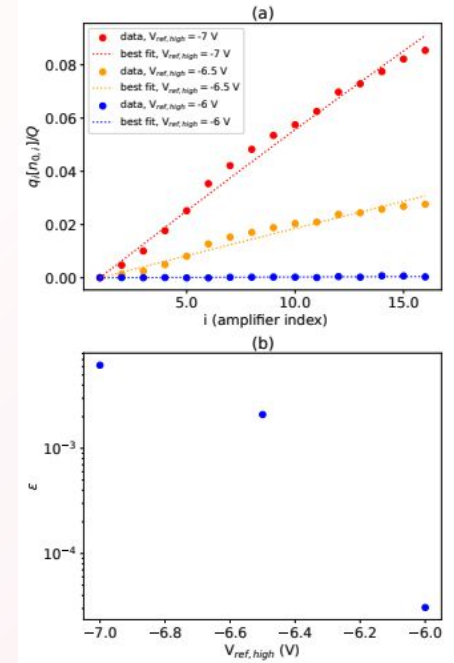
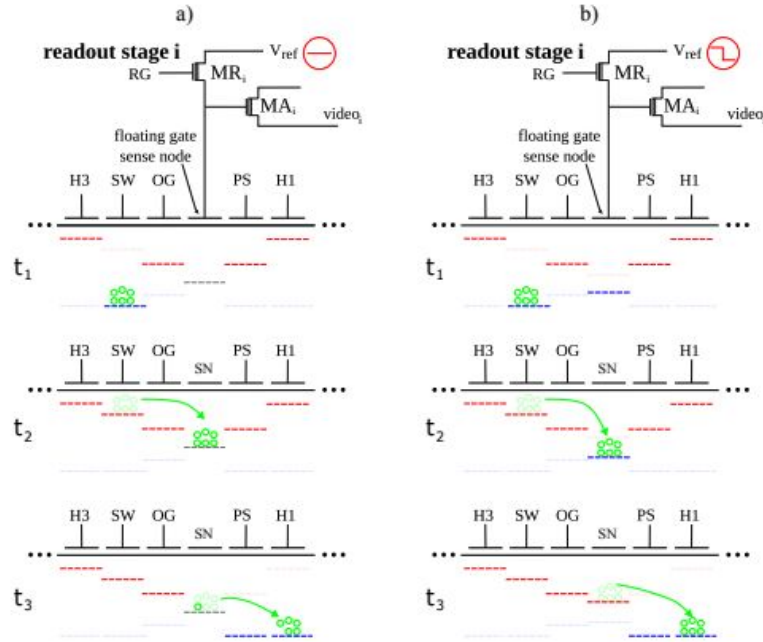
Node Removal Inefficiency (NRI)

NRI is dependent of

- ❖ The charge packet size
 - larger charge packets impose a more challenging transfer condition.
- ❖ The MAS-CCD operating voltages
 - as this define a electric field gradient.
- ❖ The time dedicated for transferring the charge from the SN back to the serial register
 - as we want to minimize readout time.



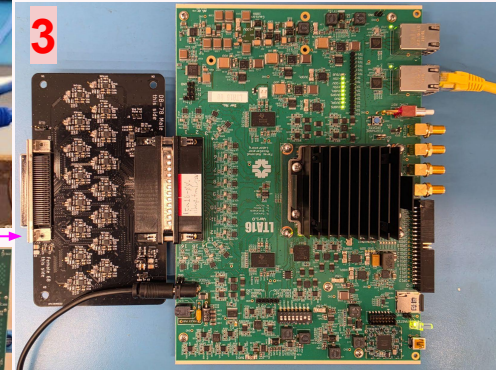
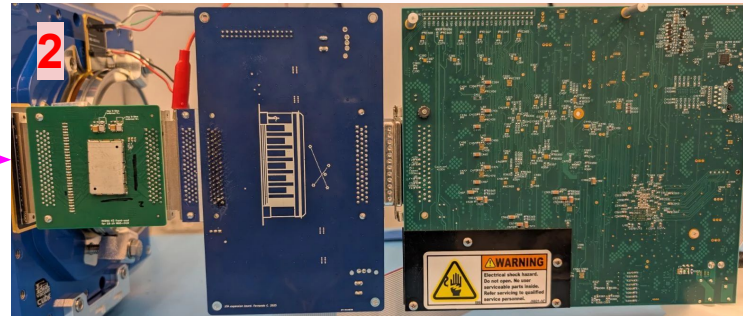
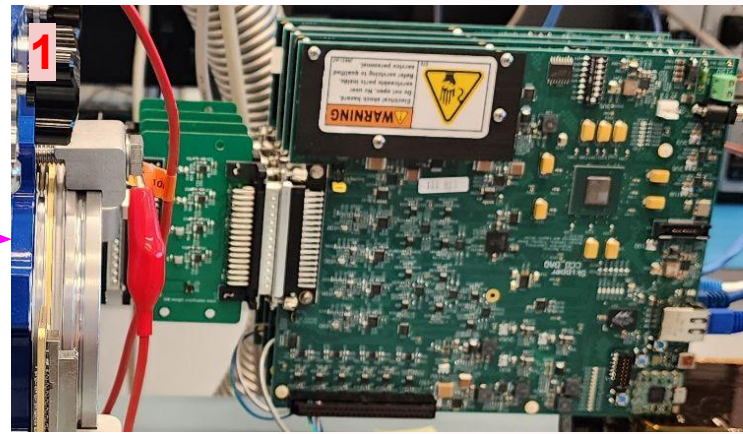
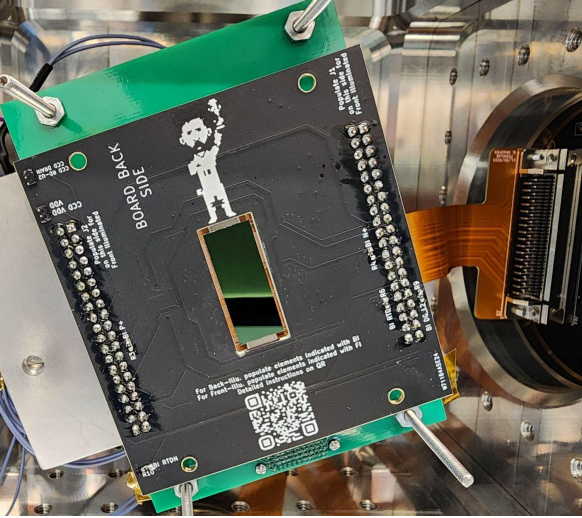
Node Removal Inefficiency (NRI) - mitigation technique



0.5 V step

1 V step

We explored a mitigation technique that consists in clocking V_{ref} generating a bigger voltage gradient. This helps the charge to be transferred from underneath the SN back to the next pixel in the serial register. [6]



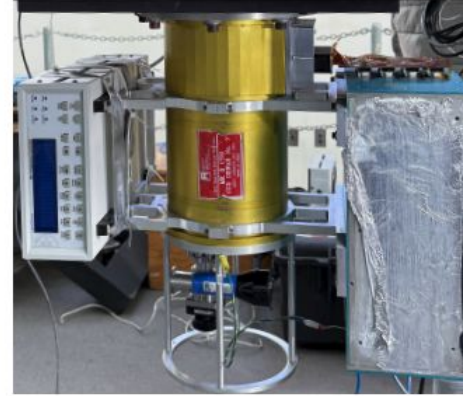
Different readout solutions for 16 output MAS-CCD:

1. Multi LTA scheme → 4 LTAs v2, driving 4 output channels each
2. MIDNA + LTA v2 → MIDNA analog integrates the pixel and multiplexes the output
3. LTA v3 → Drives 16 channel outputs

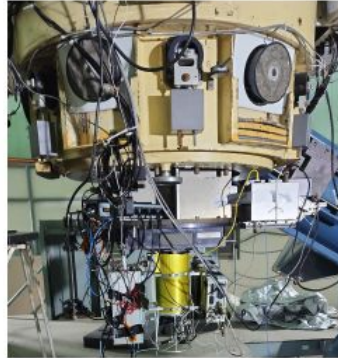
Cerro Tololo Inter-American Observatory – SMARTS 0.9m telescope



(a)



(b)



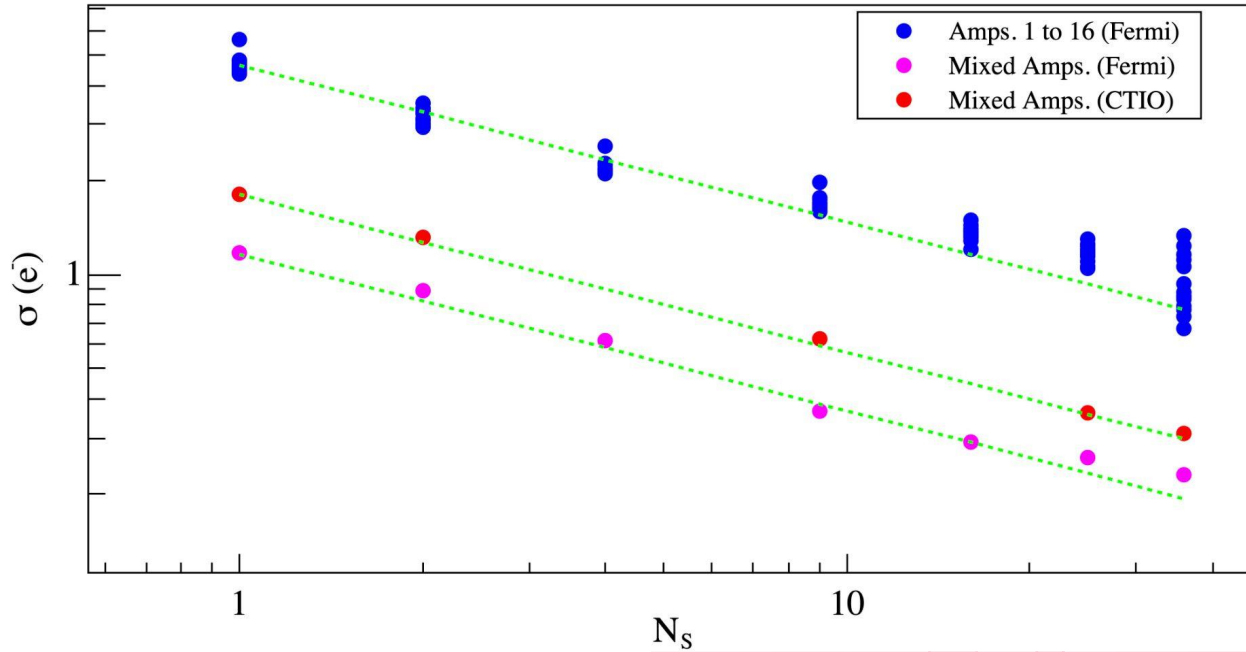
(c)



(d)

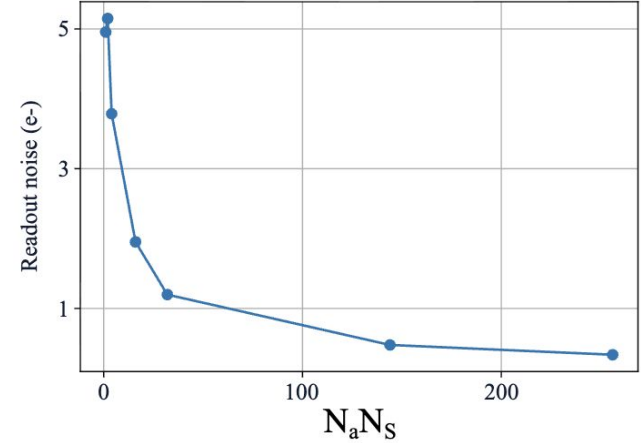
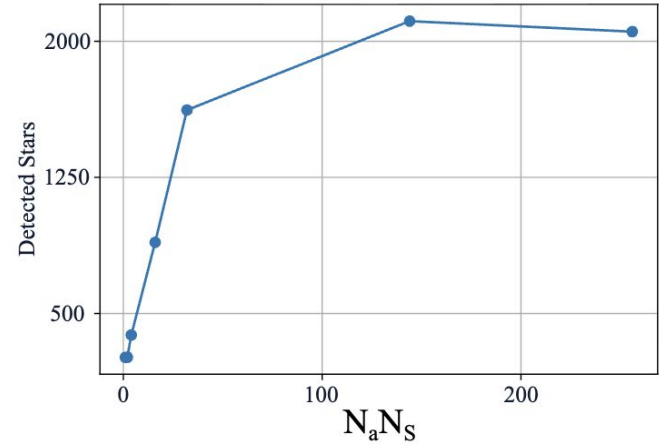
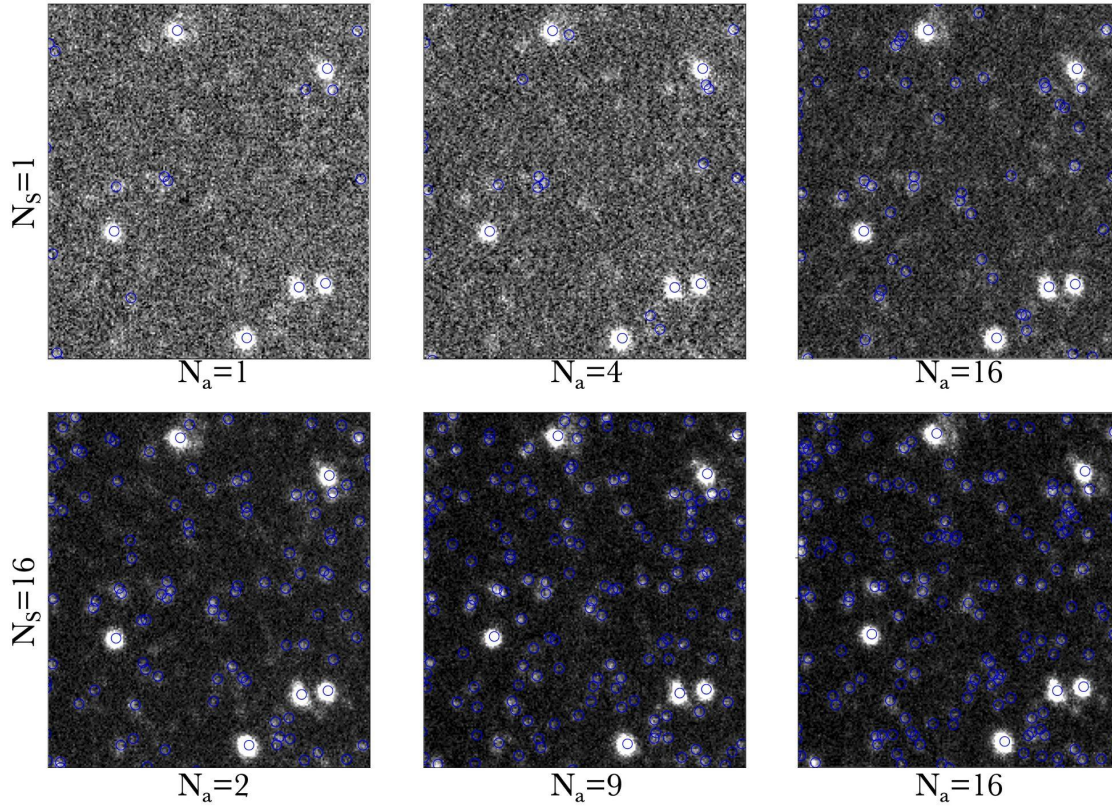
The entire readout system was compacted to camera space constraints

Noise performance



Single sample noise was higher for some of the channels in the telescope environment.

Noise performance



Improving readout noise performance has a direct impact in detected stars. [11]

Node Removal Inefficiency (NRI)

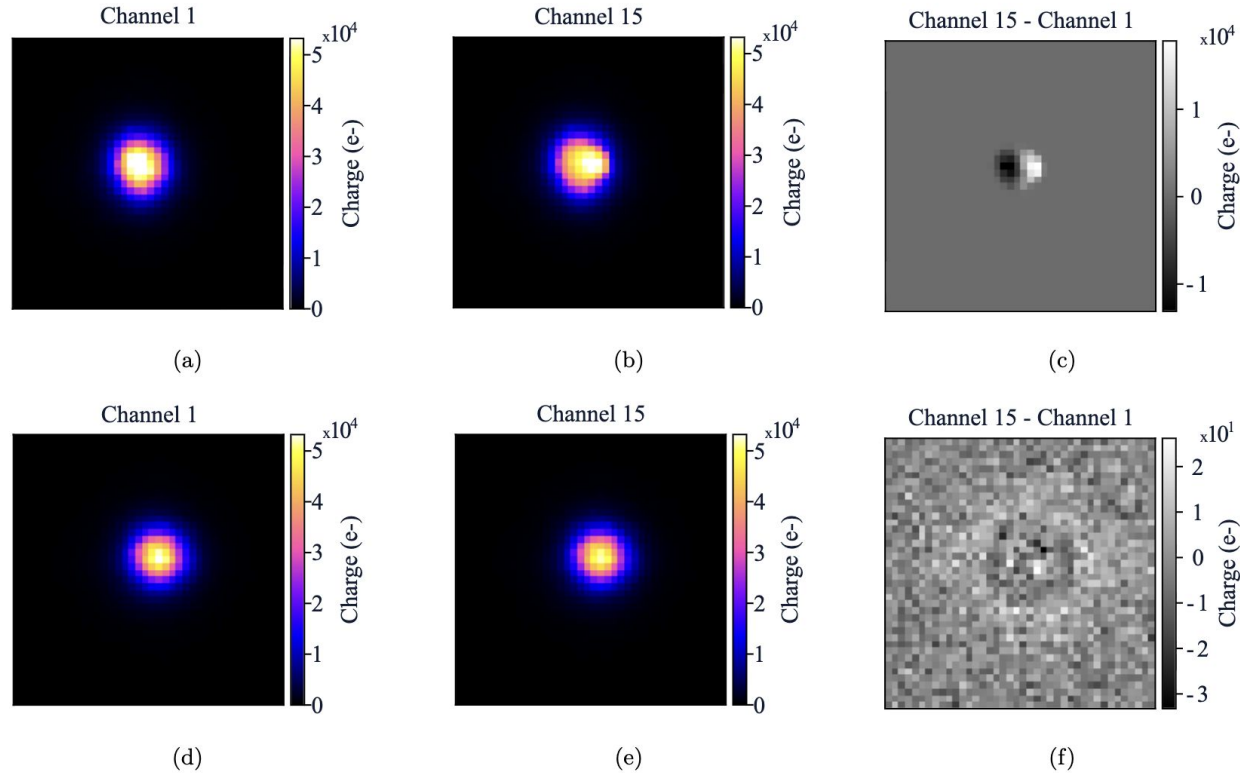


Figure 11. (a) 1st amplifier, (b) 15th amplifier, and (c) its subtraction for the fixed V_{ref} configuration. (d) 1st amplifier, (e) 15th amplifier, and (f) its subtraction for clocking V_{ref} configuration.

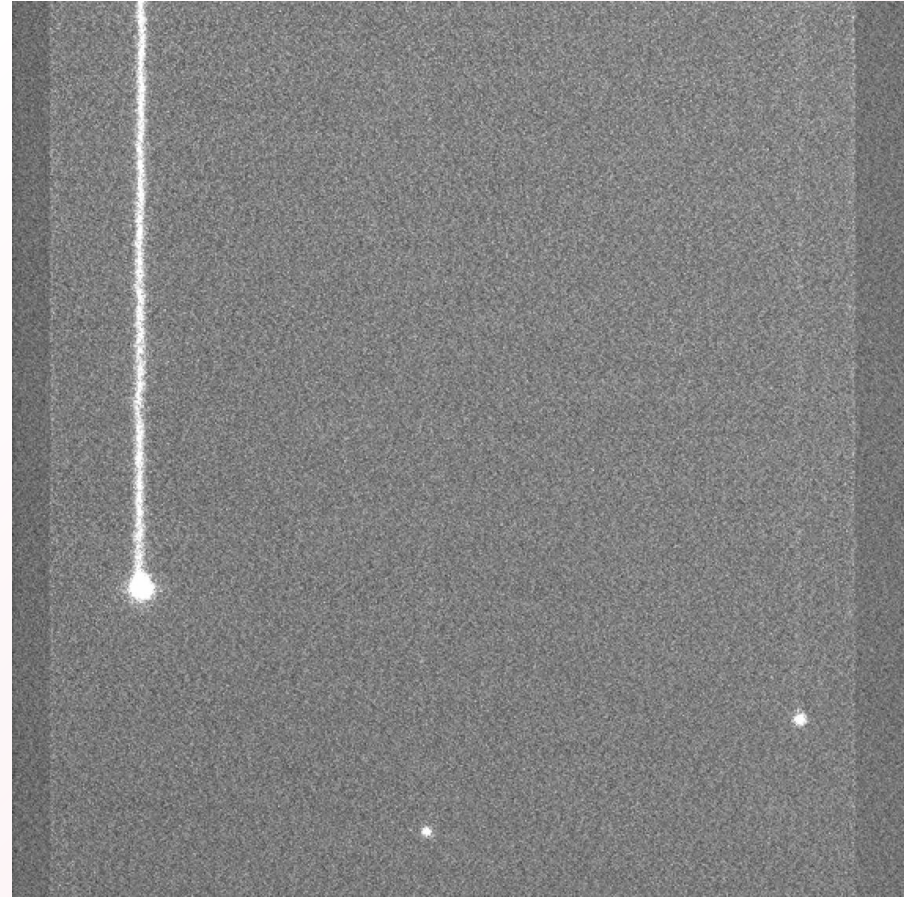
The systems must incorporate a clock signal to control V_{ref} to mitigate the NRI effects.

Observation of fast-cadence objects

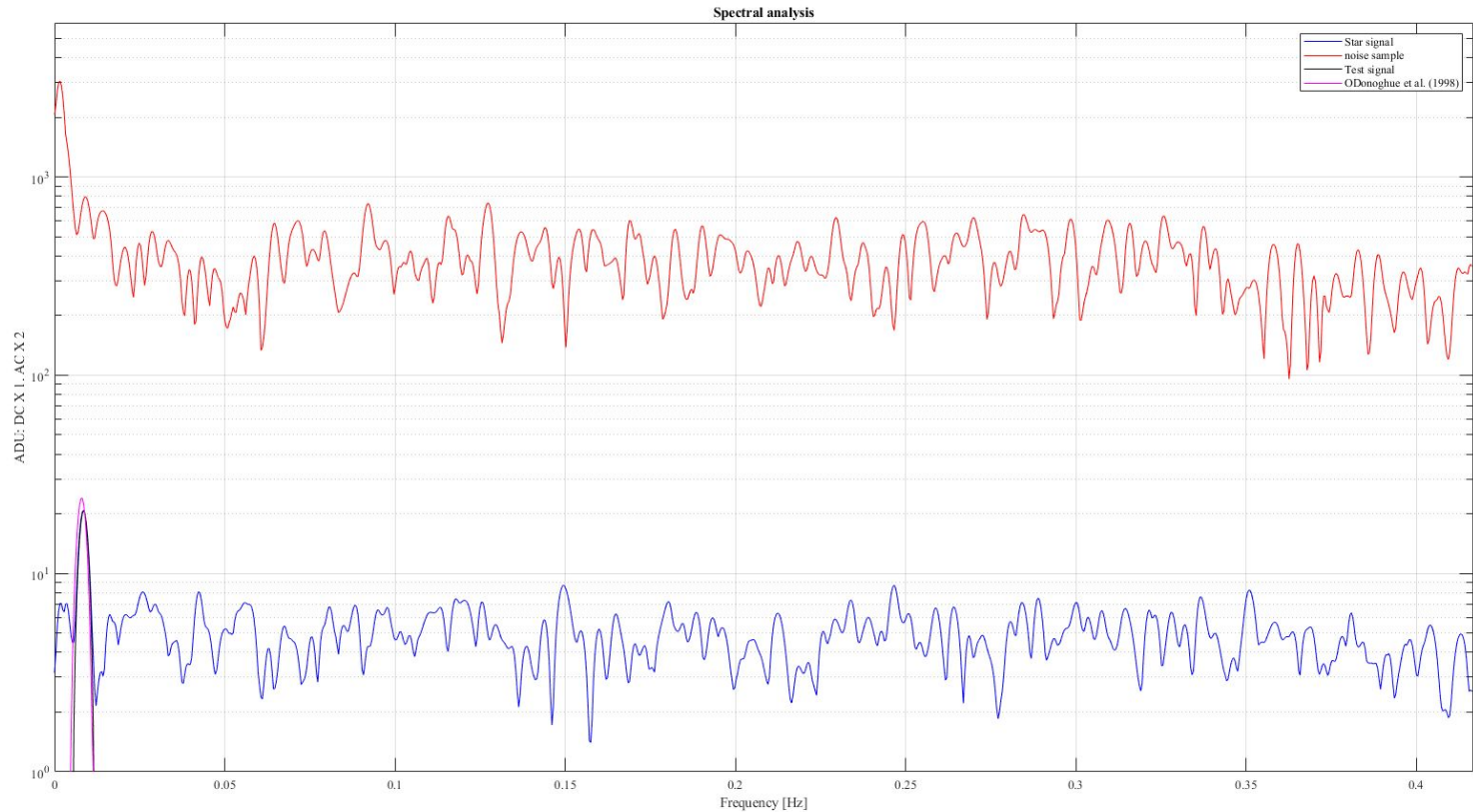
PB8783 - Pulsating Star [12]

Main mode 8.152 mHz (122.7 s); amplitude ≈ 9 mmag (≈ 0.8 % in flux); $V \approx 12.32$.

Images with 50k and 100k rows were obtained for this pulsating star, with a 12ms row time by leaving the shutter open while reading.



Observation of fast-cadence objects



PB8783 - Pulsating Star

The preliminary data processing reveals a possible **peak at expected frequency (@~8mHz)**, showing **agreement with published article**.

Nice pictures ! :)



Galaxy NGC 7793

As a remainder, each
RGB is composed of
16 (N_a) different
images, due to the
number of amplifiers.



Galaxy NGC 6563

Key takeaways

- ❑ MAS-CCD allows multiple channel outputs to be averaged to further reduce the readout noise
 - ❑ Or to operate at higher speeds maintaining **low** readout noise performance
- ❑ Successfully identified a sensor inefficiency : node removal inefficiency (NRI)
 - ❑ A technique to mitigate this effect was also developed.
- ❑ Observing run @ CTIO
 - ❑ Preliminary data of a pulsating star indicates agreement with published article
 - ❑ Improving signal to noise ratio (SNR) allows us to improve stars detection
 - ❑ NRI mitigation technique is something we must incorporate in the systems



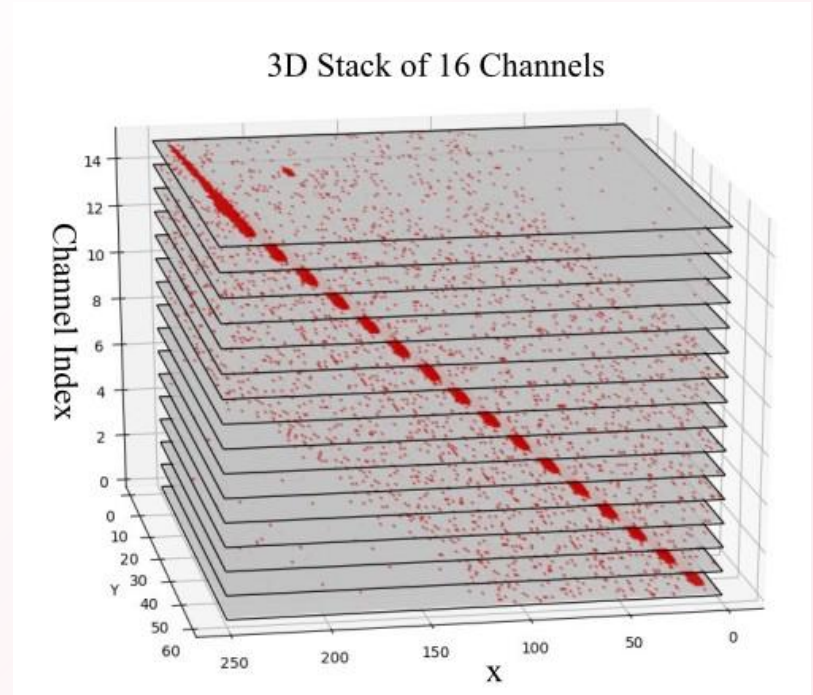
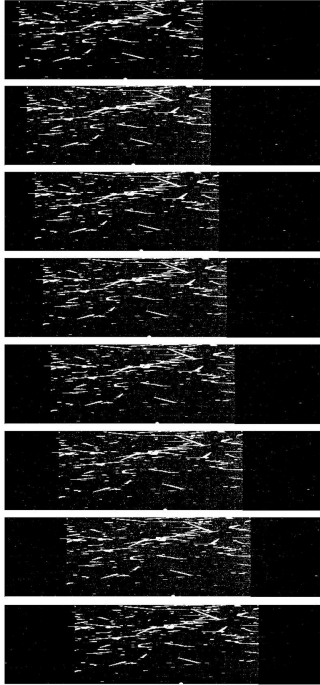
References

1. S. E. Holland et al., “Fully Depleted, Back-Illuminated Charge-Coupled Devices Fabricated on High-Resistivity Silicon,” *IEEE Trans. Electron Devices* 50, 225–238 (2003).
2. S. E. Holland, “Fully Depleted Charge-Coupled Device Design and Technology Development,” *Astron. Nachr.* 344, e20230072 (2023).
3. A. M. Botti et al., “Single-Quantum Measurement With a Multiple-Amplifier Sensing Charge-Coupled Device,” *IEEE Trans. Electron Devices* 71, 3732–3738 (2024).
4. A. M. Botti et al., “Readout Optimization of Multi-Amplifier Sensing Charge-Coupled Devices for Single-Quantum Measurement,” *Proc. SPIE, X-Ray, Optical, and Infrared Detectors for Astronomy XI* (2024).
5. G. I. Cancelo et al., “Low Threshold Acquisition Controller for Skipper Charge-Coupled Devices,” *J. Astron. Telesc. Instrum. Syst.* 7, 015001 (2021).
6. B. J. Irigoyen Gimenez et al., “Multiple-Amplifier Sensing Charged-Coupled Device: Model and Improvement of the Node Removal Efficiency,” arXiv:2502.15644 [astro-ph.IM] (2025).
7. A. J. Lapi et al., “Sixteen Multiple-Amplifier Sensing Charge-Coupled Devices and Characterization Techniques Targeting the Next Generation of Astronomical Instruments,” *J. Astron. Telesc. Instrum. Syst.* 11, 011203 (2025).
8. Chierchie, F. et al. (2020). “Smart-readout of the Skipper-CCD: Achieving Sub-electron Noise Levels in Regions of Interest.” arXiv:2012.10414 [physics.ins-det]
9. F. Chierchie et al., “Smart Readout of Nondestructive Image Sensors with Single Photon-Electron Sensitivity,” *Phys. Rev. Lett.* 127, 241101 (2021).
10. E. Marrufo Villalpando et al., “Characterization and Optimization of Skipper CCDs for the SOAR Integral Field Spectrograph,” *Publ. Astron. Soc. Pac.* 136, 045001 (2024).
11. E. Bertin and S. Arnouts, “SExtractor: Software for Source Extraction,” *Astron. Astrophys. Suppl. Ser.* 117, 393–404 (1996).
12. Koen, C., Kilkenny, D., O’donoghue, D., Van Wyk, F., & Stobie, R. S. (1997). A new class of rapidly pulsating star—II. PB 8783. *Monthly Notices of the Royal Astronomical Society*, 285(3), 645-650.

Back-up slides



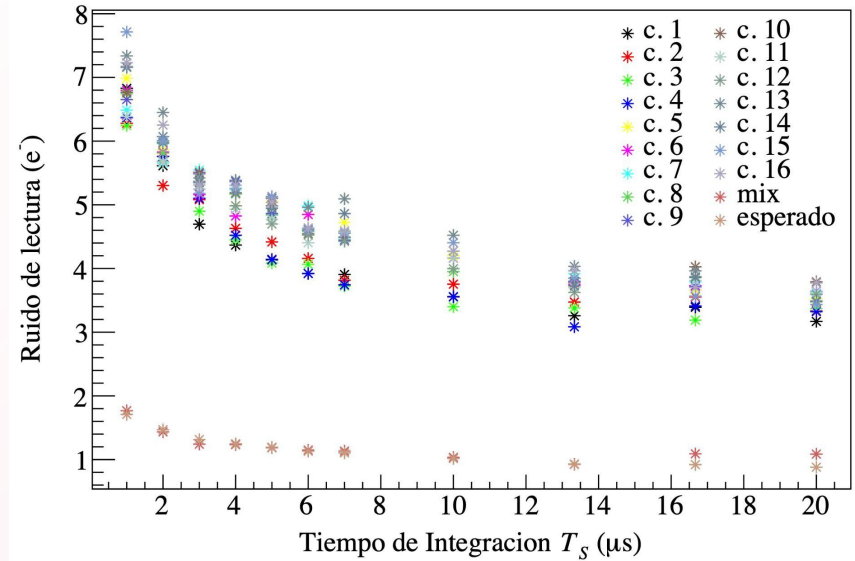
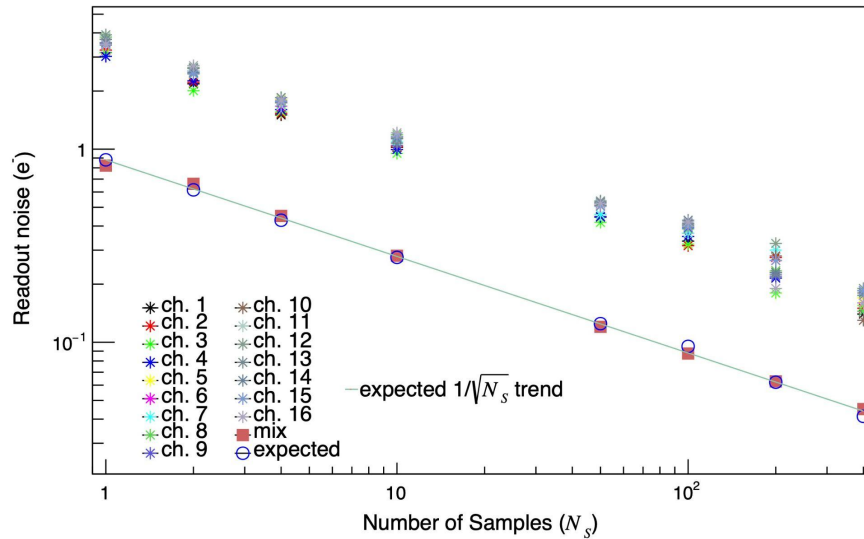
MAS-CCD



Output images for eight and sixteen format devices.

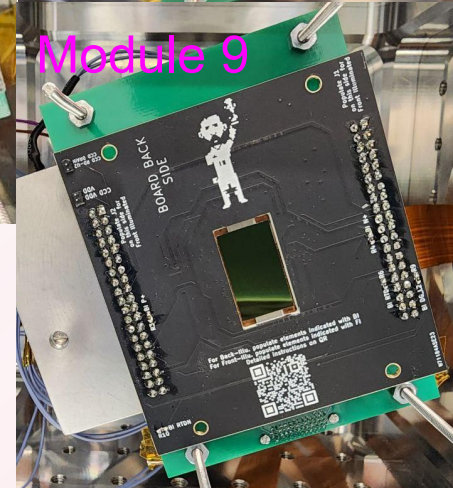
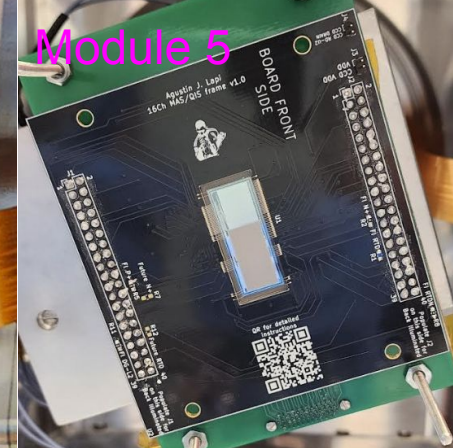
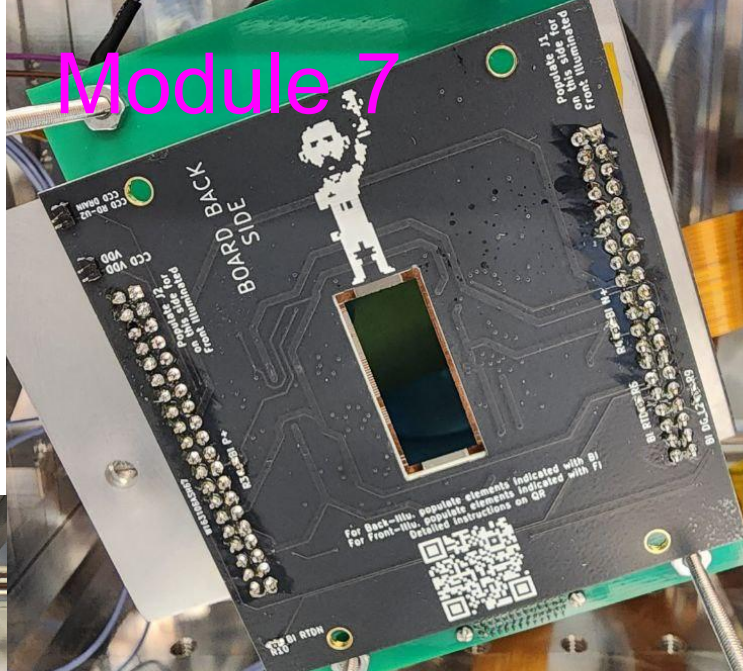


MAS-CCD



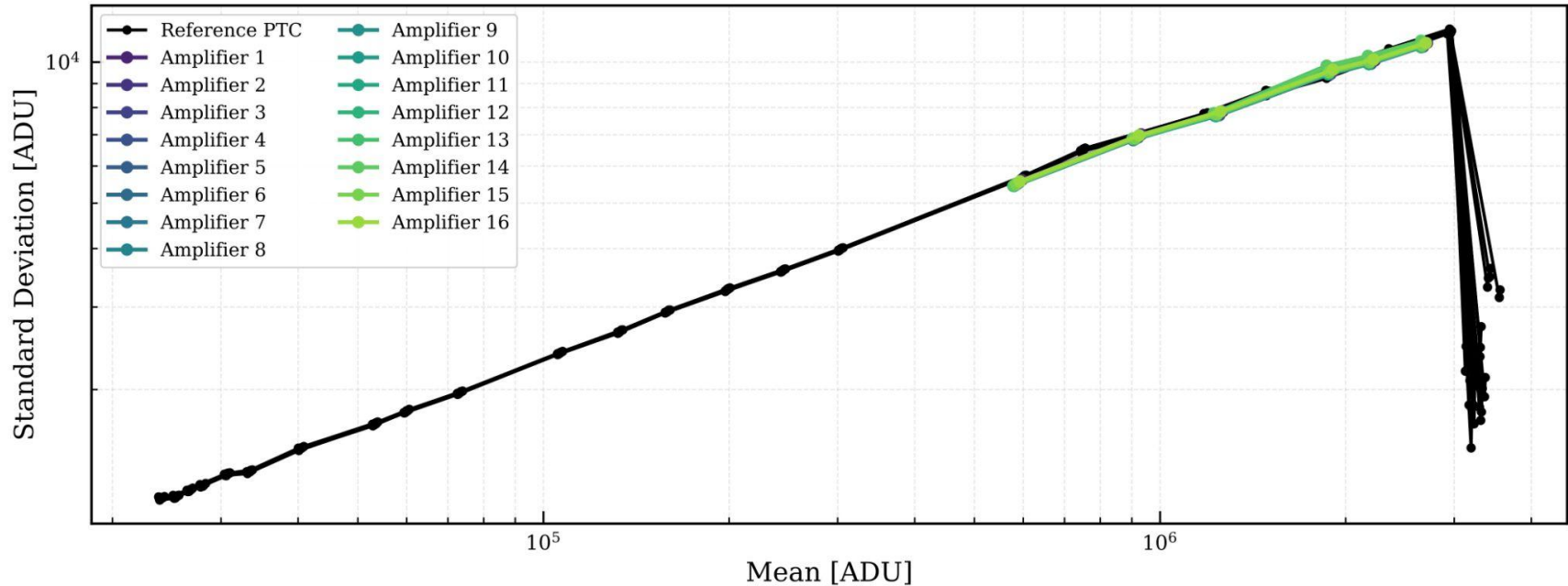
First performance parameters regarding integration time T_s and number of samples N_s .
 $T_s = 16.66 \mu s$ for the N_s span.

MAS-CCD



Ongoing efforts characterizing sensors at FNAL, different 8 and 16 channels variantes, BI and FI. Optimization towards observation run @ CTIO was performed.

MAS-CCD Full Well Capacity



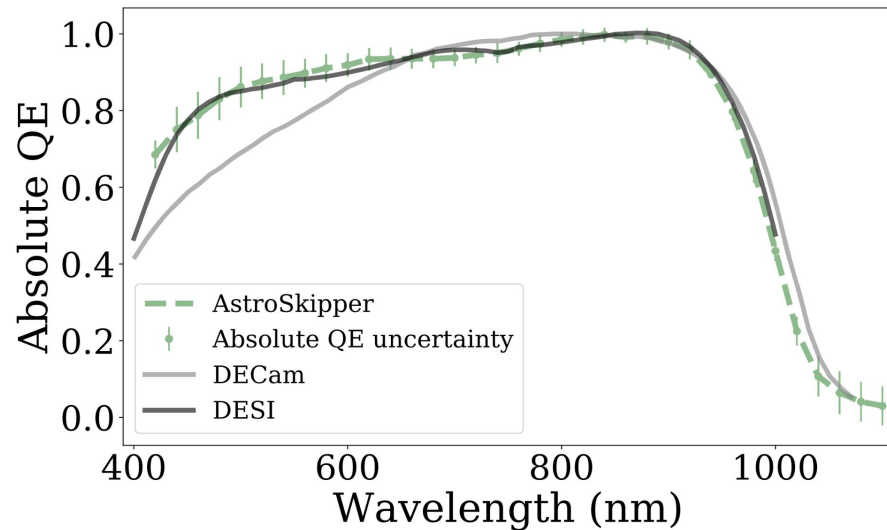
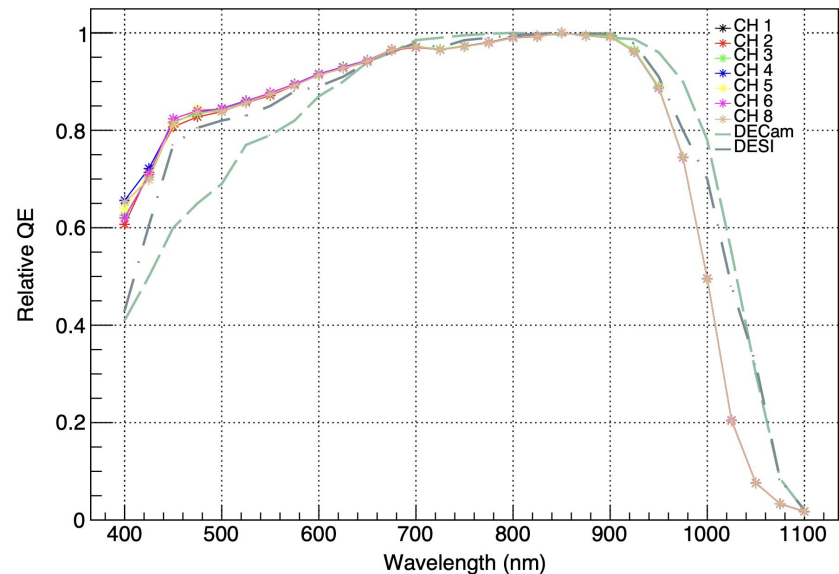
Optimized and measured for the observation run.

Black data curves → Reference MAS-CCD detector

Green color palette → Science commissioned sensor



Quantum Efficiency



Measured QE of a 8 channel MAS-CCD and an AstroSkipper-CCD, both in the same fabrication run wafer. [10]

Region of Interest and Energy of Interest

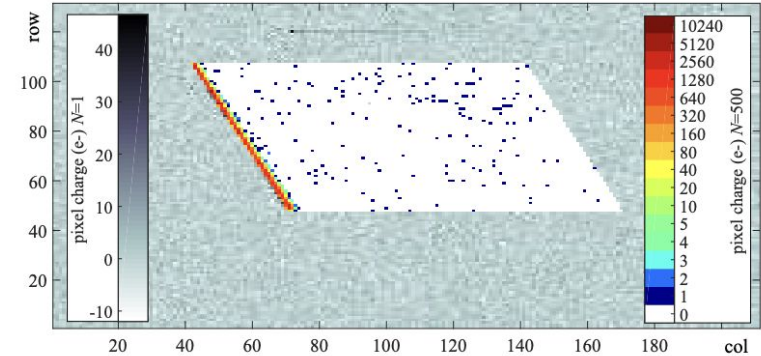
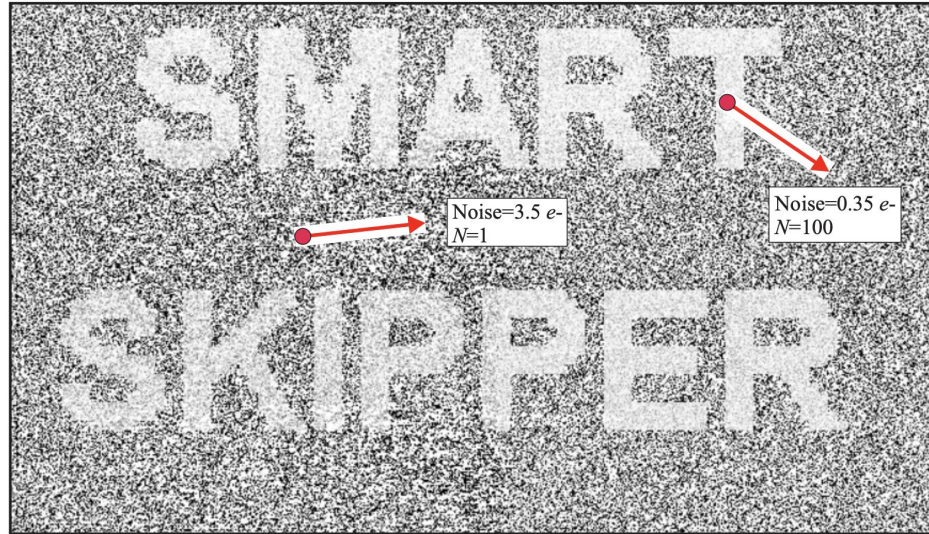
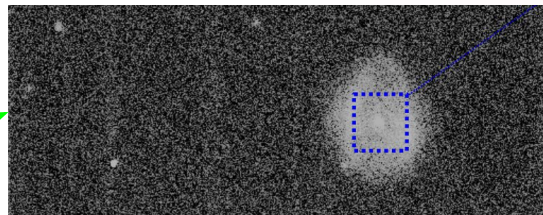
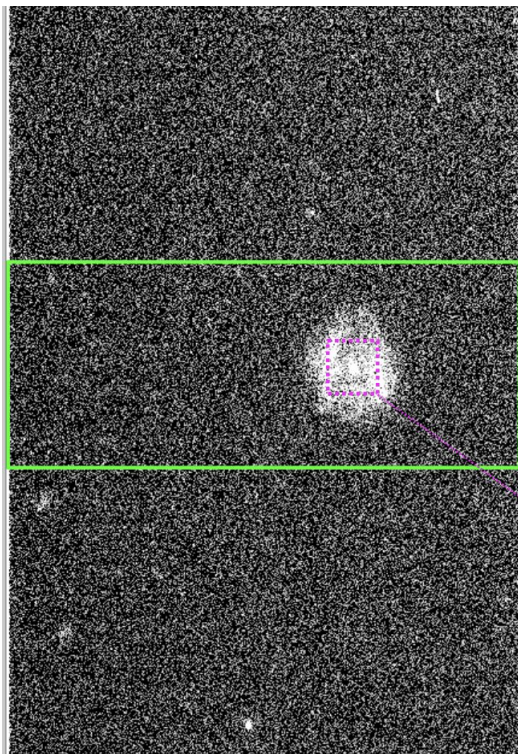


FIG. 6: Experiment combining ROI and EOI. Two color scales: on the left pixels with $N = 1$ and a noise of $3 e^-$, and on the right pixels with $N = 500$ and a readout noise of $0.13 e^-$ (and therefore quantized charge).

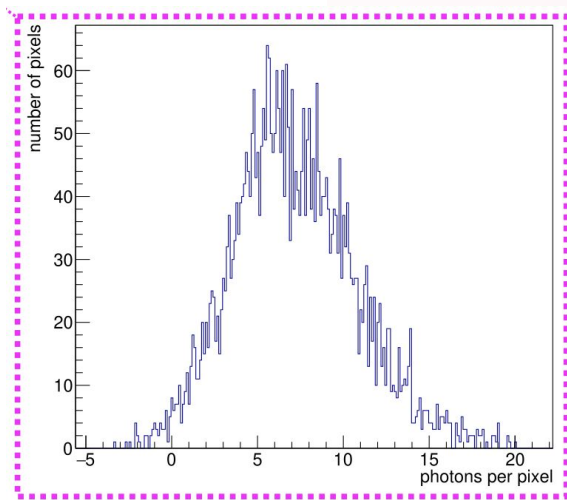
More advanced readouts involve Region of Interest (ROI) and/or Energy of Interest (EOI). A ROI with low noise readout can be defined.

On Sky Region of Interest →

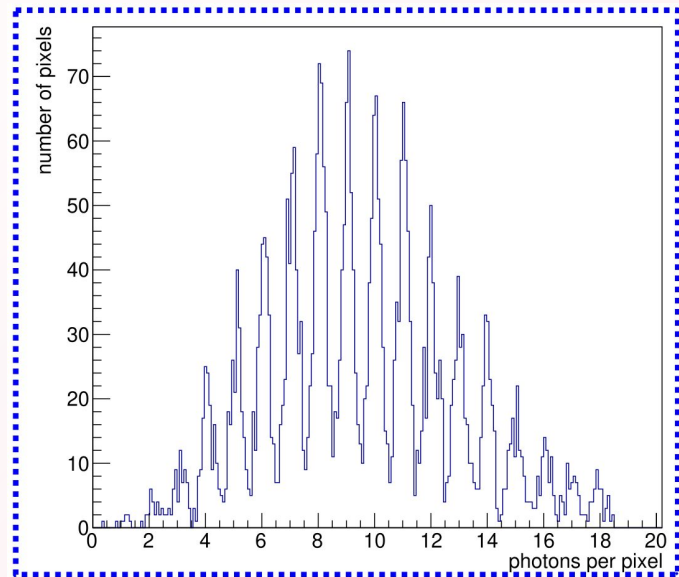
Target : NGC6153



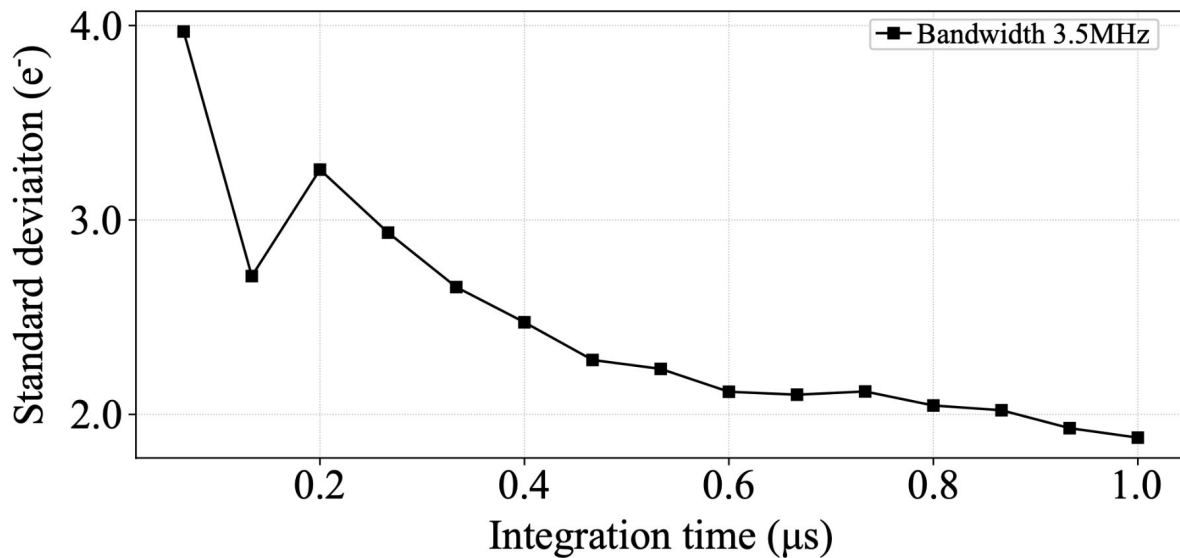
$$N_S = 36$$



$$N_S = 1$$



MAS-CCD readout speed vs noise performance



Black line acquired with tProc firmware, mixing all the 16 channels using $N_s=1$.
System BW is limited to 3.5MHz.

No prescan readout, AKA, **continuous readout**

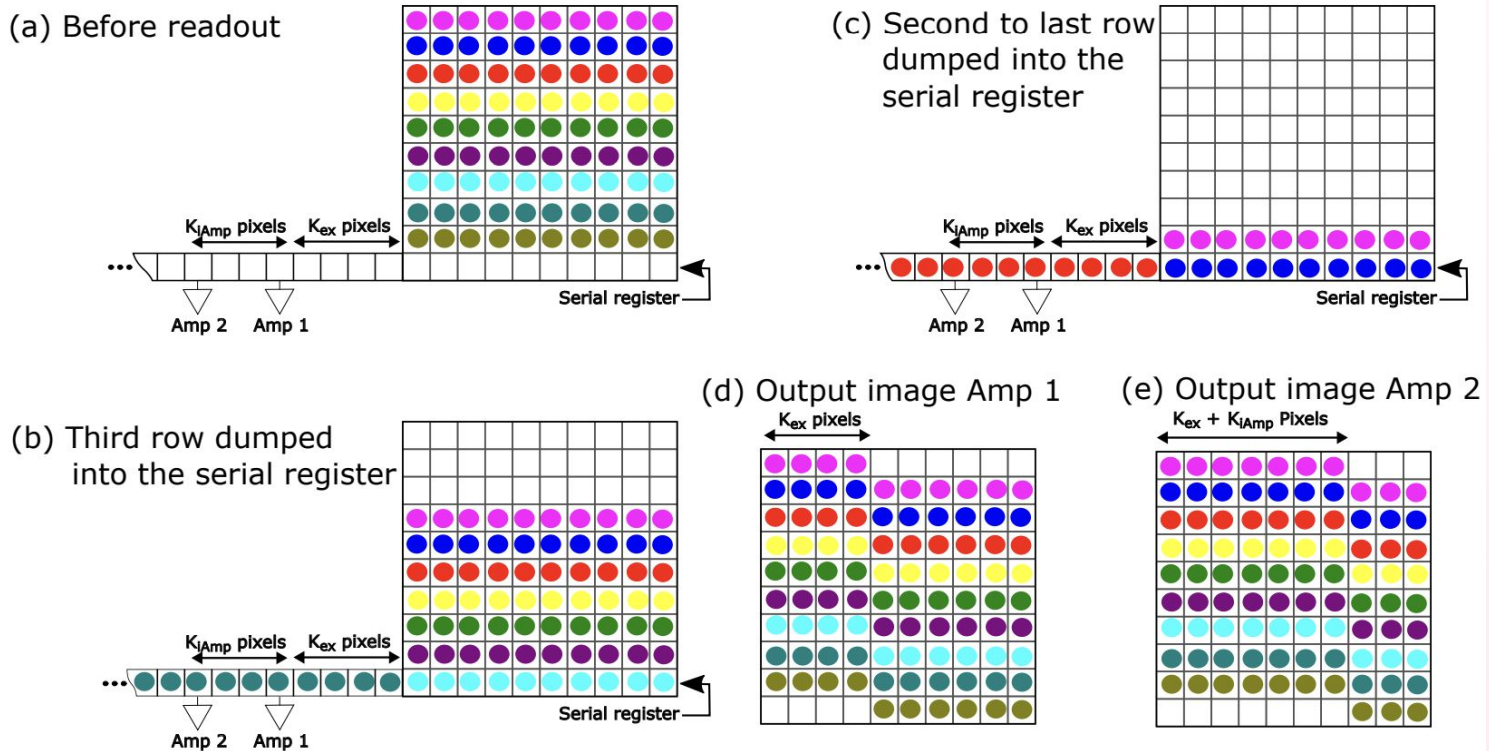
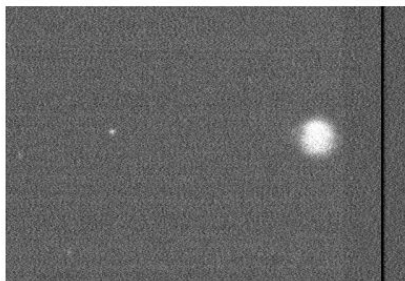


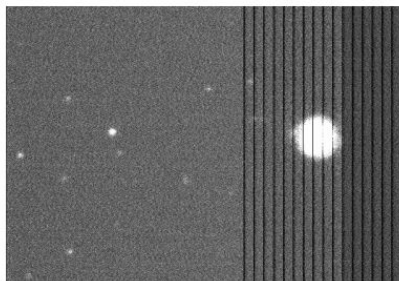
Figure 3. The process steps of the continuous readout scheme are shown in figures (a), (b), and (c). (e) and (f) representation of our output image using the method.

The extended serial register doesn't have an impact on readout time. [4]

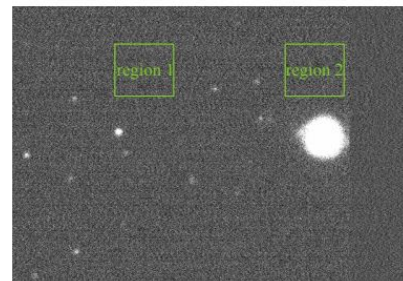
Continuous readout target→NGC3918



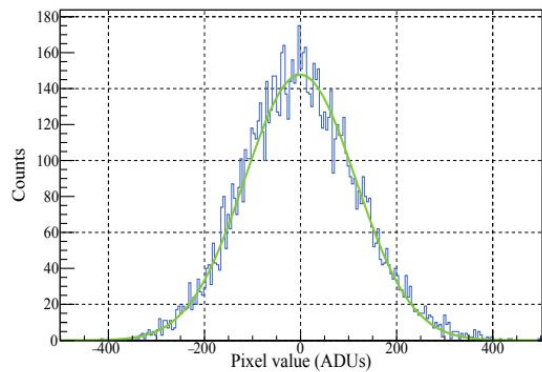
(a)



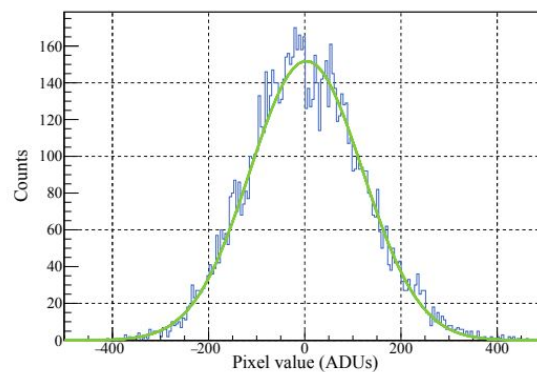
(b)



(c)

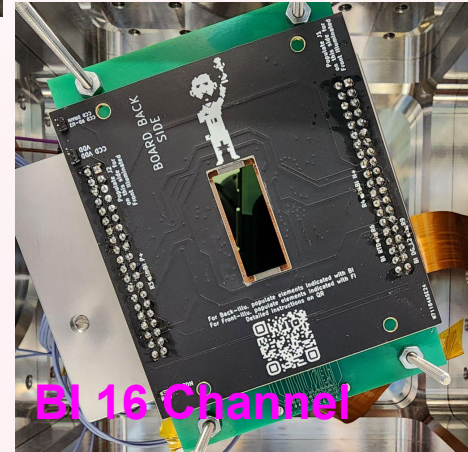
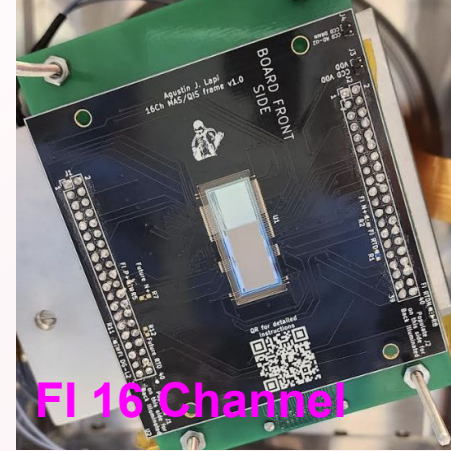
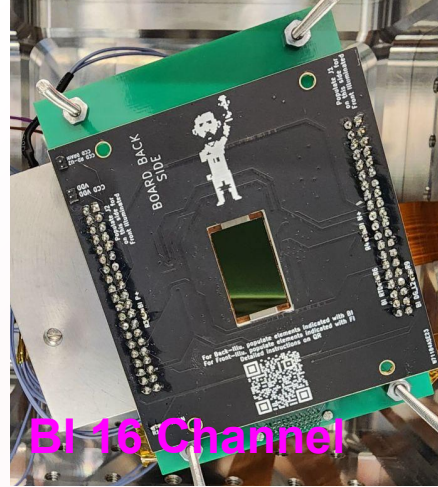
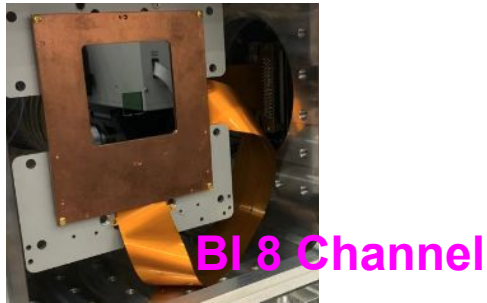
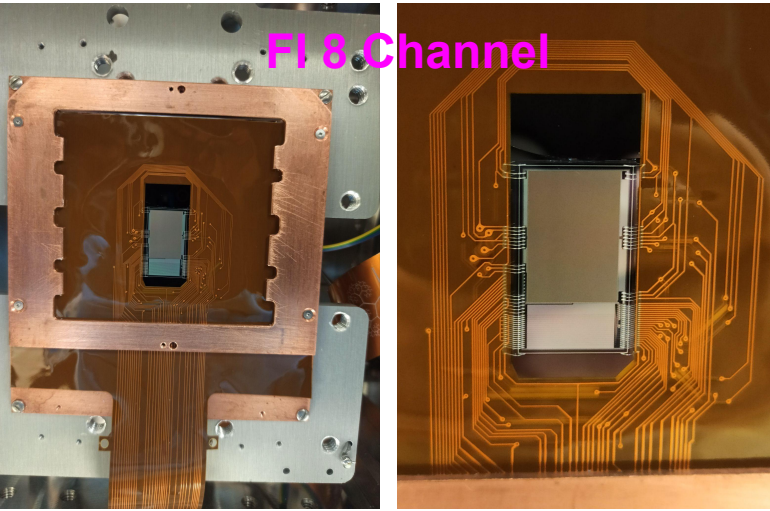


(d)



(e)

Packaged sensors:



Different packages, copper tray for first 8 channel MAS-CCDs version, front with back window for back. Mirrored picture frame solution for back and front sensors, 8 and 16 MAS-CCD variants.

Packaged sensors:

between the regions from each amplifier corresponds to the physical spatial separations of the amplifiers in the output stages chain. In this particular sensor with 8 output transistors, the video signal from the seventh amplifier was not giving any charge signal, so we decided to directly exclude the channel from the analysis without performing a thorough debugging of the electronic chain to identify the source of the problem.

[4]

- ❑ 3 copper tray 8 channel MAS-CCDs
 - ❑ 2 front, 1 back illuminated
 - ❑ 1 picture frame 8 channel MAS-CCD
 - ❑ 5 picture frame 16 channel MAS-CCDs
 - ❑ 2 front, 3 back illuminated
- This adds up to 9 sensors, 112 output stages.
- 111 out of 112 working output stages (success rate 99.1%).

