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Sub-electron noise CCDs with the MAS Architecture for astronomy

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New Detector Technologies Track ISPA 2024 @ SLAC

Berkeley
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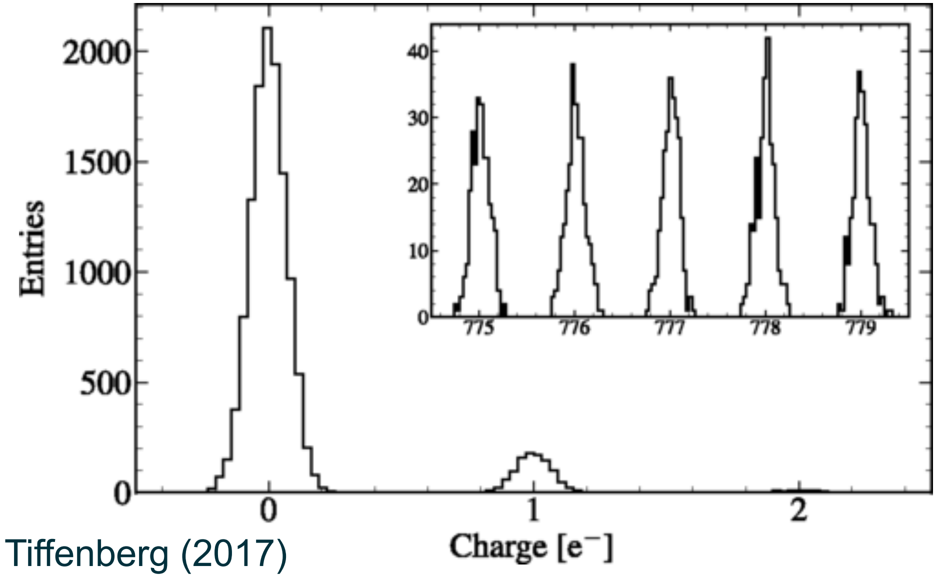
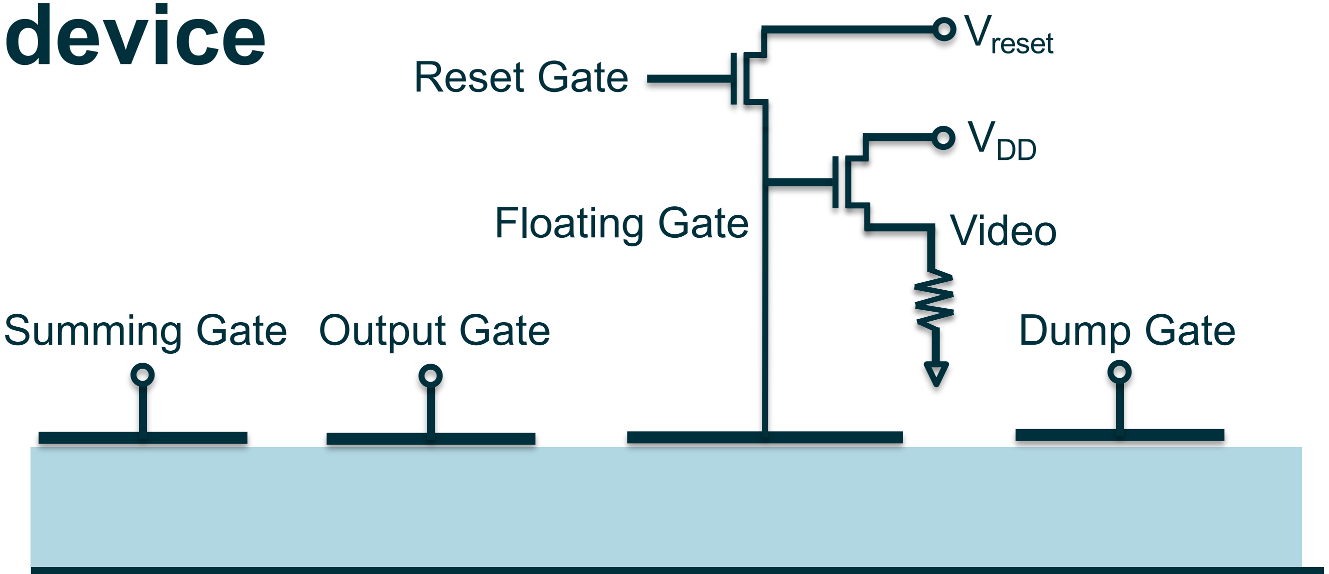
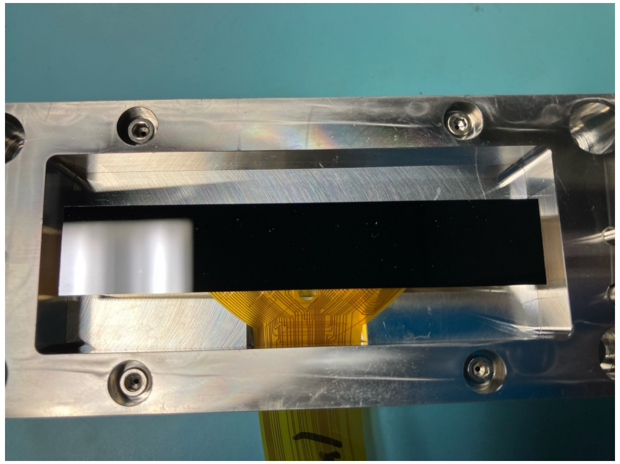
Skipper CCDs: a mature device



J. Tiffenberg (2017)



Skipper CCDs: 0.13 e- rms/pix 300 samples

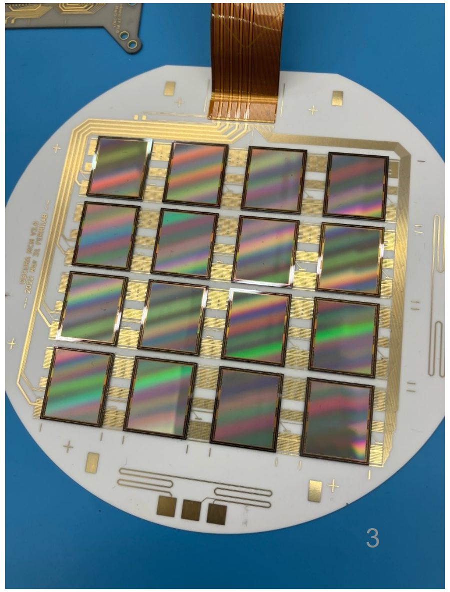


Skipper CCDs have found applications in:

DAMIC-M, SENSEI dark matter direct detection experiments

2024: SOAR SIFS – 4 Skipper CCDs
arXiv:2210.03665

2030? OSCURA – 26,000 Skipper CCDs
arXiv:2202.10518



Unique challenges for astronomy

Astronomical silicon detector requirements

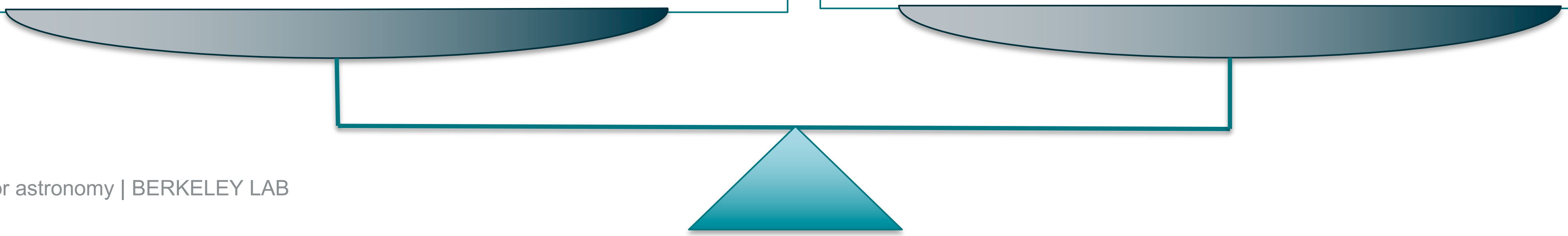
- Linear response across wide dynamic range ($\gtrsim 10^5$ e- for imaging, 10^4 e- for spectroscopy)
- High quantum efficiency in blue to near-IR wavelengths
- For space: radiation tolerance and passive cooling

Readout noise

- Low-background, low signal observations (e.g., blue wavelengths)
- Ground-based spectroscopy of diffuse or distant objects (low SNR per pixel)
- Space-based photon-counting applications

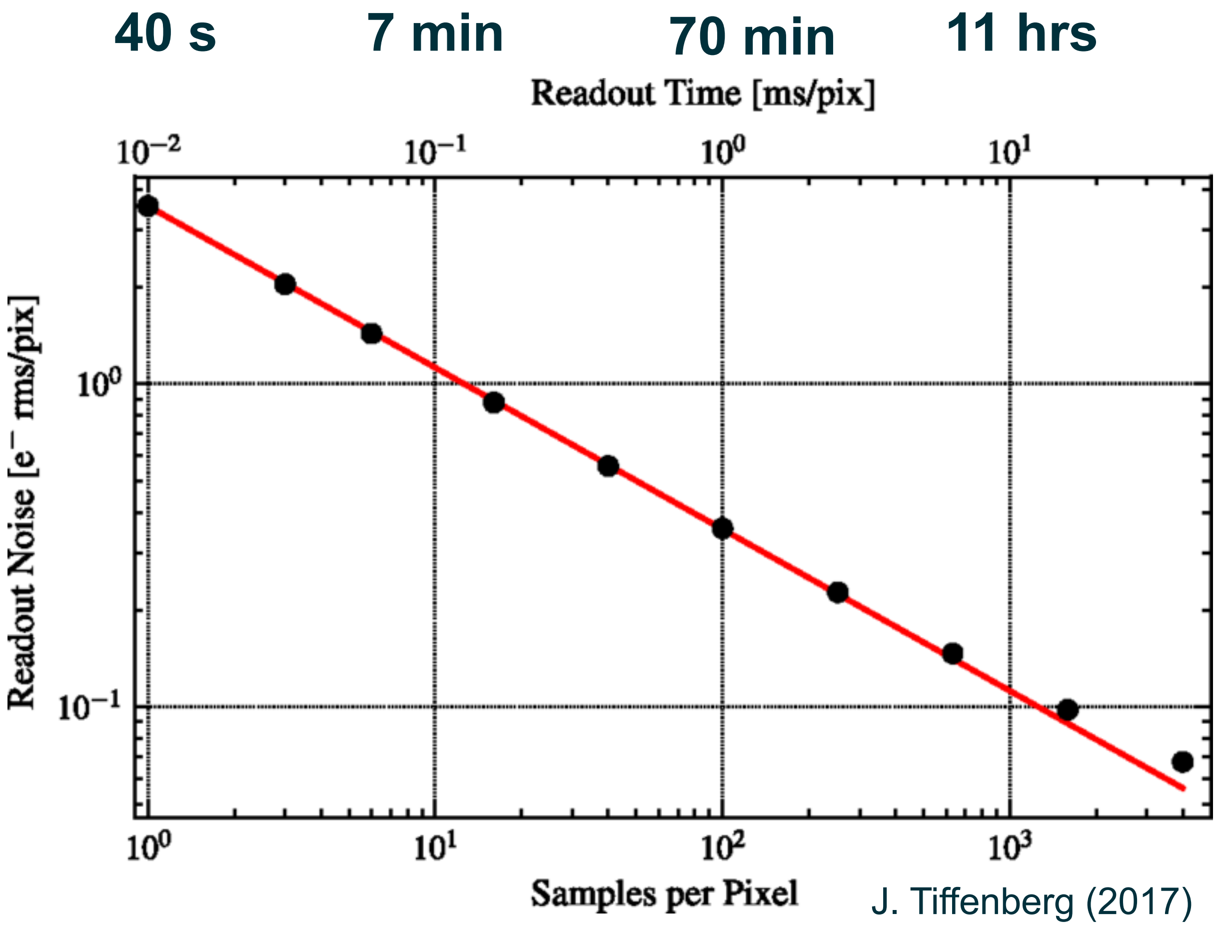
Readout time

- Pixel corruption from cosmic ray incidence
- Fast-evolving transient targets
- Impacts survey cadence, efficiency, and cost (e.g., DESI-II, Spec-S5)



Skipper sampling scales with readout time

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



J. Tiffenberg (2017)

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

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

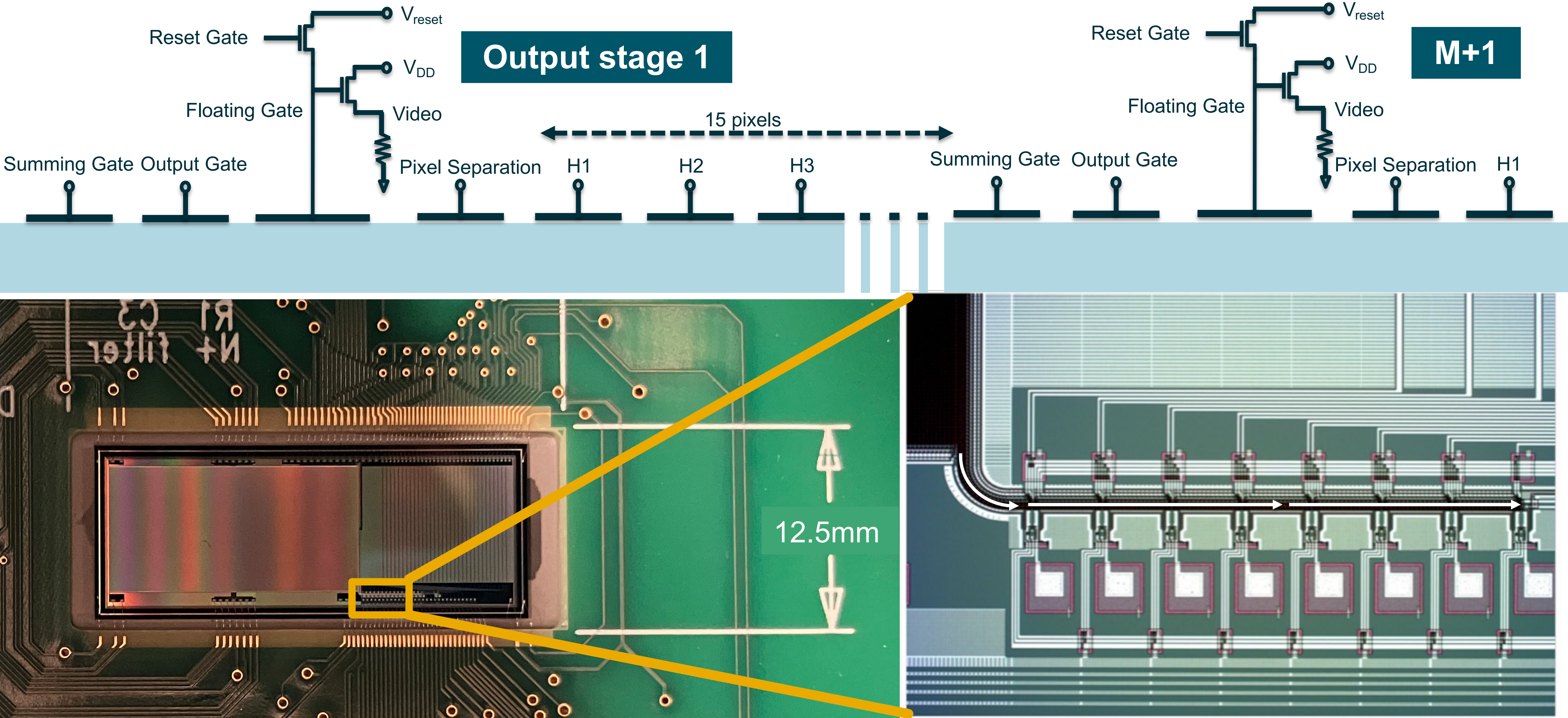
Skipper readout solutions being explored:

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

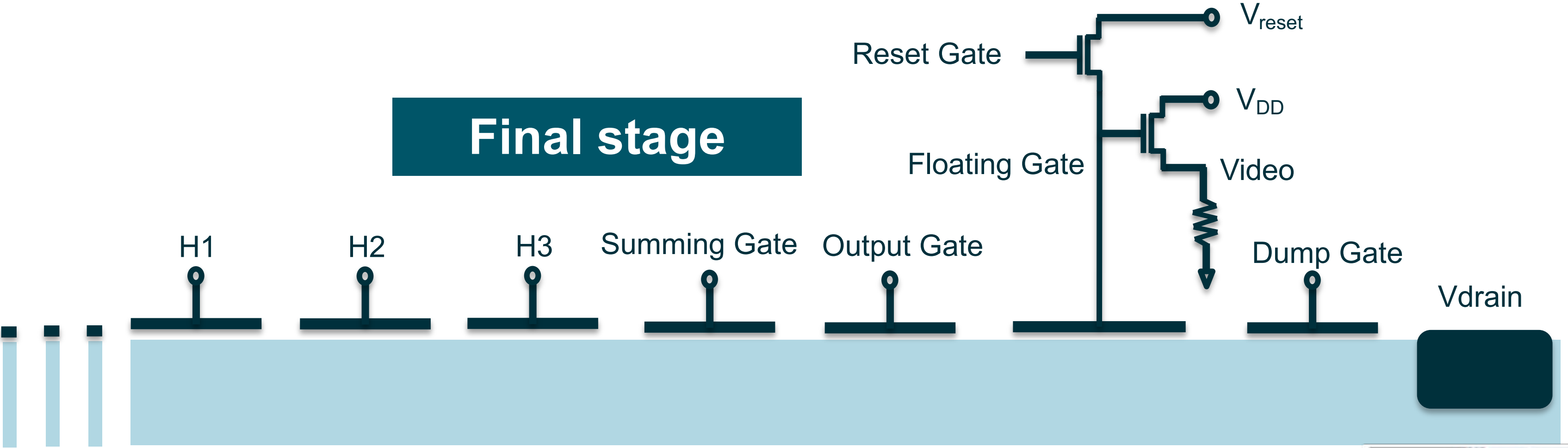
Alternate architectures:

- SiSeRO CCD (previous talk)
- Skipper-in-CMOS
- **This work: Multi-Amplifier Sensing CCD**

MAS architecture: distributed floating gates



MAS architecture: distributed floating gates

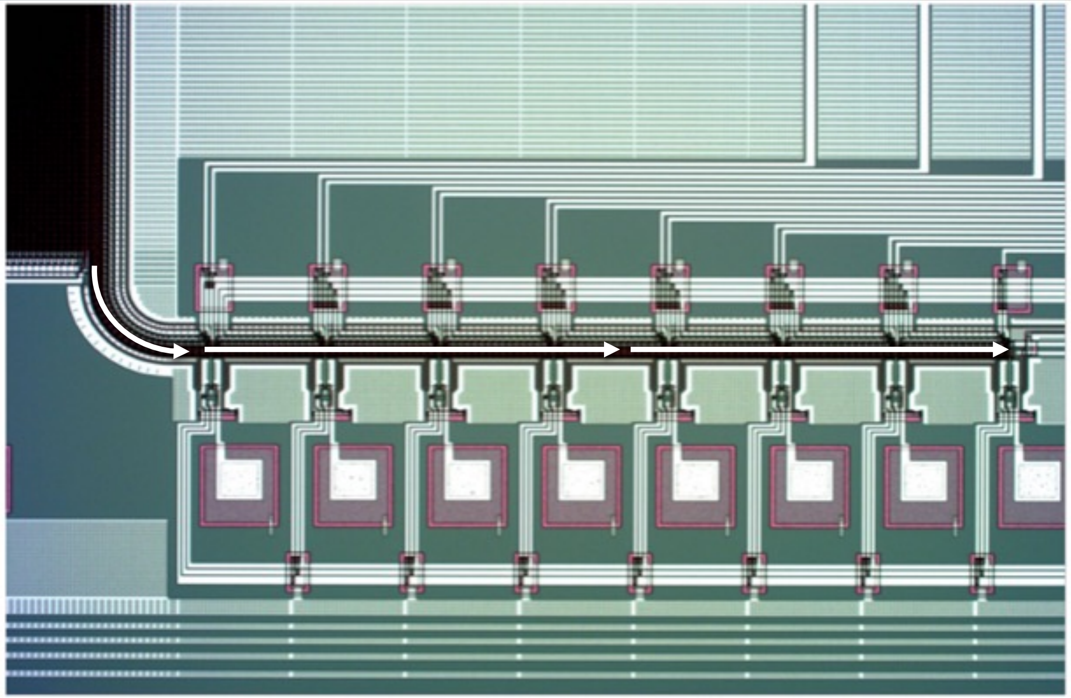


$$\sigma_N = \frac{\sigma_1}{\sqrt{N}\sqrt{M}}$$

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

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

- Designed at Lawrence Berkeley National Laboratory (S. Holland, *Astronomische Nachrichten* 2023)
- Retains repetitive non-destructive "skipping" capability
- Fabrication at Teledyne DALSA Semiconductor and LBNL MicroSystems Laboratory (for back-illumination)

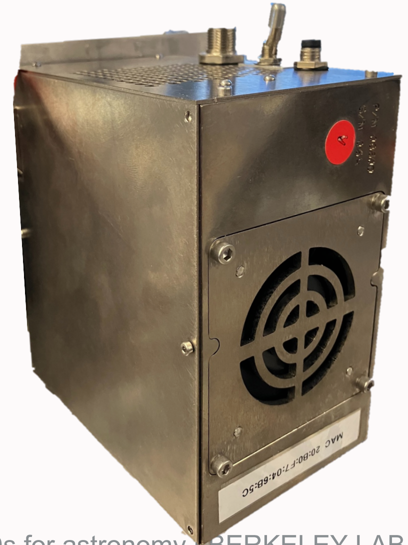


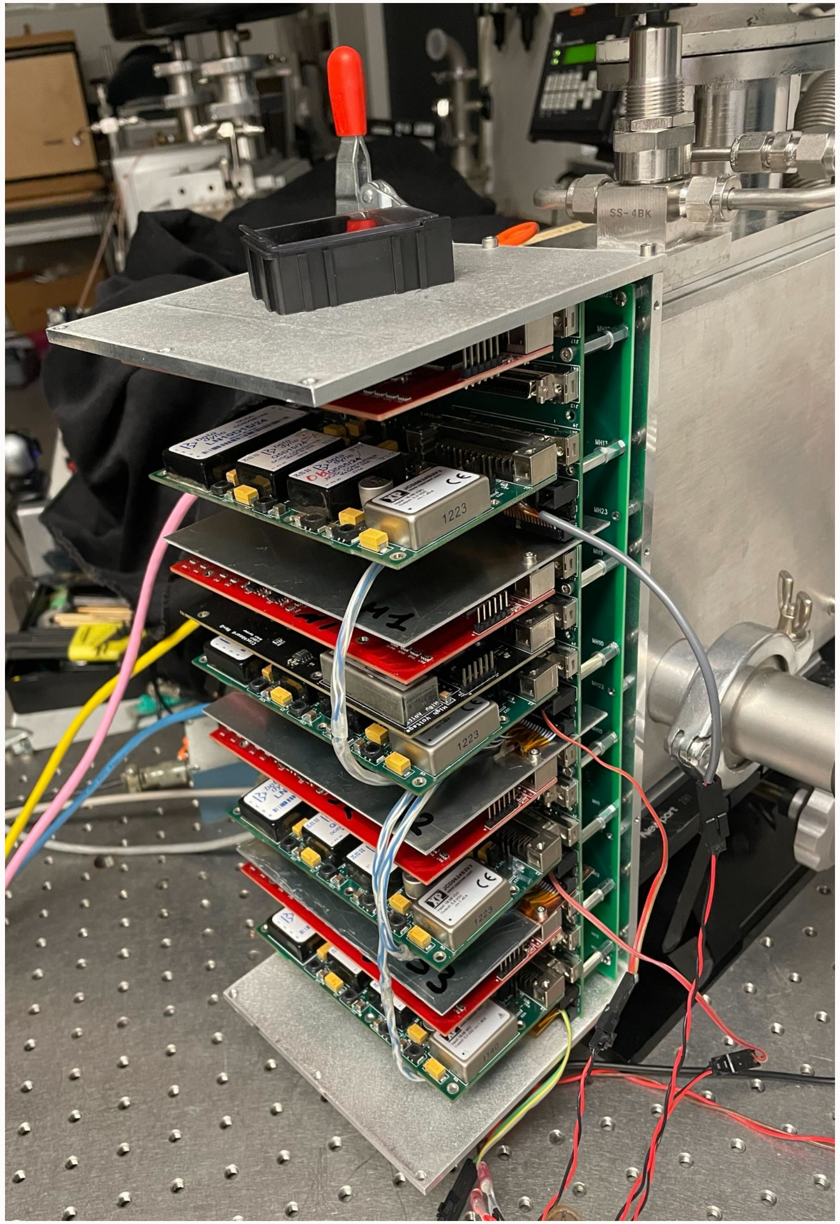
Prototype testing at LBNL

Type	p-channel on high-resistivity n-type substrate
Format	1024 x 512
Pixel size (& pitch)	15 µm
Thickness	650 µm
Readout channels	16
Illumination	Frontside
Operating temperature	~140 K
Fabrication	Teledyne DALSA / LBNL
Controller	DESI Front-end Electronics

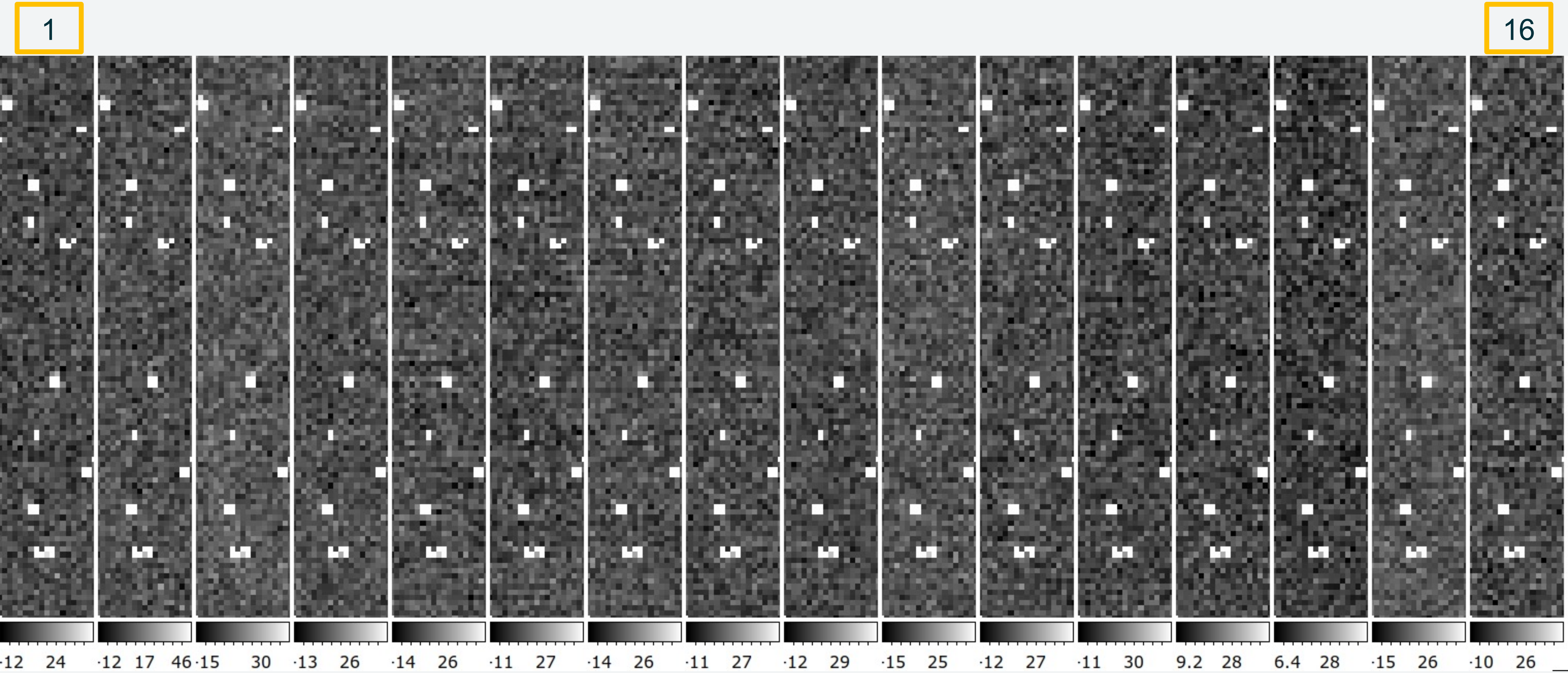
Hydra readout electronics

- 4 synchronized DESI front-end electronics (FEE) in master-slave configuration
- For each subunit: 4-ch video processing, power generation, Linux-based ARM CPU + FPGA module
- Master FEE provides clock driver
- 68 nF capacitive parallel clock shaping, no serial shaping

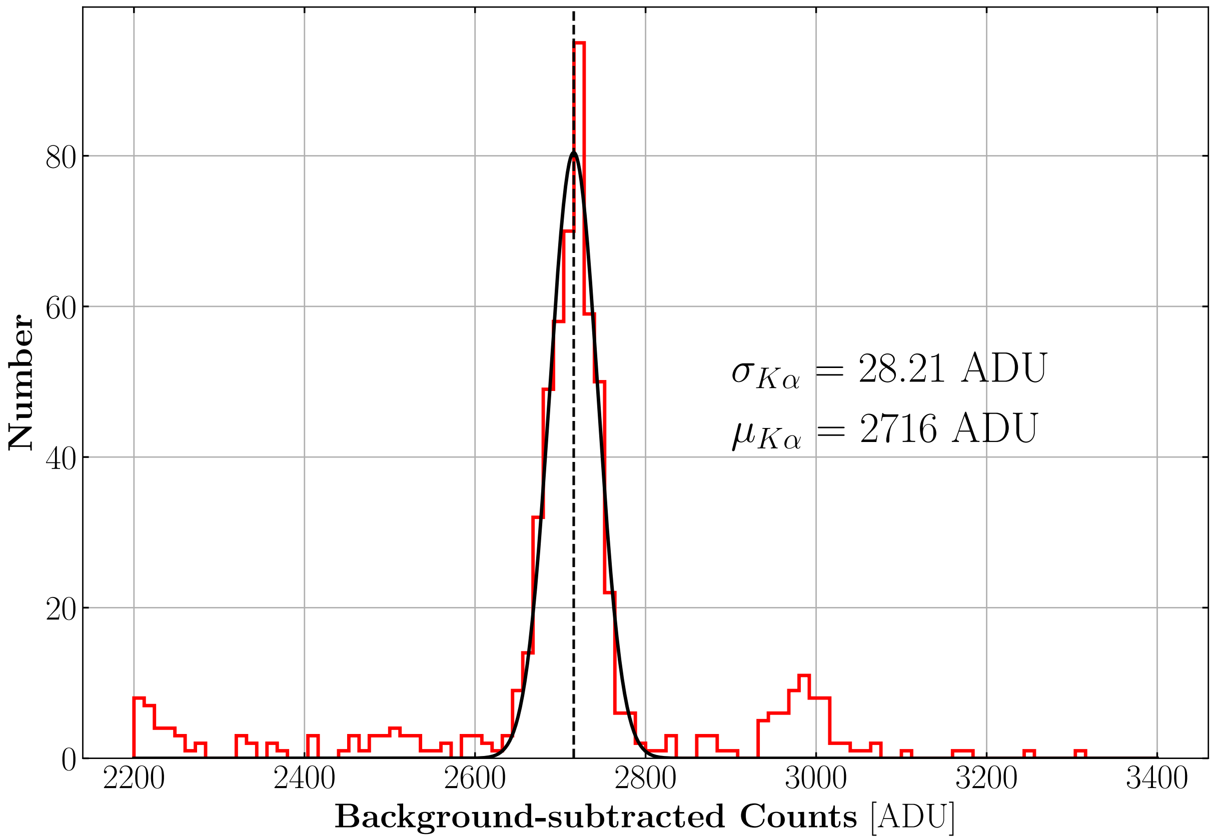


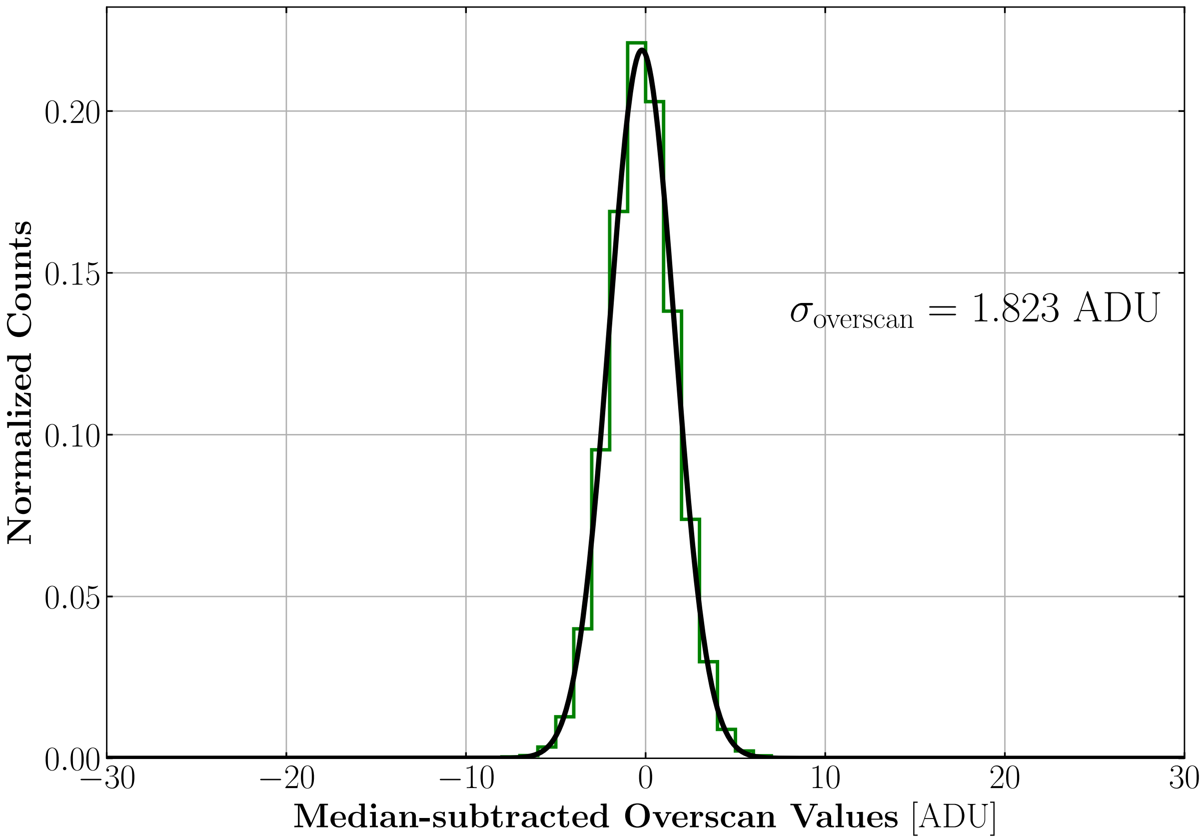


MAS-CCD X-ray image output



Our lowest demonstrated noise performance





^{55}Fe Kα 5.9 keV peak gives gain ~ 1.728 ADU/e-

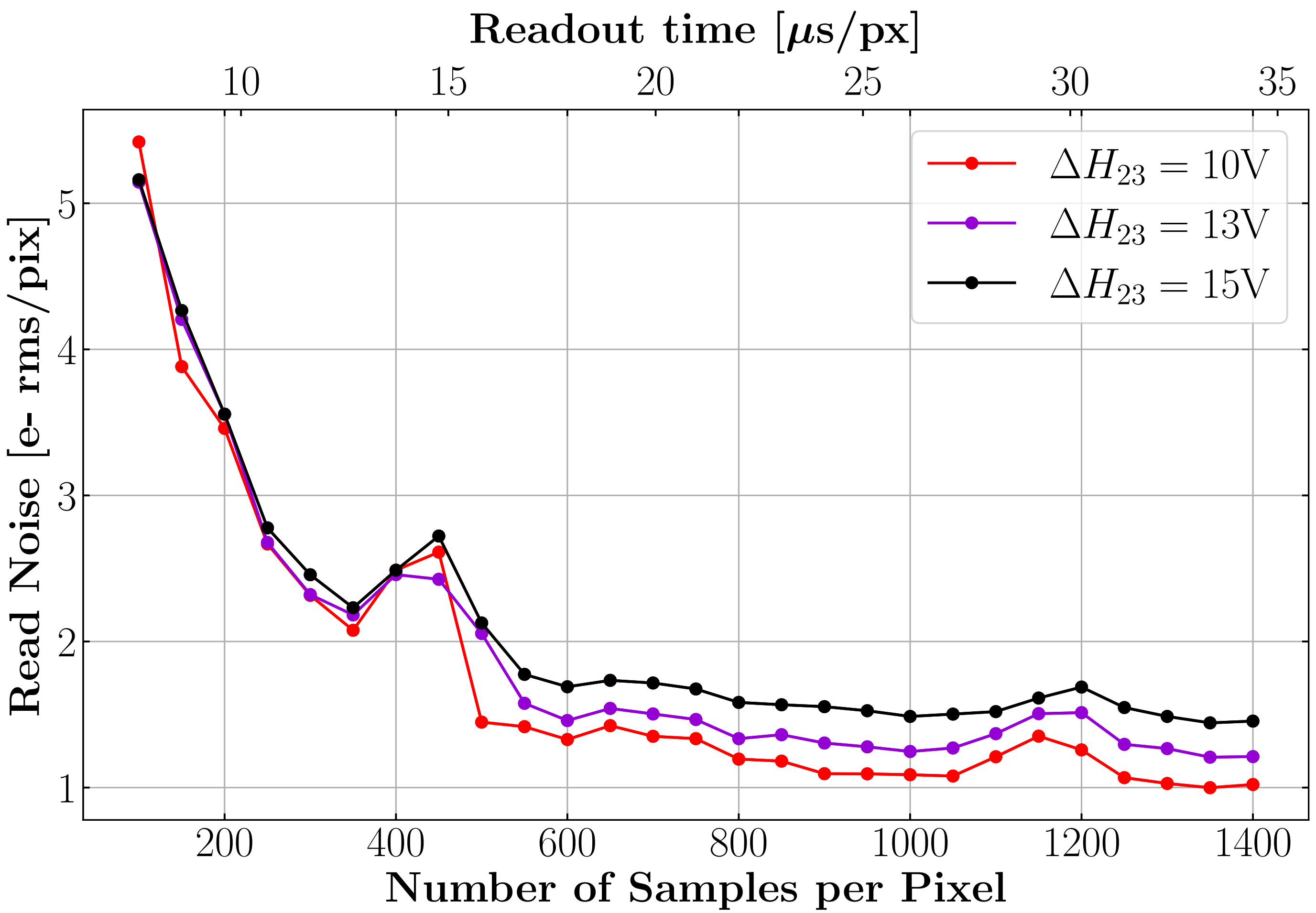
16-ch combined noise ~ 1.06 e- rms/pixel

Pixel rate

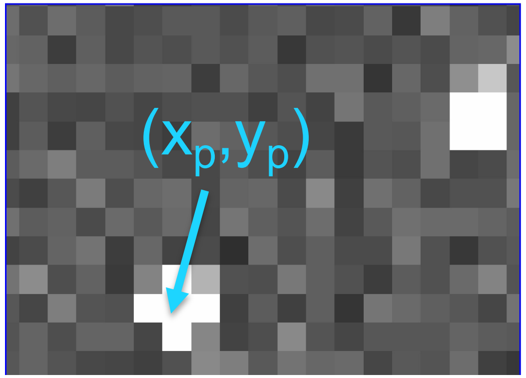
- The number of digital samples per pixel sets the integration time
- Operating at integration time: 1000 samples per pixel
- 2.5 e- rms/pixel noise for DESI integration time = 400

For our lowest noise configuration:
40 kHz or **25 µs/pixel**

- Reducing serial clock voltage swings improves noise performance, to a floor of ~1 e-



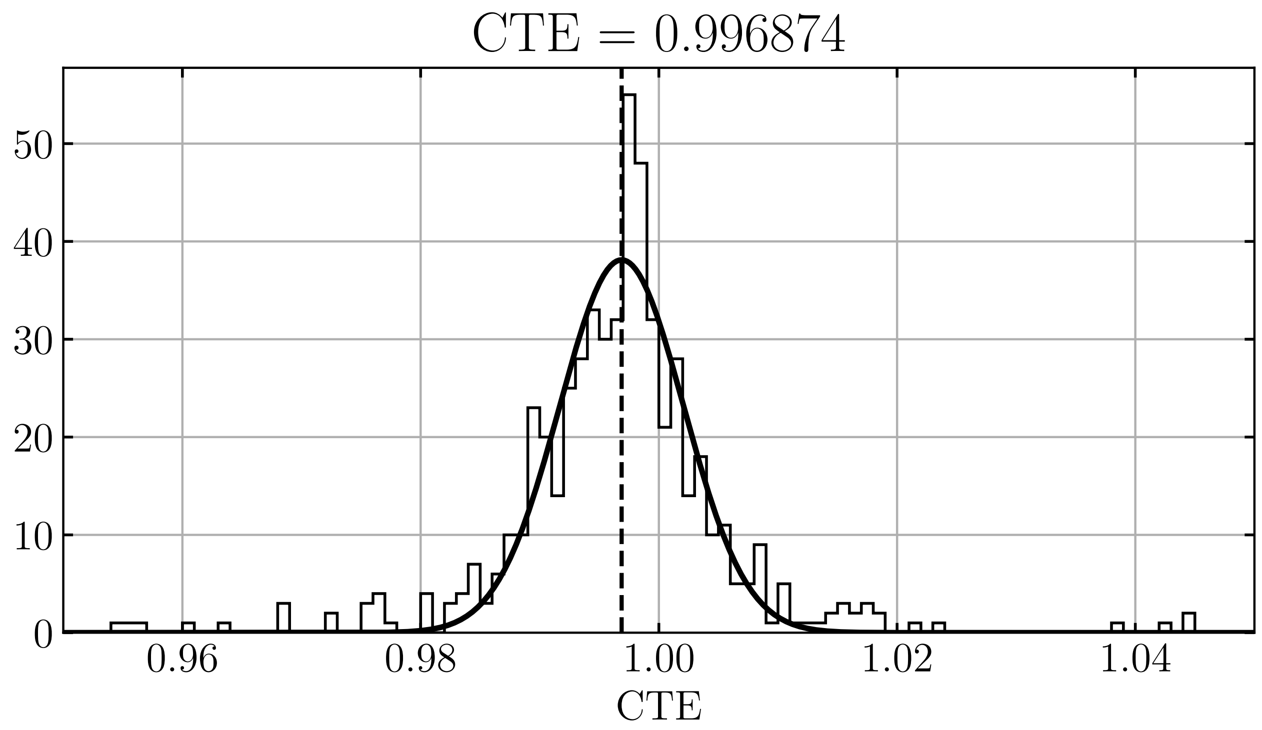
Inter-amplifier charge transfer efficiency

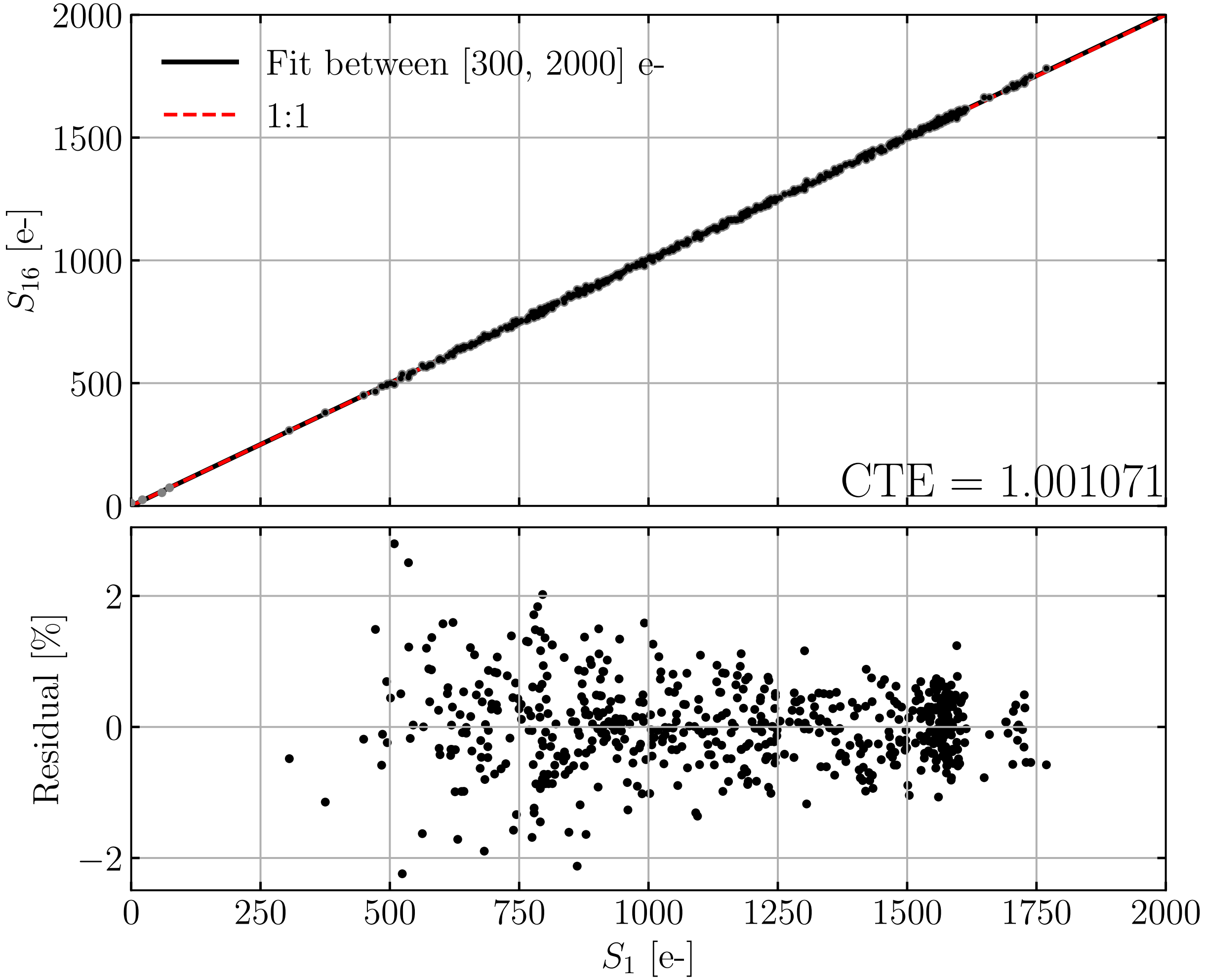


Low signal levels (~1500 e-) evaluated with x-ray statistics

- Maximum of x-ray hits between S_1 and S_{16}
- Linear model fitting:

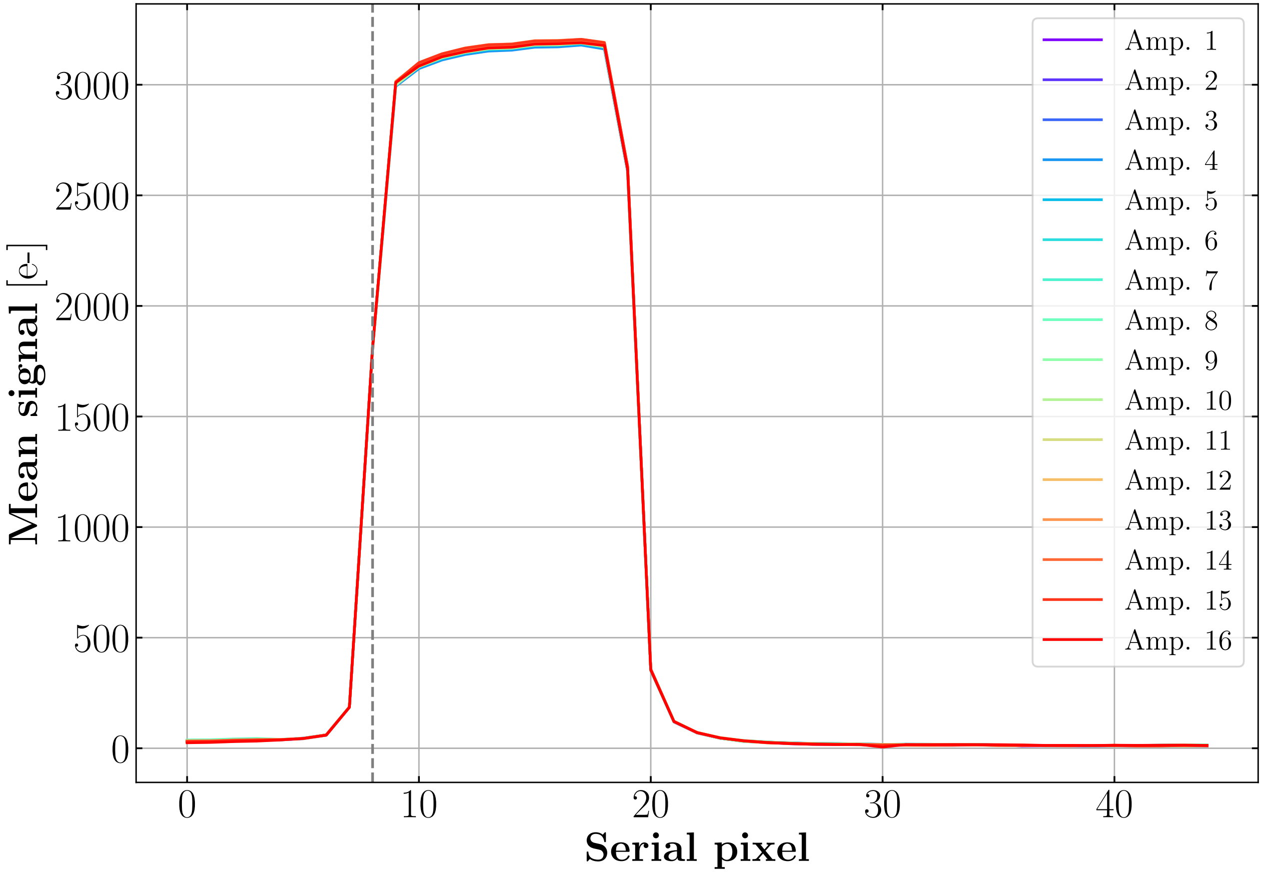
$$S_M(x_p+1, y_p) = (1-\mathrm{CTI}) * S_1(x_p+1, y_p) + \mathrm{CTI} * S_1(x_p, y_p)$$

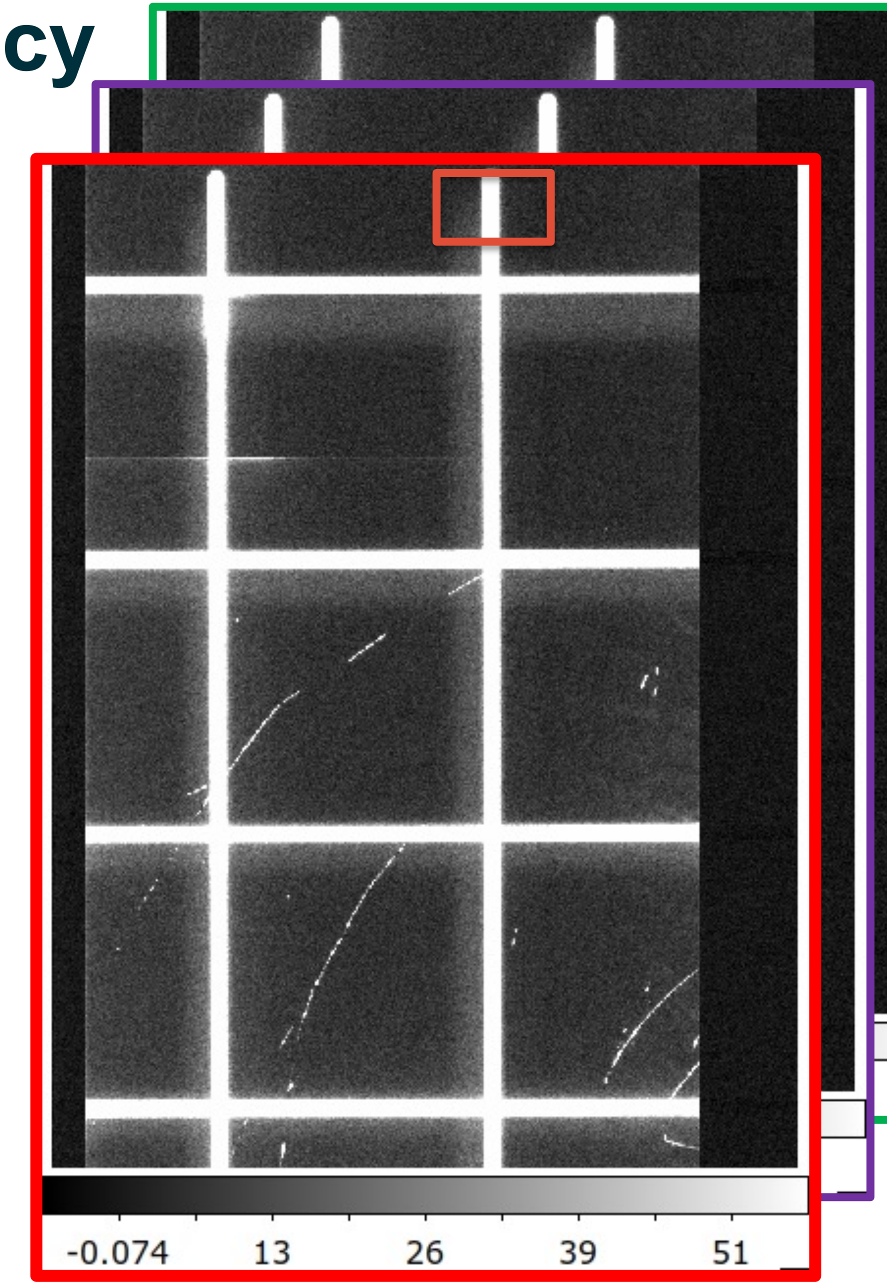




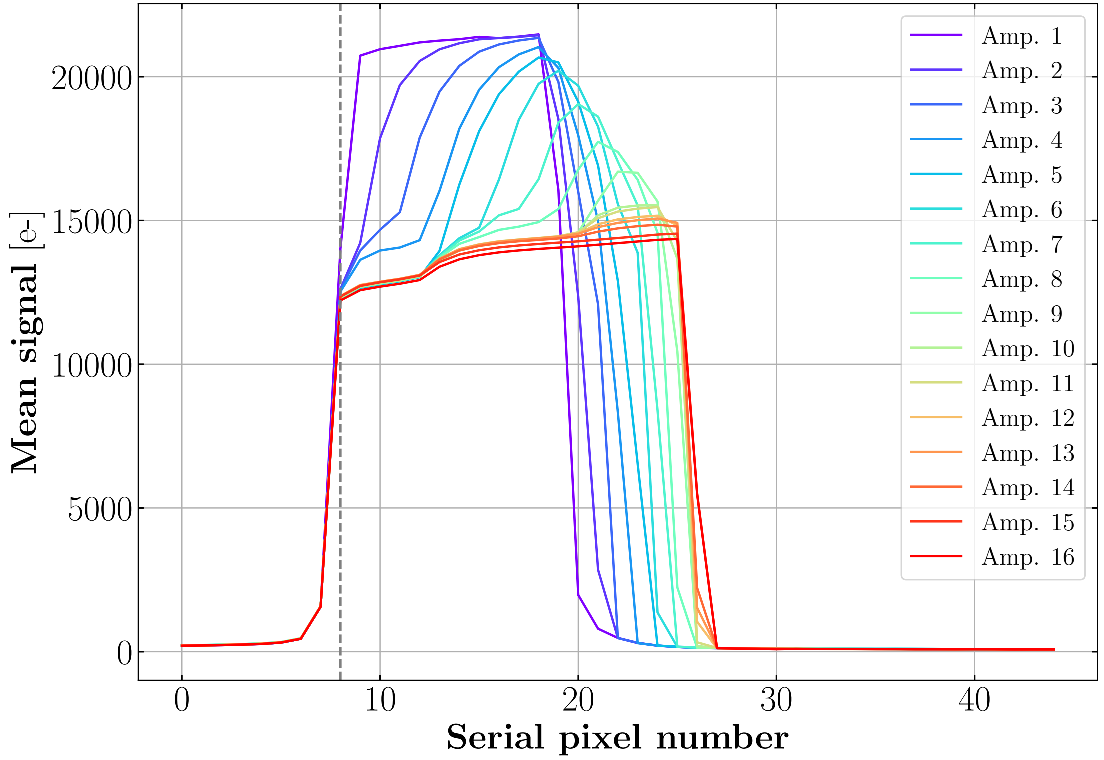
Inter-amplifier charge transfer efficiency

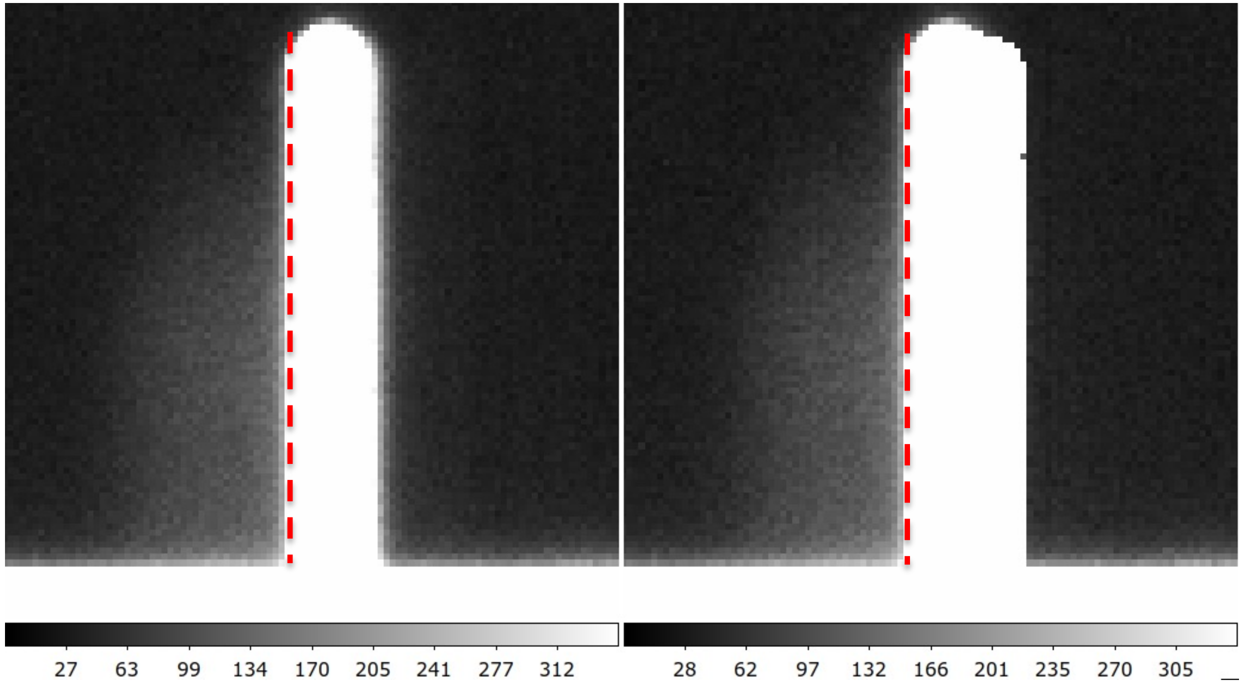
In the high signal level regime (≳10,000 e-), CCD is illuminated by an aligned mask grid pattern





CTI before optimization at high signal levels



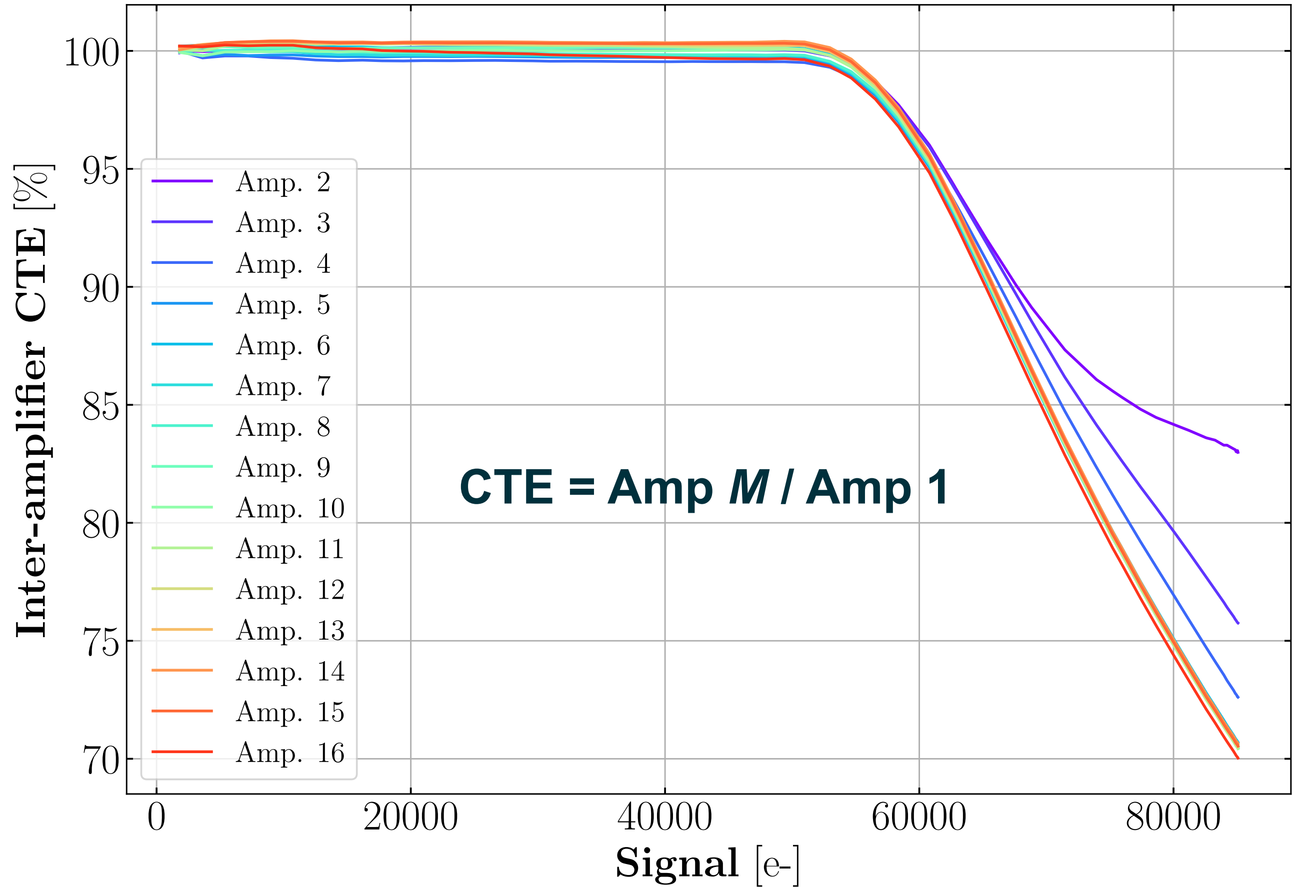


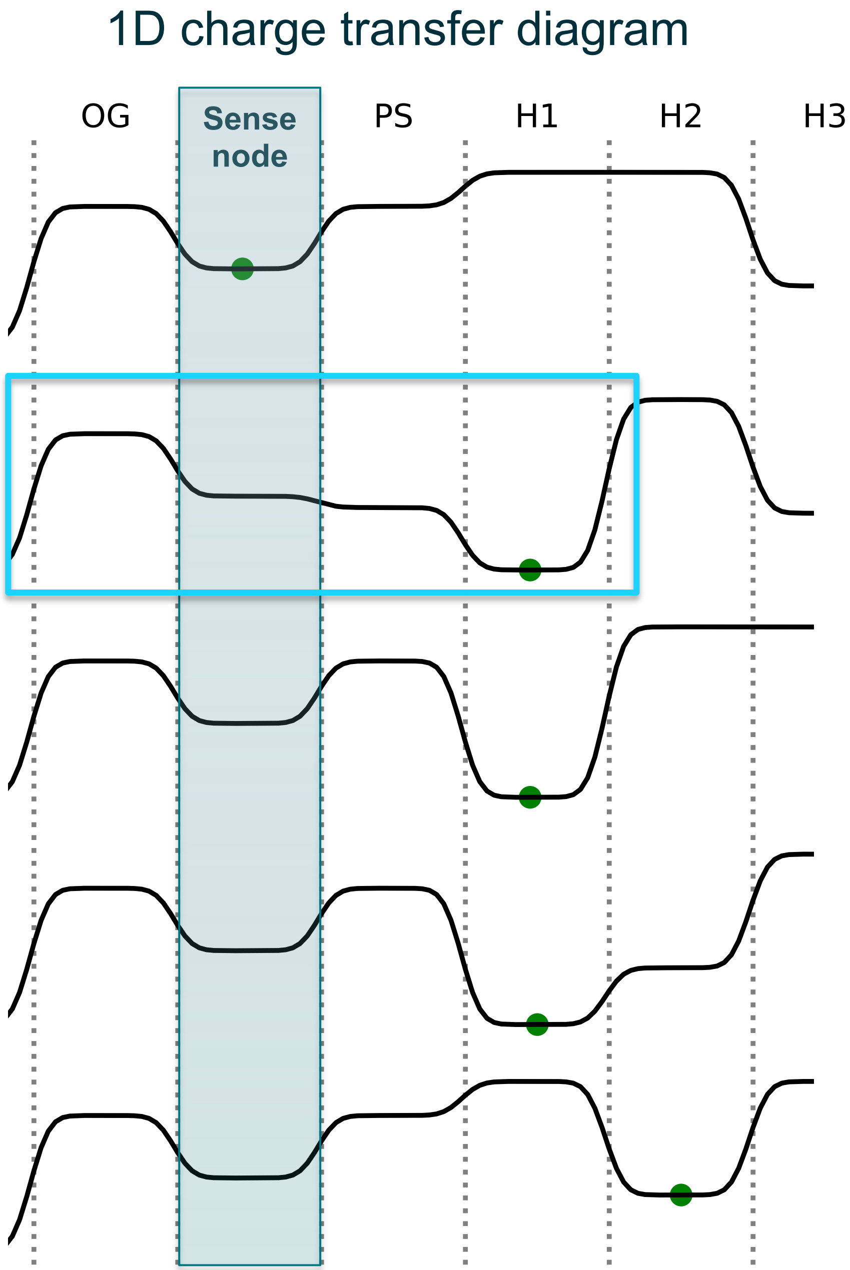
Take first CCD column of illuminated grid columns to quantify horizontal profile CTE degradation

Cautionary tale before voltage optimization: significant CTI identified at signal levels ~ 20,000 electrons at certain low-noise voltage parameters not observed with x-ray analysis

Inefficiency at high signal levels

>0.99 CTE until ~50,000 electrons, entering nonlinear regime
Limited by potential well depths between PS and H1 phases





Plans for further MAS-CCD development

- Goal: 4k x 4k with $\sigma_M \lesssim$ 1e-/pixel at < 15 μs/pixel
- Currently under development:
  - Blue-optimized large-format MAS-CCD design (talk later today by Greg Bredthauer)
  - 4-corner compact MAS serial register design
  - DESI FEE upgrade: 64-channel readout electronics & firmware
- Complementary efforts at Fermilab
  - 16-ch LTA readout electronics development
  - ASIC multiplexing solutions for large channel counts
  - First AstroSkipper CCDs on an astronomical IFU (Thursday talk by Alex Drlica-Wagner)

Summary

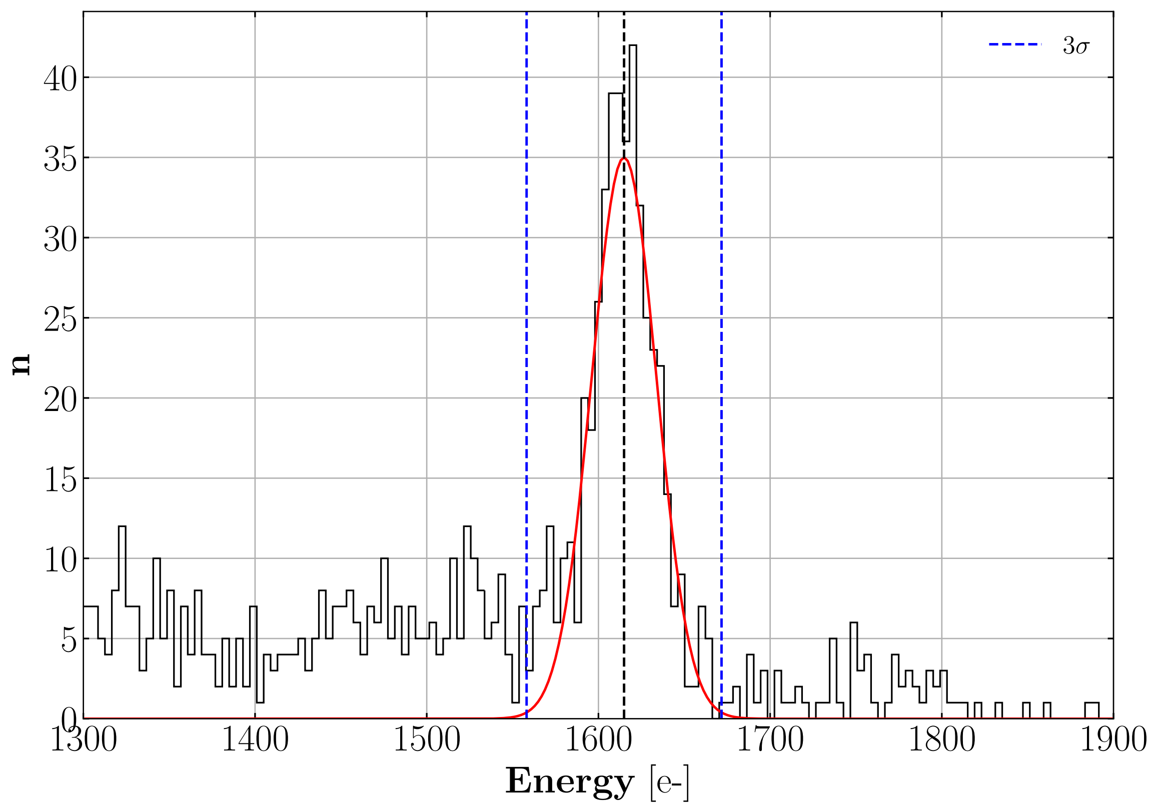
- We have a proof-of-concept for the 16-ch MAS CCD using DESI-based read electronics
- Single-sample read noise ~ 1.1 electrons rms/pixel
- Total read time at low-noise configuration ~ 25 μs/pixel
- No low-signal level charge transfer inefficiency in extended MAS serial register
- Effective full well approaching 50,000 electrons, bounded by nonlinear regime
  - Limitation not intrinsic to device but results from optimization of noise and dynamic range
  - Other operating parameters could allow for higher dynamic range
  - 50,000 electrons is sufficient for some spectroscopic applications like DESI

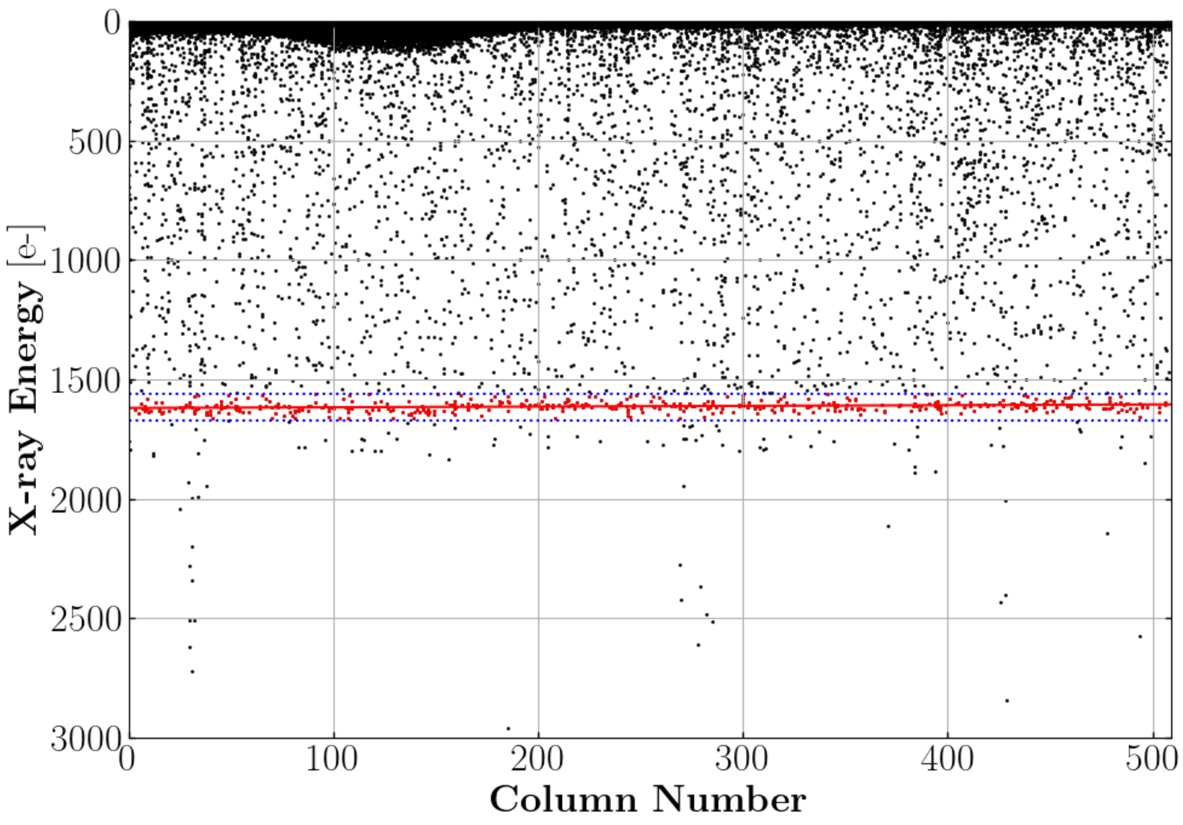
What's ahead?

- Varying reset sampling options: reset per line clocking reduces sampling frequency to enable more time to read signal

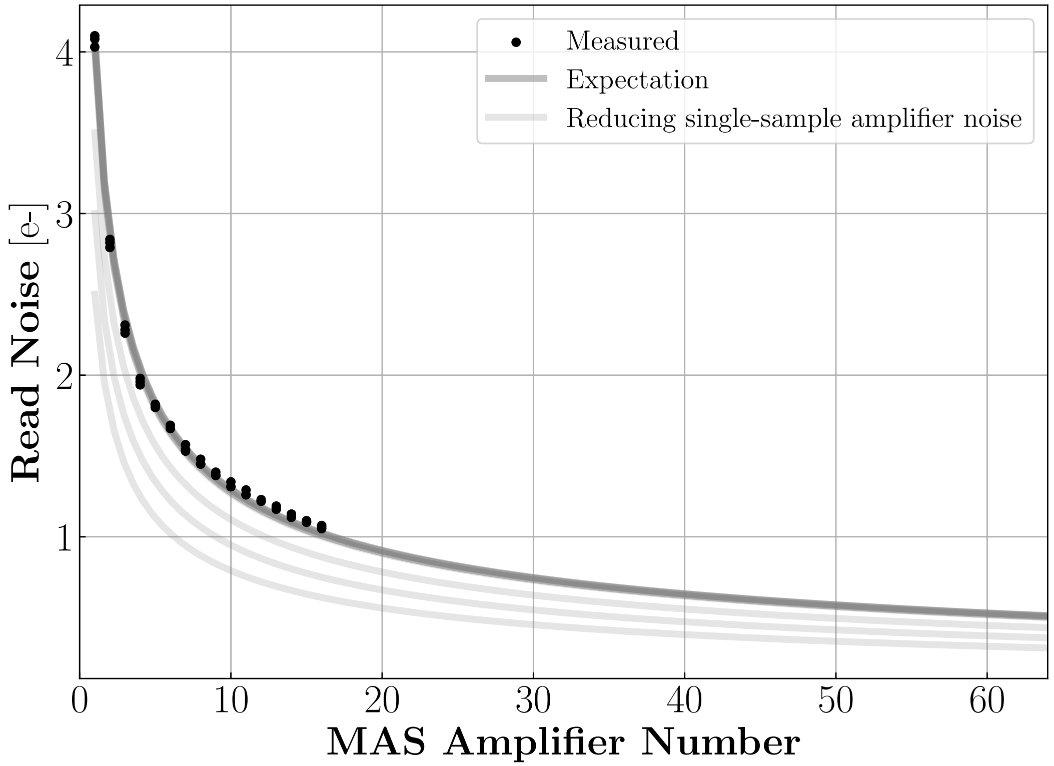
CTE at amplifier 1

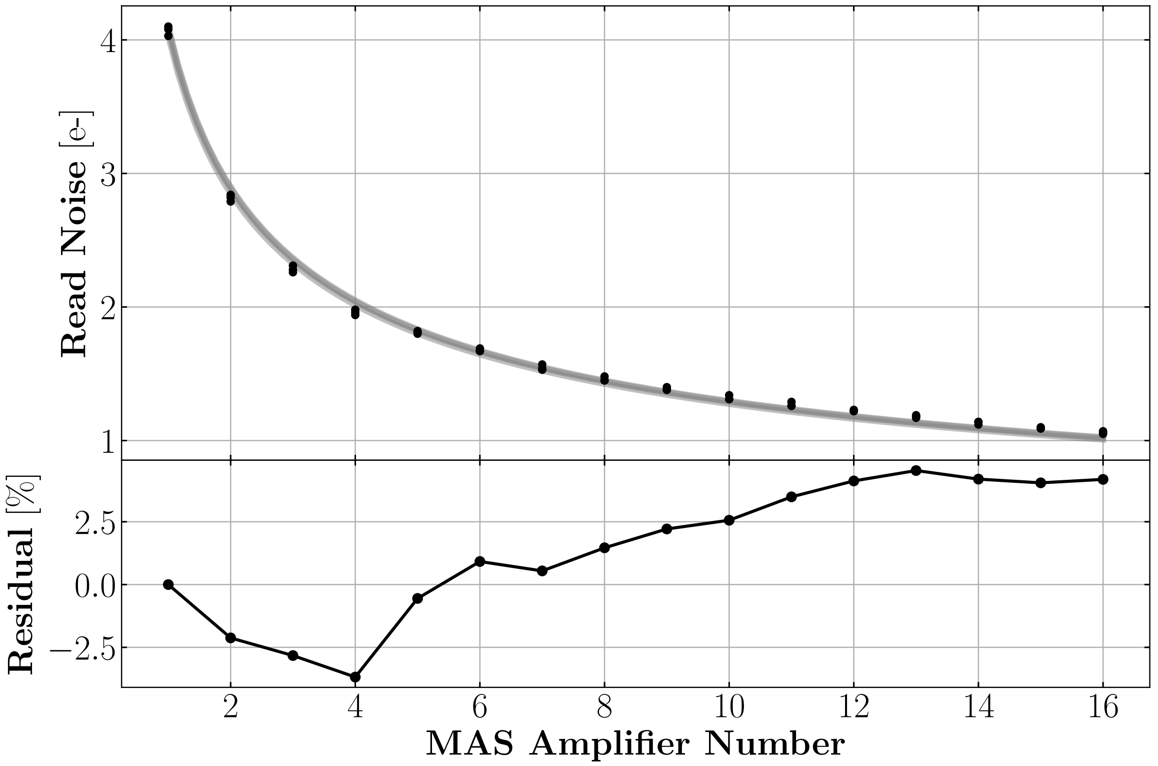
Lower limit > 0.99998 using ^{55}Fe X-ray-stacking calculation





MAS noise reduction compared to expectation





Noise measurements per amplifier

- Stable amplifier gains to 10^{-2} level
- Single amplifier noise close to 3.5-4.3 e- rms/pixel single-sample AstroSkipper noise range after optimization (arXiv:2311.00813)

Amplifier	Gain [ADU/e-]	RMS	Read noise [e-]
1	1.78	6.44	3.62
2	1.78	7.38	4.15 (3.87)
3	1.76	6.47	3.66
4	1.77	6.20	3.51
5	1.78	7.02	3.94
6	1.77	6.87	3.89
7	1.77	7.02	3.97
8	1.76	7.15	4.07
9	1.77	6.99	3.94
10	1.76	6.85	3.88
11	1.78	7.34	4.16
12	1.76	7.52	4.27
13	1.77	6.92	3.90
14	1.76	6.58	3.74
15	1.77	6.64	3.75
16	1.78	6.84	3.85
Combined	**1.77**	**1.97**	**1.11**
Expectation for independent samples			**0.98**