Skipper CCDs for Astrophysical Applications

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† As part of the **S**ub-**E**lectron-**N**oise **S**kipperCCD **E**xperimental **I**nstrument

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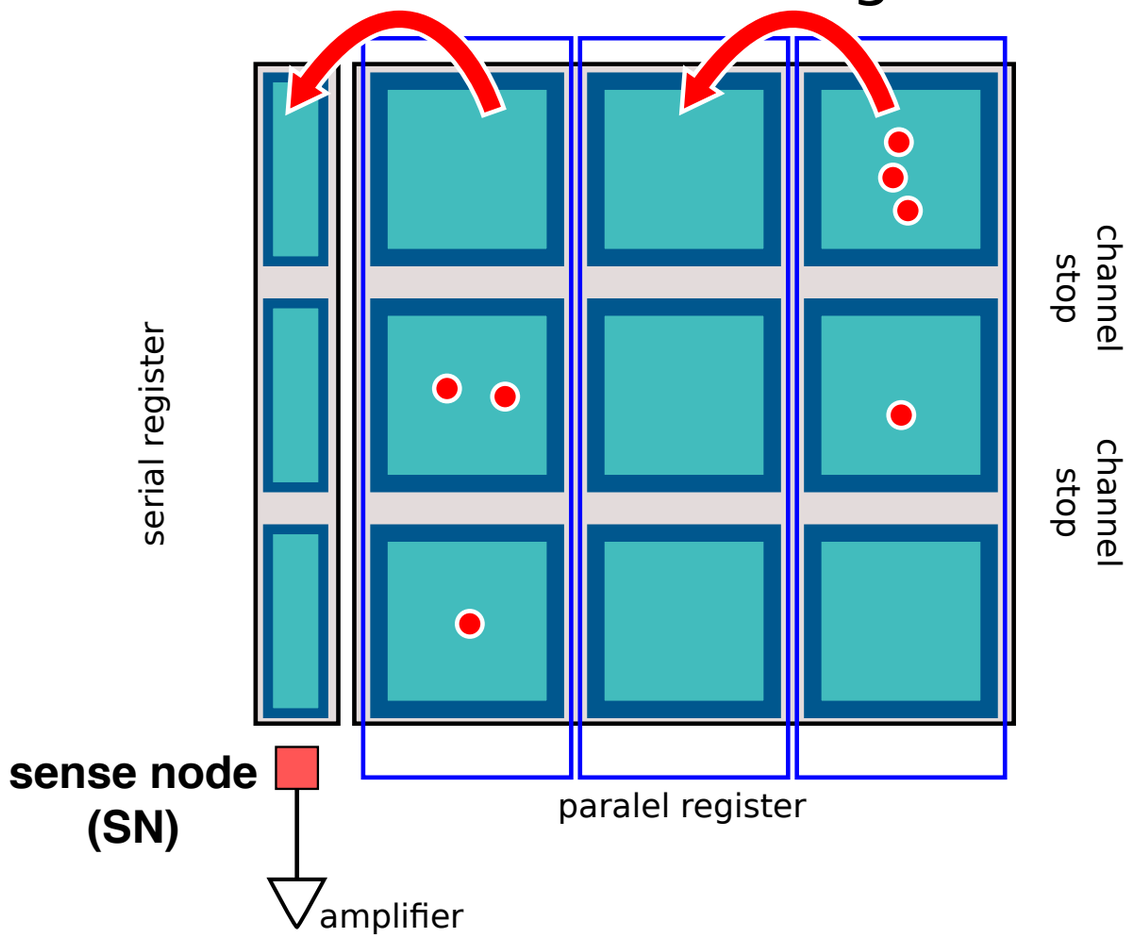
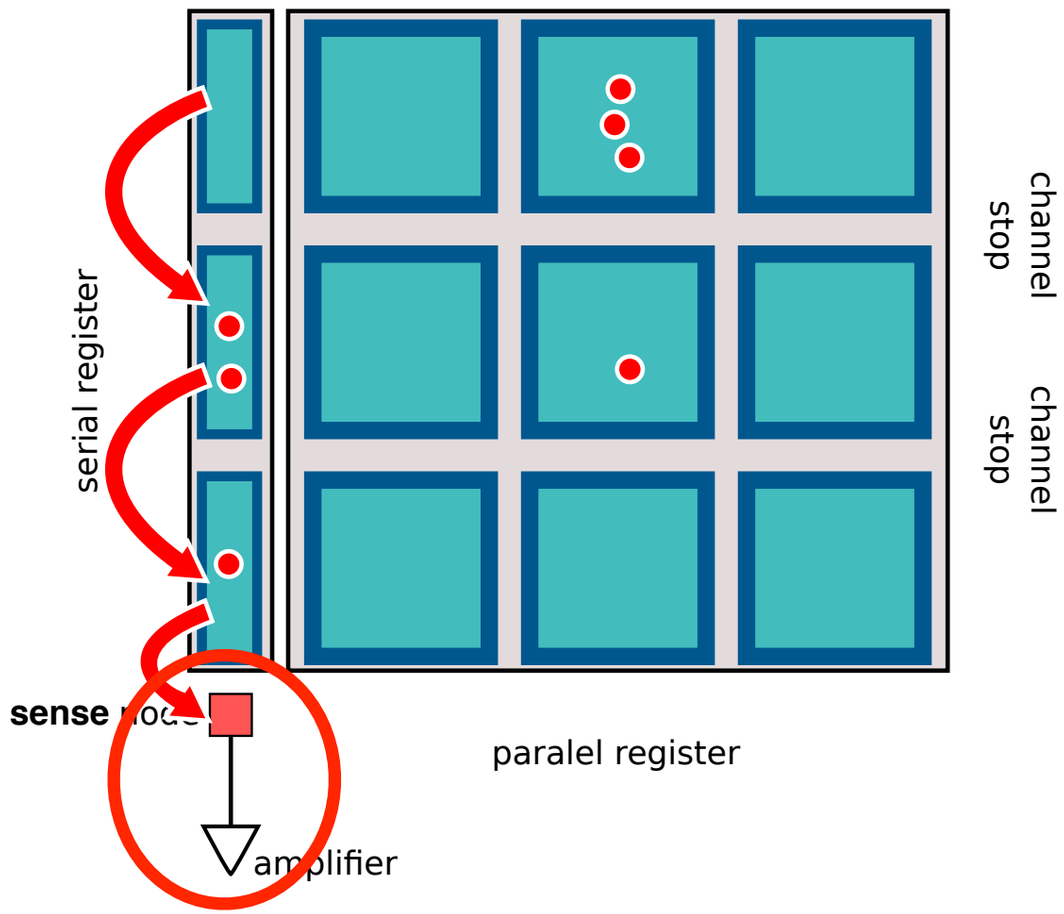
CCD: readout

3x3 pixels CCD

Shift charge one column to tha right



Shift charge in serial register one pixel down (3 times)

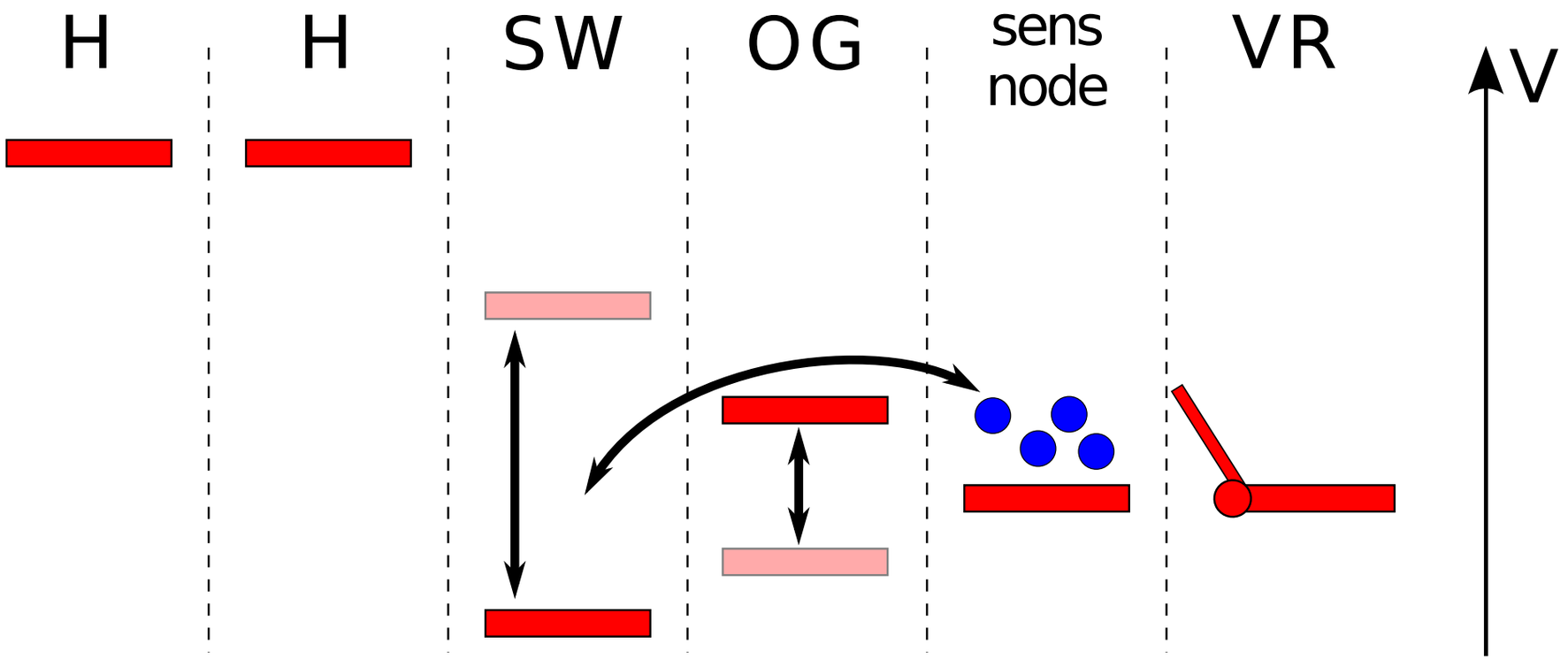


Only modifying the readout stage

capacitance of the system is set by the SN: C=0.05pF$\rightarrow$ 3μV/e

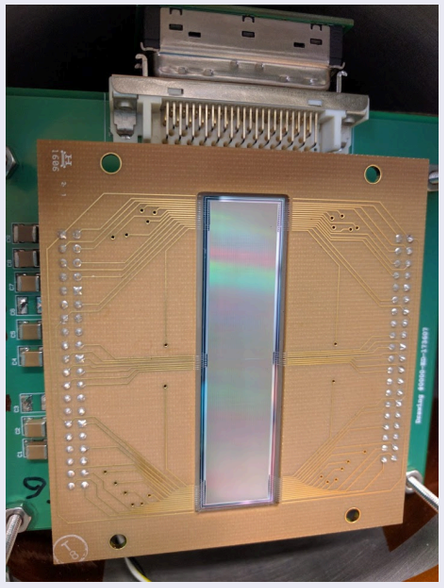
Lowering the noise: Skipper CCD

- **Main difference:** the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  $\mathbf{Pixel\ value} = \frac{1}{N}\Sigma_i^N\,\mathbf{(pixel\ sample)_i}$
- Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)



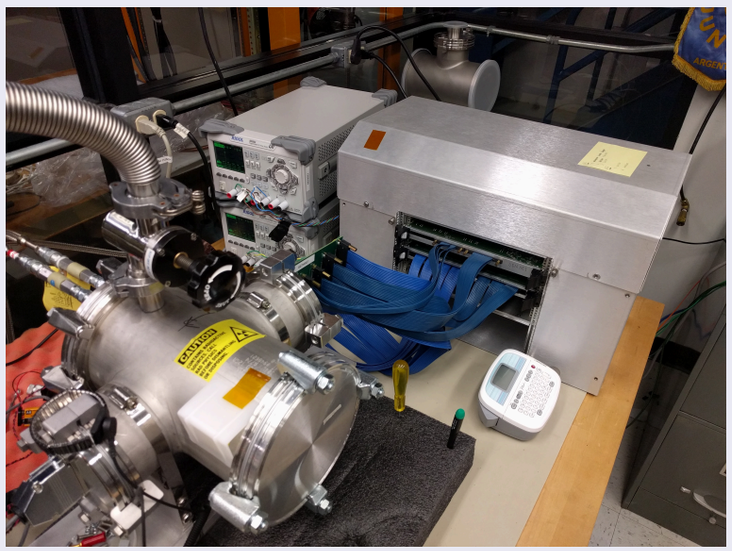
SENSEI: First working instrument using SkipperCCD tech

Sensors



- Skipper-CCD prototype designed by **LBL MSL**
- 200 & 250 μm thick, 15 μm pixel size
- Two form factors 4k×1k (0.5gr) & 1.2k×0.7k pixels
- Parasitic run, optic coating and Si resistivity ∼10kΩ
- 4 amplifiers per CCD, three different RO stage designs

Instrument



- System integration done at Fermilab
- Custom cold electronics
- Modified DES electronics for read out
- Firmware and image processing software
- Optimization of operation parameters

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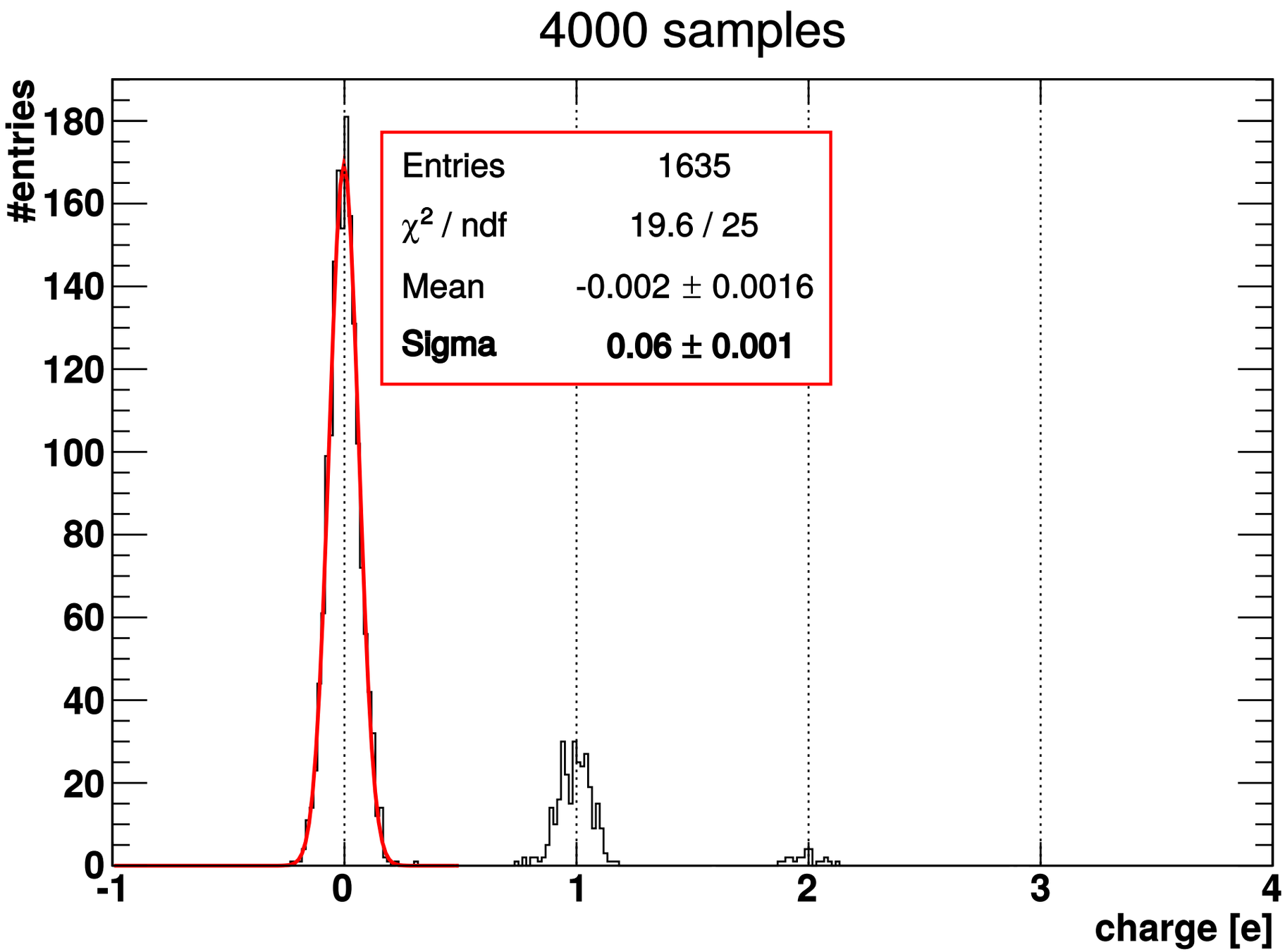
Charge in pixel distribution. Counting electrons: 0, 1, 2..



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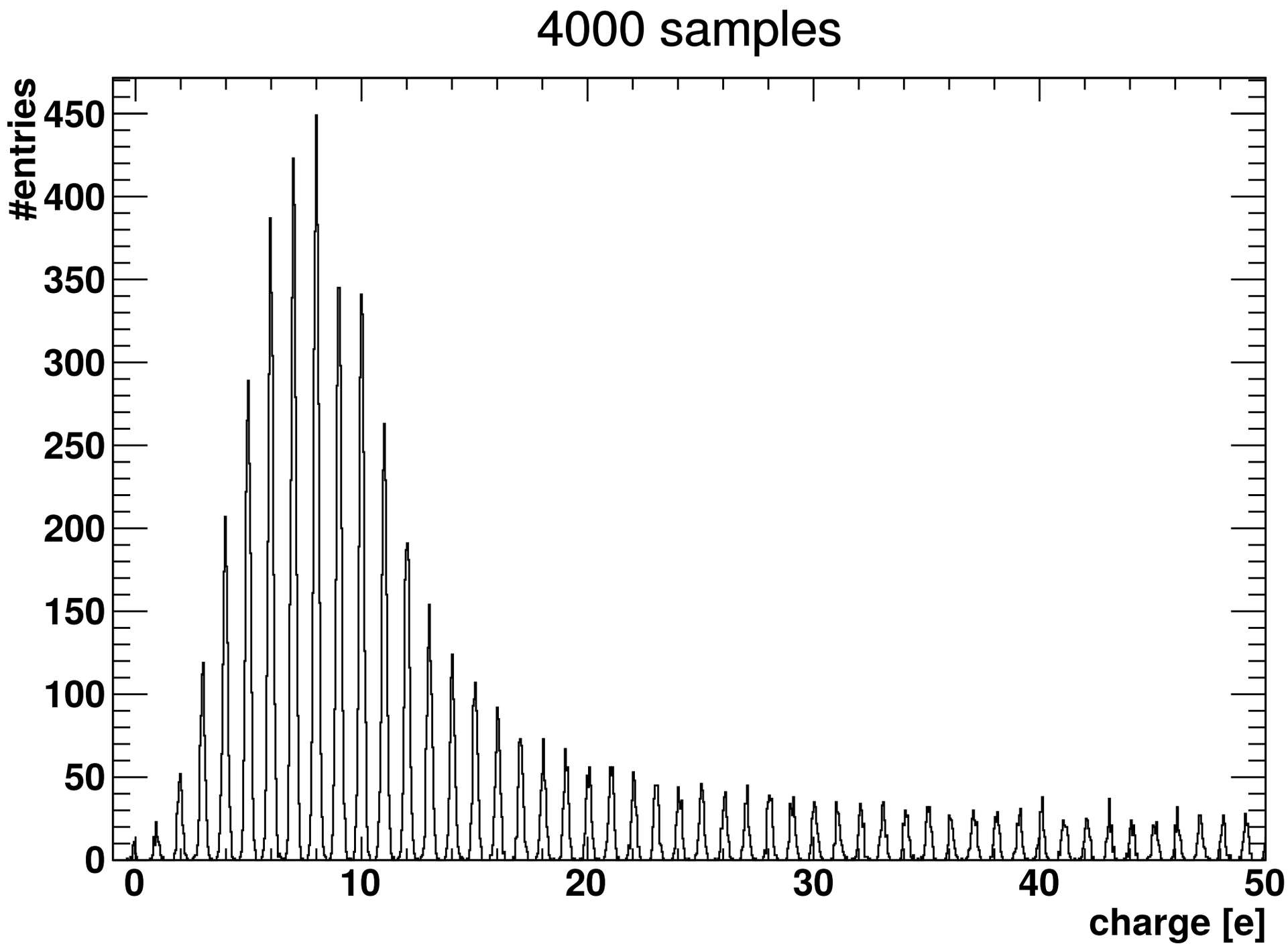
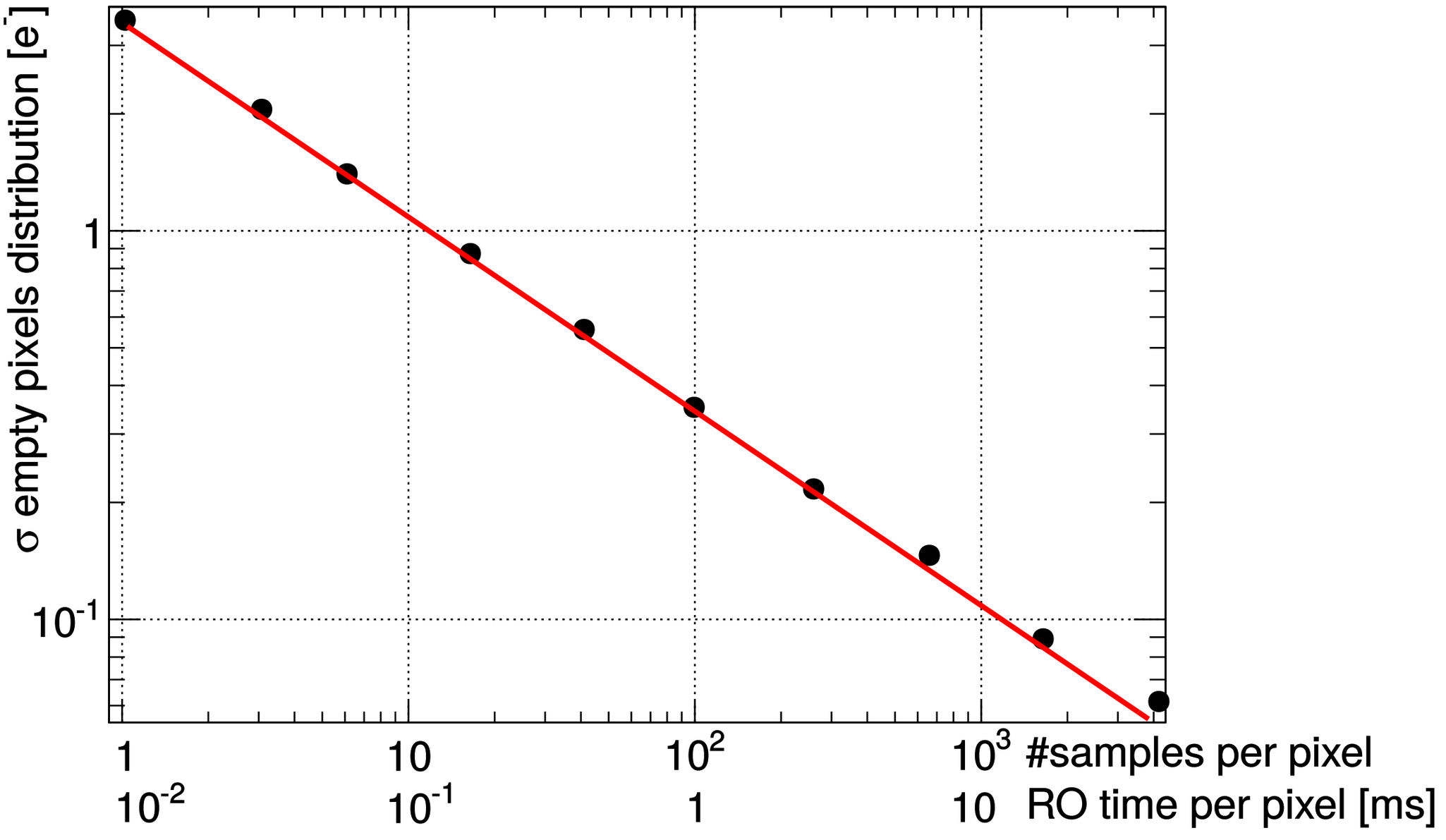
Counting electrons: ..48, 49, 50..



Noise vs. #samples - $1/\sqrt{N}$



Skipper-CCDs for Astrophysics

Opportunities for Astrophysics

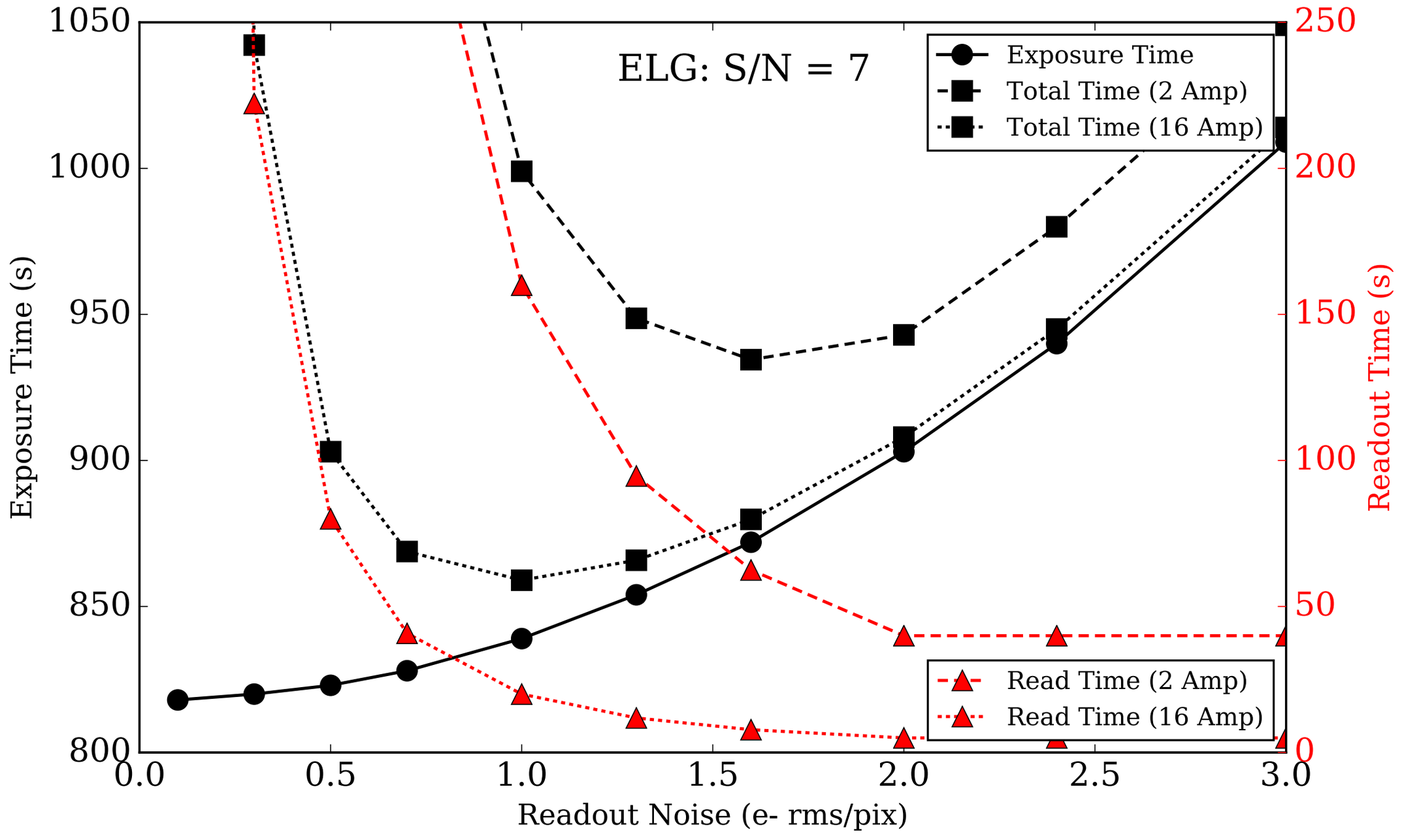
- Number of reads can be dynamically configured in firmware/software
- A Skipper-CCD in single-read mode reduces to a conventional CCD
- Number of reads can be configured pixel-by-pixel or based on the charge measured during the first read.

Challenges for Astrophysics

- Skipper-CCDs are optimal for the low-signal, low-background regime
- The error budge is usually dominated by Poisson noise for bright sources and sky background for faint sources
- Readout time increases with lower readout noise: $t \propto \mathrm{RN}^{-2}$

DESI Exposure Time

Reduce time for DESI to observe ELGs at fixed $\mathrm{S/N} = 7$
DESI CCDs ($\sim 2\,\mathrm{e}^-\,\mathrm{rms/pixel}$) read with 2 amps in 42s
Explore decreased readout time with 16 amps



Reducing Readout Time

The Problem

- Current generation of Skipper-CCDs have single-read noise of $\sim 3.5\,\mathrm{e^-\,rms/pixel}$ which equates to a readout time:
  $100\,\mu\mathrm{s/\,pixel}$ with $\mathrm{RN} = 1\,\mathrm{e^-\,rms/pixel}$
  $10\,\mathrm{ms/\,pixel}$ with $\mathrm{RN} = 0.1\,\mathrm{e^-\,rms/pixel}$
- For a large format detector (2048×4096) with 4 amplifiers, this is 200 s and 2×10^4 s, respectively.

Paths for Development

- Reduce starting readout noise (DESI CCDs have $\sim 2\,\mathrm{e^-\,rms/pixel}$)
- Repeated readout for only a subset of pixels (known line position)
- Increase the number of readout channels/amplifiers ($\geq$ 16 amps?)
- Use frame shifting to readout during subsequent exposure

Summary

- Skipper CCDs can achieve ultra-low noise ($< 0.1\,\mathrm{e^-\,rms/pixel}$) by sampling the charge in each pixel multiple times
- The number of samples can be dynamically adjusted exposure-by-exposure or pixel-by-pixel in software/firmware
- Skipper CCDs reduce to conventional CCDs in the single-sample case: **There should be no downside!**
- Skipper CCD readout time must be reduced to be viable for future spectroscopic instruments
- Other potential applications for space-based imaging/spectroscopy