Skipper CCDs for Cosmological Applications

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CPAD Instrumentation Frontiers Workshop

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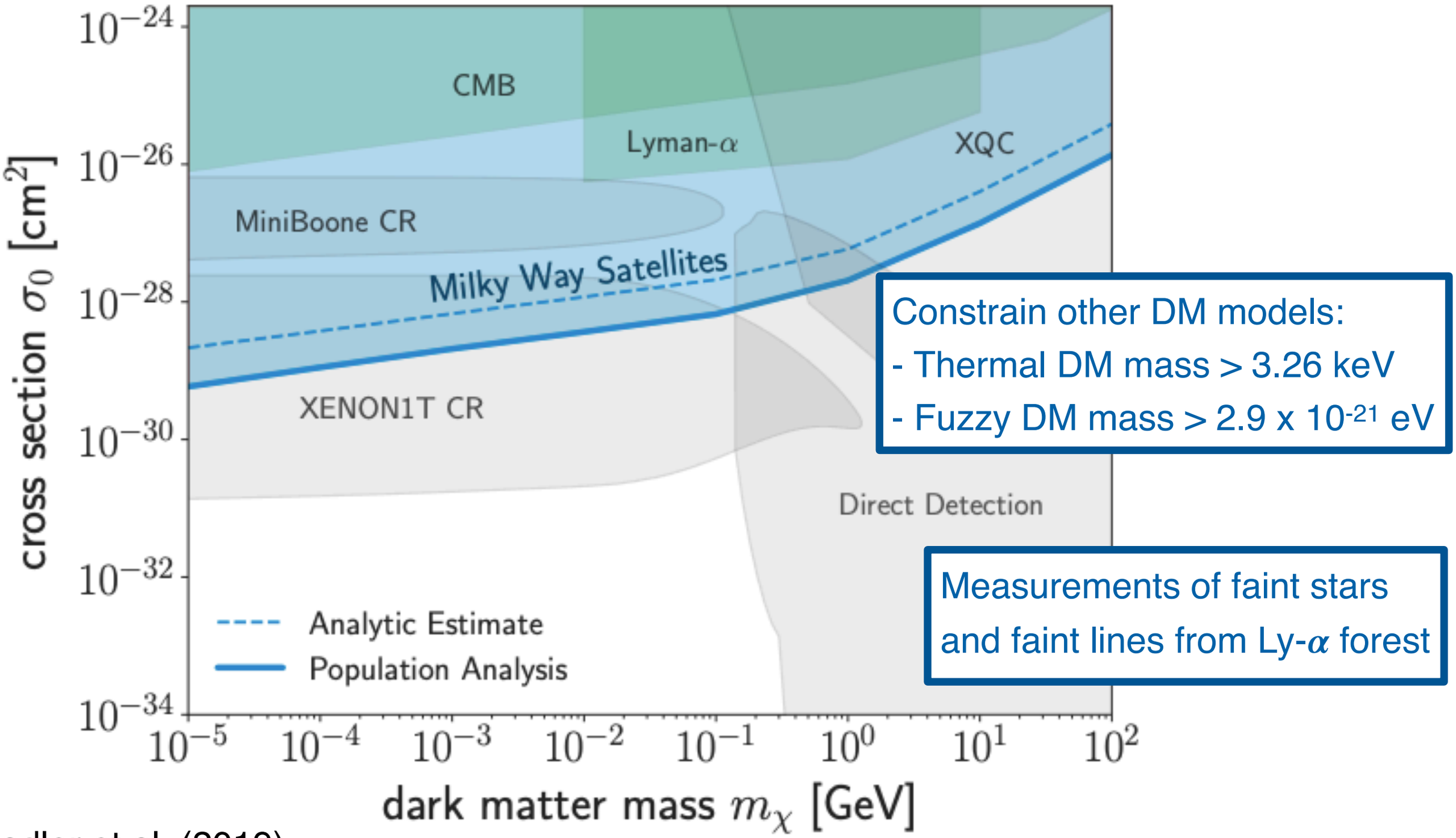
Small-Scale Structure and Dark Matter Microphysics



Constrain other DM models:

- Thermal DM mass > 3.26 keV
- Fuzzy DM mass > 2.9 x 10^{-21} eV

Measurements of faint stars and faint lines from Ly-α forest

Nadler et al. (2019)

Skipper CCDs for Cosmology

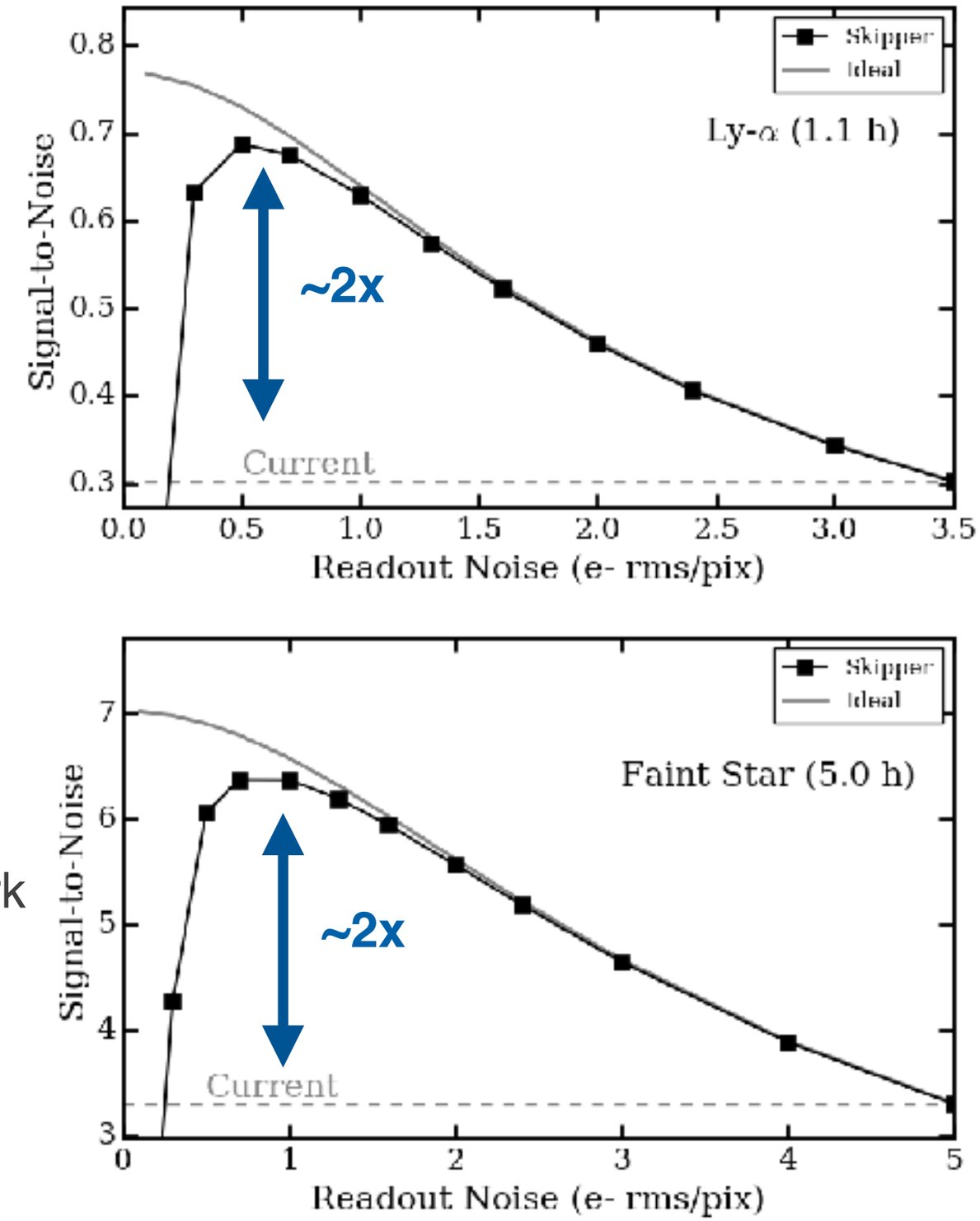
- **Modern astronomical observations can control…**
  - Where the telescope is pointing (the object you are looking at)
  - Wavelength of light (energy of photons you collect)
  - Exposure time (how many photons you collect)
  - Detector binning (trade resolution for readout time/readout noise)

- **Modern astronomical observations are limited in…**
  - Sometimes you are photon starved (can't integrate any longer)
  - Sometimes exposure time is limited (instrument stability, cosmic ray pile-up, etc.)
  - Sometimes you can't sacrifice resolution (don't want to bin)
  - Sometimes you are looking at many different sources at once

- **The Skipper CCD for Cosmology pitch…**
  - Skipper CCDs allow you to **control readout noise** directly on a **pixel-by-pixel** basis
  - Configurable **per object** and **per exposure**
  - **Every CCD used for astronomical observations should be a Skipper CCD**

Readout Noise and Cosmology

- **Skipper CCDs provide dynamic, configurable control over readout noise.**
- **Readout noise is important in regime of small signal and small background**
  - Multiplexed spectroscopy of faint objects (observing many objects at the same time)
  - High resolution spectroscopy (signal is a line while background is continuum)
  - Space-based spectroscopy (significantly reduced background)
- **Cosmological applications**
  - Small scale structure of dark matter (fuzzy dark matter, warm dark matter, self-interacting dark matter)
  - Faint emission line galaxies (dark energy, large-scale structure, etc.)
  - Things I haven't thought of… come talk to me!



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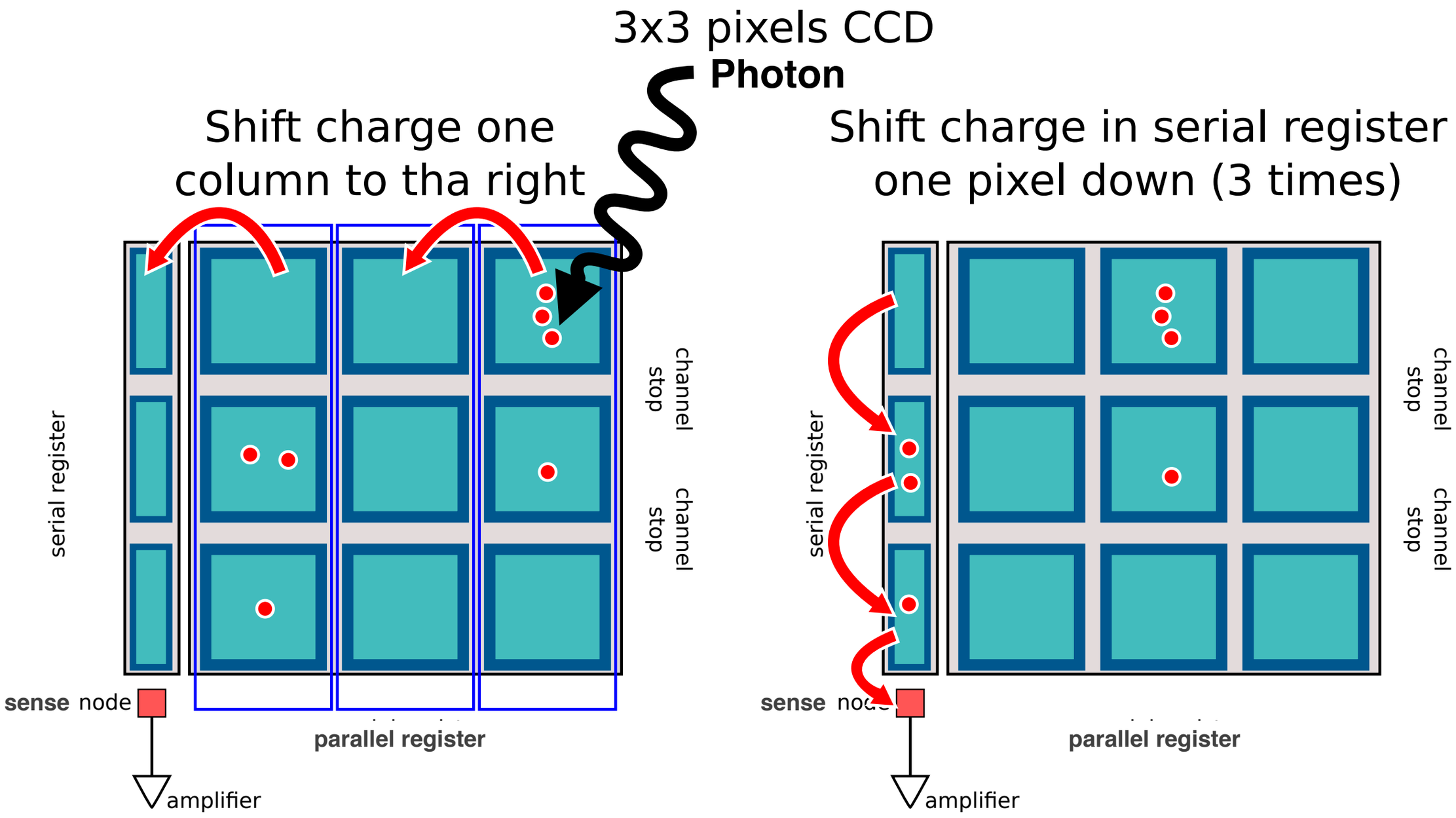
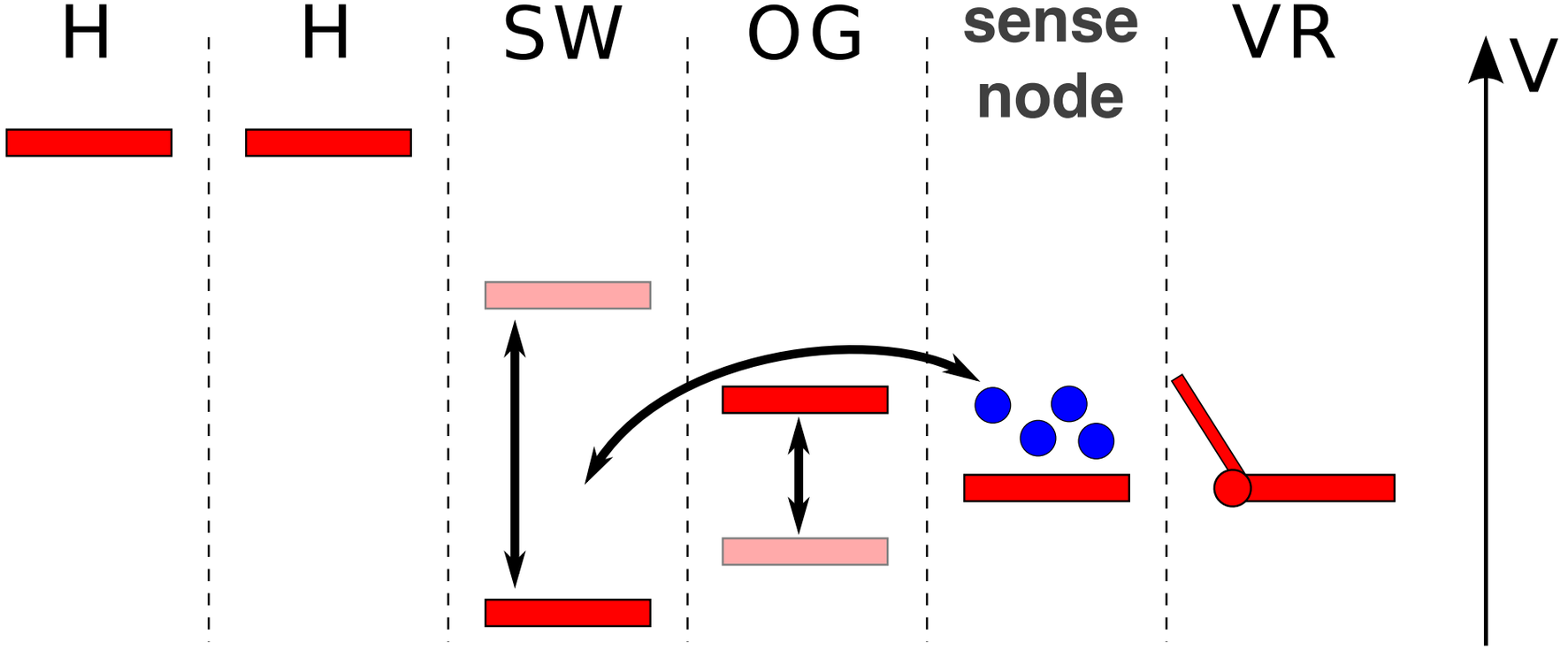
CCD Readout

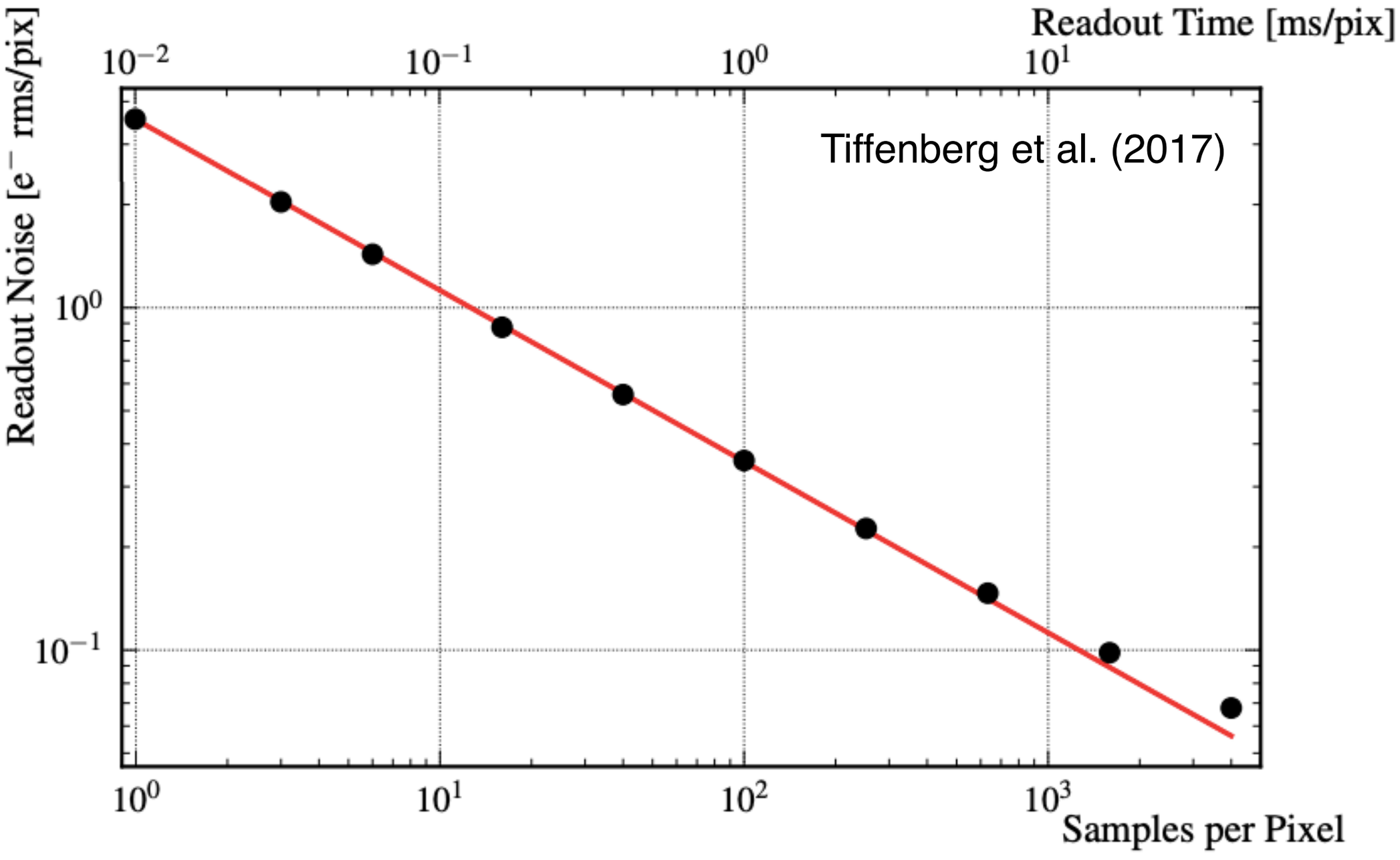

3x3 pixels CCD
Photon
Shift charge one column to tha right
Shift charge in serial register one pixel down (3 times)
serial register
channel stop
channel stop
sense node
amplifier
parallel register
serial register
channel stop
channel stop
sense node
amplifier
parallel register

Lowering Readout Noise: Skipper CCDs

- **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)



Readout Noise vs. Number of Samples for Skipper CCD



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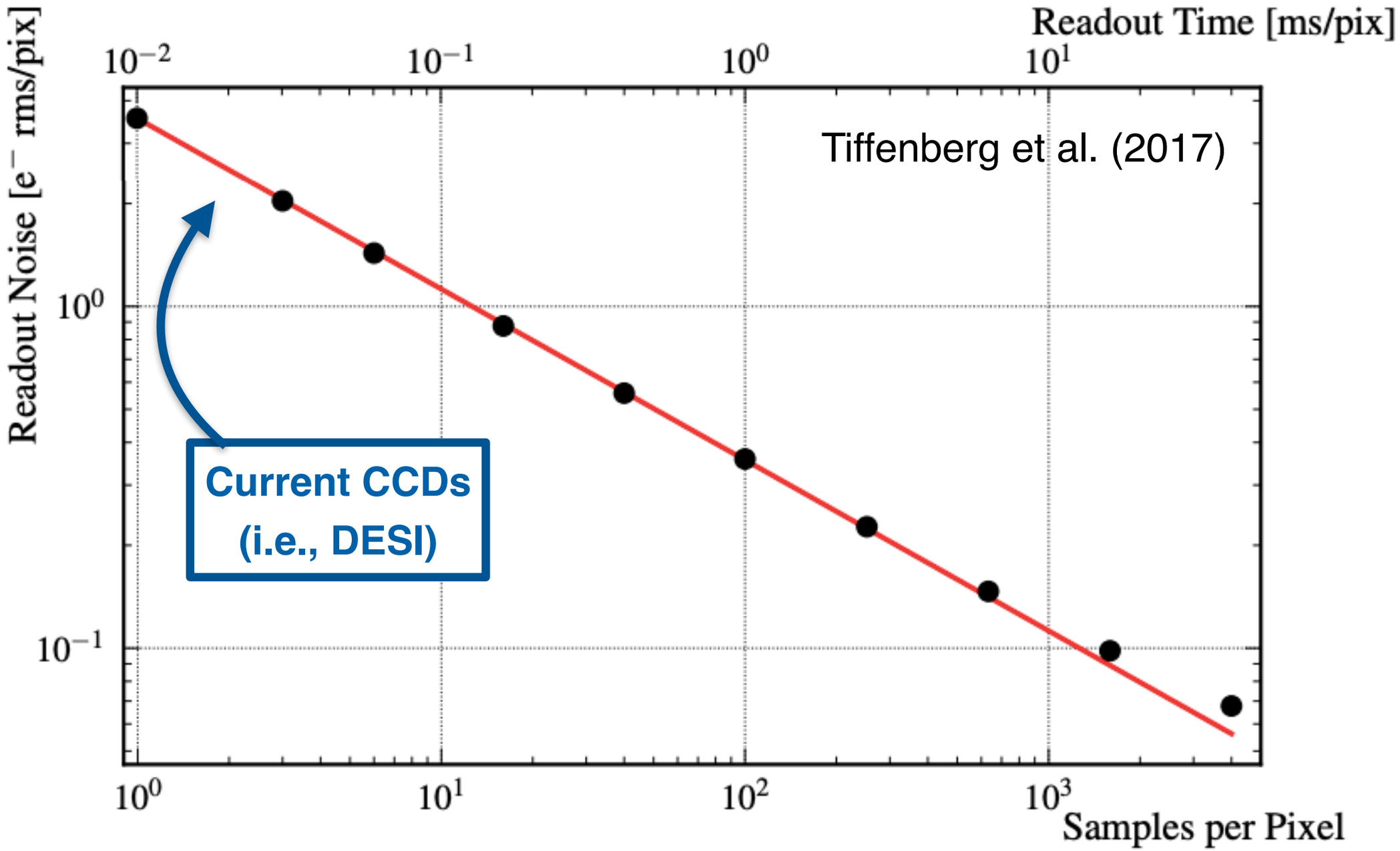

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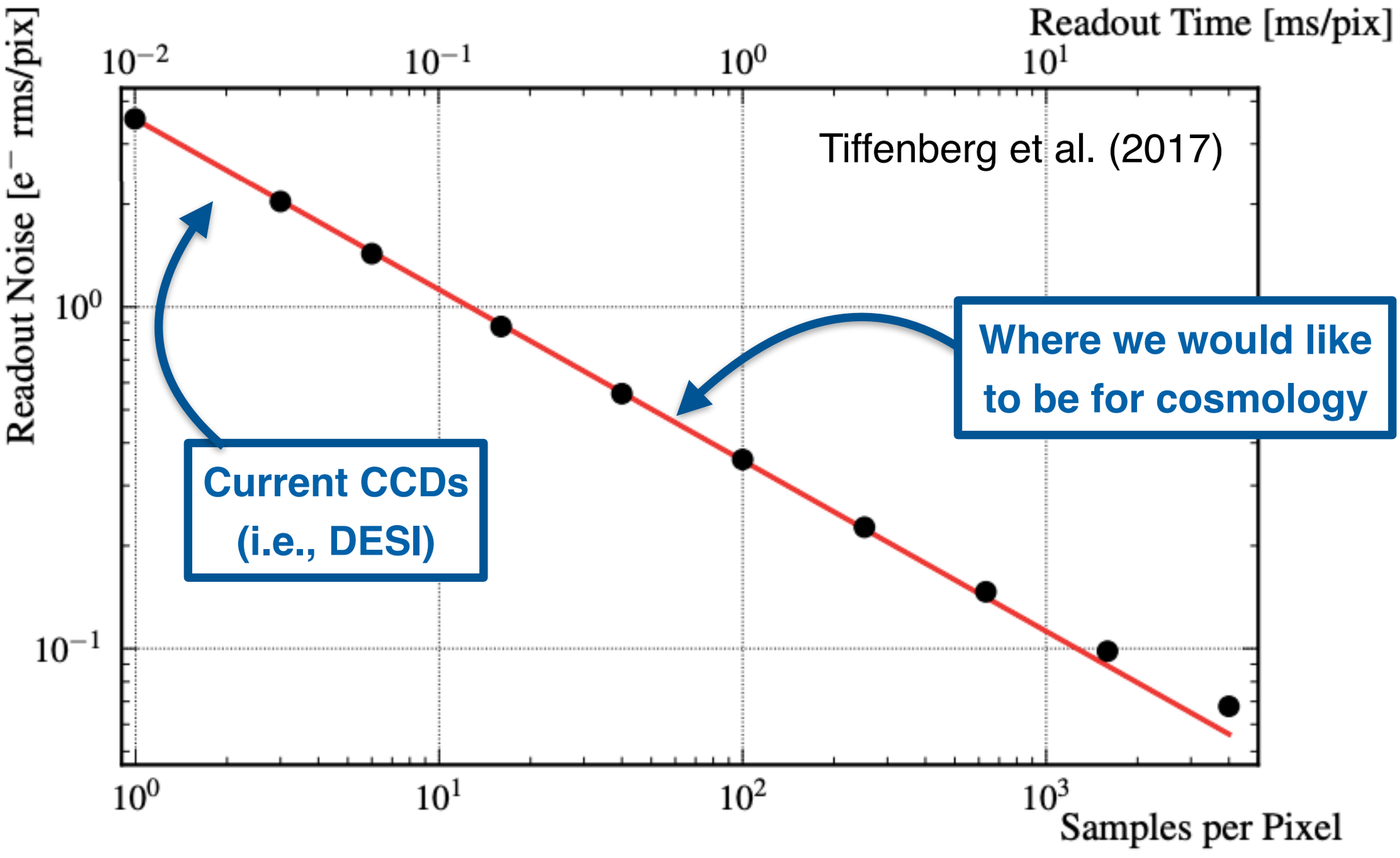

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Things to note about Skipper CCD

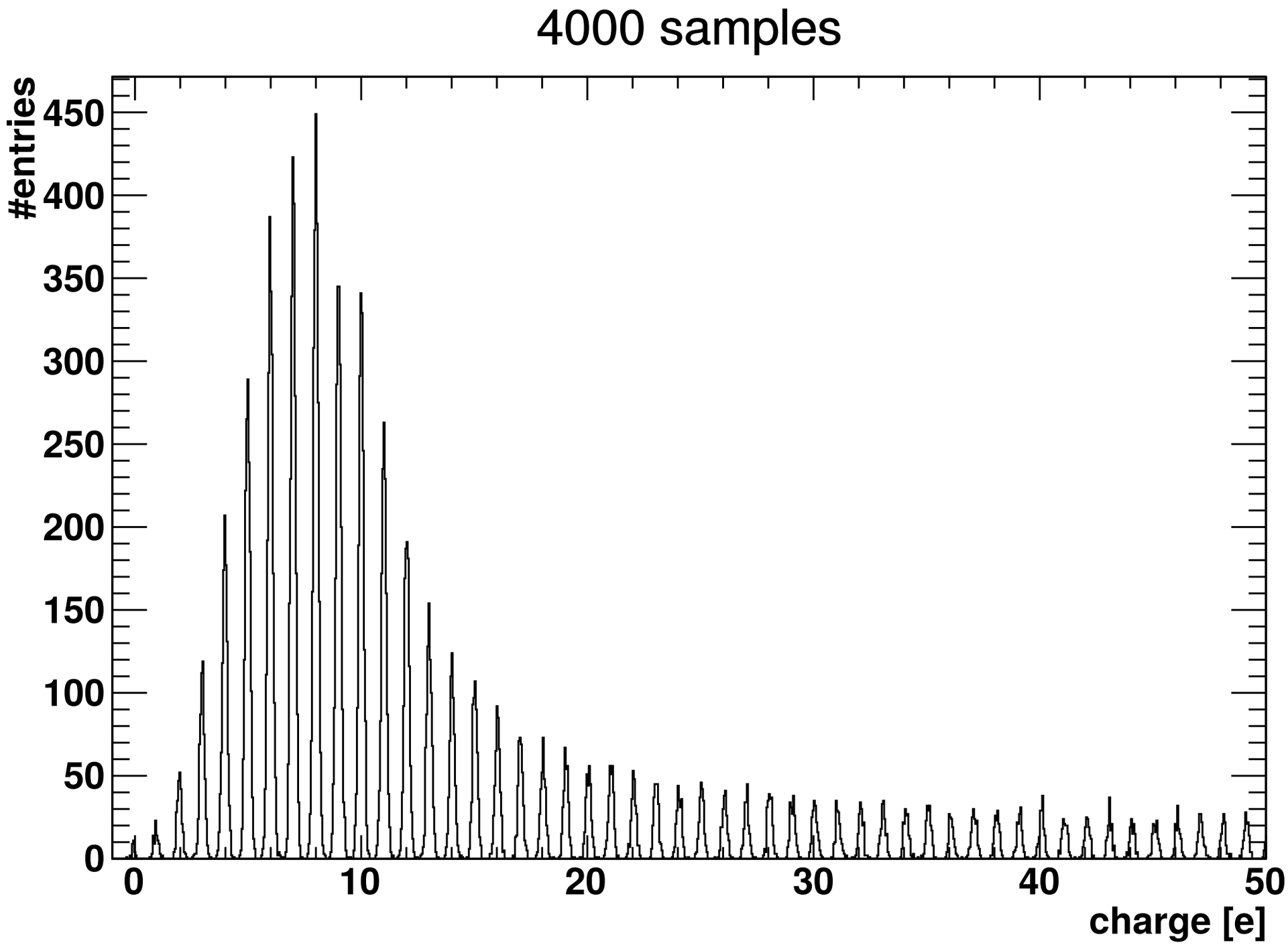
- The only change is to the readout structure
  - Otherwise performs like the standard CCDs we have grown to know and love

- If you don't want to skip, you don't have to
  - A Skipper CCD read with one sample *is* a standard CCD

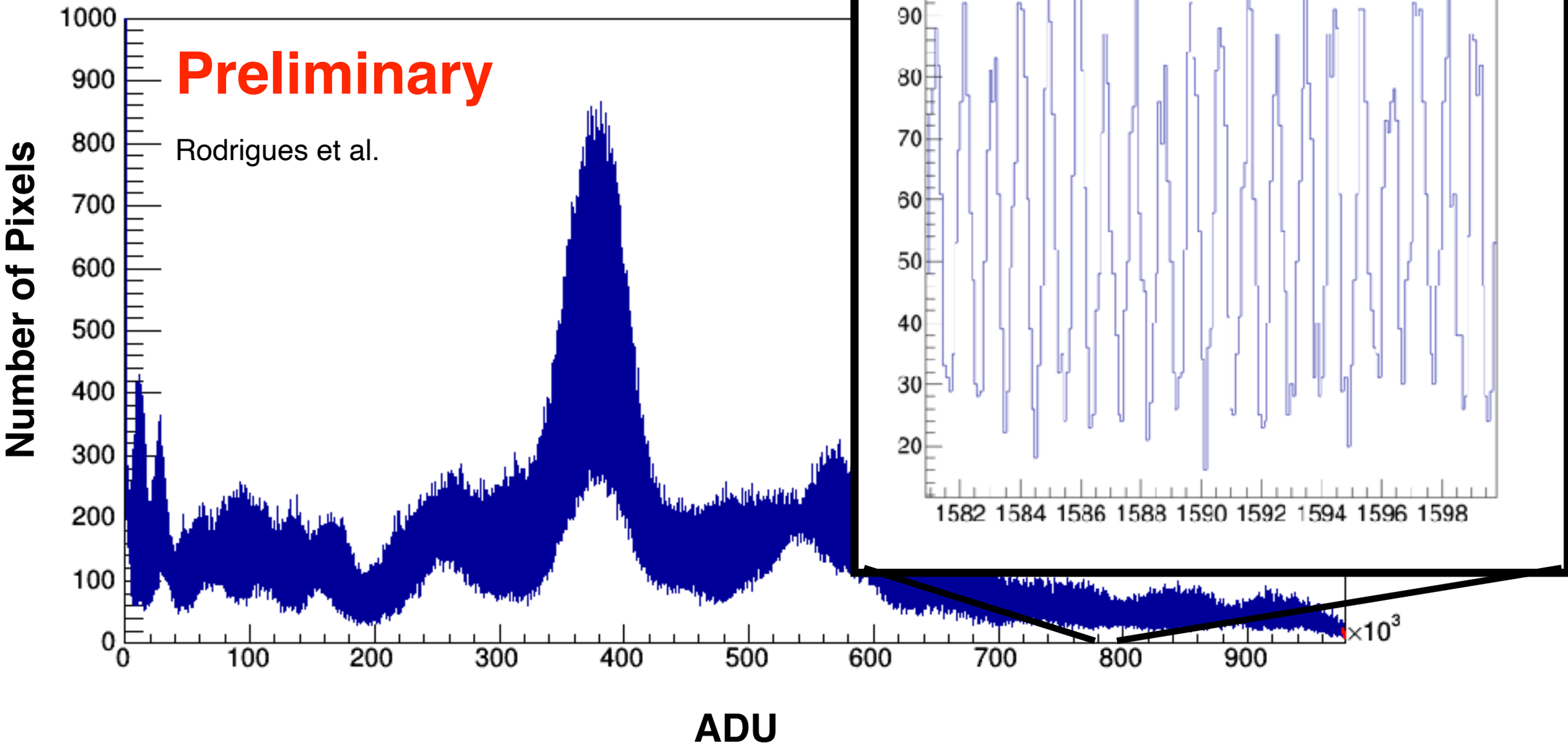
- Skipping takes time (linear in the number of samples)
  - There is an optimum between readout time and exposure time

- Skipping is fully configurable on the pixel-by-pixel level
  - We can choose the readout noise in each pixel

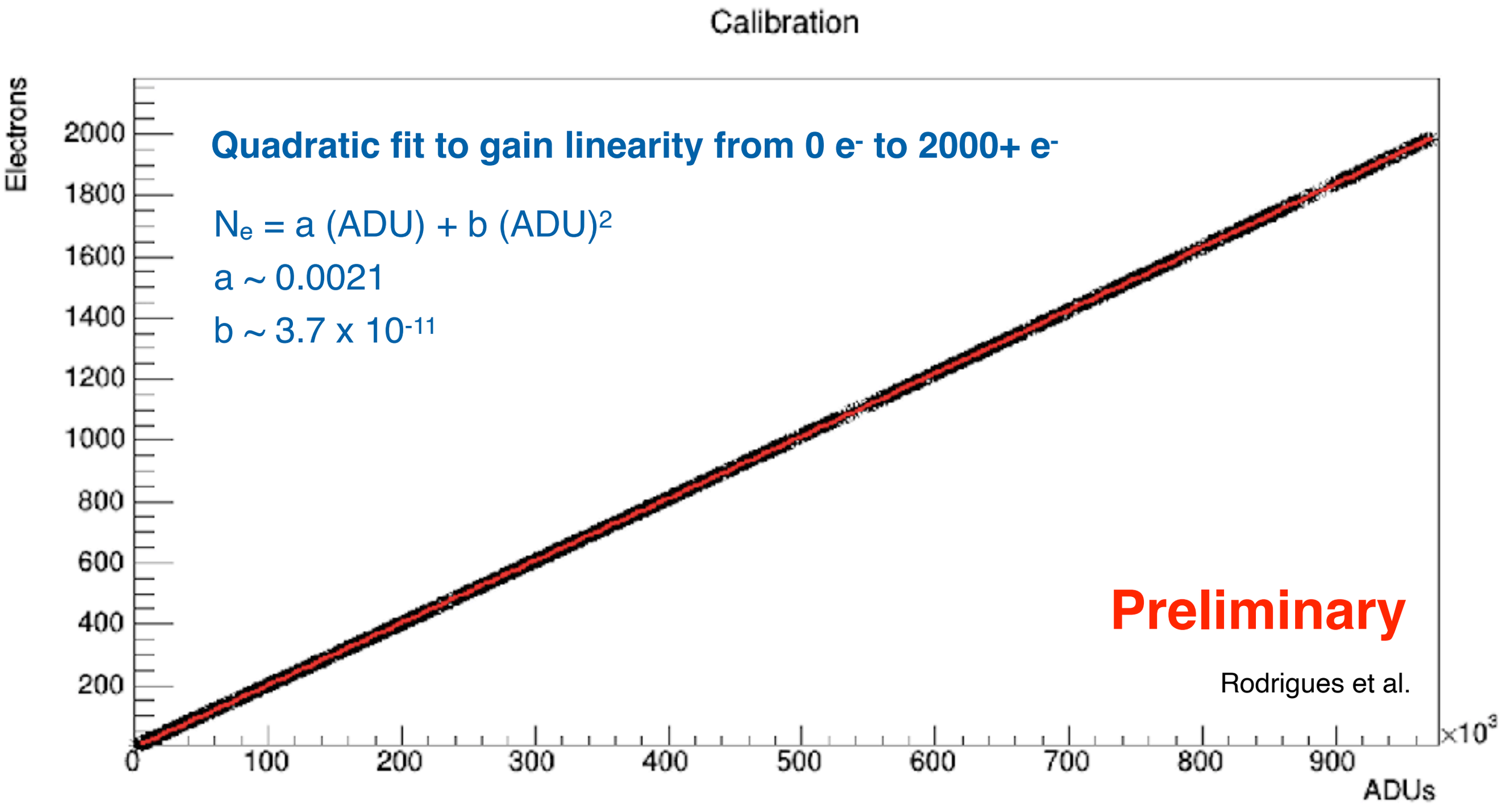
Counting electrons (0e$^-$, 1e$^-$, 2e$^-$, …, 40e$^-$, 41e$^-$, 42e$^-$, …)



Counting electrons (0e$^-$, 1e$^-$, 2e$^-$…, 1581e$^-$, 1582e$^-$, 1583e$^-$, …)

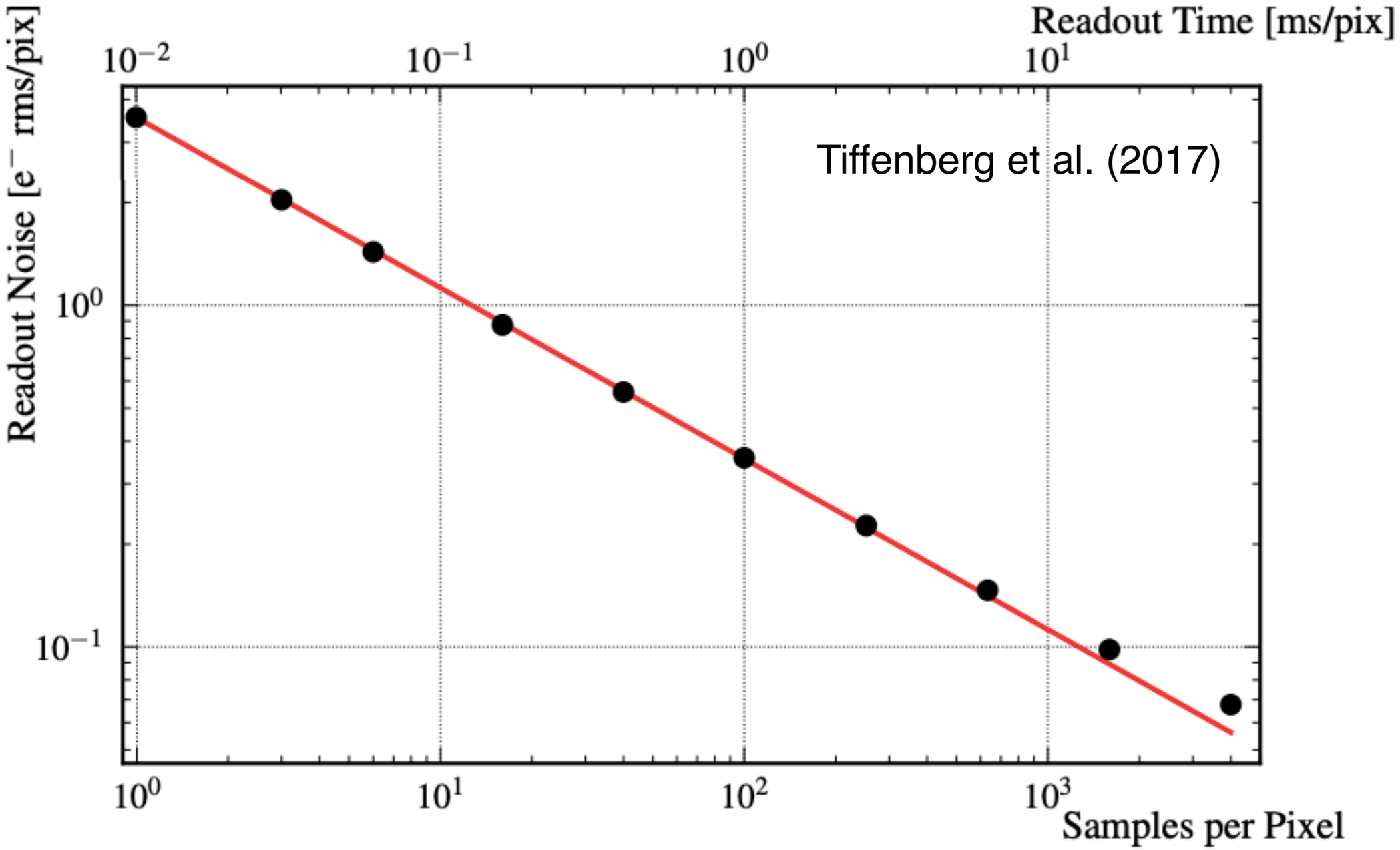


Direct measurement of Linear Gain



Readout Noise vs. Number of Samples for Skipper CCD

20s **3 min** **30 min** **5.5 hours** ← **2Mpix/channel**



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Faster Readout Strategies

- **Reduce single sample noise**
  - Current Skippers at ~3.5 e^- rms/pix (DESI is ~2 e^- rms/pix)

- **Targeted readout:**
  - Only readout the pixels that you need (Smart Skippers)

- **Multiplexed readout**
  - Ideas for multiplexed sense nodes

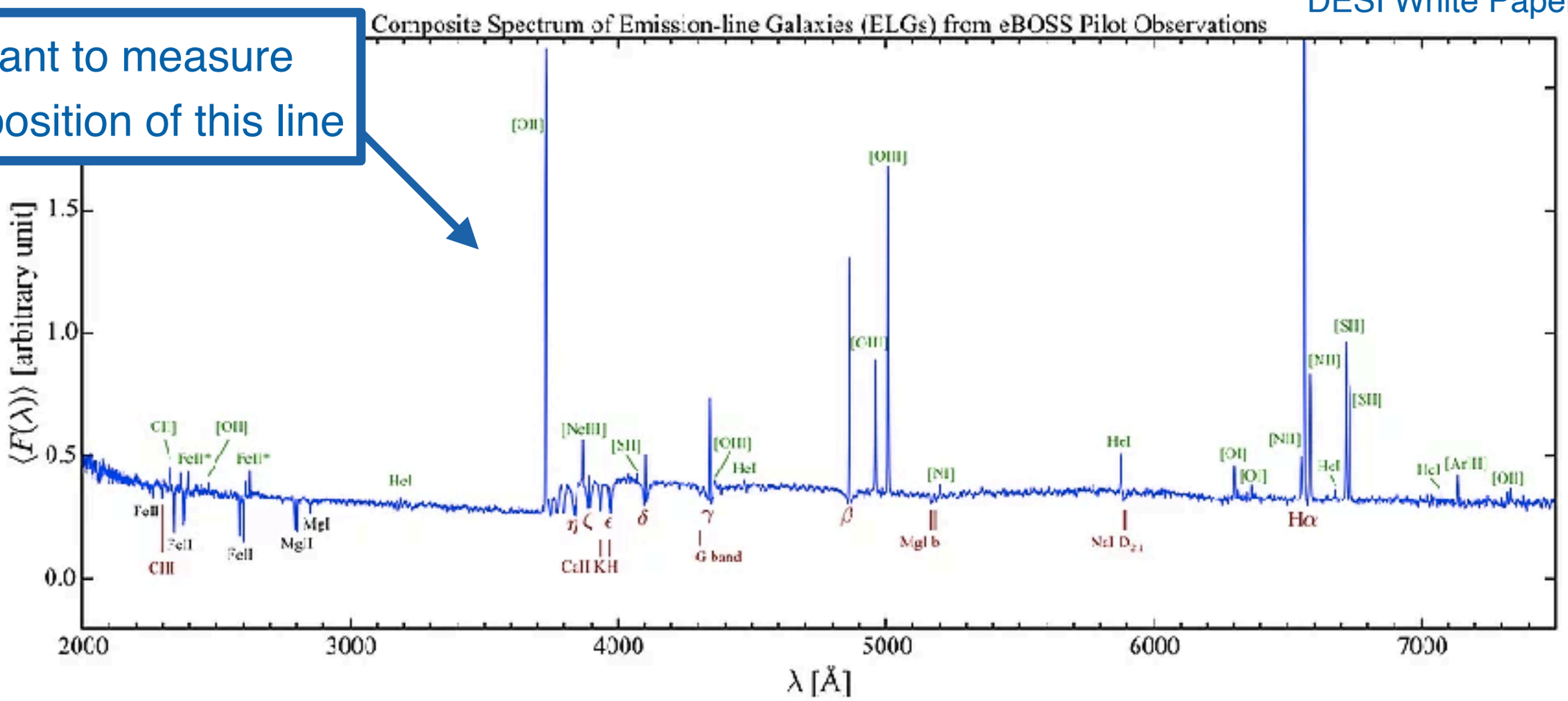
- **More amplifiers**
  - DECam = 2 channels; LSST = 16 channels; R&D = 256 channels

- **Frame Shifting**
  - Shift charge so readout can be done in parallel with next exposure

Faster Readout: Targeted Readout

DESI White Paper

Want to measure
the position of this line



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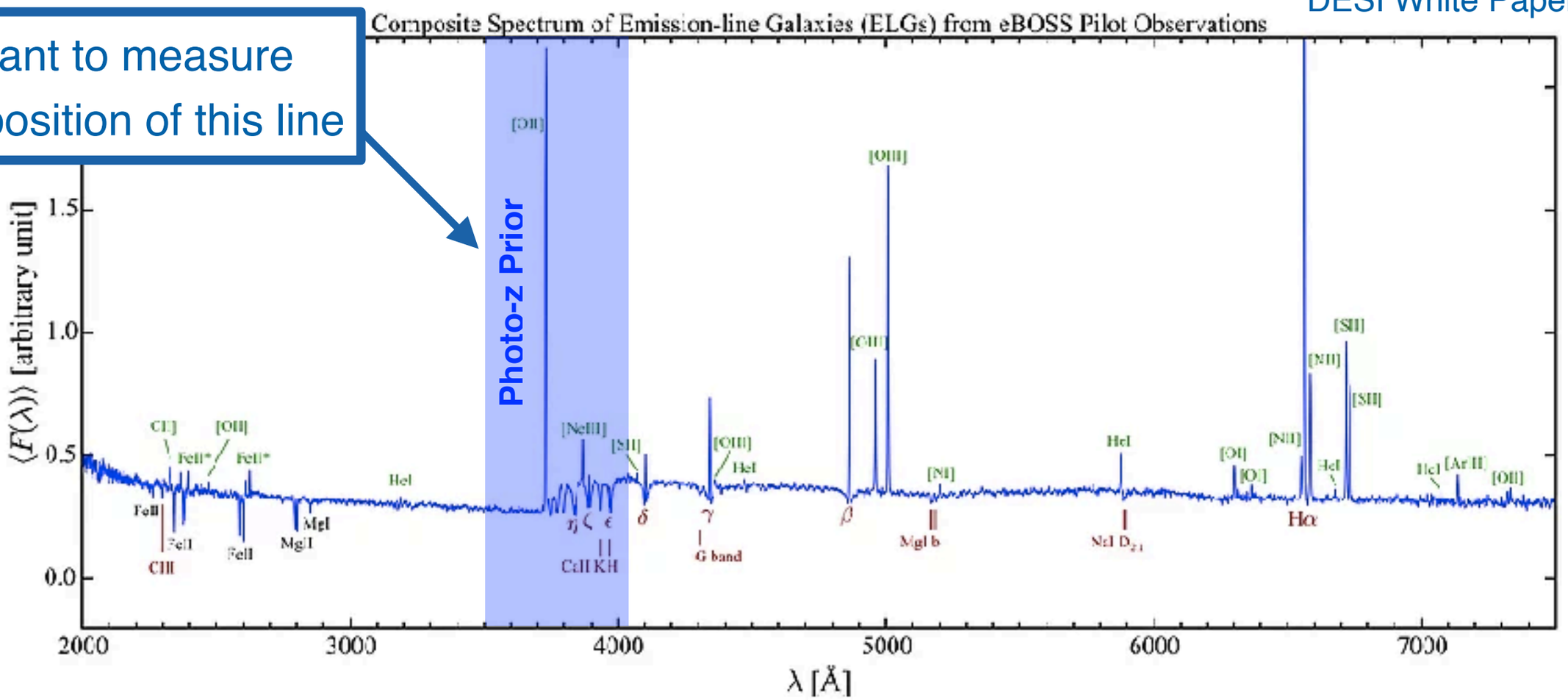

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Faster Readout: Targeted Readout

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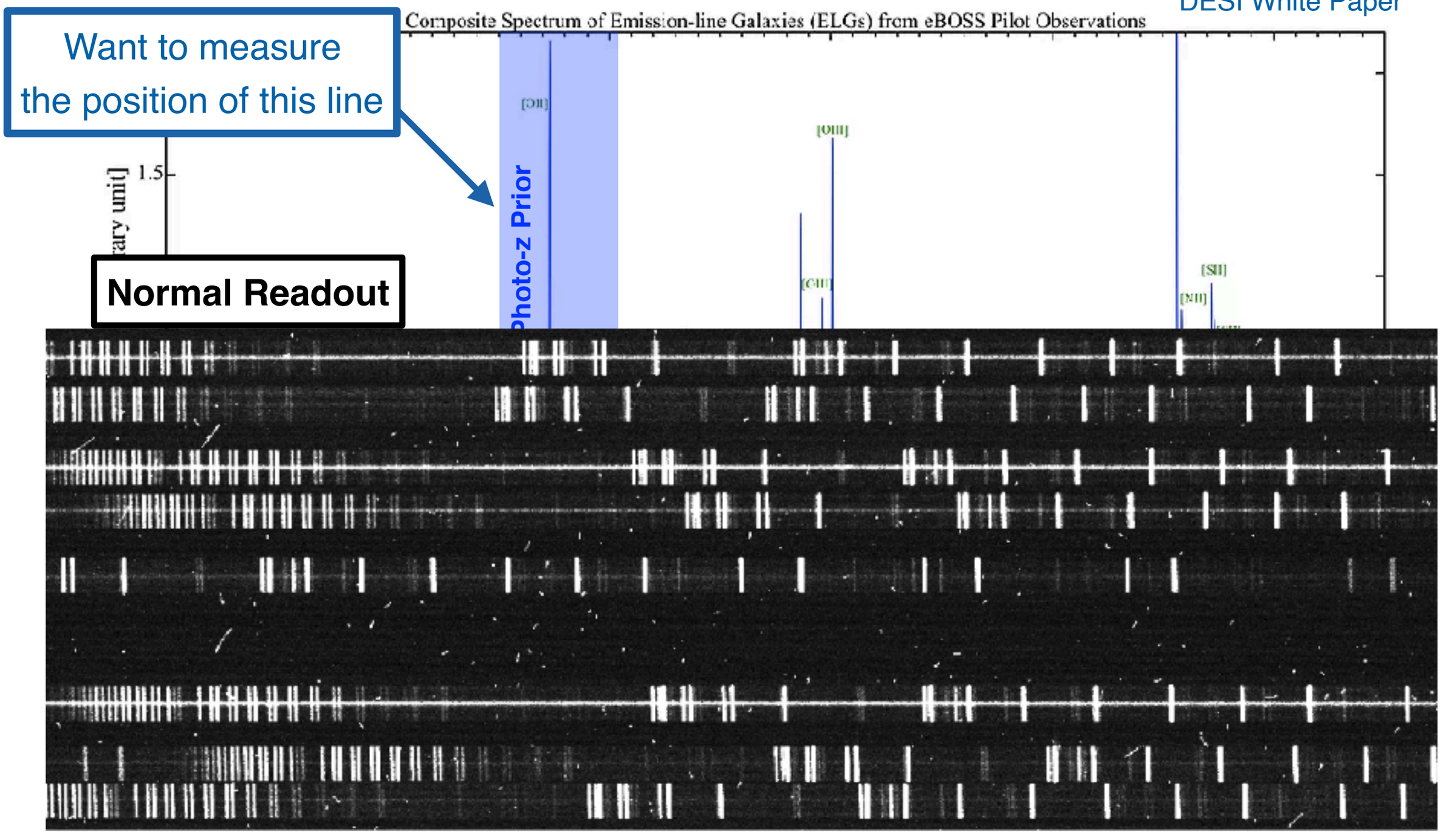


IMACS Spectra

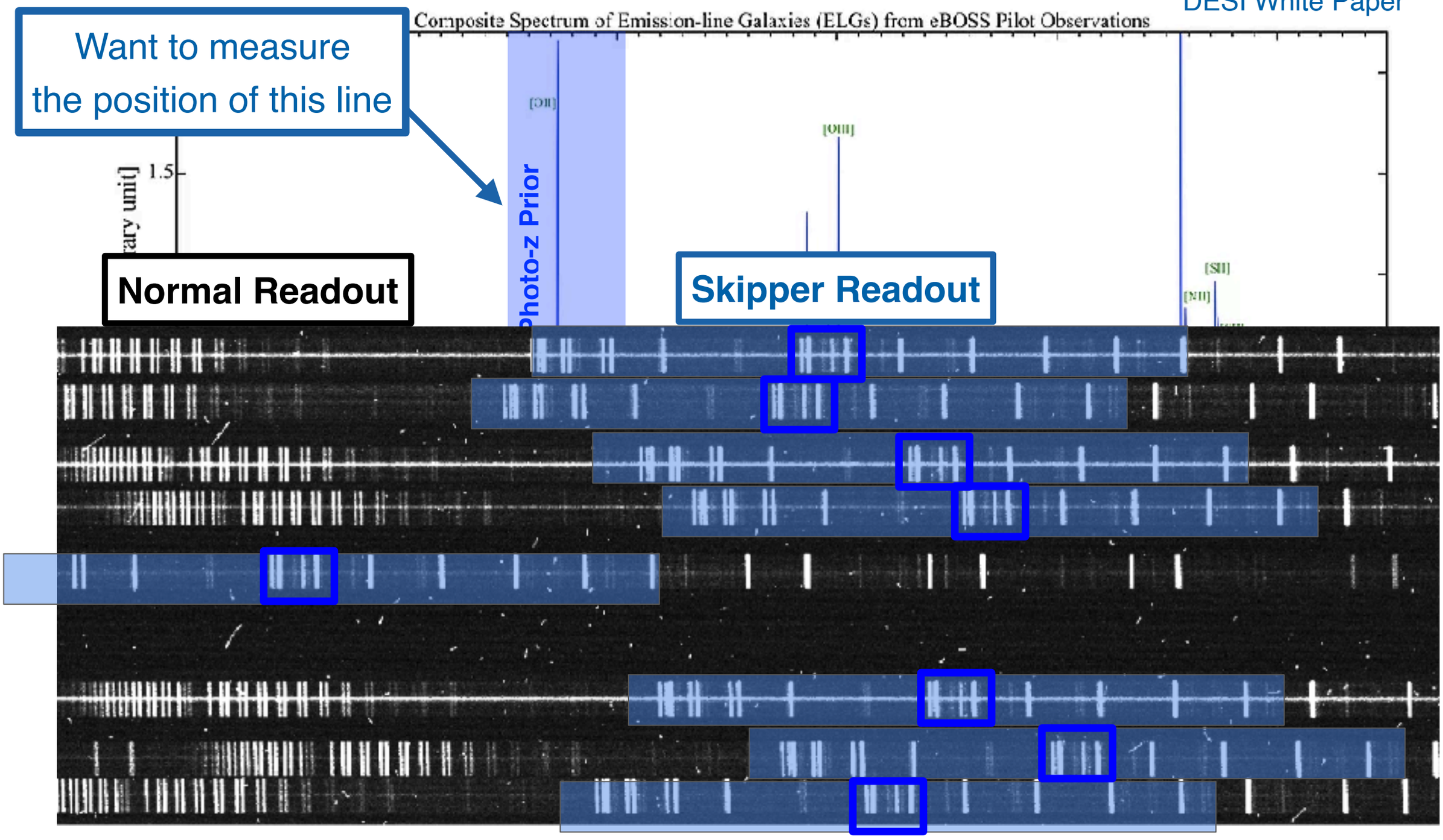
Faster Readout: Targeted Readout

DESI White Paper

Want to measure
the position of this line

Normal Readout

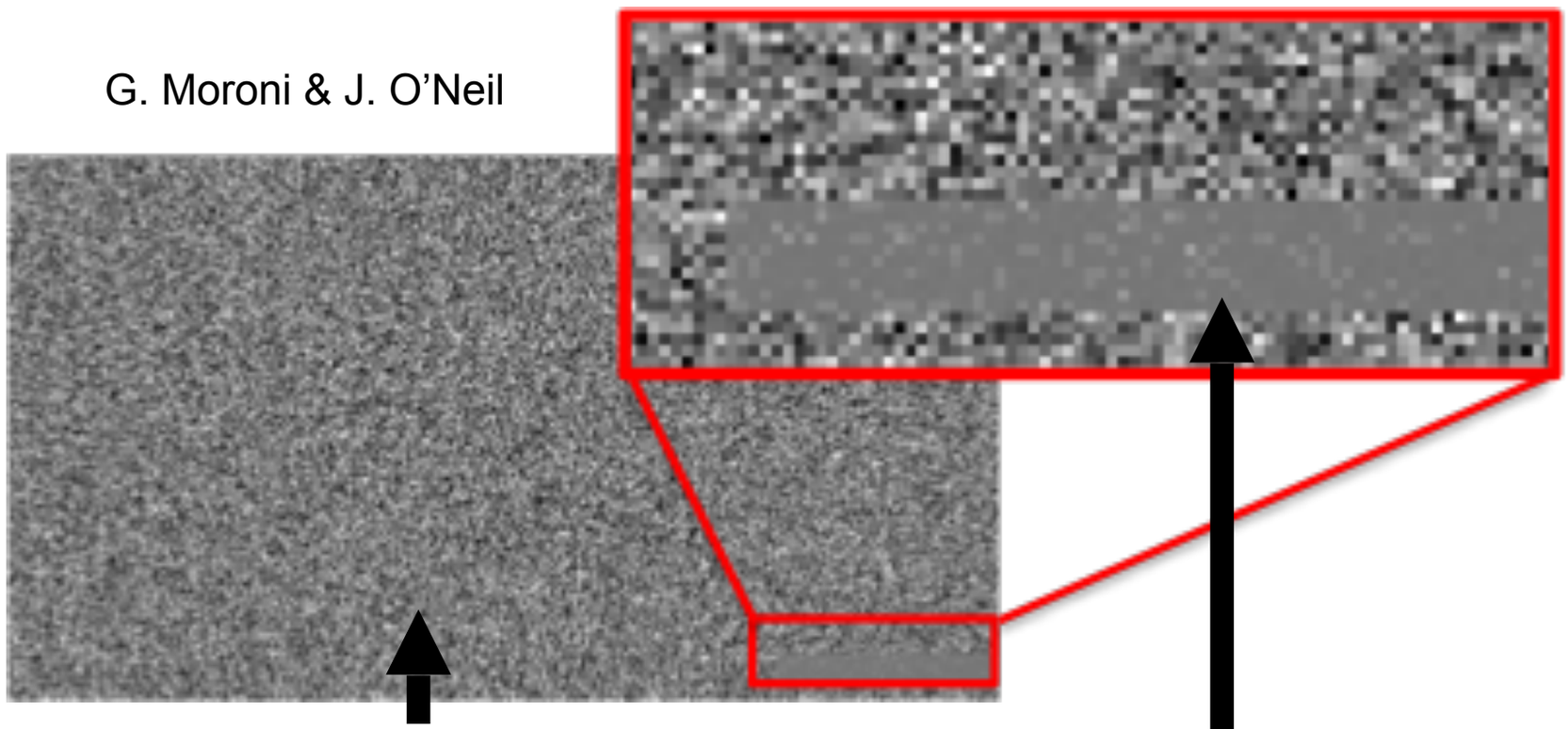
Skipper Readout



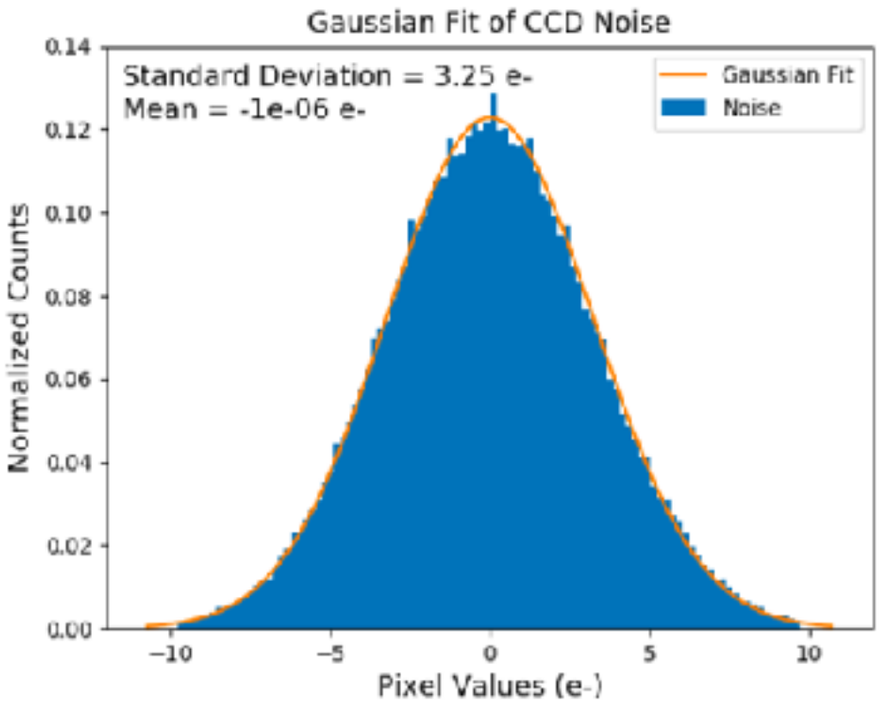
IMACS Spectra

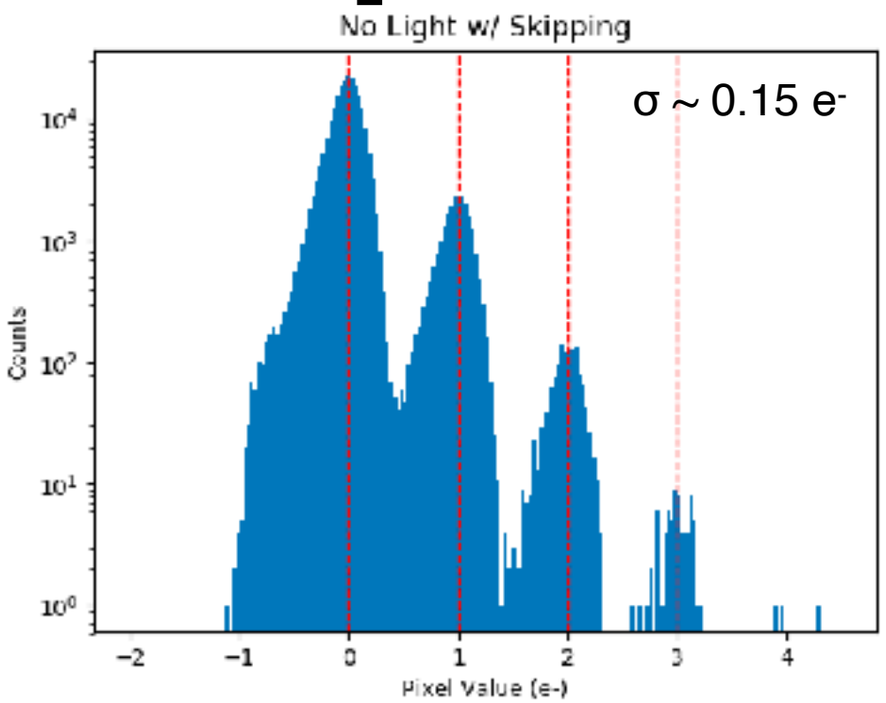
Faster Readout: Smart Skippers

G. Moroni & J. O'Neil



G. Moroni & P. Simbeni





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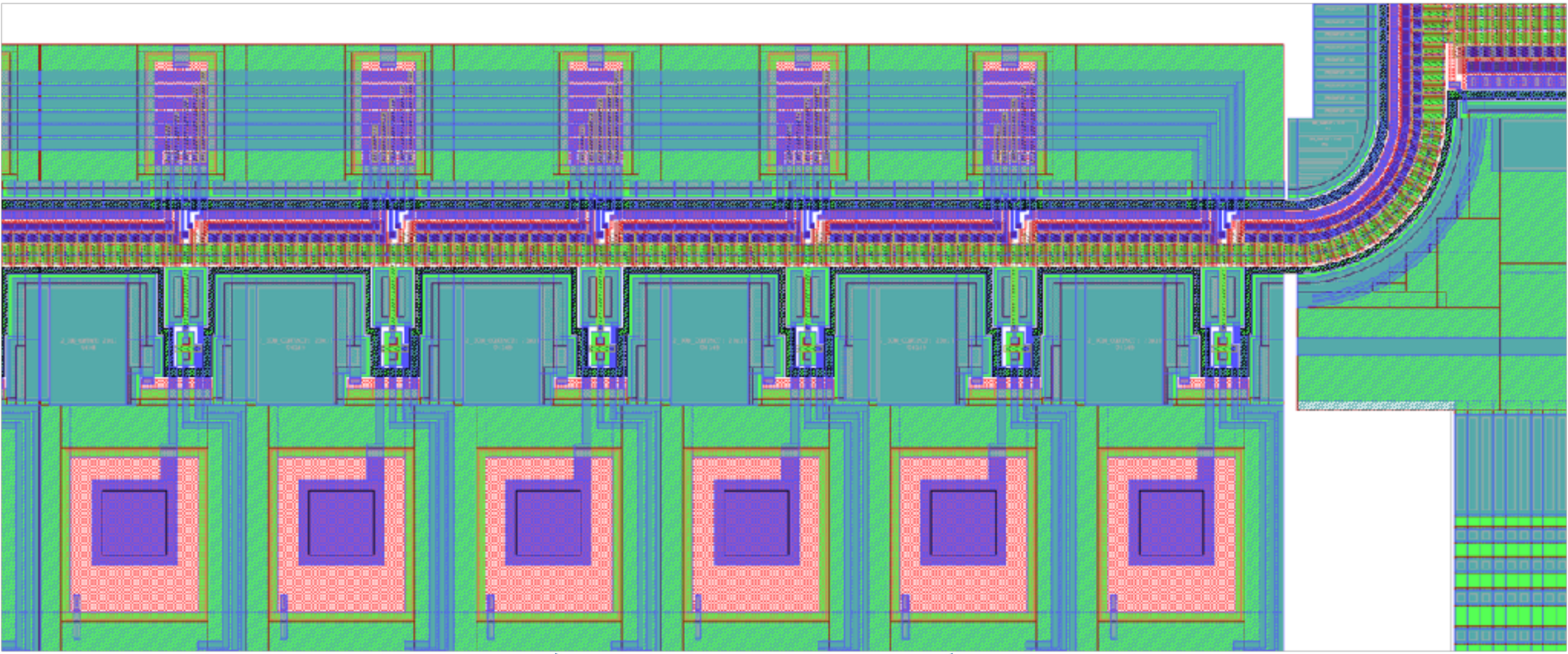
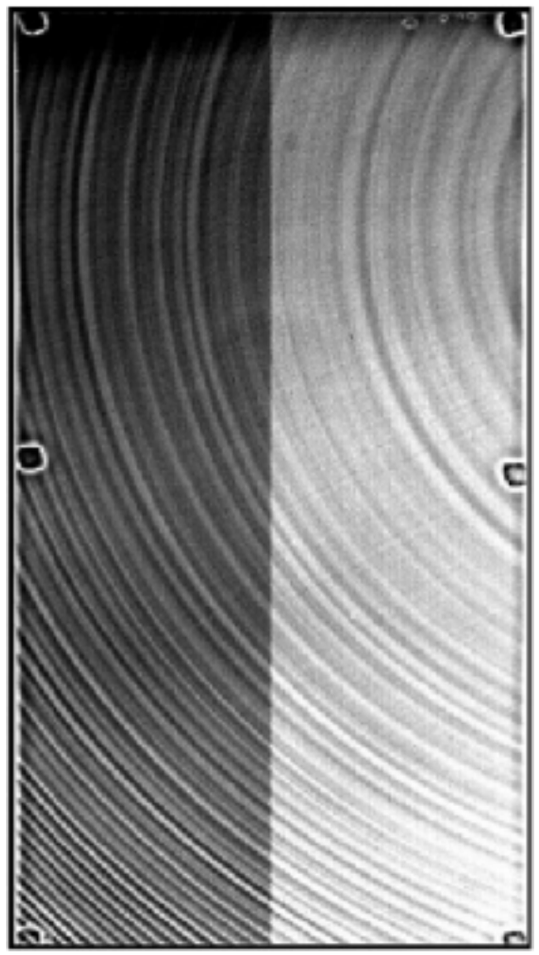
Faster Readout: Multiplexed Readout



R&D: 6x Multiplexing in Readout Structures

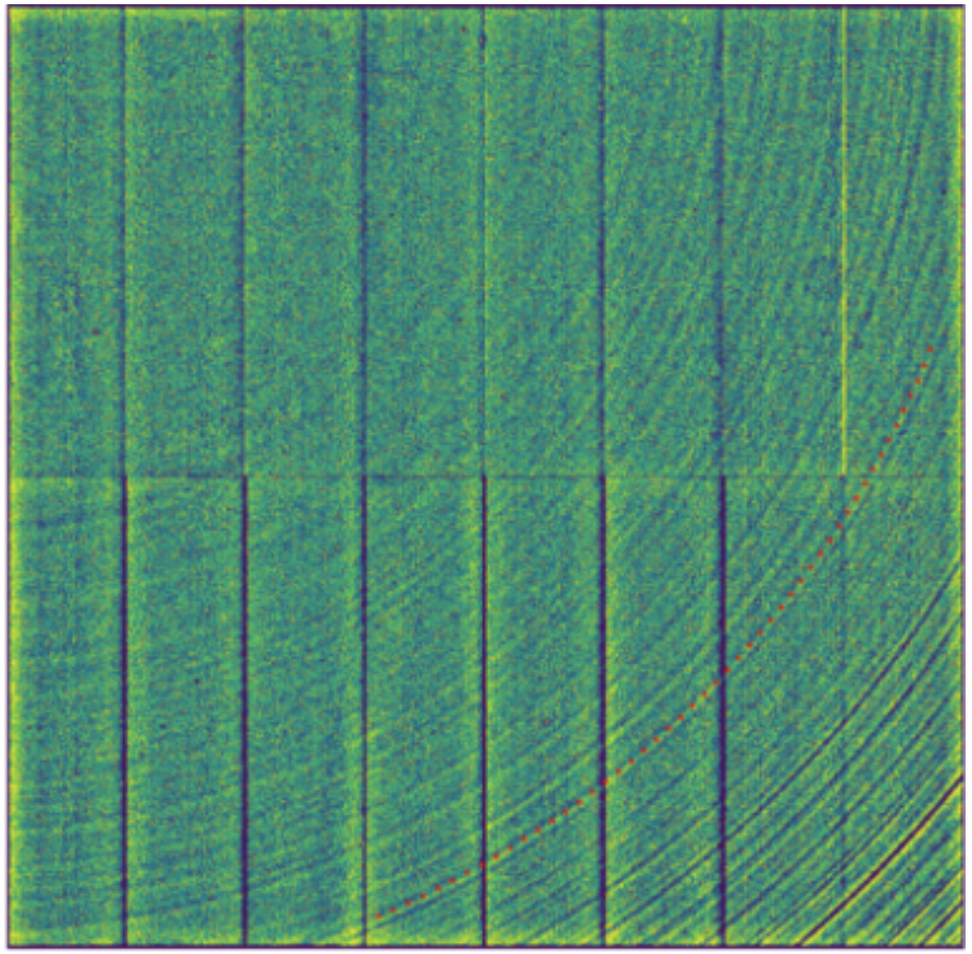
Faster Readout: More Amplifiers

DECam (2 channels)



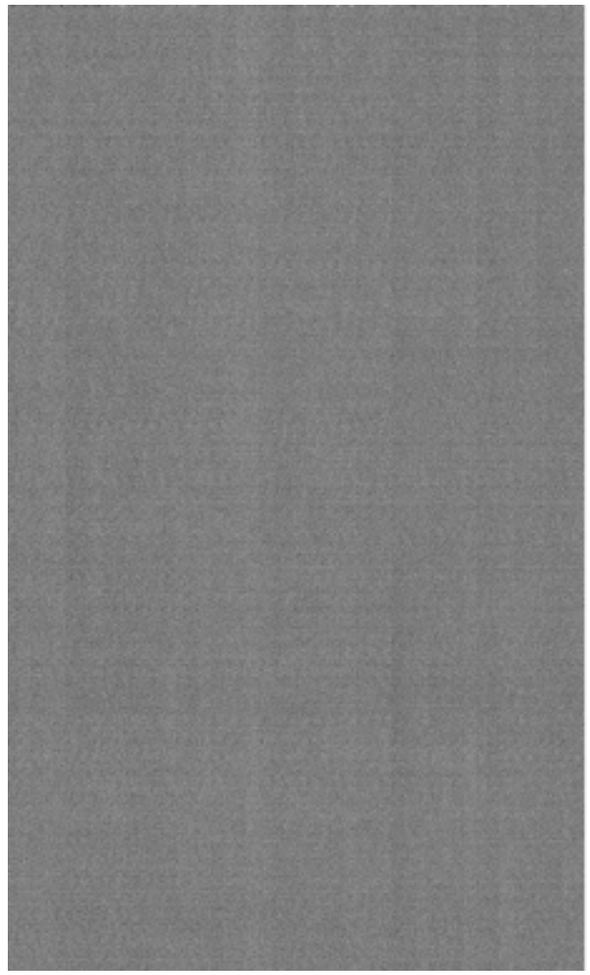
Plazas et al. (2014)

LSST (16 channels)



Park et al. (2017)

1kFSCCD (192 channels)



Weizeorick et al. (2012)

Faster Readout: Frame Shifting

Doering et al. (2012)

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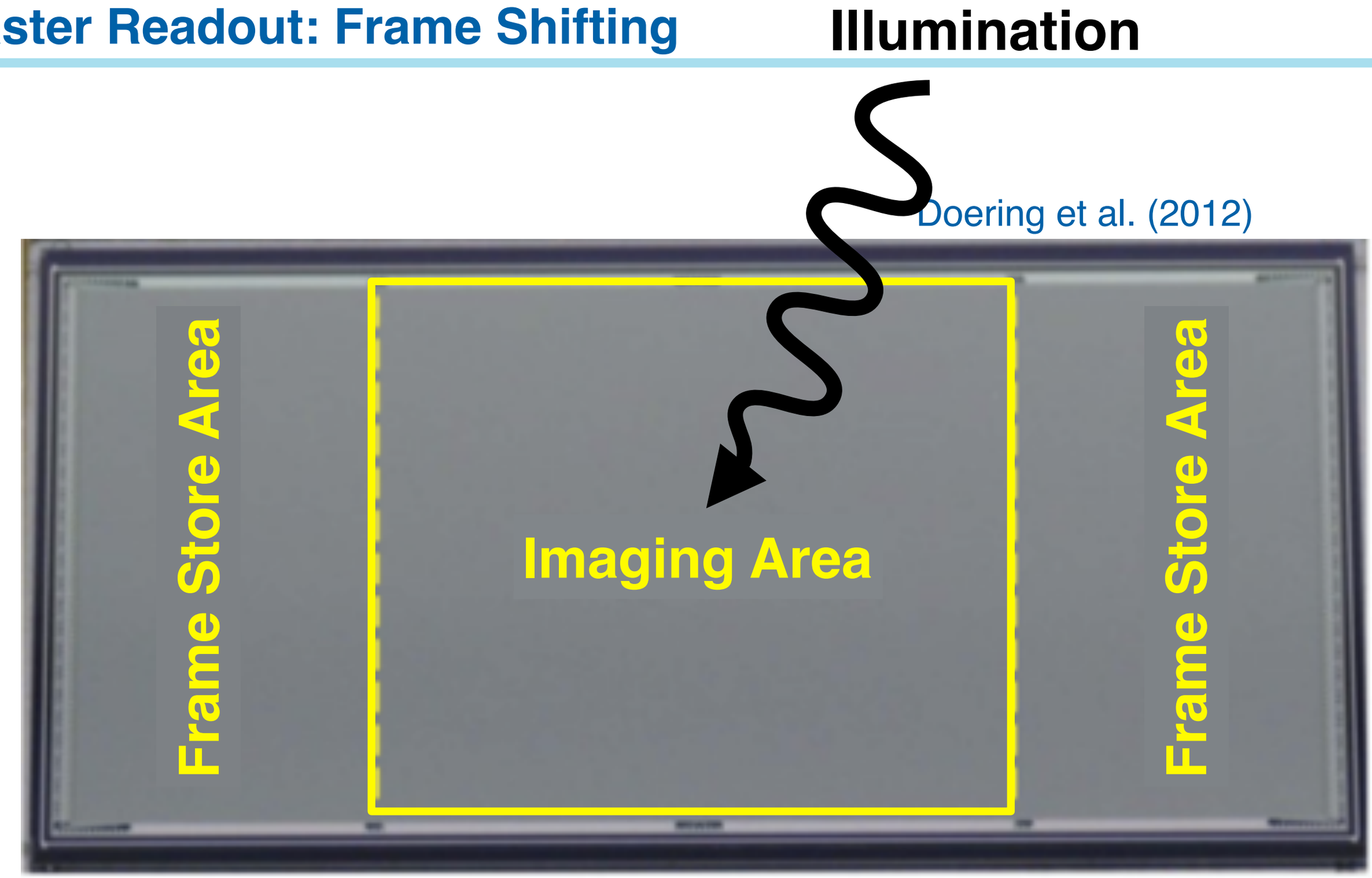
Faster Readout: Frame Shifting



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Faster Readout: Frame Shifting

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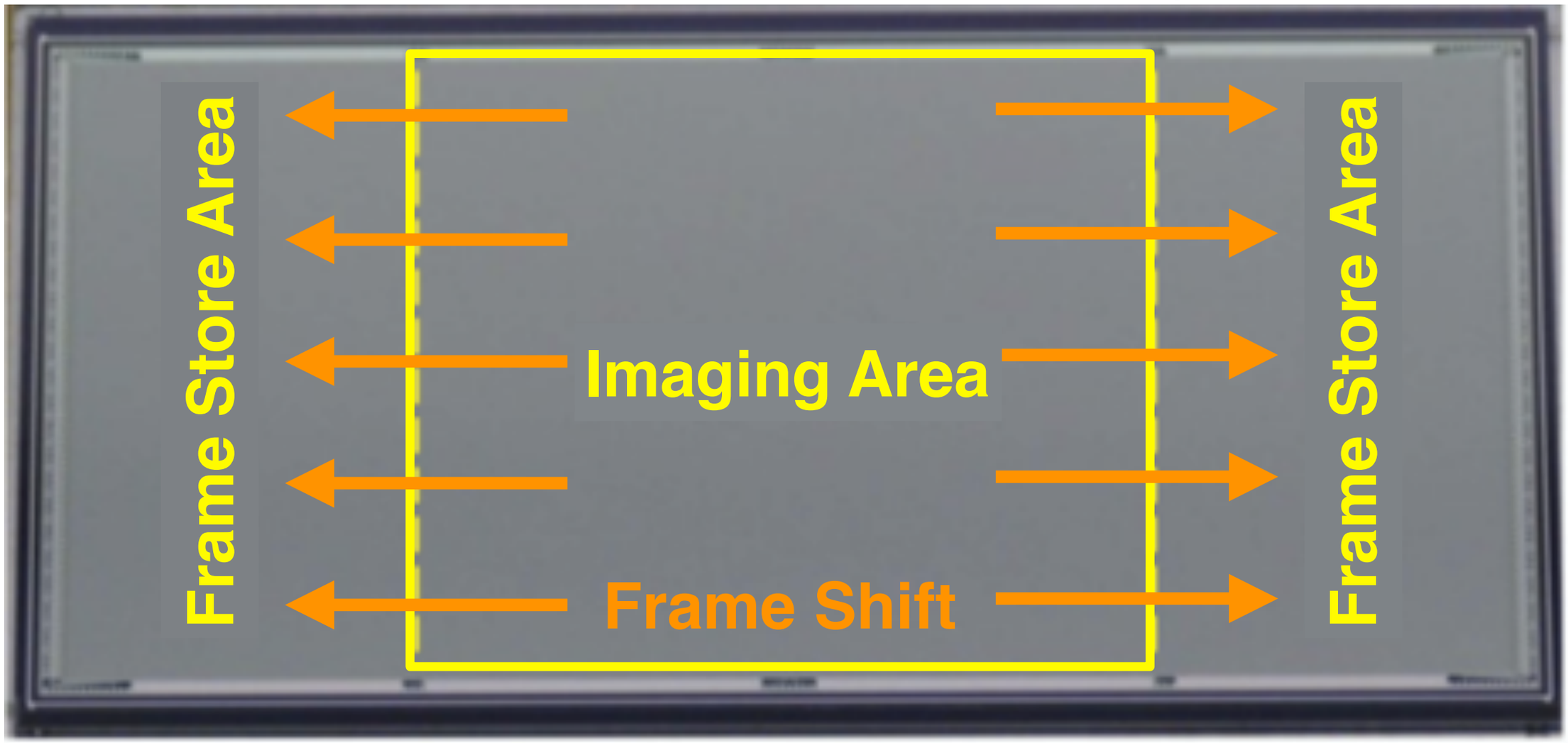

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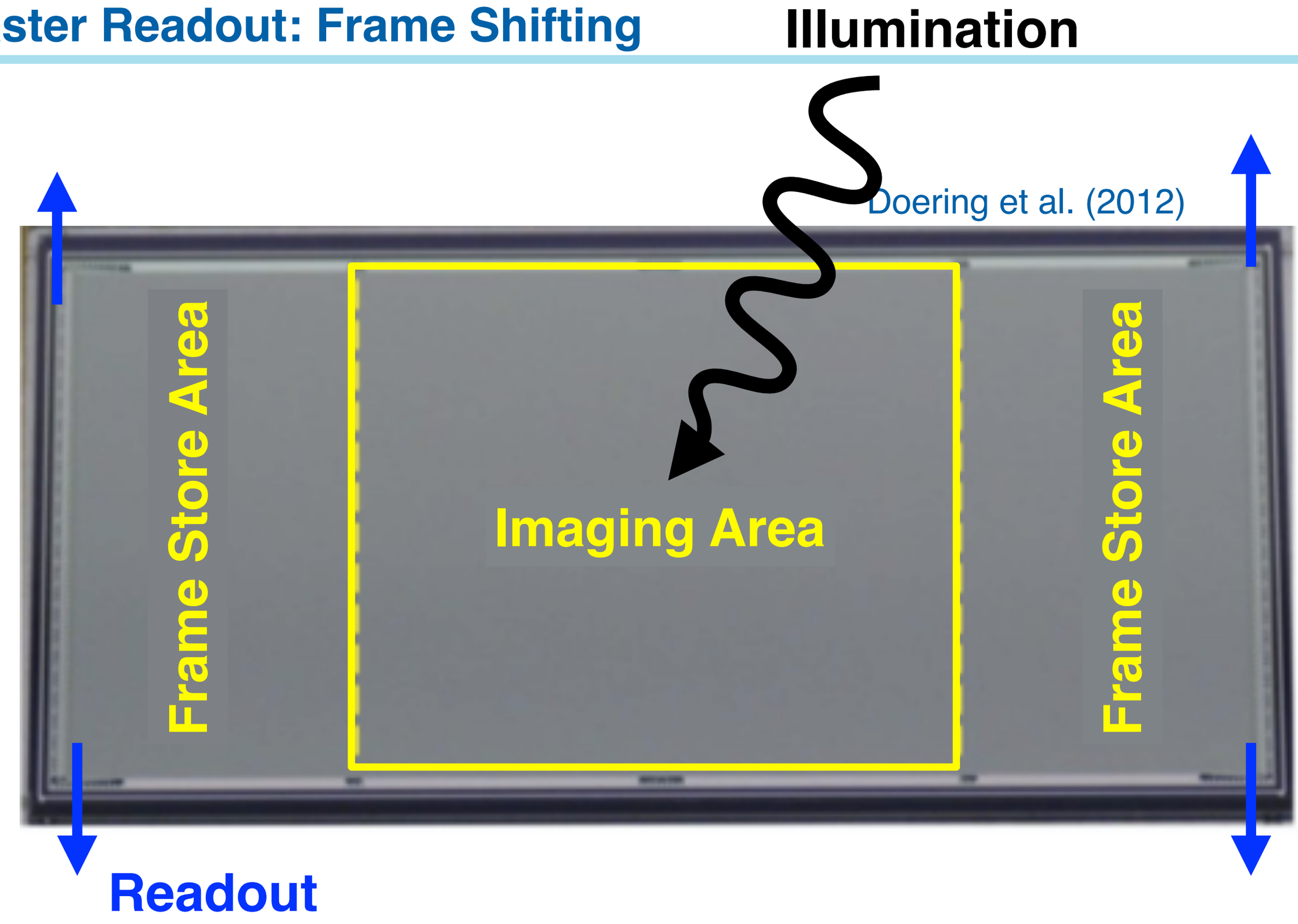
Faster Readout: Frame Shifting



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Summary: Skipper CCDs for Cosmology

- **The Skipper CCD pitch…**
  - Skipper CCDs allow you to control readout noise directly on a pixel-by-pixel basis
  - Configurable per object and per exposure
  - Every CCD used for astronomical observations should be a Skipper CCD

- **Readout time is the major challenge facing Skipper CCDs for cosmology**

- **Several ideas being explored for reducing readout time**
  - Reduce single-sample noise
  - Smart Skippers
  - Multiplexed Skipper sampling
  - More output channels
  - Frame shifting

Skipper CCD Characteristics

- We have been using Skipper CCDs from the same fabrication batch as used for the results in Tiffenberg et al. 2017 (1706.00028).
- They are p-channel devices fabricated on high-resistivity (~10 kΩ cm) n-type silicon that was fully depleted at a substrate voltage of 40 V.
- Our detectors are smaller format than the one used in the 2017 paper.
- More characteristics of the devices can be found below:
  - Format: 1248 pix x 724 pix
  - Pixel Scale: 15 um
  - Thickness: 200 um
  - Operating Temperature: 140 K
  - Number of Amplifiers: 4

Installation in astronomical dewar from IR Labs