Skipper CCDs for Cosmological Applications

Alex Drlica-Wagner
CPAD Instrumentation Frontiers Workshop
December 8, 2019
Constrain other DM models:
- Thermal DM mass > 3.26 keV
- Fuzzy DM mass > $2.9 \times 10^{-21}$ 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!
CCD Readout

Shift charge one column to the right

3x3 pixels CCD

Photon

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

Capacitance of the system is set by the SN: $C = 0.05 \text{pF}$

3 $\mu \text{V/e}$
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
  \[
  \text{Pixel value} = \frac{1}{N} \sum_{i=1}^{N} (\text{pixel sample})_i
  \]
- Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)
Readout Noise vs. Number of Samples for Skipper CCD

Tiffenberg et al. (2017)
Readout Noise vs. Number of Samples for Skipper CCD

Tiffenberg et al. (2017)

Current CCDs (i.e., DESI)
Readout Noise vs. Number of Samples for Skipper CCD

Current CCDs (i.e., DESI)

Where we would like to be for cosmology

Tiffenberg et al. (2017)
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\textsuperscript{-}, 1e\textsuperscript{-}, 2e\textsuperscript{-}, …, 40e\textsuperscript{-}, 41e\textsuperscript{-}, 42e\textsuperscript{-}, …)

4000 samples
Counting electrons (0e⁻, 1e⁻, 2e⁻, ..., 1581e⁻, 1582e⁻, 1583e⁻, ...)

Preliminary

Rodrigues et al.
Direct measurement of Linear Gain

Quadratic fit to gain linearity from 0 e⁻ to 2000+ e⁻

\[ N_e = a \times \text{(ADU)} + b \times (\text{ADU})^2 \]

a \sim 0.0021
b \sim 3.7 \times 10^{-11}

Preliminary

Rodrigues et al.
Readout Noise vs. Number of Samples for Skipper CCD

Tiffenberg et al. (2017)

Readout Noise vs. Number of Samples for Skipper CCD

Tiffenberg et al. (2017)
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

Want to measure the position of this line.
Want to measure the position of this line
Faster Readout: Targeted Readout

Want to measure the position of this line

Normal Readout

Composite Spectrum of Emission-line Galaxies (ELGs) from eBOSS Pilot Observations

DESI White Paper

IMACS Spectra
Faster Readout: Targeted Readout

Want to measure the position of this line

Normal Readout

Skipper Readout

Composite Spectrum of Emission-line Galaxies (ELGs) from eBOSS Pilot Observations

DESI White Paper

IMACS Spectra
Faster Readout: Smart Skippers

G. Moroni & J. O’Neil

Gaussian Fit of CCD Noise

Standard Deviation = 3.25 e-
Mean = -1e-06 e-

Gaussian Fit
Noise

Normalized Counts

Pixel Values (e-)

Counts

Pixel Value (e-)

σ ~ 0.15 e-

No Light w/ Skipping

SMART SKIPPER

G. Moroni & P. Simbeni
Faster Readout: Multiplexed Readout

R&D: 6x Multiplexing in Readout Structures
Faster Readout: More Amplifiers

DECam (2 channels) | LSST (16 channels) | 1kFSCCD (192 channels)

Faster Readout: Frame Shifting

Doering et al. (2012)
Faster Readout: Frame Shifting

Doering et al. (2012)
Faster Readout: Frame Shifting

Doering et al. (2012)
Faster Readout: Frame Shifting

Doering et al. (2012)

Illumination

Frame Store Area

Imaging Area

Frame Store Area

Readout
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