Snowmass2021 - Letter of Interest

Skipper CCDs for Cosmic Surveys of Dark Energy and Dark Matter

Thematic Areas: (check all that apply □/■)

■ (IF2) Photon Detectors
□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics

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Abstract:

Cosmic survey experiments aim to understand the fundamental physics that governs dark energy and dark matter, which together comprise 95% of the Universe. Our understanding of the dark sector has advanced dramatically over the past several decades due to the development of silicon charge coupled devices (CCDs). The next generation of CCD technology, called the "Skipper" CCD, provides tunable, sub-electron resolution over millions of pixels on a stable, large-area detector. Skipper CCDs provide the flexibility to adjust electronic readout noise on an object-by-object, or even pixel-by-pixel, basis. Current spectrographs would benefit from the improved signal-to-noise, and future instruments would have more opportunity to leverage these improvements in their design. This LOI promotes the development and application of Skipper CCDs for the next generation of cosmic survey experiments.

Introduction:

Dark matter and dark energy comprise 95% of the Universe. The existence of this "dark sector" is strong experimental evidence for fundamental physics beyond the Standard Model of particle physics. Cosmological and astrophysical observations provide the only robust, positive empirical measurements of the dark sector and are sensitive to the particle physics that governs it.[1] For example, the cosmological distribution and clustering of dark matter constrains the mass and self-interaction cross section of particle dark matter candidates.[2] Similarly, the expansion history of the Universe provides strong constraints on the types of fundamental fields and modifications to gravity that could drive cosmic expansion.[3] To illuminate the dark sector, it is essential to test the concordance model of cosmology, $\Lambda\mathrm{CDM}$, at higher levels of precision and under more extreme conditions. An observed deviation from the predictions of $\Lambda\mathrm{CDM}$ would have immediate implications for the experimental particle physics program.

Cosmological tests of $\Lambda\mathrm{CDM}$ using optical/near-infrared survey experiments rely on the precise measurement of large samples of faint and/or distant astronomical systems. Spectroscopy, the measurement of relative photon flux as a function of photon energy, is used to measure the line-of-sight motion of objects via the redshift of elemental spectral lines. Spectrographs disperse light from faint astronomical sources over a large detector area, resulting in low signal-to-noise in each detector pixel. In this regime, detector readout noise can have a large impact on the efficiency and sensitivity of cosmic surveys. Skipper CCDs can drastically reduce detector readout noise, and we recommend the development this technology for applications in next-generation spectroscopic survey experiments to probe the nature of dark matter and dark energy.

Skipper CCDs:

Skipper CCDs use a floating gate output stage to allow for multiple, non-destructive measurements of the charge in each pixel, which.[4,5] These measurements can be combined to reduce readout noise relative to the single-sample value. While the Skipper CCD concept was proposed in 1990,[4] it has only recently been demonstrated to provide stable performance in a large-area detector.[5] The newest generation of Skipper CCDs demonstrate readout noise that scales inversely with the square root of the number of samples ($\mathrm{RN} \propto 1/\sqrt{N}$) providing readout noise of 0.068 $\mathrm{e^-\ rms/pix}$ at ~ 4000 samples.[5] These novel detectors have begun to find widespread application in dark matter searches, neutrino measurements, and quantum imaging.[6–9]

Most significant gains in cosmological applications can be achieved by reaching readout noise levels of $\sim 0.5\,\mathrm{e^-\ rms/pix}$. For "signal starved" observations where noise contributions are dominated by readout noise and Poisson shot noise, Skipper CCDs can achieve S/N $\sim$ 3–7 per pixel $\sim 200\%$ faster than conventional CCDs. Potential applications to dark matter and dark energy science include ground-based observations of the Lyman-α forest, faint stars in dark-matter-dominated dwarf galaxies, and emission line galaxies. Broader applications exist in the low-background regime of space-based imaging and spectroscopy. Furthermore, greater gains could be achieved by coupling Skipper CCD readout technology with alternative, smaller band-gap substrate materials, such as germanium, to extend sensitivity to higher redshift.[10]

The primary challenge facing cosmological applications of Skipper CCDs is the increased readout time required by multiple measurements of the charge in each pixel. The current generation of Skipper CCDs require ~ 50 samples to achieve readout noise of $\sim 0.5\,\mathrm{e^-\ rms/pix}$; however, this $50\times$ increase in readout time is unacceptable for many applications. There are several promising avenues to address the readout time challenge, many of which are currently topics of R&D at DOE national laboratories:

1. *Reduced Single-Sample Noise*—Readout time at fixed readout noise decreases quadratically with the single-sample readout noise. In laboratory tests, Skipper CCDs achieve a single sample noise of $\sim 3.5\,\mathrm{e^-\ rms/pix}$ with a readout time of $10\,\mu\mathrm{s}$ per pixel per sample.[5] Conventional CCD amplifiers have been demonstrated to routinely reach $2\,\mathrm{e^-\ rms/pix}$ with a readout time of $4\,\mu\mathrm{s}$ per pixel per sample.[11] A Skipper CCD with single-sample performance comparable to the best conventional CCD

would reach $\mathrm{R/N} \sim 0.5\,\mathrm{e^-}\,\mathrm{rms/pix}$ approximately $6\times$ faster than current devices.

2. *Regional Selection*—Skipper CCDs can be flexibly configured such that the number of samples (and hence the readout noise) is different in different sections of the CCD. Such sub-selection can be tuned on an object-by-object basis (i.e., targeting only the faintest astronomical objects) or even for a specific spectral range of an object (i.e., if prior information is known from photometry). Firmware developments could enable dynamic control at the pixel-by-pixel level, which could ensure that readout noise is subdominant for each individual pixel. Assuming that reduced readout noise is only required over 5%–10% of the CCD area, the readout time could be reduced by $> 10\times$.
3. *Parallel Readout*—Conventional CCD cameras accomplish fast readout through multi-channel output (i.e., each LSSTCam CCD has 16 output channels) with > 48 on-chip amplifiers well within the reach of existing technology.[12,13] Additional parallelization within the Skipper CCD readout structure could offer additional benefits. Readout time decreases linearly with the number of readout channels.
4. *Frame Transfer*—Frame-transfer CCDs shift the charge from an active, light collecting region to a shielded readout region.[14] This allows for readout to occur while the next image is being exposed. As long as the readout time is less than the exposure time (~ 10 minutes for current multiplexed spectroscopic surveys, ~ 30 minutes planned for some future surveys), readout time does not negatively impact overall survey speed.[15,16]

Recommendations for Snowmass:

The current generation of Skipper CCDs are ready for on-sky testing. In the near future, Skipper CCDs could be used to upgrade existing spectroscopic instruments (i.e., DESI). With additional R&D, Skipper CCDs could play a fundamental role in future massively multiplexed spectroscopic surveys. We make the following recommendations:

1. Support CCD fabrication facilities and technology as critical components of the Cosmic Frontier.
2. Support future massively multiplexed optical/near-infrared cosmic surveys to study the dark sector.
3. Support Skipper CCDs as a detector technology for application in future spectroscopic surveys.
4. Support CCD development with alternative substrates (i.e., germanium), which could be combined with Skipper CCD readout technology to enable greater redshift reach for future cosmic surveys.

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