Sub-GeV dark matter and neutrino searches with Skipper-CCDs: status and prospects.

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Abstract: Thick fully-depleted charge-coupled devices (CCDs) with high-resistivity silicon are used in a wide range of scientific applications, from particle detection to astronomical imaging. Their low noise and high charge collection efficiency allow us to reach unprecedented sensitivity to physical processes with low-energy transfers. The newly-developed Skipper-CCD enhances this sensitivity by reducing the read-out noise reaching a sub-electron resolution. In this work, we introduce the fundamentals of the skipper-CCD operation and the prospects for both sub-GeV dark matter searches and the detection of coherent elastic neutrino-nucleus scattering. A brief discussion of the challenges associated with the construction of the foreseen detectors with multi-kilogram target mass is also presented.

1. Charge Couple Devices (CCDs)

Pixel array on silicon substract

Borad range of industrial and scientific applications

Incident radiation produces electron-hole pairs in silicon bulk
· Nuclear or electron recoil
· Scattering or absorption

Sensitive to low-energy transfers (silicon bandgap)

Implemented in rare-event searches

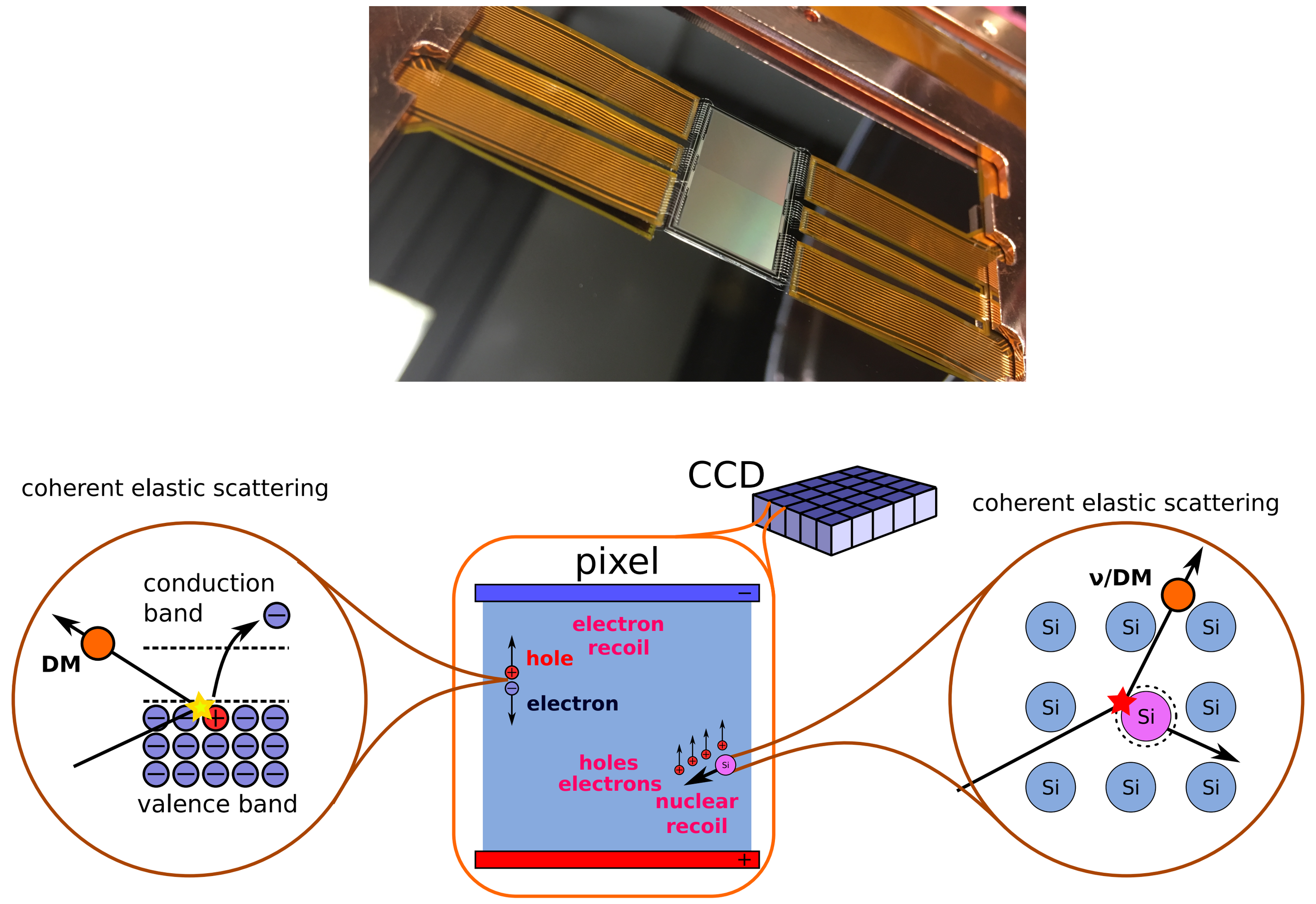

Figure 1: (Top) image of prototype skipper-CCD used in dark-matter searches. (Bottom) schematics of CCD working principle.

2. Skipper-CCD read-out

Charges in electron bulk acelerated to surface

Vertical clocks to transport charges to read-out stage

Non-disruptive measurement allows multiple reads

Horizontal clocks to move charges to floating gate

Correlated double sampling to reduce high-frequency noise

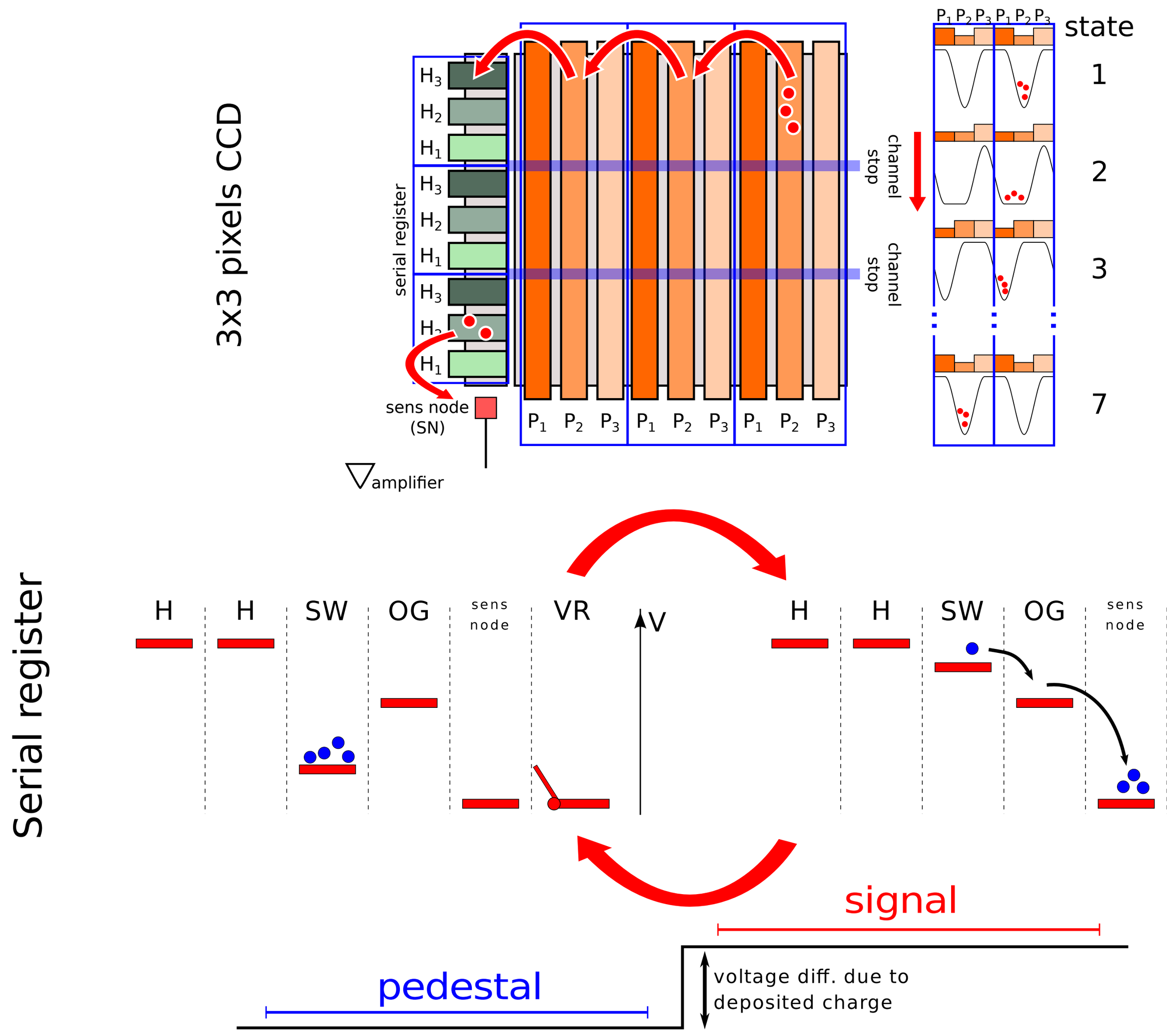

Figure 2: Schemtics of Skipper-CCD read-out. (Top) charge transport from pixel to read-out stage (Bottom) multiple non-disruptive reads of the charge.

3. Read-out noise

Multiple measurements to control ow-frequency read-out noise

Uncorrelated Gaussian noise follows $\sigma_1/\sqrt{N}$

0.055 e⁻ noise with 4000 samples

Empty pixels distinguishable from pixels with 1 charge

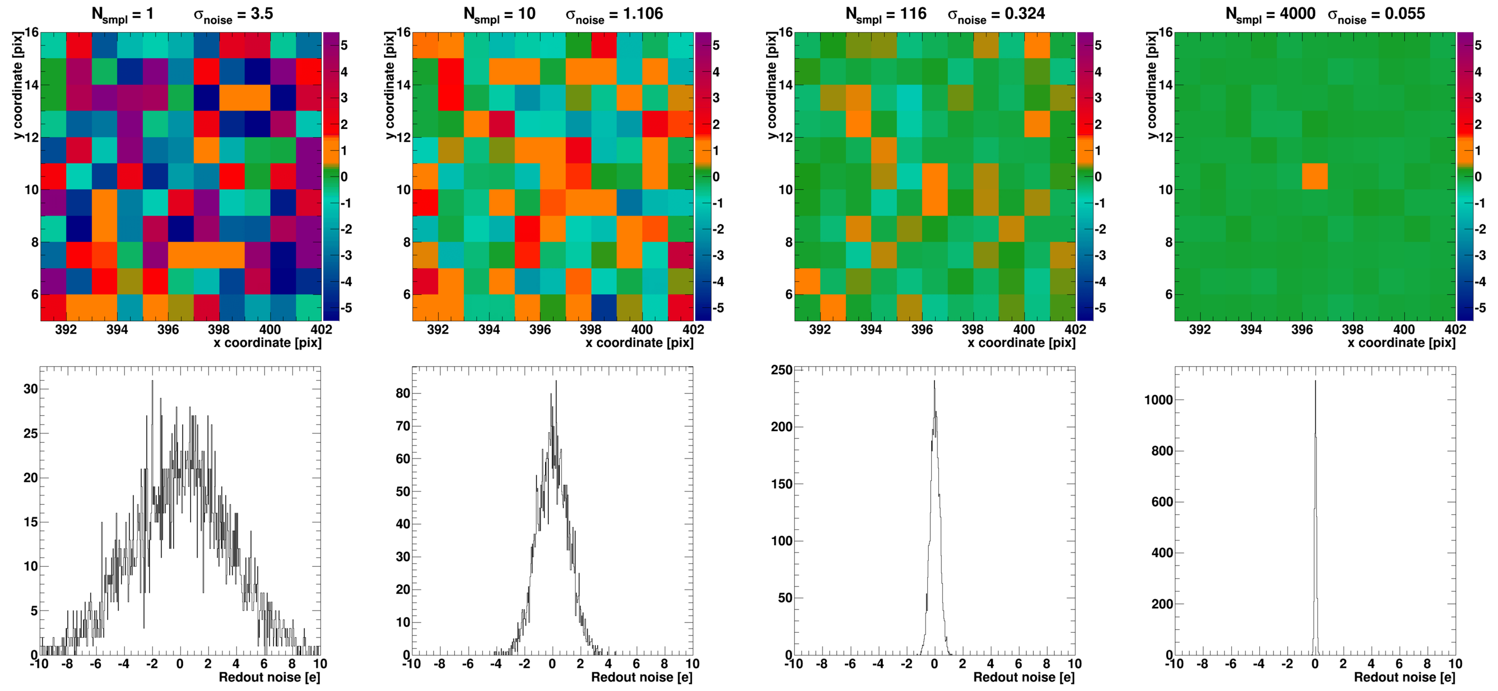

Figure 4: (Top) cropped images obtained with a non-illuminated skipper-CCD using 1, 10, 116 and 4000 samples. (Bottom) charge histogram for image pixels on top.

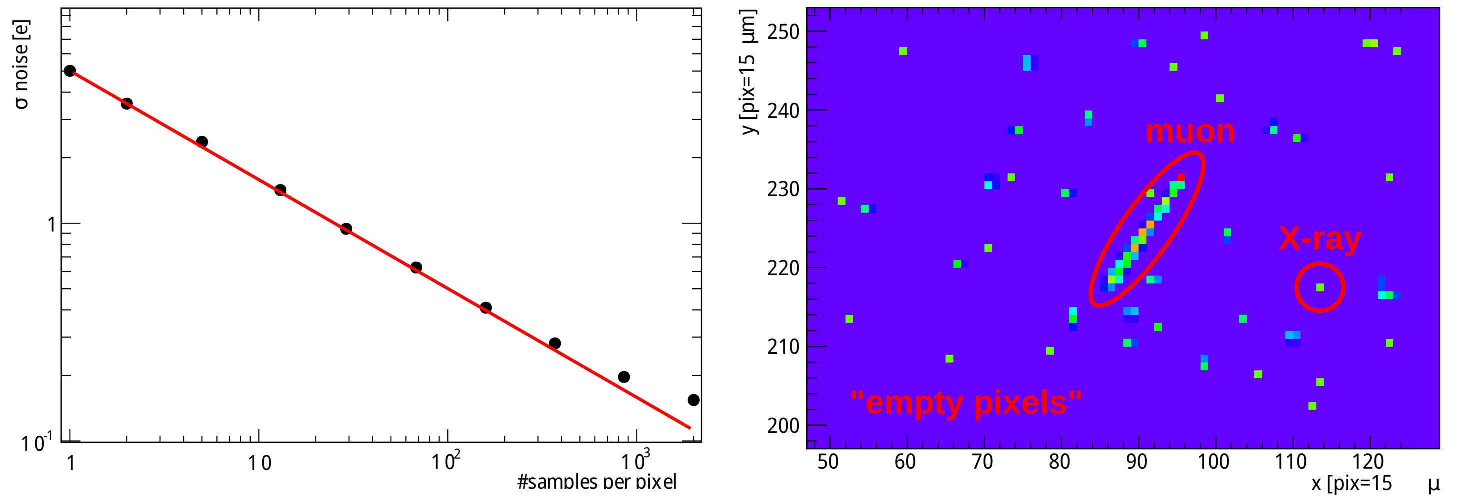

Figure 5: (Left) read-out noise as a function of number of samples. The red line is the expectation given the noise for one read. (Right) cropped image obtained using 4000 samples.

4. Performance

Sub-electron resolution

Absolute calibration possible without a dedicated setup

Distinguishable number of charges in each interaction

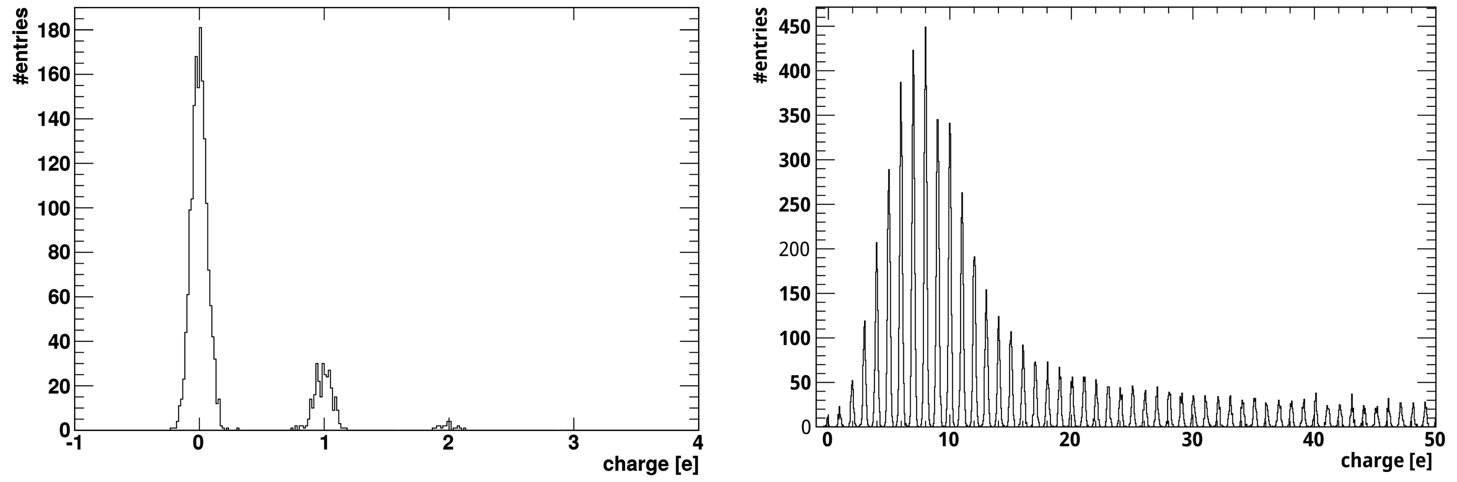

Figure 5: charge distribution for a non-illuminated CCD (left) and illuminated with a LED (right)

5. Prospects in rare-events searches

Dark-matter direct:
· SENSEI: 100 g by 2021
· DAMIC-M: 1 kg by 2024
· OSCURA: 10 kg by 2027

Dark-matter modulation:
· DM²: 0.1 g at south hemisphere

Reactor neutrinos: CONNIE, νIOLETA

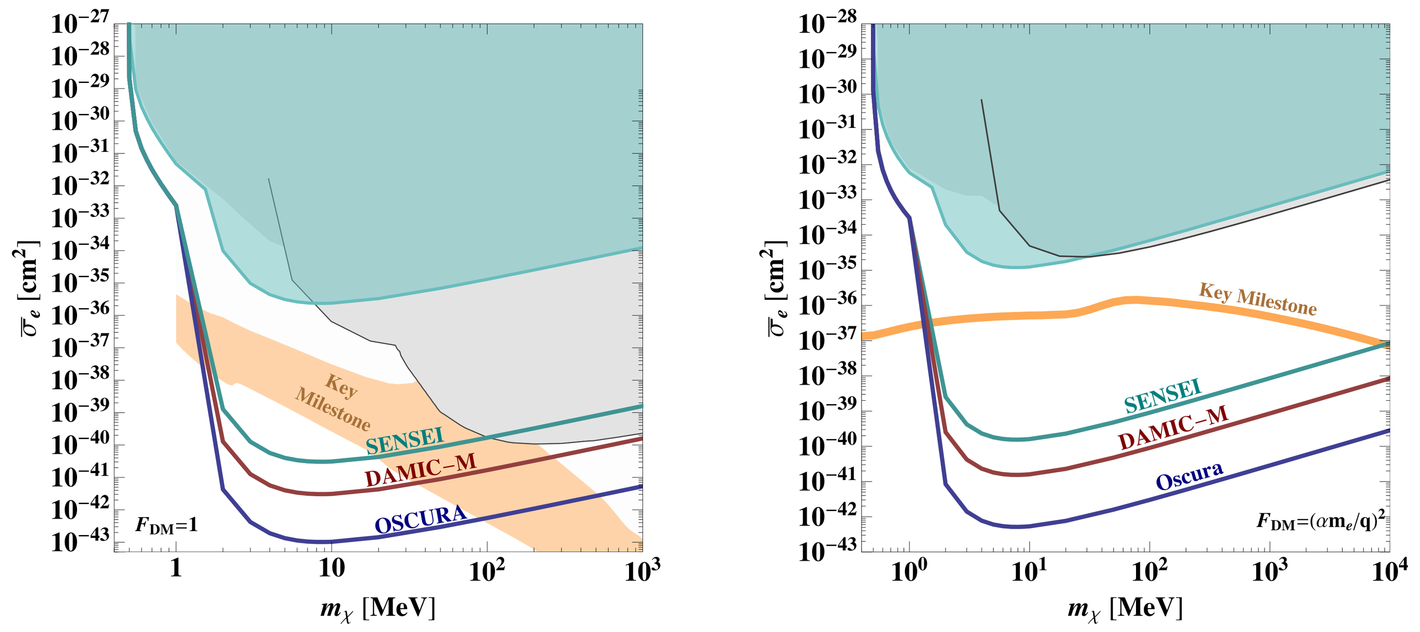

Figure 6: expectations for sub-GeV dark-matter detection with skipper-CCDs compared with current limits (gray and cyan shadows) for light (left) and heavy (right) mediators. Adapted from OSCURA at SNOWMASS

SUMMARY

- Sub-electron resolution achieved with Skipper-CCDs
- Sensitive to energy transfers as low as silicon bandgap
- Absolute calibration possible without a dedicated setup
- New generation of detectors projected for sub-GeV dark-matter and reactor neutrinos

More information and references here