



The DarkNESS mission: searching for dark matter with a skipper-CCD satellite observatory

Nate Saffold

July 11, 2024

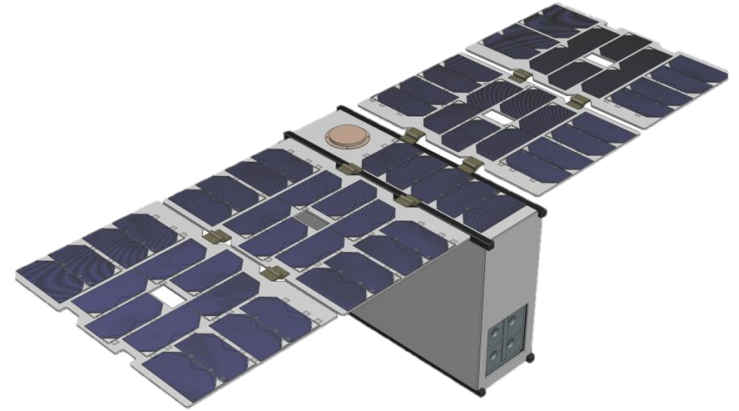
IDM 2024

The DarkNESS Mission

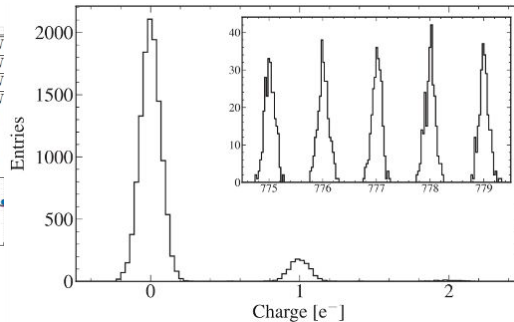
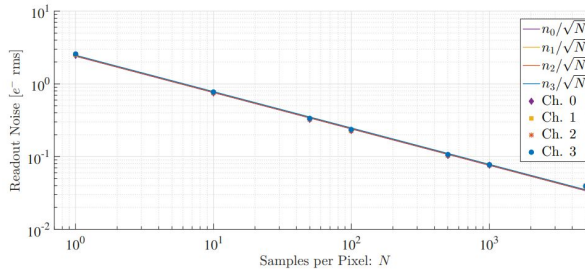
DarkNESS: Dark matter **N**anosatellite **E**quipped with **S**kipper **S**ensors

- Since their invention, skipper-CCDs have been used for:
 - Direct dark matter searches (DAMIC, SENSEI)
 - Neutrino experiments (CevNS)
 - Ground-based astronomy
- There is interest in using skipper-CCDs as single-photon counting and X-ray detectors for space-based imaging, but skipper-CCD operation in **space** has not been demonstrated

DarkNESS is a 6U CubeSat housing four 1.3 Mpix skipper-CCDs that will search for dark matter (DM)

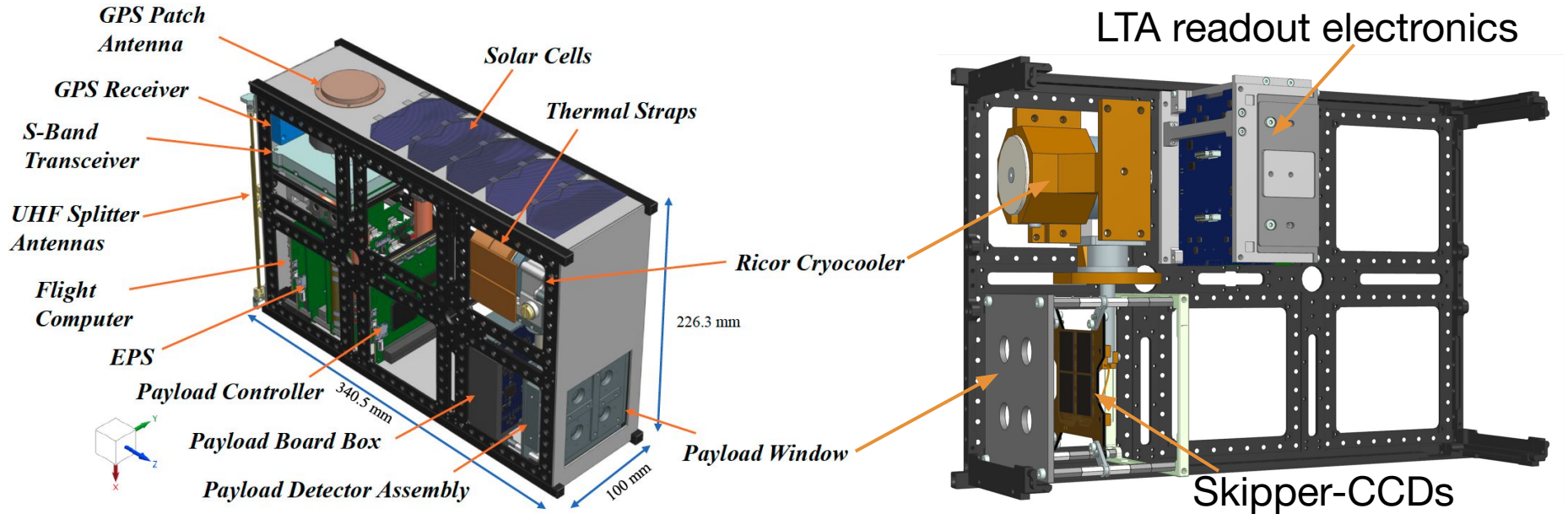


Collaboration between Fermilab and UIUC Laboratory for Advanced Space Systems at Illinois (LASSI)



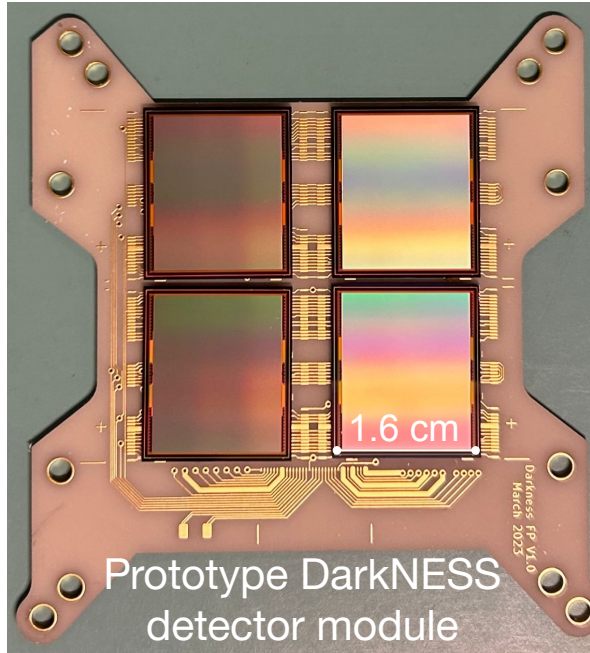
DarkNESS instrument

- Small form factor of 6U CubeSat precludes use of optics
- Payload window has apertures to allow photons from a $\sim 20^\circ$ FOV
- Fermilab in charge of payload development (detectors and electronics)

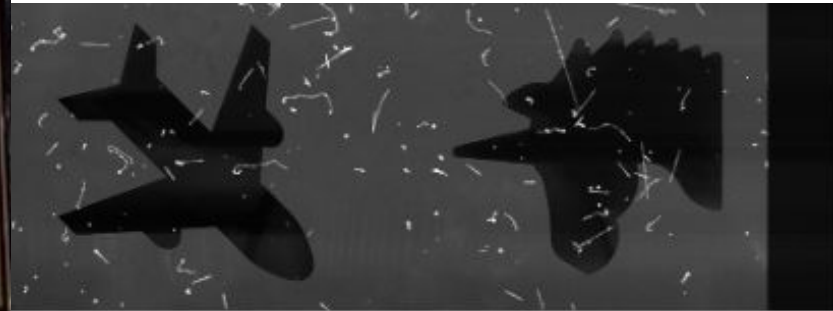


DarkNESS detectors

- Four 1.3 Mpix skipper-CCDs with sub-electron noise, wirebonded to ceramic PCB
- Aluminum layer on CCDs acts as X-ray entrance window, blocks visible and IR photons

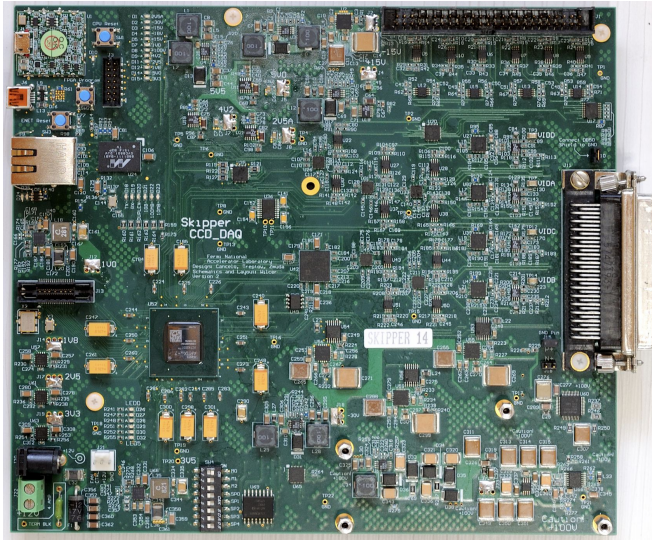


Prototype CCD with aluminum light shield
For more details see poster #130 by Ana Botti



DarkNESS readout electronics

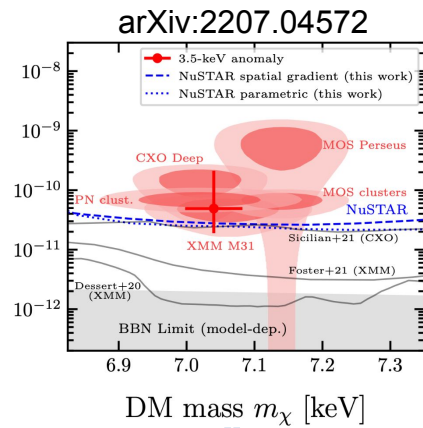
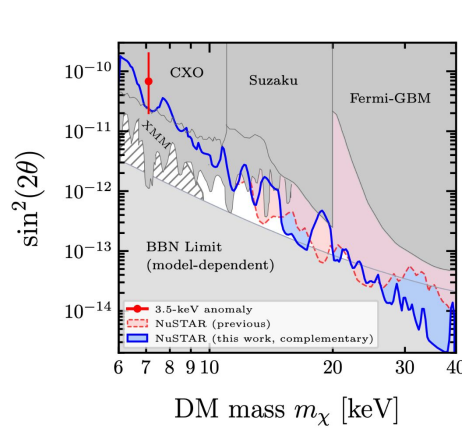
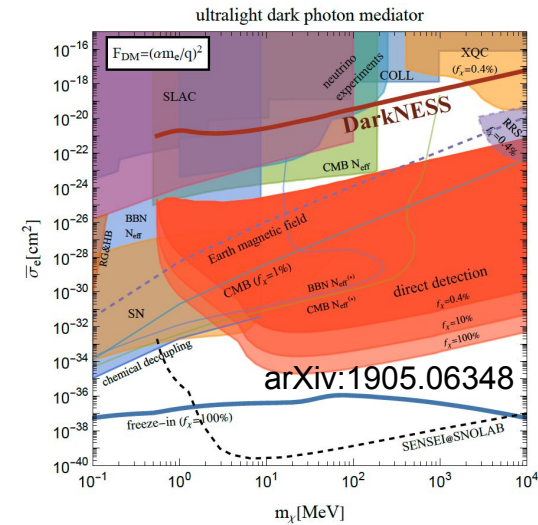
- Custom space-Low Threshold Acquisition (LTA) readout board, designed to fit into 6U CubeSat form factor
- LTA functionality split into three separate boards



[1.JATIS.7.1.015001]

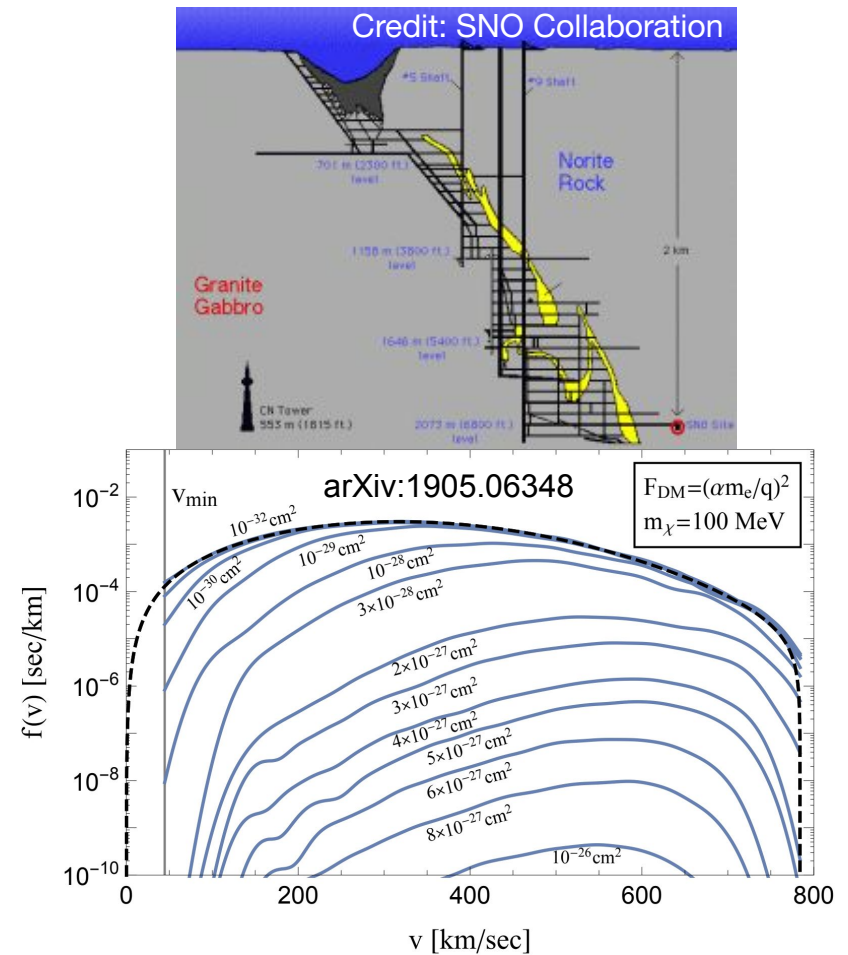
DarkNESS science goals

- Search for electron recoils from strongly-interacting sub-GeV DM
- Observe the diffuse X-ray background, search for signatures of DM decay



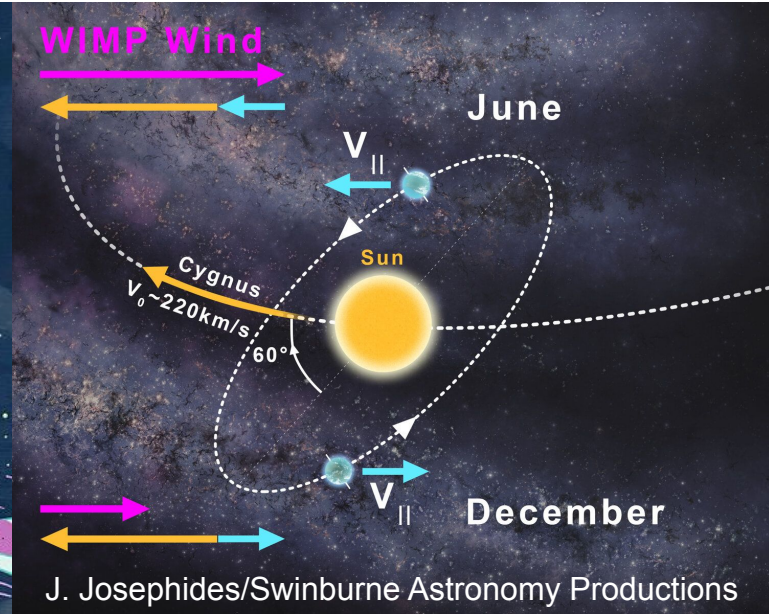
Strongly-interacting sub-GeV DM

- Typically DM searches are conducted underground to mitigate cosmogenic backgrounds
- For DM models with higher cross sections, the DM would be attenuated by the Earth's atmosphere and crust, and not reach detectors underground or on the Earth's surface
- Need a space-based mission to probe these models
- Must be subdominant component of DM ($f_\chi < 0.4\%$)



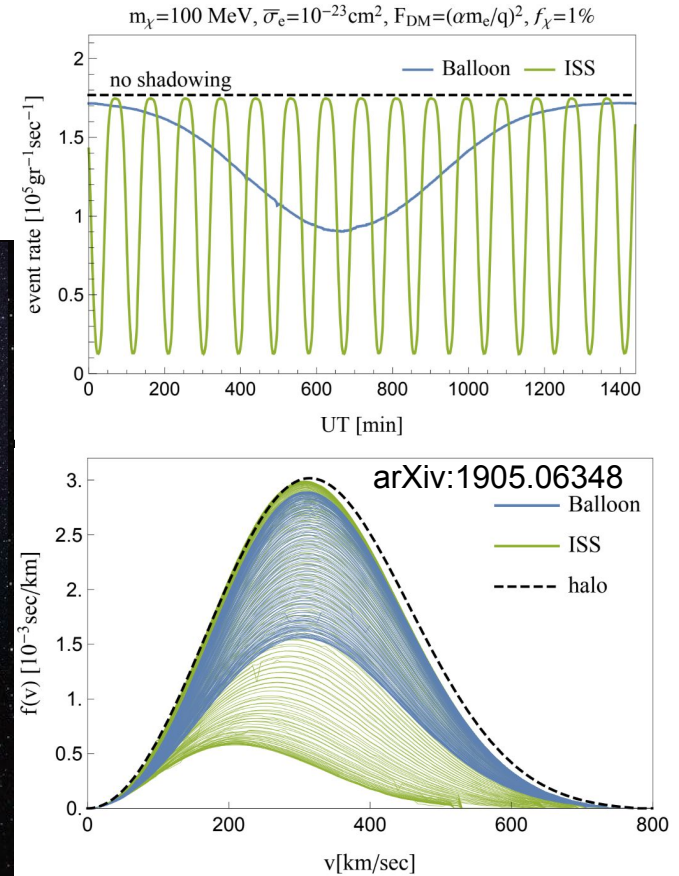
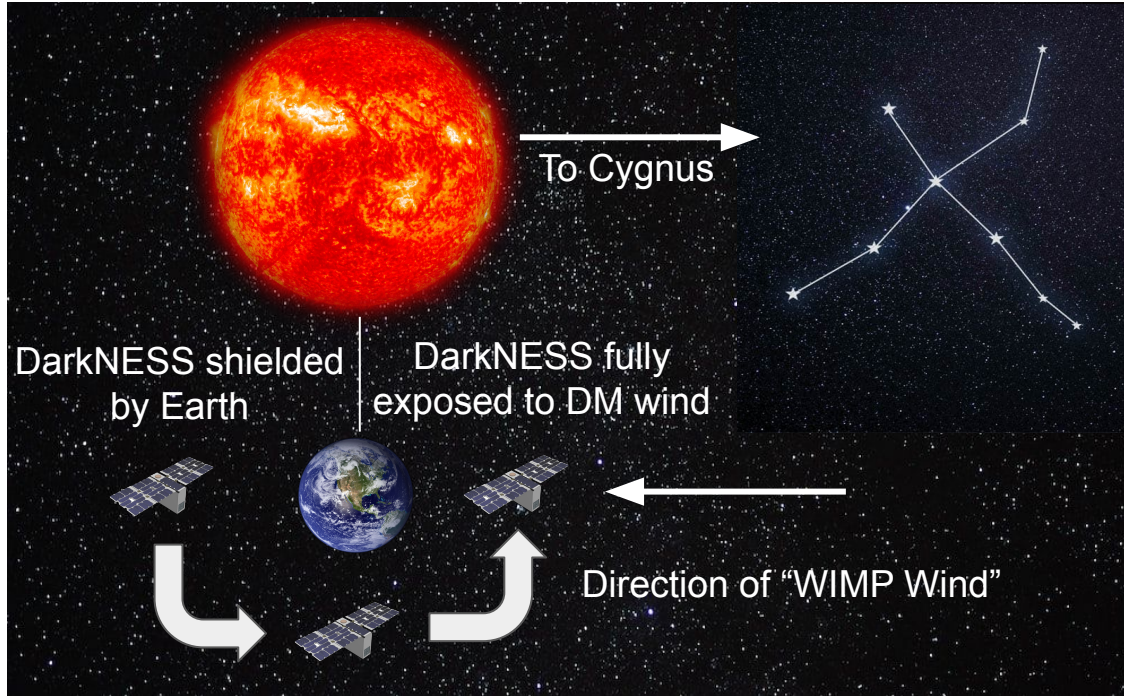
“WIMP Wind”

- Interaction rate proportional to relative velocity between DM and target
- This effect has been exploited for annual (and daily) modulation searches



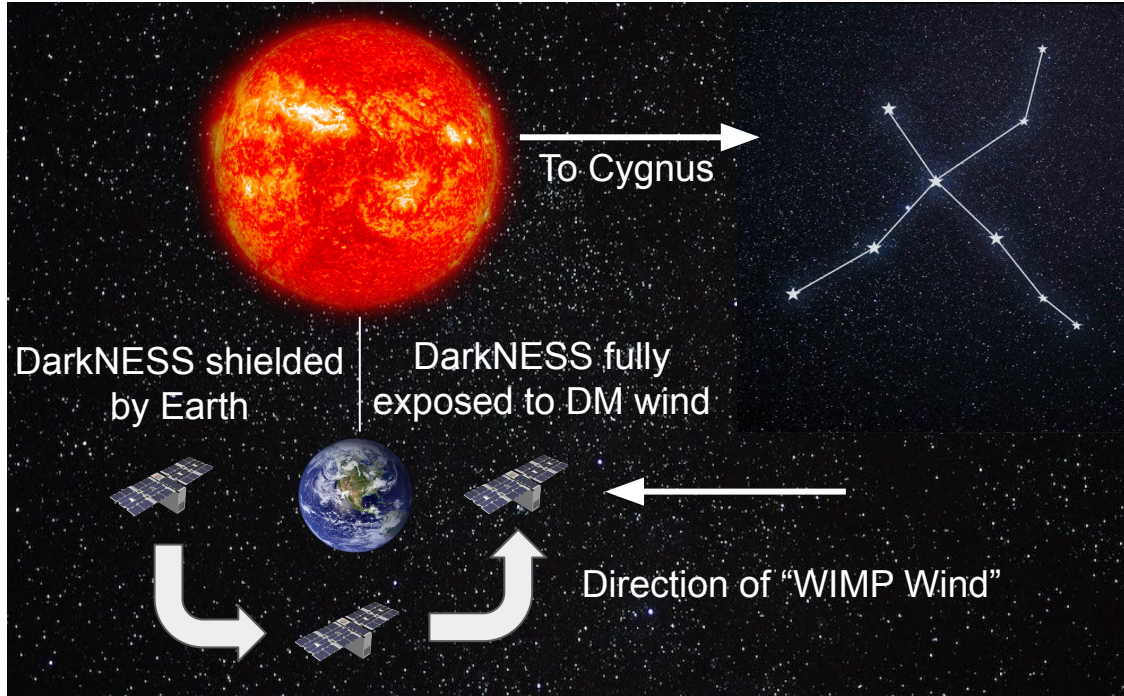
Strongly-interacting sub-GeV DM

- Large modulation in signal rate over orbital period due to Earth's shadowing effect

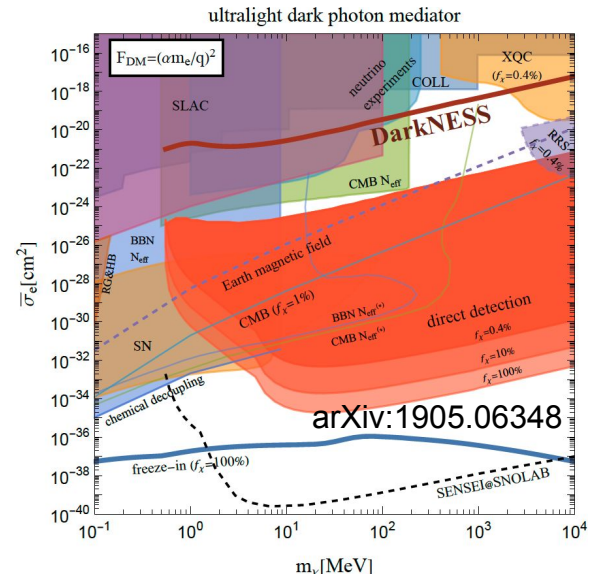


Strongly-interacting sub-GeV DM

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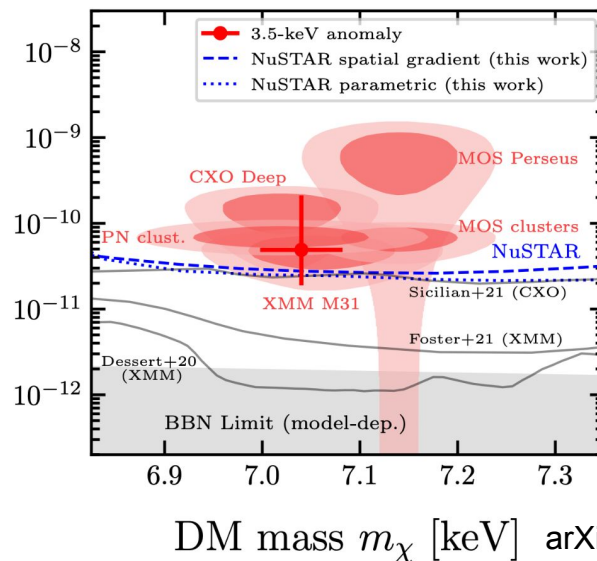
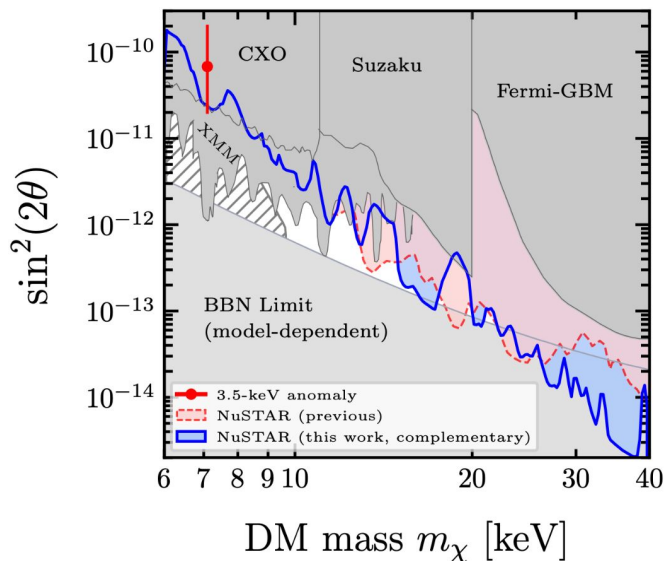
DarkNESS will set new constraints on DM-electron interactions



DarkNESS limit projections for 0.1 g-month exposure

X-rays from decaying dark matter

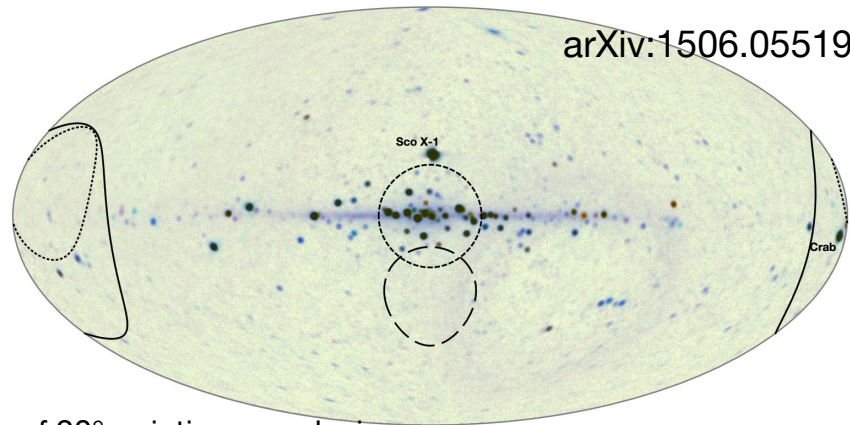
- Sterile neutrinos are a DM candidate that could decay to \sim keV photons
- Unidentified X-ray line purportedly observed at ~ 3.5 keV in 2014 [1402.2301], follow-up observations in tension with this result



X-rays from decaying dark matter

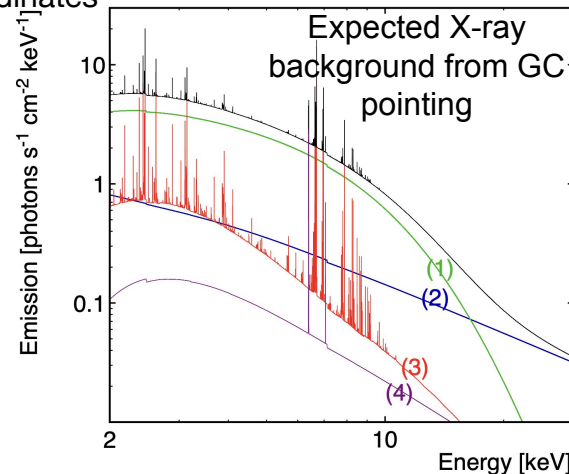
- Using wide (20°) FOV observations of diffuse X-ray sky, DarkNESS will search for unidentified X-ray lines, probing sterile neutrino decay
- Signal flux increases with FOV, but so does background
- Work ongoing to determine sensitivity, including optimal pointing strategy, and background rejection techniques

$$\mathcal{F} = \frac{\Gamma}{m_s} \frac{1}{4\pi} \int_{FOV} \underbrace{\int_0^\infty \rho(r(\ell, \psi)) d\ell}_{\text{D-factor (integrate DM density in line of sight)}} d\Omega$$



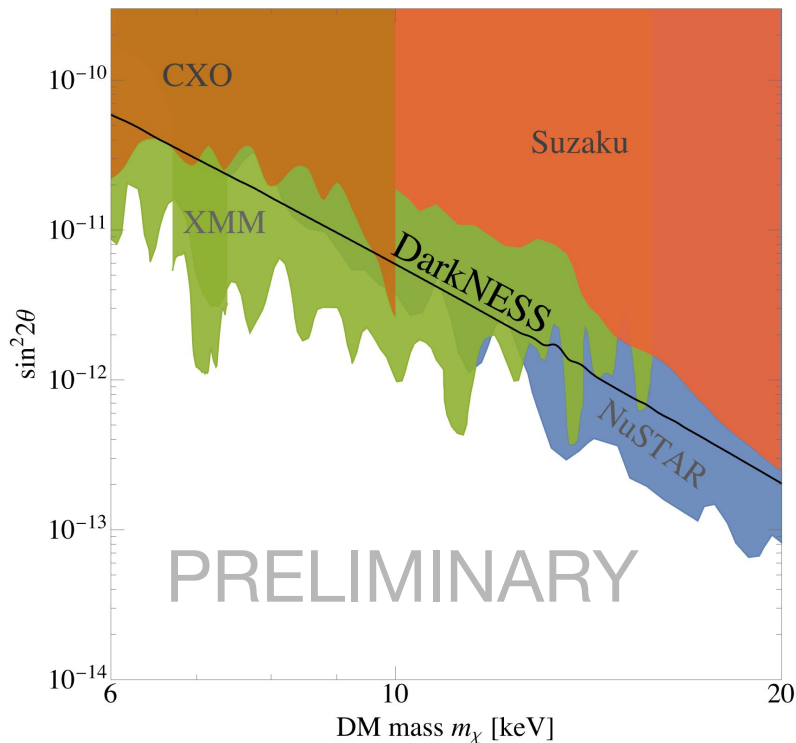
arXiv:1506.05519

Example of 20° pointings on sky in Galactic coordinates



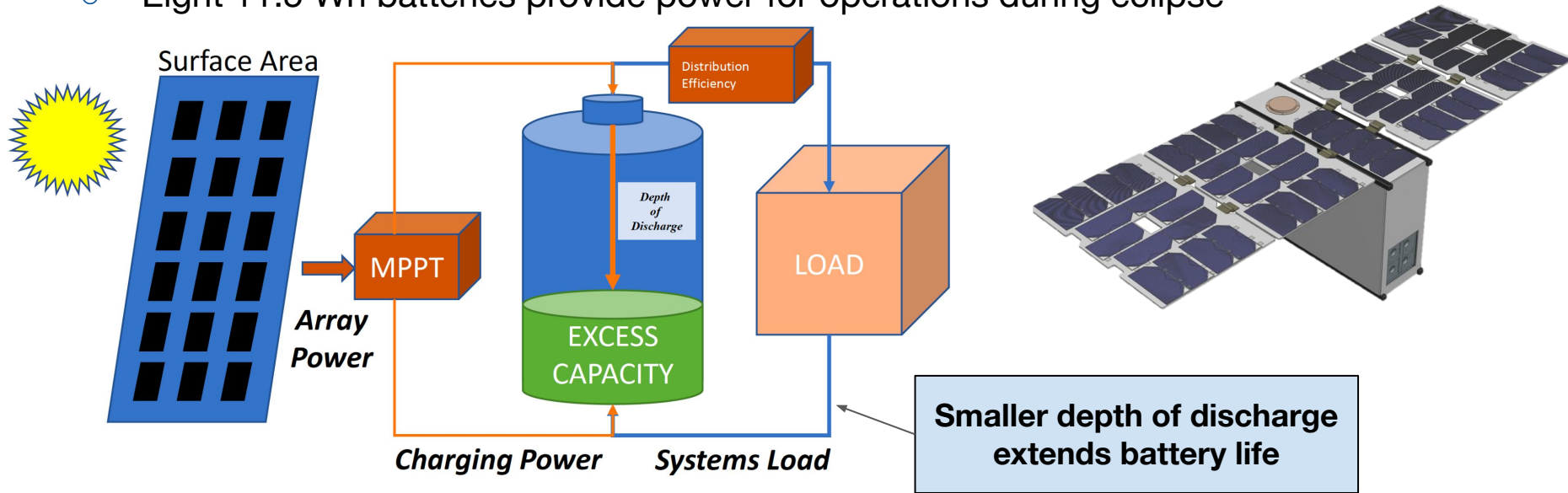
Sterile neutrino sensitivity

- DarkNESS projected sensitivity to sterile neutrino DM
 - 100 minute exposure time (50 x 2 minute exposures), pointing at Galactic Center with 20° FOV
 - Assume energy resolution of typical CCD [arXiv:1510.02126]
 - $\sigma_E \sim 40$ eV at 3.7 keV
 - Dominated by Fano noise at ~keV energies
 - Fraction of CCD area masked due to cosmic ray impingement



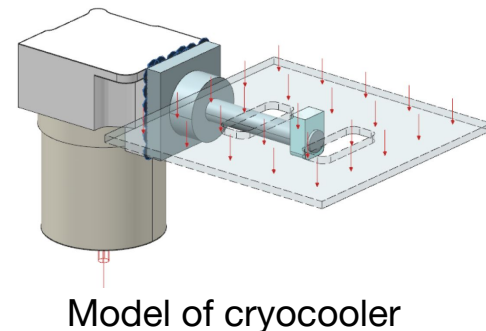
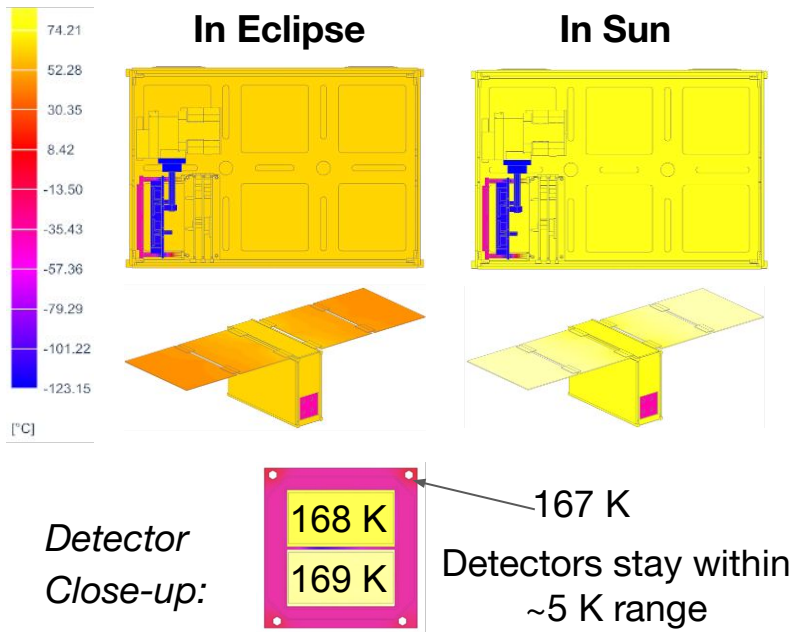
Challenges of space-based operation

- Power requirements:
 - Peak power required: 68 W (cryocooler on high, communications on, charging current)
 - Solar panels provide 72 W (~72 Wh/orbit), meeting peak loads in sunlight
 - Eight 11.5 Wh batteries provide power for operations during eclipse



Challenges of space-based operation

- Thermal management:
 - Need to cool detectors to 170K using cryocooler
 - Need to remove heat from cryocooler, detector module, and readout electronics



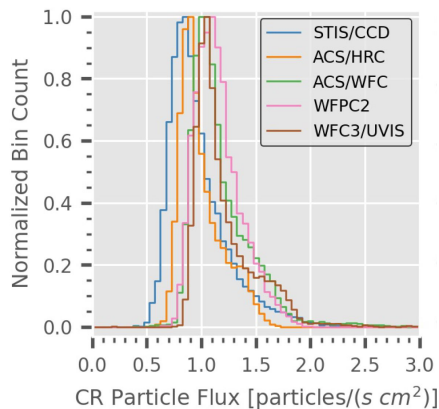
In thermal model, the cryocooler was able to maintain the skipper-CCD temperature at $170 \text{ K} \pm 5 \text{ K}$ during eclipse and sun-exposed time periods

TVAC testing ongoing to validate thermal model

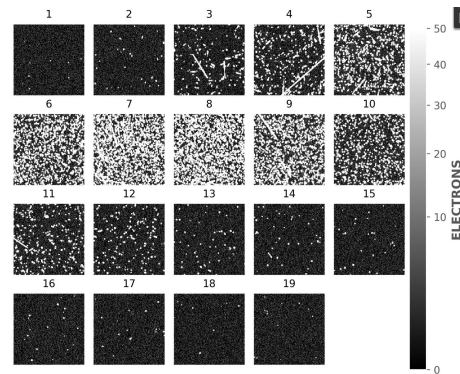
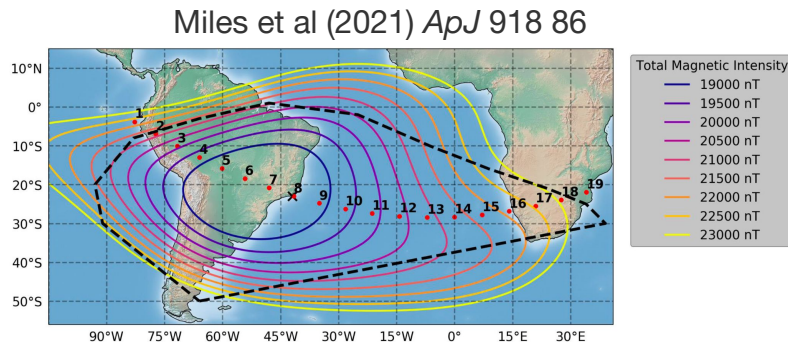
Challenges of space-based operation

- Cosmic ray backgrounds

- Expect ISS-like orbit (51° inclination)
- Background simulations in progress using Geant4, building off previous work (Cuevas 2019)
- Optimal operating mode driven by tradeoff between exposure time and CCD occupancy due to energy depositions from cosmic rays
- Minimize readout time: developing faster non-destructive readout technologies



Hubble data indicates
~1 particle/cm²/s



Expect significant increase in background rate during passages
through South Atlantic Anomaly (SAA)

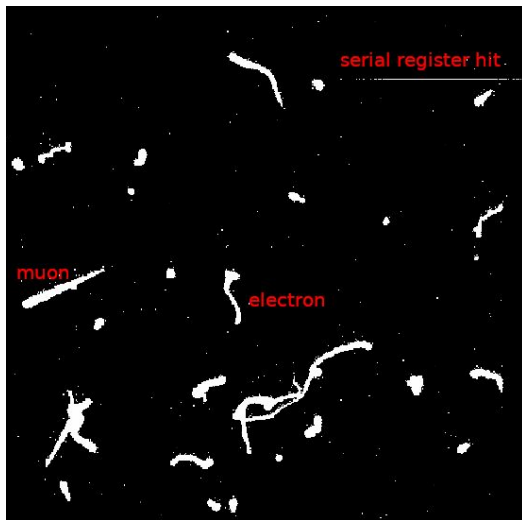
Challenges of space-based operation

- Communications with the CubeSat
 - Data is downlinked to ground station
 - Data rate is limited by radio type and access to ground stations
 - Plan to downlink histograms (spectra) and housekeeping data regularly
 - Downlink raw images files occasionally for quality assurance
 - Ground station capable of uplinking commands to CubeSat

Radio	Total bytes per pass	Passes to transmit raw image (32 MB)
UHF	576 kB/pass	70
S-Band	9 MB/pass	5
X-Band	6 GB/pass	<1

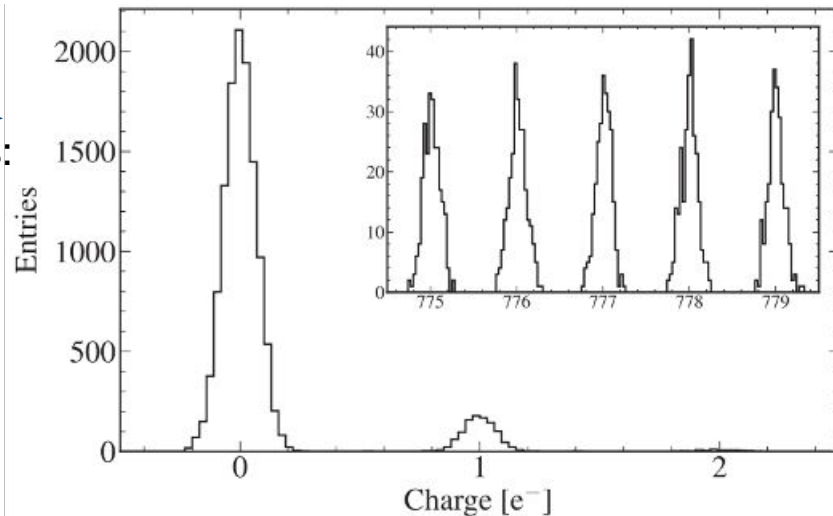
In-flight analysis pipeline

- To reduce data throughput, Fermilab is developing an in-flight analysis pipeline to convert images to spectra for downlink to ground station
- Two operating modes:
 - Single-sample mode (X-ray data processing)
 - Multi-sample mode (Low-threshold DM search)



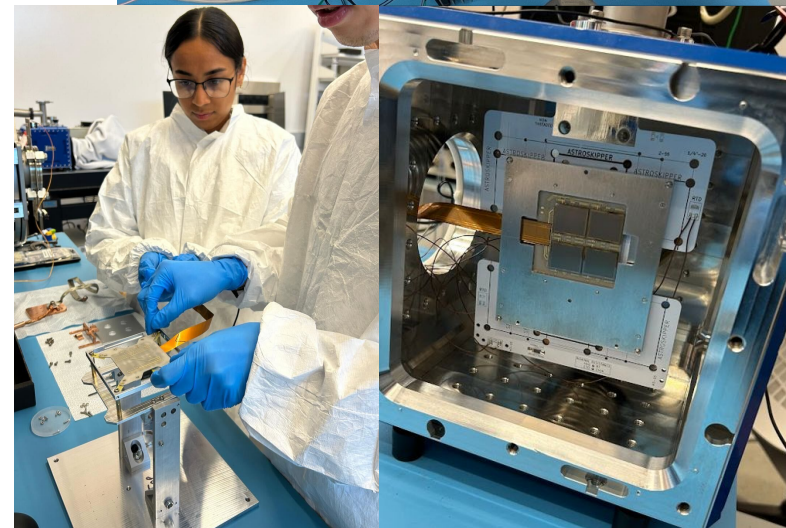
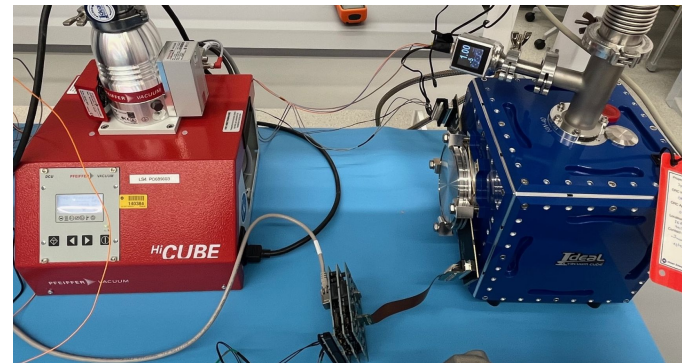
Analysis pipeline performs:

- Baseline subtraction
- Skipper averaging
- Energy calibration
- Clustering
- Masking



Current Status

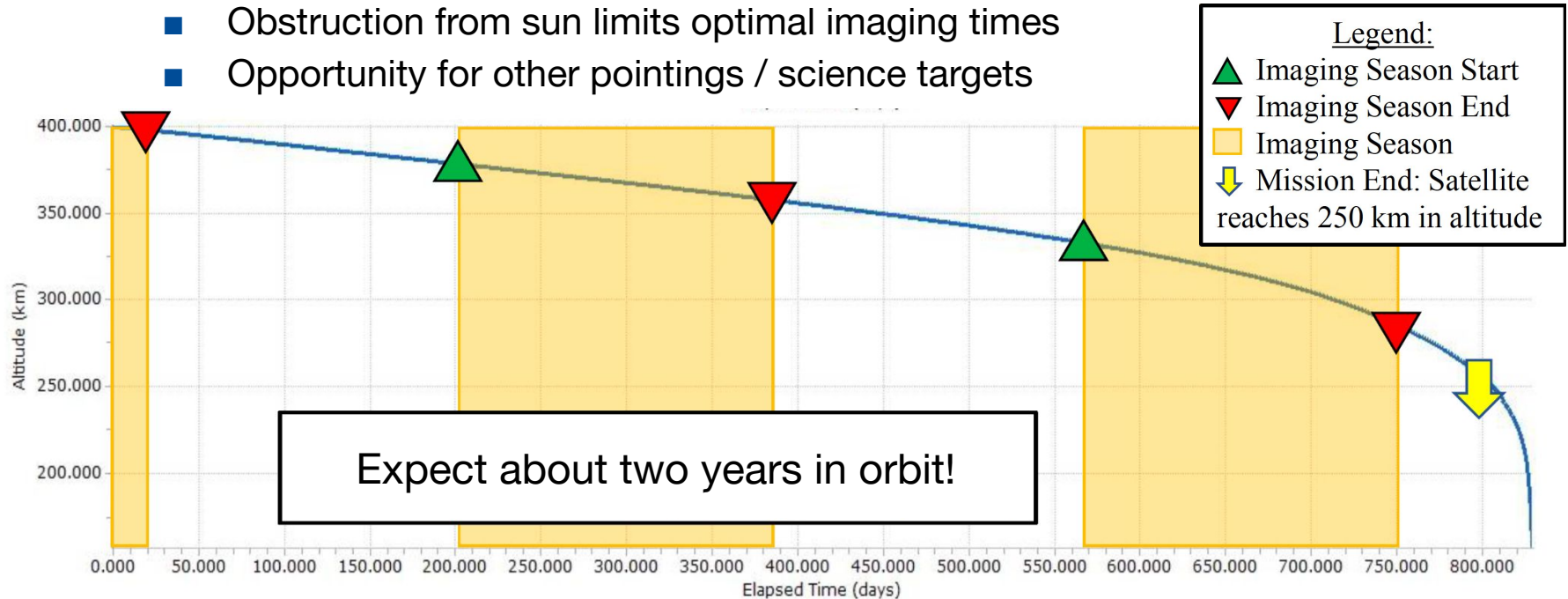
- TVAC testing ongoing at UIUC
- Detector characterization and in-flight software development ongoing at Fermilab
- Developing Geant4 simulation to assess particle backgrounds and determine observational strategy
- CDR underway and will be completed by the end of August 2024
- Secured launch opportunity for late 2025-early 2026 through Firefly Aerospace's DREAM program



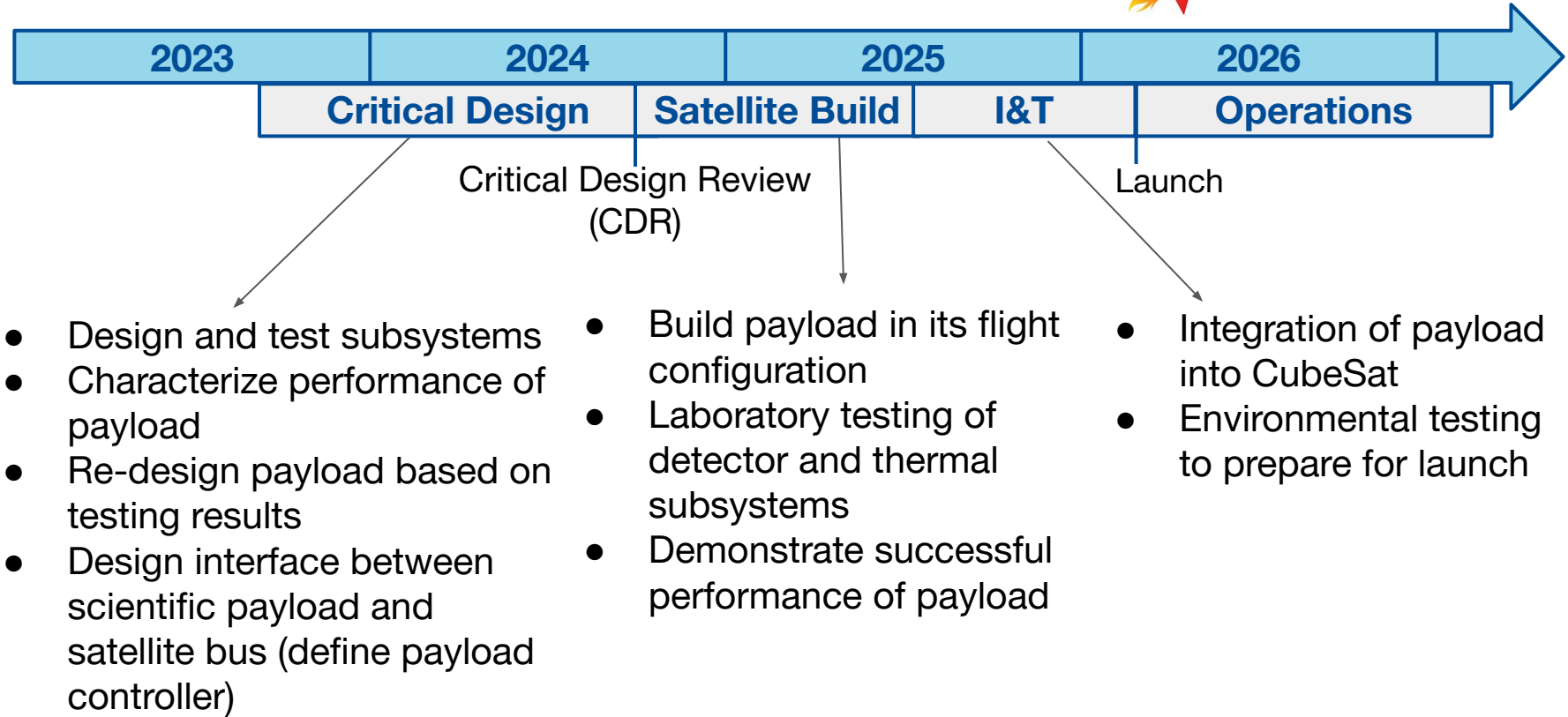
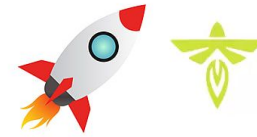
DarkNESS test stand at FNAL

Orbital Analysis

- Expected orbital lifetime of DarkNESS mission
 - Imaging season calculated for pointings at GC
 - Obstruction from sun limits optimal imaging times
 - Opportunity for other pointings / science targets



Project Timeline and Milestones



DarkNESS Collaboration

Fermilab: Juan Estrada, Nate Saffold, Roni Harnik

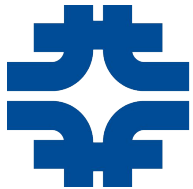
University of Illinois: Eric Alpine, Michael Lembeck, Chris Young, Samriddhi Bhatia

University of Chicago: Alex Drlica-Wagner, Graydon Schulze-Kalt

Stony Brook University: Rouven Essig

Universidad Nacional del Sur/CONICET: Fernando Cherchie

Tel Aviv University: Erez Etzion



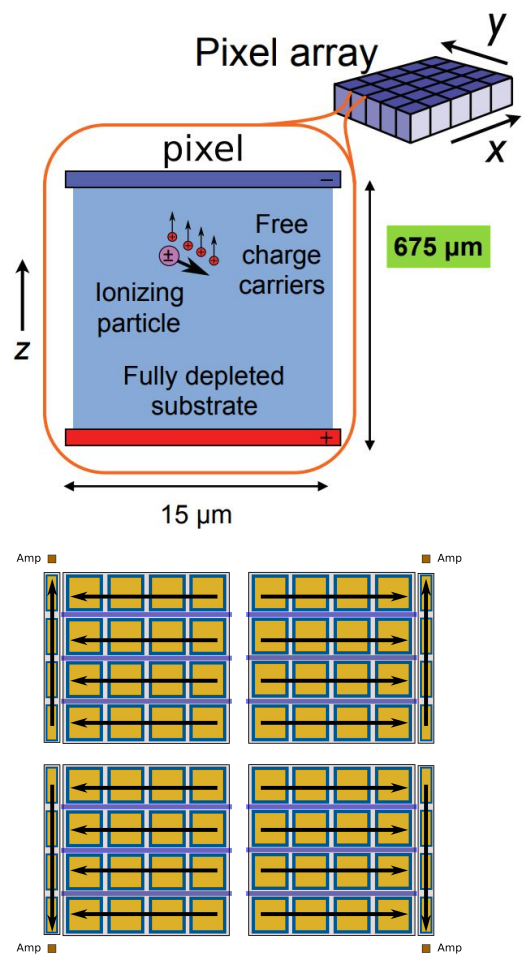
Thank you!



Backup

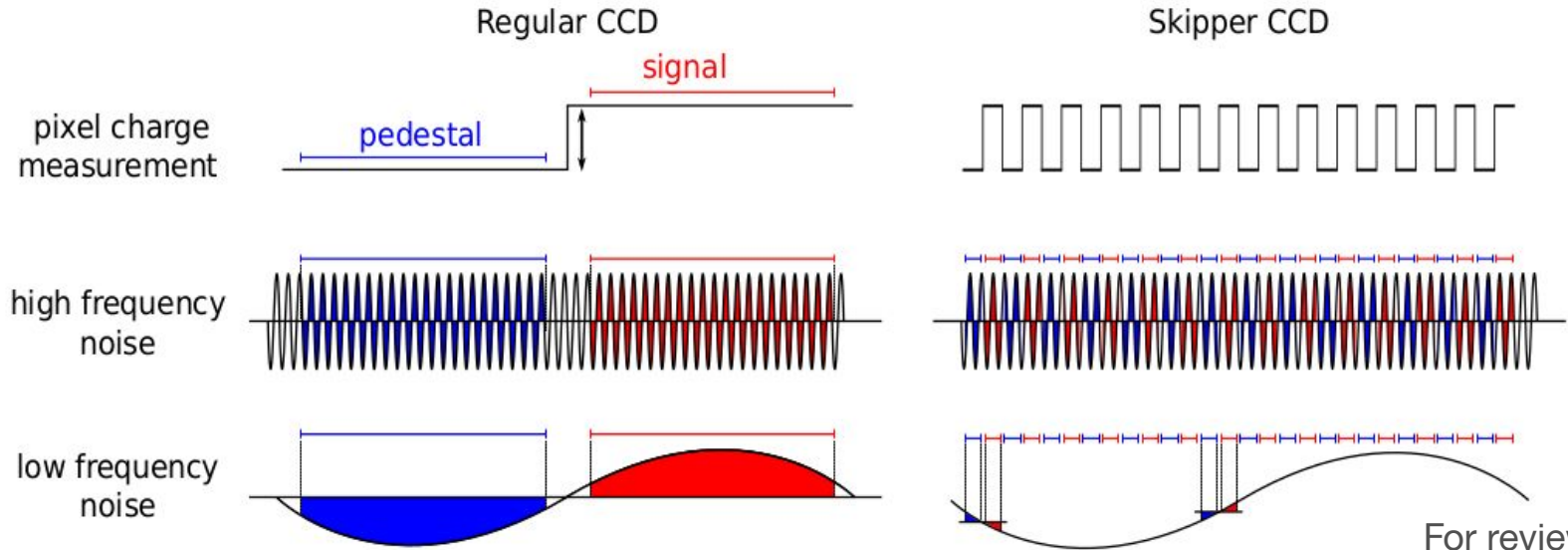
CCDs

- Charge coupled devices (CCDs) are integrated circuits that produce images of the energy depositions in a pixelated Si substrate
- Holes drift through substrate and collect in pixels near the surface
- Charge packets are shifted to a shared amplifier (1 per quadrant) for readout
- CCDs for DM are designed by LBNL MSL, based on fully-depleted CCD designs proven in astronomy
 - High-efficiency charge collection and transport, low dark current
 - Thickness limited only by capabilities of commercial foundries
- Conventional CCDs are limited to noise of $\sim 2e^-$



Skipper Readout

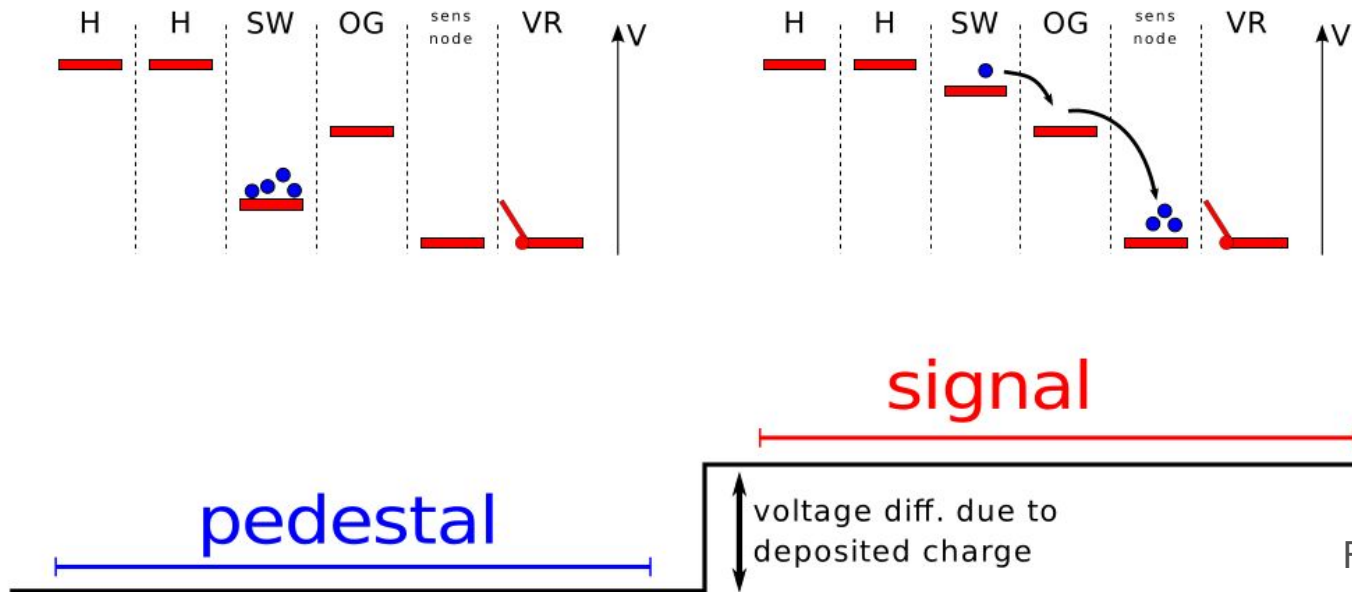
- In a conventional CCD, charge moved to the sense node must be drained
 - You can integrate longer, but you cannot beat the $1/f$ noise
- The Skipper amplifier lets you make multiple non-destructive measurements!



For review see:
[arXiv:1106.1839](https://arxiv.org/abs/1106.1839)

Skipper Readout

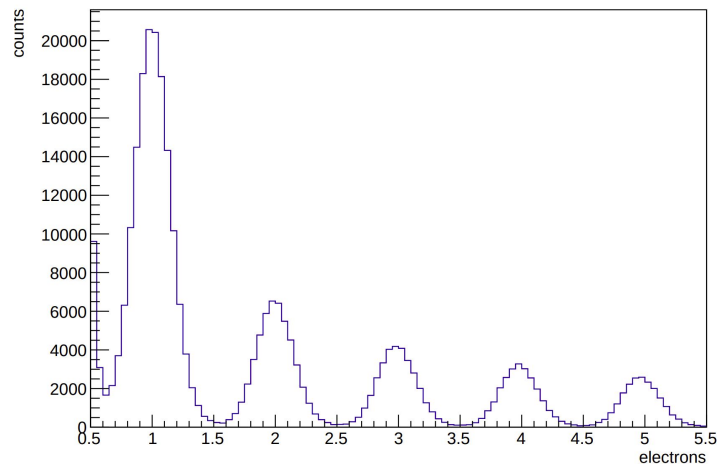
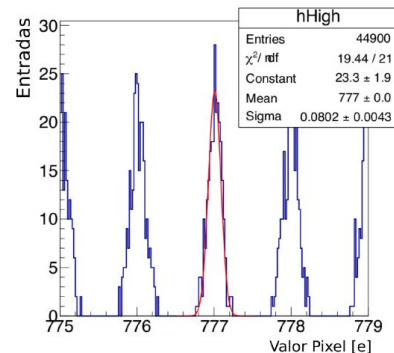
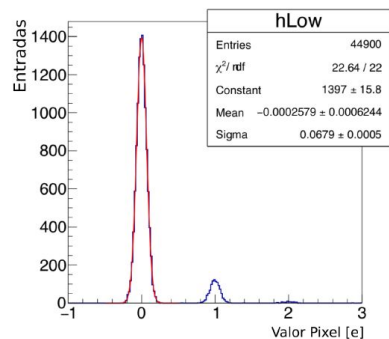
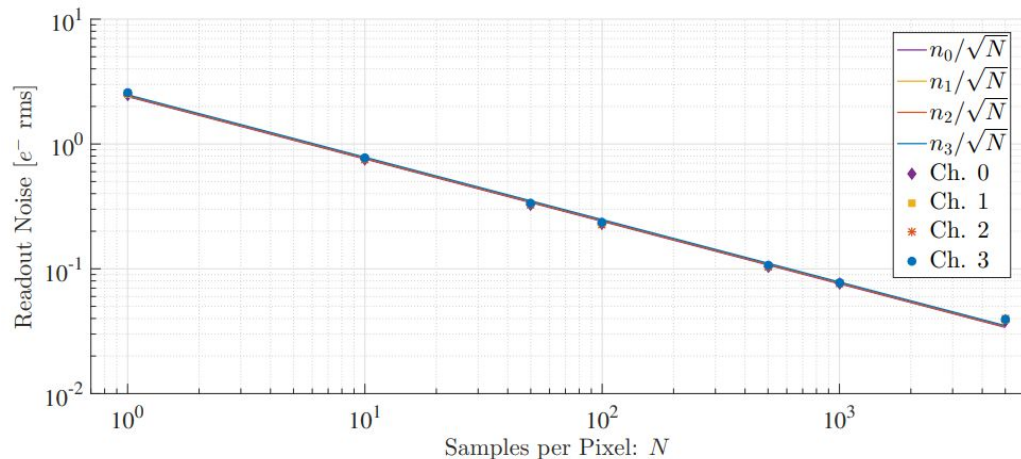
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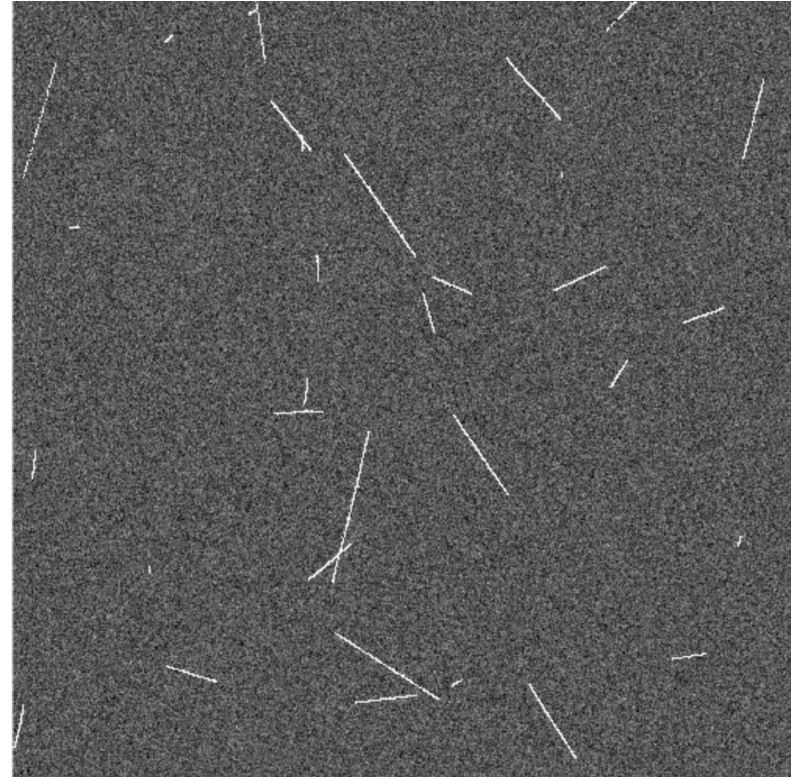
Sub-electron readout noise

- Skipper noise scales as $1/\sqrt{N}$:
 - trade charge resolution for speed
- We can count single electrons:
self-calibrating charge measurement



Geant4 Background Simulations

- Simulated image of a 5-minute CCD exposure to the trapped proton spectrum expected in Low Earth Orbit
- Simulations are used to estimate the expected CCD occupancy (fraction of pixels affected by ionizing radiation) as a function of exposure time
- Trapped proton fluxes provided by [SPENVIS](#)
- Simulation framework described in [10.1109/CHILECON47746.2019.8988076](#)



DarkNESS Instrument Specifications

DarkNESS Instrument Specifications	
Detector Area	1.6 x 1.9 cm ²
Thickness	250 um
Bias Voltage	80 V
Operating Temperature	170 K
Readout Speed	250 kpix/s