DarkNESS

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

Erez Etzion, TAU

ALPS-2024

Mission

Deploy a 6U CubeSat to perform a search for **d**ark **m**atter (DM) and demonstrate the single-photon counting capabilities of skipper-CCDs for space-based imaging.

Skipper-CCDs in space

- Since demonstrating sub-electron noise in 2017, skipper-CCDs have been used at:
  - 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.

Scientific Goals

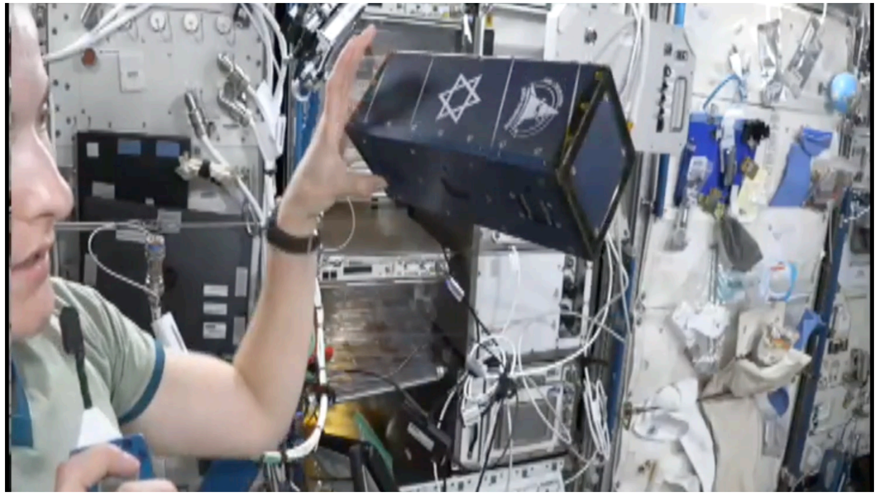
- Search for decaying DM by mapping the **diffuse X-ray** background of the **G**alactic **C**enter (GC) and searching for unidentified X-ray lines.
- Search for electron recoils from **S**trongly **I**nteracting **DM** (**SIDM**) that would not penetrate the Earth's atmosphere.
- The first operation of Skipper-CCDs in space (R&D of sensors operation).

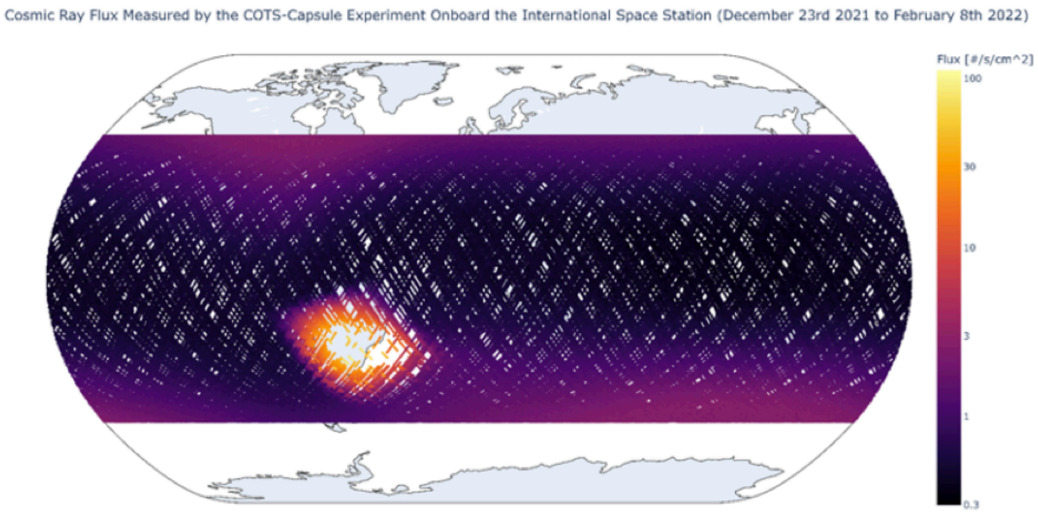
DarkNESS Collaboration

Fermilab: Juan Estrada, Nate Saffold, Donna Kubik, Roni Harnik
University of Illinois: Eric Alpine, Michael Lembeck, Chris Young
University of Chicago: Alex Drlica-Wagner
Stony Brook University: Rouven Essig
Universidad Nacional del Sur/CONICET: Fernando Cherchie
Tel Aviv University: Erez Etzion

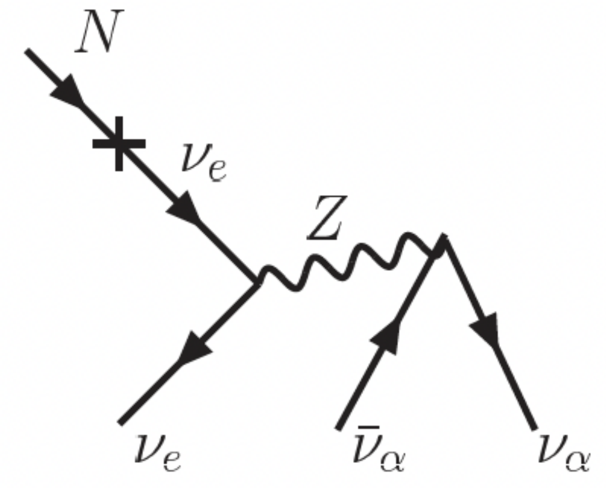
Previous (TAU team) experience in Space: COTS Capsule on ISS

- High-energy particles produce latch-up effects that irreversibly damage electronics in space.
- COTS-Capsule – a novel unobtrusive radiation characterizing and mitigation system.
- Enable the use of modern high-end electronics in the space environment.
- In a short time successfully designed, built and launched to the ISS in December 2021 and took 3 weeks of data in orbit.
- Next stage: a complete solution onboard a CubeSat.

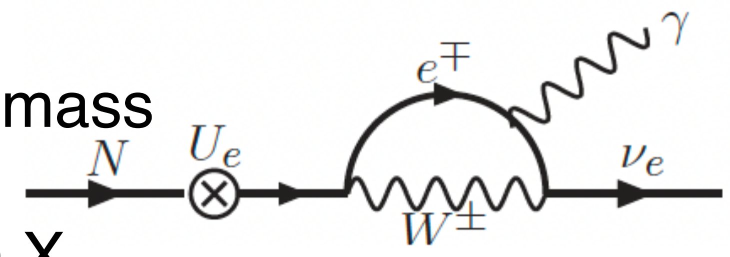




Sterile Neutrino DM

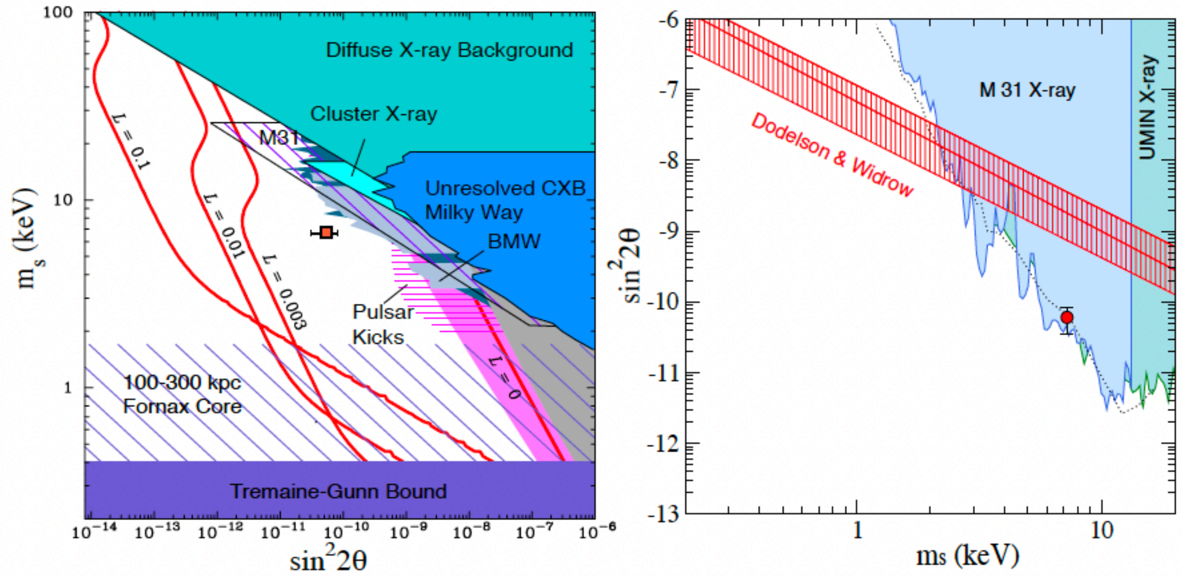


- The main decay channel of the sterile neutrino with mass below 2m$_e$ is to three neutrinos $N \to \nu\bar{\nu}\nu$.
- Sterile neutrino DM can have radiative decay channel $N \to \nu\gamma$.
- Therefore, if the sterile neutrino is a main ingredient of DM it may be detectable in X-ray observations.
- The signture is a narrow energy line at energy ½ of the mass of the sterile neutrino.
- The null results of many searches for DM decay lines in X ray resulted in an upper limit on the DM sterile neutrino mixing angle vs mass.

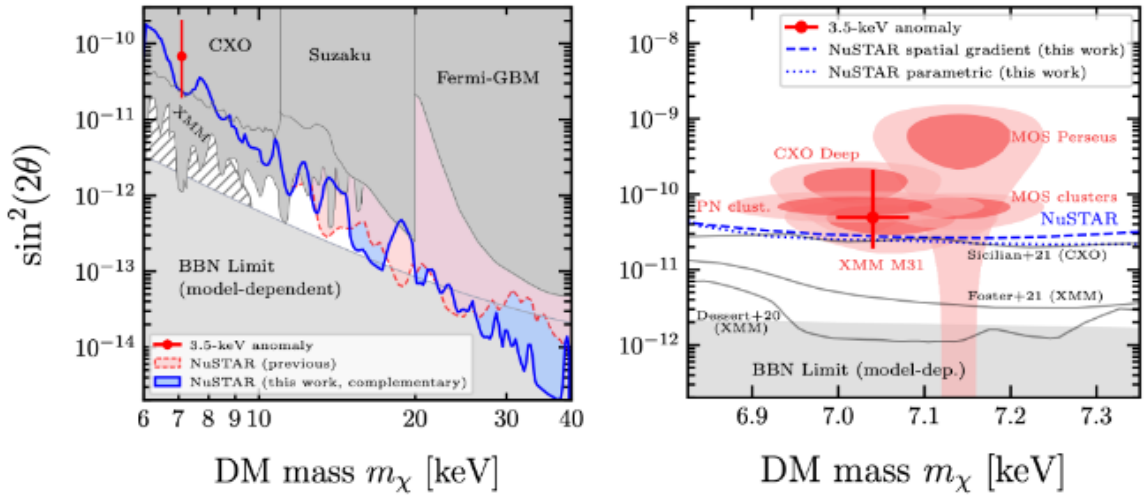


3.5 KeV observation

- An unidentified X-ray observed by Bulbul et al at ~3.5 KeV in 2014 resulted in several follow-up observations. There are disagreements in the results of these observations e.g. NuSTAR "*strongly disfavor a ~7-keV sterile neutrino decaying into a 3.5-keV photon*".



arXiv:1402.2301 (Bulbul et al.)

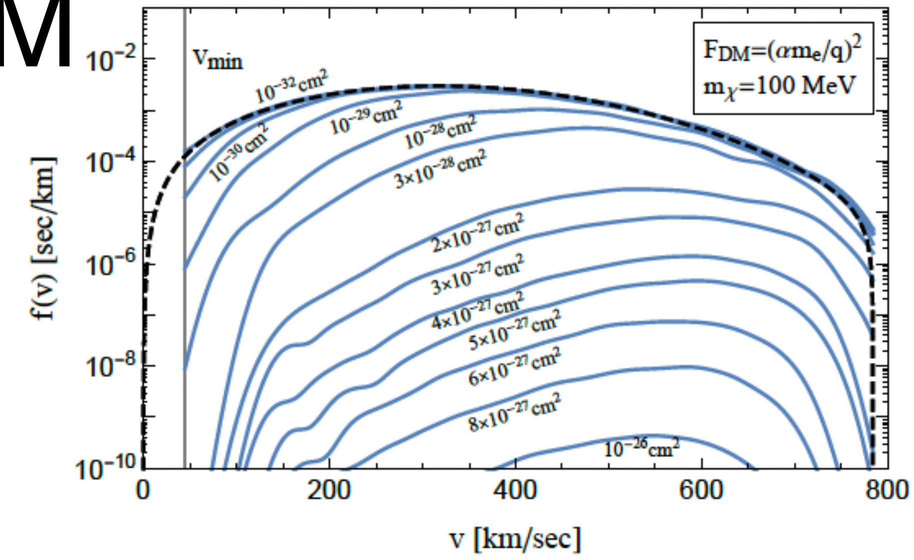


NuSTAR arXiv:2207.04572

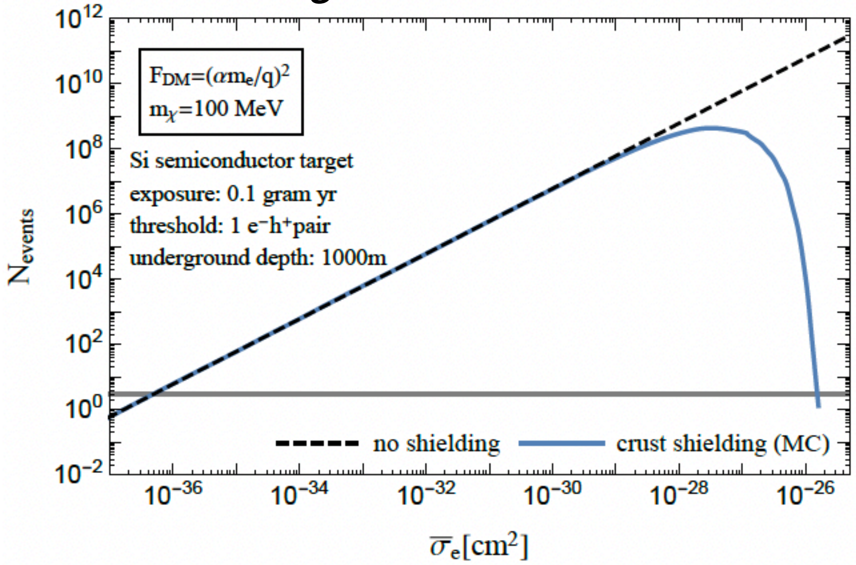
Strongly-Interacting sub_GeV DM

arXiv:1905.06348 **Timon Emken et al.**

- DM searches are shielded and conducted underground to reduce cosmic and radiogenic backgrounds.
- For DM models with higher cross-section, the DM would be attenuated by the Earth's atmosphere and crust, and not reach detectors underground or on the Earth's surface.
- Assume DM-SM interaction through an electric dipole moment, DM may interact only with electrons and not quarks and nuclei.
- Can use balloon / space-based missions to probe these models.
- It must be a subdominant component of DM to avoid bounds from CMB.

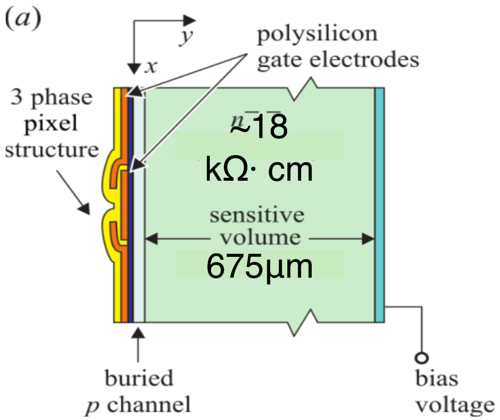


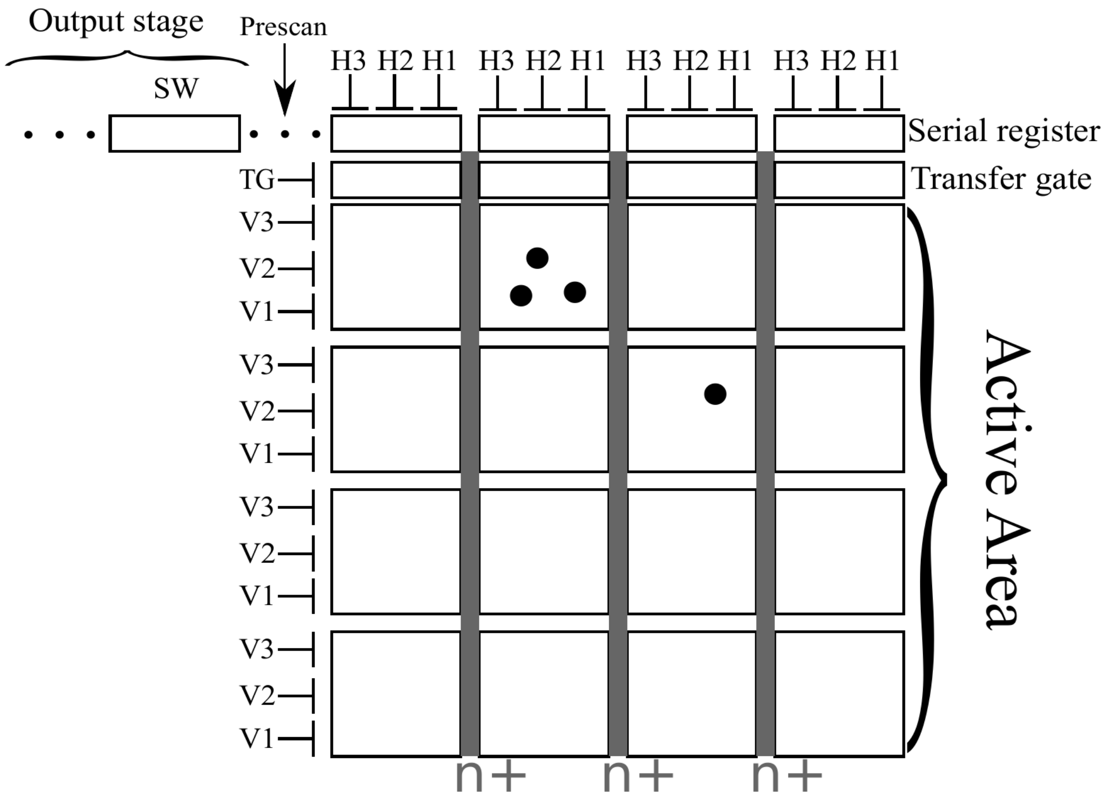
Distortion of the DM speed distribution due to underground scatterings on nuclei in 1 km of rock.



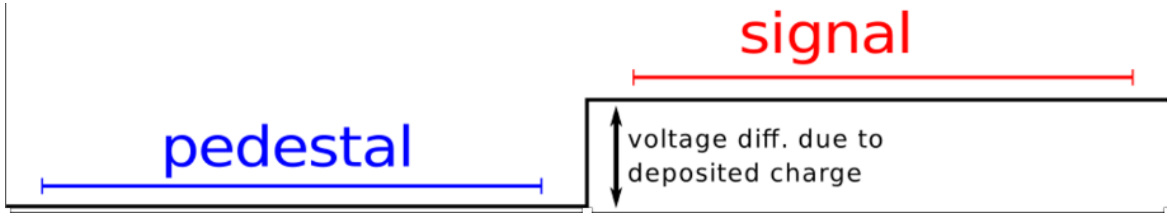
Attenuation of the number of expected events in a generic semiconductor experiment.

CCD Technology





- **CCD = pixelated silicon array.**
- High-resistivity fully-depleted silicon.
- **~100%** charge collection and transfer efficiency.
- The charge is moved to the sense node and readout **once,** then it is **drained** and the charge is **lost**.



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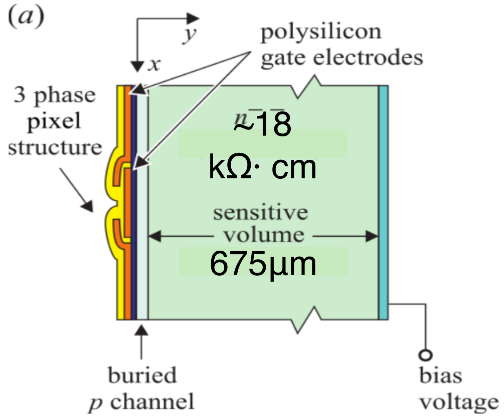

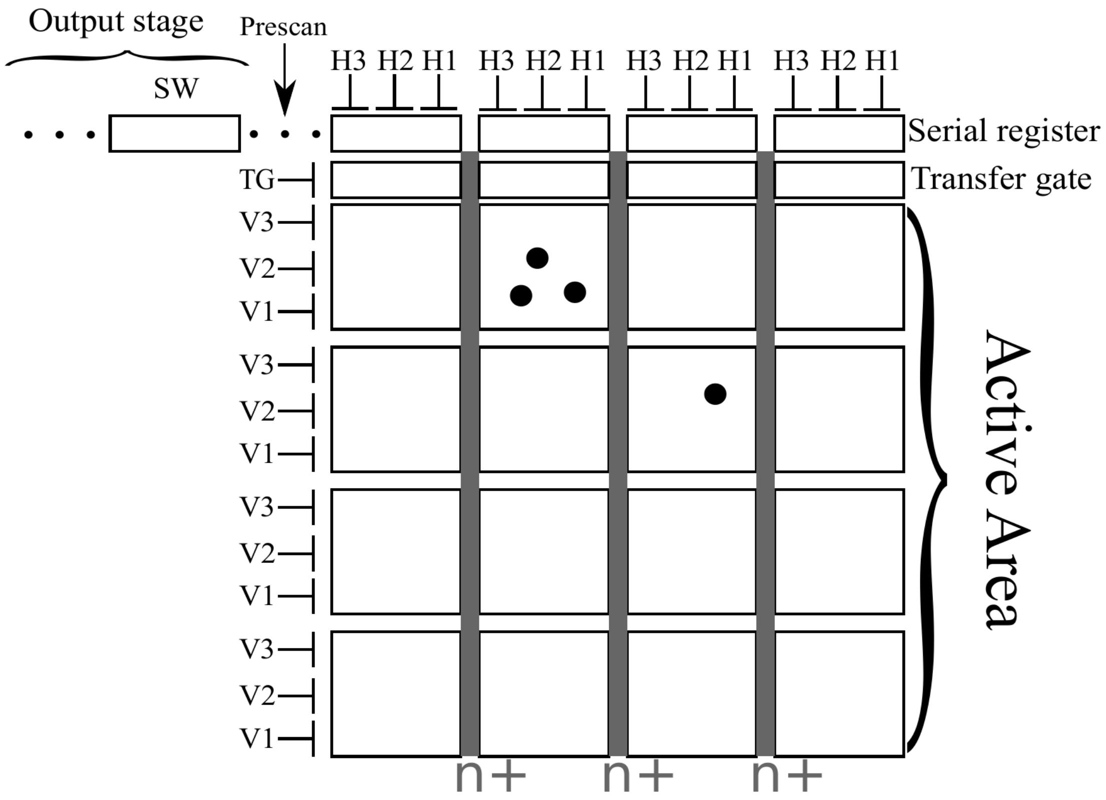

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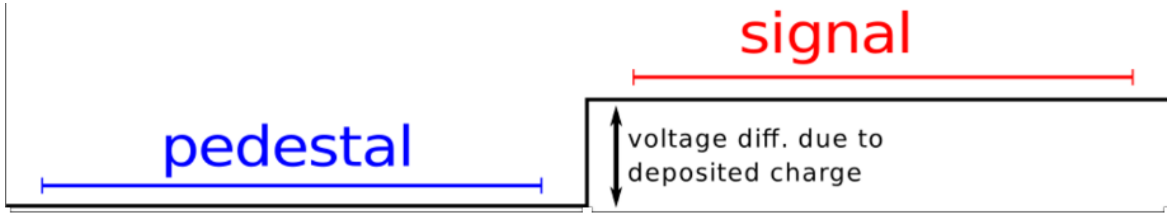
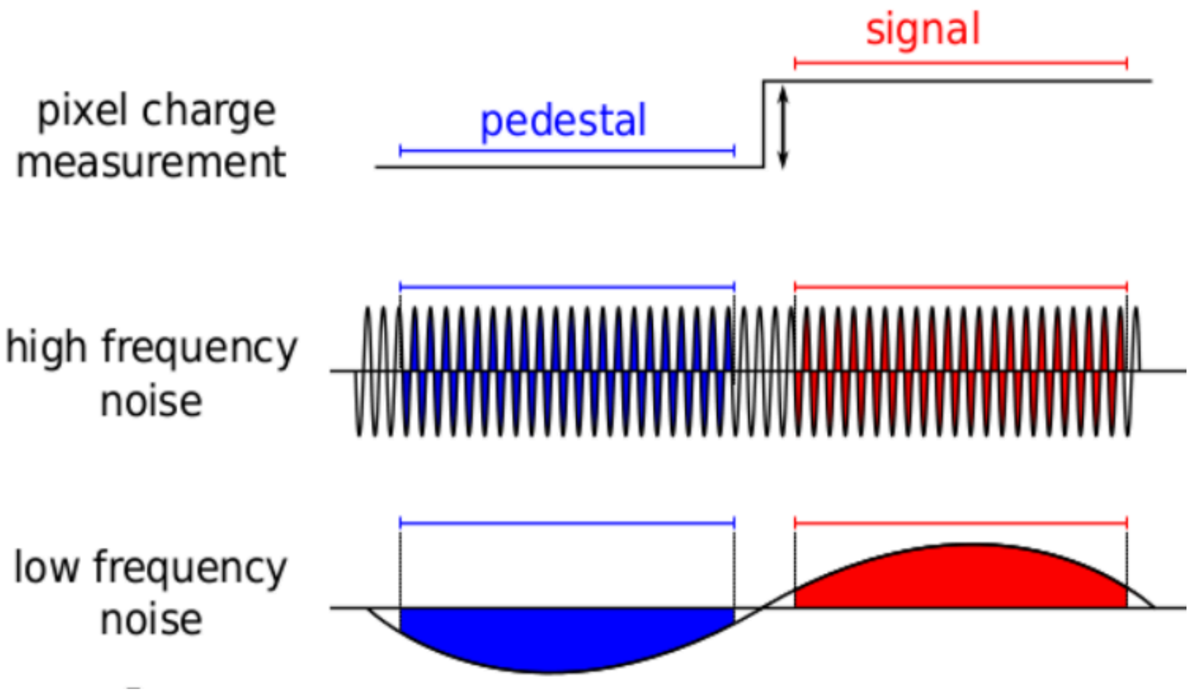


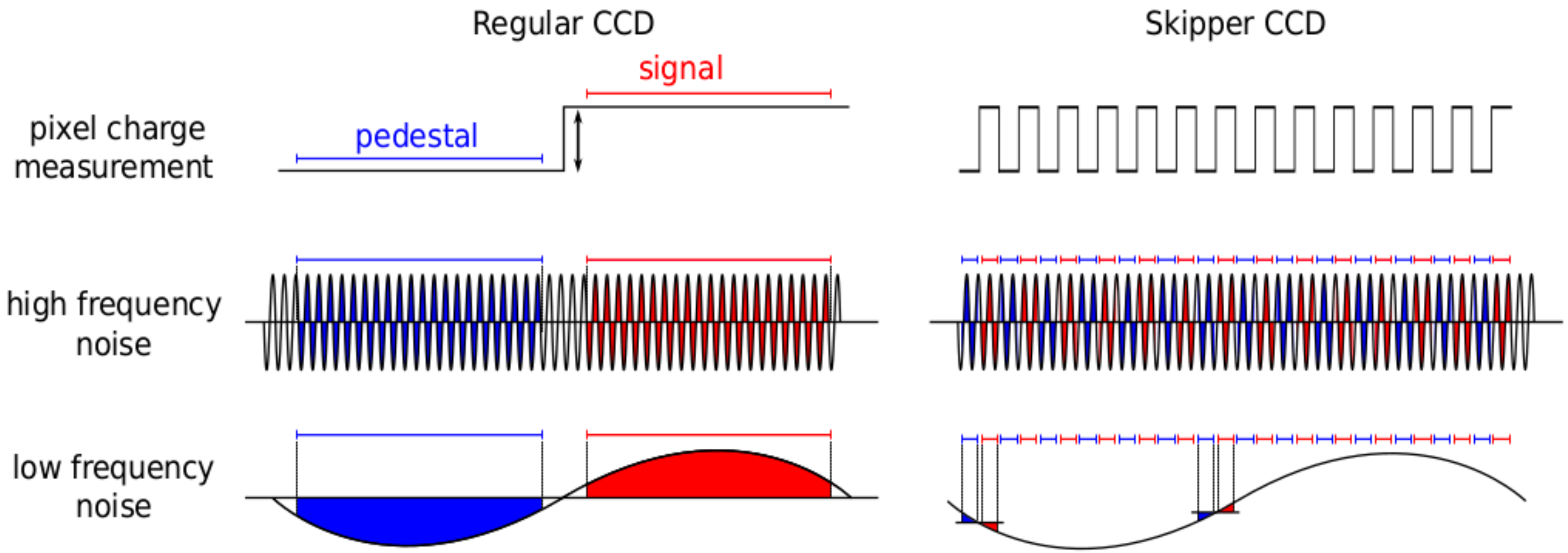
CCD Technology

- Charge = signal-pedestal.
- Longer integration reduces high frequency noise but cannot reduce **1/f** noise.

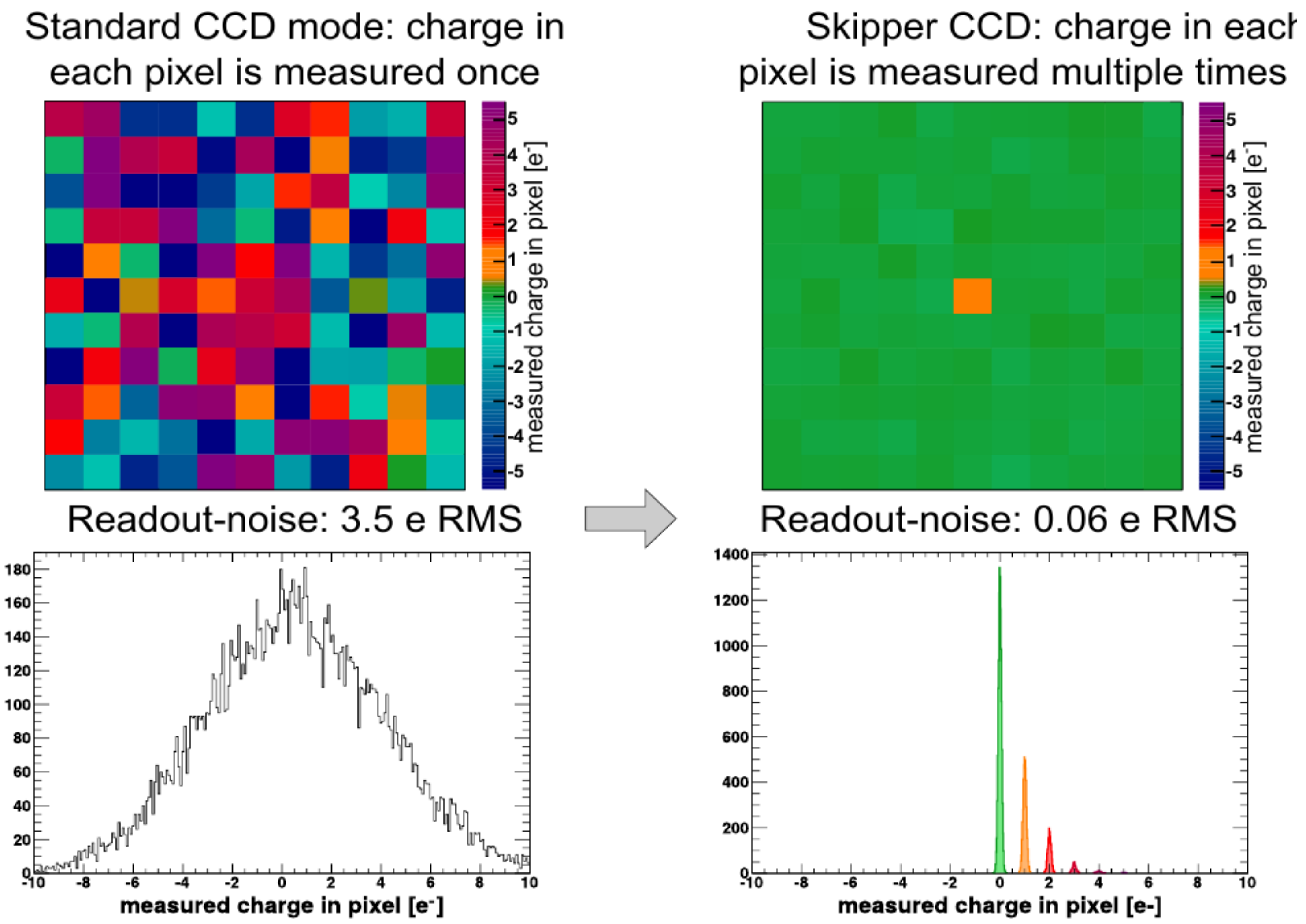


Skipper-CCD Technology

- Skipper-CCD moves charge forward and backward to the floating sense node to achieve multiple readout.
- **Repeat** the readout process large number of times.
- **Average** all samples.
- As a result, reduce both high- and low-frequency noise

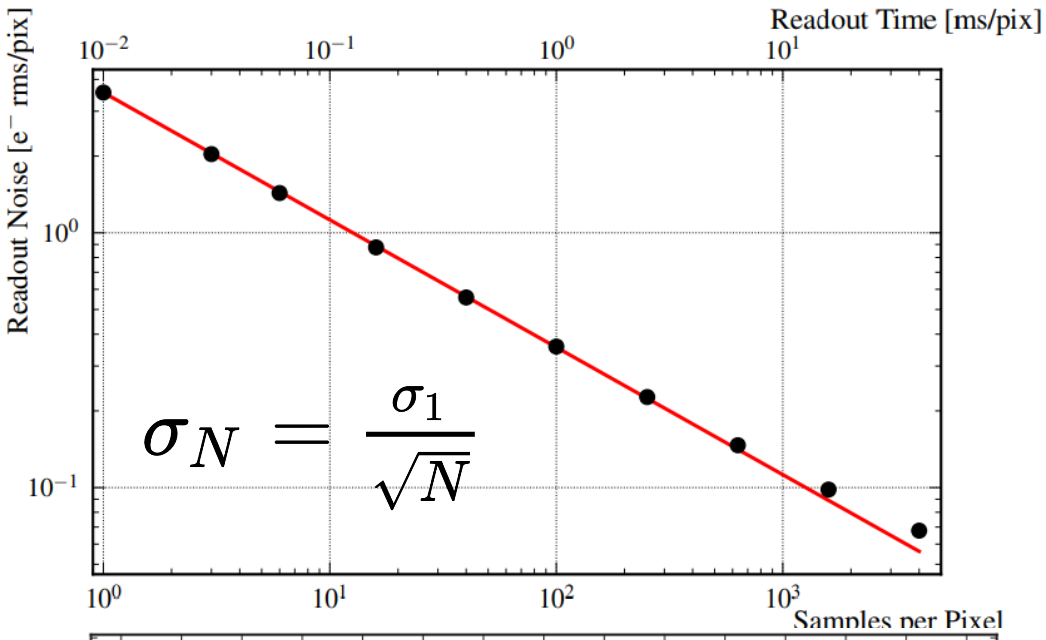


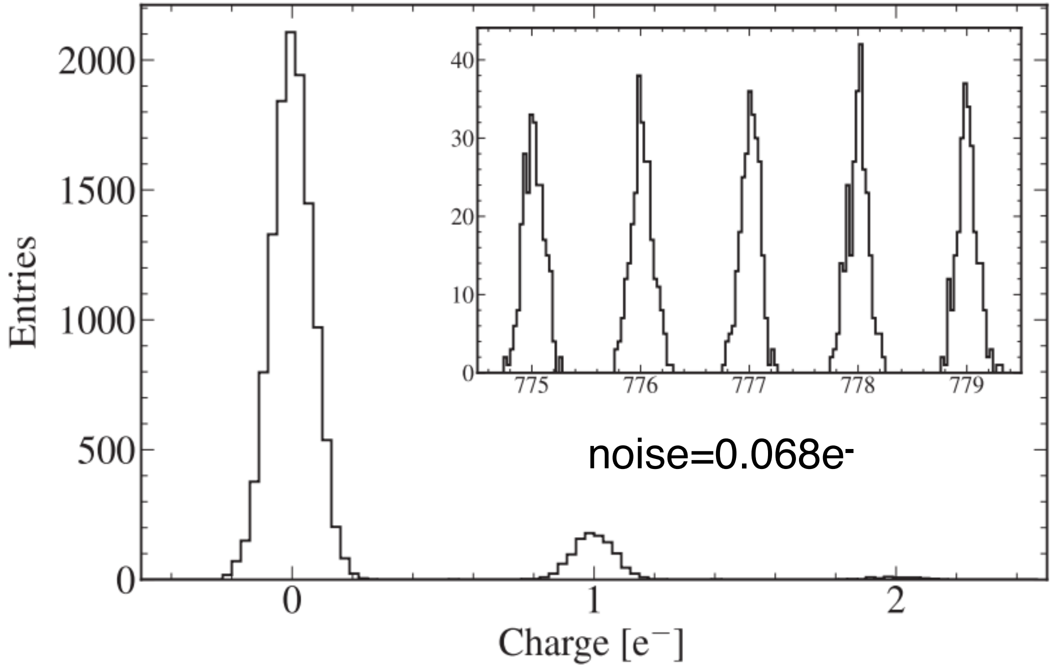
Skipper-CCD Readout noise



Skipper-CCD Readout noise

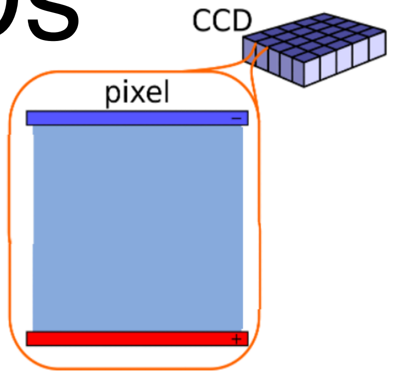
- *Skipper-CCD* technology allows reading repeatedly the *same pixel* to achieve **sub-electron noise.**
- ~2e$^-$ readout noise goes to ~**0.1e**$^-$ using *skipper-CCD* technology.
- Low energy threshold down to **~1.2eV**.
- Capability of unambiguously **counting clusters** of few electrons.
- *Skipper-CCD* noise scales as $1/\sqrt{N}$, HOWEVER, trade resolution for speed. With N=300 (13 ms/pixel) reached the noise of ~0.14 e$^-$.





10.1103/PhysRevLett.119.131802

DM Search with CCDs



- Light-**DM** mass relevant ranges:
  - Electron recoil: **1-1000 MeV.**
  - DM Photon absorption: **1~1000 eV.**
- Sensitivity to **1, 2, 3 e$^-$** signals needed: achievable with **Skippers-CCD**!
- However, requires an excellent understanding of the background.

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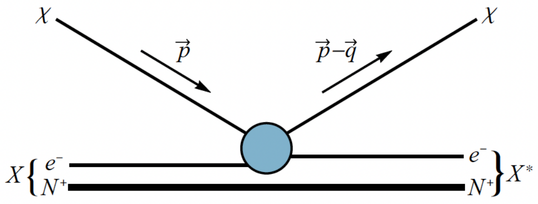

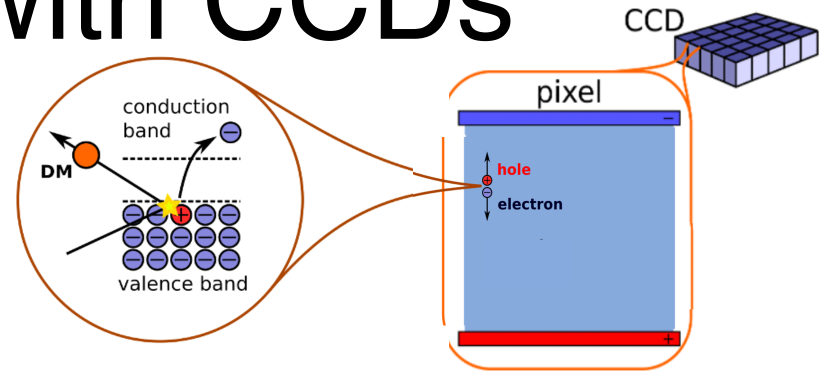

DM-electron scattering

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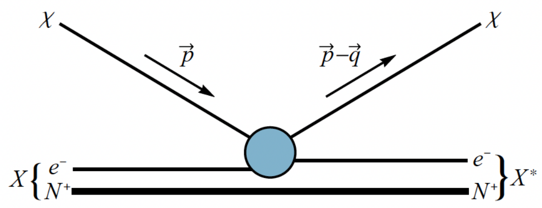
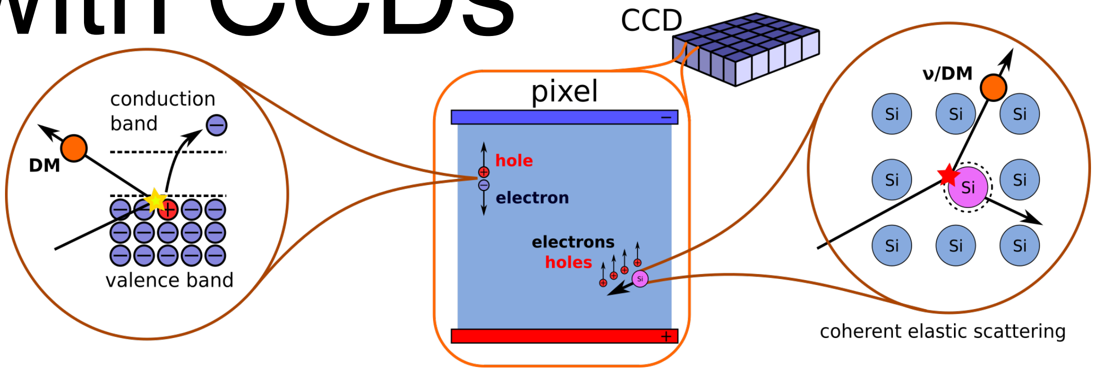




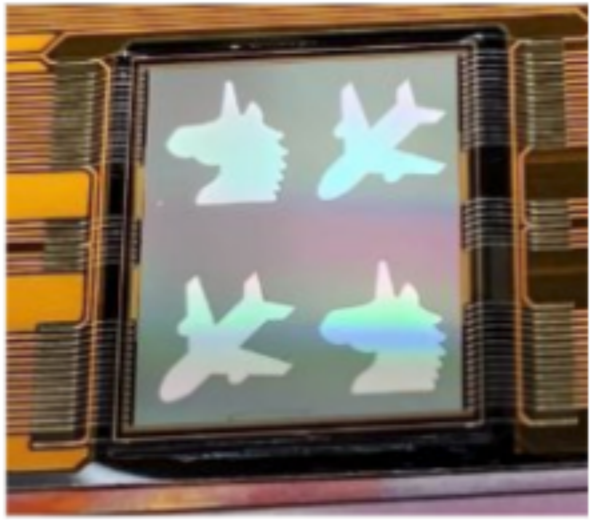
DM-electron scattering

DM-Nucleus scattering

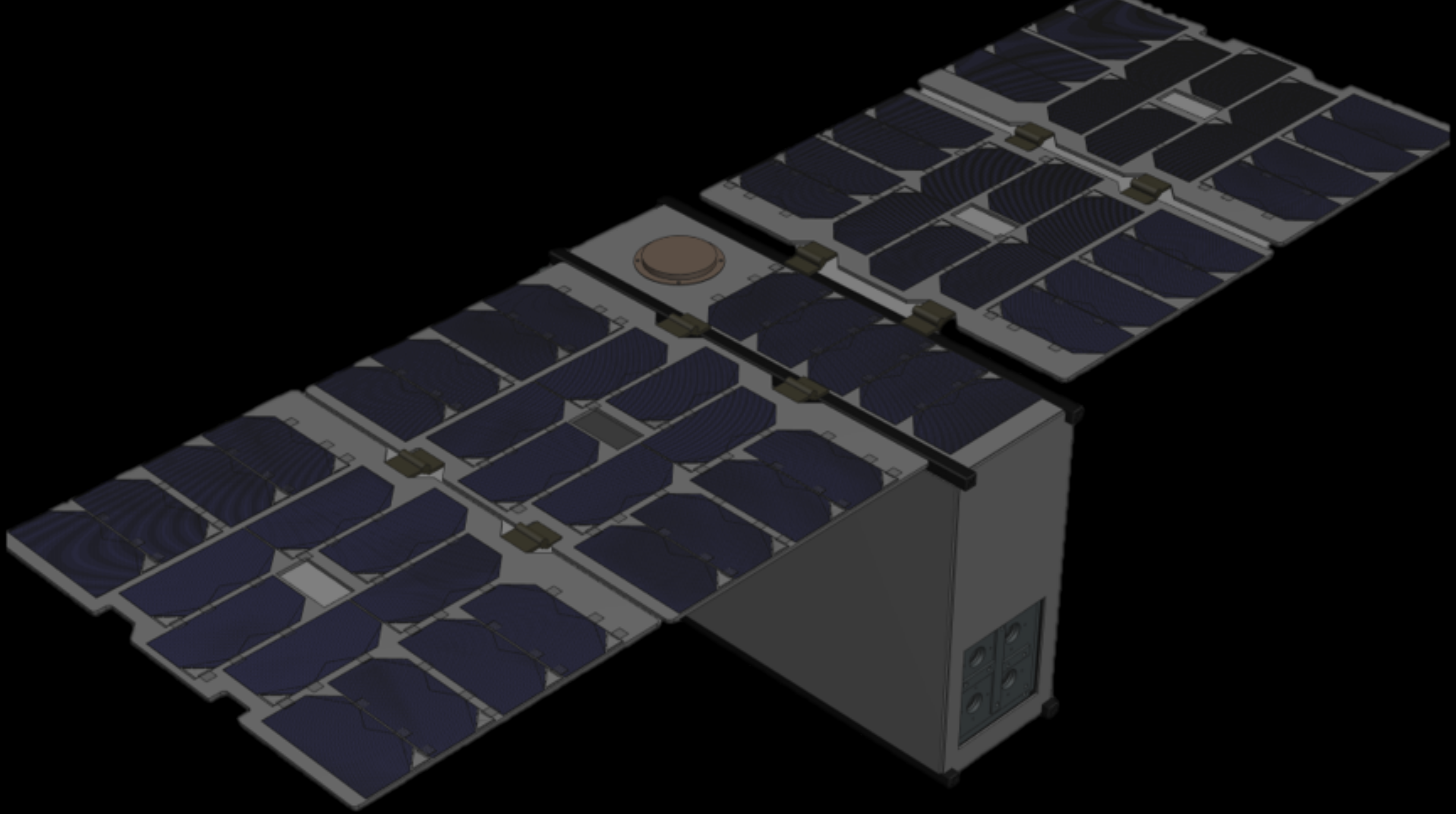
- Light-**DM** mass relevant ranges:
  - Electron recoil: **1-1000 MeV.**
  - DM Photon absorption: **1~1000 eV.**
- Sensitivity to **1, 2, 3 e$^-$** signals needed: achievable with **Skippers-CCD**!
- However, requires an excellent understanding of the background.

Adjustments for X-ray measurement in Space

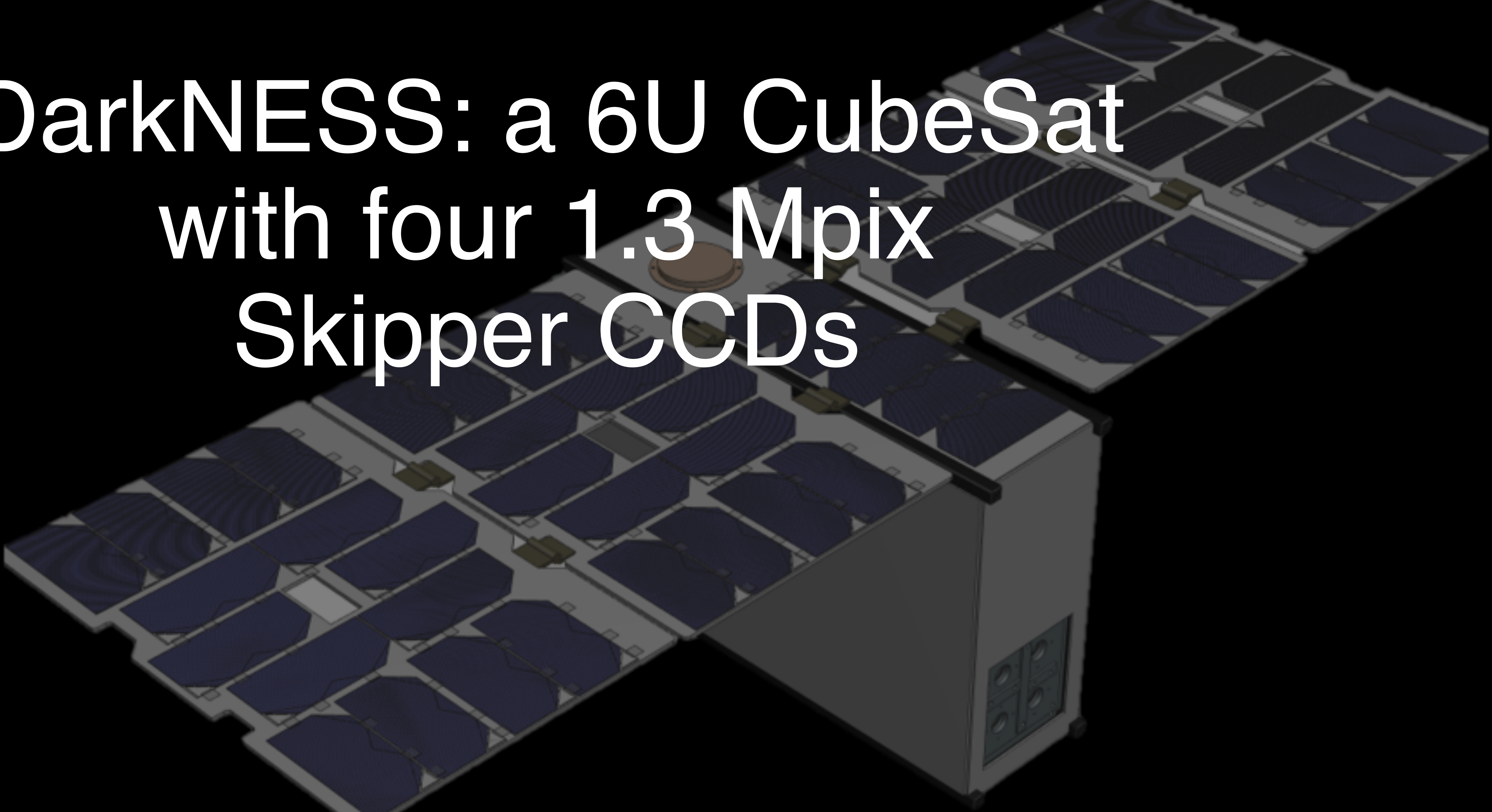
- The sensor's fully depletion design allows pixels up to 725 μ which absorb a large number of photons, leading to high quantum efficiency, low noise, and uniform electric field which is good for charge collection and high resolution.
- A thin layer of aluminum (500 nm thick) is deposited over the front side of the silicon detector to make it blind to visible, and IR photons.
- Plan to thin the detector and optimize it to X-ray in the region of interest.
- Packaging will be adjusted (using a lightweight ceramic package) and optimized for the mission.
- A challenge is the generation of very low-energy hits by secondary radiation in space.

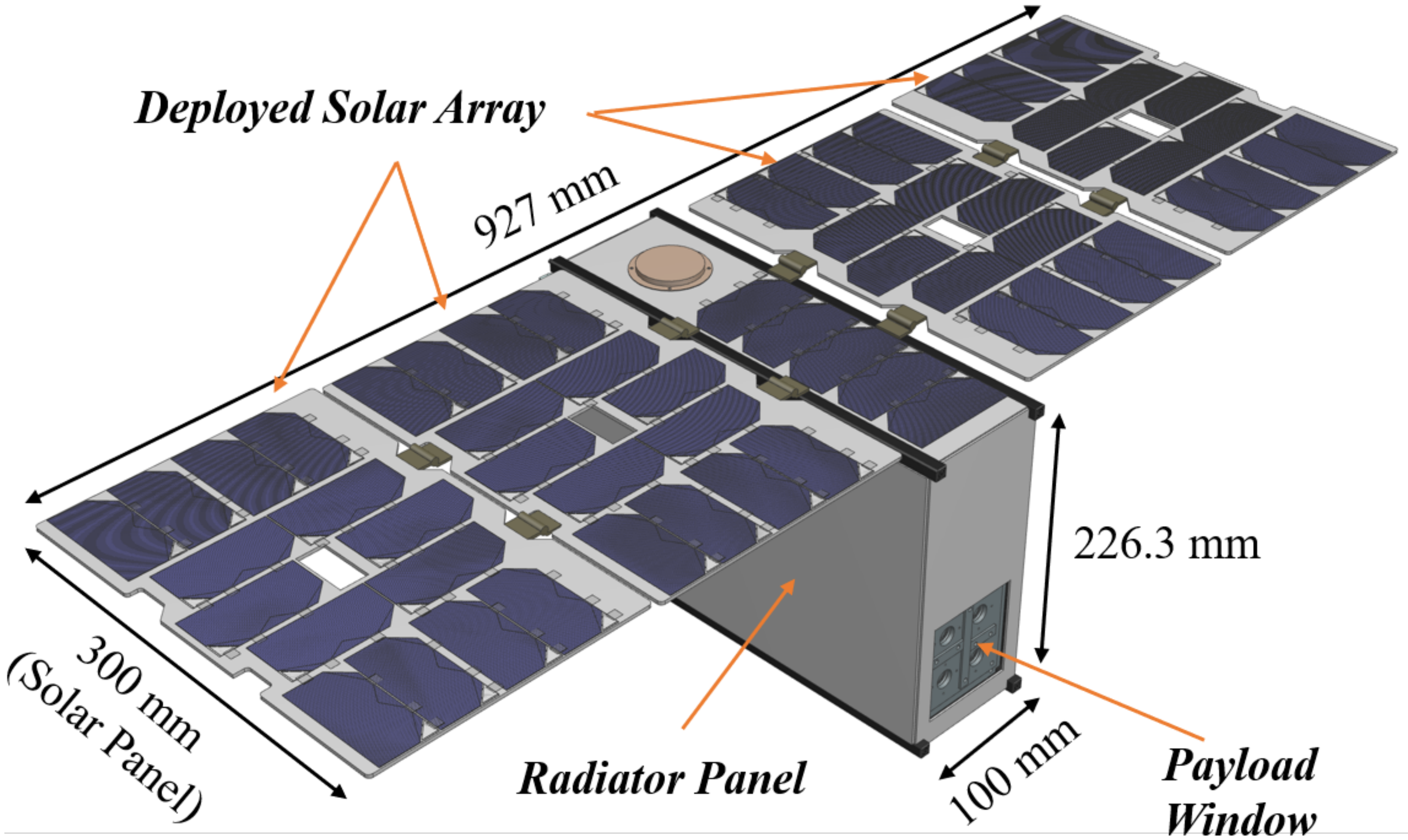


The shapes (unicorn and plane) are made with an aluminum film deposited directly on the CCD, used to measure the performance of the light shield compared to the regions without aluminum.



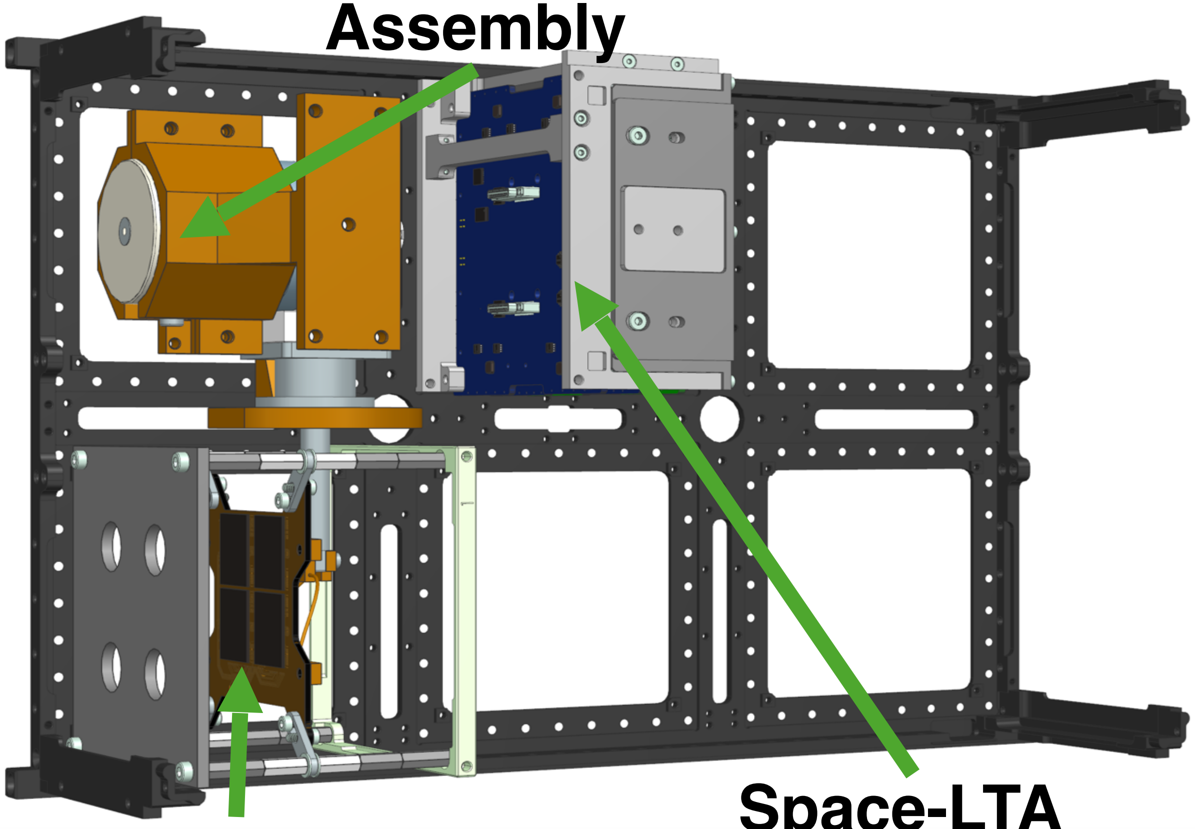
DarkNESS: a 6U CubeSat with four 1.3 Mpix Skipper CCDs




Deployed Solar Array
927 mm
226.3 mm
300 mm
(Solar Panel)
Radiator Panel
100 mm
Payload
Window

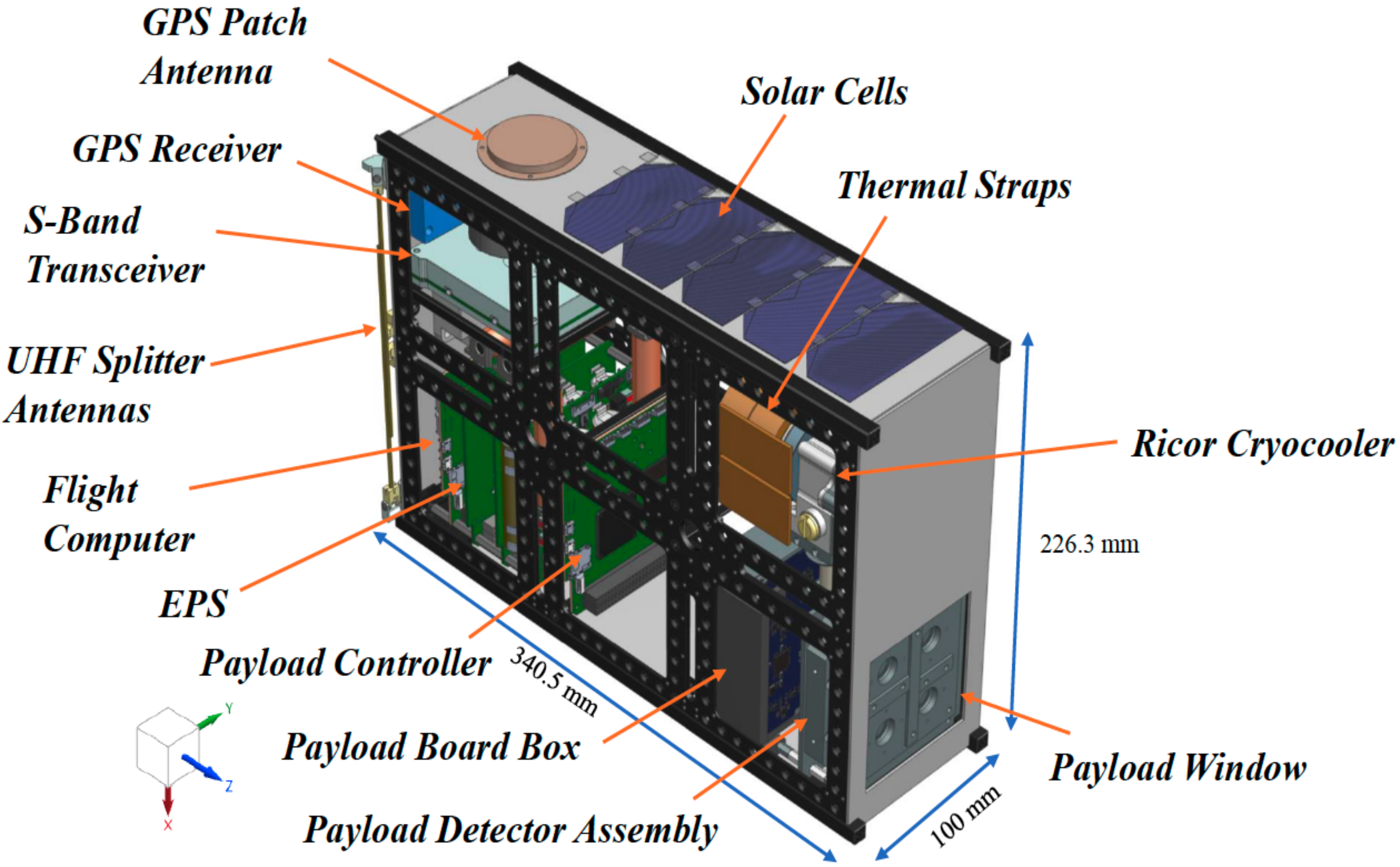
DarkNESS instrument

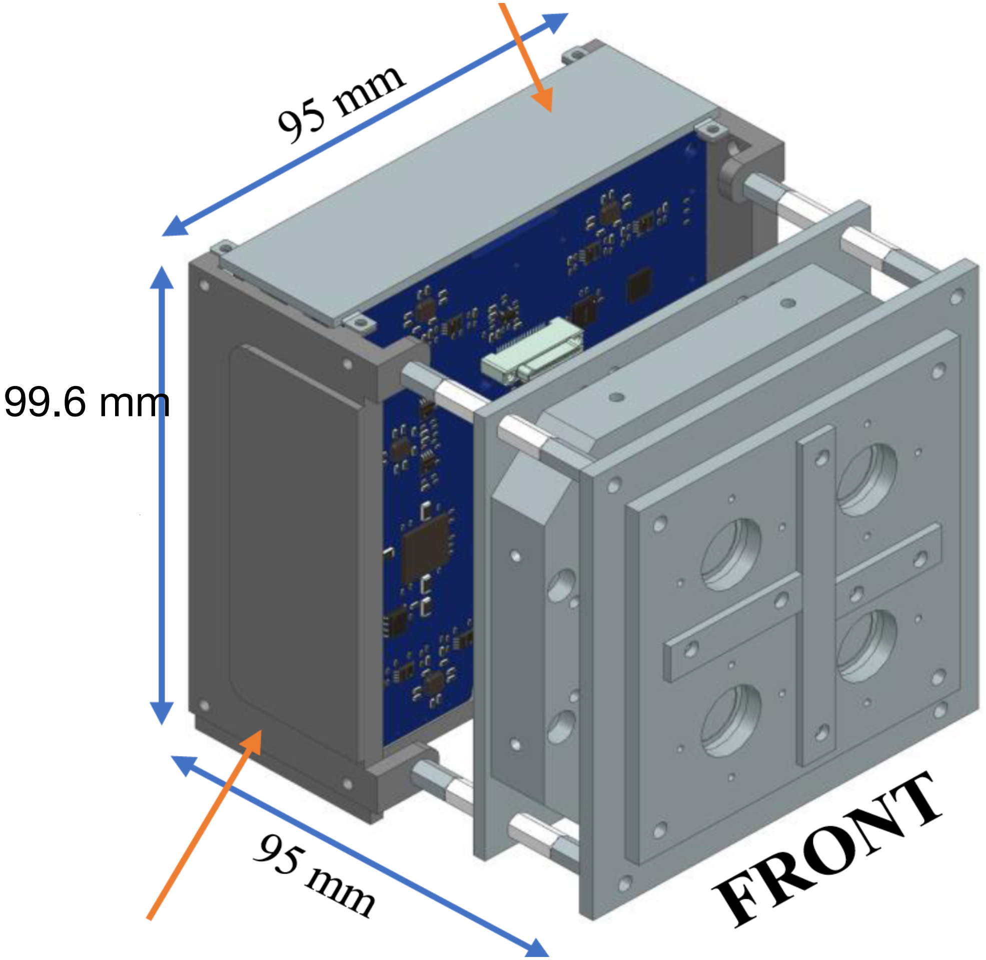
- The detector module will consist of four 1.3 Mpix skipper-CCDs and an entrance window.
- The CCDs and a flex cable are epoxied and wire - bonded onto an AlN ceramic substrate.
- Each CCD is biased and read out using a small-format **L**ow **T**hreshold **A**cquisition (LTA) readout electronics board.
- The detectors are cooled to 170 K with a compact cryocooler.



DarkNESS instrument

- The small size of the 6U CubeSat excludes the use of optics.
- The payload window designed to allow photons from a ~20° FOV

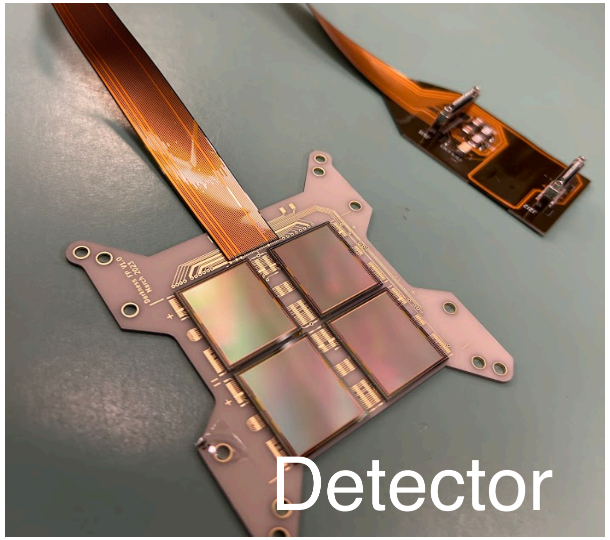




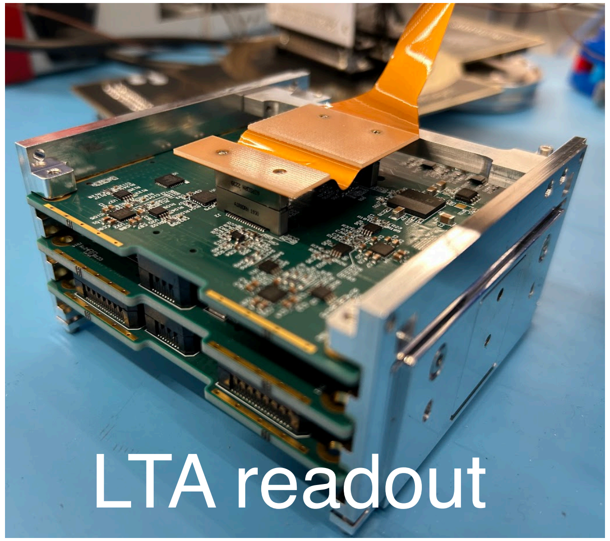
DarkNESS detectors and readout electronics

DarkNESS Instrument Specifications	
Detector Area	1.6 x 1.9 cm^2
Thickness	250 µm
Weight	100 gr
Bias Voltage	80 V
Power	~0.2 Watt
Operating Temperature	170^o K (-103^o C)
Readout Speed	250 kpix/s

Multi Chip Module (MCM)



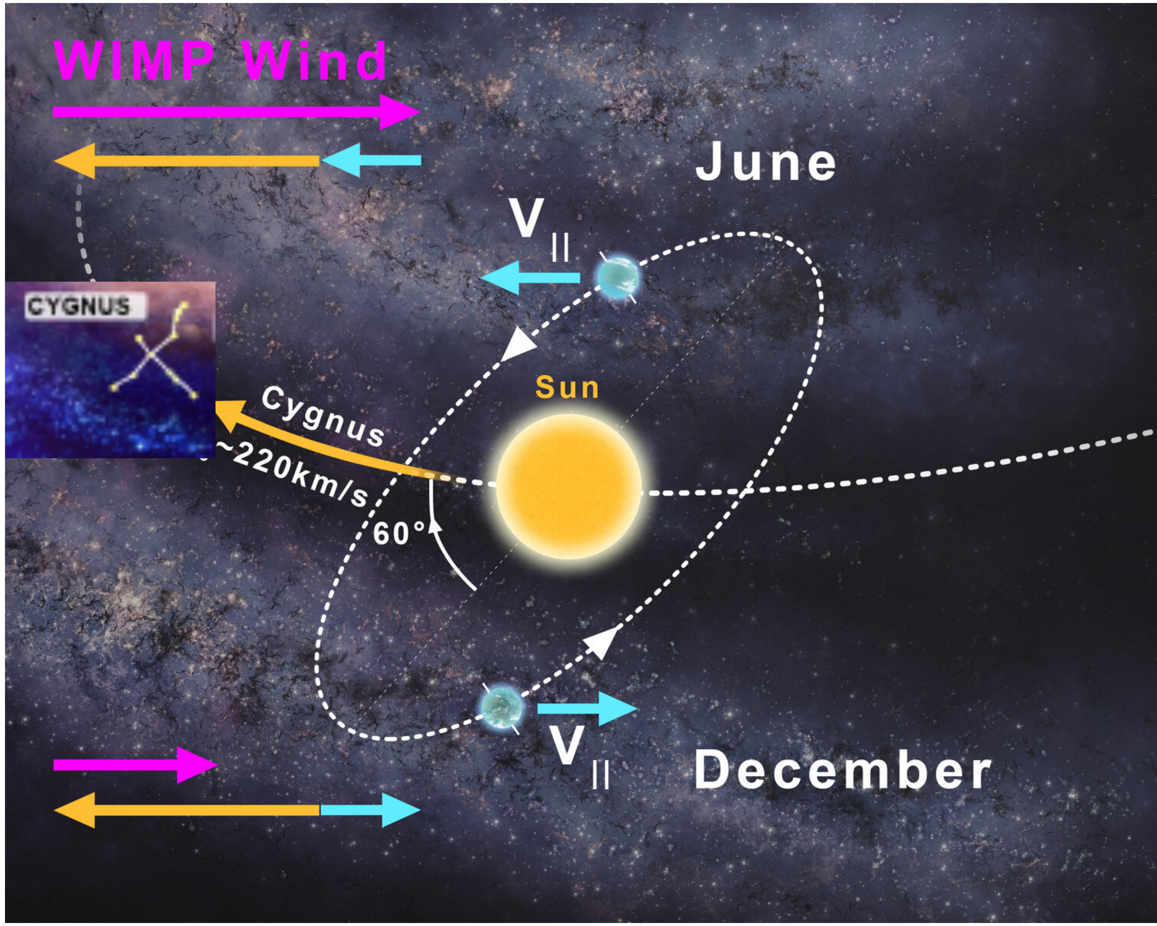
Custom space-Low Threshold Acquisition (LTA) readout board, designed to fit into 6U CubeSat.



The Cygnus concept

The relative movement of the Solar System with the Galaxy creates an anisotropy in the incoming directions of dark matter particles, namely the direction of the Cygnus constellation, at the Solar System.

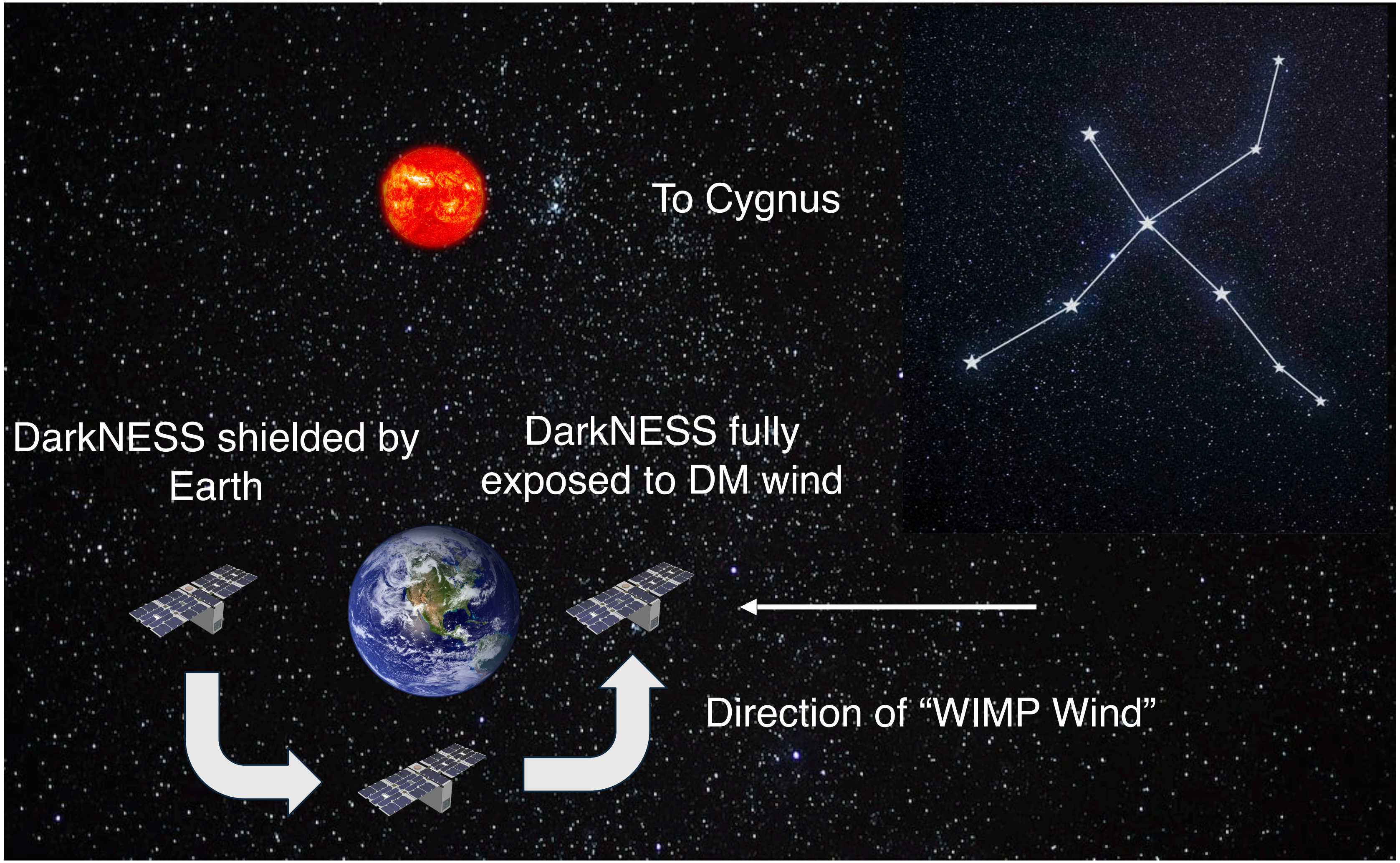
The effect of modification in the relative velocity between the DM and the CubeSat directly affects the interaction rate with DM. It has been studied for annual (and daily) modulation searches



Earth Shadowing

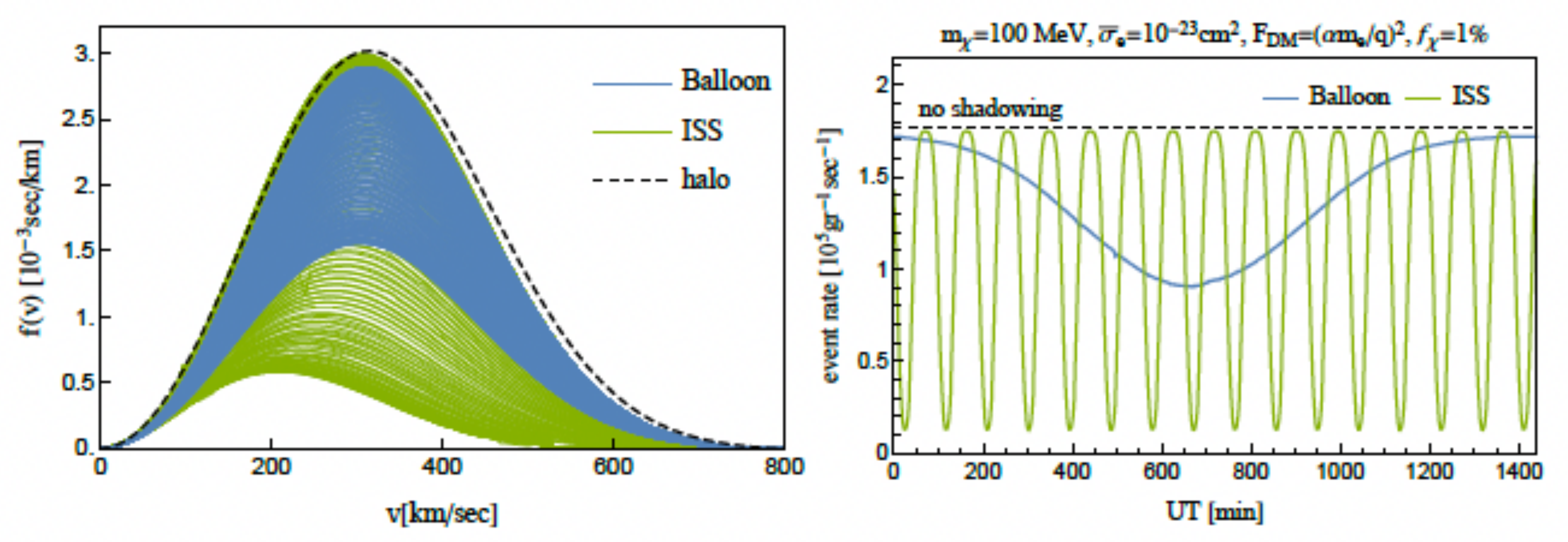
LEO CubeSat (ISS like) orbit is 90 min.

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



Daily orbital modulation

arXiv:1905.06348 **Timon Emken et al.**



Right: signal rate corresponds to 100 MeV,

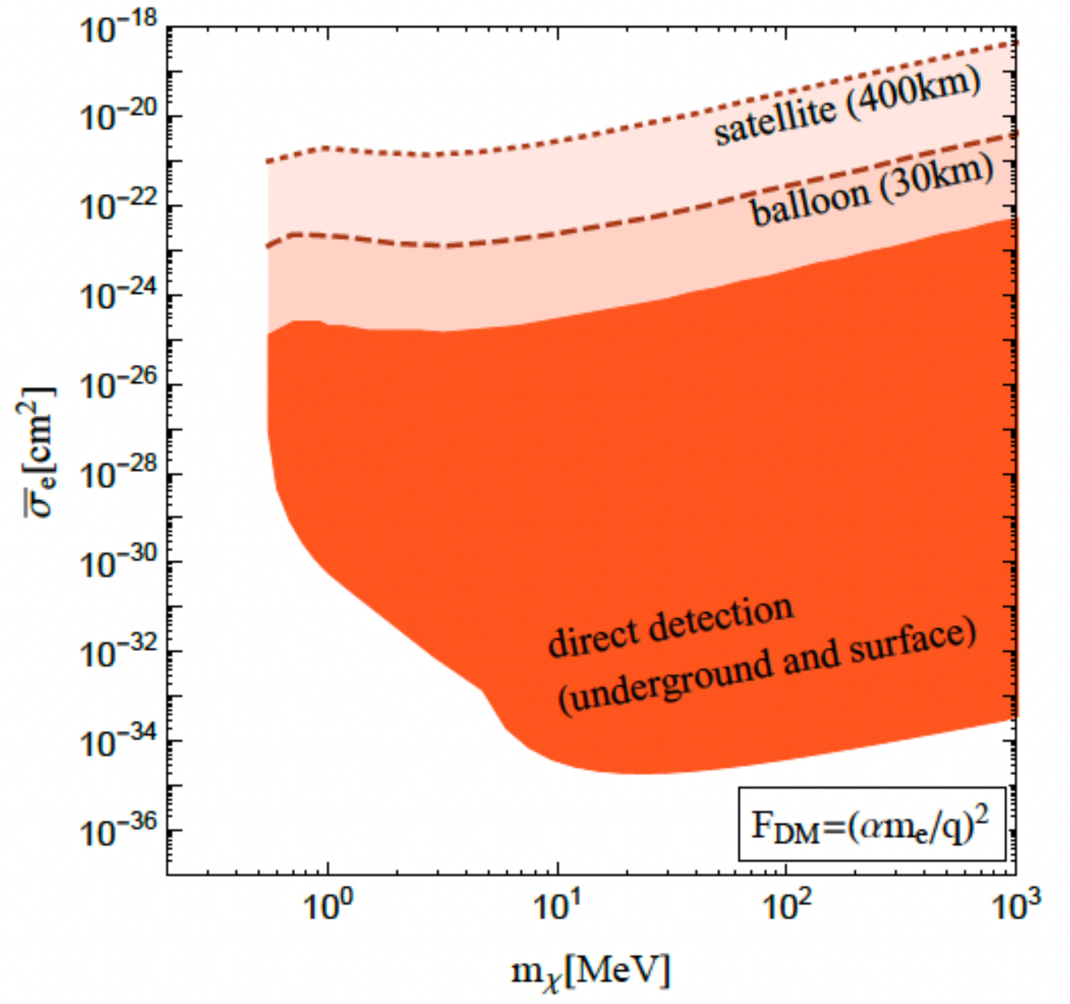
$\bar{\sigma}_e = 10^{-23}$ cm², ultralight mediator, and low DM abundance (1%).

Discovery reach SIDM

arXiv:1905.06348 **Timon Emken et al.**

Assume that 50% of the time the GC will be blocked by Earth or Sun and not visible to DarkNESS. During these times, we plan low-noise readouts pointing toward Cygnus for direct DM detection.

The reach with ~300 x 15-minute exposures, and 50% of the sensors usable (subtracting higher energy hits) expect a 0.1 gram-month and 10^9 BG exposure to achieve this sensitivity



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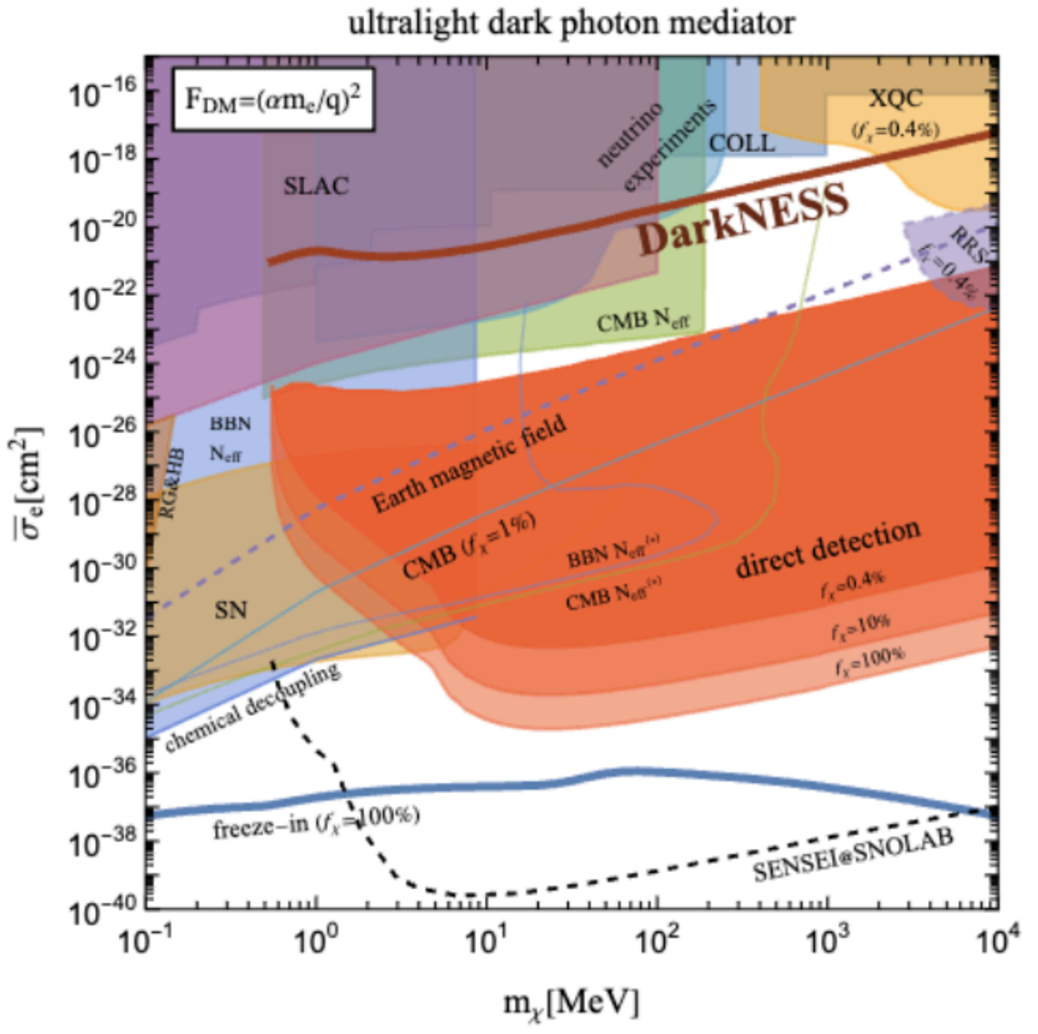


With current constraints from the 1987A supernova, CMB, COLD, LSND, MiniBooNE as well as direct detection exps: SENSEI, CDNS, XENON etc..

X-rays from sterile neutrinos

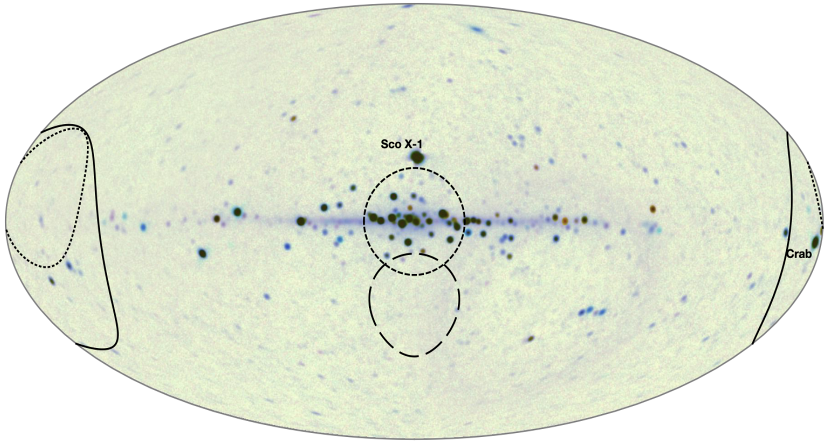
Figueroa-Feliciano et al. arXiv:1506.05519

- Using wide (20°) FOV observations of diffuse X-ray sky, DarkNESS will search for unidentified X-ray lines, probing sterile neutrino decay.

- The signal flux increases with FOV, but so does background

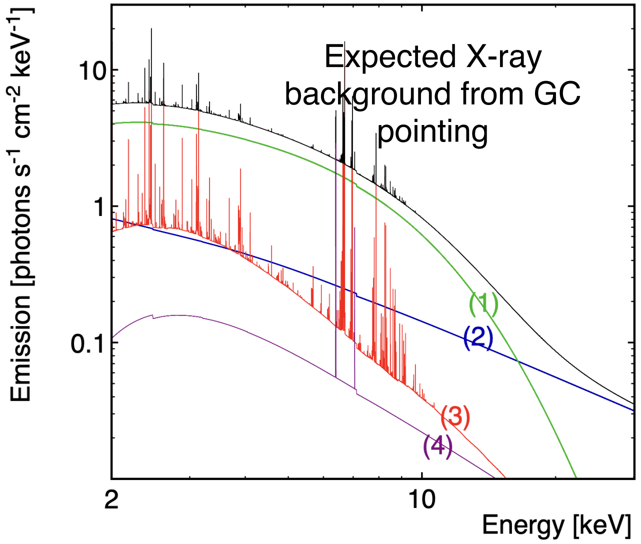
- Work ongoing to determine sensitivity, including optimal pointing strategy, and background rejection techniques

(1) Emission from the brightest low-mass X-ray binaries
(2) Emission from the cosmic X-ray background
(3) Thermal components from the galactic diffuse background
(4) Contribution from ionized cold ISM neutral Fe.

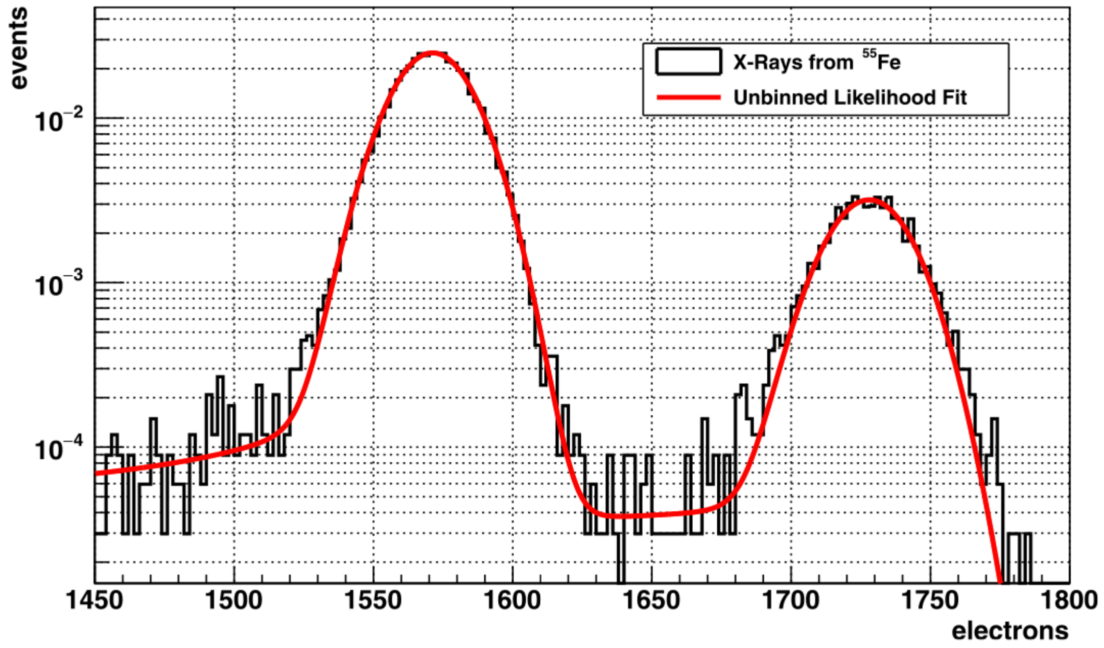


Example of 20° pointings on the sky from the ISS. 2-4 keV, 4-10 keV, 10-20 keV.

Figueroa-Feliciano et al.



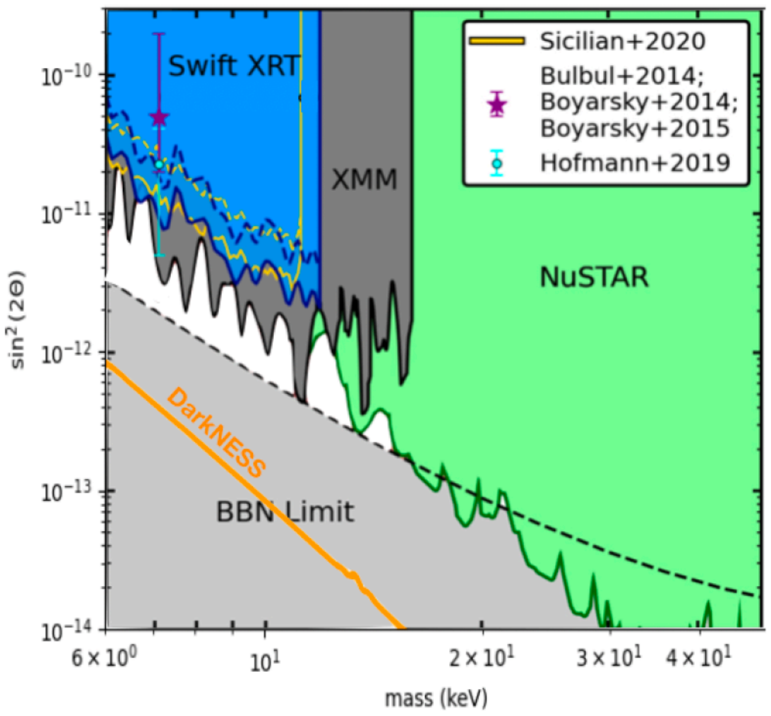
X-rays with Skipper-CCDs



The low-noise Skipper sensors can provide excellent energy resolution. Here charge distribution was measured in skipper-CCD for 5.9 keV and 6.5 keV X-rays from ^{55}Fe source, the measured energy resolution in this data is 50 eV

Sterile Neutrino Sensitivity

- DarkNESS projected sensitivity to sterile neutrino DM
  - Plan 500-2K (100) x 15 (one) minute exposure time (conservative), pointing at Galactic Center with 20° FOV
  - Energy resolution of typical CCD (DAMIC [arXiv:1510.02126])
    - $\sigma_E \sim$ 40 eV at 3.7 keV
  - Fraction of CCD area masked due to cosmic ray impingement
- The combined large field of view and excellent resolution make DarkNESS very sensitive to the X-ray spectrum.



90% C.L. detection limit for the sterile neutrino DM mixing angle θ, using the X-ray spectrum for DarkNESS, with 1 Mega-second exposure on the Galactic Center (orange). Compared with the best current limits from XMM (dark gray) NuSTAR (green) , and SWIFT (blue). Figure from D.Sicilian et al. ApJ, 941(1):2022,

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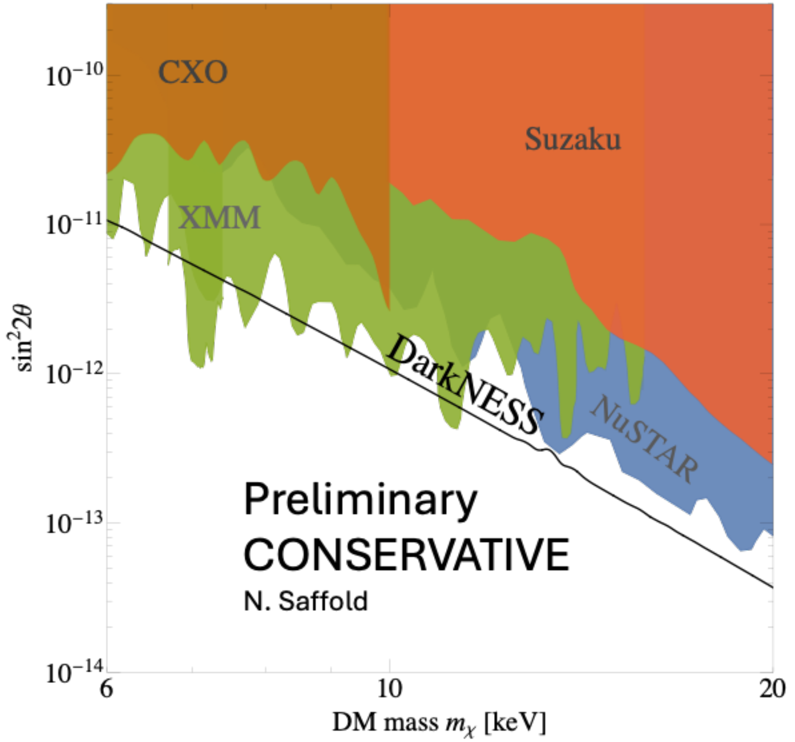

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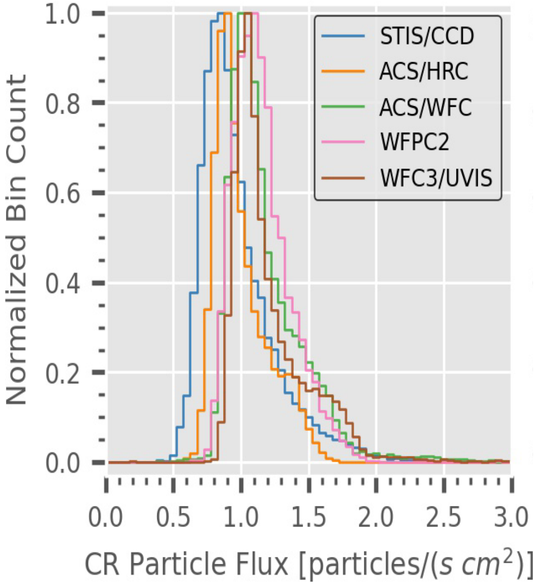
Skipper-CCDs in LEO: Radiation

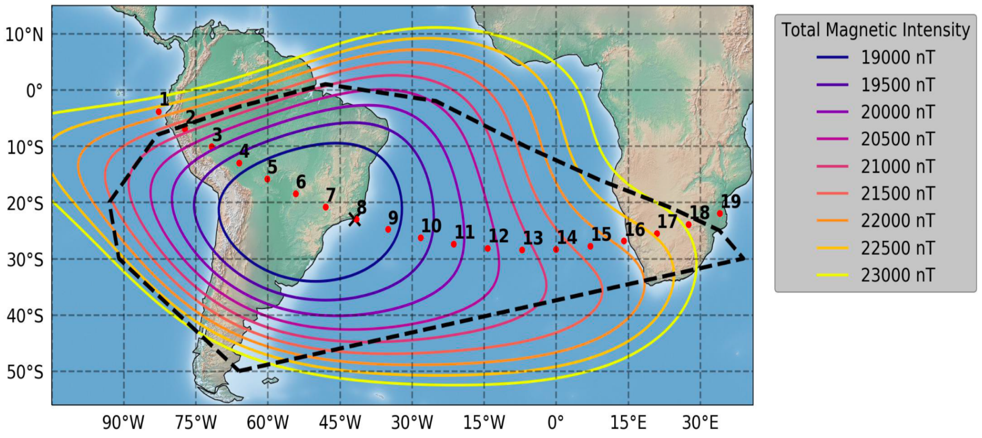
arXiv:2006.00909v4 [astro-ph.IM] N. Miles et al

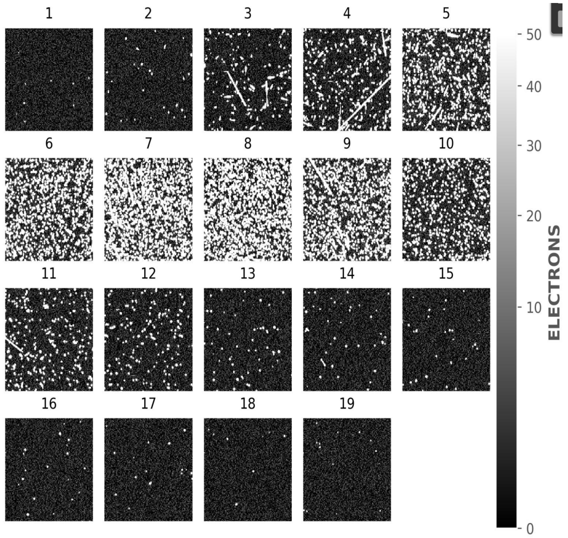
- Cosmic ray (CR) backgrounds
  - Expect ISS-like orbit (51° inclination)
  - Background simulations in progress using Geant4, building off previous work (Cuevas 2019)
  - Optimal operating mode driven by tradeoff between exposure time and CCD occupancy due to CR energy depositions
  - Minimize readout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



Hubble data indicates ~1 particle/cm^2/s

Miles et al (2021) *ApJ* 918 86

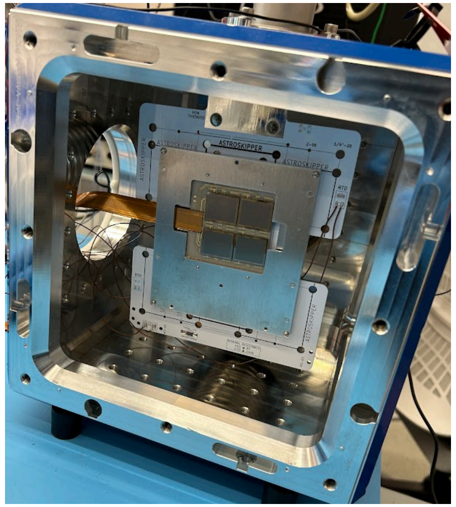




Expect significant increase in background rate during passages through South Atlantic Anomaly (SAA)

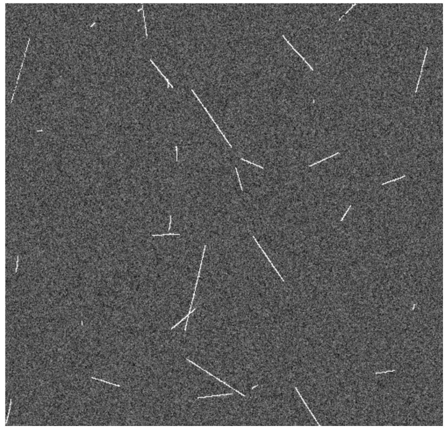
Skipper-CCDs in LEO: Radiation

- Irradiation testing is ongoing to assess the radiation hardness of p-channel CCDs.



Skipper-CCDs mounted in a test chamber at Fermilab for detector characterization studies and development of an in-flight software analysis pipeline.

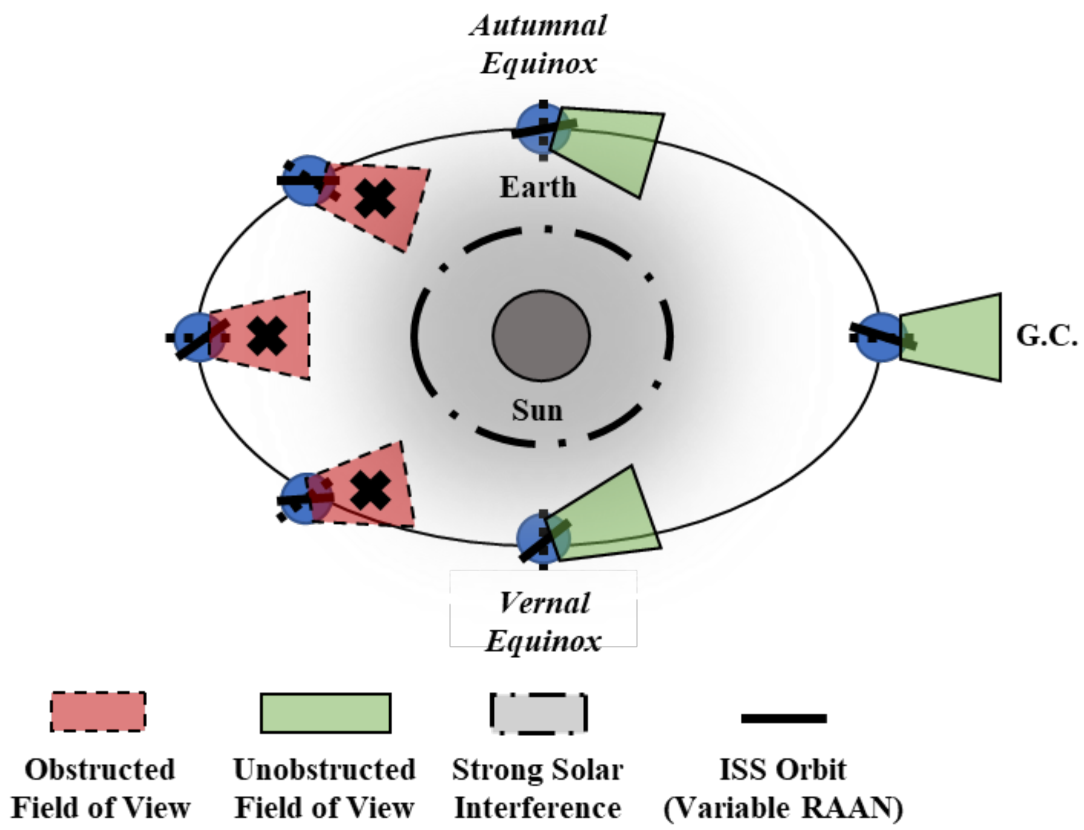
- The optimal exposure and readout time will be determined using Geant4 simulations.

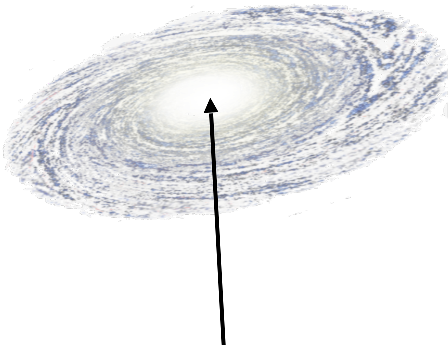


Simulation is used to assess the CCD occupancy as a function of exposure time due to **background radiation** at LEO

Geant4 500 x 500 - pixel image of a 5-minute exposure and includes a trapped proton spectrum.

Skipper-CCDs in LEO: Instrument Obstruction

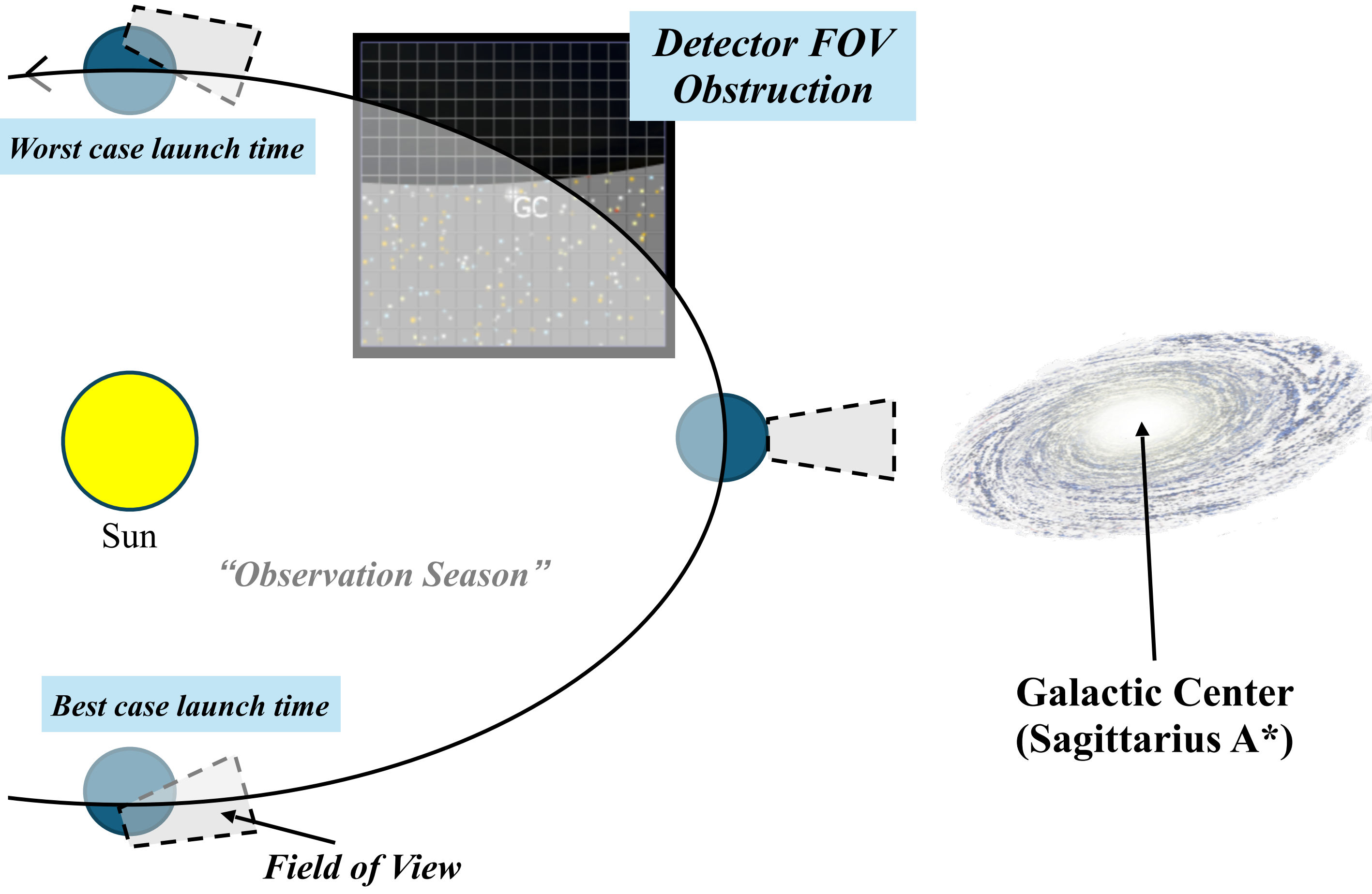




Obstructions introduced by seasonality and orbit geometry drives the DarkNESS mission requirements

Skipper-CCDs in LEO: Instrument Obstruction

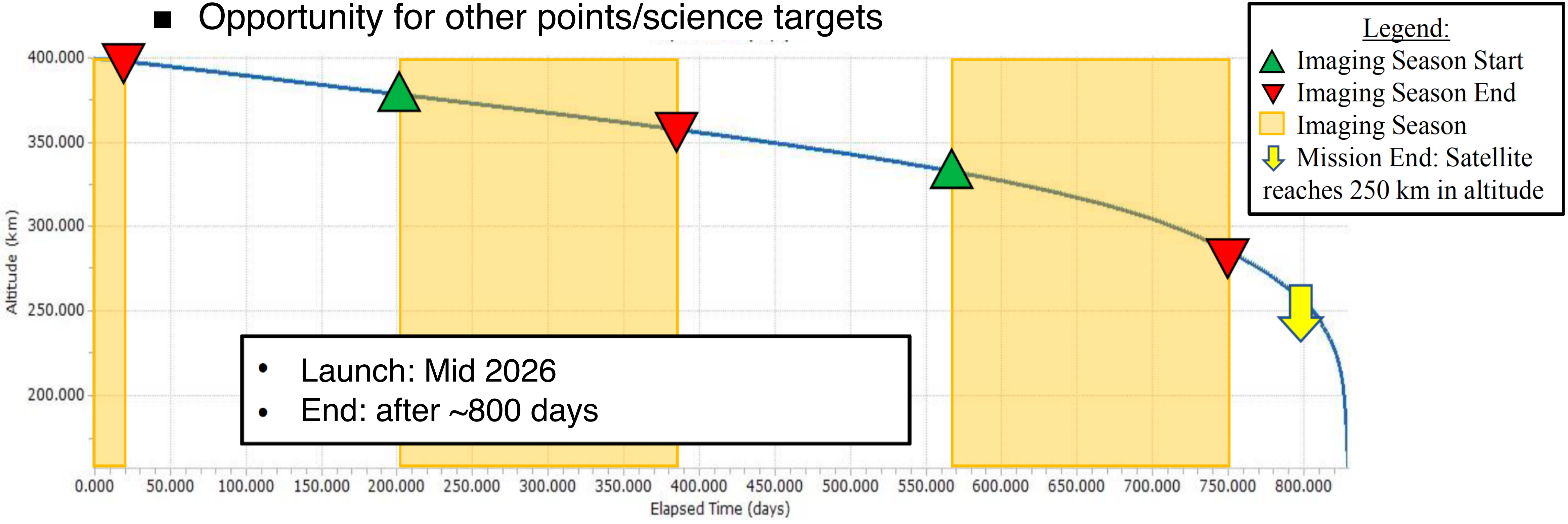
- ***The observation season*** is the period marked by March through September when the Galactic Center is not obscured by the sun
- The detector Field-of-View is also periodically ***obstructed*** by the Earth as the satellite moves through its orbit
- The effect of recession of the ***Right Ascension of the Ascending Node*** (RAAN) throughout the season dictates the obstruction.



Obstructions introduced by seasonality and orbit geometry drives the DarkNESS mission requirements

Skipper-CCDs in LEO: Orbital analysis

- The expected orbital lifetime of DarkNESS mission
  - ~800 days in orbit before re-entry
  - Require point at inertial target in the Milky Way for 15-min observation
  - Imaging season calculated for pointing at GC
    - Opportunity for other points/science targets



Skipper-CCDs in LEO: Communication

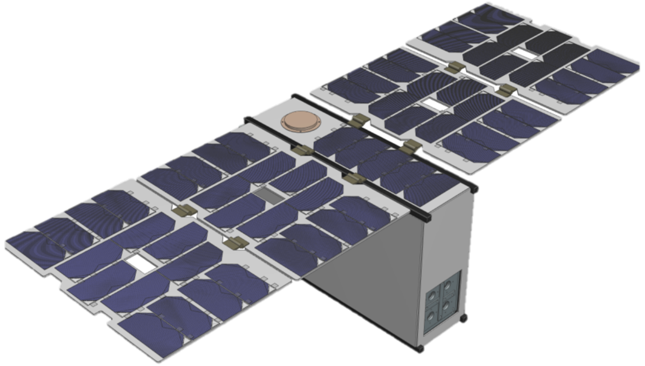
- Data is downlinked to ground station
  - Data rate is limited by radio type and access to ground stations
  - Plan to downlink histograms (spectra) and housekeeping data regularly
  - Downlink raw images files occasionally for quality assurance

Data	Total Bytes per pass
Satellite telemetry	~5 KB
Image histogram	~2.5 KB
Overhead	25%
Total bytes per pass	**~9.4 KB**
Raw image	32 MB

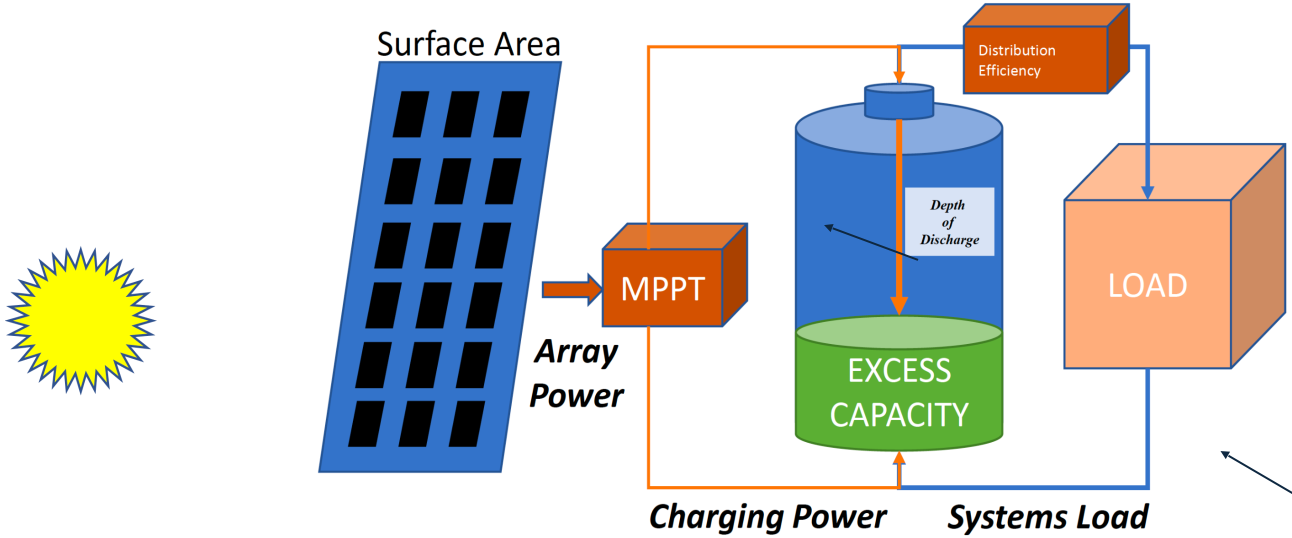
Radio	Total bytes per pass	Passes to transmit raw image (32 MB)
UHF	576 kB/pass	70
S-Band	9 MB/pass	5
X-Band	6 GB/pass	<1

- The detector can create two formats of data: 32 MB image or 2.5 KB binned histogram
- S-Band will be sufficient for the downloading full images in low-frequency

Skipper-CCDs in LEO: Power



- 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
  - Use Maximum Power Point Tracking (MPPT) for energy optimization.

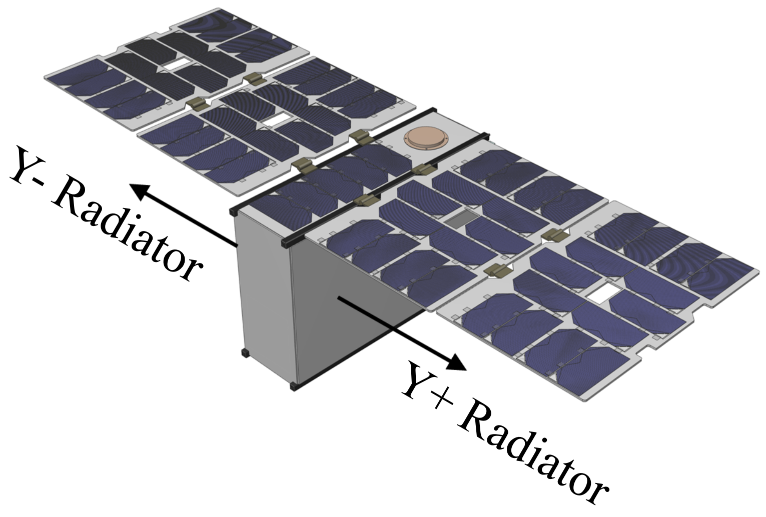


Smaller depth of discharge extends battery life

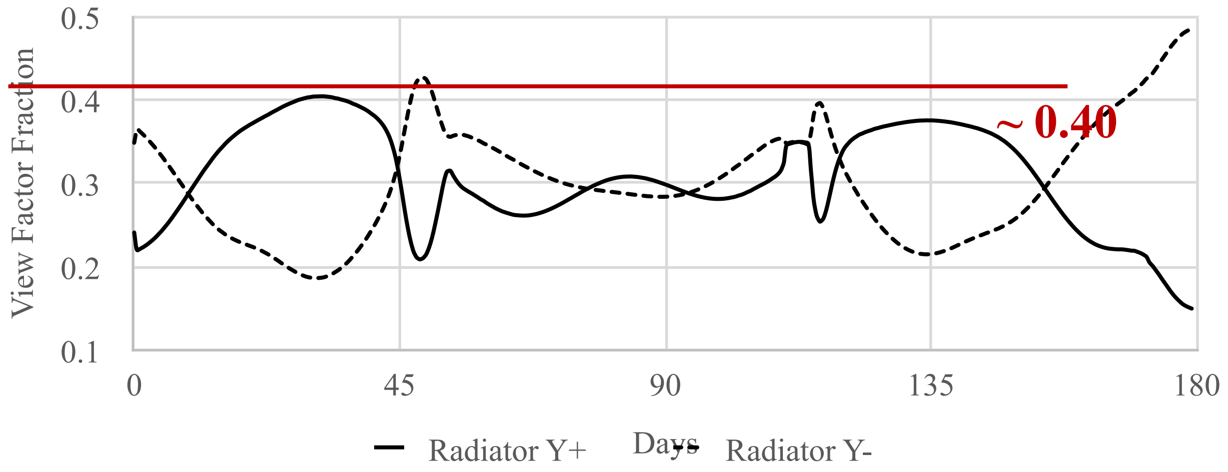
- Double deployable solar panels provide the required power

- Eight 11.50 Wh batteries maintain an excess margin for sustained cryocooler peaks.

Radiator View Factor

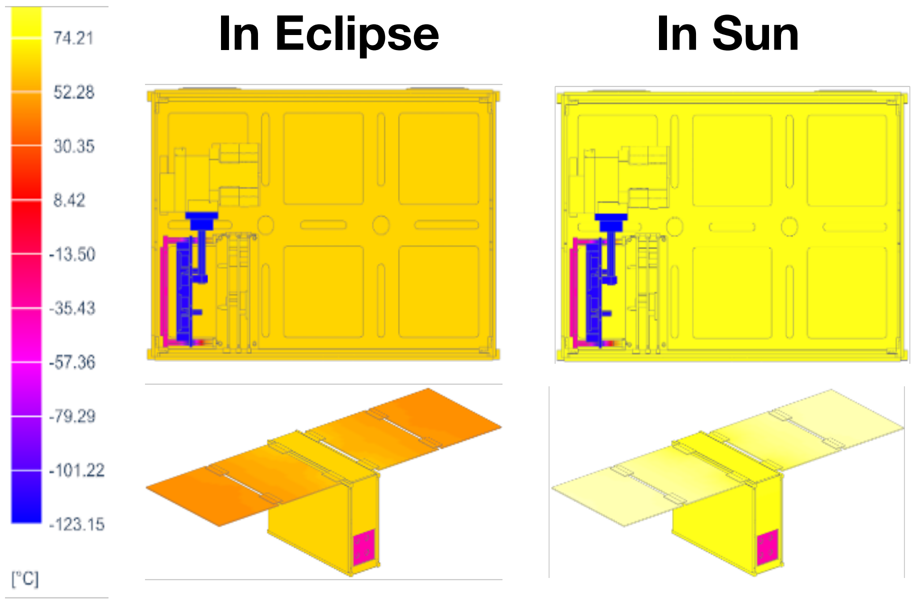


- The challenge is to manage the satellite (payload and bus) heat loads
- The goal is to minimize the view factor for efficient radiative power
- The solution tested is two body mounted radiator panels on the two sides of the CubeSat.
- This is checked with a FreeFlyer simulation code.
- The proposed model requires Active Attitude Control to balance the view factor exposure

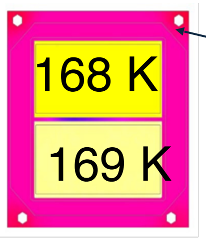


Skipper-CCDs in LEO: Cooling

- Thermal management:
  - Need to keep the detectors at 170K during the observation season (use cryocooler)
  - Need to remove heat from cryocooler, detector module, and readout electronics
  - Verified with a thermal model by Siemens NX Space system simulating the satellite and it’s instrumentation



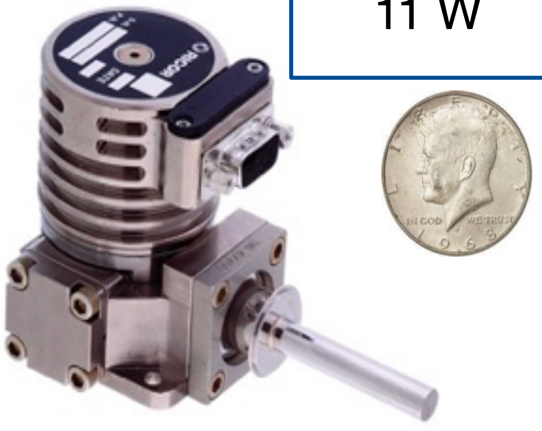
Detector Close-up:



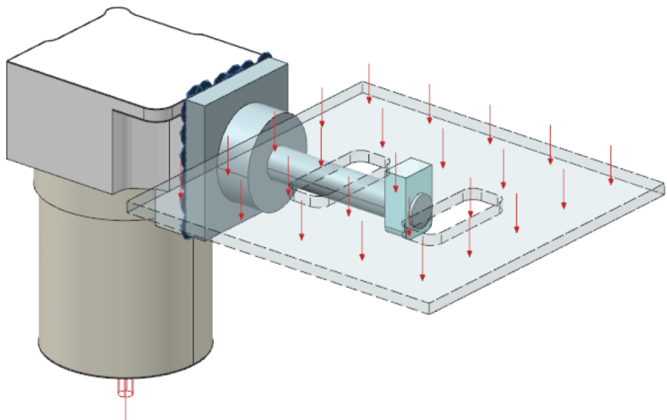
167 K

Detectors stay within ~5 K range

11 W



Ricor K508N cryocooler

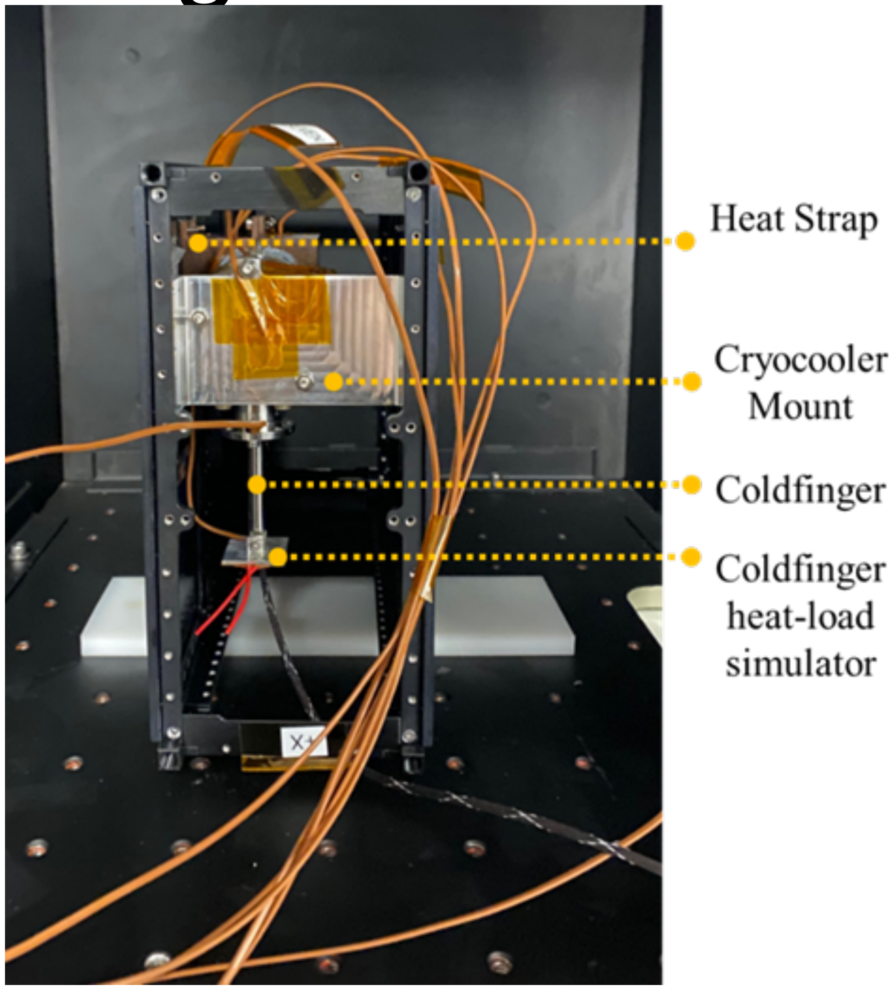


Model of cryocooler

- Thermal Vacuum (TVAC) testing is ongoing at UIUC to optimize the thermal design.

Skipper-CCDs in LEO: Cooling

- Risk mitigation integrates near-flight payload with passive thermal hardware and simulated heat loads
- Testing demonstrated that some modifications are still required to offload the cryocooler and minimize the internal radiation reaching the cold finger and the detector
    - Reduce vibration of the cryocooler
    - Adding cold-finger flange
    - Redesign to improve heat transfer
    - Reduce the mass of the detector ceramic to improve efficiency..
- Consulting with Ricor to improve the setup



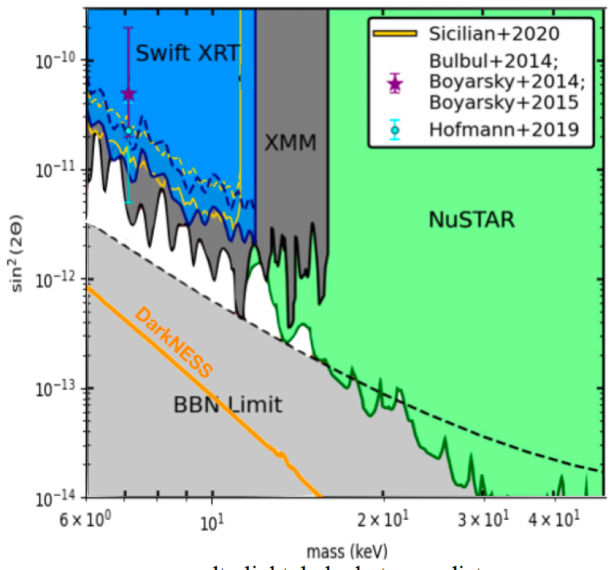
Thermal tests in TVAC

Main challenges

- Sensors performance: aim at reaching good energy resolution with a readout speed of 250 kpix/sec in good efficiency between 0.5-20 KeV.
- Study in detail (modeling, simulation, and lab tests) of the effects of low-energy hits from radiation in space.
- Launch and space-related operation issues: power, cooling, communication, vibration..

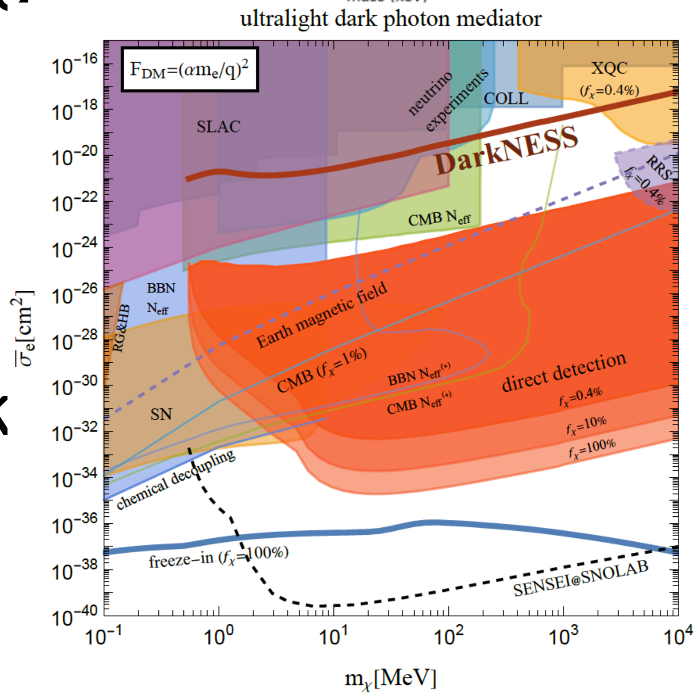
Summary

- DarkNESS will search for decaying dark matter by mapping the diffuse X-ray background of the Galactic Center and searching for unidentified X-ray lines.



Expected sensitivity to sterile neutrino decaying into DM as a function of DM mass with 1 mega-second exposure pointing at GC
FOV = 20° .

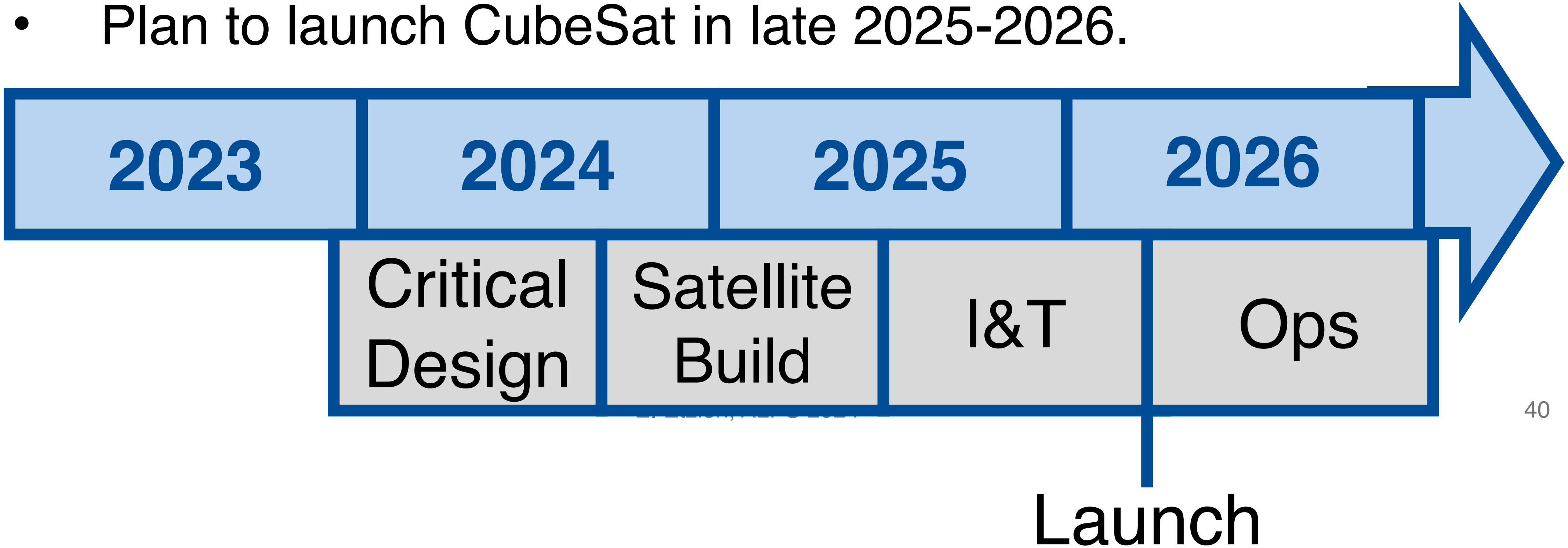
- DarkNESS will search for electron recoils from strongly-interacting dark matter that would not penetrate the Earth's atmosphere



Expected upper limit on DM-electron cross section for strongly-interacting sub-GeV DM

Current status

- DarkNESS is currently in the Critical Design Review (CDR) process to finalize the design.
- Preparing for the build phase still this year to test instrument performance in flight configuration.
- Plan to launch CubeSat in late 2025-2026.



Acknowledgment
Some of the slides provided by Nate Saffold, Juan Estrada and Eric Alpine