The DarkNESS mission: probing dark matter with a skipper-CCD CubeSat

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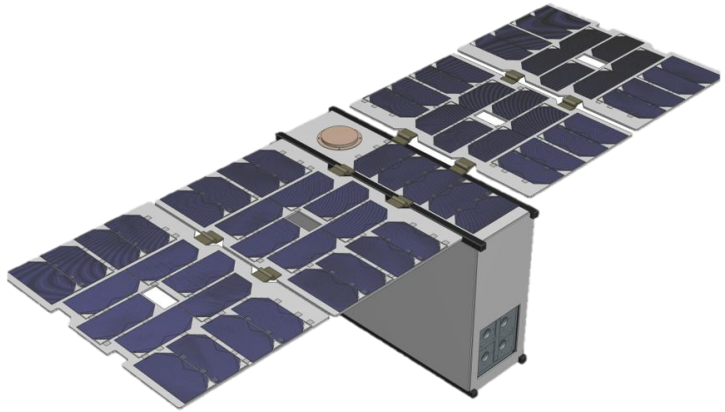
8/31/2023

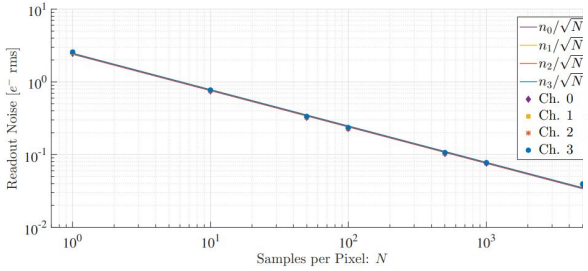
The DarkNESS Mission

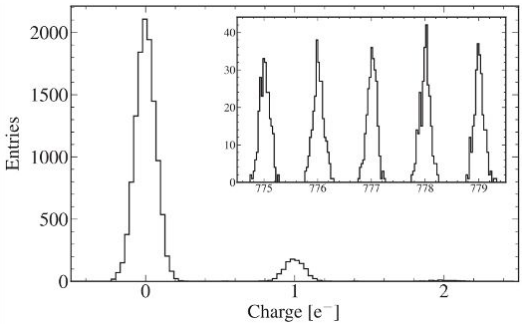
DarkNESS: Dark matter **N**anosatellite **E**quipped with **S**kipper **S**ensors

- 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)





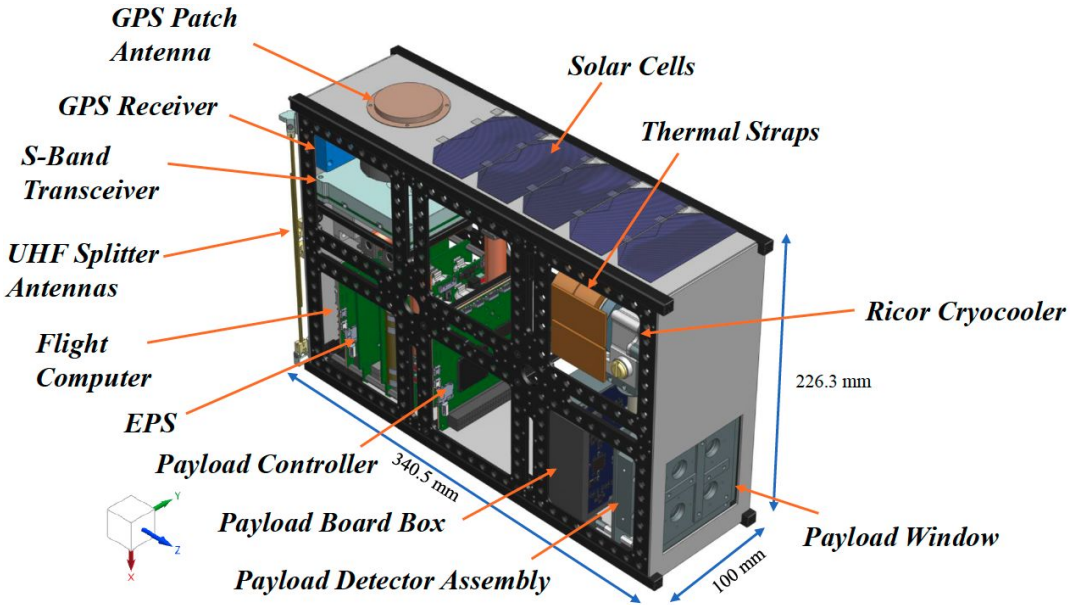


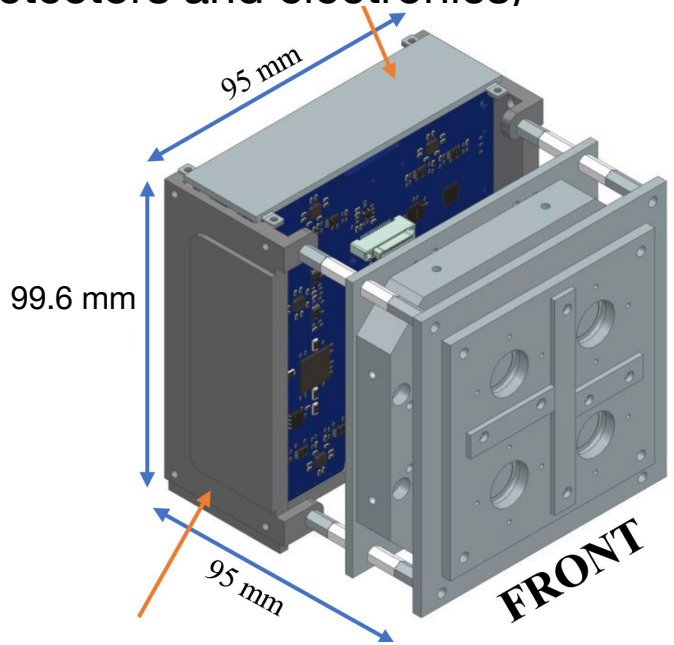
Collaboration between Fermilab and UIUC Laboratory for Advanced Space Systems at Illinois (LASSI)

Fermilab

DarkNESS instrument

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





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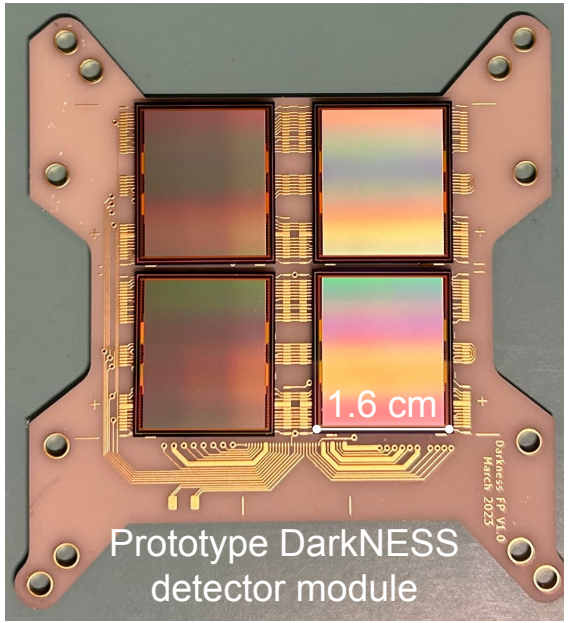
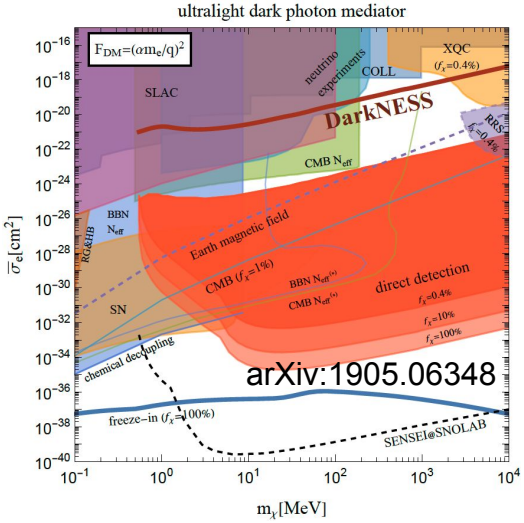
DarkNESS detectors and readout electronics

- Four 1.3 Mpix skipper-CCDs with sub-electron noise, wirebonded to Multi Chip Module (MCM)
- Custom space-Low Threshold Acquisition (LTA) readout board, designed to fit into 6U CubeSat form factor



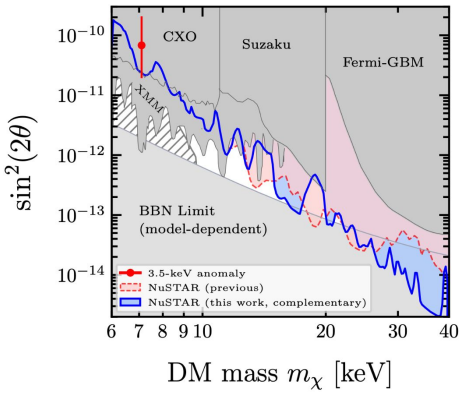
DarkNESS science goals

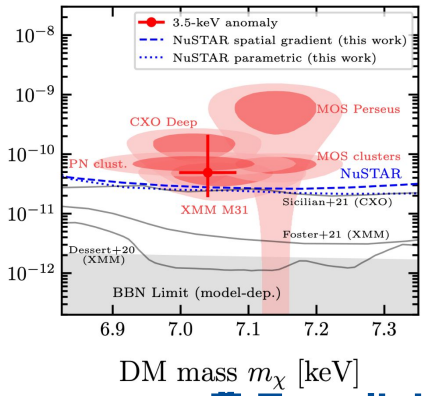
- Search for electron recoils from strongly-interacting sub-GeV DM



- Observe the diffuse X-ray background, search for signatures of DM decay

arXiv:2207.04572





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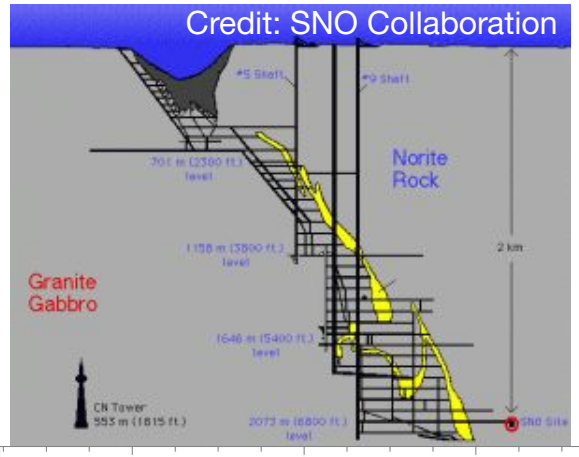
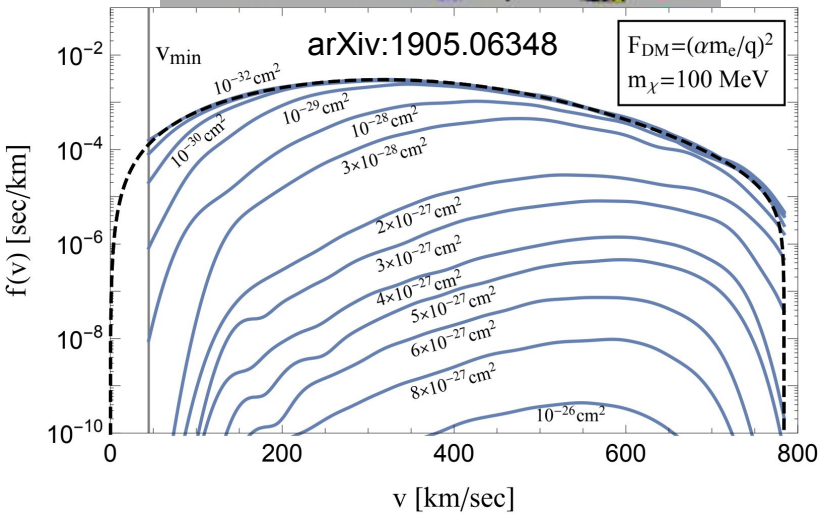
Strongly-interacting sub-GeV DM

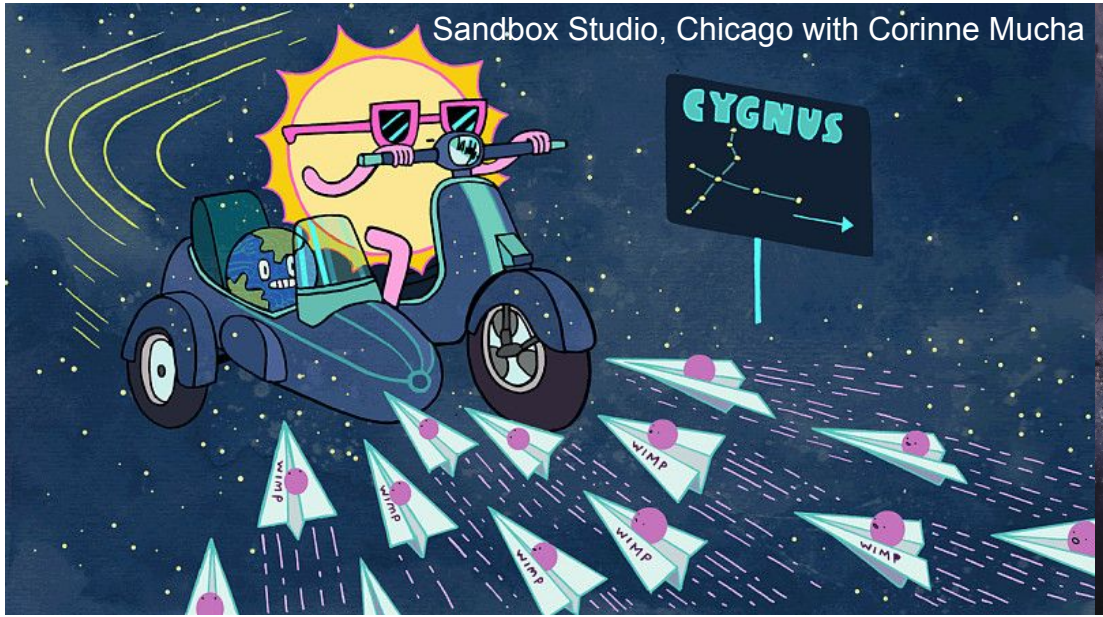
- Typically DM searches are conducted underground to mitigate cosmogenic backgrounds
- For DM models with higher cross section, the DM would be attenuated by the Earth's atmosphere and crust, and not reach detectors underground or on the Earth's surface
- Need a space-based mission to probe these models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

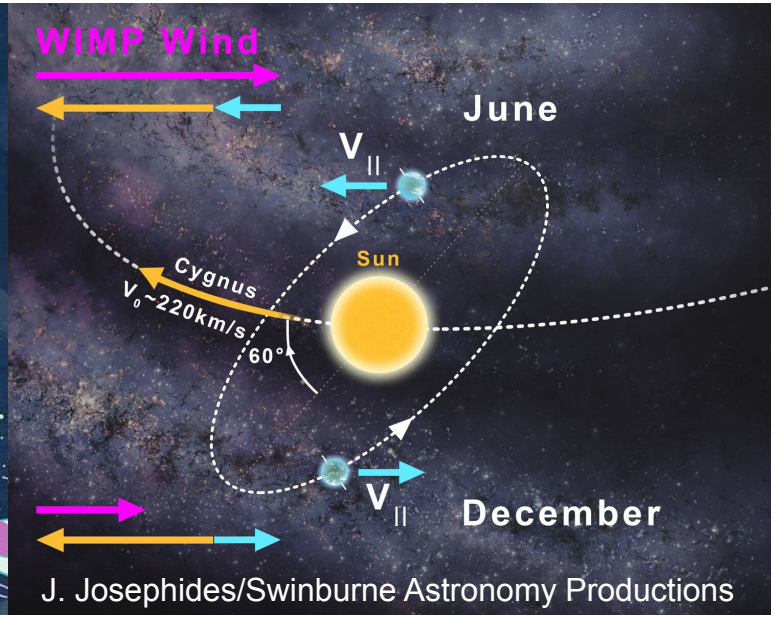




“WIMP Wind”

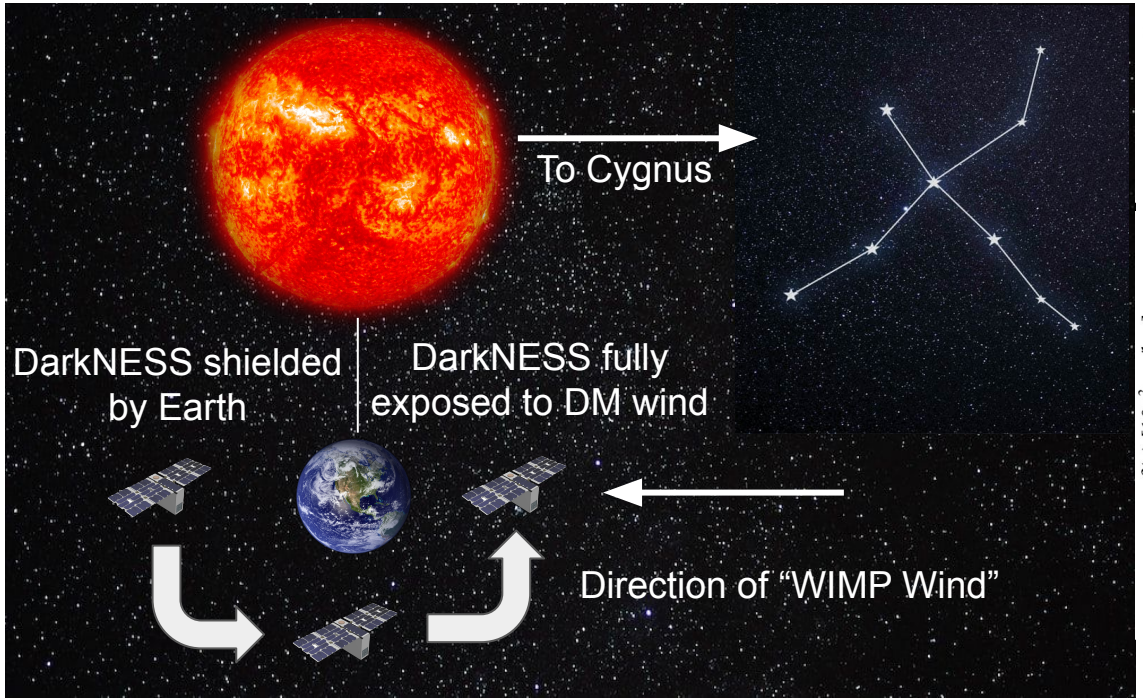
- Interaction rate proportional to relative velocity between DM and target
- This effect has been exploited for annual (and daily) modulation searches

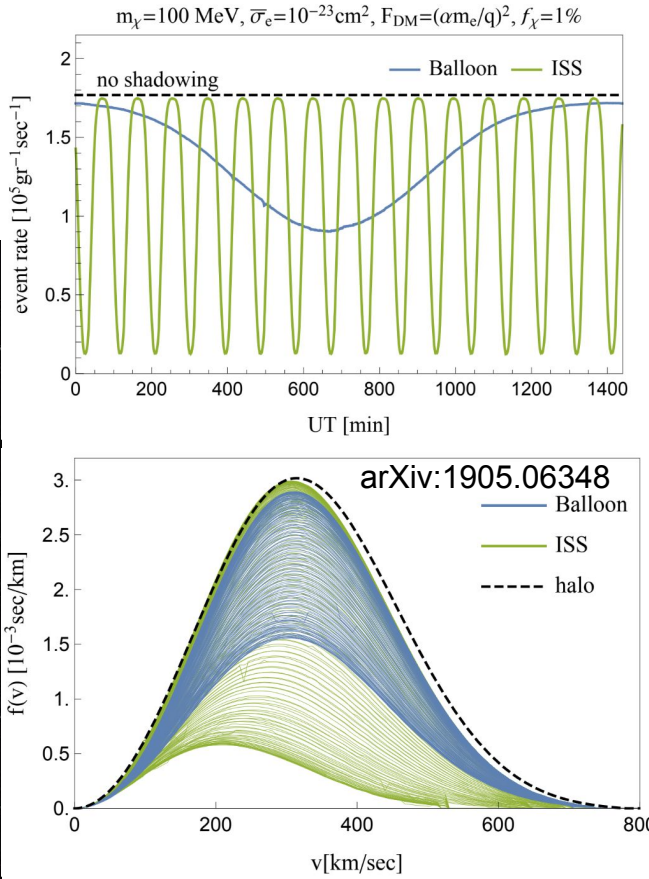




Strongly-interacting sub-GeV DM

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





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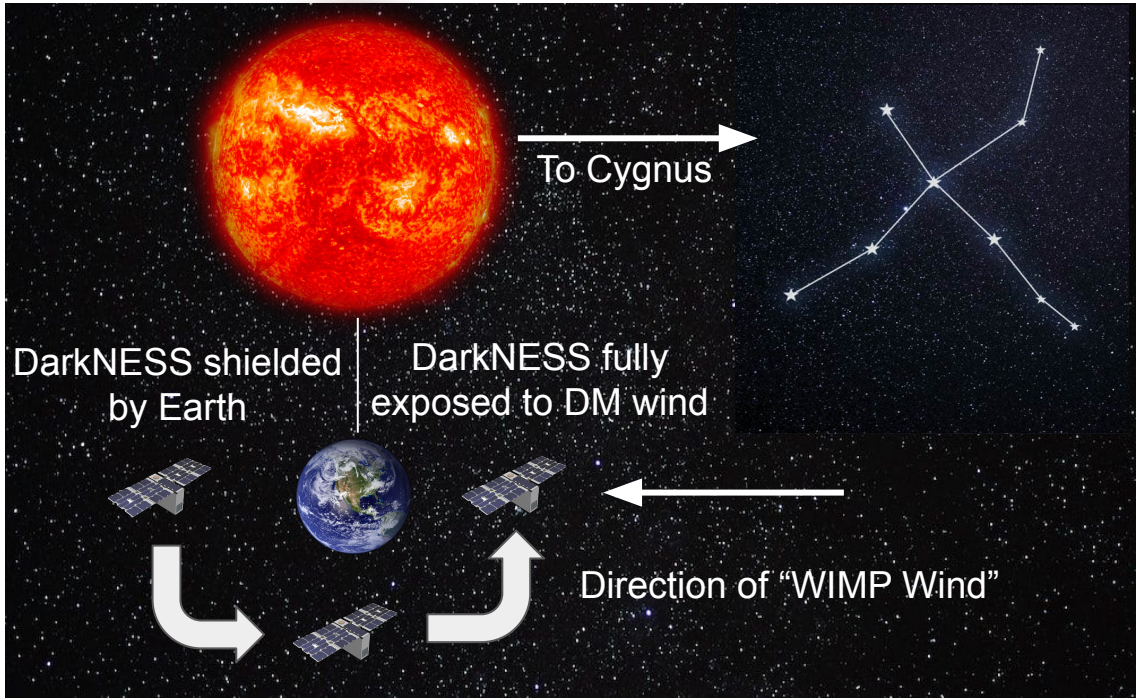
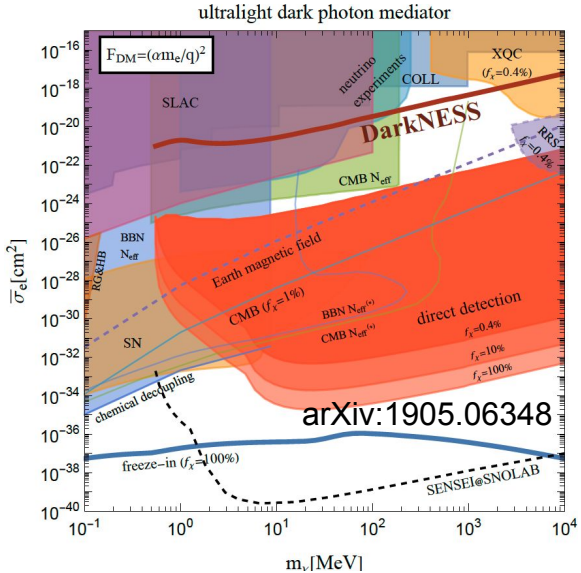


DarkNESS will set new constraints on DM-electron interactions



DarkNESS limit projections for 0.1 g-month exposure

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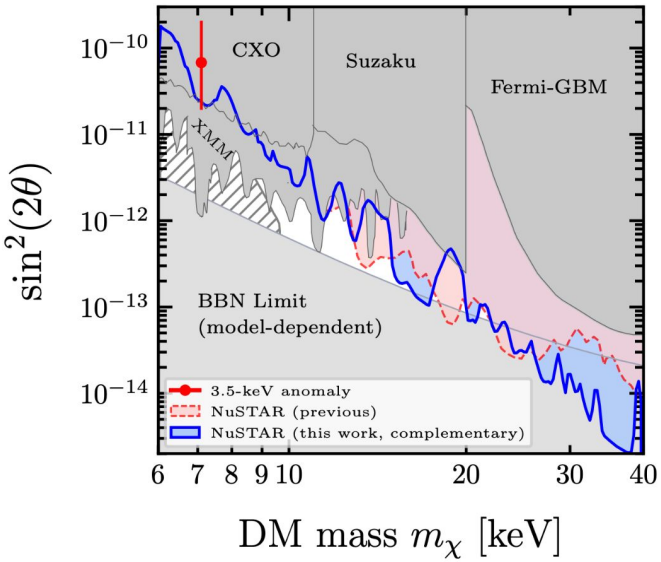
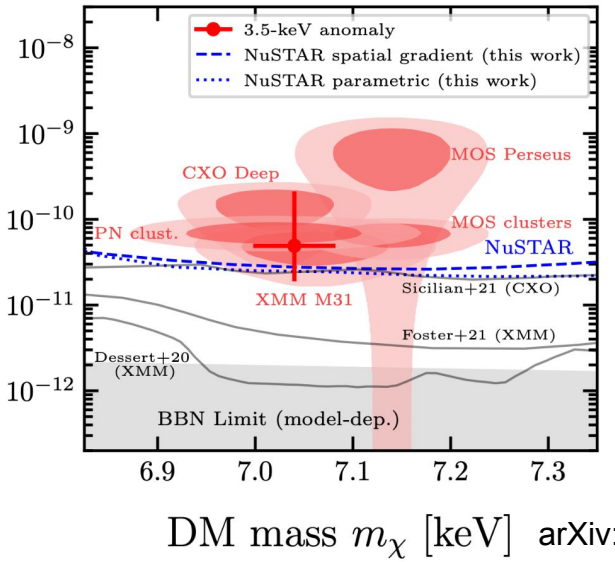
X-rays from sterile neutrinos

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





arXiv:2207.04572

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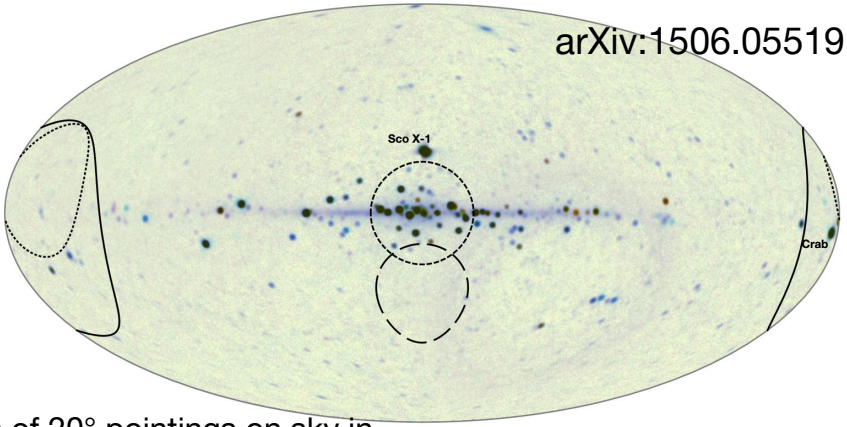
X-rays from sterile neutrinos

- 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

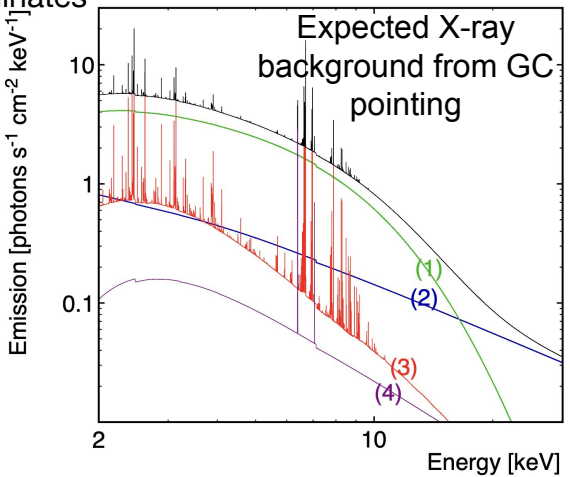
arXiv:1506.05519



Example of 20° pointings on sky in Galactic coordinates

$$\mathcal{F} = \frac{\Gamma}{m_s}\frac{1}{4\pi}\int_{FOV}\underbrace{\int_0^\infty \rho(r(\ell,\psi))\, d\ell}\, d\Omega$$

D-factor
(integrate DM density in line of sight)



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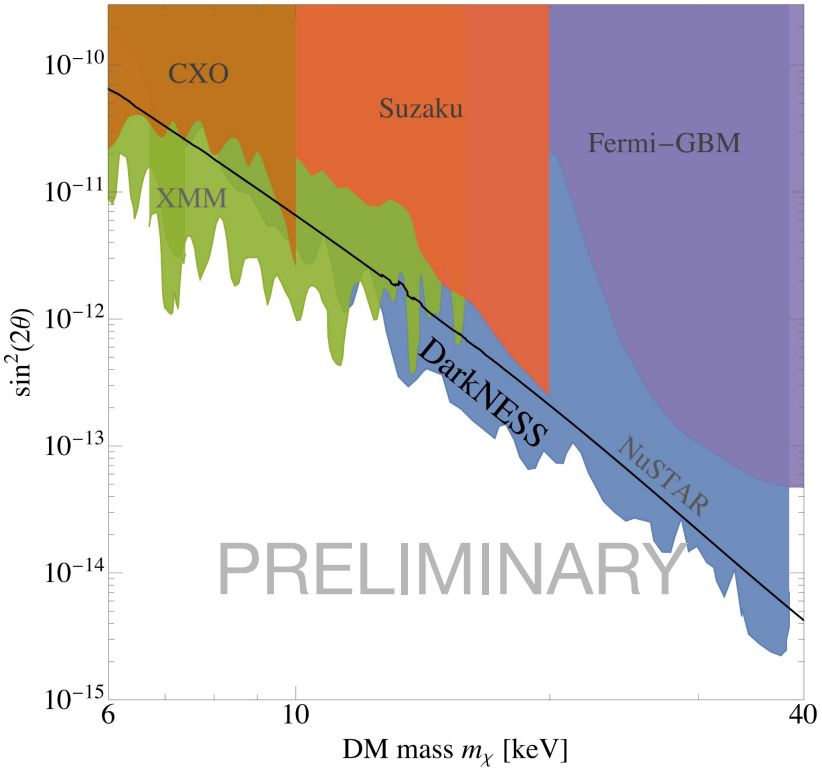
Sterile Neutrino Sensitivity

- DarkNESS projected sensitivity to sterile neutrino DM
  - 100 minute exposure time (100 x one minute exposures), pointing at Galactic Center with 20° FOV
  - Energy resolution of typical CCD [arXiv:1510.02126]
    - σ_E ~ 40 eV at 3.7 keV
  - Fraction of CCD area masked due to cosmic ray impingement



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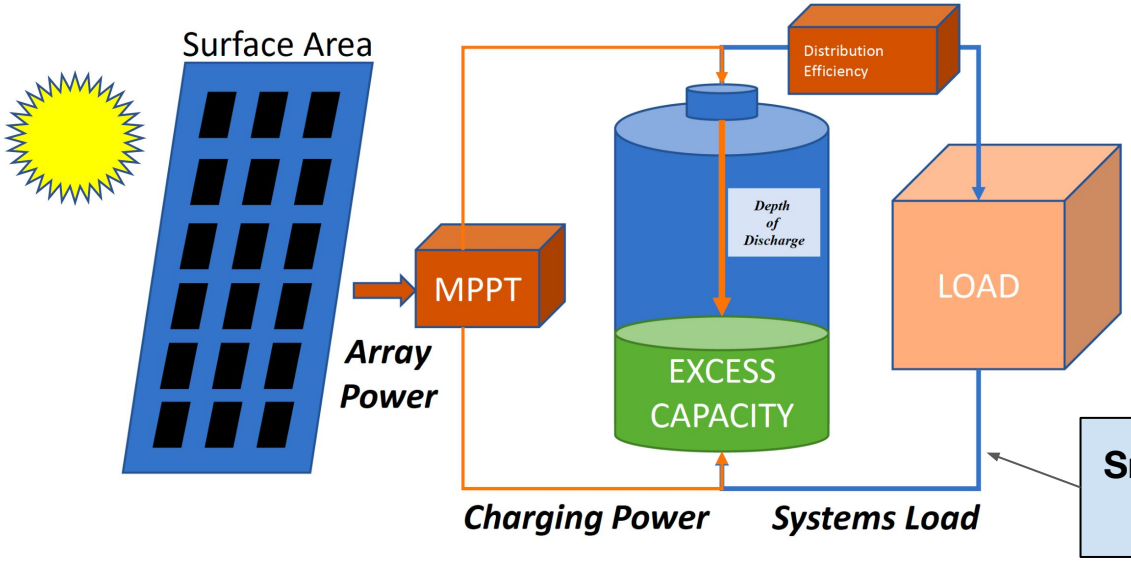
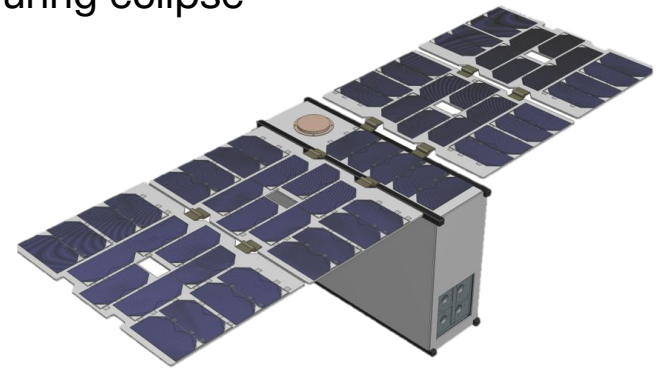
Challenges of space-based operation

- 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





Smaller depth of discharge extends battery life

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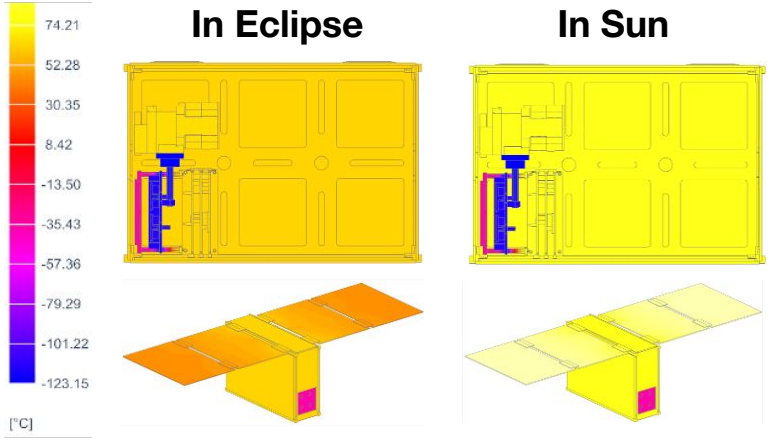
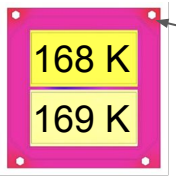
Challenges of space-based operation

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



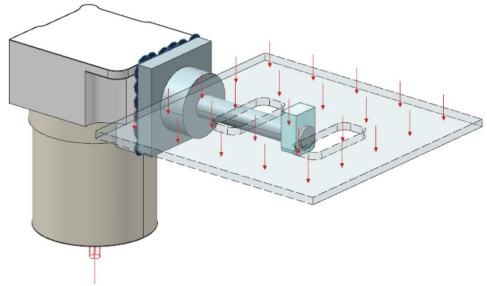
Detector Close-up:



167 K

Detectors stay within ~5 K range

Ricor K508N cryocooler



Model of cryocooler

In thermal model, the cryocooler was able to maintain the skipper-CCD temperature at 170 K ± 5 K during eclipse and sun-exposed time periods

TVAC testing ongoing to validate thermal model

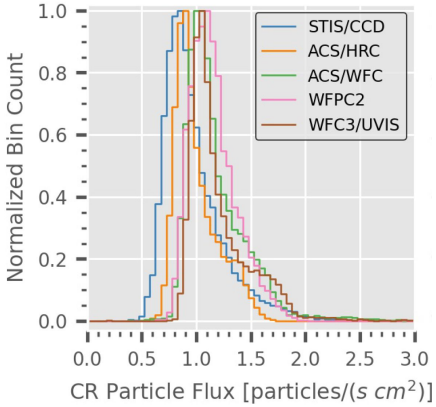
Challenges of space-based operation

- 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

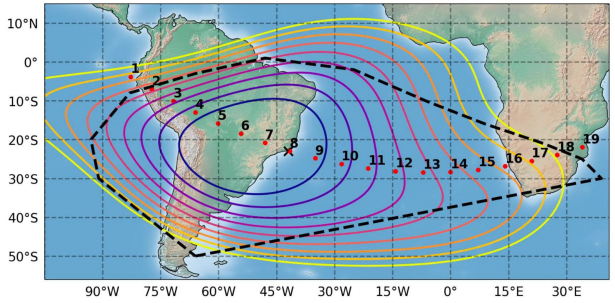
Challenges of space-based operation

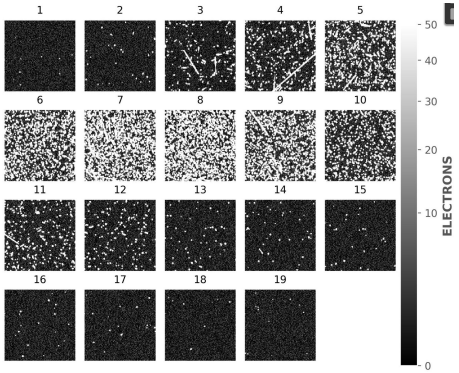
- Cosmic ray (CR) backgrounds
  - Expect ISS-like orbit (51° inclination)
  - Background simulations in progress using Geant4, building off previous work (Cuevas 2019)
  - Optimal operating mode driven by tradeoff between exposure time and CCD occupancy due to CR energy depositions
  - Minimize readout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



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

Miles et al (2021) *ApJ* 918 86

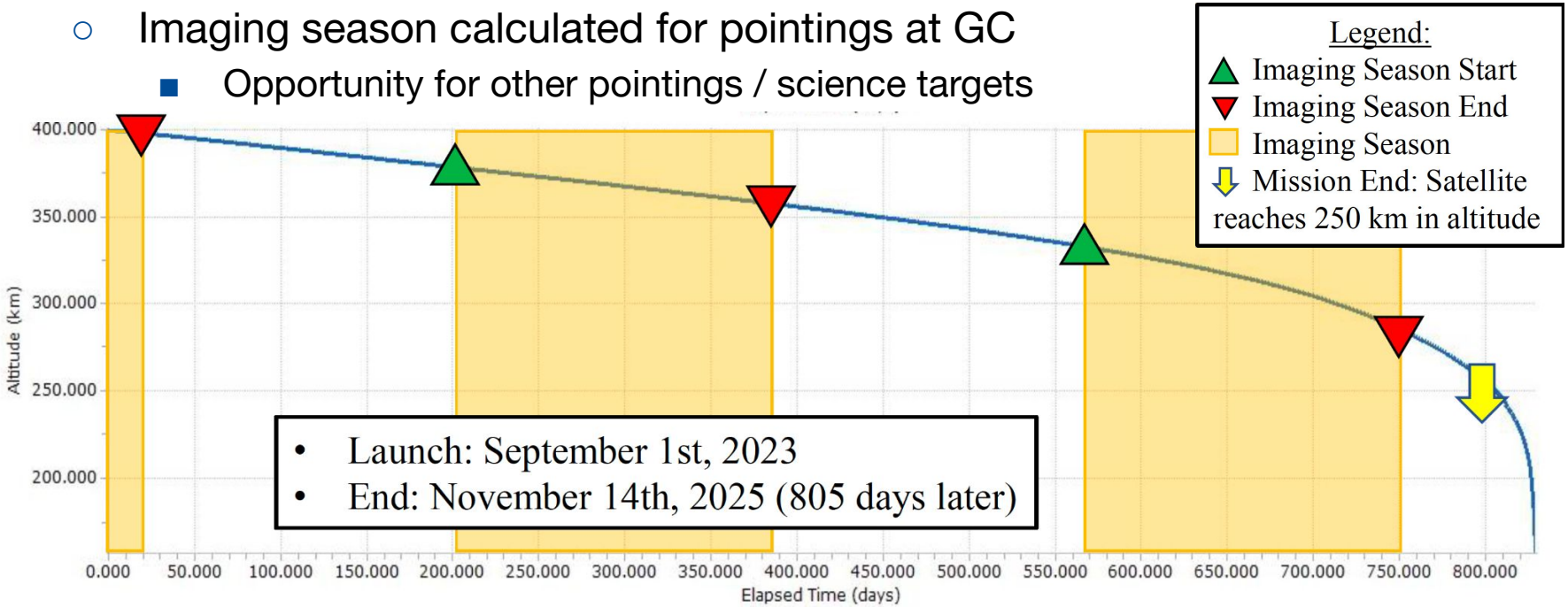




Expect significant increase in background rate during passages through South Atlantic Anomaly (SAA)

Orbital Analysis

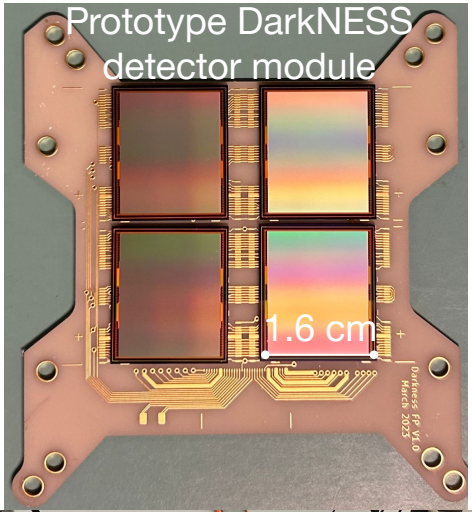
- Expected orbital lifetime of DarkNESS mission
  - ~800 days in orbit before re-entry
  - Imaging season calculated for pointings at GC
    - Opportunity for other pointings / science targets

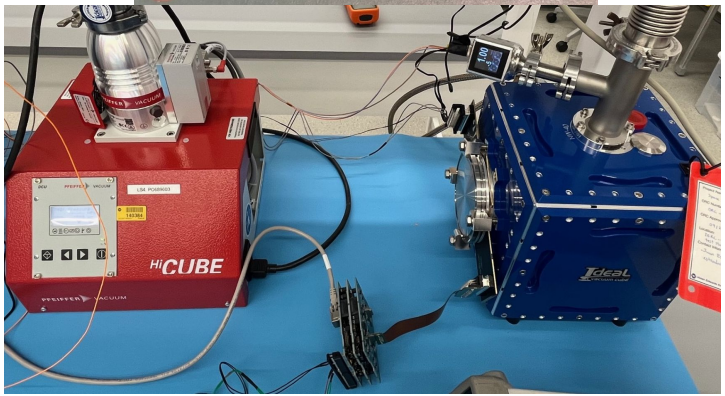


Fermilab

Current Status

- TVAC testing ongoing at UIUC to demonstrate cryocooler performance in CubeSat configuration
- First prototype focal plane module recently received at Fermilab, preparing to test response to X-rays (Fe_{55})
- Developing Geant4 simulation to assess particle backgrounds and determine instrument's efficiency/effective area
- Preparing for CDR and seeking launch opportunities





DarkNESS X-ray test stand

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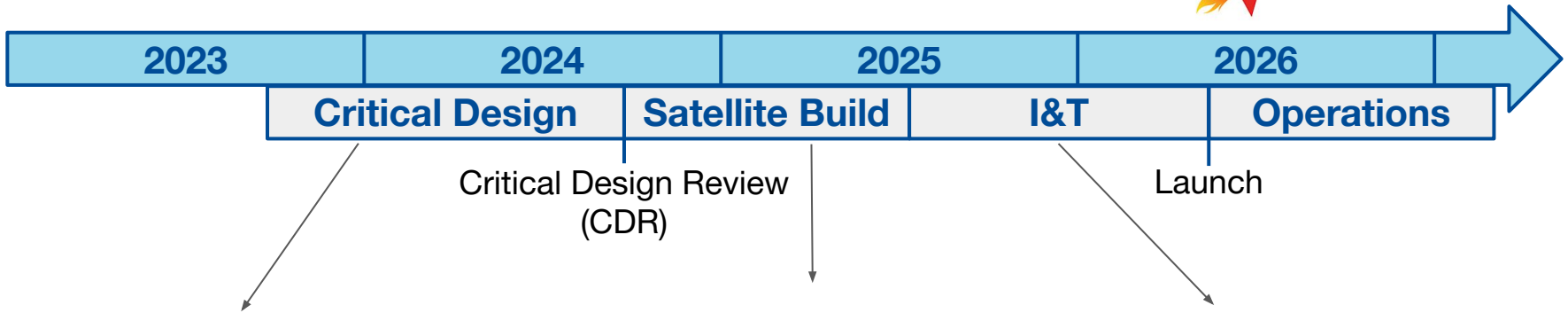
Project Timeline and Milestones



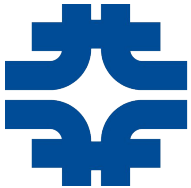
- Establish X-ray test stand
- Characterize payload
- Re-design payload based on testing results
- Design interface between scientific payload and satellite bus (define payload controller)

- Build payload
- Demonstrate successful performance of payload
- Design interface between scientific payload and satellite bus (define payload controller)

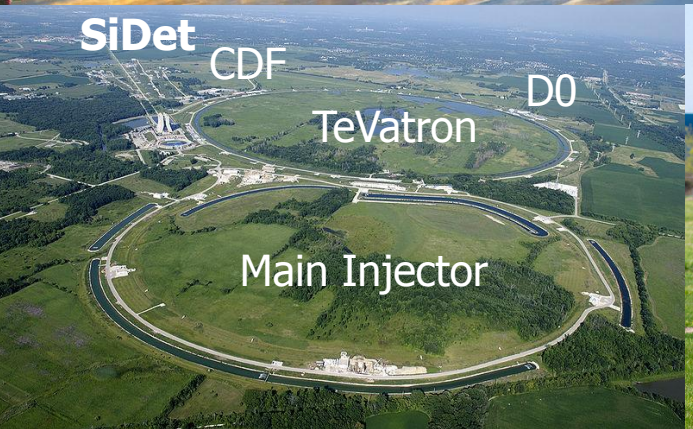
- Integration of payload into nanosatellite
- Environmental testing to prepare for launch

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



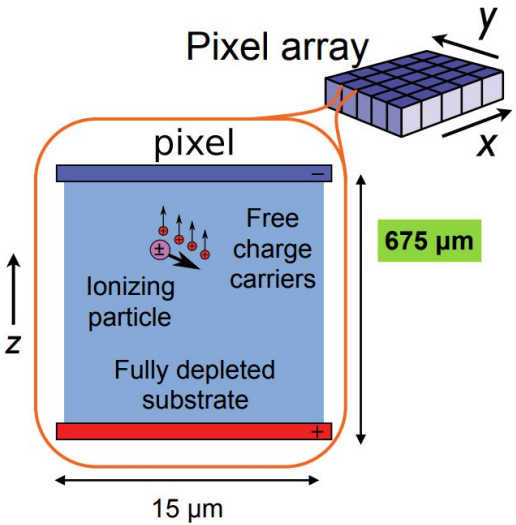

Thank you!

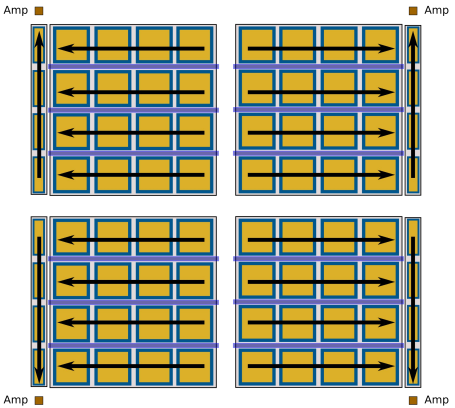


Backup

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 ~2e^-





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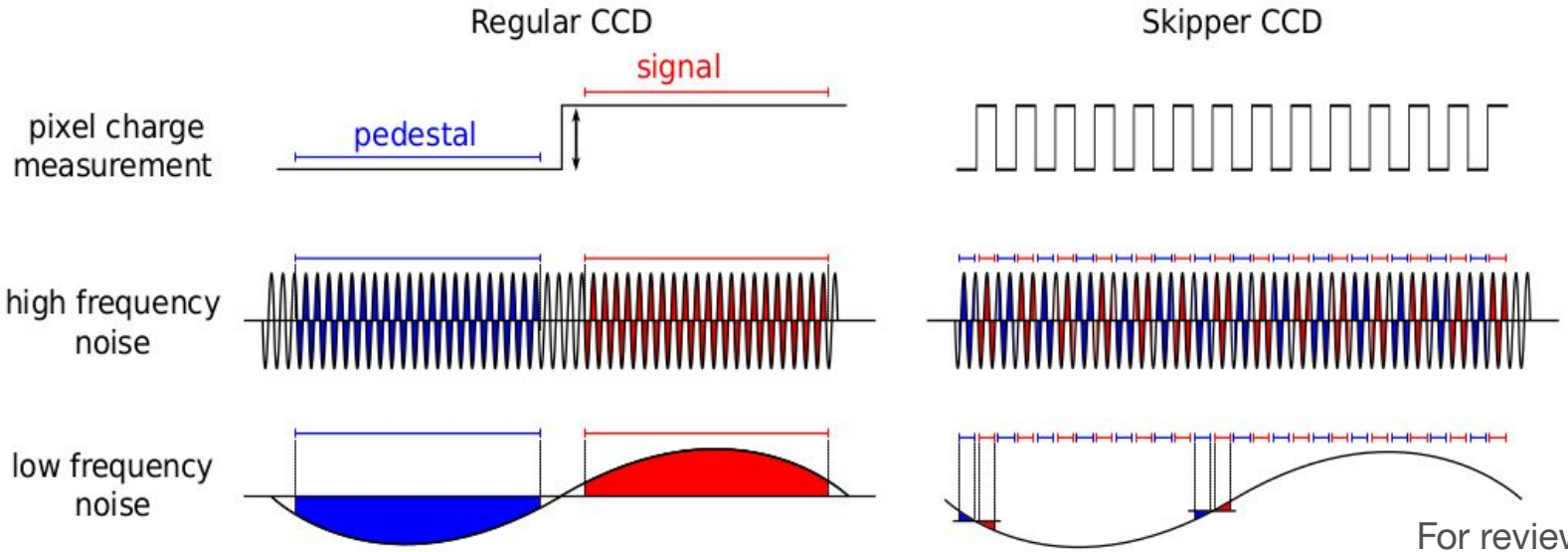
Skipper Readout

- 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

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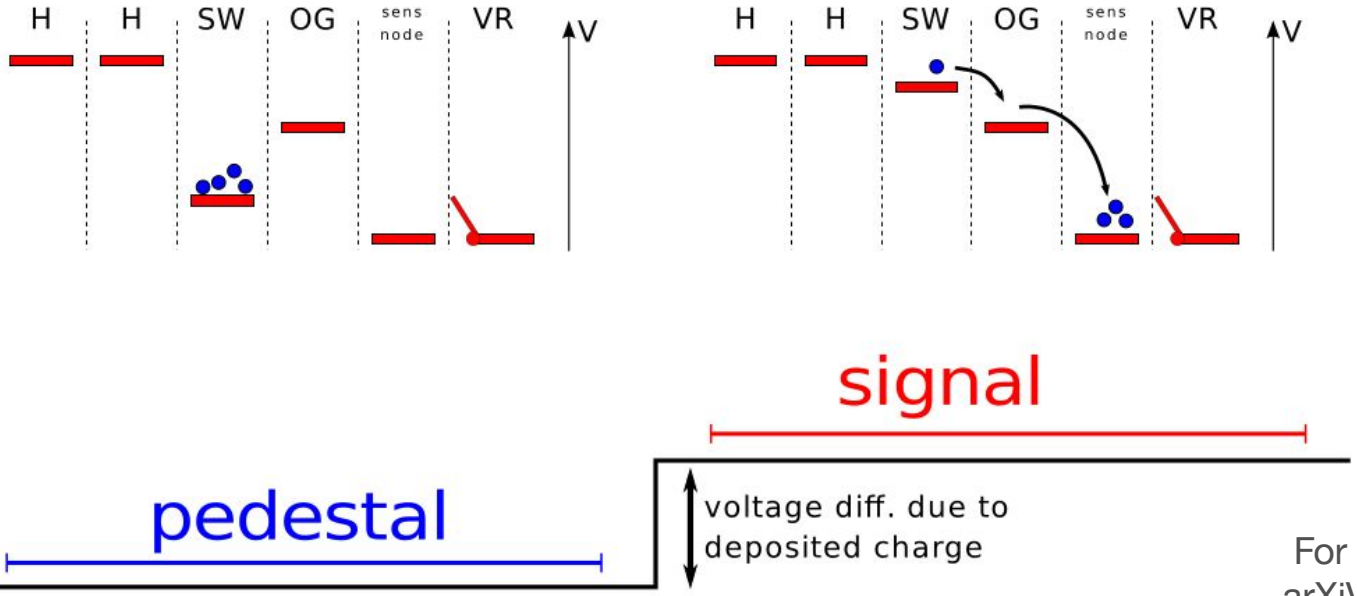

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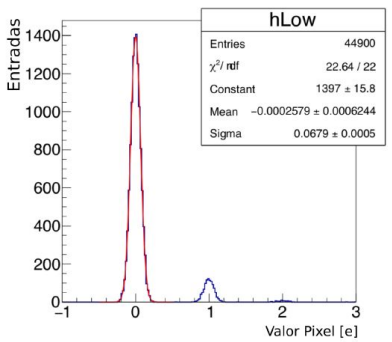
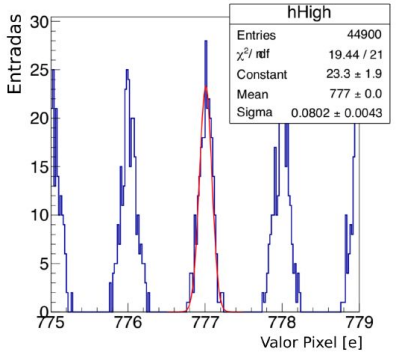
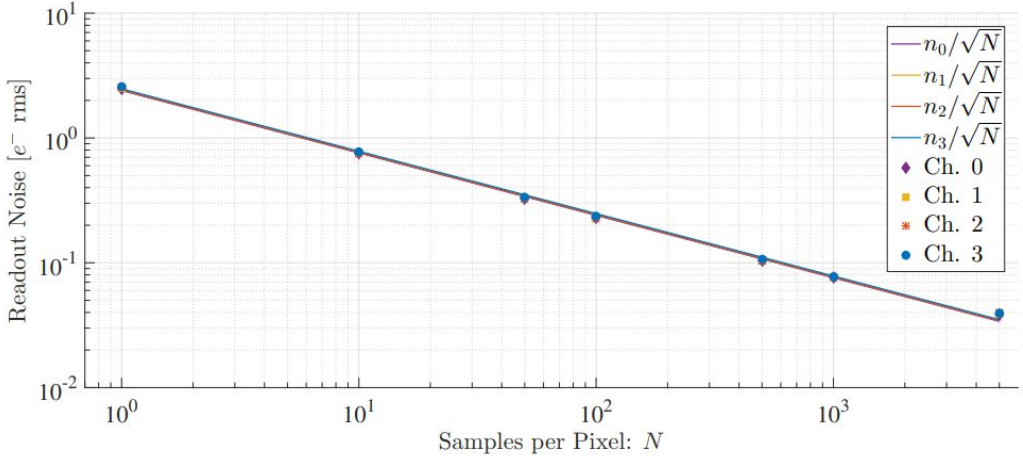
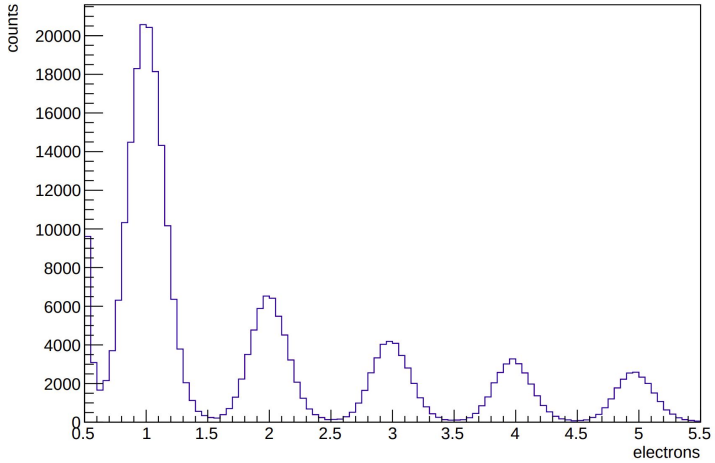
Sub-electron readout noise

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









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