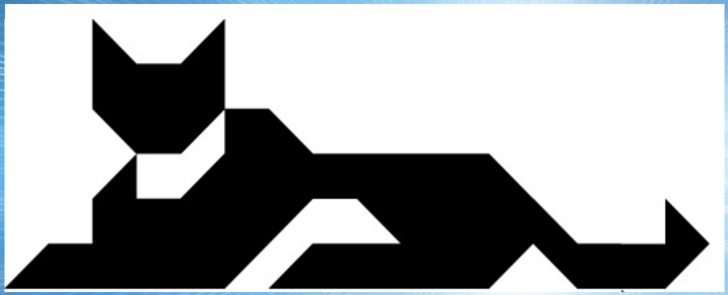
BlackCAT
Black hole Coded Aperture Telescope



Abe Falcone
(Penn State)

Co-I's: D. Burrows, T. Chattopadhyay, D. Fox, D. Palmer

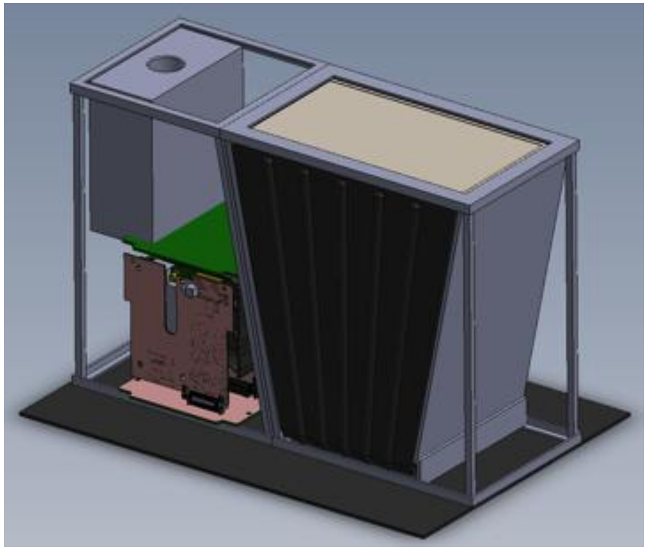
Science

The BlackCAT CubeSat is a soft X-ray sky monitor, transient finder, and burst detector for high-energy and multi-messenger astrophysics

- Soft X-ray response with wide-FOV is tuned to discover ***high redshift GRBs*** and probe the epoch of cosmic star formation in the early universe
- locate the **EM counterparts of the gravitational wave events** with sub-arcminute accuracy (as well as other potential multi-messenger events such as HE neutrinos)
- **Monitor the transient sky** and trigger alerts from Galactic transients, blazars, Short GRBs, tidal disruption events, XRFs, supernova shock breakouts, etc. using wide sky nearly continuous X-ray monitoring

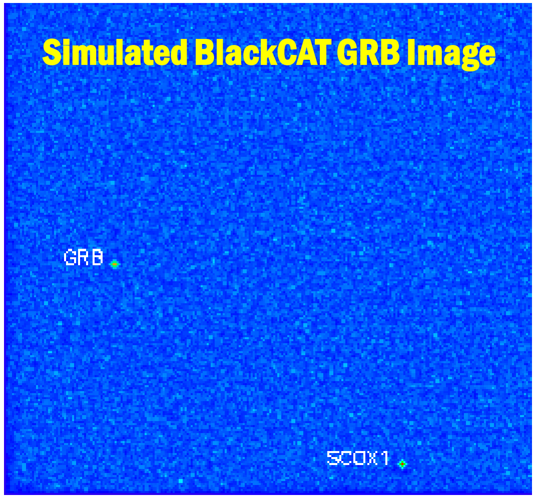
Overview

Table 1. Mission overview	
Instrument	Soft X-ray coded mask telescope with hybrid CMOS detectors
Spacecraft	Standard 6U CubeSat (from Clyde Space)
Orbit	Sun-synchronous LE orbit
Science	Detection of EM counterparts of gravitational waves, high reshift GRBs, transients, monitoring

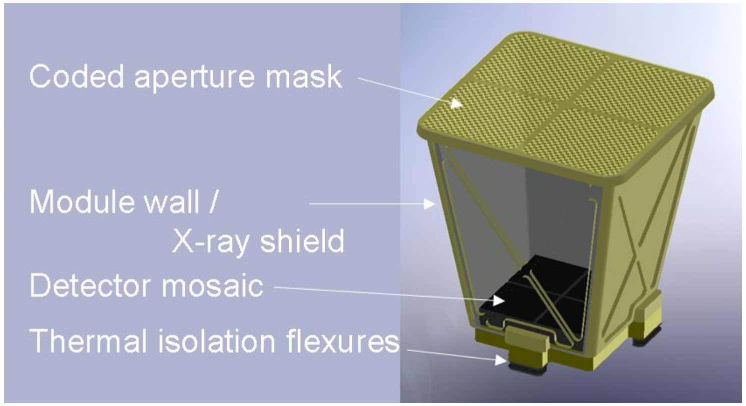


Response and localization

- BlackCAT detects and localizes Gamma Ray Bursts, transients, and GW counterparts
  - determines GRB position to ~ 60” in < 30 s
  - sends position to S/C and to ground
  - telemeters light curve and spectral info



Coded Mask



- Each mask will consist of a ribbed frame that supports electroformed Nickel coated with gold

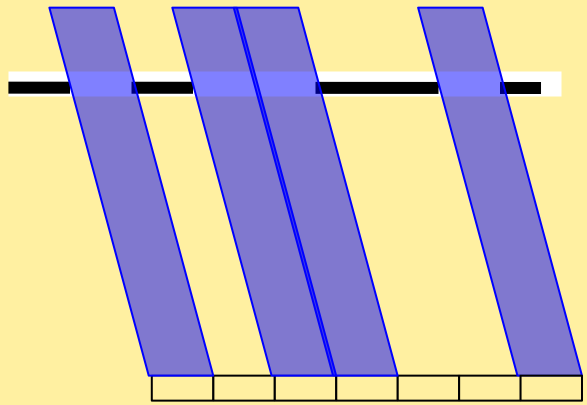
- Mask pitch of 320 um matches that of detector superpixels

Table 2: BlackCAT Mask Parameters	
Parameter	Value
Focal Length	158 mm
Mask size (aperture)	170 x 88 mm
Mask element	320 x 320 µm
Detector superpixel	320 x 320 µm
DM FOV	0.95 sr
Open element size	263 x 263 µm
Mask Transmission	>40%
Image Scale	52 "/pixel
	6.9 arcmin/superpixel

Coded Mask Imaging

Coded Aperture Mask + Silicon Hybrid CMOS Detectors

Source 1

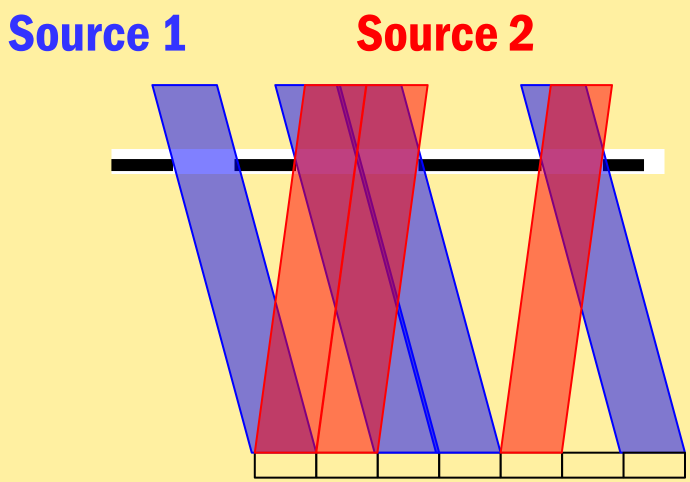


Same technique as INTEGRAL IBIS and Swift BAT, but at lower energies.

- Mask pattern casts X-ray shadows on detector for E < 20 keV.

Coded Mask Imaging

Coded Aperture Mask + Silicon Hybrid CMOS Detectors



Same technique as INTEGRAL IBIS and Swift BAT, but at lower (soft X-ray) energies.

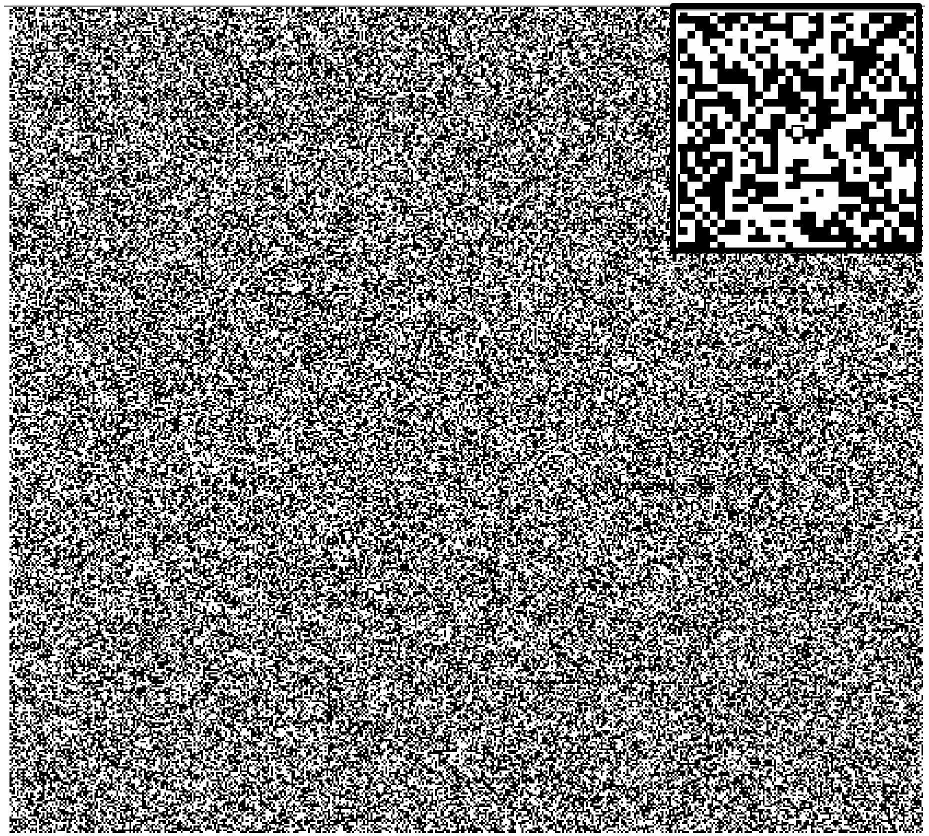
- Mask pattern casts X-ray shadows on detector for E < 20 keV.
- Deconvolution of detector image with mask pattern produces sky image

Imaging is a multi-step process using the same sophisticated algorithms used by the *Swift* BAT:
1) Reconstruct sky image with superpixel resolution.
2) Back-project sources at full resolution.

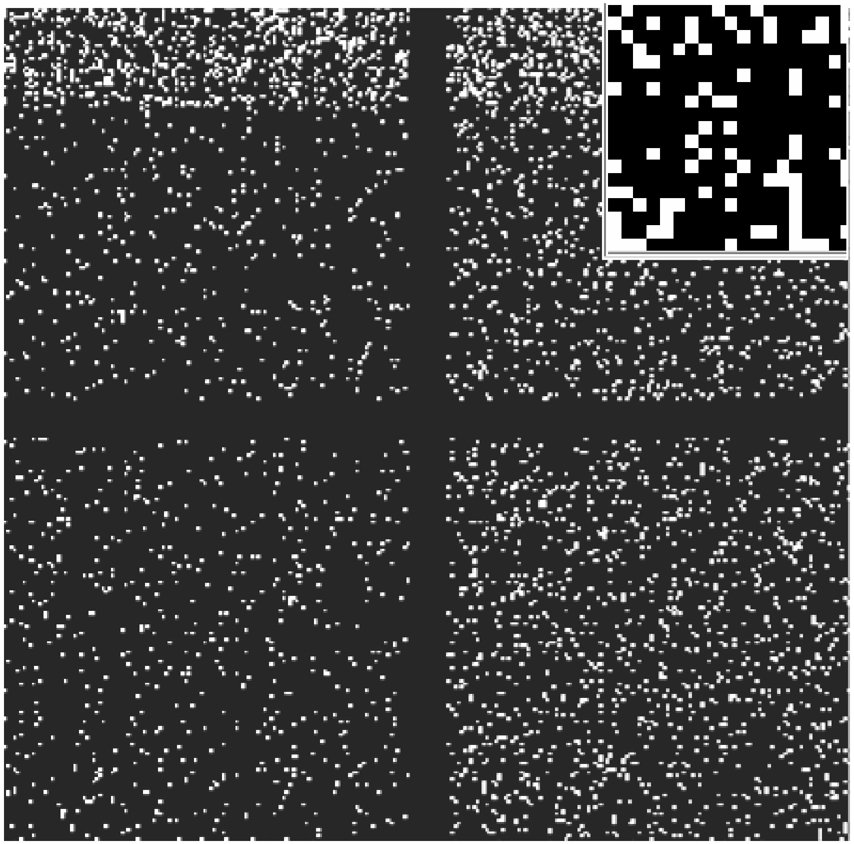
BlackCAT Imaging Simulation

Simulation of 6 s image (single module with H2RG) of field containing Sco X-1, a GRB, and the X-ray background.

2D Coded Aperture Mask



Detector Plane Image



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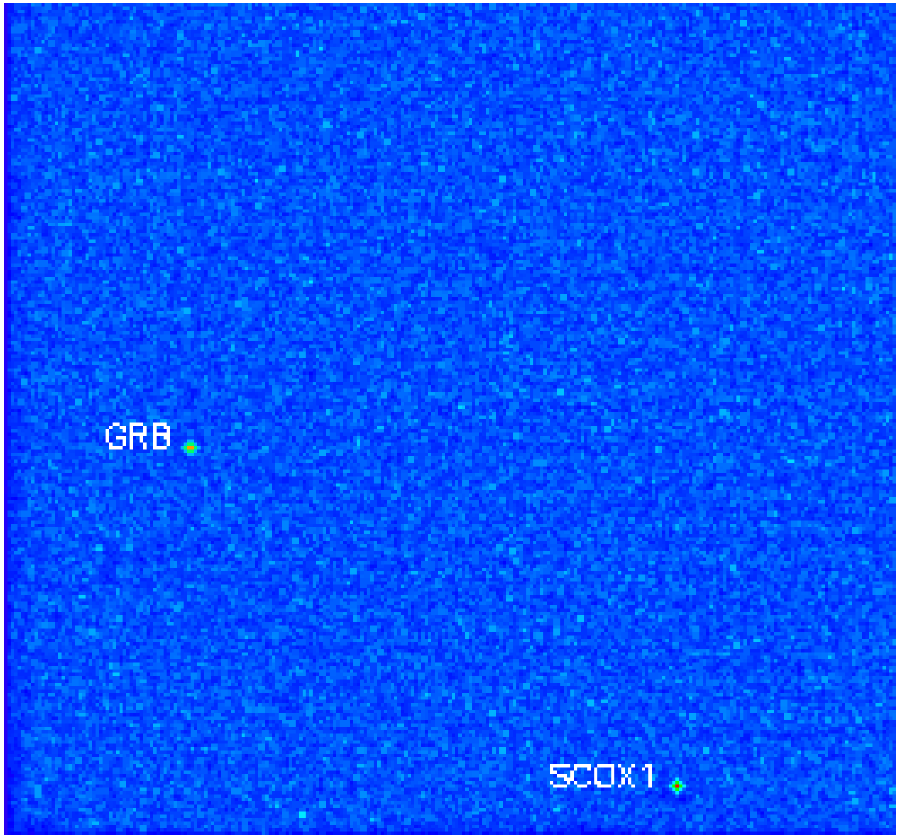
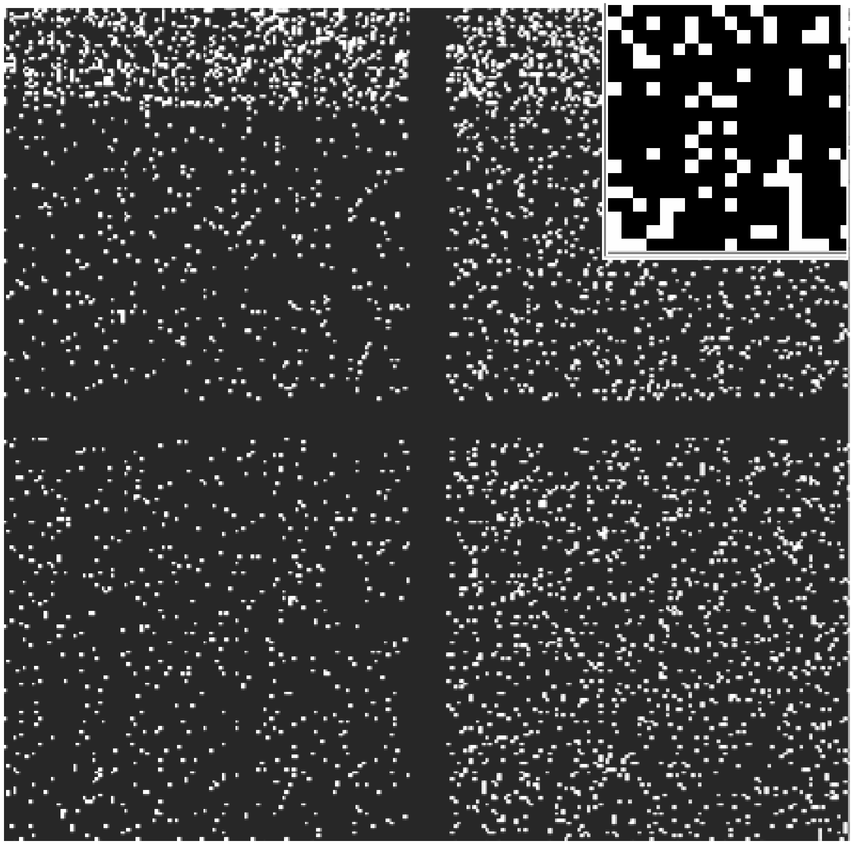
Sky Image



Detector Plane Image



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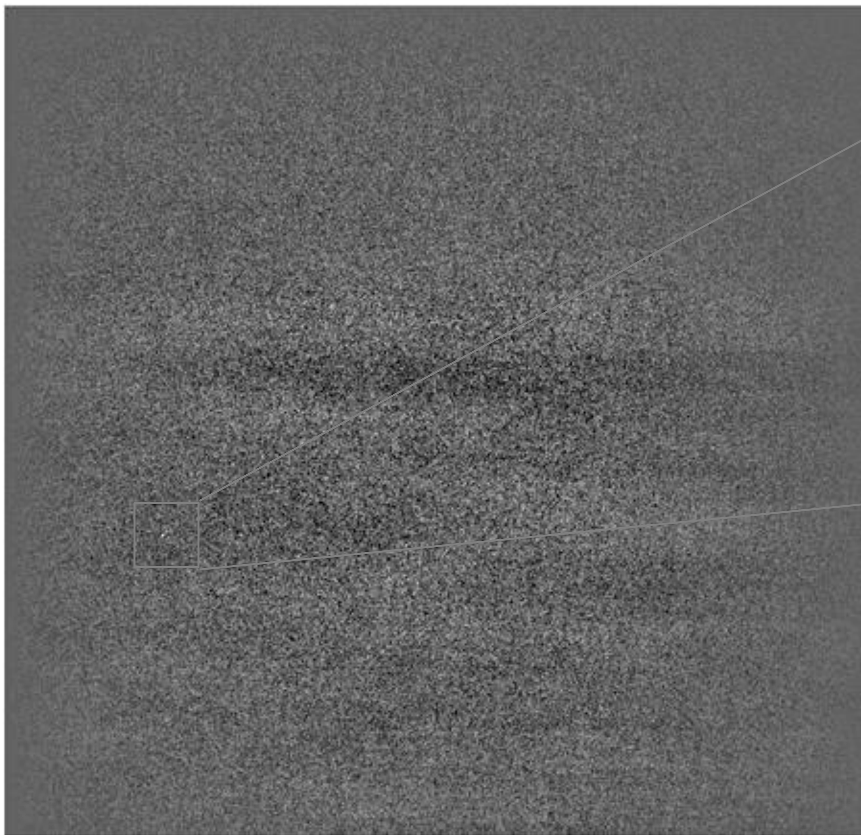
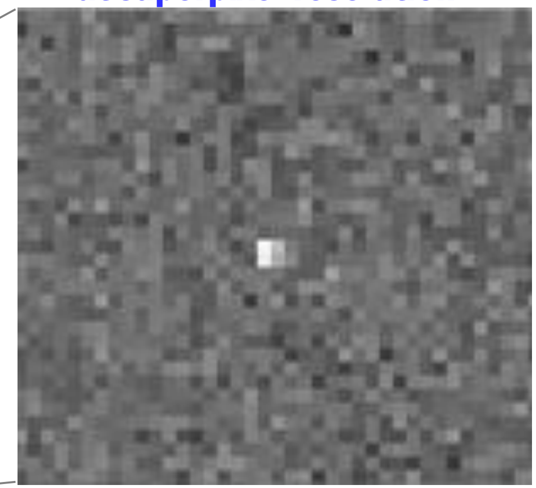
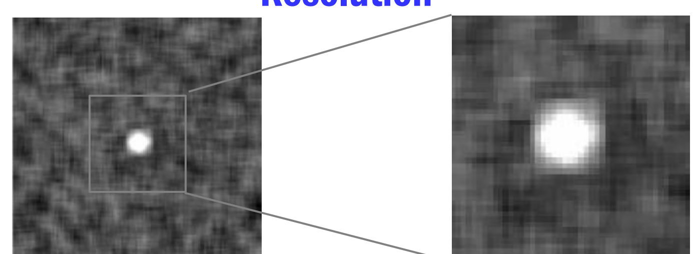
Reconstructed Sky Image



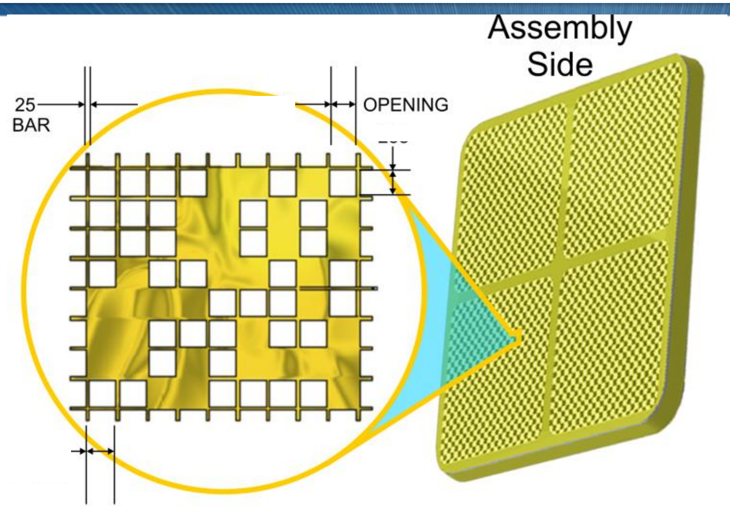
Blowup of GRB Image at superpixel resolution



Back-projected Sky Image at Full Detector Resolution



Coded Mask



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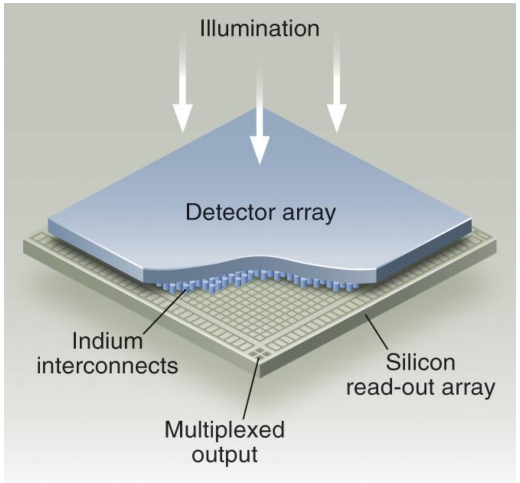
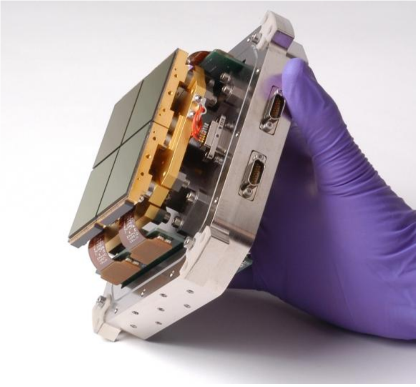
Detectors



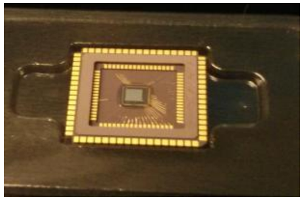


- **Each focal plane detector consists of 4 Si hybrid CMOS detectors (Speedsters)**
- **The intrinsic pixel pitch is 40 um (binned to 8x8 superpixels)**
- **passively cooled to below ~ -60 C to achieve sufficiently low dark current**

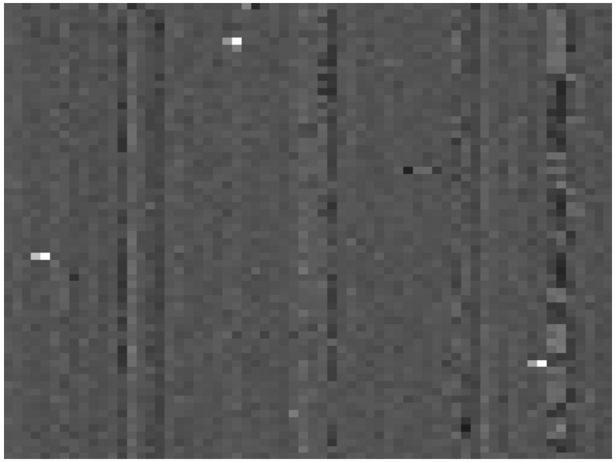
Table E.6.a.1.1-3: *Detector Parameters*

Parameter	**Value**
Type	Si Hybrid CMOS
Absorber material	Silicon
Absorber thickness	100 μm
Detector Format	550 x 550
Readout	Sparse Event Driven
Readout rate	1 kHz
Pixel Size	40 x 40 μm
Software binning	8 x 8
Power	~ 100 mW
Operating Temp.	~ -60° C
Time resolution	1 msec

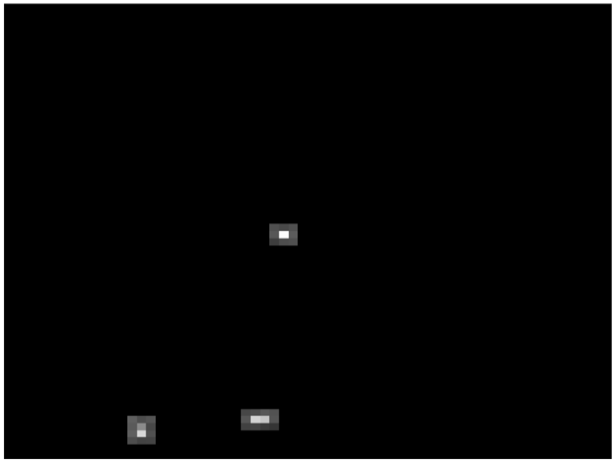
The Speedster Event Driven X-ray Hybrid CMOS Detector



By reading only the pixels with x-ray events, effective frame rates can be faster by orders of magnitude!



Full Frame Read Out Mode:
Comparator threshold set below the noise floor



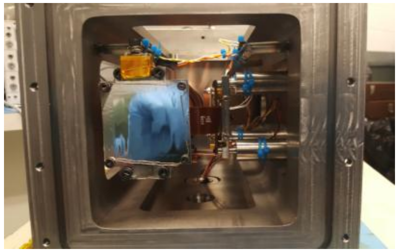
3x3 Sparse Read Out Mode:
Comparator threshold set above the noise floor

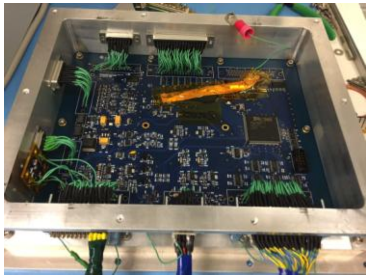
Prototype detector (64x64 pixels with 40 micron pitch and 100 micron fully-depleted depth) successfully tested with its in-pixel comparators. The Speedster also has in-pixel CDS, no measurable interpixel crosstalk, and selectable gain (up to ~200 μV/e). Read noise ~12 e^-
(Griffith et al. 2016)

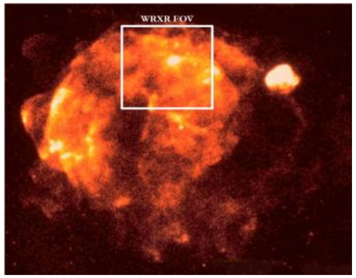
A larger format device (550x550) with on-chip digitization is being developed now.

HCDs on WRX Rocket
(X-ray Hybrid CMOS is now high TRL)

- In collaboration with McEntaffer group at PSU, we launched Water Recovery X-ray Rocket (WRX-R) with a soft x-ray spectrometer that includes an off-plane reflection grating array and H2RG hybrid CMOS detector
- Launched April 4, 2018. First NASA astrophysics sounding rocket payload to achieve water recovery
- Key test of x-ray HCDs in space environment; raises X-ray H2RG to TRL-9
- Raises our Camera Interface Board to TRL-9
- Target: Vela supernova remnant; instrument optimized for 3rd and 4th order OVII; analysis in-progress
- Provided flight hardware experience for students







BlackCAT sensitivity (first module)

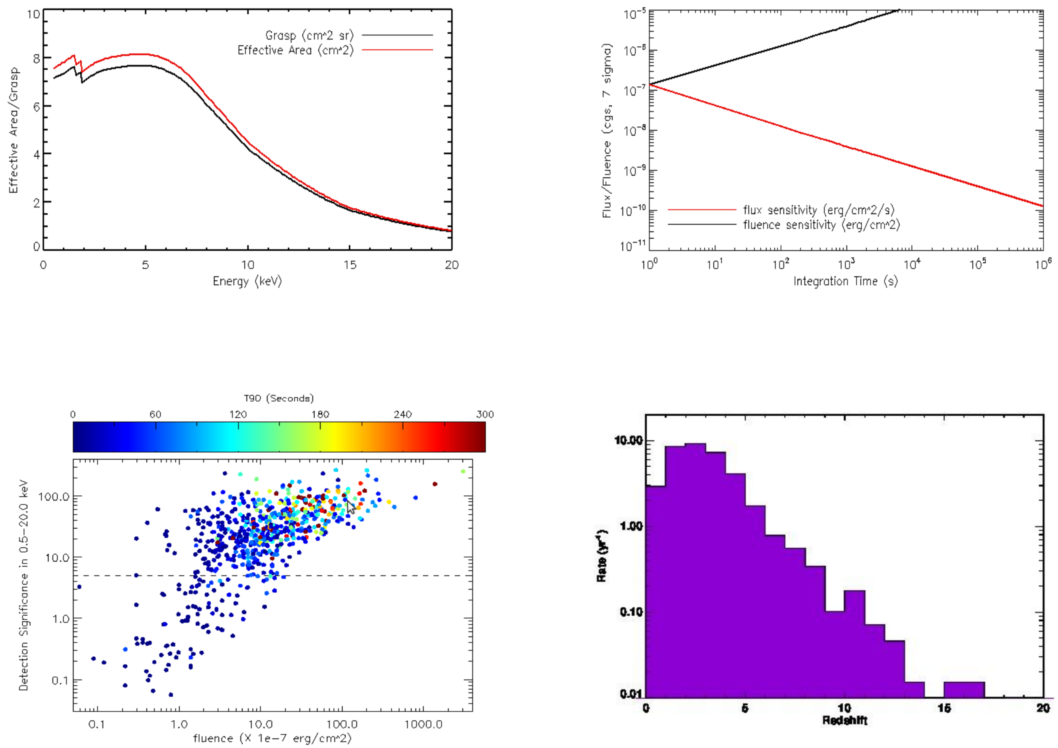
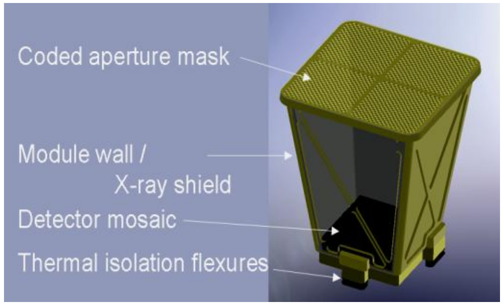


Fig 1: Top: Effective area (left) and sensitivity (right) for the proposed 1st BlackCAT configuration, using four 550x550 detectors. Bottom: Distribution of GRB fluence and T_{90} with BlackCAT 5σ detection threshold (left) and redshift distribution of the detectable GRBs with BlackCAT (right).

BlackCAT x N Parameters & Requirements

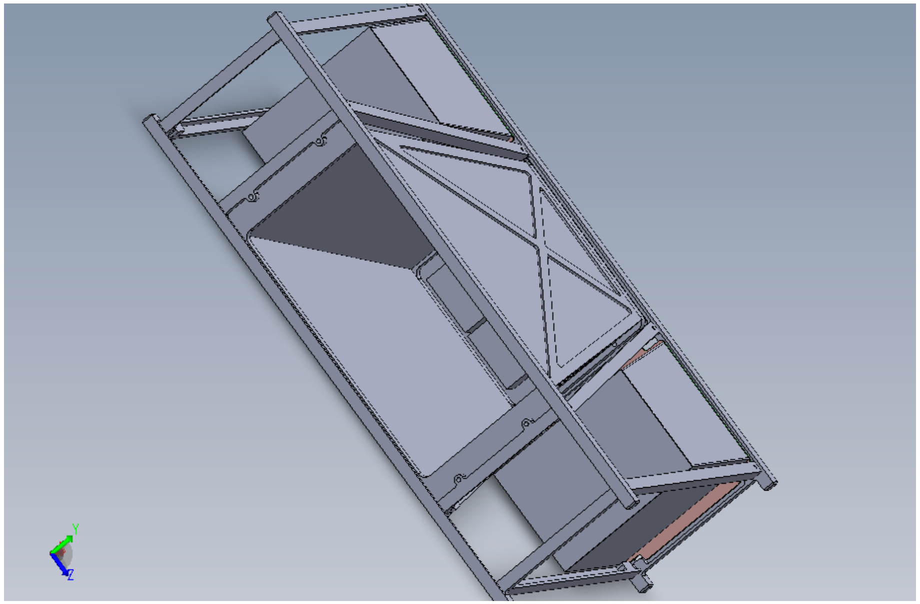


× *N*

- ***N*** **Independently flying identical modules (N=1, or 4-10)**
- **Each module contains a coded mask in front of an array of 4 Si hybrid CMOS detectors**

Parameter	BlackCAT single module
Bandpass	1 – 20 keV (goal 0.5-20 keV)
FoV	1.2 sr (~3.5 sr for 6 modules with anti-Sun offsets)
Angular Resolution	6.3 arcmin (FWHM)
Position Accuracy	1 arcmin (30 arcsec for bright GRBs)
Module opening area	17.0 x 8.8 cm
ΔE/E	<5% at 5.9 keV (goal of <3%)
DXRB rate	~ 540 cts s^{-1} (TBD?)
Internal Bkgnd	< 1 cps
Pt Src Sensitivity	~ 240 mCrabs (7σ, 30s, 1 module) (with H2RGs)

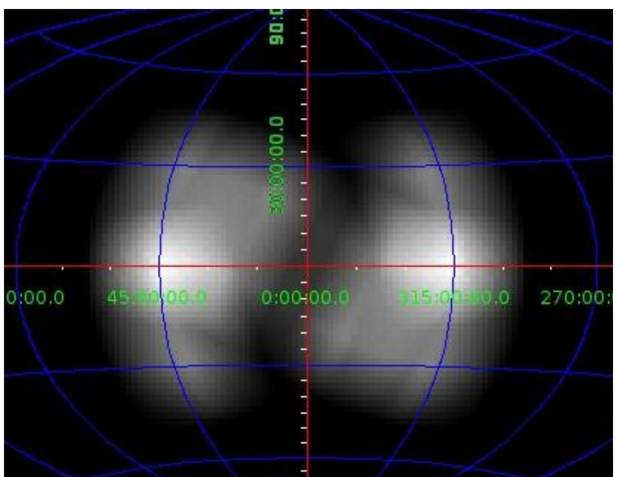
BlackCAT/s orbit and orientation



- BlackCAT is currently proposed as a single 6U cubesat

  ... we envision an eventual expansion to 4-10 detector modules spaced in Sun synchronous orbits on individual spacecraft

- FOV faces anti-Sun
- solar panels (on side opposite the FOV) always face Sun
- radiator on large side always facing away from Earth
- antenna on large side always facing Earth



Simulation of 6 separately orbiting BlackCAT modules

Offsets of 20° (2 DMs) and 40° (4 DMs) from horizon

Stray Light

- Detectors coated with 1000 Å Aluminum
  - Optical transmission < 10^{-6}
  - No damage to detectors from Bright Objects
  - No degradation from Moon
  - Earth is opaque, so no degradation from bright Earth

BlackCAT Pointing Needs & Positioning

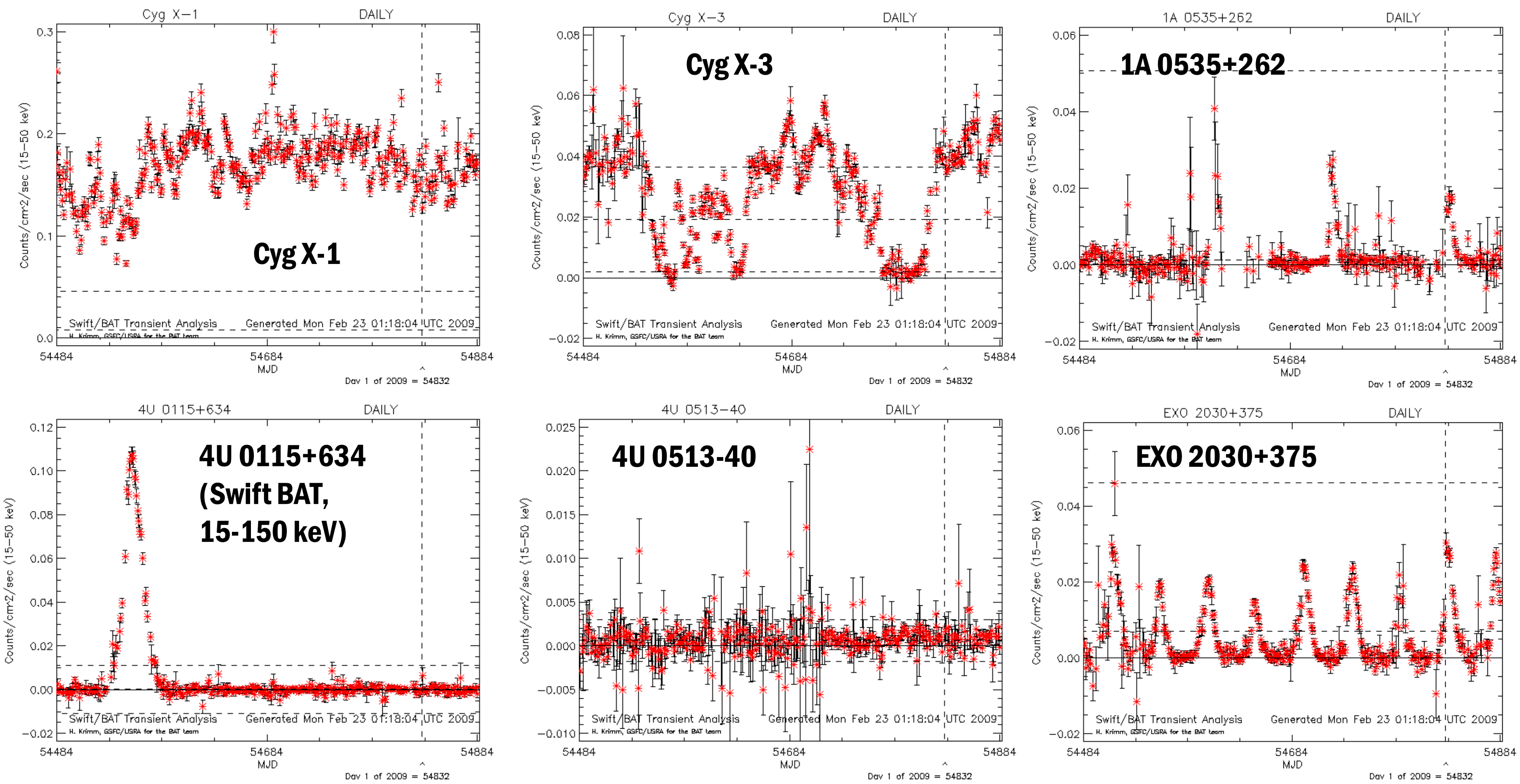
Table 3: ADCS	Performance
Pointing Knowledge (3σ)	<30 arcsec
Pointing accuracy (RMS)	<30 arcmin
Stability (deg/s)	±0.0004
Jitter	<50 arcsec

BlackCAT expects to obtain the following centroided position accuracy for GRBs (90% confidence *radius*):

- **70 arcsec for dim GRBs**
- **41 arcsec for bright GRBs**

BlackCAT Transient Survey

BlackCAT will also survey the sky and produce light curves (0.5-20 keV) of hundreds of transient X-ray sources



Concluding Remarks

BlackCAT has been proposed to NASA as a small CubeSat mission, with a proposed launch in April 2022.

This small mission would detect high redshift GRBs and gravity wave counterparts during this prime-time for multi-messenger missions accompanying advanced GW detectors, as well as LSST and neutrino detectors.

It would pave the way for a network of several enhanced versions of BlackCAT to monitor a larger solid area of the sky with multiple cheap CubeSats viewing different directions.

Extra Slides

Monitoring sensitivity (1 Module)

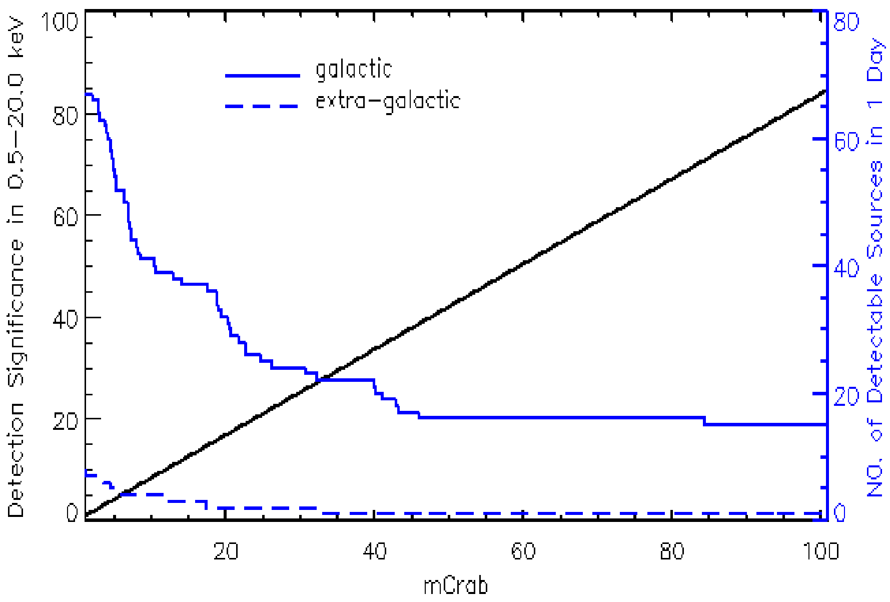


Fig 2. Daily monitoring sensitivity of BlackCAT (black solid line) assuming 50% of duty cycle. Detectable galactic and extra-galactic sources in 1 day is shown in blue solid and blue-dashed lines, respectively.

High redshift GRB Science

Measure the cosmic star formation rate over 5<z<12 by detecting and observing high-redshift gamma-ray bursts and their afterglows.

- *Single module w*ill detect many bursts at *z*>5, and ~1/year at z>8
- redshift derived from ground data
- *B*urst redshifts will reveal the cosmic star formation rate over 5 < *z* < 12
- Stellar light was likely the dominant cause of the cosmic reionization
- Star formation estimates are crucial to constructing a full picture of reionization