

Micro-X: Transition Edge Sensors for X-ray Astrophysics, to Cas A and Beyond



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SLAC FPD Seminar



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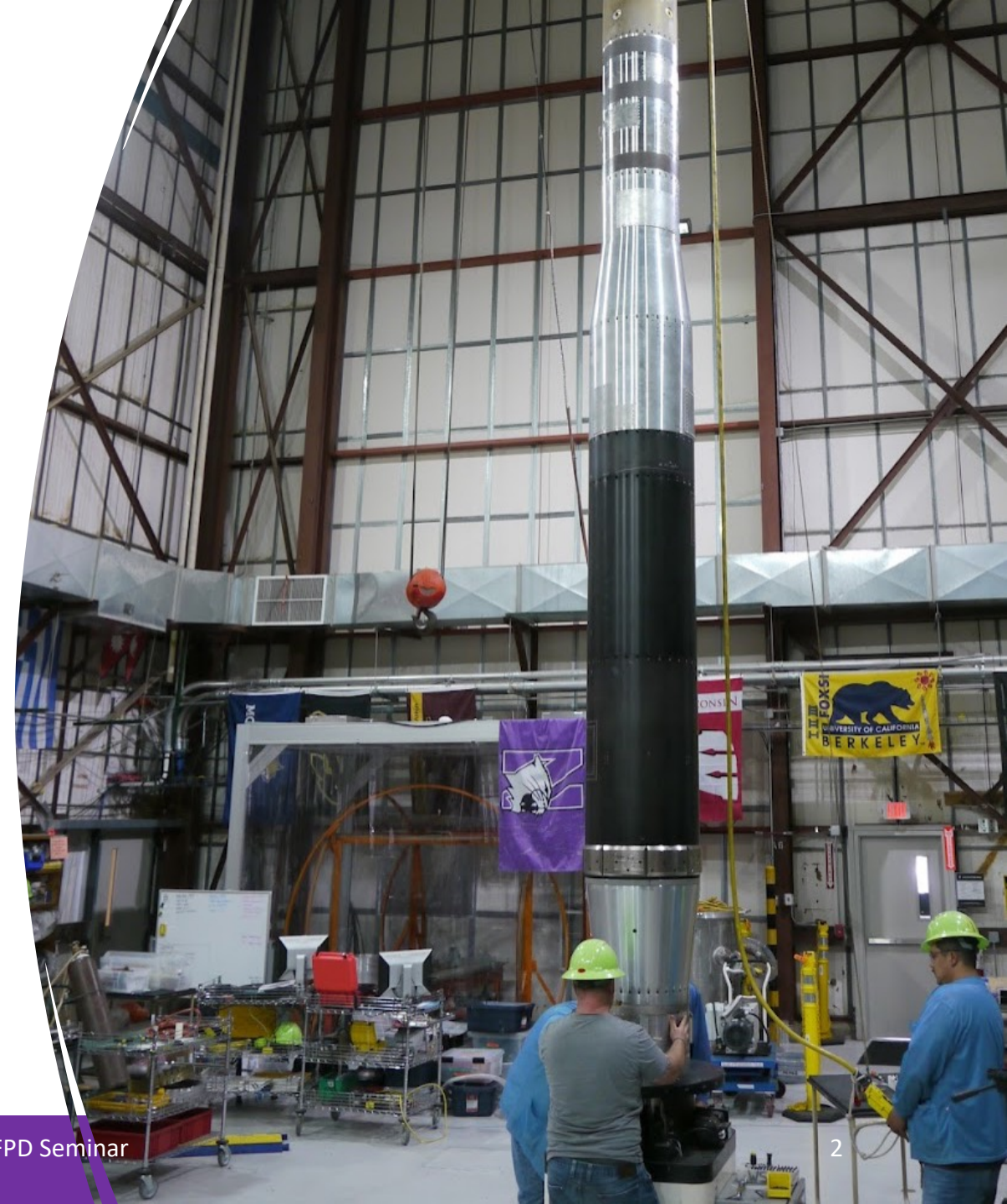
Northwestern

NIST



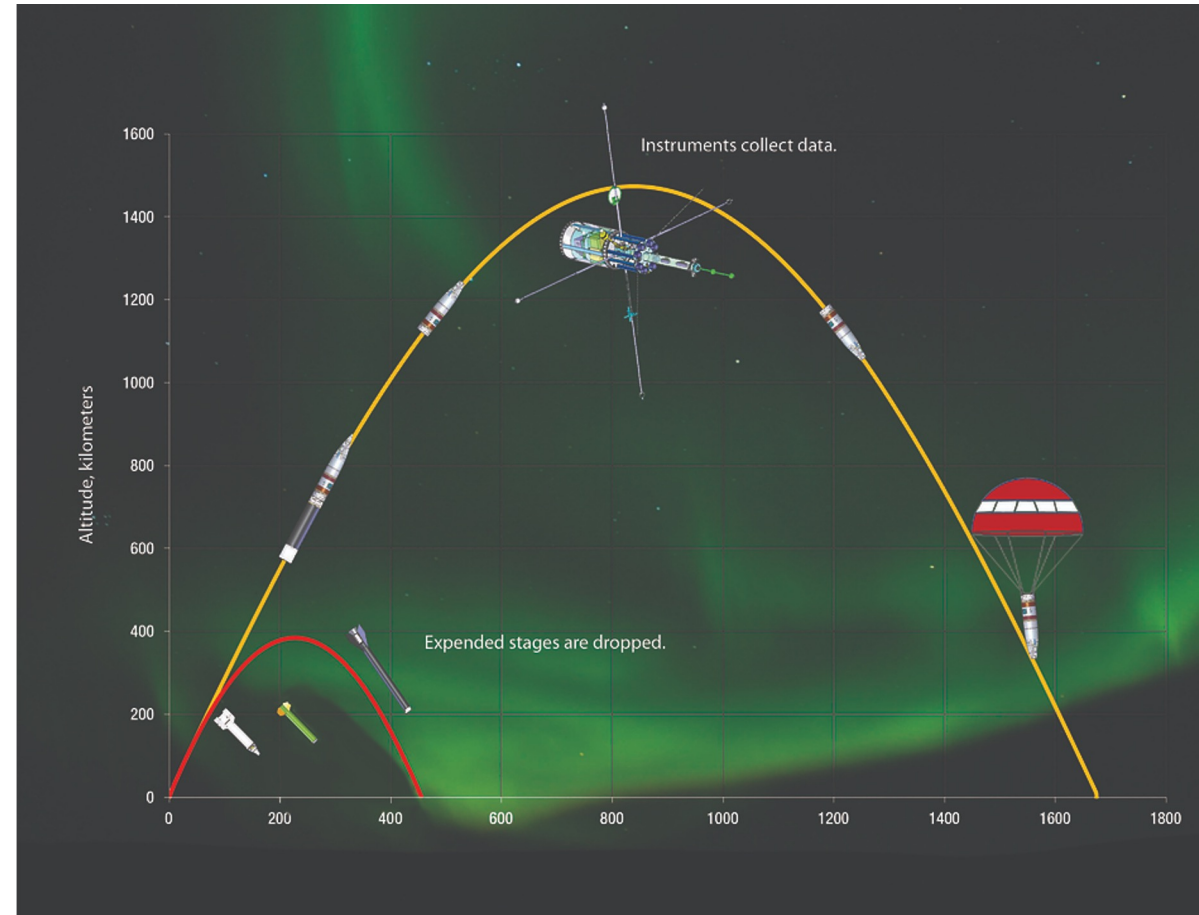
Talk Overview

- Why Sounding Rockets? Why TESs? Why Micro-X?
- Overview of the Micro-X Instrument
- Flight 1 (2018) and the first TES operation in space
- Flight 2 (2022) and the first TES astrophysics
 - Measuring the supernova remnant Cas A
- TESs for x-ray space observatories of the future

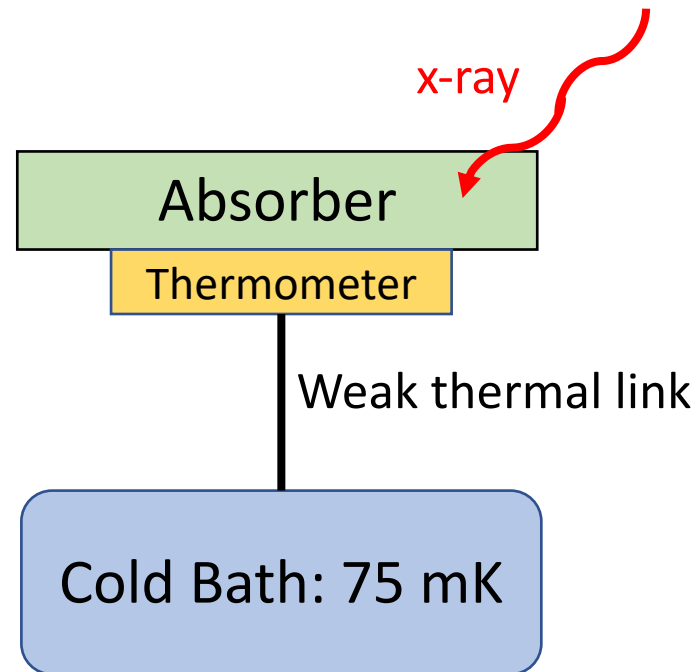


Why Sounding Rockets?

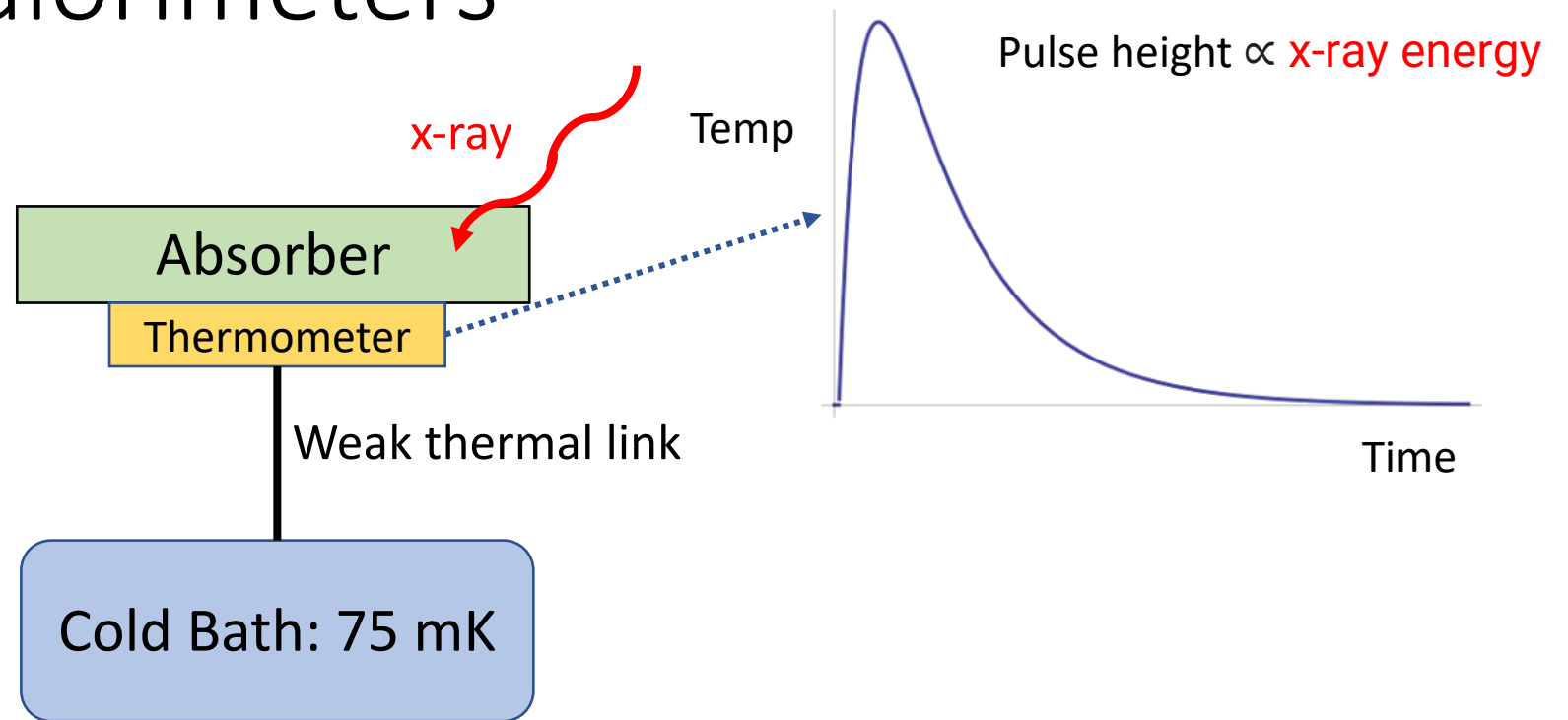
- Sub-orbital rocket flight lasting only 15 minutes
 - Orders of magnitude cheaper than a proper space observatory
- Five-minute observation window above 160 km to measure x-rays
 - More x-rays than a months long balloon flight
- Recoverable and reusable payload
 - 2018: First operation of TES+SQUIDs in space
 - 2022: First astrophysical data collection with TESs+SQUIDs in space



Intro to Microcalorimeters



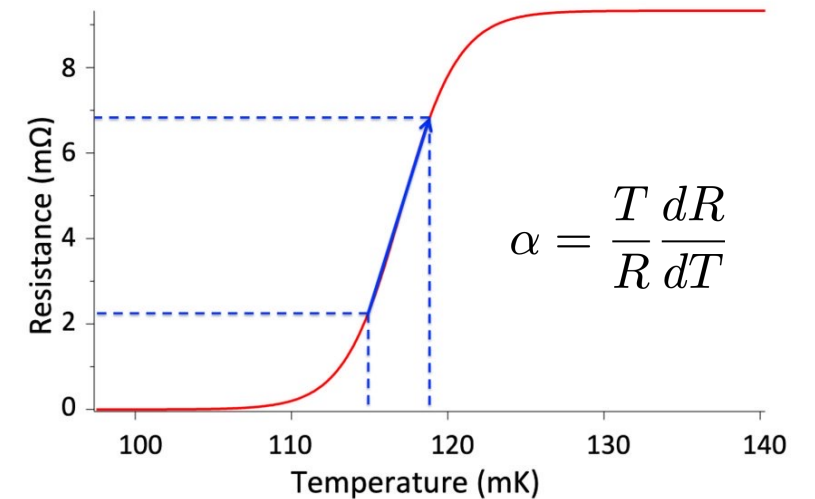
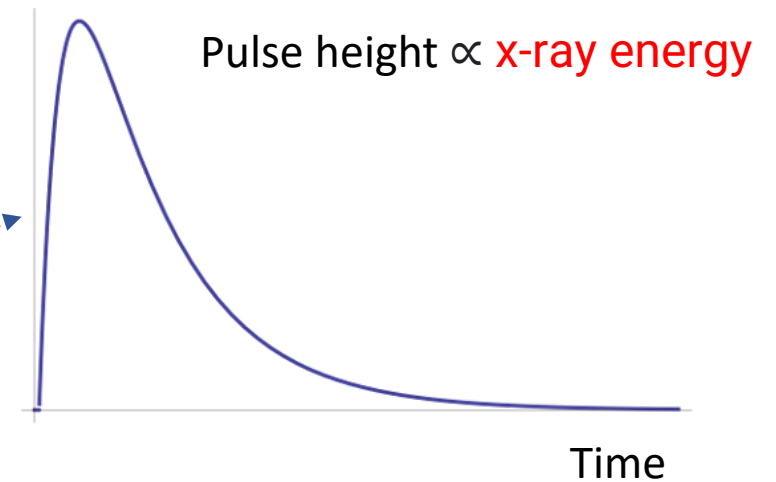
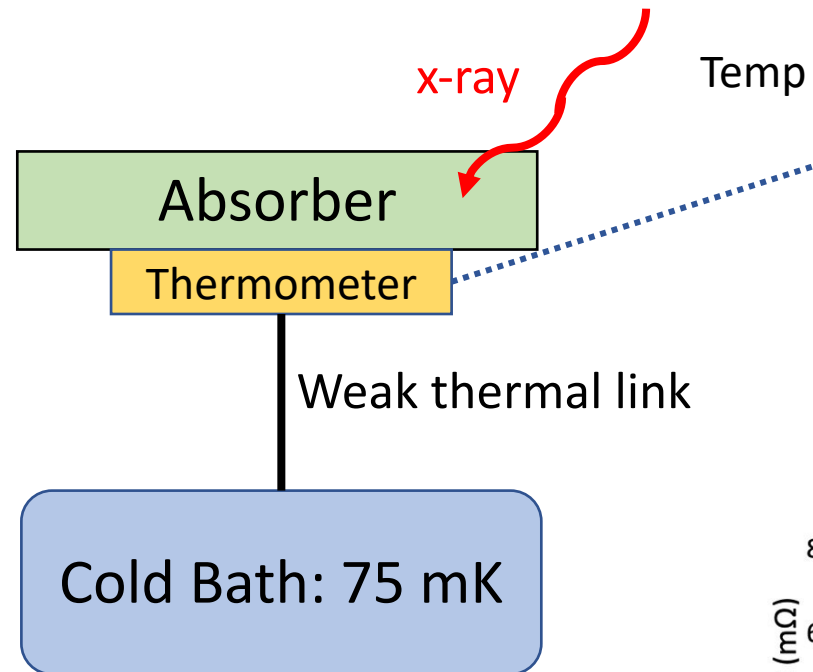
Intro to Microcalorimeters



Intro to Microcalorimeters

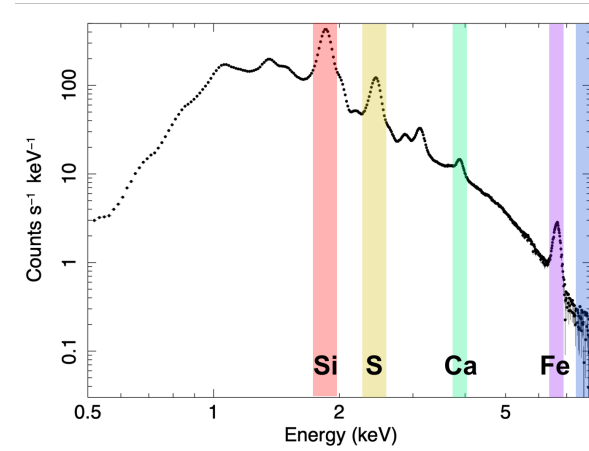
Transition Edge Sensors!

- Highly sensitive thermometers for microcalorimeters
- Low resistance change measured by SQUID
 - SQUID multiplexing to read out large TES arrays



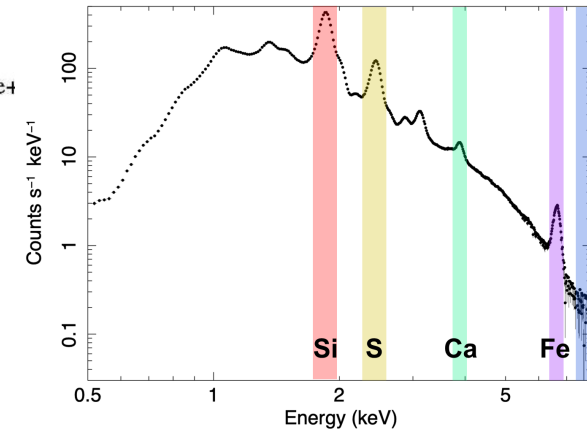
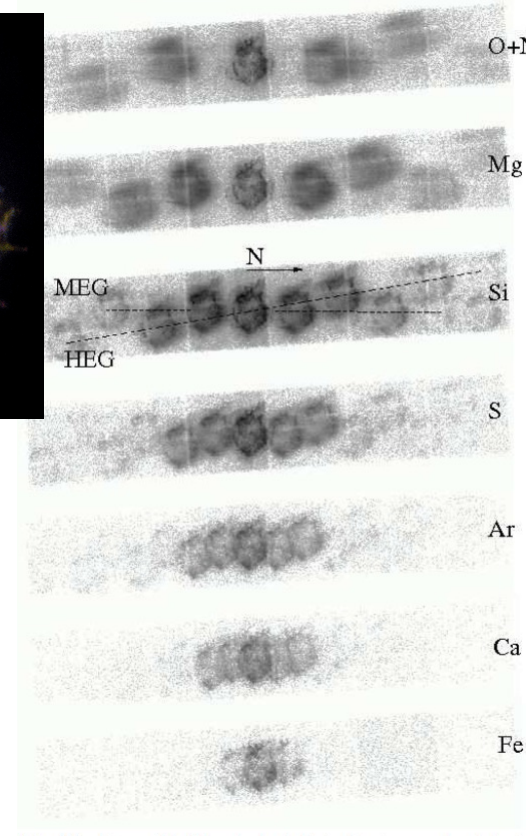
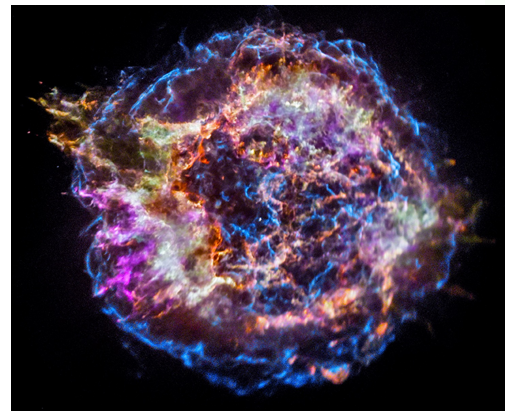
TES for X-ray Astronomy

- High energy resolution spectra from diffuse x-ray sources
 - CCDs have excellent spatial resolution, but moderate energy resolution



TES for X-ray Astronomy

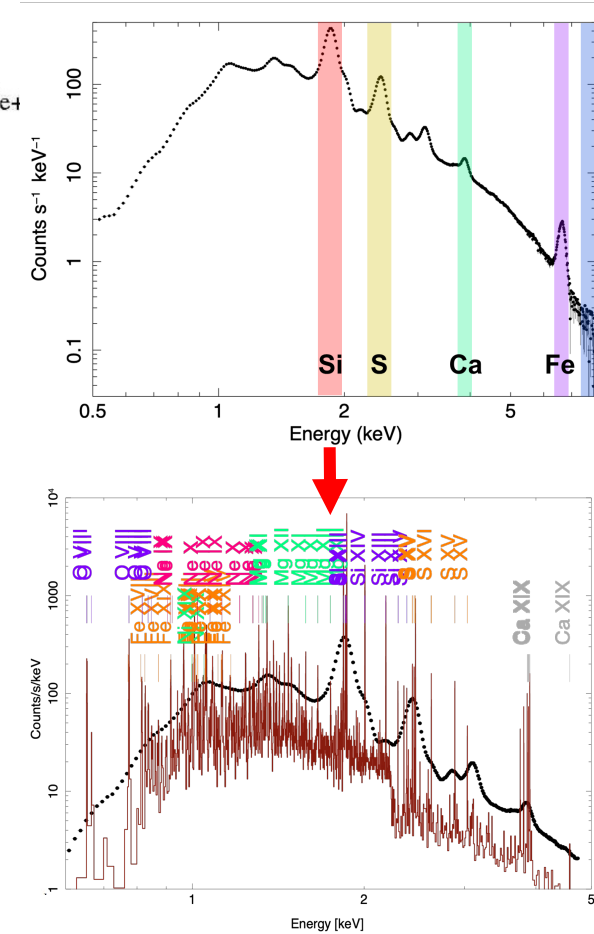
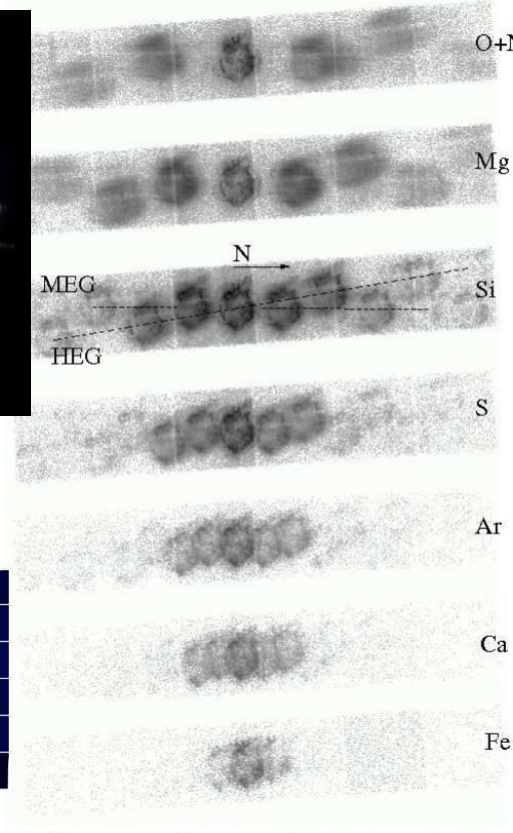
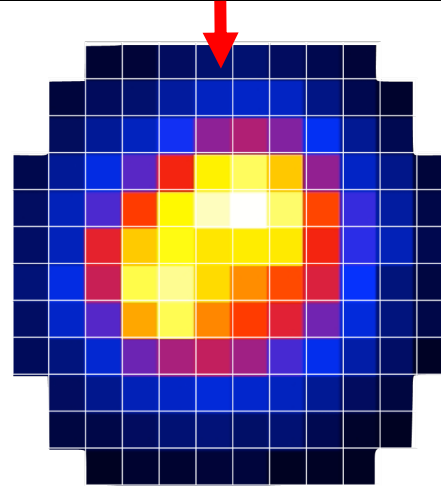
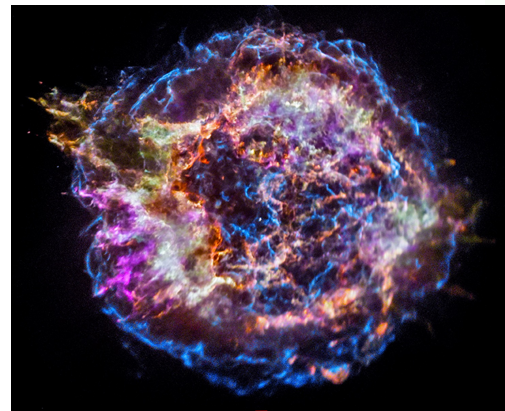
- High energy resolution spectra from diffuse x-ray sources
 - CCDs have excellent spatial resolution, but moderate energy resolution
 - Grating spectroscopy works best for point sources or small, bright features within diffuse objects



Chandra HEG + ACIS-S DOI 10.1086/507481

TES for X-ray Astronomy

- High energy resolution spectra from diffuse x-ray sources
 - CCDs have excellent spatial resolution, but moderate energy resolution
 - Grating spectroscopy works best for point sources or small, bright features within diffuse objects
- Microcalorimeters:
 - X-ray spectroscopy of diffuse sources
 - Optimizable for a wide variety of applications

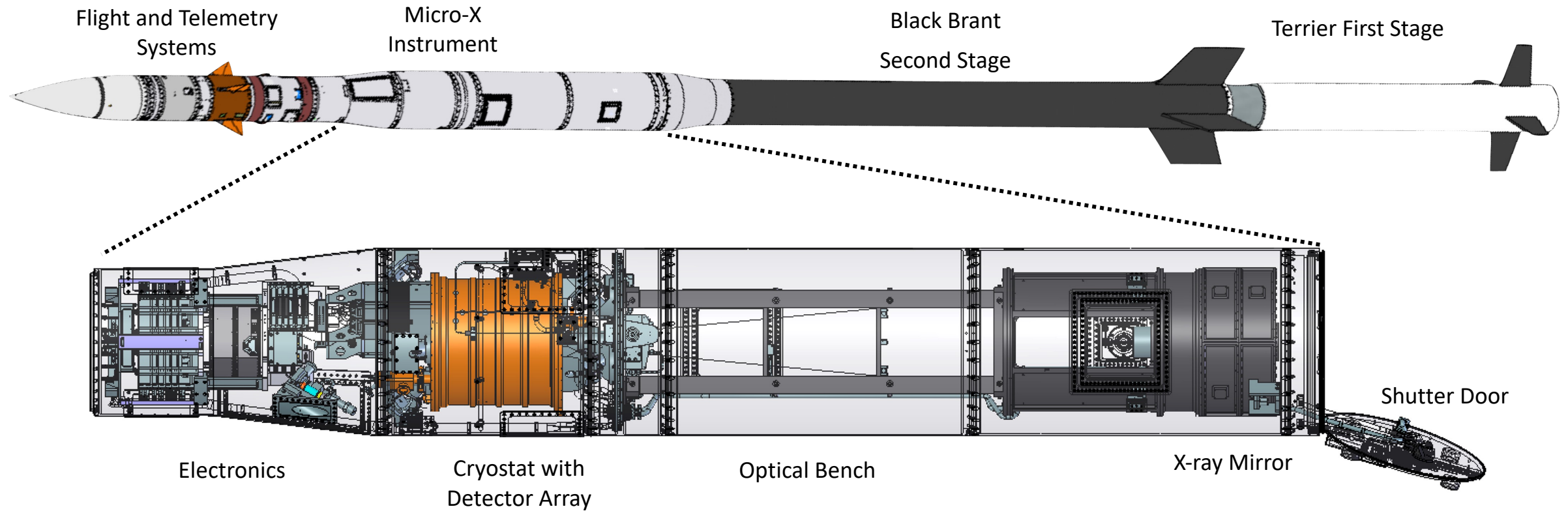


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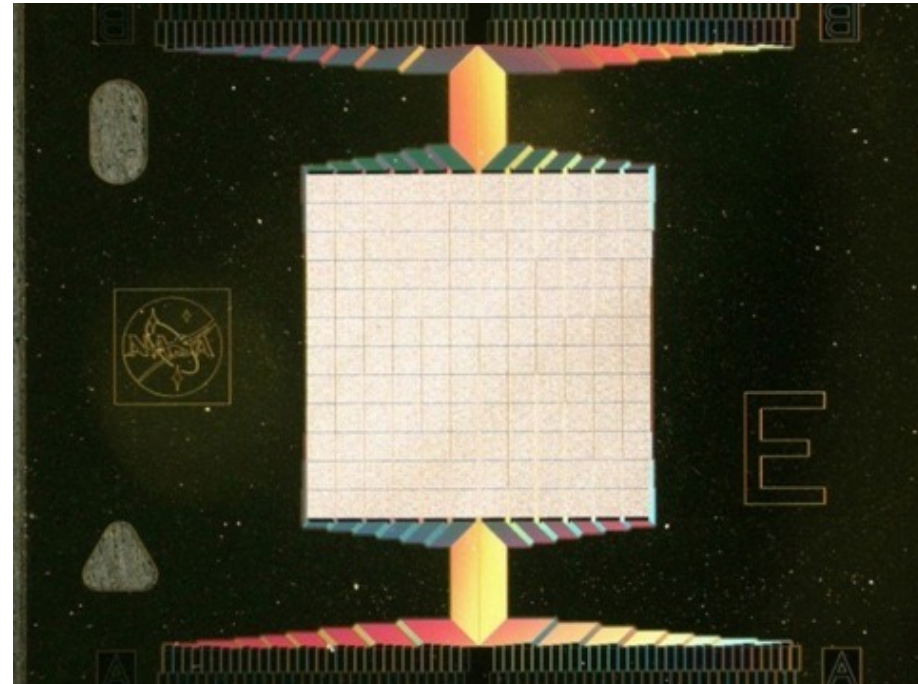
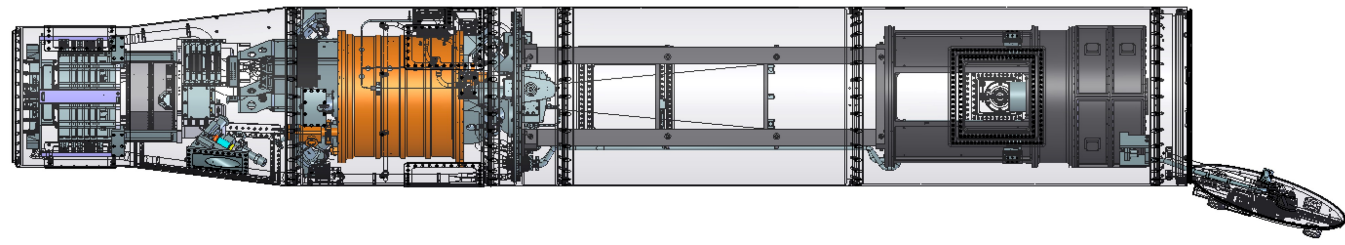


The Micro-X Sounding Rocket

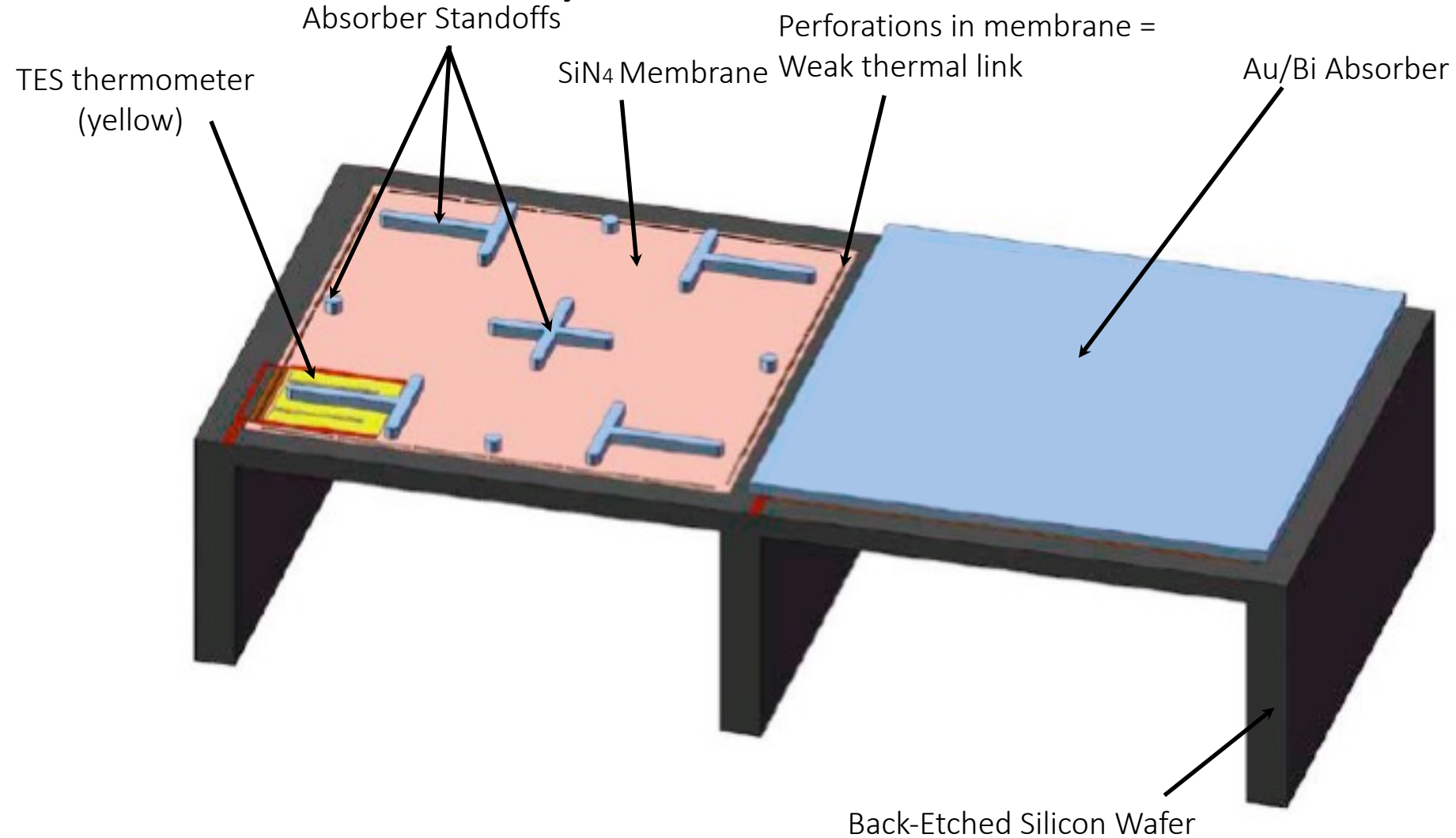
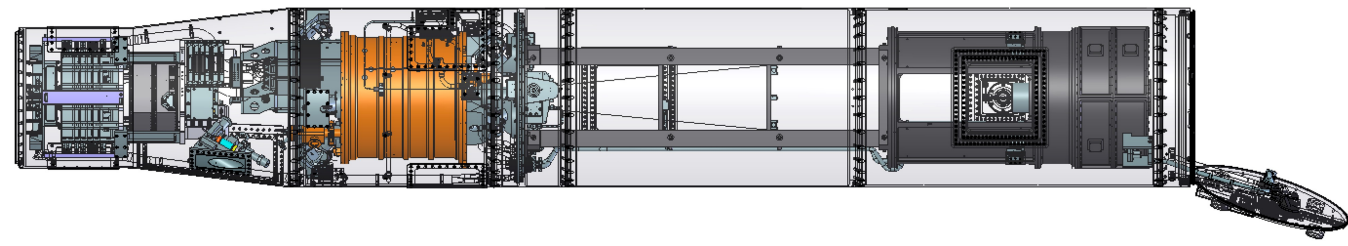
Micro-X Instrument



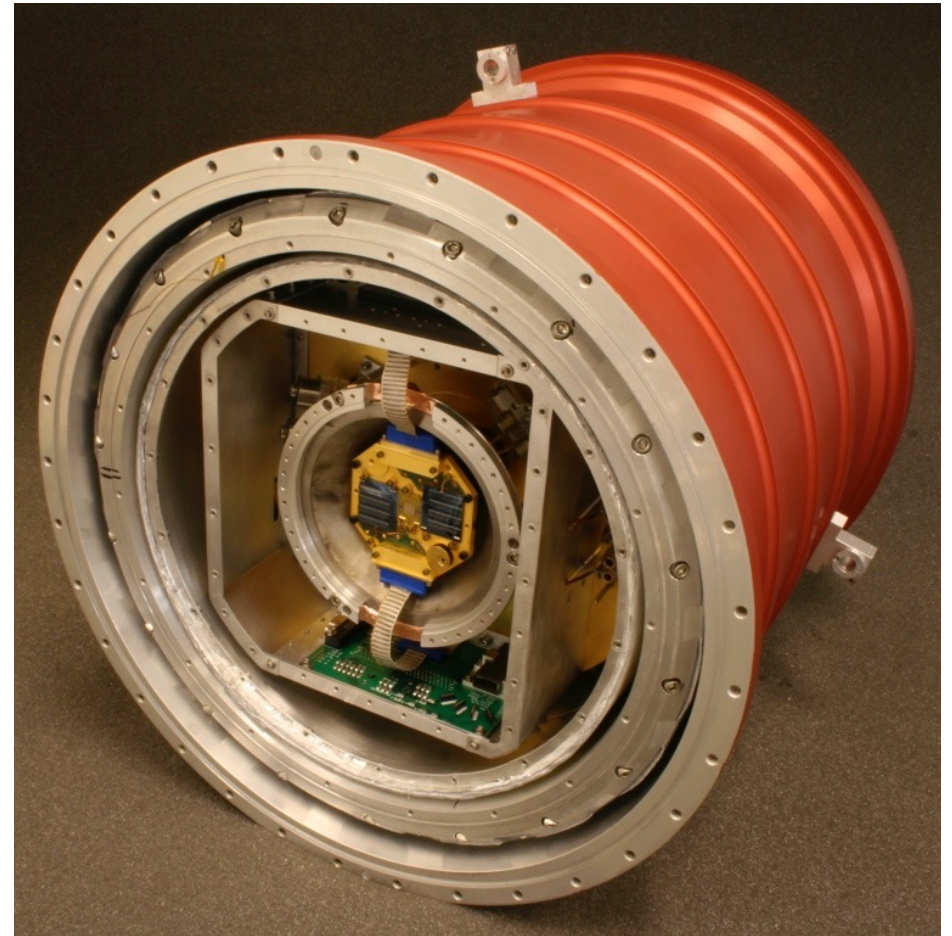
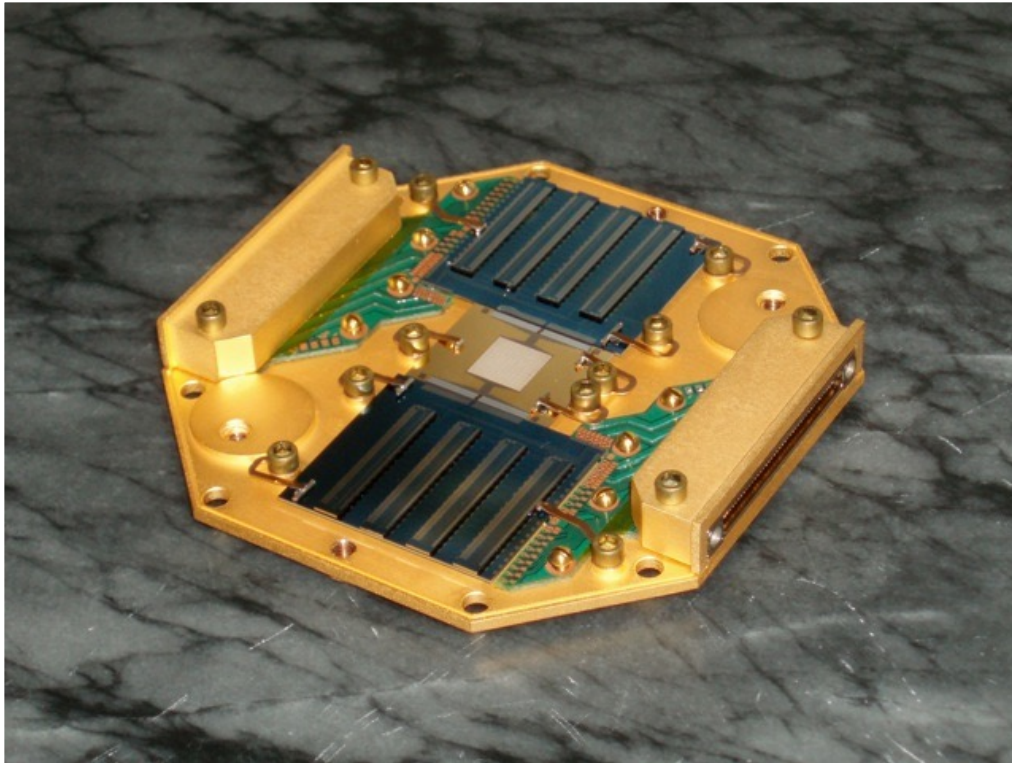
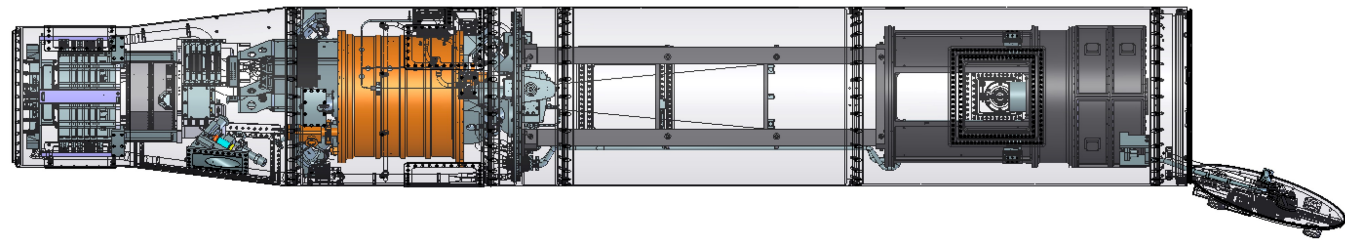
Micro-X TES Array



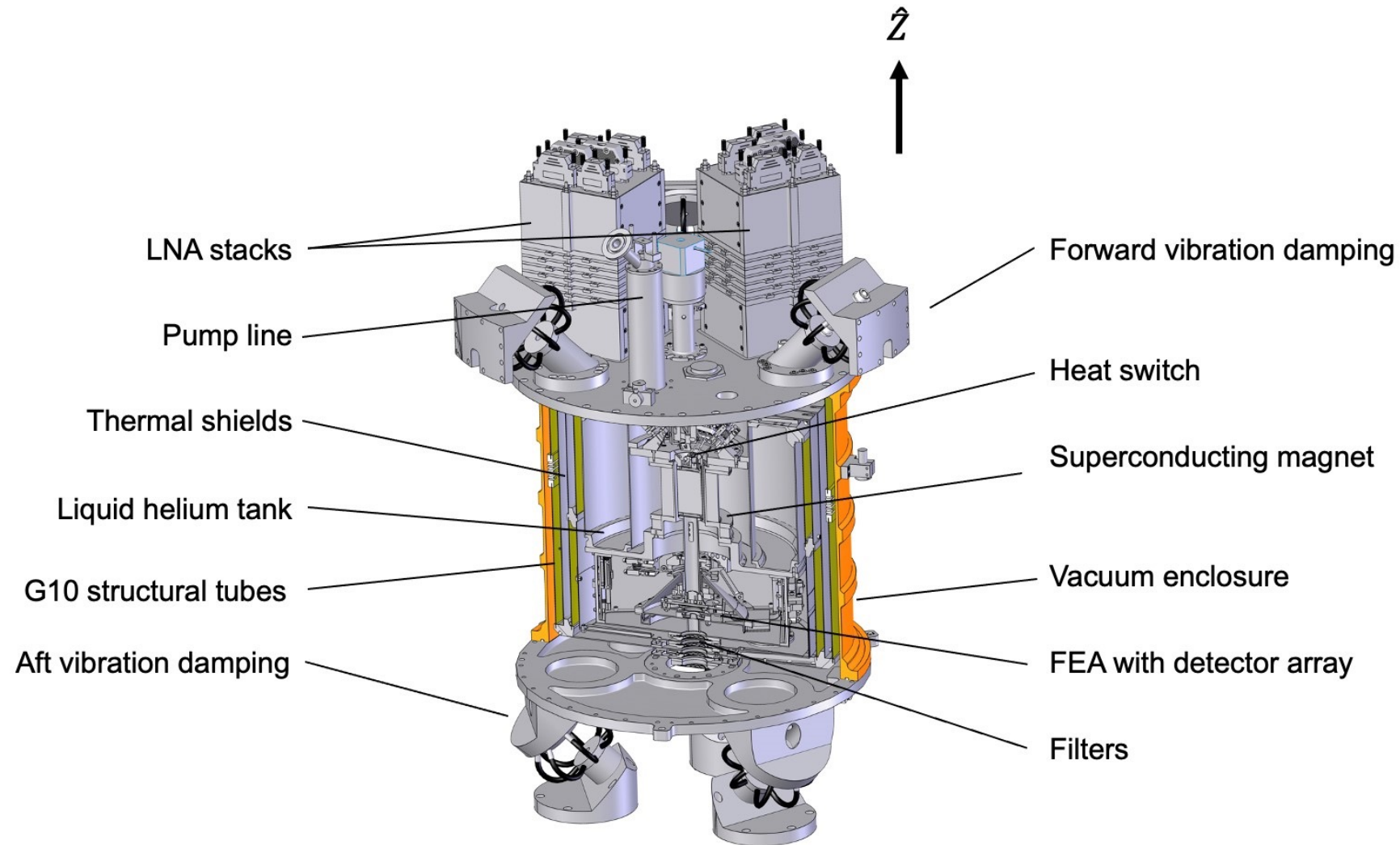
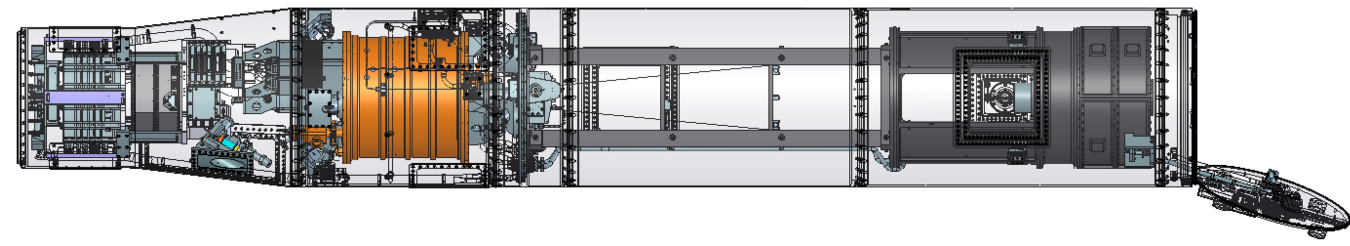
Micro-X TES Array



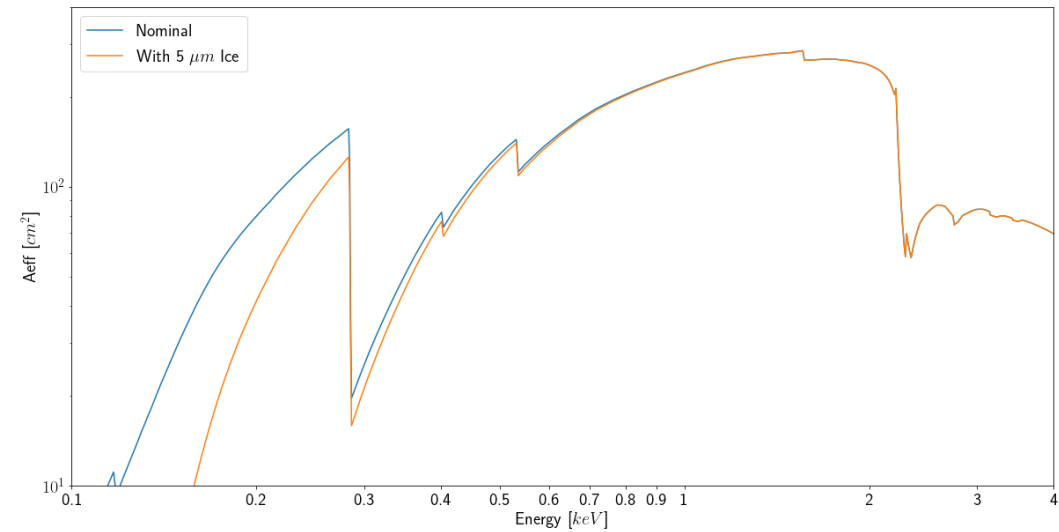
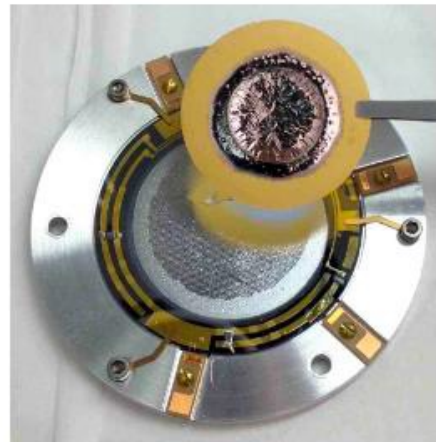
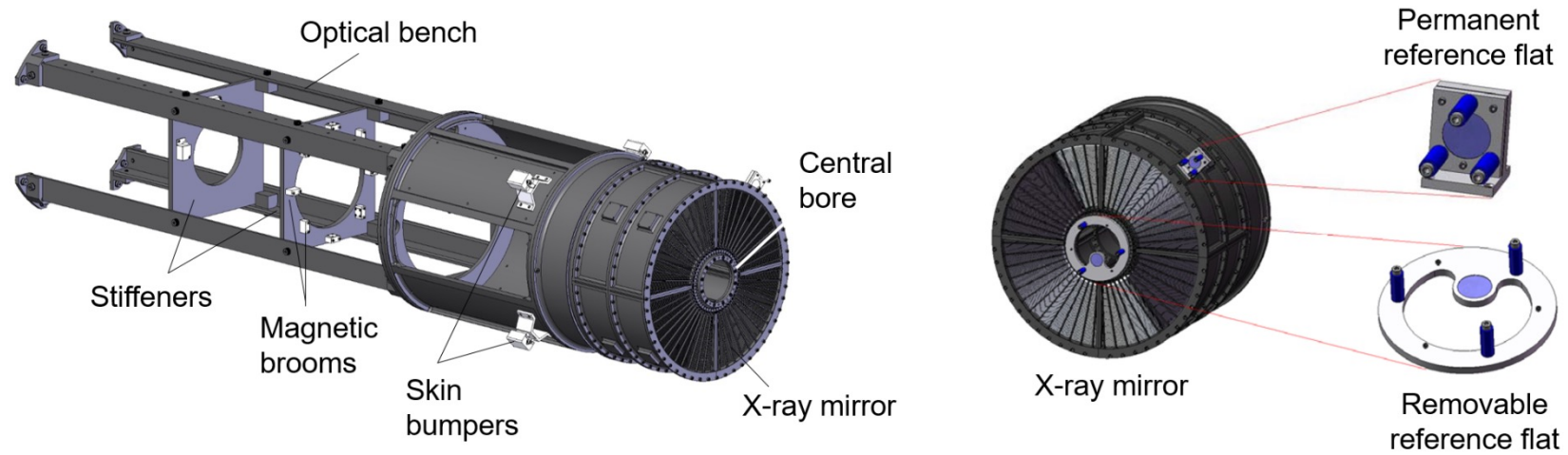
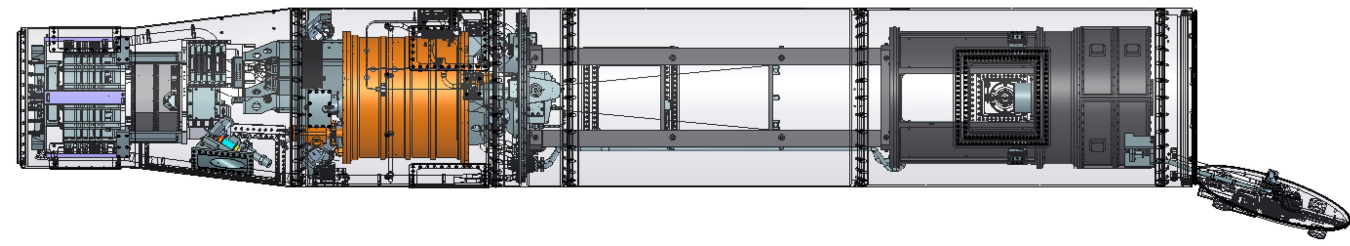
Micro-X TES Array



Micro-X Cryostat



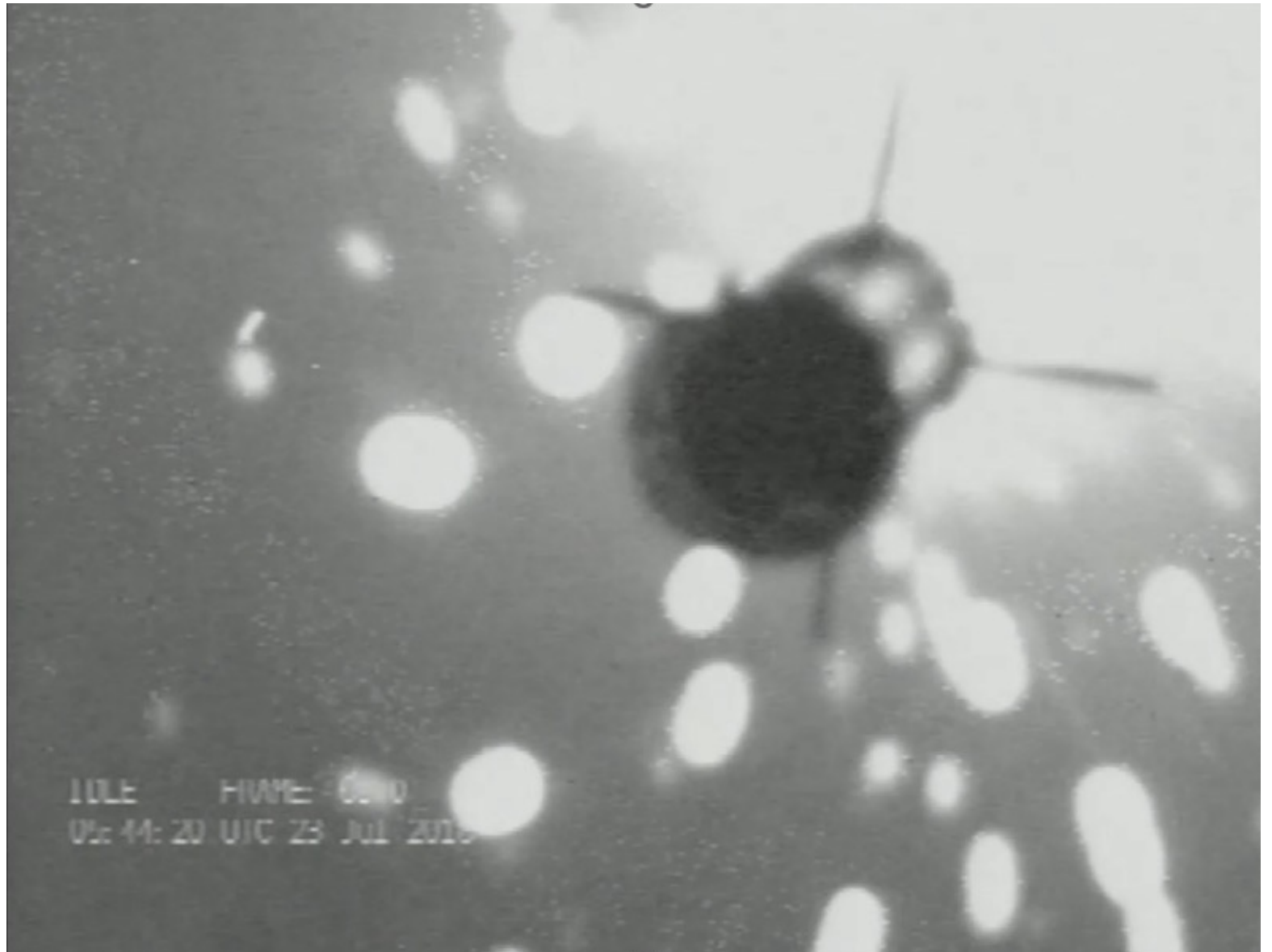
Micro-X Optics



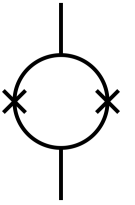
Micro-X Instrument Overview

The Micro-X Instrument	
Science Observation	300 s
Bandpass	0.2 – 2.5 keV
Field of View	11.8 arcmin
X-Ray Optics	Collecting area: 300 cm ² @ 1 keV Focal Length: 2.1 m Half Power Diameter: 2.4 arcmin
Microcalorimeter Array	128 TES Pixels operated at 75 mK Pixel pitch: 600 um (59 arcsec per pixel) 8x16 SQUID TDM Readout 5-10 eV Resolution @ 1 keV
Cryogenics	ADR hold time: >6 hours at 75 mK

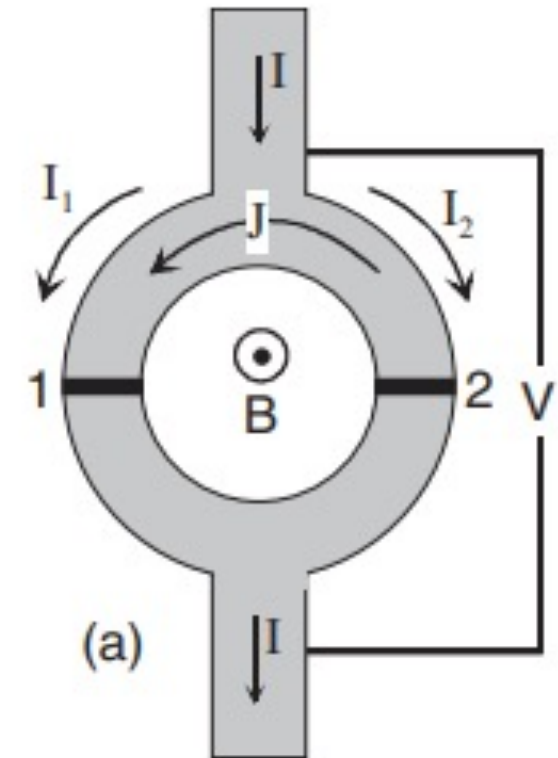
The Micro-X First Flight (2018)



Intro to SQUIDs

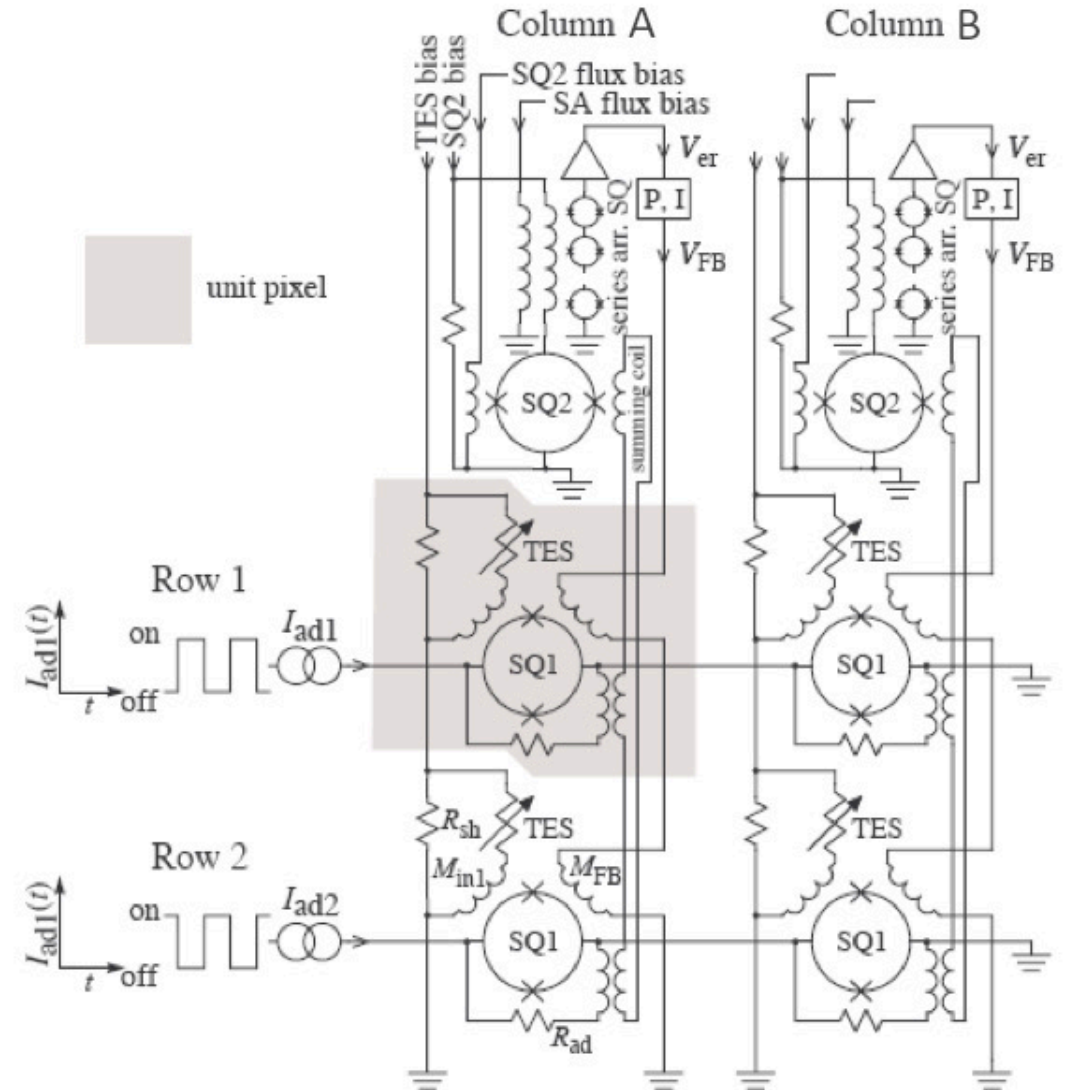


- Superconducting and inherently “quantum” electronic devices
 - Incredibly sensitive magnetometers
 - Acts as a flux-to-voltage transformer
 - Has a period flux to voltage relationship, or “ $V-\phi$ ”
 - Results from a combination of flux quantization and Josephson tunneling



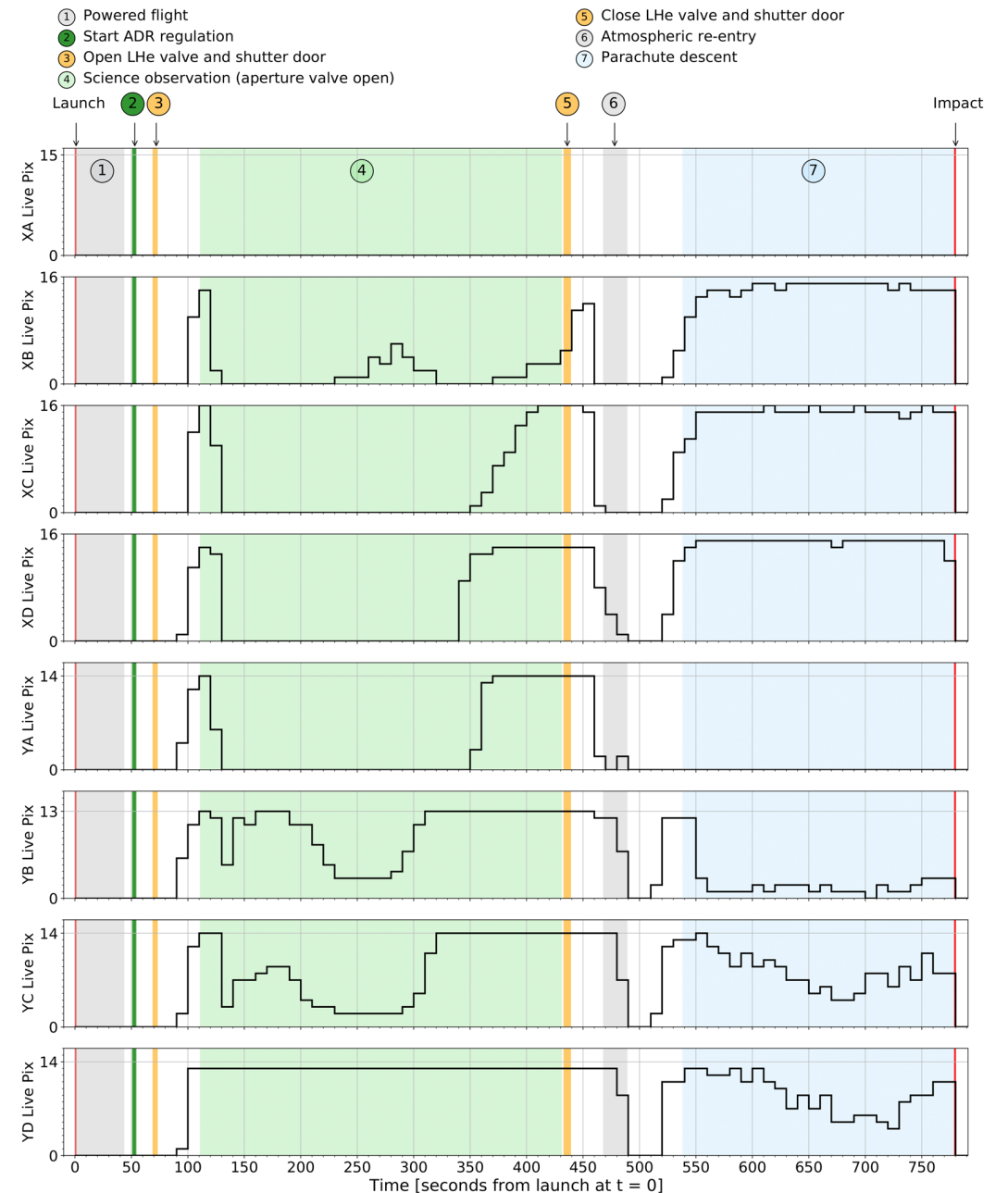
Intro to SQUIDS

- Used to read out TES signals with several advantages
 - Easily impedance matched to the very small TES resistance
 - Amplifies the signal at cryogenic temperatures to be read by room temperature electronics
 - **Can be “locked” in a flux-locked-loop (FLL) to linearize the output signal and measure signals > 1 flux quantum**
 - Very high bandwidth – can create multiplexed readout schemes to measure large arrays of TESs with fewer wires



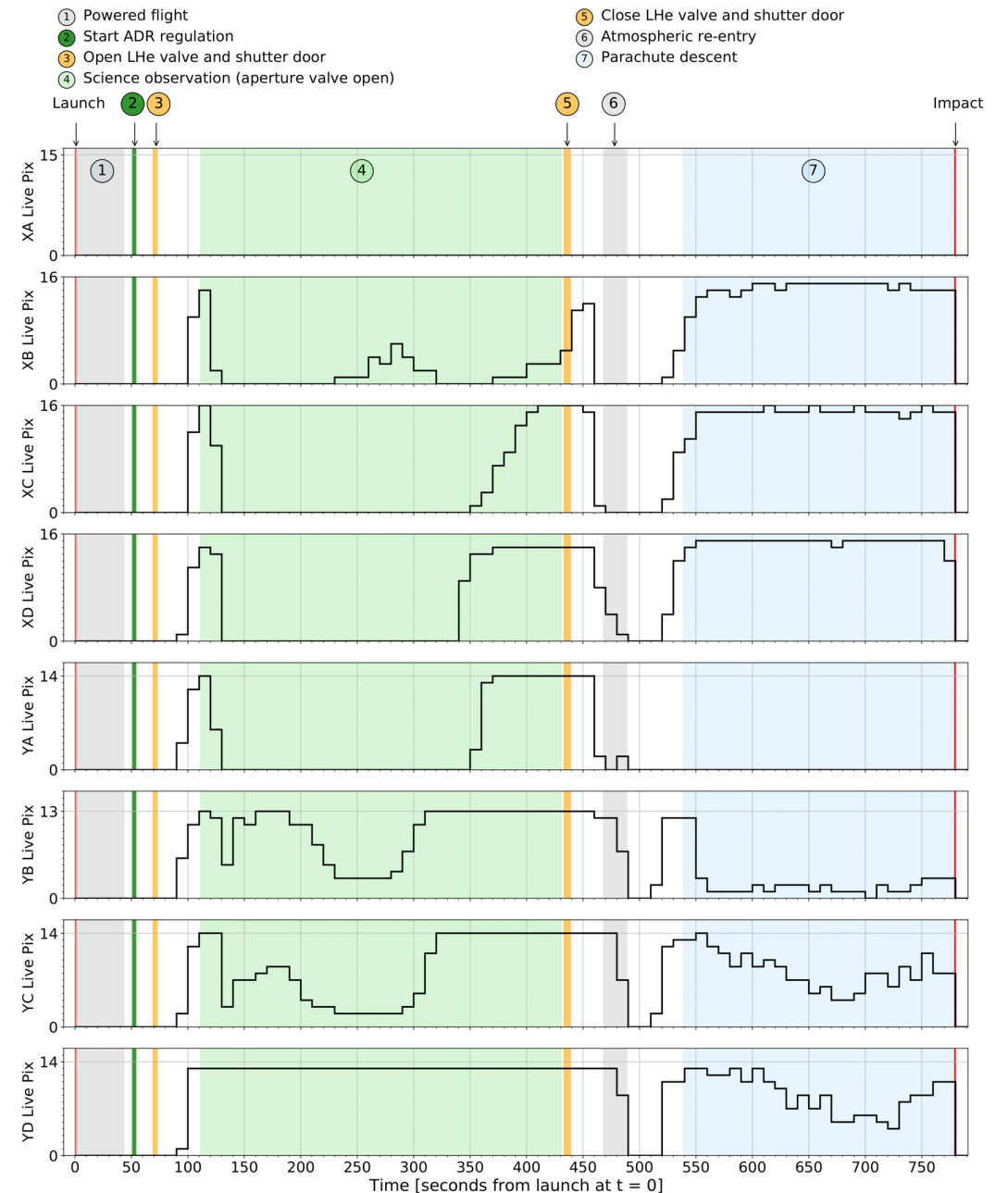
SQUID Unlocking

- Due to an ACS failure, the rocket tumbled during the first flight
- SQUIDs initially locked with the TESs at 75mK
- Some SQUIDs proceeded to drift in and out of lock during the science observation period



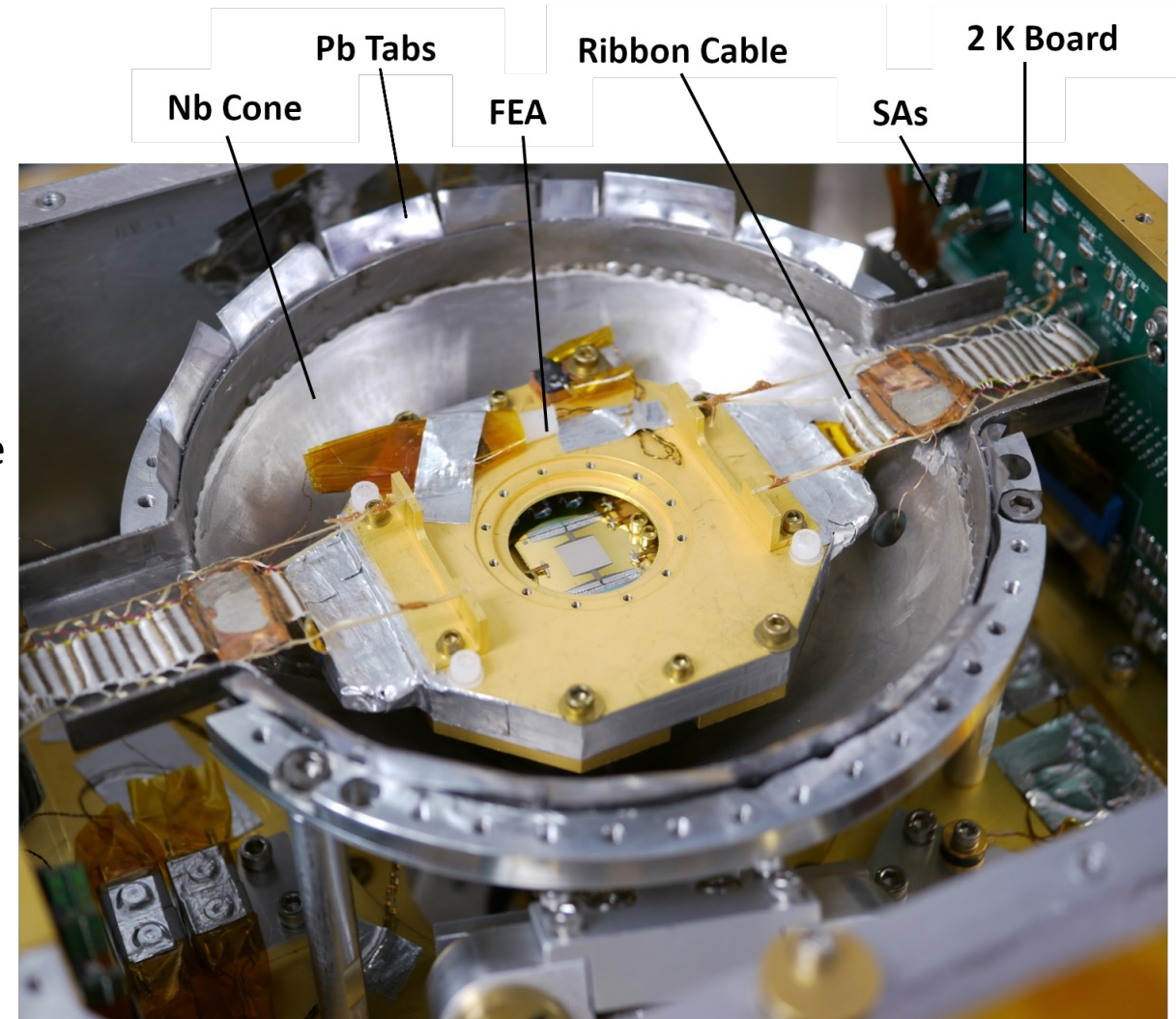
SQUID Unlocking

- Hypothesis: SQUIDs responding to changing orientation in Earth's magnetic field
- Questions:
 - What is the unlocking mechanism?
 - Why do the two detector sides (X and Y) respond differently?
 - Why do pixels tend to lock/unlock as a column?
 - Can we explain all the observed pathologies?



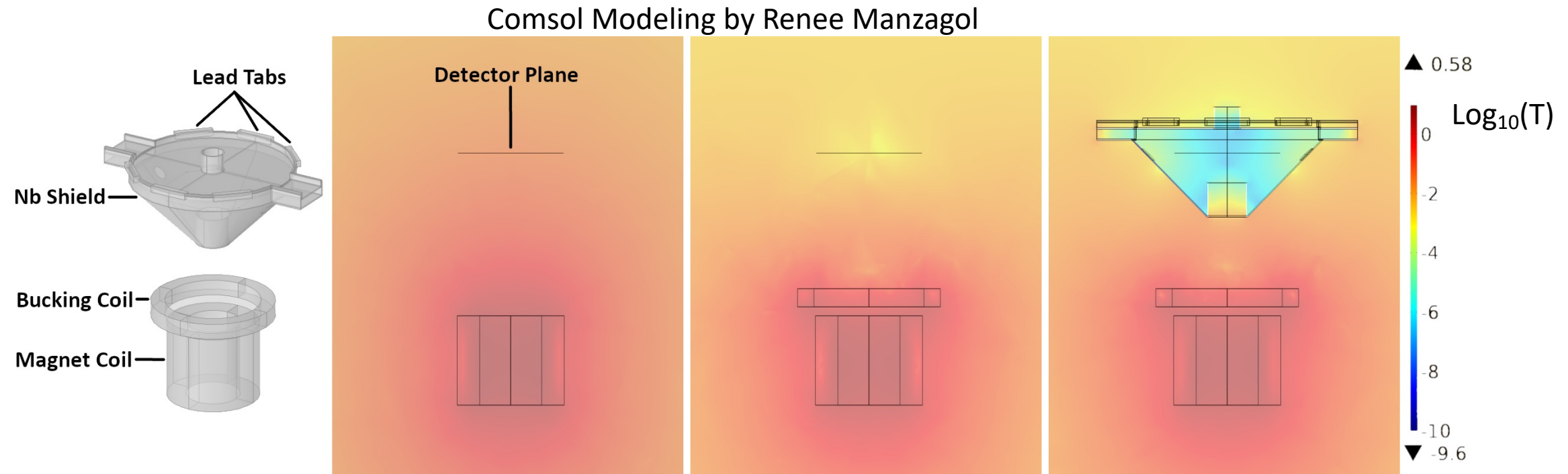
Magnetic Shielding

- SQUID MUX Chips and TESs protected by a superconducting Nb shield
 - Two parts: conical base + lid
 - Joined by a Pb “zipper” to make a superconducting joint
- SA SQUIDs are outside the primary Nb shield and are contained in their own 4-sided Nb box
- The instrument is wrapped in a Metglas blanket during cooldown to minimize flux trapping



Magnetic Shield Modeling (Comsol)

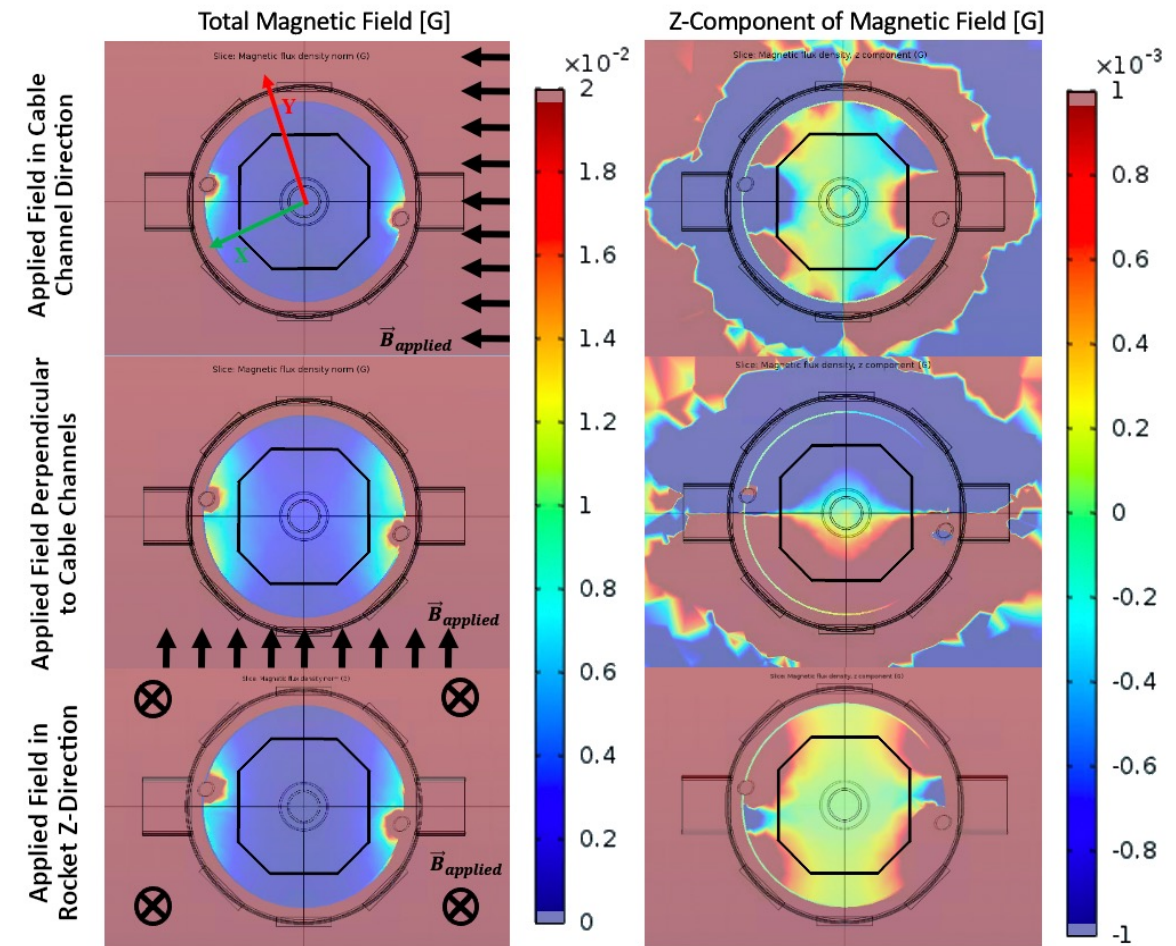
- Nb can provides excellent shielding of the TESs from the ADR magnet
- Nb modeled as “Magnetic Insulation”: $(\nabla \times A)_n = 0$



Magnetic Shielding of B_{Earth}

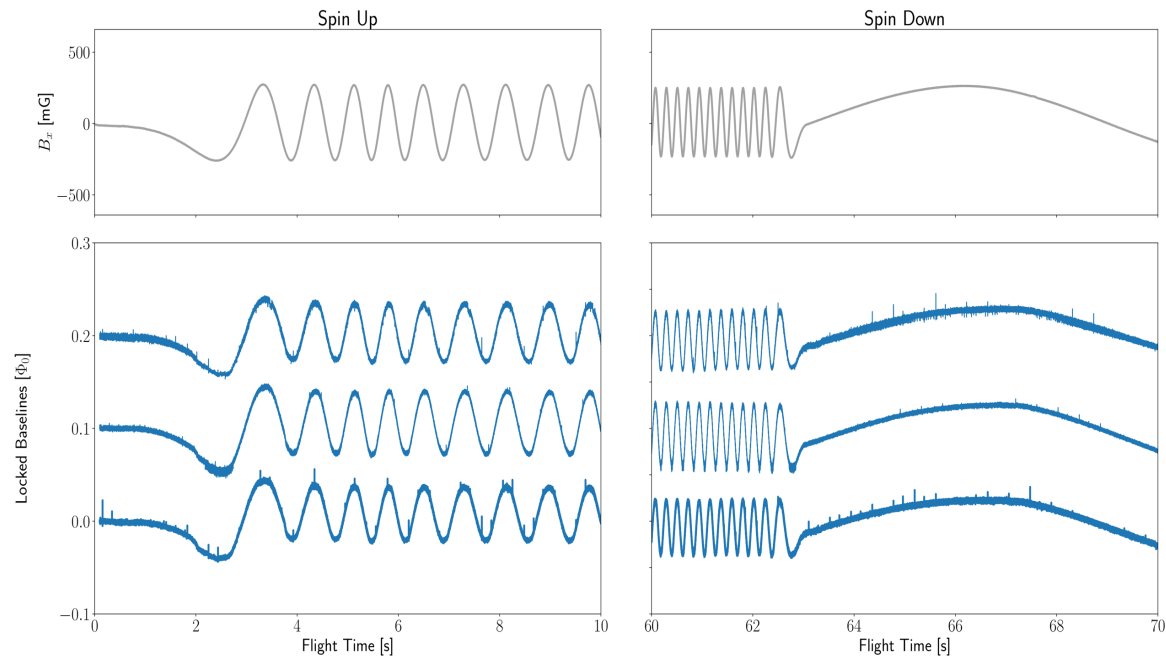
- B_Z Inside shield up to $\sim 1\text{mG}$
- Asymmetric B_Z across the shield
 - *Expect opposite SQUID response between detector side X and Y*, confirmed with Helmholtz coil tests
- Magnitude and phase of B_Z at the MUX chips varies with the Pb tabs

Comsol Modeling by Renee Manzagol

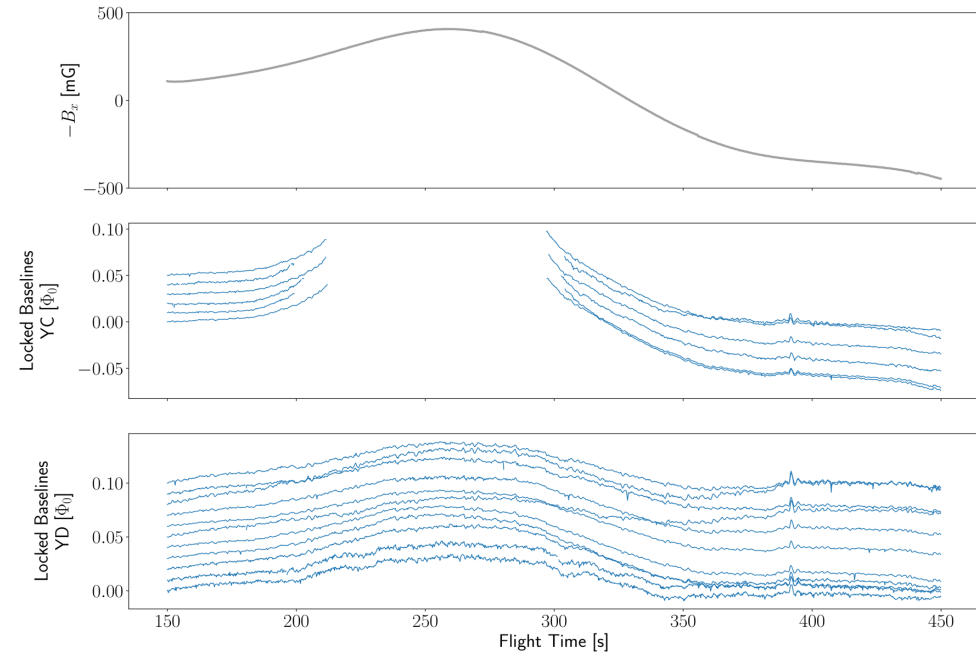


SQUID Response

Powered Flight



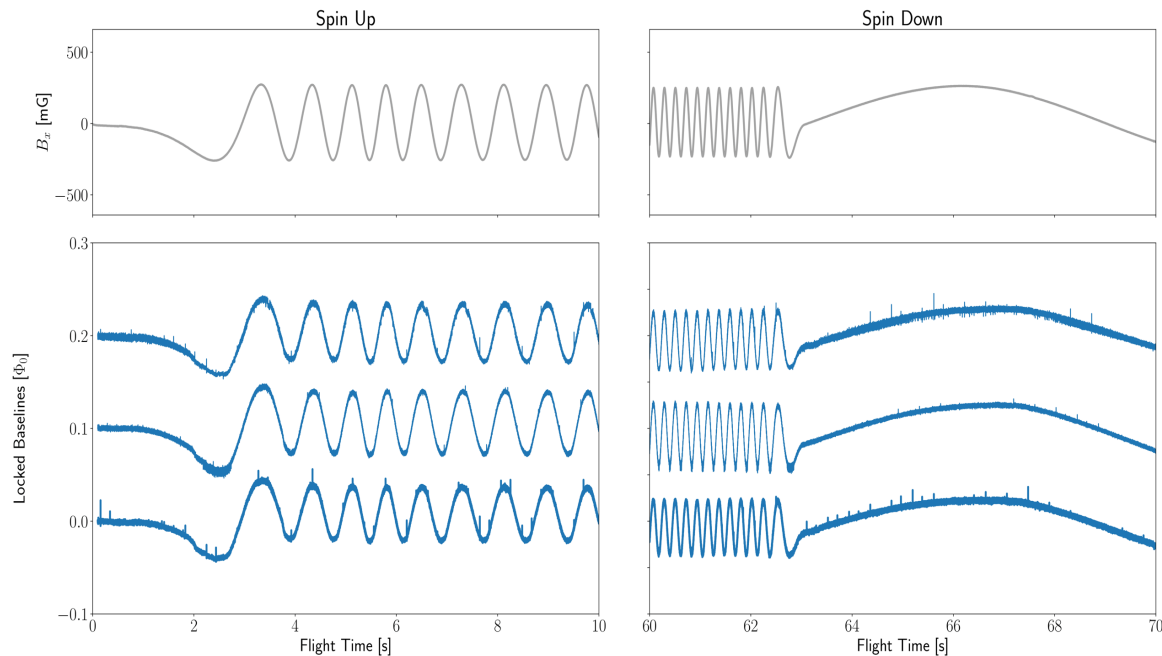
Science Observation



SQUID Response

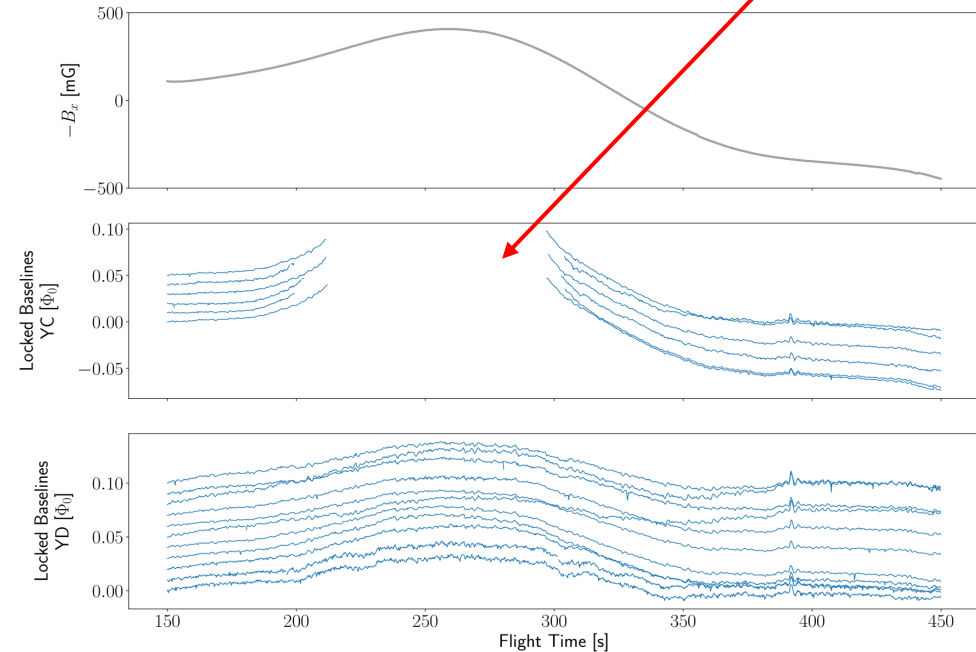
Many YC SQUIDs unlocked here

Powered Flight



- Random tune: TESs @ 300mK, ADR > 1 Amp
- SQUID Response only (TESs normal)
- Simple $B(r, t)$ as the rocket spins at 4 Hz

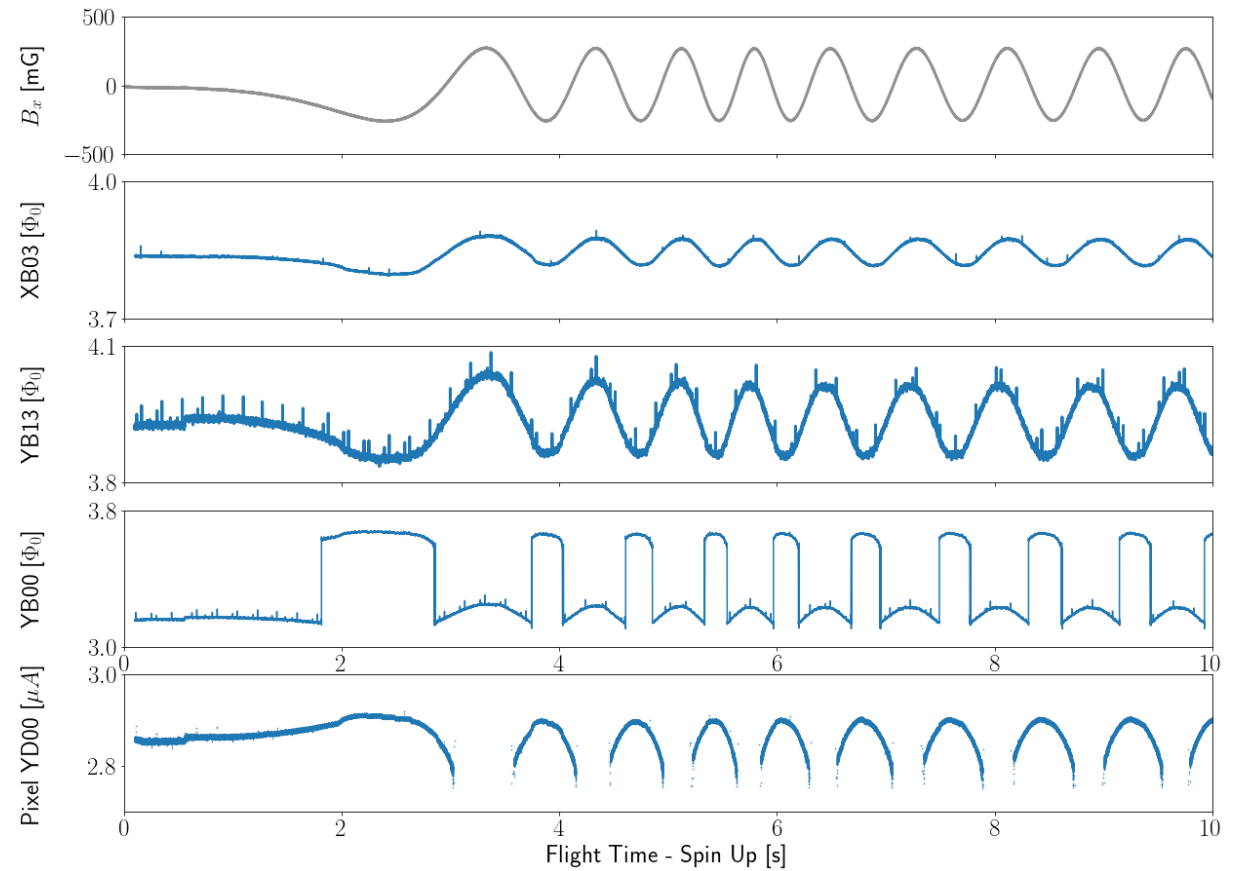
Science Observation



- TES effect + Complicated $B(r, t)$ as the rocket tumbles

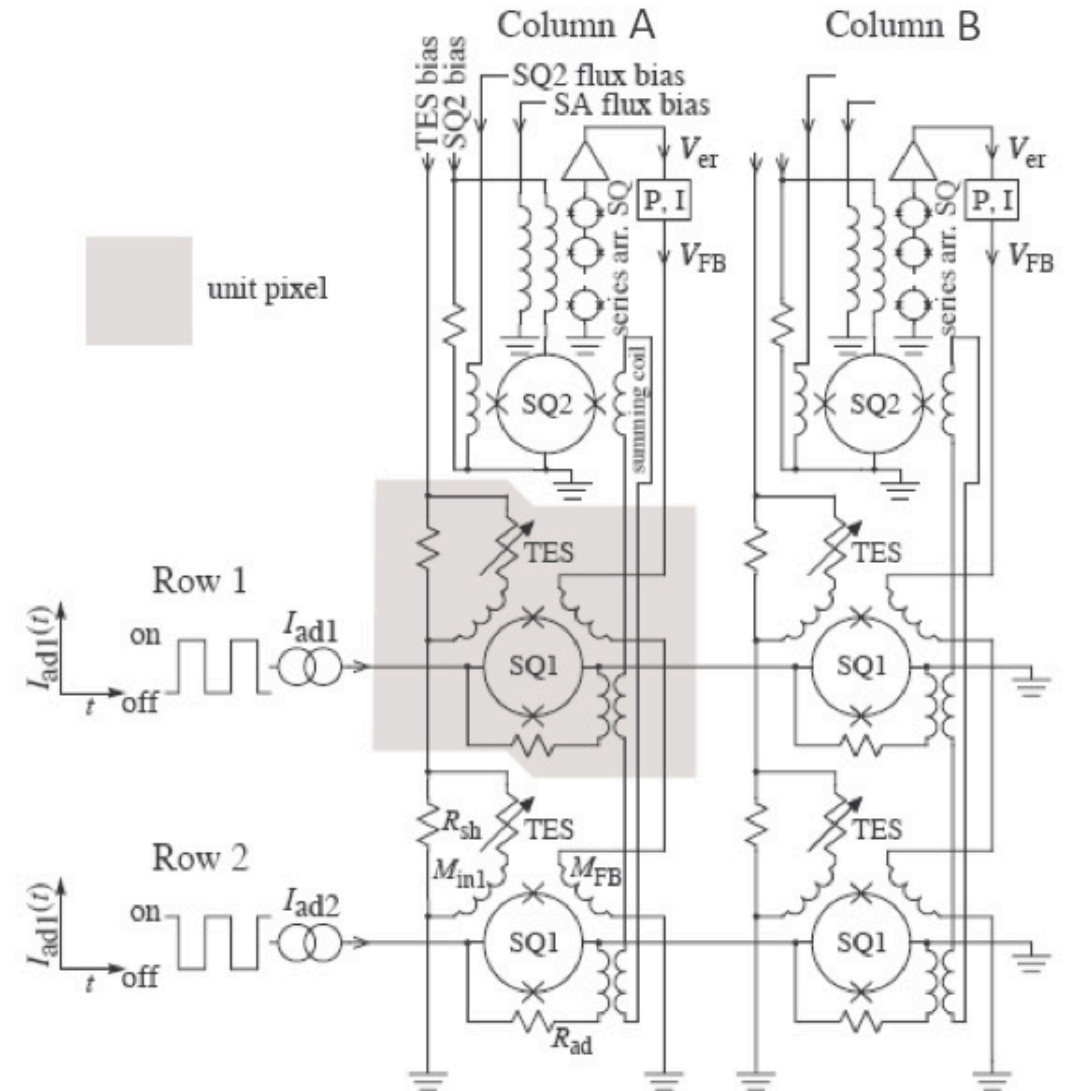
SQUID Response

- Various pathologies observed in powered flight
- Pathologies were generally consistent per column

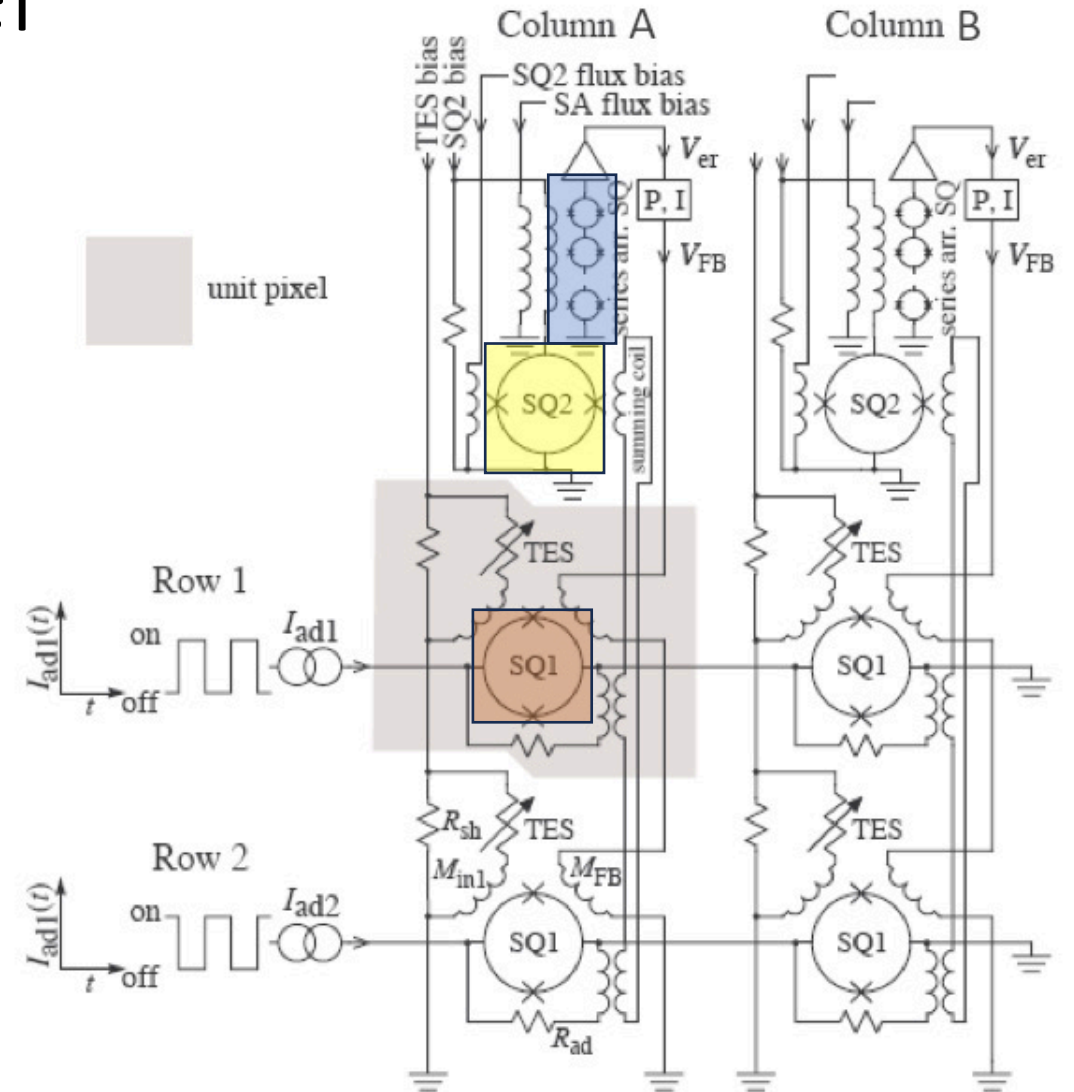
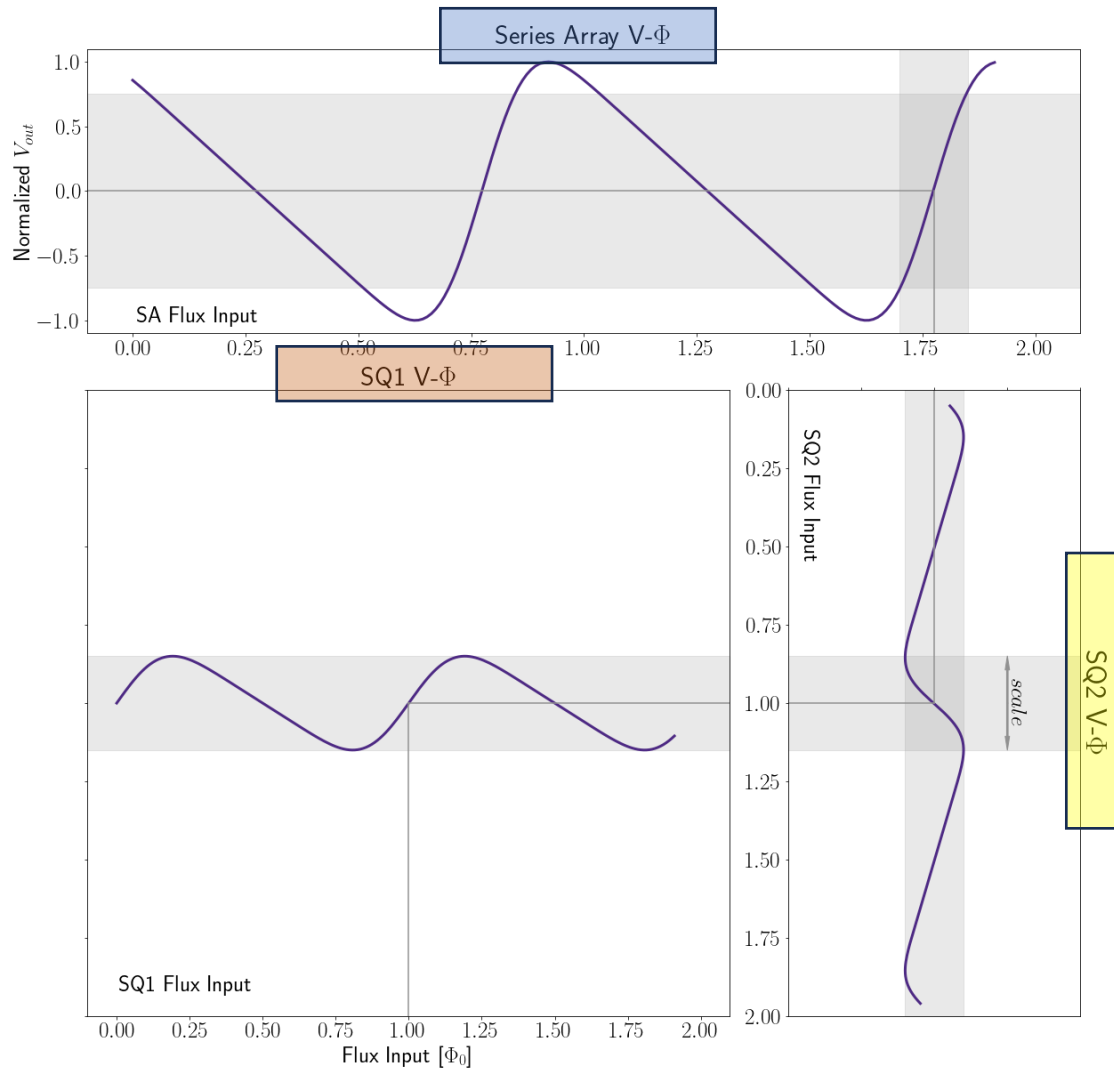


TDM SQUID Circuit

- NIST MUX06a SQUID chips:
 - Three stage SQUID TDM design
 - Asymmetric V- Φ s
 - Linear SA SQUID response over the output of SQ2
 - Output of SQ1 over coupled to the input of SQ2
 - **Large SQ2 A_{eff} due to the summing coil topology ($468.5 \mu\text{m}^2$)**

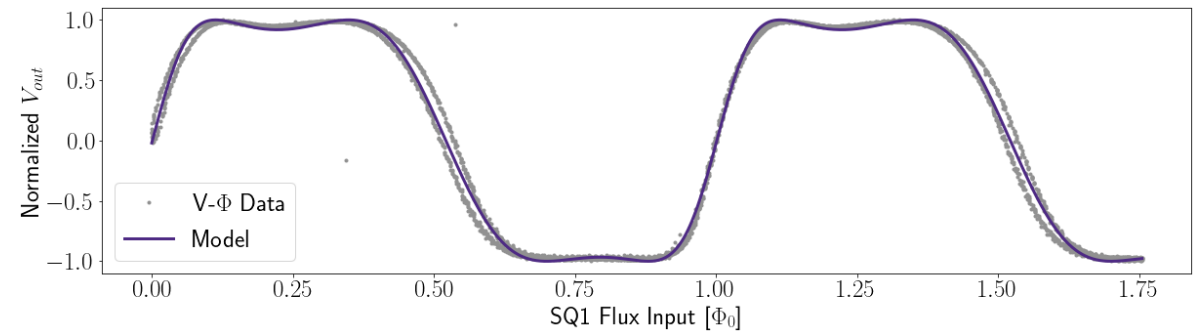
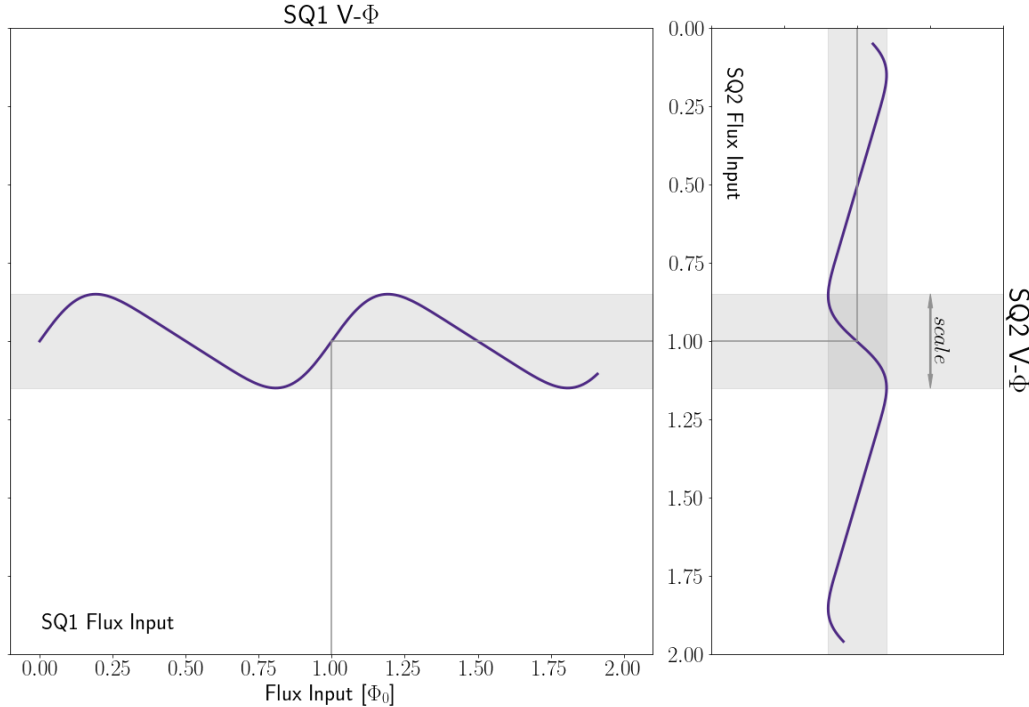
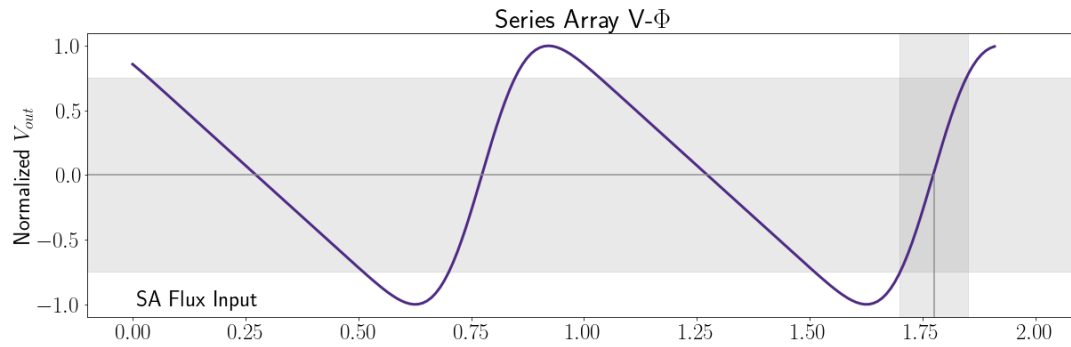


TDM SQUID Circuit Model



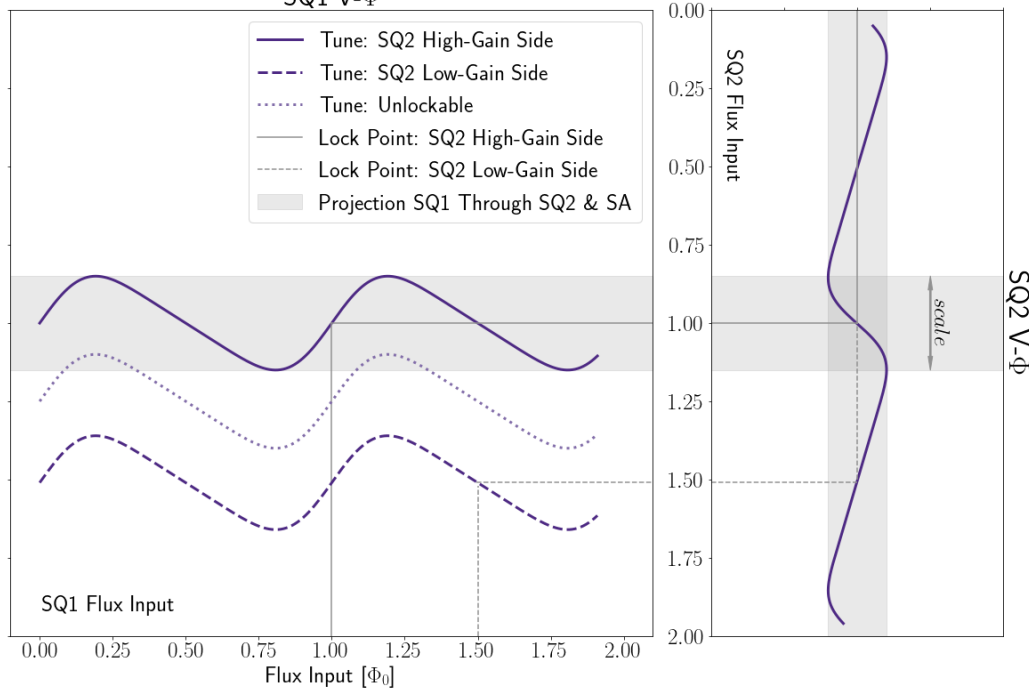
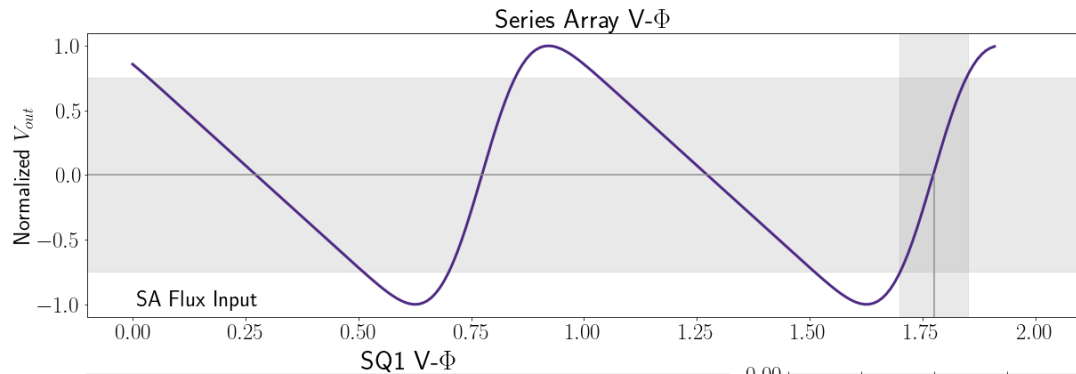
TDM SQUID Circuit Model

$$\sum_{k=1}^n \frac{\binom{2n}{n-k}}{\binom{2n}{n}} \frac{\sin kx}{k}$$



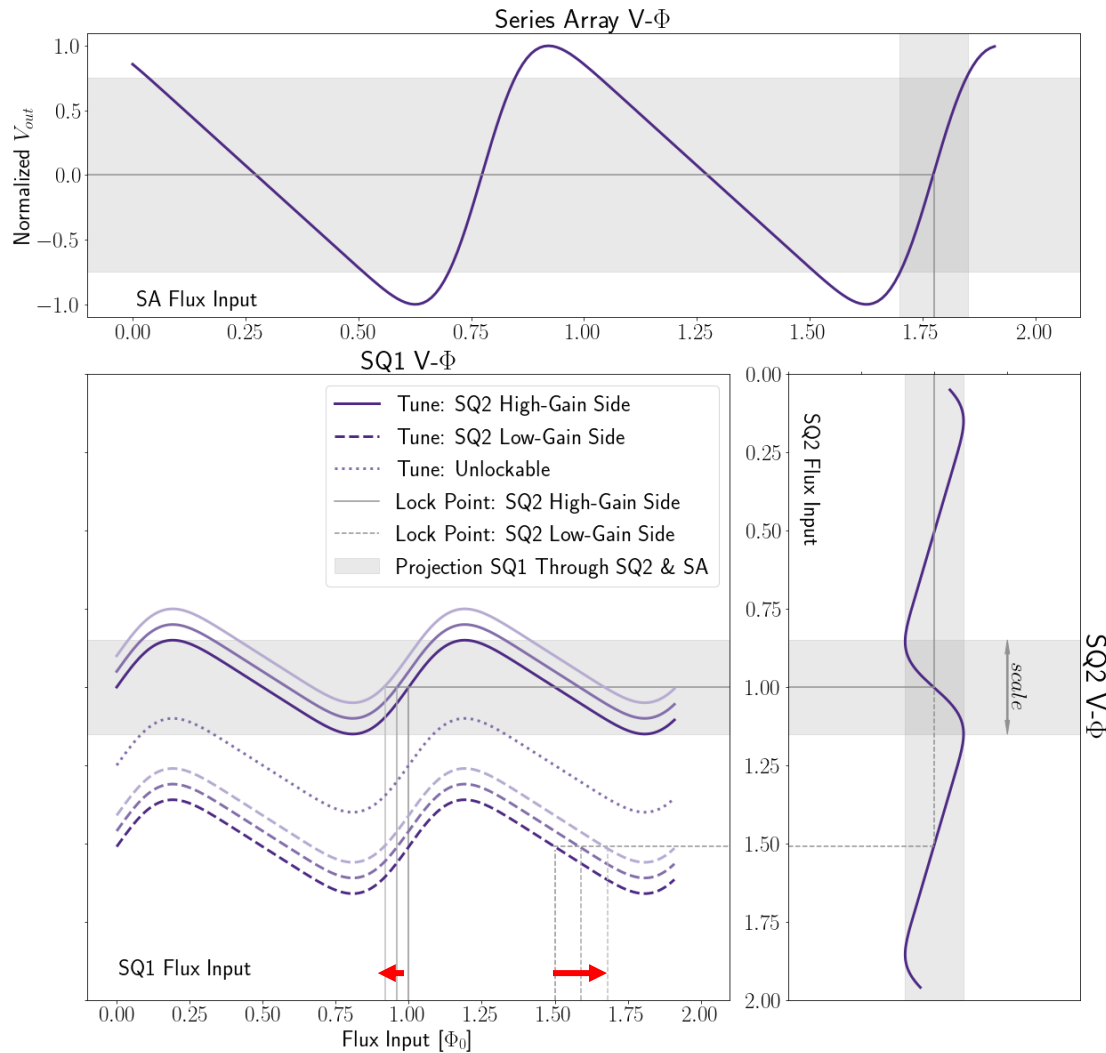
- Model each SQUID stage as a truncated sawtooth series
 - More terms = more asymmetry
- Assume SA is linear over the SQ2 output
- Fit asymmetry and “scale” of SQ1 output onto SQ2 input using V- Φ data

TDM SQUID Circuit Model



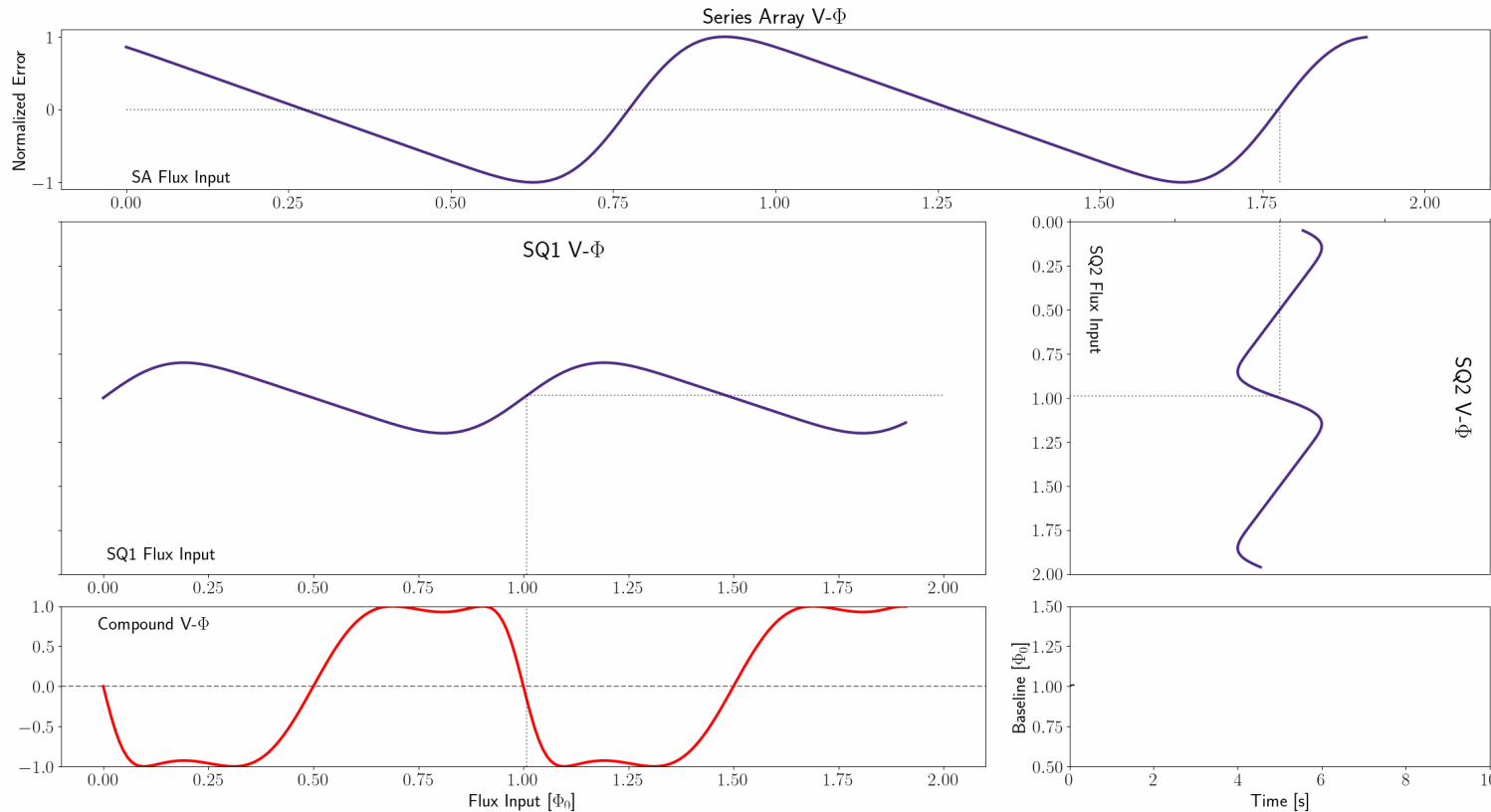
- Relationships between the 3 SQUID are set manually by tuning biases and flux offsets
- SQUIDs can lock on the high- or low-gain side of the SQ2
 - Incurs $\frac{1}{2} \Phi_0$ jump to the other slope of the SQ1 V- Φ
- May be unlockable if SQ1 output is between SQ2 lock points

TDM SQUID Circuit Model



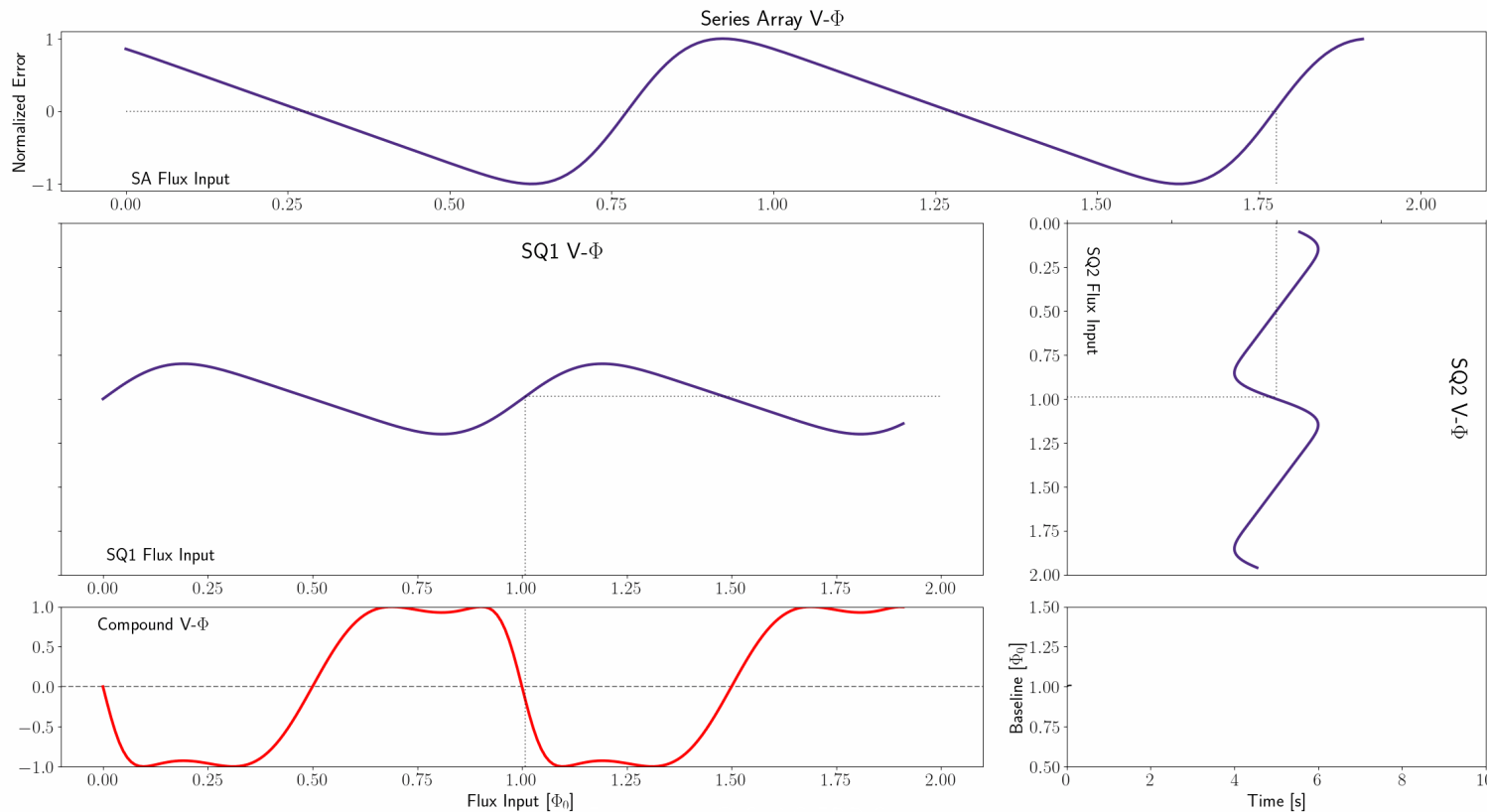
- An external magnetic field can be modeled as an additional SQ2 flux input due to the large A_{eff}
 - SQ2 $A_{eff} \sim 100x$ larger than SQ1
 - Effectively shifts SQ1 relative to SQ2
 - **Changing B_{ext} produces a changing locked baseline**

External Field Coupling to SQ2 Input High Gain Tune



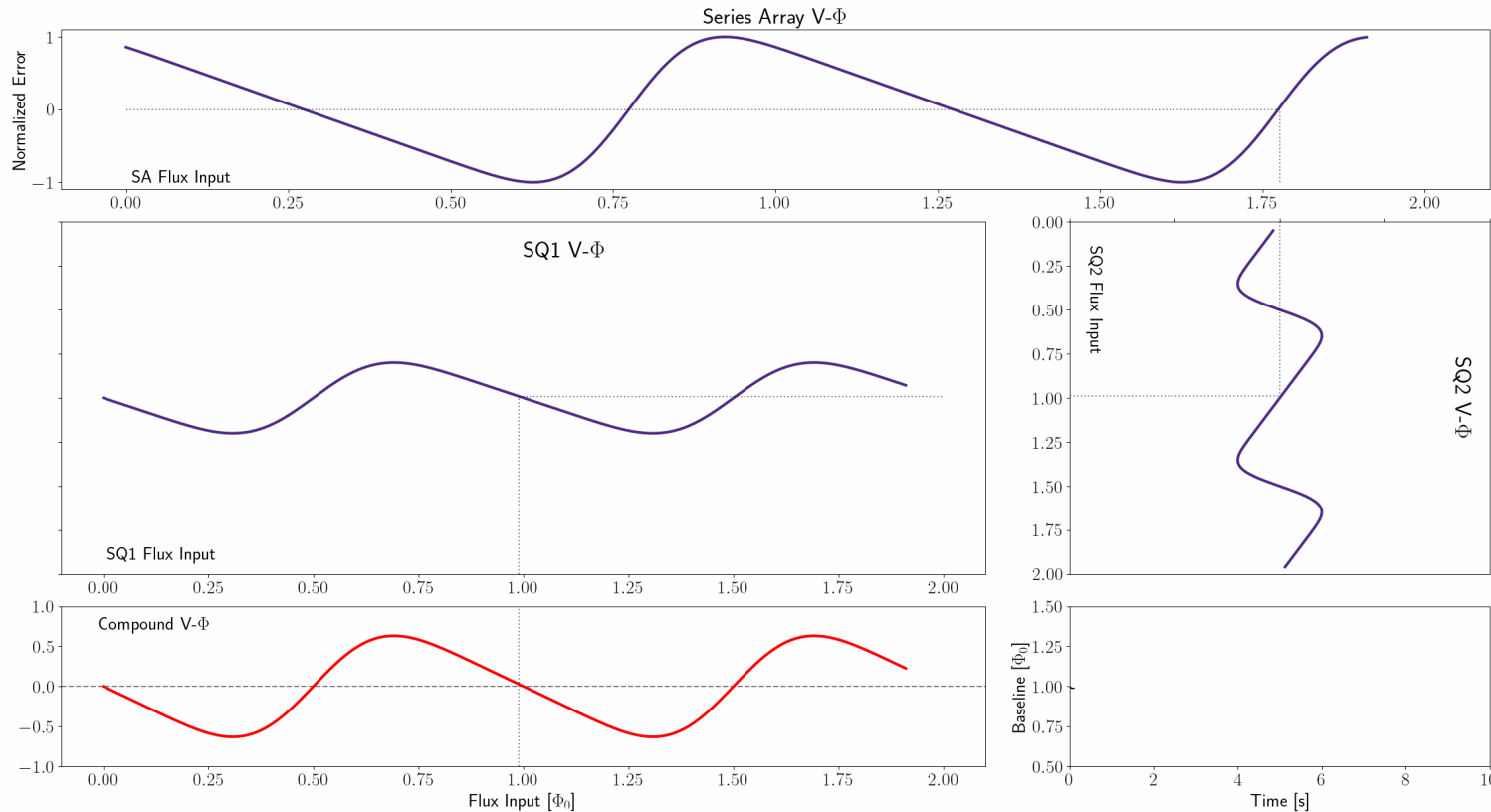
- **Baseline response mirrors B_{ext} input to SQ2**

External Field Coupling to SQ1 Input



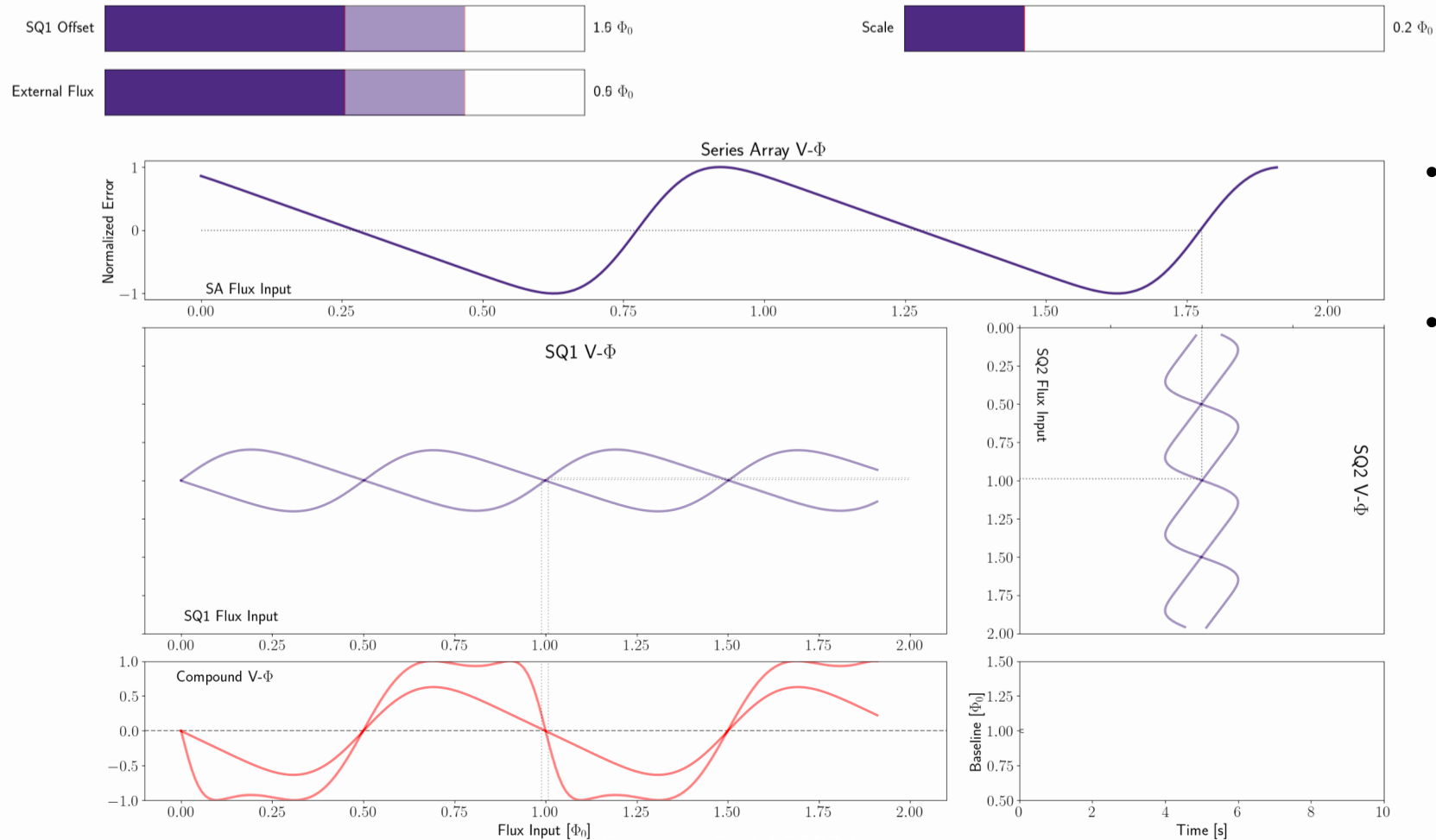
- **Similar baseline response**
- **BUT a stable lock point always exists**

External Field Coupling to SQ2 Input Low Gain Tune



- **Baseline response is larger and opposite than the high-gain response**

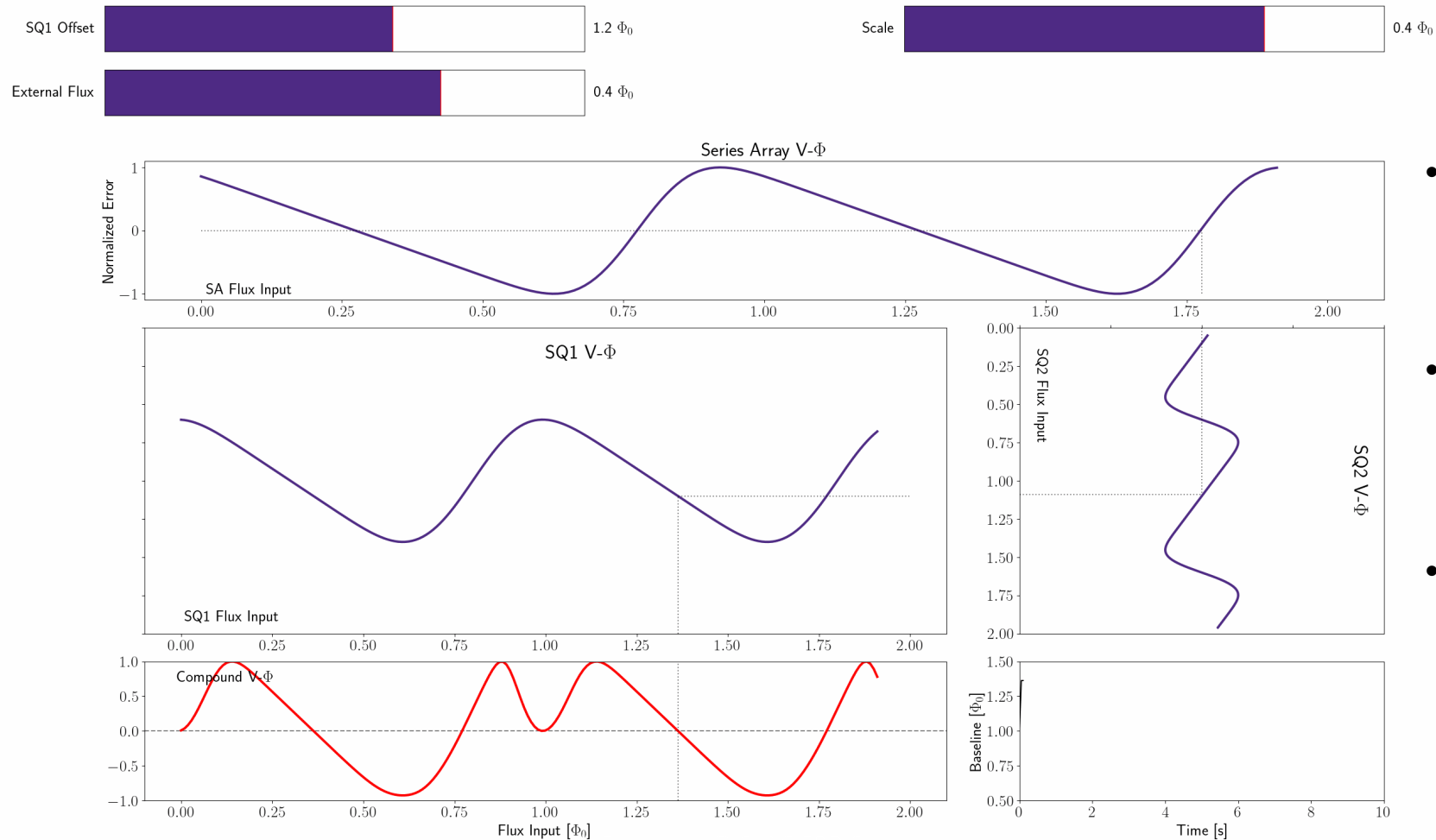
External Field Coupling to SQ2 Input (Overlaid) High *and* Low Gain Tunes



- Inverted baseline response
- 1.6x Larger response when tuned on the *low*-gain side of the V- Φ

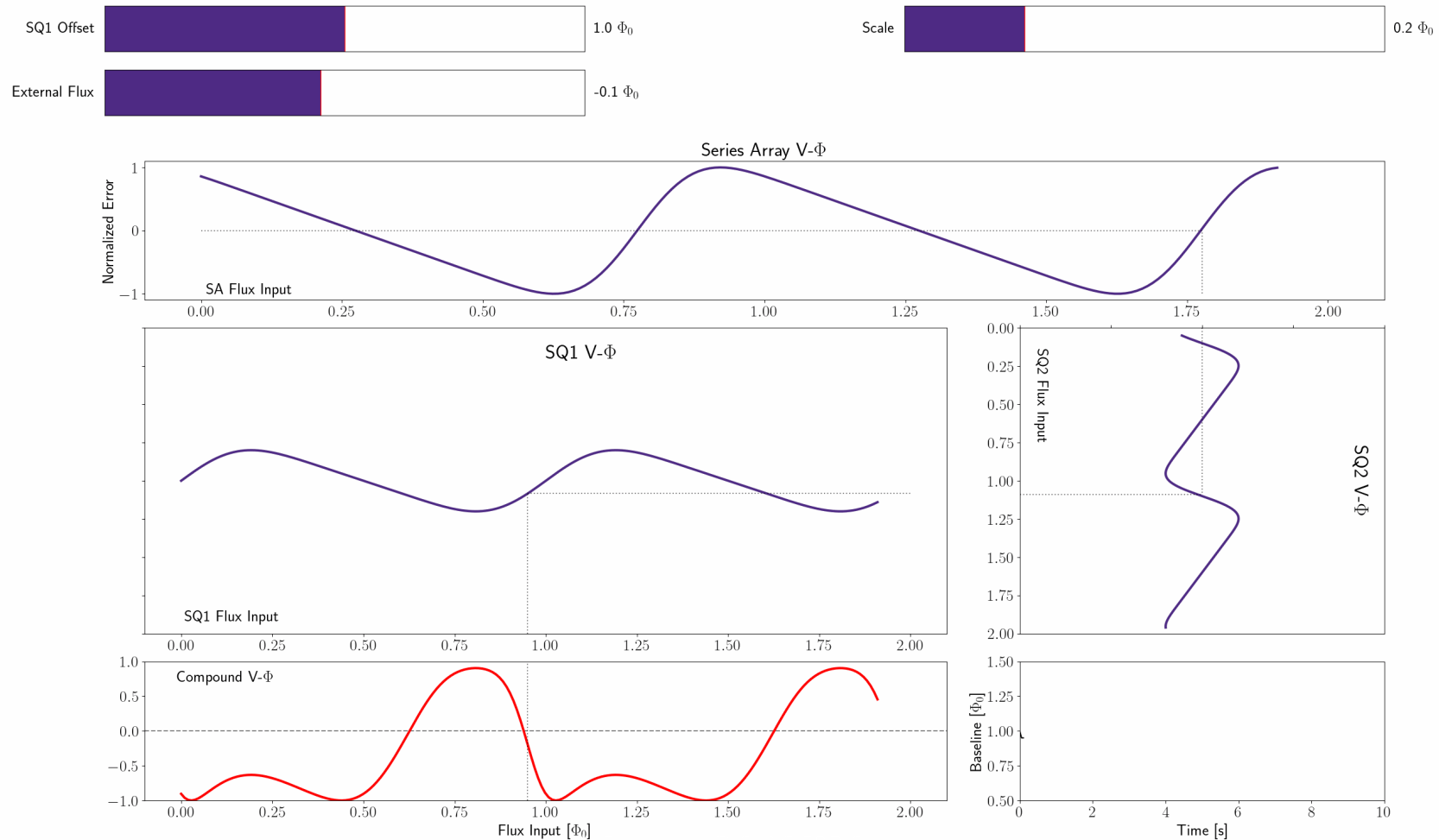
External Field Coupling to SQ2 Input

$\frac{1}{2} \Phi_0$ Jumps - High to Low Gain Tunes



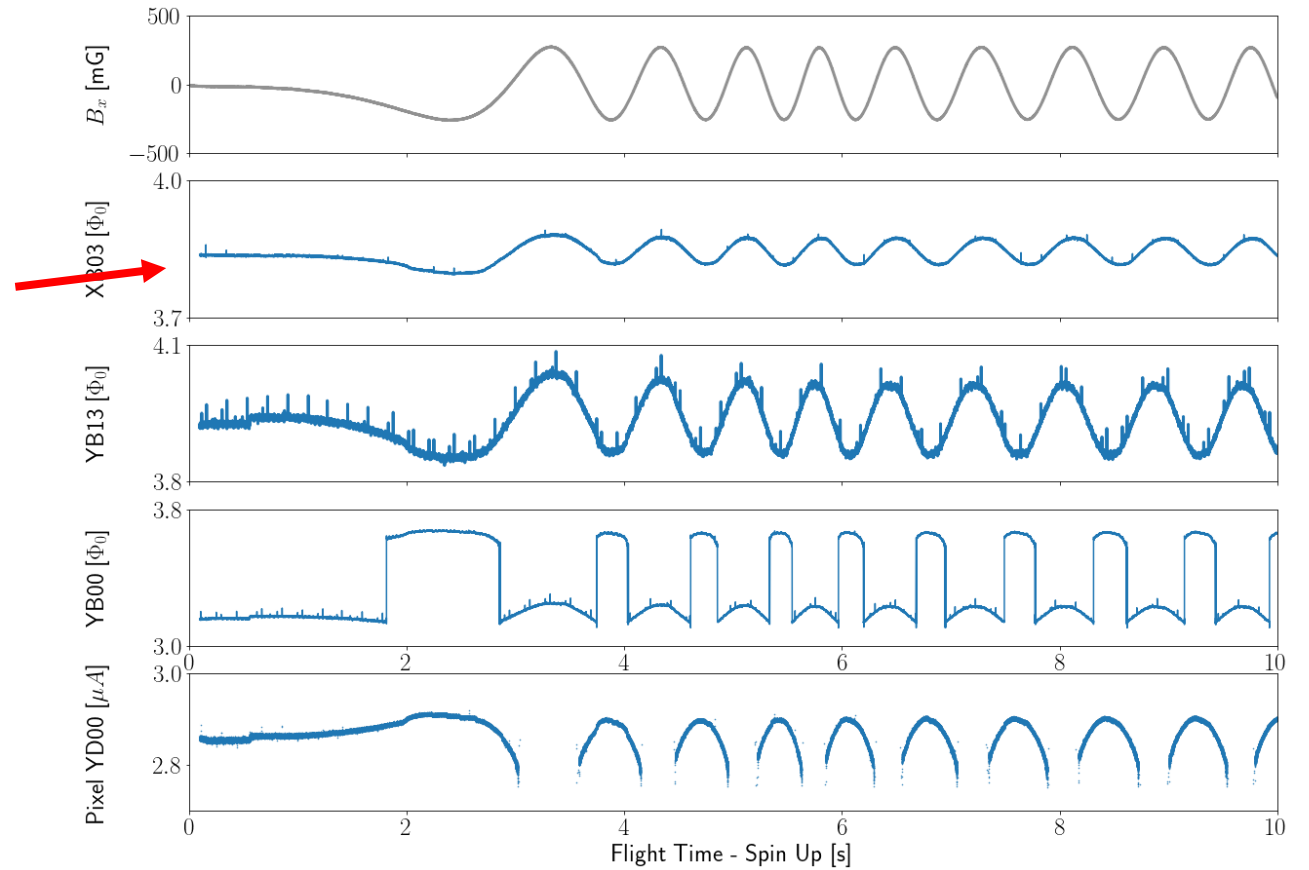
- Occurs if SQ1 output overlaps two lock points
- $\frac{1}{2} \Phi_0$ jumps & inversion of baseline response
- Larger baseline response on the low-gain side

External Field Coupling to SQ2 Input Off-center Low Gain Tune



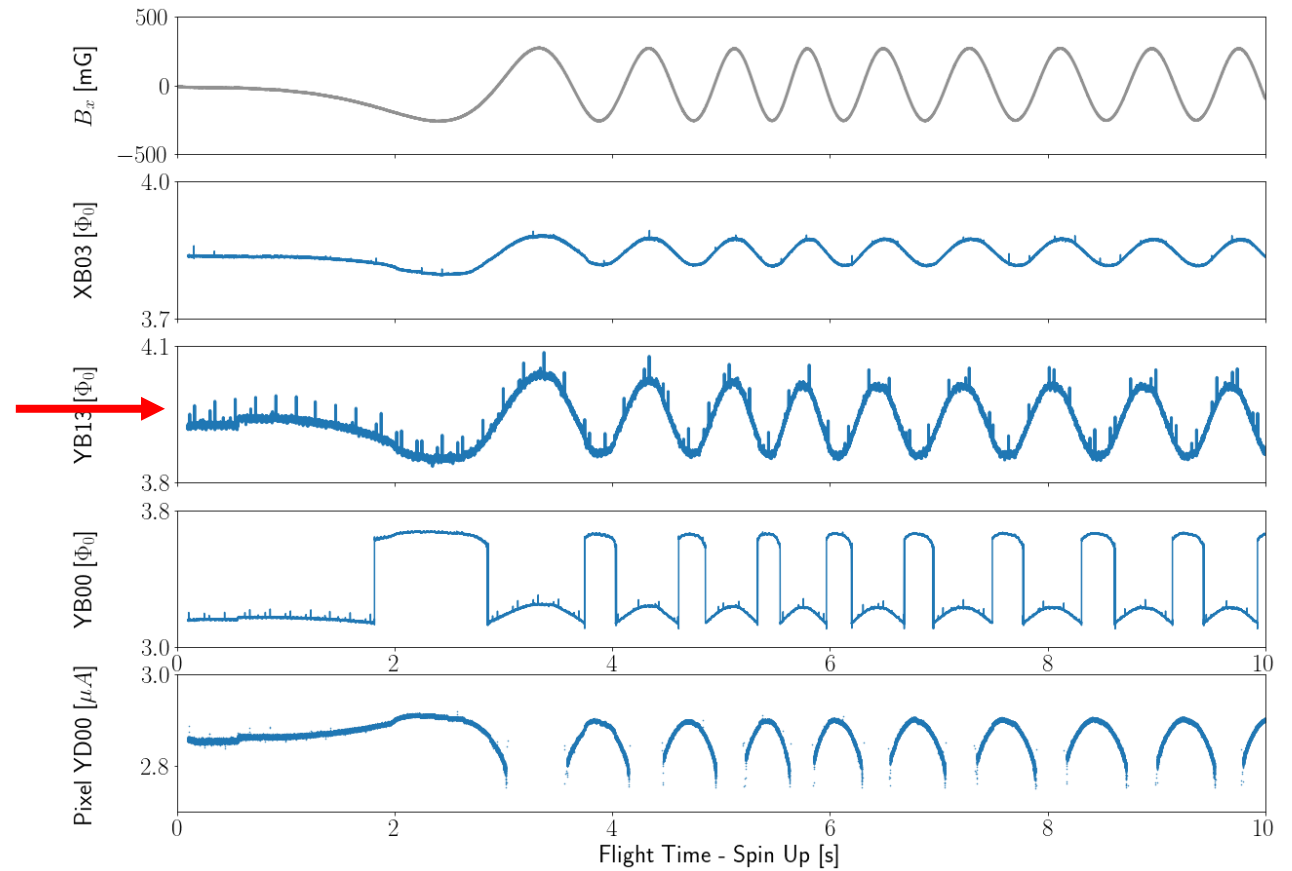
Powered Flight Pathologies

- Locked on the **high-gain** side



Powered Flight Pathologies

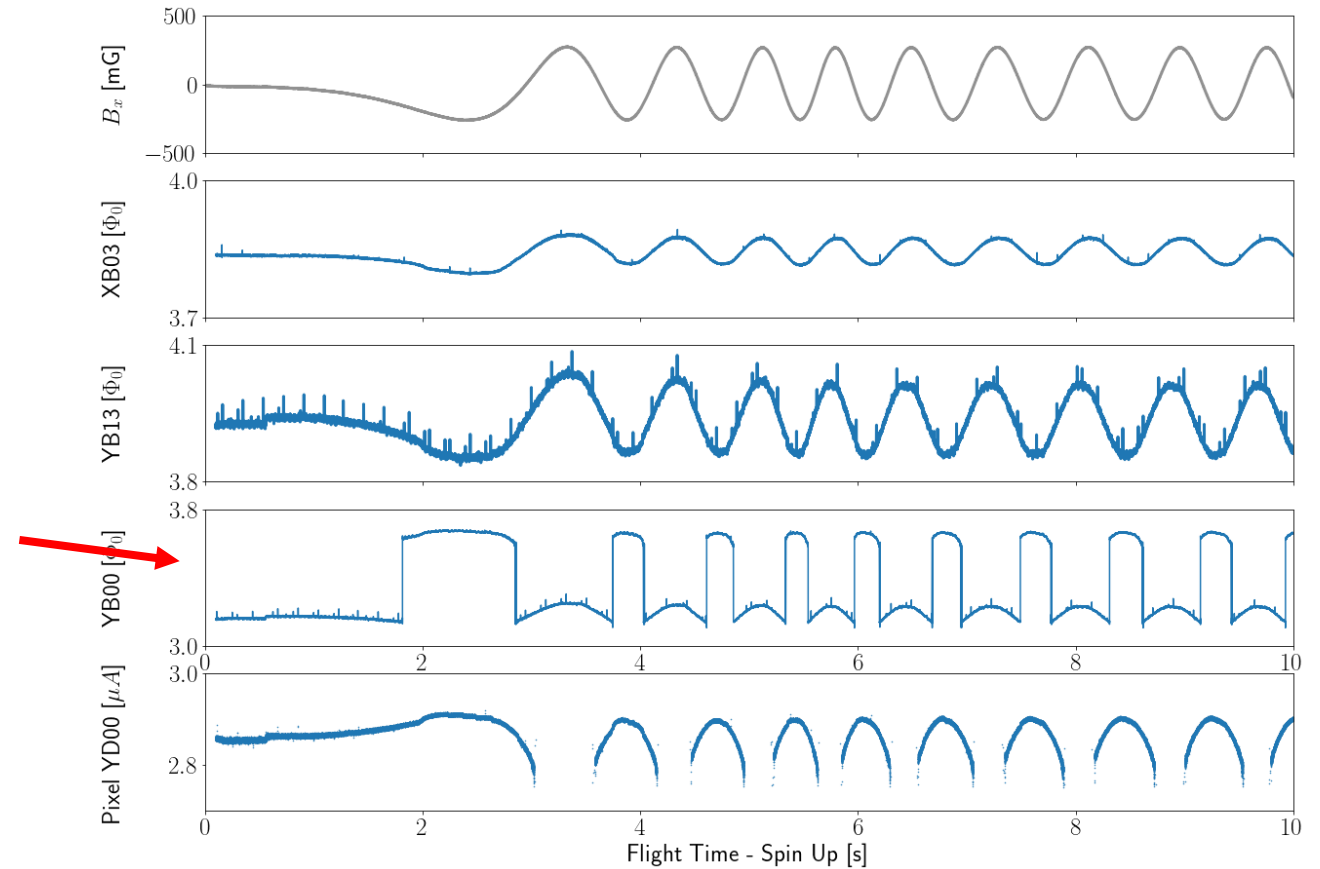
- Locked on the **high-gain** side
- Locked on the **low-gain** side*



*Two baseline flips: high- to low-gain side; detector side X to detector side Y

Powered Flight Pathologies

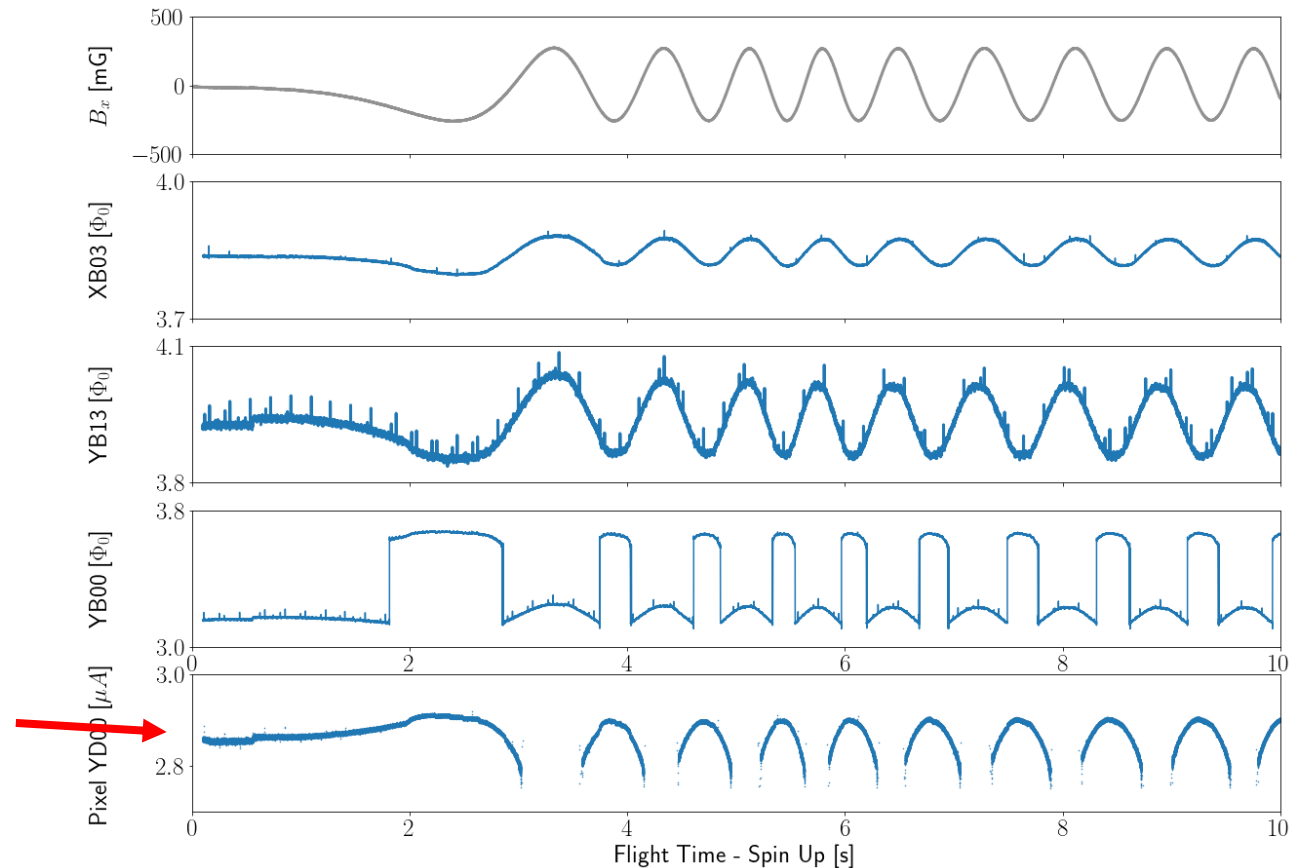
- Locked on the **high-gain** side
- Locked on the **low-gain** side*
- $\frac{1}{2} \Phi_0$ Jumps between high- and low-gain sides



*Two baseline flips: high- to low-gain side; detector side X to detector side Y

Powered Flight Pathologies

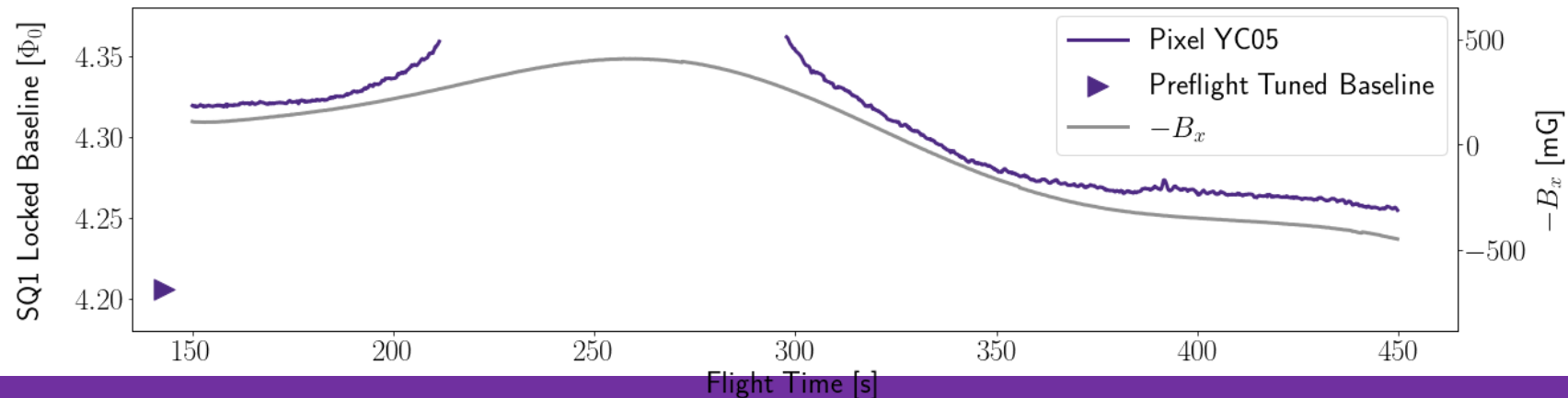
- Locked on the **high-gain** side
- Locked on the **low-gain** side*
- $\frac{1}{2} \Phi_0$ Jumps between high- and low-gain sides
- Oscillating between high-gain side and unlocked state



*Two baseline flips: high- to low-gain side; detector side X to detector side Y

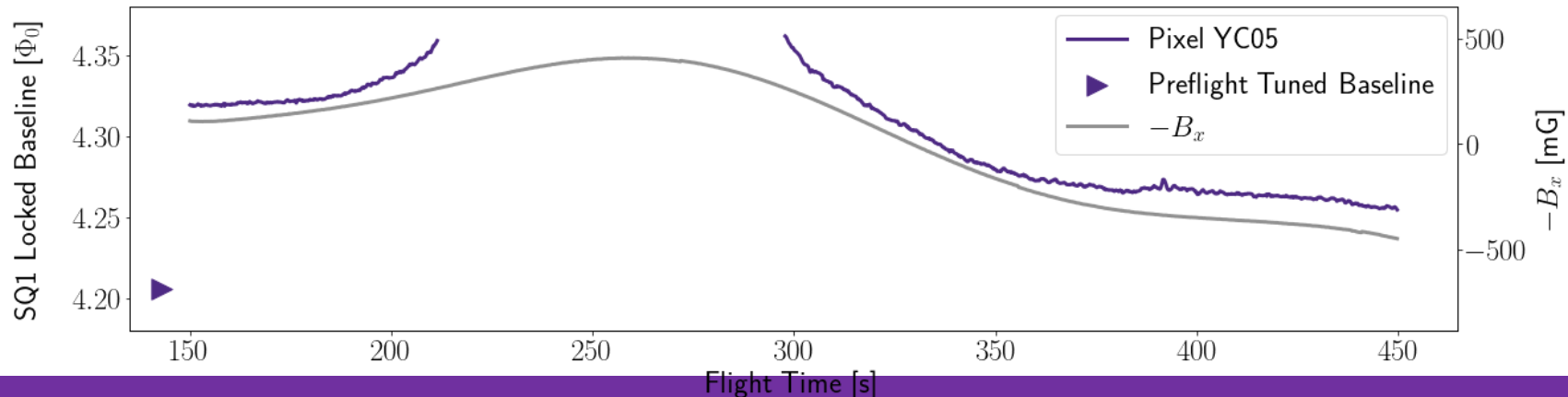
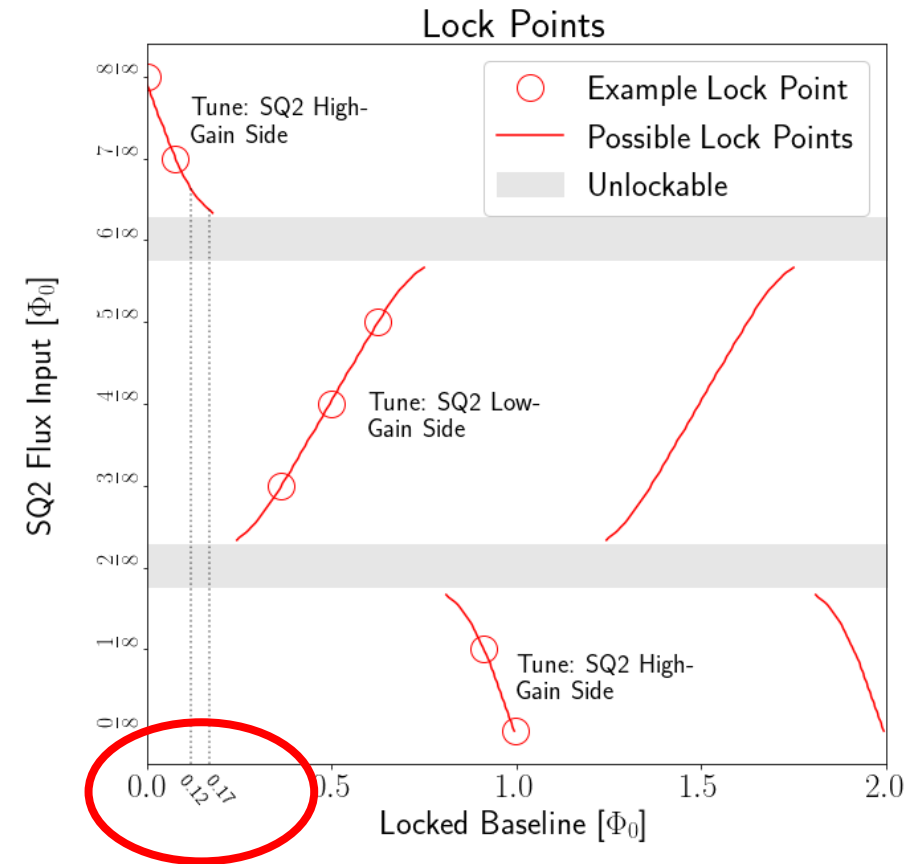
Observation Pathologies

- Example unlocked pixel: YC05
- Considered “well-tuned” before flight
- Baseline response accelerates when $>0.12\Phi_0$ from the well-tuned baseline
- Pixel unlocks $>0.16\Phi_0$ from the well-tuned baseline



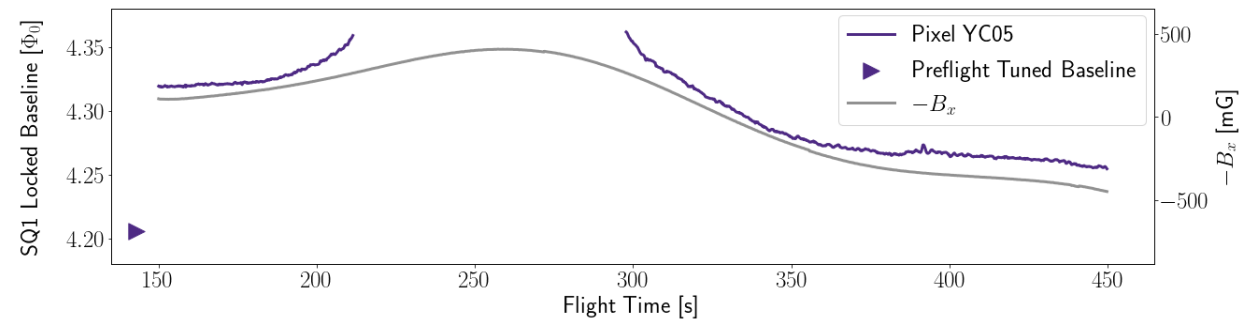
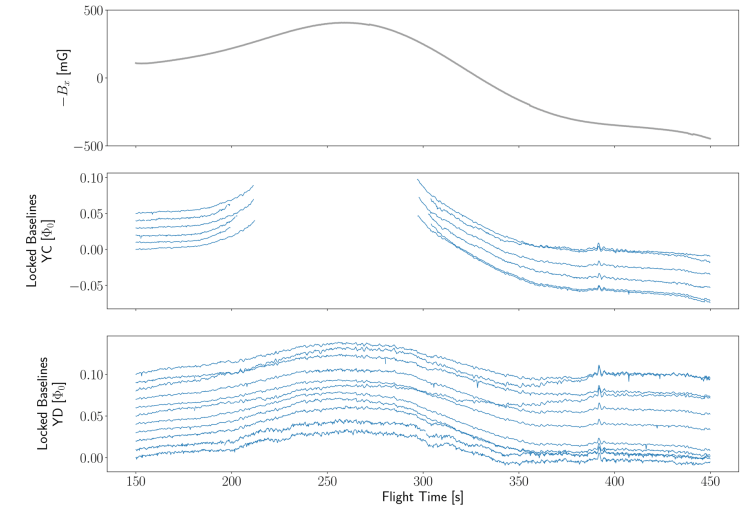
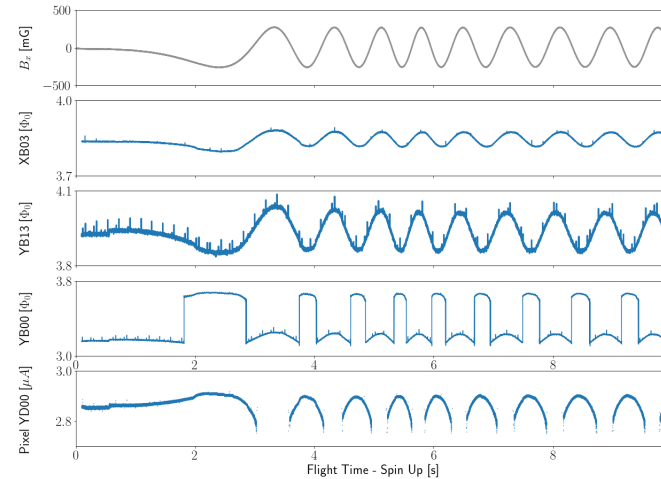
Observation Pathologies

- Example unlocked pixel: YC05
- Considered “well-tuned” before flight
- Baseline response accelerates when $>0.12\Phi_0$ from the well-tuned baseline
- Pixel unlocks $>0.16\Phi_0$ from the well-tuned baseline



Comsol + SQUID Modeling Results

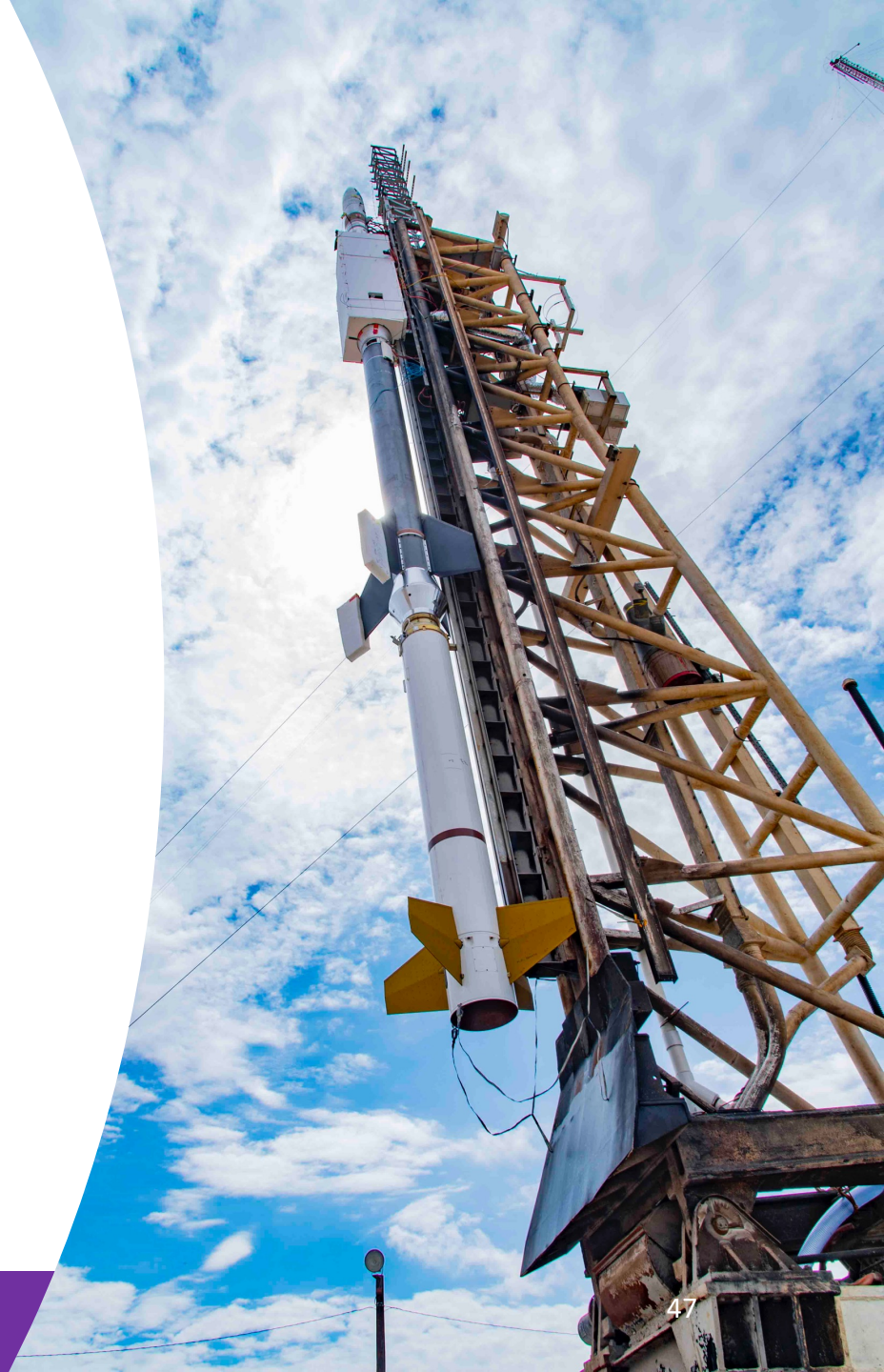
- ✓ Explain powered flight pathologies
- ✓ Provide unlocking mechanism during the science observation
- ✓ Consistent with baseline pathologies during science observation



The Micro-X Second Flight (2022)

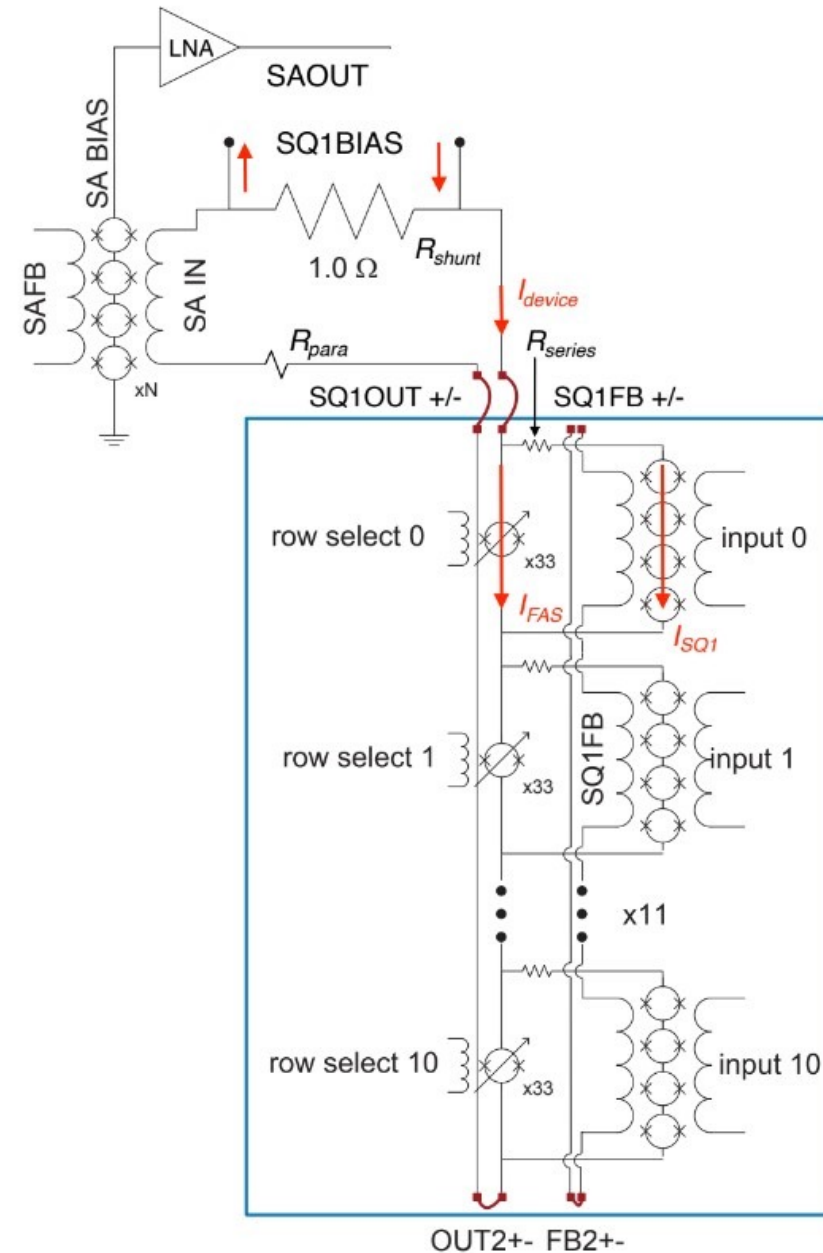
12/12/2023

Josh Fuhrman @ SLAC FPD Seminar



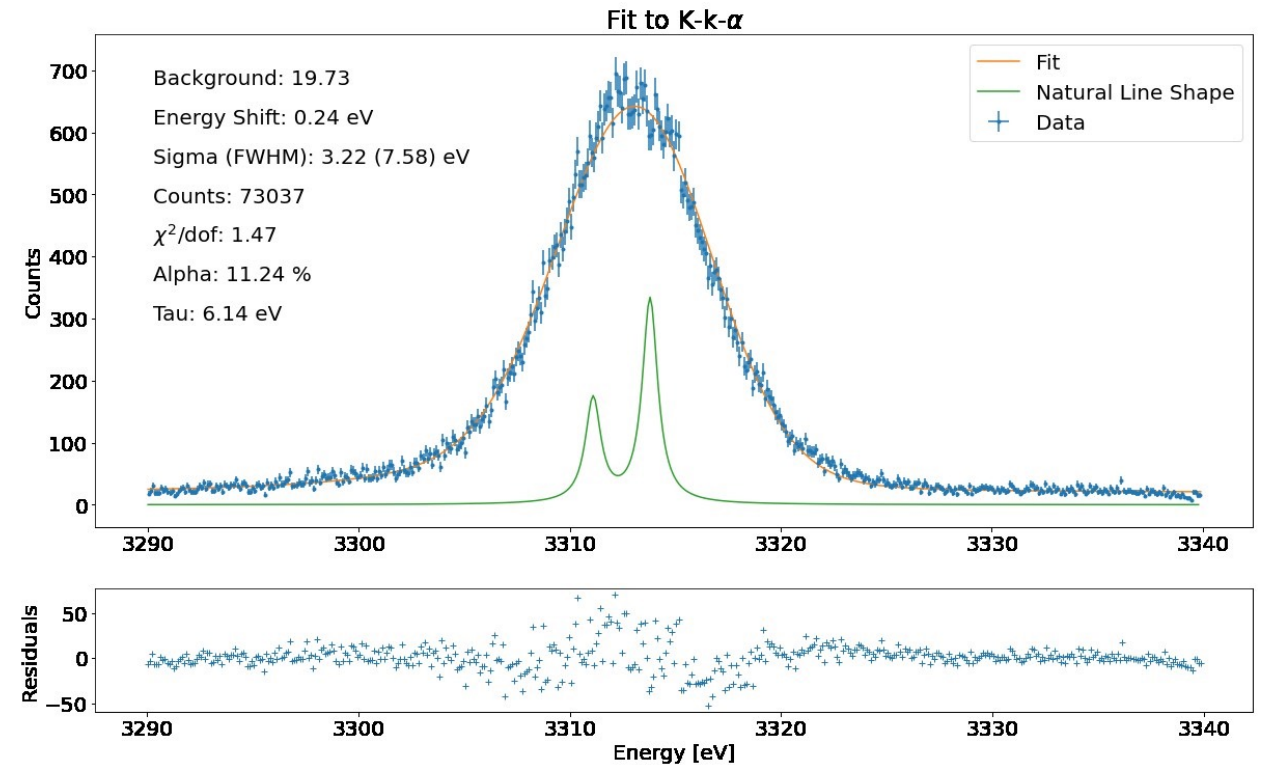
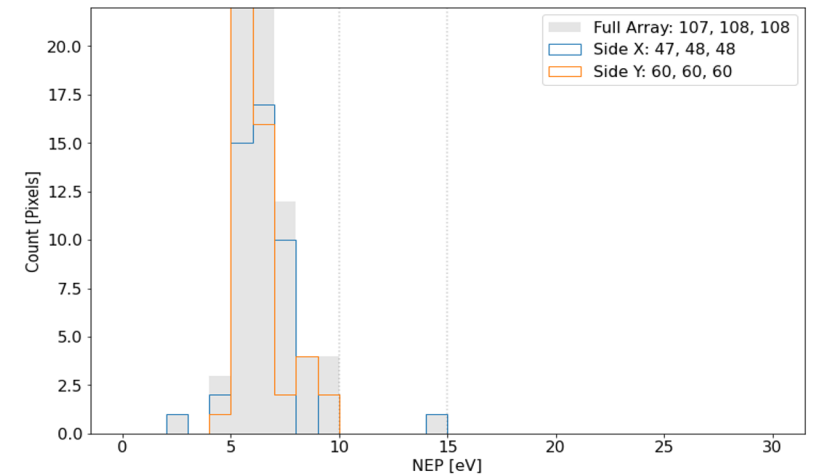
New SQUIDs!

- Updated SQUID chips to NIST MUX18b
 - Flux-actuated design (galvanically isolated row switches)
 - **Single SQUID stage – can't unlock the same way as in flight 1**
 - Generally reduced SQUID effective area without the SQUID-2 summing coil



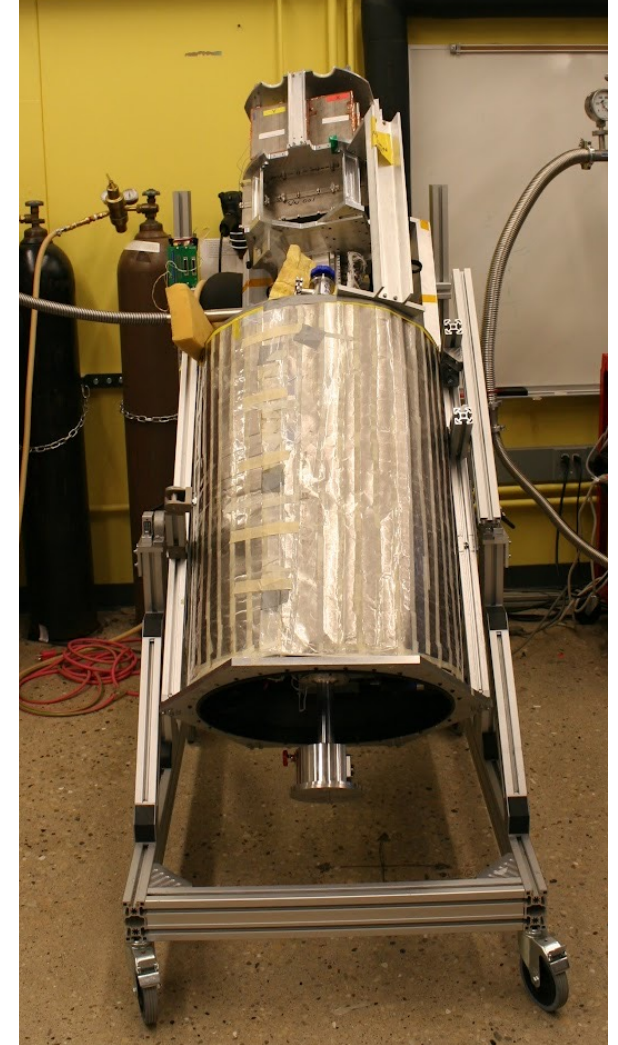
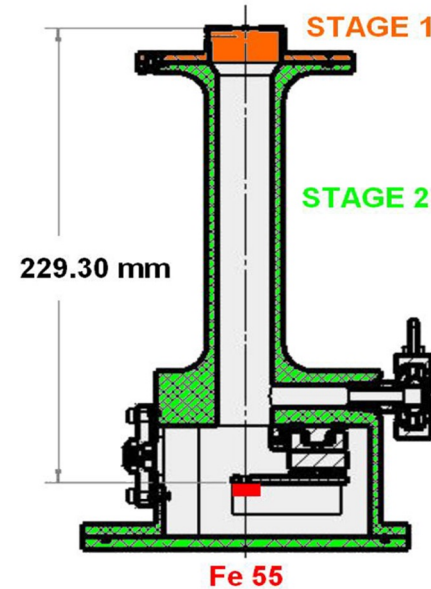
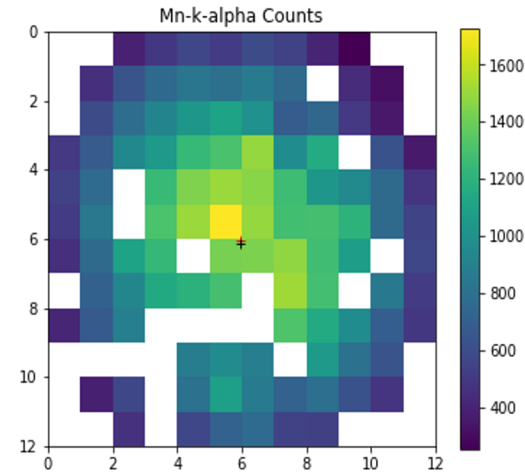
Micro-X Instrument Ground Performance

- Improved cooldown procedures to minimize trapped flux
- Reduced RF pickup dramatically through identification and mitigation of on-instrument noise sources
 - Shorter cabling
 - Improved cables & routing
 - Filters on FB lines
 - Buffered multiplexed HK lines
- Eliminated beating between desynced clocks
- Co-added spectra from internal calibration source
 - **7.0 eV FWHM at 2.6 keV**
 - 7.6 eV FWHM at 3.3 keV
 - Low-E tail 11%, 6eV



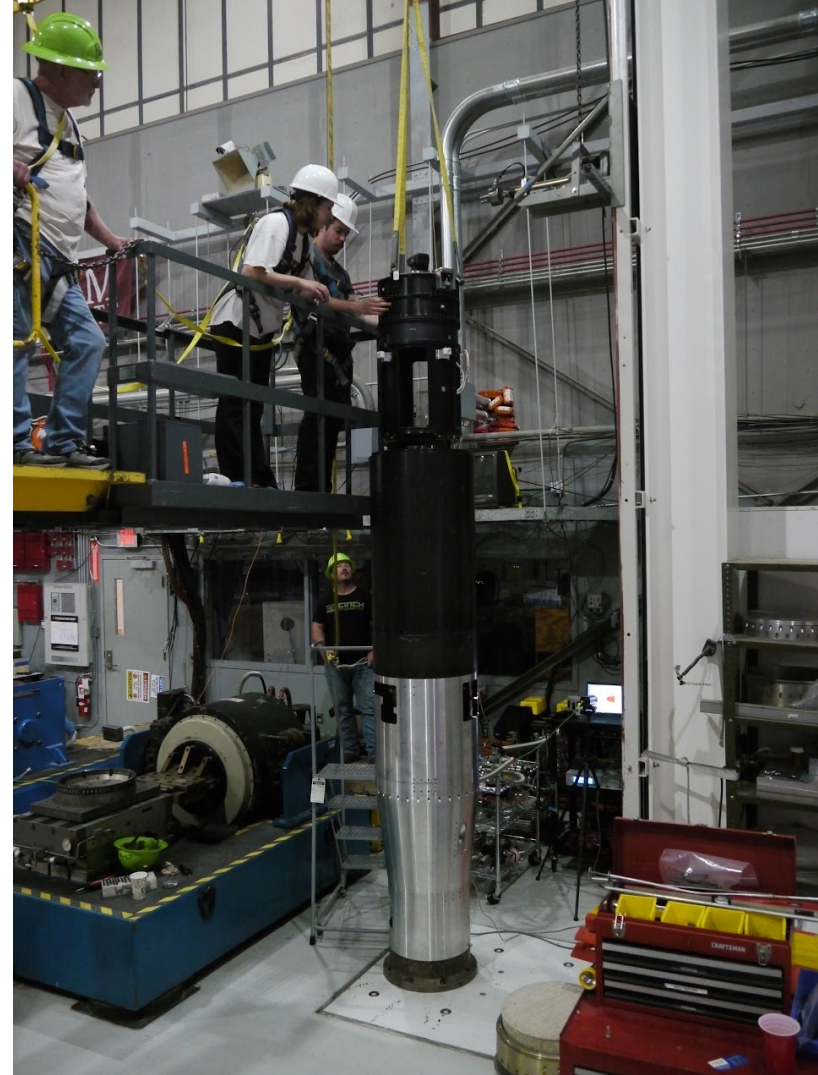
Optics Alignment: Step 1

- An external apparatus containing an Fe55 source fluoresces the array (Stage-2) through a small aperture acting as a pinhole camera (Stage-1)
- Centroid measured to within uncertainty ($\pm 5''$ or $1/12$ or a pixel) of array center



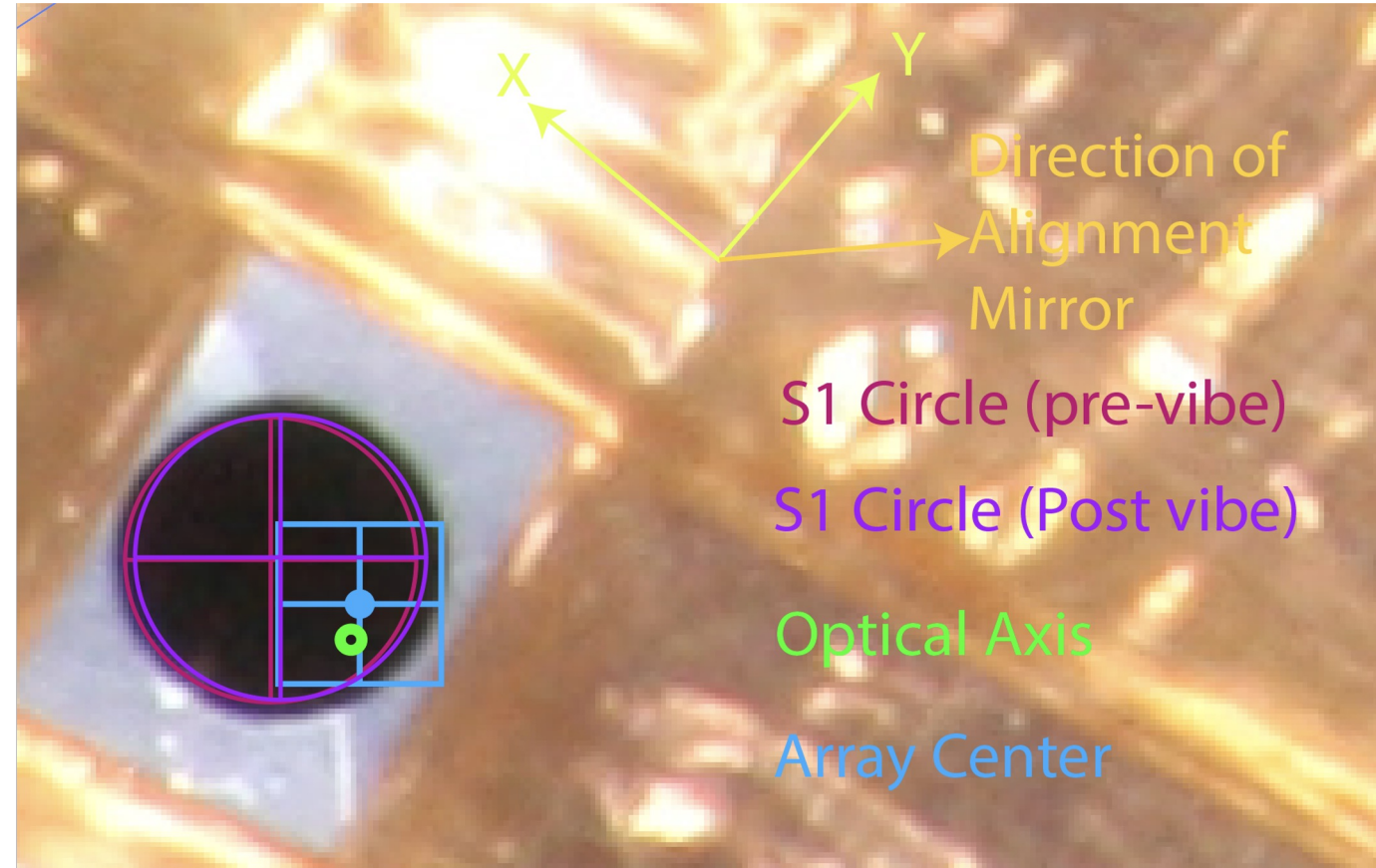
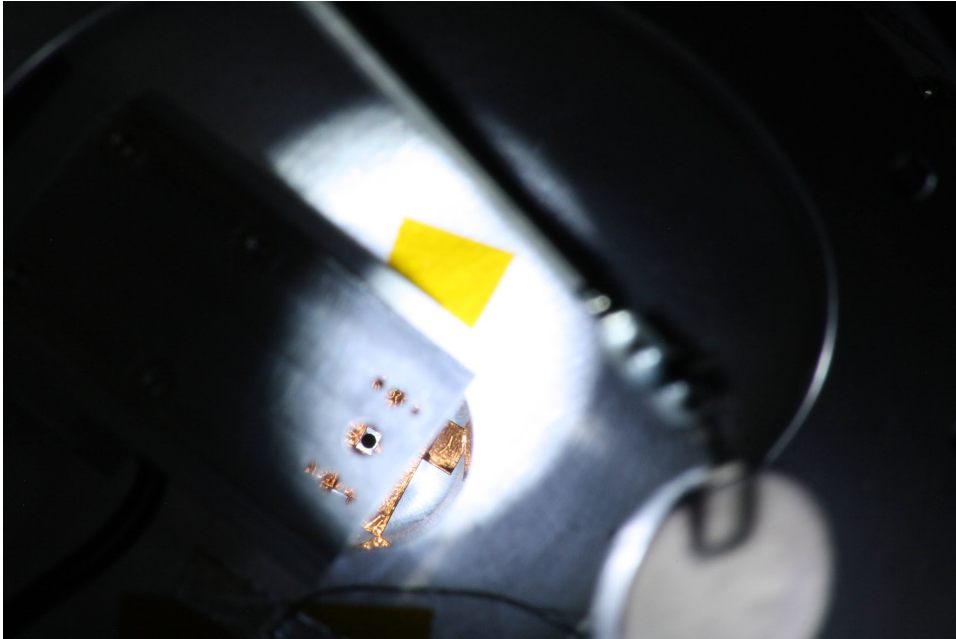
Optics Alignment: Step 2

- An alignment camera is mounted to the x-ray optics and images the Stage-1 aperture
- The mirror is shimmed until the optical axis of the alignment camera matches the predicted array center relative to Stage-1



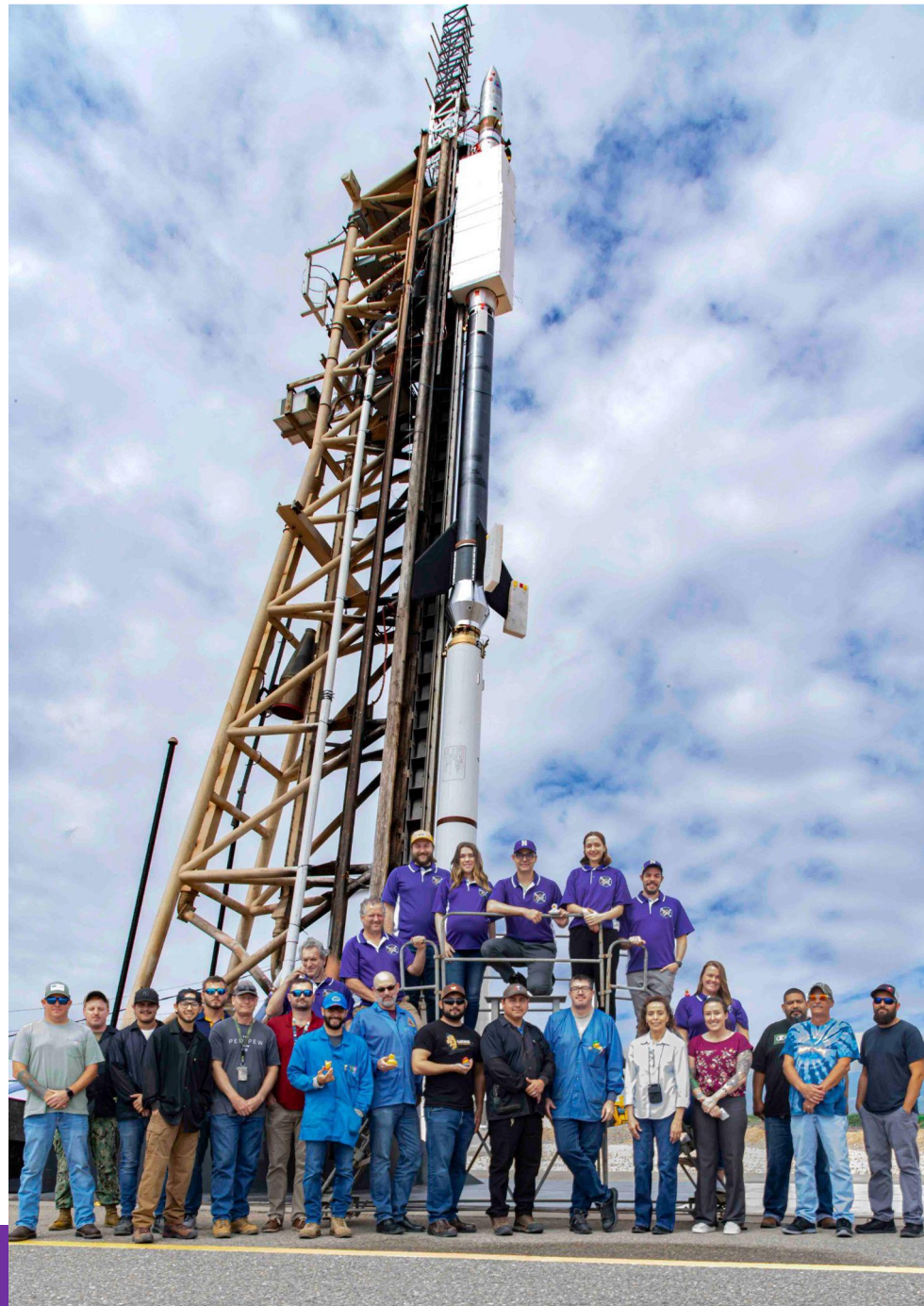
Optics Alignment: Step 2

- X-ray mirror was aligned within 1/3 arcmin of array center



Flight Day 2022

T-12hrs



T-10min



T-5min



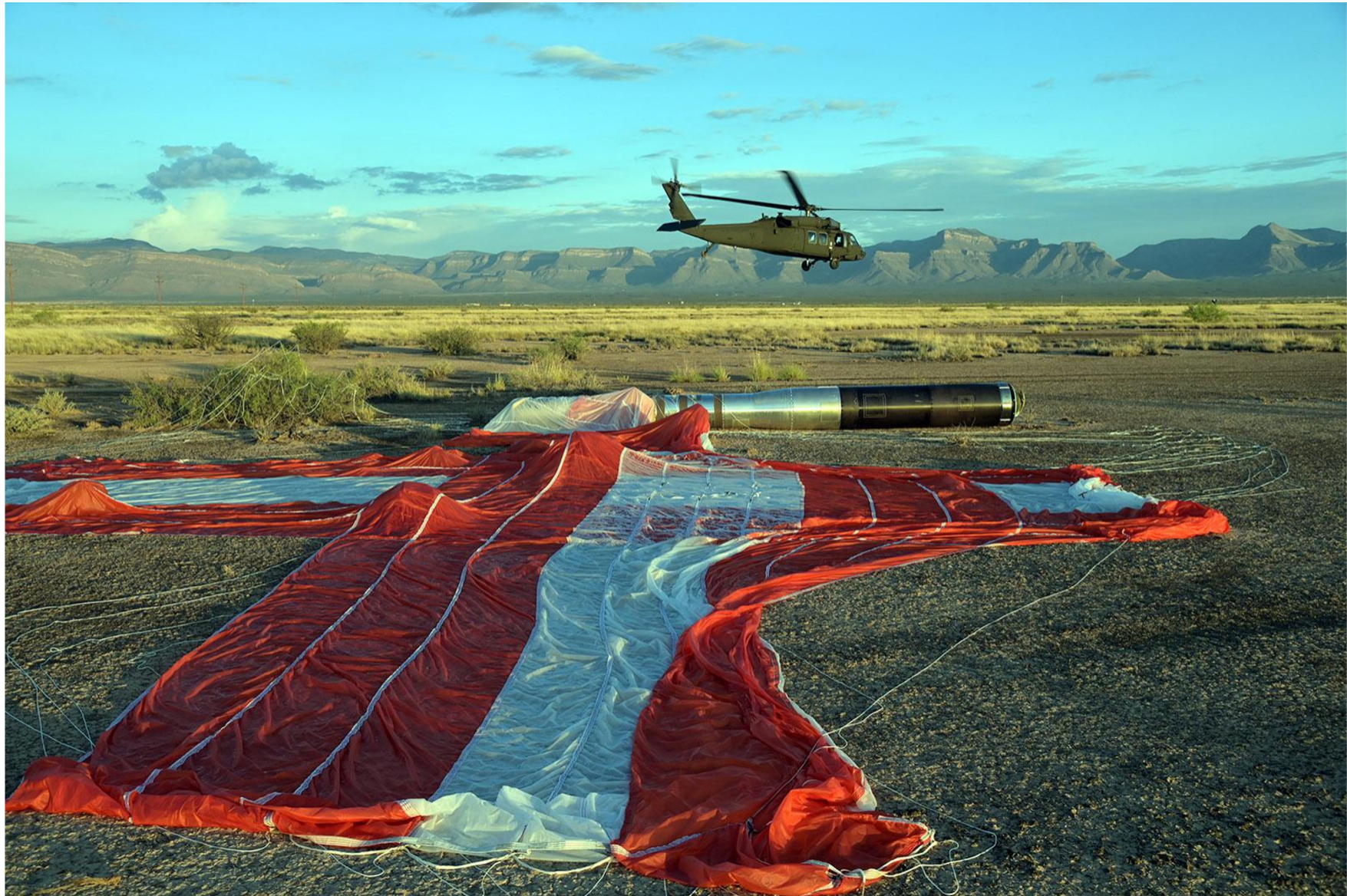
T-60s



T-10s

The Next Day...



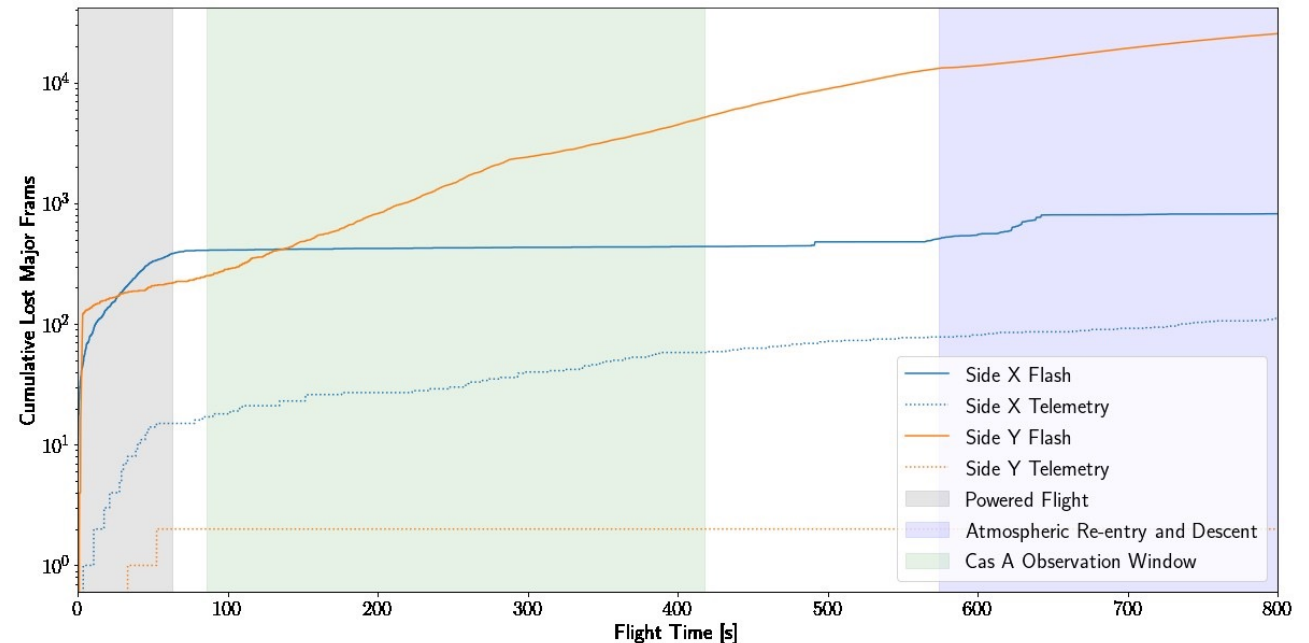
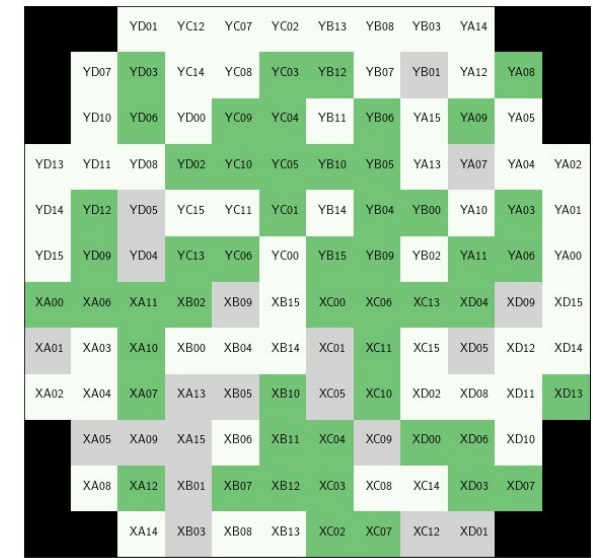






Flight 2 Results – Data Quality

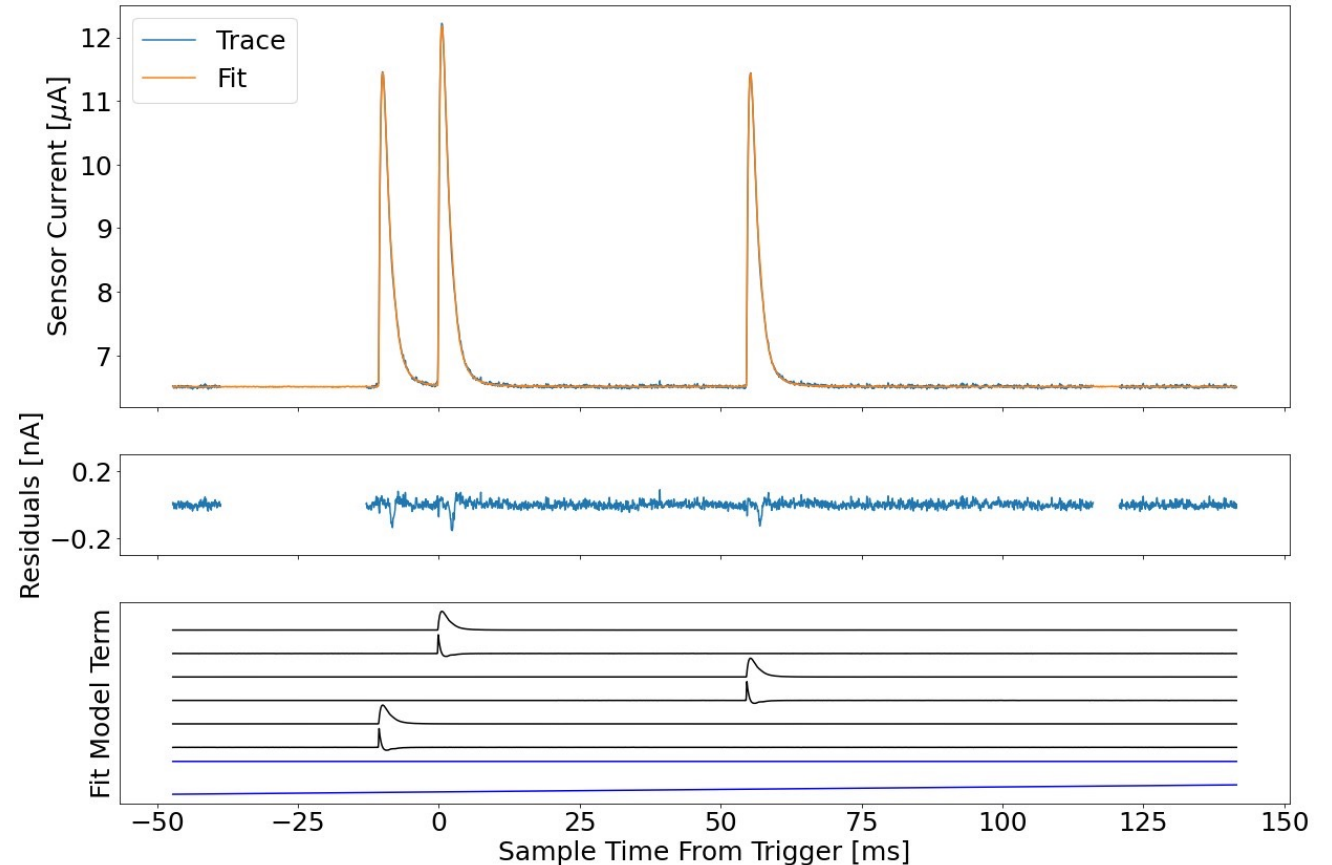
- Flash data on side Y lost many data packets
- Four data streams:
 - Telemetry (only 1/3 of pixels)
 - Flash (all pixels, recovered after flight)
 - Detector side X
 - Detector side Y
- Integrating with the rocket telemetry re-introduced sources of RF mitigated in the science-instrument-only configuration
 - Cyclic data transmission modulates an RF driven baseline response
 - Affects pixels unevenly depending on analogue signal wire and trace locations
 - In the future, could be mitigating by bit-stuffing the transmission lines



Flight 2 Results – Pulse Analysis

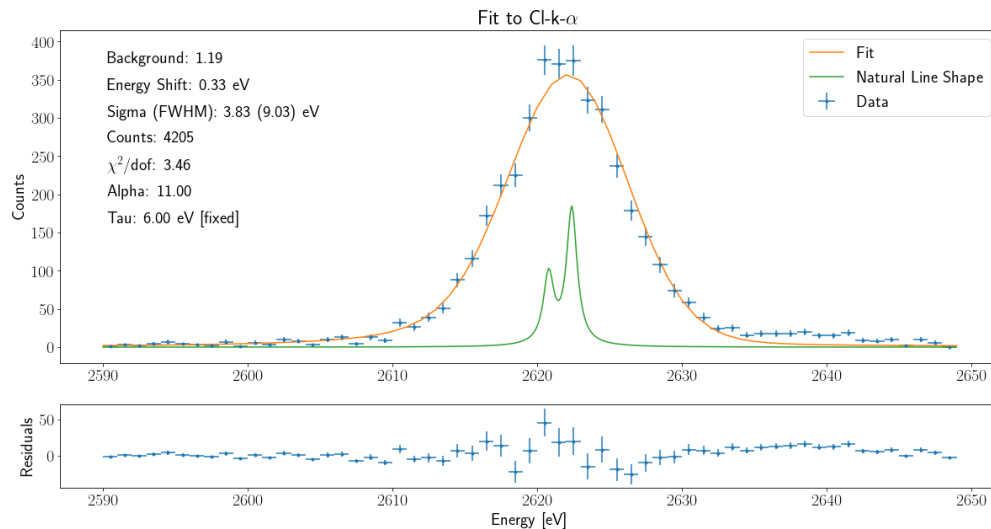
- Normal pulse analysis uses an “optimal filter” (OF) as an unbiased and minimum variance estimator of the pulse heights
- Employ a NIST multi-pulse fitting to handle pileup and data drops
- Equivalent to a normal OF for single pulses without data drops
- X-ray pulses with missing data are fit with a noise-weighted least squares model
 - Too computationally intensive for real-time pulse processing, but works well for a single data set

$$\hat{\mathbf{p}} = (\mathbf{M}^T \mathbf{R}^{-1} \mathbf{M}) \mathbf{M}^T \mathbf{R}^{-1} \mathbf{d} = \hat{\mathbf{f}}^T \mathbf{d}$$

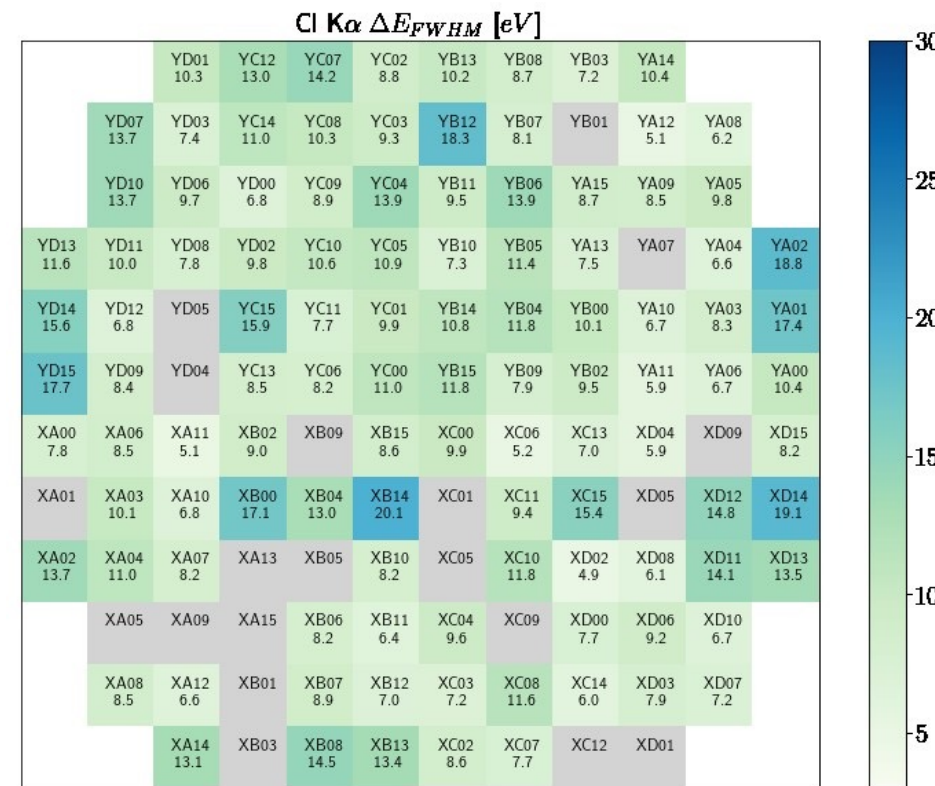
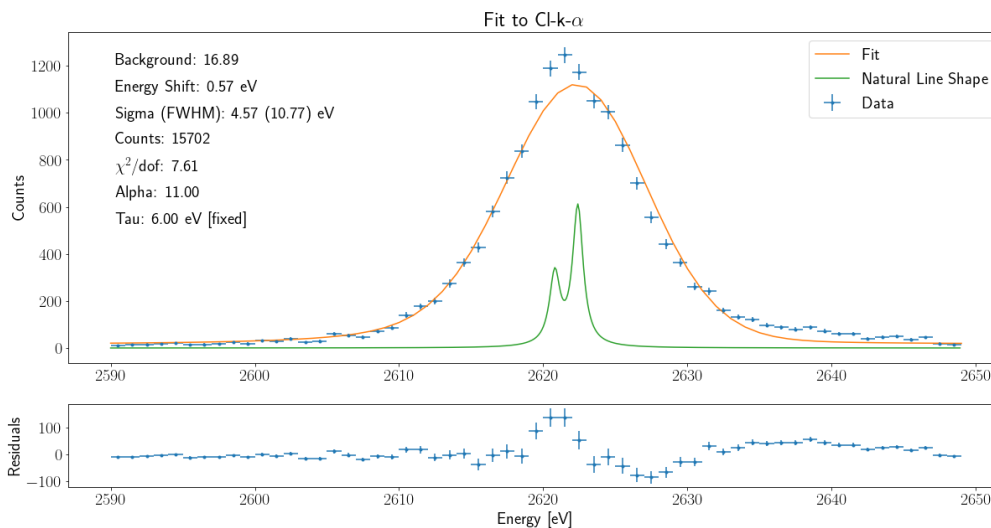


Flight 2 Results – Data Quality

**Strong Quality
Cuts:
9.07 eV FWHM**

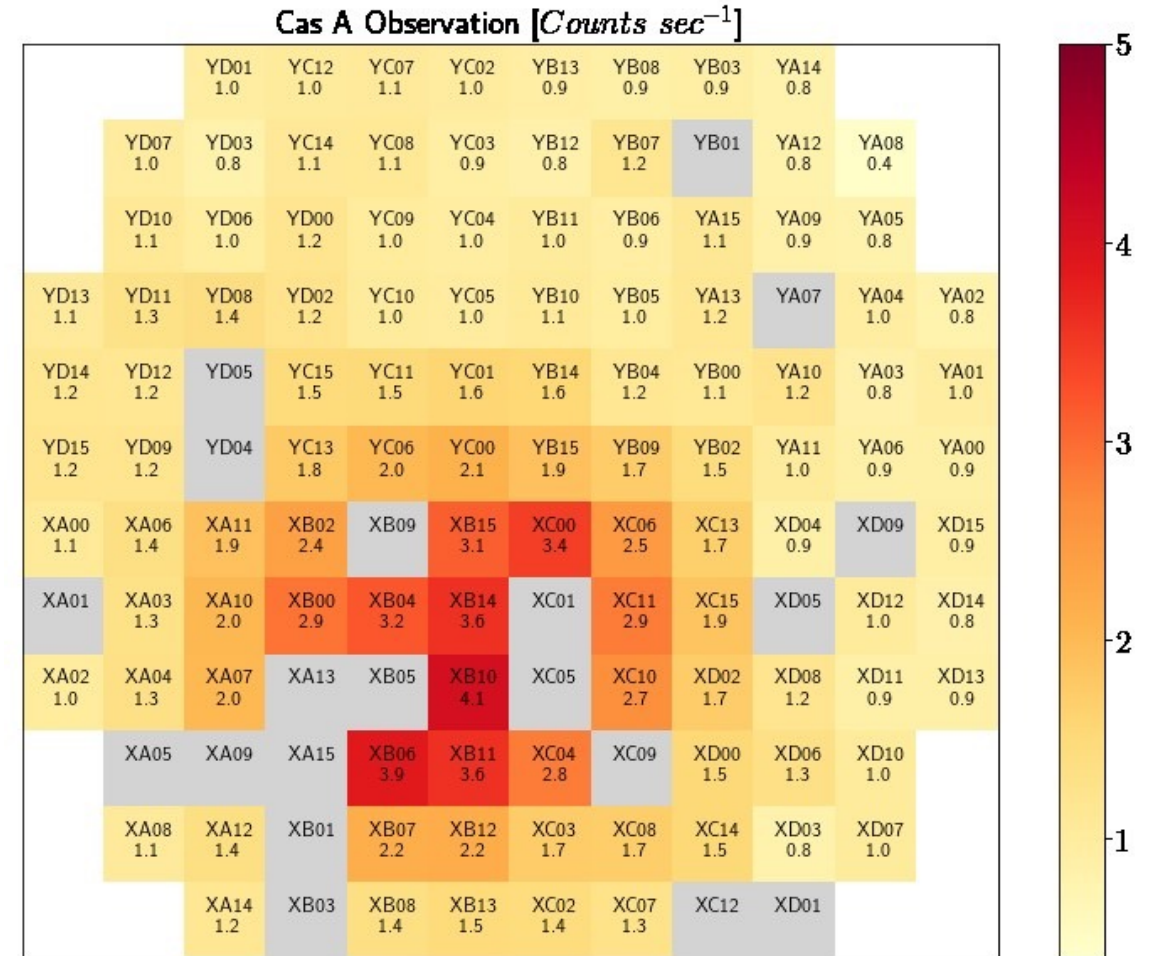


**Weak Quality
Cuts:
10.77 eV FWHM**

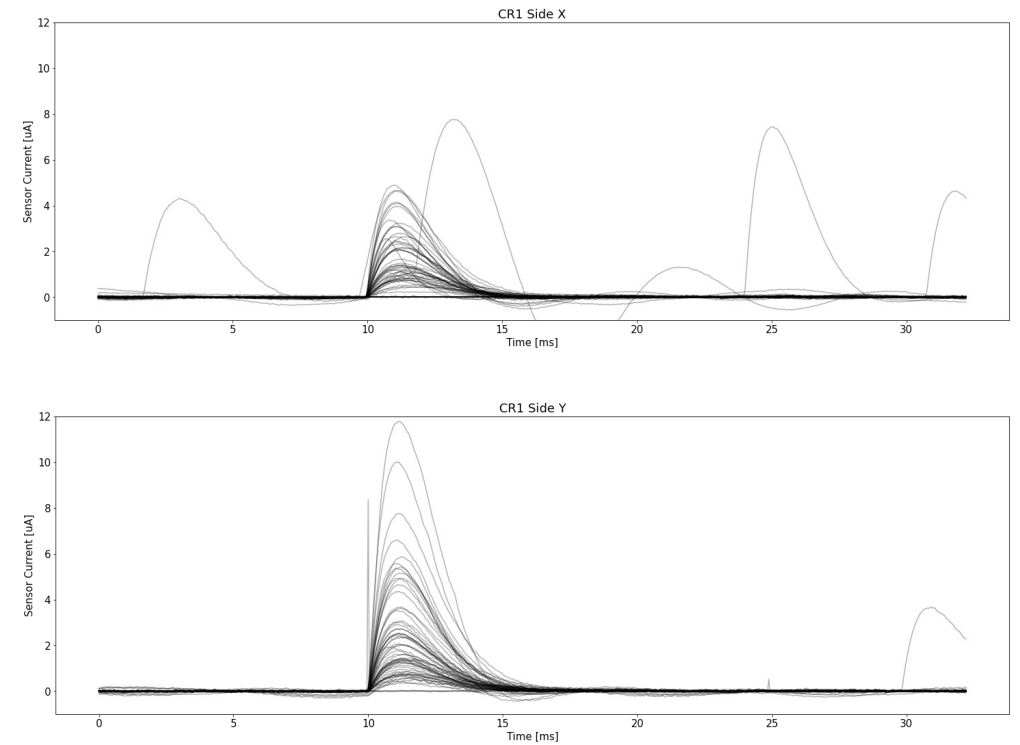
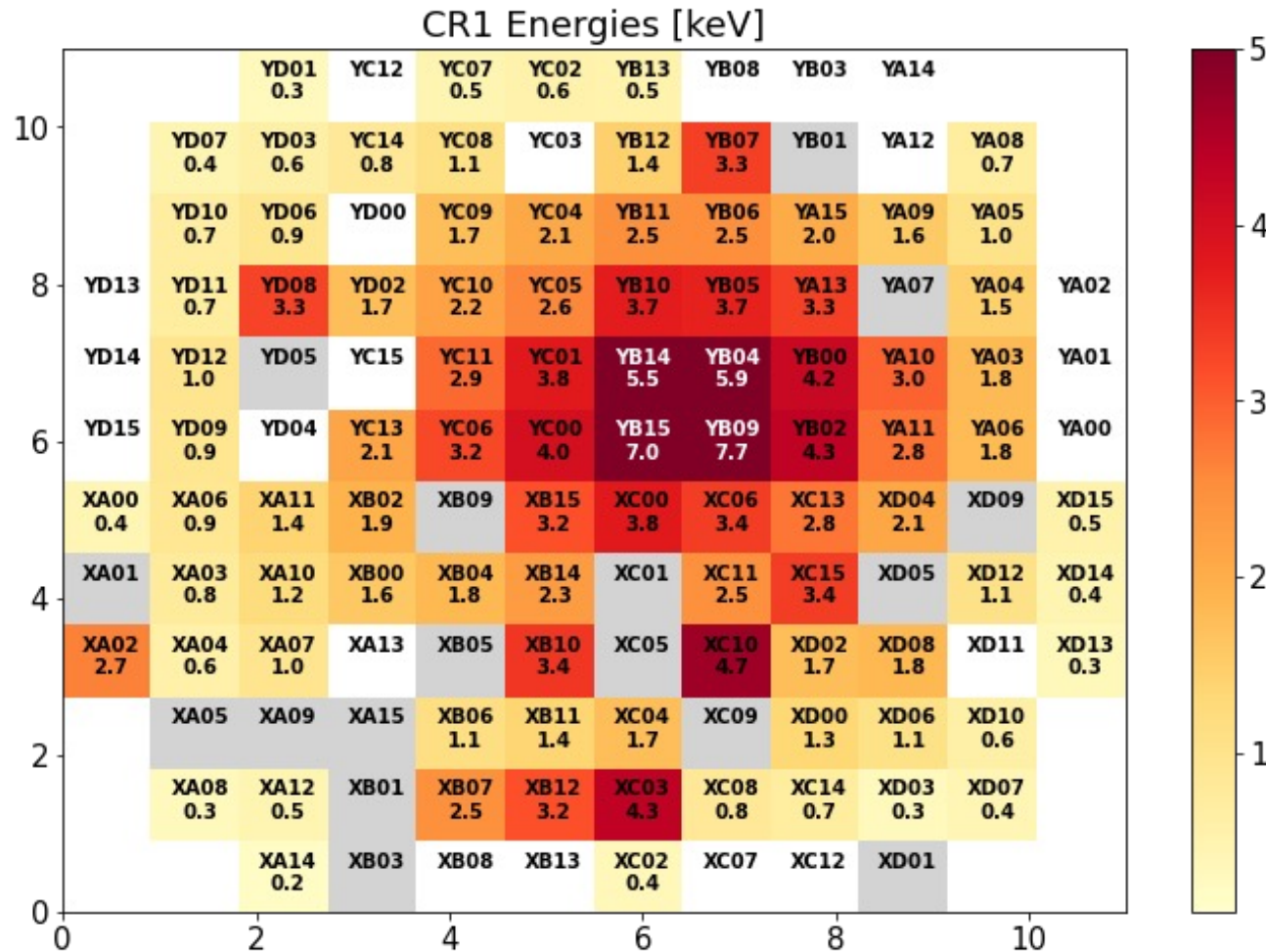


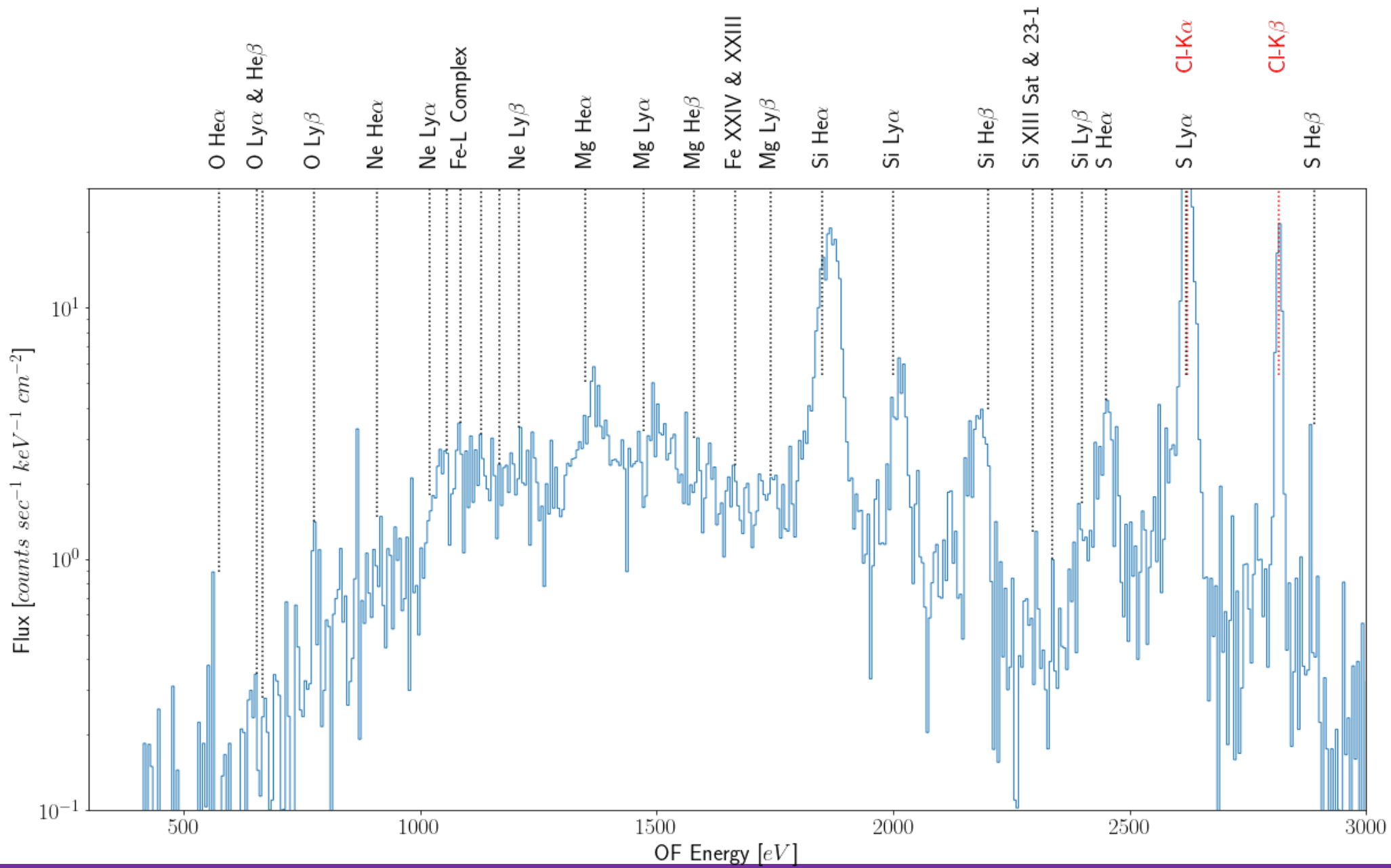
Flight 2 Results – Optics Alignment

- Live time adjusted counts per second
- Cas A appears about 2' off center
- Good agreement with post-flight alignment checks
 - Most likely the mirror shifted during the vibrational load of flight

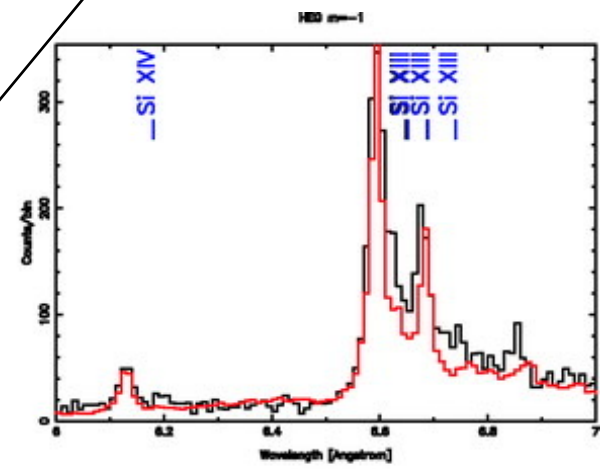
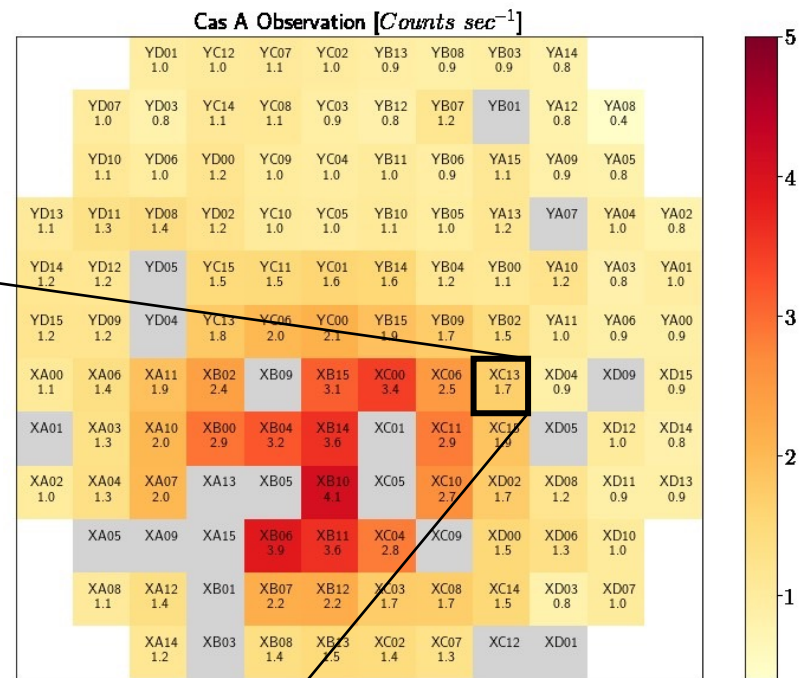
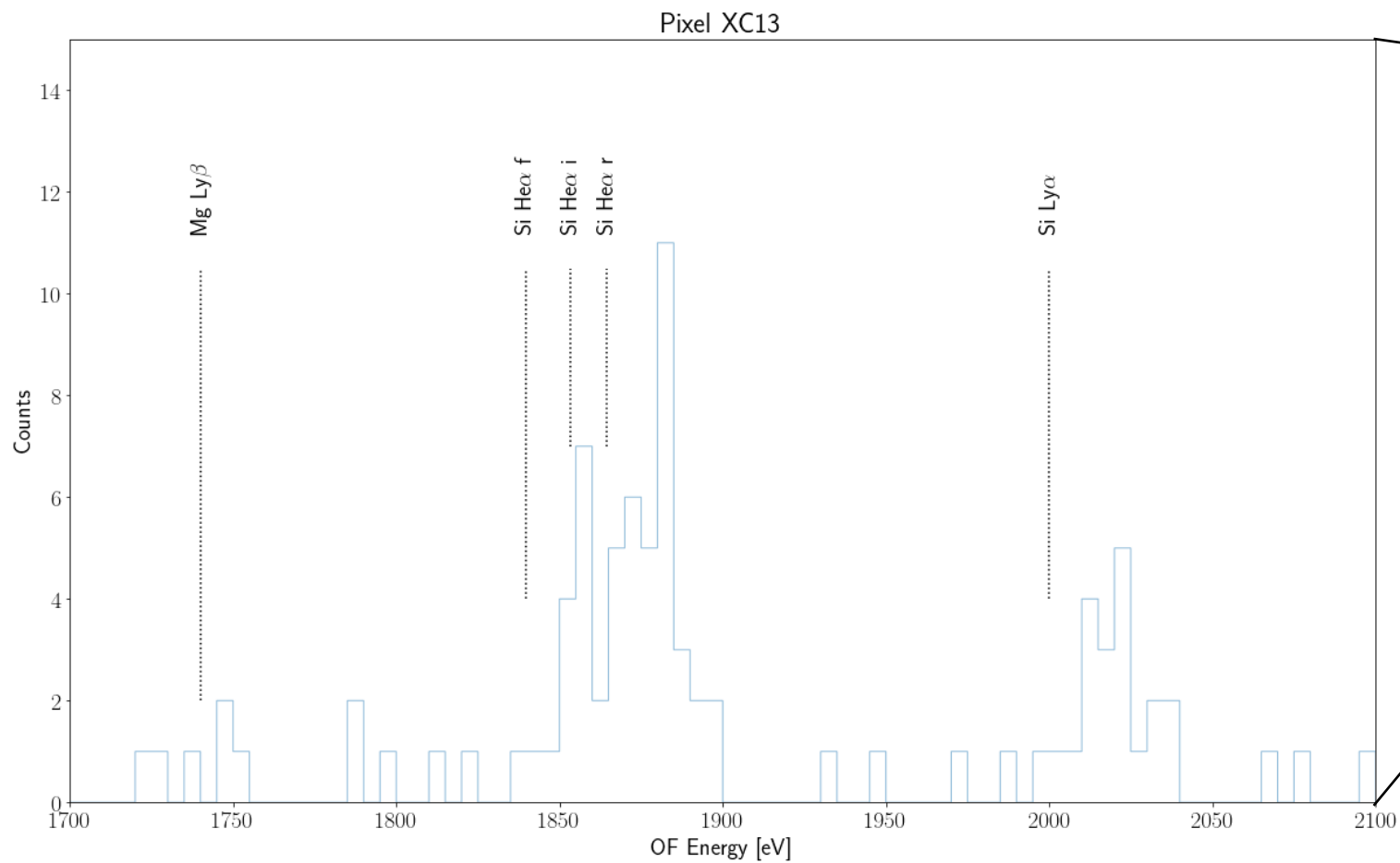


Two Cosmic Ray Events





Example Pixel: XC13



Chandra HEG + ACIS-S DOI 10.1086/507481

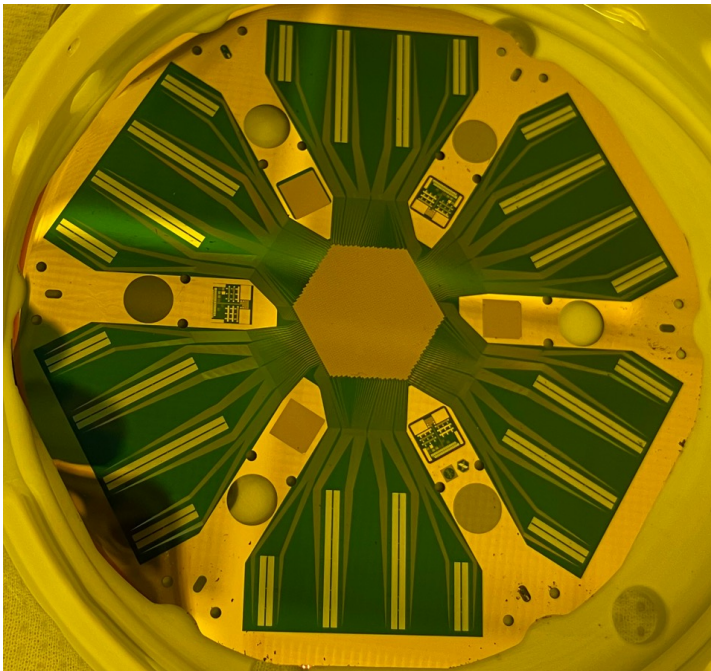
Next Generation TES Microcalorimeter Arrays

Goddard Space Flight Center

Future X-ray Observatories

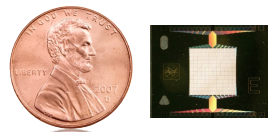
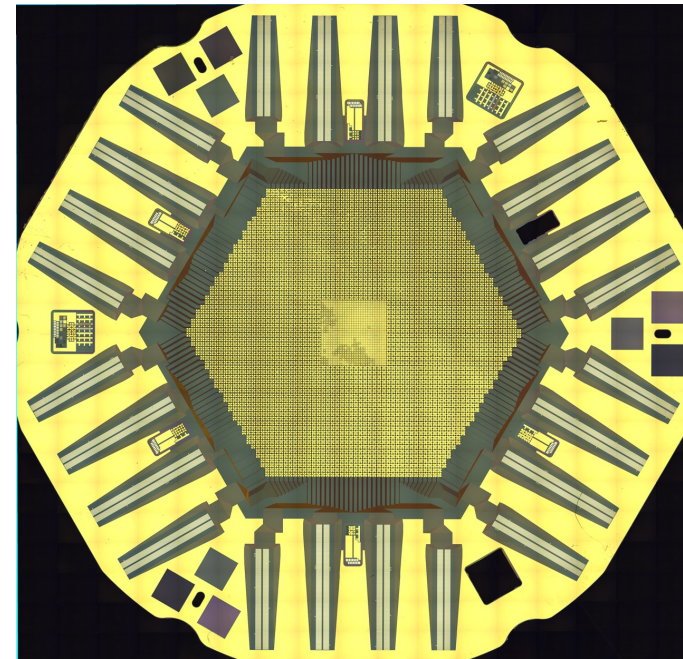
Athena

- > 1000 pixels
- Image quality angular resolution
- Improved energy resolution



LEM

- Low energy (<2 keV) optimization
- “Hydra” TES pixels
 - even more spatial pixels
 - Very large FOV



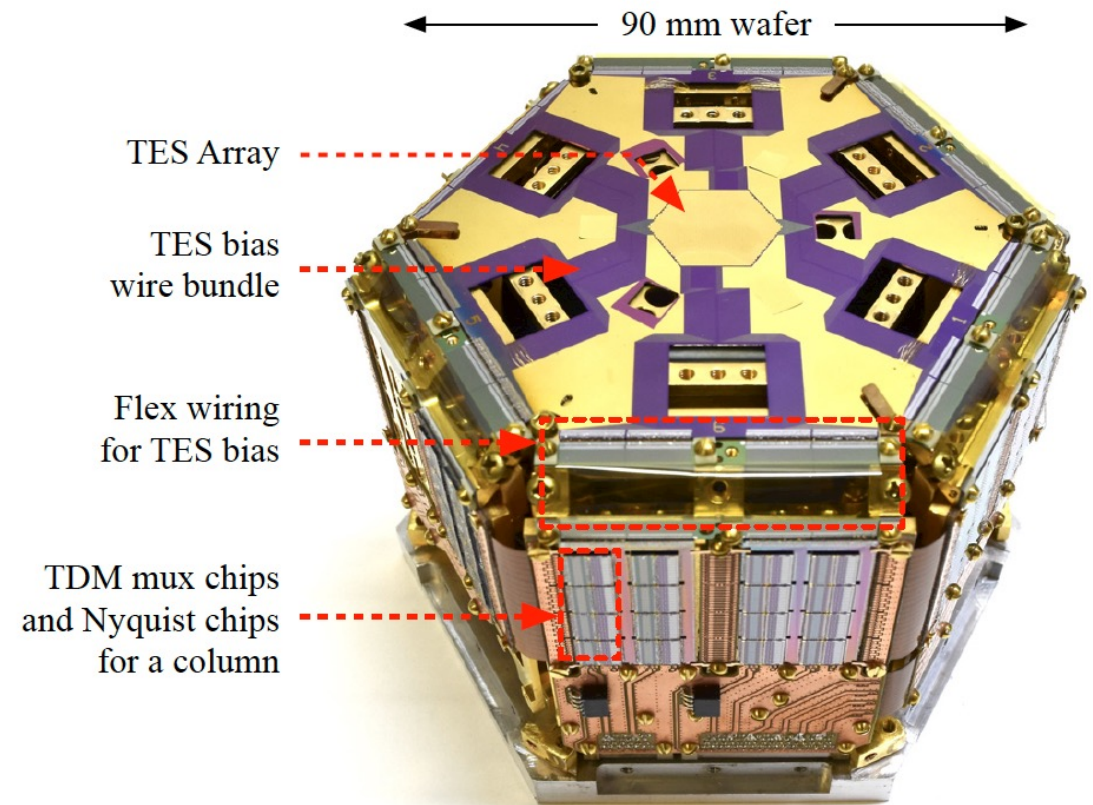
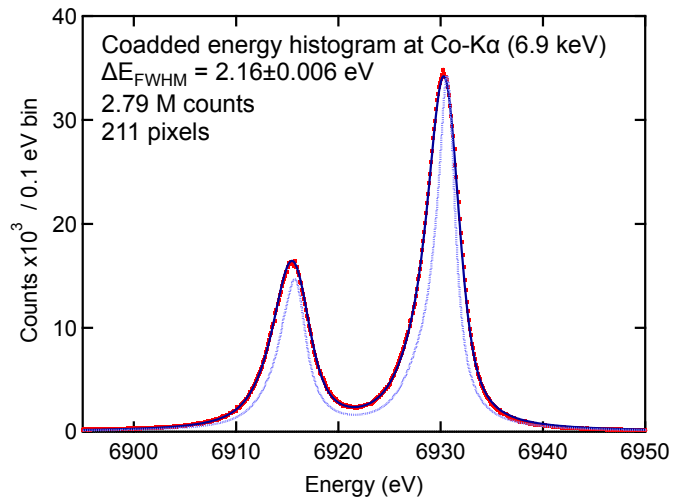
Micro-X for scale

Microcalorimeter X-ray Observatories

	Micro-X	XRISM	Athena	LEM
Energy Band [keV]	0.3 – 2.5	0.4 – 15	0.2 – 12	0.2 – 2
Peak Effective Area [cm ²]	300	300	6000	1600
Field of View	12'	3'	5'	30'
Angular Resolution	2.4'	1'	5"	15"
Spectral Resolution [eV]	< 10	5	2.5	1 – 2
Detector Array, pix	12x12	6x6	50x50	118x118

Athena

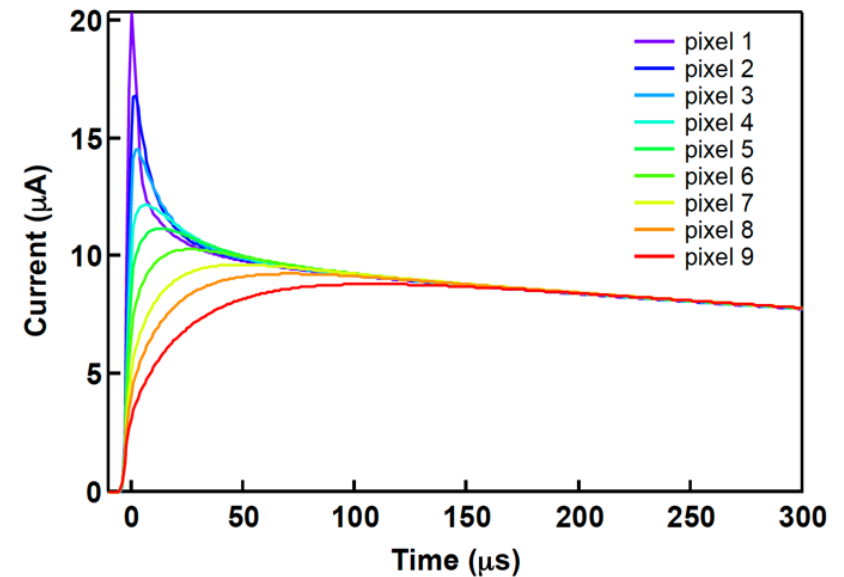
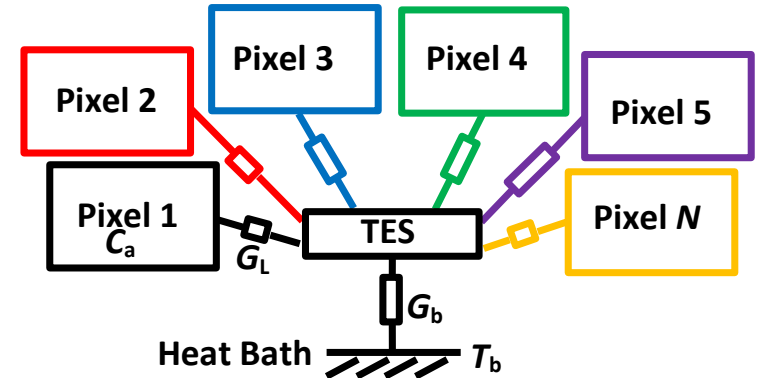
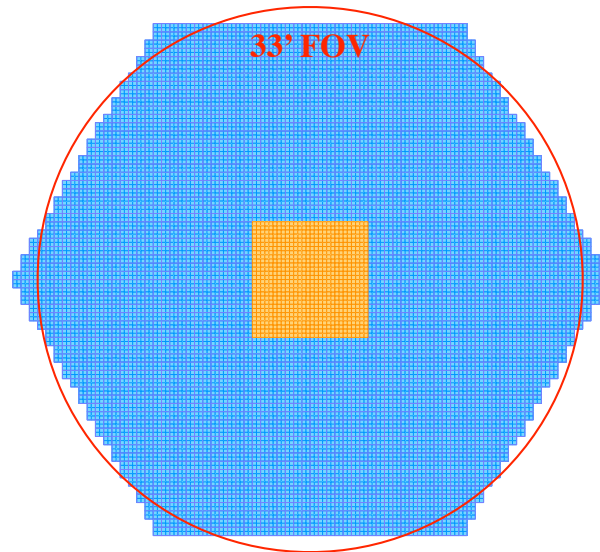
- Improved energy resolution:
 - Micro-X: 4.5eV single-pixel; 6eV multiplexed
 - Athena: 2.16eV multiplexed
 - Lower critical temperature, bath temperature, and pixel heat capacity
 - Faster row timings for improved multiplexing factor
 - Simpler TES design produces a more even transition shape



Line Emission Mapper (LEM)

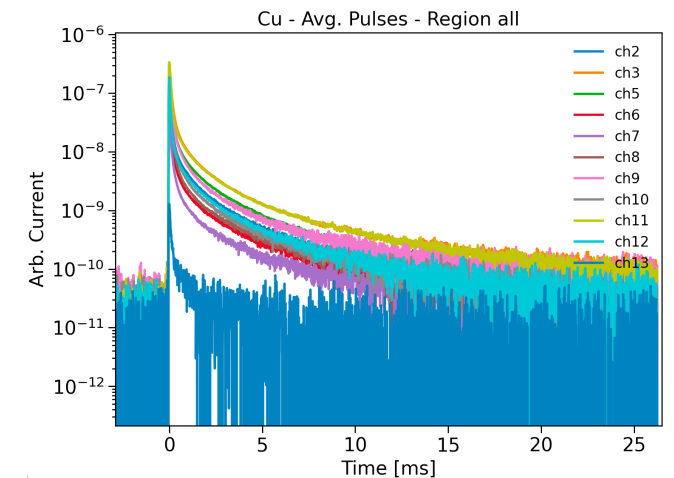
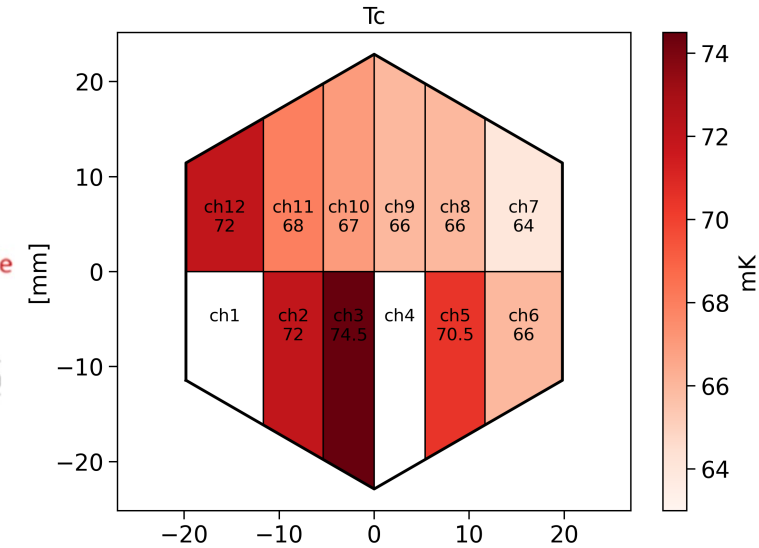
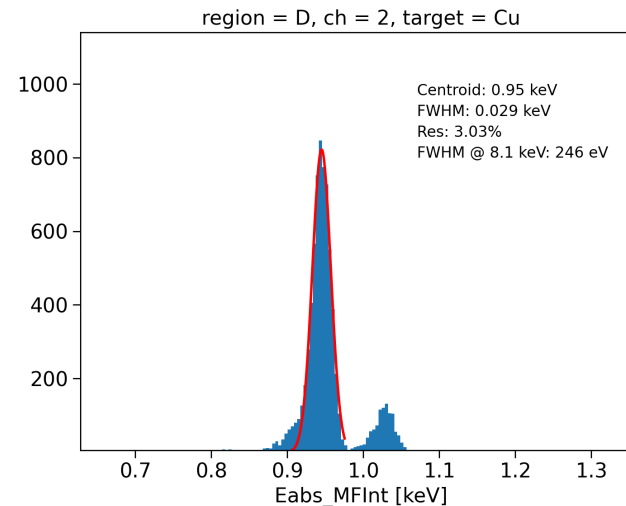
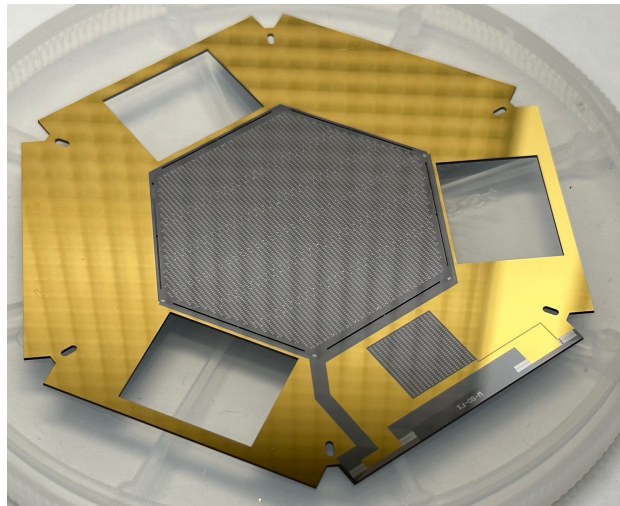
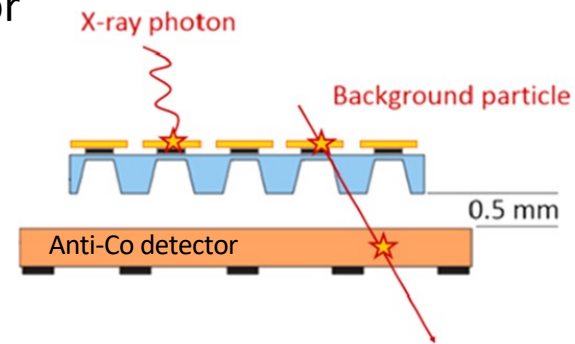
- Currently proposed as a NASA probe class mission
- Focused on low energy x-rays with a very high grasp
- TES Hydra pixels:
 - One TES attached to many absorbers
 - LEM: 4 absorbers per TES
 - Lynx: 25 absorbers per TES

- Single-pixel inner array
- Hydra-pixel outer array



LEM Anticoincidence Detector

- Required to have low energy threshold of 20 keV or better
- 12 channels, each consisting of a parallel network of W-TES QETs
- Designed/fabbed in collaboration between SLAC/NU/GSFC

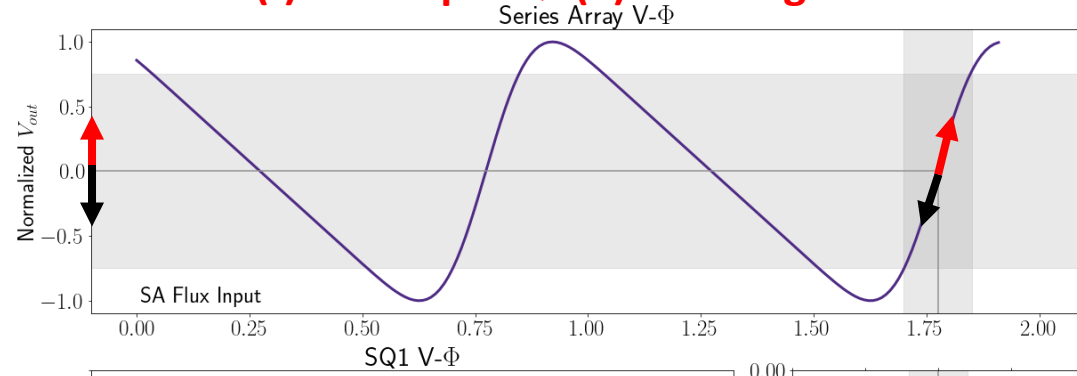


Thank you!

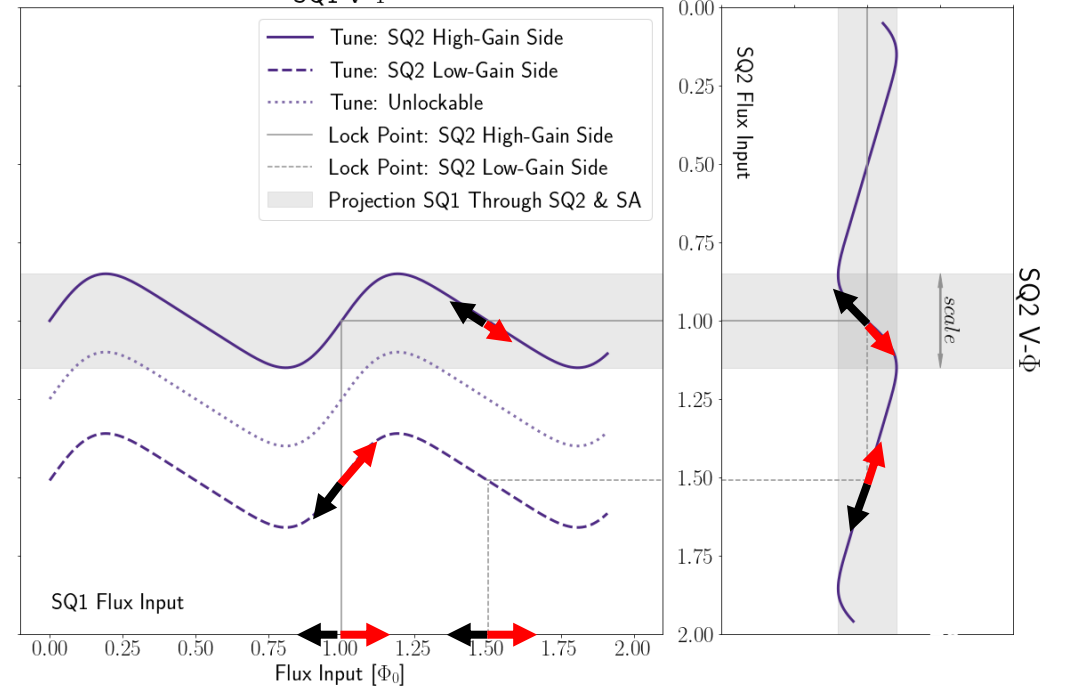
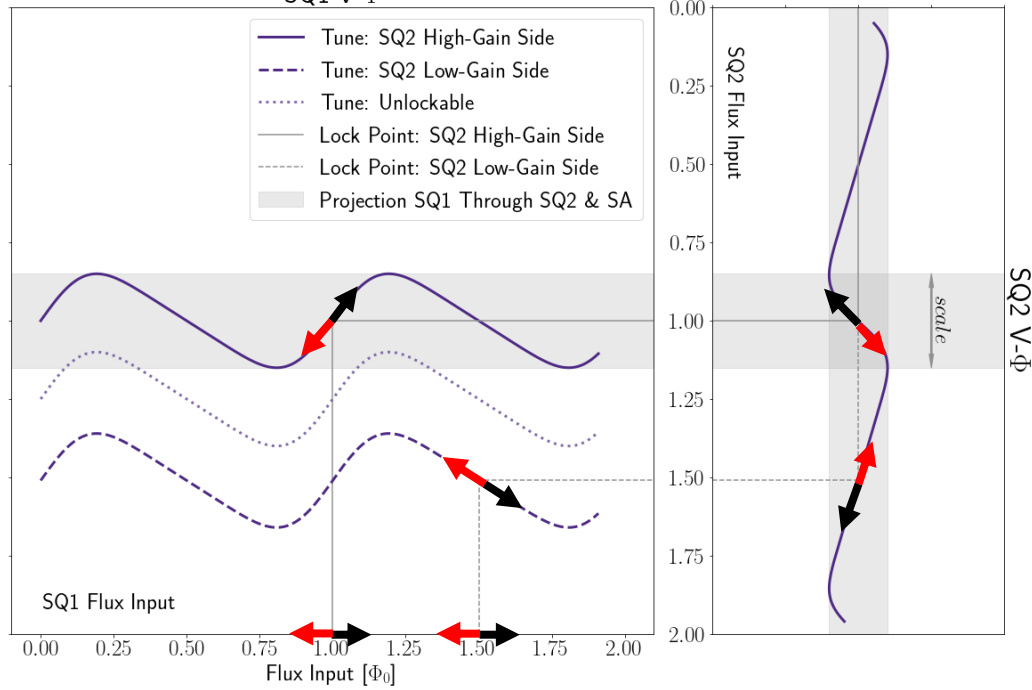
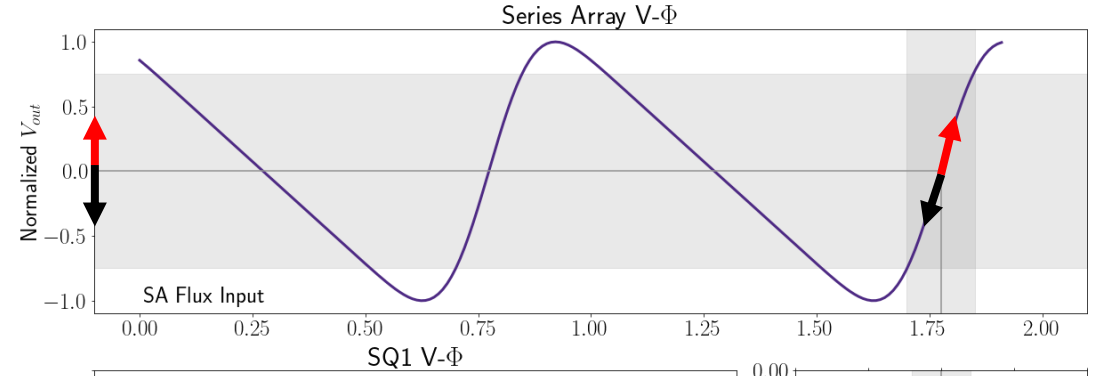


Reference

(+) Flux Input \rightarrow (-) Error Signal
(-) Flux Input \rightarrow (+) Error Signal



(-) Flux Input \rightarrow (-) Error Signal
(+) Flux Input \rightarrow (+) Error Signal



Current Source Assembly



TES Array

Calibration x-ray path

Bolts connecting Pb shield to Al housing

Lead Shield

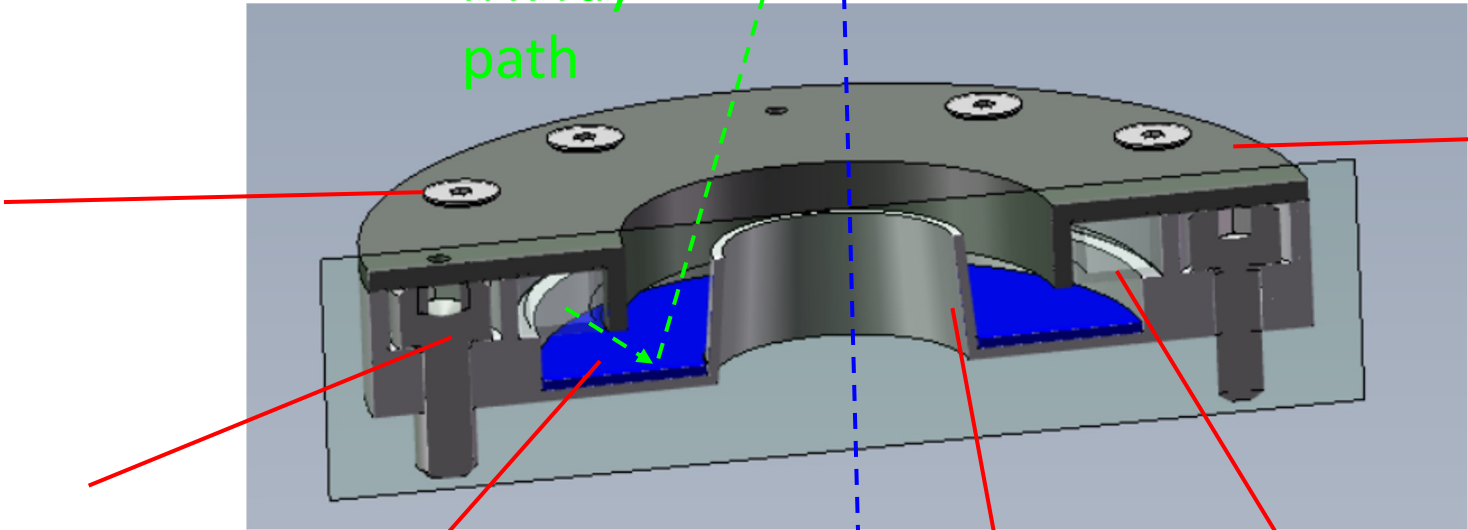
Bolts connecting Al housing to Nb can lid

KCl deposit

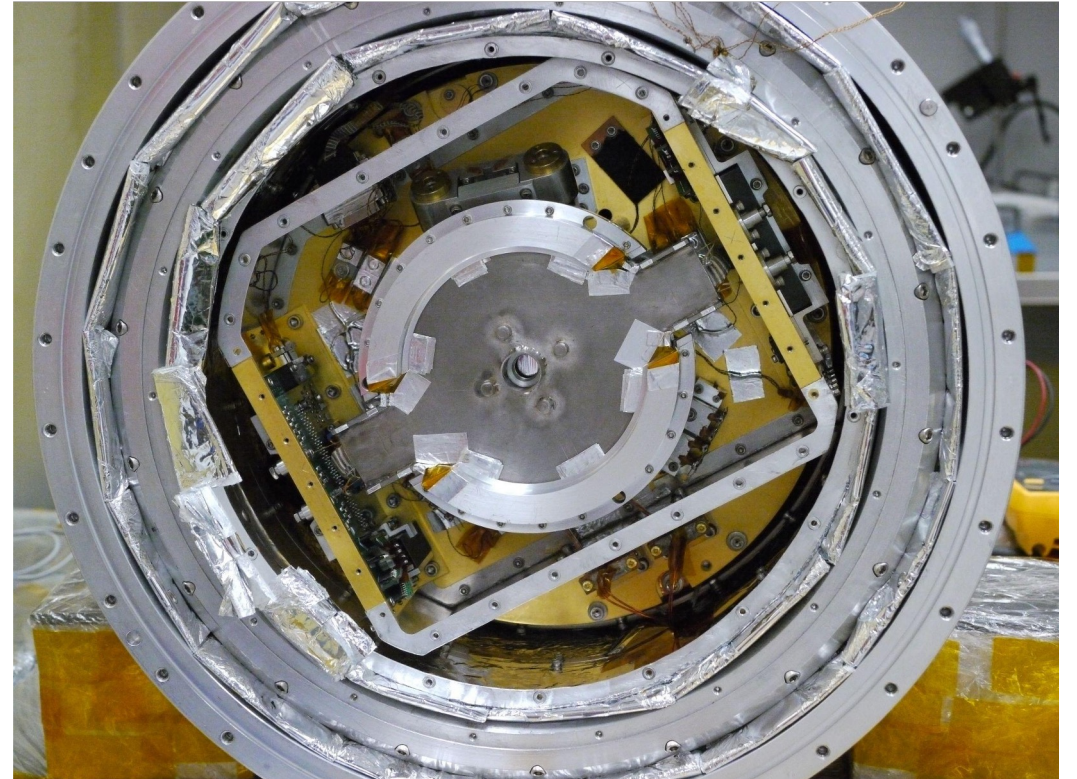
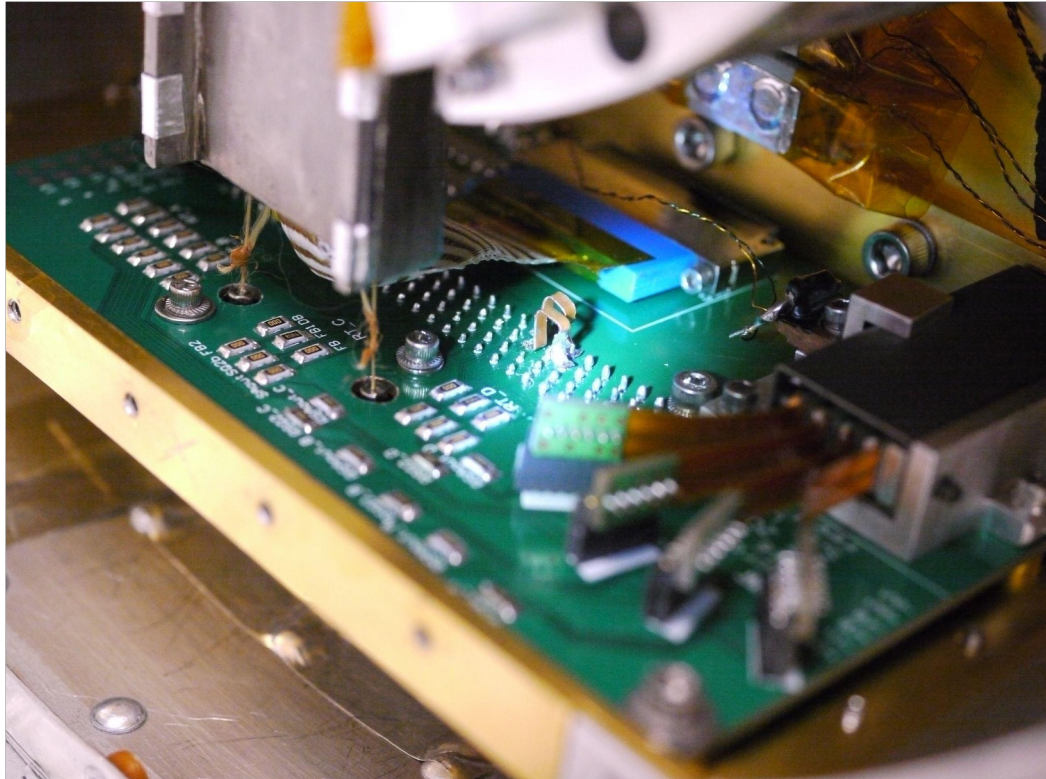
Science x-ray path

Fe 55 Source

Al housing



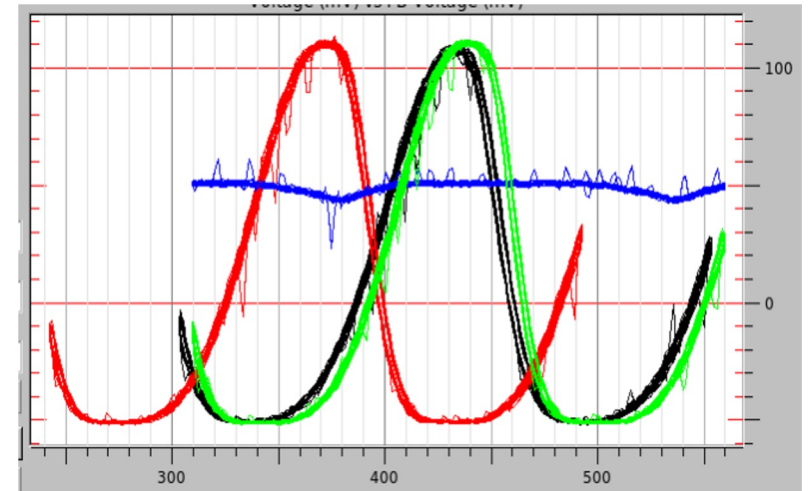
Col XD Fix



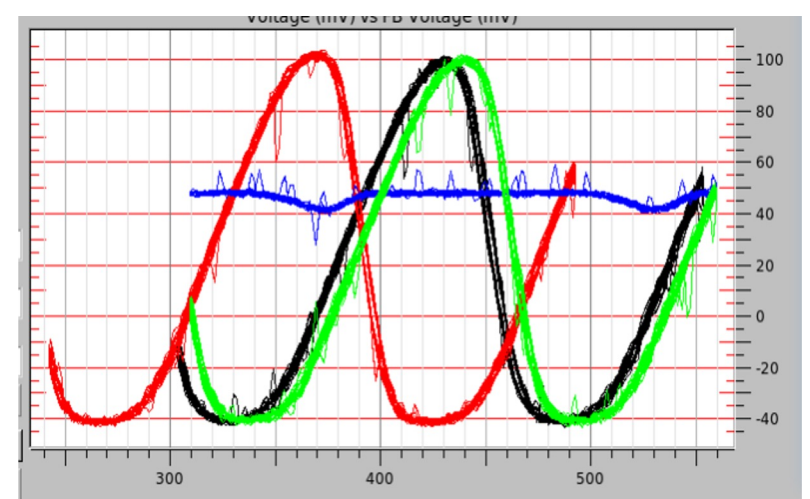
Example Flux Trapping + RF Effects

- Small amount of trapped flux
 - Visible on the disconnected SQUID in blue
- Increase RF pickup on the FB lines from increased cable length
 - V- Φ modulation reduced 11%
 - Rounded (more asymmetric) V- Φ response

Short FB Cables
165mV depth



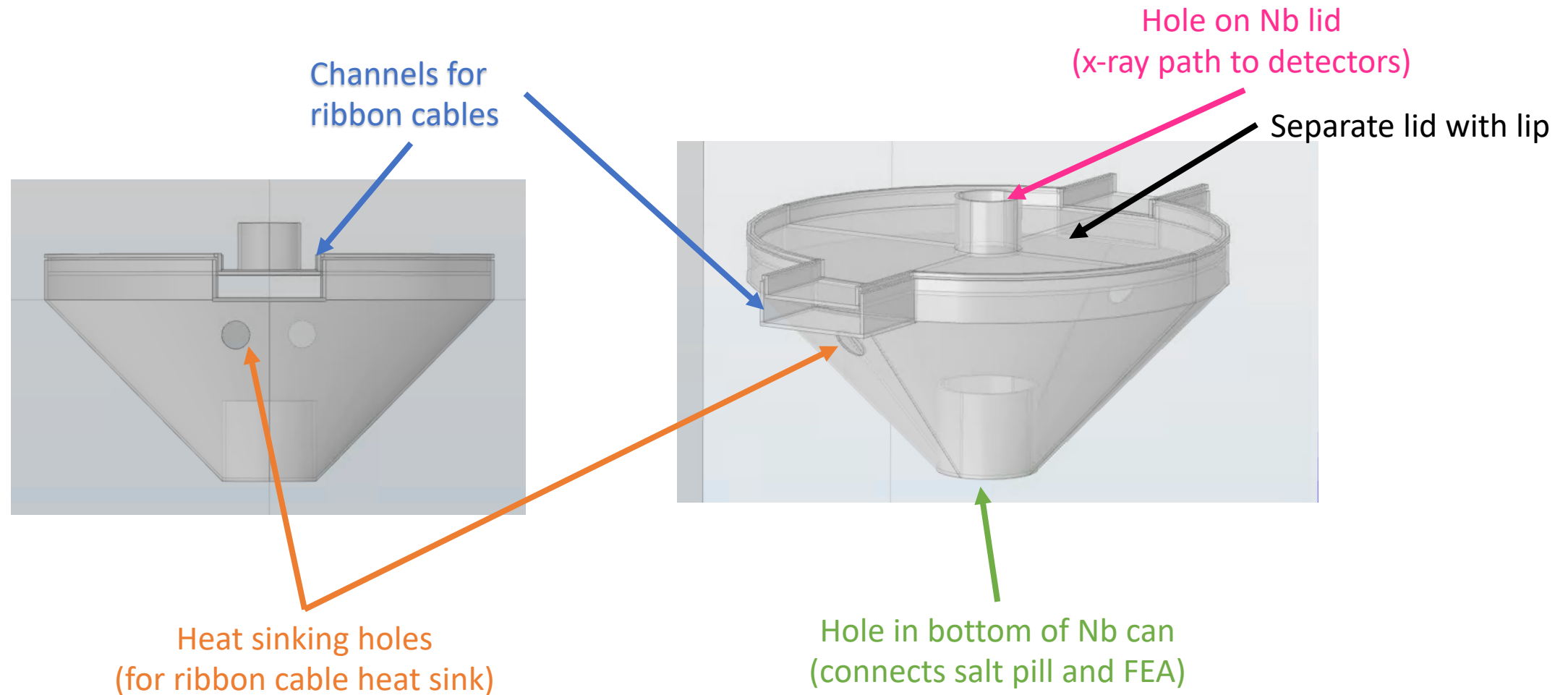
Long FB Cables
147mV depth



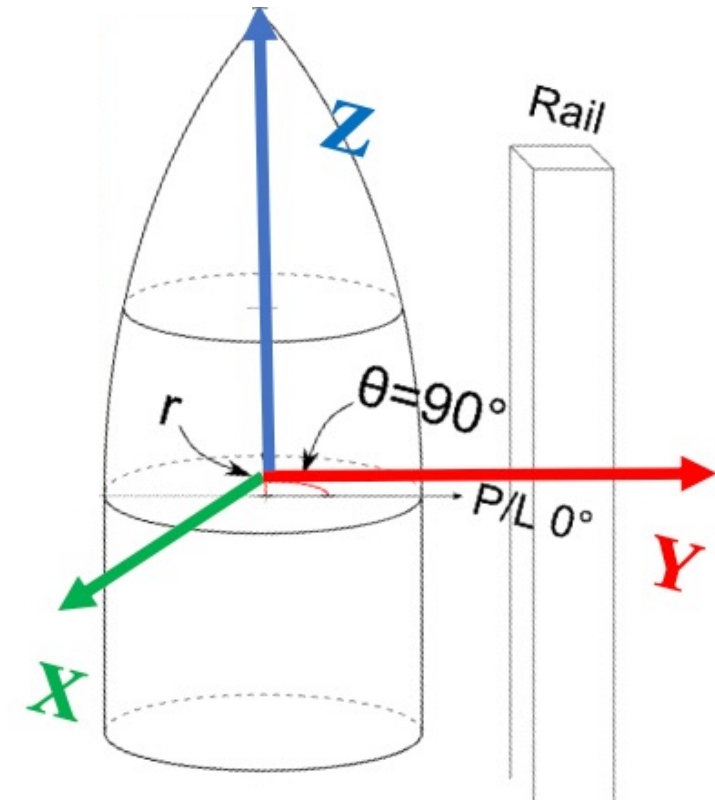
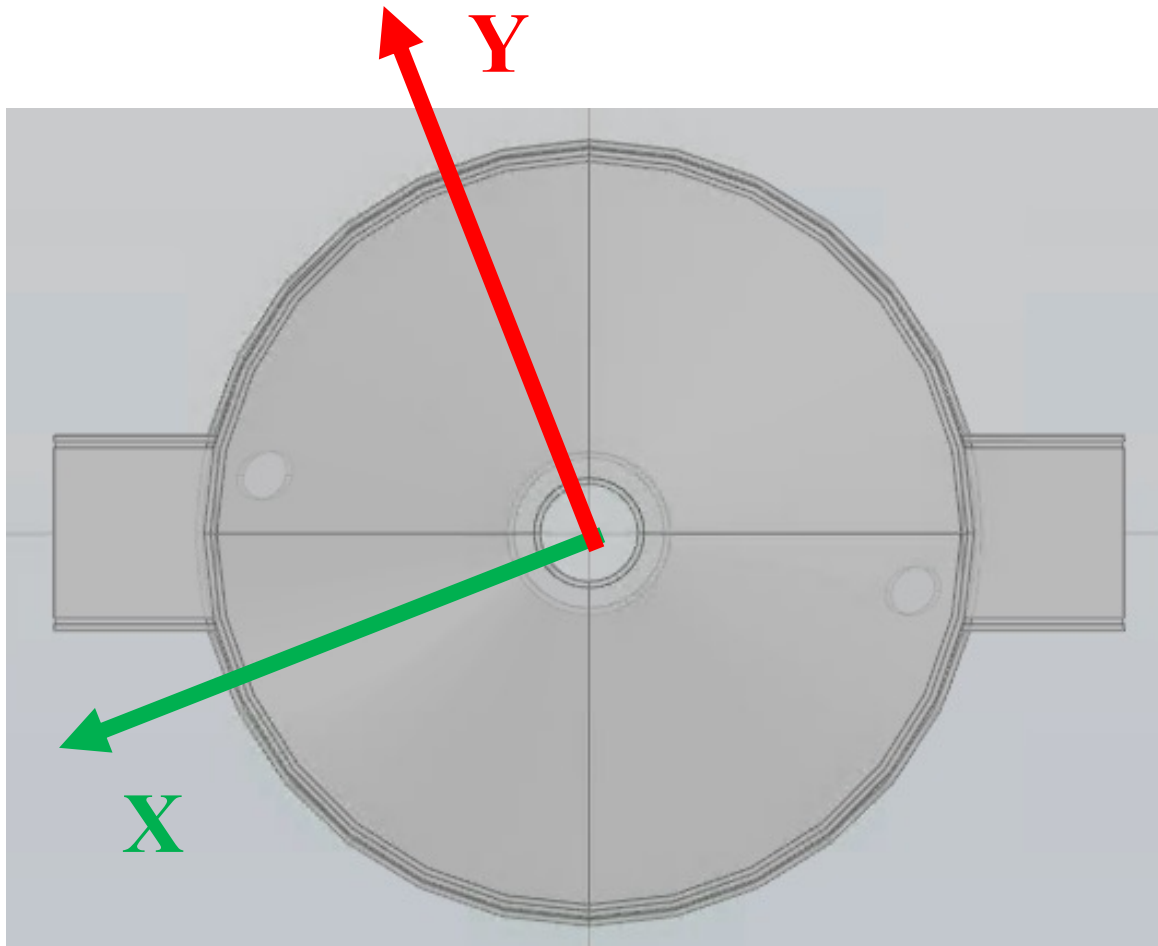
DOI: 10.1109/77.233588

DOI: 10.1063/1.113046

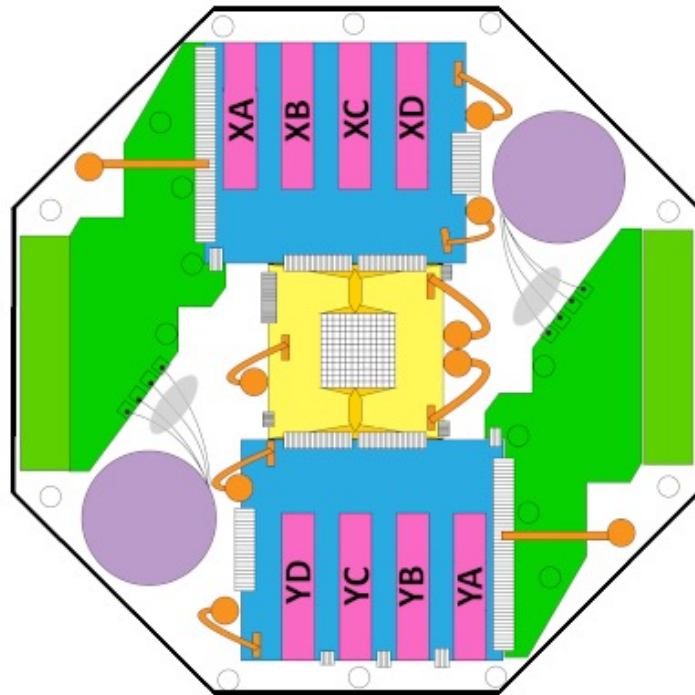
Magnetic Shielding



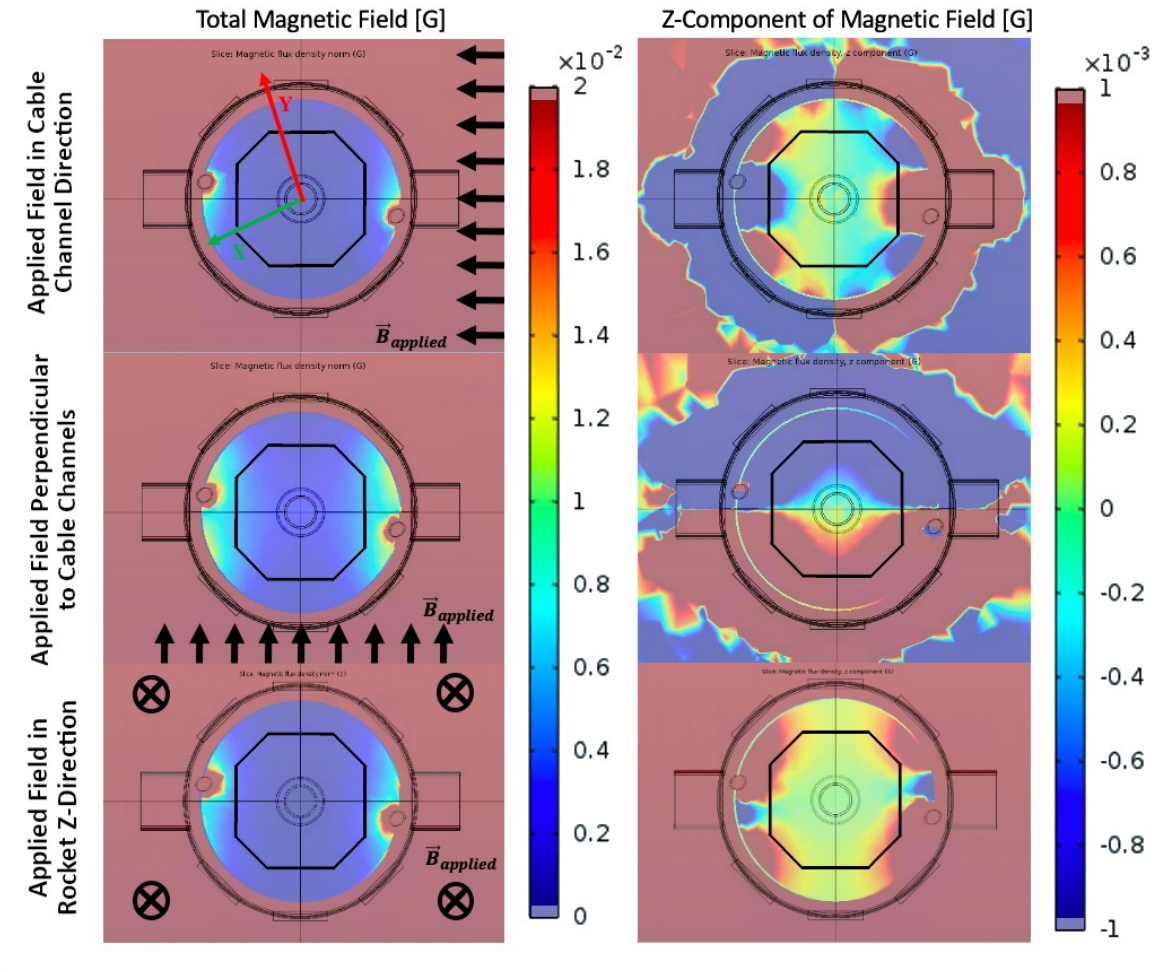
Magnetic Shielding



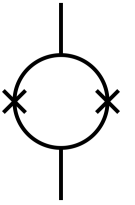
Magnetic Shielding of B_{Earth}



Comsol Modeling by Renee Manzagol

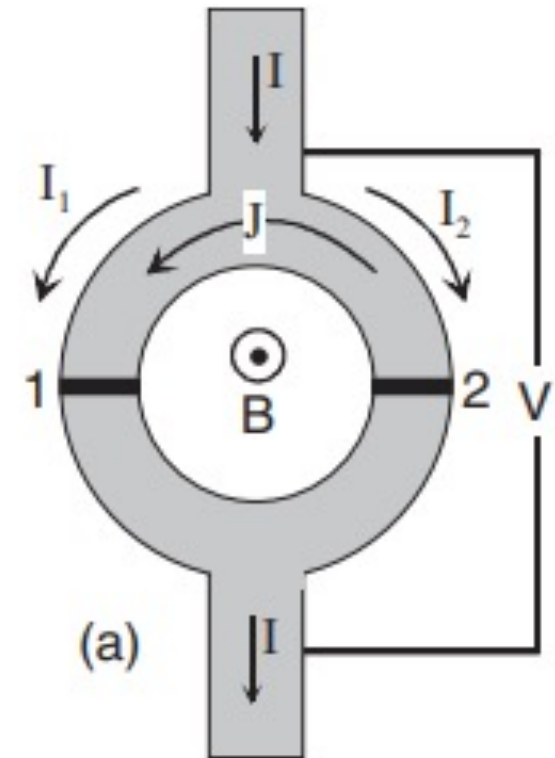


Intro to SQUIDs

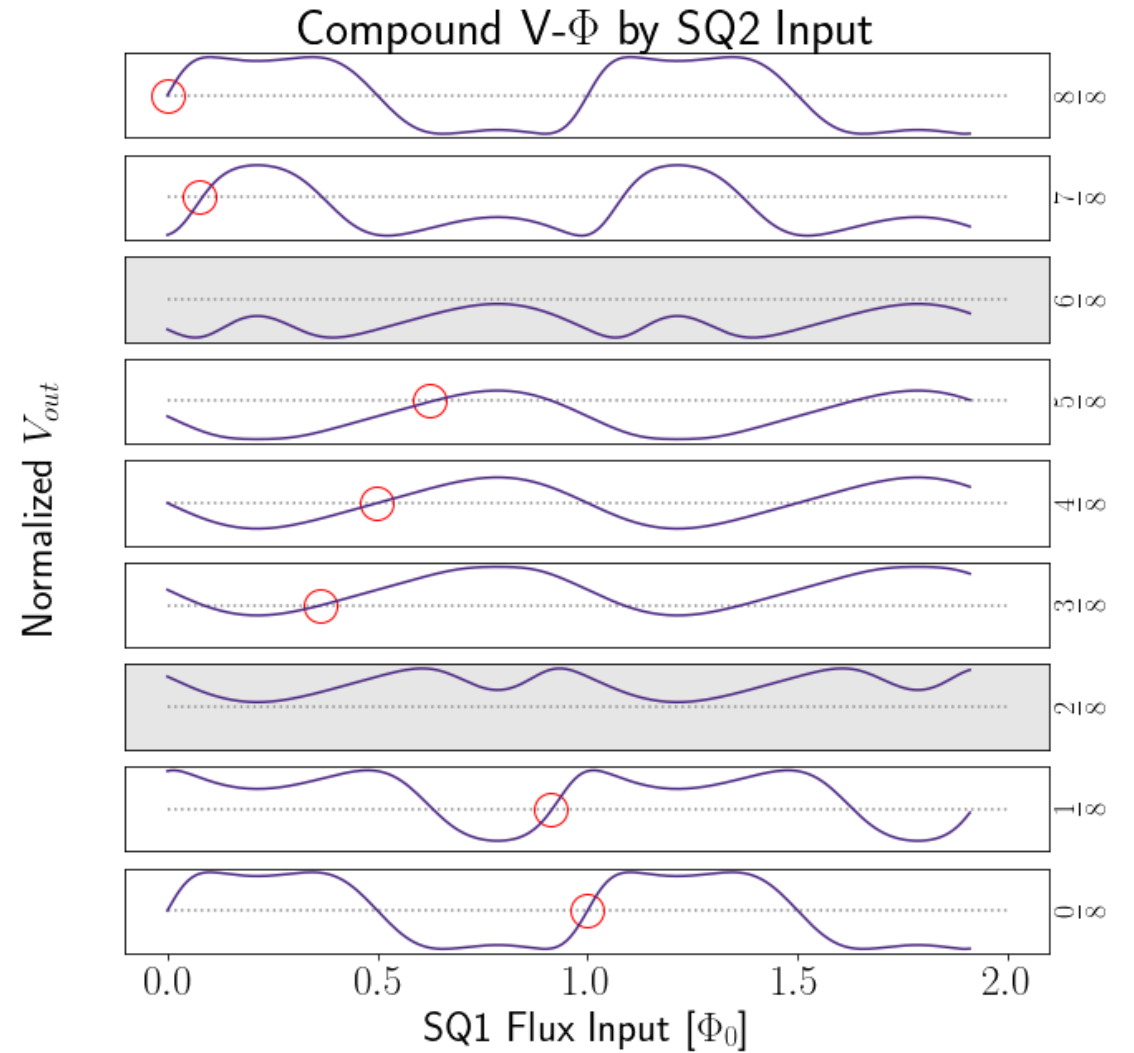
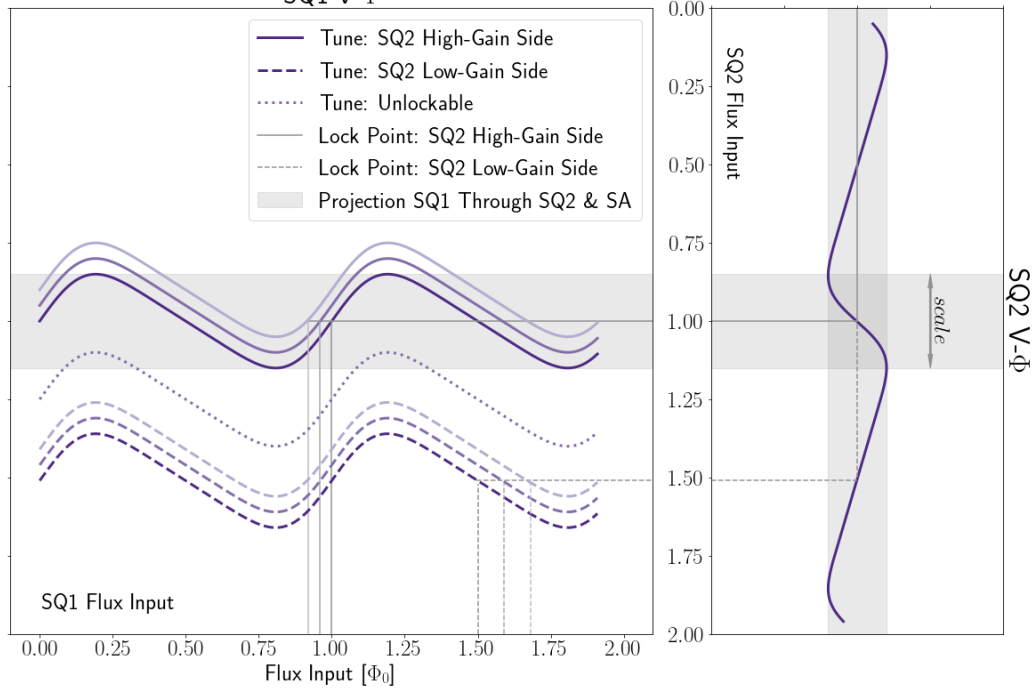
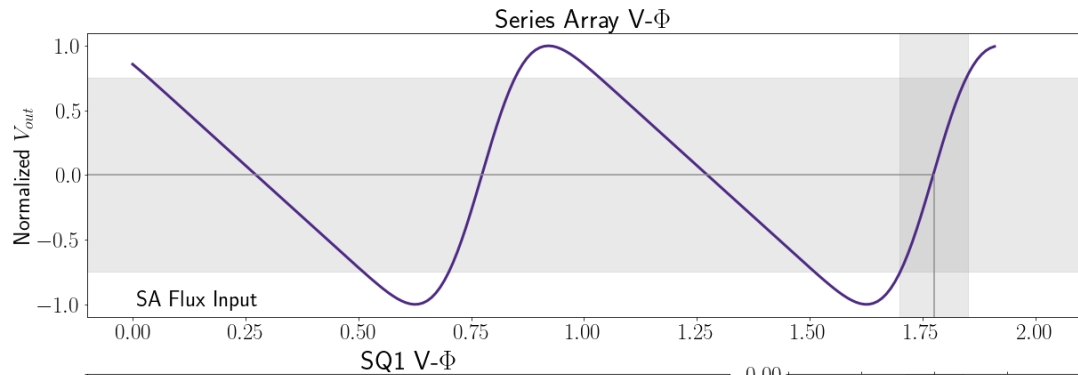


- Superconducting and inherently “quantum” electronic devices
 - Incredibly sensitive magnetometers
 - Acts as a flux-to-voltage transformer
 - Has a periodic flux to voltage relationship, or “V- ϕ ”
 - Results from a combination of flux quantization and Josephson tunneling

$$I_s = I_0 \sin \delta \qquad \frac{d\delta}{dt} = \frac{2\pi}{\Phi_0} U$$



TDM SQUID Circuit Model



TDM SQUID Circuit Model

