Searching for Dark Matter with the Micro-X Sounding Rocket

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Micro-X Science

1st flight: December 2017

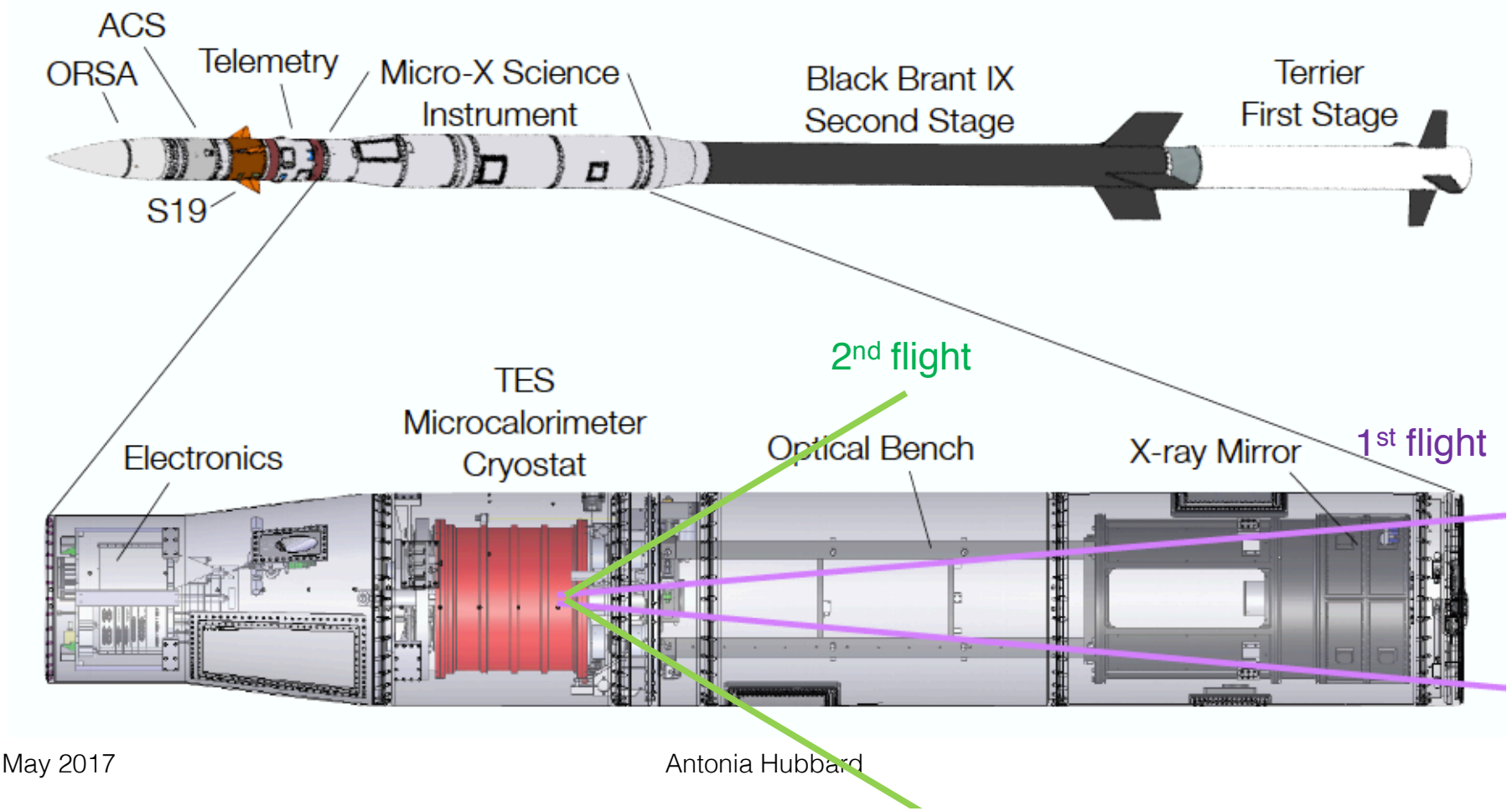
Puppis A SNR observation

- Energy and spatial information
- 2.5' PSF

2nd flight: August 2019

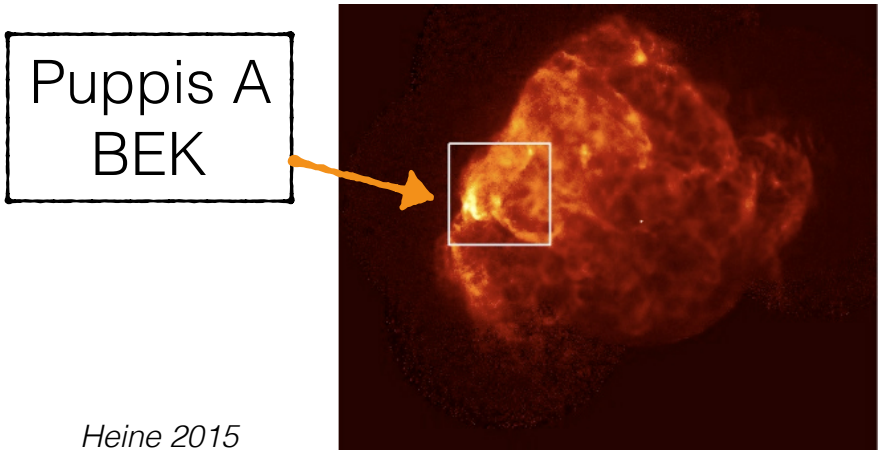
Sterile neutrino search

- Photon bucket
- 20° FOV

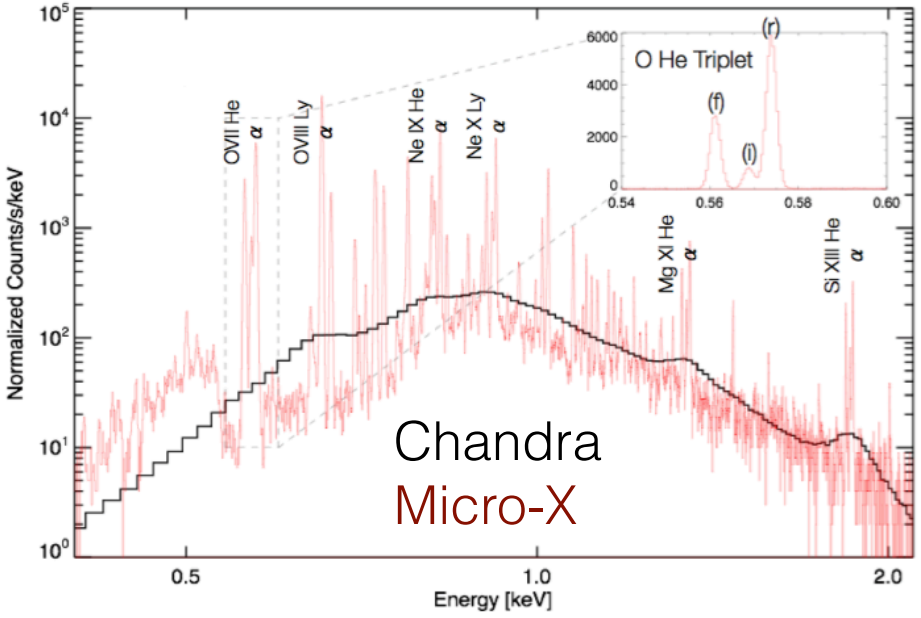


Up first: SNRs

- High spectral/angular resolution observation of extended X-ray sources with unique combination of bandpass, collecting area, resolution
  - SNR size makes high spectral resolution observations with grating instruments challenging
- Microcalorimeters can study detailed atomic physics of the plasma
  - Determine temperature, turbulence, elemental abundances
  - Look for evidence of charge exchange
  - Look for clues to gamma-ray emission from shock regions



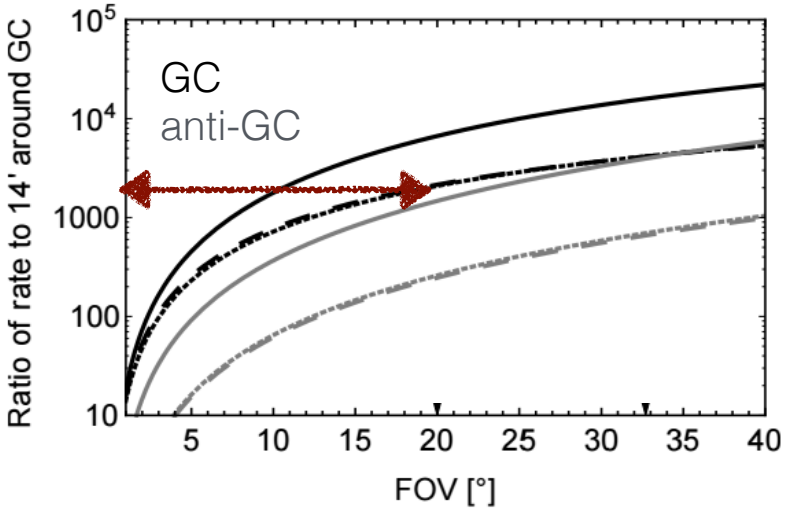
Heine 2015

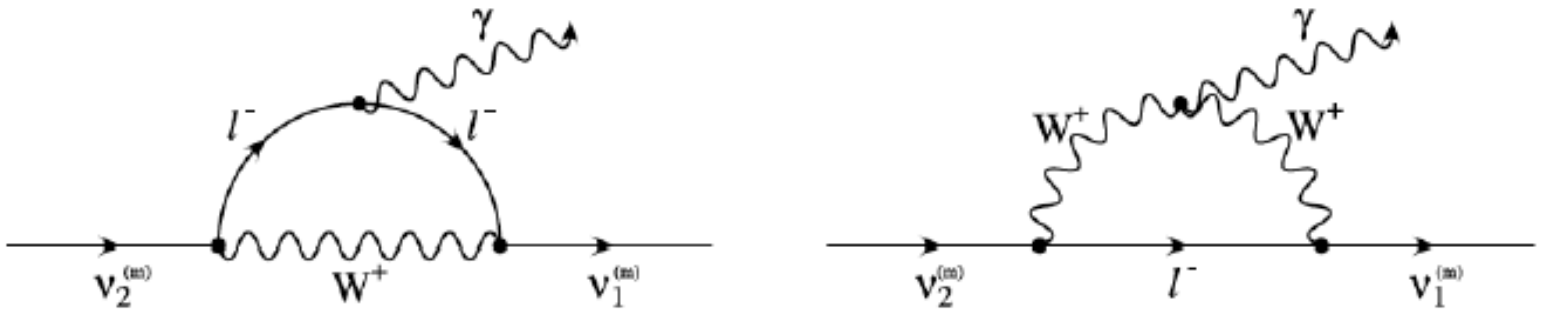


Detecting Sterile Neutrinos

- **Indirect detection:** decay to a photon and active neutrino in a loop-suppressed process mediated by oscillation between the active and sterile states
  - X-ray line at half the neutrino mass
- All-sky signal due to our location within the dark matter halo of the MW
  - Signal depends on flux along line-of-sight
  - Sensitivity improved by increasing FOV

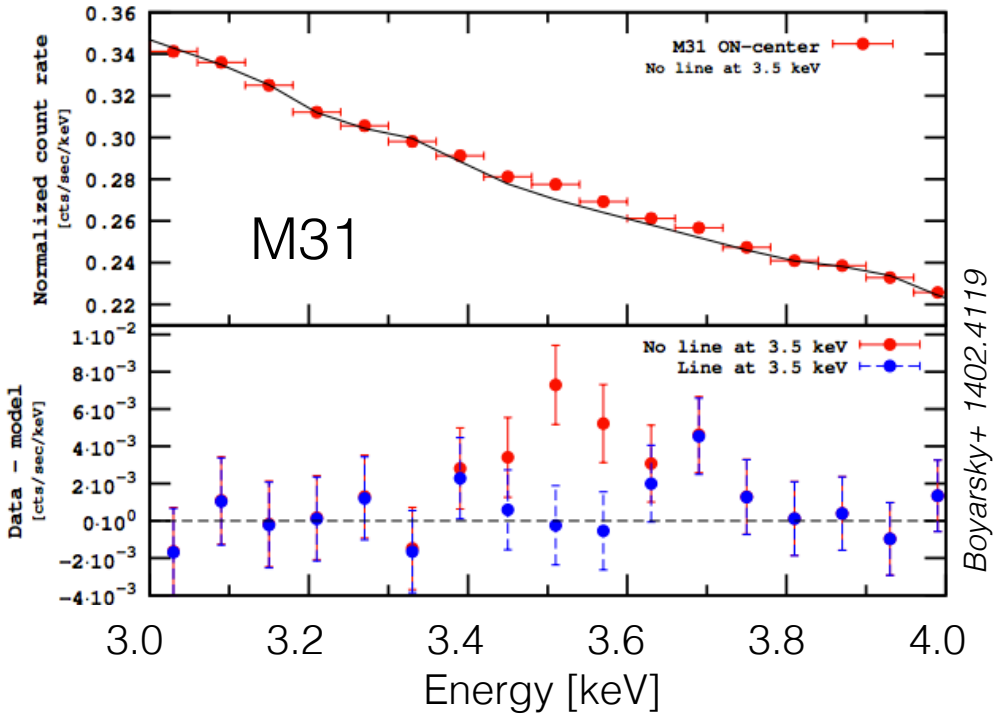
Figueroa+ 1506.05519



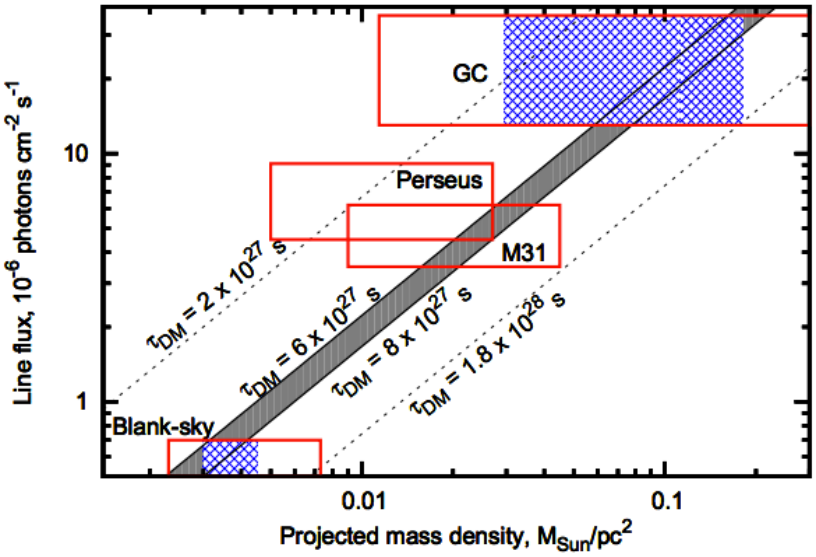


Have we found dark matter?

- Sterile neutrino in the keV range is a good dark matter candidate
- Anomalous line at 3.5 keV detected in XMM-Newton, Chandra, Suzaku, and NuSTAR data to high significance
- Instrumental explanation is unlikely
  - Observed across 6 detectors
  - Proper redshift
- Atomic explanation is not trivial
  - Must explain observations and non-observations
  - Anomalous line ratios of 10-20x required
  - Varying line flux contradicts atomic data



Boyarsky+ 1402.4119



Status of the field

	XMM-Newton	Chandra	Suzaku	Hitomi
Stacked clusters	+			
Andromeda	±			
Perseus	+	+	±	-
Coma, Virgo, Ophiucus	+	-	-	
MW GC	+	-		
Other clusters	+			
Stacked galaxies	-	-		
MW dwarfs	-			
Draco	±			

Riemer-Sorenson (1405.7943)
Jeltema & Profumo (1408.1699)
Boyarsky et al (1408.2503)
Malyshev et al (1408.3531)
Iakubovskyi et al (1508.05186)
Anderson et al (1408.4115)
Urban et al (1411.0050)
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Bulbul et al (1402.2301)
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Franse et al (1604.01759)
Bulbul et al (1605.02034)
Aharonian et al (1607.07420)
Cappelluti et al (1701.07932)

Status of the field

These observations are systematics-dominated - we need higher resolution detectors!

	XMM-Newton	Chandra	Suzaku	Hitomi
Stacked clusters	+			
Andromeda	±			
Perseus	+	+	±	-
Coma, Virgo, Ophiucus	+	-	-	
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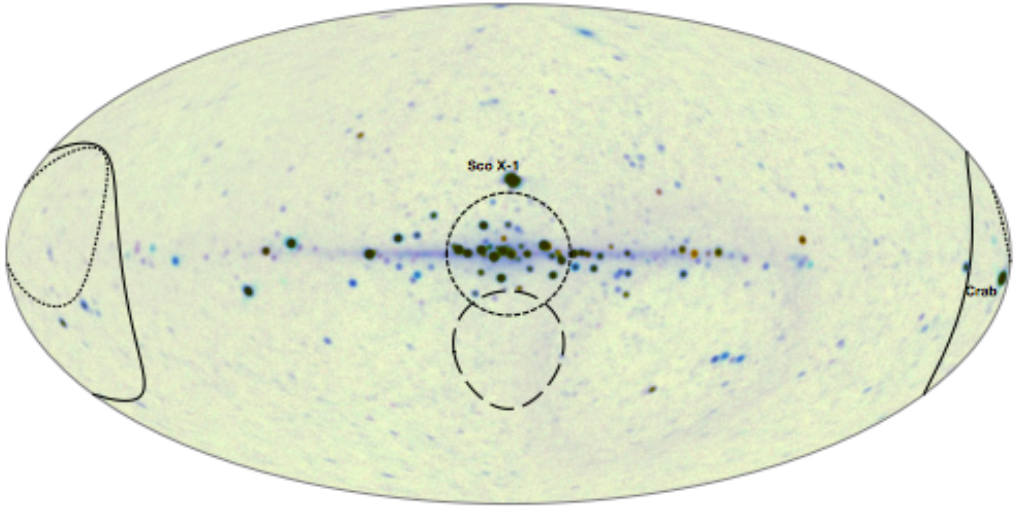
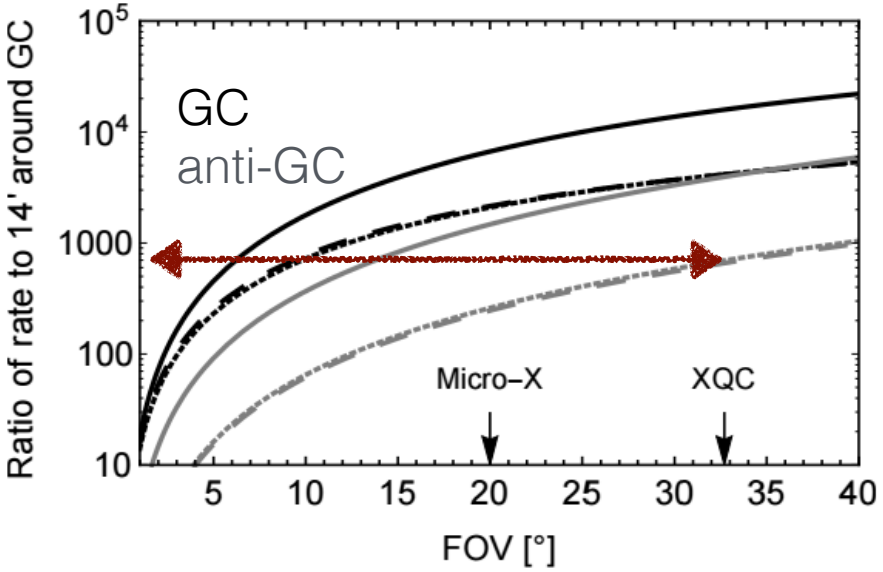
Dark Matter with Sounding Rockets

- XQC (Wisconsin): 6 flights from 1995 - 2014
  - Si thermistor array with a ~50 mK operating temperature
  - High resolution (23 eV FWHM at 3.3 keV) and wide FOV (32.3° radius)
- 2011 anti-GC observation (l = 165° , b = –5°) with an effective exposure of 106 s
  - Large FOV observations of the GC have better signal-to-noise since the signal is all-sky while backgrounds are dominated by GC/GR (±5° from the plane) rather than CXB





XQC Sterile Neutrino Results

Data

Total background

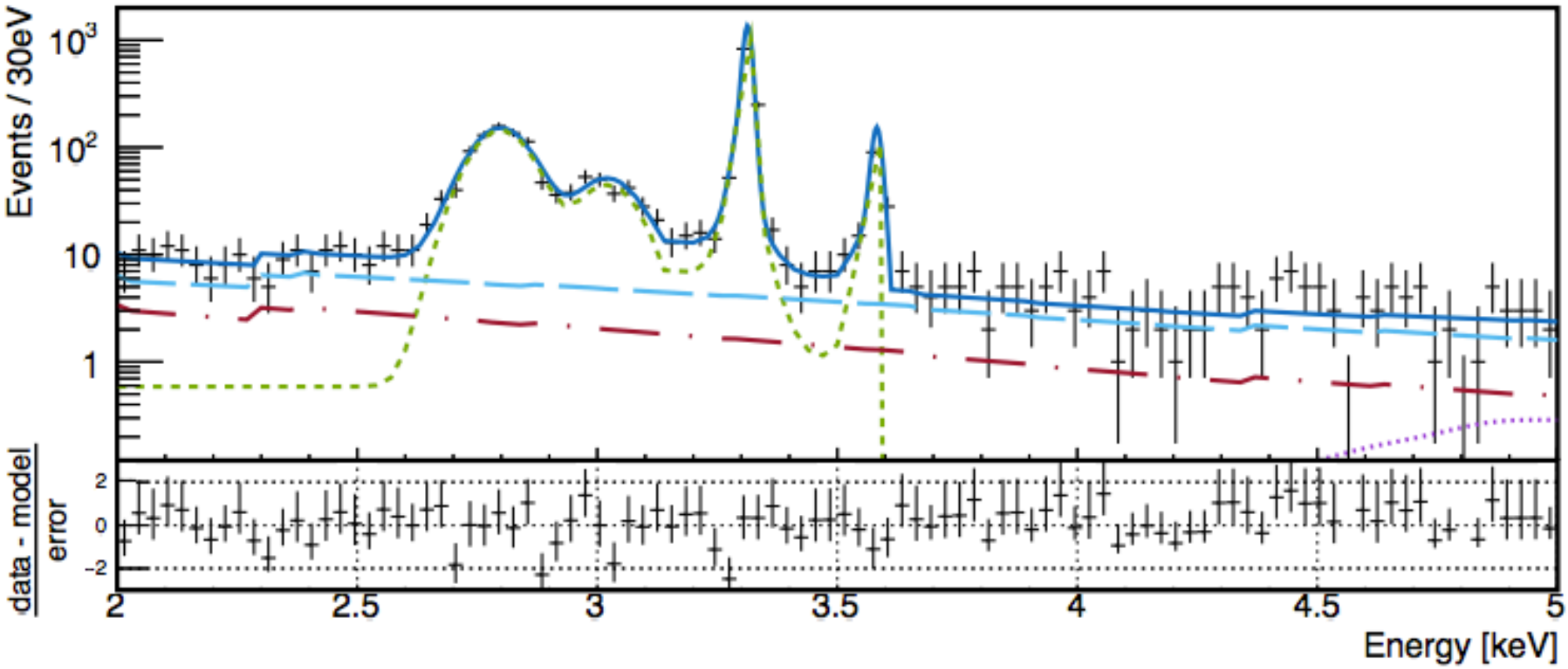
Diffuse X-ray background (Hickox & Markevitch 2006)

Crab (Mori et al 2004)

Cosmic rays (GEANT simulation)

^{41}Ca calibration source

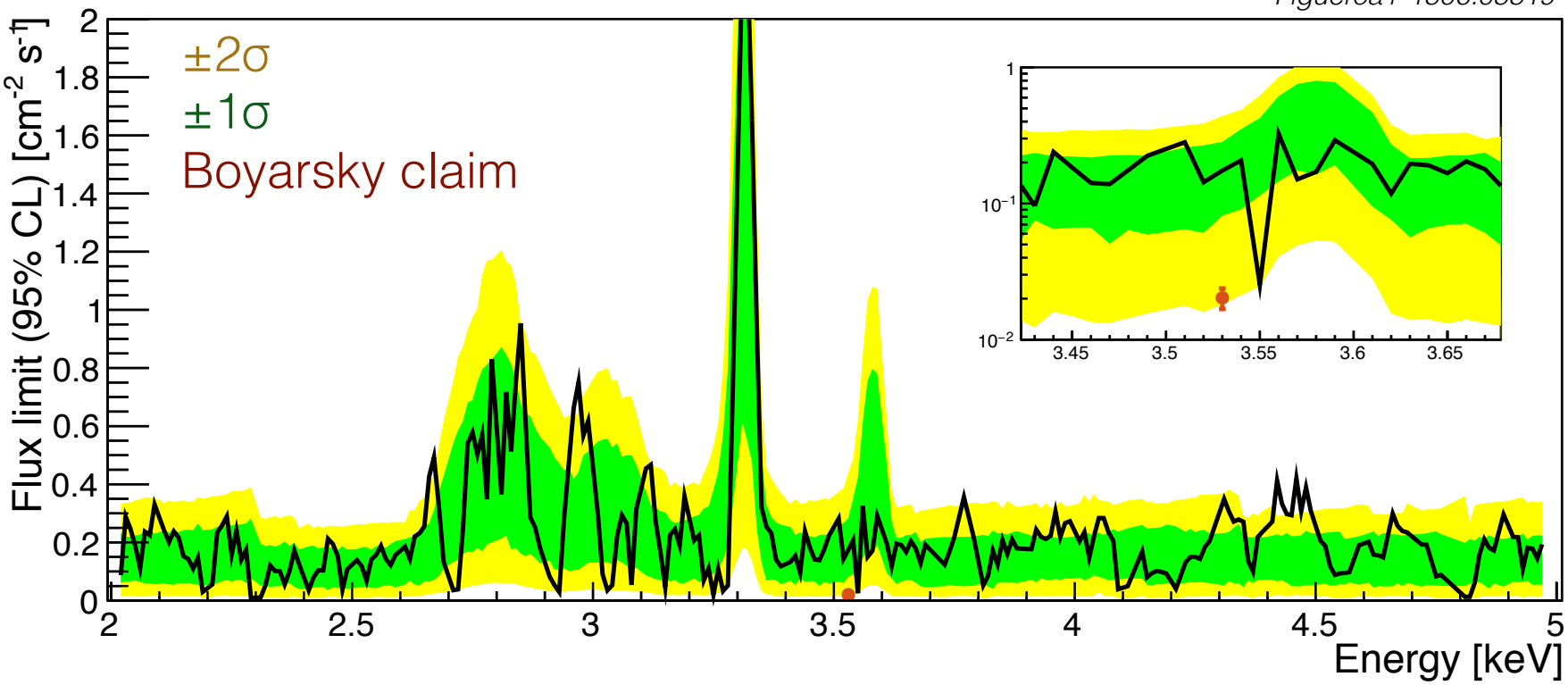
Figueroa+ 1506.05519



XQC Sensitivity

- Unbinned maximum likelihood set the upper limit for an unidentified line above the background model
- Upper limit on the flux of 0.17 counts/cm^2/s at 95% CL
  - Not sensitive enough to rule out Boyarski's MW detection
  - Requires more data (photon-starved)

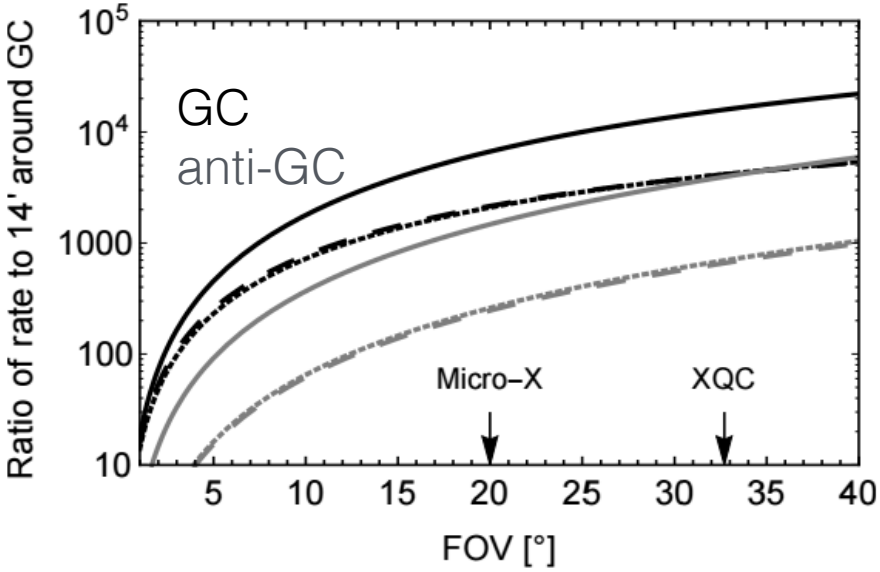
Figueroa+ 1506.05519



The Micro-X Concept

Fly a 128-pixel TES microcalorimeter array in a vibration-isolated ADR on a sounding rocket

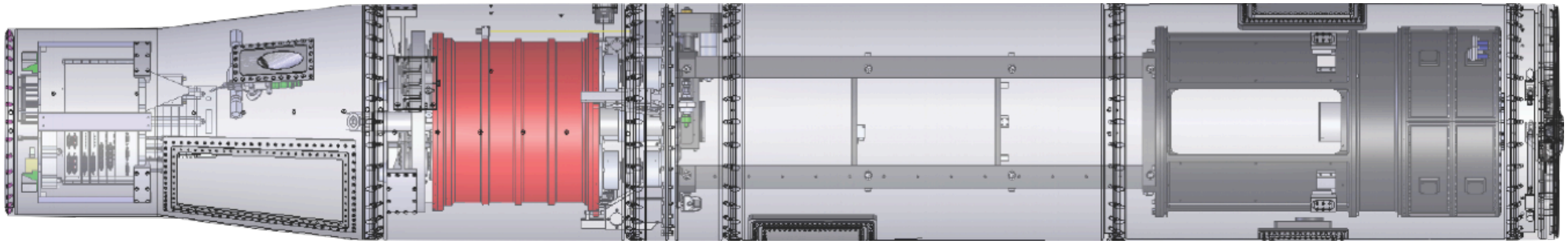
Figueroa+ 1506.05519



Electronics

Cryostat

Optics

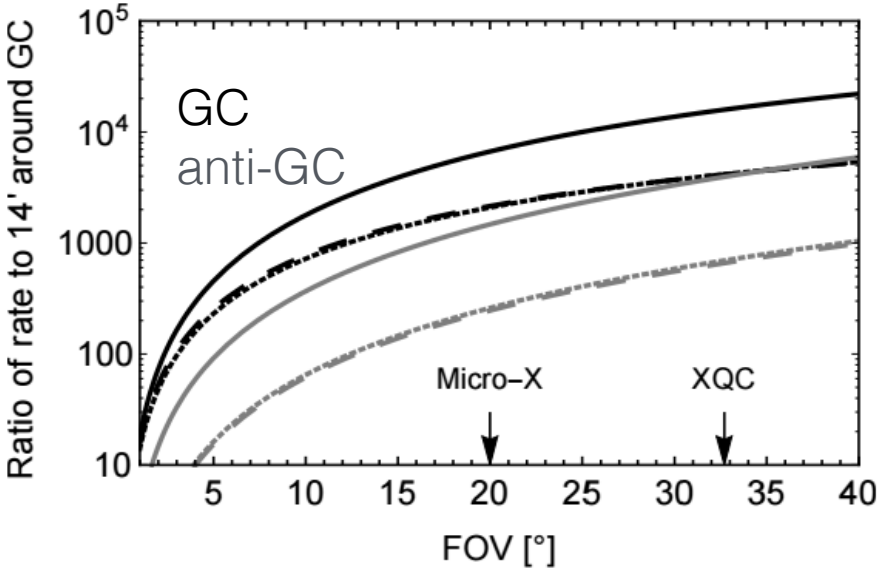


The Micro-X Concept

Fly a 128-pixel TES microcalorimeter array in a vibration-isolated ADR on a sounding rocket

4 eV at 3 keV

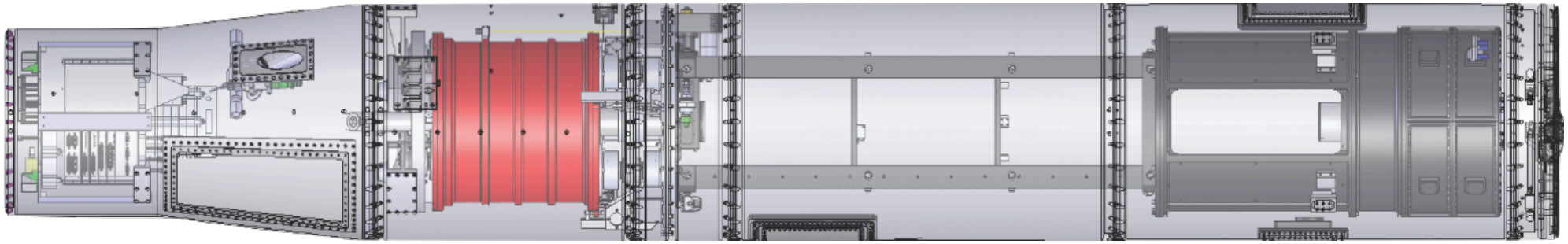
Figueroa+ 1506.05519



Electronics

Cryostat

Optics



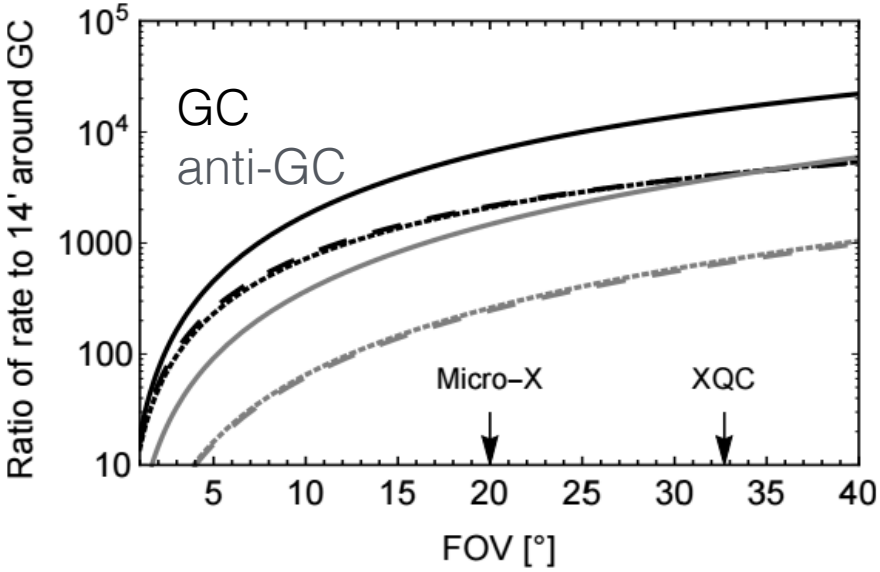
The Micro-X Concept

Fly a 128-pixel TES microcalorimeter array in a vibration-isolated ADR on a sounding rocket

4 eV at 3 keV

75 mK

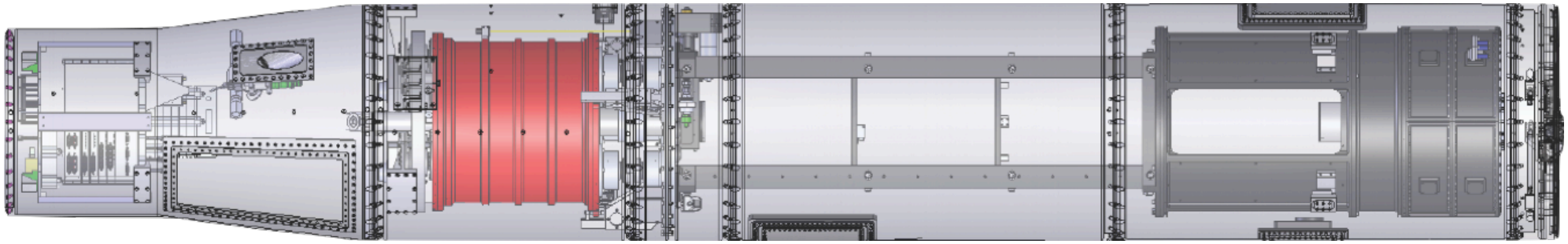
Figueroa+ 1506.05519



Electronics

Cryostat

Optics



The Micro-X Concept

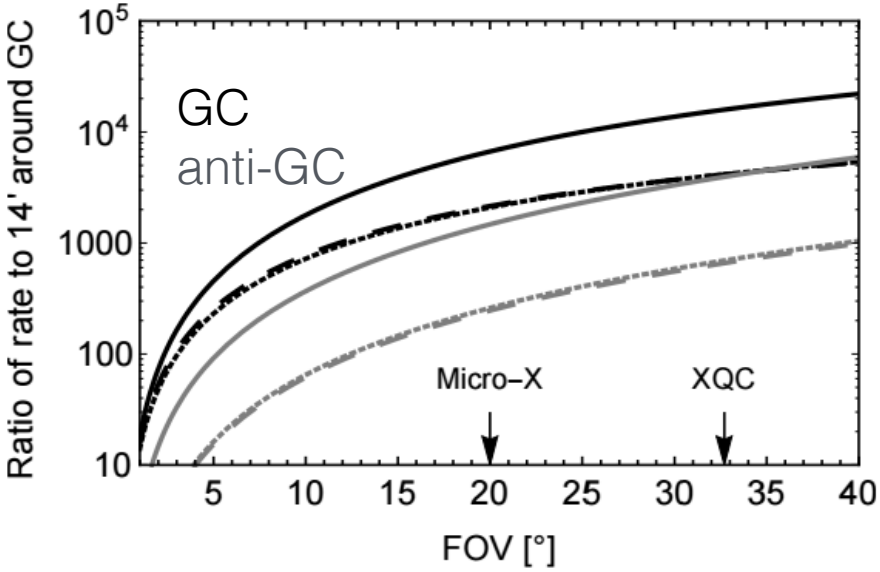
Fly a 128-pixel TES microcalorimeter array in a vibration-isolated ADR on a sounding rocket

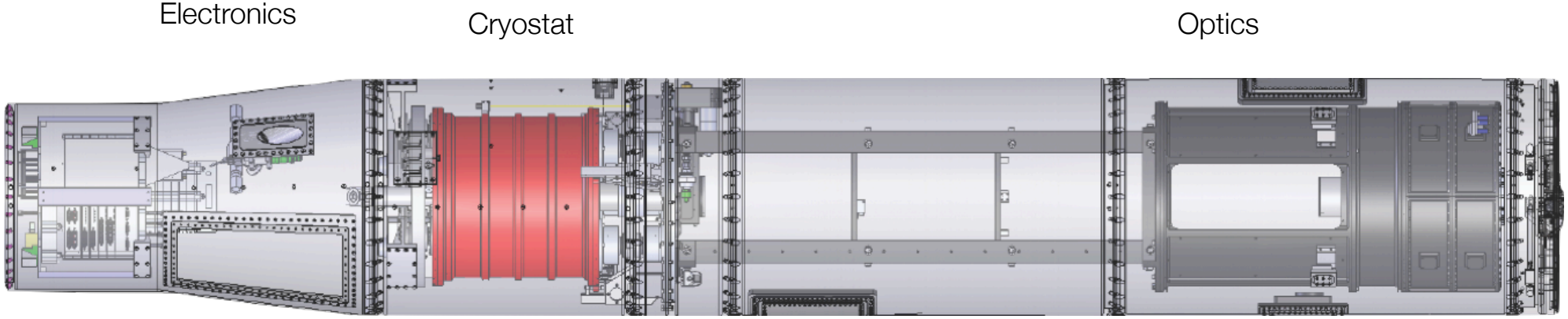
4 eV at 3 keV

75 mK

5 minutes of data in the upper atmosphere

Figueroa+ 1506.05519





The Micro-X Concept

12' - 20°

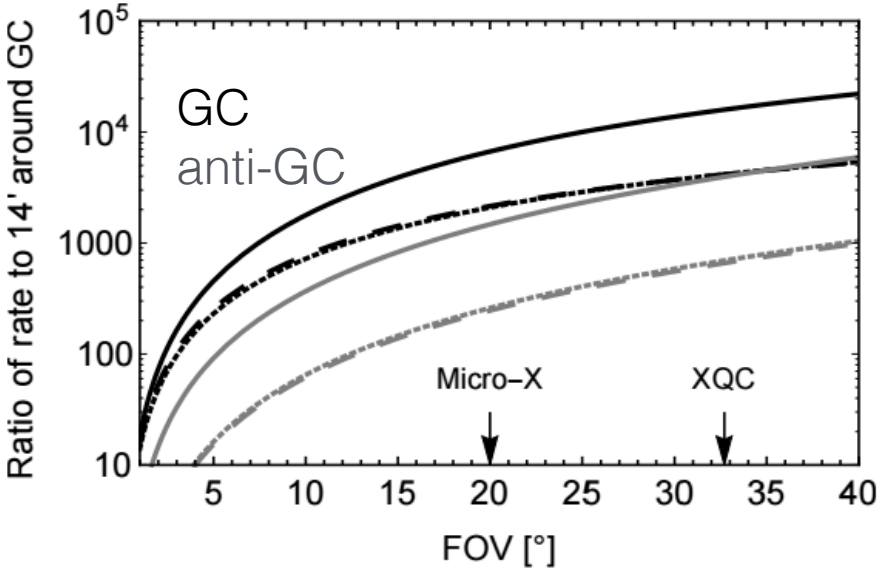
Fly a 128-pixel TES microcalorimeter array in a vibration-isolated ADR on a sounding rocket

4 eV at 3 keV

75 mK

5 minutes of data in the upper atmosphere

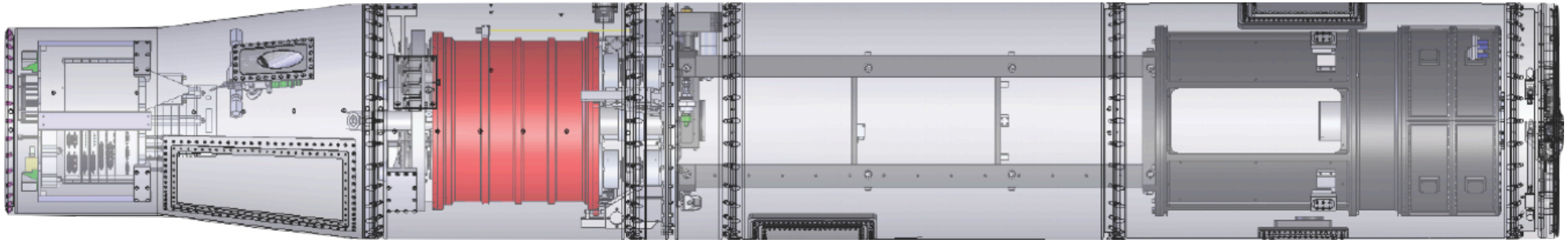
Figueroa+ 1506.05519



Electronics

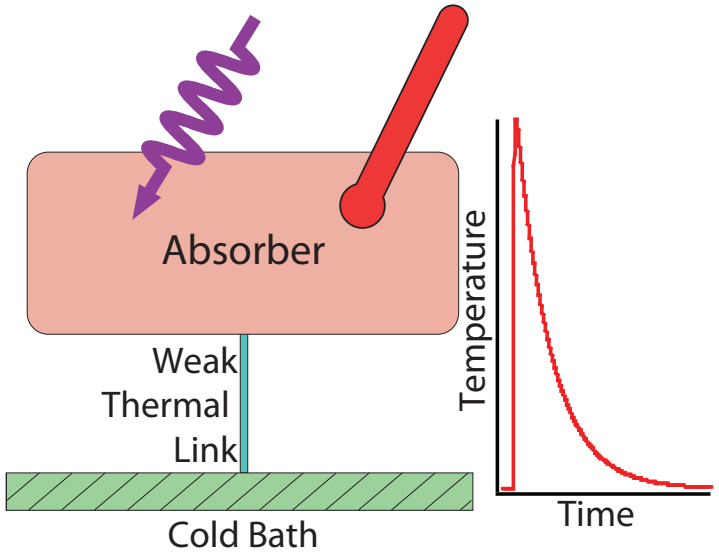
Cryostat

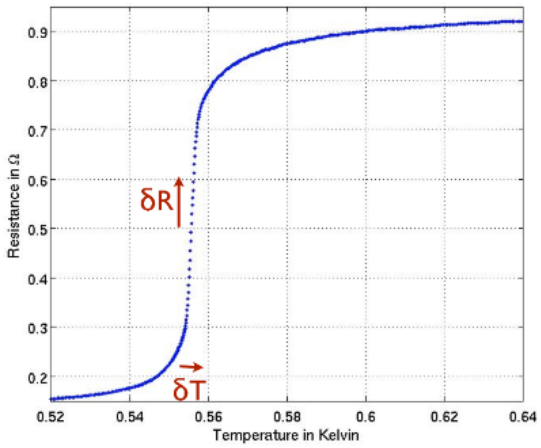
Optics

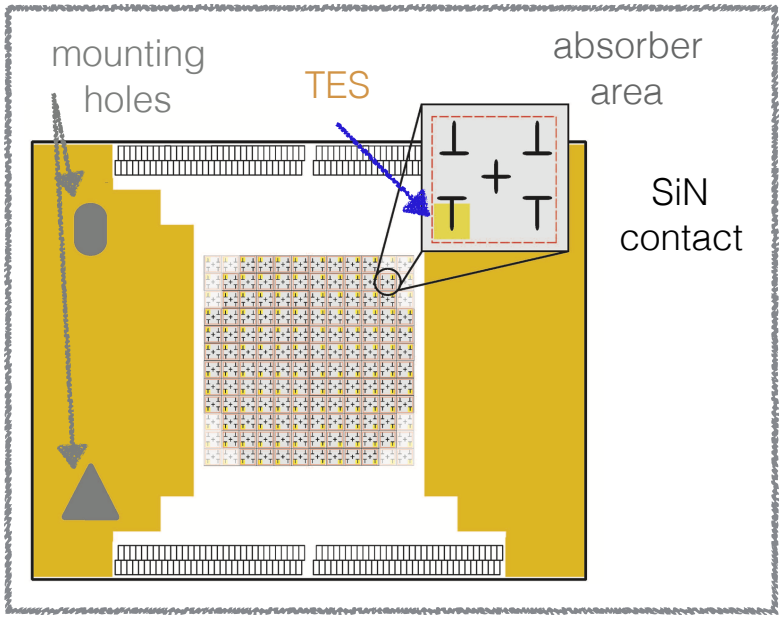


Micro-X Detector: TESs

- X-rays hit an absorber weakly connected to a cold bath and create a “pulse”
- TESs use a superconducting film biased into the transition to yield large resistance changes for small temperature changes
  - Demonstrated 2 eV (FWHM) resolution at 6 keV
- The Micro-X array: 128 590 μm x 590 μm pixels
  - Au/Bi absorbers with a Mo/Au TES

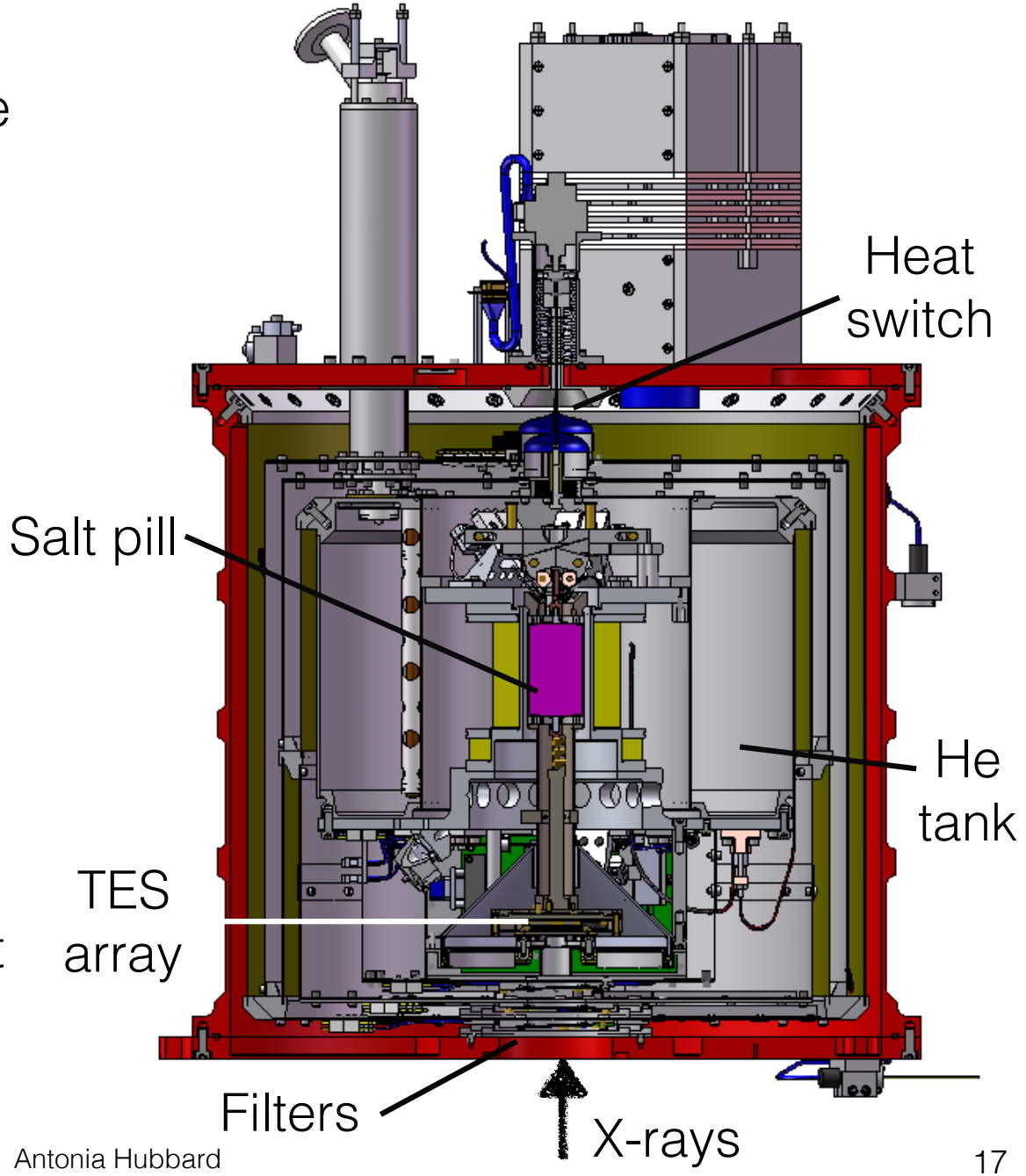






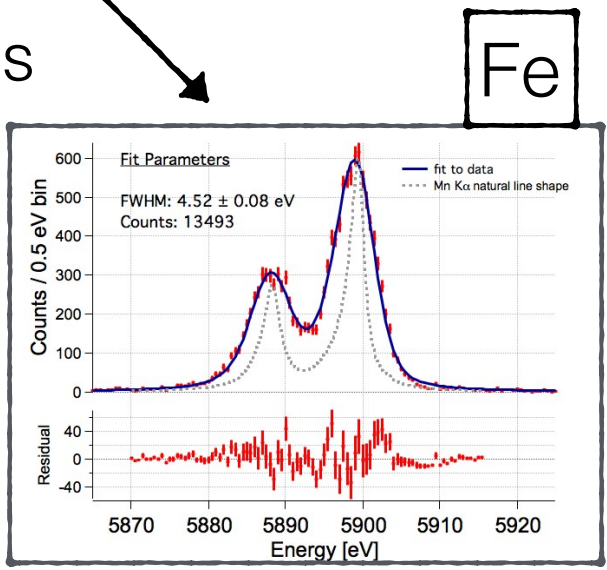
Micro-X Detector: Overview

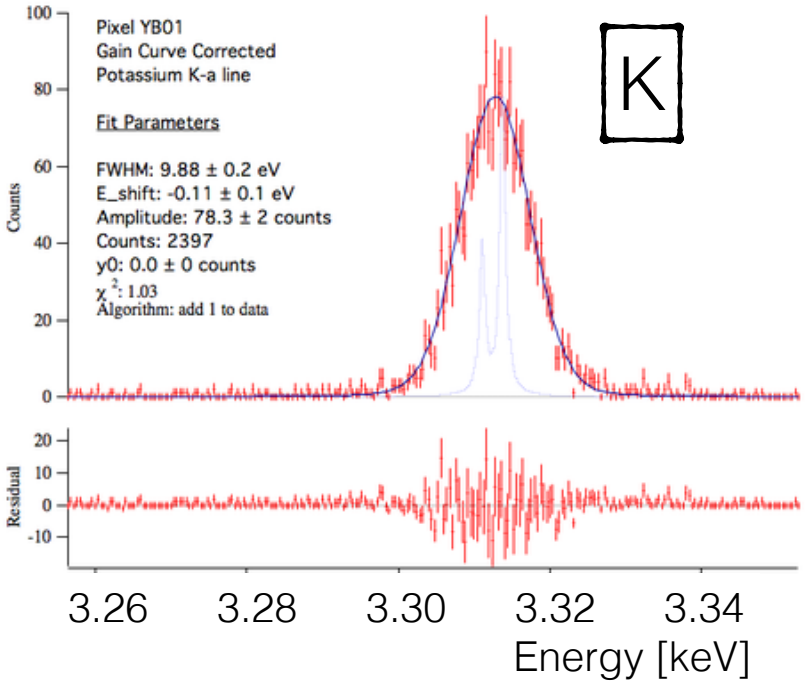
- X-rays enter the telescope through a gate valve
- 5 filters allow X-rays while blocking IR/optical photons
- Calibration source (KCl fluoresced by Fe-55) directly adjacent to detectors tracks changes
- 2 readout chains store data (16 GB) and transmit 30% in-flight (44 Mbit/s)

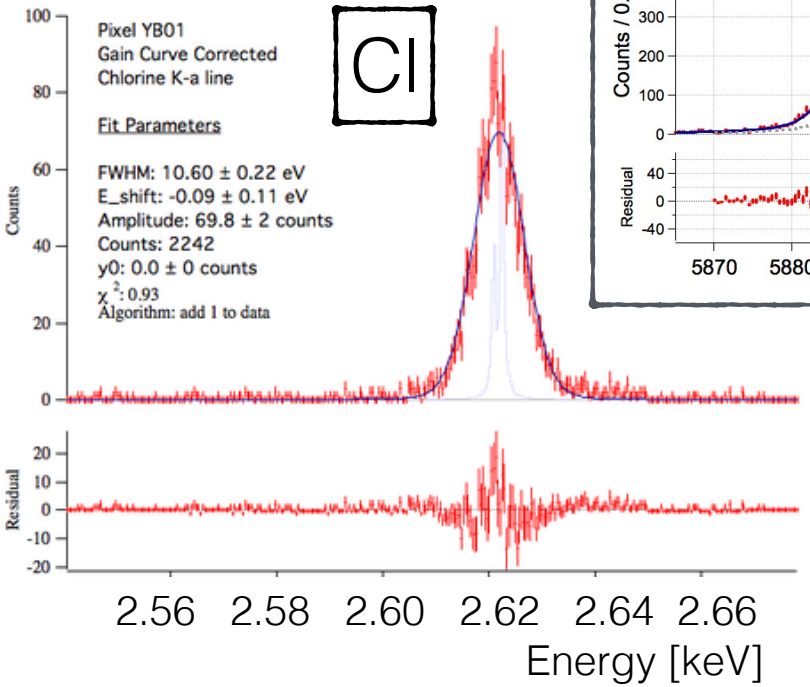


Micro-X Data: Resolution

- Best current resolution is 9.88 eV at 2.6 keV
  - These detectors hit 4.5 eV in lab setting
- Noise mitigation is underway to improve this
  - RF shielding, electronics stability

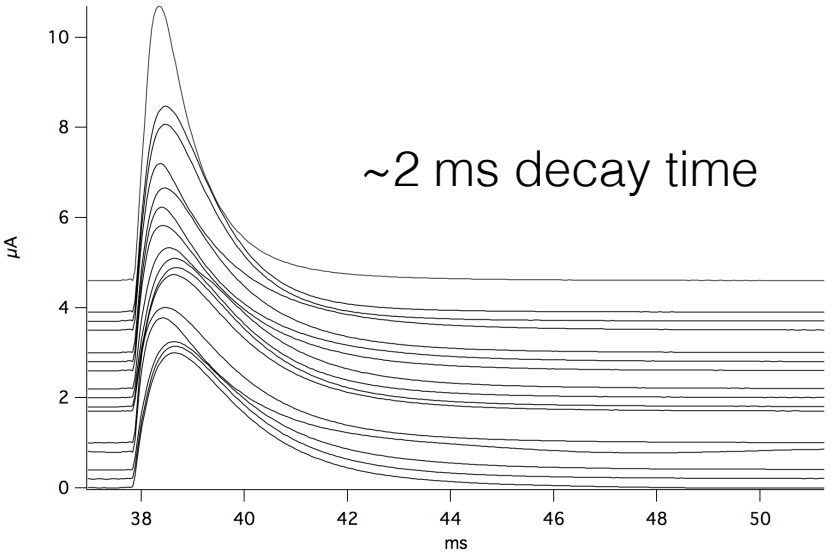


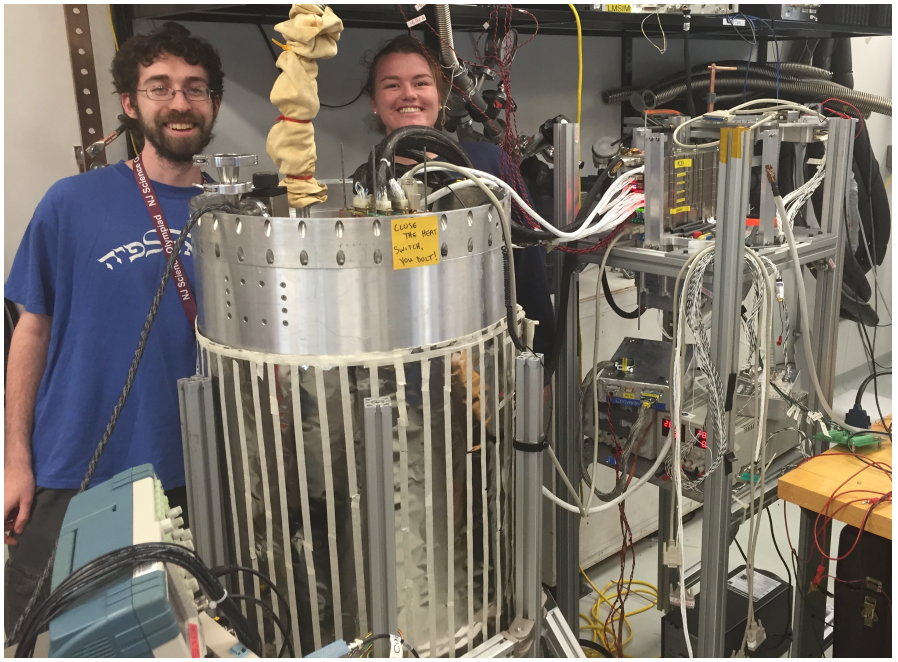




Micro-X Status

- Taking pulse data in flight configuration
  - Cryostat, calibration source, time-multiplexed SQUID readout, flight electronics, data readout
- Past 18 months: instrument has passed all functionality tests and improved mechanical, thermal, electrical performance
  - Vibration isolation: stay at 75 mK for 9 hours and can withstand 5 “launches”
  - Improved electronics noise
  - ADR flight controls (temperature, magnet)
- Current work: optimization and full system integration
  - Noise abatement and minimization of electrical crosstalk
- **Launch expected January 2018**





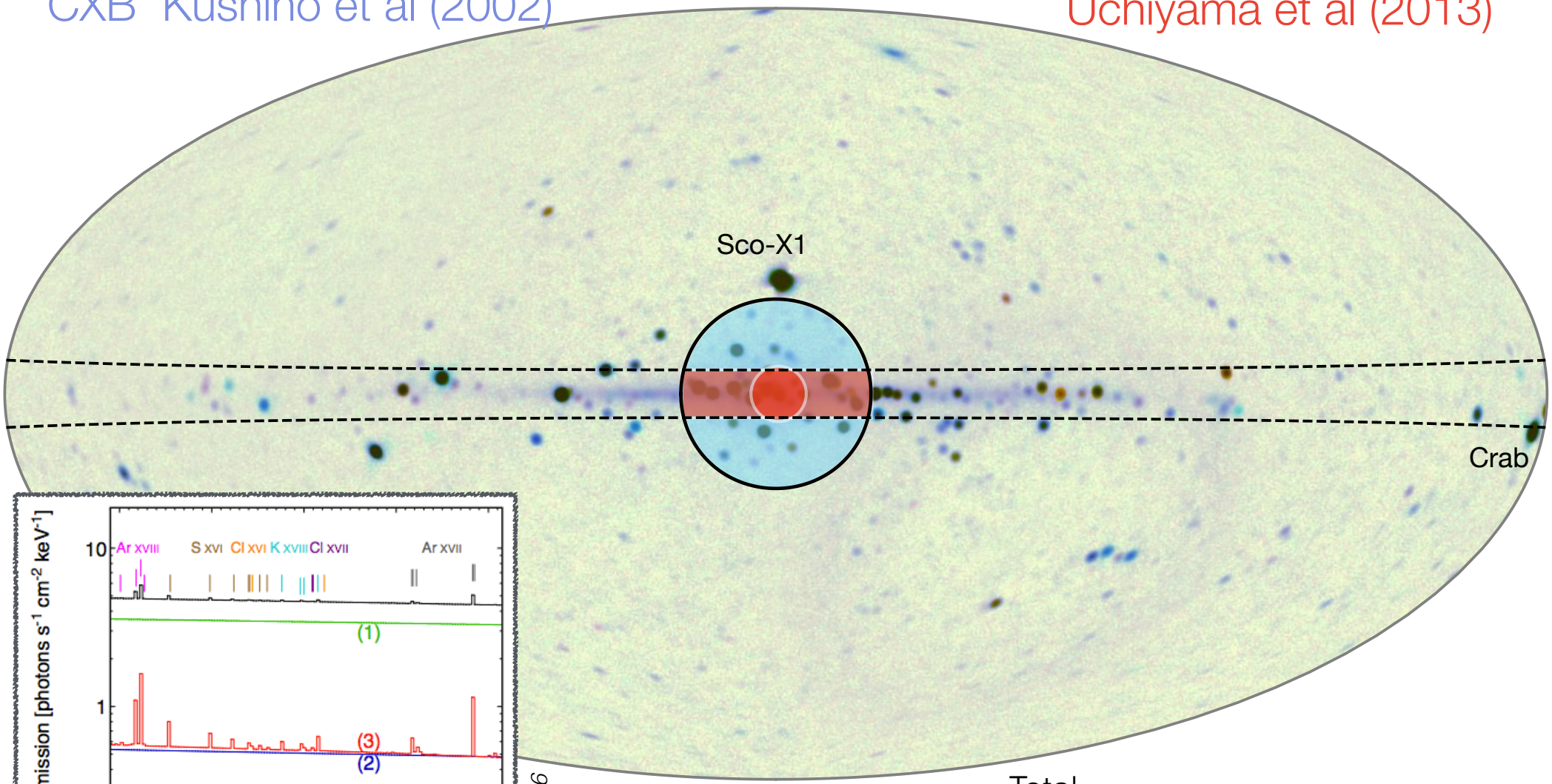
GC Backgrounds

LMXBs

CXB Kushino et al (2002)

Galactic Thermal Model

Uchiyama et al (2013)



Figueroa + 2016

Total

Brightest low mass X-ray binaries

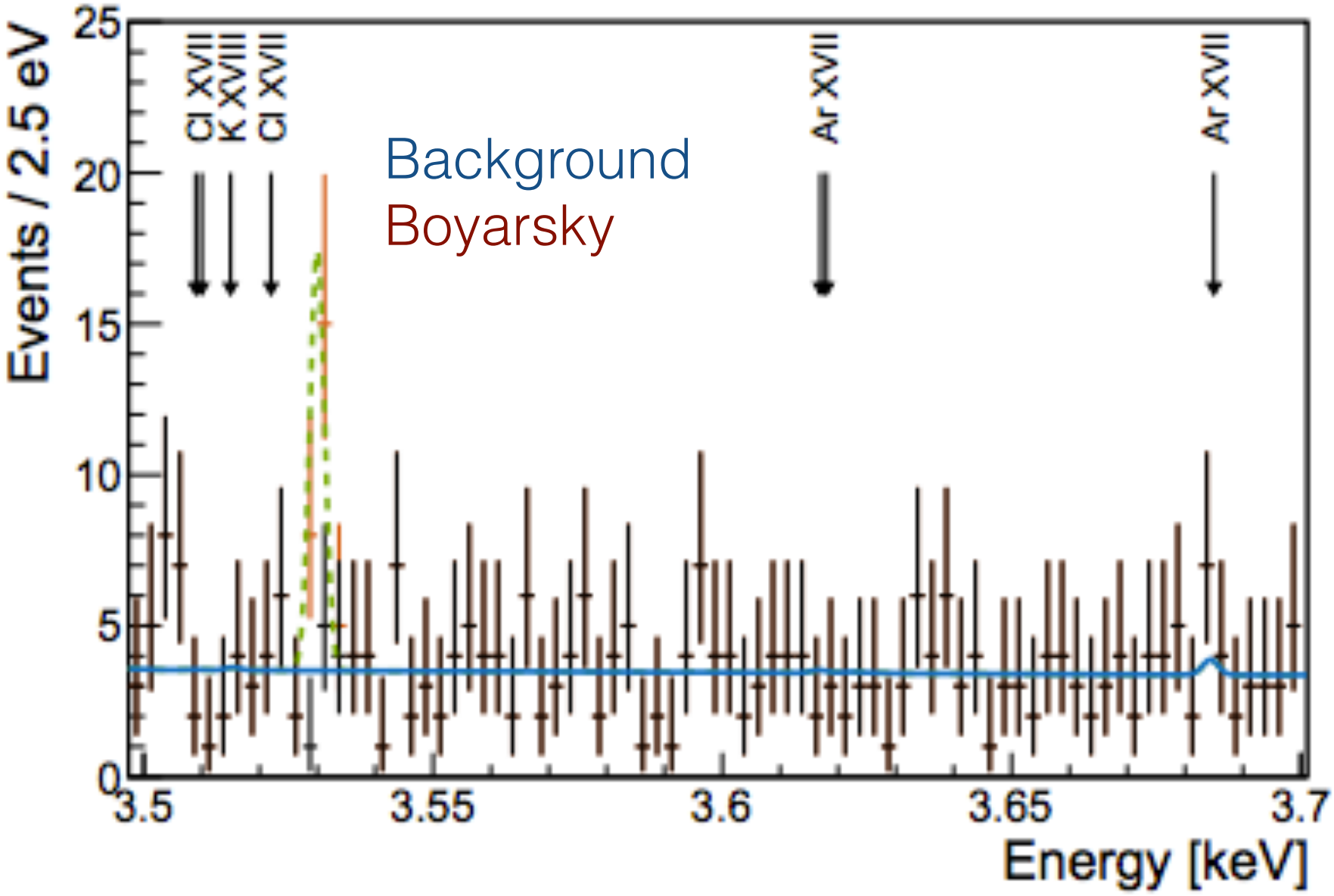
CXB

Galactic diffuse background

Ionized cold ISM neutral Fe

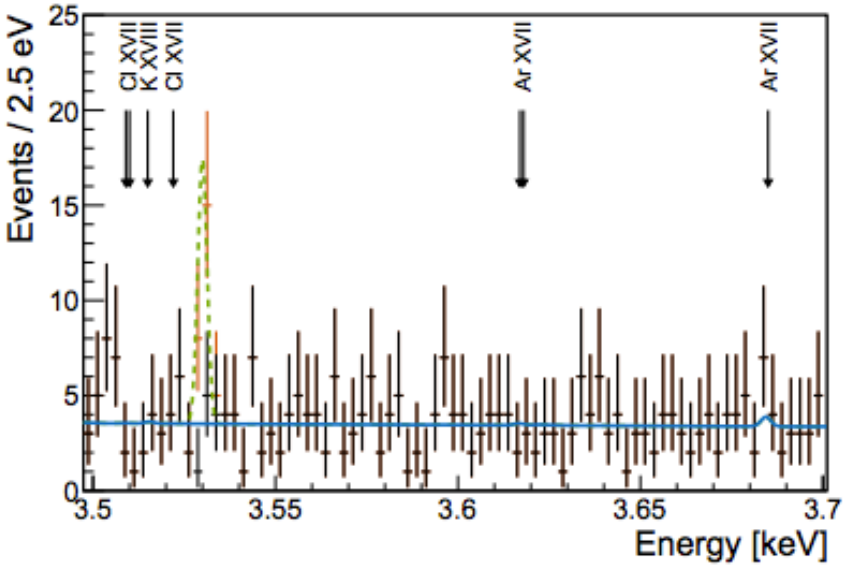
Micro-X Projected Spectrum

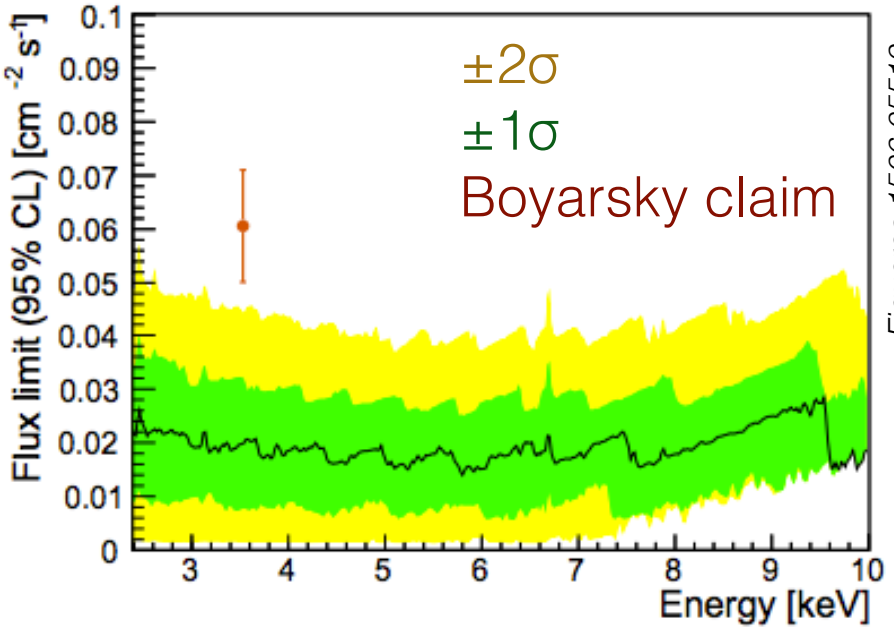
Figueroa 1506.05519



Sterile Analysis Modeling: Signal

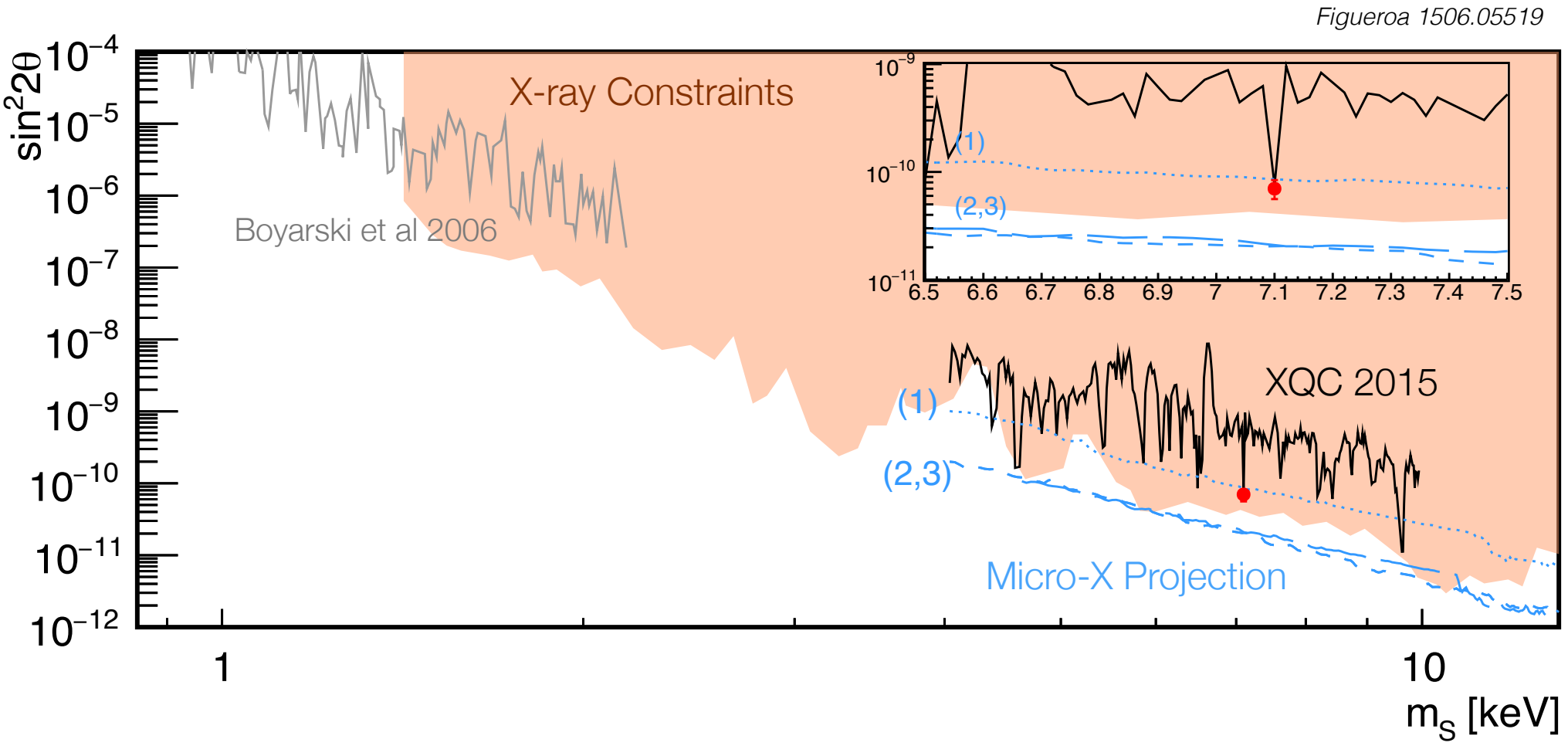
- Projected 300s GC observation corresponds to 5.6σ significance
  - 18.2 total signal events
  - 3.4 background events in 2.5 eV (±1σE) bin
    - 4.5 cts/cm^2/s/keV at 3.5 keV
  - Boyarsky: 1.4 Ms with 7,500 signal and 500,000 background counts
- Strongest lines are from K XVIII and Cl XVII, with <1 event/ observation





Figueroa 1506.05519

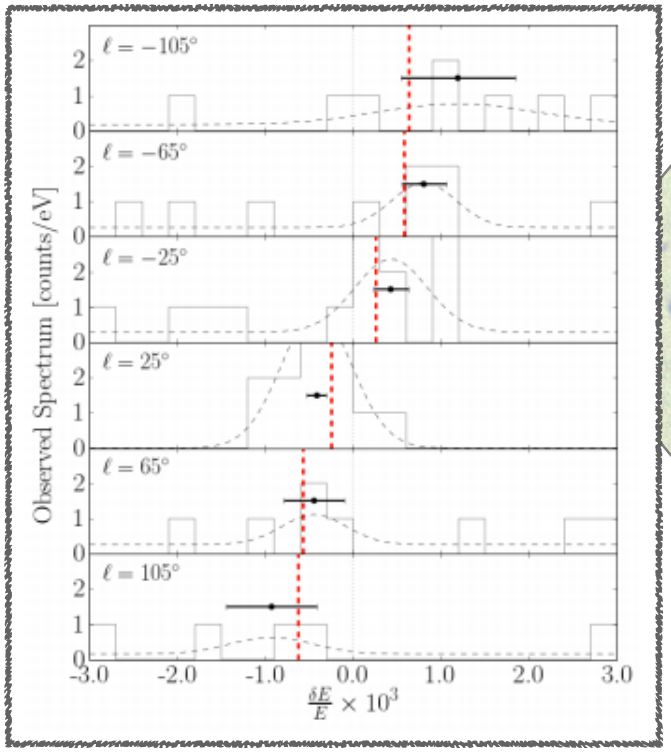
Projected Limits

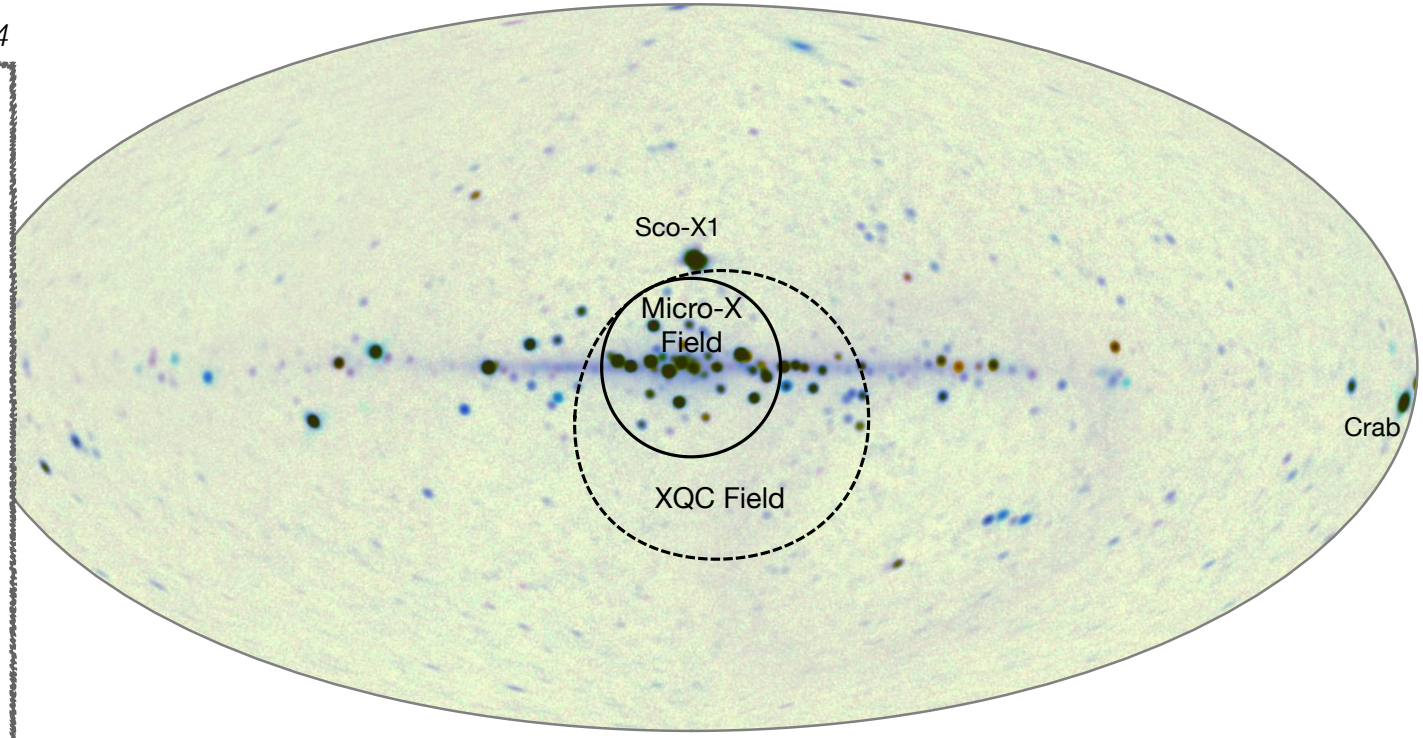


3.5 keV Morphology

- Back-to-back flights of XQC and Micro-X will allow profile measurements of a 3.5 keV observation
- The flux in the XQC's wider FOV compared to that in Micro-X observation will distinguish between a point-source or extended-source origin
- Multiple Micro-X flights will allow Doppler mapping of an observed line

Powell 1611.02714



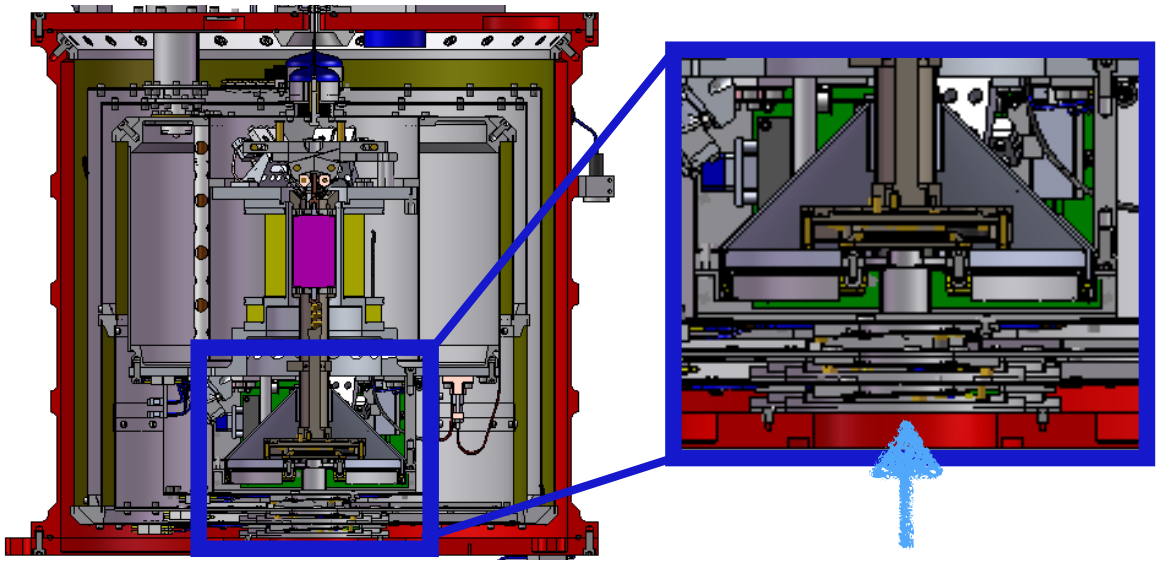


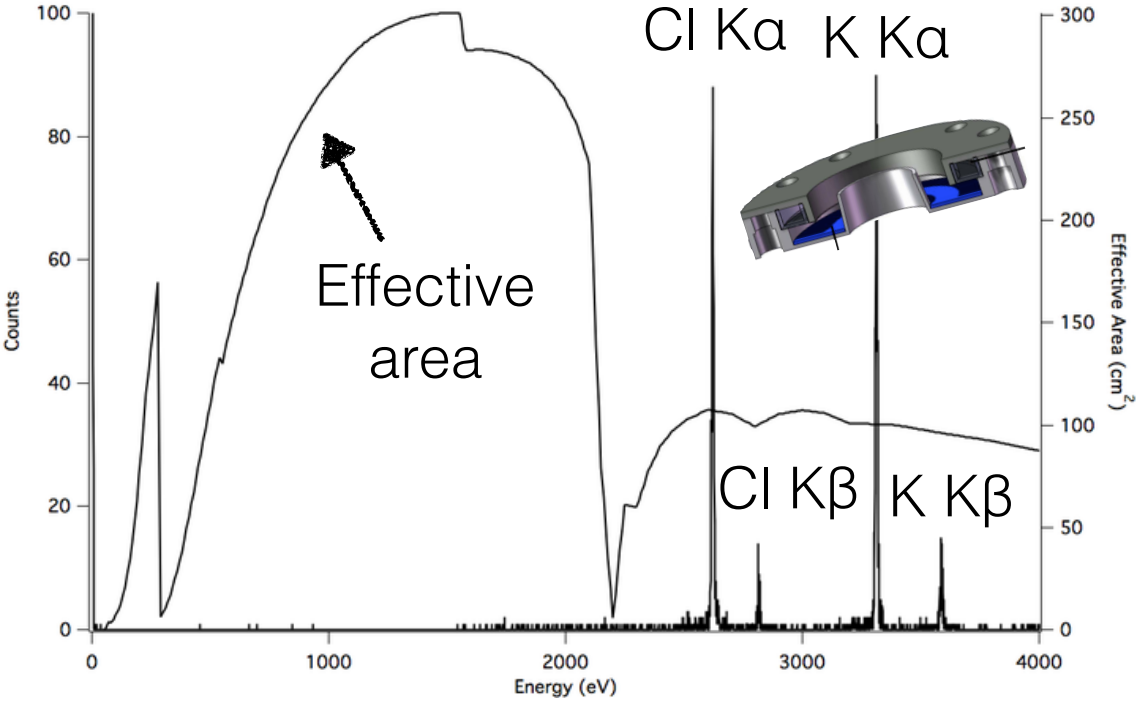
Conclusions

- Large FOV sounding rocket micro-calorimeters have unique sensitivity to X-ray signatures from dark matter interactions
  - Open up new sensitivity beyond what we can do with current satellites!
- These flights are photon-starved, so more flights = higher sensitivity
- First flight (SNRs) in December 2017, and sterile neutrino flight from Australia in 2019

Micro-X Data: Acceptance

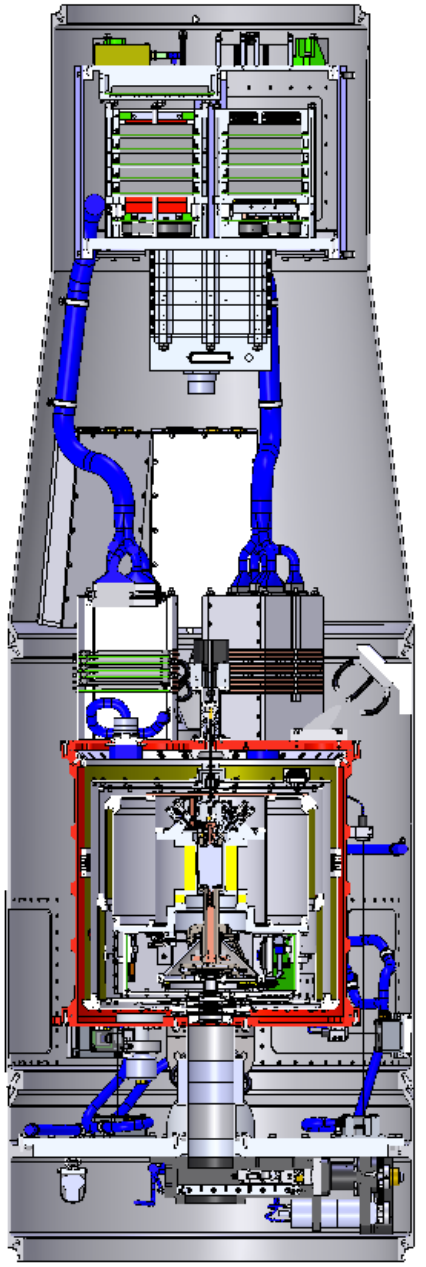
- X-rays enter the telescope through a gate valve
  - 11.8’ FOV
- 5 filters allow X-rays while blocking IR/optical photons
  - 0.2 - 3 keV bandpass
- Calibration source (KCl fluoresced by Fe-55) directly adjacent to detectors tracks changes





Micro-X Detector: Electronics

- Multiplexed SQUID readout system passes through all temperature stages to minimize thermal noise and minimize number of wires
- On-board electronics continuously record all data and transmit select data streams
  - 2 independent readout chains
  - 66 Mbit/s rate to 16 GB data storage on-board
  - Transmit 30% of recorded data (40 Mbit/s) in case of non-recovery
  - Transmit housekeeping information for real-time monitoring (1.5 Mbit/s)
- All in-flight actions occur via timer

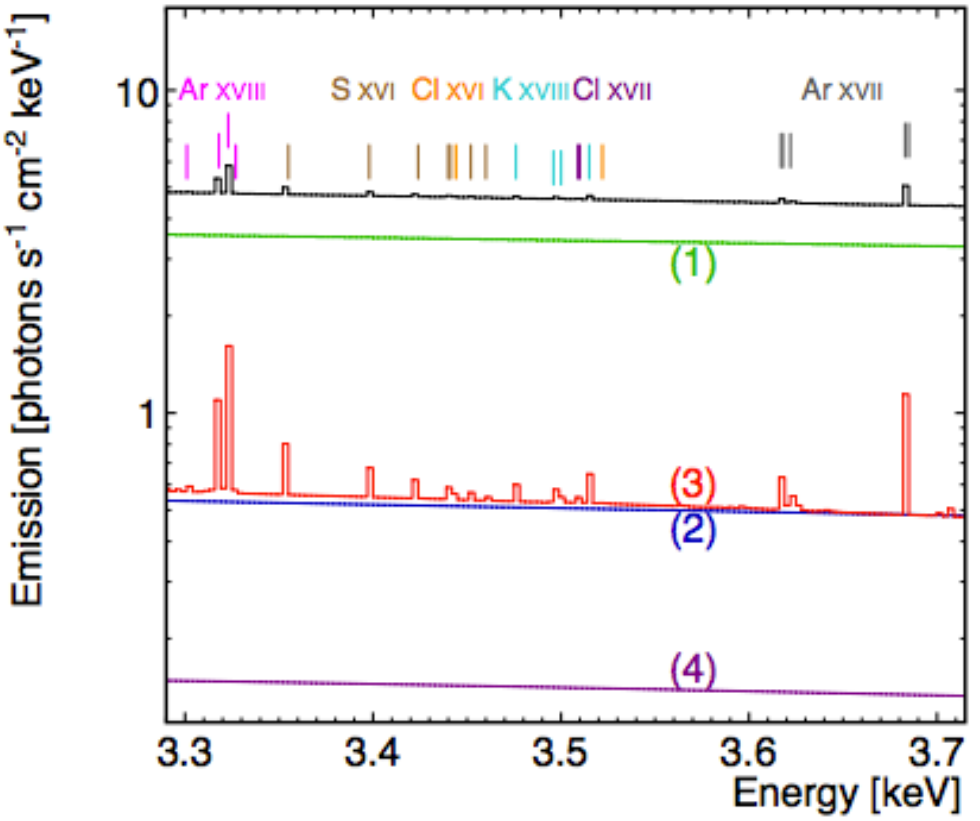


Sterile Analysis Modeling: Backgrounds

- Backgrounds are astrophysical (both diffuse and from bright sources) and instrumental
  - Diffuse: thermal GC/GR components (Suzaku estimates), isotropic CXB (ASCA estimates), ionized cold ISM neutral Fe
  - Instrumental backgrounds: calibration source and cosmic rays (~1 Hz)
- Point sources: ROSAT All Sky Survey – Bright Source Catalogue (Voges+ 1999)
  - 558 sources within 20° of GC, with the 12 brightest sources creating 80% of the counts

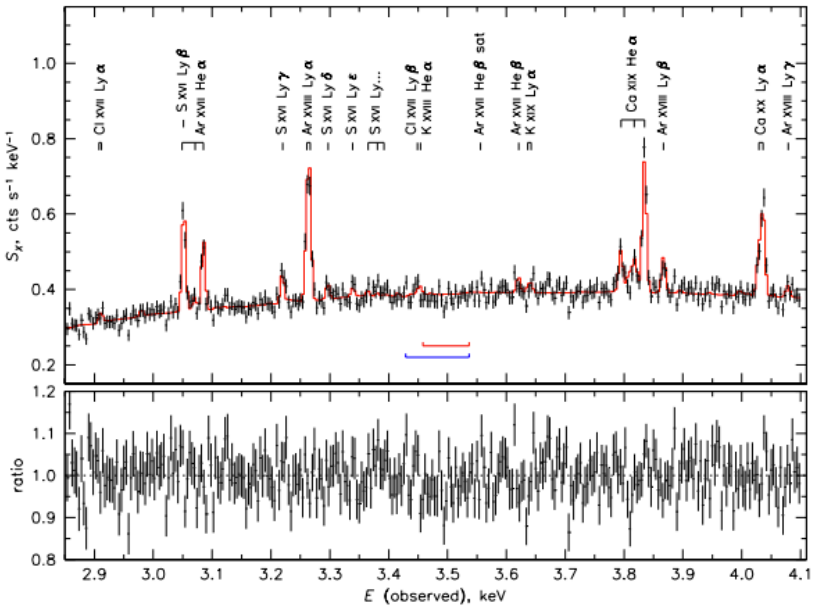
Total
Brightest low mass X-ray binaries
CXB
Galactic diffuse background
Ionized cold ISM neutral Fe

Figueroa 1506.05519

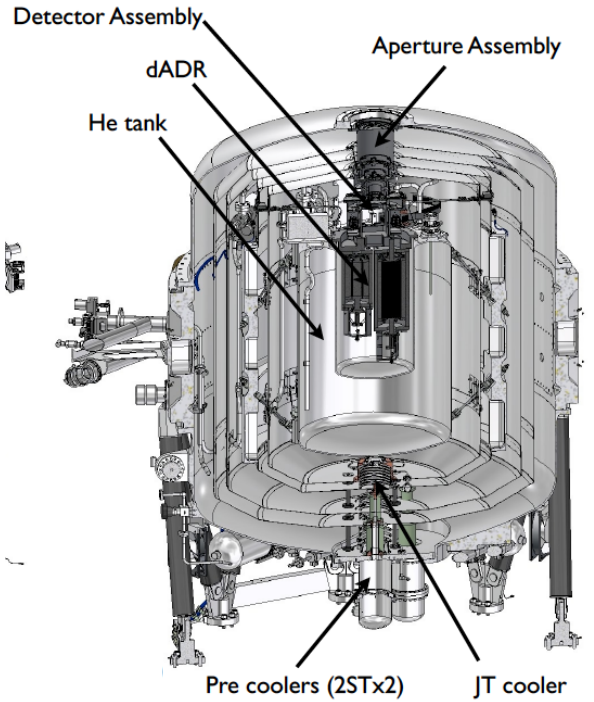


Hitomi Dark Matter Results

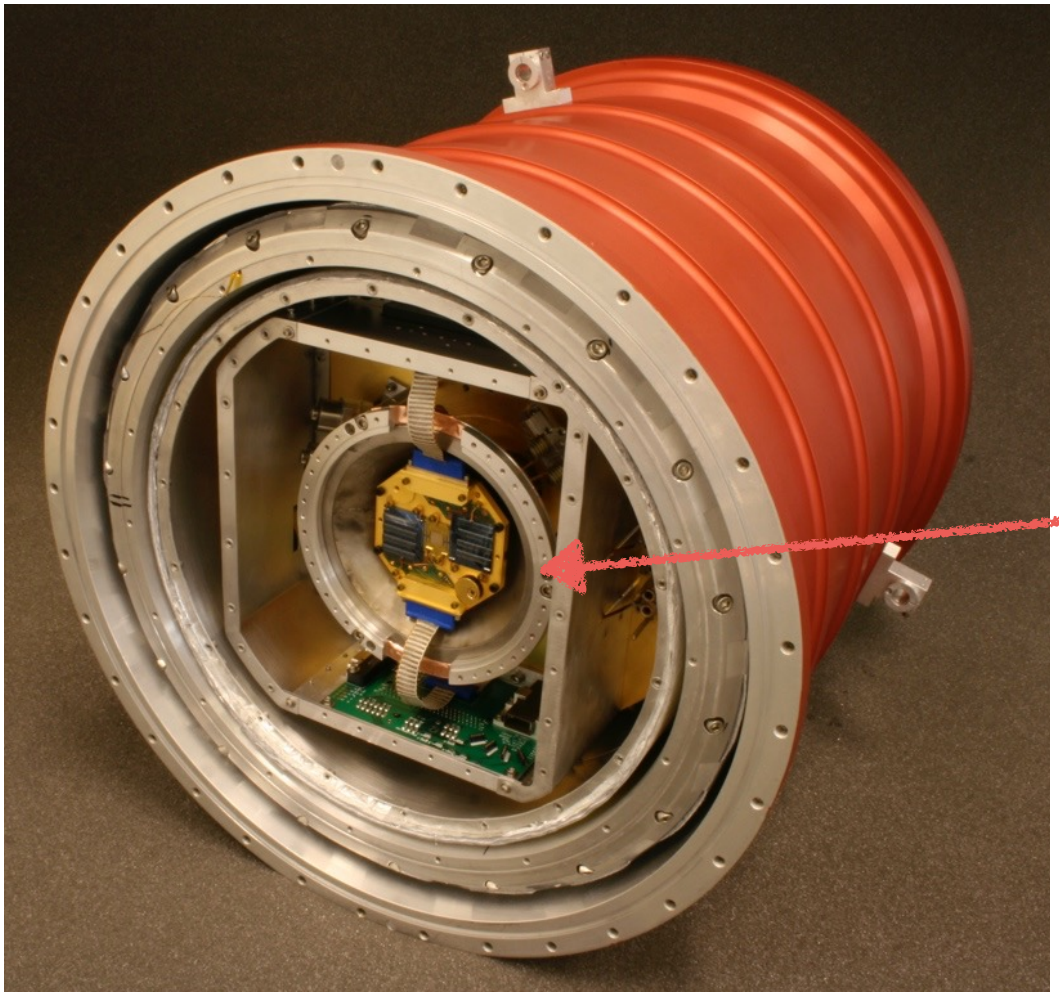
- 35 Si thermistor microcalorimeter pixels
- 70 ks Perseus observation did not see the 3.5 keV line (not high significance)
  - 275 ks with gate valve closed
  - No anomalously high K, Ar or S lines 3-4 keV region
    - Nearby atomic lines did not get the statistics to be well-resolved
  - Excludes K XVIII or Ar XVII explanation
  - Potential excess at 3.44 keV (near S XVI)

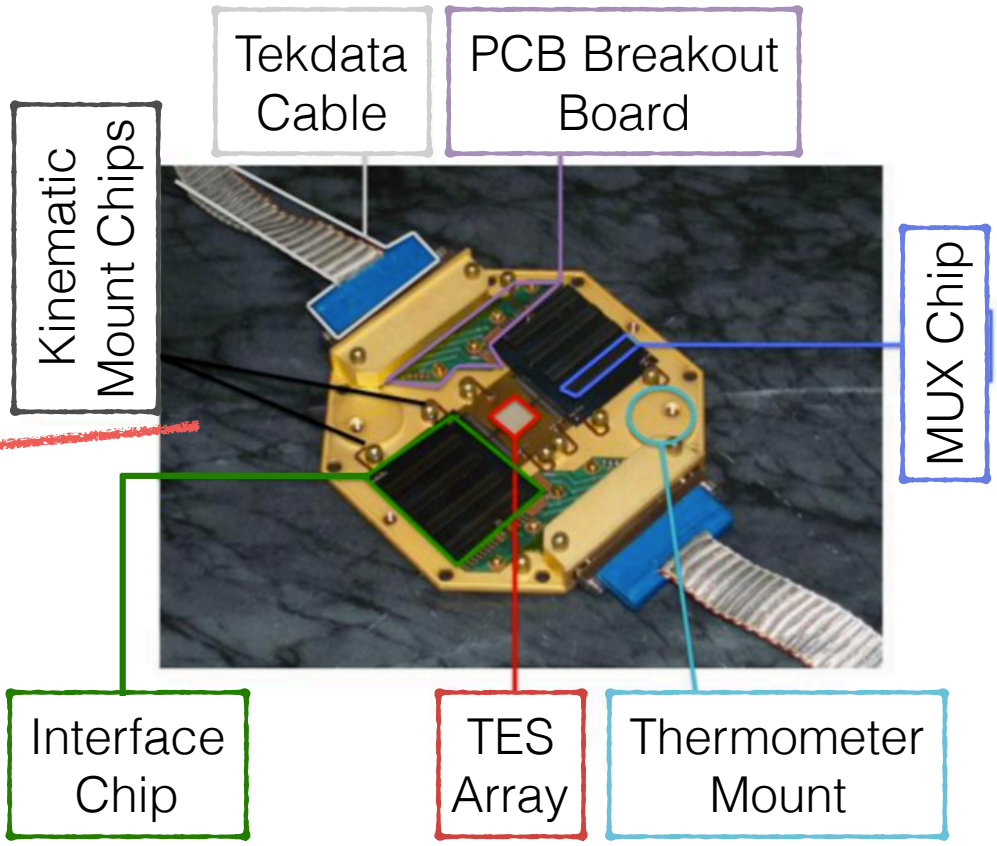


Aharonian+ 1607.07420



Micro-X: Focal Plane

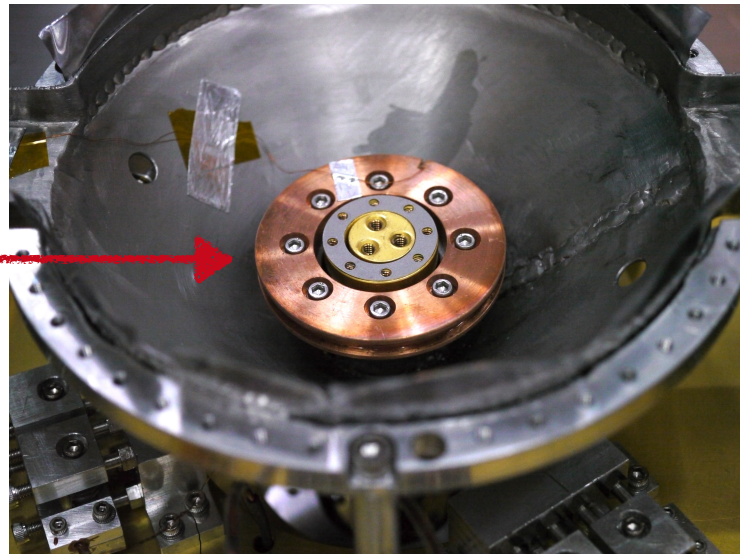


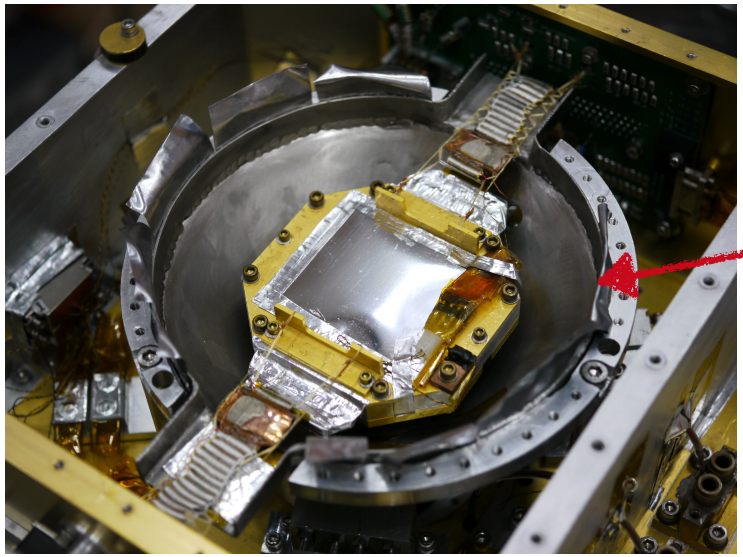


Micro-X Detector: Magnetic Shielding

- TES and SQUIDs are very sensitive to magnetic fields
- ADR operates with a 4T magnet
  - Shielding is designed to keep ADR magnet field <100 nT at the detectors
- Superconducting niobium shield expels external fields
- Field coil cancels out remaining field

Field coil



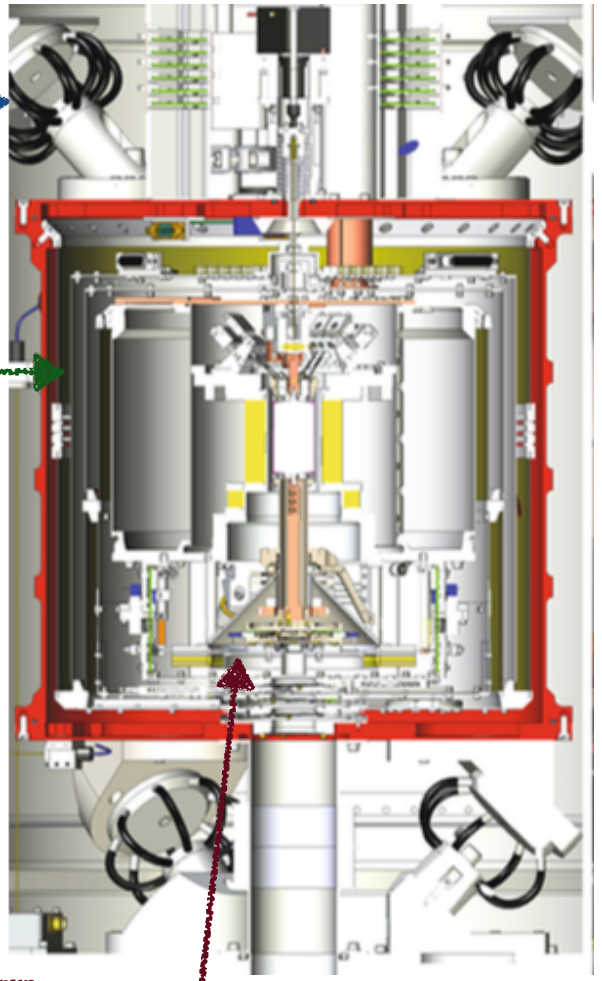


Nb shield

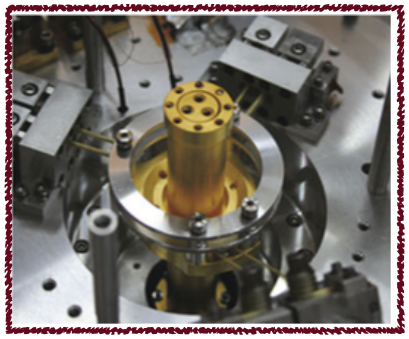
“Passing Vibe”

Wire rope isolators
30 Hz
(skin - dewar)

G10 tube + spring
90 Hz
(dewar - He can)



- 3-stage vibration isolation system protects detectors
- Resonant frequencies of each stage are staggered
  - Cold stage frequency is damped by each of the lower frequency external stages
- July 2015: passed vibe!
  - 5 mK (X), 14 mK (Y), 9 mK (Z)
  - Control at 75 mK post launch



Kevlar suspension
325 Hz
(He can - detector stage)

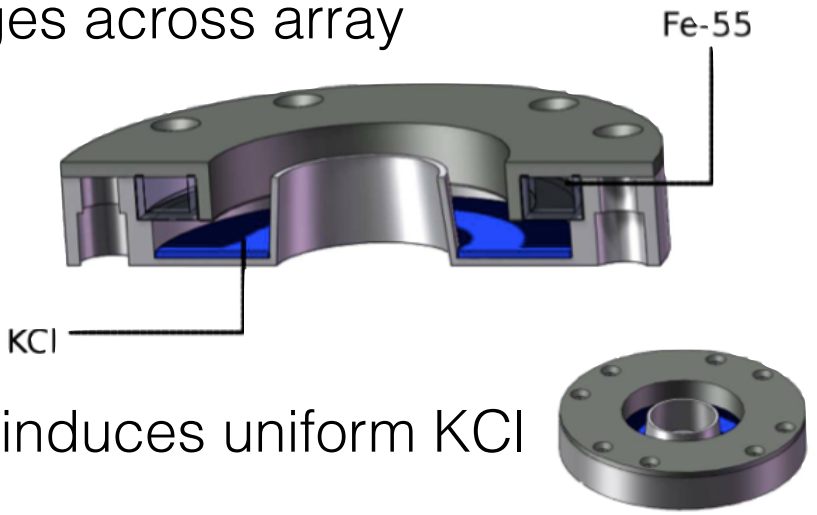
X-Ray Satellites

	Detector	Resolution	FOV
Chandra	ACIS-S	~100 eV	8’ x 50’
Chandra	ACIS-I	~100 eV	17’ x 17’
XMM-Newton	EPIC - MOS	~100 eV	30’ diameter
XMM-Newton	EPIC - PN	~100 eV	30’ diameter
Suzaku*	XIS	~100 eV	18’ x 18’
NuSTAR		400 eV	13’ x 13’
Hitomi*	SXS	5 eV	3’ x 3’

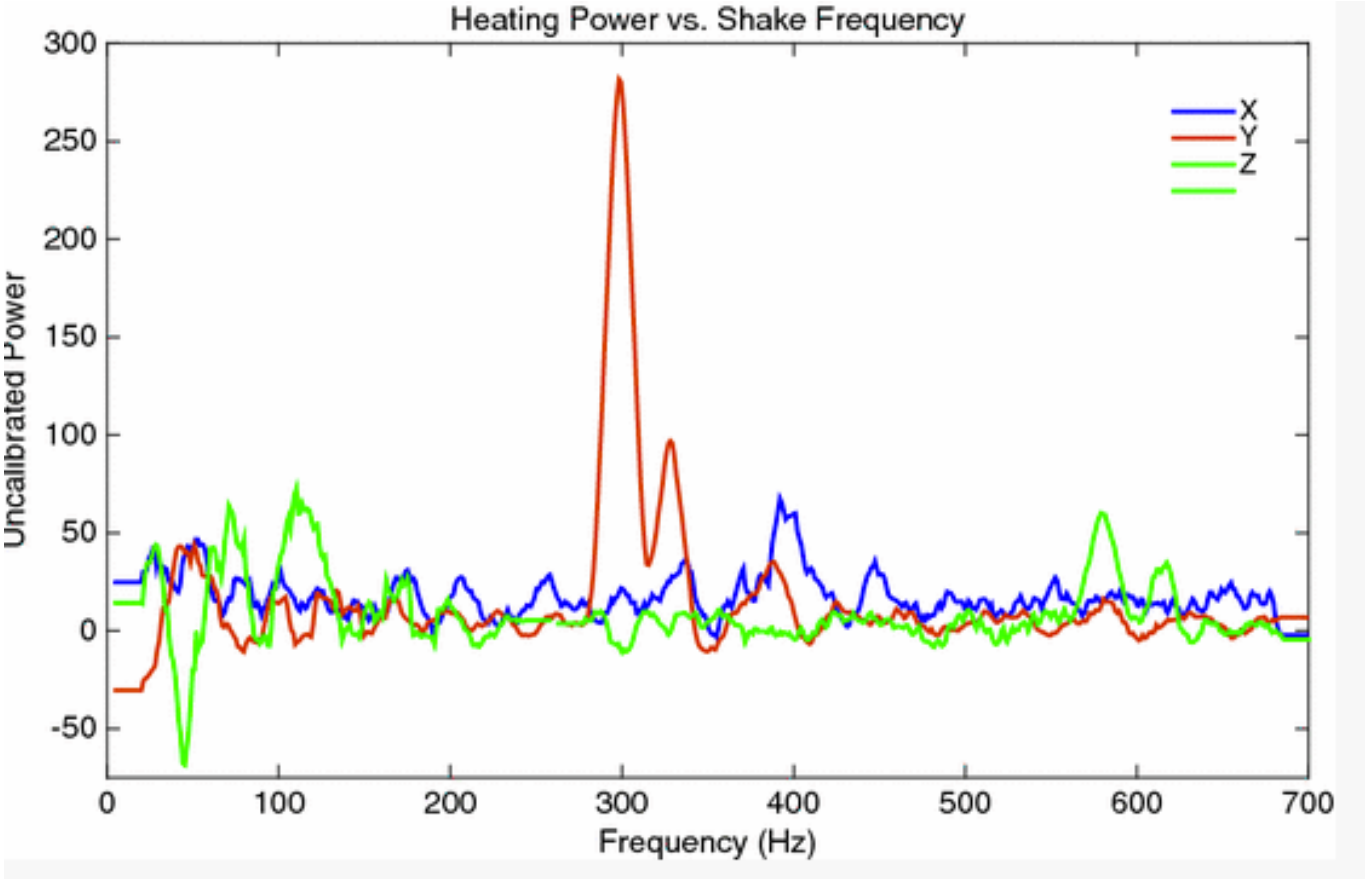
* no longer in operation

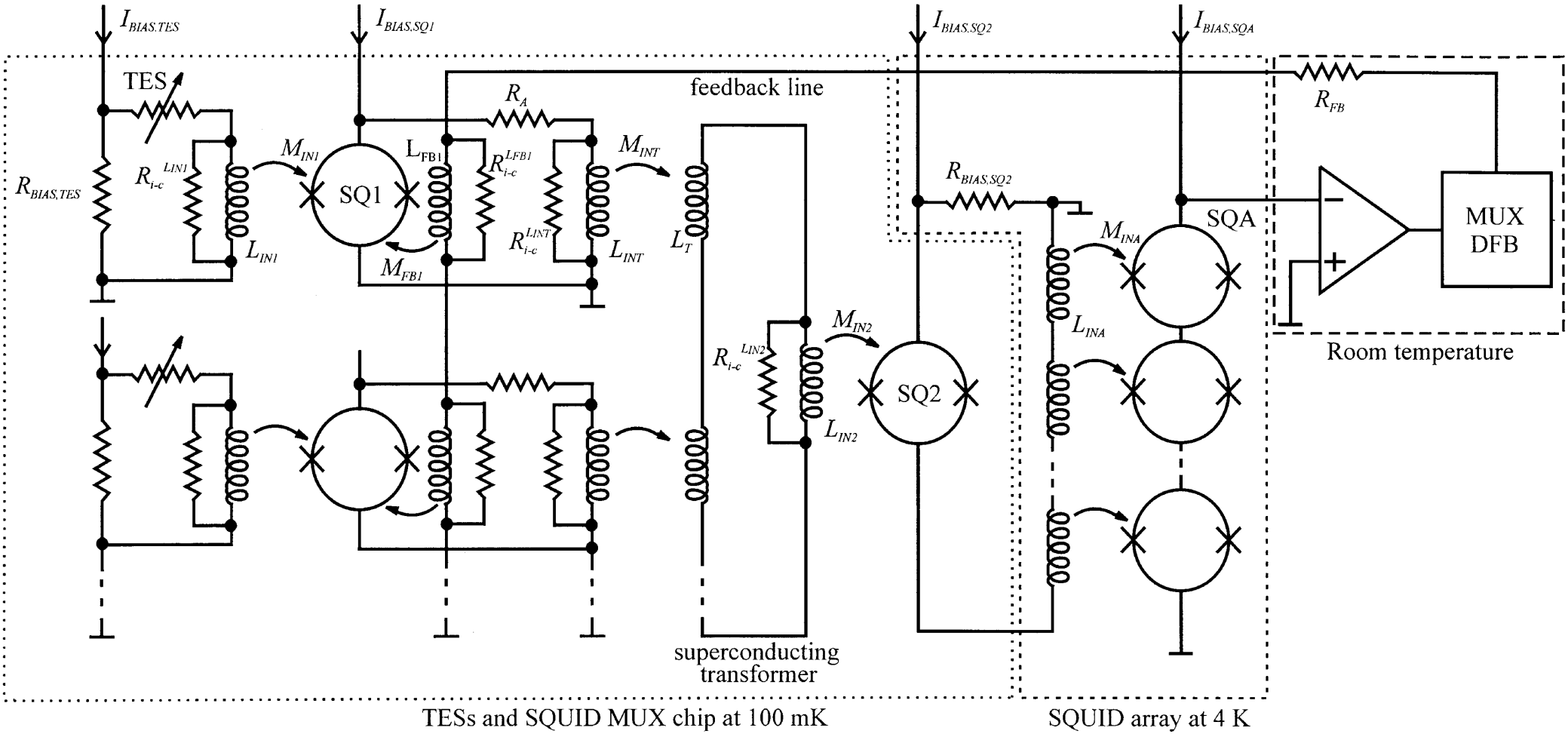
Micro-X Detector: Calibration

- In-flight calibration tracks potential changes across array
  - Vibration, temperature, magnetic field
- 1st flight: KCl fluoresced by Fe-55
  - Fe-55 is blocked by Pb from array but induces uniform KCl scintillation
  - Calibration lines at 2.62 (Cl Kα), 2.81 (Cl Kβ), 3.31 (K Kα), 3.58 (K Kβ) keV
  - Just outside energy band of interest (0.3 - 2.5 keV)
- 2nd flight: change to NaCl
  - Lines at 1.04 (Na Kα), 1.07 (Na Kβ), 2.62 (Cl Kα), 2.81 (Cl Kβ)



Vibration Testing




$I_{BIAS,TES}$
$I_{BIAS,SQ1}$
$I_{BIAS,SQ2}$
$I_{BIAS,SQA}$
TES
feedback line
R_A
R_{FB}
$R_{BIAS,TES}$
R_{i-c}^{LIN1}
M_{IN1}
SQ1
L_{FB1}
R_{i-c}^{LFB1}
M_{INT}
$R_{BIAS,SQ2}$
SQA
MUX
DFB
L_{IN1}
M_{FB1}
R_{i-c}^{LINT}
L_{INT}
L_T
M_{INA}
M_{IN2}
R_{i-c}^{LIN2}
SQ2
L_{INA}
L_{IN2}
Room temperature
superconducting
transformer
TESs and SQUID MUX chip at 100 mK
SQUID array at 4 K