Sgr A* X-ray Visionary Project

Frederick K. Baganoff, Michael A. Nowak (MIT Kavli Institute), Sera Markoff (API, University of Amsterdam) and Sgr A* XVP Collaboration

www.sgra-star.com

Science Goals

- Obtain first high-resolution X-ray spectra of Sgr A* and diffuse emission in the central pc
- Spatially and spectrally resolve accretion flow within Sgr A*'s Bondi radius (~1.5")
- Measure energy and width of known Fe Kalpha line(s) at ~6.6 keV in ACIS-I Spectrum
- Detect optically thin plasma emission lines, (e.g., Si, S, Fe), if present at levels predicted by RIAF models
- Measure relative abundances of emitting plasmas and absorbing column along LOS

Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Science Goals

- Radio polarization measurements indicate most accreting matter does not reach Sgr A*'s event horizon --- dynamics and thermal structure of plasma will tell us how matter flows in and how much and where some of it flows out
- Monitor X-ray flares of Sgr A* with increased cadence and minimal pile-up
- Perform coordinated multi-wavelength monitoring of flares from radio up to gamma-rays, including mm VLBI
- Constrain 3D GRMHD simulations of Sgr A* accretion flow using MW properties of flares and 1mm VLBI imaging

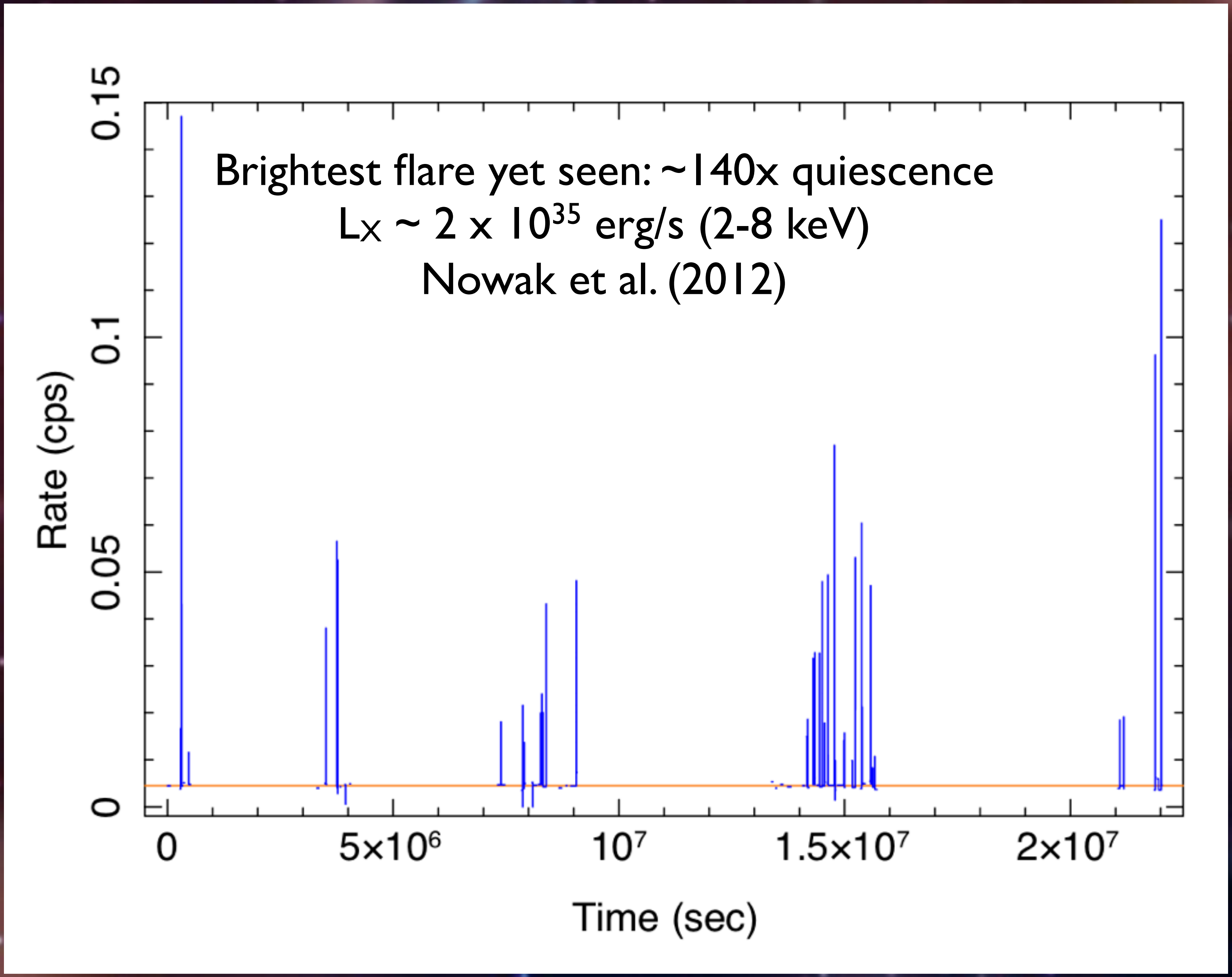
Observational Overview

- Completed 3Ms exposure of Sgr A* with Chandra/HETGS
- 38 separate observations from 2012 February 6 to October 31
- Observing constraints were very challenging:
  - Desired specific roll angles to minimize background: 76.4 (6), 76.6 (1), 92.2 (10), 268.7 (7), 270.7 (1) & 282.3 (13) degrees
  - Desired long exposures for multi-wavelength monitoring of Sgr A* flares: > 90ks (14)

Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Chandra X-ray Observatory
chandra.harvard.edu

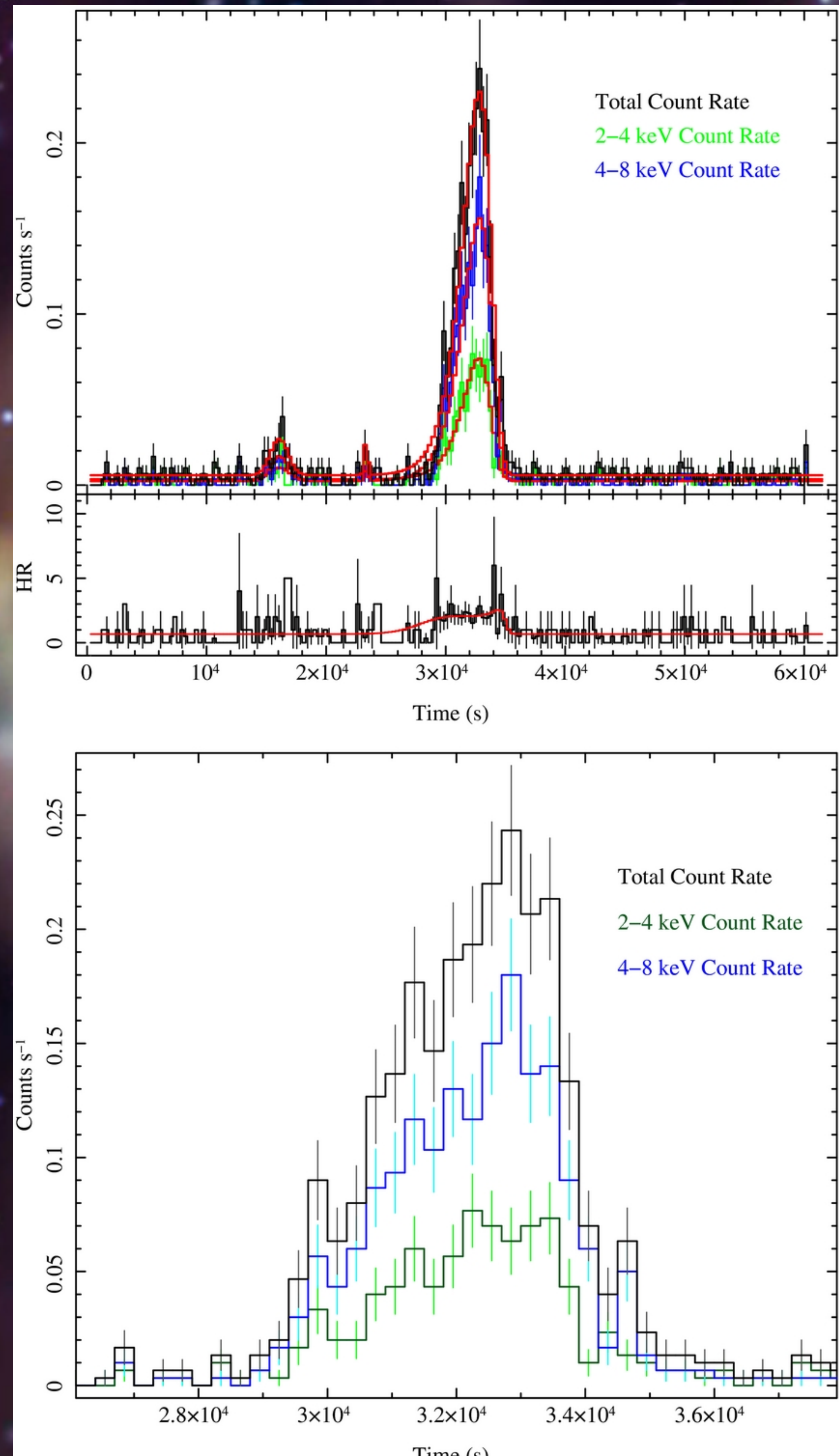
Sgr A* XVP Cumulative Light Curve



Performed 6 campaigns with subsets of HESS, VERITAS, Fermi, INTEGRAL, NuSTAR, Chandra, XMM, Keck, VLT, ALMA, SMA, CSO, VLA, VLBA & EHT

Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

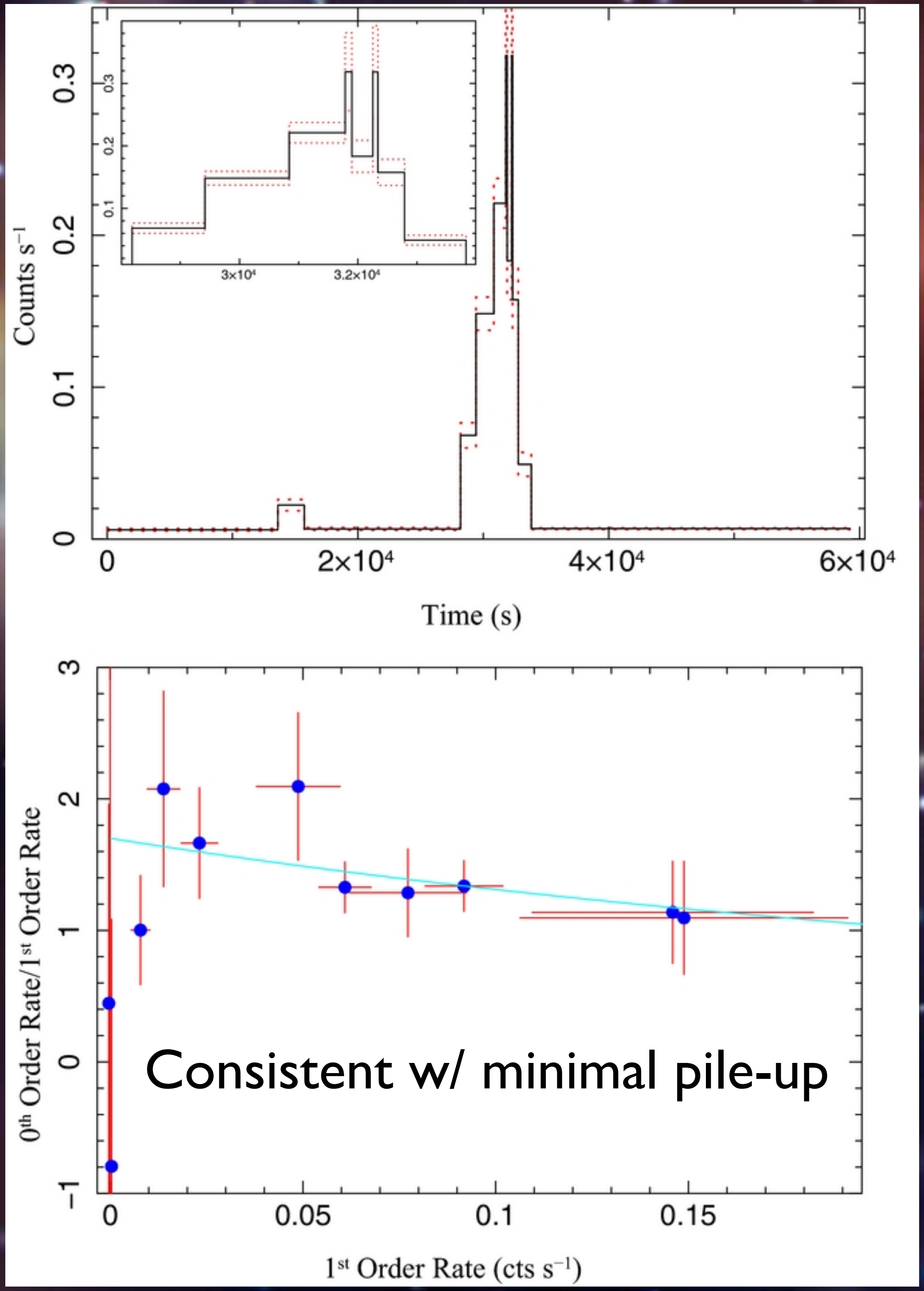
Chandra X-ray Observatory
chandra.harvard.edu



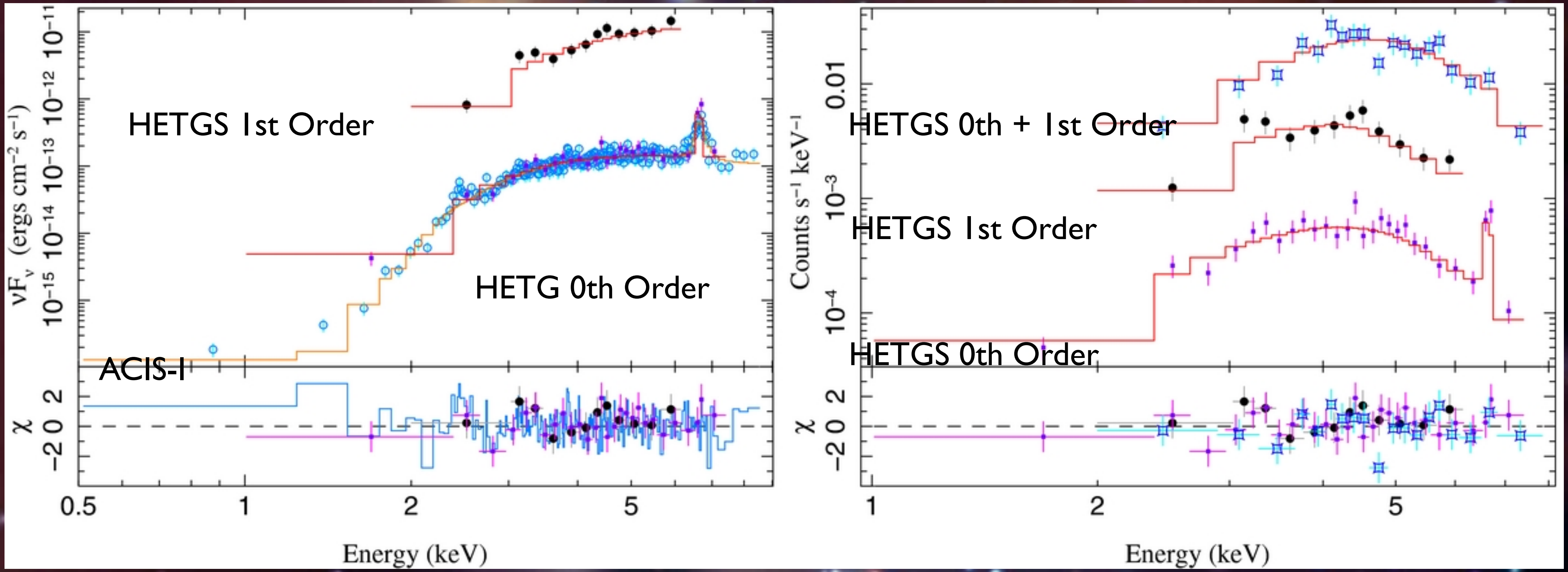
Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Brightest Flare Light Curve

Bayesian Blocks finds structure at peak

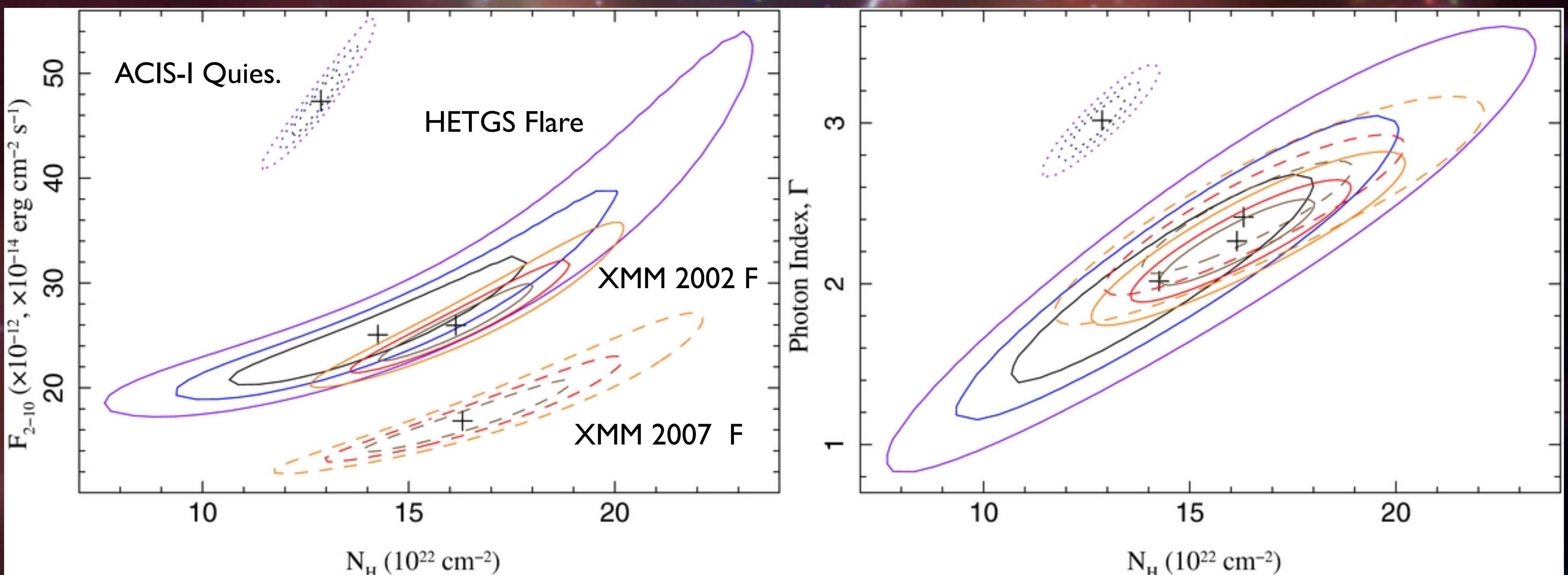


Sgr A* Flare and Quiescent Spectra -- ACIS-I & HETGS



He-like Fe Kalpha line at 6.7 keV; <u>No 6.4 keV line predicted by Sazonov et al. (2012)</u>; See Wang et al. (2013) and talk

Consistent Flare Properties for Brightest Chandra & XMM Flares



Photon index ~ 2 and N_H ~ 15 x 10^{22} cm^{-2}

Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Chandra X-ray Observatory
chandra.harvard.edu

Properties of Brightest X-ray Flare

Table 1
Joint Fit to *Chandra* Flare and Quiescent Spectra from the Sgr A* Region

State	$F_{2-8}^{\rm abs}$	$F_{2-8}^{\rm unabs}$	$F_{2-10}^{\rm unabs}$	$L_{2-10}^{\rm unabs}$	$F_\nu^{\rm abs}$	$N_{\rm H}$	Γ	$E_{\rm line}$	$\sigma_{\rm line}$	EW	χ^2/DoF
		(10^{-12} erg cm^{-2} s^{-1})		(10^{34} erg s^{-1})	(nJy)	(10^{22} cm^{-2})			(keV)		
Flare mean	$8.5^{+0.9}_{-0.9}$	$21.6^{+10.3}_{-5.2}$	$25.1^{+9.4}_{-4.8}$	$19.2^{+7.2}_{-3.7}$	770	$14.3^{+4.4}_{-3.6}$	$2.0^{+0.7}_{-0.6}$	...	...	...	267/256
Quiescent	$0.147^{+0.004}_{-0.003}$	$0.45^{+0.04}_{-0.04}$	$0.47^{+0.05}_{-0.03}$	$0.36^{+0.04}_{-0.04}$	9.6	$12.9^{+0.8}_{-0.8}$	$3.0^{+0.2}_{-0.2}$	$6.63^{+0.02}_{-0.02}$	$0.02^{+0.04}_{-0.02}$	$0.78^{+0.14}_{-0.12}$	267/256
Flare peak	21^{+3}_{-3}	54^{+27}_{-15}	63^{+25}_{-14}	48^{+19}_{-11}	...	...	...	...	...	...	...

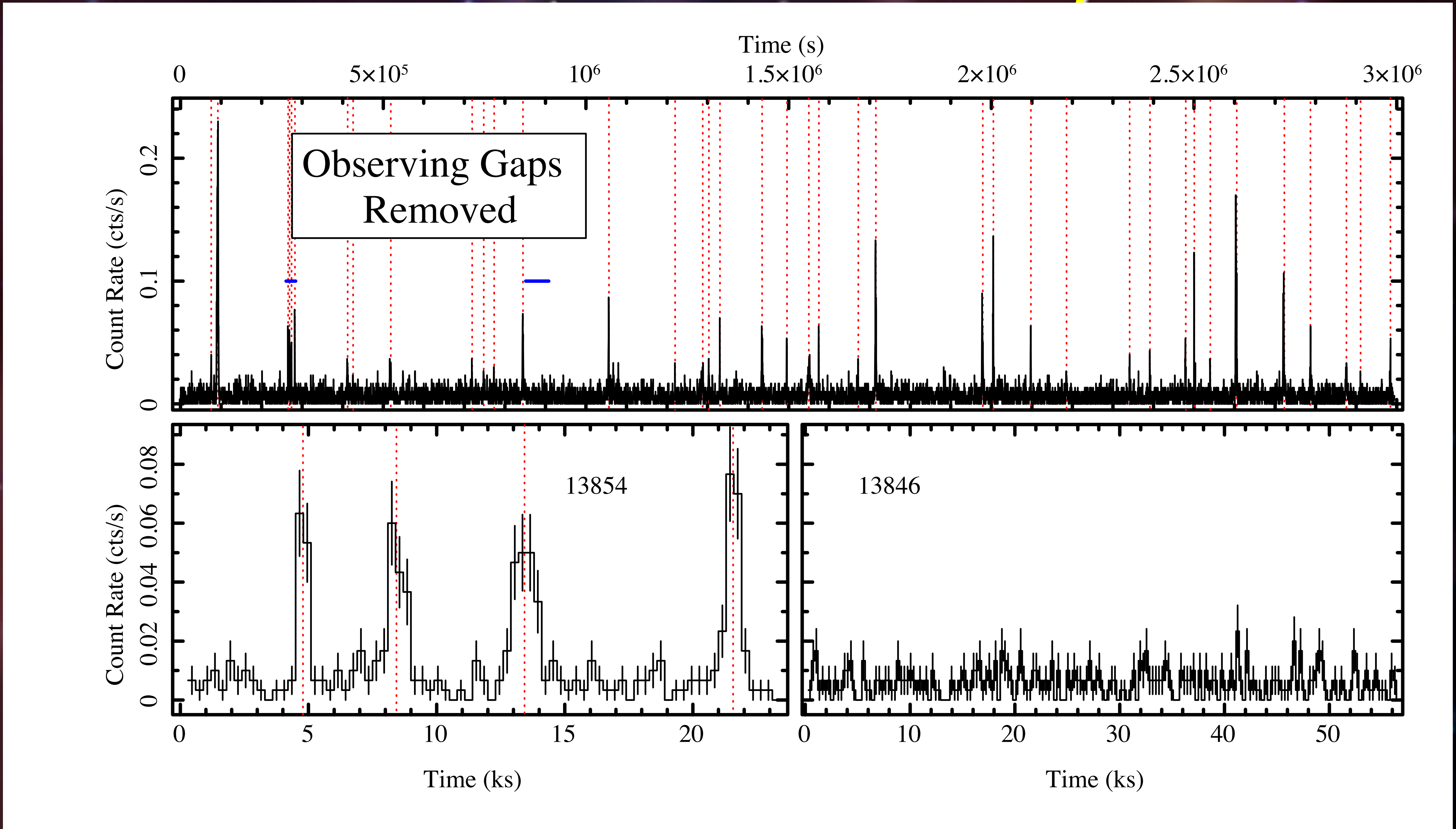
Notes. The model, `dustscat×TBnew×(powerlaw+gaussian)`, is applied separately to the quiescent spectrum and the flare spectrum. No Gaussian is included during the flare. We model the zeroth-order spectrum during the flare as the sum of the quiescent emission and flare emission; for the HETG flare spectrum, we subtract the quiescent emission and diffuse extended emission as background. In lieu of model normalizations, we measure the integrated 2–8 and 2–10 keV fluxes F with the `cflux` convolution model. We report both absorbed (superscript abs) and unabsorbed (superscript unabs) fluxes; the 2–10 keV luminosity L presumes isotropic emission at a distance of 8 kpc. $F_\nu^{\rm abs}$ is the best-fit model flux density at 6 keV (no errors given). $N_{\rm H}$ is the equivalent hydrogen column density, Γ is the power-law index, and $E_{\rm line}$, $\sigma_{\rm line}$, and EW are the energy, 1σ width, and equivalent width of the Gaussian emission line. Errors are 90% confidence level for one interesting parameter. Peak flux values are derived assuming a peak/mean flux ratio of 2.5 ± 0.3 (90% CL), with errors combined in quadrature. Due to pileup, this ratio may in fact be ≈10% too low (see the text).

Good agreement with two brightest XMM flares
(Nowak et al. 2012, ApJ, 759, 95)

Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Chandra X-ray Observatory
chandra.harvard.edu

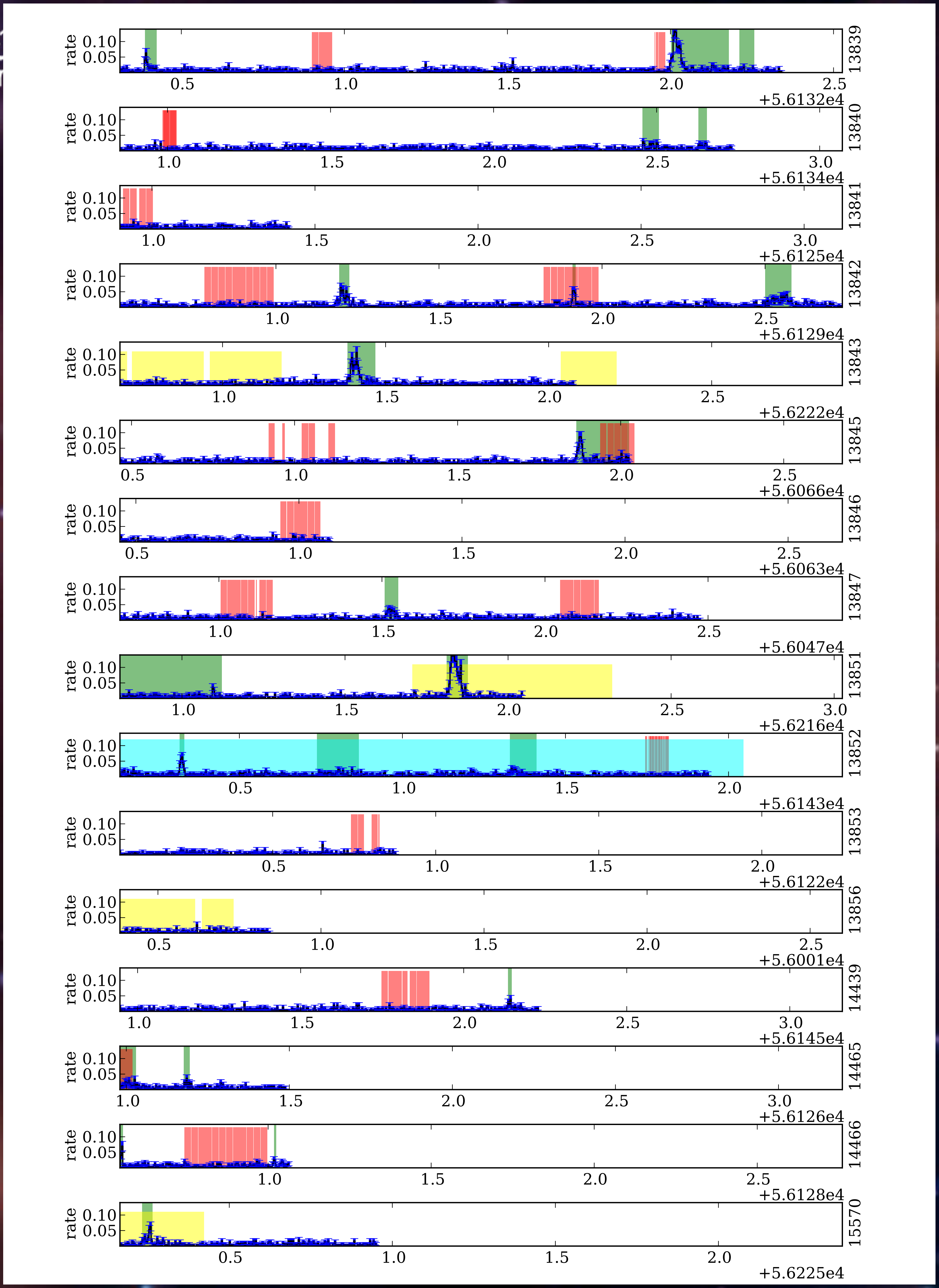
39 X-ray Flares in 3Ms Exposure: 1.12 +/- 0.18 flares/day



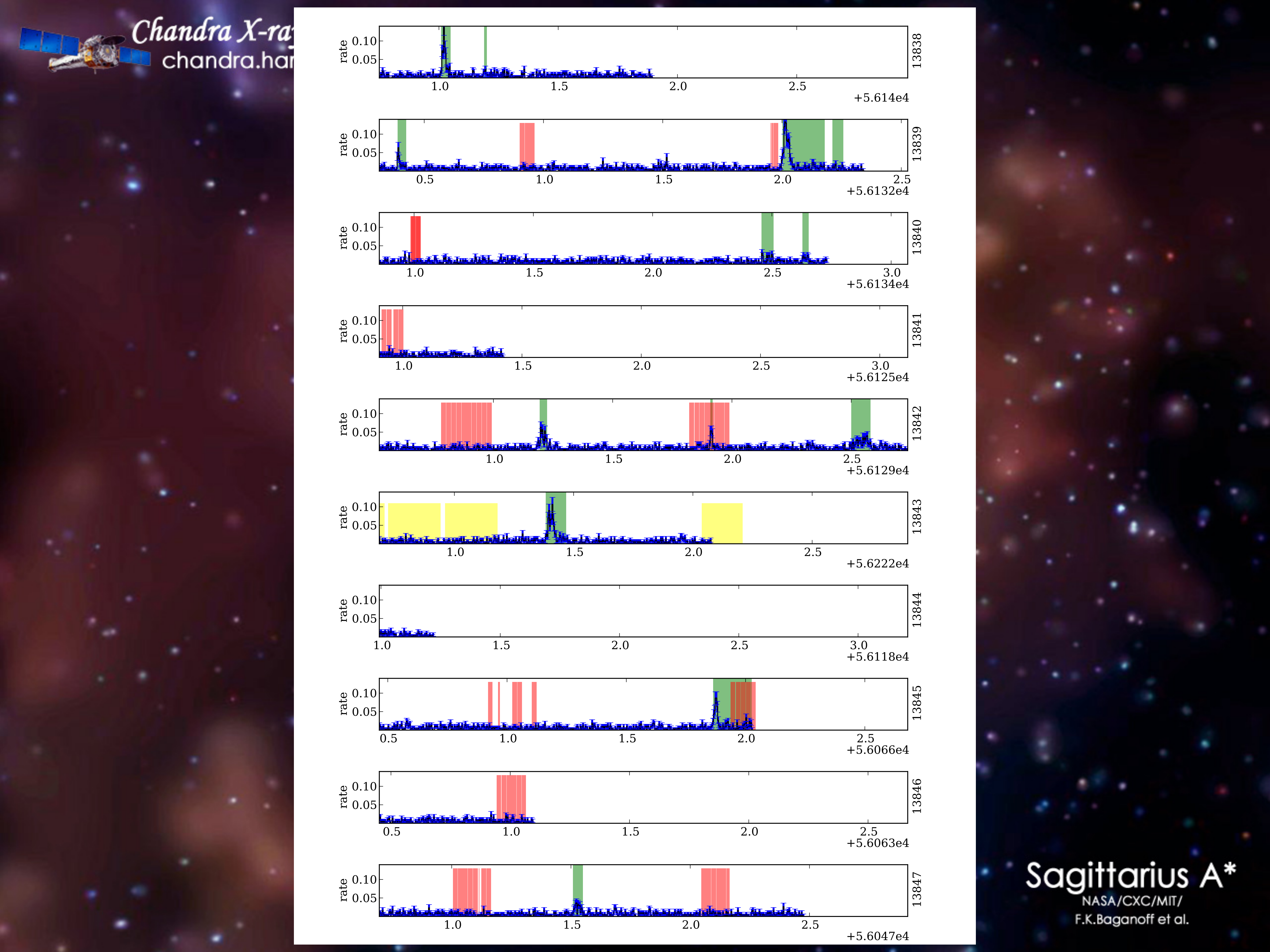
See Neilsen et al. (2013) and talk

Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Chandra X-ray
chandra.har

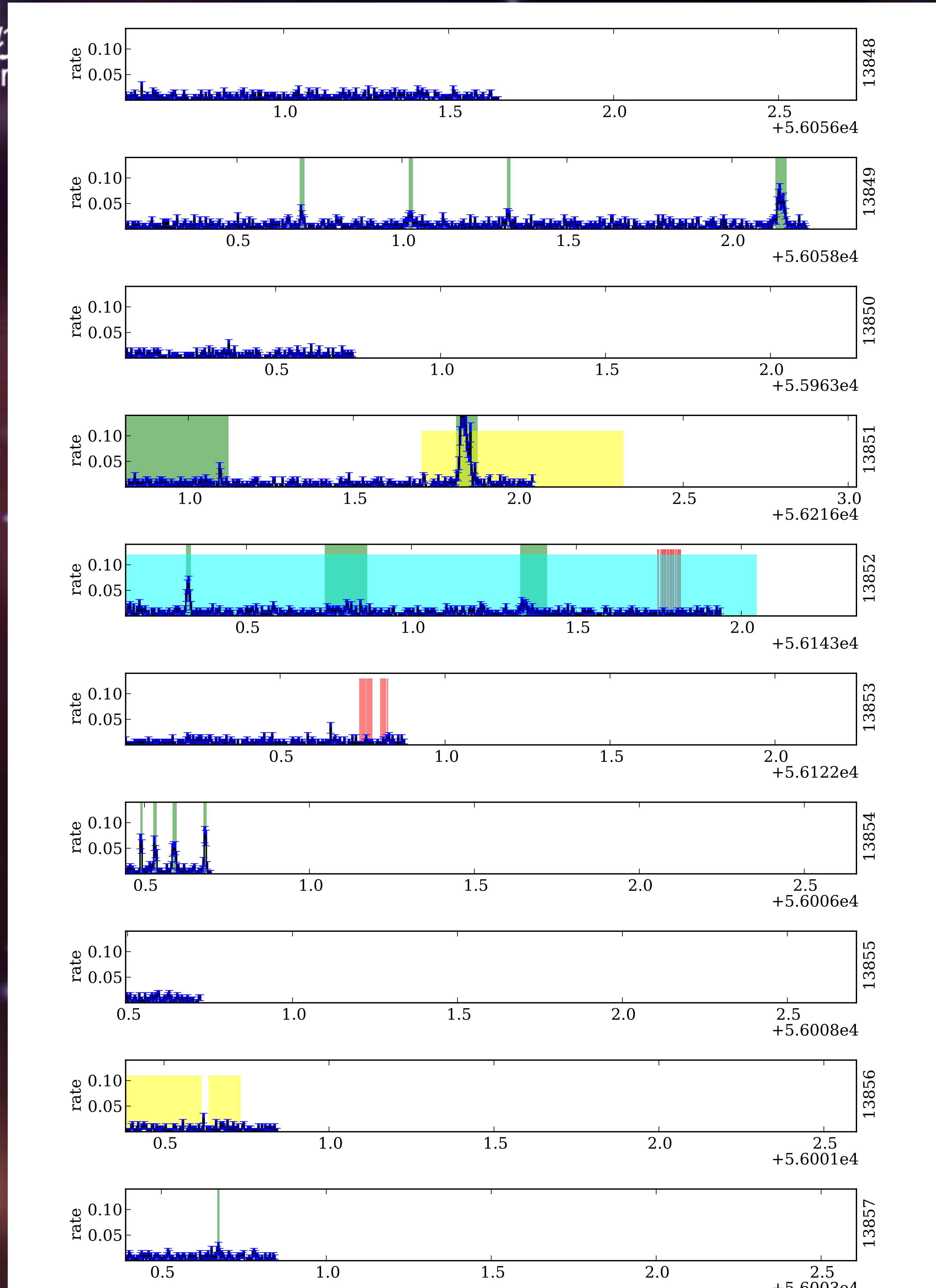


Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.



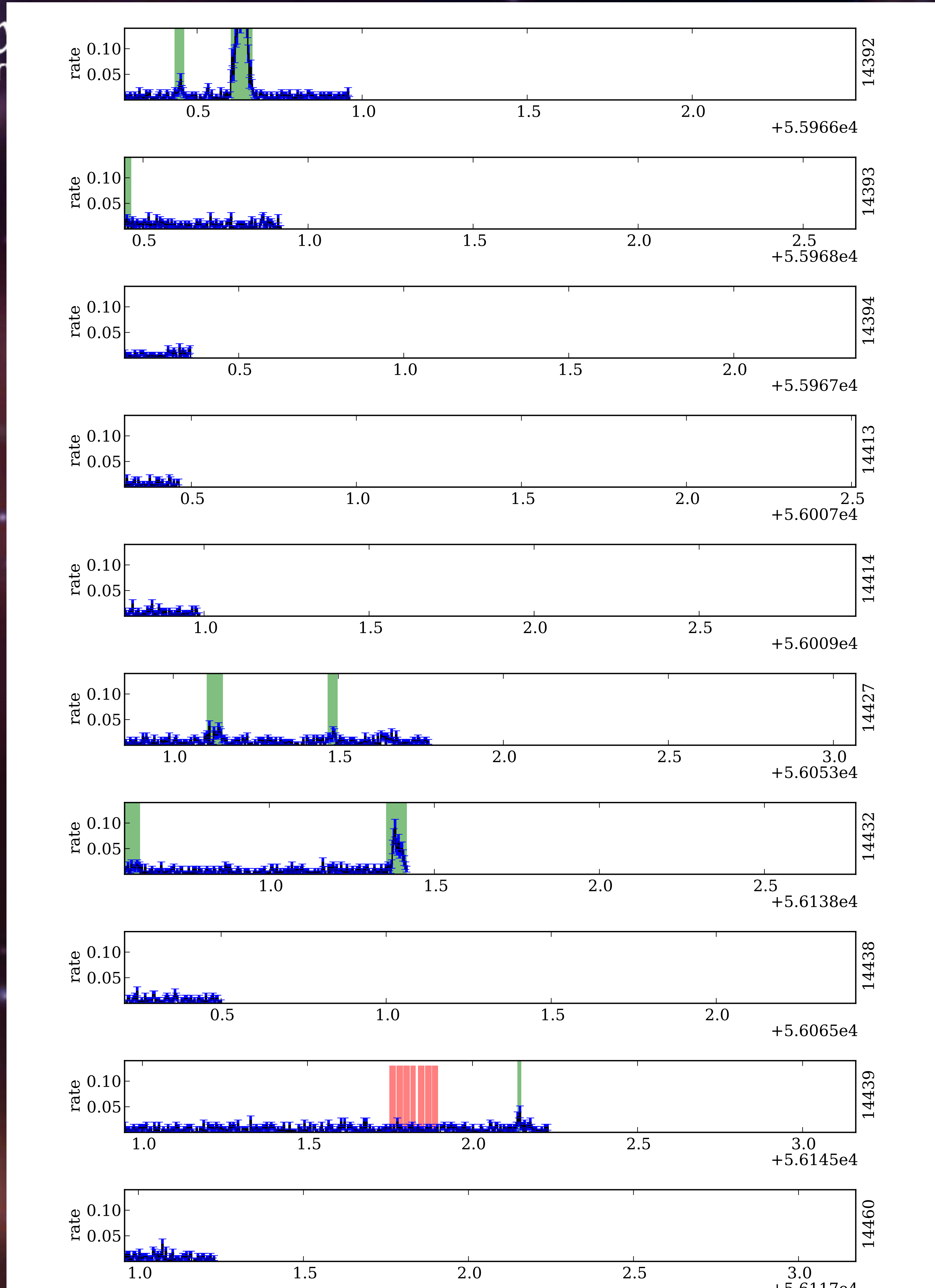
Chandra X-ray
chandra.har
rate
0.10
0.05
13838
+5.614e4
13839
+5.6132e4
13840
+5.6134e4
13841
+5.6125e4
13842
+5.6129e4
13843
+5.6222e4
13844
+5.6118e4
13845
+5.6066e4
13846
+5.6063e4
13847
+5.6047e4
Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Chandra X-ra
chandra.har



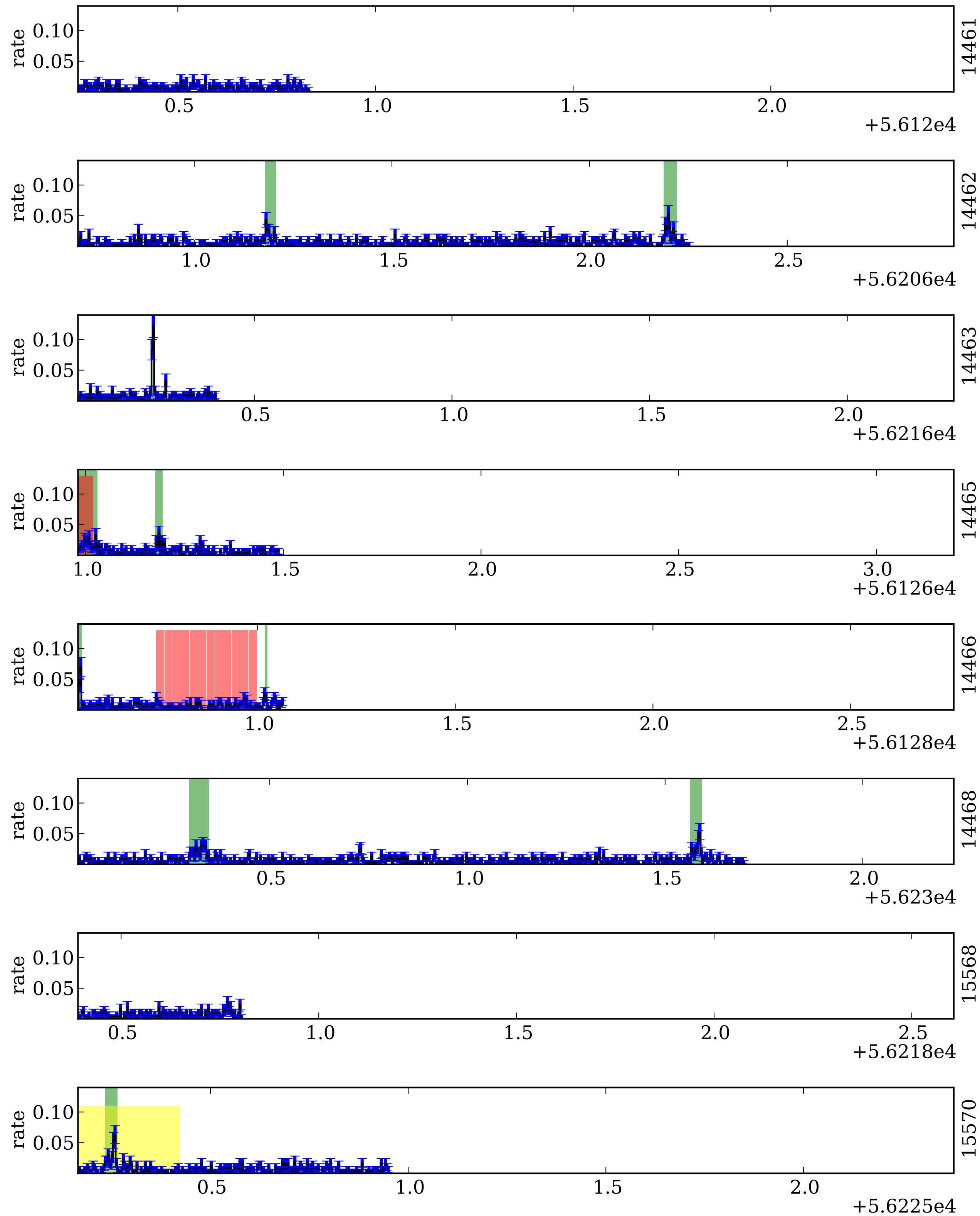
Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Chandra X-ray
chandra.har



Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

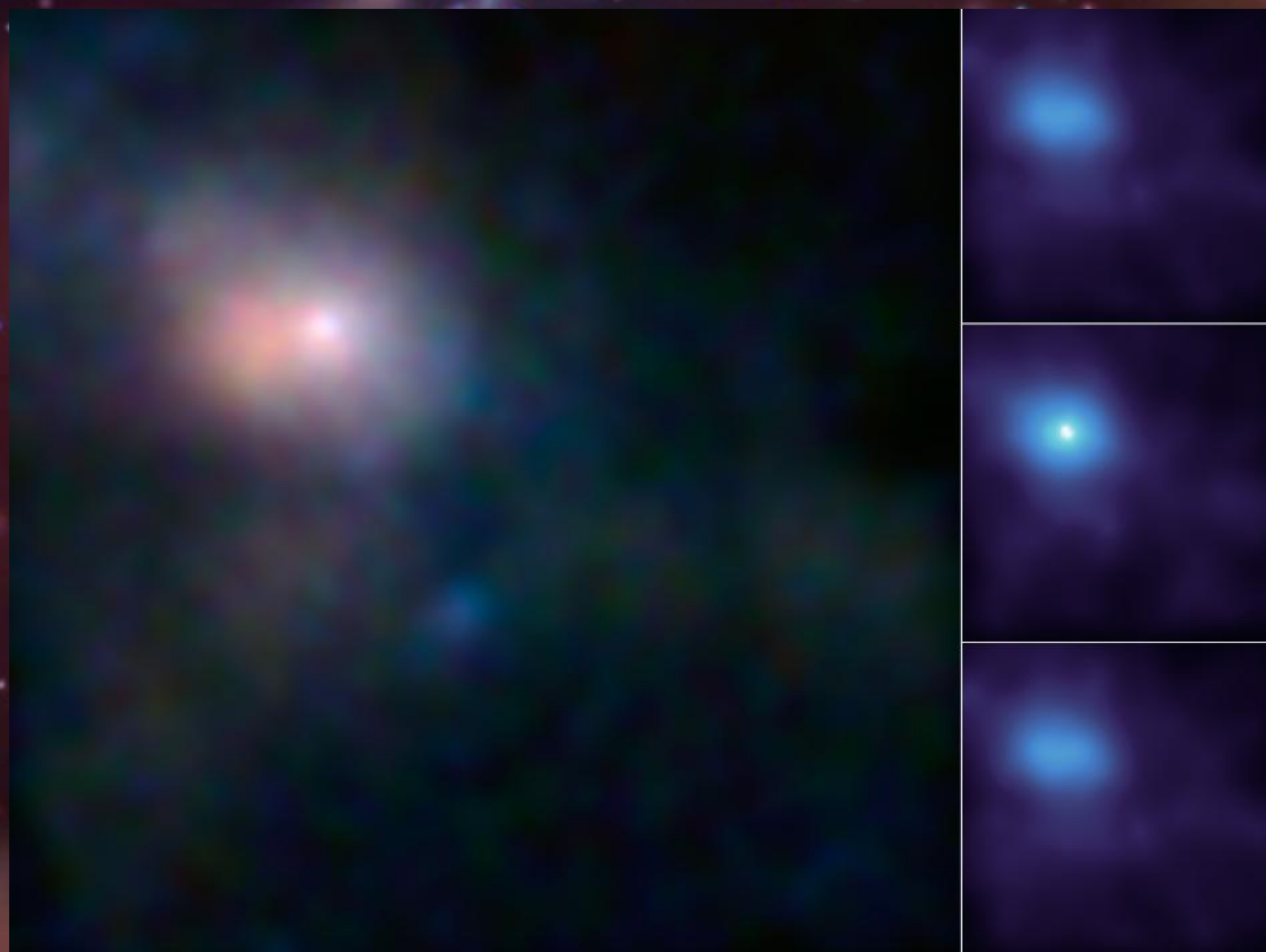
Chandra X-ra
chandra.har



Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Chandra X-ray Observatory
chandra.harvard.edu

NuSTAR Detects Sgr A* Flare!



See Barriere et al. talk and Zhang et al. poster
NuSTAR PI: F. Harrison (Caltech)

Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Sgr A* Flare Science Topics

- X-ray flares are non-thermal but mechanism is still undetermined: synchrotron with cooling break (SB), external Compton (EC) or synchrotron self-Compton (SSC)?
- X-ray & NIR flares appear related (opt thin process)
- What causes variable X-ray-to-NIR flux ratio?
- mm/radio events are weaker & longer timescale (~opt thick process)
- Are mm/radio events correlated with X-ray/NIR?
    - If so, do they lead, lag or sometimes lead other times lag?
    - Need sufficient sample of MWL flares to establish or refute correlation with X-ray/NIR flares

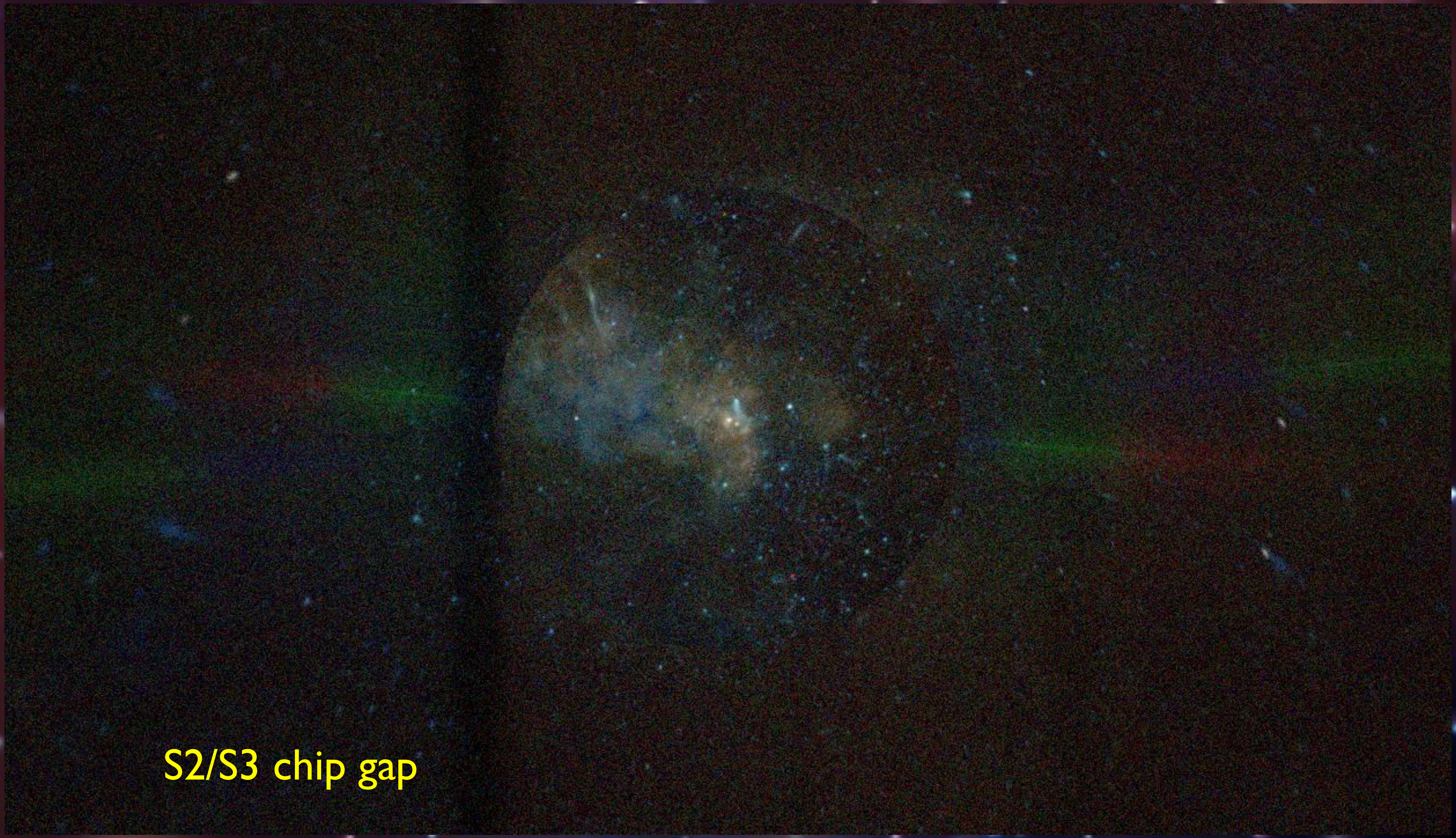
Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Sgr A* Flare Science Topics

- Origin(s) of flares undetermined:
  - magnetic reconnection?
  - shock in jet or inner accretion flow?
  - stochastic acceleration?
  - magnetic excitation by infalling asteroids?
- What determines flare duty cycle and energy budgets?
- Need broad-band flare spectra and time evolution observations to understand flares
- What do flares tell us about innermost environment of Sgr A*'s accretion flow?
- Does this phenomenon scale to other LLAGN?
- Will G2 or similar events change Sgr A*'s rate of flaring and its accretion state?

Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

3Ms Chandra HETGS Image of Sgr A*

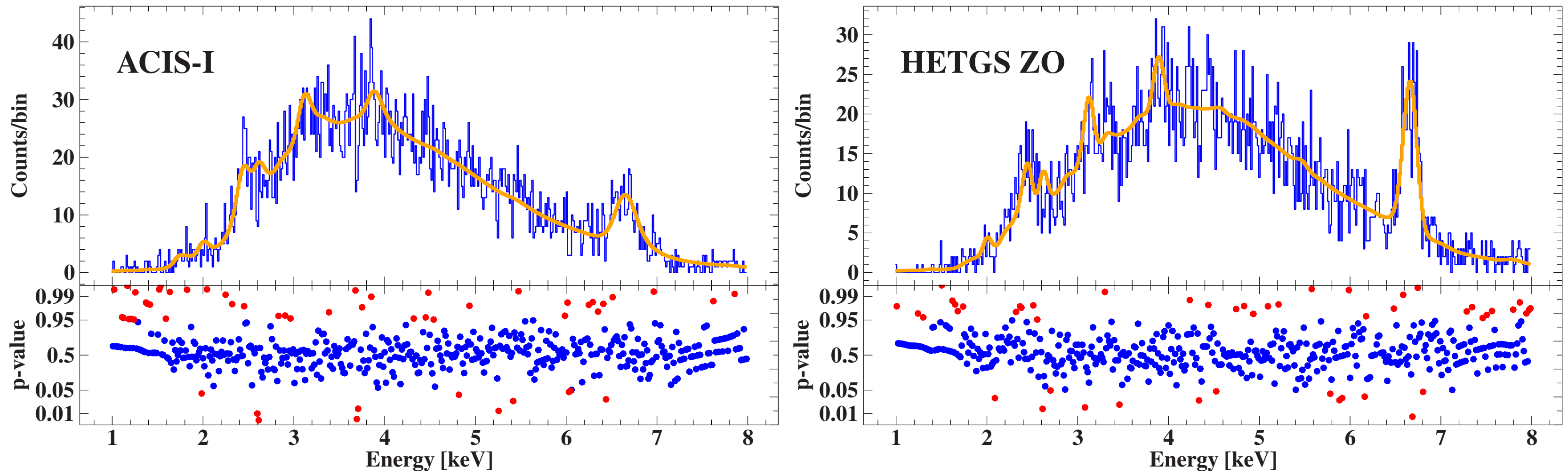


- Events projected to common tangent plane
- Events outside ~250 pixels rotated to align grating arms
- Moderate smearing of co-aligned spectra

Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

HETGS Quiescent Background

Joint Fit to ACIS-I and HETGS CCD Spectra



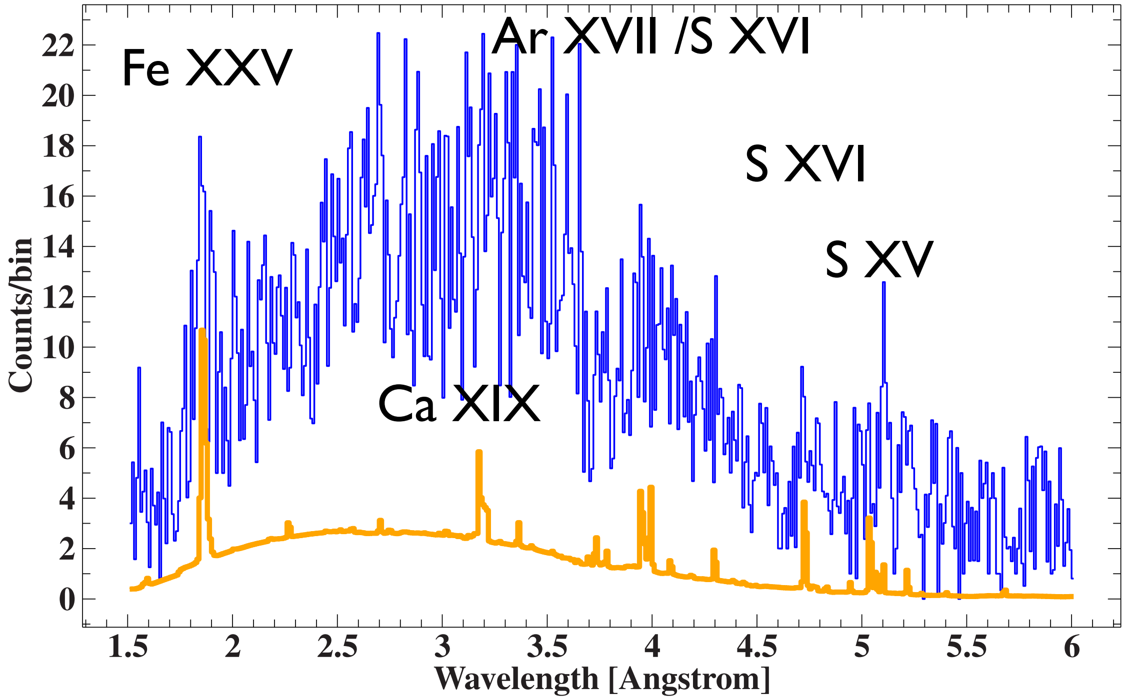
phabs(1)*(apec(1)+powerlaw(1))

idx	param	tie-to	freeze	value	min	max	
1	phabs(1).nH	0	0	10.56378	5	15	10^22
2	apec(1).norm	0	0	0.0005789178	0	0.1	
3	apec(1).kT	0	0	1.59543	0.008	64	keV
4	apec(1).Abundanc	0	1	1.5	0	2	
5	apec(1).Redshift	0	1	0	-0.999	10	
6	powerlaw(1).norm	0	0	3.35018e-05	0	0.001	
7	powerlaw(1).PhoIndex	0	0	1.573605	-2	4	

HETGS Quiescent Background

Expected HEG+1 Spectrum

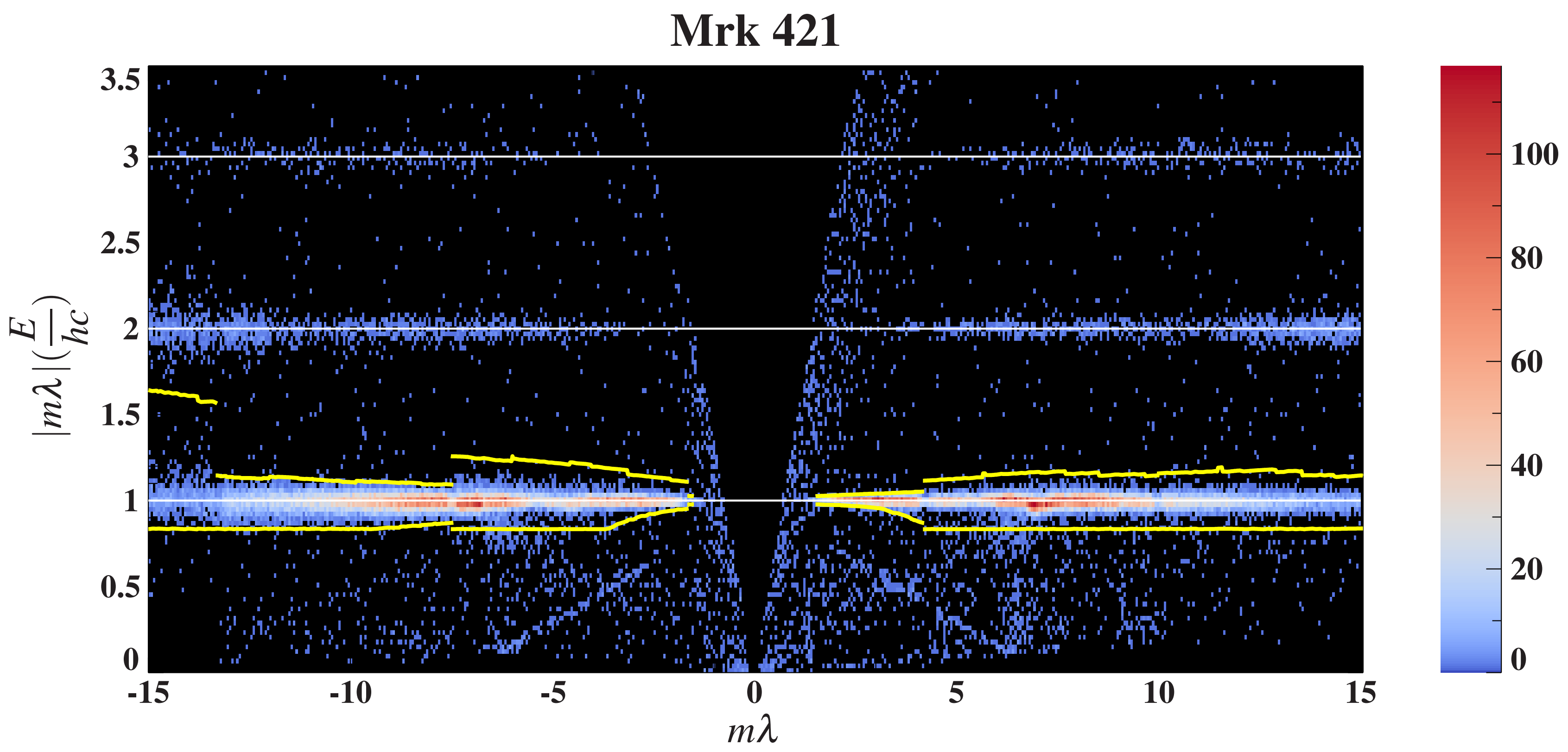
The observed zeroth order HETG CCD spectrum may be used to predict the expected number of counts in first order.



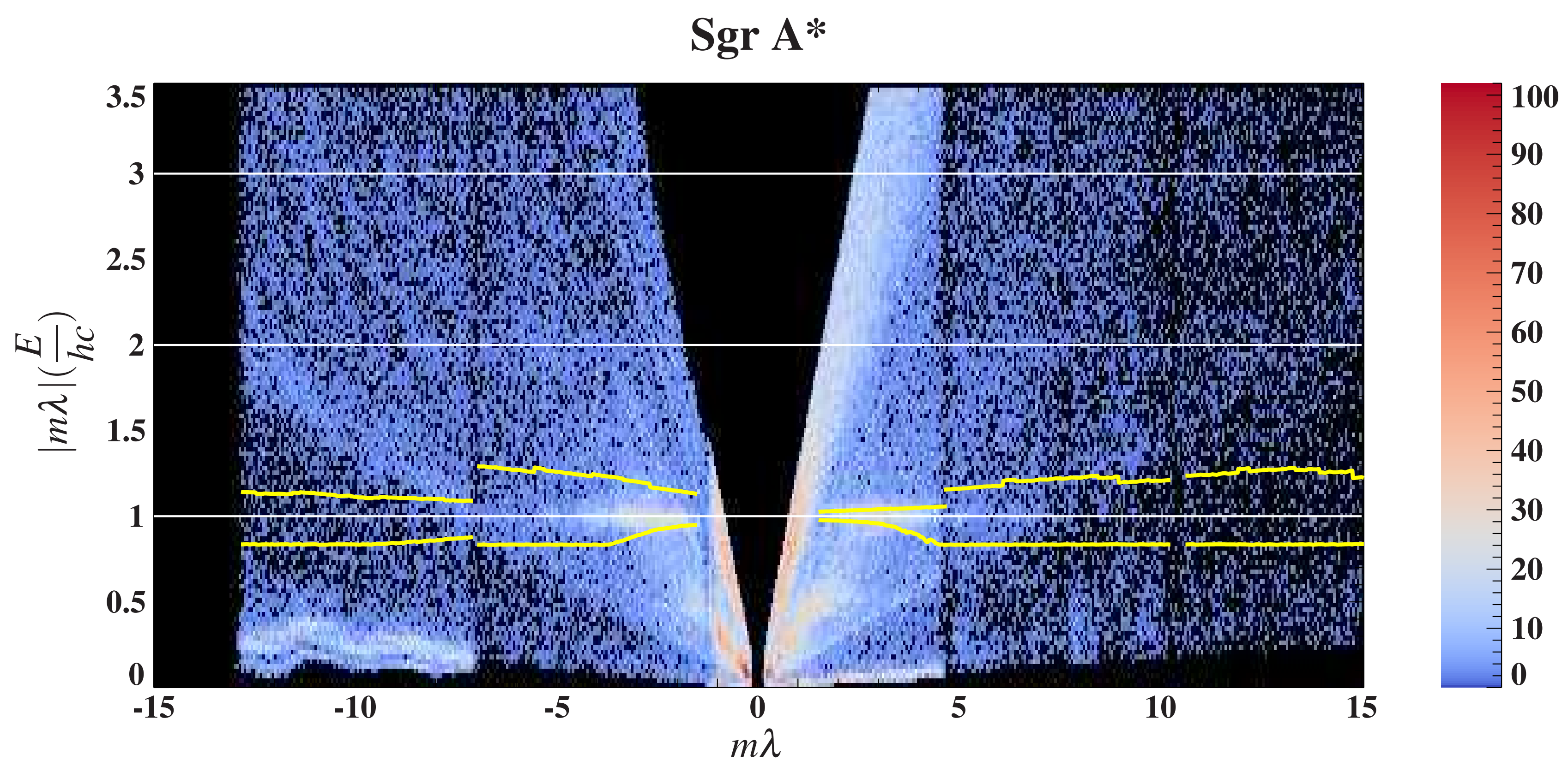
What can be done to reduce the background?

HETGS Quiescent Background

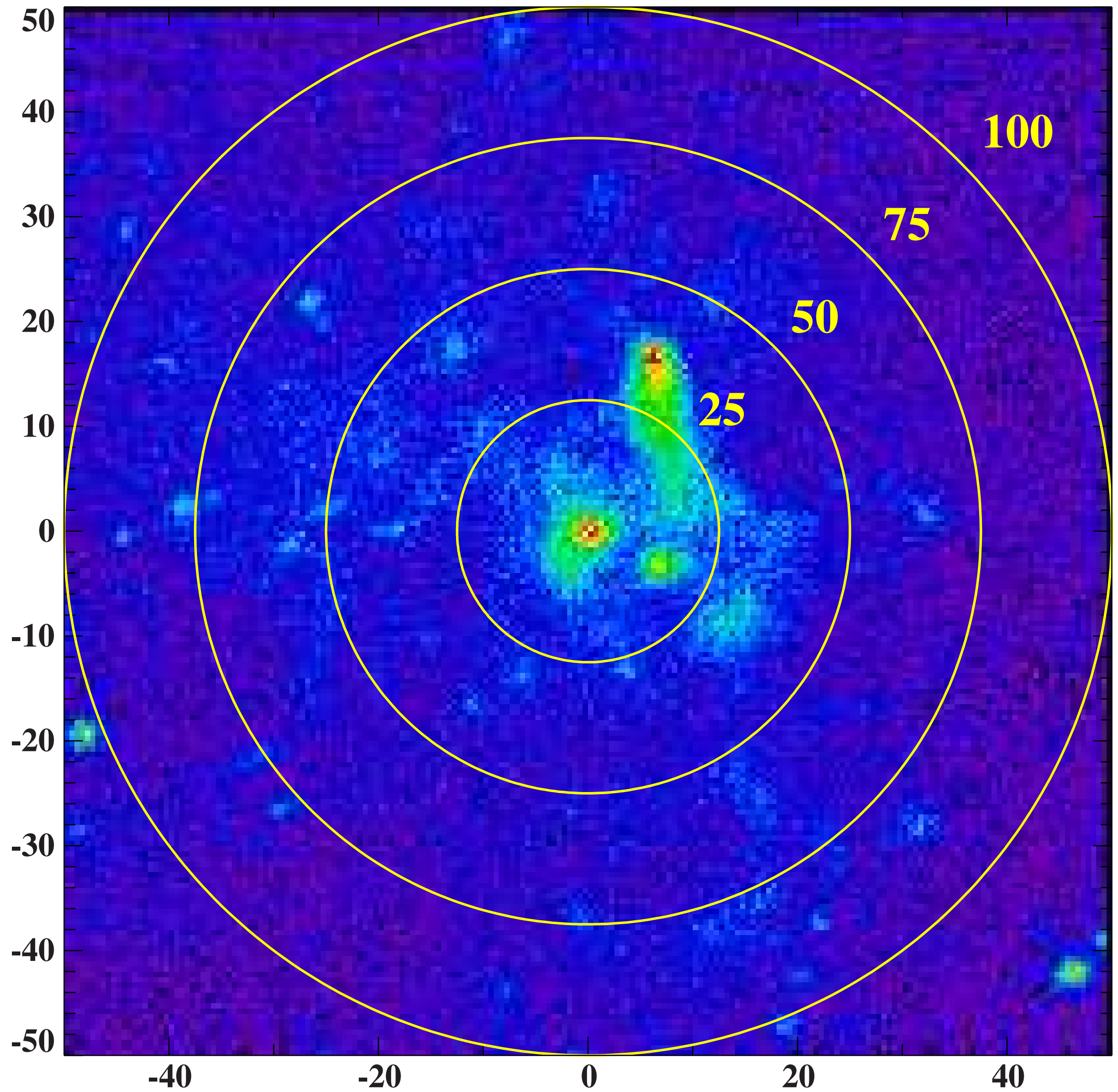
Order-Sorting Plot



HETGS Quiescent Background

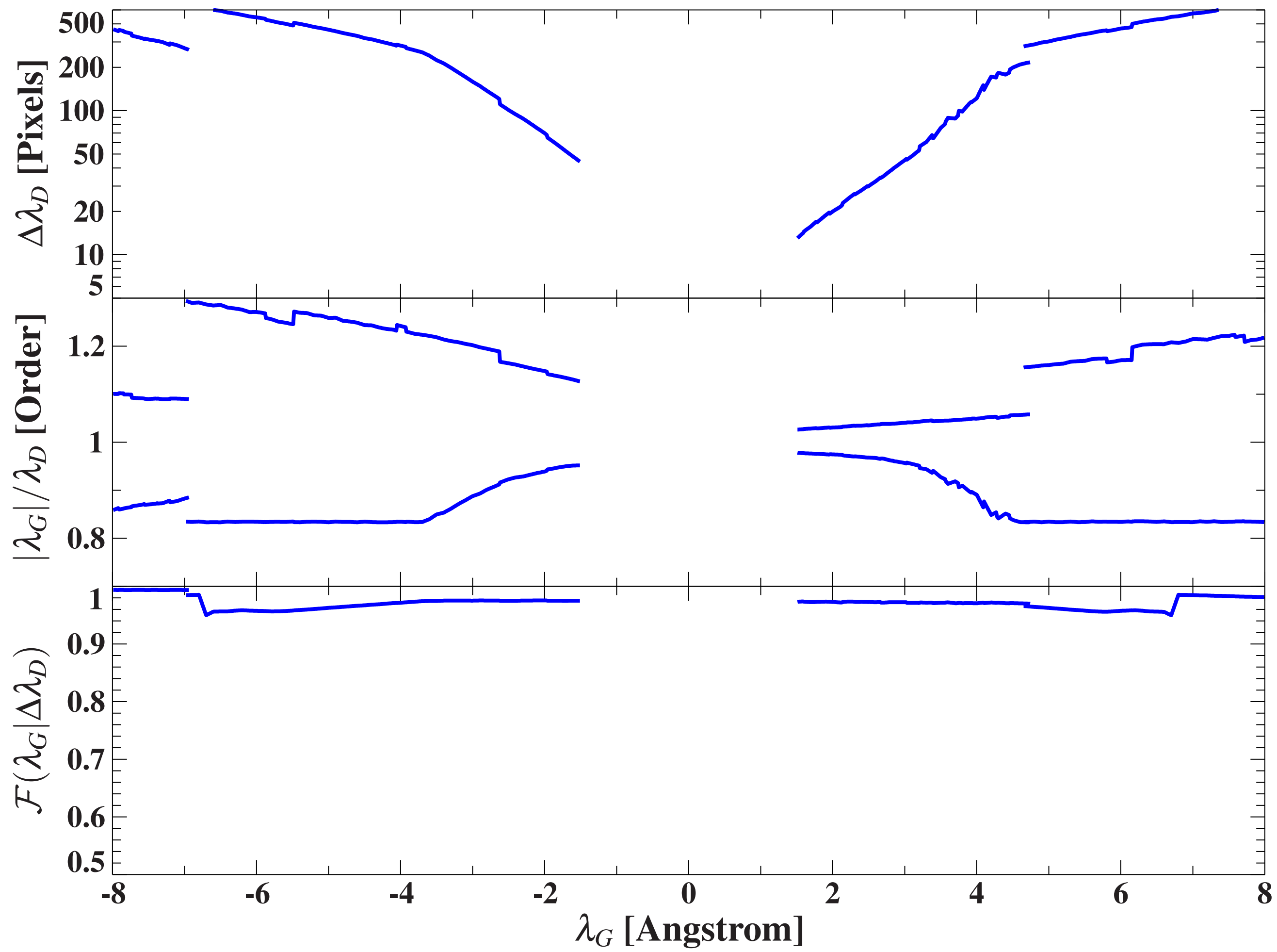


HETGS Quiescent Background



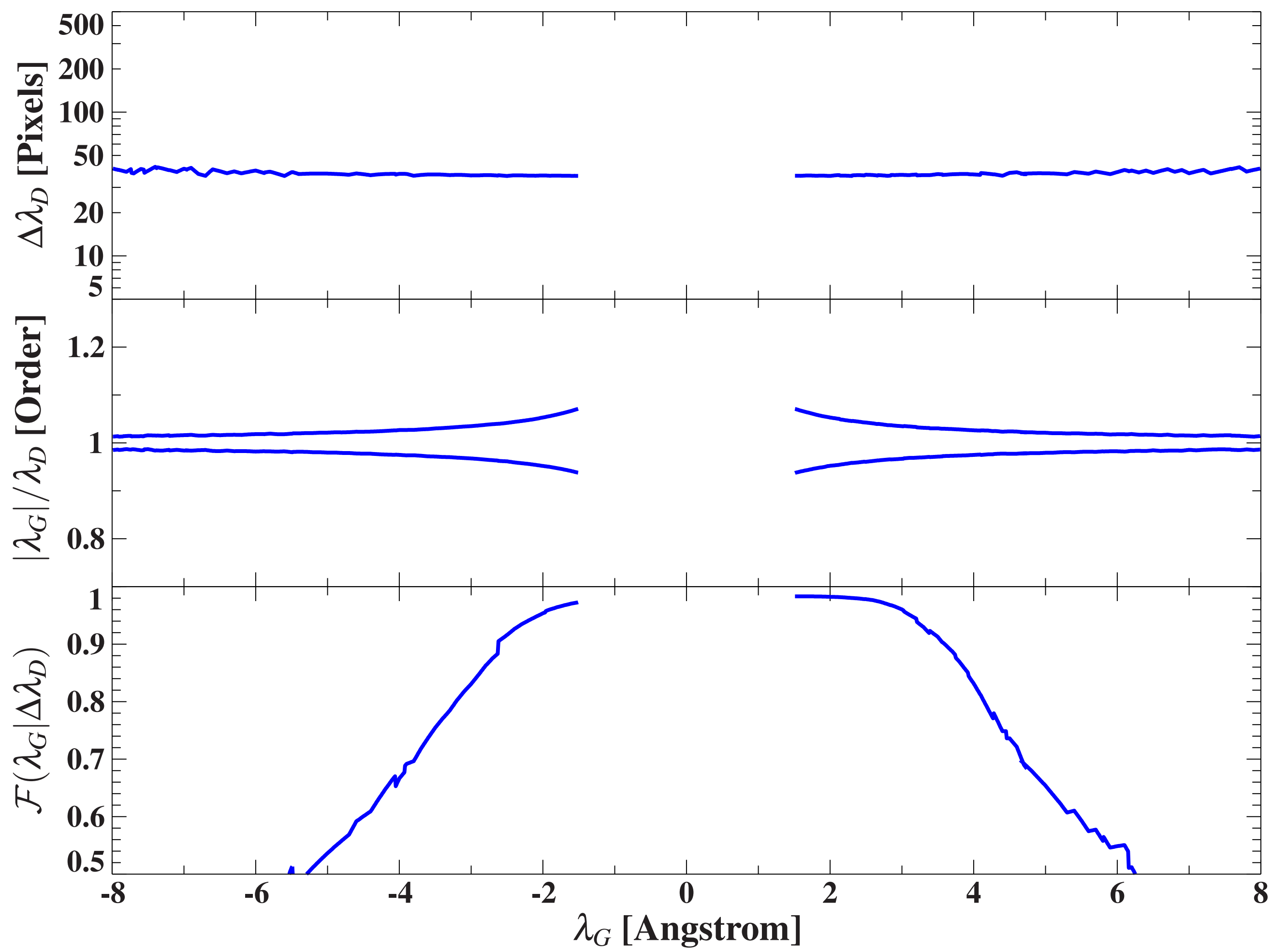
HETGS Quiescent Background

Chandra CALDB Order-Sorting File



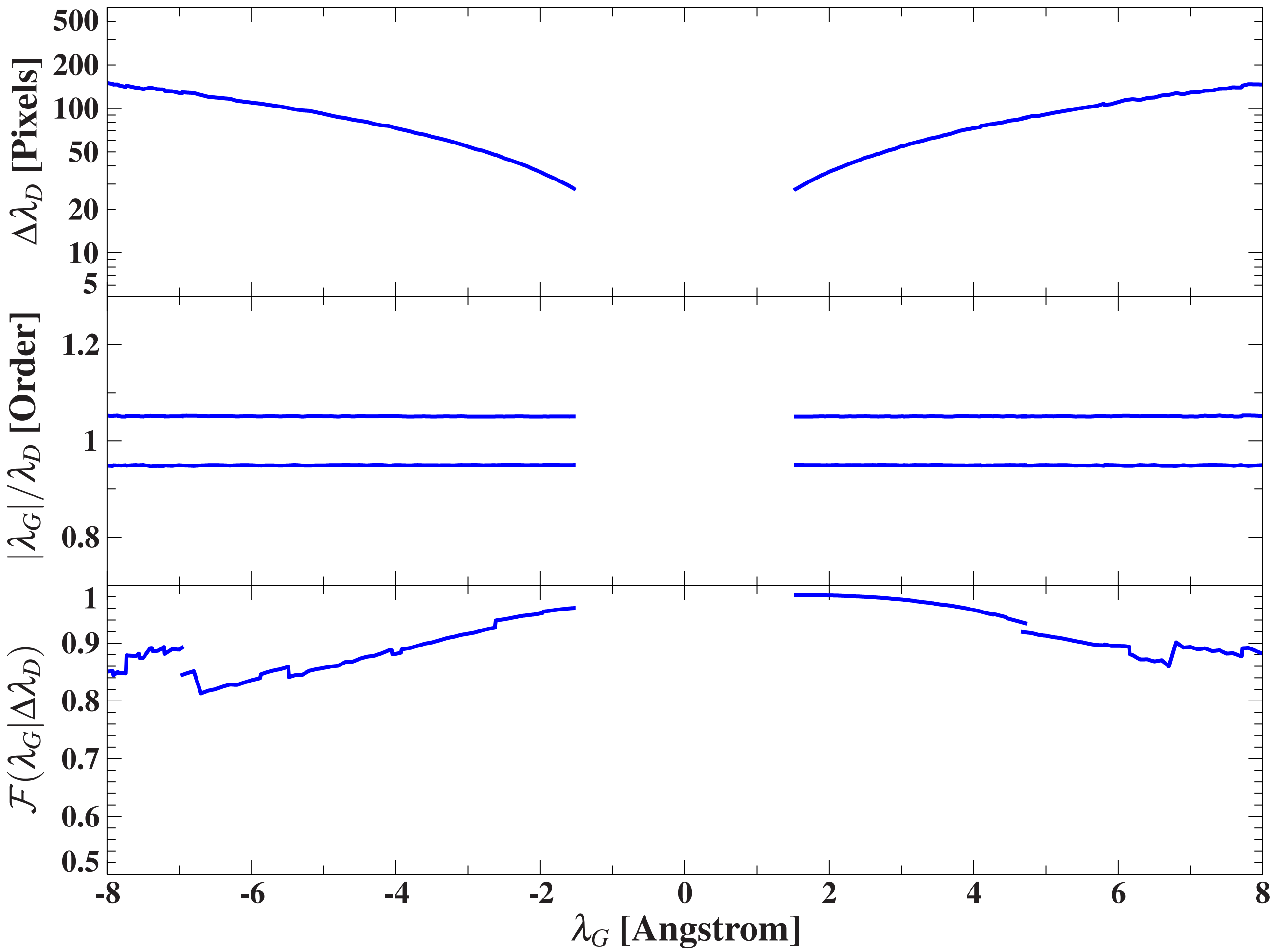
HETGS Quiescent Background

$\Delta\lambda_D = 0.1$ Angstroms



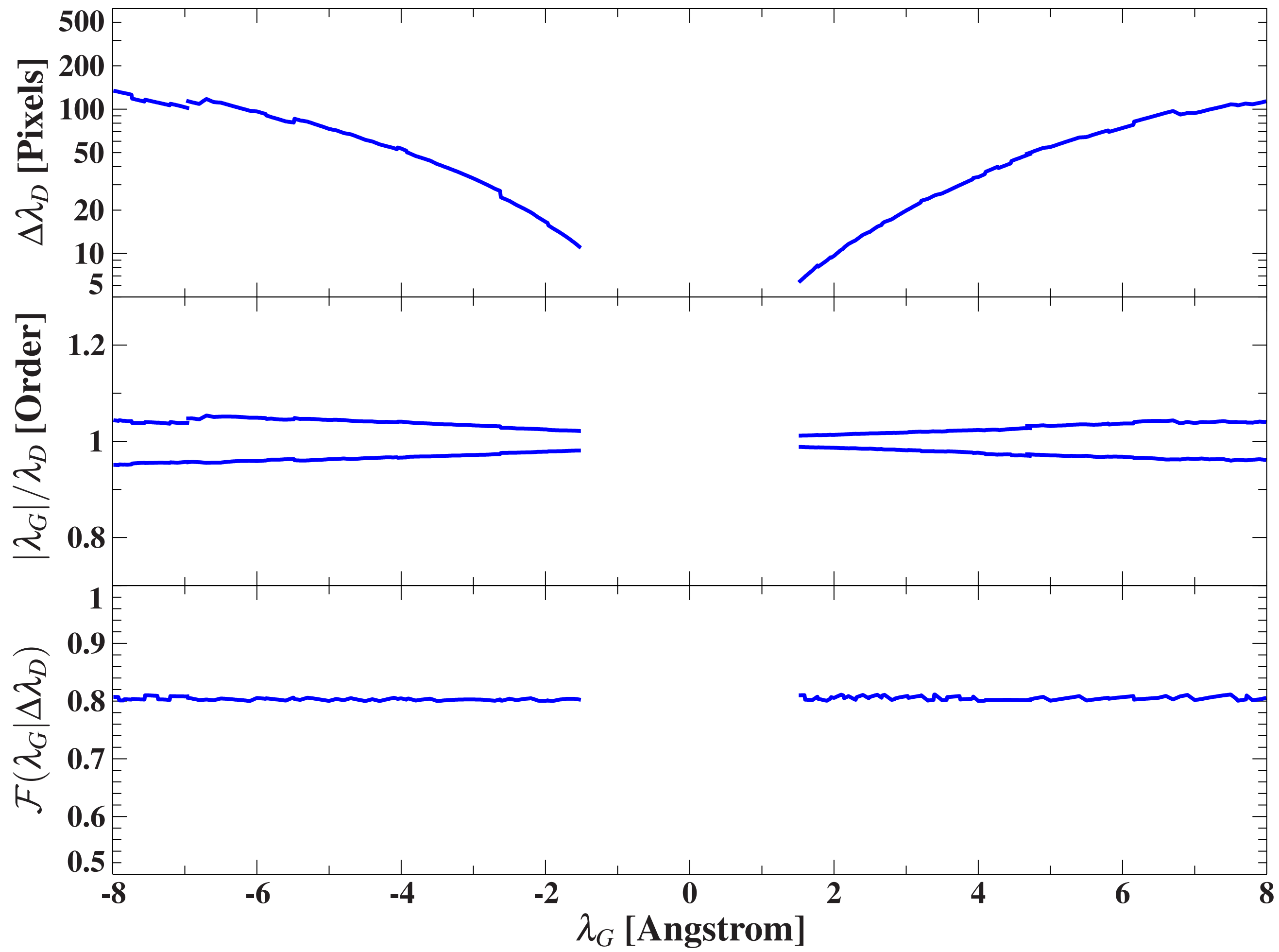
HETGS Quiescent Background

Constant Order: 0.95 - 1.05



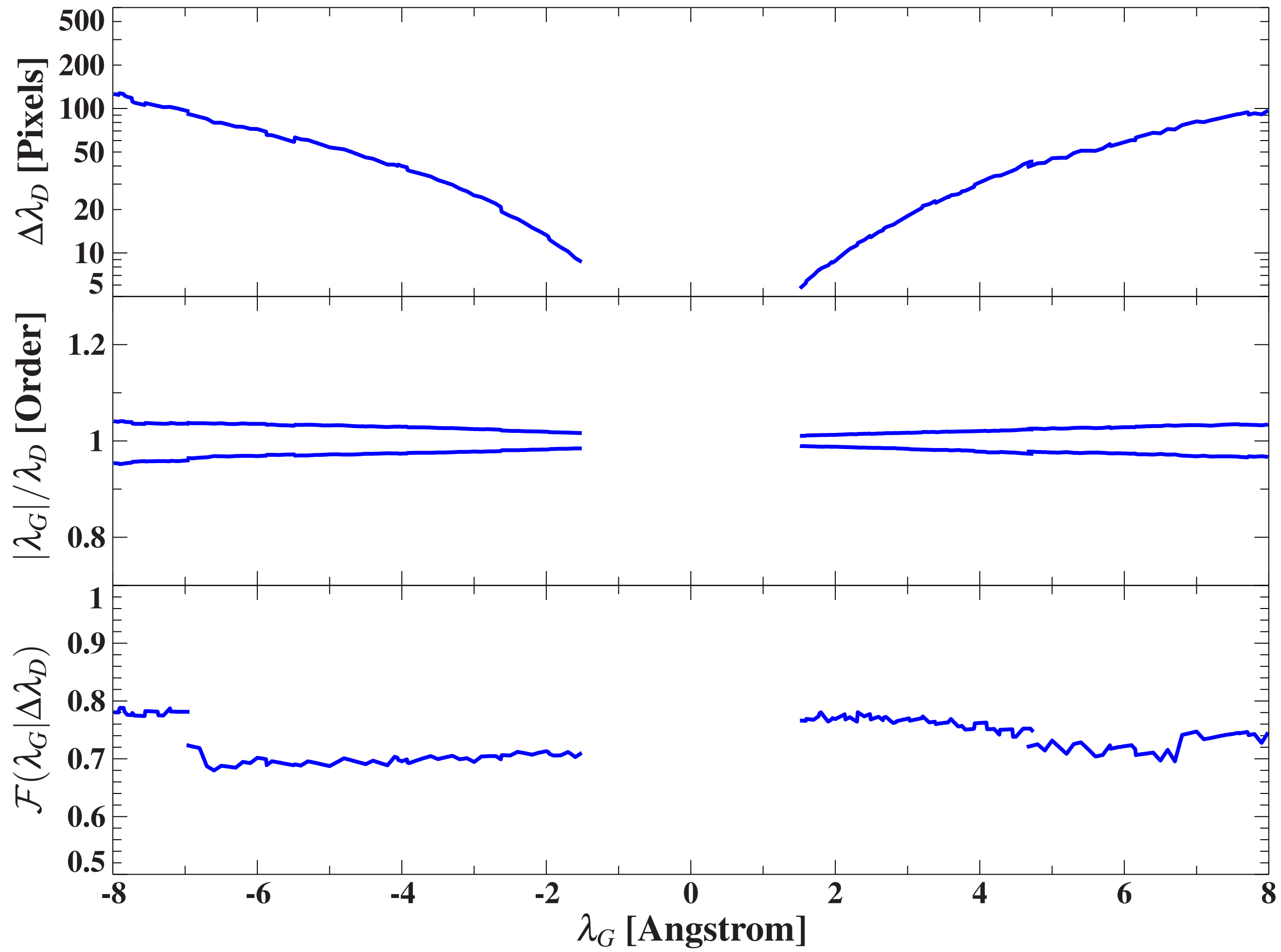
HETGS Quiescent Background

Constant $\mathcal{F}(\lambda|\lambda_G, \Delta_D) = 0.8$



HETGS Quiescent Background

$\Delta\lambda_D$ = FWHM



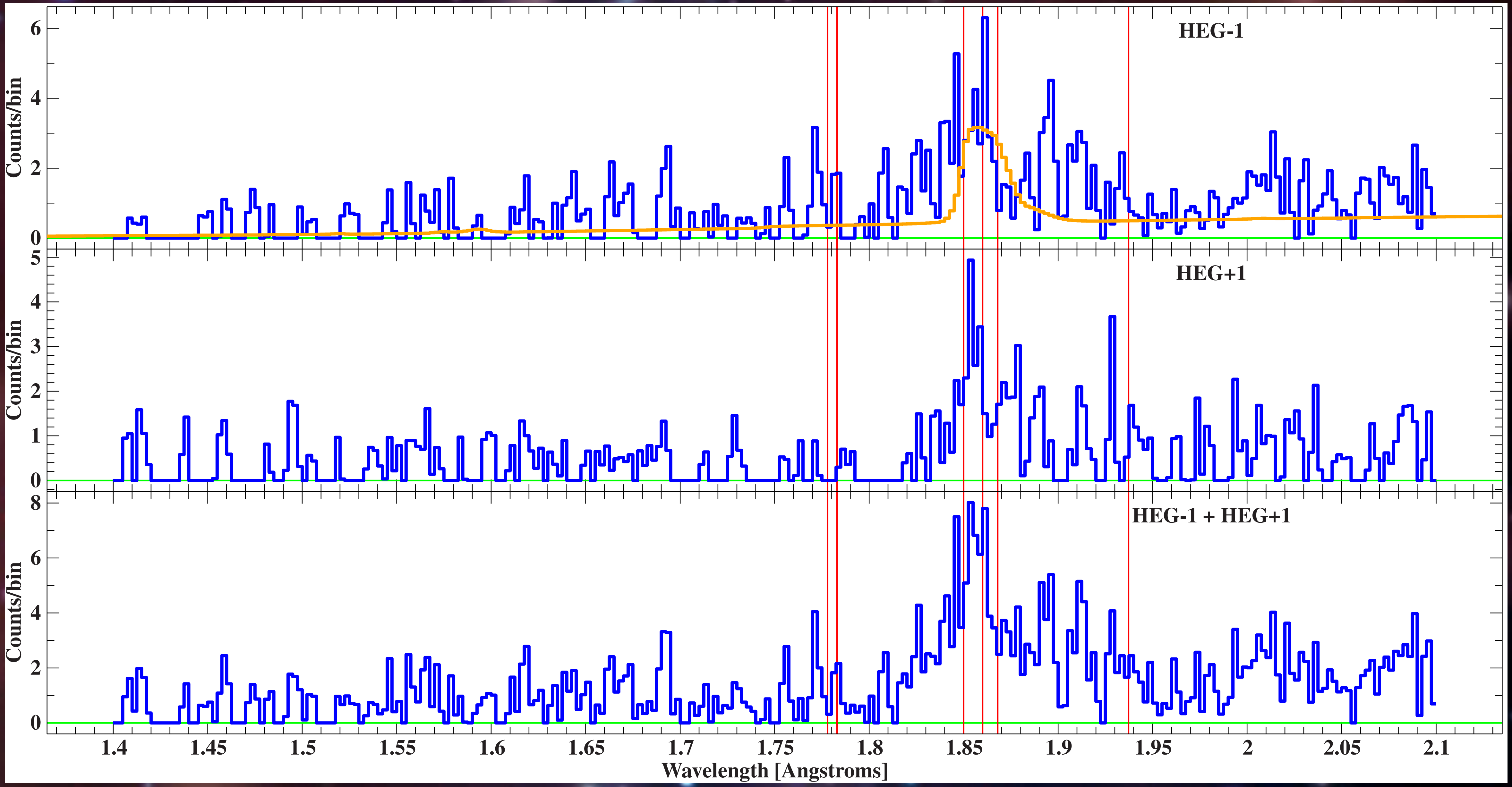
HETGS Quiescent Background

Summary

- The HETG quiescent spectrum is severely impacted by dispersed background events.
- The size of the spatial background region depends upon the order-sorting window used to filter the events.
- Several order sorting filters were proposed but none are ideal.

Chandra X-ray Observatory
chandra.harvard.edu

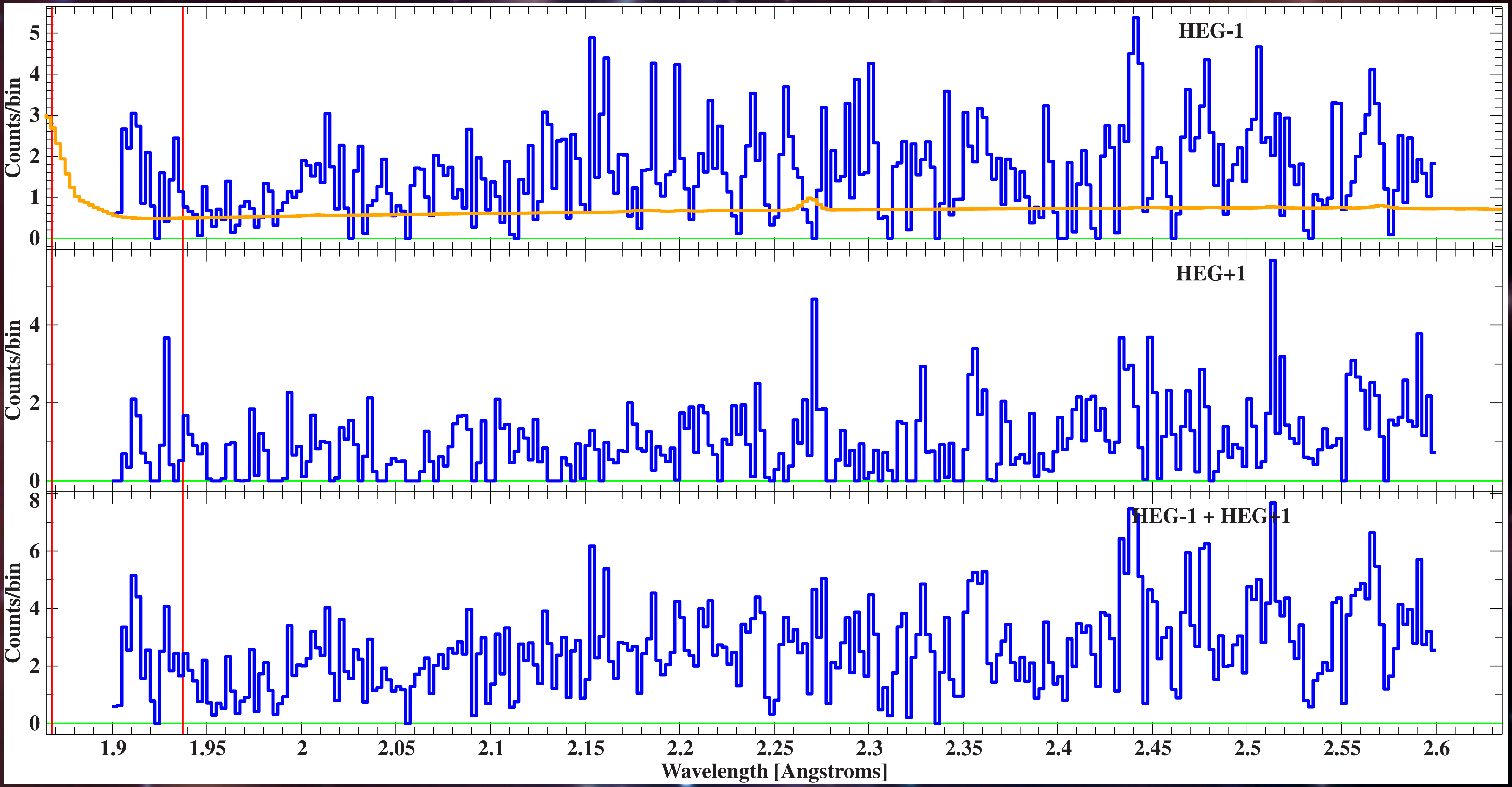
Fe XXV 1.8505 Angstroms



Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Chandra X-ray Observatory
chandra.harvard.edu

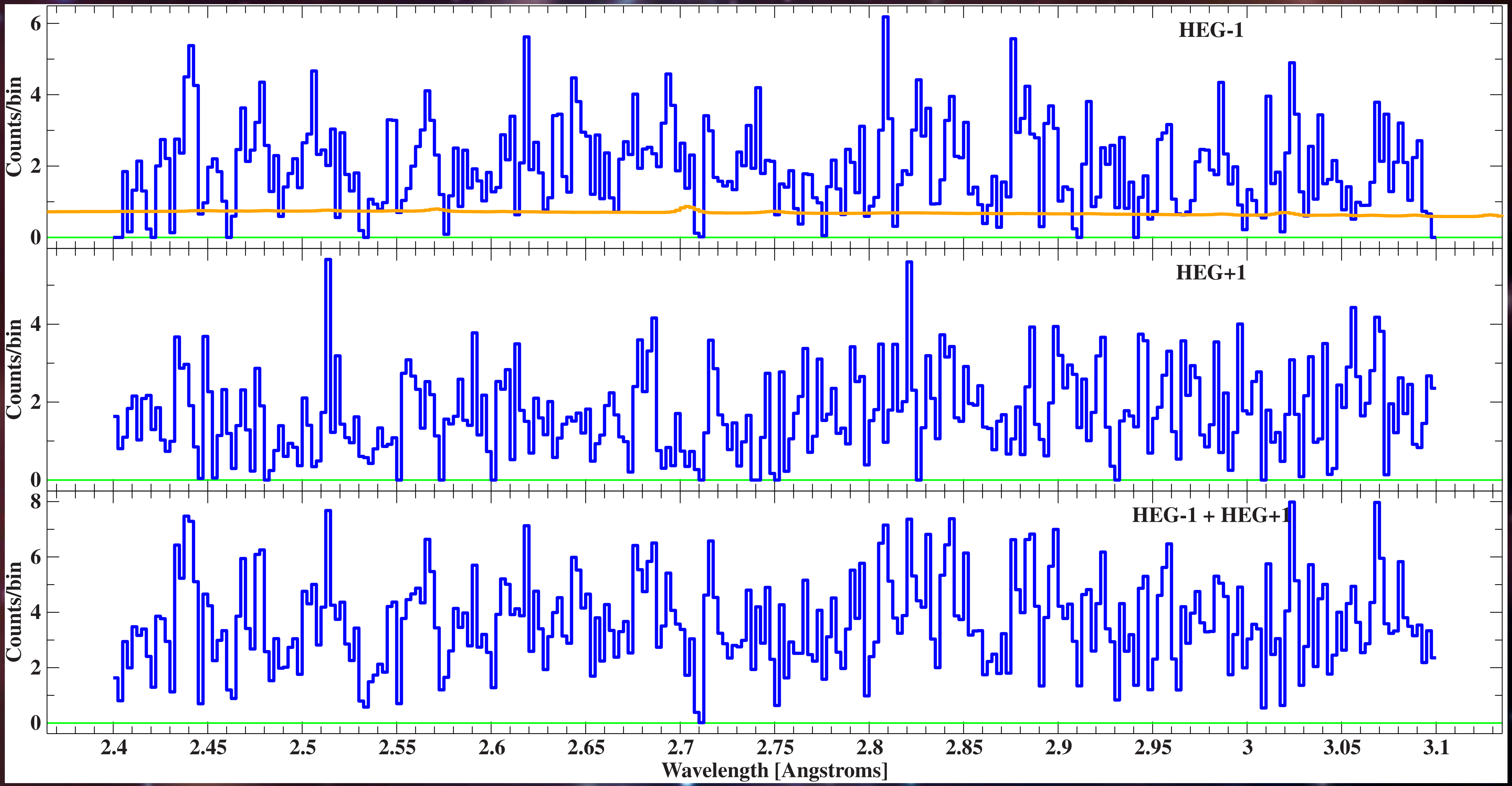
No Detectable lines



Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Chandra X-ray Observatory
chandra.harvard.edu

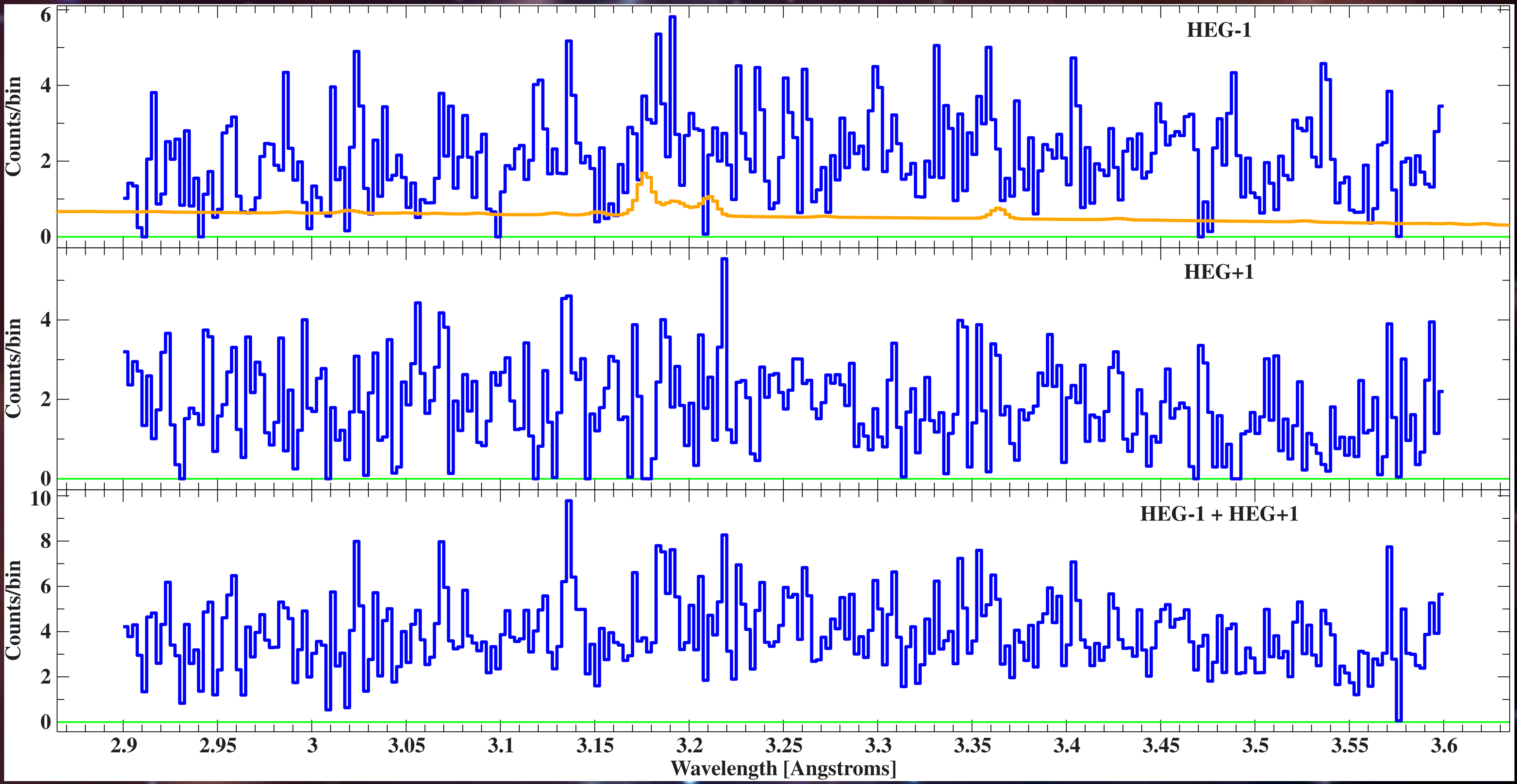
No Detectable lines



Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

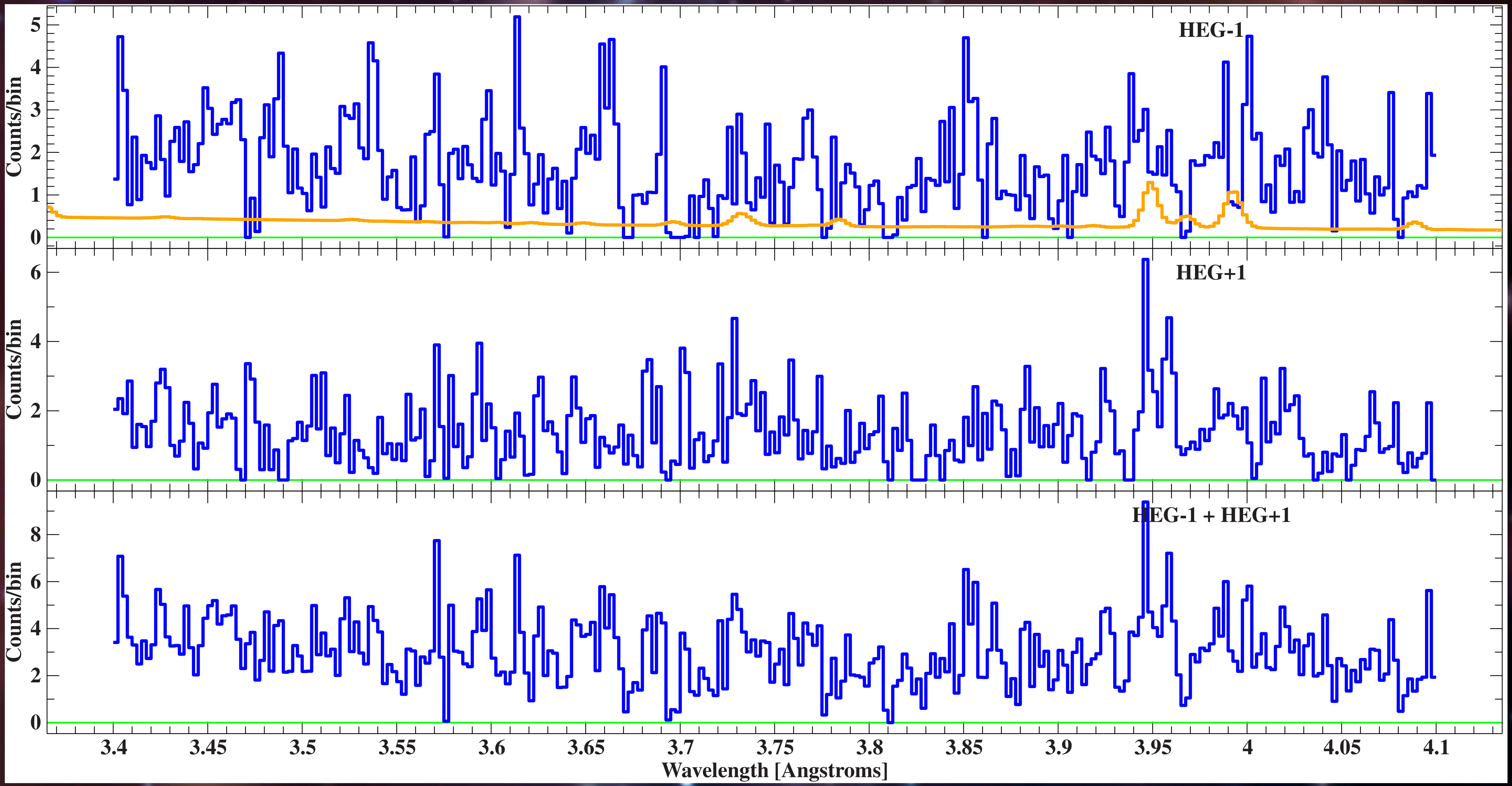
Chandra X-ray Observatory
chandra.harvard.edu

Ca XIX 3.177 & 3.211 Angstroms



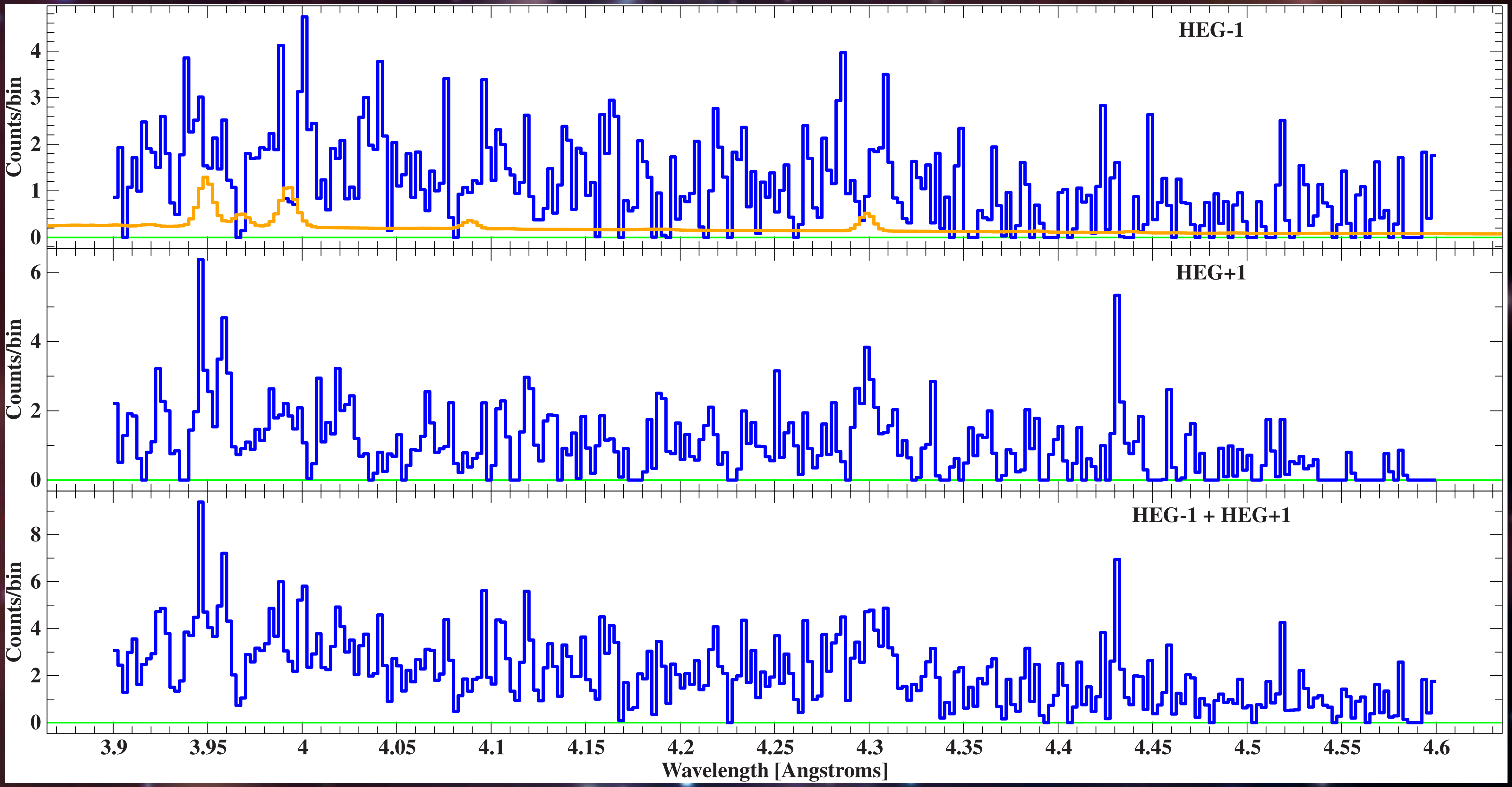
Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Ar XVII 3.95 & Ar XVII/S XVI 3.995 Angstroms



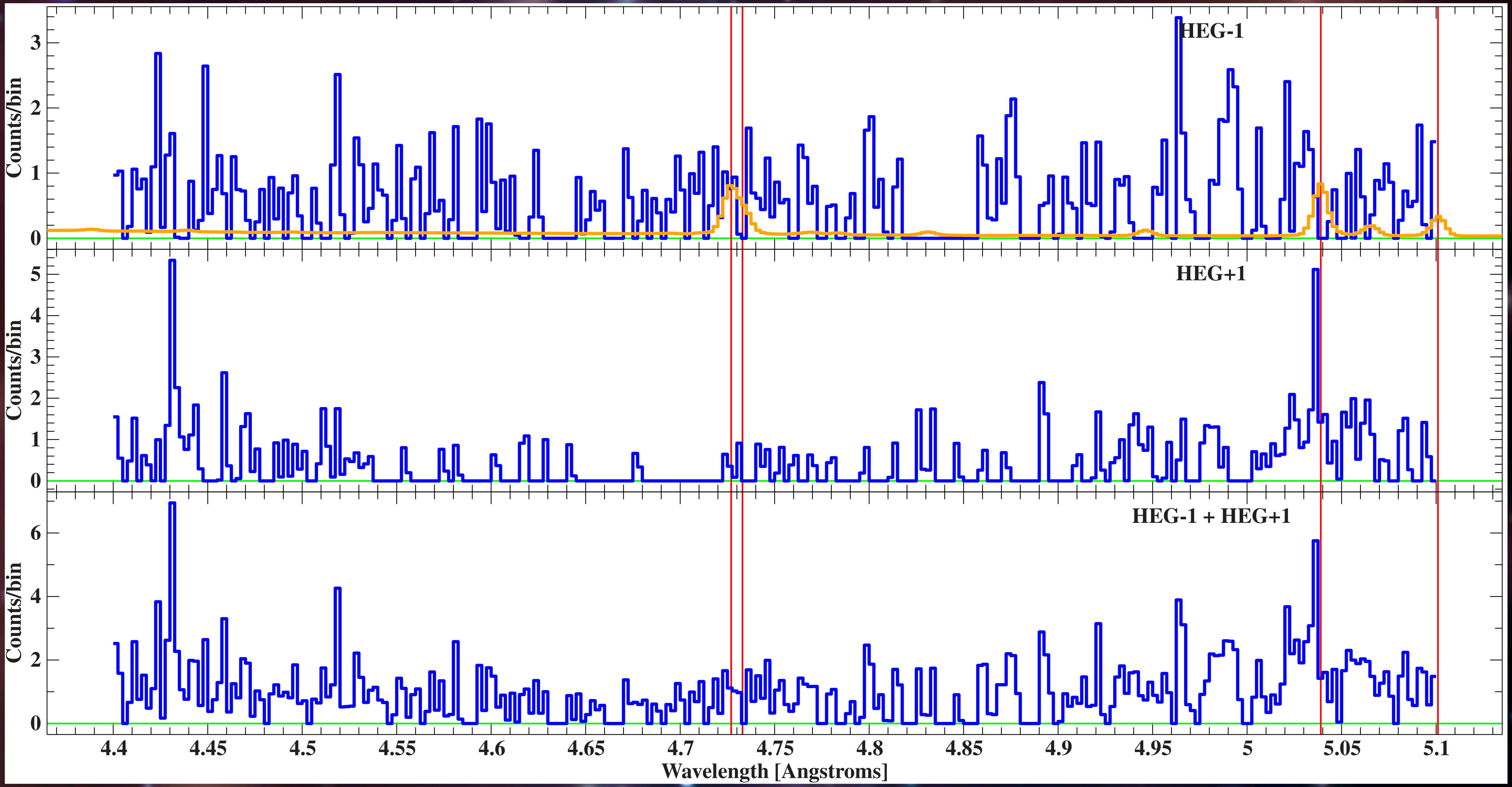
Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Ar XVII 3.95 & Ar XVII/S XVI 3.995 Angstroms



Chandra X-ray Observatory
chandra.harvard.edu

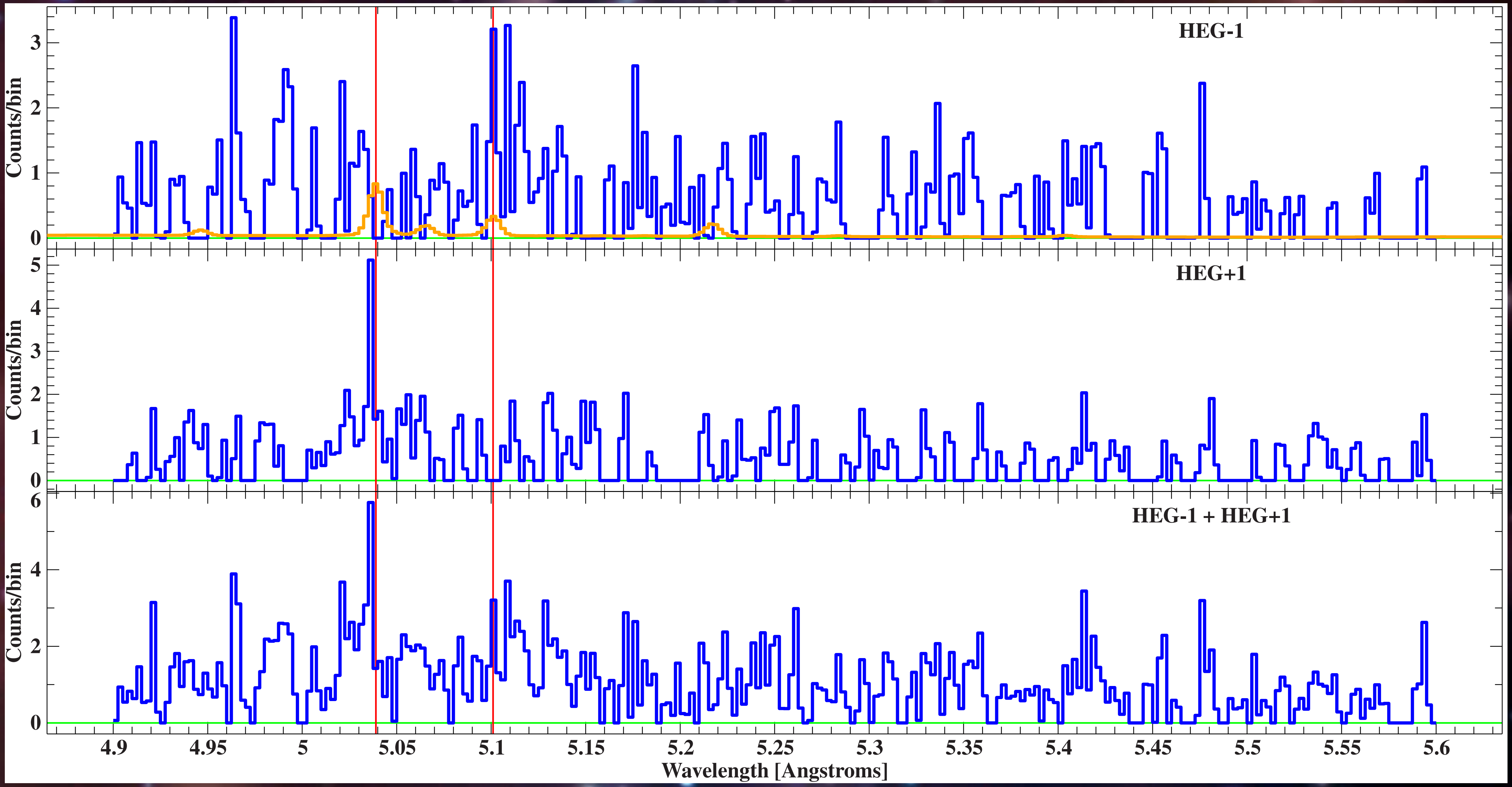
S XVI 4.727 & 4.733 S XV 5.039 Angstroms



Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Chandra X-ray Observatory
chandra.harvard.edu

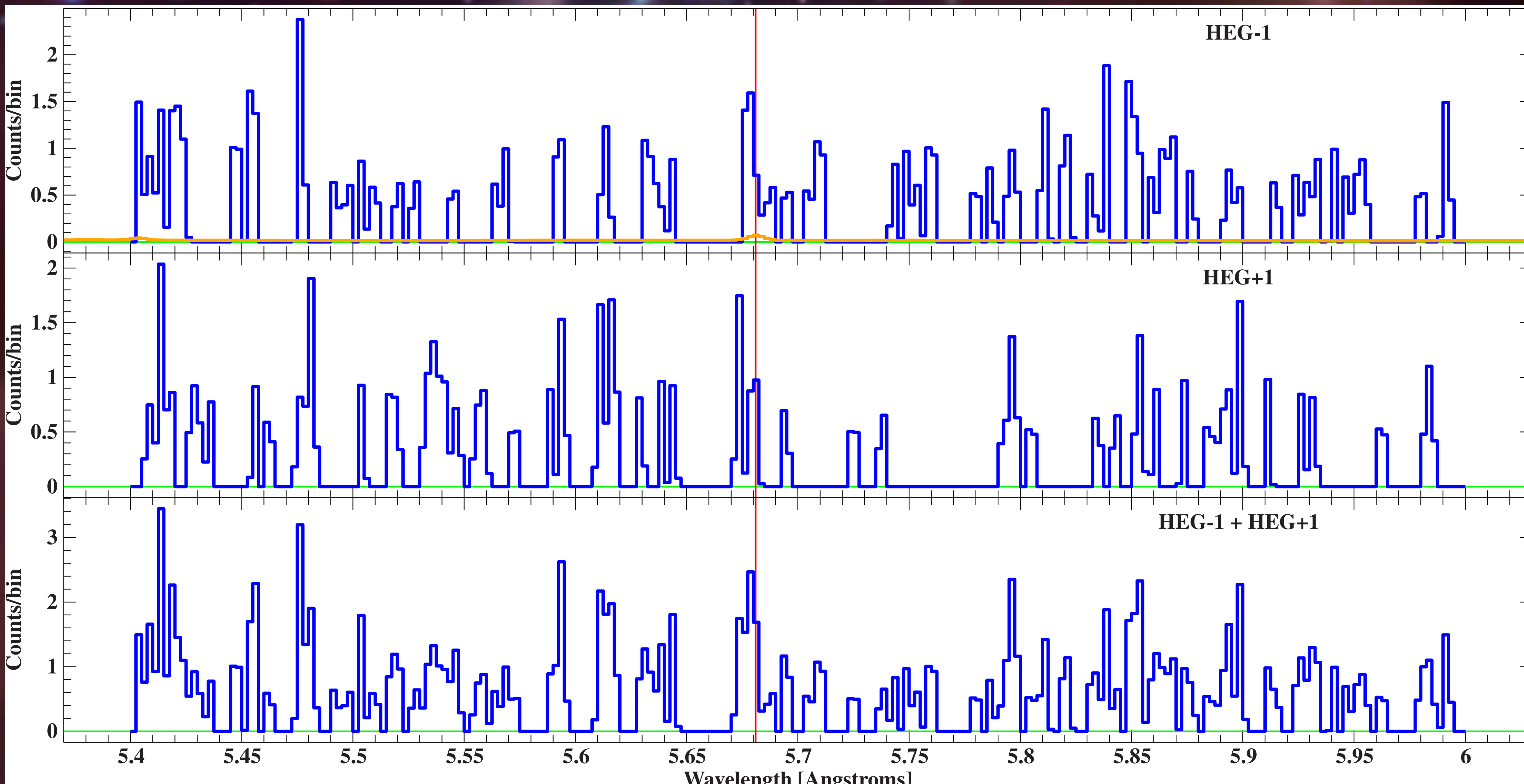
S XV 5.039 & 5.101 Angstroms



Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Chandra X-ray Observatory
chandra.harvard.edu

No Detectable Lines



Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.

Progress Summary

- Number of X-ray flares tripled and essentially pile-up free: flare distributions may hint at multiple mechanisms
- 0th-order quiescent spectrum (Fe Kalpha) disagrees with Sazonov et al. (2012) model for origin of extended emission vs RIAF
- Brightest flare properties consistent with two brightest XMM flares: photon index ~ 2 and N_H ~ 15 x 10^{22} cm^{-2}
- Modeling background to produce cleanest gratings spectrum of Sgr A* in quiescence
- Believe that we have good detection of He-like Fe line; working to reduce background to detect additional lines => possible relative abundance measurements
- Held team workshops in January and this Sunday to plan detailed analyses and publications of these large MW data sets

Special Thanks to the Chandra Mission Planning Teams!

<u>Science Operations</u>

Pat Slane
Jan Vrtilek
Dan Patnaude
Scott Randall
Dillon Foight*
Ashley Carlton
Jerica Green

<u>Uplink Support</u>

Herrman Marshall

<u>Flight Operations</u>

Brent Williams
John Scott
David Balke
Mike Leger
Brian Vegetabile
Scott Blanchard
Bad Bissell
James May

Sagittarius A*
NASA/CXC/MIT/
F.K.Baganoff et al.