# X-arithmetic: Decoding AGN Feedback

Hannah McCall[1*], Irina Zhuravleva[1], Eugene Churazov[2], William Forman[3], Christine Jones[3], Yuan Li[4], Congyao Zhang[1]
*hannahmccall@uchicago.edu

(1) Dept. of Astronomy and Astrophysics, University of Chicago, IL, USA (2) Max-Planck-Institut für Astrophysik, Garching, Germany (3) Center for Astrophysics, Harvard & Smithsonian, MA, USA (4) Dept. of Physics, University of North Texas, TX, USA

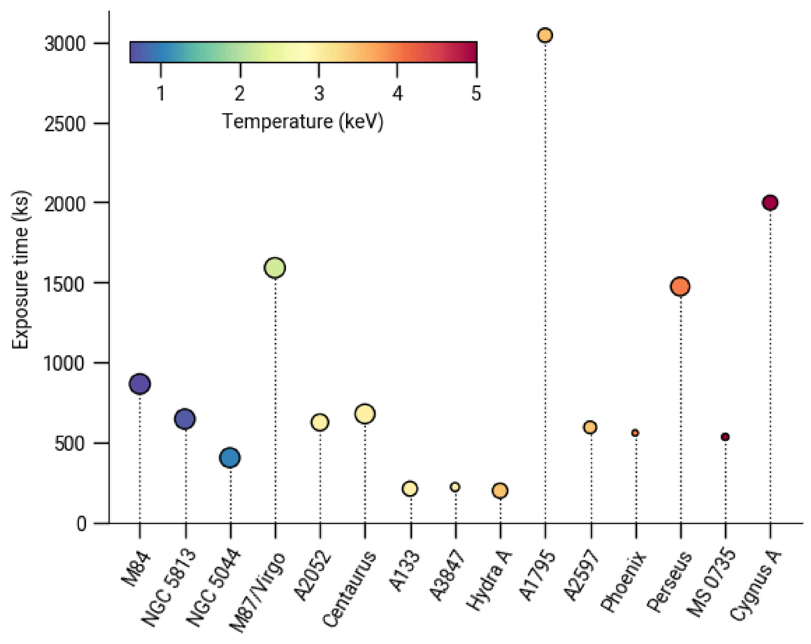
QR code

## Abstract

Feedback from Active Galactic Nuclei (AGN) is a key process in the evolution of massive systems in the Universe. New observational information on feedback is crucial for better implementation of numerical models. In this work we apply a new image-manipulation technique, X-arithmetic, on a sample of 15 galaxy clusters and groups deeply observed with Chandra. This technique decomposes perturbations in feedback-dominated regions into images excluding either (1) weak shocks, (2) cooling and slow gas motions, or (3) bubbles inflated by jets. We verify previously identified features and reveal the nature of new ones, further unraveling the complexity of feedback.

## Sample

**Figure 1.** The sample consists of X-ray bright galaxies, groups, and clusters that have been deeply observed with Chandra (> 200 ks). Displayed are Chandra archive exposure times (ACIS-I/S), characteristic temperatures (color), and redshift (size, largest 0.004 to smallest 0.597).




## Method

The X-arithmetic method categorizes gas perturbations produced by:

(i) weak shocks and sound waves (i.e., processes that do not change gas entropy, resulting in perturbations that appear "adiabatic")

(ii) gently inflated bubbles of relativistic plasma or X-ray cavities (can be interpreted as a variation of the thermal gas density at constant temperature, i.e. the perturbations are "isothermal")

(iii) subsonic gas motions and gas cooling (i.e., pressure does not change, the perturbations appear "isobaric").

By measuring a proportionality coefficient between density and temperature perturbations (essentially, an effective equation of state), the type of perturbation can be determined. Gas density and temperature have unique signatures in soft and hard energy bands of X-ray images. Therefore, the three types of perturbations imprint differently on the X-ray images in two bands. The ratio of these two bands can be predicted for each perturbation type.

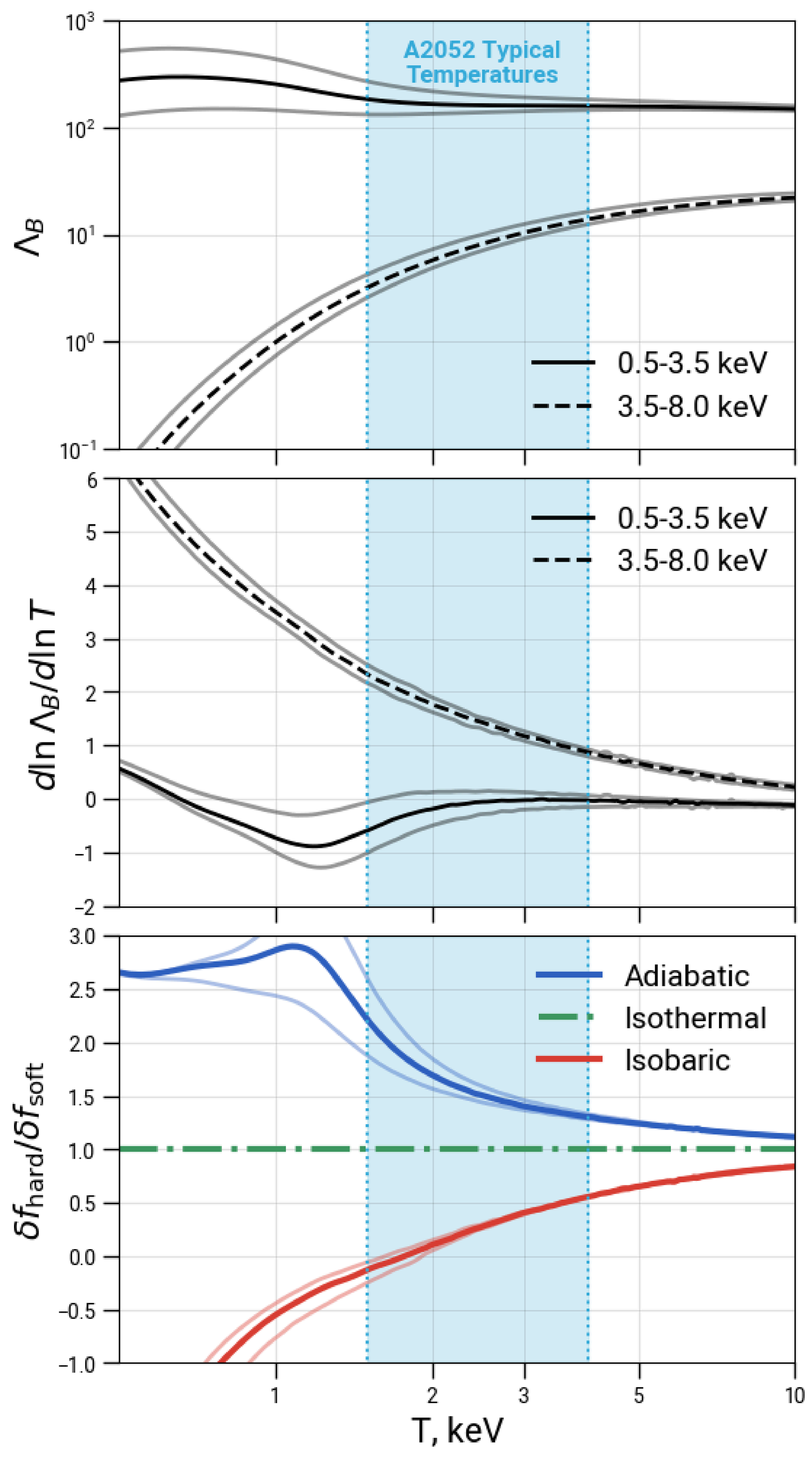


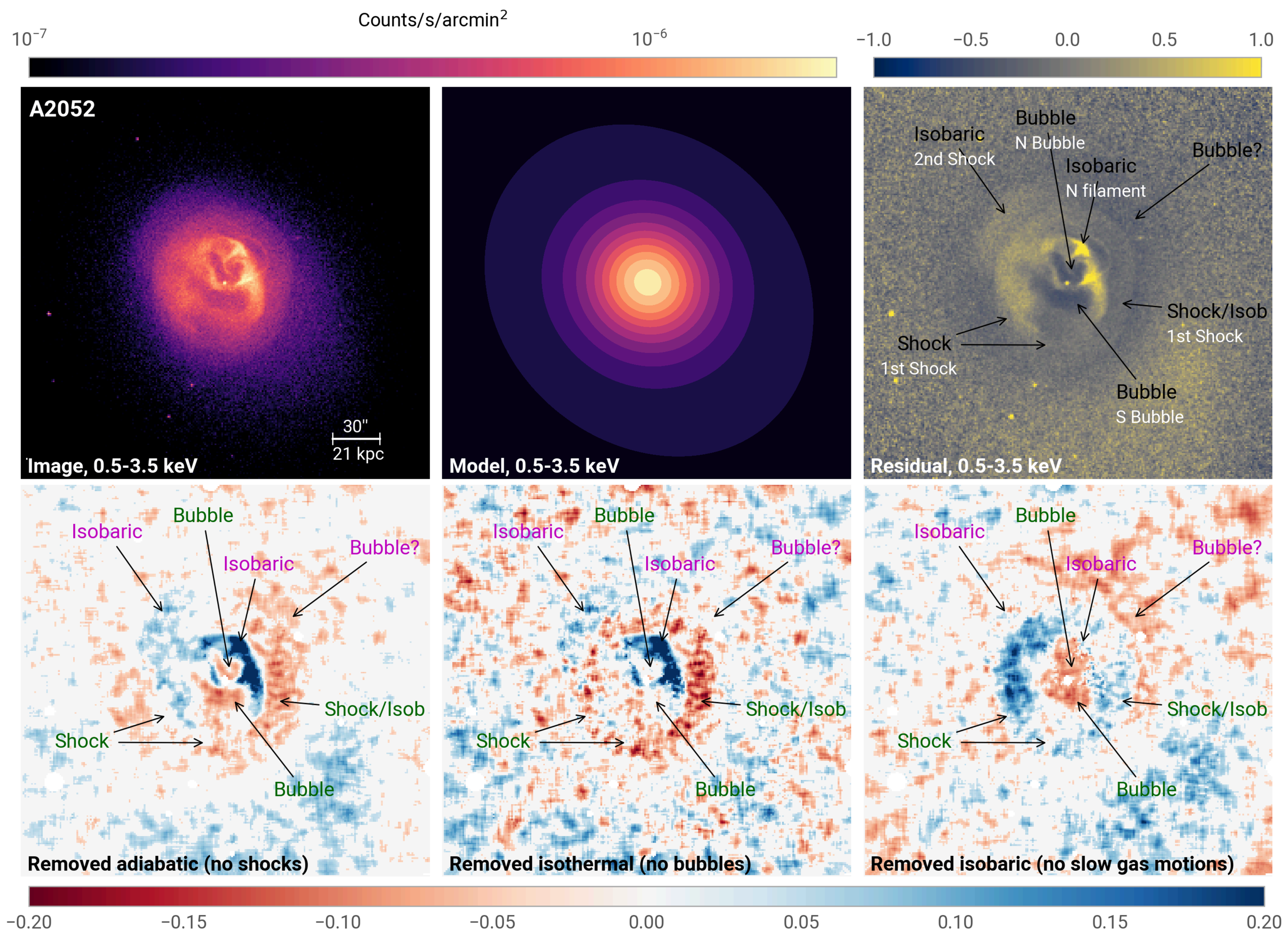

**Figure 2.** *Top:* X-ray emissivity as a function of temperature for the soft (solid line) and hard (dashed line) bands of A2052 calculated using XSPEC and APEC.

*Middle:* $\frac{d\ln\Lambda_B}{d\ln T}$ as a function of temperature for A2052.

*Bottom:* Flux ratios in the hard to soft band for different types of perturbations vs. gas temperature in A2052. In this cluster, pure adiabatic (isobaric) perturbations are stronger in the hard (soft) band. The lighter lines (gray in top two panels, blue and red in third panel) show how the ratios vary for a reasonable range (0.2 to 1.0 solar) of abundances.

## Perturbation Maps

**Figure 4.** Application of X-arithmetic to A2052. *Upper left:* Soft band Chandra image. *Upper middle:* Global model of X-ray surface brightness distribution in the soft band. *Upper right:* Soft band residual image (the image divided by the model). Black labels point to features we identified via the X-arithmetic method, while white text shows previous identification of these features by Blanton et al. 2011. Residual images were also created for the hard band. *Bottom:* From left to right, the residual images are combined to exclude, in turn, perturbations caused by (1) weak shocks and sound waves (adiabatic fluctuations), (2) bubbles (isothermal), and (3) subsonic motions and/or gas cooling (isobaric). Green labels identify features confirmed with X-arithmetic and pink labels highlight features that were newly identified or further unraveled.




A central isobaric feature, originally called the northern filament, is evident in the first two images but absent (close to zero, i.e. white) in the third. Bubbles, as expected, are absent in the central image, but can be identified south of the AGN on the right and left images. A shock front and shock-heated gas, originally identified as the first shock, which appear as a ring around the central regions, are absent in the first image. The SW part of the "shock" structure is a mix of isobaric and shock perturbations. The NE feature earlier tentatively identified as the second shock has an isobaric nature and is likely associated with sloshing of the gas.

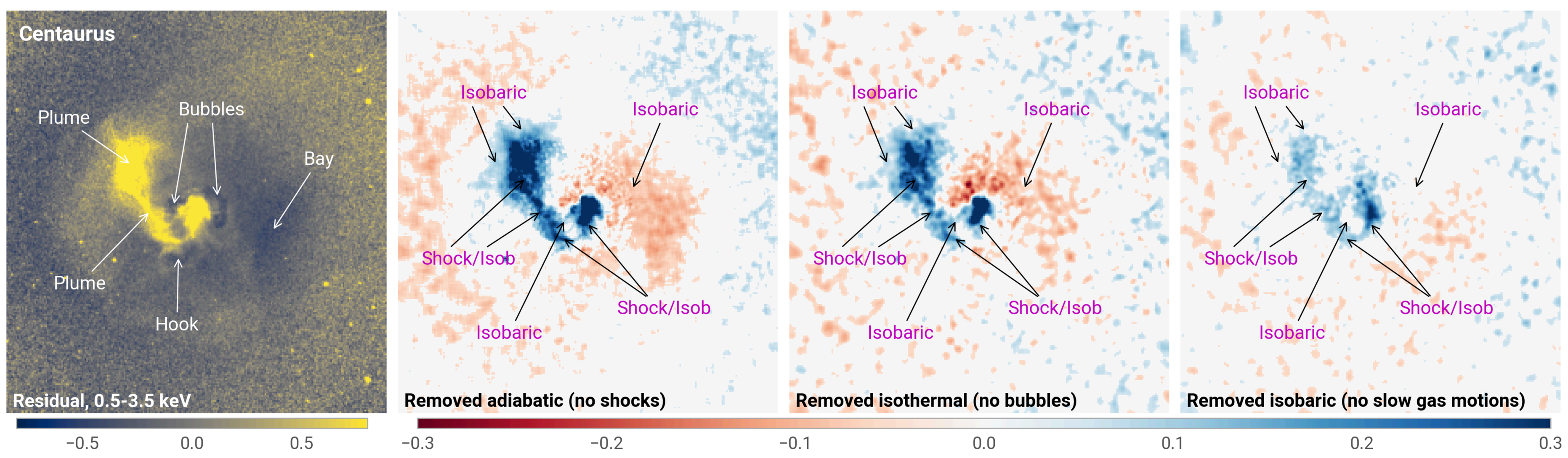
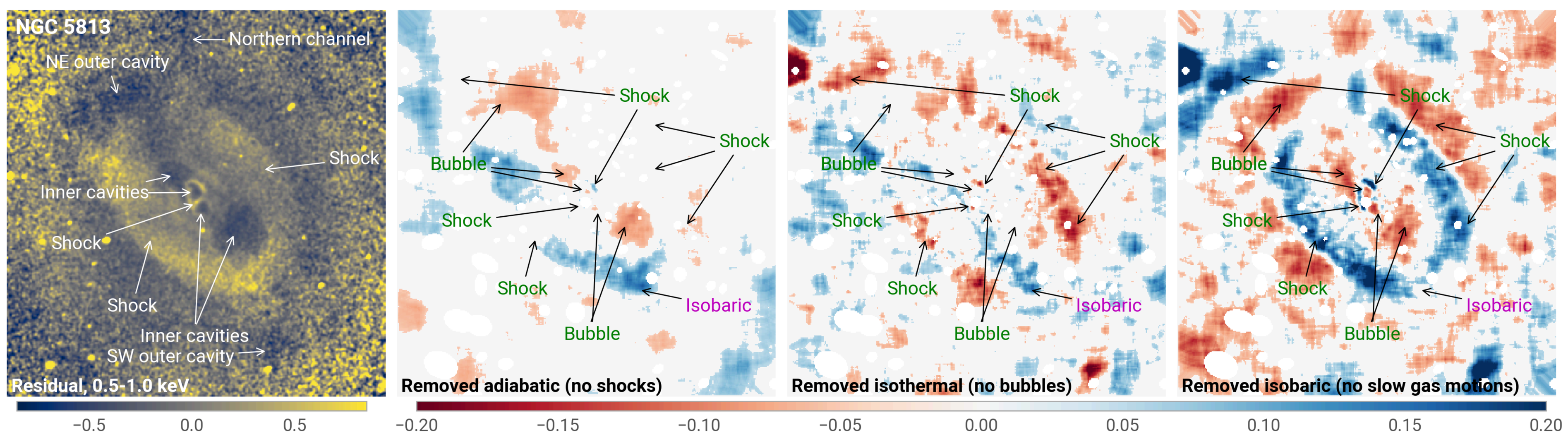



**Figure 5.** Application of X-arithmetic to the Centaurus cluster. The soft band residual image contains labels from Sanders et al. 2016. The perturbation map order is the same as Fig. 4.

**Figure 6.** Application of X-arithmetic to galaxy group NGC 5813. The soft band residual image contains labels from Randall et al. 2015. The perturbation map order is the same as Fig. 4.



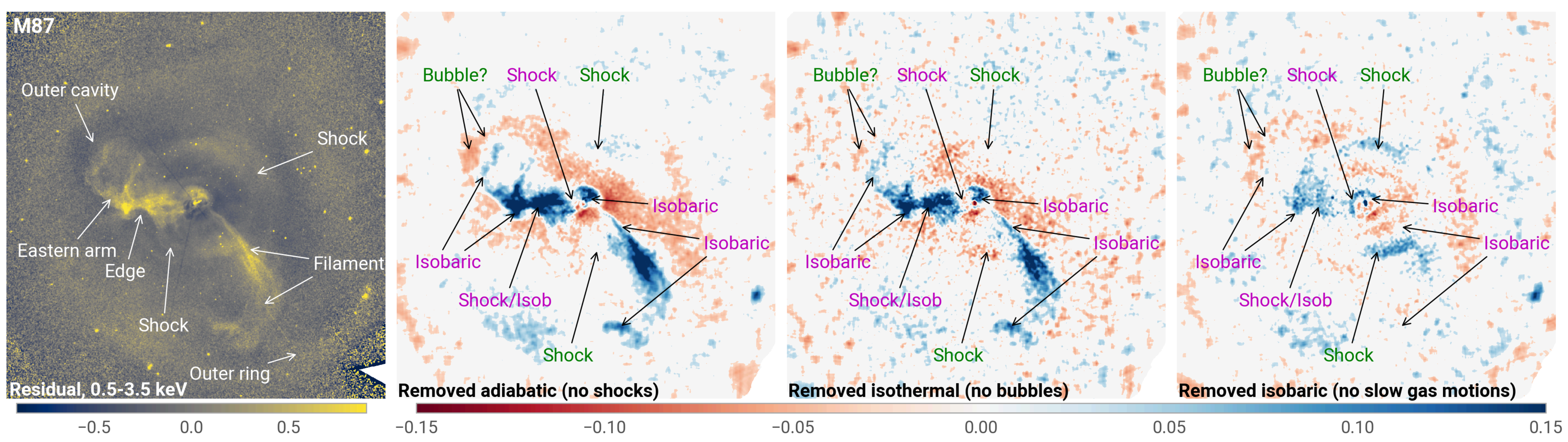




**Figure 7.** Application of X-arithmetic to M87. The soft band residual image contains labels from Forman et al. 2007. The perturbation map order is the same as Fig. 4.

## Conclusion

- X-arithmetic works best for shocks and isobaric structures
- We identify several new, interesting structures, which we will follow up with spectroscopic analysis
- We will next apply X-arithmetic to simulations, where it can be used to test different feedback prescriptions

## References

Blanton, E. L., Randall, S. W., Clarke, T. E., et al. 2011, ApJ, 737, 99
Churazov, E., Arevalo, P., Forman, W., et al. 2016, MNRAS, 463, 1057
Forman, W., Jones, C., Churazov, E., et al. 2007, ApJ, 665, 1057
Sanders, J. S., Fabian, A. C., Taylor, G. B., et al. 2016, MNRAS, 457, 82
Randall, S. W., Forman, W. R., Giacintucci, S., et al. 2010b, ApJ, 726, 86
Randall, S. W., Nulsen, P. E. J., Jones, C., et al. 2015, ApJ, 805, 112