# Spatially Resolved Measurements of the Highest Redshift Dynamically Relaxed Cool Core Galaxy Cluster

Anthony M. Flores[(a,b)*], Adam B. Mantz[(b)], Steven W. Allen[(a,b,c)], Glenn R. Morris[(a)], Haley R. Stueber[(a,b)], Abigail Yu Pan[(a,b)], and Taweewat Somboonpanyakul[(d)]

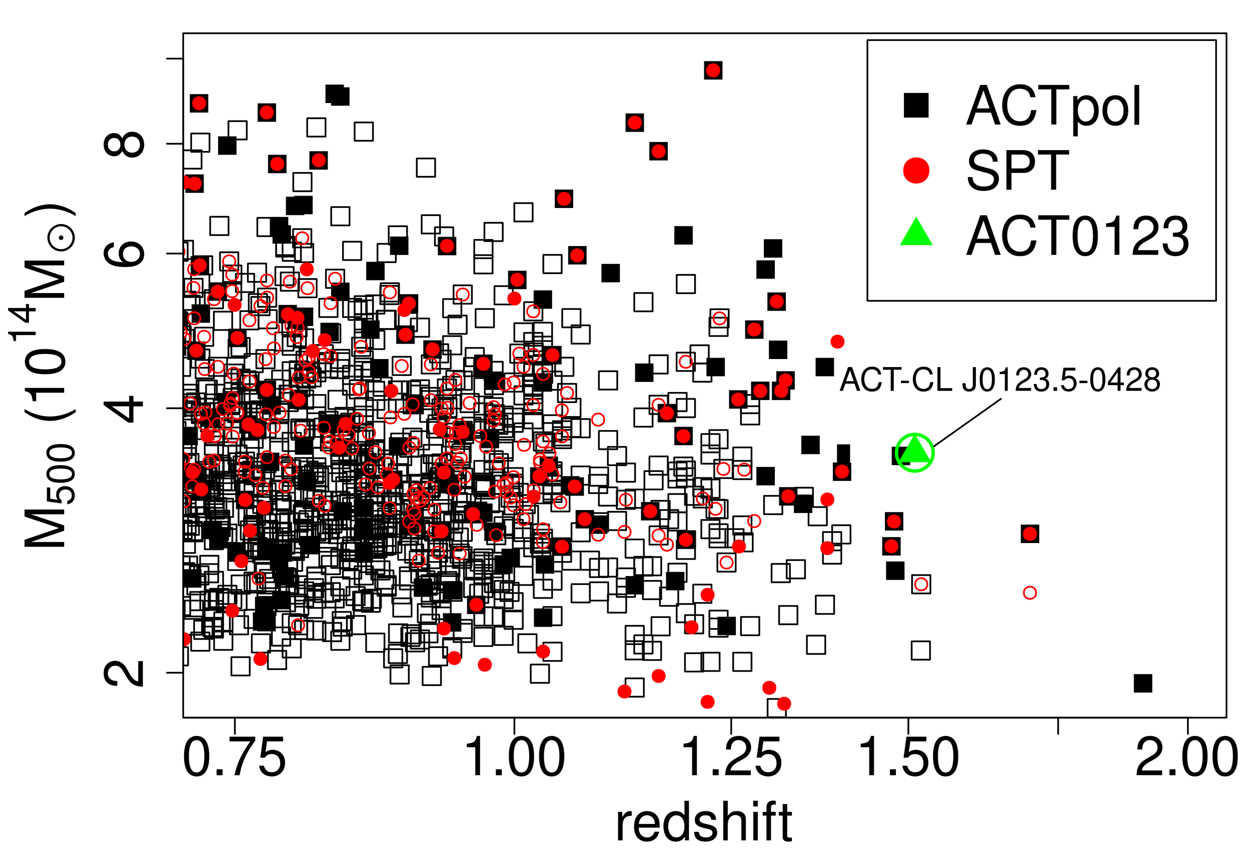
[(a)]Dept. of Physics, Stanford University; [(b)]Kavli Institute for Particle Astrophysics and Cosmology, Stanford University; [(c)]SLAC National Accelerator Laboratory; [(d)]Dept. of Physics, Chulalongkorn University;

## Abstract

Dynamically relaxed galaxy clusters are the systems that most closely align with the astrophysical assumptions of spherical symmetry and hydrostatic equilibrium. Here, we present a joint (Chandra + XMM-Newton) characterization of ACT-CL J0123.5-0428, the newly identified highest redshift relaxed cool core system. At $z = 1.5$, the spatial resolution of Chandra is critical to resolve gas on the 5-10kpc scales necessary to classify its morphology and probe the nature of the cluster core, whereas the XMM-Newton data allow us to better understand the properties at larger radii ($r \sim r_{500}$).

## Introduction

Dynamically relaxed galaxy clusters sit at the pinnacle of cosmic structure formation. Left undisturbed by major/minor mergers, these massive objects will evolve to most closely reflect both spherical symmetry and hydrostatic equilibrium. Thus, they are incredibly useful for studies of cosmic expansion and structure growth [1]. Moreover, the flow of efficiently cooling gas into cores of these clusters make them essential laboratories for the study of feedback processes that shape the evolution of both the Intracluster Medium (ICM) and cluster member galaxies. Identifying dynamically relaxed galaxy clusters at high redshift is crucial for these types of cosmological and evolutionary studies; however, currently only a handful have been discovered at $z > 1$. The dearth of high-z relaxed clusters is compounded by the fact that, at these redshifts, a full spatial characterization of the ICM is impossible with either Chandra or XMM-Newton alone. The most effective way to explore the detailed physics of both the sharply peaked cores and faint outskirts of relaxed systems at high redshift is using a **joint** approach that leverages the high spatial resolution of Chandra to inform the modeling of cluster parameters at all radii (and additionally identify and model contaminating point sources).

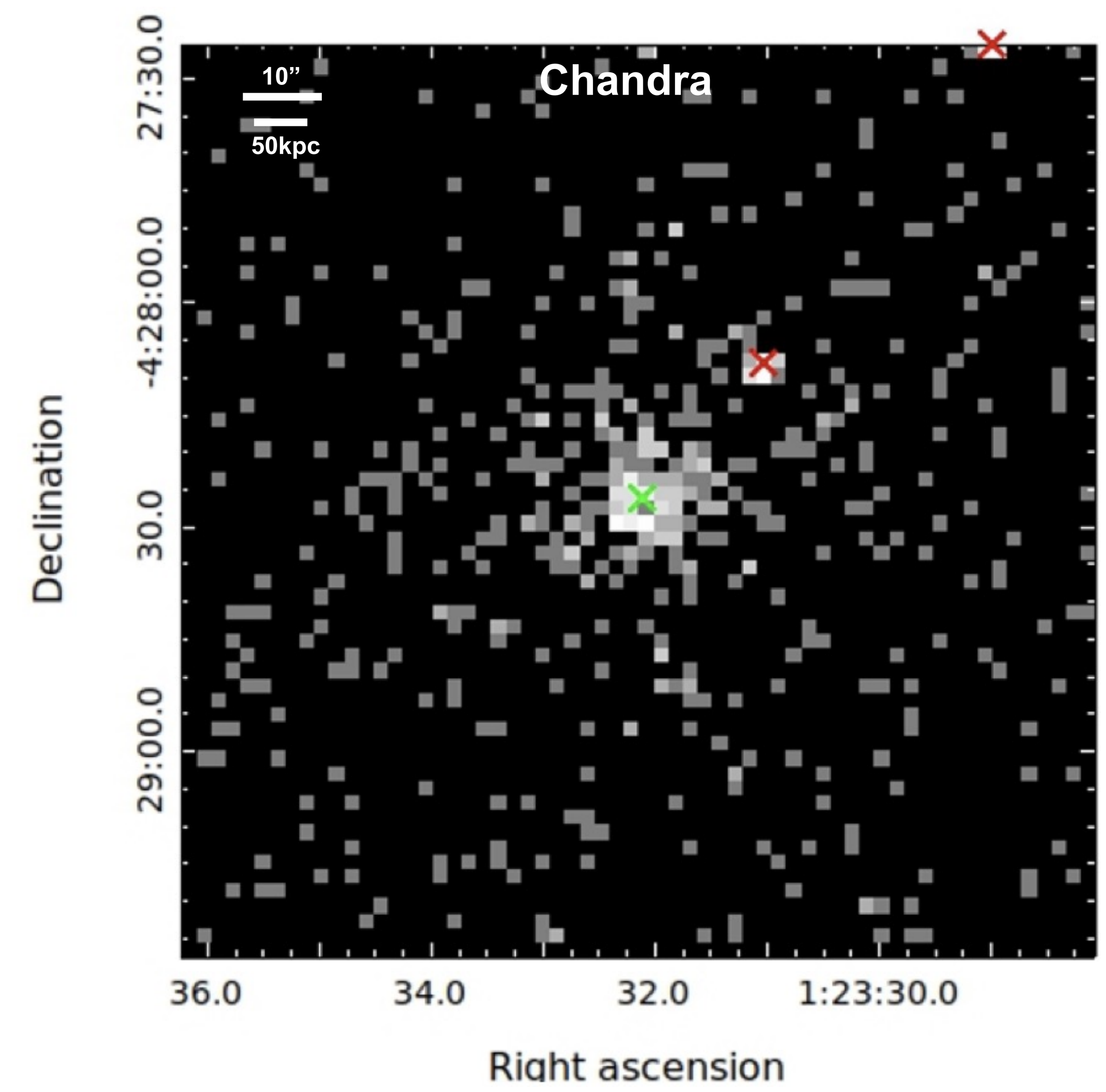



SZ cluster detections for the Atacama Cosmology Telescope (ACT [2]; filled squares have X-ray coverage) and the South Pole Telescope (SPT [3]; filled circles have X-ray coverage), limited to $z > 0.7$ and S/N $> 5$. ACT-CL J0123.5-0428 is one of the most extreme systems known at high-z, lying on the diagonal representing the most massive and highest redshift clusters contained within the SZ survey fields.

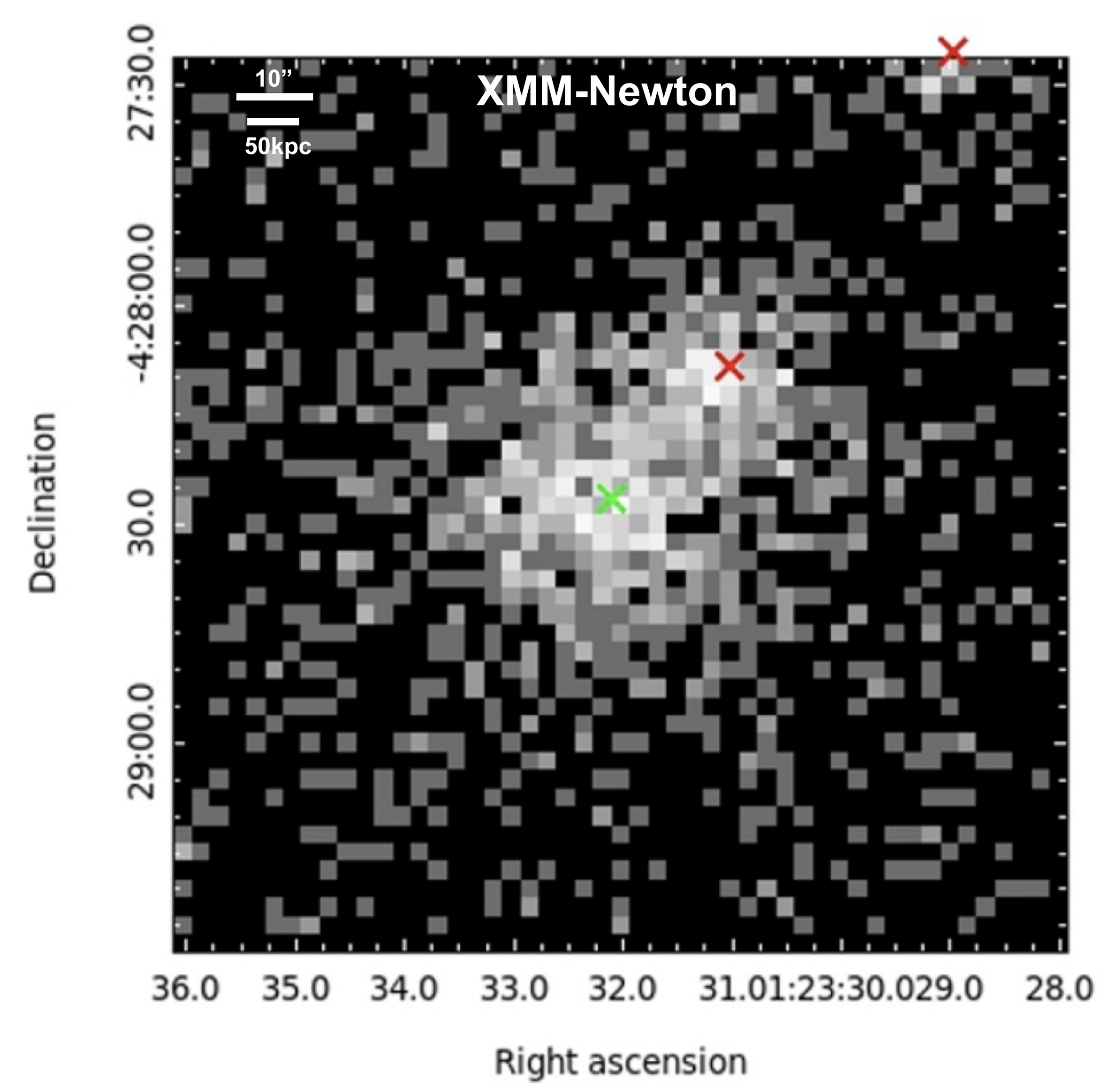
## A New, Highest-z Relaxed Cluster Candidate

ACT-CL J0123.5-0428 (ACT0123) was discovered by the Atacama Cosmology Telescope (ACT) via the thermal Sunyaev-Zel'dovich (SZ) effect [2]. ACT has surveyed >13,000 deg$^2$ of the Southern sky to detect thousands of massive galaxy clusters, and ACT0123 is one of the $\sim 10$ most extreme (i.e., highest mass at a given redshift) systems present in the ACTPol cluster catalog. X-ray measurements of the Fe K-$\alpha$ line complex (6.7keV rest frame) confirm a spectroscopic redshift of $z_{spec} = 1.50 \pm 0.03$. Based on existing VLASS and WISE survey data, there is no indication of AGN activity near the BCG. Applying the Symmetry, Peakiness, and Alignment (SPA; [4]) morphological metrics to the Chandra data, we further identify ACT0123 as the highest redshift dynamically relaxed galaxy cluster.

## Joint Analysis



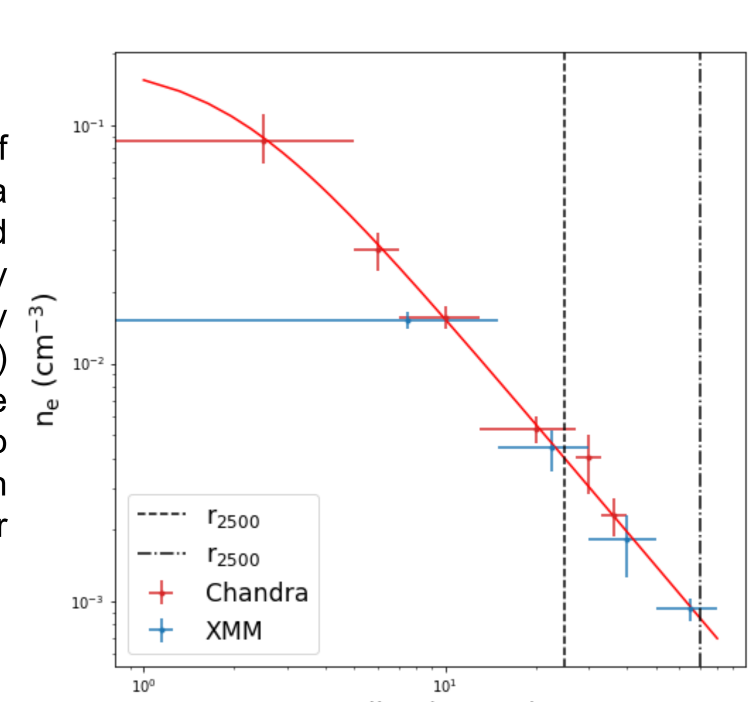

Soft band (0.6—2.0 keV) 51.2ks Chandra image. The cluster center is identified by a green cross. Point sources identified with the CIAO tool WAVDETECT are marked with a red cross and are masked in all imaging and spectral analyses.



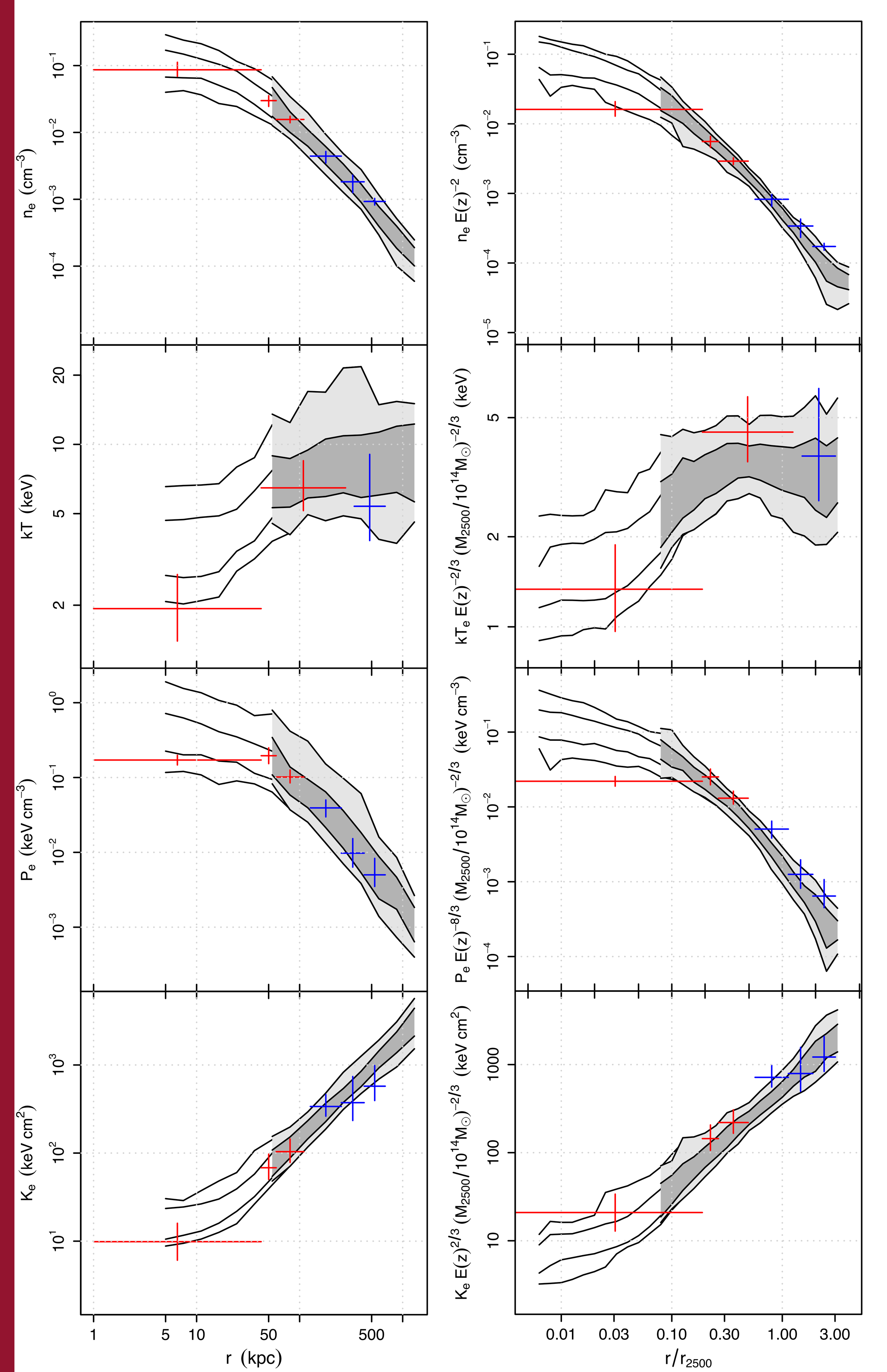

0.4-4.0 keV stacked XMM Newton image of 15ks (MOS1/2) and 11.6ks (pn). The cluster center (from the Chandra data) is marked in green. Point sources identified by Chandra are handled in imaging and spectral analyses with a combination of masking and modeling.

To obtain a full spatial characterization of the ICM of ACT0123, we jointly use the Chandra and XMM data, forward modeling cluster and point source characteristics where appropriate. Chandra resolves the properties of the cluster core; notably, we observe a sharp peak in density and decrease in temperature within the inner ~50kpc down to $1.8 \pm 0.6$keV. Additionally, fits to the Chandra surface brightness profile can be used to generate a geometric and instrumental (i.e. PSF) mixing model for spectral analysis in XMM-Newton, which extends constraints on density and thermodynamics out beyond $r_{500}$ (~600 kpc). Combined with models of instrumental- and observation-specific backgrounds, this provides a robust description of cluster properties out to large radius despite fewer than 1300 counts between both instruments.

Electron density profiles of ACT0123. While Chandra constraints (red, with fitted beta-model) peak significantly higher in the core, they only extend to ~$r_{2500}$. XMM (blue) cannot resolve structure within 10", but probes out to ~$r_{500}$ and agrees well with Chandra at large radii under our joint analysis procedure.




## Cluster Thermodynamics




Thermodynamic profiles of ACT0123 unscaled (left) and scaled (right) for evolution in redshift and radial overdensity, compared to the profiles of 40 other relaxed clusters at $z \lesssim 1.0$ when including and excluding emission from the cluster core (denoted by grey shading) [5]. Red points are from Chandra, while blue points are from XMM.

## Conclusions and Next Steps

Our joint Chandra+XMM-Newton study of ACT-CL J0123.5-0428 identifies it as the highest redshift dynamically relaxed galaxy cluster discovered to date. Our X-ray analysis provides a full spatial characterization out to $r_{500}$, identifying a cool core with low central cooling time within ~40kpc. Not shown here are measurements of cluster metallicity, which XMM constrains to be $Z/Z_\odot = 0.6 \pm 0.3$ (hinting at a strong metallicity gradient). Deeper X-ray data are required to produce both a spatially-resolved description of ICM metallicity and a description of the 3D (dark matter inclusive) mass profile. As one of the most extreme systems discovered at high redshift, ACT0123 serves as an important probe for astrophysical and cosmological studies as we prepare for next-generation cluster samples and instrumentation.

## Acknowledgements

We acknowledge support from the National Aeronautics and Space Administration under Grant No. 80NSSC23K1484, issued through the NASA Future Investigators in NASA Earth and Space Science and Technology (FINESST) Program; and in part from the U.S. Department of Energy under contract number DE-AC02-76SF00515.

## References

[1] Allen S. W., Evrard A. E., Mantz A. B., 2011, ARA&A, 49, 409
[2] Hilton M. et al., 2021, ApJS, 253(1), 3
[3] Bleem L. E., et al., 2015, ApJS, 216, 27.
[4] Mantz A. B. et al., 2015, MNRAS, 449, 199
[5] Mantz A. B. et al., 2016, MNRAS, 456, 4020