TESTING A NEW, LOW-SCATTER MASS PROXY AT HIGH REDSHIFTS FOR USE IN UPCOMING SURVEYS OF GALAXY CLUSTERS

Massive clusters at high redshifts possess significant cosmological constraining power. Chandra is the only current telescope that can be used to test a low-scatter mass proxy, the centre-excised x-ray luminosity L_{ce}, in high-redshift regimes. If the $L_{ce} - M$ relation were shown to remain valid at high redshifts, it could become an invaluable tool in upcoming cluster surveys as it can be used directly on many newly discovered distant clusters to estimate their total mass. We demonstrate that this test can be performed by observing 15 confirmed x-ray clusters within $0.9 < z < 1.6$ *requiring a total exposure time of only 300 ks.*

Galaxy clusters are the largest known virialized objects, formed from matter overdensities in the early Universe. The intra-cluster medium (ICM) is an x-ray emitting gas that sits in the potential well of a cluster, providing a clear outline of the cluster's structure. This makes x-rays a powerful way to detect clusters. Of the many upcoming cluster surveys, eROSITA launches in 2019 to embark on its 4-year all-sky survey that will reveal an expected 10^5 clusters in the x-ray [4].

With the formation of structures, the spatial density of clusters evolves according to the matter, dark matter and dark energy content of the Universe. Different cosmological models predict largely different evolutionary patterns for the number densities of clusters of a given mass [1]. Out to at least $z \approx 1$, this depends predominantly on Ω_m and at $z = 1 - 1.5$, Ω_Λ has a significant dynamical effect on cluster formation. The right panel of figure 1 shows how future surveys, by amassing large samples of high-z clusters, will be able to break the degeneracy between Ω_m and σ_m and also constrain Ω_Λ.

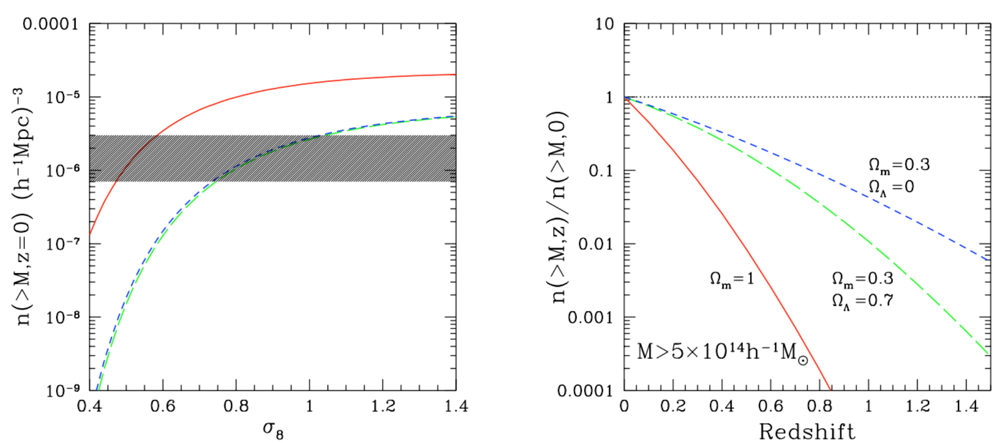

Figure 1: The sensitivity of the cluster mass function to cosmological models. Left: The cumulative mass function at $z = 0$ for $M > 5 \times 10^{14} h^{-1} M_\odot$, for three cosmologies, as a function of σ_8. Right: Evolution of the number density for the same cosmologies and the same mass limit. Adapted from [8].

ΛCDM structure growth models predict mass limits as a function of redshift above which no clusters should be found. This is why observations of suprisingly massive galaxy clusters at redshifts $z > 0.8$ have attracted significant attention in the last few years. The discovery of more distant clusters with sufficient mass constraints could thus provide a new tool to test the standard model. The eROSITA survey will enable a dense sampling of the most relevant mass-redshift plane [6].

The cluster mass, however, is never a directly observed quantity and so it is important to have an observable that correlates tightly with total mass. Two key considerations in the choice of this mass proxy are: (1) the instrinsic scatter, i.e. scatter due to real cluster-to-cluster variation and (2) observing resources required to measure it. While x-ray luminosity, L_X requires only tens of source counts, it also shows a large intrinsic scatter. A scaling relation with low intrinsic scatter is especially important for distant or low-mass clusters. **In the context of eROSITA, which will reveal cluster populations out to high redshifts (at least $z \approx 1.6$), a low-scatter max proxy that is easy to measure from short x-ray observations will be invaluable.**

When massive clusters were first discovered at redshifts of around unity, it was recognized that searching for more of these objects could be highly lucrative [8]. Although the redshift boundary for x-ray clusters has been pushed relentlessly in recent years, the discovery and the study of clusters at $z > 1.3$ has the strongest leverage on testing cosmologies. As the search progressed to higher redshifts, it also became increasingly more challenging and costly without the availablility of a low-scatter and simultaneously cost-efficient mass proxy. This remains a serious observational challenge with x-ray searches due to the limited survey areas covered at faint fluxes.

A NEW, LOW-SCATTER MASS-PROXY: Previous work has suggested that a measurement of the x-ray luminosity in an annulus, excluding the cluster center, provides a scaling relation with very low intrinsic scatter, comparable to that of gas mass and temperature [3, 7, 5]. This is because the ICM shows the greatest variation in the cores of clusters. Additionally, measuring this centre-excised x-ray luminosity, L_{ce} requires very short exposure times. This opens up the possibility of using L_{ce} to estimate cluster masses directly from eROSITA survey data, provided that its scaling relation is well-understood and accurately calibrated.

Recent work outlined a procedure for estimating L_{ce} in a sample of clusters from *Chandra* follow-up data [4]. They constrained a $L_{ce} - M$ scaling relation (see equation 1), confirmed that it had a low intrinsic scatter (see figure 2), and that its predictions of total mass were consistent with those derived from other mass proxies up to a redshift of at least $z = 1.1$. **Since we increase cosmological constraining power by estimating many high-redshift cluster masses, it would be useful to validate the previously-estimated $L_{ce} - M$ scaling relation in these regimes and confirm that its intrinsic scatter remains low.**

$$\frac{E(z)^{-1} L_{ce}}{10^{45} \mathrm{erg\ s}^{-1}} = e^{(-0.86 \pm 0.04)} \left[\frac{E(z) M_{500}}{10^{15} M_{\odot}} \right]^{0.99 \pm 0.02} \tag{1}$$

CONFIRMED DISTANT X-RAY CLUSTERS: Given the large amount of time needed to observe clusters at such a high redshift, a crucial requirement is to have an x-ray selected target. Fortunately, confirmed x-ray luminous clusters have been discovered by the XMM-Newton Distant Cluster Project (XDCP). Comprising 22 distant clusters, this is the largest published sample of distant x-ray luminous galaxy clusters at redshifts $0.9 < z < 1.6$ [2]. Table 6 of [2] summarizes the x-ray properties of each of these clusters. While L_X-based mass estimates for these clusters are available, they are fairly uncertain and based on scaling relations. We would like to make measurements of L_{ce} for these x-ray clusters using *Chandra* to explore the validity of L_{ce} as a low-scatter mass proxy. It is therefore necessary to also have measurements of the total mass and/or gas mass for as many of these clusters as possible in order to verify the mass predictions made by the $L_{ce} - M$ relation.

Several such measurements already exist. Two of these, a *Chandra* 380 ks observation of the most distant of these clusters, XDCP J0044.0-2033 at $z = 1.58$ [10] and another of XMMU J2235.3-2557 for 200 ks at $z = 1.39$ [9] yielded surprisingly high mass results, triggering a large number of

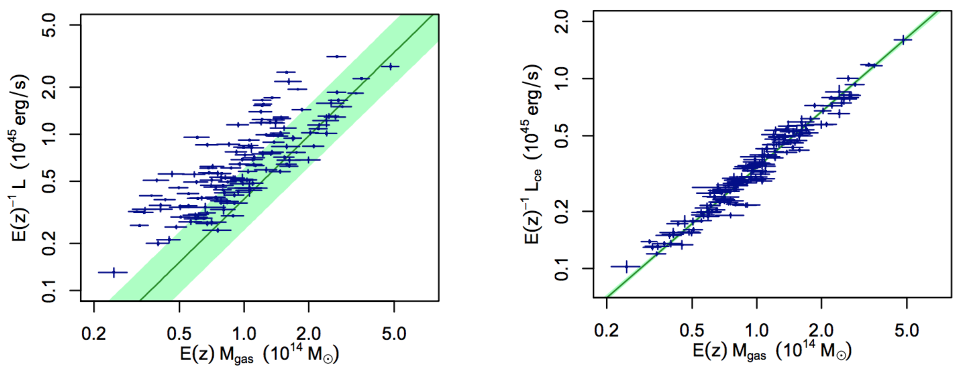

Figure 2: Comparing scaling relations of L_X (left) and L_{ce} (right) with M_{gas}. Green lines and shading show the best-fitting scaling relations and their 68.3 per cent probability predictive intervals, including intrinsic scatter. Adapted from Ref. [4].

z	Official Name	M_{200} ($10^4 M_\odot$)
1.457	XMMXCS J2215.9-1738	1.9 (T)
1.396	XDCP J2235.3-2557	6.6 (HE/WL)
1.335	SpARCS J0035.8-4312	2.3 (T)
1.237	RDCS J1252.9-2927	2.9 (HE)
1.227	XDCP J2215.9-1751	0.7 (T)
1.050	XLSS J0224.0-0413	2.0 (HE)
1.000	XDCP J2215.9-1740	0.8 (T)
0.975	XDCP J1230.2 + 1339	5.1 (T)
0.959	XDCP J0027.2 + 1714	4.2 (T/M_g/WL)

Table 1: Properties of XDCP galaxy clusters for which more accurate mass estimates are available, with the corresponding method indicated (T, x-ray temperature based; HE, hydrostatic equilibrium method; WL, weak lensing; and M_g, gas mass-based) adapted from Ref. [2].

theoretical speculations on their cosmological implications. A summary of all XDCP clusters for which additional mass estimates have been made is provided in table 1.

We propose to follow-up all XDCP clusters that are as of yet uncovered by *Chandra* with short observations. The *Chandra* archive coverage of this sample is less than 30%.

To make L_{ce} measurements, only 10-30 ks exposures are required. Following the method outlined in [4], L_{ce} refers to the intrinsic (unabsorbed) x-ray luminosity of a cluster, projected within an annular aperture with an inner radius of 0.15 r_{500} and an outer radius of r_{500}. The particular choice of inner radius is intended to comfortably exclude the variability observed in cluster centers.

With the current generation of x-ray telescopes, only *Chandra* is well-suited for this task because obtaining L_{ce} for distant clusters of a wide mass range requires a fine resolution (HEW$<$ 0.5”). This is because a given telescope's point spread function must reliably permit the central portion of the cluster to be excised. If not, photons leaked from cluster centres can increase the intrinsic scatter.

Chandra and XMM archives are populated by mostly low-redshift, high-mass clusters. For future cluster surveys like eROSITA, many new observations would thus focus on higher-redshift, lower-mass clusters. Although L_{ce} can be estimated directly from x-ray survey data for many more clusters than other x-ray mass proxies, these newly discovered clusters will have lower signal-to-noise and a fraction of them will require follow-up with *Chandra*. Additionally, follow-up observations of clusters discovered in mm-wavelength and optical surveys can be much shorter if the goal is to measure L_{ce}. Therefore, a test of *Chandra*'s ability to measure L_{ce} for high-z, lower-mass clusters is a secure scientific investment.

Below, we summarize the main points of the propsal:

- Cluster masses in the redshift range $z = 1.3 - 2$ need to be explored in order to unveil their formation processes, for which predictions made by different cosmological models diverge.
- Upcoming x-ray surveys (e.g. eROSITA) will discover many new such objects and will require significant investment in follow-up time. A low-scatter x-ray mass proxy such as L_{ce} requires significantly less exposure time than others with comparable instrinsic scatter.
- The $L_{ce} - M$ scaling relation needs to be well-understood in high-z regimes before it can be applied to future surveys.
- *Chandra* is the only instrument currently capable of reliably extracting L_{ce} for high-z clusters.

In short, *Chandra* observations of 15 *bona fide* high-z clusters will provide valuable scientific return for a total observational time investment of 300 ks.

References

[1] S. Borgani, P. Rosati, P. Tozzi, S. Stanford, P. R. Eisenhardt, C. Lidman, B. Holden, R. Della Ceca, C. Norman, and G. Squires. Measuring ?m with the rosat deep cluster survey. *The Astrophysical Journal*, 561(1):13, 2001.

[2] R. Fassbender, H. Böhringer, A. Nastasi, R. Šuhada, M. Mühlegger, A. de Hoon, J. Kohnert, G. Lamer, J. Mohr, D. Pierini, et al. The x-ray luminous galaxy cluster population at 0.9¡ z? 1.6 as revealed by the xmm-newton distant cluster project. *New Journal of Physics*, 13(12):125014, 2011.

[3] A. Mantz, S. W. Allen, H. Ebeling, D. Rapetti, and A. Drlica-Wagner. The observed growth of massive galaxy clusters–ii. x-ray scaling relations. *Monthly Notices of the Royal Astronomical Society*, 406(3):1773–1795, 2010.

[4] A. B. Mantz, S. W. Allen, R. G. Morris, and A. von der Linden. Centre-excised x-ray luminosity as an efficient mass proxy for future galaxy cluster surveys. *Monthly Notices of the Royal Astronomical Society*, 473(3):3072–3079, 2017.

[5] B. Maughan. The lx-yx relation: Using galaxy cluster x-ray luminosity as a robust, low-scatter mass proxy. *The Astrophysical Journal*, 668(2):772, 2007.

[6] A. Merloni, P. Predehl, W. Becker, H. Böhringer, T. Boller, H. Brunner, M. Brusa, K. Dennerl, M. Freyberg, P. Friedrich, et al. erosita science book: mapping the structure of the energetic universe. *arXiv preprint arXiv:1209.3114*, 2012.

[7] G. Pratt, J. H. Croston, M. Arnaud, and H. Böhringer. Galaxy cluster x-ray luminosity scaling relations from a representative local sample (rexcess). *Astronomy & Astrophysics*, 498(2):361–378, 2009.

[8] P. Rosati, S. Borgani, and C. Norman. The evolution of x-ray clusters of galaxies. *Annual Review of Astronomy and Astrophysics*, 40(1):539–577, 2002.

[9] P. Rosati, P. Tozzi, R. Gobat, J. Santos, M. Nonino, R. Demarco, C. Lidman, C. Mullis, V. Strazzullo, H. Böhringer, et al. Multi-wavelength study of xmmu j2235. 3-2557: the most massive galaxy cluster at z¿ 1. *Astronomy & Astrophysics*, 508(2):583–591, 2009.

[10] P. Tozzi, J. Santos, M. Jee, R. Fassbender, P. Rosati, A. Nastasi, W. Forman, B. Sartoris, S. Borgani, H. Boehringer, et al. Chandra deep observation of xdcp j0044. 0-2033, a massive galaxy cluster at z¿ 1.5. *The Astrophysical Journal*, 799(1):93, 2015.