X-LoVoCCS: X-ray observations of local clusters with individual weak-lensing maps

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1. Abstract

We propose *XMM* observations of galaxy clusters with individual weak-lensing mass maps to achieve modern X-ray coverage (i.e. *XMM* and *Chandra*) of a volume-limited ($0.03<z<0.12$) sample complete for 0.1-2.4 keV $L_{\rm X}^{\rm MCXC}>10^{44}$ erg s^{-1} **and** Sunyaev–Zeldovich (SZ) $\log_{10}{\rm Y}_{500}>-5.9$; enabling assessment of the population scatter in X-ray/SZ/weak-lensing, and detailed studies of individual systems. We target **16** clusters from the Local Volume Complete Cluster Survey (LoVoCCS) for **174 ks** (244 ks with overheads). The survey consists of 147 massive, local, clusters (selected from MCXC); the southern sample contains 107, of which 104 have optical/near-IR observations in hand. Our proposal provides each cluster of the southern sample with a companion modern X-ray observation. Of these, 6 have not been observed by any modern X-ray telescope, 6 have *XMM* observations but have <3000 counts, partial coverage, or are flared, and 4 have *Chandra* observations but have <1000 counts or partial coverage. Our targets are at the lower-luminosity end of the sample, but are X-ray bright nonetheless, at $z\sim0.1$, making high-quality *XMM* observations relatively inexpensive. The scale and detail of the individual weak-lensing measurements are without precedent, and once complemented by X-ray observations, provide an unique opportunity to probe the astrophysics of these objects, while aiding cluster cosmology efforts.

2. Description of the proposed programme

A) Scientific Rationale:

Galaxy clusters are powerful probes of astrophysics and cosmology and are priority targets for current and upcoming large scale surveys. The combination of multiple wavelengths can help overcome the biases of each and place better constraints on the fundamental properties of clusters; the key quantity is mass, which the Local Volume Complete Cluster Survey (LoVoCCS; Fu et al., 2022) will measure with weak-lensing.

LoVoCCS is observing an X-ray luminosity complete ($L_{\rm X,500}^{0.1-2.4{\rm keV}}>10^{44}\,{\rm erg\,s^{-1}}$) set of local ($0.03<z<0.12$) galaxy clusters selected from the Meta Catalogue of X-ray detected Clusters (MCXC; Piffaretti et al., 2011). Optical observations have been taken with the Dark Energy Camera (DECam; LoVoCCS-south, 107 clusters) and Hyper Suprime Cam (HSC; LoVoCCS-north, 40 clusters). The primary science products of the new optical observations are **individual** weak-lensing mass maps for all clusters.

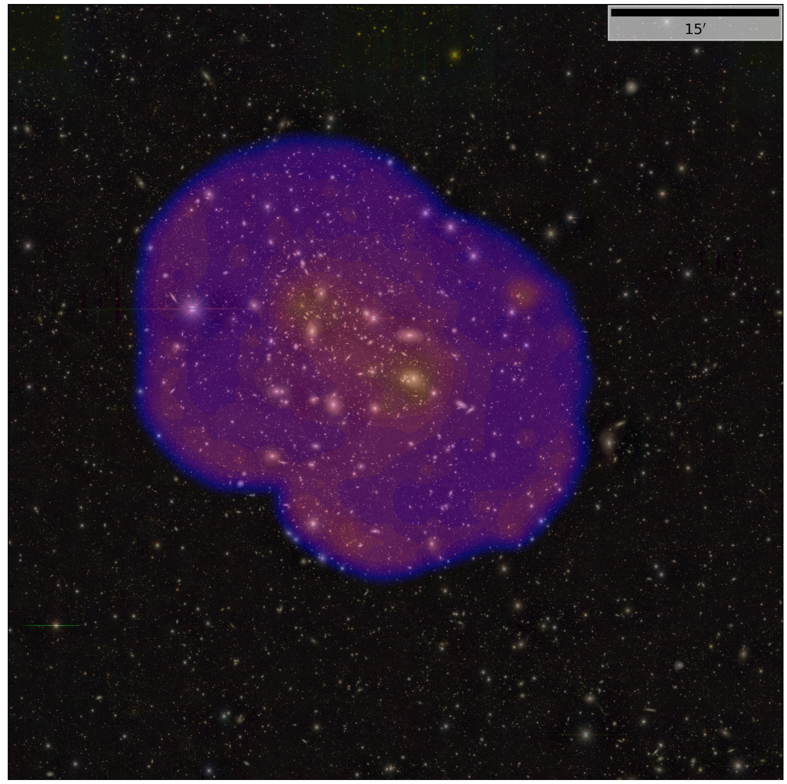

Figure 1: An optical+X-ray image of one of the LoVoCCS sample, Abell 3128; we do not propose to observe this system further. The optical data represent approximately one quarter of the DECam field-of-view. Available *XMM* observations have been processed, smoothed, and overlaid on the optical data. The ICM, and galaxy distribution, are clearly bimodal - this is also the case in the weak-lensing mass map.

The LoVoCCS individual 2D weak-lensing mass maps are a **unique** scientific resource. Weak-lensing analyses for low-redshift clusters are extremely rare due to the required field of view to measure the shear of background galaxies. In previous work, at best only radial profiles of lensing mass are created, and stacking of multiple systems is often required to attain a high enough signal-to-noise (Rozo et al., 2011; McClintock et al., 2019); stacking means we cannot assess the scatter of individual clusters from the behaviour predicted through scaling relations, which must be understood for cluster cosmology analyses to be successful (Bleem et al., 2020; Costanzi et al., 2021). A multi-wavelength approach allows us to extract the maximum scientific value from LoVoCCS.

We are leveraging the existing archive of *XMM* observations (395 of which are relevant to the LoVoCCS sample) to measure the properties of the hot intra-

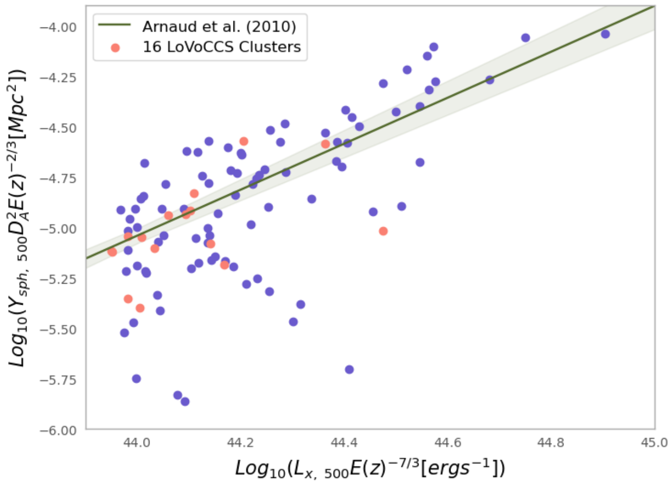

Figure 2: Planck measured Compton-Y parameter vs MCXC measured X-ray luminosity (0.1-2.4 keV) for the LoVoCCS sample, both measured within MCXC R_{500}. Targets of this proposal are highlighted in red. A comparable scaling relation measured by Arnaud et al. (2010) is overlaid for context.

cluster medium (ICM) for each of the LoVoCCS clusters. Modern X-ray observations provide more accurate measurements of cluster centroids and peak positions than the *ROSAT* All-Sky Survey (RASS) that MCXC (thus LoVoCCS) is drawn from. Coordinates defined through analysis of the ICM provide useful context to the weak-lensing maps, as the ICM has been demonstrated to be a better trace of the potential well of clusters (Yan et al., 2020) than the central positions defined through optical observations. Differences between X-ray and optical central position can be used to assess the dynamical state of the clusters; peak coordinates and centroids are already in hand for those clusters with *XMM* data. We are also using *XMM* data to define the morphology of these systems, in combination with the tracer of the total mass distribution provided by the LoVoCCS weak-lensing. Figure 1 shows an example of a LoVoCCS DECam observation with X-LoVoCCS processed archival *XMM* data overlaid.

Modern X-ray observations are required for measurements of ICM properties such as temperature, as *ROSAT* provides almost no temperature information. Measurements of global temperature, luminosity, and metallicity have been made, and radial profiles of baryon density and temperature are in hand for LoVoCCS clusters with existing *XMM* observations. We can also measure hydrostatic mass profiles and entropy profiles. Spatially resolved ICM properties can be cross-correlated with LoVoCCS weak-lensing, as each cluster has individual weak lensing mass maps; as such they are a key goal for the X-ray follow-up project. All LoVoCCS X-ray analyses are performed using the X-ray: Generate and Analyse (XGA;[1] Turner et al., 2022, 2023) Python module, an open source analysis package for X-ray emitting sources. It contains many cluster specific routines, including the ability to measure density, temperature, entropy, and mass profiles. New analyses developed for X-LoVoCCS are added to XGA, so they can be used by the community. Each X-LoVoCCS publication will be accompanied by its code, as well as the generated data products, to allow for easy replication of our work. The X-LoVoCCS-Data[2] repository stores code necessary to assemble the X-ray data archive, as well as visualisations, data notes, and files relevant to proposals.

The LoVoCCS X-ray follow-up project is multifaceted, with science goals that are relevant to topics from cluster cosmology to hydrodynamical simulations of clusters; these include **a)** bench-marking cluster scaling relations at $z = 0$; **b)** measuring the scatter in various scaling relations; **c)** assessing mass dependence of intrinsic property covariance; **d)** measuring precisely how hot gas and stellar mass correlate at fixed halo mass; **e)** assessing the fidelity of log-normal scatter model; **f)** testing simulation expectations within and across radial zones; **g)** providing a catalogue of quantitative cluster morphologies. These goals rely on our quantifying the whole population; to maximise the data and to minimise the statistical selection effects, we need to be able to analyse the X-ray emission of all LoVoCCS clusters. With completeness comes the proportions of the cluster population that are, for instance, relaxed, or merging (as well as the timescales), or cool-core. Only local volume-limited samples such as LoVoCCS can be feasibly completed.

SZ observations also benefit our goals by directly probing ICM pressure, determining cluster dynamical state, classifying morphology, and identifying substructure. Combinations of X-ray and SZ can also answer cosmological questions, such as measuring the value of H_0 (Wan et al., 2021). LoVoCCS scaling relations with SZ properties will provide further insight into scatter between cluster observables in the local cluster population. Clusters with the same $T_{\mathrm{X},500}$ or $L_{\mathrm{X},500}$ values can have significantly different SZ integrated surface brightness, which is why we require complete samples to properly quantify the scatter; this applies to all other cluster observables. We are using updated background methodologies to perform

[1] X-ray: Generate and Analyse GitHub
[2] X-LoVoCCS Archive Assembly

Table 1: Properties of the targets, ordered by descending priority. Column (1): Name (non-Abell names have been shortened); (2): Hydrogen column density at coordinates [10^{20}cm^2]; (3): MCXC redshift; (4): 0.1-2.4 keV flux derived from MCXC X-ray luminosity measured within R_{500} [10^{-11} erg cm^{-2} s^{-1}]; (5): Predicted 0.5-2.0 keV PN+MOS1+MOS2 count rate [ct s^{-1}] (6): Cluster temperature estimated from MCXC luminosity [keV]; (7): requested exposure time [ks].

Name	nH	z	$F_{\rm X}$	cps	$T_{\rm X,500}^{\rm est}$	$t_{\rm exp}$
J1139.4	5.3	0.108	0.411	2.71	3.78	11.5
A1023	4.77	0.118	0.305	2.03	3.62	15.0
A42	1.41	0.112	0.435	2.87	3.97	10.5
A2871	1.95	0.119	0.317	2.09	3.69	14.5
J2125.2	6.66	0.115	0.296	1.97	3.53	15.5
J1459.0	6.47	0.104	0.361	2.41	3.53	12.5
J0034.6	2.88	0.081	0.769	5.12	3.87	14.0
A2988	1.71	0.115	0.340	2.25	3.70	13.5
A1809	1.92	0.079	0.683	4.57	3.62	7.0
A2703	3.66	0.116	0.45	2.98	4.14	10.5
A2033	2.69	0.082	0.852	5.42	4.03	7.5
A1285	3.39	0.107	0.893	5.67	4.98	7.5
J1215.4	6.72	0.119	0.498	5.92	4.36	9.5
A2837	5.51	0.114	1.009	3.29	5.47	7.5
A2554	1.75	0.111	0.453	3.00	4.00	10.0
A3998	1.51	0.089	0.814	6.69	4.24	7.5

analyses on Planck data for the LoVoCCS sample. See Figure 2 for an illustration of the relation between Y_{500} measured from Planck sky maps, and $L_{\rm X,500}$ measured by MCXC. Figure 3 also demonstrates this, by showing the different SZ signals for three clusters predicted to have very similar temperatures.

We propose to observe 16 LoVoCCS-south galaxy clusters; all targets have in-hand LoVoCCS optical observations. Of the proposed targets, 6 lack any modern observations (i.e. they only have *ROSAT* data), 4 have coverage by *Chandra* but of insufficient quality, and 6 have existing *XMM* observations, but none of sufficient quality (some are very shallow, some have been badly affected by flaring, some are extremely off-axis, achieving only partial coverage).

In addition to the possibility of detailed studies of the individual systems, particularly the 6 that do not have modern X-ray data, our selection achieves statistical completeness in both X-ray luminosity (0.1-2.4 keV $L_{\rm X}^{\rm MCXC} > 10^{44}\,\text{erg s}^{-1}$) and SZ ($\log_{10}{\rm Y}_{500} > -5.9$) parameter spaces. It also guarantees that every LoVoCCS-south 2D weak-lensing map has a modern X-ray companion. The opportunity to achieve statistical completeness of two samples simultaneously is rare, and combined with our weak-lensing maps, is unique; the bright, local, nature of the clusters make this a low hanging fruit for *XMM*.

B) Immediate Objective:

The object of these proposed observations is to attain LoVoCCS sample completeness in three parameter spaces; X-ray luminosity, the SZ Y-parameter, and LoVoCCS weak lensing coverage. They will provide the following scientific benefits for the X-ray component of the LoVoCCS project:

(1) For those sources with no modern observations we must verify that the MCXC source is not a blended detection due to the low spatial resolution of the RASS. Several members of the initial LoVoCCS sample were found to have an enhanced MCXC luminosity measurement due to blending with a nearby source. **(2)** The definition of accurate X-ray centroids and peaks for these systems, particularly for those clusters with no modern observations. We also quantify their X-ray morphology. Measured position and morphology can be significantly affected by low spatial resolution observations due to the potential blending of sources. Accurate coordinates compared to the lensing mass, BCG, and red-sequence peak positions enables us to probe the dynamical state of the clusters, and identify misalignments similar to the Bullet cluster archetype. **(3)** Complete measurements of temperature and gas density profiles for the sample, and by extension global measurements of temperature, luminosity, gas mass, and hydrostatic mass. **(4)** Exploring the correlation between temperature, density, and entropy of the ICM, and the distribution of the total mass identified through LoVoCCS weak-lensing. **(5)** Comparisons between X-ray and SZ observations including making scaling relations, determining morphology, and contrasting SZ and X-ray derived pressure profiles.

3. Justification of requested observing time, feasibility and visibility

Properties and requested exposure times of the sample are presented in Table 1, with highest priority at the top of the table and lowest priority at the bottom. Highest priority is given to targets with no modern X-ray observations.

We examined each of our targets in Planck SZ maps, and located signal for each of them; an important check for the targets with no modern X-ray observation, demonstrating a population of high-energy electrons. Figure 3, shows a subset of the targets, all

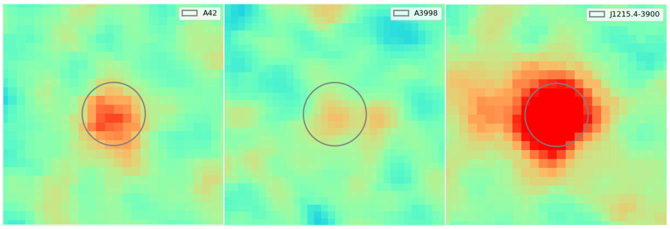

Figure 3: Planck SZ visualisations of three of our target galaxy clusters, selected as they are similar in predicted temperature but different in SZ signal. Images are centered on MCXC coordinates and are labelled with the system name. The circle on each represents the MCXC R_{500}.

with similar estimated X-ray temperatures, and very different SZ signals. Complete samples are necessary to properly understand the scatter in different observables (the SZ effect is not dependant on redshift, so the differences are not a matter of distance).

We have ensured that no usable X-ray data from *Chandra* or *XMM* exists; several of the proposed targets do have *Chandra* or *XMM* data, but it is of insufficient quality. LoVoCCS-south clusters will be covered by the upcoming *eROSITA* All-Sky Survey (eRASS), but the exposure times of 150-200 s are insufficient for our needs. We note 15 *XMM* currently proprietary observations relevant to LoVoCCS, none are of any target in this proposal, there are also no pending observations. We also use the visibility checker tool to ensure the feasibility of our proposed observations; all targets are visible for considerably longer than our proposed exposure times, and at low-background parts of the orbit phase.

Exposure times were calculated to **a)** produce very well constrained temperature and luminosity measurements within R_{500}, and **b)** measure gas temperature, density, and hydrostatic mass profiles. The local nature of LoVoCCS clusters make this possible without unfeasibly long exposure times. To this end a target of a minimum of 30000 0.5-2.0 keV X-ray counts was set, which will be sufficient to produce well constrained profiles. We **do not** add 40% to each requested exposure time. The observations are relatively short, fairly numerous, and could be repeated, so we will submit a fulfil program proposal if any observations are affected by flaring.

We can use *ROSAT* luminosities to perform simulations of cluster spectra and predict the 0.5-2.0 keV count-rates that would be observed by *XMM* instruments. MCXC luminosity and redshift values are used to calculate the 0.1-2.4 keV flux (presented in Table 1). To model the target emission, we also need an estimate of the cluster temperature, as they are not available for MCXC clusters. They are inferred from MCXC luminosity measurements using a T_{X}-L_{X} relation fit from cluster properties presented by Lovisari et al. (2020). The temperature measurements were made using *XMM*, and the luminosity measurements are within the MCXC energy band (0.1-2.4 keV). Predicted temperatures for our targets are shown in column 6 of Table 1.

Finally, WebPIMMS is used to calculate count-rates for PN and MOS, which are combined and shown in column 5 of Table 1; nH values at the MCXC coordinates are retrieved from the full-sky HI survey by the HI4PI Collaboration et al. (2016), and we assume a metallicity value of 0.4 $Z_{\odot}$. We calculate assuming the thin filter. The count target is divided by the count-rate to establish an exposure time and rounded up to the nearest 0.5 ks; any exposure less than 7 ks is set to 7 ks. This results in a total exposure time of 174 ks for our sample.

4. Report on the last use of XMM-Newton data

PI Turner has analysed hundreds of clusters for the *XMM* Cluster Survey (XCS); this has included measurement of hydrostatic masses for optically selected clusters, and performing XMM analyses of eFEDS clusters. They have also created substantial software packages for *XMM* analysis, XGA and DAXA.

5. Most relevant proposer's publications

Turner D. J. et al, 2022, arXiv:2202.01236, `XGA`: A module for the large-scale scientific exploitation of archival X-ray astronomy data

Turner D. J. et al, 2022, arXiv:2109.11807, The *XMM* Cluster Survey: An independent demonstration of the fidelity of the eFEDS galaxy cluster data products and implications for future studies

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