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The Future Landscape of High-Redshift Galaxy Cluster Science

Thematic Areas: • Cosmology and Fundamental Physics • Galaxy Evolution

Abstract:

Modern galaxy cluster science is a multi-wavelength endeavor with cornerstones provided by X-ray, optical/IR, mm, and radio measurements. In combination, these observations enable the construction of large, clean, complete cluster catalogs, and provide precise redshifts and robust mass calibration. The complementary nature of these multi-wavelength data dramatically reduces the impact of systematic effects that limit the utility of measurements made in any single waveband. The future of multi-wavelength cluster science is compelling, with cluster catalogs set to expand by orders of magnitude in size, and extend, for the first time, into the high-redshift regime where massive, virialized structures first formed. Unlocking astrophysical and cosmological insight from the coming catalogs will require new observing facilities that combine high spatial and spectral resolution with large collecting areas, as well as concurrent advances in simulation modeling campaigns. Together, future multi-wavelength observations will resolve the thermodynamic structure in and around the first groups and clusters, distinguishing the signals from active and star-forming galaxies, and unveiling the interrelated stories of galaxy evolution and structure formation during the epoch of peak cosmic activity.

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1 Introduction

Observations of clusters of galaxies provide a powerful probe of cosmology and astrophysics (Voit 2005, Allen, Evrard & Mantz 2011, Borgani & Kravtsov 2011). Statistical measurements of the evolution of the cluster population over time constrain both the growth of cosmic structure and the expansion history of the Universe. Such observations have played a key role in establishing the current “concordance” model of cosmology, in which the mass-energy budget of the Universe is dominated by dark matter and dark energy, with the latter being consistent with a cosmological constant (e.g. White et al. 1993, Allen et al. 2004, Vikhlinin et al. 2009, Mantz et al. 2010). Clusters are also remarkable astrophysical laboratories, providing unique insights into, e.g., the physics of galaxy evolution (von der Linden et al. 2010) and structure formation (Simionescu et al. 2019, Walker et al. 2019), the role of feedback processes (Fabian 2012, McNamara & Nulsen 2012), the history of metal enrichment (Mernier et al. 2018), the nature of dark matter (Clowe et al. 2006), and the physics of hot, diffuse, magnetized plasmas (Markevitch & Vikhlinin 2007, Brunetti & Jones 2014, van Weeren et al. 2019). Clusters also serve as natural gravitational telescopes with which to observe the most distant reaches of the Universe (Treu et al. 2015).

The key observations enabling robust population studies of galaxy clusters are: a sky survey on which cluster finding can be systematically performed with a clean selection function (below), accurate redshift estimates, robust absolute mass calibration (typically provided by weak lensing measurements), and targeted follow-up observations (especially at X-ray wavelengths) to provide precise centers and relative masses for the clusters, and measurements of their dynamical states.

2 Exploiting multi-wavelength synergies in cluster searches

Galaxy clusters produce observable signals across the electromagnetic spectrum. At X-ray wavelengths, spatially extended bremsstrahlung emission from the hot intracluster medium (ICM) can be clearly identified. In optical and IR data, we can search for overdensities of galaxies, as well as the red colors typical of cluster members. At mm wavelengths, the spectral distortion of the cosmic microwave background (CMB) due to inverse-Compton scattering with the ICM (the Sunyaev-Zel’dovich or SZ effect) provides a nearly redshift-independent way to find clusters.

The primary observation enabling galaxy cluster science is a sky survey on which cluster finding can be systematically performed, ideally over a large sky area and wide range in redshift. While the construction of cluster catalogs in any single waveband can quickly become a frustrating endeavour hampered by systematic limitations, the complementary nature of X-ray, optical and mm-wavelength data provides direct, observational solutions to most issues. X-ray observations, for example, can provide clean, complete catalogs of clusters, as well as multiple low-scatter mass proxies: quantities that are relatively immune to projection effects, correlating tightly with the true, three-dimensional halo mass. The primary disadvantages of X-ray measurements are the need to make them from space (which brings associated cost and risk), the impact of surface brightness dimming (though this is mild at $z > 1$; Churazov et al. 2015), and the inability to provide precise absolute mass calibration directly. SZ surveys provide a more uniform selection in redshift, with only their sensitivity determining the mass down to which clusters can in principle be detected. This technique provides our best route for finding clusters at high redshifts, although care is needed to understand the impact on selection of radio- and infrared-emissive cluster galaxies, especially at higher redshifts. Future SZ surveys will also have the ability to provide absolute cluster mass calibration through CMB-cluster gravitational lensing (e.g. Hu et al. 2007). Like X-ray surveys, optical and near-infrared (OIR) surveys are most effective at low-to-intermediate redshifts,

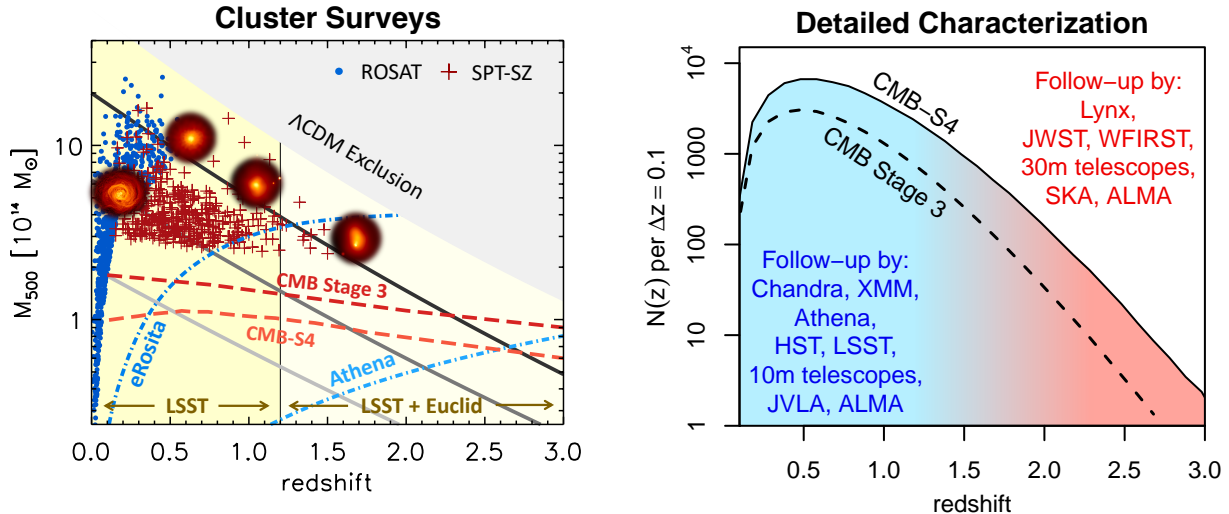


Figure 1: Left: Mass–redshift plot showing some existing cluster catalogs used extensively for astrophysics and cosmology (ROSAT in X-rays, SPT-SZ at mm wavelengths; Ebeling et al. 2000, 2010, Böhringer et al. 2007, Bleem et al. 2015), and the discovery space for the Stage 3 CMB (SPT-3G, Advanced ACT, Simons Observatory), CMB-S4, eROSITA, LSST and *Athena* projects. In the standard cosmological model, clusters are not expected to exist in the gray “exclusion” region. Solid lines show “evolutionary” tracks, tracing out the progenitors of present-day massive clusters. Right: The number of SZ cluster detections expected as a function of redshift from Stage 3 SZ surveys and the proposed CMB-S4 project. Blue to red shading shows the transition to the $z \gtrsim 2$ regime that will be unveiled by new cluster surveys, for which high spatial resolution and throughput are key requirements for extracting information about halo centers, relative masses, dynamical states, internal structure, and galaxy/AGN populations. The proposed new programs will enable the first detailed studies of virialized structure at these redshifts.

but have the benefit of finding larger numbers of clusters down to lower masses. The primary challenges for optical cluster selection are projection effects (which can lead to overestimated richnesses for some clusters) and the relatively complex nature of the intrinsic mass–observable scaling relations. Nonetheless, optical surveys provide an essential complement to X-ray and SZ data in cluster identification, and uniquely provide essential redshift information (from precise multi-band photometry or spectroscopy) and precise absolute mass calibration (through galaxy-cluster lensing). Supporting these observational cornerstones, numerical simulations have emerged as a powerful, complementary tool, providing informative priors on the expected correlations between the measured signals (Stanek et al. 2010, Farahi et al. 2018, Truong et al. 2018).

Figure 1a illustrates the mass-redshift coverage for two of the leading, current cluster surveys, which have been used extensively for both cosmology and astrophysics studies, and the expected reach of a number of projects, most of which are approved and funded (for more detail see Section 3). The figure demonstrates how the forthcoming surveys will vastly increase the size and redshift reach of cluster catalogs, extending out to the epoch when massive clusters first formed and when star formation and AGN activity within them peaked.

Uncovering this distant cluster population is non-trivial. At X-ray wavelengths, it requires an imaging facility with a large collecting area (especially at soft X-ray energies, < 1 keV) and sufficient spatial resolution to distinguish truly extended emission from the intracluster medium (ICM) from associations of point-like AGN sources. SZ surveys likewise require a combination of sensitivity and spatial resolution to detect clusters, as well as sufficient frequency coverage to spec-

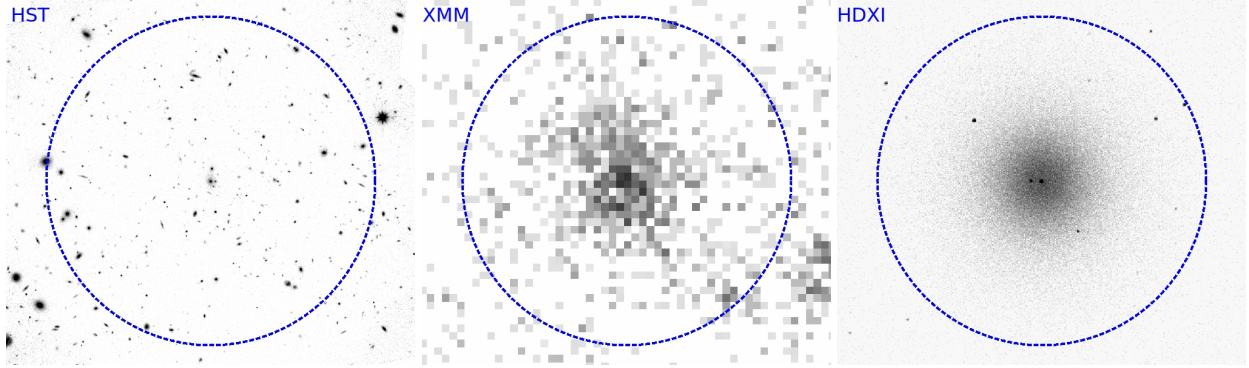


Figure 2: Images of the $z = 2$ cluster XLSSC 122: *Hubble* F140W (left; Willis et al. 2019, in prep), XMM-Newton X-ray (center, 100 ks), and simulated *Lynx* HDXI (right, 100 ks). Dashed circles show the characteristic radius, $r_{200} \sim 54''$. Realistic densities and luminosities have been generated for cluster and background AGN in the *Lynx* simulation, which includes a simple β model for the ICM, based on the XMM data. Groundbreaking studies of this high- z cluster have benefited from investments of time with XMM, HST, *Spitzer*, ALMA, CARMA, and other ground-based observatories (Willis et al. 2013; Mantz et al. 2014, 2018). Such multi-wavelength studies will be routinely superseded by observations with future facilities such as *Athena*, JWST, single-dish bolometric mm-wavelength observatories, and 30 m-class telescopes. High spatial resolution across the electromagnetic spectrum is particularly important for unambiguously identifying galaxy and AGN counterparts.

trally distinguish measurements of the SZ effect from emissive radio and infrared sources (which contaminate the SZ signal at lower and higher frequencies, respectively). To provide both good redshift estimates and accurate shape measurements for a robust weak lensing mass calibration, optical surveys require exquisite photometric calibration and image quality. To extend the reach of optical measurements significantly beyond $z \gtrsim 1$, space-based near IR measurements are needed, with sufficient resolution and depth to appropriately complement the optical data.

3 The Landscape of Approved Projects

A number of facilities that are approved and in construction will contribute substantially to the future of cluster science. Of special note are the new, dedicated survey instruments: eROSITA in X-rays, LSST and *Euclid* at OIR wavelengths, and several “Stage 3” ground-based mm-wavelength observatories. Also of note is the *Athena* observatory, which will devote a significant fraction of its observing time to performing a deep X-ray survey of several hundred square degrees.

The German-Russian SRG mission, bearing the eROSITA X-ray survey instrument (Merloni et al. 2012), will launch later in 2019. eROSITA will have 30–50 times the sensitivity of the previous all-sky X-ray survey by ROSAT. Figure 1a shows that the all-sky eROSITA survey is expected to identify essentially all groups out to $z \sim 0.3$, all intermediate mass clusters to ~ 0.6 , and the most massive clusters at $z \lesssim 2$. The FoV-averaged spatial resolution of $26''$, while an improvement over ROSAT, will be limiting at high redshifts, where the angular extent of clusters is small. Distinguishing ICM and AGN contributions to the emission from faint, modestly extended sources will require follow-up measurements with higher-spatial-resolution X-ray observatories.

LSST will survey the entire southern sky in *ugrizy* over a 10 year period, beginning in 2022. It will identify clusters down to the group scale, constrain their redshifts photometrically, and provide precise, stacked weak lensing mass measurements out to a redshift of ~ 1.2 (LSST Dark Energy Science Collaboration 2012). Note that the redshift limit reflects the redshift at which the 4000 \AA

break moves out of the reddest band. Combining LSST data with near-IR data from *Euclid*, an ESA M-class mission scheduled for launch in 2021, will extend the range further. Conversely, while *Euclid* will identify overdensities of IR-luminous galaxies out to high redshifts (Laureijs et al. 2011), its ability to characterize the cluster population will be enhanced greatly through combination with precise LSST photometry (as well as complementary X-ray and mm observations).

The “Stage 3” CMB (i.e. mm-wavelength) surveys most relevant to cluster science are those by SPT-3G, AdvancedACT (both ongoing), and the planned Simons Observatory and CCAT-prime. Taking advantage of the SZ effect, these surveys will break new ground in providing the first large, robustly selected catalogs of clusters at $z > 1.5$, as well as the first informative absolute mass calibration from CMB-cluster lensing. They will find > 3000 clusters at $z > 1$ and ~ 50 at $z > 2$ (Benson et al. 2014, De Bernardis et al. 2016, The Simons Observatory Collaboration 2018, Stacey et al. 2018). However, few detections are expected above $z \sim 2.3$ (Fig. 1).

Athena, an ESA mission with NASA involvement, will be the next flagship-class X-ray facility (Nandra et al. 2013). Scheduled for launch in 2031, *Athena* will combine an order of magnitude increase in effective area compared to XMM-Newton, with a smaller $5''$ (HPD) PSF on axis, degrading only to $\sim 10''$ at $30'$ radius. *Athena*’s grasp significantly exceeds that of any previous X-ray instrument, including eROSITA. *Athena* will also carry the first large, high-spectral-resolution IFU X-ray calorimeter. With all these advances, we expect to find (Zhang et al. 2019, in prep) and study (Ettori et al. 2013, Pointecouteau et al. 2013) very distant galaxy groups and clusters at $z \gtrsim 2$ over a modest fraction of the sky with *Athena*, revolutionizing studies of cluster evolution, dynamics, thermodynamics and metal enrichment. However, due to the small size of these objects (typically $\lesssim 50''$ in diameter), these studies will rely on spectral modeling to distinguish emission from AGN and the ICM, rather than directly resolving AGN and small-scale structure within clusters.

4 New Opportunities

While the projects described above will undoubtedly transform cluster studies, they are limited in their ability to probe the highest redshifts of interest ($z > 2$; due to limited sensitivity and/or sky coverage) and, especially, in their ability to study the astrophysical processes within and around these systems. To do so will require new multi-wavelength facilities with improved sensitivity and enhanced spatial and spectral resolution (Figure 2).

At X-ray wavelengths, the primary requirement is for an observatory with comparable throughput and spectral capabilities to *Athena*, but an order of magnitude higher spatial resolution ($\sim 0.5''$). This would open the door to groundbreaking astrophysical measurements, especially (though not exclusively) in the high- z regime (Figure 1b). Recent advances in lightweight, high-resolution, high-throughput X-ray optics have made this goal achievable, as is discussed by the *Lynx* and *AXIS* teams (Zhang et al. 2018, The Lynx Team 2018). The ability to spatially resolve and separate AGN within clusters, and to cross-match these sources with ground- and space-based observations in other wavebands, will transform our ability to study how the triggering and quenching of star formation and AGN activity correlates with the evolution of galaxies and their surrounding large scale structure. Resolving the thermodynamic structure and turbulent gas motions within halos, and the distribution of metals within the diffuse cluster gas, will reveal the interwoven stories of galaxy evolution and structure formation, and the roles of feedback from AGN and stars (e.g. Gaspari et al. 2012, McDonald et al. 2018), spanning the epochs when the massive virialized structures first formed and AGN and star formation activity within them peaked.

For surveys at mm wavelengths, the primary requirements are for greater sensitivity and im-

proved spectral coverage. At high redshifts, even the largest clusters formed have modest spatial extent, making sensitivity and sufficient ($\sim 1'$) spatial resolution the keys to identifying them through the SZ effect, and to providing precise mass calibration from CMB cluster lensing. Adequate spectral coverage is also crucial to separate the SZ effect from emission due to star formation and AGN activity in cluster member galaxies, which are expected to become increasingly important at high redshifts. Configurations such as those being studied for CMB-S4, using multiple, large-aperture telescopes and large, multichroic detector arrays, appear highly promising (CMB-S4 Collaboration 2016, Madhavacheril et al. 2017). These measurements would also provide precise (percent-level) absolute mass calibration and similarly precise measurements of the mean pressure and density profiles of the hot gas around clusters (out to many virial radii), from the stacked thermal- and kinetic-SZ signals. Follow-up SZ measurements with even higher spatial resolution ($\lesssim 10''$) and/or greater spectral coverage (extending above the SZ null) will be possible with ALMA interferometry or single-dish observatories (using successors to the MUSTANG-2 and NIKA-2 instruments and/or new proposed facilities such as CCAT-prime or AtLAST; Stacey et al. 2018, Mroczkowski et al. 2019). From space, a new survey such as the proposed PICO mission could build on the legacy of WMAP and Planck, providing all-sky coverage from 20–800 GHz (albeit with lower spatial resolution than ground-based telescopes), and producing its own catalog of clusters and protoclusters (Hanany et al. 2019). All these measurements could be complemented by high-spectral resolution X-ray grating spectroscopy of background AGN. Together, these new X-ray and SZ facilities would provide an unprecedented view of the hot, high-redshift Universe.

At OIR wavelengths, WFIRST will provide exquisite data for measuring redshifts and weak lensing of high- z clusters (e.g. Akesson et al. 2019). These capabilities, along with those of LSST and *Euclid*, should be complemented by high-throughput spectrographs with high-multiplexing capabilities on scales of $\sim 10'$. Such instruments would enable detailed studies of the star-formation and AGN properties of cluster galaxies, spanning the period when they transition from being dominated by star-forming systems to being red-sequence-dominated. Comprehensive multi-object spectroscopy will also provide a valuable complement to X-ray measurements for dynamical studies of clusters, and will be vital for calibration of photometric redshifts in cluster fields.

Powerful synergies will also be found at radio wavelengths, where SKA and its precursors (e.g. JVLA, LOFAR, MWA, HERA), working in concert with X-ray facilities, will extend studies of AGN feedback out to the highest redshifts. The detection of radio halos and relics, and the correlation of these signals with the dynamic and thermodynamic structure observed at X-ray, optical and mm wavelengths, will reveal the acceleration of particles during subcluster merger events and provide further insight into the virialization process.

ALMA follow-up will open the door to measurements of molecular gas in high-redshift clusters. At the highest redshifts ($z > 4$), observations of dusty, star forming galaxies detected by mm surveys will extend studies of dense environments into the pre-virialized, protocluster regime (e.g. Miller et al. 2018). Finally, combining the most powerful facilities across all wavelengths, we will continue to use clusters as gravitational cosmic telescopes, to probe the earliest phases of galaxy evolution, and the roles of young stars and AGN in the reionization of the Universe.

Extracting science from more sensitive measurements requires concurrent advances in modeling, including simulations designed to map physical models directly to the space of observable features. Empowering the interpretation of new observational capabilities over the coming decade will require large simulated ensembles of massive halos from cosmological volumes, as well as improvements in resolution and new physical treatments.

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