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CHANCES: A CHileAN Cluster galaxy Evolution Survey

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CHANCES, the CHileAN Cluster galaxy Evolution Survey, will study the evolution of galaxies in and around ~ 150 massive galaxy clusters, from the local Universe out to $z \sim 0.45$. It will target ~ 300 000 $r_{AB} < 20.5$ galaxies with 4MOST, providing comprehensive spectroscopic coverage of each cluster out to $5r_{200}$ in synergy with eROSITA. Its wide and deep scope will trace massive and dwarf galaxies from the surrounding filaments and groups to the cores of galaxy clusters, enabling the study of galaxy pre-processing and the role of the evolving environment on galaxies. We will also study the effect of clusters on the cold circumgalactic medium by targeting 50 000 cluster–QSO pairs.

Scientific context

Understanding what drives the evolution of galaxies and determines whether they end up as star-forming spirals or quiescent early-type galaxies by the present day remains a fundamental task within astrophysics. Both internal energetic mechanisms (like active galactic nucleus feedback or stellar winds) and external environmental processes are expected to play major roles in transforming galaxies. While most isolated galaxies remain as gas-rich star-forming spirals to the present day, the bulk of galaxies within massive clusters have lost their gas and have been transformed into quiescent elliptical or lenticular galaxies. A variety of physical mechanisms capable of transforming galaxies as they fall into the clusters have been proposed, including gas stripping by the intracluster medium (ICM; for example ram-pressure stripping and starvation), and gravitational interactions among galaxies or between the galaxies and the cluster (Boselli & Gavazzi, 2006; Cortese, Catinella & Smith, 2021).

Adding to the complexity is the fact that the matter distribution in the Universe evolves dynamically within a web-like large-scale structure in which filaments connect and feed massive galaxy clusters located at their nodes. These structures are composed of dark matter and galaxies, as well as diffuse matter that dominates the baryon budget. In this picture, each galaxy is surrounded by a multi-phase, metal-enriched, and diffuse circumgalactic medium (CGM) shaped by the interplay between accretion from the intergalactic medium and feedback processes occurring within galaxies. Any attempt to comprehend galaxy formation and evolution must therefore measure observational signatures of galaxy and CGM properties against a wide range of environments — both locally and on large scales.

There is a growing appreciation of the need to place massive galaxy clusters in their full cosmological context, not only to explain their own growth and assembly, but also to understand the evolution of their member galaxies. A corollary of the current concordance ΛCDM cosmology is that galaxy clusters continue to grow with cosmic time, doubling their masses since $z \sim 0.5$. In fact, a large fraction of cluster galaxies were accreted within galaxy groups (McGee et al., 2009) and filaments (Kuchner et al., 2020), which can 'pre-process' the galaxies prior to entering the cluster (Zabludoff et al., 1996). Recent observations have confirmed that significant pre-processing of galaxies is indeed required (Haines et al., 2015; Bianconi et al., 2018), but large homogeneous studies that are both deep and wide are still rare. Hydrodynamical simulations of galaxies around massive clusters find a systematic depletion of both hot and cold gas in cluster galaxies caused by ram-pressure stripping, that translates into a lower fraction of star-forming galaxies as far out as ~ $5r_{200}$ from the host cluster, where r_{200} is the virial radius inside which the average density is 200 times the critical density (Bahé et al., 2013), motivating large-scale environmental studies.

CHANCES[1], the CHileAN Cluster galaxy Evolution Survey, is a 4MOST community survey designed to uncover the relationship between the formation and evolution of galaxies and hierarchical structure formation as it happens, through deep and wide multi-object spectroscopy. It will target cluster galaxies out to $5r_{200}$, the distance at which environmental effects acting on infalling galaxies are expected to be sufficient to start removing their extended hot gas atmospheres, starving them of future gas, and well beyond the maximum distance of 2–$3r_{200}$ to which 'back-splash' galaxies can reach. CHANCES will permit the effects of pre-processing of galaxies in infalling X-ray groups and filaments (detectable by eROSITA) to be quantified in unprecedented detail. The survey will also have an important legacy value, by providing detailed spectroscopic information which will complement X-ray observations of clusters and groups by eROSITA, and future radio observations by the Square Kilometre Array and the Australian SKA Pathfinder (ASKAP), as well as current and planned large optical surveys such as the DESI Legacy Survey DR10 (LSDR10), the Southern Photometric Local Universe Survey (S-PLUS) and the Legacy Survey of Space and Time (LSST).

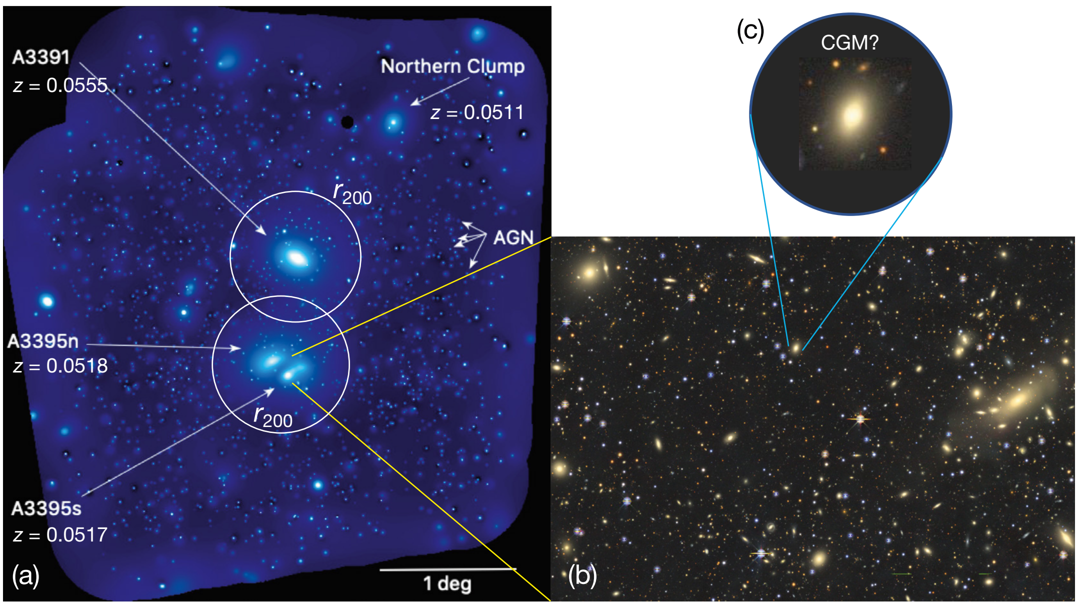

Figure 1. An example of a CHANCES target from the Low-z sub-survey: the A3391/A3395 galaxy cluster system at $z \sim 0.05$ observed by eROSITA (panel a; from Reiprich et al., 2021) and Legacy Survey DR10 (panel b; from *Sky Viewer*). The large-scale structure around the system and the many substructures visible are ideal laboratories in which to study the effect of pre-processing of galaxies. Panel c represents our CHANCES-CGM sub-survey (although at $z > 0.35$), in which we explore the effect of the environment in the circumgalactic medium (CGM) of galaxies, poorly understood to date.

Specific scientific goals

CHANCES comprises three sub-surveys, described below, each with different scientific objectives.

The CHANCES Low-z sub-survey will quantify the impact of environment on galaxies from high masses (10^{11} $M_\odot$) down to the dwarf regime (10^{8-9} $M_\odot$). Dwarf ellipticals (dE) are the numerically-dominant population in galaxy clusters (Binggeli, Sandage & Tammann, 1988). Their formation via cluster-related processes and evolution remains largely unexplored outside local clusters such as Virgo and Fornax (for example, Eigenthaler et al., 2018; Choque-Challapa et al., 2021), as is their evolution in the infall regions beyond r_{200}.

This sub-survey will provide a large-scale homogenous spectroscopic dataset for galaxies covering more than three orders of magnitude in stellar mass, in and around a representative sample of clusters. It will enable us to constrain many open questions, including: the efficiency of cluster mechanisms transforming galaxies; the timescales for quenching star formation; the long-term survivability of dwarfs in groups and clusters; the role of pre-processing in groups and filaments; and the contribution of galaxy disruption to intracluster light. There is also a natural synergy with ongoing and future HI surveys from ASKAP and MeerKAT, since most HI detections from these surveys will be from dwarf galaxies, owing to their high gas fractions. Their large HI discs are highly susceptible to gas and tidal stripping processes, making HI a sensitive trace of environmental effects.

The CHANCES Evolution sub-survey aims to continuously track the evolution of cluster galaxies over the last four billion years, and measure when, where and how quickly spiral galaxies are being transformed in and around clusters. Cluster galaxies have not always been as inactive as they are at the present epoch. The fraction of blue (star-forming) galaxies among cluster members increases from almost zero in the local Universe to 20% by $z \sim 0.4$ (the Butcher–Oemler effect; Butcher & Oemler, 1984), implying a rapid evolution in the cluster galaxy population. Moreover, since more than half of the galaxy populations of local clusters were only accreted after $z \sim 0.4$, the transformation of star-forming spirals into quiescent early-types as they encounter group or cluster environments is mostly taking place at late epochs. The previous large cluster galaxy evolution surveys (WINGS, LoCuSS) were limited to a single epoch, while attempts to track the evolution of cluster galaxies over $0 < z < 0.5$ have had to resort to aggregating heterogeneous datasets from the literature, and with only a handful of clusters beyond $z = 0.3$. While WINGS and LoCuSS have allowed us to quantify where galaxies are being transformed within clusters and on what timescales at a single epoch, CHANCES will permit us to extend these analyses over four billion years of cosmic time within a single overarching survey.

The CHANCES CGM sub-survey will study the effect of group and cluster environments on the diffuse gaseous content of galaxies traced by MgII absorption towards projected QSOs at redshifts $0.35 < z < 0.7$. Although MgII probes cold (10^4 K) gas, given that the CGM is multiphase, it provides a good opportunity to test models of gas disruption in clusters as a function of cluster- and absorber-centric distances (for example, Dutta, Sharma & Nelson, 2022). CHANCES CGM is similar to the ‘quasars behind clusters’ survey (Lopez et al., 2008), the difference being that special attention is given to biases and selection effects by positioning fibres not only in cluster-selected sightlines but also on control samples. In addition, and in contrast to what has been previously done, CHANCES CGM will also provide a wealth of information on the projected population of galaxies close to the QSO sightlines over CGM scales. Results from this survey will have implications for the relation between dark matter halos and the properties of galaxies in these dense and extreme environments, and for the overall population of MgII systems.

Target selection

CHANCES targets are taken from the LSDR10 outside the Galactic plane (|b| > 20°).

The CHANCES Low-*z* survey will target 50 clusters at $z < 0.07$ and with a mass range of 10^{13}–10^{15} $M_{\odot}$, as well as large regions around known superclusters such as Shapley and Horologium-Reticulum, each containing > 20 clusters within a rich cosmic web.

The cluster sample is X-ray selected, using latest cluster samples that combine a reanalysis of ROSAT all-sky X-ray survey data, detecting X-ray emission for unresolved sources (CODEX; complete down to the flux level of 2×10^{-13} ergs s^{-1} cm^{-2}; Finoguenov et al., 2020) and extended sources on scales of 6–24 arcminutes (CODEX3; complete down to 6×10^{-13} ergs s^{-1} cm^{-2}; Finoguenov et al., in preparation) with the redMaPPer cluster red sequence finder applied to LSDR10. We essentially select the most massive clusters applying a redshift-dependent mass threshold, and add lower-mass clusters randomly, preferring clusters with auxiliary data. Our sample includes well-studied clusters such as those from the WINGS survey, and the nearby Fornax and Hydra clusters. An example of a low-redshift target, the galaxy cluster system A3391/A3395 at $z \sim 0.05$, is shown in Figure 1.

For each cluster, 4MOST targets are first selected from the LSDR10 (Figure 1b) as galaxies brighter than $r_{AB} = 20.5$ and within $5r_{200}$ of the cluster centre. To improve the efficiency of observing cluster members rather than background galaxies, we use photometric redshifts from S-PLUS (Mendes de Oliveira et al., 2019) that is imaging ~ 8000 deg^2 of the southern sky in 12 optical bands to $r_{AB} \sim 21$ using the T80-South 0.8-metre telescope at Cerro Tololo Inter-American Observatory in Chile. The S-PLUS photometric system has been shown to deliver much more accurate photometric redshifts than standard broadband surveys and has been shown to be particularly effective at selecting members of $z \sim 0.05$ clusters with photometric redshift uncertainties of ~ 0.02 $(1 + z)$ at $r_{AB} \sim 19.7$ (Lima et al., 2022). Additionally, we have been carrying out our own T80 observing programmes to cover those $z \sim 0.05$ clusters outside the S-PLUS main survey footprint, including the entirety of the Shapley supercluster. For brighter cluster galaxies we require spectra with signal-to-noise ratios greater than 20 Å^{-1} in the continuum to permit velocity dispersions and stellar population parameters to be measured, while the spectral requirement for the faintest low-surface brightness dwarf galaxies will be to measure a redshift.

The CHANCES Evolution sub-survey will target 50 of the most massive galaxy clusters distributed evenly over $0.07 < z < 0.45$. We use the second Planck catalogue of Sunyaev–Zeldovich sources (PSZ2; Planck Collaboration et al., 2016), which provides a homogenous sample of massive clusters over this redshift range, selecting the 50 most massive galaxy clusters in four redshift intervals. At $0.2 < z < 0.45$ this corresponds to $M_{200} > 7 \times 10^{14}$ $M_{\odot}$, while at lower redshifts the mass limit is progressively reduced to account for the smaller volume available. Most of the CHANCES Evolution cluster sample is covered by the CHEX-MATE XMM Heritage programme (Arnaud et al., 2021), providing high-quality X-ray data suitable for characterising the ICM and mass distribution of each CHANCES cluster.

To select probable cluster members and exclude foreground/background galaxies and stars we use infrared photometry. Specifically, we use the linear relation in the $(J–K)$ vs. K colour–magnitude diagram, which has been demonstrated to be bias-free with respect to star formation activity (Haines et al., 2009). For this purpose, CHANCES Evolution clusters have been observed with VIRCAM on the 4-metre VISTA telescope at Paranal. In addition to the $J–K$ selection, we require targets to have $r_{AB} < 20.5$, to lie within $5r_{200}$ of each cluster, and to have a signal-to-noise ratio greater than 5 Å^{-1} in the continuum to be sure of obtaining a reliable redshift measurement.

The CHANCES CGM sub-survey is composed of three main selections: i) targeted MgII in clusters already identified from the SDSS at Dec. < +5° and corresponding control samples; ii) blind MgII searches in clusters targeting QSOs (confirmed and candidates) in the southern sky covered by different 4MOST surveys; and iii) targeting QSOs behind CHANCES Evolution clusters. In all of these we target not only the QSOs but also $r_{AB} < 20.5$ galaxies within ~ 1 arcminute (Figure 1c) around each QSO sightline probing relevant CGM scales. For the QSOs we aim at a signal-to-noise greater than 10 Å^{-1} in the continuum, allowing us to reach MgII absorption down to 0.3 Å rest-frame equivalent width, a regime where MgII strongly correlates with the presence of galaxies.

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Links

[1] CHANCES website: https://chances.uda.cl/