Evolving Morphologies of Cluster Red Sequence Galaxies

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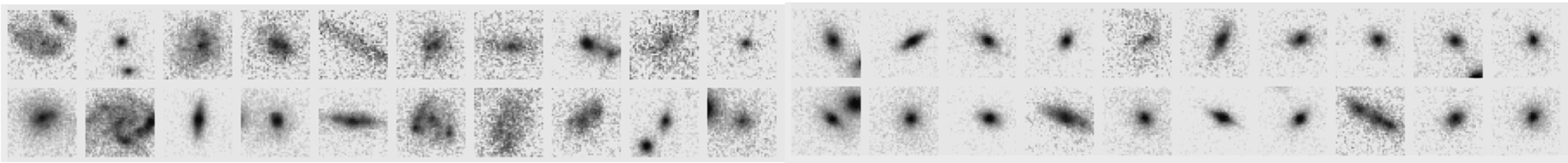
Using HST imaging of galaxy clusters out to *z*=1.4 in rest-frame B and R-bands, we have identified evolution in the typical morphologies of cluster red sequence galaxies (CRSGs). Despite the bulk of their stellar populations passively evolving in the past ~10Gyr, a significant fraction of ~L* *z*>1 CRSGs display obvious (late-type) disk components and associated radial colour gradients which subsequently reduce in prominence and evolve to the present-day configurations by z~0.5 to 0.6. This indicates that for all but the most massive CRSGs, morphological evolution continues for 3-4 Gys after quenching of large-scale star formation. The existing HST data limits more detailed study, which requires higher spatial resolution (to carry out multi-component morphological decomposition) and observations in the same rest-frame bands at higher redshift. In contrast, such work is ideally-suited to the capabilities of JWST.



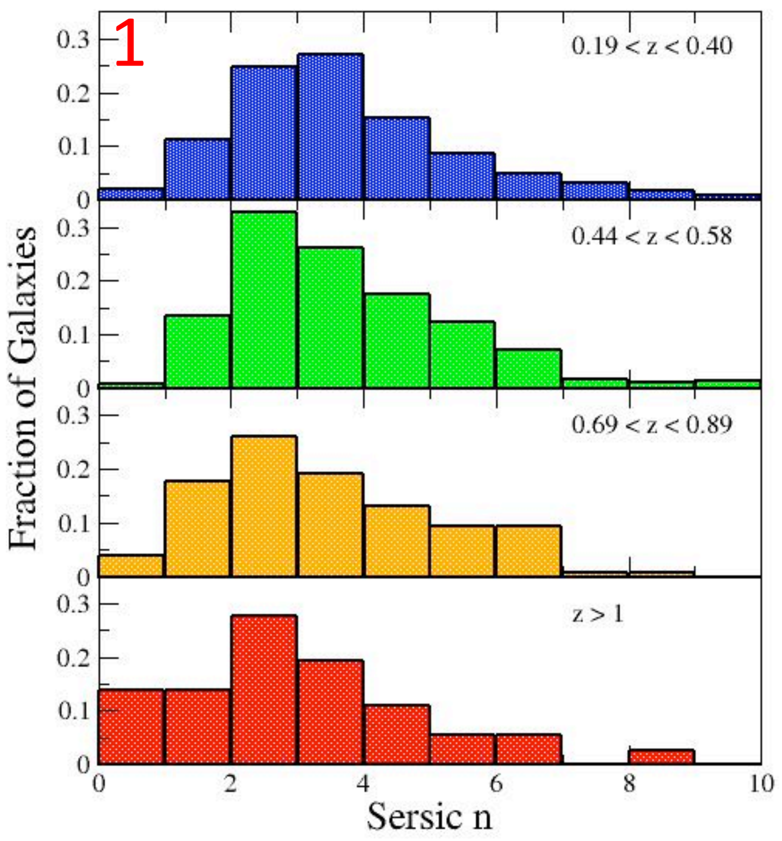
BACKGROUND

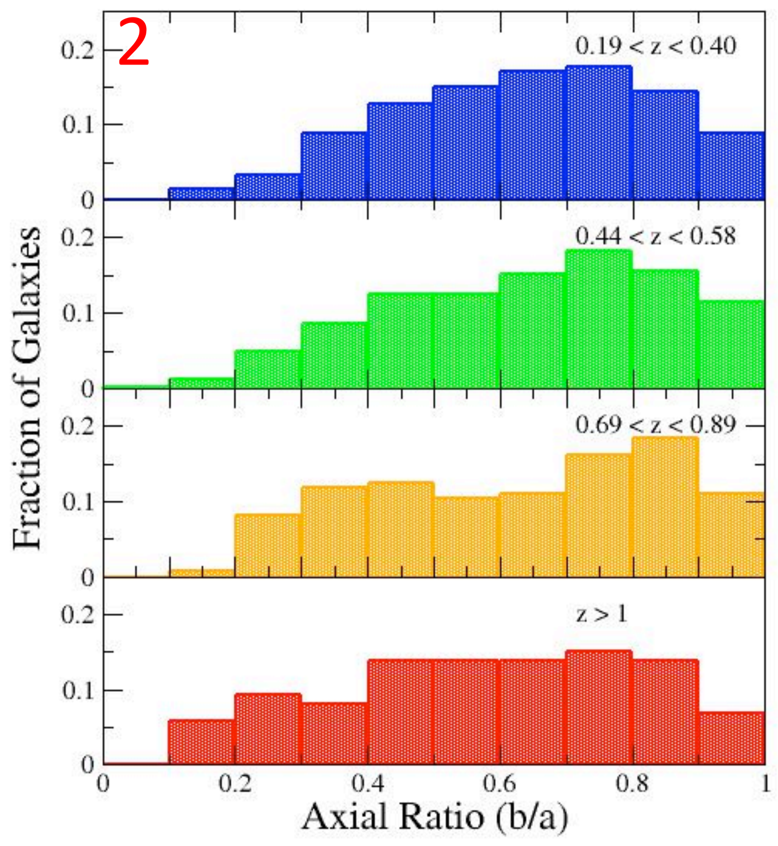
It is well known that early type galaxies in clusters appear to have finished forming the bulk of their stellar populations at high redshift and appear to have then passively evolved over the past ~10 Gyrs or so, forming the so-called red sequence in photometric studies of galaxy clusters. However, we have shown (**De Propris, Bremer, Phillipps, 2015, MNRAS, 450,1268** and 2015, MNRAS, submitted) that this passive behaviour does not extend to their morphologies over this time.

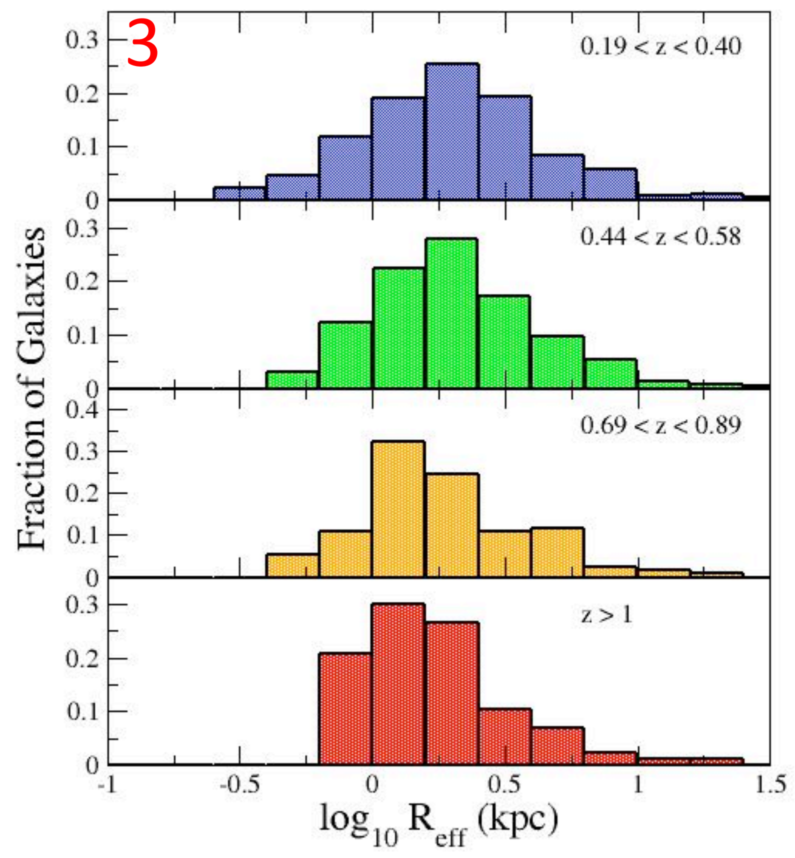
SAMPLE SELECTION AND ANALYSIS

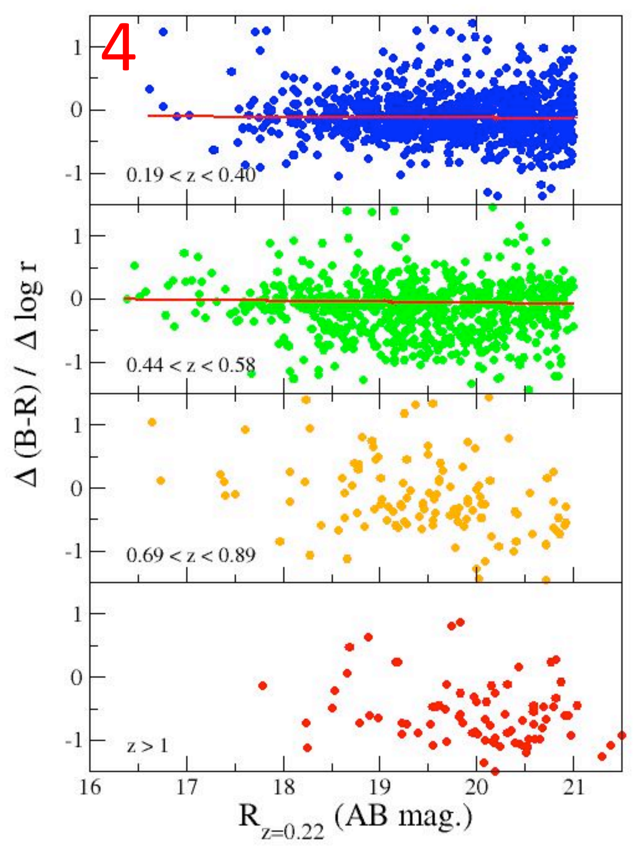
We photometrically selected galaxies on the rest-frame B-R red sequences of all clusters out to z=1.4 with appropriate archival HST ACS and WFC3 data available before mid 2014. We selected objects down to 2.5 magnitudes below L* for each cluster (fainter than this red sequence selection becomes too compromised by photometric uncertainties). The upper redshift limit was set by the reddest HST band (F160W). We used GALFIT to determine single component Sérsic fits to all objects in both bands. This was to be consistent at all redshifts as bulge-disk decomposition was not uniformly reliable at the higher redshifts. Sérsic indices, effective radii and axis ratios were measured and colour gradients derived from the ratio of effective radii in the two bands (again resolution limited any attempt at pixel-by-pixel gradient determination at high redshift).

***Figures**: **Top band** shows 2"x2" ACS postage stamps of n<2 cluster red sequence galaxies drawn from four clusters at 1<z<1.4. Below: **1**: Histograms of Sérsic Index (n) distributions of CRSGs split into four redshift bins. **2**: Histogram of axial ratios for same objects. **3**: Histogram of rest-frame R-band effective radius from Sérsic fit for same objects. **4**: Scatter plots of derived colour gradients for the same objects, -ve gradients indicate bluer towards the outside. All plots support the higher redshift objects being more disk dominated (by relatively thin disks) than those at lower redshift and having stronger (age related) colour gradients. All results are consistent with disks fading, reddening and thickening between 1.4>z>0.5.*









RESULTS

With the present data we see clear evolution in the measured and derived properties of the population of CRSGs over the redshift range 0.5<z<1.4 (look-back times of ~5 to ~9 Gyr). Below z~0.5 the population appears to evolve little in these morphological parameters. We see no evidence for evolution in the most massive red sequence galaxies:- our analysis indicates that they typically remain high Sérsic index (n>3) ellipticals over the entire time period.

However, for the typical ~L* cluster red sequence population, morphology evolves. While systems with significant disks – those with n<2 – are almost absent from red sequences at z<0.6, a non negligible fraction of CRSGs have such a morphology at z>1 (**see postage stamps** of z>1, n<2 CRSGs) and the entire Sérsic index distribution moves to lower values (**Fig.1**). Similarly, the distribution of axial ratios evolves with redshift, with highly flattened galaxies (i.e. those with late-type edge on disks) largely disappearing between z=1.4 and z=0.5-0.6 (**Fig. 2**). The distribution of axial ratios at low redshift are entirely consistent with a mix of spheroid-dominated systems - true ellipticals and S0s (with comparatively thick disks) – seen in nearby cluster red sequences. At the same time, the overall sizes (as measured by the red band effective radius, **Fig. 3**) barely change contrary to what is seen in the passively evolving field population over the same redshifts.

Using the effective radii measured in the two bands we can derive a measure of the radial colour gradient for each object using the prescription of La Barbera et al., (2003, A&A 409, 21) (**Fig. 4**). At z<0.6 gradients are negative (bluer on the outside) but close to zero and are usually explained as a result of metallicity gradients in the stellar populations. However at z>1, typical gradients are far larger (statistical uncertainties from GALFIT on individual points much smaller than the scatter in the points) and can only be explained by radial age gradients in the sources (younger on the outside).

INTERPRETATION

Our results clearly indicate that at z>1 a significant fraction of otherwise red and apparently passively evolving CRSGs have clear disk components in addition to their bulges. Axial ratios indicate that the disks are thinner than those of lower redshift Sa and S0 galaxies and the colour gradients indicate there is either some ongoing star formation, or that quenching occurred later in the disks than the bulges. At lower redshifts both the bulge and disk components age, but the disk component fades and reddens faster than the bulge because of the more recent quenching of star formation until after 3-4 Gyr the colour difference between the components becomes dominated by any residual metallicity gradient and the disk is much less prominent as its M/L evolves more than that of the bulge. Simultaneously, the disk thickens due either to multiple low-level gravitational interactions with other cluster members heating the disk, or through secular processes in the disk. By z~0.6 the red sequence population has the same range of morphological properties as those displayed by z~0 clusters, implying a linkage between the quenching of star formation (3-4 Gyrs earlier at z>1.4) and subsequent morphological evolution in the population.

LIMITATIONS OF HST-BASED ANALYSIS AND THE NEED FOR JWST

While our HST work points to clear morphological evolution for the typical galaxies on the red sequences of clusters over the past 9Gyr, the use of HST data also limits our work. As is clear, this evolution occurs at z>0.5 and the likely crucial interplay between quenching of star formation and subsequent morphological evolution will be set by conditions above z=1.4. The HST data allow us to explore the broad parameters of the subsequent evolution, but limits us in two ways. Firstly the lack of imaging in bands longer than F160W means a consistent rest frame B & R band analysis must stop at z~1.4, when the redshift range from this redshift to z~2.5 is going to be crucial for understanding exactly how quenching and morphology interact. Secondly, the obvious ways of exploring evolution in both morphology and colour gradients – through multi-component decomposition and colour mapping from pixel to pixel- were not available to us over the entire redshift range due to the near-IR spatial resolution and signal-to-noise of the HST data. Both these limitations will be removed with the advent of JWST. The existing HST archive can be used for the rest-frame blue data where necessary while JWST imaging will overcome both limitations in the observed IR. This will enable us to perform multi-component (bulge-disk) decomposition reliably out to the redshifts most sensitive to the interaction between quenching and morphological evolution.