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The Growth & Observability of Galaxy Clusters

J. F. Ider Chitham[1⋆]
[1]*Astrophysics Group, H.H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL*

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ABSTRACT
This paper aims to provide an overview of the fundamental physical processes that narrate the evolution and detection of clusters and the relevance of their implications. Although this area of galaxy formation theory is still partially phenomenological, I attempt to identify the precursors of the most massive galaxy clusters $M \approx 10^{15}\,\mathrm{M}_{\odot}$ and alleviate ambiguities in the literature by evaluating four iconic cluster surveys (~ 3000 clusters) up to $z \lesssim 1.5$, with a maximum look back time of approximately $9\,\mathrm{Gyr}$. I generate theoretical evolution paths for the homogenised cluster populations through cosmic time by implementing numerical simulations and attempt to draw conclusions from these predictions via expectational comparison. These conclusions will heavily influence my forthcoming work.

Key words: Key words: cosmology: observations - catalogues - galaxies: clusters: general - X-rays: galaxies: clusters

1 INTRODUCTION

Galaxy clusters rule the cosmic evolutionary hierarchy as the most massive, gravitationally bound celestial bodies in the universe, with masses ranging from approximately $10^{13}\,\mathrm{M}_{\odot}$ for small groups and protoclusters, to $10^{15}\,\mathrm{M}_{\odot}$ for the richest clusters. These can be up to several Mpc in radius and contain thousands of galaxies that follow a morphology-density relation which evolves with the cluster (Dressler 1980; Dressler et al. 1997). Cluster evolution supports a hierarchical scenario of large scale structure development (Peebles 1980) via gravitational instabilities (Jeans 1902; Lifshitz 1946), cumulative merging and accretive processes (Press & Schechter 1974). According to the concordance Λ Cold Dark Matter (ΛCDM) cosmological model (Peacock & Dodds 1994; Kauffmann et al. 1999; Allen, Schmidt & Fabian 2002): precursory subclumps of matter originally deviated from the Hubble flow, as density perturbations during primordial events in the early universe have larger amplitudes on smaller mass scales allowing them to undergo gravitational relaxation. These members then merge and coalesce to form progressively larger structures.

Clusters are a particularly rich sources of information and provide a sensitive probe of cosmological parameters, as generalising universal expansion in terms of Hubbles Law relates a galaxy cluster's cosmological redshift z with a unique time $t(z)$ since the Big Bang (Eisenstein 1997). Their present-day spatial abundance coincides with our knowledge of baryonic acoustic oscillations (Seo & Eisenstein 2003), anisotropies across the cosmic microwave background radiation (CMB hereafter) (Komatsu et al. 2011) and can be used to parametrise the initial conditions of the universe.

Clusters of galaxies must have formed relatively late in the history of the Universe, since the mean density of matter in the Universe ρ scales as $\sim (1+z)^3$ and corresponds to a density parameter $\Omega_m \approx 0.3$. At the present day, the average densities of gravitationally bound systems such as clusters are much greater than this value with over-densities[1] of $\Delta \approx 1000$ (Longair 2008).

These are important conclusions as they suggest that the structures we observe today did not begin to form in the inaccessibly remote past, but at redshifts which are in principle accessible by observation. This enables us to identify prospective progenitors of the most massive clusters and make observational predictions based on their evolutionary model. This is the premise of our investigation.

This paper employs a Friedmann-Robertson-Walker cosmological model described by the parameters; $\Omega_0 = 1$, $q_0 = 0.5$, and $H_0 = 72\,\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$.

2 CLUSTER EVOLUTION

Clusters are dynamically dominated by dark matter (Zwicky 1933) in the form of nonlinear, quasi-equilibrium haloes whose universial density profile plays a pivotal role in modern theories of galaxy formation (Navarro, Frenk & White 1997). These haloes assemble through several different processes; the diffuse accretion of unresolved haloes or dark matter particles, and through mergers with comparable mass or smaller satellite haloes (Fakhouri & Ma 2010; Lidman et al. 2013). During mergers, which can occur at an upper limit of $\sim 4700\,\mathrm{kms}^{-1}$ (Clowe, Randall & Markevitch 2007), the gaseous baryonic component collapses, creating strong shocks that

[1] If $\delta\rho$ is the enhancement in density of some region due to gravitational attraction, over the average background density ρ we define the over-density as $\Delta = \delta\rho/\rho$.

⋆ E-mail: ji1333@my.bristol.ac.uk (JIC)

raise the entropy of the material allowing it to lose energy via radiative cooling as it is compressed. If this process is inefficient, the system relaxes to hydrostatic equilibrium, with its self-gravity balanced by pressure gradients (Mo, van den Bosch & White 2010). On the other hand collisionless matter (e.g. CDM or stars) causes no shocks as it violently relaxes into virial equilibrium.

Tracing the mass accretion histories $M(z)$ of the most massive progenitor halo is a useful way to quantify a halo's mass assembly history (McBride, Fakhouri & Ma 2009; Fakhouri, Ma & Boylan-Kolchin 2010). This is an important technique used in statistical studies of the distributions of halo formation redshifts, and the correlations between formation time and other halo properties such as relative contributions to mass growth from major and minor mergers. Moreover, the time derivative of the $M(z)$ gives the mass growth rate of dark matter haloes and is directly related to the accretion rate of baryons from the cosmic web onto dark matter haloes (Fakhouri, Ma & Boylan-Kolchin 2010). For a more in depth review refer to §5.

3 OBSERVABILITY

The mass distribution in clusters of galaxies can be measured by many complementary methods such as dynamical estimates[2] (Ider Chitham 2013) and routines that utilise general relativity theory independently of the distribution of baryonic matter, such as weak and strong gravitational lensing (Einstein 1915; Zwicky 1937). In §3.1 and §3.2 I focus on the two techniques most relevant to the investigation.

3.1 X-ray emissivity and the ICM

Observation occurs frequently in the X-ray regime as rich clusters are strong extended X-ray sources with a density squared (n_e^2) dependence that allows them to be efficiently found over a wide redshift range (Gursky et al. 1971; Forman et al. 1972; Kellogg et al. 1972). This emission originates from the thermal bremsstrahlung of hot, diffuse intracluster gas (plasma) (Felten & Morrison 1966) with characteristic luminosities of $\sim 10^{43}$ to 10^{45} ergss^{-1}. The implied mass of this intracluster medium (ICM) is typically an order of magnitude larger than the total stellar mass in the member galaxies (due to inefficient formation), making it the dominant baryonic component in clusters (White et al. 1993; Allen, Schmidt & Fabian 2002). If the ICM is in hydrostatic equilibrium, its density and temperature profiles can be used to infer the total dynamical mass, however this state of relaxation is not necessarily expected unless a cluster formed a long time ago, as most tend to be dynamically young.

3.2 The Thermal Sunyaev-Zel'dovich Effect

Outside of the X-ray domain, the redshift-independent thermal Sunyaev-Zel'dovich (SZ) effect (Sunyaev & Zeldovich 1970) is emerging as an efficient way to detect distant, massive clusters that fall below the flux limits of X-ray surveys. The SZ effect describes the Compton scattering of CMB photons by the electrons in a reservoir of hot plasma. It causes a decrement in the intensity of the Rayleigh-Jeans region of the spectrum and a slight excess in the Wien region. This can be observed in the direction of a cluster of galaxies due to the effective temperature change of the CMB (Birkinshaw 1990). Measurements of the effect provide distinctly different information about cluster properties in contrast to X-ray imaging data (Birkinshaw 1999; Bonamente et al. 2006), while the combination of SZ and thermal bremsstrahlung observations leads to new insights into the structures of cluster atmospheres. This is imposed to very high sensitivities by experiments such as the Planck mission (Planck Collaboration et al. 2014).

3.3 Scaling Relations

X-ray scaling relations are of interest, as correctly modelling their forms tests our understanding of the physical processes that heat and shape the ICM over cluster lifetimes (Finoguenov, Reiprich & Böhringer 2001; Reiprich & Böhringer 2002; Sanderson et al. 2003). One of the most important properties is the total cluster mass. Although not directly observable, it is common practice to utilise the correlations between X-ray properties as a way to overcome this inconvenience (Lloyd-Davies 2010; Clerc et al. 2014). Simple theoretical arguments lead to power-law scaling relations between cluster masses and observables (Kaiser 1986; Bryan & Norman 1998). The luminosity-mass ($L-M$) relation has a potentially large scatter $\sim 50\%$ (Reiprich & Böhringer 2002) so is frequently calibrated by independently measuring cluster masses using a combination of the aforementioned proxies (Borgani et al. 1999) (e.g. using a combination of the mass-temperature ($M-T$) and X-ray luminosity-temperature ($L-T$) relation (Mitchell et al. 1979; Pratt et al. 2009; Maughan 2014)). Scaling relations evolve as a function of redshift and are often extrapolated as necessary. In future work translations from our mass estimates will be relevant in the context of the investigation when making predictions about what can be observed.

4 CLUSTER CATALOGUES & DATA COMPILATION

A substantial dataset is a fundamental prerequisite when attempting to decipher astrophysical data. A complete sample of heterogeneously assembled clusters was selected by evaluating four surveys using a single method (as in Fassbender et al. (2011)). The approach implemented was that of Piffaretti et al. (2011), during the compilation of the The Meta-Catalogue of X-ray detected Clusters of galaxies (MCXC)[3]. Based on the ROSAT All Sky Survey and serendipitous cluster catalogues, each total cluster mass M_{500} and luminosity L_{500} is standardised in the $[0.1-2.4]$ keV band to an overdensity of 500. The respective $L-M$ scaling relation (1), derived by Pratt et al. (2009) and updated by Arnaud et al. (2010) has an evolutionary dependency characterised by $E^2(z) = \Omega_m(1+z)^3 + \Omega_\Lambda$ with $\log(\eta) = -3.79$, $\alpha = 1.64$.

$$E(z)^{-7/3}\left(\frac{L_{500}}{10^{44}\,\mathrm{ergs}^{-1}}\right) = \eta\left(\frac{M_{500}}{10^{12}\,\mathrm{M}_\odot}\right)^{\alpha} \qquad (1)$$

Unlike the other catalogues, the all-sky Planck catalogue (Planck Collaboration et al. 2014) determines cluster masses using a newly-proposed SZ-mass proxy (§3.2). The XXIX release is

[2] Using the virial theorem to yield a simple relation between the mass of the cluster, the radial velocity dispersion of the member galaxies and the characteristic radius of the galaxy distribution.

[3] This decision was one of practicality as the MCXC is the largest considered catalogue as shown in Table. 1.

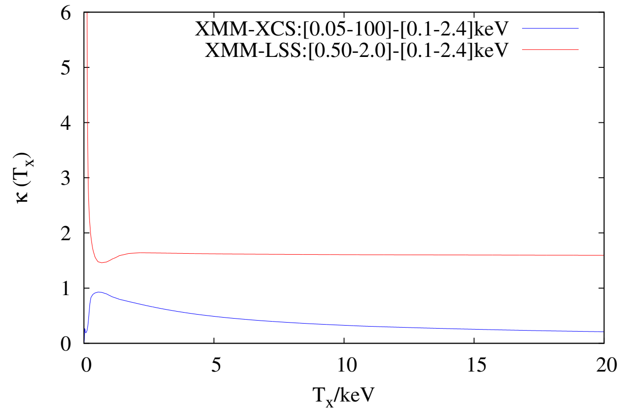


Figure 1. `Xspec` Luminosity conversion functions, $\kappa(T_x)$ for XMM-XCS **(blue)** and XMM-LSS **(red)** cluster surveys for a range of relevant X-ray temperataures. Note the increasing nonlinearity as $T_X \to 1\,\text{keV}$ and the maxima/minima at yet lower temperatures. This form can be intuively predicted given that in the respective cases the luminoisty observational ranges significantly exceed and are marginally narrower than $[0.1 - 2.4]\,\text{keV}$.

Table 1. Comparision of the summarised data content and observational information for each custer catlagoue. The respective band conversion factors can be found in Fig.1

Cluster Survey	$N_{clusters}$	Band/ keV	Proxy
MCXC	1743	$0.1 - 2.4$	X-ray
PCCS-SZ XXIX	813	N/A	SZ-mass
XMM-XCS DR1	401	$0.05 - 100$	X-ray
XMM-LSS	52	$0.5 - 2.0$	X-ray

the deepest all-sky cluster catalogue, with redshifts up to about one, and spans the broadest cluster mass range.

The XMM X-ray Cluster Survey (XMM-XCS) (Mehrtens et al. 2012) is a serendipitous search for galaxy clusters which aims to measure cosmological parameters and trace the evolution of X-ray scaling relations (§3.3). This first data release consists of X-ray clusters with bolometric luminosities measured in the $[0.05 - 100]\,\text{keV}$ band. The XMM large scale structure (XMM-LSS) survey (Willis et al. 2013; Clerc et al. 2014) is also well placed to contribute to this investigation: covering 11 deg^2 with X-ray imaging to a depth of $\sim 10^{14}\,\text{ergs}^{-1}\text{cm}^{-2}$ for extended sources in the $[0.5 - 2]\,\text{keV}$ waveband, accompanied by optical and mid-infra-red (MIR) photometry.

To unify the samples, suitable X-ray temperature dependant flux conversion factor functions $\kappa(T_X) = L_X^{[0.1-2.4]}/L_X$ were required for both XMM surveys. Occasionally modified fluxes can be obtained assuming a fixed conversion factor (Willis et al. 2013) providing the waveband has a narrow range (note the rough uniformity of XMM-LSS from $T \gtrsim 1\,\text{keV}$ in Fig. 1), however the procedure is more complex for vast wavebands such as that used in the XMM-XCS. Conversion factors were computed iteratively using `Xspec` (implementing an APEC emission model (Smith et al. 2001)), a quasi-continuous depiction is summarised in Fig. 1.

5 EVOLUTIONARY ANALYSIS

The mean magnitude of cluster mass accretion over a given period of time is heavily dependant on the chosen cosmology (Voit 2005; Benson et al. 2013) and to fully understand the of the details of these hierarchical merging processes, numerical simulations are required. Fakhouri, Ma & Boylan-Kolchin (2010) constructed merger trees of dark matter haloes, improving on the work of McBride, Fakhouri & Ma (2009) and quantifying merger and mass growth rates using a joint dataset from the Millennium (Springel et al. 2005) and Millennium-II simulations. Their simple and accurate fitting formula for the mean mass growth rate of haloes as a function of mass and redshift (2) has been further adapted to visualise how our cluster populations evolve in the (M, z) plane.

$$\langle \partial M/\partial t\rangle = (\xi/10^{12}\,\mathrm{M}_\odot)(M/10^{12}\,\mathrm{M}_\odot)^{\phi}E(z)\,\mathrm{yr}^{-1} \tag{2}$$

Eisenstein's time-redshift relation then allows us to transform (2) into an equation that describes the evolution of a cluster's mass as a function of redshift (3).

$$\Delta M \approx -\int_{z(t_1)}^{z(t_2)} \frac{\xi M^{\phi}}{H_0(1+z)}\frac{E(z)}{\sqrt{\Omega_0(1+z)^3+\Omega_\Lambda}}\mathrm{d}z \tag{3}$$

Numerical integration was implemented to yield a solution for all mass and redshift increments (given that $\xi \approx 46$ and $\phi \approx 1.1$), this translates to approximate evolutionary paths for all mass accretion histories $M(z)$ and current day masses M_0. N.B. Future work will be complimented with the respective lookback times via an analogous method (Hogg 1999).

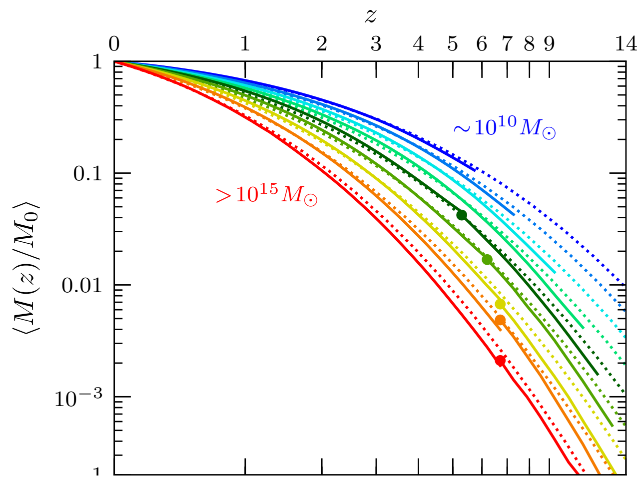
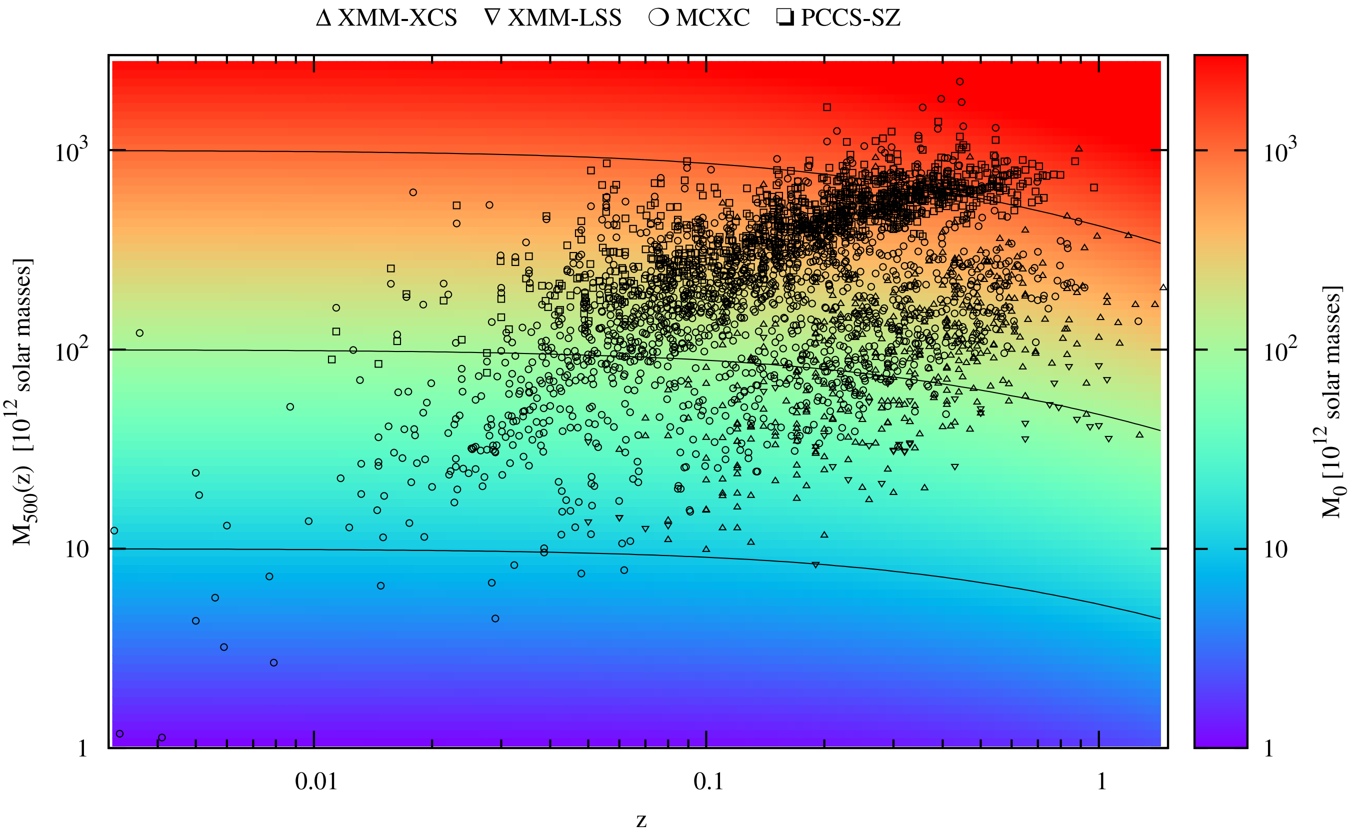


Figure 2. Taken from Fakhouri, Ma & Boylan-Kolchin (2010): Mean mass assembly history $M(z)$ of all $z = 0$ resolved dark matter haloes in the two Millennium simulations (solid curves). The dotted curves show the predictions given by integrating the mean of their fitting formula (2).

6 DISCUSSION & FUTURE WORK

The homogenised cluster data agrees with expectations, however each composite catalogue is the subject of observational flux limitations to a varying extent (soon to be portrayed graphically). Note each datasets tendency to plateau at higher masses, luminosities and redshifts in the linear version of Fig. 3. Underlying issues also arise due to inconsistencies in terms of selection and assembly bias.

On a cosmological and evolutionary basis, preliminary simulations appear in accordance with that of Fakhouri, Ma & Boylan-Kolchin (2010) as Fig. 2 was used as a systematic consistency check prior to the production of Fig. 3. This gives us an insight to how each sample member has evolved over time, outlining both the mass and redshift of prospective progentitors.



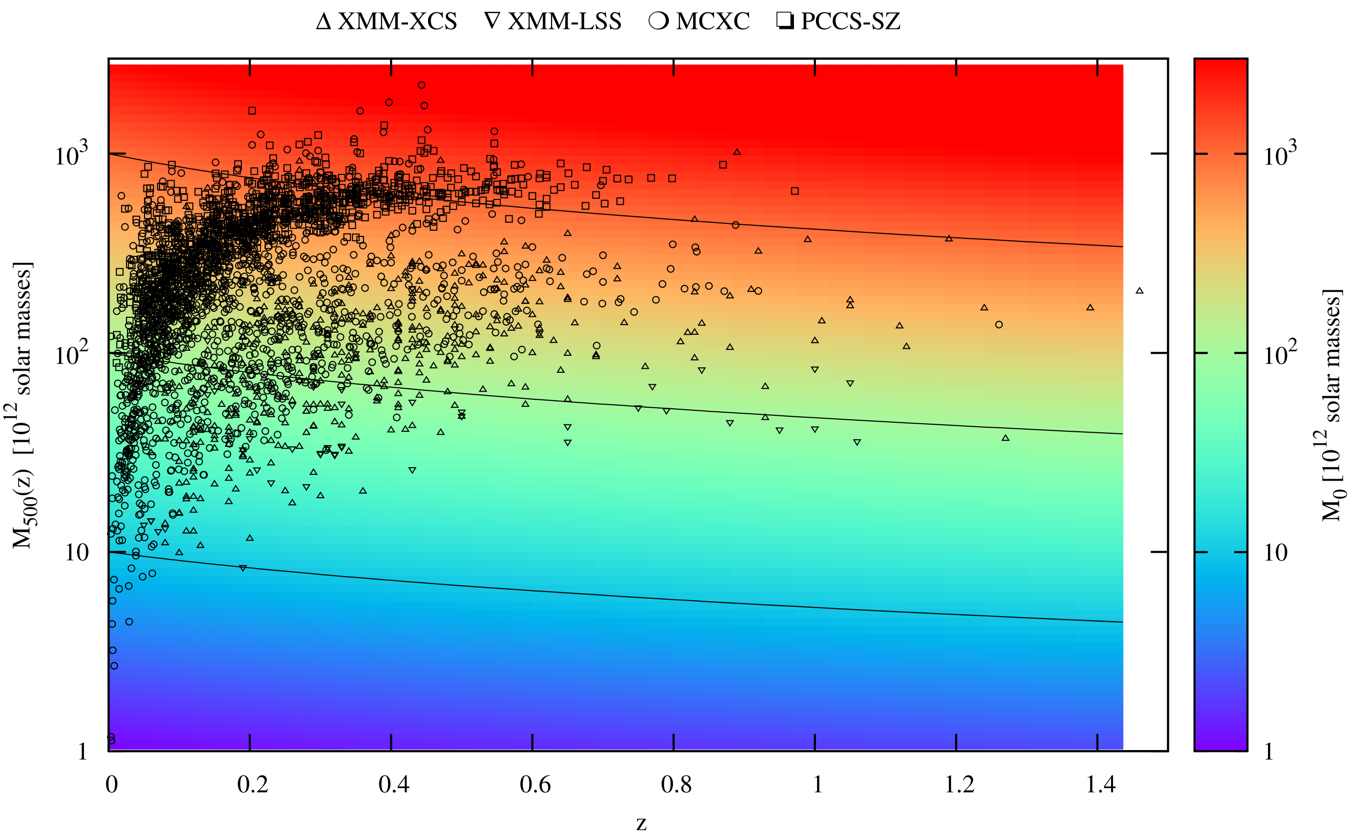


Figure 3. Logarithmic (above) and linear (below) observational and evolutionary homogenised cluster survey data. Each composite cluster survey (converted as neccessary) overlayed on top of a recreation of Fakhouri, Ma & Boylan-Kolchin's cluster mass acretion rate in the form of a surface plot. Isocontours of colour depict an increasing current day mass from **(blue)**-**(red)**.The corresponding luminosity $L(z)$ figures will be made available in the final publication.

In future work I intend to amend these primary results with more probabilistically distributed evolution paths based on the respective rate of each method of mass accretion (e.g. frequency of minor and major mergers). I also propose enforcing more rigorous statistical considerations as in Harrison & Hotchkiss (2013) who highlight observational limitations and the underlying naivety of preceding statistical analysis. Given the infancy of the investigation it is difficult to draw in depth conclusions from the observations and evolutionary analysis, however significant progress will be made in the follow up paper.

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