arXiv:2304.09169

The role of mass and environment in the build up of the quenched galaxy population since cosmic noon

ABSTRACT

We conduct the first study of how the relative quenching probability of galaxies depends on environment over the redshift range $0.5 < z < 3$, using data from the UKIDSS Ultra-Deep Survey. By constructing the stellar mass functions for quiescent and post-starburst (PSB) galaxies in high, medium and low density environments to $z = 3$, we find an excess of quenched galaxies in dense environments out to at least $z \sim 2$. Using the growth rate in the number of quenched galaxies, combined with the star-forming galaxy mass function, we calculate the probability that a given star-forming galaxy is quenched per unit time. We find a significantly higher quenching rate in dense environments (at a given stellar mass) at all redshifts. Massive galaxies ($M_* > 10^{10.7}$ $M_\odot$) are on average 1.7 ± 0.2 times more likely to quench per Gyr in the densest third of environments compared to the sparsest third. Finally, we compare the quiescent galaxy growth rate to the rate at which galaxies pass through a PSB phase. Assuming a visibility timescale of 500 Myr, we find that the PSB route can explain $\sim 50\%$ of the growth in the quiescent population at high stellar mass ($M_* > 10^{10.7}$ $M_\odot$) in the redshift range $0.5 < z < 3$, and potentially all of the growth at lower stellar masses.

Key words: galaxies: evolution – galaxies: formation – galaxies: luminosity function, mass function – galaxies: high-redshift

- Construct stellar mass function: M* (galaxy type, environment density, redshift)
  - Galaxy type: quiescent, post-starburst (PSB) galaxies
  - Environment density: high, medium, low
  - Redshift range: $0.5 < z < 3$
- Result: quenching rate is high in dense environments at all redshifts

1. Introduction

- Key issue: how galaxies transition from highly star-forming structures to passive systems?
- Role played by environment in quenching galaxies remains unclear at $z > 1$
- Previous researches: Post-starburst galaxies (PSBs) are more abundant in denser environments to $z \sim 1$

➔ suggesting a strong link to environmental quenching

- Post-starburst galaxies (PSBs): undergone a recent and major burst of star formation followed by rapid quenching

- No studies of the link between PSBs and environment at higher redshifts ($z > 1.5$)

2. Data and method

- Data: UDS Data Release 11 (DR11) catalogue
  - UDS: the deepest NIR survey conducted by the United Kingdom Infrared Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007)
- Photometric redshifts: EAZY code
- Applying simple stellar population (SSP) templates
- Stellar masses calculation: Bayesian analysis (Wild et al. 2016)
- Separating star-forming galaxies, passive galaxies, and PSBs: principal component analysis (PCA) technique (Wild et al. 2014 and 2016)
- Measuring galaxy environment: statistical manner, following Lani et al. (2013)

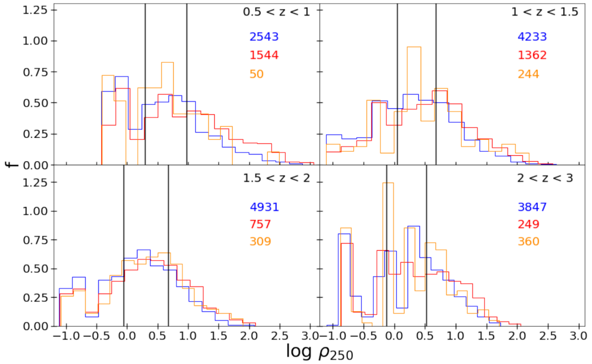


Figure 1. Histograms of environmental density ρ250 in our four redshift intervals, displayed separately for the star-forming (blue), quiescent (red) and post-starburst (yellow) galaxy populations. Solid black vertical lines in each panel represent the ρ250 values at which we split the total (combined) population to provide three density bins containing equal numbers of galaxies.

3. Result

3.1 Global mass functions

- Star-forming galaxy (blue): almost constant across cosmic time
- Quiescent galaxy (red): large build up in number density towards low redshift
- PSB mass function (yellow)
  - At $z<1.5$: similar to the star-forming galaxy (blue) population
  - At $z>1.5$: similar to the quiescent galaxy (red) population (increase relative number of PSBs at lower stellar masses)

➔ PSB and quiescent mass functions are essentially same at the highest redshifts

- Kolmogorov–Smirnov (KS) test: same underlying distribution, p = 0.27

➔ Support hypothesis of the PSB and quiescent stellar mass function in the redshift range $2 < z < 3$

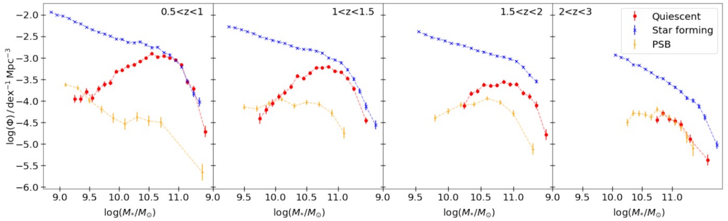


Figure 2. Global stellar mass functions for the quiescent (red), star-forming (blue) and PSB (yellow) populations as a function of redshift. The mass functions are cut off at the 90% mass completeness limit for each population, evaluated at the upper end of each redshift bin. Poisson error bars are shown.

3.2 Mass functions split by environment

1. Star-forming galaxy
- Stellar mass functions (SMF) are very similar overall in different environments

2. Quiescent galaxy
- Growth in the number density towards low redshift
- In $0.5<z<1.5$, increase abundance of quiescent galaxies in dense environments
- In $1.5<z<3$, the mass functions across all three density environments are similar

➔ Quenching is more effective in dense environments at lower redshift

3. PSB
- In $z<1.5$, increase abundance of PSBs in dense environments at low stellar mass ($M_* < 10^{10}$ $M_\odot$)
- PSBs are similar in all environments at $z > 2$

➔ Environment may only play a role in rapid quenching at lower redshifts

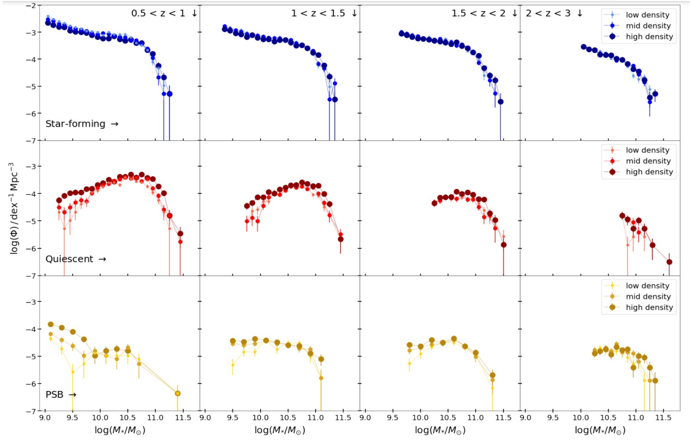


Figure 3. Global stellar mass function for the star-forming (blue), quiescent (red), and PSB (yellow) populations as a function of redshift and environment (low, mid, and high density).

3.3 The growth in the number of passive galaxies and the dependence on environment

: Estimate quenching rate (rate of growth in the number density of passive galaxies)

- Assumption: combine PSBs and older quiescent galaxies into a single 'passive' galaxy population
- Figure 4: number density of quenched galaxies is higher in high-density environments at all redshifts

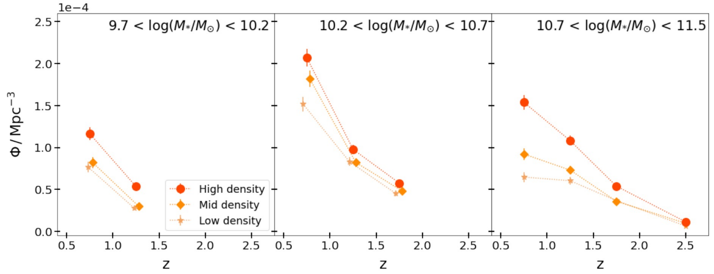
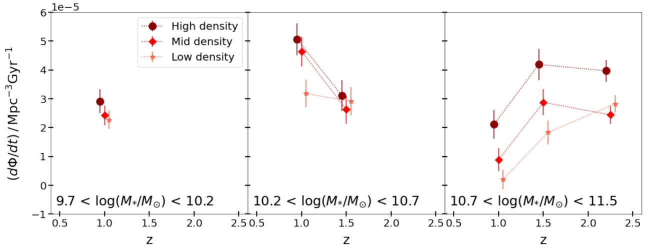


Figure 4. The evolution of passive galaxy number density as a function of redshift, split by mass and environment. Density bins are given in the legend, with darker colours and larger markers representing denser environments. Points are plotted at the midpoint of their respective redshift interval and are offset slightly for clarity. Poisson error bars are shown.

- Figure 5: growth rate in the passive galaxy number density

➔ The slope of the number density evolution is steepest for the highest density environments



$$\frac{d\phi_{red}}{dt} \approx \frac{\phi_{red,\ low\ z} - \phi_{red,\ high\ z}}{\Delta t}$$

$\phi_{red,\ low\ z}$: passive galaxy number densities in the lower redshift bins

$\phi_{red,\ high\ z}$: passive galaxy number densities in the upper redshift bins

Δt: difference in Gyrs between the midpoint of each redshift bin.

Figure 5. The number density growth rate of passive galaxies as a function of redshift, split by mass and environment. Density bins are given in the legend, with darker colours and larger markers representing denser environments. Points are plotted at the boundary between the two redshift intervals used in their calculation and are offset slightly for clarity. Errors are propagated from the Poisson error.

3.4 The probability of quenching and its dependence on environment

- Figure 6: the fraction of star-forming galaxies in a given mass and environment bin that are quenched (fraction of star-forming galaxies that were available to be quenched)

➔ 1. Quenching rate is higher in the high density environments at all redshifts and stellar masses
2. Quenched fraction increases with stellar mass

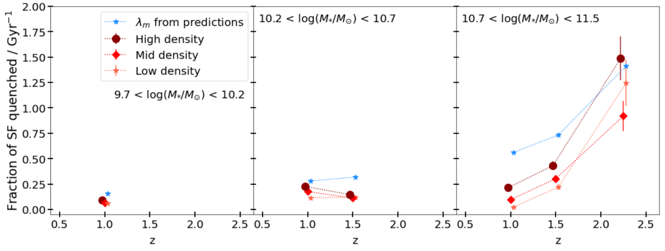


Figure 7. A simple comparison of the quenched fraction of star-forming galaxies (red points) to λ_m predictions

3.5 Comparison to low redshift empirical trends

- Key interest: whether the effects of galaxy environment and stellar mass on quenching are separable
- Peng et al. (2010): The mass quenching rate λ_m depends only on the SFR → $\lambda_m = \left(\frac{\mathrm{SFR}}{40\, M_\odot\, \mathrm{yr}^{-1}}\right) \mathrm{Gyr}^{-1}$
- To minimize the potential influence of environment, compare observed mass quenching rate at low-density environments (small red star marks) with predicted mass quenching rate λ_m (small blue star marks)

➔ The overall trends are similar. However, there is a difference between the quenching rates