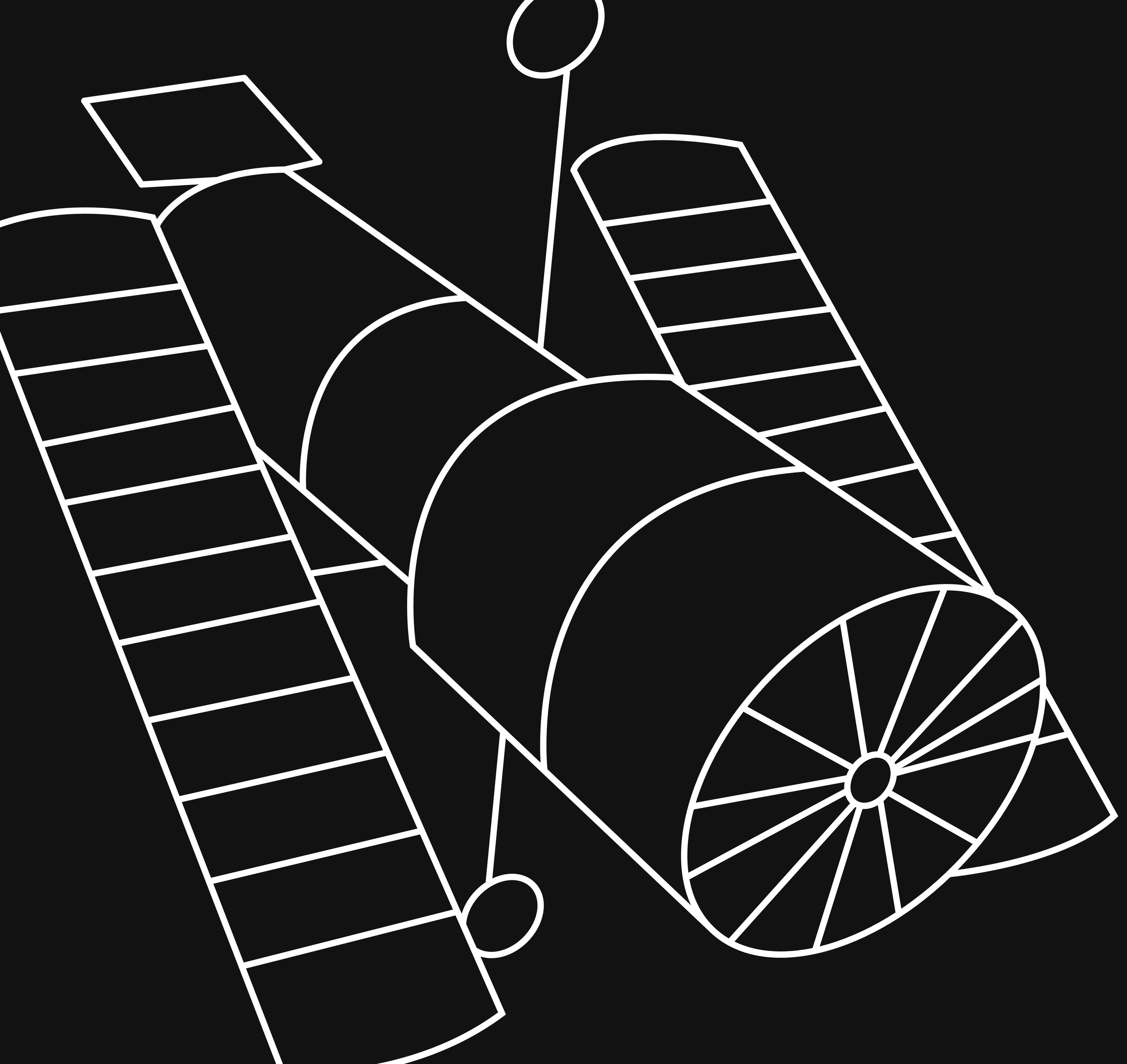

A key question in studies of galaxy evolution is when and how present-day galaxy structural relations came into existence. Studies indicate that there is a lot of morphological variation up to z~2. However, detailed analysis has been difficult due to limitations in resolution, imaging depth and wavelength coverage. With the new HST Wide Field Camera 3 it has become possible to analyze high-redshift galaxies to an unprecedented level of detail. Using ultradeep NIR data over the HUDF we investigate the rest-frame optical morphologies of a mass-selected sample of galaxies at z~2.

THE HUBBLE SEQUENCE AT Z~2

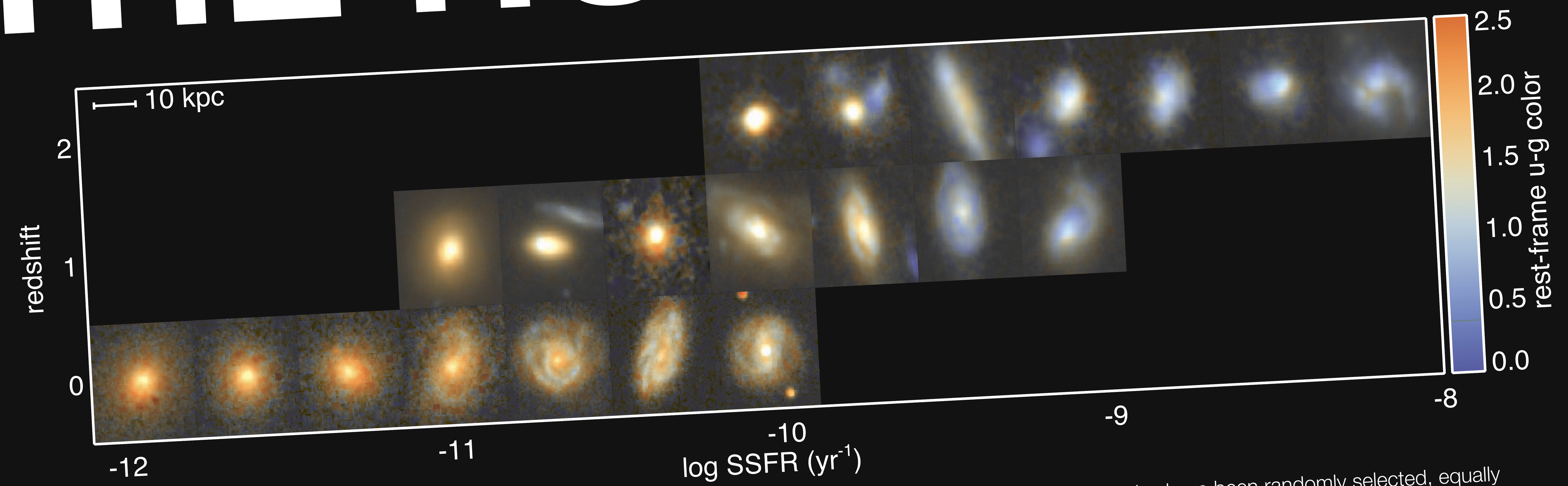

Figure 4: morphology as a function of redshift and specific star formation rate. From each redshift sample seven galaxies have been randomly selected, equally spaced in log SSFR. Colors are obtained from rest-frame u-g colors. Signs of a Hubble sequence (i.e., high SSFR galaxies are "diskier", more extended and bluer than low SSFR galaxies) appear to exist at z~2.

Morphologies

Complex, multicomponent objects

The sixteen most massive z~2 galaxies in the HUDF are shown in Figure 1. These galaxies show a large variation in morphology, size and color. One can distinguish red, smooth, compact galaxies; blue galaxies with disk-like structures; and other star forming galaxies which appear more irregular. Most of the galaxies have a well-defined, red core, and seem to consist of multiple components with different in stellar populations.

Morphology is a strong function of wavelength. Rest-frame ultraviolet morphologies are always clumpier and more irregular than rest-frame optical morphologies.

Color profiles

Negative color gradients

We measure surface brightness profiles of the z~2 galaxies, and of galaxies at z~1 (from the same dataset) and z=0 (from SDSS) in the same mass range. The surface density profiles of the z~2 galaxies (derived assuming a constant M/L) show a similar amount of variation as those of z~1 and z=0. Profile shapes range from exponential profiles to de Vaucouleurs profiles.

The galaxies' rest-frame u-g color profiles (Figure 2, middle row) confirm that the cores of most of the galaxies are redder than the outer regions. From these profiles we can derive color gradients (Figure 2, bottom panels). The median color gradients do not evolve strongly between z~2 and z=0.

Galaxy structure

Same correlations from z~2 to z=0

The deep and detailed surface brightness profiles which we have measured allow us to derive structural parameters such as size and Sersic index *n*. The relations between structure, color and specific star formation rate (SSFR) are shown in Figures 3 and 4. There is a clear relation between these parameters at all redshifts: star-forming galaxies have "diskier" (lower *n*) profiles and bluer colors than quiescent galaxies. The z~2 galaxies span a large range in SSFR, color and Sersic index, and the spread in these parameters is of roughly the same order of magnitude as at lower redshift.

Thus we find that the variation in galaxy structure at z~2 is as large as at z=0. Furthermore, the systematic relationships between different structural parameters are very similar between z=0 and z~2. This, in addition to the lack of evolution in the color gradients shown in Figure 2, suggests that the underlying mechanisms that give rise to the Hubble sequence at z=0 may already be in place at z~2.

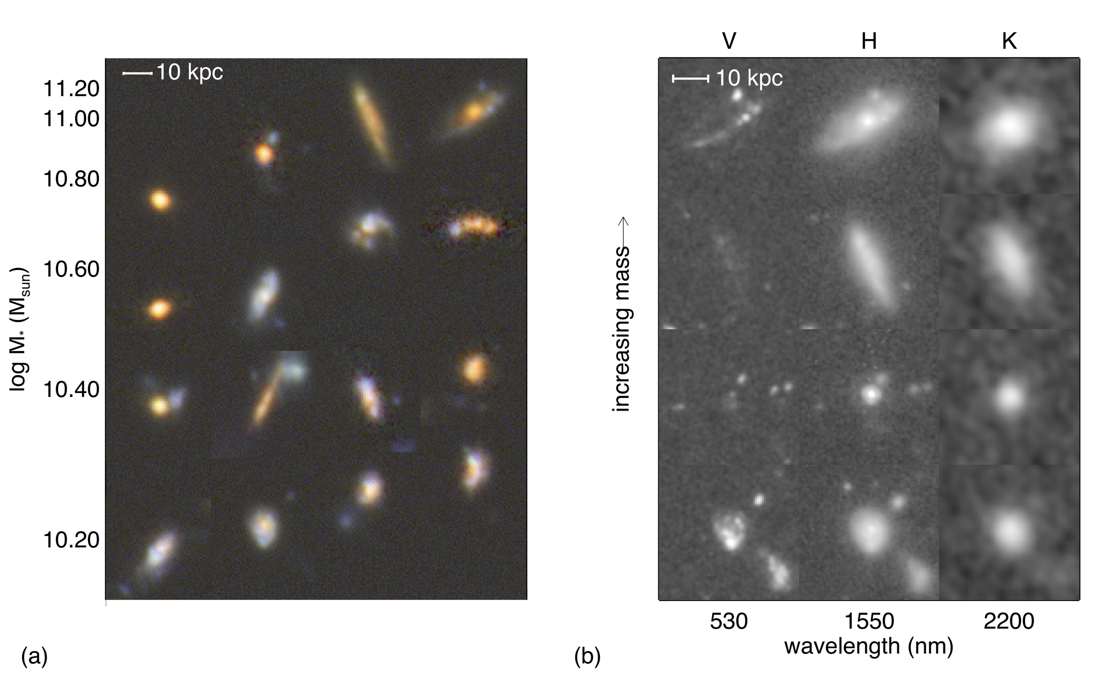

Figure 1: morphologies of galaxies in the HUDF with $1.5 < z < 2.5$ and $1.2\times10^{10}\ M_{sun} < M_{stellar} < 1.3\times10^{11}\ M_{sun}$. Color images composed of HST/ACS i_{775}, HST/WFC3 Y_{105} and HST/WFC3 H_{160} imaging are shown in Panel a. Morphology as a function of wavelength is shown for a small selection of galaxies in Panel b. Morphologies are varied and complex, and depend strongly on wavelength. Almost all galaxies contain a red core, presumably containing old stellar populations.

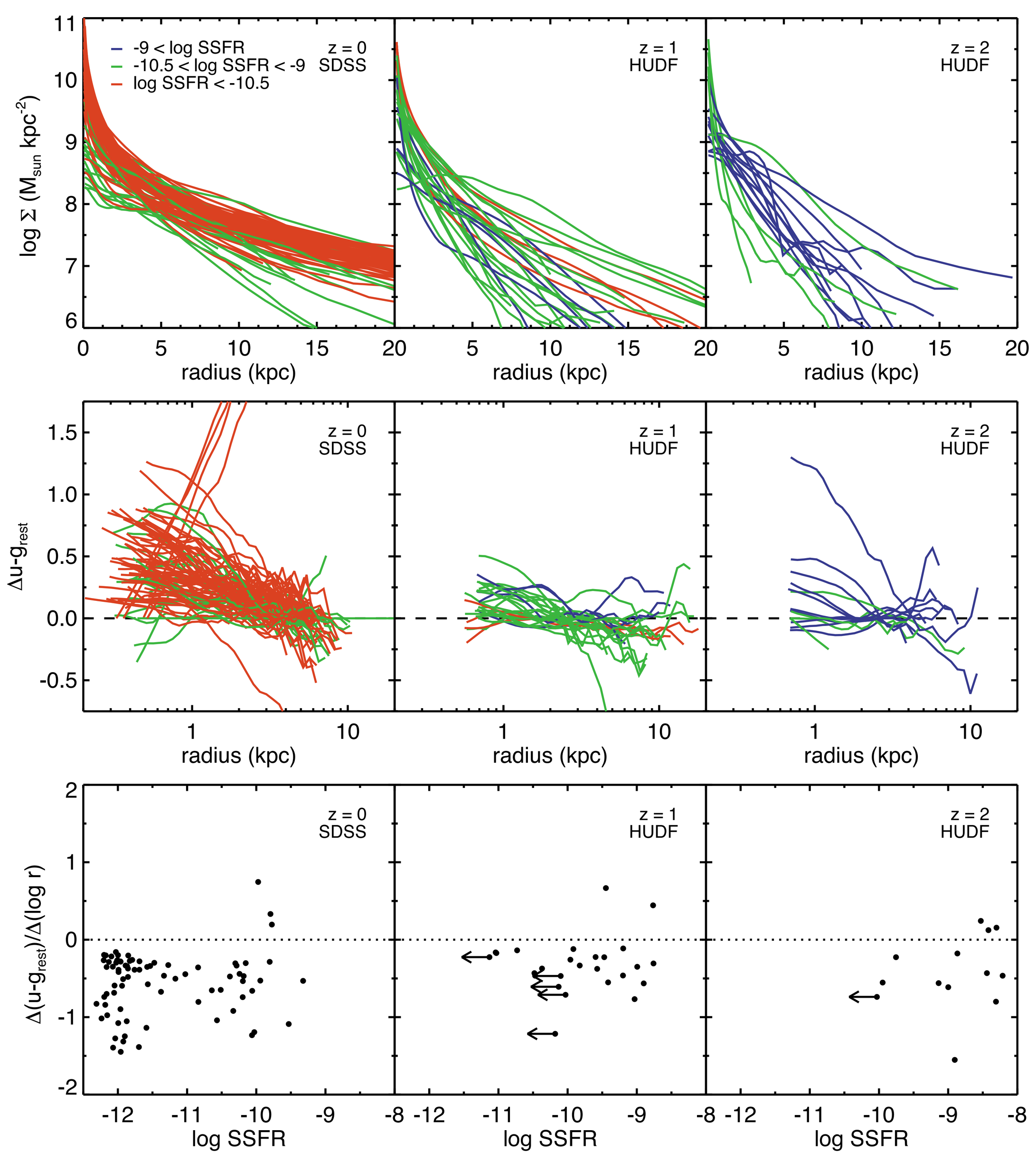

Figure 2: surface density profiles, rest-frame u-g color profiles, and color gradients of the z~2 galaxies, as well as galaxies at z~1 and z=0 within the same mass range. The range in profile shapes of z~2 galaxies is comparable to that at lower redshifts. The color profiles and color gradients show that most of the massive z~2 galaxies contain red cores. There seems to be little evolution in the color gradients with redshift.

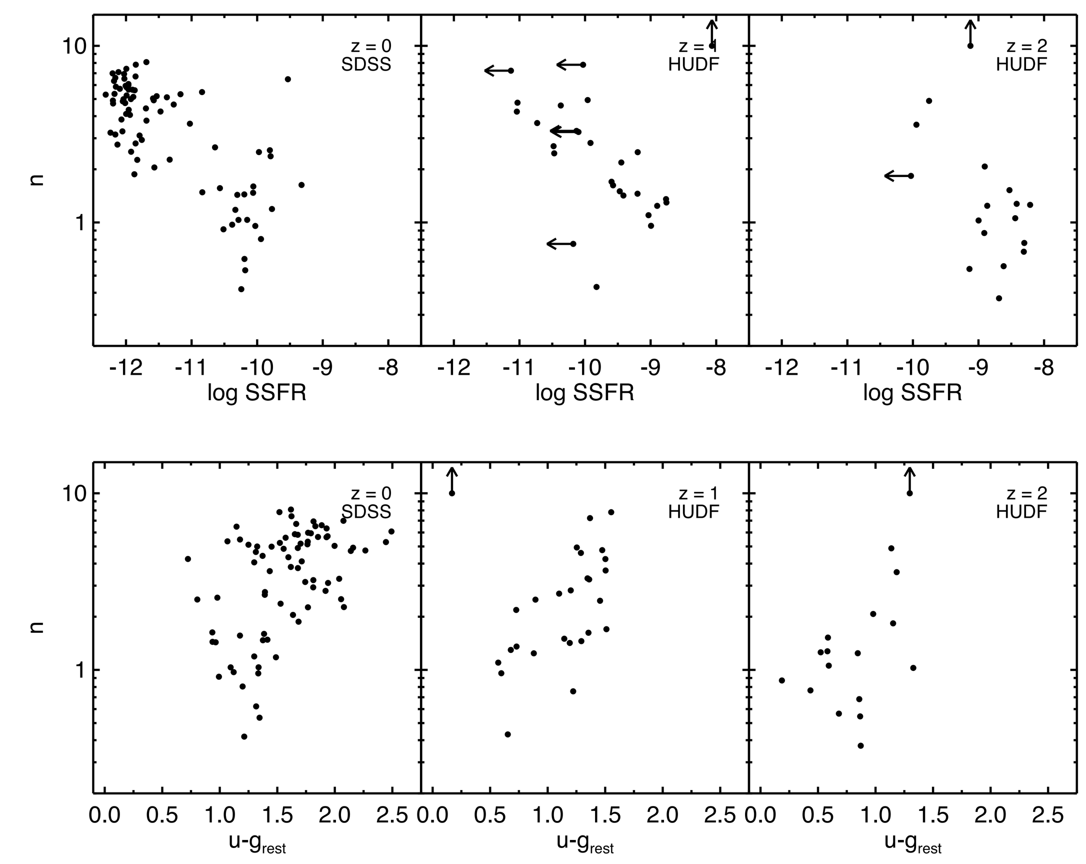

Figure 3: relations between Sersic index, color and specific star formation rate, as a function of redshift. There is significant evolution in these parameters: high-redshift galaxies are "diskier", bluer, and have higher SSFRs than low-redshift galaxies of similar mass. However, the overall correlations at z~2 are similar to those at low redshift: star-forming galaxies are bluer and have lower Sersic indices than quiescent galaxies. This suggests that a Hubble sequence exists for massive galaxies at these early times.

Based on "Morphological evolution of galaxies from ultradeep HST WFC3 imaging: the Hubble sequence at z~2", D. Szomoru[1], M. Franx[1], R. J. Bouwens[1], P. G. van Dokkum[2], I. Labbe[1], G. D. Illingworth[3] and M. Trenti[4], 2011, ApJL, 735, L22

[1] Leiden University - [2] Yale University - [3] University of California, Santa Cruz - [4] University of Colorado

Daniel Szomoru - szomoru@strw.leidenuniv.nl
http://www.strw.leidenuniv.nl/~szomoru/