Distant Red Galaxies

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Motivations

To understand how galaxies form and evolve, we must have unbiased samples of galaxies at high redshift that we can study.

Time and budget limitations make a large spectroscopic survey of high redshift galaxies impossible.

High redshift galaxies may give us clues to understand the star formation process in galaxies.

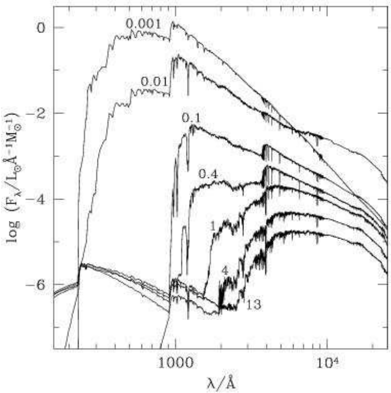
A young stellar population ($\sim 10^6$ yr) is dominated by star from young stars with strong UV.

Around 10^7 yr the most massive stars become red supergiants.

From 10^8 yr to 10^9, AGB stars keep NIR luminosity high.

Old Stellar Popluations

Spectral Evolution



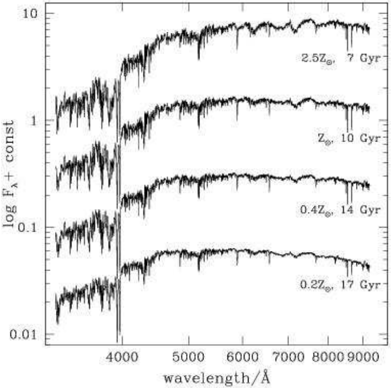
Bruzual & Charlot 2003

The Balmer break at 3646 Å corresponds to the $\infty \rightarrow 2$ hydrogen transition. Most prominent in A-type stars of intermediate age (0.3–1 Gyr).

The 4000 Å break is due to ionized metals in old late type stars' atmospheres.

These breaks shift from the UV to the NIR for objects at $z \approx 2$.

Old Stellar Popluations
Age-Metallicity Degeneracy



Bruzual & Charlot 2003

The interpretation of galaxy spectra is hampered by degeneracies in the adjustable parameters in stellar population models.

The effects of metallicity on spectra are similar to the effects of aging.

Some absorption lines that react differently to age and metallicity may be used if available for metallicity studies.

Lyman Break Technique Limitations

Normal galaxies are too large and too faint in the far-UV to be selected as LBGs at high redshift.

The Lyman break technique will preferentially select relatively unobscured, actively star-forming galaxies.

Stellar ages of LBGs are typically $\sim 3 \times 10^8$ yr, suggesting that the descendants of galaxies that started forming stars at higher redshifts may be underrepresented in surveys using the Lyman break technique.

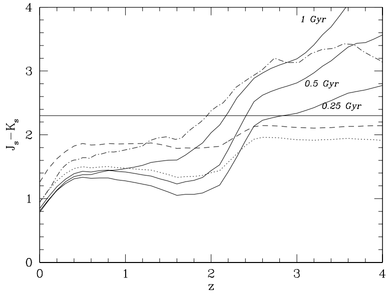
Building large samples of spectroscopically confirmed galaxies at high redshift is a time-consuming process.

Techniques for preselecting high-redshift targets are required to focus the spectroscopic capabilities on the interesting objects.

An efficient alternative to either photometric redshifts or magnitude-limited surveys is offered by simpler single- or two-color criteria (For example U-dropout technique).

Distant Red Galaxies

Photometric Selection

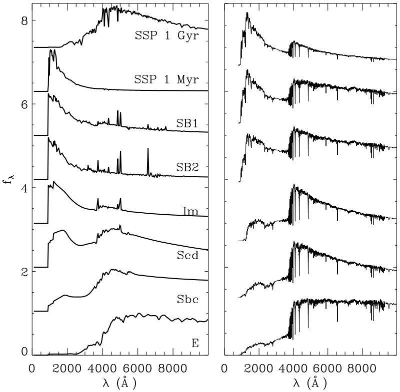


Franx et al. 2003

$J - K$ Color for single age stellar population at different redshifts.

The dotted and dashed s curves indicate models with continuous star formation.

The colors exceed $J - K = 2.3$ only for $z > 2$ as a result of the Balmer/4000 Å break moving into the J band.

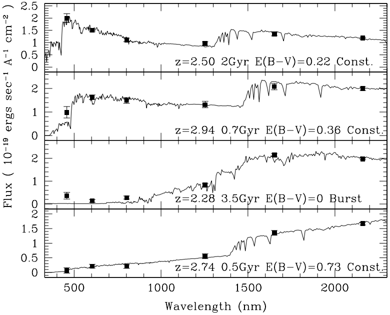


Kriek et al. 2008

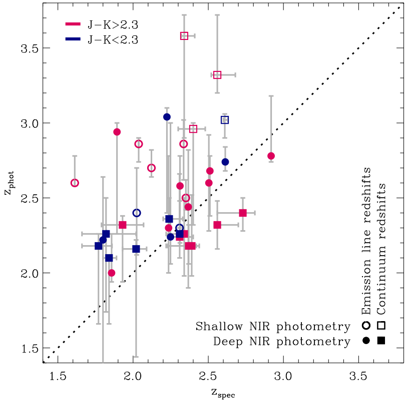
Empirical spectral templates from Hubble types E, Sbc, Scd, and Im.

Fit linear nonnegative superpositions of these templates to broadband photometry using χ^2 minimization.

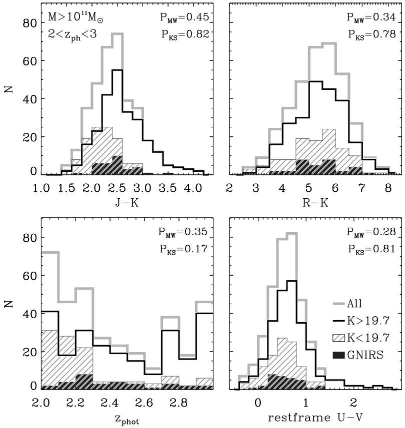
Scatter of $\Delta z/(1+z) = 0.13$ and systematic offset of $\Delta z/(1+z) = 0.08$.



Franx et al. 2003



Kriek et al. 2008

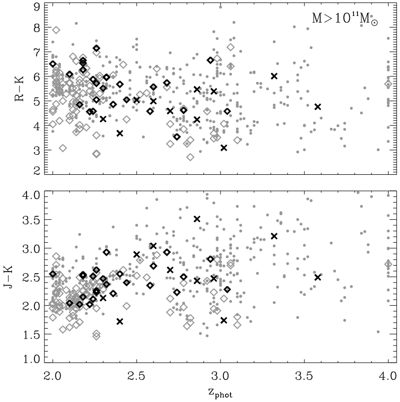


Kriek et al. 2008

Galaxies selected from MUSYC with $2.0 \lesssim z_{phot} \lesssim 3$, and $K \lesssim 19.7$.

To a good approximation, the total K-band light traces the accumulation of stellar mass (For $z \sim 2$ observed K band probes rest frame R band).

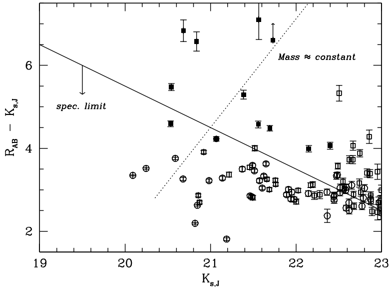
Mass limited sample from the deep MUSYC fields ($M > 10^{11} M_{\odot}$).



Kriek et al. 2008

Unlike LBGs samples, these technique gives a representative sample of galaxies at high redshift.

LBGs and DRGs selected from the HDF-S are almost disjoint samples.



Franx et al. 2003

DRGs at $2 < z < 3.5$:
$n = (1.0 \pm 0.4) \times 10^{-4}\mathrm{Mpc}^{-3}$
$\rho = (2.6 \pm 0.8) \times 10^{7} M_{\odot}\mathrm{Mpc}^{-3}$
$M_s \sim 10^{11} M_{\odot}$
Give 24 % of K-band light.

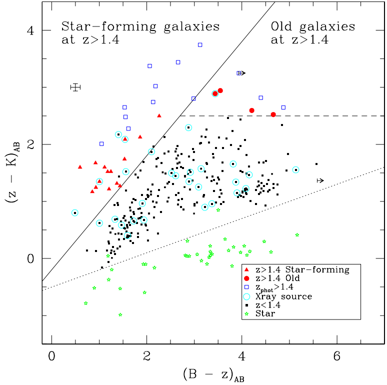
LBGs at $2 < z < 3.5$:
$n \sim 10^{-5}\mathrm{Mpc}^{-3}$
$\rho \sim 10^{5} M_{\odot}\mathrm{Mpc}^{-3}$
$M_s \sim 10^{10} M_{\odot}$
Give 55 % of K-band light.

It's expected that moderately old, or moderately reddened, objects exist at high redshift that would be missed by both the red color techniques and by the UV techniques.

The BzK selection technique is designed to pick up massive but still star-forming objects.

Distant Red Galaxies

Photometric Selection



Daddi et al. 2004

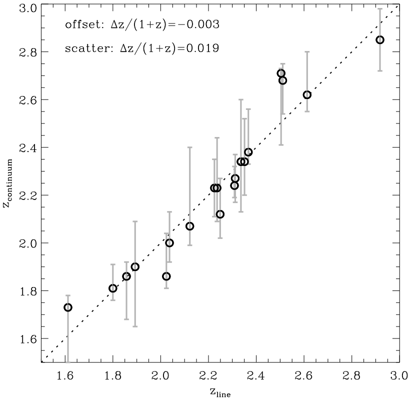
$$BzK \equiv (z-K)_{AB} - (B-z)_{AB}$$

$z > 1.4$ star-forming galaxies are selected by:

$$BzK \geq -0.2$$

Classification relies on $[\mathrm{O_{II}}]\lambda3727$ emission, $\mathrm{C_{IV}}$ absorption at 1550 Å and other features.

Distant Red Galaxies
Continuum Redshifts



Kriek et al. 2008

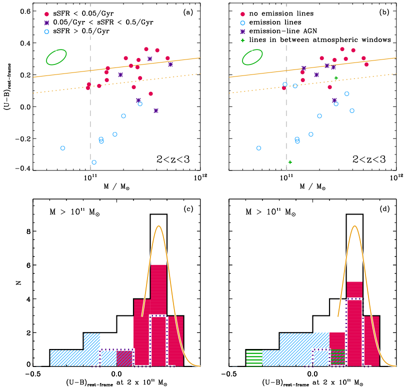
Derived from the continuum emission alone. Possible because of the Balmer/4000 Å break.

Fit binned spectra with the Bruzual & Charlot (2003) stellar population models assuming Salpeter IMF. Adjust reddening $0 < A_v < 4$.

Assume exponentially declining star formation histories with the characteristic timescale varying between 10 Myr and 10 Gyr.

Distant Red Galaxies Properties

Evidence of a Red Sequence at $z \sim 2$



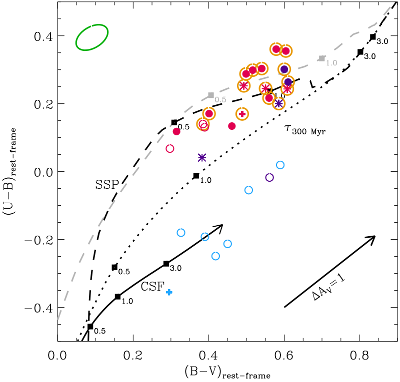
Kriek et al. 2008

$sSFR = SFR/M_s$

The distribution exhibits a conspicuous peak at $(U - B) \sim 0.25$ mag.

The odds of finding the detected red sequence by chance are less than 0.1 %.

No evidence of red sequence in LBGs samples.



Kriek et al. 2008

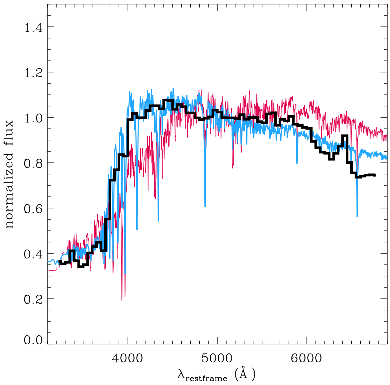
Are these dusty starburst galaxies?

The dashed line is a SSP models, the dotted line an exponentially declining model, and the solid line a CSF model. Dashed grey is a SSP with $Z = 2.5Z_{\odot}$.

Also, no detected rest-frame optical emission lines.

Distant Red Galaxies

Star Formation History



Kriek et al. 2008

The stellar light of a recently quenched galaxy is dominated by A-type stars, resulting in stronger Balmer breaks.

These is indication that the red-sequence was just beginning to form at $z \sim 2.3$.

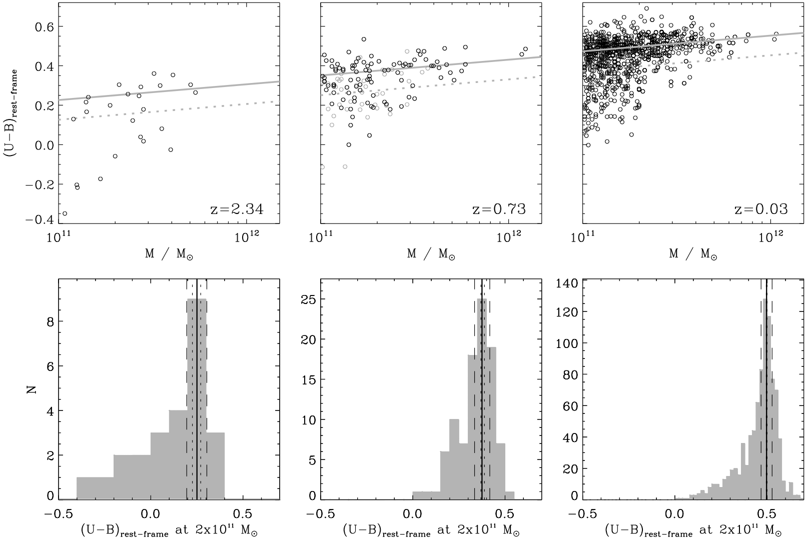
Two spectroscopic massive galaxy samples ($> 10^{11} M_{\odot}$) extracted from the Sloan Digital Sky Survey (SDSS; York et al. 2000):

(1) At $0.02 < z < 0.045$ Data Release 5 (DR5; Adelman-McCarthy et al. 2007).

(2) At $0.6 < z < 1.0$ theGreatObservatoriesOrigins Deep Survey (GOODS;Giavalisco et al. 2004).

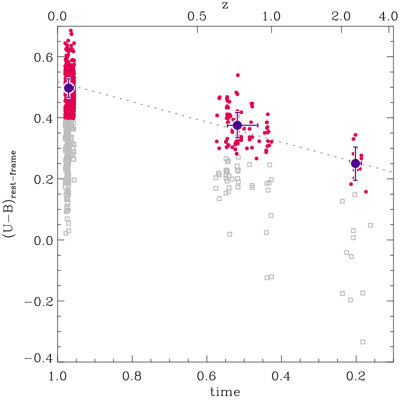
Distant Red Galaxies

Evolution of Red Sequence



Distant Red Galaxies
Evolution of Red Sequence

$$(U - B)_z = 0.19 + 0.33t$$

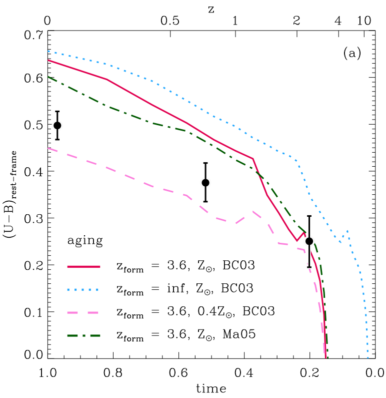


Kriek et al. 2008

PROPERTIES OF THE RED SEQUENCE ($>10^{11}\ M_{\odot}$)

Property	$z \sim 0.03$	$z \sim 0.73$	$z \sim 2.34$
Slope (dex^{-1})	0.08^{a}	0.08^{b}	0.08^{b}
$U - B$ at $2 \times 10^{11}\ M_{\odot}$	$0.50^{+0.03}_{-0.03}$	$0.38^{+0.04}_{-0.04}$	$0.25^{+0.06}_{-0.06}$
$\sigma_{(U-B)}$	$0.048^{+0.002}_{-0.002}$	$0.055^{+0.011}_{-0.000}$	$0.069^{+0.005}_{-0.010}$
$N_{\mathrm{RS}}/N_{\mathrm{total}}$	$0.77^{+0.02}_{-0.02}$	$0.71^{+0.04}_{-0.04}$	$0.56^{+0.08}_{-0.12}$
$M_{\mathrm{RS}}/M_{\mathrm{total}}$	$0.78^{+0.02}_{-0.02}$	$0.77^{+0.03}_{-0.04}$	$0.62^{+0.06}_{-0.11}$
$\rho_N (10^{-4}\ \mathrm{Mpc}^{-3})$	$8.89^{+1.45}_{-1.46}$	$7.46^{+2.82}_{-2.83}$	$1.11^{+0.37}_{-0.41}$
$\rho_M (10^{8}\ M_{\odot}\ \mathrm{Mpc}^{-3})$	$1.63^{+0.26}_{-0.27}$	$1.36^{+0.52}_{-0.52}$	$0.26^{+0.07}_{-0.08}$

[a] Adopted from van der Wel et al. (2007).
[b] $z \sim 0.03$ slope assumed.



Kriek et al. 2008

Passive evolution of single burst models.

Reasonable fit by passively evolving SSP model with subsolar metallicity.

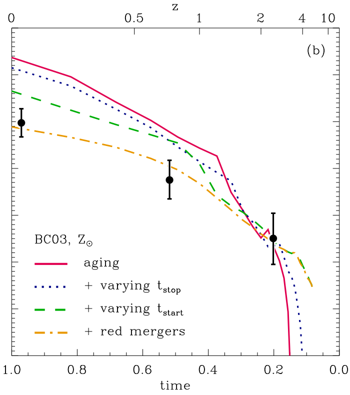
These contradicts results of metallicity studies of massive elliptical galaxies, which imply solar to supersolar metallicities (e.g., Worthey et al. 1992).

Kriek et al. 2008 explore more complicated models with an exponential distribution for galaxy formation time and star formation quenching time:

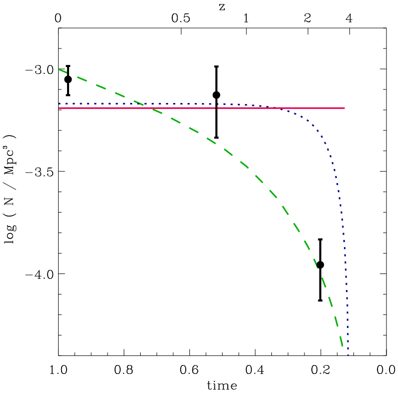
$$P(t_{\rm start}) \propto \exp(-t/\tau_{\rm start})$$

$$P(t_{\rm stop}) \propto \exp(-t/\tau_{\rm stop})$$

Distant Red Galaxies
Evolution of Red Sequence

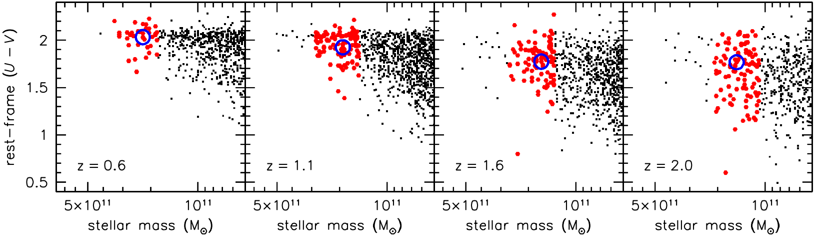


Kriek et al. 2008



Kriek et al. 2008

Data from the NOAO/Yale NEWFIRM.

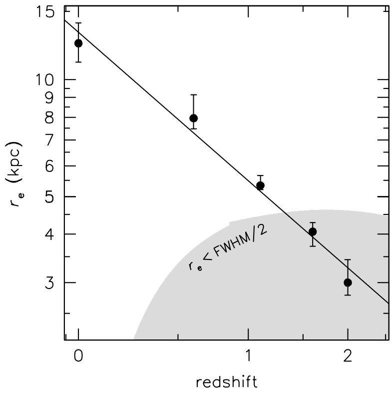


vanDokkum et al. 2010

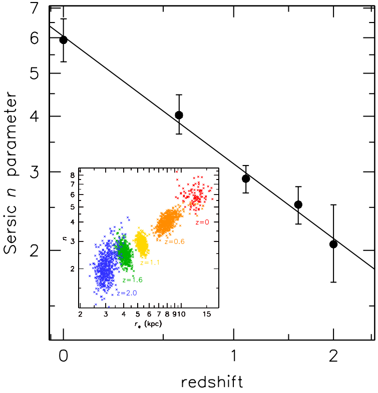
Distant Red Galaxies

Evolution of Red Sequence

$$\ln I(R) = \ln I_0 - kR^{1/n}$$



vanDokkum et al. 2010



MOSFIRE/NIR Spectrographs

MOSFIRE

Multi-Object Spectrometer for Infra-Red Exploration

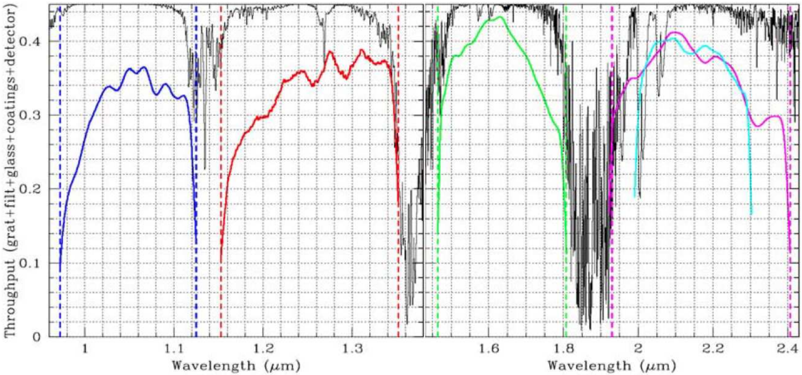
Multi-object spectrometer and imager for Keck 1. First light on Keck in April 2012.

Provides near-infrared (0.97 to 2.41 μm) multi-object spectroscopy over a 6.1' $\times$ 6.1' field of view with a resolving power of $R \sim 3,500$ for a 0.7" slit.

MOSFIRE is also a wide field camera, the bars that form the slits can be removed.

MOSFIRE/NIR Spectrographs

One atmospheric band at a time: Y(0.97-1.12 μm), J(1.15-1.35 μm), H (1.46-1.81 μm), or K(1.93-2.45 μm).



McLean et al. 2012

Conclusions

Photometric selection of distant red galaxies is a very convenient technique, and it gives reasonably accurate redshifts (Saves a lot of telescope time).

The red sequence was already formed at $z \sim 2.3$, and the data suggests that this is its starting point.

Passive evolution of stellar populations can't explain the evolution of the red sequence.

Multiple episodes of star formation, and mergers may play an important role.

References

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van Dokkum, Pieter G. et al., The Growth of Massive Galaxies Since $z = 2$, The Astrophysical Journal, Volume 709, Issue 2, pp. 1018-1041, 2010.