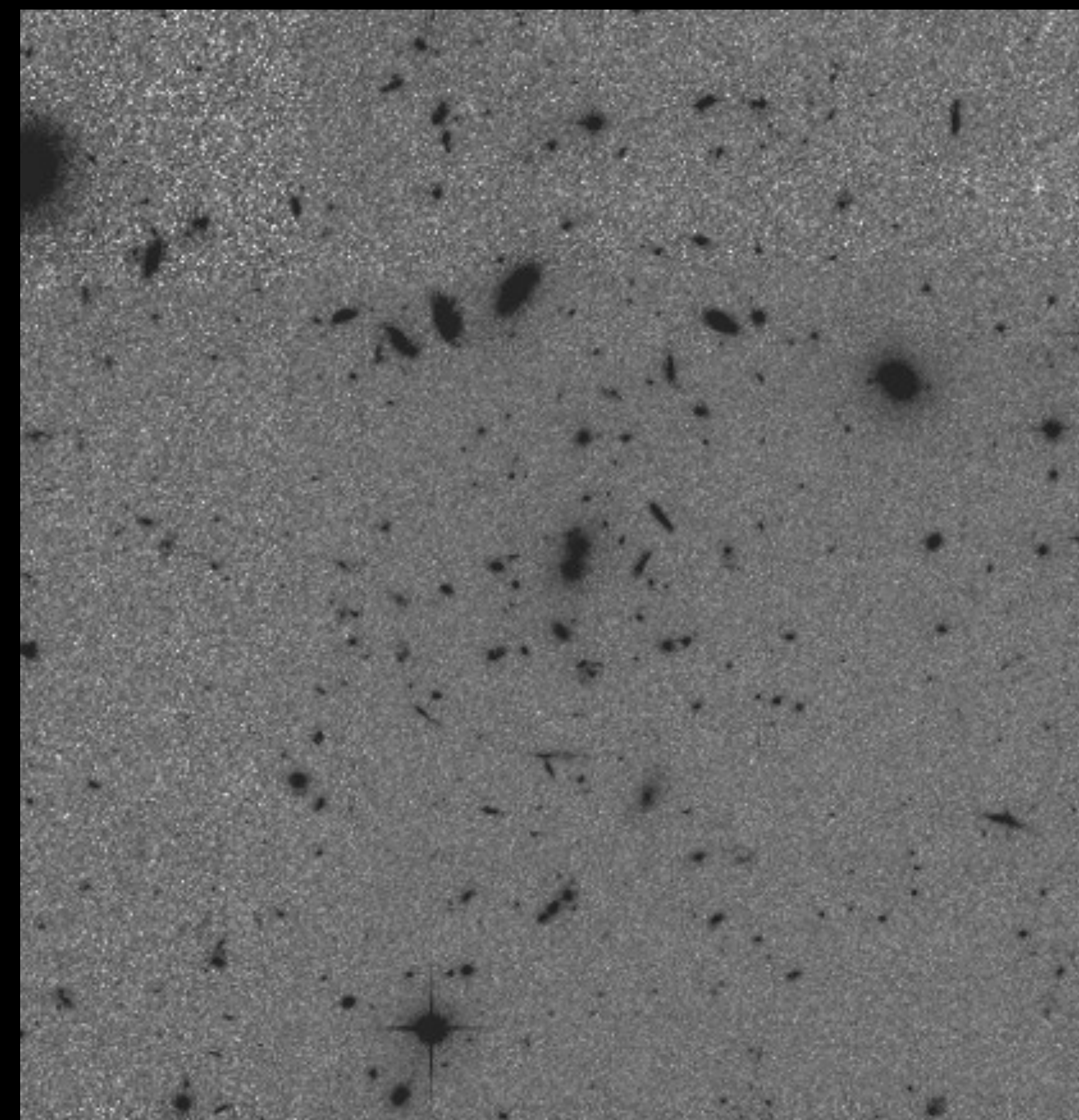
Already Big but Still Growing

Comparing Galaxy Evolution in Clusters at z ~ 1.2 and z ~ 0.8



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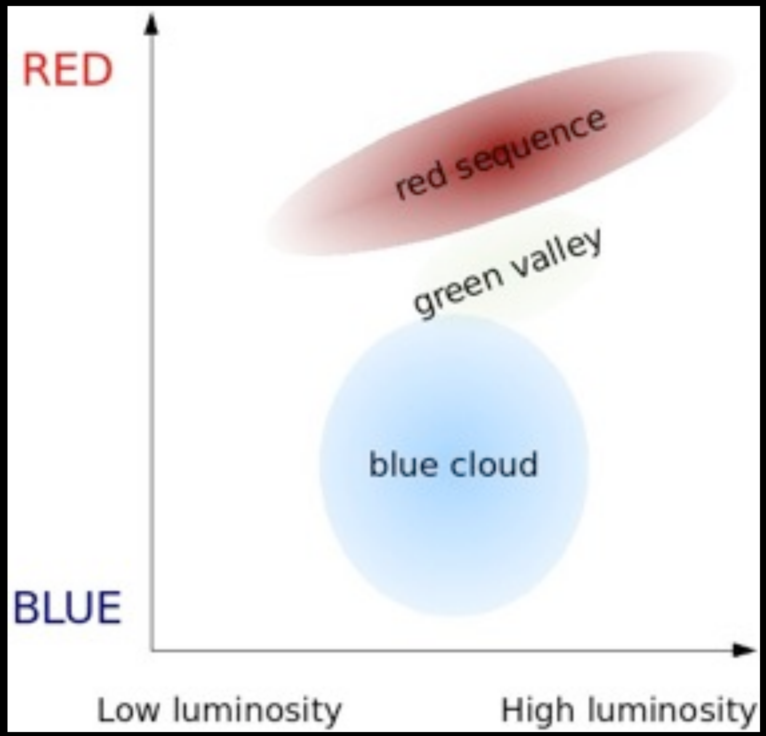
Clusters and the "Death" of Galaxies

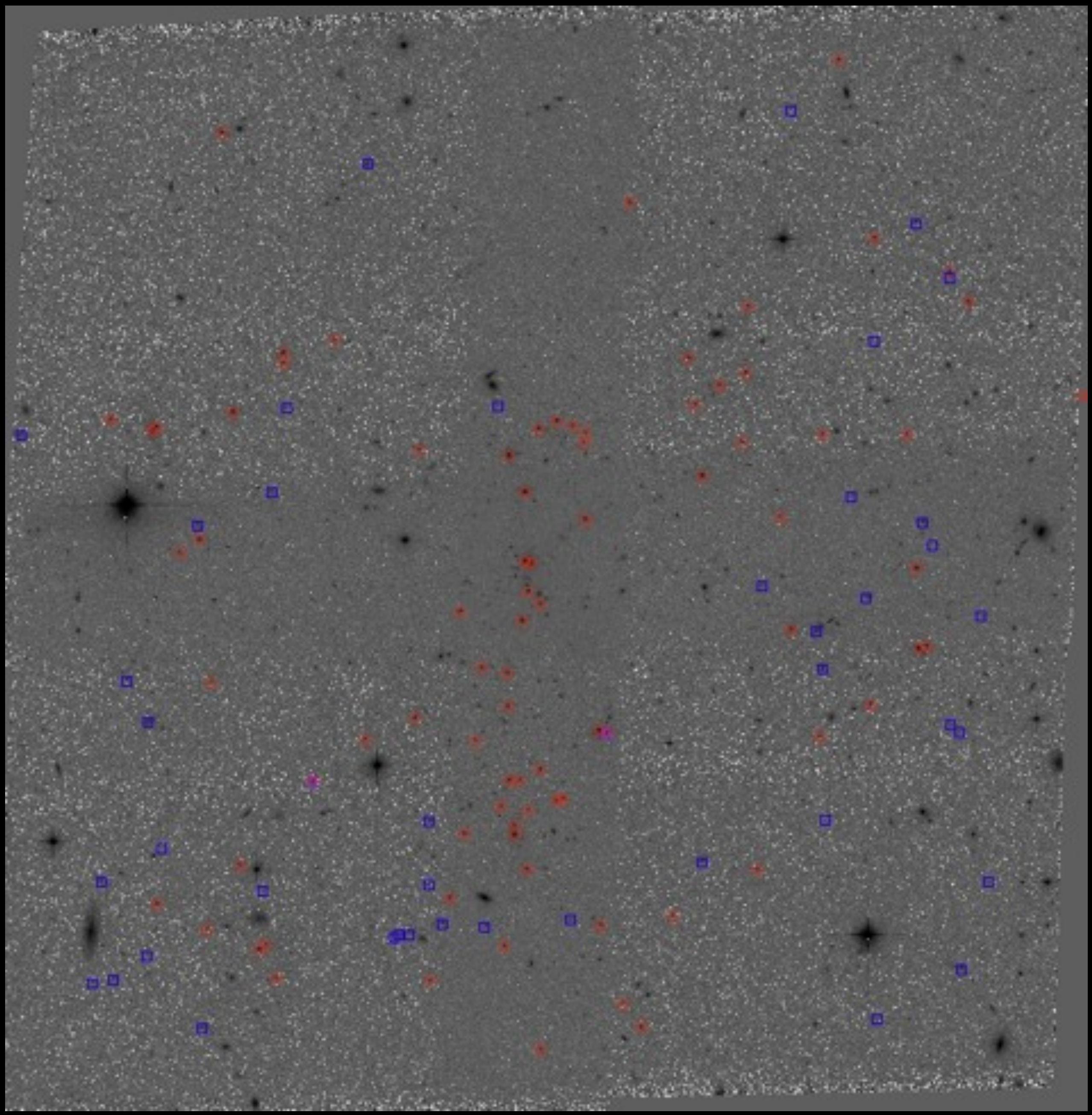
- Since at least z~1, even out to z~1.5, rich galaxy cluster cores mostly dominated by bright, non-star-forming Red Sequence (E/S0) galaxies. But at z>2, many clusters/protoclusters still found with even brightest galaxies still forming stars.
- Thus, many galaxies in rich clusters must have "died" and joined Red Sequence between redshifts of about 1 and 2, especially between redshifts 1.5 and 2. But when, where, and how exactly? (Self-quenching? Mergers? Strangulation? Ram pressure? Harassment? Outskirts, core, or in between? And at what redshifts?)
- Clusters at 1.5<z<2 still hard to find & study spectroscopically, but 0.8<z<1.5 increasingly easy to analyze in detail, and they still show evolution away from the blue cloud and towards the red sequence among their infalling galaxies.



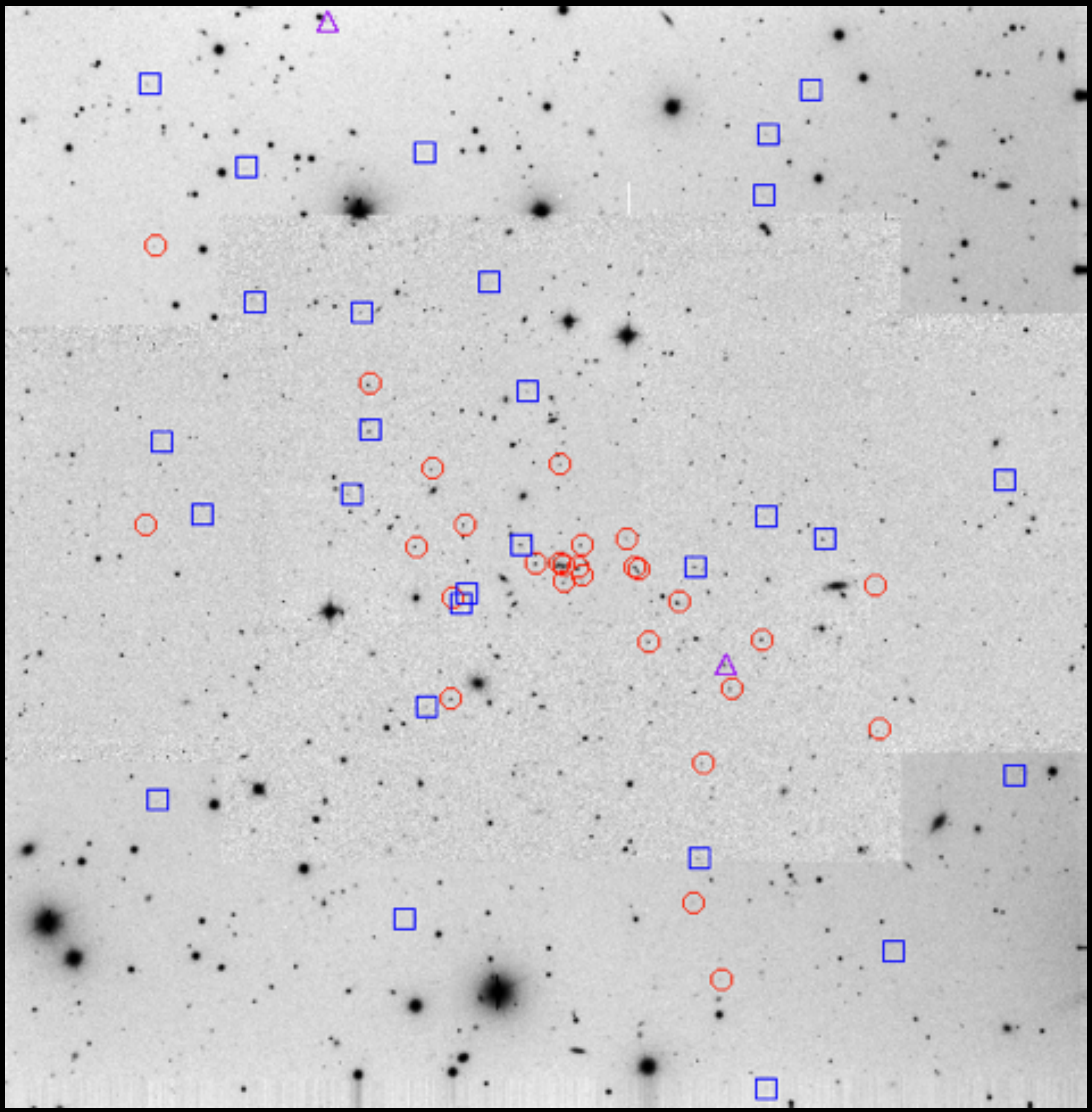
Schematic color-magnitude diagram for galaxies.
Credit: Josh Schroeder, Wikipedia

Ram-pressure-stripped galaxies NGC 4522 (top) and NGC 4402 (bottom) in Virgo cluster.
Credit: NASA/ESA (Hubble)

J0152.7 and J1252.9: Rich, growing labs of galaxy evolution



J0152.7, z = 0.84, 134 spectroscopic members, about 1/3 star-forming, in FORS1 + FORS2.
Image 5.88’ x 6.05’, 2.69 x 2.77 Mpc
shows ~124 members



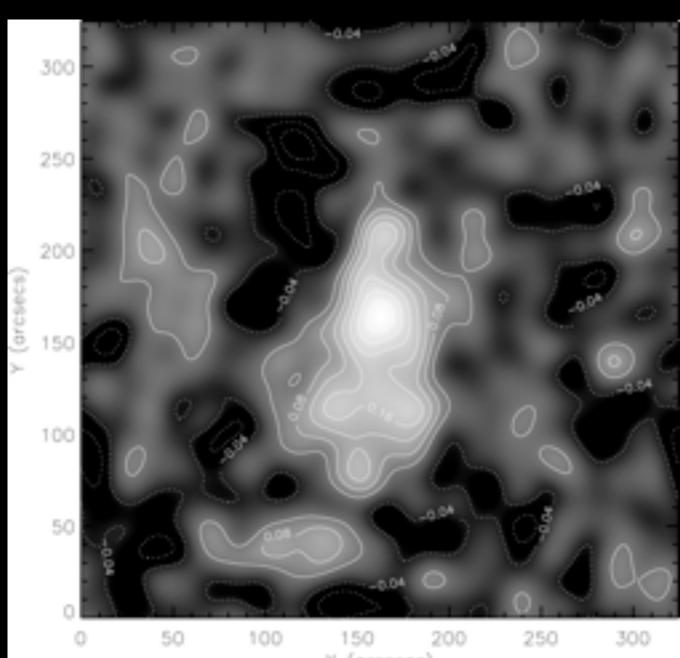
J1252.9, z = 1.24, 58 spectroscopic members, about half star-forming, in FORS1 and FORS2 (20 newly confirmed)
Image 6.67’ x 6.67’, 3.34 x 3.34 Mpc
shows all members

How can these clusters tell us where and when galaxies evolve?

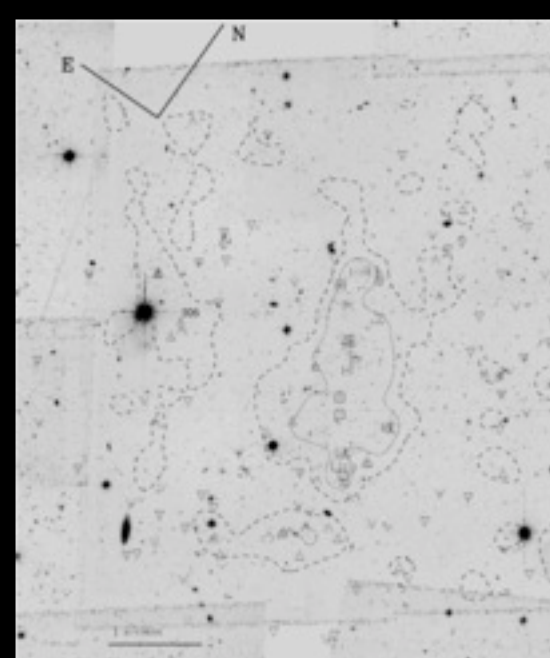
- Both clusters are massive and X-ray bright, and home to substantial spectroscopically confirmed populations of passive and star-forming galaxies of all Hubble types.

- Member galaxies' spectra can be stacked to improve S/N, and smoothed to some reference rest-frame resolution (e.g. 14 A) for comparison with SSP models and low-redshift work (and to improve the S/N).

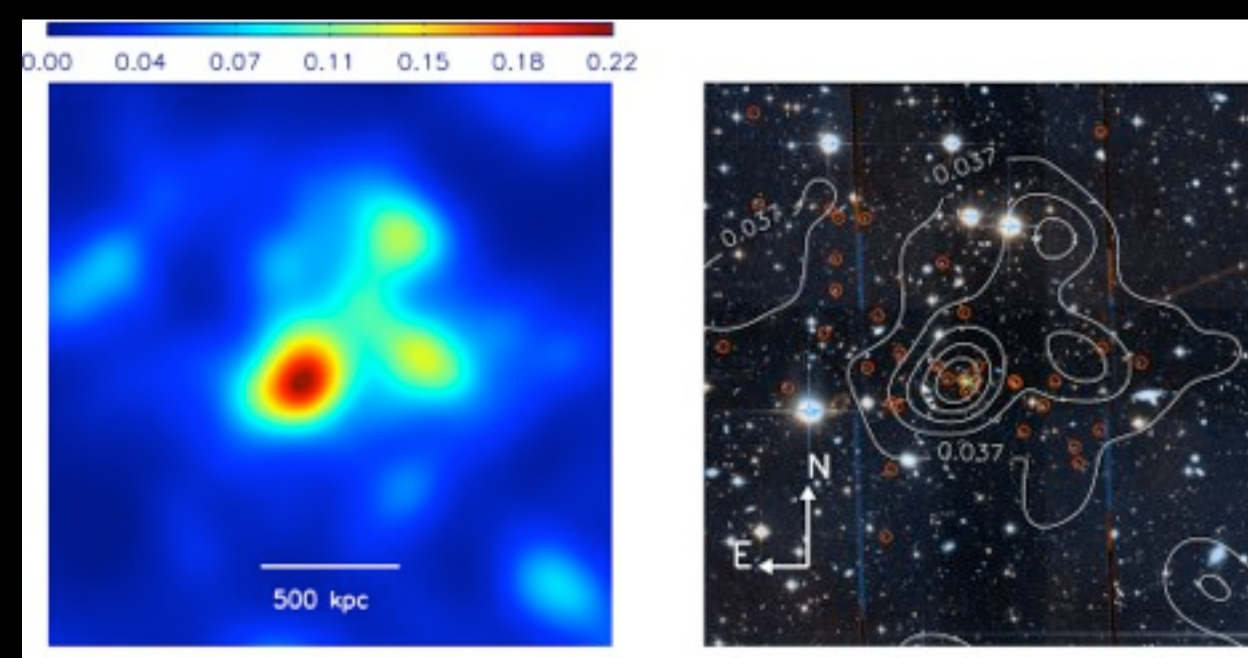
- Stacks by K-band magnitude and weak-lensing "kappa" (~dark matter density, Jee et al. 2005, 2011) can be analyzed to tell us the state of galaxy evolution in different regions and at different magnitudes. We can thus see which galaxies in which locations are most actively evolving at and between the two cluster redshifts.



J0152.7 weak lensing map as grayscale and contours
Jee et al. 2005



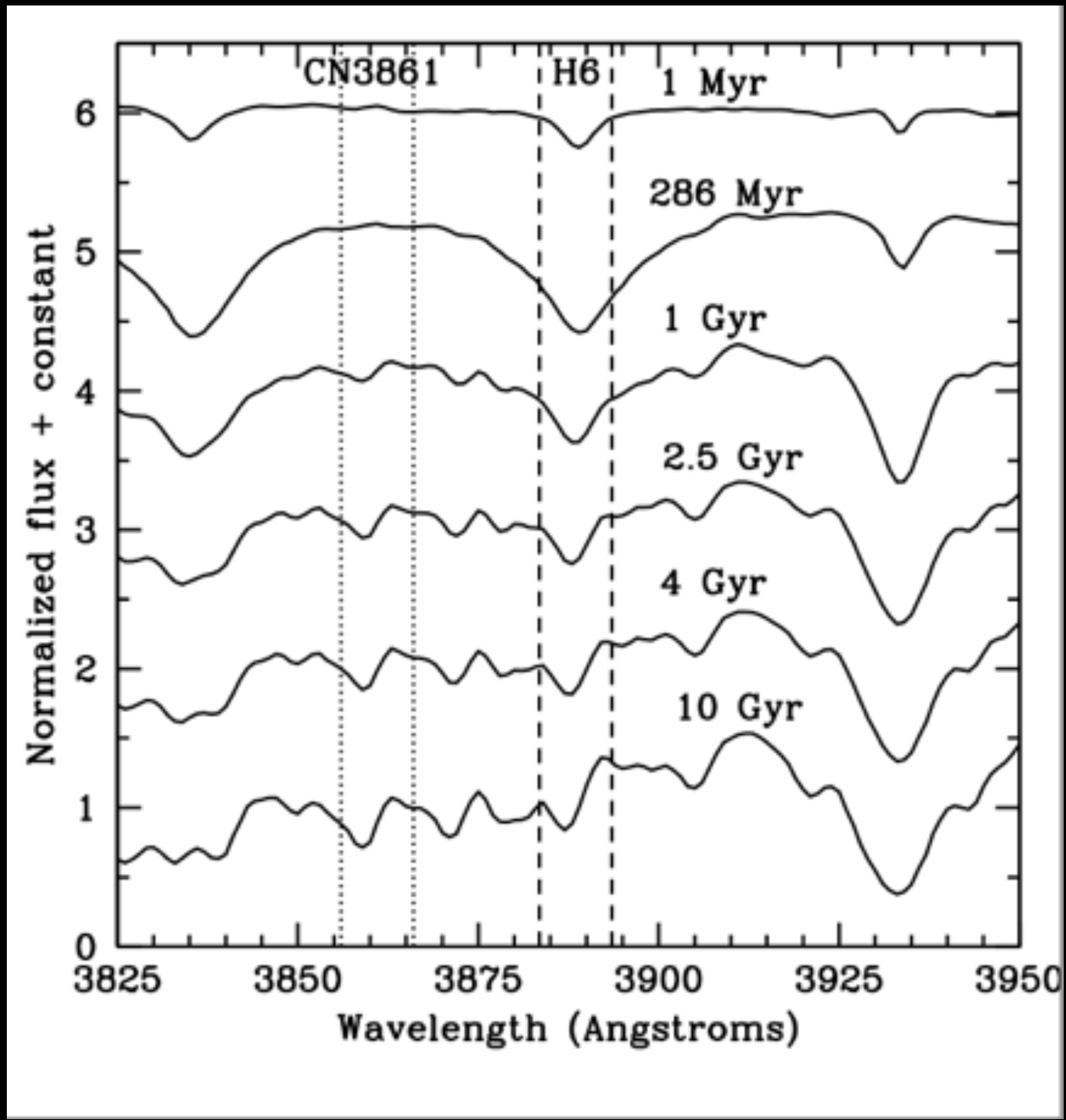
J0152.7 dark matter map based on weak lensing contours, over Hubble image
Demarco et al. 2010



J1252.9 weak lensing map as false color and contours over Hubble image
Jee et al. 2011

Divide, Stack, and Analyze

- Excluding obvious AGN and S/N < 1, galaxies stacked according to Bright (K < K*+1) and Dim (K > K*+1), and High (kappa > 0.11 or 0.12), Intermediate (0.04 < kappa < 0.11), and Low (kappa < 0.04) environmental density, after correcting all galaxies to rest frame using known redshifts.
- [OII]-emitting "late type" and non-emission-line "early type" galaxies analyzed separately, to eliminate bias from how much harder it is to find passive galaxies at higher redshift.
- Smoothing: We assume limiting case velocity dispersion of 330 km/s,* divide instrumental resolution (11-16 A for most galaxies) by 1+z (resulting in ~6-8 A effective instrumental resolution), and smooth to ~14 A and ~20 A rest frame total resolution. For J0152.7, galaxies in lowest-resolution masks (FORS1, grism 150I) excluded from ~14 A sample. Spectra also analyzed unsmoothed.
- Spectral indices measured: Dn4000 and a new H6 index ("CN3861/H6") defined as a ratio of the mean flux in a 10 A range centered on 3861 A, which includes a CN trough (3859) and a blue pseudocontinuum peak (3863), and a 10 A range centered on the trough of H6 (3888.5)

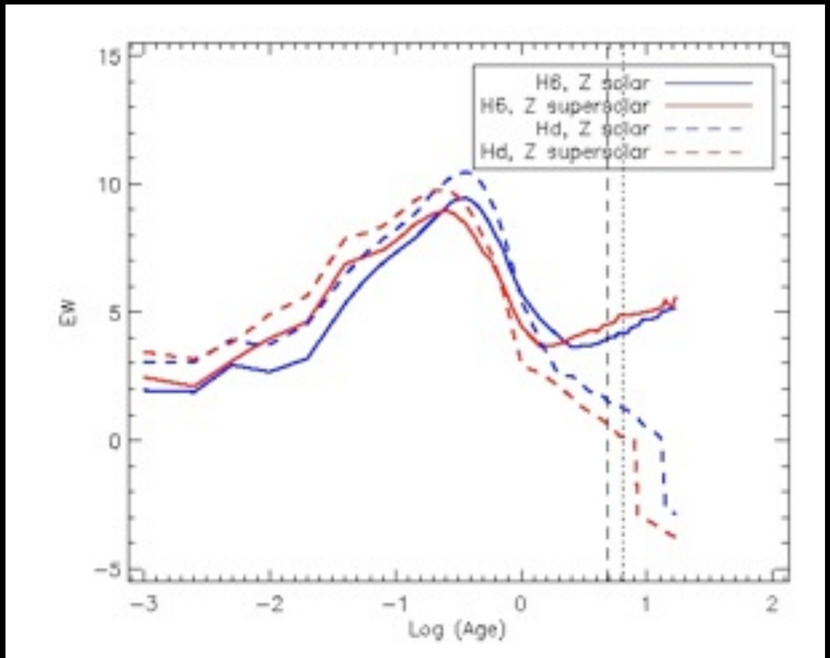


Bruzual & Charlot (2003) models with CN3861 and H6 wavelength bands used to define the CN3861/H6 index.

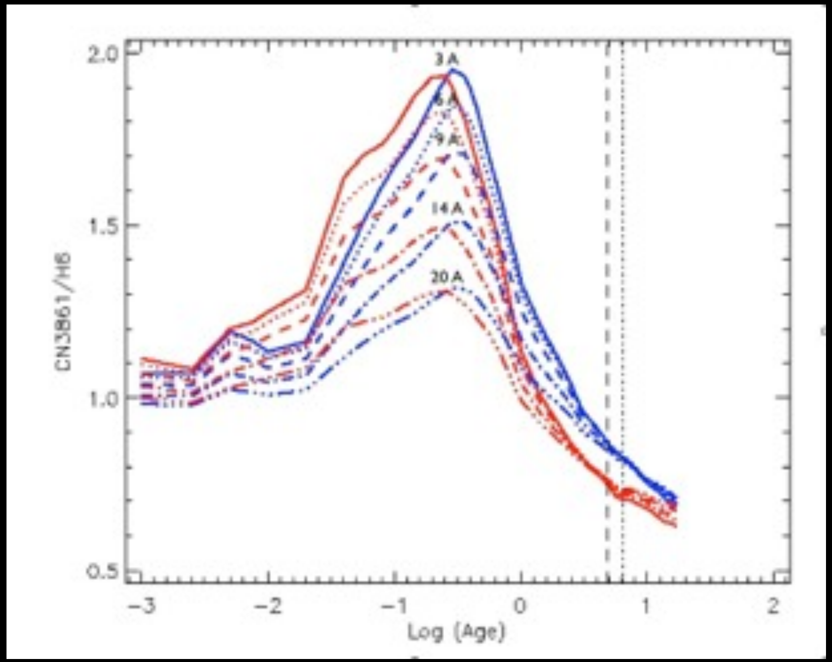
*Holden et al. (2005) find vel. disp. of 323 km/s for one of the brightest galaxies in J1252.7

Why define a new H6 index?

1. The Accuracy Problem



H6 EW and Hd at 14 A resolution. H6 EW turns over at a couple Gyr. in BC03 models. CN band lowers H6 and blue continuum flux while red continuum flux remains high.

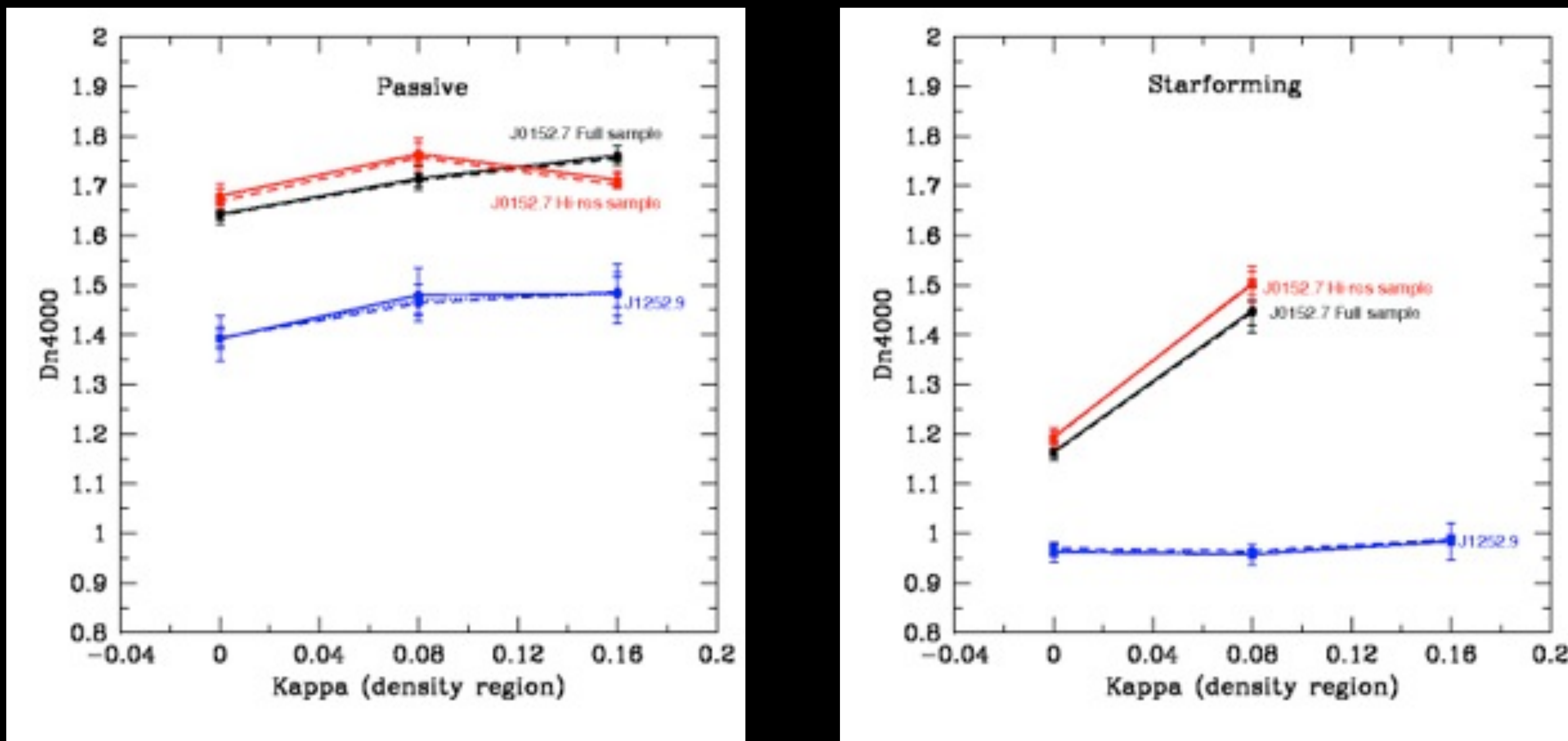


CN3861/H6 at various resolutions. Index continues to decrease with age, like Hd, since the two wavelength bands are both affected similarly by CN.

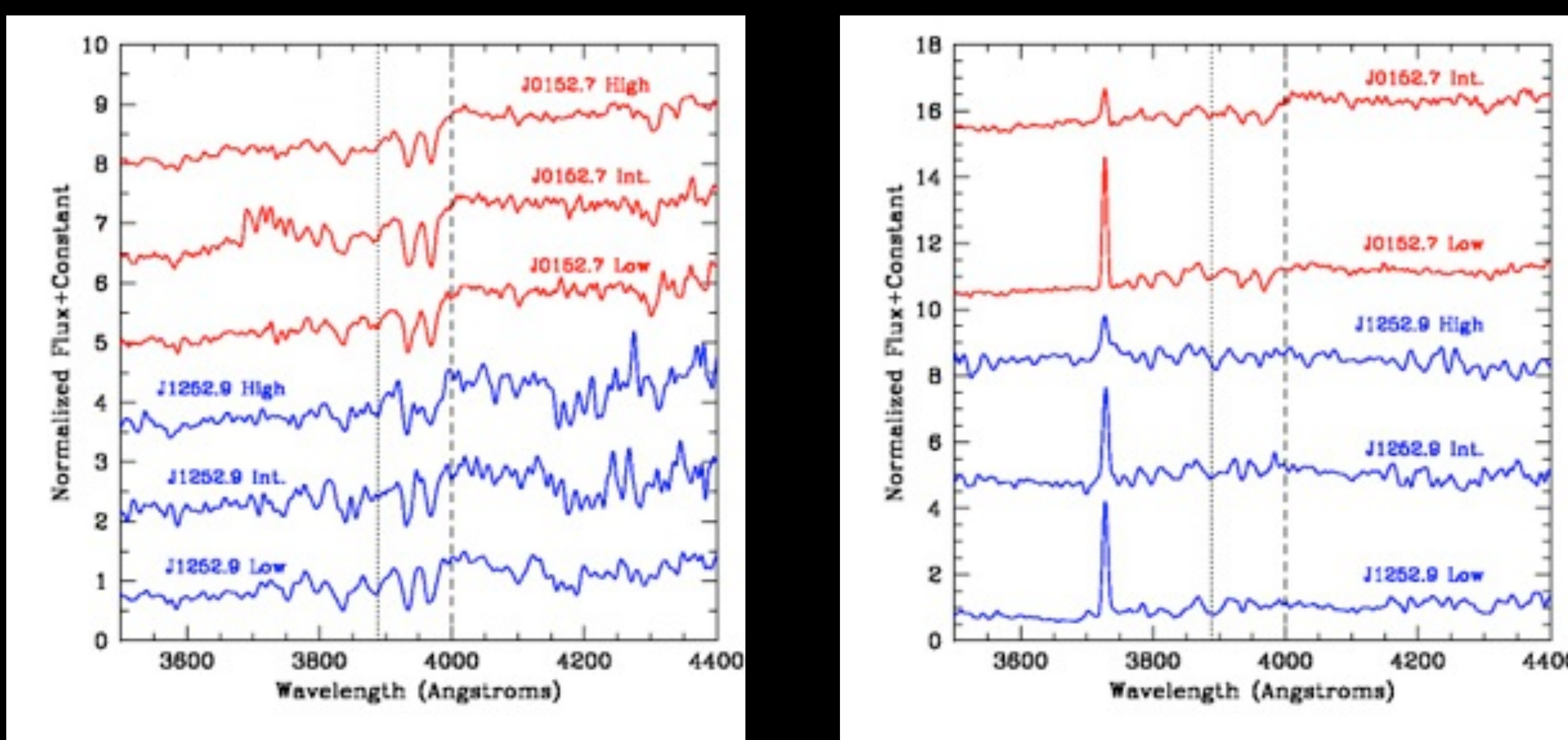
2. The Redshift Problem

- For Hd, good S/N necessary out to 4161 A rest frame (red continuum).
- For CN3861/H6, we only need good S/N out to 3893.5 A rest frame (end of H6 trough region)
- Ground-based spectra often become very noisy at 10,000 A observed frame, and moderately noisy at 9300 A.
- The red continuum of Hd hits 10,000 A at z = 1.403, while the red end of CN3861/H6 doesn't hit 10,000 A until z = 1.568.
- Therefore...CN3861/H6 shows promise as an alternative to Hd for higher redshifts where Hd may not be detectable or S/N may be poorer.

D4000 vs. Density Region



Dn4000 values: solid lines = unsmoothed, dotted = 14 A, dashed = 20A

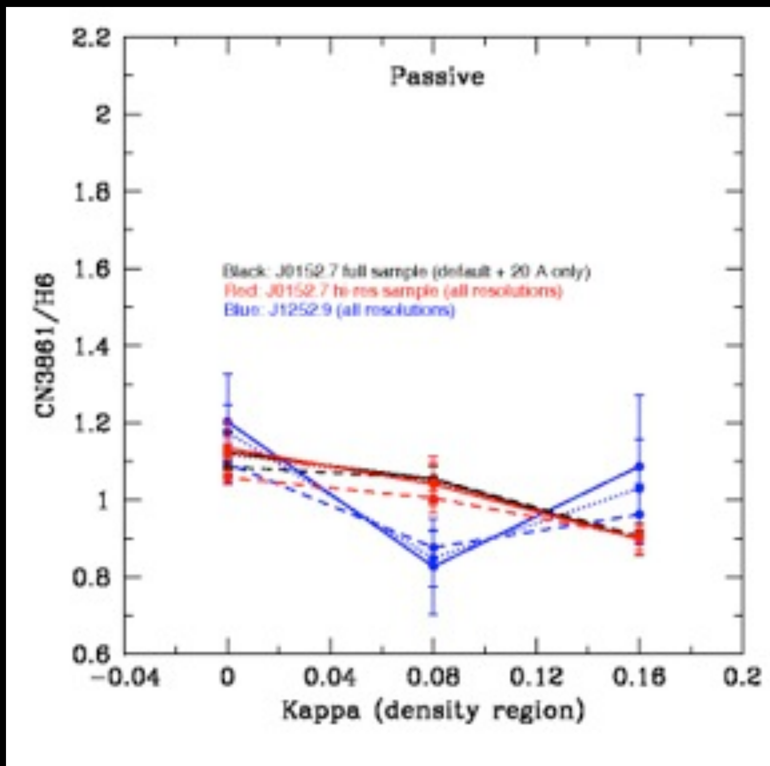


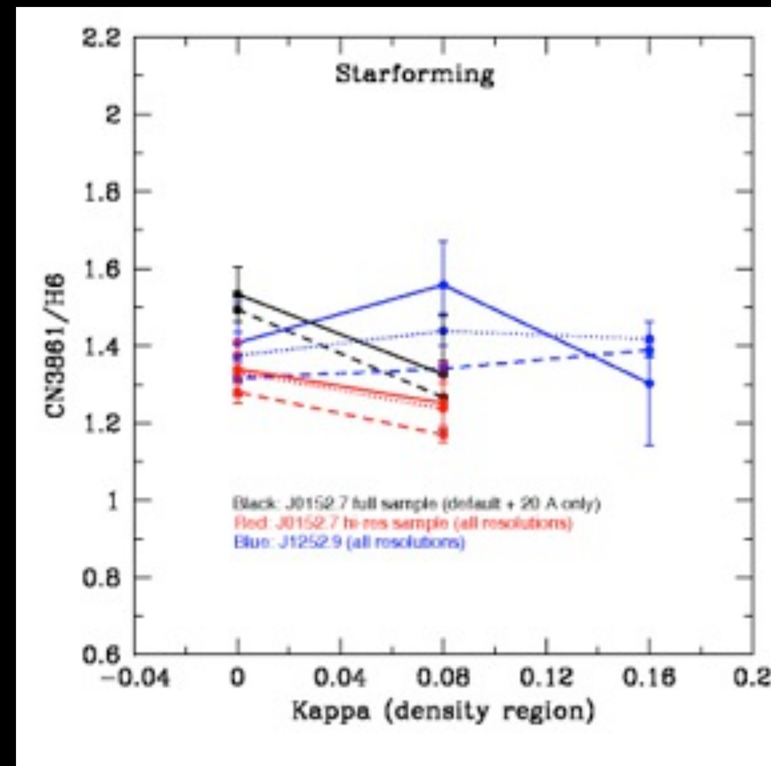
Stacks at 14 A: dotted vertical line = H6, dashed = 4000 A

Star-forming galaxies in intermediate-density regions of J0152.7 have much higher D4000 than in J1252.9. In fact, their D4000 is comparable to the passive galaxies of J1252.9! This suggests notable evolution of late types toward the Red Sequence in 1.5 Gyr.

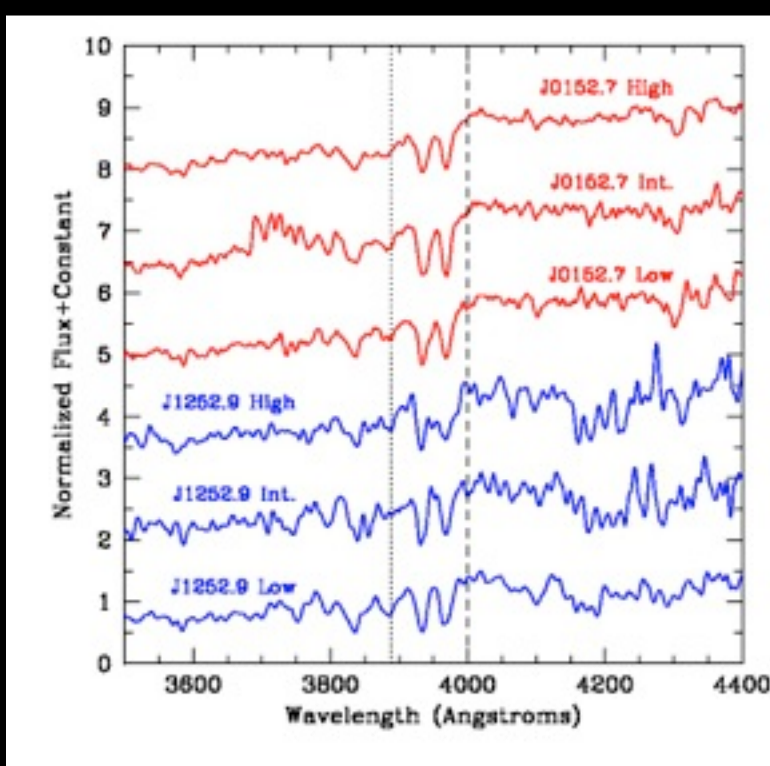
D4000 difference between the clusters among all groups of passive galaxies suggest age difference around 2 Gyr between the two clusters assuming BC03 models (2.3-3.4 Gyr at solar metallicity,1.1-1.5 Gyr at 2.5x solar metallicity for 14 A resolution). Not much difference seen within a given cluster.

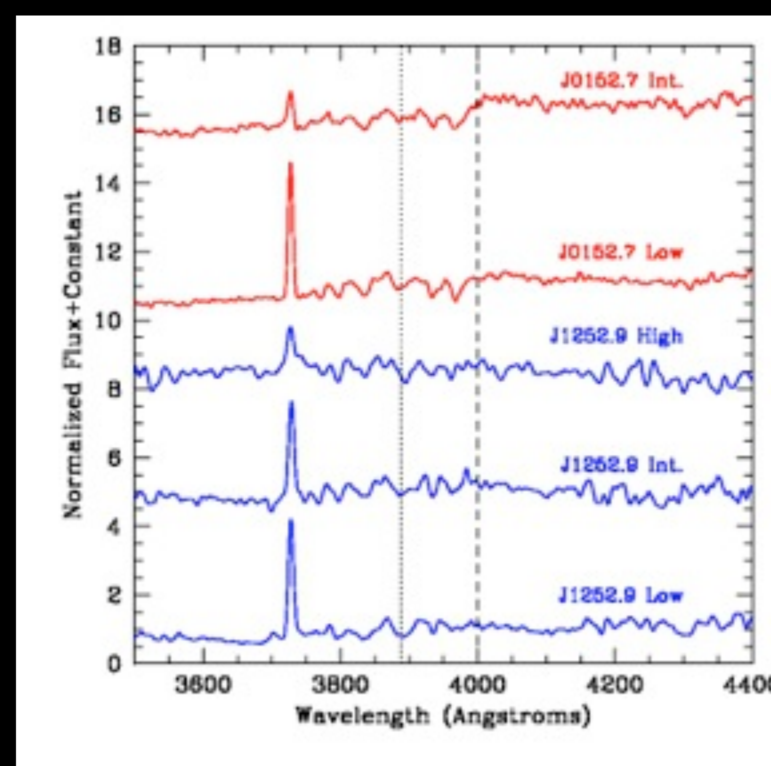
CN3861/H6 vs. Density Region





CN3861/H6 values: solid lines = unsmoothed, dotted = 14 A, dashed = 20A



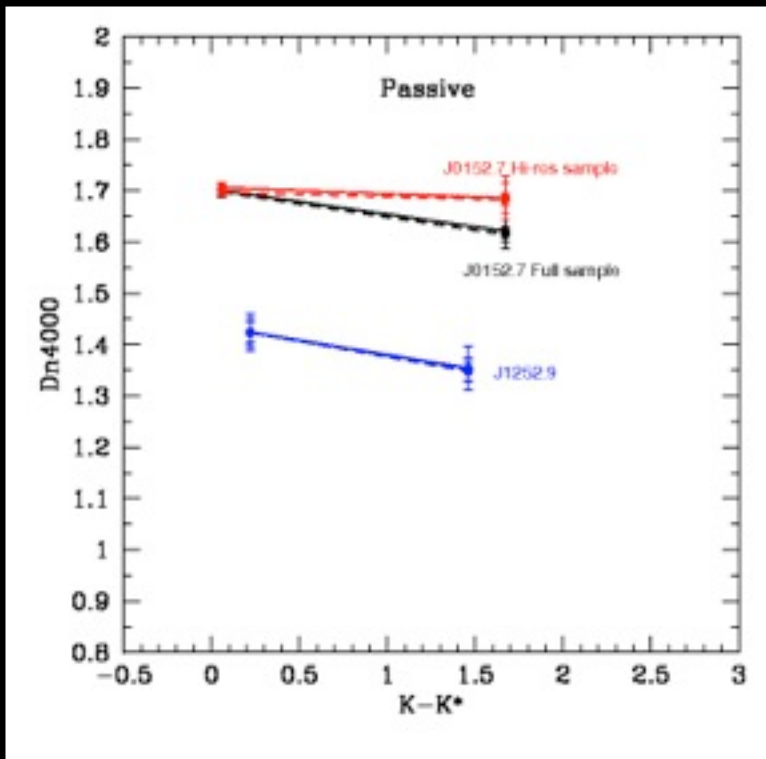


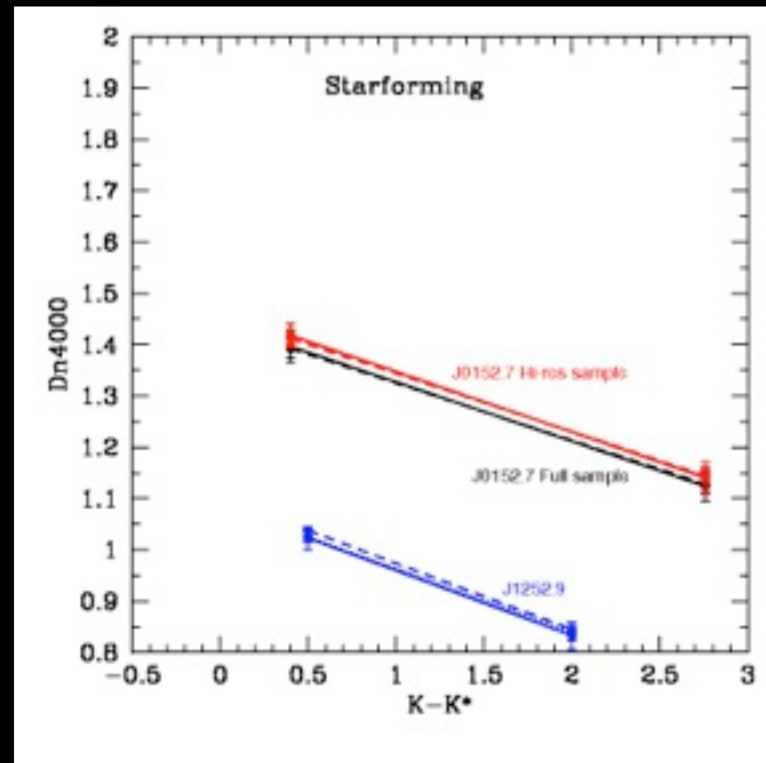
Stacks at 14 A: dotted vertical line = H6, dashed = 4000 A

Little significant H6 index value difference seen among either passive or starforming galaxies with redshift or regional density. Dip in J1252 passive intermediate density sample probably due to quality problems in spectra.

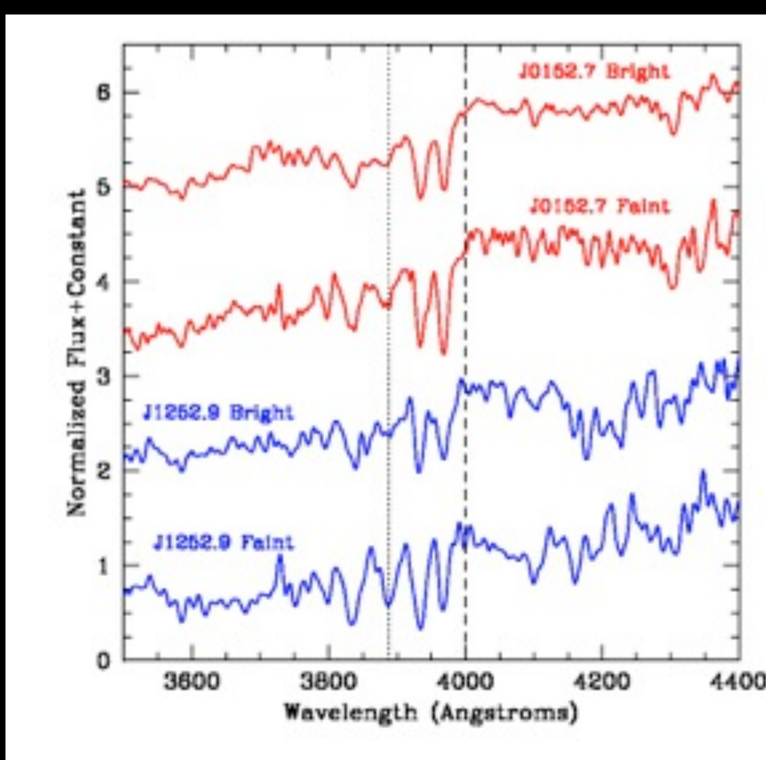
Only a small difference in CN3861/H6 between J1252.9 and J0152.7 for intermediate-density-region starforming galaxies, compared to their large Dn4000 difference. This is probably due to their being on opposite sides of the post-starburst Balmer "peak" at ~300 Myr stellar age (still very young/starburst in J1252.9, and near 1 Gyr of age in J0152.7).

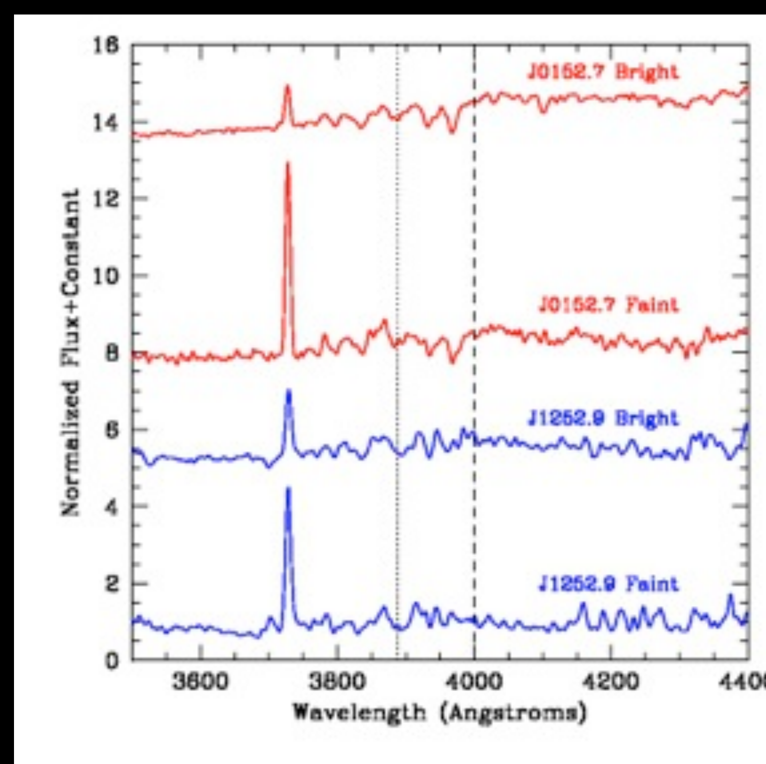
Dn4000 vs. Magnitude





Dn4000 values: solid lines = unsmoothed, dotted = 14 A, dashed = 20A



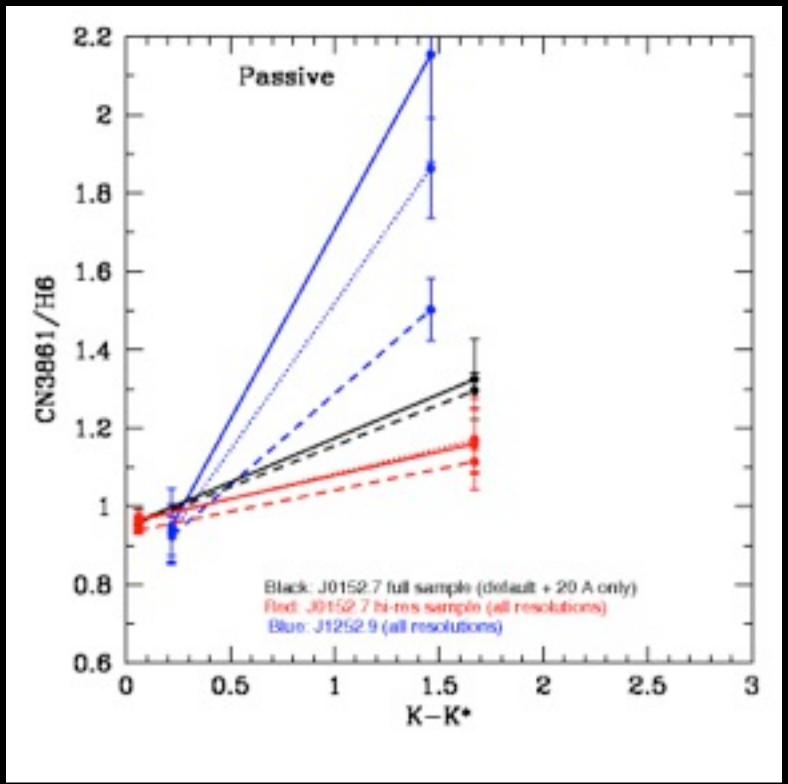


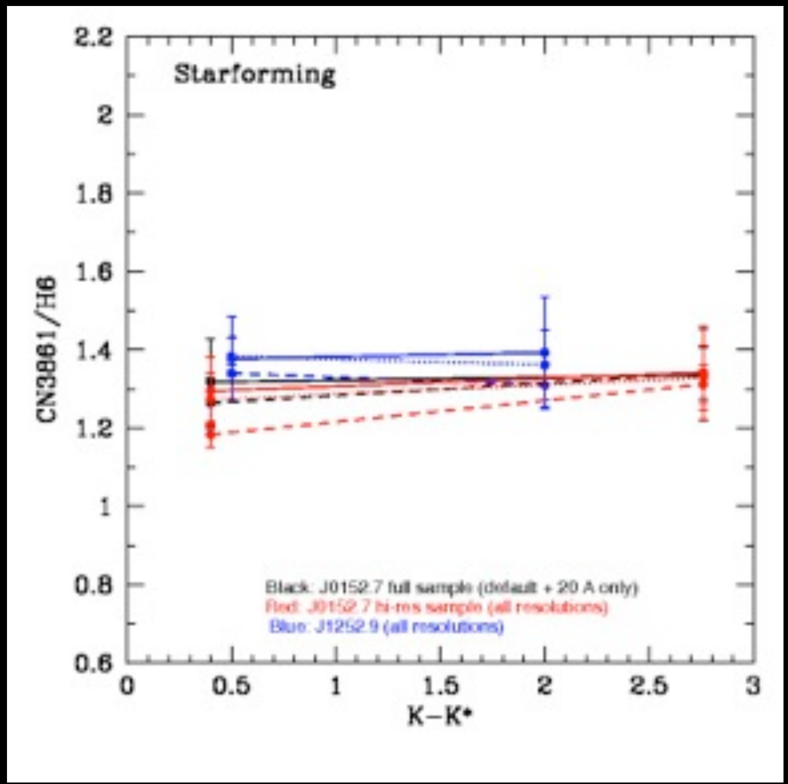
Stacks at 14 A: dotted vertical line = H6, dashed = 4000 A

Only a small D4000 difference among bright vs. faint passive galaxies in the same cluster. Similar across-the-board difference in age between the clusters still seen in passive populations sorted by magnitude.

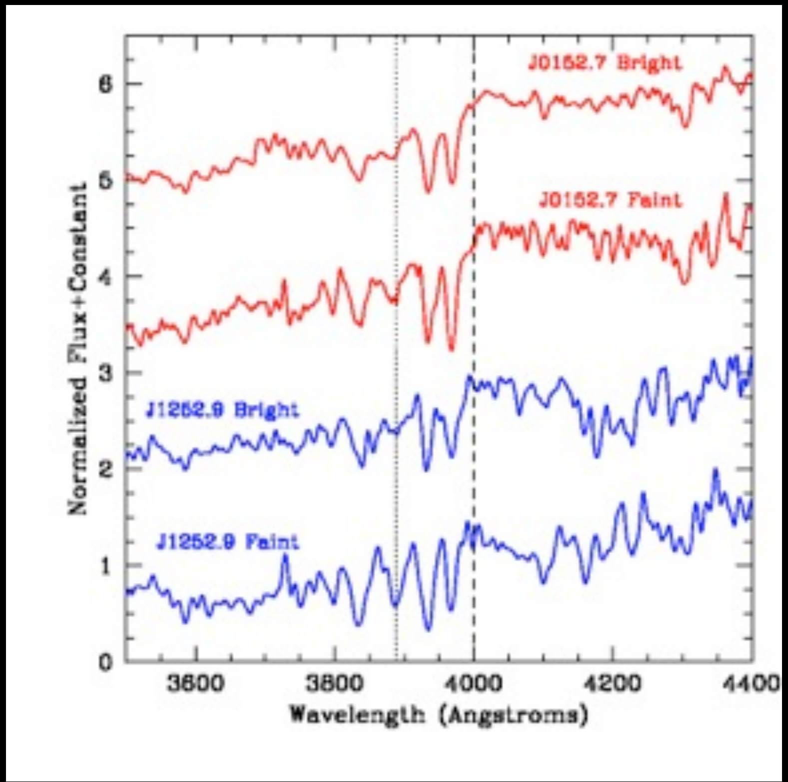
For both clusters, bright star-forming galaxies have larger Dn4000 than faint ones, though the corresponding age difference is small for J1252.9. Also note the higher Dn4000 values in general for J0152.7, suggesting an older typical stellar population.

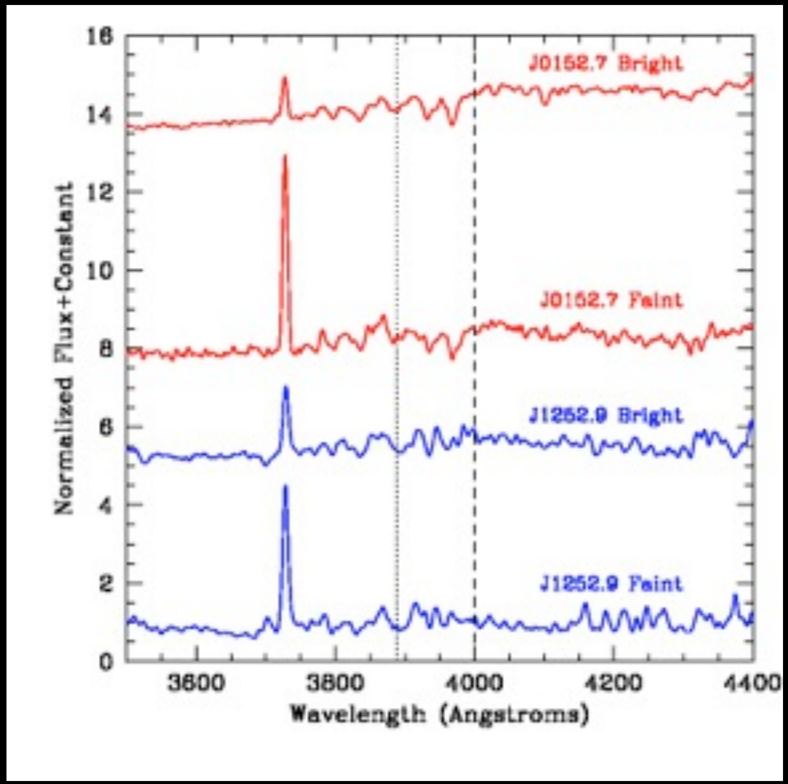
CN3861/H6 vs. Magnitude





CN3861/H6 values: solid lines = unsmoothed, dotted = 14 A, dashed = 20A





Stacks at 14 A: dotted vertical line = H6, dashed = 4000 A

Faint passive galaxies in J1252.9 have strong H6 - suggests very recent evolution onto Red Sequence. Some H6 difference also exists (especially in full sample) between bright and faint in J0152.7 as well, consistent with findings of Demarco et al. (2010) that many fainter, bluer passive galaxies in J0152.7 are relatively recent arrivals to the red sequence population.

Bright and faint starforming galaxies in both clusters have similar H6. The faint galaxies appear to be starburst-dominated in both clusters (before the post-starburst H6 peak), while the bright starforming galaxies in J0152.7, like the intermediate-density region sample (with which it overlaps considerably) are probably past the 300 Myr peak. The bright star-forming galaxies in J1252.9 have less [OII] than the faint ones, but the stellar population still looks young.

So what does this all mean?

- Among passive galaxies, the *faint early-types at z = 1.24* show post-starburst (E+A) features, with a large CN3861/H6 ratio and modest D4000. They therefore seem to represent the most recent evolution onto the Red Sequence before the epochs of observation of either cluster.

- Very active evolution seems to be happening in this time interval among s*tarforming galaxies in the intermediate-density regions:* at z = 1.24 they're still quite young in appearance, while at z = 0.84 they are more "green valley" with moderate D4000 and intermediate-age features with relatively weak star formation.

- Thus, at z ~ 1, the most active Red Sequence building seems to be occurring among star-forming galaxies in the intermediate-density regions, and the most recent Red Sequence building before this seems to have occurred among what at z = 1.24 are faint, passive galaxies. (Most of which are found in the intermediate to low density regions.) Another project in progress regarding morphology in J0152.7 also suggests a lot of evolution in the intermediate density regions.

- Next step (awaiting revised photometry) is to perform a similar analysis with stacks according to stellar mass, and devise the more detailed star formation histories with spectrophotometric analyses using the methods of Gobat et al. (2008) and Rettura et al. (2010).

- Now that we have an idea **where** galaxies are dying at z ~ 1, we need to find out **how** they are dying. 3-D spectroscopy of galaxies in "intermediate-density" regions and outskirts of clusters could help to narrow down the processes (strangulation, harassment, stripping, etc.)