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Evolving Galaxies in Evolving Environments

Concluding remarks
The Environmental Revolution

Key ingredients governing `environmental revolution’
- Morphology – density relation \((T - \Sigma)\)
- Rising blue fraction \(f_B(z)\)

Slide from Richard Ellis’ talk at “Galaxy Evolution and Environment” Malaysia 2009
The Environmental Evolution

- Galaxies in dense environments are more massive, redder, show less SF; also older and more concentrated than galaxies in less dense environments; established over $0 < z < 1, 1.5$ in a range of galaxy environments (e.g. Dressler 1980, Kauffmann et al. 2004, Cucciati et al. 2010, Kovač et al. 2010, Quadri et al. 2012)

- Emerging picture: galaxies are getting transformed from blue, SF (and late) to red, non-SF (and early)

- Evolution mainly driven by mass

Environment is equivalent to $> 2$ Gyr retardation

A delay in physical processes or an indication of two different processes?

Bolzonella, Kovač + zCOSMOS 2010
What is environment? (Gray, Mamon)

1. Continuous environments = galaxy counts
2. Groups/clusters = virialised (bound) structures
   - not so simple in practice

Gray:

- please be specific when you talk about environment!
  - tell us how you measured it, and remember that ‘high density’ isn’t really meaningful
  - different measures will be appropriate to probe different physical regimes
Are our environment measures too simplistic?

1. $9 < \log_{10} M_{\text{group}} < 11$

2. $11 < \log_{10} M_{\text{group}} < 12$

3. $12 < \log_{10} M_{\text{group}} < 15$

env class: void, filament, sheet, cluster

“Tentative statement: at fixed group/halo mass ... no dependence of the stellar assembly time on geometric/global environment”

Tojeiro (also Cibinel)
Moving to $z>1.5,2$

K.-G. Lee: Ly$\alpha$ Forest as a Probe of the Cosmic Web

Note: Negative $\delta_F$ corresponds to higher densities

Orsi, Lemaux, Koyama, Gray: Tracing protoclosters
- Ly$\alpha$ blobs
- Radio galaxies
- Quasars
Excess of massive galaxies in proto-cluster PKS1138-262 consistent with Lemaux, also zCOSMOS-deep

(Koyama et al. 2013b)
SFR vs environment

• (s)SFR of star-forming galaxies do not dependent on environment (Peng et al. 2010, McGee et al. 2014)

Kauffmann et al. 2004

Steele:
Holds also for all “emission class” objects in GAMA

Peng, Lilly, Kovač et al. 2010
Cluster vs. Field comparison out to $z \approx 2$

The MS location is always independent of environment since $z \approx 2$!

From $L(\text{H}\alpha) + M\star$-dependent dust correction

From rest-frame R-band photometry + M/L correction

$\log(\text{M}/M_\odot)$

$\text{H}\alpha$ emitters with EW$\alpha > 30$A

Clusters: SSFR depends on environment

Haines

Field galaxies
Cluster (<1.5r_{500})
0.15<z<0.25

Noble

z ≈0.9

Galaxies accreted at earlier time
Mass and environment in the galaxy evolution

Red fraction of galaxies depends both on stellar mass and environment (also ChangHoon Hahn PRIMUS results):

$$f_{\text{red}}(\rho, m) = 1 - \exp\left[\left(-\left(\frac{\rho}{p_1}\right)^{p_2} - \left(\frac{m}{p_3}\right)^{p_4}\right)\right]$$ (Baldry et al. 2006, Peng et al. 2010)

$$= \varepsilon_m(M_\star) + \varepsilon_\rho(\delta) - \varepsilon_m(M_\star)\varepsilon_\rho(\delta)$$

Separability holds to a good degree at least up to \(z<0.7\); possible cross-term within the errors
Mass and environmental quenching over time

Dominant mechanism for the quenching of galaxies changes with time

Model from Peng et al. (2010) based on the assumption of separability of the mass and environmental quenching up to high redshift

Importance of the environmental quenching increases with cosmic time and with decreasing stellar mass – qualitatively consistent with the growth in the LSS and infall of (lower mass) satellites to the larger structures producing the observed environmental effects

Lucrative idea from the theory: many physical processes suggested
Satellite quenching efficiency (z=0)

\[ \varepsilon_{\text{sat}}(m) = \frac{f_{r,\text{sat}}(m) - f_{r,\text{cen}}(m)}{f_{b,\text{cen}}(m)} \]

\[ \varepsilon_{\text{sat}}(m,\rho) = \frac{f_{r,\text{sat}}(m,\rho) - f_{r,\text{cen}}(m,\rho)}{f_{b,\text{cen}}(m,\rho)} \]

also van den Bosch et al. (2008)

(Peng et al. 2012)

At z~0 and log(M*/M_{\odot})<11: 1) red fraction of centrals does not show strong dependence on environment

2) satellite quenching constant with mass and responsible for most of the observed environmental quenching
Satellites are the major drivers of the overall observed environmental effects up to (at least) 0.7

Knobel, Lilly, KK+ et al. 2013
Kovač et al. 2014
4 THE DEPENDENCE OF QUIESCENT GALAXIES ON THEIR ENVIRONMENT

4.1 The fraction of quiescent galaxies as a function of density

In this section, we investigate how model predictions of quiescent fractions as a function of environment deviate from observations. We consider the importance of halo mass, central vs. satellite galaxies, and strong density dependence.

**Observations:**
- Overall density dependence mainly driven by satellites (Kovac et al., 2013)
- Similar behavior of centrals & satellites & strong density dependence

**Models:**
- Centrals & satellites behave differently & weaker density dependence
- Over-estimating quiescent satellites (e.g. Kimm+09)
- Under-estimating quiescent centrals

Does it just reflect a dependence on halo mass, a theoretical measure for environment?
Satellites are the major drivers of the overall observed environmental effects... but... some centrals are the same as satellites.
True centrals: No dependence on density

Backsplash centrals: Responsible for over-all density dependence ⇒ environment mainly relevant for low mass centrals at high densities

Spend on average 1.5-3 Gyrs at z=0.5-2 as a satellite (depending on density & mass)
Satellites are the major drivers of the overall observed environmental effects ... but ... some centrals are the same as satellites.

Kiobel, Lilly, Woo, Kovač 2014
Satellites are the major drivers of the overall observed environmental effects ... but ... properties of satellites depend on properties of their central

Hartley
Satellites are the major drivers of the overall observed environmental effects... but... properties of satellites depend on properties of their central

Satellites of the quenched centrals have a larger probability to be quenched than the satellites of the star-forming centrals (conformity)
Assembly bias and conformity

Correlation with the formation time (in this case C) can explain the observed conformity signal

Paranjape+ Hartley, Kovač in prep)
Do we need satellite-specific quenching at all?

SFR of a galaxy is determined by its dark matter halo formation history

Satellites (at a given mass) are redder because their subhaloes form earlier than host haloes

Watson et al. 2014

Hearin et al. 2014
Smoking guns (of ongoing environmental transformation)

Gavazzi

ESO137–001 in Norma cluster

Fumagalli+14 First MUSE s.v. paper (28/7/2014)
27/64 (42%) LTGs display extended asymmetric ionized gas!
“JELLYFISH” GALAXIES IN OMEGAWINGS

Poggianti

In prep.
**Comparing with a simple RAM pressure model**

Dashed grey line: to the left of which MW-like galaxies are expected to be completely stripped of HI gas.

Solid green where galaxies are stripped enough to fall below our HI detection limit.

**Poggianti (also Cybulski)**

A simple model following Gunn & Gott prescription, a beta cluster model and galaxy parameters for the Milky Way.

"Virialized region roughly at $r<R_{200}$ and $A_v<1.5\sigma$, where many of the galaxies have passed pericenter more than once, thus have been in the cluster for $>2$ Gyr."
Stripping in action?

\[ M_{\text{sat}} \propto (R_s / R_{200})^{2/3} \] [Gao et al. 2004]

- \[ \text{GAMA}x\text{KiDS (This Work)} \]
- \[ \text{SDSS}x\text{CFHTLenS (Li et al. 2014)} \]
Quenching: a stronger function of central stellar mass density (bulge) rather than stellar mass

Omand+ 2014
Central galaxies

Quenching: a stronger function of central stellar mass density (bulge) rather than stellar mass.

Figure 13. Passive fraction vs. stellar mass (left panel) and halo mass (right panel) both divided by bulge mass range as indicated on the stellar mass plot. The error on the passive fraction computed via the jack-knife technique, and bin size, are displayed as the error bars. Note the large variation in the passive fraction across bulge mass ranges at both a fixed stellar mass and halo mass. This can be compared to the variation in the passive fraction at a fixed bulge mass with stellar mass (Fig. 10 top middle panel) and halo mass (Fig. 11 top left panel). There is distinctly less variation in the passive fraction at a fixed bulge mass with varying stellar and halo mass ranges than at a fixed halo or stellar mass with varying bulge mass ranges.

Figure 14. Left panel: Passive fraction vs. bulge mass divided by disk mass range, as indicated on the plot. Right panel: Passive fraction vs. disk mass divided by bulge mass range, as indicated on the plot. The error on the passive fraction computed via the jack-knife technique, and bin size, are displayed as the error bars. Note that there is larger variation in the passive fraction at a fixed disk mass with varying bulge mass than at a fixed bulge mass with varying disk mass, which demonstrates that bulge mass is more constraining of the passive fraction than disk mass. However, there is still significant variation in the passive fraction at a fixed bulge mass due to variation in disk mass, which implies that disk mass is a significant secondary correlator to the passive fraction.

Comparing these values to the values for bulge mass split by halo mass ($f_{\text{passive}}^{b,m} = 0.10 \pm 0.01$, $f_{\text{max}}^{p} = 0.42 \pm 0.02$) and stellar mass ($f_{\text{passive}}^{b,m} = 0.10 \pm 0.01$, $f_{\text{max}}^{p} = 0.48 \pm 0.03$), reveals that variation at a fixed bulge mass with halo mass and stellar mass leads to significantly smaller areas contained and lower maximum differences in the passive fraction than with varying bulge mass at fixed stellar and halo masses. Thus, we conclude that whatever process(es) give rise to the transition from the blue cloud to the red sequence in central galaxies are coupled primarily to bulge mass, over halo mass, stellar mass, and B/T.

Given that we have established that there is least variation in the passive fraction at a fixed bulge mass in terms of the remainder of our observables, we are now in a position to assess what is next most important. At a fixed bulge mass, we have seen that there is some residual widening of the passive fraction relation due to both stellar mass and B/T ratio. This immediately suggests that the disk properties may be the root cause of the variation at a fixed bulge mass. To test this we show the $f_{\text{passive}}^{M_{\text{bulge}}} \text{ relation in Fig. 14 (left panel), split by disk mass. There is a larger variation at a fixed bulge mass with varying disk mass than for any other variable (compare to Figs. 10 – 12, bulge mass plots), implying that disk mass is the next most constraining variable after bulge mass, even though as a contender for the dominant position it performed particularly poorly (see, e.g., bottom right panels of Figs. 11 & 12).
AGN and environment

- **Best:** Radiative mode can keep the quenched galaxies quenched
- **Sabater:** (at fixed mass) decrease of optical AGN fraction and increase of the fraction of radio AGN in denser environments
- both enhanced by (one-on-one) galaxy interactions (Patton)
- with central star formation matched: only indirect effect of environment
Central galaxies

Centrals in “groups”, i.e. with “high”-\(M_h\) (sample C2), have younger ages, higher \([Z/H]\), lower \([\alpha/Fe]\), and higher \(A_V\) than those with low \(M_h\) (sample C1).

“ETGs in C2 underwent gas-rich interactions more than those in C1”
BCGs as special centrals

Yen-Ting Lin

central location controls how they feed

HST
BCGs as special centrals

Yen-Ting Lin

Ling: little stellar mass growth in real BCGs since z<0.5

Fraser-McKelvie: (WISE) SF in BCGs is rare

Zhao: cDs tend to be more massive and reside in higher densities than elliptical BCGs: cDs build-up through minor mergers?

Central location controls how they feed
What about mergers?

Saintonge: The old picture: merger-driven galaxy evolution

from mid-80s to 5-10 years ago: merging of galaxies seen as the main driver of galaxy evolution
near-IR IFU work: z~ 2 galaxies with high SFRs are in large part well ordered discs, and not major mergers.

What about mergers?

Saintonge: The global picture: accretion-driven galaxy evolution

Forster Schreiber et al. (2006)
What about mergers?

Specific rate of formation through major mergers

Galaxies

DM haloes

Guo & White 2008
Discussion

• Importance of mergers/interactions
• Structure/morphological transformation w.r. to mass and environmental quenching
• Quenching timescales
• Growth of structure
• Overall quenching?
THANKS to the Organizers...
...and have a safe journey home!