

# Constraining galaxy formation models with dwarf ellipticals in clusters

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**Abstract.** Recent observations demonstrate that dwarf galaxies in clusters, despite their faintness, may be a critical galaxy type for understanding the physical processes behind galaxy formation. Dwarfs are the most common type of galaxy and are particularly abundant in rich galaxy clusters. The dominate model for explaining the formation of these systems thorough Cold Dark Matter models is that the bulk of their stellar mass formed early, and within their present environments. Recent results however suggest that some dwarfs appear in clusters after the bulk of its members form, a scenario not predicted in standard hierarchical structure formation models. Many of these systems appear to be younger and more metal rich than dwarfs in lower density areas, suggesting they are possibly created by a tidal process induced by the cluster. Several general galaxy cluster observations, including steep luminosity functions and the origin of intracluster light, are natural outcomes of these processes.

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## 1. Introduction

Although dwarf galaxies are the faintest and lowest mass galaxies in the universe, they likely hold important clues for understanding galaxy formation and the nature of dark matter. The reason for this is quite simple: low-mass galaxies, and particularly low-mass galaxies in clusters, are the most common galaxies in the nearby universe (Ferguson & Binggeli 1994). Any ultimate galaxy evolution/formation theory must be able to predict and accurately describe the properties of these objects. In popular galaxy formation models, such as hierarchical assembly (e.g., Cole *et al.* 2000), massive dark halos form by the mergers of lower mass ones early in the universe, and the first galaxies likely have low stellar mass. By understanding dwarf galaxies, we are also thus potentially studying the very first galaxies to form. On the other hand, observations reveal that few low-mass galaxies could have formed all of their stars early in the universe at  $z > 7$ , with considerable evidence for star formation occurring in the last few Gyrs in dwarf spheroidals (e.g., Mateo 1998).

The traditional approach to studying low-mass galaxies is to examine those in the Local Group (LG). It is now well established that LG dwarf elliptical and dwarf spheroidal galaxies have varying star formation histories, with metal-poor populations as old as classical halo globular galaxies but also with evidence for recent star formation (see e.g., Mateo 1998). There are also some low-mass LG galaxies, such as Sagittarius, that contain surprisingly metal-rich populations given their luminosities (e.g., Ibata, Gilmore & Irwin 1995). Because LG dE galaxies are close we can resolve their stellar populations, and thus we can learn much more about them than we do dwarfs in more dense, but distant environments. Because of this we know a great deal concerning LG dwarf properties including their internal kinematics and star formation histories. Many of the lowest mass galaxies in the LG, such as Draco and Ursa Minor, have very high inferred central  $M_{\text{tot}}/L$  ratios (Kleyna *et al.* 2002) and apparently contain the densest dark matter halos of all known galaxies, in qualitative agreement with the original CDM predictions (e.g., Lake 1990). Low-mass galaxies in clusters, however, have different kinematic and spatial properties

than these LG systems (e.g., Conselice, Gallagher, & Wyse 2001,2003), suggesting they might have a different formation scenario.

Observationally, dwarf galaxies are typically faint ( $M_B > -18$ ), with low surface brightnesses ( $\mu_B > 23$  mag arcsec<sup>2</sup>). Since dwarfs are so common, they are in every sense normal galaxies. The most common type among dwarfs are dwarf ellipticals/spheroids, which dominate the number density of galaxy clusters down to  $M_B = -11$  (Ferguson & Bingelli 1994; Trentham *et al.* 2002). Based on studies of luminosity functions in clusters, there are also more dwarf ellipticals per giant in denser regions than in the field. This implies that clusters of galaxies cannot form through simple mergers of galaxy groups. Some dwarf systems must form within the cluster environment. The nature of this over-density may be the result of initial conditions, or ‘non-standard’ galaxy formation. That is, dwarfs may have formed after the cluster was in place. There is now evidence for this, the implications of which can explain several galaxy cluster phenomenon. On the other hand, there is also evidence that some dwarf ellipticals/spheroidals in clusters are dominated by old stellar populations. In this paper we review the current observations of dwarfs in clusters and attempt to interpret these systems in terms of known properties of Local Group dwarf ellipticals/spheroidals, and in the milieu of theoretical ideas concerning low mass galaxy formation in a cosmological context.

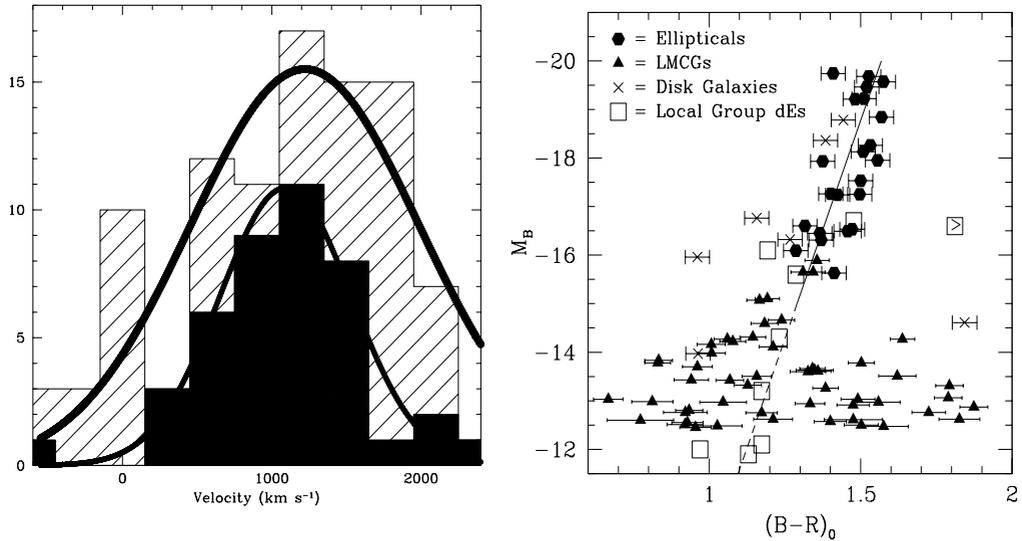
## 2. Cluster Dwarf Galaxy Properties

Dwarfs have been studied in detail in nearby rich clusters, such as Virgo, Fornax and Coma, and Perseus. Most of the data we discuss therefore comes from these sources. In particular a significant fraction of the data presented in this article comes from the papers by Conselice, Gallagher & Wyse (2001,2002,2003) and Conselice *et al.* (2003b). We list below our current understanding of dwarf properties in terms of various observational quantities.

**Number Densities:** The luminosity function (LF) in all galaxy environments are dominated by dwarf galaxies. The over-density of dwarfs in clusters is about 5–10 times that in groups, that is the dwarf to giant ratio is nearly a factor of ten higher. Another way to quantify this is through the faint end slope of the LF,  $\alpha$ . The value of  $\alpha$  in rich clusters, such as Virgo is typically around  $\alpha = -1.2$  to  $-1.5$  (Sandage *et al.* 1985; Trentham *et al.* 2002), with some results suggesting even steeper LFs with  $\alpha = -1.6$  (Sabatini *et al.* 2003). This is steeper than field values, such as in the Local Group ( $\alpha = -1.1$ ; van den Bergh 1992), yet flatter than the value predicted by CDM for all environments ( $\alpha = -2$ ). Environment clearly affects the way these systems are produced, which is generally not a prediction in CDM models (cf. Tully *et al.* 2002). This also suggests that clusters of galaxies *cannot* simply form from the mergers of lower density groups of galaxies.

**Spatial Positions:** While Local Group dwarf galaxies, particularly dwarf ellipticals, are strongly clustered around giant galaxies in the Local Group, the opposite is found for low-mass galaxies in clusters, where most are neither clustered around, nor distributed globally similar to, giant elliptical galaxies (Conselice *et al.* 2001). Both dwarf ellipticals and irregulars also have a broader distribution within clusters, that is they are not clustered towards the center, but are spread throughout (e.g., Conselice *et al.* 2001). This is also the pattern seen for spirals and irregulars in clusters.

**Radial Velocities:** The radial velocities of low-mass cluster galaxies, including S0s, spirals, dwarf irregulars and dwarf ellipticals have a wider distribution than the ellipticals (see Figure 1a). For example, Virgo cluster elliptical galaxies have a narrow Gaussian

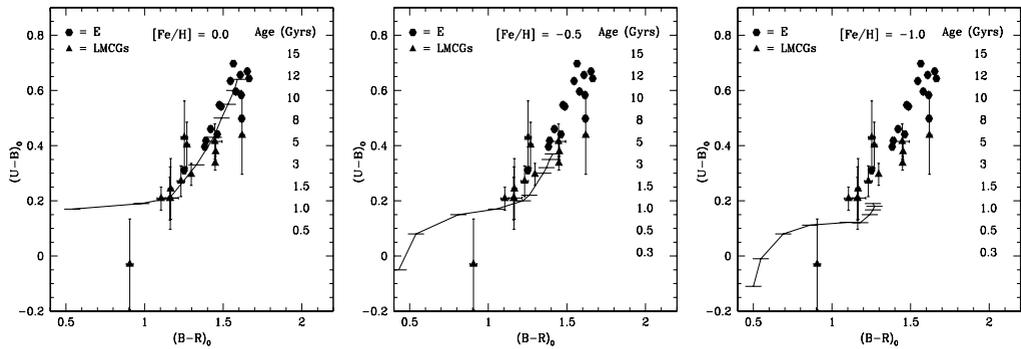


**Figure 1.** (a) Velocity histograms for giant ellipticals (solid) and dwarf ellipticals (shaded) in the Virgo cluster (Conselice *et al.* 2001). (b) Color magnitude diagram for galaxies in the Perseus cluster, demonstrating the large color scatter for systems with  $M_B > -15$ . The solid boxes are where Local Group dEs/dSphs would fit on this plot. Dwarf ellipticals are labeled as low mass cluster galaxies (LMCGs).

velocity distribution, with  $\sigma = 462 \text{ km s}^{-1}$ , concentrated at the mean radial velocity of the cluster. The other populations, including the over 100 classified dwarf ellipticals in Virgo with radial velocities, have much broader, and non-Gaussian, velocity distributions ( $\sigma \sim 700 \text{ km s}^{-1}$ ), all with velocity dispersion ratios with the ellipticals consistent with their being accreted (e.g., Conselice *et al.* 2001). There is also significant sub-structure within these velocity distributions, unlike the case for the giant ellipticals.

**Stellar Populations:** Currently, we know with some certainty that dwarf galaxies have either young/metal rich or old/metal poor stellar populations (e.g., Poggianti *et al.* 2001). This is further seen in complete color-magnitude diagrams in nearby rich clusters, such as Perseus, down to  $M_B = -12$  (Conselice *et al.* 2002, 2003a). Fainter dwarfs also tend to be even more heterogeneous, with a large scatter from the color-magnitude relationship (CMR) (Conselice *et al.* 2003a; Rakos *et al.* 2001) (Figure 1b). This trend is found in several nearby clusters, including Fornax, Coma and Perseus, and can be explained by different dwarfs having mixtures of ages and metallicities (e.g., Poggianti *et al.* 2001; Rakos *et al.* 2001; Conselice *et al.* 2003a). Stromgren and broad-band photometry reveal that the redder dwarfs are metal enriched systems (Figure 2). However, old stellar populations do exist in dwarf galaxies (Poggianti *et al.* 2001) and in the globular clusters surrounding dwarfs (e.g., Conselice in prep).

**Internal Kinematics:** One key observational test for the origin of dwarf ellipticals is whether they rotate or not. Models show that a dwarf elliptical which has been transformed from a spiral should reveal some rotation. Using 8-10 meter class telescopes, the evidence is ambiguous with some dEs showing rotation (Pedraz *et al.* 2002), while others clearly do not (Geha *et al.* 2003). There is no obvious difference between these two populations in terms of morphology or chemical abundances (Geha *et al.* 2003), although



**Figure 2.** Three stellar synthesis modeled age tracks on a UBR color-color diagram at constant metallicities of solar,  $[\text{Fe}/\text{H}] = -0.5$ , and  $[\text{Fe}/\text{H}] = -1$ . The age range is 0.3 Gyrs to 15 Gyrs for the  $[\text{Fe}/\text{H}] = -0.5$  and  $-1$  models and 0.5 Gyrs to 15 Gyrs for the solar metallicity models. Dwarf ellipticals are labeled as low mass cluster galaxies (LMCGs).

these samples are still very small. The central velocity dispersions of these systems is also quite low, indicating that dark matter does not dominate, at least in their centers.

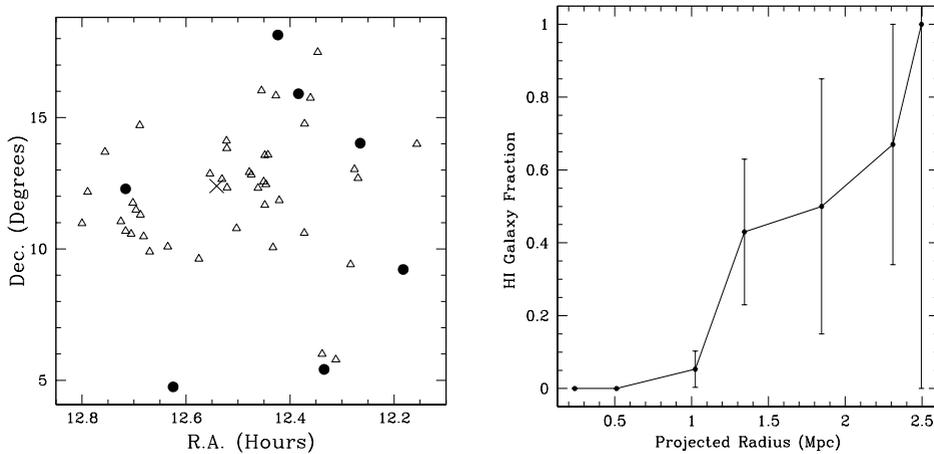
Furthermore, in addition to predicting low-metallicity systems, Dekel & Silk (1986) show, based on their model assumptions, how the internal velocities of low-mass galaxies should correlate with  $M_{\text{tot}}/L$  ratios and luminosities,  $L$ . The relationship they predict is  $M_{\text{tot}}/L \sim L^{-0.37}$ , and  $\sigma \sim L^{0.19}$ . These predictions can be tested utilizing Virgo Cluster dE internal velocity measurements made by Pedraz *et al.* (2002) and Geha *et al.* (2003). After fitting a power law to the relationship between  $\sigma$  and  $L$ ,  $\sigma \sim L^{0.31 \pm 0.05}$ . The fitted exponent on  $L$  is  $2\sigma$  away from the relationship predicted by Dekel & Silk. This is another indication that cluster dwarf ellipticals are possibly formed through multiple methods.

**Gas Content:** Surprisingly, some dEs in clusters contain evidence for gas in various phases, both cold HI (Conselice *et al.* 2003b; Buyle *et al.* 2005) and warm gas in the form of  $\text{H}\alpha$  (Michielsen *et al.* 2004). These studies have only been performed in the nearest clusters, Virgo and Fornax due to the difficulty of making these observations. Although 15% of dEs have evidence for HI, all of these systems are located in the outer parts of Virgo (Conselice *et al.* 2003b) and Fornax (Buyle *et al.* 2005). Figure 3 shows the location of HI emitters in the Virgo cluster and the fraction of dEs with HI emission as a function of radius from the center of the Virgo cluster.

### 3. Cluster Dwarf Galaxy Origins

Any successful theory of dwarf galaxies, particularly for explaining how dwarf ellipticals form, must account for the following properties: over-density in relation to massive galaxies in rich environments, mix of stellar populations, ability to survive in dense environments, diffuse spatial and velocity structure, and mixtures of rotation. This theory must also explain why fainter dwarfs are more heterogeneous than brighter ones.

In the simple collapse + feedback scenarios (Dekel & Silk 1986), dwarfs are formed when gas collapses and forms stars. These stars produce winds that expel gas from these systems, halting any future star formation. In this formation scenario dwarfs formed before the cluster ellipticals, or at least formed within groups that later merged to form clusters. Fainter dwarfs however, cannot all be born in groups which were later accreted



**Figure 3.** (a) Distribution on the sky of dE galaxies observed at 21 cm in the Virgo Cluster. The open triangles represent non-detections, while the filled circles show the locations of the dE galaxies with detected H I. The cross toward the center shows the location of the giant elliptical M87. (b) Fraction of Virgo classified dwarf elliptical galaxies detected in H I as a function of projected distance from the center of the cluster.

into clusters along with the massive galaxies, due to the high dwarf to giant galaxy ratio found in clusters (Conselice *et al.* 2001, 2003a).

One idea to explain this, as suggested by Tully *et al.* (2002), is that the dark matter halos of dwarfs are ‘squashed’ in lower density environments due to a large ultraviolet background after the universe was reionized. This explains the differences in  $\alpha$  between different environments, but does not explain how within the same environment there is a great diversity in the dwarf population. It also does not easily explain why many dwarfs appear to have recently been accreted into clusters.

The above evidence suggests that simple low-mass galaxy formation scenarios can be safely ruled out for some dwarfs. The first clue that dwarfs are not produced through standard methodologies came from studies that showed dwarfs are generally found in abundance in dense areas such as nearby clusters. In fact, in standard CDM scenarios dwarfs should be more common in lower density environments, but we see the direct opposite (Trentham *et al.* 2002). Dwarfs within dense environments also have a broader distribution, both spatially and in terms of their radial velocities, than giant ellipticals, similar to the pattern of infalling spirals. This is an indication that both are recent additions to clusters (Conselice *et al.* 2001). Internal dynamic evidence also suggests that at least some dwarfs are rotating (e.g., Geha *et al.* 2003), a feature not seen in Local Group dEs. Finally, the stellar populations of some faint  $M_B > -15$  dwarf galaxies appear to be metal rich (near solar), implying that the dwarf population itself is inhomogeneous and may have multiple origins. We discuss several scenarios which have been proposed to explain these observations and argue that one method which can reproduce these trends involves the formation of dwarfs from already existing galaxies through a tidal effect.

One alternative idea is that some modern dwarfs formed after the cluster itself was in place by collapsing out of enriched intracluster gas. Another is that the intracluster medium (ICM) is able to retain enriched gas that in the Dekel and Silk (1986) paradigm would be ejected by feedback, but remains due to the confinement pressure of the ICM (Babul & Rees 1992). This scenario would explain the higher metallicities of some of the fainter dwarfs.

An alternative scenario, now gaining in popularity, is that dwarfs form in clusters through a tidal origin. Two main possibilities for this are tidal dwarfs (Duc & Mirabel 1994), and as the remnants of stripped disks or dwarf irregulars (Conselice *et al.* 2003a). The velocity and spatial distributions of dwarfs suggests that they were likely accreted into clusters during the last few Gyrs (Conselice *et al.* 2001). This, combined with the high metallicities of these cluster dwarfs, and the fact that their stellar populations are fundamentally different than field dwarfs (e.g., Conselice *et al.* 2003a; Figure 1b; Figure 2) suggests that the cluster environment has morphologically transformed, or stripped, accreted galaxy material into dwarfs.

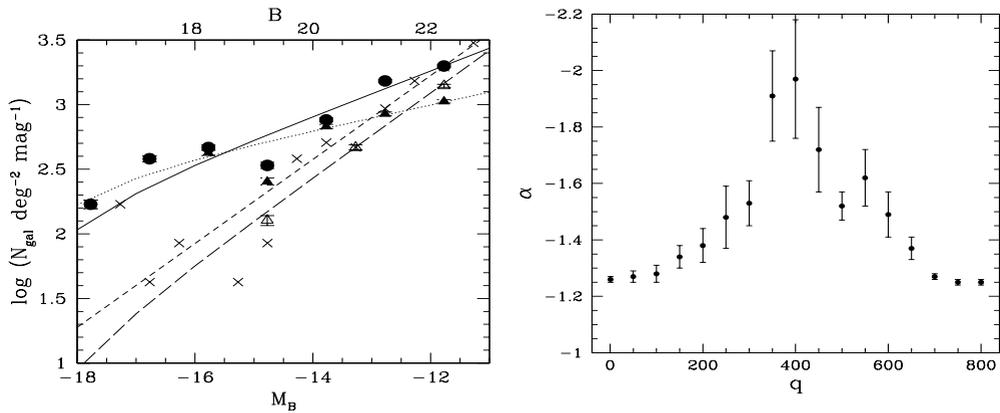
There is evidence for this process currently occurring in nearby clusters (e.g., Conselice & Gallagher 1999). If dEs form from infalling spirals then there should also be systems now being transformed which appear morphologically as dEs, but retain some of the gas left over from their precursor. These systems would only exist in the outer parts of clusters, as any that dwarfs venturing towards the core will be rapidly stripped of material. For example, very deep Arecibo observations of Virgo dEs reveal that  $\sim 15\%$  of a sample of 56 have HI detections, all of which are located outside the core of the cluster (Conselice *et al.* 2003b). Other detailed morphological investigations of nearby cluster dwarf ellipticals show that they contain a wide diversity of structures, some with tidal features, and others with apparent spiral structures (e.g., Jerjen *et al.* 2000; De Rijcke *et al.* 2003; Barazza *et al.* 2003; Graham *et al.* 2003).

Despite the above, there is considerable evidence that some dEs in clusters are indeed an old population, some with metal poor populations (e.g., Lotz *et al.* 2004). A single cluster dwarf scenerio is unlikely to explain the great diversity we see, thus multiple formation methods are likely necessary.

#### 4. Implications of Late Dwarf Formation in Clusters

Environment likely plays a role in all aspects of galaxy formation and evolution. If indeed any dwarfs form after their host cluster due to a tidal process, there are several cluster features these processes can possibly explain. The first is that the LF of clusters will change after these lower mass galaxies form. The LF of galaxies in the Perseus cluster becomes flatter, with a similar faint end slope ( $\alpha$ ) as the field, after removing these red galaxies (Figure 4). Figure 4 shows how the luminosity function changes slope from  $\alpha = -1.4$  to  $\alpha = -1.2$  due to galaxies in the Perseus cluster which are redder than  $2\sigma$  from the color-magnitude relation, defined by the giant cluster galaxies (Conselice 2002).

There are several implications for this process, beyond possibly steepening the luminosity function. One of these is the origin of intracluster light, which can make up 50% of the light coming from dense clusters (e.g., Adami *et al.* 2005). If cluster dEs originate from tidally disturbed galaxies then the amount of light liberated is enough to account for all of this intracluster light as arising from the debris from tidally disturbed galaxies (Conselice *et al.* 2003a). For example, the total luminosity of intracluster light in the Virgo Cluster within  $2^\circ$  of M87 is  $2 \times 10^{11} L_\odot$ . If this material originates from tidally striped objects whose remnants are dwarfs, we can compute how much material on average each dE must have lost. There are 170 dEs, 148 dE,Ns, and 14 S0 galaxies within this radius in Virgo. On average, if all the dE and dE,N galaxies are remnants of stripped galaxies then  $0.6 \times 10^9 L_\odot$  of light was lost by each object. If we consider only dE galaxies as remnants of this process then  $1.1 \times 10^9 L_\odot$  was lost by each dE. Therefore, if we assume that dEs were once as massive as a typical disk galaxy, then the amount of



**Figure 4.** (a) The Perseus cluster luminosity function plotted in various ways down to  $M_B = -11$ . The solid round points, and fitted solid line, is the total luminosity function of the central region of Perseus. The luminosity function for dEs redder and bluer than the CMR prediction are plotted as open and solid triangles and long dashed and dotted lines. The crosses mark the density of background galaxies. (b) Modeled cluster luminosity function slope,  $\alpha$ , as a function of the number of high-speed maximum interactions ( $q \sim \text{time}$ ) cluster galaxies undergo during evolution in a Perseus like cluster (see Conselice 2002).

material these systems lost through tidal effects is enough to account for the intracluster light in rich clusters of galaxies.

There are still however many questions that need to be answered by observing dwarfs in clusters in more detail. There has never been a spectroscopic survey of dwarfs fainter than  $M_B = -15$  in clusters of galaxies, for example. We are also just learning about the internal properties of dwarfs through high resolution imaging and spectroscopy. Making progress on these topics will require surveys of dwarfs in all environments, and connecting these observations with galaxy evolution in higher redshift clusters.

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## Discussion

FERGUSON: In the Virgo and Fornax clusters, the spatial distributions of nucleated and non-nucleated dEs brighter than  $M = -14$  appear to be different. The dE<sub>N</sub>s are as concentrated toward the cluster centers as the giant Es. It will be interesting to see if this still holds with the new classifications from the ACS Virgo cluster survey.

CONSELICE: Yes, that is indeed the case, and this probably reflects the fact that there exists an old population of dEs in clusters, as well as a younger population of dEs. The bright nucleated dEs are likely taken from the population of older or original dEs, while pure dEs may be from the newer formed population.

MIESKE: If the red LSB galaxies are stripped bulges, shouldn't then there be huge amounts of galaxies in the process of disruption and also many more that got totally destroyed? Seeing a population of LSB galaxies  $\approx 500$  times fainter than possible progenitors seems like a huge coincidence "snapshot". Taking into account that there should be more massive, intermediate ones and also more very faint (possibly entirely disrupted) ones, can you get such a high number of luminous progenitors?

CONSELICE: The galaxies we see today as red dEs at  $M_B > -15$  may still be losing mass and over time could disappear entirely. There are examples in clusters of red more luminous galaxies, such as amorphous or disk-like galaxies, but these aren't dEs yet. In the past, clusters had more of these infalling galaxies, as seen in the Butcher-Oemler effect, and these may be the progenitors of today's dEs.

KROUPA: It could be conceivable that the dE populations in clusters are tidal-dwarf galaxies (Okazaki & Taniguchi 2000). This would explain their wide distribution and different chemical properties as they would have formed from pre-enriched material in merging parents.

CONSELICE: Yes, the red dEs could be produced through tidal dwarfs, we have a discussion of this possibility in the paper Conselice *et al.* (2003). It does not matter, in a sense, if the new dEs are produced in tidal dwarfs or from the stripped remains of a larger galaxy. Both processes will produce red dEs with large spatial and velocity distributions.