Effects of large and small-scale environments on galaxy properties

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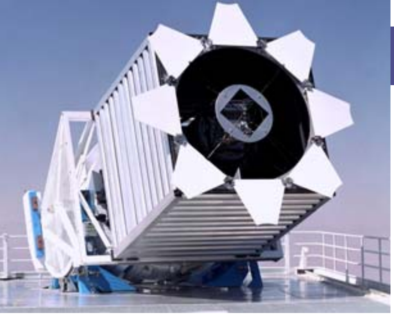
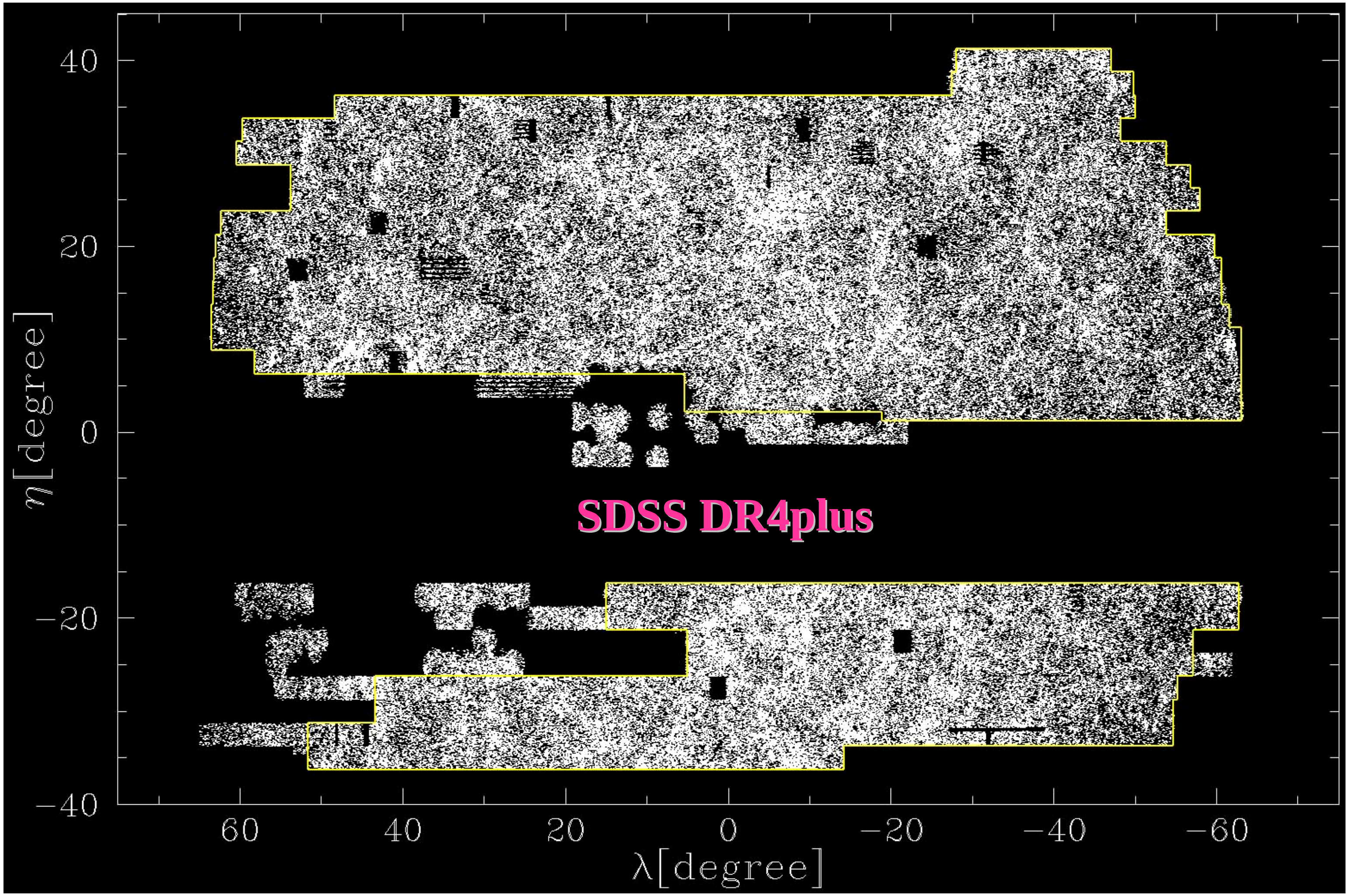


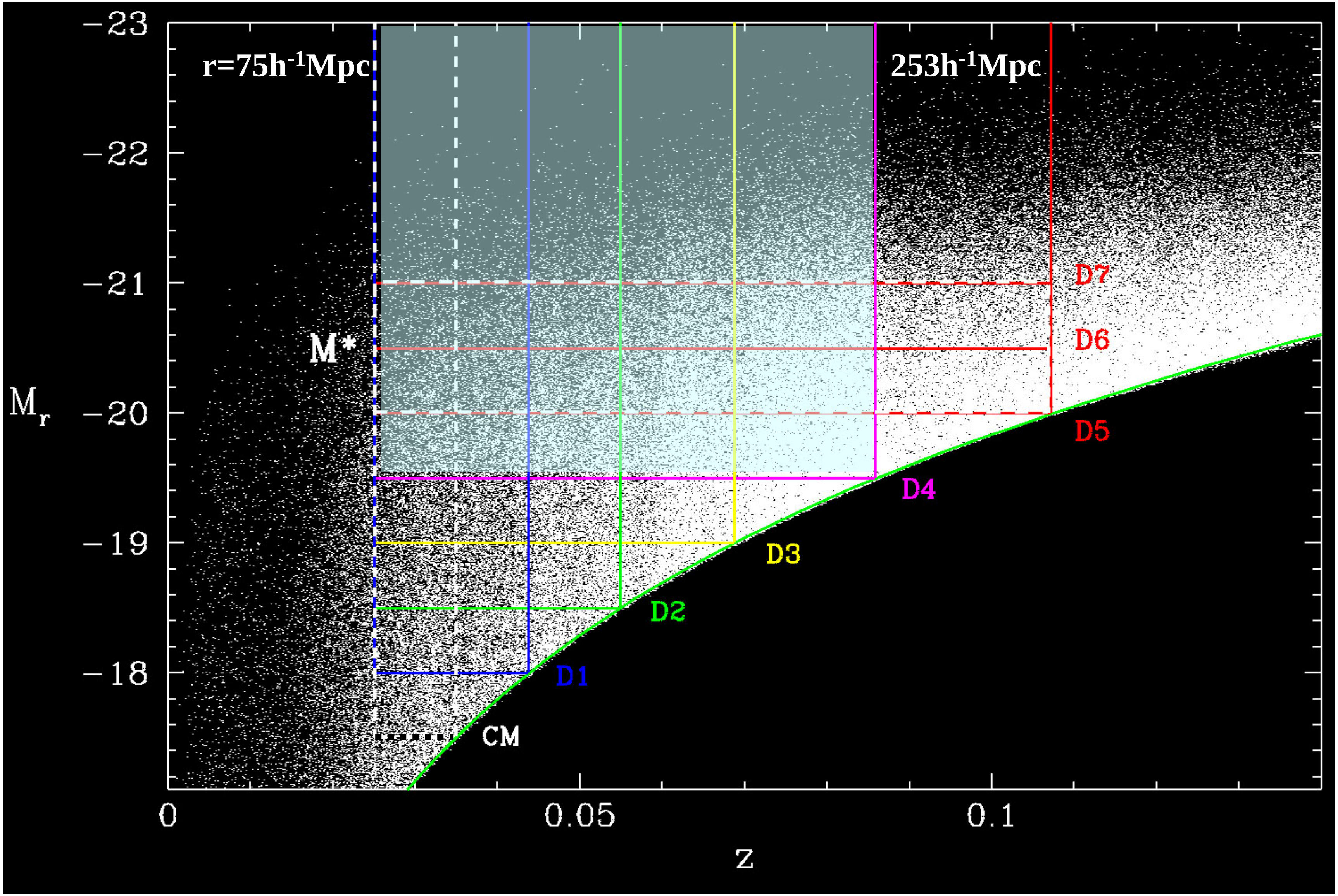
Sloan Digital Sky Survey



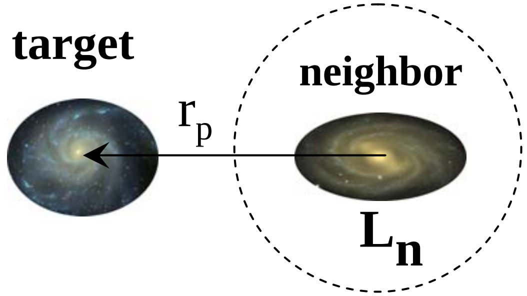
Volume-limited subsamples

Bright galaxies added

Extinction, K-correction,
L-evolution corrected



Environmental factors



1. Nearest neighbor galaxy's morphology

2. Local density due to the nearest neighbor

$$\rho_n(\mathbf{x})/\bar{\rho} = 3\gamma_n L_n / 4\pi r_p^3 \bar{\rho}$$

3. Large-scale background density (20 nearby galaxies)

$$\rho_{20}(\mathbf{x})/\bar{\rho} = \sum_{i=1}^{20} \gamma_i L_i W_i(|\mathbf{x}_i - \mathbf{x}|)/\bar{\rho}$$

$$\bar{\rho} = \sum_{\text{all}} \gamma_i L_i / V$$

where mass-to-light ratios $\gamma_E = 2\gamma_L$ based on $\sigma_E^2 \approx 2\,\sigma_L^2$, $\Delta v_E^2 \approx 2\,\Delta v_L^2$

(In the case of D4, 20 nearby galaxies with M_r<-19.5)

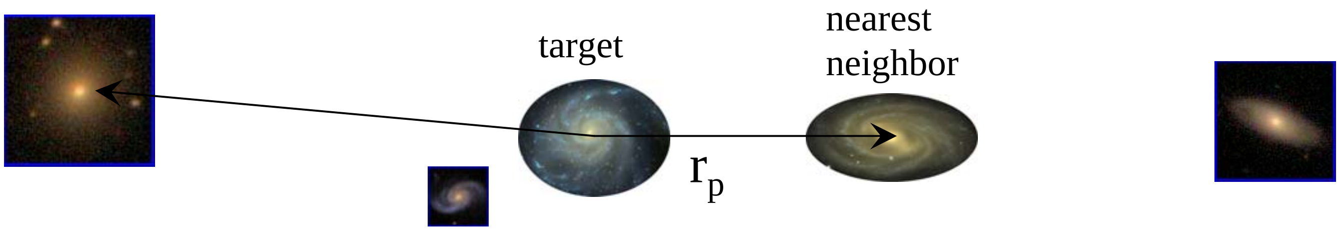
Definition of the nearest neighbor

For a galaxy with M_r & V

1. Smallest projected distance

2. Magnitude M_r(neighbor) < $M_r + 0.5$

3. Velocity difference Δv < 600 or 400 km/s for early or late type targets



Large-scale background density

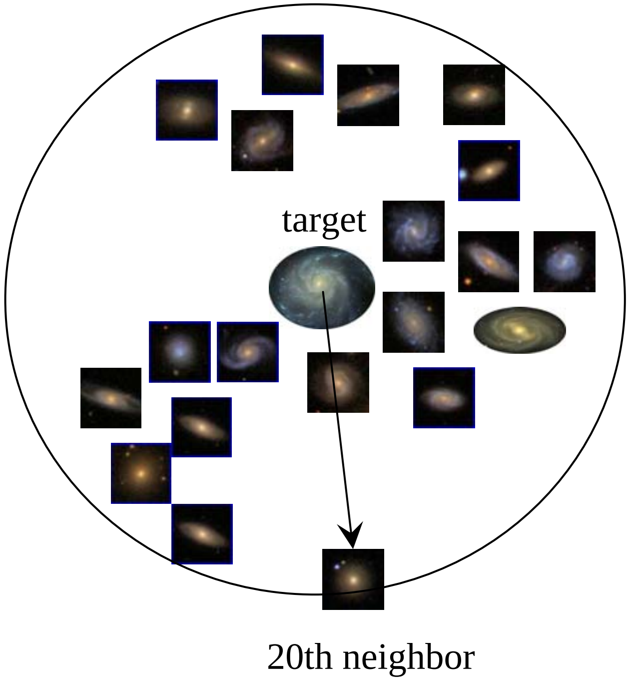
- Spline smoothing kernel

$$\rho(\mathbf{x}) = \sum_j m(\mathbf{x}_j) W(|\mathbf{x} - \mathbf{x}_j|)$$

where $W(q) = \frac{1}{\pi h^3}(1 - \frac{3}{2}q^2 + \frac{3}{4}q^3)$ **for 0<q<1**

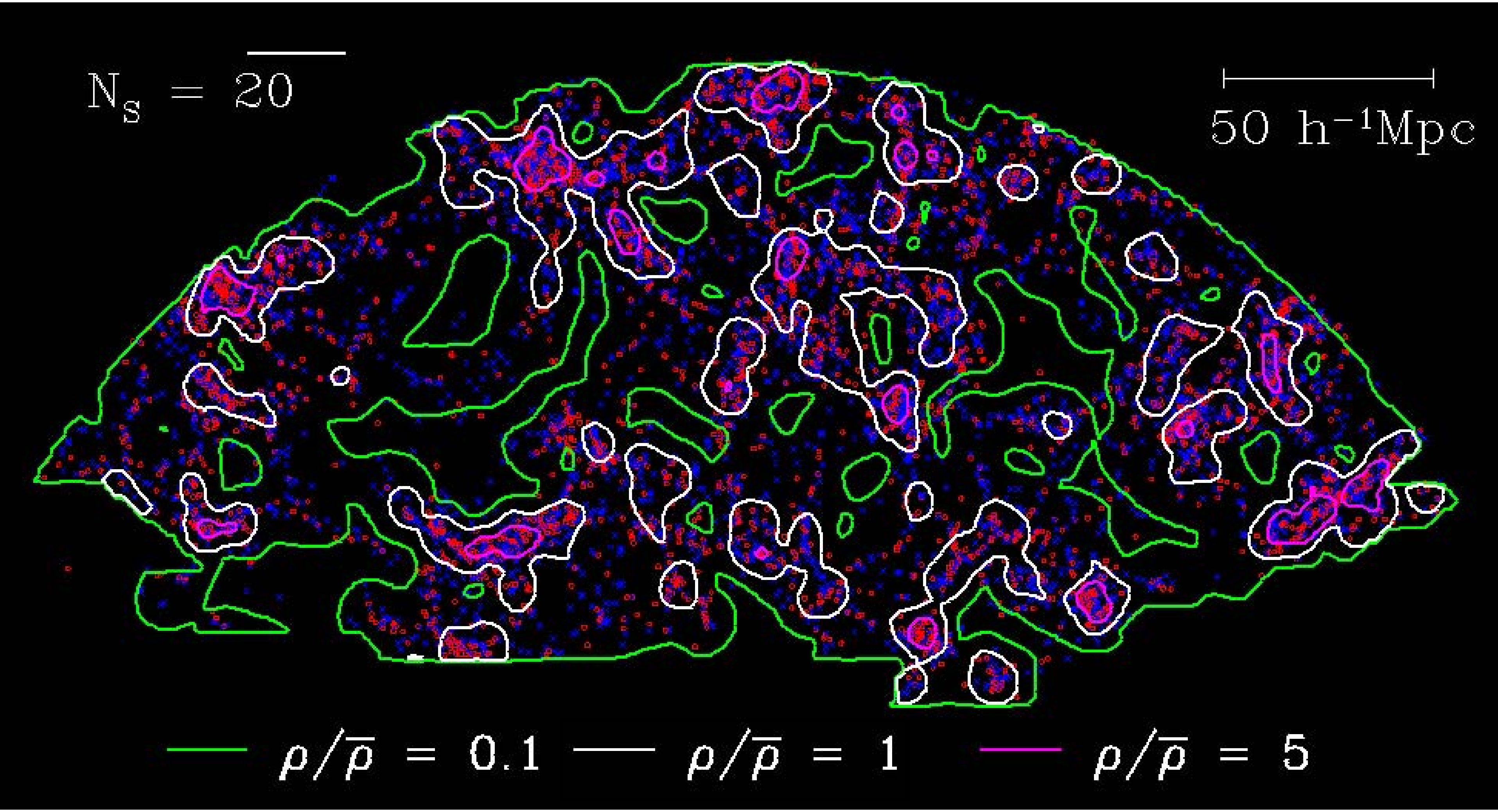
$\frac{1}{4\pi h^3}(2-q)^3$ **for 1<q<2**

$$q = r/h$$



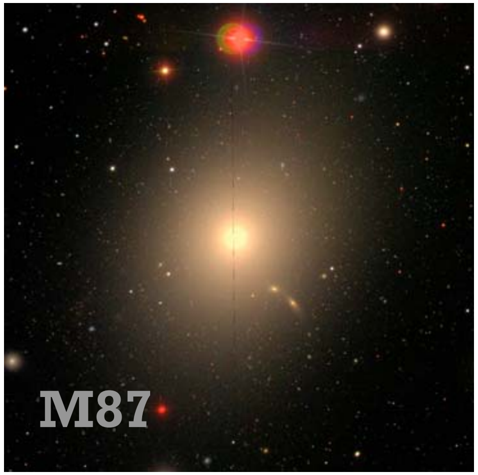
Number of neighbor galaxies within the smoothing volume **N=20**

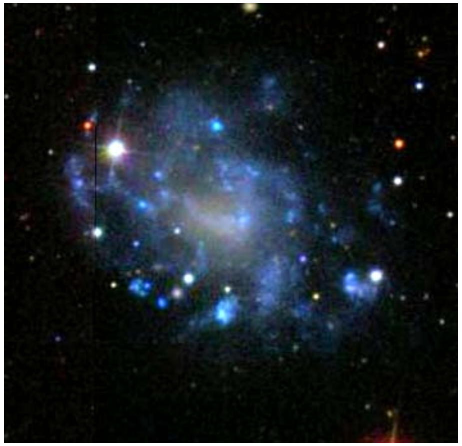
Large scale background (number) density (Park et al. 2007, ApJ, 658, 898)



What causes this? : galaxy morphology

= Initial morphology + **evolution (transformation)**





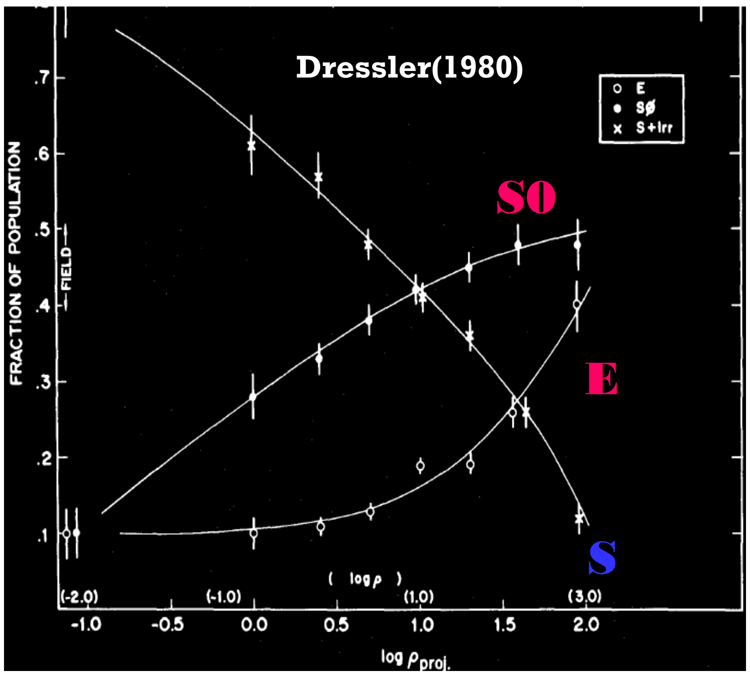
Morphology - Environment relation

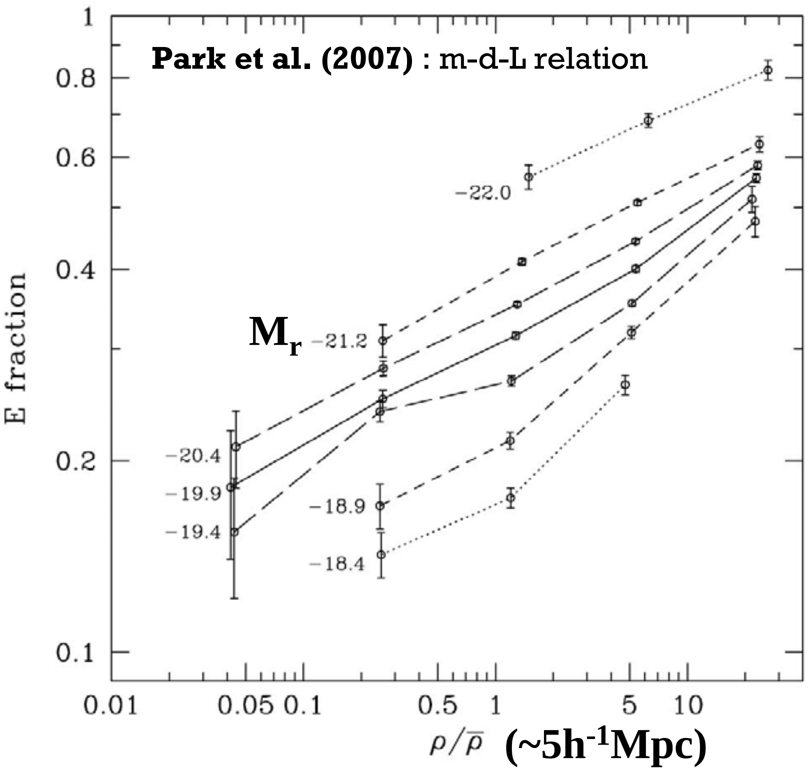
Hubble & Humason(1931) : clusters dominated by E & S0. ∴ Environment matters

Oemler(1974) : morphology-radius relation. Late type decreases as r increases

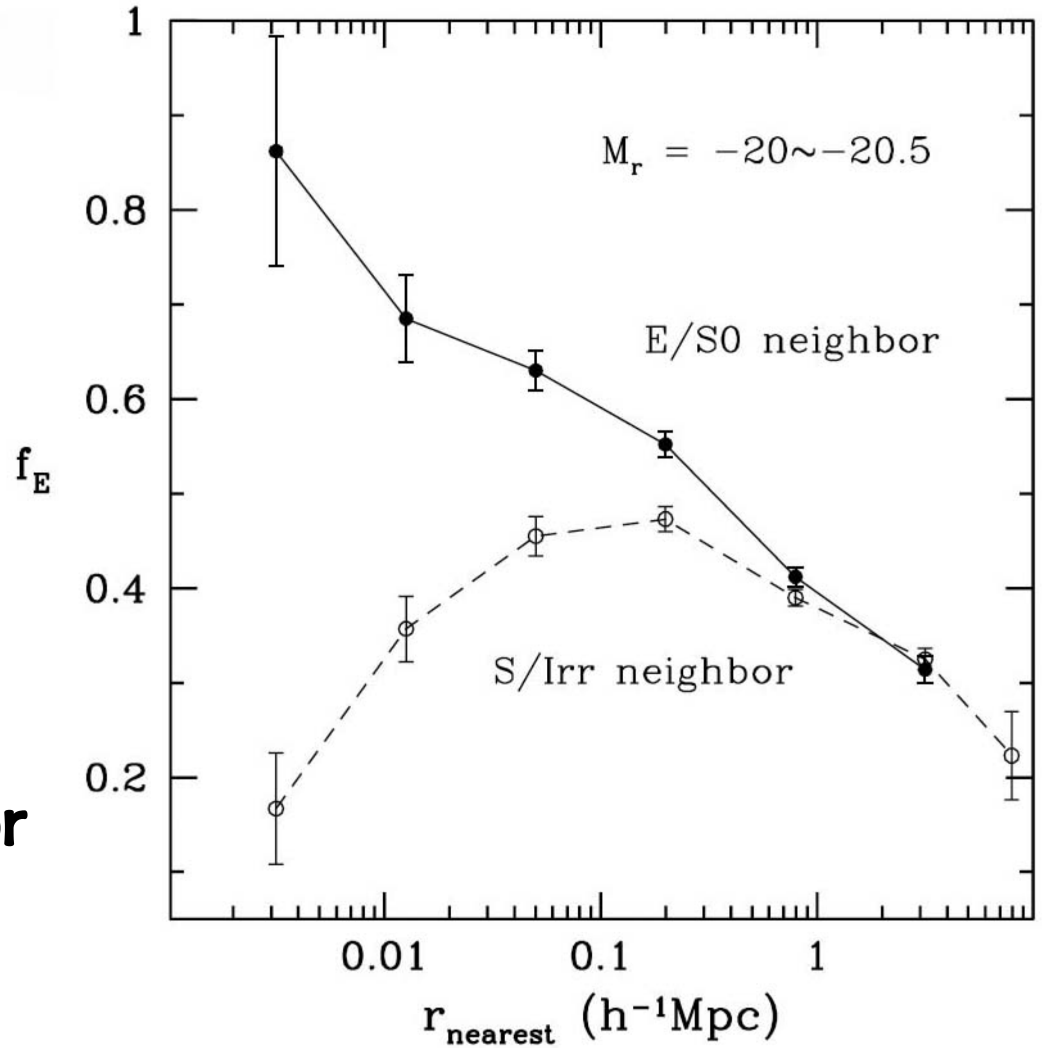
Dressler(1980) : morphology-density relation. Local galaxy density matters.

Postman & Geller(1984) : m-d relation down to group environment





Probability that a randomly chosen galaxy is an early type

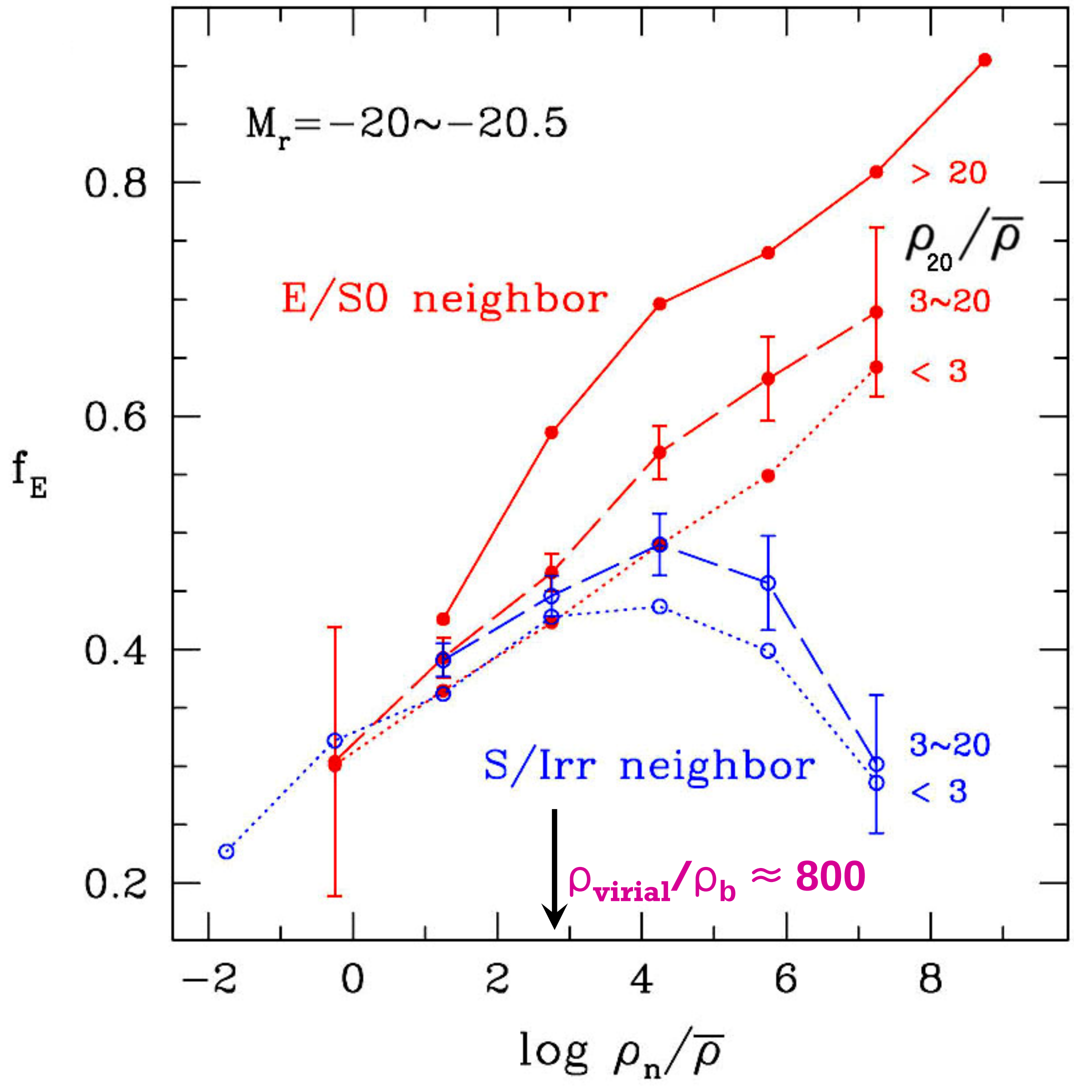


Effects of close neighbor galaxies are critical !

(Park, Gott & Choi 2008, ApJ, in press)

Morphology depends on

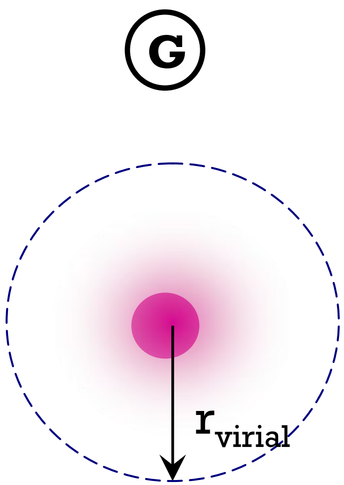
1. Local density due to the nearest neighbor
2. Neighbor's morphological type
3. Background density when within the neighbor's virial radius

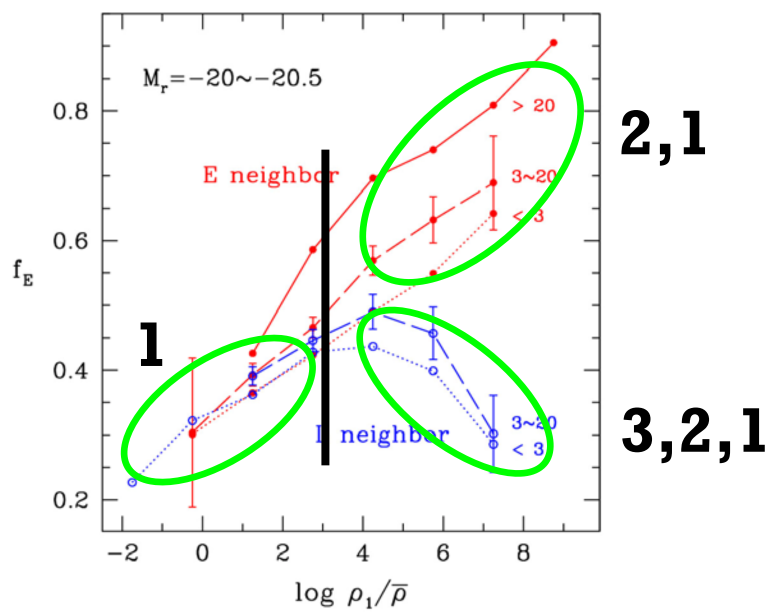


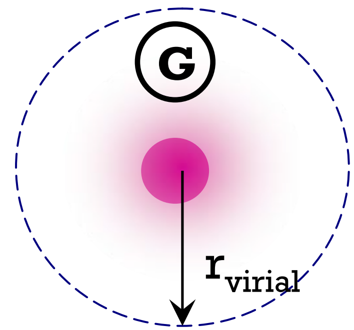
Morphology transformation by mechanisms working at a distance

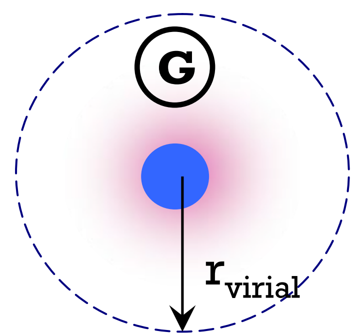
1. **Tide**
2. **Hot gas pressure and ionizing radiation**
3. **Cold gas transfer**

] **work only within r_{vir}**









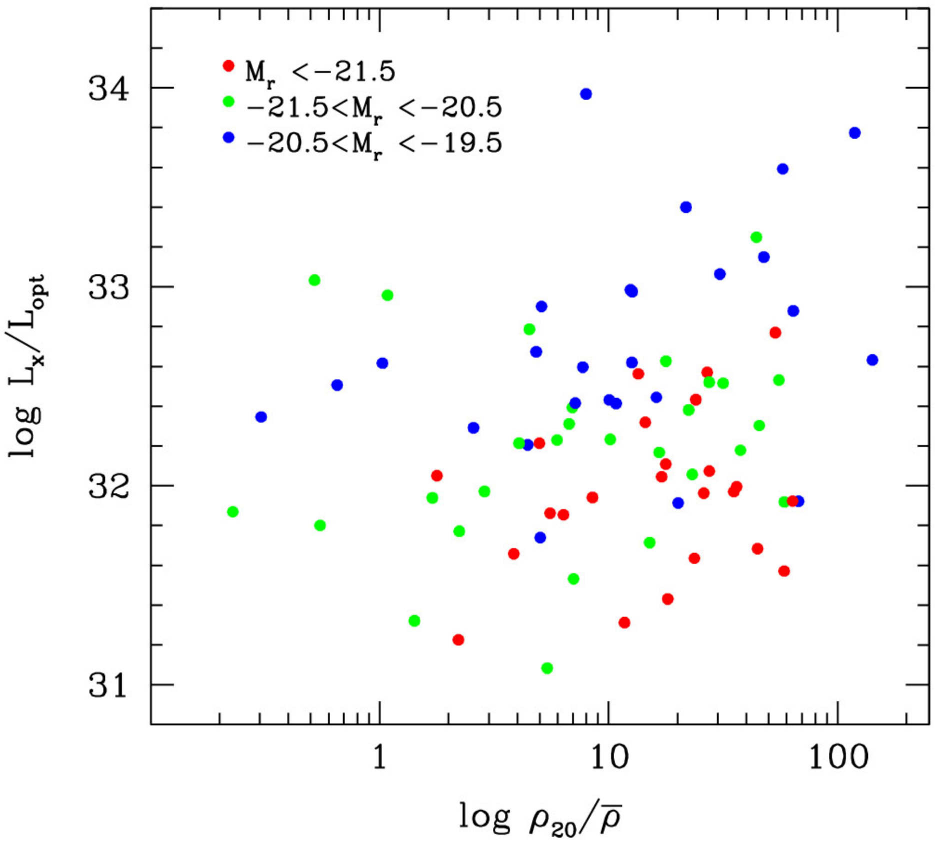
L_X of early types located at different background densities

Choi & Park (2008)

ROSAT All-Sky Survey vs D4 (M_r < -19.5)

---> 82 matches

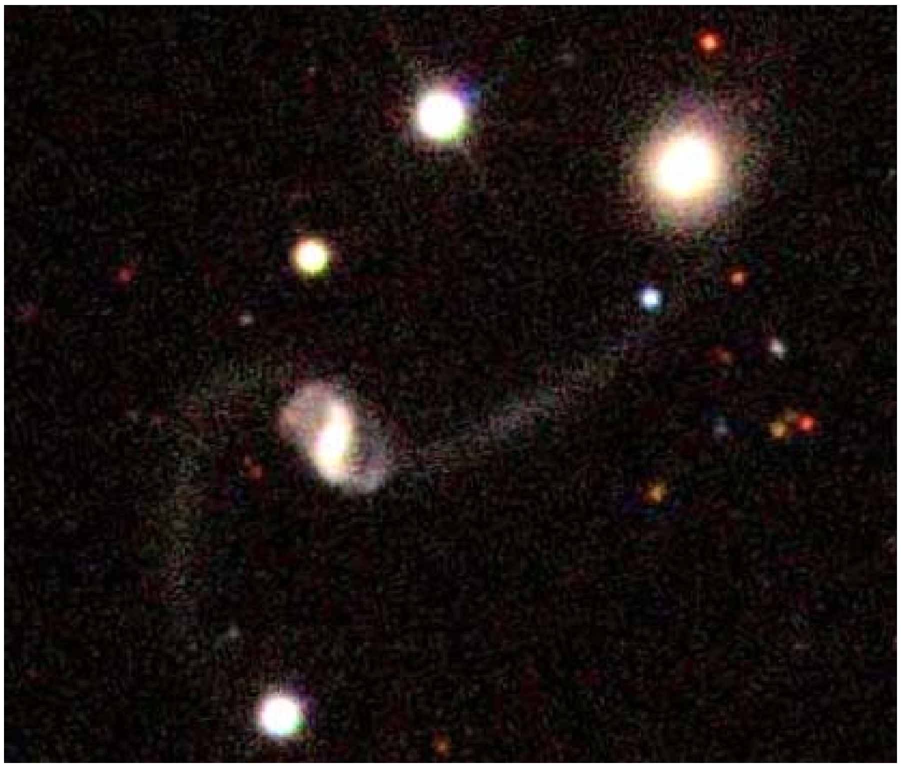
---> L_X / L_r versus ρ_{20}

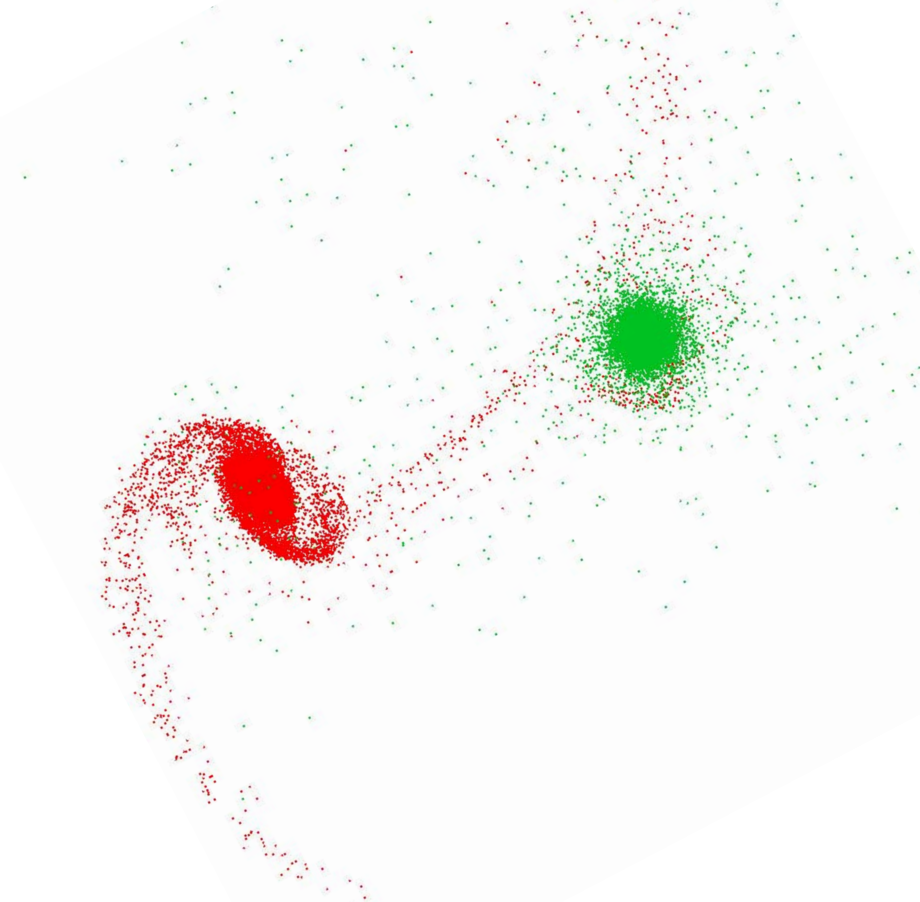


∴ X-ray emission of early types is stronger at high ρ_{20} at fixed optical brightness !!

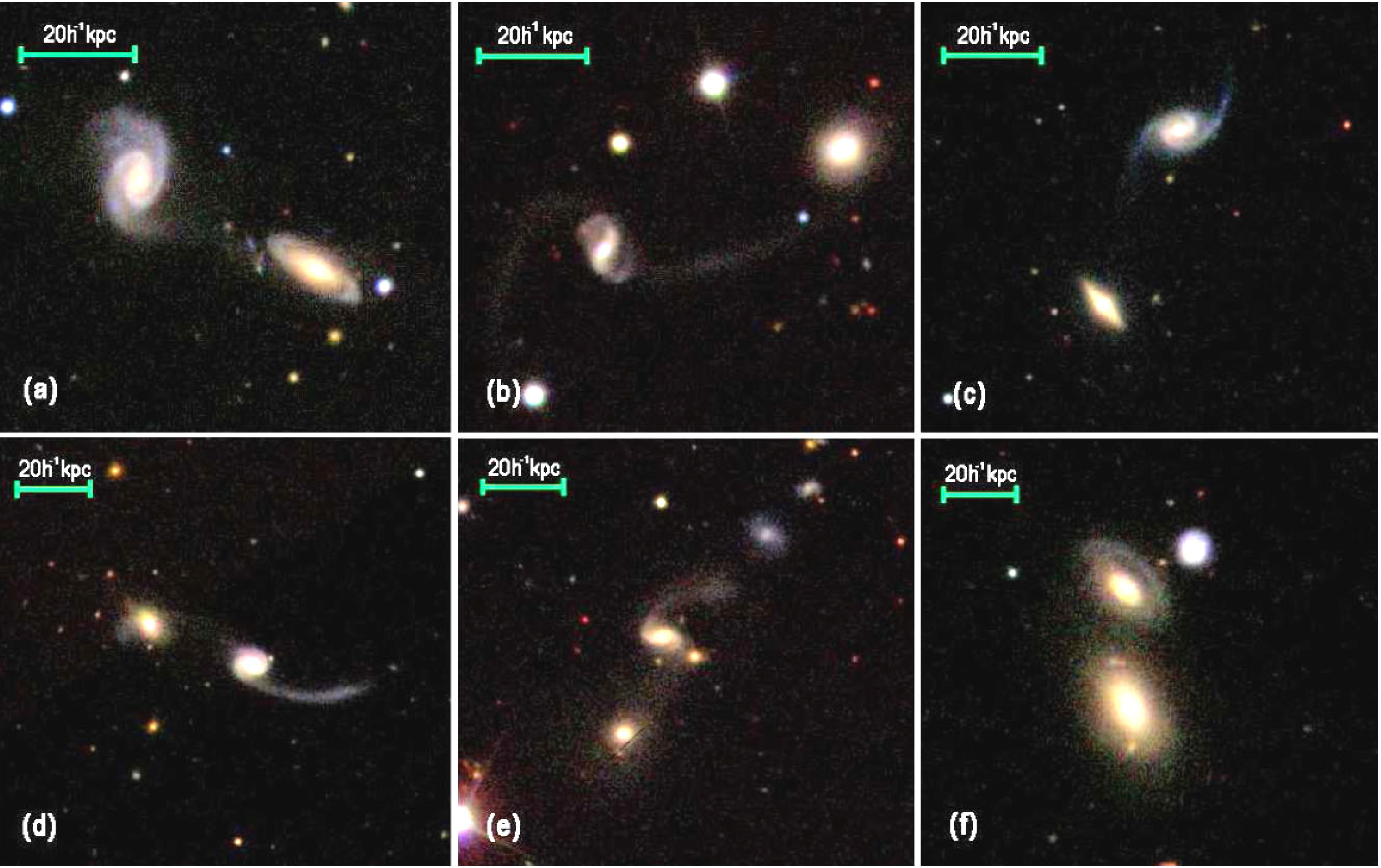
---> Early types at high densities has hotter & denser halo gas

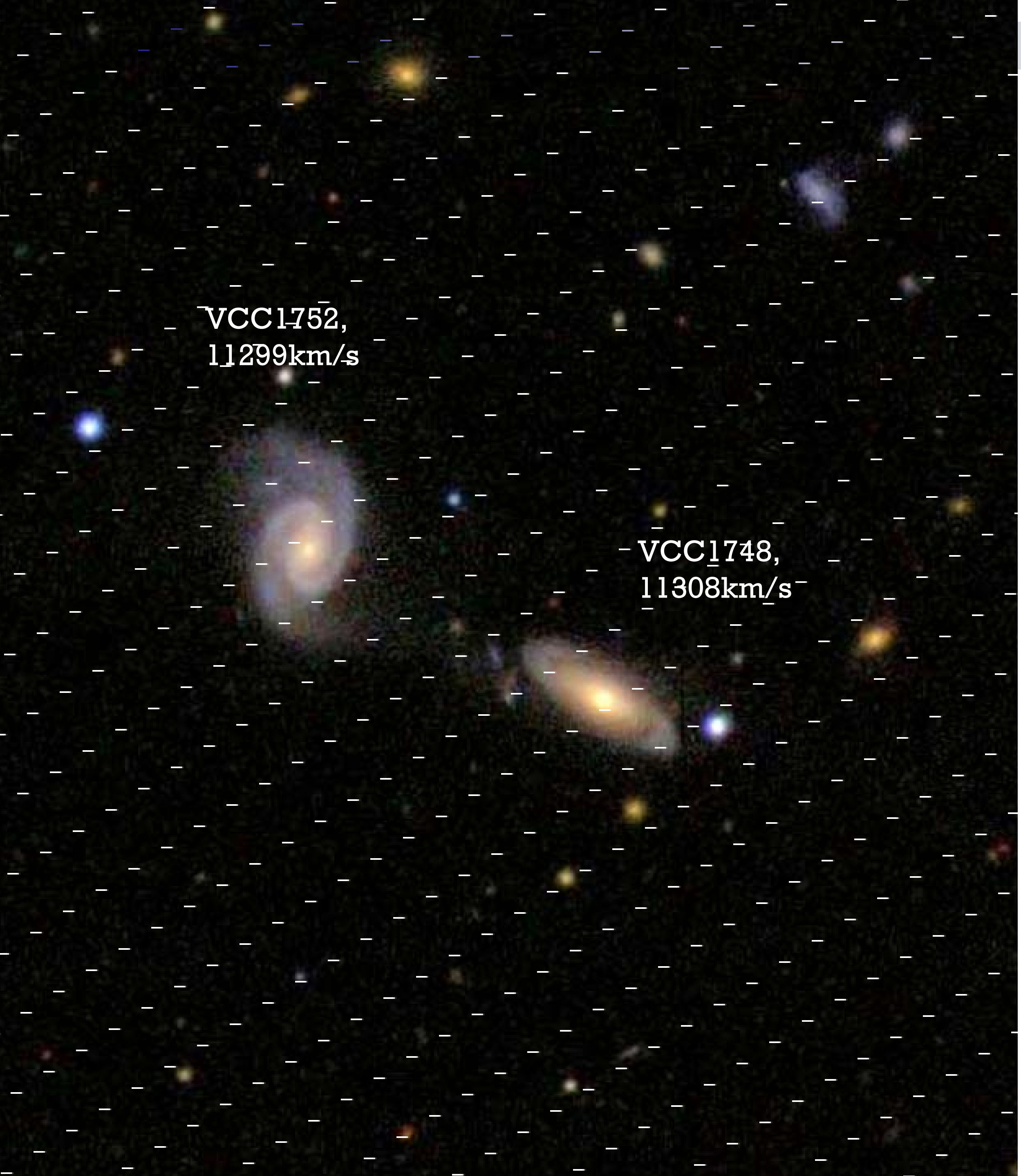
Evidence for mass transfer between close galaxies

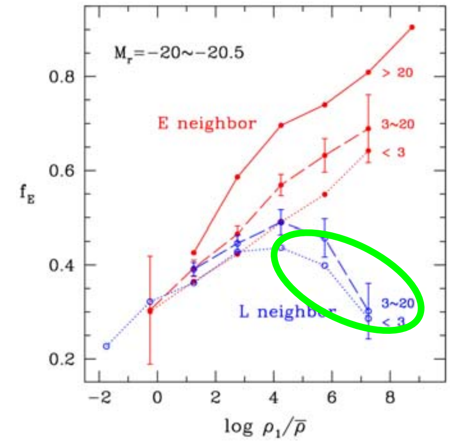




Cullen et al. (2007) simulating Arp104


20h⁻¹kpc
(a)
20h⁻¹kpc
(b)
20h⁻¹kpc
(c)
20h⁻¹kpc
(d)
20h⁻¹kpc
(e)
20h⁻¹kpc
(f)



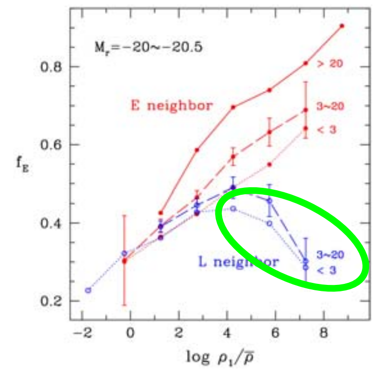


[ρ_n/ρ_b =3.5x10^5
late type neighbor]

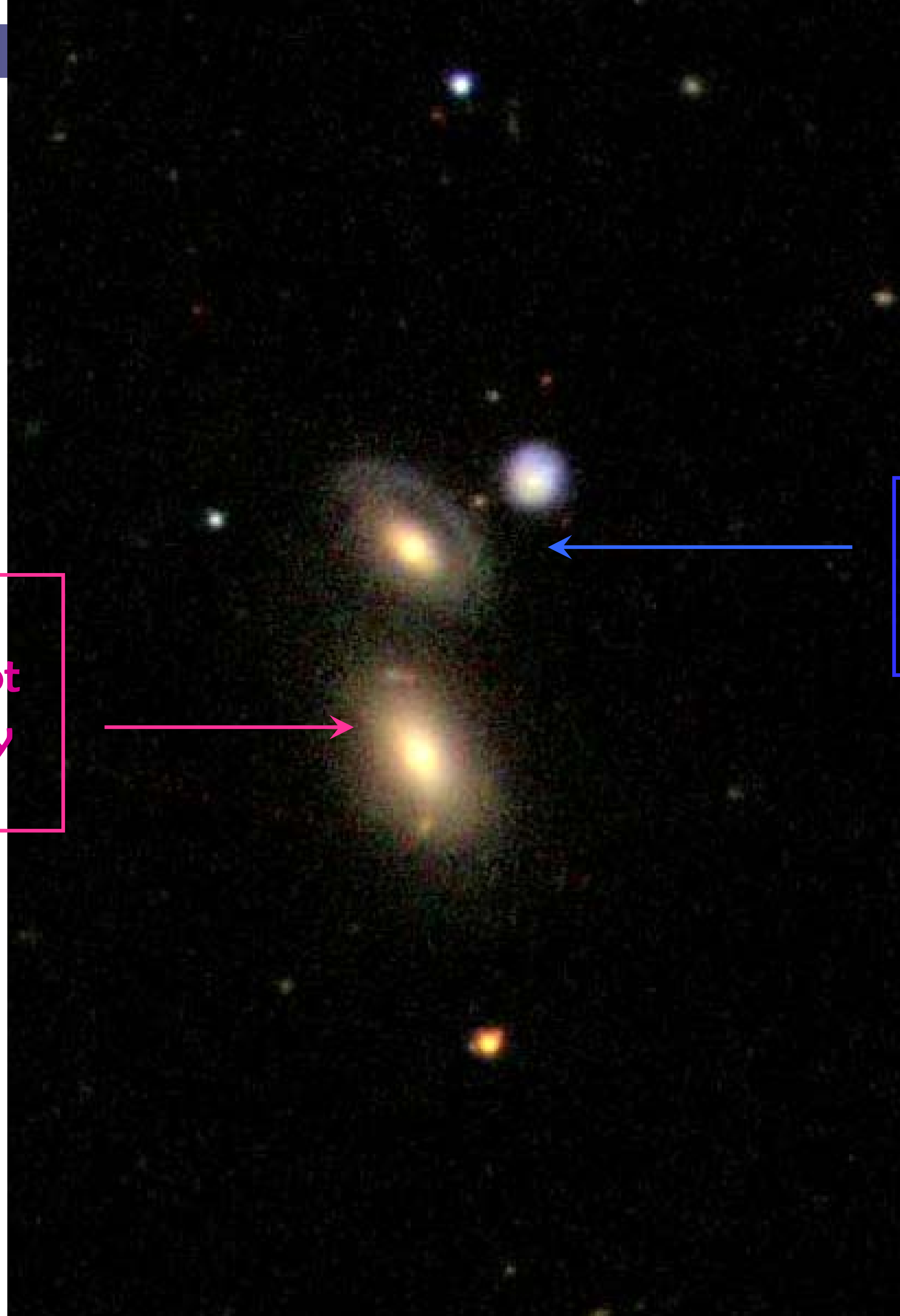
r_p = 34h^{-1}kpc

SBa (Binggeli, Sandage, & Tamman 1985)

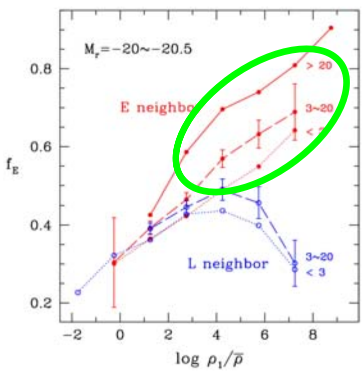
Early-to-late transformation by cold gas inflow from neighbor?



cold gas inflow from late type neighbor..



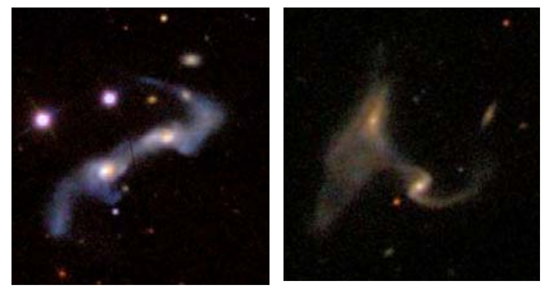
Pressure and ionization by hot halo gas of early type neighbor..



Effects of interaction on galaxy properties other than morphology

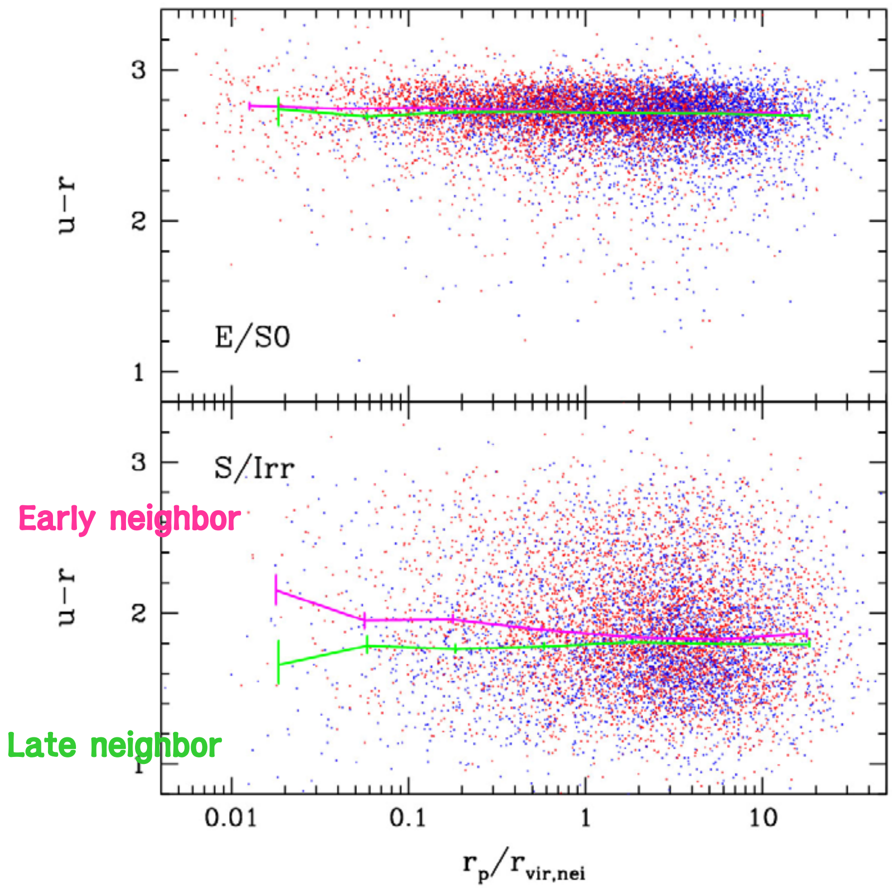
E+E

E+L

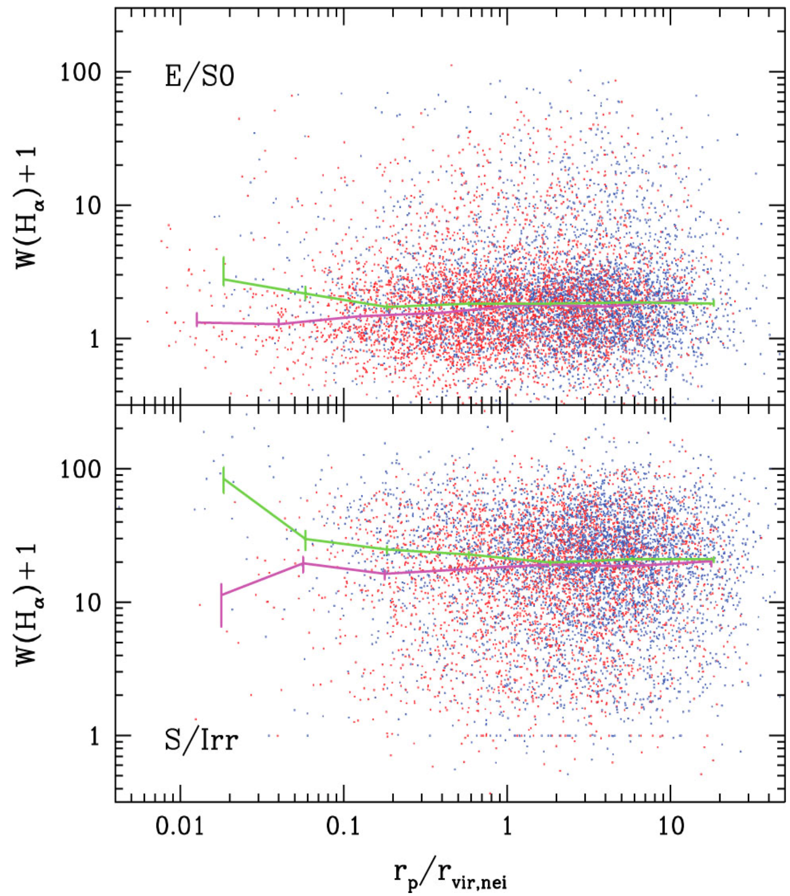


L+L

u-r color (recent star formation history)



W(Hα) (current star formation rate)

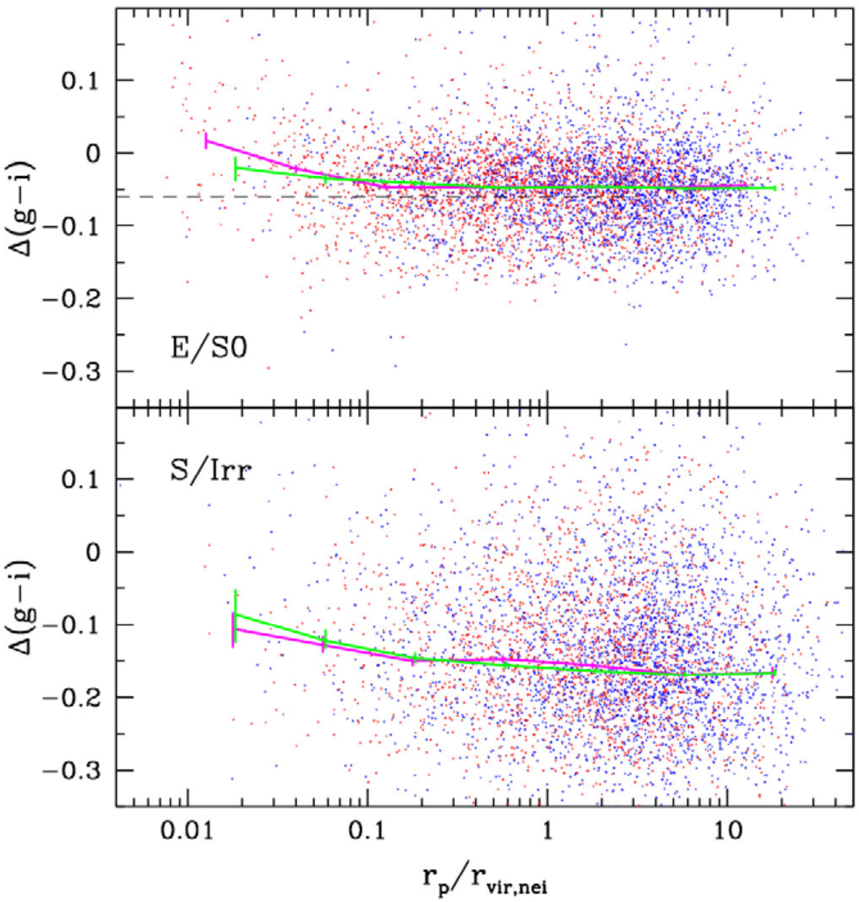


(Park & Choi 2008)

color gradient (locality of star formation history)

Early neighbor

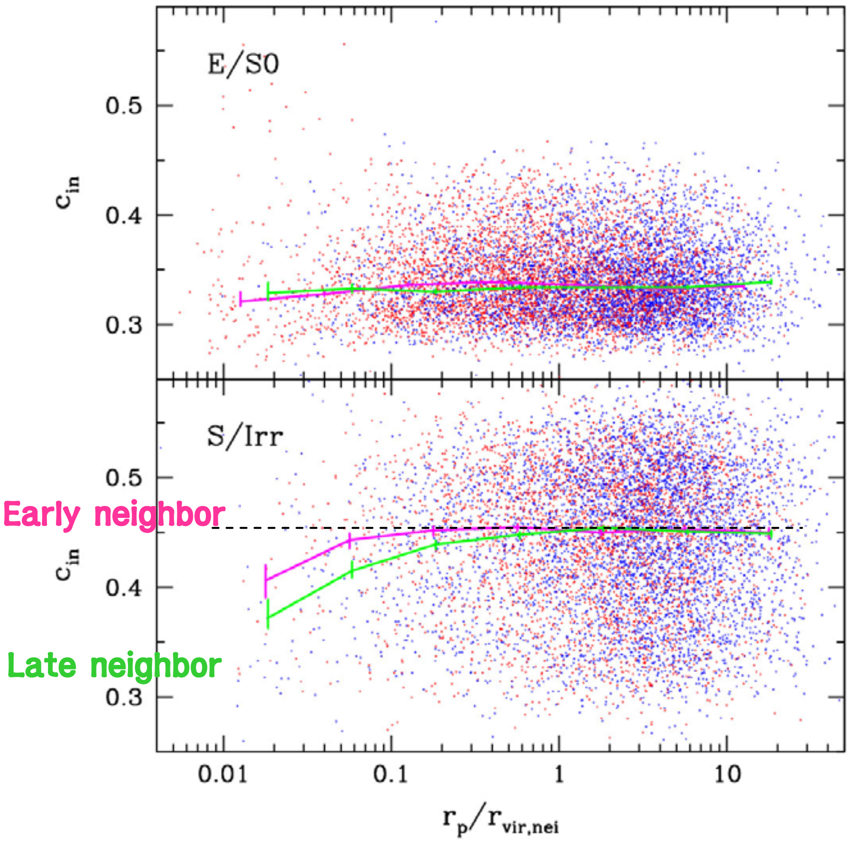
Late neighbor



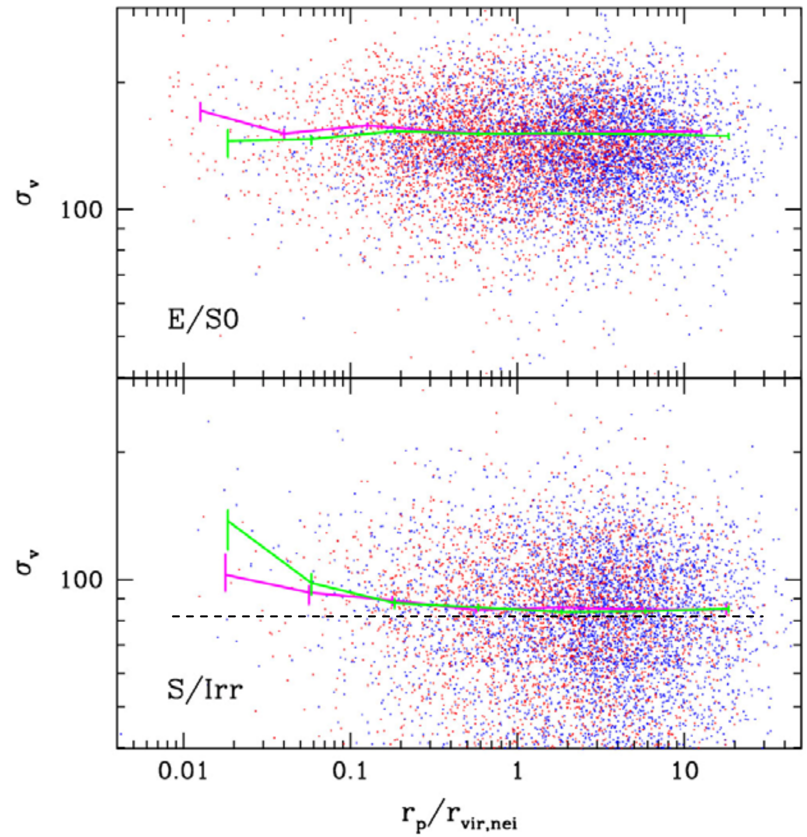
Targets : -19.5 > M_r > -20.5

Neighbors : -19.0 > M_r

Concentration
(radial structure)

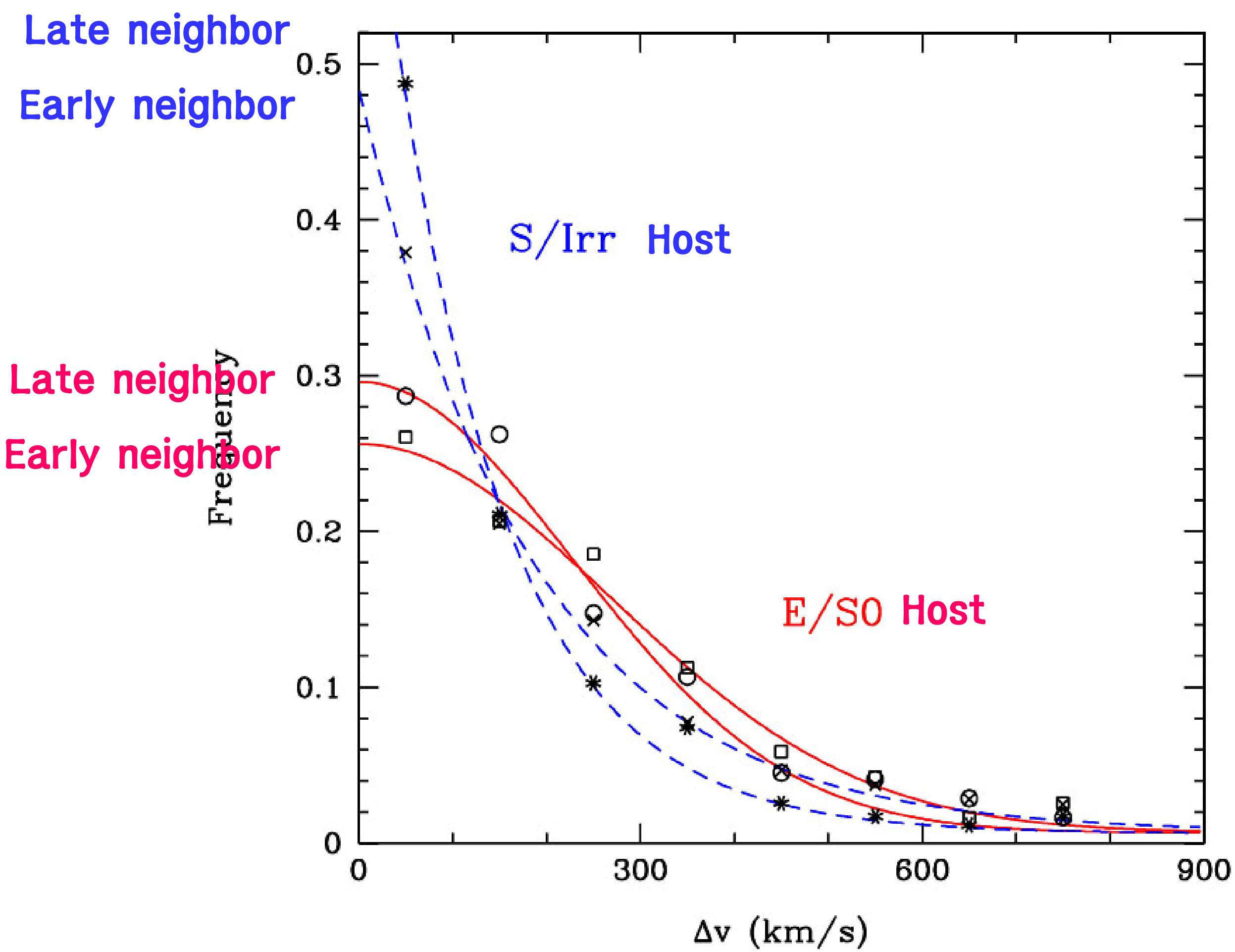


Velocity dispersion
(internal kinematics)



(Park & Choi 2008)

Pairwise peculiar velocity difference between a target galaxy and its neighbors



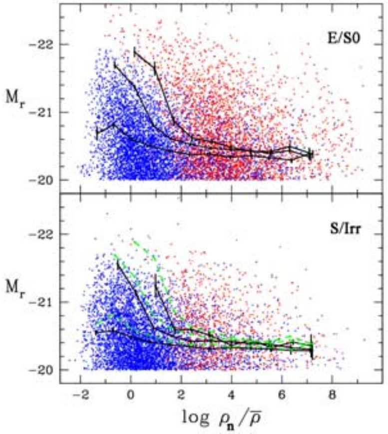
Targets : -19.5 > M_r > -20.5

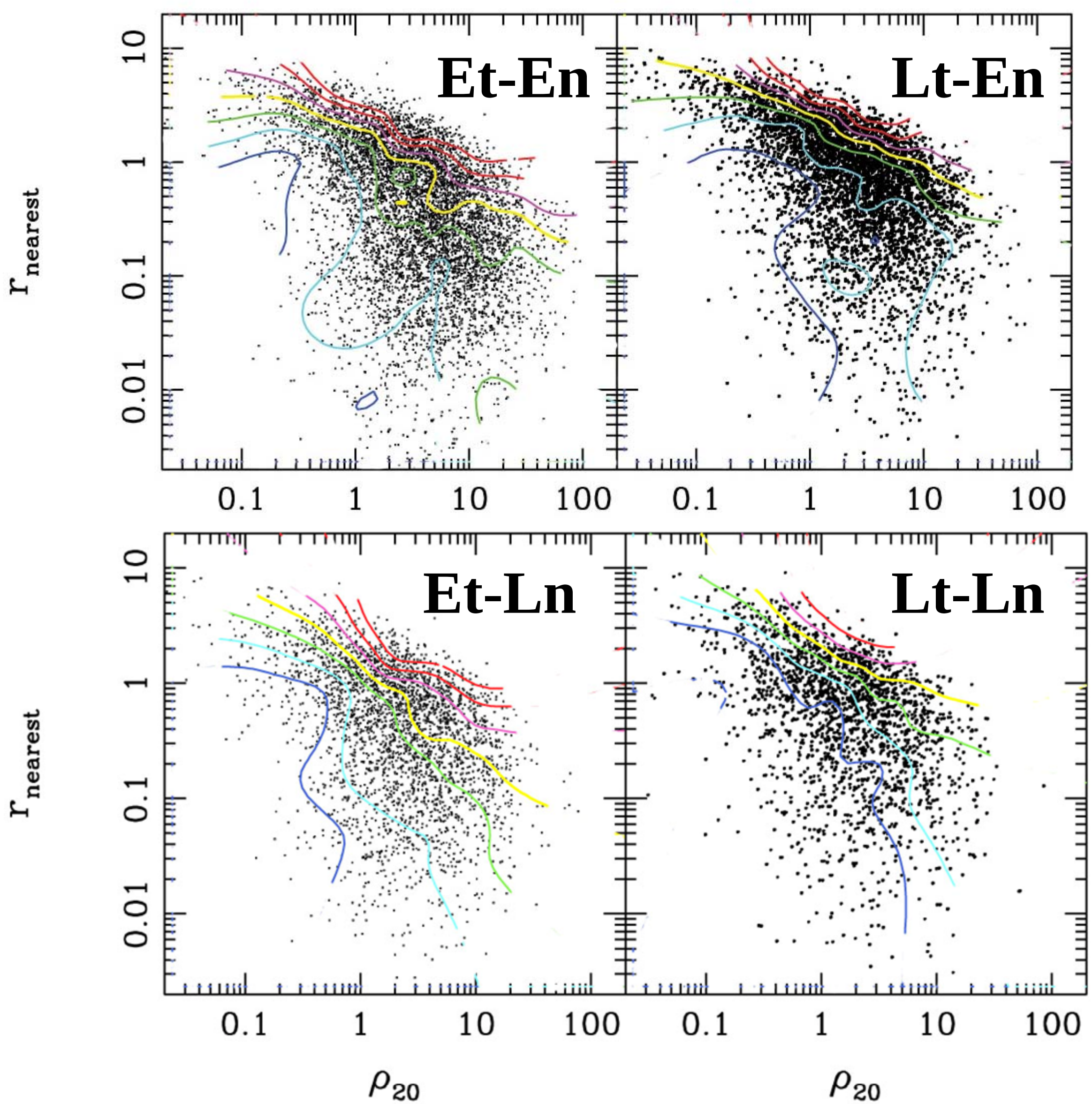
Neighbors : -19.0 > M_r

0.01 < r_p < 0.1 h^{-1}Mpc

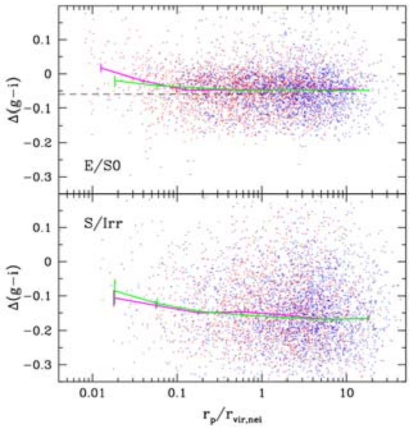
σ = 300, 250, 180, 125 km/s

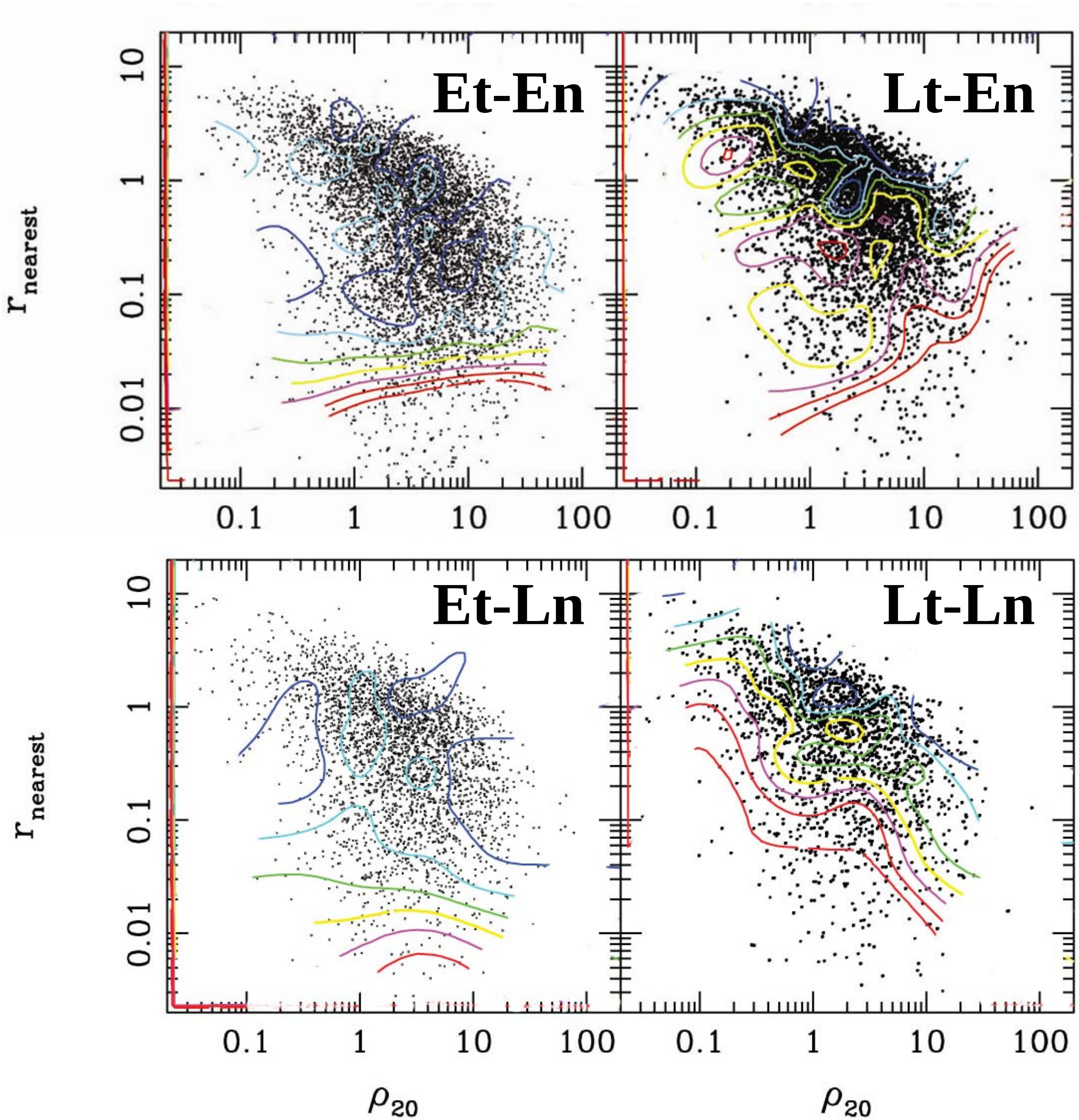
Luminosity Change





Color Gradient Change





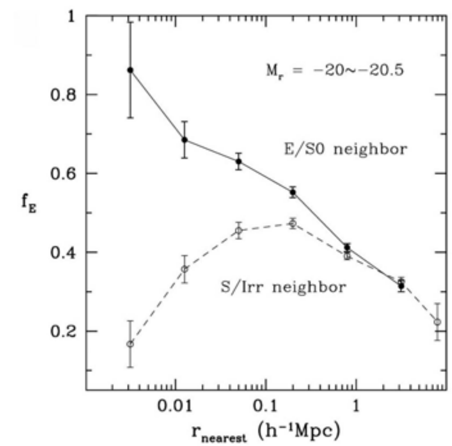
(Park, Gott & Choi 2008, ApJ, Feb.20)

Contrary to the common sense

1. Morphology-density relation is mostly due to the effects of the nearest neighbor

- effects of the nearest neighbor on morphology are great!

- previously thought it was marginal. Needs early/late separation



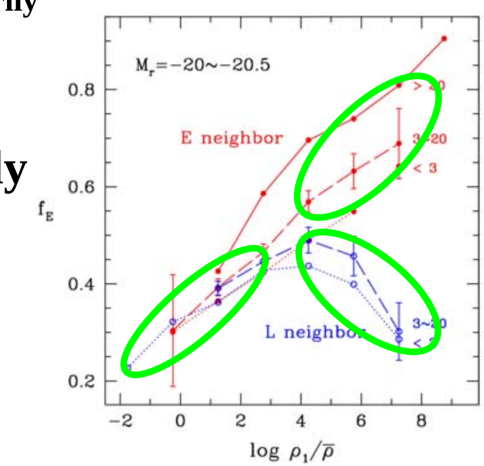
2. Effects of neighbor reach beyond 1Mpc!

- previously thought that it was effective at << 50kpc when merger occurs

- not only merger, but also close/distant interactions are effective

3. Morphology transformation from early to late! at least temporarily

- previously talked only about transformation from spiral to elliptical



4. Large-scale background environment itself does not directly cause morphology evolution. (maybe except for cluster centers)

- previously it was not clear whether the m-d relation was caused by the large-scale density affecting the initial morphology or by later evolution.

Summary

1. Morphology is affected by

- local density due to the nearest neighbor (tide)
- neighbor's morphology (hydrodynamic/tide & radiative effects)
- large-scale background density (controls neighbor's hot gas)

2. Three stages of interaction

A. encounter: $r>r_{vir}$, B. trapped: $r_{gal} < r < r_{vir}$, C. merger: $r < r_{gal}$

3. The morphology - density relation

is mostly due to the statistical correlation between the large-scale background density and the mean galaxy separation.
It is the neighbor density which is really responsible for the relation.

4. Morphology and luminosity transformation are coupled

Galaxies seem to change morphology and luminosity through a series of close interactions and mergers

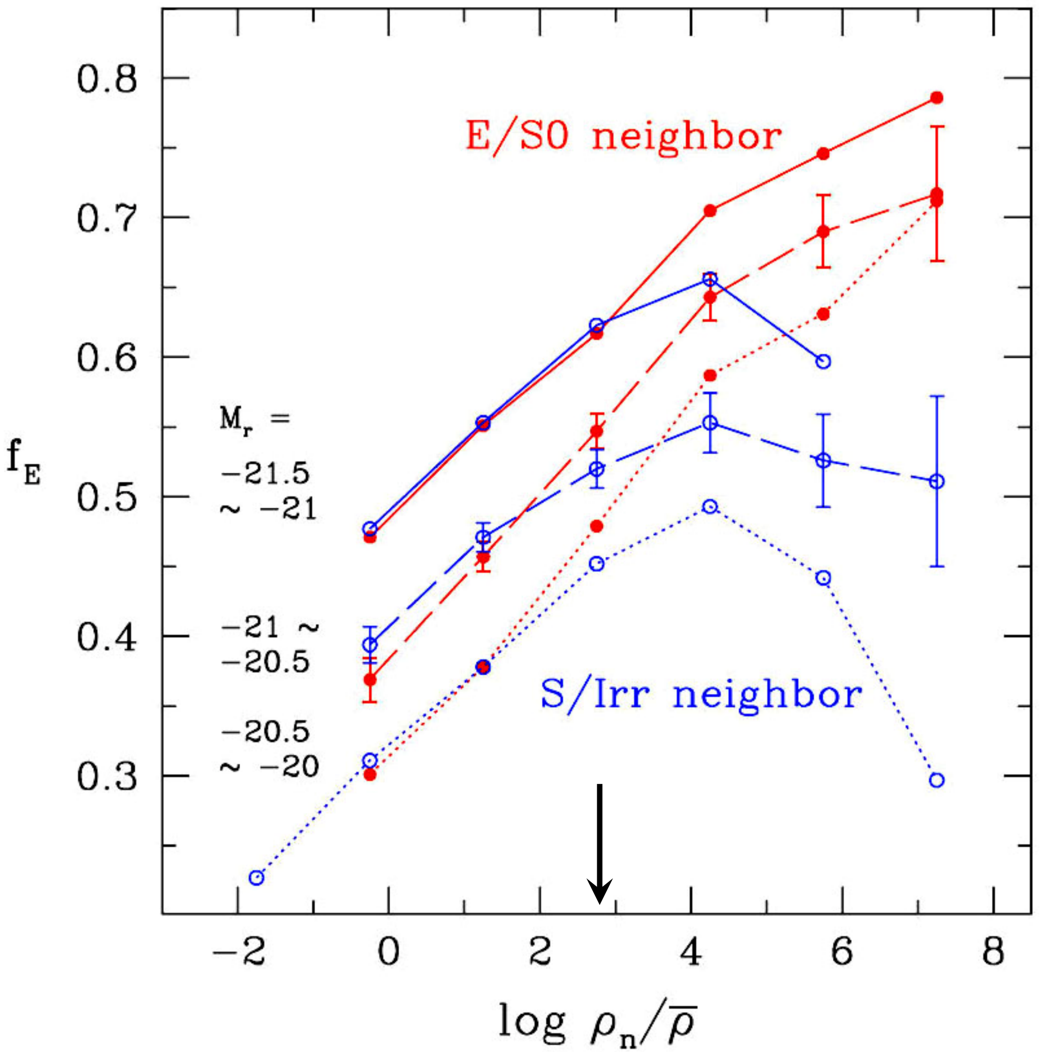
Morphology transformation in conjunction with luminosity class transformation

It is actually the luminosity-morphology-density relation that we should understand.

One should understand the evolution of morphology and luminosity at the same time as a function of environment

Luminosity dependence of the f_E-ρ_n relation

f_E - ρ_n relation scales monotonically as luminosity increases !

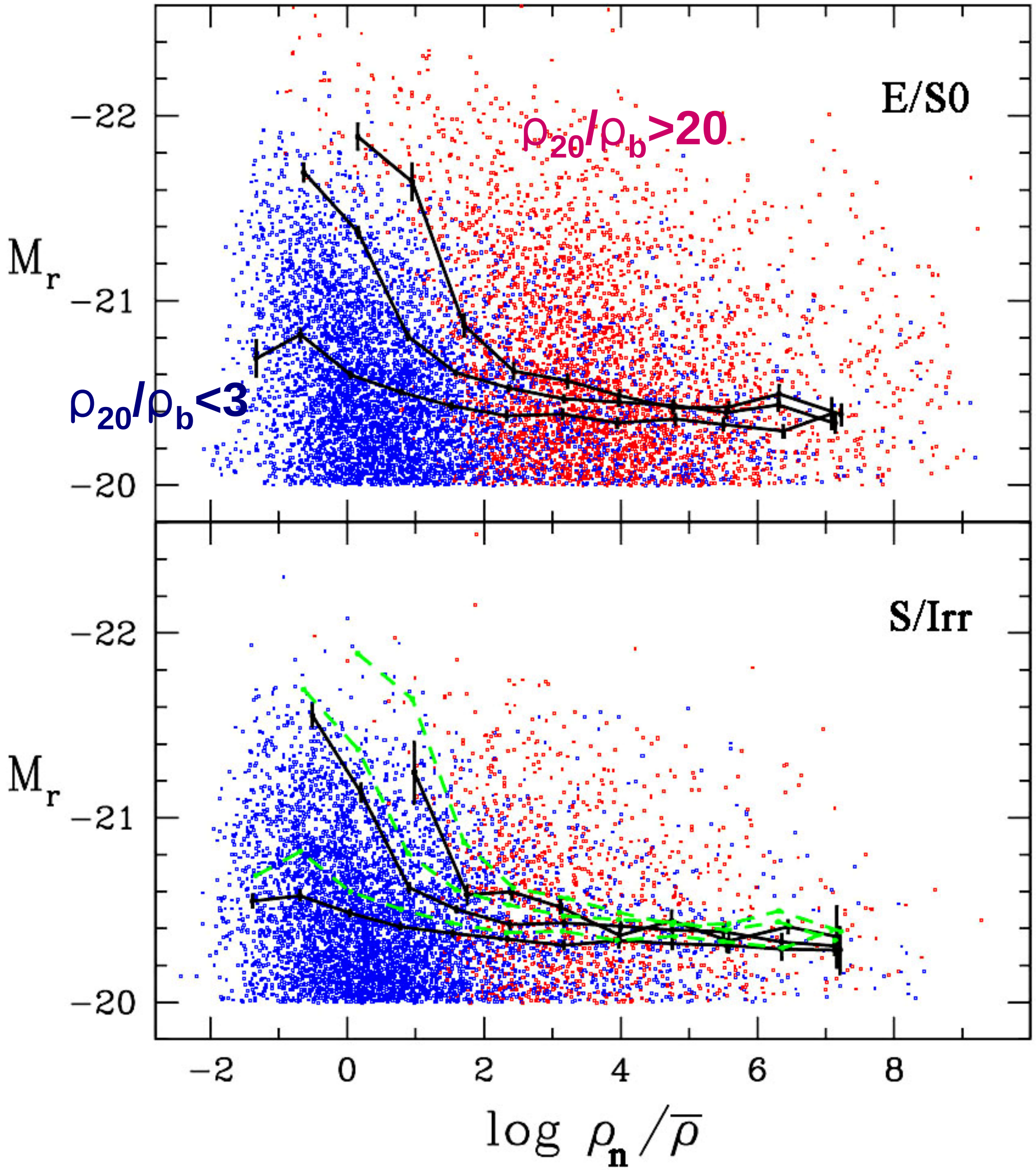


Dependence of luminosity on ρ_n at fixed ρ_{20}

- **The brighter, the earlier**

- **Bright galaxies are more isolated from influential neighbors at high ρ_{20} !!**

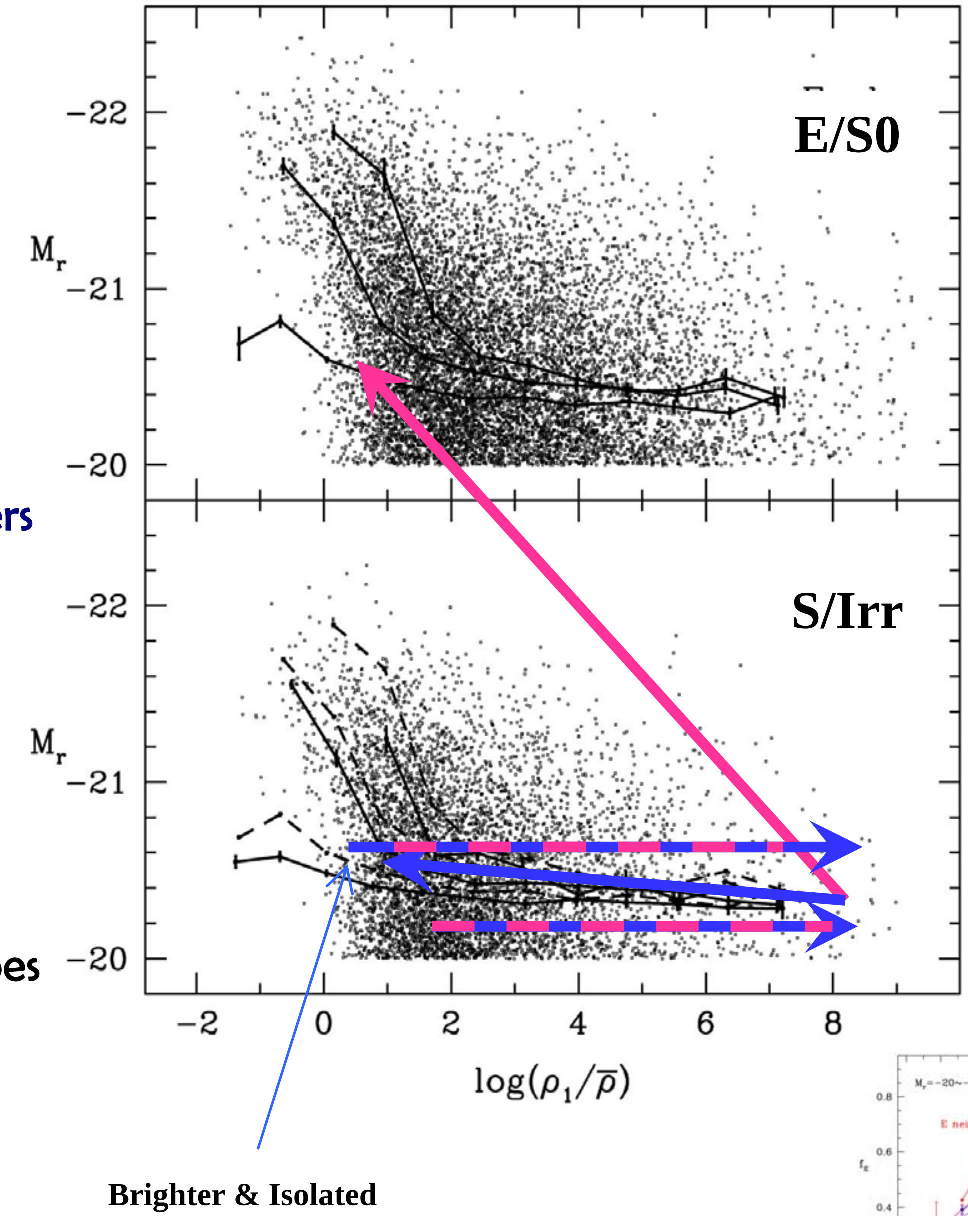
- **At fixed ρ_{20} more isolated galaxies are more likely to be recent merger remnants**

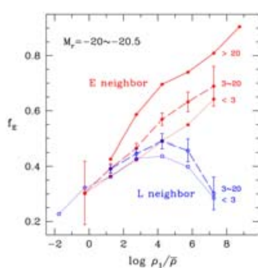


A series of close interactions & mergers results in transformation of L & morphology

Merger results in consumption of cold gas

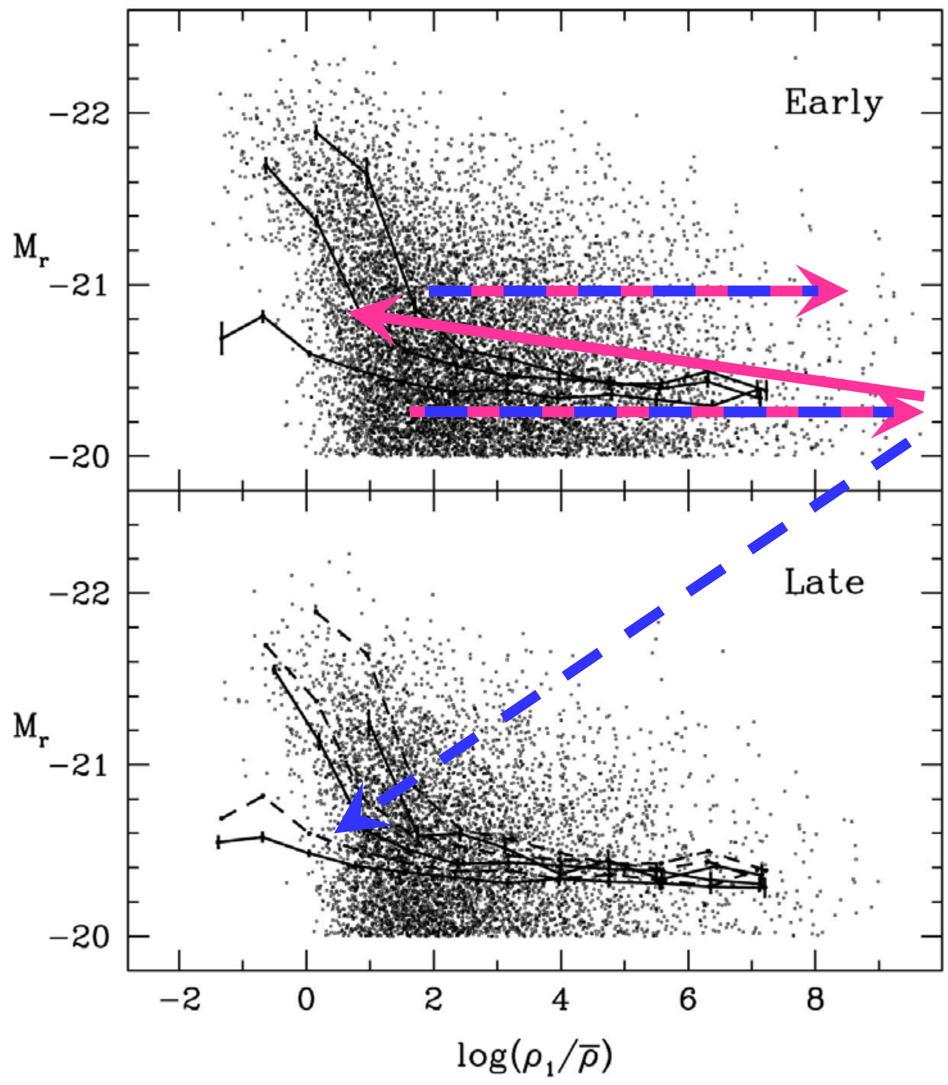
By the time M_r reaches about -21.5 ~all late types transform to early types





As time passes,

more bright E galaxies appears



The scenario requires

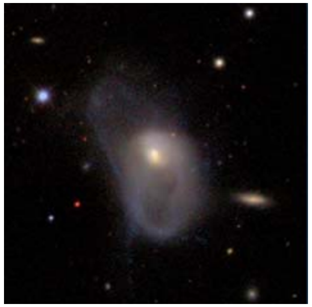
1. Merge rate is higher at higher ρ_{20} ∵ ρ_n dependence of M_r is higher at higher ρ_{20}

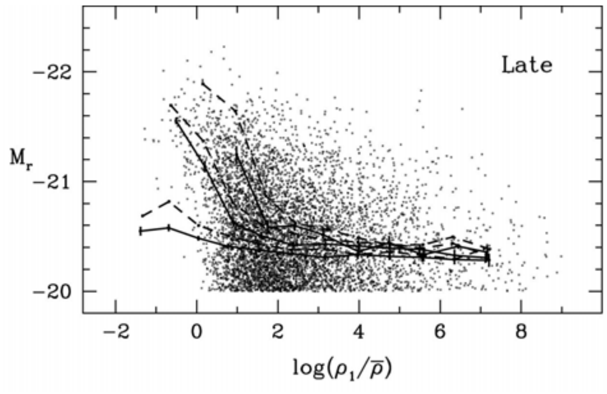
: Fraction of galaxies currently undergoing major merger

= 3.0, 4.8, 6.8% for ρ_{20}/ρ_b <3, 3~20, >20 (for galaxies with M_r<-20)

2. At a given L, there are more recently merged galaxies at lower ρ_n

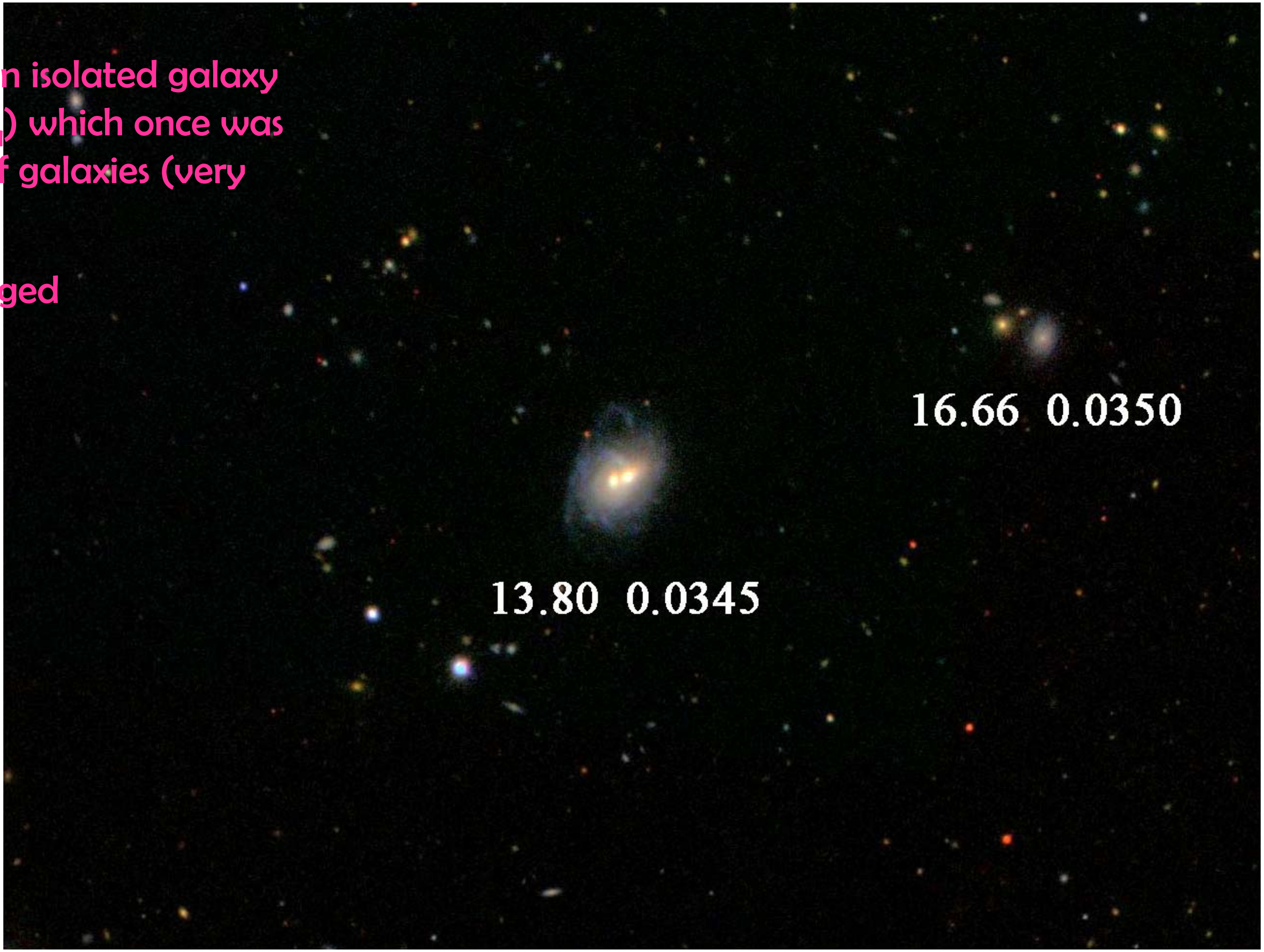
: Fraction of galaxies showing post-merger features = 11 & 4 % for galaxies with Mr=-20.8 ~ -21.6 located at $\rho_1 < \rho_{virial}$ & > ρ_{virial} !!





Example of an isolated galaxy (very small ρ_1) which once was a close pair of galaxies (very large ρ_1)

Recently merged



Explains & Implies

1. Morphology-density-luminosity relation
-- higher density → closer neighbors → faster evolution toward E types

2. Conformity in morphology, color, * formation rate in pairs & groups
-- tidal/hydrodynamic interactions between close neighbors

3. Morphology-dependent large-scale clustering
-- faster cold gas consumption in galaxies in high density regions

4. Existence of early type galaxies in underdense regions
-- tidal effects and merger

5. Initial morphology at the time of formation is mostly late type.
-- f_E ~0 for very isolated and faint galaxies

6. Isolated galaxies are likely to be recently merged ones
-- at a given background density. Thus not keeping primordial conditions

7. Large perturbation of dark halos at large separation (several 100kpc) and the corresponding effects on galaxy properties

8. At high z, galaxies should be bluer, later morphology & less massive.
-- Galaxies at high densities evolve more rapidly (∵ higher interaction rates)
-- * formation at higher densities is higher in the past (∵ less cold gas consumption)