What has the Sloan Digital Sky Survey taught us about galaxies?

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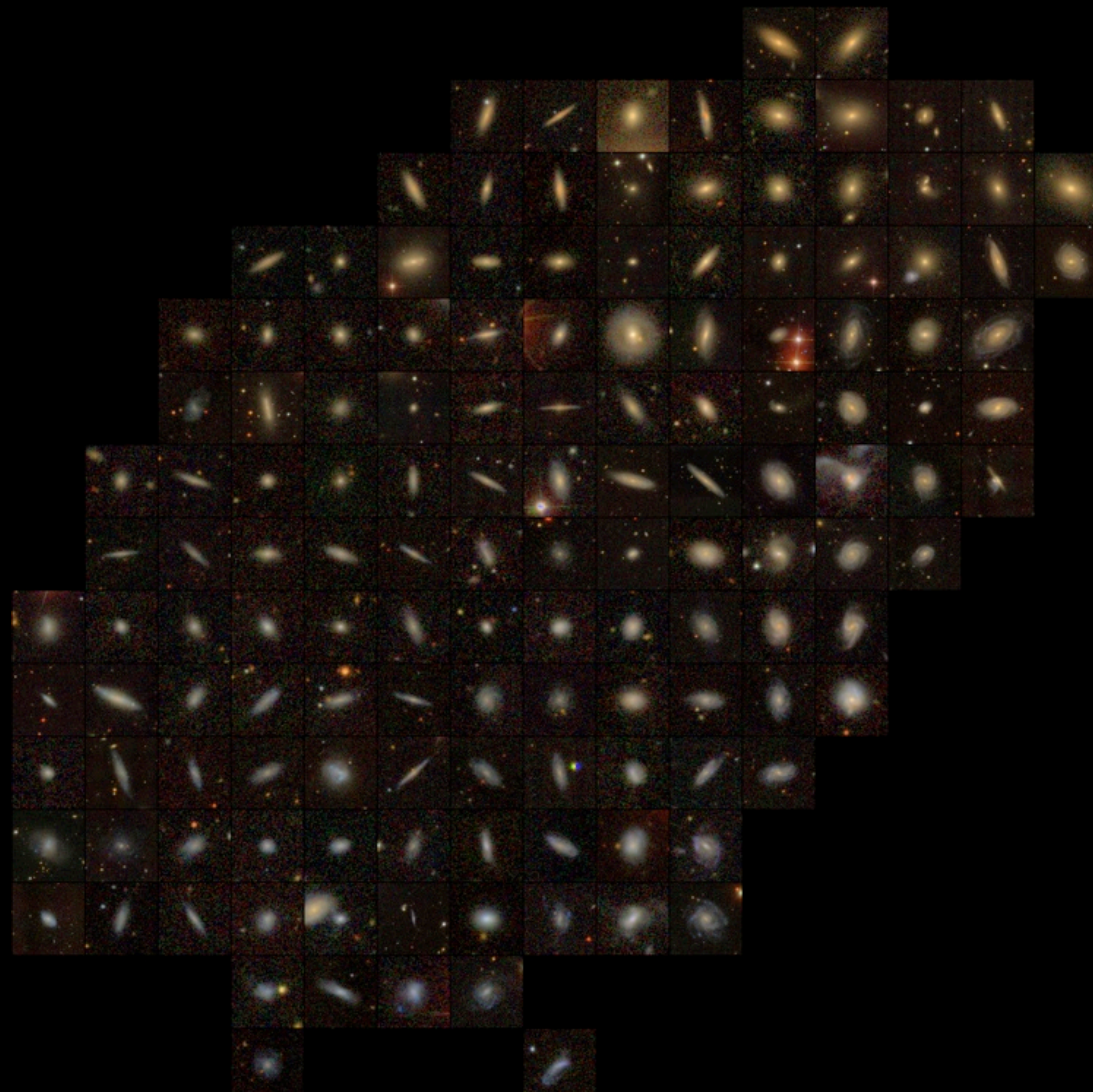
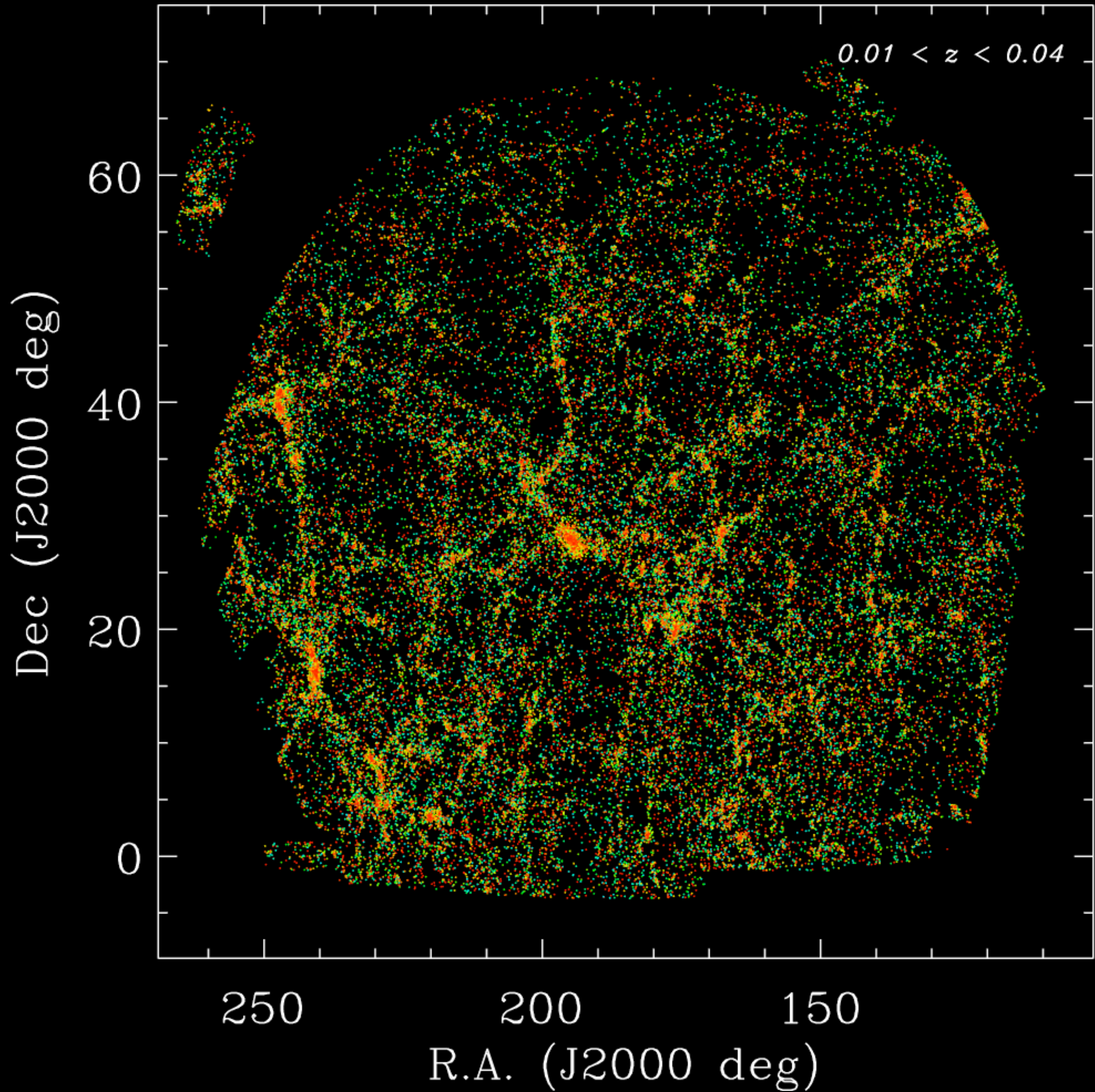
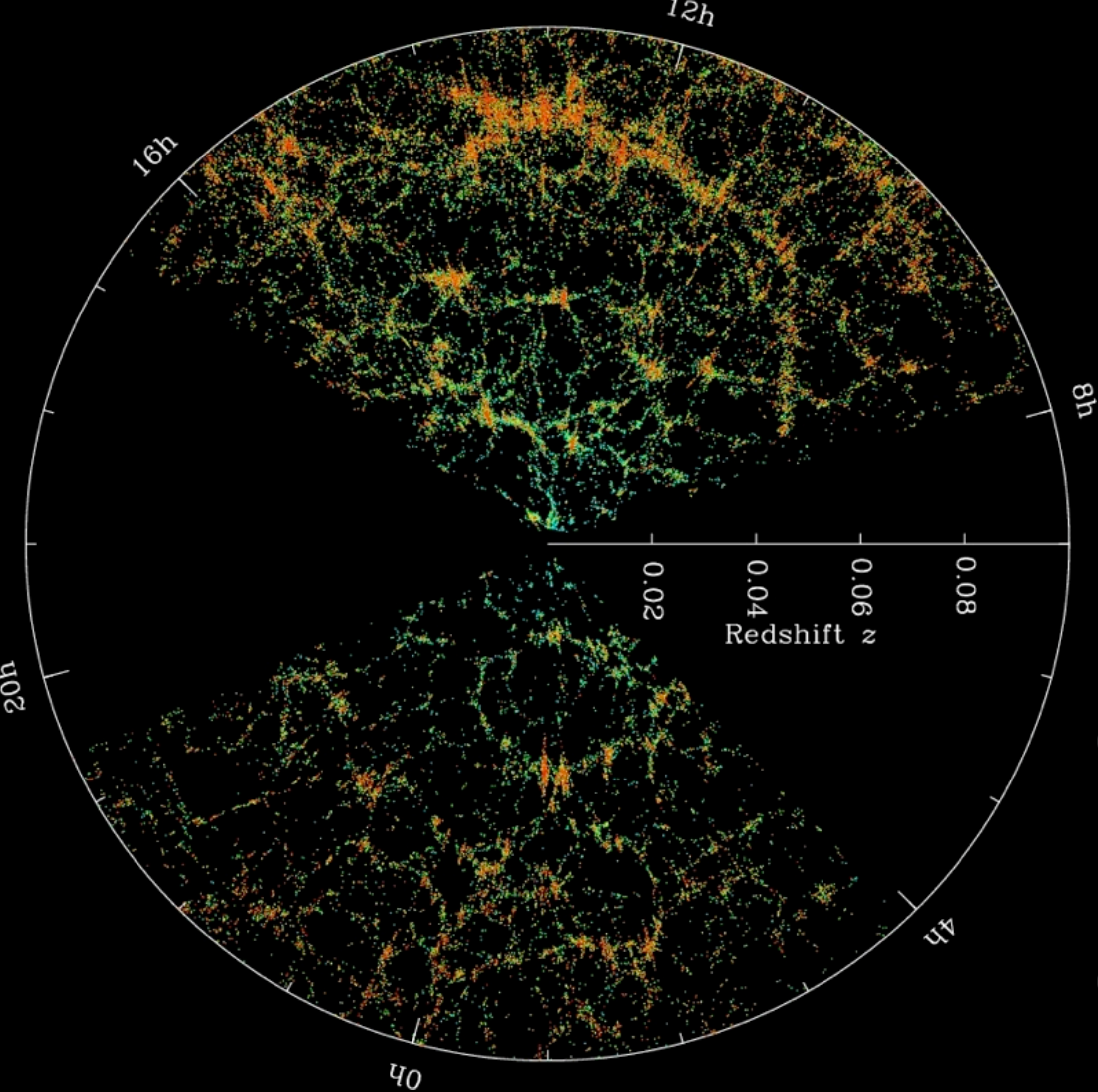
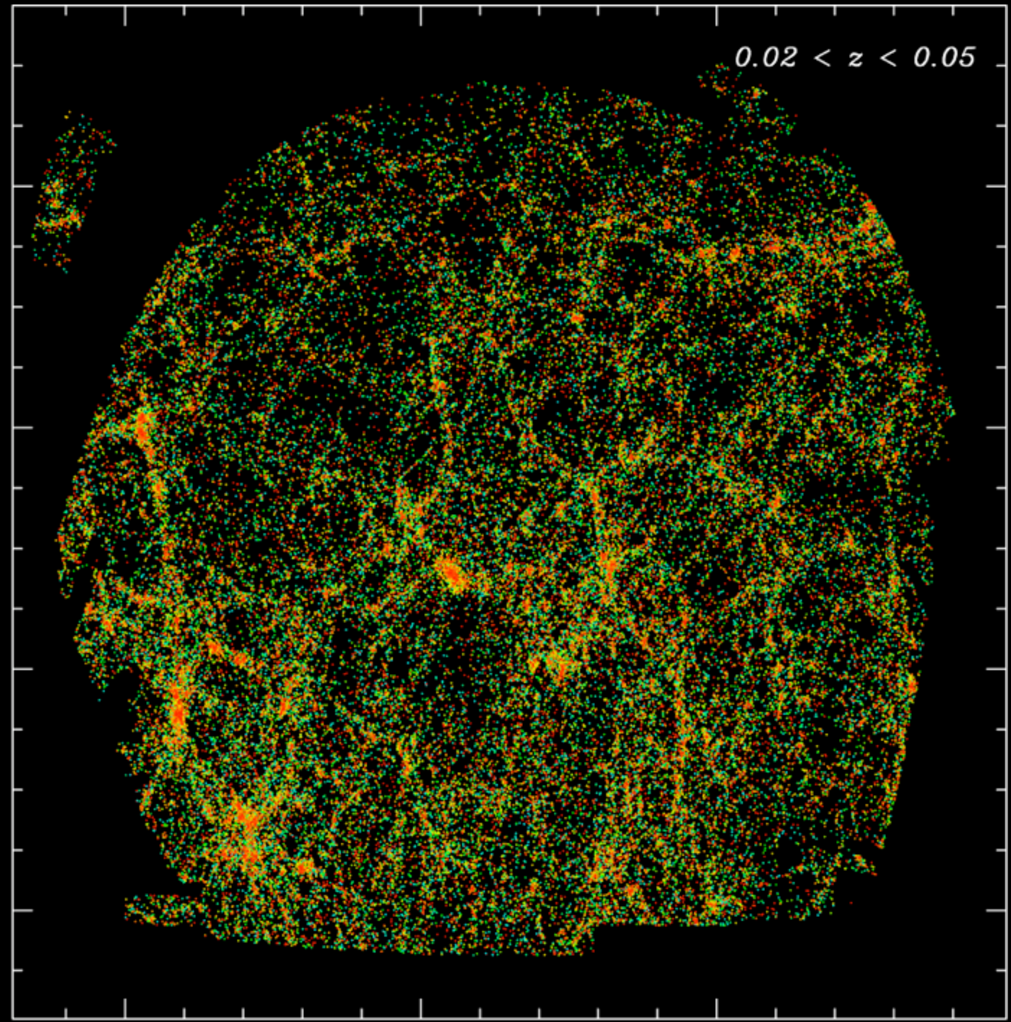
SDSS



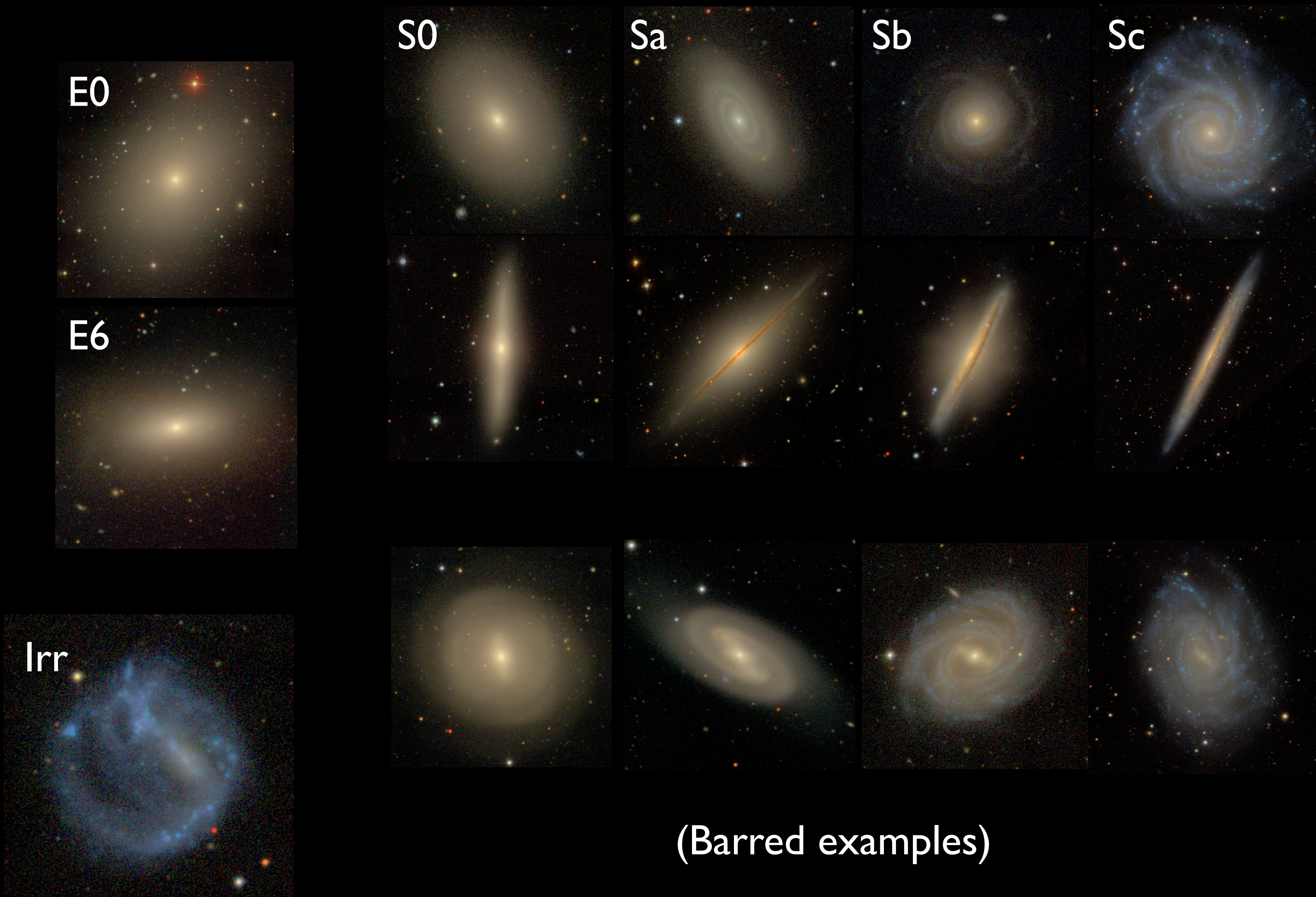


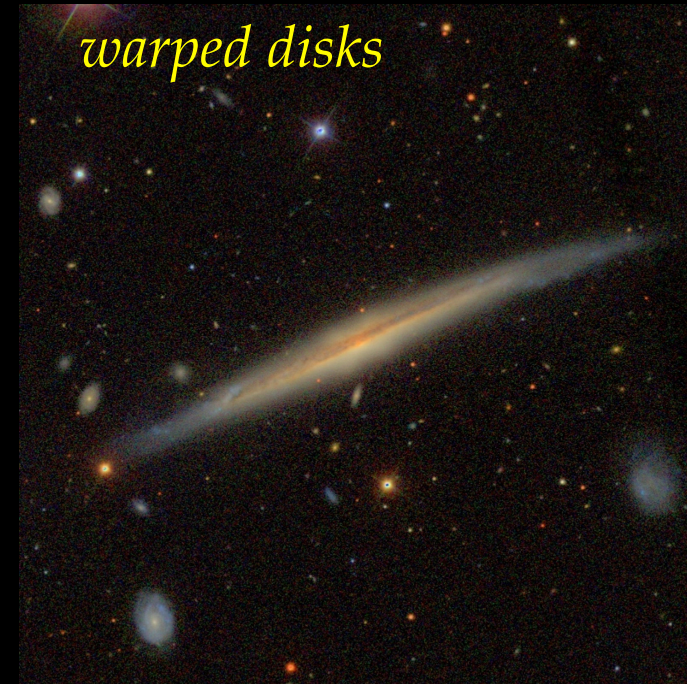
0.01 < z < 0.04
Dec (J2000 deg)
60
40
20
0
250
200
150
R.A. (J2000 deg)


12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
Redshift z

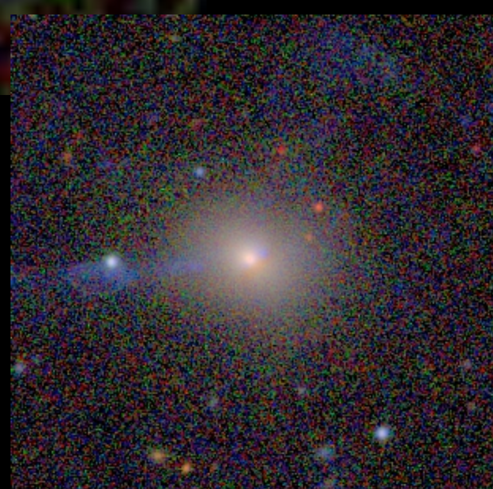

0.02 < z < 0.05

some common species ...

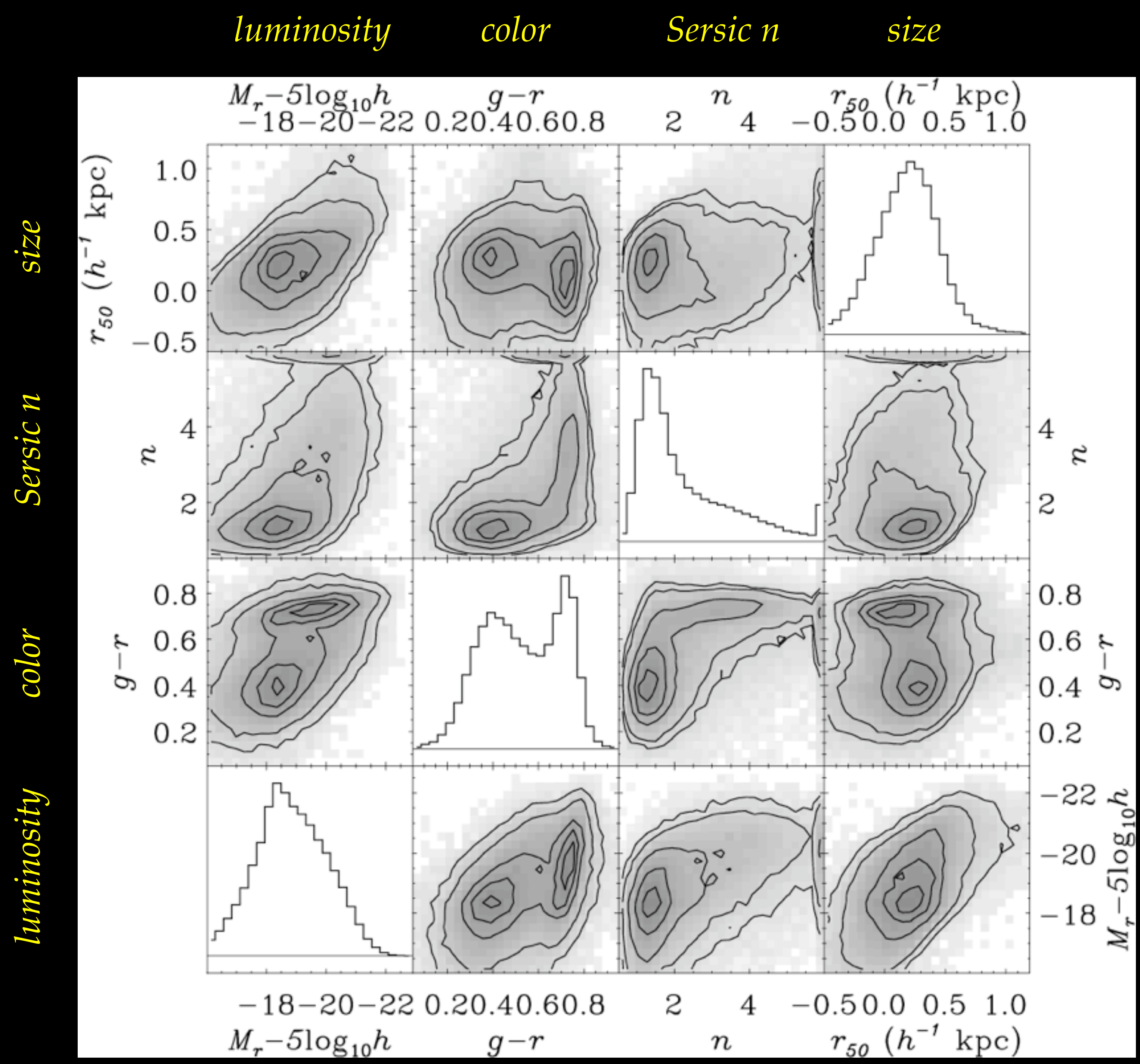




... and
some
rarer
species



Broad-band galaxy properties



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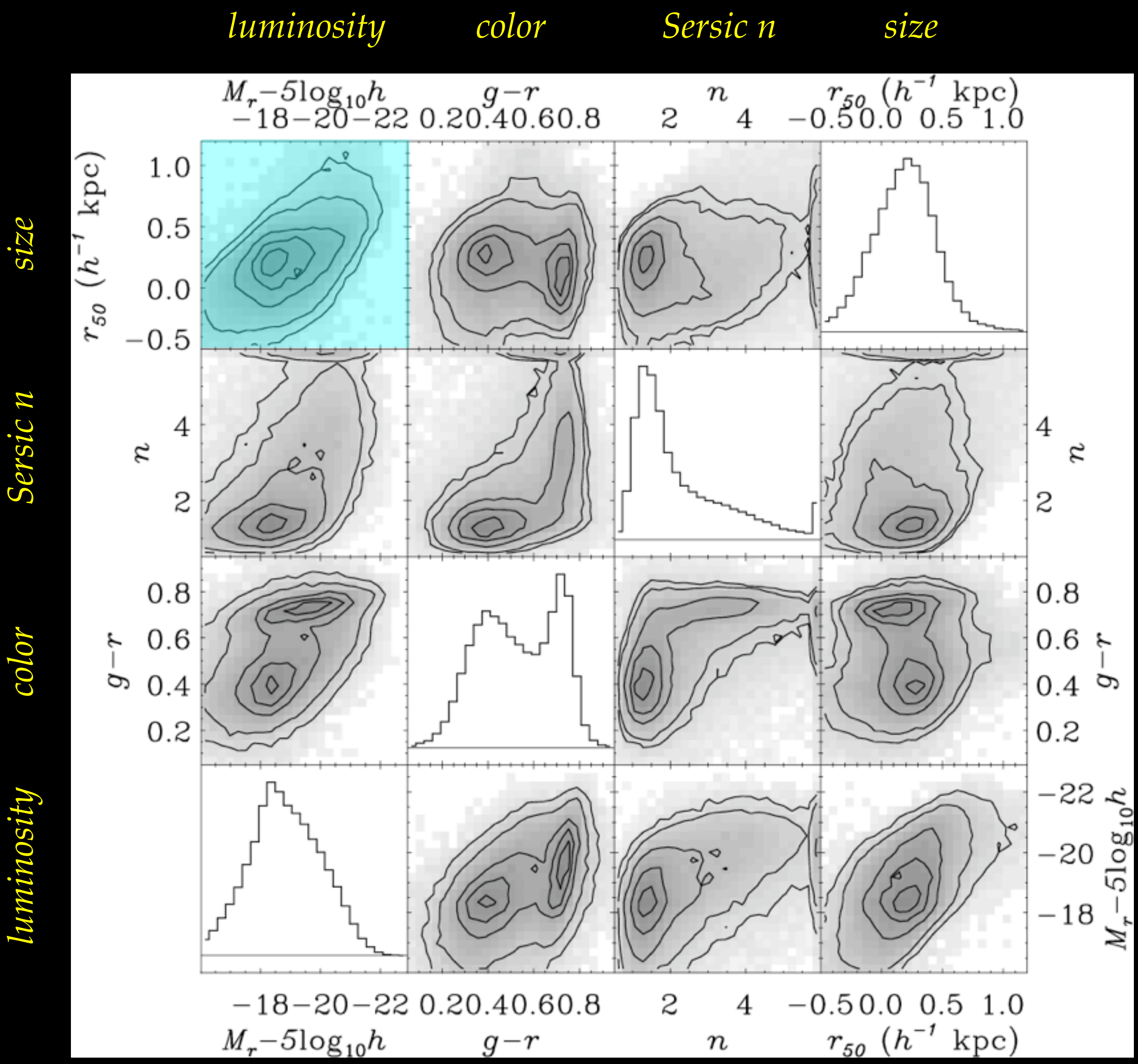


Broad-band galaxy properties

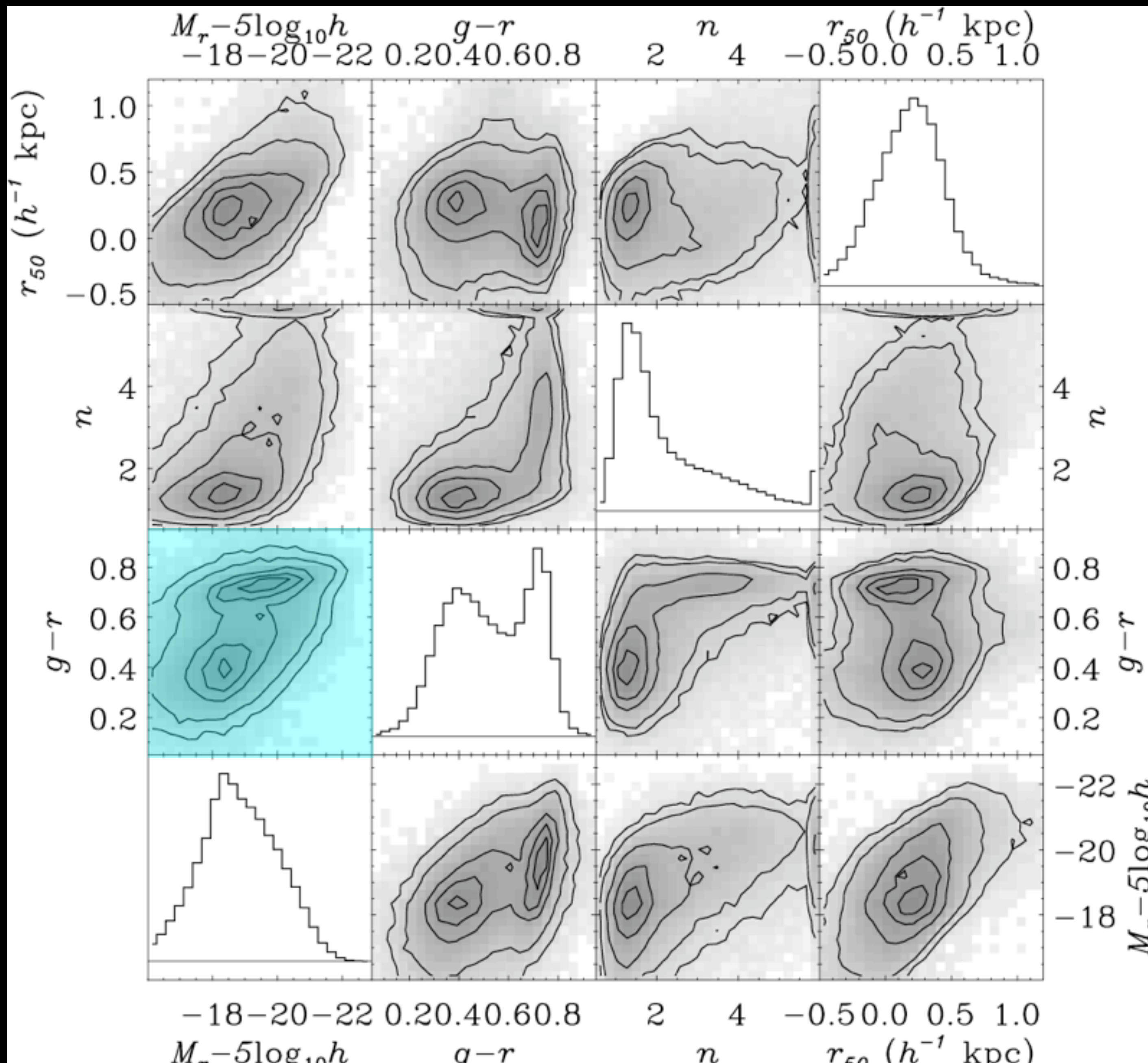
luminosity *color* *Sersic n* *size*

size

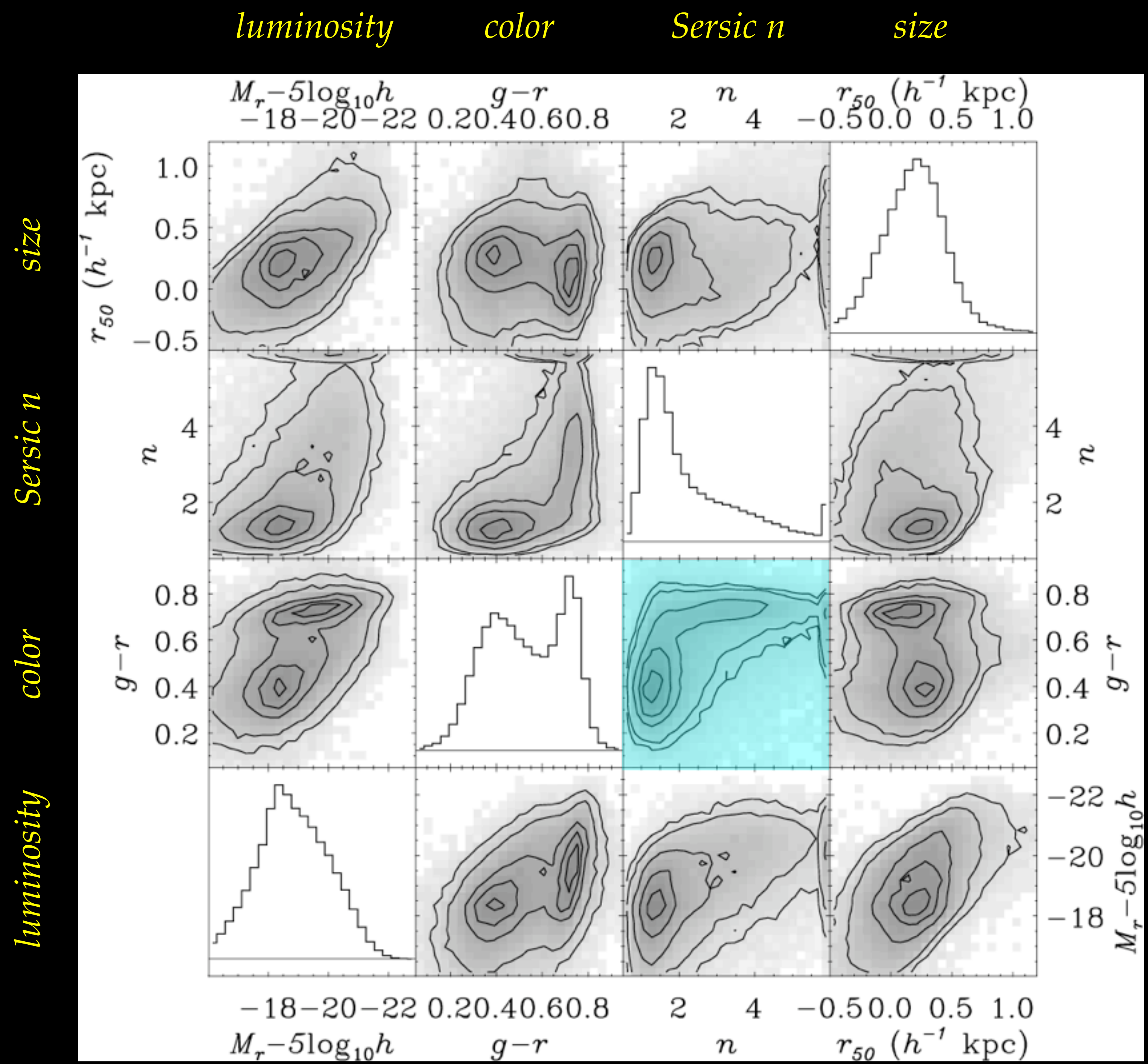
Sersic n

color

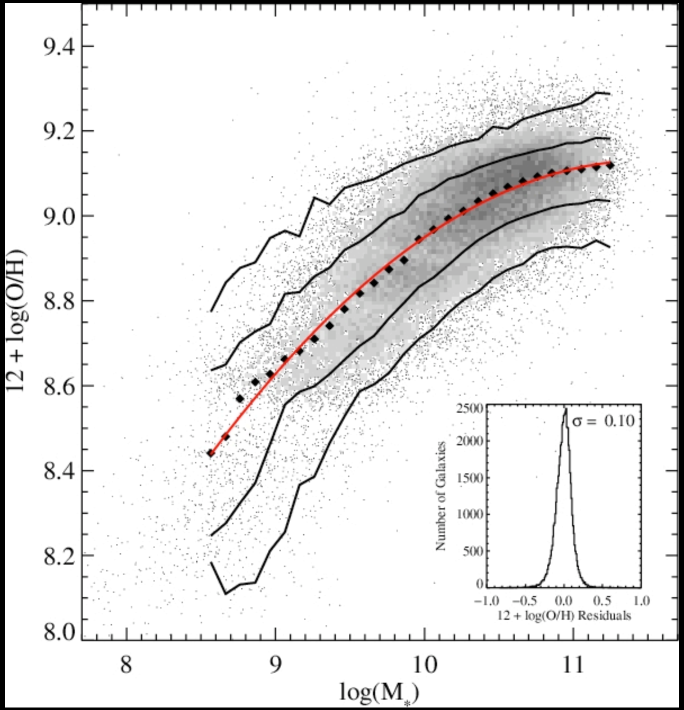
luminosity



Broad-band galaxy properties

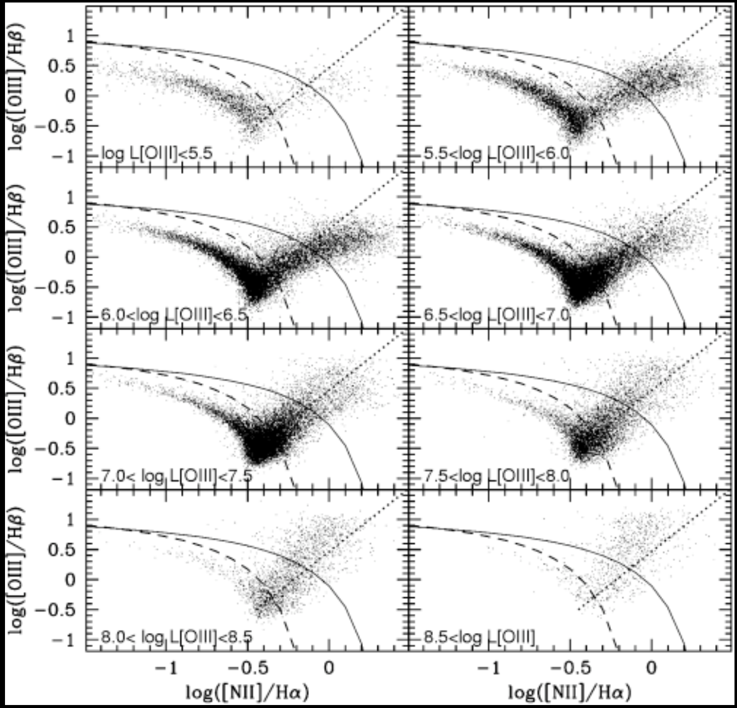


Tremonti et al (2005)



gas phase metallicity

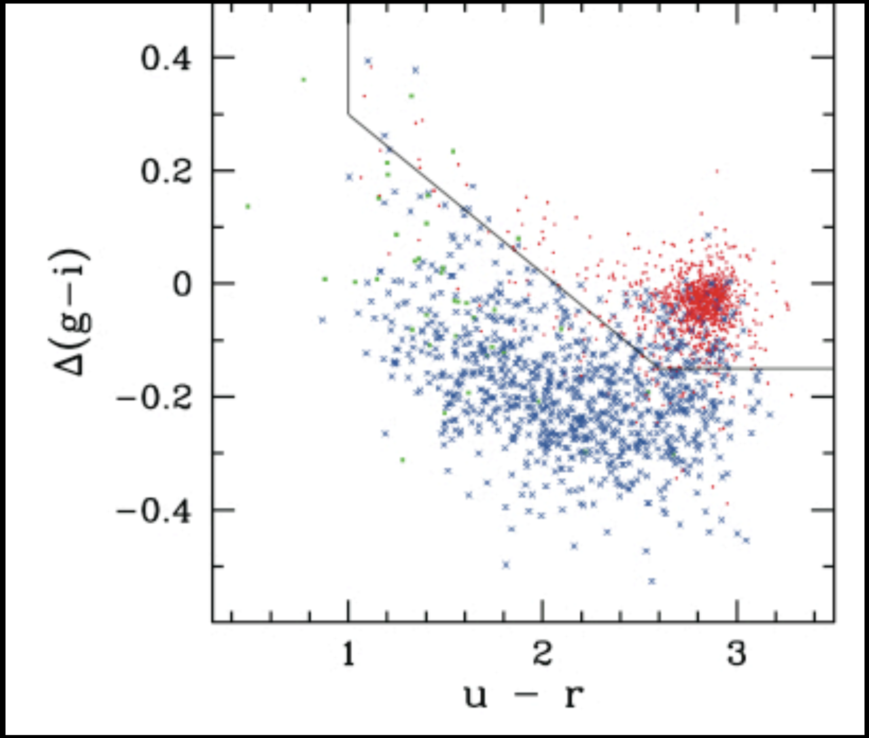
log stellar mass



incredibly detailed BPT diagram (Kauffmann, Heckman, etc)

metal-rich outflows (and low specific star-formation rates) at low mass?

but of course there's more ...

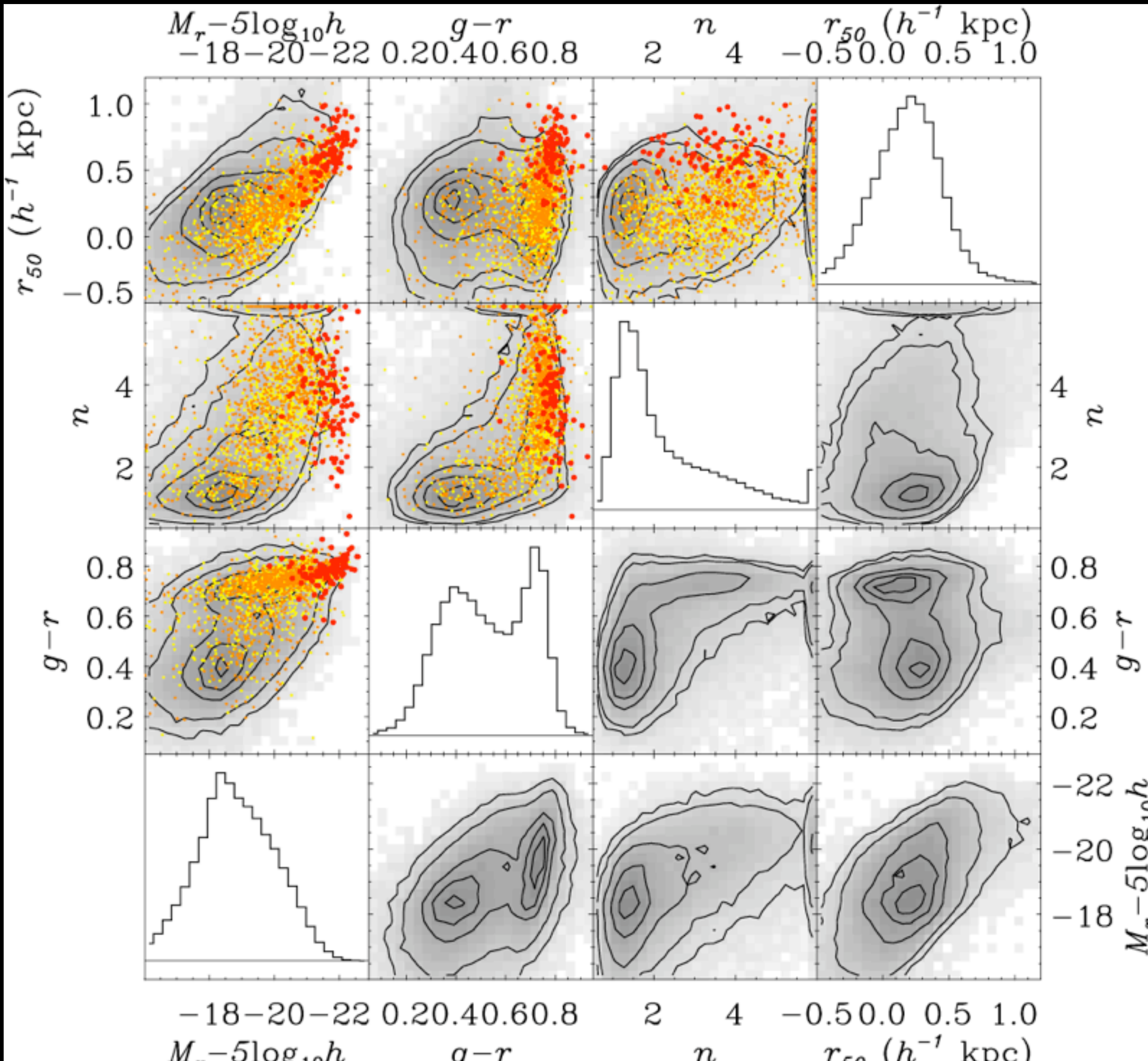


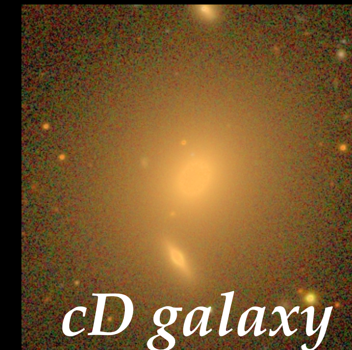
more detailed photometric analysis: color-gradients (Park & Choi)

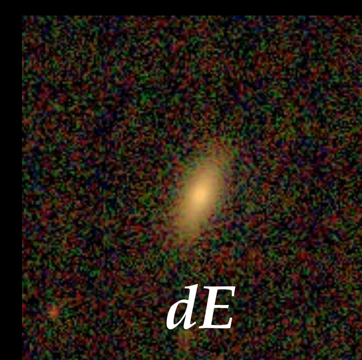
S0 galaxies

E galaxies

BCG/cD galaxies



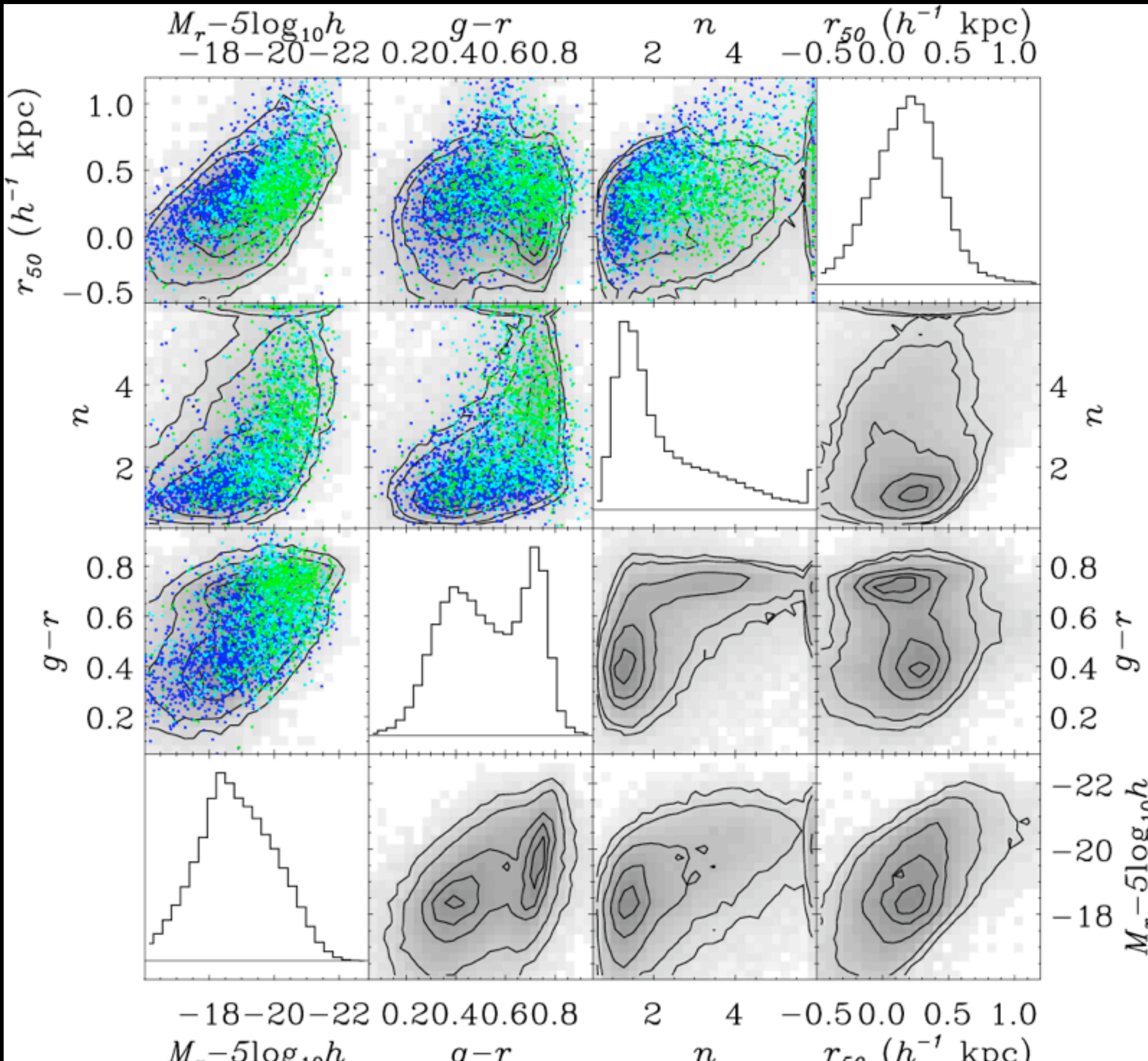


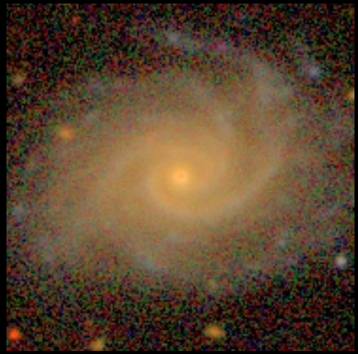


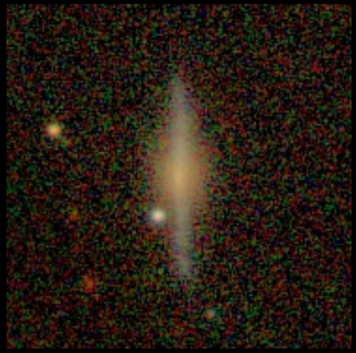
Sc/Sd galaxies

Sb galaxies

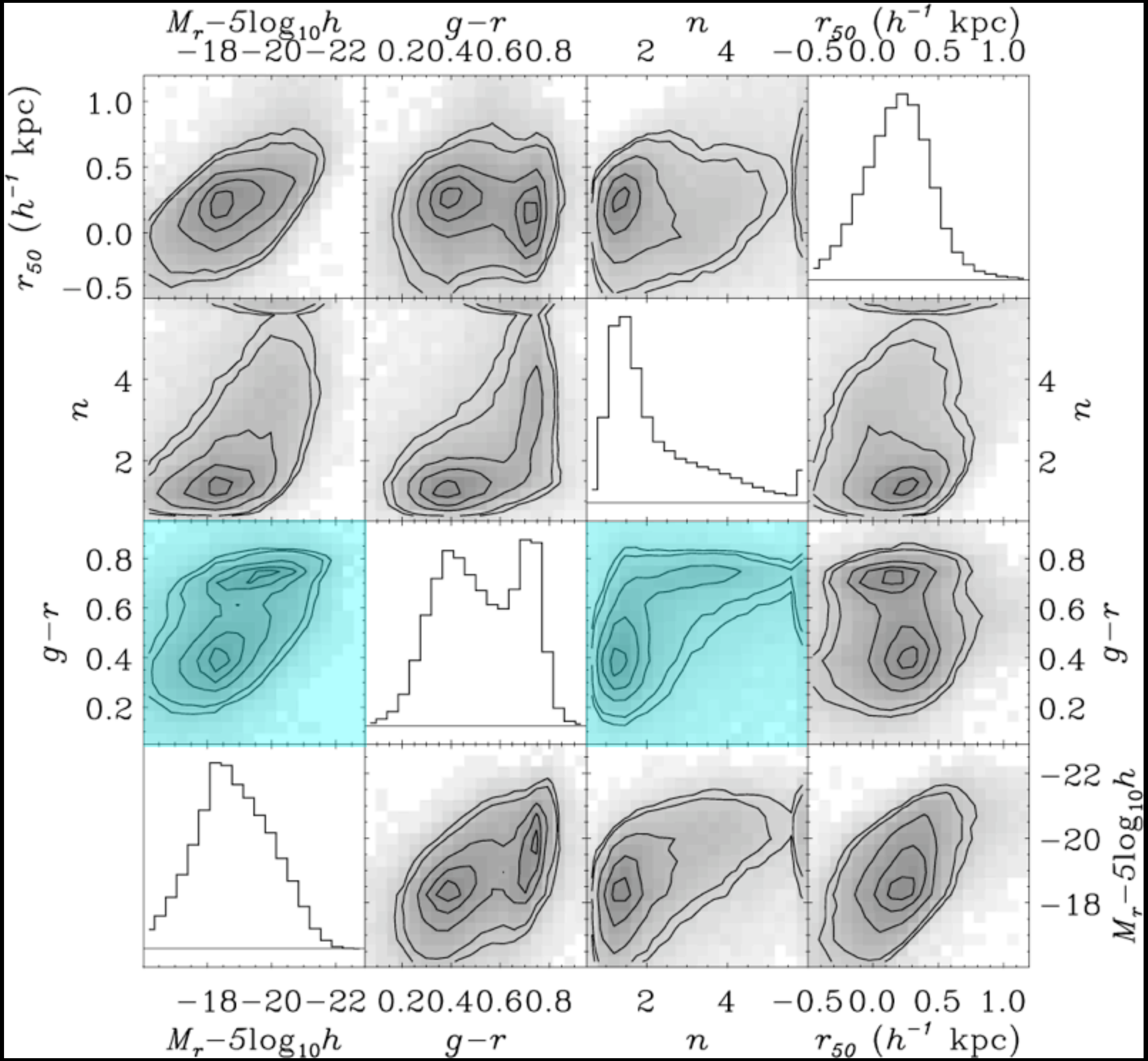
Sa galaxies



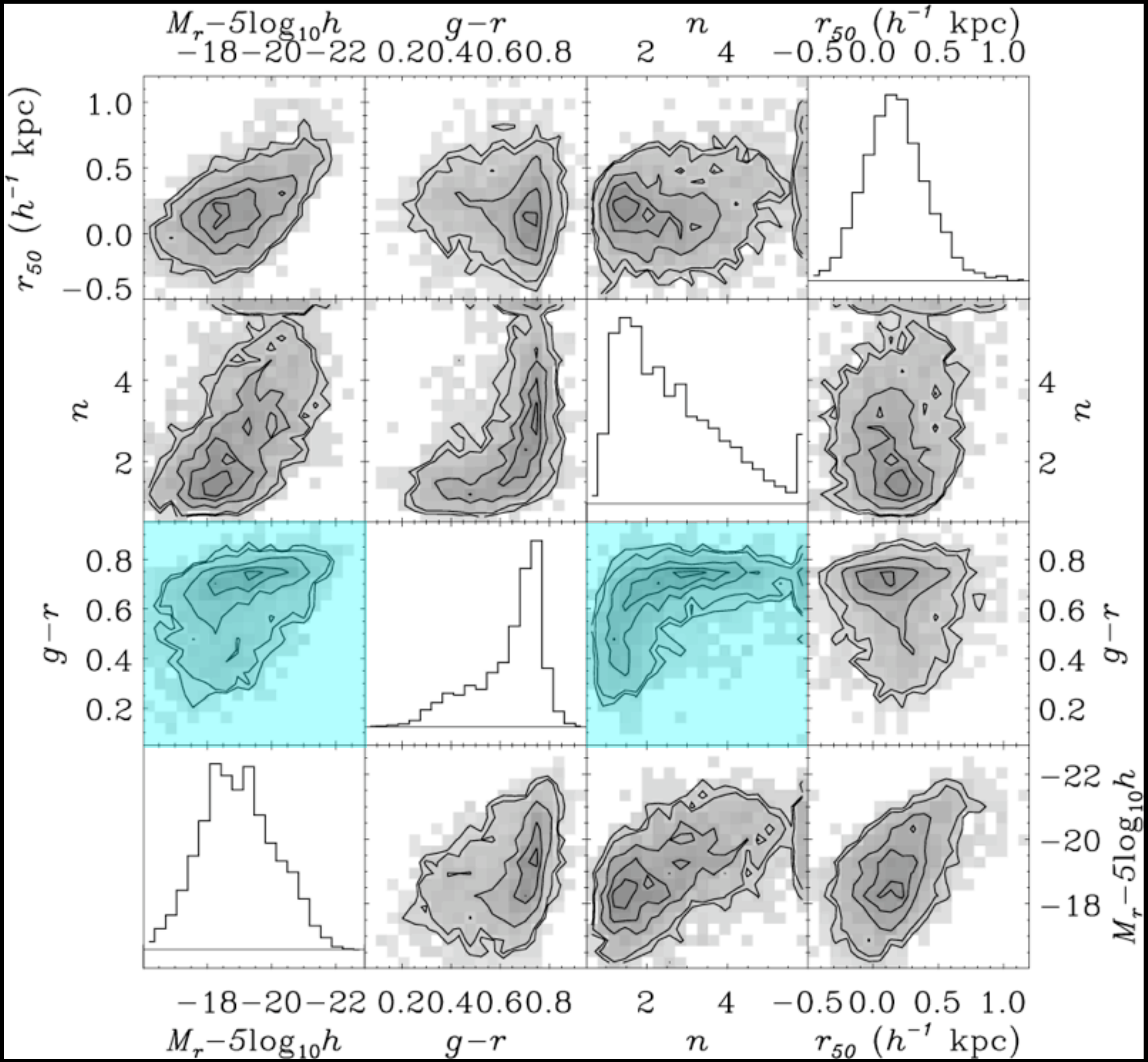




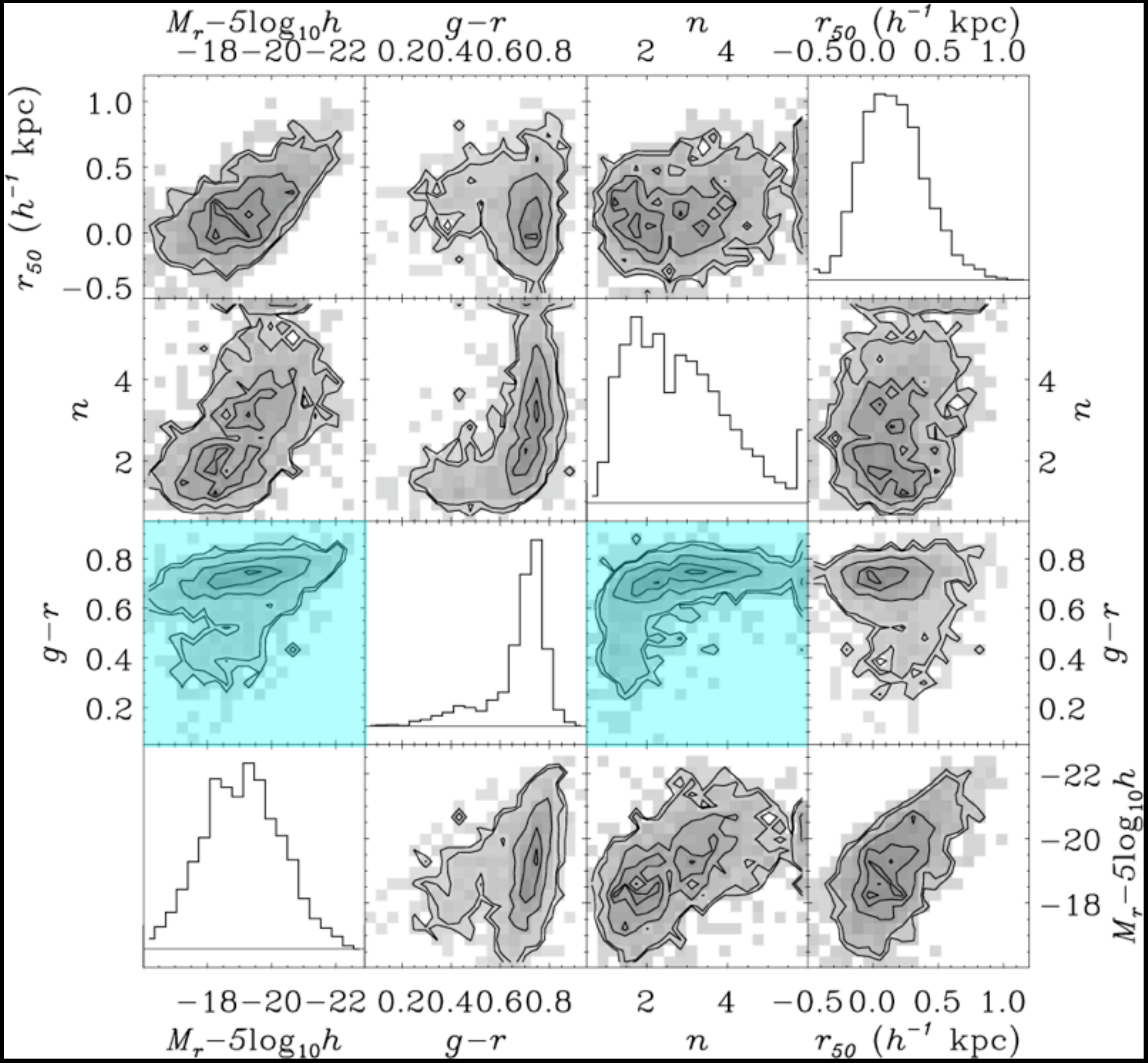
field galaxies (r > 1 Mpc from big cluster)



cluster fringe galaxies
(0.4 < r < 1 Mpc from big cluster)



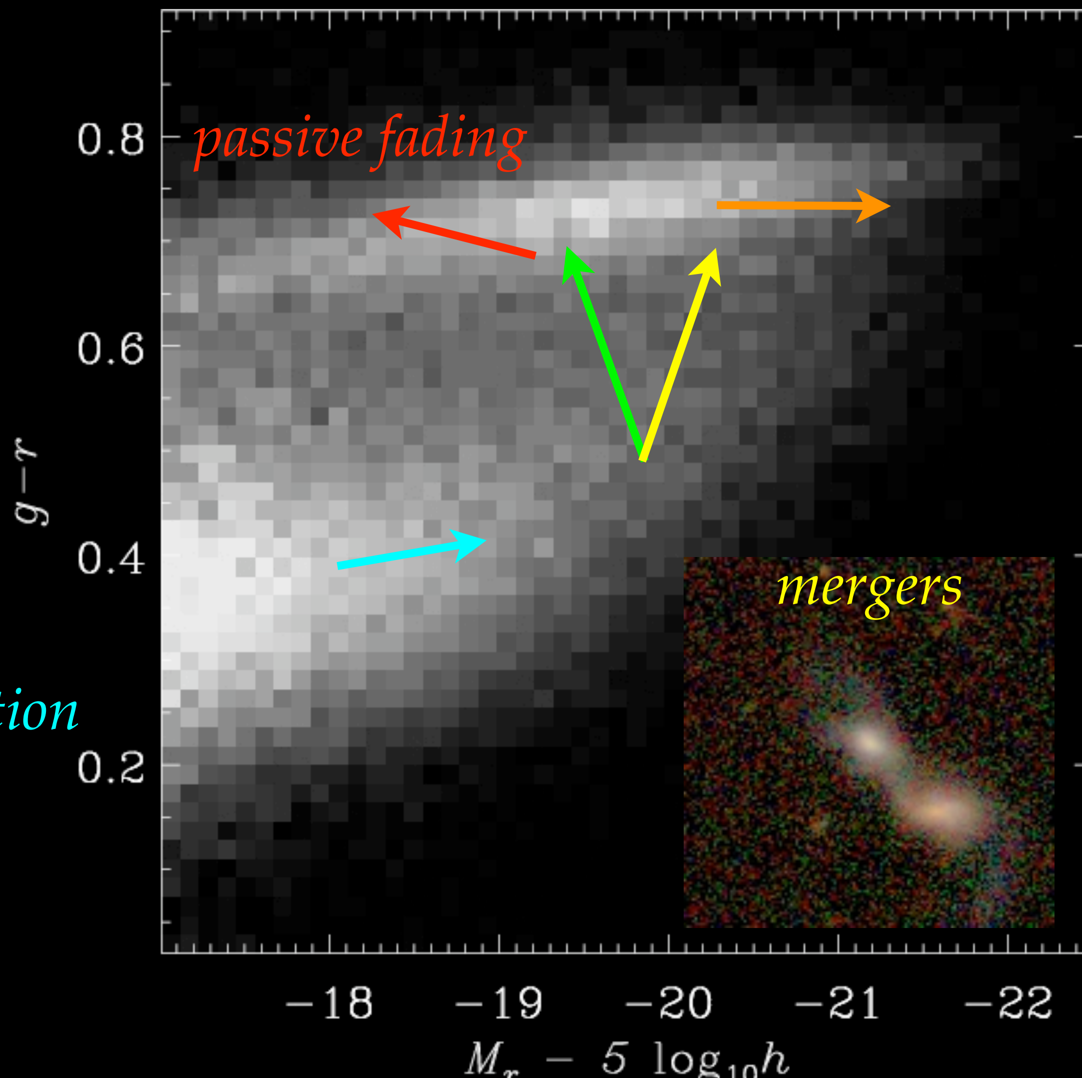
cluster core galaxies
(r < 0.4 Mpc from big cluster)



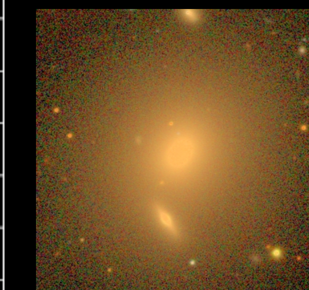
Processes affecting colors and magnitudes

"quenching" due to ram pressure, starvation, AGNi, gas depletion

ongoing star-formation



"dry" mergers



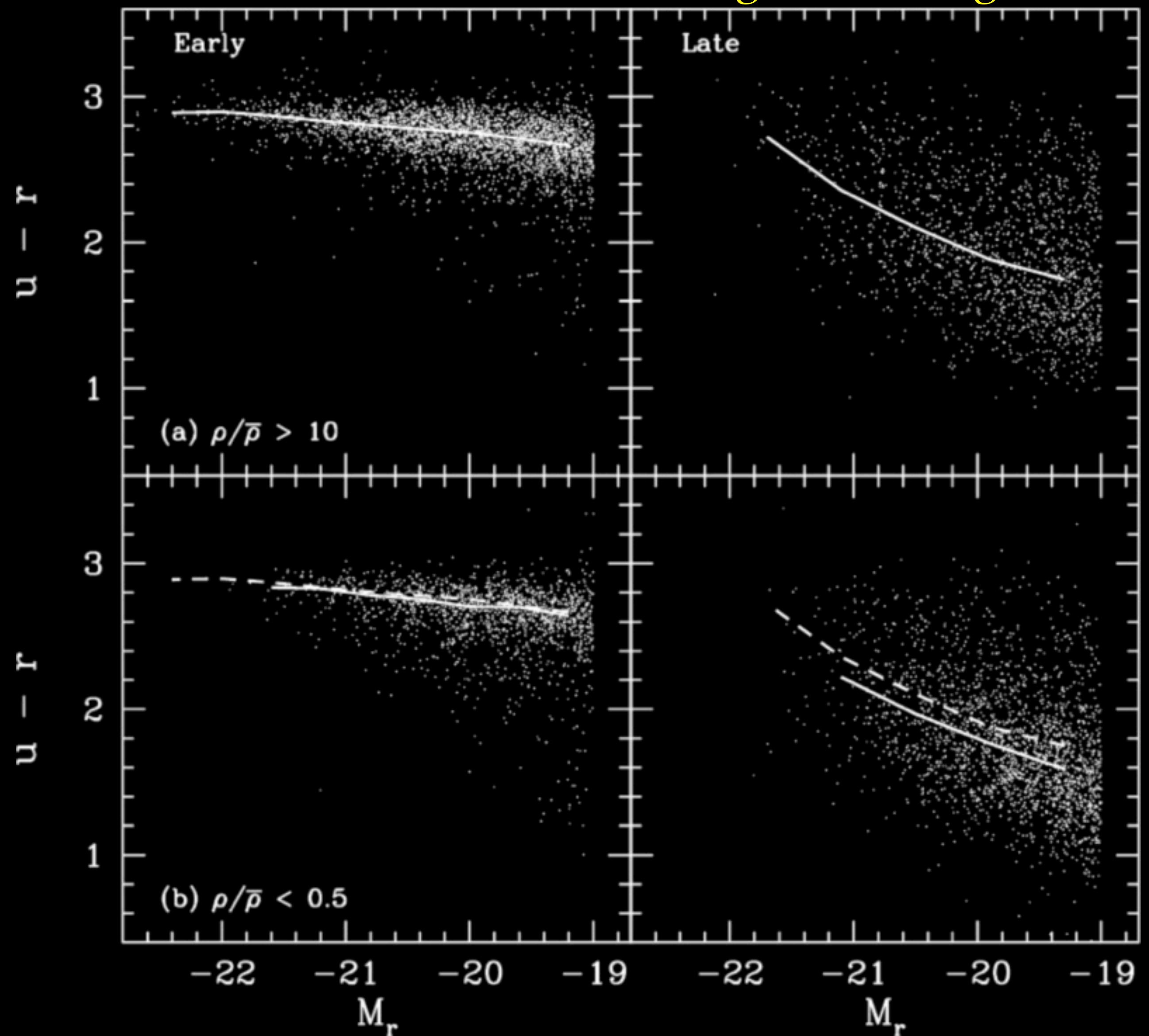
FAINT → BRIGHT

What have we learned about these processes and the effect of environment on galaxy formation?

1. What properties does a galaxy's surroundings affect?
   changes early-type fraction, but not properties of early and late classes
   (Park et al. 2007 has most thorough investigation of this effect)
2. On what time scales does the influence of environment act?
   relatively slowly (>1 Gyr) --- slower than ram pressure stripping
3. What features about the environment matter?
   only the host halo -- except maybe for the central galaxy
   matters even at low density, not a "cluster" phenomenon -- ditto exception!
4. Are the effects different for central galaxies than for satellites?
   affects central luminosity; affects satellite age

Early-type fraction changes; galaxy scaling relations don't

Park et al. (2007) -- color magnitude diagram

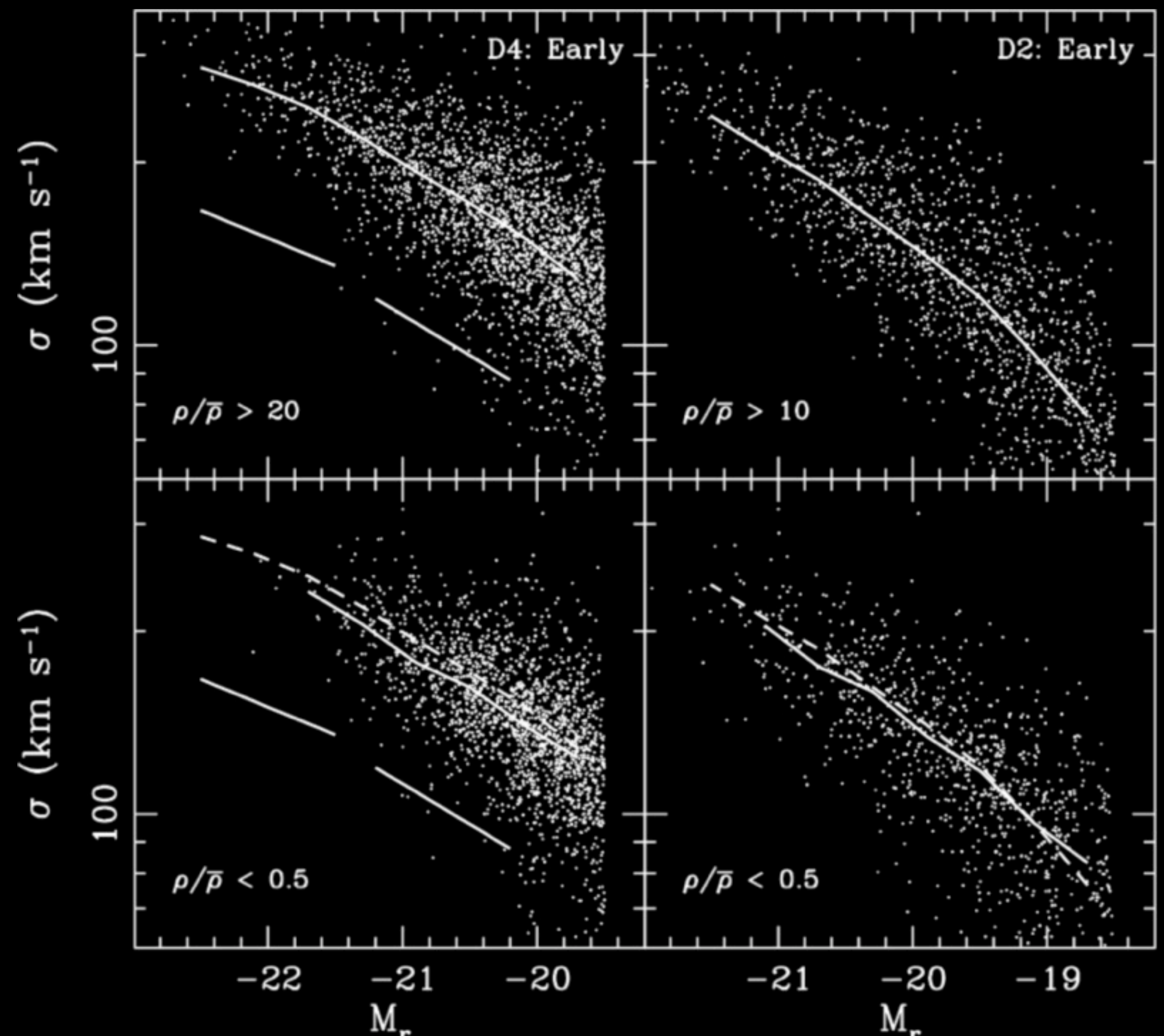


dense

underdense

Early-type fraction changes; galaxy scaling relations don't

Park et al. (2007) -- Faber-Jackson relationship

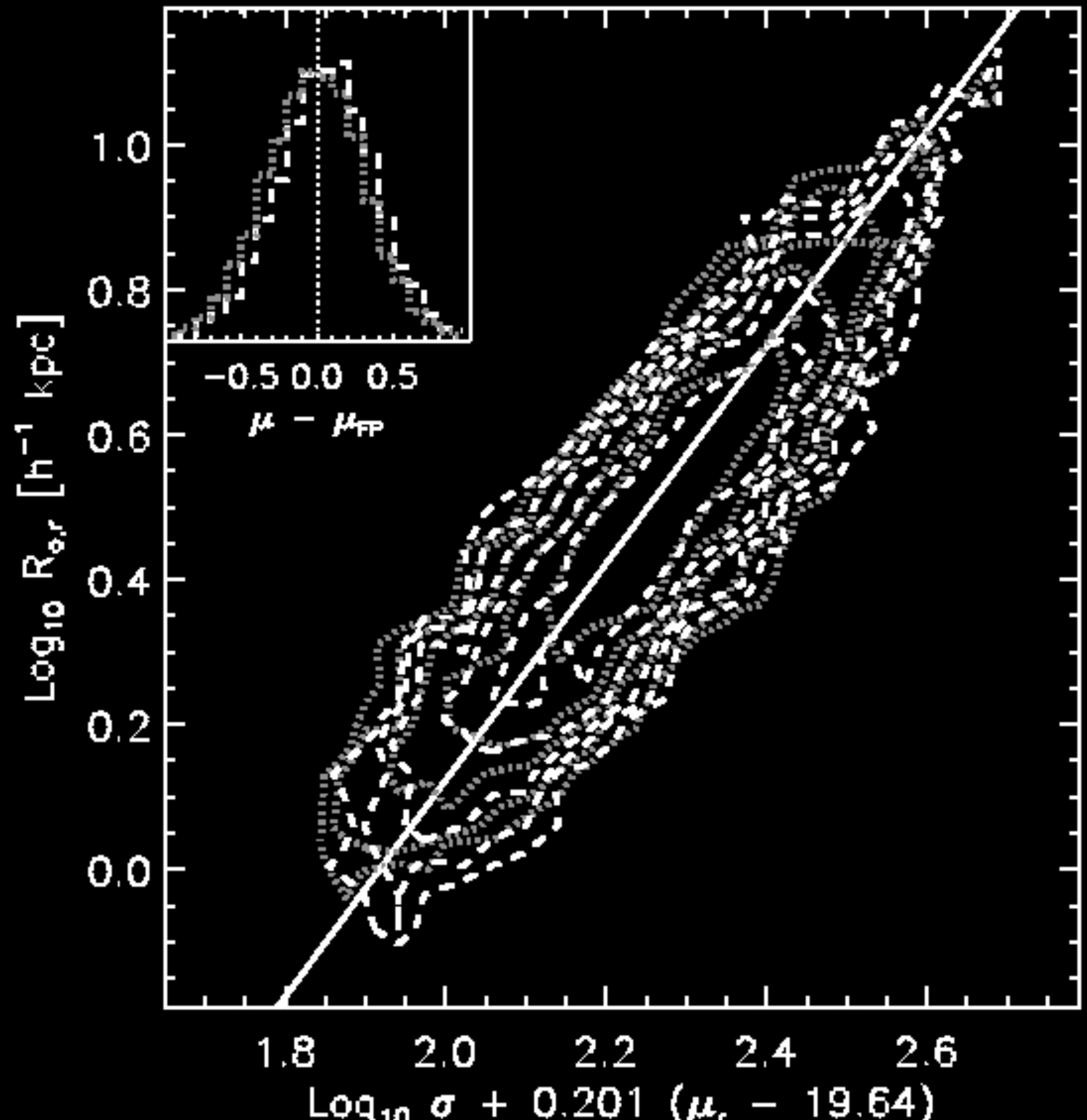


dense

underdense

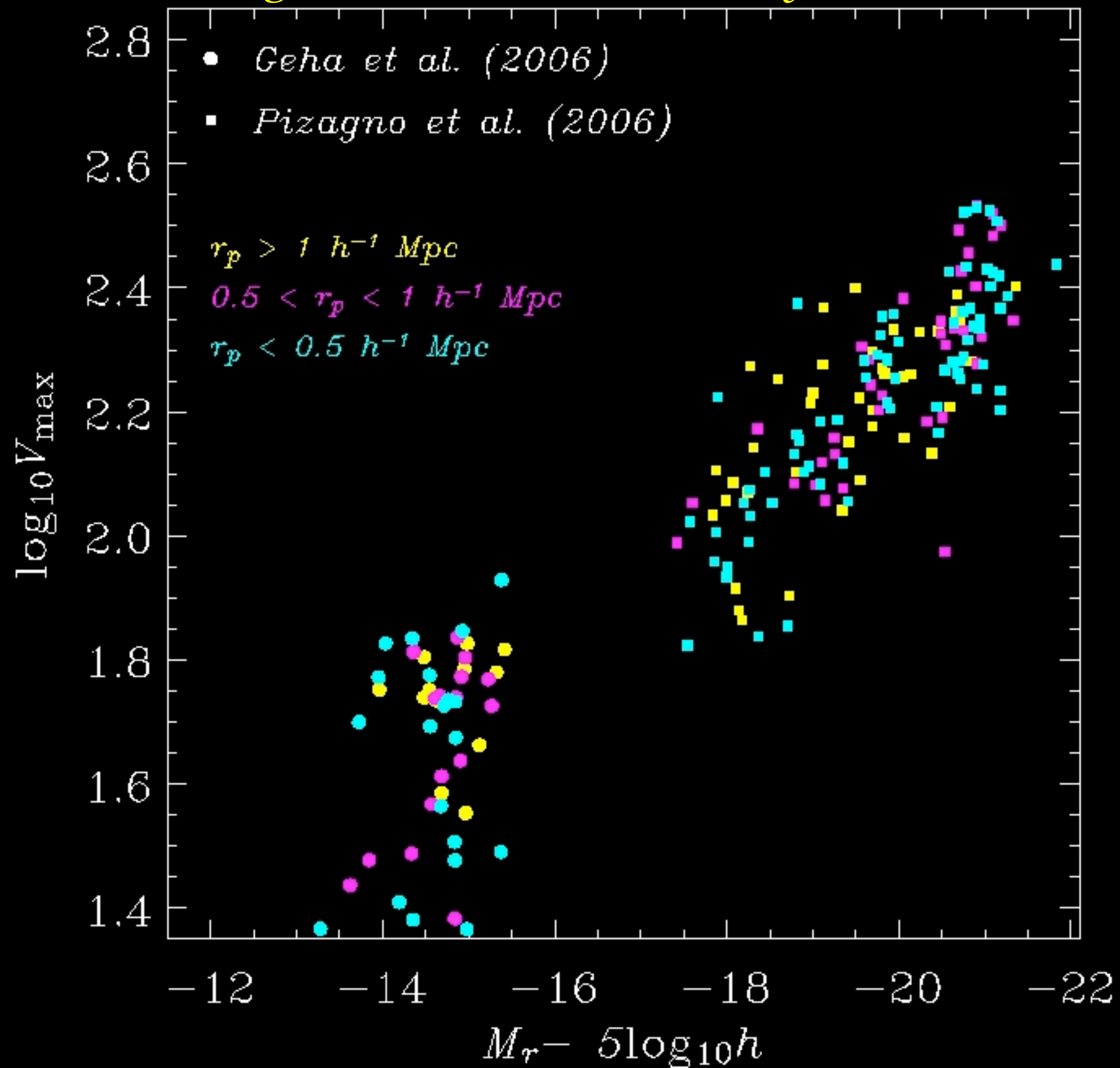
Early-type fraction changes; galaxy scaling relations don't

Bernardi et al. (2006) -- Fundamental Plane

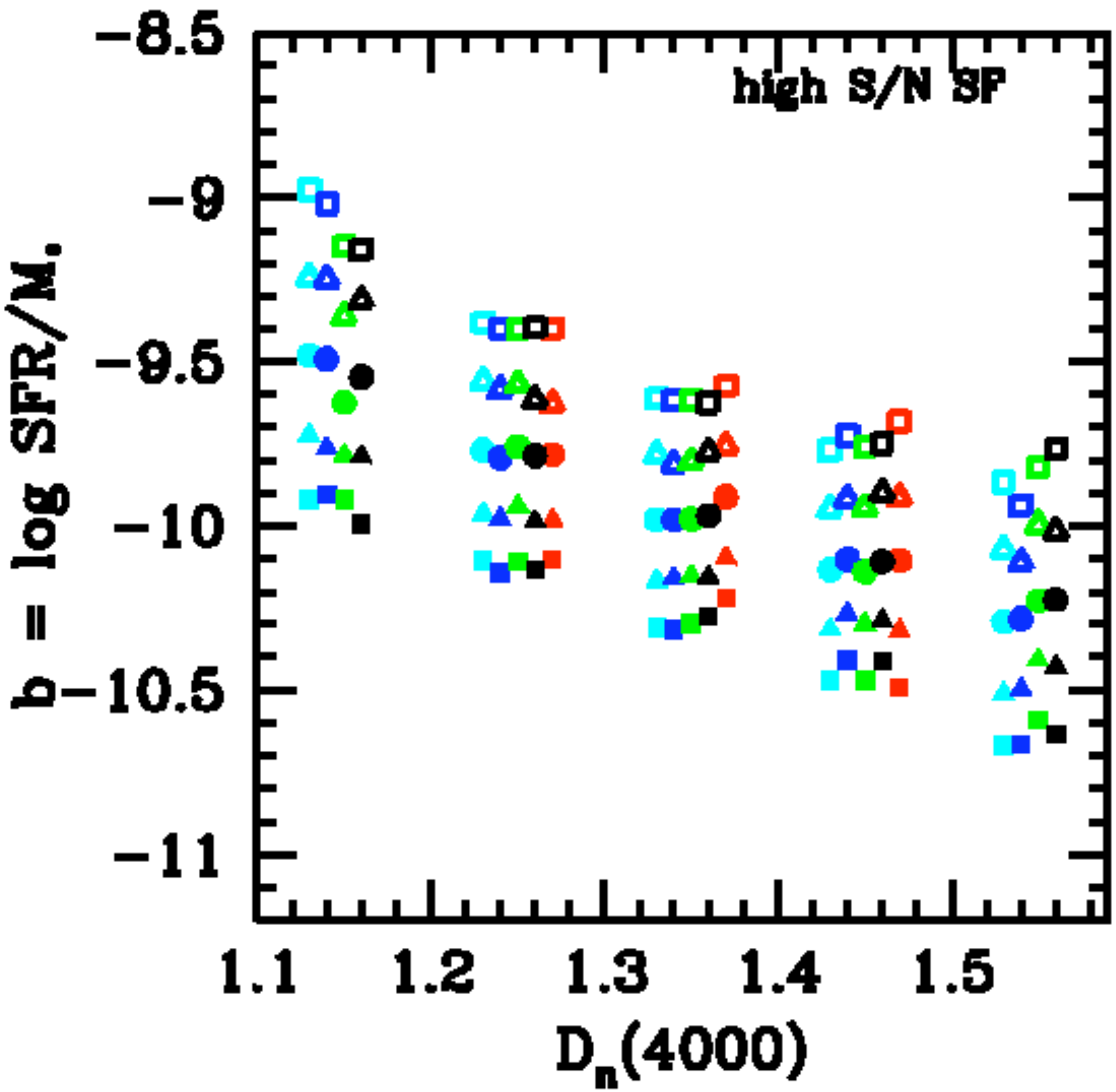


Early-type fraction changes; galaxy scaling relations don't

Pizagno et al. (2006) -- Tully-Fisher



The time-scale of transformation due to environment is slow

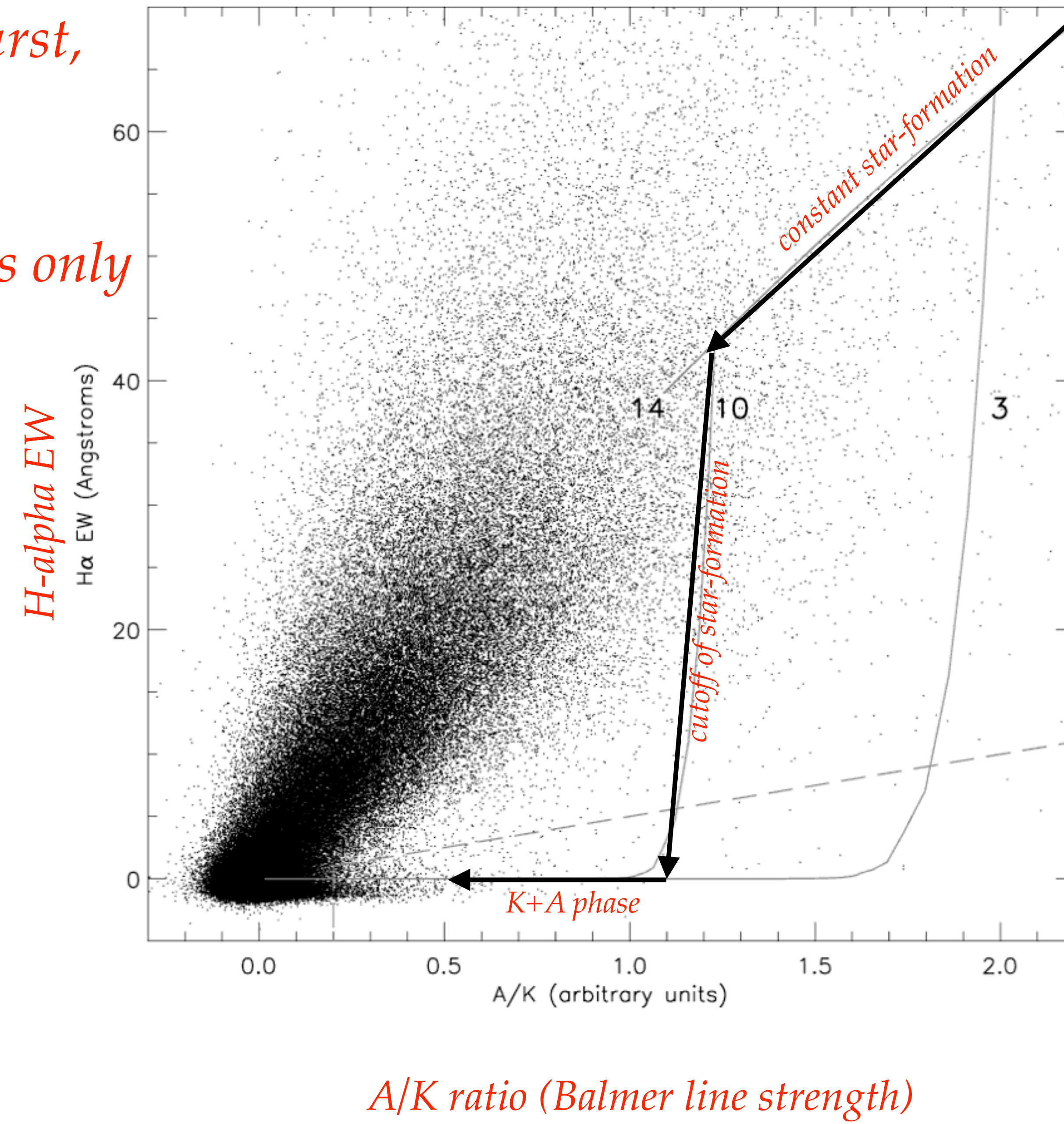


Kauffmann et al (2004): distribution of D4000 and current star-formation rate independent of environment

The time-scale of transformation due to environment is slow

Quintero et al (2004): post-starburst, K+A galaxies, are rare objects.

Hogg et al (2006): K+A fraction is only weakly related to environment



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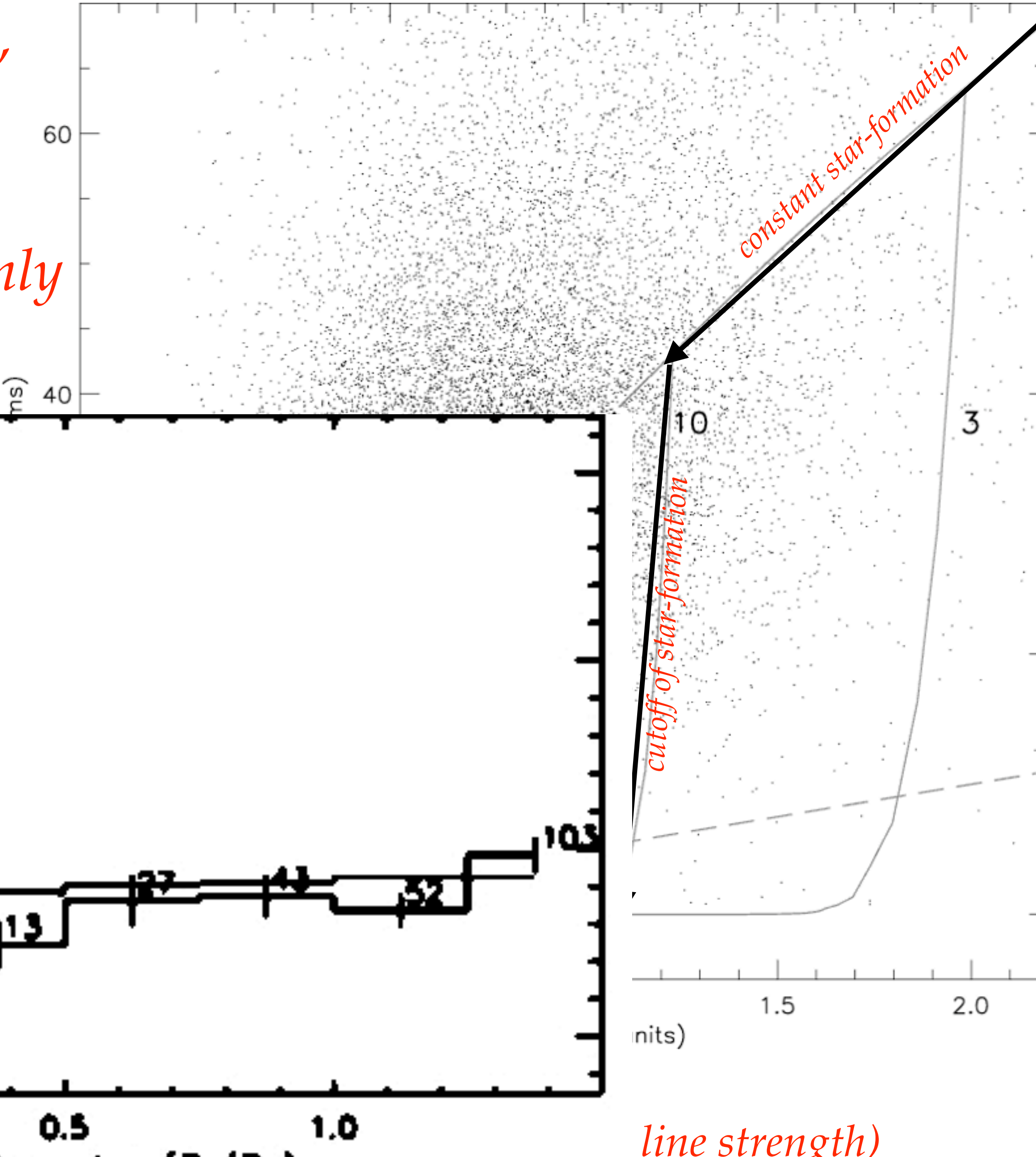
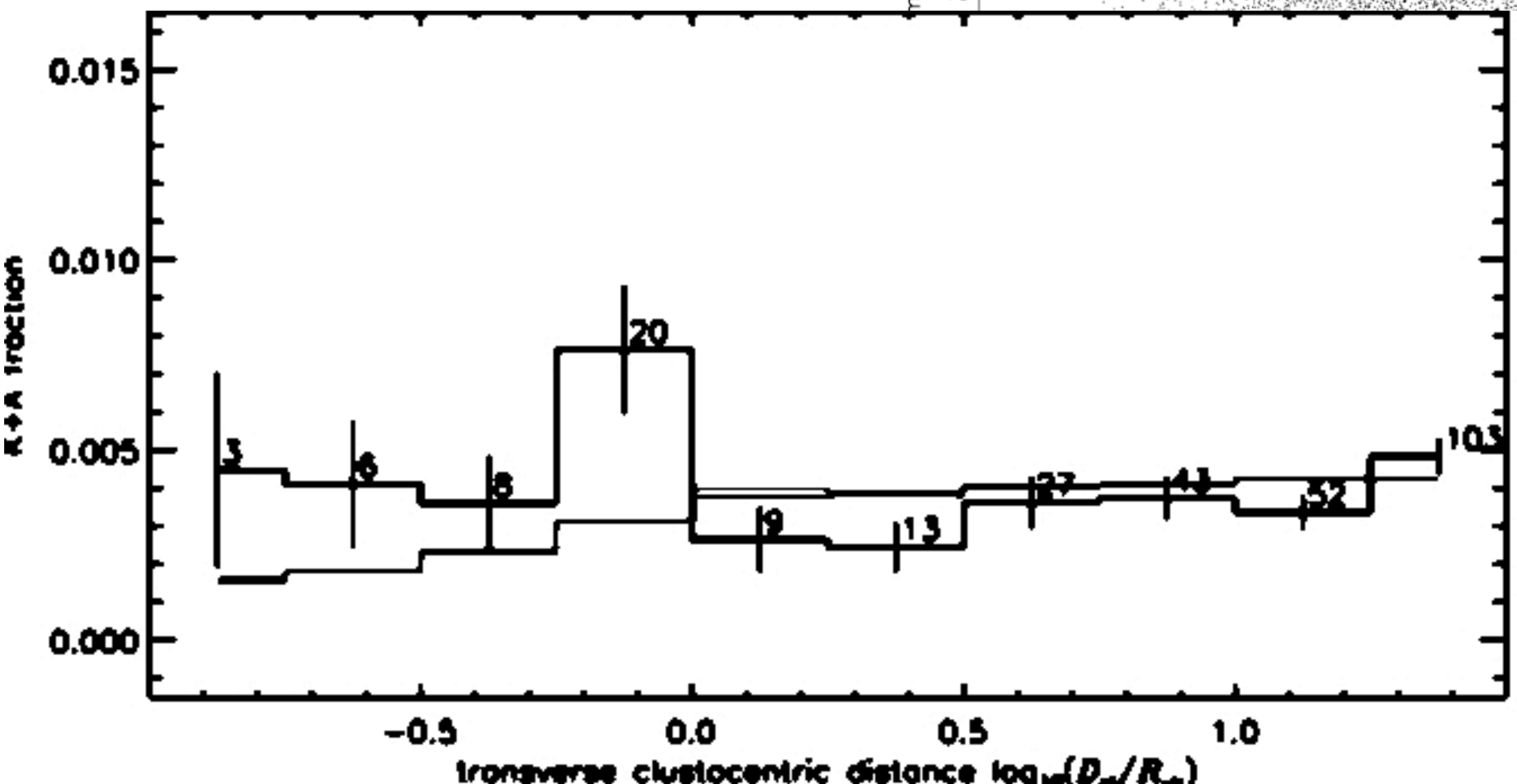
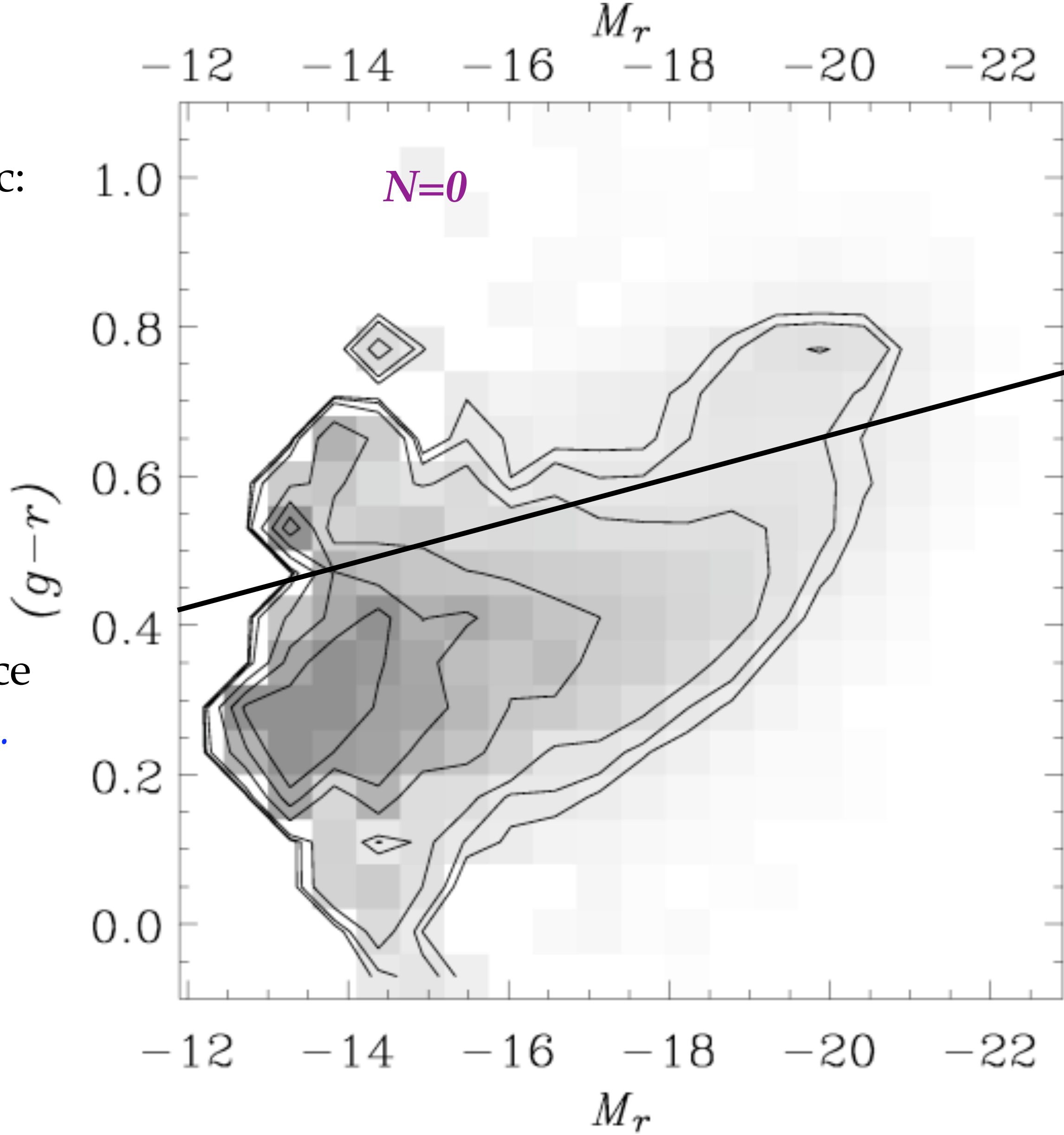




Even very low density differences matter

1. Sort by # of galaxies M < -18.5, d < 0.5 Mpc:
   a. *N = 0*
   b. *1 < N < 6 (Local Groupish)*
   c. *N > 6*
2. Even at low densities, relative numbers of red and blue galaxies change with environment
3. Location of red sequence and blue sequence weak function of environment *(Balogh et al. 2003; Baldry et al. 2004; Hogg et al. 2004)*



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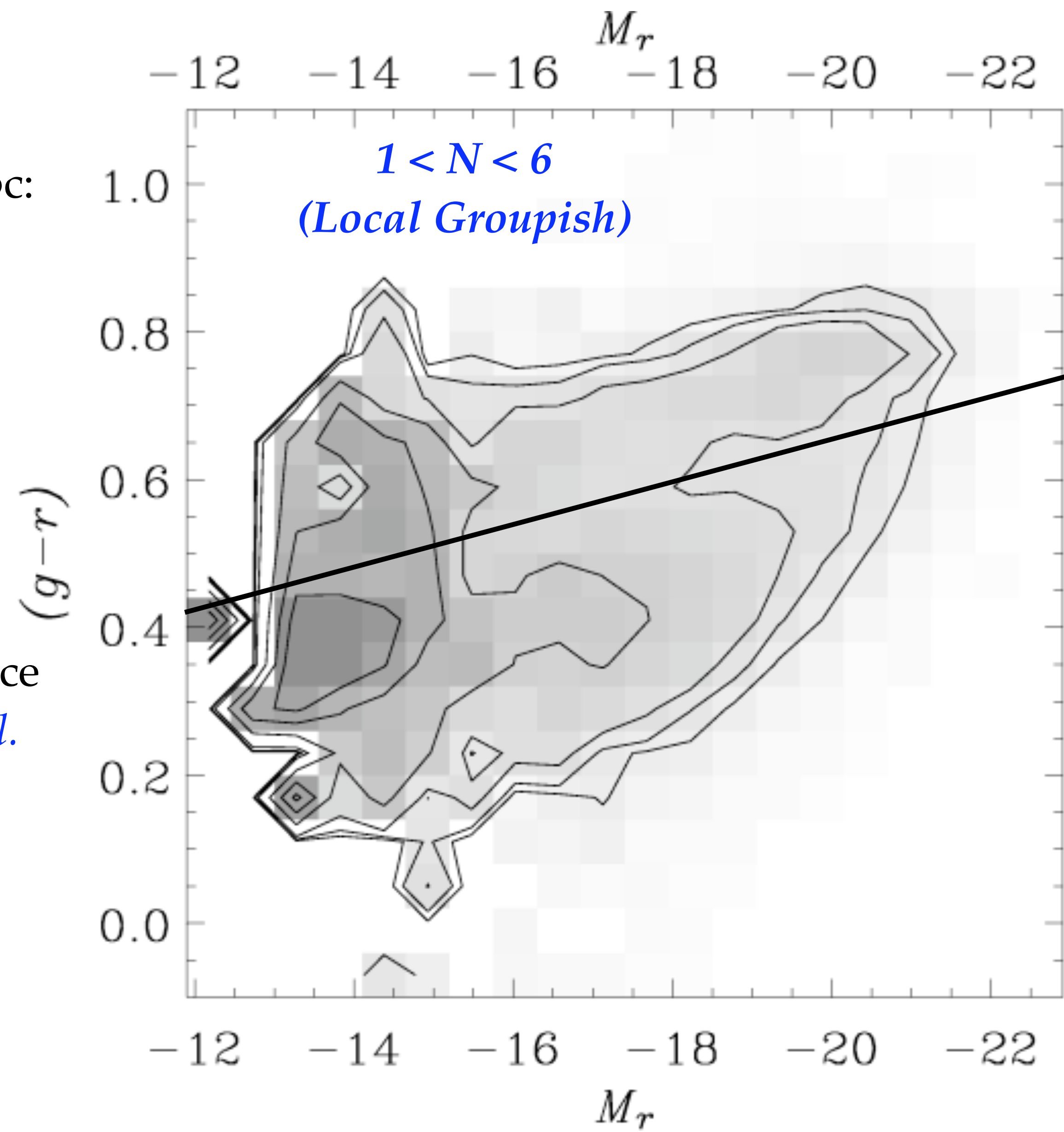

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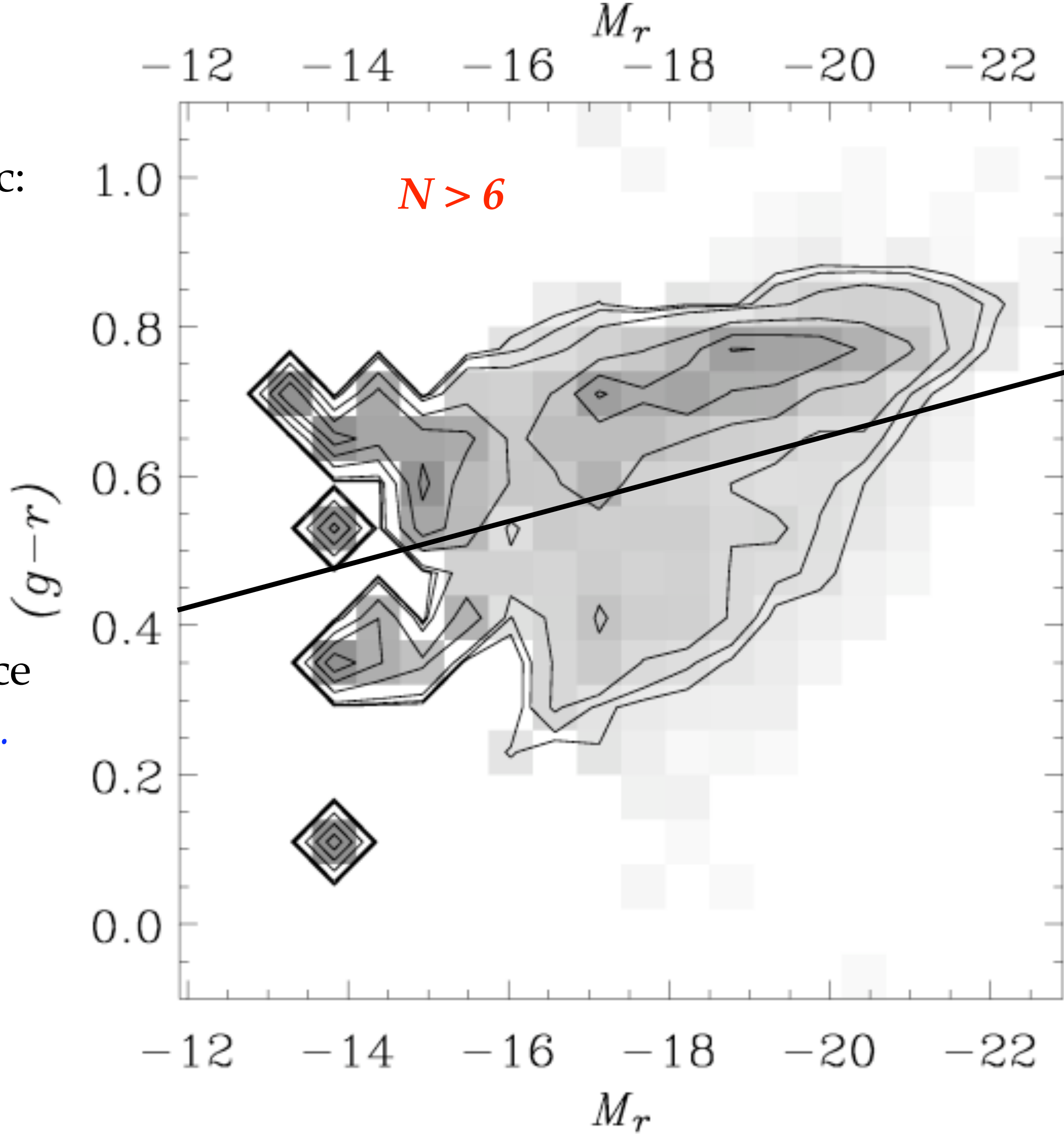
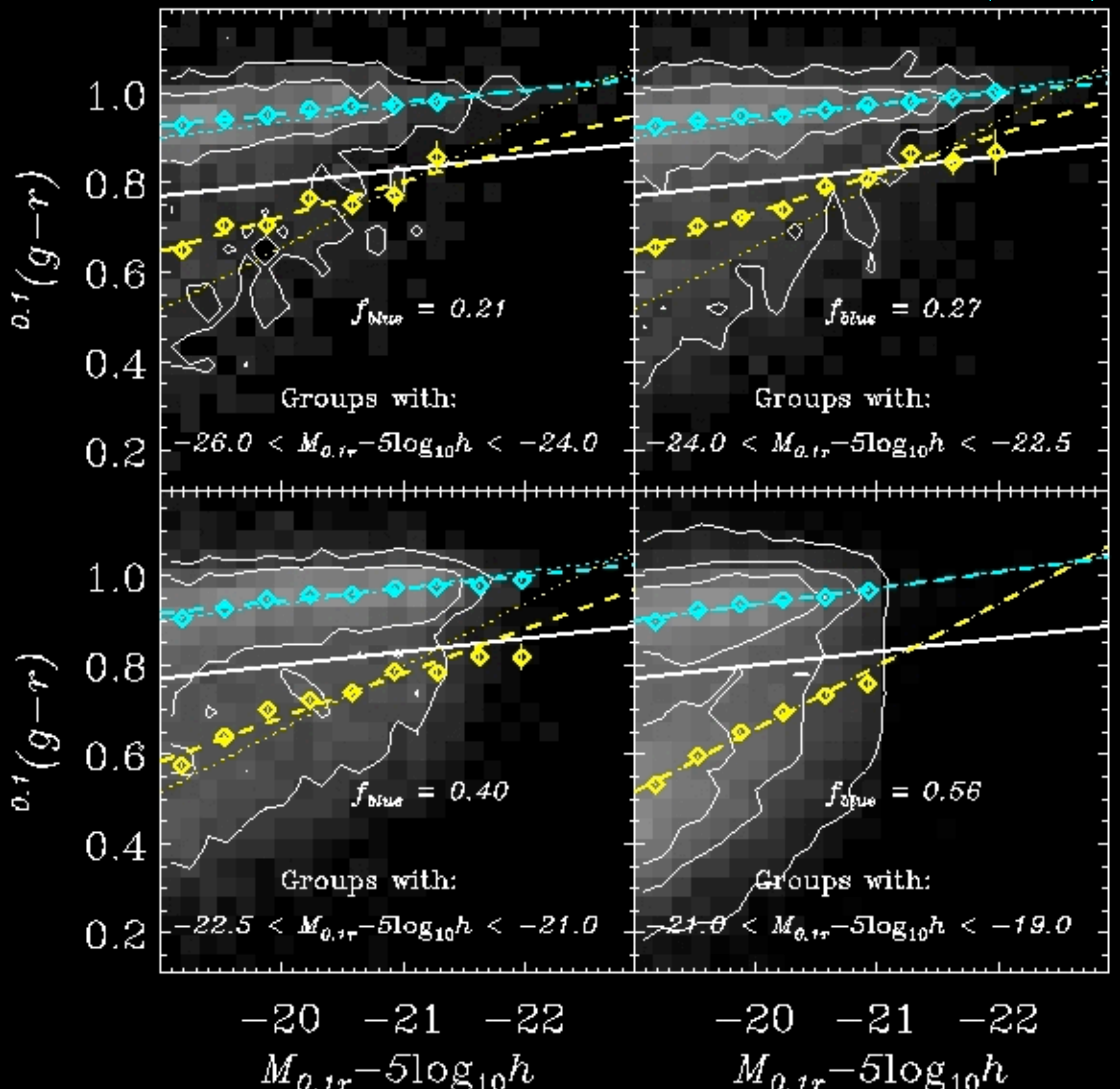


Only the local halo matters …

1. Consider galaxies in groups of *Berlind et al. (2006)*
2. Define environment in two ways:
   a. *host group luminosity*
   b. *density in surrounding 6<r<10 Mpc*
3. Compare them:
   a. *Larger groups: lower blue fraction*
   b. *But no correlation with larger scales*
4. Similar results: *Kauffmann et al. (2004); Lewis et al. (2002); Park et al (2007)*

Blanton & Berlind (2007)



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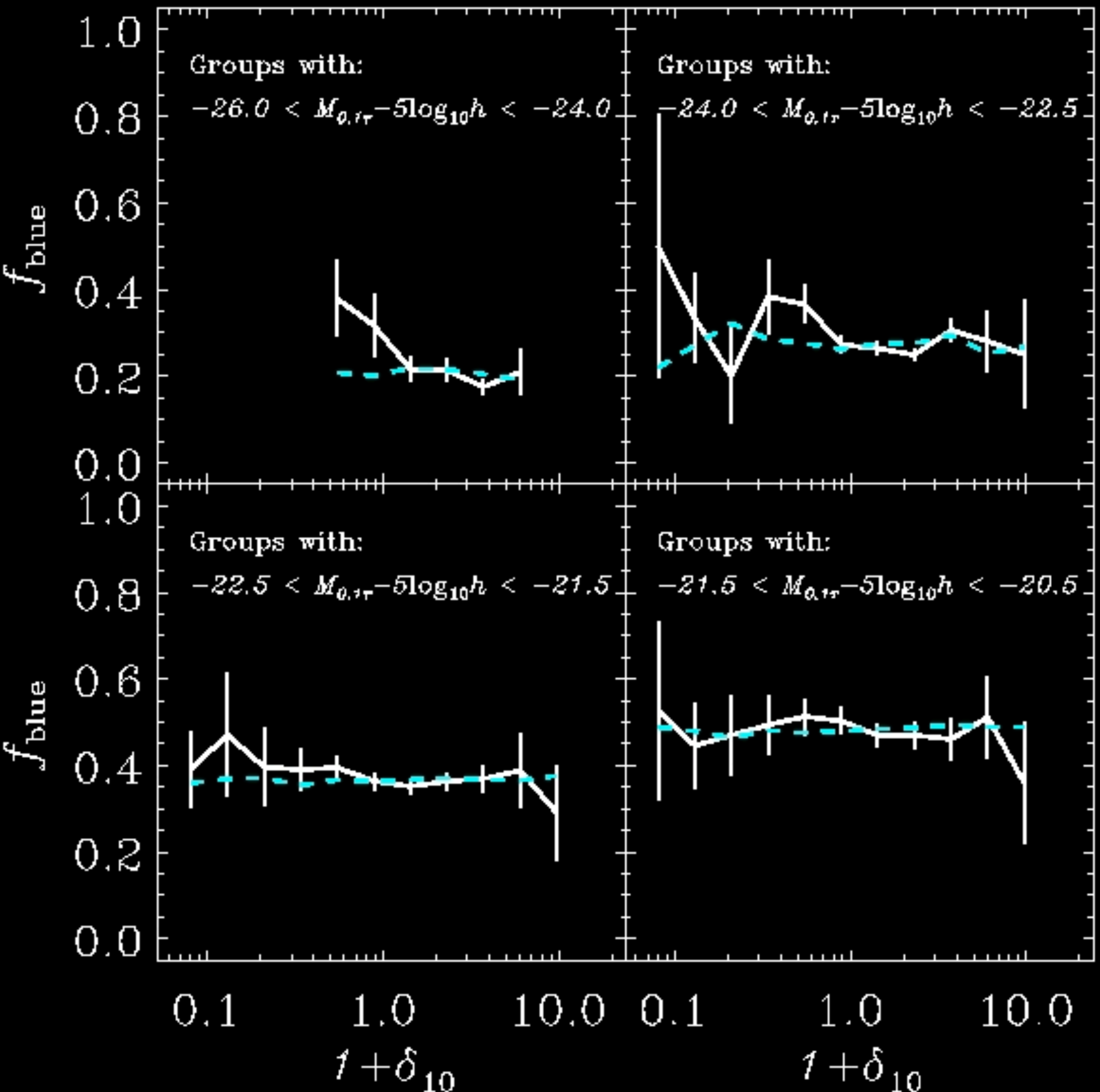
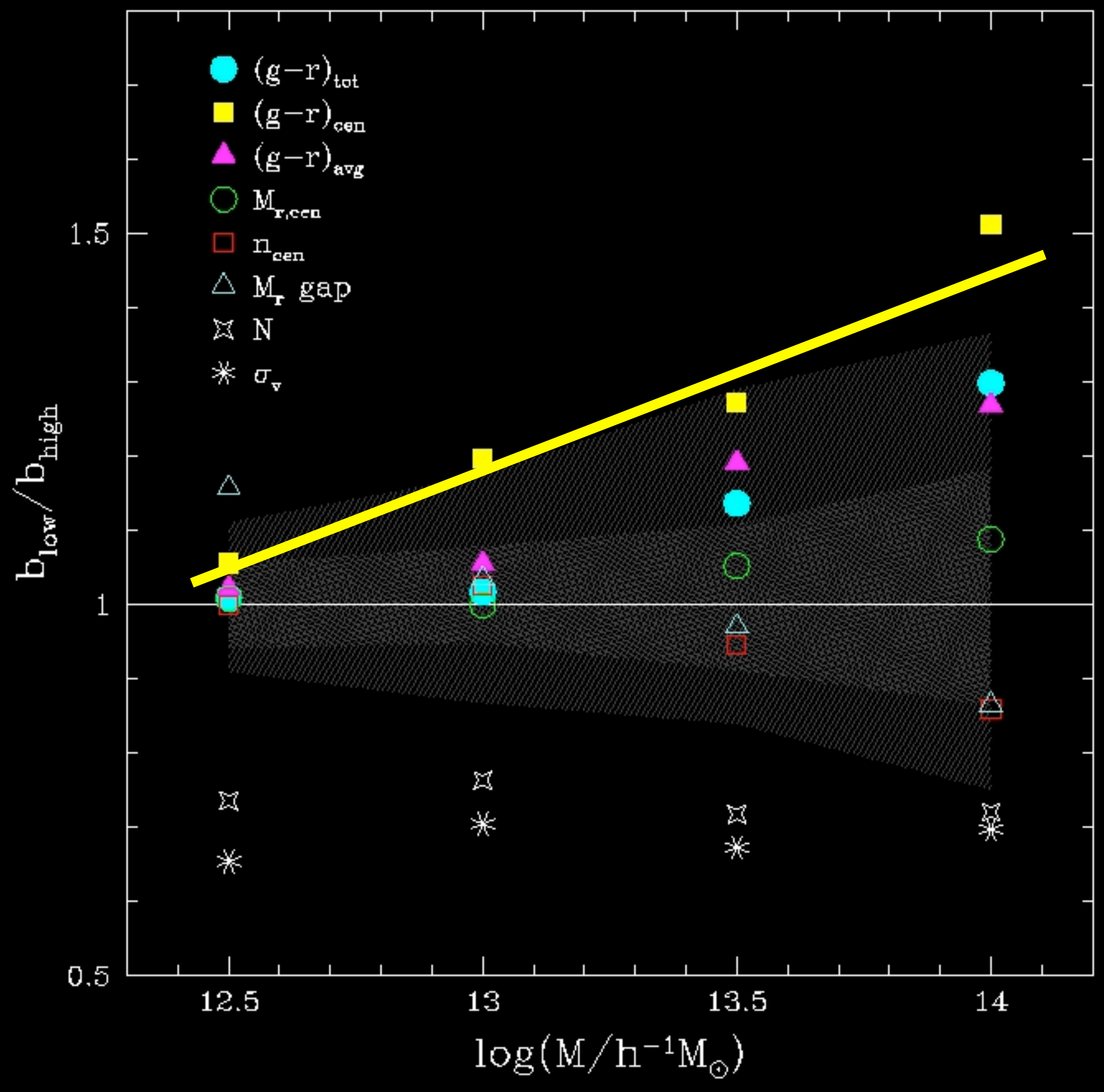


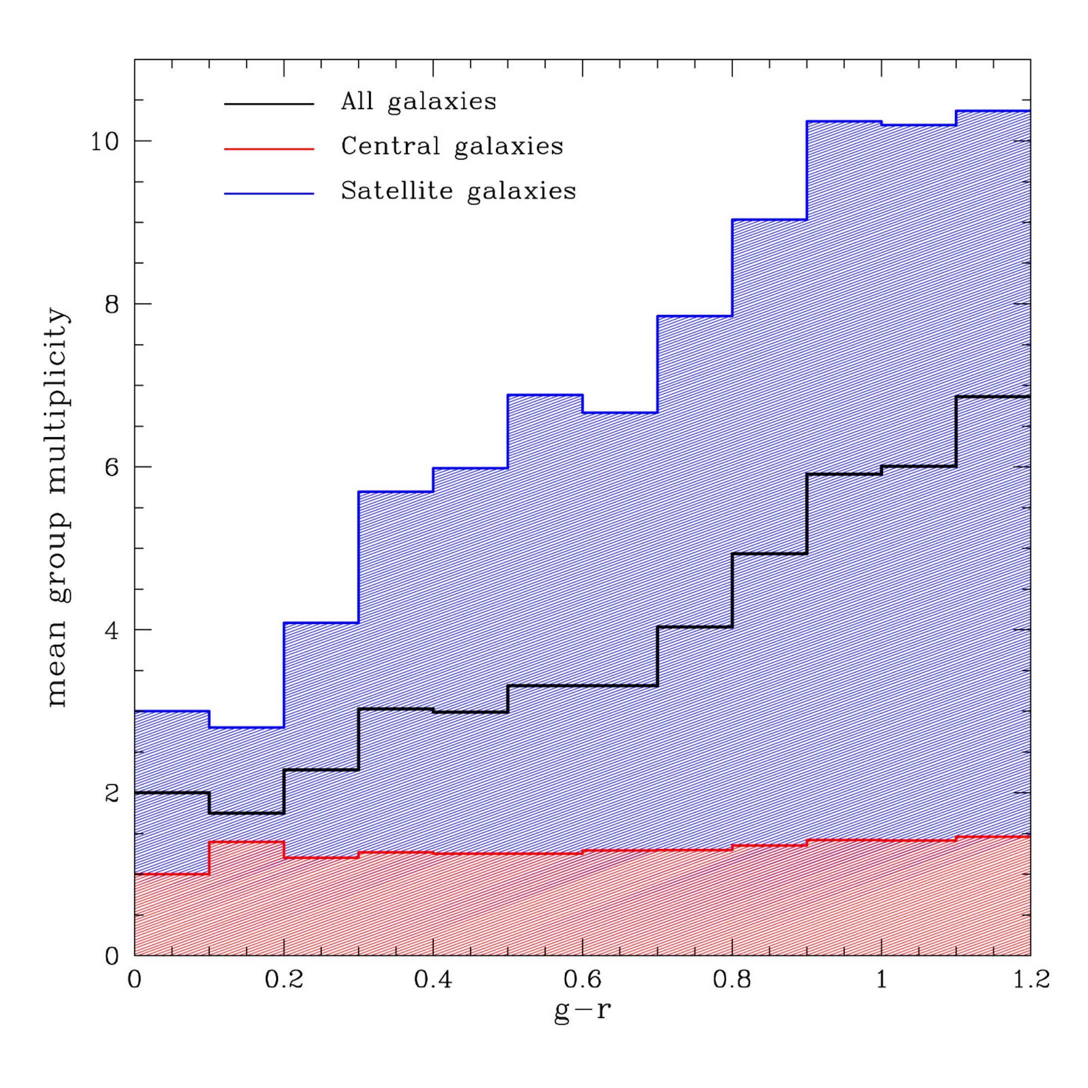
... except maybe for central galaxies?

Berlind et al. (2007)

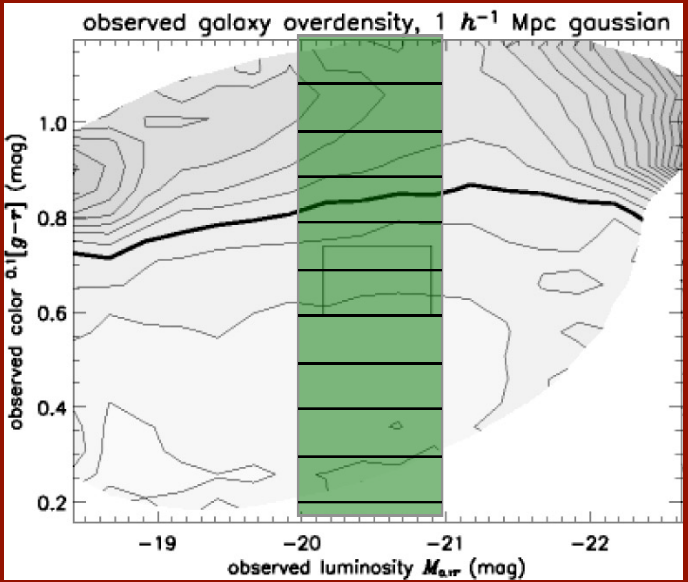


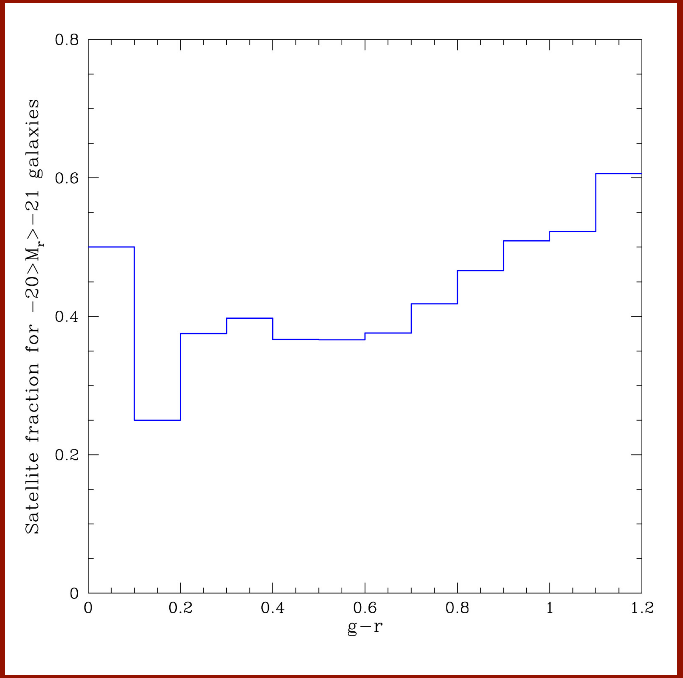
1. At high mass, clusters with blue central galaxies are in denser regions than those with red central galaxies
2. Younger central galaxies are in groups embedded in denser regions: halo assembly bias? *(Wechsler et al. 2006; Gao et al. 2006)*

Satellite galaxy host masses relate primarily to their color: ram pressure stripping or starvation?



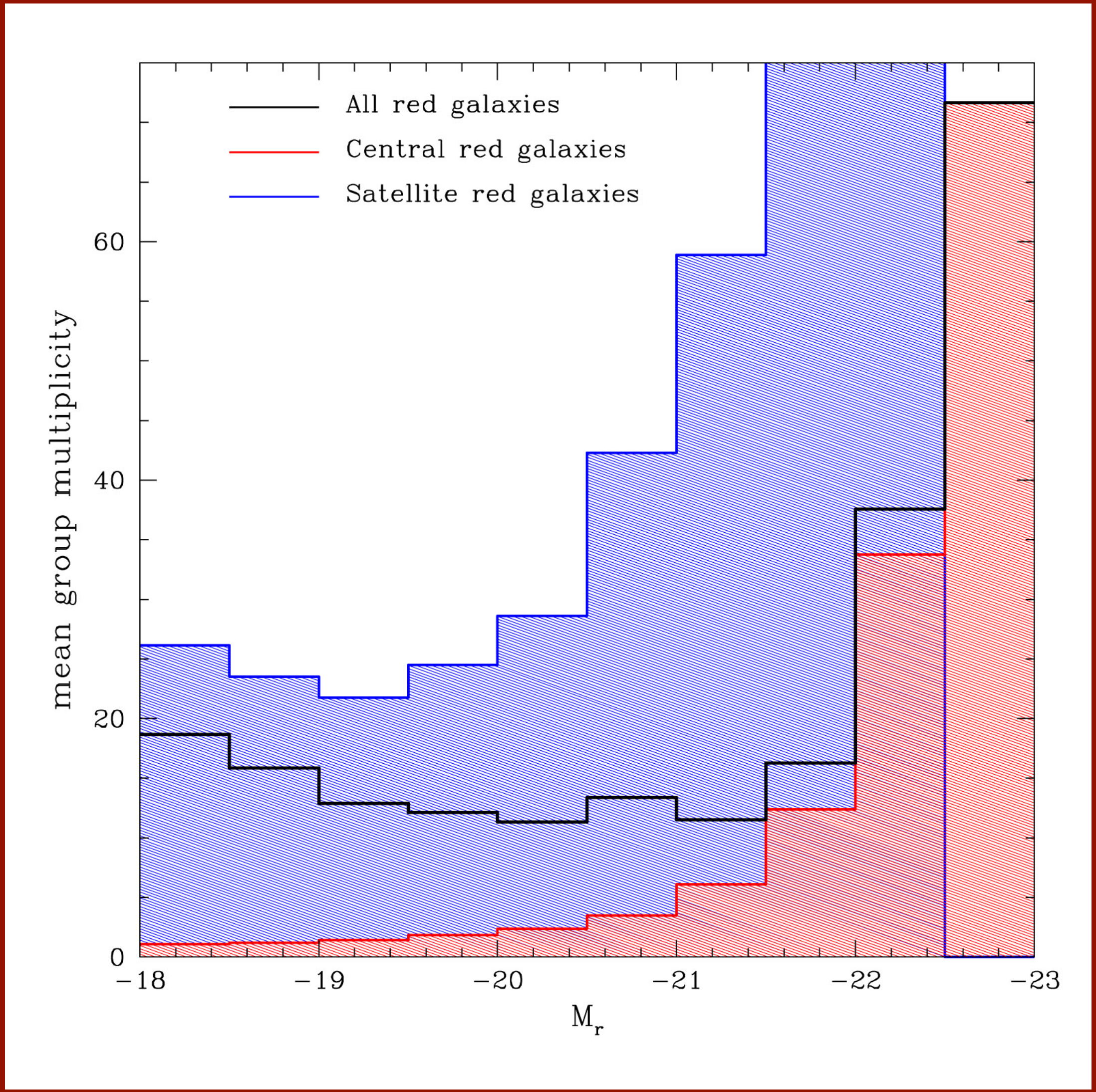
Mean group multiplicity vs. color



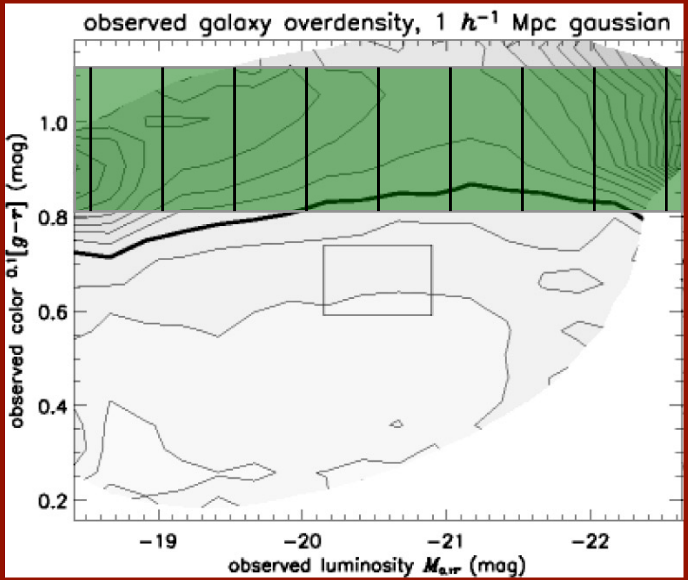


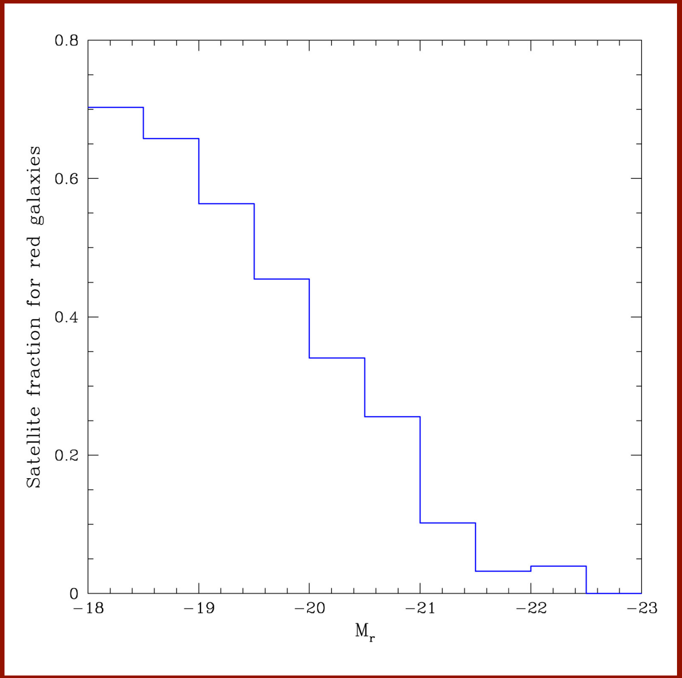
color

Central galaxy host masses related primarily to luminosity: dry mergers?



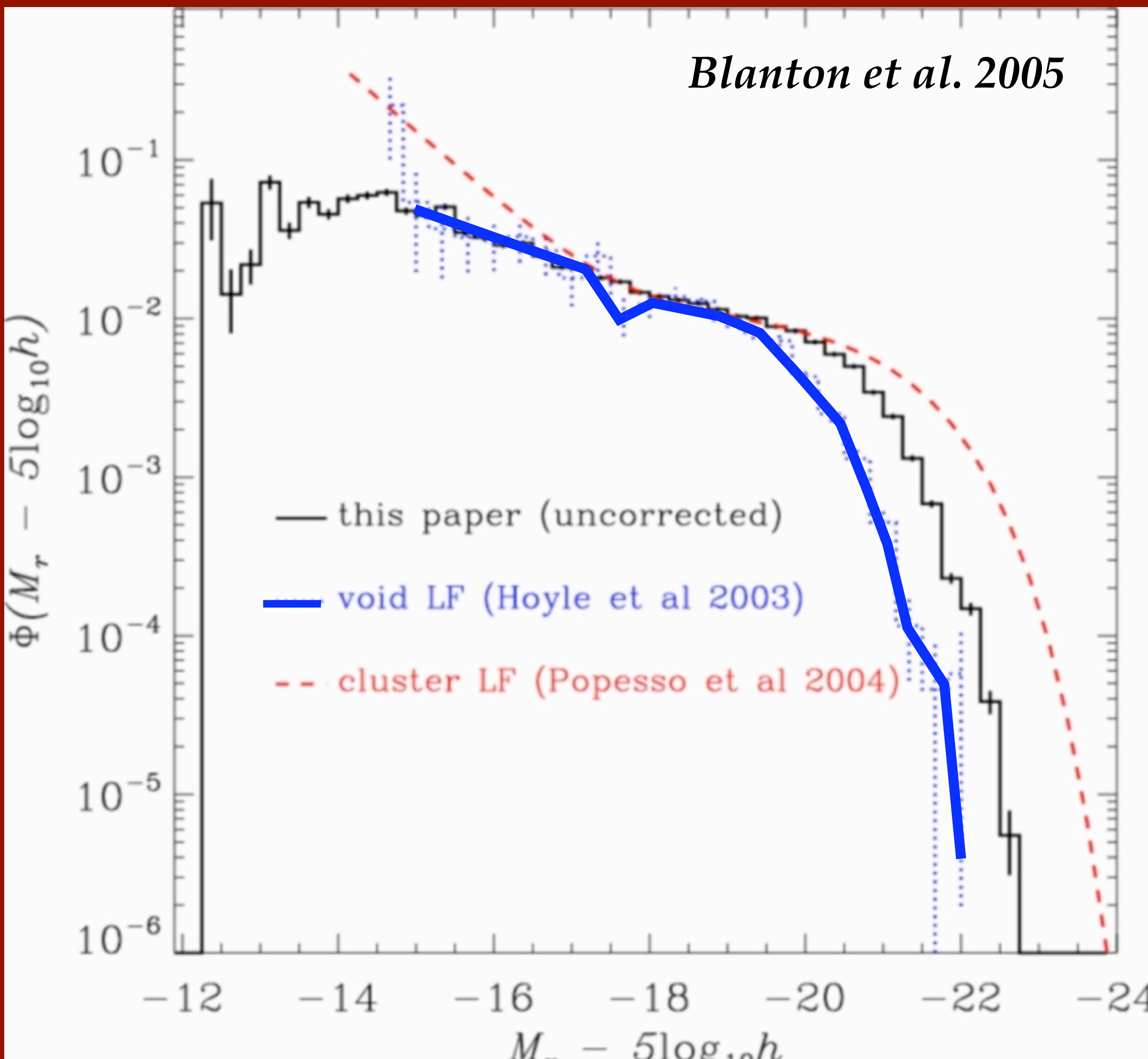
Mean group multiplicity vs. luminosity

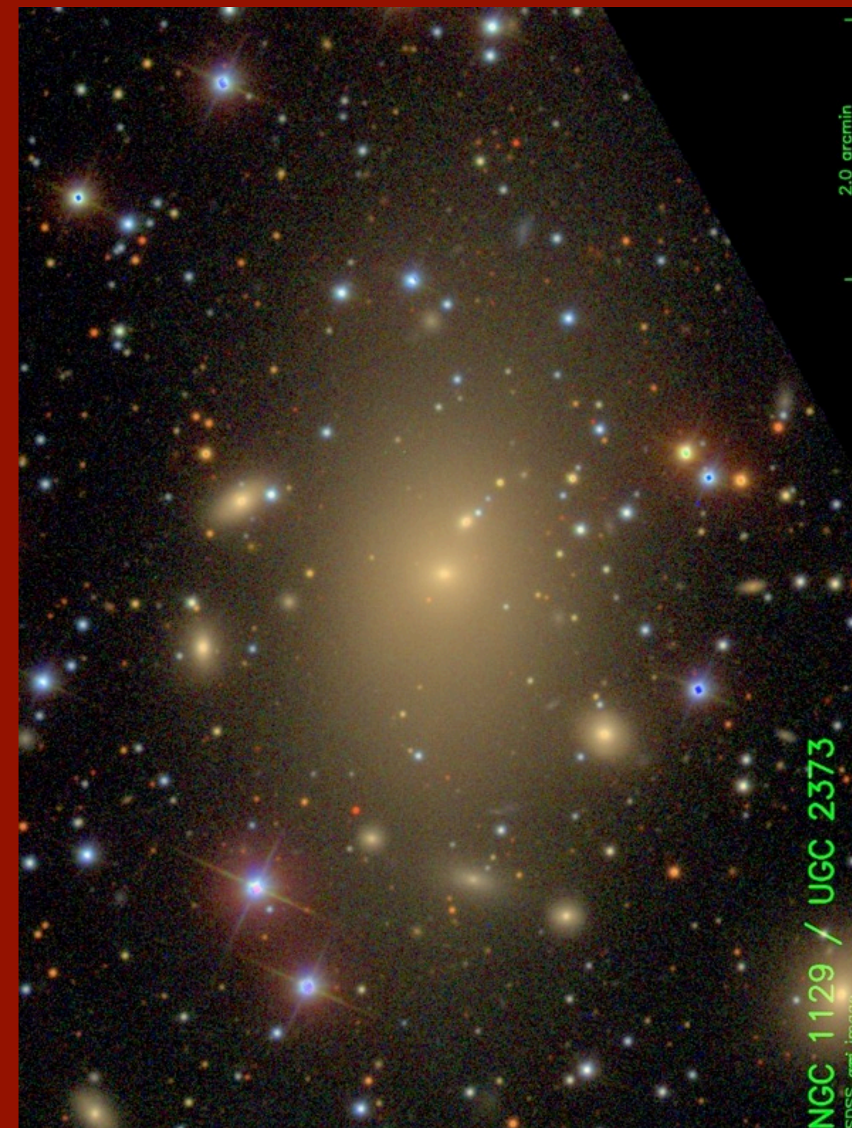




luminosity

Related to the sensitivity of the bright-end luminosity function cutoff to density: possibly driven by dry mergers onto BCGs? (e.g. Cooray & Milosavljevic 2005)

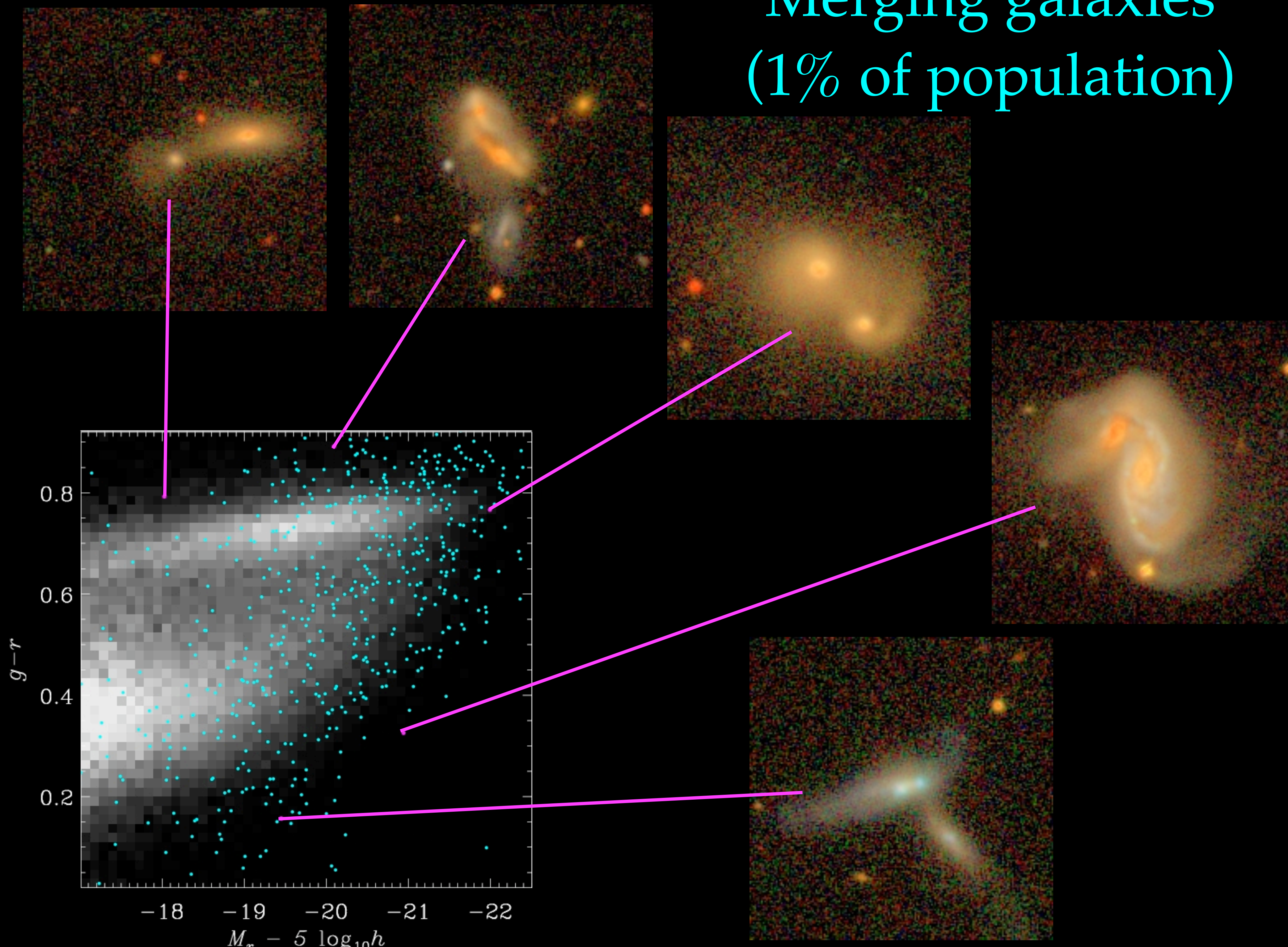




incredibly detailed statistics from SDSS: what is the common thread?

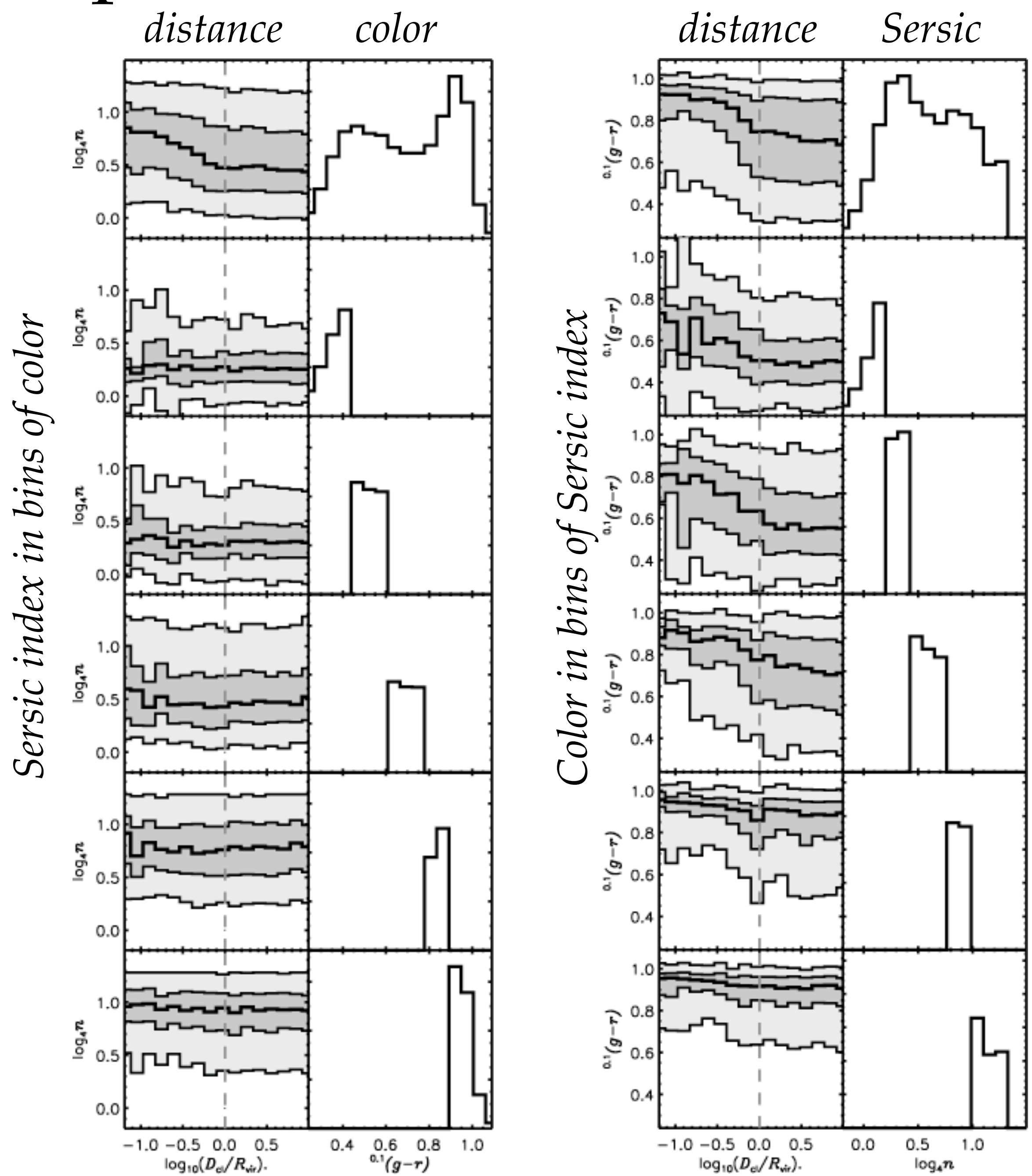
1. Overall, these results yield circumstantial evidence for the importance of the group-scale processes: so-called "pre-processing" of galaxies in groups before they enter clusters.
    a. *local halo is the most important environmental parameter*
    b. *effects kick in even at very low densities (not "cluster" phenomena)*
    c. *scaling relations fixed across large range of densities*
2. What about our mechanisms? what do these observations say?
    a. *ram pressure stripping too fast, only in clusters*
    b. *starvation (denial of gas accretion) looks very likely*
    c. *effects due to merger history variation also possible (necessary?)*
    d. *mergers appear important to growth of largest galaxies*
3. Small detectable deviations for normal galaxies; larger ones for BCGs and probably dwarf galaxies; but this is the basic picture for L* galaxies.

Merging galaxies (1% of population)



Structure doesn't depend on environment

1. Structure quantified here using the Sersic index
2. Sersic index and color both decline with distance from cluster center.
3. At fixed color, no dependence of Sersic index on distance.
4. Meanwhile, color depends on distance no matter what.
5. Note that in this formulation of the problem, unlike that of Blanton et al. (2005) or Kauffmann et al. (2004), intrinsic uncertainty in Sersic index matters very little.



Quintero et al (2006)

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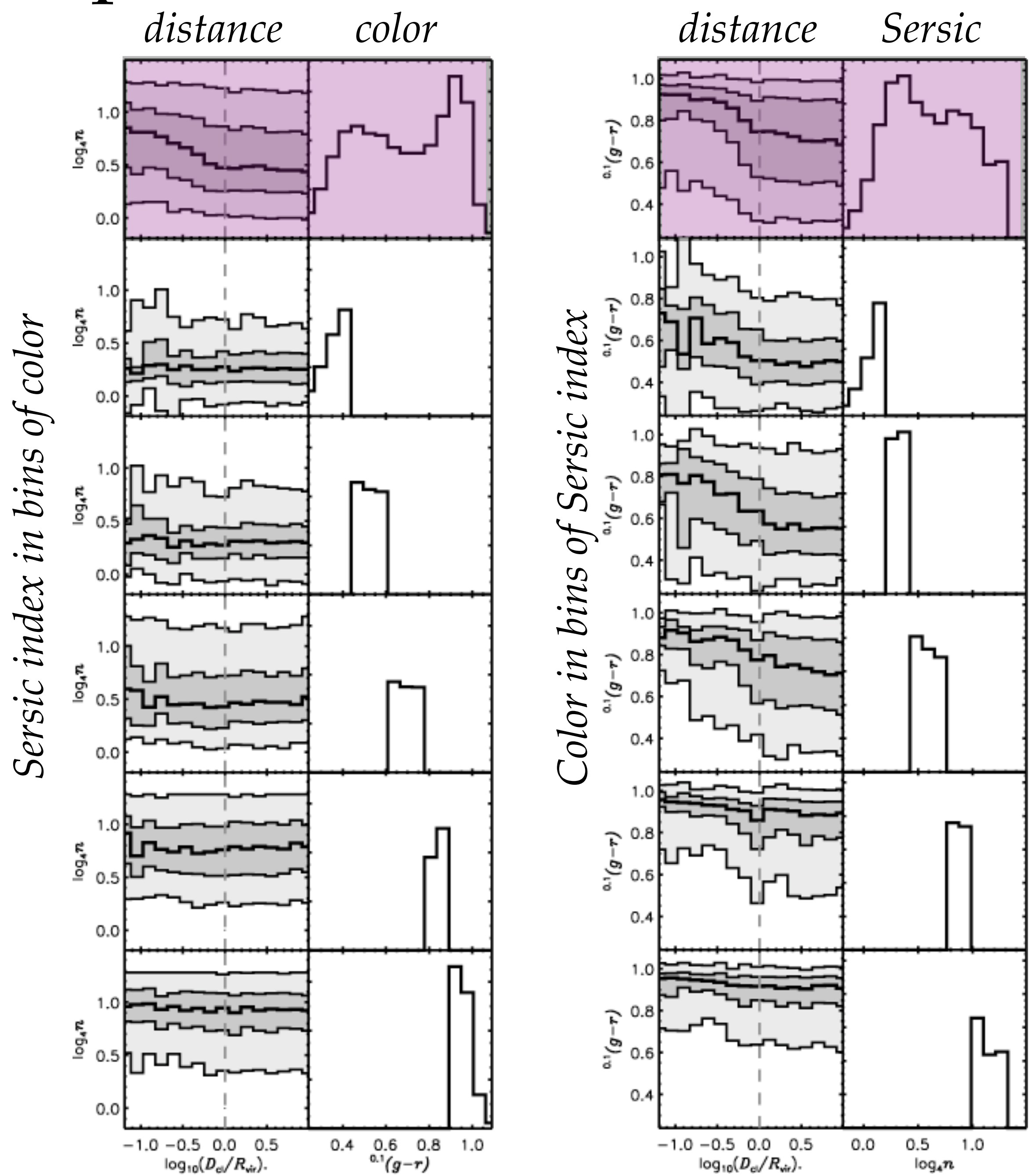

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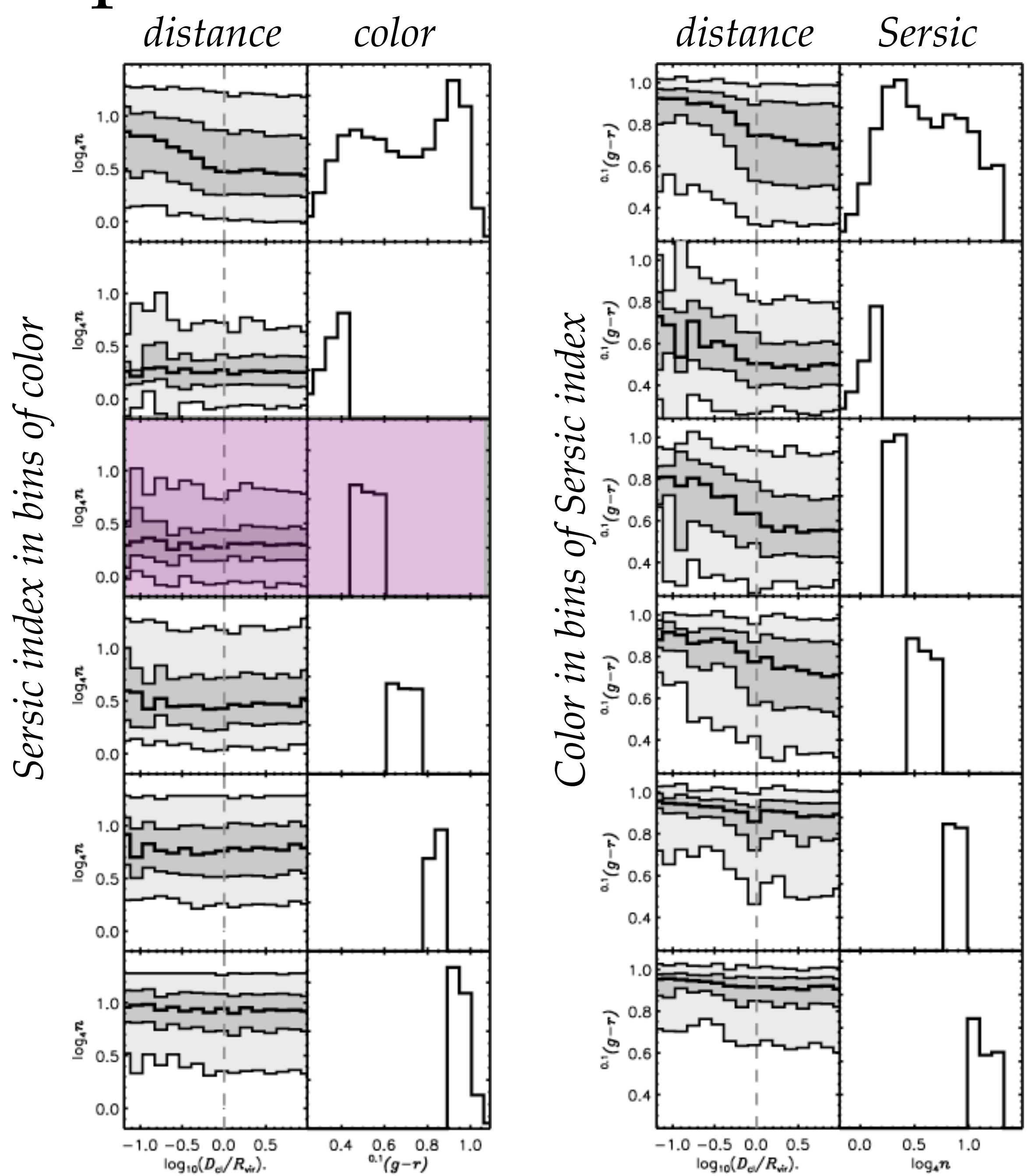

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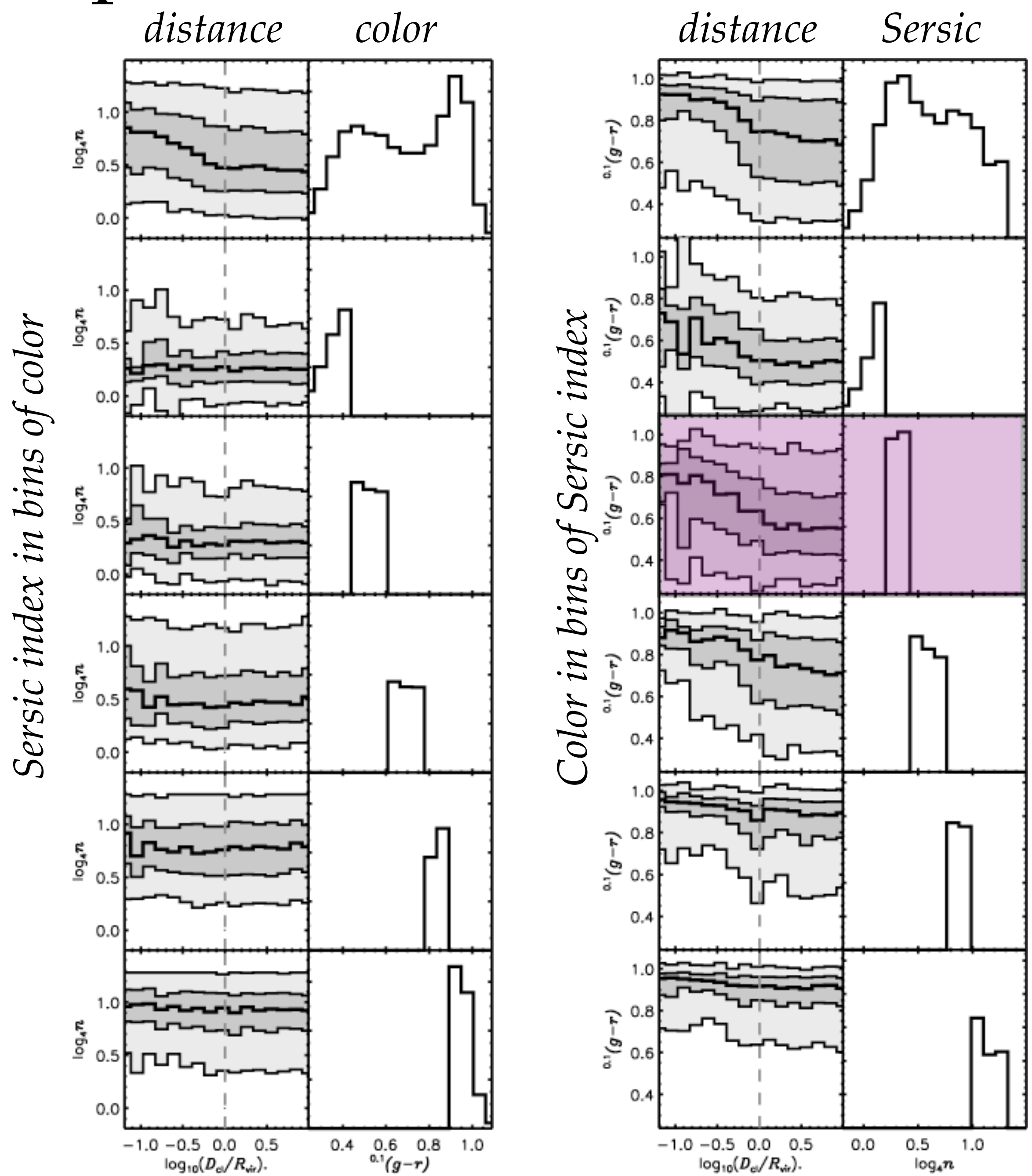
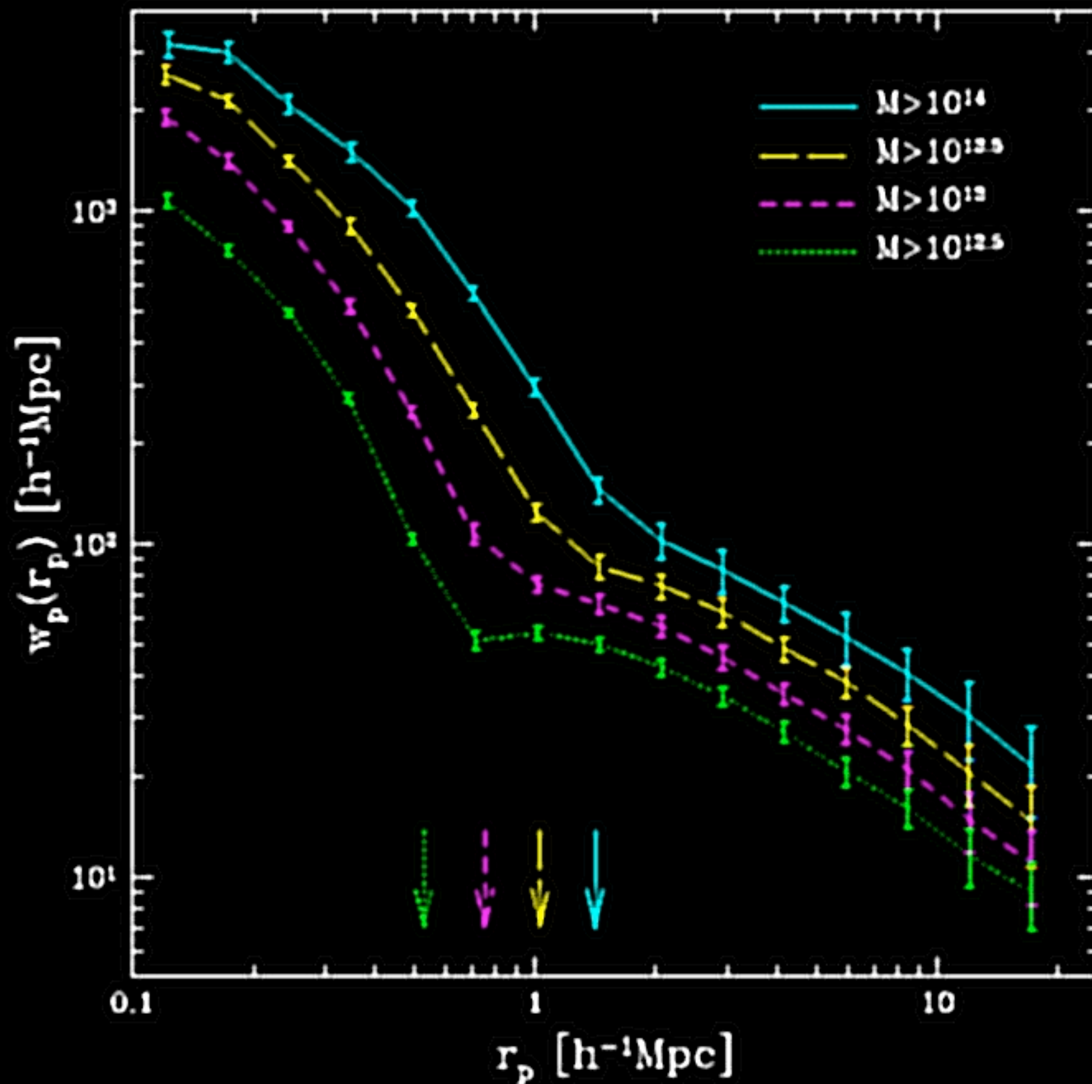


Quintero et al (2006)

Only the local halo matters …

1. Consider galaxies in groups of Berlind et al. (2006)
2. Define environment in two ways:
    - *a. density in redshift space in 6<r<10 Mpc annulus (projected)*
    - *b. group luminosity and groupocentric distance*
3. Compare them:
    - *a. Larger groups: low blue fraction*
    - *b. Larger groups: dense environments*
    - *c. Fixed group luminosity: no correlation of blue fraction with environment*
4. Similar results: Kauffmann et al. (2004), Lewis et al. (2002)

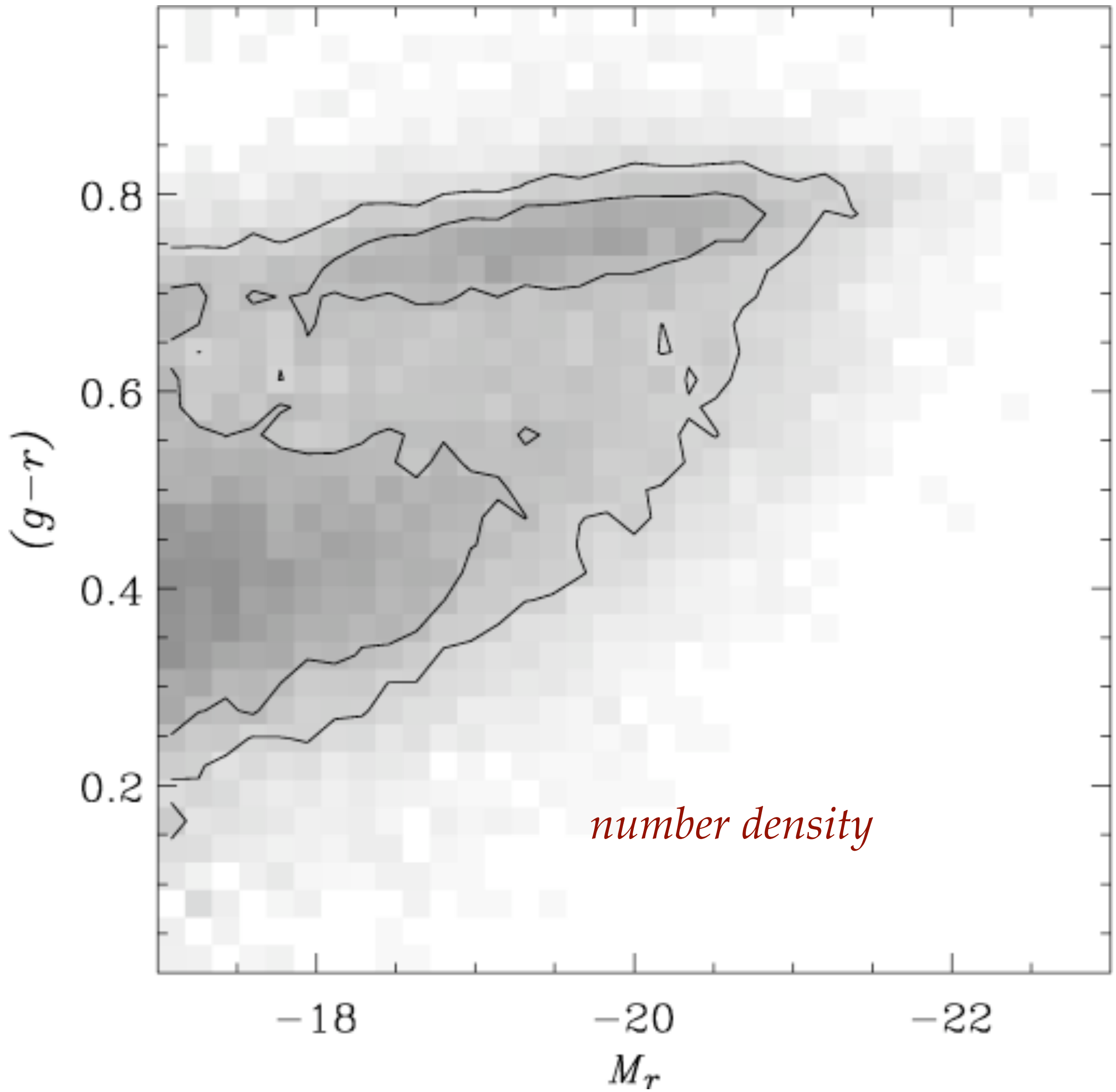
Berlind et al. 2007



Dependence on luminosity

1. Two sequences in color and absolute magnitude

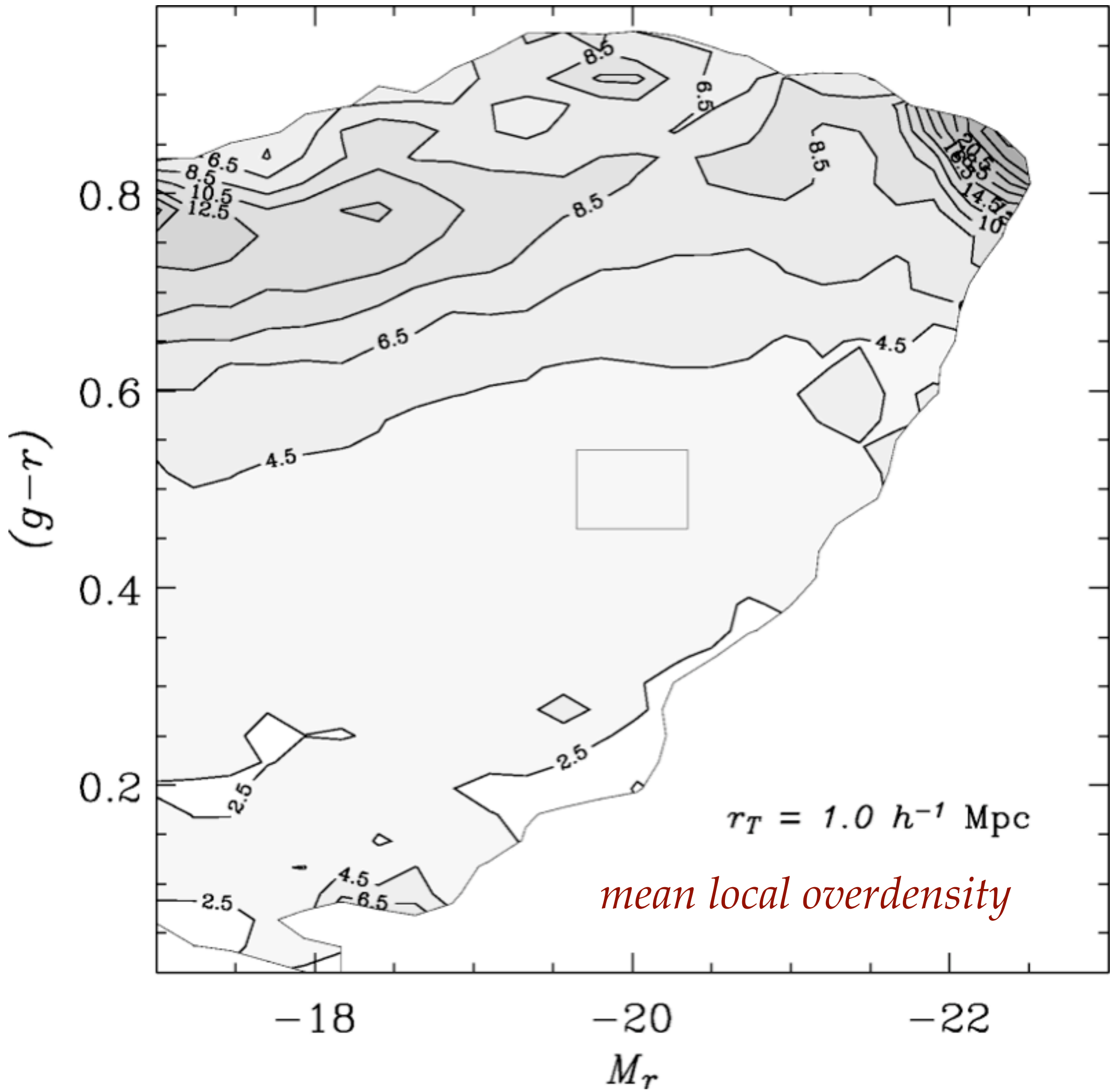
2. How does environment vary among these galaxies?
   a. *strong function of luminosity at high luminosity*
   b. *increasingly strong function of color at low luminosity*



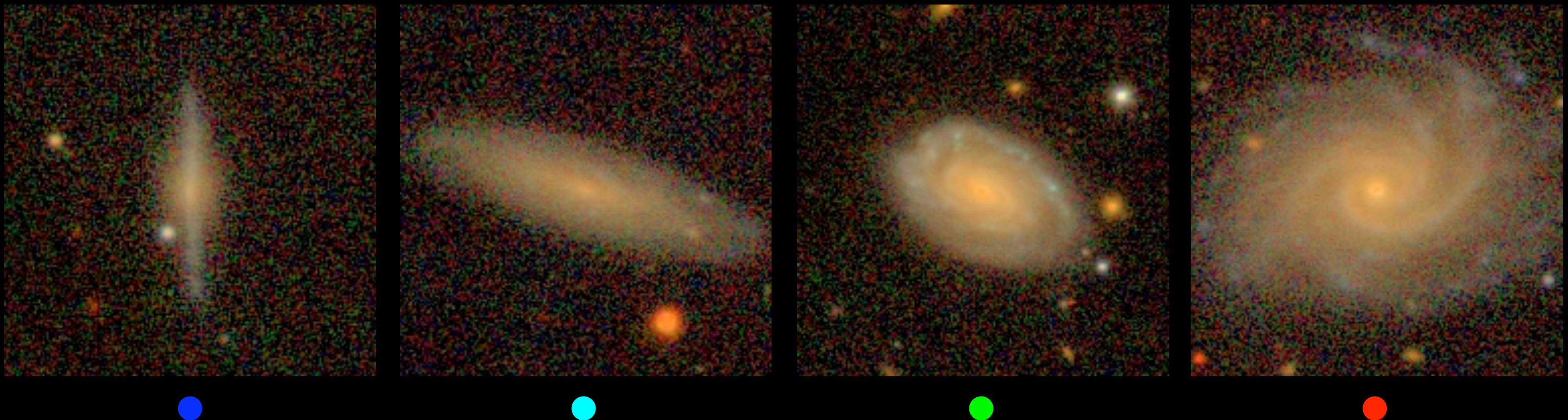
Dependence on luminosity

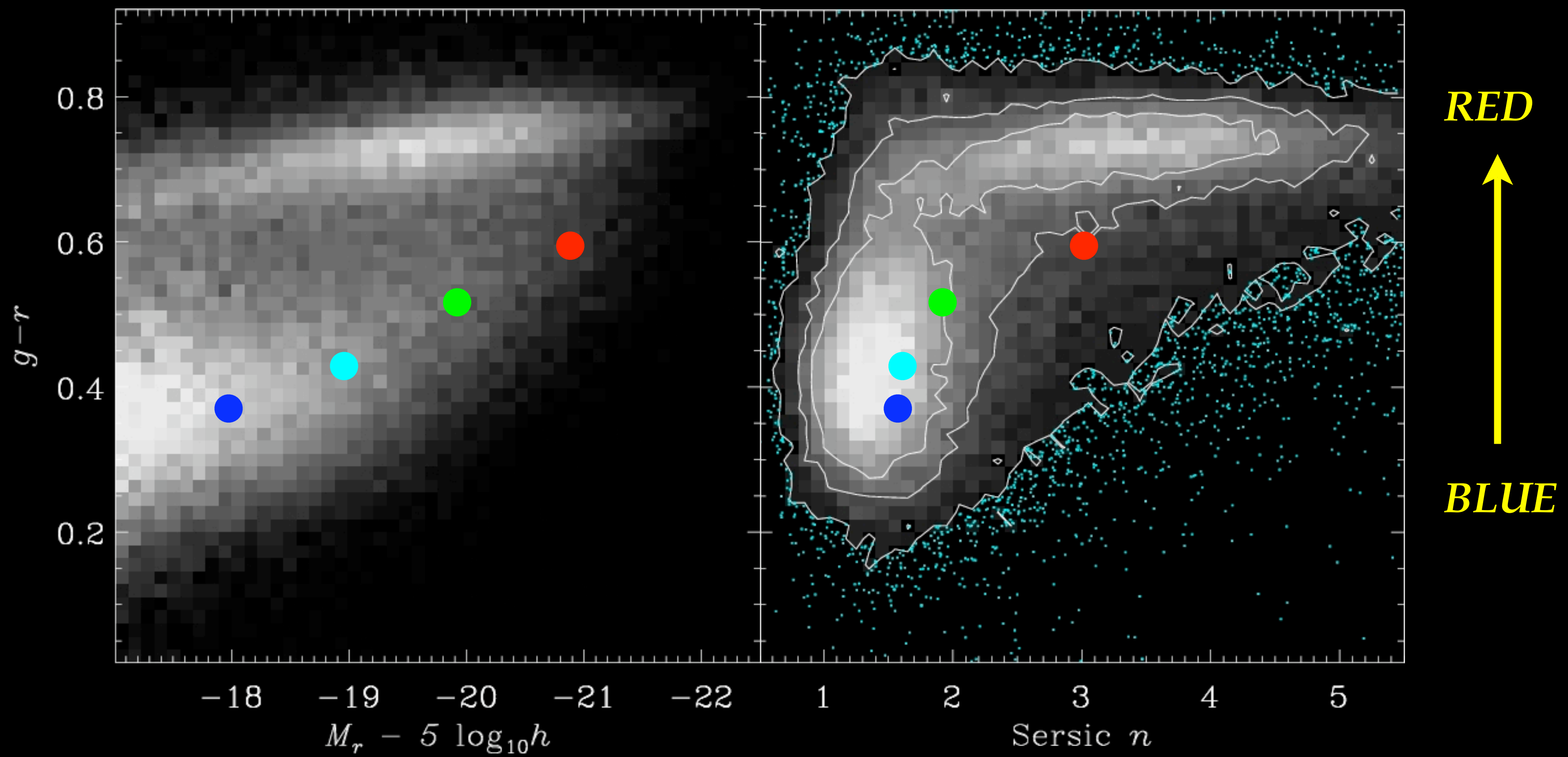
1. Two sequences in color and absolute magnitude

2. How does environment vary among these galaxies?
   a. *strong function of luminosity at high luminosity*
   b. *increasingly strong function of color at low luminosity*

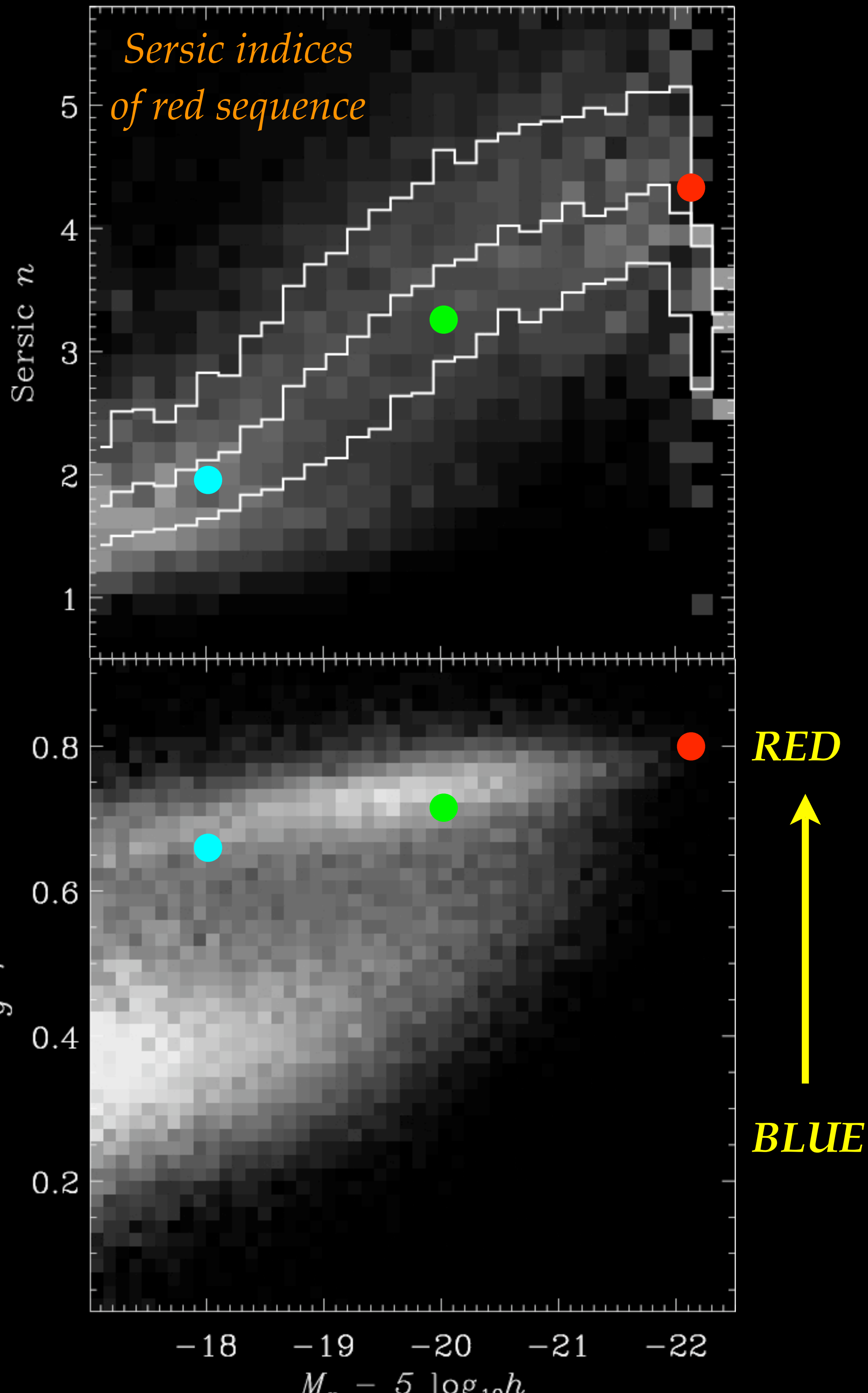


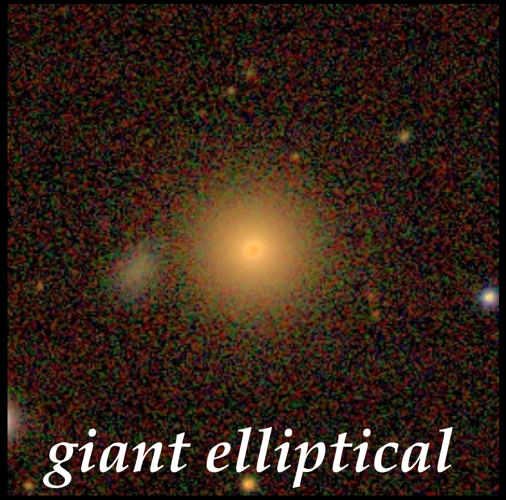
Blue sequence: spirals



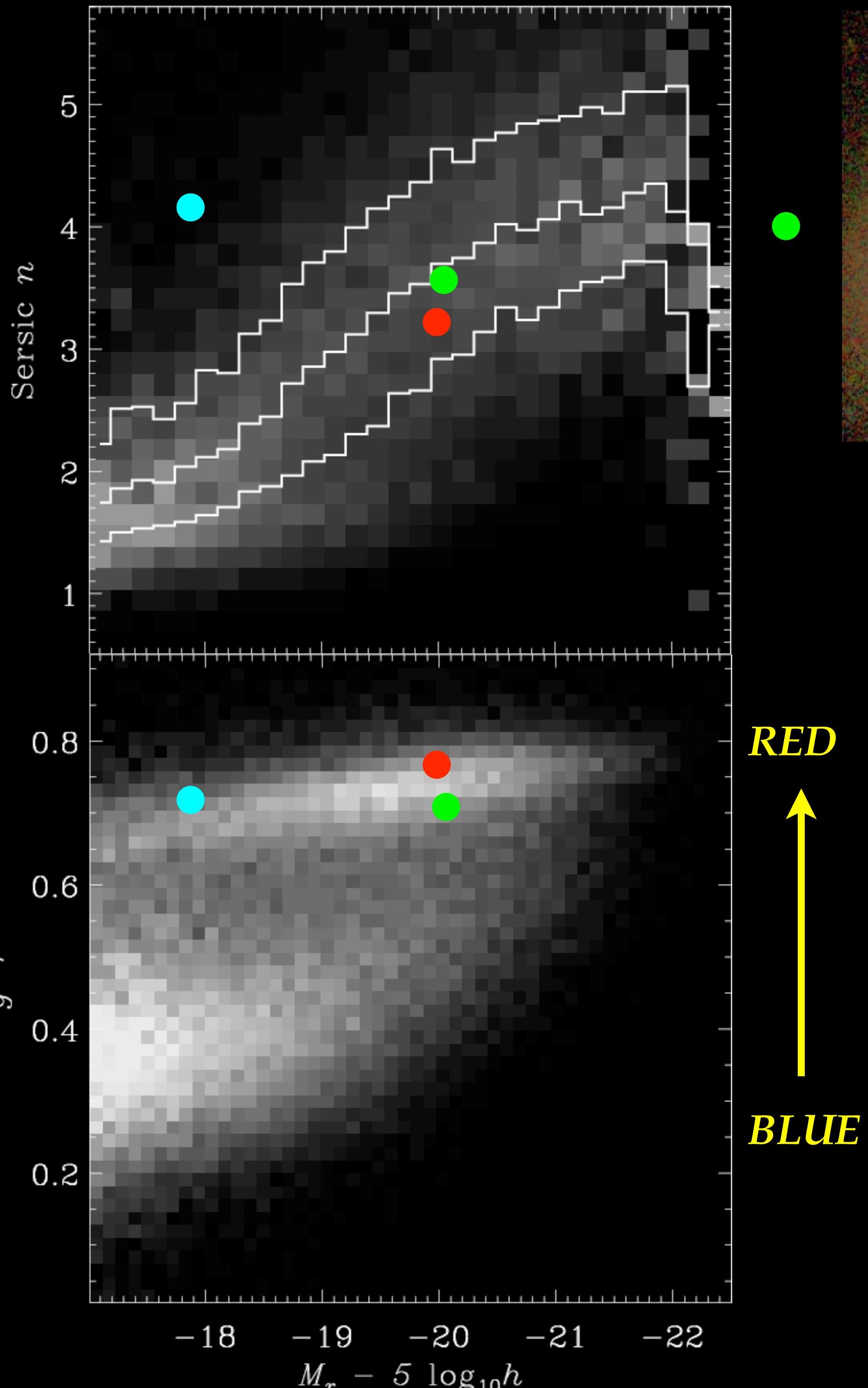


Red sequence

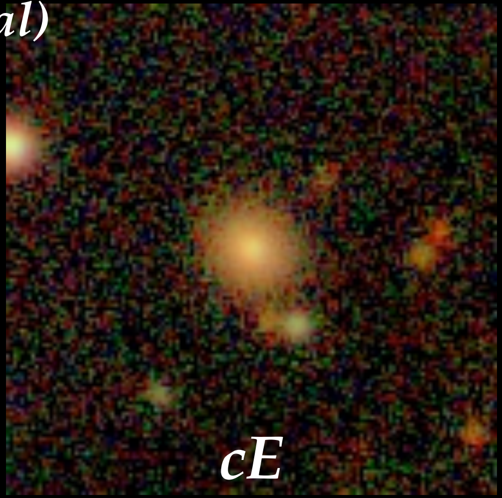




"Interlopers" on the red sequence



(Maller et al)



Dependence on luminosity

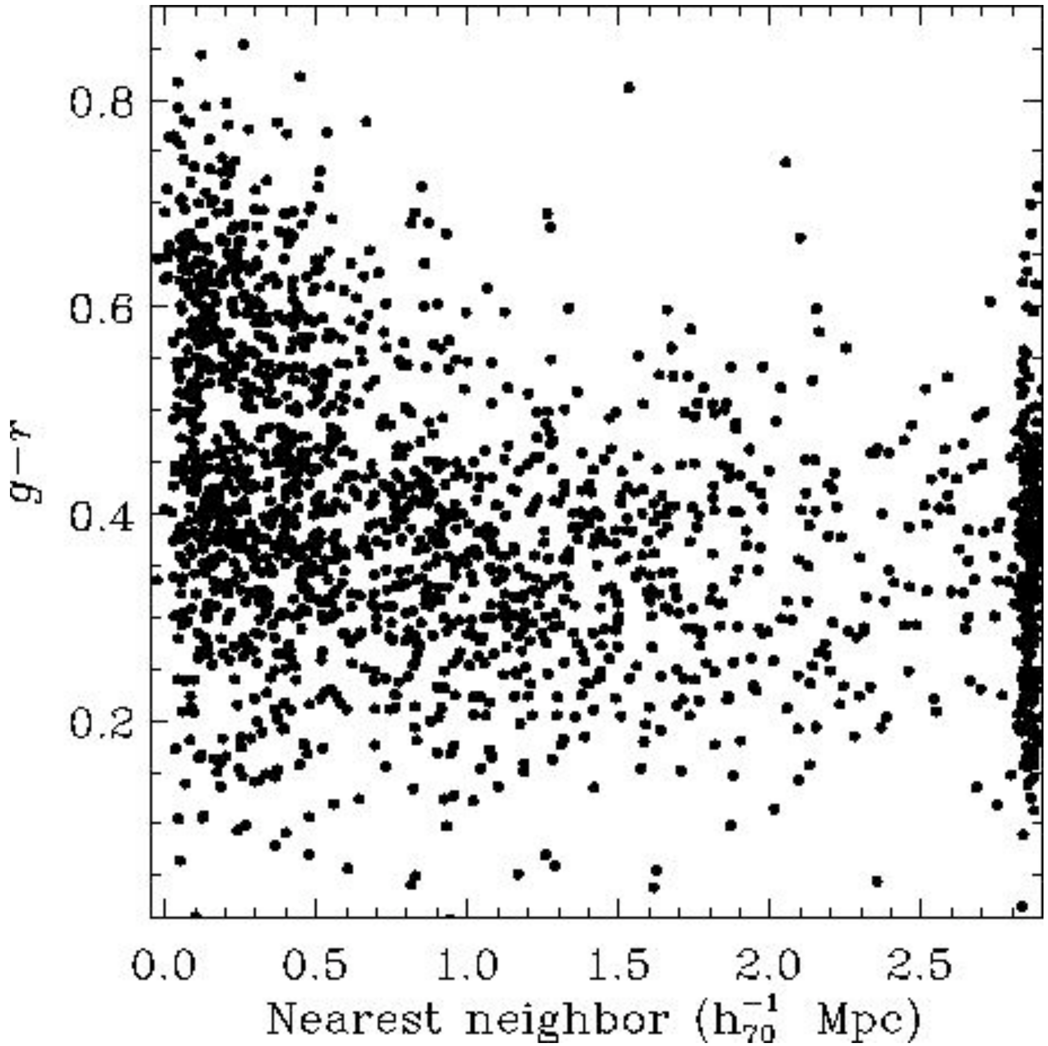
1. At even lower luminosities this effect becomes even more striking.

2. Extremely sensitive dependence: only a tiny fraction of isolated dwarf galaxies are red.

3. Is an interaction with a large galaxy the only way star-formation can end in dwarf galaxies?

dwarf galaxy sample from SDSS

$M_r - 5\log_{10} h > -16$



Evolution of environment trends

1. DEEP2 results show:
    a. *at all redshifts some low density galaxies are red (but at 5% dust is a real issue)*
    b. *fraction of red galaxies in dense regions declines at higher redshift*
2. Epoch of creation or assembly of red galaxies? (Is it long enough ago to be the former?)
3. To explore this change more fully we need much larger samples.

Cooper et al. (2007)