The Formation of Massive Galaxies

Massive Galaxies over Cosmic Time

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Outline of talk

Part I: What fraction of massive galaxies formed after z = 1?

- L^* vs. $4L^*$
- Downsizing based on the lum and mass function? Complex.
- Downsizing based on stellar ages? Yes.

Part II: Red-sequence formation as part of the wider phenomenon of star-formation shutdown at late times (Noeske et al. 2006)

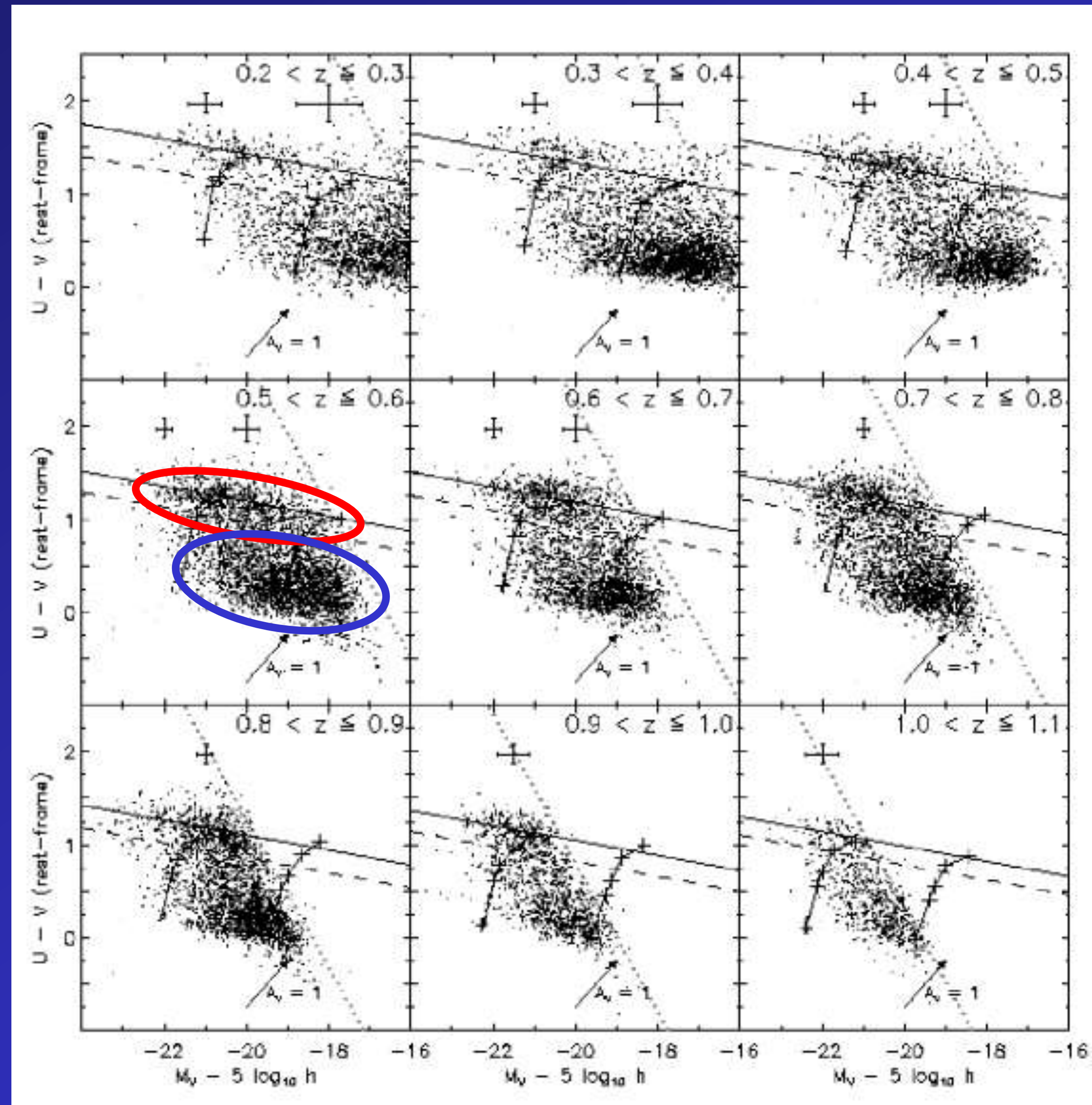
Part III: Quenching by massive dark halos vs. quenching by AGN feedback

- Varieties of AGN quenching
- A semi-analytic model based on halo quenching

Color bimodality persists out *to at least z ~ 1*

Combo-17 survey:

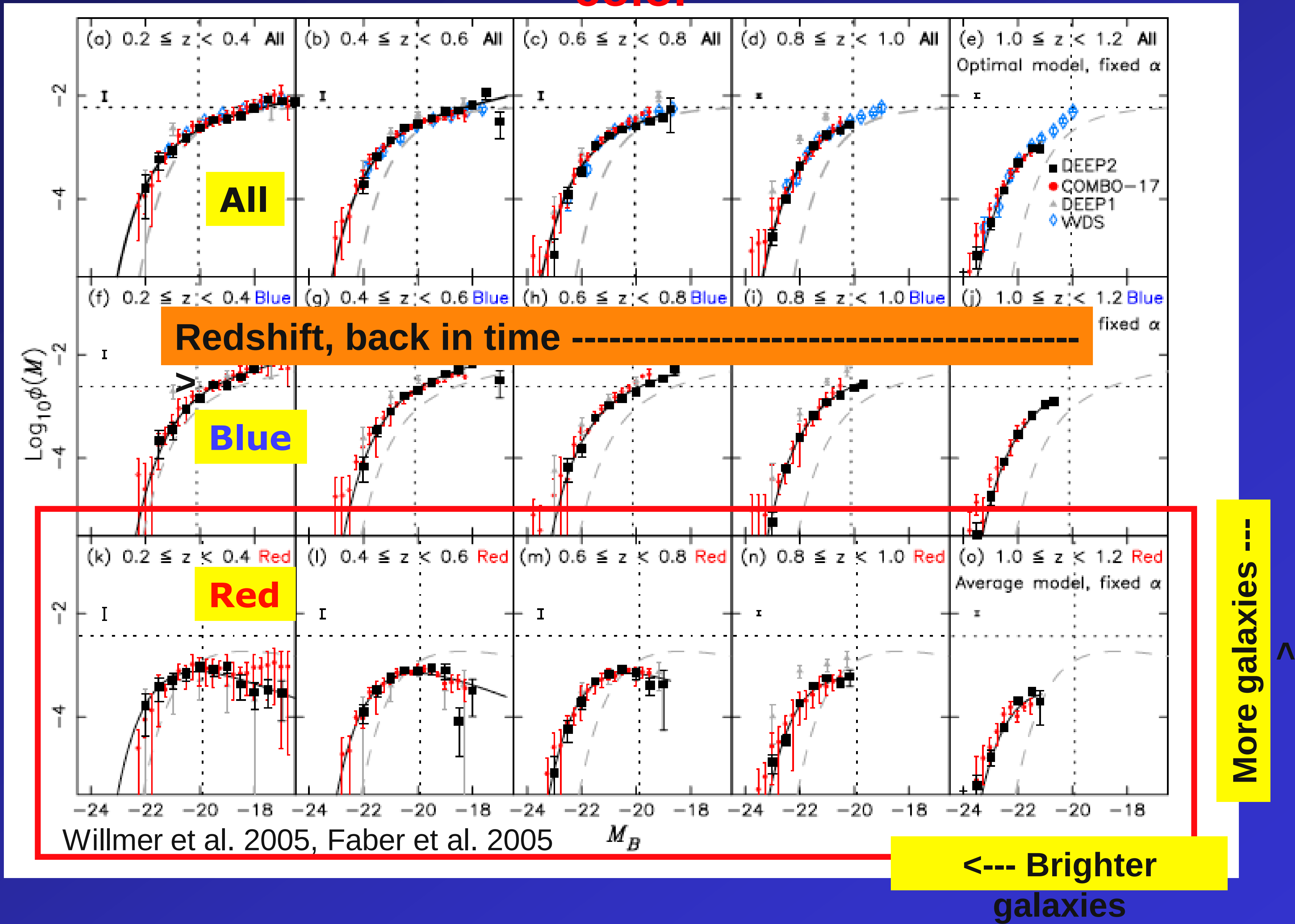
- 25,000 galaxies
- R-band selected to R - 24
- 17-color photo-z's



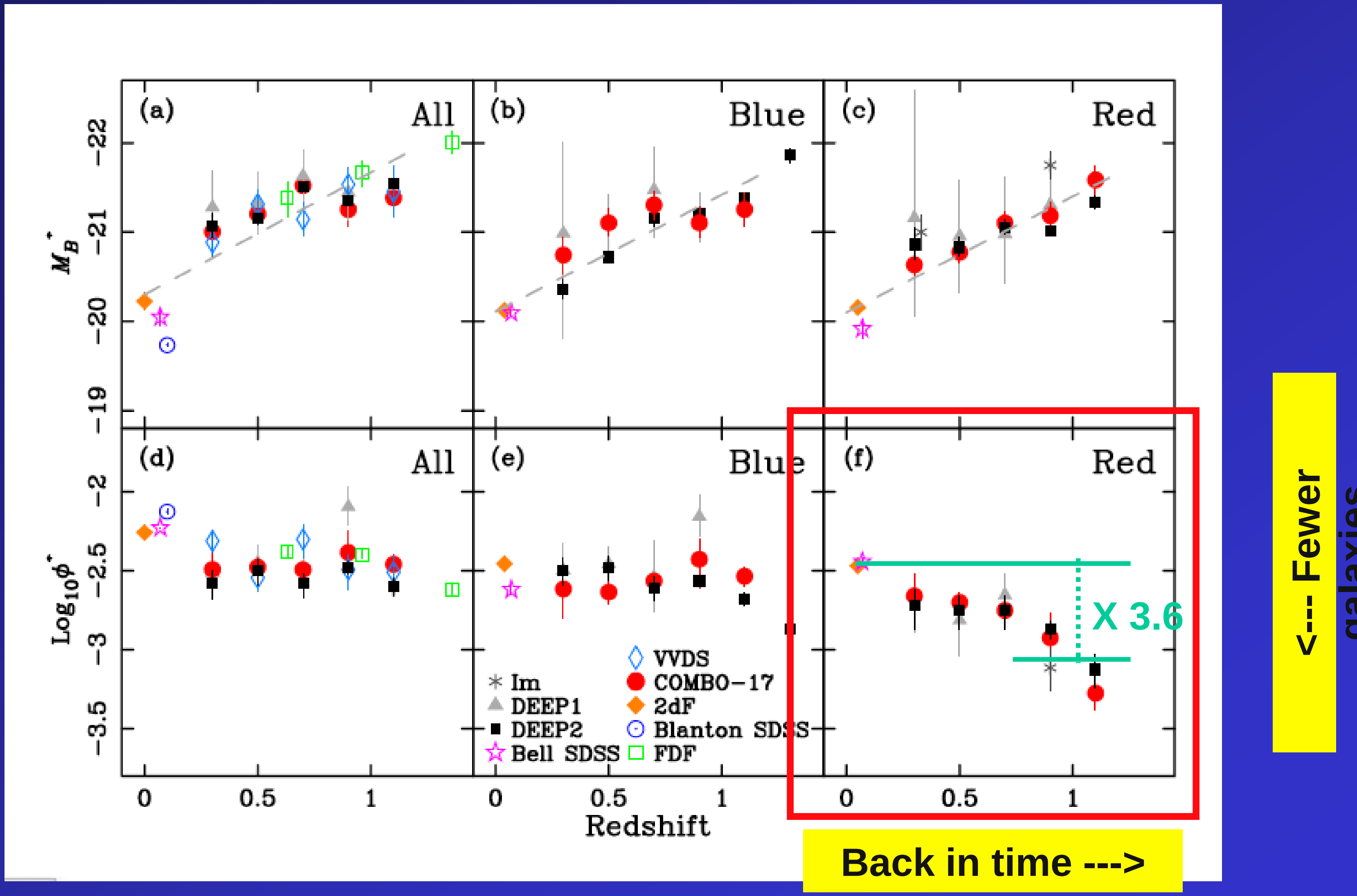
What causes color bimodality? At what epoch did it set in?

Bell et al. 2004

DEEP2 and COMBO-17 luminosity functions by color



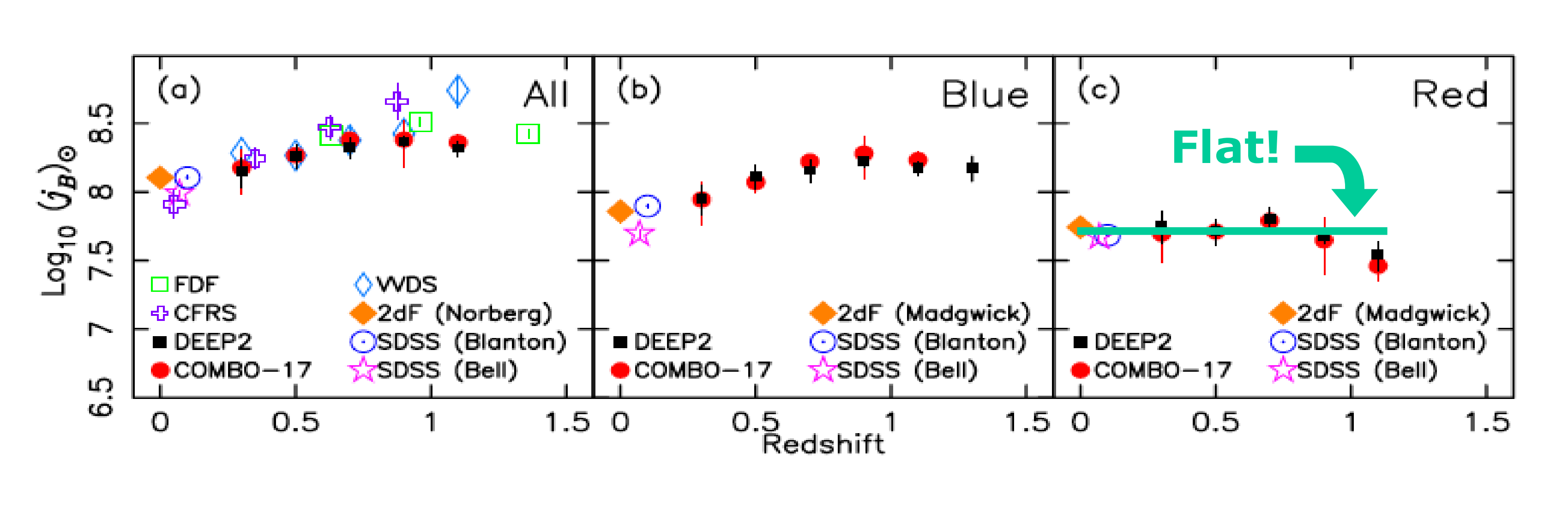
DEEP2 and COMBO-17: At least half of all spheroidal galaxies were quenched *after* z = 1



Bell et al. 2004, Willmer et al. 2006, Faber et al. 2005

The luminosity density in red sequence galaxies is constant back to z ~ 1

Which means that TOTAL STELLAR MASS must be increasing by M/L, i.e., by 1-1.5 mags, or x 2.5-4 (Bell et al. 2004)



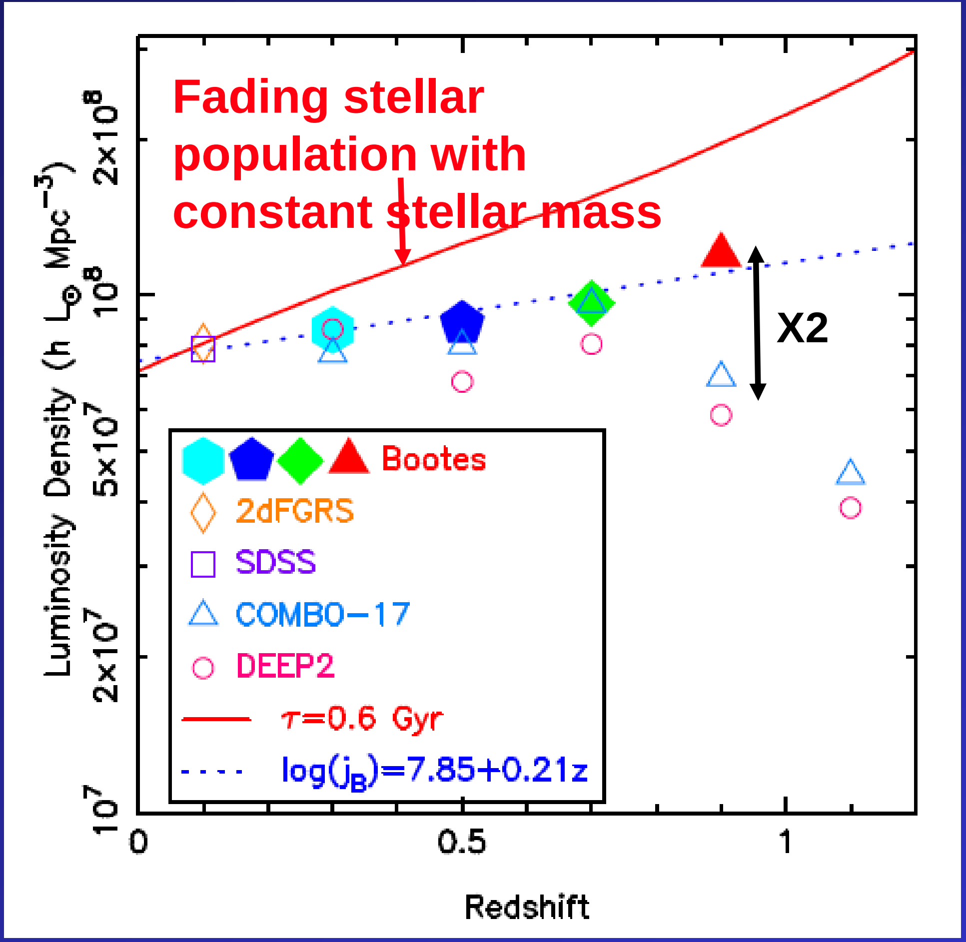
Faber et al. 2005

Results from the NOAO Deep-Wide Survey

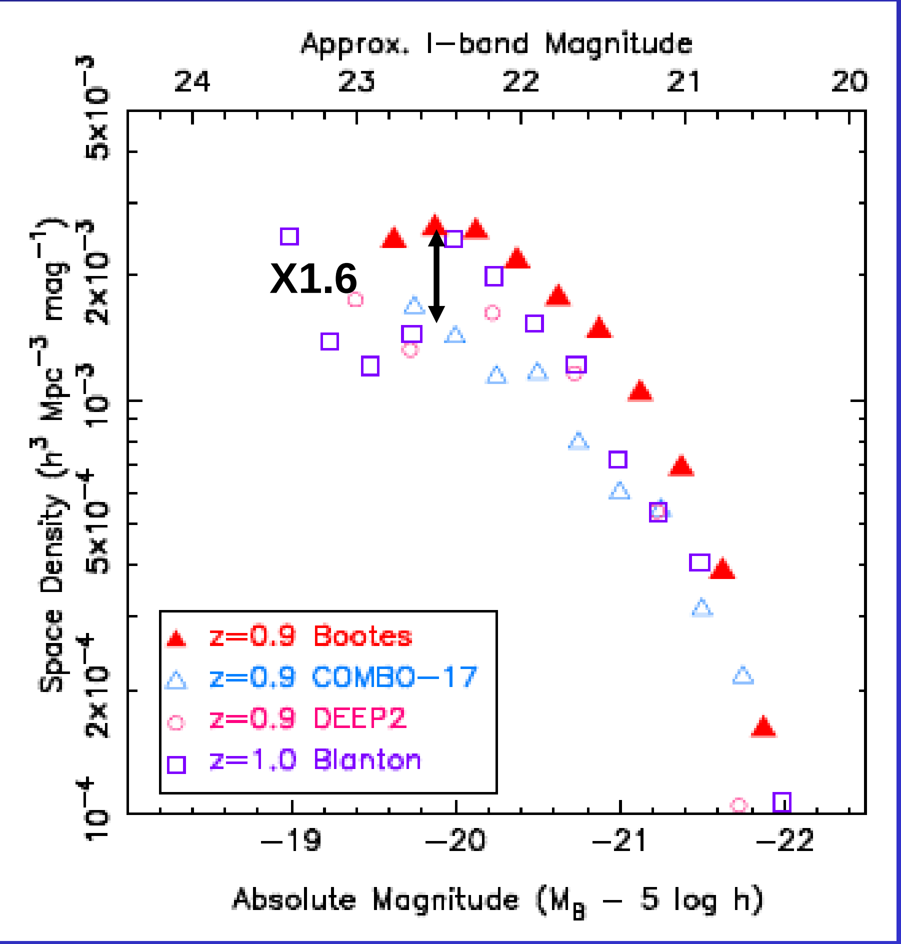
Luminosity density higher than COMBO-17 and DEEP2 but stellar mass still doubles since z = 1

Brown, Dey et al. 2006

Luminosity density back in time



Raw functions compared at z = 0.9



Growth in red galaxies since z = 1: Summary of recent work

Zucca et al. (2005), red SEDs, stellar mass density x 2

Ilbert et al. (2005), red spheroids, number density x 3

Ferreras et al. (2005), all spheroids, number density x 5

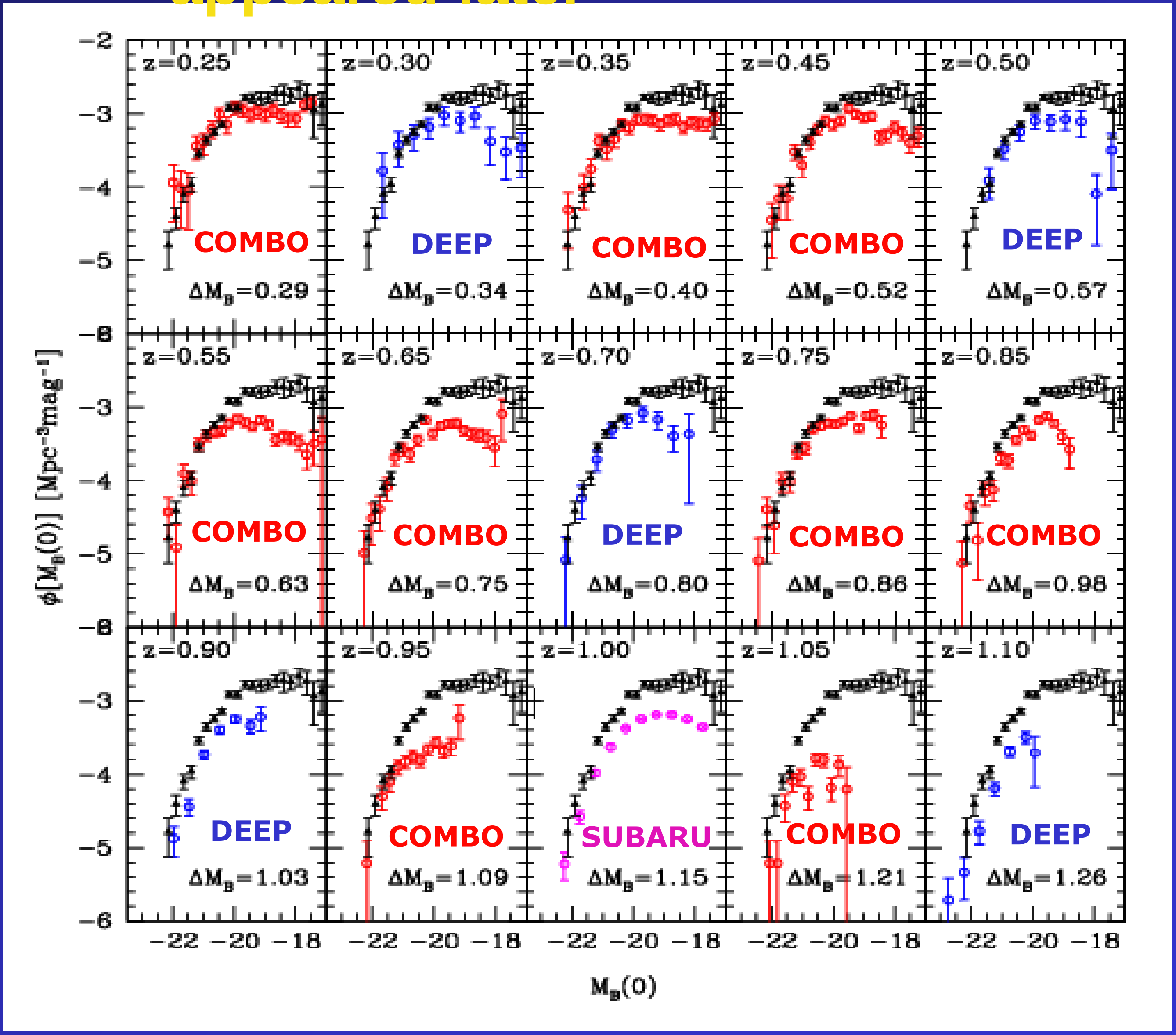
Bundy et al. (2006), red stellar mass function, number density x 2

Pannella et al. (2006), red stellar mass function, stellar mass density x 2

Cimatti et al. 2006: the most massive RS galaxies were already in place by z = 1; smaller ones appeared later

DEEP2, COMBO, and Subaru counts have been evolved to z = 0.25 assuming that M_B ***fades by 1.15 mag*** since z = 1.

This conclusion depends critically on ***photometric accuracy*** for the brightest galaxies and the ***assumed fade***.

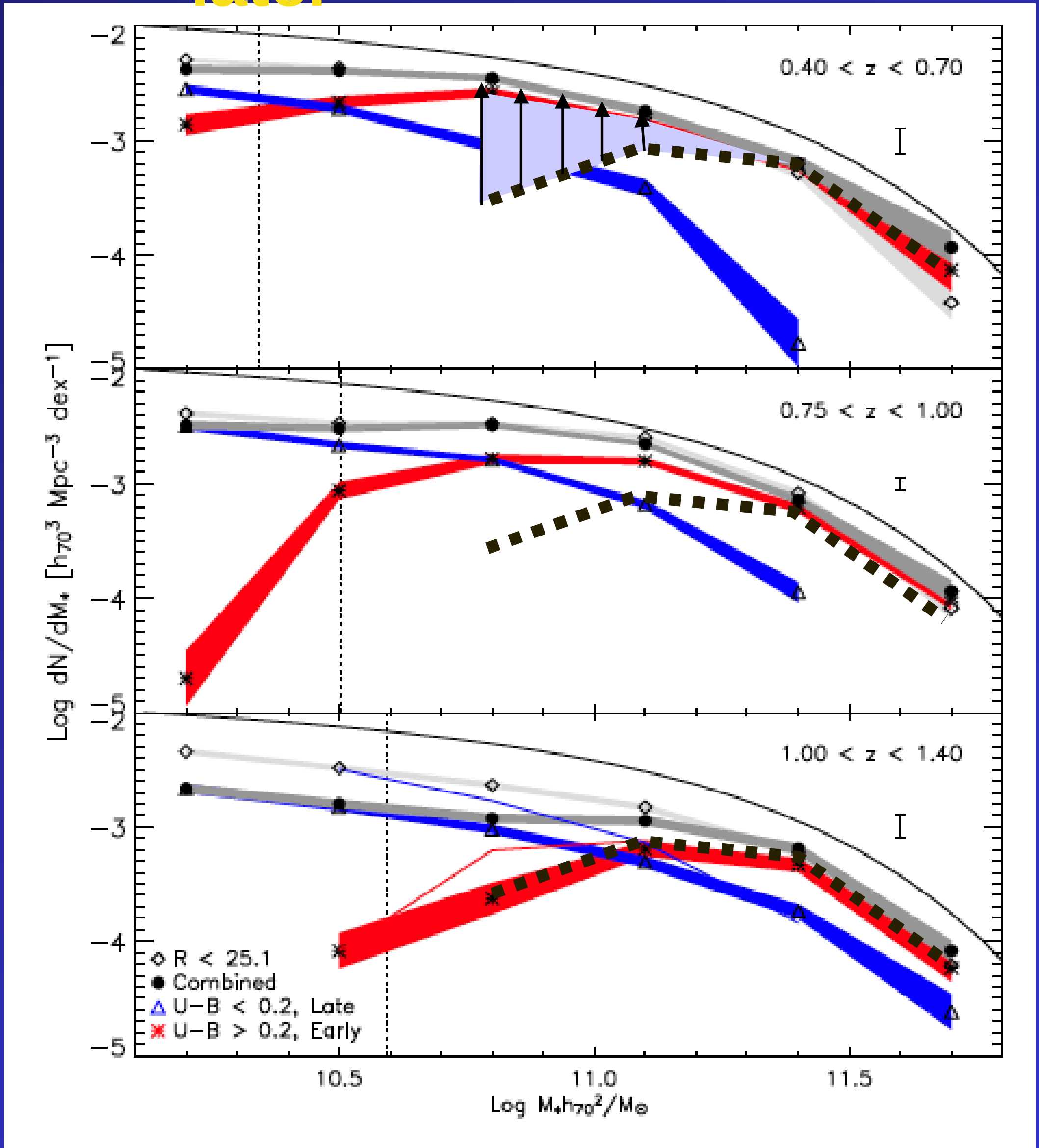


Bundy et al. 2006: most massive RS galaxies were already in place by z = 1; smaller ones appeared later

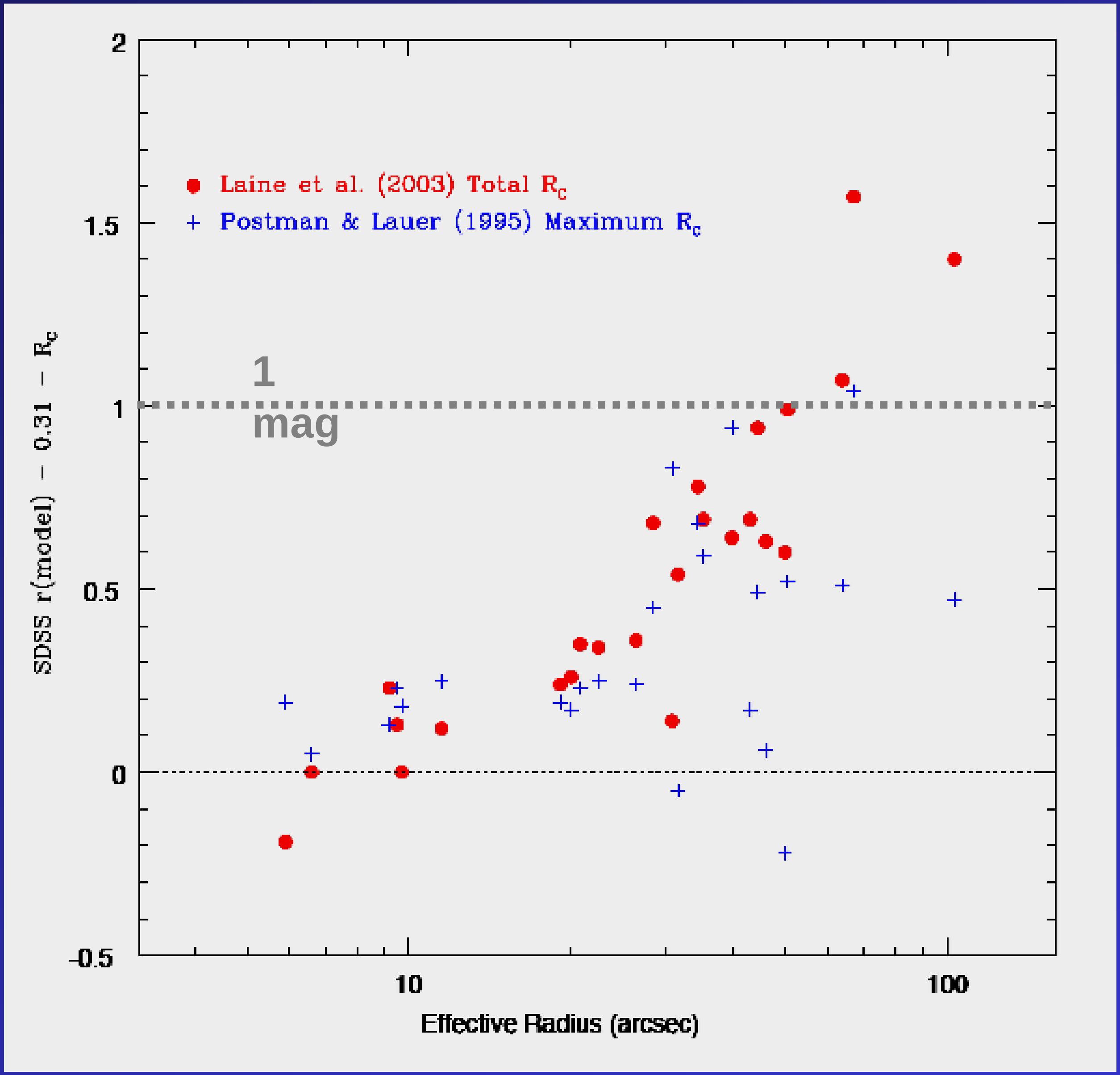
Stellar masses are determined from SED fitting.

The most massive RS galaxies were already in place by z = 1. Smaller ones appeared later.

Smaller red galaxies ***appear after*** z = 1.

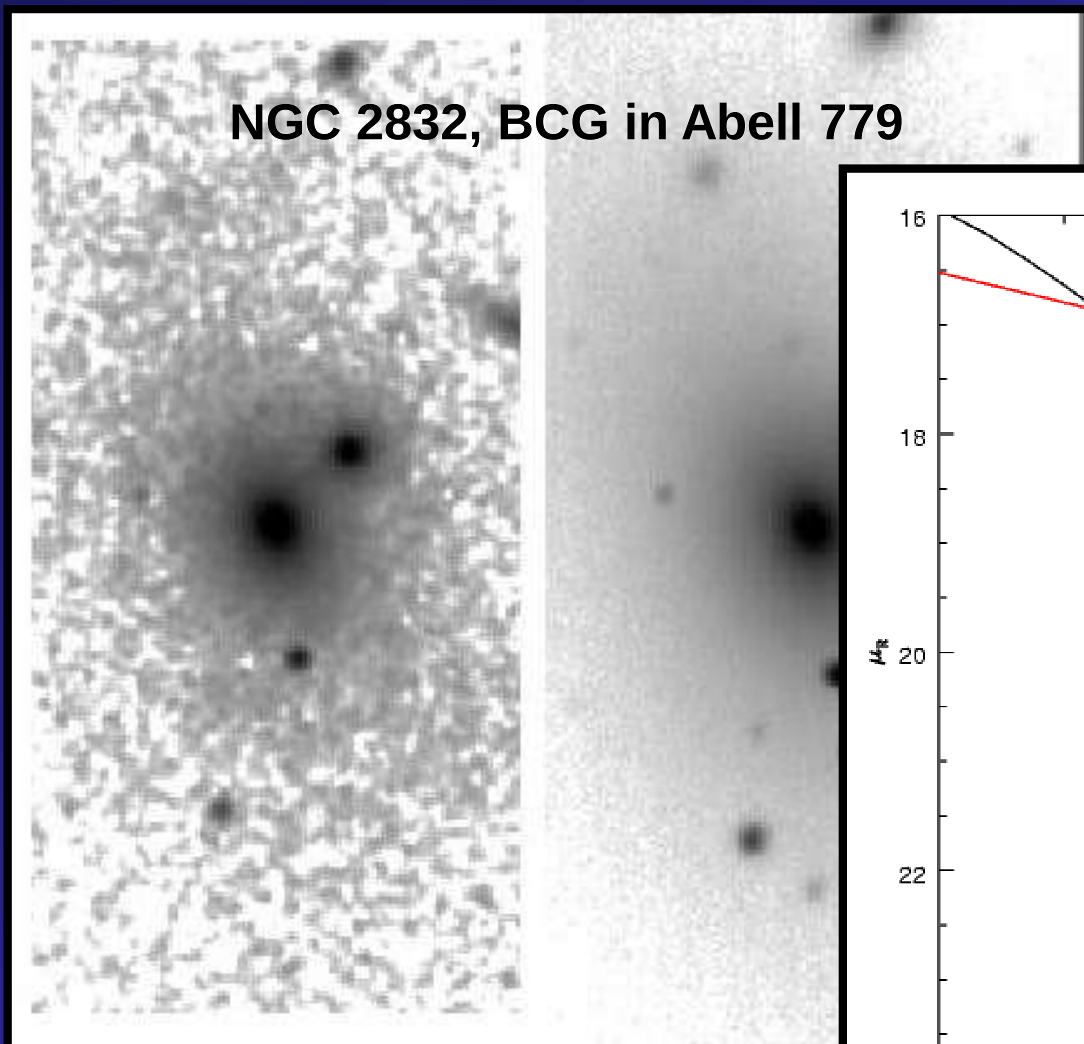


Magnitude errors for nearby bright SDSS BCGs



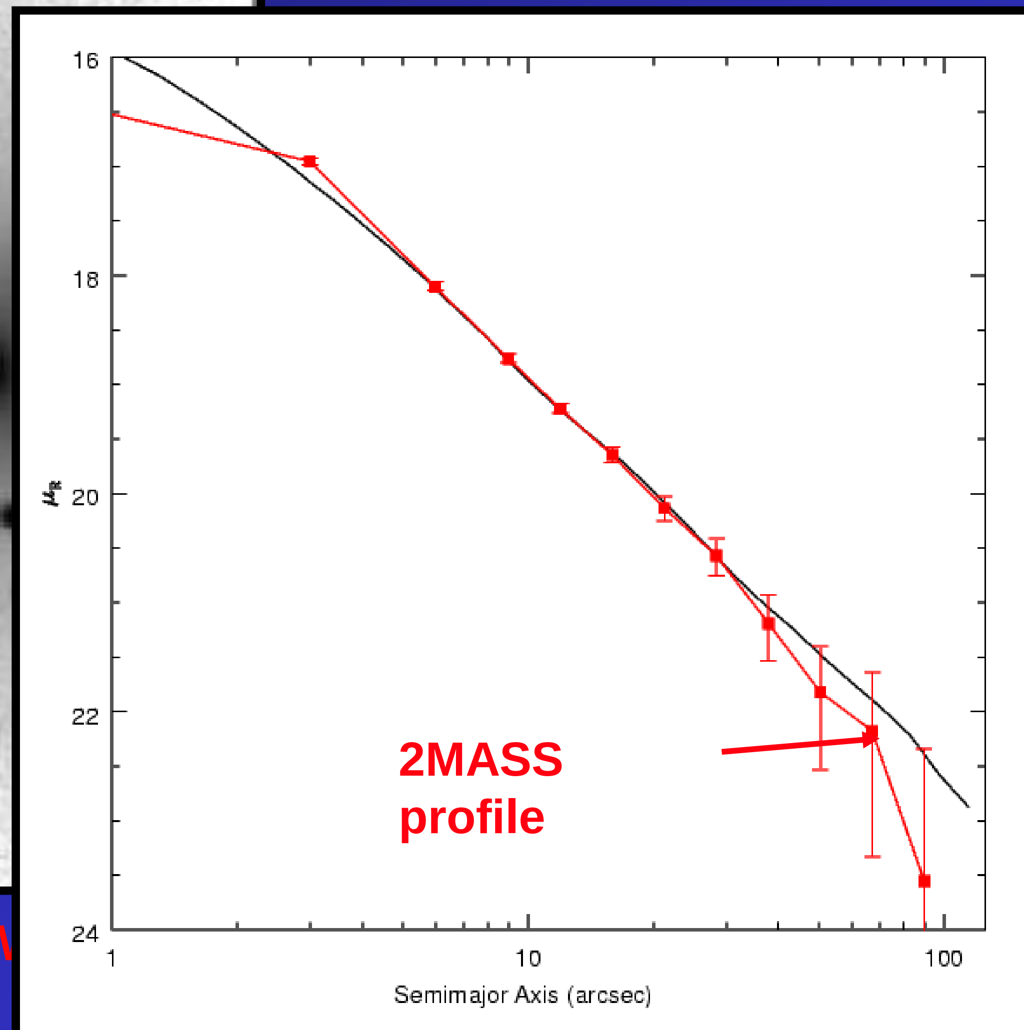
Lauer et al. 2006

2MASS does not solve the problem



2MASS R-band W

Lauer, private communication



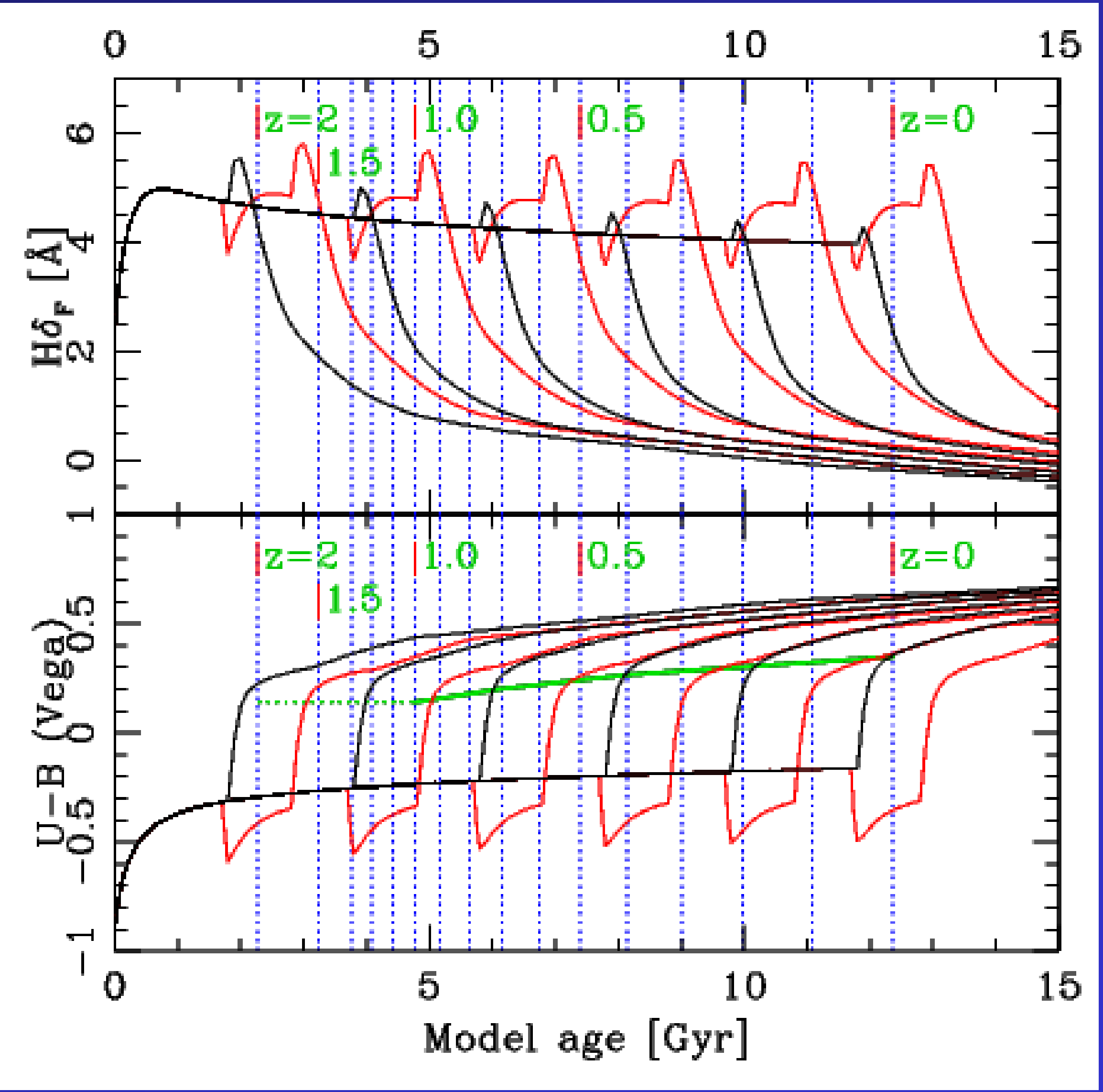
Quenching scenario: galaxies assumed to arrive on red sequence at *uniform rate* starting at time z_{quench}

Black are pure quenching.

Red are preceded by starburst.

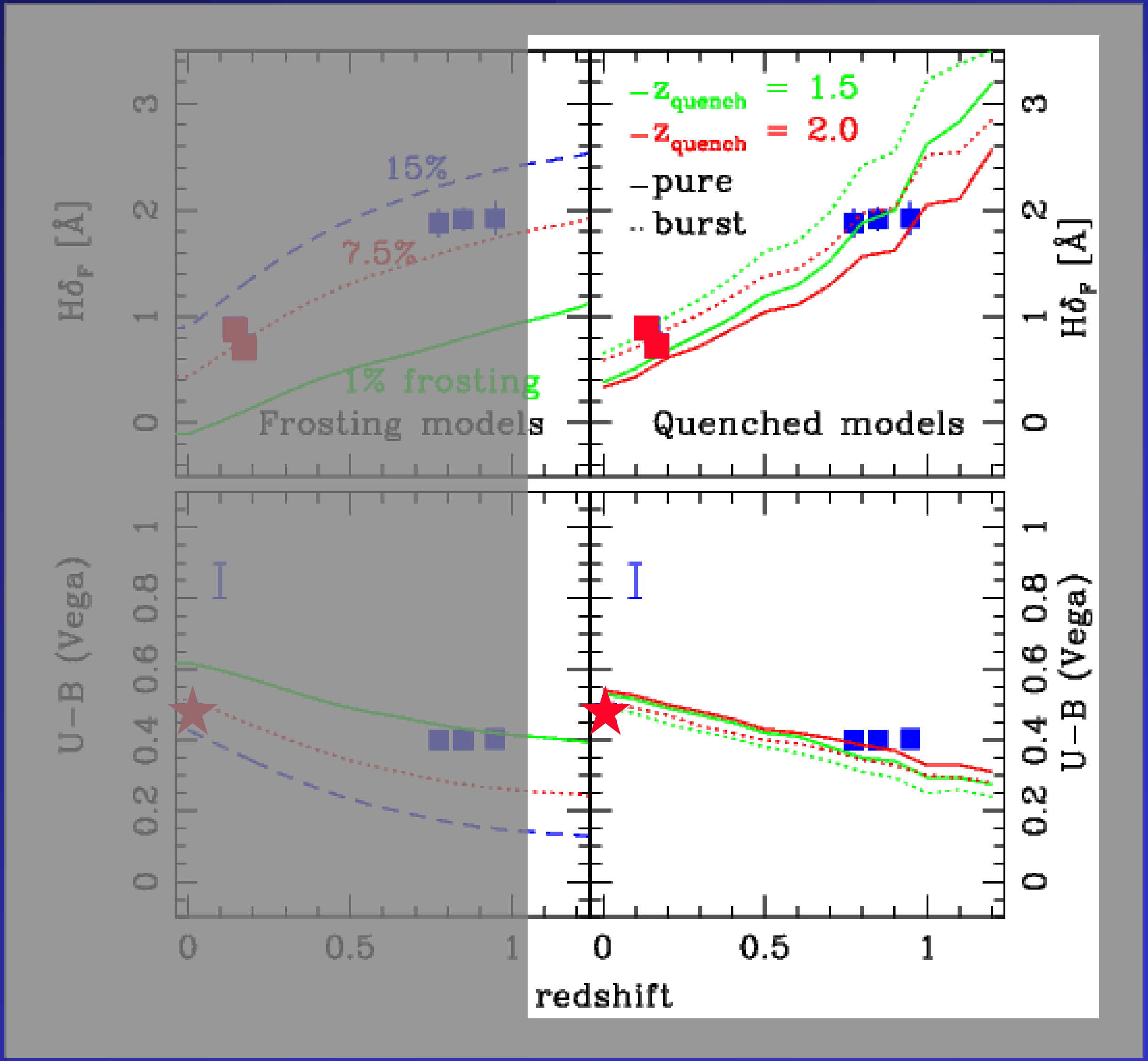
Either one fits.

z_{quench} --> 1.5-2.



Harker et al. 2006

Quenched models fit both color and Balmer lines



Harker et al. 2006

Sample Selection

SDSS DR4 Galaxy Spectra

$0.06 < z < 0.08$

$r < 17.77$

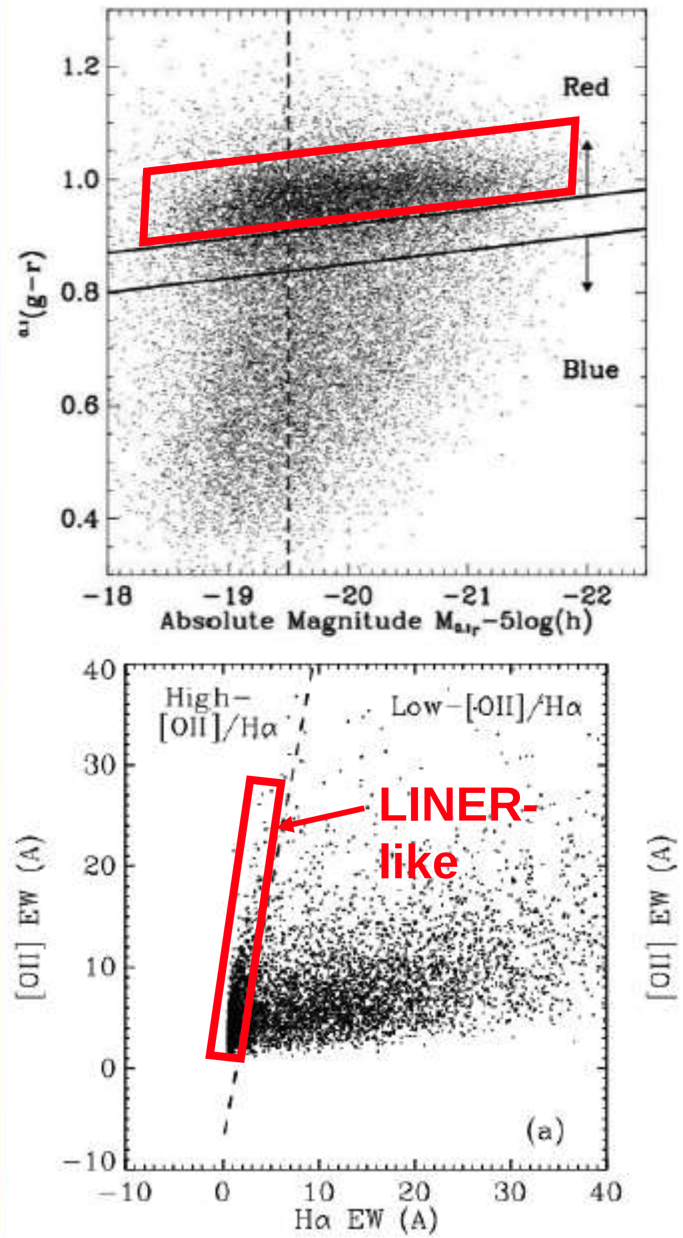
- color cut
- [OII]λ3727 vs. Hα

} LINER-like

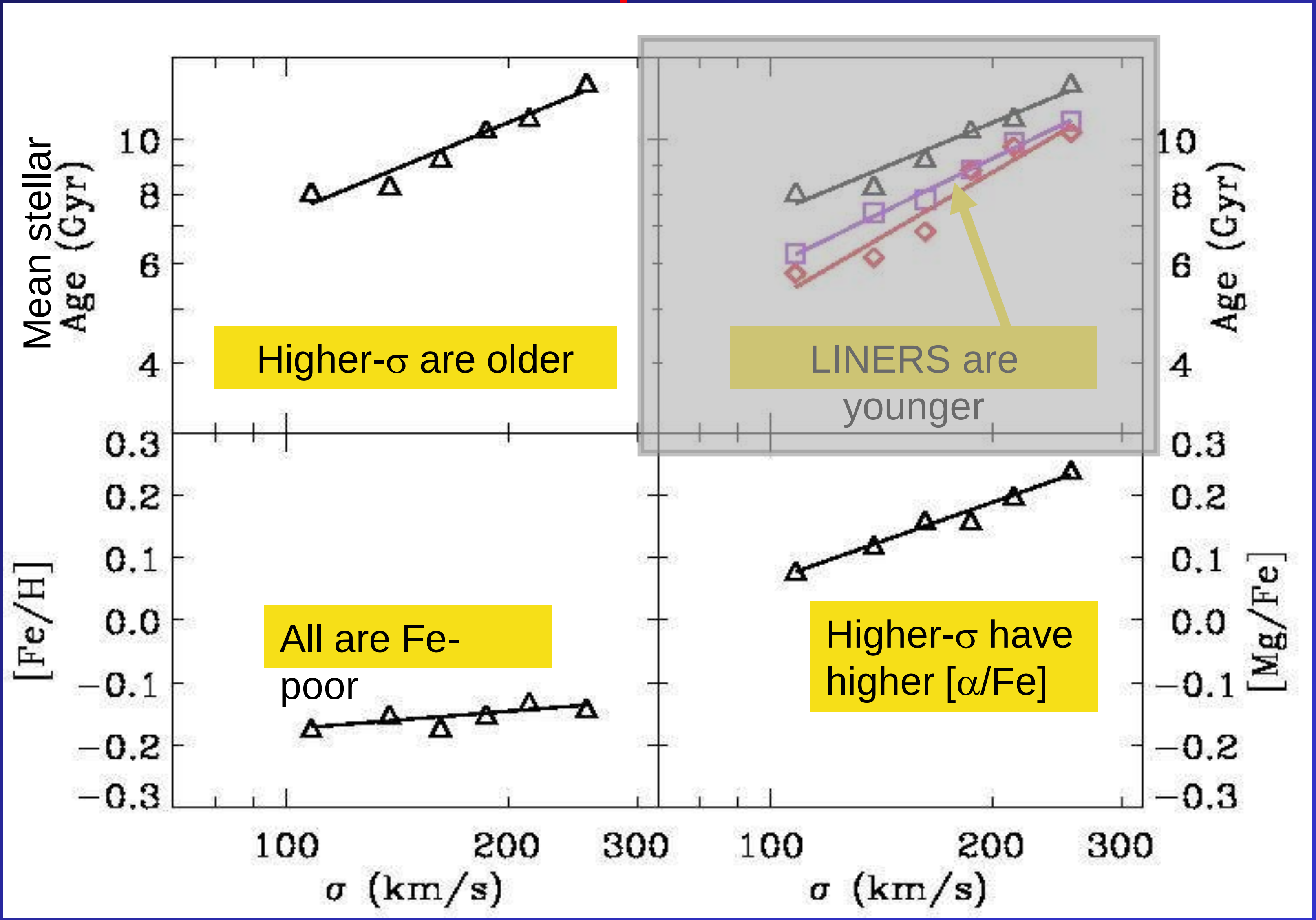
- σ from NYU VAC

Bin & stack spectra for high S/N, do stellar population analysis

→ stack by LINER strength and σ
all galaxies smoothed to 300 km/s

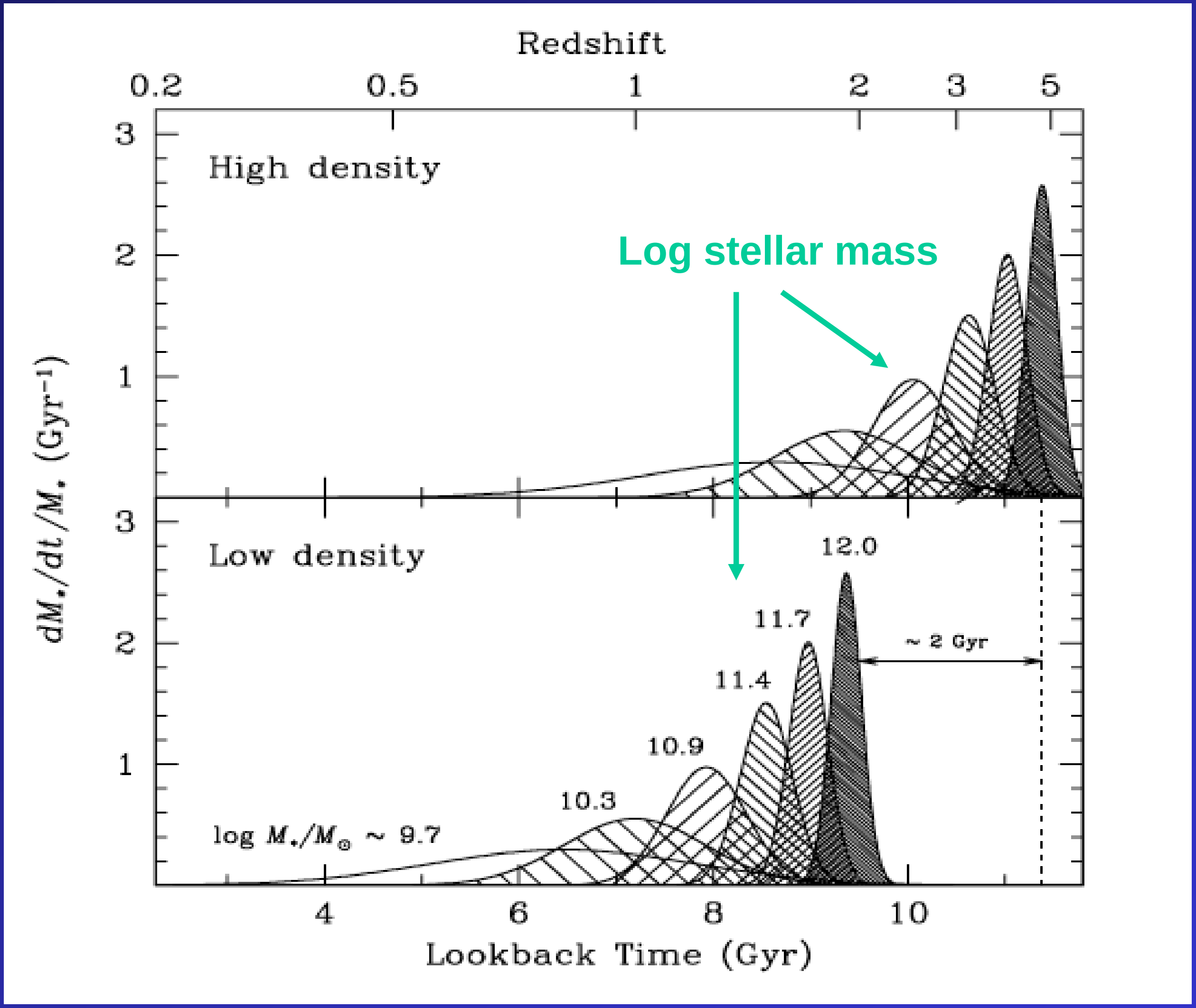


Light-weighted stellar population parameters: SDSS red sequence



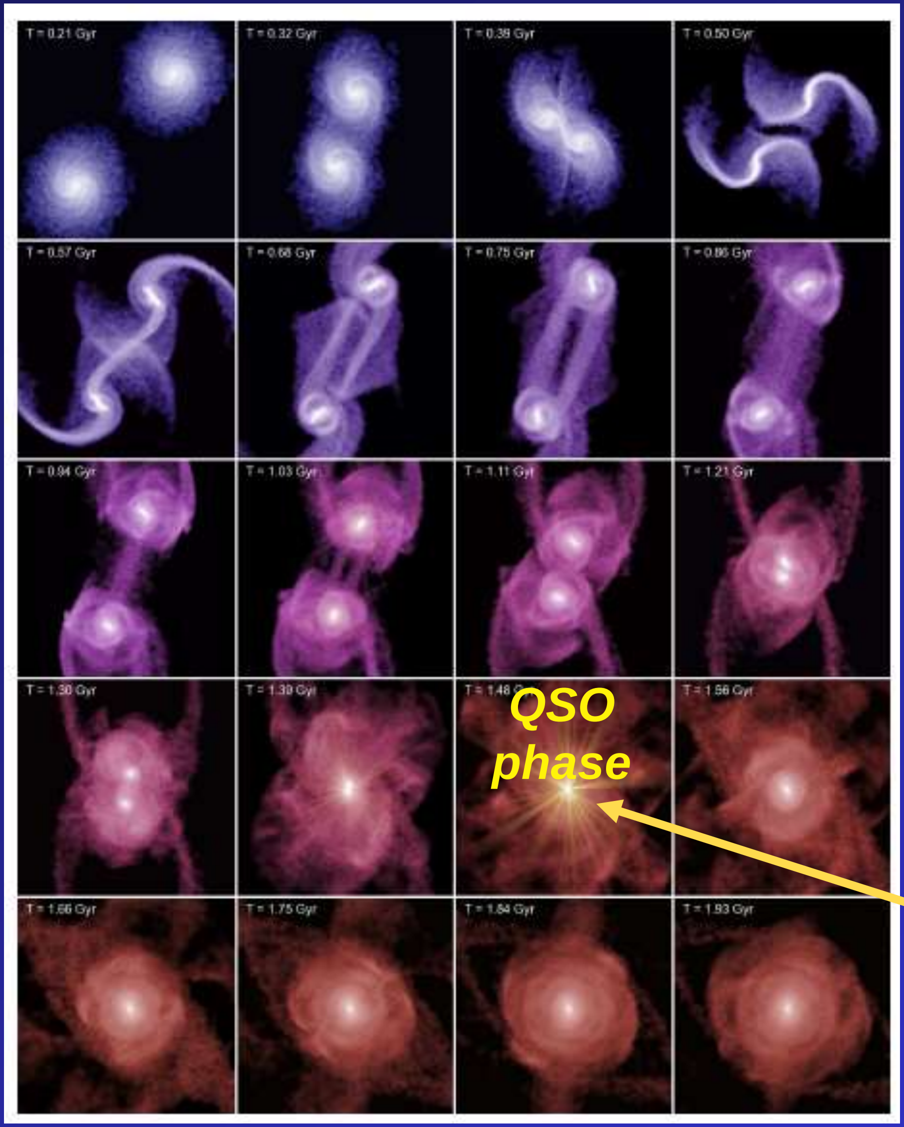
Graves et al. 2006, also Thomas et al. 2005 and Nelan et al. 2005

Mean SFR histories of E/S0s from age and [Mg/Fe]



Local sample: Thomas et al. 2005

Feedback from BHs born in mergers *(QSO mode)*



Hopkins, Hernquist et al. 2005:

Sources of "feedback" during a merger:

- Gas is funneled into the central regions, fueling a starburst and creating a wind (Mihos & Hernquist 1994).

- Orbital kinetic energy is converted to heat in cloud-cloud collisions, which drives a wind (Cox et al. 2005).

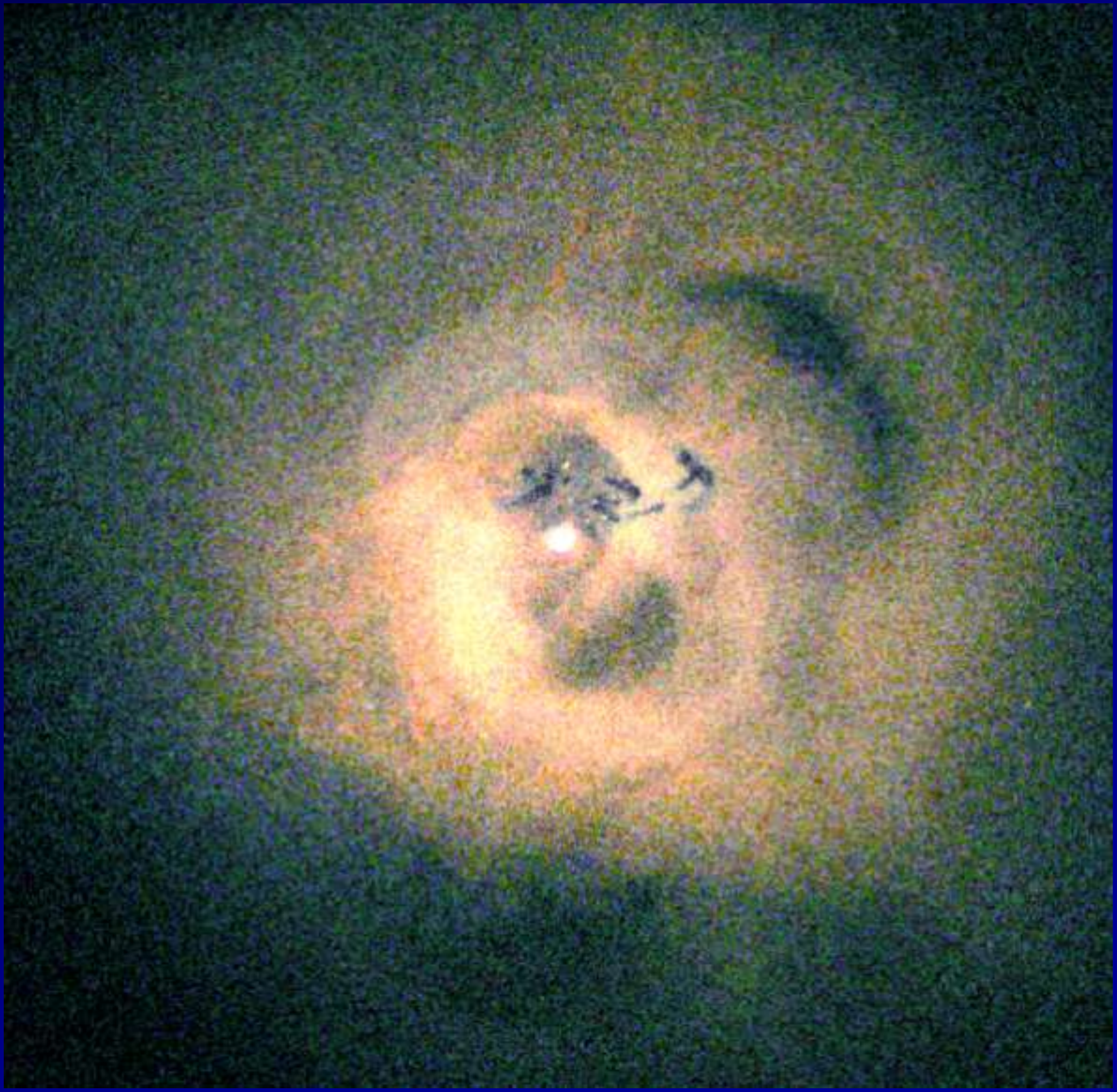
- Gas driven to the center fuels a black hole, creating a ***quasar (QSO)*** whose feedback quenches further infall and star formation (Hopkins et al. 2005).

Disturbed hot gas around Perseus A *(radio mode)*

Perseus A is a massive spheroidal galaxy with an optical AGN and radio jets. It is located at the center of the Perseus cluster of galaxies.

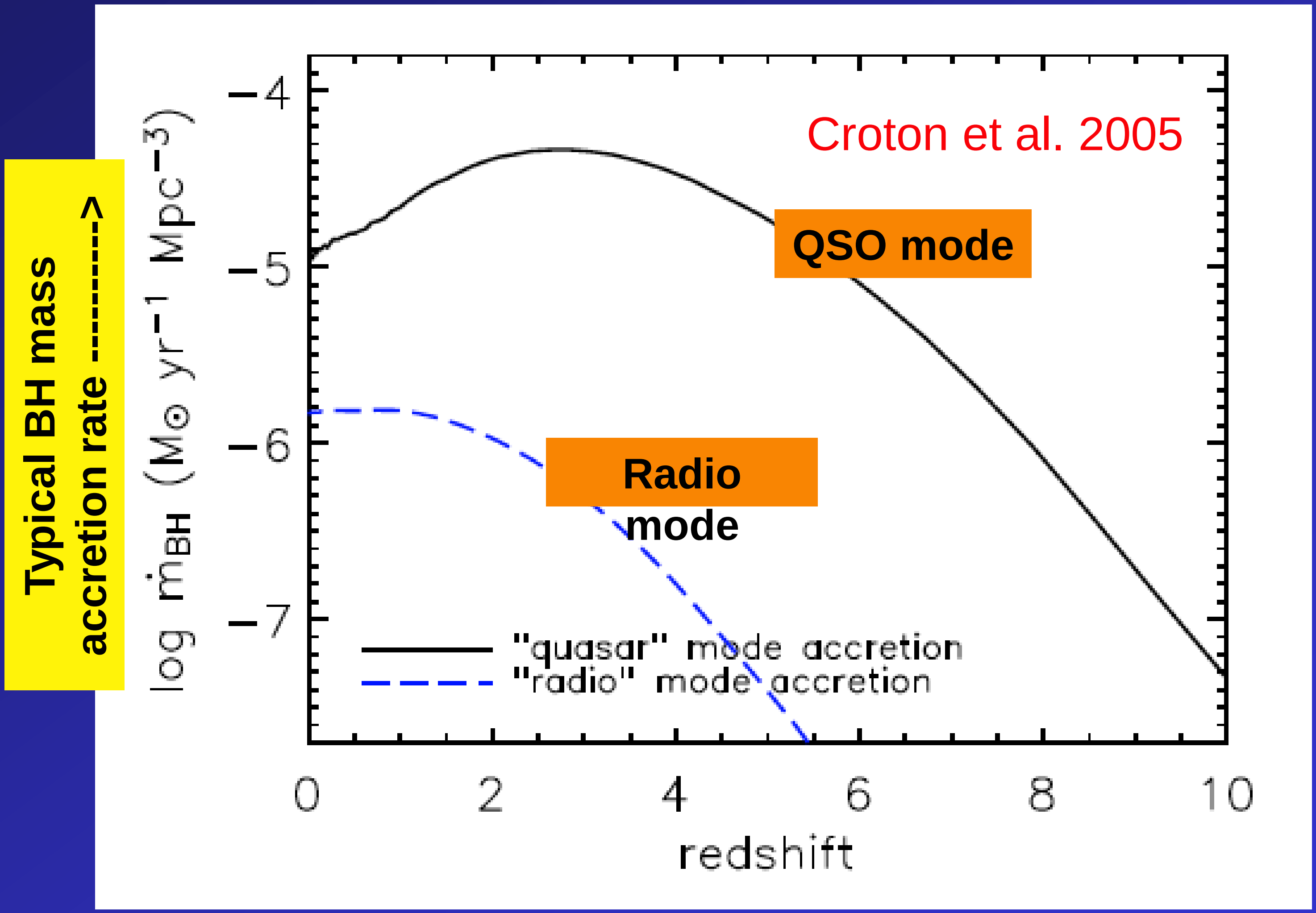
The inner cluster gas has been disturbed by energy ejected by the central radio source

Fabian et al. 2003

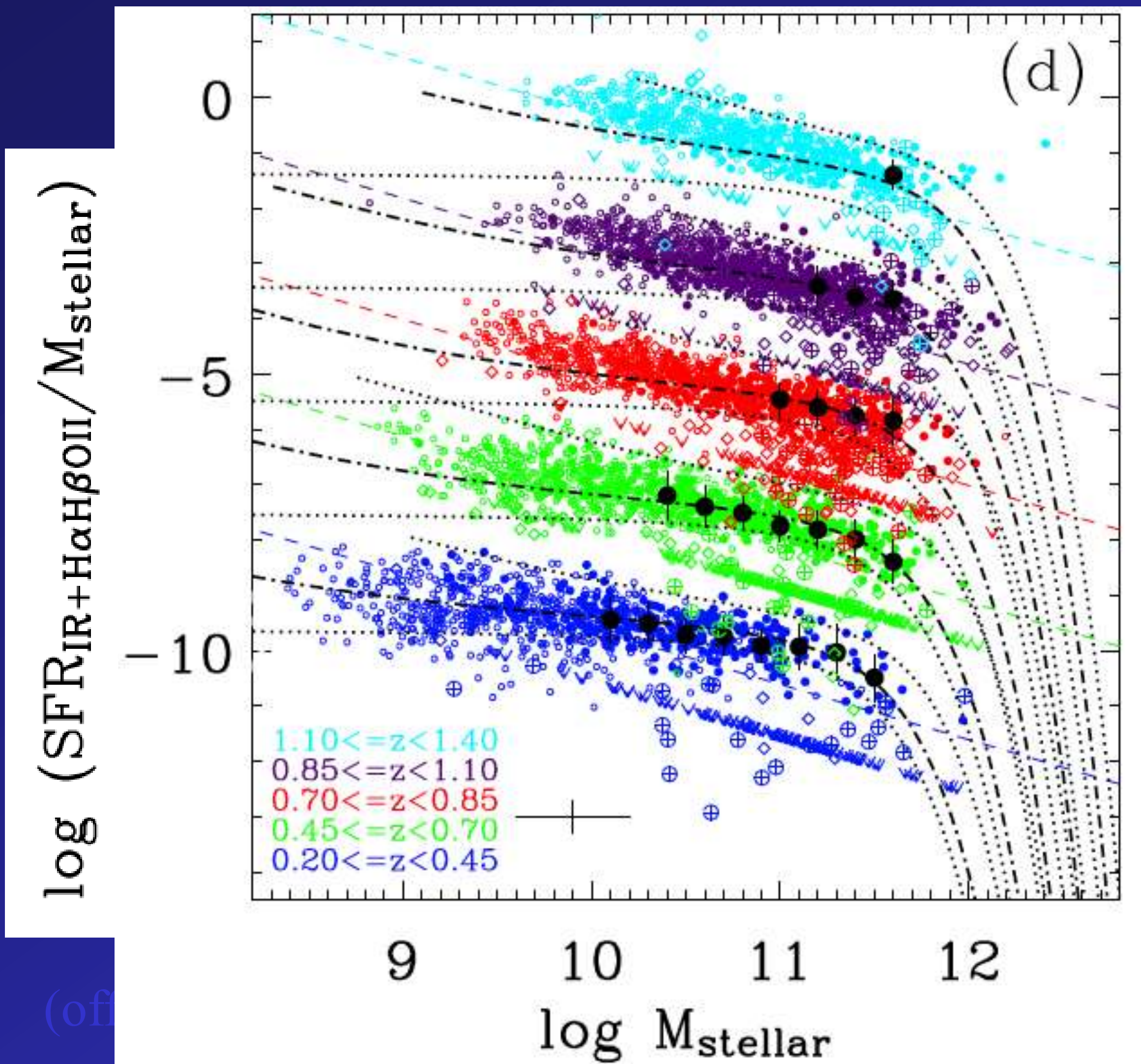


Radio-mode feedback is a *later* phenomenon

Sets in only after hot massive static halos have formed. Most BH mass is accreted earlier, in merger-driven QSO mode.



A smoothly declining *exponential model* fits the star-forming histories of most galaxies



Noeske et al. 2006

The model has

SFR ~ $e^{-t/\tau(M)}$

starting at ***z_f*,** where

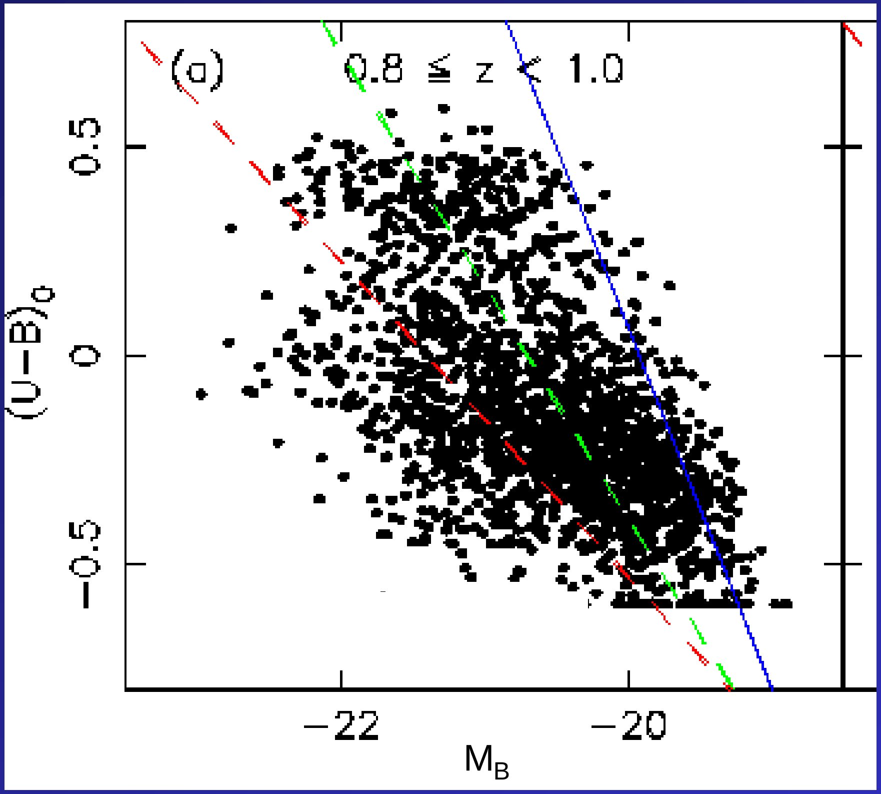
$z_f = 4.5 \times (M_*/10^{12})^{0.33} - 1$

and

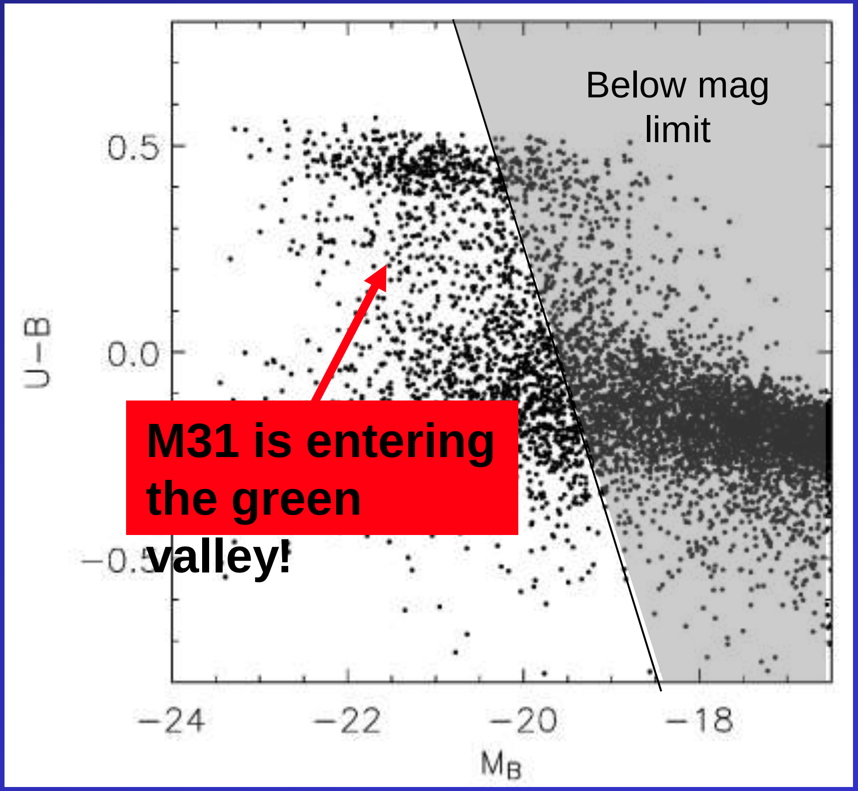
$\tau(M) = 1\ \mathrm{Gyr} \times (M_*/10^{11})^{-1}$.

In the model, ***larger galaxies start forming stars sooner and decline more rapidly (downsizing, Cowie et al. 1996).*** The stellar populations in larger galaxies are older. Most star formation seems to be in "quiescent" mode; the contribution by "starbursts" seems to be relatively small.

A downsizing model produces bimodality naturally by *shutting off SFR in massive galaxies* at late times. Downsizes both mean stellar age and quenching epoch.

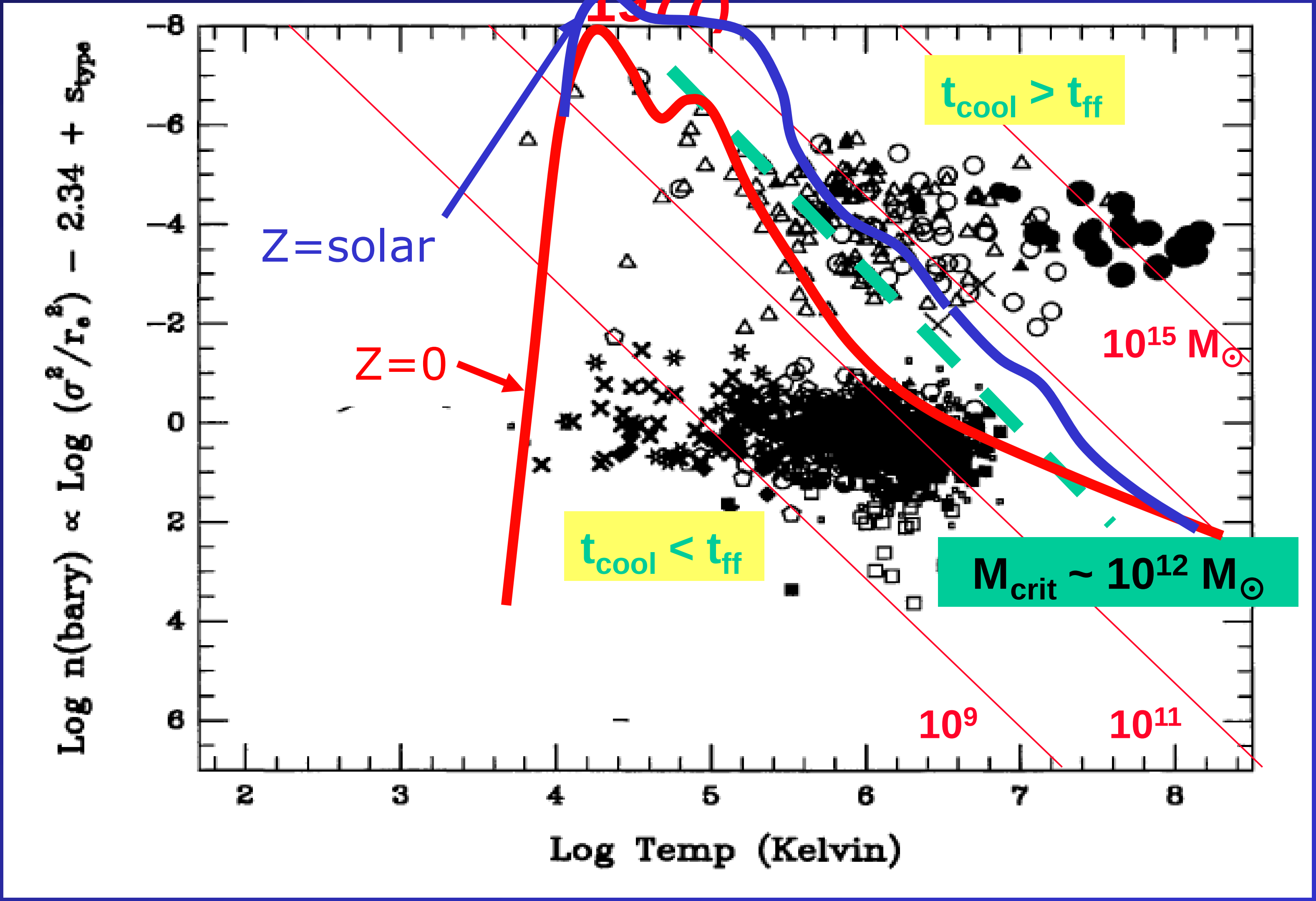


CM diagram of distant galaxies from DEEP2 survey (Willmer et al. 2006)



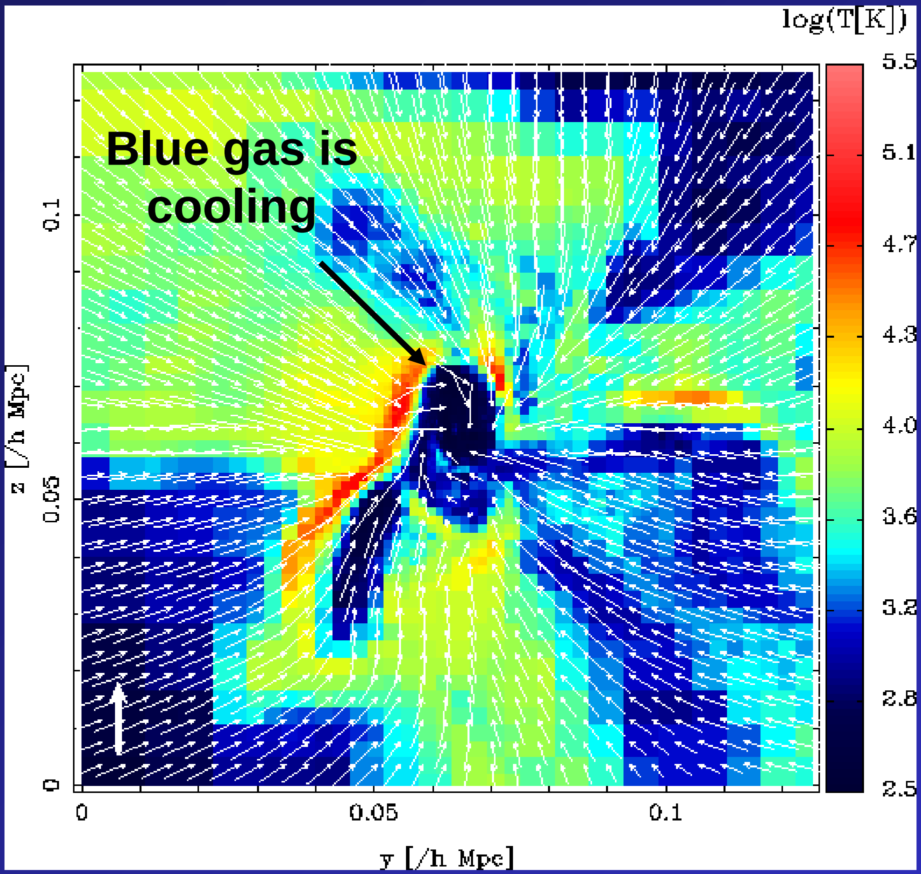
Model CM diagram using downsizing SFR model by Noeske et al. (2006)

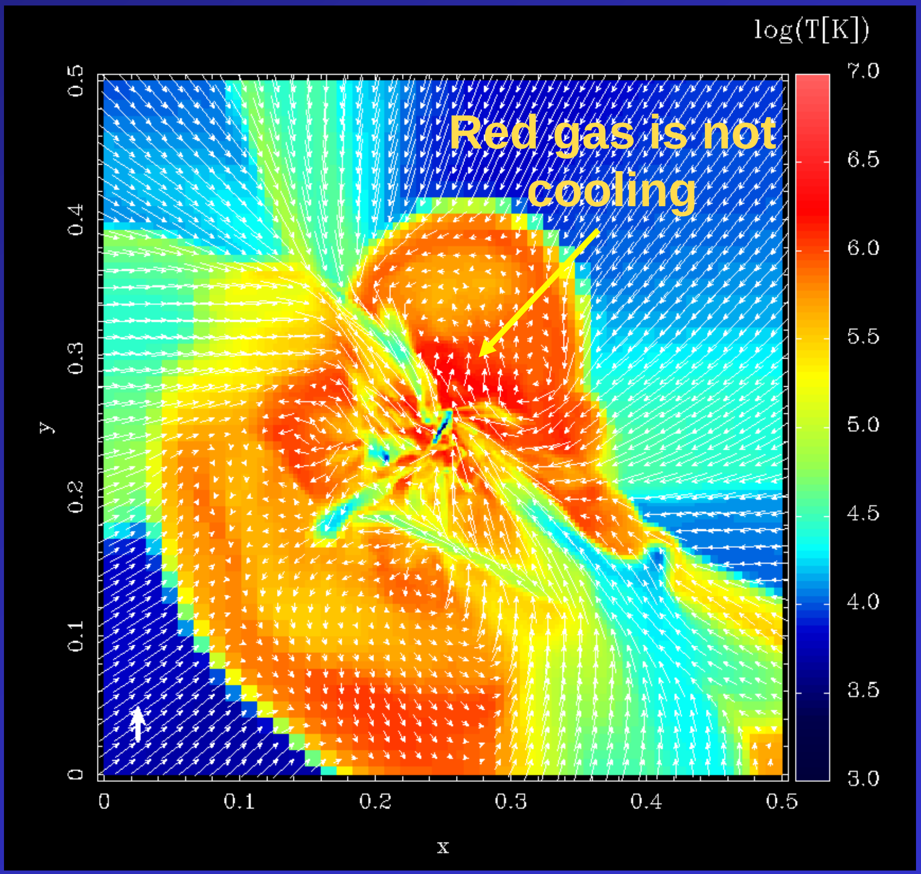
Cooling predicts a dividing line between galaxies and clusters at halo mass *M_{crit} ~ 10^{12} $M_{\odot}$* (Rees & Ostriker 1977)



Data: Burstein, Bender, Faber, and Nolthenius 1996 Cooling curves: Blumenthal et al. 1984

Full hydro simulations with gas + DM show *cooling boundary* *at halo mass $M_{crit} \sim 10^{12} M_\odot$*





Small halo, mass = $10^{11} M_\odot$

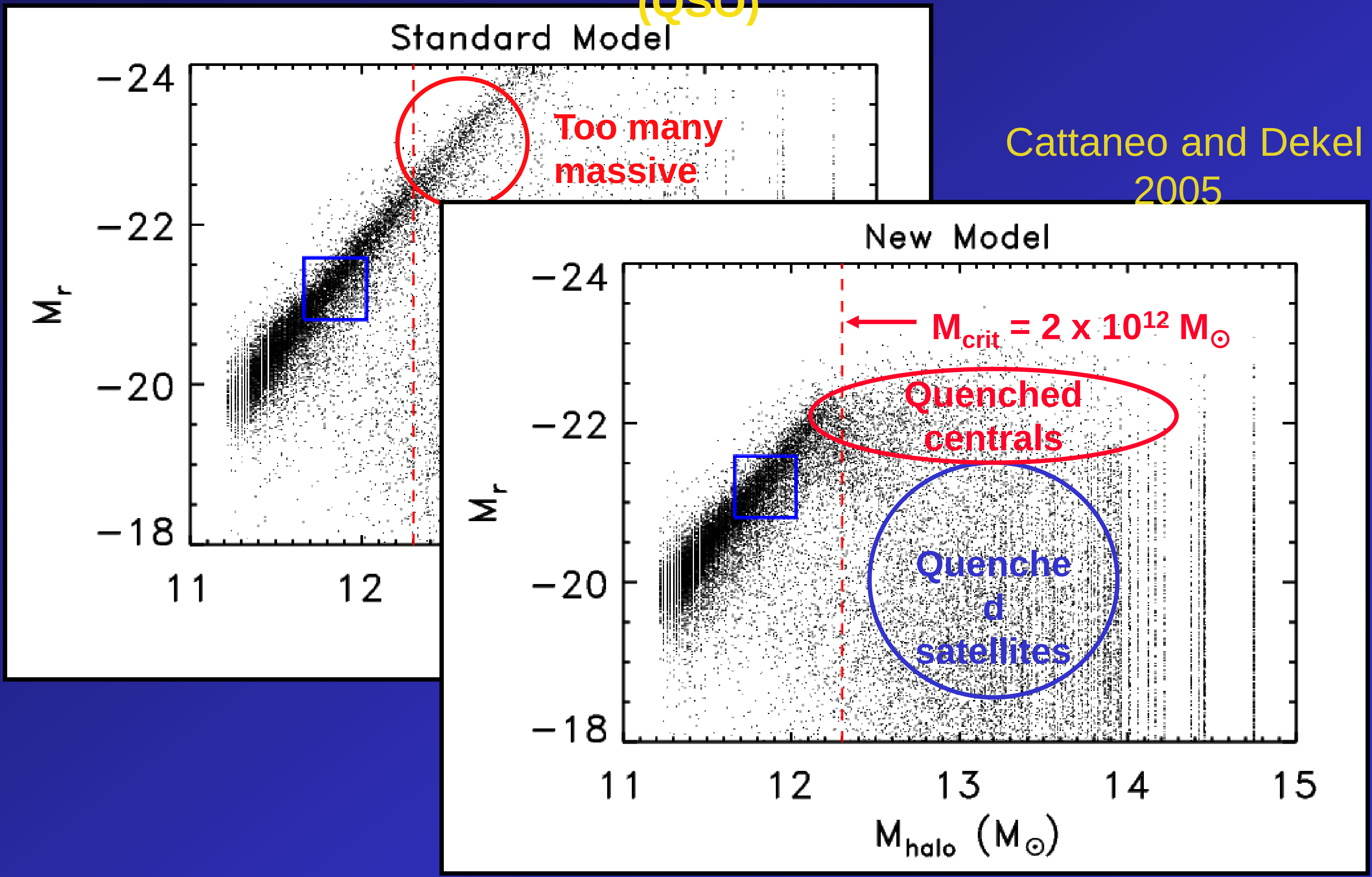
Large halo, mass = $10^{13} M_\odot$

Dekel & Birnboim 2005

Hydrodynamic simulations by Andrei Kravtsov

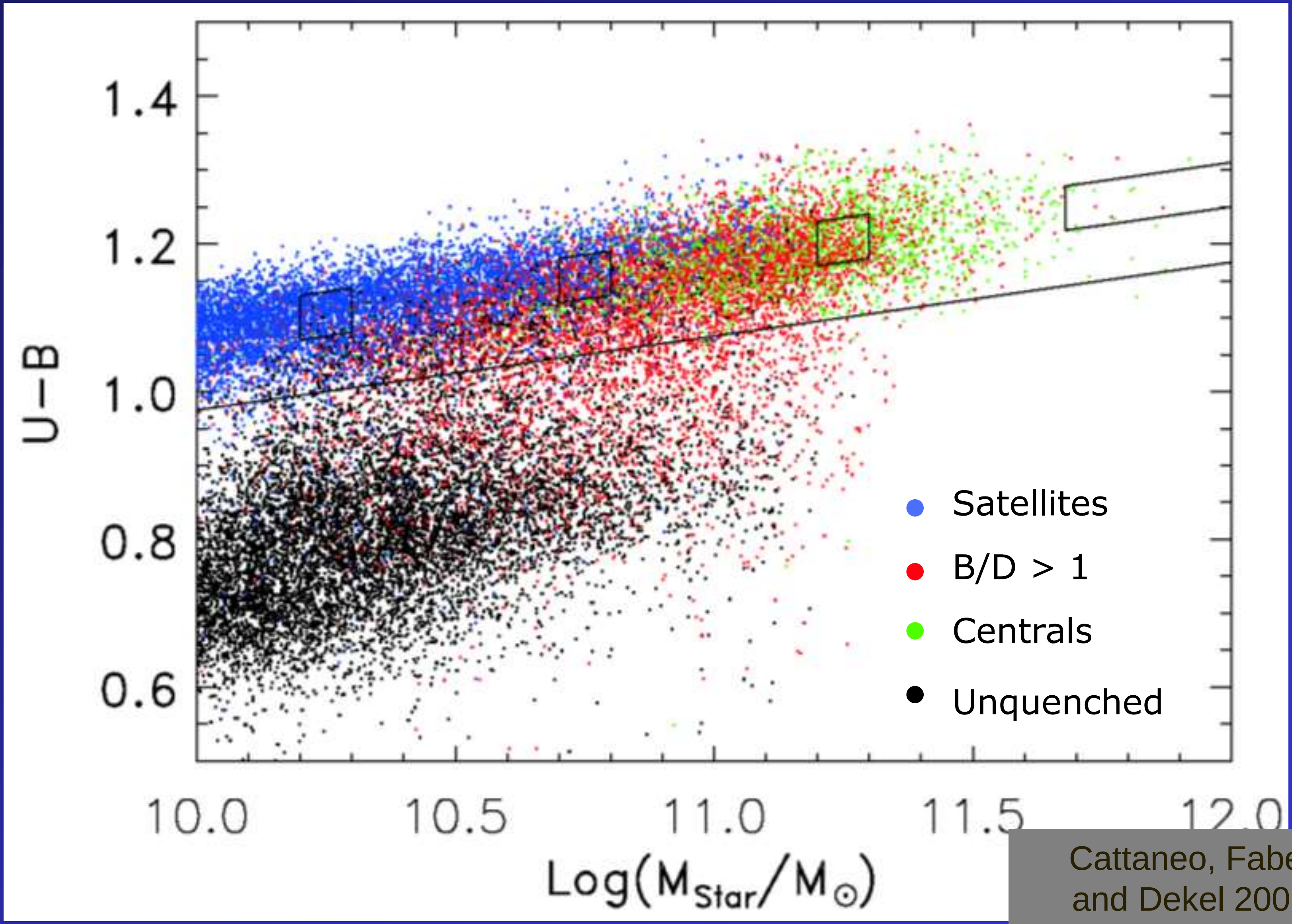
A semi-analytic model with halo and B/D quenching

BH feedback is supportive: $M_{halo} > 2 \times 10^{12} M_\odot$ (radio) and B/D > 1 (QSO)



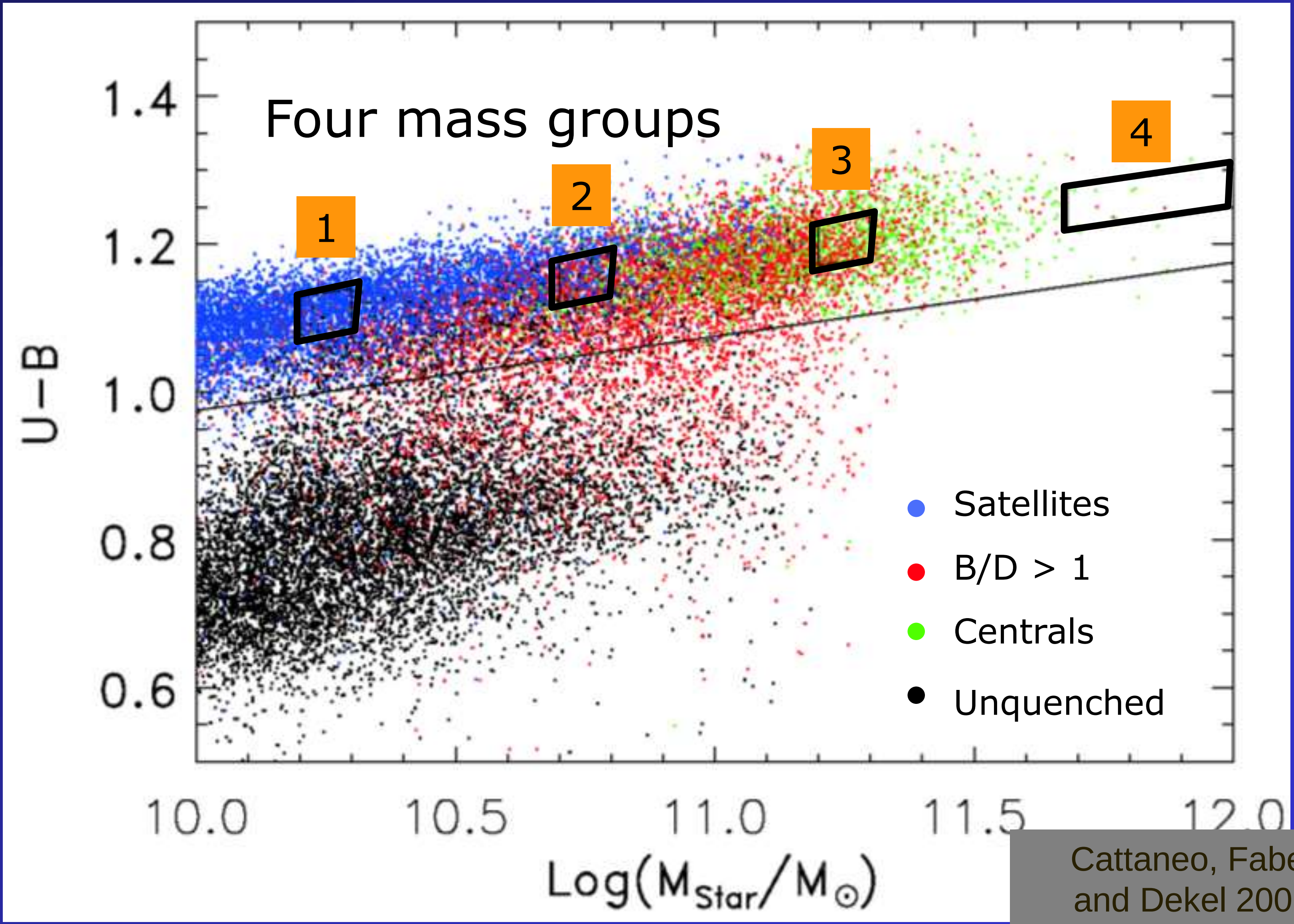
Cattaneo and Dekel 2005

Color-mass diagram at *z* = 0 is bimodal



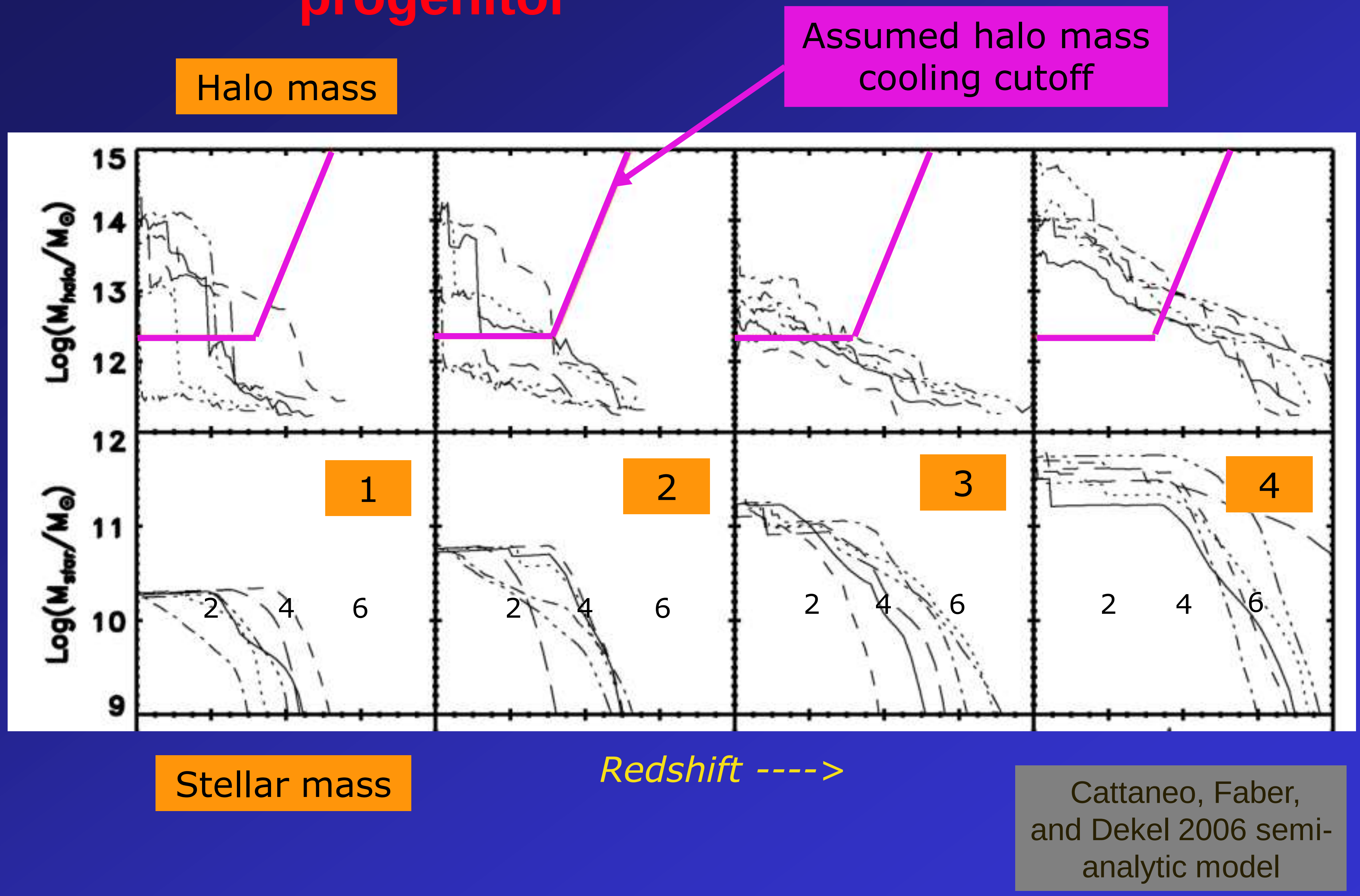
Cattaneo, Faber, and Dekel 2006
Semi-analytic model

Color-mass diagram at *z* = 0 is bimodal



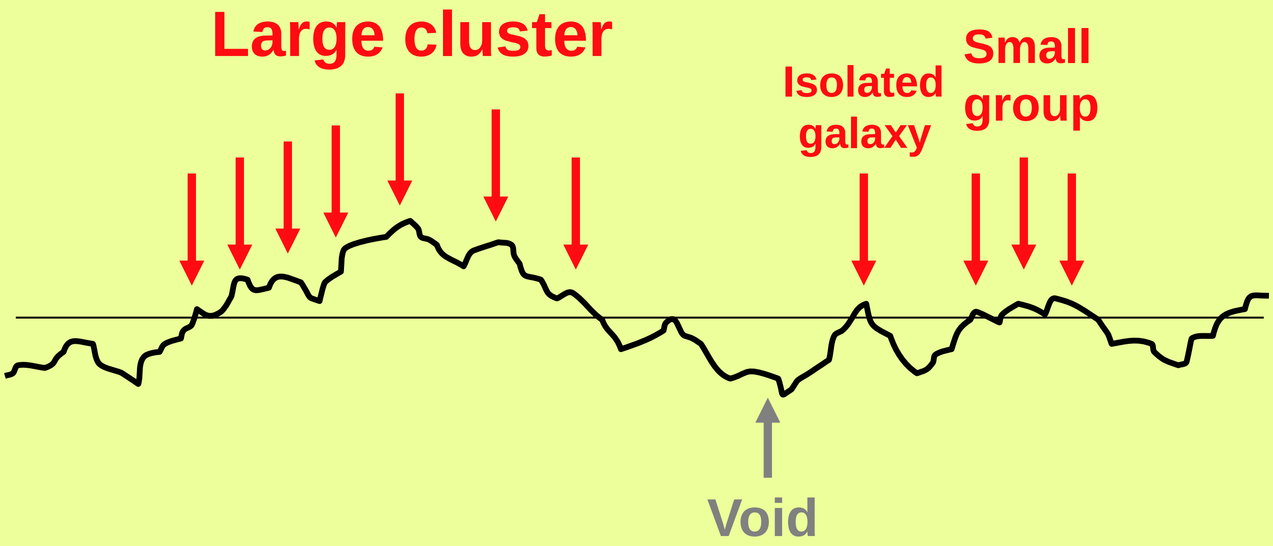
Cattaneo, Faber, and Dekel 2006
Semi-analytic model

History of most massive progenitor



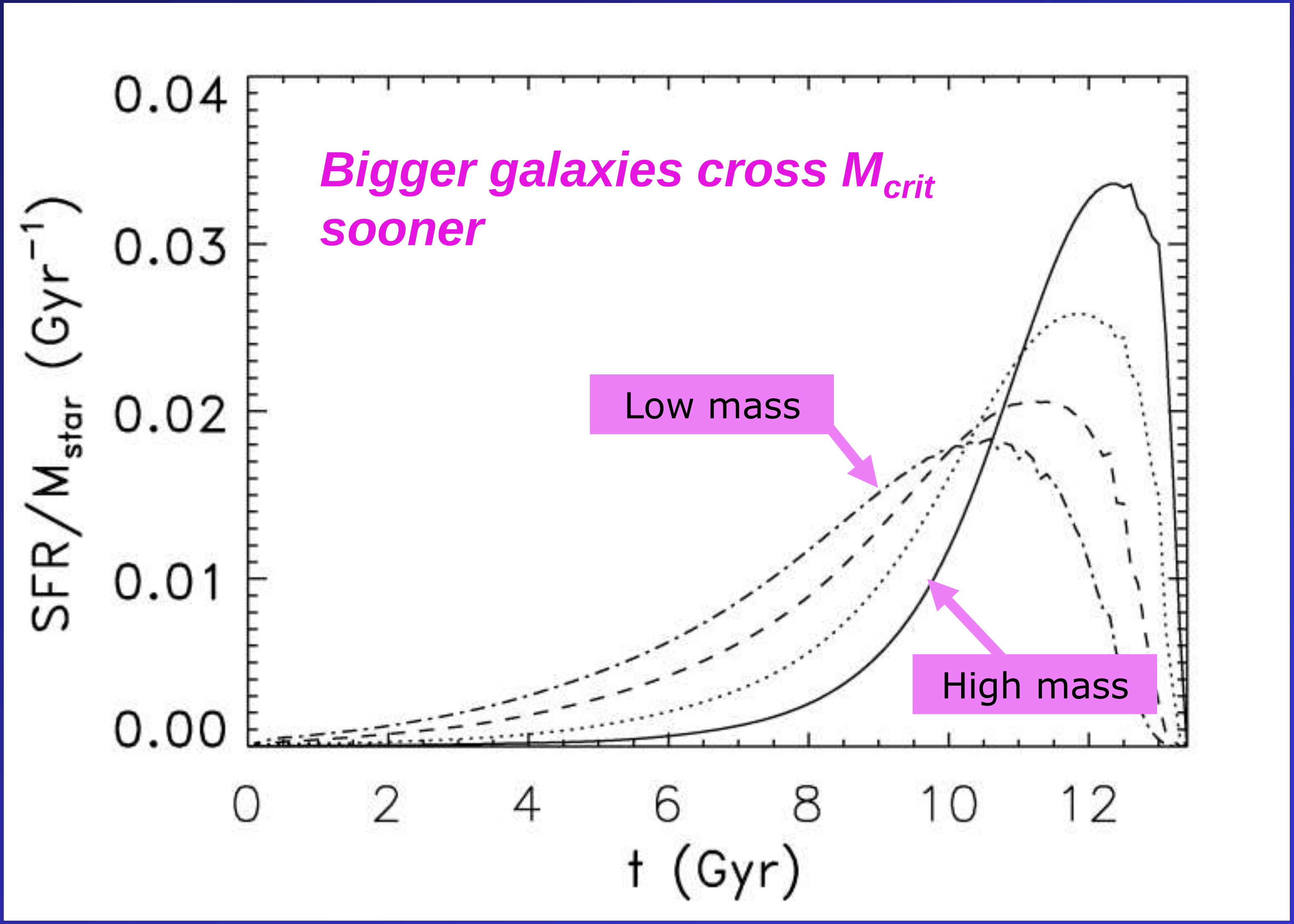
Many properties of galaxies can be read off by inspection from the density fluctuation spectrum of Cold Dark Matter.

$\delta\rho/\rho$ along a line in the early Universe:



The most massive galaxies start to form early from the highest peaks and eventually populate the densest regions

New model: substantial downsizing

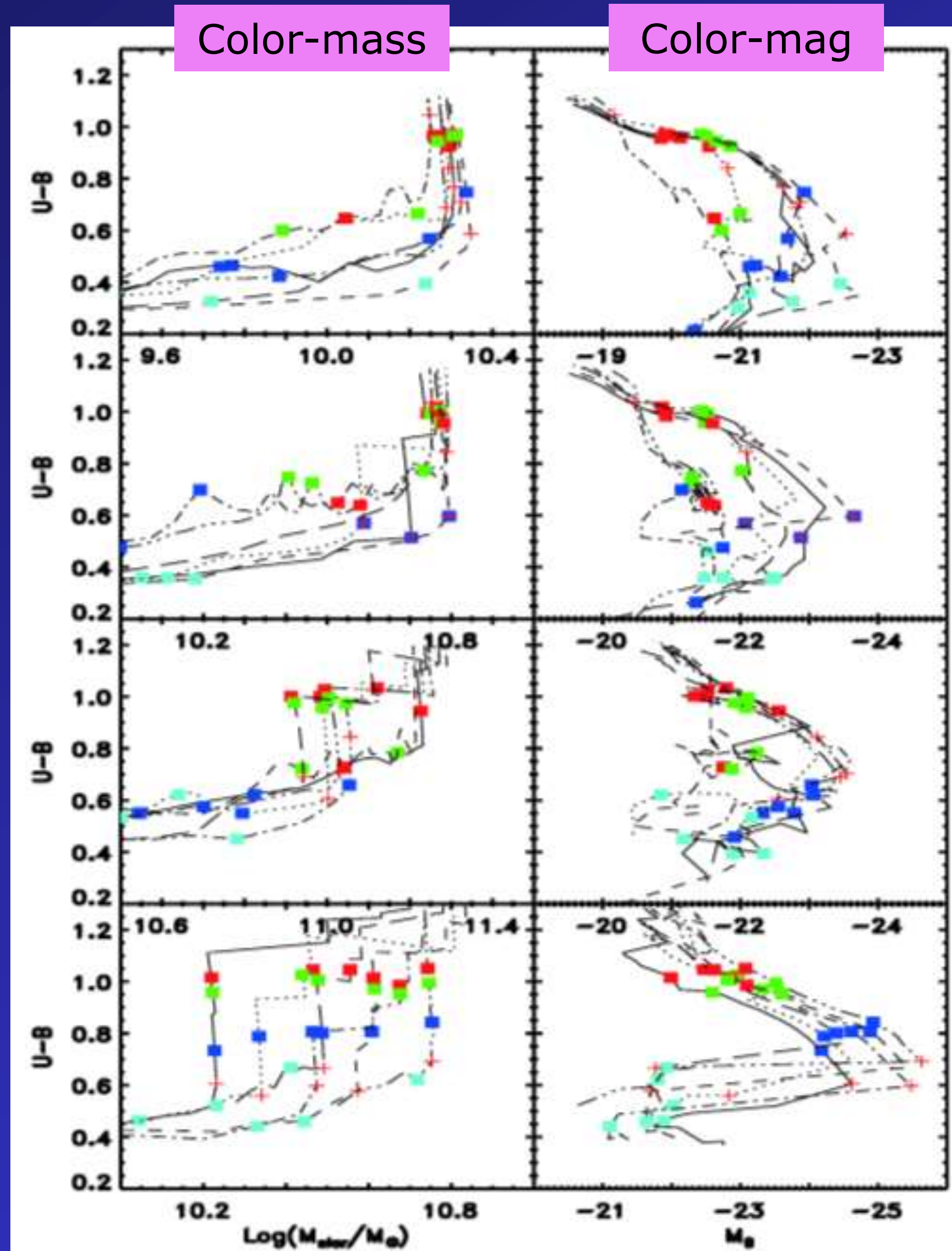


Low mass
1

2

3

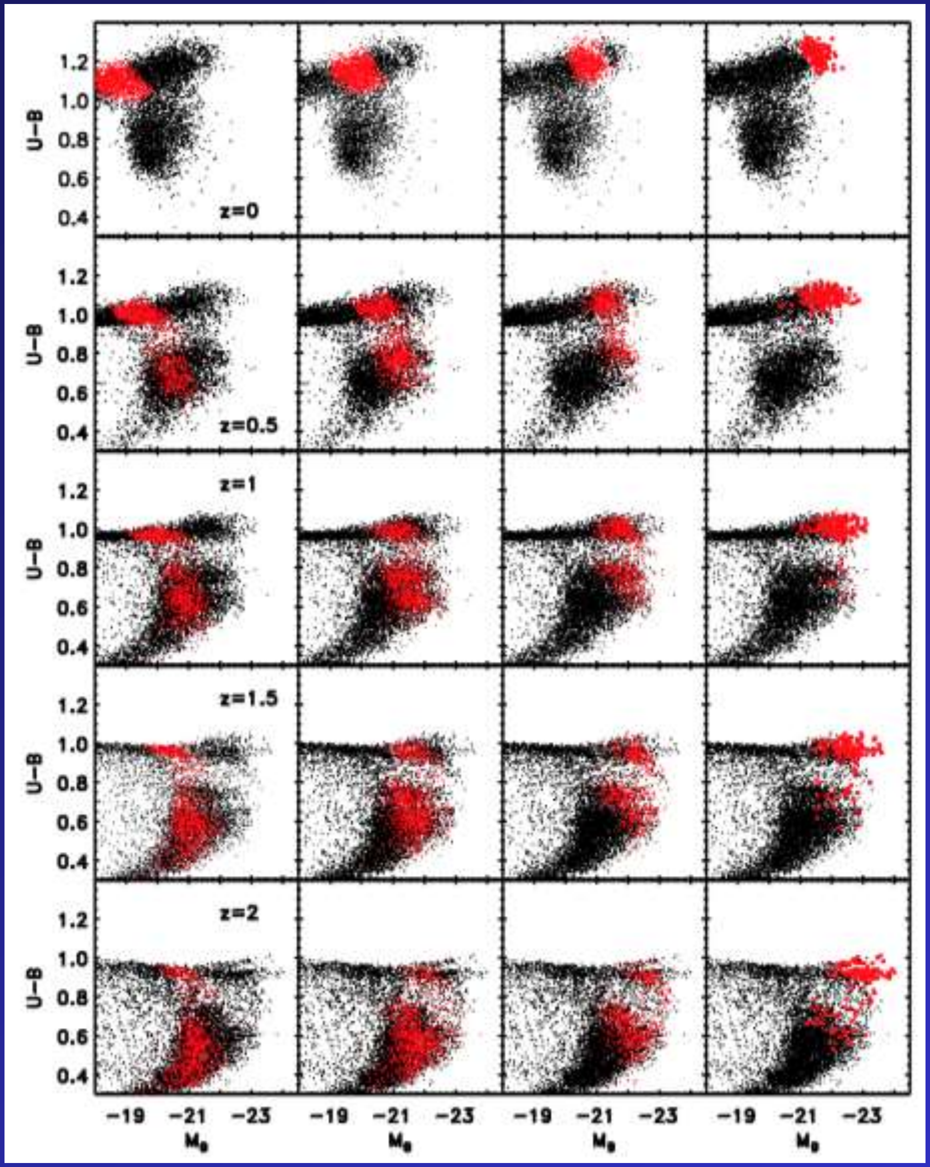
High mass
4

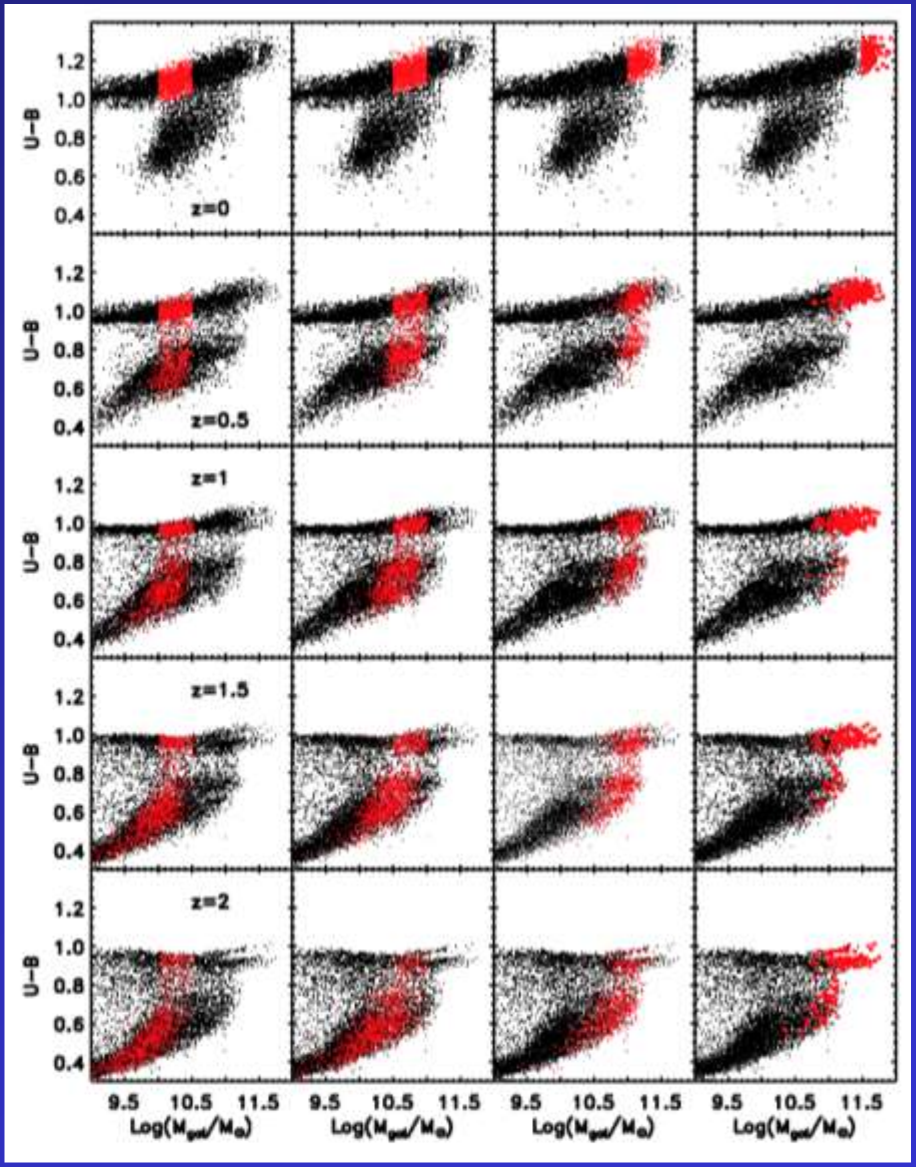


Color-mag and color-mass diagrams back in time

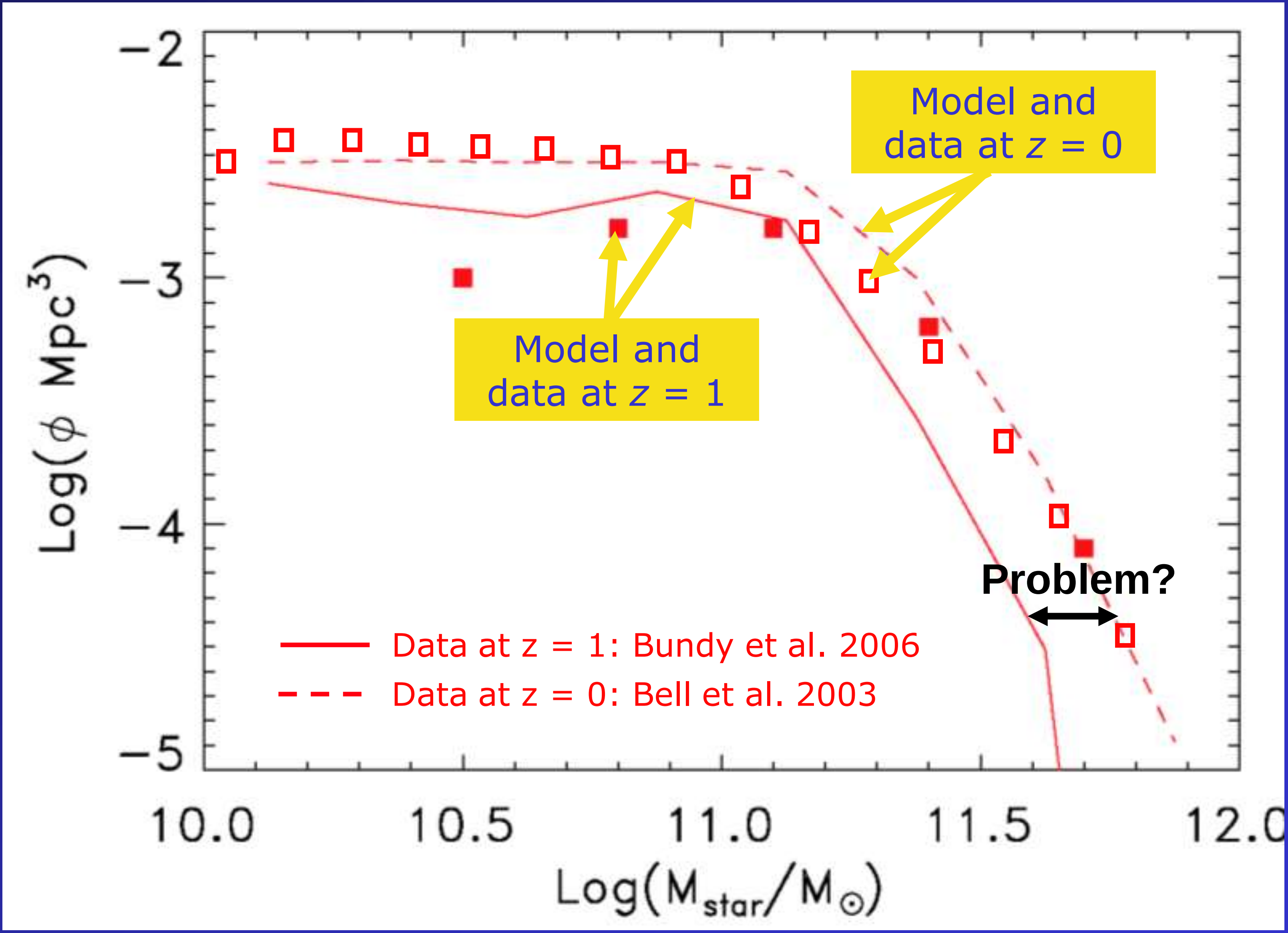
Color-mag

Color-mass





Mass functions: new model, red sequence only



Non-homology in the structural relations of spheroidal galaxies

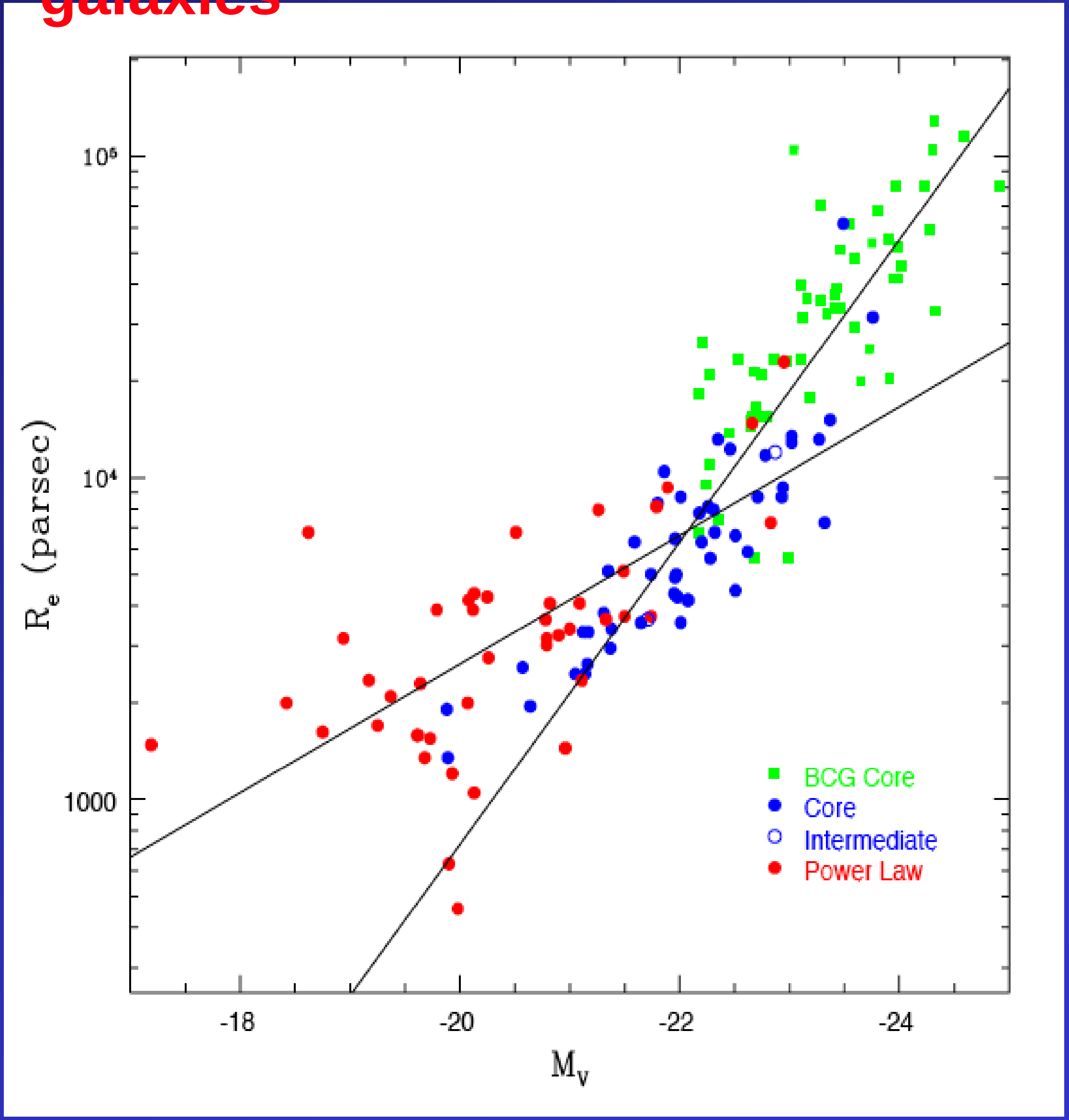
Examples:

R_{eff} vs. mag (Lauer et al. 2006)

Envelope structure, Sersic index (Graham et al. 2003, Ferrarese et al. 2006)

Intracluster light (Monaco et al. 2006)

N-body merger models (Boylan-Kolchin et al. 2006)



Quenching by halo occurs nearly simultaneously with B/D

Mass when crossing B/D vs. mass when crossing M_{crit}