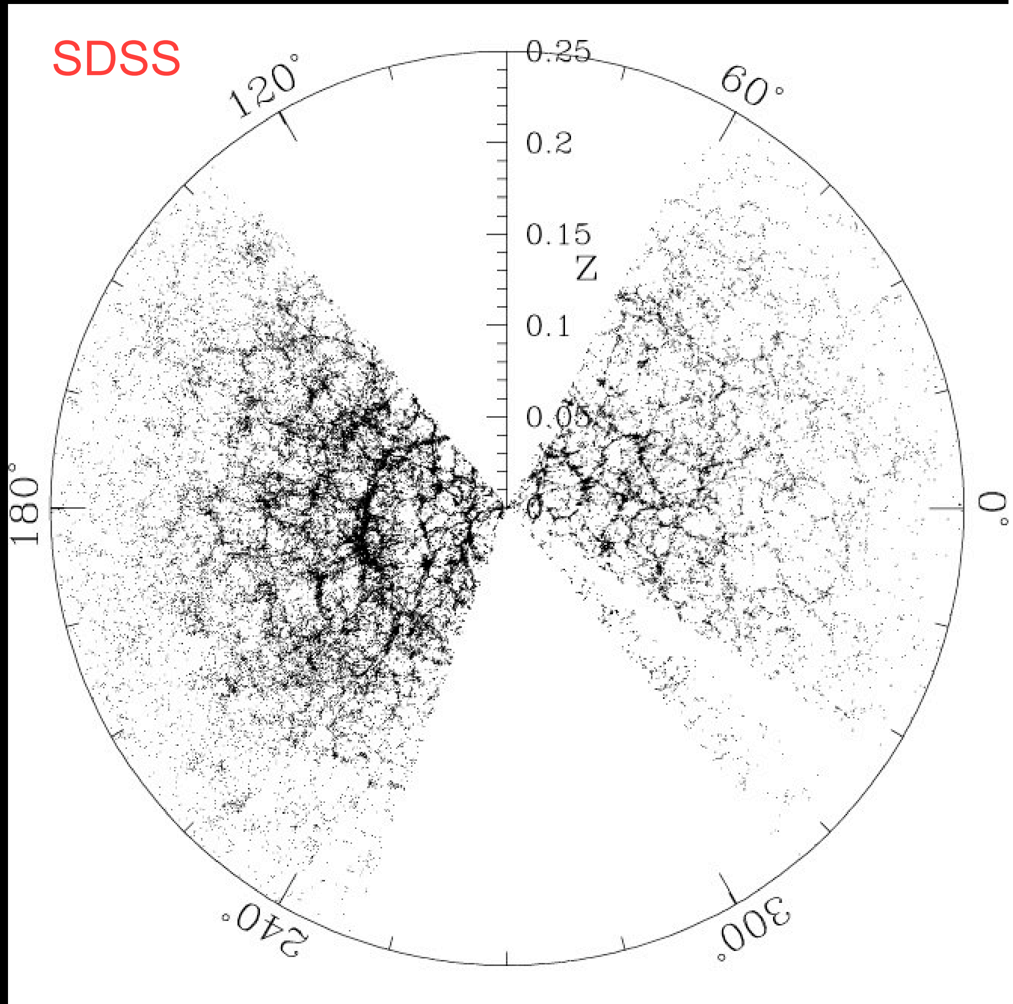

Characterising the last 8 Gyr
The present-day Universe

Luminosity and mass functions

- Redshift survey
  - Apparent magnitude limited
- e.g., SDSS
  - 14.5<r<17.77

- 2 choices for LF
  - Thin shells
    - Limited dynamic range, small number statistics
  - V_{max}
    - Evolution and k-corrections get mixed up with LF…



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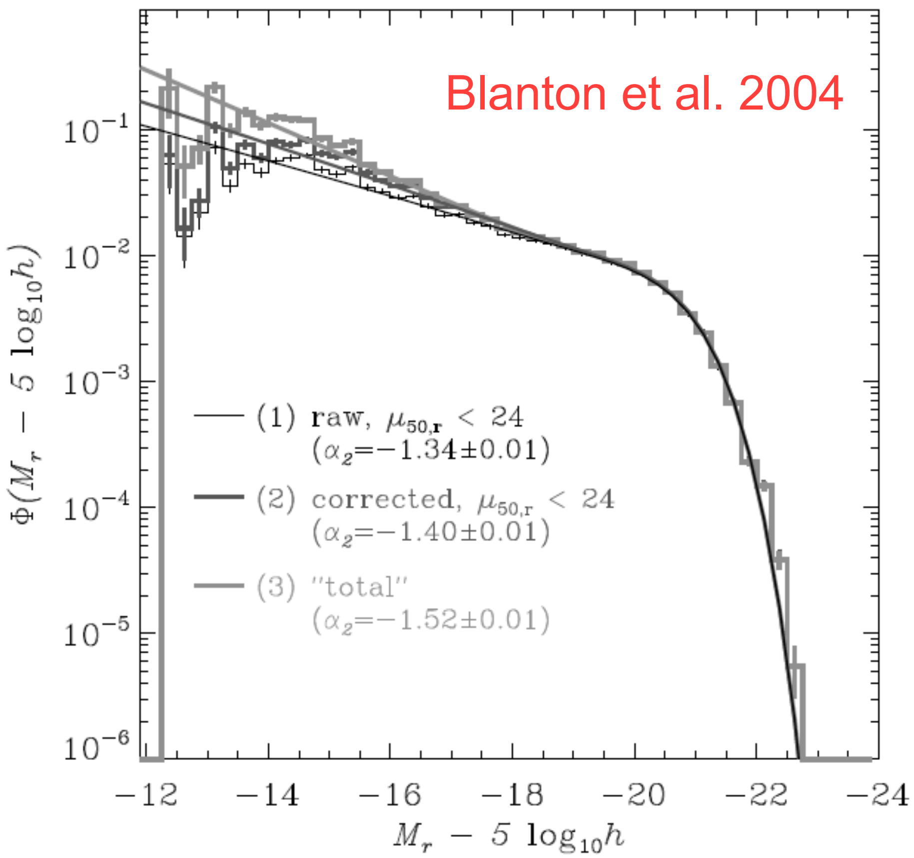
Luminosity and mass functions : V_{max} method

- Instead of making histogram of luminosities or masses of galaxies as observed, weight them by $1/V_{max}$
  - V_{max} is the maximum volume over which a galaxy can be seen
- V_{max} should account for k-corrections, and one can debate over how one deals with evolution
- If stellar mass, no k-corrections needed for luminosities, but still needed for V_{max}

Result

Schechter (1976) function to the $V/V_{\rm max}$ data points:

$$\phi(L)\mathrm{d}L = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) \frac{\mathrm{d}L}{L^*},$$



The smooth lines in Figure 7 represent fits to the luminosity function using a double Schechter function:

$$\Phi(L)dL = \frac{dL}{L_*} \exp(-L/L_*) \left[\phi_{*,1}\left(\frac{L}{L_*}\right)^{\alpha_1} + \phi_{*,2}\left(\frac{L}{L_*}\right)^{\alpha_2}\right] \quad (6)$$

Stated in terms of absolute magnitude $M = -2.5\log_{10}(L) +$ const this equation is:

$$\Phi(M) = 0.4\ln 10 dM \exp\left(-10^{-0.4(M-M_*)}\right)\left[\phi_{*,1}10^{-0.4(M-M_*)(\alpha_1+1)} + \phi_{*,2}10^{-0.4(M-M_*)(\alpha_2+1)}\right] \quad (7)$$

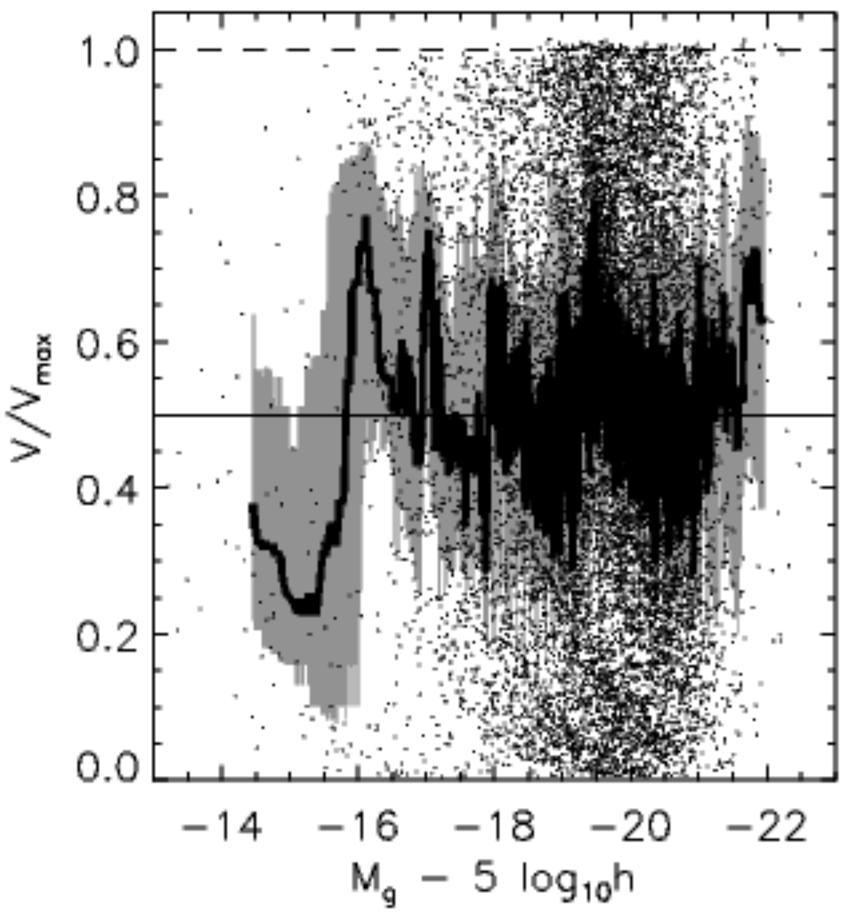


FIG. 10.— $V/V_{\rm max}$ against g-band absolute magnitude. The median (*thick solid line*), and upper and lower quartiles (*shaded area*), are shown as a function of g-band absolute magnitude. The average value for the whole sample is 0.509 ± 0.003, reasonably consistent with the expected value of 0.5 (*thin solid line*).

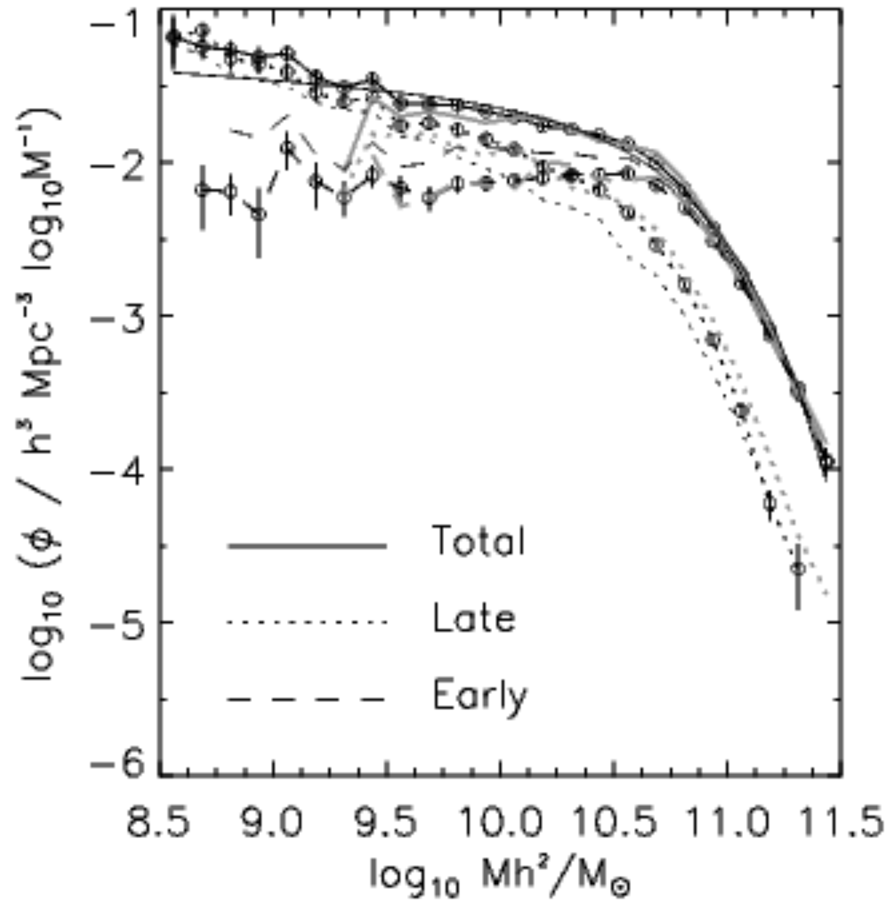


FIG. 17.— g-band derived stellar MF. The solid line represents the total MF. The black dotted and dashed lines represent the MF for late and early-type galaxies, separated using the $c_r = 2.6$ criteria. The thin solid line is our Schechter function fit to the MF. Overplotted in grey are the K-band derived stellar MFs for the total sample and the two morphological subsamples from Fig. 16. The thin black dashed and dotted lines show the g-band MFs of color-selected early and late-type galaxies. The data points included in this plot are tabulated in Table 5.

TABLE 2

SYSTEMATIC ERROR BUDGET

Quantity (1)	Error (2)	Source (3)
		Luminosity Function
ϕ^*	10%	Uncertainty in exact sky coverage (3%), completeness (7%), Poisson error in normalization (1%), and differences between behavior of the $10 < K < 13.5$ sample and our EDR sample
M^*	5%	Uncertainty in absolute calibration of *ugrizK* system
	10%	*K only:* Extrapolation to total
α	0.1?	*Optical:* from departures from a Schechter function
	$^{+0.1}_{-0.6}$	*NIR:* from strong departures from a Schechter function, and LSB galaxy incompleteness
j	15%	*Optical:* from ϕ^* and M^* uncertainty
	$^{+35\%}_{-15\%}$	*NIR:* from ϕ^*, M^* and α uncertainty
		Stellar Mass Function
M^* & ρ	30%	Dust, bursts of SF, galaxy age, and absolute calibration uncertainty
	$^{+0\%}_{-60\%}$	Stellar IMF

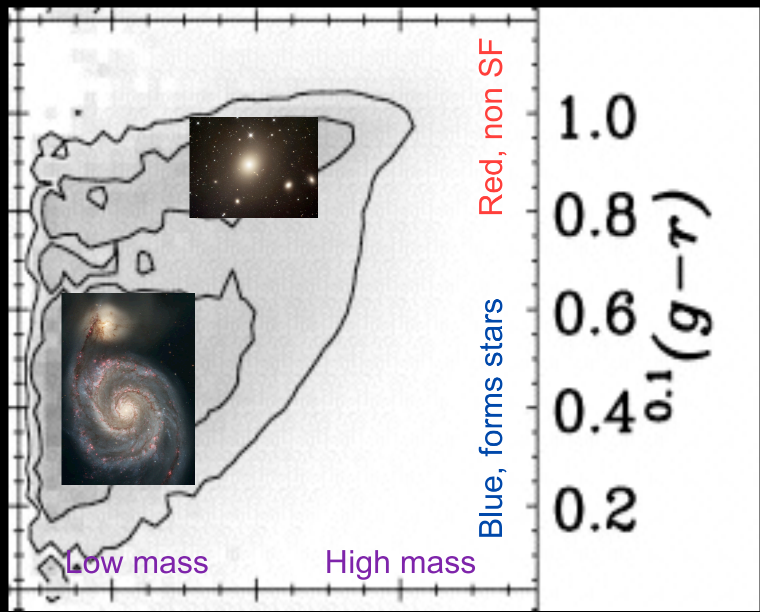
References. — (1) Fukugita et al. (1996)

Note. — Column (1) describes the quantity, (2) the contribution to the systematic error budget, (3) describes the error in more detail, and (references (section number or literature citation).

Key observation : correlation between structure and star formation history

Blanton et al. 2003; ApJ, 594, 186

- A bimodal galaxy population - transition mass of 3e10
  - Red sequence
    - Mostly non-star-forming
    - Bulk of galaxies bulge-dominated
    - Most massive galaxies
  - Blue cloud
    - Star-forming
    - Bulk of galaxies disk-dominated
    - Lower mass galaxies



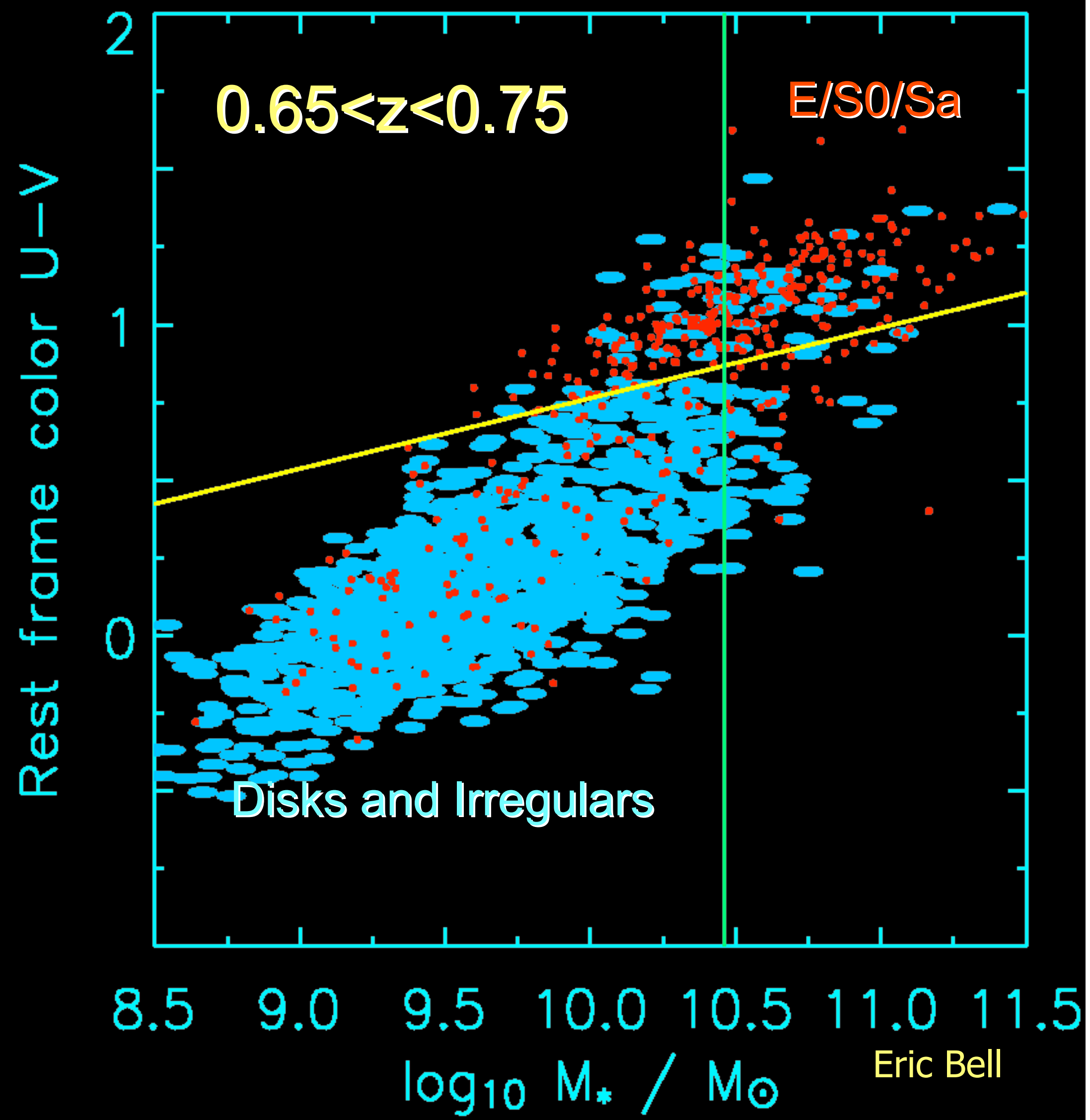
-18 -20 -22

Absolute magnitude in i-band

Cessation (quenching) of star formation is empirically correlated with the existence of a prominent spheroid

GO TO BLANTON

Red sequence vs. blue cloud



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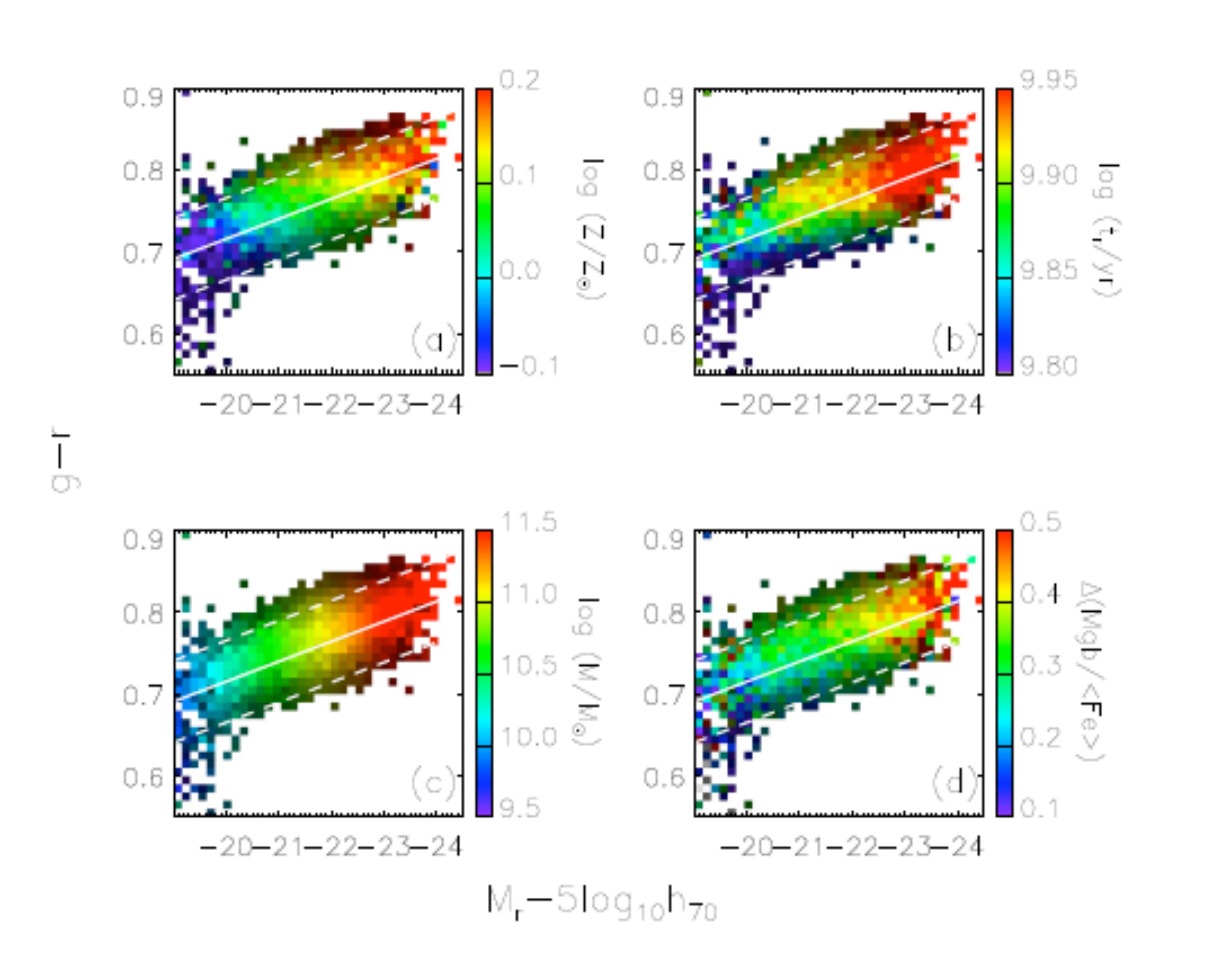
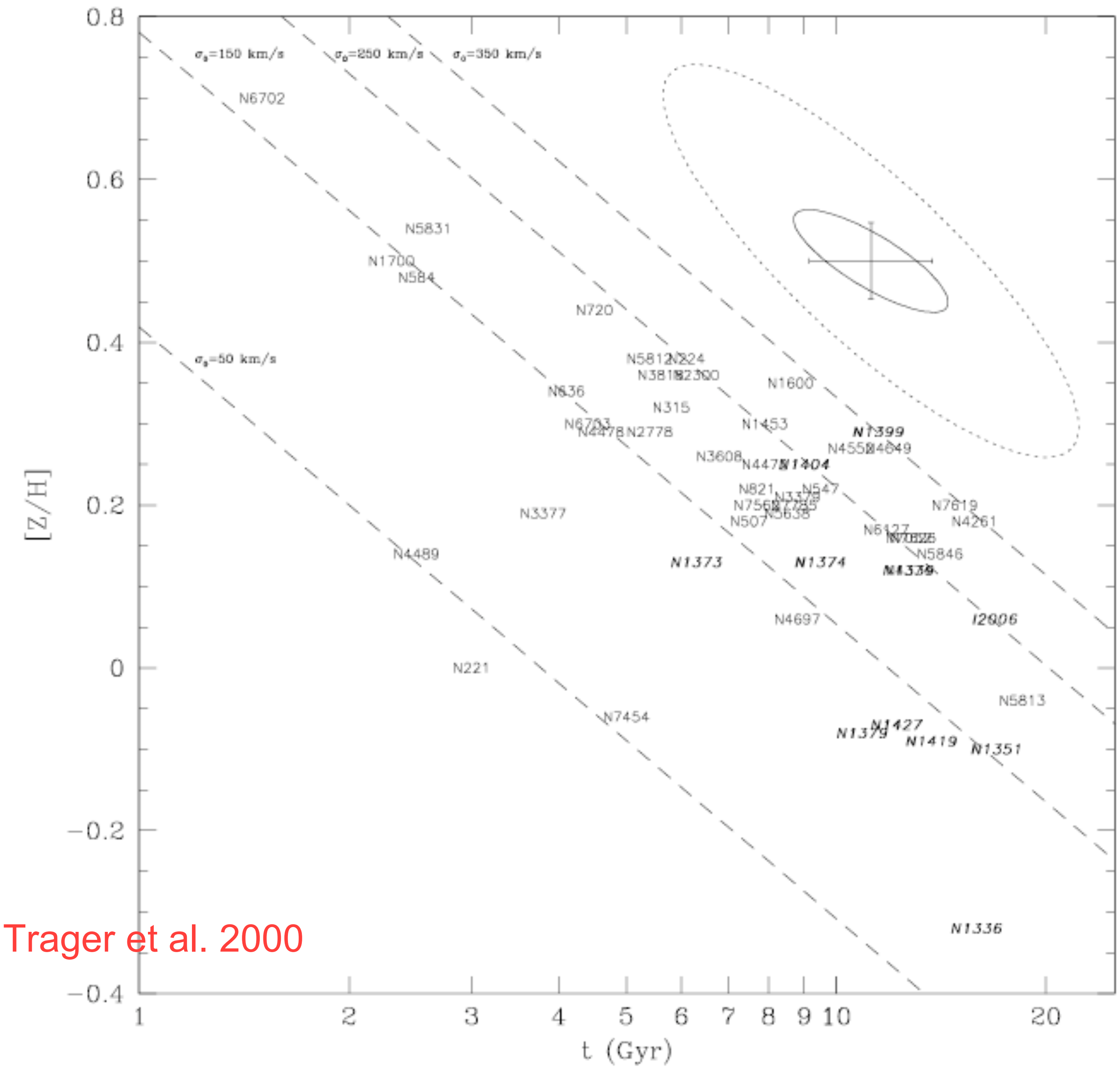
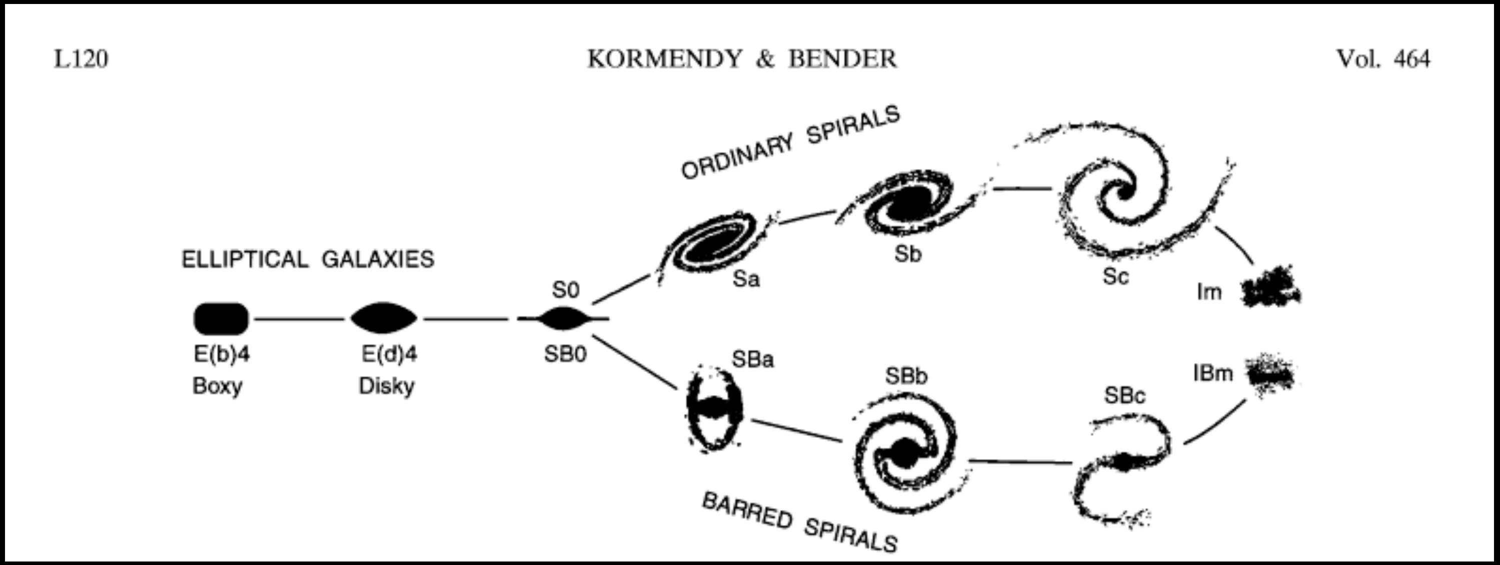


Gallazzi et al. 2005



Trager et al. 2000



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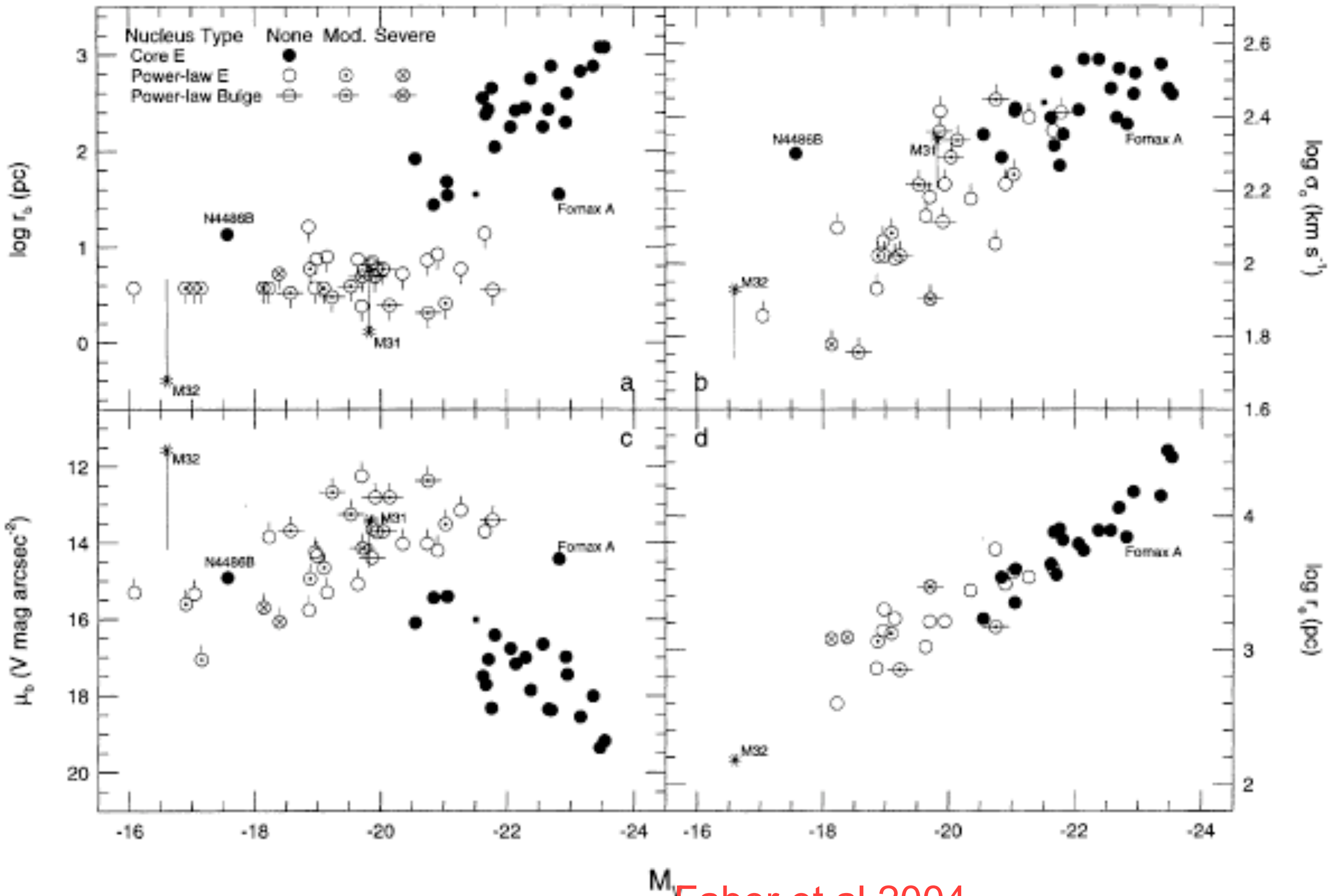

Faber et al 2004

FIG. 4. *HST* measurements of central parameters of hot galaxies, as a function of absolute V magnitude. Hubble type and nucleus types are taken from Table 1; "bulges" are S0-Sb galaxies. r_b and μ_b for power laws are limits $r_b^{\rm lim}$ and $\mu_b^{\rm lim}$ from Table 2. M31 and M32 are plotted twice: asterisks show data as observed, and tails indicate their positions as they would appear 24 times farther away near Virgo. The small black square is the S0 galaxy NGC 524, which is the only core within a bulge. The apparent turndown in surface brightness at faint magnitudes in panel (c) is probably a resolution effect (cf. M32). Effective radii are plotted in panel (d), to be compared with break radii in panel (a): the strong impressions of scatter at intermediate magnitudes ($-22 < M_V < -20.5$) and of two types of galaxies in panel (a) are absent in panel (d).

conclusions

- Met/mass relation
- Type of merger
  - Core/cusp
  - Boxy/disky
  - Rotating/not

  - Gas-rich - faint E
  - Gas-poor - bright E

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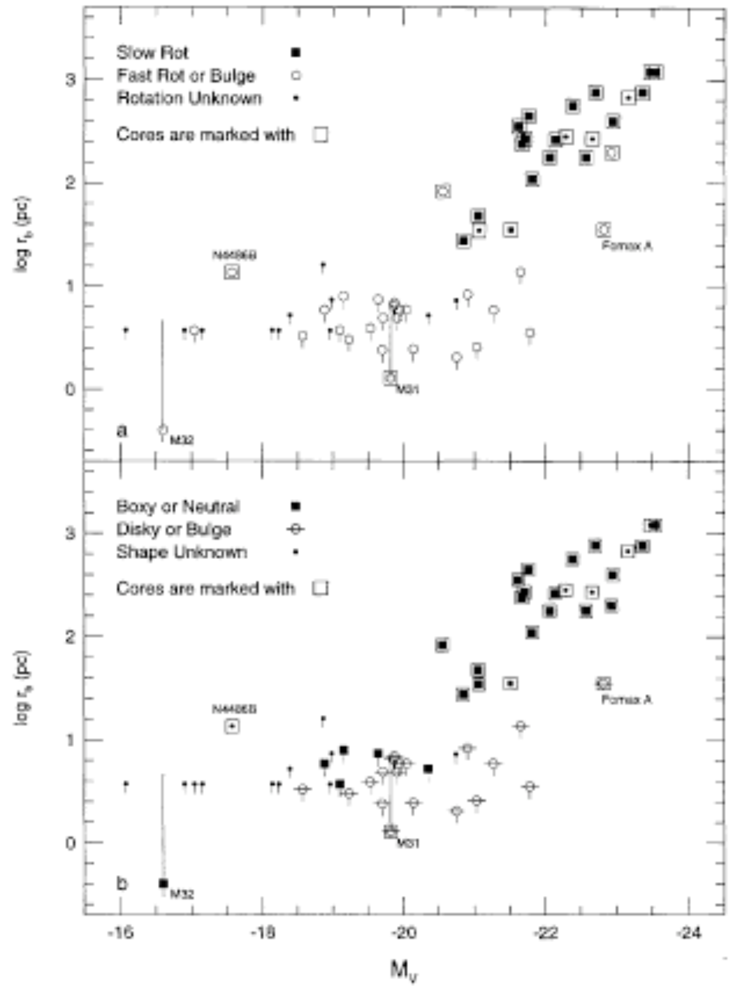


FIG. 7. (a) Replot of Fig. 4(a) with symbols indicating rotation speed $(v/\sigma)_*$. Slow rotators (filled symbols) have $(v/\sigma)_* < 0.51$; fast rotators (open circles) have $(v/\sigma)_* \geq 0.51$. Bulges lacking data are classed as fast rotators. Galaxies with core profiles are indicated by the enclosing squares; all others are power laws. The data indicate a tendency for fast rotators to have power-law profiles. (b) Same as (a) but with symbols indicating isophotal shape a_4/a. Galaxies are classed as disky if $a_4/a \geq 0.4$, otherwise as boxy/neutral. Irregular profiles with variable a_4/a are also classed as boxy/neutral. Bulges (Hubble types S0-Sb) are classed as disky. The data indicate a tendency for disky galaxies to have power-law profiles.

Blue cloud galaxies

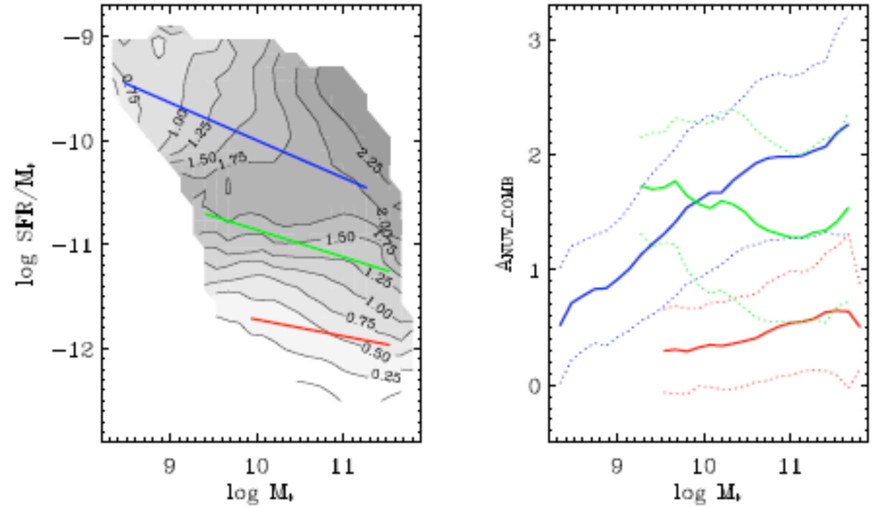
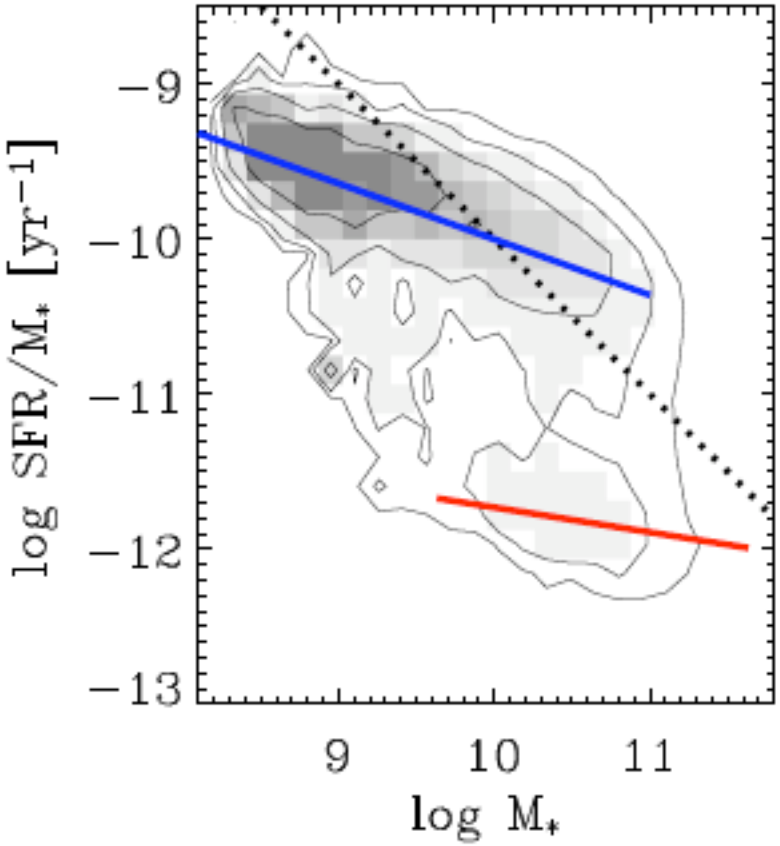


FIG. 9.— *Left*: Weighted mean of NUV-band atttenuation, $A_{NUV,comb}$. *Right*: Weighted mean and $\pm 1\sigma$ distribution width for $A_{NUV,comb}$ along similarly colored curves in above plots. (See caption of Fig. 8 for explanation.)



Schiminovich et al. 2008

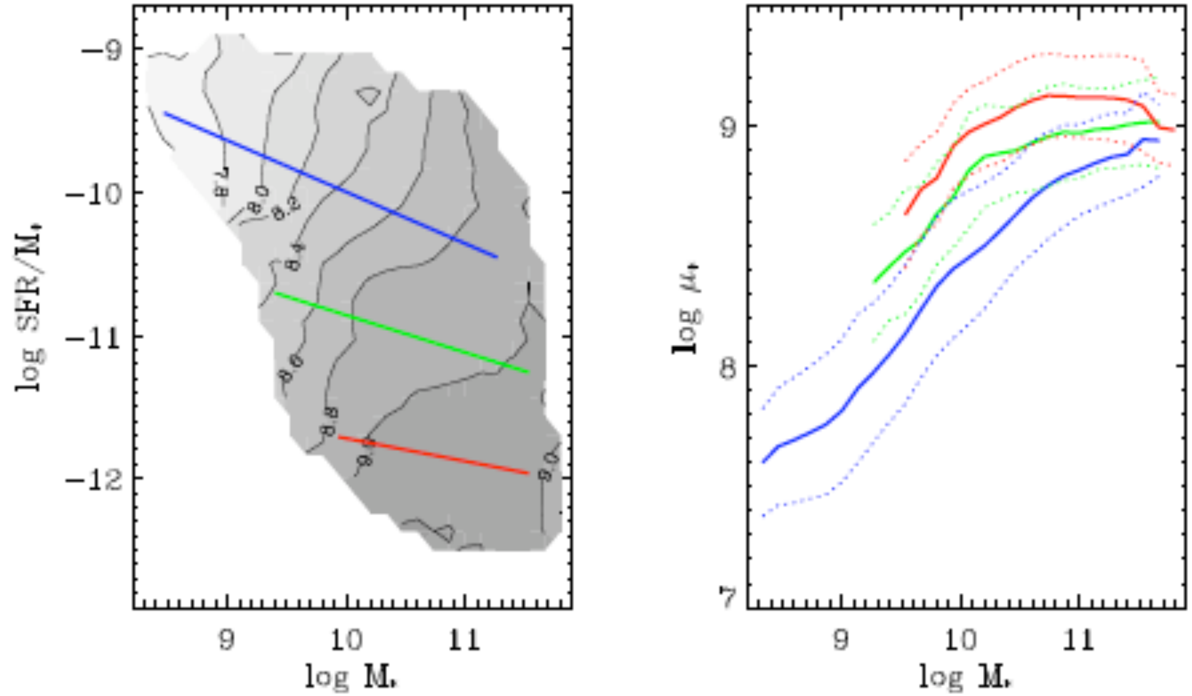


FIG. 13.— *Left*: Weighted mean of logarithm of the stellar mass surface density $\log \mu_\star$. *Right*: Weighted mean and $\pm 1!\sigma$ distribution width for $\log \mu_\star$ along similarly colored curves in above plots. (See caption of Fig. 8 for explanation.)

Environmental dependence

At high masses:
Weak env. Dep.

At lower masses:
Strong env. Dep.

Baldry + 2006

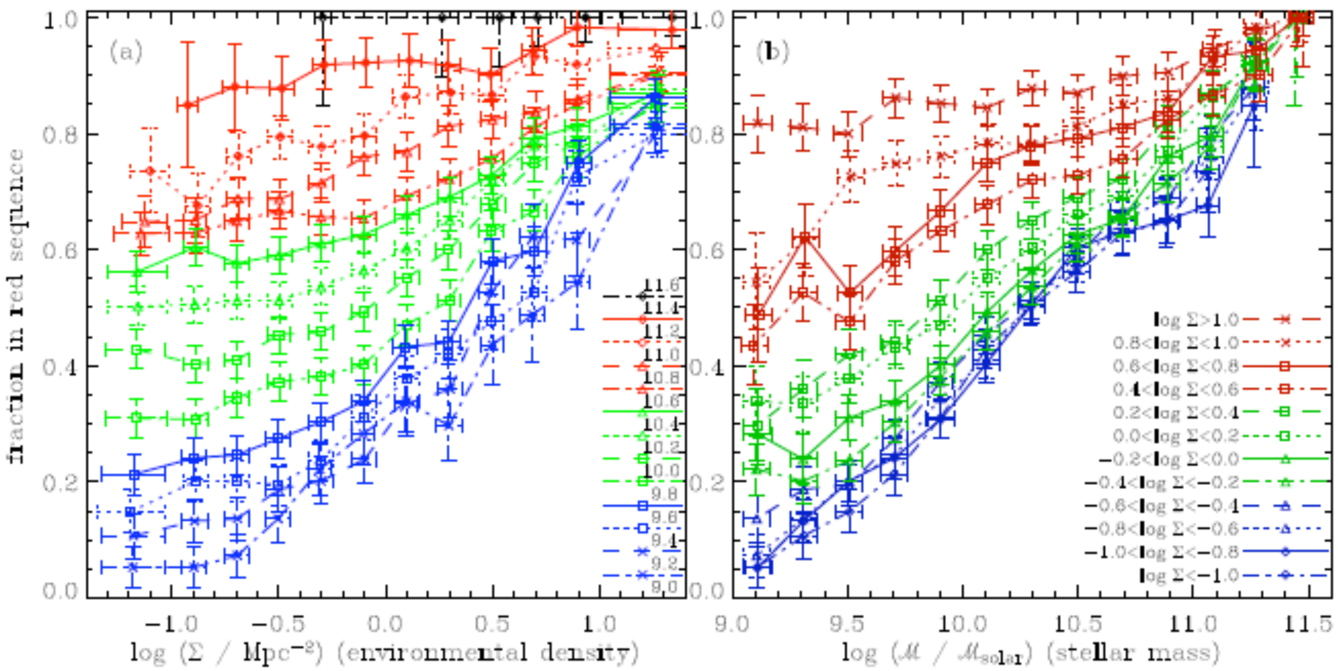


Figure 11. Fraction of red-sequence galaxies versus environment and versus stellar mass. In panel (a), the symbols and lines represent different stellar masses as shown in the legend (log $\mathcal{M}$ from 9.0 to 11.6). In panel (b), the lines represent different environmental densities. Systematic errors of 0.03 were added in quadrature to the Poisson errors. Note the similarity between the two plots leads to the unification schemes shown in Fig. 12.

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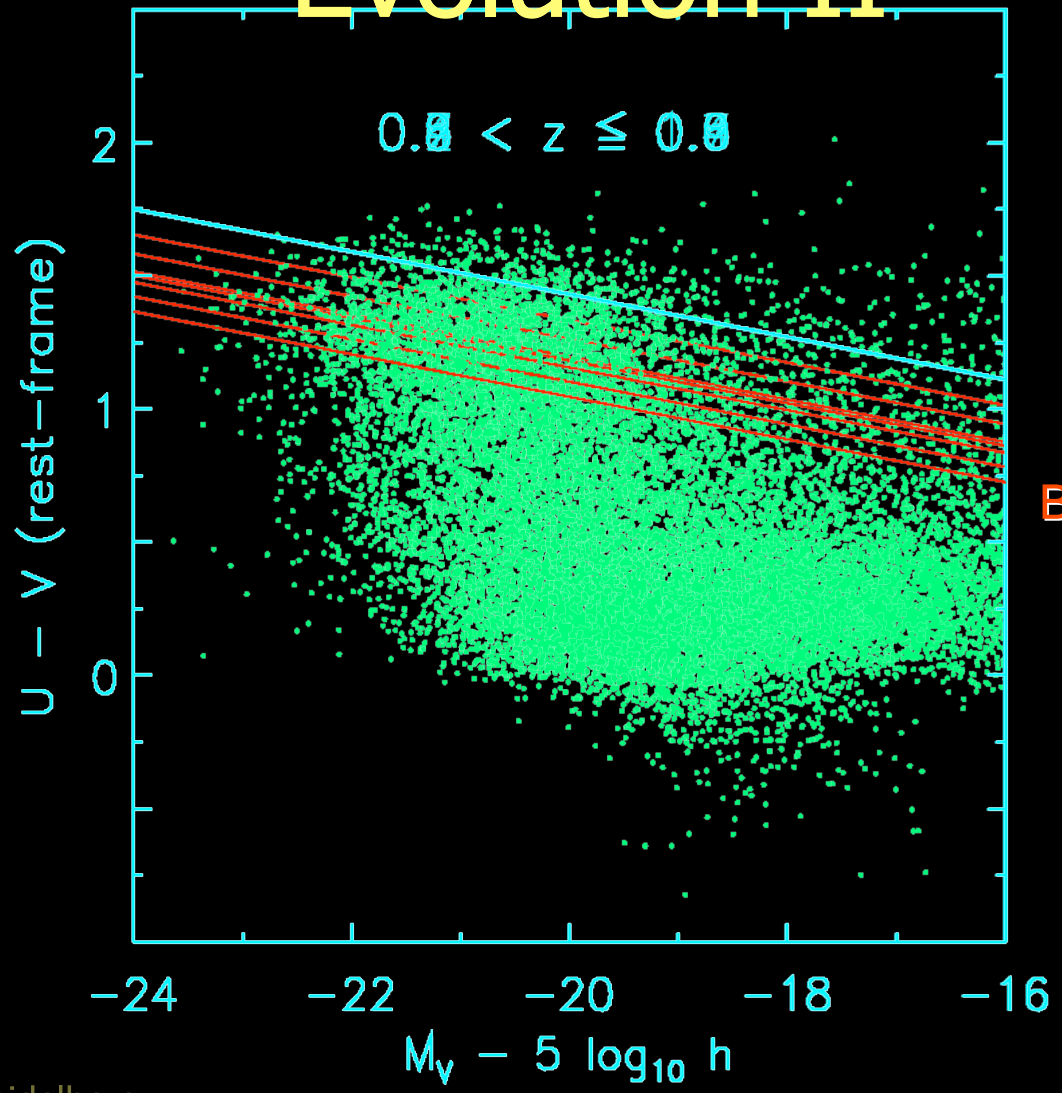
Evolution II

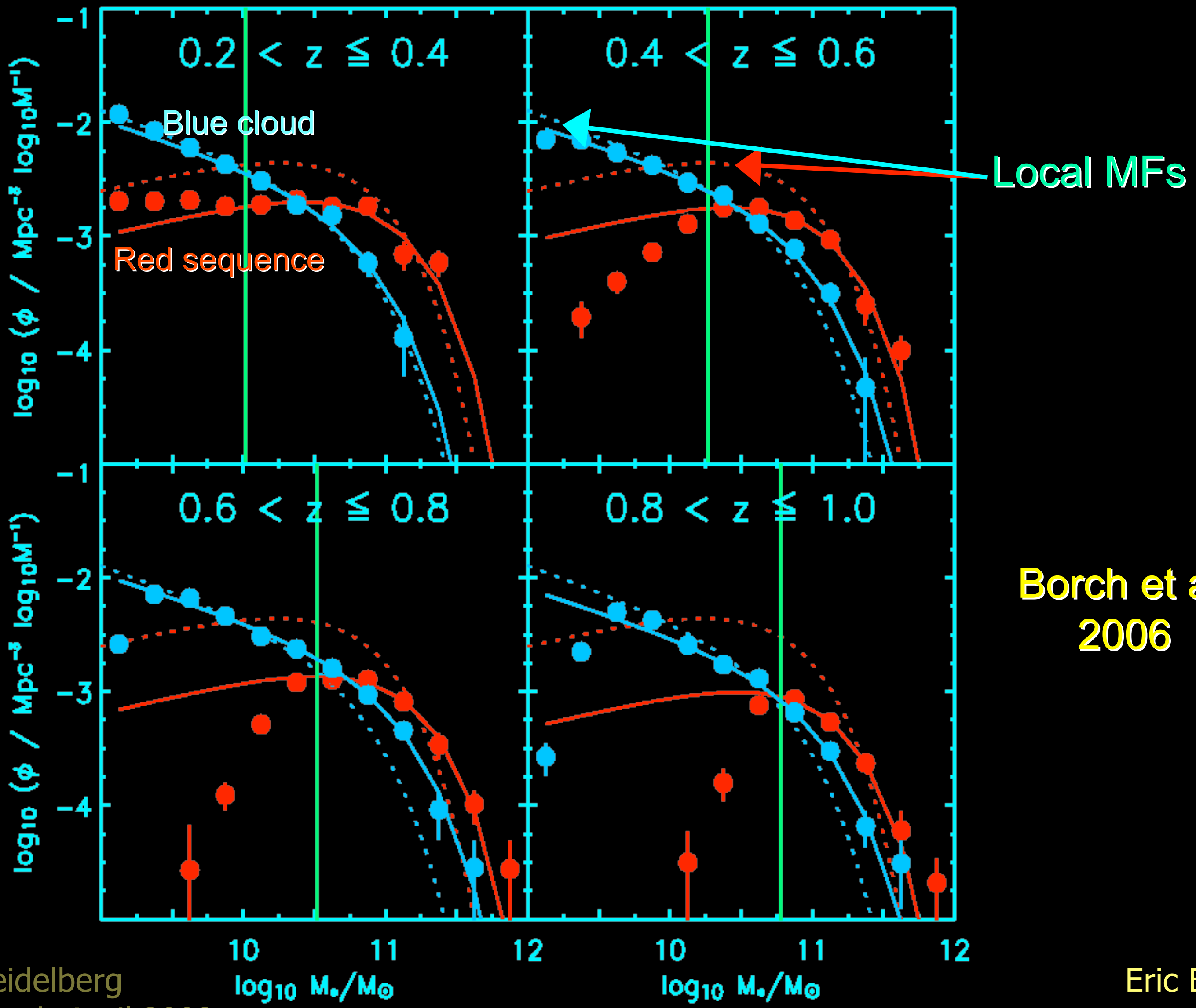


Bell et al. 2004

Mass function: color split

Weak evolution in blue guys (= disks)

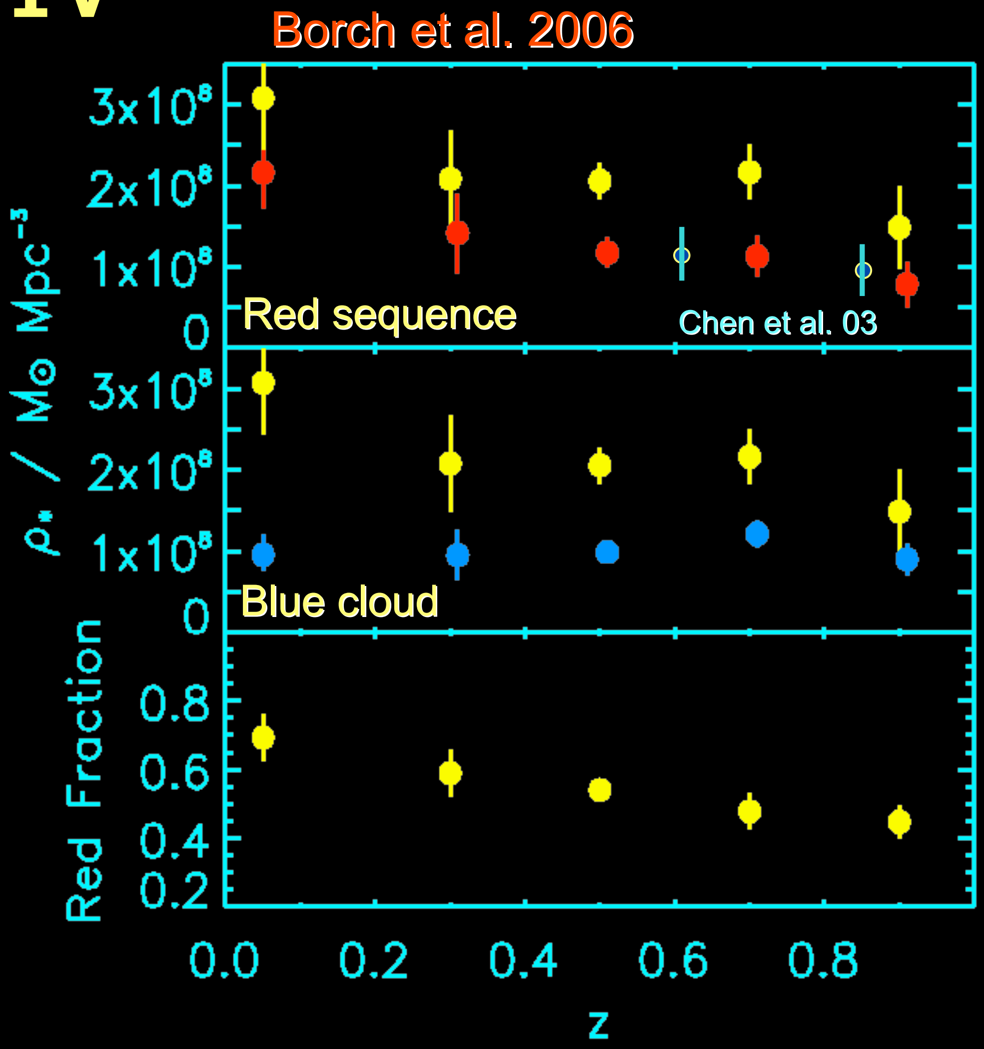
Strong evolution in red guys at L<2L* at least (= spheroids)



Borch et al. 2006

Evolution IV

- Always a pronounced blue cloud
  - Color redder with time
- Red sequence builds up with time
  - Color of ancient stars at every epoch
  - Build-up of x3 or so since z~1 (Bell et al. 2004; Chen et al. 2003; Willmer, Faber et al. 2005)
  - In agreement with at least some models (Cole et al. 00; Somerville et al. in prep)



Where's the mass?

- A red sequence
  - Dominated by spheroids at z<1
  - Color evolves ~ passively
  - ➔ stellar mass density increases by x2 or more
  - Most mass is in spheroids at redshifts below ~0.7
- A blue cloud
  - Dominated by disks
  - Color reddens towards present day
  - Stellar mass function more or less constant since z~1

Demographics of the evolving galaxy population

Where is the star formation?

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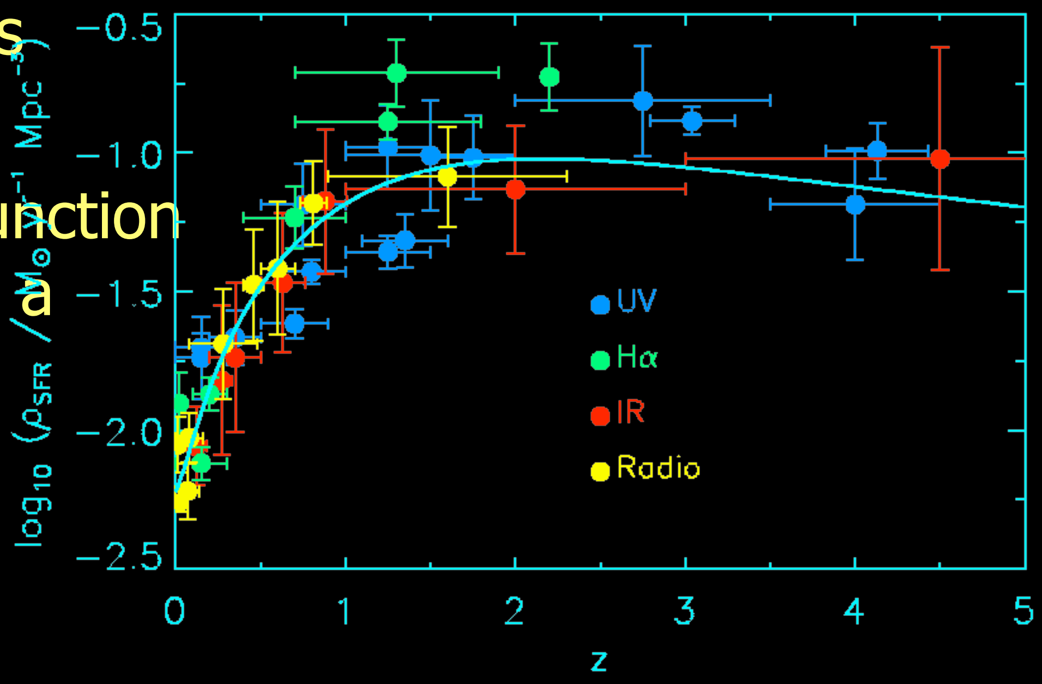
Cosmic SFR

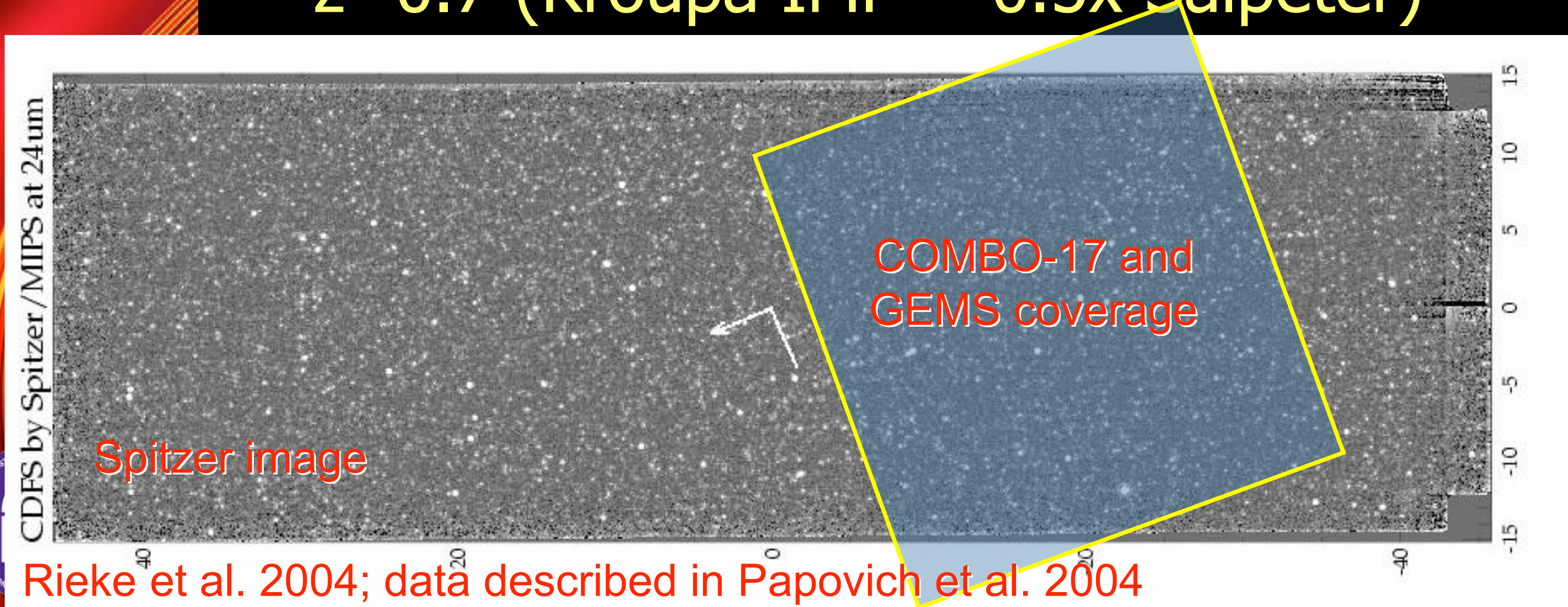
- UV / IR / radio / emission lines
- Luminosity function extrapolation a challenge
- Reasonable agreement



Hopkins 2004

Spitzer: new insights

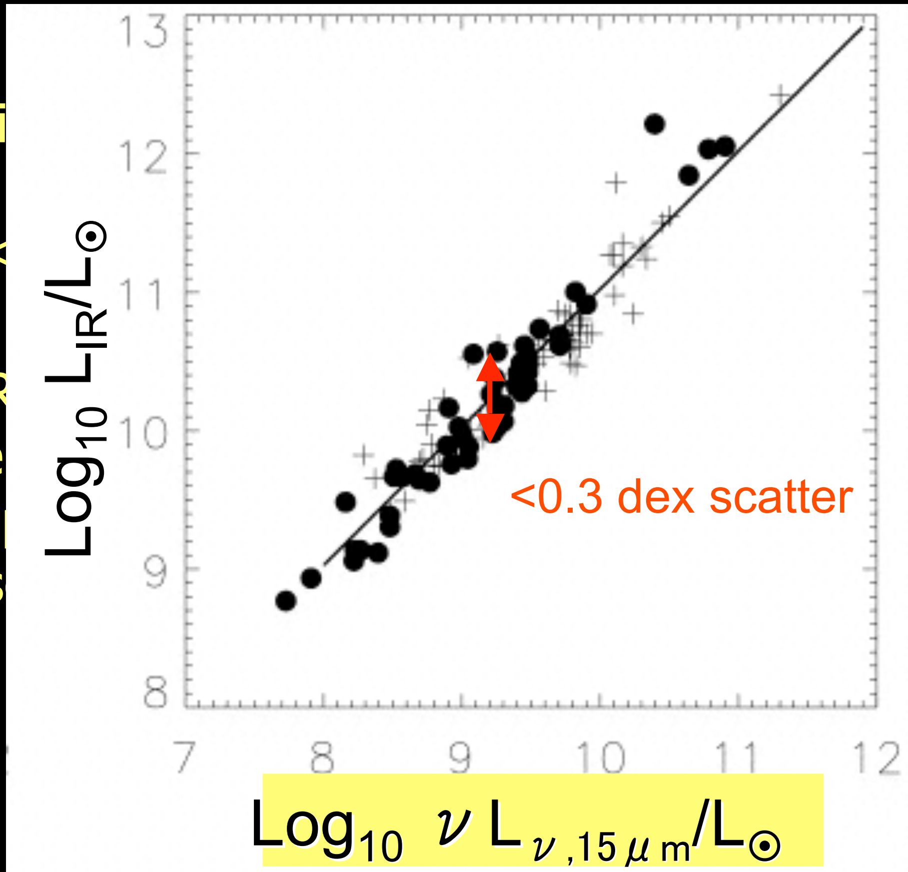
- Spitzer 24μm data from the MIPS instrument team for the CDFS
- 83μJy limit corresponding to $3M_{\odot}\ yr^{-1}$ at z~0.7 (Kroupa IMF ~ 0.5x Salpeter)



Rieke et al. 2004; data described in Papovich et al. 2004

IR luminosity from 24µm flux

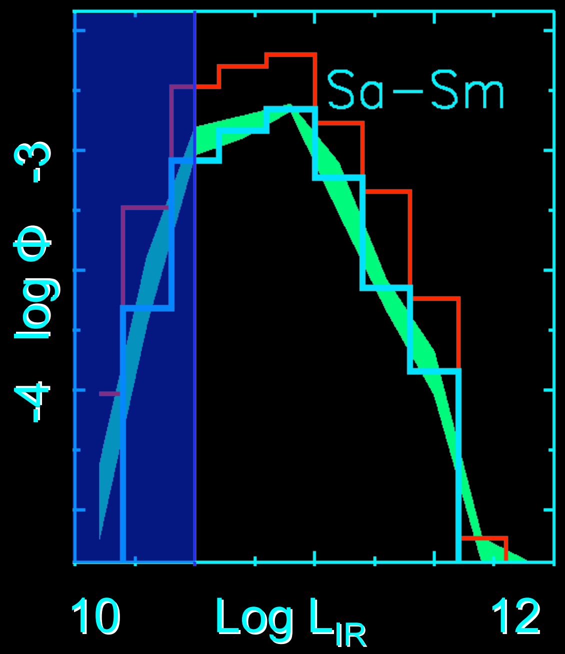
- Rest-frame 12-15µm correlates strongly wi total IR luminosity in local Universe, with < scatter
- Will be able to test IR estimates with Spitze 70,160µm, Apex 350 and 870µm and Hers PACS and SPIRE



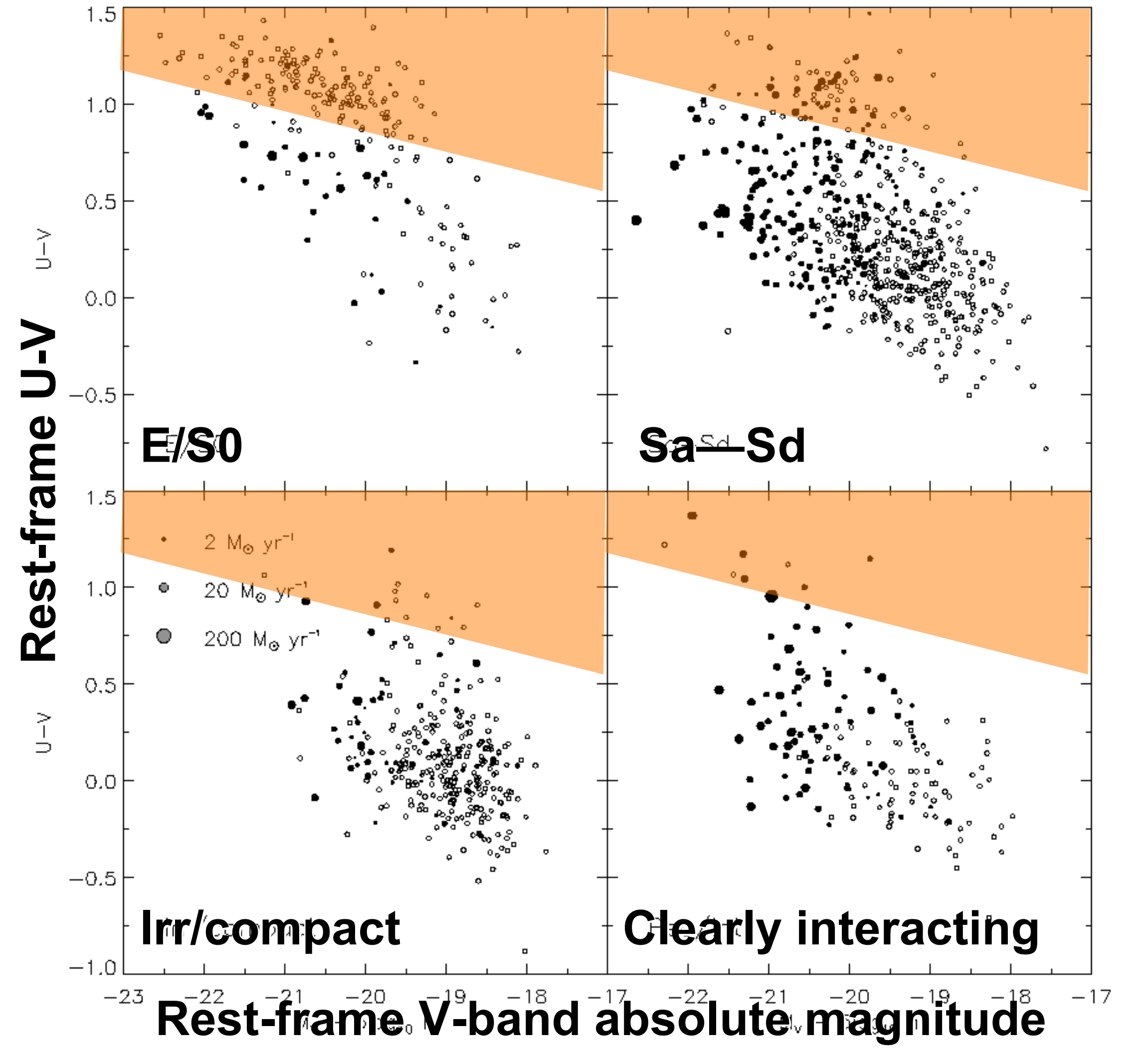
Chary & Elbaz 2001; Papovich & Bell 2002

Which galaxies form stars?

- Red E/S0s are non-star-forming
- Most SF is in spiral galaxies



Bell et al. 2005



Demographics of the evolving galaxy population

SFR vs. SFH

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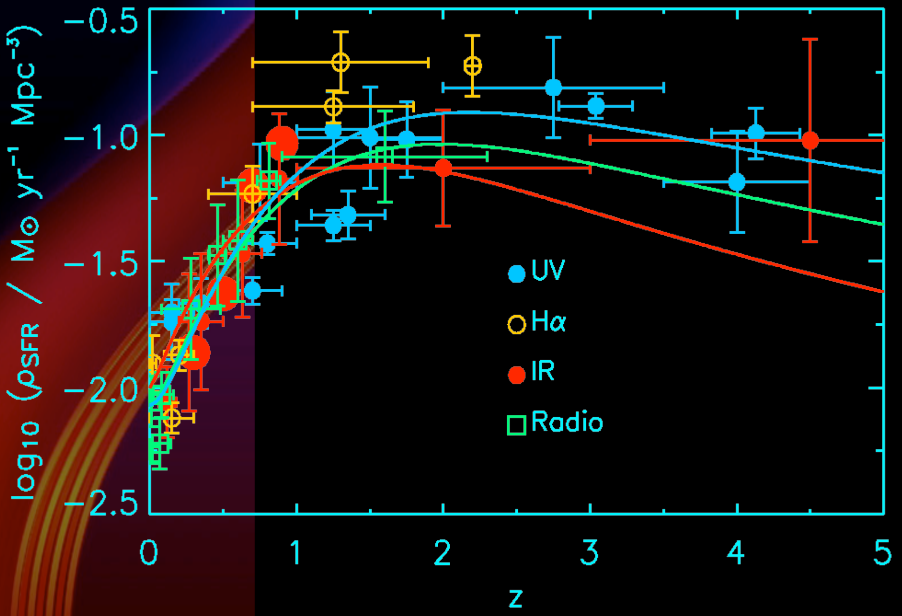
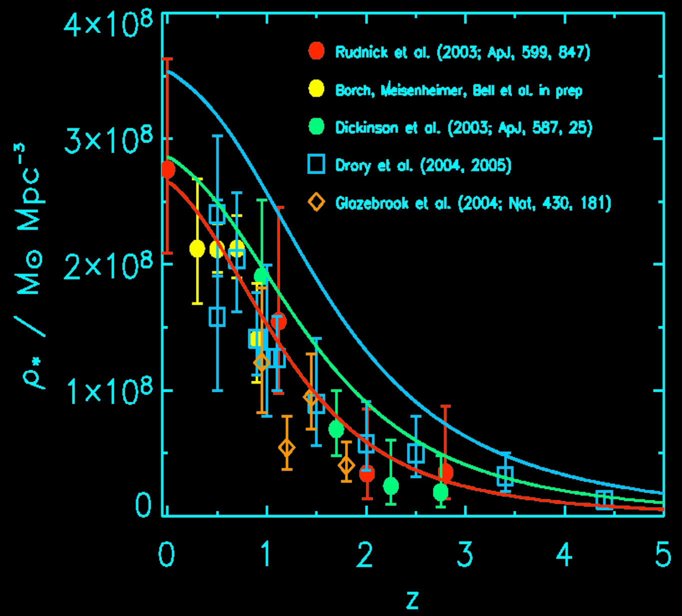
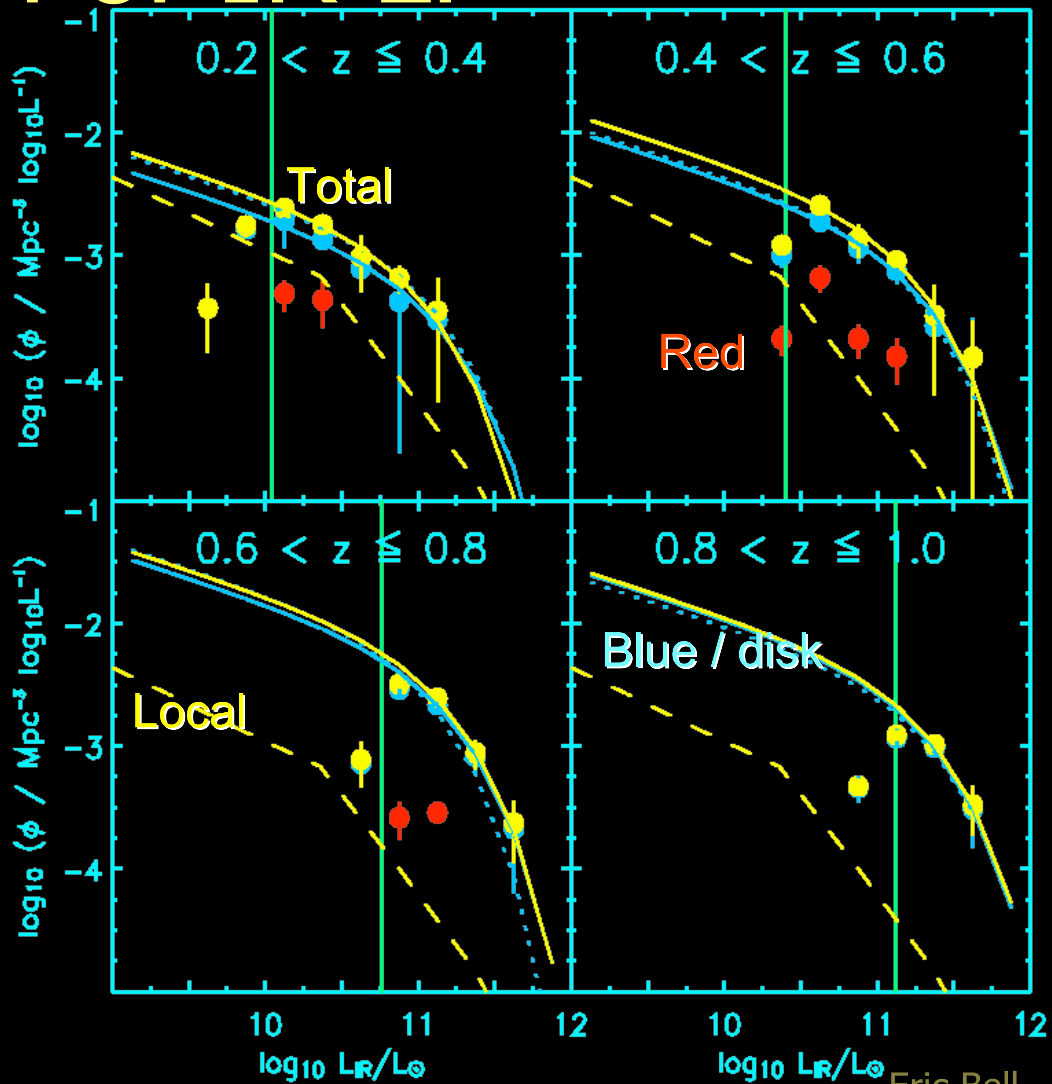
SFR vs. SFH





Borch et al. 2006

Evolution of IR LF



IR LF very strongly evolving

Almost all SF is in blue disks

Le Floc'h et al. 2005
Bell et al. 2005

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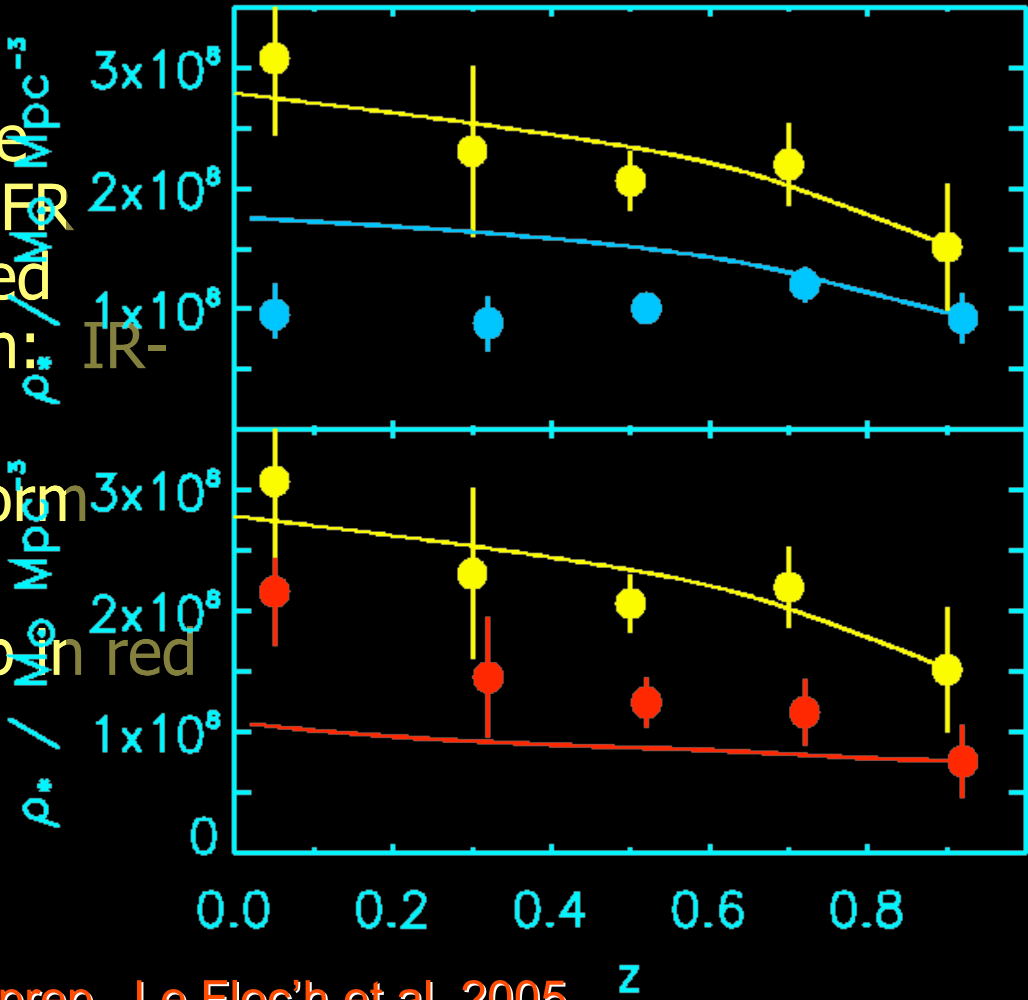
Split by color

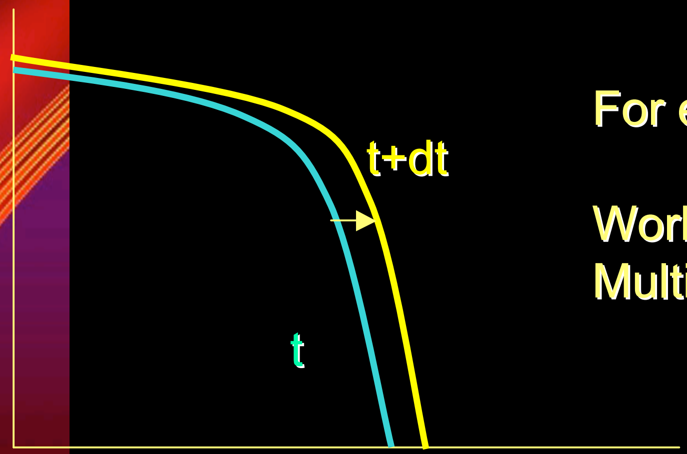
- Can compare integrated SFR with observed mass growth: IR-derived
- Blue disks form stars
- Stars end up in red spheroid-dominated galaxies



Bell et al., in prep., Le Floc'h et al. 2005

The evolution of the mass function…

- Can estimate evolution of the mass *function* with time

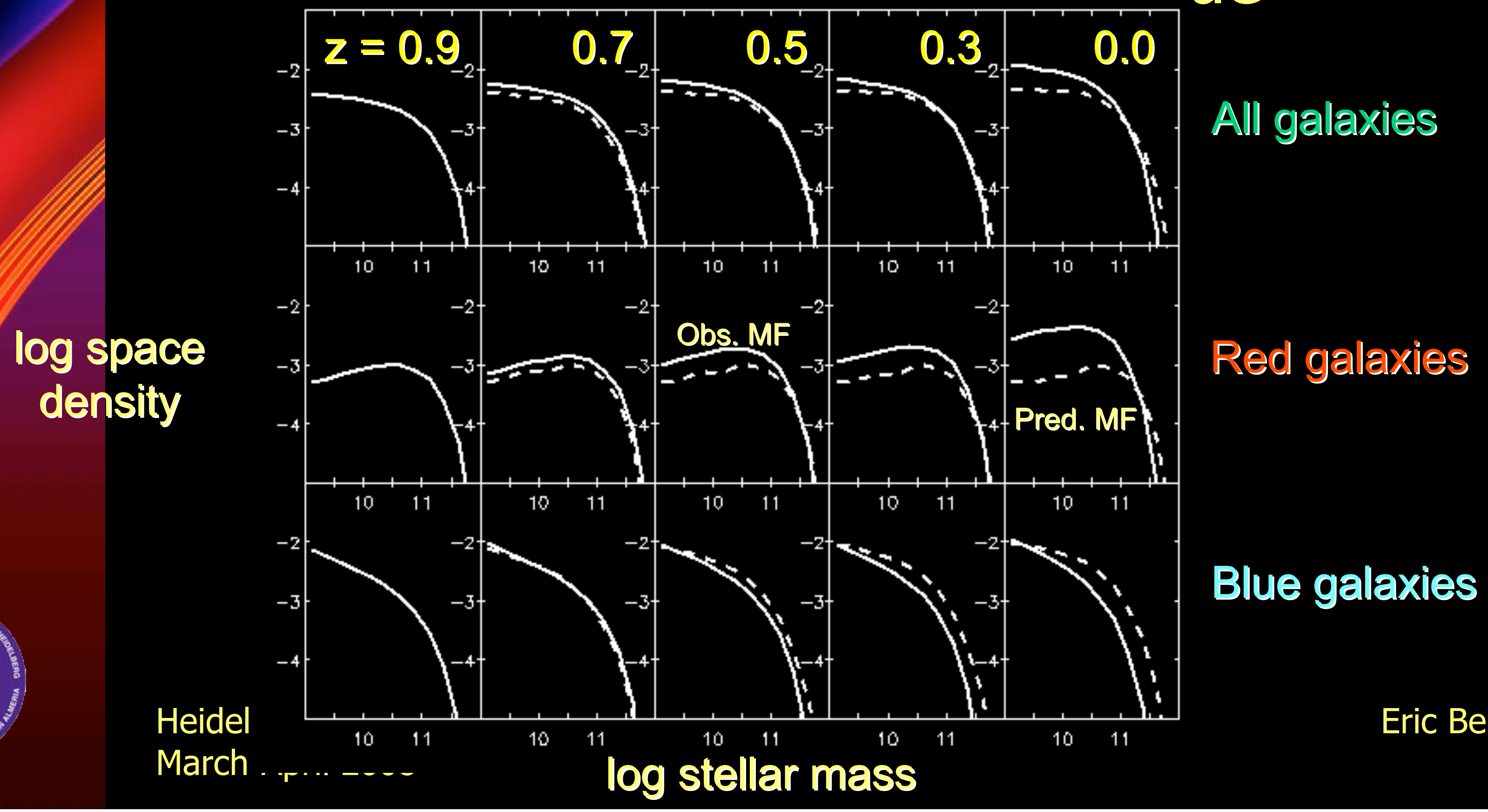


For each mass bin:

Work out average dM*/dt
Multiply by Δt to work out ΔM*

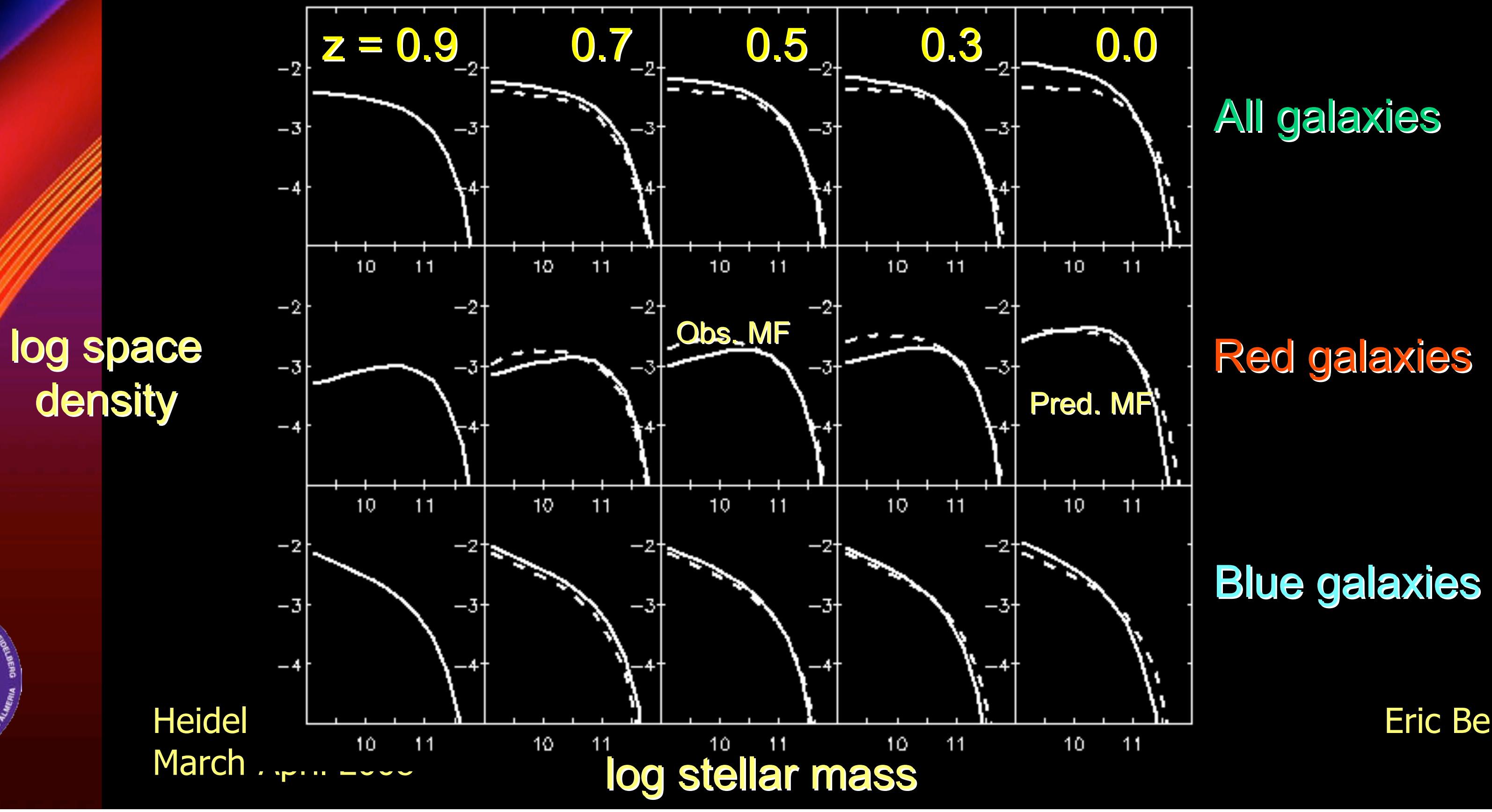
Results

- Hypothesis 1: SF in red → red
  SF in blue → blue



Results

- Hypothesis 1: All SF → red



Conclusions

- Assumption of Universal IMF gives a consistent, if unconventional, picture of the interrelationship between the evolution of star formation and stellar mass – both integral and mass function
- Growth of stellar mass in blue cloud counteracted by sink term into red sequence
- Primary mode of growth of red sequence is through truncation of star formation in massive blue galaxies

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Scaling relations

- Intense SF in disks + transformation of disks to early-types implies…
  - Disk galaxies are always growing
  - Scaling relations offer insight into evolving galaxy population
    - Luminosity/mass size
    - Tully-Fisher relation

Introduction

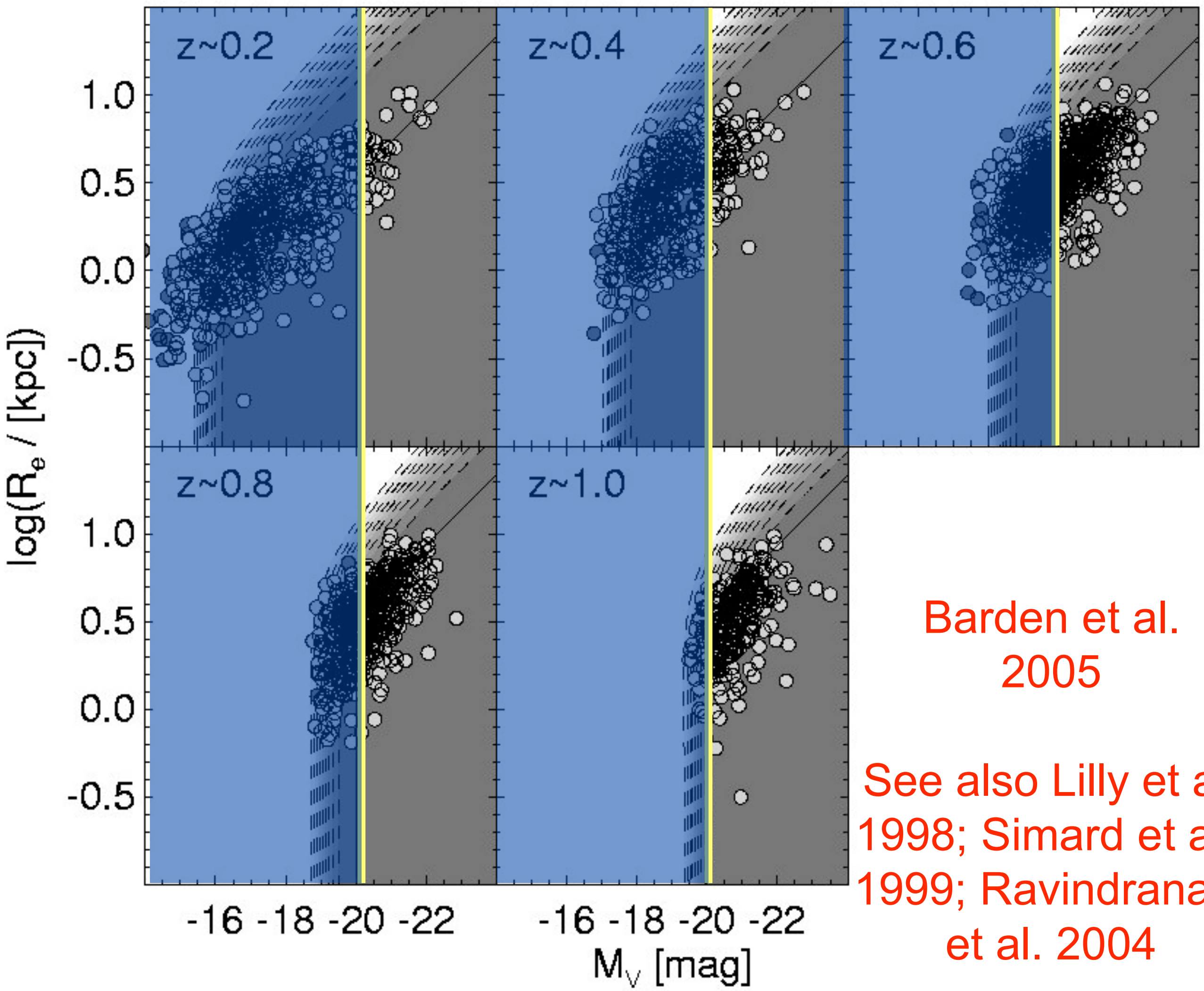
Star formation in disks

Transformation of disks to early types

Scaling relations

Summary and Outlook

Luminosity-size: disks

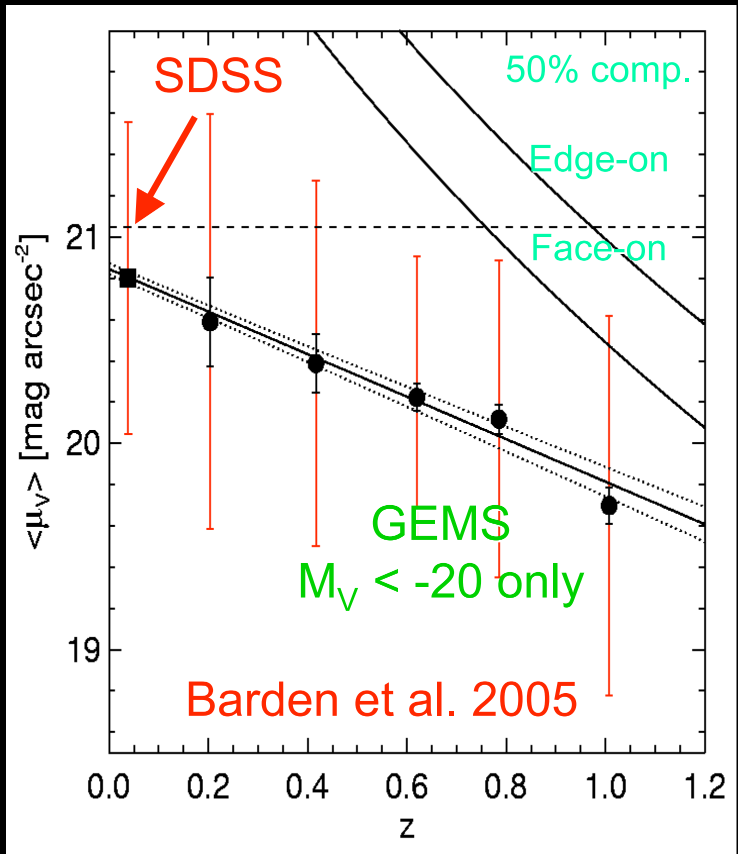


Barden et al. 2005

See also Lilly et al. 1998; Simard et al. 1999; Ravindranath et al. 2004

Luminosity-size: disks

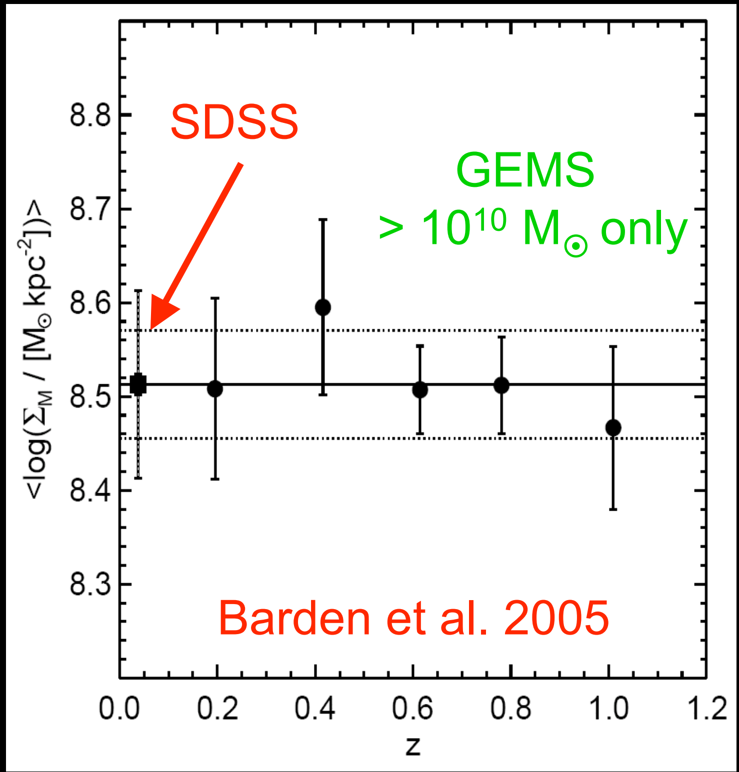
surface brightness evolution



- Strong surface brightness evolution
  - ~1 mag/arcsec^2 per unit redshift in rest-frame V-band
  - But, the disks are forming stars, are bluer and so have lower M/Ls….

Stellar mass-size: disks

surface density evolution



- No strong evolution in surface density
- Stellar mass-size relation is ~constant over last 8 Gyr!
- See talk by Somerville

Introduction

Star formation in disks

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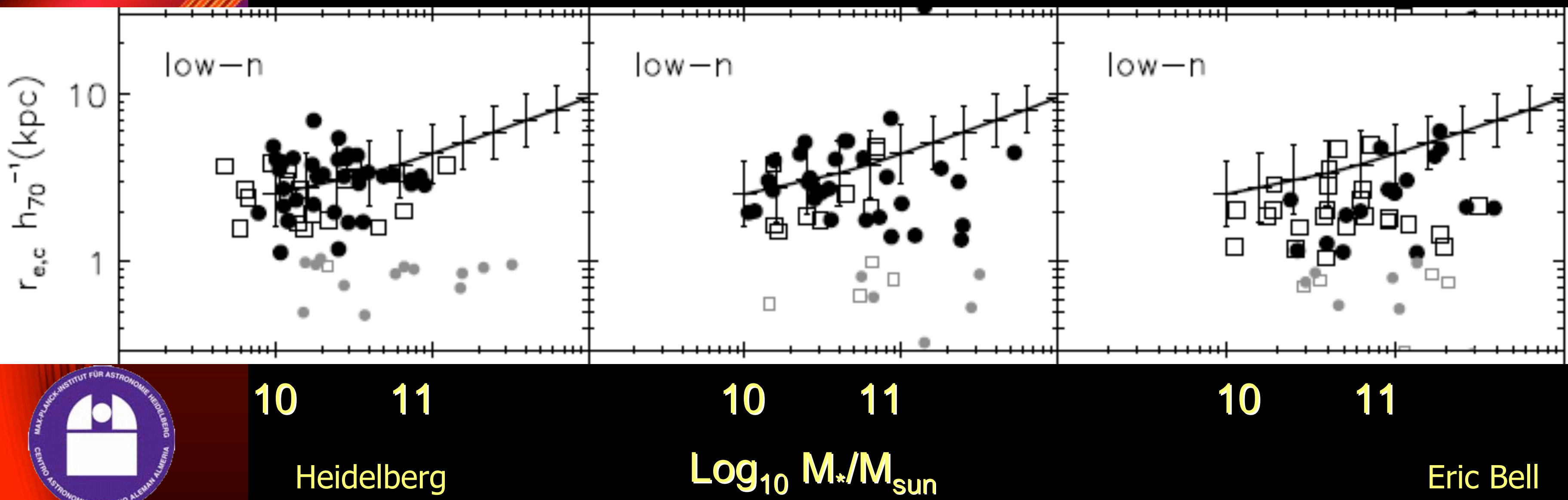
Summary and Outlook

Stellar mass-size at z>1

- Tendency towards smaller sizes for most massive galaxies at higher redshift
  - Mass errors?
- Trujillo et al. 2006



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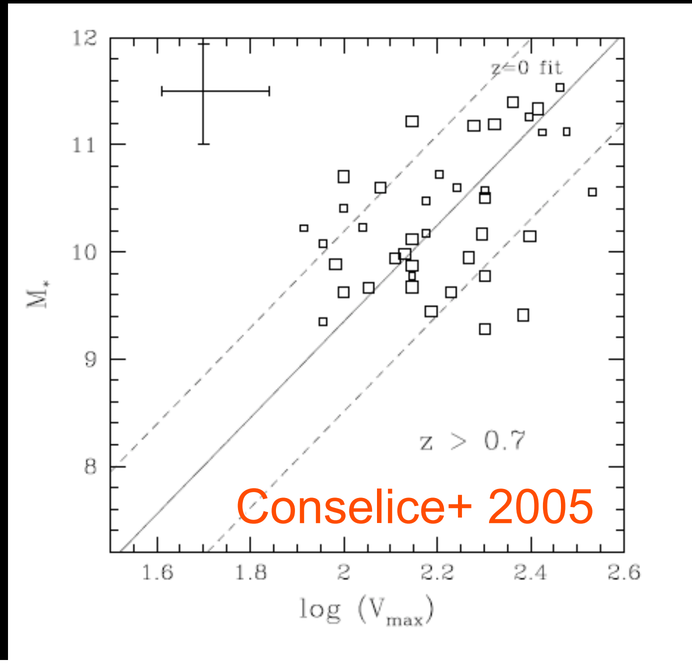
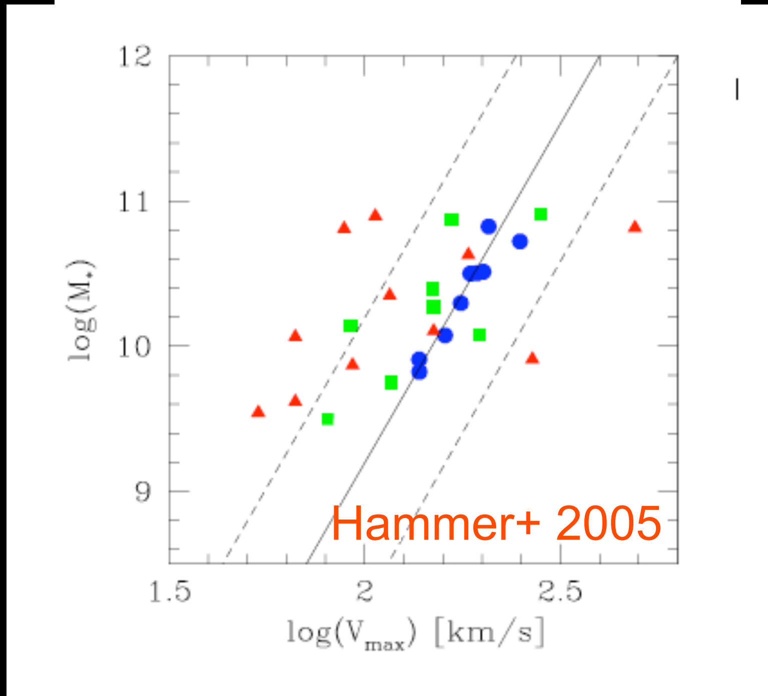
Tully-Fisher relation

- <~ 1 mag brightening in B
  - large astrophysical scatter; selection and survey details become important
- Small change in stellar mass TF
  - Conselice+ 2005; Hammer+ 2006; Kassin+ 2006; Weiner+ 2006; Boehm+ 2004; Koposov+ in prep.
  - See Vogt's talk





Introduction

Star formation in disks

Transformation of disks to early types

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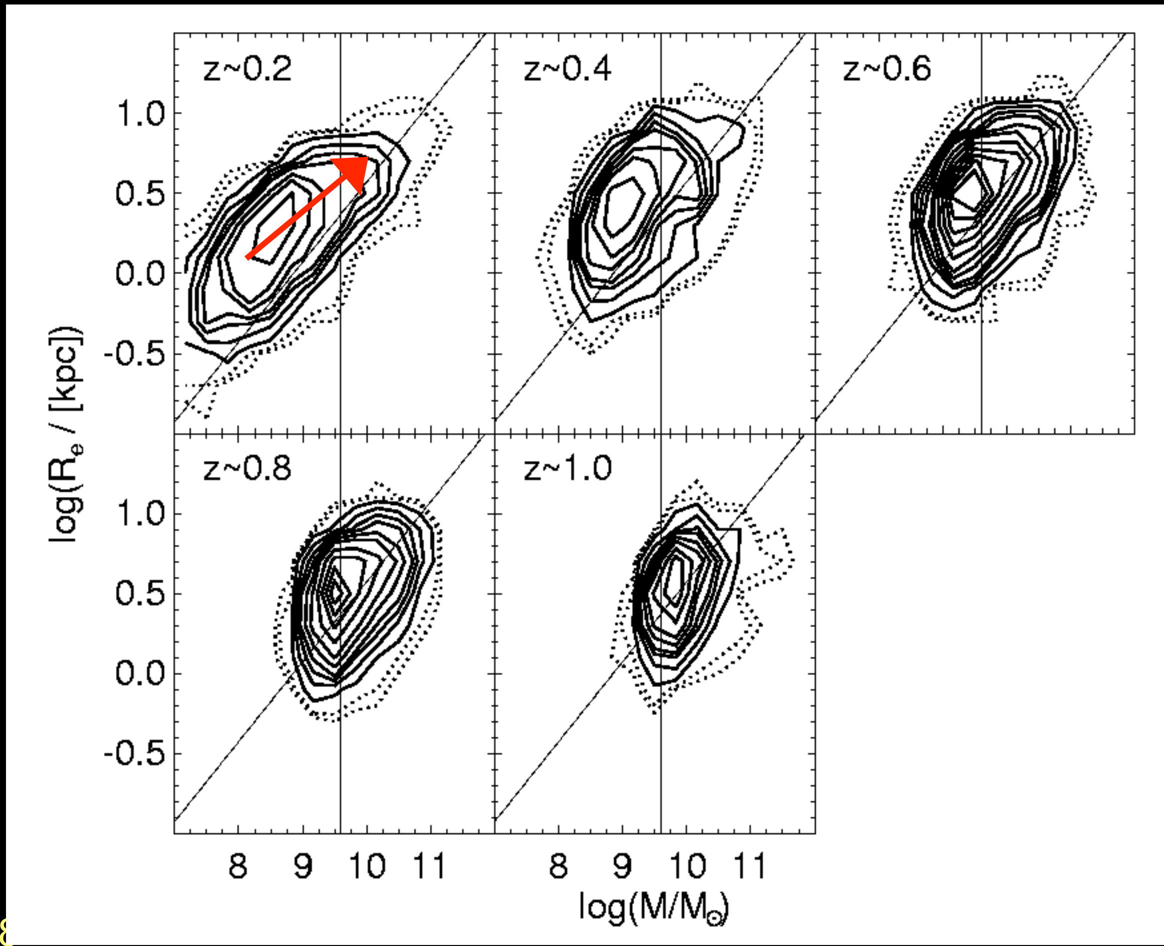
Summary and Outlook

Discussion I

- Disk galaxies grow inside-out, at least on average



Discussion II

- Stellar mass TF relation unchanging
  - As stellar mass grows, rotation velocity grows also
  - For inside-out growth, I may not have expected this
    - Instead, expected *lower* rotation velocity (if assumed baryonic TF relation fundamental)
  - SFR 5x higher; gas mass 3-5x higher (i.e., gas fractions of up to 50%)
    - Expected offsets <~0.3 dex
  - BUT, if stellar masses are overestimated at z~1, easier to understand…

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Introduction

The growth of the red sequence

Can mergers drive growth of the red sequence?

introduction
merger rates
assumptions
results

Summary

Galaxy merging - driving the growth of the red sequence?

i) Mergers create spheroids

ii) Merger initiates feedback which quenches SF

(recall spheroids empirically associated with quenched SF)

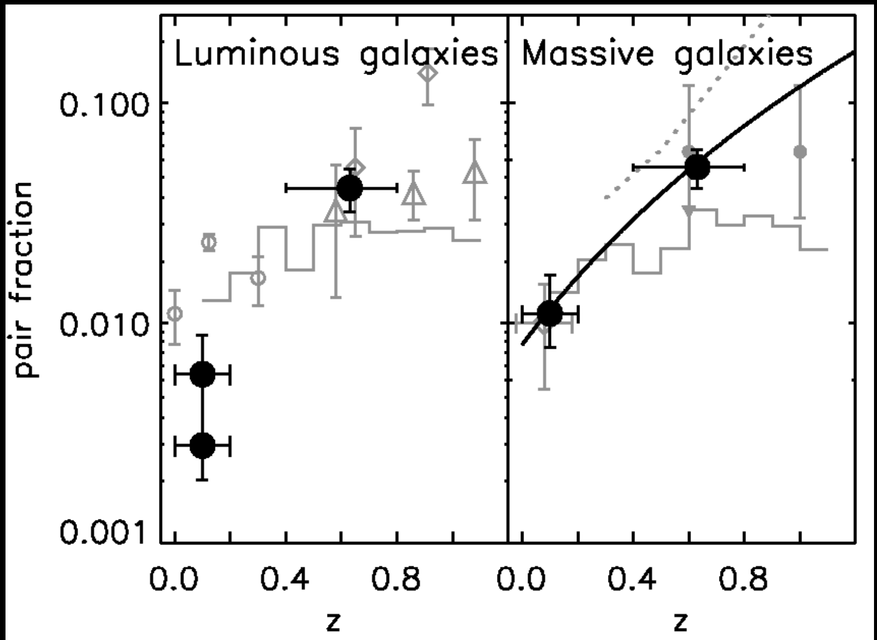
Springel, MPA

I. Merger rates

- Merger rates
  - 2 point correlation function --> fraction of galaxies in close pairs in 3D space (through deprojection)

$M_B < -20$

z~0.6 COMBO-17
z~0.1 2dFGRS



$M > 2.5x10^{10}\ M_\odot$

z~0.6 COMBO-17
z~0.1 SDSS/2MASS

Bell et al. 2006

II. Assumptions

- Assume
  - Mergers between galaxies $2.5\times10^{10}\ M_\odot$ galaxies ➔ red galaxies with $> 5\times10^{10}\ M_\odot$
  - All r<30kpc pairs merge (limit)
  - Timescale ~ 2πr / v
    - r_{av} ~ 15kpc, v ~ 150km/s ➔ timescale ~ 0.4Gyr
    - Very uncertain
  - Only way to make z<1 $5\times10^{10}\ M_\odot$ galaxy is through merging
- Predict rate of growth of number of red galaxies with $> 5\times10^{10}\ M_\odot$

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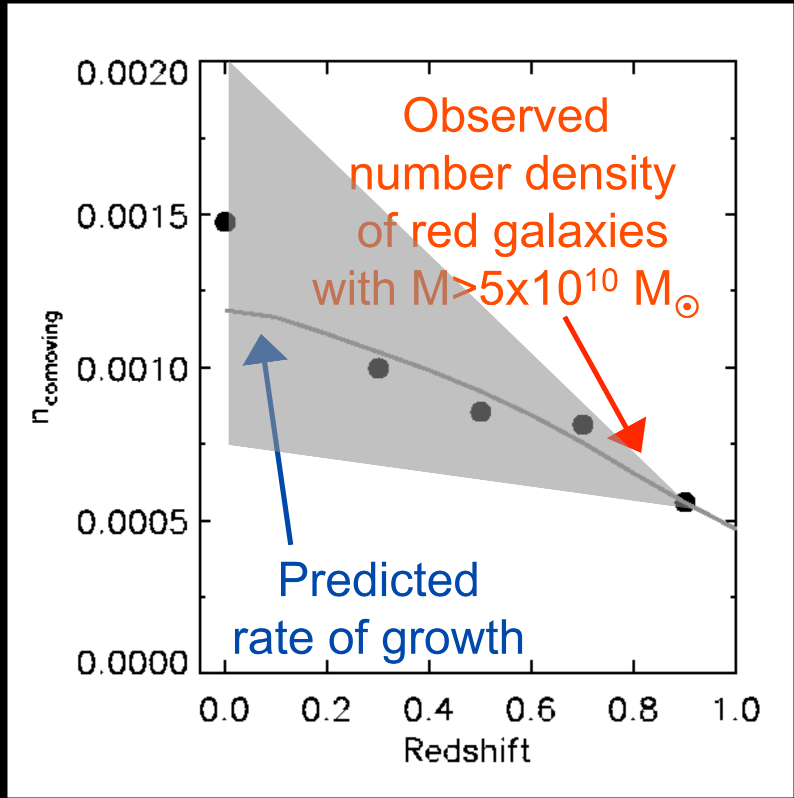
III. Results

- IF all mergers between gals with $M > 2.5 \times 10^{10}\ M_\odot$ → red sequence galaxy $M > 5 \times 10^{10}\ M_\odot$
  - There are enough mergers to plausibly feed the growth of red sequence



Introduction

The growth of the red sequence

Can mergers drive growth of the red sequence?

Summary

Galaxy Mergers

- Galaxy Merging
  - Insight into dark matter-driven galaxy assembly and therefore galaxy structures
  - Potential driver of star formation history
- Key results
  - Correlation between structure and star formation history
  - Ongoing red galaxy/spheroid creation
  - Rates of growth consistent with merger rate
- Challenges
  - Larger datasets - better pair fractions and environments
  - Simulations calibrate timescales and merger probabilities
  - Extension to infrared opens up $z>1$ Universe

Heidelberg
March-April 2008

Eric Bell

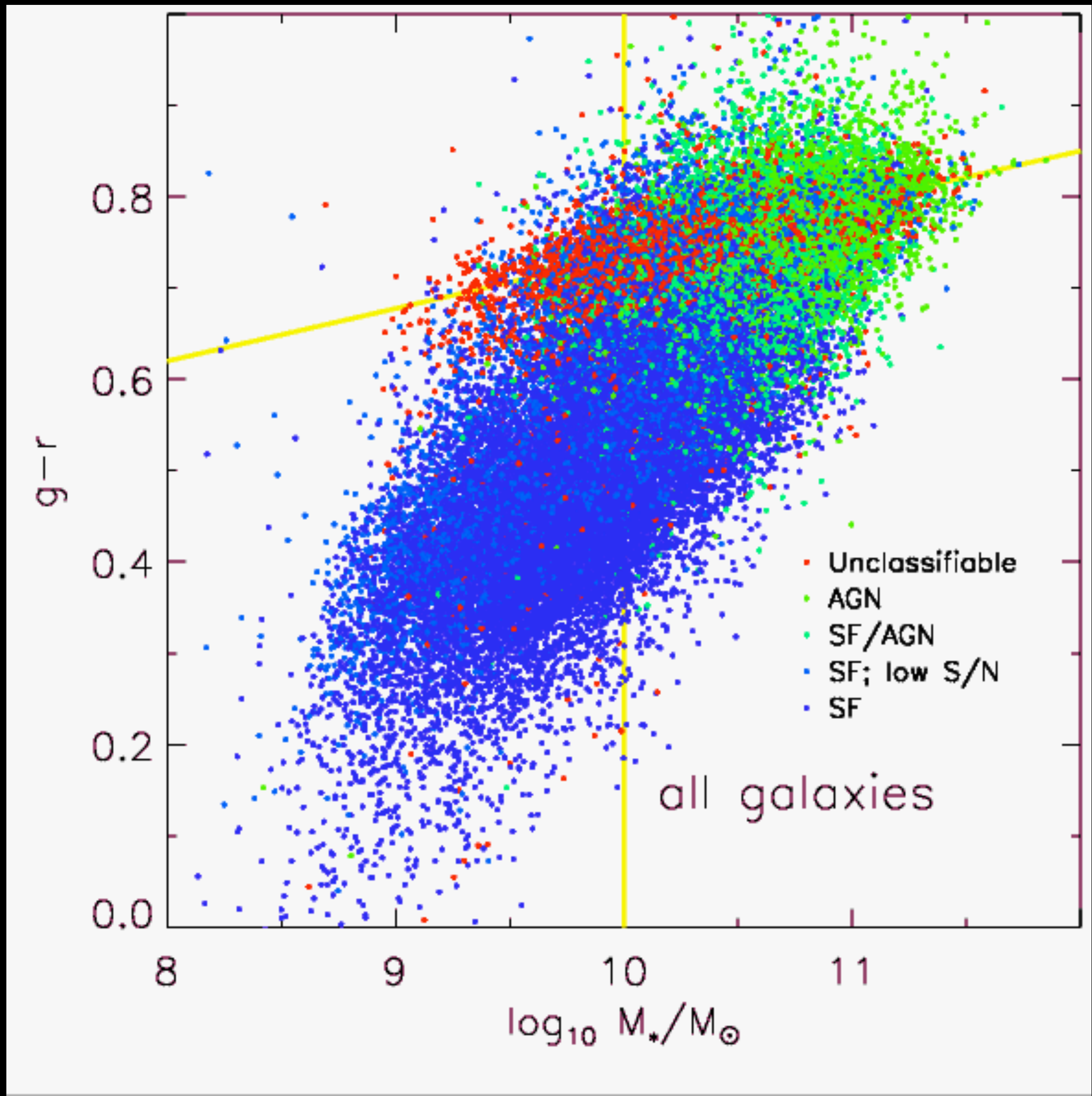
Introduction

Star formation in disks

Transformation of disks to early types

Scaling relations

Summary and Outlook



SDSS DR2

NYU VAGC
Blanton+05

Group catalog
Yang et al 05

SF/AGN
Brinchmann+04

Bell, submitted to ApJ

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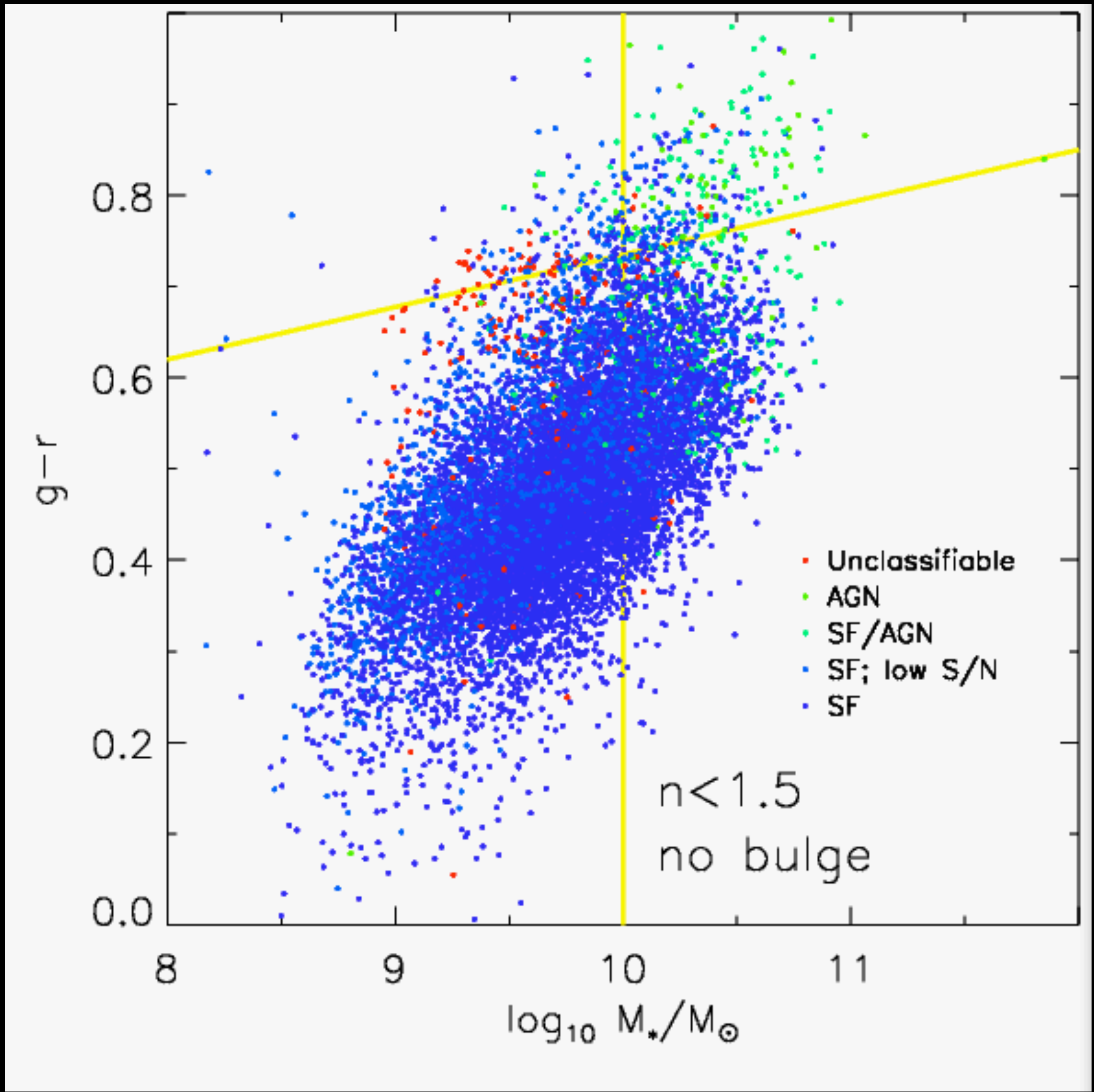

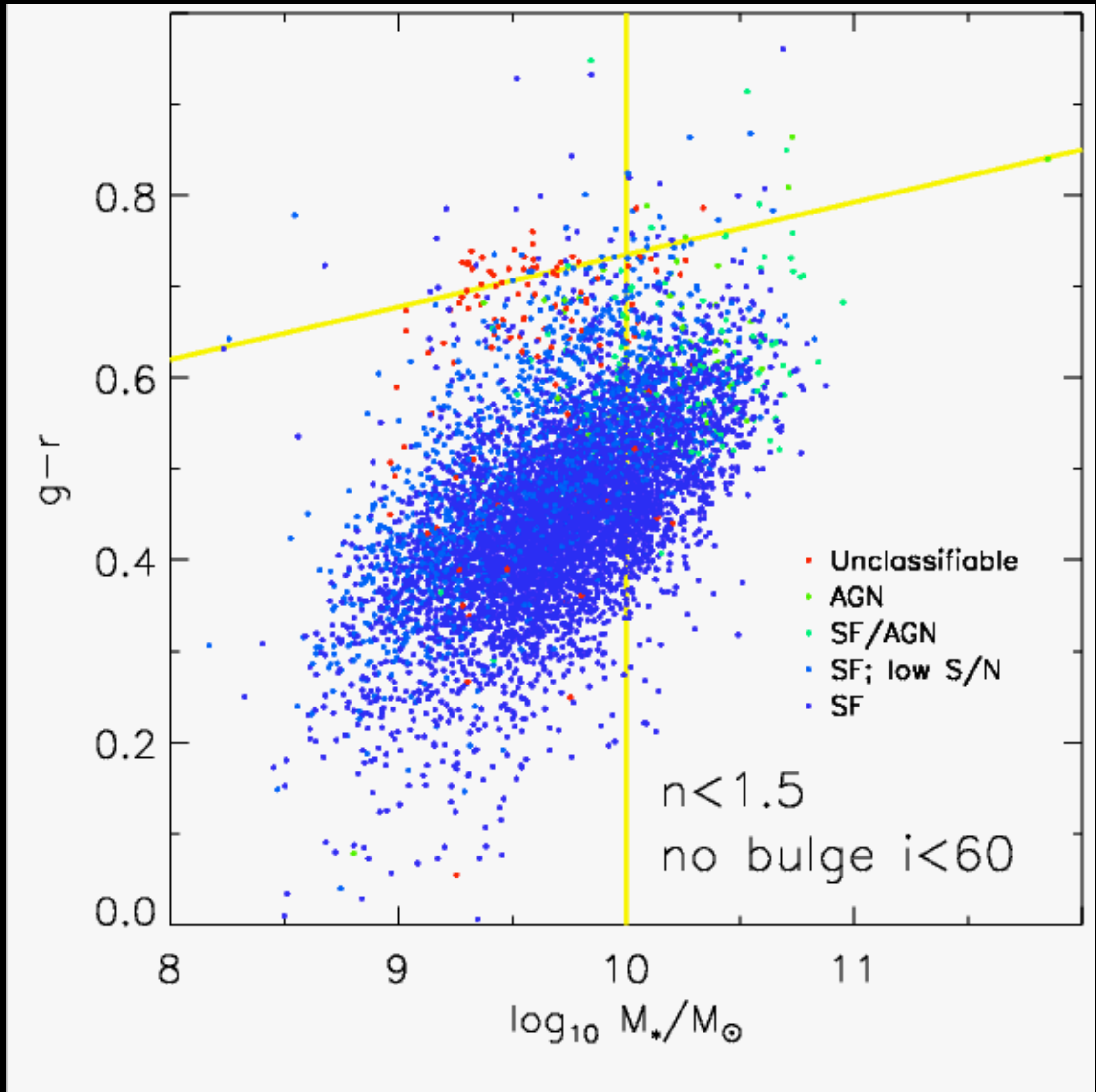
0.8
0.6
0.4
0.2
0.0
g−r
8
9
10
11
log10 M*/M⊙
Unclassifiable
AGN
SF/AGN
SF; low S/N
SF
n<1.5
no bulge i<60

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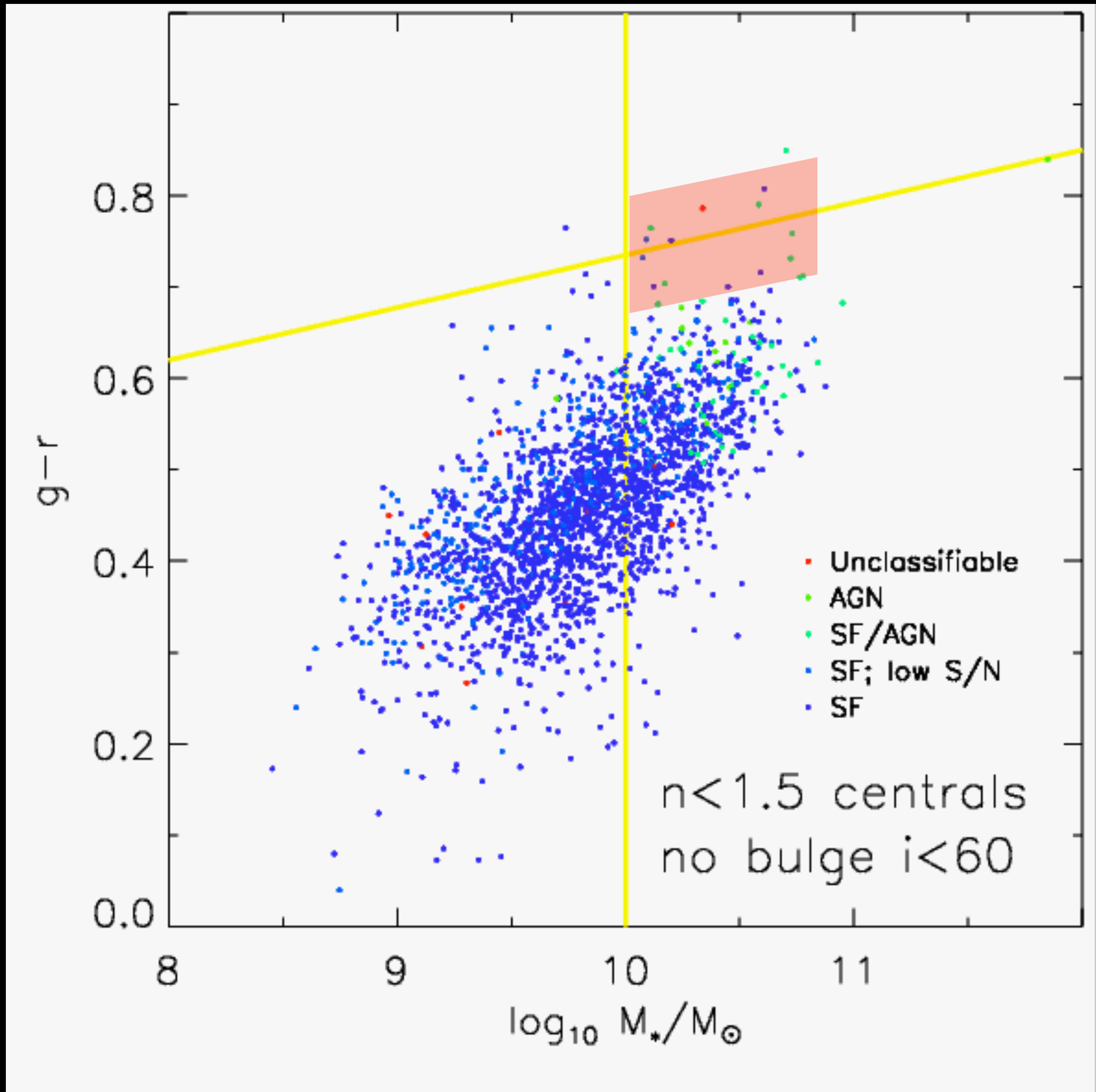

Many red sequence n<1.5 have AGN

* Internally-driven transform Sd-Im to Sph unlikely (predict all Sph satellites)

Bulge (SMBH) requirement for quenching for central galaxies