Galaxies and Extragalactic Astrophysics

4. Global Properties of Galaxies

4. Global Properties of Galaxies

4.1 Introduction

- Observationally, galaxies are studied in two ways
  - imaging: observing the integrated flux in a relatively broad wavelength range (in a filtre or in a band)
  - spectroscopy: observing the integrated flux using a dispersing element
- These observations are interpreted with theoretical models and numerical simulations

4. Global Properties of Galaxies

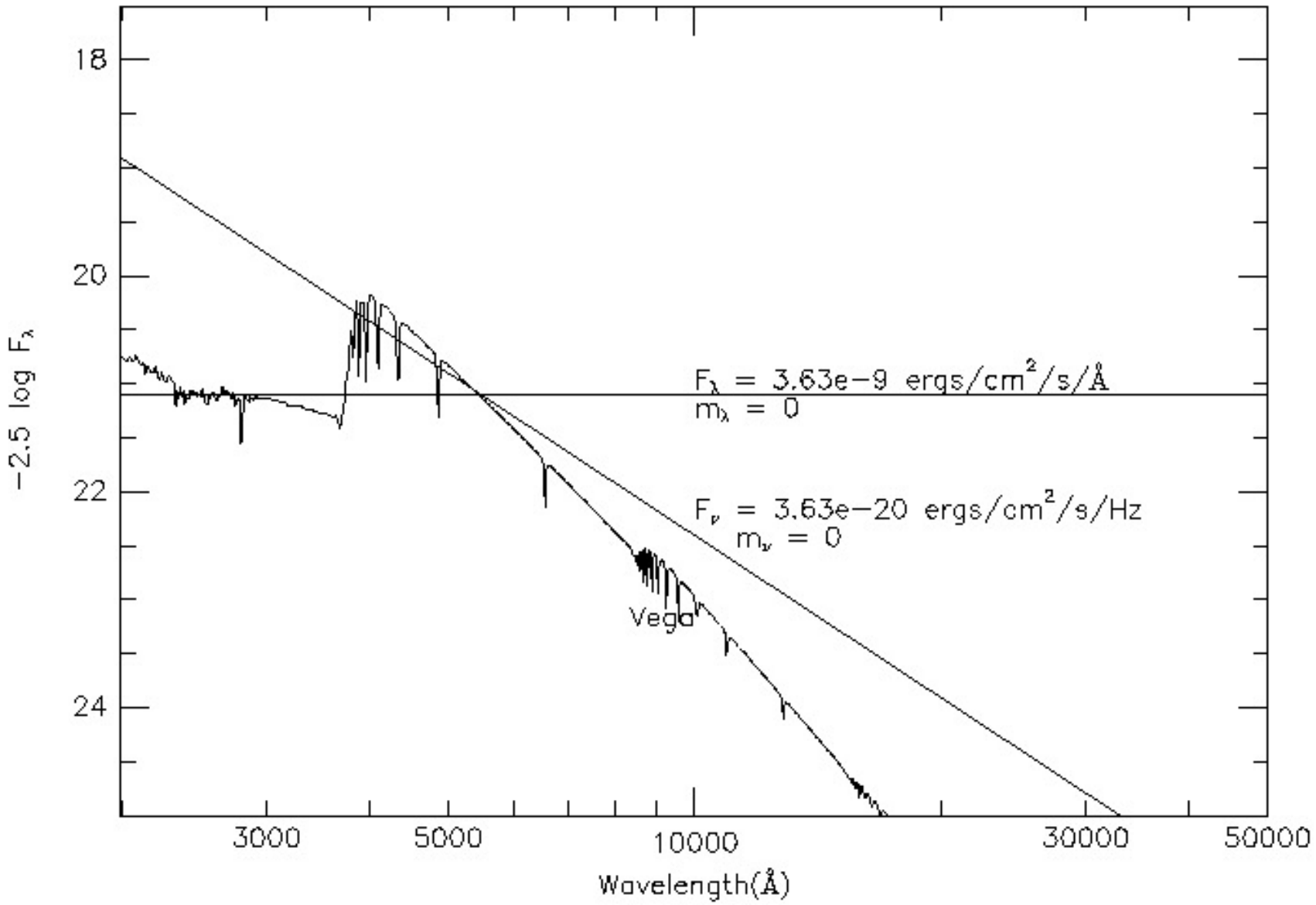
4.2 Photometric Properties

- Luminosity: emitted energy per unit time
  - bolometric: total luminosity (in the whole spectral range)
  - band: luminosity in a determined spectral range
  - units: solar units (Lsolar = 3.9 10^{33} erg/s), erg/s, W
- Flux: received energy per unit time and unit area
  - $f = L / 4\pi d_l^2$ (luminosity distance)
  - units: erg/s/cm^2
- Flux density: received energy per unit time, unit area and unit frequency (or wavelength)
  - units: erg/s/cm^2/Hz, erg/s/cm^2/Å, Jy (=10^{-26} W/m^2/Hz)

4. Global Properties of Galaxies

4.2 Photometric Properties

- Magnitude: flux in logarithmic units
  - apparent and absolute
  - magnitude measurement: aperture magnitude, isophotal magnitude, model magnitude, total magnitude, Petrosian magnitude, Kron magnitude
  - units: Vega and AB systems
- Colour: magnitude difference (or flux ratio) in different wavelengths
  - hardness ratio
  - optical colours
  - flux ratios


18
20
22
24
−2.5 log F_λ
F_λ = 3.63e−9 ergs/cm^2/s/Å
m_λ = 0
F_ν = 3.63e−20 ergs/cm^2/s/Hz
m_ν = 0
Vega
3000
5000
10000
30000
50000
Wavelength(Å)

4. Global Properties of Galaxies

4.2 Photometric Properties

- Size: (radius or semiaxes)
  - radius from a light profile model (R_e, R_d)
  - isophotal radius
  - light percentage radius (R_{50})
  - units: angular radius (“), metric radius (kpc)
  - angular distance: $d_a \sim r / \theta$

4. Global Properties of Galaxies

4.2 Photometric Properties

- Surface brightness : brightness per unit area
  - brightness within the radius coming from a light profile model (R_e, R_d)
  - brightness within the radius encompassing 50% of the flux (R_{50})
  - mean surface brightness at the effective radius: $\langle I \rangle_e$, $\langle \mu \rangle_e$
  - $\langle \mu \rangle_e = -2.5 \log \langle I \rangle_e$
  - $\langle I \rangle_e = (L/2)/\pi R_e^2$
  - $\langle \mu \rangle_e = m + 2.5 \log (2\pi R_e^2)$
  - $\langle \mu \rangle_e = m + 2.5 \log (2\pi R_e^2) - K(z) - 10 \log (1+z)$
  - units: μ (mag/arcsec^2), I (erg/s/cm^2/arcsec^2)

4. Globals Properties of Galaxies

4.3 Morphological Properties

- Morphological type: global structure of the galaxy: ellipticals, spirals, irregulars,…
- Inclination: (for flattened systems) angle between the line of sight and the perpendicular to the rotation plane
- Ellipticity (elongation): ratio of semiaxes sizes
- Light distribution
- moments of the light distribution (position, ellipticities)

4. Global Properties of Galaxies

4.4 Spectroscopic Properties

- Spectrum: F_λ, F_ν
- Redshift: $(1+z) = \lambda_{obs}/\lambda_{rest}$
- Spectral type
- Spectral lines

  equivalent widths: $EW = \int (F_\lambda^c - F_\lambda)/F_\lambda^c \, d\lambda$

  Line fluxes

4. Global Properties of Galaxies

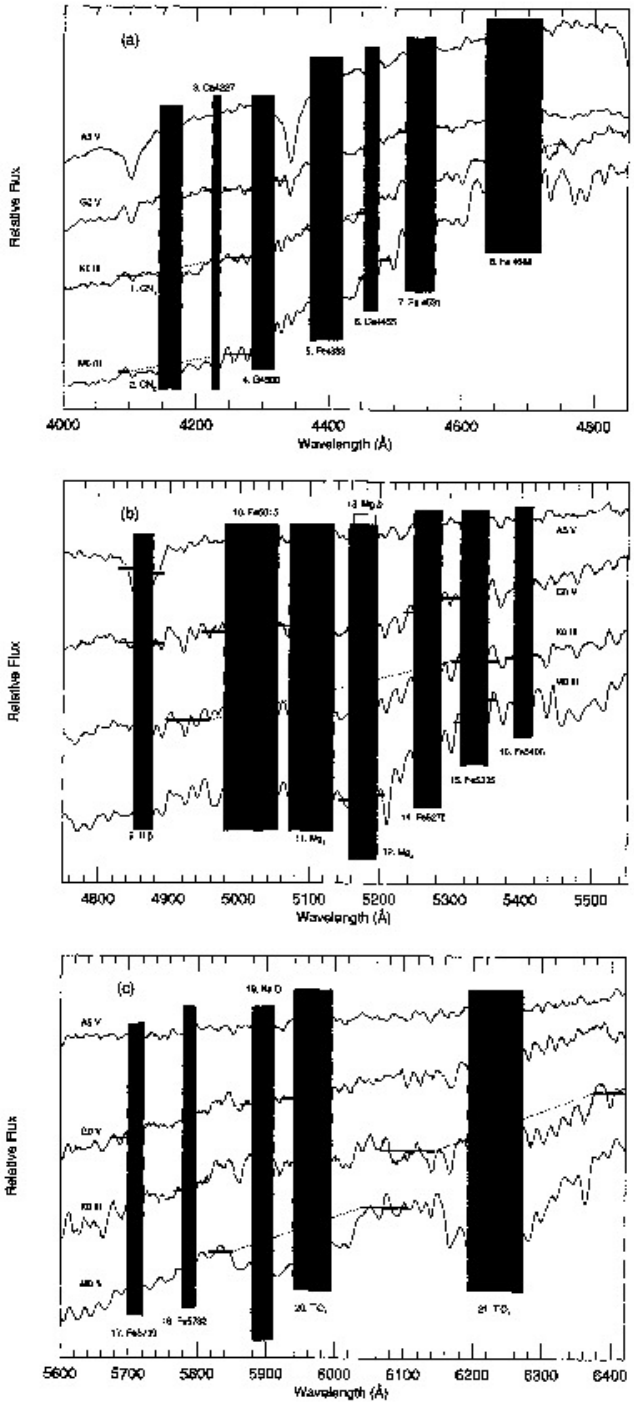
4.4 Spectroscopic Properties

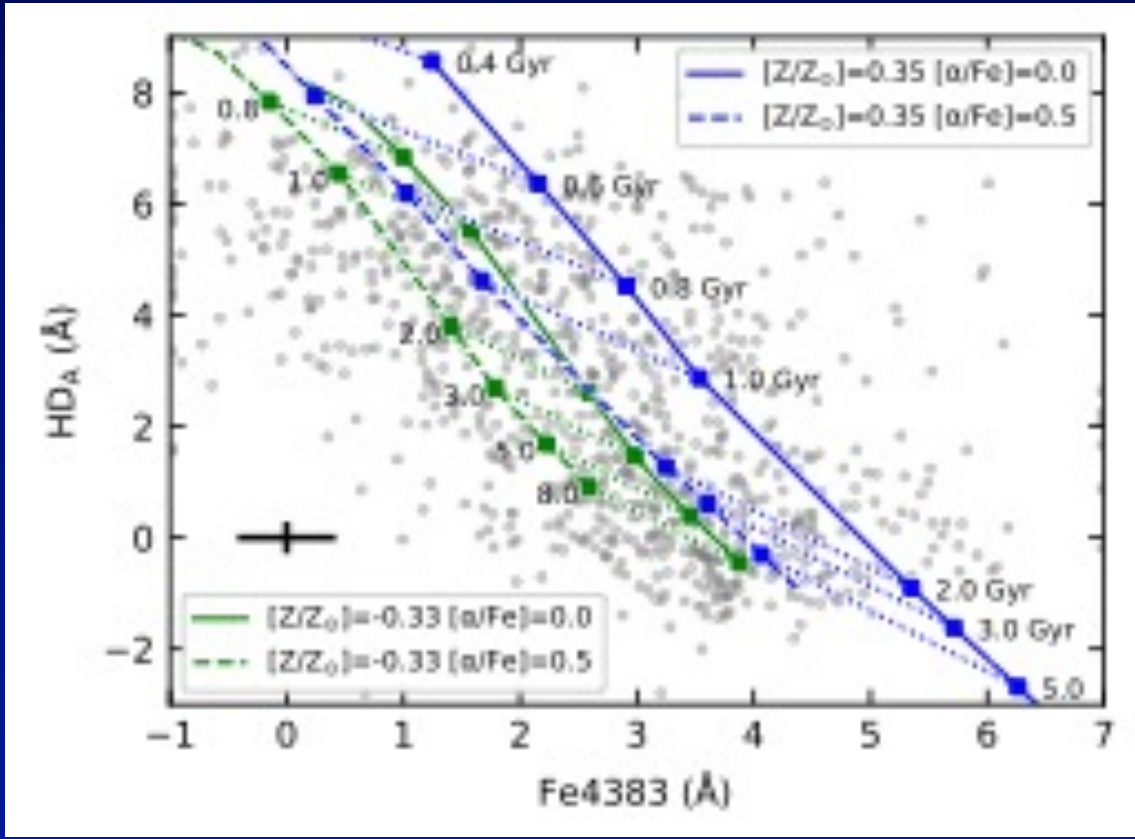
- Metallicity

  Z, Z/Zsolar (Zsolar=0.02), [M/H], 12+log[O/H] (solar=8.69)

- Age of the stellar population
- Lick indices (EW, mag)
- Star formation rate (SFR)
- Initial mass function (IMF)

Lick indices





Lick indices

4. Global Properties of Galaxies

4.5 Dynamical Properties

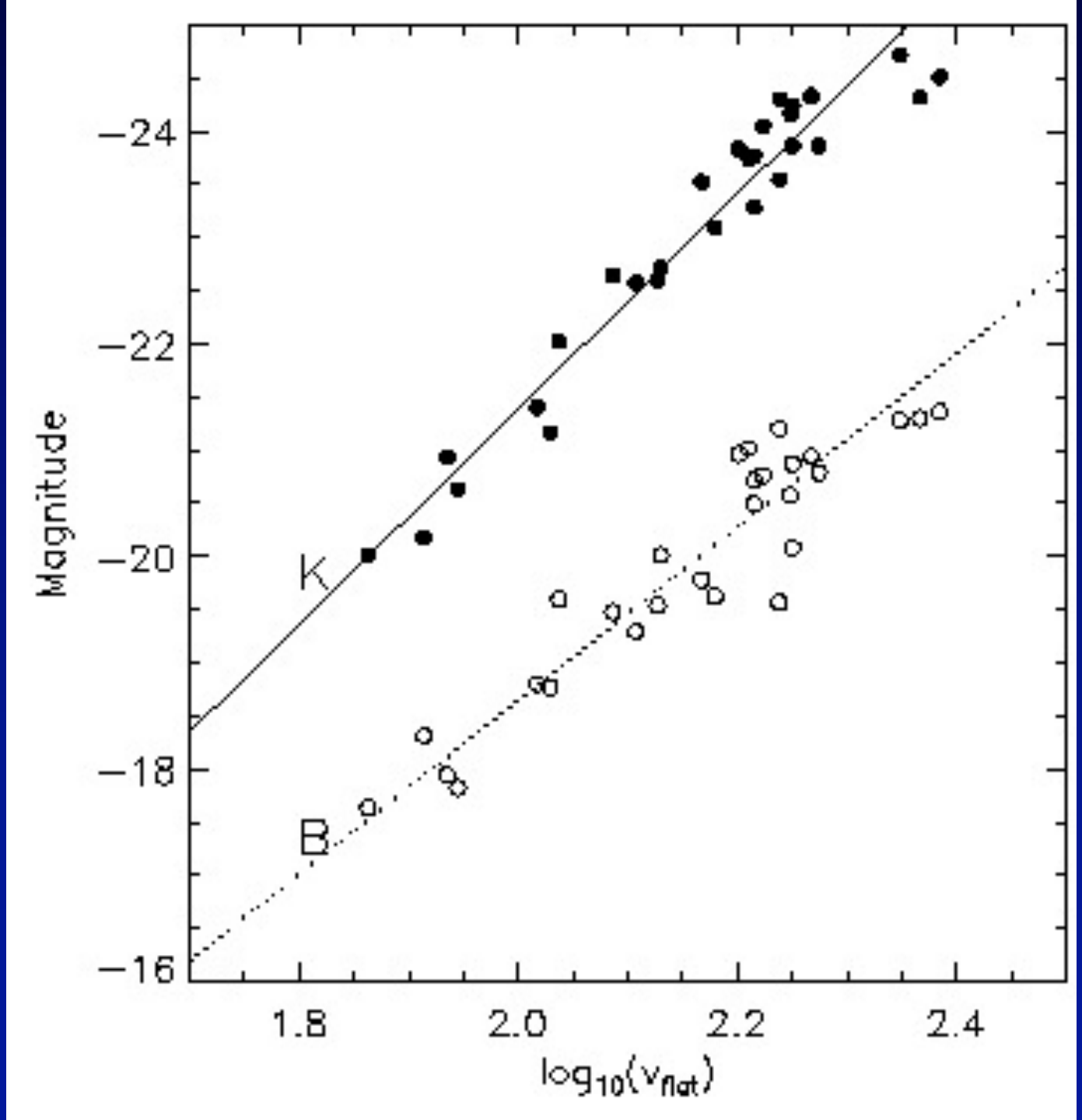
- line of sight distribution function and its moments
- velocity dispersion
- rotation velocity
- mass
- mass-to-light ratio

  solar units

4. Global Properties of Galaxies

4.6 Correlations between parameters

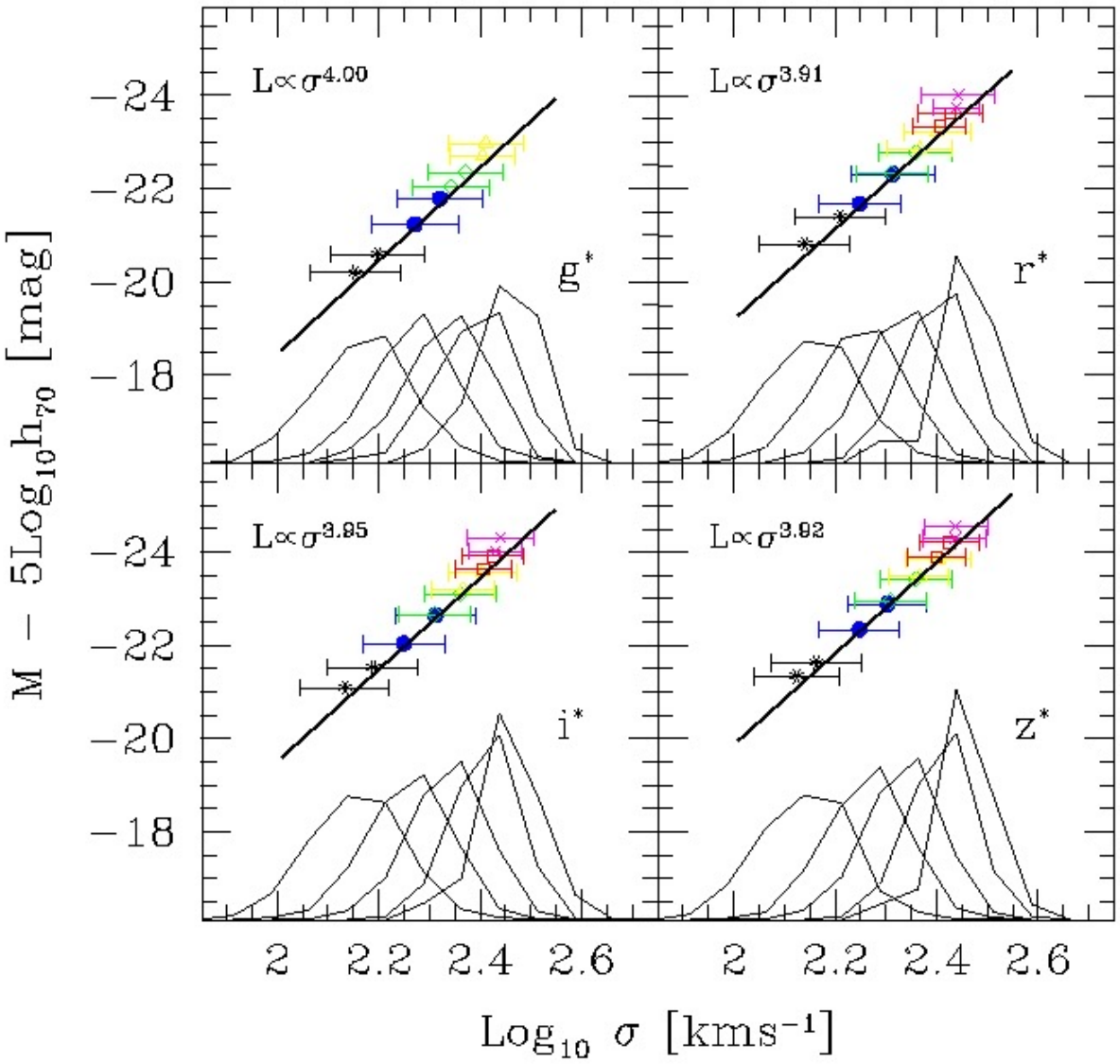
- Tully-Fisher
  - Tully & Fisher (1977) found a correlation between the luminosity (or absolute magnitude) of spiral galaxies and their rotation velocity
  - $L \alpha v_c^4$
  - distance indicator


−24
−22
−20
−18
−16
Magnitude
K
B
1.8
2.0
2.2
2.4
log10(vflat)

4. Global Properties of Galaxies

4.6 Correlations between parameters

- Faber-Jackson
  - Faber & Jackson (1976) found a correlation between the luminosity (or absolute magnitude) of elliptical galaxies and their velocity dispersion
  - $L \alpha \sigma^4$


L∝σ4.00
L∝σ3.91
L∝σ3.85
L∝σ3.92
g*
r*
i*
z*
−24
−22
−20
−18
2
2.2
2.4
2.6
M − 5Log10h70 [mag]
Log10 σ [kms−1]

4. Global Properties of Galaxies

4.6 Correlations between parameters

- D_n-σ
  - Dressler (1987) defined a photometric parameter D_n that correlates well with the central velocity dispersion
  - D_n is the diameter at a surface brightness of 20.75 in the B band
  - Advantage: it's easy to measure in a robust way
  - elliptical and lenticular galaxies
  - correlation with intrinsic scatter of 15%
  - $(D_n/\mathrm{kpc}) = 2.18\ (\sigma/100\ \mathrm{km/s})^{1.33}$ (Virgo at 17 Mpc)
  - Distance indicator

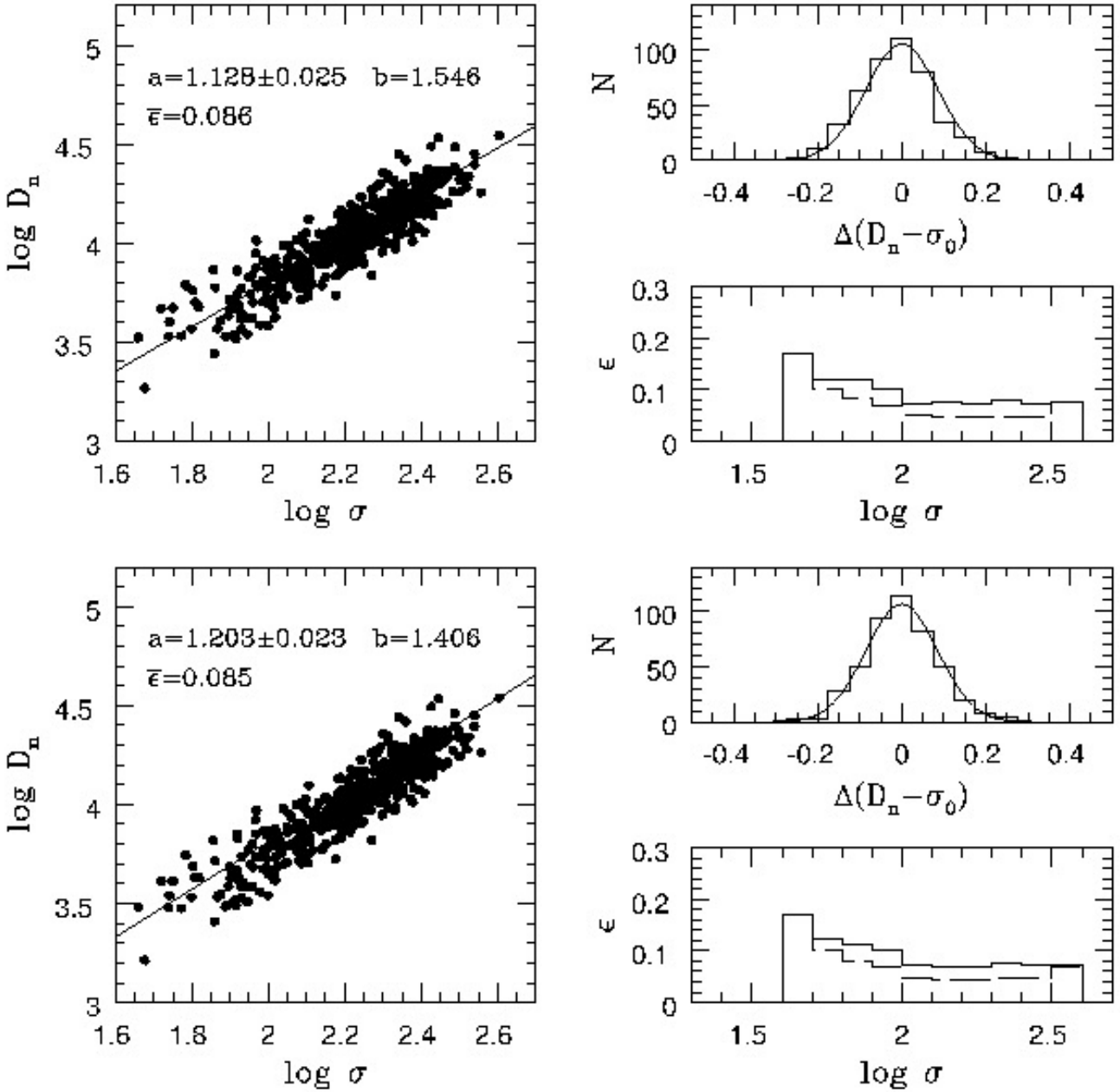


FIG. 4. *Left panels:* Measurements before the bias correction is applied (*upper panel*) and the final corrected values derived from the iterative process (*lower panel*) as a function of σ. The line shows the derived distance relation. The values of the slope (a), zero point (b), and mean rms scatter ($\bar{\epsilon}$) are also shown. *Right panels:* Distribution of the residuals relative to the D_n-σ relation, as well as the distribution of the corresponding observed scatter (*solid line*) and intrinsic scatter (*dashed line*) as a function of σ.

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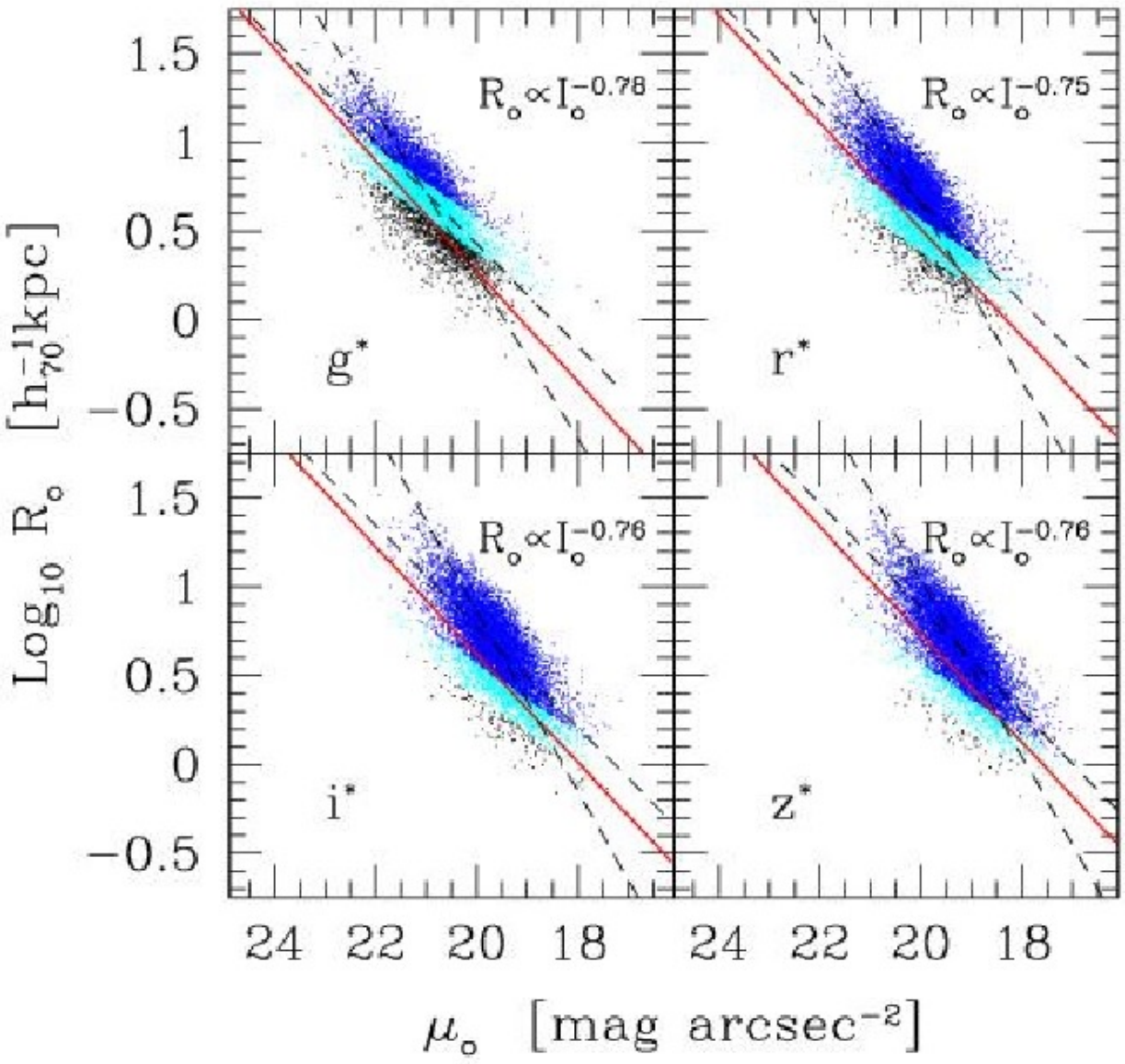
4.6 Correlations between parameters

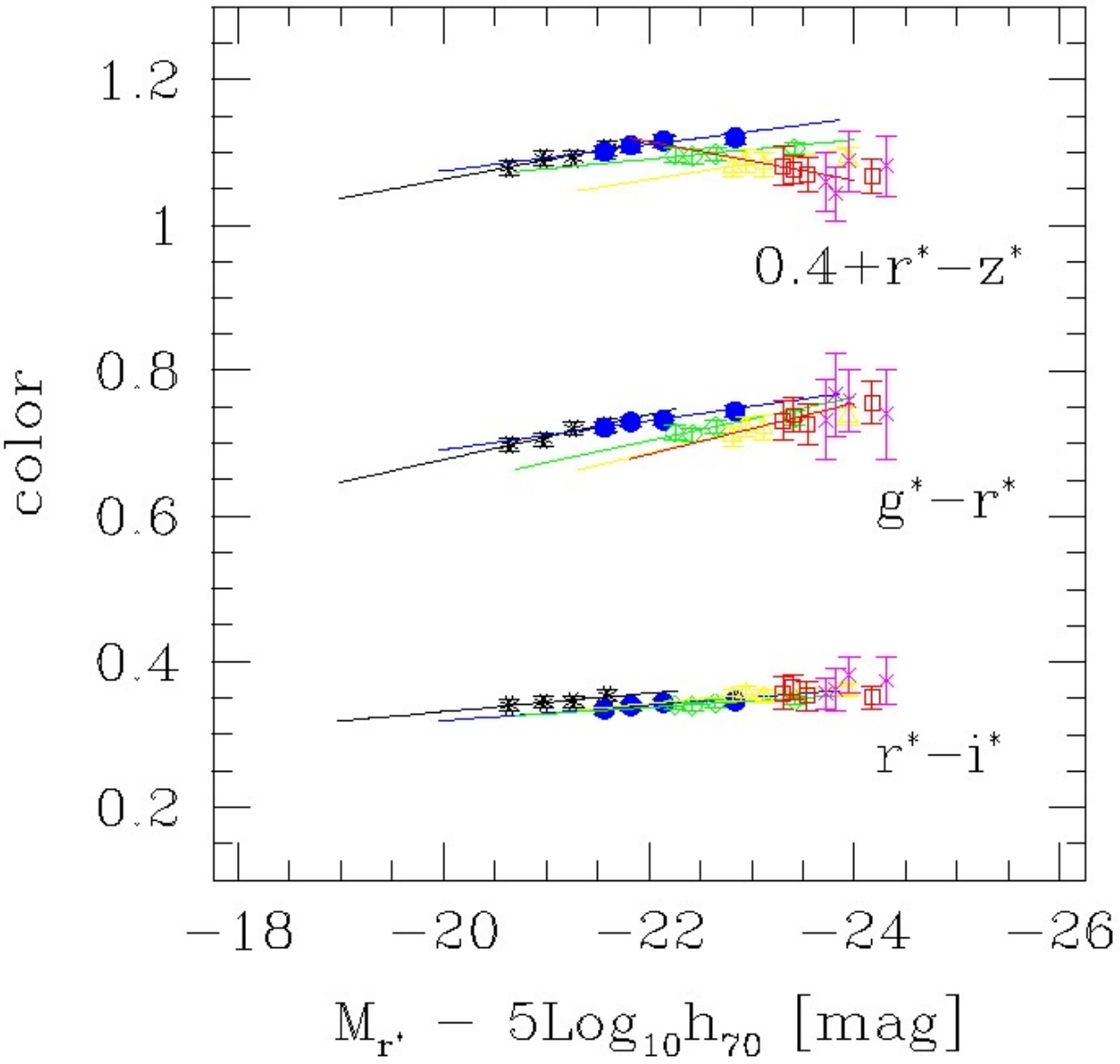
- Kormendy
  - Kormendy (1977) found a correlation between the surface brightness and the effective radius of elliptical galaxies
  - $R_e \alpha \langle I \rangle_e^{-0.75}$
  - The larger ellipticals present a fainter surface brightness

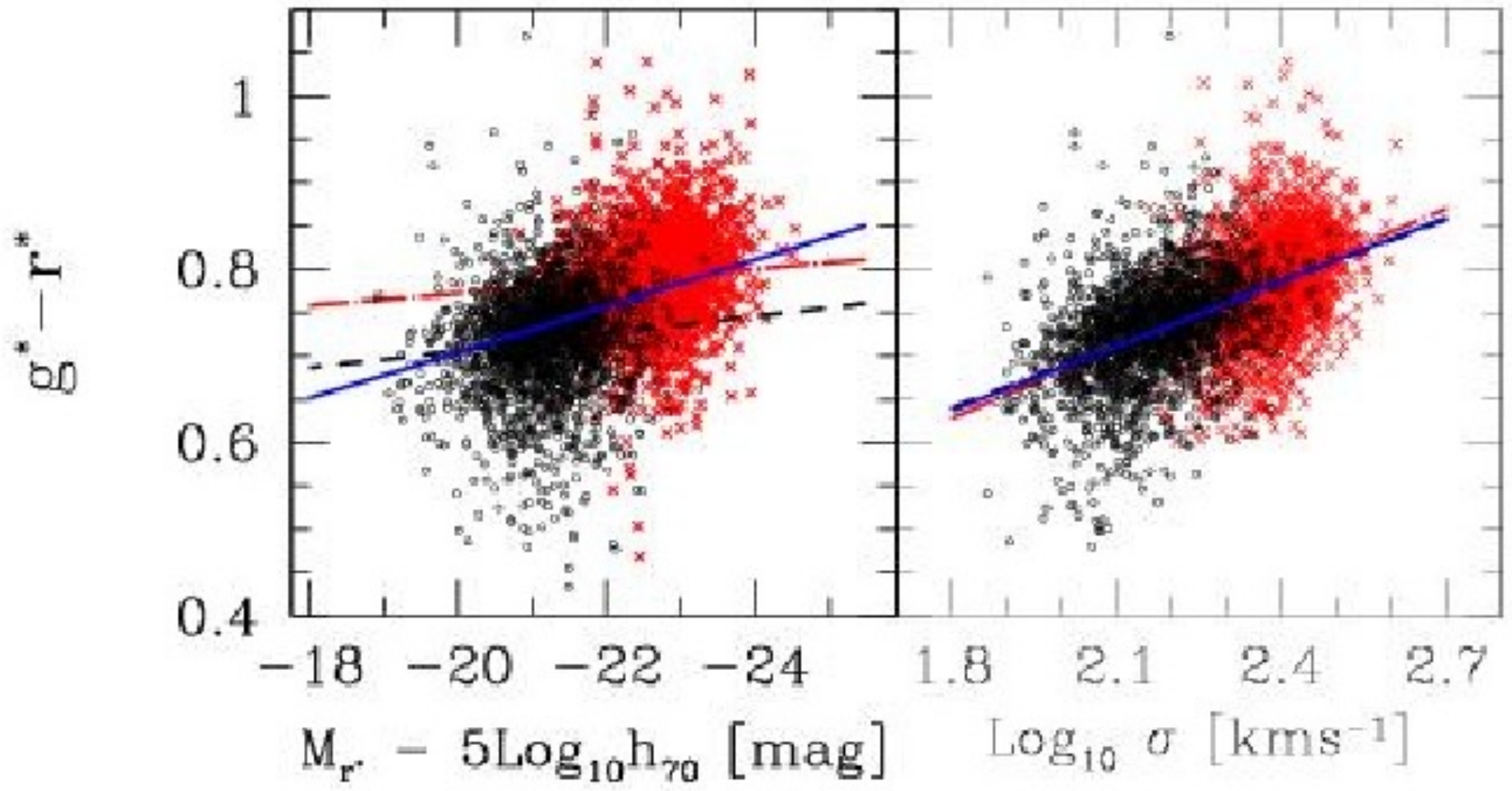

$R_o \propto I_o^{-0.76}$
$R_o \propto I_o^{-0.75}$
$R_o \propto I_o^{-0.76}$
$R_o \propto I_o^{-0.76}$
g*
r*
i*
z*
$\mathrm{Log}_{10}\ R_o\ [h_{70}^{-1}\mathrm{kpc}]$
μ_o [mag arcsec^{-2}]
1.5
1
0.5
0
−0.5
24
22
20
18

4. Global Properties of Galaxies

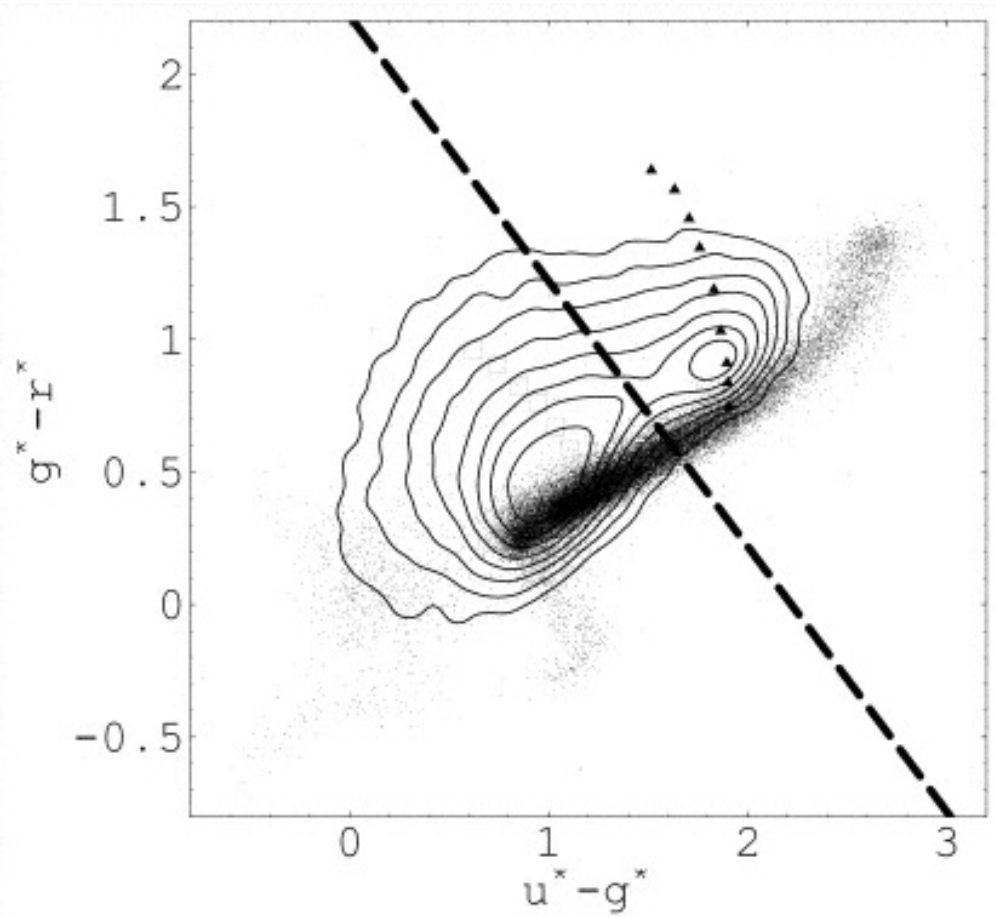
4.6 Correlations between parameters

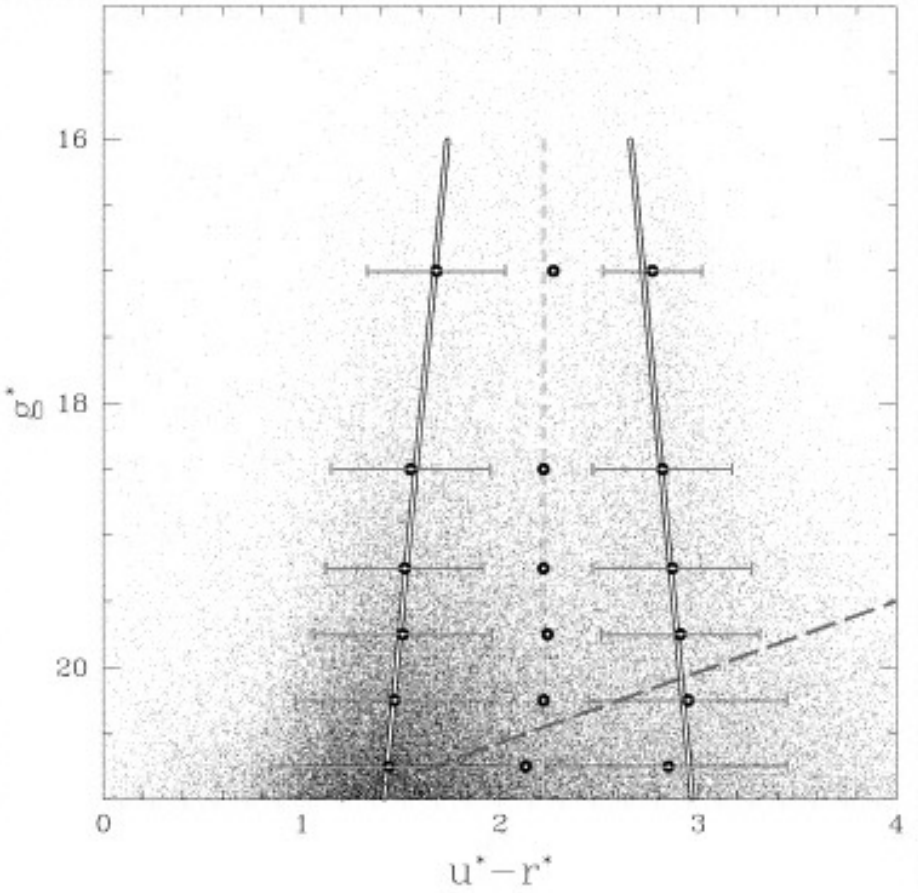
- Colour-magnitude relation
  - Visvanathan & Sandage (1977) found a correlation between the colour and magnitude of elliptical galaxies
  - The brightest ellipticals are the reddest
  - the slope value depends on the filters used


color
1.2
1
0.8
0.6
0.4
0.2
0.4+r*−z*
g*−r*
r*−i*
−18
−20
−22
−24
−26
M_r' − 5Log_10h_70 [mag]

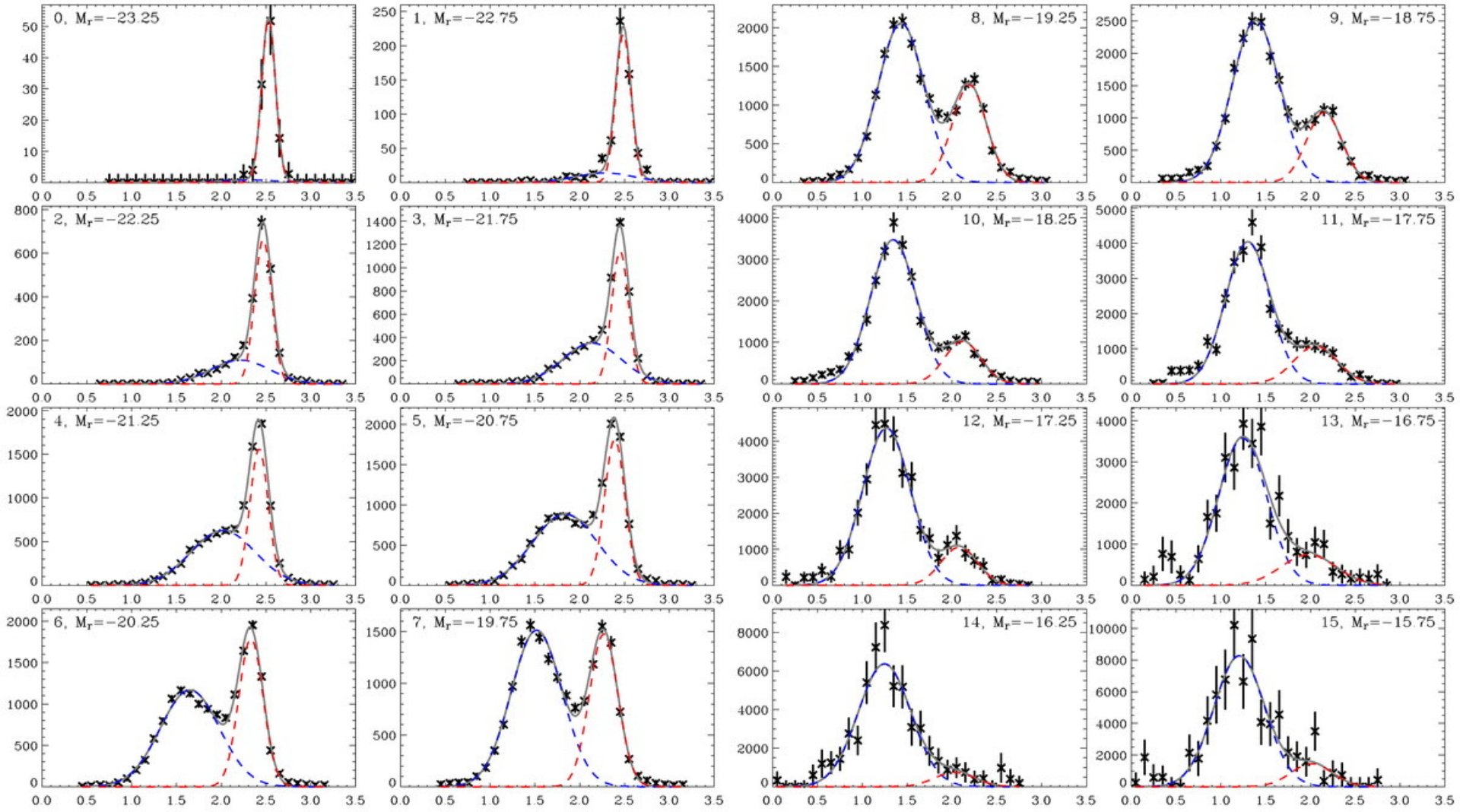

$^{*}g - r^{*}$
1
0.8
0.6
0.4
−18 −20 −22 −24
$M_{r^*} - 5\mathrm{Log}_{10}h_{70}$ [mag]
1.8 2.1 2.4 2.7
$\mathrm{Log}_{10}\,\sigma$ [kms^{-1}]

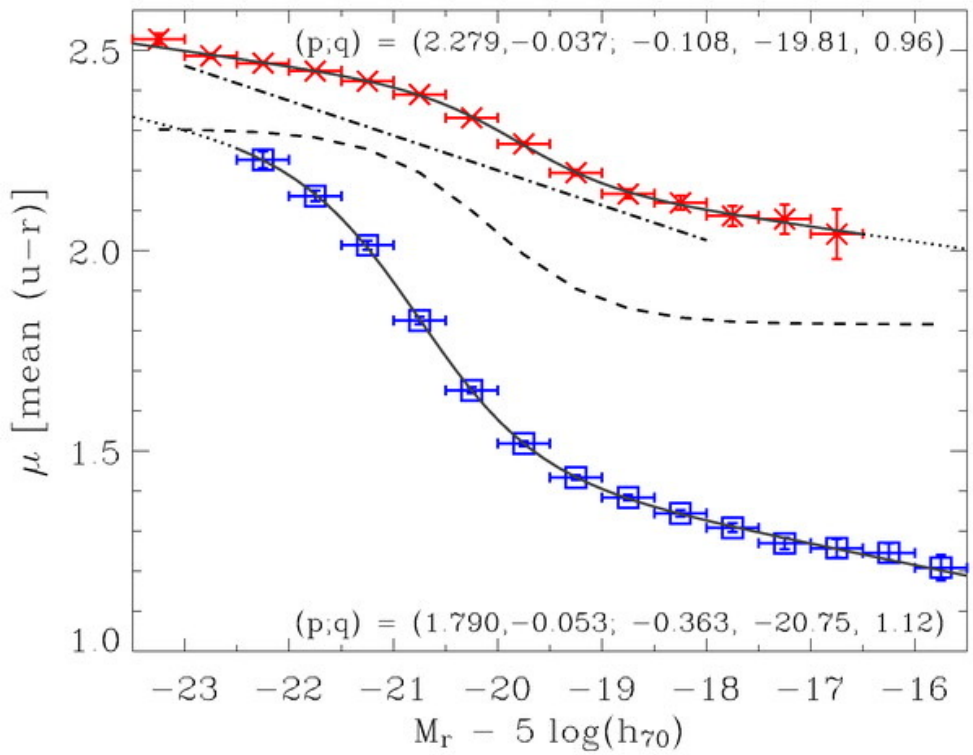
Strateva et al 01

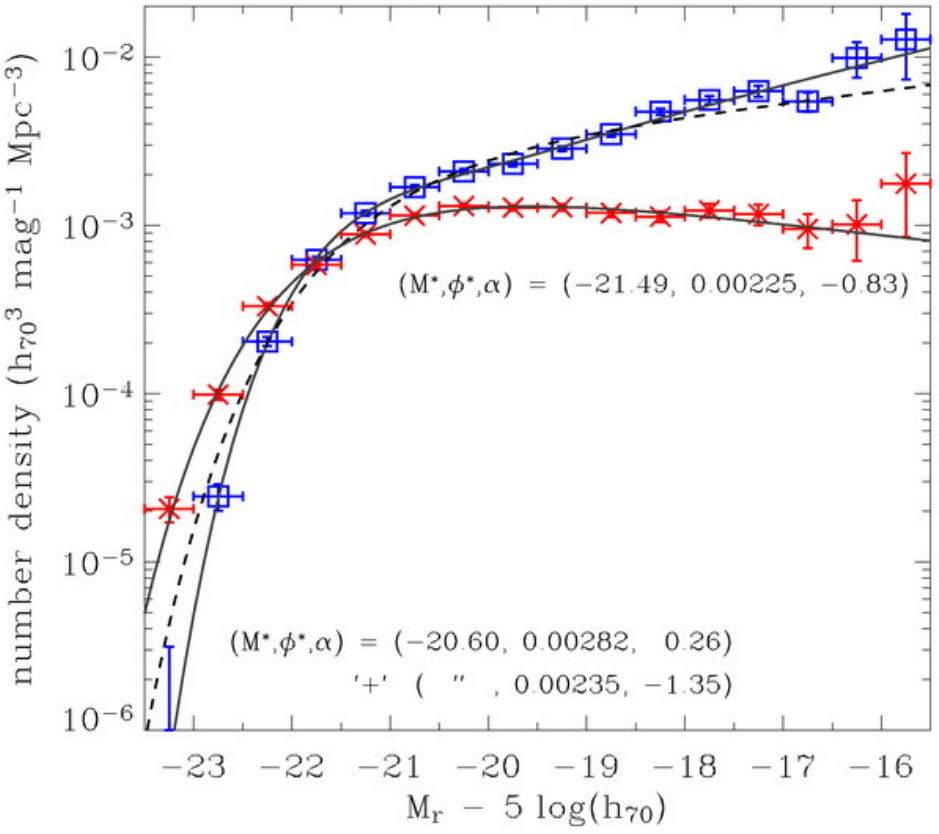




Baldry et al 04

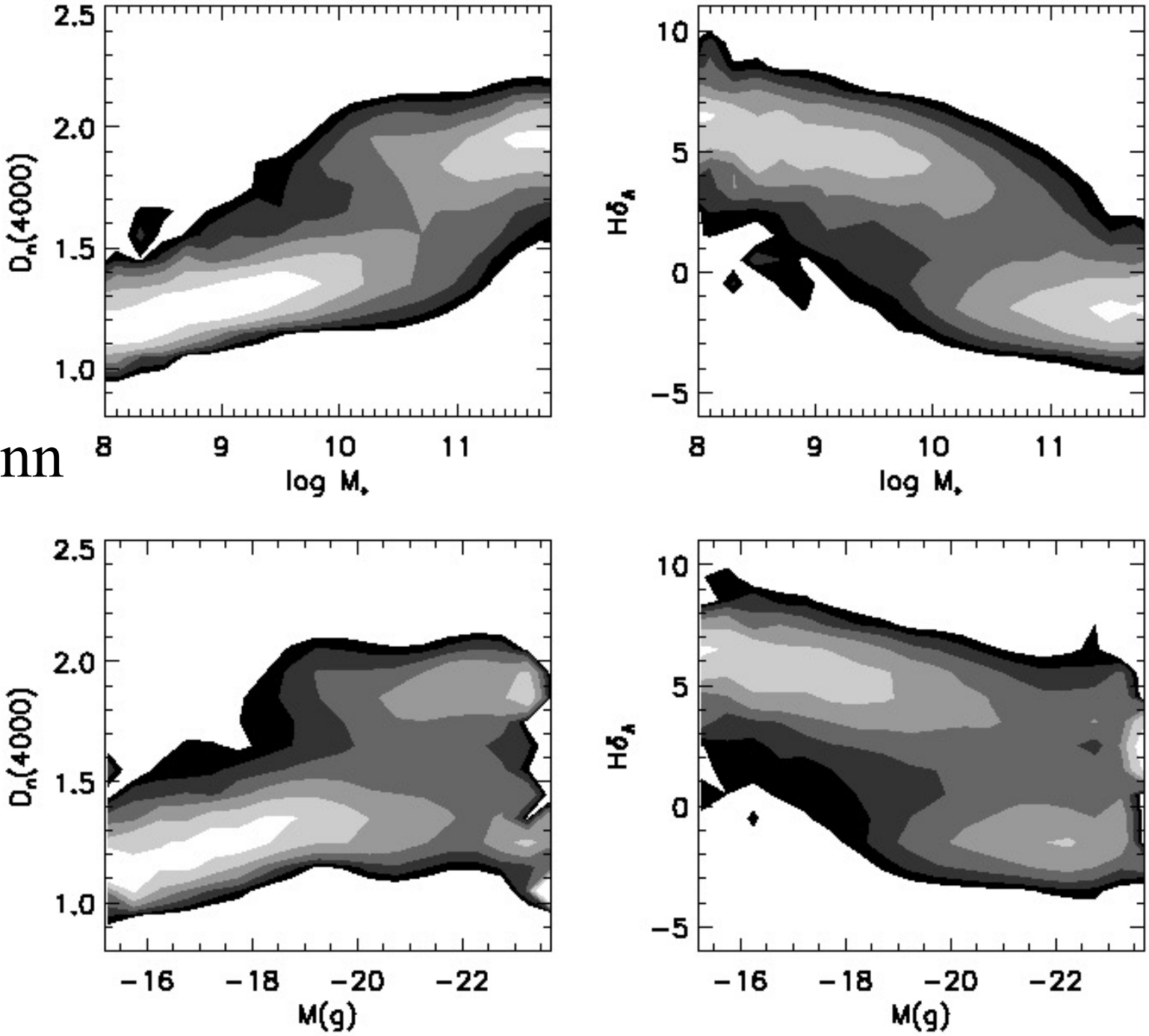






Baldry et al 04

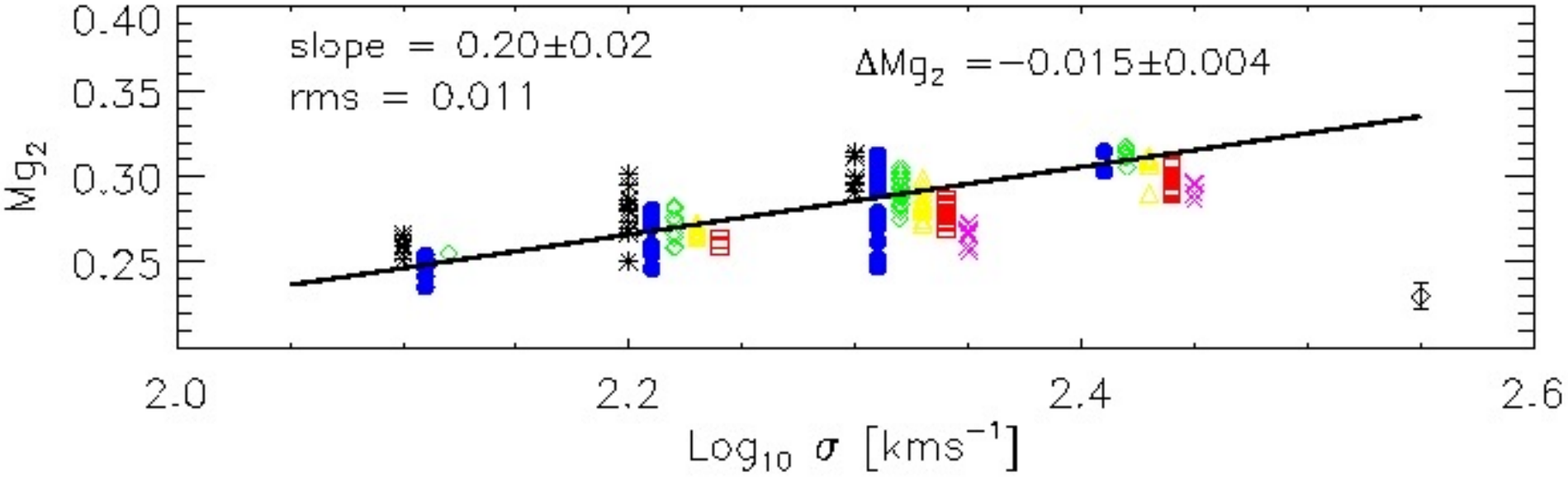
Kauffmann et al 03b

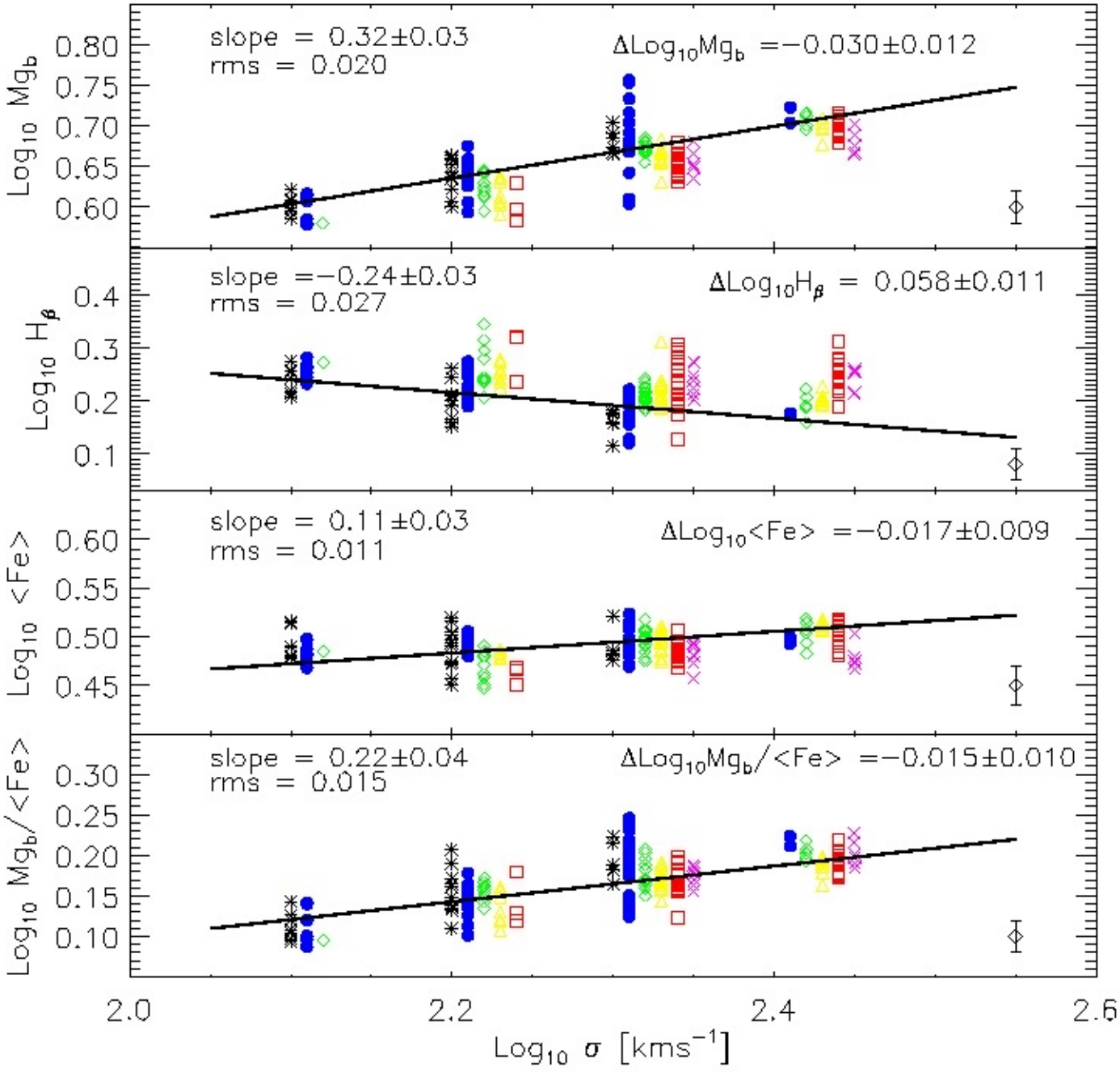


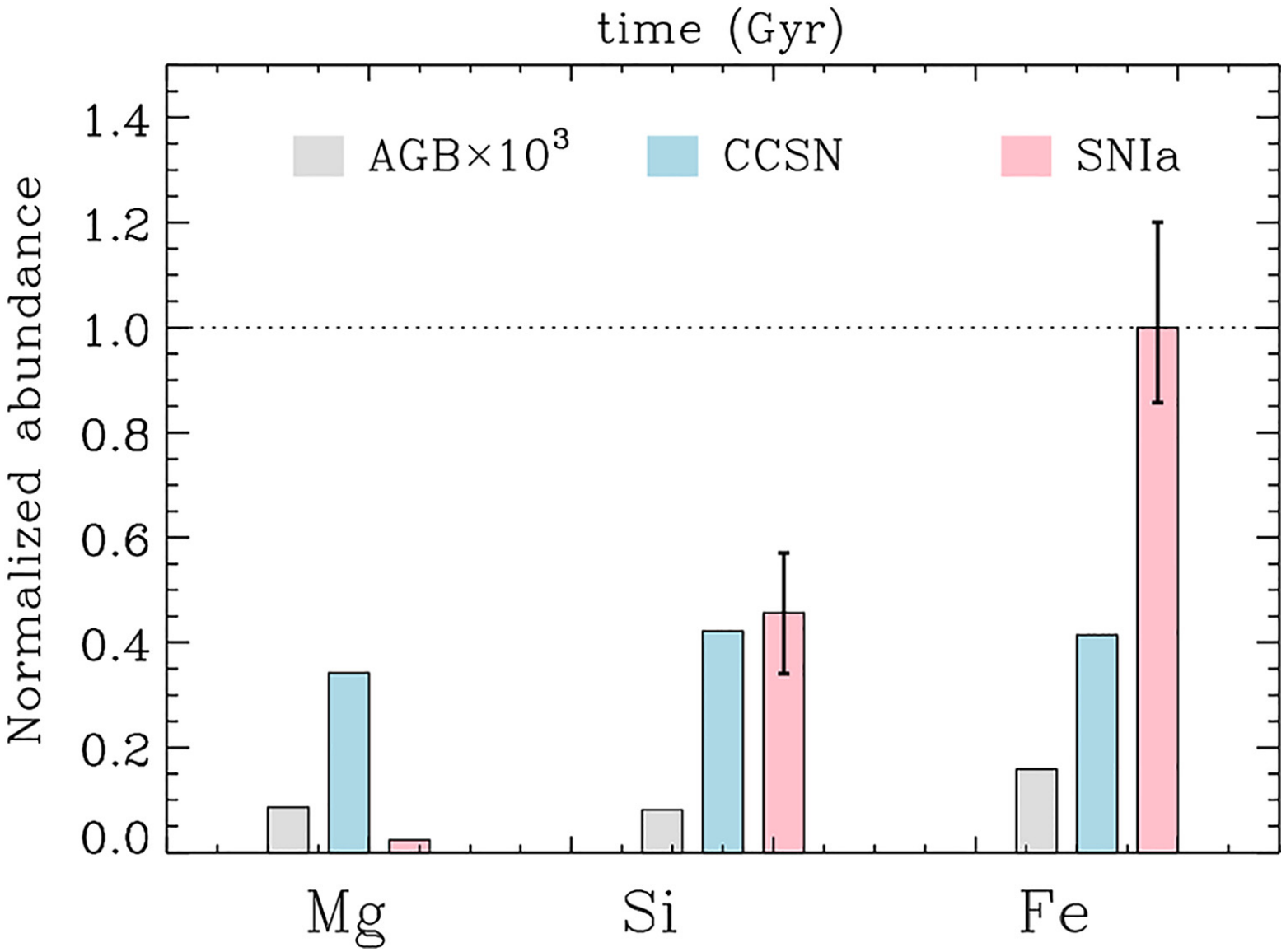
4. Global Properties of Galaxies

4.6 Correlations between parameters

- Metallicity-velocity dispersion relation
  - The ellipticals with a larger velocity dispersion have more metals
  - the slope value depends on the metallicity indicator


slope = 0.20±0.02
rms = 0.011
ΔMg2 =−0.015±0.004
Mg2
0.40
0.35
0.30
0.25
2.0
2.2
2.4
2.6
Log10 σ [kms−1]

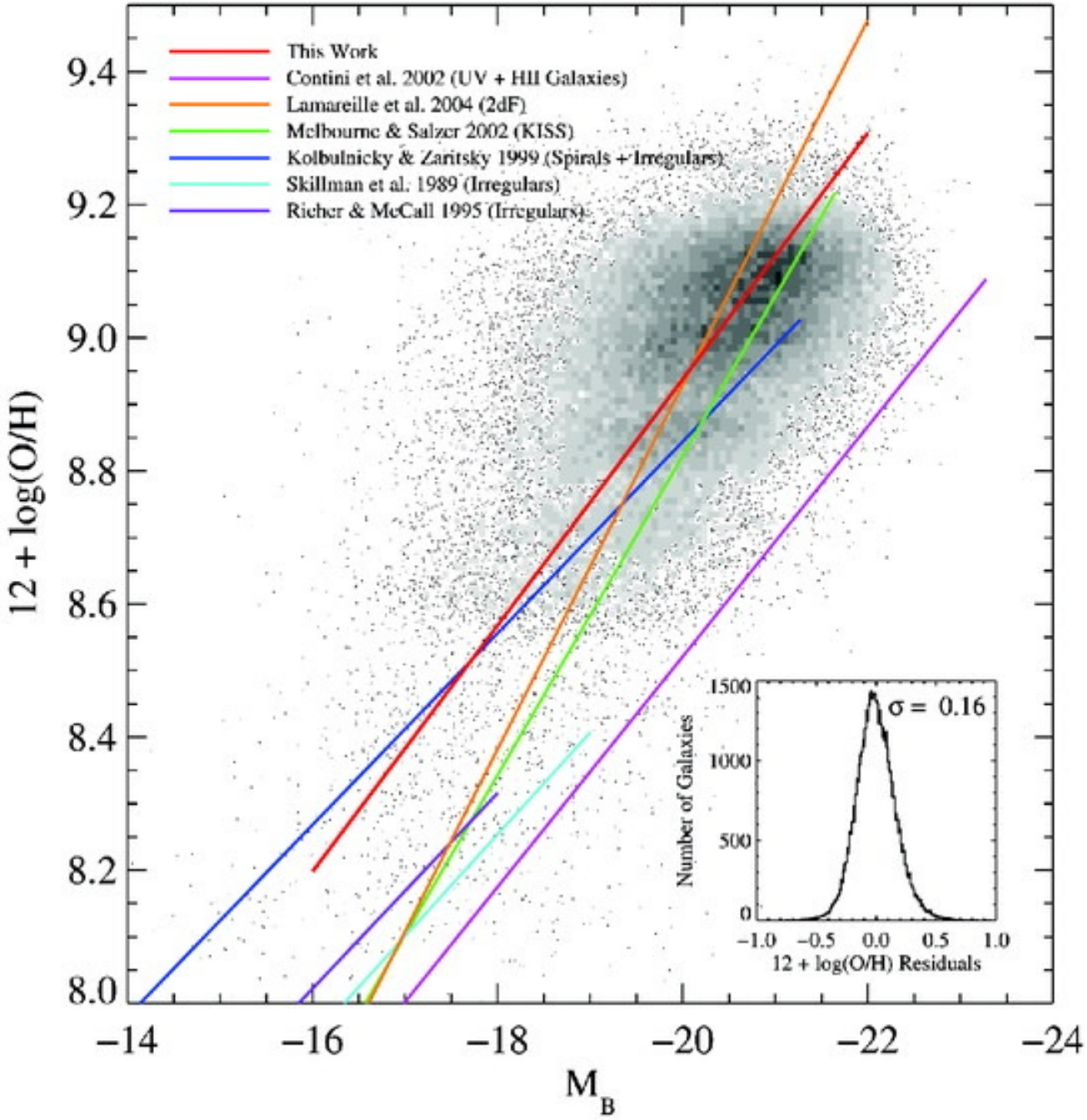

slope = 0.32±0.03
rms = 0.020
ΔLog10Mgb =−0.030±0.012
Log10 Mgb
slope =−0.24±0.03
rms = 0.027
ΔLog10Hβ = 0.058±0.011
Log10 Hβ
slope = 0.11±0.03
rms = 0.011
ΔLog10<Fe> =−0.017±0.009
Log10 <Fe>
slope = 0.22±0.04
rms = 0.015
ΔLog10Mgb/<Fe> =−0.015±0.010
Log10 Mgb/<Fe>
Log10 σ [kms−1]


time (Gyr)
AGB×10³
CCSN
SNIa
Normalized abundance
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Mg
Si
Fe

4. Global Properties of Galaxies

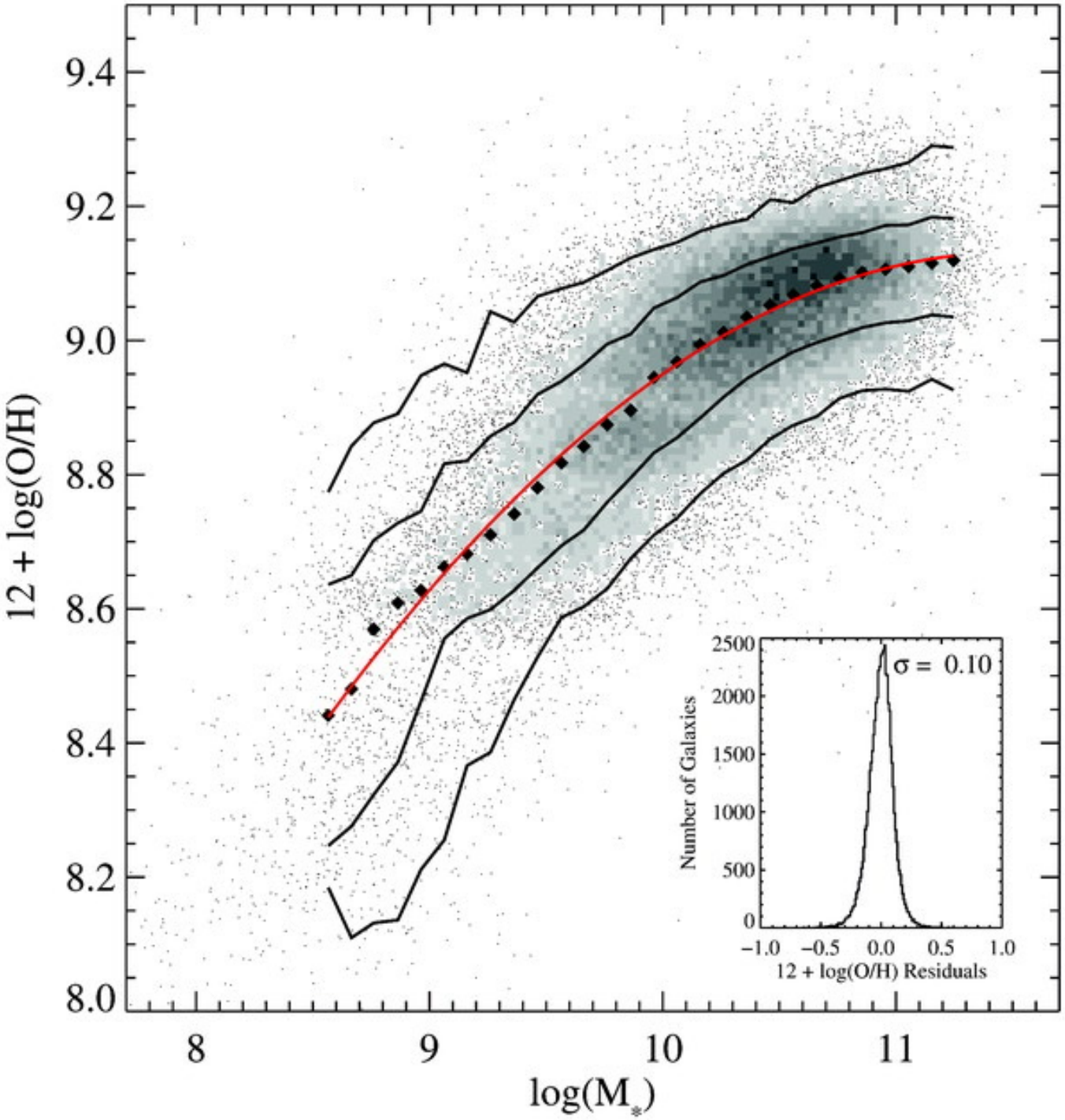
4.6 Correlation between parameters

- Metallicity-stellar mass relation
  - the metallicity is larger for galaxies with a higher stellar mass (and brighter absolute magnitude)
  - constraints models of galaxy formation



Tremonti et al 04

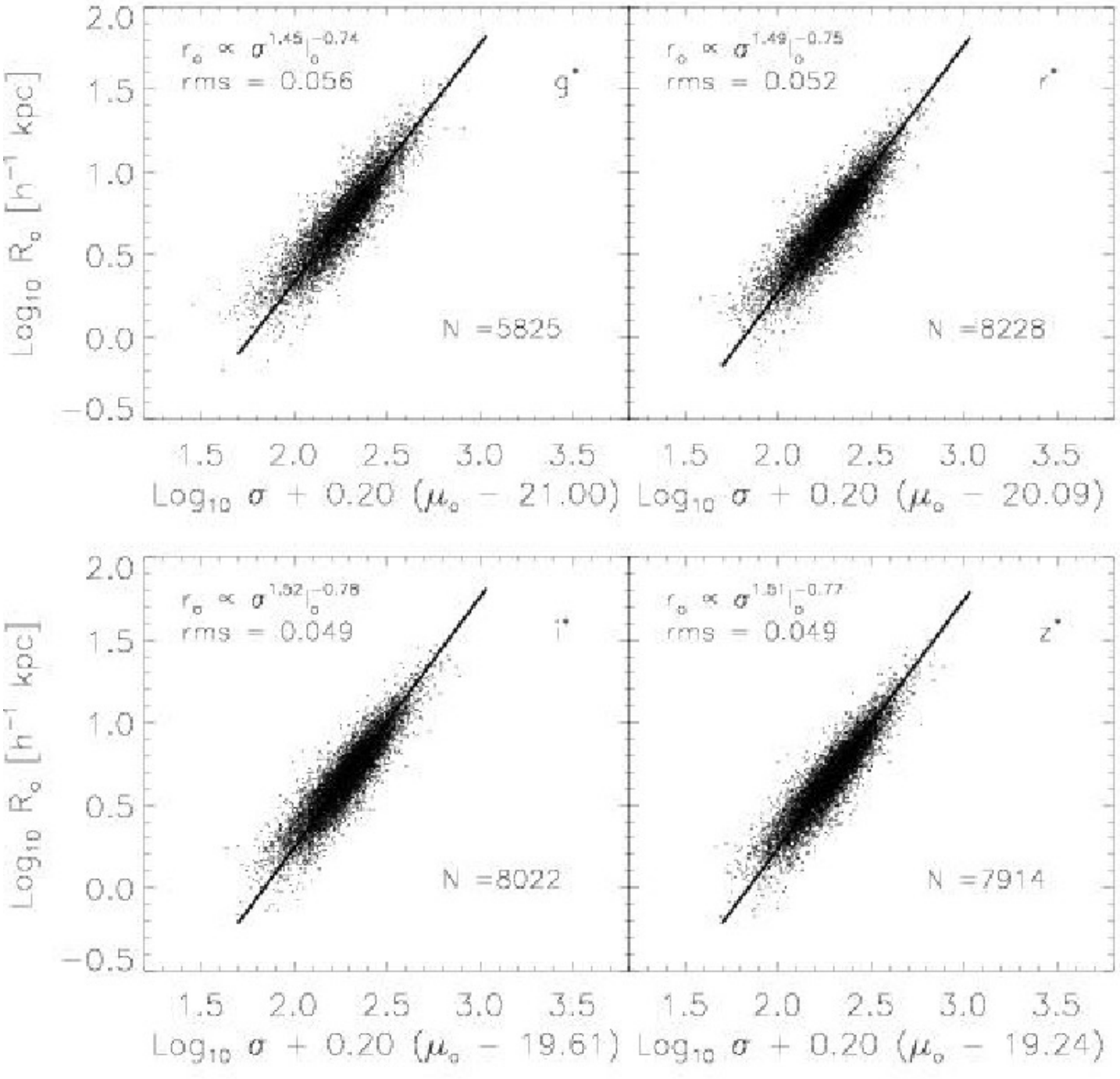
Tremonti et al 04



4. Global Properties of Galaxies

4.6 Correlations between parameters

- Fundamental Plane
  - in the parameter space of effective radius, surface brightness and velocity dispersion elliptical galaxies are distributed in a plane
  - $R_e \alpha \langle I \rangle_e^{-0.75} \sigma^{1.5}$

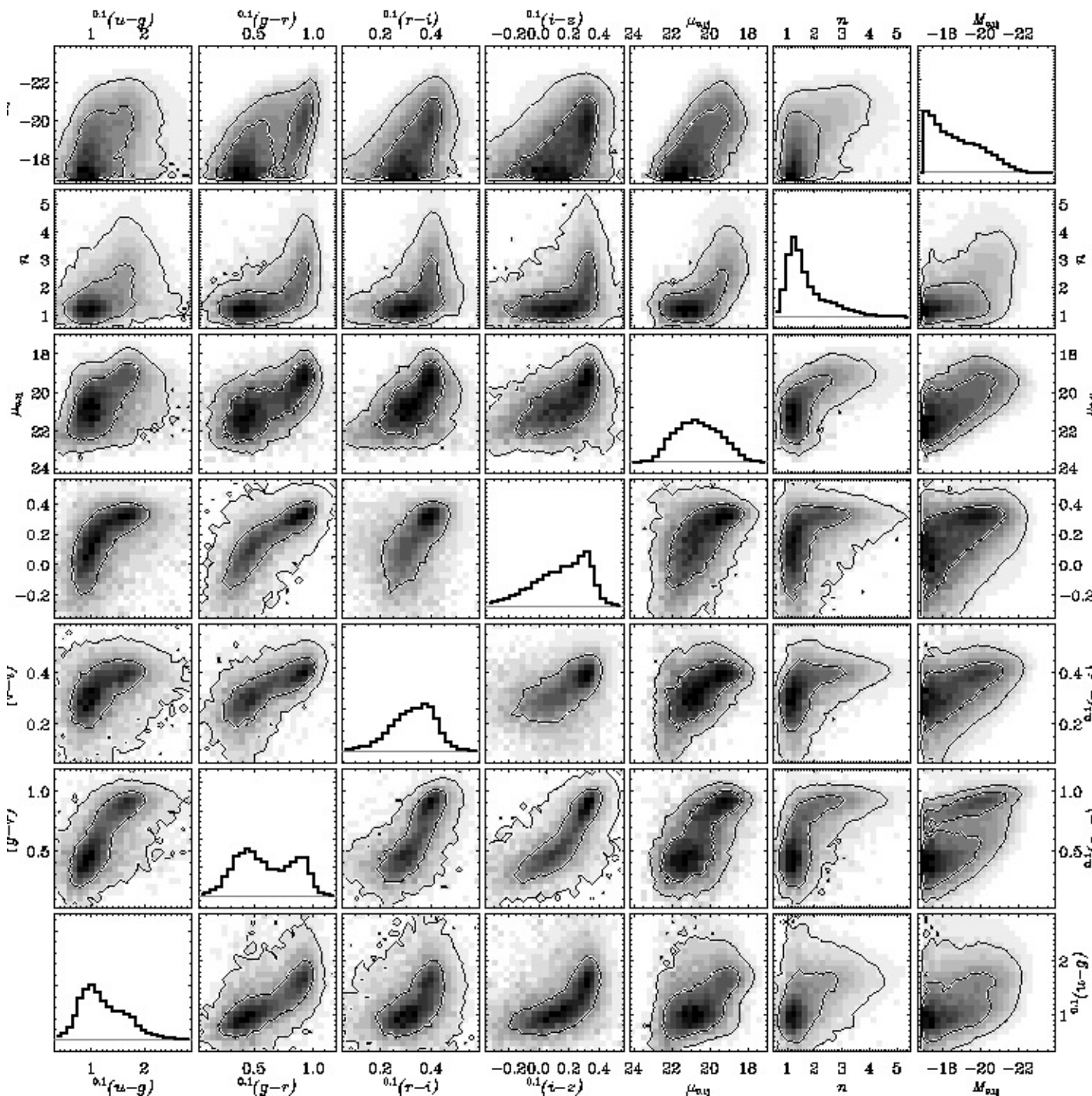

$r_o \propto \sigma^{1.45}|_o^{-0.74}$
rms = 0.056
g*
N =5825
$r_o \propto \sigma^{1.49}|_o^{-0.75}$
rms = 0.052
r*
N =8228
$r_o \propto \sigma^{1.52}|_o^{-0.78}$
rms = 0.049
i*
N =8022
$r_o \propto \sigma^{1.51}|_o^{-0.77}$
rms = 0.049
z*
N =7914
$\mathrm{Log}_{10}\, R_o\ [h^{-1}\ \mathrm{kpc}]$
$\mathrm{Log}_{10}\, \sigma + 0.20\ (\mu_o - 21.00)$
$\mathrm{Log}_{10}\, \sigma + 0.20\ (\mu_o - 20.09)$
$\mathrm{Log}_{10}\, \sigma + 0.20\ (\mu_o - 19.61)$
$\mathrm{Log}_{10}\, \sigma + 0.20\ (\mu_o - 19.24)$

4. Global Properties of Galaxies

4.6 Correlations between parameters

- parameters distributions

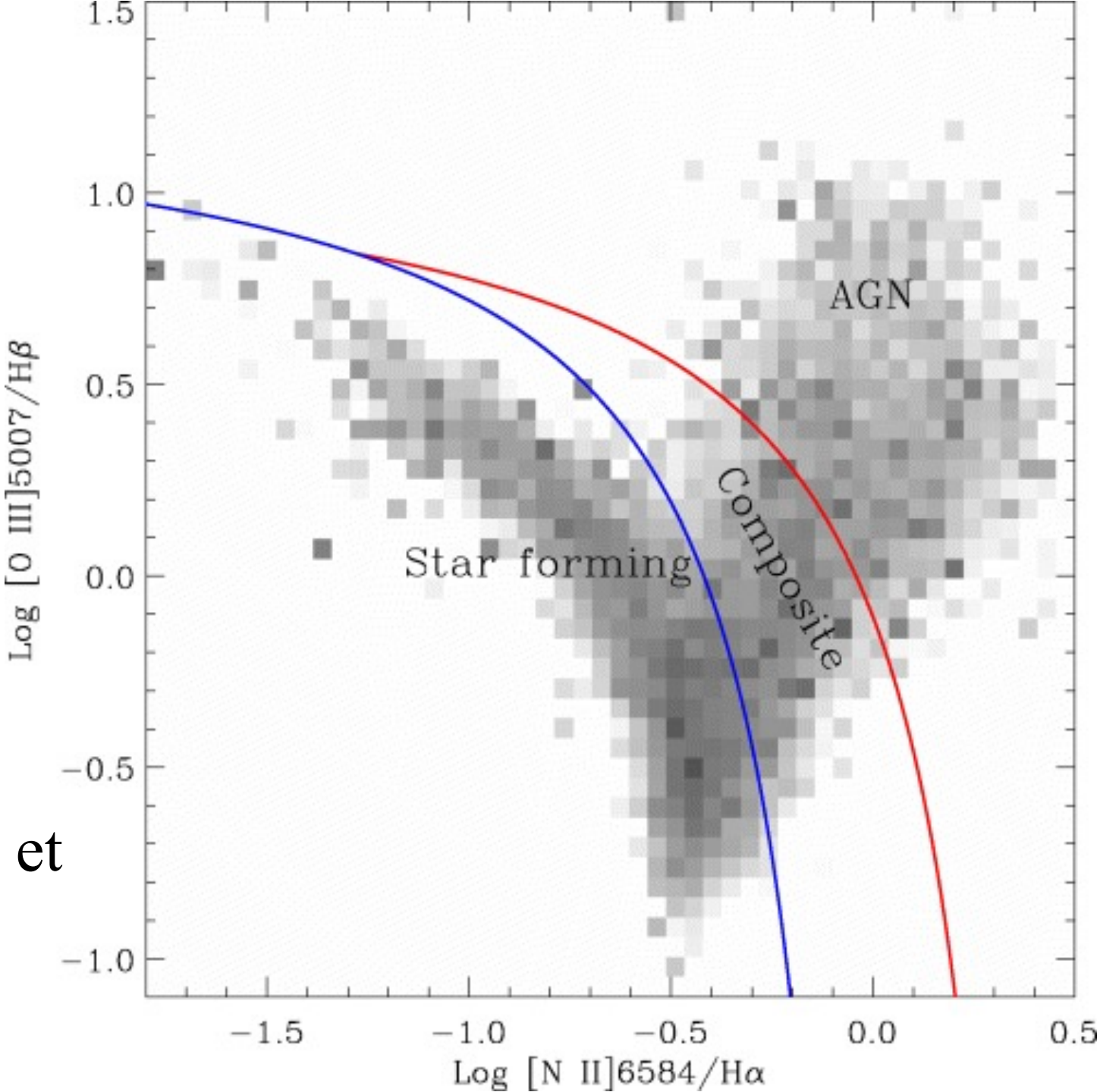
Blanton et al 2003



4. Global Properties of Galaxies

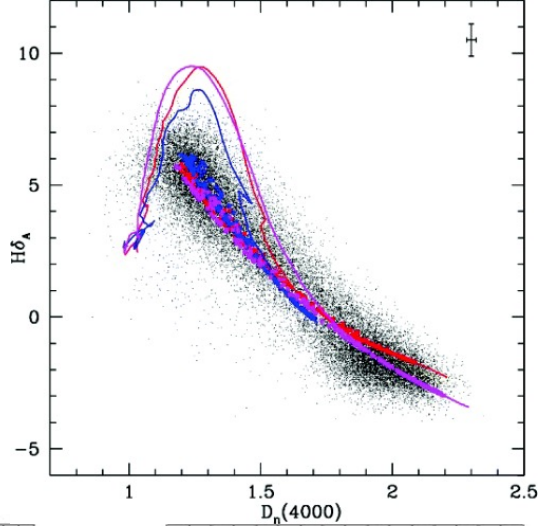
4.6 Correlations between parameters

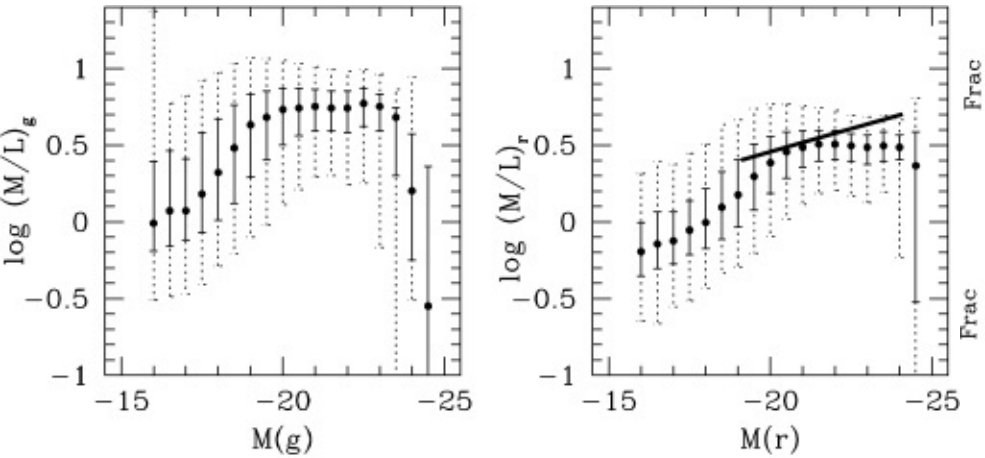
- Star formation indicators parameters
  - UV luminosity
  - Halpha
  - Infrared emission

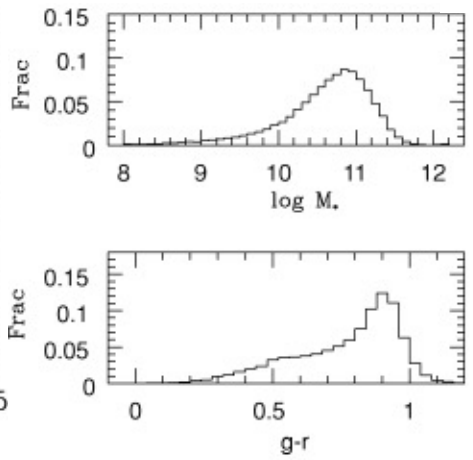


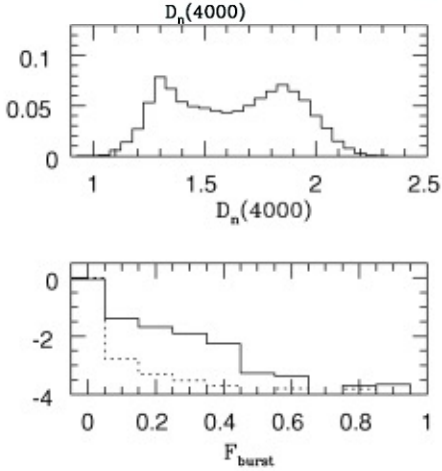
Brinchmann et al 04

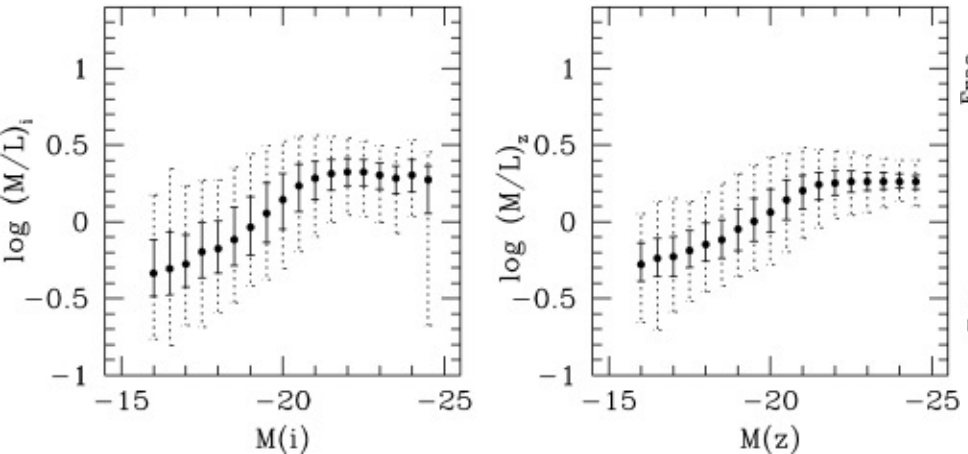
Kauffmann et al 03

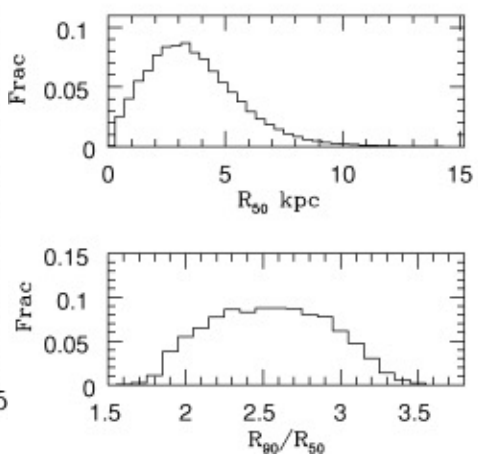


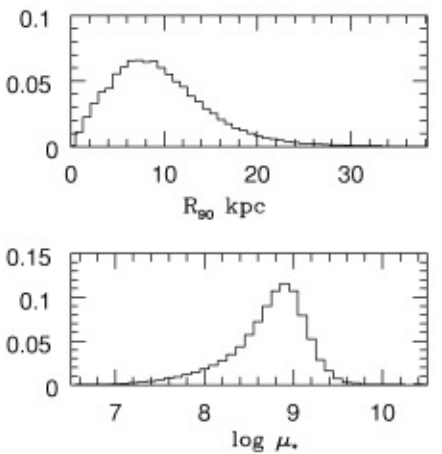












4. Global Properties of Galaxies

4.7 Density and Mass Profiles

- Studying the dynamics of galaxies one can deduce the mass distribution causing the observed kinematics

- Excluding the central parts, the flat rotation curves and velocity dispersions suggest that the mass increases proportional to the radius ($M \alpha r$) within the range where it can be measured and therefore the density profile scales as $\rho \alpha r^{-2}$

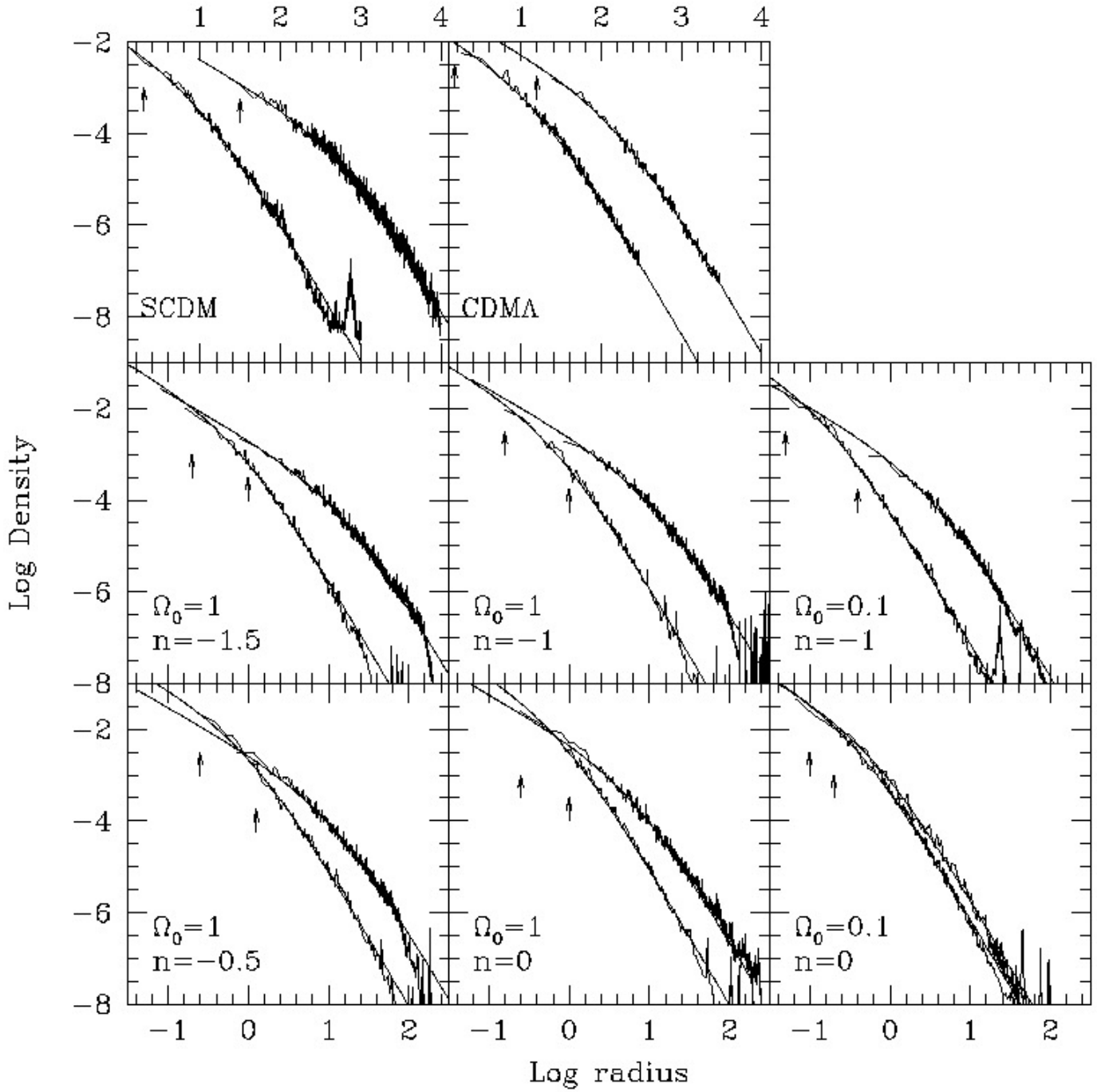
- gravitational lensing studies find that the galaxy density profiles are consistent with singular isothermal sphere models

$\rho \alpha \sigma^2/r^2$

4. Global Properties of Galaxies

4.7 Density and Mass Profiles

- Numerical simulations find that density profiles of dark matter halos present a universal profile named NFW (Navarro, Frenk & White 1997)


SCDM
CDMA
Ω_0=1
n=−1.5
Ω_0=1
n=−1
Ω_0=0.1
n=−1
Ω_0=1
n=−0.5
Ω_0=1
n=0
Ω_0=0.1
n=0
Log Density
Log radius

4. Global Properties of Galaxies

4.7 Density and Mass Profiles

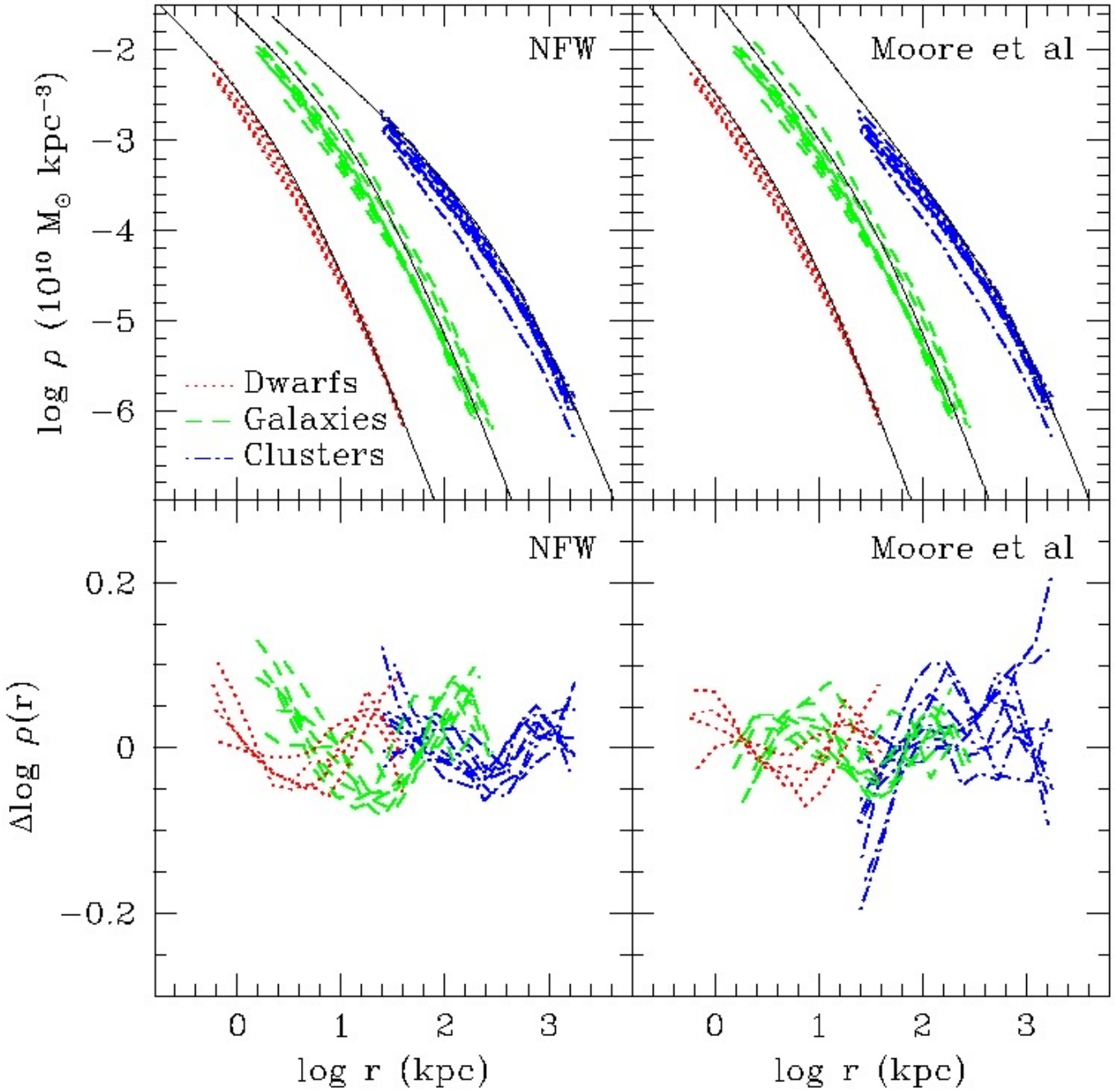
NFW profile

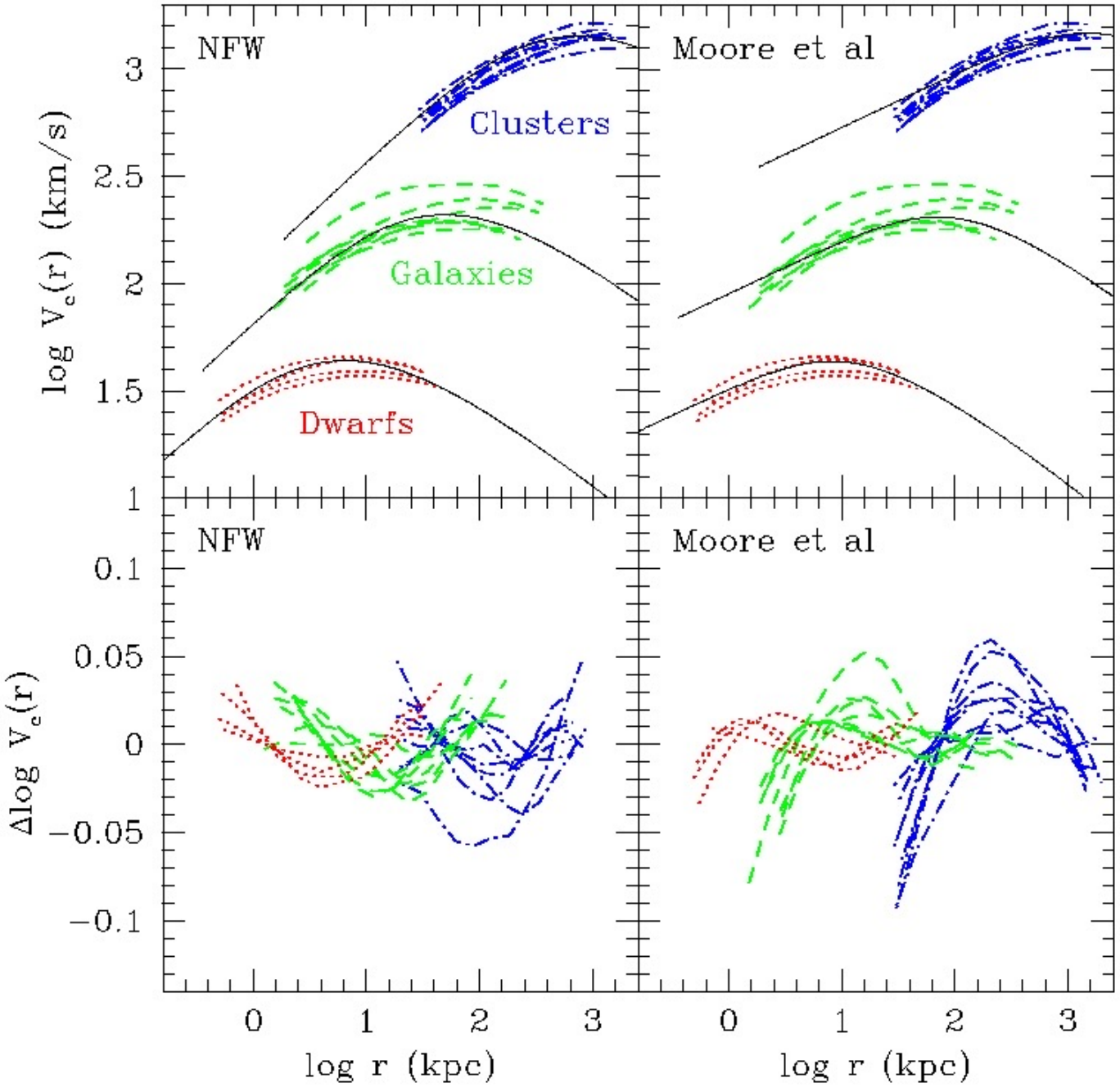
$$\rho(r) = \frac{\delta_c \rho_c}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

$$M(r) = 4\pi\delta_c\rho_c r_s^2 \left[ln\left(1+\frac{r}{r_s}\right) - \frac{r}{r+r_s} \right]$$

$$\phi(r) = -4\pi G\delta_c\rho_c r_s^2 \left[\frac{ln\left(1+\frac{r}{r_s}\right)}{\frac{r}{r_s}} \right]$$

$C = r_{200}/r_s$

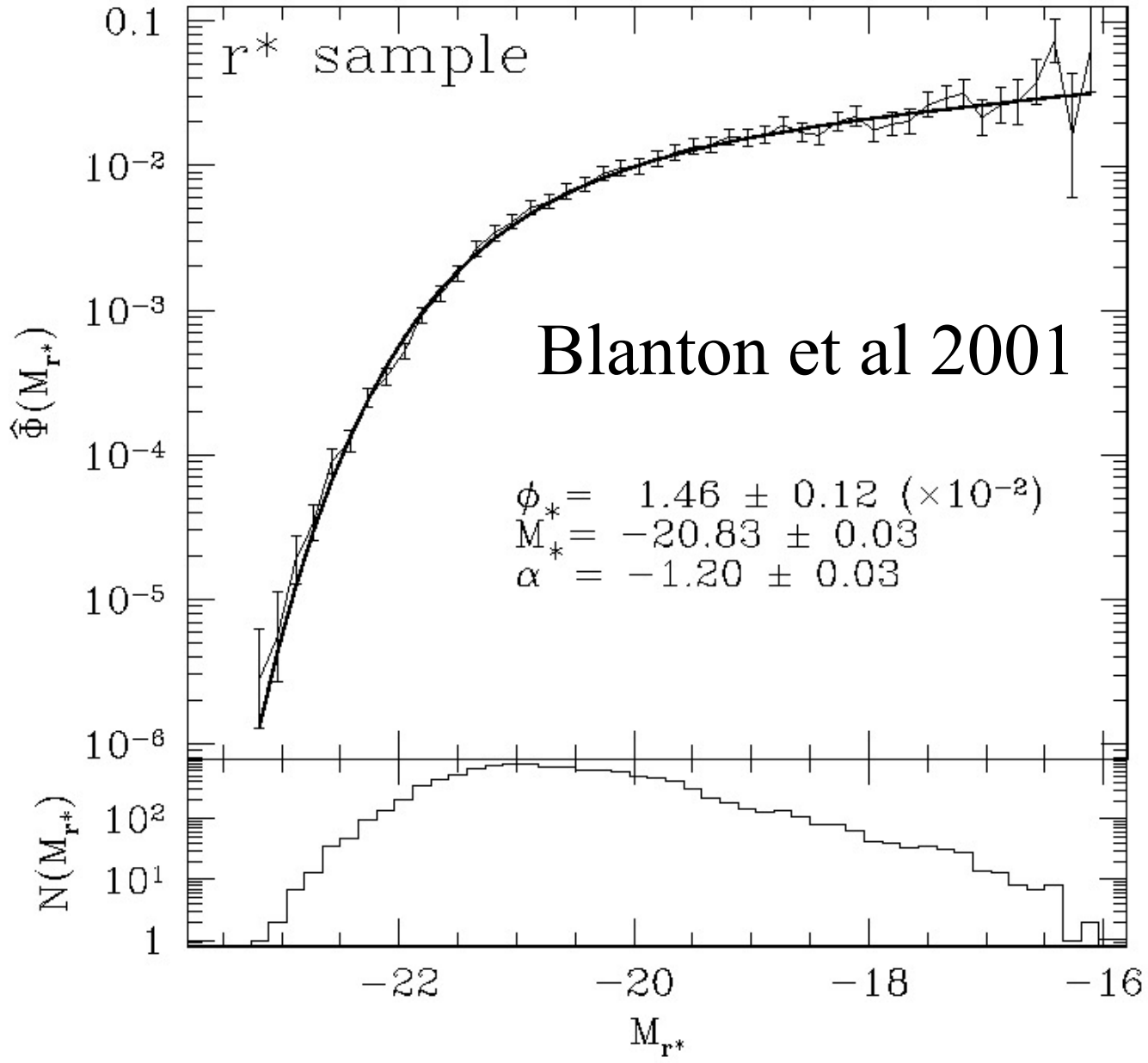

NFW
Moore et al
log ρ (10¹⁰ M⊙ kpc⁻³)
−2
−3
−4
−5
−6
Dwarfs
Galaxies
Clusters
NFW
Moore et al
Δlog ρ(r)
0.2
0
−0.2
0
1
2
3
log r (kpc)
log r (kpc)


NFW
Moore et al
Clusters
Galaxies
Dwarfs
log $V_c(r)$ (km/s)
Δlog $V_c(r)$
log r (kpc)
log r (kpc)

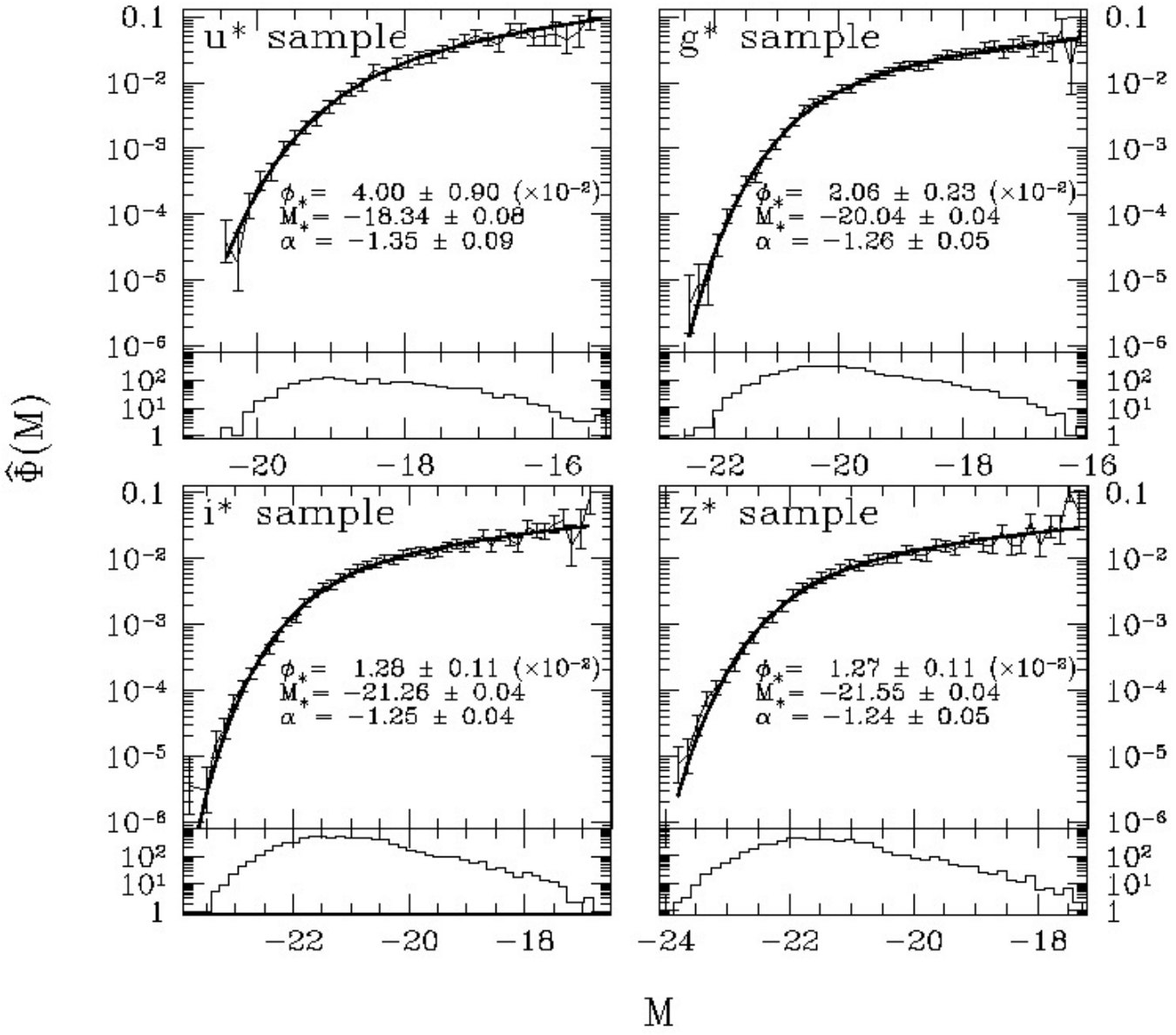
4. Global Properties of Galaxies

4.8 Luminosity Function

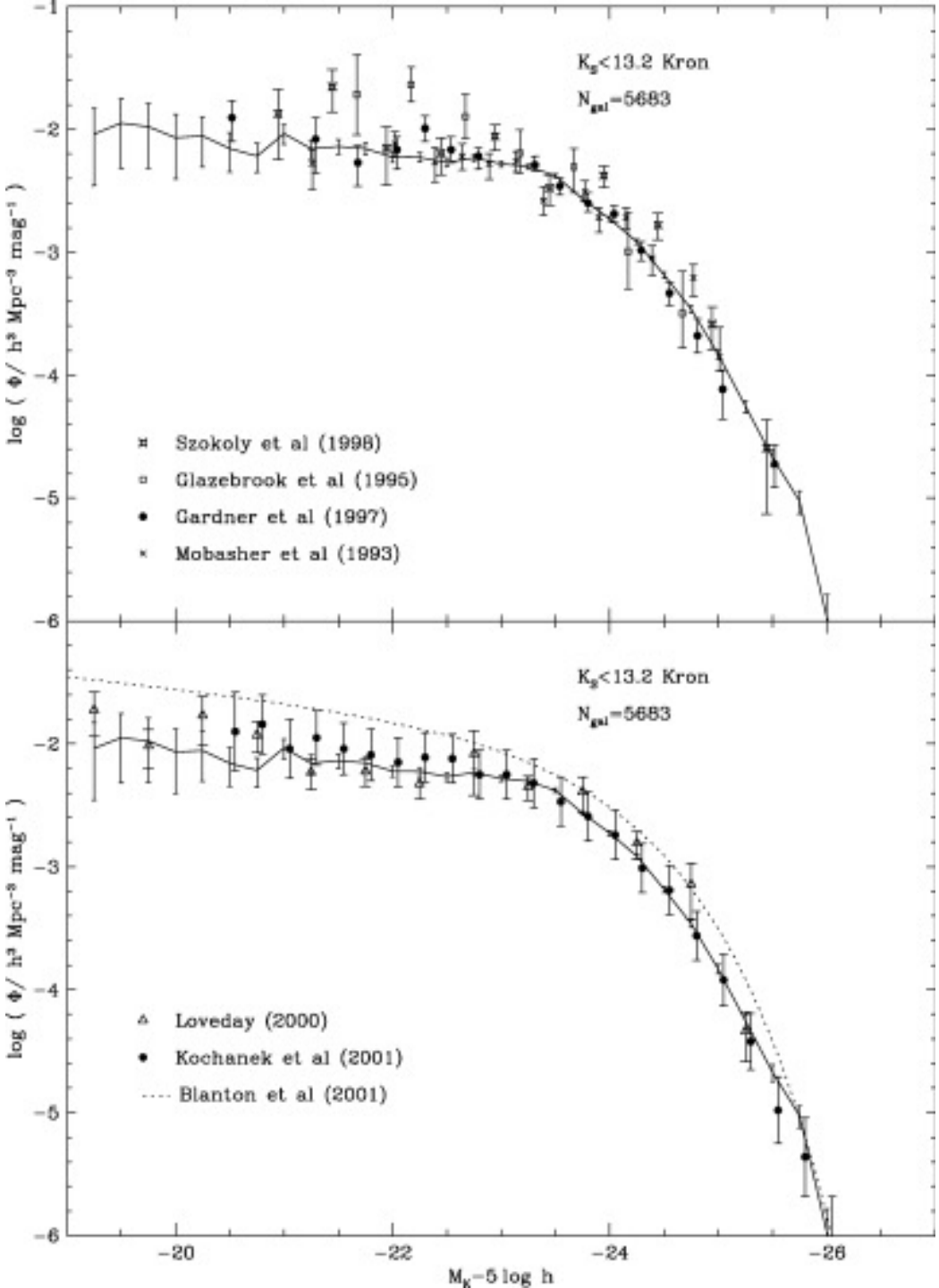
- the luminosity function, $\Phi(M)$, gives the number of galaxies per unit volume with an absolute magnitude M (or in the range M, M+dM)
- Luminosity function determination
- Parametric methods: Schechter function
- non-parametric methods: V_{max} weighting


r* sample
Blanton et al 2001
ϕ_*= 1.46 ± 0.12 (×10⁻²)
M_*= −20.83 ± 0.03
α = −1.20 ± 0.03
$\hat{\Phi}(M_{r^*})$
$N(M_{r^*})$
M_{r^*}
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^1
1
−22
−20
−18
−16

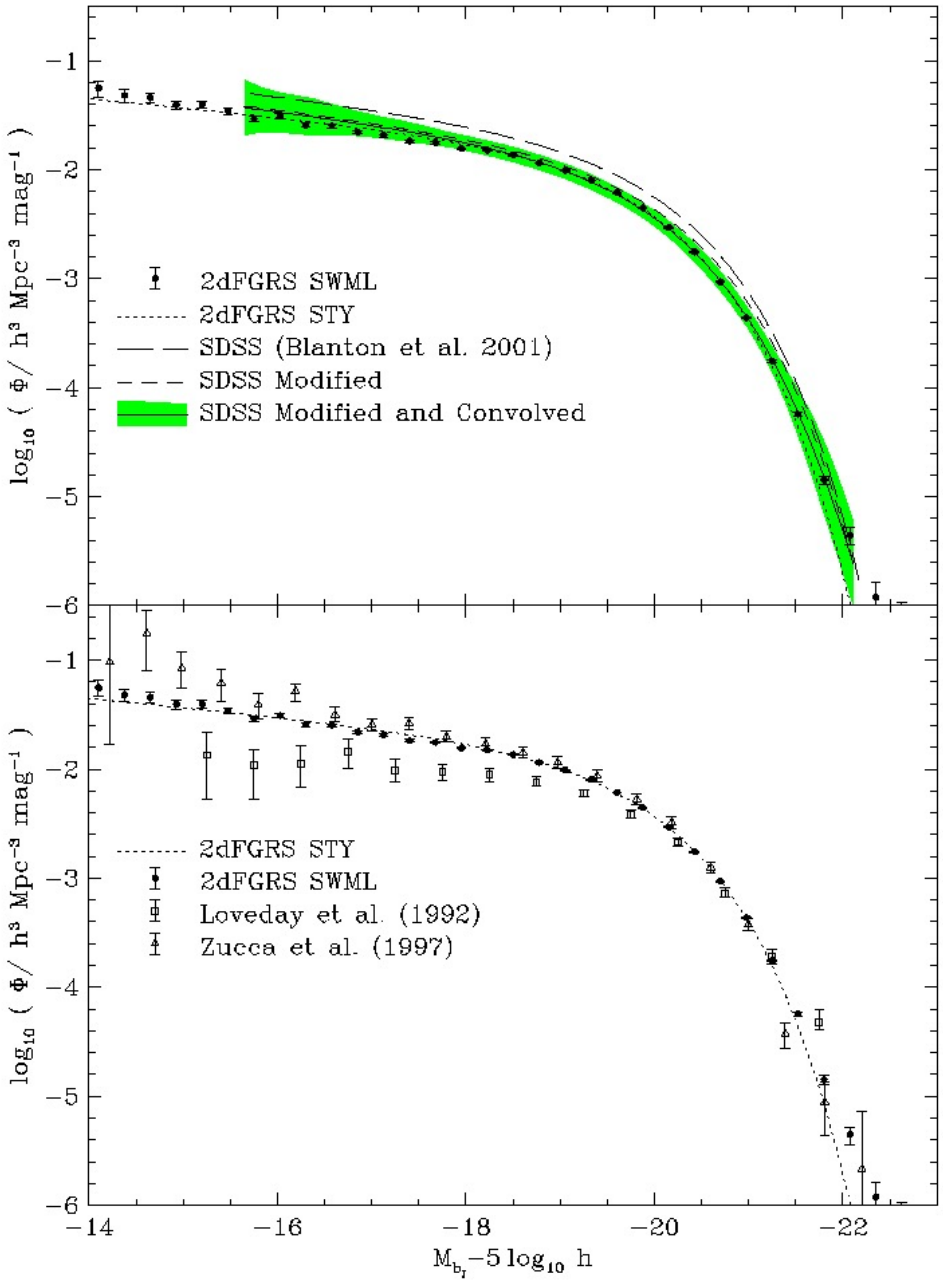
Blanton et al 2001



Cole et al 2003



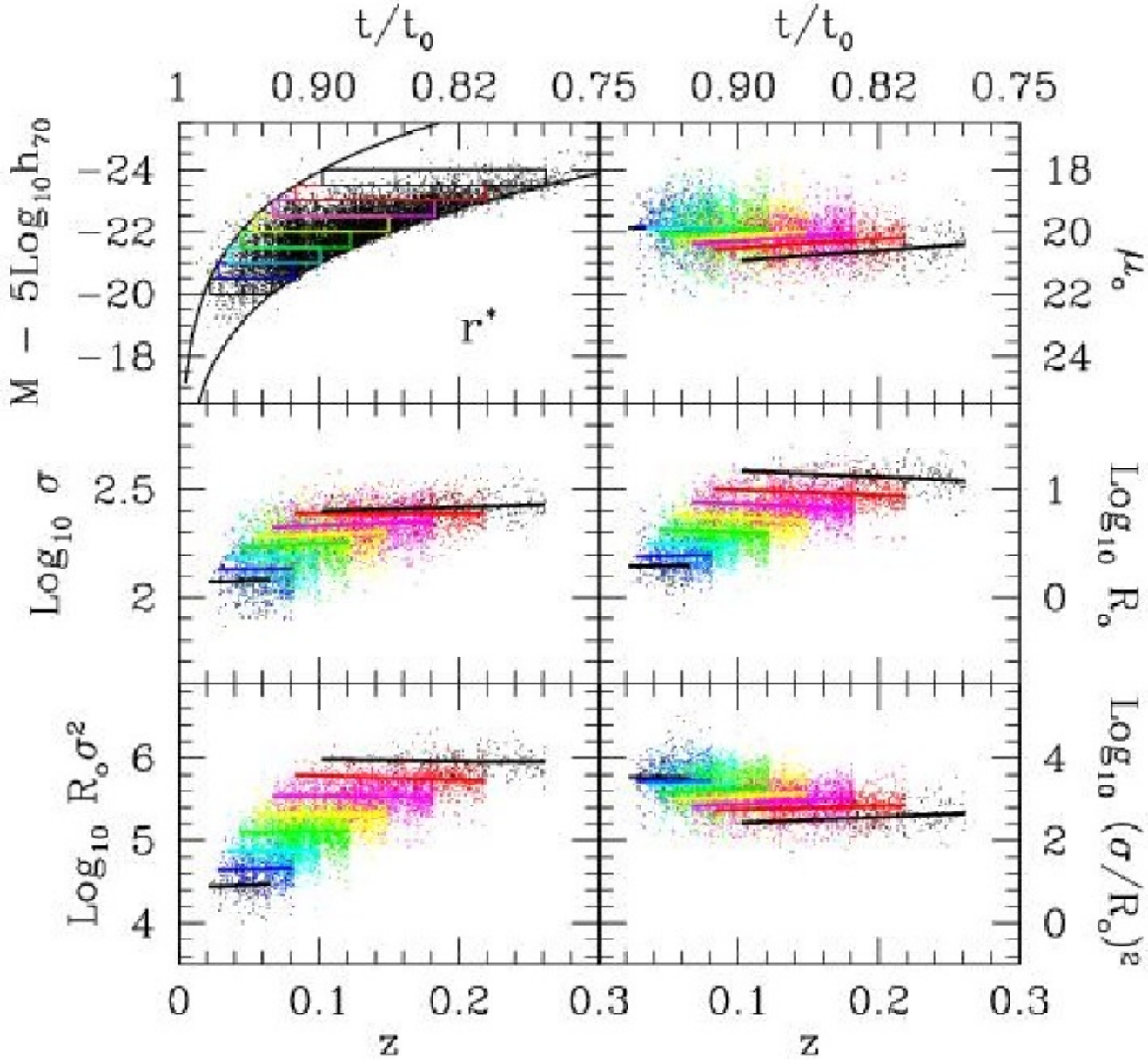
Norberg et al 02

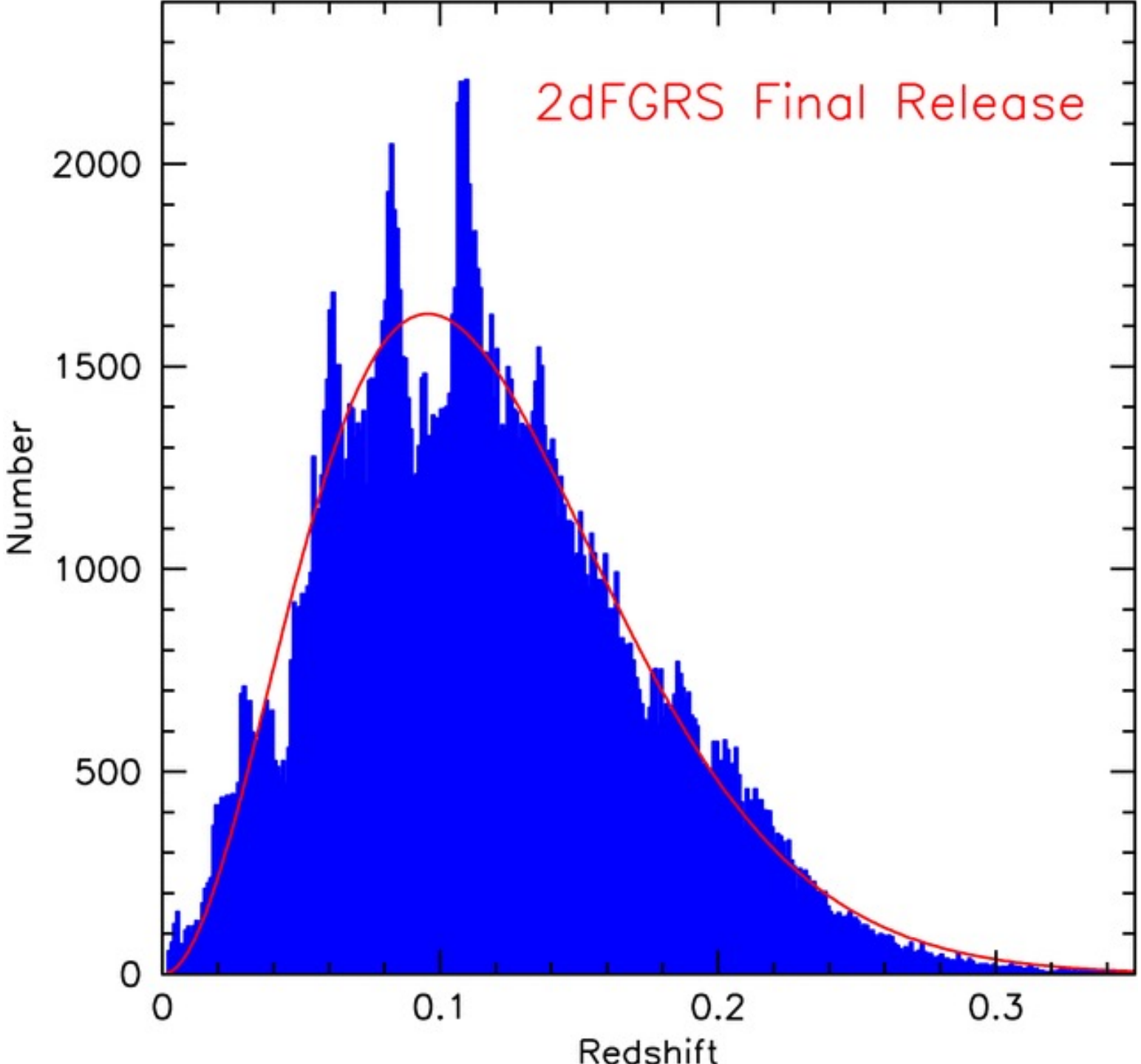


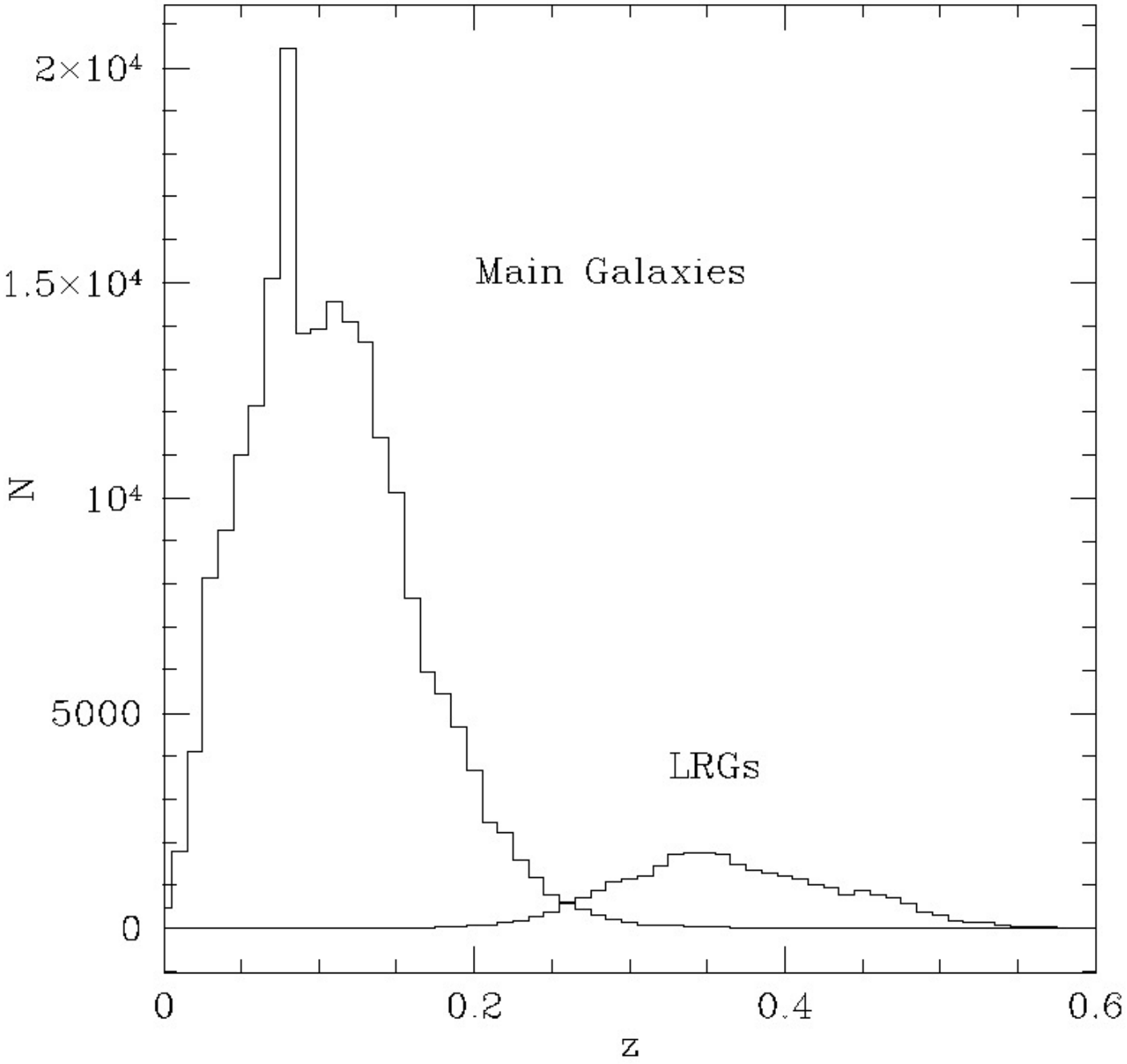
4. Global Properties of Galaxies

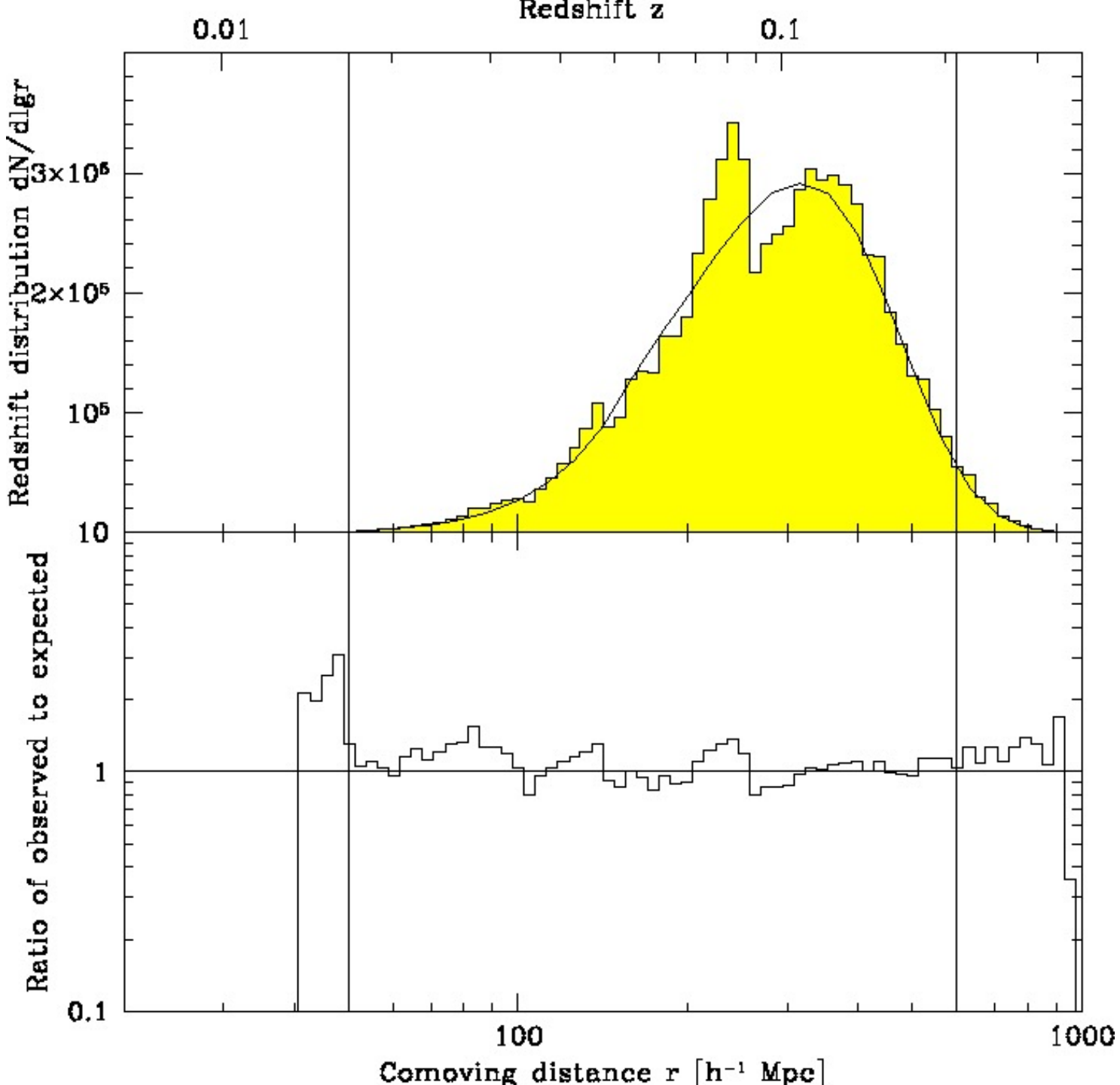
4.8 Luminosity function

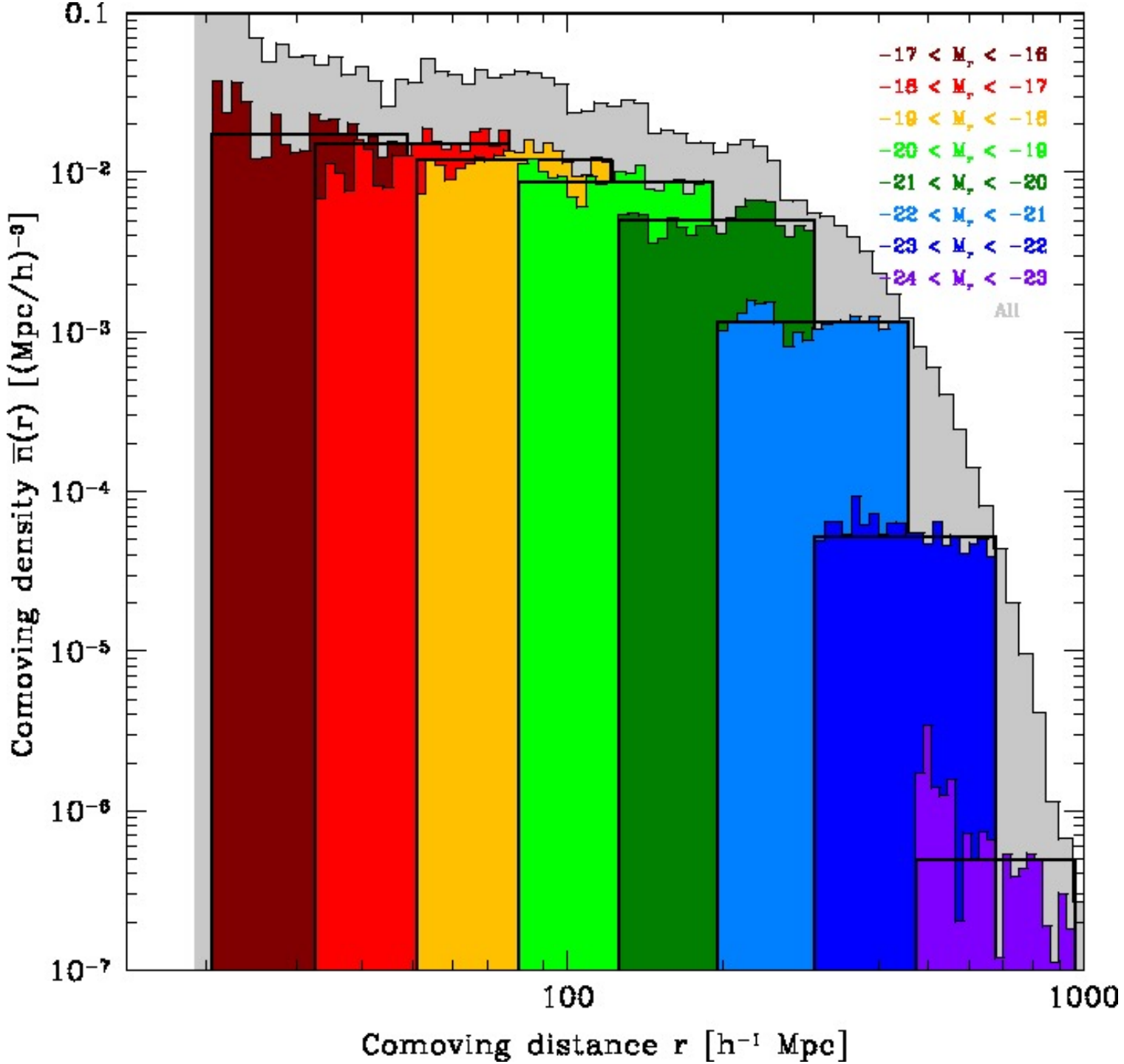
- Selection effects
- Flux limited samples
- Volume limited samples
- Malmquist bias
- K correction
- evolutionary effects

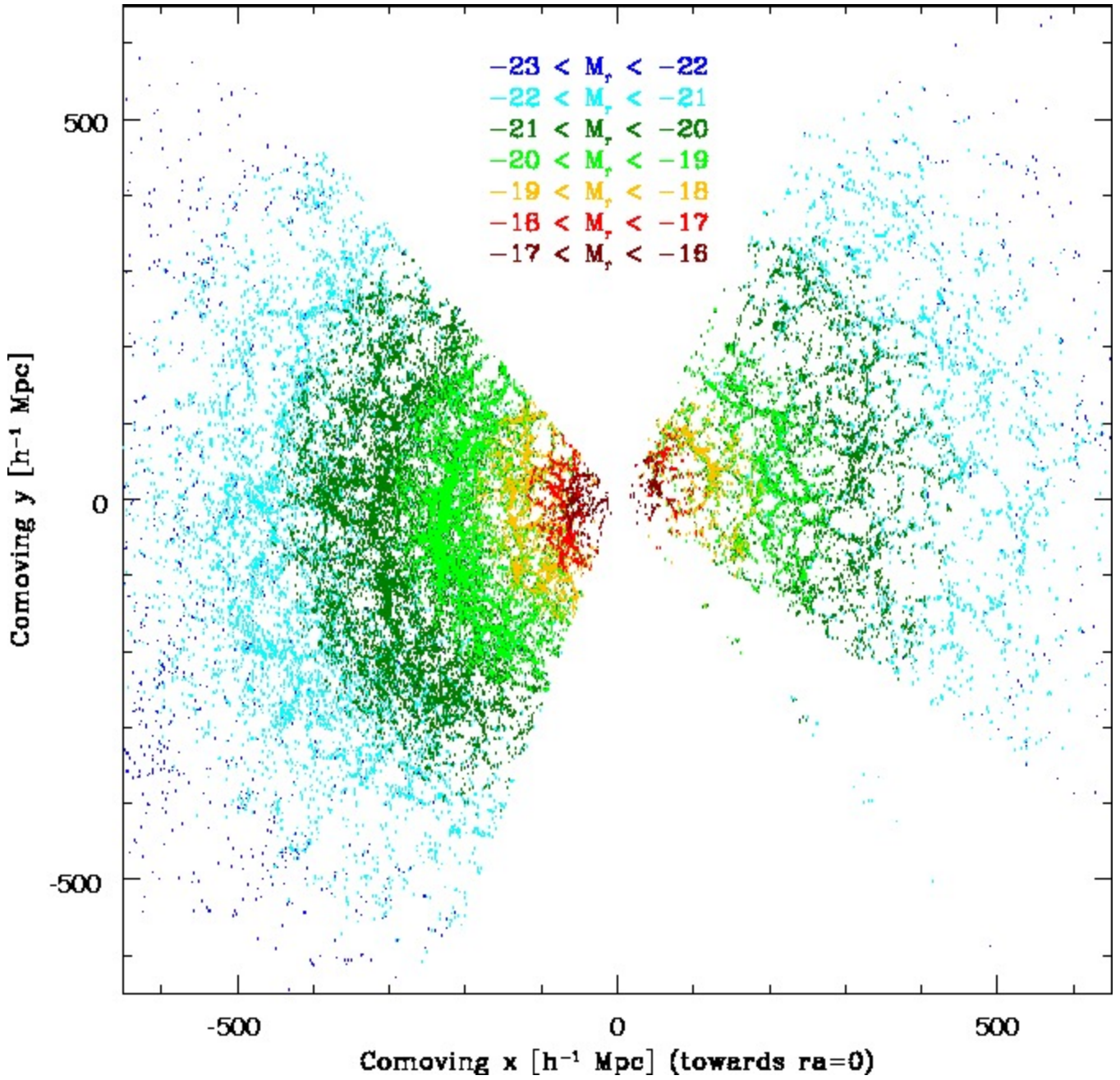

t/t0
1
0.90
0.82
0.75
M − 5Log10h70
−24
−22
−20
−18
r*
μo
18
20
22
24
Log10 σ
2.5
2
Log10 Ro
1
0
Log10 Roσ2
6
5
4
Log10 (σ/Ro)2
4
2
0
0
0.1
0.2
0.3
z

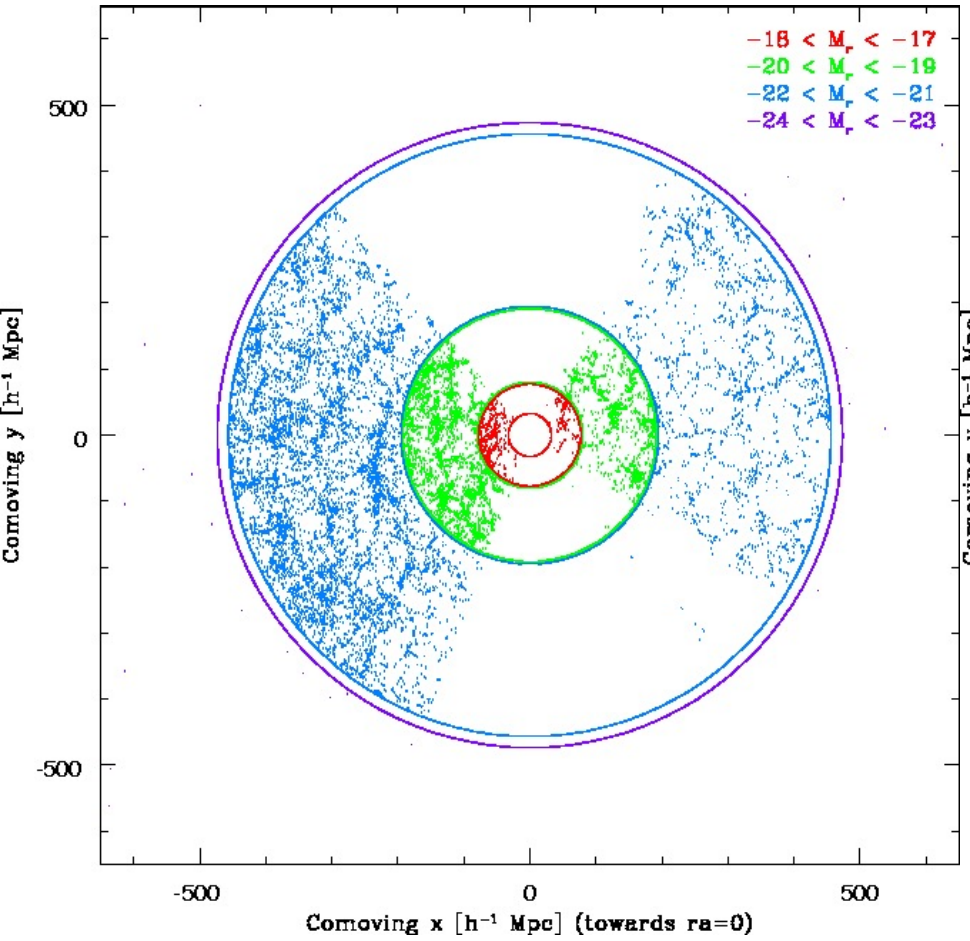

2dFGRS Final Release
Number
2000
1500
1000
500
0
0
0.1
0.2
0.3
Redshift

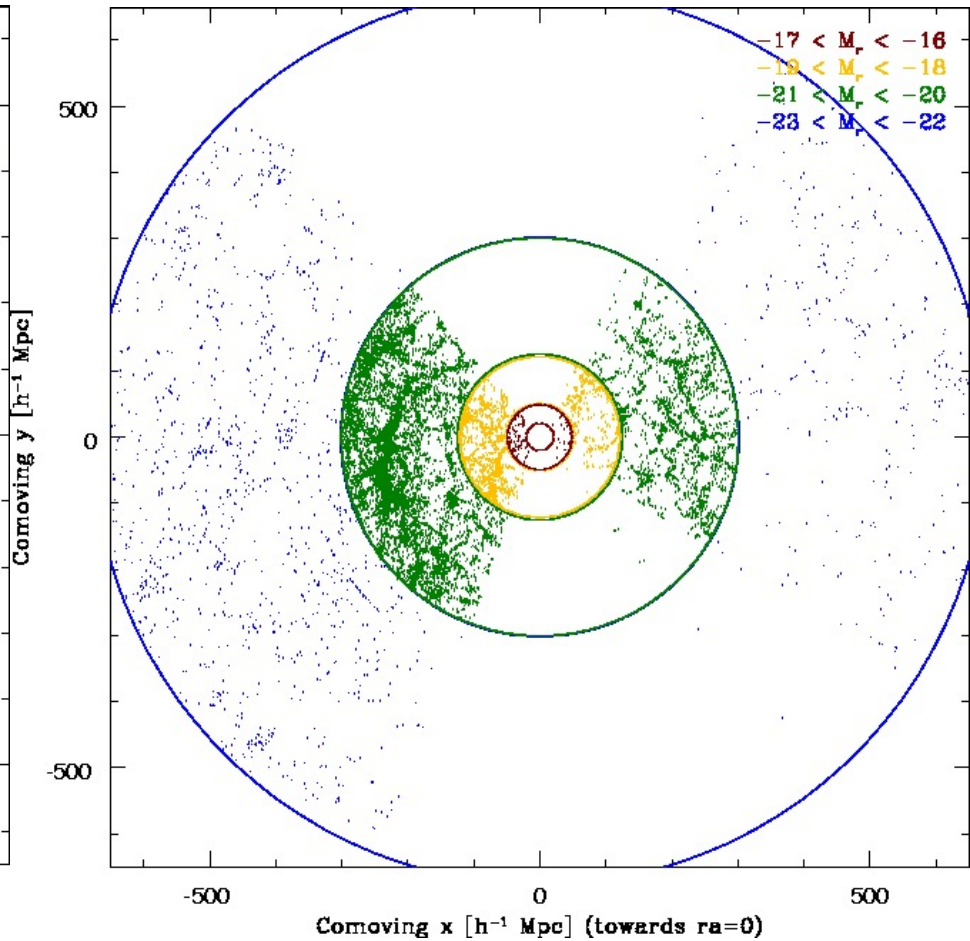

2×10⁴
1.5×10⁴
10⁴
5000
0
N
Main Galaxies
LRGs
0
0.2
0.4
0.6
z


Redshift z
0.01
0.1
Redshift distribution dN/dlgr
3×10⁵
2×10⁵
10⁵
10
Ratio of observed to expected
1
0.1
100
1000
Comoving distance r [h⁻¹ Mpc]

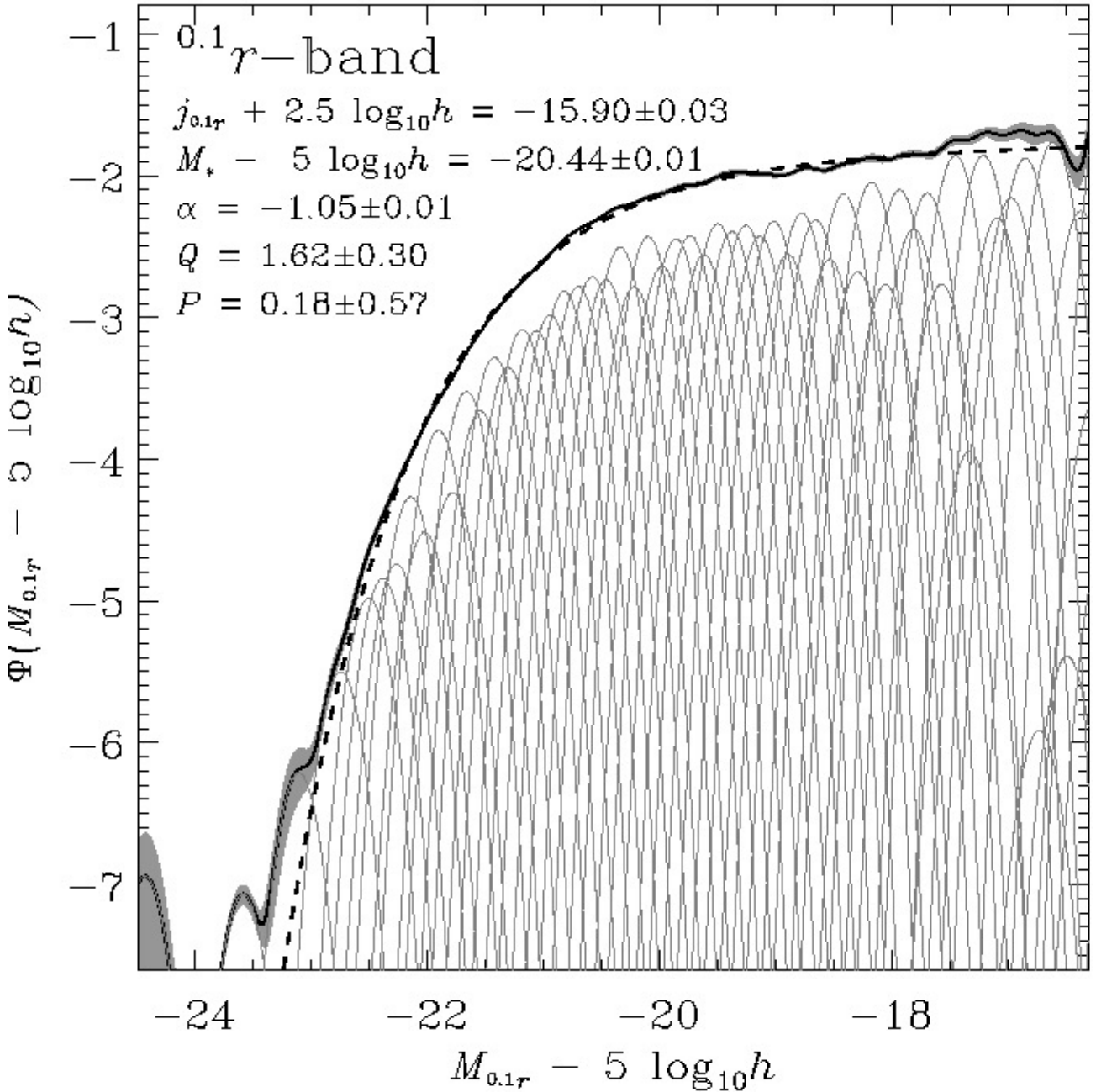

0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Comoving density $\bar{n}(r)$ [(Mpc/h)$^{-3}$]
100
1000
Comoving distance r [h^{-1} Mpc]
$-17 < M_r < -16$
$-18 < M_r < -17$
$-19 < M_r < -18$
$-20 < M_r < -19$
$-21 < M_r < -20$
$-22 < M_r < -21$
$-23 < M_r < -22$
$-24 < M_r < -23$
All


−23 < M_r < −22
−22 < M_r < −21
−21 < M_r < −20
−20 < M_r < −19
−19 < M_r < −18
−18 < M_r < −17
−17 < M_r < −16
500
0
-500
-500
0
500
Comoving y [h⁻¹ Mpc]
Comoving x [h⁻¹ Mpc] (towards ra=0)


−18 < M_r < −17
−20 < M_r < −19
−22 < M_r < −21
−24 < M_r < −23
500
0
-500
-500
0
500
Comoving y [h⁻¹ Mpc]
Comoving x [h⁻¹ Mpc] (towards ra=0)


−17 < M_r < −16
−19 < M_r < −18
−21 < M_r < −20
−23 < M_r < −22
500
0
-500
-500
0
500
Comoving y [h⁻¹ Mpc]
Comoving x [h⁻¹ Mpc] (towards ra=0)

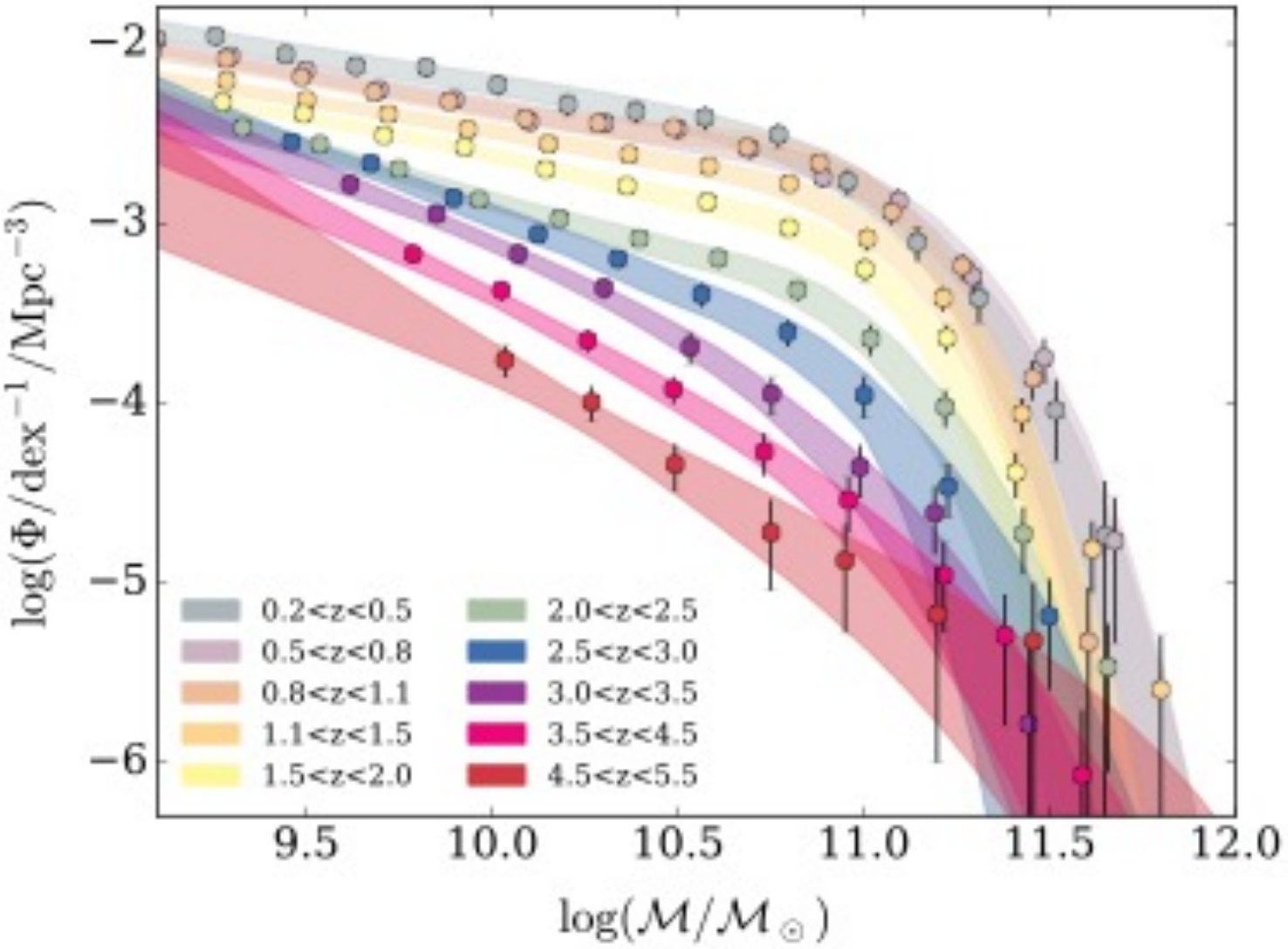
Blanton et al 2003



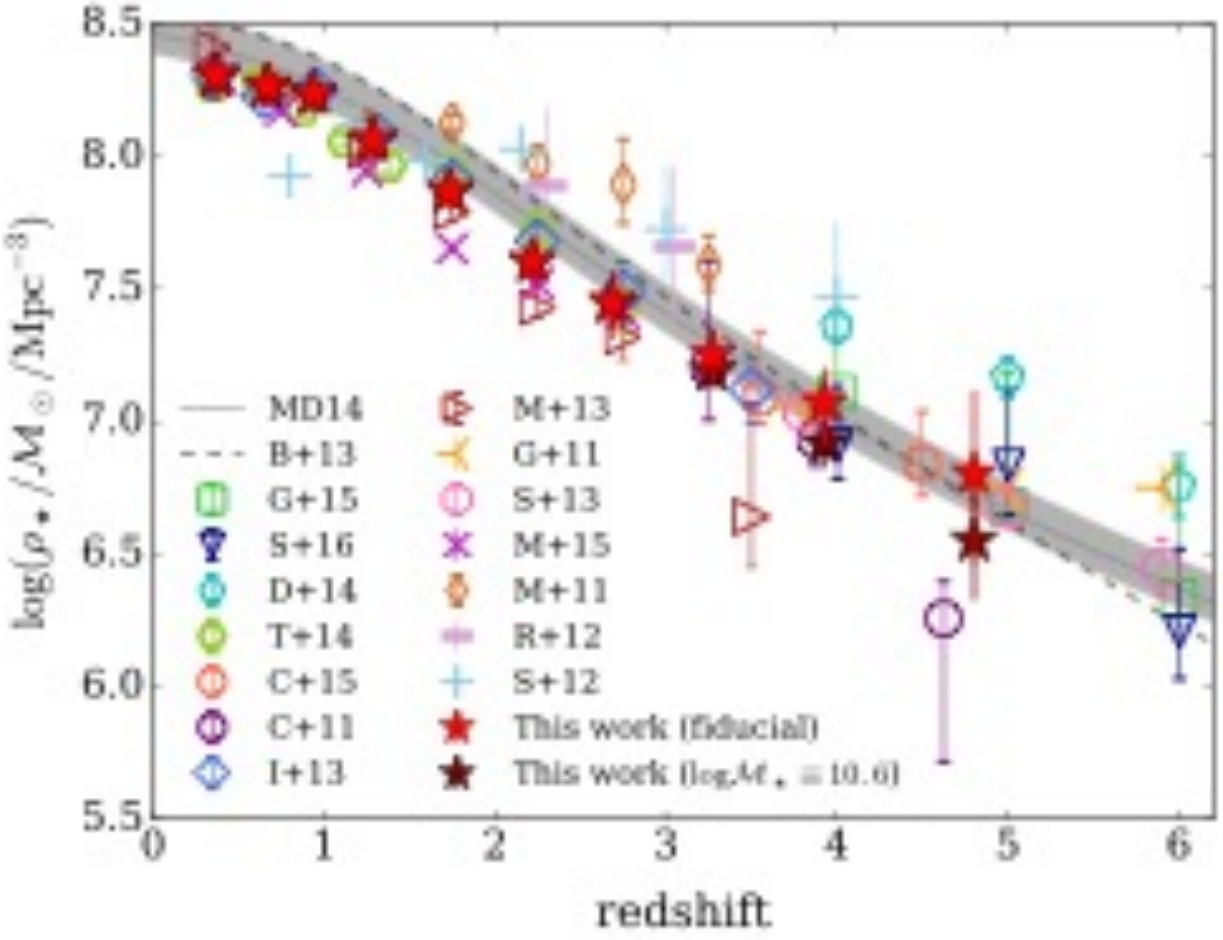
4. Global Properties of Galaxies

4.8 Stellar Mass function

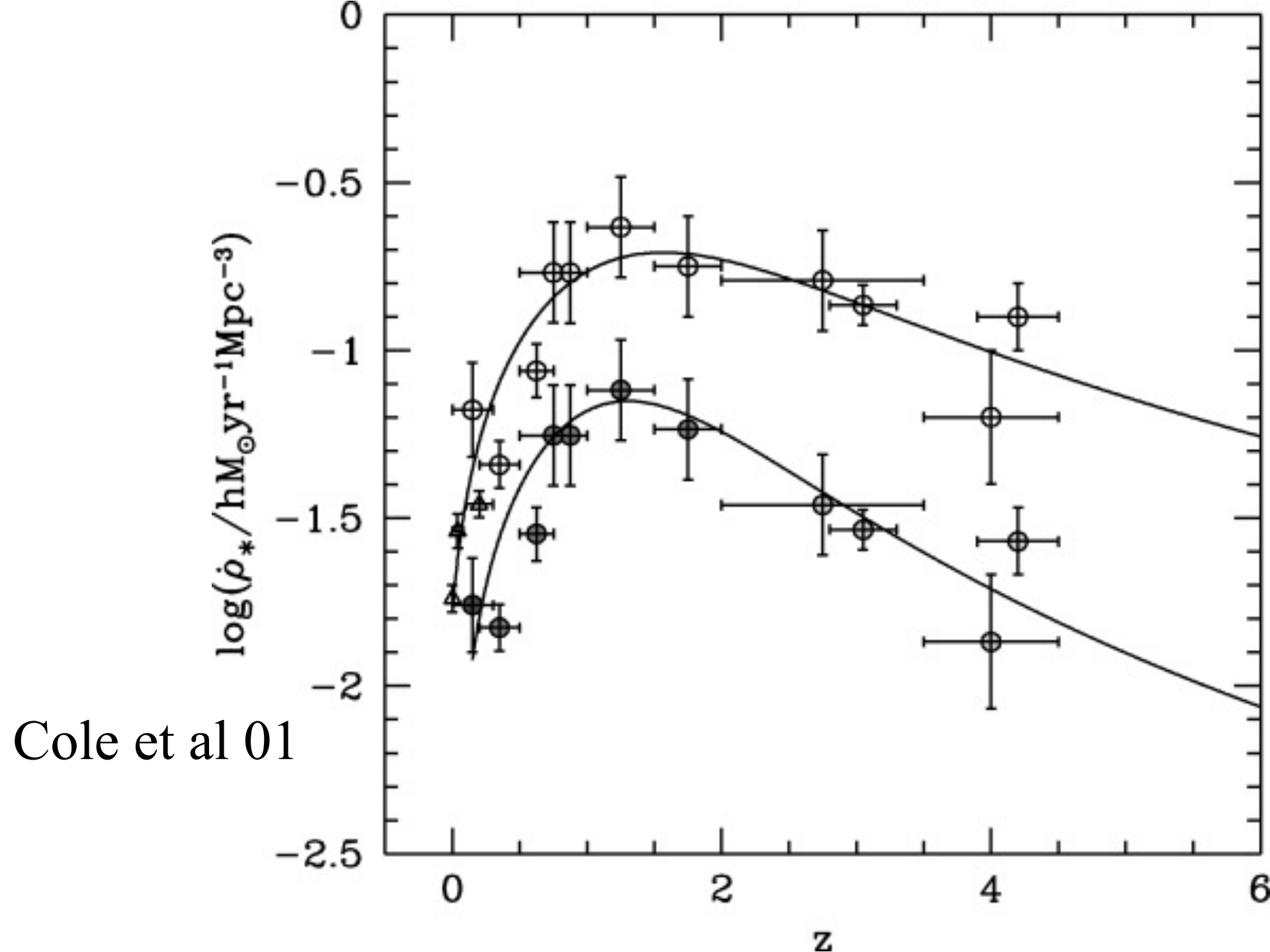
- Similar to LF
- difference of M/L as a function of luminosity/stellar mass



Davidzon et al 2017



Davidzon et al 2017

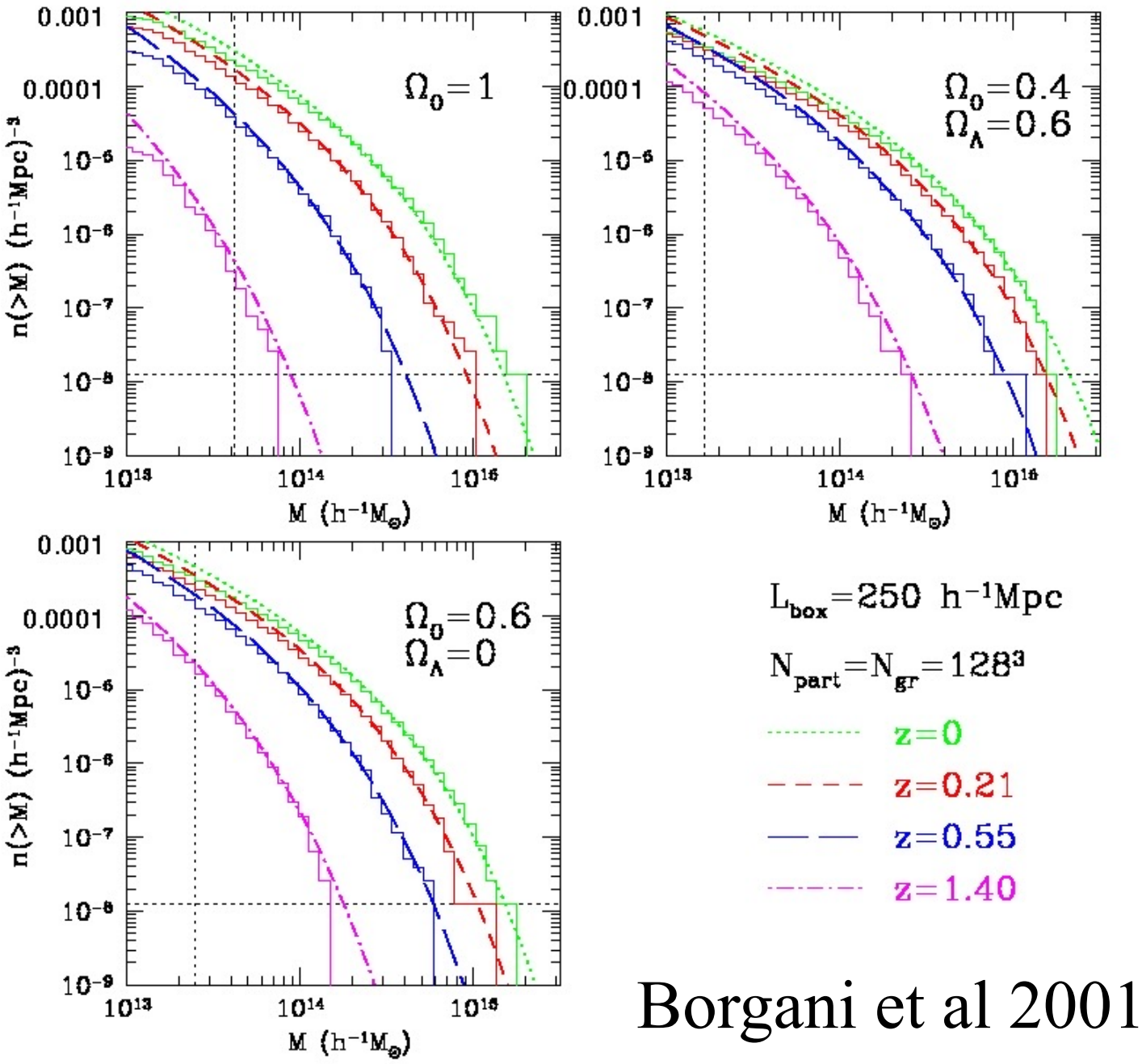


Cole et al 01

4. Global Properties of Galaxies

4.9 Mass function

- The mass function, $\Phi(M)$, gives the number of galaxies per unit volume with a mass M (or in the range M,M+dM)
- Mass is the best observable to compare with theory
- Theoretical Mass Functions (Press-Schechter, Seth & Tormen)
- Numerical simulations



Borgani et al 2001