Components of a Galaxy

1) 3 galaxy 'components'
- Stellar distribution: bulge, disk, bars,
- Distribution of gas (and dust)
- Dark matter

2) The galaxy components only occupy a small part of phase space
- Tully-Fisher, the 'Fundamental Plane' and the Kormendy relations
- Morphology, mass vs. kinematics
- Stellar mass vs. halo mass

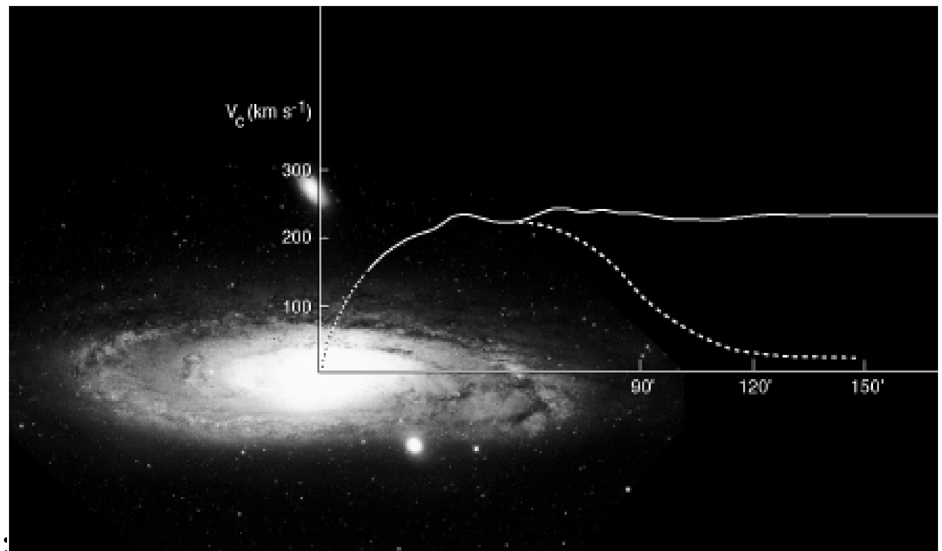
3) Morphology and structure vs. formation history
- the sizes of disk galaxies
- the shapes of massive galaxies

The fraction of galaxies with given properties and the nature of those properties changes with cosmic time in an 'organized' way (downsizing)

also morphologies change 'systematically' (no grand design spirals at high z, fewer classical ellipticals- more odd objects

Evidence for Dark Matter

- Galaxy rotation curves (stars and gas)
- Stability of hot gas in elliptical galaxies and clusters
- Gravitational lensing (strong/weak)
- CMB results
- Big Bang Nucleosynthesis
- Velocity field of globular clusters and satellite galaxies around big galaxies

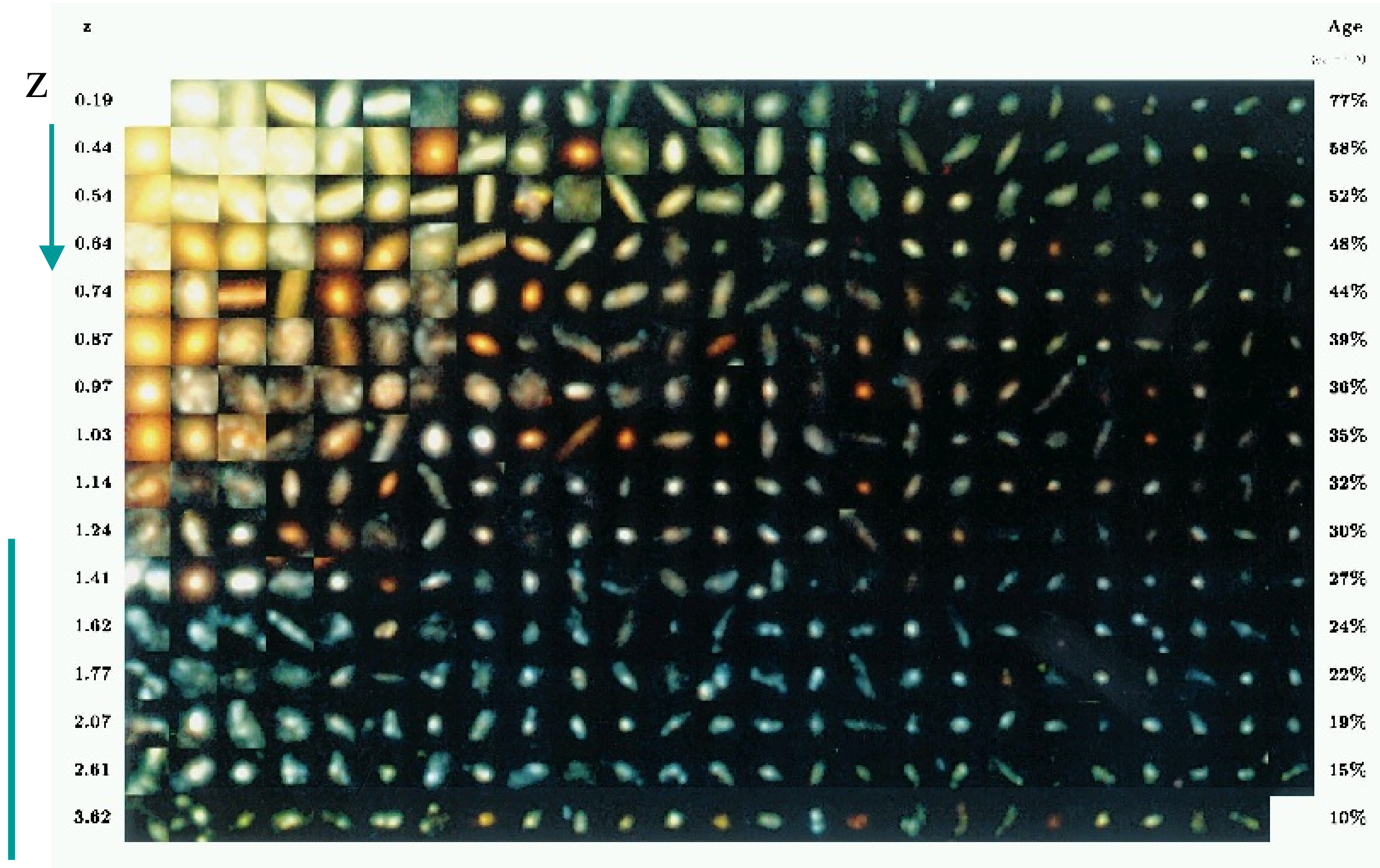


- We will be discussing these a lot more in the class

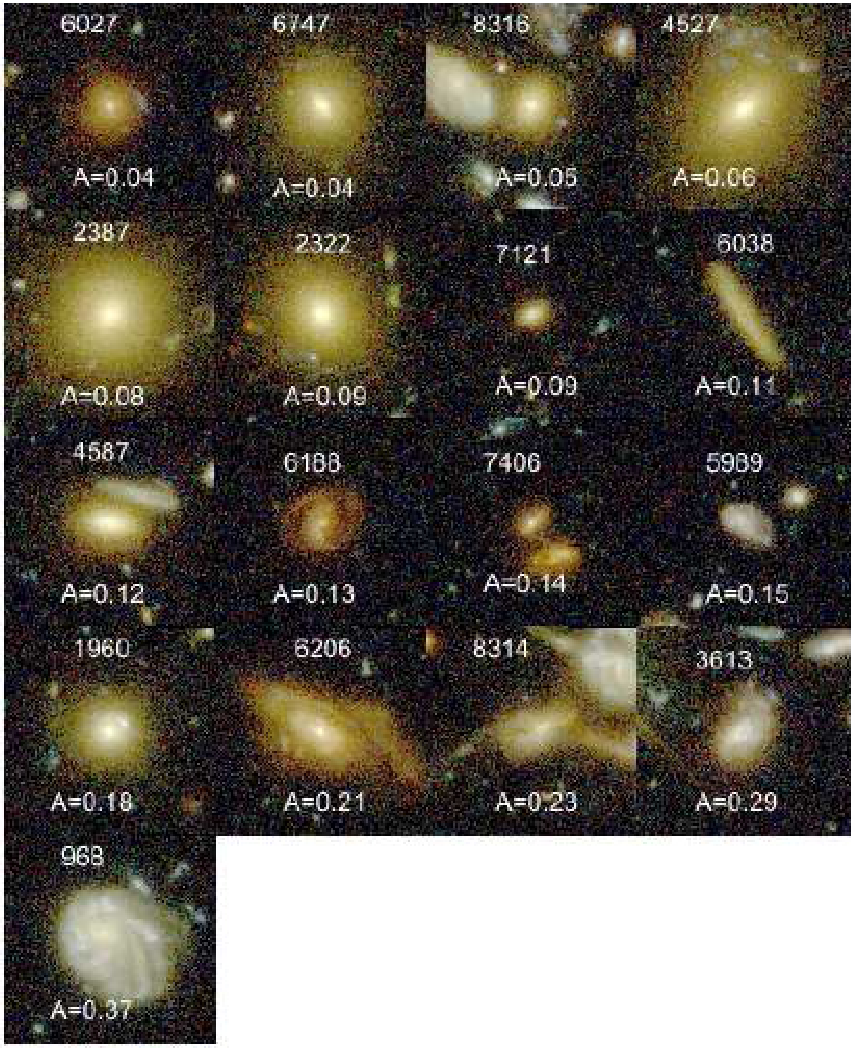
- Dark matter is a indispensible ingredient in modern theories of structure formation;
- As one goes to larger scales DM gets more and more important- there is a wide range of baryonic to DM in galaxies

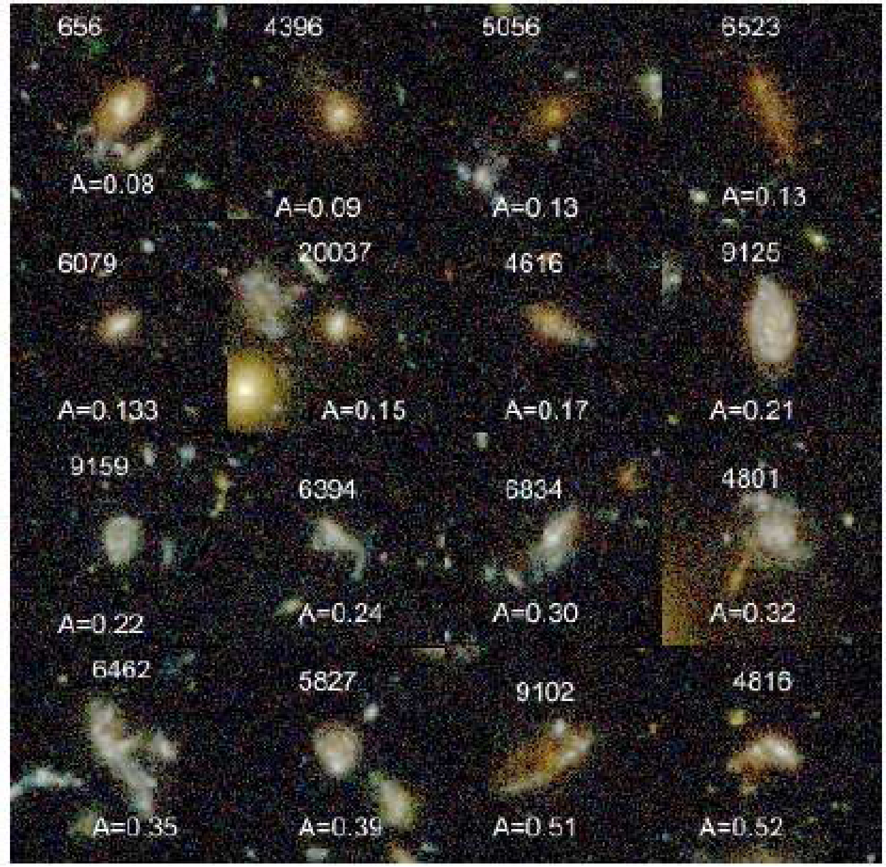
HST galaxy populations in HDF-N

Driver et al 1998



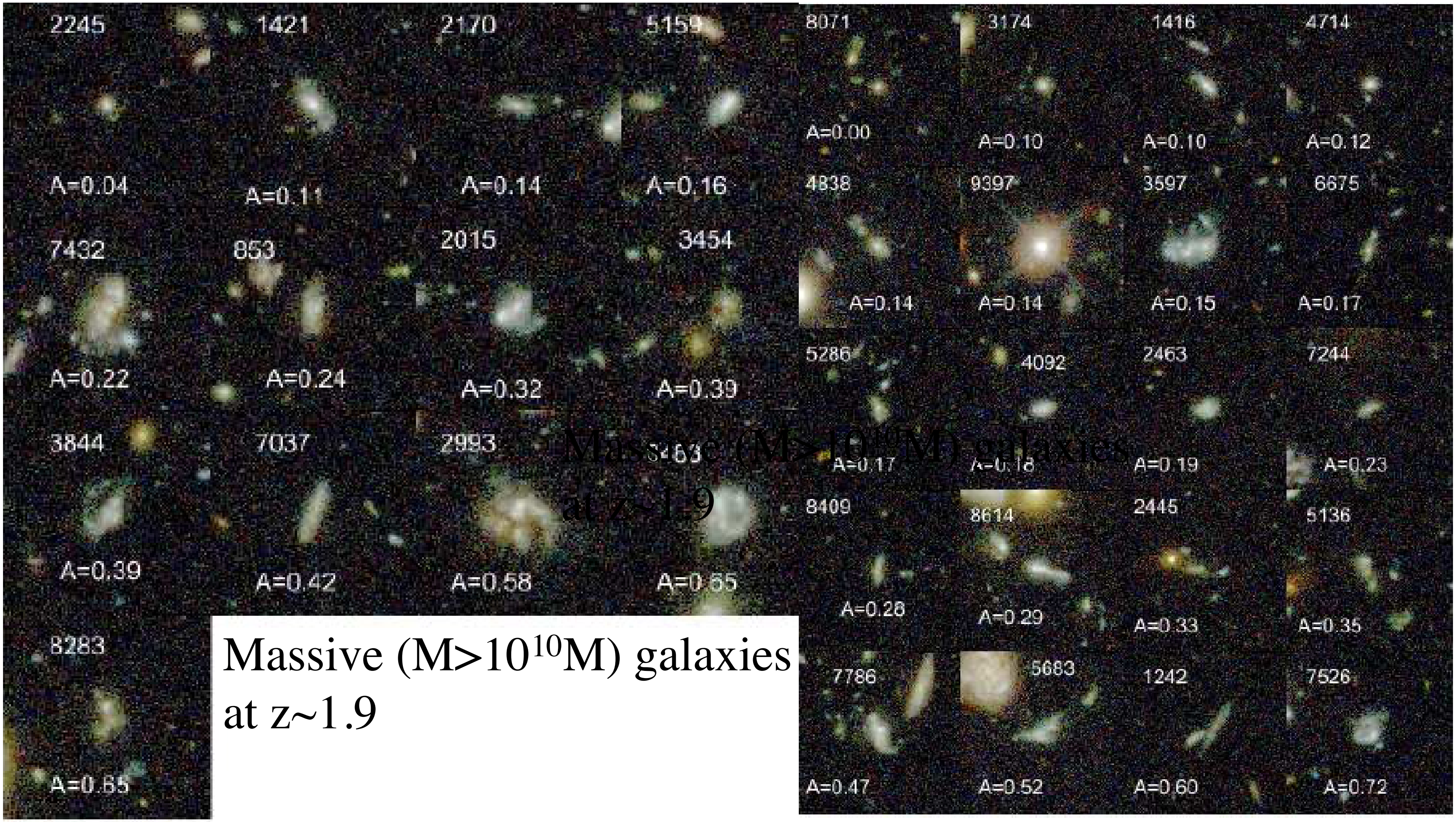
There is a major transition at z ~ 1.4. Red galaxies appear to “end” there, and a population of blue irregulars and compacts appears.





Massive ($M>10^{10}M$) galaxies at z~0.8

Massive ($M>10^{10}M$) galaxies at z~1.4



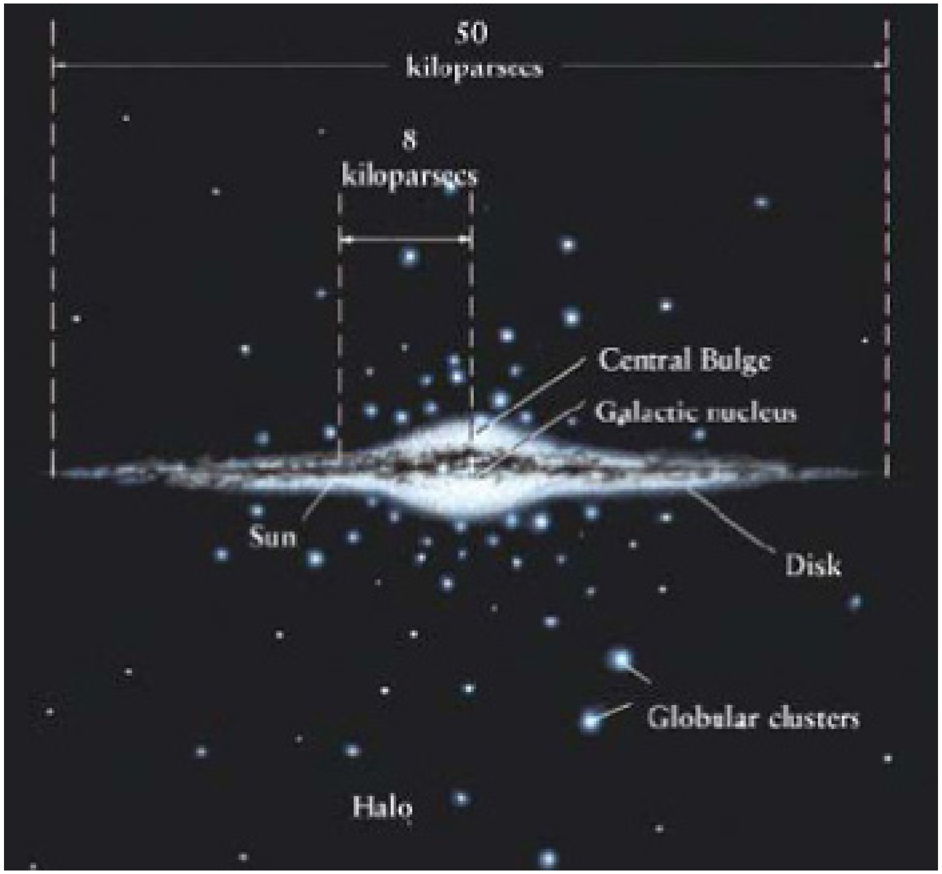
Massive (M>10^{10}M) galaxies
at z~1.9

Systematic evolution
in massive galaxy
morphologies (Conselice et al 2008)

Massive (M>10^{10}M) galaxies
at z~2.6

Globular Clusters

- compact stellar systems $M \sim 10^{5-6} M_\odot$ which lie in a roughly sphereoidal distribution around most galaxies
- Stars are old and metal poor
- Velocity field has little rotation
- MW has ~250 of them



All massive galaxies have globular clusters
Central galaxies of clusters have lots more than expected
Properties of glob clusters and host galaxies weakly connected

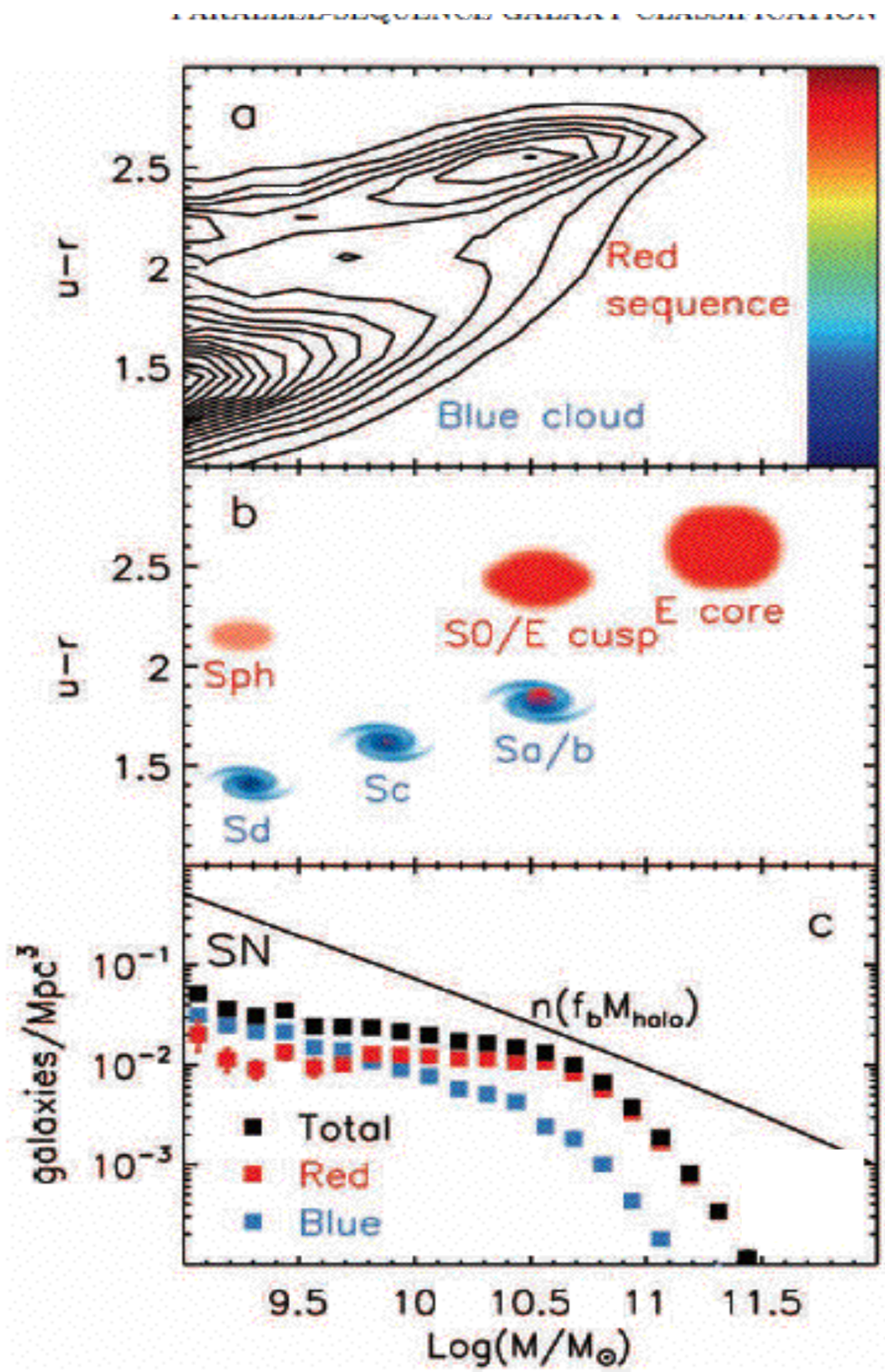
The Big Picture- Two Populations

- top panel color distribution vs mass of a large sample of local galaxies from the SDSS

Middle panel is the morphologies that dominate at each mass

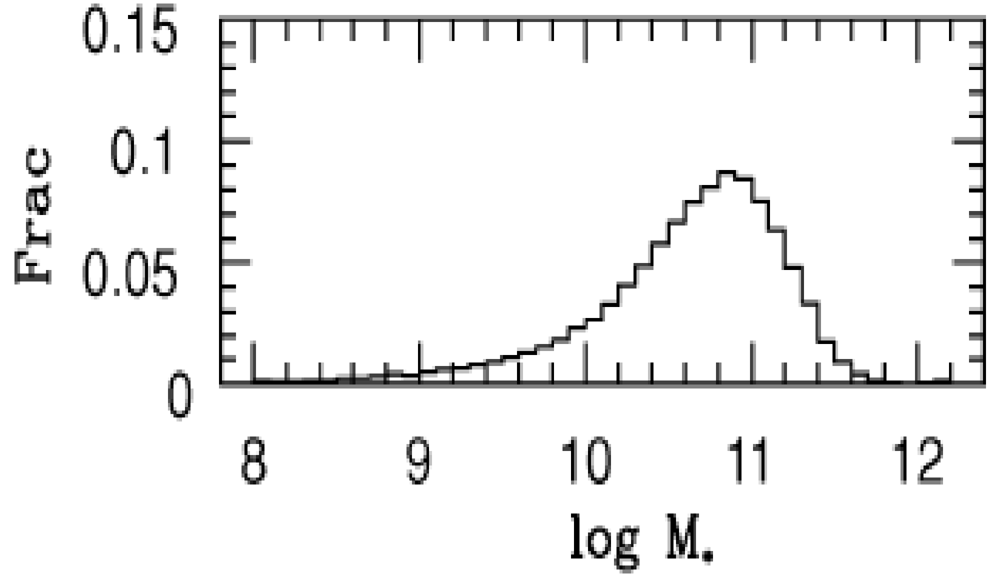
bottom panel shows the galaxy mass function divided by color (Cattaneo et al 2009)-

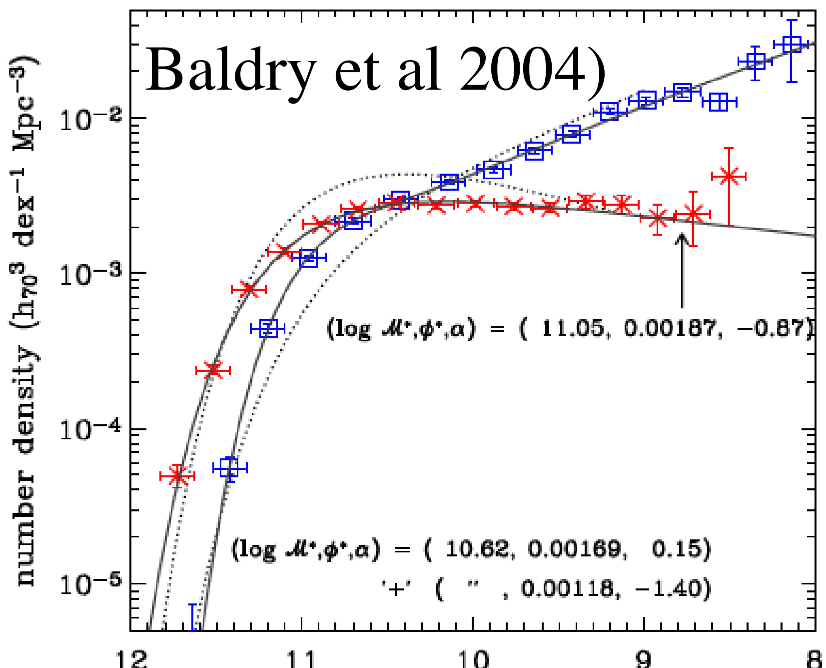
the black solid line is the prediction from cold dark matter theory of the number density of halos vs mass- <u>notice does not agree with the galaxy mass distribution</u>



Where is the Stellar Mass

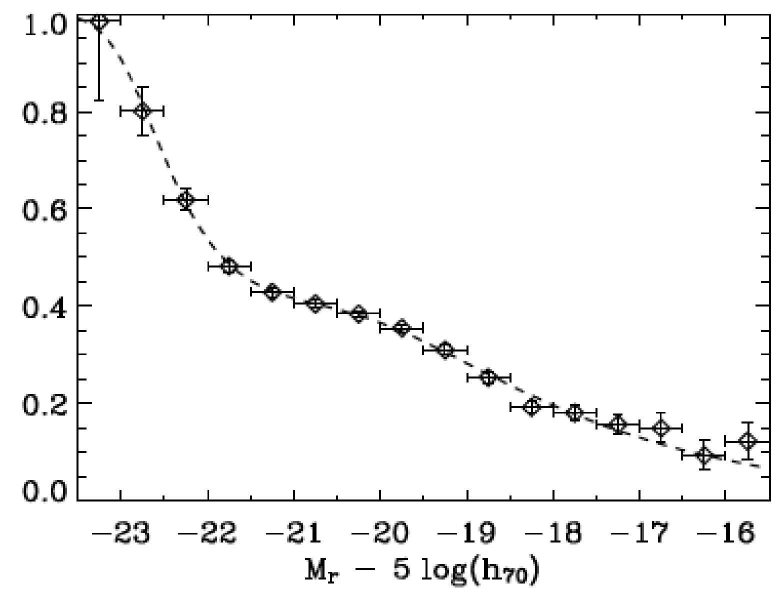
- The stellar mass lies mostly between
- log M=10.5-11.4
- In what galaxies does the stellar mass lie?
  - most massive galaxies are red (ellipticals)
  - at lower masses there is an increasing ratio of spirals to ellipticals





log total mass (stars =DM)

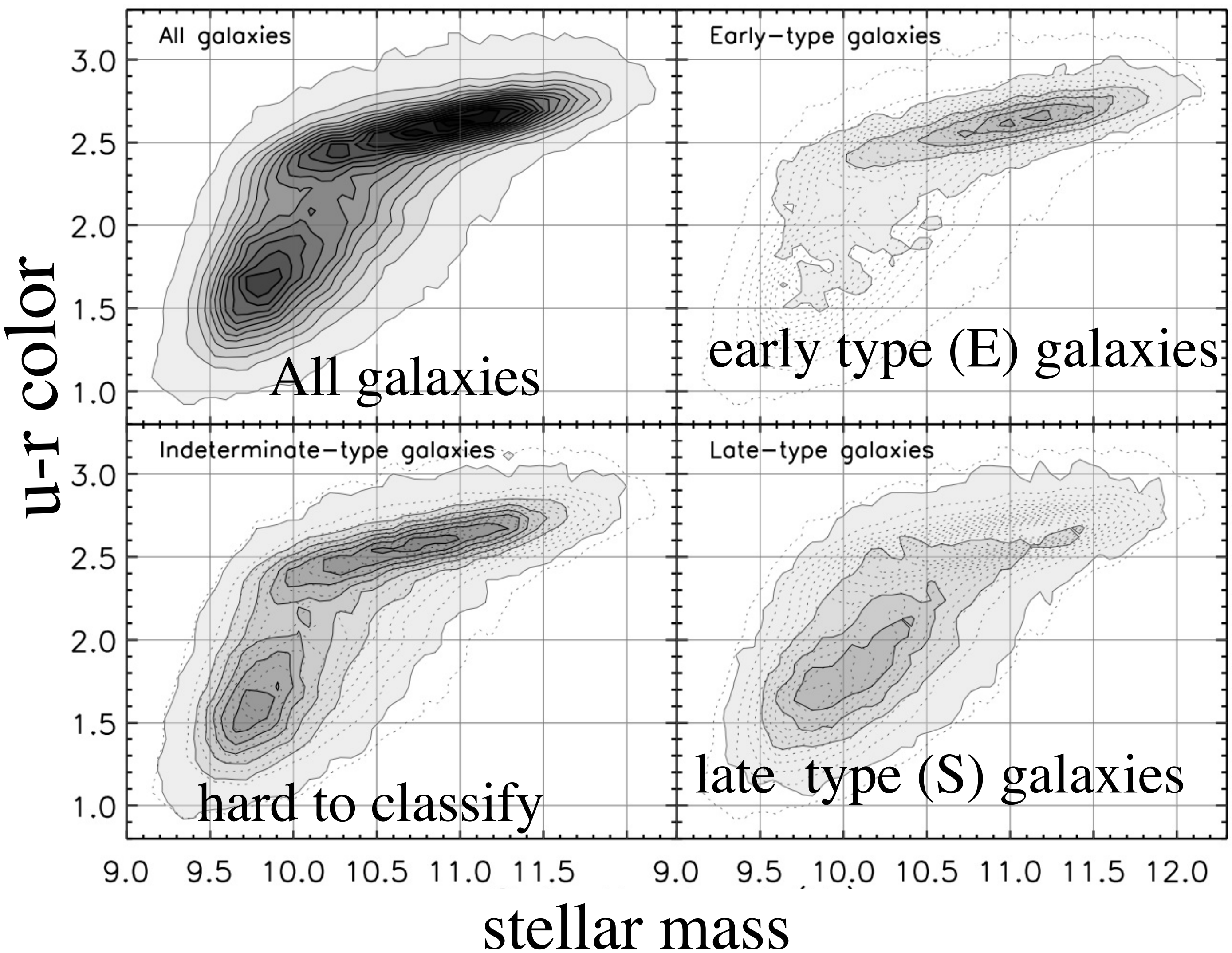
fraction in red cloud



absolute mag

Morphology/ Color and Mass

A result of the 'Galaxy Zoo' project- eyeball classification of 10s of thousands of galaxies by citizen scientists

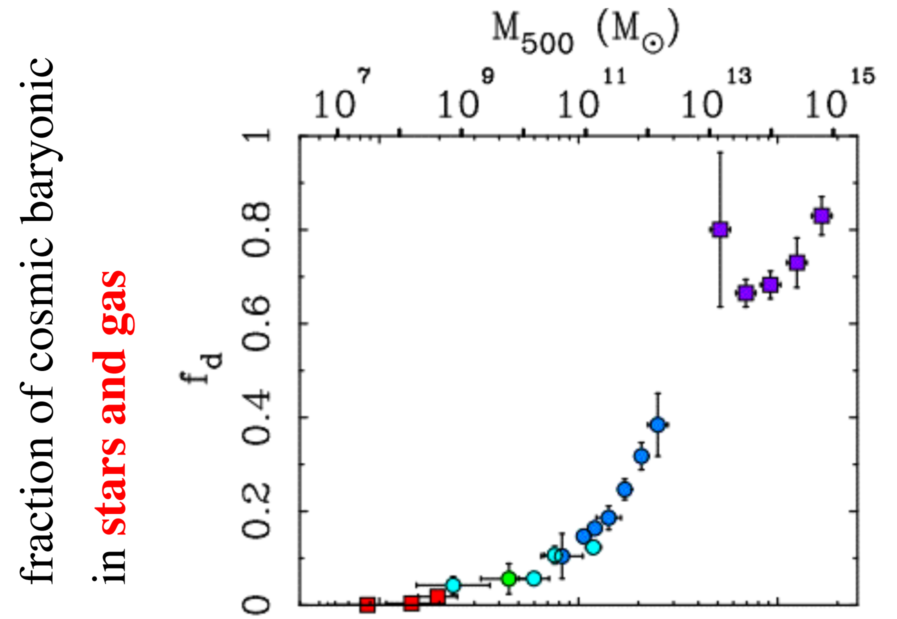


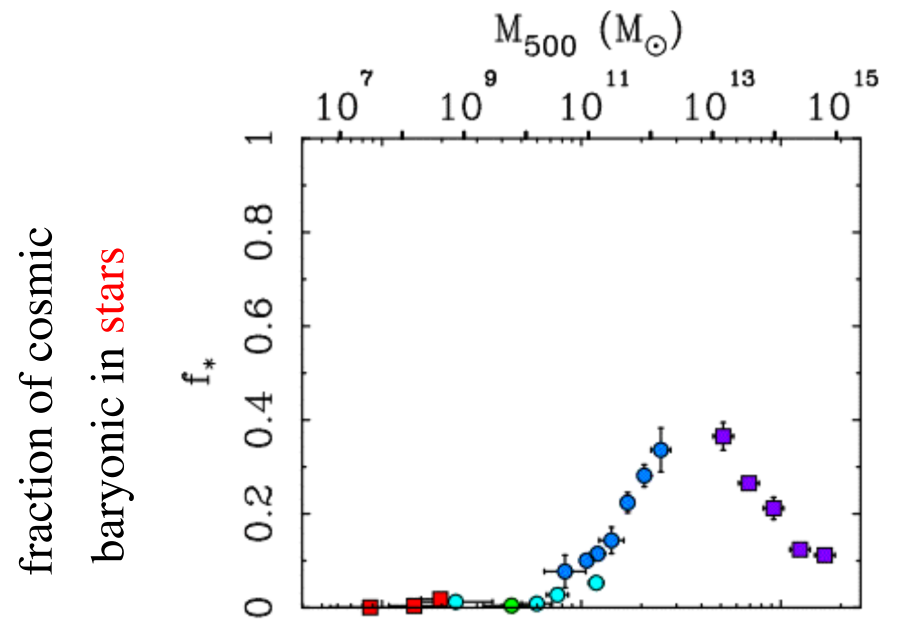
- Strong relation of mass, color and morphology

Schawinski 2010

Baryons vs Total Mass

- Big bang nucelosyntheis , cosmic microwave background and type I SN determine the amount of baryons and their cosmic ratio to dark matter ***f***.
- Galaxies are 'baryon poor'- they have less than the cosmic value of ***f***
- In addition there is a pattern, the more massive the system the larger is the baryonic fraction.
- ***f*** only gets close to 1 for clusters of galaxies, but in them most of the baryons are in gas.
- Most of the baryons in the universe are not in collapsed structures (galaxies and clusters)!

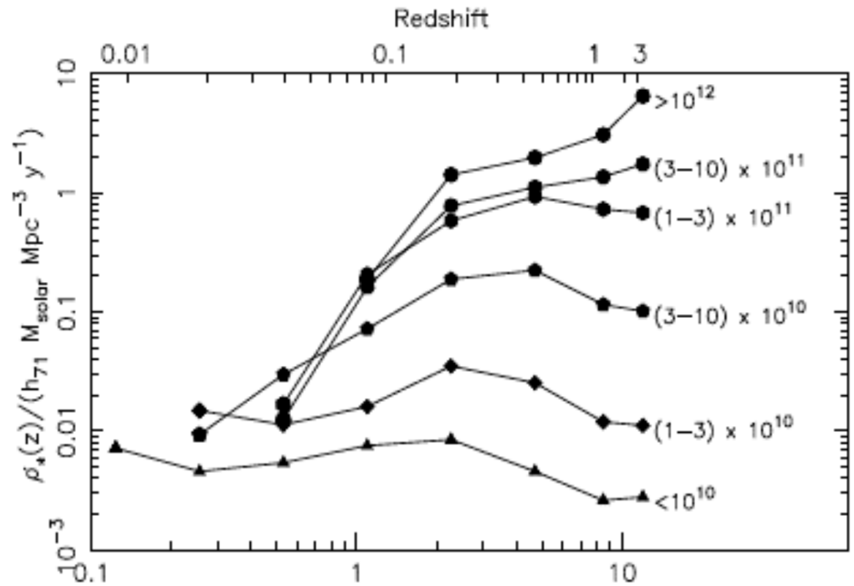




McGaugh 2009

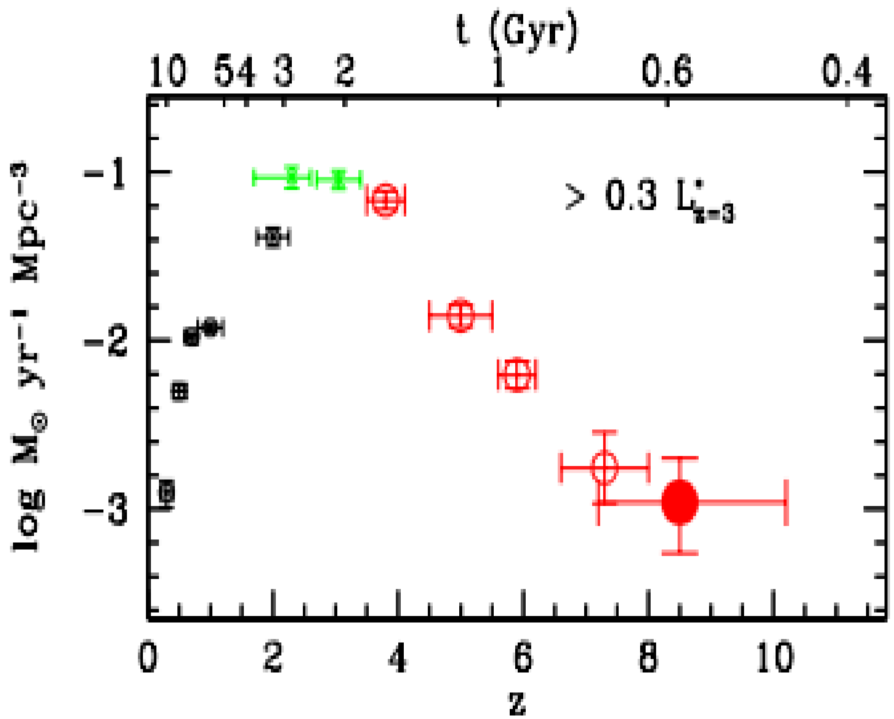
When Did Galaxies Grow

- The star formation rate peaked at z~2 and has declined since
- More massive galaxies formed first and stopped growing at z~1, low mass galaxies are still



look back time (Gyr)

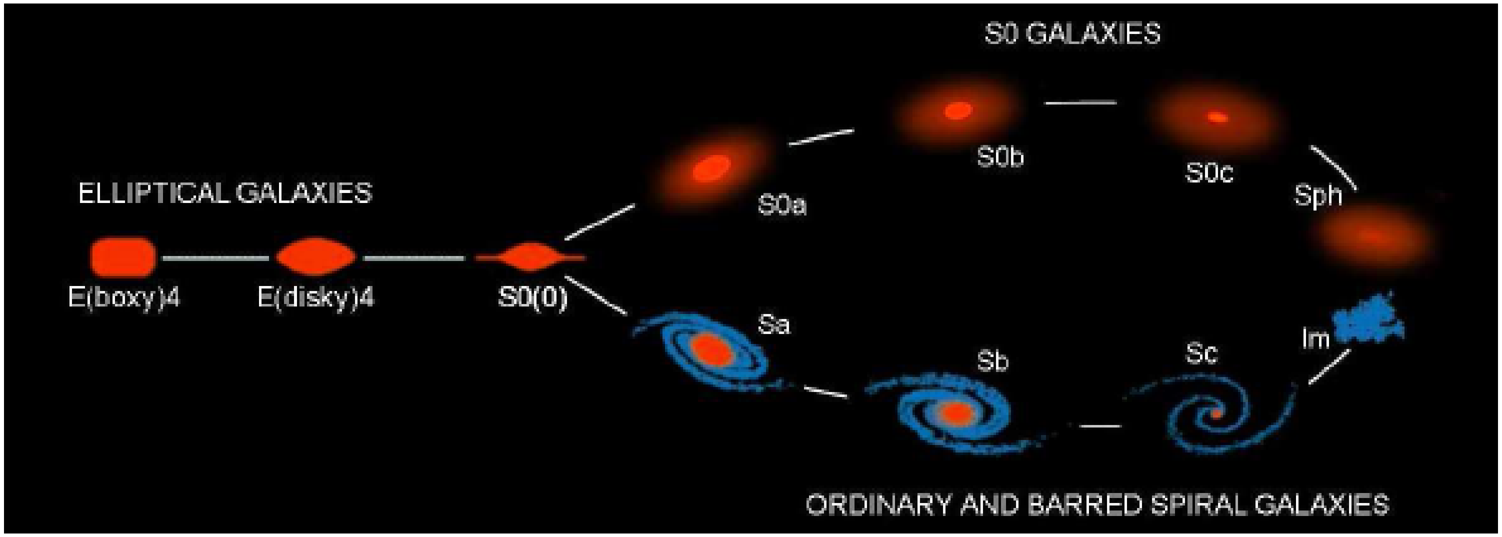
Star formation rate for galaxies of given mass



star formation rate per unit volume averaged over all galaxies

Galaxy Classification

- There are many ways of classifying galaxies
  - morphology (shapes)
  - colors
  - spectra
  - location (field, groups, clusters)
  - mass etc
- What is surprising is that these are very strongly related and that there is PHYSICS in the arcane nomenclature



Elliptical Galaxies

- 'Giant' ellipticals tend to be
  - massive
  - red (old stellar population)-narrow range of colors (called PopII)
  - lack dust and cold gas
  - more often lie in dense regions
  - show little internal structure
  - have little present day star formation
  - more massive ellipticals tend to be more 'metal' enriched
  - 'pressure' supported (stellar velocity field is random)
  - have luminous x-ray emitting atmospheres
  - Surface brightness well described by a 'cored' profile
  - Most hosts of radio galaxies are in giant E's

•'Dwarf' ellipticals
core less
tend to rotate
'younger' stars
weak x-ray atmospheres
do not often host radio sources

Elliptical Galaxies

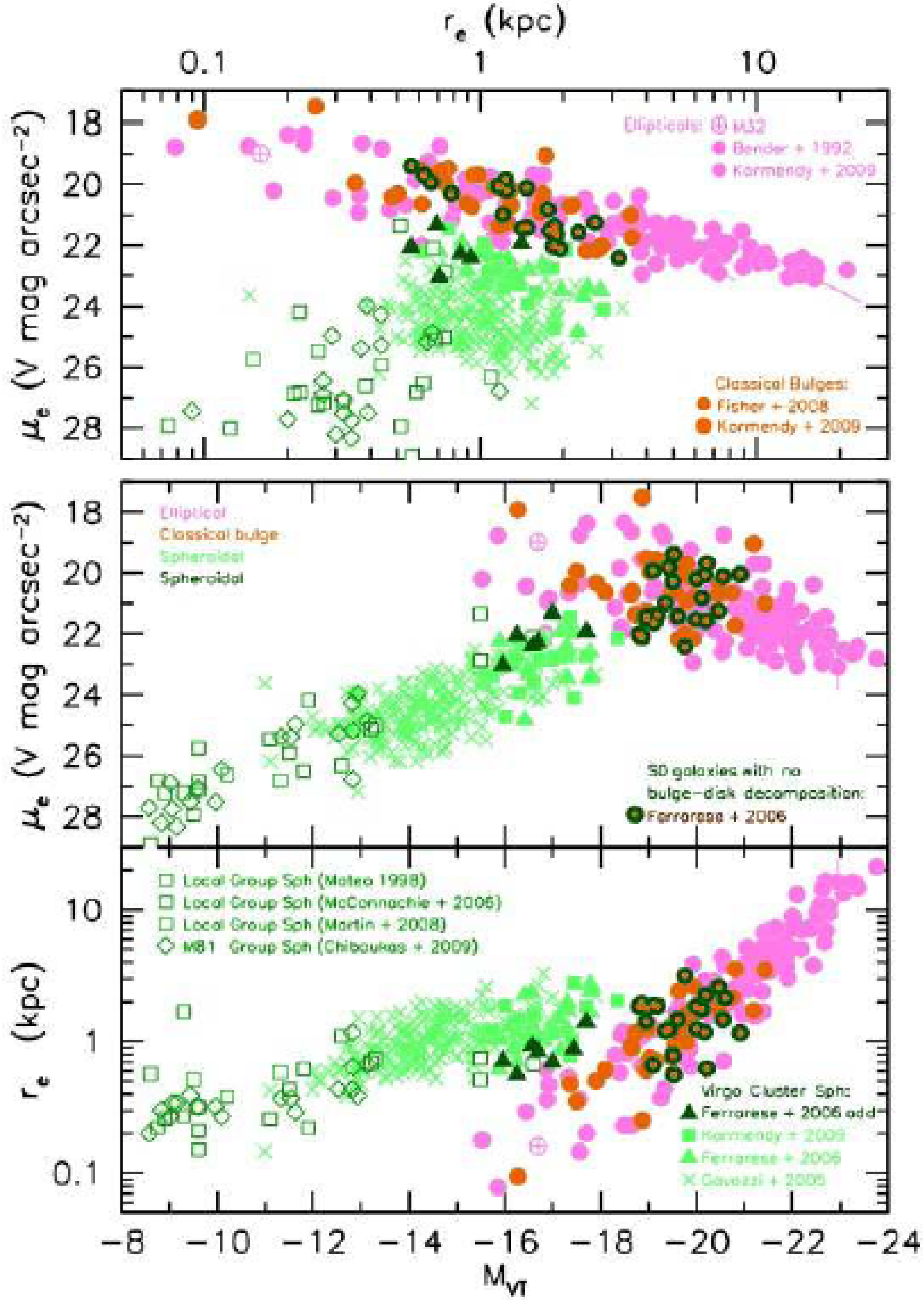
- There are a set of correlations (fundamental plane) which describe virtually all ellipticals

  μ= surface brightness

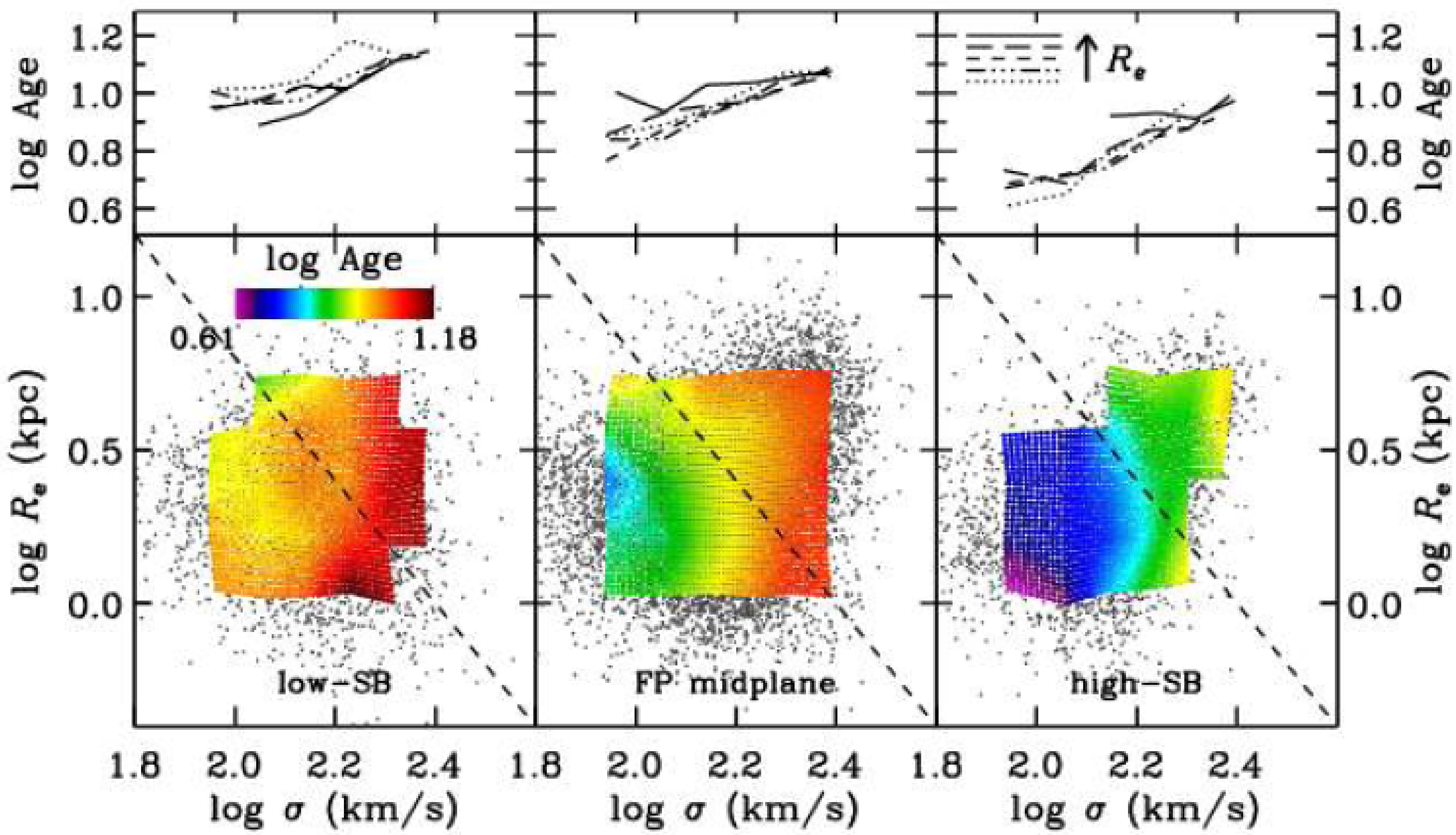
  r_e= scale length

  Bulges in spirals and ellipticals are related but not identical

Global parameter correlations for ellipticals (pink), classical bulges (light brown), and spheroidals (light green) from Kormendy et al. (2009:



Relationship Between Surface Brightness,Size, Velocity and Age of Stars

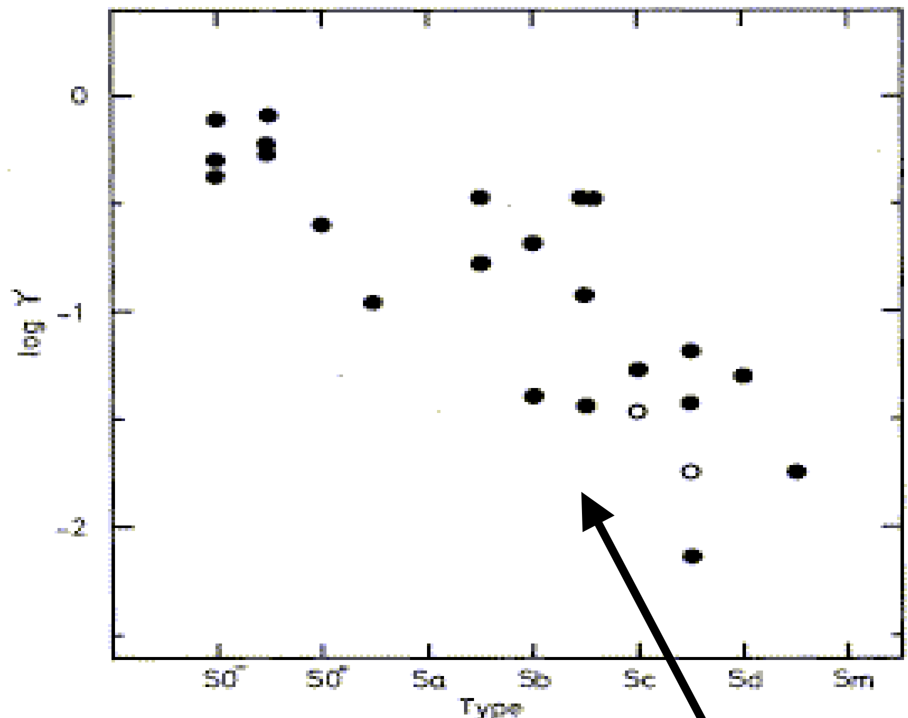


- lines of constant age run nearly vertically, indicating that stellar population age is independent of R_e (scale length in Sersic fit) at fixed σ (stellar velocity dispersion.
- However,comparing the age ranges (indicated by the color scale)between the different panels, there are systematic differences.

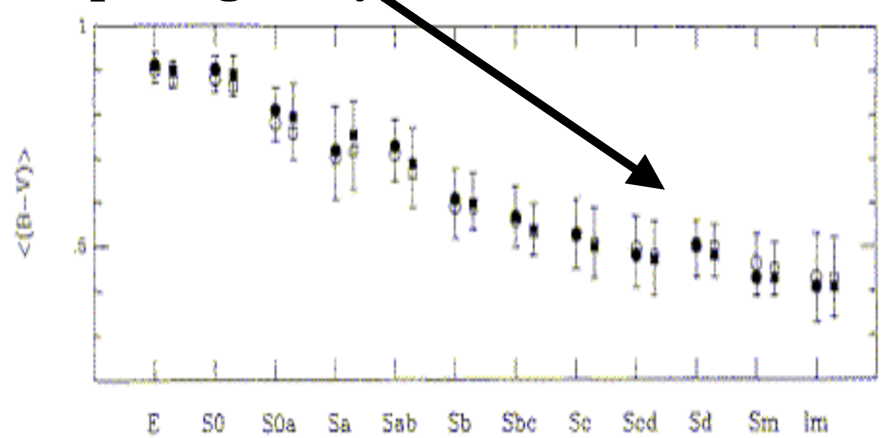
Spirals

The Hubble type of a spiral correlates with

- bulge/disk luminosity ratio
- relative content of cool gas (H I)
- mass concentration
- stellar population (how many young/old stars)
- nuclear properties
- chemical abundances in the ISM
- star formation history and integrated stellar spectrum
- bulges of spirals tend to have old stars, disks younger stars
- *A lot of the detail depends on what wavelength one observes in (e.g. the UV favors hot young stars, the IR dust, x-rays hot gas and binaries)*

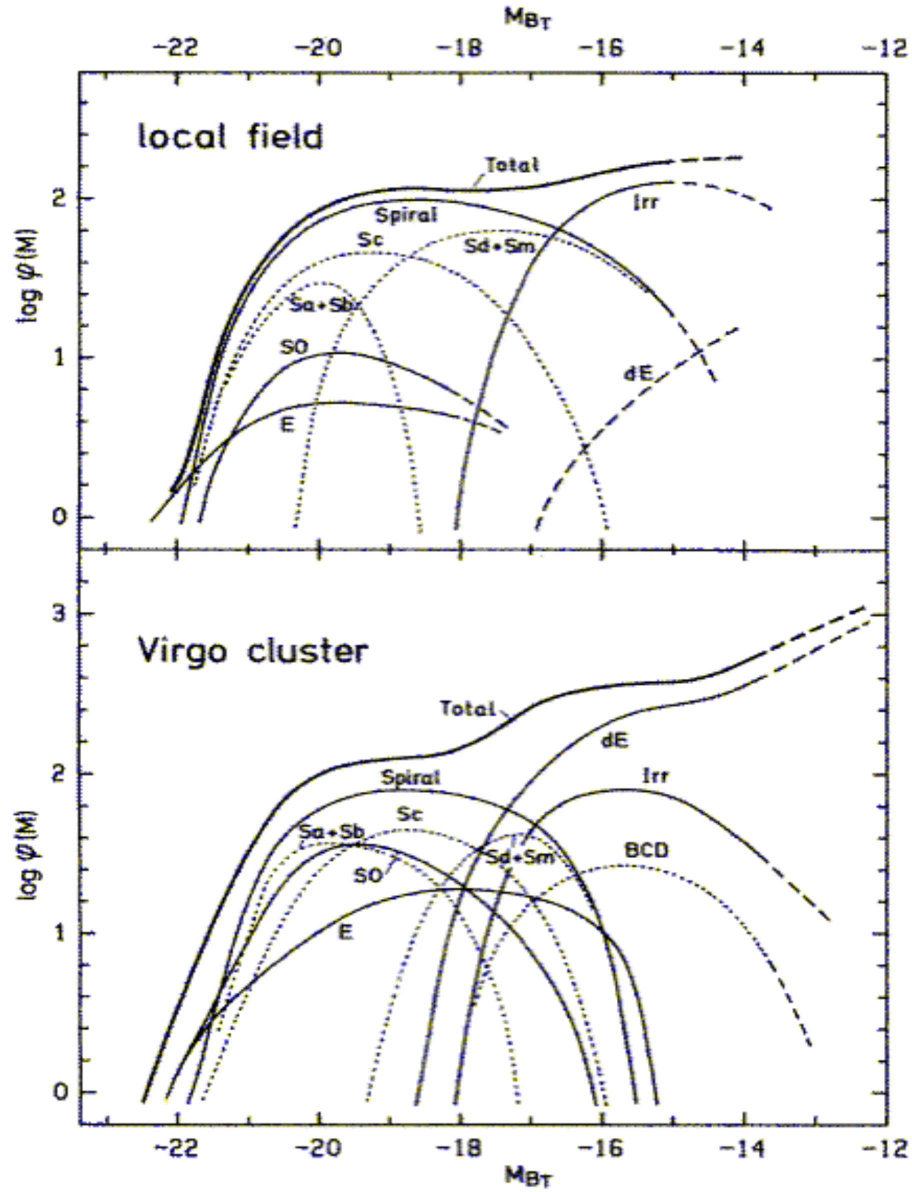


Ratio of bulge to disk luminosity and color as a function of morphological type



How Many of Which??

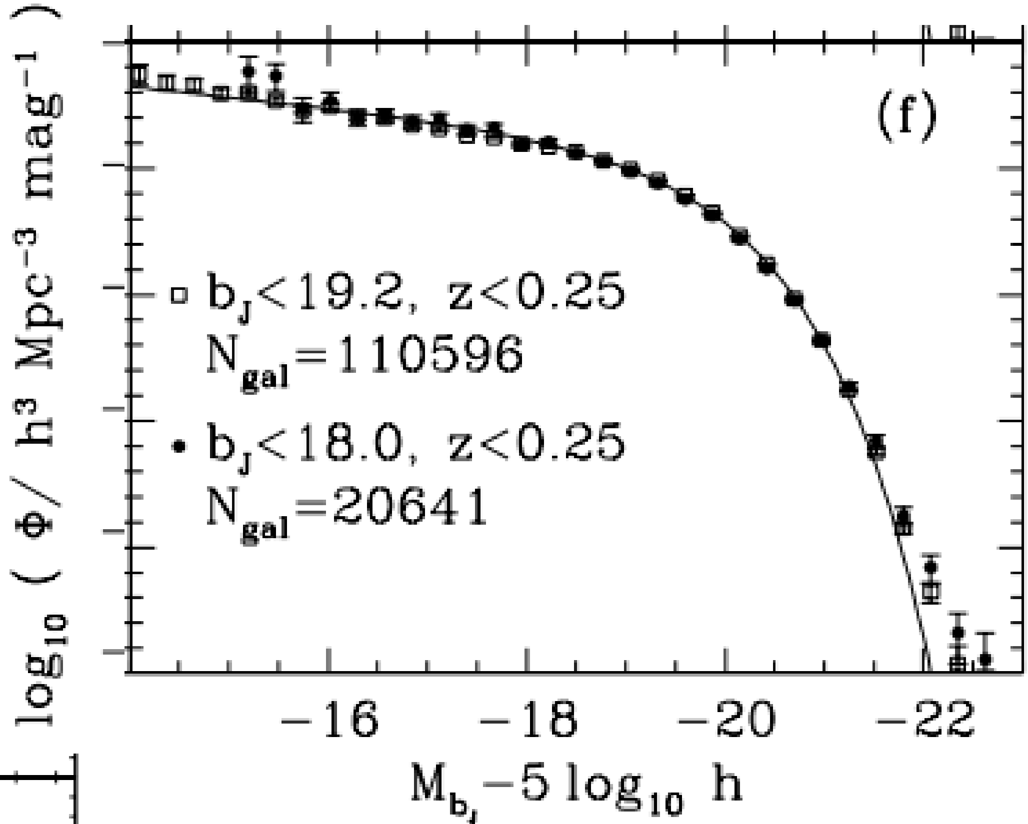
- the relative number and mass fraction of each 'type' of galaxy depends on the environment
- the 'luminosity function' (the number of galaxies per unit luminosity per unit volume) vs absolute magnitude.
- this does not represent the mass function since the relationship between mass and luminosity (M/L)is a complex function of galaxy properties
  - (e.g ellipticals tend to have a high M/L since their light is dominated by an old stellar population) - the M/L for spirals is a strong function of color since the blue light is dominated by massive young stars with a low M/L.
  - create your own http://www.mso.anu.edu.au/~jerjen/dial_a_LF/dial_a_lf.html

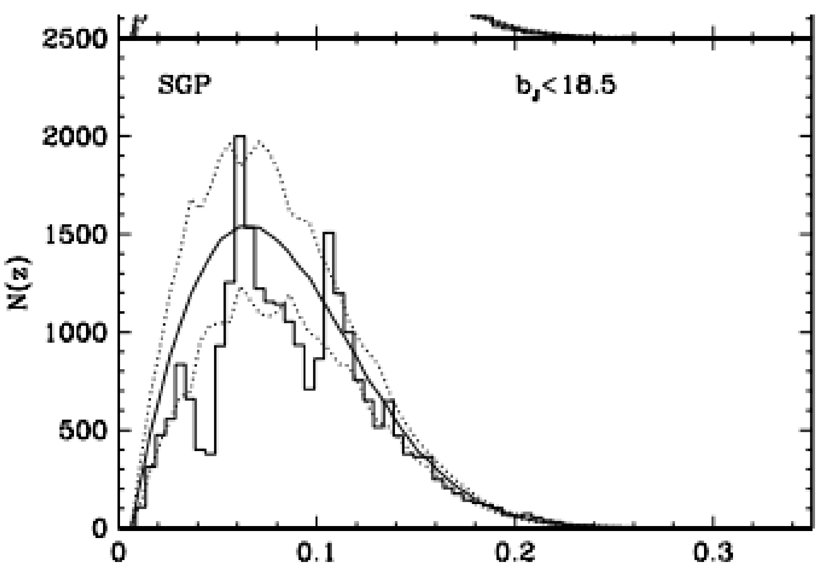


Binggeli, Sandage, and Tammann 1988

Luminosity Function

- The combined luminosity function of all galaxies is fitted by the Schecter function- a power law at low L and an exponential cutoff at high L

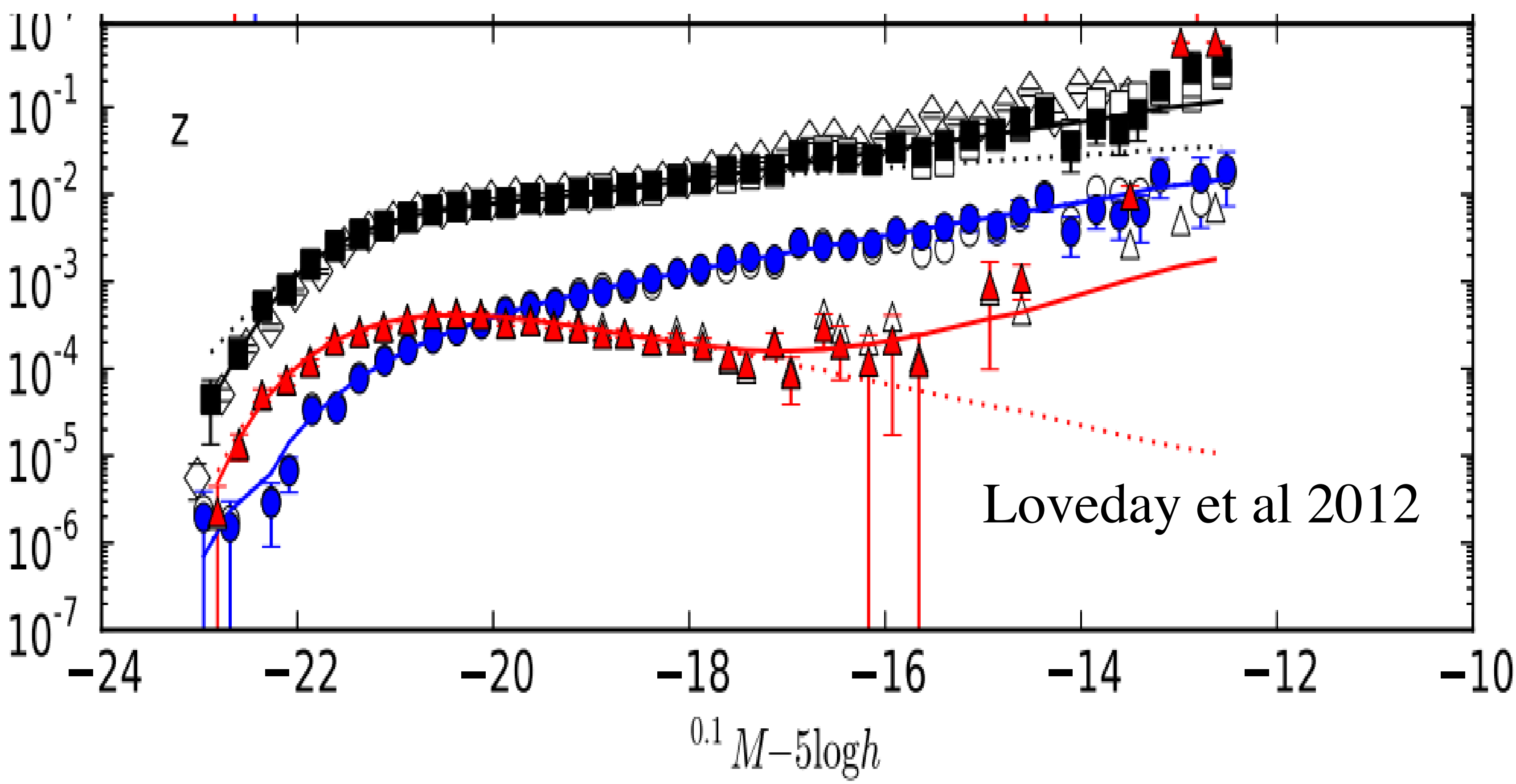




Redshift distribution is not uniform (e.g. large scale structure makes derivation of f(L) unstable at high L where objects are rare

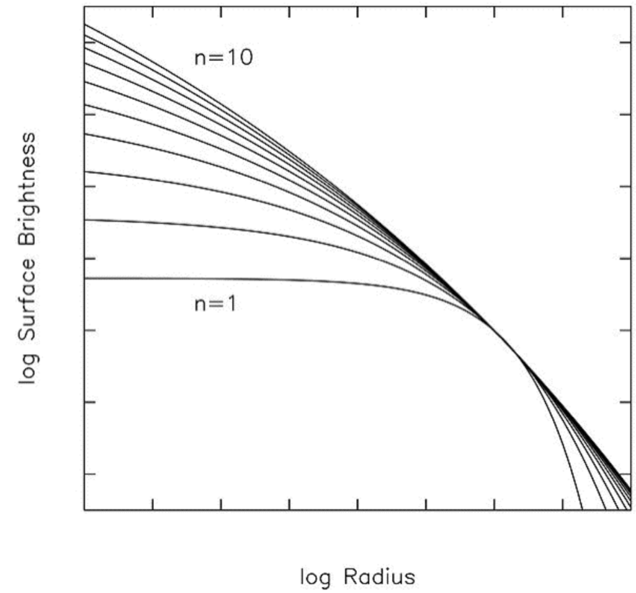
Red and Blue Luminosity Functions

Despite differences in populations the red (mostly ellipticals) and blue (mostly spiral) galaxy luminosity functions add smoothly together and are well fit with a Schechter function



Descriptions of Galaxy Optical Surface Brightness

- For most massive galaxies a two component description of the surface brightness is a reasonable approximation to the azimuthally averaged data
  - – Bulges/spheroids
  - – Disks
- The ratio of these two components has wide variation
- Both can be described by a 'Sersic' profile $\lambda\nu\Sigma(r)=\ln\Sigma(0-)\exp(-k\,[(r/r_e)^{1/n}-1]$; $k \sim 2n-0.331$ (who called for that!) where r_e is a characteristic (scale length)
- Disks have n~1 (exponential profile) while spheroids have n~2-5 (a special value is n=4, the DeVacouleurs profile)
- Most spirals have a bulge and thus the surface brightness is the sum of 2 Sersic profiles (the bulge usually dominates for small r)



$$L = 2\pi \int_0^\infty I(R)\,R\,dR = \frac{2\pi n \Gamma(2n)}{(\beta_n)^{2n}} I_0 R_e^2,$$

total luminosity of Sersic profile

Stellar Distribution-

radial average

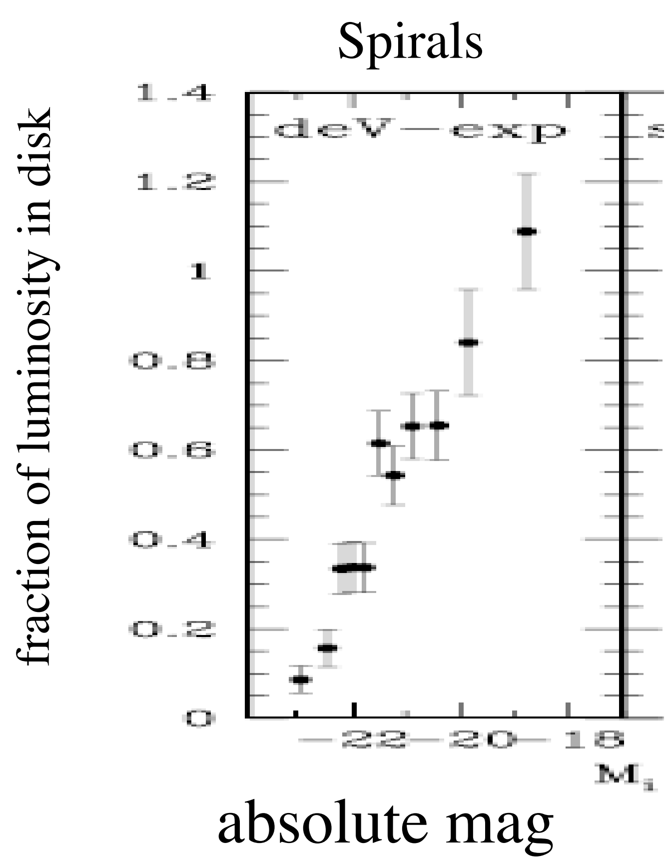
- Massive galaxies (spirals and ellipticals) can be described by a '2' component radial profile model:
  - disk; n~1
  - bulge; n~2-5 (n~4 for giant ellipticals

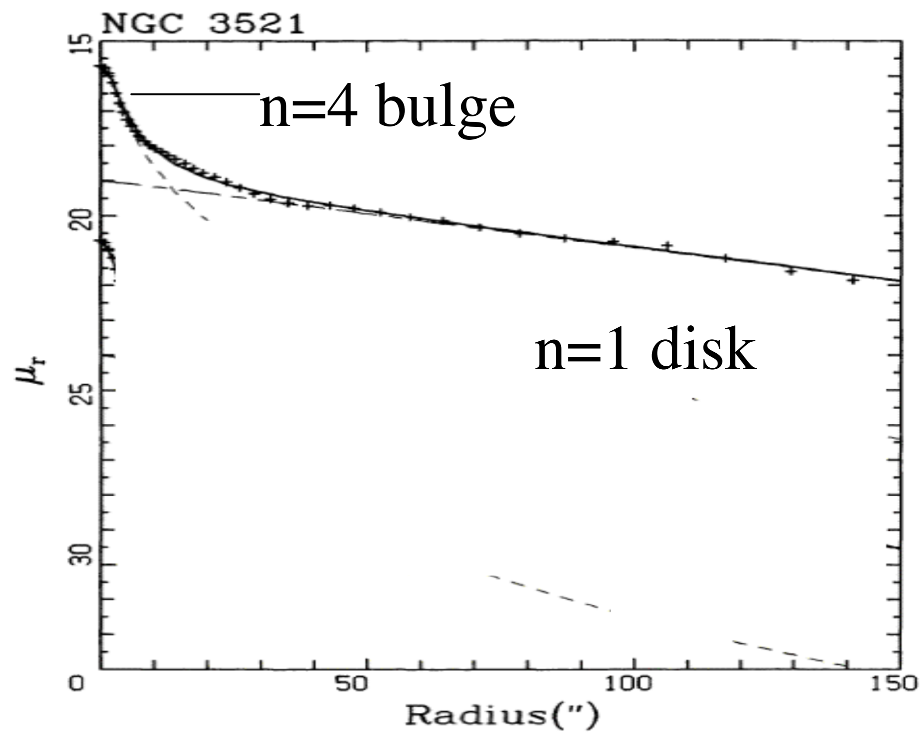
$$\Sigma(r) = \Sigma_e e^{-\kappa[(r/r_e)^{1/n}-1]}$$

$$\kappa \approx 2n - 0.331$$

Sersic(1968) profile

More massive galaxies have a higher fraction of their light (mass) in the bulge





Spirals

- Spirals tend to
  - have cold gas and dust
  - present day star formation
  - many have internal structure (spiral arms and bars)
  - a bulge and disk (large range in relative importance)
  - host radio quiet AGN
  - are more frequent in lower density environments
  - appearance of galaxy can change radically depending on the 'stretch'
  - x-ray luminosity is dominated by binaries
  - ISM is highly structured

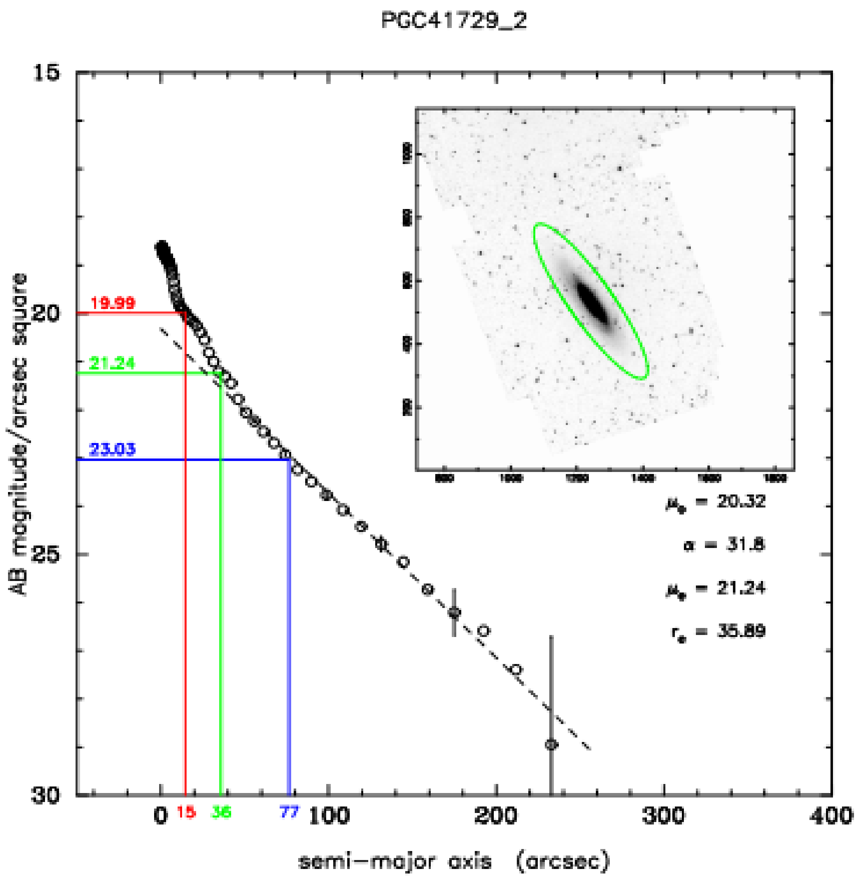

NGC 4594 Hubble Heritage

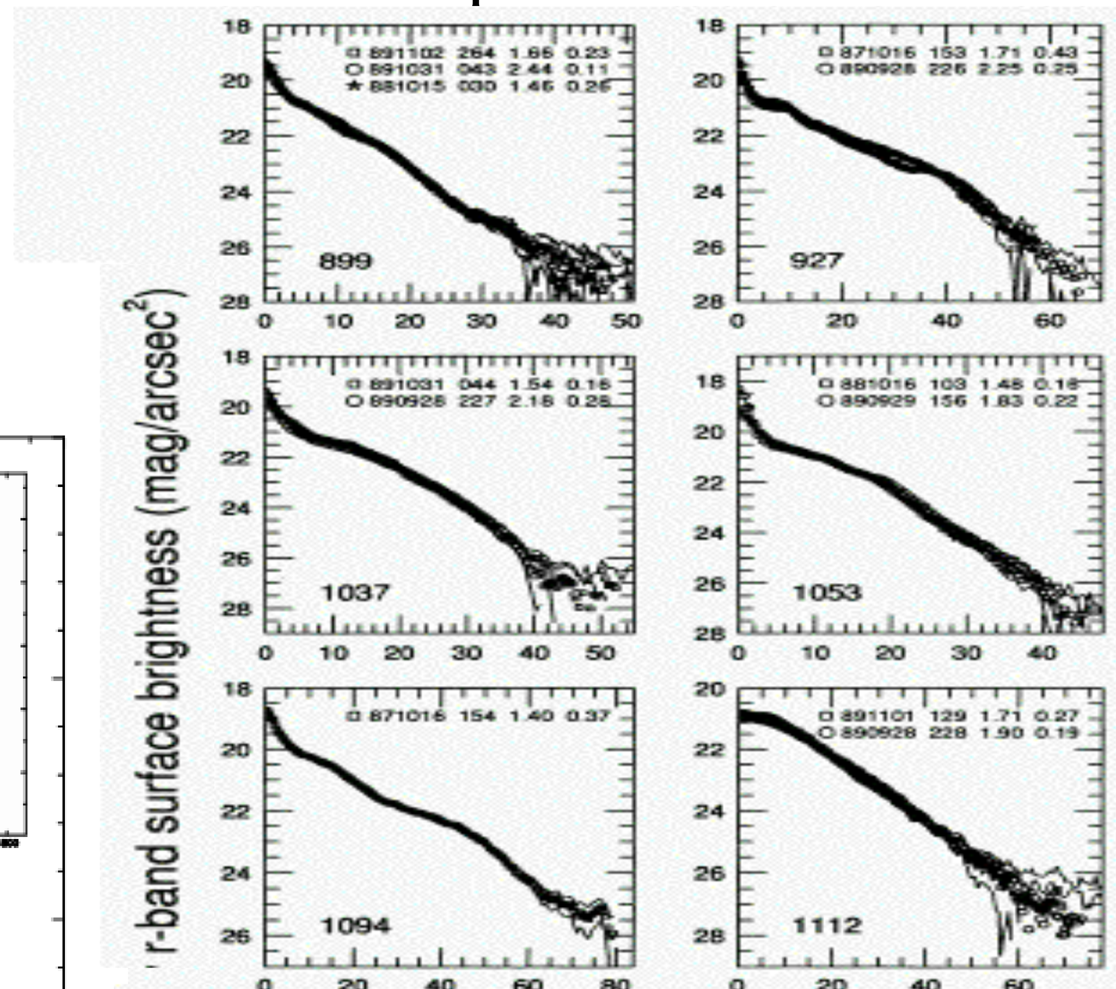

NGC 4762 SDSS gri

Typical disk surface brightness profiles

Pure exponentials would be straight lines.

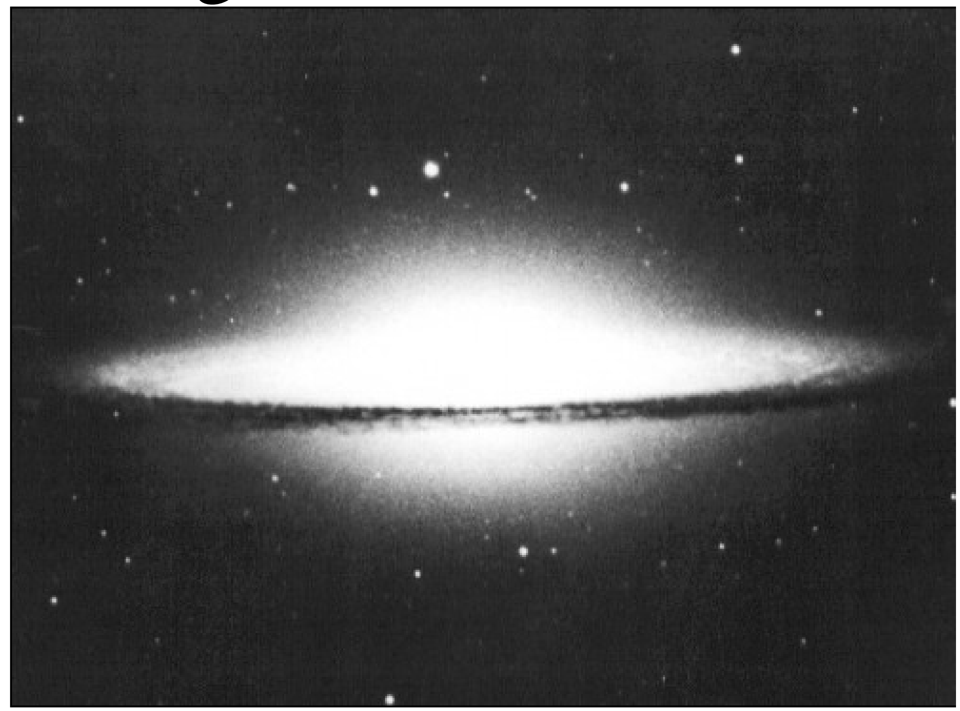
The exponential scale length α is a measure of the size of the baryonic disk.- Most of the light is inside 2 scale lengths





Courteau, ApJS, 103, 363, 1996

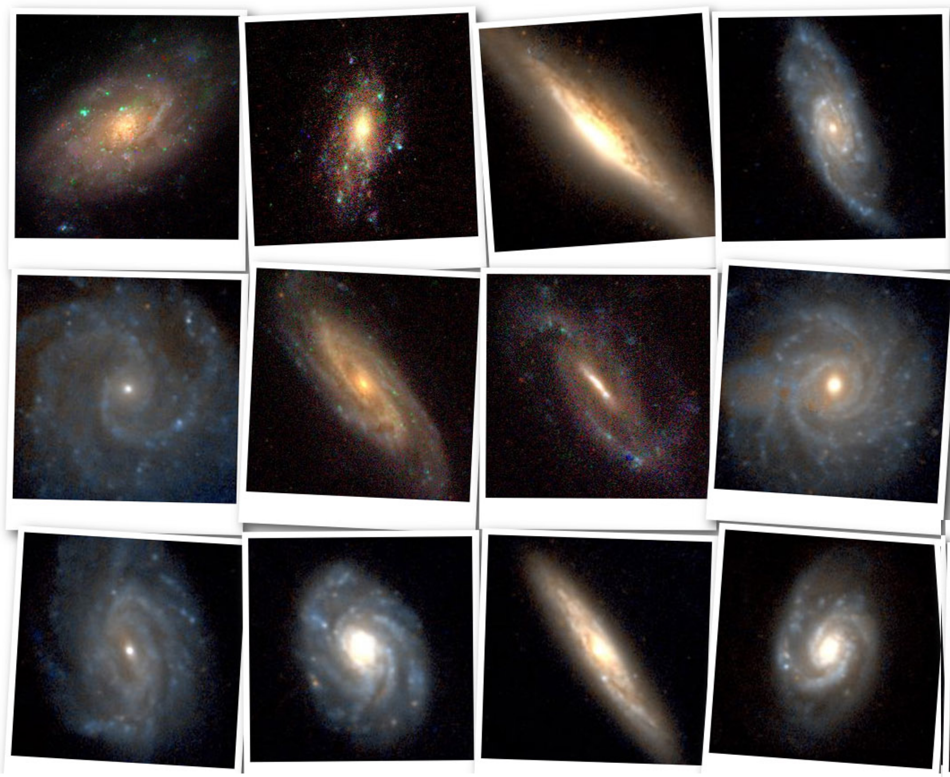
Physical Difference Between Bulges and Disks



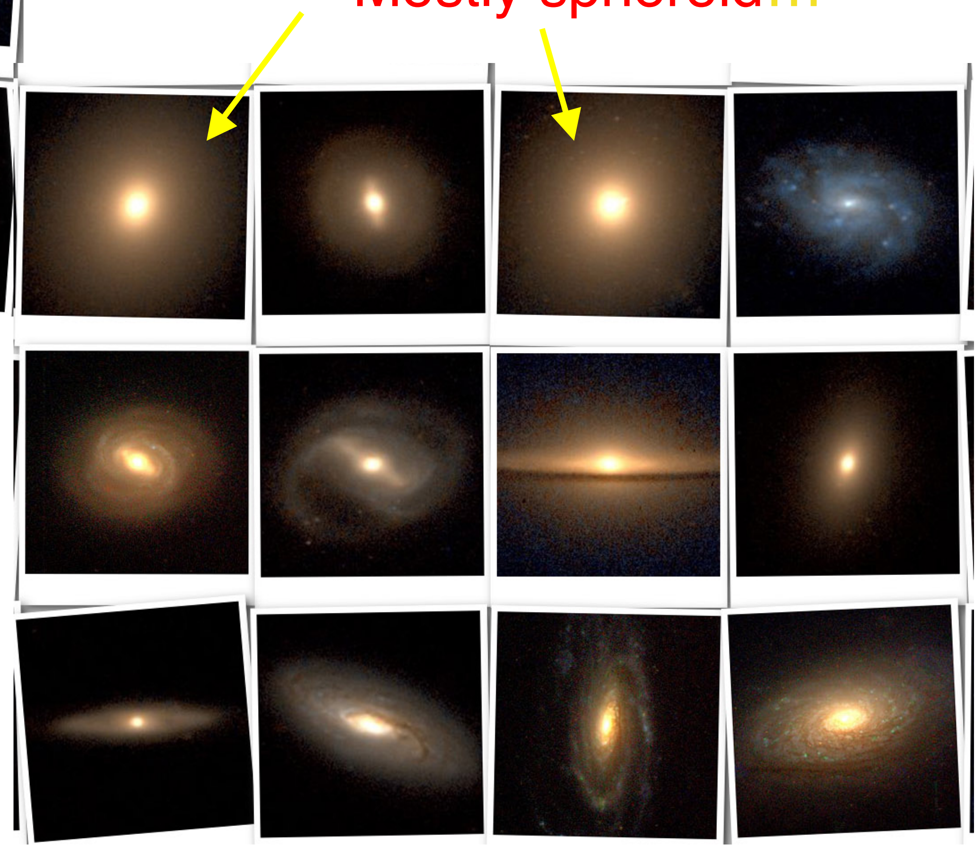
- In spiral galaxies
  - the stars in the disk have lots of angular momentum and a wide variety of ages.
  - stars in the bulge tend to be old, have little angular momentum and have low metallicity*
    - (globular clusters may be part of this population)
- Disks are rotationally supported (dynamically cold)
- Bulges are dispersion supported (dynamically hot)

•* while superficially elliptical galaxies 'look like' bulges their stars are frequently metal rich, not metal poor.

Mostly disk…



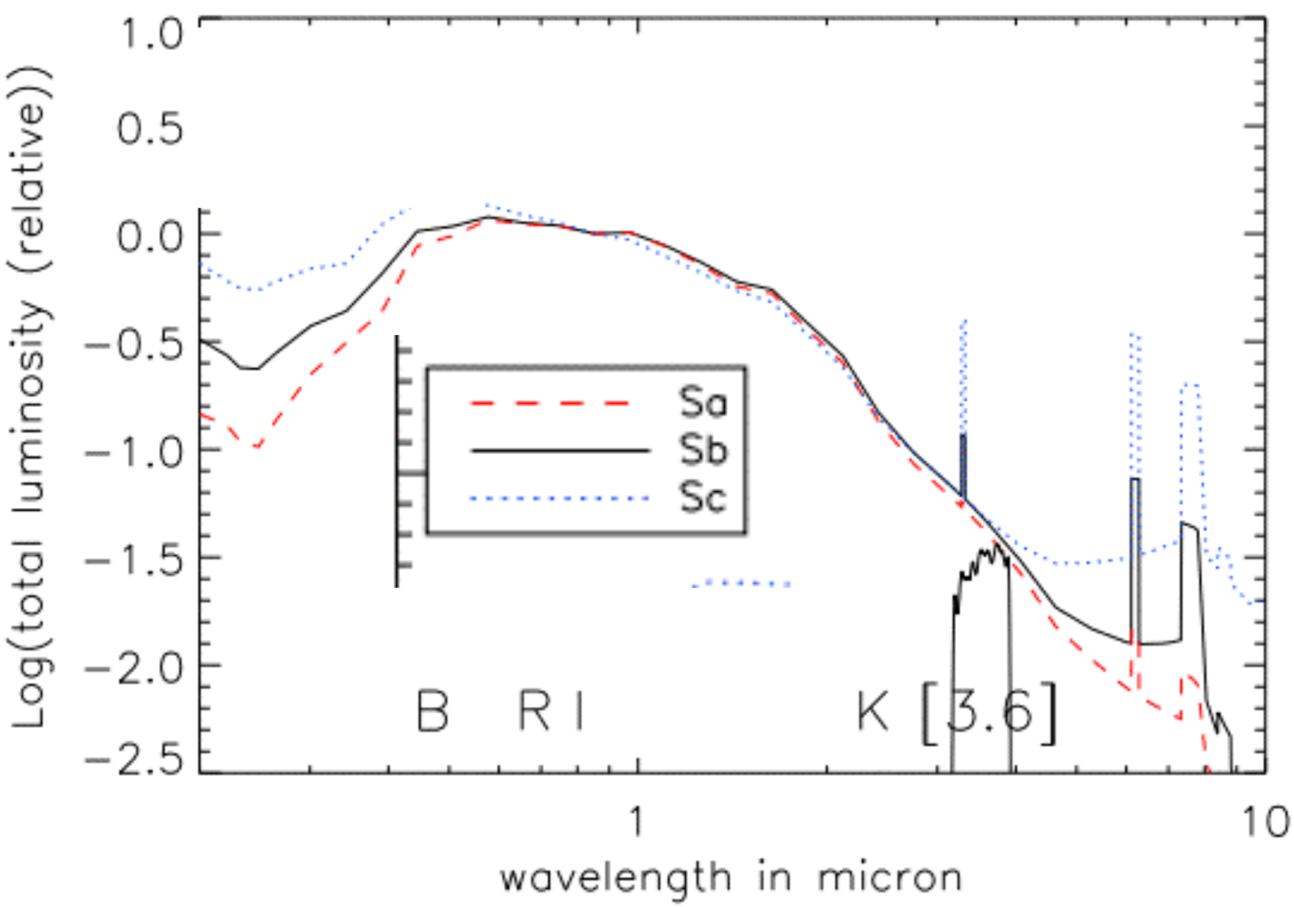
Mostly spheroid…



- Disk-bulge separation is tricky and influenced by inclination angle and dust and wavelength observed (disks standout in the blue, bulges in the red)

Galaxy spectra

- Galaxies have composite spectra. They integrate contributions from different stars of different stellar populations, gas and the effects of dust
- The overall continuum shape is modulated by the gas, the stars, as well as by the presence of dust.



Spiral SED normalized at 8000A with emphasis on near IR spectral features (PAHs)

Galaxy spectra

- Galaxies have composite spectra. They integrate contributions from different stars of different stellar populations, gas and the effects of dust
- The emission lines trace the ionized gas and its excitation mechanism.
- The absorption lines trace the stellar populations, their ages and metallicities.
- The overall continuum shape is modulated by the gas, the stars, as well as by the presence of dust.
- color of line is based on g-r color

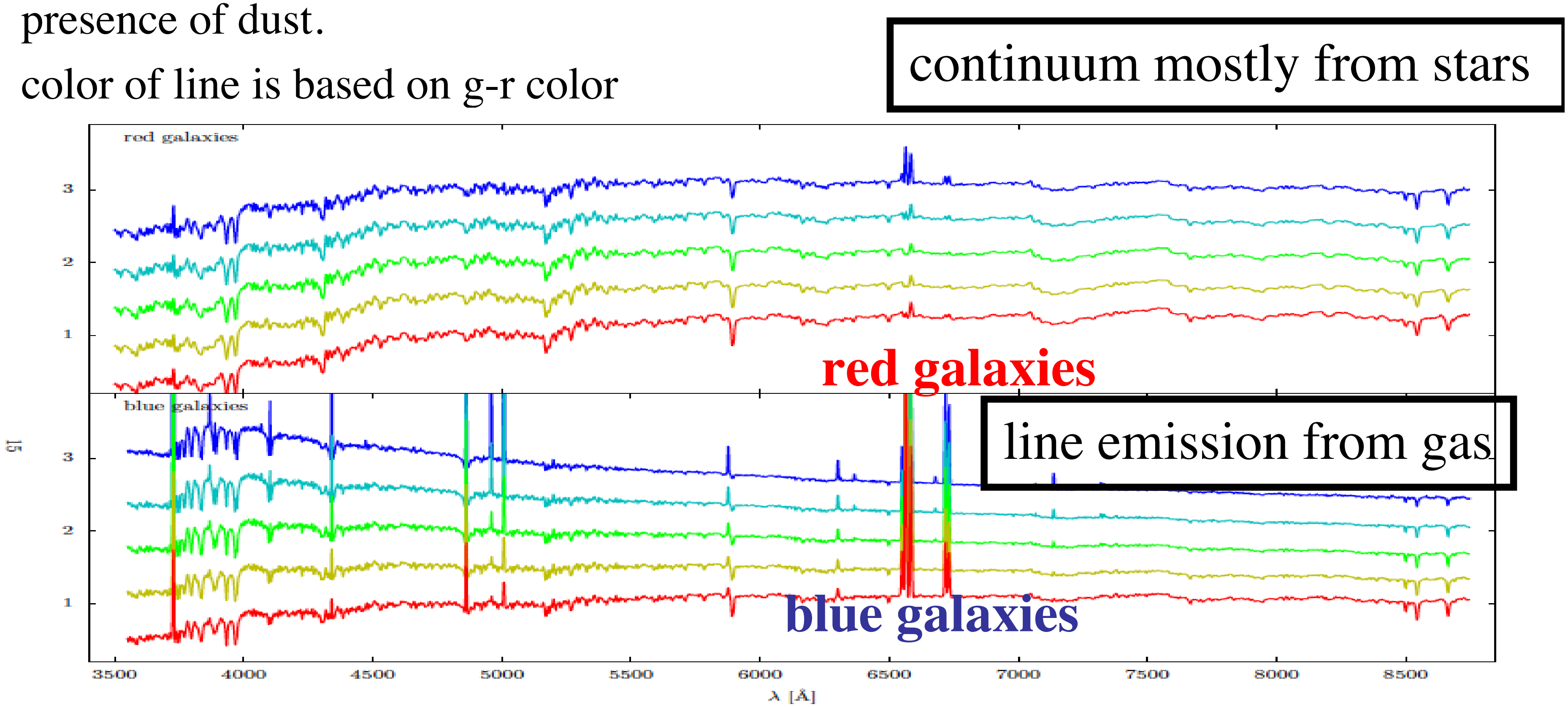
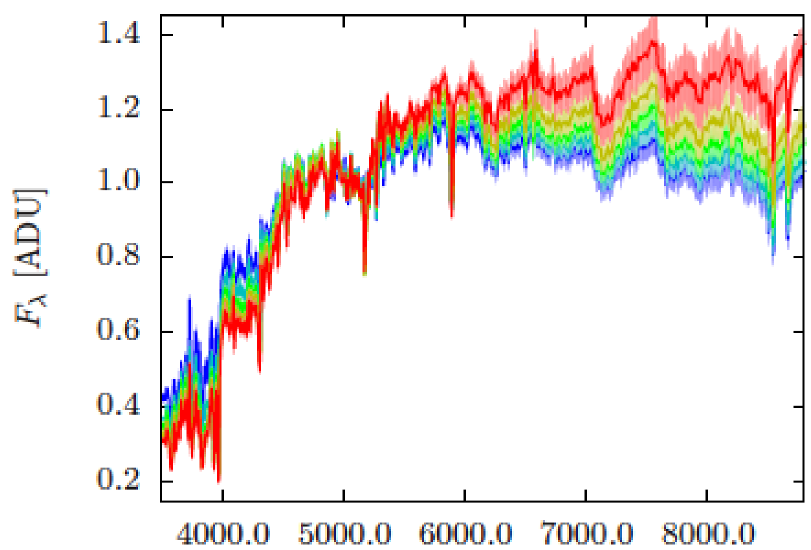
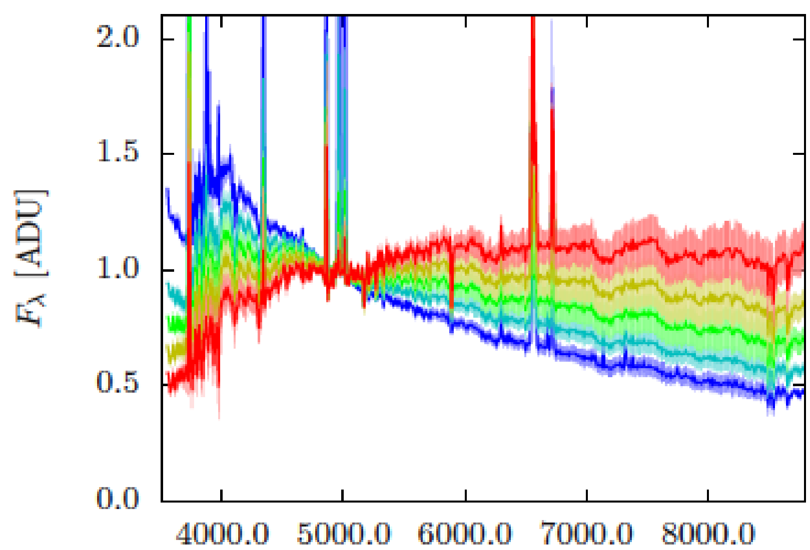


Figure 12: Composite spectra of the refined colour classes as described in Sec. 3.4. The curves are colour-coded from blue (top) to red (bottom) based on the $g-r$ colour of the galaxies. See the online edition for a colour version of this plot.

Galaxy spectra

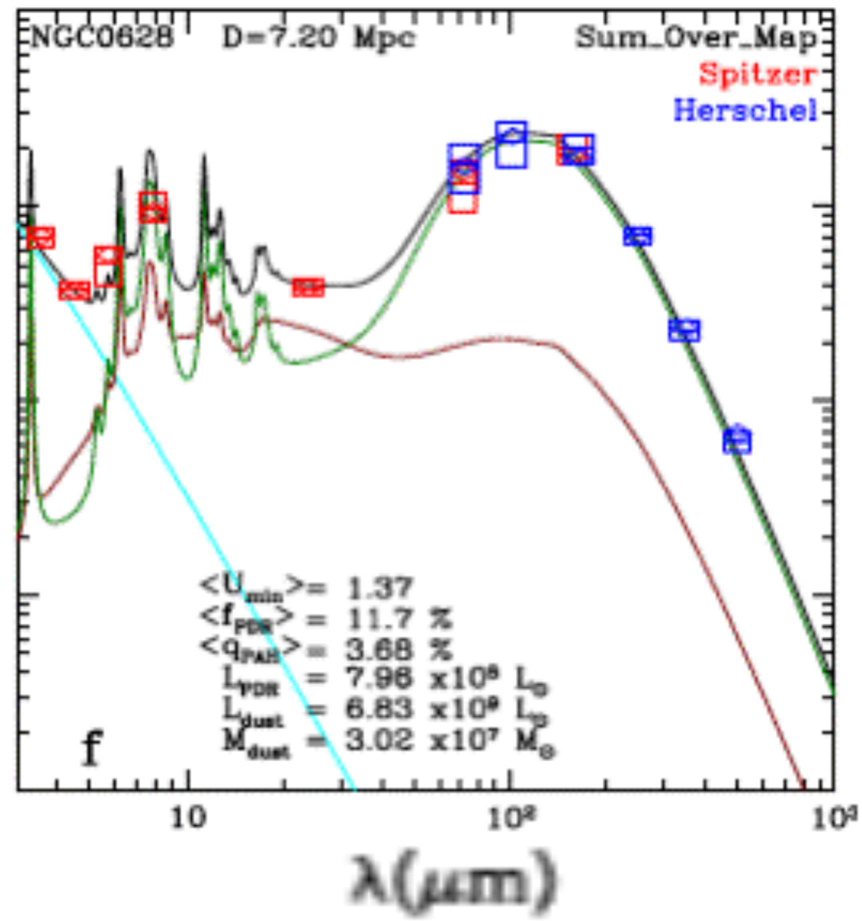
- Sequence of ages of a composite SSP population (left is a non-starforming population, right is star forming)
- Note that the non-star forming galaxies are dominated by stellar absorption lines and a severe lack of 'blue' light
- The star forming galaxies show emission lines (from ionized gas) and much more blue light (especially when they are young)

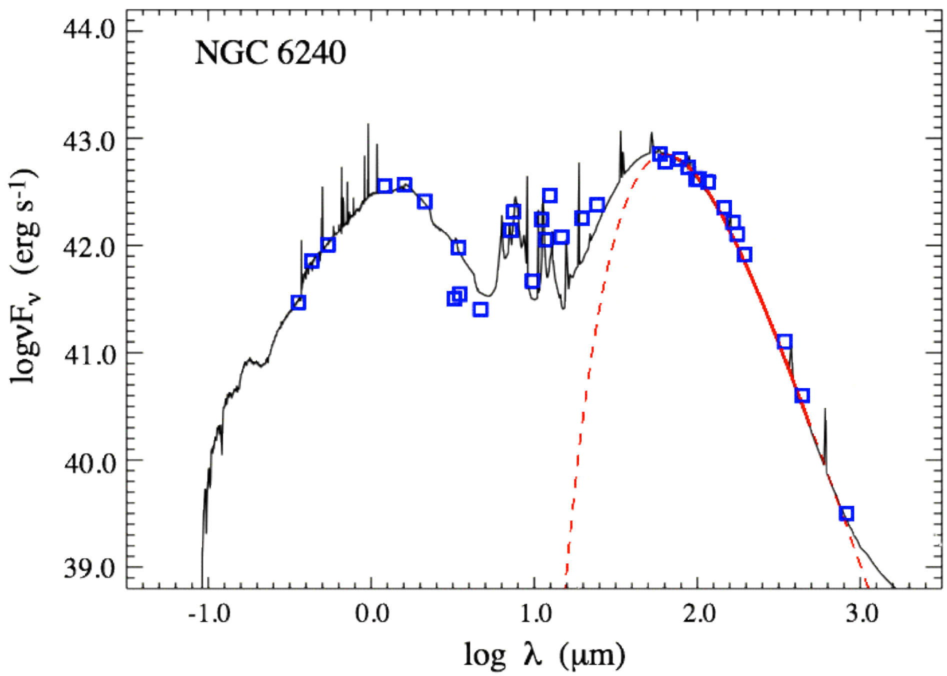




Galaxy Spectra -IR

- At L>5μ in most galaxies continuum dominated by emission from dust -there are atomic and molecular features as well
- In many galaxies L(opt)~L(IR)
  - dust heated by star light - temperature to which it is heated depends on geometry and the nature of the stars
- dust can be very patchy as can star formation

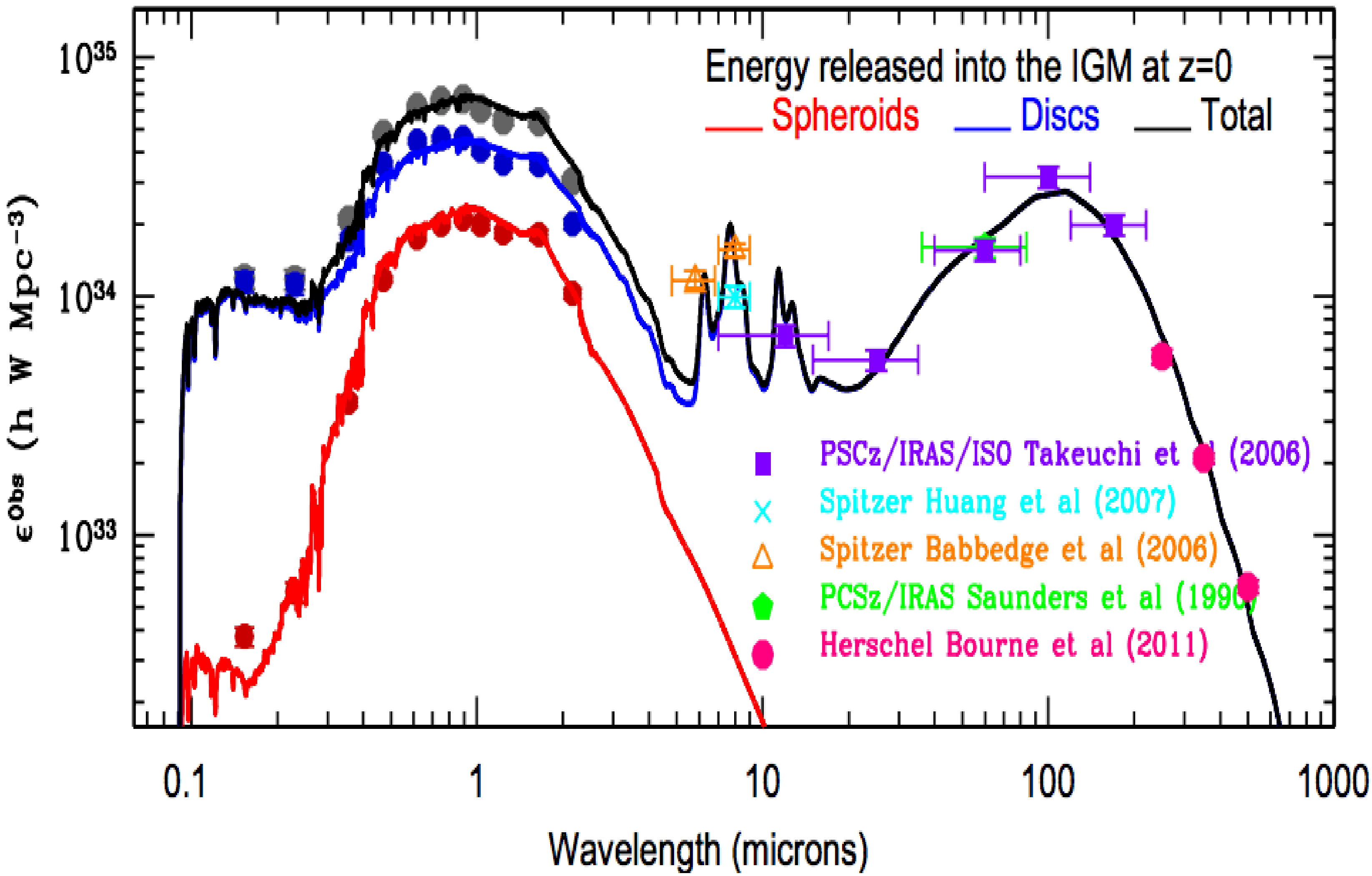




Cyan=stars
Green= dust heated by hot stars
Red dust heated by other stars

Energy Released By Galaxies

- Extensive galaxy surveys have allowed the measurement of the total energy released by all low z galaxies across the UV-far IR spectrum 1.3x1035 W/Mpc^3(Driver ... in



Galaxy spectra

- Classical indicators of what is going on:
- Historically specific stellar absorption features over narrow wavelength intervals were used obtain the ages and metallicities of the stellar populations
  - For galaxies with old stellar populations, the Lick/IDS system of ~25 narrow-band indices was used (Worthey1994.
- For actively star-forming galaxies, the 4000A break (Balogh etal.1999) and Balmer absorption line features, such as the Hδ index, provide important information about stellar age and recent star formation history.

Does G have emission lines? if YES then

- ⋆ if the lines are broad then .... **QSO or Seyfert 1**
- ⋆ if lines are not broad then apply BPT
  - if [NII]λ6583 < Hα/2.5 then
    - . if [NII]λ6583 << Hα then .... **low-metal starburst**
    - . else .... **high-metal starburst**
  - if [NII]λ6583 > Hα/2.5 then
    - . if [OIII]λ5007 < Hβ then .... **LINER-like**[1]
    - . else .... **Seyfert 2**
- ⋆ if G does not have metal absorption lines then
  - if Hβ > 30 Å .... **young starburst / HII G**
  - else .... **starburst**

Does G has absorption lines? if YES then

- ⋆ *Does G show the Balmer break at 3650 Å?*
  - if YES then *Does G show the* 4000 Å *break?*
    - . if YES then .... **mixed young-old stellar populations**[2]
    - . if NO then .... **young stellar populations**[2]
  - if NO then *Does G show the* 4000 Å *break?*
    - . if YES then .... **old metal-rich stellar populations**[2]
    - . if NO then .... **odd**

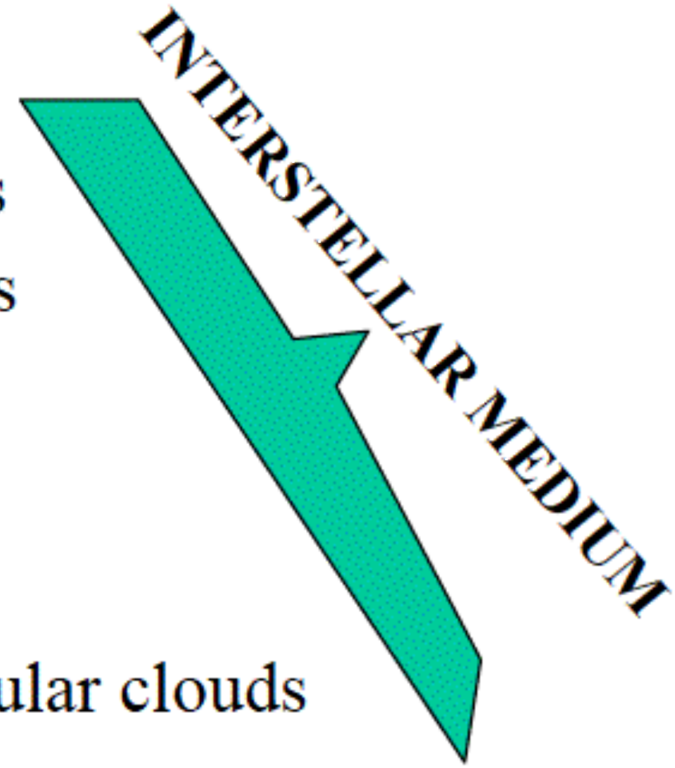
Neither emission nor absorption? if YES then .... **BL Lac**

Does the continuum rise beyond 6000 Å? if YES then .... **dust reddened G**

[1] LINER, or retired G, or X-ray emitting gas or ...
[2] Age and metallicity can be determined through calibrated indexes

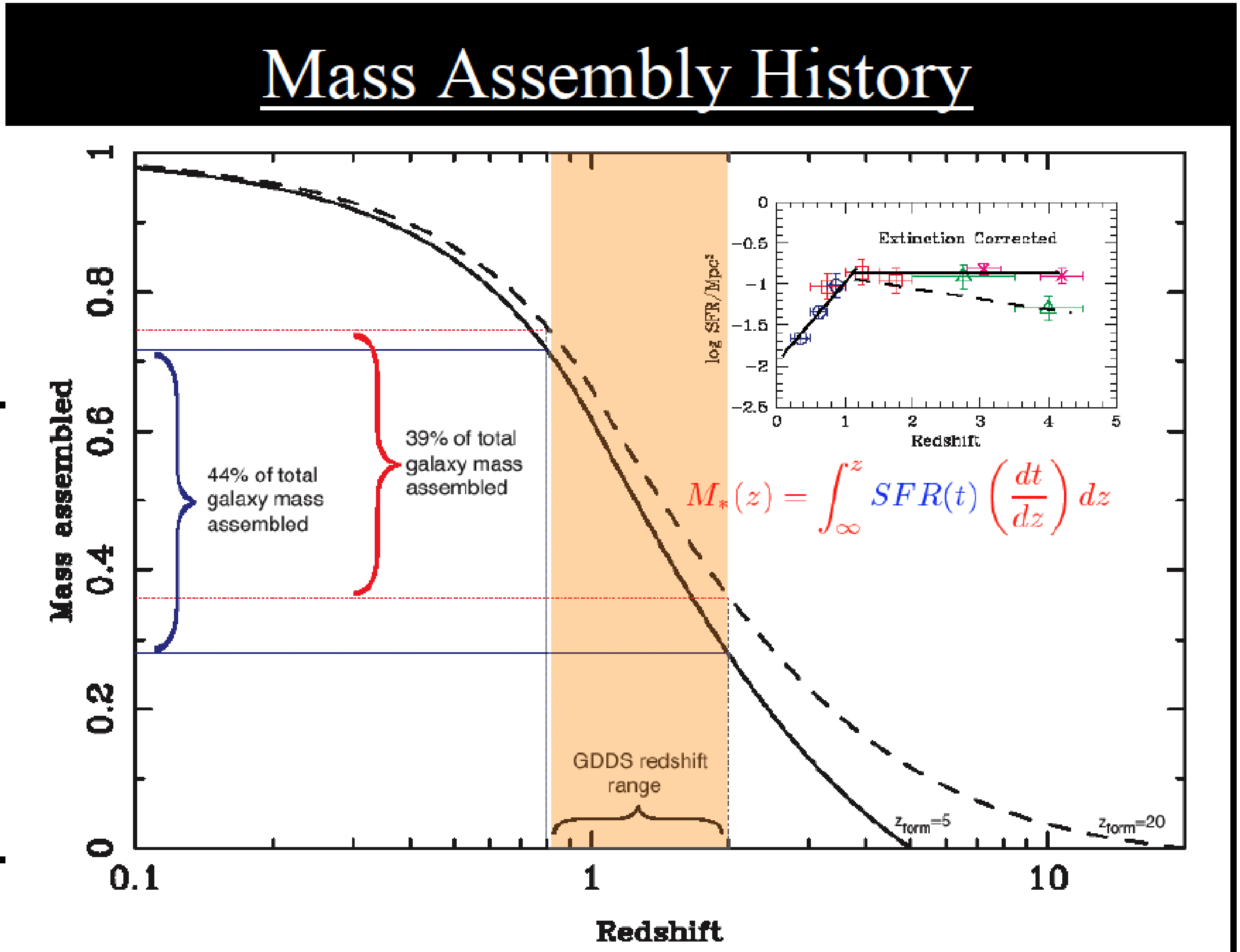
Composition of Average Spiral

- Stars ~80% of mass
  - DISK ~80% of stars
  - BULGE ~20% of stars
- Gas ~20% of mass
  - atomic gas ("H I") ~2/3 of gas
  - molecular gas (H_2) ~1/3 of gas
  - hot, ionized gas ("H II")
- Dust
  - between stars
  - mostly in spiral arms & molecular clouds



When Did Galaxies Grow

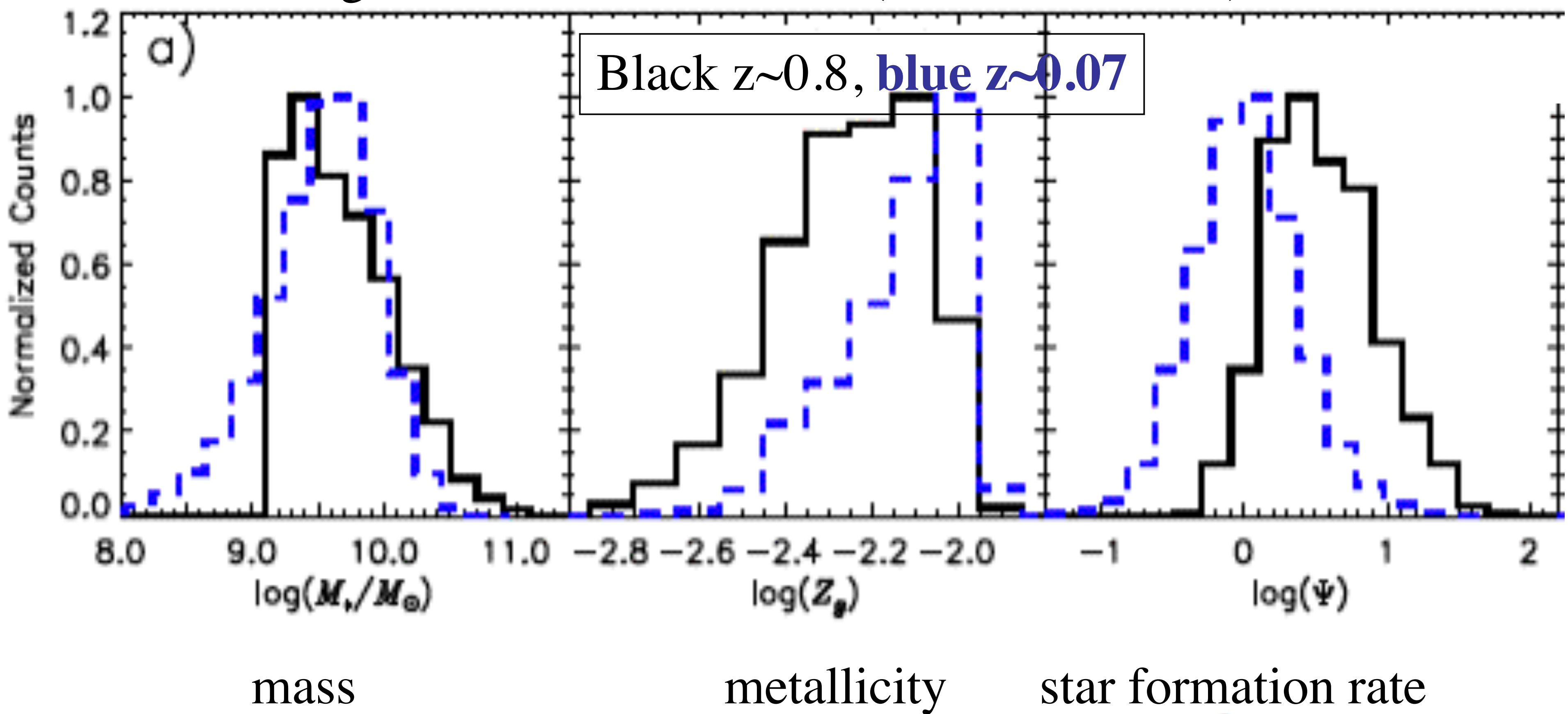
- ~50% of all stellar mass in galaxies formed after z~1
- 10% at z>3



P. McCarthy

How Do Galaxies Grow

- At higher redshift there is little change in the mass distribution of observed galaxies but metallicity distribution skewed to lower values and higher star formation rates (Zahid et al 2012)

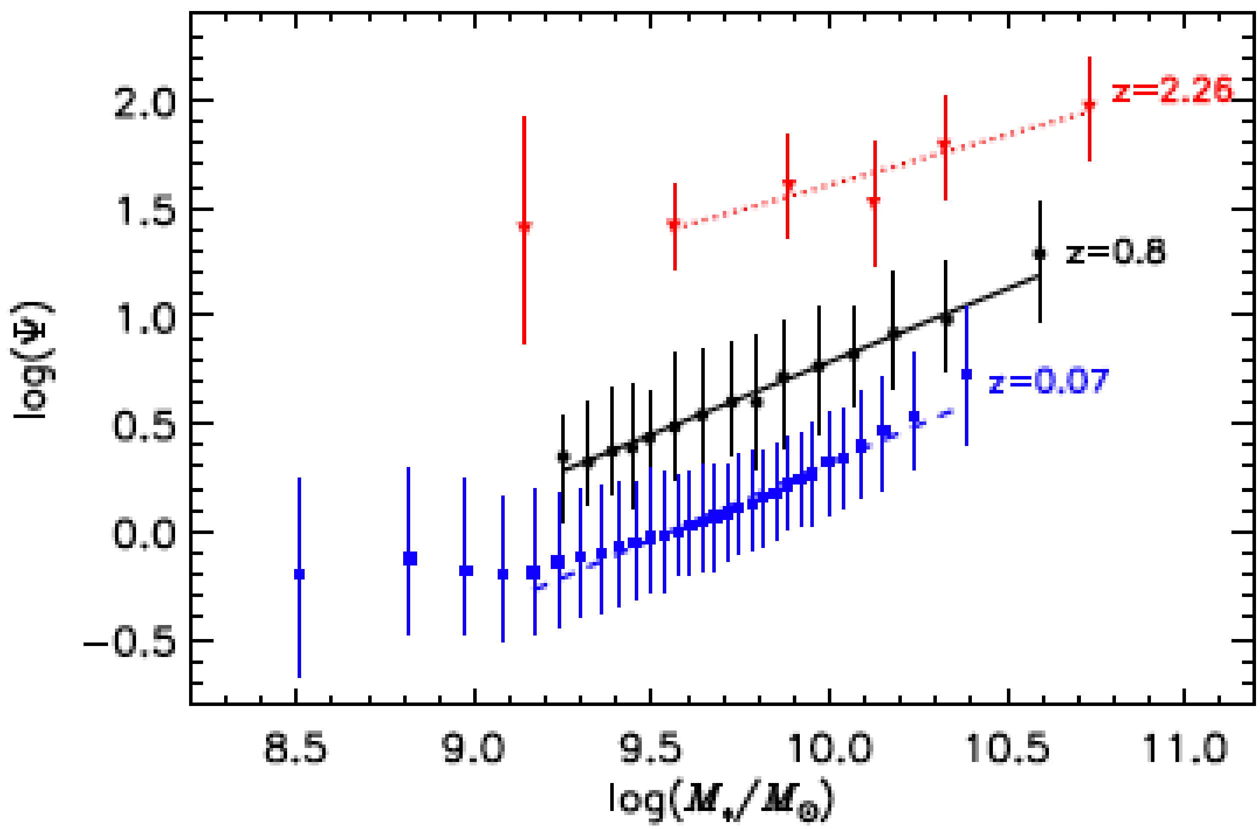


– A histogram of the a) stellar mass, b) metallicity, c) SFR ($M_\odot$ yr^{-1}) and d) the fitted
(dashed blue) samples. The values for the 6 binned data points of E06 are shown by the

How Do Galaxies Grow

- At higher redshift there is a systematic change in the relationship between mass and star formation rate (Zahid et al 2012)
- Big galaxies grow first and fastest- *downsizing* (compared to CDM)

log star formation rate

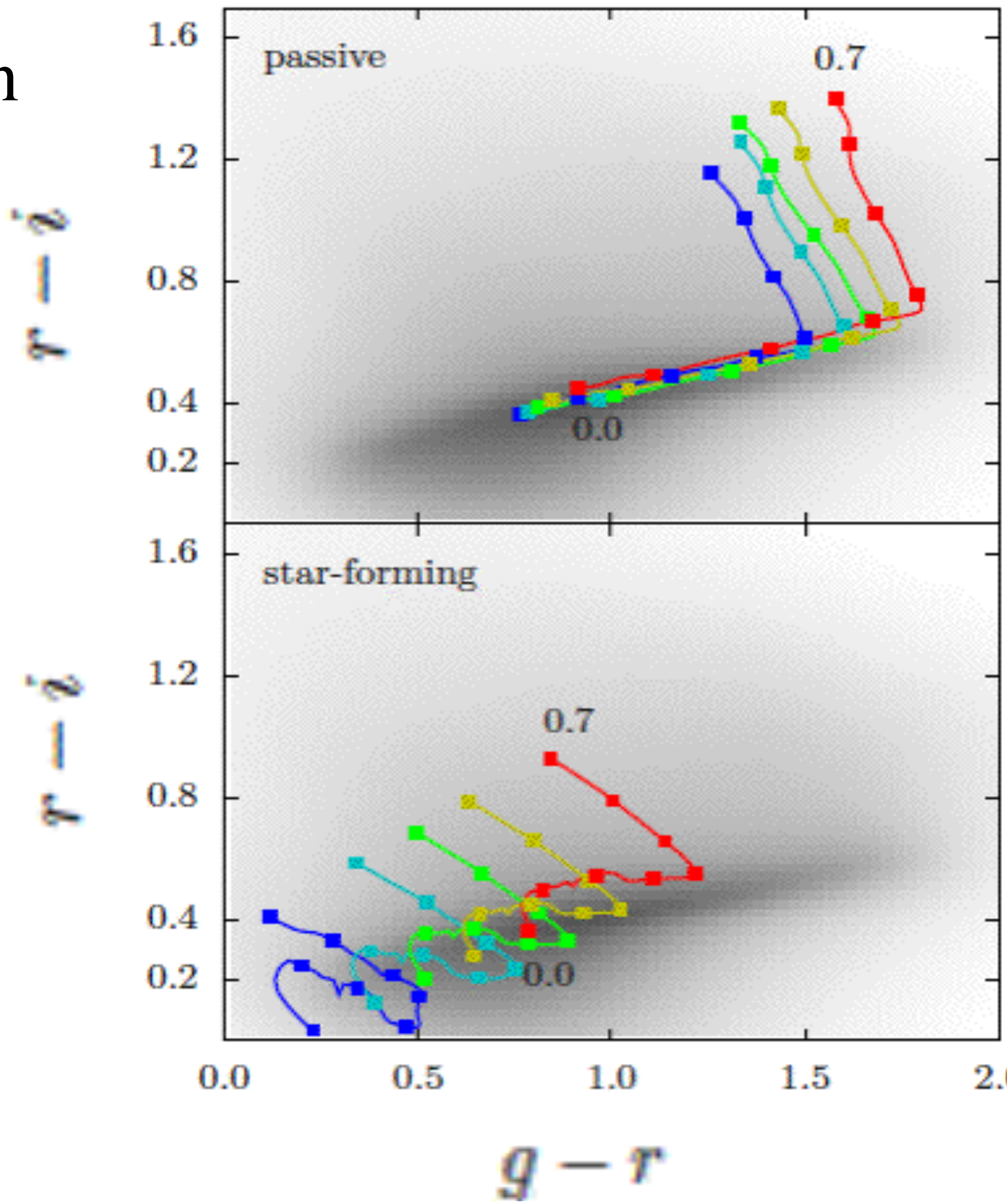


log mass

•Black z~0.8, **blue z~0.07**, red z~2.26

Colors As a Function of Redshift

- When trying to obtain galaxy samples over a wide range of redshifts one needs to take the redshift (K-correction) into account
- This also allows an estimate of the galaxy redshift from its colors (photometric redshift)



Next Time

- Stars and stellar populations- this material is scattered about in Sparke an Gallagher
- Its clearly organized in MBW sec 10.1-10.3
- the first two chapters of MBW are on-line at

http://www.astro.umass.edu/~hjmo/astro330/htmldir/reading.pdf and contain a nice summary of much of what we have been presenting so far

A 600Myr old population color code is density of star in a given pixel