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

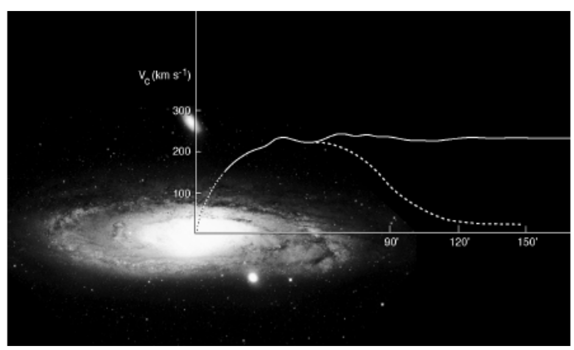
The fraction of galaxies with given properties and the nature of those properties changes with cosmic time in an 'organized' way (downsizing)

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

•in the multi-dimensional phase space of mass, baryonic content gas fraction, angular momentum velocity field, chemical abundance etc only a small fraction is occupied- there are strong patterns

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

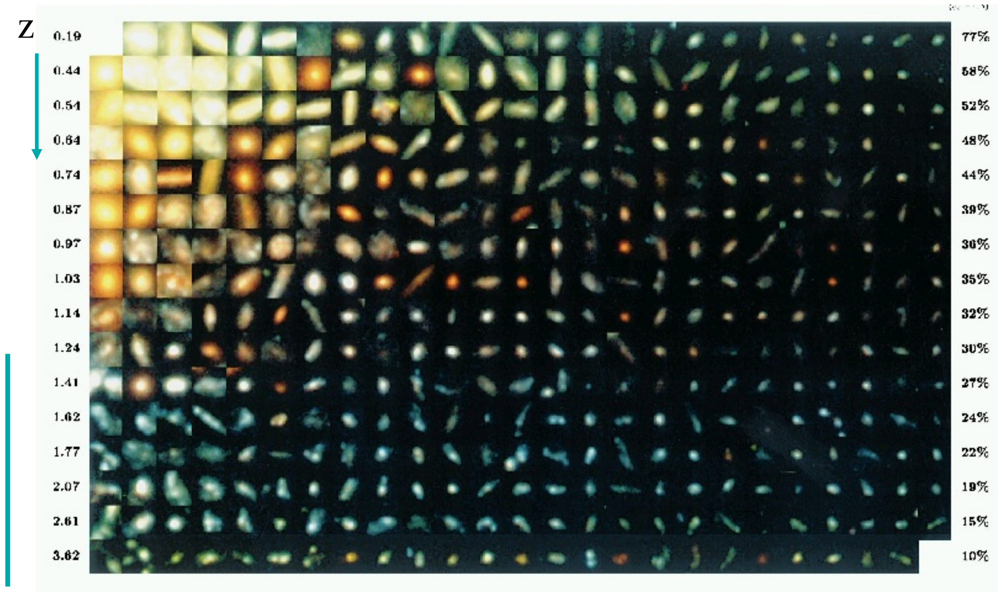


- We will be discussing these a lot more in the class
- Dark matter is a indispensible ingredient in modern theories of structure formation;
- As one goes to larger scales DM gets more and more important- there is a wide range of baryonic to DM in galaxies

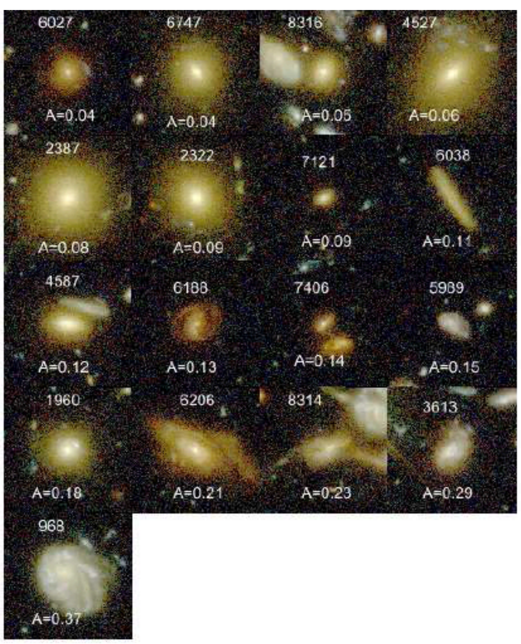
Pattern of how DM and baryons 'relate' is major problem in the field.
Can calculate distribution of DM as a function of mass,redshift from numerical simulations

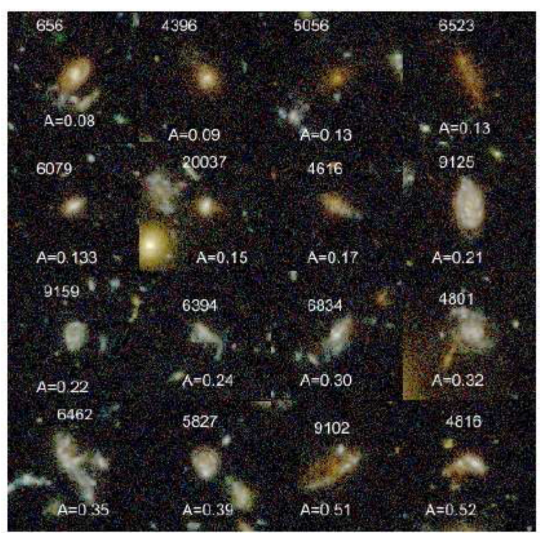
Change in Galaxy morphology
over time

HST galaxy populations in HDF-N
Driver et al 1998



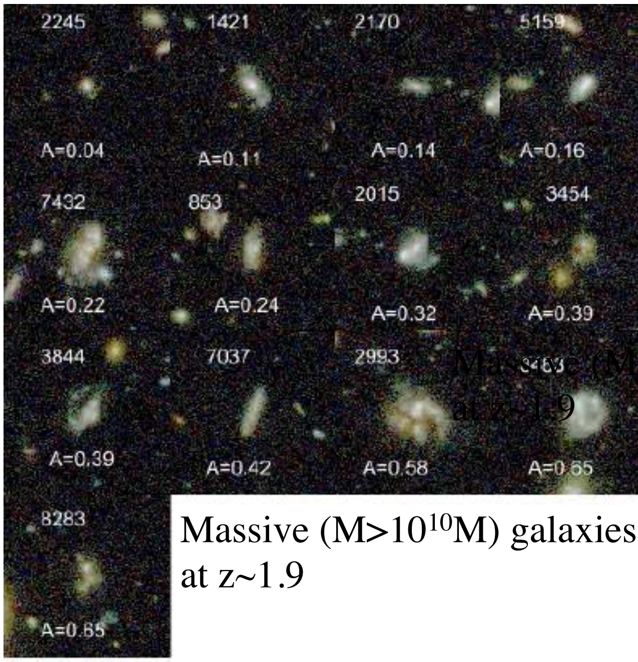
There is a major transition at z ~ 1.4. Red galaxies appear to "end" there, and a population of blue irregulars and compacts



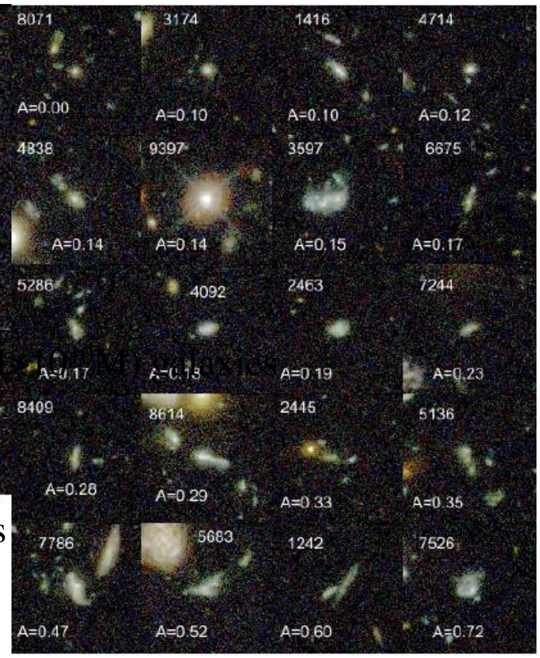


Massive ($M>10^{10}M$) galaxies at z~0.8

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



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

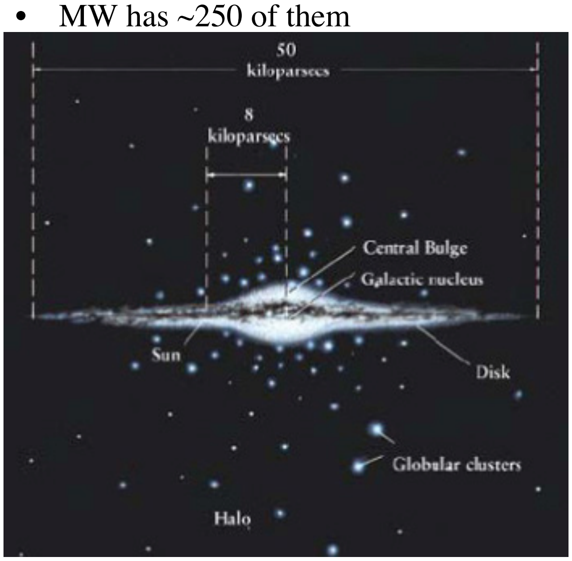


Systematic evolution in massive galaxy morphologies (Conselice et al 2008)

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

Globular Clusters

- compact stellar systems $M \sim 10^{5\text{-}6}\, M_\odot$ which lie in a roughly sphereoidal distribution around most galaxies
- Stars are very 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 GCs and host galaxies weakly connected
Will not discuss much in this class
Only massive systems which show no evidence for Dark Matter

The Big Picture- Two Populations

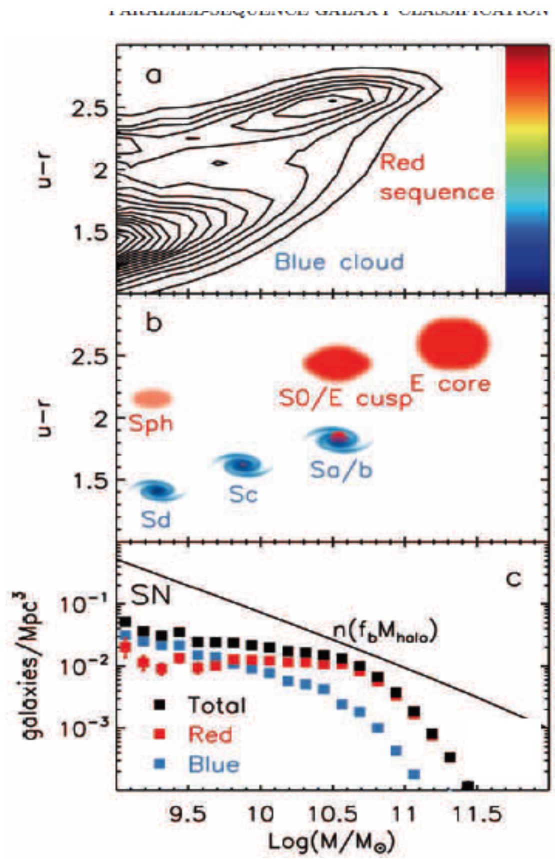
- Color* distribution vs mass of a large sample of local galaxies from the SDSS top panel

  Middle panel is the morphologies that dominate at each mass

  bottom panel shows the galaxy mass function divided by color (Cattanec 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 galax mass distribution</u>

* there is a discussion of astronomical color conventions in sec 2.1.1of MWB, pg 6-8 of B&T ; S&G have an extensive discussion in ch 1.1.1-1.1.3

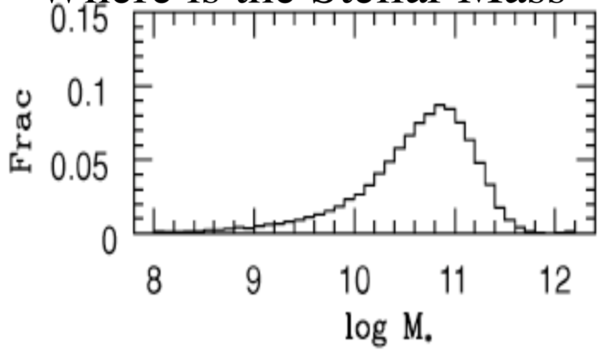


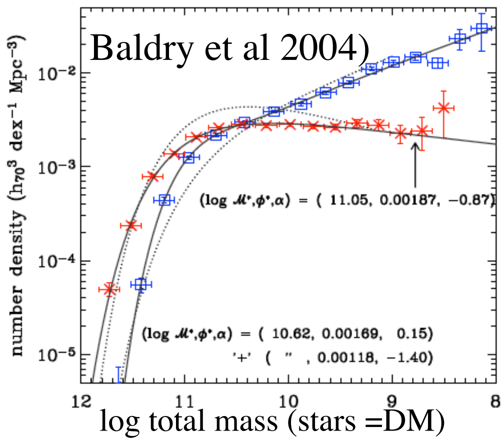
Halos

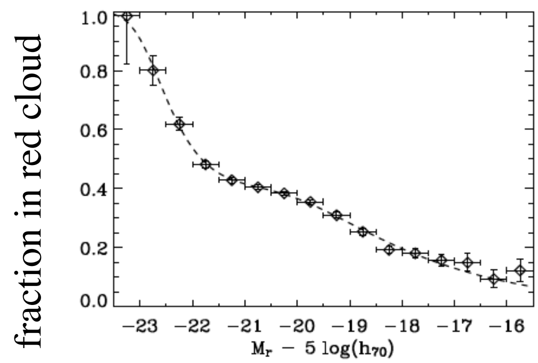
- See MWB pg 319-321 for an introduction to the concept- see review paper on the web site.
- Dark matter halos are the hosts of galaxies.
- these quasi-equilibrium structures seen in numerical simulations are associated with the extended dark matter distributions that are observed to surround galaxies and galaxy clusters
- Deciding which material belongs to a halo and what lies beyond it is a non-trivial question
- In analytic models halo definitions are based on a simple spherical collapse model
- The virial theorem (later lecture) predicts that the final halo radius is 0.5 of its turnaround radius and that this "virial radius" occurs at an overdensity of 178 times the critical density of the universe in an Einstein-deSitter cosmology.

- The stellar mass lies mostly between
- log $M_{\odot}$=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

Where is the Stellar Mass



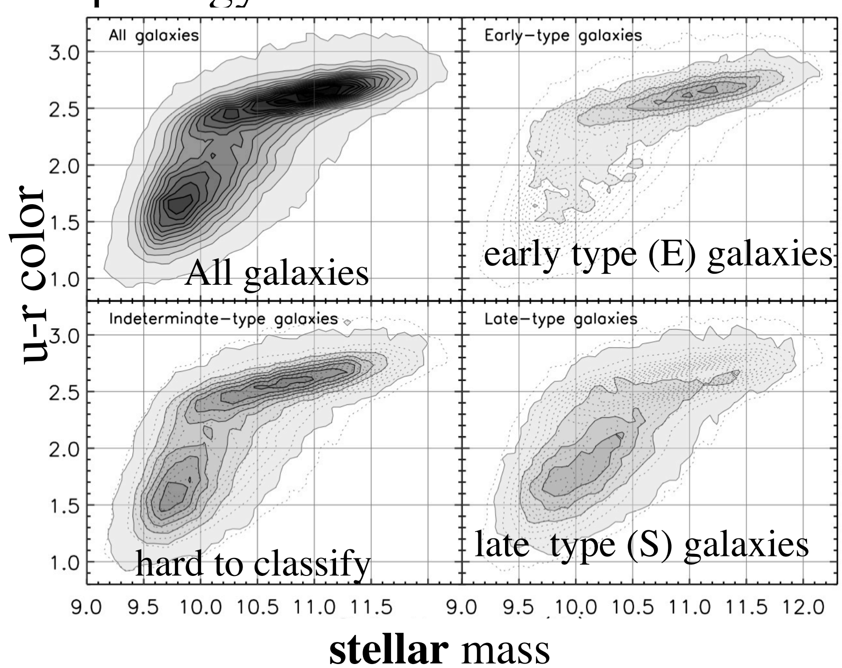




absolute mag

Morphology/ Color and Mass

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

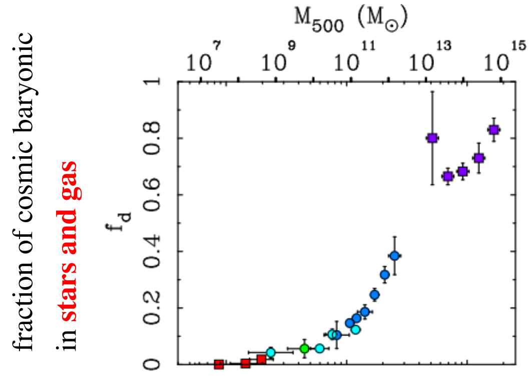


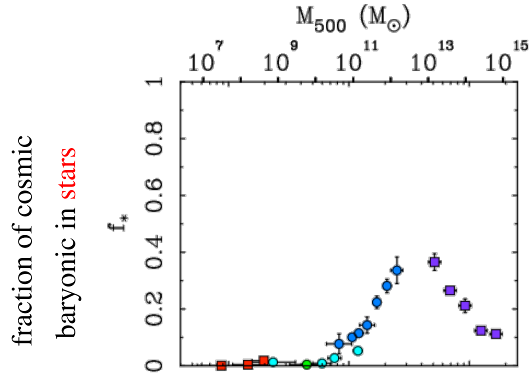
- Strong relation of mass, color and morphology

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 clusters 80% of the baryons are in hot gas.
- Most of the baryons in the universe are not in collapsed structures (galaxies and clusters)!



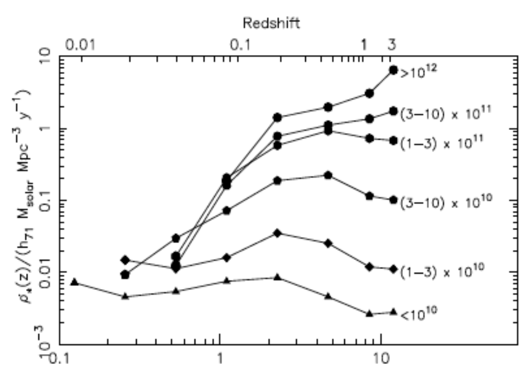


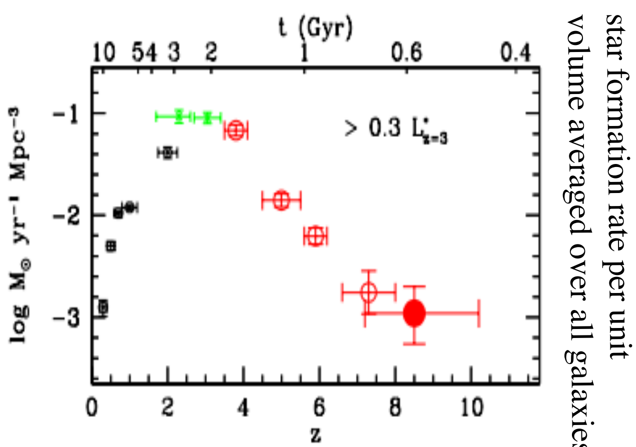
McGaugh 2009

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

15



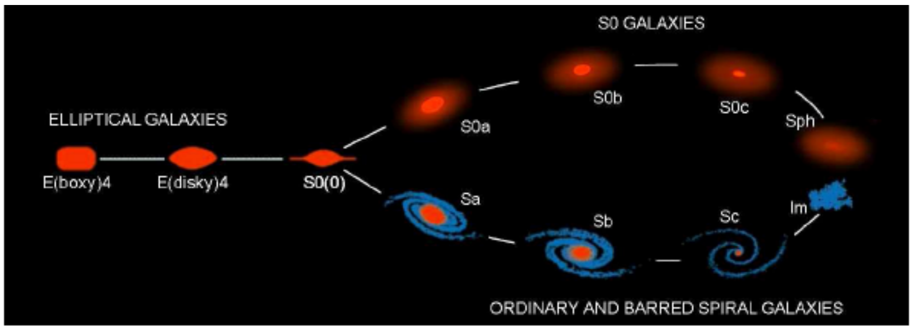


look back time (Gyr)

Star formation rate for galaxies of given mass

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-Mass is the decisive parameter in setting properties



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

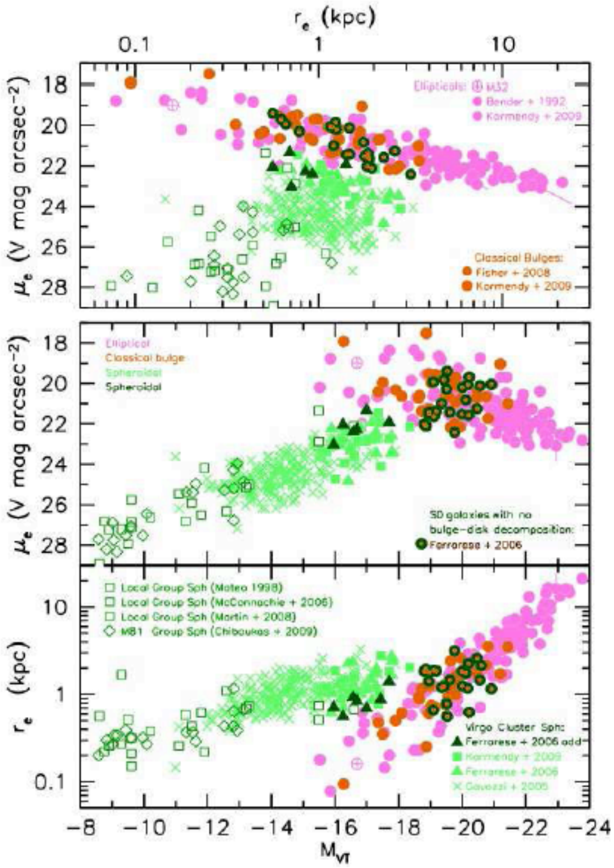
  μ= surface brightness

  r_e= scale length

  Bulges in spirals and ellipticals are related but not identical

  Surface brightness (MWB pg 26) is used because it does not depend on distance but only redshift (MWB pg112)

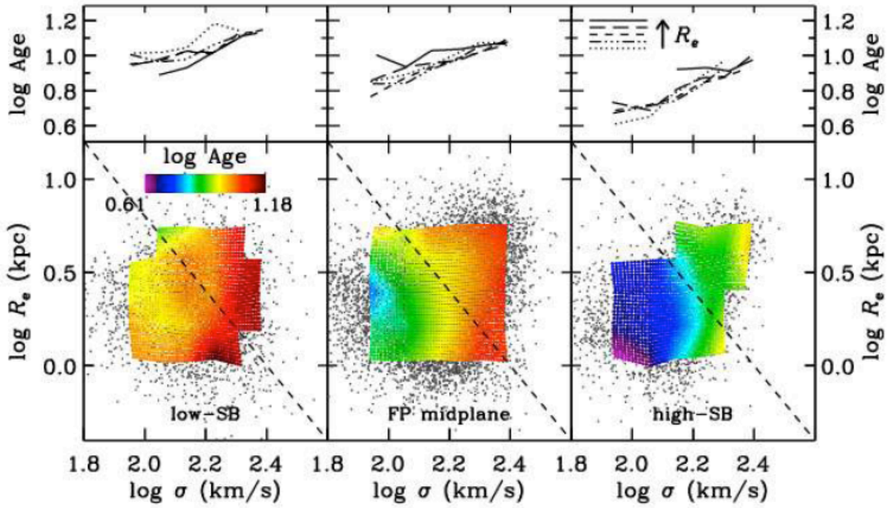
Global parameter correlations for ellipticals (pink), classical bulges (light brown), and spheroidals (light green) from Kormendy et al. (2009:



Jargon Alert

- We have in the last few slides used terms like :Big bang nucelosynthesis , cosmic microwave background, type I SN, look back time, R_e, B-V, Sa,Sb, velocity dispersion etc etc .
- Do we need a bit of a discussion about this?
- Today's homework problem: find 12 undefined uses of jargon in today's lecture and define them in 1 sentence each.

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

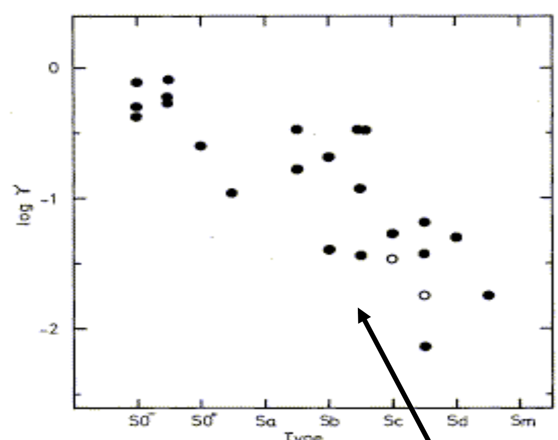


- lines of constant age run nearly vertically, indicating that stellar population age is independent of R_e (scale length in Sersic fit) at fixed σ (stellar velocity dispersion).
- However, comparing the age ranges (indicated by the color scale)between the different panels, there are systematic differences.

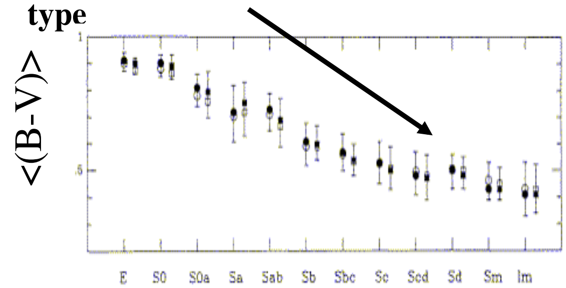
Spirals

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)*

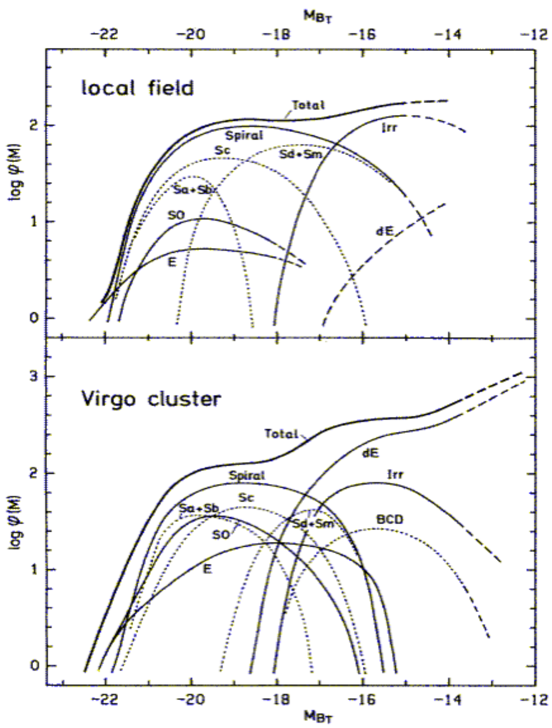


Ratio of bulge to disk luminosity and color as a function of **morphological type**



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

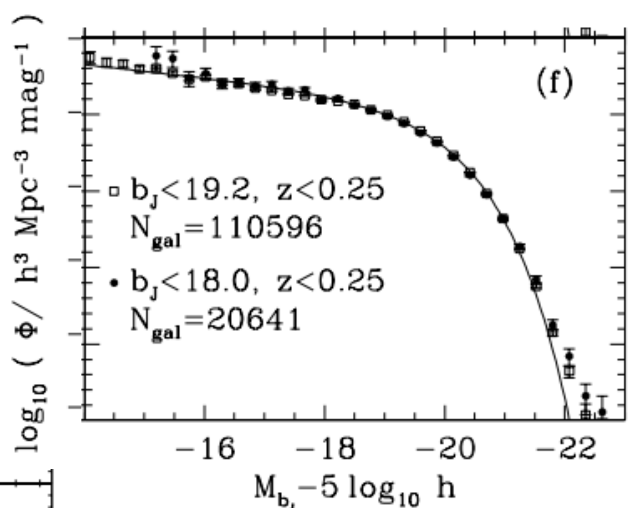


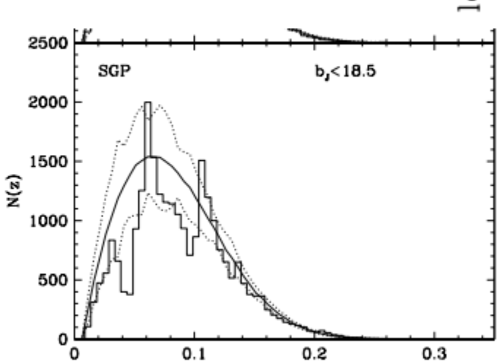
Binggeli, Sandage, and Tammann 1988

Luminosity Function

- definition: LF=φ(N,L,V)= number of objects per unit volume per unit luminosity
- The combined luminosity function of all galaxies is fitted by a Schecter function

$\varphi = C(L/L_*)^{-\alpha} \exp(L/L_*)$ a power law at low L and an exponential cutoff at high L

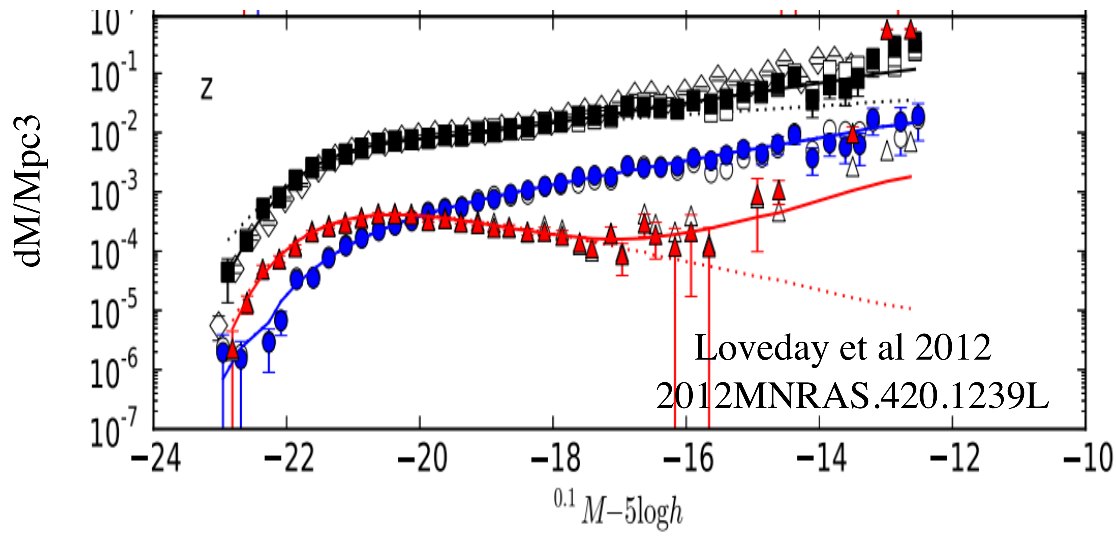




Redshift distribution is not uniform (e.g. large scale structure makes derivation of φ(L) unstable at high L where objects are rare

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

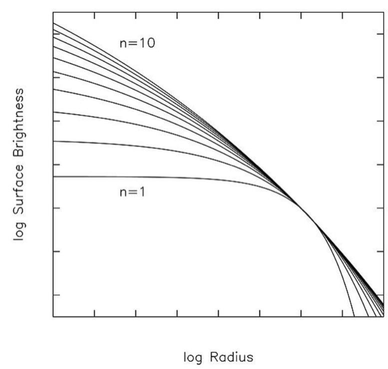


Descriptions of Galaxy Optical Surface Brightness

- 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

  $\Sigma(r)=\Sigma(0)\exp(-k\,[(r/r_e)^{1/n}-1]$; k ~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)



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

total luminosity of Sersic profile

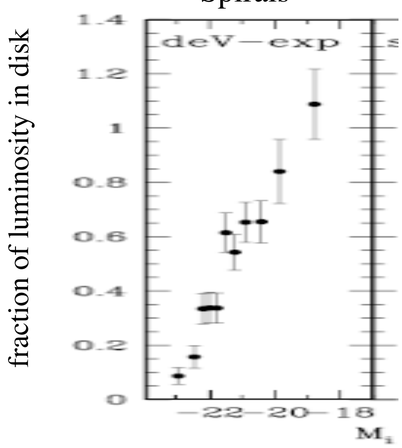
Stellar Distribution-
radial average

- 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

$$\Sigma(r) = \Sigma_e e^{-\kappa[(r/r_e)^{1/n} - 1]}$$
$$\kappa \approx 2n - 0.331$$

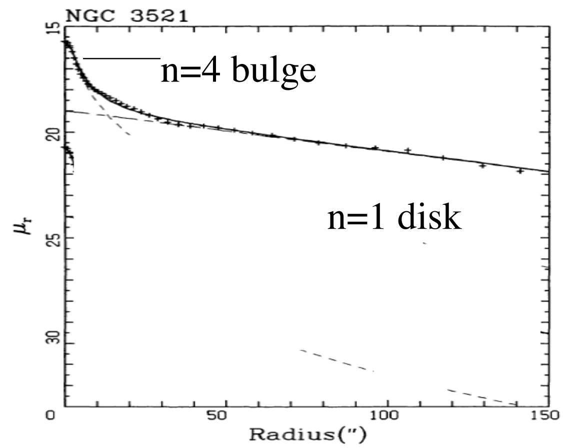
Sersic(1968) profile

Spirals



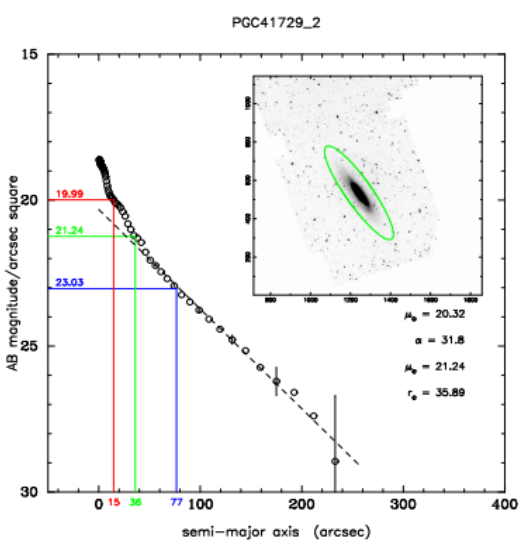
absolute mag

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

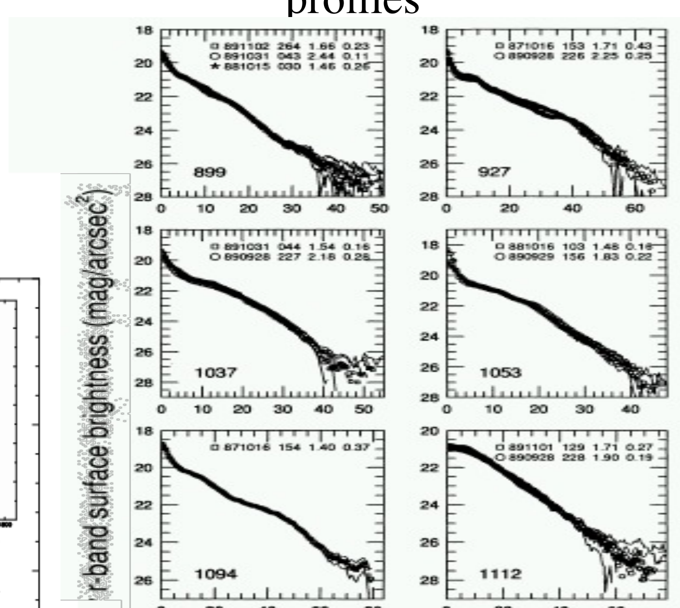


Pure exponentials would be straight lines.

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



Typical disk surface brightness profiles



Courteau, ApJS, 103, 363, 1996

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

Physical Difference Between Bulges and Disks

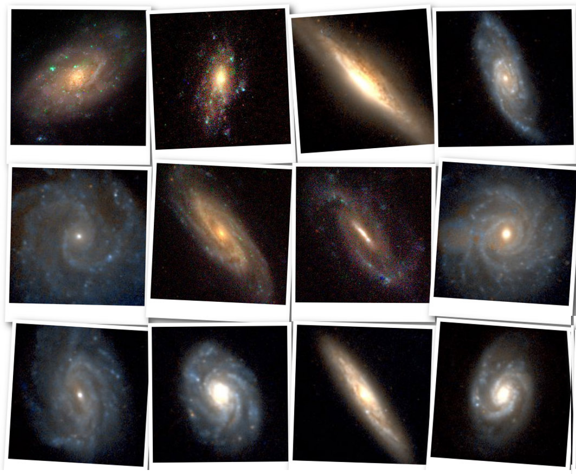
- In spiral galaxies
  - the stars in the disk have lots of angular momentum and a wide variety of ages.
  - stars in the bulge tend to be old, have little angular momentum and have low metallicity*
    - (globular clusters may be part of this population)
- Disks are rotationally supported (dynamically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

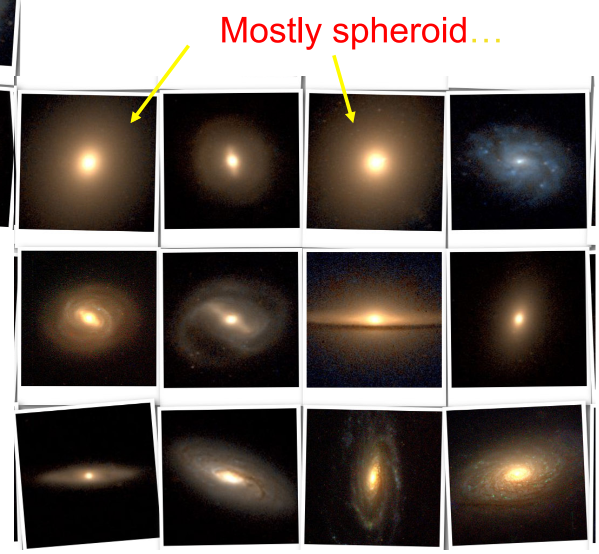
*Metallicity is astronomical jargon for the relative amount of heavy elements (C,N,O,Fe....) to hydrogen

- While, superficially, elliptical galaxies 'look like' bulges their stars are frequently metal rich, not metal poor.

Samples of Galaxy Images

Mostly disk…

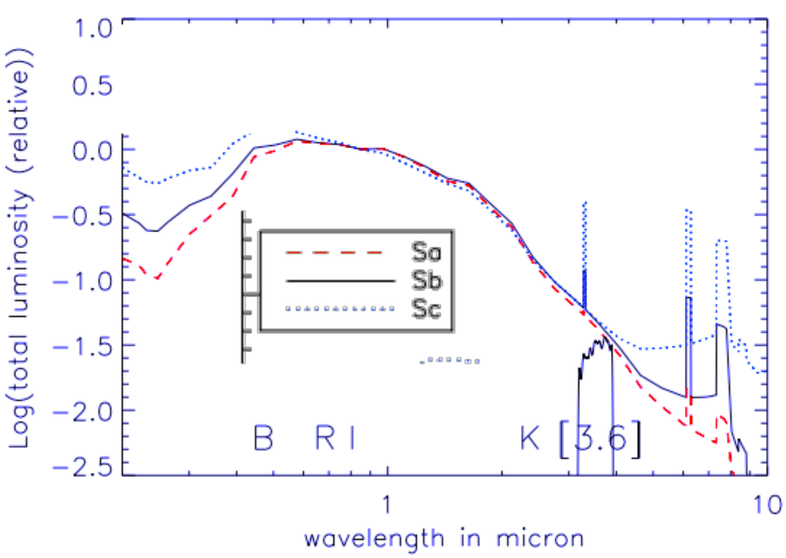




- Disk-bulge separation is tricky and influenced by inclination angle and dust and wavelength observed (disks standout in the blue, bulges in the red)

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)-
poly-cyclic aromatic hydrocarbons

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 in plot is based on g-r color

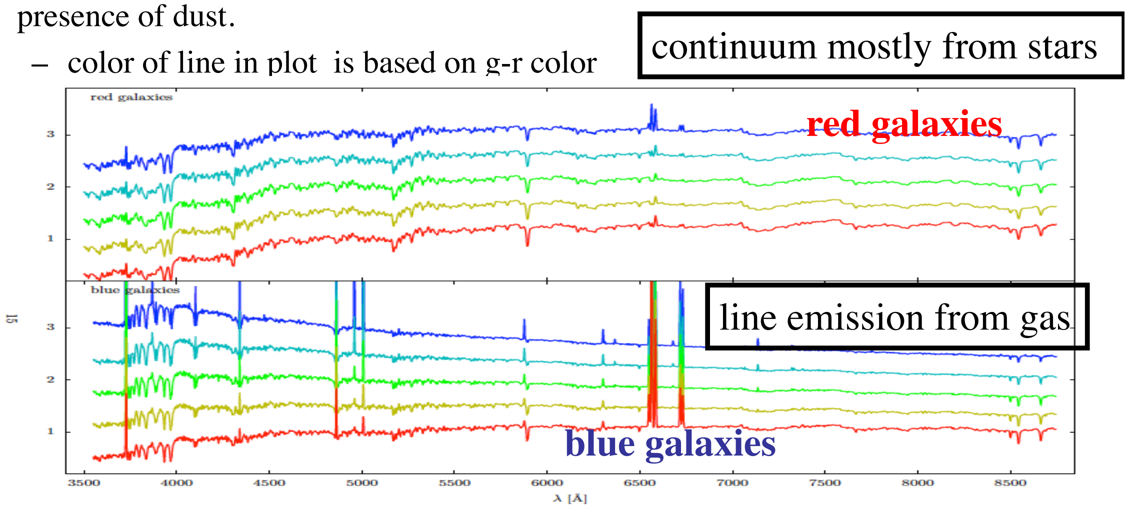
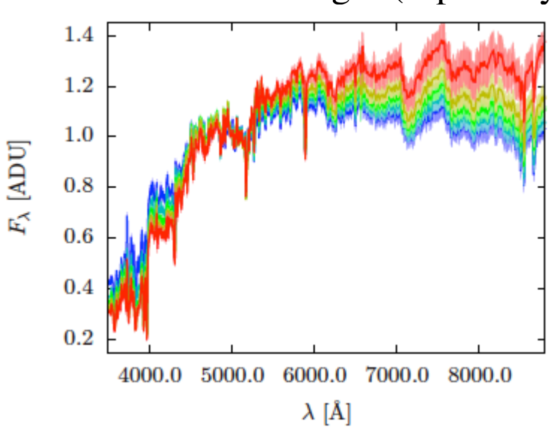
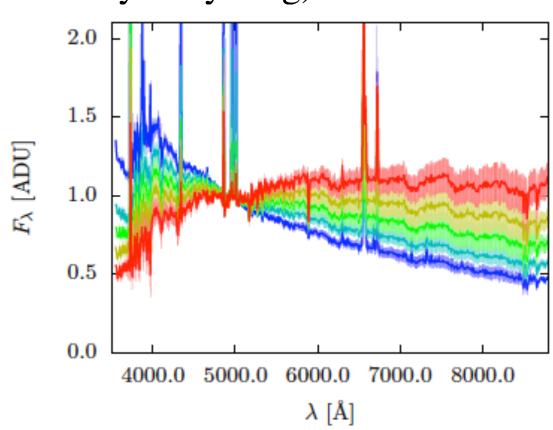


Figure 12: Composite spectra of the refined colour classes as described in Sec. 3.4. The curves are colour-coded from blue (top) to red (bottom) based on the $g - r$ colour of the galaxies. See the online edition for a colour version of this plot.

Galaxy spectra

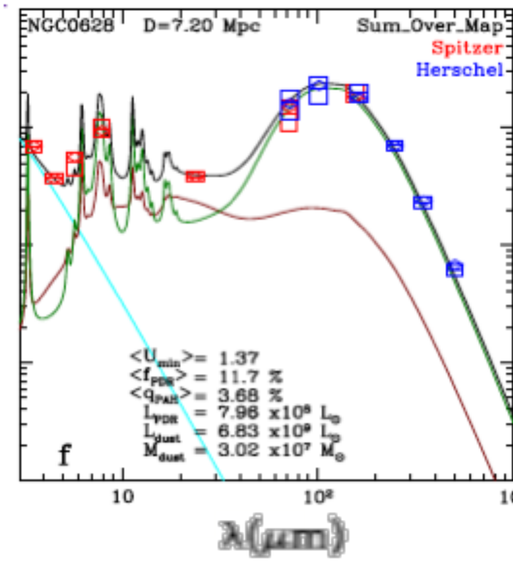
- Sequence of ages of a composite **SSP** population (left is a non-starforming population, right is star forming)
- Note that the non-star forming galaxies are dominated by stellar absorption lines and a severe lack of 'blue' light- get redder when older
- The star forming galaxies show emission lines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



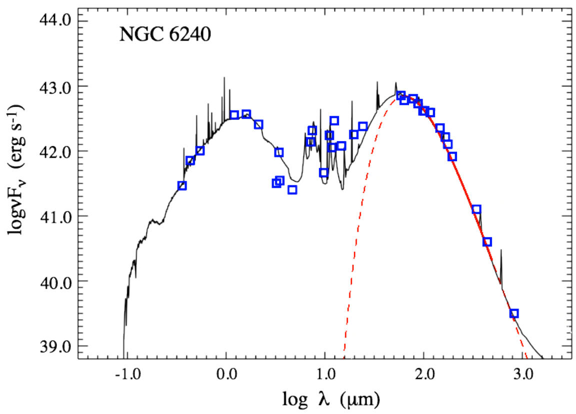


Galaxy Spectra -IR

- At λ>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

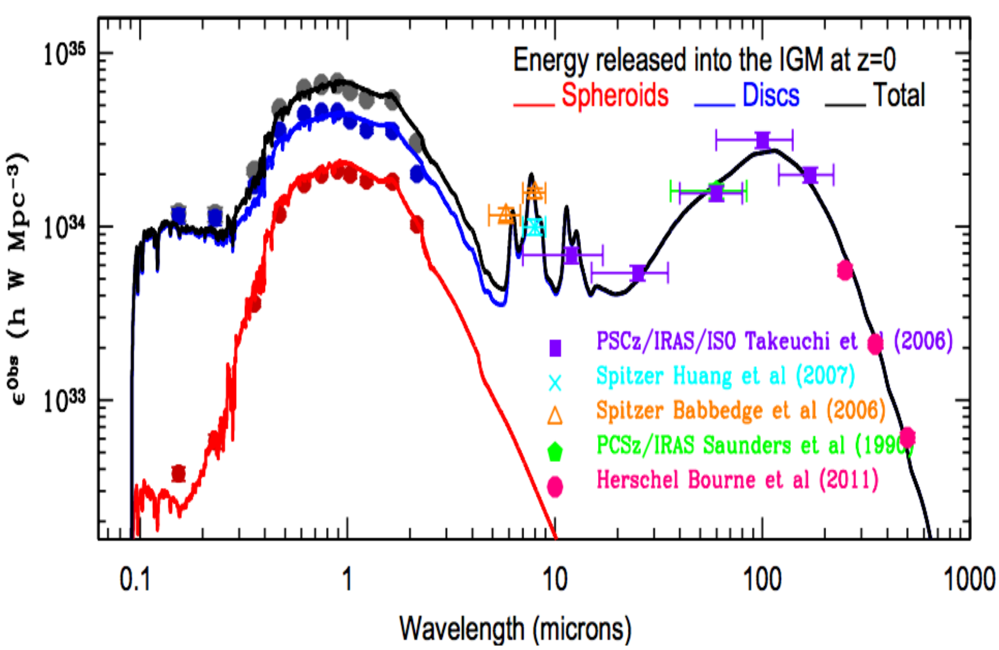


Cyan=stars
Green= dust heated by hot stars
Red dust heated by other stars



Energy Released By Galaxies

- Large galaxy surveys have allowed the measurement of the **total energy** released by all low z galaxies across the UV-far IR spectrum ~1.3x10^{35} W/Mpc^3(Driver 2012) 35-45% of energy generated by stars is absorbed by dust and re-radiated in IR.



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 et al.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**

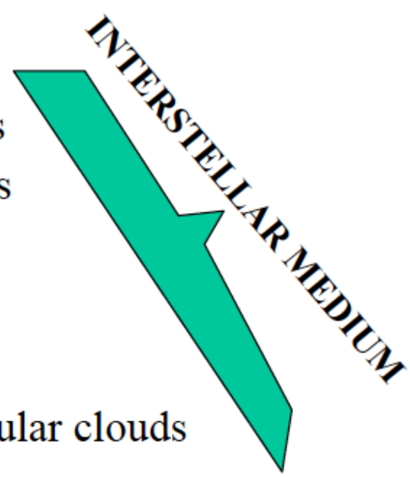
Neither emission nor absorption? if YES then .... **BL Lac**

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

Baryonic Composition of Average Spiral

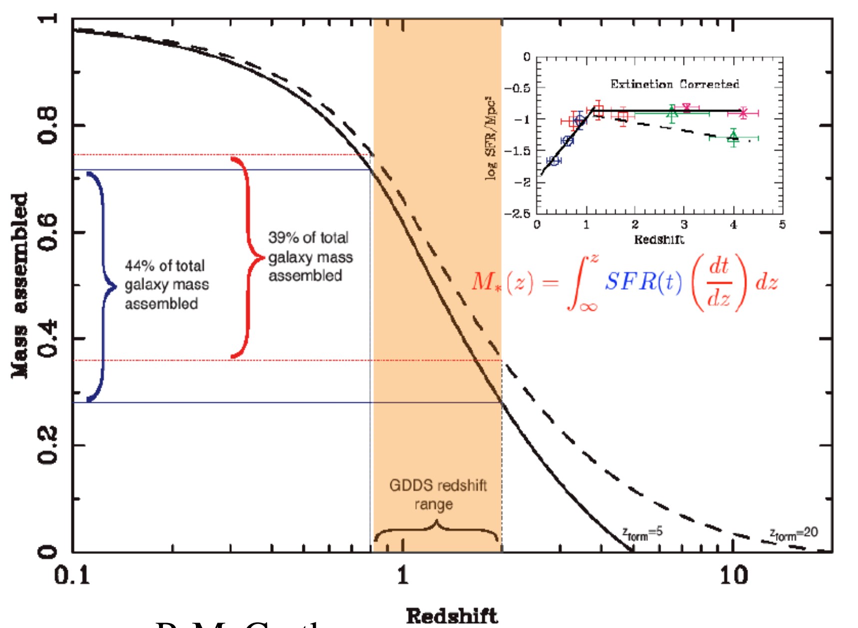
- Stars ~80% of mass
  - DISK ~80% of stars
  - BULGE ~20% of stars
- Gas ~20% of mass
  - atomic gas (“H I”) ~2/3 of gas
  - molecular gas (H_2) ~1/3 of gas
  - hot, ionized gas (“H II”)
- Dust (very little mass)
  - between stars
  - mostly in spiral arms & molecular clouds



When Did Galaxies Grow

Mass Assembly History

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



P. McCarthy

Theoretical Calculations of Growth of DM Halos

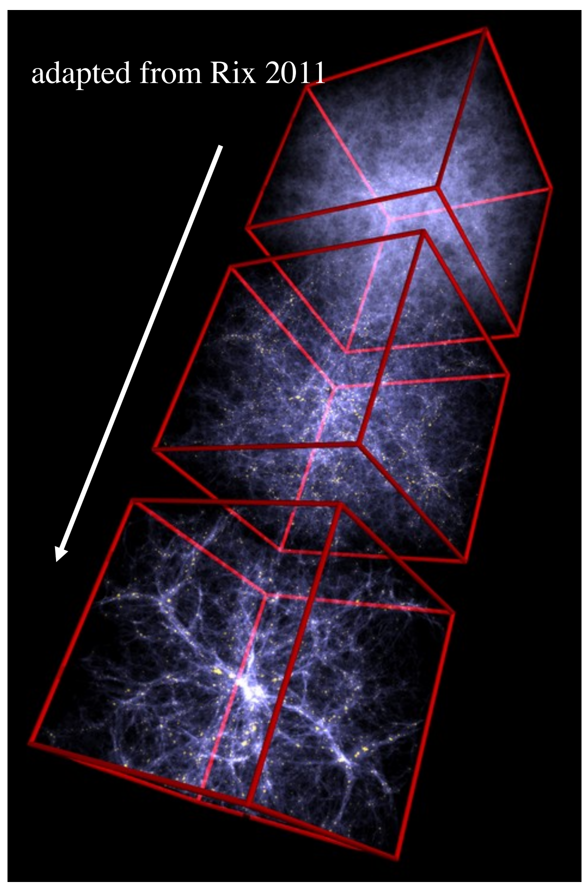
Good cosmological numerical models exist,

Details depend on cosmological parameters :

- Initial fluctuation spectrum
- Ω, Λ ,σ_8, Ω_b, H_0, n

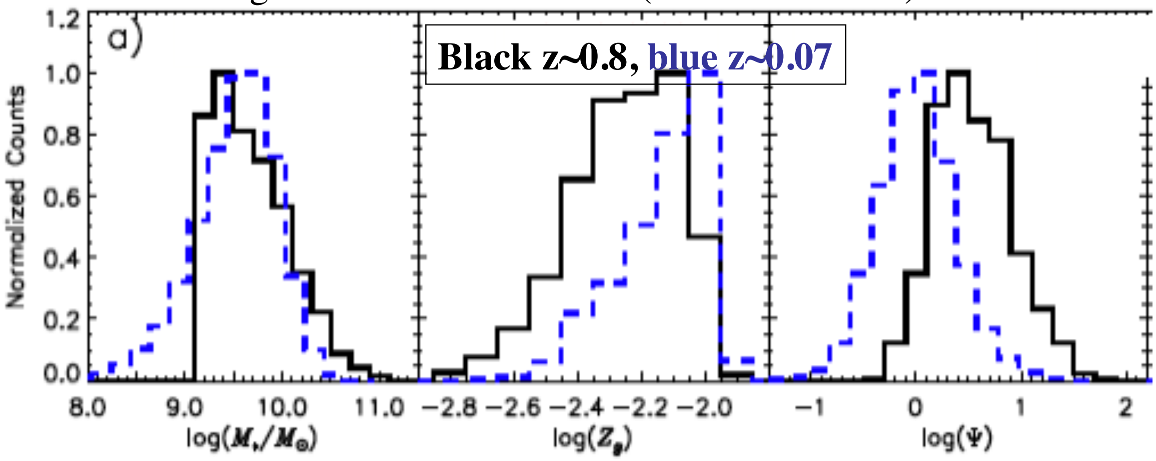
- Output of simulations calculates the growth of the DM structure
- But the baryonic component (e.g. the observable properties of galaxies, groups and clusters) is very uncertain

Because the baryonic physics on $1M_o$ and 10^{11} M_o is strongly coupled and involves time dependent heating and cooling



How Do Galaxies Grow

- Since z~0.8 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)



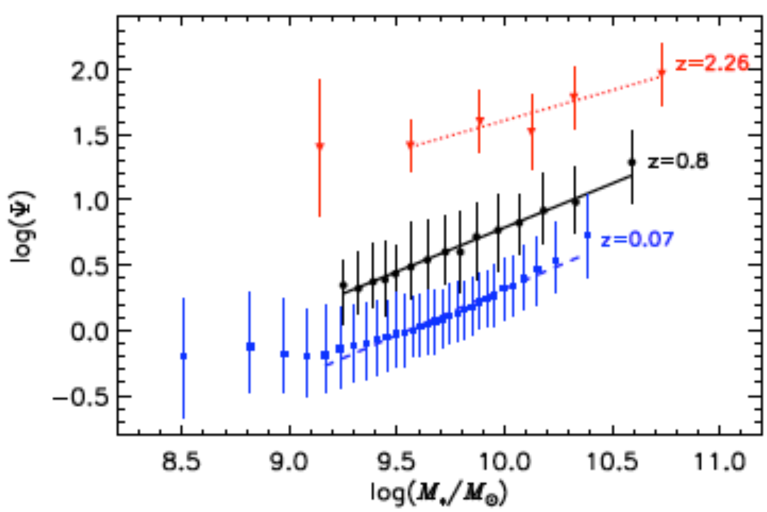
stellar mass metallicity star formation rate

– A histogram of the a) stellar mass, b) metallicity, c) SFR ($M_\odot$ yr^{-1}) and d) the fitted
; (dashed blue) samples.

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

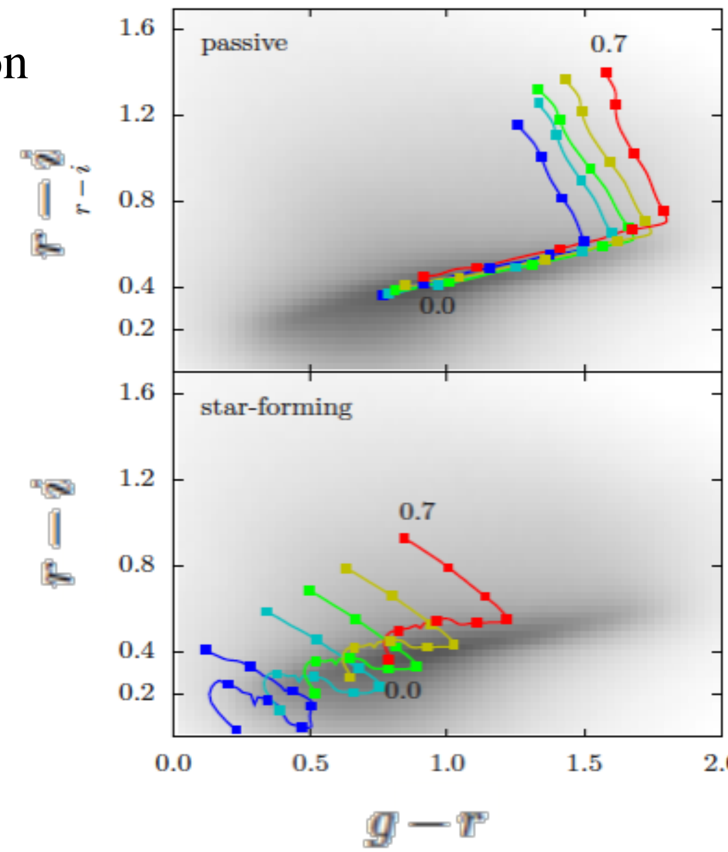


log mass

•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 stars in a given pixel