Summary of Tuesdays Lecture Local Group

- Introduction of Tully-Fisher scaling relation- how to compare galaxies- much more in discussion of spirals this week.
- Discussion of detailed properties of M31, M33 comparison to MW; differences in how they formed; MW very few 'major mergers' M31 more; not all galaxies **even those close to each other do not have the same history.**
- Dynamics of local group allow prediction that M31 and MW (and presumably the Magellanic

The Components

Disks:

Rotationally supported, lots of gas, dust, star formation occurs in disks, spiral arms

Origin in CDM models: disk galaxies form in halos with high angular momentum and quiet recent assembly history, ellipticals are the slowly-rotating remnants of repeated merging events. Disks, form out of gas that flows in with similar angular momentum to that of earlier-accreted material

Halo

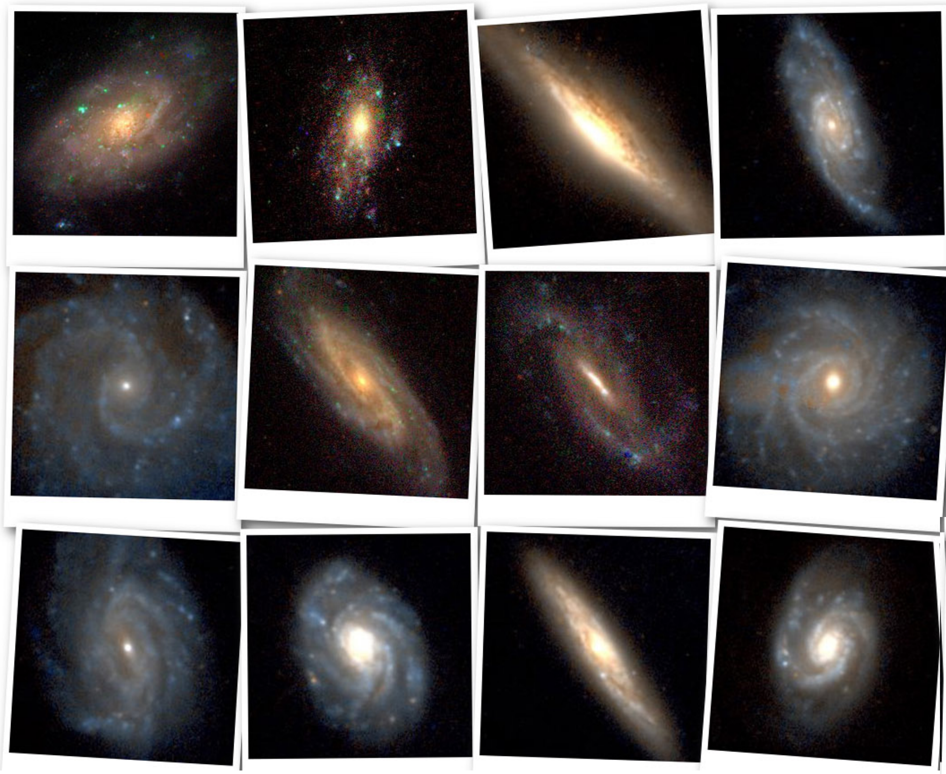
- Totally dominated by dark matter but does have gas (HI) ,some field stars and globular clusters

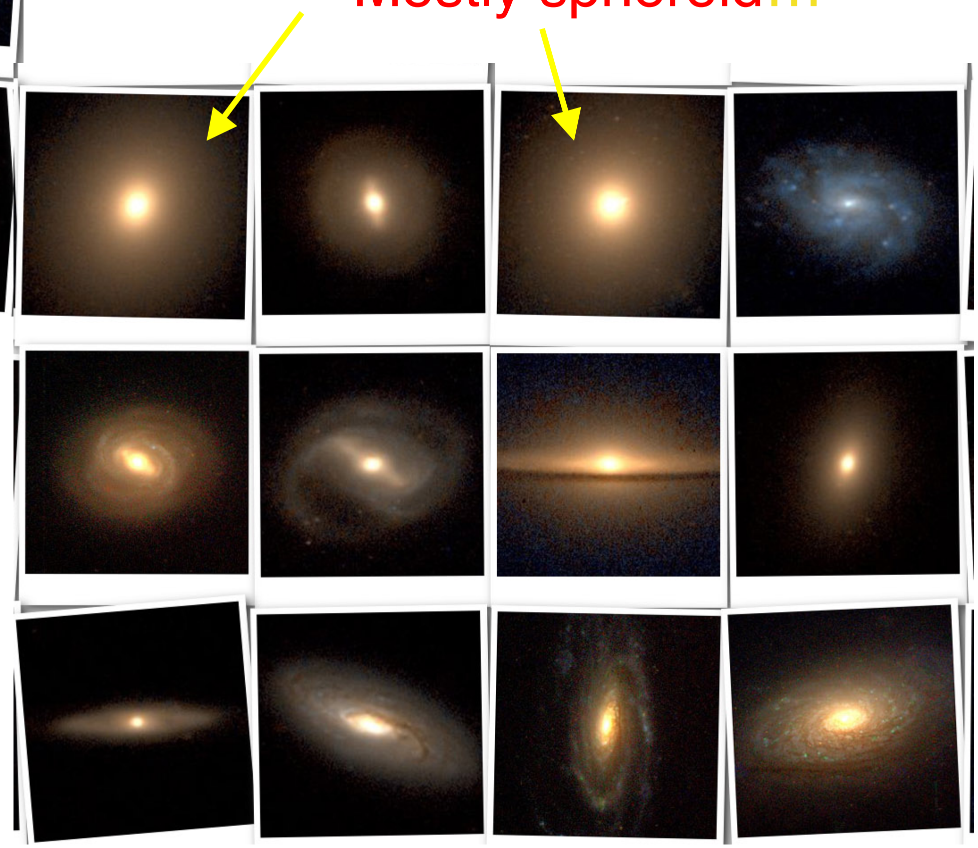
TABLE 23.1 Overall Properties of the Galactic Disk, Halo, and Bulge

GALACTIC DISK	GALACTIC HALO	GALACTIC BULGE
Highly flattened	Roughly spherical—mildly flattened	Somewhat flattened and elongated in the plane of the disk ("football shaped")
Contains both young and old stars	Contains old stars only	Contains both young and old stars; more old stars at greater distances from the center
Contains gas and dust	Contains no gas and dust	Contains gas and dust, especially in the inner regions
Site of ongoing star formation	No star formation during the last 10 billion years	Ongoing star formation in the inner regions
Gas and stars move in circular orbits in the Galactic plane	Stars have random orbits in three dimensions	Stars have largely random orbits but with some net rotation about the Galactic center
Spiral arms	No obvious substructure	Ring of gas and dust near center; Galactic nucleus

From Chaisson

A Bit of the Galaxy Zoo





- Disk-bulge separtation is tricky and influenced by inclination angle and dust and wavelength

Some Guidelines

- Take a look a the solutions to the HW posted at http://www.astro.umd.edu/~qw/astr421/index.html
- Some of you might not have noticed it.. there is also additional material there

- We will have the review after the class... hopefully in this room, but if not possible in the astronomy dept library.

- Guidelines to exam: short answers may be better

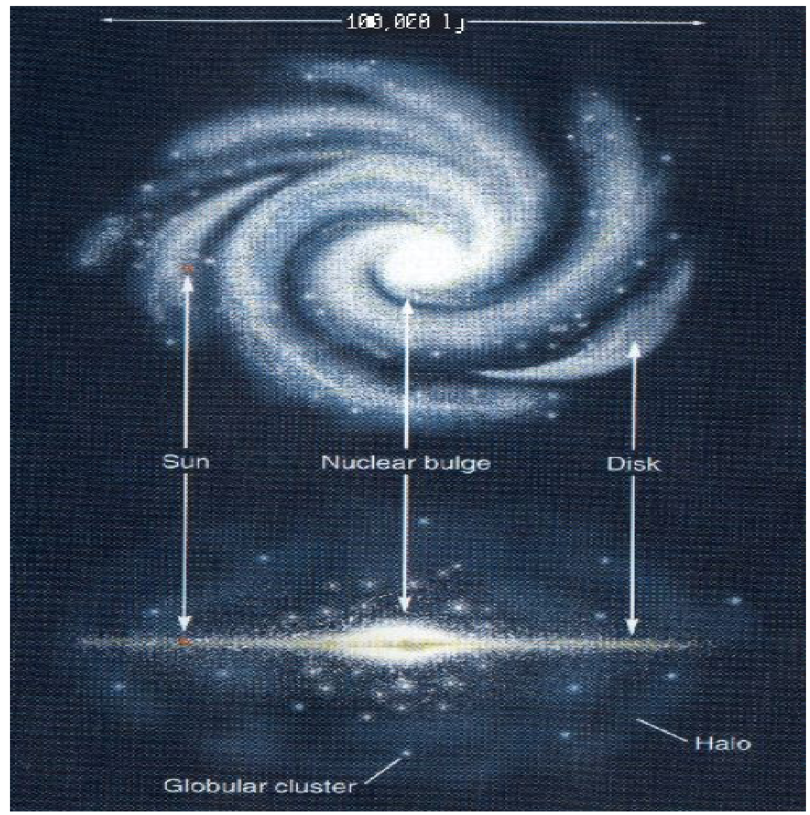
Spirals

- Composed of 3 components
  - disk
  - bulge
  - halo
- Bulge-oldish stars-tends to be metal poor
- Disk - young stars

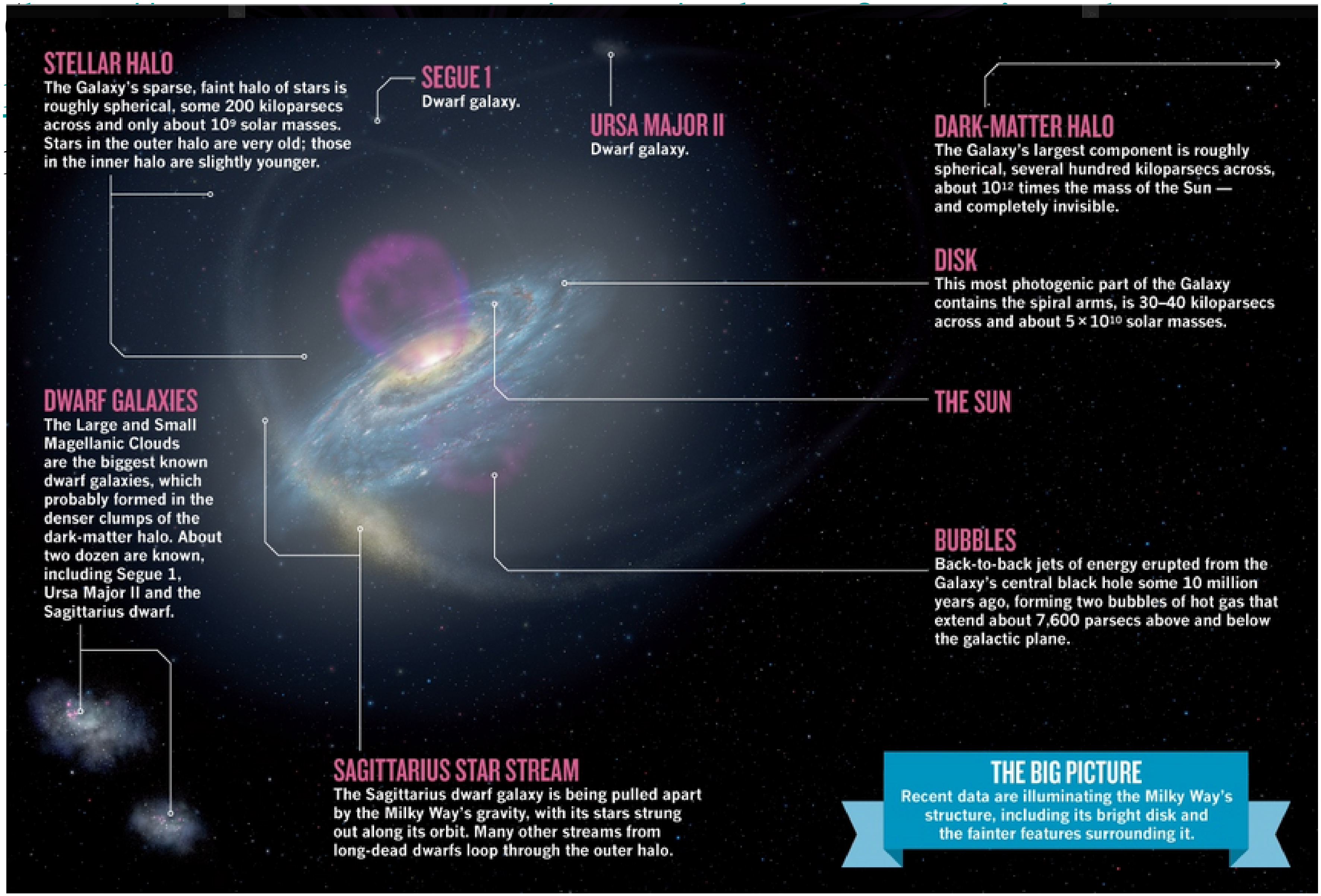
  The disk contains a large quantity of gas & dust, the bulge essential none

  Disks are cold (rotationally supported)

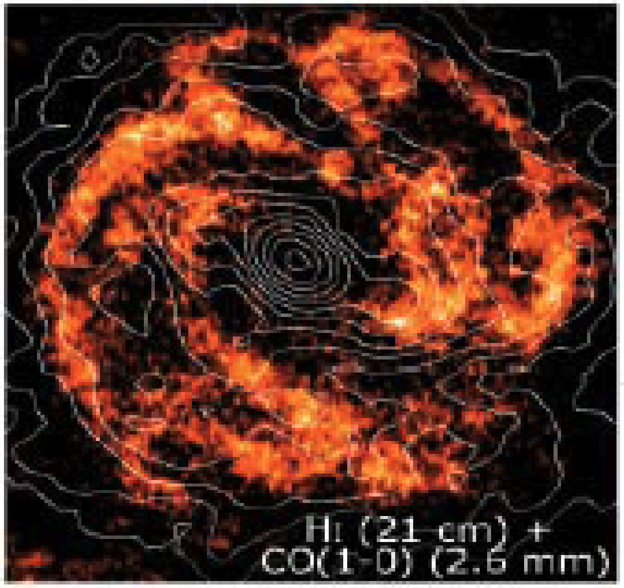
  Bulges are 'hot' supported by random motions



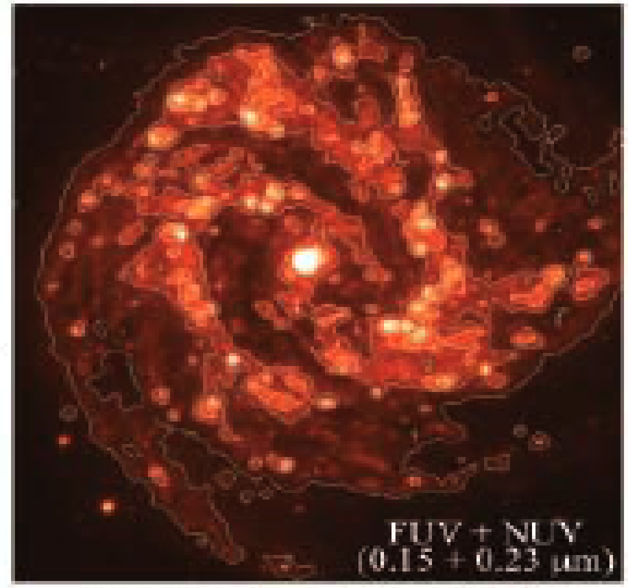
- there is a major review article in Nature last week called" Galaxy formation: The new Milky Way"



M 83: from Gas to Stars



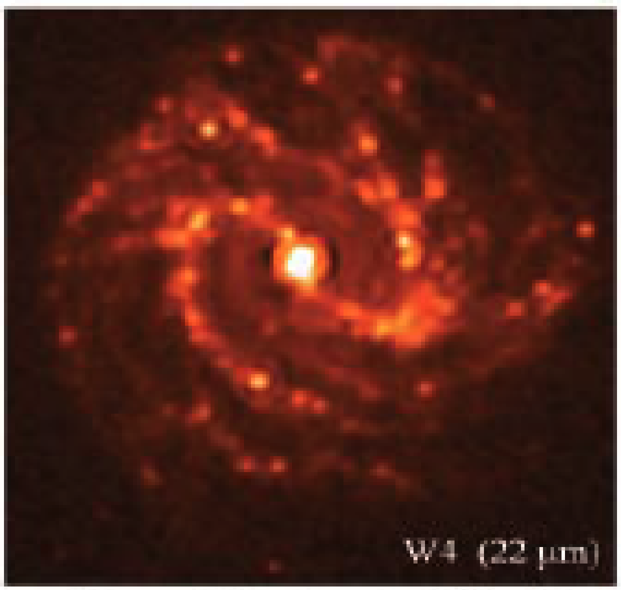
Neutral gas is the *reservoir*, molecular gas fuels the star formation



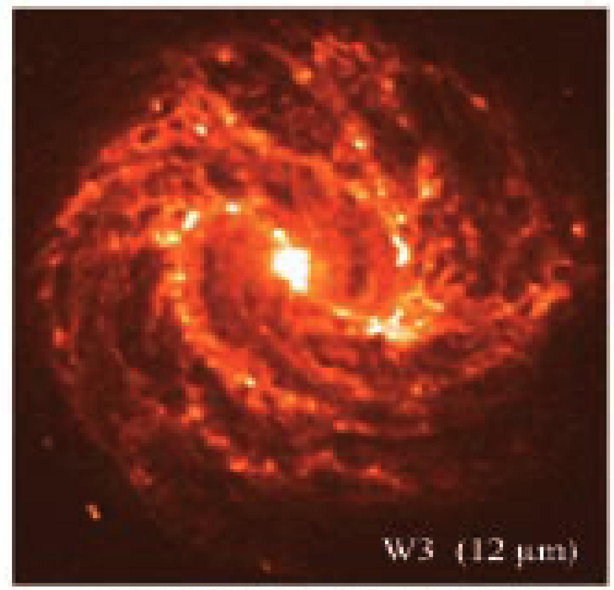
Young hot stars represent the current epoch of star formation

Evolved star population constitutes the *Stellar Backbone*

Spiral galaxies are panchromatic objects different physical process are best shown in different wavebands



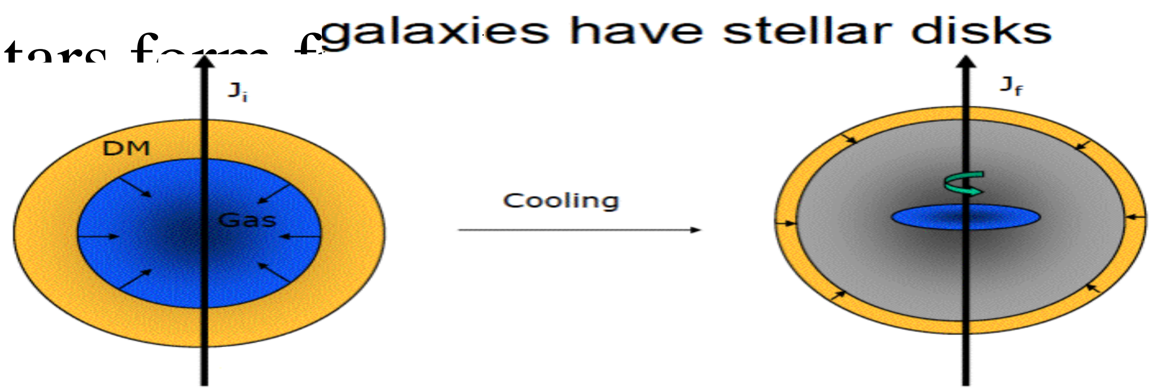
Very small dust grains efficiently reprocess energy from star formation



Excited PAH molecules due to *ISM heating* by hot stars

Simple Model of Why Galaxies Have Disks

- A circular orbit has the lowest energy for an initial angular momentum J- thus since angular momentum is conserved, if the in falling gas loses energy (cools) will tend to form a disk
- I… e in a d…



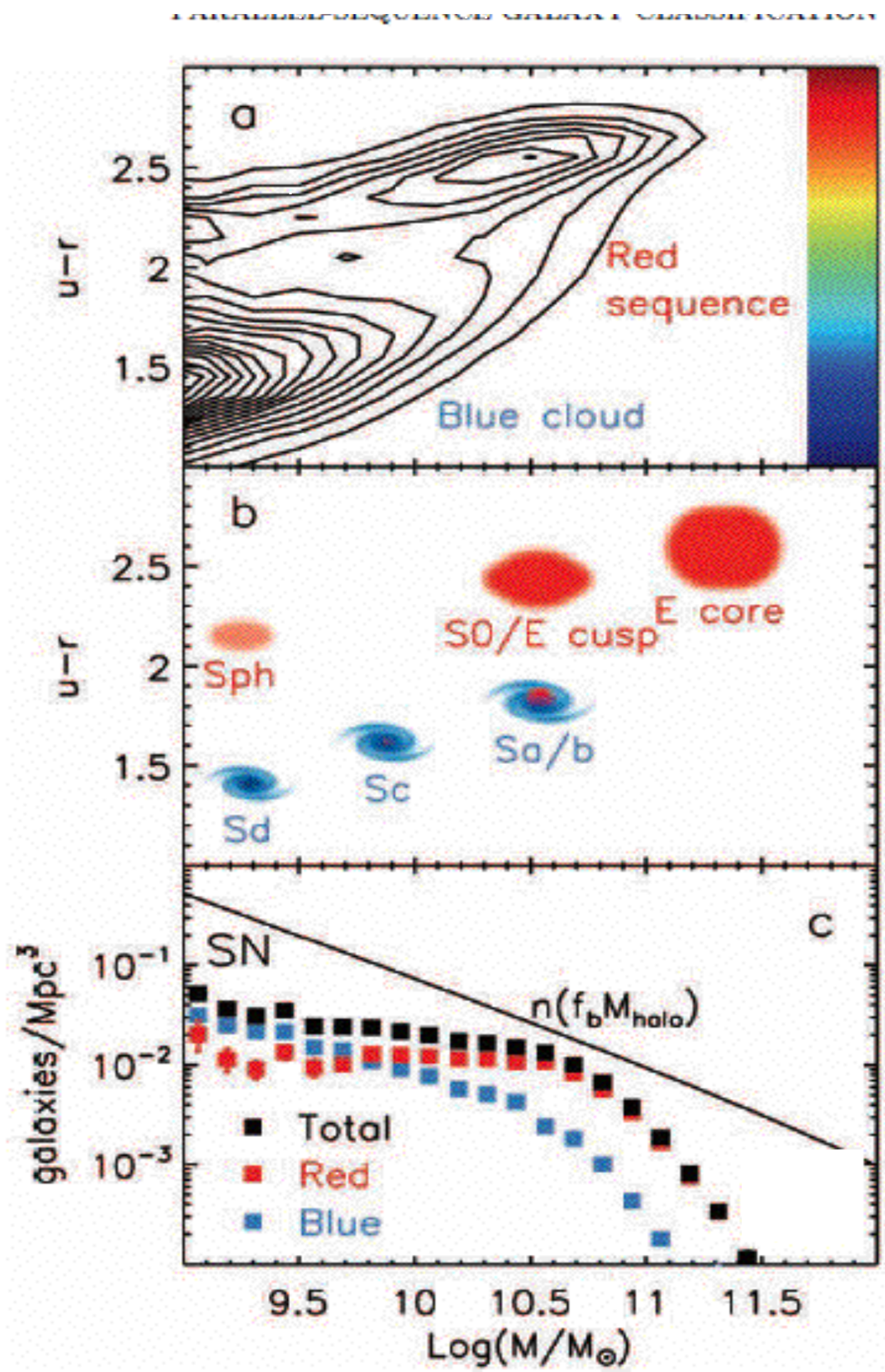
However In A Hierarchical Universe Things are More Complex

The Big Pictur
Two Populatio

- 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- the



Summary of Tuesdays-Lecture Spirals

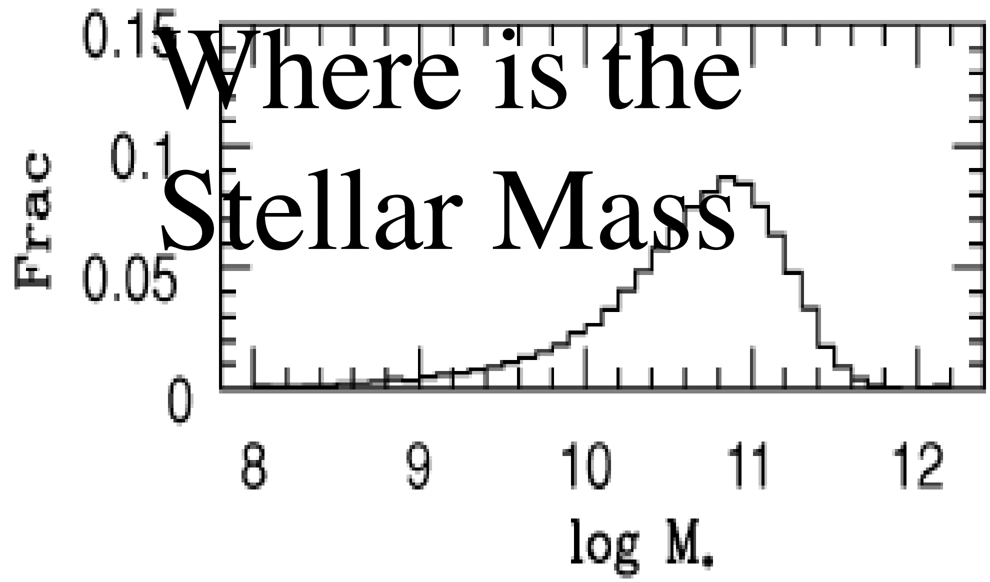
- Components of Spirals
    - bulge
    - disk
    - halo
  - each has a different stellar population, gas content.
- Connection between color, mass, morphology for galaxies as a whole.

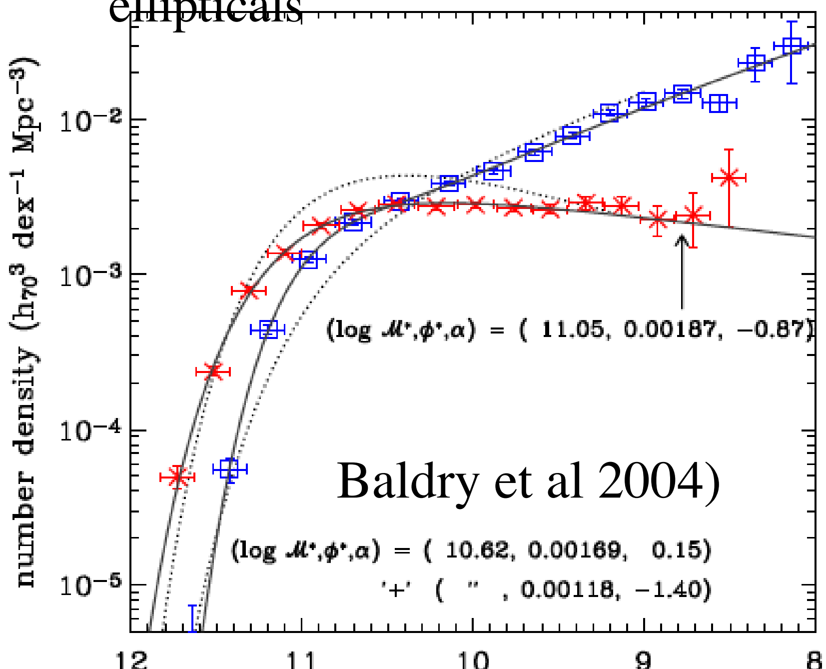
Top Level Summary-Spirals

- Galaxies have a wide variety of morphologies, from spheroids , disks with and without bars and irregular galaxies.
- Their physical properties (e.g. gas content, average stellar age, the rate of current star formation, mass etc) correlate with morphology.
- disks are predominantly rotationally flattened structures
- spheroids have shapes largely supported by velocity dispersion.

Where is the Stellar Mass

- The stellar mass **integrated over ALL galaxies** 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

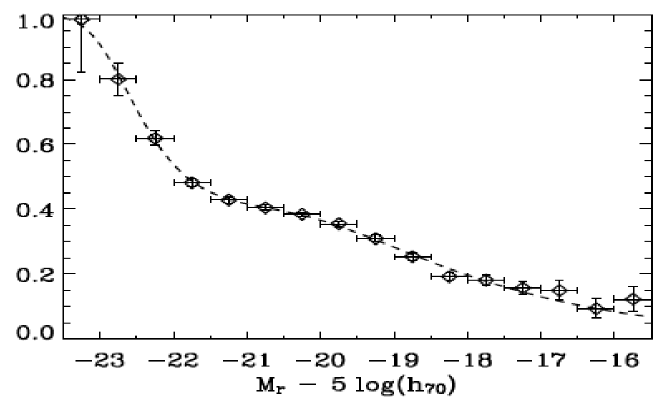




Baldry et al 2004)

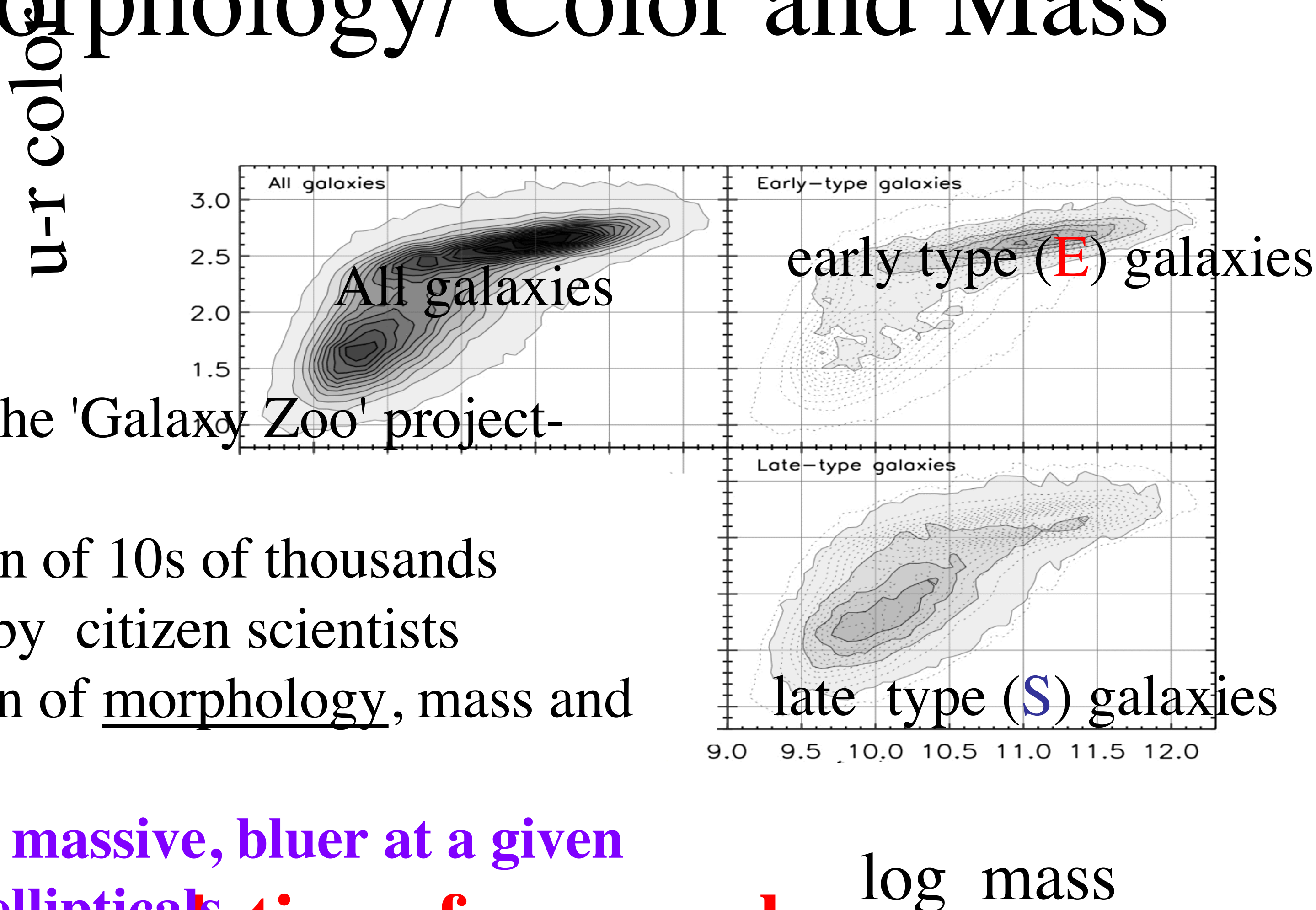
log total mass (stars =DM)

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

Combination of <u>morphology</u>, mass and **color**

Spirals less massive, bluer at a given mass than ellipticals

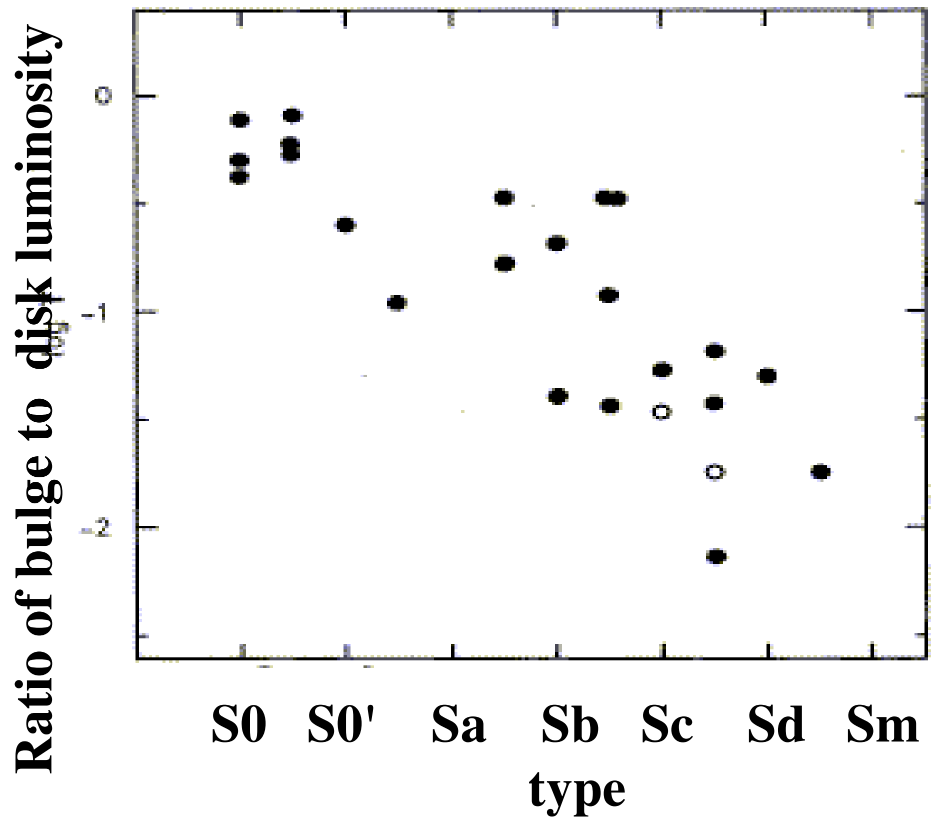
- **Strong relation of mass, color and morphology**

Schawinski 2010

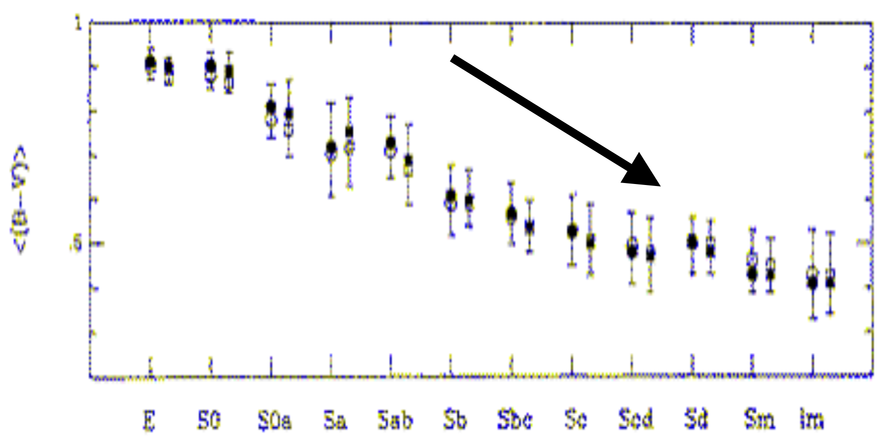
Spirals

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)



color vs morphological type

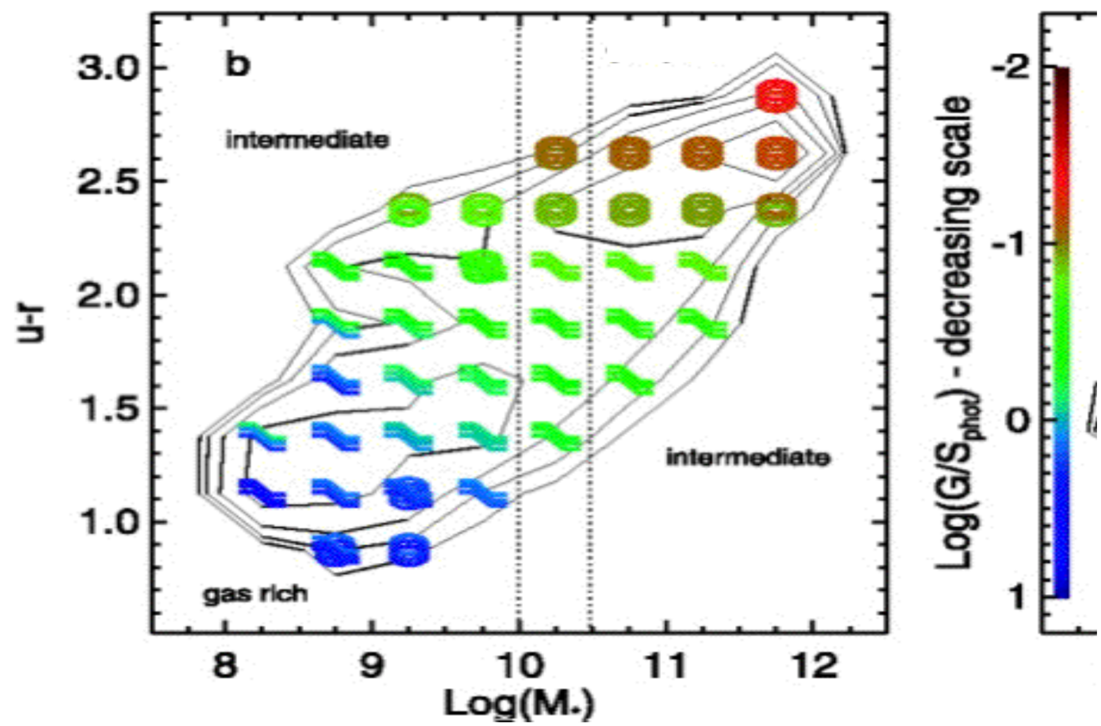


Spirals and Gas

Gas to light ratio in log scale

cold gas poor

- The ISM of spiral galaxies is quite complex and show wide variations with position
- However

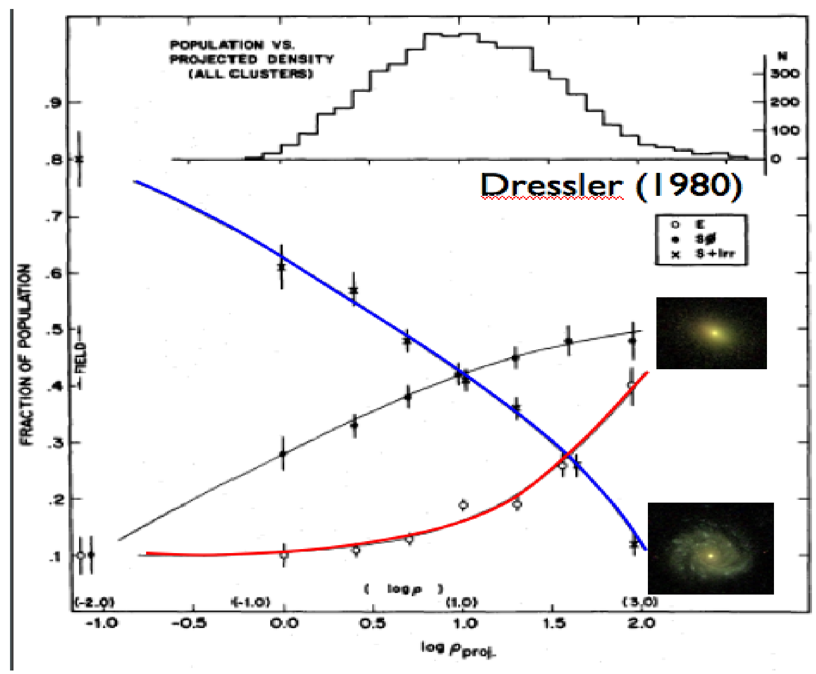


Spirals- More Trends with Morphology (Sd → Sa)

- Total luminosity decreases
- M / L_B rises
- M (HI) / $M_{(total)}$ rises
- Bulge / Disk decrease
- Tightness of the spiral arms decreases
- Scale length drops
- color reddens- star formation history

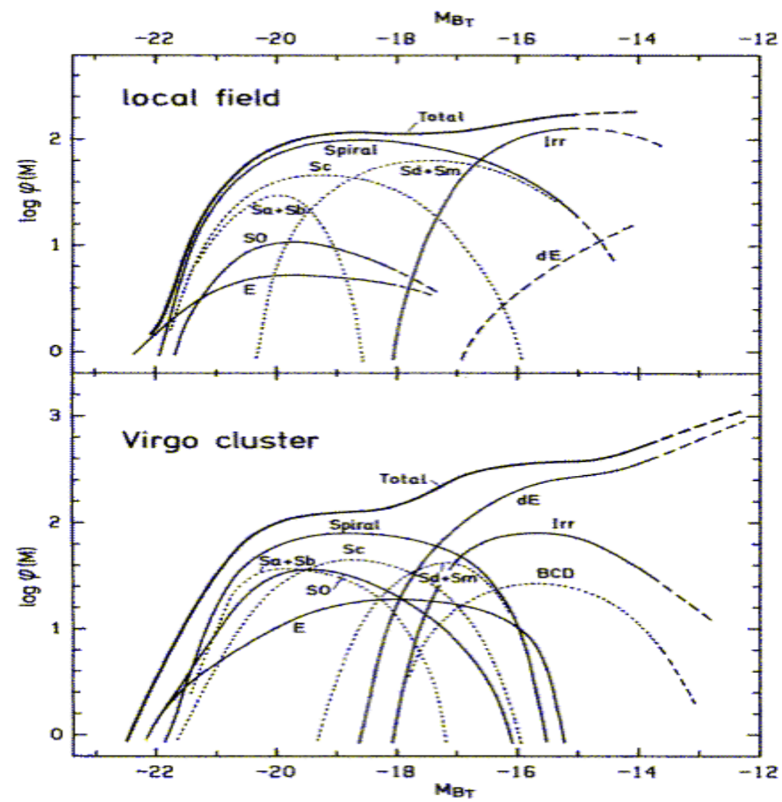
"Where" Do Galaxies of a Given Type Reside

- In low density regions most of the galaxies are spirals (blue line)
- As the density of galaxies increases the fraction which are S0(black) and E (red) increase dramatically- this reaches it limit in massive clusters of galaxies whose cores



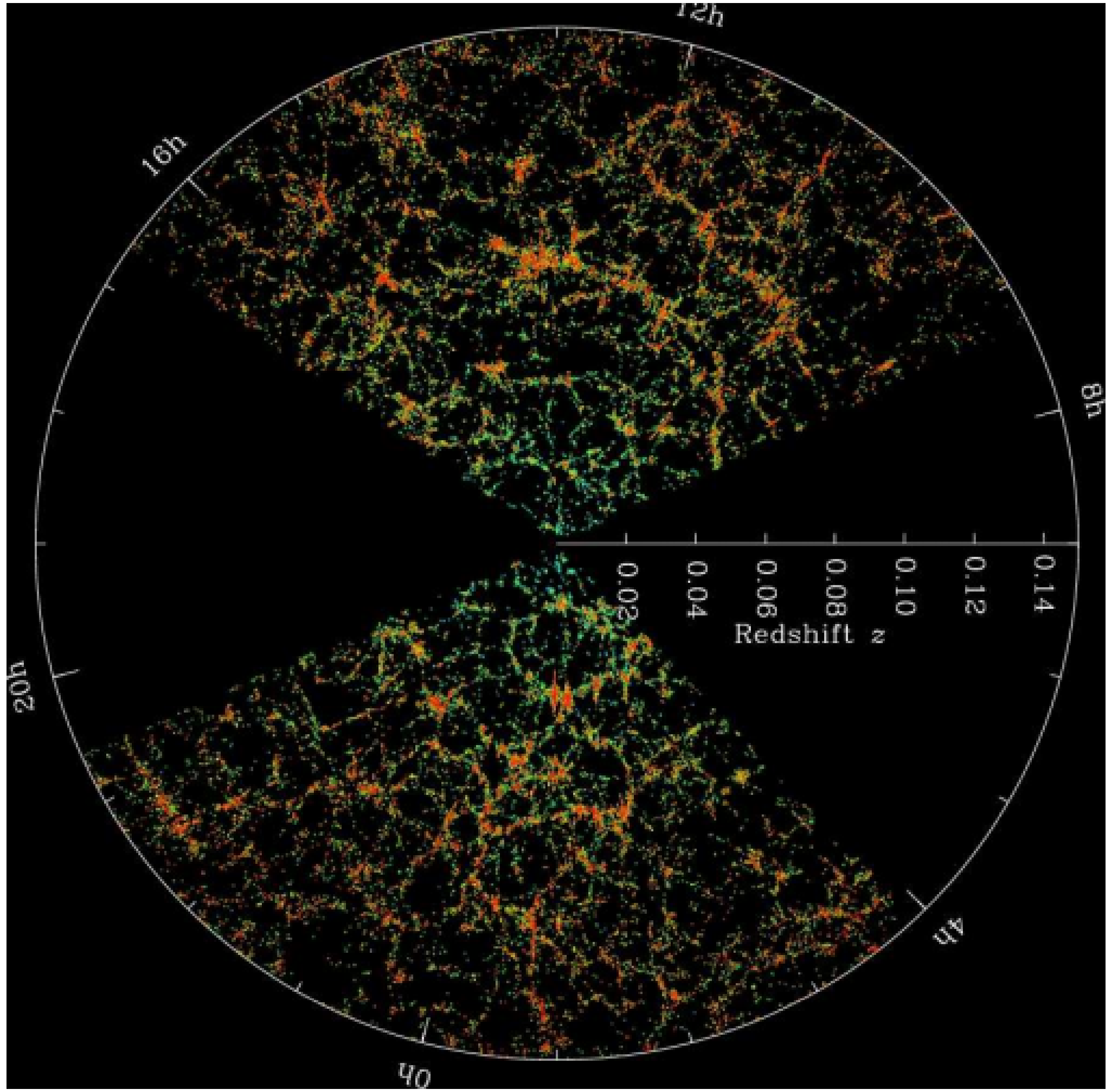
How Many of Which??

- 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



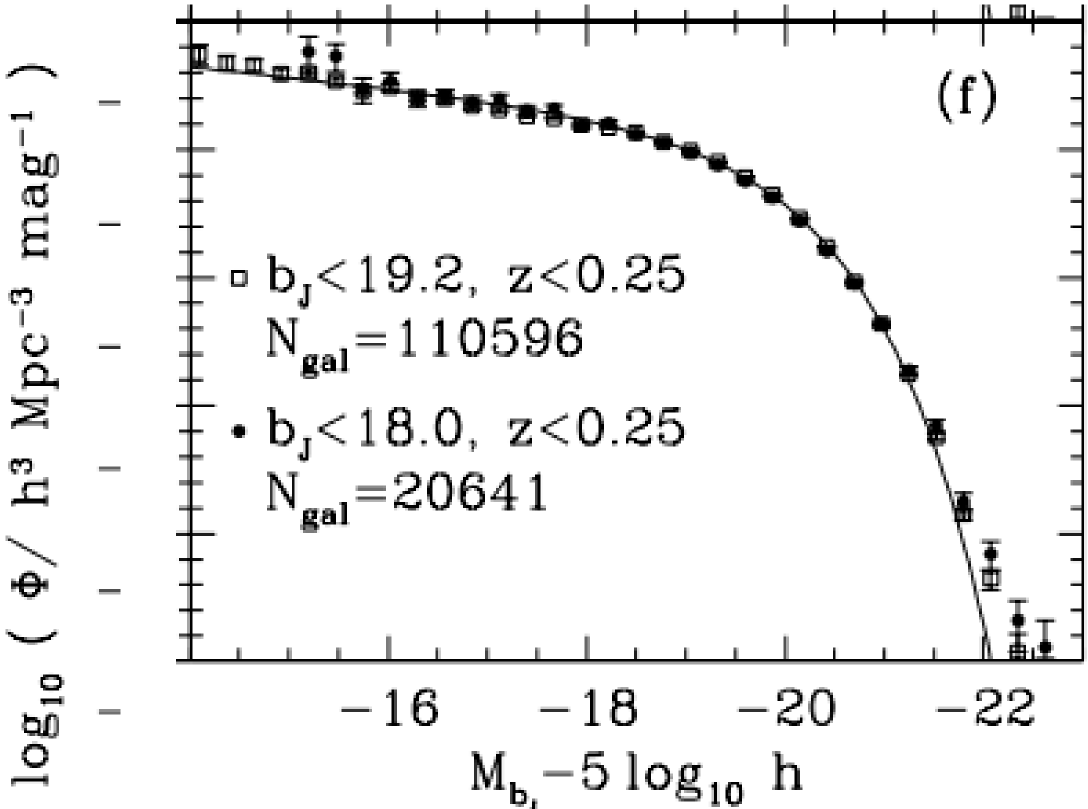
Binggeli, Sandage, and Tammann 1988

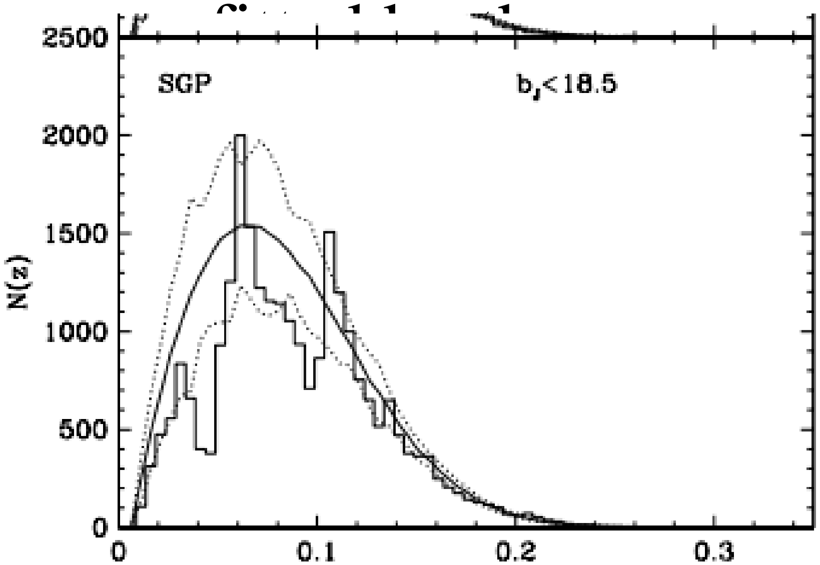
- Distribution of red and blue galaxies out to z-0.15 from the SDSS (M. Blanton)
- Notice that red



Luminosity Function

- The combined luminosity function of **all** galaxies is



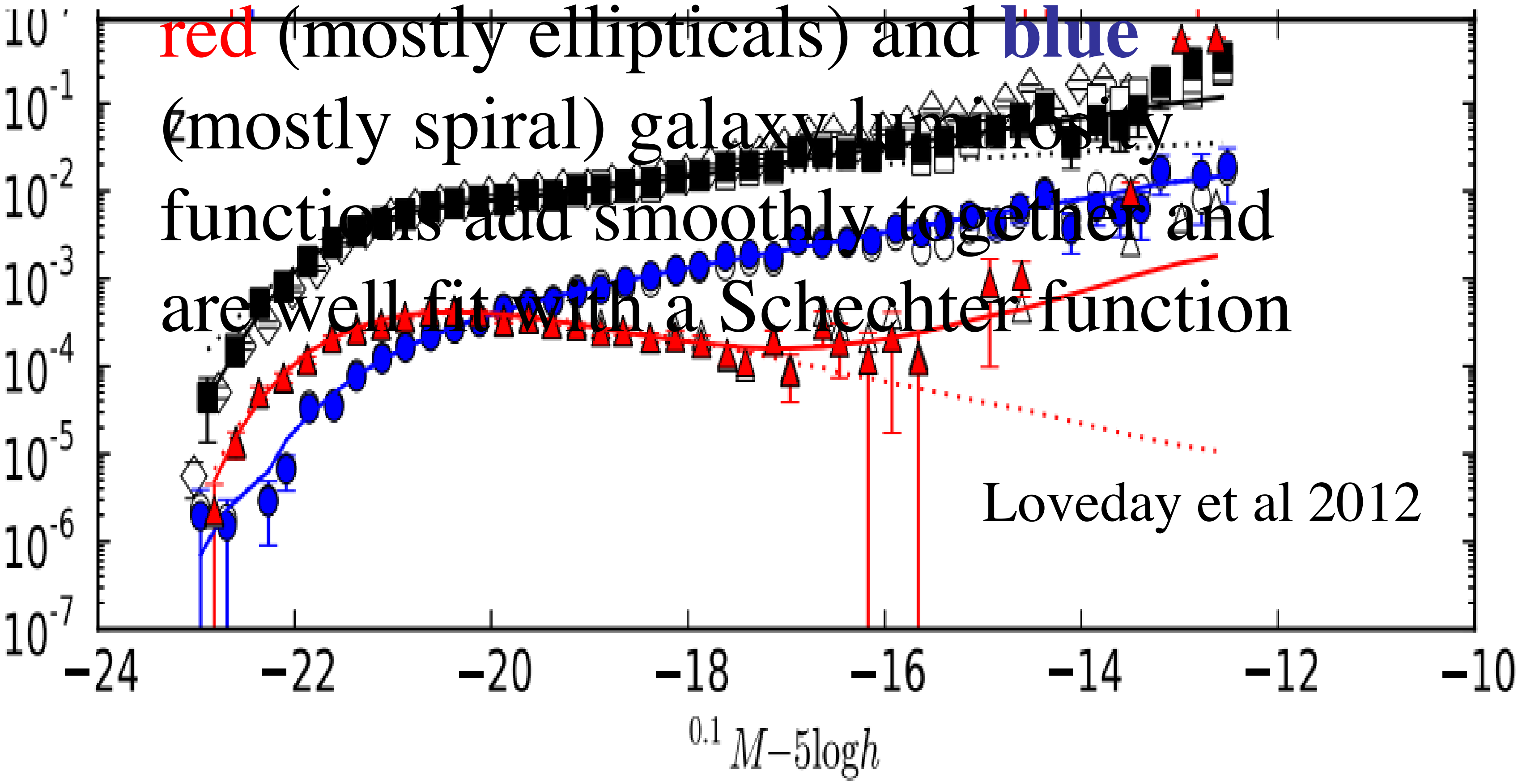


Redshift

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

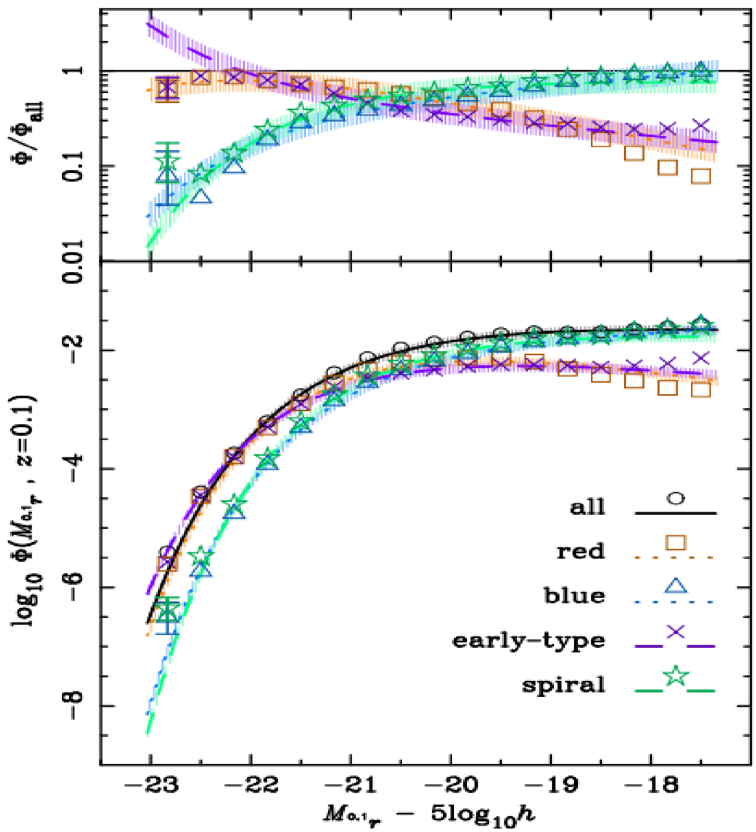
Despite differences in populations the red (mostly ellipticals) and **blue** (mostly spiral) galaxy luminosity functions add smoothly together and are well fit with a Schechter function



Loveday et al 2012

Red and Blue are not exactly Elliptical and Spiral

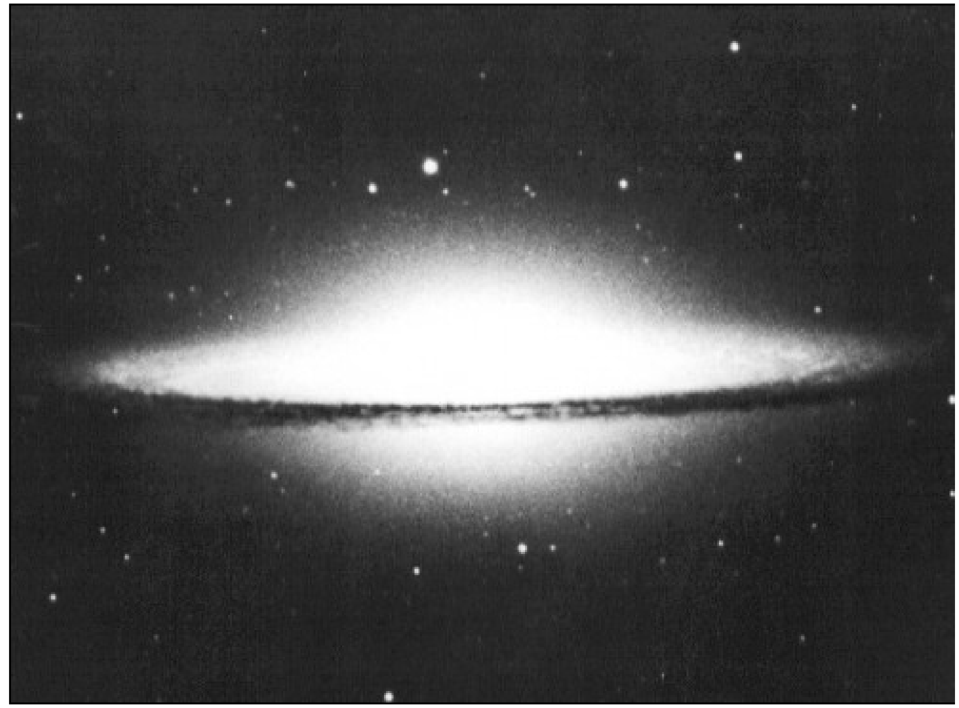
- With the galaxy zoo one can get the morphology and color of the galaxies.
- Cresswell (2011) shows the luminosity function of red, blue, elliptical and spiral and the relative numbers of each class vs absolute magnitude.



Spirals

- 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
-

Physical Difference Between Bulges and Disks

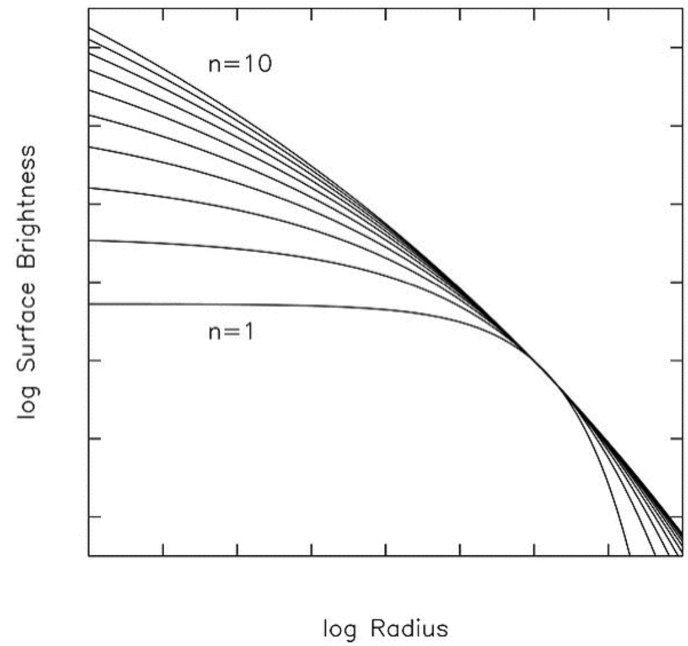


- In spiral galaxies
  - the stars in the disk have lots of angular momentum and a wide variety of ages.
  - stars in the bulge tend to be old, have little angular momentum and have low metallicity*
    - (globular clusters

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

Descriptions of Gala
Surface Brigh

- 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



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

total luminosity of Sersic profile- Γ is the gamma function

Stellar Distribution- radial average

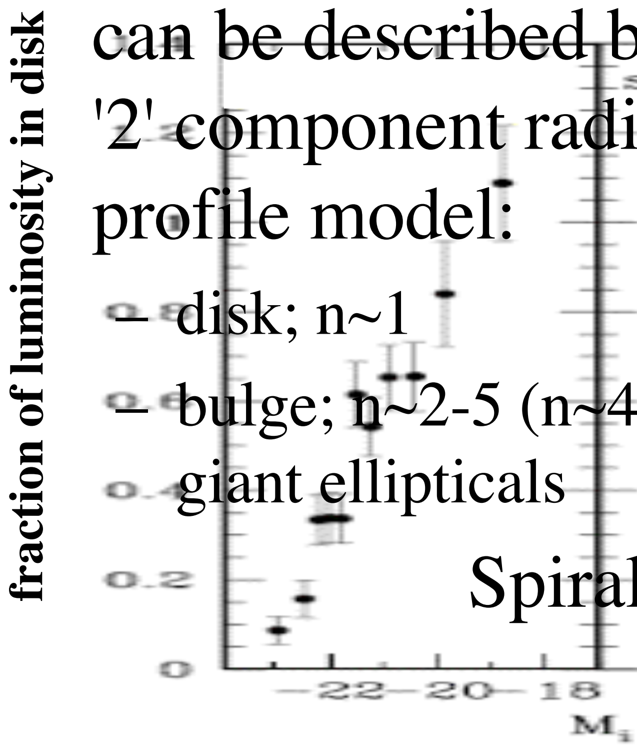
$$\Sigma(r) = \Sigma_e e^{-\kappa[(r/r_e)^{1/n}-1]}$$

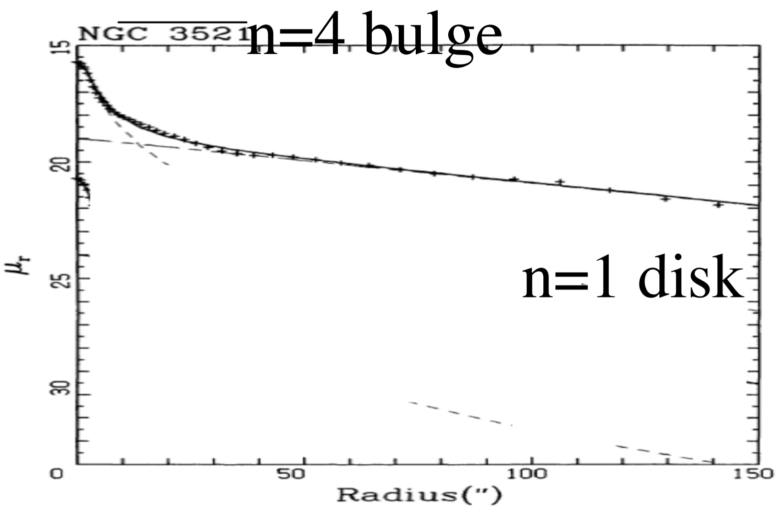
$$\kappa \approx 2n - 0.331$$

Sersic(1968) profile S+G eq 3.13

- 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

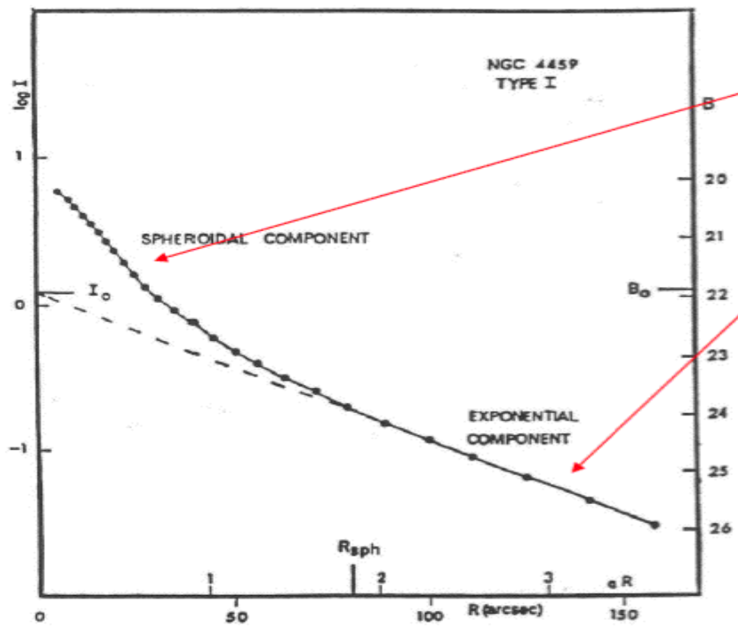
More massive galaxies have a higher fraction of their light (mass) in the bulge (and by defintion 'earlier' type





Azimuthally Averaged Light Profiles

- Bulge is more concentrated than the disk:



$$\log I \propto R^{1/4} \quad \text{(inner)};$$

$$I(R) = I_0 e^{-\alpha r} \quad \text{(outer)}$$

α is the inverse scale height

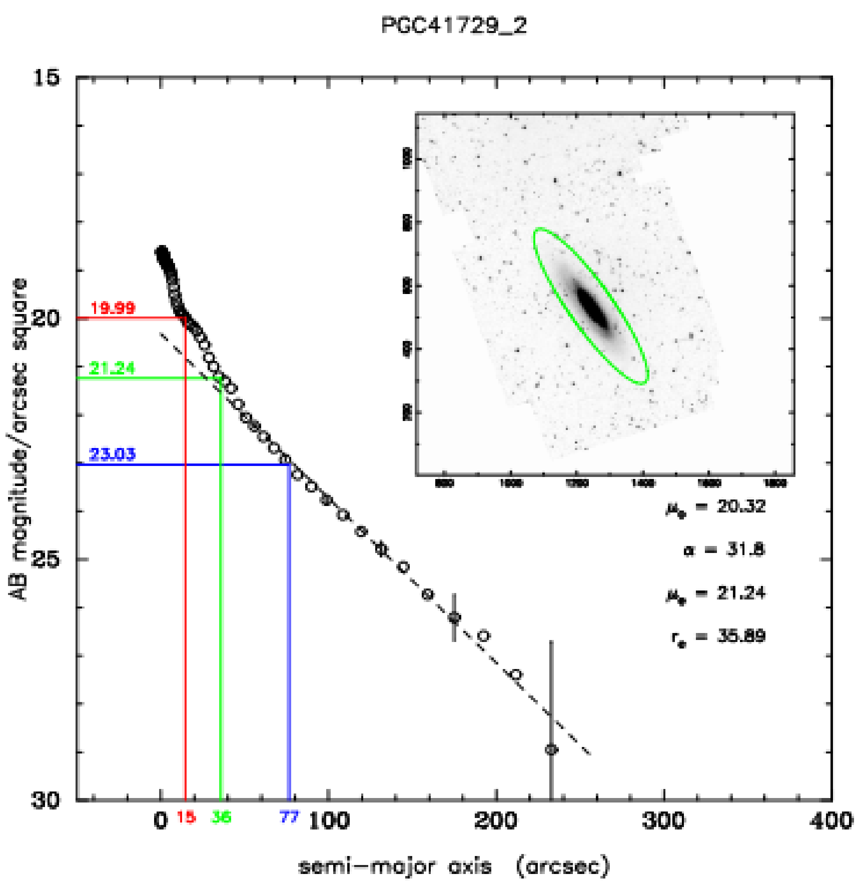
(Freeman 1970)

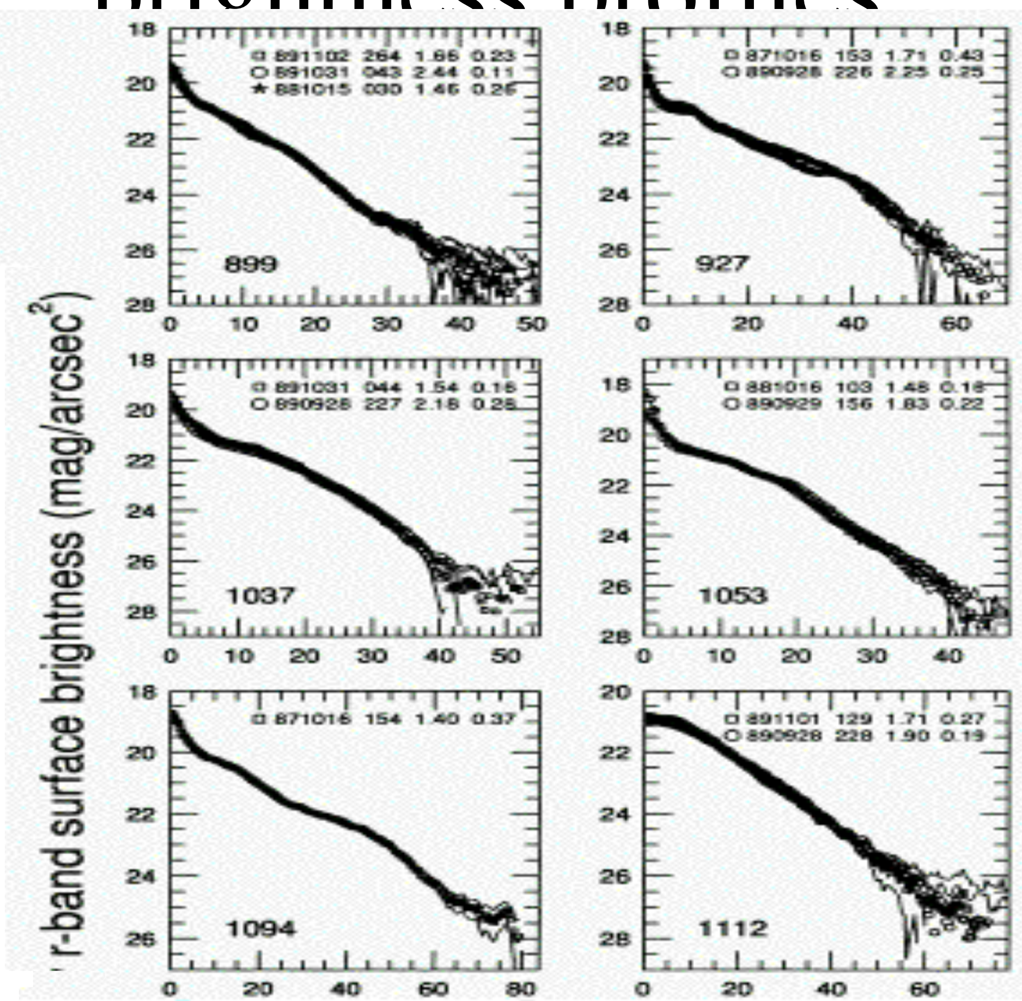
This is an approximation, galaxies with strong bars or other non-azimuthally symmetric features will clearly change this

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

What's Important So Far

- The class of galaxies called spirals (based on morphology in the optical)

  has a set of strongly correlated properties (mass, star formation, dust, gas, color) - so there is physics in morphology

The big bifurcation between color, mass, morphology classification by color,mass, morphology gives similar but NOT identical results

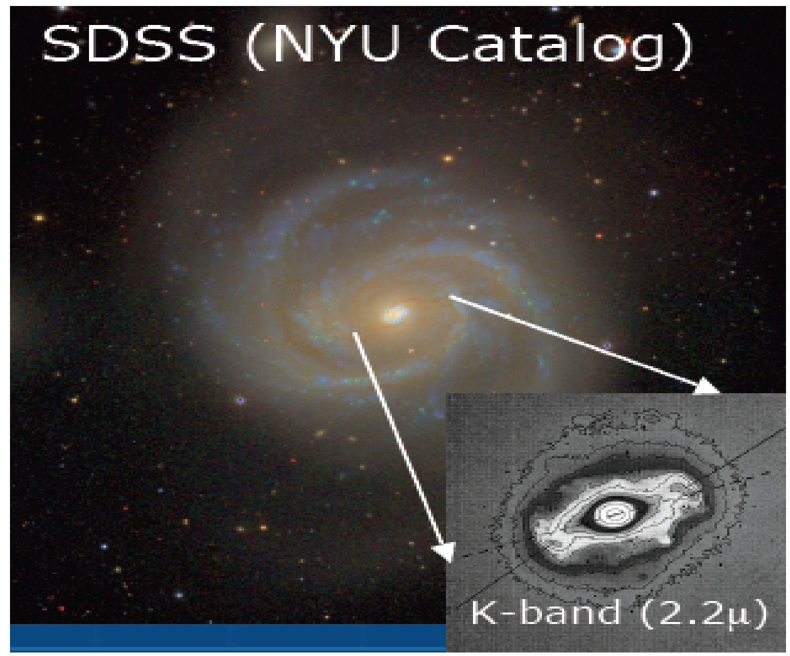
- At one lower level (e.g sub-divisions in morphology (Sa,Sb,Sc etc) there are also trends.

Summary of Surface Brightness Profiles

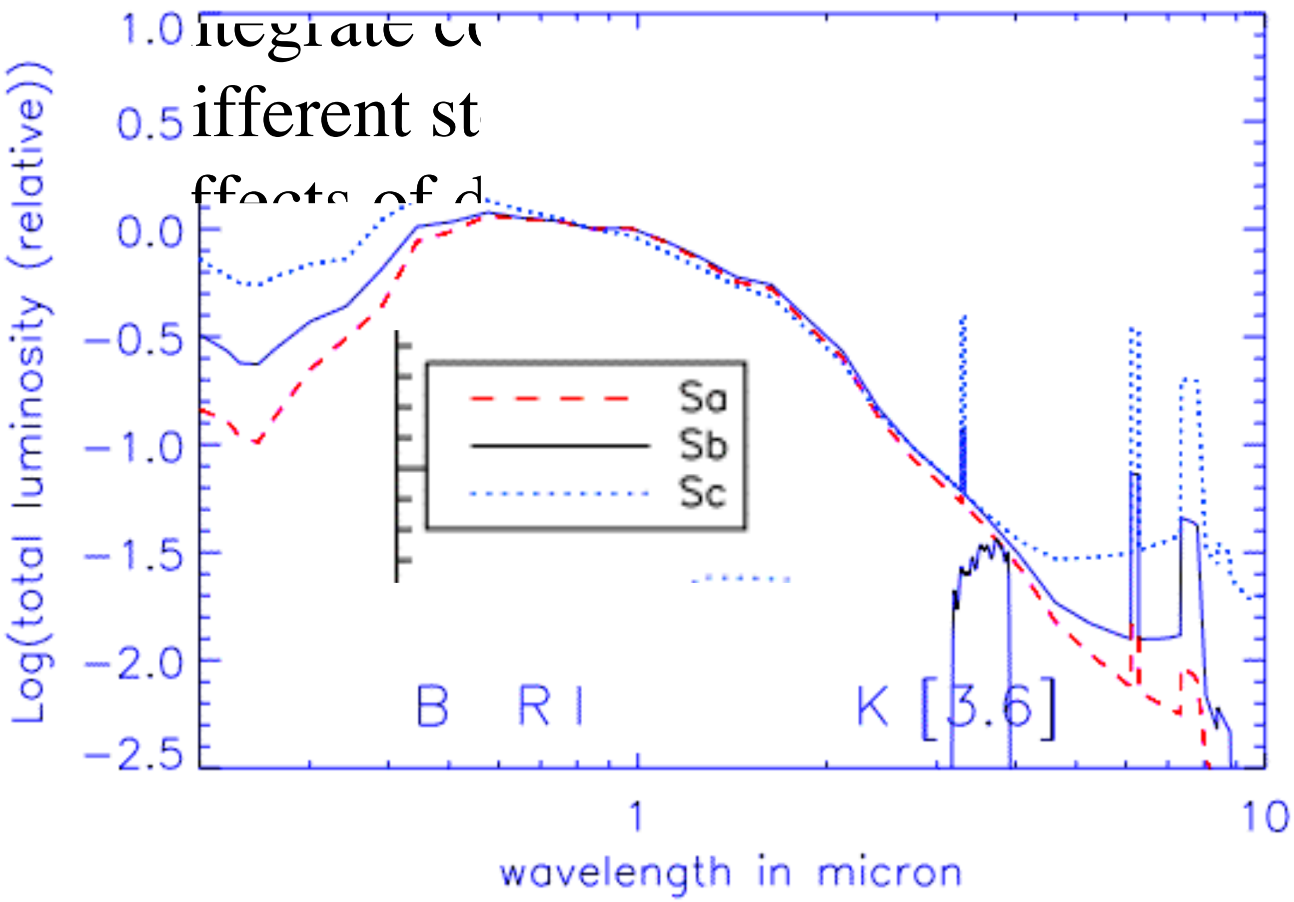
- Most galaxies can be well fit with the Sersic profile, spirals have lower values of 'n' for the disk and 2 components to the profile (bulge, disk)
  - Sersic profile 2 asymptotic forms
    - low n ~exponential: $I(R)=I(0)(\exp-[(R/R_d)]$ where R_d is the disk scale length $I(R)=(1/e)I(0)$; total flux $I_{tot}=2\pi R^2{}_d I(0)$
    - high n - $R^{1/4}$ profile
  - deVacouleurs profile $I(R)=I(R_e)(\exp-7.67[(R/R_e)^{1/4}-1]))$

Spirals- Disk Components

- Stellar bars are common
  - Often only recognized in near-IR images (less dust)
  - Consequence of disk instability
    - Effective means of angular momentum transport



Spiral Galaxy spectra



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

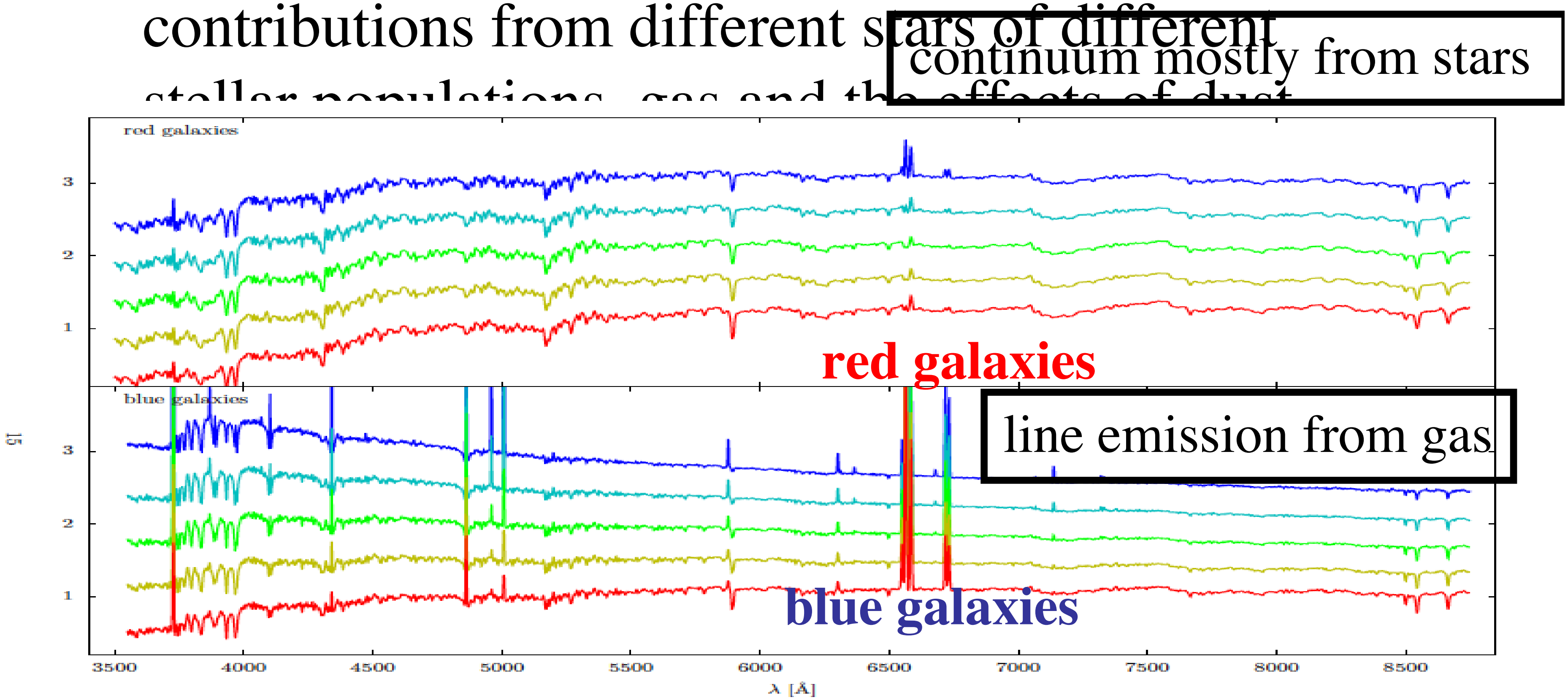
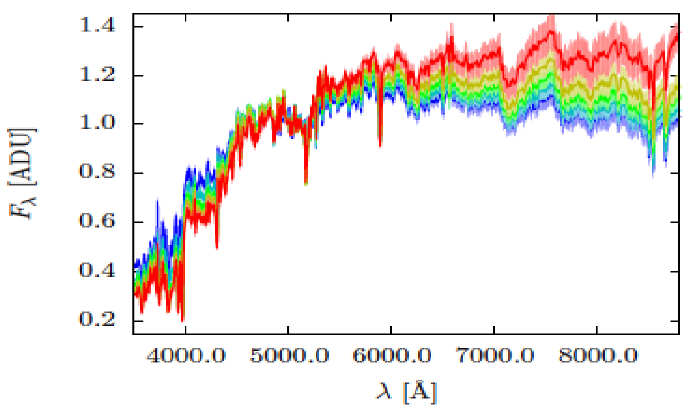
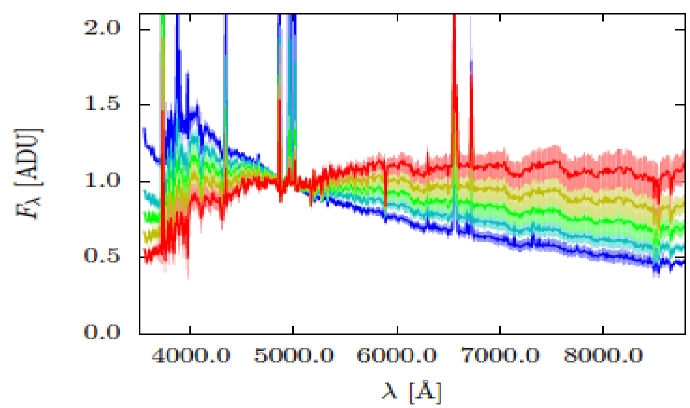


Figure 12: Composite spectra of the refined colour classes as described in Sec. 3.4. The curves are colour-coded from blue (top) to red (bottom) based on the $g - r$ colour of the galaxies. See the online edition for a colour version of this plot.

Galaxy spectra

- Sequence of ages of a composite SSP population (star forming-spiral population)
- bulges are dominated by stellar absorption lines and have little 'blue' light

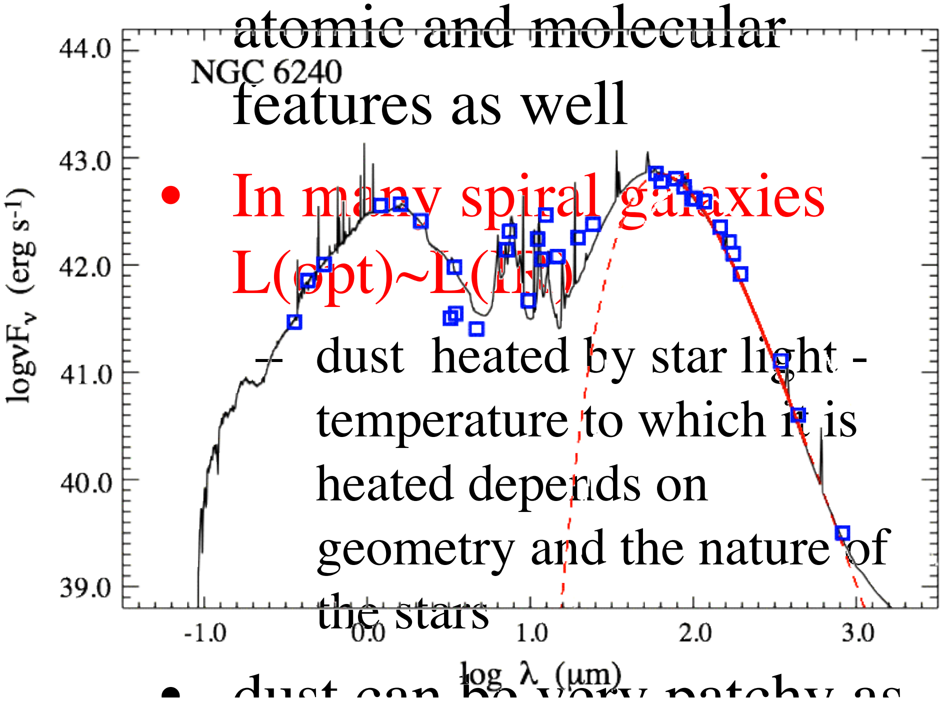


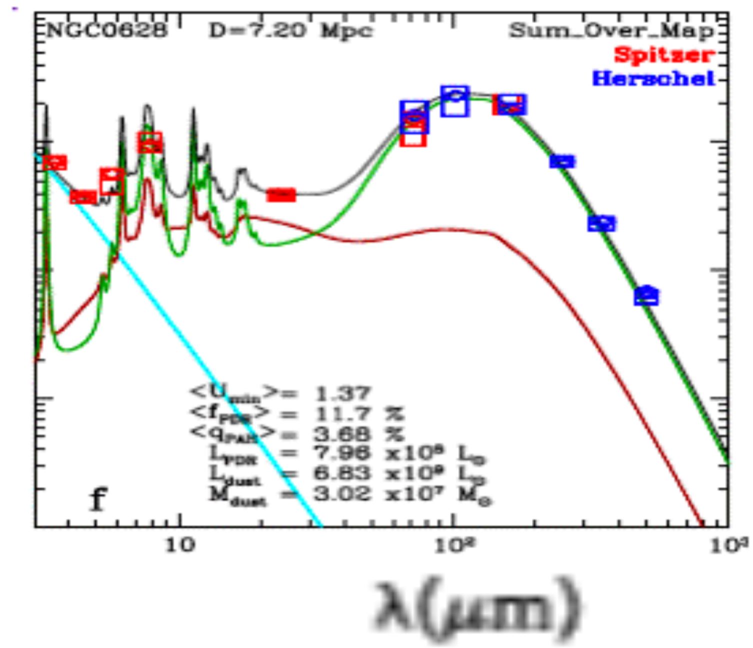


young)

Galaxy Spectra -IR

- At λ>5μ in most spiral galaxies continuum dominated by emission from dust -there are atomic and molecular features as well
- In many spiral 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

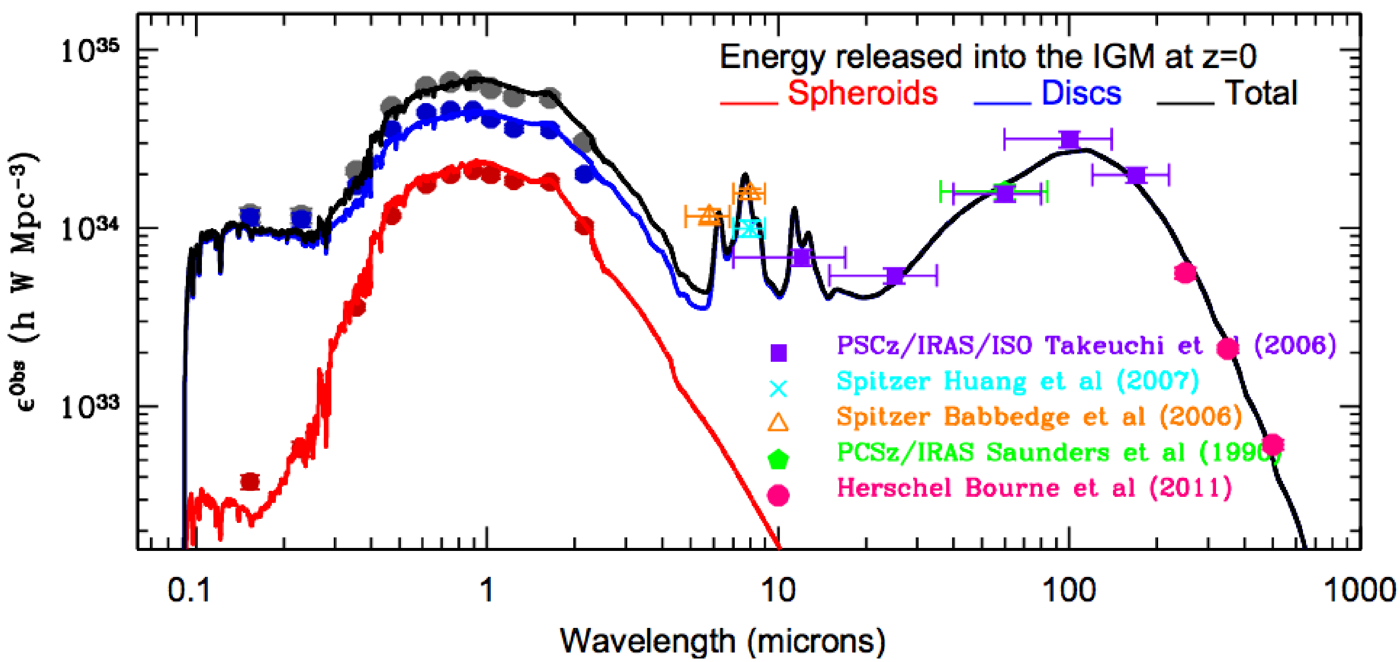




Cyan=stars
Green= dust heated by hot stars
Red dust heated by other stars

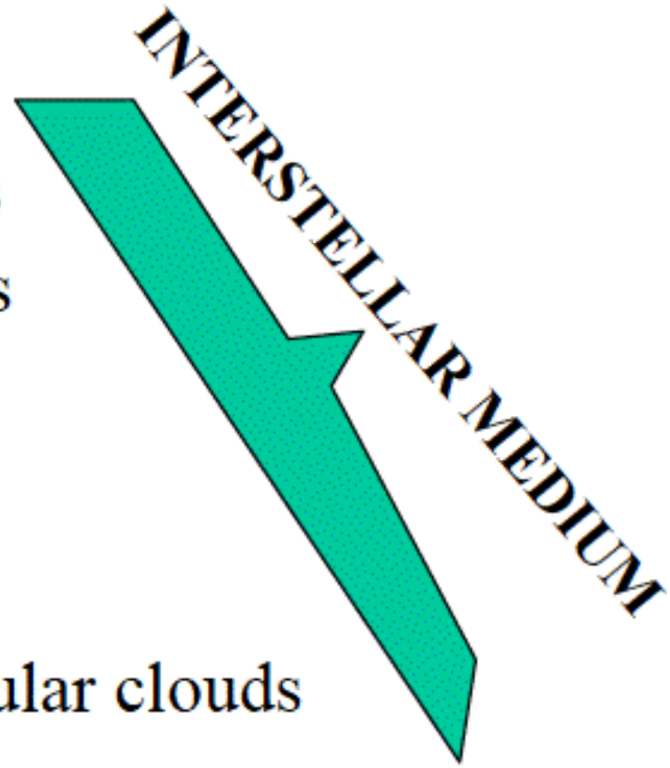
Energy Released By Galaxies

- Extensive galaxy surveys have allowed the measurement of the total energy released by all low z galaxies across the UV-far IR spectrum 1.3x10^{35} W/Mpc^3(Driver 20120; 35-45 of energy generated by stars is absorbed by dust and re-radiated in IR- this occurs predominately in spirals



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



Reminder of Big Picture

- Disks :

Metal rich stars and ISM

Nearly circular orbits with little (~5%) random motion & spiral patterns

Both thin and thick components

- Bulge :

Wide range of metals poor to super-rich stars (only in nuclear regions)

- $V(rot)/\sigma \sim 1$, so dispersion (random velocity-hot systems) support important.

General Patterns- reminder, please review lectures 1-3

- Relationship of 'class' (e.g. S0,Sa,Sb..) to physical properties -
- Correlations of surface brightness, size, color, star formation etc etc
- 'Later' types, lower mass, more of baryons in gas, higher specific star formation rates (today):
- Sa -> Sb -> Sc -> Sd in order of decreasing bulge size.
- Patterns
  – More luminous galaxies have larger V_{max}

Gas Motions

- If there is a well defined disk, inclined at some angle i to the plane of the sky and rotating perpendicular to this angle (fig 5.18 in text)
- 2 sets of coordinates

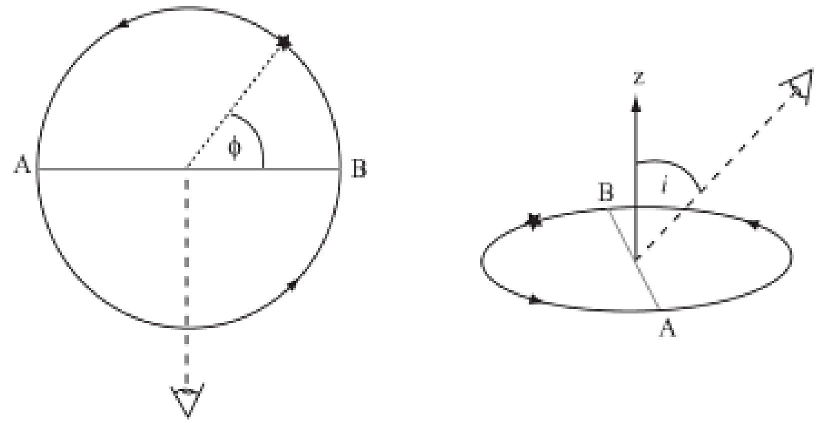
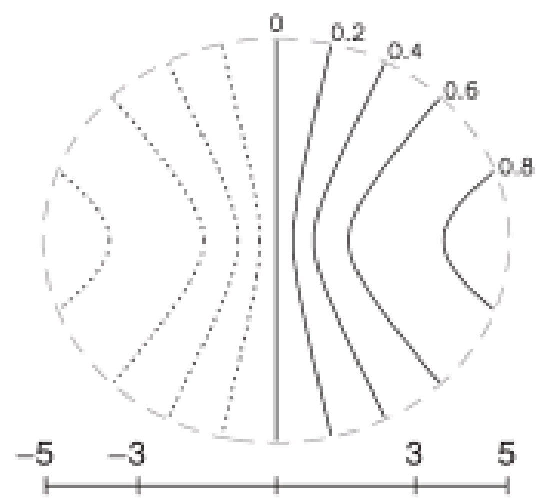


Fig. 5.18. Left, a rotating disk viewed from above. Azimuth ϕ, measured in the disk plane, gives a star's position in its orbit; an observer looks from above the disk, perpendicular to diameter AB. Right, the observer's line of sight makes angle i with the disk's rotation axis z.



contours of constant v_r, velocity pattern disk observed at i=30

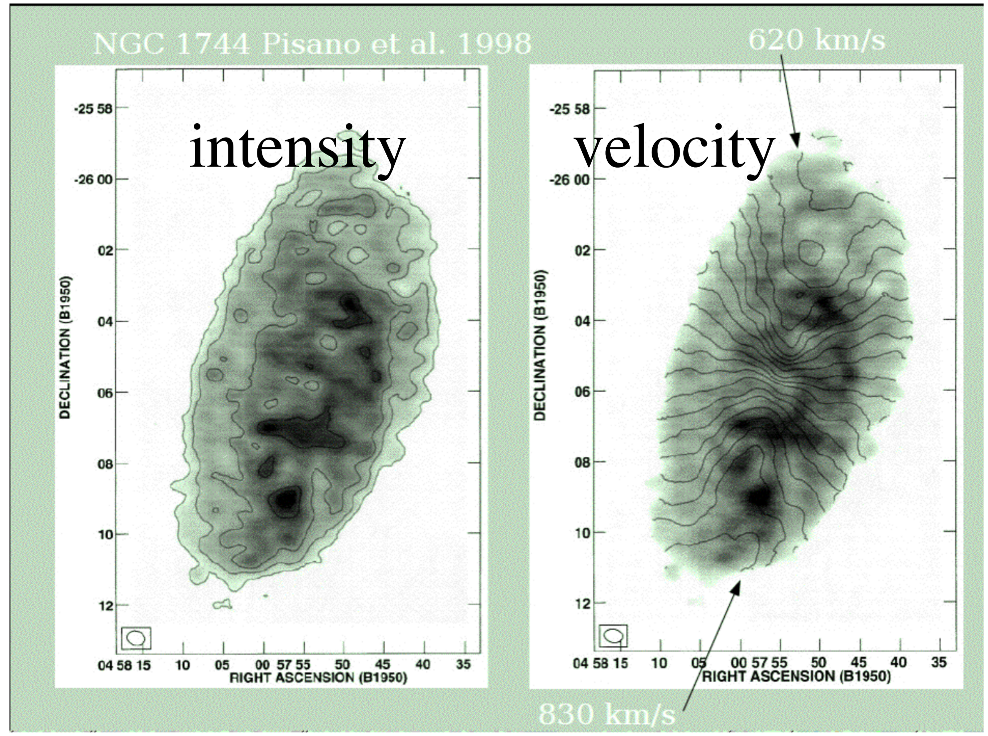
negative velocities ----

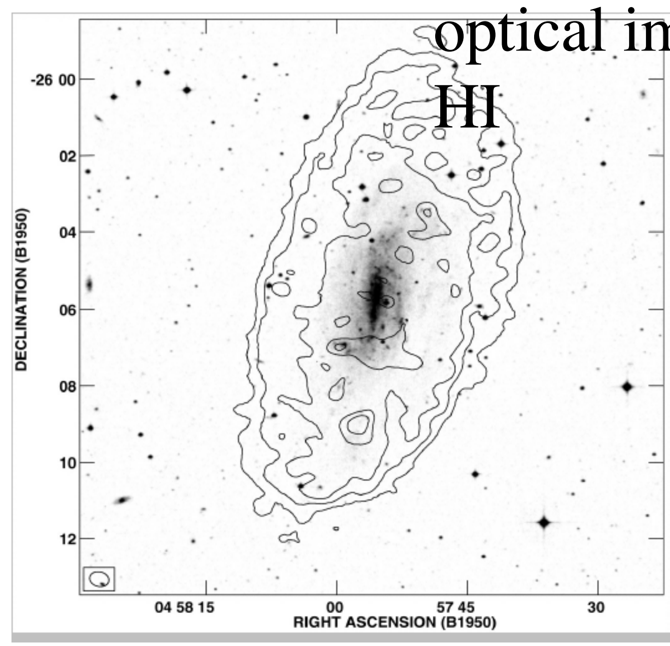
HI

- Spirals have large HI disks

– This gas is optically thin

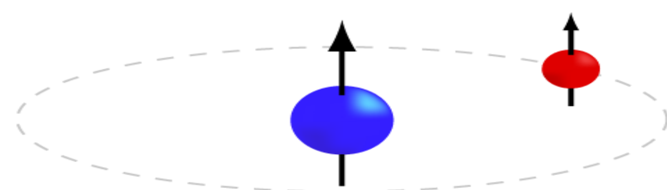
This means that we see all the gas and can measure the amount directly from the line intensity





Physics of 21cm Line

- Hydrogen is the most abundant element in the ISM, but the symmetric H_2 molecule has no dipole moment and hence does not emit a spectral line at radio frequencies. But it is detectable in the 21 cm (λ=1420.405751 MHz) hyperfine line a transition between two energy levels due to the m ized el lative spins cl hoton is emitted. Collisions excite the line.



One λ = 21 cm photon is emitted when the spins flip from parallel to antiparallel.

- The equilibrium temperature of cool interstellar HI

Gas Motions- continued

- Circular disk tilted by an angle i, projects to an ellipse
- What to look for in the 'spider' plot
  - Kinematic major axis - line through nucleus perpendicular to velocity contours- should be aligned to photometric axis if mass is traced by light

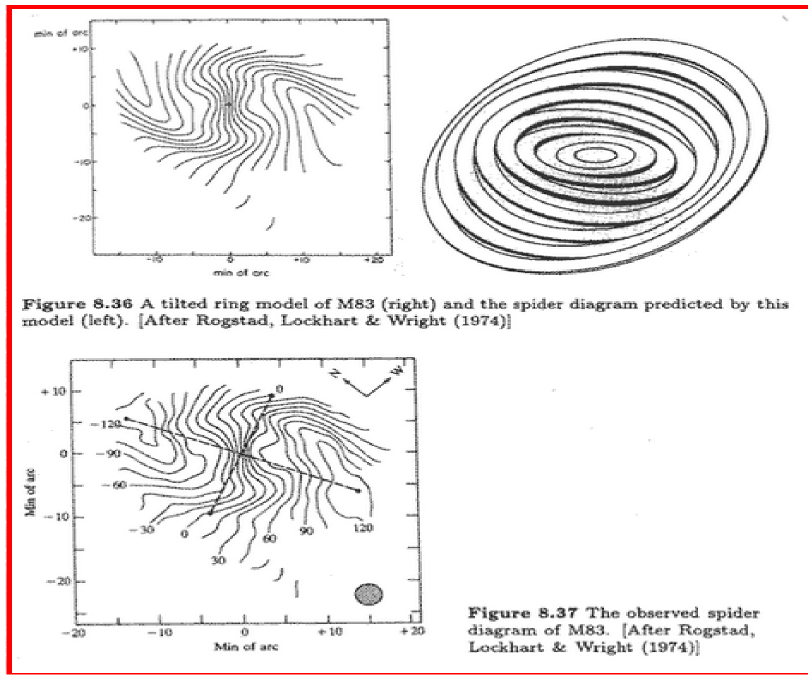
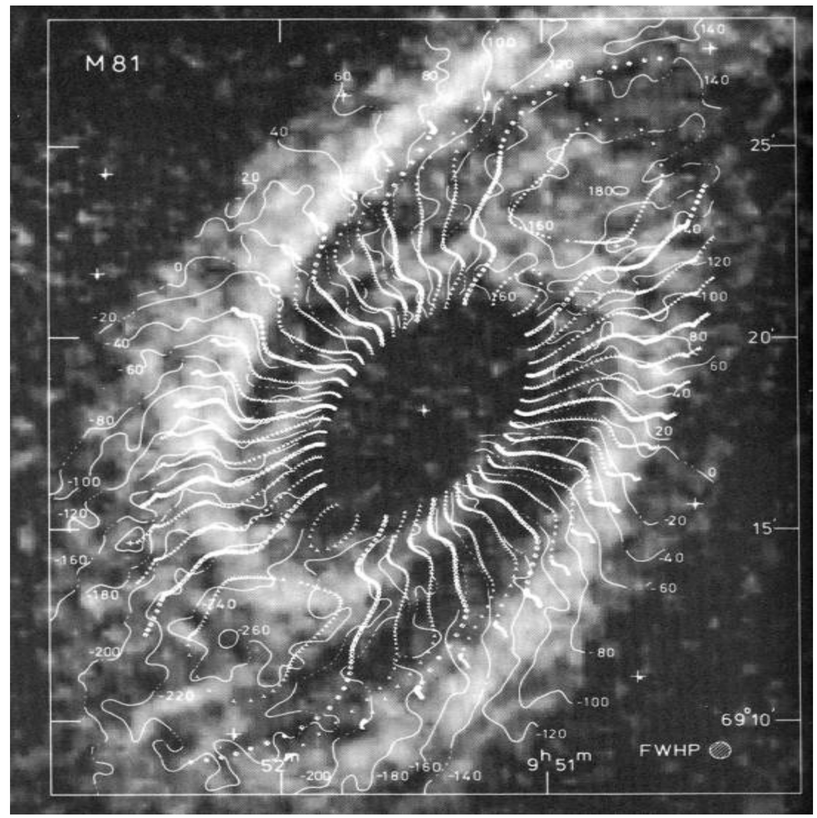


Figure 8.36 A tilted ring model of M83 (right) and the spider diagram predicted by this model (left). [After Rogstad, Lockhart & Wright (1974)]

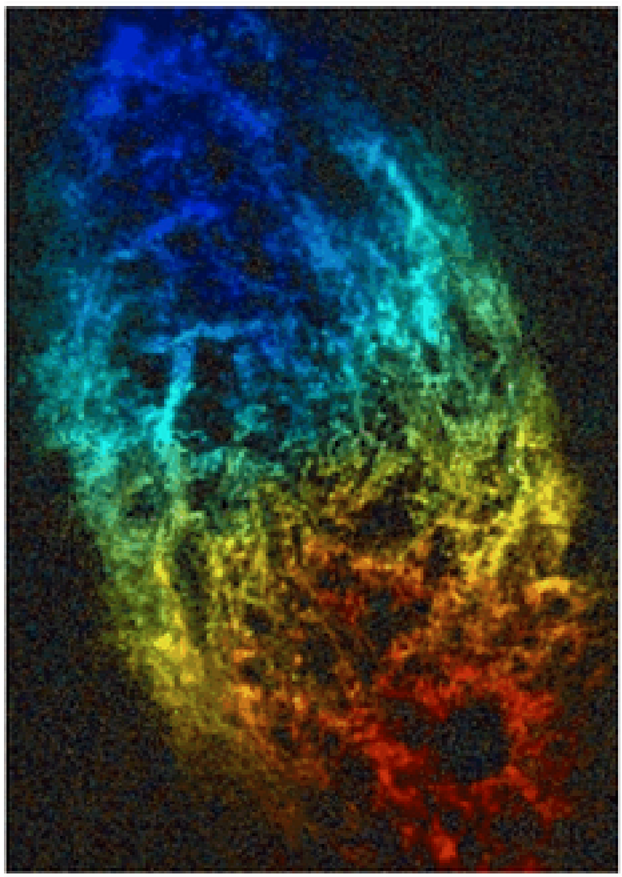
Figure 8.37 The observed spider diagram of M83. [After Rogstad, Lockhart & Wright (1974)]

Gas Motions

- This is what is seen in 'real' galaxies in the motion of HI(fig 5.13 S=G)
- e.g spider diagram is 'A diagram that gives the equations for lines of constant radial velocities as seen for a rotating galaxy inclined to the

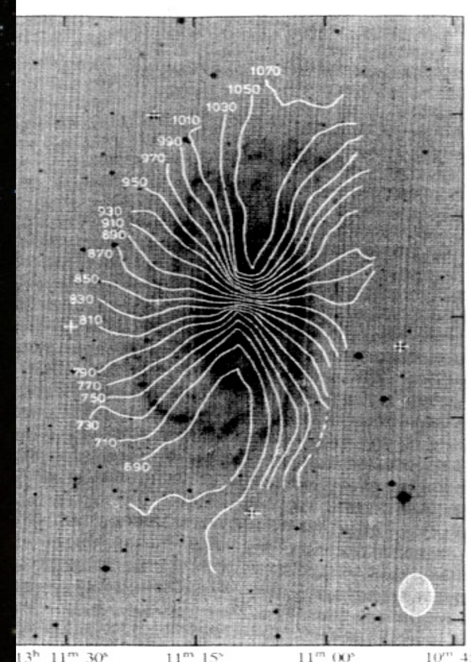


Optical Image and Velocity Field of NGC5033



hydrogen velocity

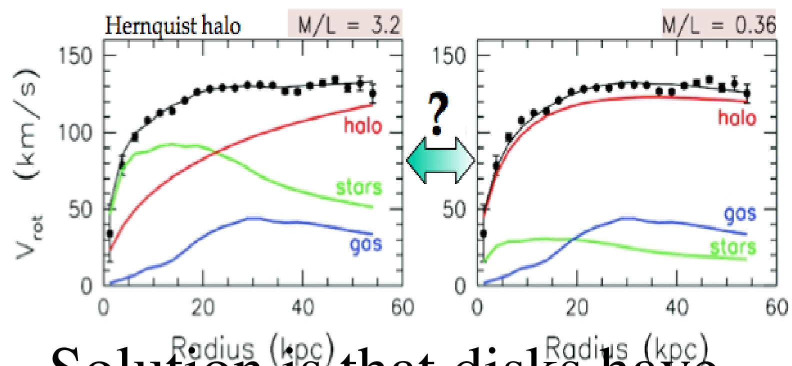
ocity field



Bershady et al

Spirals and Dark Matter

- Rotation-curve decomposition - primary tool for measuring the distribution of dark matter in spiral galaxy halos, **but** uncertainties in the mass-to-light ratio of the luminous disk and bulge make accurate estimates difficult (IMF-mass degeneracy)
- Disk-halo conspiracy- there is no 'feature' in the rotation curve indicating where dark matter starts to dominate- smooth transition!



Solution is that disks have less mass than the maximum allowed by IMF, colors-

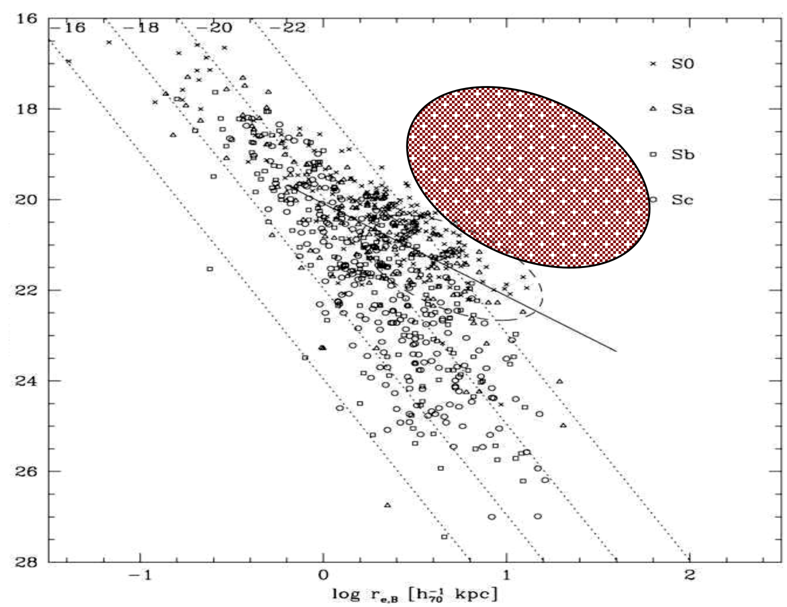
At the radius where the velocity curve flattens ~15-30% of the mass is in baryons

Build your own rotation curve (!)

http://burro.astr.cwru.edu/JavaLab/RotcurveWeb/main.html

Bulge Scaling Relations

- The properties of the bulges of lenticulars follow closely the relations obeyed by Es
- Dwarfs have different bulges (large n values, scale lengths and higher surface brightness)
- The more luminous bulges of all Hubble



Spiral Arms in Spirals (sec 11.6 in MBW- sec 5.5.2 in S+G)

- Defining feature of spiral galaxies - what causes them?

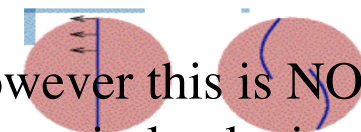
- Observational clues

Seen in disks that contain gas, but not in gas poor S0 galaxy disks.

- Defined by blue light from hot massive stars. Lifetime is << galactic rotation period.

When the sense of the galactic rotation is known, the spiral arms almost always trail the rotation.

- First ingredient for producing spiral arms is differential rotation.



Tips of spiral arms point away from direction of rotation.

(From P. Armitage)

However this is NOT SOLELY why spiral galaxies have spiral arms- they would wrap up into a tight spiral in time scale $\Delta R/R=2\pi R/vt$

putting in values near the sun $\Delta R/R=0.25\ (t/\mathrm{Gyr})^{-1}$

e.g. The Winding Problem

If arms were "fixed" w.r.t. the disk
With flat rotation (V ~ const), **inner parts rotate many times compared to outer parts**
E.g. for one rotation at R, two rotations at R/2, four at R/4, 8 at R/8.
This leads to very tightly wound arms.

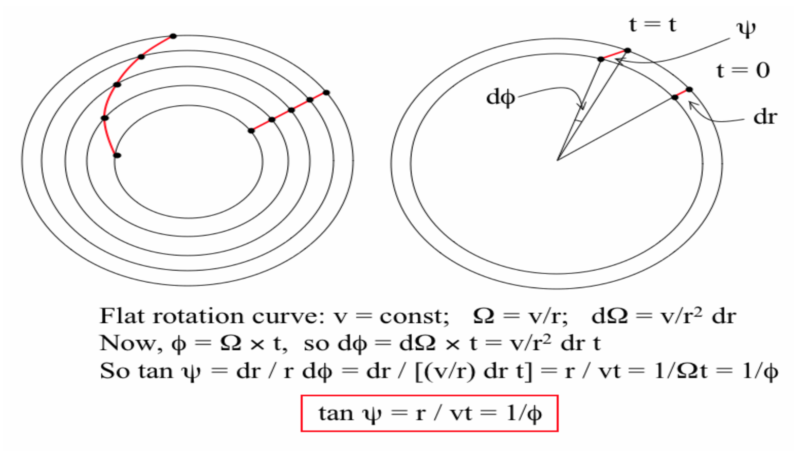
Winding?

- Angular frequency $\omega=V_c/R$- spirals have flat rotation curve $V_c=$ constant

$d\omega/dr=v/r^2$ angle $\phi=\omega t$
$d\phi=td\omega=v/r^2\ tdr$

so $\tan\psi=dr/r\ d\phi=r/vt=1/\phi$

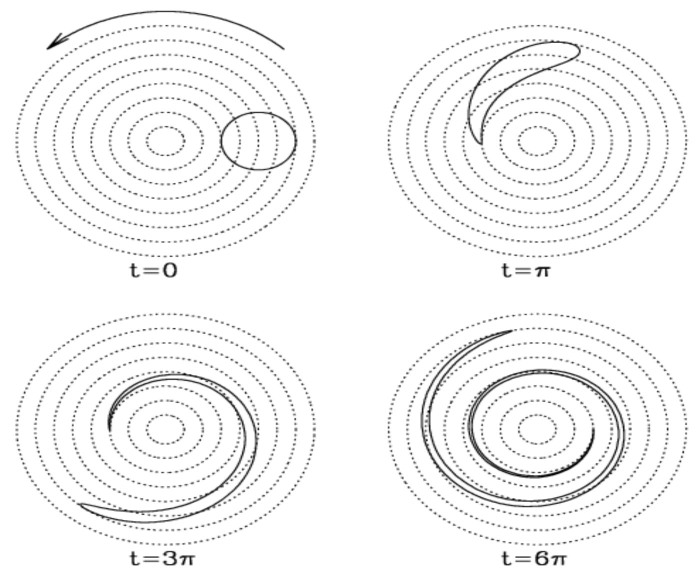
pitch angle,ψ , steadily decreases as the pattern rotates- after 1 rotation $\tan\psi=1/2\pi$



M. Whittle's web site

Spiral Arms

- 'Visually' spiral arms are associated with star formation/molecular gas.
- How to describe: if the arms are 'sinusoidal' $\Sigma(R,\phi)=\Sigma_0(R)+\Sigma_1(R)\cos[m\phi+f(r)]$
- f(r) shape function of the spiral- if spiral is



MBW, fig 11.3)

Spiral Density Waves- One Possible Answer

- Properties of spiral arms can be explained if they are continuously generated and destroyed

- density waves provide the perturbation which gets sheared :

Spiral arms are where the stellar orbits are such that stars are more densely packed-waves of compression that move around the galaxy

Gas is also compressed, triggering star formation and young stars

• In isolated disk, creation of a density wave requires an instability. Self-gravity of the stars and / or the gas can provide this.

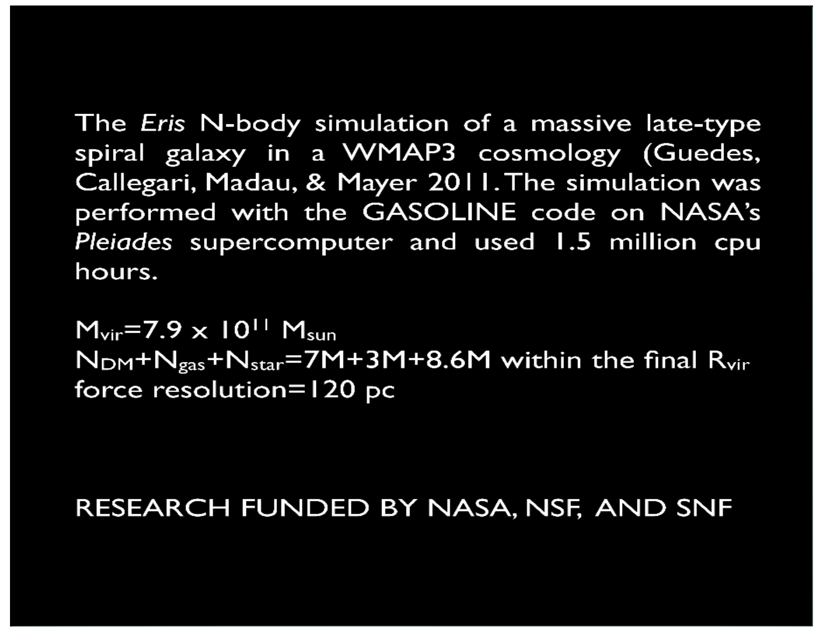
Simplest case to consider is gas. Imagine a small perturbation which slightly compresses part of the disk:

• Self-gravity of the compressed clump will tend to compress it further.

• Extra pressure will resist compression. If the disk is massive (strong self-gravity) and cold (less pressure support) first effect wins and develop spiral wave pattern.

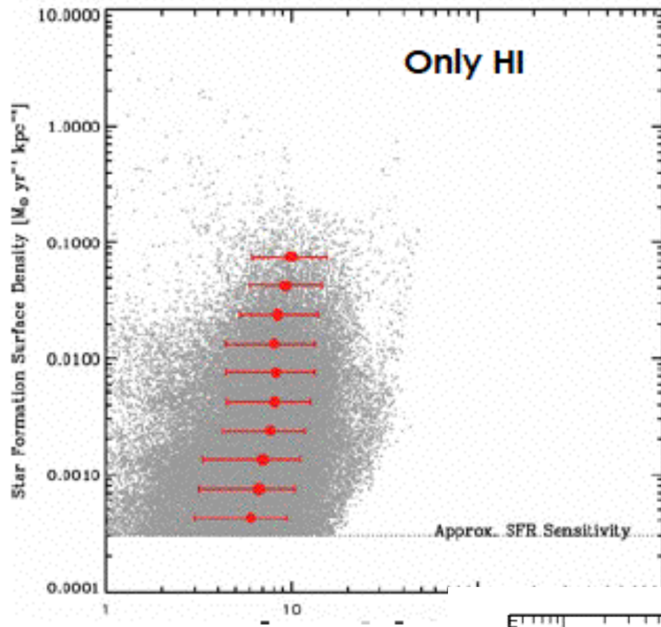
Spiral Arm Formation

- Its actually best to say that the fundamental cause of spiral arm formation is not well understood.
- In this movie spiral arms are formed due to a merger (http://www.nature.com/news/galaxy-formation-the-new-

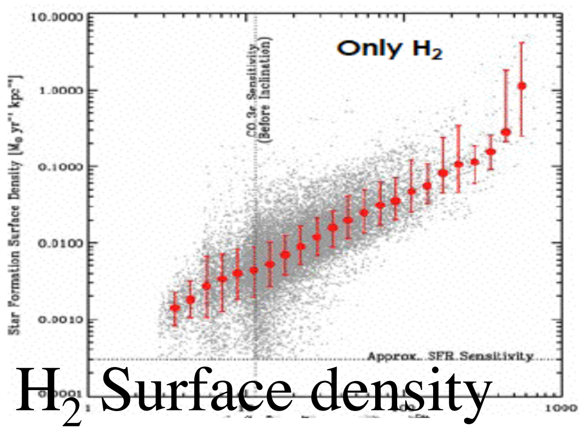


Only H_2 Counts

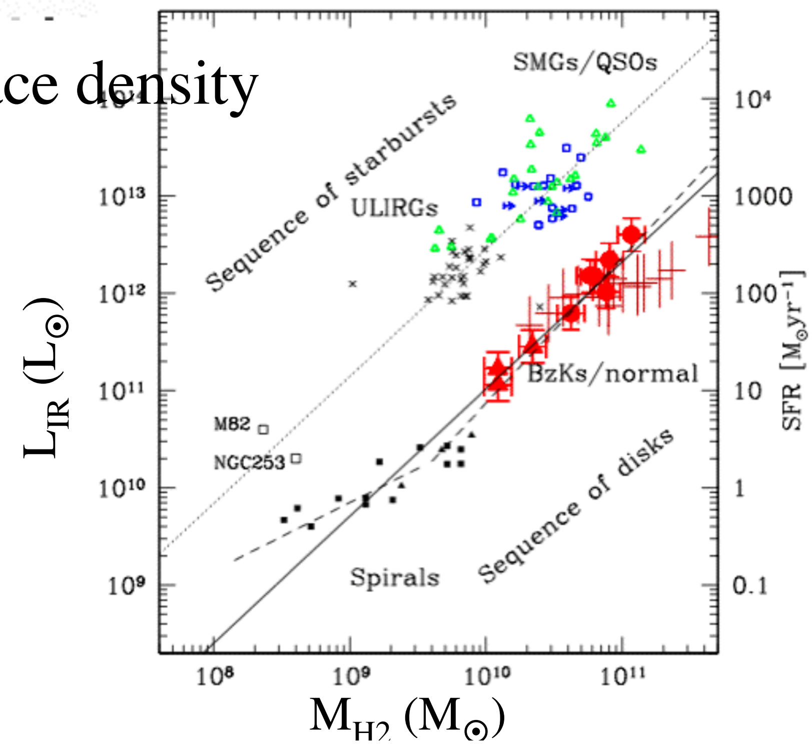
Bigiel et al. 2008/10, Leroy et al. 2008/11



HI Surface density



H_2 Surface density



- In the low redshift universe there are very few, very high SFR objects- these are much more important in the high z universe
- It appears that the relations for