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 clouds) will merge in ~6 gyr
- A supermassive black hole exists in the centers of 'all' massive galaxies- properties of BH are related to the bulge and not the disk of the galaxy
- Use 'timing argument' to estimate the mass of the local group (idea is that this is the first time MW and M31 are approaching each other and the orbit is radial) use 'simple' mechanics to get mass
- Local group is part of a larger set of structures- the 'cosmic web' galaxies do not exist in isolation

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

Bulges:

- somewhat spheroidal featureless (no spiral arms,bars, rings etc) that stick out of the disk plane,
- mostly old stars (not much dust or star-forming regions),
- kinematically hot, i.e. dynamically supported by the velocity dispersion of their stars- but they do rotate more significantly than ellipticals

Origin

- thought to form via mergers (i.e. accretion of usually smaller external units)- disks reform later after merger by accretion of gas.

Halo

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

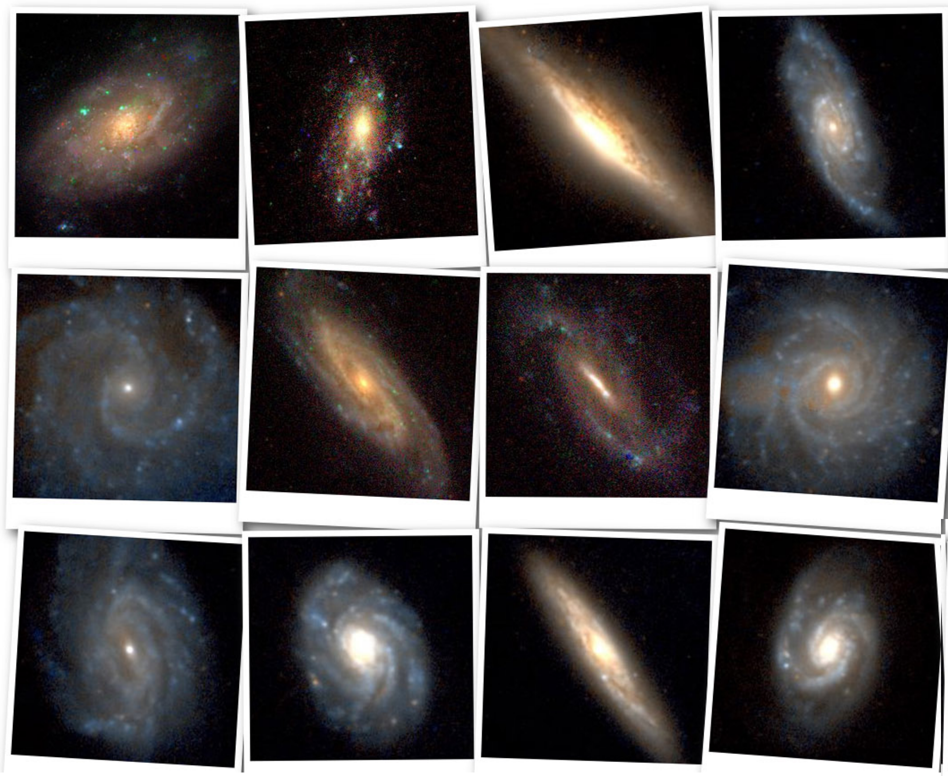
TABLE 23.1 Overall Properties of the Galactic Disk, Halo, and Bulge

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

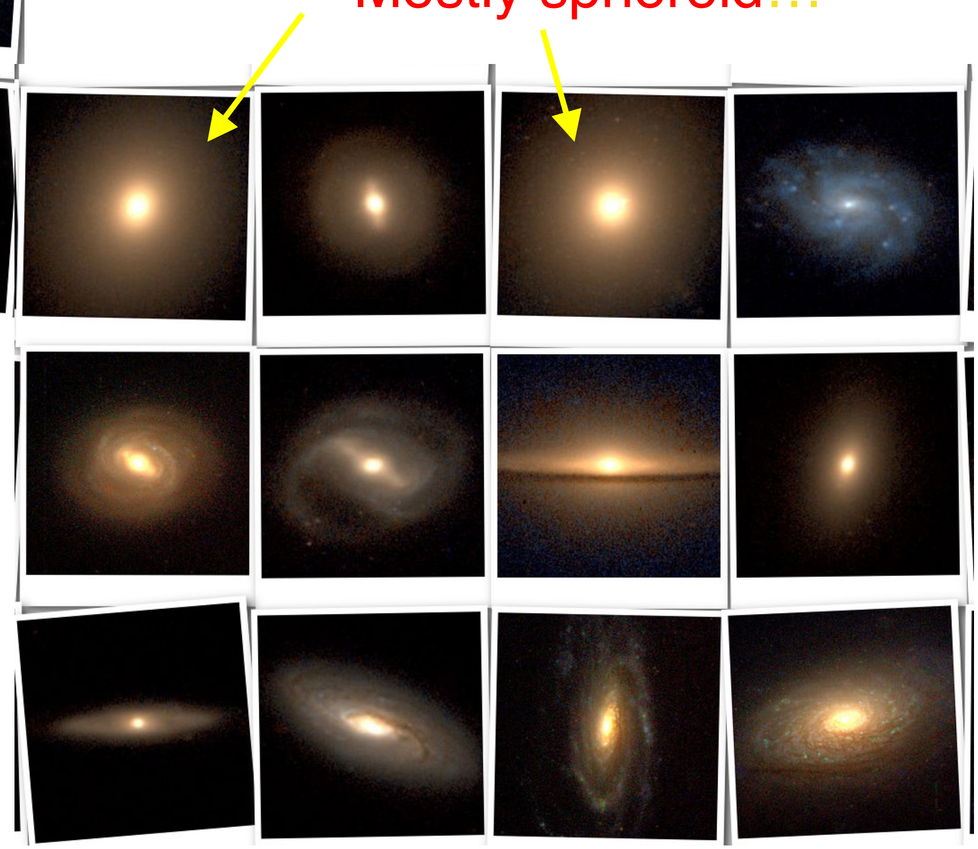
From Chaisson

A Bit of the Galaxy Zoo

Mostly disk…



Mostly spheroid…



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

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 than long ones.
- No complex integrals will be required.
- Stress on concepts...

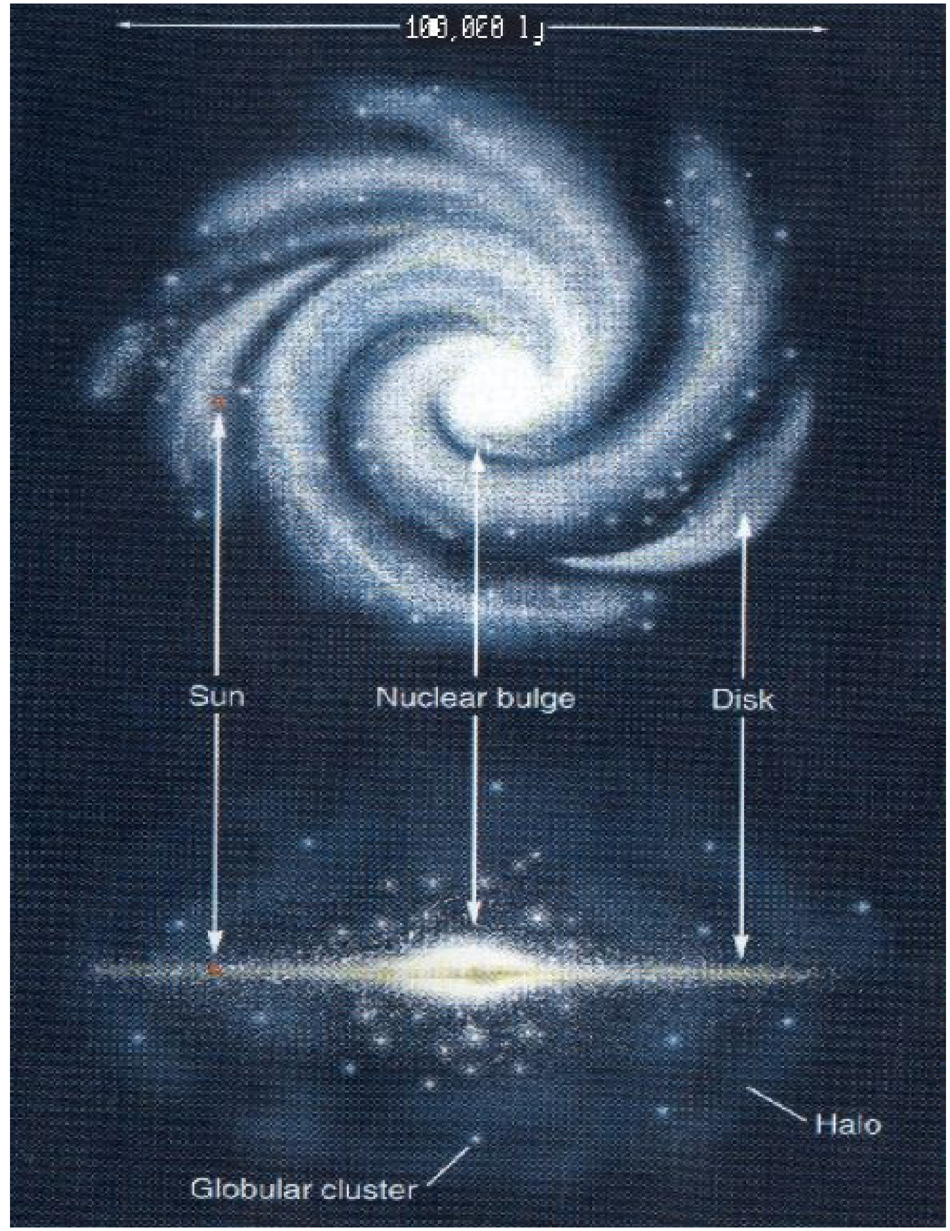
Spirals

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

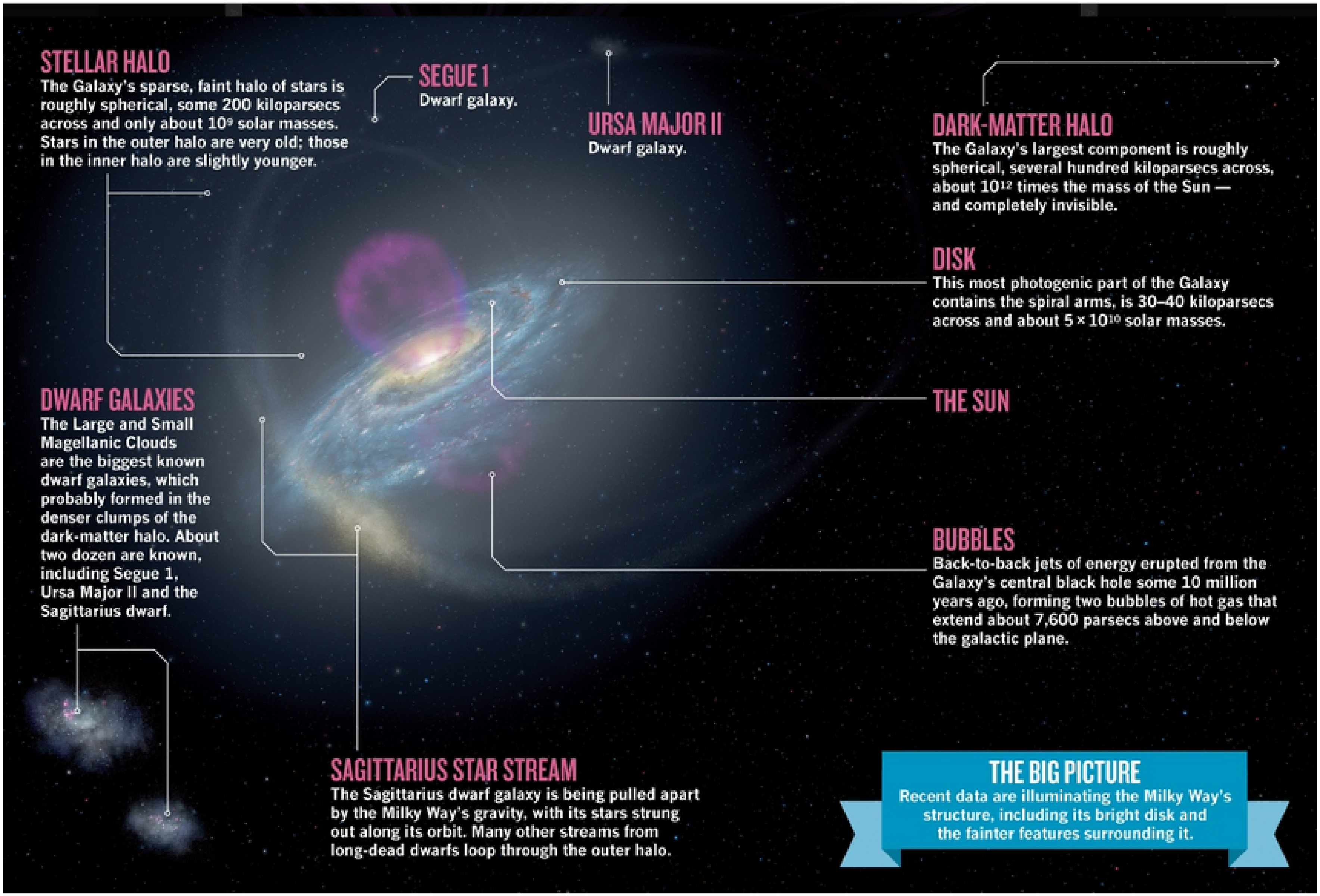
  The disk contains a large quantity of gas & dust, the bulge essential none

  Disks are cold (rotationally supported)

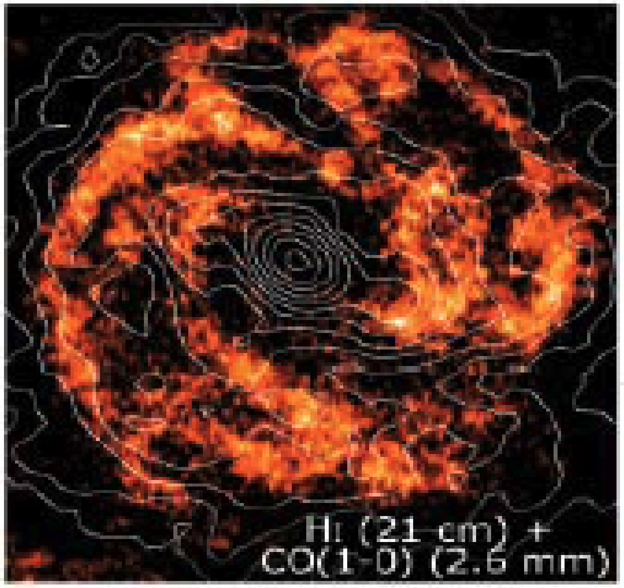
  Bulges are 'hot' supported by random motions
- The rotation curves of spiral galaxies rise like a solid body in the central regions, then flattens out (i.e., v(r) = constant). This flattening is due to the presence of a **dark matter halo**.



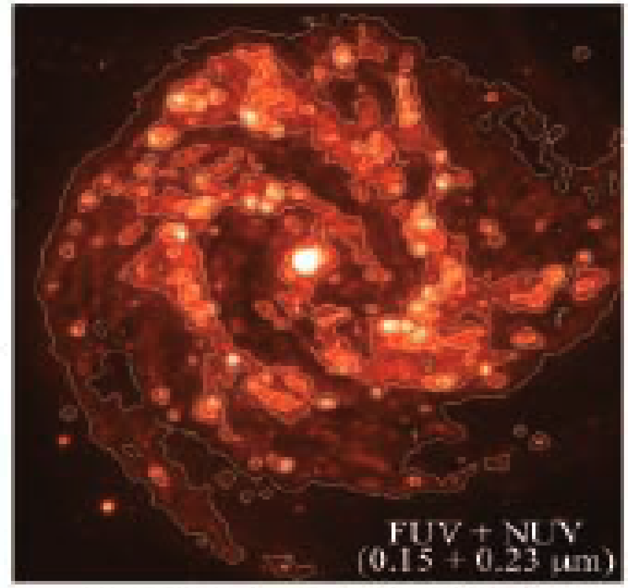
- there is a major review article in Nature last week called" Galaxy formation: The new Milky Way" (http://www.nature.com/news/galaxy-formation-the-new-milky-way-1.11517). This overlaps considerably with the material we have been covering!



M 83: from Gas to Stars

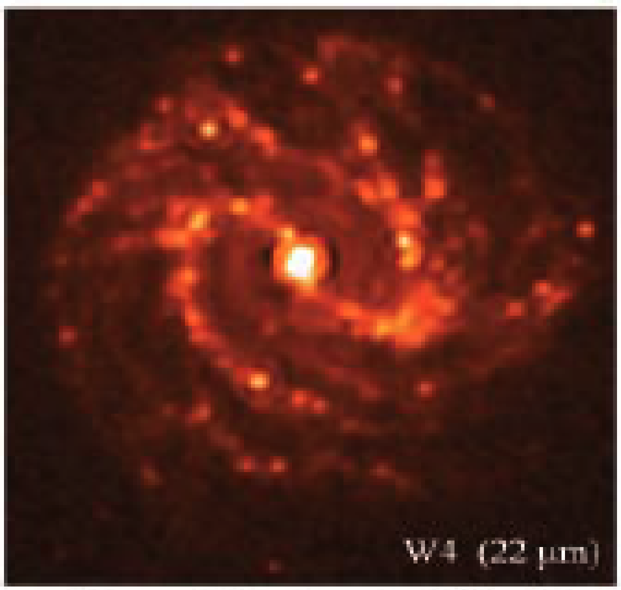


Neutral gas is the *reservoir*, molecular gas fuels the star formation



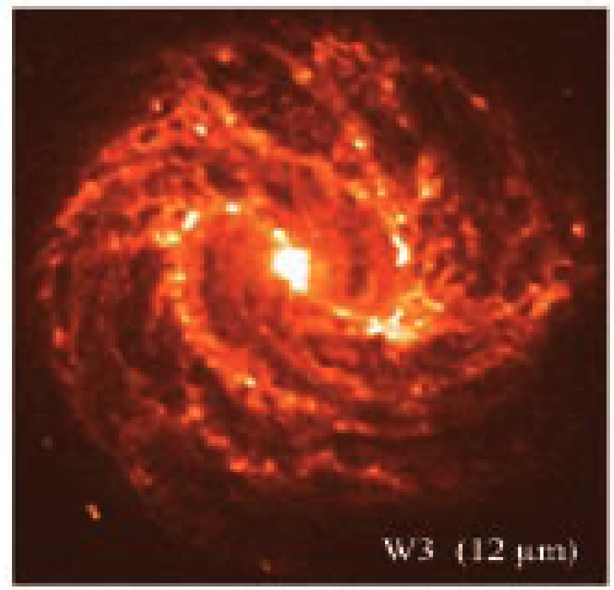
Young hot stars represent the current epoch of star formation

Evolved star population constitutes the *Stellar Backbone*



Very small dust grains efficiently reprocess energy from star formation

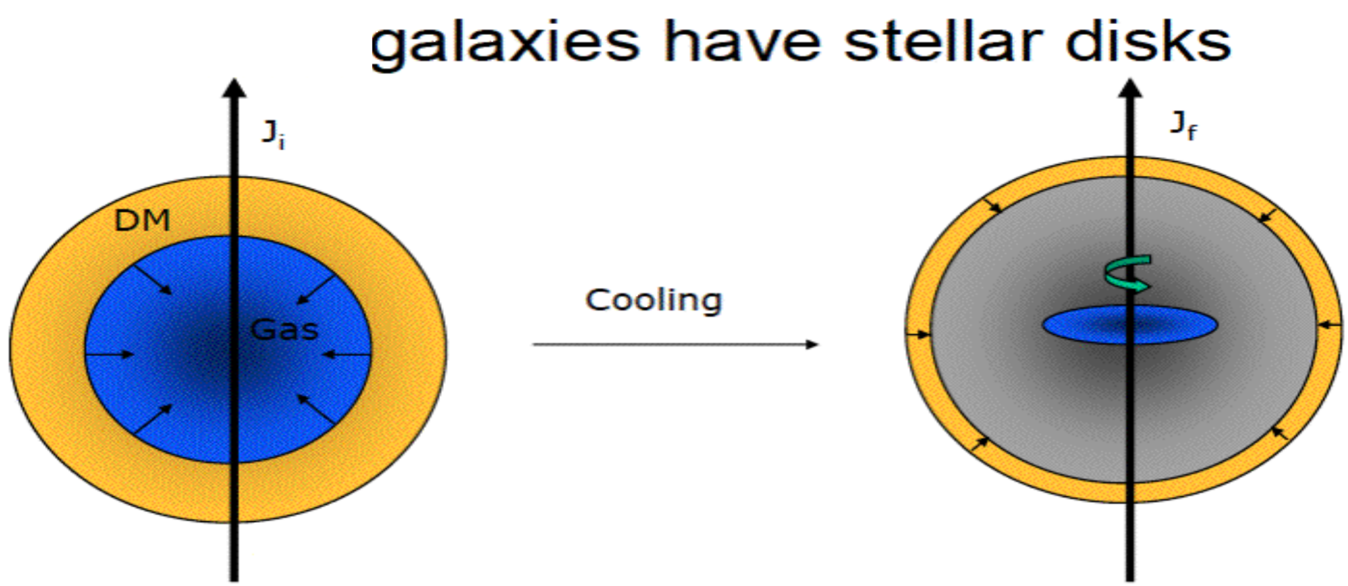
Spiral galaxies are panchromatic objects different physical process are best shown in different wavebands



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
- If stars form from dense gas they will also be in a disk.



However In A Hierarchical Universe Things are More Complex

The Big Picture- Two Populations

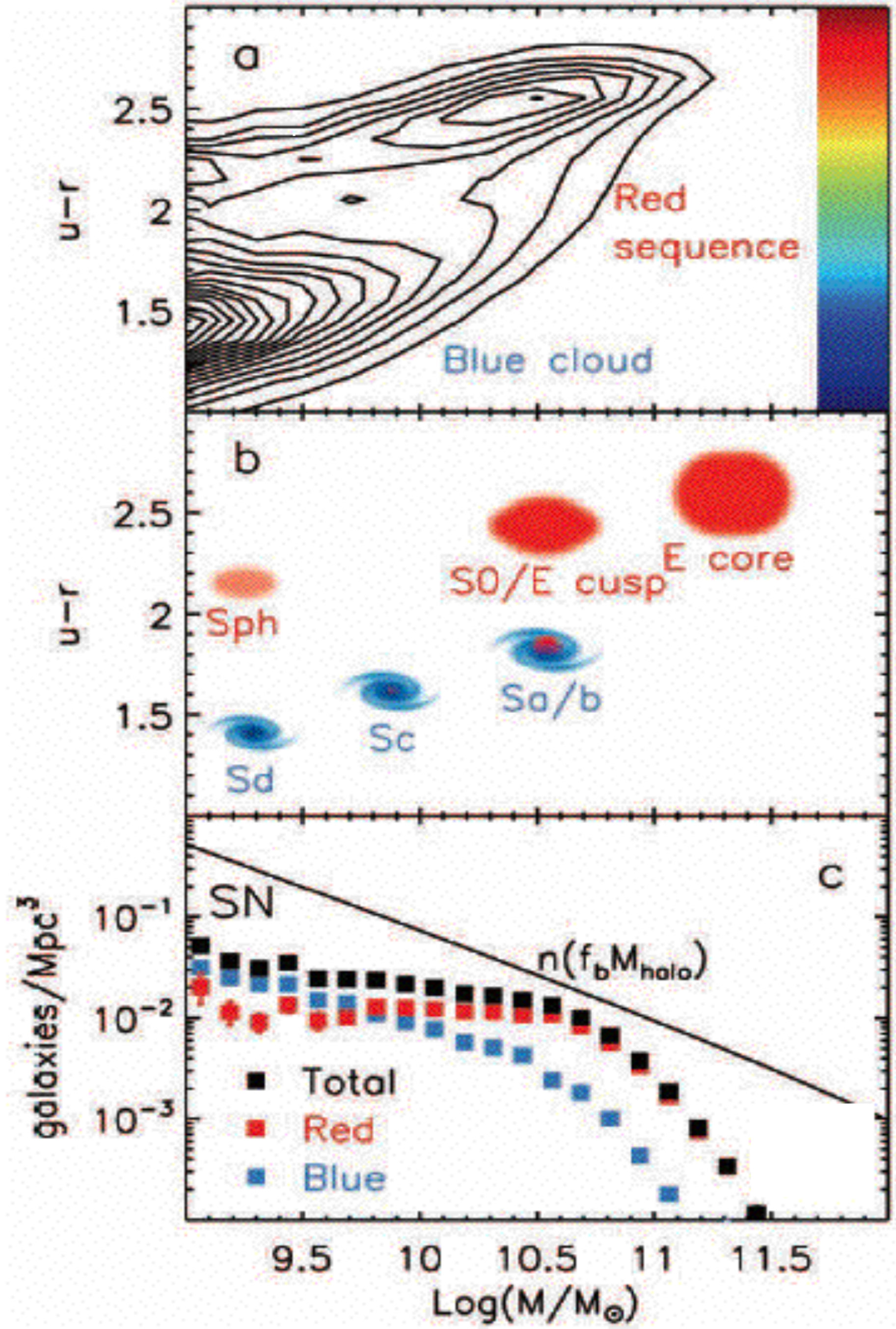
- top panel color distribution vs mass of a large sample of local galaxies from the SDSS

  Middle panel is the morphologies that dominate at each mass

  bottom panel shows the galaxy **mass function** divided by color- the **spirals are mostly blue** (some S0s are red) (Cattaneo et al 2009)-

  spirals tend to be less massive than ellipticals

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



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

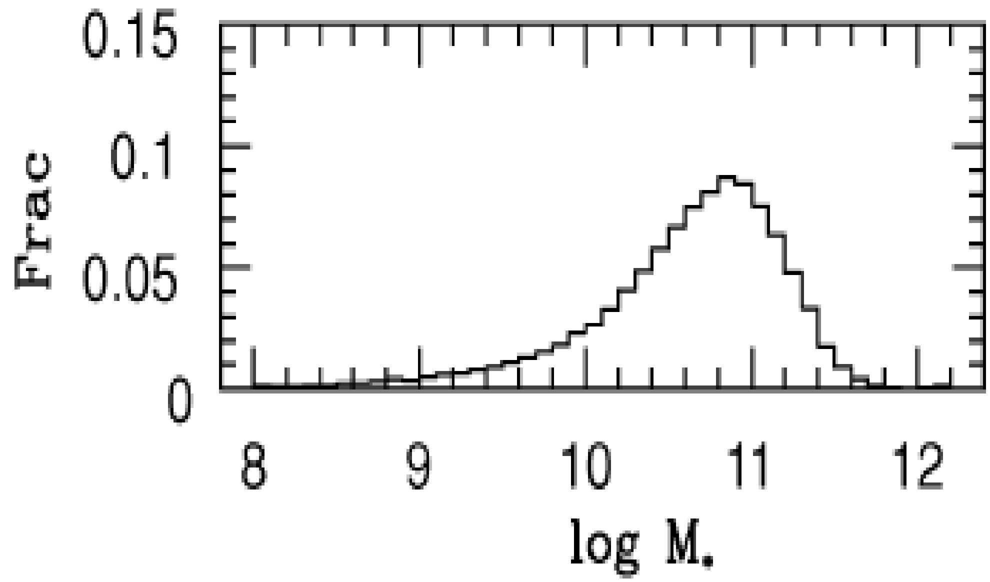
- Galaxies have a wide variety of morphologies, from spheroids , disks with and without bars and irregular galaxies.
- Their physical properties (e.g. gas content, average stellar age, the rate of current star formation, mass etc) correlate with morphology.
- disks are predominantly rotationally flattened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

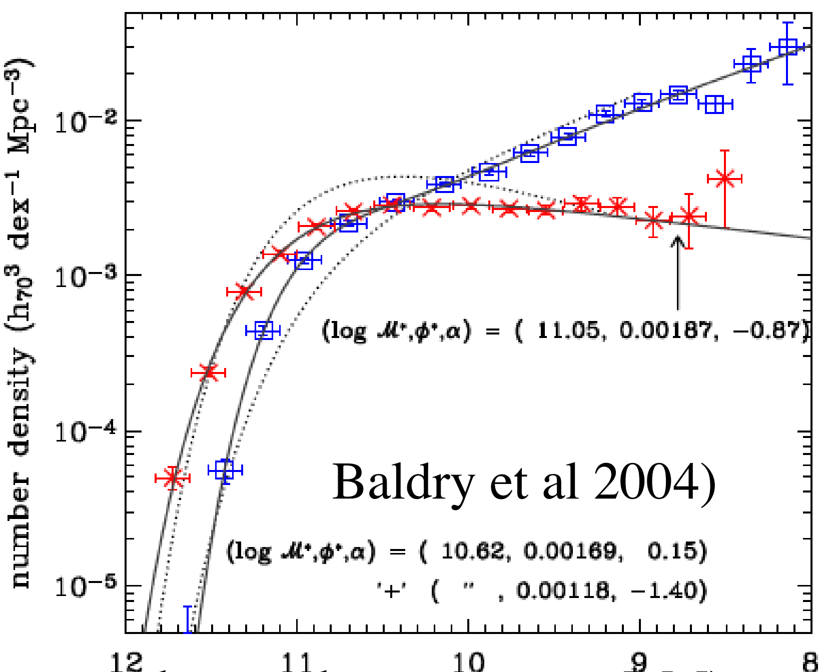
- Conventional theoretical 'wisdom' : disks form at the center of dark matter halos as a consequence of angular momentum conservation during the dissipational collapse of gas (Fall & Efstathiou 1980) , spheroids result predominantly from merger events
- Thus morphology is a transient feature of the hierarchical formation of a galaxy:
  - a disk galaxy may be transformed into a spheroidal one after a major merger, but could then re-form a disk through further gas accretion only to be later disrupted again by another merger
- this scenrario is now being challenged by the new generation of detailed numerical simulations (Sales et al 2012).

Where is the Stellar Mass

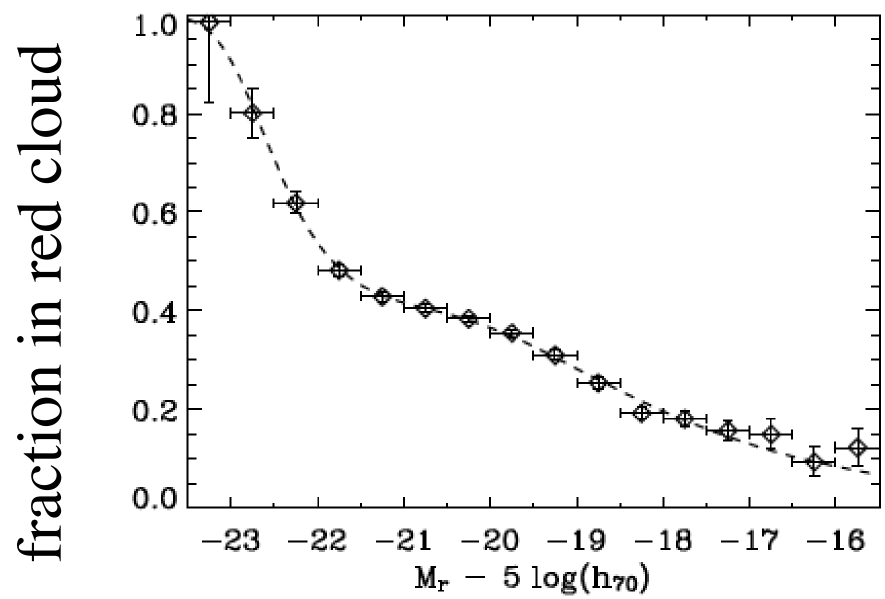
- The stellar mass **integrated over ALL galaxies** lies mostly between

  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



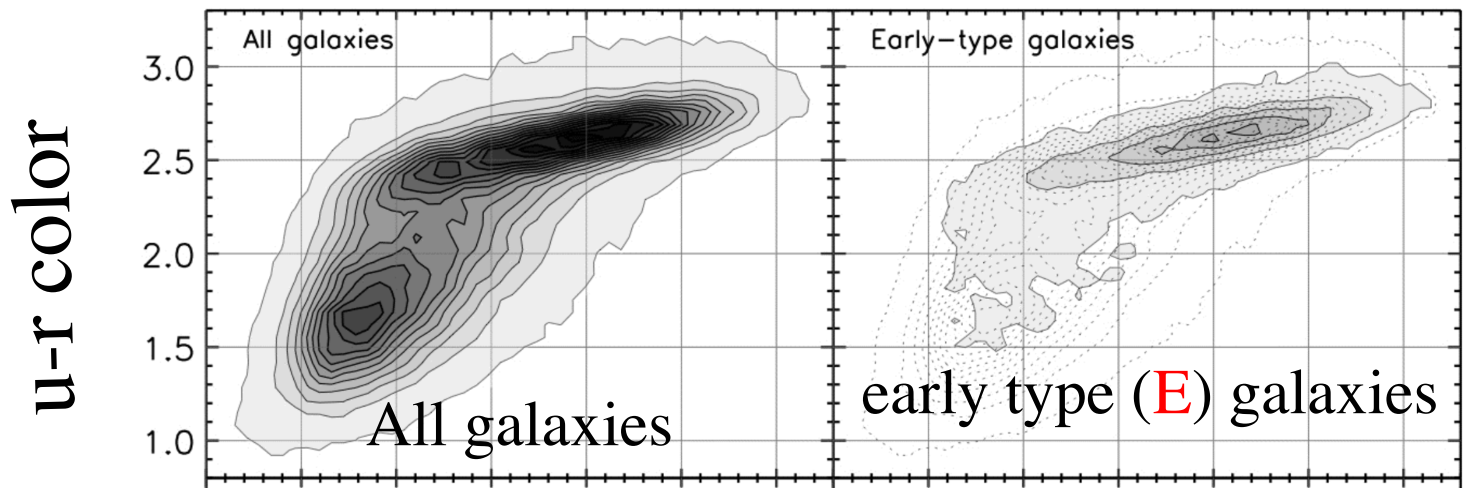


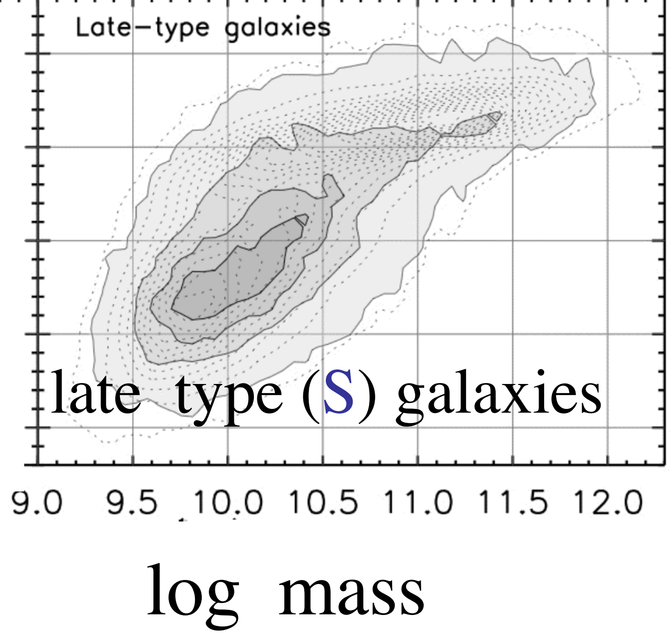
log total mass (stars =DM)



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 morphology, mass and color

Spirals less massive, bluer at a given mass than ellipticals

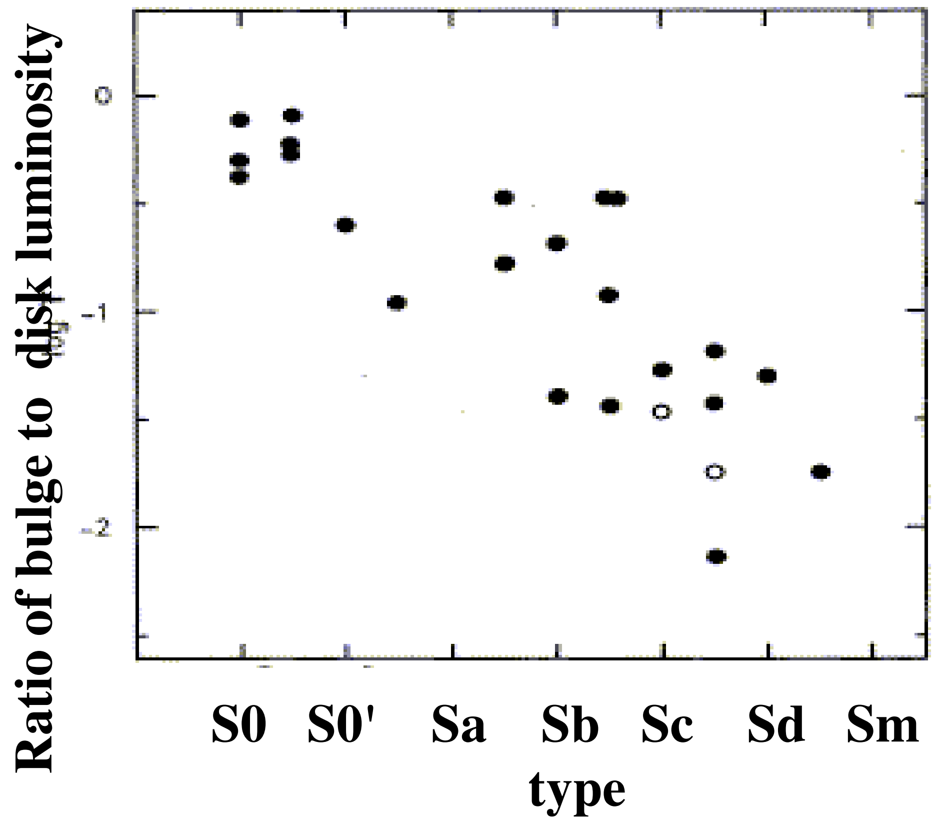
- **Strong relation of mass, color and morphology**

Schawinski 2010

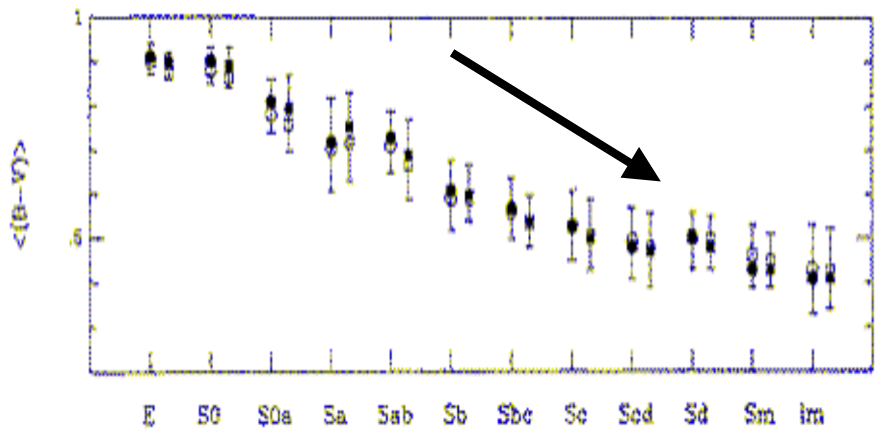
Spirals

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)
- 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)*



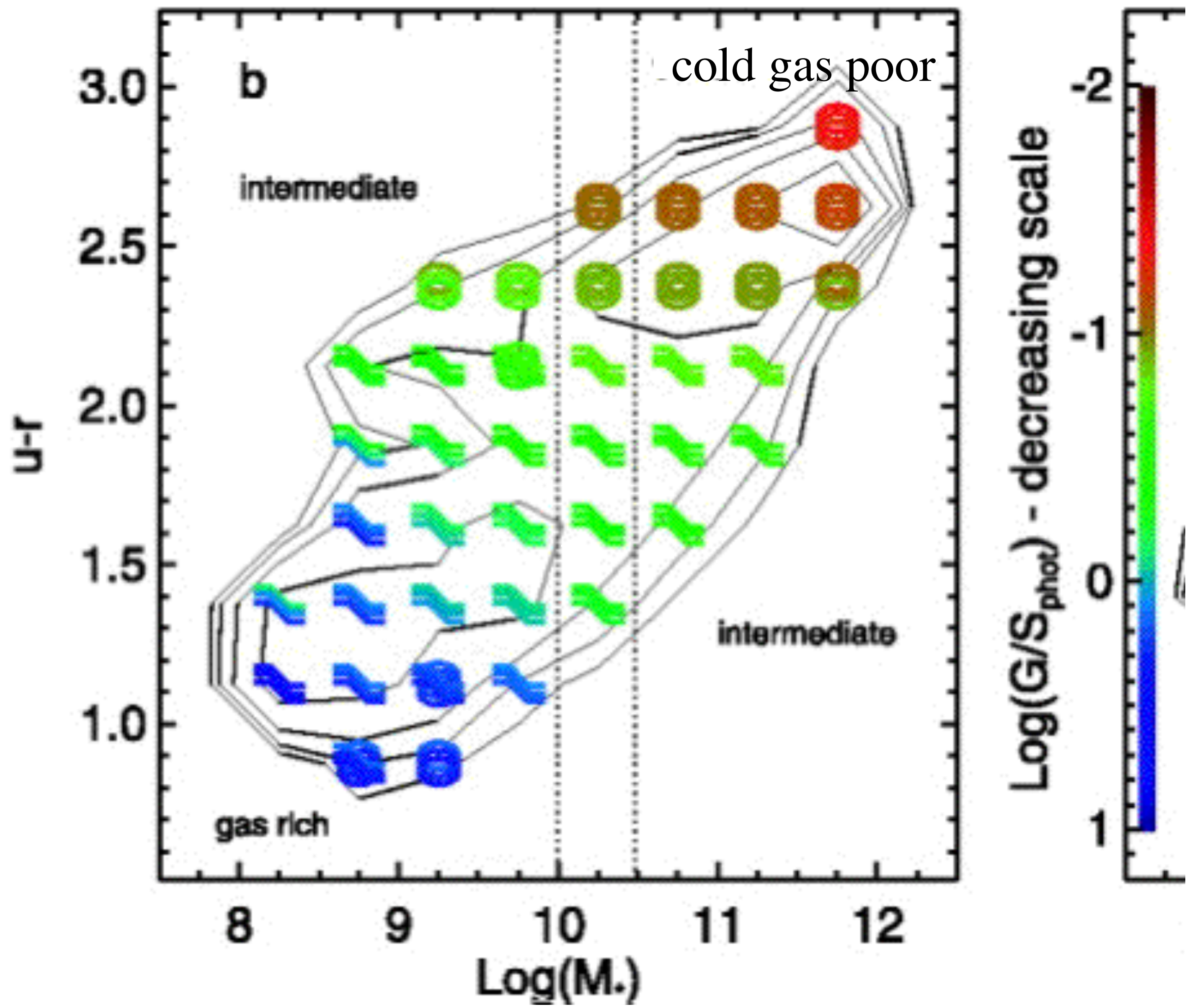
color vs morphological type



Spirals and Gas

- The ISM of spiral galaxies is quite complex and show wide variations with position
- However there are certain trends - the lower the mass and the 'bluer' the galaxy the higher is the baryonic fraction in cool/cold gas.- there seems to be a characteristic stellar mass $\sim 3 \times 10^{10}$M where things change.
- Luminous red galaxies have hot ISMs

Gas to light ratio in log scale



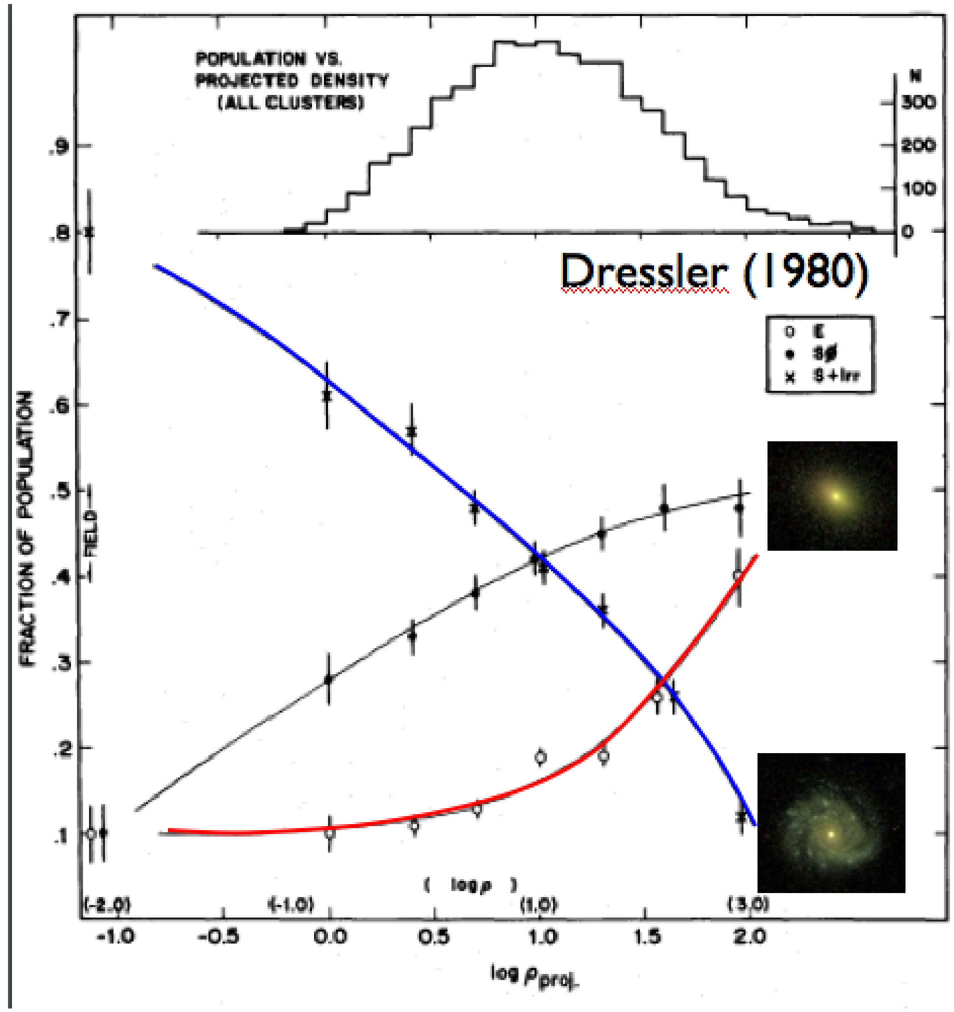
Spirals- More Trends with Morphology (Sd $\Rightarrow$ Sa)

- 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
- The question is what are the primary eigenvectors of the correlations... it seems to be mass

The stress on 'B' band comes from history- before CCDs photographic plates were used and they were most sensitive in the 'B' band.

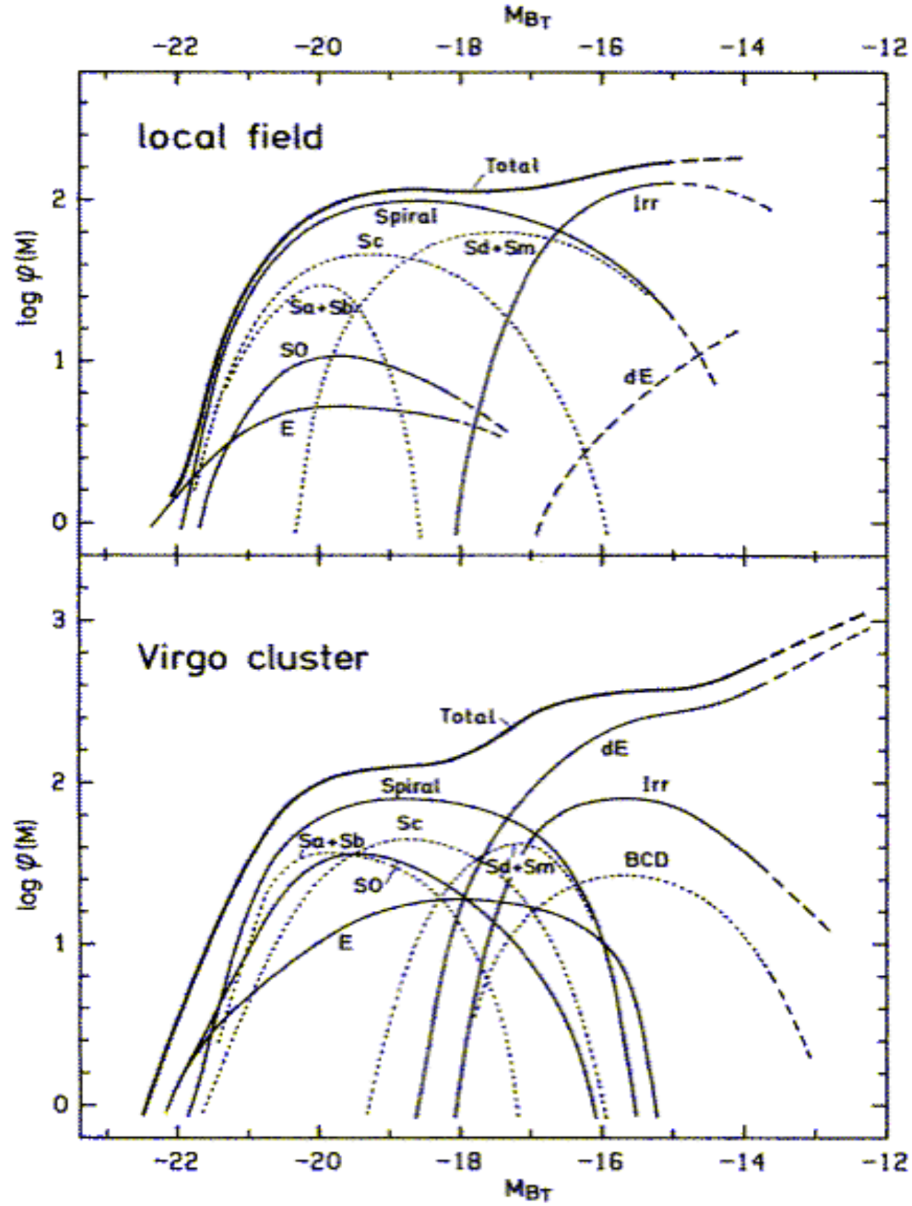
"Where" Do Galaxies of a Given Type Reside

- 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 have almost no spirals
- **Thus the morphology of galaxies 'knows' about the environment- not clear if this is nature (formed that way) or nuture (spirals converted into S0's)**



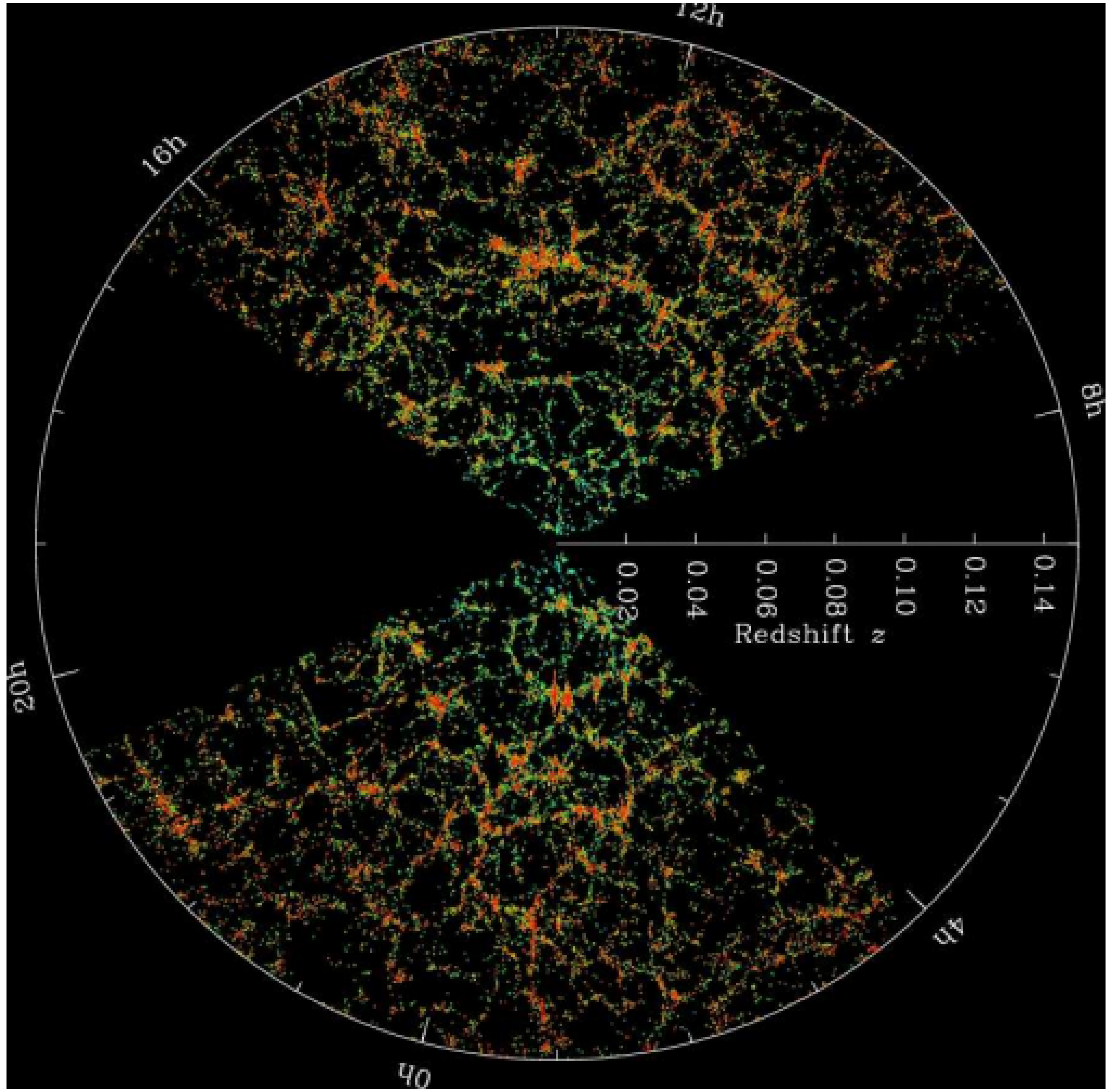
How Many of Which??

- 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



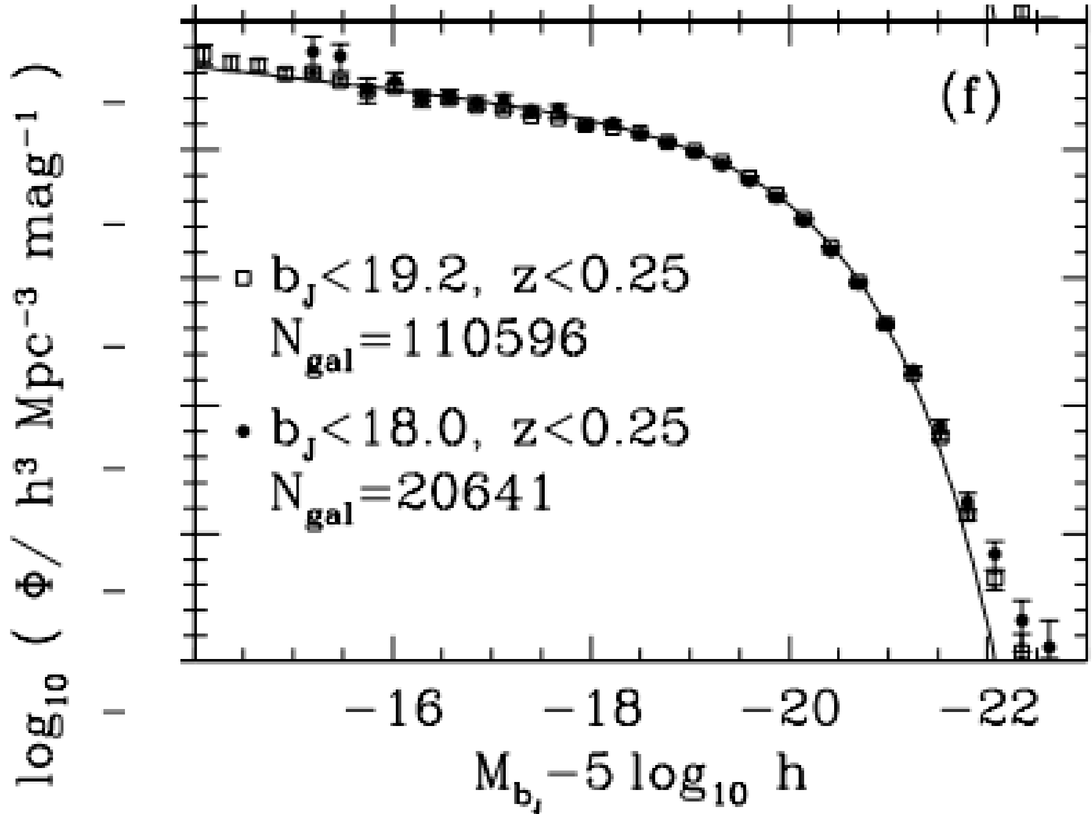
Binggeli, Sandage, and Tammann 1988

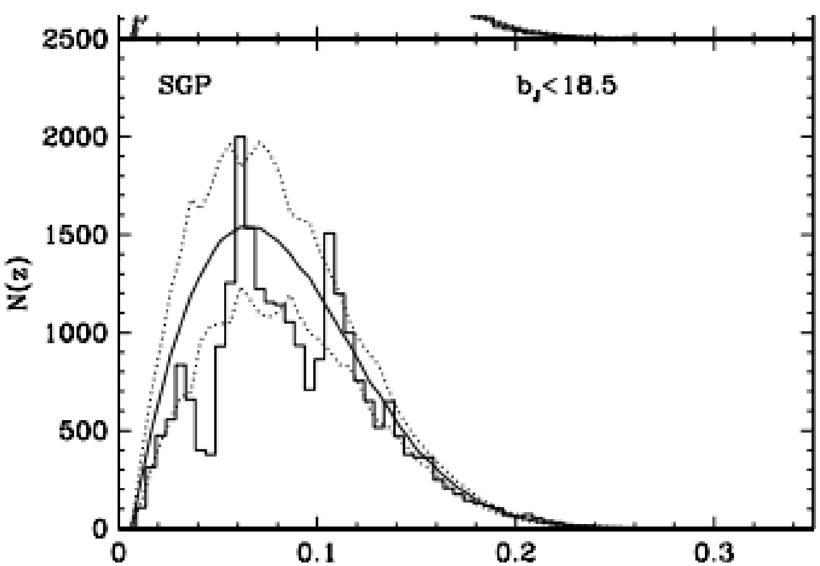
- Distribution of red and blue galaxies out to z-0.15 from the SDSS (M. Blanton)
- Notice that red galaxies are highly concentrated in dense regions while blue galaxies are in the filaments



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



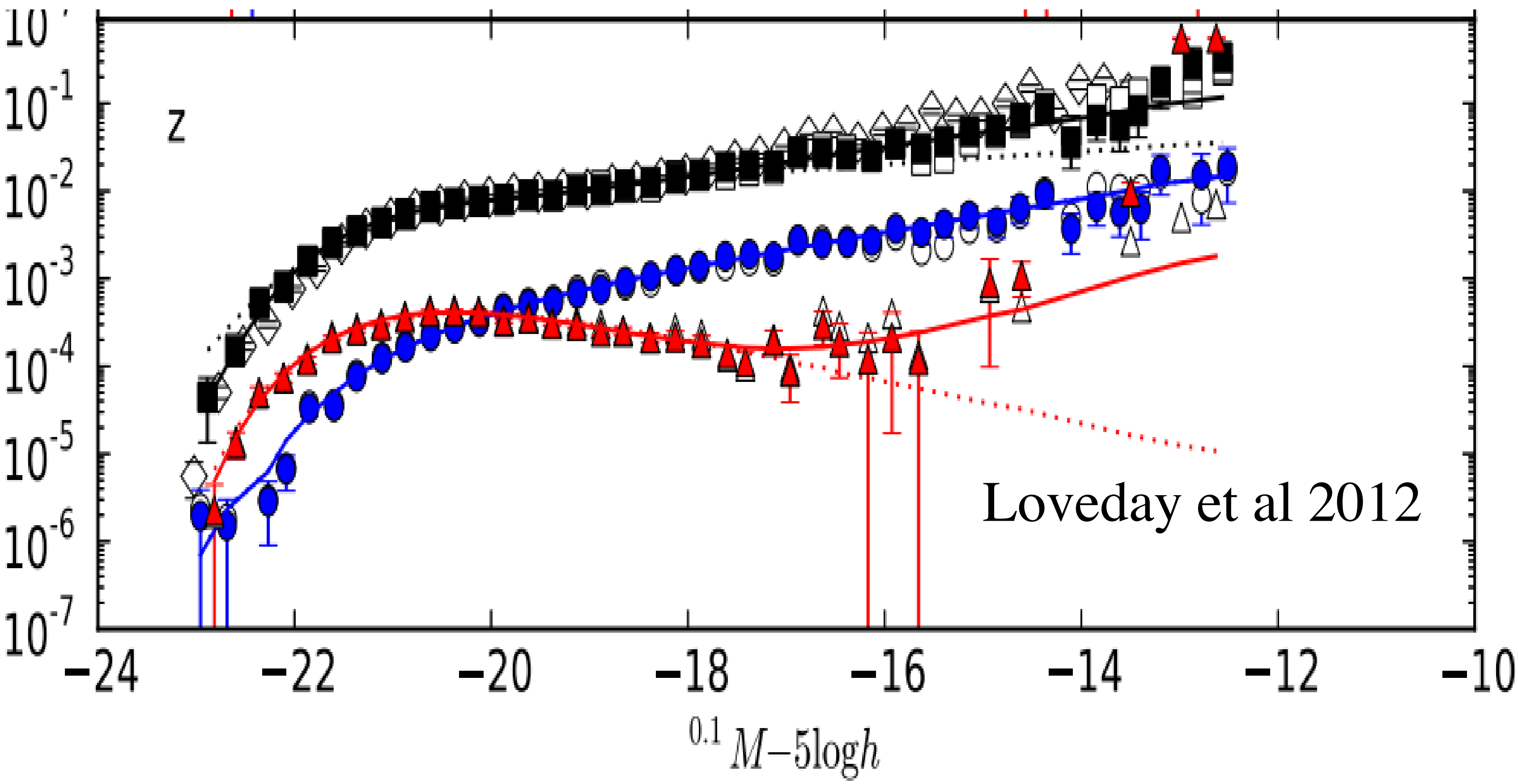


Redshift

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

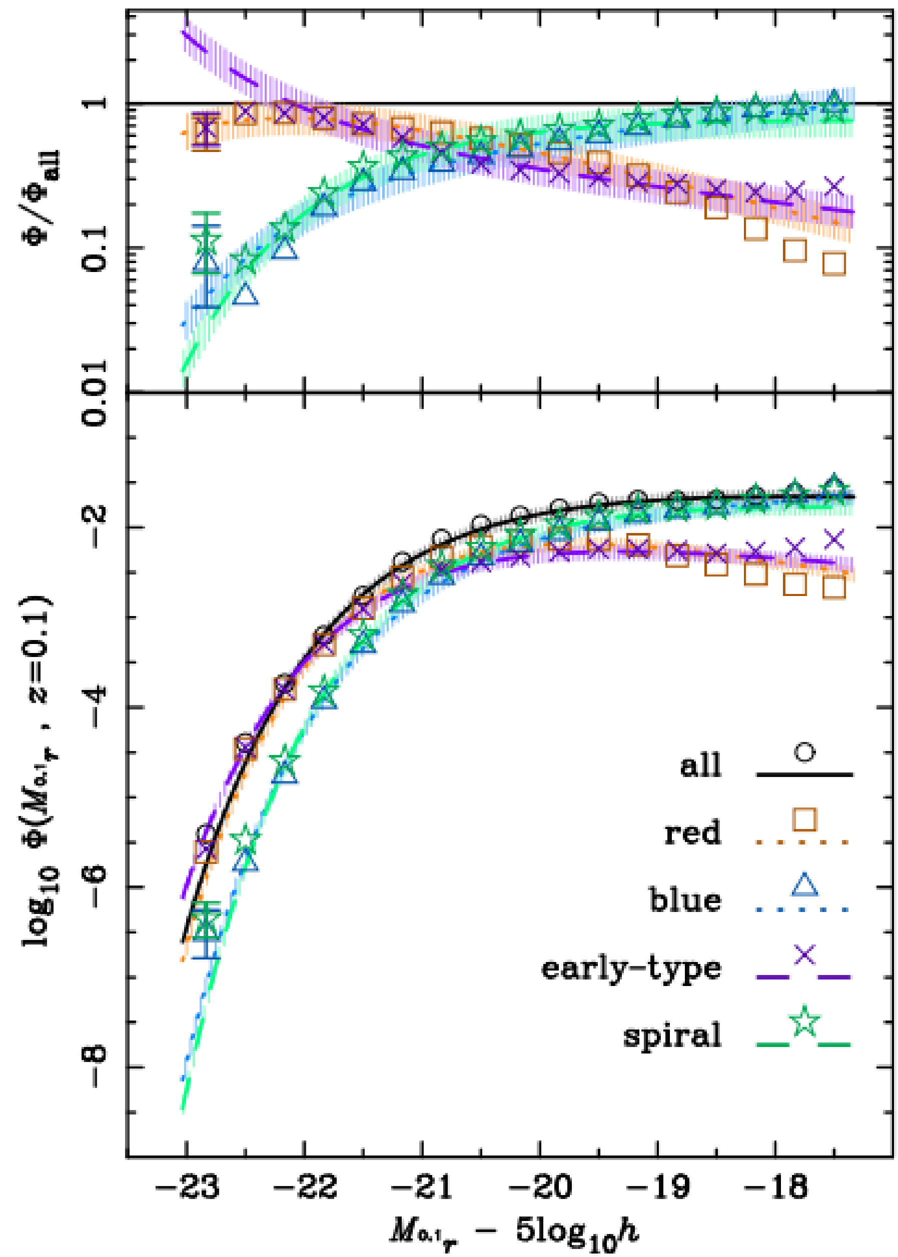
Red and Blue Luminosity Functions

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



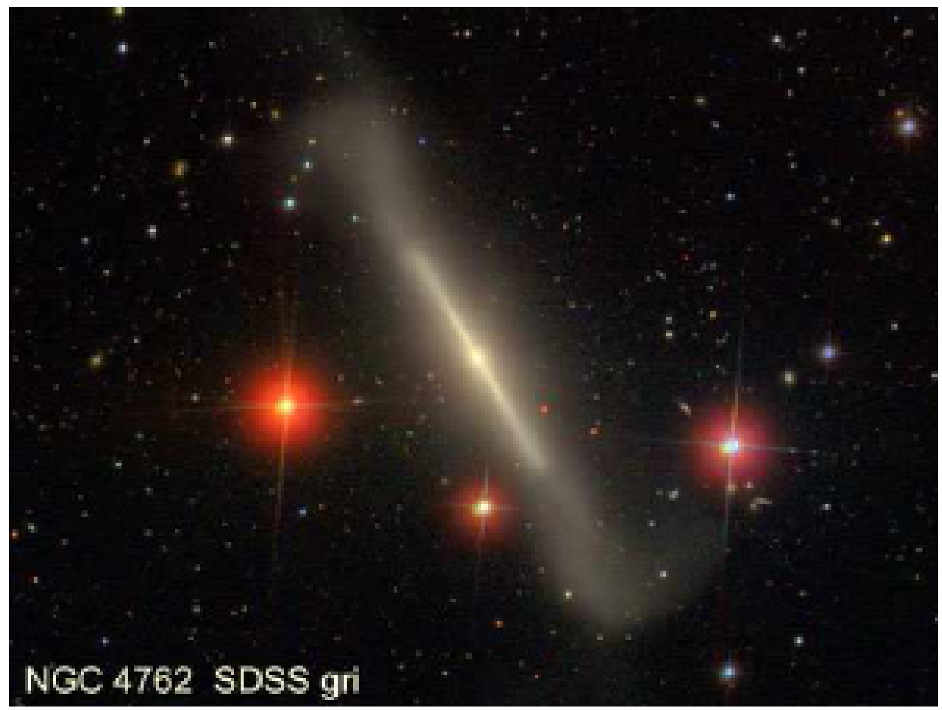
Red and Blue are not exactly Elliptical and Spiral

- 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.

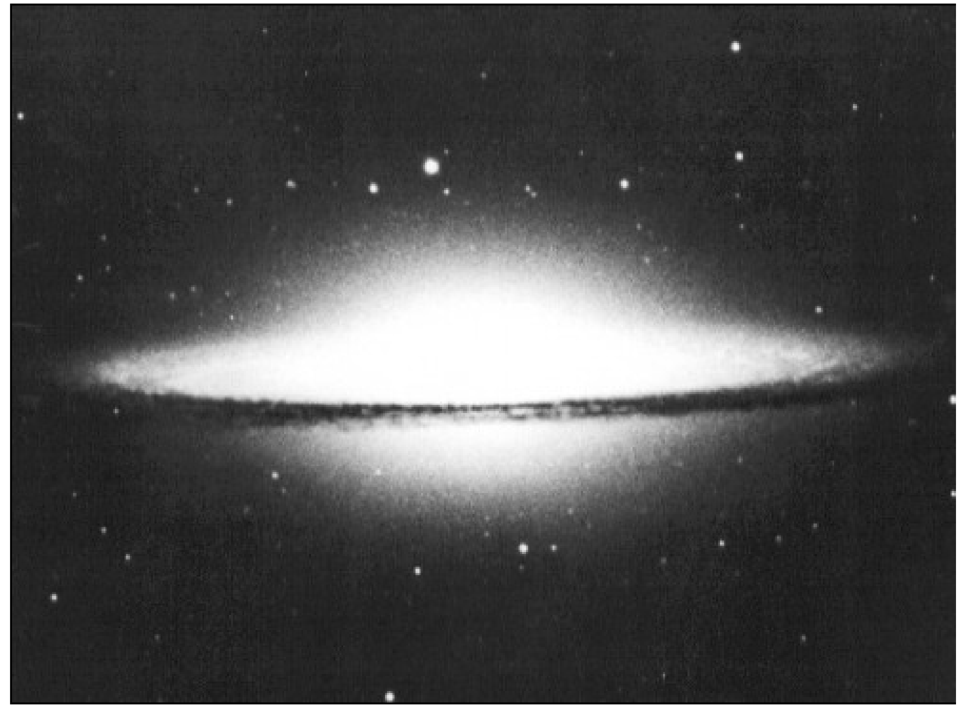


Spirals

- 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
- ISM is highly structured



Physical Difference Between Bulges and Disks

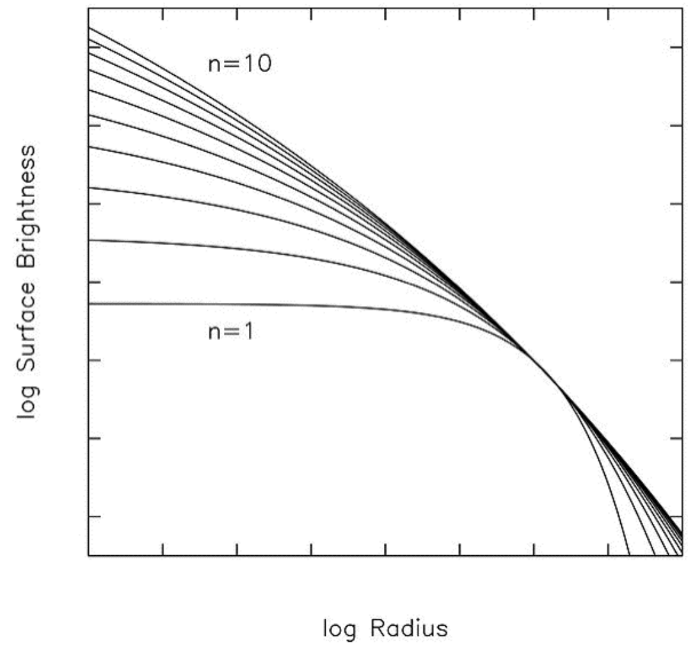


- In spiral galaxies
  - the stars in the disk have lots of angular momentum and a wide variety of ages.
  - stars in the bulge tend to be old, have little angular momentum and have low metallicity*
    - (globular clusters may be part of this population)
- Disks are rotationally supported (dynamically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

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

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 $\Sigma(r)=\Sigma(0)\exp(-k\,[(r/r_e)^{1/n}-1]$; $k \sim 2n-0.331$ (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- Γ is the gamma function

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

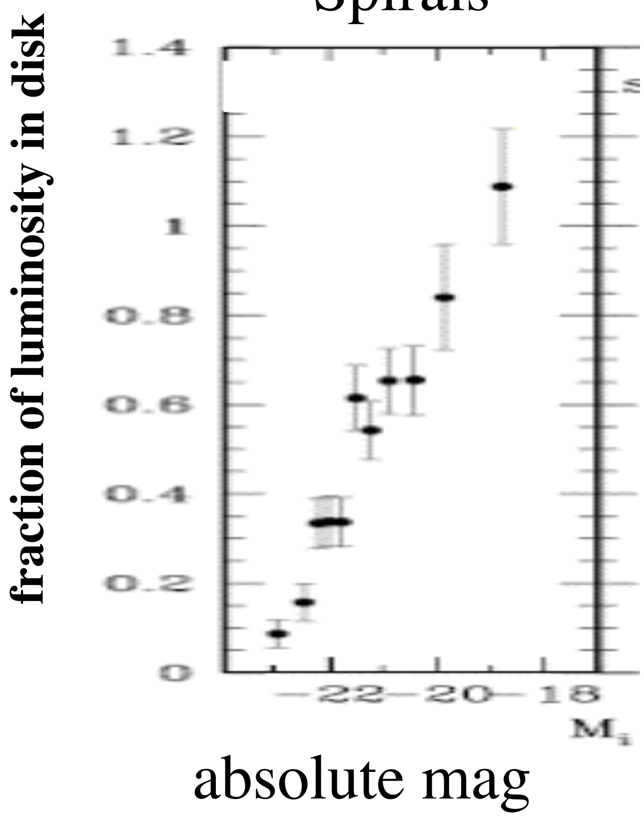
$$\Sigma(r) = \Sigma_e e^{-\kappa[(r/r_e)^{1/n}-1]}$$

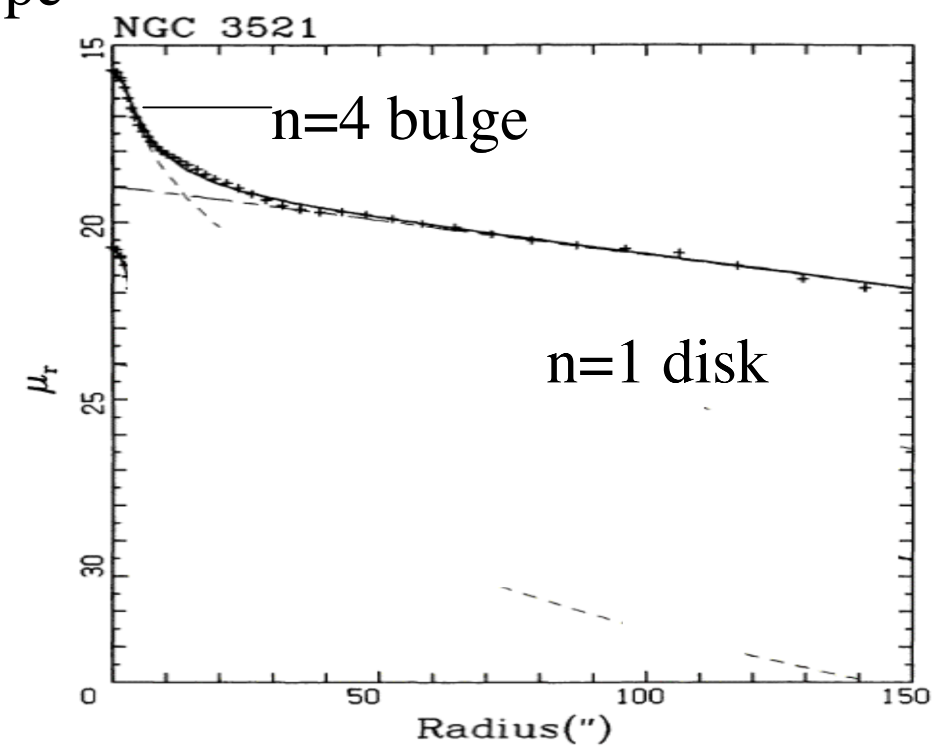
$$\kappa \approx 2n - 0.331$$

Sersic(1968) profile S+G eq 3.13

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

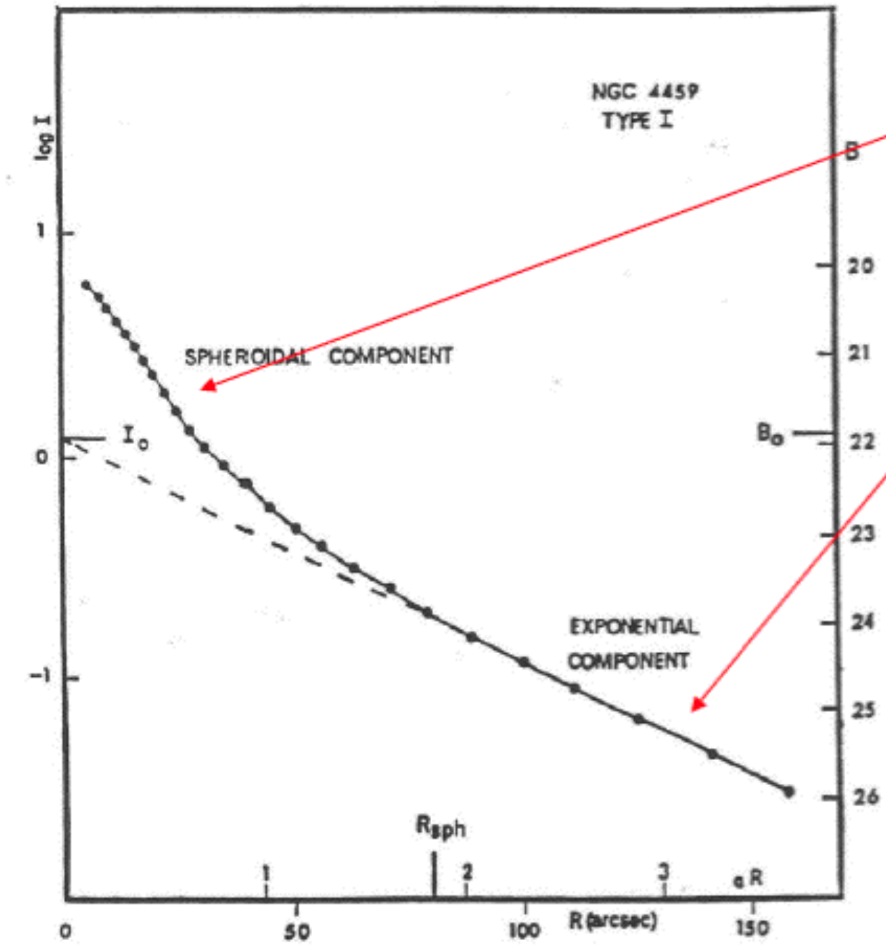
Spirals





Azimuthally Averaged Light Profiles

- Bulge is more concentrated than the disk: bulge is described by Sersic profile, disk by an exponential profile



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

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

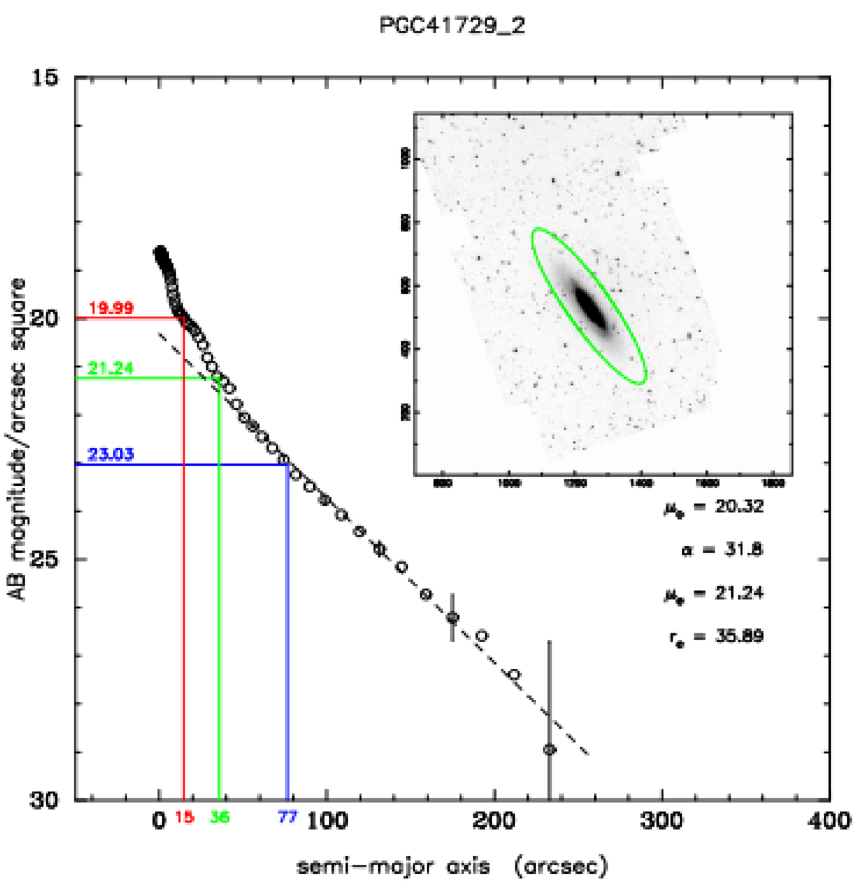
α is the inverse scale height

(Freeman 1970)

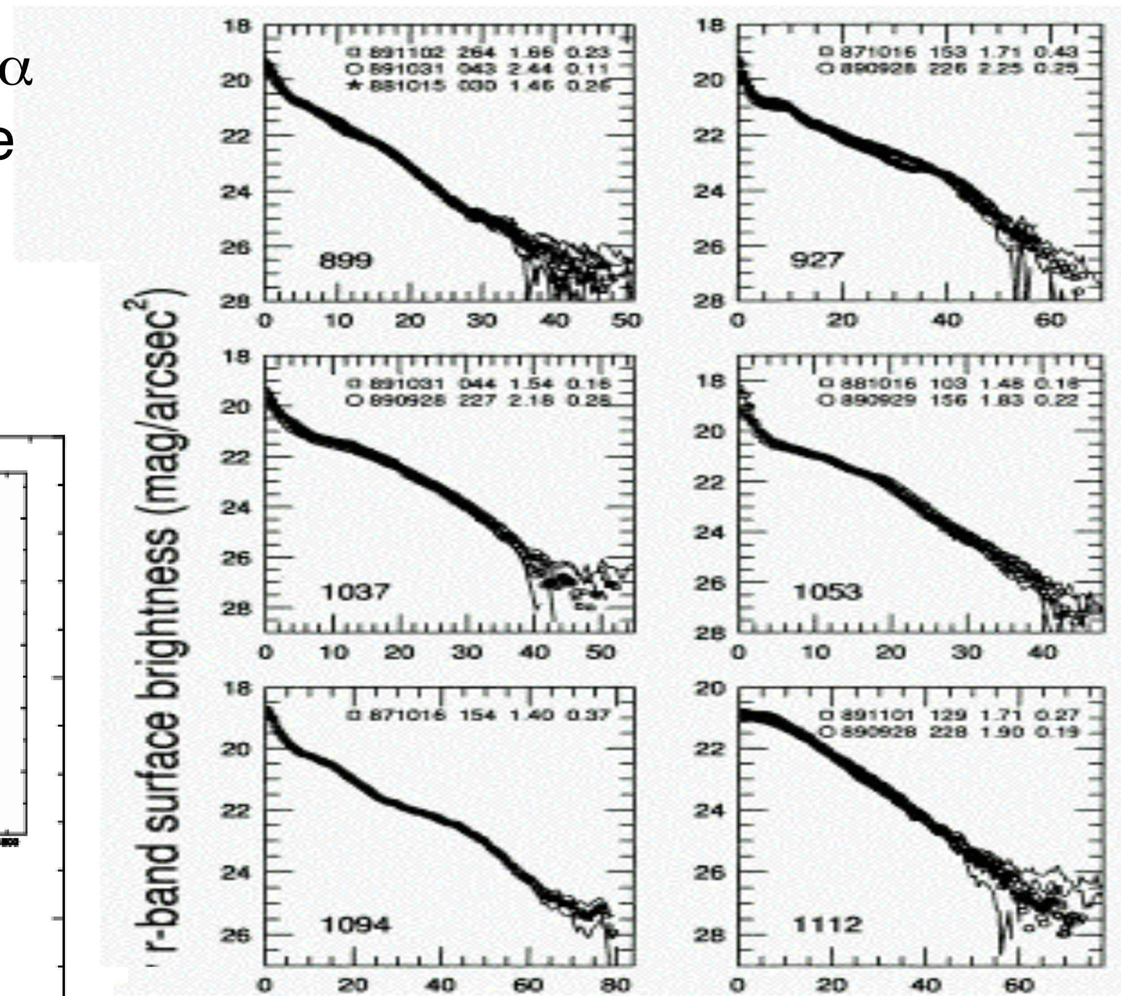
This is an approximation, galaxies with strong bars or other non-azimuthally symmetric features will clearly change this

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

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.
- the luminosity function of galaxies is fit by a simple function (Schechter function) which is different for ellipticals and spirals but sums together into a smooth form
- spirals tend to 'live in the field' low density regions
- ellipticals in denser regions

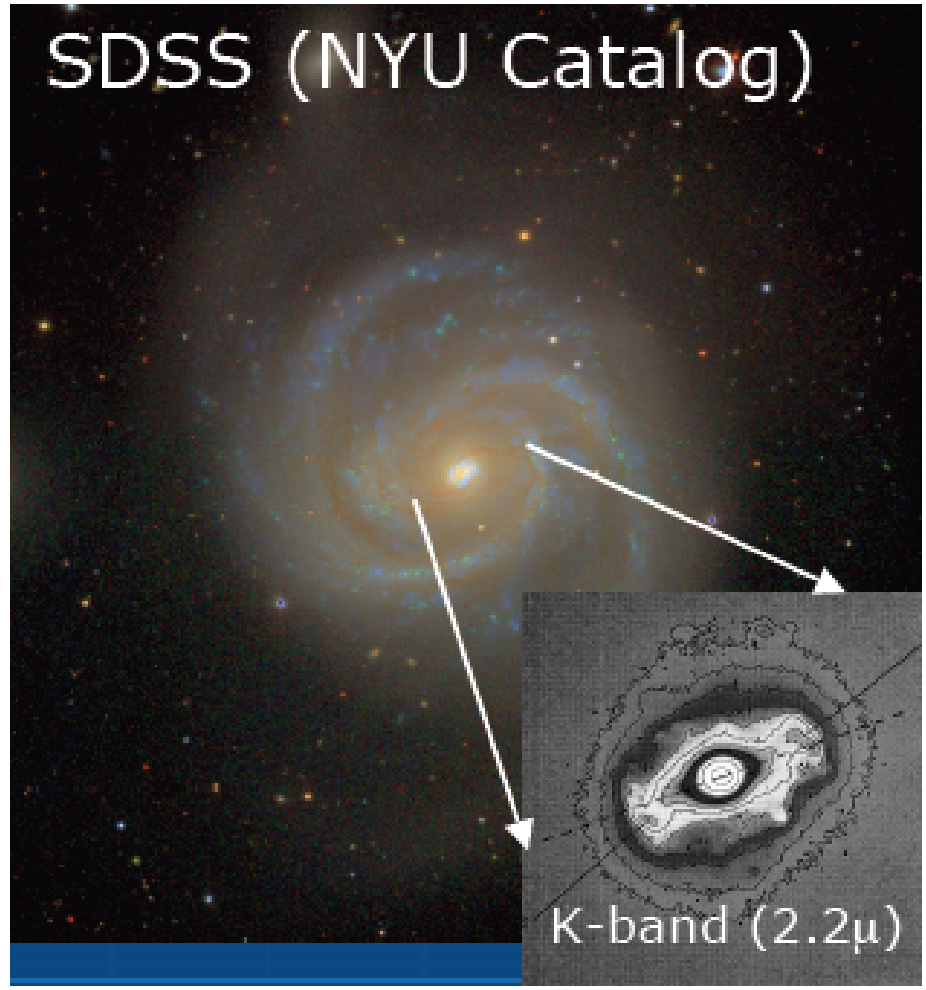
(morphology density relation- Dressler 1978)

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 $I(R)=I(R_e)(\exp-7.67[(R/R_e)^{1/4}-1]))$
  - R_e is the half light radius

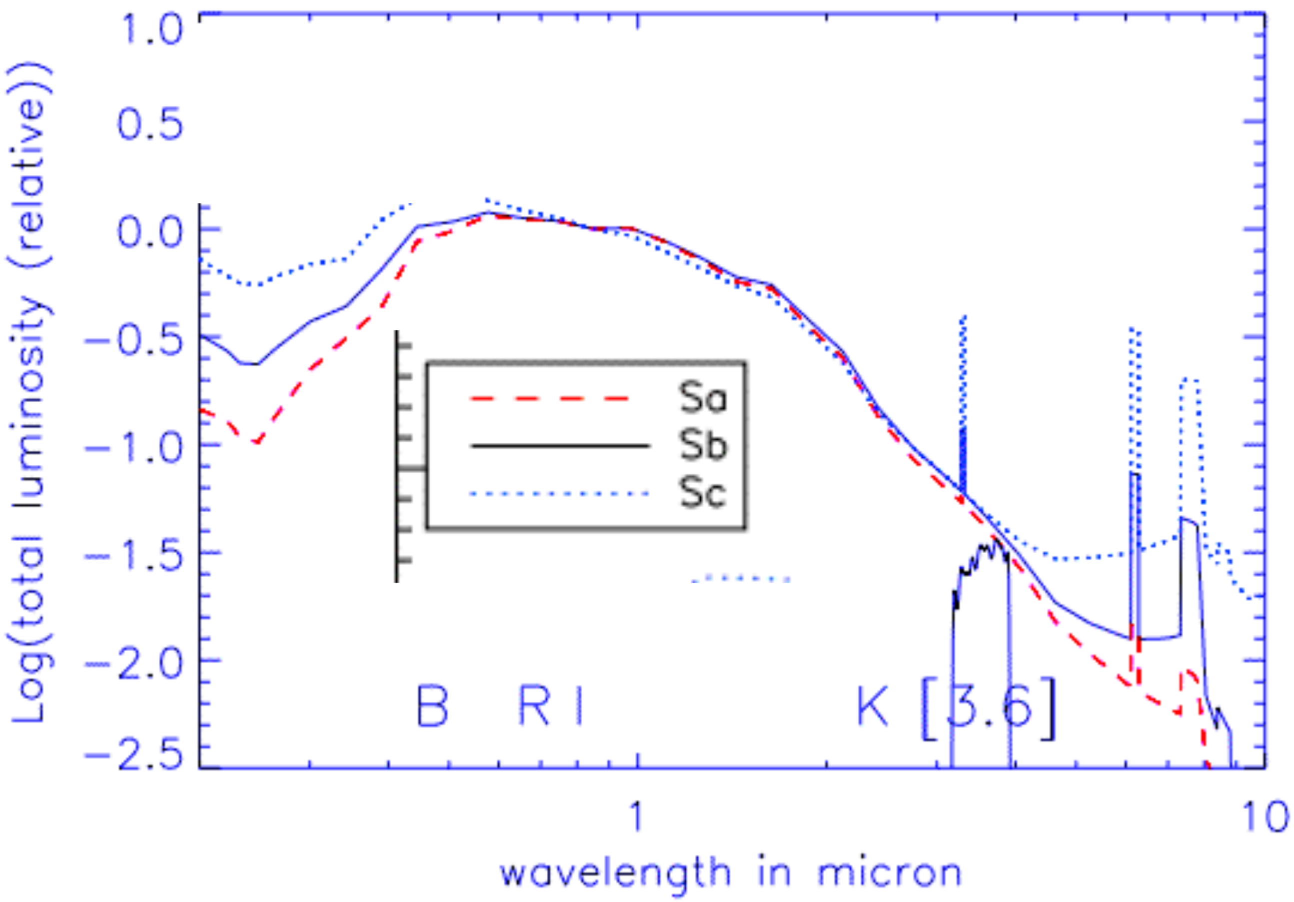
Spirals- Disk Components

- Stellar bars are common
  - Often only recognized in near-IR images (less dust)
  - Consequence of disk instability
    - Effective means of angular momentum transport
- Spiral arms are common and coherent features– even after accounting for young stars (while often spiral arms are the locations of star formation they are also seen in the light of older stars).



Spiral 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

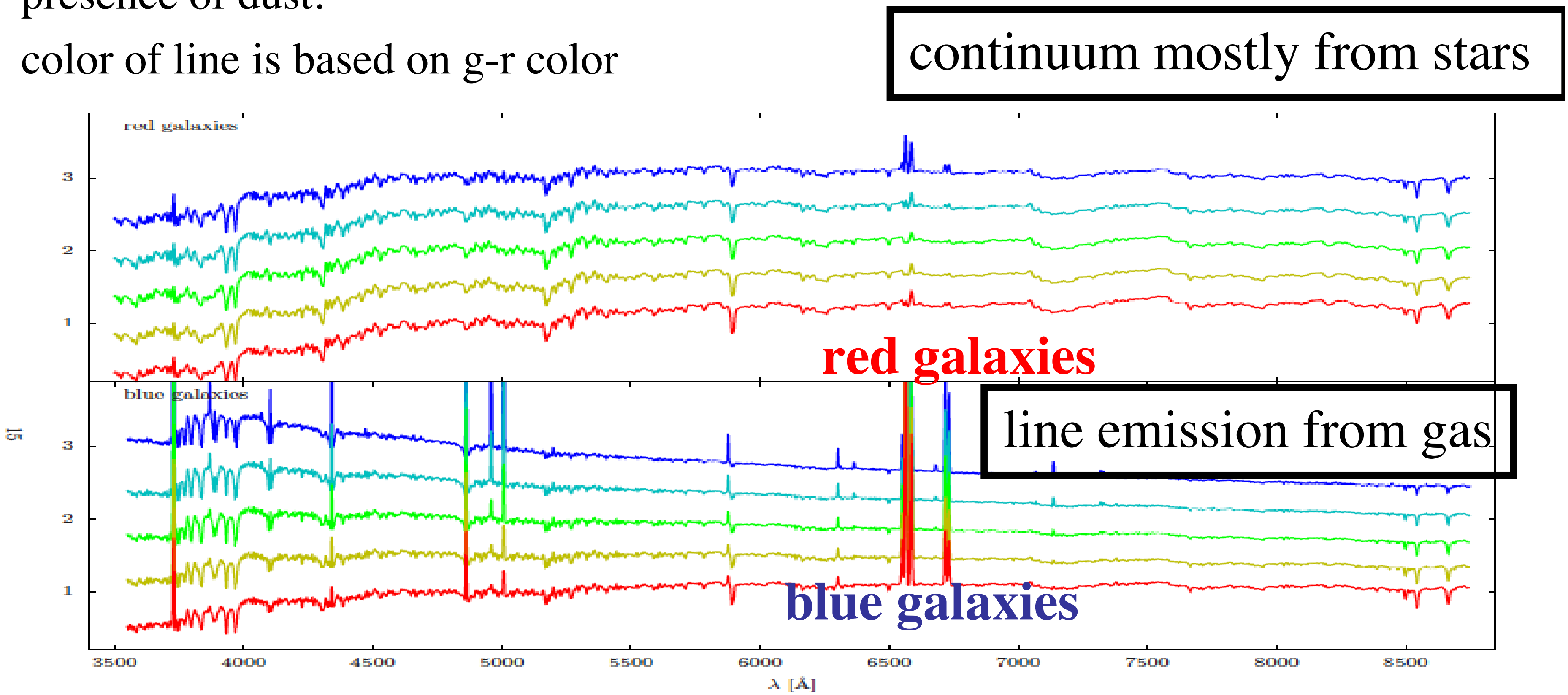
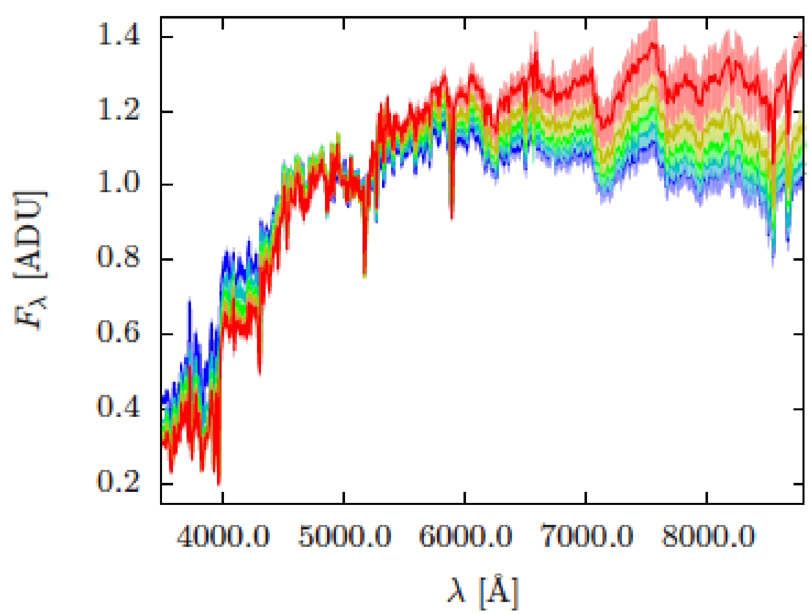
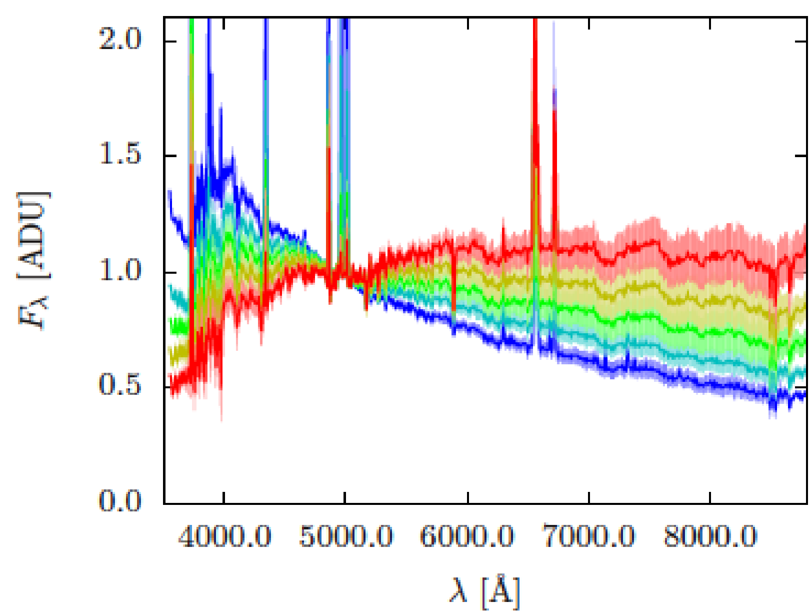


Figure 12: Composite spectra of the refined colour classes as described in Sec. 3.4. The curves are colour-coded from blue (top) to red (bottom) based on the $g-r$ colour of the galaxies. See the online edition for a colour version of this plot.

Galaxy spectra

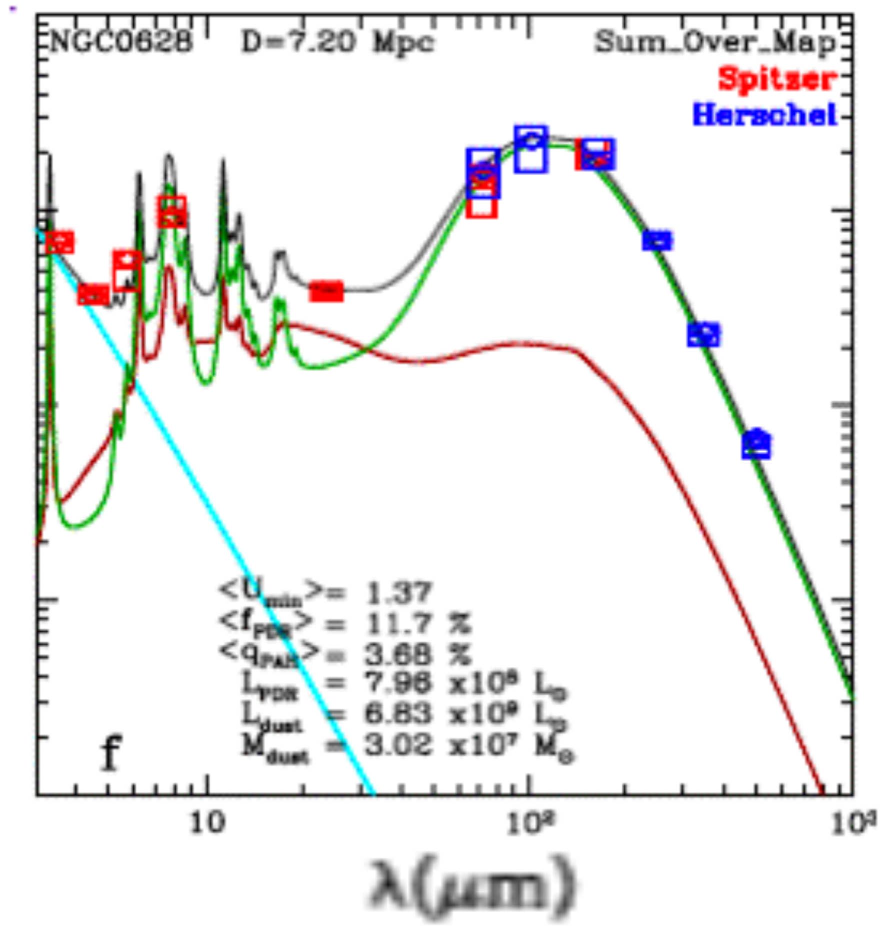
- Sequence of ages of a composite SSP population (star forming-spiral population)
- bulges are dominated by stellar absorption lines and have little 'blue' light
- The star forming galaxies- *almost all spirals at low redshift*, show emission lines (from ionized gas) and much more blue light (especially when they are young)

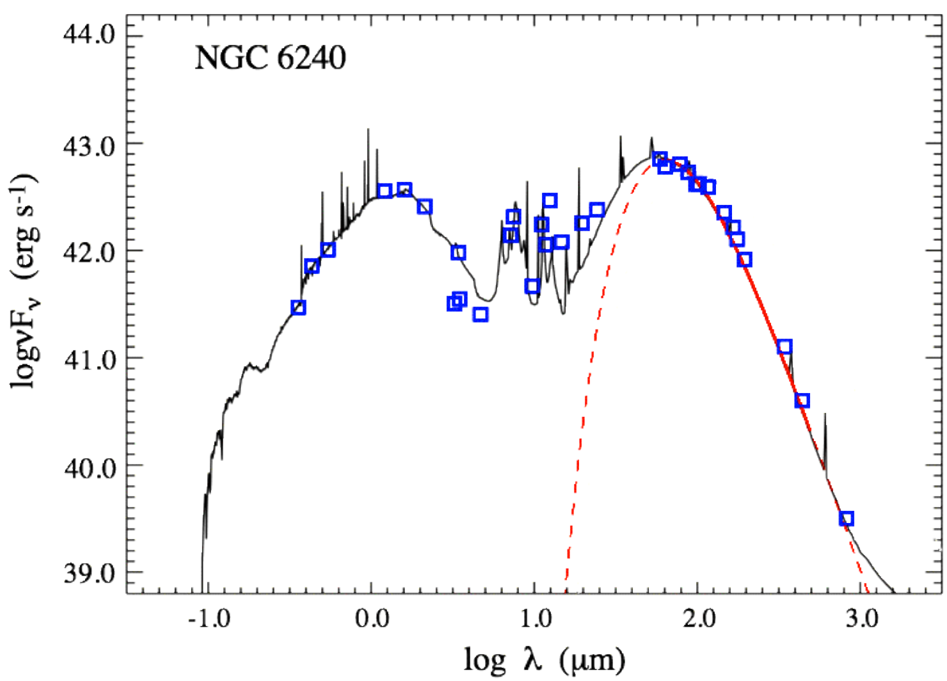




Galaxy Spectra -IR

- 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 can star formation

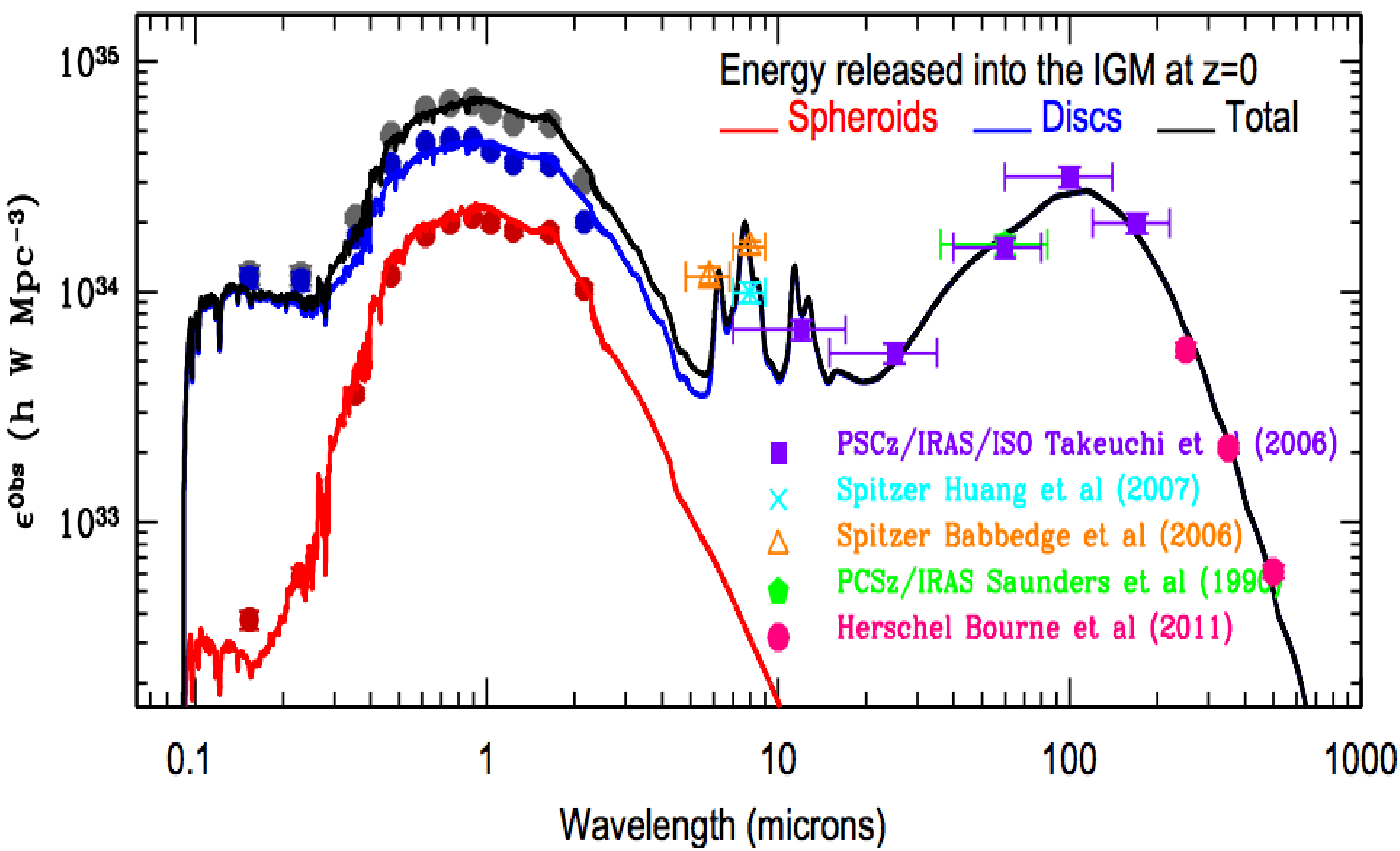




Cyan=stars
Green= dust heated by hot stars
Red dust heated by other stars

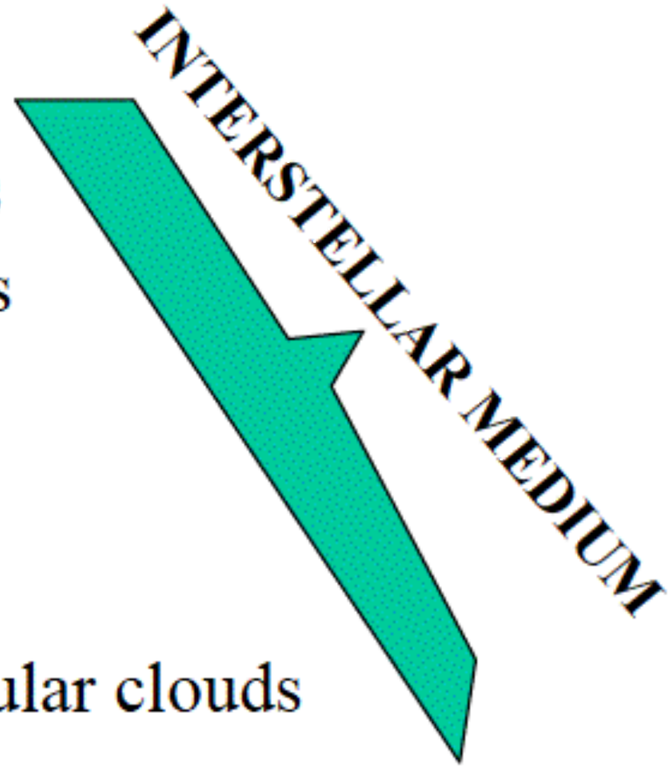
Energy Released By Galaxies

- Extensive galaxy surveys have allowed the measurement of the total energy released by all low z galaxies across the UV-far IR spectrum 1.3×10^{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)/σ ~ 1, so dispersion (random velocity-hot systems) support important.

- Bar/Spiral Patterns/rings :
- Dense'cold' ISM +star formation
- Stellar Halo :

Very low surface brightness; ~few % total light; little/no rotation

Metal poor stars; GCs, dwarfs; low-density hot gas

- Dark Halo :

Dark matter dominates mass (and potential) outside ~a few scale lengths

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}
  - Earlier Hubble-type galaxies rotate faster for the same L
  - Fraction of DM inside optical radius increases with decreasing V_{max}
- Large fraction of energy radiated in the IR due to dust
- Spectroscopic signature of gas in spirals in form of emission lines from hydrogen, oxygen etc; gives information about physical conditions (temperature, density, velocity field)

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
  - disk of galaxy $R\ \phi$
  - plane of sky $\rho\ \theta$
- When $\theta=\phi$ line of nodes
- The measured radial velocity of gas in circular orbits is
- $v_R(\rho, \theta)=v_{system}+v_R(R, \phi)\sin\phi\sin\mathbf{i}+v_\phi(R,\phi)\cos\phi\sin\mathbf{i}+v_z(R,\phi)\cos\mathbf{i}$

v_R velocity in radial direction

v_ϕ angular speed

v_z vertical speed

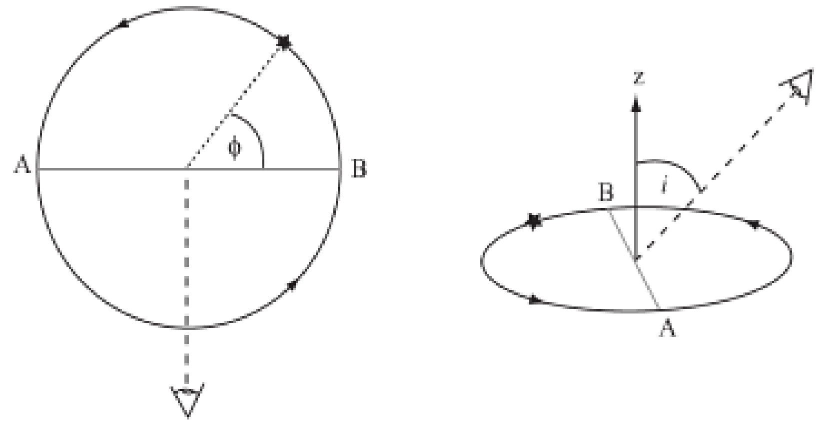
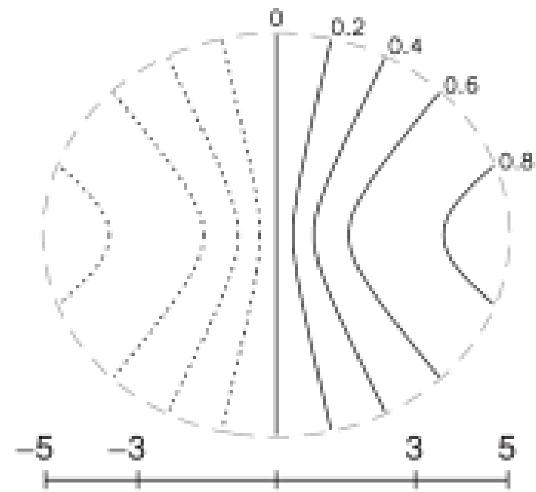


Fig. 5.18. Left, a rotating disk viewed from above. Azimuth ϕ, measured in the disk plane, gives a star's position in its orbit; an observer looks from above the disk, perpendicular to diameter AB. Right, the observer's line of sight makes angle i with the disk's rotation axis z.



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

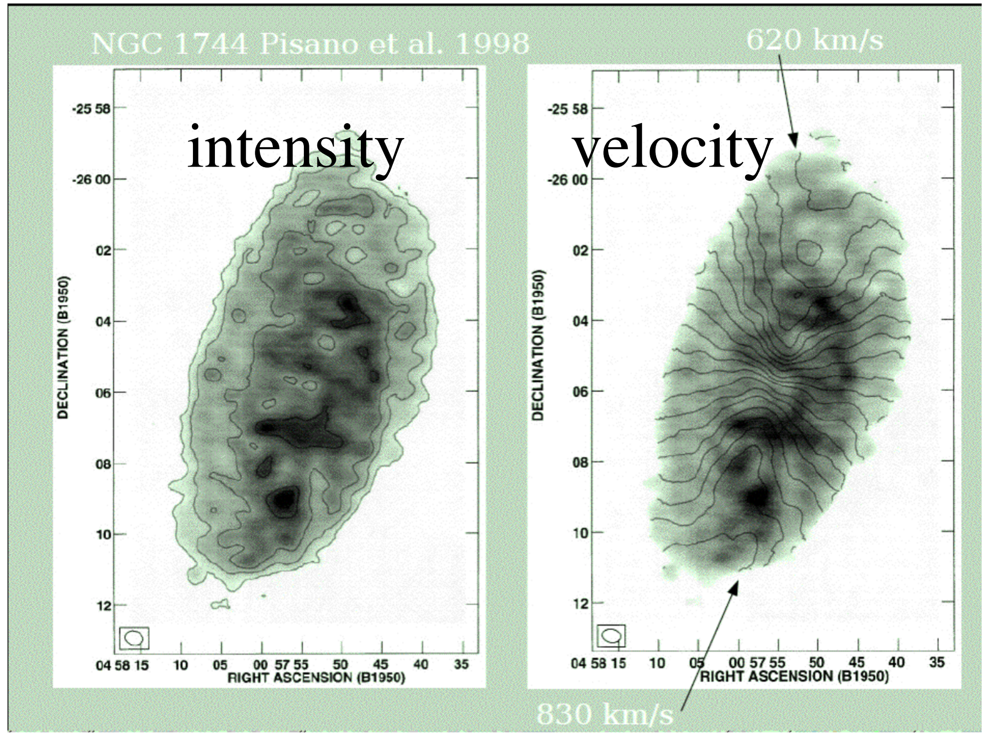
HI

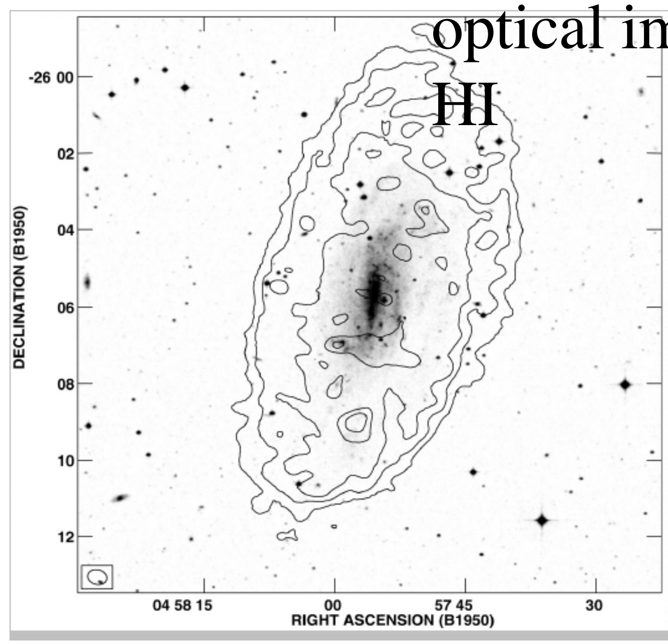
- Spirals have large HI disks

– This gas is optically thin

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

- HI gas is much more extended than the optical light, $r_{HI} > 2.5\ R_{25}$
- – Gives a unique tracer for the velocity in spiral galaxies

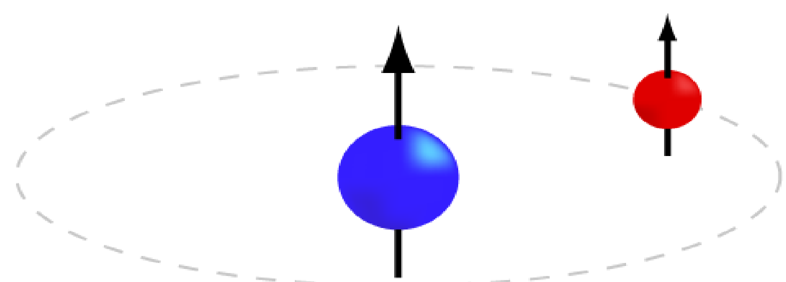




Physics of 21cm Line

- 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 magnetic interaction between the quantized electron and proton spins. When the relative spins change from parallel to antiparallel, a photon is emitted. Collisions excite the line.
- The equilibrium temperature of cool interstellar HI is determined by the balance of heating and cooling. The primary heat sources are cosmic rays and ionizing photons from hot stars. The main coolant in the cool ISM is radiation from the fine-structure line of singly ionized carbon, CII, at =157.7 μ.

http://www.cv.nrao.edu/course/astr534



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

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
  - If V(r) is flat at large radii outer contours are radial
  - if V(r) is declining at large radii contours close in a loop
  - spiral arms give perturbations to pattern near arms
  - warped disk (see figure)

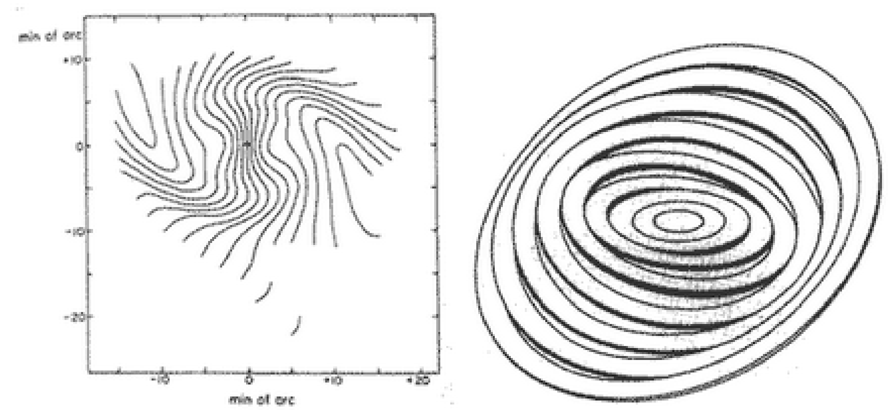


Figure 8.36 A tilted ring model of M83 (right) and the spider diagram predicted by this model (left). [After Rogstad, Lockhart & Wright (1974)]

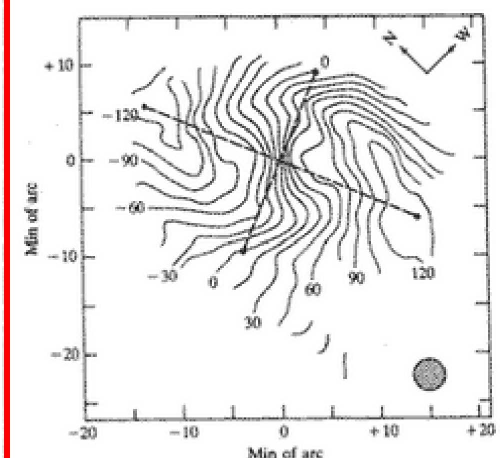
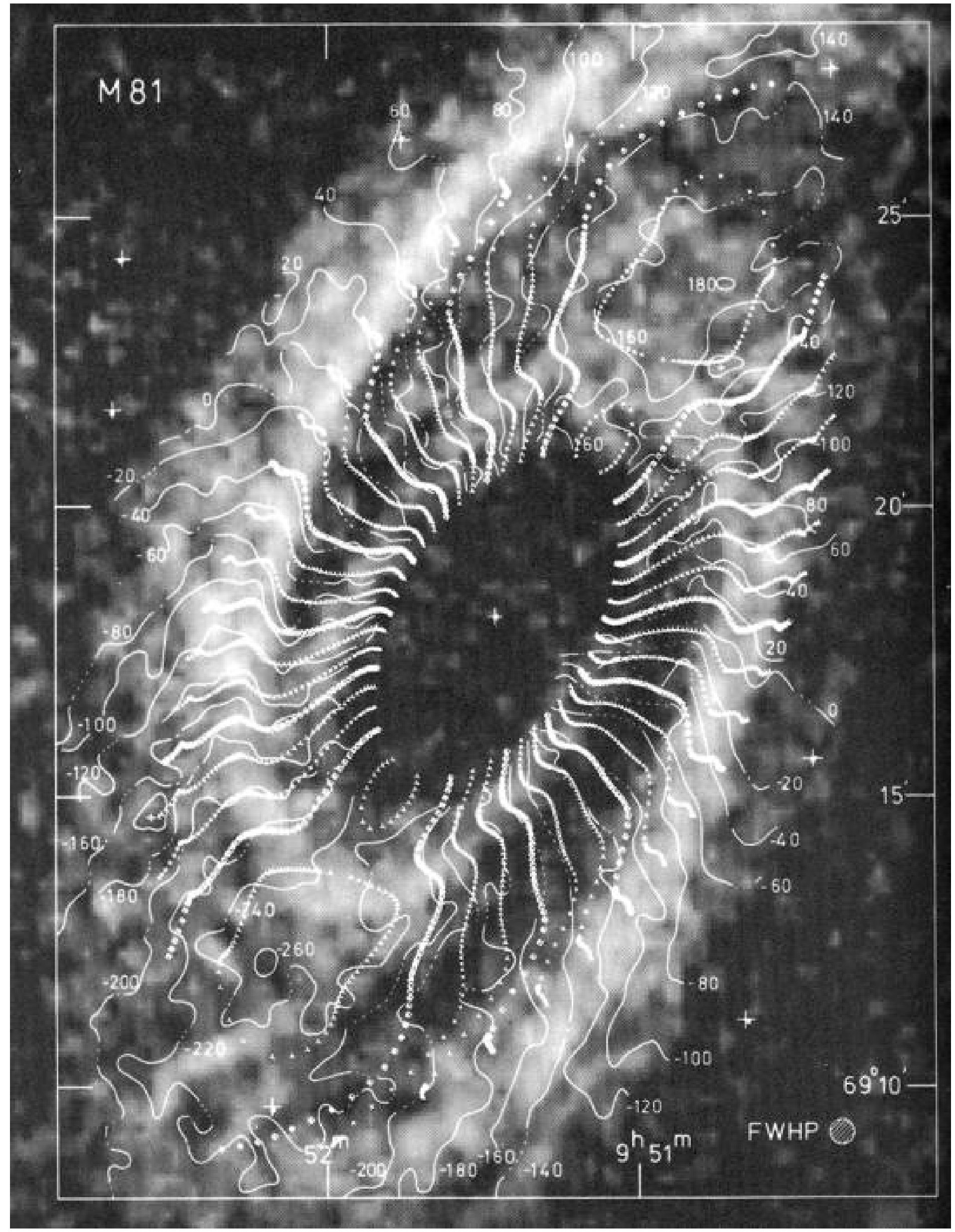


Figure 8.37 The observed spider diagram of M83. [After Rogstad, Lockhart & Wright (1974)]

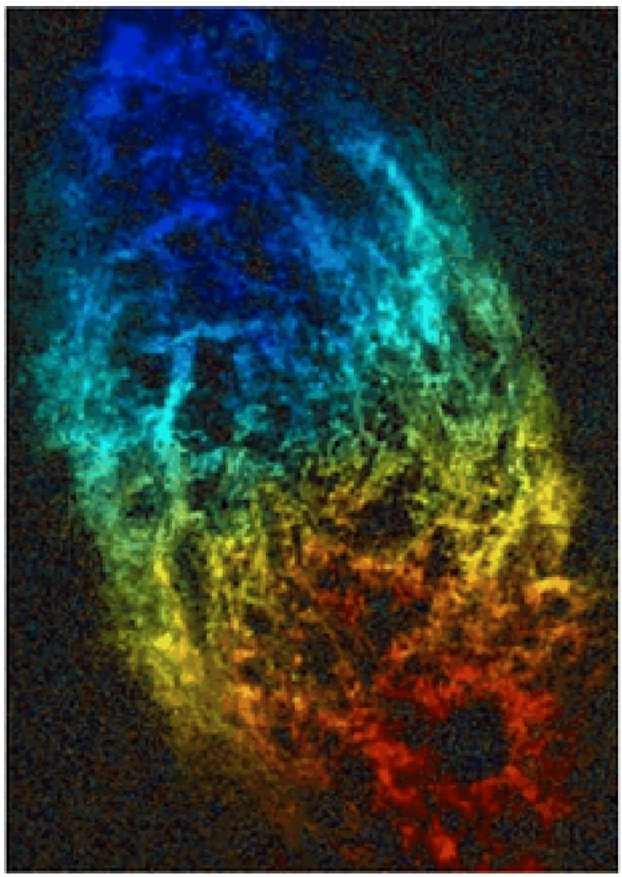
Gas Motions

- 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 observer's line of sight."
- Gas sees all the matter- deviation from Spider plot in M81 shows influence of spiral arms (real density increases- not just light increases)

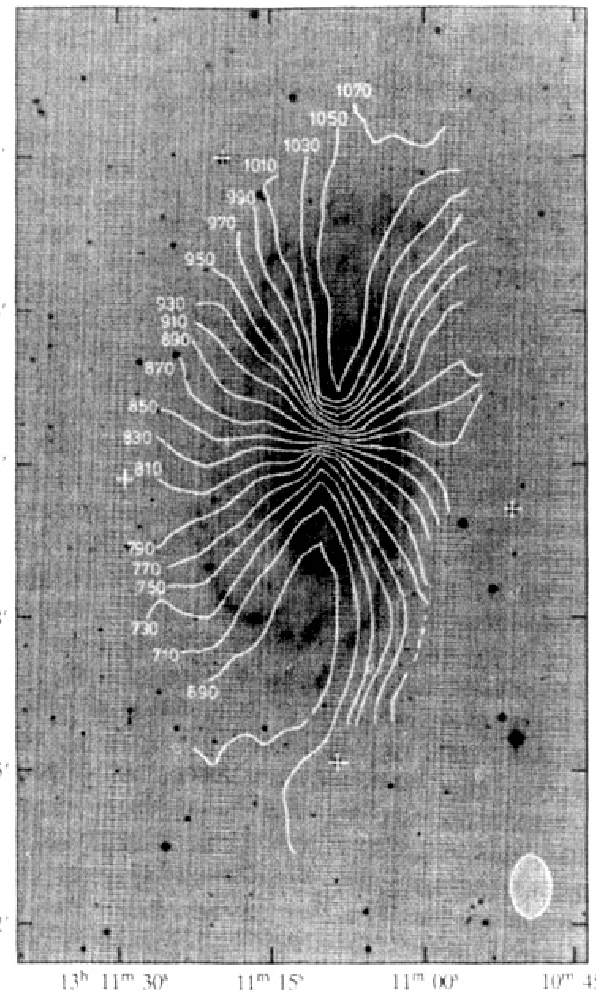


Optical Image and Velocity Field of NGC5033

- Spider plot is the contours of the velocity field



hydrogen velocity



Spirals and Dark Matter

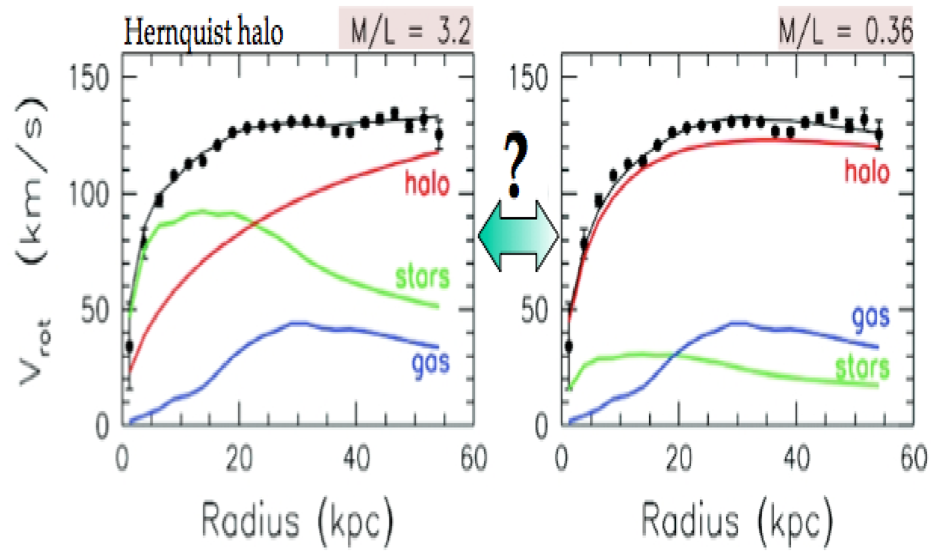
- Rotation-curve decomposition - primary tool for measuring the distribution of dark matter in spiral galaxy halos, **but** uncertainties in the mass-to-light ratio of the luminous disk and bulge make accurate estimates difficult (IMF-mass degeneracy)
- Disk-halo conspiracy- there is no 'feature' in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

- Solution is to observe face-on galaxies - position by position, measure both rotation and dispersion components of the velocity
- Disks in equilibrium

  Rotation provides total mass within a given radius.

  Vertical oscillations of disk stars provides disk mass within given height inside a cylinder:

Bershady et al



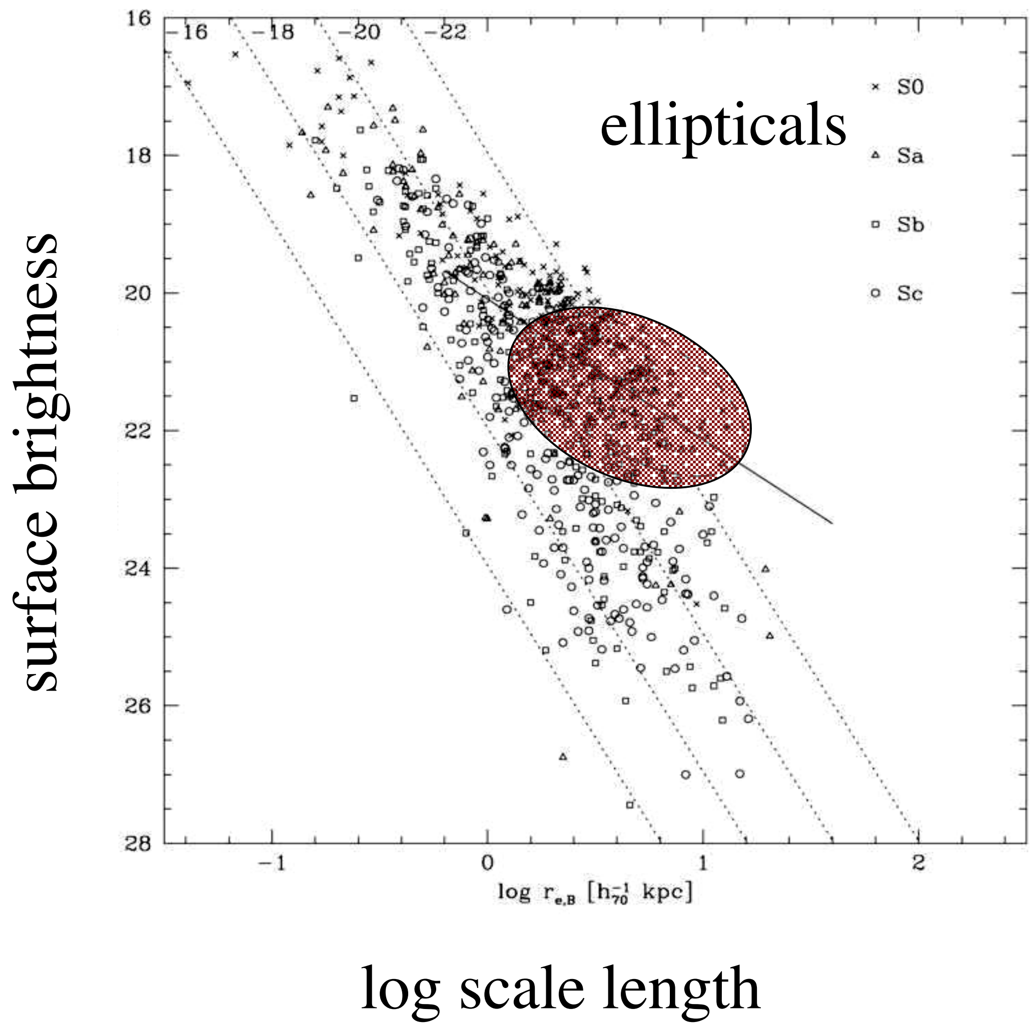
Solution is that disks have less mass than the maximum allowed by IMF, colors-
At the radius where the velocity curve flattens ~15-30% of the mass is in baryons

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 types show similarities in various correlations but ellipticals have a smaller range of parameters than spiral bulges.



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.

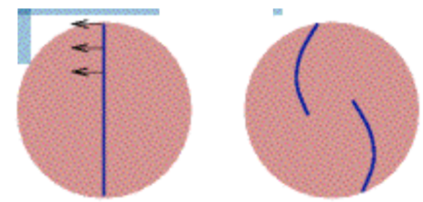
When the sense of the galactic rotation is known, the spiral arms almost always trail the rotation.

- First ingredient for producing spiral arms is differential rotation.
- For galaxy with flat rotation curve:

$V(R)$ = constant

$\Omega(R) = V/R$ Angular velocity~$1/R$

- Any feature in the disk will be wrapped into a trailing spiral pattern due to 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?

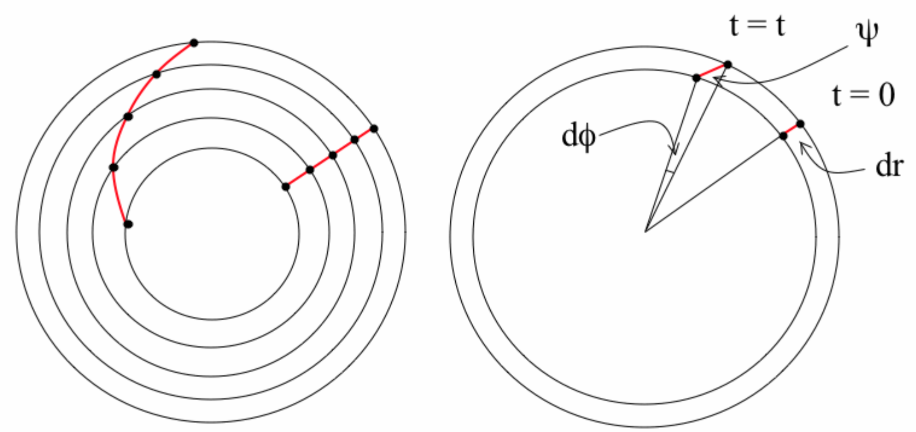
- Angular frequency $\omega = V_c/R$- spirals have flat rotation curve V_c= constant

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

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

pitch angle, ψ , steadily decreases as the pattern rotates- after 1 rotation $\tan\psi = 1/2\pi$ ($\psi = 9^\circ$)e.g winds up! - 2 rotations 4.5° etc

In Sa's $\psi \sim 5^\circ$ while in Scs $\psi \sim 10\text{-}30^\circ$



Flat rotation curve: $v = \text{const}$; $\Omega = v/r$; $d\Omega = v/r^2\, dr$
Now, $\phi = \Omega \times t$, so $d\phi = d\Omega \times t = v/r^2\, dr\, t$
So $\tan\psi = dr / r\, d\phi = dr / [(v/r)\, dr\, t] = r / vt = 1/\Omega t = 1/\phi$

$\tan\psi = r / vt = 1/\phi$

SO since galaxies have been around for >> 2 orbital times

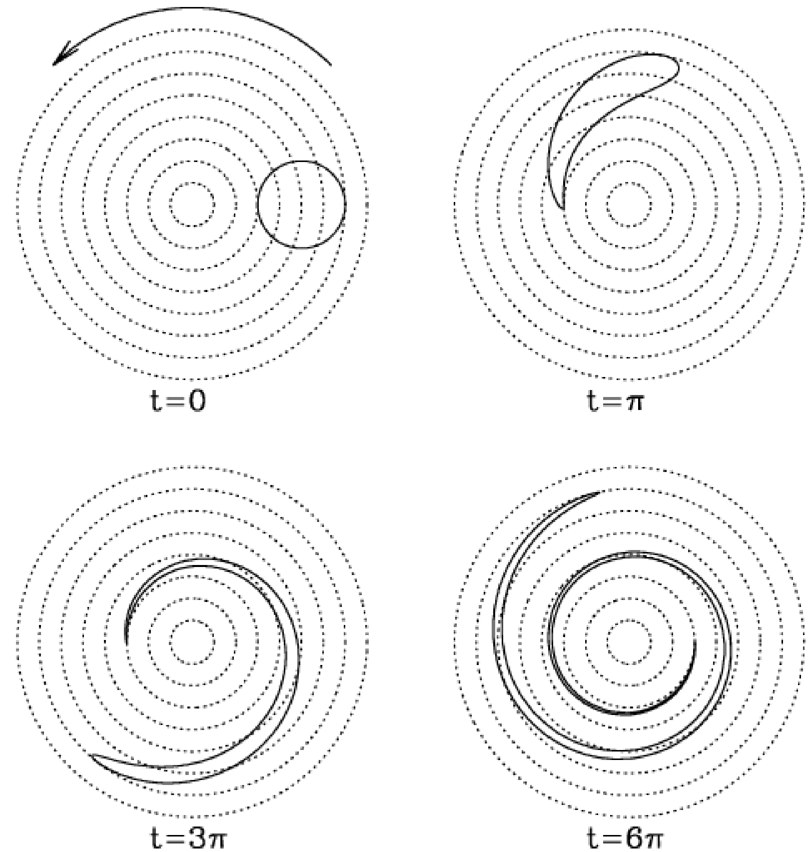
- Long lived spiral arms are **not** material features in the disk they are a pattern, through which stars and gas move

- Short lived spiral arms can arise from temporary patches pulled out by differential rotation

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 tightly wound $\partial f/\partial r$ is large arms are tighly wrapped.
- Argument #1- differential rotation of disk - for V(r)=constant, $\Omega=V/R$ must vary with R.
- So a line with a constant azimuthal angle $\phi=\phi_0$ will be sheared into a spiral curve $\phi(R,t)=\phi_0+Vt/R$ at time t.
- thus a 'blob' will be sheared into a spiral structure



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.

Stars pass through the spiral arms unaffected

Arms rotate with a pattern speed which is not equal to the circular velocity - i.e. long lived stars enter and leave spiral arms repeatedly.

Pattern speed is less than the circular velocity - partially alleviating the winding up problem.

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

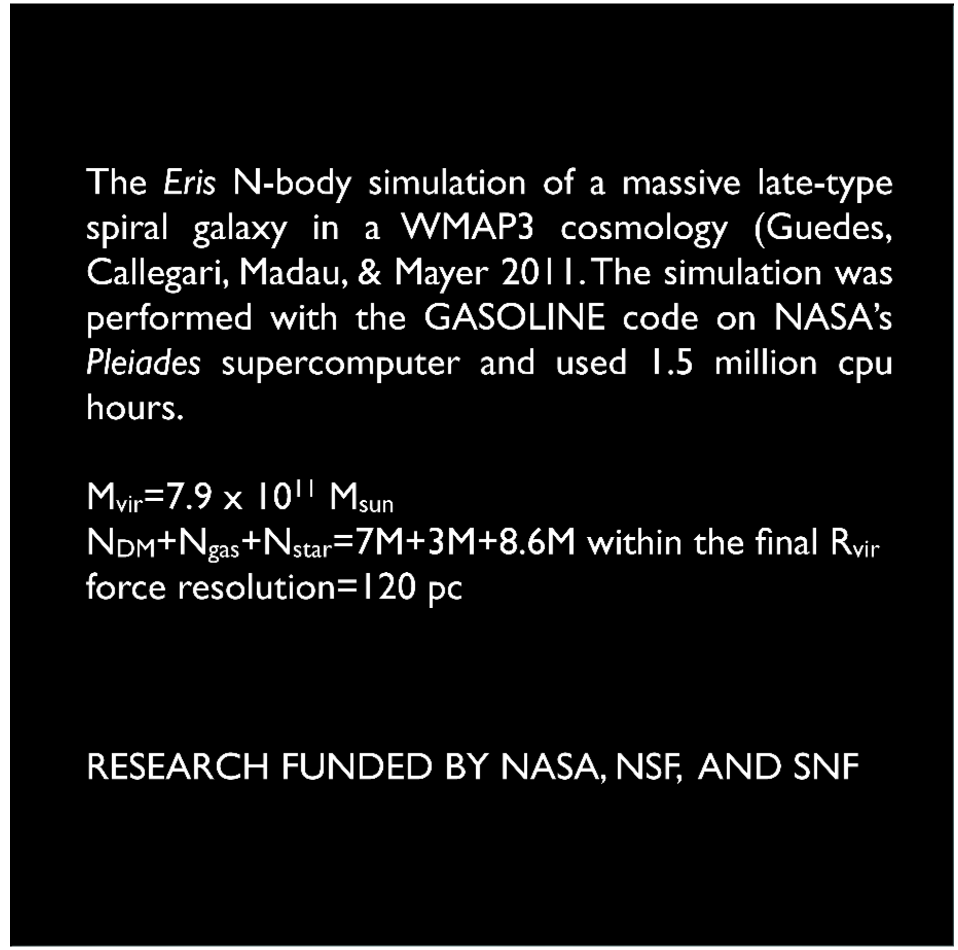
Simplest case to consider is gas. Imagine a small perturbation which slightly compresses part of the disk:

• 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-milky-way-1.11517)



Summary of Last Lecture

- Spiral galaxy optical-IR spectrum is the sum of stars, gas and dust.
  - the ionized gas emits spectral lines indicative of its temperature, density, chemical composition and velocity field
  - the stars have absorption lines that contain information about the stellar type, chemical composition and velocity
  - the IR radiation is mostly due to dust heated by hot young stars but also contains spectral features (PAH) due to big molecules
- ~40% of energy generated by stars is absorbed by dust and re-radiated in IR- this occurs predominately in spirals
- Use HI to trace the velocity field- it often extends far beyond stellar disk light and the gas is in the disk
  - what we observe depends on geometry (inclination of disk)
  - 'spider' pattern -lines of constant velocity
- Origin of spiral arms
  - winding problem
  - Spiral density waves
  - numerical simulation shows that things are more complex

Mass and Luminosity

- The normalization of the surface mass profile $\Sigma(0)=(M/L)\ I(0)$ where $I(0)$ is the normalization of the surface brightness profile IF M/L is constant

$\Sigma(R)=\Sigma(0)e^{-r/r_0}$ for an exponential profile

If we make the approximation that the disk is an infinitely thin sheet

$M(r)=2\pi r\Sigma(r)$ integrating this from 0 to r

$M(\rho)=2\pi\int r\Sigma(0)e^{-r/r_0}\ dr=2\pi r\Sigma(0)r^2_0[1-(1+r/r_0\ ))$ and as r goes to infinity $M(\propto)=2\pi r\Sigma(0)r^2_0$

So important observables derivable from surface brightness fits: $\Sigma(0)$ and r_0

Spiral Arms - Continued

- The full-up math behind the spiral density wave is rather complex.. set pg 533 of MBW.

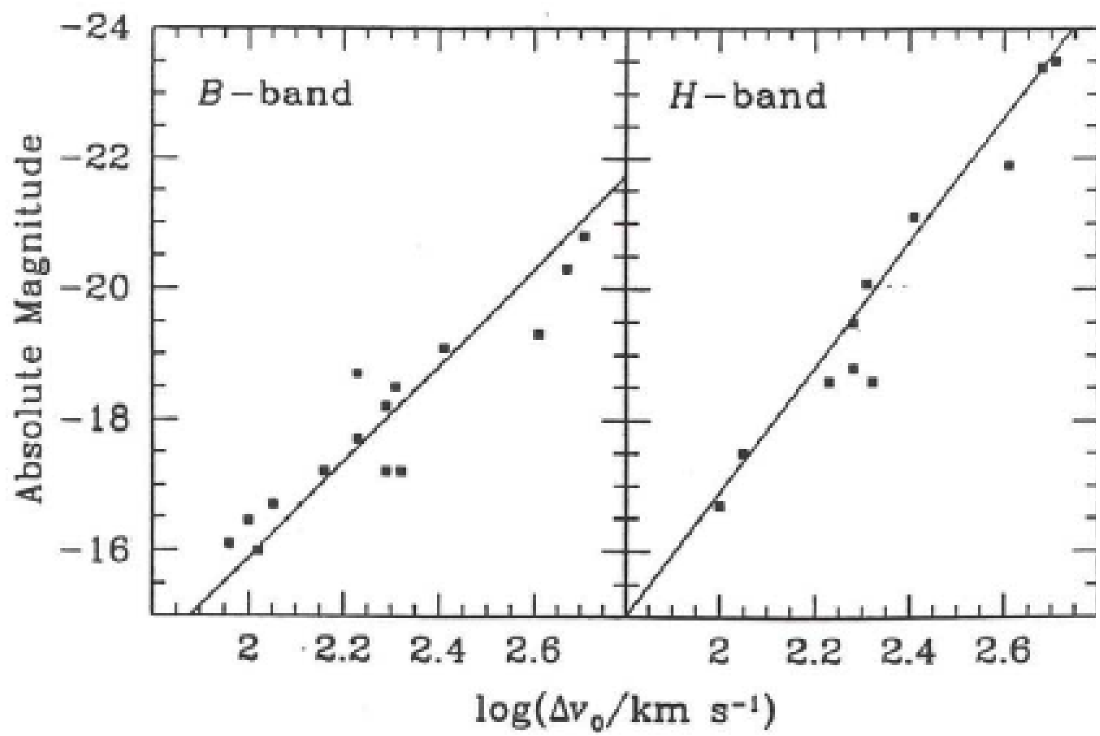
Scaling Relation -Tully Fisher

- Use a tracer (HI, stars) to determine the rotation velocity vs r of the disk
- If the orbits are circular $v^2 \sim (GM/r)$ and the luminosity $L \sim I(0)r^2$
- a little algebra

$v^4 \sim (GM/r)^2 \sim\sim (GM)^2 I(0)/L$ and thus

$L \sim v^4/(I(0)(M/L)^2) \sim v^4$ **if** <u>M/L is constant</u>

- this is confirmed with real data - of course to use this one has to measure L- which requires knowing the distance; alternatively *one can estimate L and thus the distance with this relation if it has a small scatter*.
- And $I(0)(M/L)^2$ must be, roughly, a constant-physics of galaxy formation constraint !



Tully & Fisher (1977) recognized that V_{max} correlates with galaxy luminosity

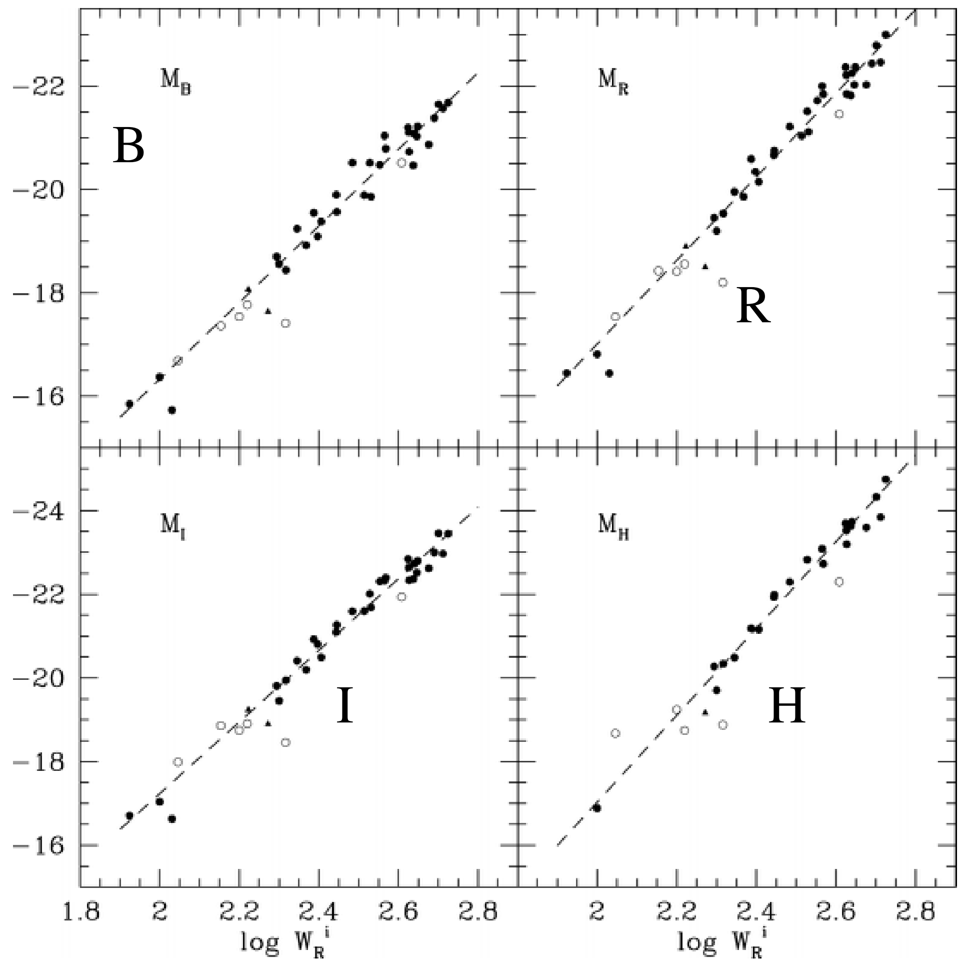
Mass of Star- Mass to Light Ratio

- in principle, the structure of dark matter halos can be determined from spiral galaxy rotation curves if the contribution from gas and stars can be properly understood. In turn, the structure of dark matter halos is a strong constraint on dark matter halo formation models
- The TF relation relates the *integrated luminosity in a given passband* to the *global dynamics of the galaxy and its dark matter halo*.

Tully-Fisher - continued

- To minimize errors (due to dust and the assumption of constant M/L) go to longer wavelengths.
- T-F frequently used to get the distances of objects since it related Luminosity, which is distance dependent to velocity, which is not. However since the T-F relation uses V_{max}, need to correct for inclination (thus always have some irreducible error)
- The confusing part of the T-F relation is that it connects light with **mass.**

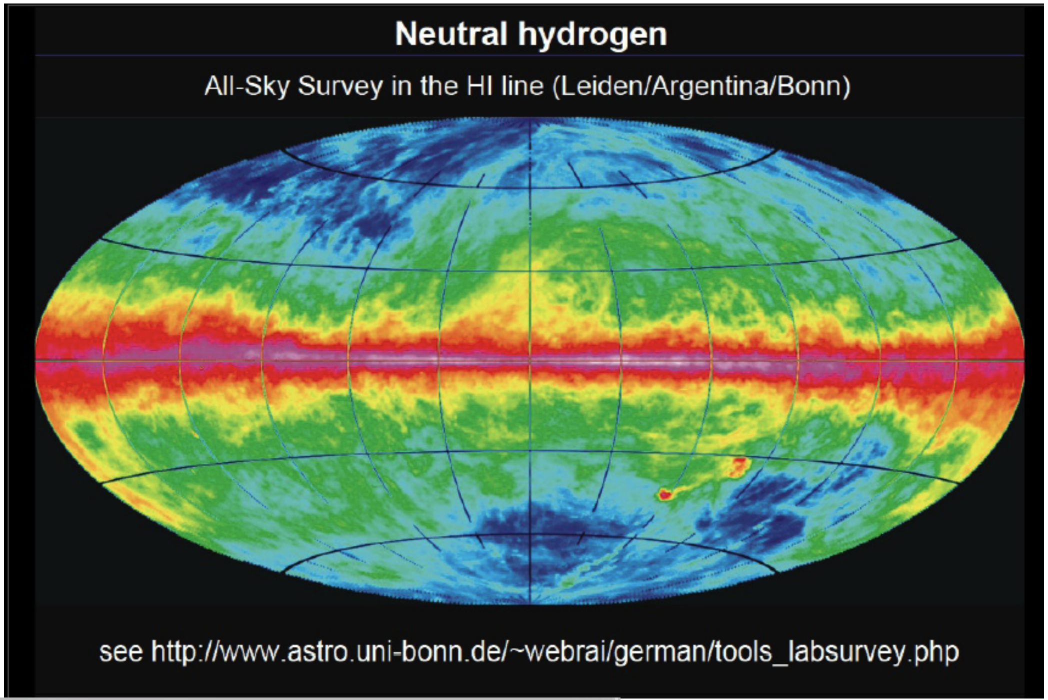
    but we know that most of the mass is due to dark matter.

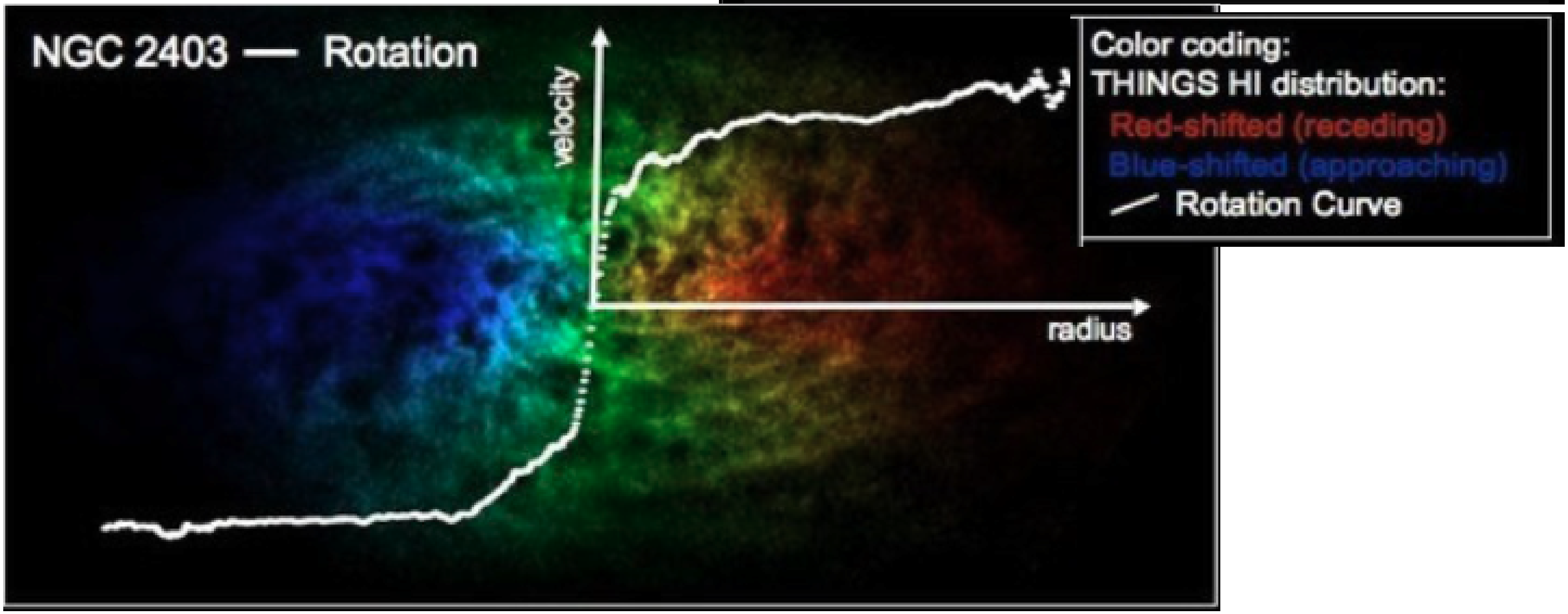


T-F relation in different bands note lower scatter as one goes to redder wavelengths

HI Map of MW

- Each of these data points is a spectrum with velocity information!

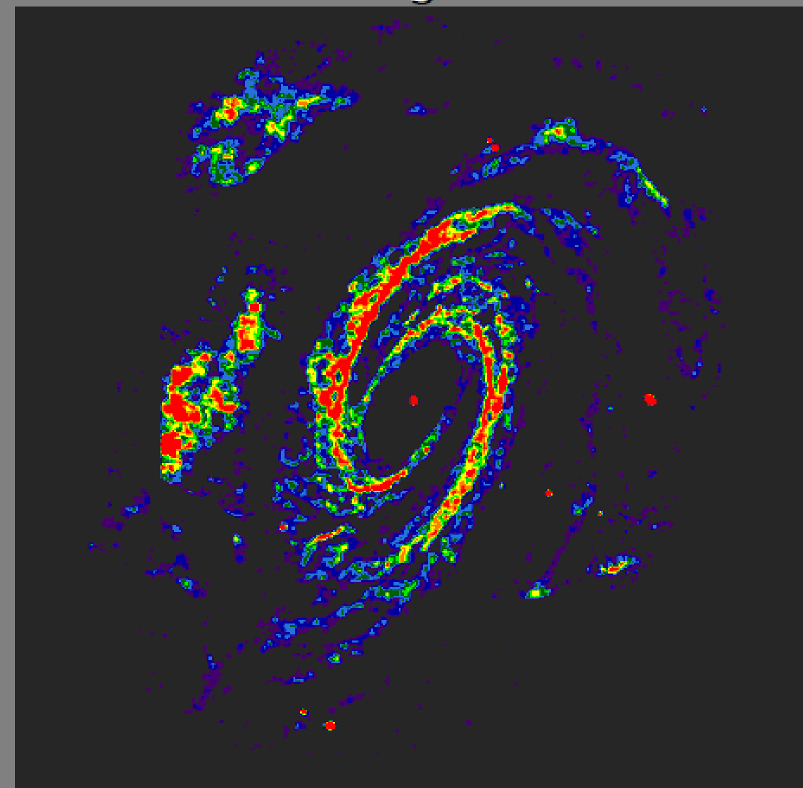




M81 optical

Bright in the center, faint in the outer parts where most of the mass is

HI gas

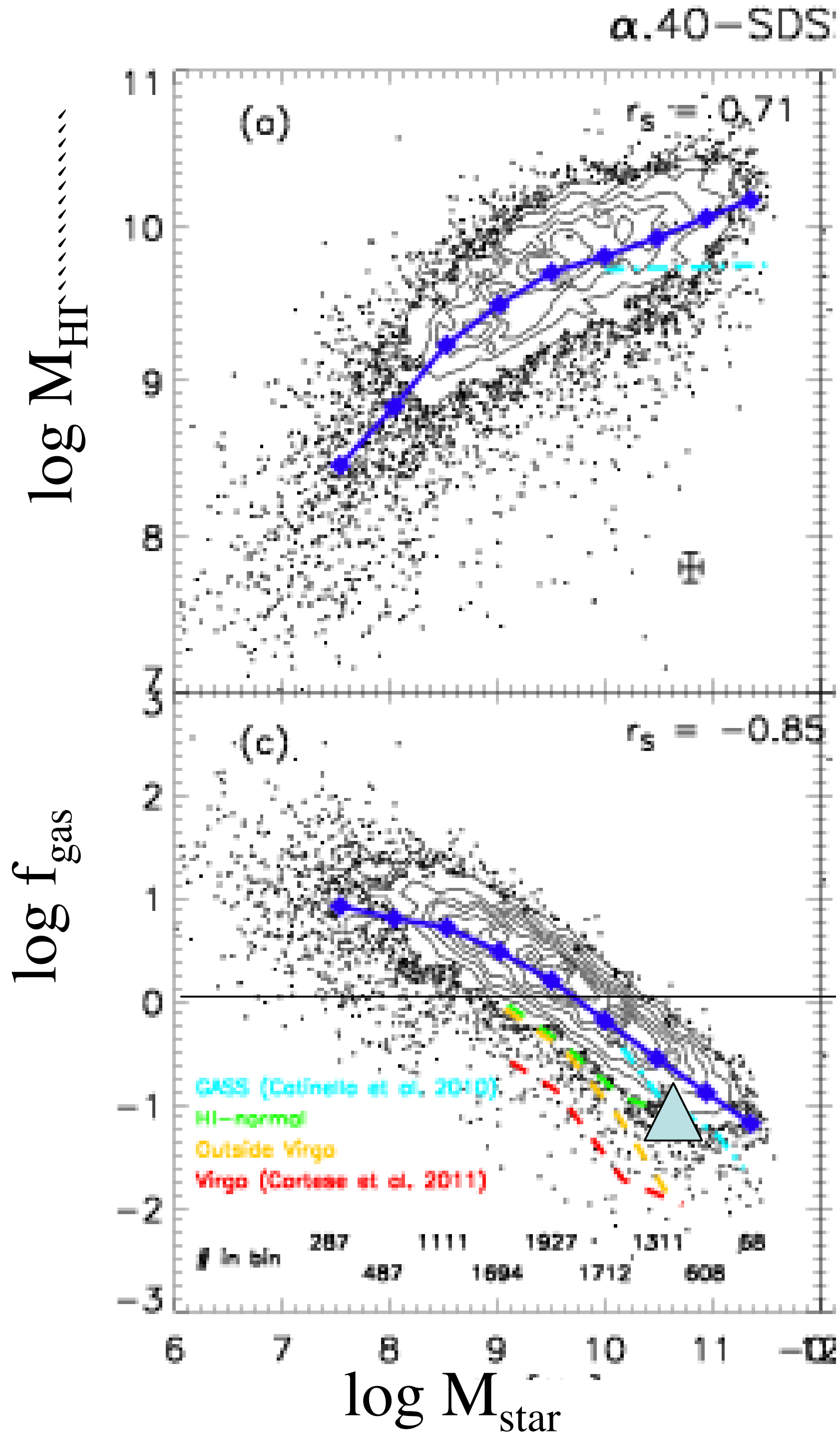


Dim in the center, brighter in the outer parts where most of the mass is

Spirals and Gas

- One of the prime ways to search for cool gas is to observe the 21cm line from HI in the radio (physics here)
- Recent large 'blind' surveys have quantified the relation between this cool gas component and other properties
- While the mass in HI gas rises with stellar mass (in blue galaxies) the fraction of mass in gas decreases- some very low mass galaxies baryon content is dominated by gas.
- Galaxies with bluer colors in general have higher f_{HI} .

Milky Way △



Summary of Spiral

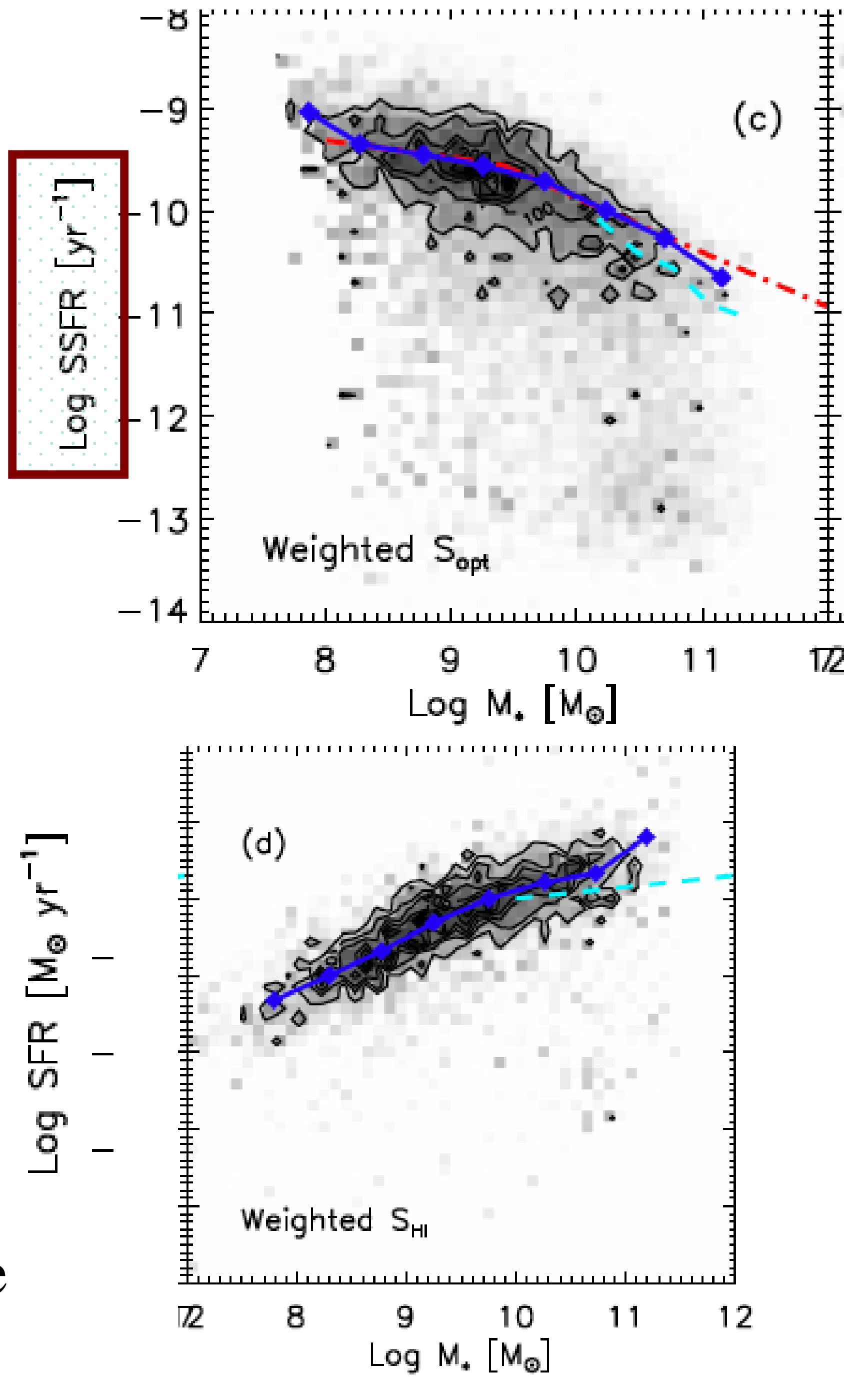
- spectra of gas shows chemical abundance, temperatures, dynamics
- Dark matter required by rotation curves, but division of total mass into components is difficult (halo/disk degeneracies)- there are ways of solving this but they are difficult and just getting started.
- Origin of spiral arms not fully understood- probably a driven instability- can also be due to mergers.

(see movie)

- Tully Fisher- relation of velocity field to luminosity- get distances this way
- HI is often used to trace dynamics- spider diagram (galaxy inclination and velocity field).
-

Star Formation and Gas

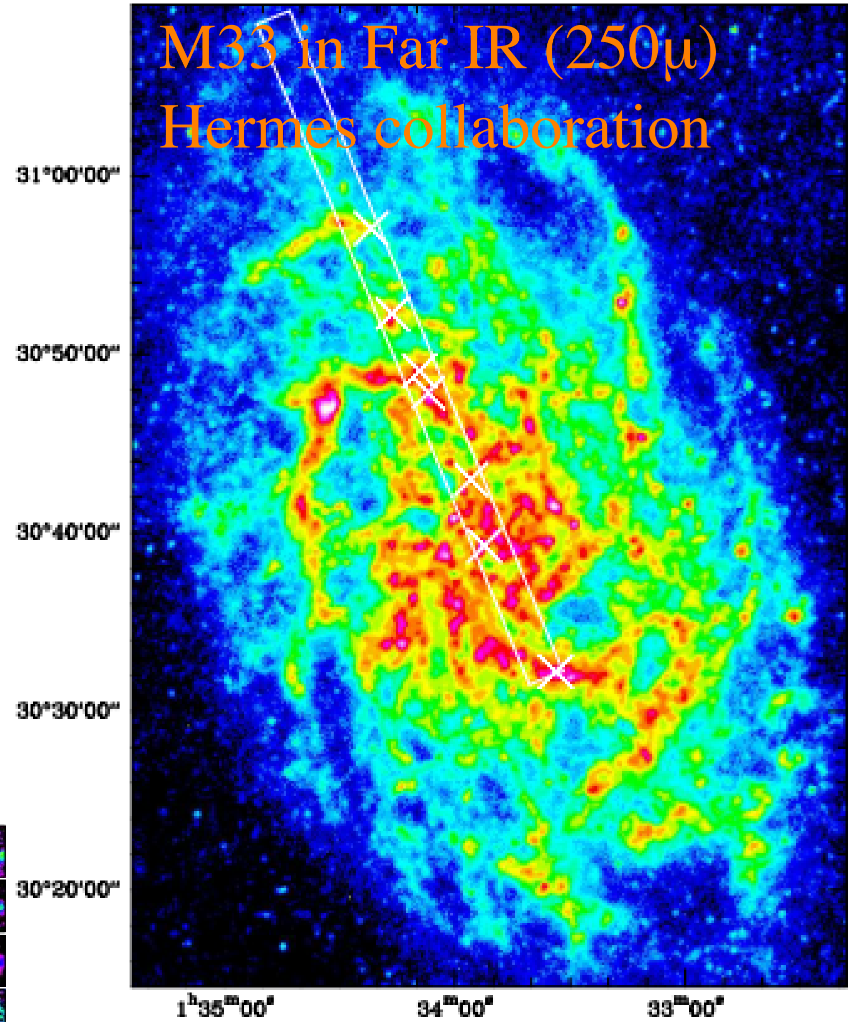
- Stars form out of cold (molecular gas) however it is difficult (at present) to perform surveys of such gas since H_2 has no strong spectral features. - use CO as a proxy- major issue is how to convert CO to H_2 it may not be constant!
- Thus one uses HI as a proxy (relation between HI and H_2 is complex-. HI and CO profiles have distinct behavior)
- Using HI one finds
  - star formation rates increase but specific SFRs decrease with increasing M_{star}
- The star formation efficiency, $SFE=SFR/M_{HI}$, mildly increases with stellar mass

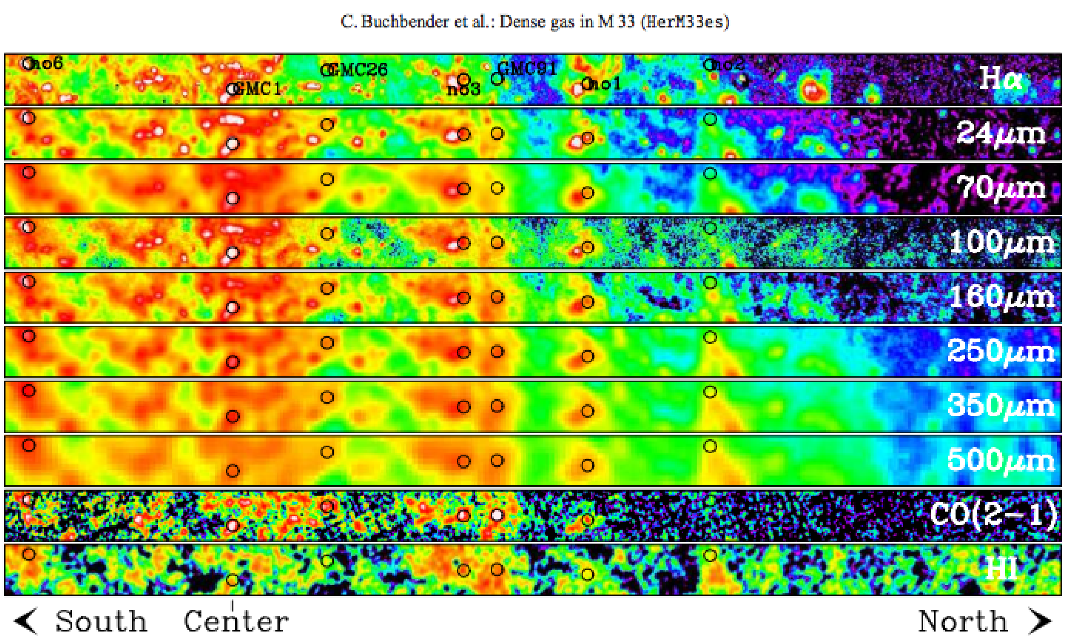


SSFR= specific star formation rate

Molecular Gas

- This is where star formation occurs
- Can now be well studied in nearby galaxies (ALMA, Herschel)





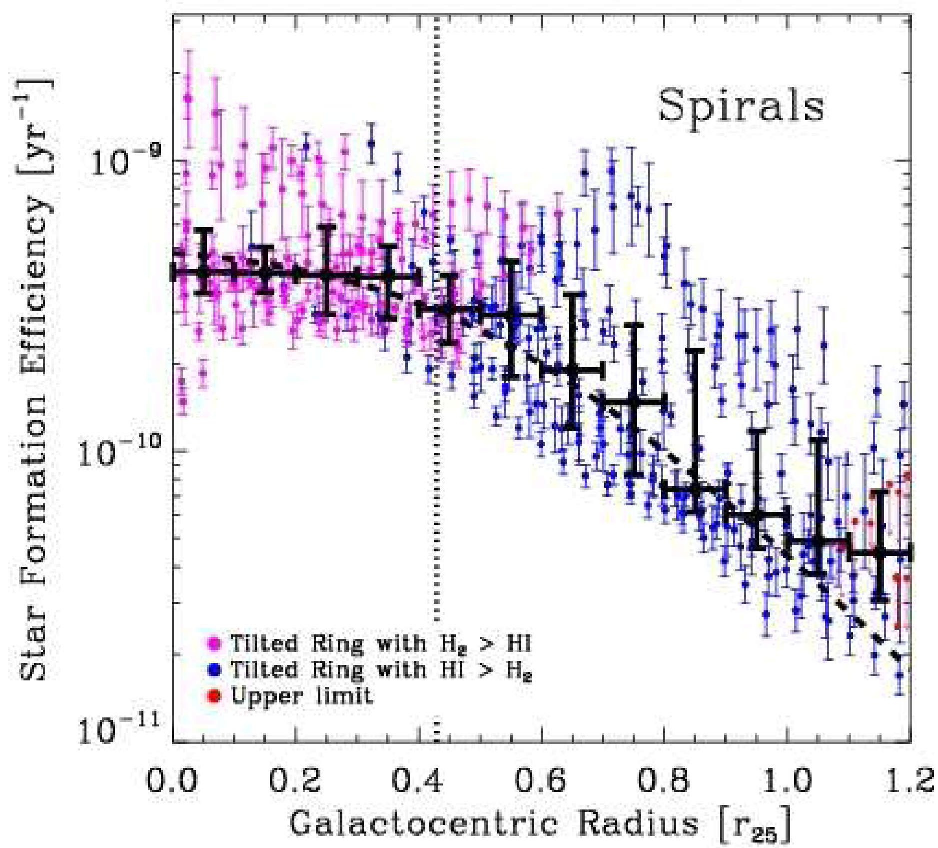
New Topic -Star Formation in Spirals

- This is an enormous subject- lots of recent work (see Kennicutt 1989 for a review)
- Broadly.. Observations of nearby galaxies have shown, over a broad range of galactic environments and metallicities, that star formation occurs only in the molecular phase of the interstellar medium (ISM).
  - Star formation is inextricably linked to the molecular clouds
  - Theoretical models show that this association results from the correlation between chemical phase, shielding, and temperature.
- Interstellar gas converts from atomic to molecular only in regions that are well shielded from interstellar ultraviolet (UV) photons, and since UV photons are also the dominant source of interstellar heating, only in these shielded regions does the gas become cold enough to be subject to Jeans instability (Krumholz 2012)
- In the MW and other well studied nearby galaxies SF occurs mostly in

  (Giant molecular clouds (GMCs, which are predominantly molecular, gravitationally bound clouds with typical masses ~ $10^5 - 10^6\ M_\odot$)- but GMC formation is a local, not a global process
- Observationally one uses CO as a tracer for H_2 (not perfect but the best we have right now). This is time consuming but lots of work has been done (Leroy et al 2008)
-

Star Formation Efficiency Vs Radius and H_2/HI

- Leroy et al (2008) - star formation efficiency (how long it would take to convert all the gas into stars) changes with galactic radius and the relative fraction of gas in H_2 and HI.
- Where H_2 is dominant the SFE is constant at about $5x10^{-10}$ yr^{-1} - takes $1/SFE \sim 2x10^{9}$ yrs to convert ALL the local gas into stars if nothing else happens (e.g. stars return gas to the ISM, gas falls into galaxy, star formation pushes gas out of galaxy...).



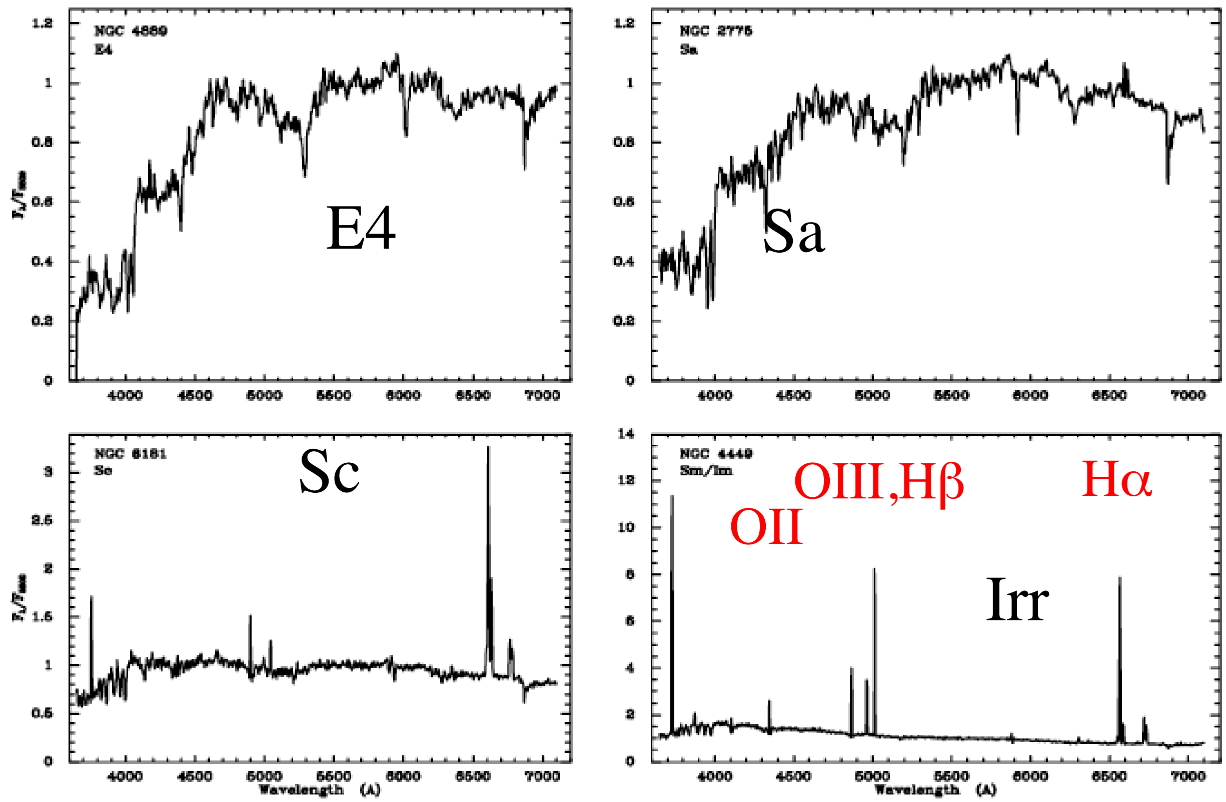
How to Normalize SFR

- Since essentially all techniques measure the total (or ionizing) luminosity of massive stars we need to transform to ALL the stars
- Use the IMF
- For Kroupa IMF
  - $\Psi(M) \sim M^{-1.4}$ $0.1<M<1$
  - $\Psi(M) \sim M^{2.5}$ $1<M<100$
- Integrate Ψ from 10-100M get .16 of all the mass (correction factor)- these are the stars which have short lifetimes and are hot and thus produce the signatures of star formation. Formation of low mass stars can only be detected in MW and Magellanic cloudsl

- How to correct various indicators
- Hα: emitted by gas ionized by stars with T_{eff}>~20,000k ($M>10M_{\odot}$) which emit photons that can ionized Hydrogen (E_{ioniz}=13.6eV) -t<20Myrs
- IR Continuum- UV light absorbed by dust
- UV continuum- direct signature of massive, young stars

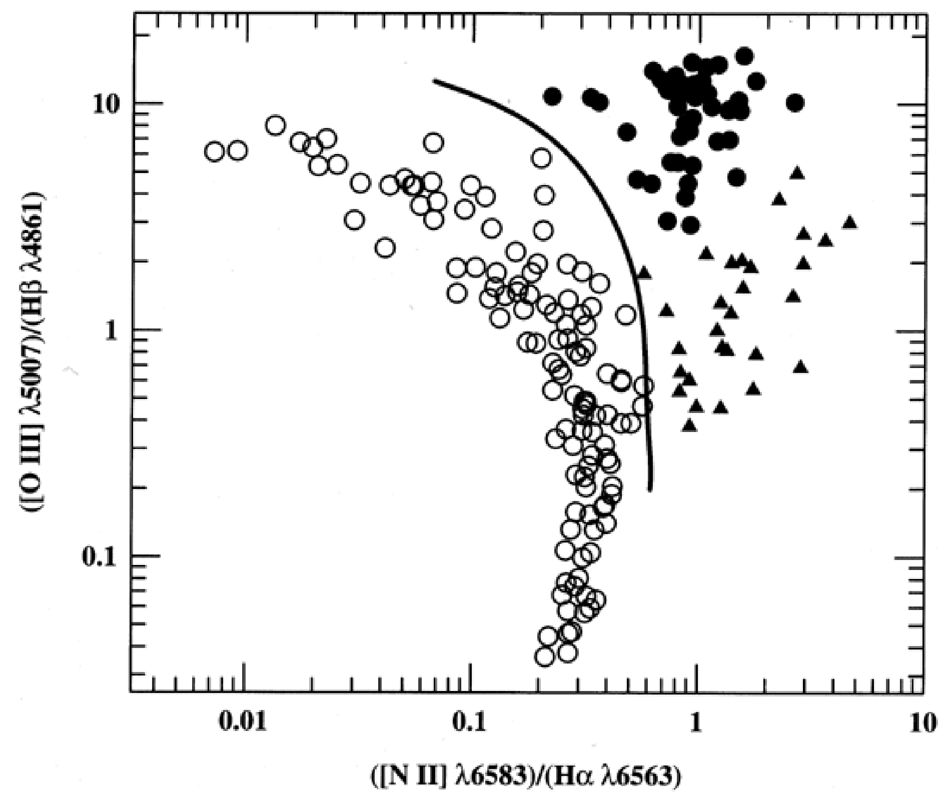
Importance of Emission Lines

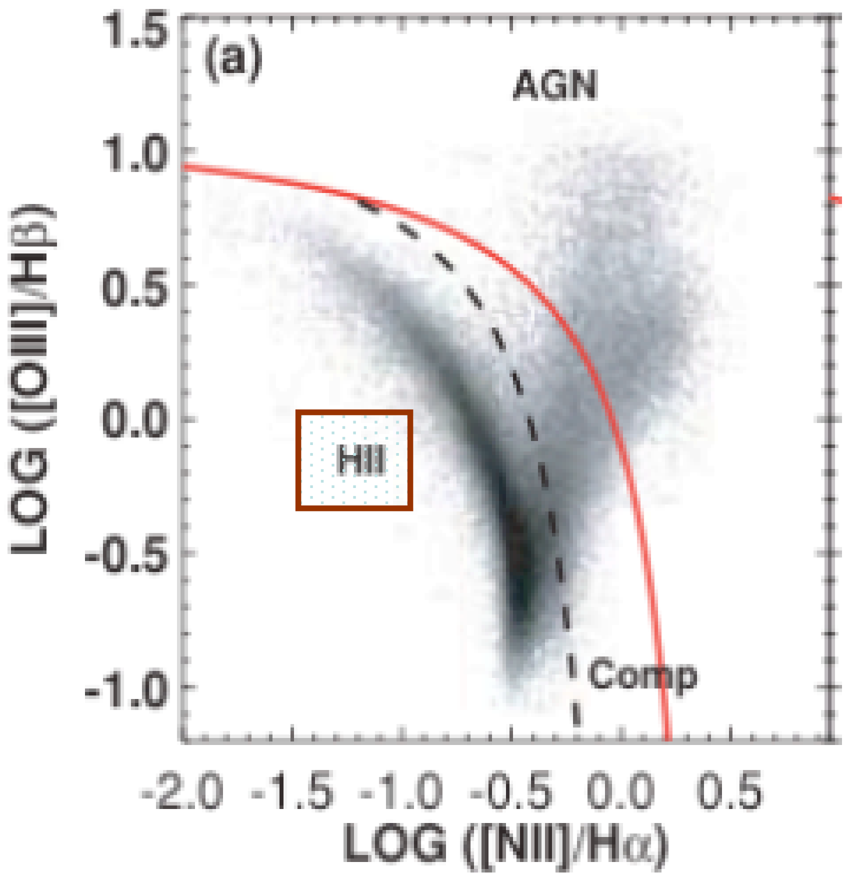
- As one moves on the Hubble sequence the galaxy spectra get more and more emission line dominates and relative prominence of lines changes
- Thus many authors use Hα or OII as SFR indicators (OIII is also produced by active galaxies and so it is often difficult to separate AGN from star formation)



Kennicutt 1998

- From spectroscopy how does one classify a galaxy as star forming or an AGN??
- Observe strong lines to make life easier- but these are not necessarily to most diagnostic.

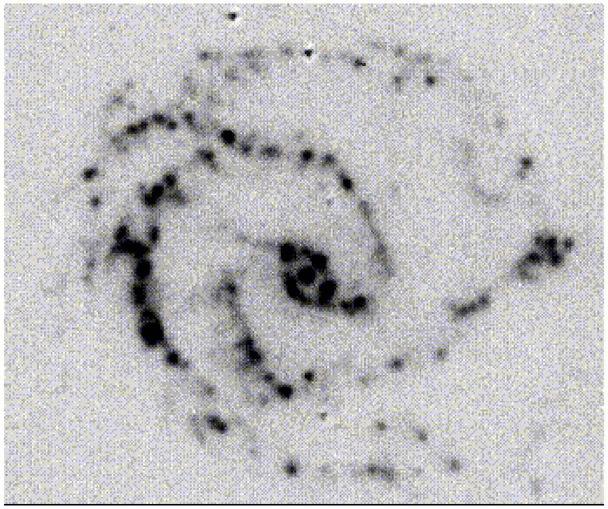




Different lines have different dependences on temperature excitation mechanism (collisions, photoionization)
Ratios of certain lines (chosen to be close in wavelength do dust is not an issue)
AGN have 'harder' radiation field (higher UV/optical) and collisional excitation less important than in star forming regions.

How to Determine SFR from Observables-Hα or Hβ

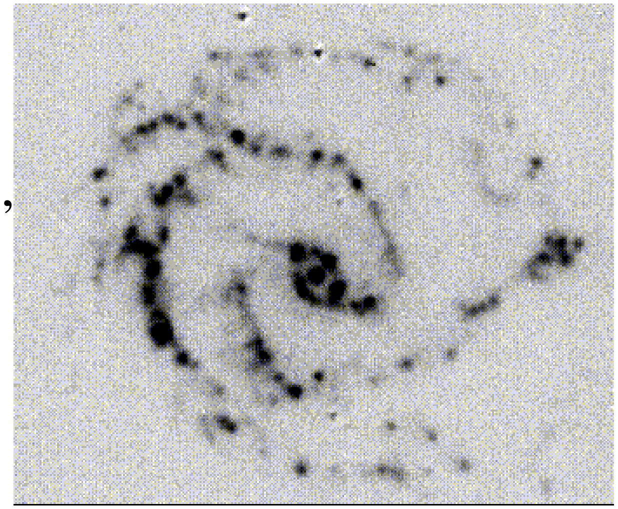
- The strength of the emission lines is the convolution of the number of ionizing photons, the fraction of them that are absorbed and the physical conditions of the gas.
- Simplifying assumptions: gas of constant temperature, given IMF, gas is internally dust free, Case B (optically thick to ionizing continuum)(Hα/Hβ=2.9)
  - Hα only comes from ionized gas (HII regions)- very non-uniform images (pearls on a string)
- For one type of star (O7) one can calculate the number of Hα photons= 10^{38}ph/sec
- Using stellar models and the IMF one ends up with SFR($M_{\odot}$/yr)=L(Hα)/7x10^{41} ergs/sec for M>10$M_{\odot}$ stars or
- SFR($M_{\odot}$/yr)=L(Ha)/1.1x10^{41} ergs/sec for all stars
- while this seems great, have to worry about dust, the age of the population- the equation assumes a zero age IMF. The older the population is, the less Hα there is- harder to see how much star formation occurred if it has turned off and the system is more than 20Myrs old.
- http://www.astr.ua.edu/keel/galaxies/sfr.html



Hα image of a star forming galaxy

How to Determine SFR from Observables-Hα or Hβ

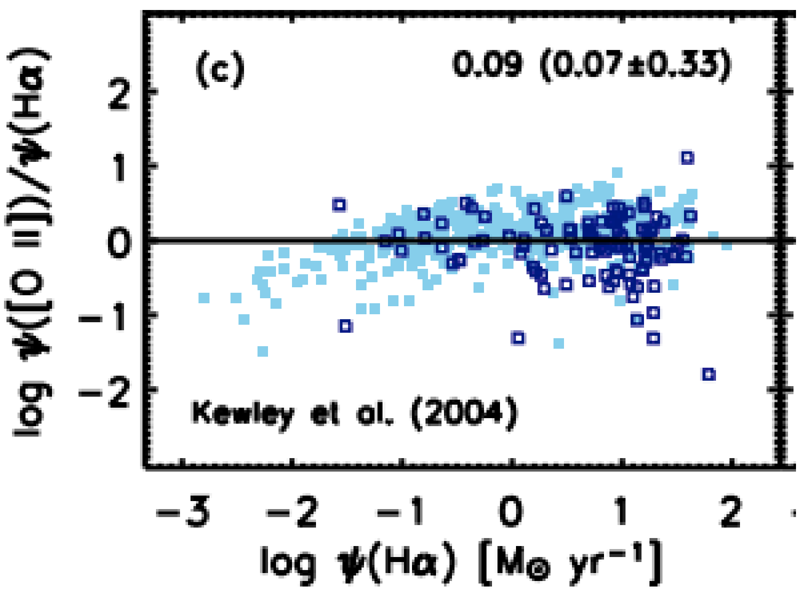
- Young, massive stars produce copious amounts of ionising photons that ionize the surrounding gas. Hydrogen recombination cascades produce line emission, including the well-known Balmer series lines of Hα (6563 A) and Hβ (4861 A), which, are strong.
- Only stars more massive than $20M_{\odot}$ produce an ionizing photon flux.
- In a stellar population formed through an instantaneous burst with a Kroupa IMF the ionizing photon flux decreases by two orders of magnitude between 5Myr and 10Myr after the burst.
- So Hα measures the 'instantaneous' star formation rate



Hα image of a star forming galaxy

How to Determine SFR from Observables-[OII]

- [OII] (a forbidden line, collisionally de-excited in dense gas) is the next most prominent line and is visible until z~1.4 from the ground (Hα is only visible to z~0.4)
- Calibrate it empirically using Hα since its luminosity is not directly coupled to the ionizing continuum (it is collisionally excited, not a cascade from photoionization) - but fairly wide variation in Hα /O[II]makes it noisier.



Ratio of SFR from [OII] to Hα rate vs Hα rate (Moustakas 2006)

UV Continuum

- in principle great- direct measure of total luminosity of young massive stars.
- Three big problems
  - DUST- UV extinction is much larger than in optical - light that is absorbed is re-emitted in the IR -the most active and luminous systems are also richer in dust, implying that they require more substantial corrections for the effects of dust attenuation;
    - effects of dust are BIG- A_V =0.9 produces a factor ten reduction in the UV continuum at 1300A.
  - Observations show that at 'low' SFR dust is not a big effect, at high values critical
  - at low redshift must observe from space -
  - VERY sensitive to IMF- at best can only constrain 15% of all the stars forming
  - For a Kroupa IMF with with constant star formation over >100Myr

$$SFR(UV) M_\odot/yr = 3.0 \times 10^{-47} L_{UV}(ergs/sec)(912\text{-}3000A)$$

IR Continuum

- Direct observations show that ~1/2 of total galaxy light in spirals appears in IR
- This is thermal emission emitted by dust as a grey body
- Wavelength at which emission peaks is related to temperature of dust

8μ ~360k, 24μ ~121k, 70μ ~40k, 160μ ~20k

$T \sim \lambda^{-1}$ but $L \sim AT^4$ so to get a lot of luminosity at long wavelengths needs a large area, A

(these are the common wavelengths for IR space borne instruments IRAS, Spitzer, WISE, Herschel)

Temperature is set primarily by equilibrium energy absorbed=energy emitted and physics of dust grains.

Most galaxies are dominated by T~20-40K dust, rapid star forming galaxies up T ~100k.

Need wide range of temperatures to produce observed spectra.

Roughly SFR (M/r)=$L_{\text{total IR}} \times 4.5 \times 10^{-44}$ ergs/sec (integrating IR from 8-1000μ)

Advantages- relatively free from extinction, can do at high z with Herschel

Problems- requires lots of assumptions and scaling. Need to assume continuous SF

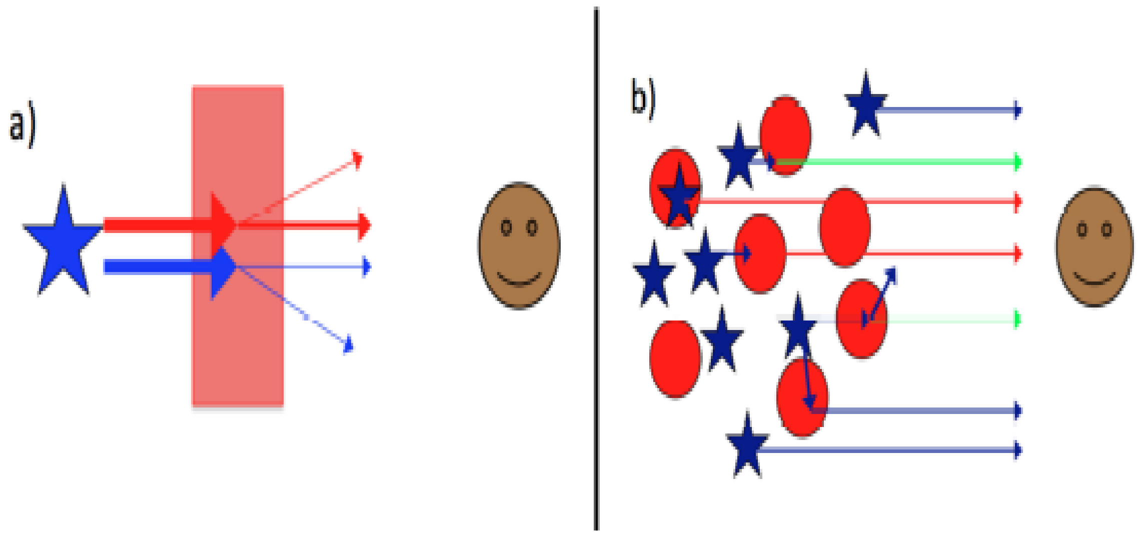
IR Continuum

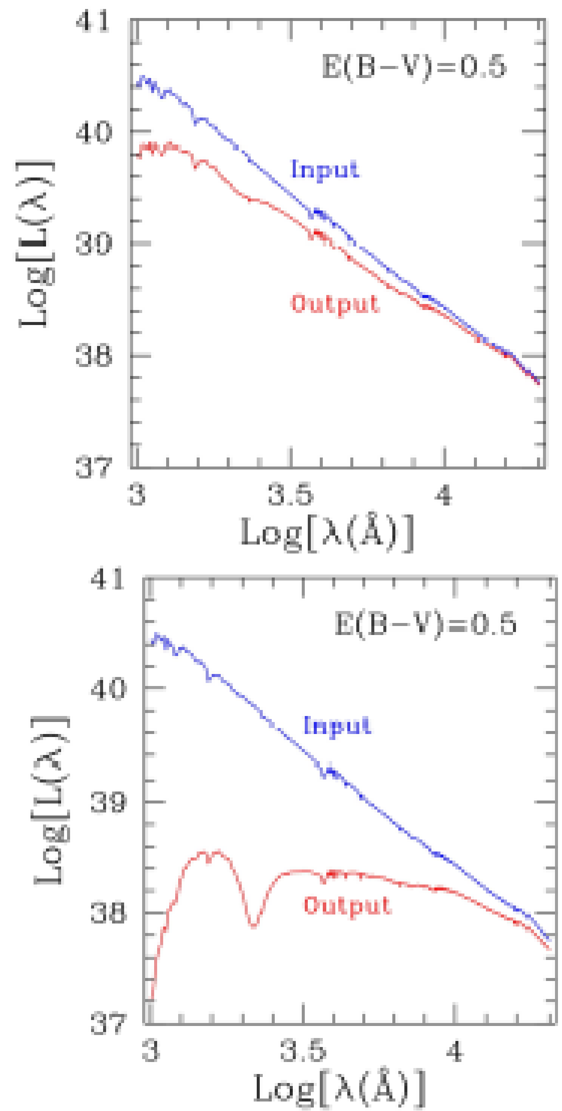
- Ideal for starburst galaxies because:
- Young stars dominate UV-optical radiation, $\tau > 1$, $L_{IR} \sim L_{SB}$

and cross-section of the dust grains for stellar light is higher in the UV than in the optical

- Not ideal for SF in disks of normal galaxies because:a fair fraction of the IR luminosity is produced by dust re-radiation of emission from 'old' stars e.g. cirrus in the MW. - that is the calibration between SFR and L_{IR} depends on the age of the system

Geometry is a serious issue- the same amount of dust has different effects

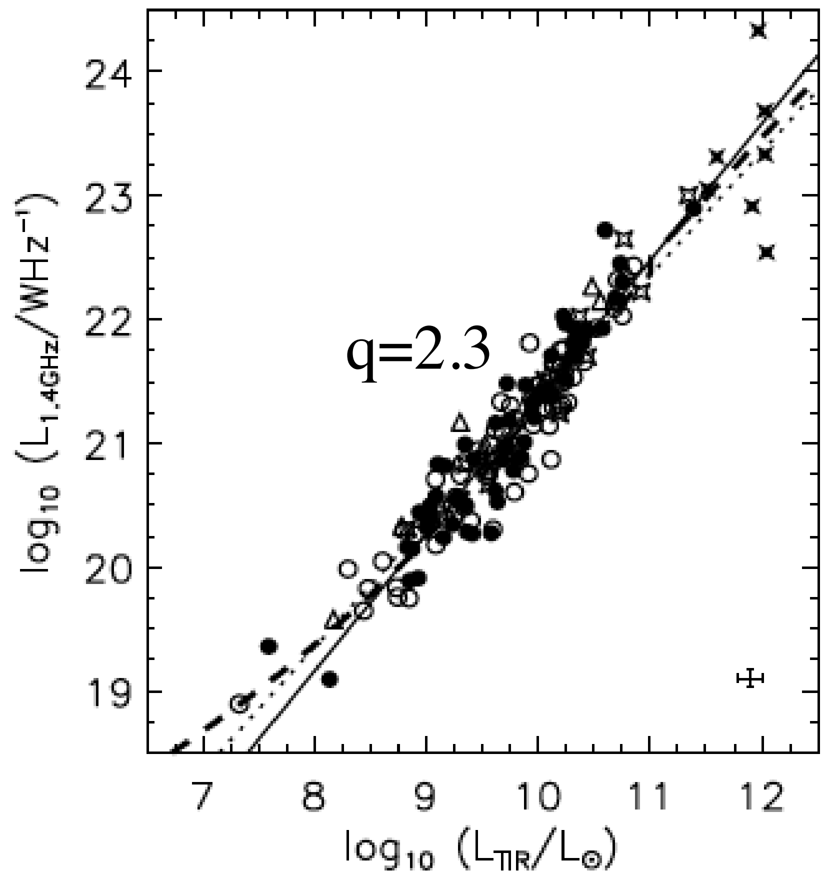




Star Formation- Radio View

- Radio continuum emission from star-forming galaxies has two components: thermal bremsstrahlung from ionized Hydrogen and non-thermal synchrotron emission from cosmic ray electrons spiraling in the magnetic field of the galax
- The relative ratio is frequency dependent because of the different spectral slopes of the 2 processes ($F_\nu \sim \nu^\alpha$, α=-0.7 for synch, 0.1 for TB)
- This method does not depend on how one handles dust or ionizing continuum, very high angular resolution, short loss time fo relativistic e-s means look at young phenomena.
- But physics is not fully understood- why cosmic rays/magnetic field are so finely tuned.

$$q = log\left(\frac{FIR}{3.75 \times 10^{12} \mathrm{W\ m^{-2}}}\right) - log\left(\frac{S_{1.4\mathrm{GHz}}}{\mathrm{W\ m^{-2}\ Hz^{-1}}}\right)$$



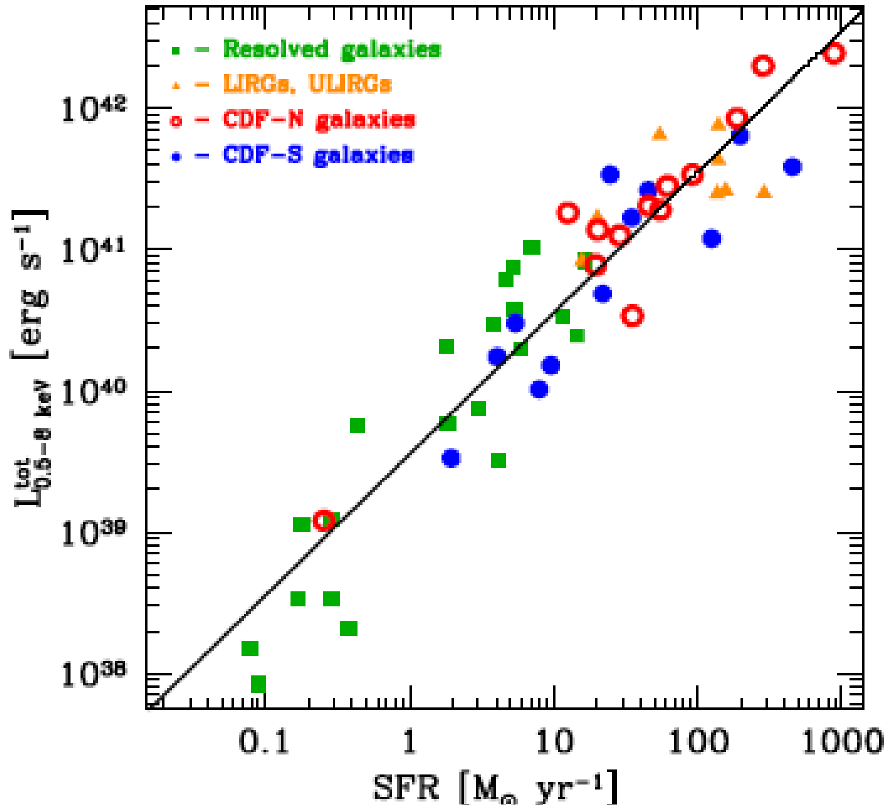
Bell 2002

Star Formation X-rays

Mineo et al 2012

- In a rapidly star forming galaxies x-rays are produced by

1) high mass x-ray binaries $\tau \sim 2x10^7$yrs
   surprisingly the luminosity function of these sources is very similar from galaxy to galaxy with only the normalization~SFR changing
2) hot gas from Supernova- results imply that only 5% of SN energy is needed to produce "diffuse" x-rays



major advantage of x-rays: do not need to be concerned about dust, can do this at high redshift

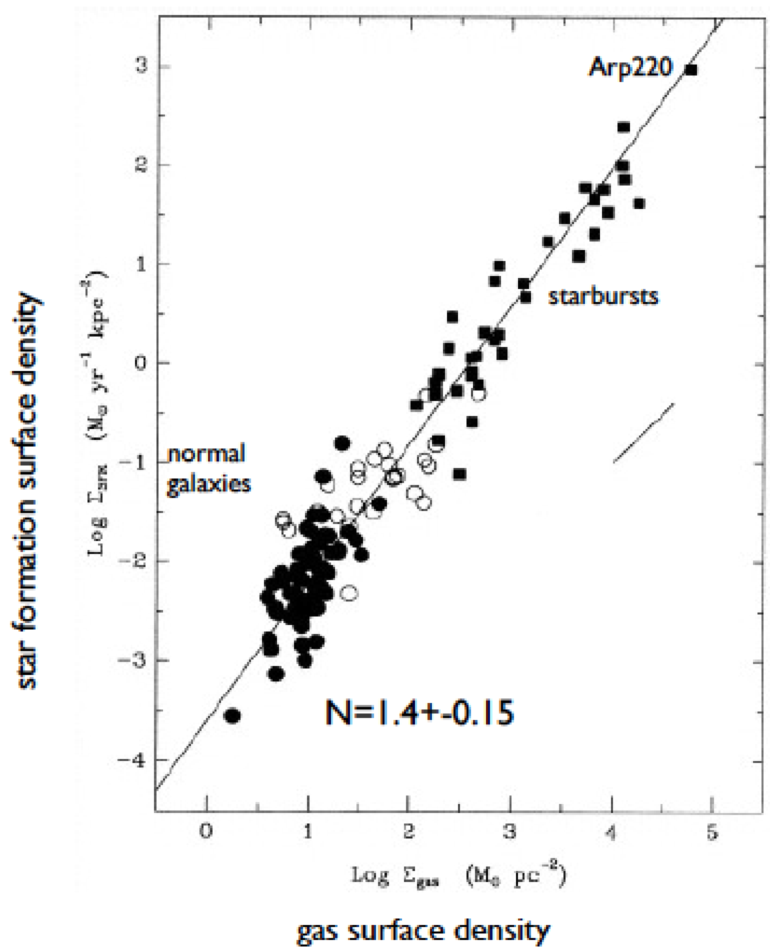
Kennicutt Schmidt Law

- Assume that SFR rate is proportional to total amount of gas
- SFR~ρ_{gas}~dρ_{gas}/dt; sol't ρ_{gas} ~$\rho(0)_{ga}e^{-t/\tau}$

- More generally assume SFR~$\rho^n{}_{gas-}$
- e.g. as gas compresses stars form more easily or there maybe another timescale in the process such as the free-fall time of the gas SFR~$\rho_{ga}/t_{freefall}$
- **Frequently this expressed in terms of surface density (an observable)**
- Σ_{SFR}=A$\sigma^n{}_{gas}$ n~1.4 can be explained by
- stars form with a characteristic timescale equal to the free–fall time in the gas disk, which in turn depends inversely on the

square root of the gas volume density, τ_{ff} ~$\rho^{-1/2}{}_{gas}$ **for a fixed scale height ρ_{gas} ~Σ_{gas}**

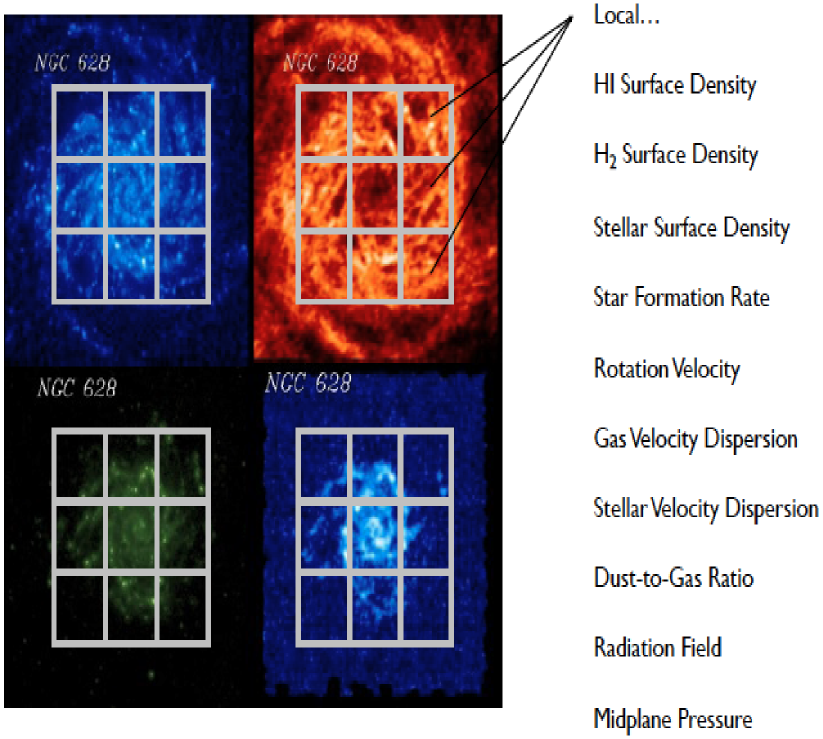
Problem is that the gas consumption efficiency is low ~1.5x10^9yrs to consume the gas



Kennicutt 1998

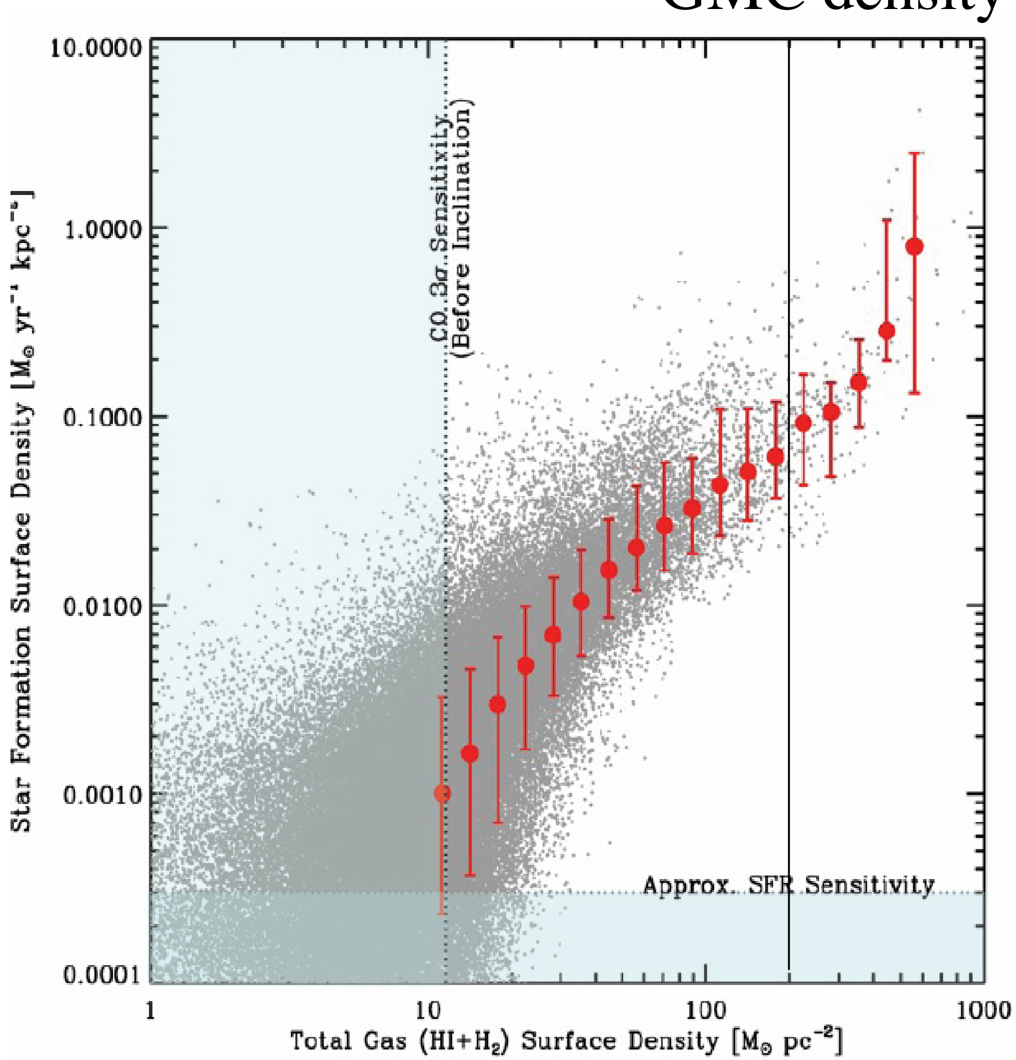
Kennicutt-Schmidt Updated

- SFR depends on surface density of molecular gas
- (red points are averages, **gray points are individual samples in galaxies)**



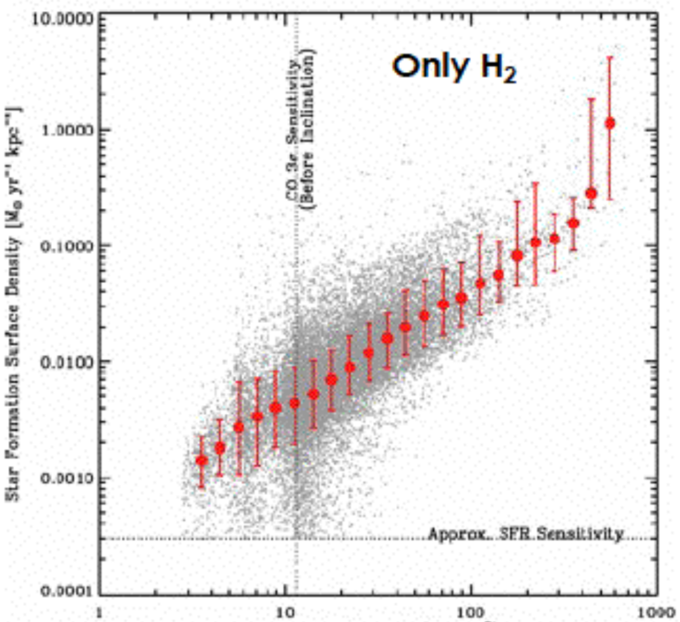
F. Walter

GMC density

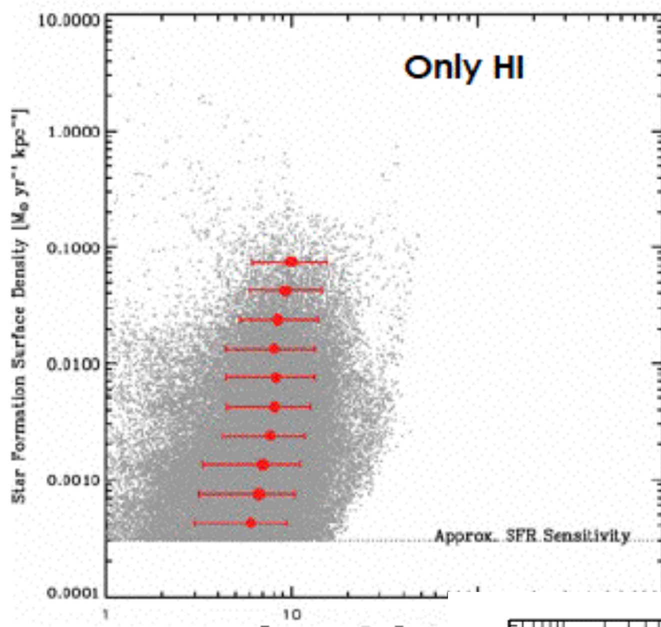


Only H_2 Counts

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

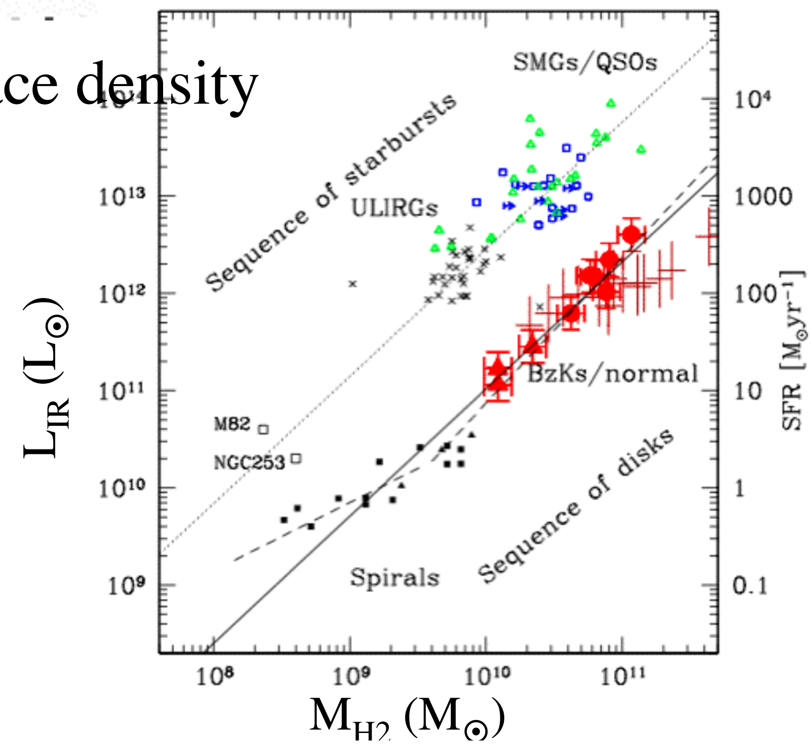


H_2 Surface density



HI Surface density

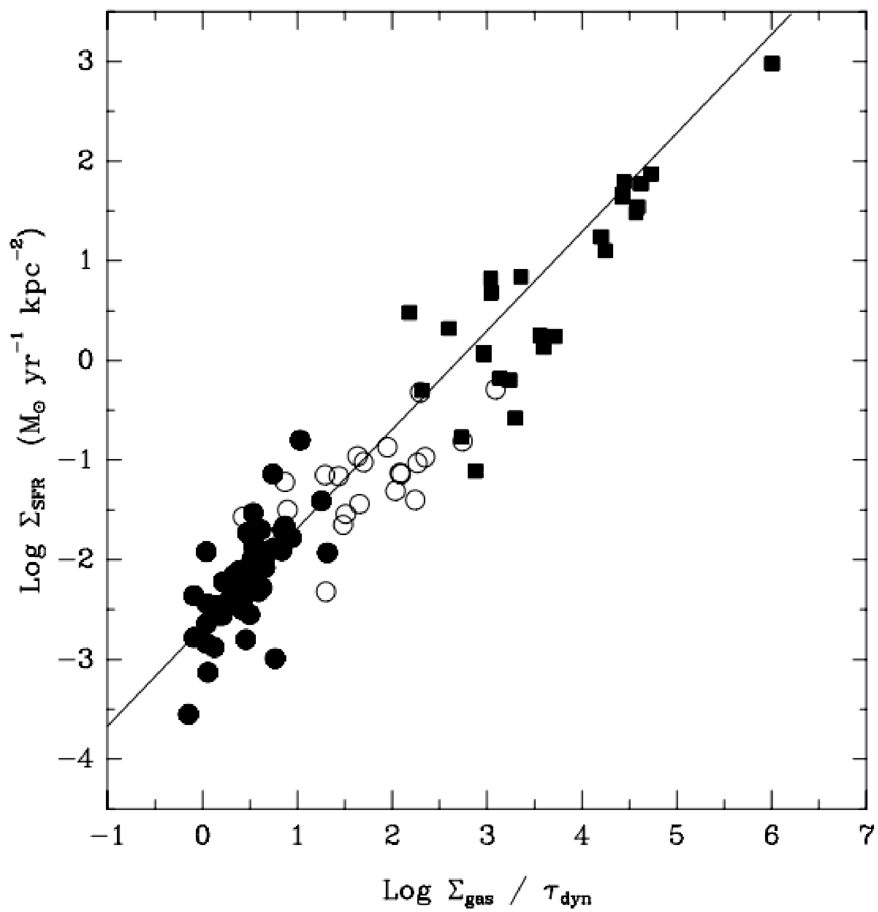
stars seem to form only in dense molecular gas...



- 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 very rapid SF galaxies are different

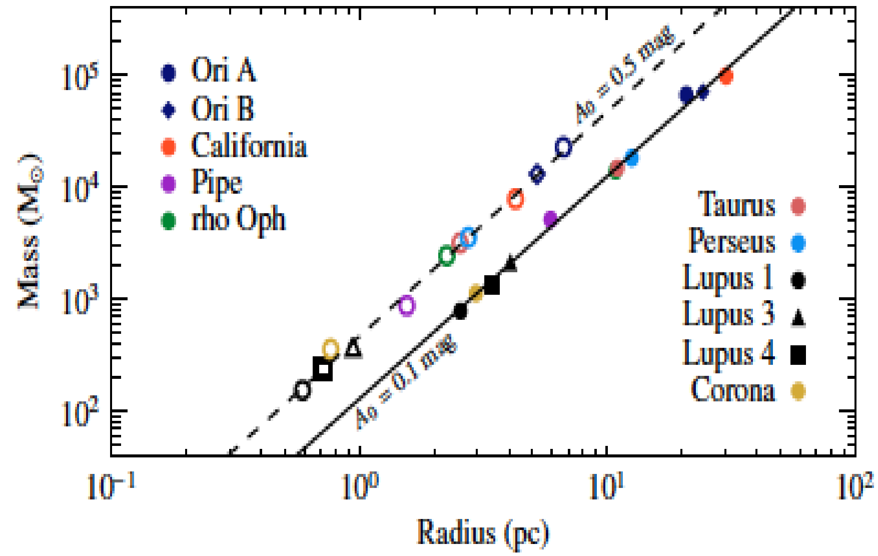
Kennicutt Schmidt Continued

- What other scaling relations seem to hold?
- Kennicutt shows that Σ_{SFR} is also correlated with $\Sigma_{gas}/\tau_{dynamical}$ in a galaxy sample (but not inside a galaxy!)
- where $\tau_{dynamical}$ is the orbital time at the radius of the star forming region $2\pi R/V_{rot}(R)$
- In a disk galaxy there is another restoring force (other than pressure) which is important for the Jeans criterion- conservation of angular momentum (Coriolis force)
- Perturbations are unstable to gravitational collapse if
- $Q=c_s\kappa/pG\,\Sigma_{mass}<1$ where κ is the epicyclic freq (MBW 9.10)
- The KS$\tau_{dynamical}$ law follows if Q<1 (Silk)



Molecular Clouds

- this is a vast subject with lots of details- not discussed in text
- As the gas density increases the fraction that is molecular increases rapidly (a sharp transition)- H_2 forms on dust grains when it is cold
- These clouds are in rough virial equilibrium $2GM/\sigma^2=R$, $M\sim R^2$, $\delta V\sim R^{1/2}\sim\rho^{-1/2}$
- $M\sim10^5$-5×10^6M, r ~10's pc $n_{H2}\sim100$-$500cm^{-3}$ but there is a lot of structure, in protostellar cores density much higher
- Cold T~10k (in MW) - UV light cannot penetrate- heating by Cosmic rays (?)- quite turbulent
- Strongly associated with young star clusters- short lived (?) $t\sim10^7$ yrs



If self gravitating isothermal spheres collapse if mass exceeds the Jeans mass

$M_j\sim40M(c_s/0.2km/sec)^3\,(n_{H2}/100)^{-1/2}$

which they do by a lot~!
collapse on free fall time

$t_{ff}=(3\pi/32G\rho)^{1/2}\sim3.6\times10^6\,(n_{H2}/100)^{-1/2}$yrs

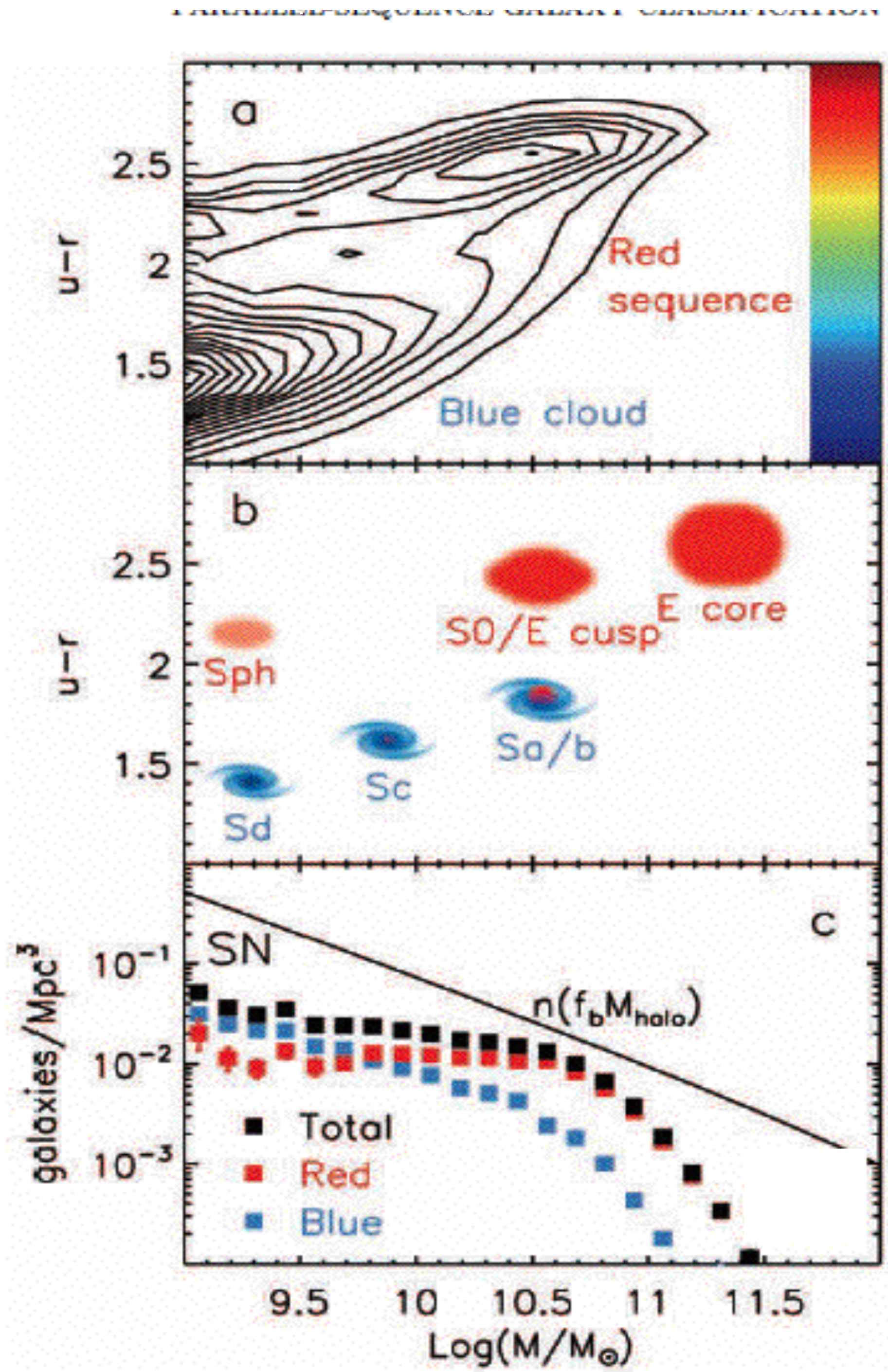
The Big Picture- Two Populations

- 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

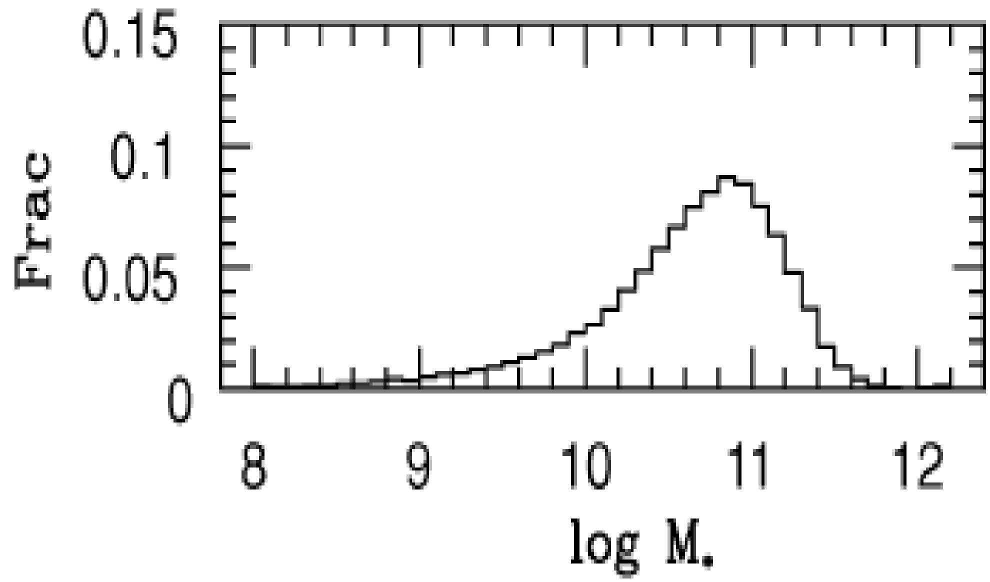
bottom panel shows the galaxy mass function divided by color (Cattaneo et al 2009)-

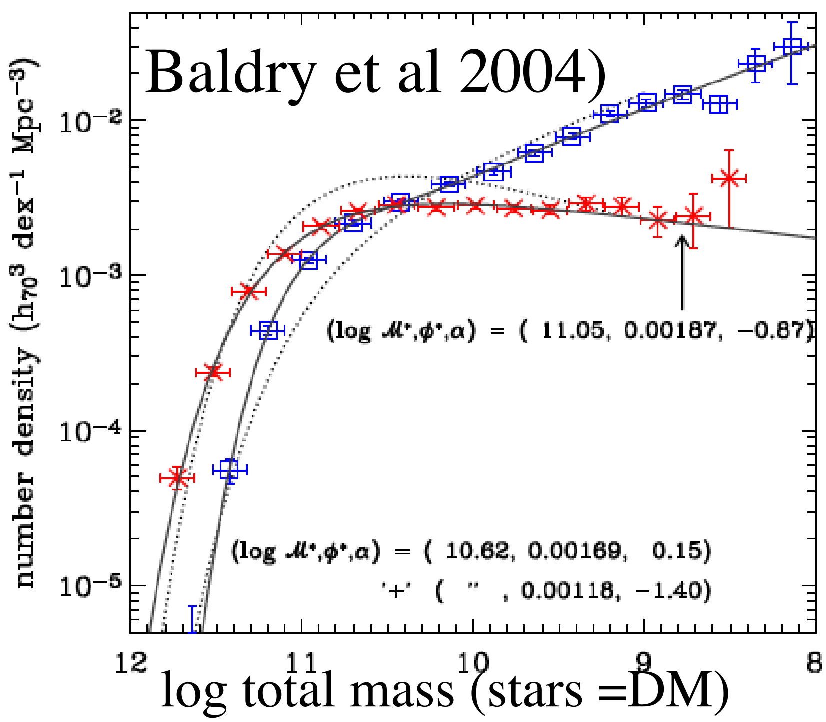
the black solid line is the prediction from cold dark matter theory of the number density of halos vs mass- <u>notice does not agree with the galaxy mass distribution</u>

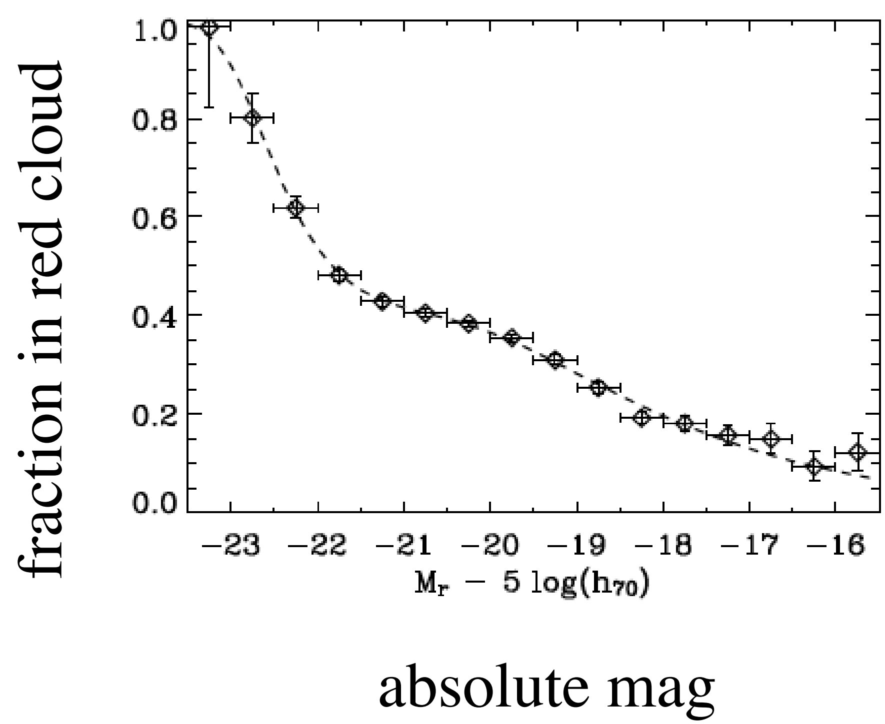


Where is the Stellar Mass

- 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

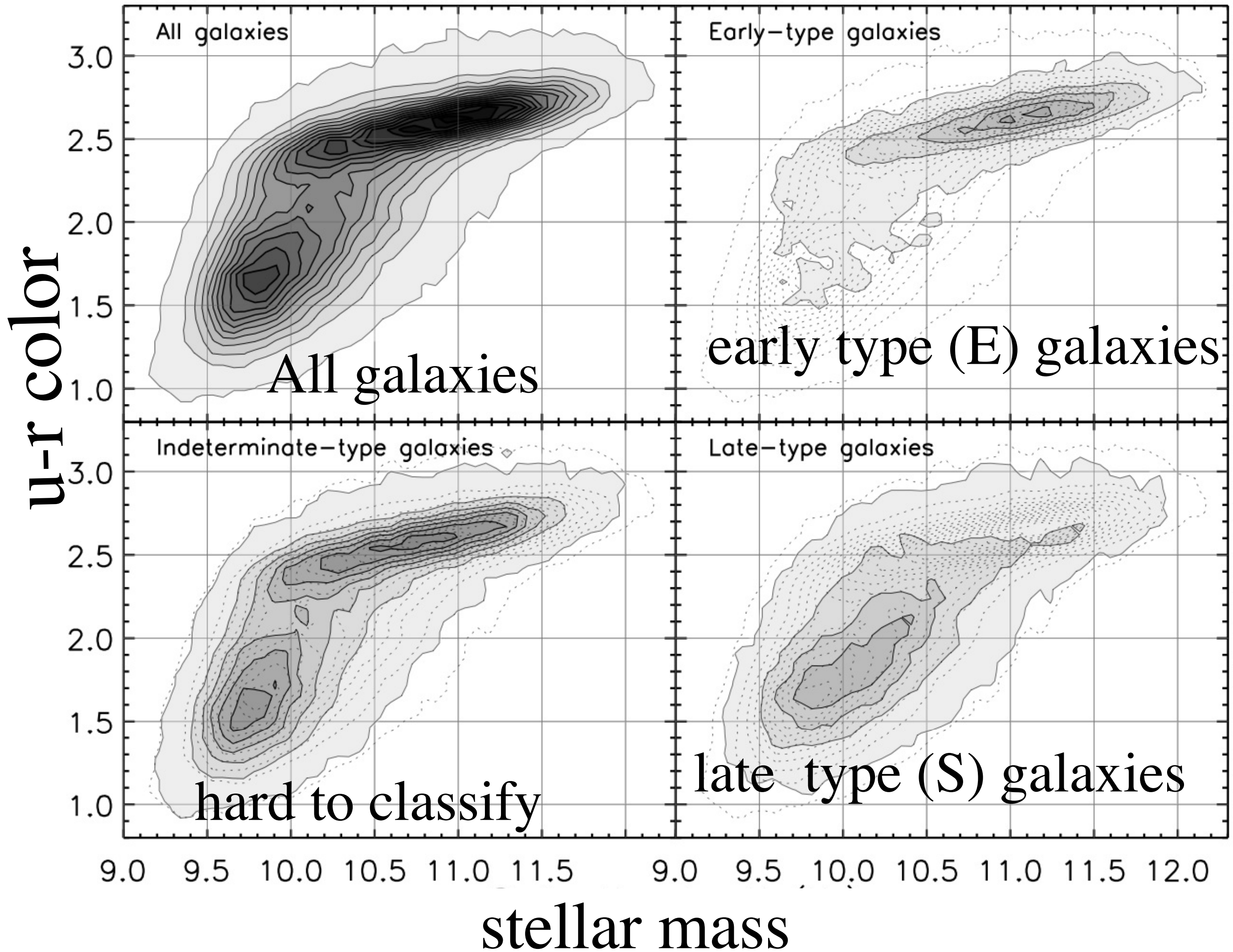






Morphology/ Color and Mass

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

Star Formation

The physics of star formation (what processes produce stars) and the astrophysics (where and when were the stars produced) are two of the dominant issues in astrophysics at present- unfortunately they are not covered by the text.

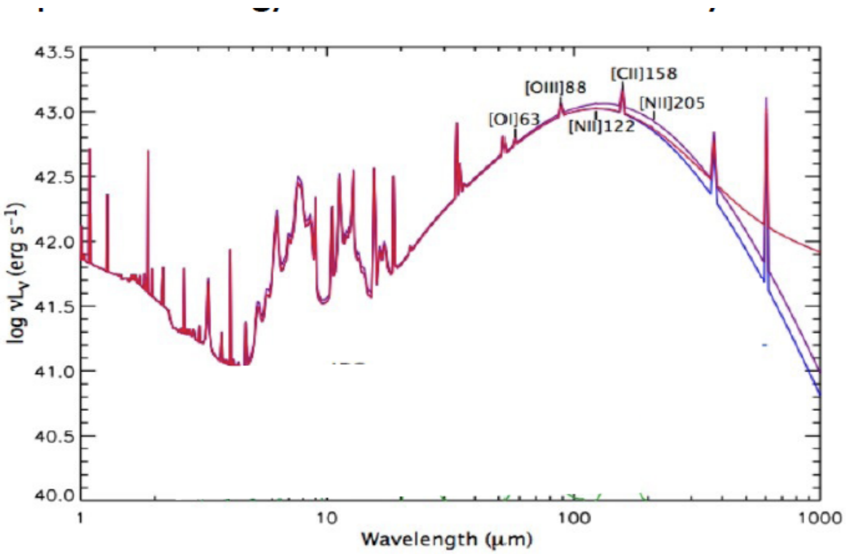
- Stars form from dense, cold gas either in disks or in gas that is violently shock compressed (in mergers)

Current SF can be estimated from a variety of techniques

- Hα observations, which gives the number of ionizing photons if one assumes that all ionizing photons are used and eventually re-emitted - ionizing photons are almost exclusively emitted by massive (hot) stars which have short lifetimes; slo the effects of dust can be large
- far-IR flux - this assumes that a constant fraction of the emitted stellar energy is absorbed by dust
- radio continuum emission - this statistically correlated very well with the IR radiation- physics is complex since radio emission comes from synchrotron radiation from relativistic electrons+ thermal bremmstrahlung from hot gas
- far-UV flux (- which is primarily emitted by young (hot) stars- but older /less massive than those responsible for Hα
- X-ray emission- produced by 'high mass' x-ray binaries (a Neutron star or black hole with a massive companion

Star Formation-IR View

- In systems with ongoing SF, the light from both newly formed and older stars can be absorbed by dust and reprocessed into the IR.
- i)What are the relative contributions of old and young stars to the IR luminosity?
  - in non-rapidly star forming galaxies it is roughly 50:50
  - in rapidly star forming galaxies almost all is due to young stars.
  - But lots of subtleties (e.g. the effect reprocessing fraction seems to be a function of star formation rate).
- ii) How much light is reprocessed into the IR?
- Observationally the effective temperature of the dust has only a small range when averaged over a whole rapidly star forming galaxy.



...long wavelengths dominated by dust emission and spectral lines.