Spiral Galaxies- alias Disk Galaxies- MBW ch 11

Brief summary of scaling relations
•Brighter disks are, on average, larger, redder, rotate faster, and have a smaller gas mass fraction
•Disk galaxies have flat rotation curves.
• The surface brightness profiles of disks are close to exponential.
• The outer parts of disks are generally bluer, and of lower metallicity than the inner parts.

Take a look at 11.1 for a review of disk potential models and orbits
we will not cover 11.2 - The origin of disk galaxies, but its worth a read

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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

NGC 4594··Hubble Heritage   NGC 4762 SDSS gri

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.

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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   4
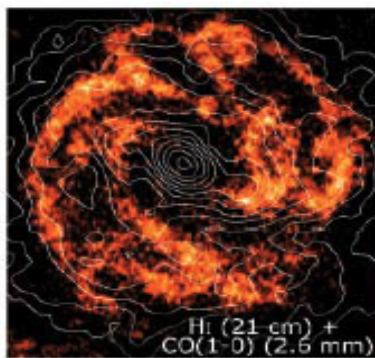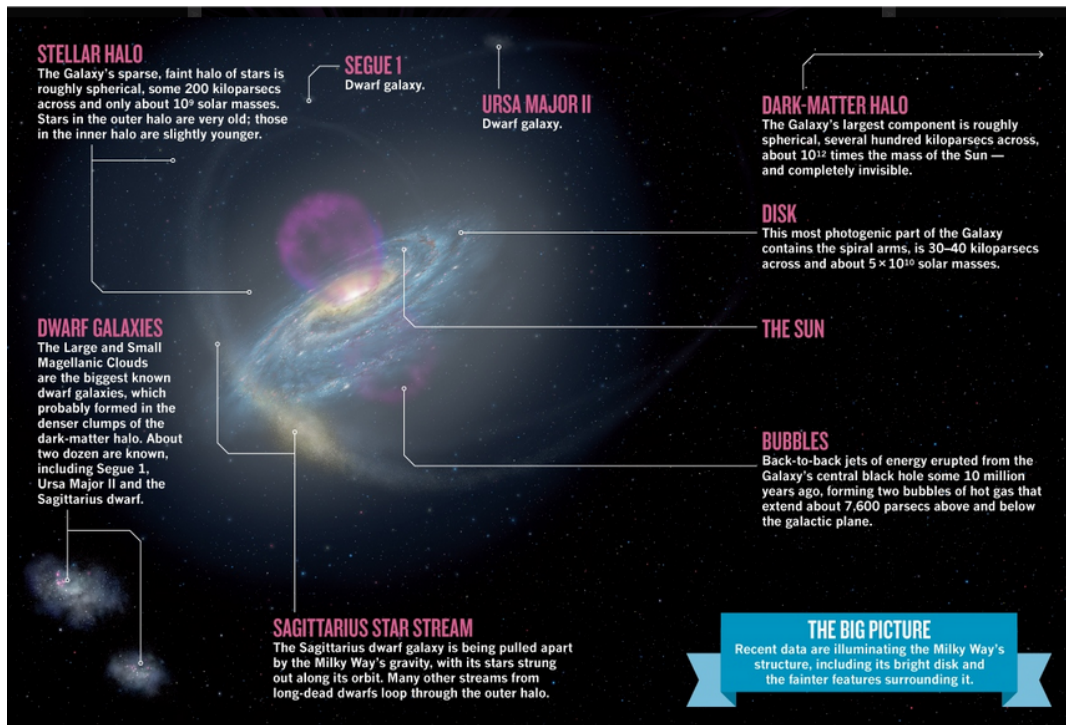
Mostly disk…

A Bit of the Galaxy Zoo
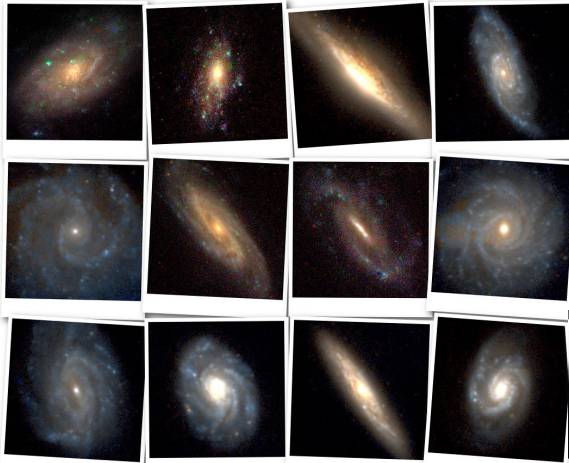
Mostly spheroid…
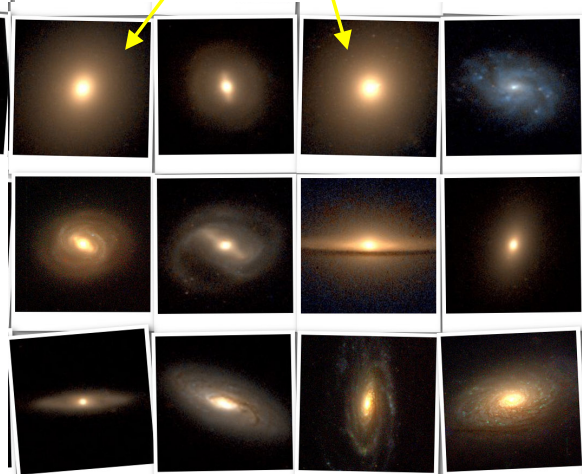
- Disk-bulge separation is tricky and influenced by inclination angle and dust and wavelength observed (disks standout in the blue, bulges in the red)

- 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**.

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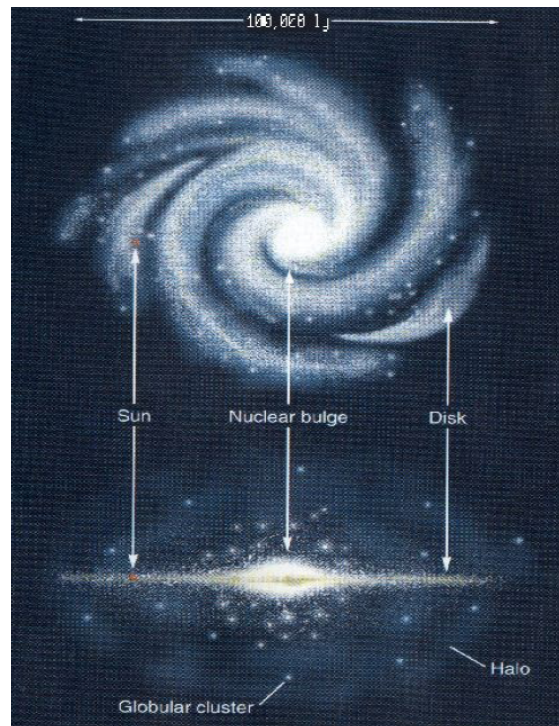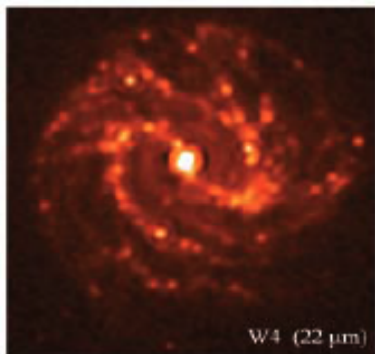
- there is a major review article in Nature last year called" Galaxy formation: The new Milky Way" (http://www.nature.com/news/galaxy-formation-the-new-milky-way-1.11517). This overlaps considerably with the material we have been covering

STELLAR HALO
The Galaxy's sparse, faint halo of stars is roughly spherical, some 200 kiloparsecs across and only about 10⁹ solar masses. Stars in the outer halo are very old; those in the inner halo are slightly younger.

SEGUE 1
Dwarf galaxy.

URSA MAJOR II
Dwarf galaxy.

DARK-MATTER HALO
The Galaxy's largest component is roughly spherical, several hundred kiloparsecs across, about 10^{12} times the mass of the Sun — and completely invisible.

DISK
This most photogenic part of the Galaxy contains the spiral arms, is 30–40 kiloparsecs across and about 5×10^{10} solar masses.

DWARF GALAXIES
The Large and Small Magellanic Clouds are the biggest known dwarf galaxies, which probably formed in the denser clumps of the dark-matter halo. About two dozen are known, including Segue 1, Ursa Major II and the Sagittarius dwarf.

THE SUN

BUBBLES
Back-to-back jets of energy erupted from the Galaxy's central black hole some 10 million years ago, forming two bubbles of hot gas that extend about 7,600 parsecs above and below the galactic plane.

SAGITTARIUS STAR STREAM
The Sagittarius dwarf galaxy is being pulled apart by the Milky Way's gravity, with its stars strung out along its orbit. Many other streams from long-dead dwarfs loop through the outer halo.

THE BIG PICTURE
Recent data are illuminating the Milky Way's structure, including its bright disk and the fainter features surrounding it.

M 83: from Gas to Stars

HI (21 cm) + CO(1-0) (2.6 mm)
Neutral gas is the *reservoir*, molecular gas fuels the star formation

FUV + NUV (0.15 + 0.23 μm)
Young hot stars represent the current epoch of star formation

W1 + W2 (3.4 + 4.6 μm)
Evolved star population constitutes the *Stellar Backbone*

W4 (22 μm)
Very small dust grains efficiently reprocess energy from star formation
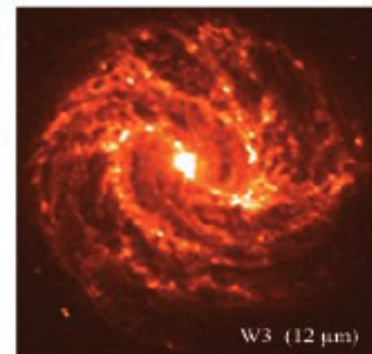
W3 (12 μm)
Excited PAH molecules due to *ISM heating* by hot stars

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

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. (11.1.2 in MBW for a detailed discussion- they point out some serious problems with this simple idea)

spiral
galaxies have stellar disks
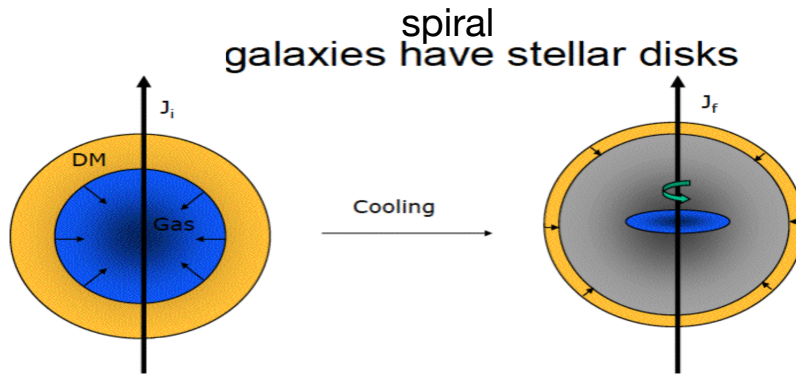
However In A Hierarchical Universe Things are More Complex

Gas Rich Mergers and Disk Galaxy Formation

Galaxy formation simulations created at the

N-body shop
makers of quality galaxies

key: gas- green new stars- blue old stars- red
credits:
Fabio Governato   (University of Washington)
Alyson Brooks   (University of Washington)
James Wadsely   (McMaster University)
Tom Quinn   (University of Washington)
Chris Brook   (University of Washington)

Simulation run on Columbia (NASA Advanced Supercomputing)

contact: fabio@astro.washington.edu

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- <u>notice does not agree with the galaxy mass distribution</u>
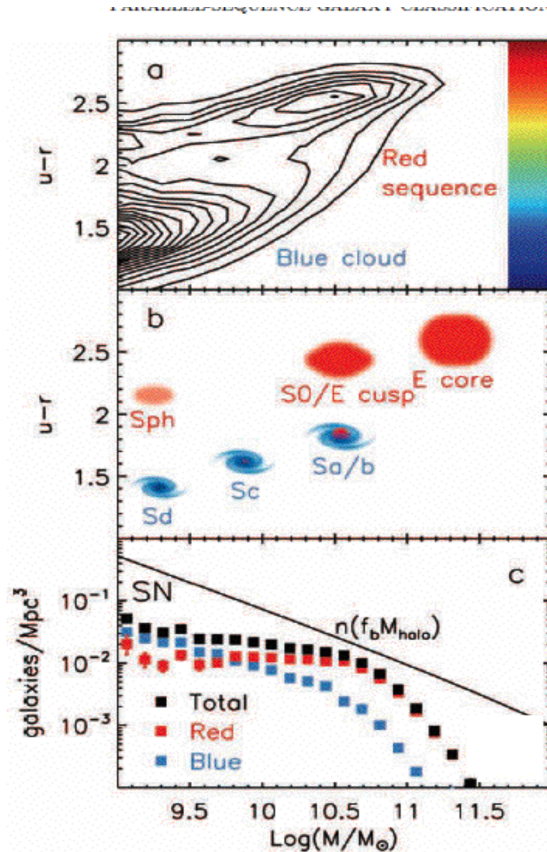
Top Level Summary-Spirals

- 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- see detailed discussion in MBW 11.2
- 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).

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- 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

Where is the Stellar Mass

Baldry et al 2004)

(log $\mathcal{M}^*,\phi^*,\alpha$) = (11.05, 0.00187, −0.87)

(log $\mathcal{M}^*,\phi^*,\alpha$) = (10.62, 0.00169, 0.15)

'+' (" , 0.00118, −1.40)

log total mass (stars =DM)

absolute mag

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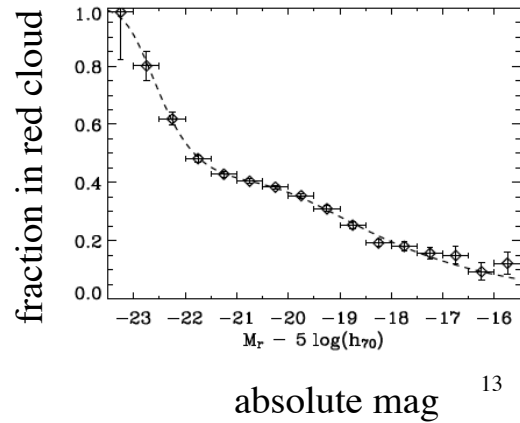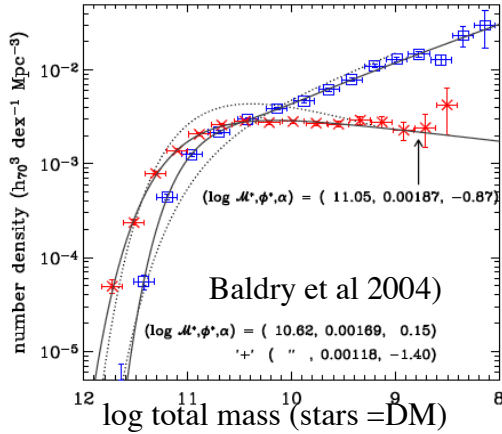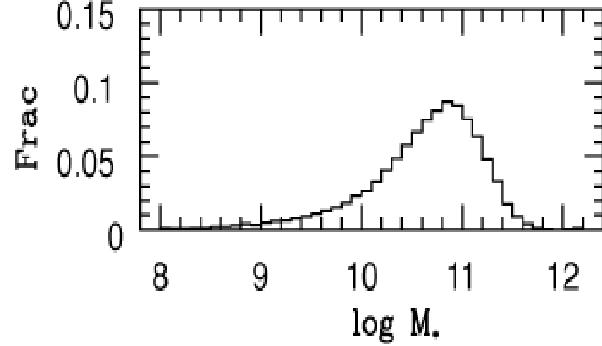
Morphology/ Color and Mass

All galaxies

early type (E) galaxies

late type (S) galaxies

log mass
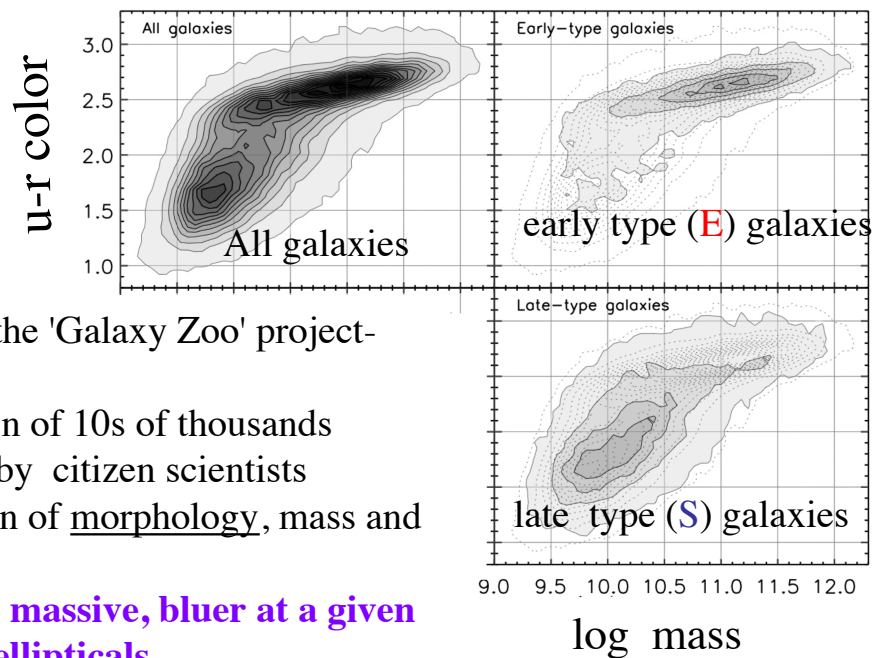
A result of the 'Galaxy Zoo' project- eyeball
classification of 10s of thousands
of galaxies by citizen scientists
Combination of <u>morphology</u>, mass and
color
Spirals less massive, bluer at a given mass than ellipticals

- **Strong relation of mass, color and morphology** Schawinski 2010

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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)*
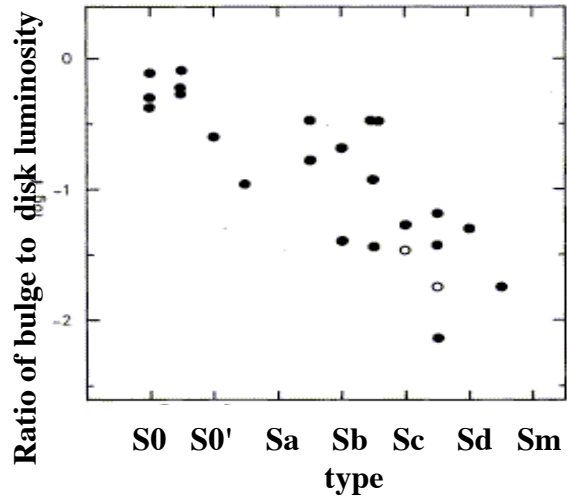
color vs morphological type
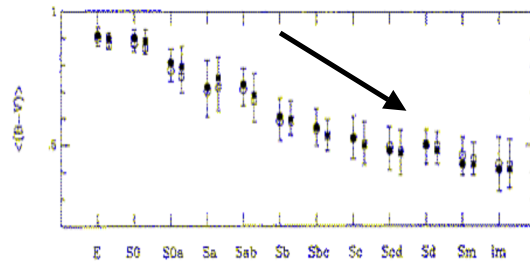
Spirals and Gas

- 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 ~3x10^{10}M where things change.
- Luminous red galaxies have hot ISMs

Gas to light ratio in log scale
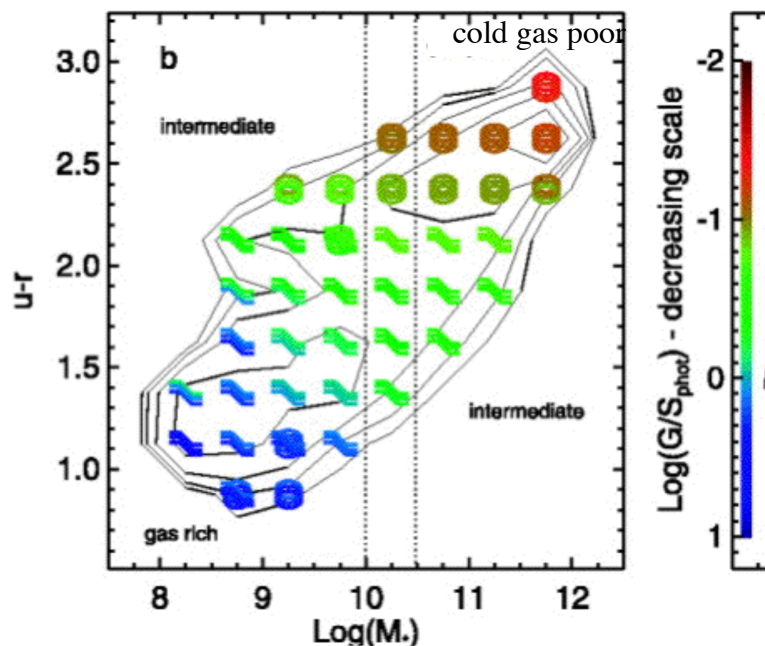
Spirals- More Trends with Morphology (Sd ⟹ Sa)

- 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
- The question is what are the primary eigenvectors of the correlations... it seems to be mass
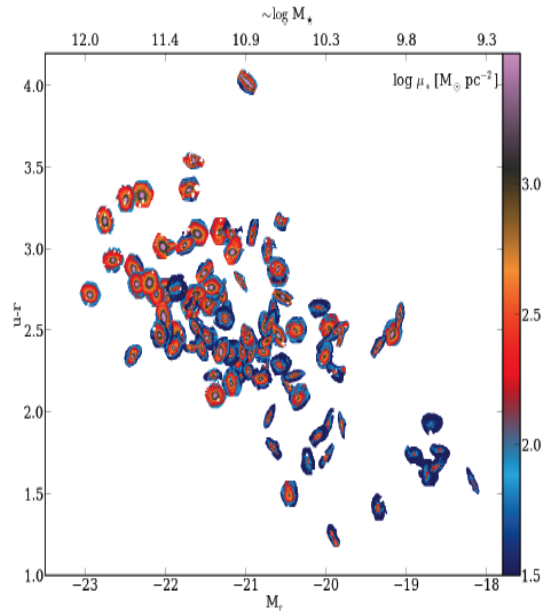
The stress on 'B' band comes from history- before CCDs photographic plates were used and they were most sensitive in the 'B' band.

CALIFA collaboration-arxiv 1310.5517

"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 nurture (spirals converted into S0's)**


Dressler (1980)
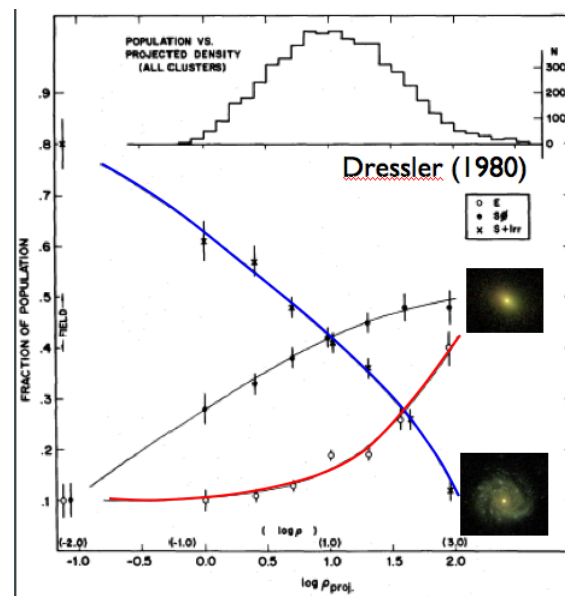
- the relative number and mass fraction of each 'type' of galaxy depends on the environment
- the 'luminosity function' (the number of galaxies per unit luminosity per unit volume) vs absolute magnitude.
- this does not represent the mass function since the relationship between mass and luminosity (M/L)is 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
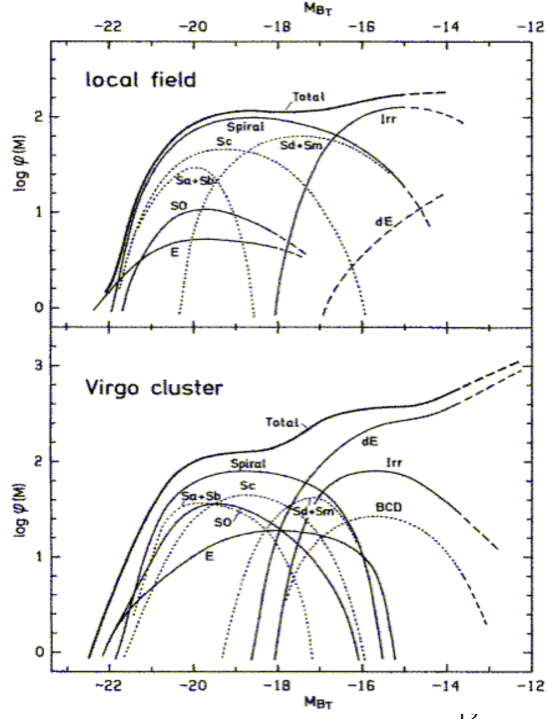
Binggeli, Sandage, and Tammann 1988

- 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
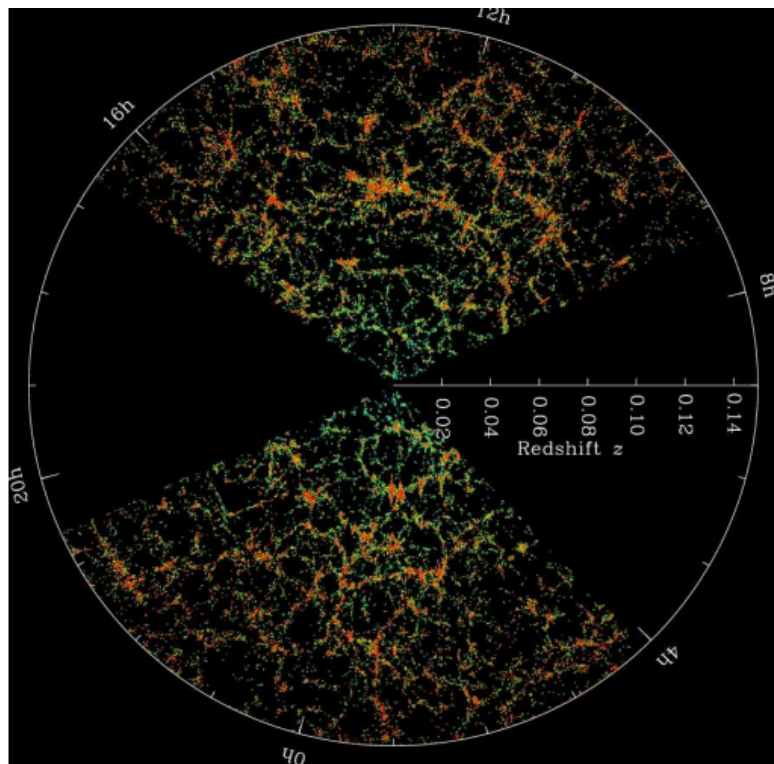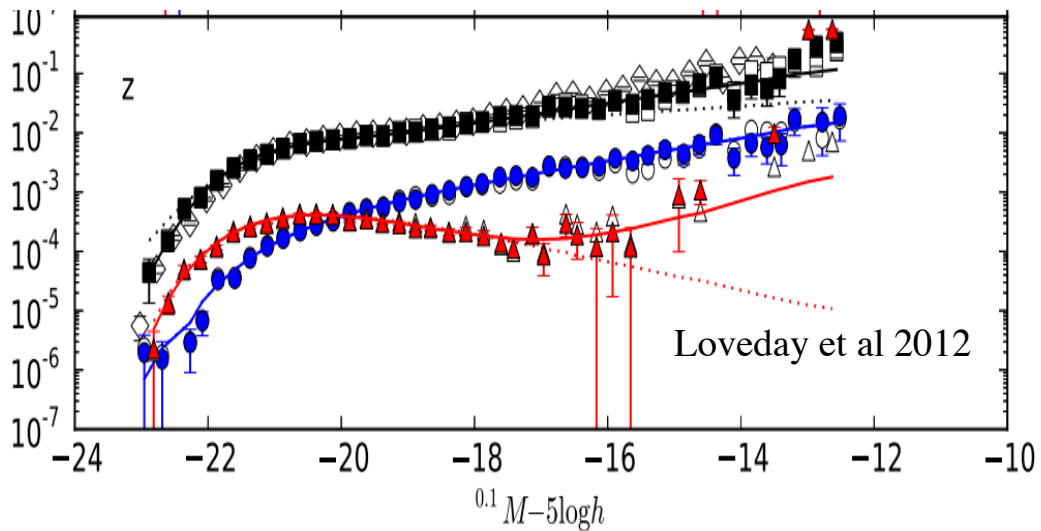
Luminosity Function

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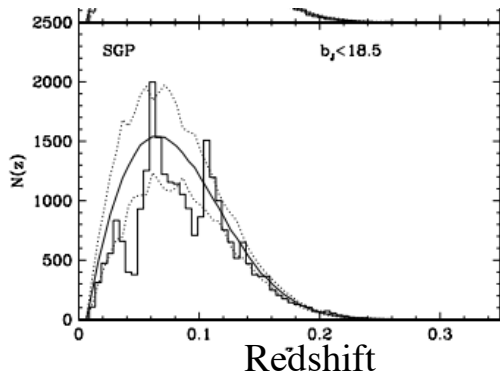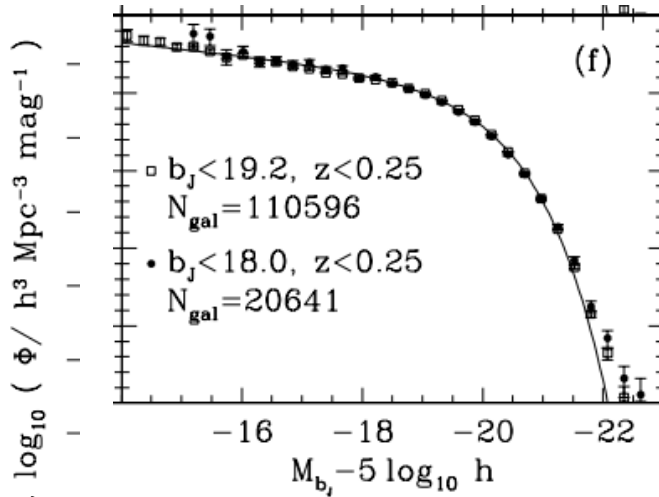
Redshift distribution is not uniform (e.g. large scale structure makes derivation of f(L) unstable at high L where objects are rare

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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.
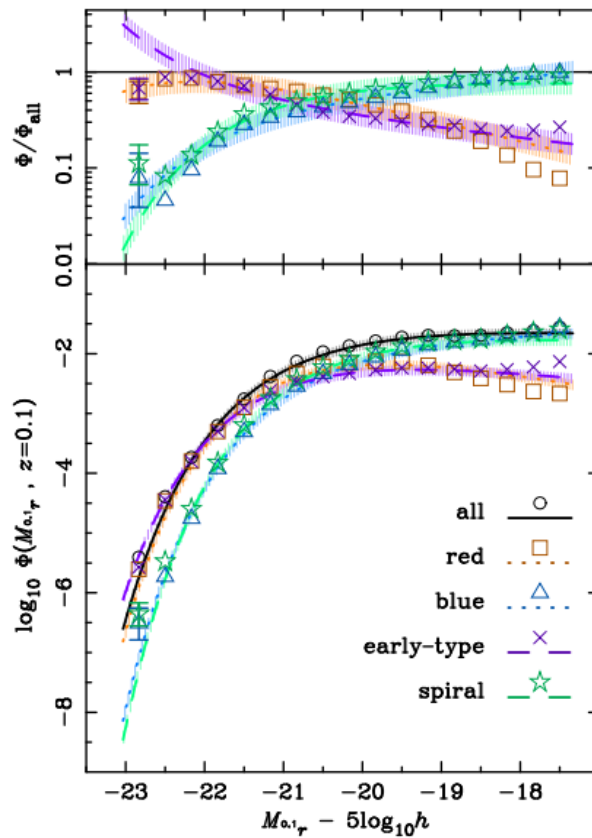

Physical Difference Between Bulges and Disks

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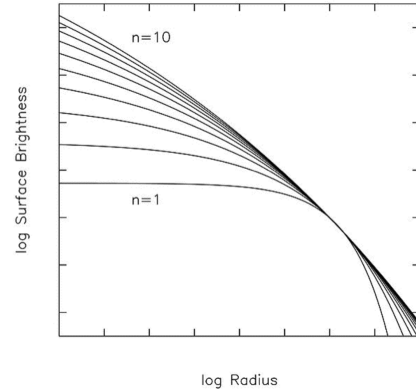
$$L = 2\pi \int_0^\infty I(R)\,R\,dR = \frac{2\pi n \Gamma(2n)}{(\beta_n)^{2n}} I_0 R_e^2,$$

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

fraction of luminosity in disk

absolute mag

NGC 3521

n=4 bulge

n=1 disk
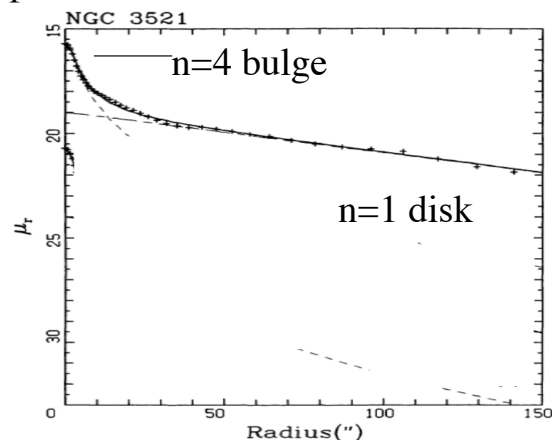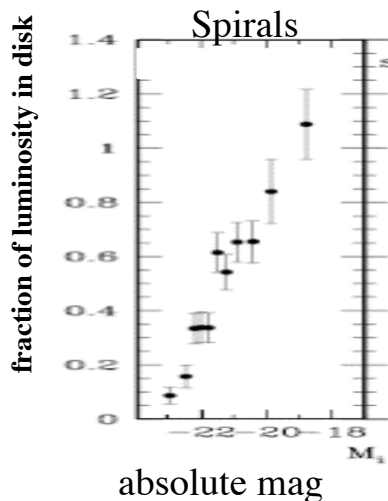
Azimuthally Averaged Light Profiles

- Bulge is more concentrated than the disk: bulge is described by Sersic profile, disk by an exponential profile
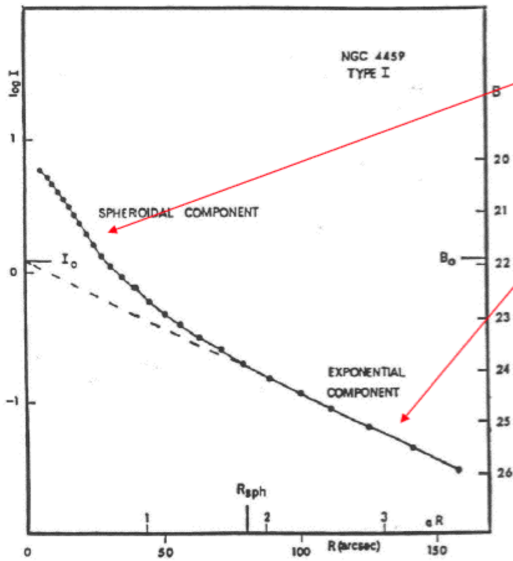
$$logI \propto R^{1/4} \quad (\text{inner});$$

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

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
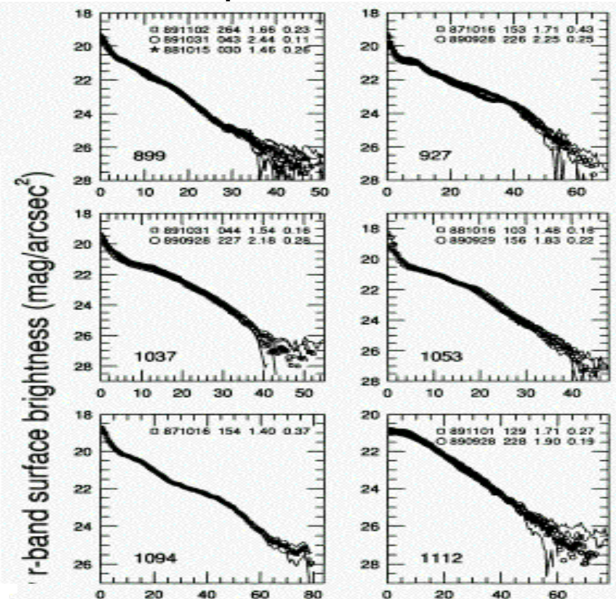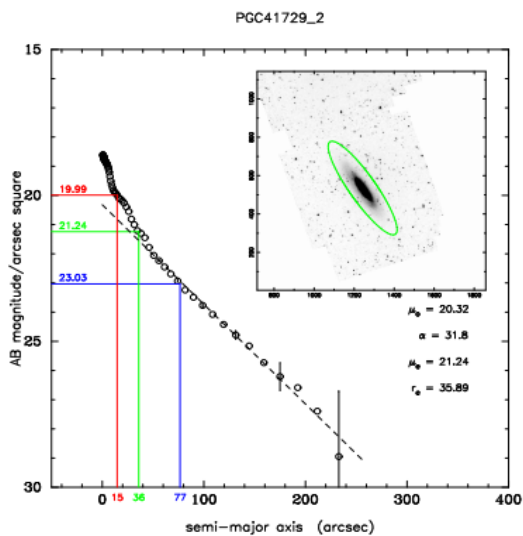

Courteau, ApJS, 103, 363, 1996

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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).

SDSS (NYU Catalog)

K-band (2.2μ)
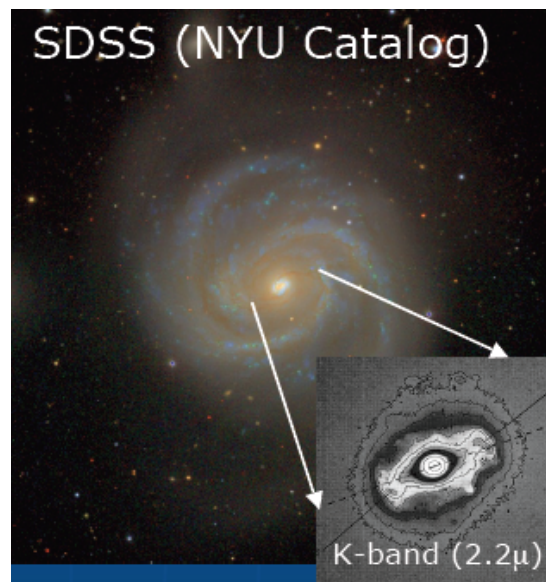
What's Important So Far

- 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)

Tully-Fisher

- Back of the envelope derivation of it
- System in equilibrium: centripetal force balances gravity
- $GM(r)/r^2 = v_c^2/r$; so $M(r) = v_c^2 r/G$; definition of surface density $\Sigma = L/r$

- If all galaxies are alike and have the same surface densities $L \sim r^2$
- Further if M/L is constant $M \sim L$
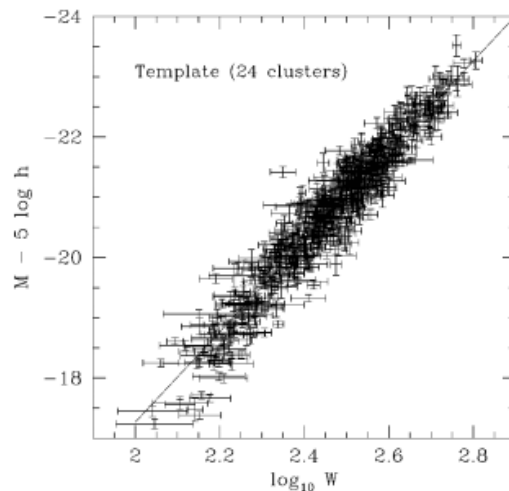- a little algebra gives $L \sim v_c^2 L^{1/2} \sim v_c^4$

FIG. 1.—Template relation based on 555 galaxies in 24 clusters. The fit is $-21.00 \pm 0.02 - 7.68 \pm 0.13$ (log W − 2.5).

Giovanelli et al 1997

Tully-Fisher II see MBW 11.3

- One might think that this was due to disk processes only (11.3(a) in MBW)
- Using the form of $V_{circular, disk} = V^2_{c,d}(R) = 4\pi G\Sigma_0 R_d y^2 [I_o(y)K_0(y) - I_1(y)K_1(y)]$

$y = R/(2R_d)$ and I and K are Bessel functions of the first and second kinds:which do not have simple asymptotic forms

Important bits: $V^2_{c,d}(R)$ depends only on radial scale length R_d and its central surface density Σ_0

this rotation curve peaks at $R_d = 2.16$ thus $V_{max} \sim 2.5 G\Sigma_0 R_d$

If we assume stars trace mass, as would be true for a disk dominated potential and the stars have a $M/L = \Gamma$ and defining the central disk luminosity density as $I_0 = \Sigma_0/\Gamma$ then $L_{disk} = 8.7 \times 10^{11} L_\odot (V_{obs}/200km/sec)^4 (I_0/100 L_\odot pc^{-3})^{-1}(\Gamma/M_\odot/L_\odot)^{-2}$ (eq 11.75 in MBW) which looks like the T-F relation.

This seems to work well EXCEPT for the predicted strong correlation of the T-F relation and I_0; thus require the mass to light ratio of the stars $\Gamma \sim I_0^{-1/2}$

T-F III

- Lets consider the disk matter to be negligible and model the halo as a single isothermal sphere.

- as shown on pg 512-514 this sort of works but only if a small fraction of baryons end up in the disk
- the bottom line conclusion is that it is extremely difficult to construct a model that can match all scaling relations simultaneously.

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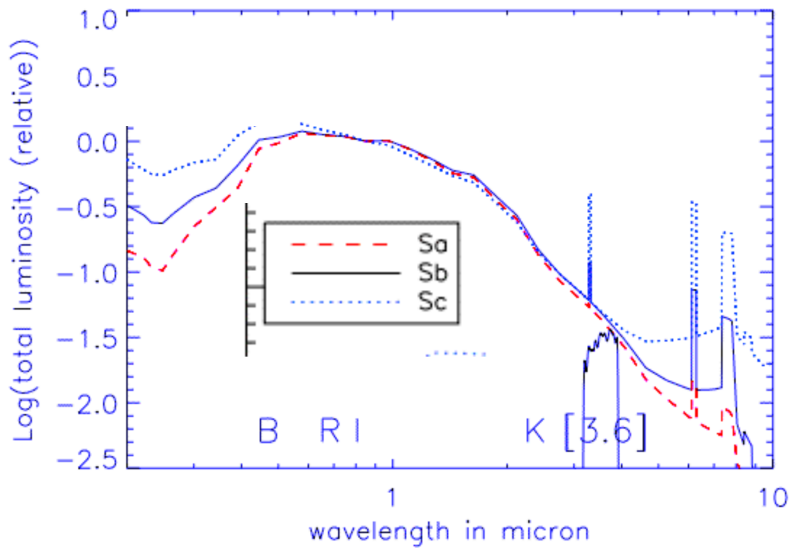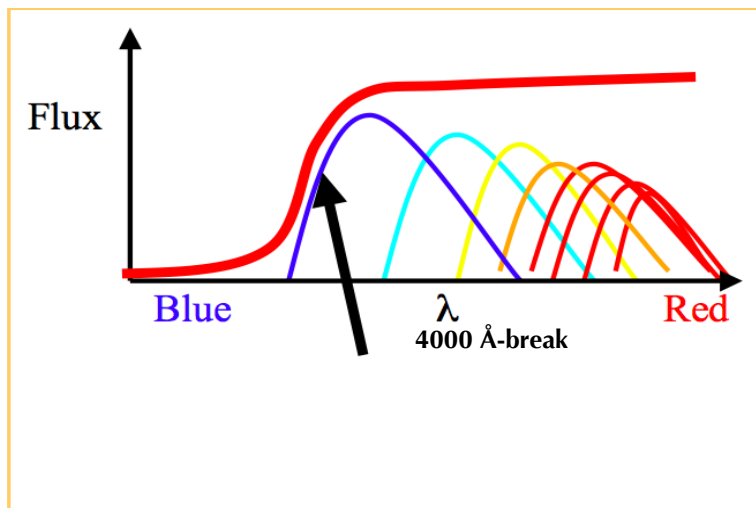
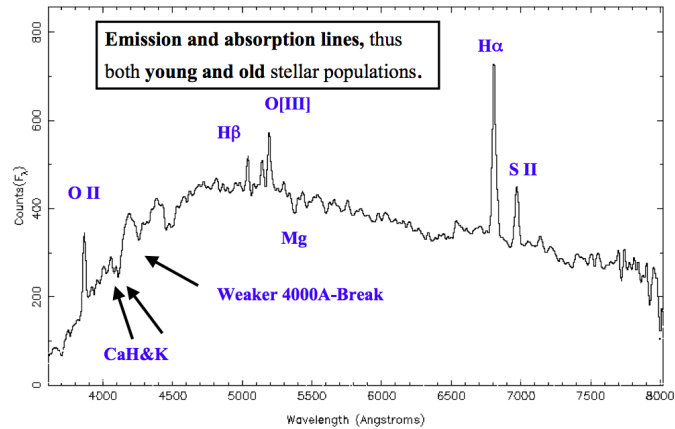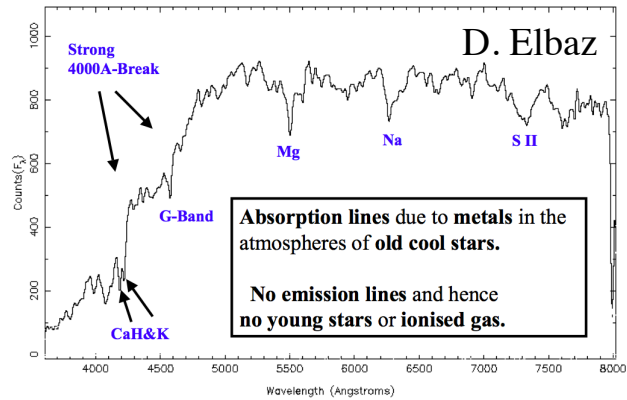*Spiral* SED normalized at 8000A with emphasis on near IR spectral features (PAHs)

Galaxy Spectra The Simple Picture

- Continuum: the combination of many Black-Body spectra (from a wide range of stellar types, spanning a range in temperatures, weighted by the IMF) **just happens** to produce a fairly flat overall spectrum

One Step Beyond Simple

D. Elbaz

Strong 4000A-Break

G-Band

CaH&K

Mg   Na   S II

Absorption lines due to **metals** in the atmospheres of **old cool stars.**

No emission lines and hence **no young stars** or **ionised gas.**

Counts(F$_\lambda$)

Wavelength (Angstroms)

Emission and absorption lines, thus both young and old stellar populations.

O II   Hβ   O[III]   Hα   S II   Mg

Weaker 4000A-Break

CaH&K

Counts(F$_\lambda$)

Wavelength (Angstroms)

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

continuum mostly from stars

red galaxies

blue galaxies

red galaxies

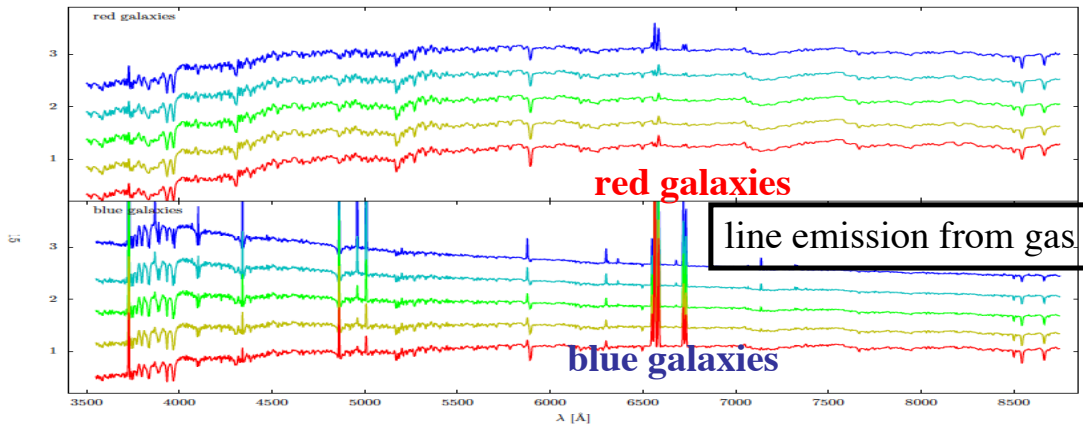line emission from gas

blue galaxies

λ [A]

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.
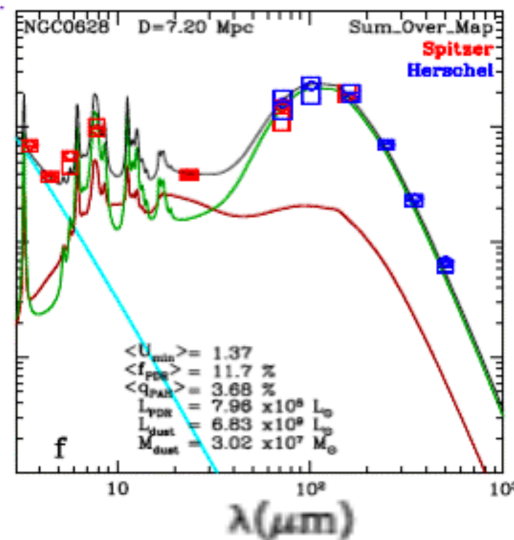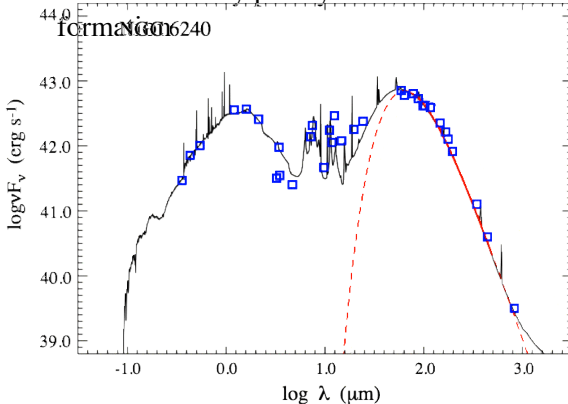
Galaxy spectra

- 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)
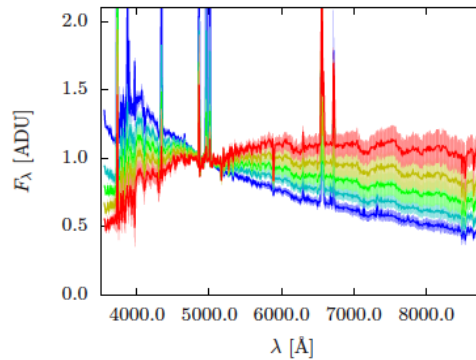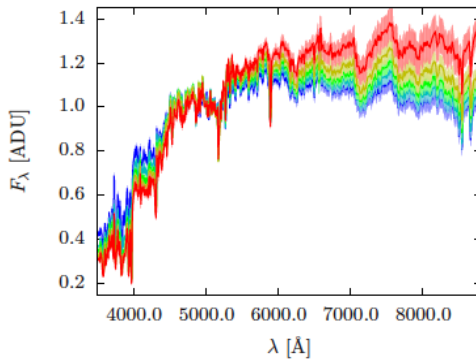
Galaxy Spectra -IR

- 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
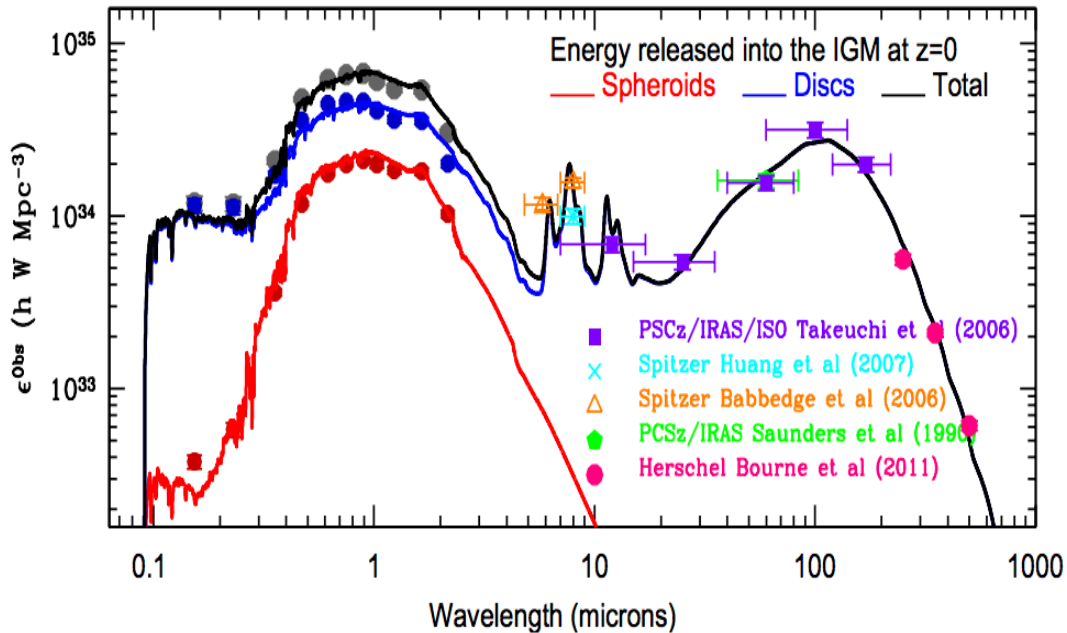
Composition of Average Spiral

- 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

INTERSTELLAR MEDIUM
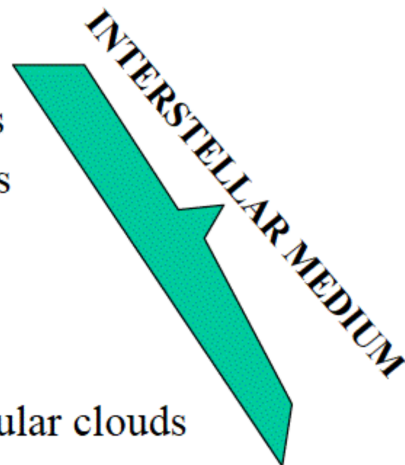
Reminder of Big Picture

- 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.

- 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 S&G)
- 2 sets of coordinates
  - disk of galaxy (R ϕ)
  - plane of sky (ρ θ)
- When $\theta=\phi$ line of nodes
- The measured radial velocity of gas in circular orbits is
- $v_R(\rho, \theta)=v_{system}+v_R(R, \phi)$ $\sin\phi\sin i+v_\phi (R,\phi) \cos\phi\sin i+v_z (R,\phi)\cos i$
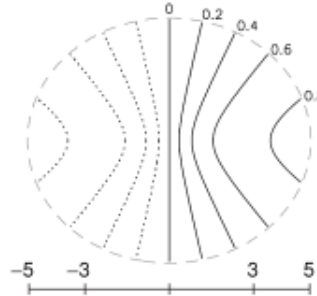
v_R velocity in radial direction

v_ϕ angular speed

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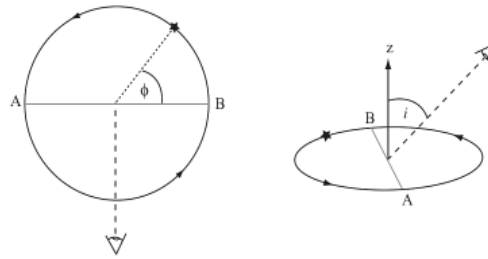
Fig. 5.18. Left, a rotating disk viewed from above. Azimuth ϕ, measured in the disk plane, gives a star's position in its orbit; an observer looks from above the disk, perpendicular to diameter AB. Right, the observer's line of sight makes angle i with the disk's rotation axis z.

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

negative velocities ----

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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
- R_{25} is the 'classical' 'edge' of the optical light and is located where the surface brightness is 25mag/arcsec^2

NGC 1744 Pisano et al. 1998   620 km/s

intensity   velocity

830 km/s

optical image and HI
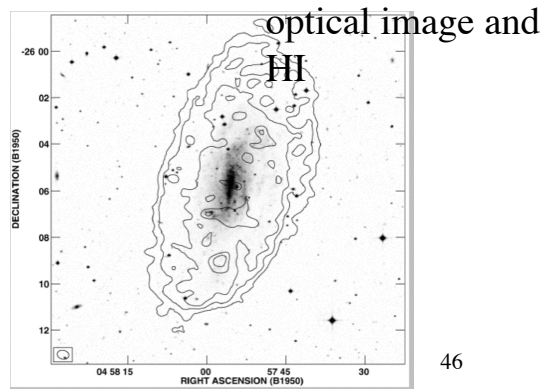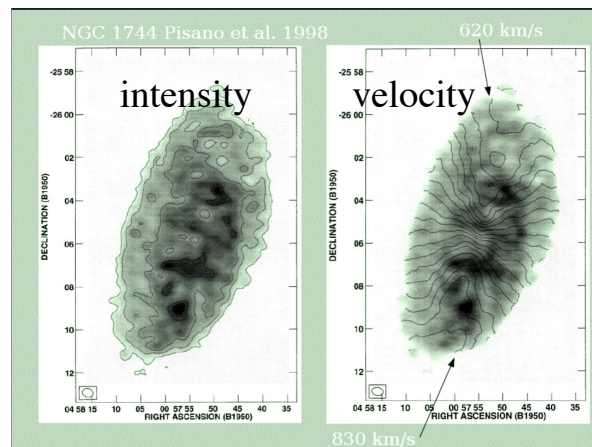
46

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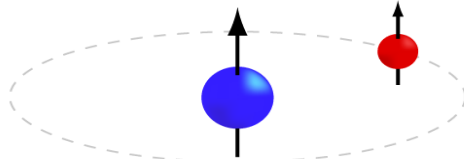
One λ = 21 *cm photon is emitted when the spins flip from parallel to antiparallel.*

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
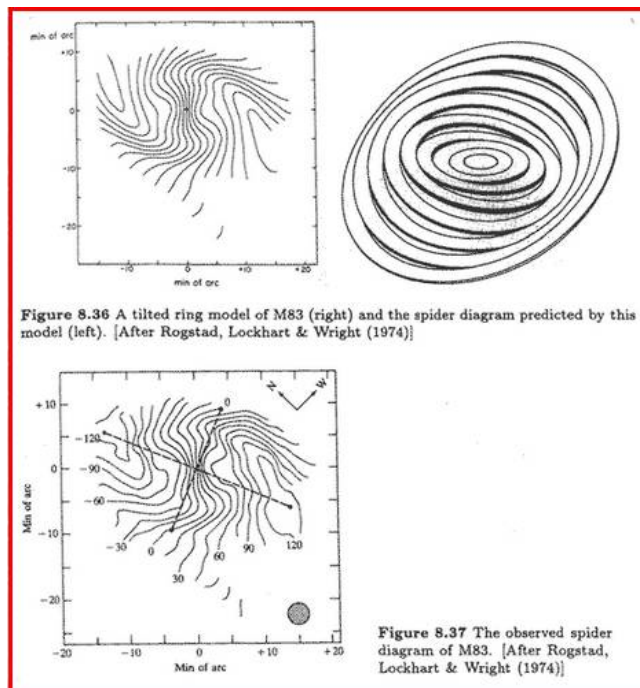 - warped disk (see figure)

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)
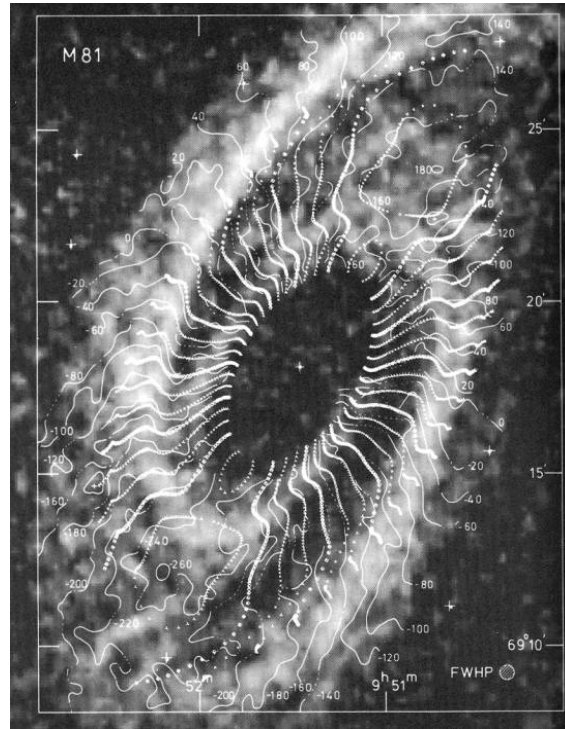
Optical Image and Velocity Field of NGC5033

- Spider plot is the contours of the velocity field
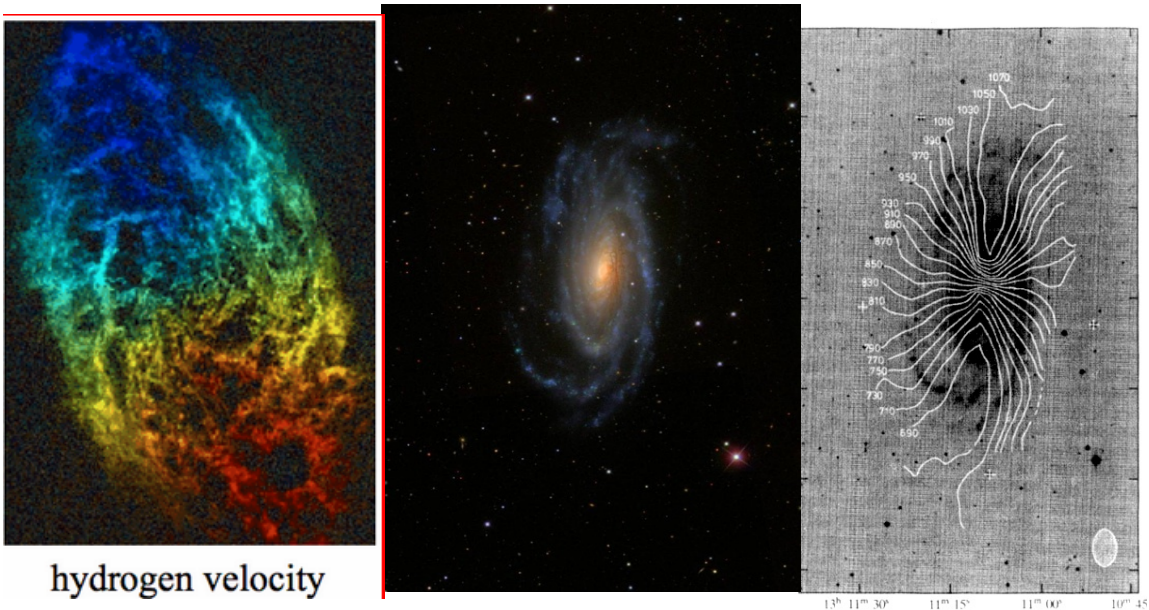
hydrogen velocity

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
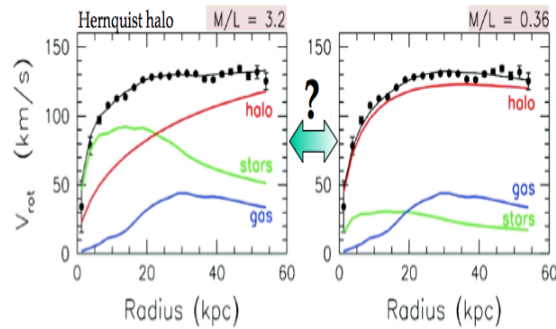
Solution is that disks have less mass than the maximum allowed by IMF, colors-
At the radius where the velocity curve flattens ~15-30% of the mass is in baryons
Build your own rotation curve (!)
http://burro.astr.cwru.edu/JavaLab/RotcurveWeb/main.html

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.

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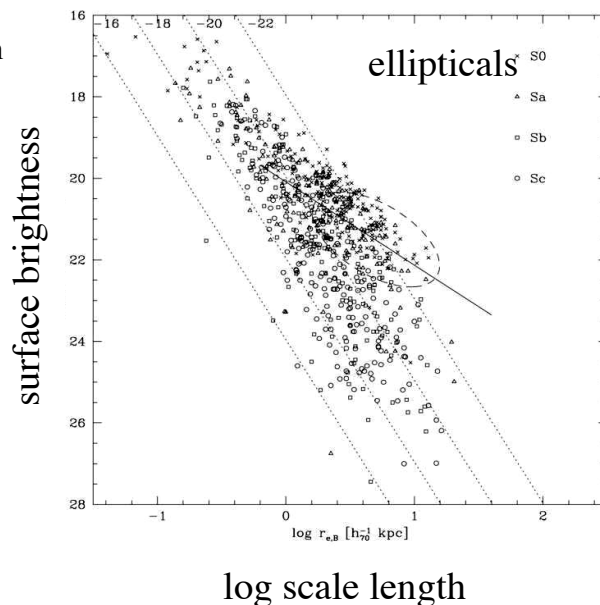
Spiral Arms in Spirals (sec 11.6 in MBW- sec 5.5.2 in S+G)

- 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.

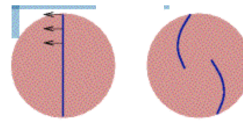When the sense of the galactic rotation is known, the spiral arms almost always trail the rotation.

- 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 $\Delta R/R = 0.25 (t/Gyr)^{-1}$

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.   53
This leads to very tightly wound arms.

Spiral Arms

- Mathematical form of spiral arm surface brightness

$\Sigma(R,\varphi) = \Sigma_0(R) + \Sigma_1(R)\cos[m\varphi + f(r)]$

$\Sigma_0(R)$ is the surface brightness of the disk (exponential form usually)

$\Sigma_1(R)$ is how the spiral arm perturbation varies radially and $f(r)$ is a shape function describing the spiral

Traditionally $f(r)$ is a logarithmic spiral

$f(r) = f_0 \ln(R) + \varphi_0$ f_0 is a constant describing how tightly wound the arms are

The 'pitch angle' i, is the angle between the local tangent of the spiral and a circle of radius R

$\tan i = mR (\partial f/\partial r)^{-1}$ or rewriting $i = \arctan(m/f_0)$ is constant -the size of the spiral increases but its shape is unaltered with each successive curve, a property known as self-similarity.

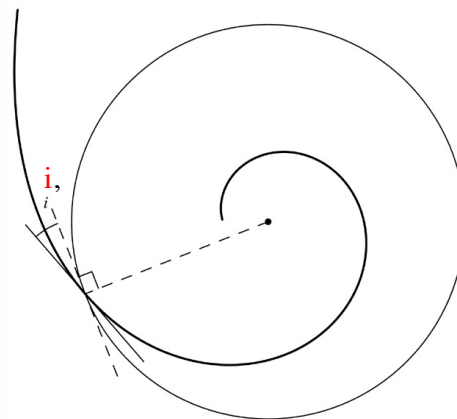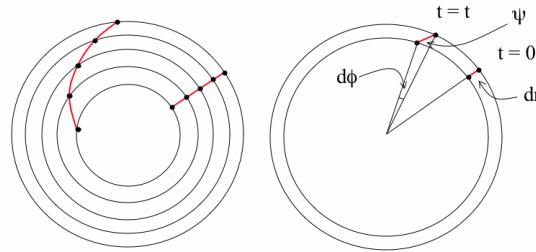the pitch angle ranges from 10^0 (tightly wound) to 30^0 (open)

Fig 5.28 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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- 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 $\psi = 1/2\pi$ ($\psi = 9°$) e.g winds up! - 2 rotations 4.5° etc

In Sa's $\psi \sim 5°$ while in Scs $\psi \sim 10$-$30°$

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

Winding?

Flat rotation curve: v = 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 $\psi = dr / r$ $d\phi = dr / [(v/r) dr t] = r / vt = 1/\Omega t = 1/\phi$

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

M. Whittle's web site

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Winding

- Thought experiment: paint a stripe on a galactic disk along $\varphi = \varphi_0$
- Disk is in differential rotation with an angular speed $\Omega(R)$
- So the equation of the stripe as a function of time is
  $\varphi(R,t) = \varphi_0 + \Omega(R)t$
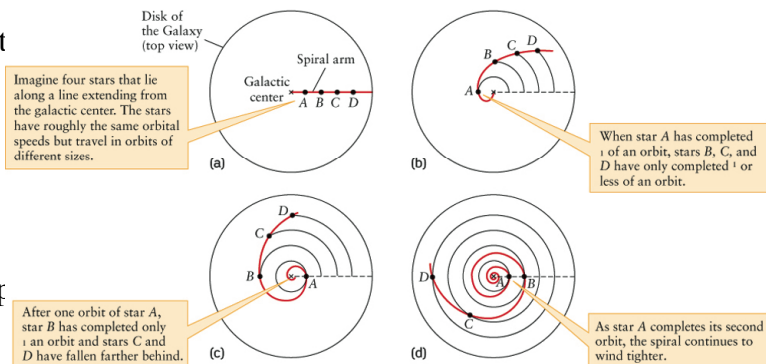
For a typical spiral galaxy with a flat rotation curve

$\Omega(R) = v_{circular}/R$; so

$d\Omega(R)/dR = v_{circular}/R^2$

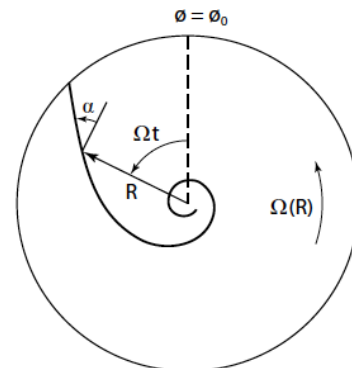near the sun =220km/sec at $R \sim 10$kpc, at $t = 10^{10}$yrs $\alpha = 0.25$deg !

Real galaxies have $\alpha \sim 5$-25 deg

In the diagram

$\cot\alpha \sim Rtd\Omega(R)/dr$

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 tightly 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
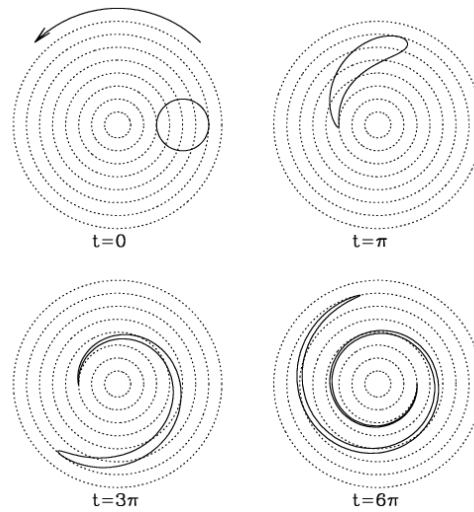
MBW, fig 11.3)

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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.

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Spiral Arm Formation

The fundamental cause of spiral arm formation is not well understood.

- To quote from https://www.cfa.harvard.edu/~edonghia/Site/Spiral_Arms.html

  'The precise nature of spiral structure in galaxies remains uncertain. Recent studies suggest that spirals may result from interactions between disks and satellite galaxies...., here we consider the possibility that the multi-armed spiral features originate from density inhomogeneities orbiting within disks.'

- In this movie spiral arms are formed due to a merger (http://www.nature.com/news/galaxy-formation-the-new-milky-way-1.11517)

The *Eris* N-body simulation of a massive late-type spiral galaxy in a WMAP3 cosmology (Guedes, Callegari, Madau, & Mayer 2011. The simulation was performed with the GASOLINE code on NASA's *Pleiades* supercomputer and used 1.5 million cpu hours.

M_{vir}=7.9 x 10^{11} M_{sun}
N_{DM}+N_{gas}+N_{star}=7M+3M+8.6M within the final R_{vir}
force resolution=120 pc

RESEARCH FUNDED BY NASA, NSF, AND SNF

Another take on spiral arm formation- see web page for paper

- For another take on the formation of spiral arms see
- https://www.youtube.com/watch?v=-ii0nksV2lY
- https://www.cfa.harvard.edu/~edonghia/Site/Spiral_Arms.html
- The authors E. D'onghia et al say

  "mass concentrations with properties similar to those of giant molecular clouds can encourage the formation of spiral arms through a process termed swing amplification. ... the response of the disk can be highly non-linear, significantly modifying the development and longevity of the resulting patterns. Contrary to expectation, ragged spiral structures can survive at least in a statistical sense long after the original perturbing influence has been removed, motivating a new interpretation of various phenomena, including disk heating, radial migration, and galaxy pattern speeds."