Summary of Last Lecture - Local Group

- 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

Spiral Galaxies-
Read Chapter 4 in S&G

5.1 The distribution of starlight
5.2 Observing the gas – covered this already
5.3 Gas motions and the masses of disk galaxies covered this already
5.4 Interlude: the sequence of disk galaxies will not cover
5.5 Spiral arms and galactic bars
5.6 Bulges and centers of disk galaxies-cover under AGN later

Physical Models of Galaxy Formation in a Cosmological Framework
Rachel S. Somerville and Romeel Dav´e

Annual Reviews of Astronomy and Astrophysics 2015

The Components

Basic picture is that disks are formed via smooth accretion of diffuse gas, which largely conserves its angular momentum, while spheroids (elliptical galaxies, bulges) are formed via gas-poor mergers that efficiently transfer angular momentum.

Disks:

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

Origin in CDM models: Old idea was that disk galaxies form in halos with high angular momentum and quiet recent assembly history, and ellipticals are the slowly-rotating remnants of repeated merging events.

The Components

Recent models show that the gas accreting from the halo does conserve its specific angular momentum and thus settles into a disk (Fall & Efstathiou 1980, Mo et al. 1998)- but this is only a small part of the story.

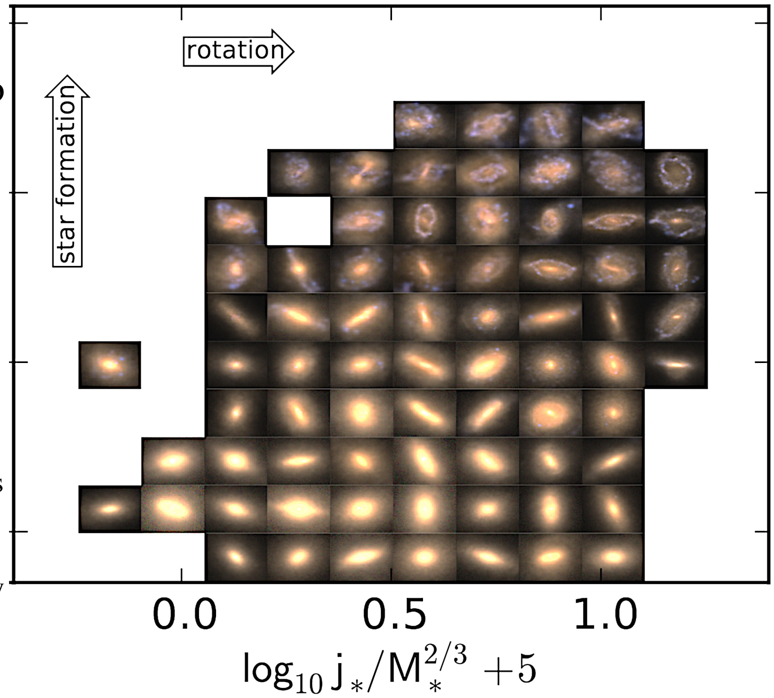
- For many years, simulations were only able to produce very compact disks with large spheroids, and were unable to produce spirals even as late-type as the Milky Way
- the general solution lay in the way stars are formed in the simulations...and the general picture is now rather complicated

Galaxy Morphologies

- Recent models (Illustris simulations) seem to be on the verge of producing 'real looking' galaxies
- To quote from Snyder et al 2016

" we hypothesize that for a model which properly regulates a galaxy's star formation, and which mitigates possible impacts on second-order structural parameters , structure formation plus galaxy physics leads naturally to the distribution of galaxy morphologies."
"

Output of simulations



specific angular mom

The Components

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 chunks)- (Unequal mass ("minor") mergers down to mass ratios of ~1:10)
- disks reform later after merger by accretion of gas. But major mergers of gas poor systems destroy disks
- Although the details of the prescriptions differ, all semi-analytic models that attempt to track galaxy morphology assume that mergers destroy disks and build spheroids.
  - However some studies have found, to varying degrees, that non-merger related mechanisms for spheroid growth may be needed

Huge Array of Sizes and Shapes

Detailed Morphology

- However the physics that determines the internal structure of disk galaxies
  - seems to be that that dark matter and diffuse gas acquire angular momentum through tidal torques and mergers

- But extensive detailed predictions on morphological demographics from numerical cosmological simulations have not yet appeared in the literature.

- So there is still a lot of work to do!

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

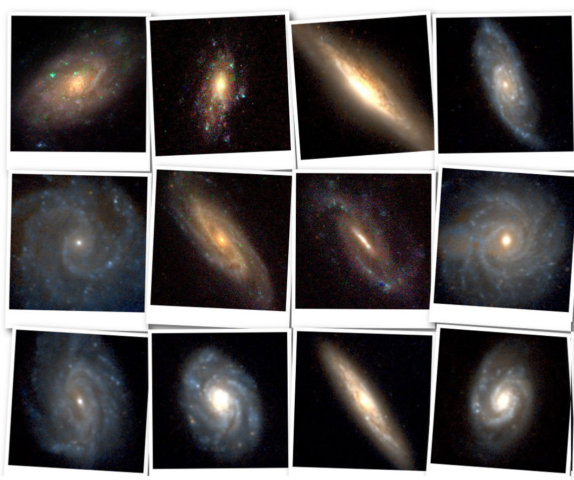
GALACTIC DISK	GALACTIC HALO	GALACTIC BULGE
Highly flattened	Roughly spherical—mildly flattened	Somewhat flattened and elongated in the plane of the disk ("football shaped")
Contains both young and old stars	Contains old stars only	Contains both young and old stars; more old stars at greater distances 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

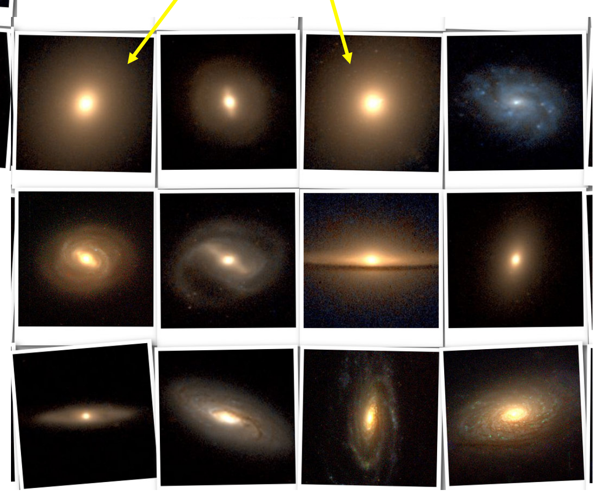
A Bit of the Galaxy Zoo

Citizen science morphological classification of SDSS galaxies

Mostly disk…



Mostly spheroid…



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

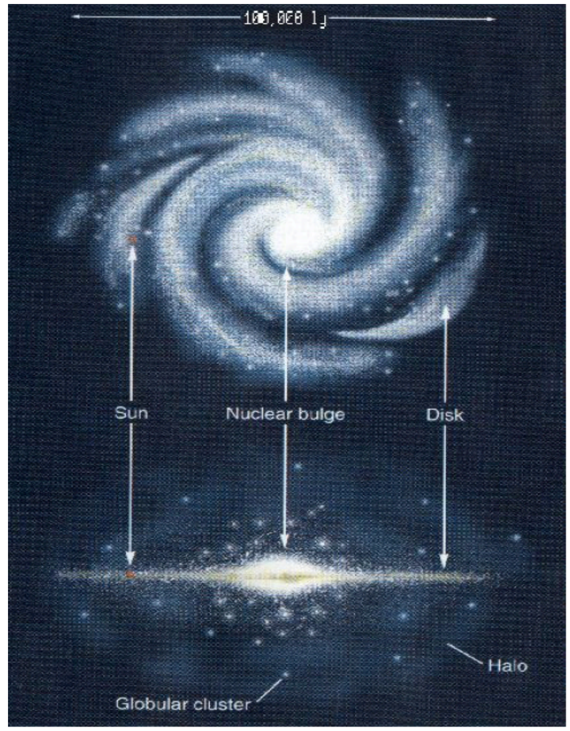
Spirals

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

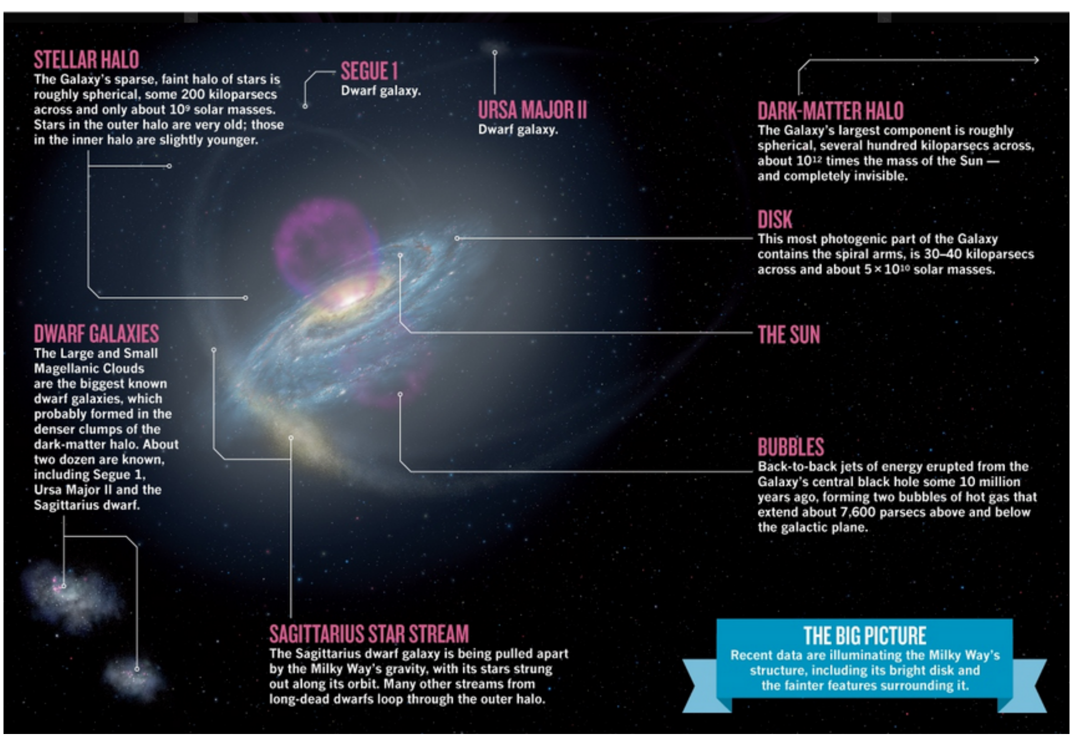
  The disk contains a large quantity of gas & dust, the bulge essentially none

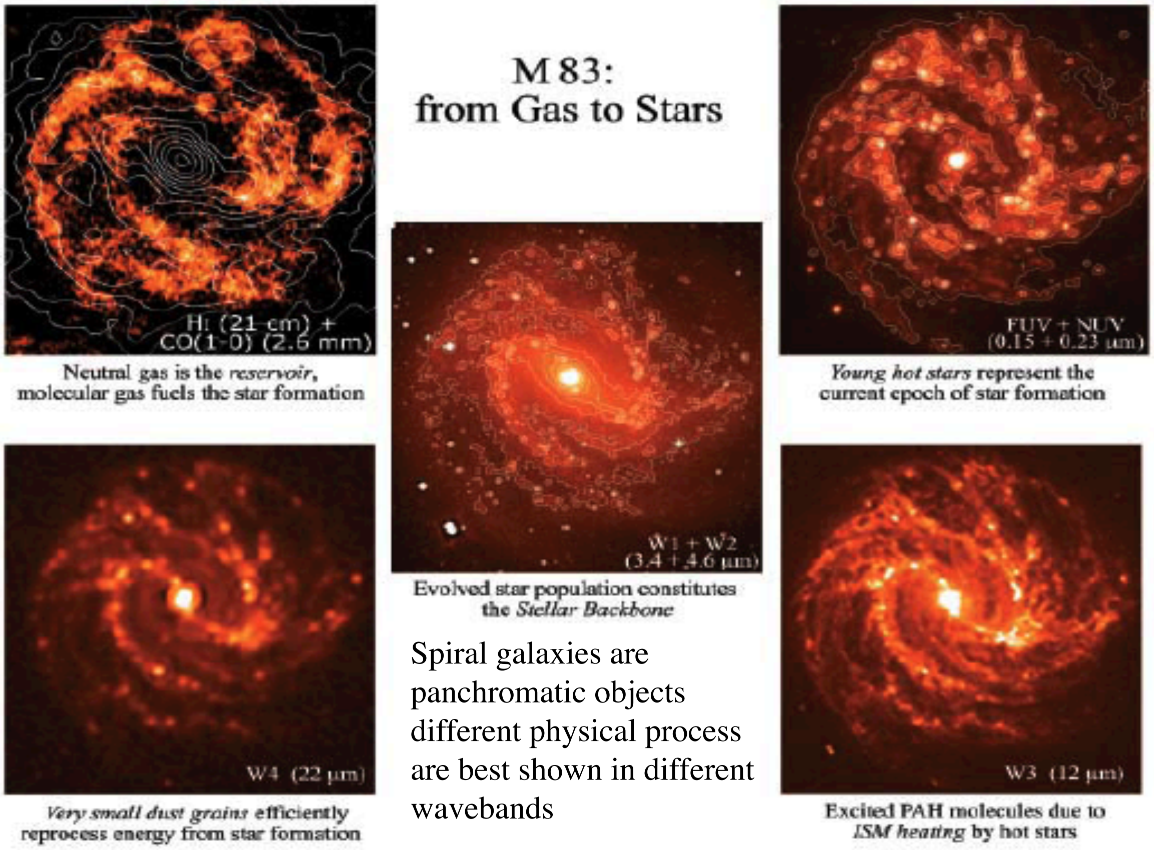
  Disks are cold (rotationally supported)

  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**.



- major review article in Nature " 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!

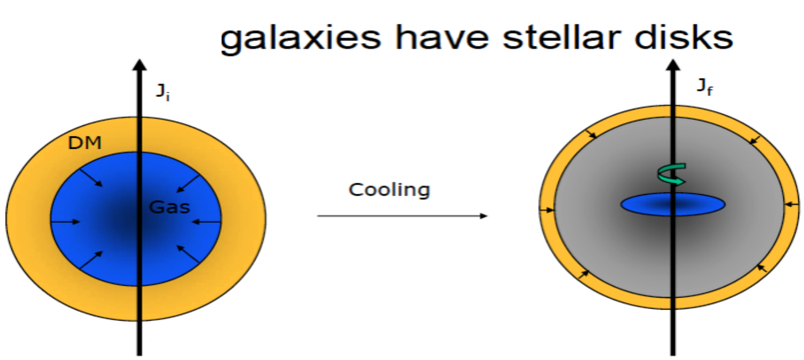




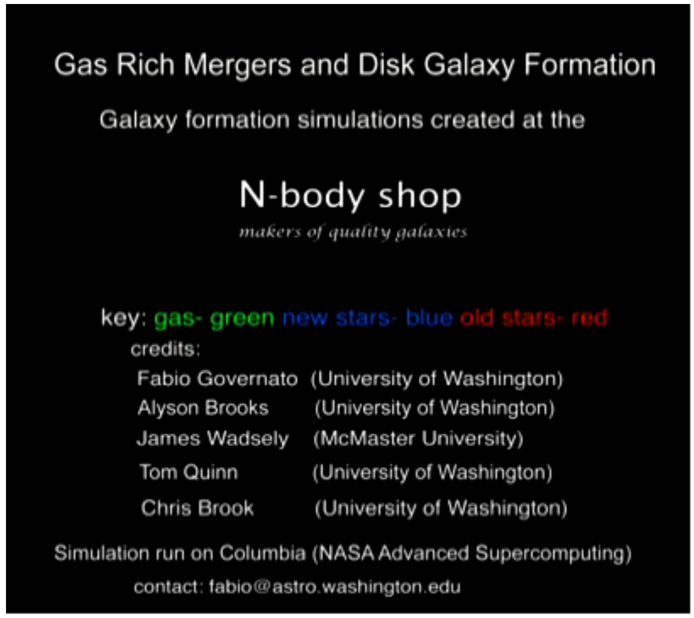
Spiral galaxies are panchromatic objects different physical process are best shown in different wavebands

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 infalling gas loses energy (cools) it will tend to form a disk
- If stars form from dense gas they will also be in a disk.
- However this simple models misses lots of the details



However In A Hierarchical Universe Things are More Complex



The Big Picture- Two Populations

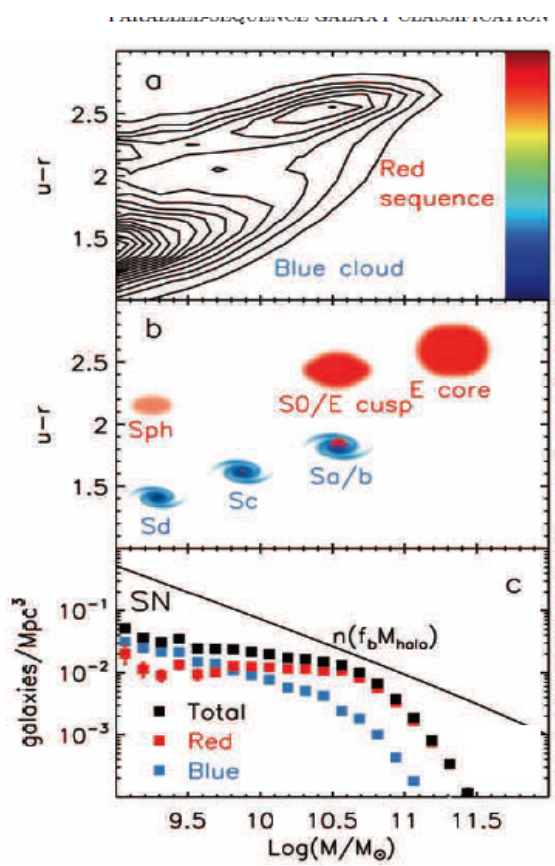
- top panel color <u>distribution vs mass</u> of a large sample of local galaxies from the SDSS

  Middle panel is the <u>morphologies</u> 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>

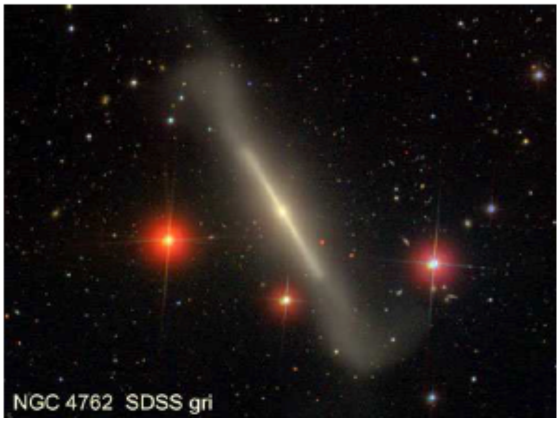


Summary of Tuesdays-Lecture Spirals

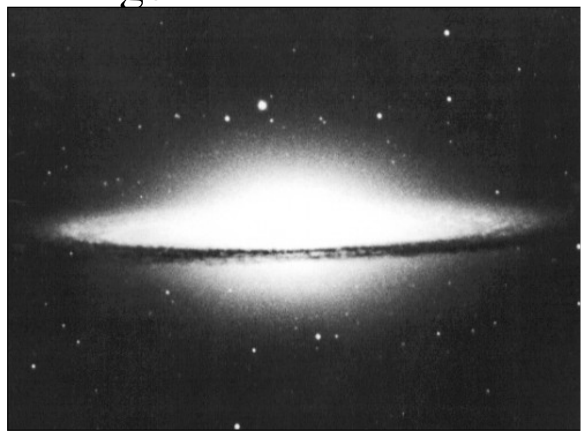
- Components of Spirals
    - bulge
    - disk
    - halo
  - each has a different stellar population, gas content.
- Connection between color, mass, morphology for galaxies as a whole.

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.

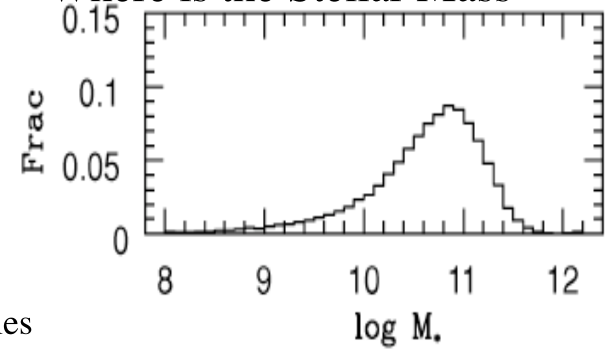
Top Level Summary-Spirals

- 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.

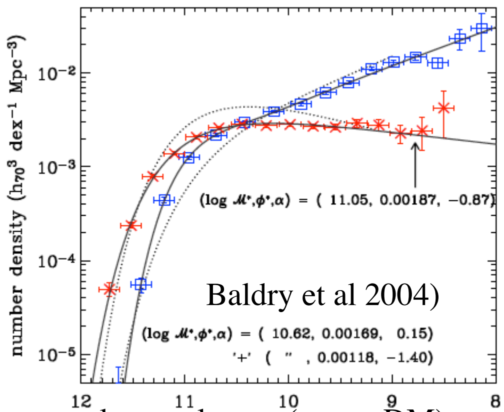
- Conventional theoretical 'wisdom' : disks form at the center of dark matter halos as a consequence of angular momentum conservation during the dissipational collapse of gas (Fall & Efstathiou 1980) , spheroids result predominantly from merger events
- Thus *morphology is a transient feature* of the 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

- 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

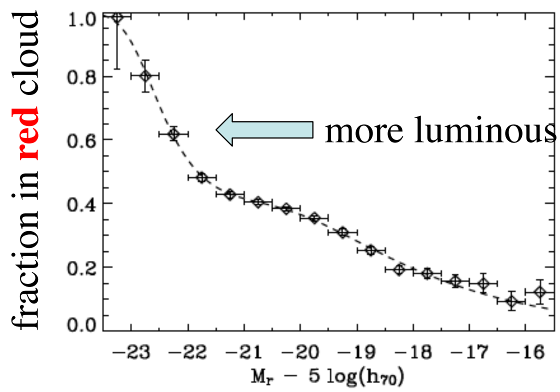
Where is the Stellar Mass



Mass function of blue and red galaxies

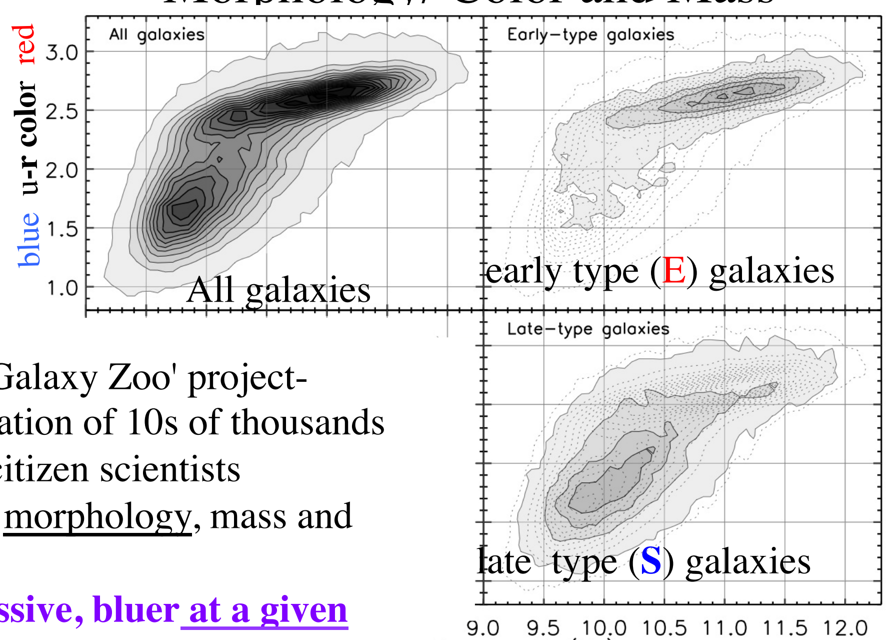


log total mass (stars =DM)



absolute mag

Morphology/ Color and Mass



log 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

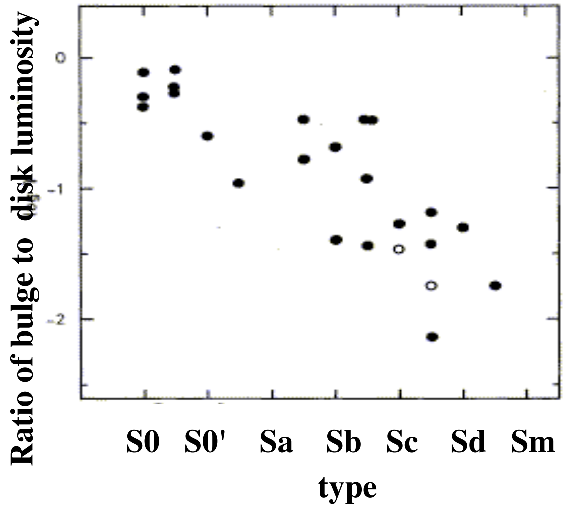
- **Strong relation of mass, color and morphology**

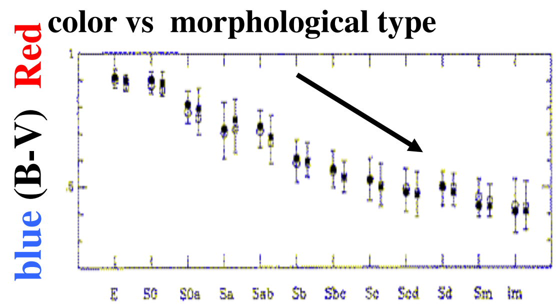
Schawinski 2010

Spirals

The Hubble type of a spiral *correlates* with

- bulge/disk luminosity ratio
- relative amount of cool gas (H I and H_2)
- mass concentration
- stellar population (how many young/old stars)
- nuclear properties **(nature of AGN)**
- 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)*

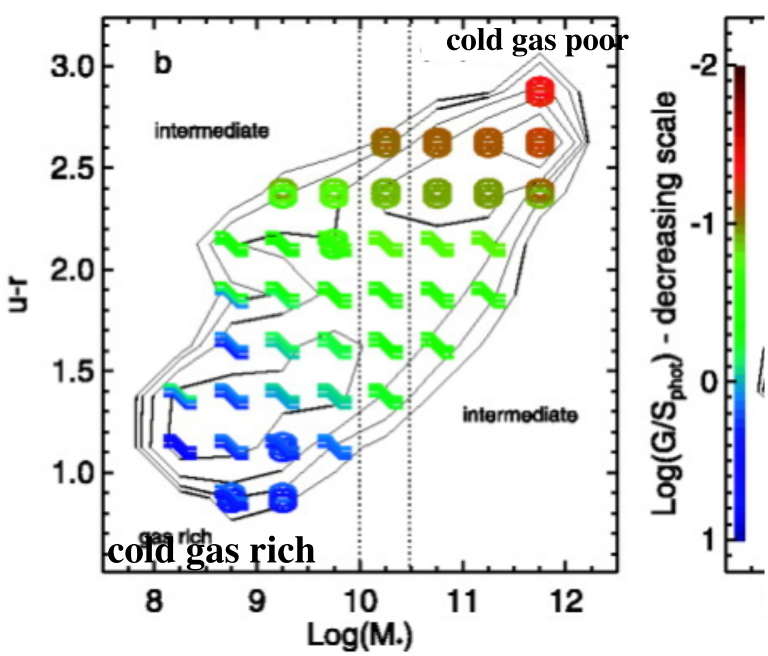




Spirals and Gas

- 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



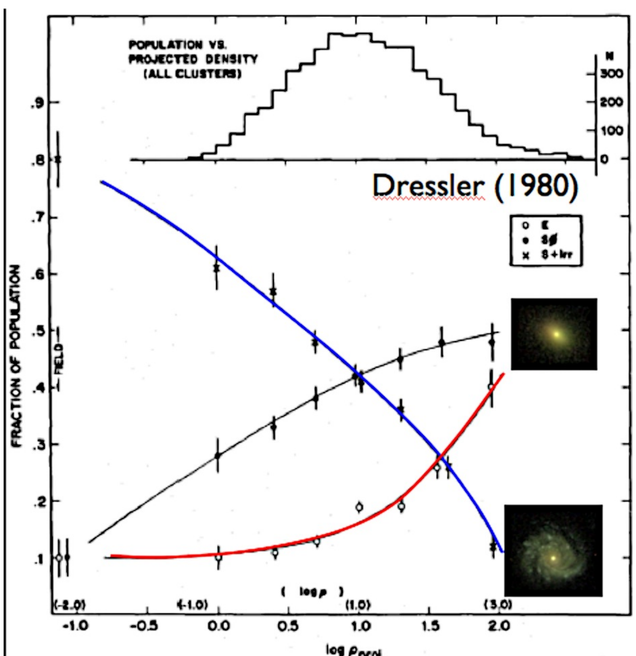
Spirals- More Trends with Morphology (Sd → Sa)

- Total luminosity decreases
- M / L_B rises
- M (HI) / M $_{(total)}$ rises
- Bulge / Disk decrease
- Tightness of the spiral arms decreases
- Scale length drops $\Sigma(r) \sim \Sigma_0 \exp(-r/r_s)$
- 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.

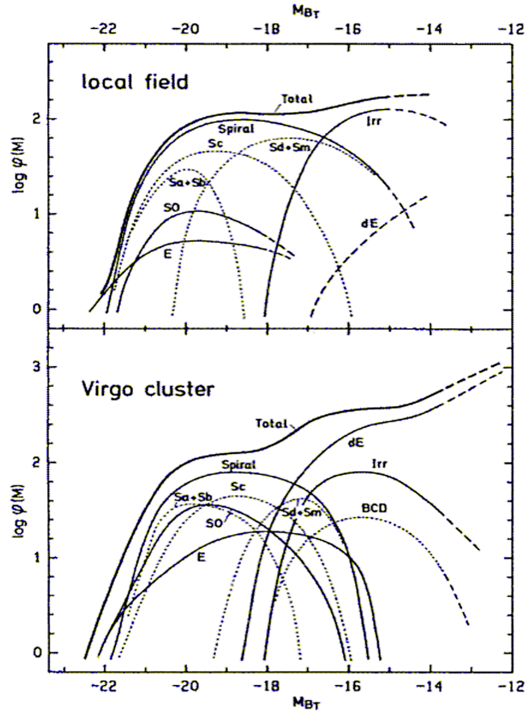
"Where" Do Galaxies of a Given Type Reside

- At low redshifts, **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)**



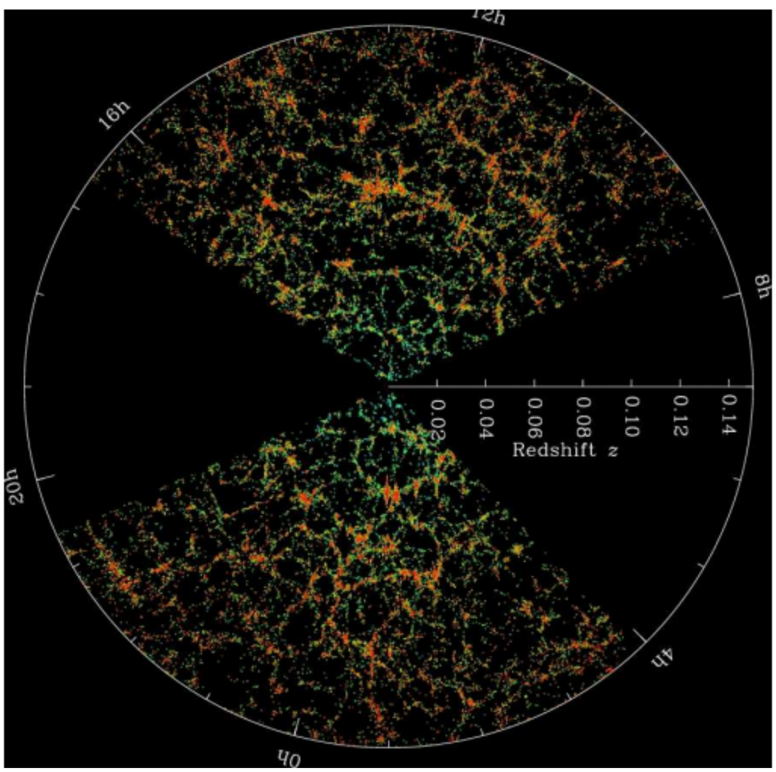
- relative number and mass fraction of each 'type' of galaxy depends on the environment
  - e.g ϕ the 'luminosity function' (the number of galaxies per unit luminosity per unit volume) vs absolute magnitude.
- this does not represent the mass function since the relationship between mass and luminosity (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 luminosity function http://www.mso.anu.edu.au/~jerjen/dial_a_LF/dial_a_lf.html

How Many of Which??



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

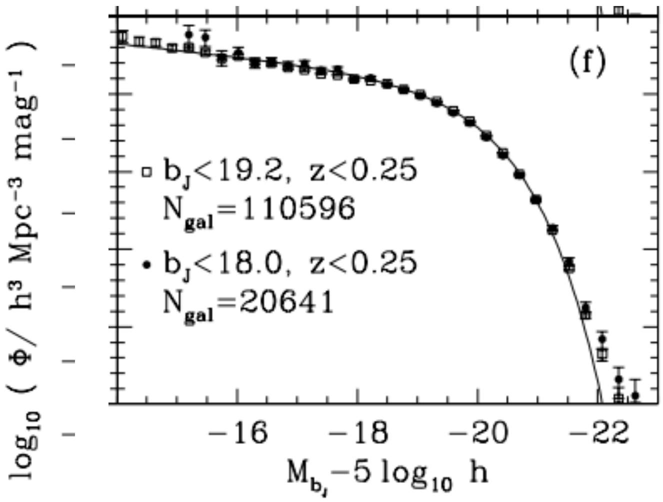


Luminosity Function

- The combined luminosity function of **all** galaxies is fitted by the Schecter function (S&G 1.24)- a power law at low L and an exponential cutoff at high L

$\phi(L) = n(L/L_*)^{\alpha}\exp(-L/L_*)$

  - where L* is a characteristic luminosity and n is a normalization



Integral is number of galaxies

$n_g \equiv \int^{\infty}_{0}\phi(L)dL = n^*\Gamma(\alpha+1)$

Γ is the gamma function

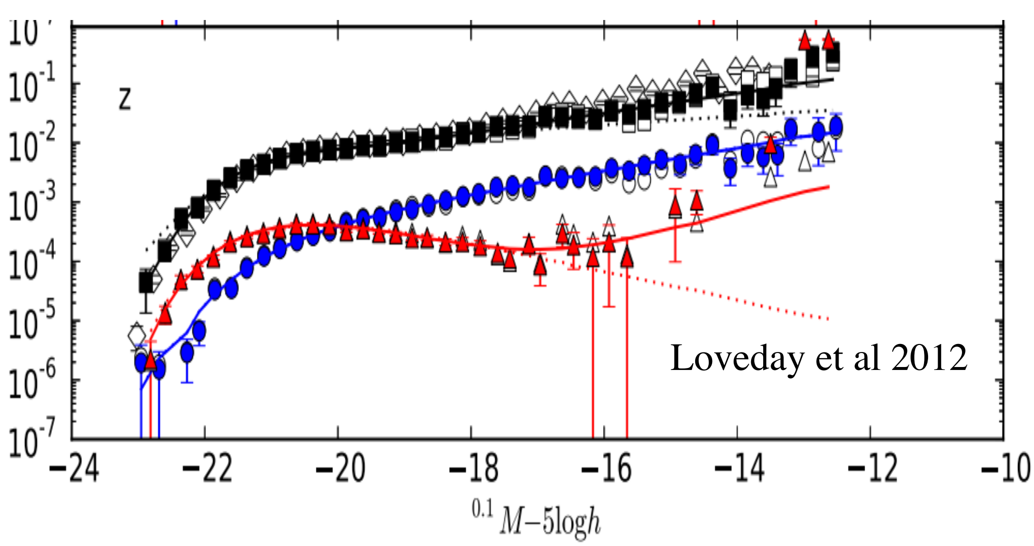
and total luminosity is

$\int^{\infty}_{0}\phi(L)LdL = nL_* {}^*\Gamma(\alpha+2)$

number density is dominated by faint galaxies while the luminosity density is dominated by bright ones

Red and Blue Luminosity Functions

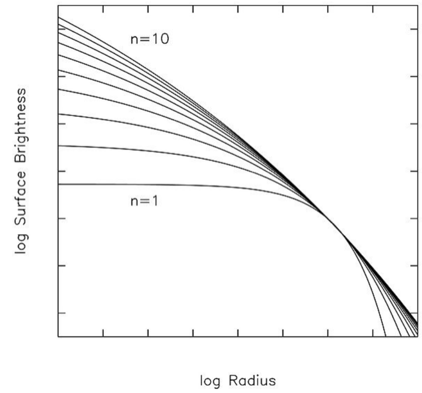
Despite differences in populations the red (mostly ellipticals) and **blue** (mostly spiral) galaxy luminosity functions add smoothly together and are well fit with a Schechter function



Descriptions of Galaxy Optical Surface Brightness

- For most massive galaxies a two component description of the surface brightness is a reasonable approximation to the azimuthally averaged data
  - Bulges/spheroids
  - Disks
- The ratio of these two components has wide variation
- Both can be described by a radially symmetric 'Sersic' profile

  $\Sigma(r)=\Sigma(0)\exp(-k\,[(r/r_e)^{1/n}-1]$; k ~2n-0.331 (who called for that!) where r_e is a characteristic (scale length)
- **Disks have n~1 (exponential profile) while spheroids have n~2-5** (a special value is n=4, the DeVacouleurs profile)
- Most spirals have a bulge and thus **the surface brightness is the sum of 2 Sersic profiles** (the bulge usually dominates for small r)



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

total luminosity of Sersic profile- Γ is the gamma function

- If one express the surface brightness in magnitudes,$\mu \propto -2.5\log(I)$, the Sersic profile can be expressed as
- $\mu(R) = \mu_e + 1.086k[\ (R/R_e^{1/n}) - 1]$

.

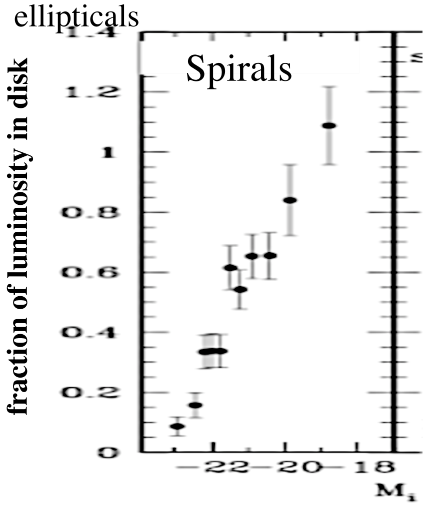
Stellar Distribution-radial average

- 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

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

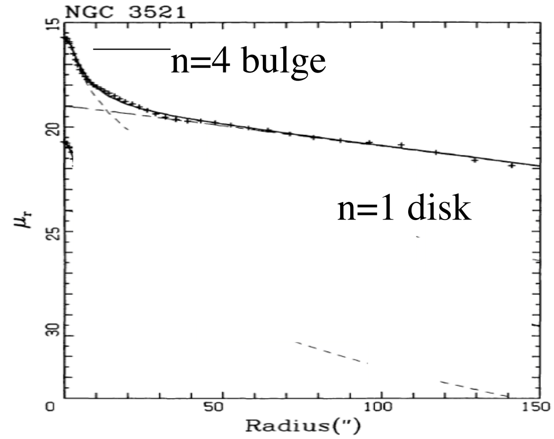
$$\kappa \approx 2n - 0.331$$

Sersic(1968) profile S+G eq 3.13



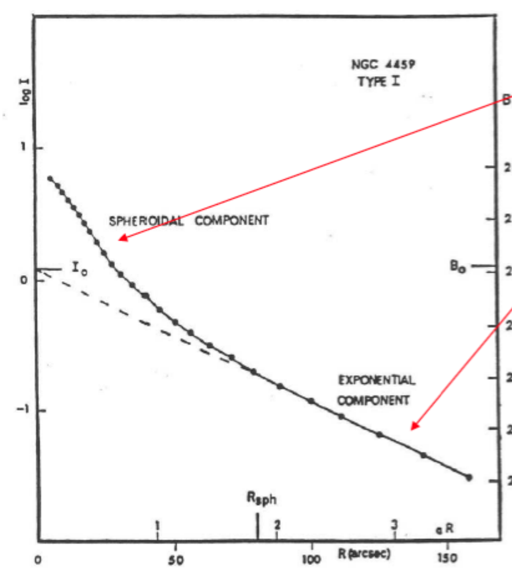
absolute mag

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



Azimuthally Averaged Light Profiles

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



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

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

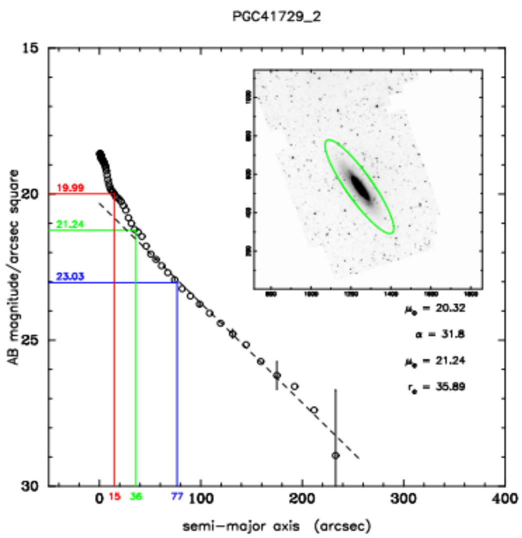
α is the inverse scale height

(Freeman 1970)

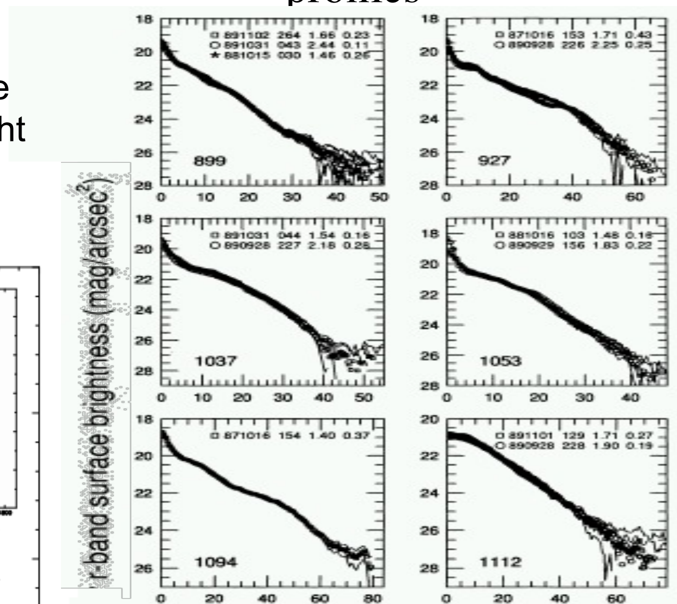
This is an approximation, galaxies with strong bars or other non-azimuthally symmetric features will clearly change this

Pure exponentials would be straight lines.

The exponential scale length 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

Typical values for the scale length are:
$1 < h_R < 10$kpc
$h_R \sim M_*^{1/3}$

In many, but not all, spiral galaxies the exponential part of the disk seems to end at some radius R_{max}, which is typically 3 - 5 h_R.

Beyond R_{max} the surface brightness of the **stars** decreases more rapidly – "edge" of the optically visible galaxy.

The central surface brightness of many spirals is ~ constant, irrespective of the absolute magnitude of the galaxy!

Presumably this arises from physics of galaxy and /or star formation.

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

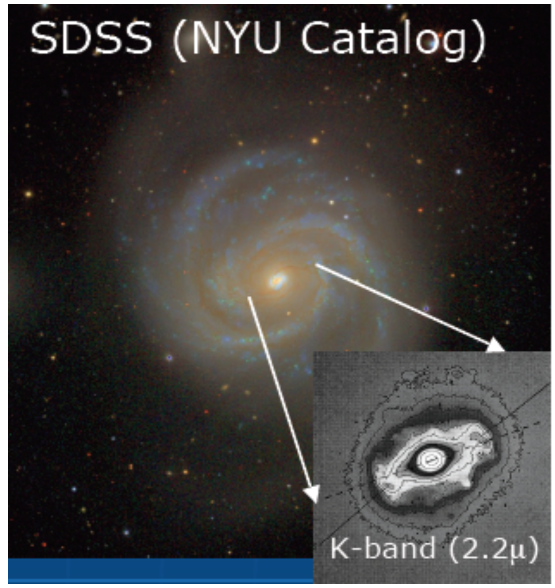
(morphology density relation- Dressler 1978)

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).



Tully-Fisher for Spiral Galaxies:S&G **5.3.3**

- Relationship between the speed at which a galaxy rotates,V, and its optical luminosity L_{opt}: (the normalization depends on the band in which one measures the luminosity and the radius at which the velocity is measures)
  - $L_{opt} \sim A v_{max}^4$
- Connects galaxy dynamics to optical luminosity
- Since luminosity depends on distance^2 while rotational velocity does not, this is a way of inferring distances

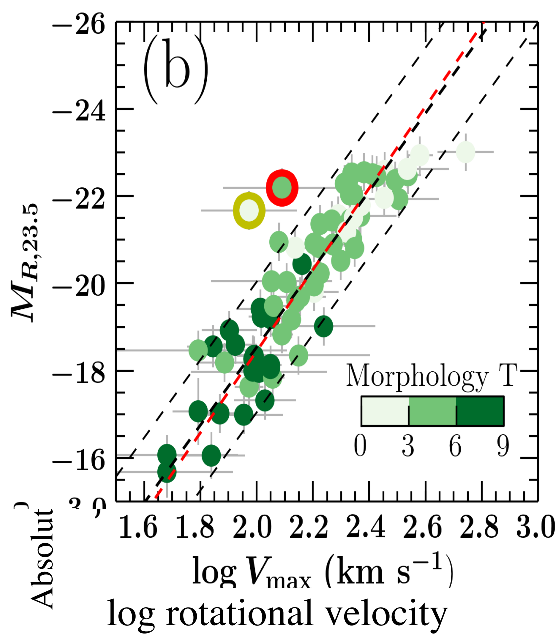


Figure shows the **T-F relation R band**

arXiv:1508.03004v1
Barbosa et al

Tully-Fisher
Back of the envelope derivation

- 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 <u>same surface densities</u> $L\sim r^2$
- Further if M/L is constant $M\sim L$
- a little algebra gives $L\sim v_c^2 L^{1/2}\sim v_c^4$
- If galaxies contained no dark matter, we could understand the Tully–Fisher relation fairly easily
- But, since the rotation speed V_{max}

is set largely by dark matter, while the luminosity comes from stars Somehow, the amount of dark matter is coordinated with the luminous mass.

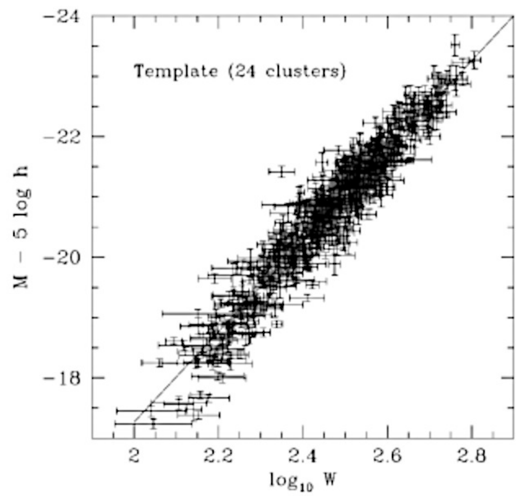


FIG. 1.—Template relation based on 555 galaxies in 24 clusters. The fit is −21.00 ± 0.02–7.68 ± 0.13 (log W − 2.5).

Giovanelli et al 10997