Spiral Galaxies-
Read Chapter 5 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 <u>will not cover in detail</u>
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

Mid term

- Based on the rubric in the intro lecture

A 86-100% – scores of 100+

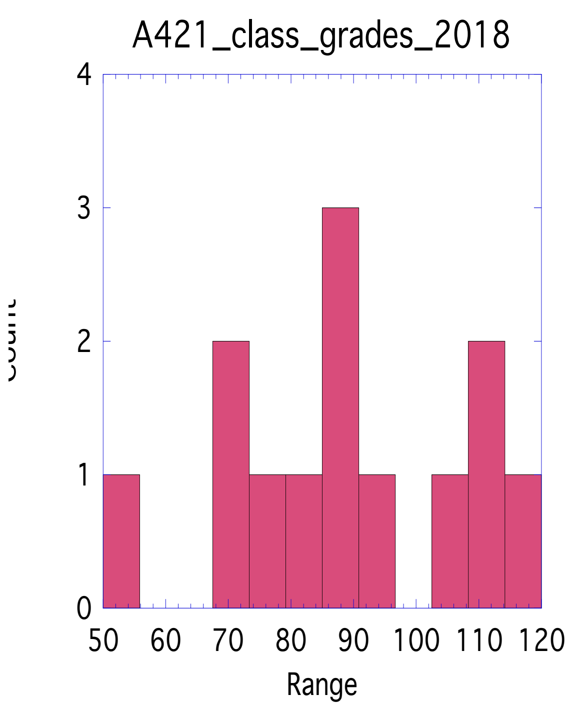
B 70-85% – scores of 82-99

C 60-69% scores of 70-81

D 40-59%

F <39%

- This is subject to revision later
- The mean was 89/120=75% close to the goal.
- This gives 33% with A,33% with a B, 25% with a C and one not pass.



Still Relevant

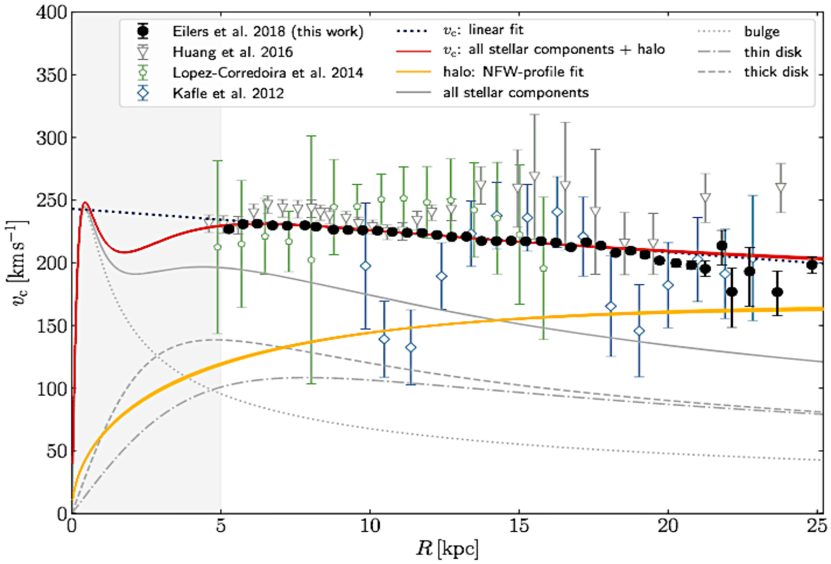
Today on astro-ph

1810.09466.pdf

The Circular Velocity Curve of the Milky Way from 5 to 25kpc

Anna-Christina Eilers,David W. Hogg,Hans-Walter Rix,and Melissa K. Ness

The circular velocity curve shows a gentle but significant decline with increasing radius



black points are new data

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.

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 models that attempt to track galaxy morphology assume that mergers destroy disks and build spheroids.

The Components

Models show that the gas accreting from the halo does conserve its specific angular momentum and thus settles into a disk - but this is only a small part of the story.

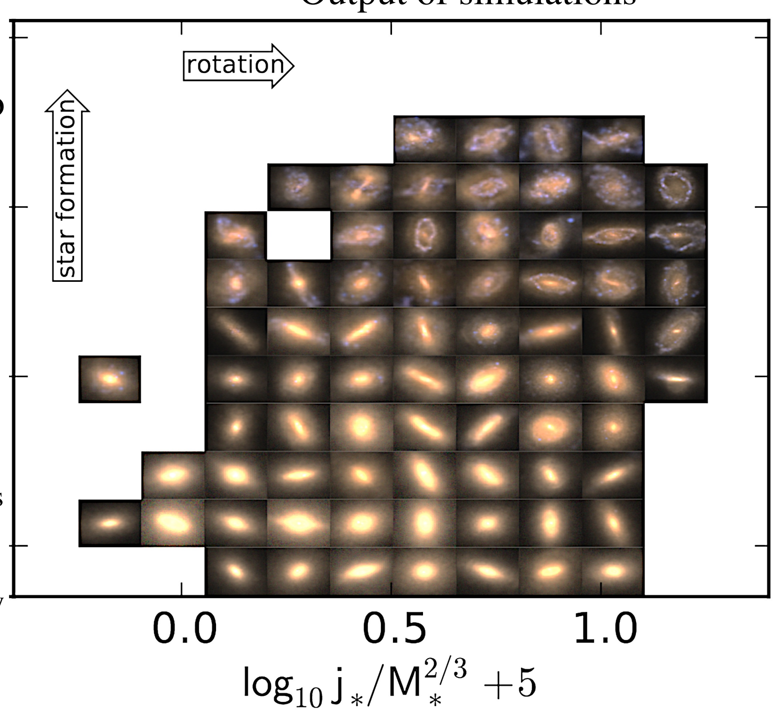
- For many years, simulations were only able to produce very compact disks with large spheroids, and were unable to produce spirals even as late-type as the Milky Way
- Things are 'fixed' now
  - the general solution lay in the way stars are formed in the simulations...and the general picture is now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

Huge Array of Sizes and Shapes

Comparison of a Massive Spiral and Elliptical

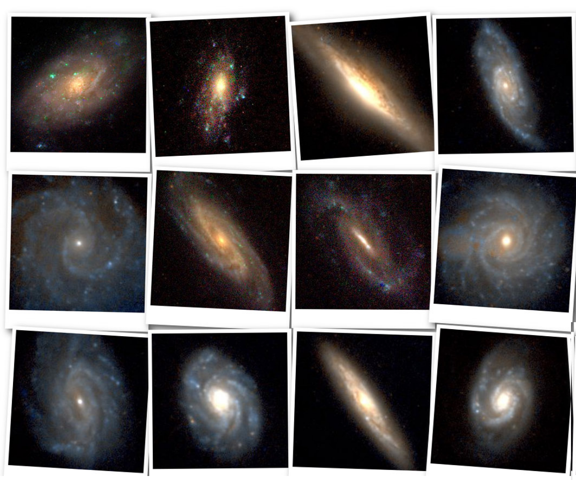
From Chaisson

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

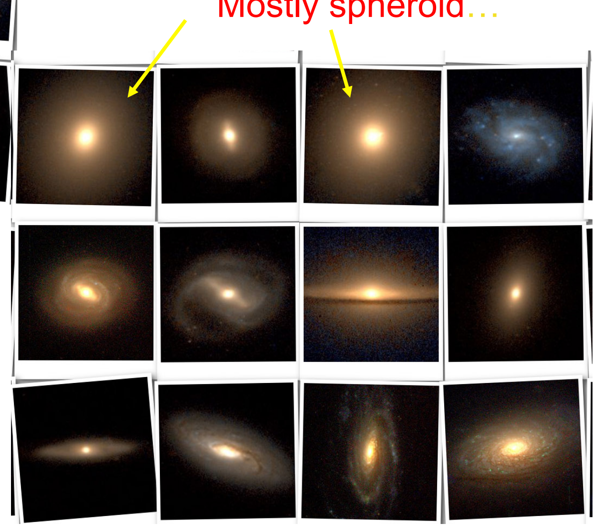
A Bit of the Galaxy Zoo

Mostly disk…



Citizen science morphological classification of SDSS galaxies

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)

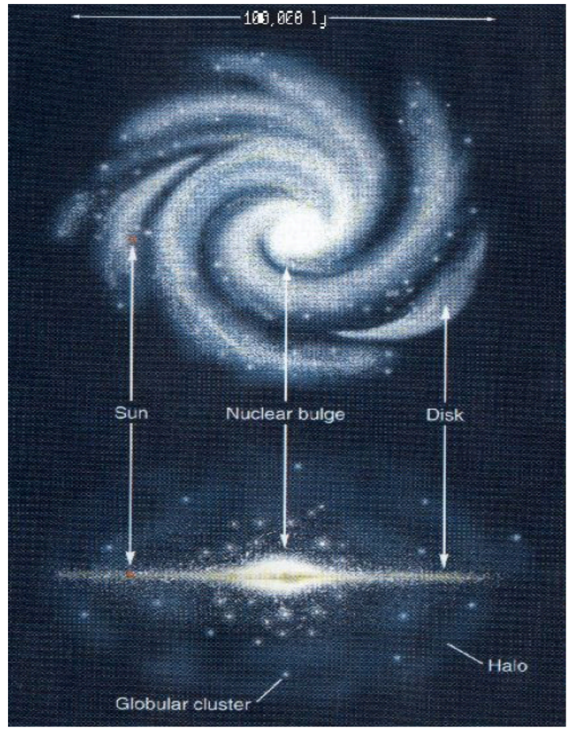
Spirals

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

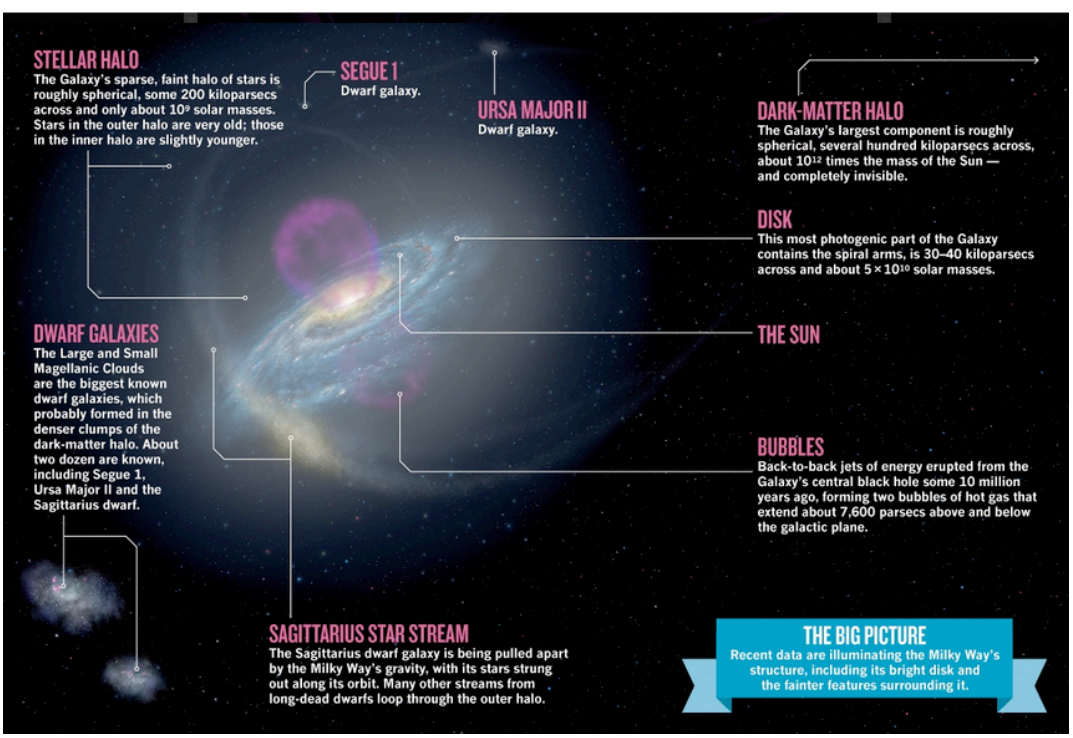
  The disk contains a large quantity of gas & dust, the bulge essentially none

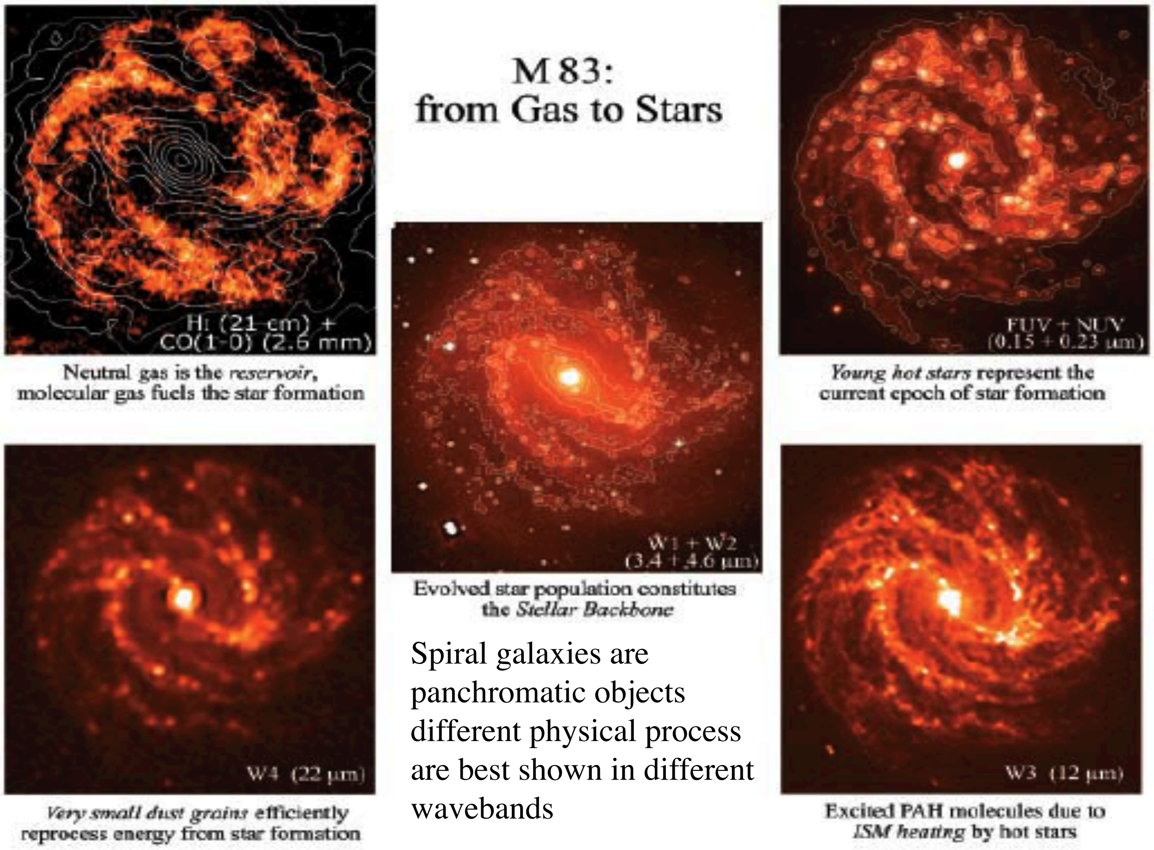
  Disks are cold (rotationally supported)

  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**.

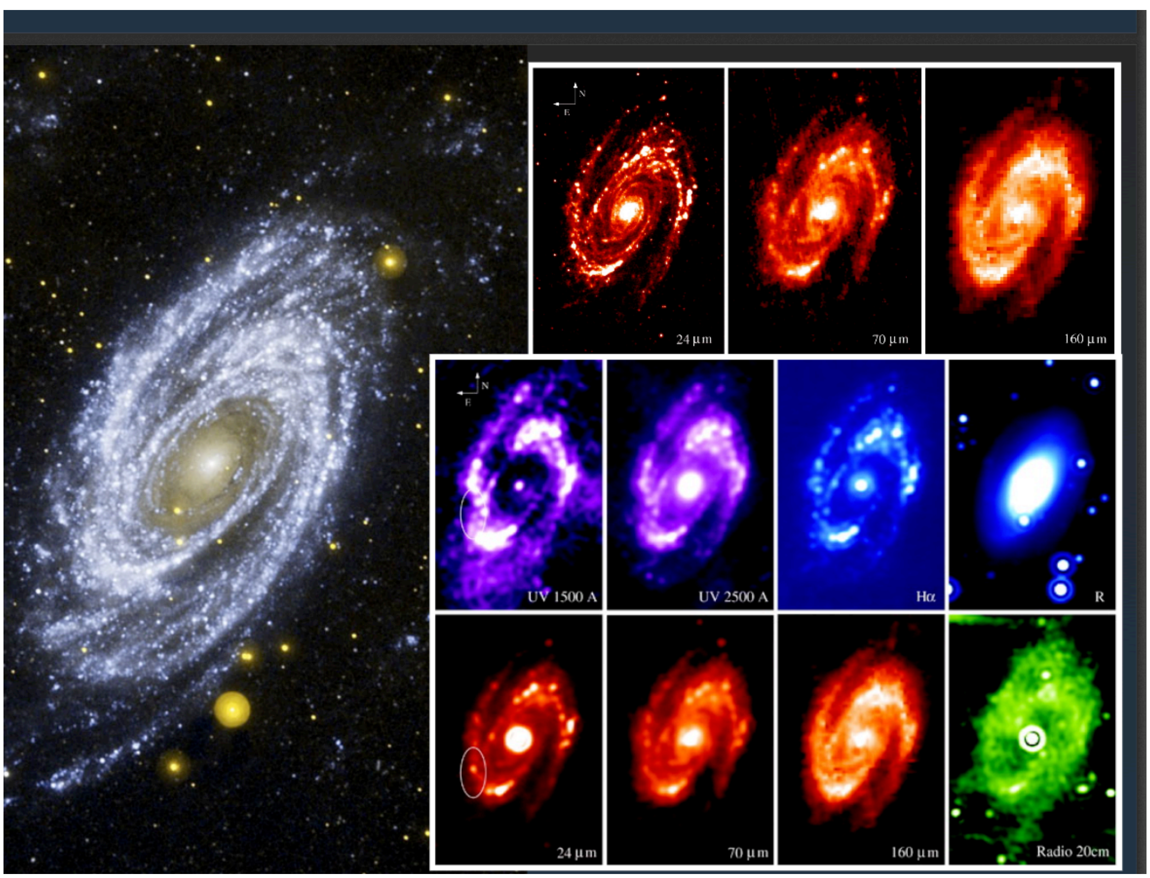


- major review article in Nature " Galaxy formation: The new Milky Way" (http://www.nature.com/news/galaxy-formation-the-new-milky-way-1.11517). This overlaps considerably with the material we have been covering!



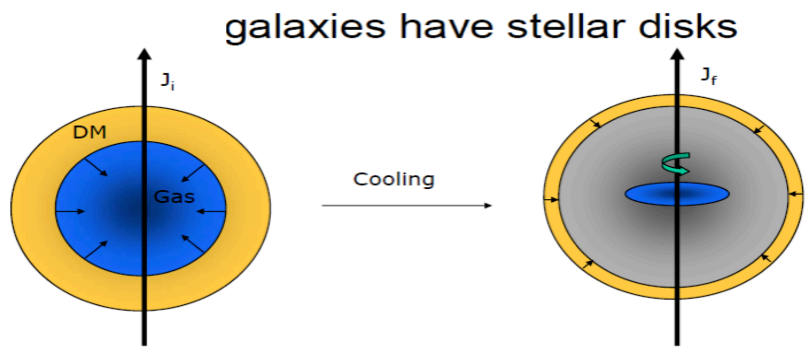


Spiral galaxies are panchromatic objects different physical process are best shown in different wavebands

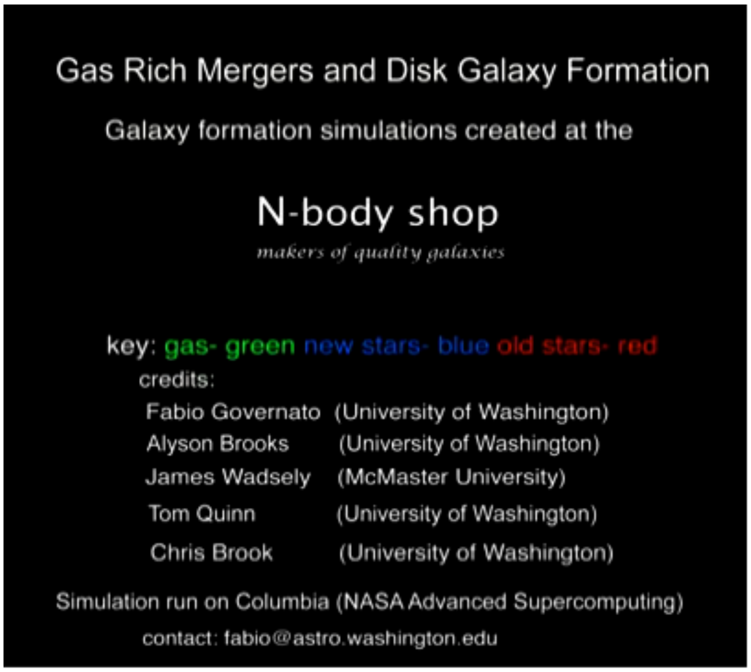


Simple Model of Why Galaxies Have Disks

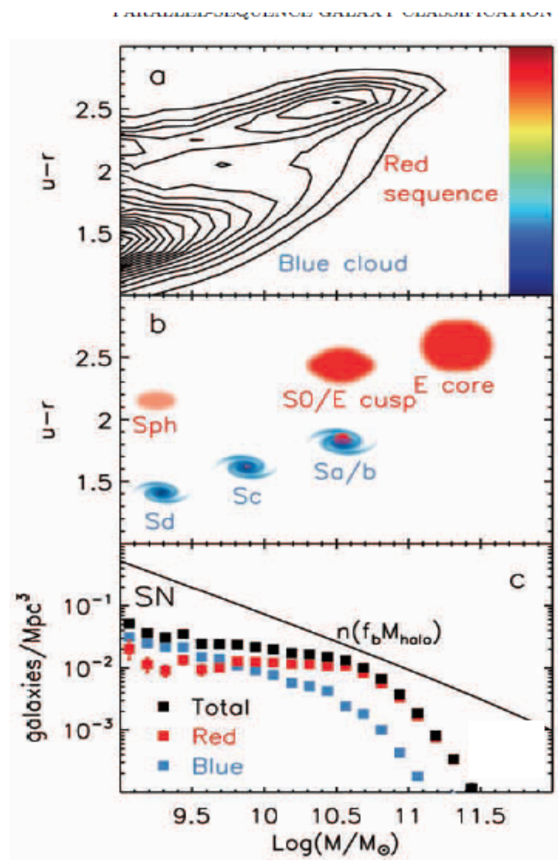
- A circular orbit has the lowest energy for an initial angular momentum J- thus since angular momentum is conserved, if the infalling gas loses energy (cools) it will tend to form a disk
- If stars form from dense gas they will also be in a disk.
- However this simple models misses lots of the details



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 so far

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

- 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 not gas
- ISM is highly structured

Spirals- General Properties

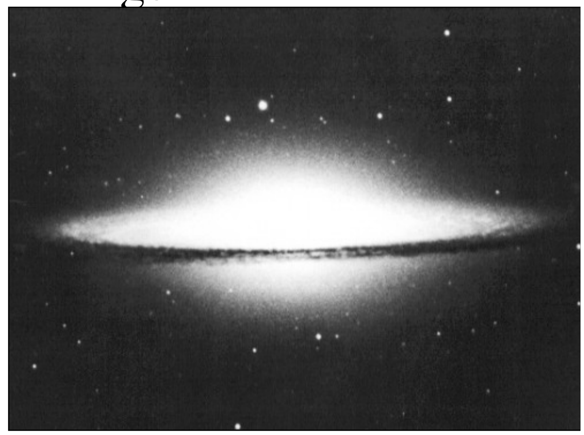
wide range in bulge/disk ratio

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.

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)

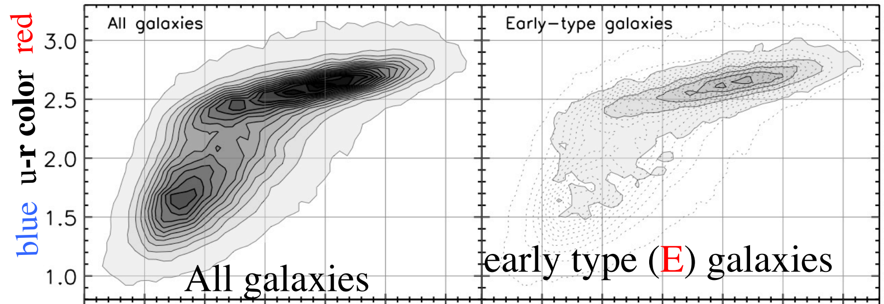
•* while superficially elliptical galaxies 'look like' bulges their stars are frequently metal rich, not metal poor.

Top Level -Spirals

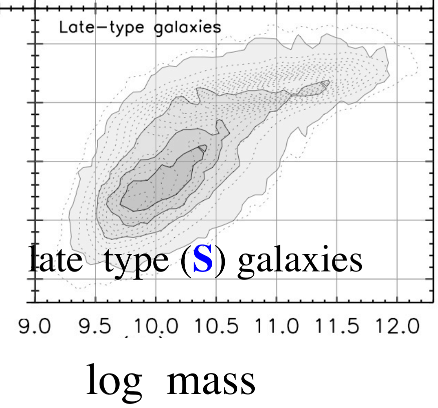
- Galaxies have a wide variety of morphologies, from spheroids , disks with and without bars and irregular galaxies.
- Their physical properties (e.g. gas content, average stellar age, the rate of current star formation, mass etc) correlate with morphology.
- disks are predominantly rotationally flattened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

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

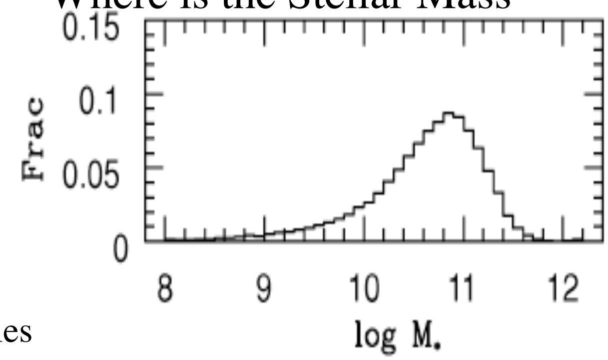


- **Strong relation of mass, color and morphology**

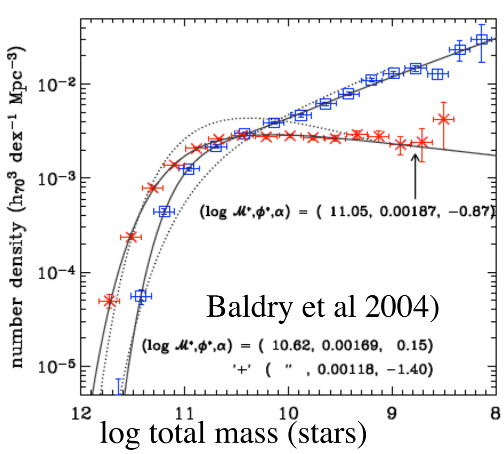
Schawinski 2010

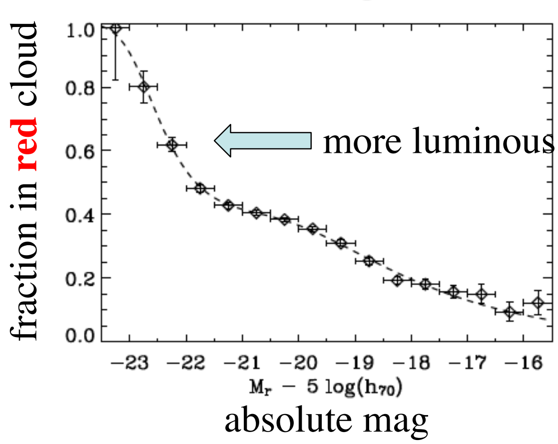
- The stellar mass **integrated over ALL galaxies** lies mostly between
  log $M_{\odot}$=10.5-11.4
- In what galaxies does the stellar mass lie?
  - most **massive** galaxies are red (ellipticals)
  - at lower masses there is an increasing ratio of **spirals** to ellipticals

Where is the Stellar Mass



Mass function of blue and red galaxies

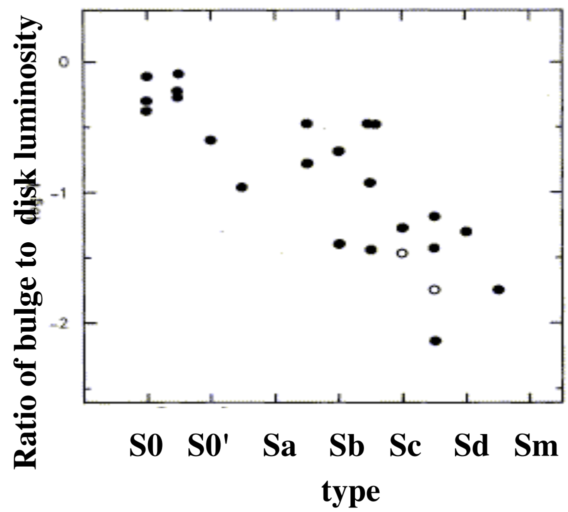


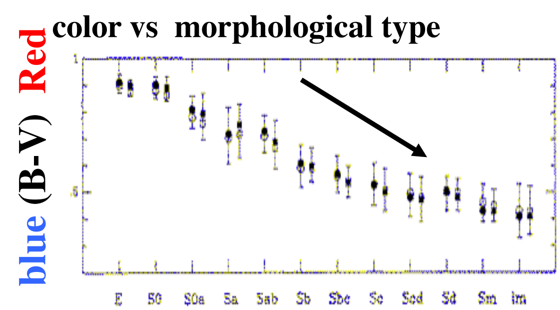


Spirals

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)*

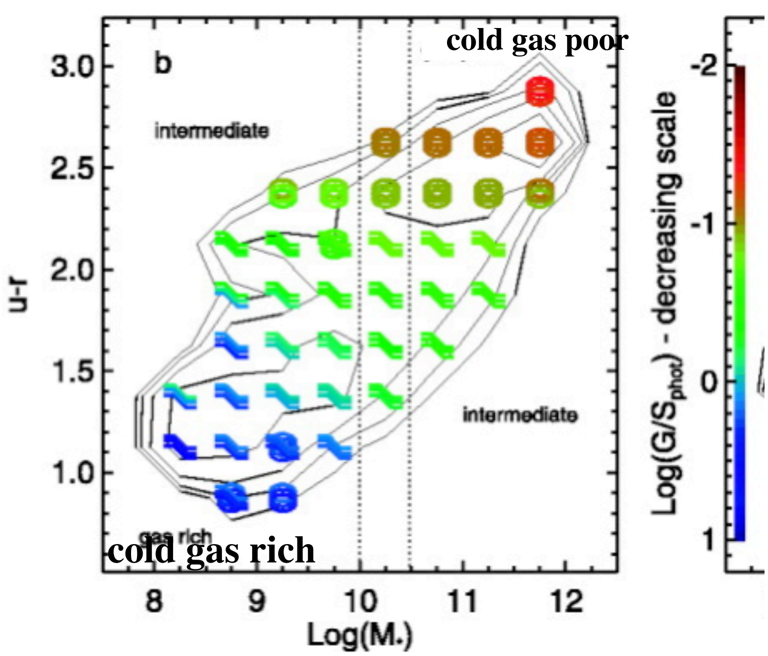




Spirals and Gas

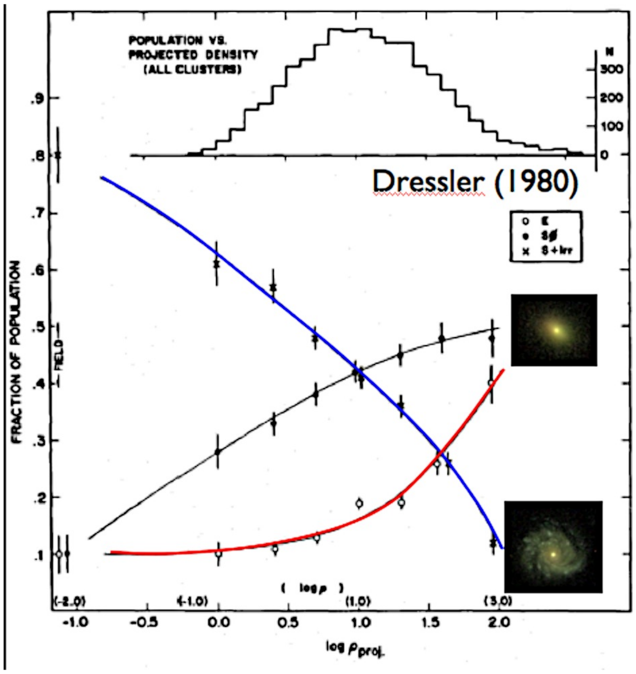
- The ISM of spiral galaxies is quite complex and show wide variations with position
- However there are certain trends - the lower the mass and the 'bluer' the galaxy the higher is the baryonic fraction in cool/cold gas.- there seems to be a characteristic stellar mass ~3x10^{10}M where things change.
- Luminous red galaxies have hot ISMs

Gas to light ratio in log scale



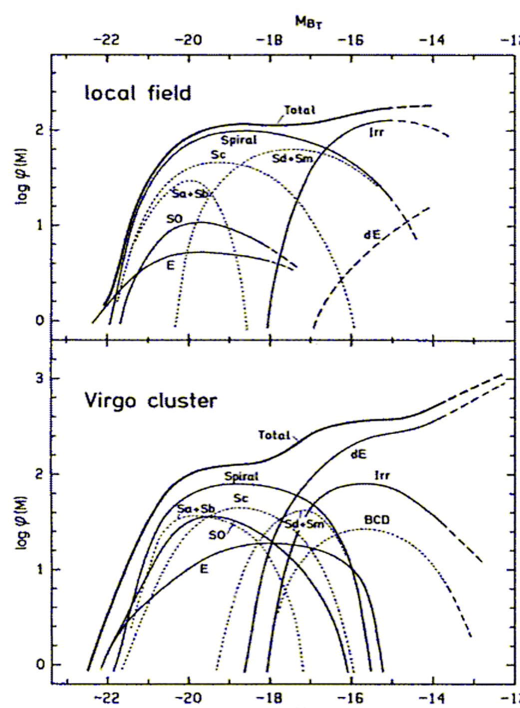
"Where" Do Galaxies of a Given Type Reside

- 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)**



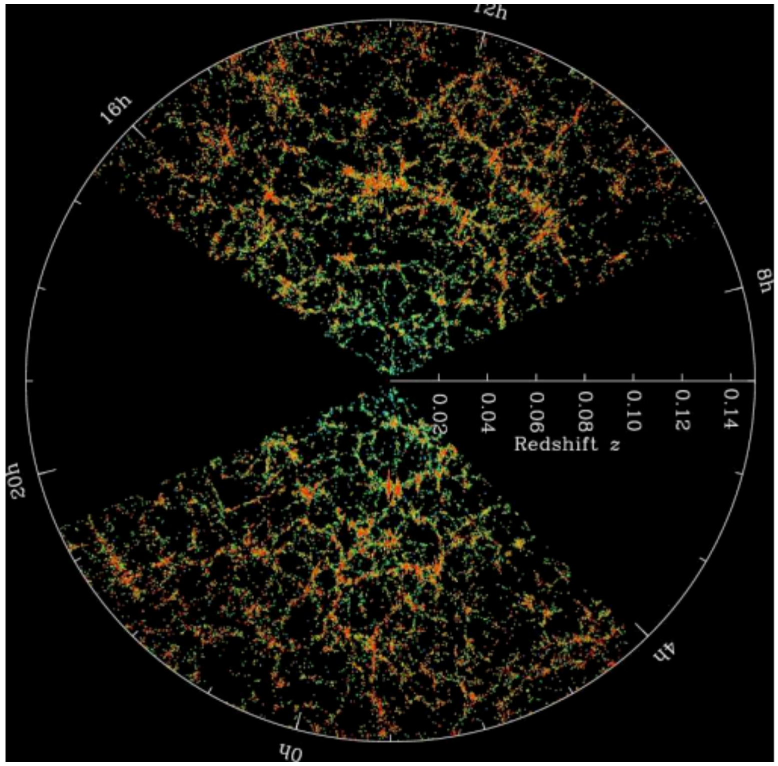
- relative number and mass fraction of each 'type' of galaxy depends on the environment
  - e.g ϕ the 'luminosity function' (the number of galaxies per unit luminosity per unit volume) vs absolute magnitude.
- this does not represent the mass function since the relationship between mass and luminosity (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

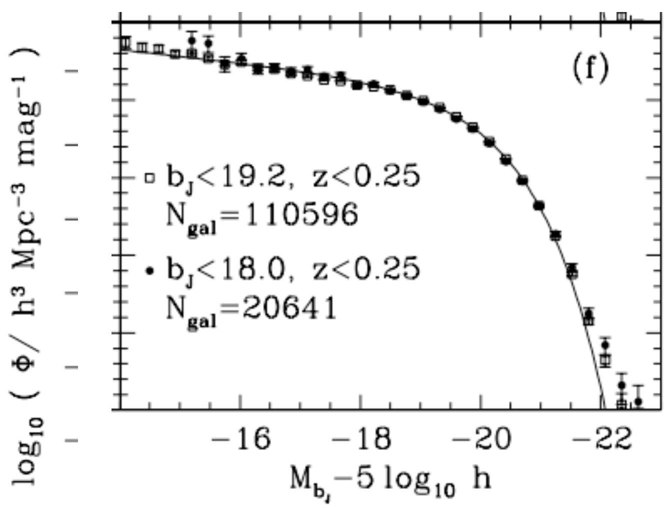


Luminosity Function

- 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*

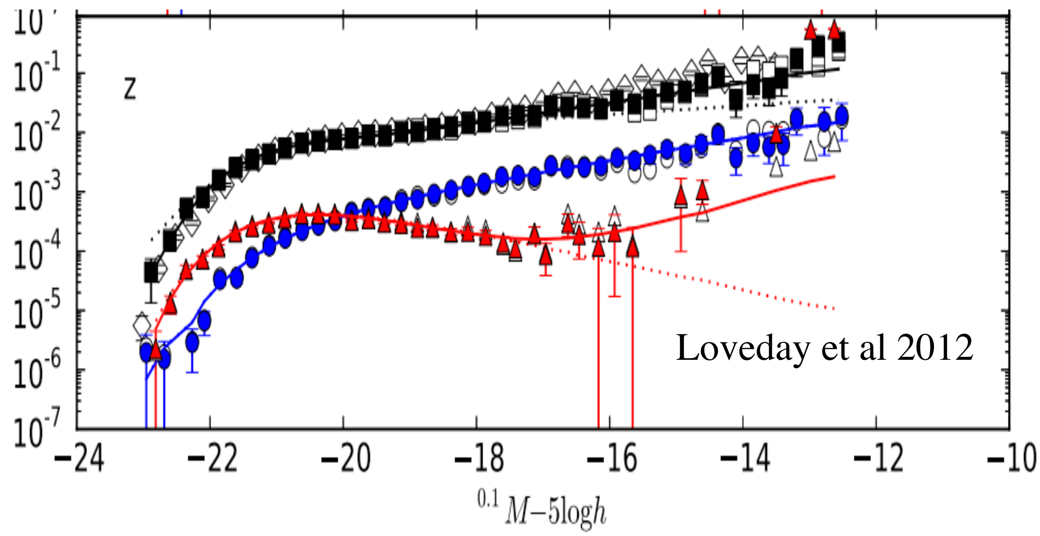
and total luminosity is

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

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

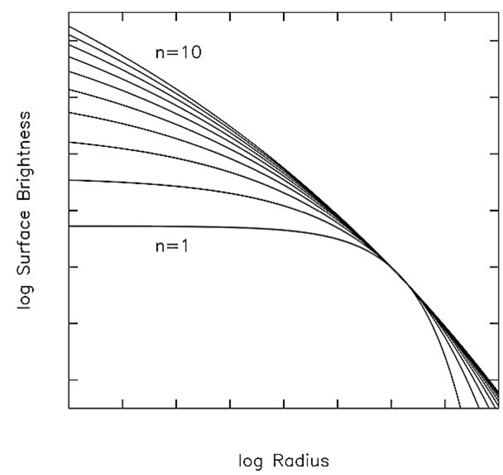


Descriptions of Galaxy Optical Surface Brightness

- 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)



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

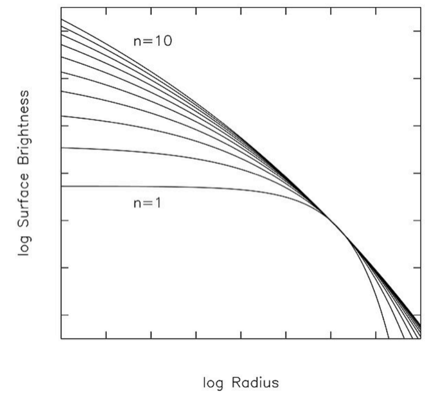
total luminosity of Sersic profile- Γ is the gamma function

Descriptions of Galaxy Optical Surface Brightness

- 'Sersic' profile (S&G eq 5.13)

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

  k ~2n-0.331 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)

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

total luminosity of Sersic profile- Γ is the gamma function

- Most spirals have a bulge and thus **the surface brightness is the sum of 2 Sersic profiles** (the bulge usually dominates for small r)

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

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