The Components of a Spiral Galaxy-a Bit of a Review- See MBW chap 11

we have discussed this in the context of the Milky Way

Disks:

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

Origin in CDM models (sec 11.2) : 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 (sec 11.5)

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

- Major Review: A very dense article

  Dawes Review 4: Spiral Structures in Disc Galaxies; C. Dobbs and J Baba arxiv 1407.5062

- While they overstate it a bit they say

  'The majority of astrophysics involves the study of spiral galaxies, and stars and planets within them, but how spiral arms in galaxies form and evolve is still a fundamental problem. Major progress in this field was made primarily in the 1960s, and early 1970s, but since then there has been no comprehensive update on the state of the field.'

Major Workshop in the Spring-The 2016 STScI Spring Symposium will convene experts in state-of-the-art observational programs and theoretical simulations to address the question: ***What physical processes shape galaxies?***"

"In the twenty years since the original Hubble Deep Field, striking advances in both ground- and space-based observational surveys and theoretical simulations have revealed the complex evolution of galaxies over much of the history of the universe. Subsequent generations of surveys have recorded the rise of spheroidal galaxies and the decline of disks and mergers, and young star-forming galaxies just the first billion years. New slit and IFU spectroscopy capabilities from the ground have demonstrated the key interplay between galaxy kinematics and their morphological structures, and new facilities at long wavelengths are providing improved tools for studying the kinematics and structures of the gas and dust content of galaxies. At the same time, theoretical studies have had remarkable success reproducing many characteristics—e.g., star formation histories, structural morphologies, and distribution functions—of the galaxy population over local and distant cosmological volumes.

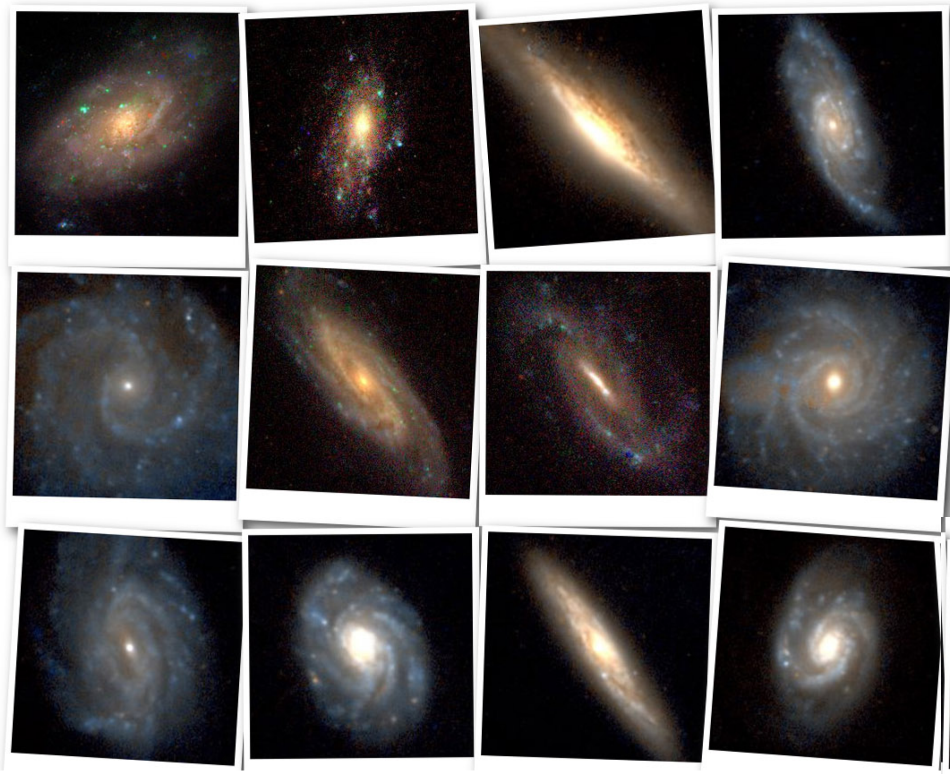
TABLE 23.1 Overall Properties of the Galactic Disk, Halo, and Bulge

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

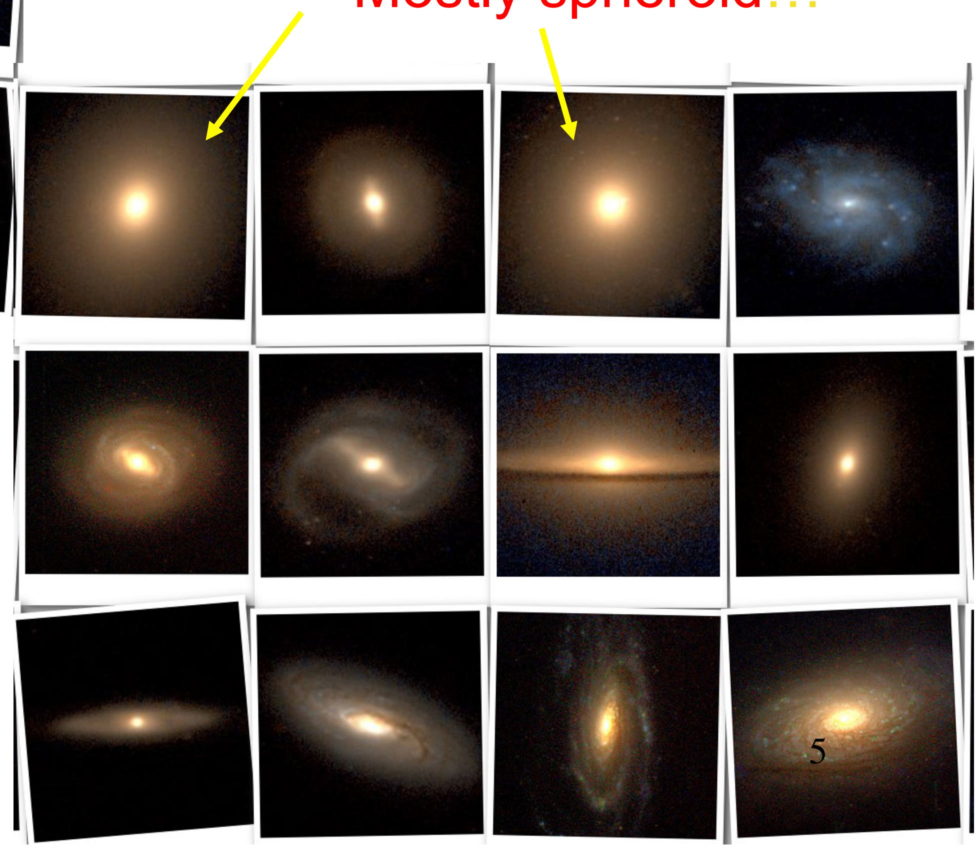
From Chaisson

A Bit of the Galaxy Zoo

Mostly disk…



Mostly spheroid…



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

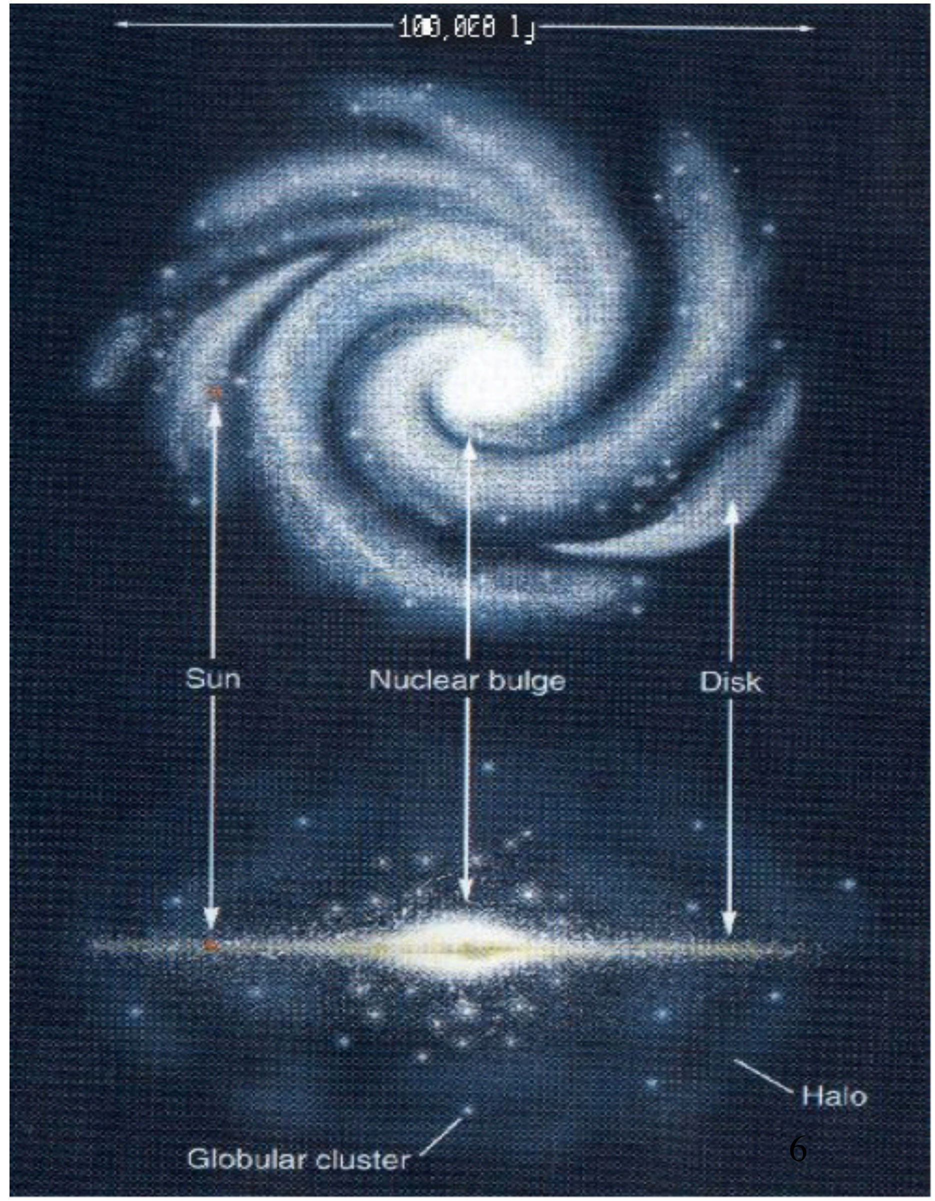
Spirals

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

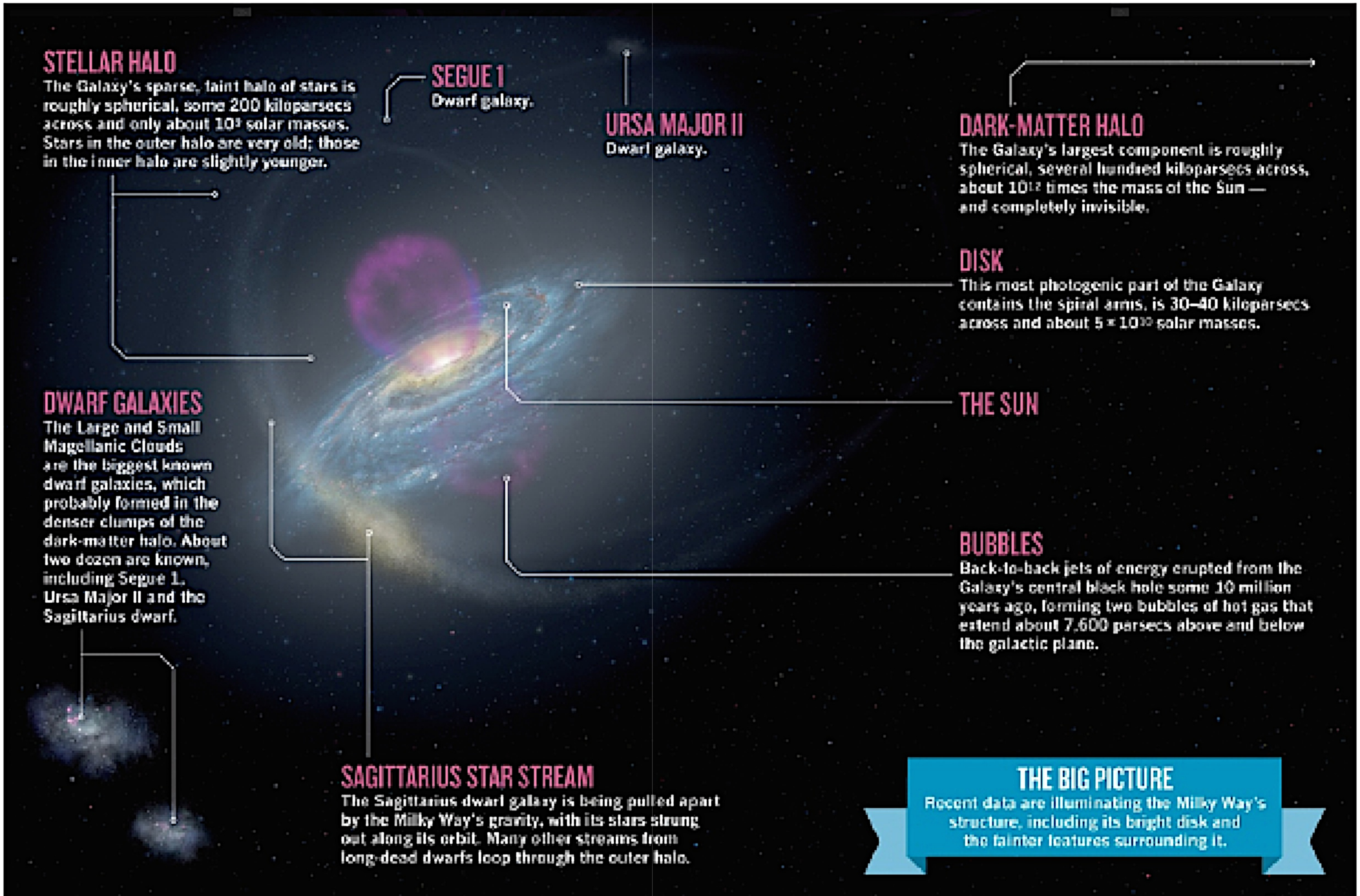
  The disk contains a large quantity of gas & dust, the bulge essentially none

  Disks are cold (rotationally supported)

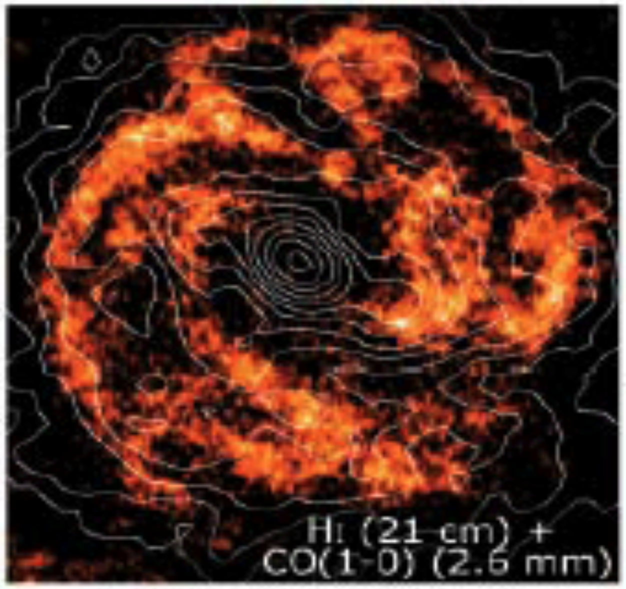
  Bulges are 'hot' supported by random motions
- The rotation curves of spiral galaxies rise like a solid body in the central regions, then flattens out (i.e., v(r) = constant). This flattening is due to the presence of a **dark matter halo**.



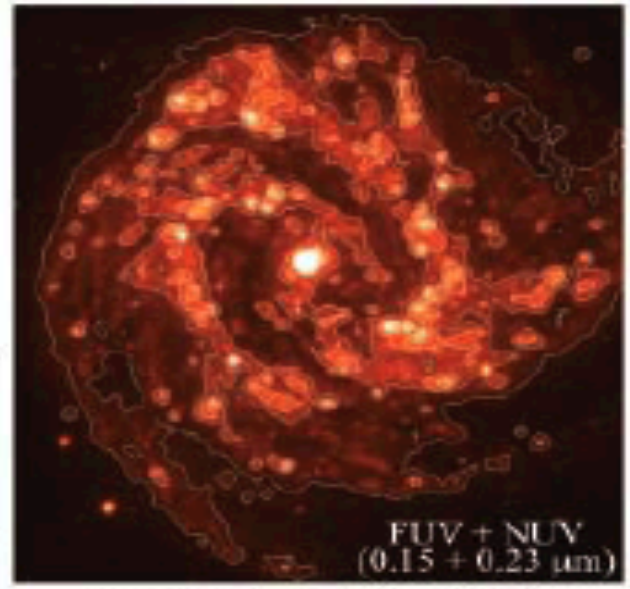
- there is a major review article in Nature last year called" Galaxy formation: The new Milky Way" (http://www.nature.com/news/galaxy-formation-the-new-milky-way-1.11517). This overlaps considerably with the material we have been covering



M 83:
from Gas to Stars

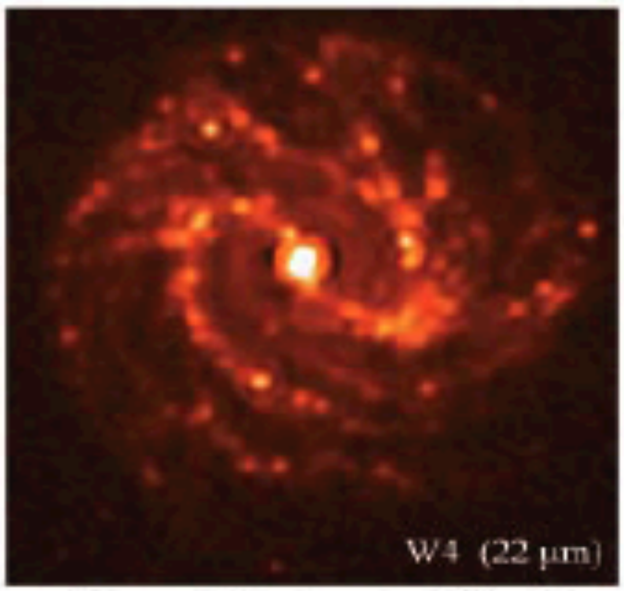


Neutral gas is the *reservoir*, molecular gas fuels the star formation

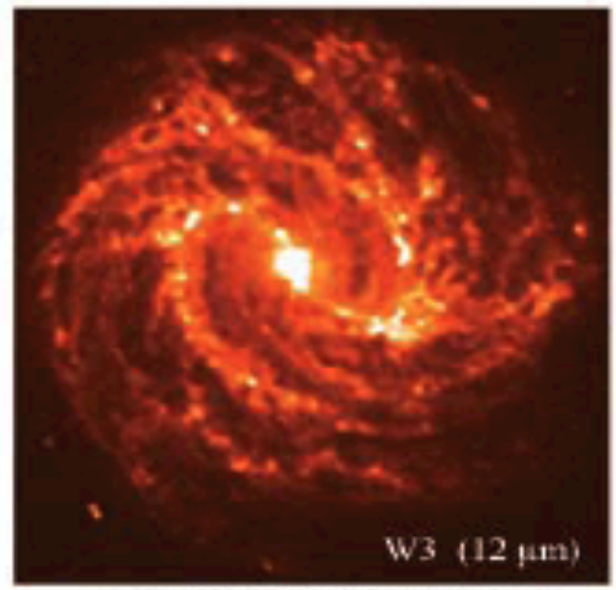


Young hot stars represent the current epoch of star formation

Evolved star population constitutes the *Stellar Backbone*



Very small dust grains efficiently reprocess energy from star formation

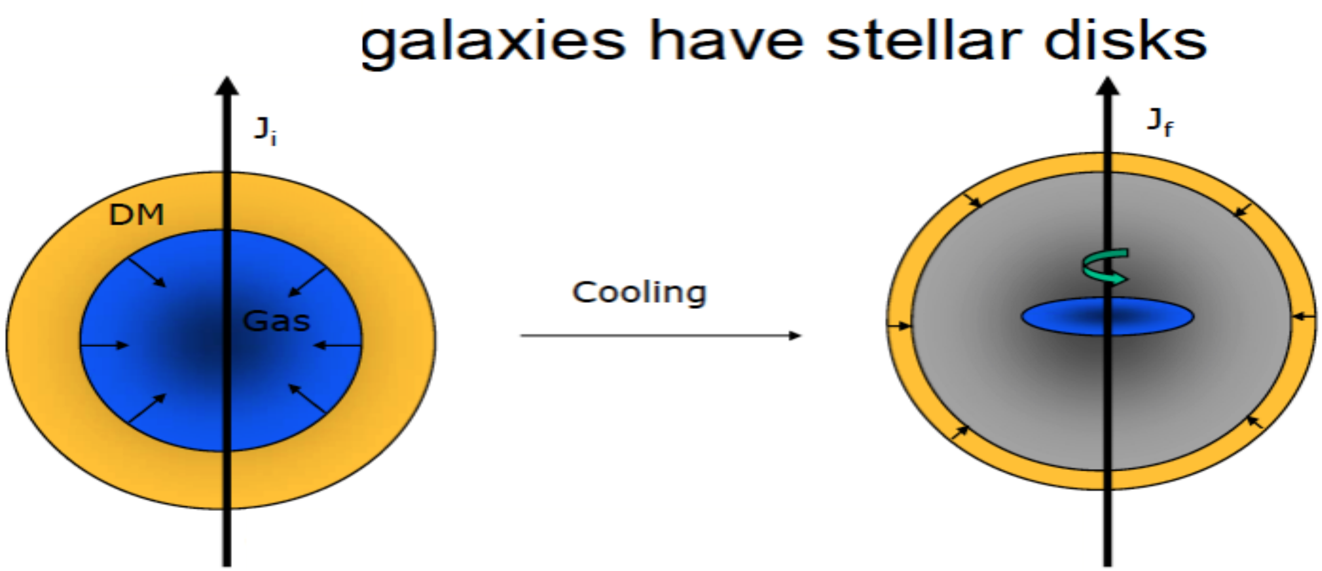


Excited PAH molecules due to *ISM heating* by hot stars

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.



Forming disks-The Bigger Picture

A natural way to form them is through the dissipational collapse of a gas cloud with some initial angular momentum.

- Consider a gas cloud for which radiative cooling is very effective)
- The cloud will radiate away its binding energy and contract, causing it to approach a state in which its energy is as low as possible
- The cloud will conserve its angular momentum producing . a rotating disk, since in such a configuration the angular momenta of

  all mass elements point in the same direction.

In sec 11.4.2, the effects of angular-momentum transfer which depends on the effective viscosity of the disk material are shown to be important.

In the absence of viscosity or non-axisymmetric structure, each mass element of the cloud will conserve its own specific angular momentum, so that the end state is a disk with surface density directly related to the initial angular momentum distribution of the cloud.

Movie of Formation of A Spiral

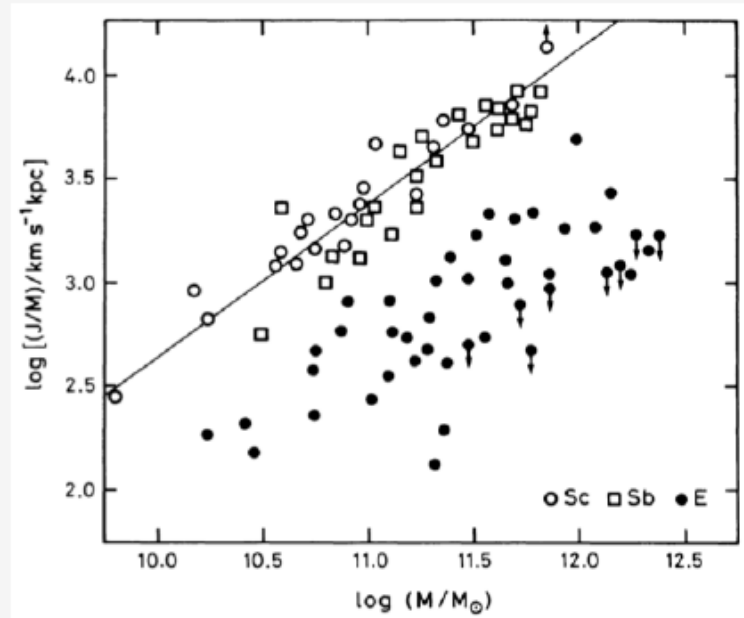
Angular Momentum

- Consider stars on a circular radius (r_0) $v^2/r_0 \sim GM/r_0^2$
- which we will re-write as $v \sim (GM/r_0)^{1/2}$
- Approximate angular momentum $J \sim Mvr_0 = r_0 GM/r_0)^{1/2} \sim K(GM^3 r_0)^{1/2}$

- where K depends on the distribution of matter, for a rotating exponential disk K~1.109 (Freeman 1970)
- Disk structure is governed by angular momentum distribution

Specific Angular Momentum vs Mass

Fall 1983

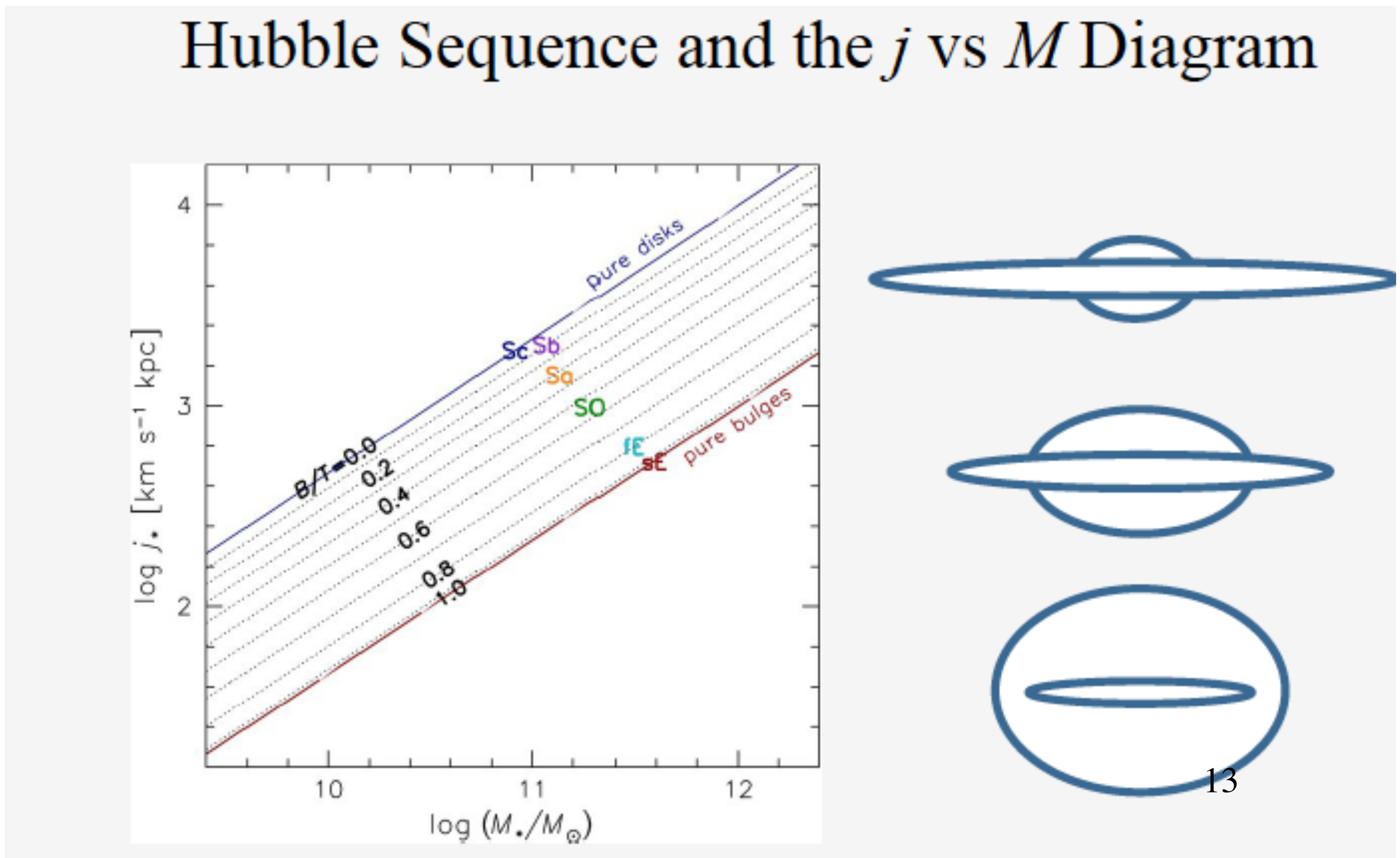


$j = J/M \ \alpha \ M^{\alpha}$ with $\alpha \approx 0.7$

S and E galaxies offset by ~6x

- The *j* vs *M* diagram is a physics-based alternative to the morphology-based Hubble sequence
- galaxies of intermediate types have intermediate *j* at each *M*.
- Shows that lenticulars are not faded spirals (Falcon-Barroso 2014)

M. Fall 2014



However In A Hierarchical Universe Things are More Complex

- Formation of a spiral galaxy

The Big Picture- Two Populations

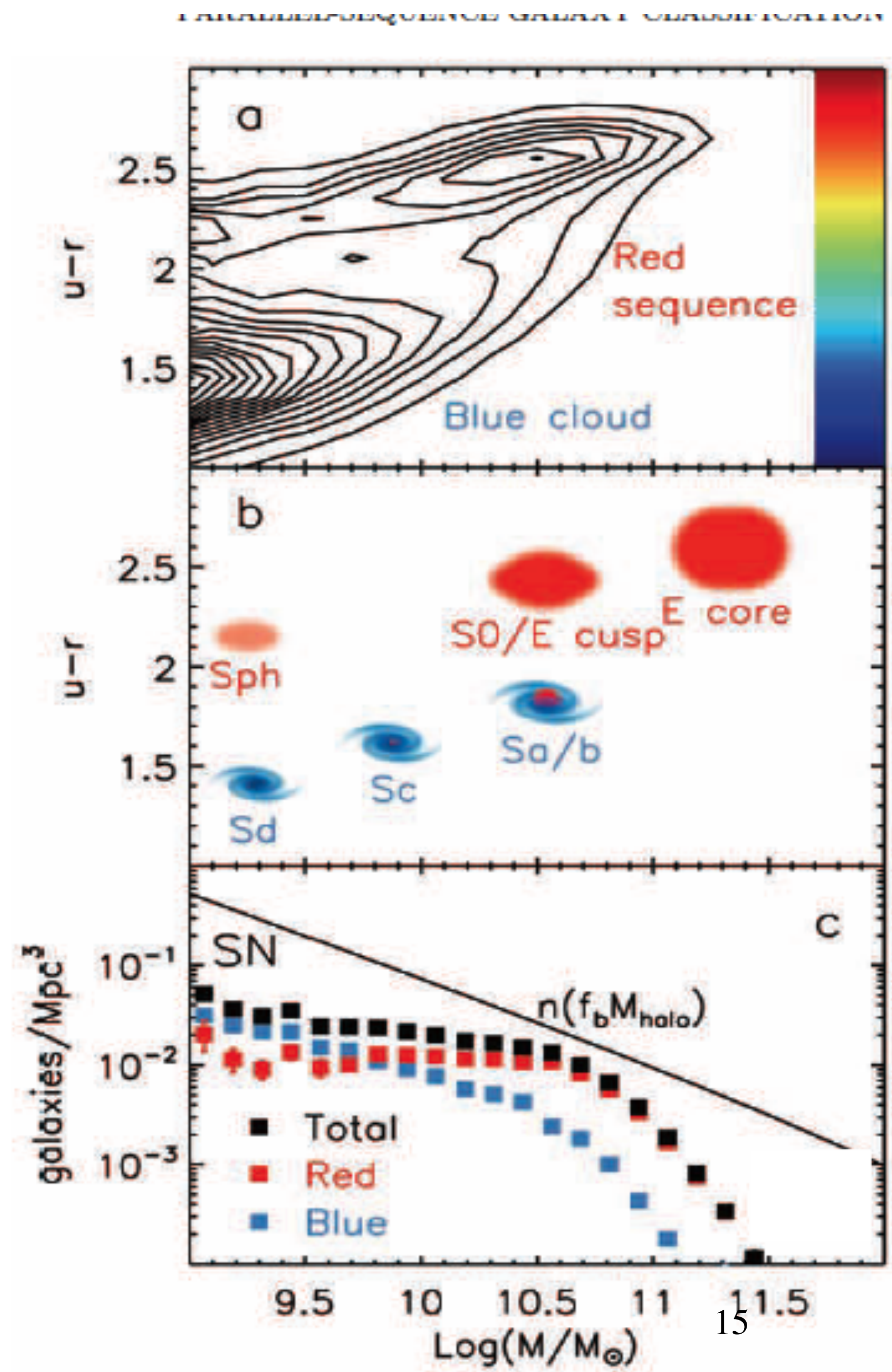
- top panel color distribution vs mass of a large sample of local galaxies from the SDSS

  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)-

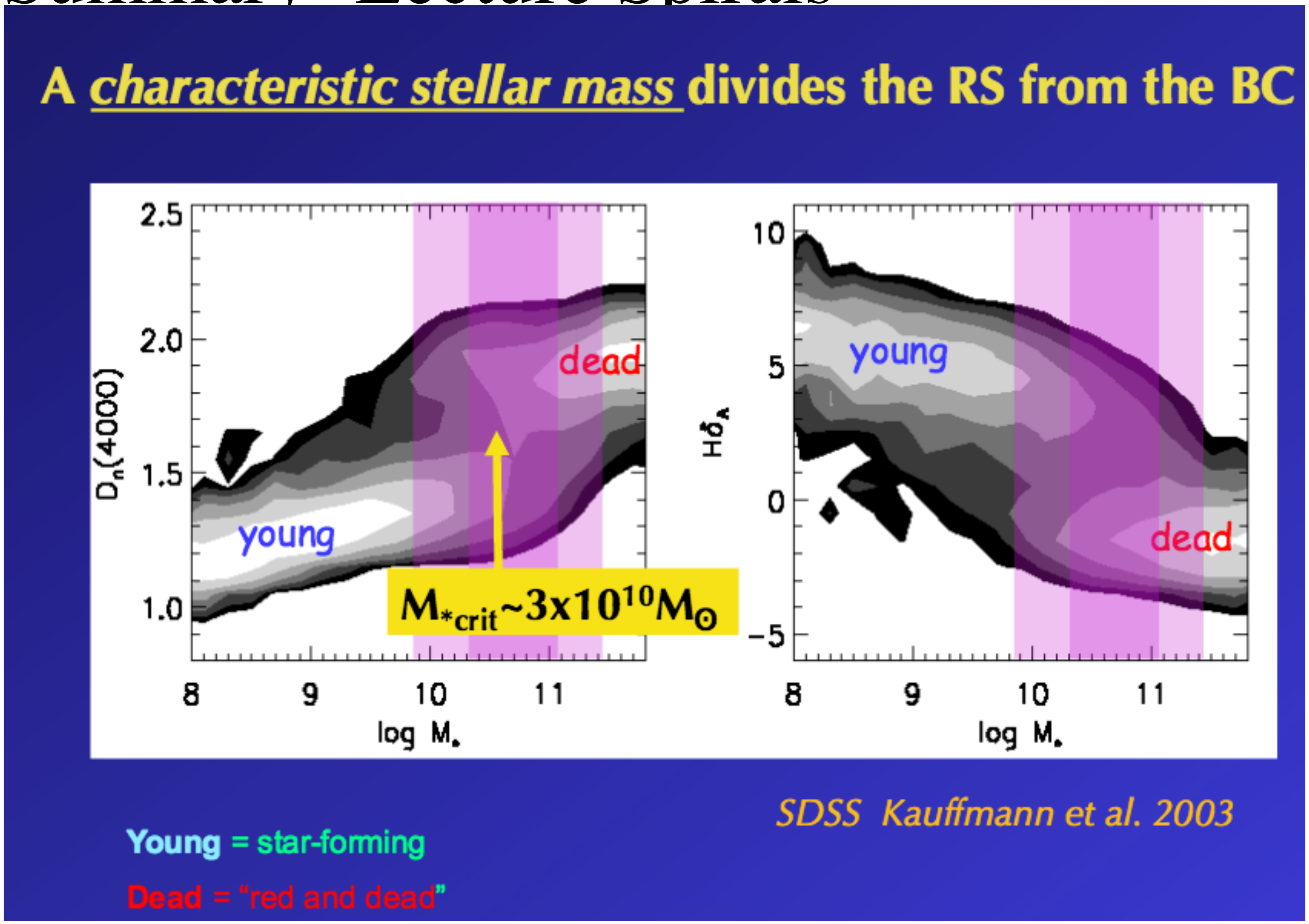
  spirals tend to be less massive than ellipticals

  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>



Summary -Lecture Spirals

- This stellar critical mass corresponds to a halo mass of ~10^{12}M, theoretically at this mass accretion switches from cold to hot accretion (cold at lower masses)



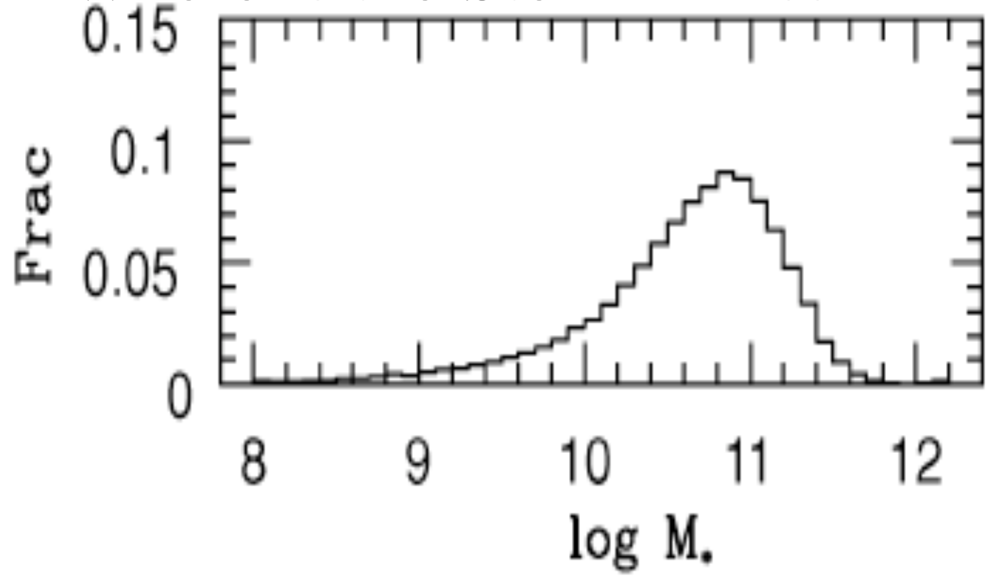
Top Level Summary-Spirals

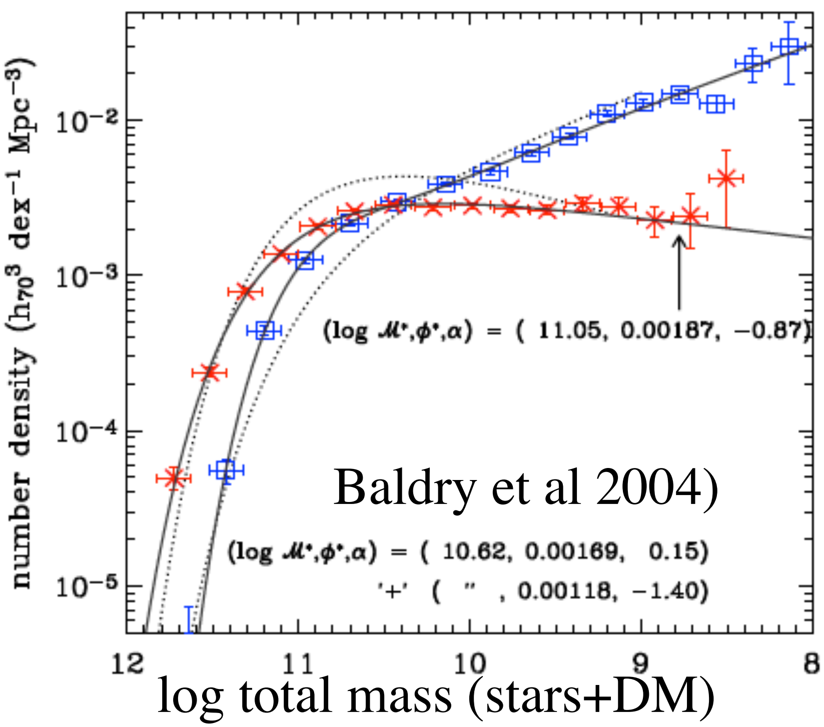
- Galaxies have a wide variety of morphologies, from spheroids , disks with and without bars and irregular galaxies.
- Their physical properties (e.g. gas content, average stellar age, the rate of current star formation, mass etc) correlate with morphology.
- disks are predominantly rotationally flattened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

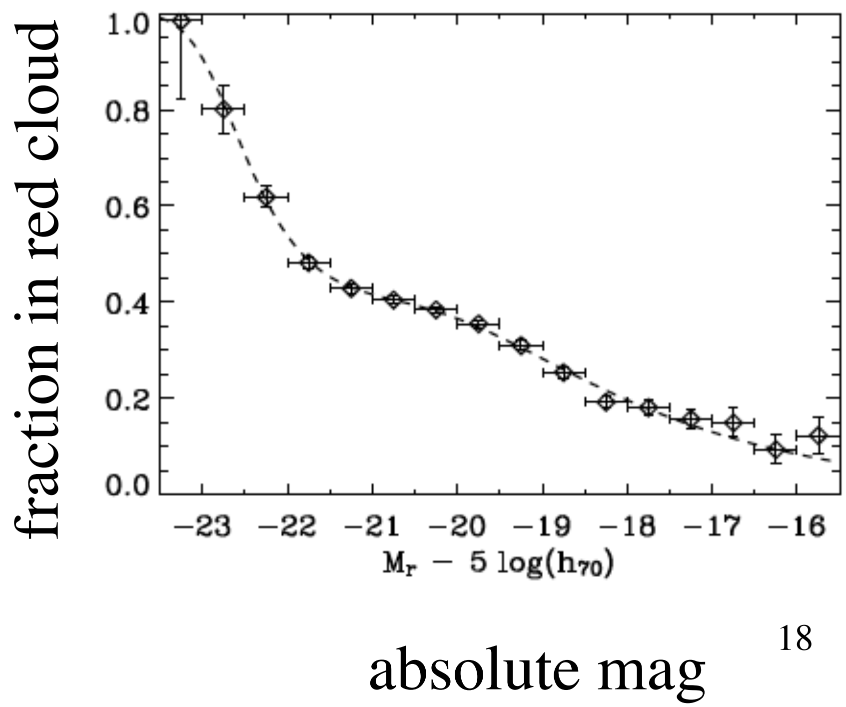
- Conventional theoretical 'wisdom' : disks form at the center of dark matter halos as a consequence of angular momentum conservation during the dissipational collapse of gas (Fall & Efstathiou 1980) , spheroids result predominantly from merger events
- Thus <u>morphology is a transient feature of the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

Where is the Stellar Mass

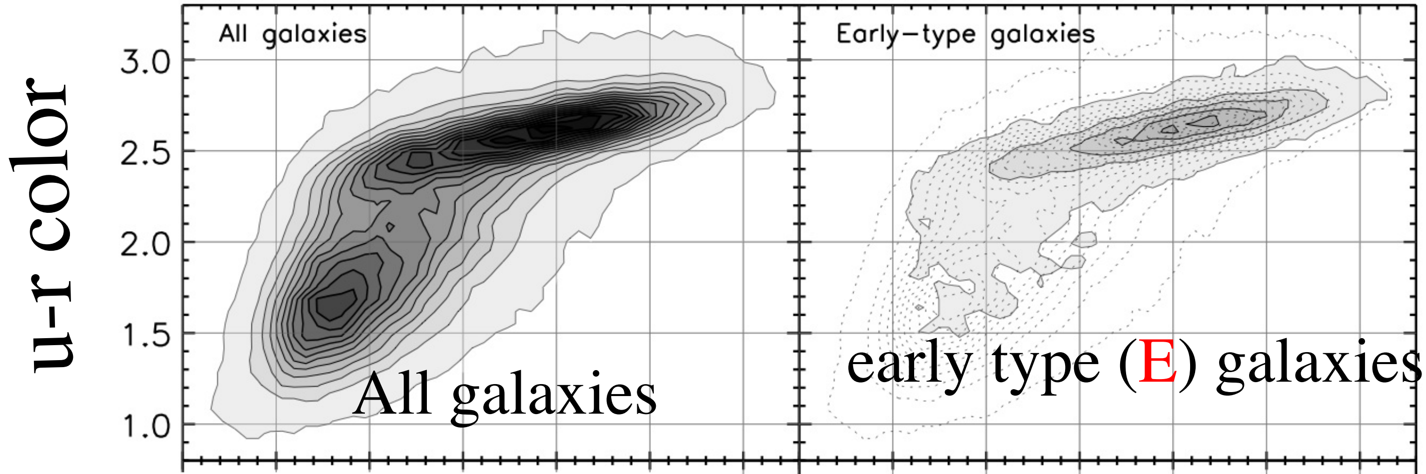
- The stellar mass **integrated over ALL galaxies** lies mostly between
  log $M_{\odot}$=10.5-11.4
- In what galaxies does the stellar mass lie?
  - most **massive** galaxies are red (ellipticals)
  - at lower masses there is an increasing ratio of **spirals** to ellipticals



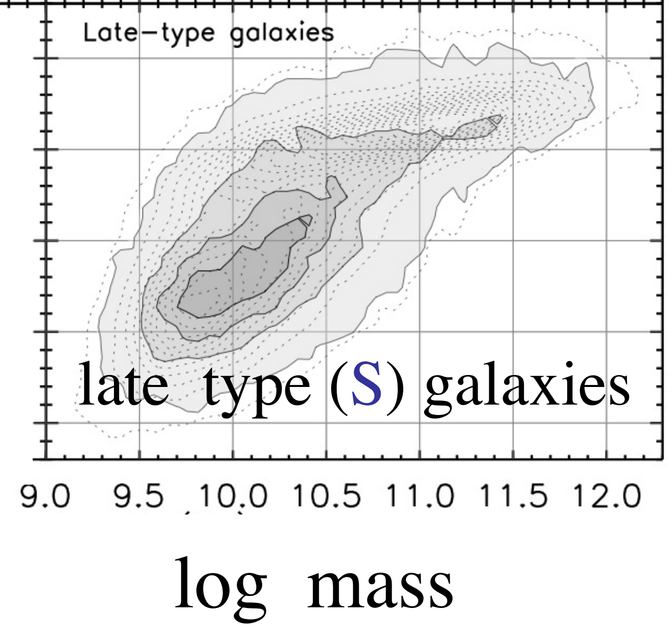




Morphology/ Color and Mass



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



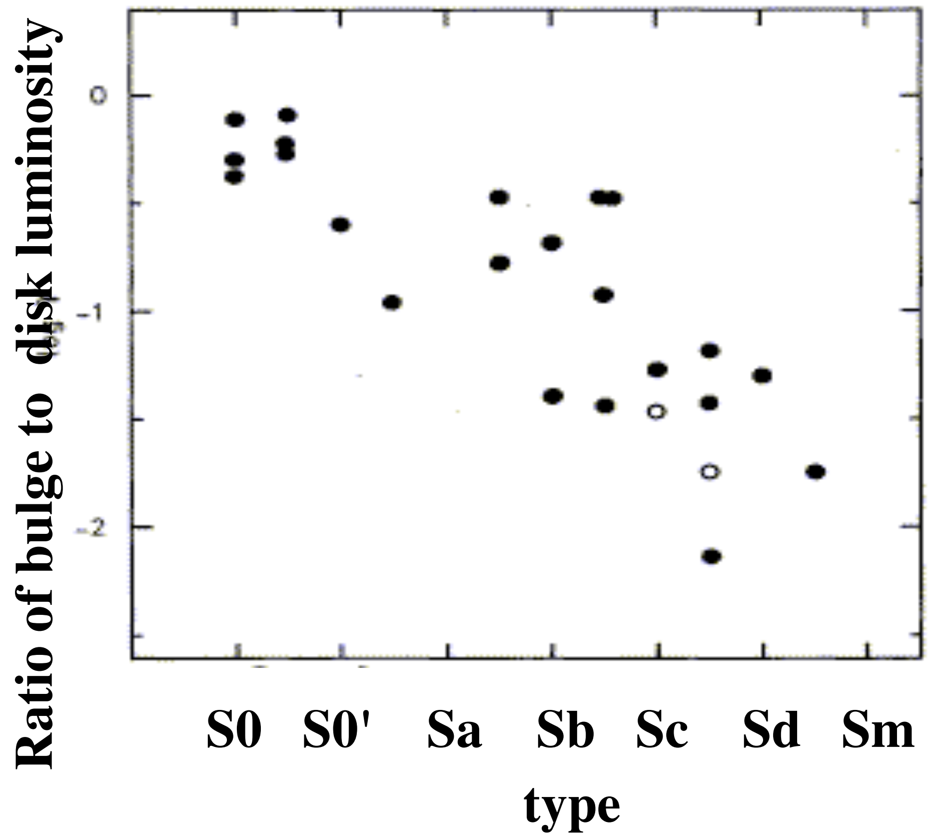
- **Strong relation of mass, color and morphology**

Schawinski 2010

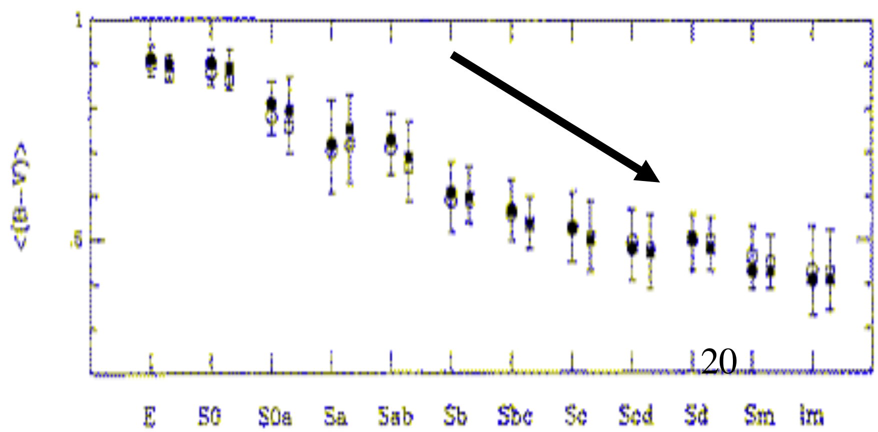
Spirals

The Hubble type of a spiral correlates with

- bulge/disk luminosity ratio
- relative content of cool gas (H I)
- mass concentration
- stellar population (how many young/ old stars)
- 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)*



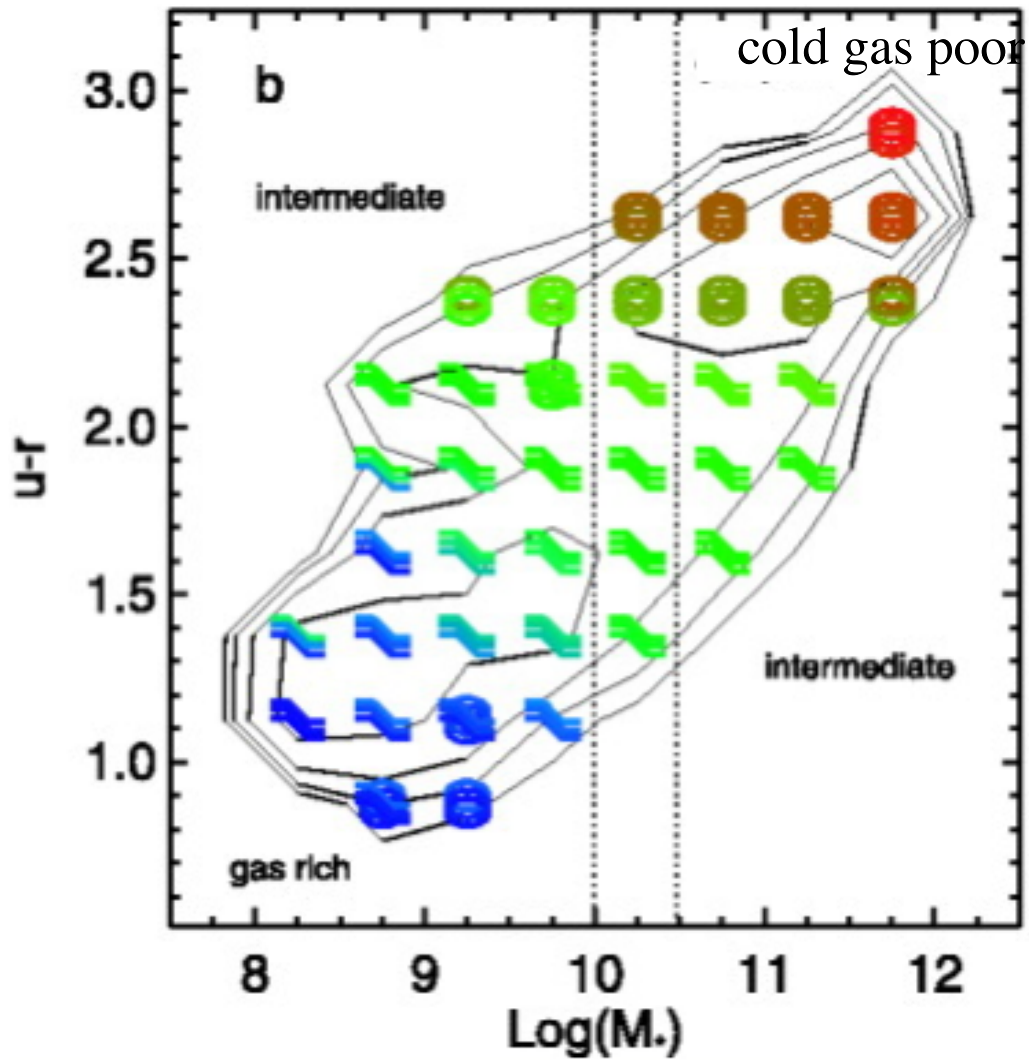
color vs morphological type



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

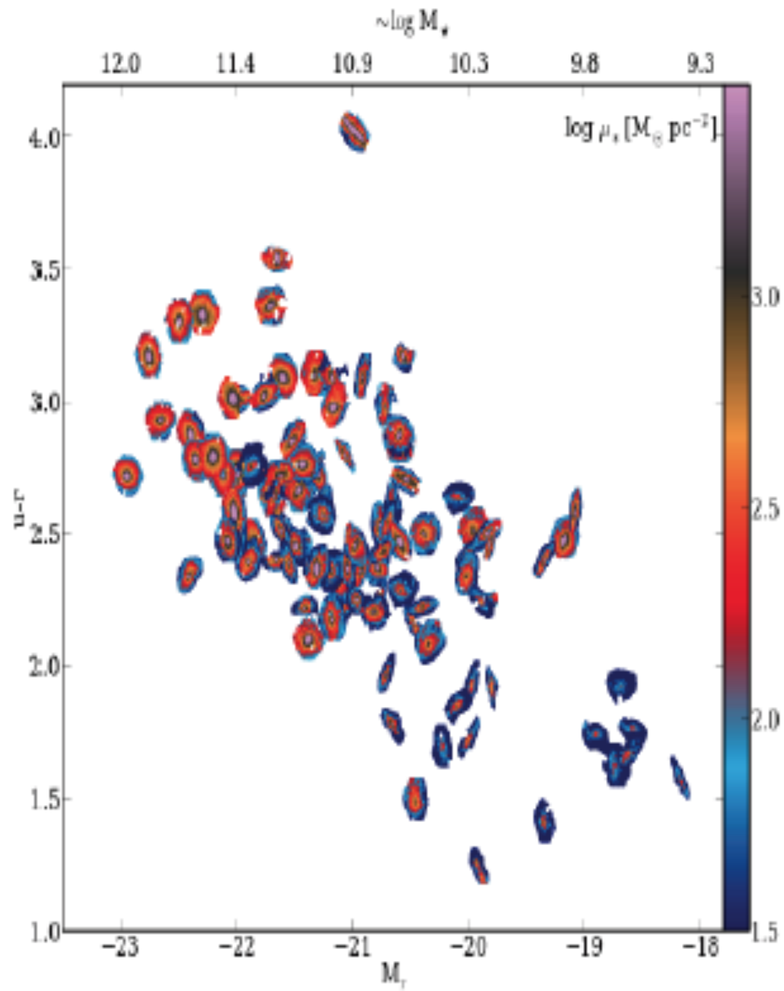
color symbols gas to light ratio in log scale



Spirals- More Trends with Morphology (Sd → Sa)

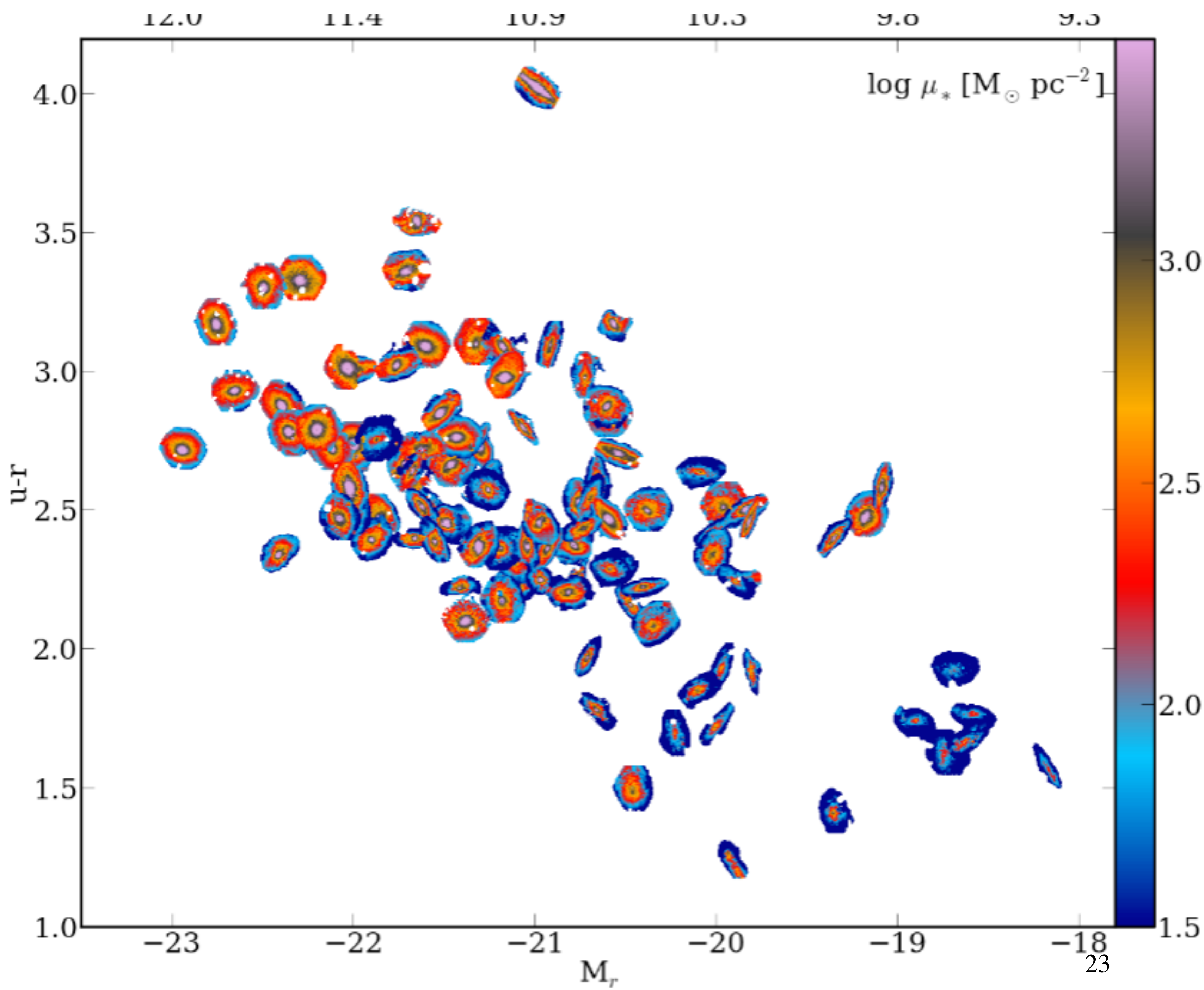
- Total luminosity decreases
- M / L_B rises
- M (HI) / $M_{(total)}$ rises
- Bulge / Disk decrease
- Tightness of the spiral arms decreases
- Scale length drops
- color reddens- star formation history
- The question is what are the primary eigenvectors of the correlations… it seems to be mass

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

2-D map of stellar density


12.0
11.4
10.9
10.3
9.8
9.3
log μ_* [$M_\odot$ pc^{-2}]
u-r
4.0
3.5
3.0
2.5
2.0
1.5
1.0
−23
−22
−21
−20
−19
−18
M_r
3.0
2.5
2.0
1.5

The star formation history of CALIFA galaxies: Radial structures
R. M. Gonzalez Delgado et al 2014

Spatially resolved ages i
Califa galaxies- clues to
formation

Negative radial gradients
of the stellar population
ages are present in most
of the galaxies,
supporting an inside-out
formation scenario

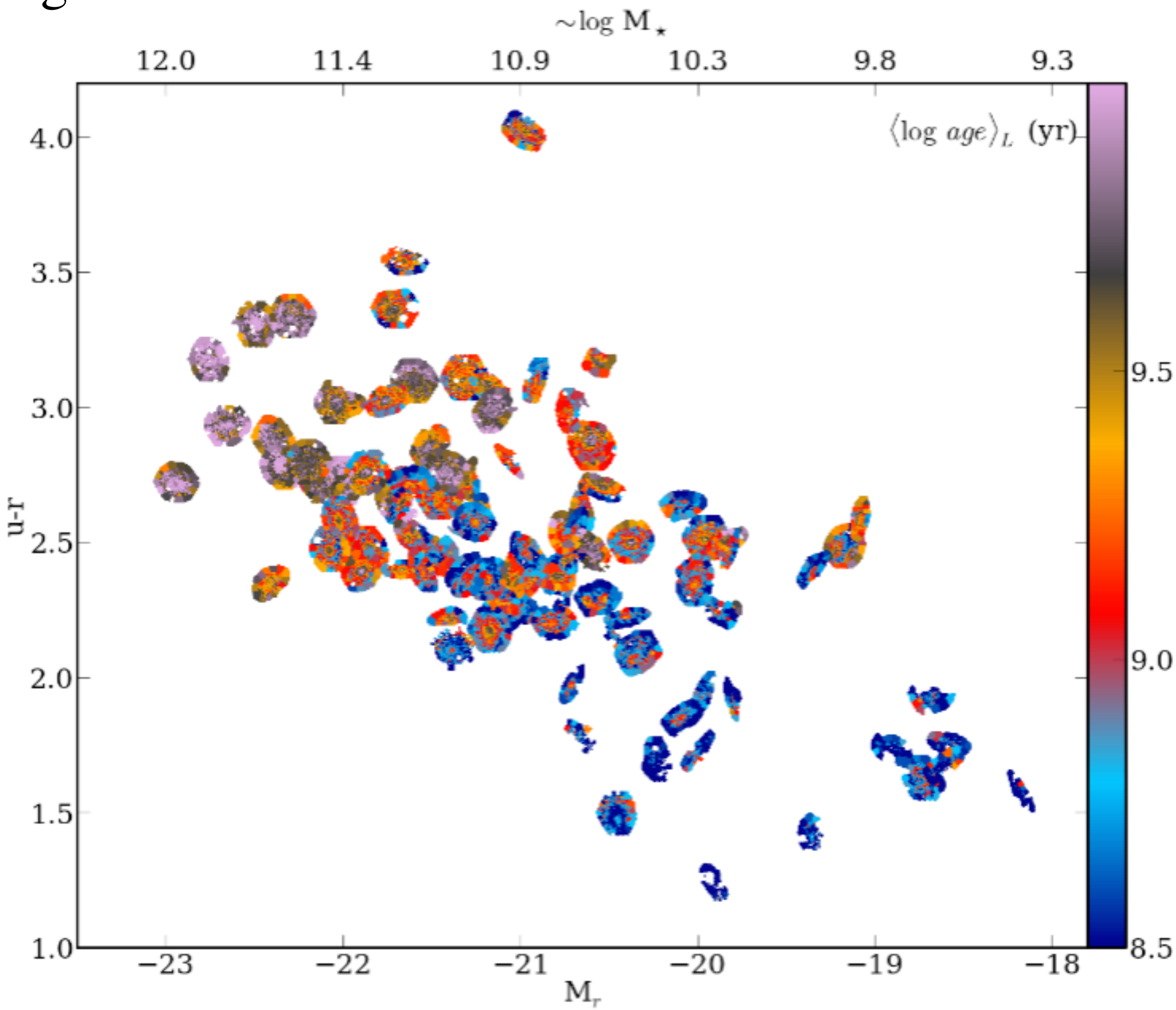
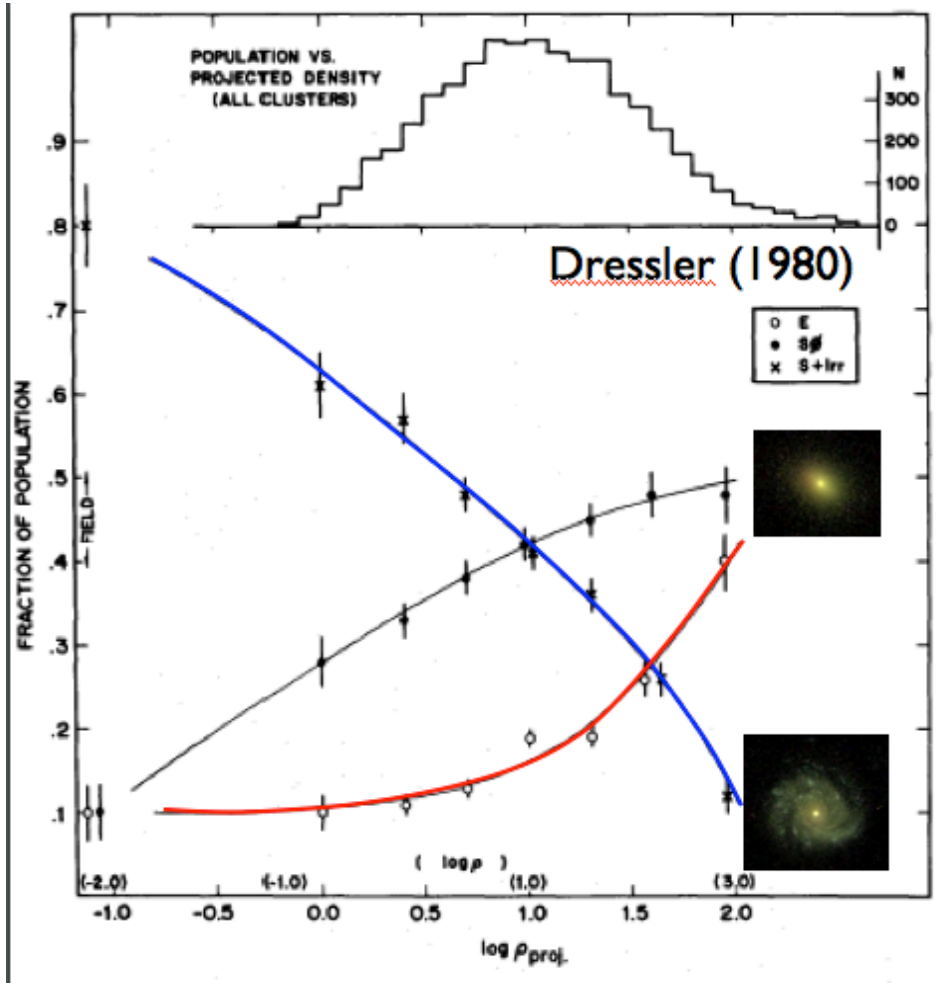


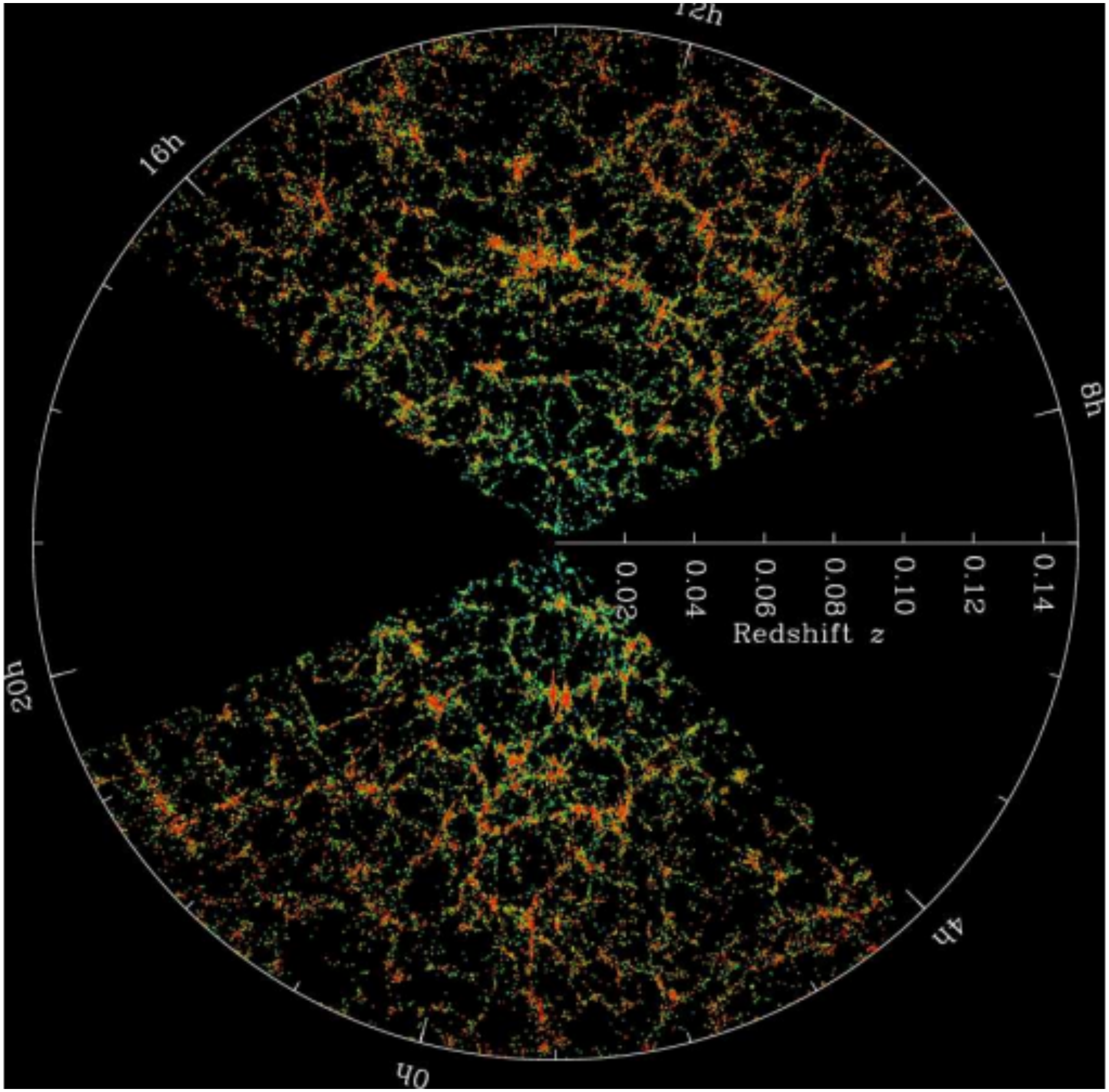
Fig. 3. As Fig. 2, but for images of the luminosity weighted mean age, $\langle \log age \rangle_L$ (in yr). Radial age gradients are visible i
in the green valley ($-22 < M_r < -20$ and $2 < u - r < 3.5$), but not in the blue cloud or red sequence. Note that

"Where" Do Galaxies of a Given Type Reside

- In low density regions most of the galaxies are spirals (blue line)
- As the density of galaxies increases the fraction which are S0(black) and E (red) increase dramatically- this reaches it limit in massive clusters of galaxies whose cores have almost no spirals
- **Thus the morphology of galaxies 'knows' about the environment- not clear if this is nature (formed that way) or nuture (spirals converted into S0's)**

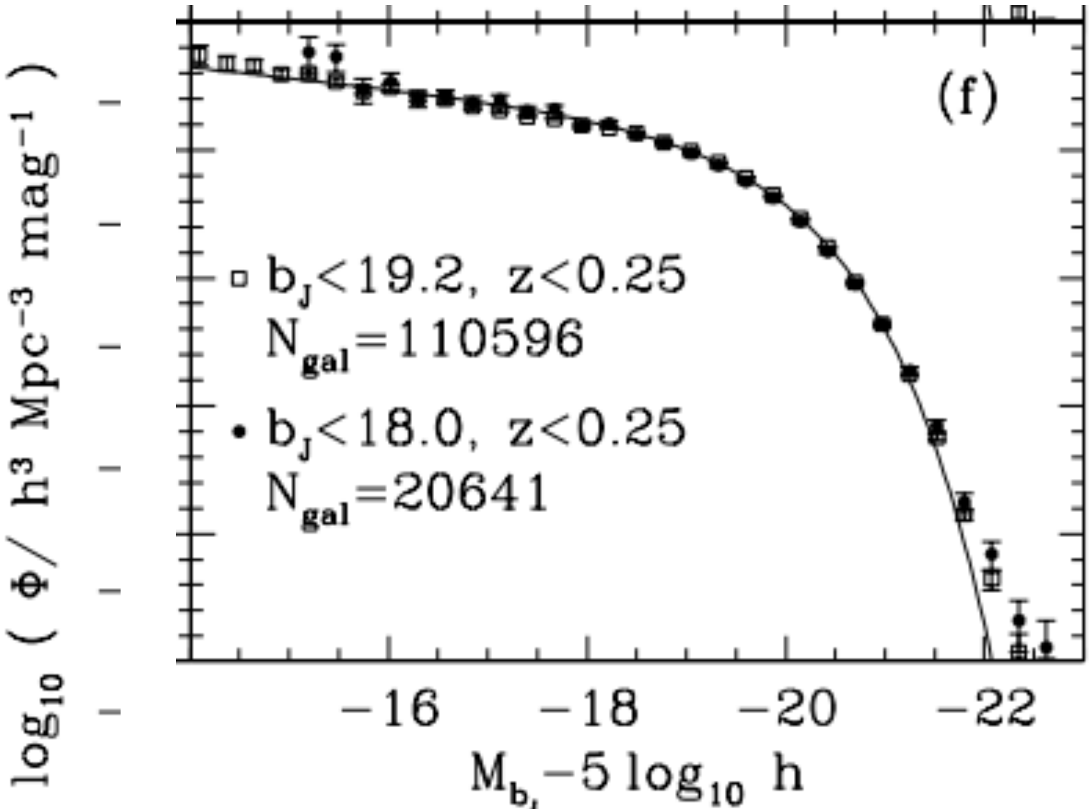


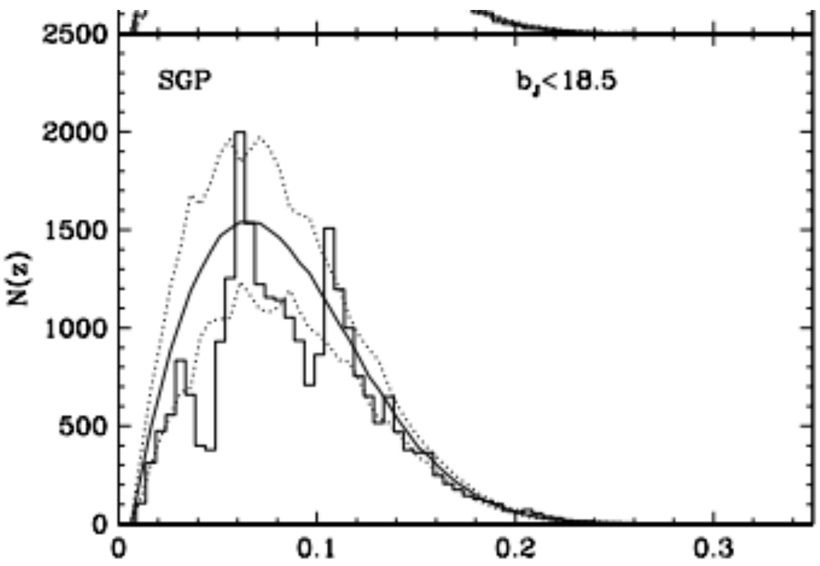
- Distribution of red and blue galaxies out to z-0.15 from the SDSS (M. Blanton)
- Notice that red galaxies are highly concentrated in dense regions while blue galaxies are in the filaments



Luminosity Function

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



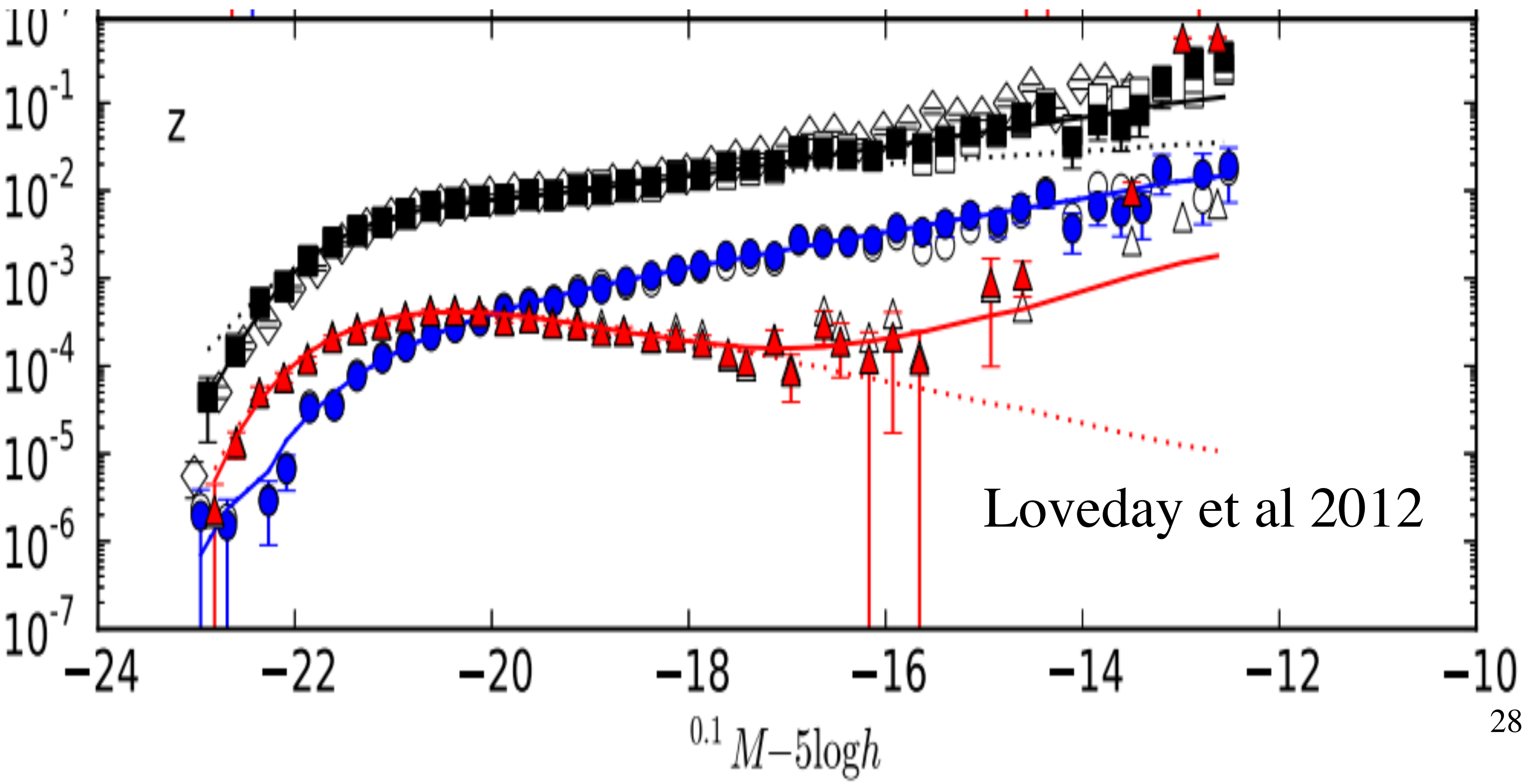


Redshift

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

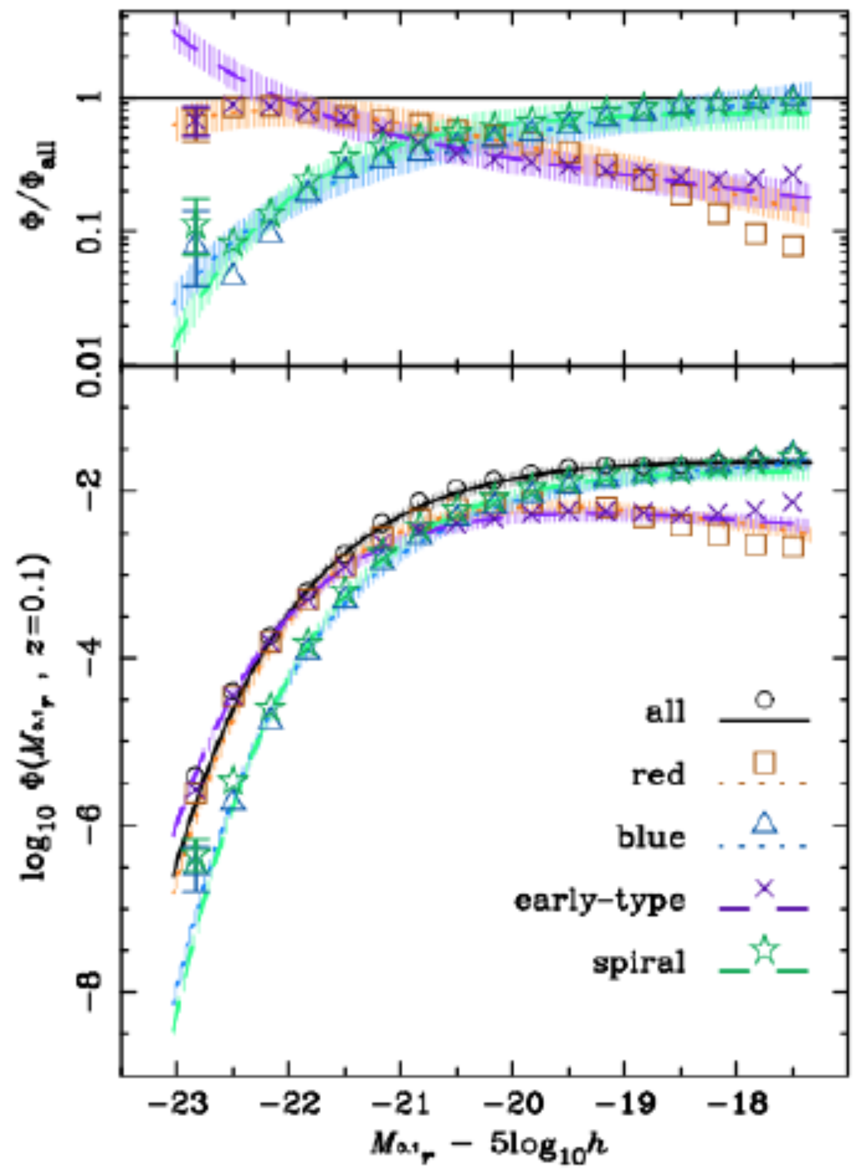
Red and Blue Luminosity Functions

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



Red and Blue are not exactly Elliptical and Spiral

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



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.

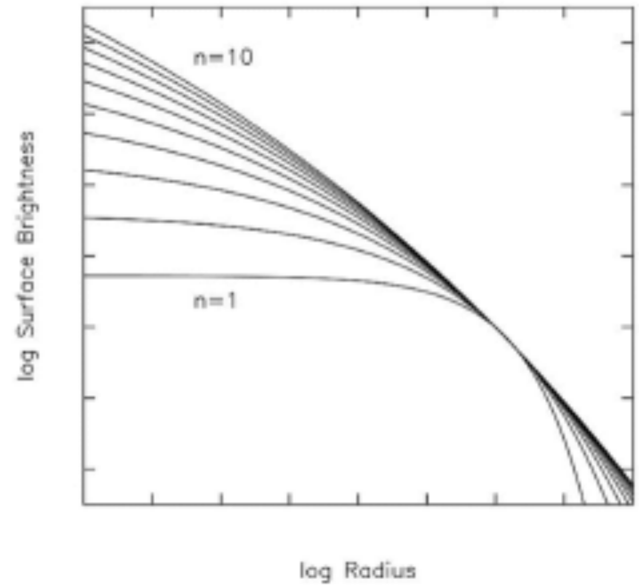
Origin of Bulges (Sec 13.6.1 MBW)

- massive bulges, found in S0 and Sa galaxies, share many properties with ellipticals of intermediate luminosities (see Wyse et al., 1997, for a review).
- massive bulges are consistent with being flattened by rotation (Fig. 2.16), and the best-fit S´ersic parameter for their surface brightness profiles scales with luminosity in the same way as for ellipticals
- They also have
  - similar color–magnitude relations ,
  - similar metallicity–luminosity relations,
  - similar fundamental plane relations
  - and the same MBH-σ relation
  - ◆ All this suggests that massive bulges form in the same way as ellipticals of intermediate luminosity (i.e. most likely via the merging of gasrich progenitor galaxies).
- BUT - there are multiple processes that may be responsible for the formation of bulges. It is almost certain that each of these processes is at work; however their relative importance varies.

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 ~2n-0.331 (who called for that!) where r_e is a characteristic (scale length-$\Sigma(r)$ is the surface brightness profile S+G eq 3.13
- **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)

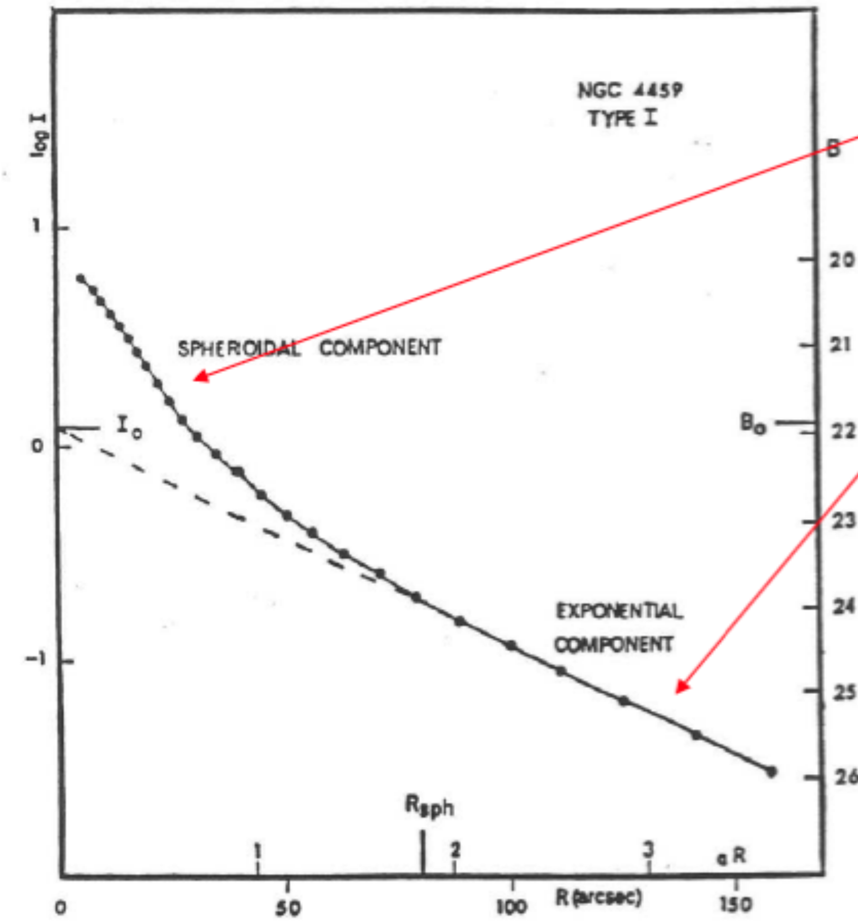


$$L = 2\pi \int_0^\infty I(R)\,R\,dR = \frac{2\pi n\,\Gamma(2n)}{(\beta_n)^{2n}}\, I_0 R_e^2,$$

total luminosity of Sersic profile- Γ is the gamma function

Azimuthally Averaged Light Profiles

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



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

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

α is the inverse scale height

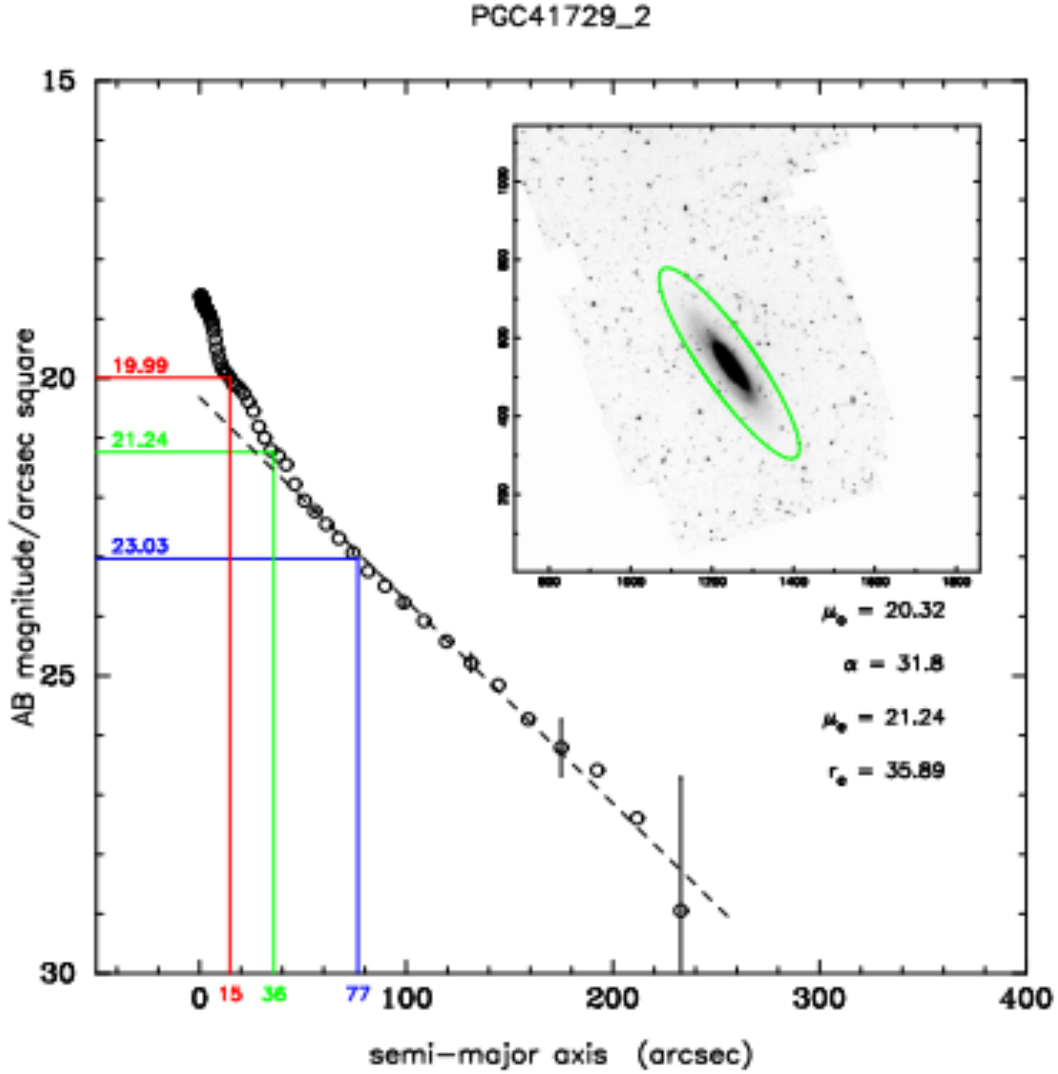
(Freeman 1970)

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

Typical disk surface brightness profiles

Pure exponentials would be straight lines.

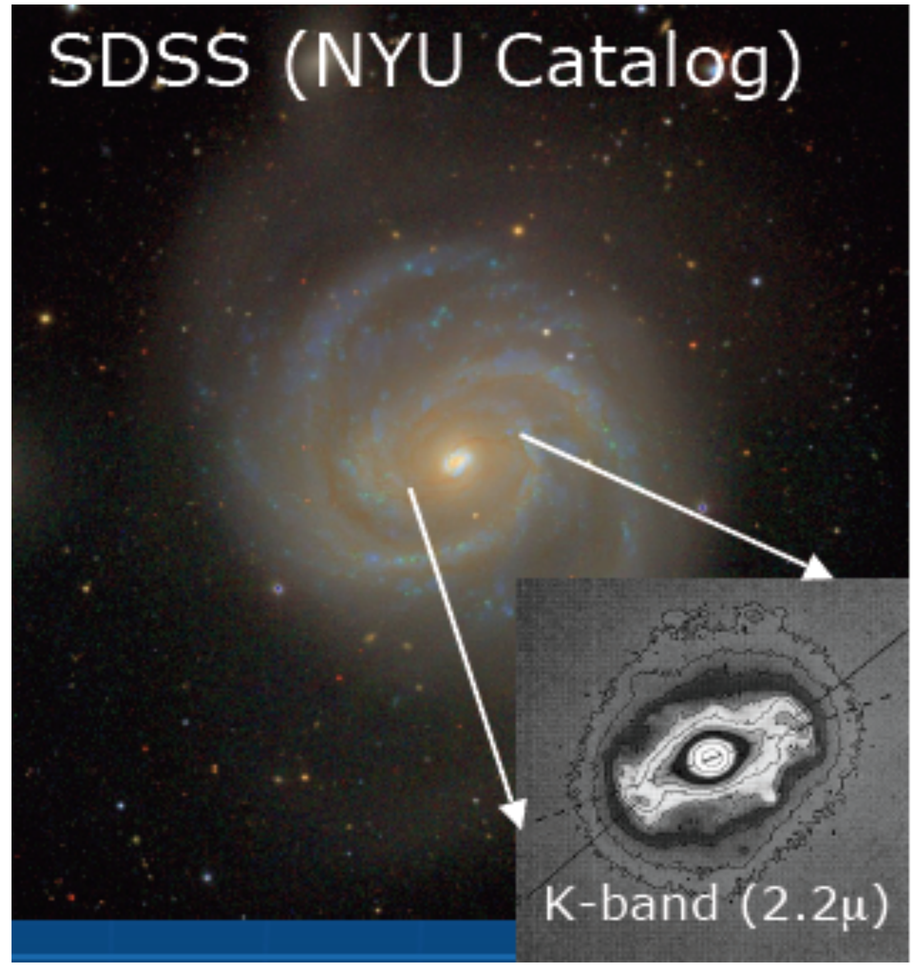
The exponential scale length α is a measure of the size of the baryonic disk.- Most of the light is inside 2 scale lengths



Courteau, ApJS, 103, 363, 1996

Other Complications - 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).



TODAY

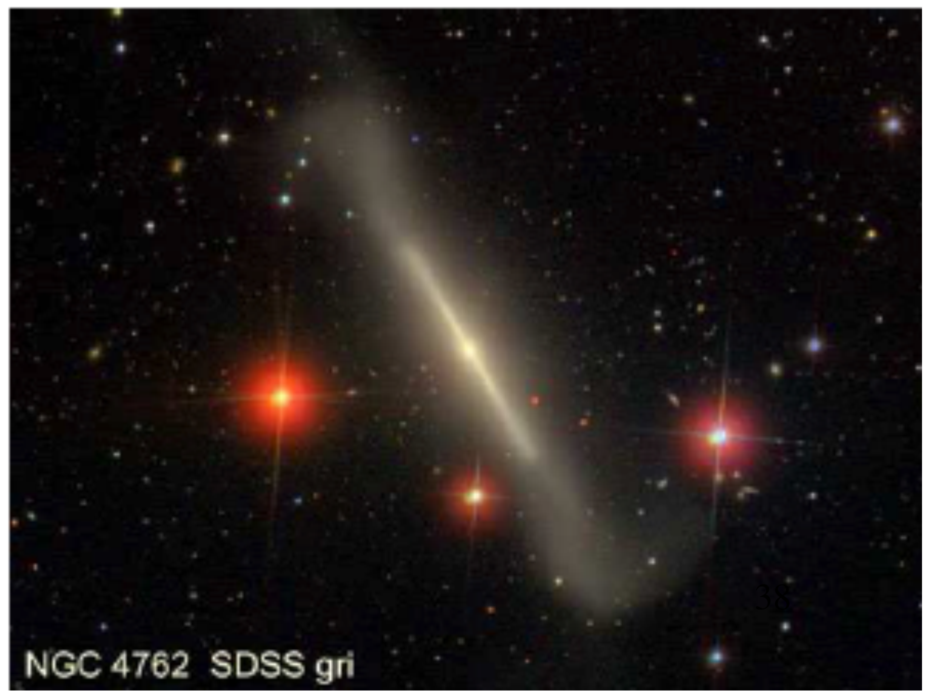
- arXiv:1511.03346 [pdf, ps, other] The Orbits and Total Mass of the Magellanic Clouds Gurtina Besla (U. Arizona)
- Comments: Conference proceeding appears in "Lessons from the Local Group: A conference in honour of David Block and Bruce Elmegreen"
- Subjects: Astrophysics of Galaxies (astro-ph.GA)
- This proceeding overviews our current understanding of the orbital history and mass of the Large and Small Magellanic Clouds. Specifically I will argue that the Clouds are on their first infall about our Milky Way and that their total masses are necessarily ~10 times larger than traditionally estimated. This conclusion is based on the recently revised HST proper motions of the Clouds and arguments concerning the binary status of the LMC-SMC pair and their baryon fractions

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 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- Summary

- 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
- x-ray luminosity is dominated by binaries
- ISM is highly structured



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)

Surface brightness can be well modeled by Sersic Law ;

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

Tully-Fisher Relation

Giovanelli et al 1997

- Relates circular velocity of test particles (gas, stars) to total **luminosity** of system

(circular velocity is related to mass,$v^2_{circ}(r) = r\, d\Phi/dr = GM(r)/r$)

- 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~L
- a little algebra gives $L \sim v_c^2 L^{1/2} \sim v_c^4$

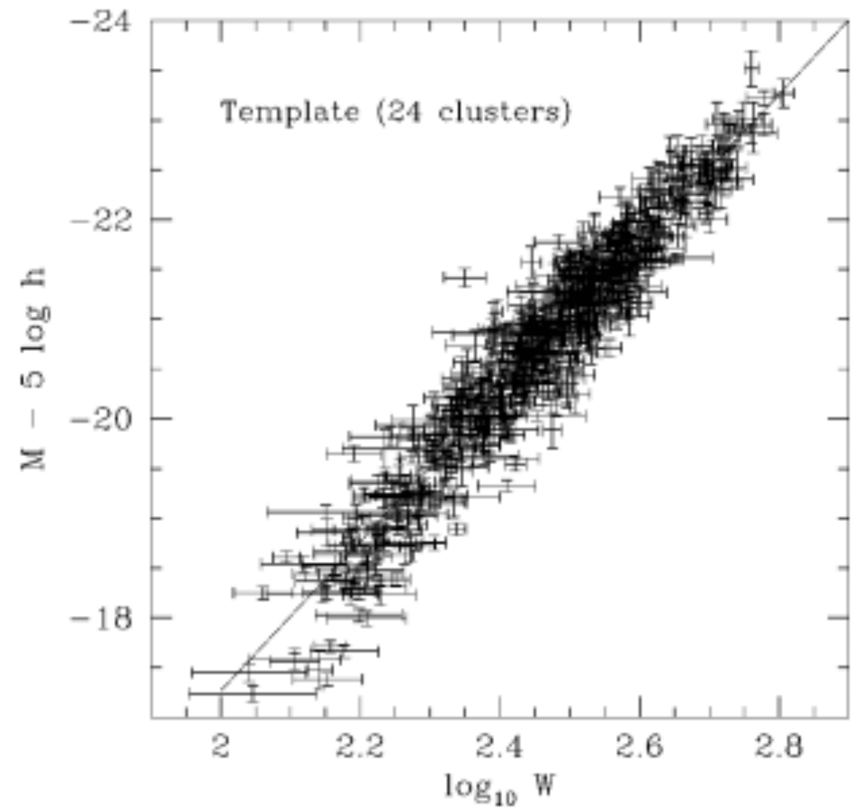


FIG. 1.—Template relation based on 555 galaxies in 24 clusters. The fit is $-21.00 \pm 0.02 - 7.68 \pm 0.13\,(\log W - 2.5)$.

Since luminosity depends on d^2xflux can get distance to object from measuring its circular velocity and apparent brightness!

Tully-Fisher MWB sec 11.3

- If MOST of the velocity is due to a isothermal sphere dark matter distribution eq 11.76-11.77 shows that one obtains the T-F relation IF there is a relation between the fraction of the total mass that is in the disk, the mass to light ratio of the stars and the maximum rotational velocity !!!

- To fit the data only 20% of the baryons have ended up in the disk

- However there are additional complications (pg 515)which include the fact that there is very little scatter in the T-F relation which gets smaller in the near IR compared to the optical (see eq 11.75) and MBW conclude that

'These studies show that it is extremely difficult to construct a model that can match all scaling relations simultaneously"

Implications of T-F

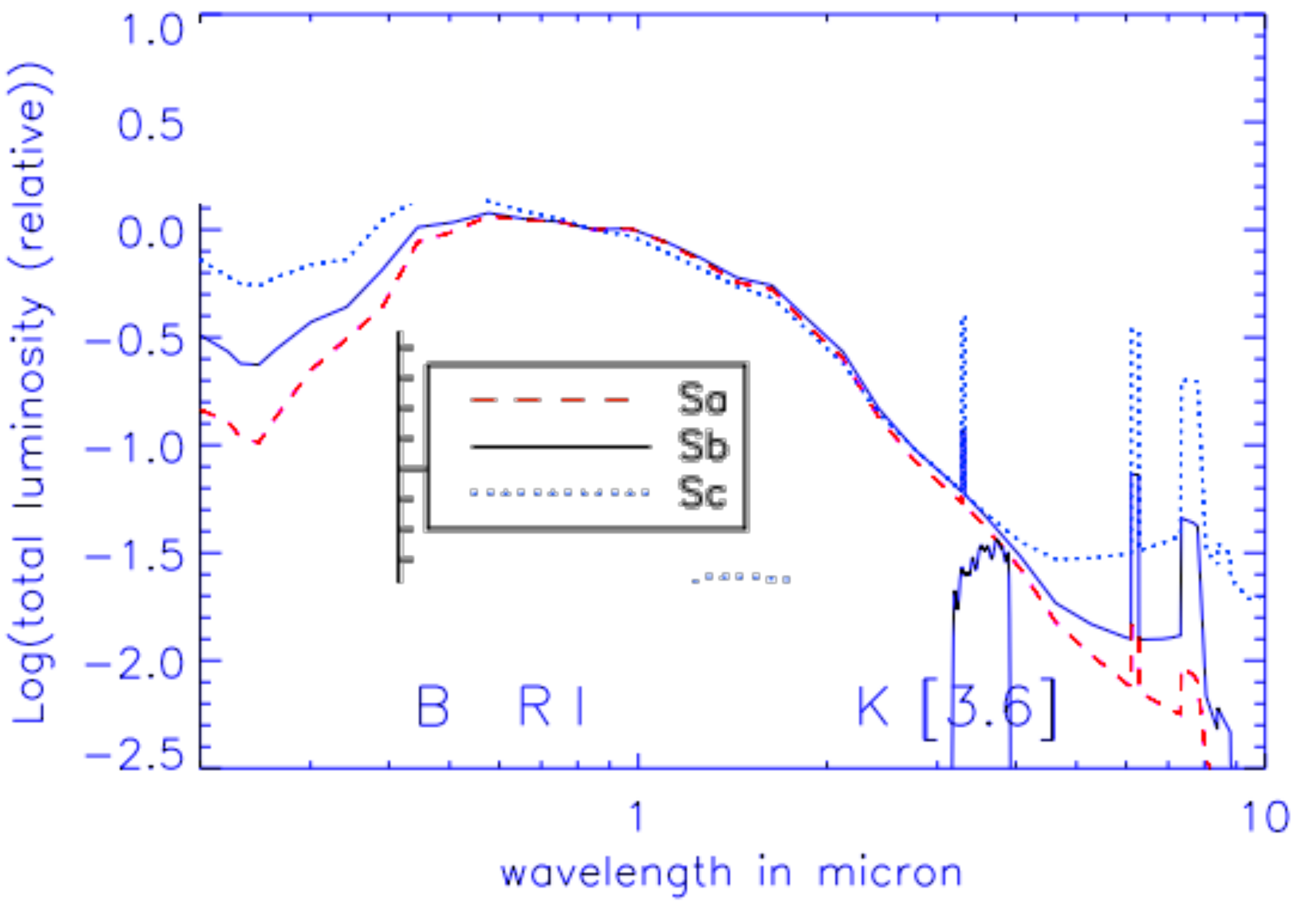
- M/L~constant from galaxy to galaxy?
- But
  - Mass is dominated by dark halo
  - Luminosity is dominated by disk
- Total mass: $M \sim [V^2_{max} h_R]$
- Total luminosity: $L \sim [I_0 h_R^2]$
- $L \sim [V^4_{max} (M/L)^{-2} I_0^{-1}]$
- A universal M/L implies remarkable constancy of the ratio of dark to luminous matter

Or worse, a fine-tuning of the dark-to-luminous mass ratio as the stellar M/L varies.

Adapted from M.Bershady lecture notes

Spiral Galaxy spectra

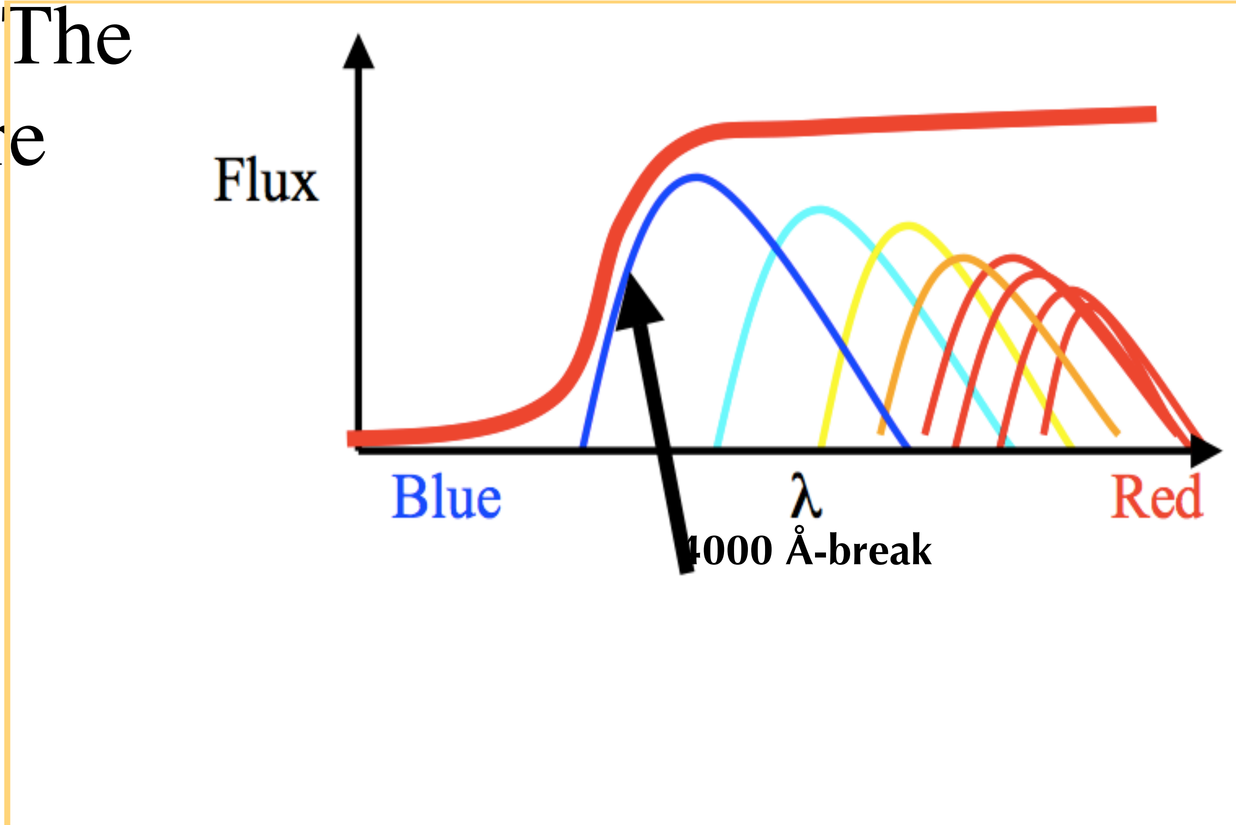
- Galaxies have composite spectra. They integrate contributions from different stars of different stellar populations, gas and the effects of dust
- The overall continuum shape is modulated by the gas, the stars, as well as by the presence of dust.



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



Star Formation Histories

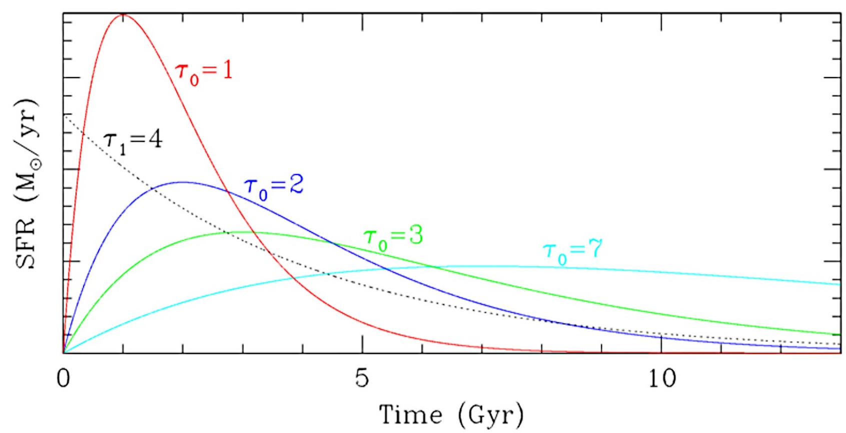
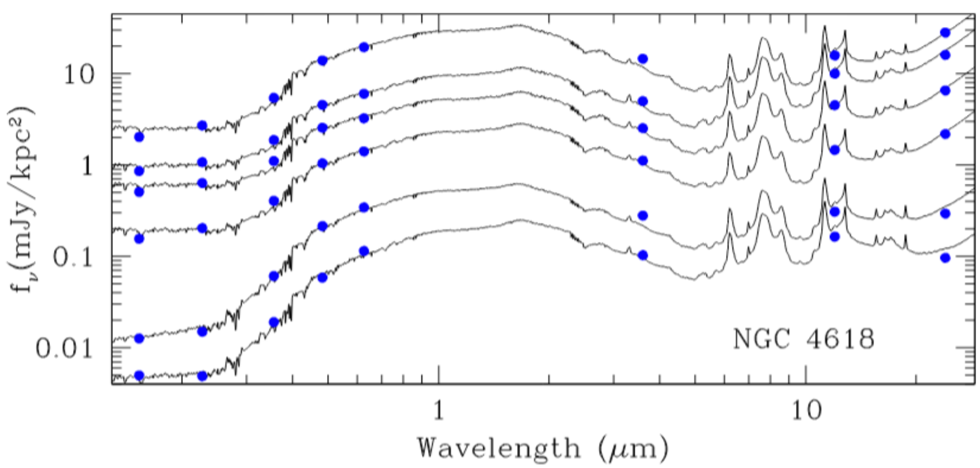
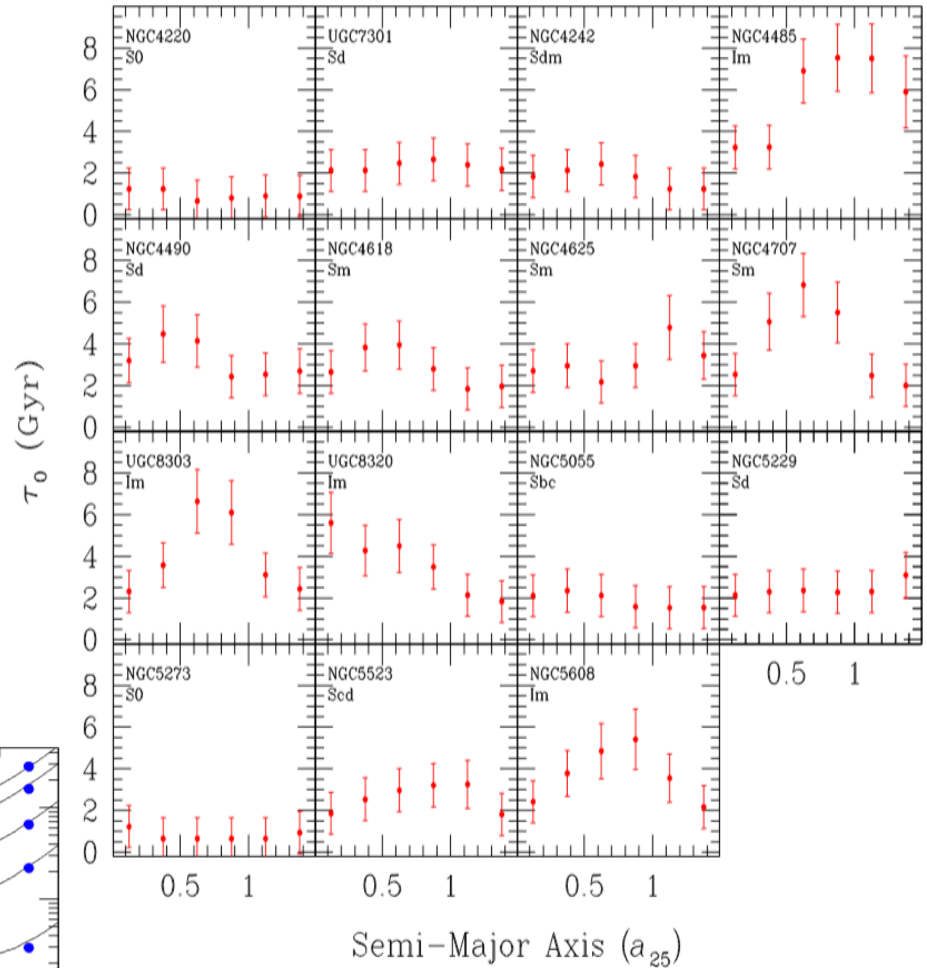


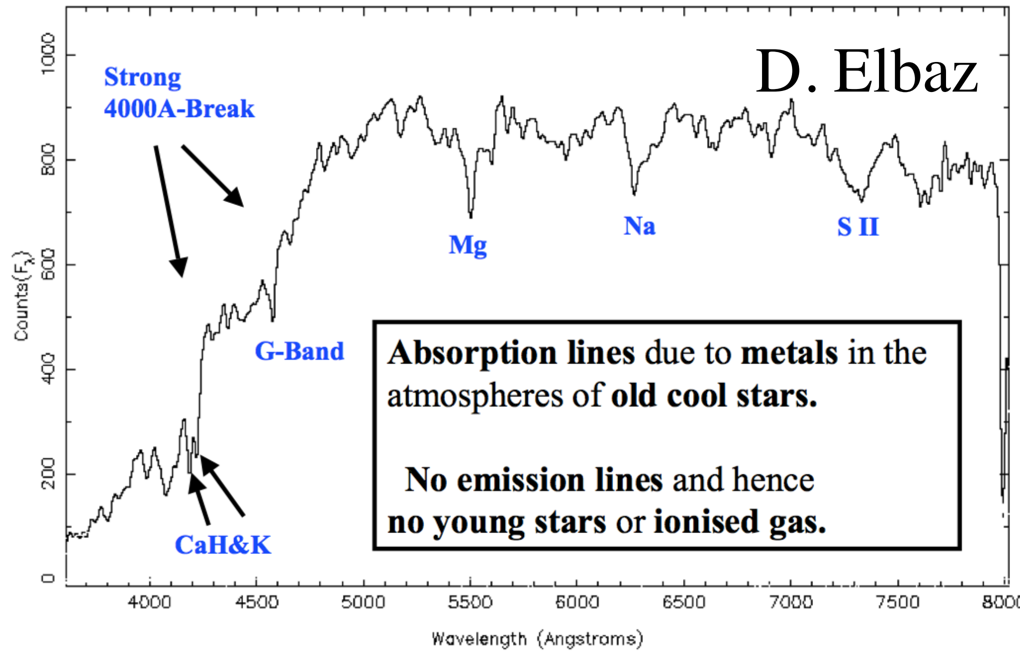
Fig. 3.— Four examples of a "delayed" star formation history along with an example of decreasing exponential star formation history (dotted curve). All values shown are in Gyr

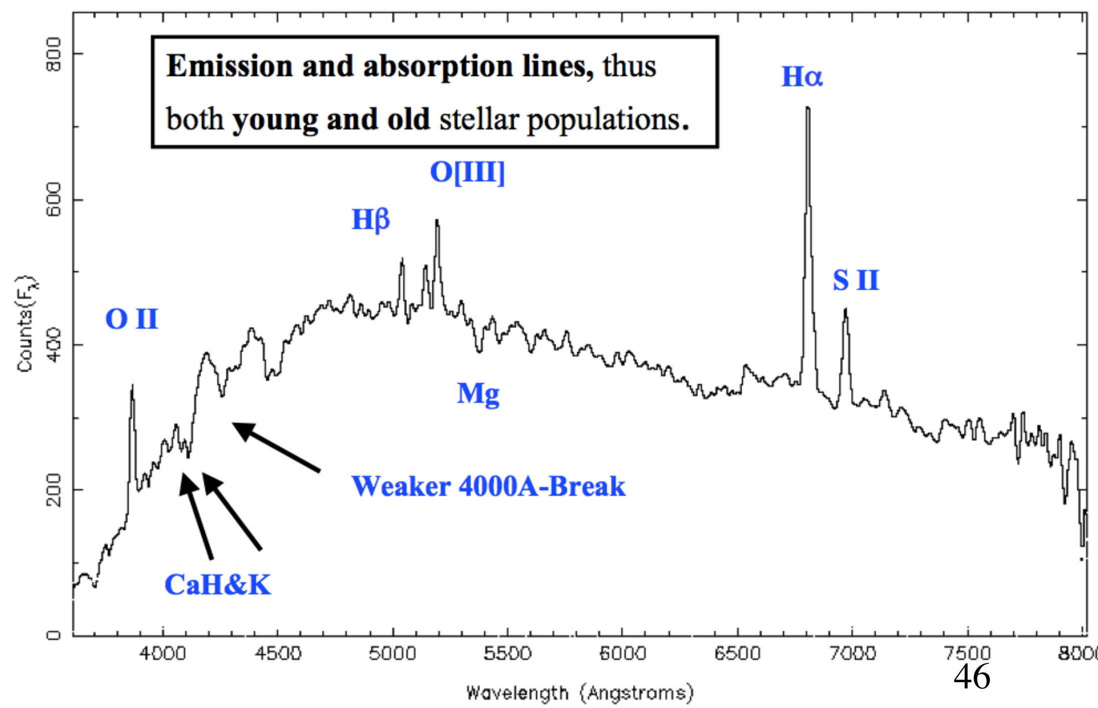




Dale et al arxiv 1511.03285

One Step Beyond Simple





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

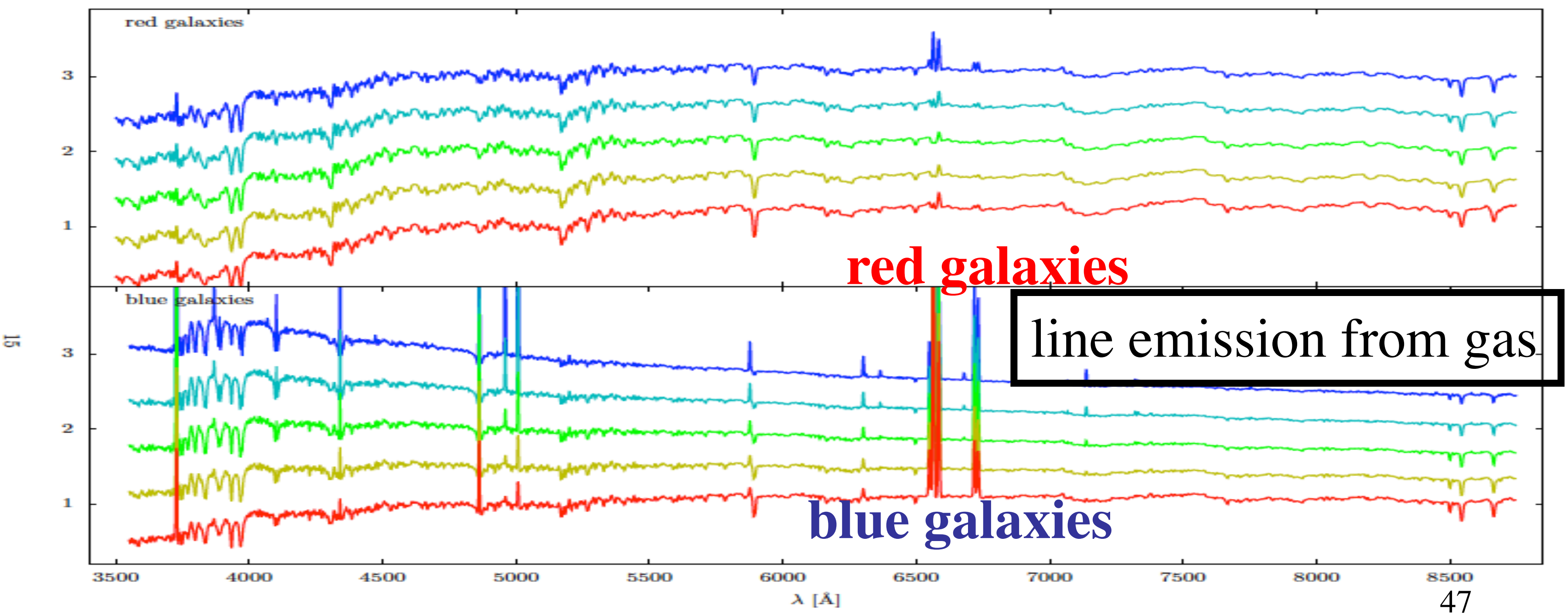
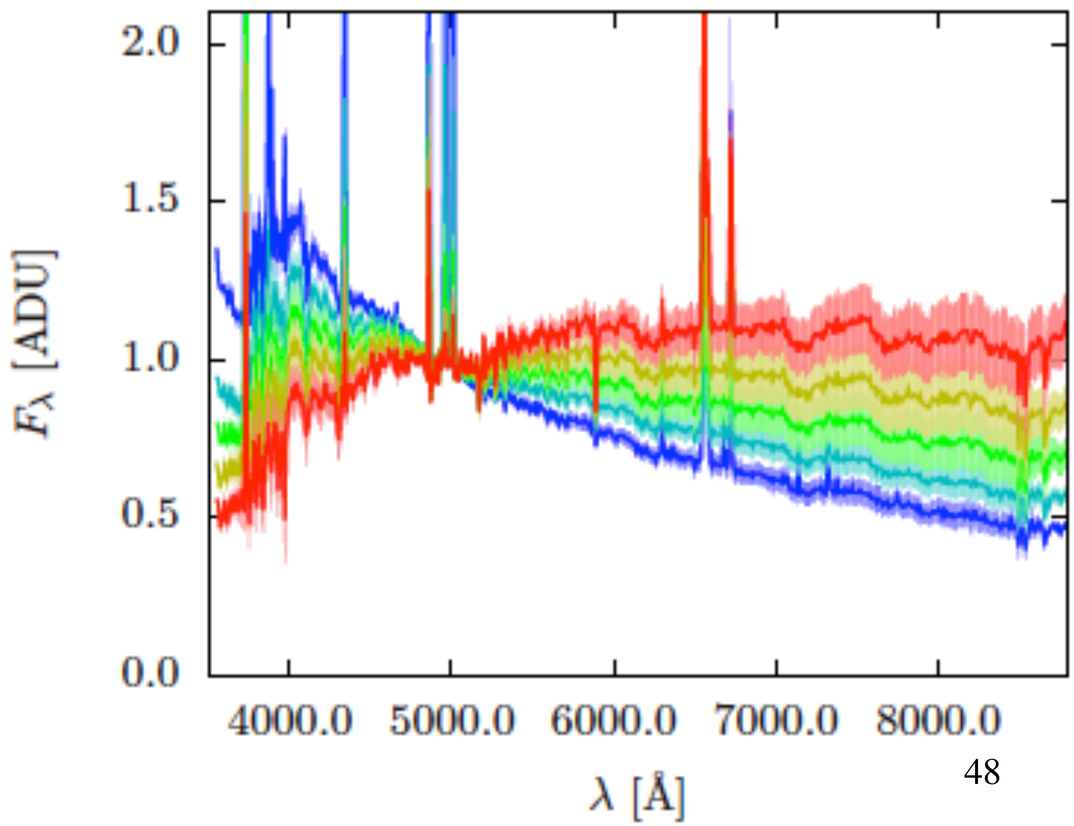


Figure 12: Composite spectra of the refined colour classes as described in Sec. 3.4. The curves are colour-coded from blue (top) to red (bottom) based on the $g - r$ colour of the galaxies. See the online edition for a colour version of this plot.

Galaxy spectra

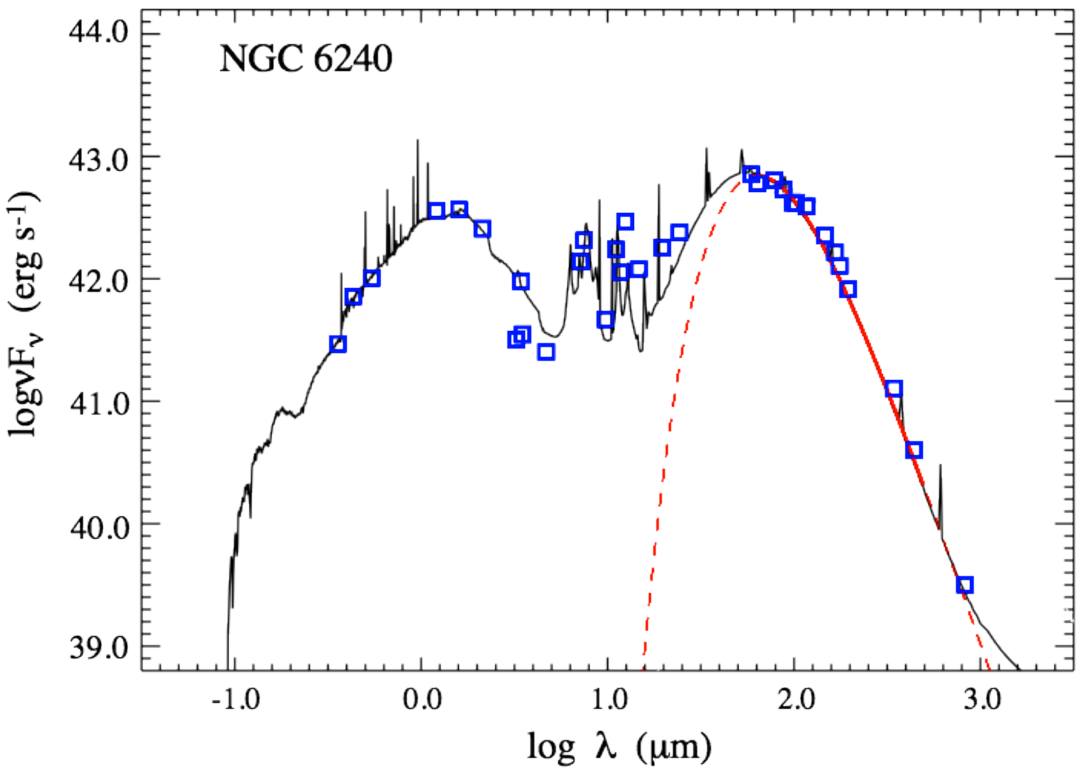
- Sequence of ages of a composite SSP population (star forming-spiral population)
- bulges are dominated by stellar absorption lines and have little 'blue' light

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- Review of Dust Lecture

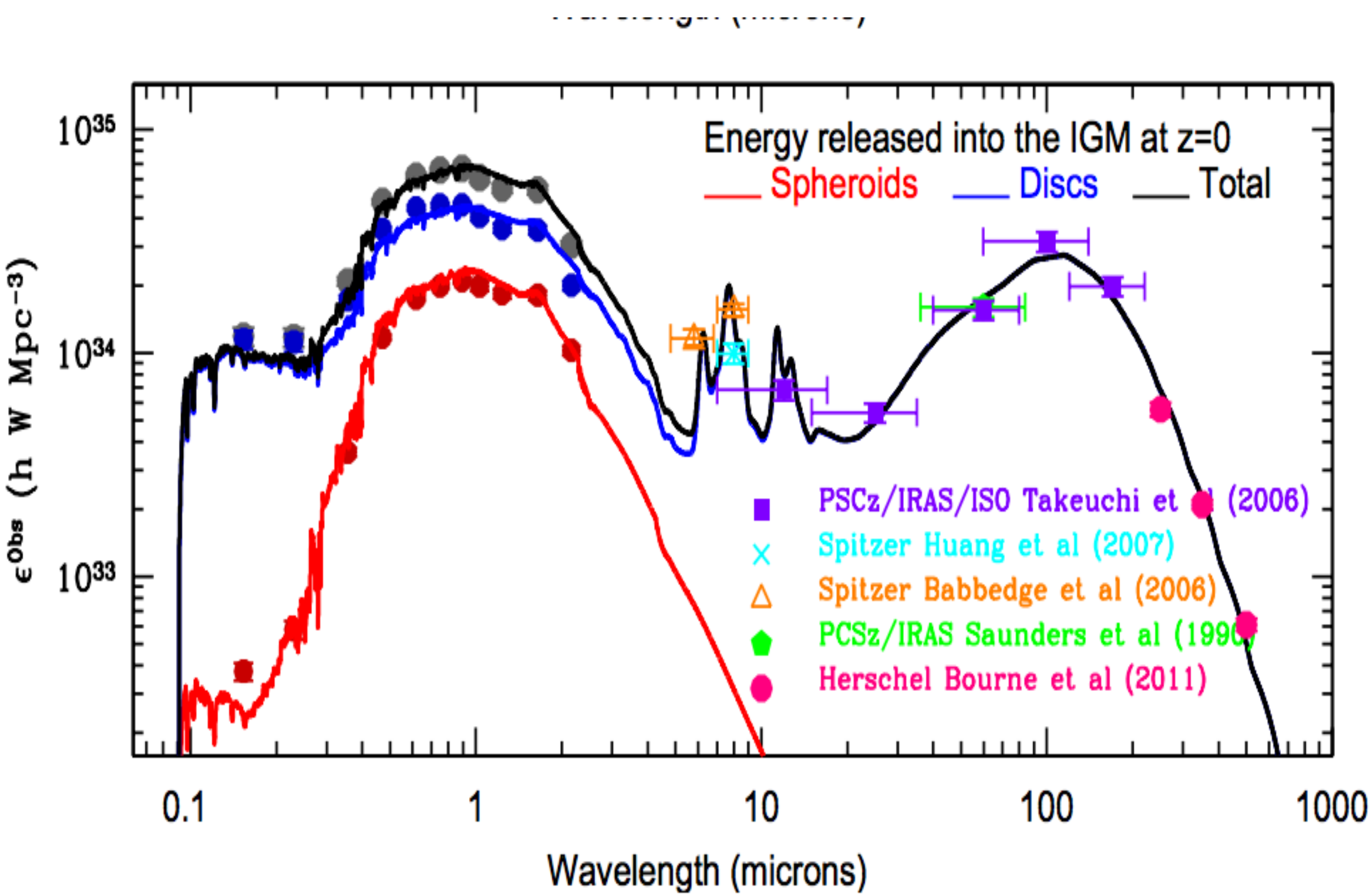
- At λ>5μ in most spiral galaxies continuum dominated by emission from dust -there are atomic and molecular features as well
- In many spiral galaxies L(opt)~L(IR)
  - **dust heated by star light - temperature to which it is heated depends on geometry and the nature of the stars**
- dust can be very patchy as can star formation



Red dotted line is grey body emission from dust

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)/σ ~ 1, so dispersion (random velocity-hot systems) support important.

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

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

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

- Dark Halo :

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

General Patterns

- Relationship of 'class' (e.g. S0,Sa,Sb..) to physical properties -
- Correlations of surface brightness, size, color, star formation etc etc
- 'Later' types, lower mass, more of baryons in gas, higher specific star formation rates (today):
- Sa -> Sb -> Sc -> Sd in order of decreasing bulge size.
- Patterns
  - More luminous galaxies have larger V_{max}
  - Earlier Hubble-type galaxies rotate faster for the same L
  - Fraction of DM inside optical radius increases with decreasing V_{max}
- Large fraction of energy radiated in the IR due to dust
- Spectroscopic signature of gas in spirals in form of emission lines from hydrogen, oxygen etc; gives information about physical conditions (temperature, density, velocity field)

Gas Motions

- If there is a well defined disk, inclined at some angle i to the plane of the sky and rotating perpendicular to this angle (fig 5.18 in text)
- 2 sets of coordinates
  - disk of galaxy R ϕ
  - plane of sky ρ θ
- When $\theta=\phi$ line of nodes
- The measured radial velocity of gas in circular orbits is
- $v_R(\rho, \theta)=v_{system}+v_R(R, \phi) \sin\phi\sin\mathbf{i}+v_\phi (R,\phi) \cos\phi\sin\mathbf{i} +v_z (R,\phi)\cos\mathbf{i}$

v_R velocity in radial direction

v_ϕ angular speed

v_z vertical speed

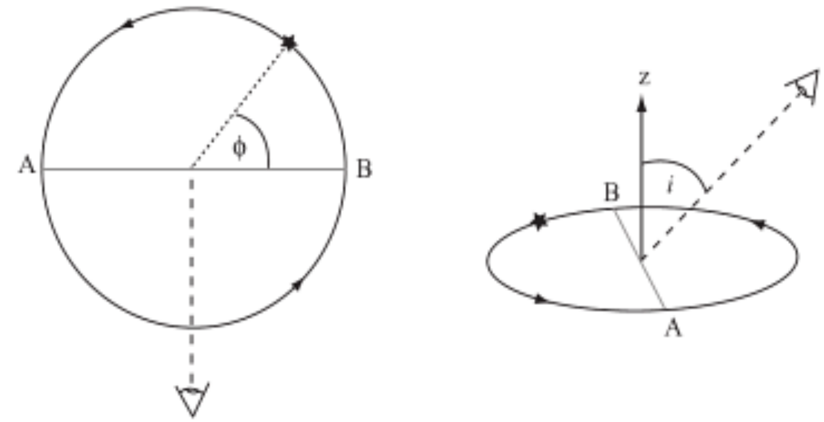
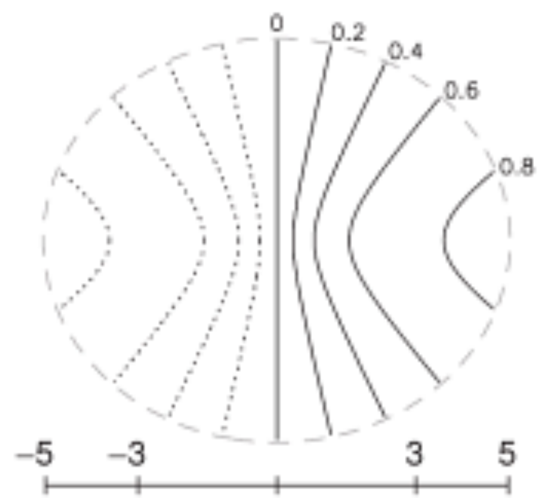


Fig. 5.18. Left, a rotating disk viewed from above. Azimuth ϕ, measured in the disk plane, gives a star's position in its orbit; an observer looks from above the disk, perpendicular to diameter AB. Right, the observer's line of sight makes angle i with the disk's rotation axis z.



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

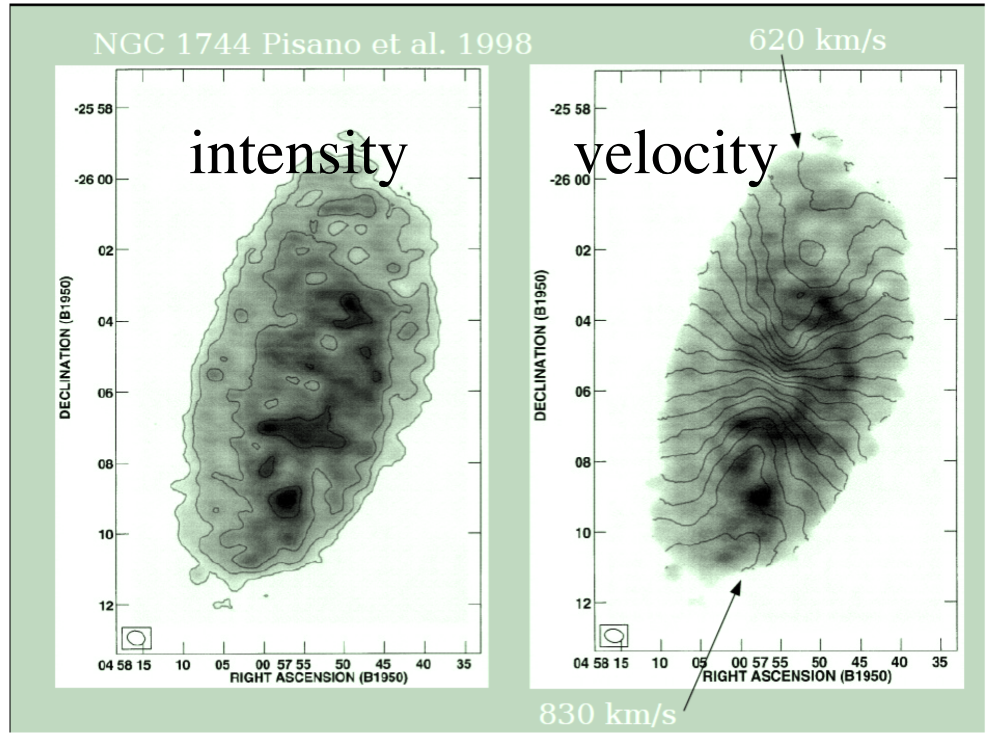
HI

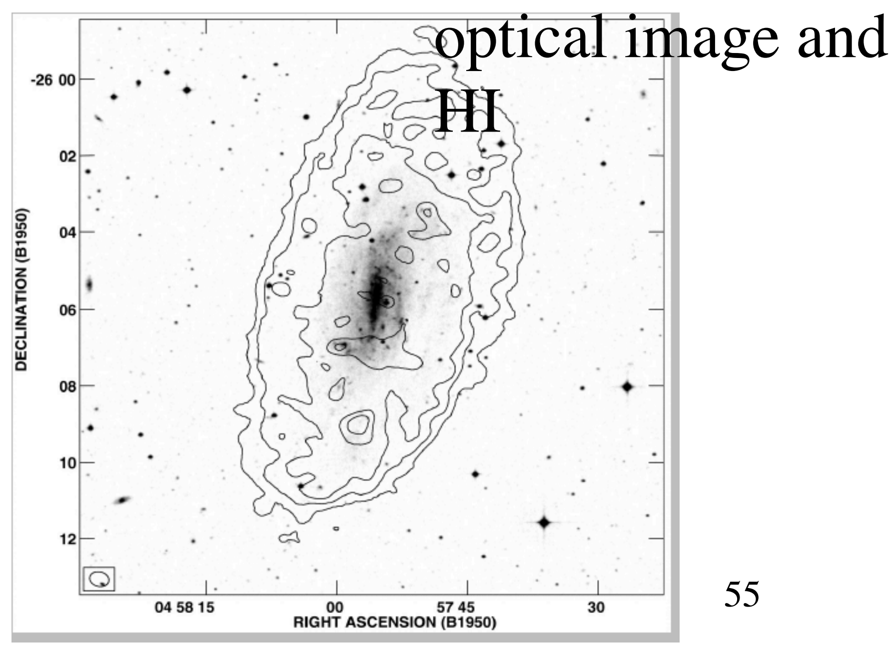
- Spirals have large HI disks

– This gas is optically thin

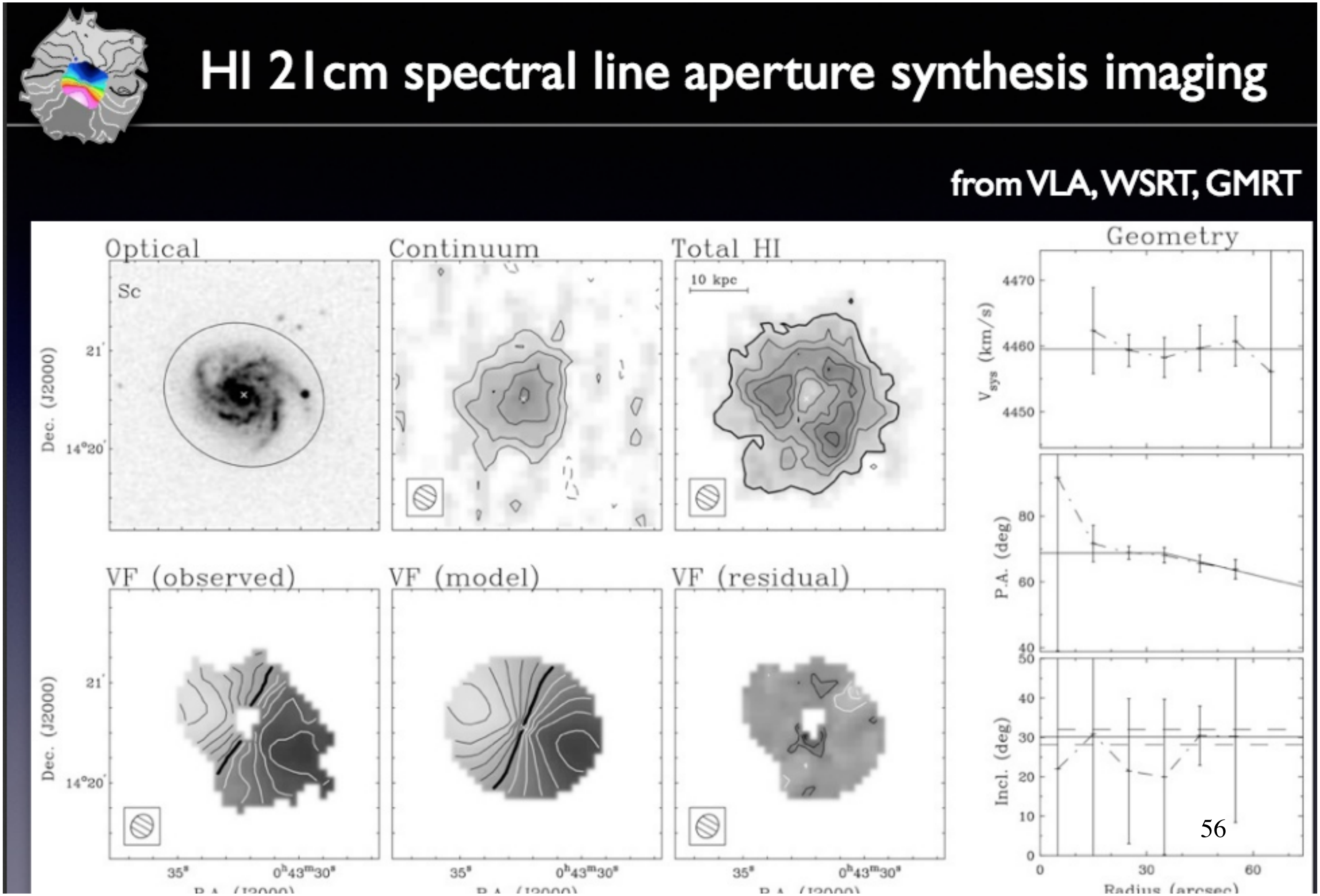
This means that we see all the gas and can measure the amount directly from the line intensity

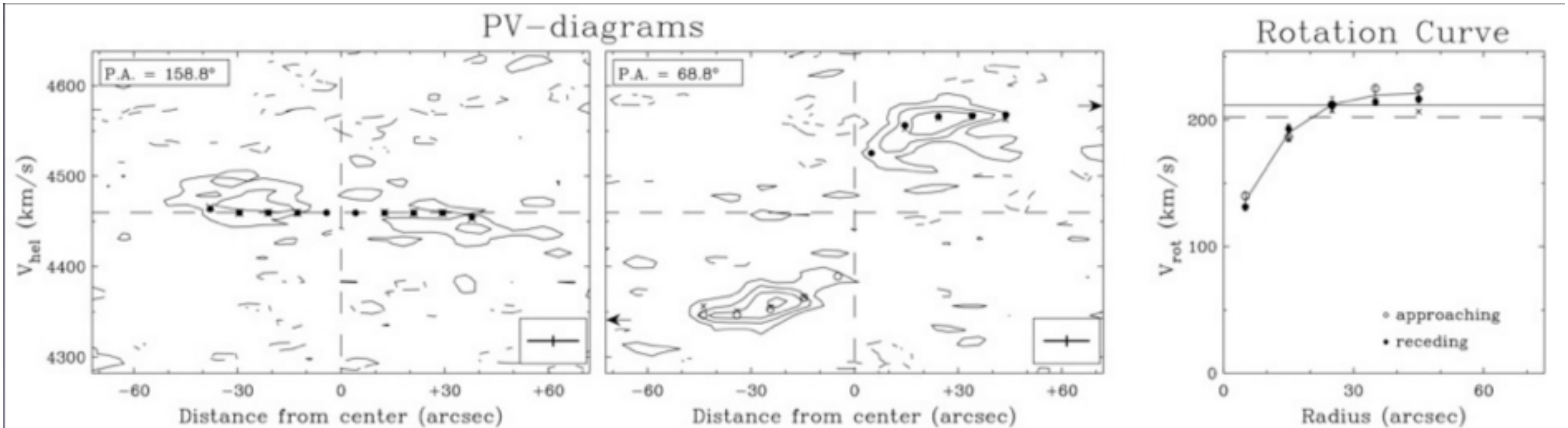
- HI gas is much more extended than the optical light, $r_{HI} > 2.5\ R_{25}$
- – Gives a unique tracer for the velocity in spiral galaxies

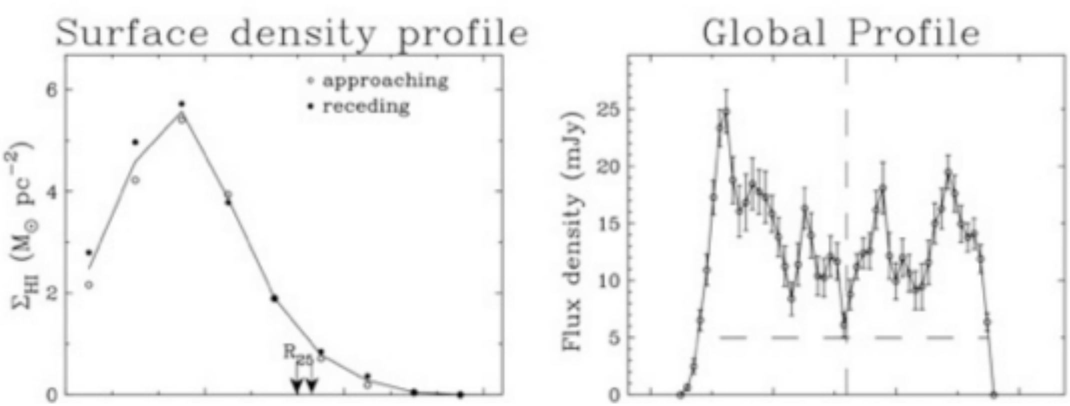




From Verheijen IAU 311



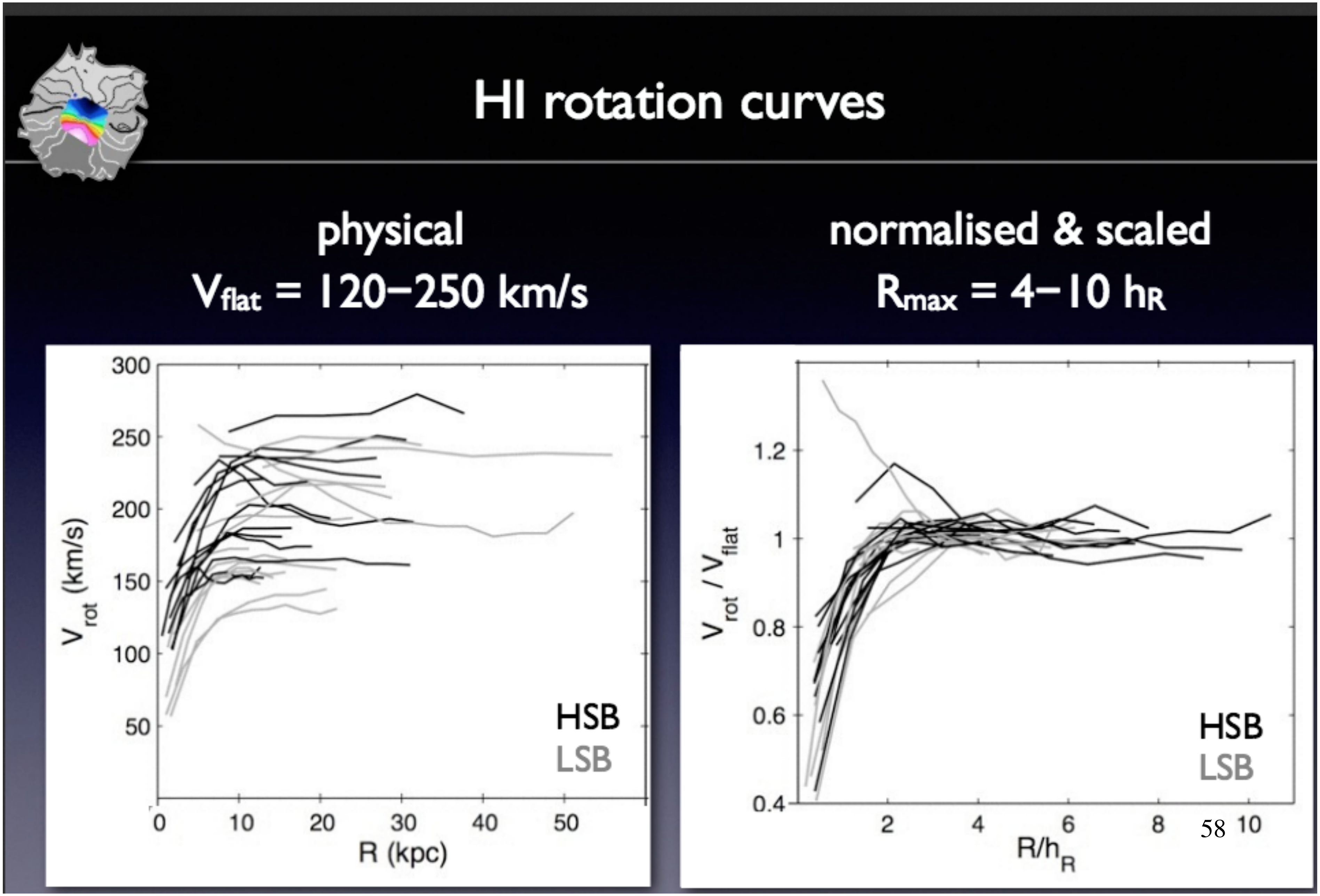




Atlas Table – UGC00463

Geometry:		**Contour levels:**	
RA	00:43:32.39 (J2000)	σ_{cont}	0.34 (mJy/beam)
Dec	14:20:33.20 (J2000)	σ_{pvd}	0.54 (mJy/beam)
V_{sys}	4459.5±0.5 (km/s)	VF (obs)	V_{sys} ± n×20 (km/s)
PA	68.8°±1.5°	VF (mod)	V_{sys} ± n×20 (km/s)
i_{TF}	30.1°±1.9°	VF (res)	±n×10 (km/s)
Flux & Densities:		**Velocity, Size & Resolution:**	
S_{21cm}	37.2±3.7 (mJy)	W_{20}	236.7 km/s
$S_{HI,max}$	24.8 (mJy)	R_{HI}	53 arcsec
$S_{HI}dv$	3.2±0.2 (Jy km/s)	Beam	14.7''×12.9''
$\Sigma_{HI,max}$	5.57 ($M_\odot$ pc^{-2})	Vel.Res	10.5 km/s

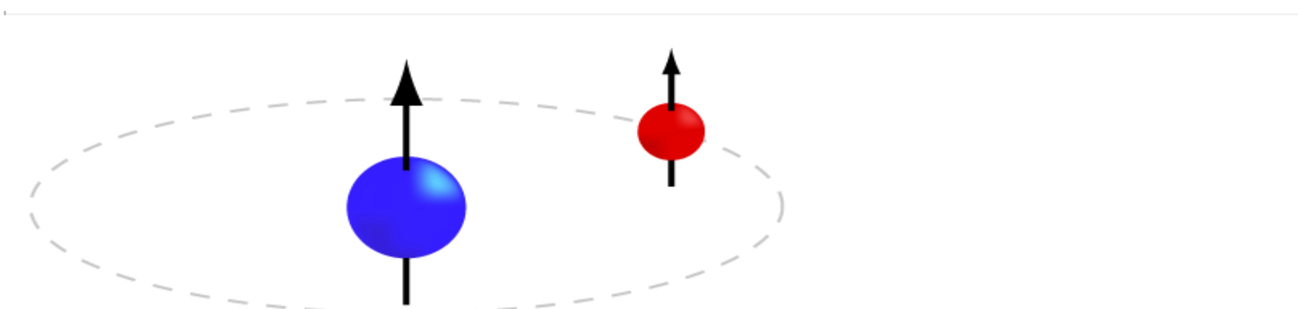
Verheijen IAU 311



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)

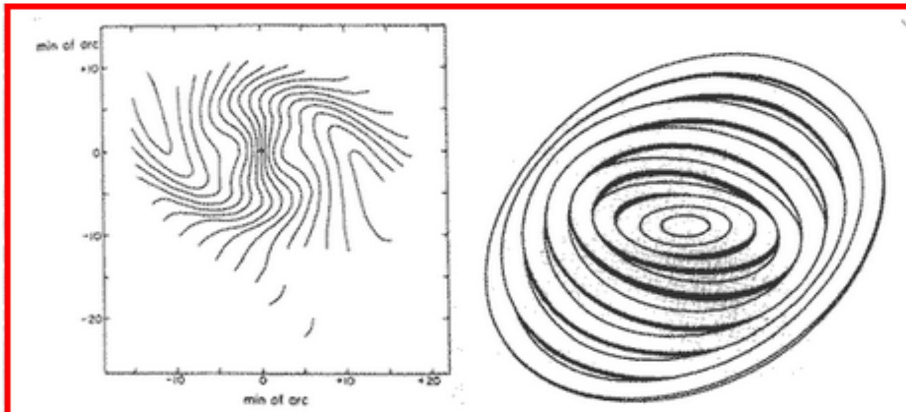


Figure 8.36 A tilted ring model of M83 (right) and the spider diagram predicted by this model (left). [After Rogstad, Lockhart & Wright (1974)]

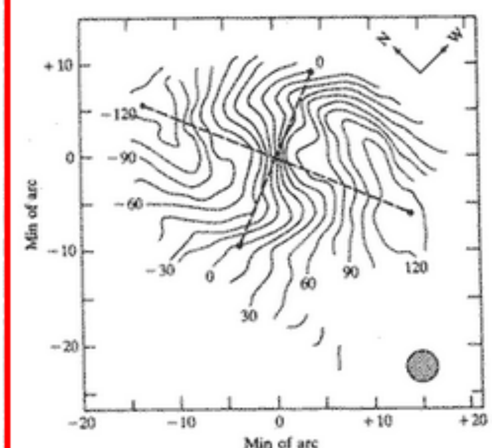
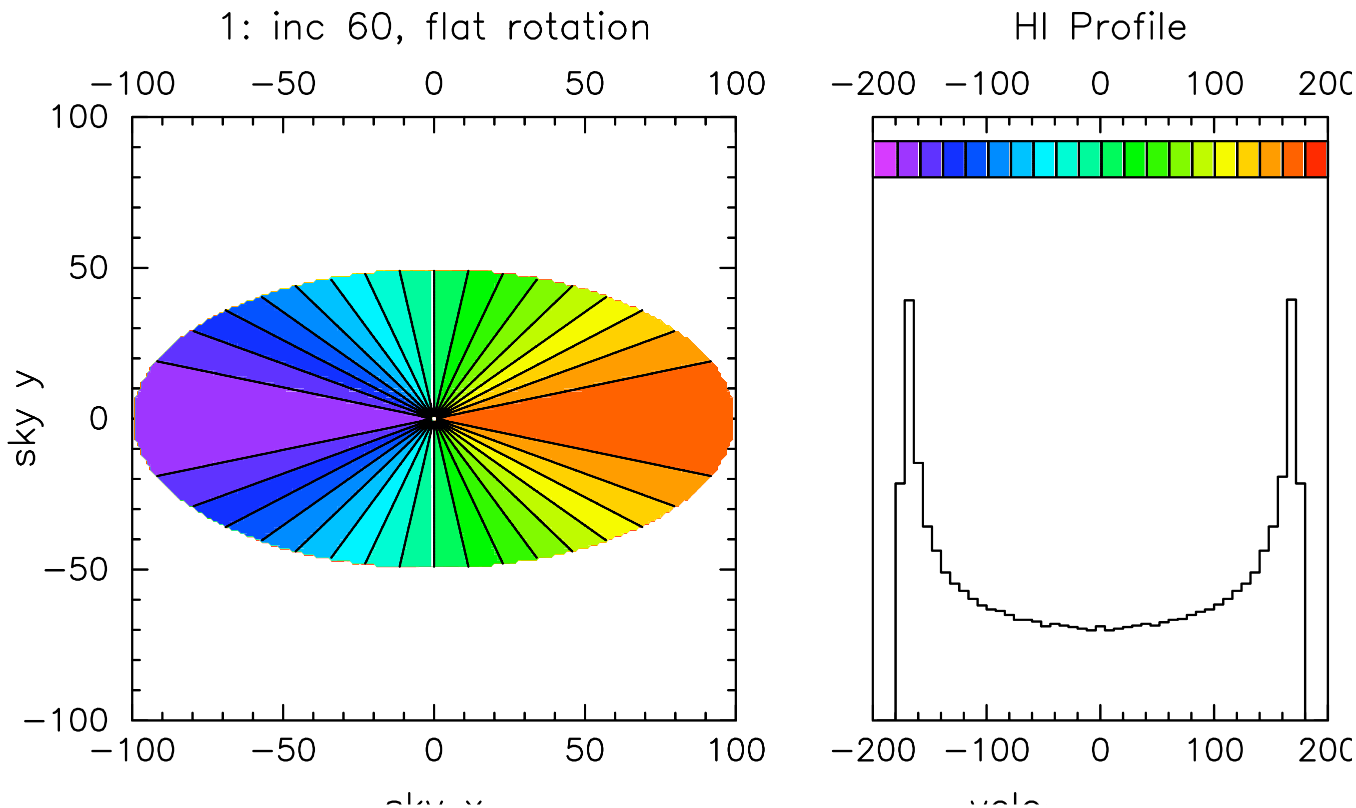
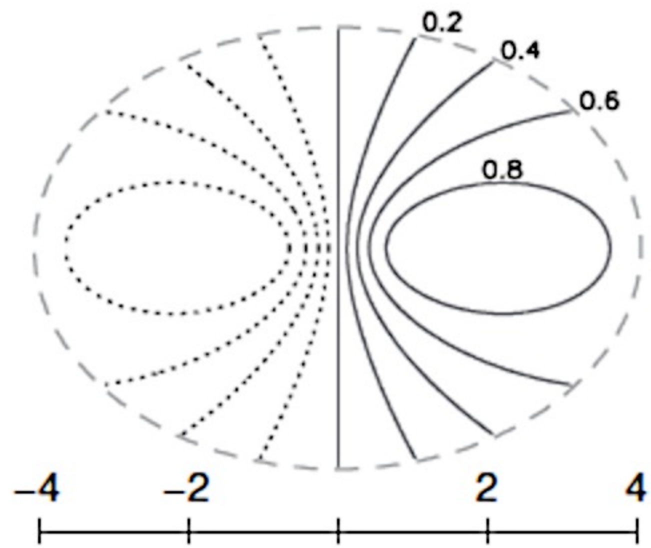


Figure 8.37 The observed spider diagram of M83. [After Rogstad, Lockhart & Wright (1974)]

Effects of Inclination on Velocity Field

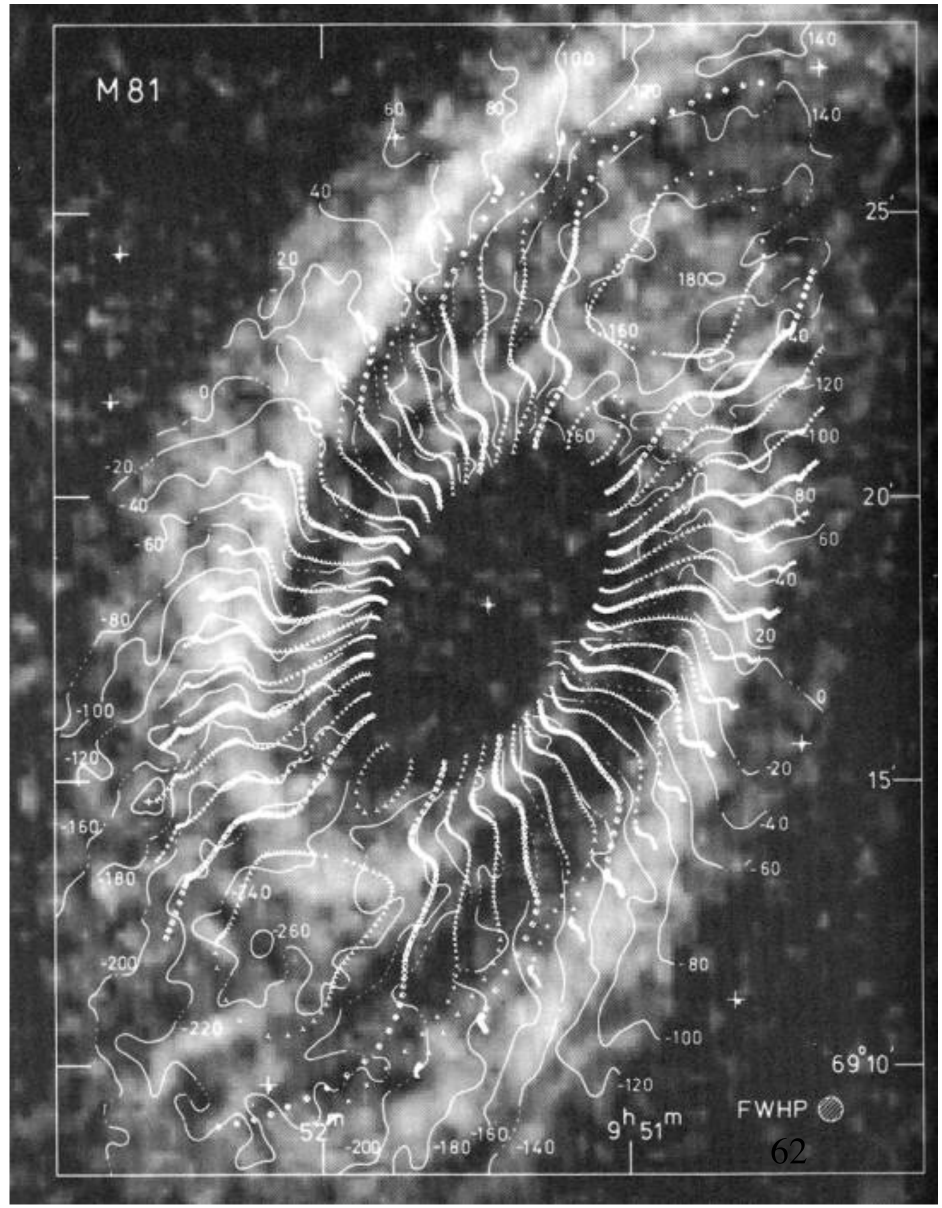


- 60 degree inclination
- 30 degree inclination



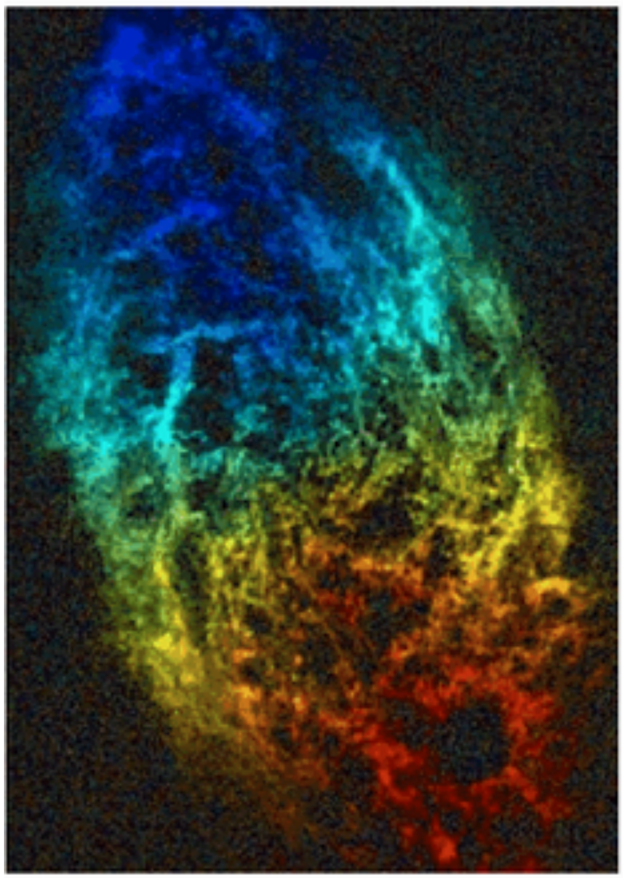
Gas Motions

- This is what is seen in 'real' galaxies in the motion of HI(fig 5.13 S=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)

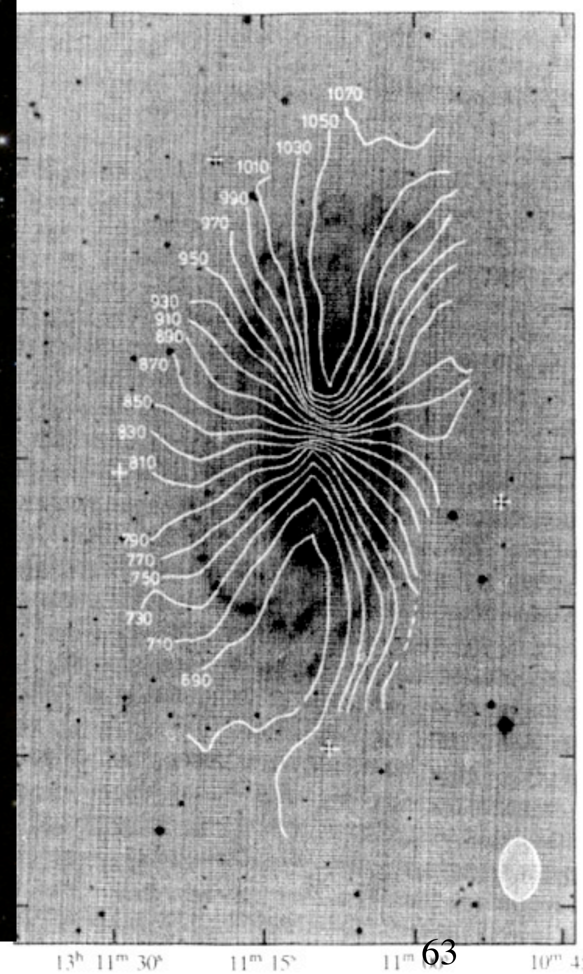


Optical Image and Velocity Field of NGC5033

- Spider plot is the contours of the velocity field



hydrogen velocity



Galaxy Masses as Constraints of Formation Models

- **IAU Symposium 311-http://www.physics.ox.ac.uk/confs/iau311/programme/**

- astro-ph 1511.01066
  Mitchell et al

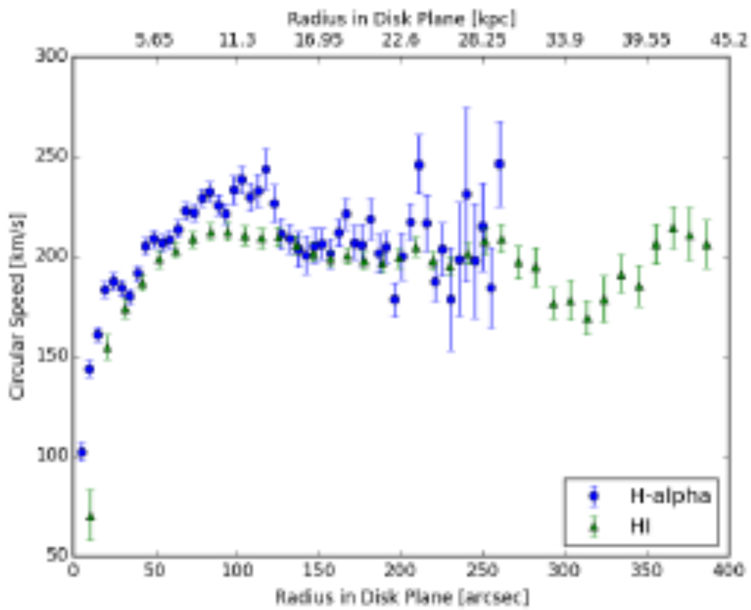


Figure 3: Rotation curves produced from our best-fitting *DiskFit* models to our Hα and HI velocity maps.

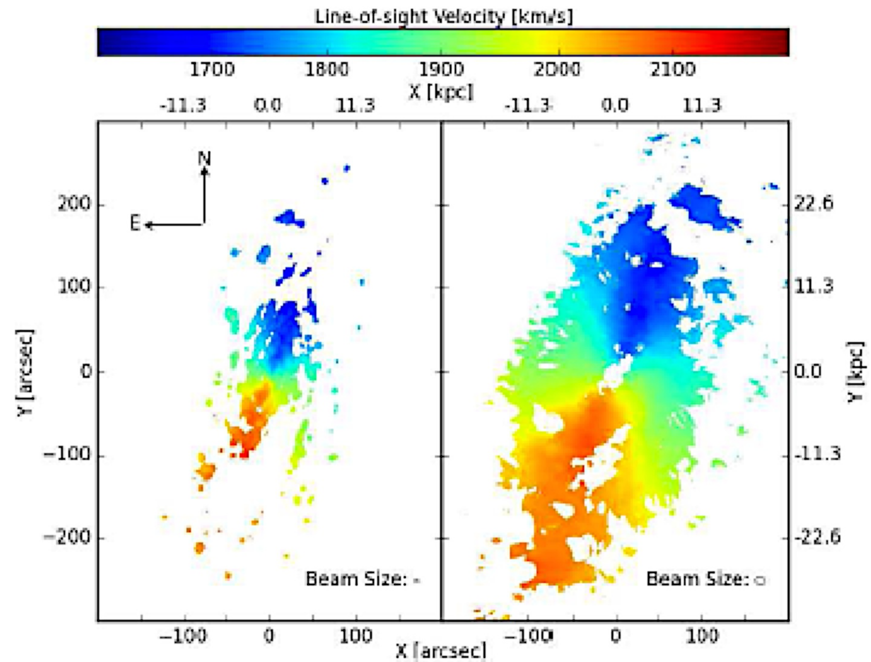


Figure 1: Our Hα (left) and HI (right) velocity fields of NGC 2280, presented on the same

Details of velocity data differ
by up to 20km/s- dynamics in the ionized gas producing Hα

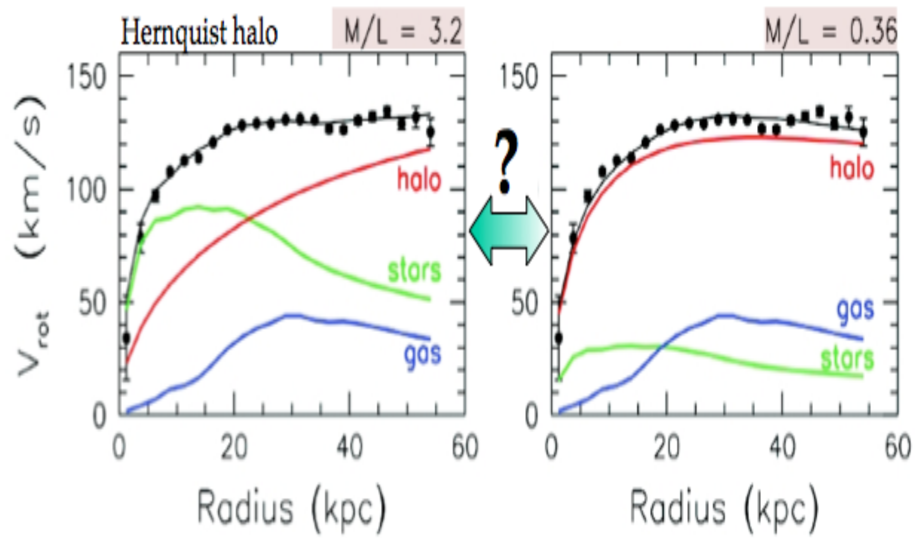
Spirals and Dark Matter- Review of Dynamics

Bershady et al [2011ApJ...739L..47B](2011ApJ...739L..47B)

http://hipacc.ucsc.edu/Lecture%20Slides/GalaxyWorkshopSlides/bershady.pdf

- 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!
- Disks in equilibrium

  Rotation provides total mass within a given radius.



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

How to Break Degeneracy

Find very similar galaxies – edge on systems rotation provides total mass, vertical motions of stars provides disk mass

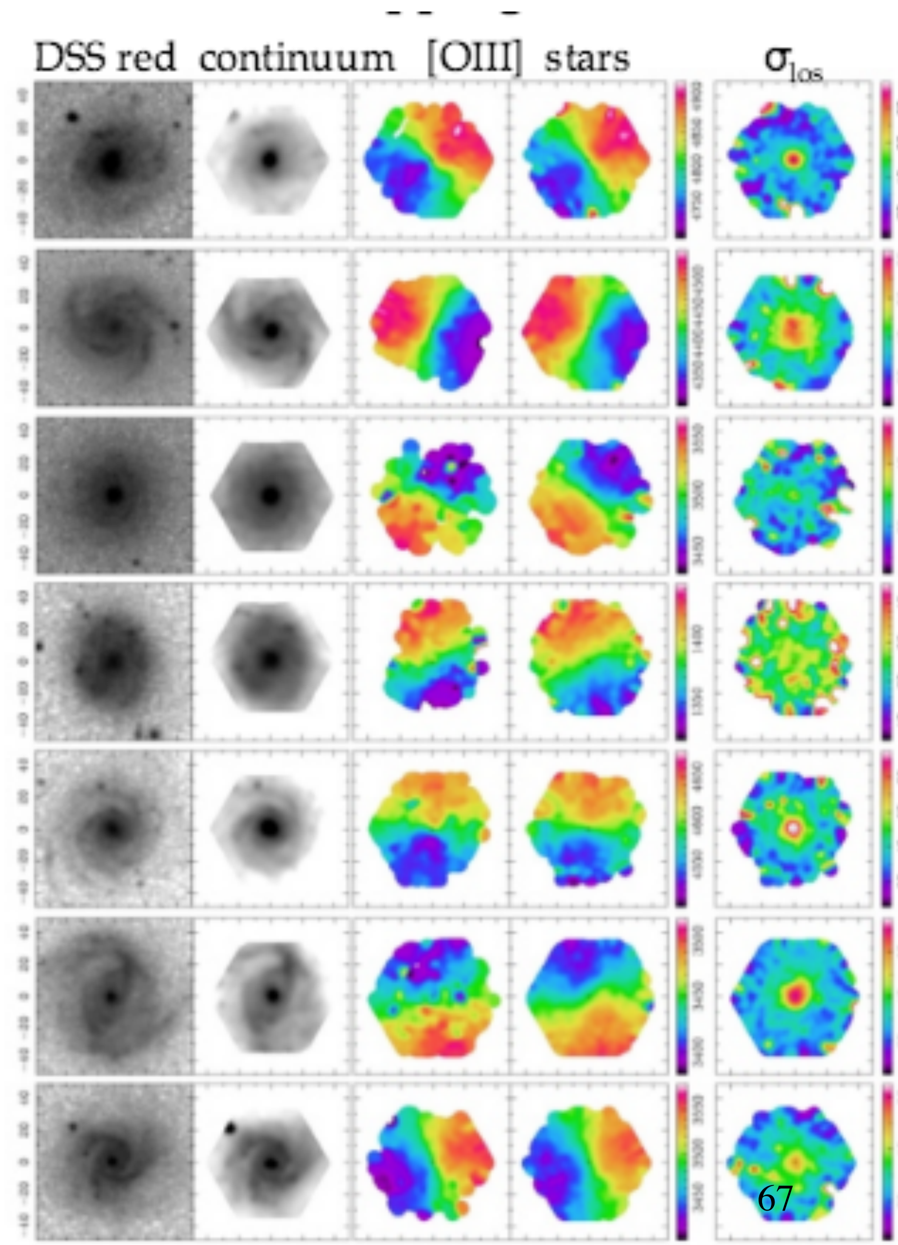
Scaling law

$\Sigma=[(Dk/h_z)\sigma_z^2]$; h- scale height of disk; D=normalization constant, k depends on nature of vertical distribution (e.g. exponential or whatever)

- Galaxy disks are sub-maximal

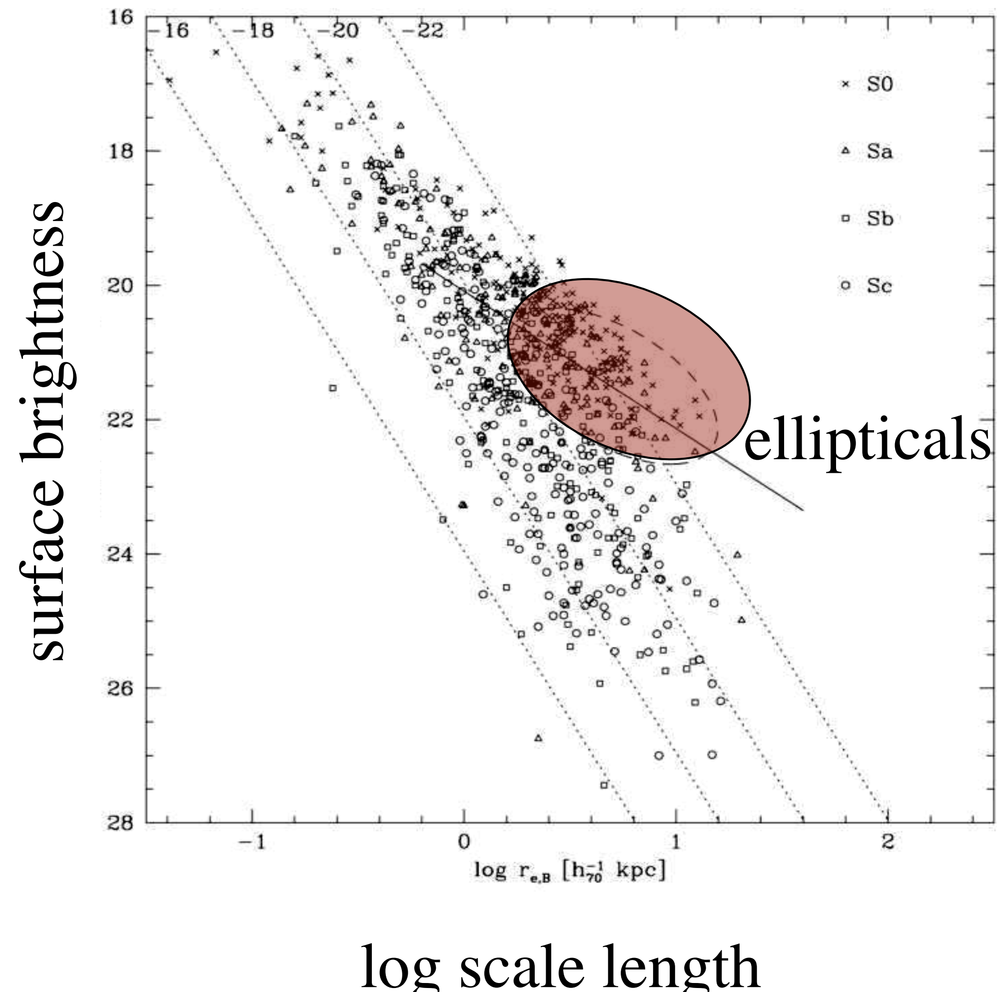
:15-30% by mass at $2.2h_R$

Little room for disk dark matter but imply very low M/L_K



Bulge Scaling Relations

- The properties of the bulges of lenticulars follow closely the relations obeyed by Es
- Dwarfs have different bulges (large n values, scale lengths and higher surface brightness)
- The more luminous bulges of all Hubble types show similarities in various correlations but ellipticals have a smaller range of parameters than spiral bulges.



Spiral Arms in Spirals (sec 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. 'Visually' spiral arms are associated with star formation/molecular gas.Lifetime is << galactic rotation period.

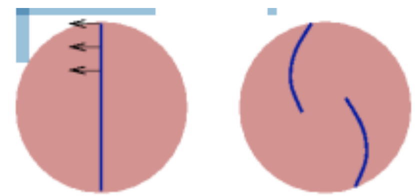
When the sense of the galactic rotation is known, the spiral arms almost always trail the rotation.

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

$V(R)$ = constant

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

- Any feature in the disk will be *wrapped* into a trailing spiral pattern due to differential rotation:



Tips of spiral arms point away from direction of rotation.

(From P. Armitage)

However this is NOT SOLELY why spiral galaxies have spiral arms- they would wrap up into a tight spiral in time scale $\Delta R/R=2\pi R/vt$
putting in values near the sun $\Delta R/R=0.25\ (t/\mathrm{Gyr})^{-1}$
e.g. The Winding Problem

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

Winding?

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

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

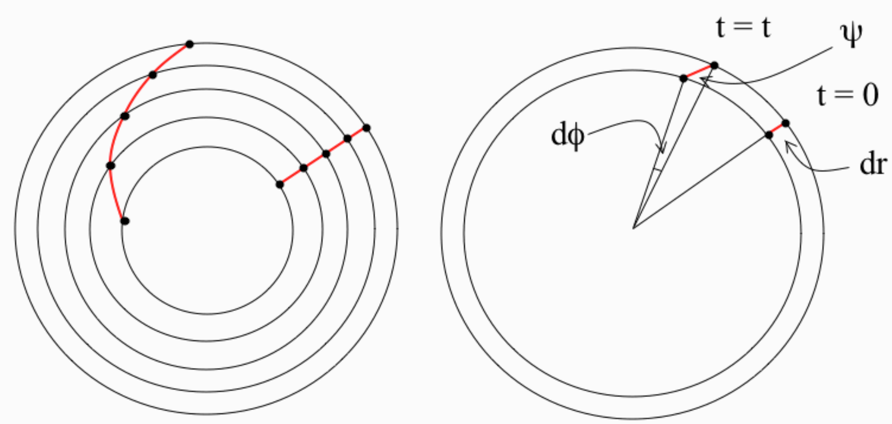
so $\tan\psi=dr/r\ d\phi=r/vt=1/\phi$

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

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

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



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 $\tan\psi = dr / r\ d\phi = dr / [(v/r)\ dr\ t] = r / vt = 1/\Omega t = 1/\phi$

$\boxed{\tan\psi = r / vt = 1/\phi}$

M. Whittle's web site

From http://www.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect24/lecture24.h

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 strip as a function of time is

$$\varphi(R,t)=\varphi_0+\Omega(R)t$$

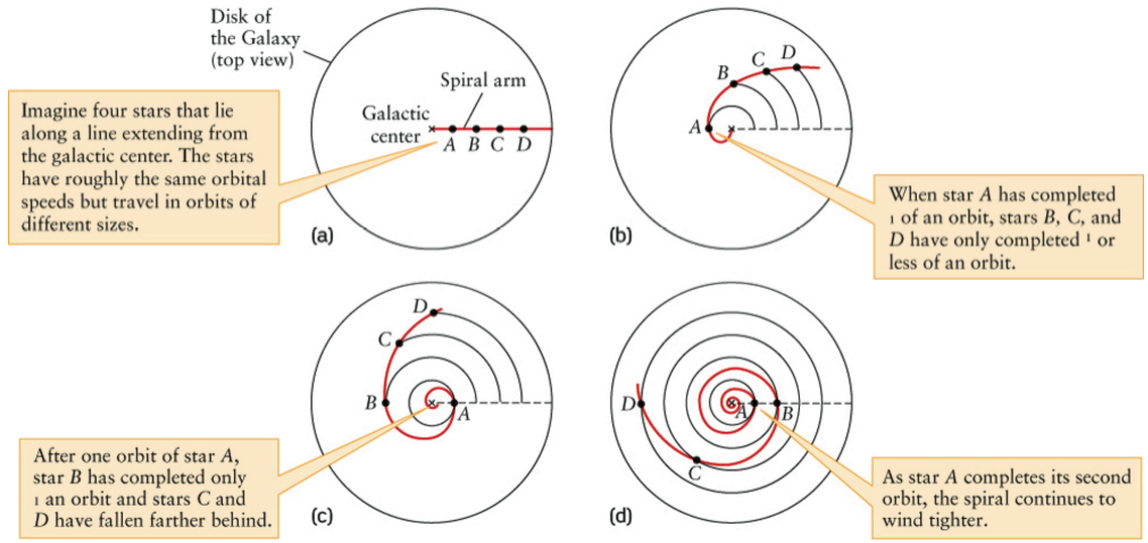
For a typical spiral galaxy with a flat rotation curve

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

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

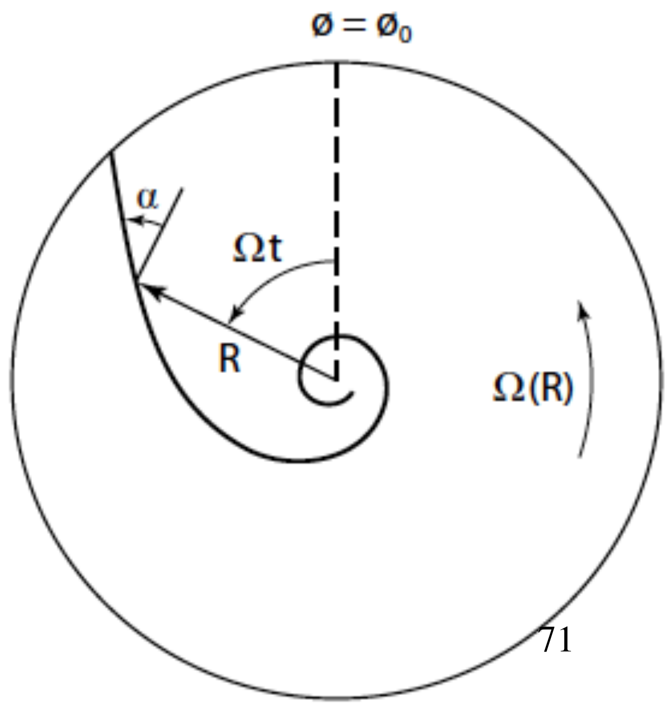
near the sun =220km/sec at R~10kpc, at t=10^{10}yrs α=0.25deg !

Real galaxies have α ~5-25 deg



In the diagram

$\cot\alpha \sim Rt\, d\Omega(R)/dr$



Spiral Density Waves- One Possible Answer

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

- density waves provide the perturbation which gets sheared :

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

Gas is also compressed, triggering star formation and young stars.

Stars pass through the spiral arms unaffected

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

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

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

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

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

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

Spiral Arm Formation

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 mergers (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

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New Results on Arms (arxiv1411.5792 Kendall et al and 1507.07000 Choi et al)

- In general, spiral morphology correlates only weakly with morphological parameters such as stellar mass, gas fraction, disc/bulge ratio, and v_{flat}.

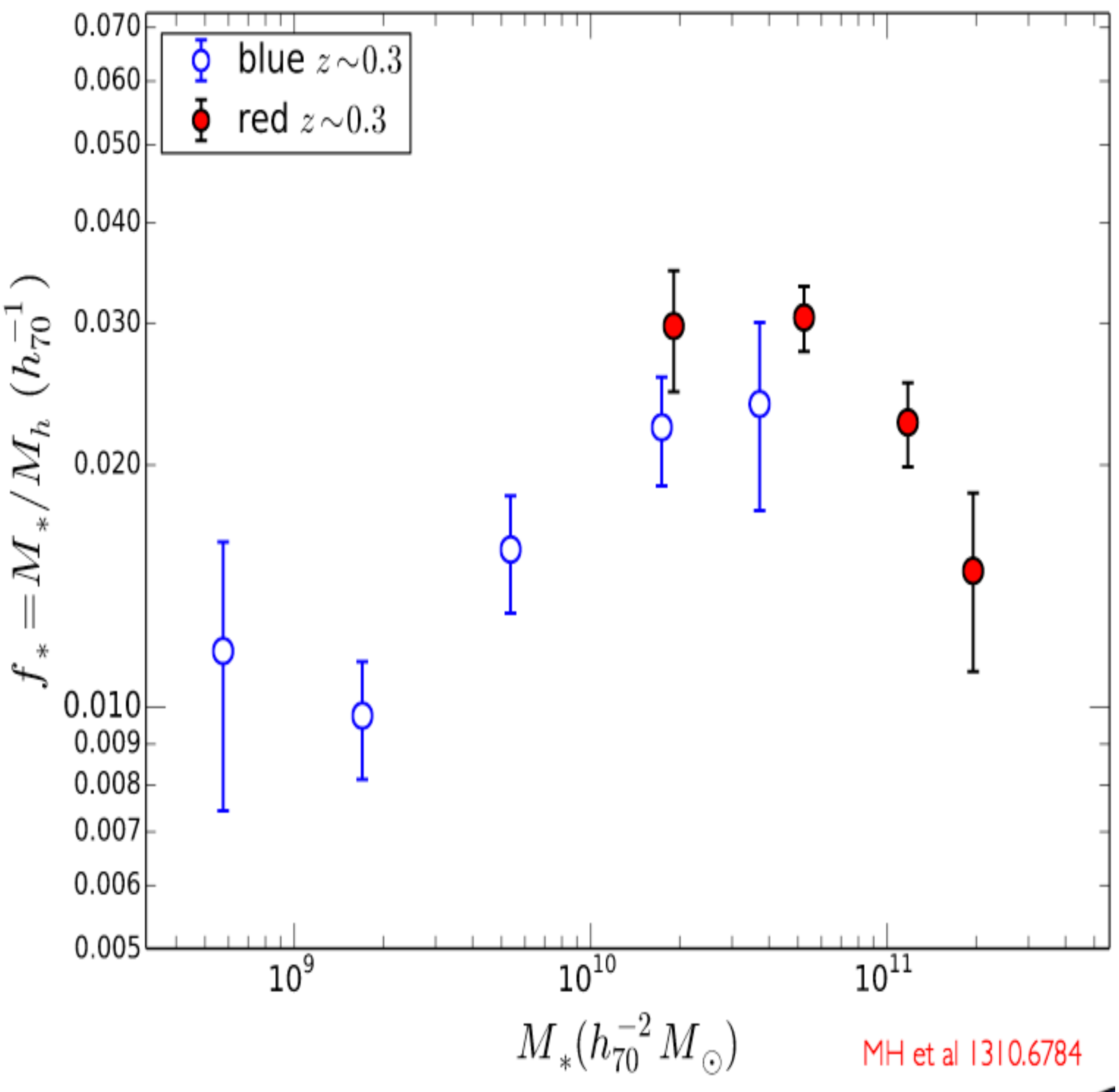
In contrast a strong link is found between the strength of the spiral arms and tidal forcing from nearby companion galaxies.

This appears to support the longstanding suggestion that either a tidal interaction or strong bar is a necessary condition for driving grand-design spiral structure.

- Stationary density waves rotating at a constant pattern speed P would produce age gradients across spiral arms.
  - however there is no evidence of star formation propagation across the spiral arm
  - thus no convincing evidence for a stationary density wave with a single pattern speed in M81, and instead favor the scenario of kinematic spiral patterns that are likely driven by tidal interactions

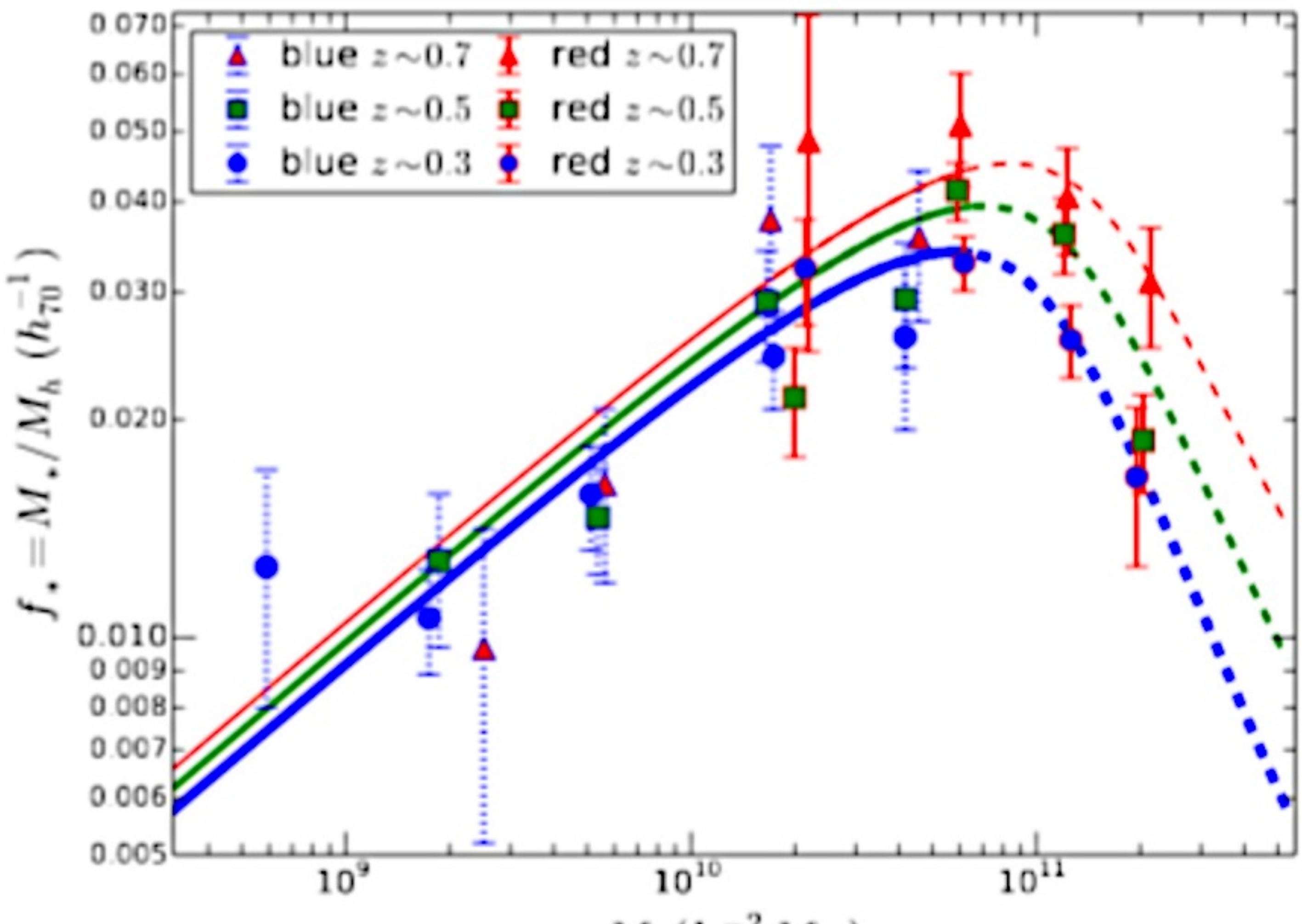
Baryonic Mass Fraction vs Mass

Hudson et al 2015 MNRAS 447,298



these ratios only vary weakly as a function of redshift out to z~.7 for blue galaxies but by 30% for red galaxies apparently SF balances accretion so to keep stellar mass function constant

Change in Baryonic Fraction Over Cosmic Time



stellar mass

- Star forming disk galaxies have an IMF consistent with that of the MilkyWay
  - bulges might have different IMF
  - Origin of Tully-Fisher is not clear
- disks are 'sub-maximal' e.g.
  - A disk contributing maximally to the gravitational potential sets a lower limit on the amount of halo dark matter in the inner regions of disk galaxies. Maximum-diskdecompositions find the disk mass produces 85±10% ofthe observed rotation velocity at 2.2 disk scale-lengths
  -