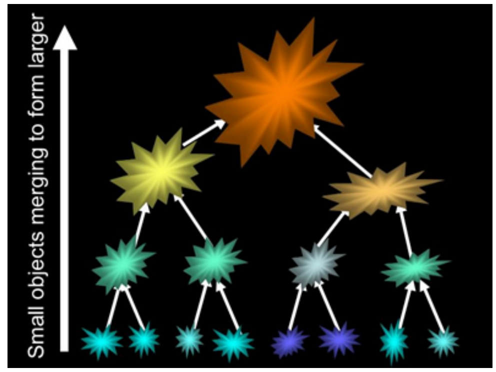
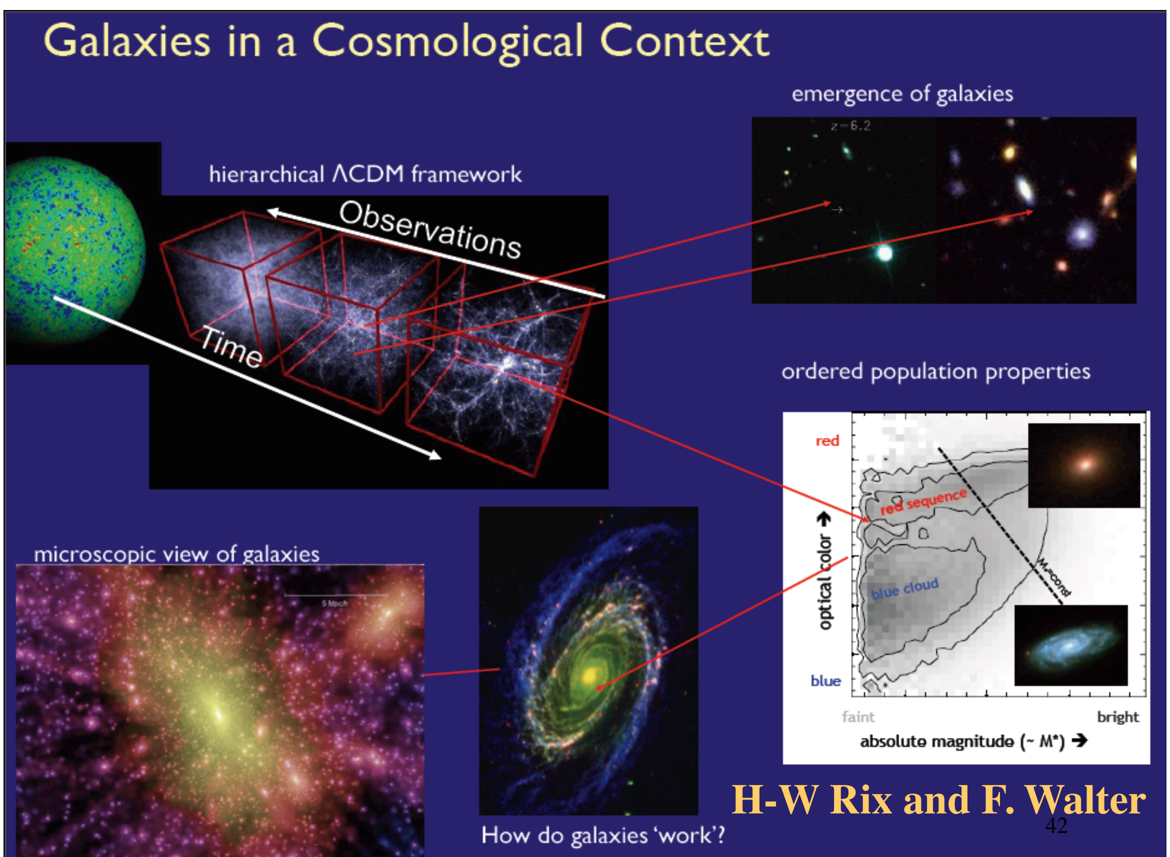
How Things Form

- Gravity acts on overdensities in the early universe making them collapse.
- As time goes on these collapsed regions grow and merge with others to make bigger things



•Hierarchical clustering (or hierarchical merging) is the process by which larger structures are formed through the continuous merging of smaller structures.

•The structures we see in the Universe today (galaxies, clusters, filaments, sheets and voids) are predicted to have formed by the combination **of collapse and mergers** according to Cold Dark Matter cosmology (the current concordance model).



Galaxy formation : Many relevant and interacting processes

Cooling (metallicity, structure, ...)

Star formation (threshold, efficiency, IMF, ...)

AGNs (BH growth, feedback, ...)

Dust (formation, distribution, heating & cooling, ...)

Galaxy formation & evolution

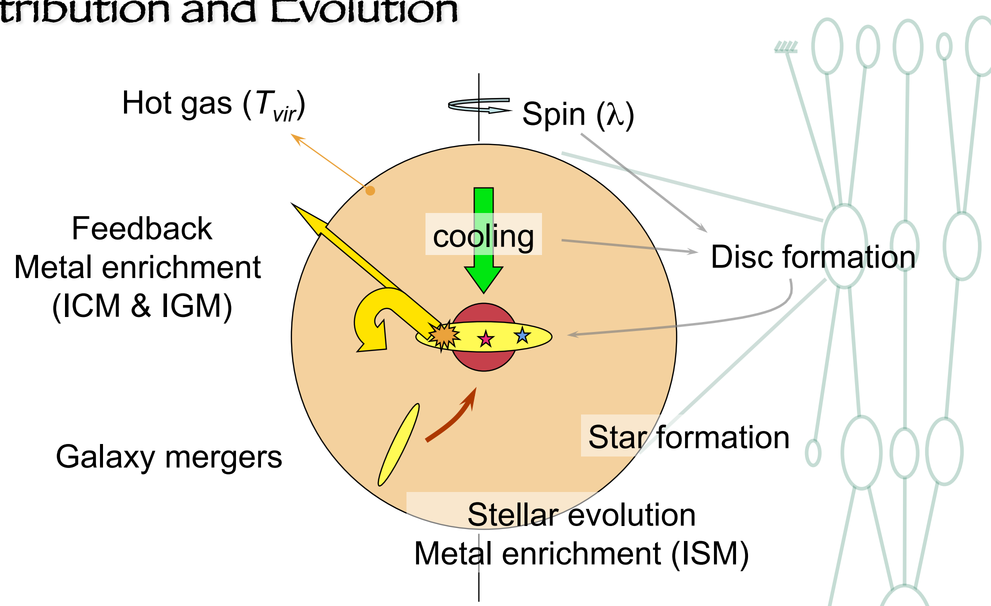
Galaxy interactions (morphological transformations, starbursts, intracluster stars, ...

Winds (IGM heating, enrichment, SN feedback, etc...)

Stellar evolution (spectro-photometric evolution, yields, SN I/II rates,...)

taken from **J. Blaizot** presentation

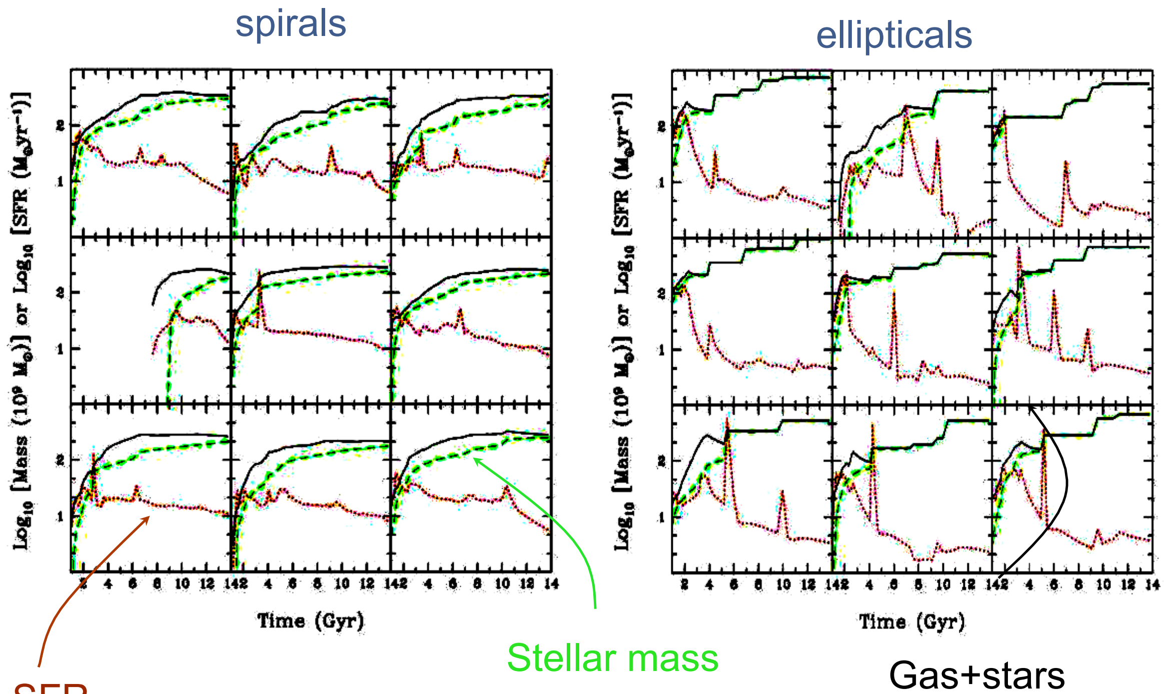
What Physics Goes on Top of the Dark Matter Distribution and Evolution



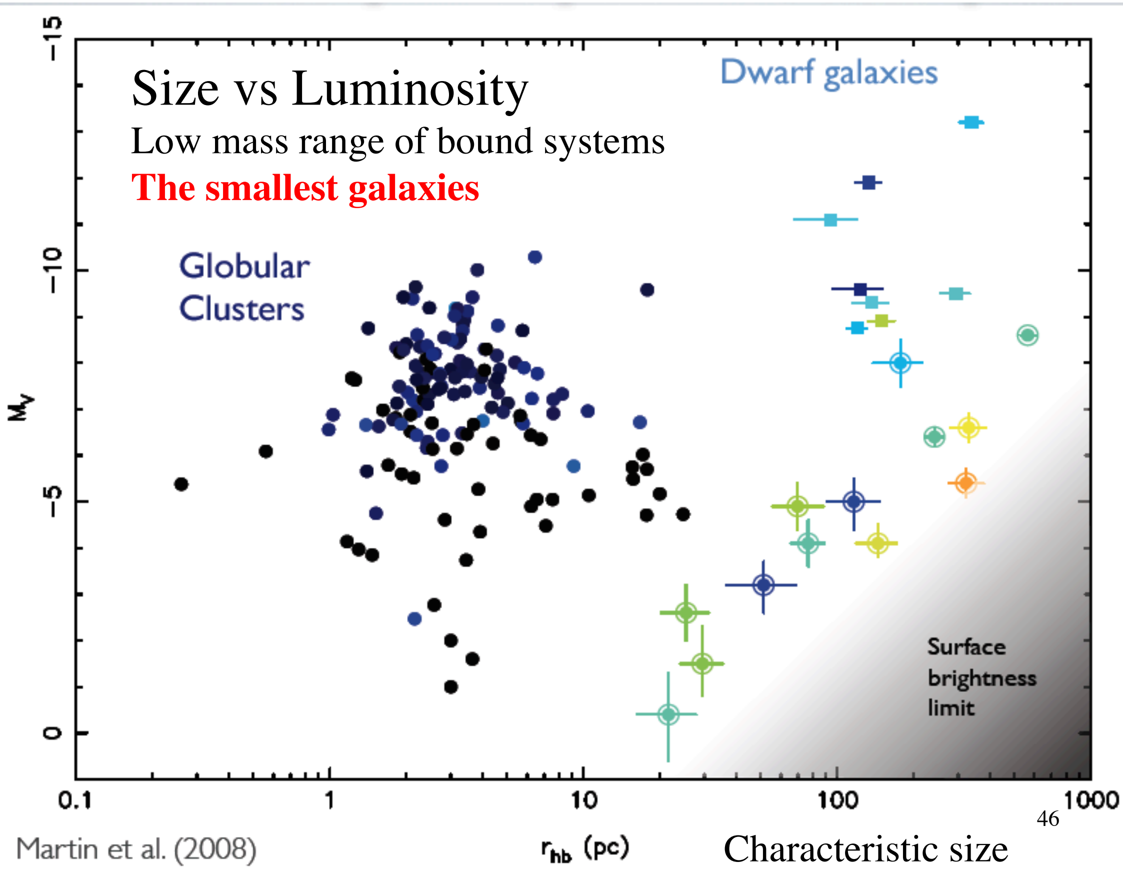
+ model of simple stellar population evolution (w/ dust)

taken from J. Blaizot presentation

A set of results from numerical simulations



notice SFR not constant
mass growth has 'jumps' - mergers J. Blaizot-



Galaxies Have Very Different Appearances in Different Wave Bands

- The physical processes which dominate in different wavebands are often very different
  - optical - starlight
  - UV- starlight from massive young stars
  - near IR- starlight from “old” stars
  - far IR - re-radiation of optical/UV by dust
  - radio - synchrotron emission from relativistic particles and emission from molecules
  - x-ray - AGN, x-ray binaries, supernova remnants and hot gas
  - γ-ray- relativistic particles interacting with dense gas

Panchromatic MilkyWay

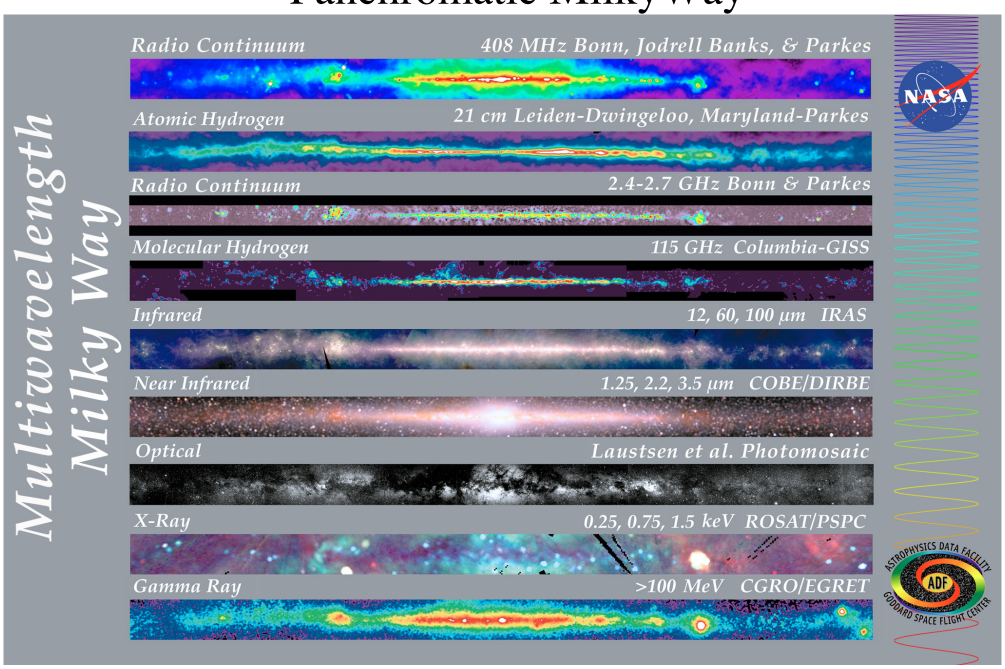
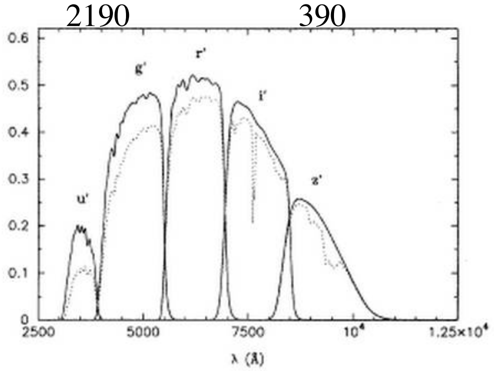


Image of MW galactic plane from radio through γ-rays

A Bewildering Variety of Bands and Names

Name	wavelength nm	$\Delta\lambda$
U	365	66
B	445	94
G	482	140
V	551	99
R	658	138
I	806	149
z	900	140
Y	1020	120
J	1220	213
H	1630	307
K	2190	390



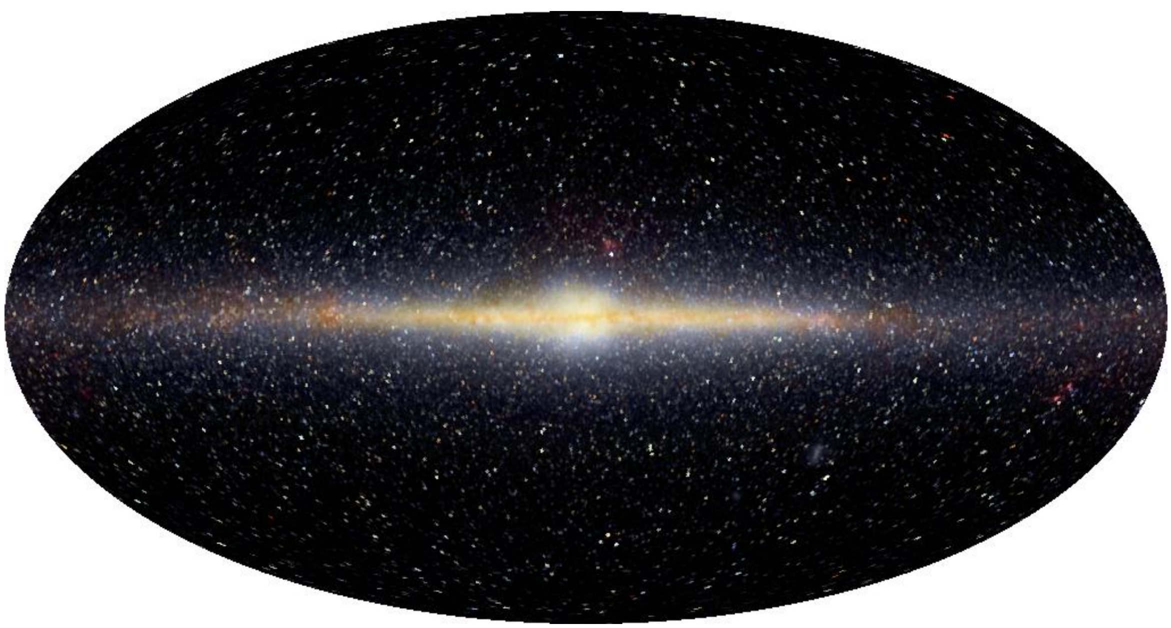
There are 2 different magnitude systems

AB system (Oke & Gunn 1983), magnitude 0 object in all bands has the same flux F_ν = 3631 Jy
a object with a flat energy distribution (F_ν=constant) has the same mag in all colors; 3631 Jy is how bright Vega is in the V band!
Absolue mag of sun in SDSS filter set
u;g;r;i;z 5 lg h = 6:80; 5:45; 4:76; 4:58; 4:51

The **Vega** system by definition, Vega's magnitudes are 0.0 in all filters.

there are many other filter 'sets' each based on different needs, uses
(the UBV data set was developed for use with photographic plates, the SDSS set for use with CCDs circa 1995 technology)

Image of MW in IR From COBE

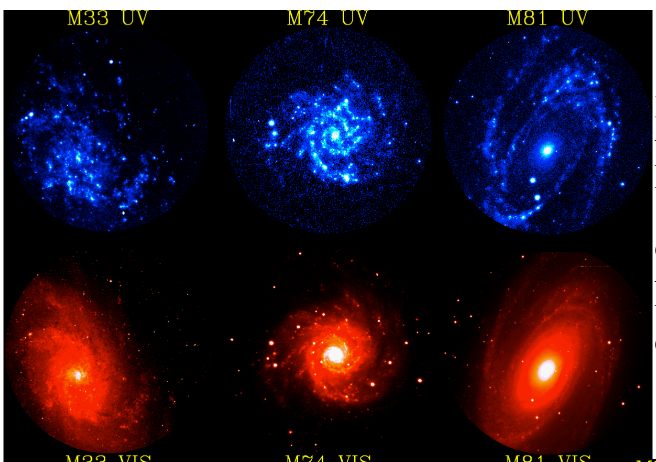


In the IR the effects of dust are minimized and one can see the true distribution of emitted radiation. In this wavelength band the emission is due mostly to old low mass stars

Different Appearances at Different Wavelengths

M31 -- 24 (MIPS),160 (PACS),350 (SPIRE) um

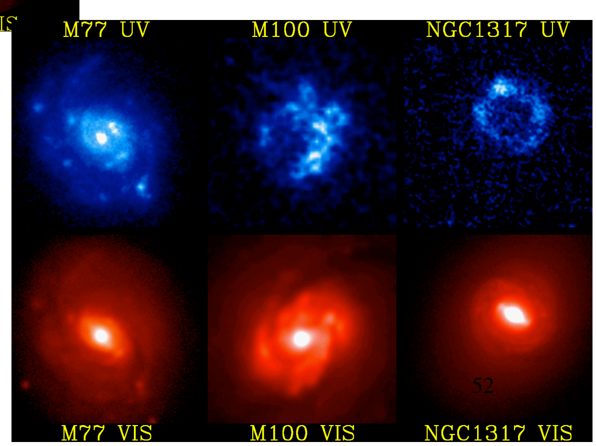
at long IR wavelengths the emission is due to dust which has reprocessed optical/UV light



12 galaxies observed in UV and optical

Notice different patterns of UV light - this is affected not only by the distribution of hot young stars but also by dust

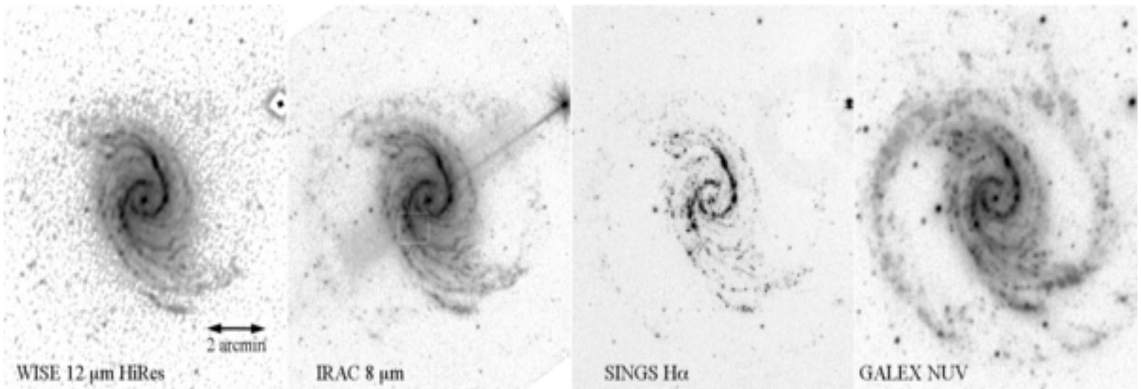
From UIT team



Difference between UV, optical and IR becomes important in studying the high redshift universe where restframe UV gets redshifted in optical band

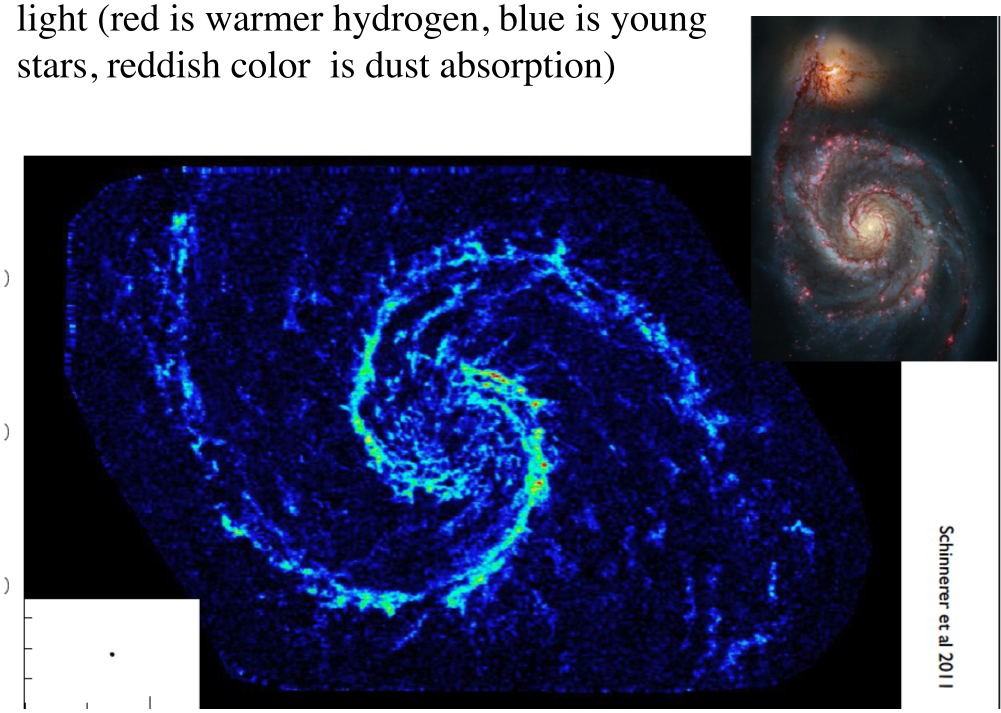
NGC1566 in 4 Bands

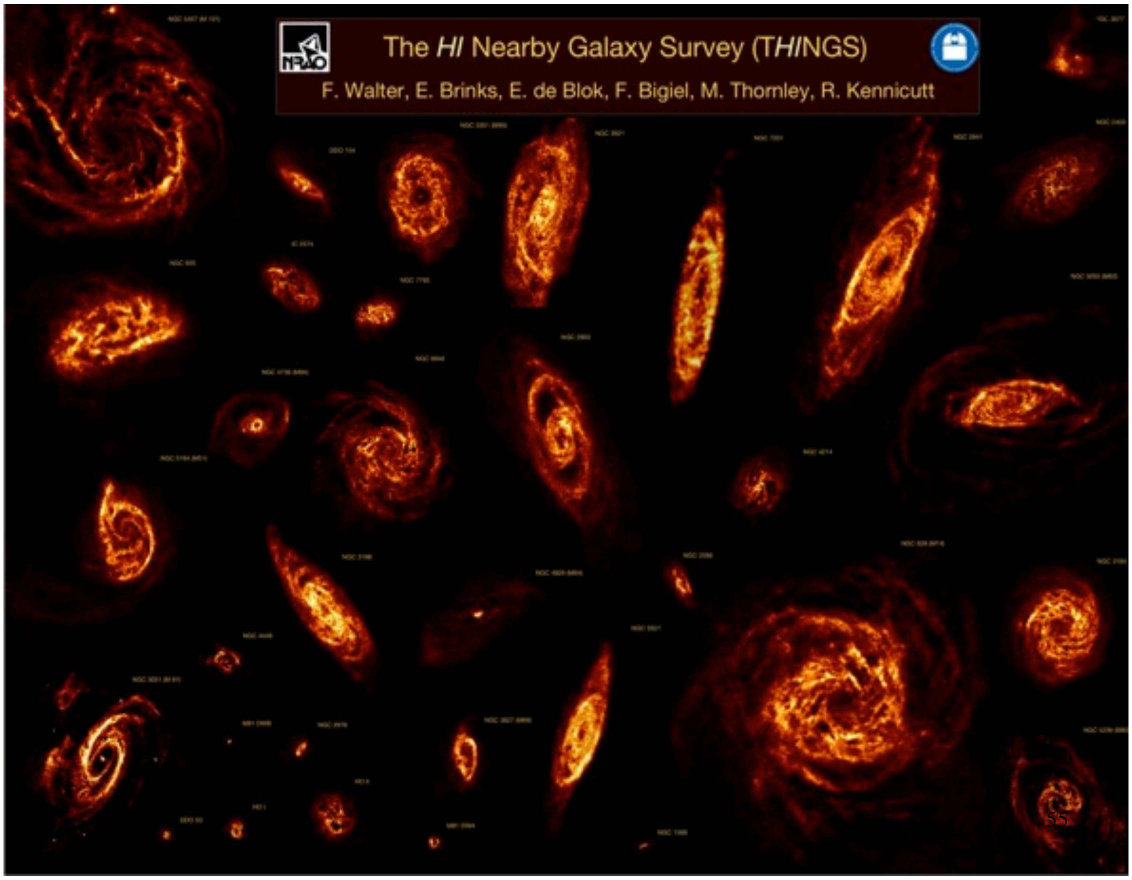
- Each of these bands reveals different information about the stars, dust and star formation rate in the galaxy
- Hα- youngest stars
- NUV young stars
- IR emission from small molecules (PAHs)
- IR emission from dust

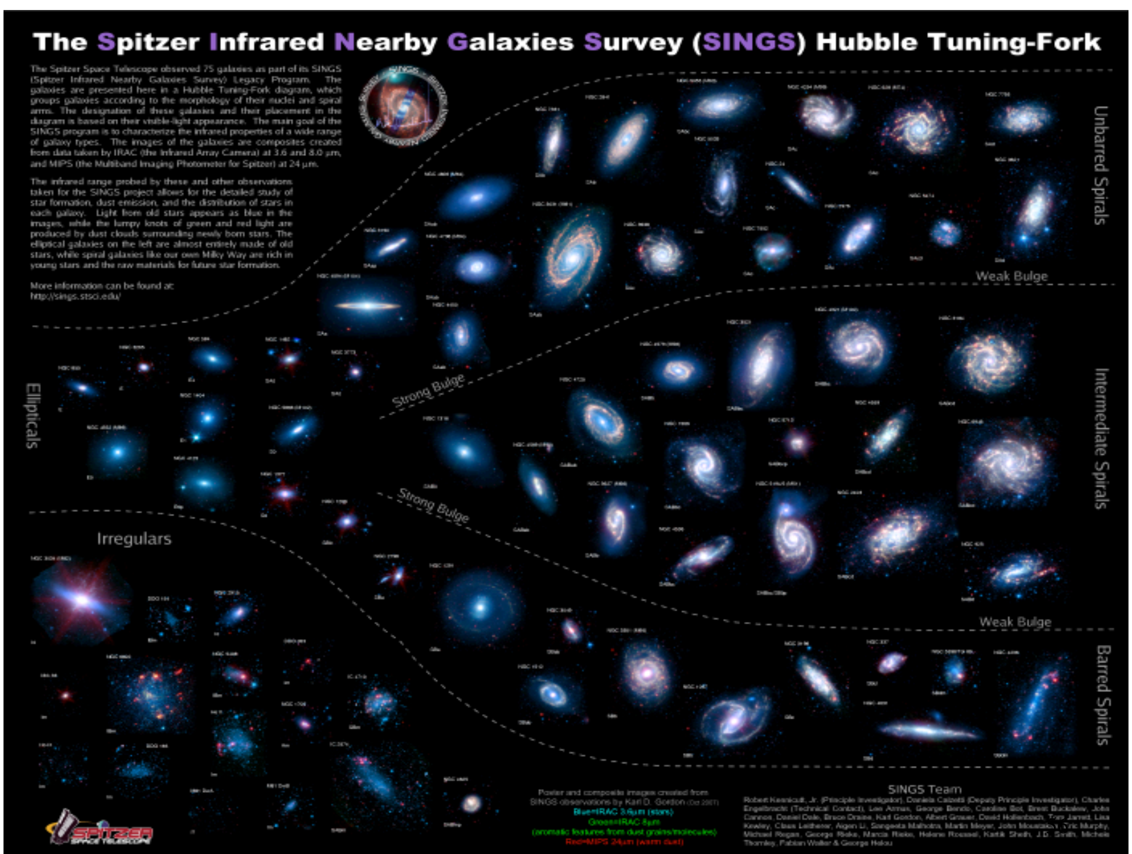


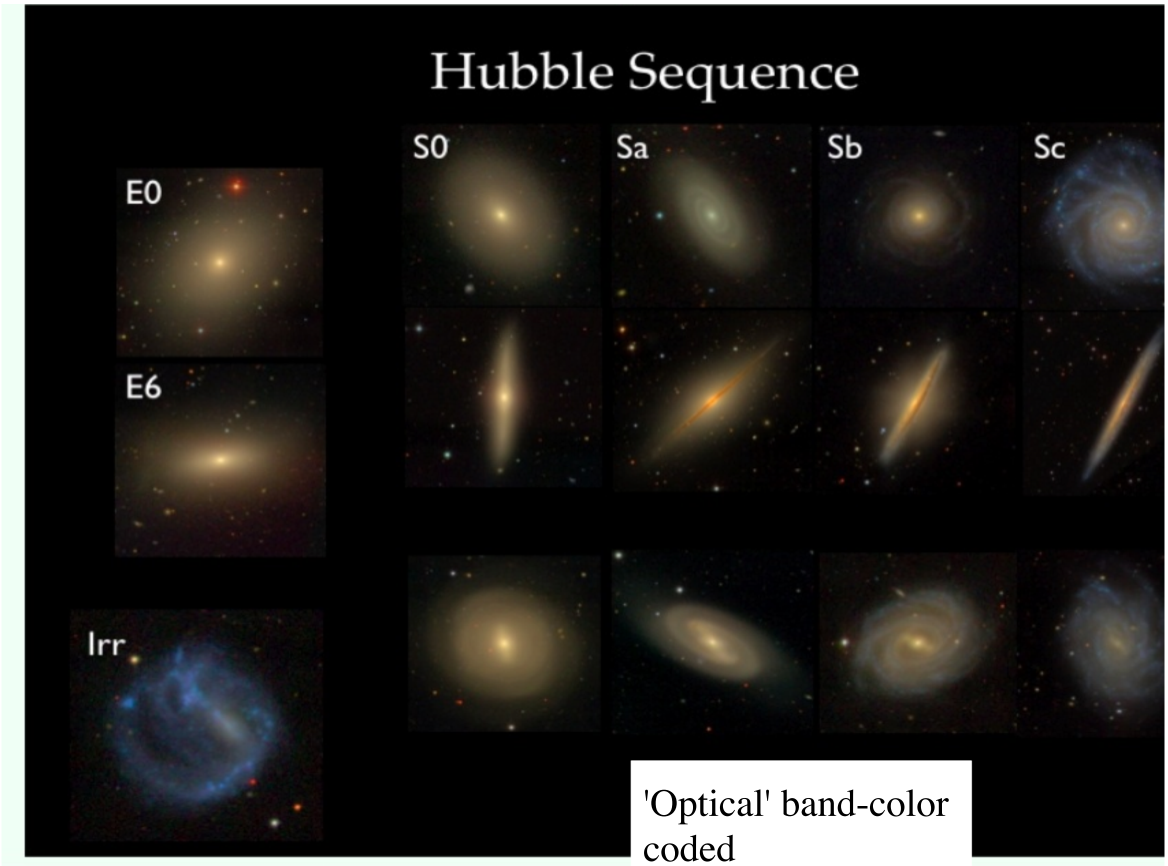
Dust PAH Hα NUV

'Cool gas' (HI-hydrogen) and color coded light (red is warmer hydrogen, blue is young stars, reddish color is dust absorption)




The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt


The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork
The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 μm, and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 μm.
The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.
More information can be found at:
http://sings.stsci.edu/
Unbarred Spirals
Weak Bulge
Strong Bulge
Ellipticals
Intermediate Spirals
Strong Bulge
Irregulars
Weak Bulge
Barred Spirals
Poster and composite images created from SINGS observations by Karl D. Gordon
Blue=IRAC 3.6μm (stars)
Green=IRAC 8μm
(aromatic features from dust grains/molecules)
Red=MIPS 24μm (warm dust)
SINGS Team



Astronomers Have a Enormous Appetite for Jargon

- "Normal" ellipticals: giant ellipticals (gE’ s), intermediate luminosity (E’ s), and compact ellipticals (cE’ s), range in absolute magnitudes from M_B ~23 to M_B ~15.
- Dwarf ellipticals (dE’ s): significantly smaller surface brightness and a lower metallicity.
- cD galaxies. extremely luminous (up to M_B~25) and large (up to R~1Mpc) galaxies found only near the centers of dense clusters of galaxies.
- Blue compact dwarf galaxies. (BCD’ s) bluer than the other ellipticals, and contain an appreciable amount of gas.
- Dwarf spheroidals (dSph’ s) exhibit a very low luminosity and surface brightness. as faint as M_B ~-8.
- **Thus 'elliptical' galaxies span an enormous range (10^6) in luminosity and mass**

Do these terms carry a physical meaning?- *Yes* the 'names' and the physics have a strong linkage- what, why and how

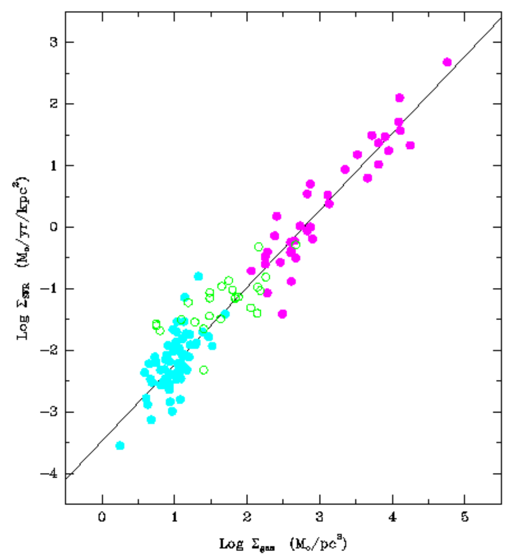
- abstracted from P. Schneider Extragalactic Astronomy and Cosmology An Introduction Springer

Generalized Galaxy Properties

- Galaxies have a set of 'regular' properties
  - Relationship of dynamics to mass (Faber-Jackson, Tully-Fisher, Kormendy relations)
  - Narrow range of stellar properties (e.g initial mass function, ages, relation of galaxy properties to star formation (spirals are forming stars **now**, ellipticals much less so)
  - Relation of mass of central black hole to galaxy bulge properties

Kennicutt 1998, ApJ, 498, 541

log surface density of star formation rate



log surface density of gas

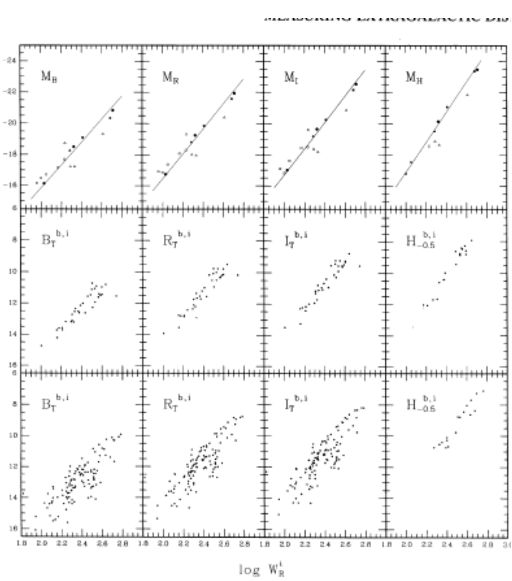
Galaxy Patterns- Continues

- Tully-Fisher for Spiral Galaxies: 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)
- $L_{opt} \sim Av^4$
- Since luminosity depends on distance^2

while rotational velocity does not, this is a way of inferring distances.

Figure shows the **T-F relation in 4 different wavebands** (blue to near-IR) for 3 different samples - scatter increases due to measurement error)

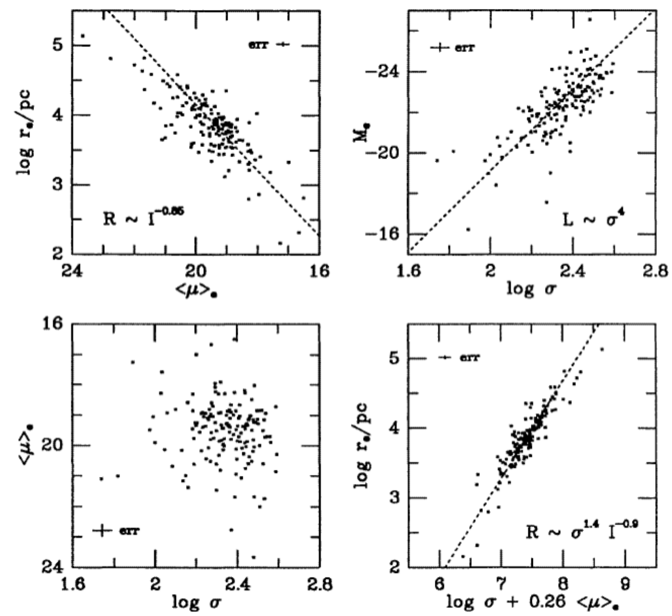
Absolute luminosity measured in magnitudes



log rotational velocity

Patterns-Continued

- Fundamental Plane of Elliptical Galaxies
- There are a set of parameters which describes virtually all the properties of elliptical galaxies



2 Projections of the fundamental parameter plane of elliptical galaxies. *Top*

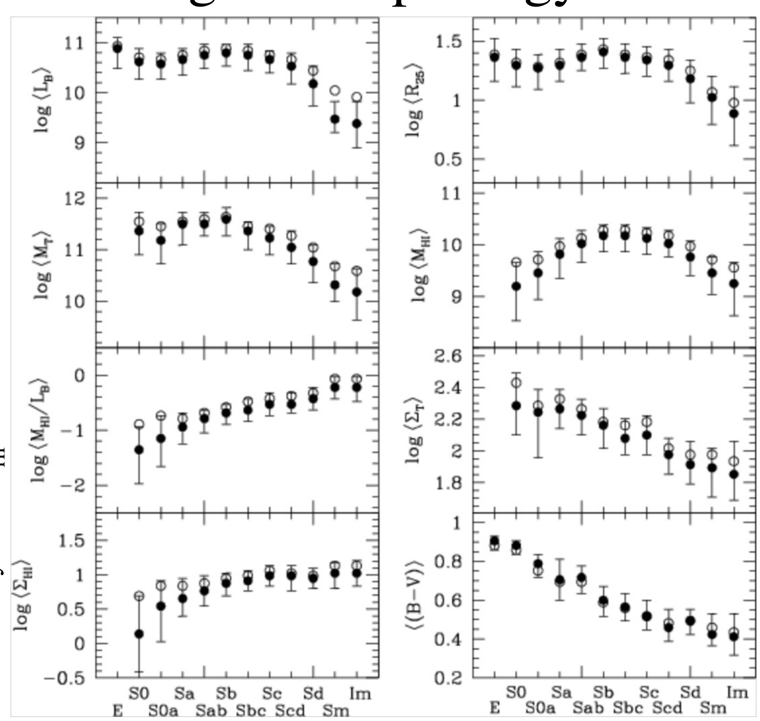
r_e= scale length
μ= surface brightness
σ= velocity dispersion
M=absolute magnitude

A Physical Meaning to Morphology?

Various measures of galaxy properties are strongly correlated with morphology ; e.g amount of cold gas, color and surface brightness

the morphological types have <u>some</u> direct connection to physical meaning - however it is more than a bit complex.

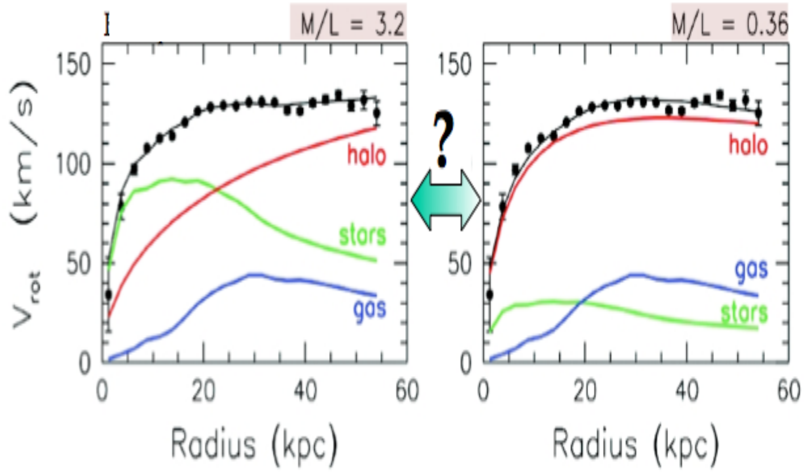
surface density of HI Σ_{HI}



Spirals and Dark Matter

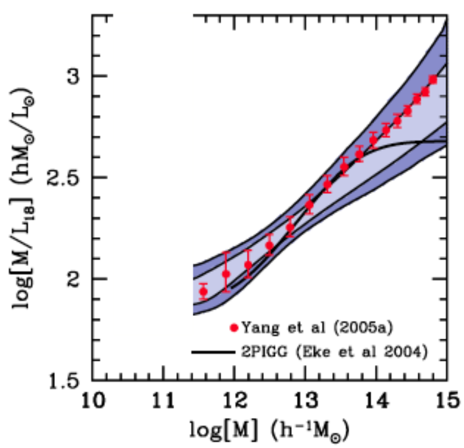
Bershady et al

- 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)
- Disks in equilibrium
  Measure of rotation provides total mass within a given radius.
  Vertical oscillations of disk stars provides disk mass within given height inside a cylinder:



At the radius where the velocity curve flattens ~15-30% of the mass is in baryons
2 plots show the effects of varying the relationship between light and mass in stars

- Different properties of individual galaxies are strongly correlated
  - M_*, L, M/L, t_{age}, SFR, size, shape, [Fe/H], σ, v_{circ}
- 'Mass' is the decisive parameter in setting properties
  - M_* or M_{halo}
  - $10^5\ M_\odot < M_*$ (galaxy) $< 10^{12}\ M_\odot$ exist
  - Most stars live in massive galaxies ($10^{10.5}\ M_o$)
  - The massive galaxies don't form stars anymore ('early types')



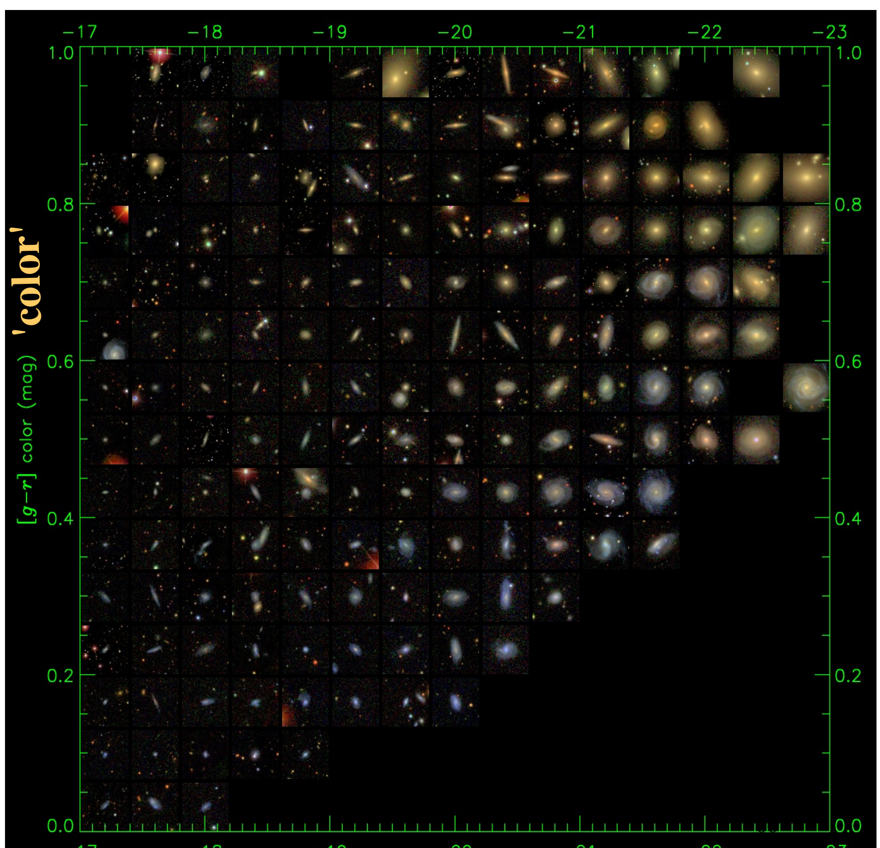
Mass to light ratio vs mass of DM halo
Red pts are data- blue is theory

Attempts to Quantify Morphology

- Galaxies have a wide variety of 'components'
- 1. disk (thin/thick)
- 2. classical bulge
- 3. bar
- 4. spiral arms
- 5. inner disk
- 6. inner bar
- 7. inner spiral arms
- 8. lens(es)
- 9. nuclear ring
- 10. inner ring
- 11. outer ring
- 12. stellar halo
- partridge in a pear tree

Which of these are meaningful? What do they tell us about the physical conditions in the galaxy and its history, Star formation rate dynamics etc etc

The present day population of galaxies only occupies a small region of phase space mass, size, age of stellar population, shape, are all correlated

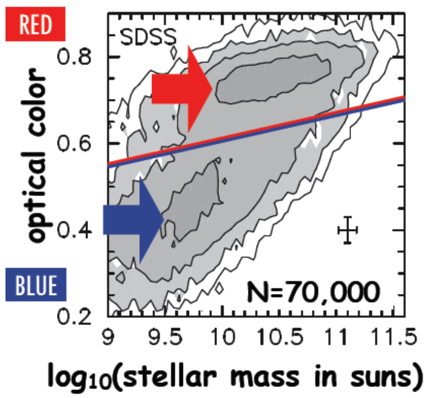


absolute magnitude

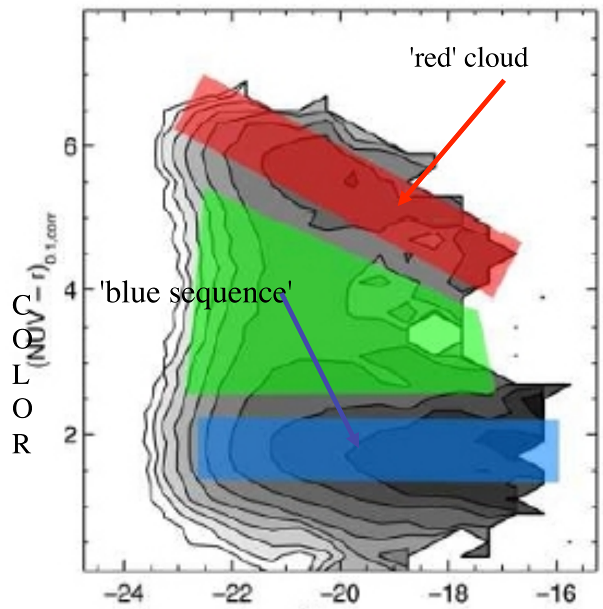
Galaxy Relations

- Density of galaxies vs color and luminosity
- Galaxies fall into 2 broad classes
  - 'red' cloud
  - **'blue sequence'**

  - Few galaxies between- 'green valley'



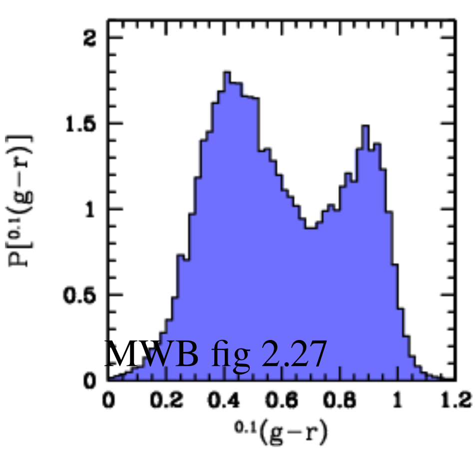
Isoplths- lines of constant galaxy density



Absolute magnitude
Baldry et al 2004

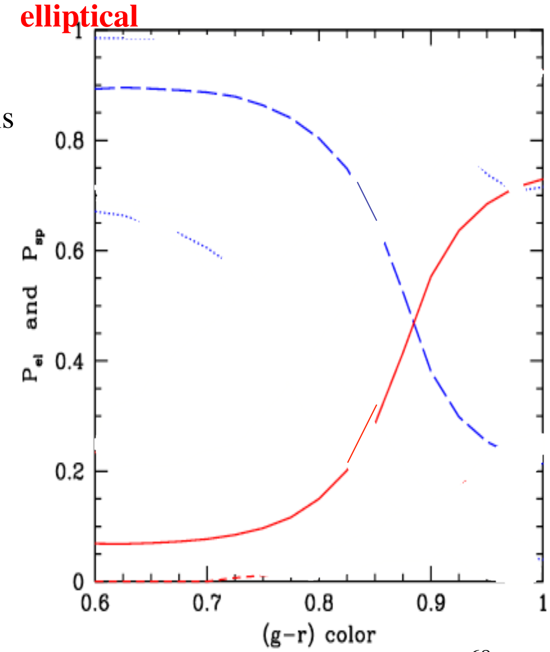
Other Projections of This Plane

- The grouping of galaxies in color, luminosity
- Blue, less luminous galaxies tend to be spirals
- Red, more luminous tend to be ellipticals



MWB fig 2.27

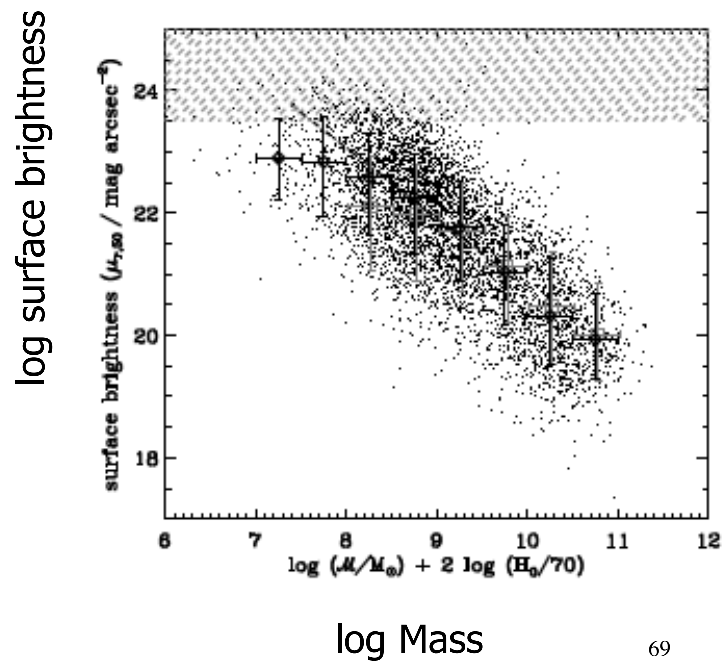
Probability that a given galaxy is a
spiral
elliptical



Skibba et al

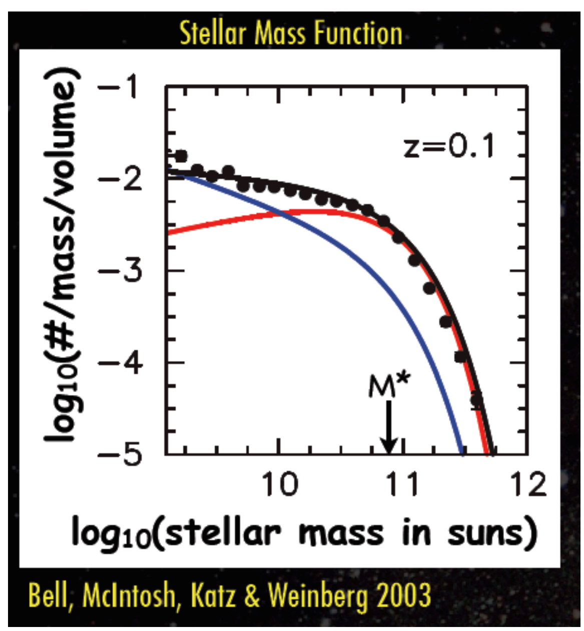
Relationship of Optical Surface Brightness to Mass

More massive galaxies (total mass) have higher surface brightness (flux per unit area) at a fixed radius



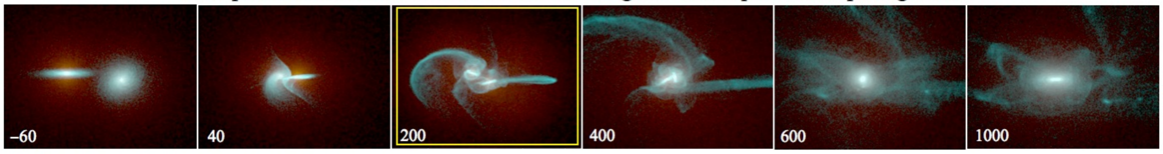
Mass Function of Galaxies

- The sum of the mass function for spheroids (red) and disks (blue) at z=0 add smoothly together
  - spirals are systematically less massive than ellipticals but the functions strongly overlap



Galaxies 'Can' Change Over Cosmic Time

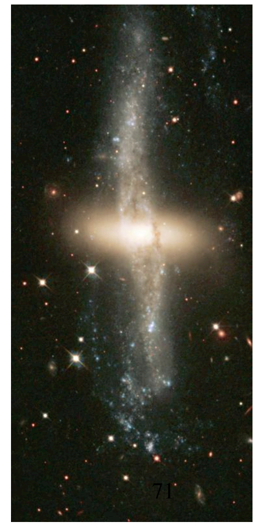
Computer calculation of the collision and merger of two equal-sized spiral galaxies



The Mice: Hubble Space Telescope

- Galaxies can grow via mergers and acquisition of gas. Mergers can be major or minor

Polar ring galaxy -evidence for gas accretion?

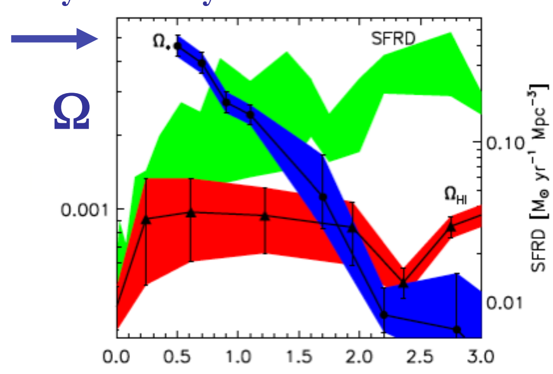


Patterns Change over Cosmic time

- The cosmological mass density of HI in galaxies (red) is nearly constant over the past~10 Gyr while the stellar density (blue) increases. Since stars must form from gas this shows the importance of ongoing gas accretion
- There has been a rapidly declining SFR (**green**) rate since z~1 (accompanied by a similar decline in active galaxies)

- Blue shows the mass density in stars compared to the closure density (**Ω_{stars}**)
- Red shows the mass density in HI gas
- Green the cosmic star formation rate

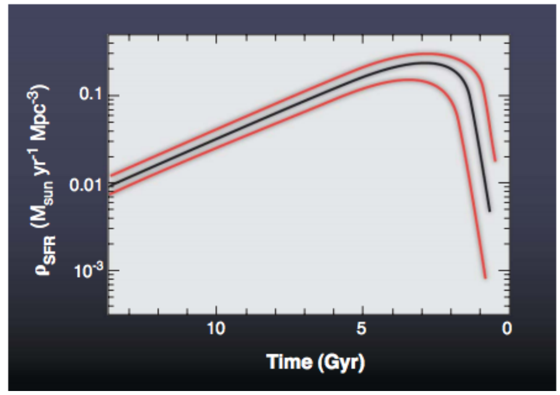
$\Omega_{star\ is}$ ~10% of the cosmic baryon density

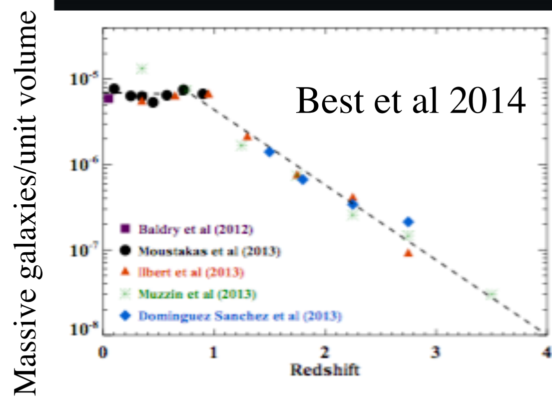


Putnam et al 2010

Things Change Over Cosmic Time

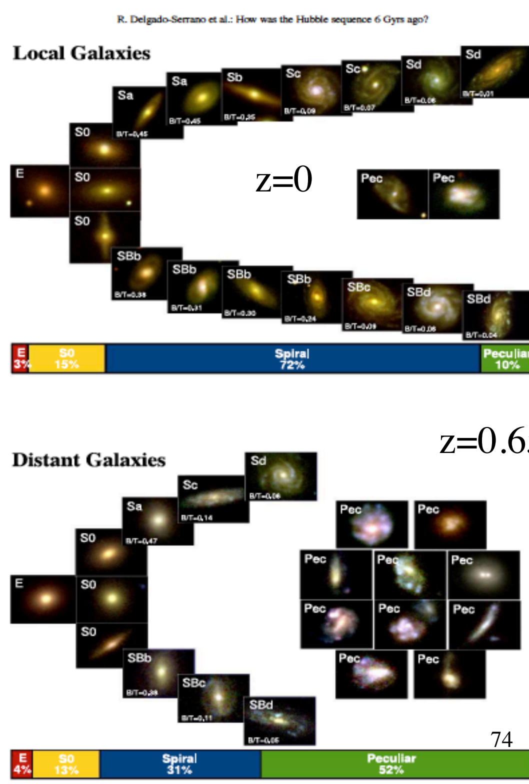
- Over the age of the universe the cosmic star formation rate (solar masses/yr/Mpc^3) has changed by over a factor of 30- dropping rapidly over the last 7 Gyrs (since z~1)
- At high redshifts most star formation occurred in the progenitors of todays luminous red galaxies, since z~1 it has occurred in the galaxies that became todays spirals.





Changes Across Cosmic Time

- The Hubble sequence was established relatively recently, z<1.
  - Each bin contains 5% of the galaxies by number (Delgado-Serrano et al 2010)
- A z<0.65 the number elliptical and lenticular galaxies is roughly constant;
  - in contrast there is strong evolution of spiral and peculiar galaxies. Spiral galaxies were 2.3 times less abundant in the past, and peculiars a factor 5 of more abundant.
- more than half of the present-day spirals had peculiar morphologies, 6 Gyrs ago



Next Time

- Please read ch 1 of Sparke and Gallagher
- Lecture will be a continuation of general galaxy properties