Summary of 2nd Lecture

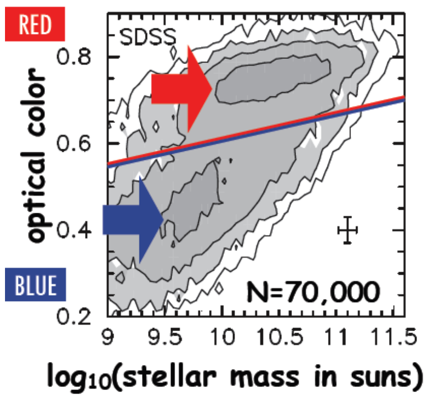
- Most of the universes baryons do not lie in galaxies
  - Dark matter is dominant
- in a LCDM universe structure tend to grow hierarchically (e.g. small things form first, then merge into larger things, but growth also occurs from infall)
- The physics of galaxy formation and evolution is complex, with needed input from almost all of astrophysics
  - star formation
  - ISM physics (cooling heating)
  - Effect of AGN
  - Dust changes the observational aspects greatly
- Visual appearance of galaxies changes strongly across the electromagnetic spectrum with different wavelength ranges best suited to observe certain phenomena
- There is a physical meaning to the classification of galaxies into spirals and ellipticals
  - they have different mass functions
  - different star formation histories

Lecture #	TOPIC
Lec 1	Introduction
Lec 2	Continuation of introduction
Lec 3	Continuation of introduction
Lec 4	Basic Galaxy Properties
Lec 5-6 -	Relevant Properties of stars
Lecs 7-8	Gas
Lec 9	Dust
Lec 10-11	The Milky Way and dynamics

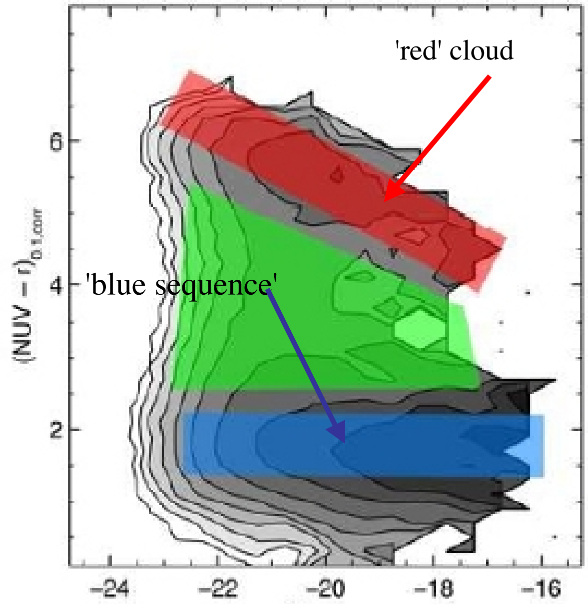
Galaxy Relations

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

  - Few galaxies between- 'green valley'

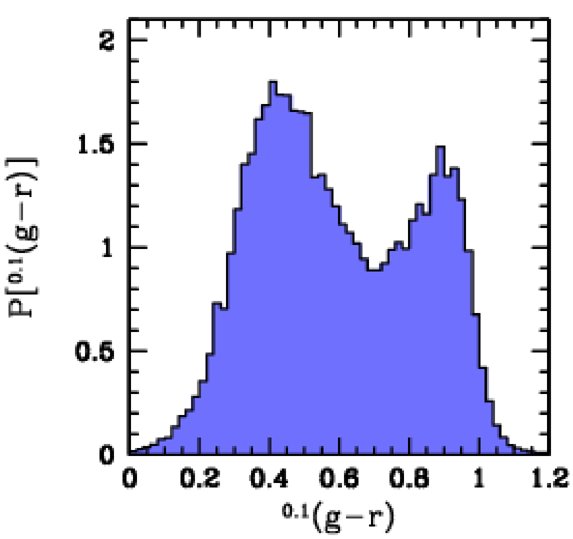


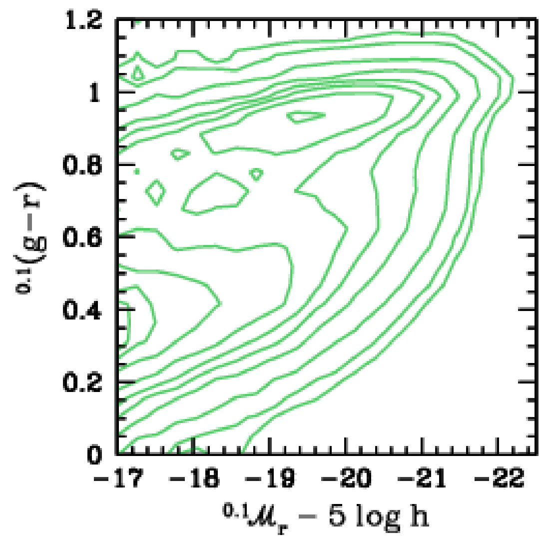
Isopleths- lines of constant galaxy density



Absolute magnitude
Baldry et al 2004

BiModal Distribution of Galaxy Properties

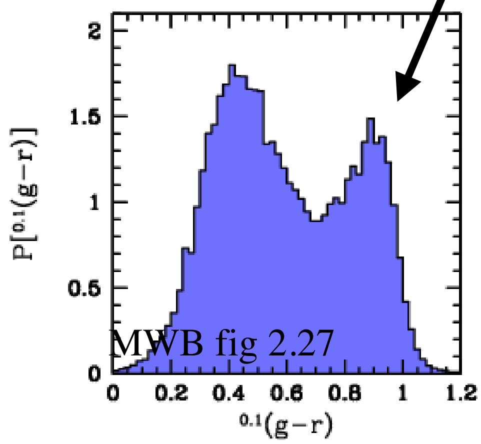




- There is a strong connection between color and luminosity MWB fig 2.27

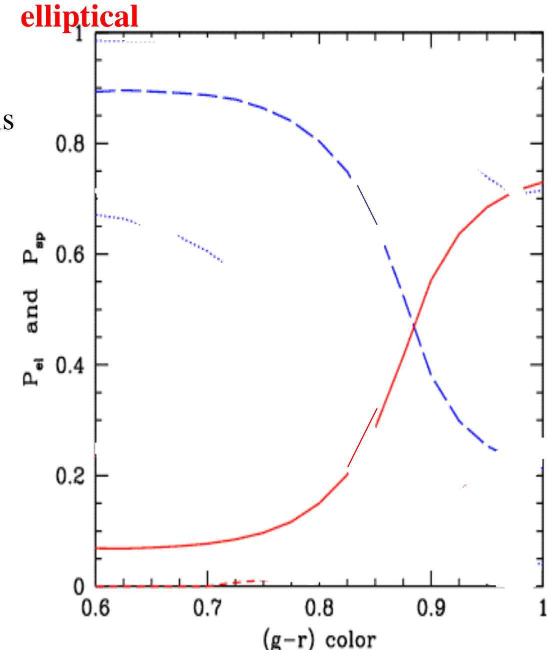
Other Projections of This Plane

- 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

There are Many Patterns in Galaxy Properties

- 'Color' of galaxy and probability of having detected emission from HI (cool gas)
- Black isophotes are the location of **all** galaxies in this color mass plane
- HI survey of galaxies tends to find objects with a particular mass and optical color-physics and selection effect.
  - Red dots are galaxies detected in HI
  - **Green triangles** are upper limits

'Red'

'Blue'

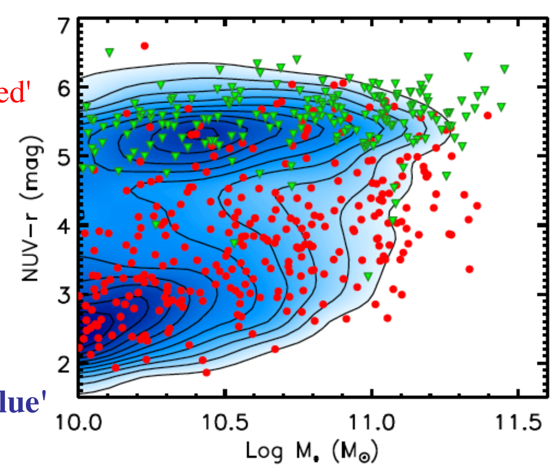


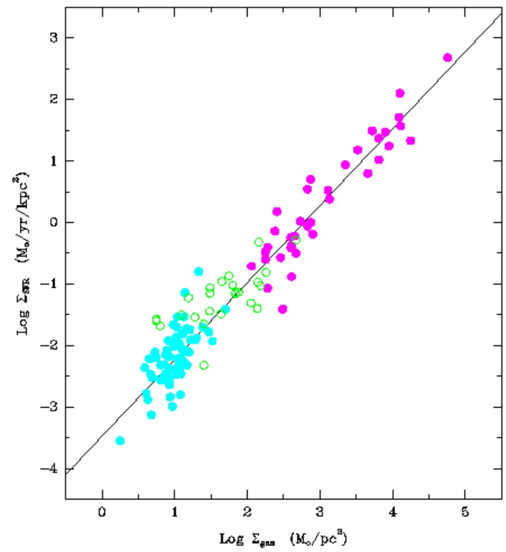
Fig. 4. Color-stellar mass diagram for the GASS *parent sample*, the super-set of ∼12,000 galaxies that meet the survey criteria (grayscales). Red circles and green upside-down triangles indicate HI detections and non-detections, respectively, from the representative sample.

Catinella et al 2012

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

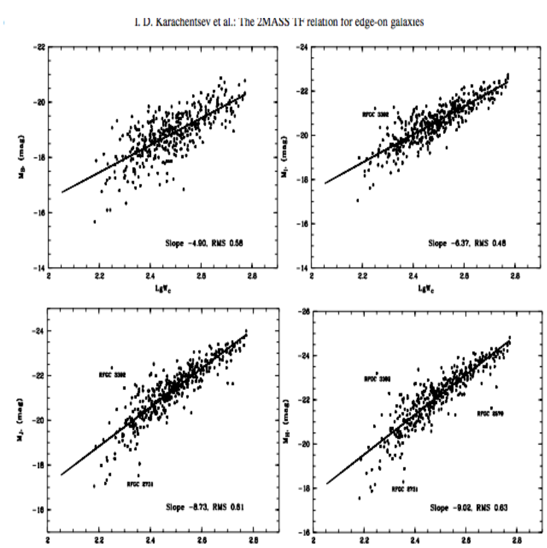


Galaxy Patterns- Continues

- 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)



Patterns-Continued

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

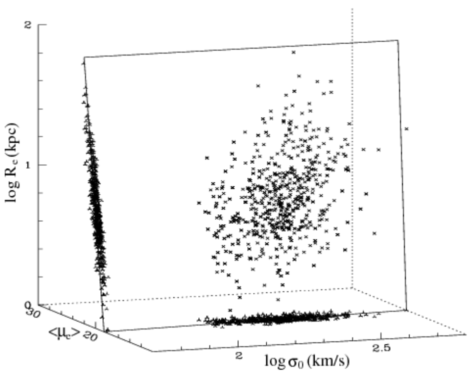
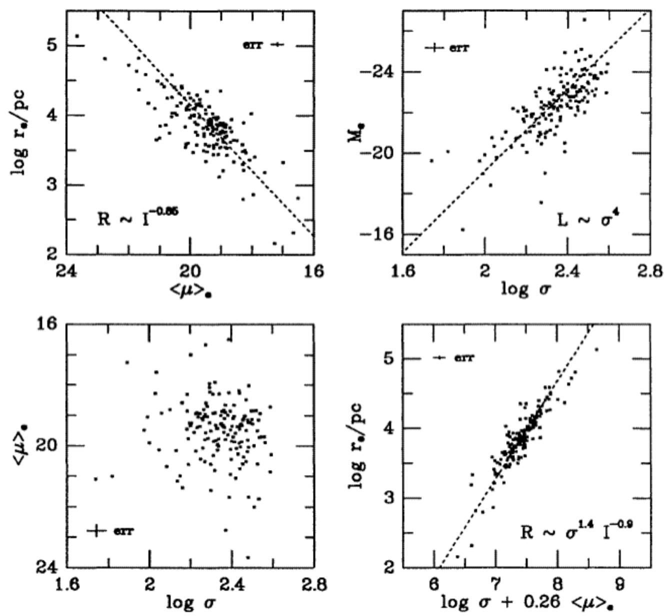


fig 2.18 MBW

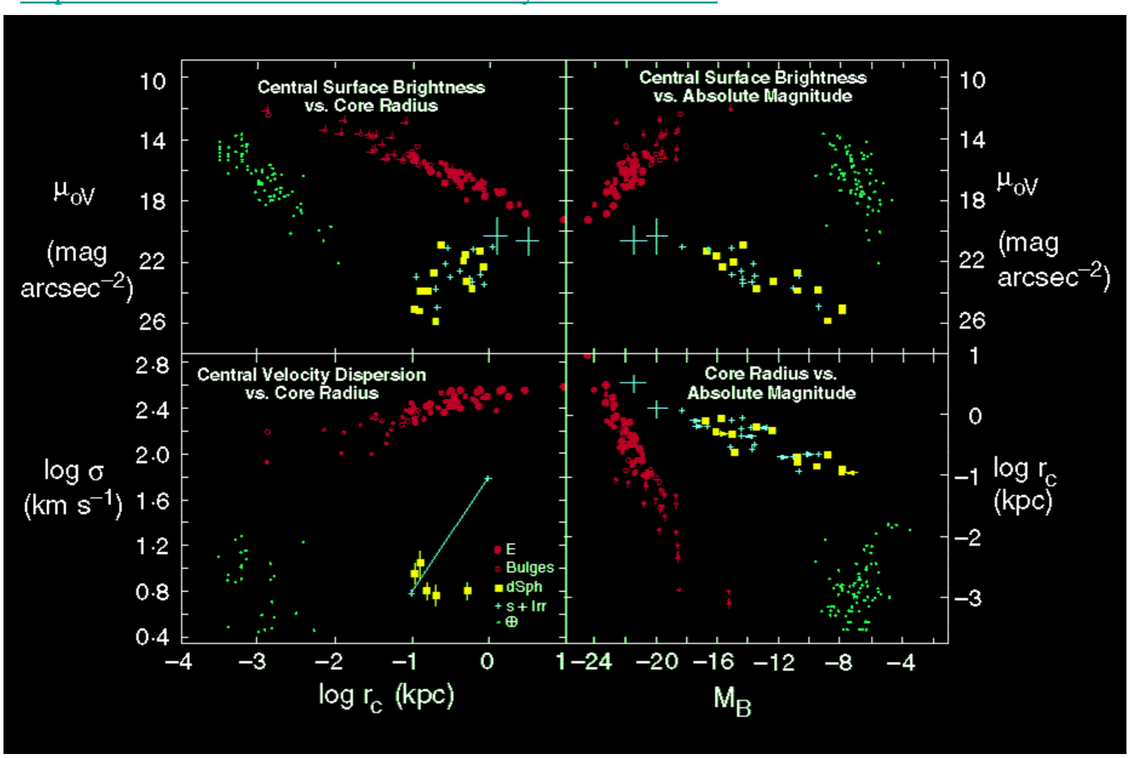


2 Projections of the fundamental parameter plane of elliptical galaxies. *Top*

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

Fundamental Plane

- http://chandra.as.utexas.edu/~kormendy/families.html



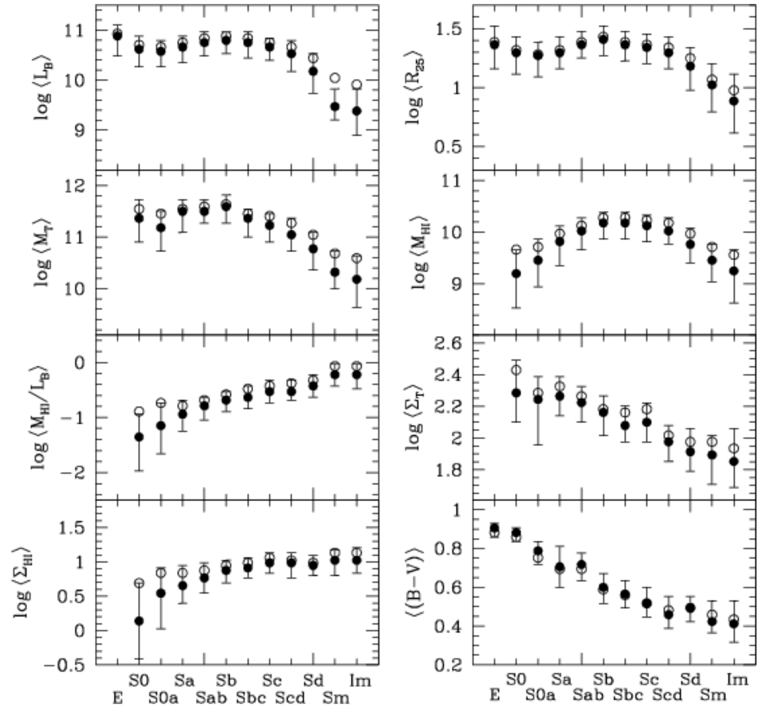
A Physical Meaning to Morphology?

Specific Star formation rate and Hubble type are strongly correlated (very little to none in E's highest in Sc's and irregulars)

Lot of other correlations particularly with the amount of cold gas, color and surface brightness

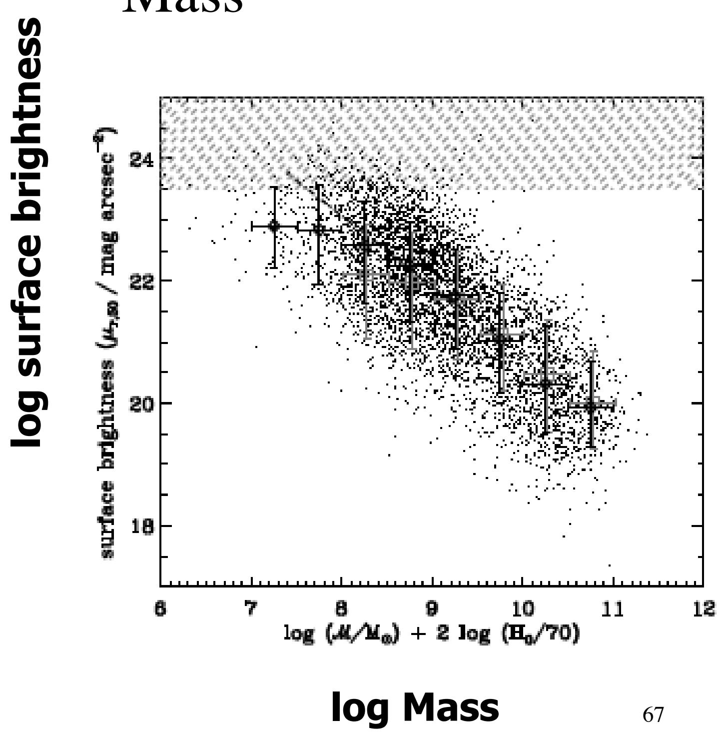
the morphological types have <u>some</u> direct connection to physical meaning - however it is more than a bit complex.

surface density of HI Σ_{HI}

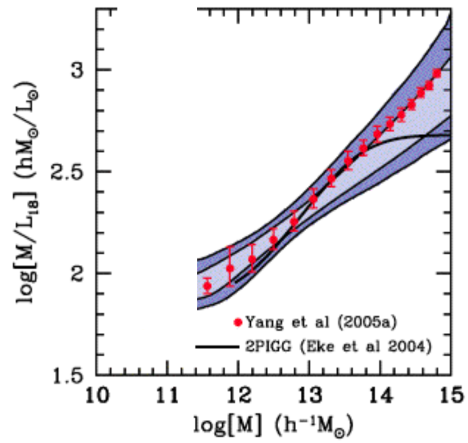


Relationship of Optical Surface Brightness to Mass

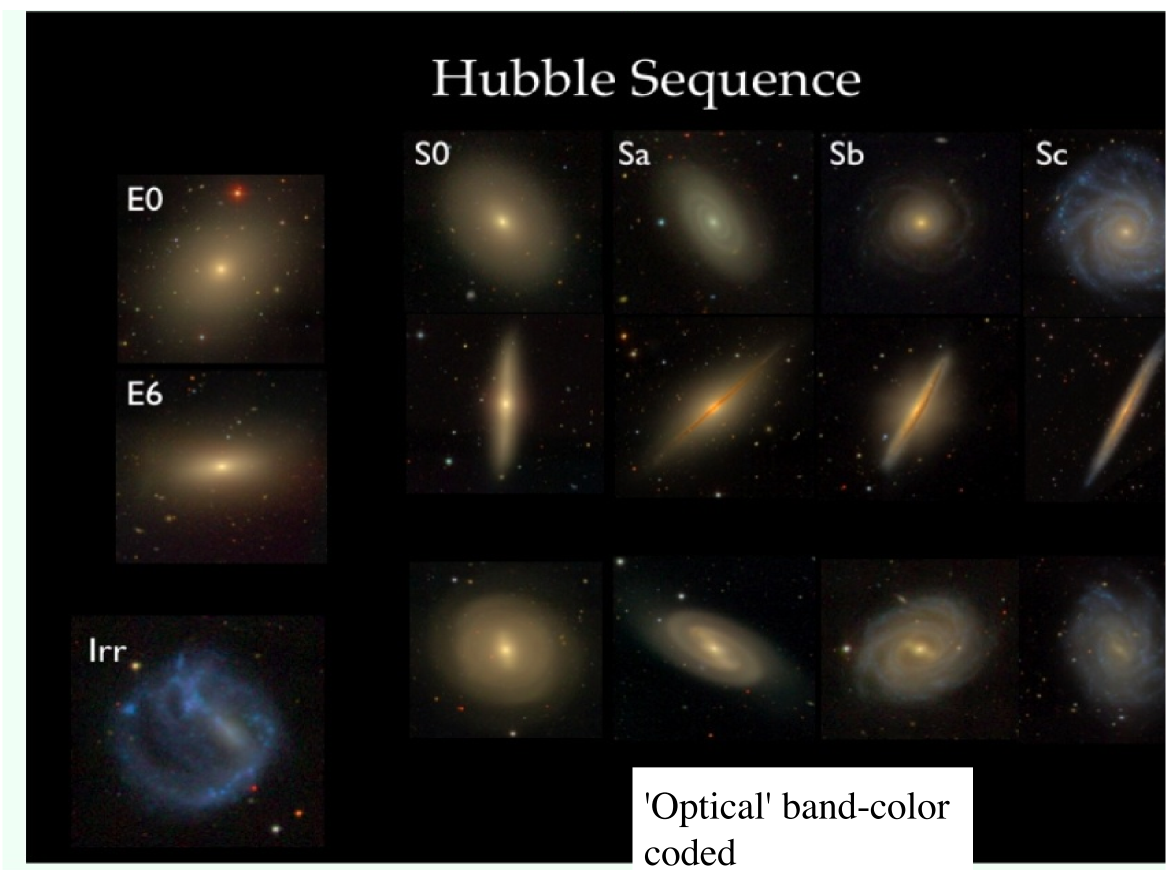
More massive galaxies (total mass) have higher surface brightness (flux per unit area) at a fixed radius



- 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 ($10^{10.5}\ M_o$)
  - Most massive galaxies don't form stars anymore ('early types')- high redshift universe very different

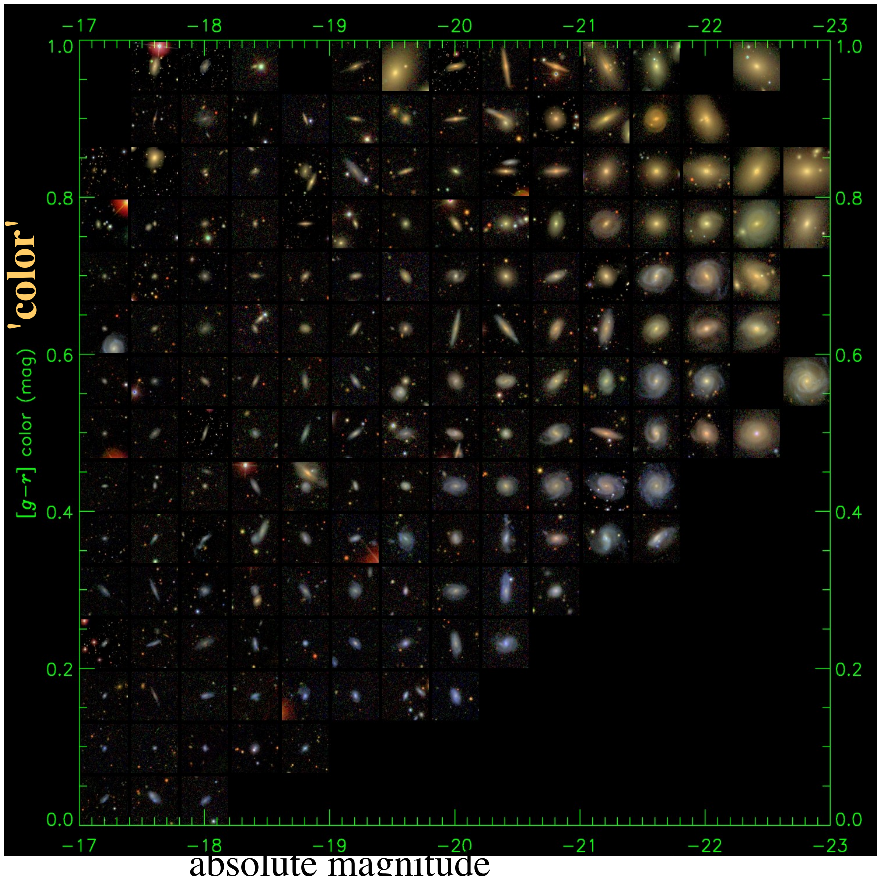


Mass to light ratio vs mass of DM halo
Red pts are data- blue is theory



'Optical' band-color coded

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



Attempts to Quantify Morphology

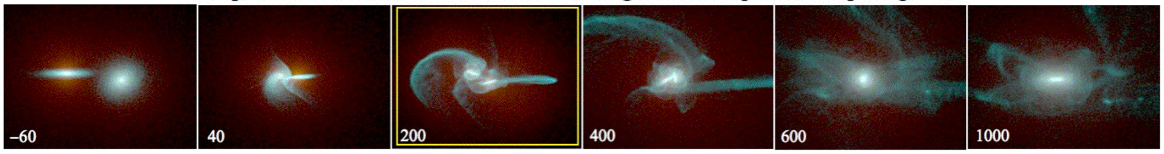
- Galaxies have a wide variety of 'components'

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
13. partridge in a pear tree
14. Central SMBH

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

Galaxies 'Can' Change Over Cosmic Time

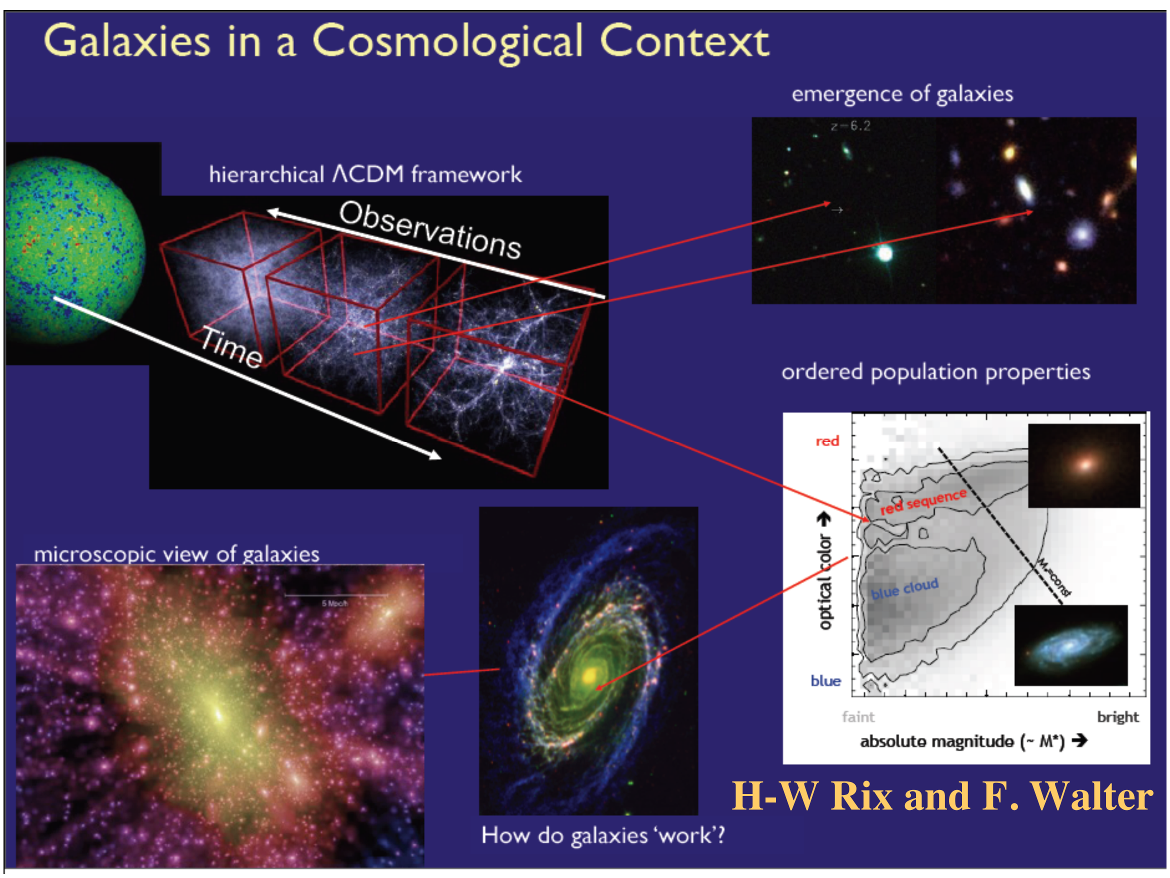
Computer calculation of the collision and merger of two equal-sized spiral galaxies



The Mice: Hubble Space Telescope

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

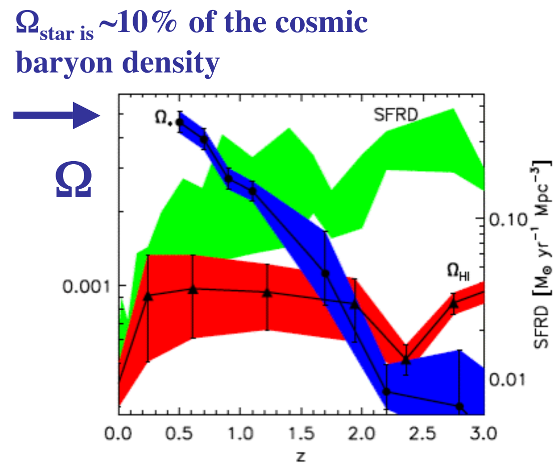
Polar ring galaxy -evidence for gas accretion?



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)

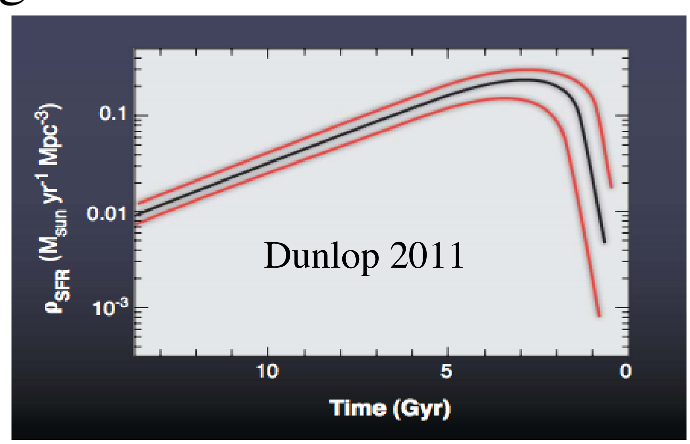
- Blue shows the mass density in stars compared to the closure density (Ω_{stars})
- Red shows the mass density in HI gas
- Green the cosmic star formation rate



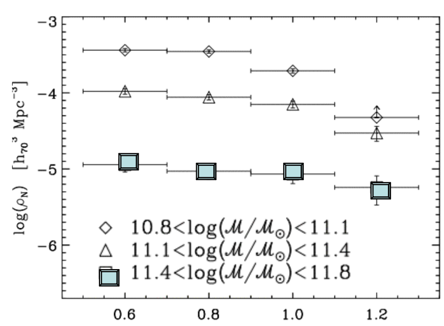
Putnam et al 2010

Things Change Over Cosmic Time

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

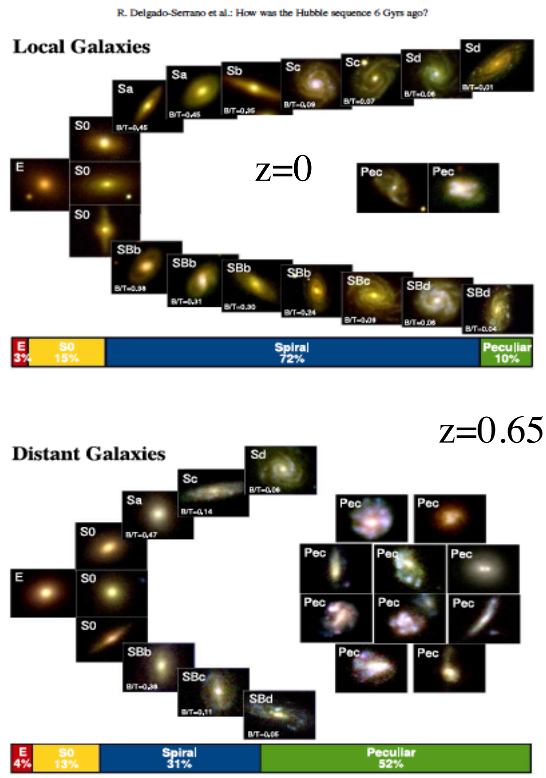


At z ~ 1.2 most of the massive galaxies with logM > 11.4 $M_\odot$ are in place, at lower masses the galaxy number density increases by a factor of ~ 3.5 from z~ 1.2 to z ~ 0.6. Davidzon et al 2013- thus while dark halos assemble hierarchically, in stellar mass this trend is inverted in the sense that the smaller the galaxy, the later is its stellar mass assembly on average.



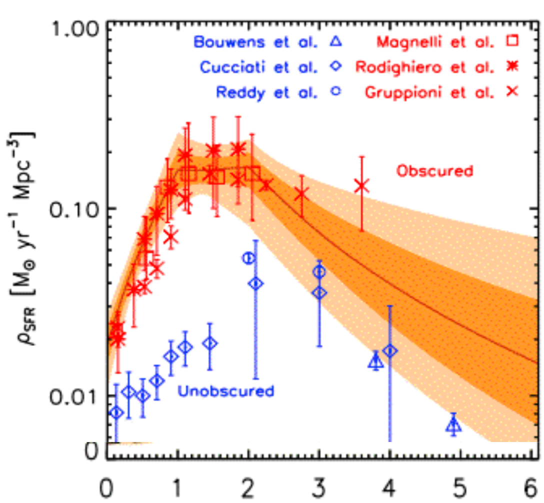
Changes Across Cosmic Time

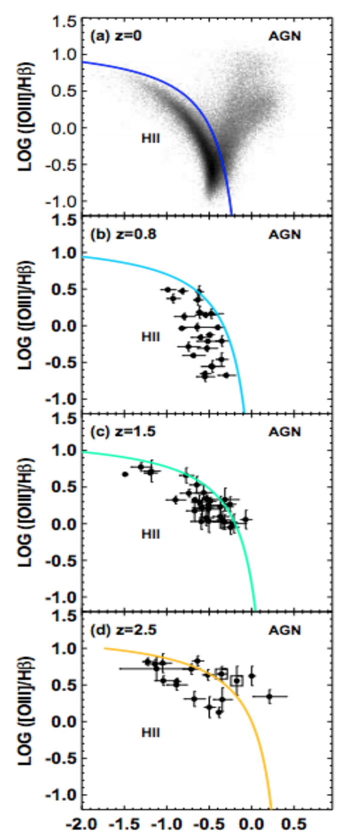
- The Hubble sequence was established relatively recently, z<1.
  - Each bin contains 5% of the galaxies by number (Delgado-Serrano et al 2010)
- A z<0.65 the number elliptical and lenticular galaxies is roughly constant;
  - in contrast there is strong evolution of spiral and peculiar galaxies. Spiral 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



Changes Across Cosmic Time

- At high redshift
  - the ionization state of gas in star forming galaxies increases (Kewley et al 2013) - probably due to a very high specific star formation rate
  - rate of star formation much higher (Ade et al 2013) and fraction of SFR that is only visible in IR change





Our text :

- Galaxy Formation & Evolution by H. Mo, F. van den Bosch & S. White
  an in-depth discussion on all topics of relevance for the formation and evolution of galaxies. (Cambridge University Press, 2010)

- Secondary texts

Galactic Dynamics (2nd Edition) by J. Binney & S. Tremaine

An excellent textbook for topics related to the collisionless dynamics of galaxies, galaxy clusters, globular clusters and dark matter haloes (Princeton University Press, 2008)

- Galaxies in the Universe: An Introduction (2nd Edition) by L. Sparke & J. Gallagher

Secondary sources

- Extragalactic Astronomy and Cosmology: An Introduction by P. Schneider
  A good reference, contains a good and up-to-date description of all key concepts in extragalactic astronomy and cosmology, but does not delve too deeply into mathematical formalisms and proofs. The book is very well illustrated
  Galactic Astronomy by J. Binney & M. Merrifield
  This textbook focuses on observational aspects of galaxies (Princeton University Press,1998; ISBN 9780691025650, paperback)- a bit out of date
- The Structure and Evolution of Galaxies by S. Phillipps textbook at the introductory level

Galaxy Research is Very Active-partial list of active research areas

- The Effective Yield: how stars form heavy elements
- The Baryonic Tully-Fisher relation: why is there a close relation between baryons and dark matter
- Galaxy Downsizing: how come DM theory says small things form first and larger later, while observations seem to imply the opposite
- ULIRGS: what is the nature of the most rapidly star forming galaxies and why are they radiate most of their energy in the IR?
- Reionization: how and when does the universe transition from being recombined to ionized, what is the source of the ionization?
- The IGM/Ly-α forest: what is the physical nature of the gas between the galaxies and how can one observe it?
- Star Formation Thresholds: what is the physical process that sets the threshold for star formation
- Star formation quenching: how come massive galaxies have stopped their star formation at $z>1$?
- What is the origin of the mass-metallicity relation of galaxies
- What is the mechanism that fine tunes the evolution of galaxies: is it AGN feedback?

Next Time

- Finish reading ch 1 and ch 2.1-2.3 of MWB - take a look at Ch 1 of B&T and Ch 1 of Sparke and Gallagher
- Develop one question that this reading or my lectures have prompted and please hand it in- find a recent (20012-2013) on this subject and summarize it briefly.
  - I will call on a few students randomly!

- Next lectures
- Basic Galaxy Properties
  - a bit of a repeat of the last 3 lectures and new material
- Stars and stellar populations (2 lectures)

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