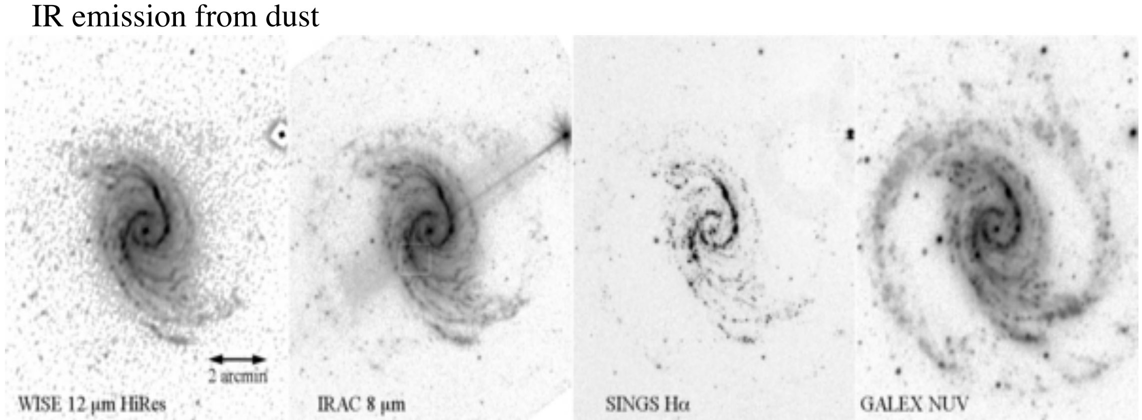
Summary of 2nd Lecture

• 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 formatiom
– 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

NGC1566 in 4 Bands- 4 Different Surveys and Telescopes

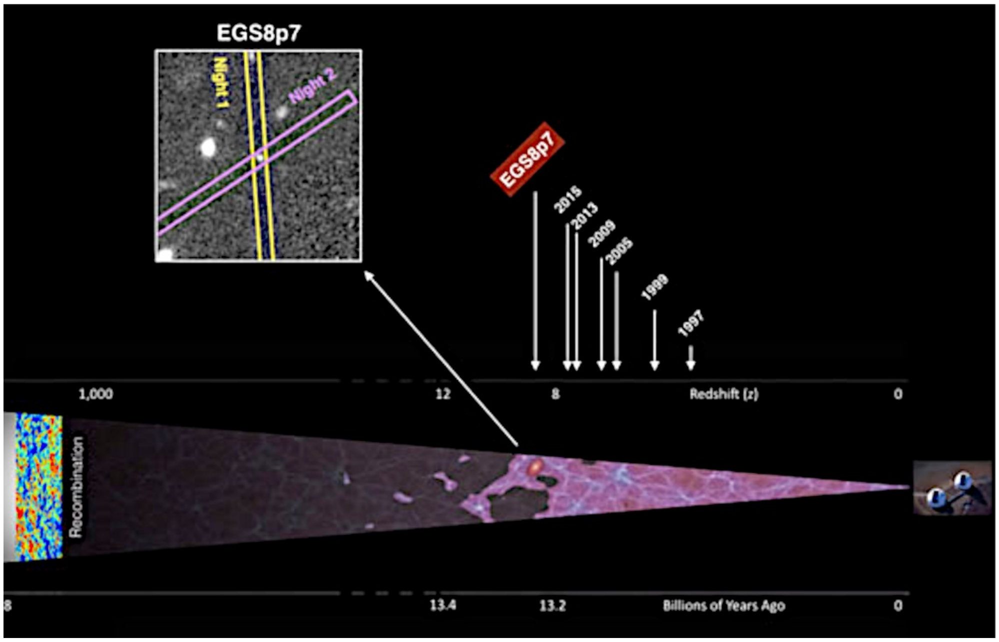
- Each of these bands reveals different information about the stars, dust and star formation rate in the galaxy
- Hα- youngest stars
- NUV young stars
- IR emission from small molecules (PAHs)
- IR emission from dust



Dust PAH Hα NUV

Hot Flash

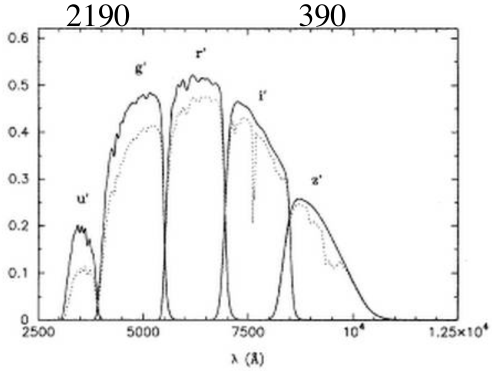
- Galaxy detected at a redshift of 8.68
- http://scitechdaily.com/caltech-astronomers-detect-the-farthest-galaxy-to-date/



NGC1566 HST

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 objec 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!
Absolute 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

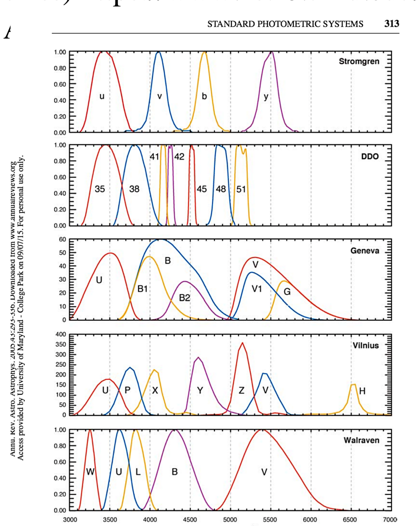
In the **Vega** system by definition, Vega's magnitudes are 0.0 in all filters.

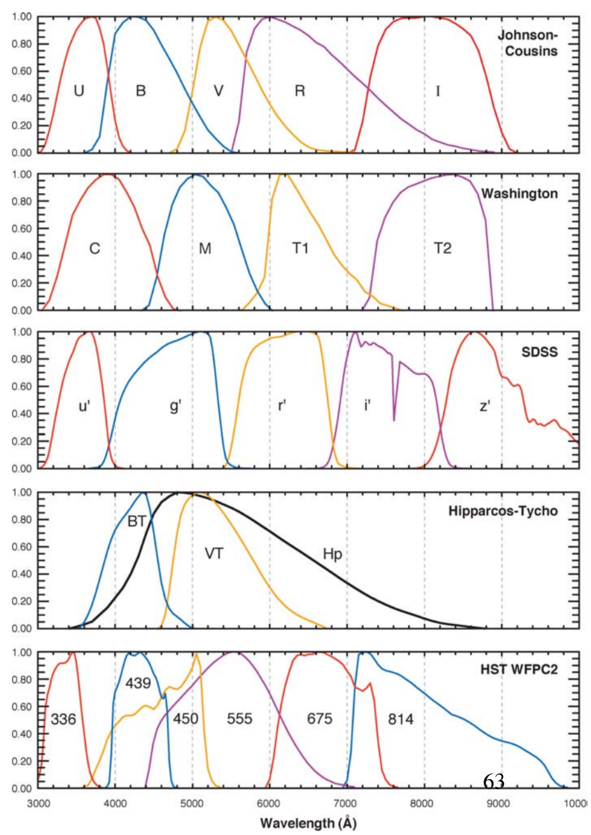
there are many other filter 'sets' each based on different needs, uses
(the UBV data set was developed for use with photographic plates, the SDSS set for use with CCDs circa 1995 technology

see Michael S. Bessell **Standard Photometric Systems ARA&A** 43: 293-336 2005)

Some Common Photometric Systems

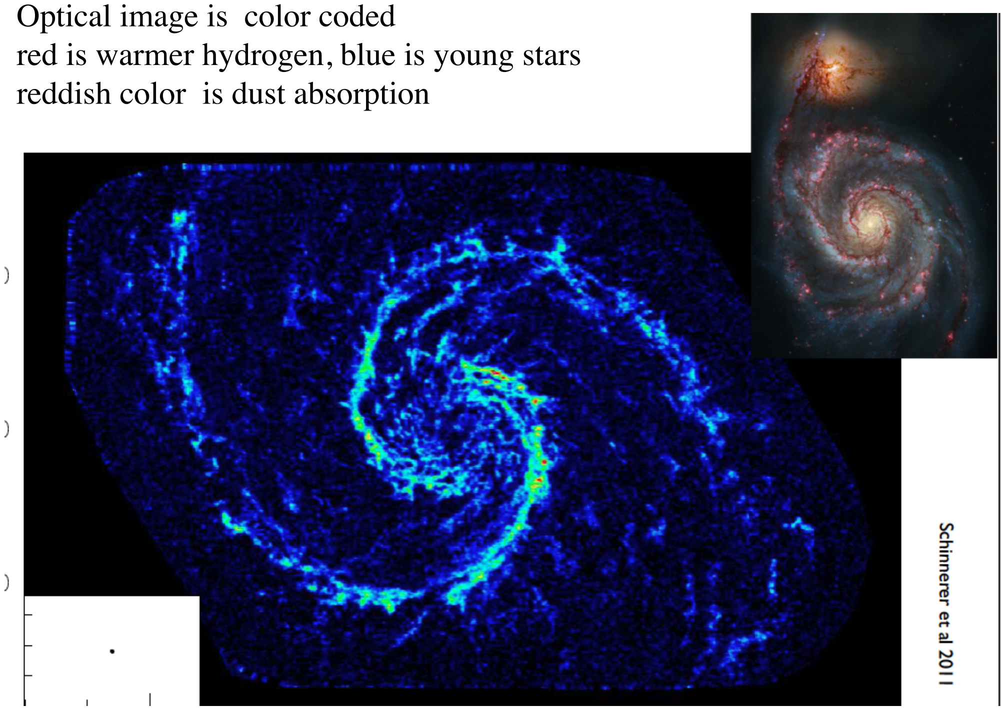
For particular purposes (Bissell 2005) ther are also narrow band systems which isolat spectral features in stellar and nebular spectra (we will not use these much in the class) https://www.astro.umd.edu/~ssm/





'Cool gas' (HI-hydrogen) from 21 cm observations .
Optical image is color coded
red is warmer hydrogen, blue is young stars
reddish color is dust absorption

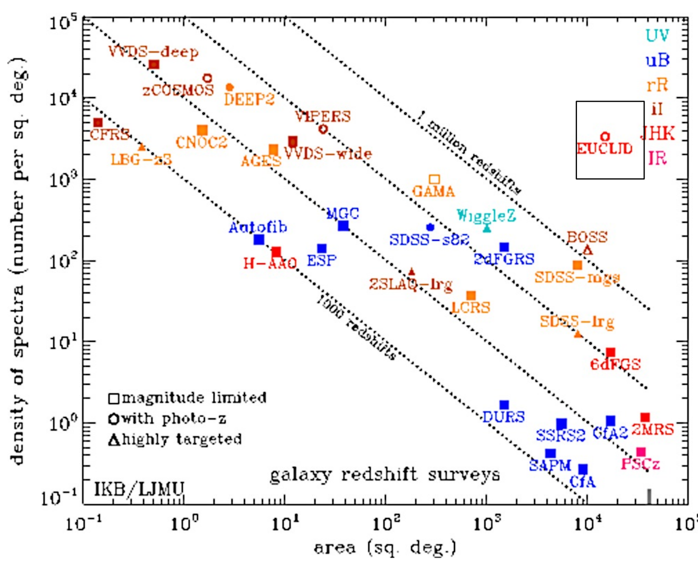
Relationship of gas to stars

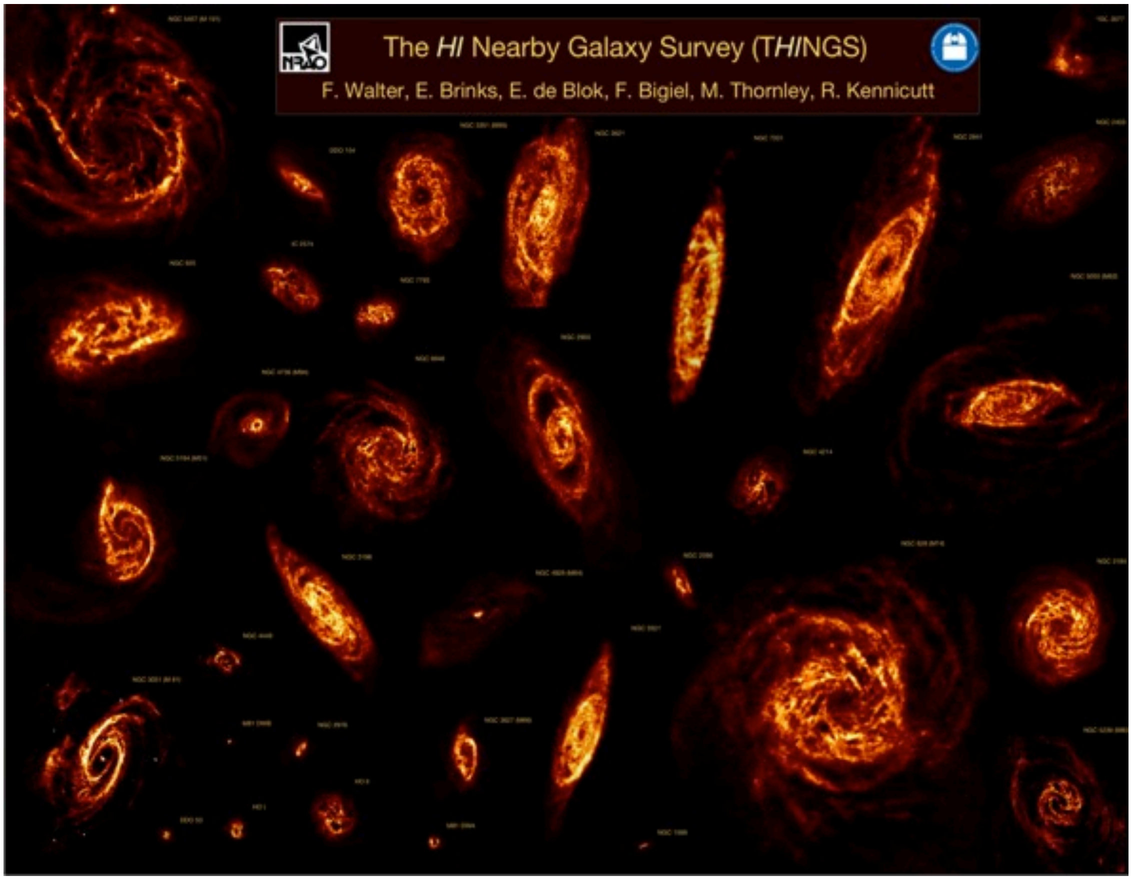


Multi-Wavelength Surveys

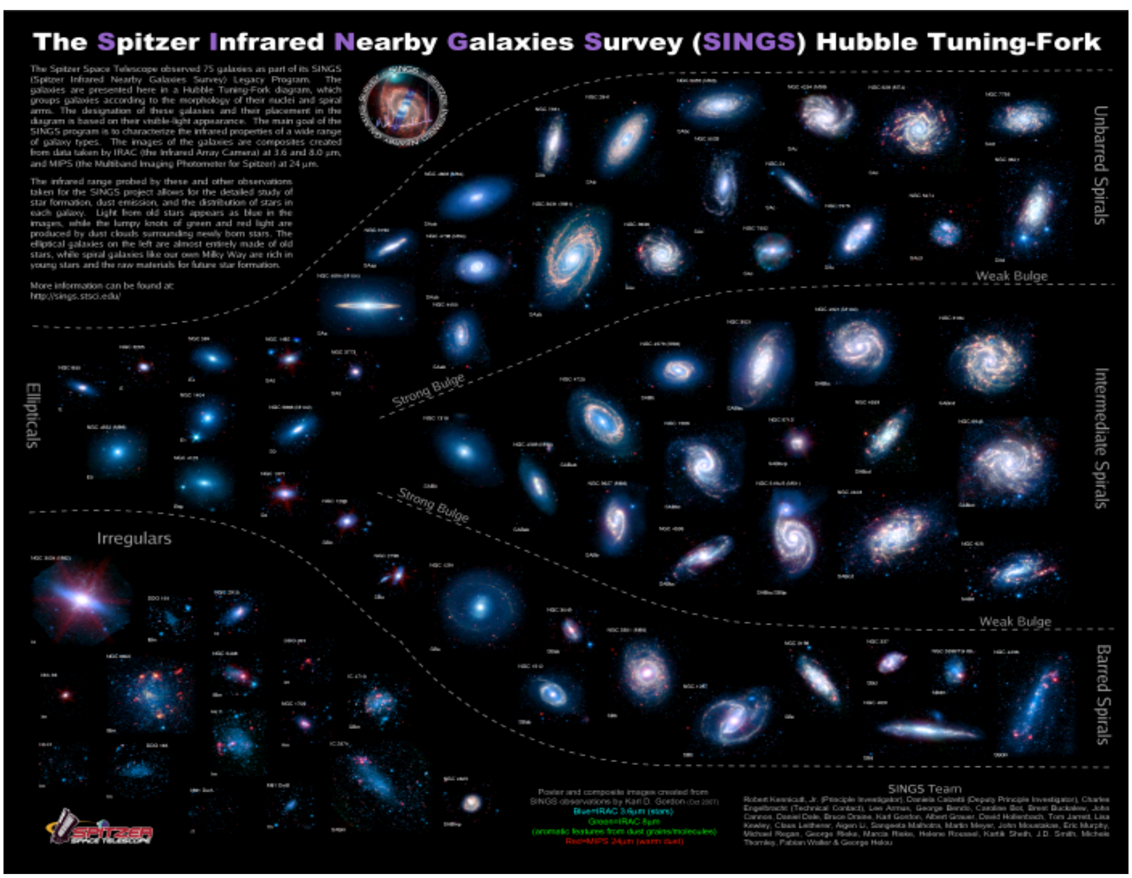
- Vast number of galaxy surveys in the last 15 years (see http://www.astro.ljmu.ac.uk/~ikb/research/galaxy-redshift-surveys.html) for a partial list of optical surveys
- These cover everything from the long wavelength radio (ALFALFA- http://egg.astro.cornell.edu/index.php/)

to the x-ray (ROSAT-ESO Flux Limited X-ray Galaxy Cluster Survey) focusing on clusters of galaxies





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
Ellipticals
Strong Bulge
Intermediate Spirals
Strong Bulge
Irregulars
Weak Bulge
Barred Spirals
Poster and composite images created from SINGS observations by Karl D. Gordon (Oct 2007)
Blue=IRAC 3.6µm (stars)
Green=IRAC 8µm
(aromatic features from dust grains/molecules)
Red=MIPS 24µm (warm dust)
SINGS Team
Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou
SPITZER SPACE TELESCOPE

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

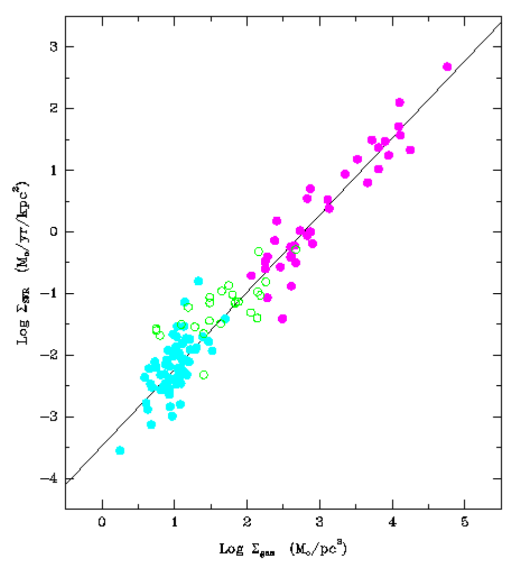
- abstracted from P. Schneider Extragalactic Astronomy and Cosmology An Introduction Springer

Patterns in 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)
  - Patterns in time: e.g.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



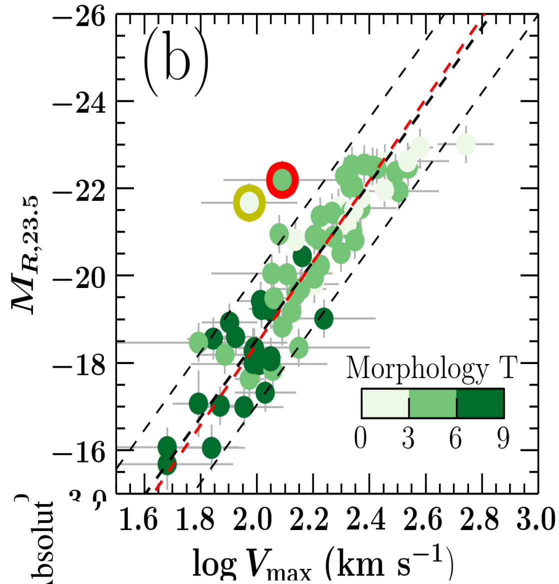
log surface density of gas

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)
  - $L_{opt} \sim Av^4$
- Connects galaxy dynamics to optical luminosity
- Since luminosity depends on distance[2]

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

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



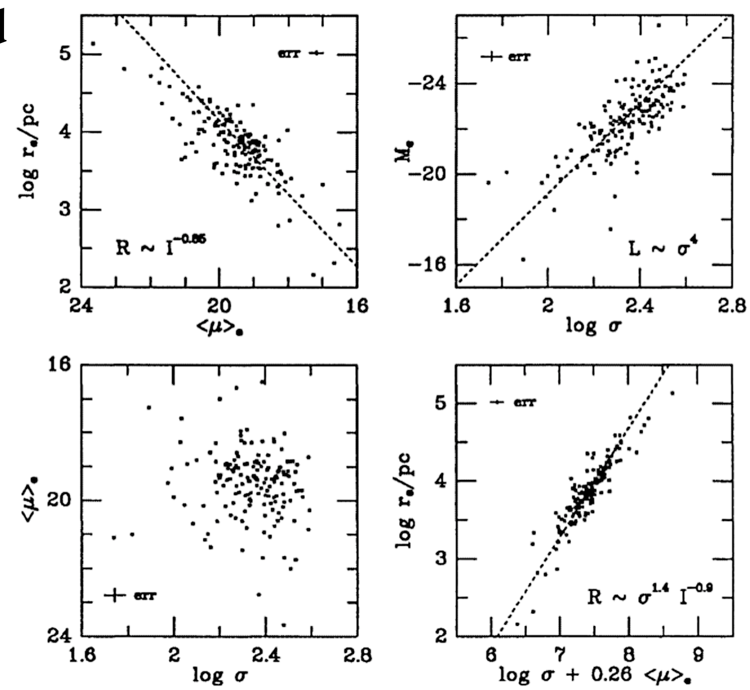
Absolut

log rotational velocity

see **arXiv:1508.03004v1** Barbosa for the latest

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*

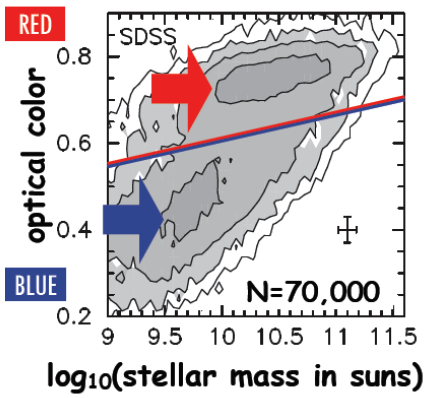
μ= surface brightness

σ= velocity dispersion

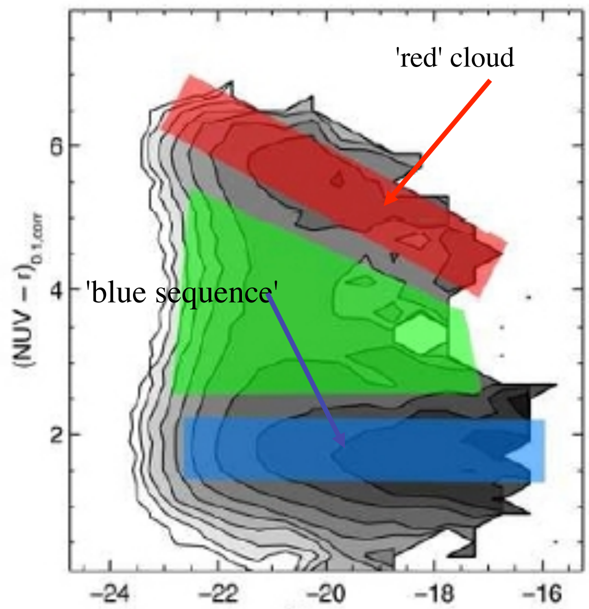
M=absolute magnitude

Galaxy Relations

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



Isopleths- lines of constant galaxy density

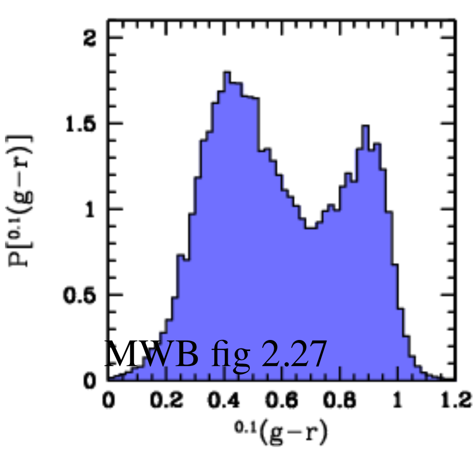


Absolute magnitude

Baldry et al 2004

Other Projections of This Plane

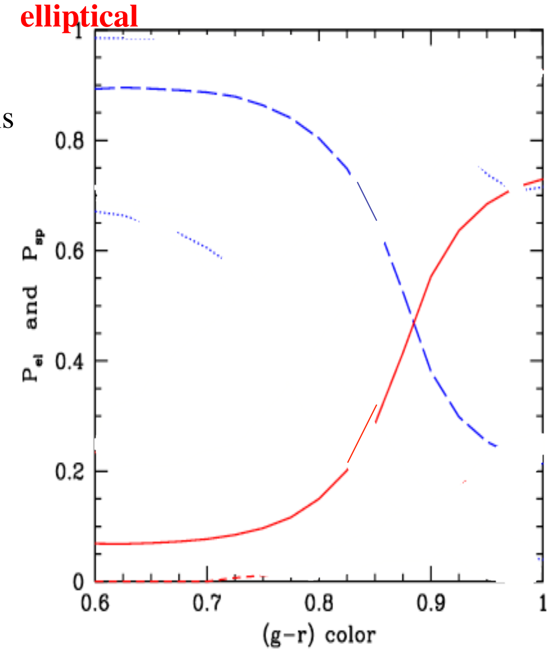
- The grouping of galaxies in color, luminosity
- Blue, less luminous galaxies tend to be spirals
- Red, more luminous tend to be ellipticals



Probability that a given galaxy is a

spiral

elliptical



Skibba et al

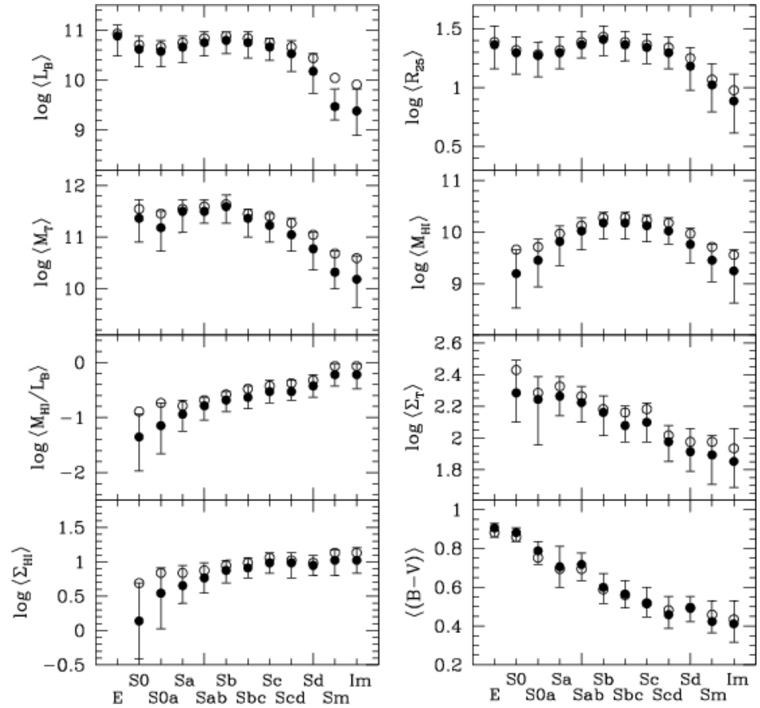
A Physical Meaning to Morphology?

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}



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
- So an 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

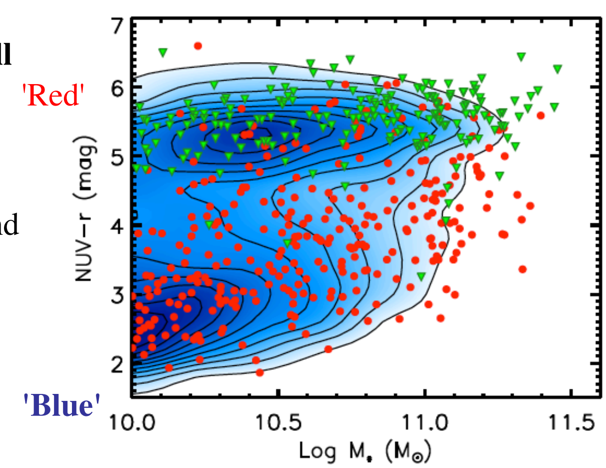
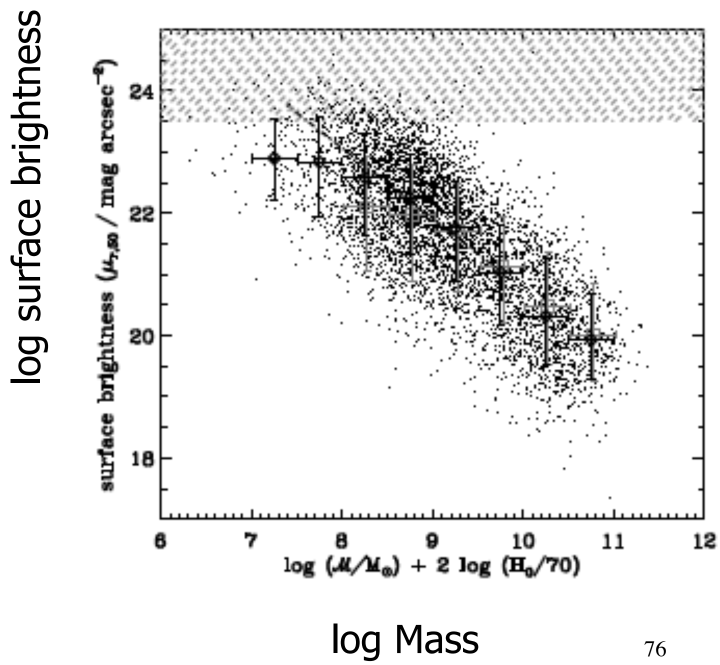


Fig. 4. Color-stellar mass diagram for the GASS *parent sample*, the super-set of ~12,000 galaxies that meet the survey criteria (grayscales). Red circles and green upside-down triangles indicate HI detections and non-detections, respectively, from the representative sample.

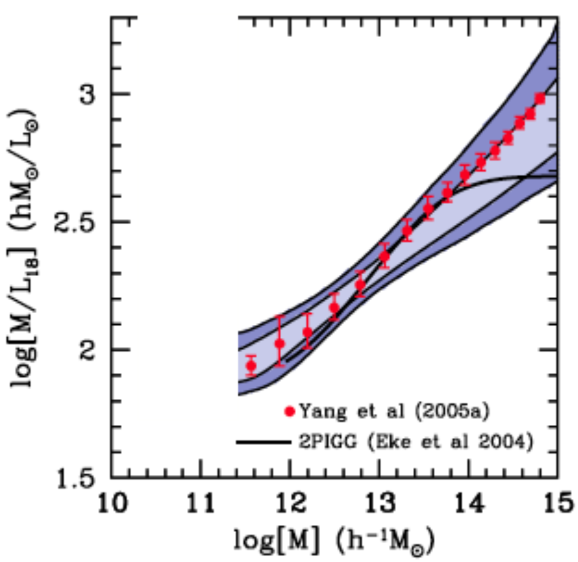
Catinella et al 2012

Relationship of Optical Surface Brightness to Mass

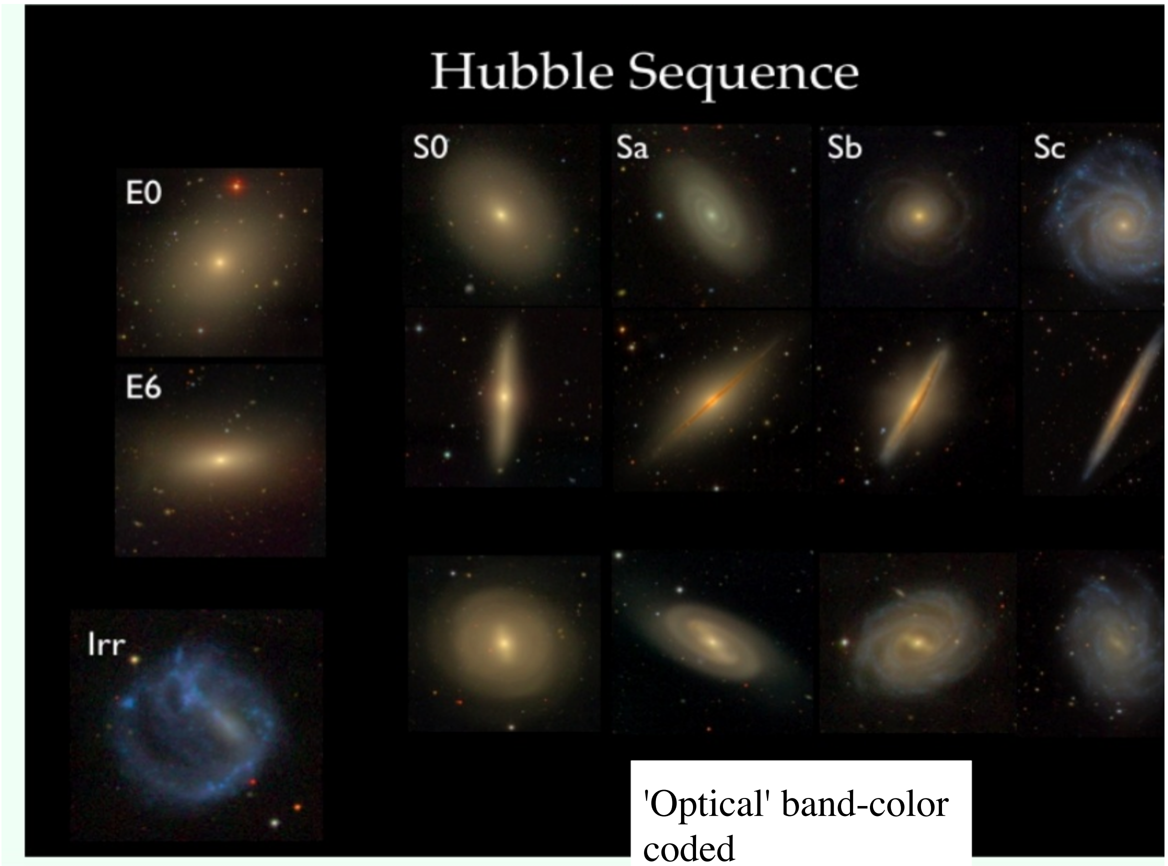
More massive galaxies (total mass) have higher surface brightness (flux per unit area) at a fixed radius



- 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 most often the decisive parameter in setting properties
  - There is a wide range in the ratio of L_*/M_{halo}



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



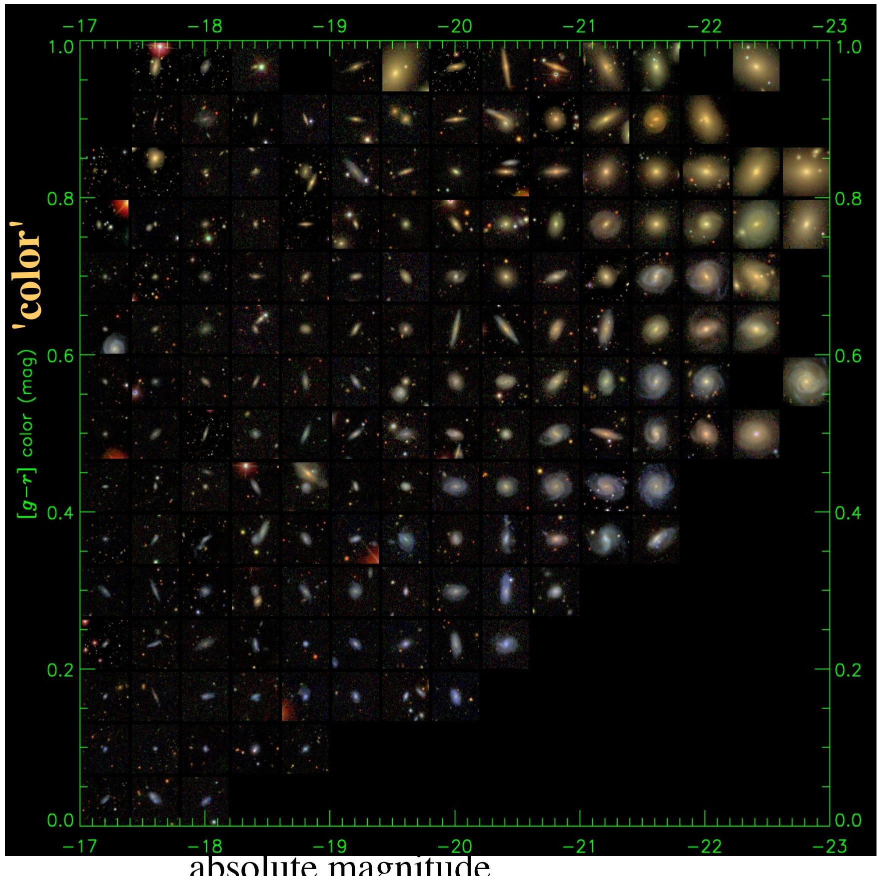
Galaxy Morphology

see Buta 1304.3529 in Secular evolution of galaxies
XXIII Canary Islands Winter School of Astrophysics for an extensive review

Galaxy morphology contains extensive information about star formation, history , mass etc

- Goal is to understand the dynamical and evolutionary mechanisms that underlie the bewildering array of forms that define the various galaxy classification schemes used
- Physical interpretations of galaxy morphology have revolved around two different domains:
  - formative evolution, where rapid, violent processes, such as hierarchical clustering and merging, led to formation of major galactic omponents,such as bulges, disks, haloes, and presumably, the Hubble sequence (e.g.,White & Rees 1978; Firmani & Avila-Reese 2003)
  - secular evolution,where disk material is slowly rearranged

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

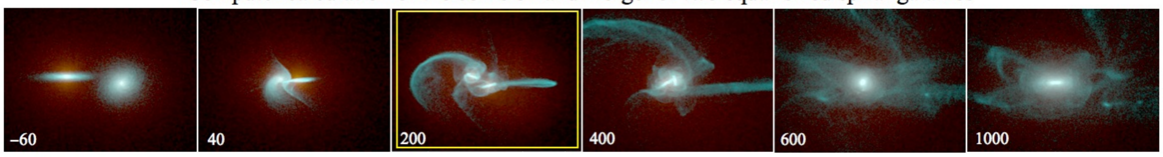
- Galaxies have a wide variety of 'components'

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

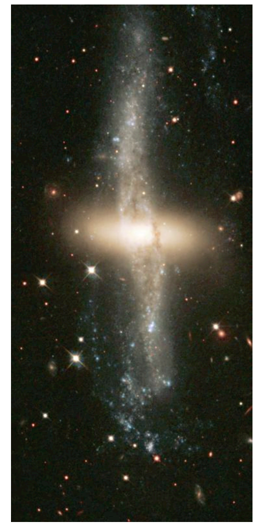
Computer calculation of the collision and merger of two equal-sized spiral galaxies

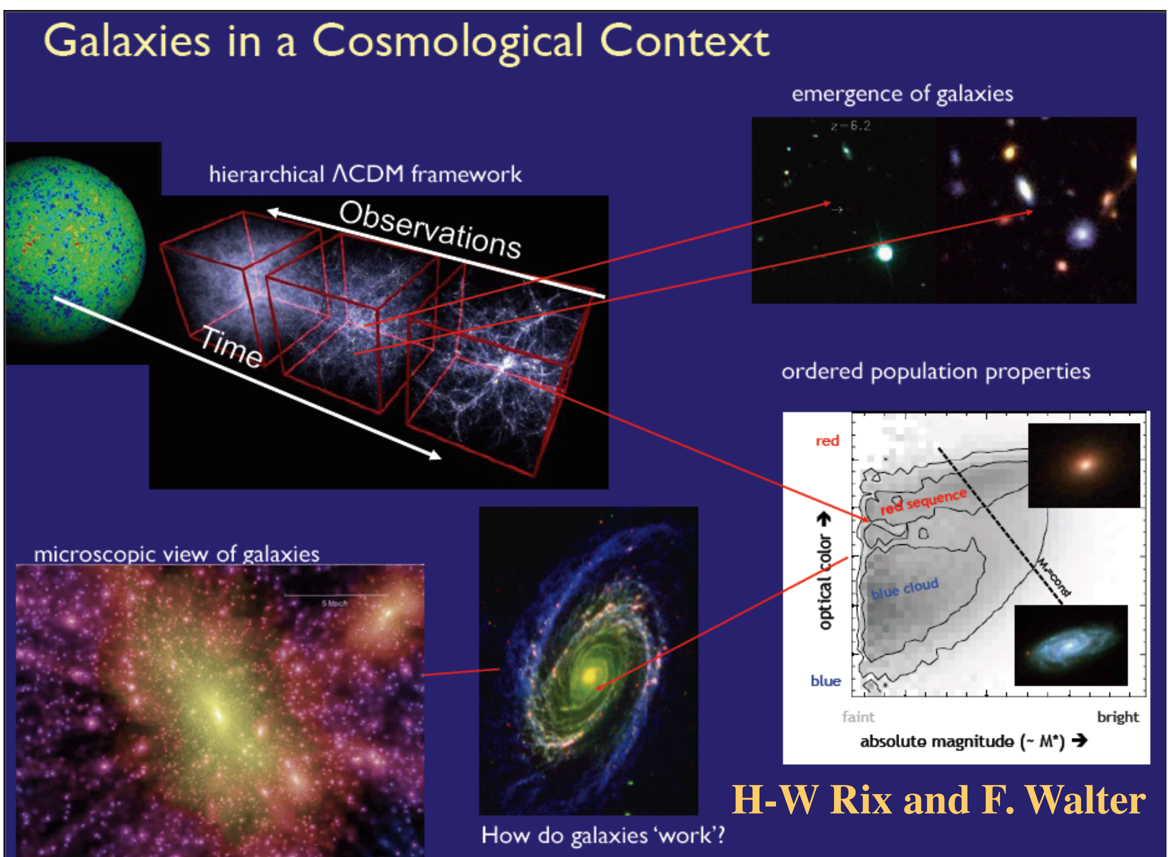


The Mice: Hubble Space Telescope

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

Polar ring galaxy -evidence for gas accretion?

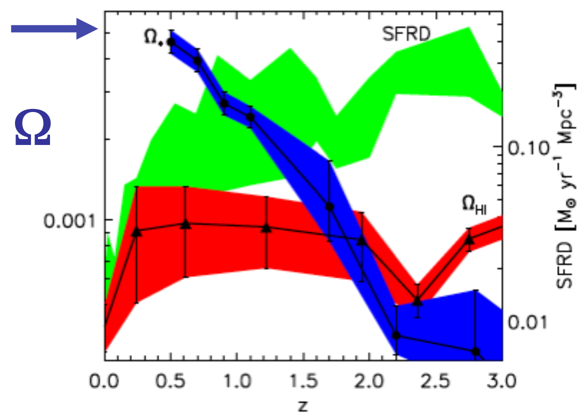




Patterns Change over Cosmic time

- The cosmological mass density of gas (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 StarFormationRate (**green**) 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

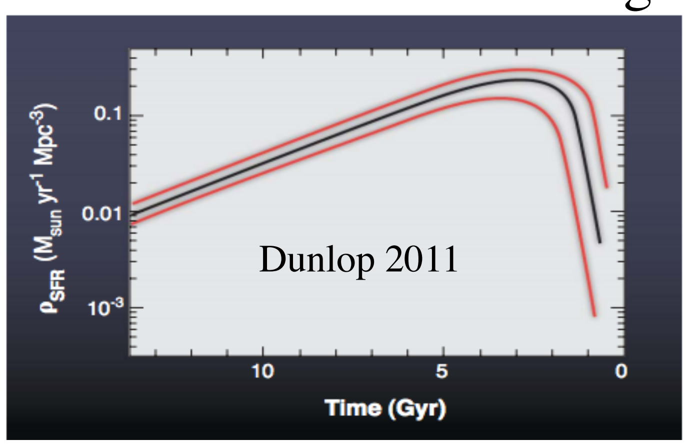
Ω_{star} is ~10% of the cosmic baryon density



Putnam et al 2010

Things Change Over Cosmic Time-downsizing

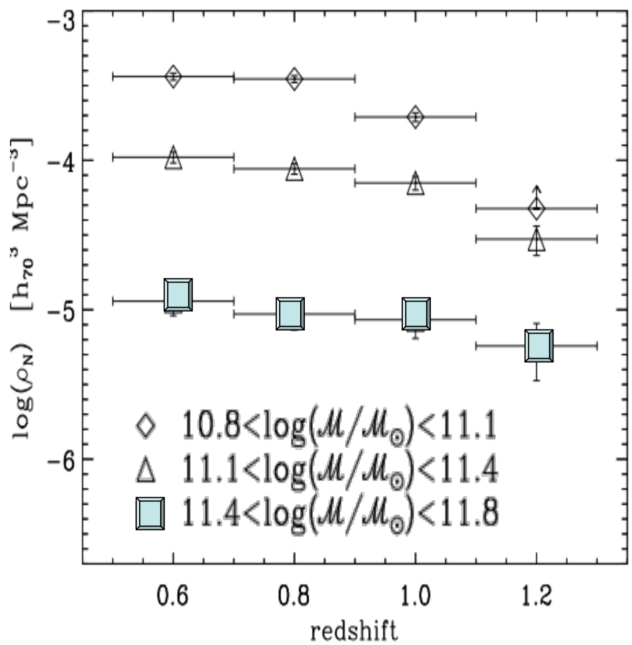
- Over the age of the universe the cosmic star formation rate (solar masses/yr/Mpc^3) has change by over a factor of 30- dropping rapidly over the last 7 Gyrs (since z~1)
- At high redshifts most star formation occurred in the progenitors of today's luminous red galaxies, since z~1 it has occurred in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



Things Change Over Cosmic Time-downsizing

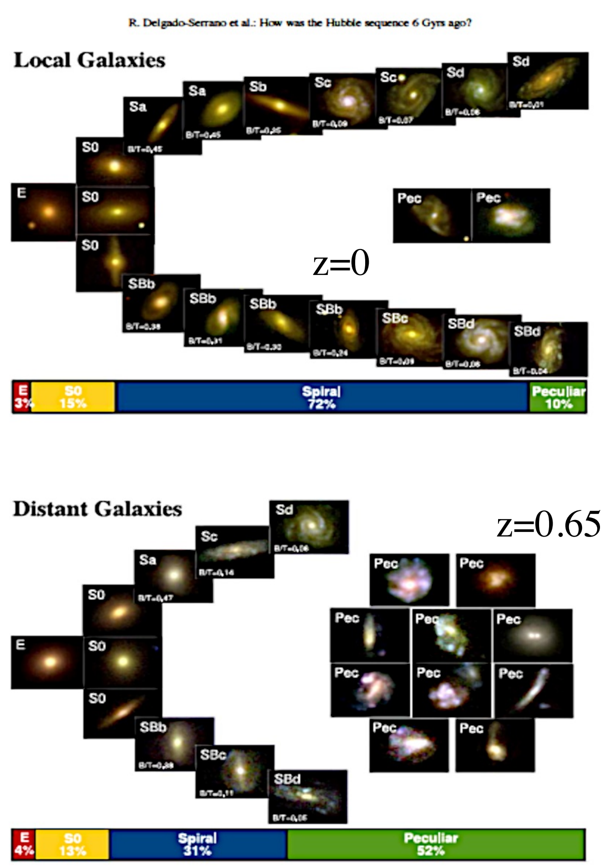
At z ~ 1.2 most of the massive galaxies with logM > 11.4 $M_\odot$ are in place,
at lower masses the galaxy number density increases by a factor of ~ 3.5 from z~ 1.2 to z ~ 0.6. Davidzon et al 2013-

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 of 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



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?