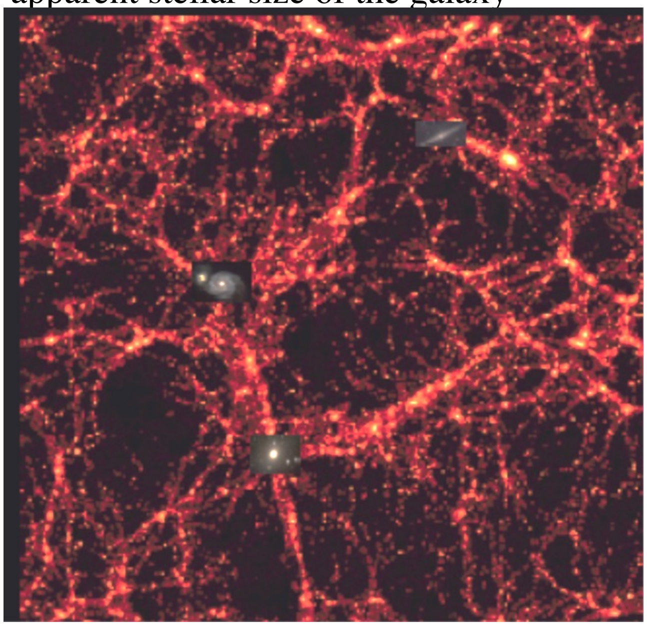
# Galaxies Do Not Live Alone

- Galaxies are part of the 'cosmic web'- representing over dense regions of baryons **and** dark matter
- The effective size of the **dark matter halo** is much larger than the apparent stellar size of the galaxy

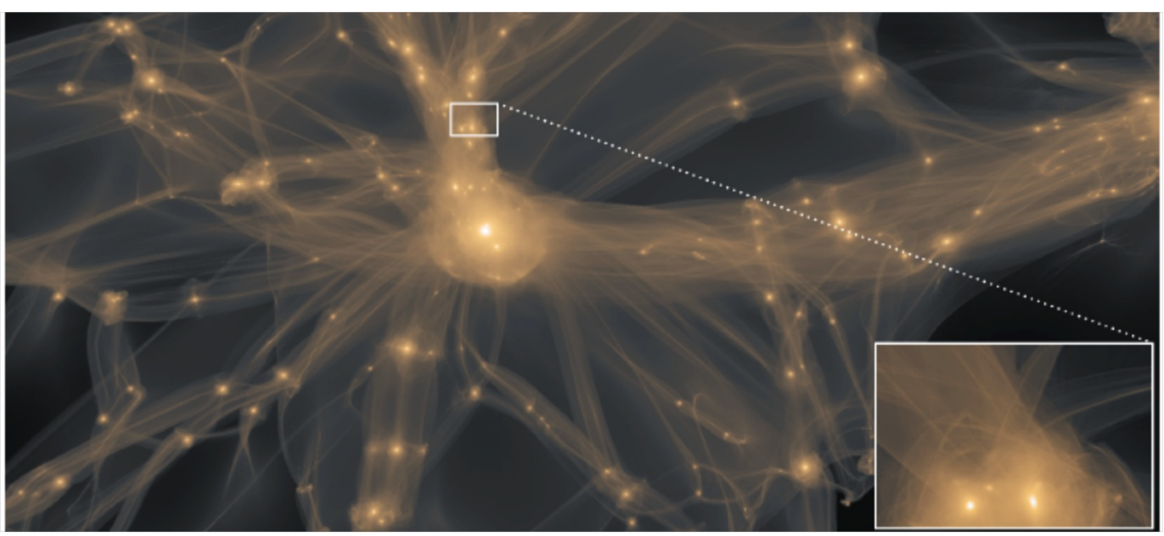


The cosmic web has structure at all scales but eventually becomes homogenous at scales >70Mpc

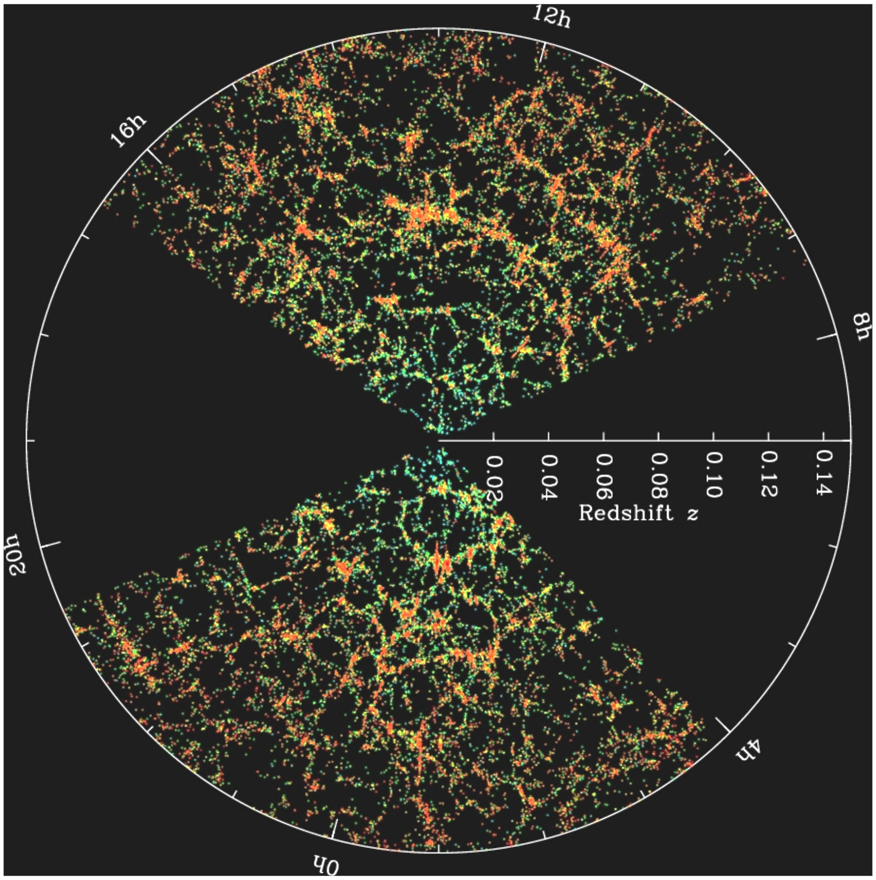
Eric Bell



# Cosmic Web- Numerical Simulation



In this rendering the large scale sheets and filaments are more easily seen- galaxies tend to reside in these sheets and filaments and are rare in voids.



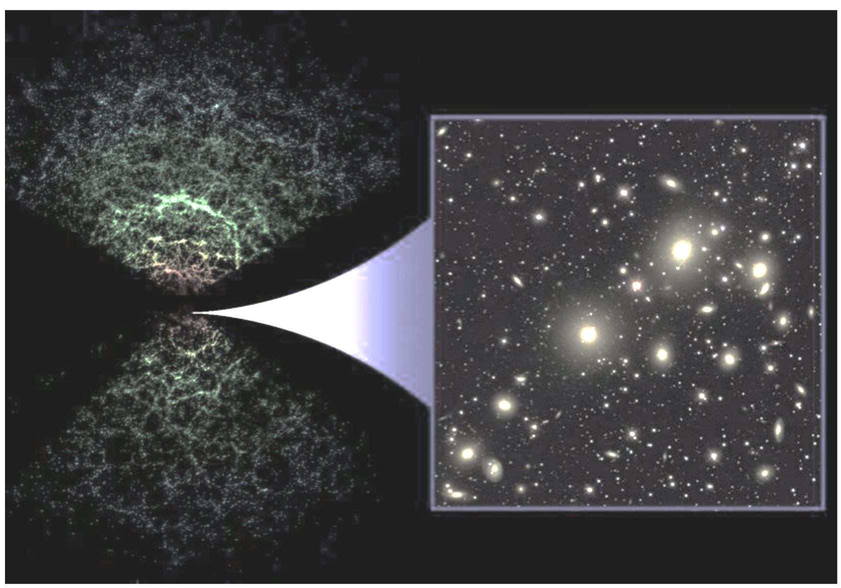

Sloan Digital Sky Survey

Galaxies color coded by the age of their stars
red= old
blue=young
http://www.sdss.org



# Large Scale distribution of galaxies

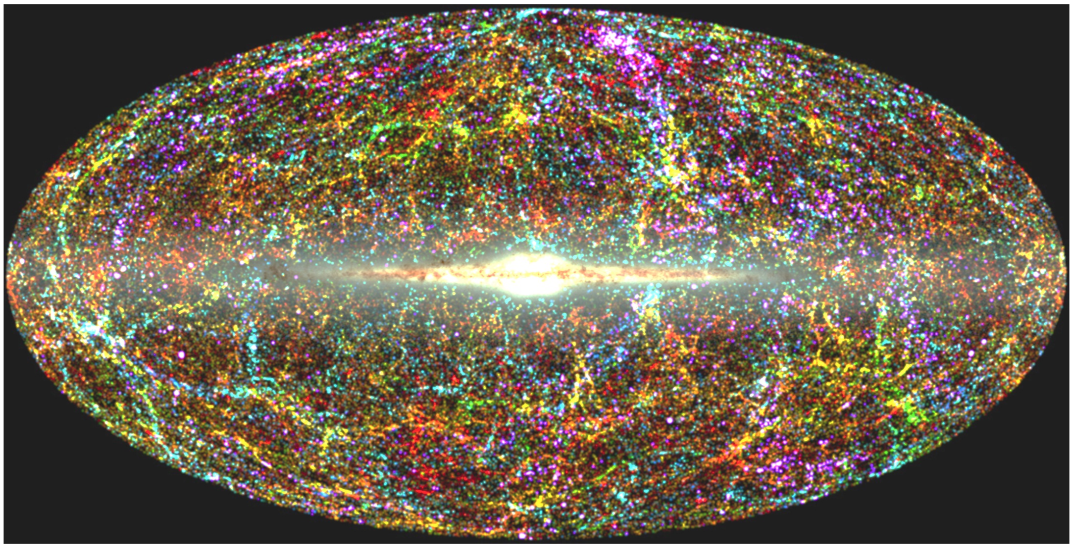
- On scales $<10^8$pc the universe is 'lumpy'- e.g. non-homogenous
- On larger scales it is close to homogenous- and isotropic



Sloan Digital Sky Survey- http://skyserver.sdss3.org/dr8/en/

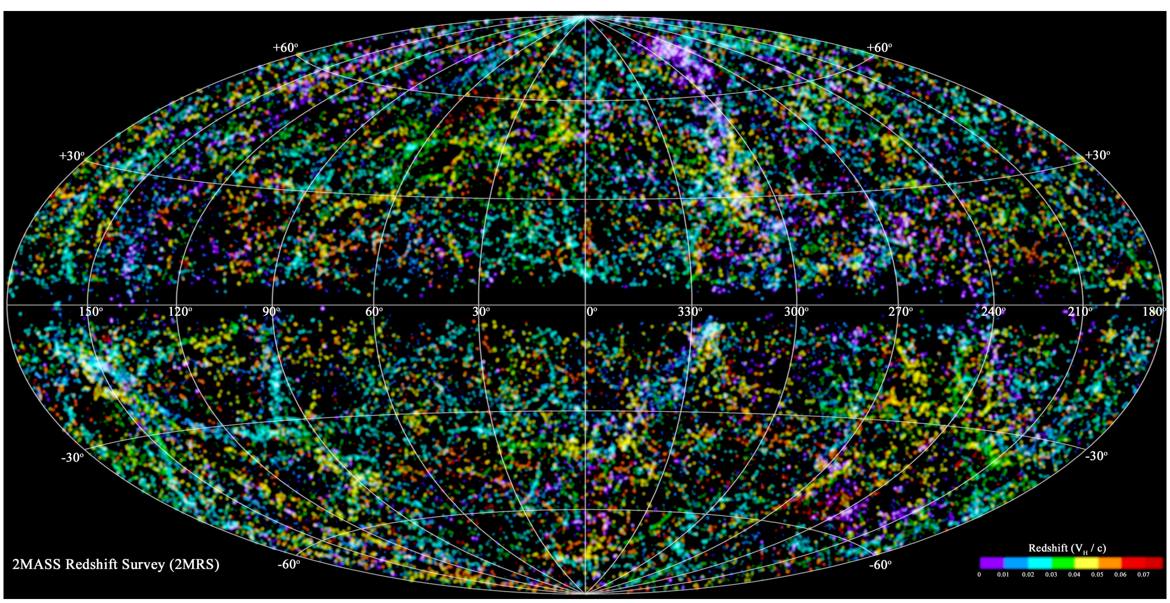
# 2MASS* view of galaxies selected by infrared flux notice filamentary structure

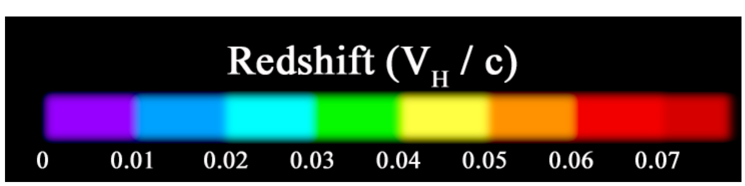
Blue: near; red: far
Credit: T. Jarrett, IPAC



*http://www.ipac.caltech.edu/2mass/

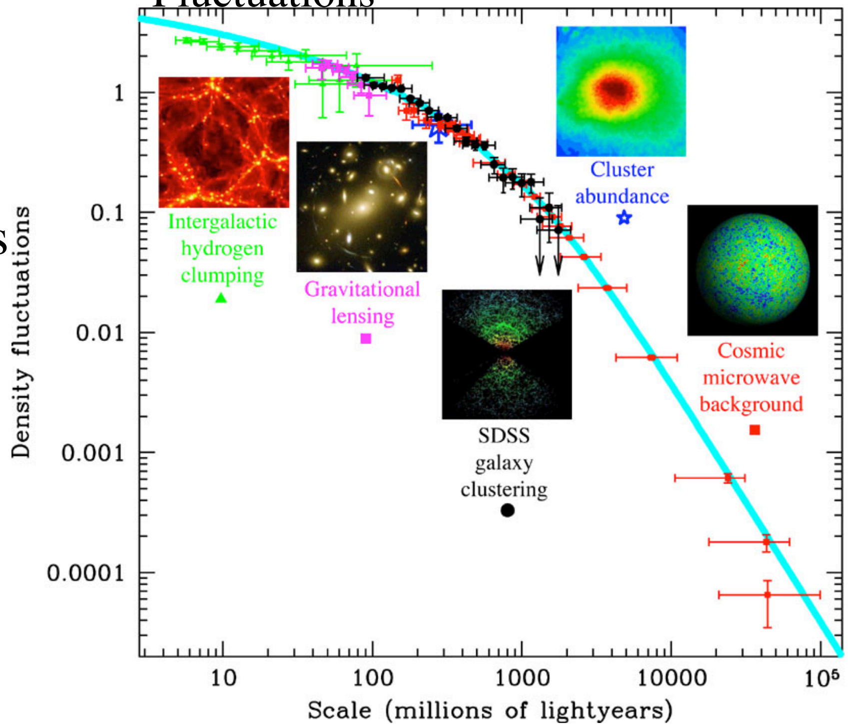




## How 'Lumpy' is the Universe-Power Spectrum of Fluctuations

- As one goes to larger scales the universe gets less lumpy (on average)




Tegmark 2004

size of box



## Dark Matter Dominates Gravity

The cosmic ratio of dark matter to baryons is 6:1

$\Omega_{baryons}/\Omega_{dark\ matter}$ =0.167

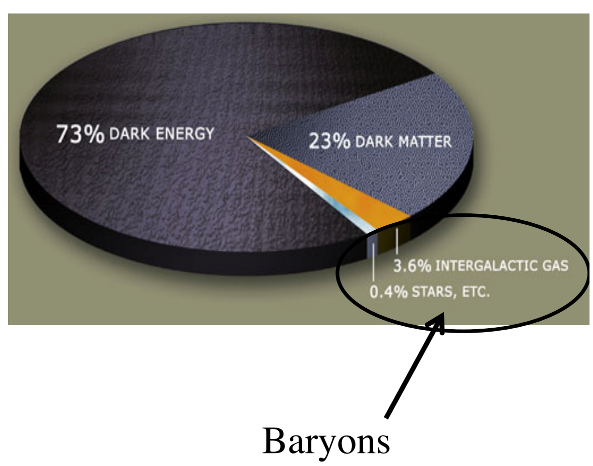
$\Omega_{baryons}$ = 0.042 ± 0.003

$\Omega_{dark\ matter}$ = 0.28

$\Omega_{baryons/\mathbf{stars}}$ = 0.0011

$\Omega_{stuff}$ is the ratio of the mass of the component to the closure density

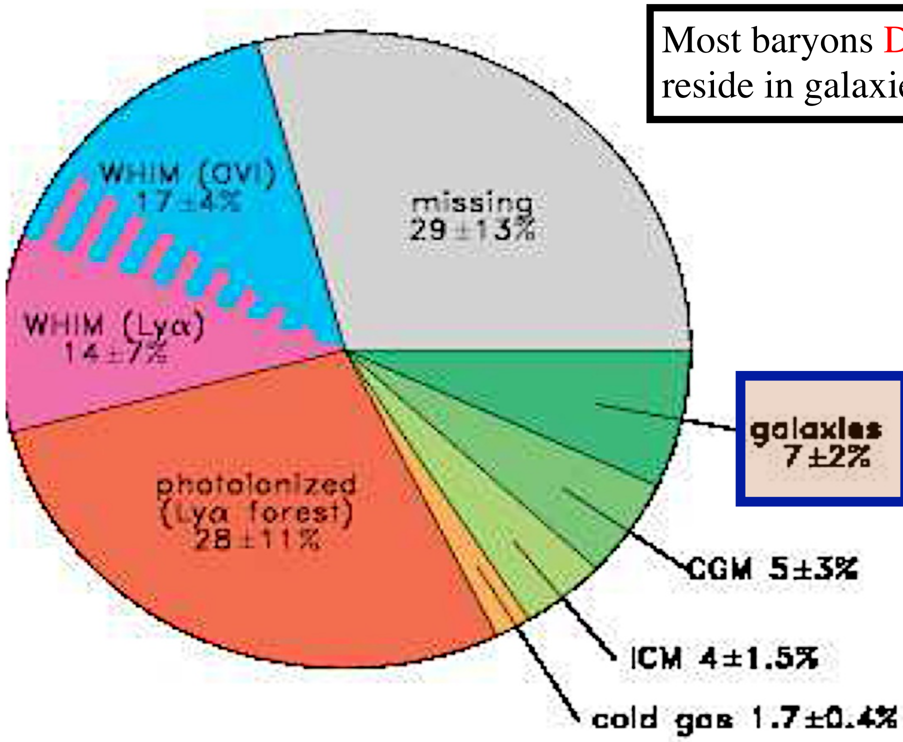
Notice how little of the universe's baryonic matter is in stars !



# Where are the Baryons

Shull Danforth 2012

Most baryons DO NOT reside in galaxies






# Dark Matter

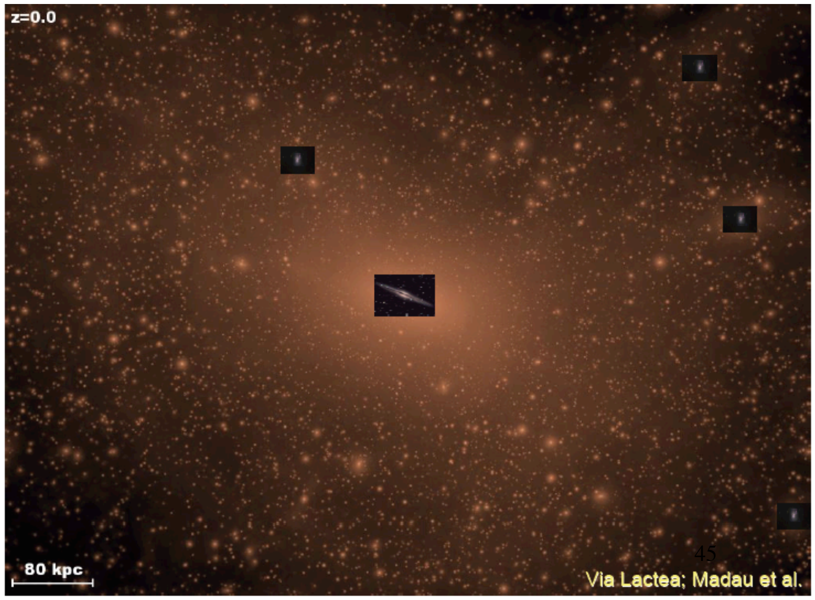
- Dark matter provides a "skeleton" on which galaxies reside and grow
- There is a very complex relation between how the dark matter and baryons (gas and stars) are related and distributed on a wide variety of scales
  - baryons are more concentrated than dark matter
  - **light** does not trace mass well
- Dark matter can only interact via gravity while baryons can interact with photons, shocks, cosmic rays, be heated and cooled.


*http://astro.berkeley.edu/~mwhite/darkmatter/essay.html for a nice essay on dark matter*

# Dark Matter Distribution and Galaxies

- A numerical simulation of the formation of structure (Madau et al 2008) shows the scale of dark matter and the baryons

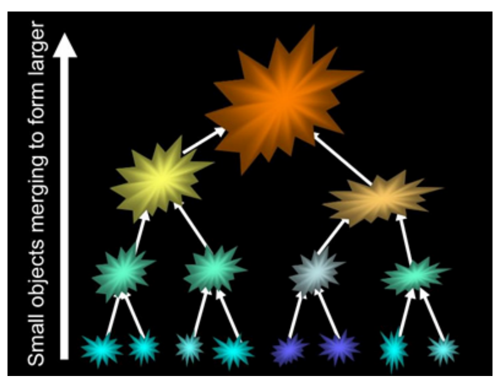
Dark matter is the 'beige' material






# How Things Form

- Gravity acts on over densities 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.

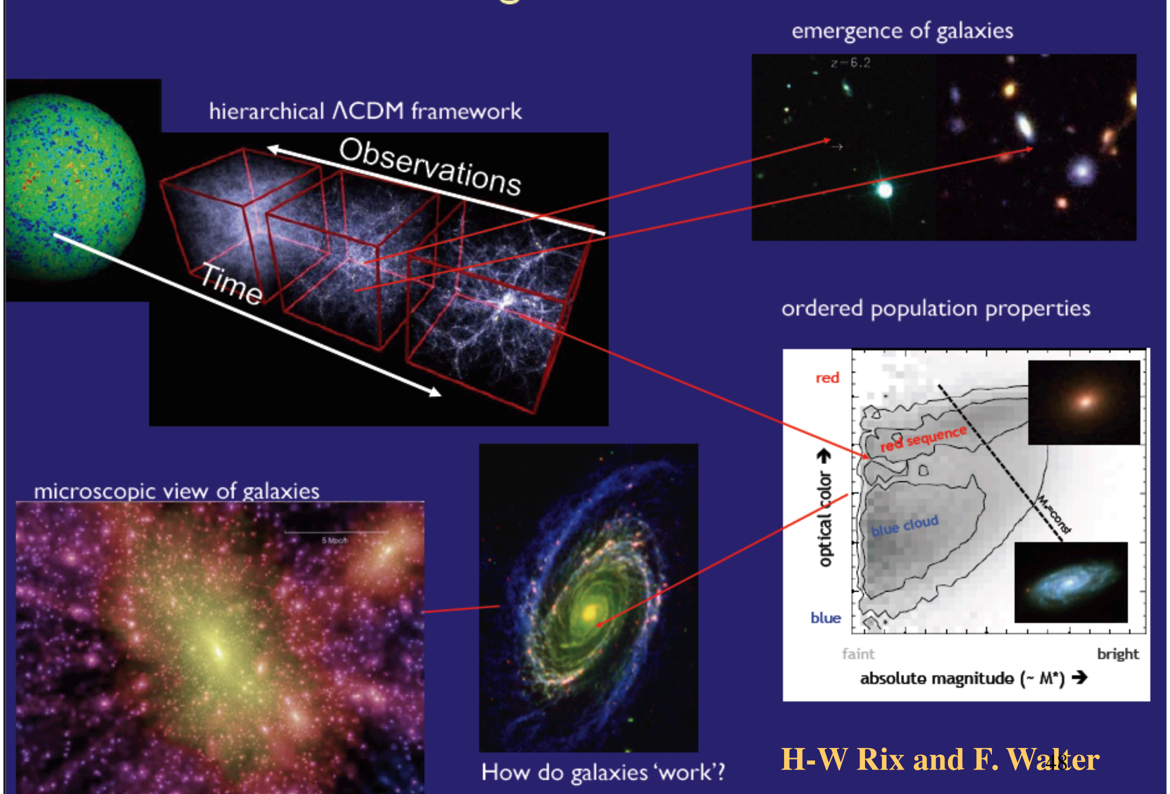
•The structures we see in the Universe today (galaxies, clusters, filaments, sheets and voids) are predicted to have formed by the combination **of collapse and mergers** according to Cold Dark Matter cosmology (the current concordance model).

# Movie of Hierarchical Growth

- http://www.caterpillarproject.org/assets/movies/CaterpillarProjectHighResBGriffen.mp4

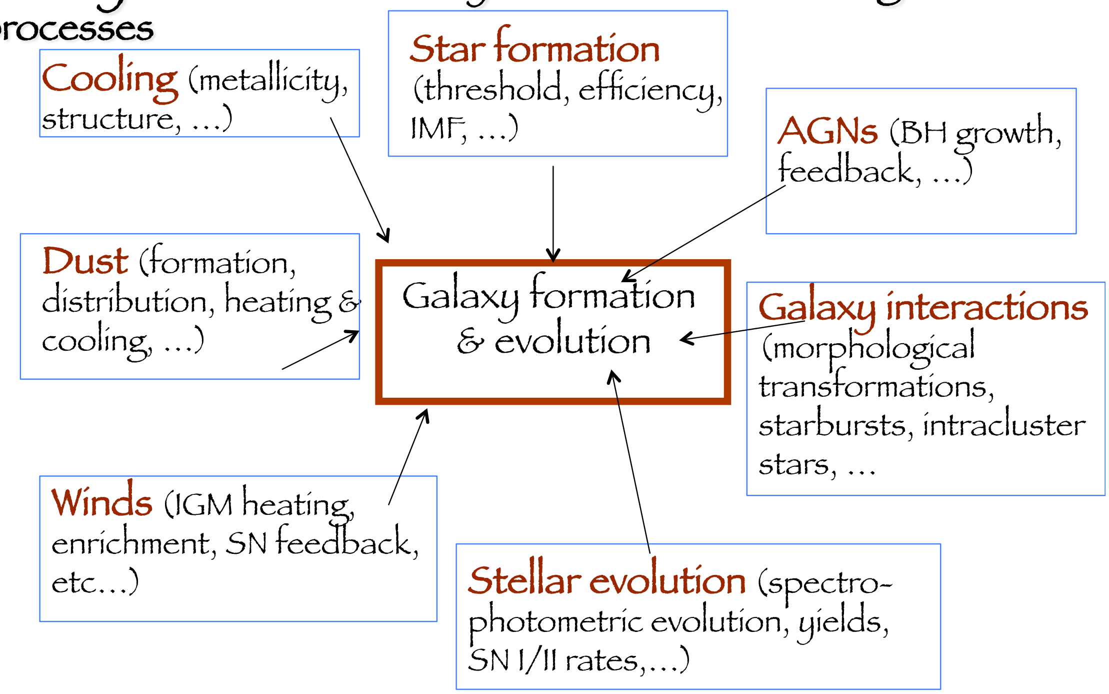


# Galaxies in a Cosmological Context




H-W Rix and F. Walter

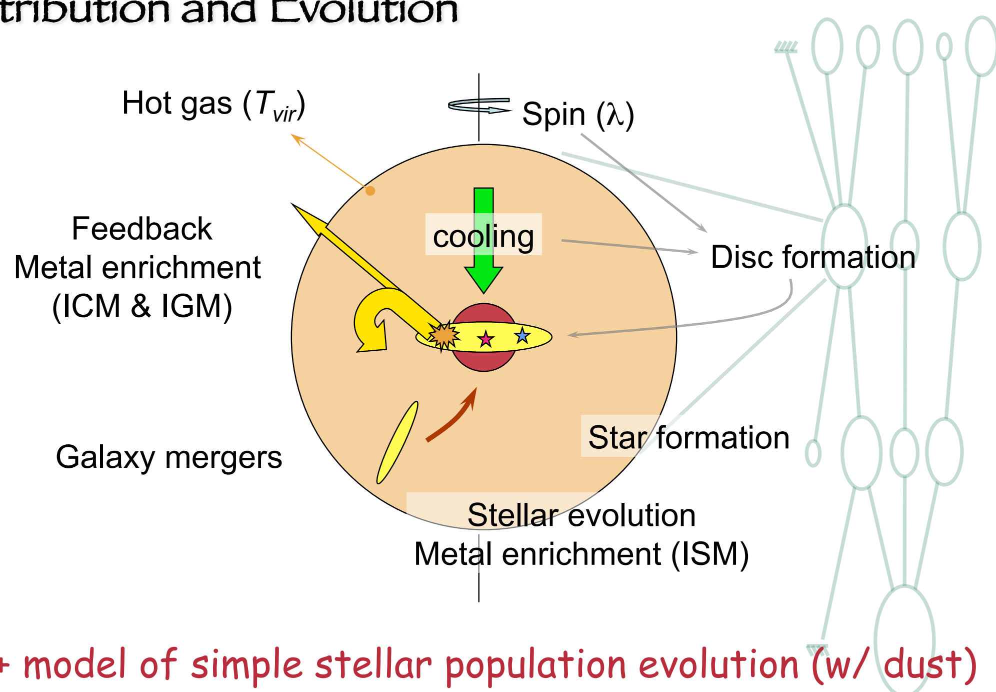
## Galaxy formation : Many relevant and interacting processes




time to only talk about *some* of these processes in detail
J. Blaizot



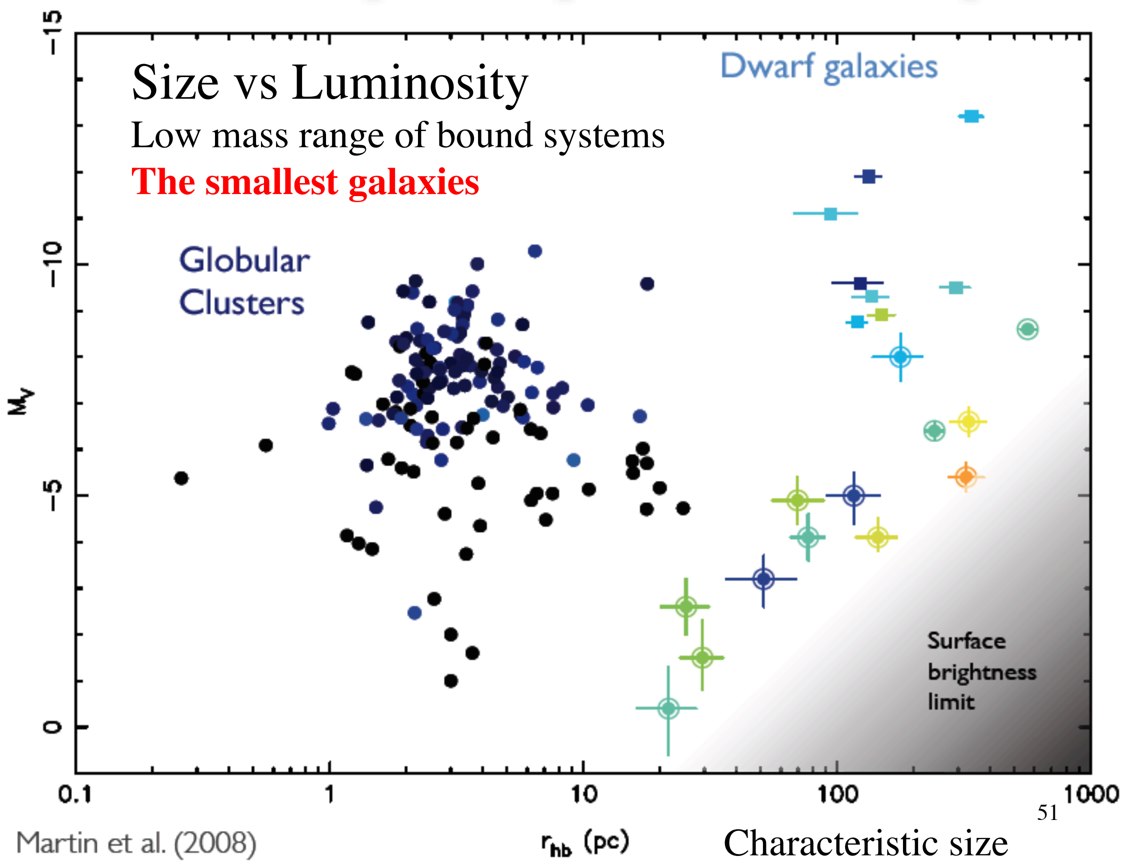
## What Physics Goes on Top of the Dark Matter Distribution and Evolution




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



taken from J. Blaizot presentation



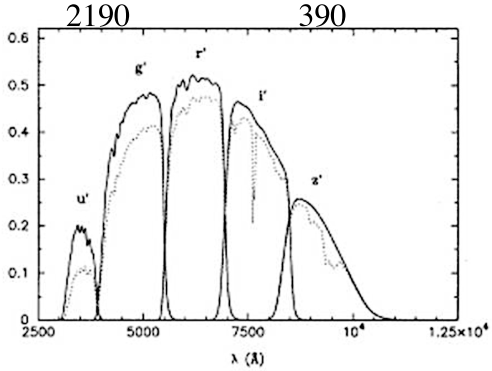



# Galaxies Have Very Different Appearances in Different Wave Bands

- The physical processes which dominate in different wavebands are often very different
  - optical - starlight
  - UV- starlight from massive young stars+AGN
  - 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

# 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),
a object with a flat energy distribution ( $F_\nu$=constant) has the same mag in all colors; 3631 Jy=mag 0 ( 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
(e.g. the UBV data set was developed for use with photographic plates, the SDSS set for use with CCDs circa 1995 technology)



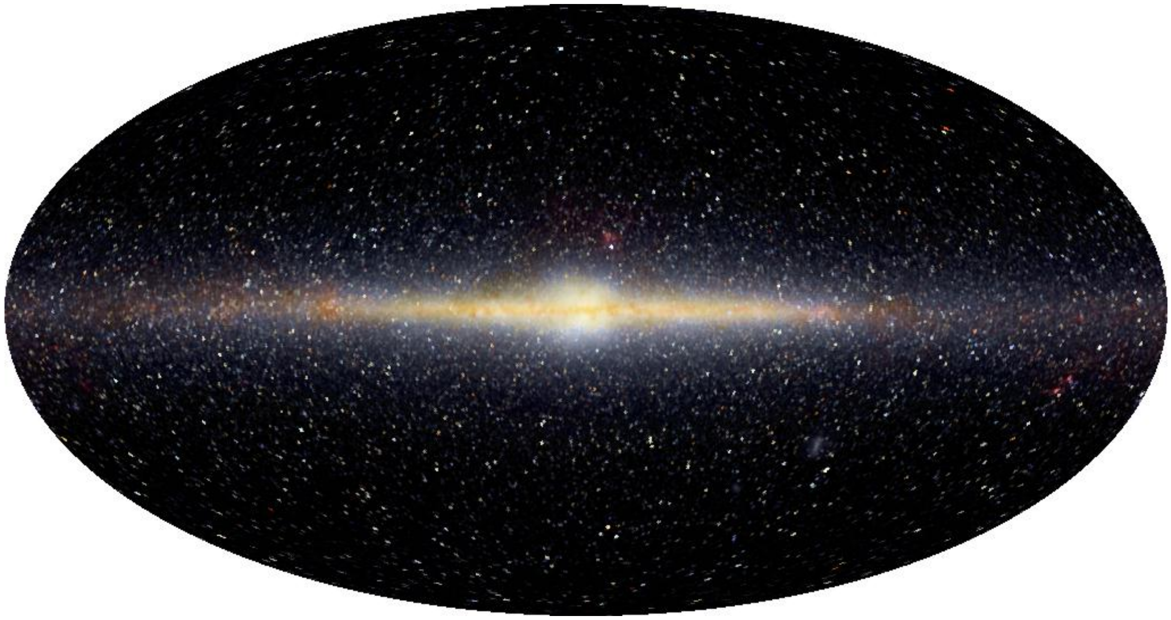
# The PanChromatic Universe

- Galaxies emit over the entire electromagnetic spectrum from radio to gamma-rays
- Each band (radio, mm, infra-red, optical, ultraviolet, x-ray, gamma-ray) contains unique information
- Require ALL the data to get the BIG picture
- However certain 'parts' of galaxies emit preferentially in one band (e.g. sun-like stars in the optical) while others (AGN) emit over the entire range.

Each band requires its 'own' special techniques and telescopes and (unfortunately) has acquired its own jargon.

Many 'bands' (mid-IR, UV, x-ray) do not penetrate the atmosphere and require observations from space

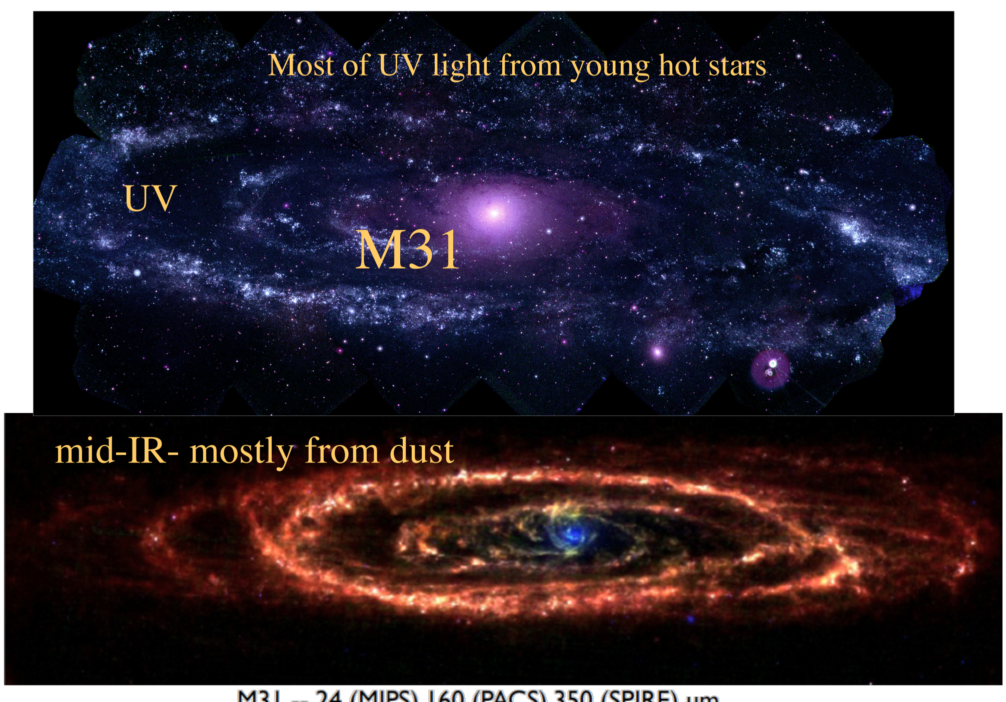
# Image of MW in IR From COBE



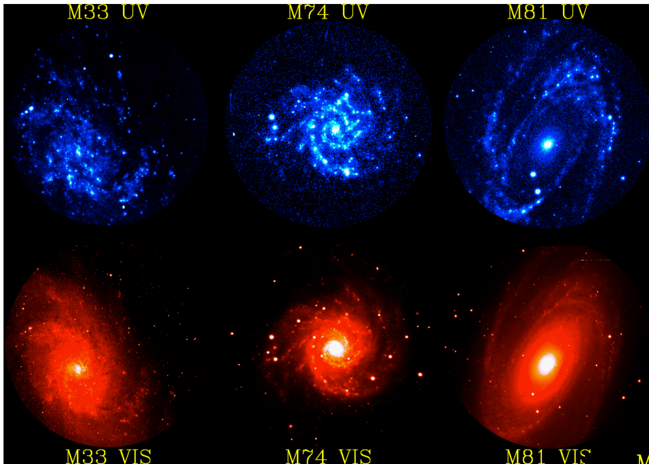
In the IR the effects of dust are minimized and one can see the true distribution of emitted radiation. In this wavelength band the emission is due mostly to old low mass stars



# Different Appearances at Different Wavelengths



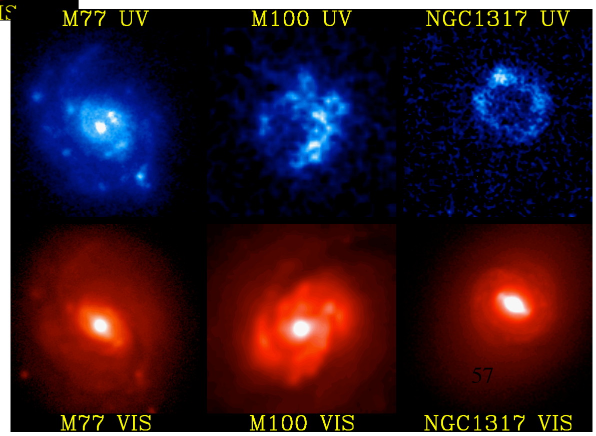

at long IR wavelengths the emission is due to dust which has reprocessed optical/UV light




# 12 galaxies observed in UV and optical

Notice different patterns of UV light - this is affected by

- distribution of hot young stars
- dust



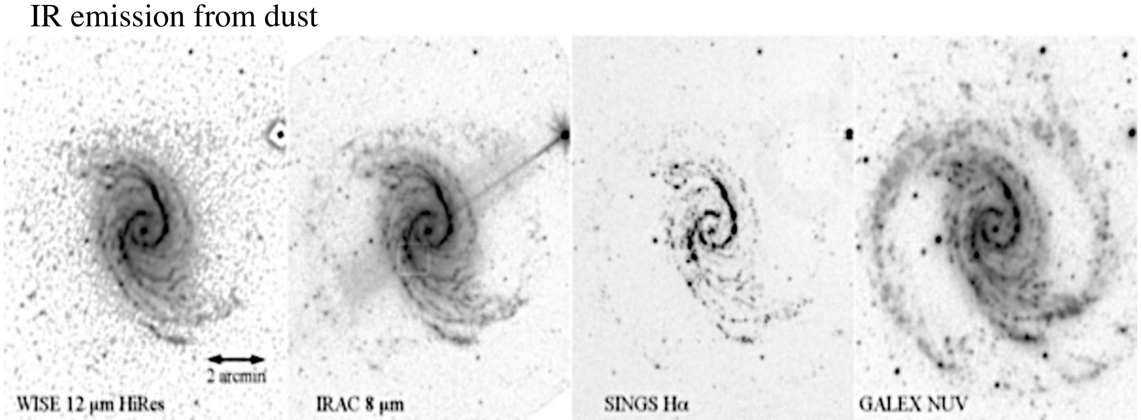

From UIT team

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



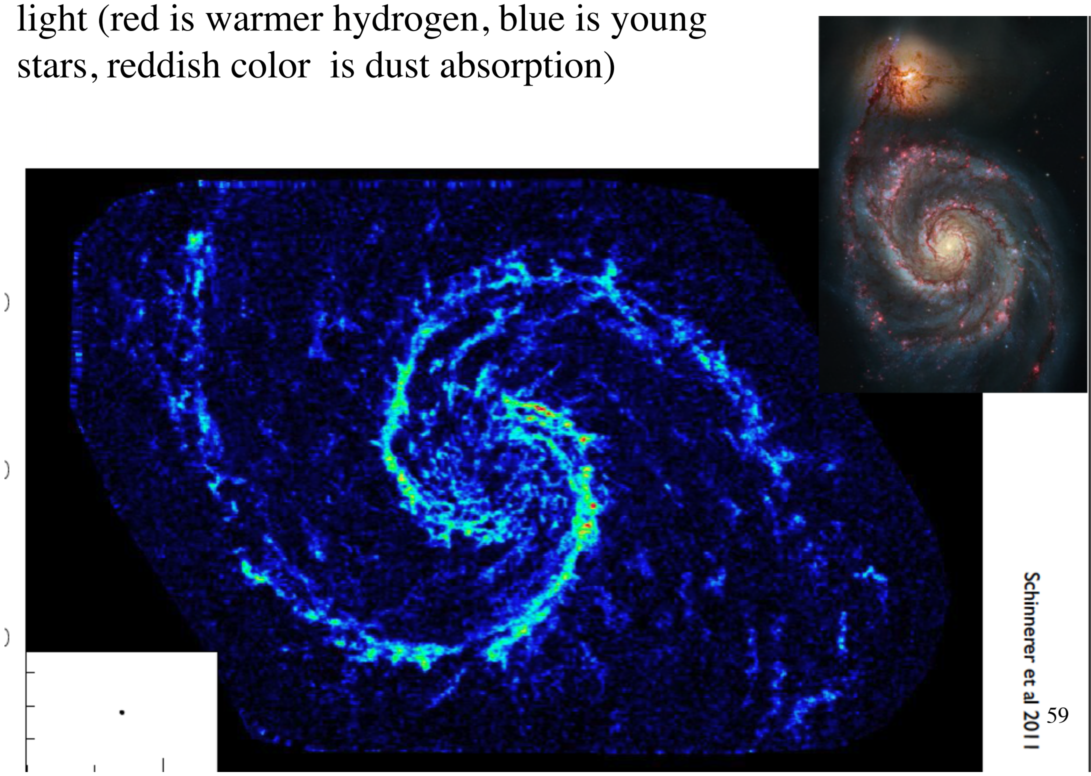
# NGC1566 in 4 Bands

- 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)

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## Panchromatic MilkyWay

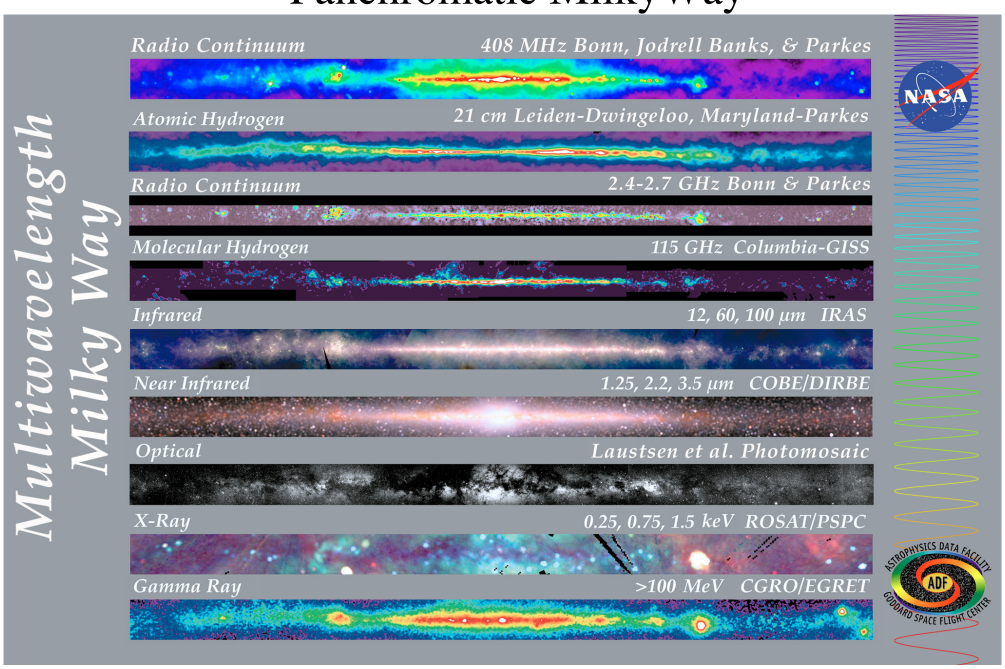


Image of MW galactic plane from radio through $\gamma$-rays

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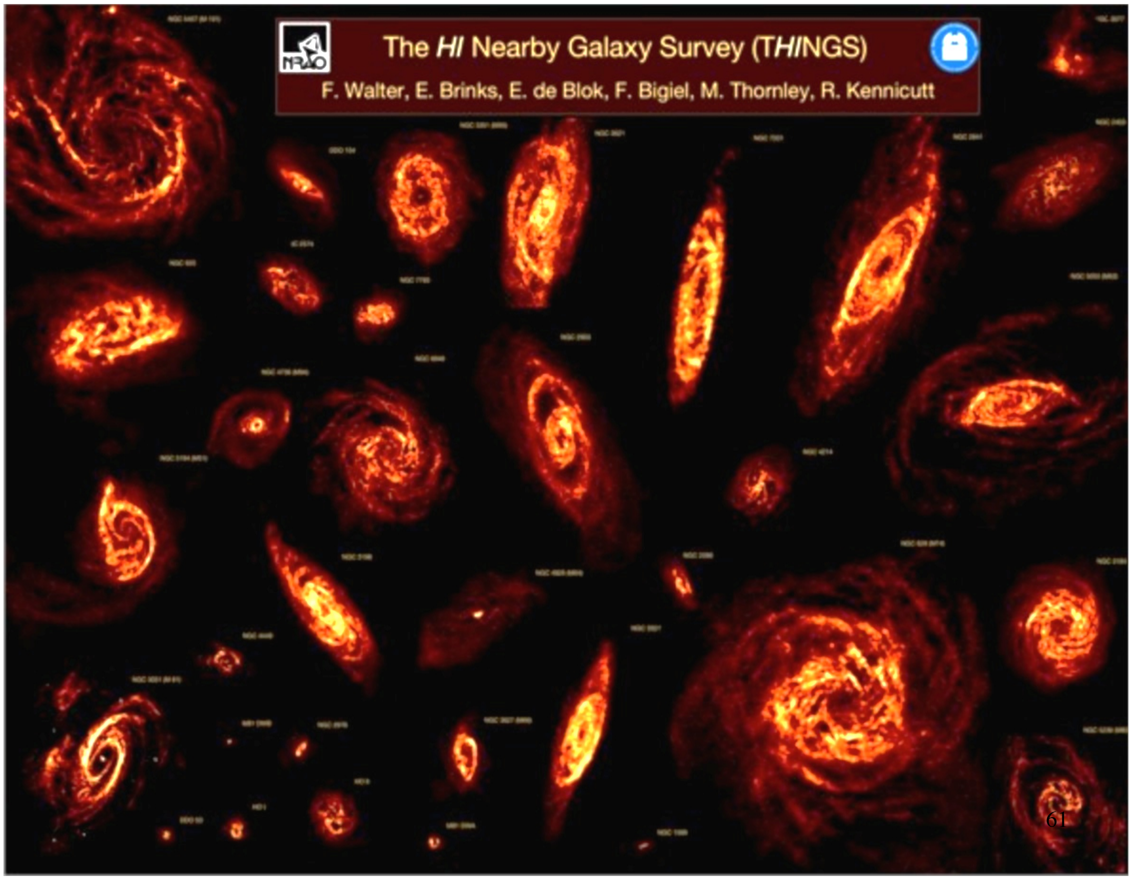
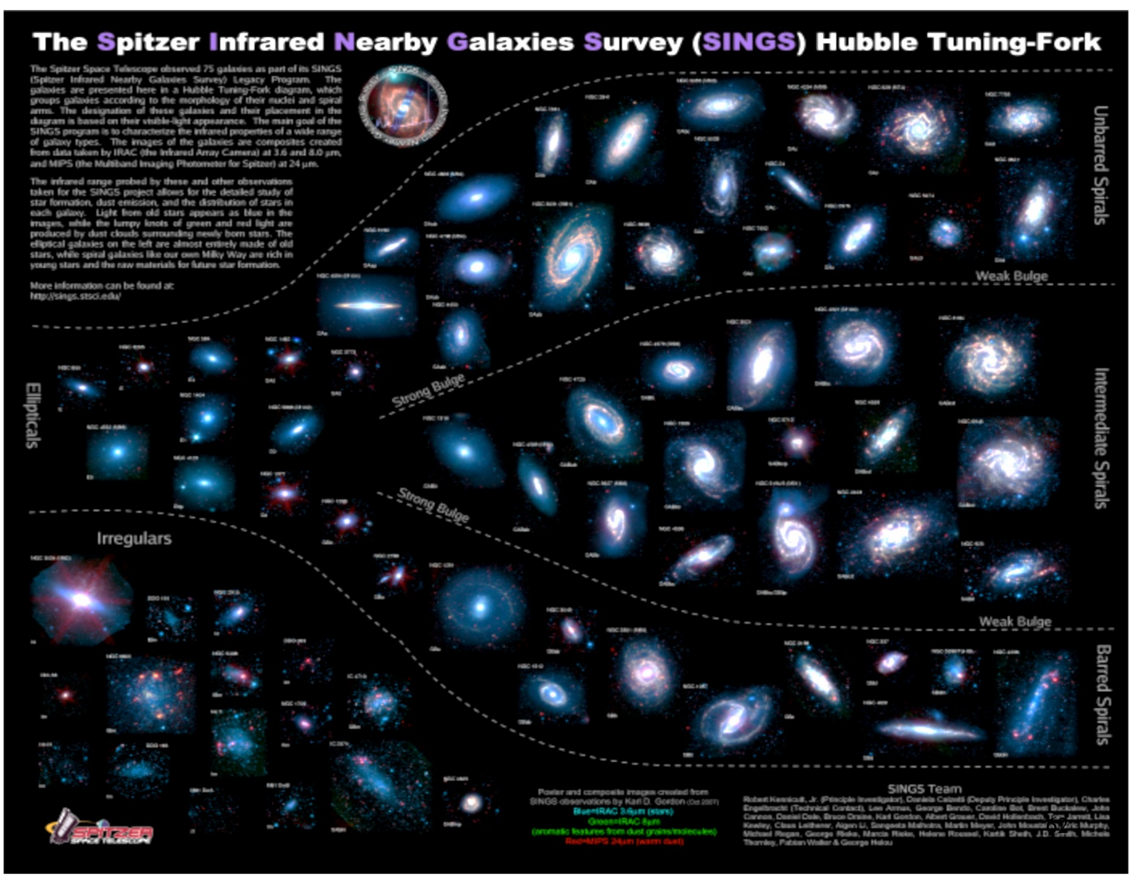

The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
61


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
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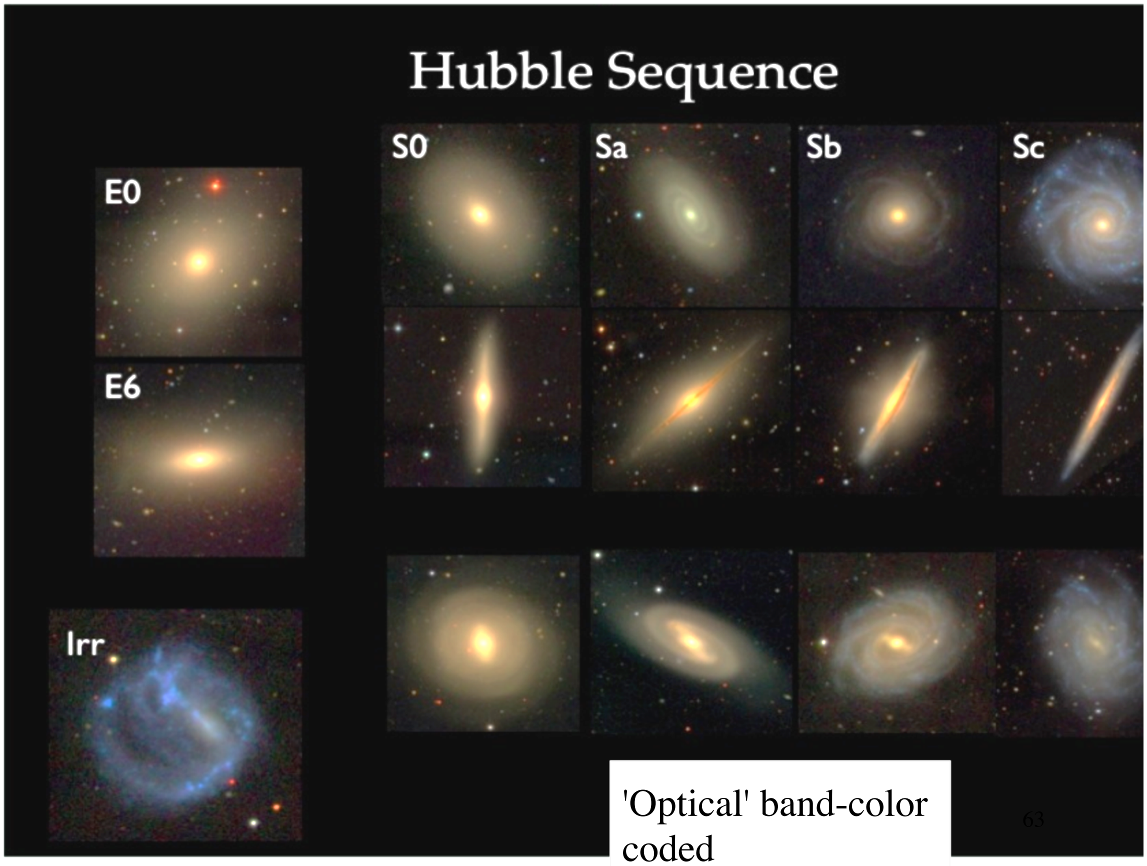
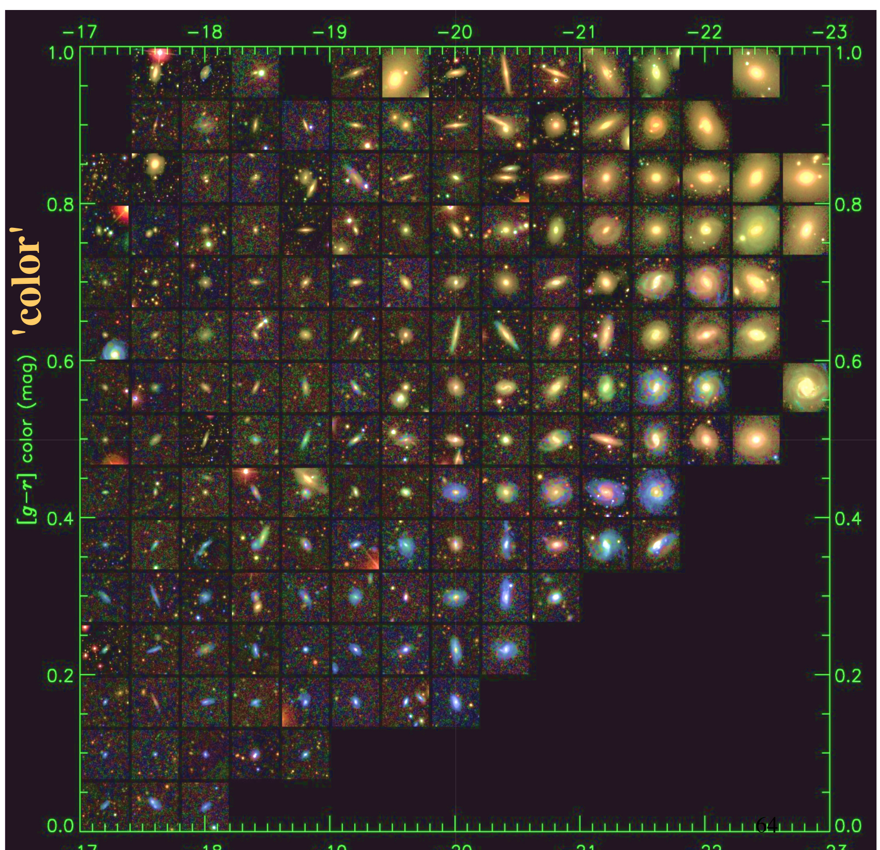



'Optical' band-color coded



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
- 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



## 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**

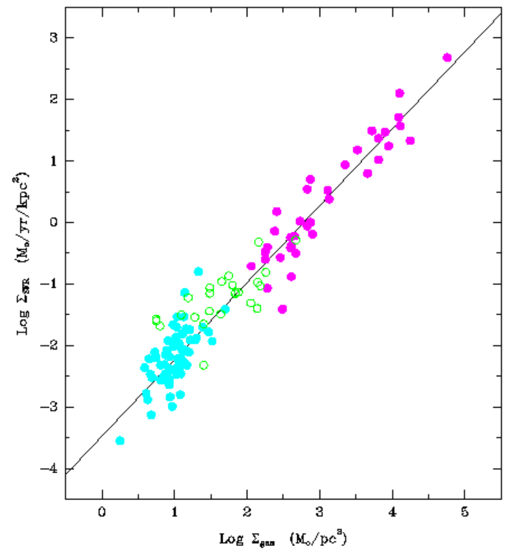
**Do these terms carry a physical meaning?- *Yes* the 'names' and the physics have a strong linkage- what, why and how**

- 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



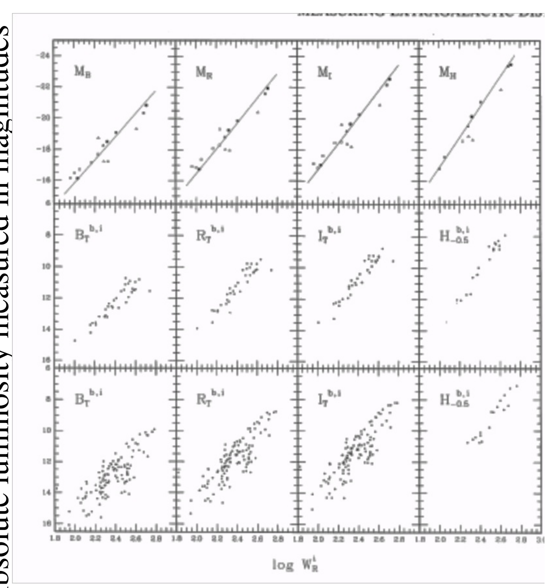

log surface density of gas



# 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.

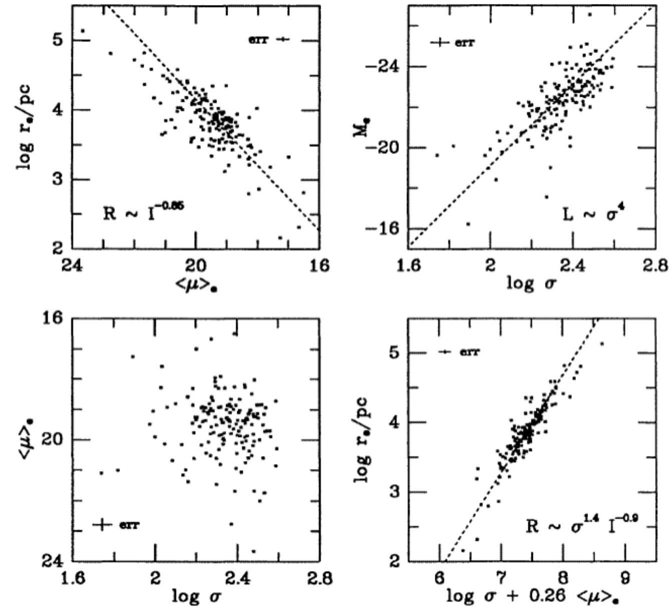



log rotational velocity

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




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

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

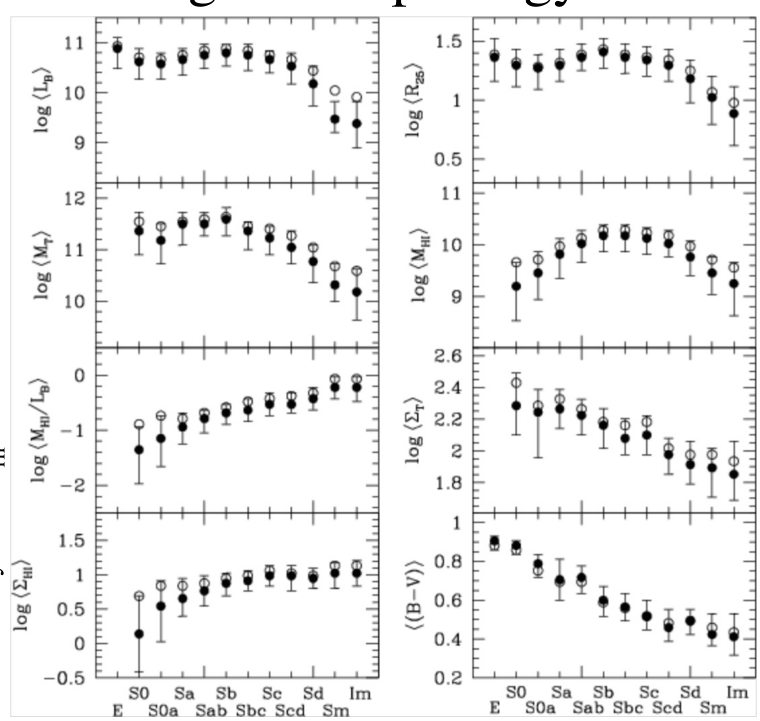


# A Physical Meaning to Morphology?

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.

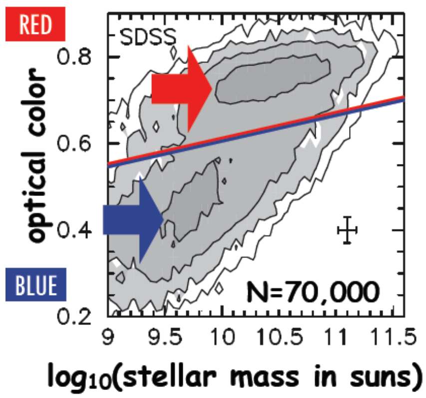
surface density of HI $\Sigma_{HI}$

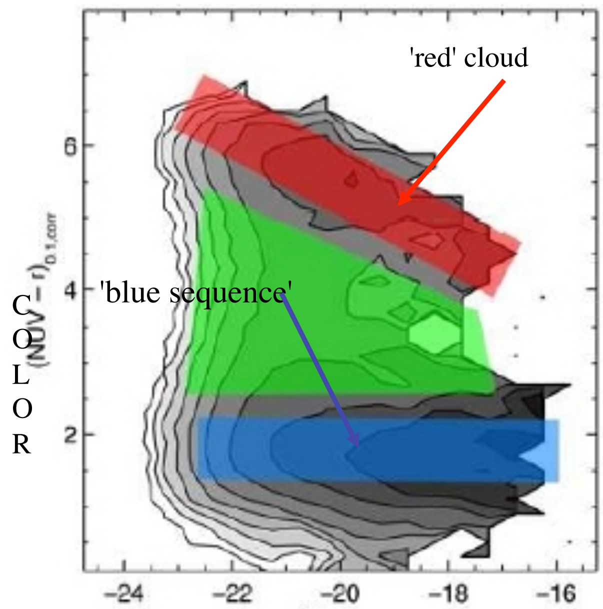


# Galaxy Relations

Isoplths- lines of constant galaxy density

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



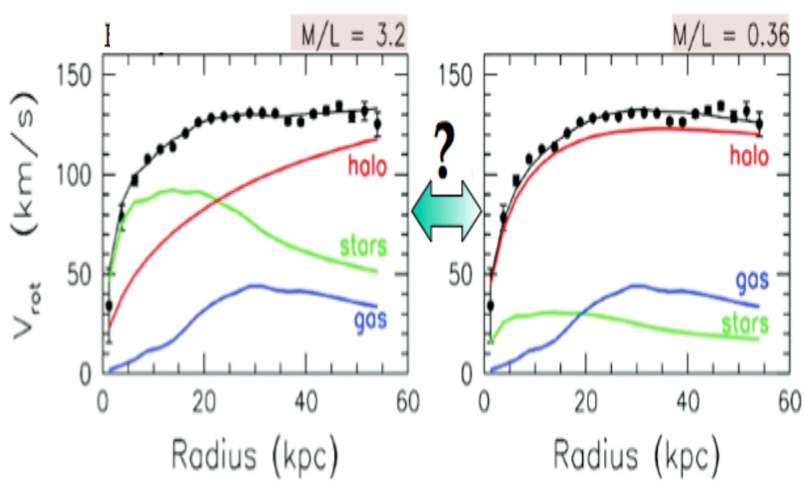

Absolute magnitude
Baldry et al 2004



# Spirals and Dark Matter

Bershady et al

- Galaxies are dominated by dark matter
- The ratio of dark matter to baryons varies with radius with DM becoming more dominant at larger radii



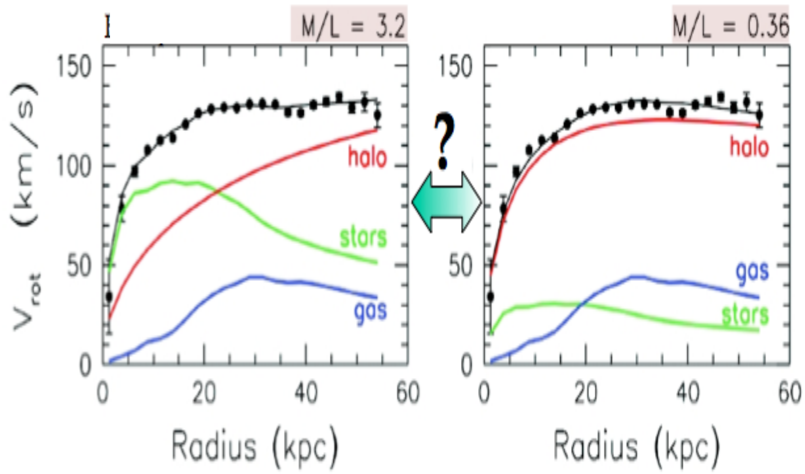

At the radius where the velocity curve flattens ~15-30% of the mass is in baryons
2 plots show the effects of varying the relationship between light and mass in stars

## Spirals and Dark Matter

Bershady et al

- Rotation-curve decomposition - primary tool for measuring the distribution of dark matter in spiral galaxy halos,
- Disks in equilibrium

  Measure of rotation provides total mass within a given radius.

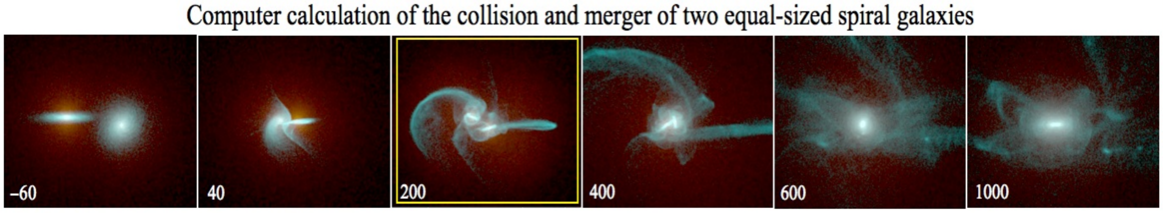



At the radius where the velocity curve flattens ~15-30% of the mass is in baryons
2 plots show the effects of varying the relationship between light and mass in stars



## Galaxies Change Over Cosmic Time

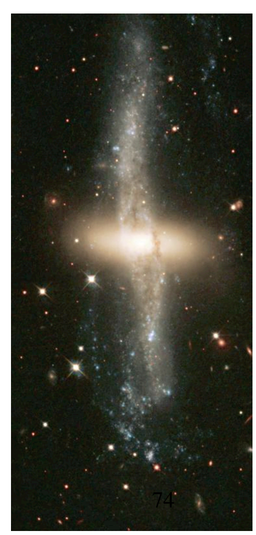
Computer calculation of the collision and merger of two equal-sized spiral galaxies




The Mice: Hubble Space Telescope

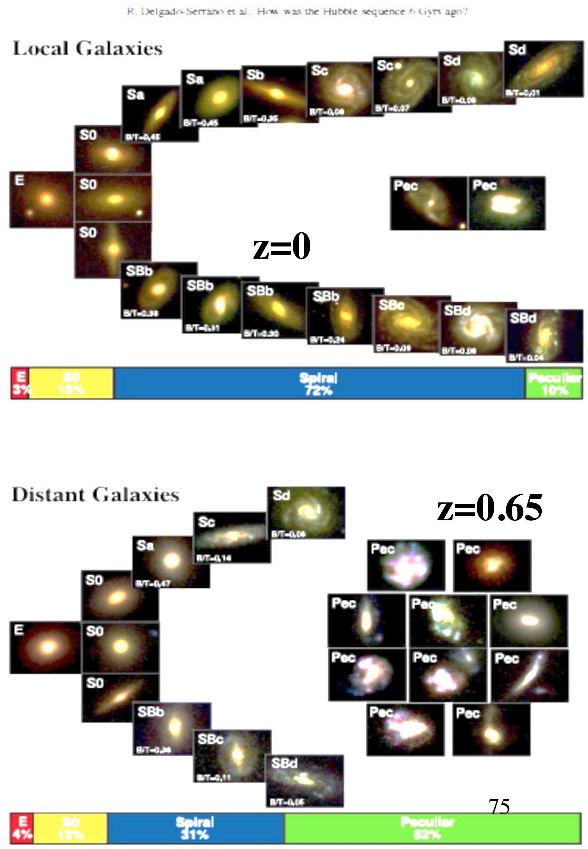
- Galaxies can grow via mergers and acquisition of gas. Mergers can be major or minor
- Star formation rates change drastically with cosmic time

Polar ring galaxy -evidence for gas accretion?



# 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.
- more than half of the present-day spirals had peculiar morphologies, 6 Gyrs ago

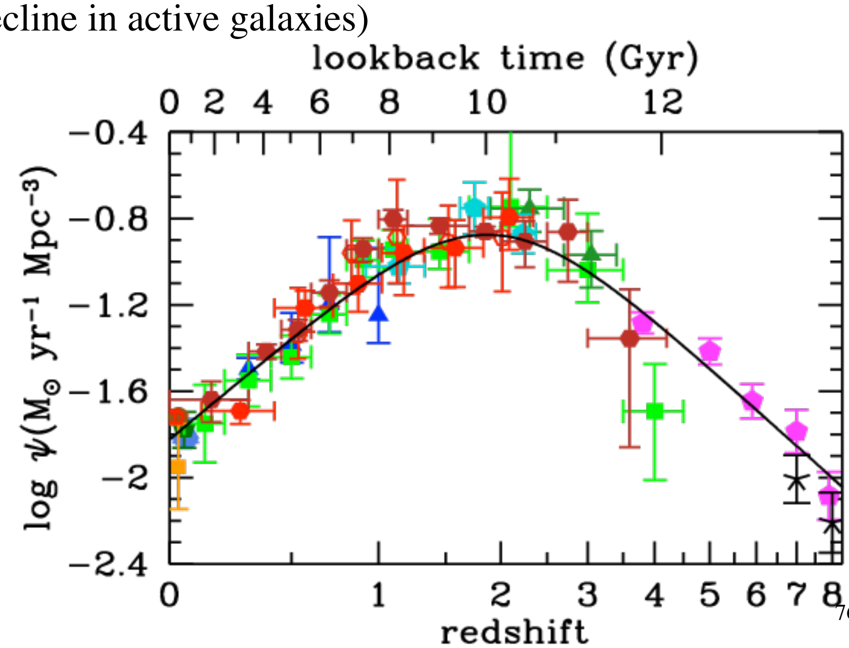




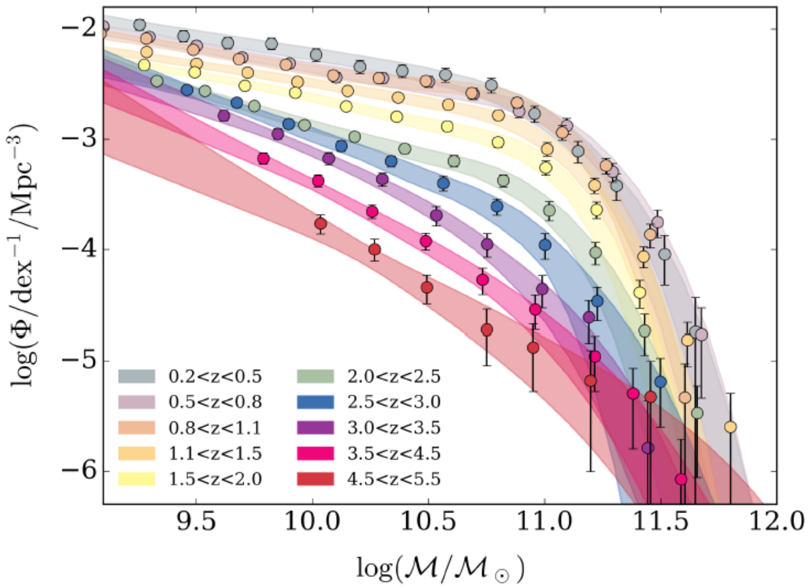

# Patterns Change over Cosmic time

- There has been a rapidly declining SFR ($\Psi$) rate since z~1.5 (accompanied by a similar decline in active galaxies)

Madau and Dickinson201



# Galaxies Grow a Lot Over Time






# Next Time

- Please read ch 1 of Sparke and Gallagher sec's 1.1,1.2 and 1.3; not necessary to read 1.4 and 1.5
  - 1.1 The stars
  - 1.2 Our Milky Way
  - 1.3 Other galaxies

    1.4 Galaxies in the expanding Universe

    1.5 The pregalactic era: a brief history of matter
- Lecture will be on stars