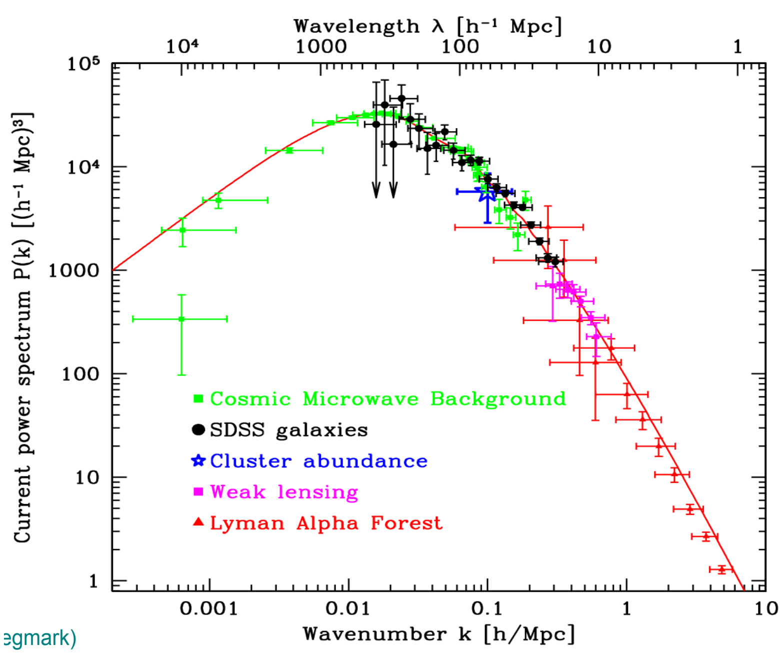
Lectures for the Semester

- Lecture 1 Introduction: Some Galaxy Properties
- Lecture 2 Introduction (continued): Some Galaxy Properties
- Lecture 3 Introduction (continued): Some Galaxy Properties
- Lecture 4 Basic Galaxy Properties
- Lecture 5 Properties of Stars I
- Lecture 6 Properties of Stars II
- Lecture 7 Gas in Galaxies Lec I
- Lecture 8 Gas in Galaxies Lec II
- Lecture 9 Dust in Galaxies
- Lecture 10-11 Milky Way Lec
- Lecture 12 Galactic Rotation
- Lecture 13 Dynamics I
- Lecture 14 Dynamics II
- Lecture 15 Dynamics III
- Lectures 16,17 Local group
- Lecture 18 Chemical Evolution
- Lecture 19 Star Formation
- Lecture 20-21-22 Spiral Galaxies
- Lecture 23-24-25 Elliptical galaxies
- Lecture 26 AGN I
- Lecture 27-28 AGN II-III

Power Spectrum of Fluctuations

- As one goes to larger scales the universe gets less lumpy (on average)
- See MBW sec 6.1 and 6.5.2 for definition
- http://ned.ipac.caltech.edu/level5/March04/Jones/Jones5_2.html



egmark)

Tegmark 2004

Power Spectrum of Fluctuations

- In cosmology, the 2-point galaxy correlation function is defined as a measure of the excess probability, relative to a Poisson distribution, of finding two galaxies at the volume elements dV_1 and dV_2 separated by a vector distance **r**:
- The shape of the function and its amplitude is sensitive to the cosmology and the processes by which galaxies form and evolve

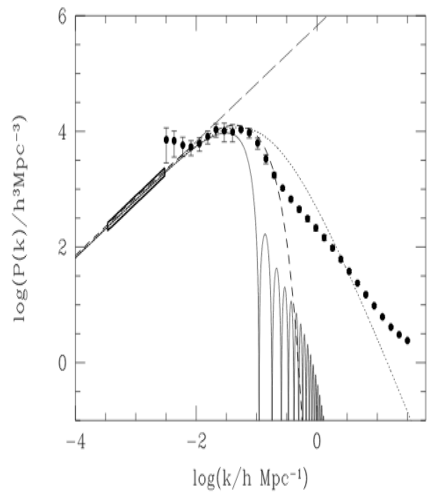
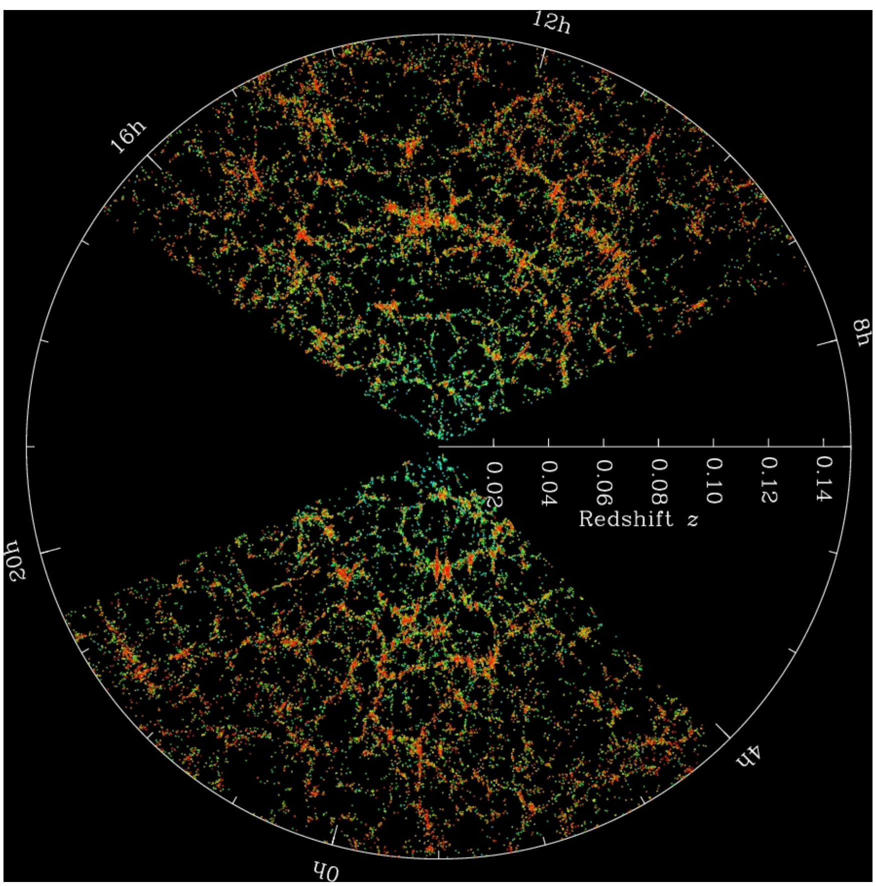


Figure 2. Examples of power spectra for universes with the critical density in mass. The long dashed line shows the Harrison–Zeldovich form of the primordial power spectrum, $P(k) \propto k$. The dotted line shows the power spectrum in a universe with the critical density in cold dark matter, the solid line shows the power spectrum when baryons contribute all the critical density, whilst the short dashed line shows a universe in which all the mass is in the form of massive neutrinos. The amplitude of the power spectra has been set to agree with the constraints from the COBE satellite measurement of temperature fluctuations in the cosmic microwave background, indicated by the box at $\log k \sim -3$. The points show a measurement of the power spectrum of galaxy clustering.

http://www.astro.caltech.edu/~george/ay21/eaa/eaa-powspec.pdf



Sloan Digital Sky Survey

Galaxies color coded by the age of their stars

http://www.sdss.org

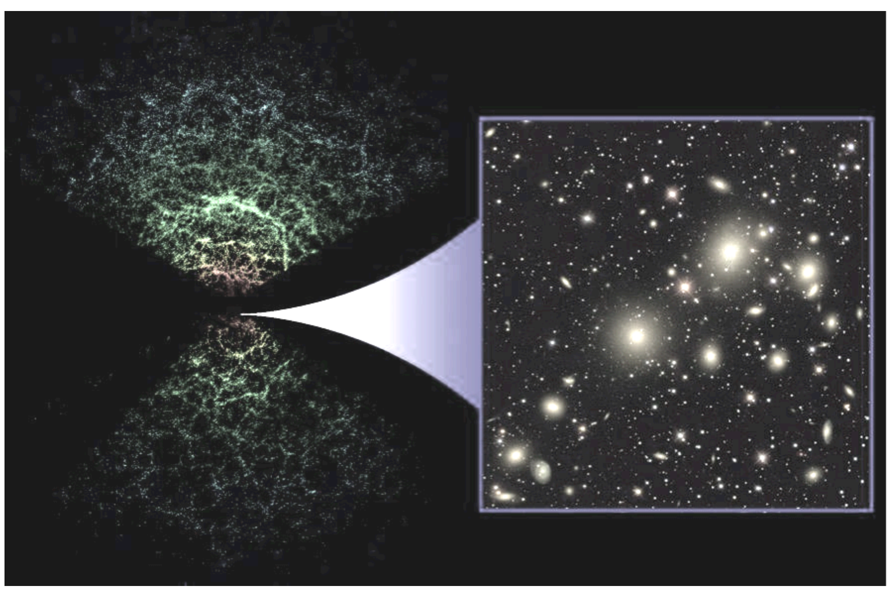
2MASS view of galaxies selected by infrared flux

Blue: near; red: far

Credit: T. Jarrett, IPAC

Large Scale distribution of normal galaxies

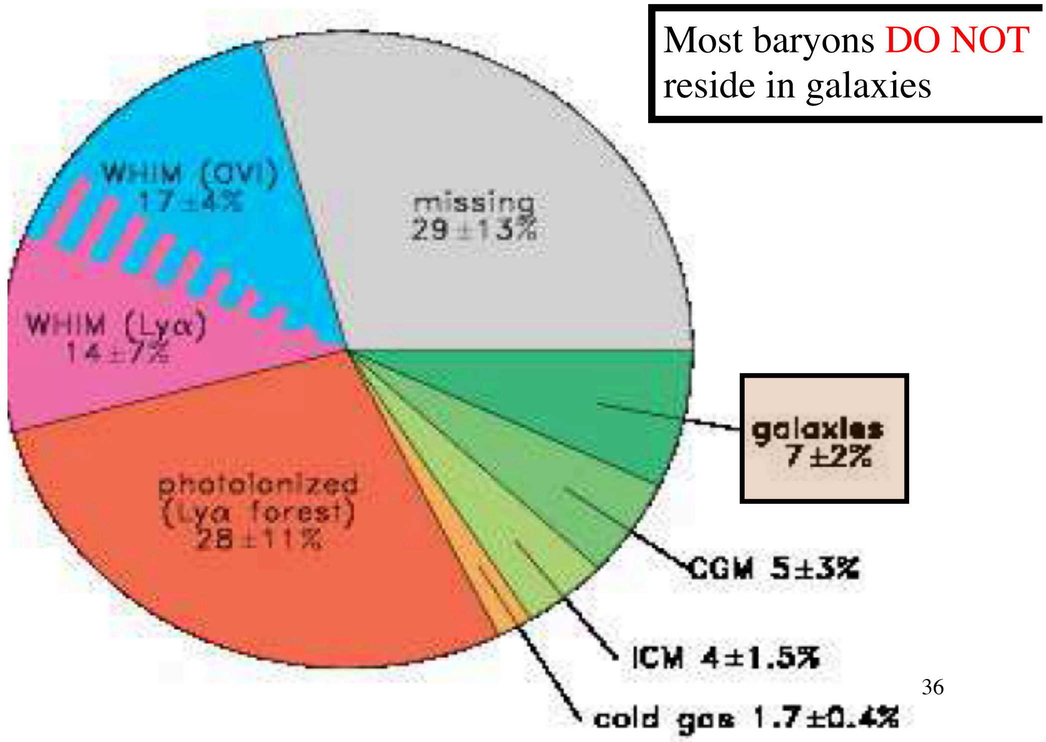
- On scales $<10^8$pc the universe is 'lumpy'- e.g. non-homogenous
- On larger scales it is homogenous- and isotropic



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

Where are the Baryons

Shull Danforth 2012



Dark Matter

- Dark matter provides a dynamic 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' may not trace mass well
- The fundamental difference is that dark matter can only interact via gravity while baryons can interact with photons, shocks, cosmic rays, be heated and cooled.
- (see http://astro.berkeley.edu/~mwhite/darkmatter/essay.html) for a nice essay on dark matter

Dark Matter Dominates Gravity

- The cosmic ratio of dark matter to baryons is ~5.4:1

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

$\Omega_{baryons}$ = 0.042 ± 0.003

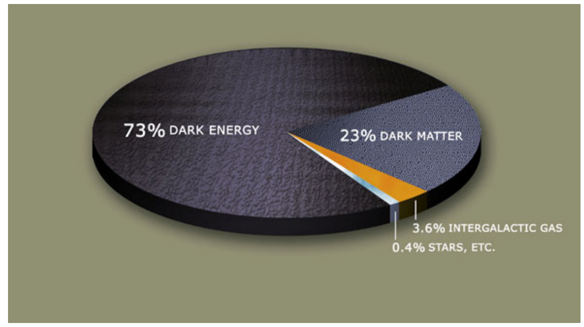
$\Omega_{dark\ matter}$ = 0.23

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

Taken from the WMAP7 results-

Planck results (http://arxiv.org/pdf/1507.02704v1.pdf)- notice ridiculously small uncertainties

$h=H_0/100$



$\Omega_b h^2$=0.02225+/-0.0016=**0.049**

Ω_m=0.3156+/-0.0091

H_0=67.27+/-0.66

Ω_Λ=0.6844+/-0.0091

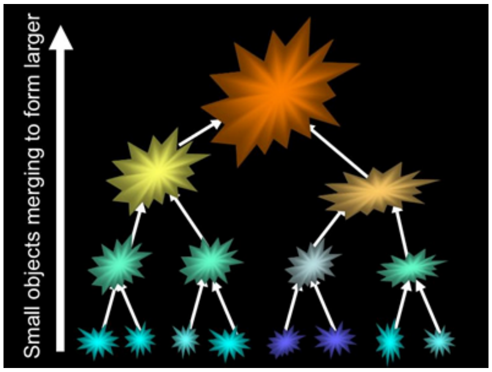
Age 13.813+/-0.026 Gyrs

Deep Breath... What Did we cover?

- Big picture of galaxy research
  - brief history
- What are galaxies
  - 2 generic classes
- How Many Galaxies are There
- How Old are Galaxies
- Galaxies do not live alone- large scale structure
- Baryons, dark matter and how they are sampled by galaxies -complex relation between how the dark matter and baryons (gas and stars) are related and distributed on a wide variety of scales

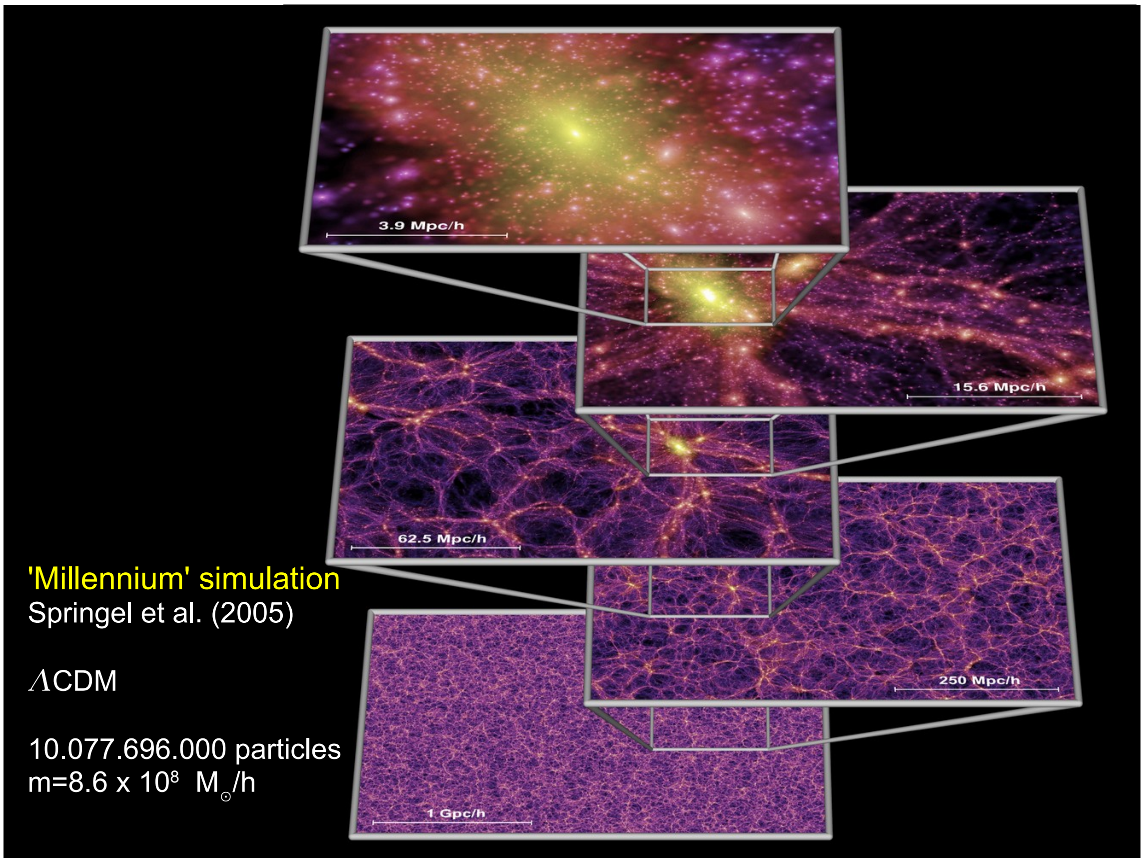
How Things Form (MBW sec. 5.6.1)

- 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



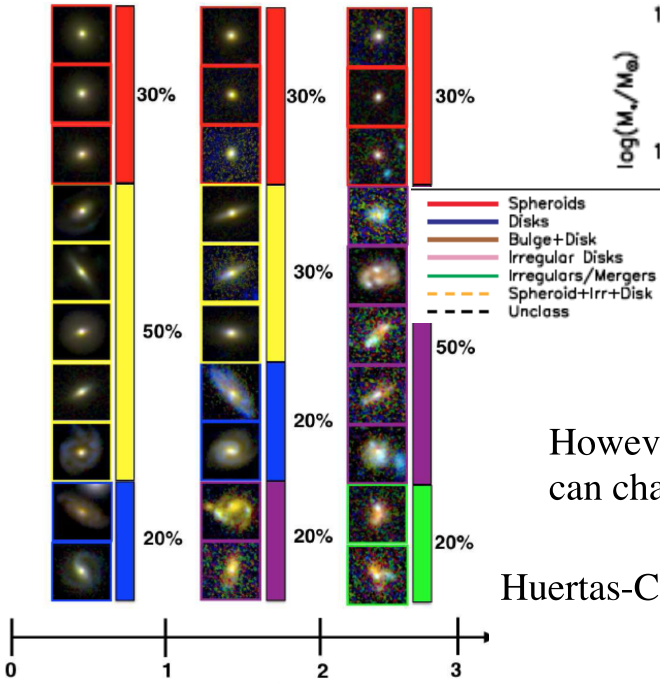
•Hierarchical clustering (or hierarchical merging) is the process by which larger structures are formed through the continuous merging of smaller structures.

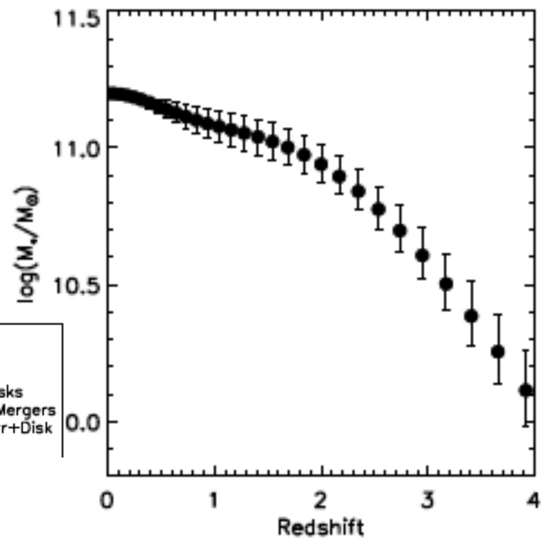
•The structures we see in the Universe today (galaxies, clusters, filaments, sheets and voids) are predicted to have formed by the combination of collapse and mergers according to Cold Dark Matter cosmology (the current concordance model).



Galaxy growth

- predicted growth of **a** massive galaxy (Behroozi et al. (2013) model).



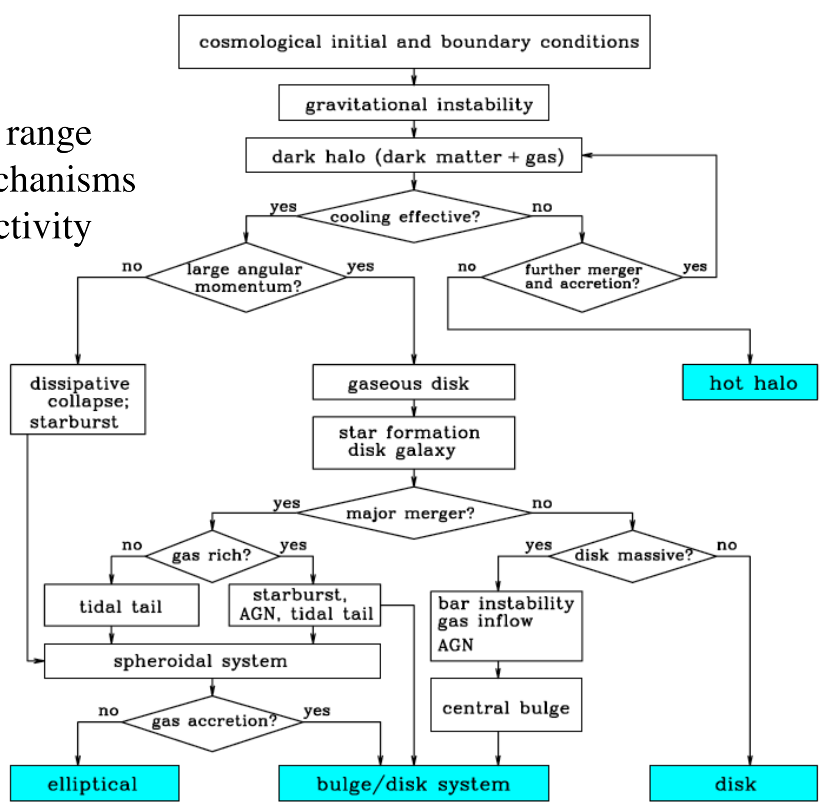


However the nature of a given galaxy can change strongly over cosmic time

Huertas-Company et al. 2015 CANDELS

1.2 Basic Elements of Galaxy Formation

MWB fig 1.1
Notice the vast range of physical mechanisms and interconnectivity



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, ...

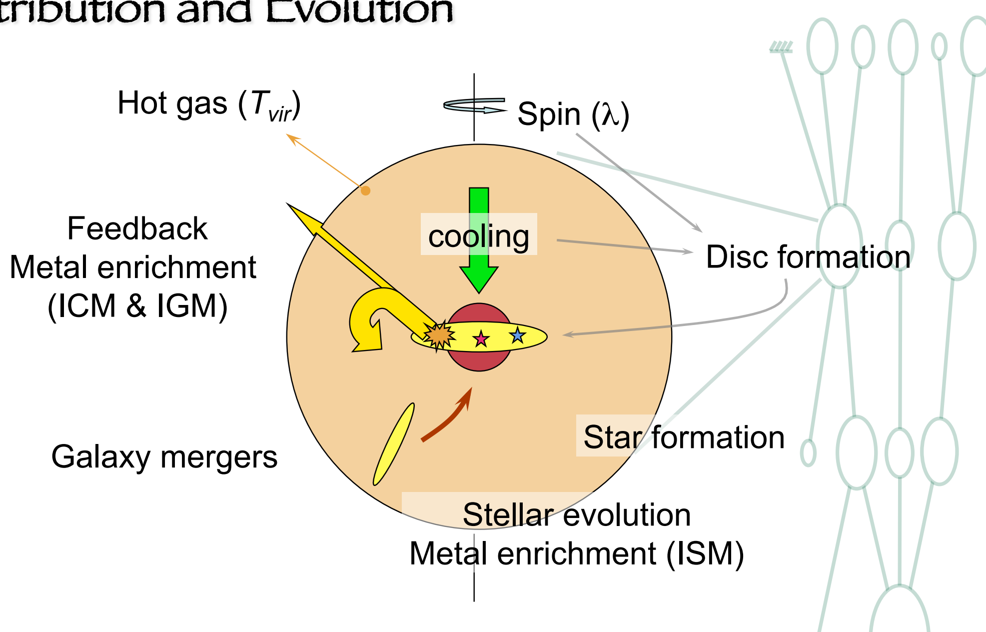
Winds (IGM heating, enrichment, SN feedback, etc...)

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

we will discuss <u>some</u> of these processes in the class

taken from **J. Blaizot** presentation

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

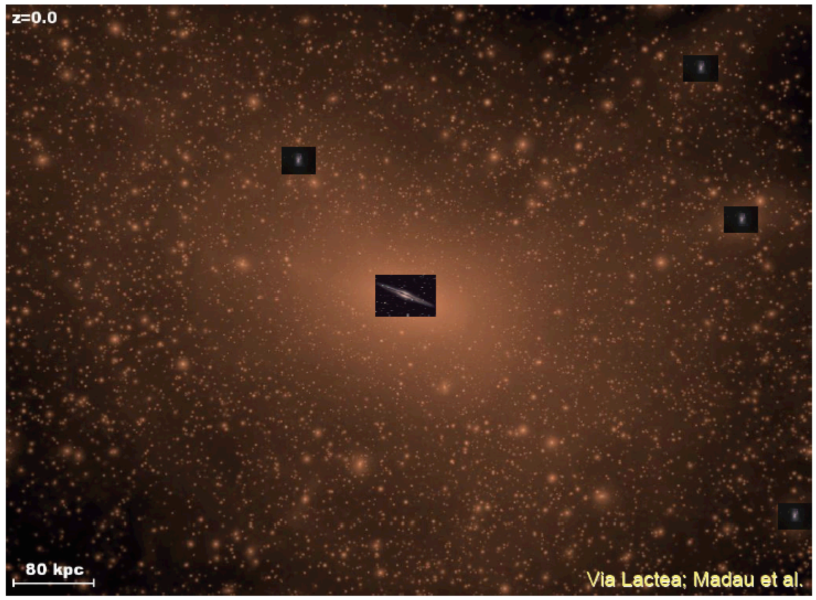


+ model of simple stellar population evolution (w/ dust)

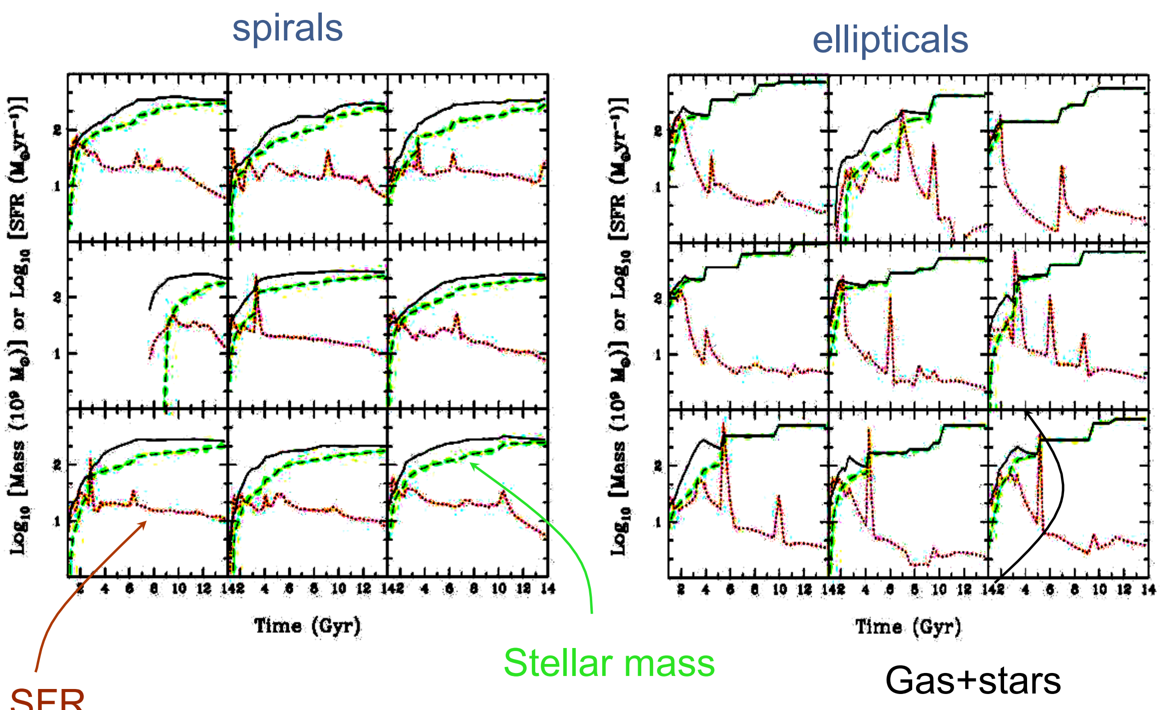
taken from J. Blaizot presentation

Dark Matter Distribution and Galaxies

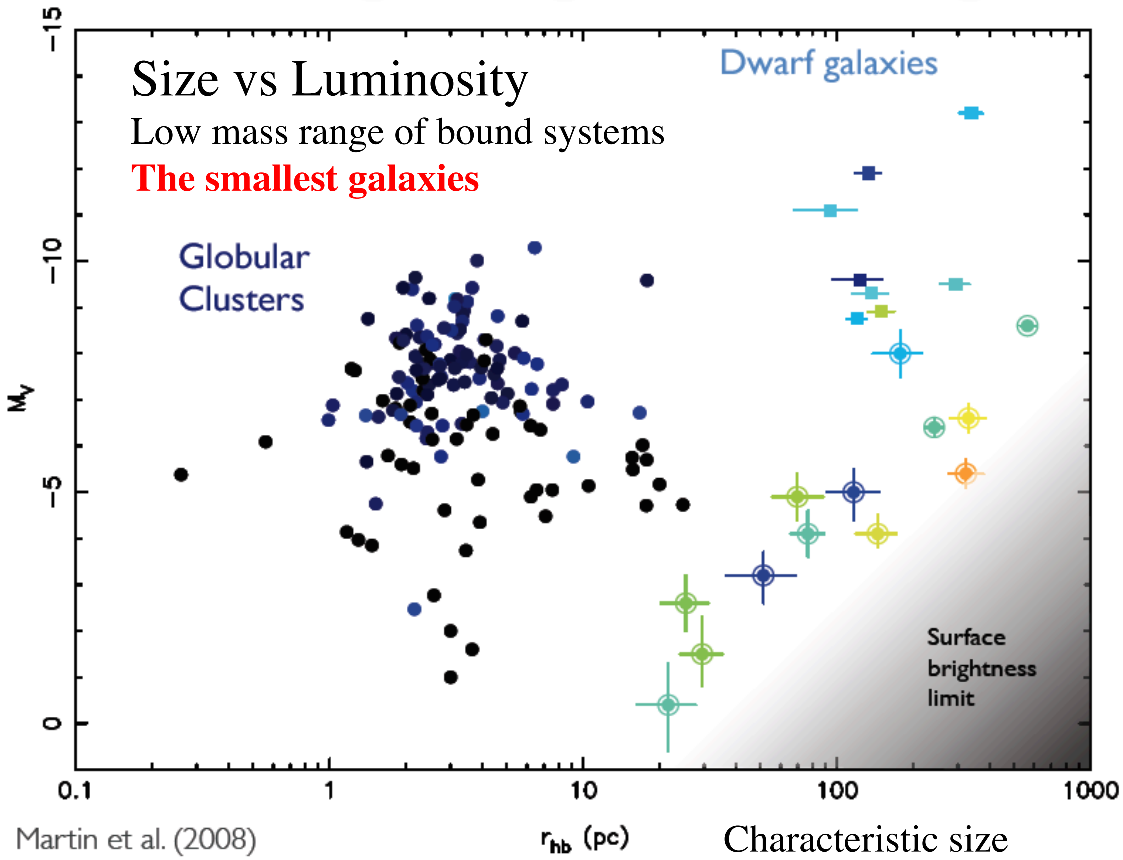
- A numerical simulation of the formation of structure (Madau et al 2008) shows the scale of dark matter and the baryons can be rather different- notice that many of the dark matter halos are NOT populated by stars.



A set of results from numerical simulations

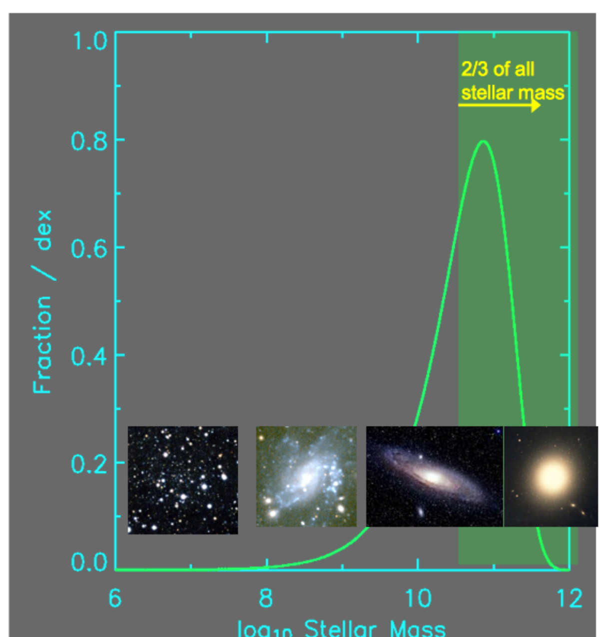


notice SFR not constant
mass growth has 'jumps' - mergers J. Blaizot-



Galaxies Have a Wide Range in Mass

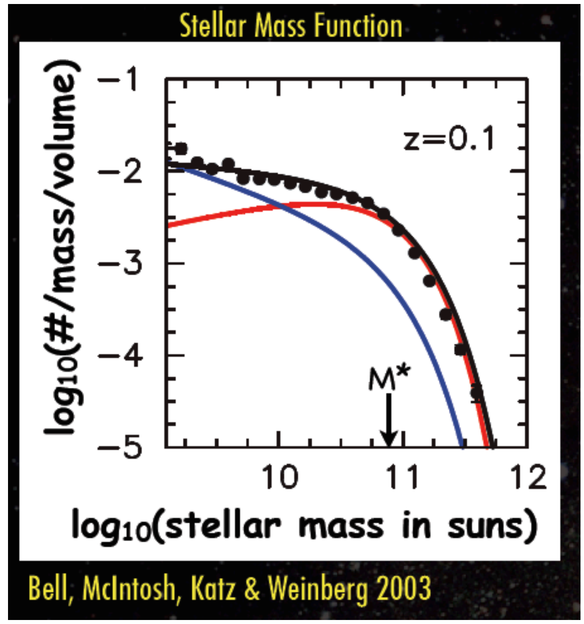
- There is a range of ~10^8 in galaxy masses- but most stars reside in galaxies in a narrow mass range ~6+/-3x$10^{10}M_\odot$ (in stars)
- The baryons are distributed in gas, stars and dust; wide range in gas/stars, relatively narrow range in dust/gas.
- Please listen carefully… I often jump back and forth between total mass and stellar mass



Bell et al. 2003

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



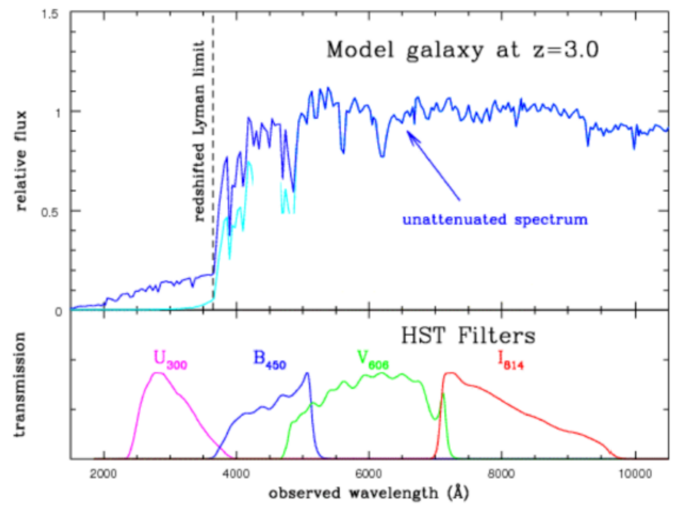
Galaxies Have Very Different Appearances in Different Wave Bands

- The physical processes which dominate in different wavebands are often very different
  - optical - starlight
  - UV- starlight from massive young stars
  - near IR- old stars
  - far IR - dust
  - radio - synchrotron emission from relativistic particles
  - x-ray - x-ray binaries and hot gas

Historically galaxy studies have been dominated by 'optical (rest frame) data.

Use of Filters to Determine Redshift of Distant Galaxy

- HST filter set is different and depends on which camera is used.
- observe galaxies in broad-band filters, and then interpret the resulting spectral energy distribution to learn about the galaxies' masses, star formation rates, ages, and metallicities.
- Need a detailed understanding of the stellar populations within the galaxy, and on accurately characterizing the luminosities and colors of the billions of stars which contribute to a galaxy's light (J. Dalcanton)



Panchromatic Milky Way

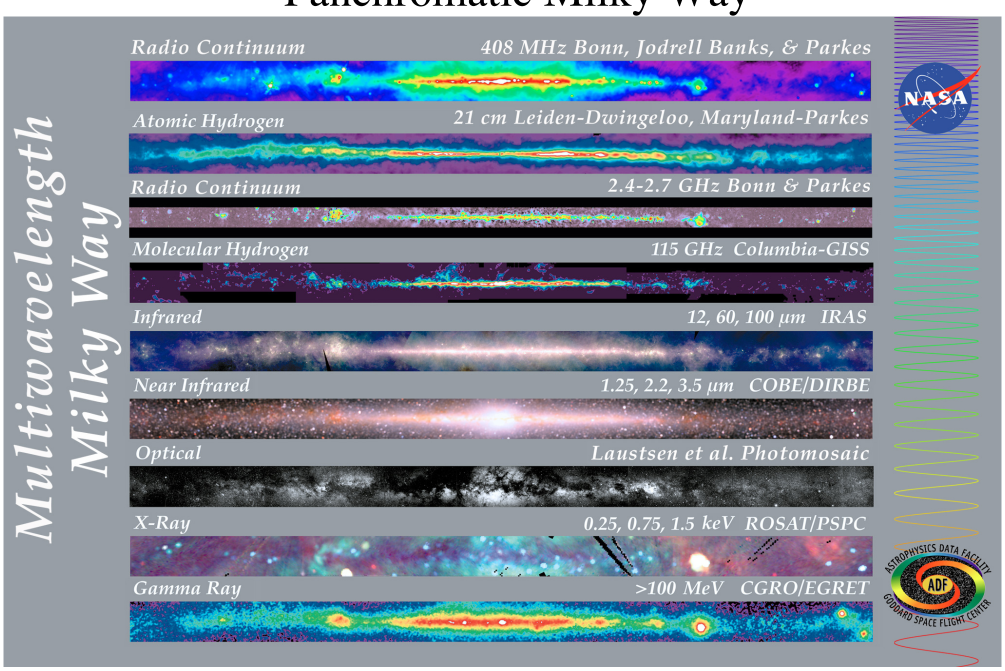
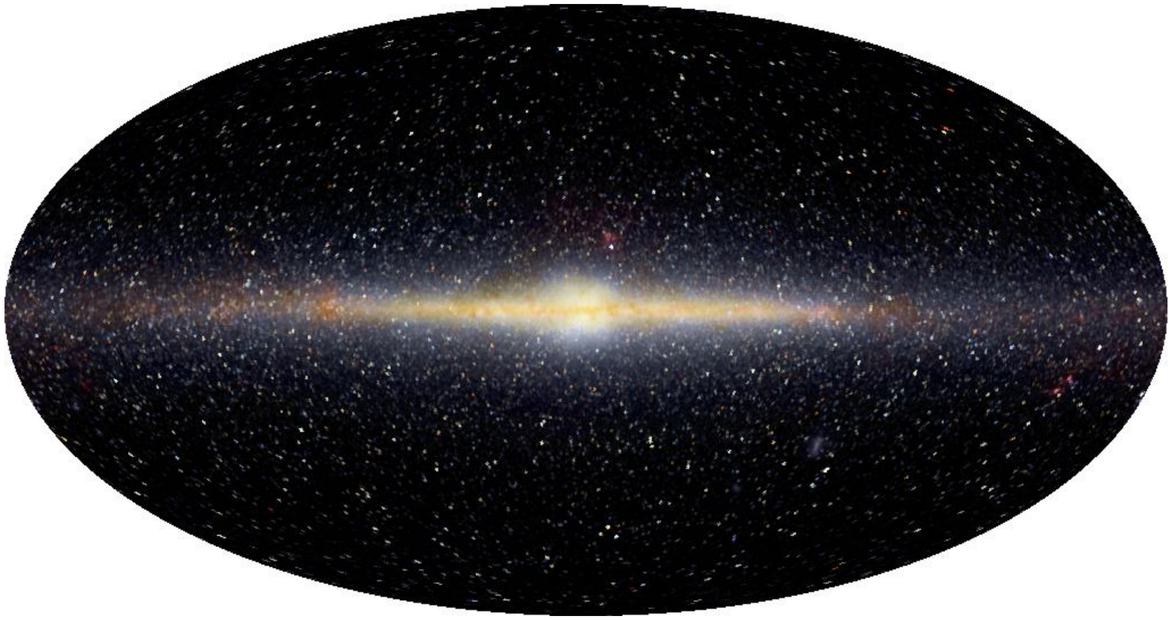


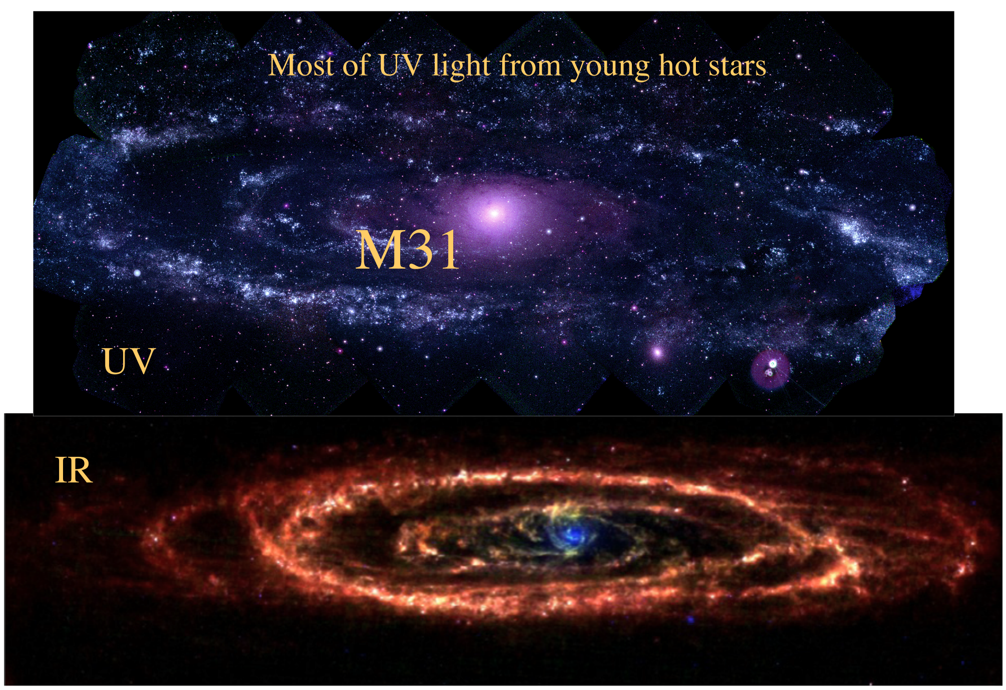
Image of MW galactic plane from radio through γ-rays

Image of MW in IR From COBE



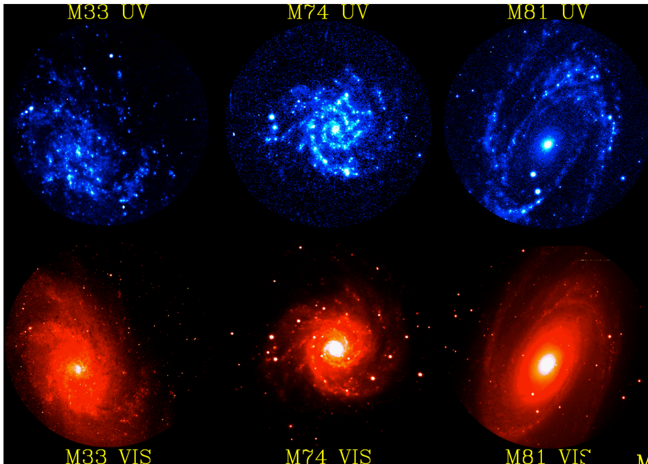
In the IR the effects of dust are minimized and one can see the true distribution of emitted radiation. In this wavelength band the emission is due mostly to old low mass stars

Different Appearances at Different Wavelengths



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

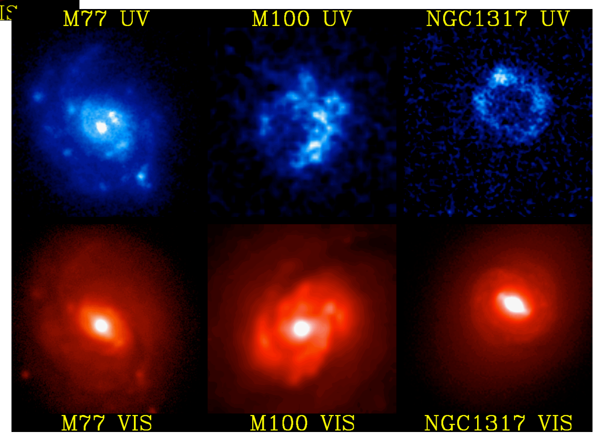
at long IR wavelengths the emission is due to dust which has reprocessed optical/UV light



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

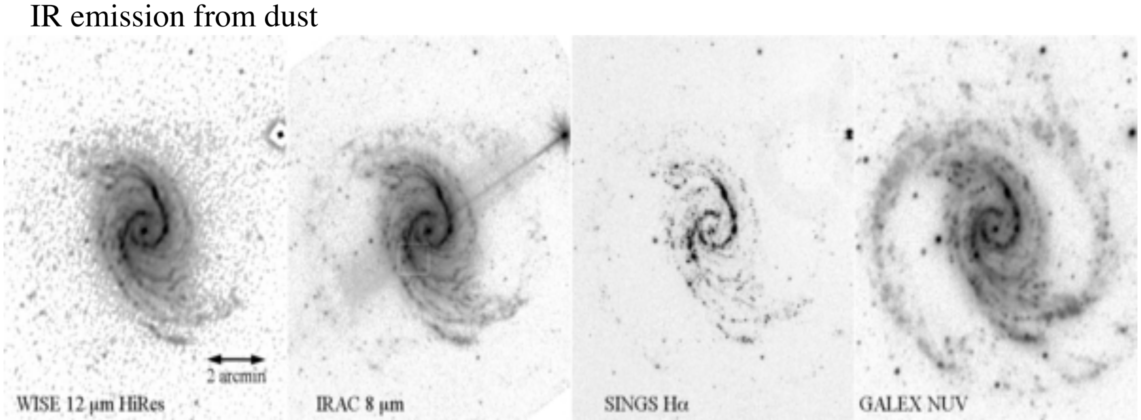
From UIT team



Difference between UV, optical and IR becomes important in studying the high redshift universe

NGC1566 in 4 Bands- 4 Different Surveys and Telescopes

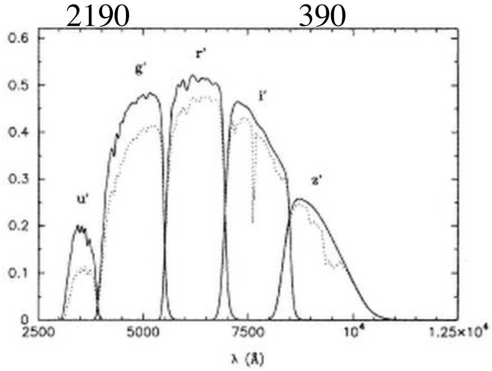
- Each of these bands reveals different information about the stars, dust and star formation rate in the galaxy
- $H\alpha$- youngest stars
- NUV young stars
- IR emission from small molecules (PAHs)
- IR emission from dust



Dust PAH $H\alpha$ NUV

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!
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