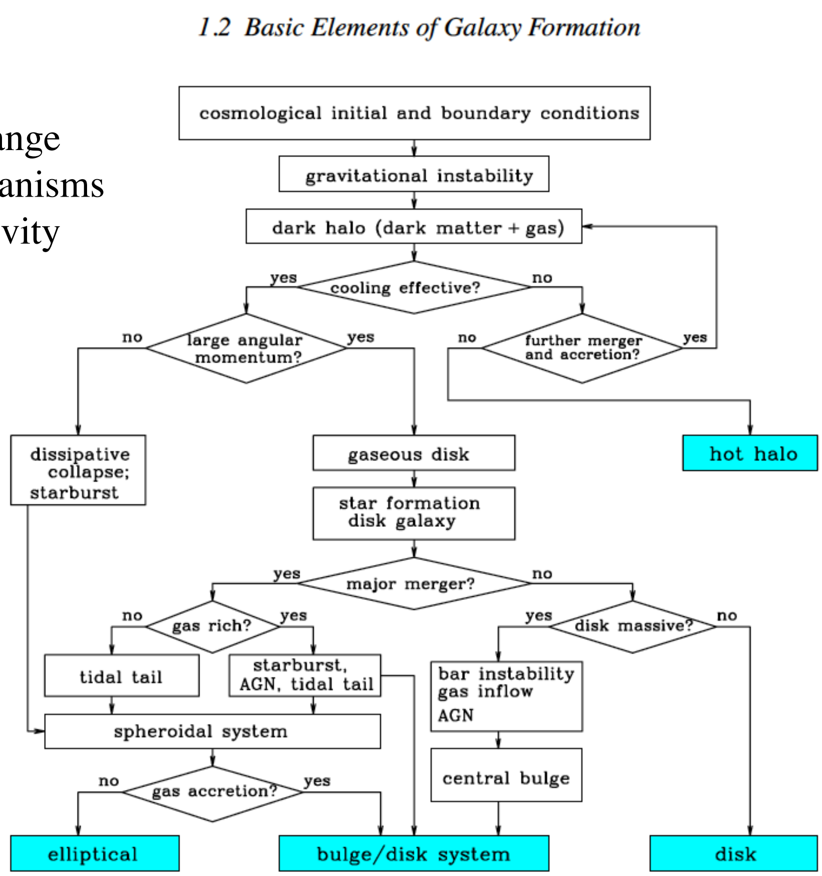
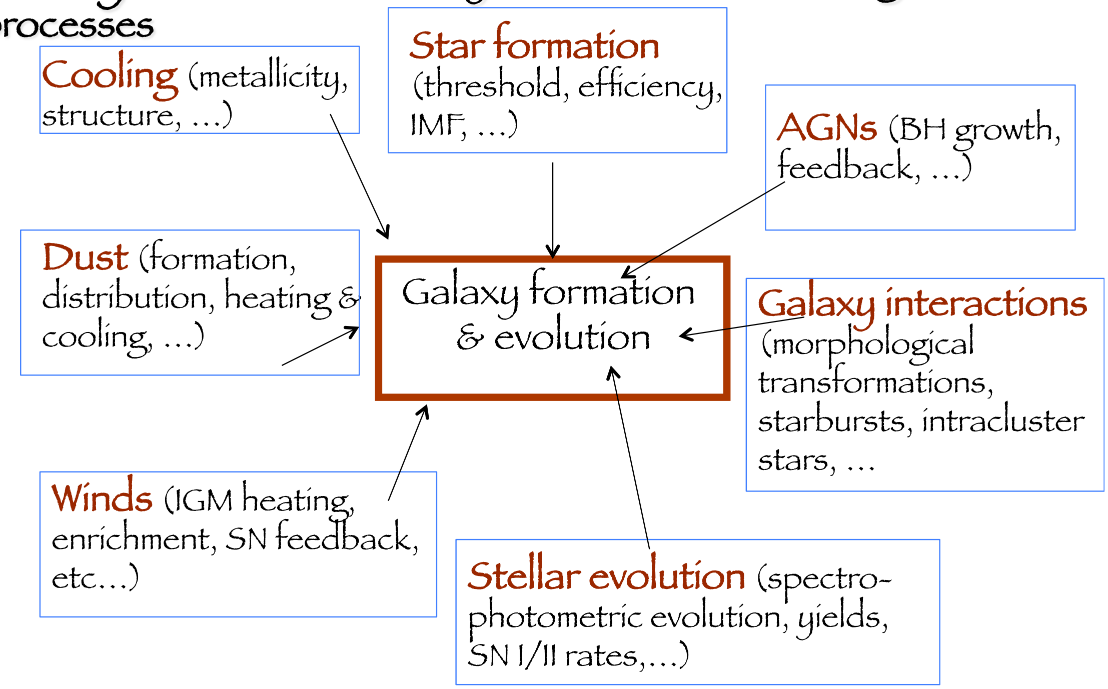
Organization of how we will have our ~10 minute presentations on literature relevant to the lectures.

Remember
MBW fig 1.1
Notice the vast range of physical mechanisms and interconnectivity

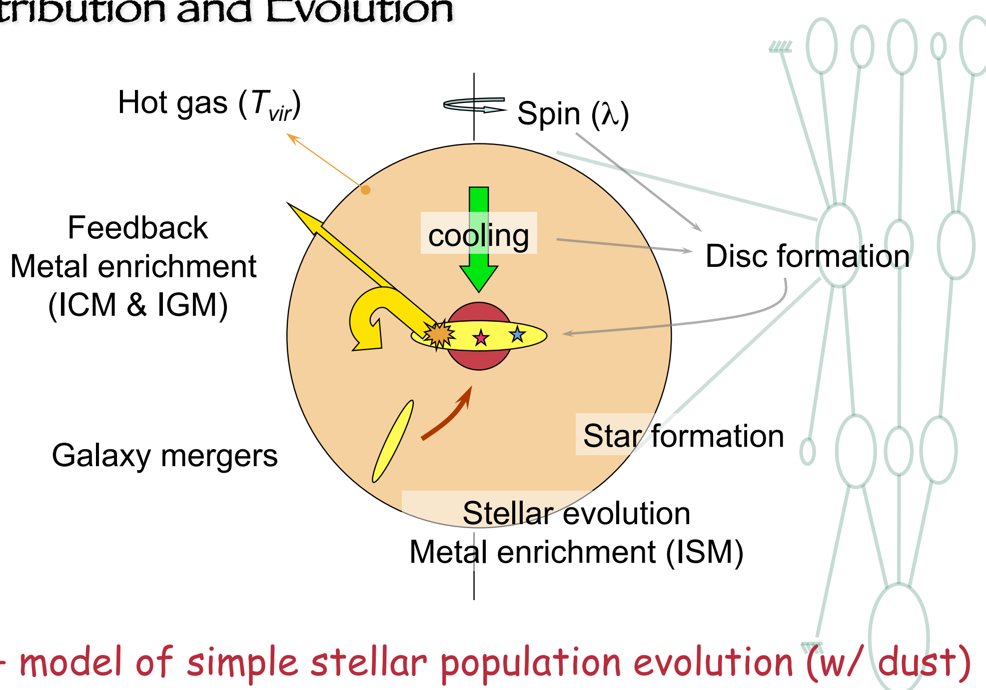


Galaxy formation : Many relevant and interacting processes



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

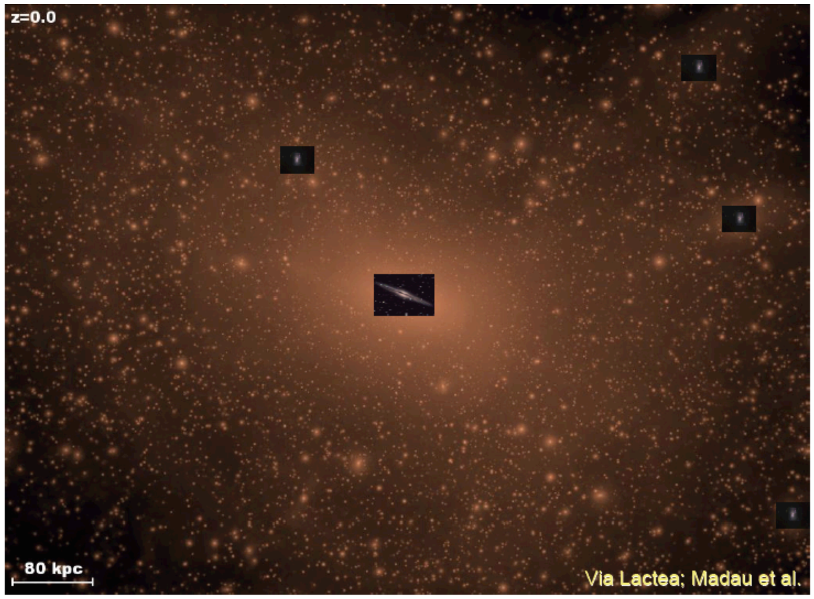


+ model of simple stellar population evolution (w/ dust)

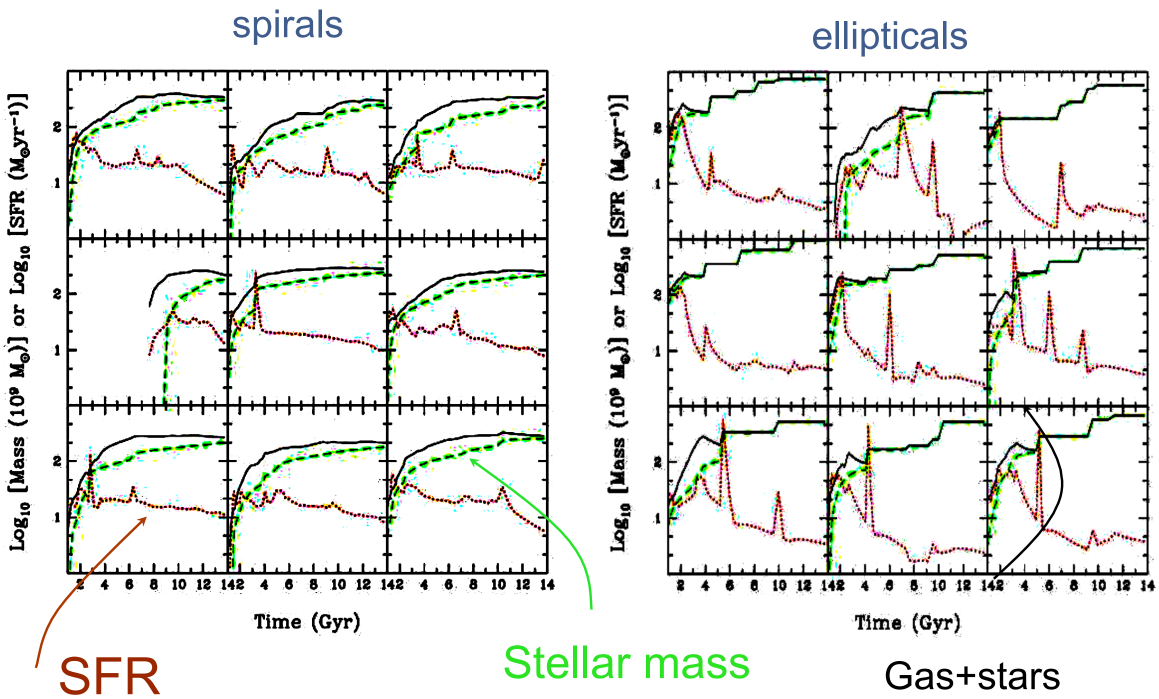
taken from J. Blaizot presentation

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

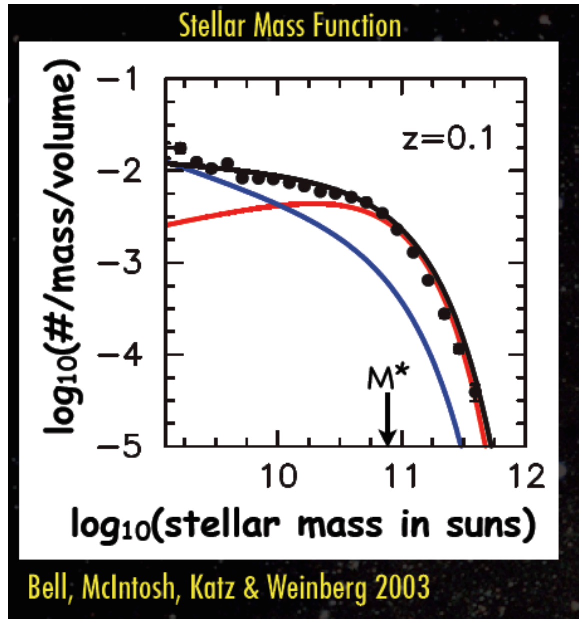


notice SFR not constant

mass growth has 'jumps' - **mergers** J. Blaizot-

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 +AGN

x-ray - x-ray binaries and hot gas+AGN

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

Panchromatic Milky Way

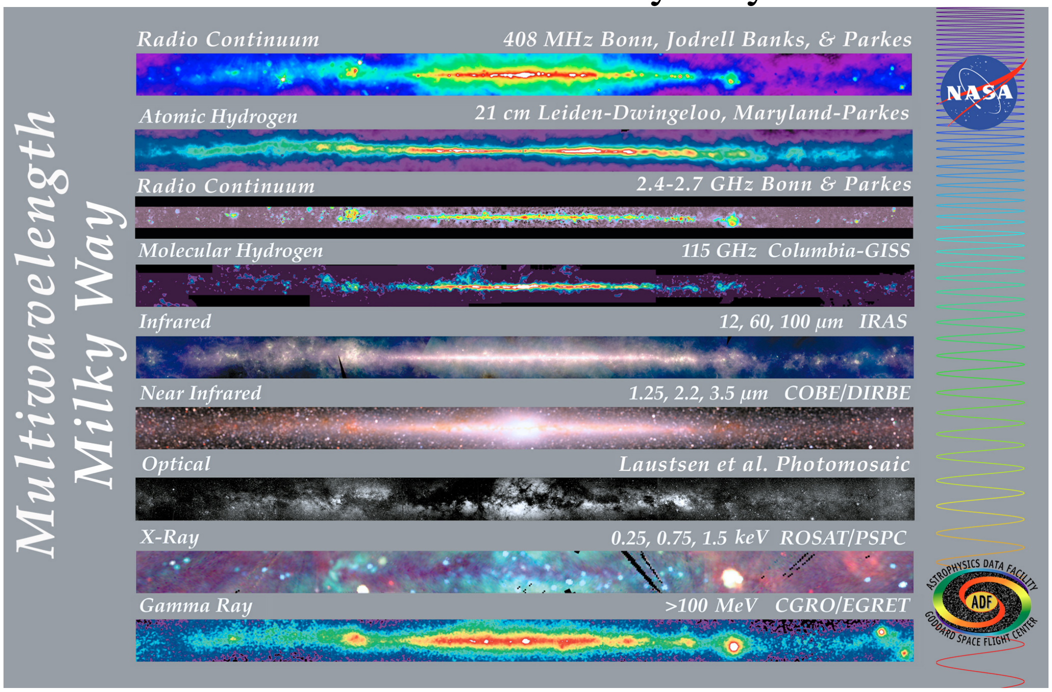
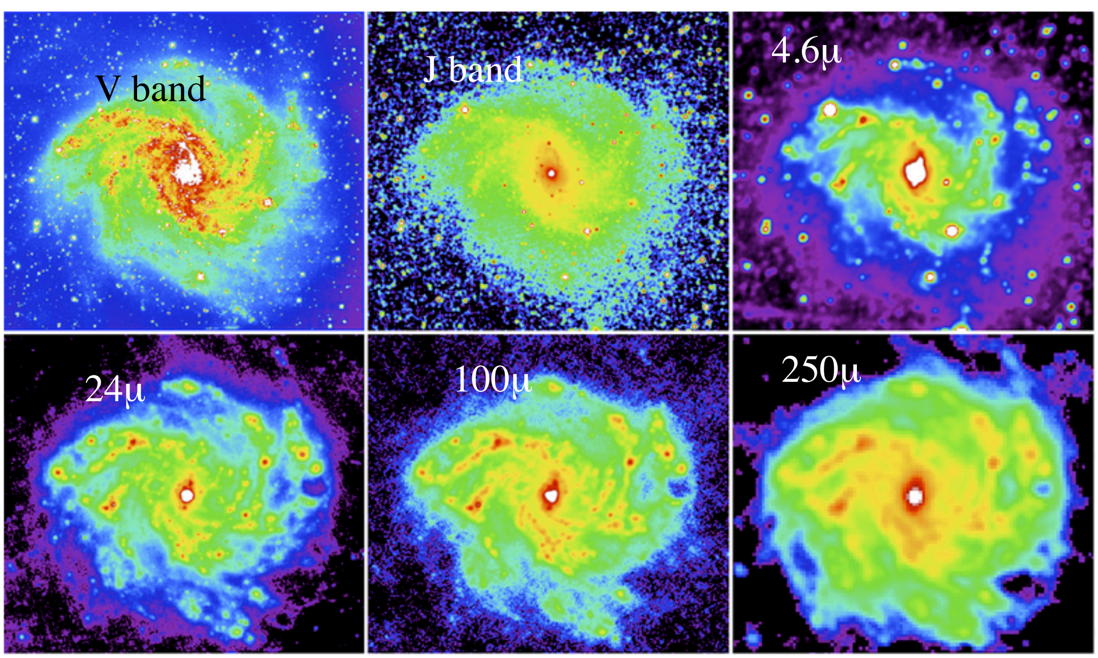


Image of MW galactic plane from radio through γ-rays

MultiWave Length Image of NGC6946
DustPedia



Images of the nearby galaxy NGC6946 - from left to right V(SDSS), J(2MASS), 4.6μm(WISE), 24μm(Spitzer), 100μm(PACS) and 250μm(SPIRE).

NGC6946

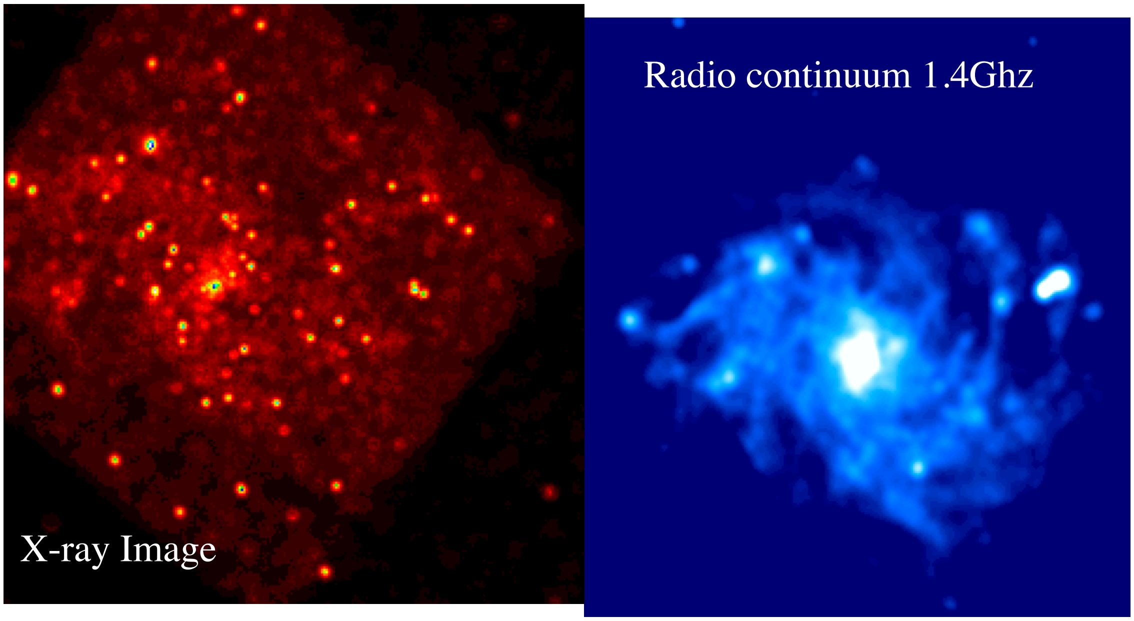
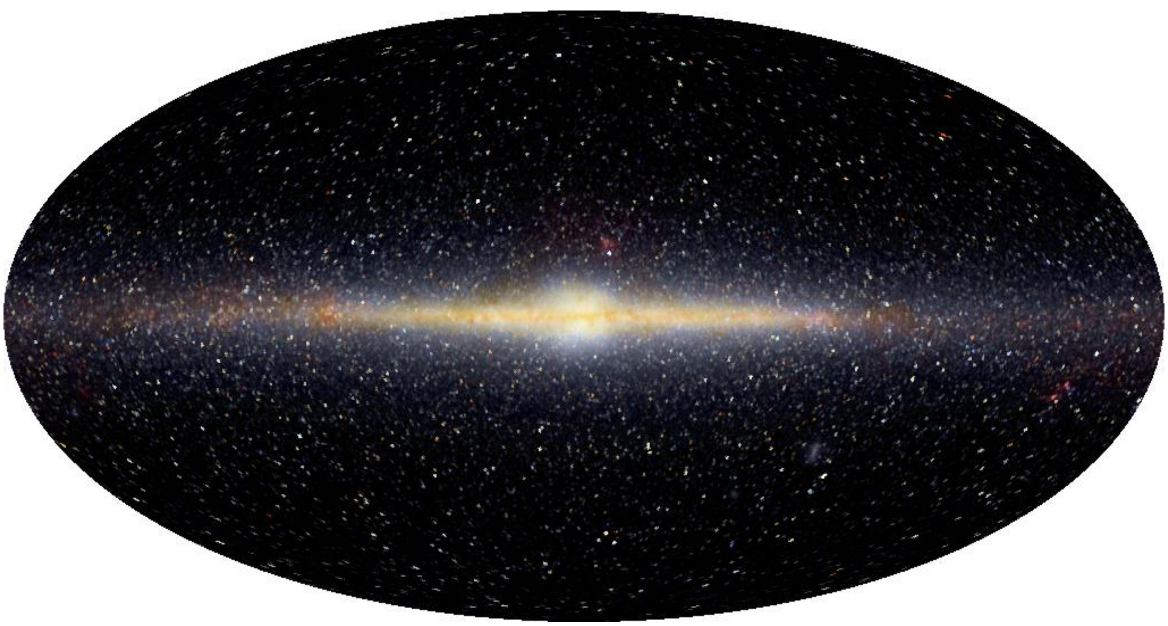


Image of MW in IR From COBE

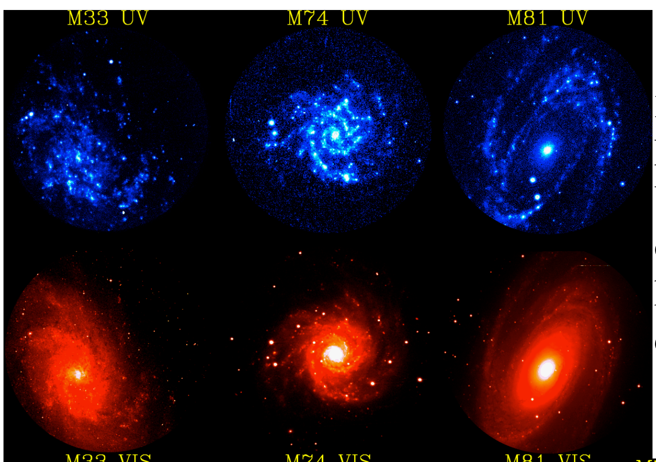


In the IR the effects of dust are minimized and one can see the true distribution of emitted radiation. In this wavelength band the emission is due mostly to old low mass stars

Different Appearances at Different Wavelengths

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

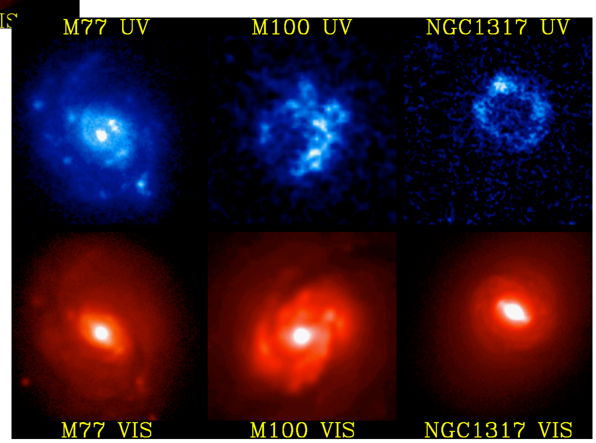
at long IR wavelengths the emission is due to dust which has reprocessed optical/UV light



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

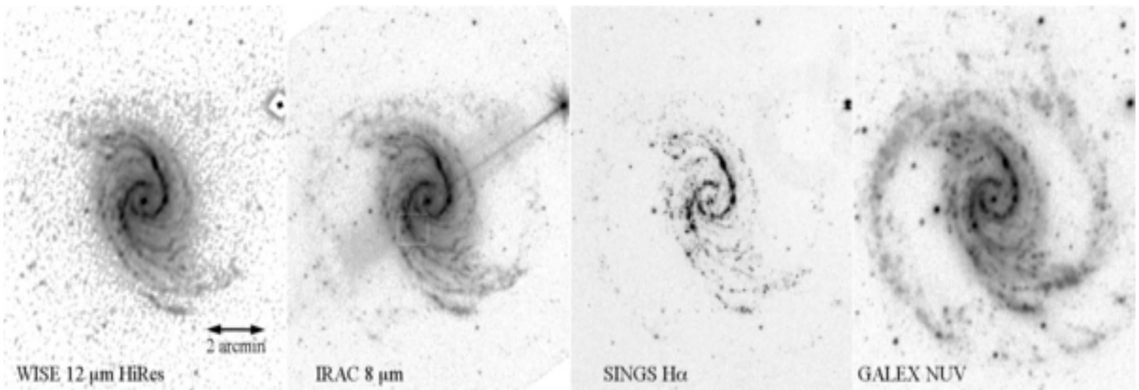
From UIT team



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

NGC1566 in 4 Bands- 4 Different Surveys and Telescopes

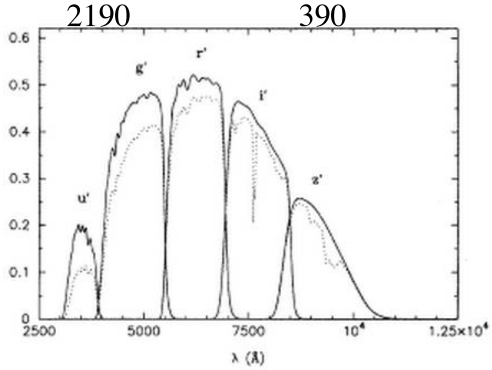
- Each of these bands reveals different information about the stars, dust and star formation rate in the galaxy
- Hα- youngest stars
- NUV young stars
- IR emission from small molecules (PAHs)
- IR emission from dust



Dust | PAH | Hα | NUV

A Bewildering Variety of Bands and Names

Name	wavelength nm	Δλ
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
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)

Outside of the Optical

- There are even more "names" and wavelengths e.g. in the radio we have

L band	1 - 2	Ghz
S band	2 - 4	
C band	4 - 8	
X band	8 - 12	
Ku band	12 - 18	
K band	18 - 27	
Ka band	27 - 40	
V band	40 - 75	
W band	75 - 110	

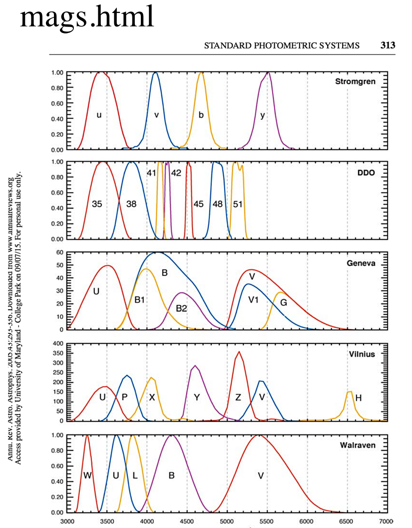
And in the IR there are

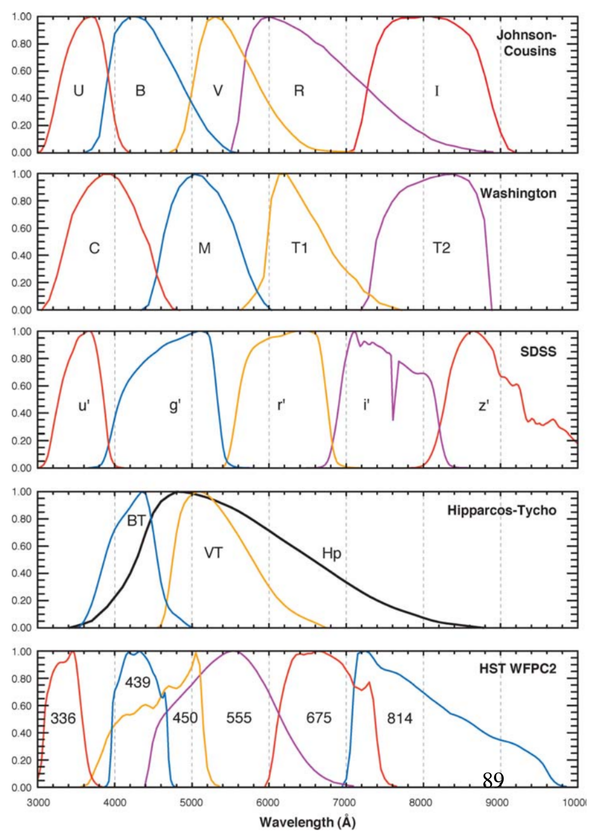
1.1 - 1.4 μ	J band
1.5 - 1.8	H band
2.0 - 2.4	K band
3.0- 4.0	L band
4.6 - 5.0	M
7.5- 14.5	N band
17 - 25	Q band
28- 40	Z band

I will try not to use these- but sometimes it can't be helped!

Some Common Photometric Systems (Bissell 2005)

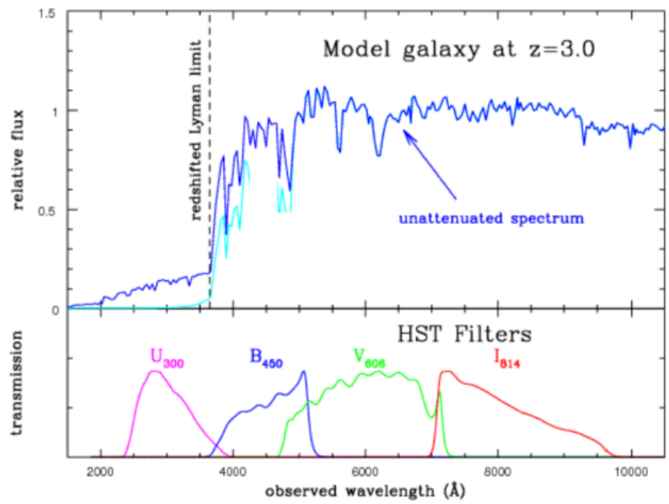
there are also narrow band systems which isolate spectral features in stellar and nebular spectra (*we will not use these much in the class*) https://www.astro.umd.edu/~ssm/ASTR620/mags.html





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)

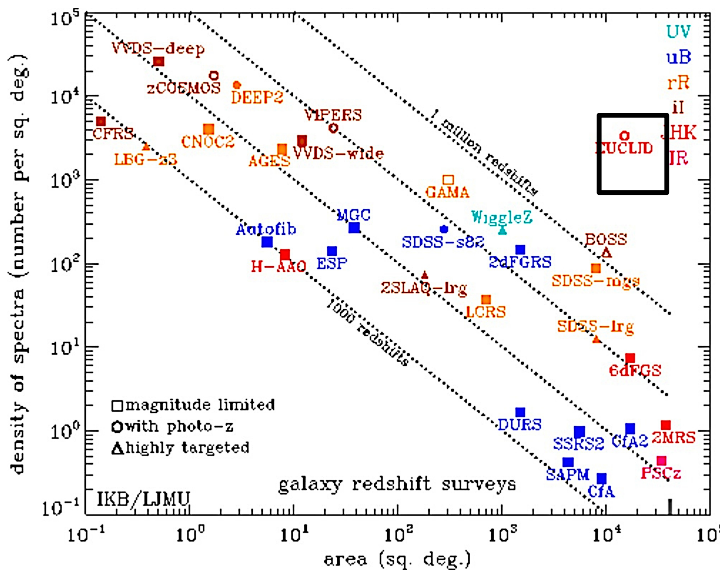


Photometric Systems

- One needs to understand what one is measuring (see Binney and Merrifield pgs 49-57)
- All instruments have a 'bandpass' which defines the frequency range of the data
- Images and sensitivity are a strong function of the 'filter'

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 Also appendix B of B&M for older work
- 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



A sample of recent optical and Near IR surveys

The Epoch of Surveys and Big Data

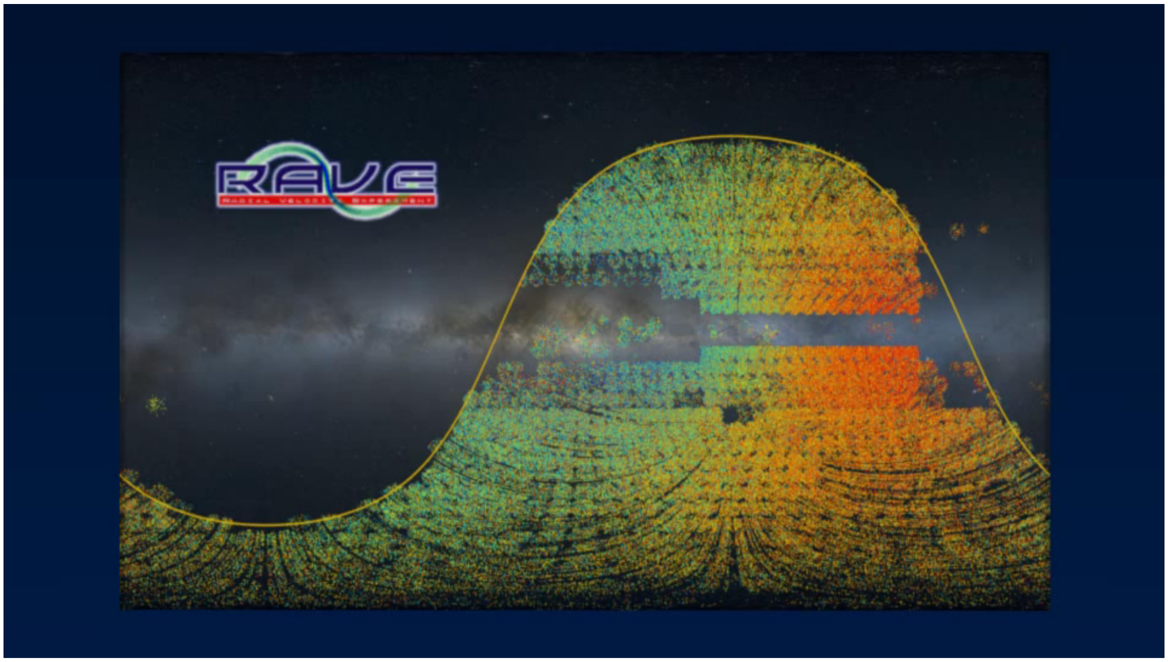
- This is the era of surveys everything from ratio to γ-ray, but especially in the optical and near IR.
- These surveys are both imaging and spectroscopic
- They are designed to
  - determine cosmological parameters
  - find supernova
  - study time variability (ZTF, LSST, PanSTARRS)
  - structure of the Milky Way (GAIA)

see Mickaelian 1511.07322.pd for a review

Survey, Catalogue	Years	Spectral range	Sky area (deg^2)	Sensitivity (mag/mJy)	Number of sources	Density (obj/deg^2)
Fermi-GLAST	2008-2014	10MeV-100GeV	All-sky		3,033	0.07
CGRO	1991-1999	20keV-30GeV	All-sky		1,300	0.03
INTEGRAL	2002-2014	15keV-10MeV	All-sky		1,126	0.03
ROSAT BSC	1990-1999	0.07-2.4 keV	All-sky		18,806	0.46
ROSAT FSC	1990-1999	0.07-2.4 keV	All-sky		105,924	2.57
GALEX AIS	2003-2012	1344-2831Å	21,435	20.8^m	65,266,291	3044.85
APM	2000	opt b, r	20,964	21.0^m	166,466,987	7940.61
MAPS	2003	opt O, E	20,964	21.0^m	89,234,404	4256.55
USNO-A2.0	1998	opt B, R	All-sky	21.0^m	526,280,881	12757.40
USNO-B1.0	2003	opt B, R, I	All-sky	22.5^m	1,045,913,669	25353.64
GSC 2.3.2	2008	opt j, V, F, N	All-sky	22.5^m	945,592,683	22921.79
Tycho-2	1989-1993	opt BT, VT	All-sky	16.3^m	2,539,913	61.57
SDSS DR12	2000-2014	opt u, g, r, i, z	14,555	22.2^m	932,891,133	64094.20
DENIS	1996-2001	0.8-2.4 μm	16,700	18.5^m	355,220,325	21270.68
2MASS PSC	1997-2001	1.1-2.4 μm	All-sky	17.1^m	470,992,970	11417.46
2MASS ESC	1997-2001	1.1-2.4 μm	All-sky	17.1^m	1,647,599	39.94
WISE	2009-2013	3-22 μm	All-sky	15.6^m	563,921,584	13669.83
AKARI IRC	2006-2008	7-26 μm	38,778	50 mJy	870,973	22.46
IRAS PSC	1983	8-120 μm	39,603	400 mJy	245,889	6.21
IRAS FSC	1983	8-120 μm	34,090	400 mJy	173,044	5.08
IRAS SSSC	1983	8-120 μm	39,603	400 mJy	16,740	0.42
AKARI FIS	2006-2008	50-180 μm	40,428	550 mJy	427,071	10.56
Planck	2009-2011	0.35-10 mm	All-sky	183 mJy	33,566	0.81
WMAP	2001-2011	3-14 mm	All-sky	500 mJy	471	0.01
GB6	1986-1987	6 cm	20,320	18 mJy	75,162	3.70
NVSS	1998	21 cm	33,827	2.5 mJy	1,773,484	52.43
FIRST	1999-2015	21 cm	10,000	1 mJy	946,432	94.64
SUMSS	2003-2012	36 cm	8,000	1 mJy	211,050	26.38
WENSS	1998	49/92 cm	9,950	18 mJy	229,420	23.06
7C	2007	198 cm	2,388	40 mJy	43,683	18.29

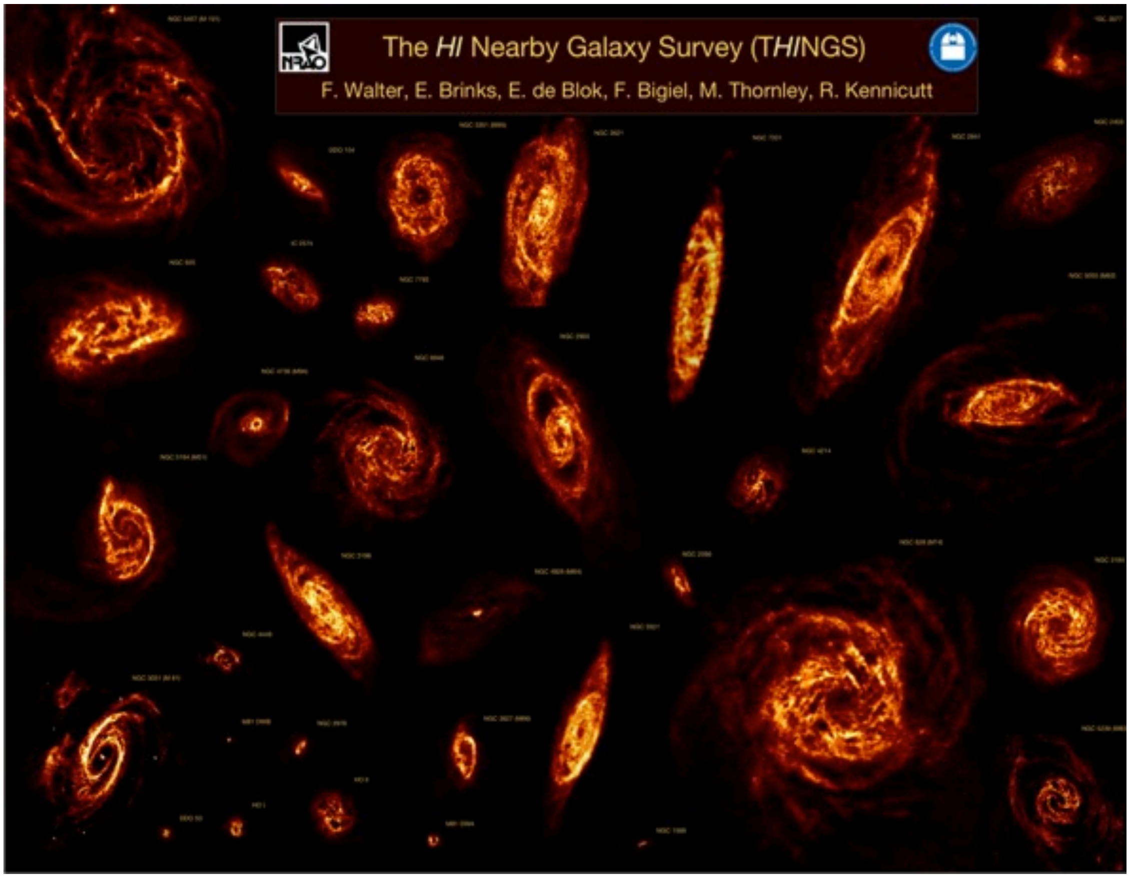
Gaia will measure accurate positions and proper motions for 1 billion stars with an accuracy of about 20 as at 15m, and 200 as at 20m;

RAVE Velocities of 483,330 stars



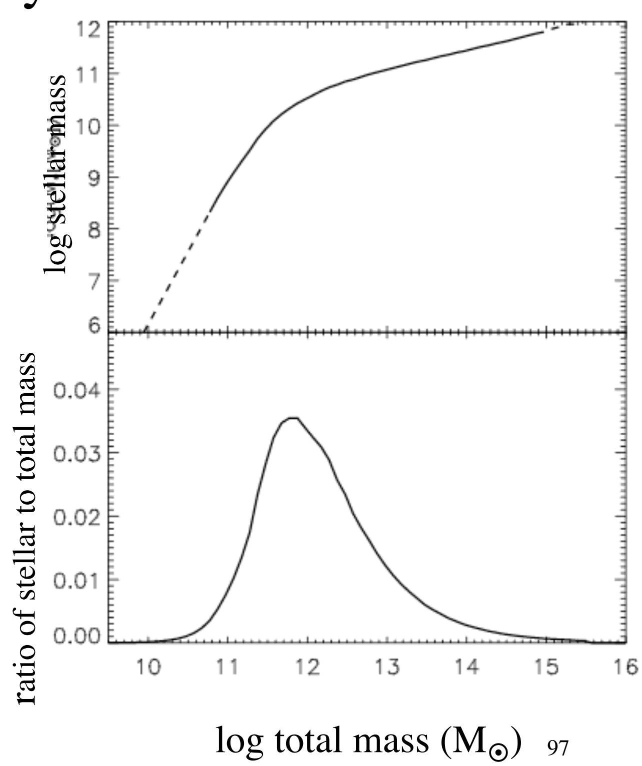
Data Sets are Getting Seriously Big

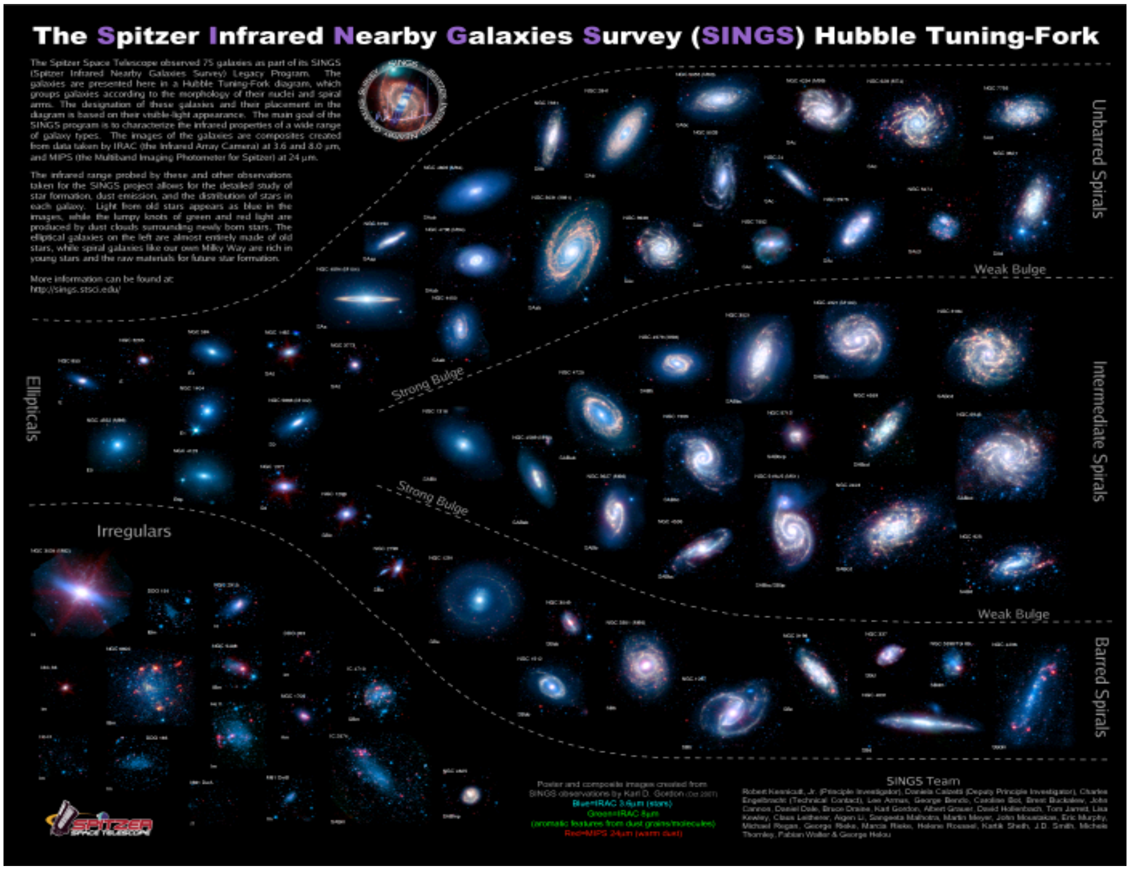
Sky Survey Projects	Data Volume
DPOSS (The Palomar Digital Sky Survey)	3 TB
2MASS (The Two Micron All-Sky Survey)	10 TB
GALEX (The Galaxy Evolution Explorer)	30 TB
SDSS (The Sloan Digital Sky Survey)	116 TB
SkyMapper Southern Sky Survey	500 TB
PanSTARRS	~ 40 PB expected
LSST	~ 200 PB expected
SKA (The Square Kilometer Array)	~ 4.6 EB expected



Dark Matter and Baryons

- While dark matter and baryons are related the ratio of the two depends strongly on the galaxy mass
- At the mass scale of the Milky Way the ratio is maximum (Guo et al 2010) at 0.035



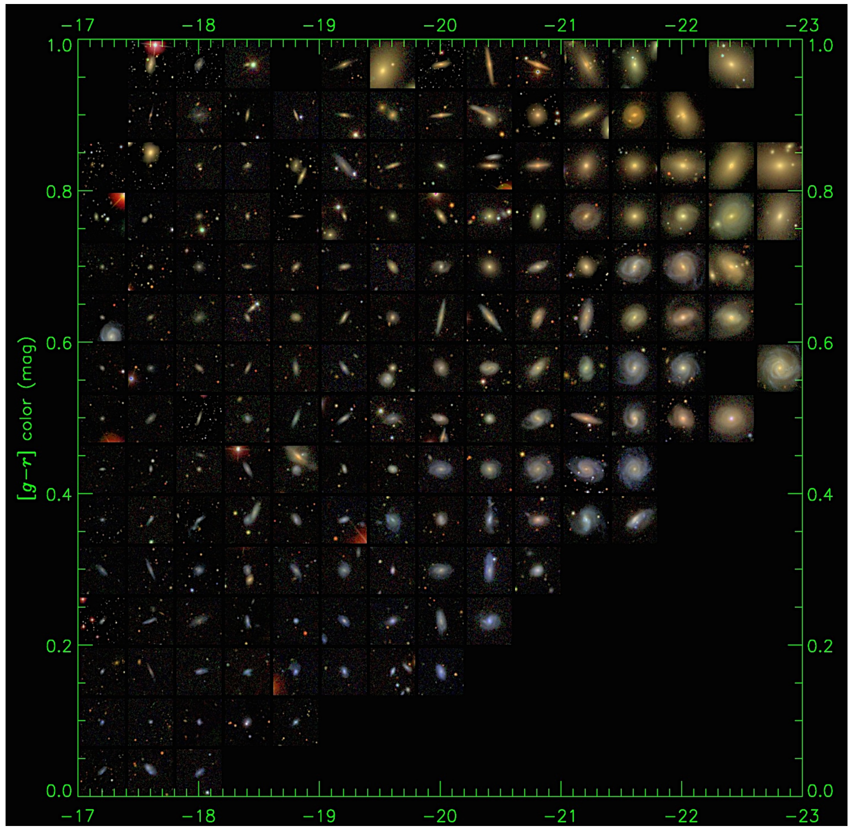


Organization of the Data

- Galaxies only occupy a small fraction of the allowed phase space.
- Thus many parameters are strongly correlated
- Some of these have been given names
  - Tully-Fisher
  - Fundamental plane
  - Faber-Jackson
  - Kormendy relation
- some just have descritptions
  - metallicity mass relation
  - red and blue sequence, green valley

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

'color'



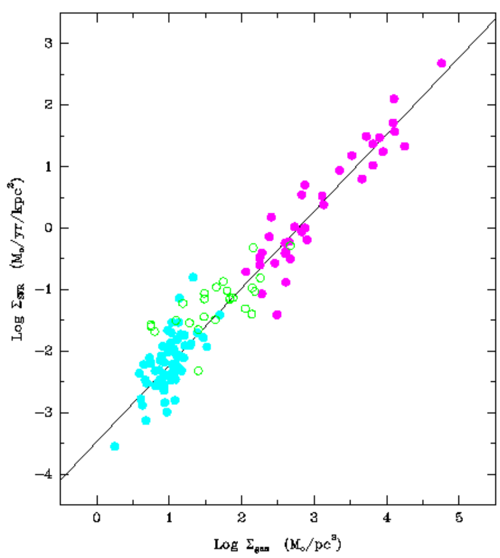
absolute magnitude

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



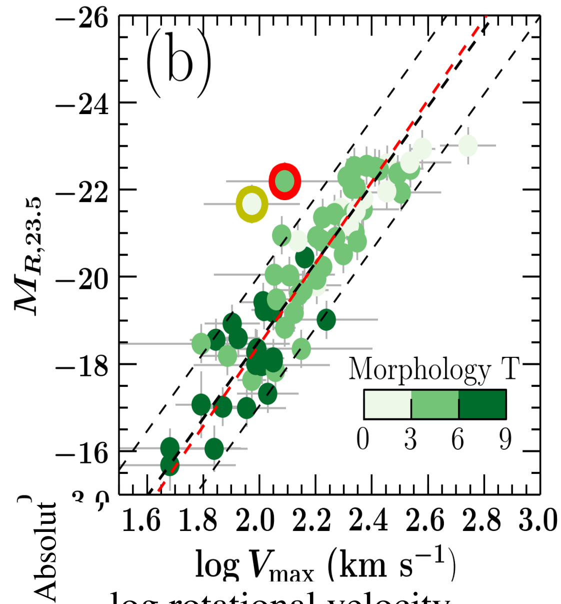
log surface density of gas

Galaxy Patterns

- Tully-Fisher (T-F) relation for Spiral Galaxies:
  - 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**



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

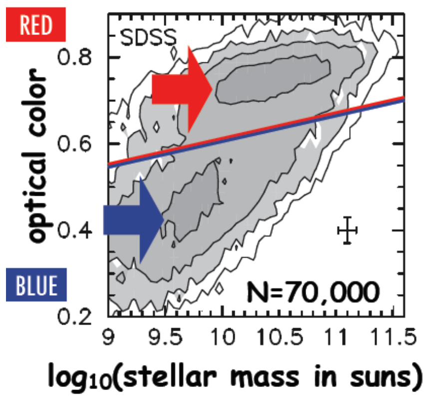
Summary of 2nd Lecture

• 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

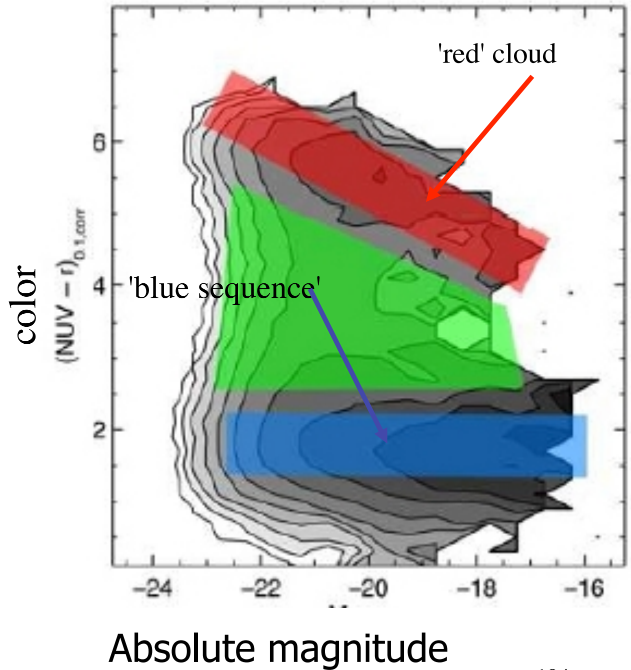
• Visual appearance of galaxies changes strongly across the electromagnetic spectrum with different wavelength ranges best suited to observe certain phenomena
• There is a physical meaning to the classification of galaxies into spirals and ellipticals
– they have different mass functions
– different star formation histories

Galaxy Relations

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



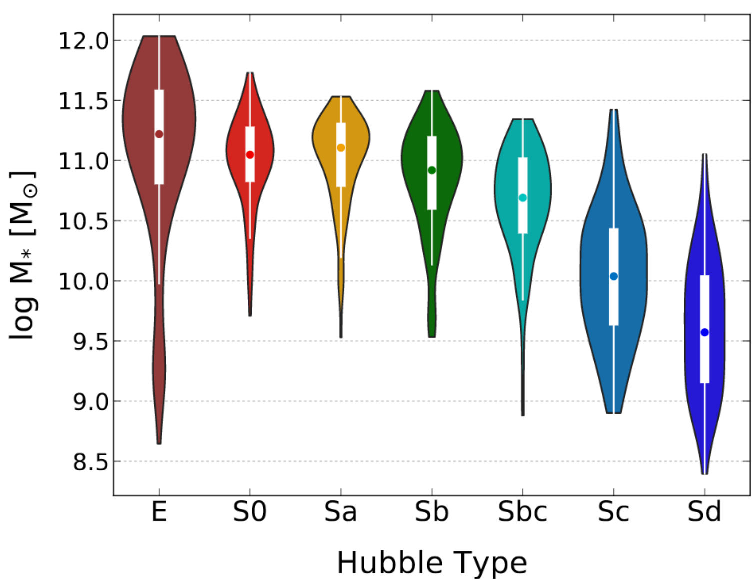
Isopleths- lines of constant galaxy density



Baldry et al 2004

Galaxy Correlations

- There is a very strong correlation between galaxy morphological type and its stellar mass (García-Benito et al 2017)
  - but there is strong overlap, such that a given mass may be obtained for a wide range of Hubble types



the dots represent the median value the width the relative number of galaxies of a given type at a given mass

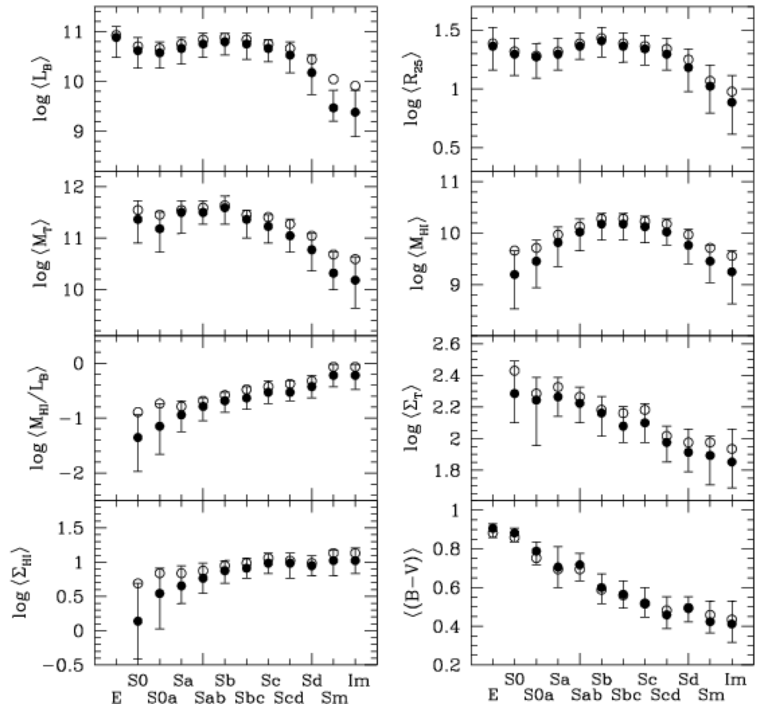
A Physical Meaning to Morphology?

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

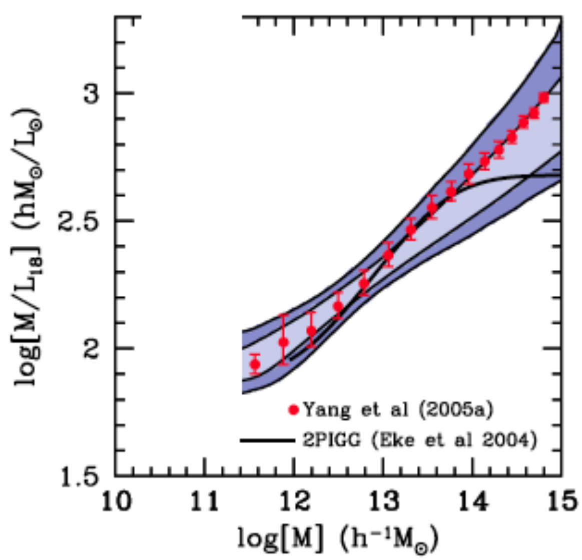
Lot of other correlations particularly with the amount of cold gas, color and surface brightness

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}



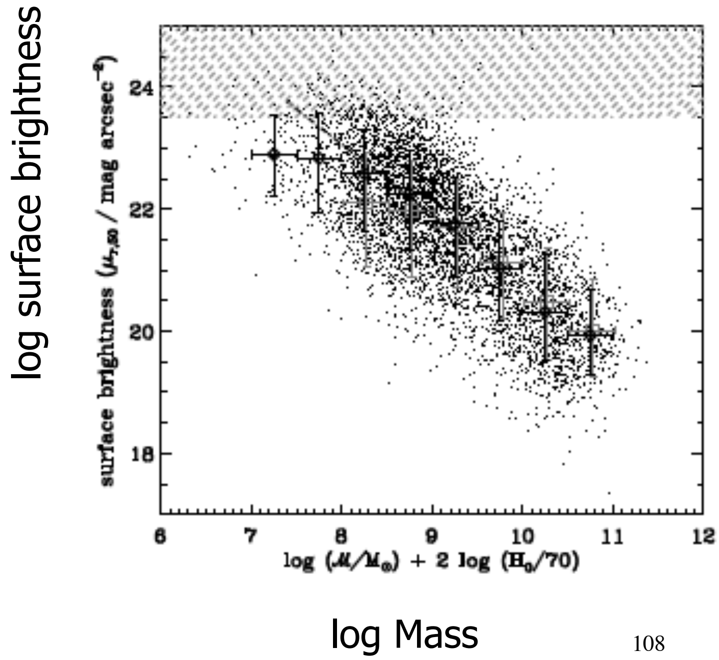
- Different properties of individual galaxies are strongly correlated
  - M_*, L, M/L, t_{age}, SFR, size, shape, [Fe/H], σ, v_{circ}
- 'Mass' is the most often the decisive parameter in setting properties
  - There is a wide range in the ratio of L_*/M_{halo}



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

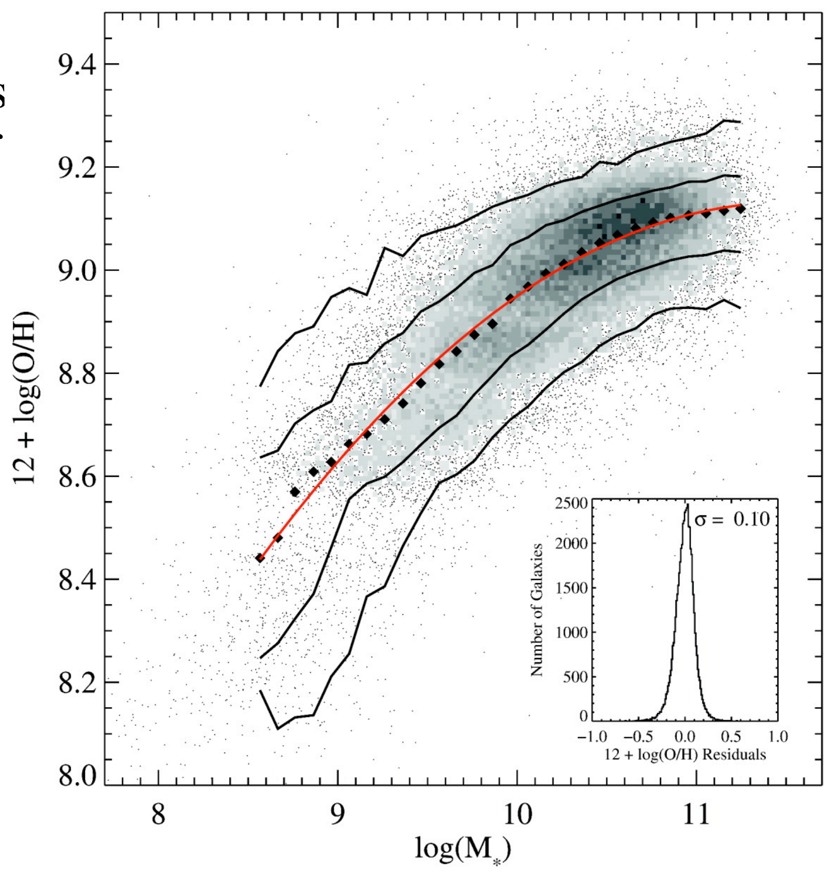
Relationship of Optical Surface Brightness to Mass

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



Chemical composition vs stellar mass of galaxy

- More massive galaxies tend to be "metal rich" (Tremonti et al 2004)



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

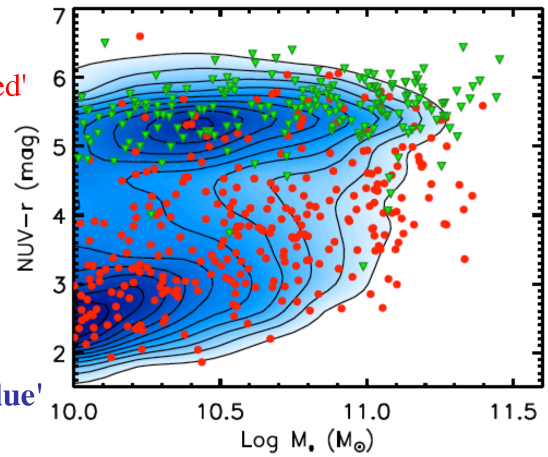


Fig. 4. Color-stellar mass diagram for the GASS *parent sample*, the super-set of ~12,000 galaxies that meet the survey criteria (grayscales). Red circles and green upside-down triangles indicate HI detections and non-detections, respectively, from the representative sample.

Catinella et al 2012

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:
  - formation process: such as hierarchical clustering and merging,which led to formation of major galactic components,such as bulges, disks, haloes, and presumably, the Hubble sequence (e.g.,White & Rees 1978)
  - secular evolution, where material is slowly rearranged through the collective interaction of instabilities, such as bars, ovals, spirals, and triaxial dark matter haloes (Kormendy & Kennicutt 2004)

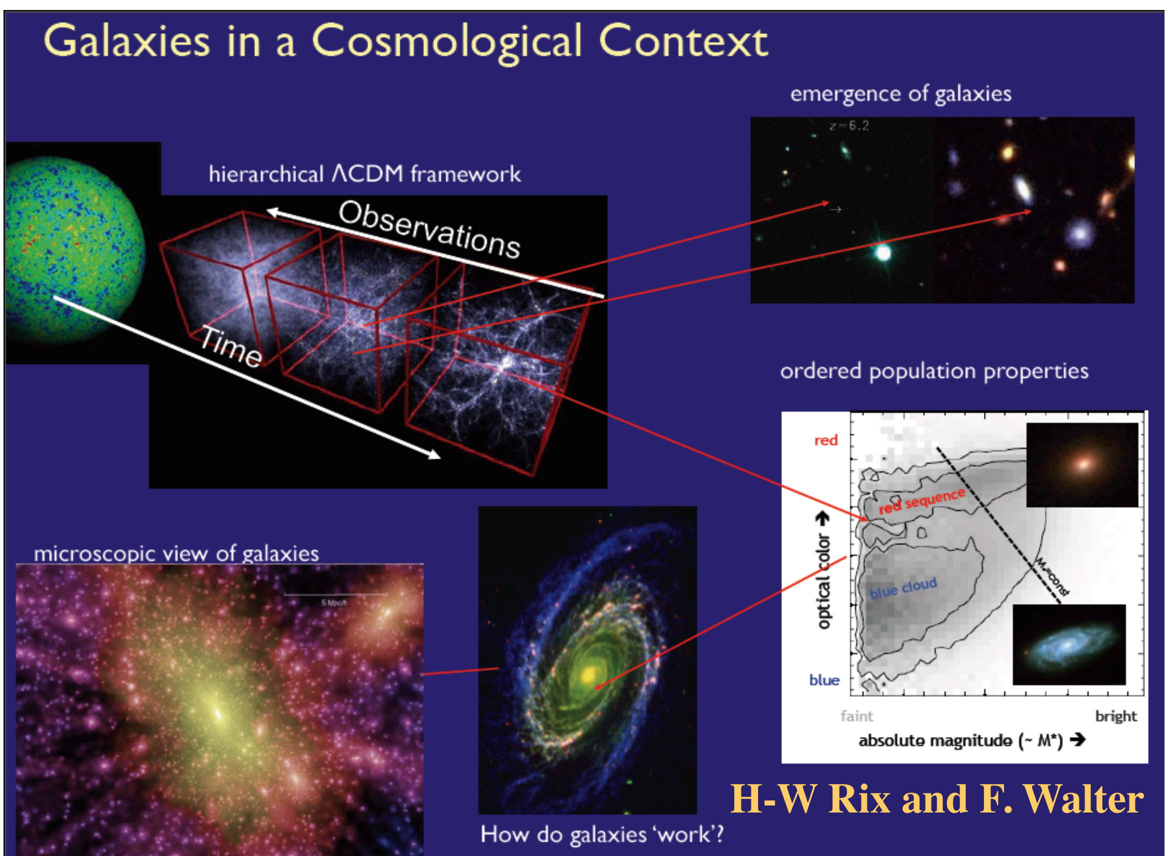
Attempts to Quantify Morphology B&M Ch 4.1

- 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

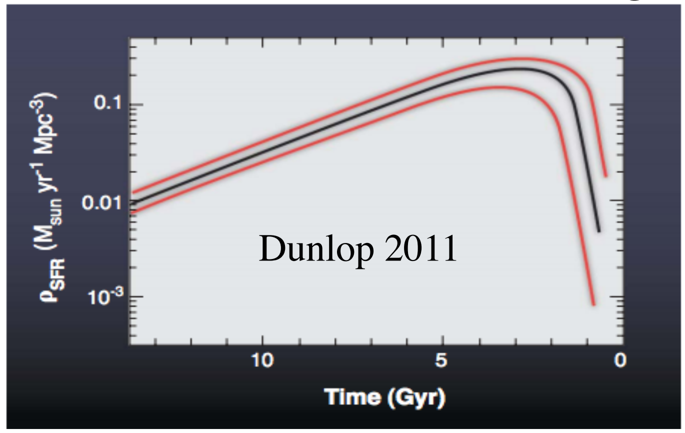
Which of these are meaningful?

What do they tell us about the physical conditions in the galaxy and its history, star formation rate dynamics etc etc



Things Change Over Cosmic Time-downsizing

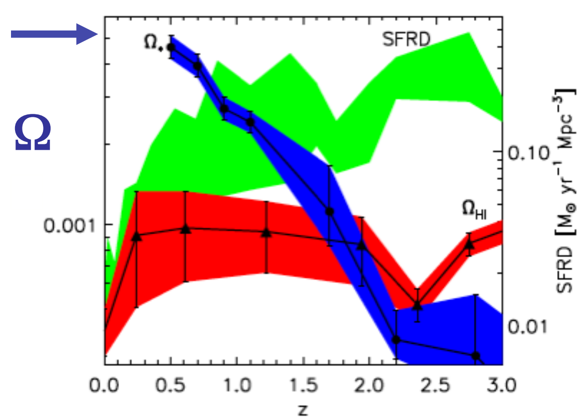
- Over the age of the universe the cosmic star formation rate (solar masses/yr/Mpc^3) has change by over a factor of 30- dropping rapidly over the last 7 Gyrs (since z~1)
- At high redshifts most star formation occurred in the progenitors of today's luminous red galaxies, since z~1 it has occurred in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



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 Star Formation Rate (**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



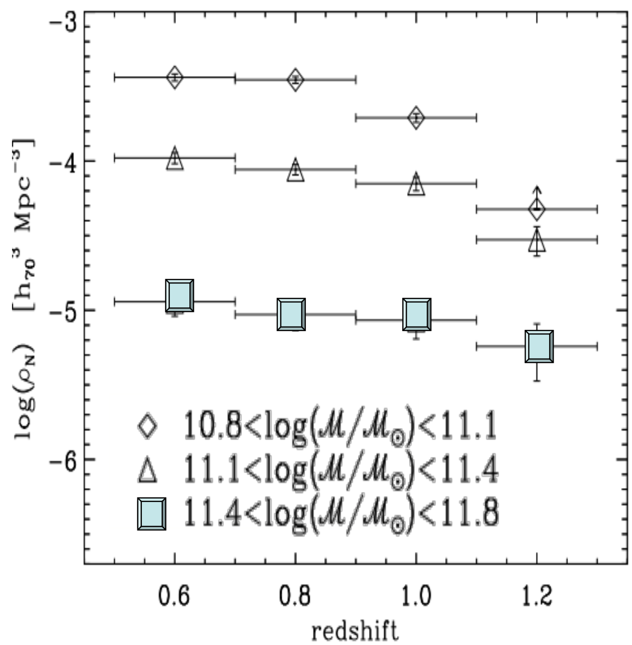
Putnam et al 2010

Things Change Over Cosmic Time-downsizing

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 <u>the less massive the galaxy, the later is its stellar mass assembly on average.</u>

Space Density of Galaxies of Different Mass vs redshift



Galaxy Research is Very Active-partial list of active research areas suitable for a term paper

- 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? (e.g arXiv:1503.08228)
- 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 Lecture-Properties of Stars

- Read sec 2.2, 9.6, 10.2.2, 10.3 (up to 10.3.7) in MBW
- Other material Binney and Merrifield Ch 3.1,3.2,3.5,3.6 and Ch 5.1