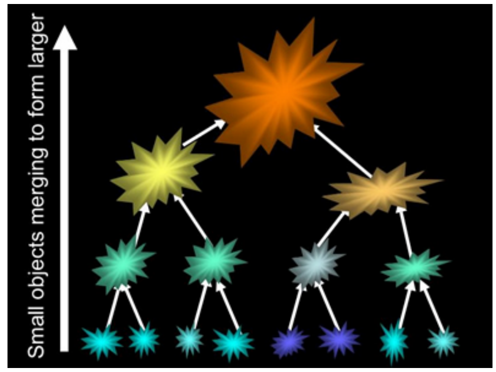
How Things Form

- 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).(see fig 8.16 in text)

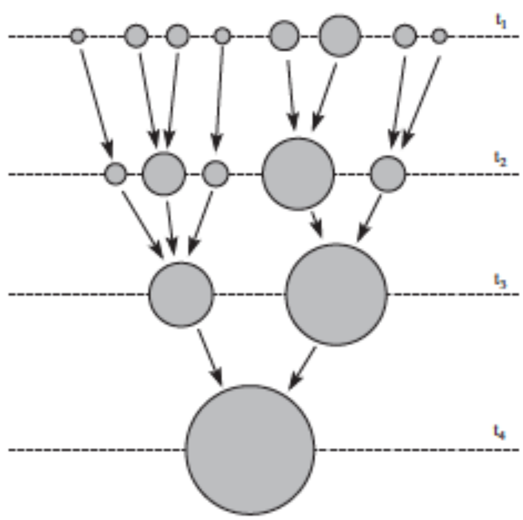
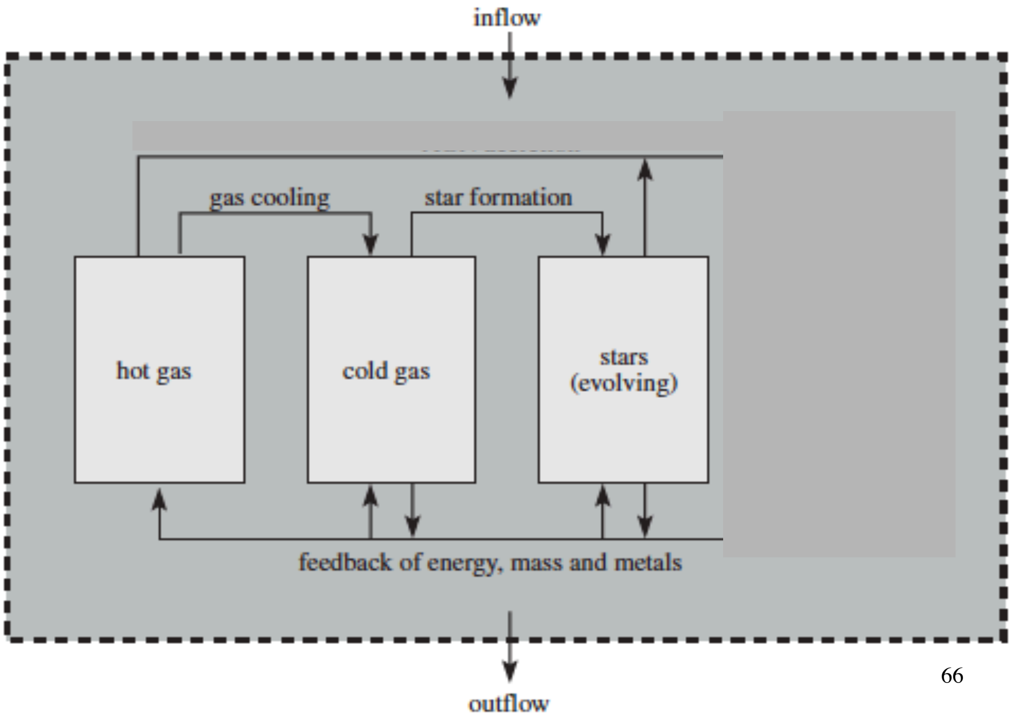
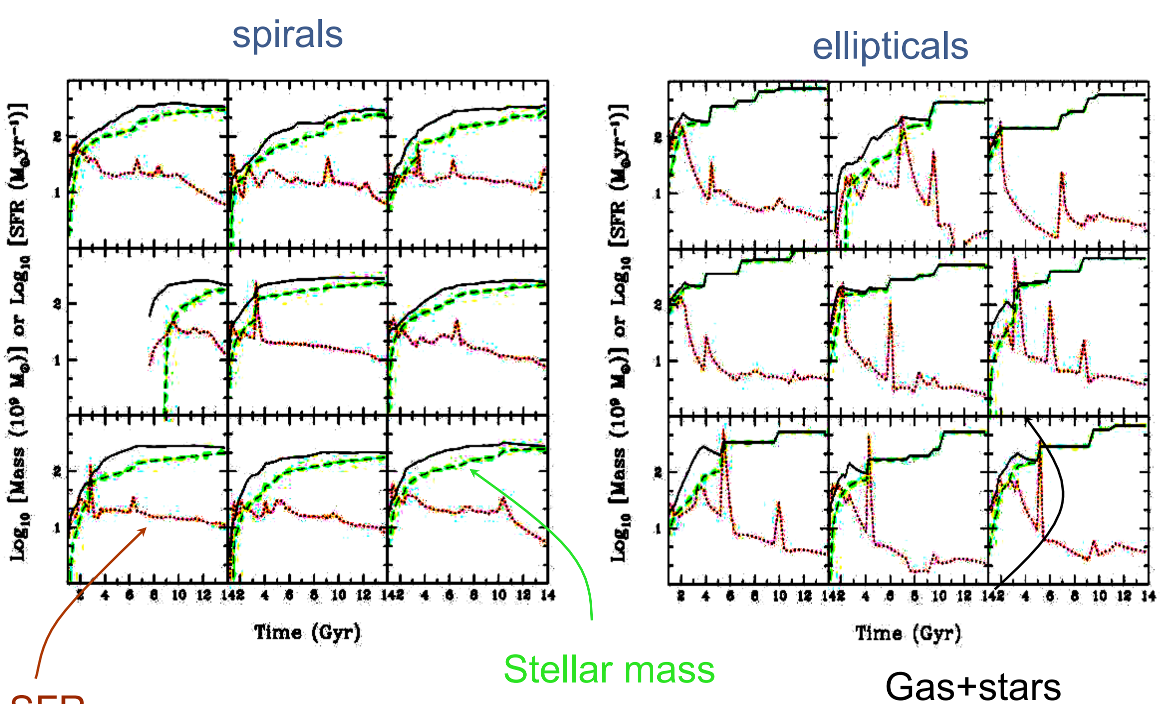


Fig. 1.3. A schematic merger tree, illustrating the merger history of a dark matter halo. It shows, at three different epochs, the progenitor halos that at time t_4 have merged to form a single halo. The size of each circle represents the mass of the halo. Merger histories of dark matter halos play an important role in hierarchical theories of galaxy formation.

Schematic of how Matter Flows in and Out- MBW fig 1.2



A set of results from numerical simulations



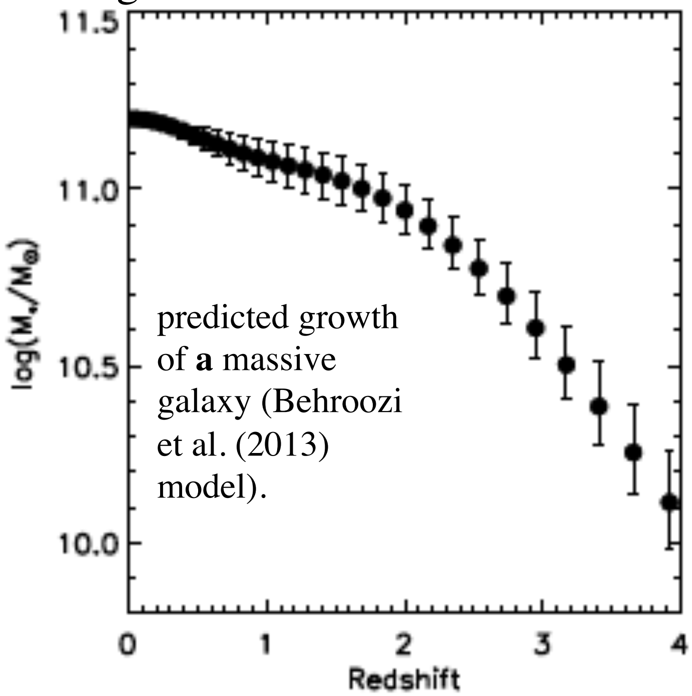
notice SFR not constant
mass growth has 'jumps' - mergers J. Blaizot-

Galaxy growth and changes over cosmic time

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

mass may increase, morphology can change

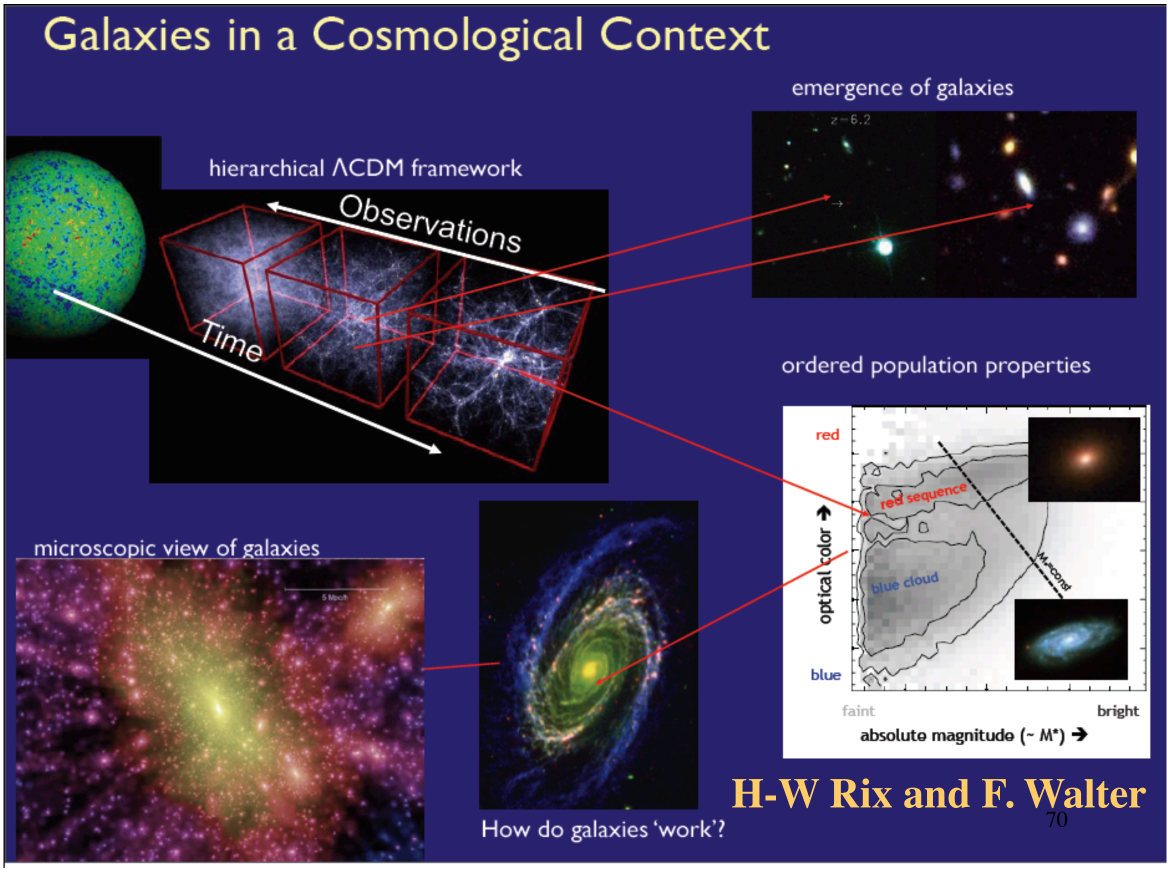
Galaxies are NOT stationary objects



Growth in mass of a elliptical galaxy over cosmic time

Movie of Hierarchical Gorwth

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



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, …

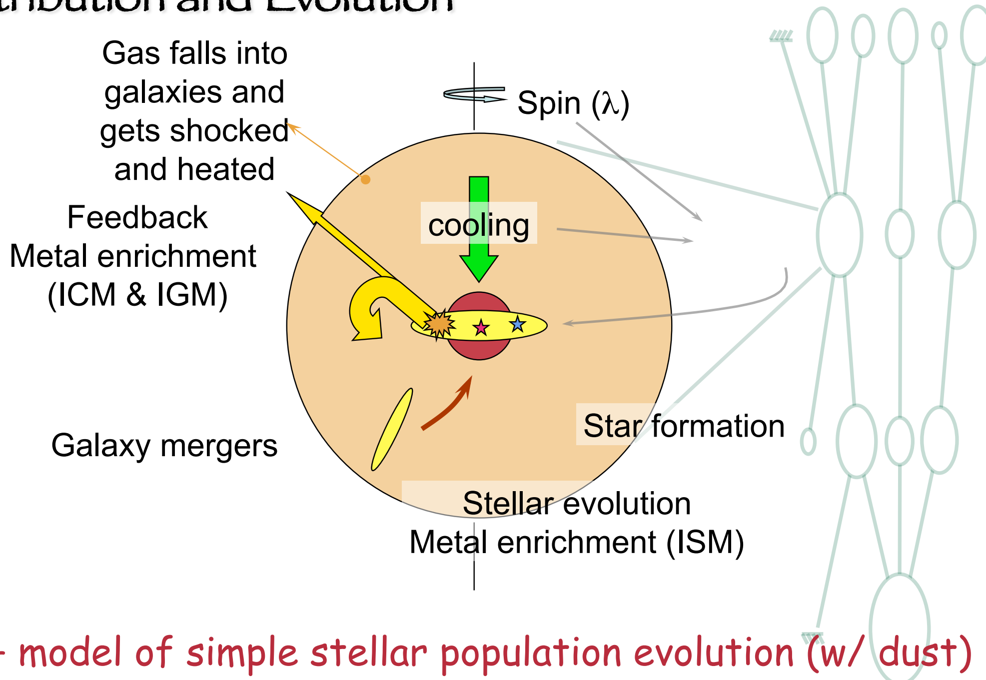
Winds (IGM heating, enrichment, SN feedback, etc…)

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

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

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

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

The PanChromatic Universe

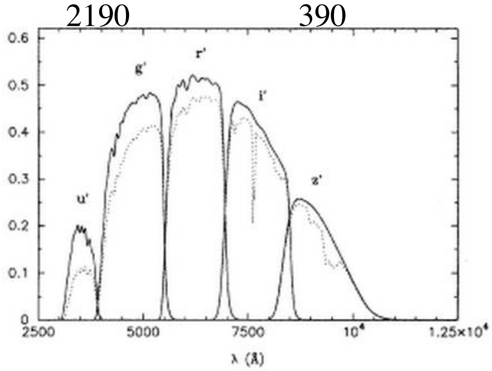
- Galaxies emit over the entire electromagnetic spectrum from radio to gamma-rays
- Each band (radio, mm, infra-red, optical, ultraviolet, x-ray, gamma-ray) contains unique information
- Require ALL the data to get the BIG picture
- However certain 'parts' of galaxies emit preferentially in one band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

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_ν=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 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)

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	

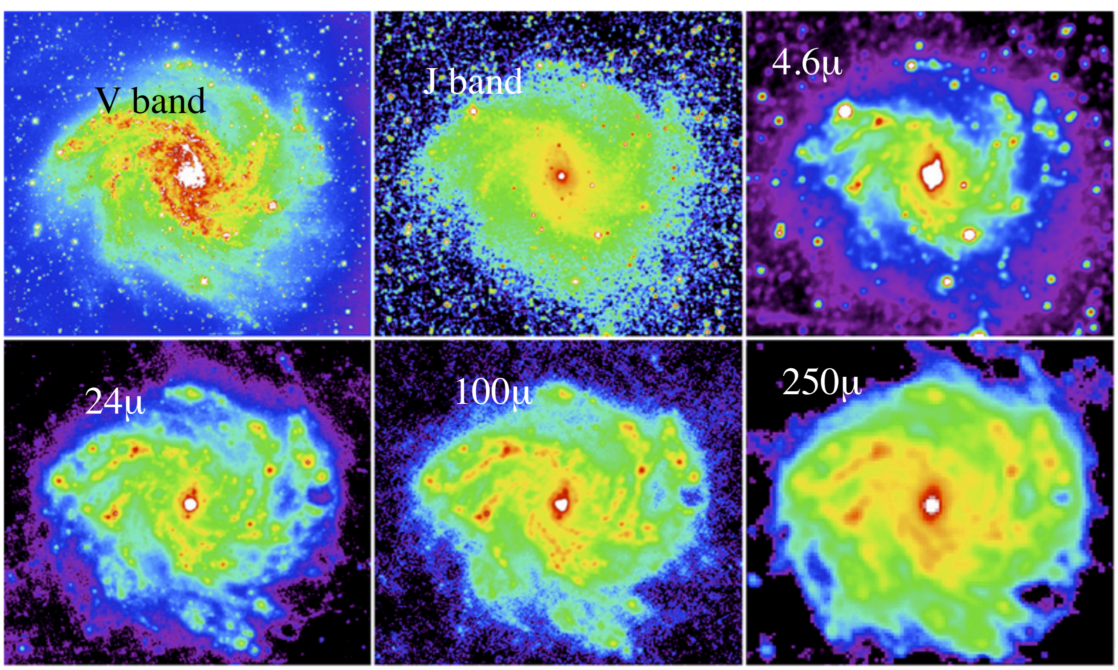
And in the IR there are

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

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

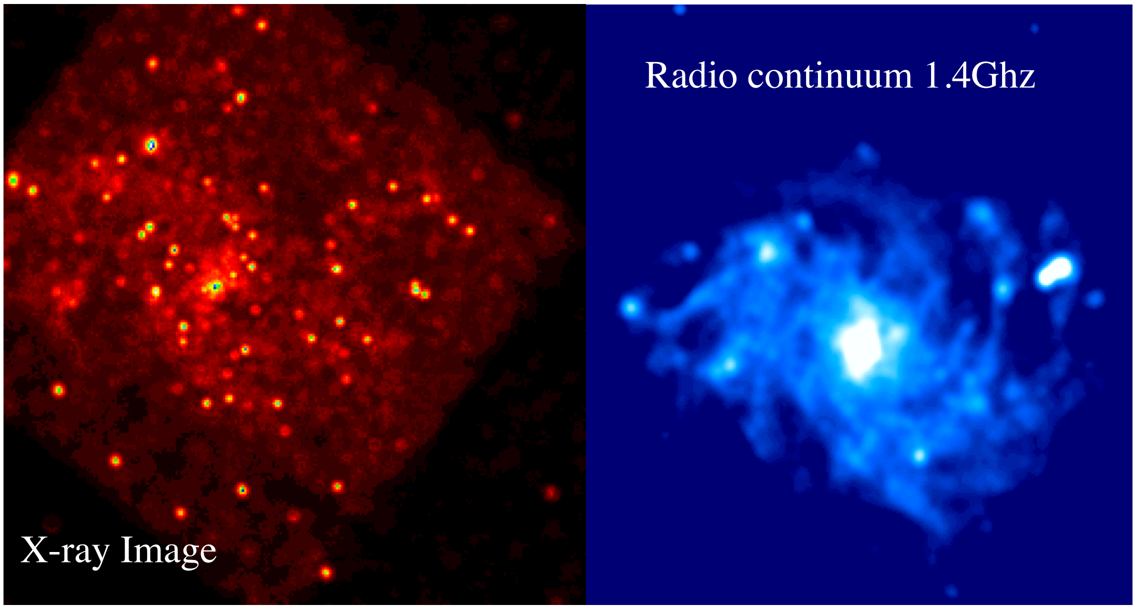
MultiWave Length Image of NGC6946

DustPedia



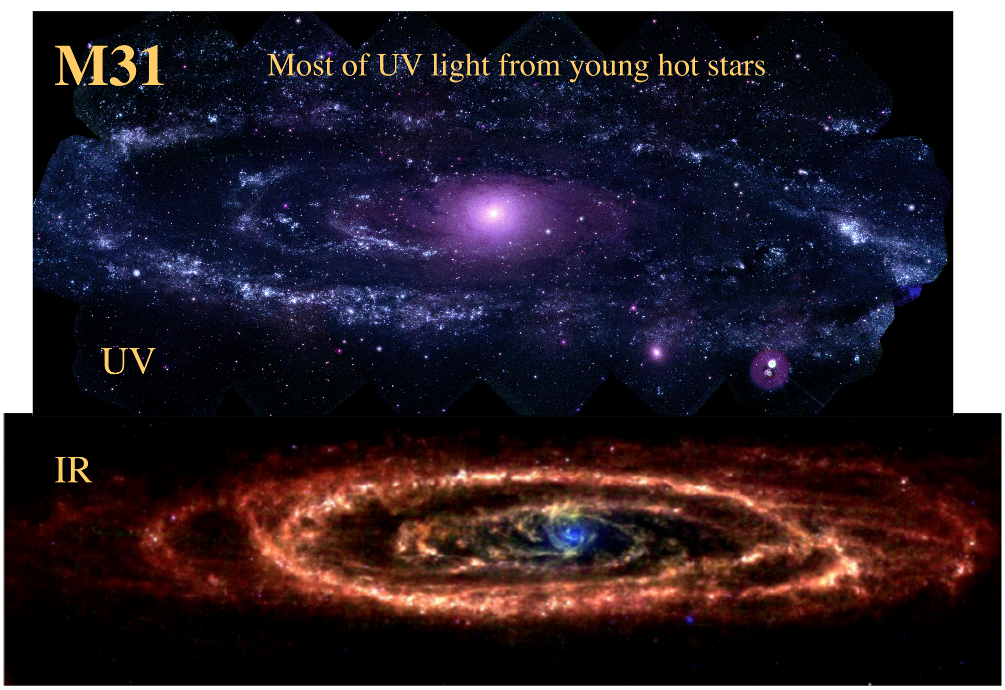
Images of the nearby galaxy NGC6946 - from left to right V(SDSS), J(2MASS), 4.6μm(WISE), 24μm(Spitzer), 100μm(PACS) and 250μm(SPIRE).

NGC6946



78

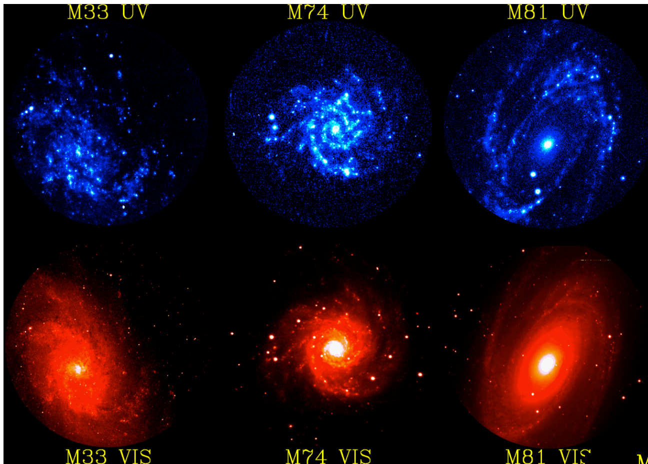
Different Appearances at Different Wavelengths



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

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

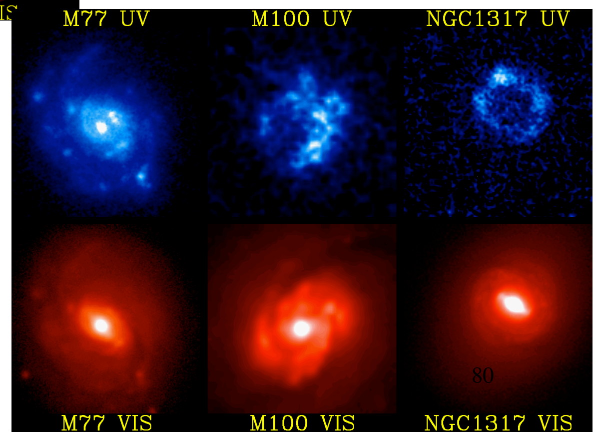
79



12 galaxies observed in UV and optical

Notice different patterns of UV light - this is affected by

- distribution of hot young stars
- dust

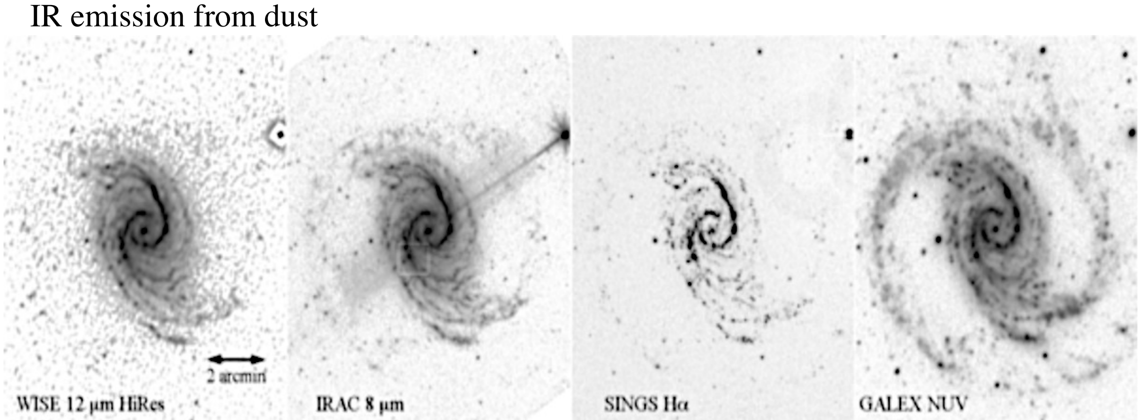


From UIT team

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

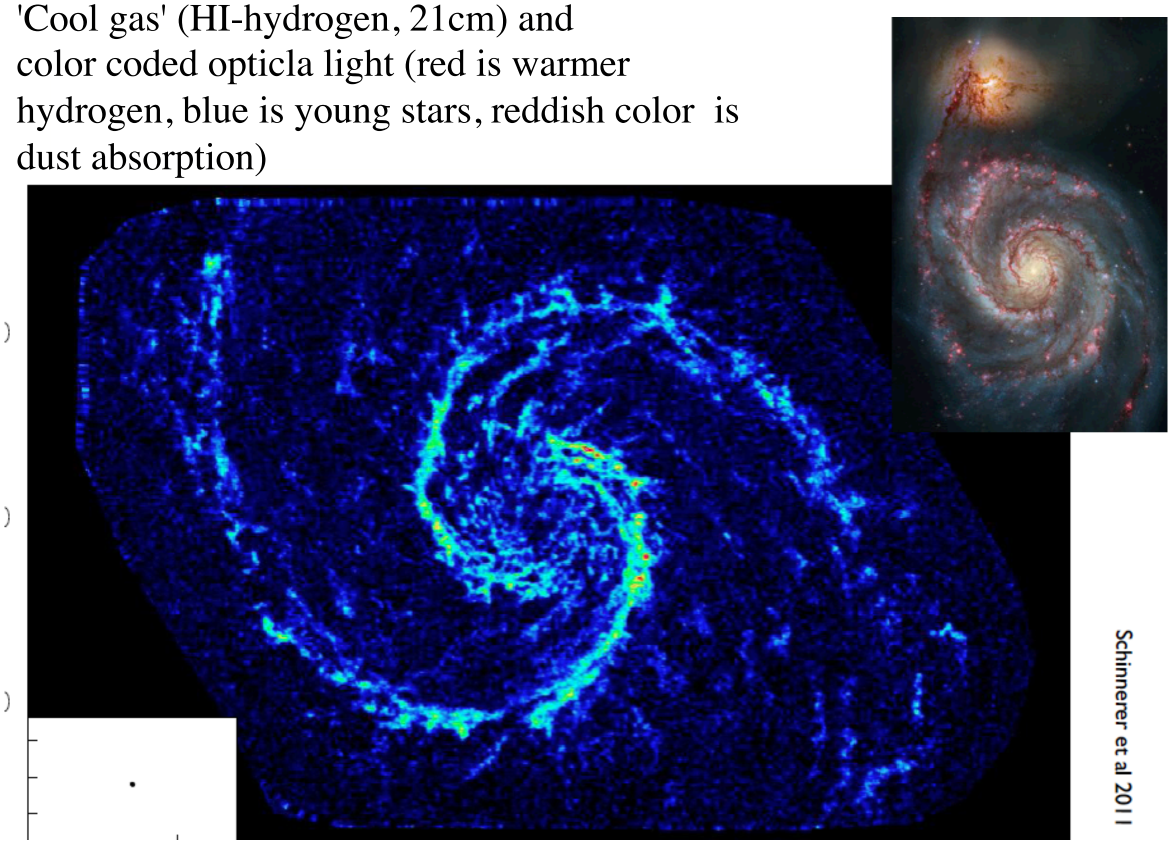
NGC1566 in 4 Bands

- 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, 21cm) and
color coded opticla light (red is warmer
hydrogen, blue is young stars, reddish color is
dust absorption)



Schinnerer et al 2011

Panchromatic MilkyWay

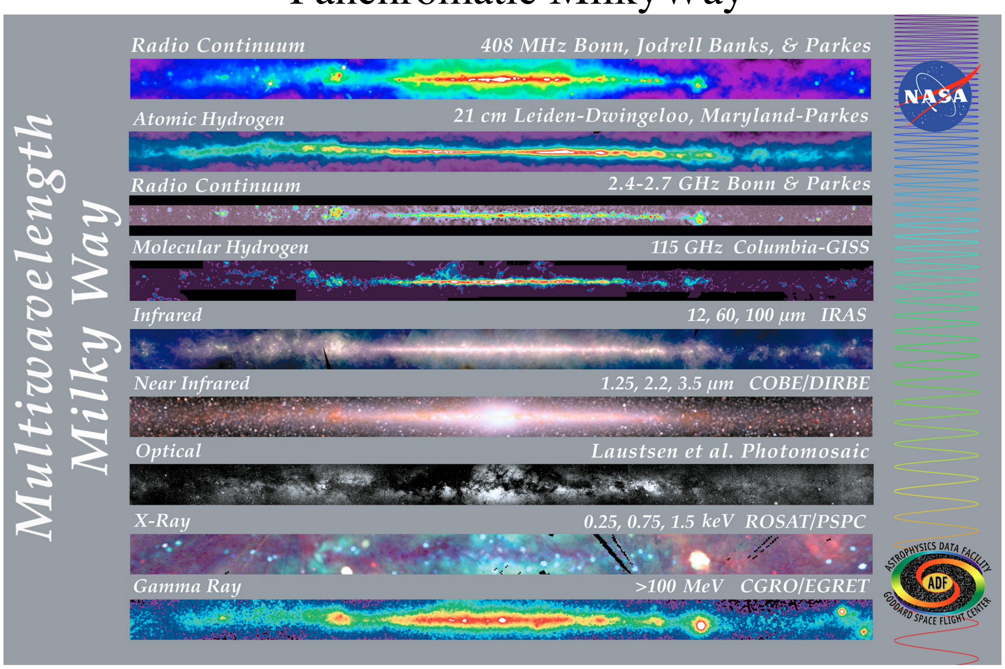
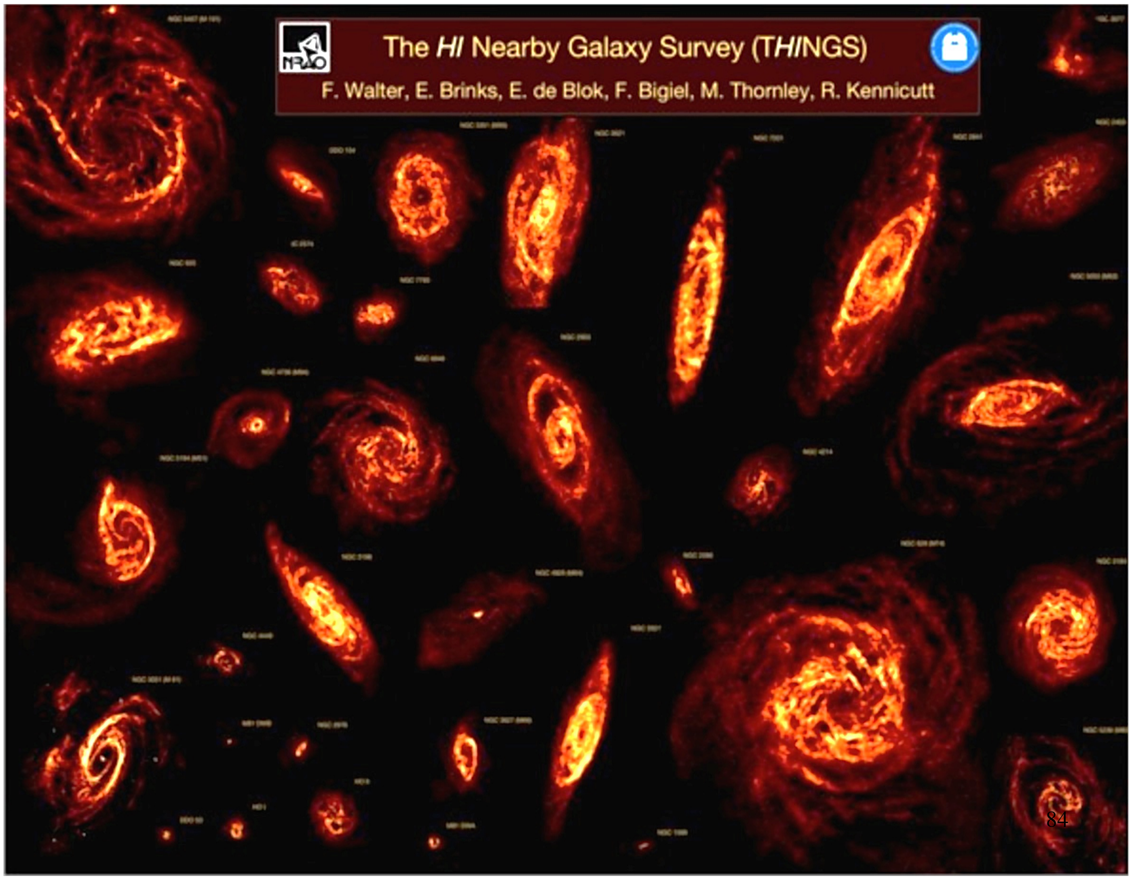
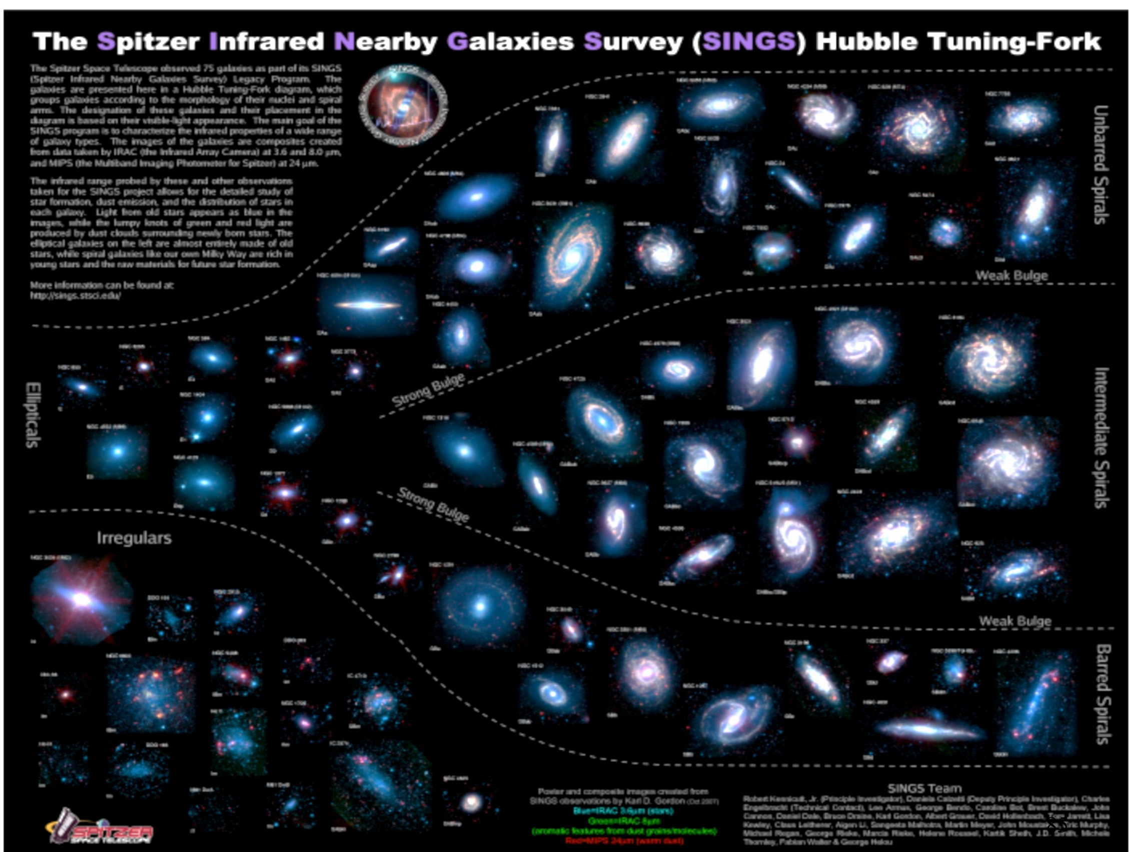


Image of MW galactic plane from radio through γ-rays
(10^{17} range in wavelength of radiation)



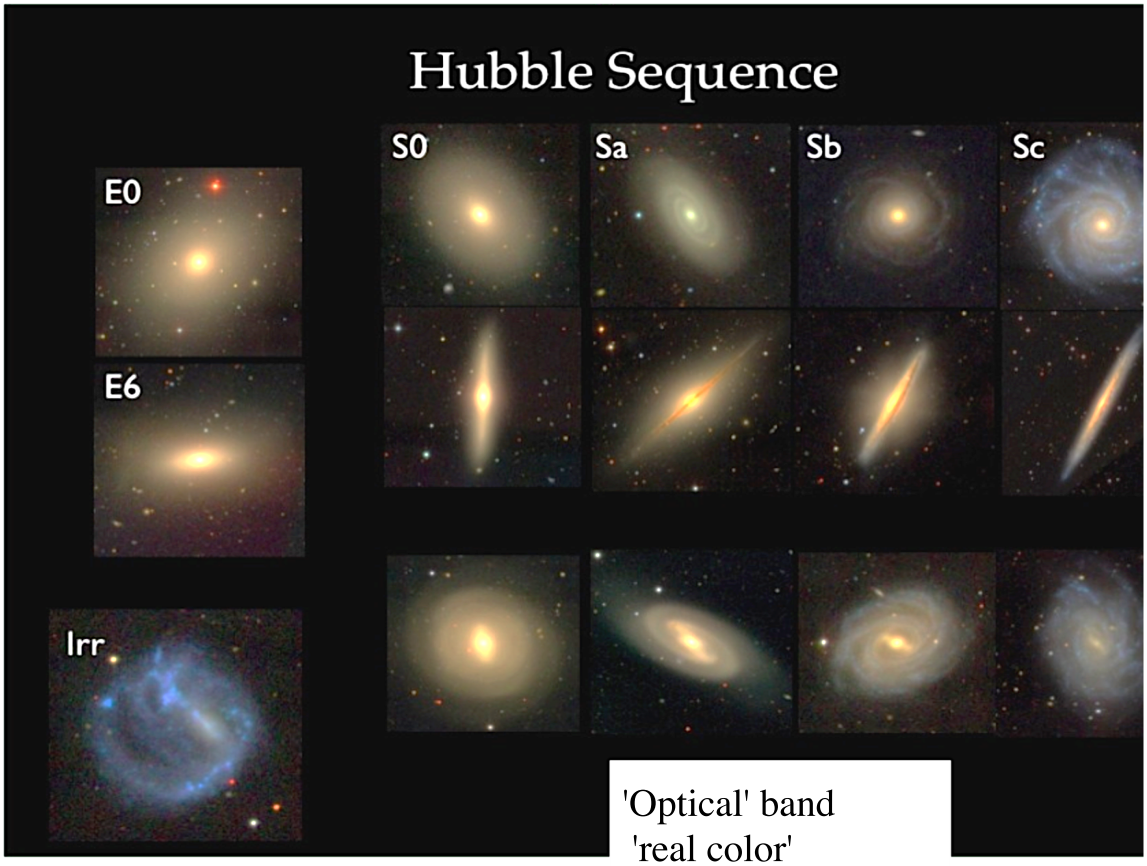
The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt

84



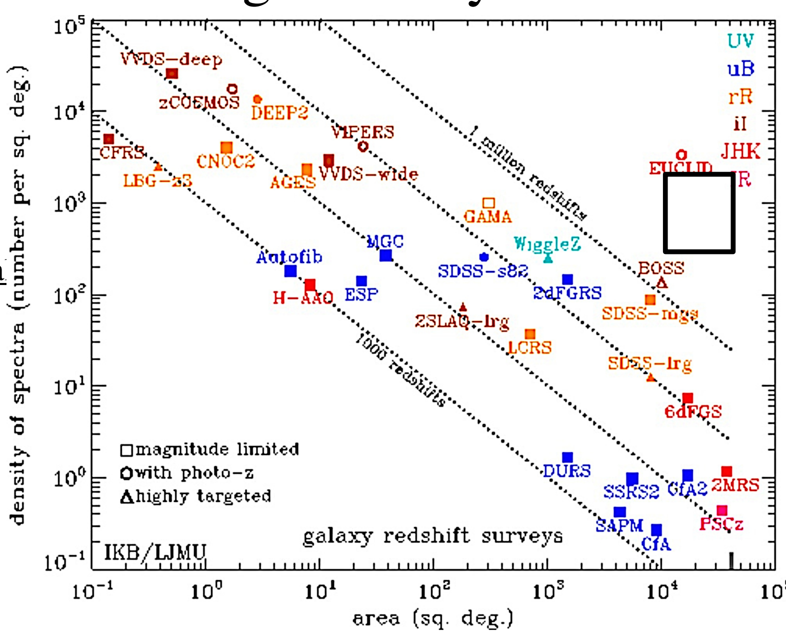
The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork
The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the 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
Strong Bulge
Ellipticals
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

85



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



A sample of recent optical and Near IR spectral surveys

The Epoch of Surveys and Big Data

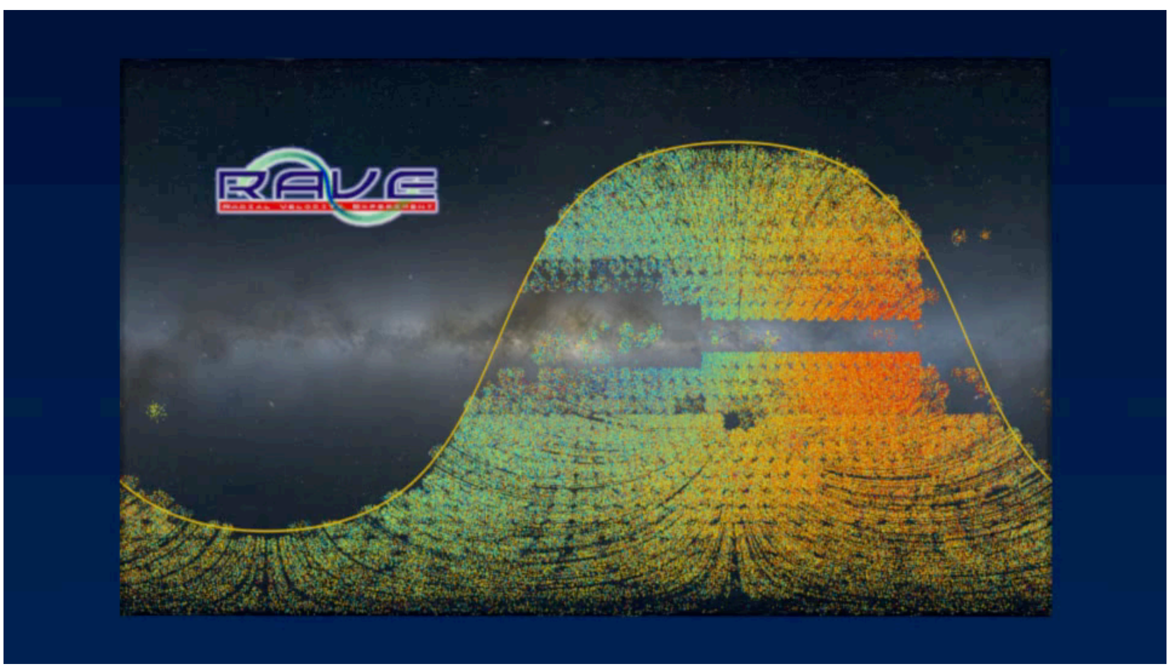
- This is the era of surveys everything from ratio to γ-ray, but especially in the optical and near IR.
- These surveys are both imaging and spectroscopic
- They are designed to
  - determine cosmological parameters
  - find supernova
  - study time variability (ZTF, LSST, PanSTARRS)
  - structure of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



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

Organization of the Data

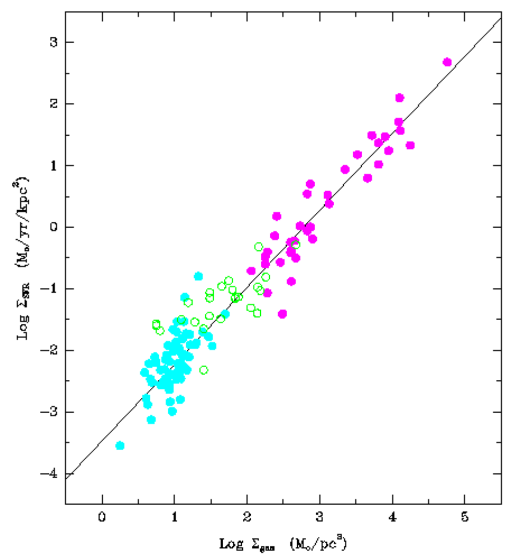
- Galaxies only occupy a small fraction of the allowed phase space.
- Thus many parameters are strongly correlated
- Some of these correlations have been given names
  - Tully-Fisher
  - Fundamental plane
  - Faber-Jackson
  - Kormendy relation
- some just have descriptions
  - metallicity mass relation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

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 **star formation rate**



log surface density of gas

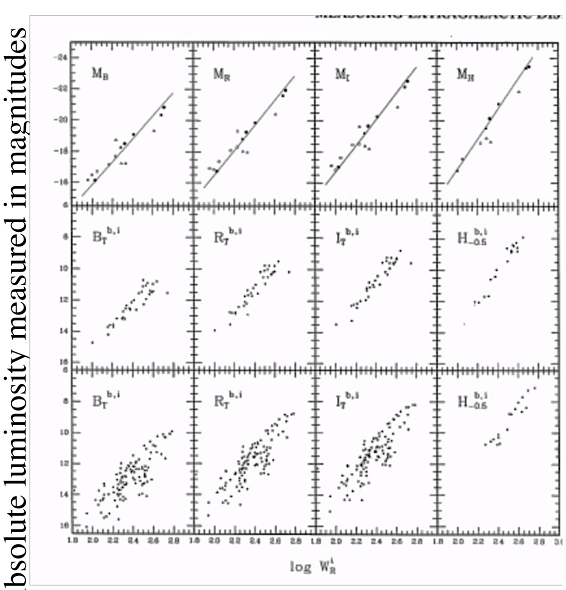
Galaxy Patterns- Continues

- 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)
- $L_{opt} \sim Av^4$
- 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)

Absolute luminosity measured in magnitudes

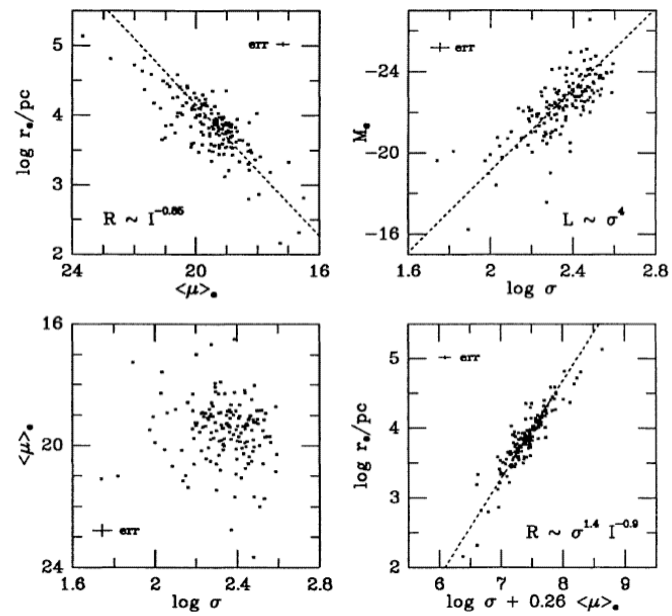


log rotational velocity

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

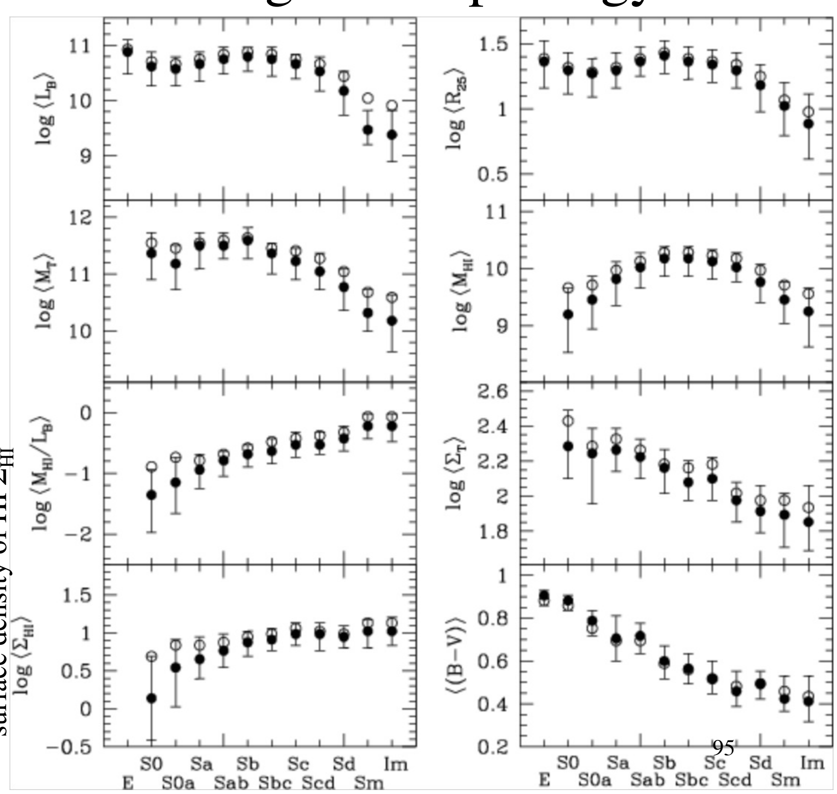
94

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 Σ_{HI}



95

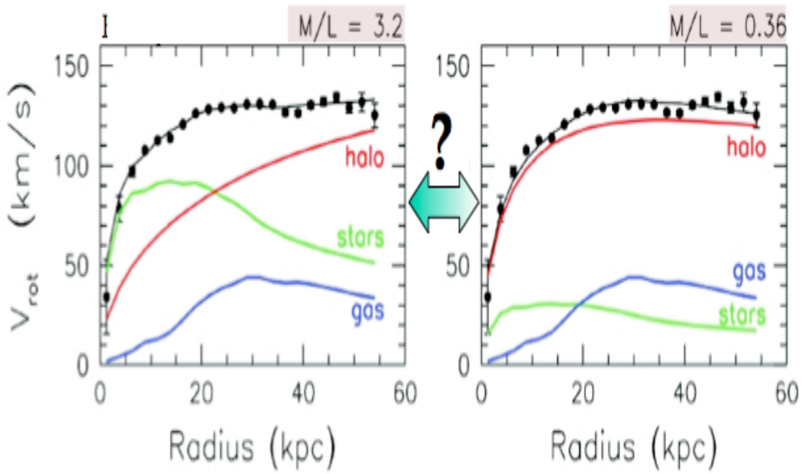
Spirals and Dark Matter (Halo)

Bershady et al

- Rotation-curve decomposition - primary tool for measuring the distribution of dark matter in spiral galaxy halos, **but** uncertainties in the mass-to-light ratio of the luminous disk and bulge make accurate estimates difficult (IMF-mass degeneracy)
- Disks in equilibrium

  Measure of rotation provides total mass within a given radius.

  Vertical oscillations of disk stars provides disk mass within given height inside a cylinder:



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

Attempts to Quantify Morphology

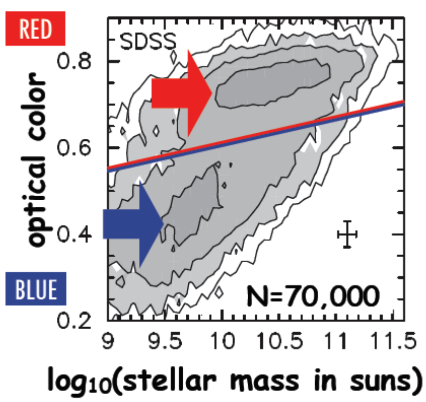
- Galaxies have a wide variety of 'components'
- 1. disk (thin/thick)
- 2. classical bulge
- 3. bar
- 4. spiral arms
- 5. inner disk
- 6. inner bar
- 7. inner spiral arms
- 8. lens(es)
- 9. nuclear ring
- 10. inner ring
- 11. outer ring
- 12. stellar halo
- partridge in a pear tree

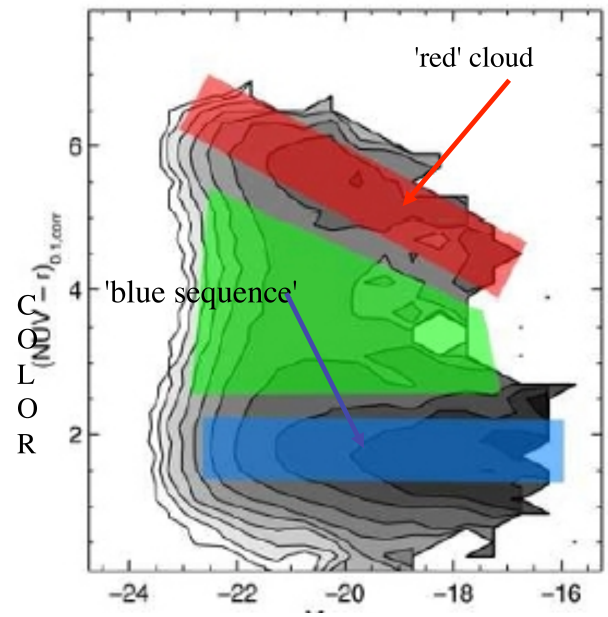
Which of these are meaningful? What do they tell us about the physical conditions in the galaxy and its history, Star formation rate dynamics etc etc

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'



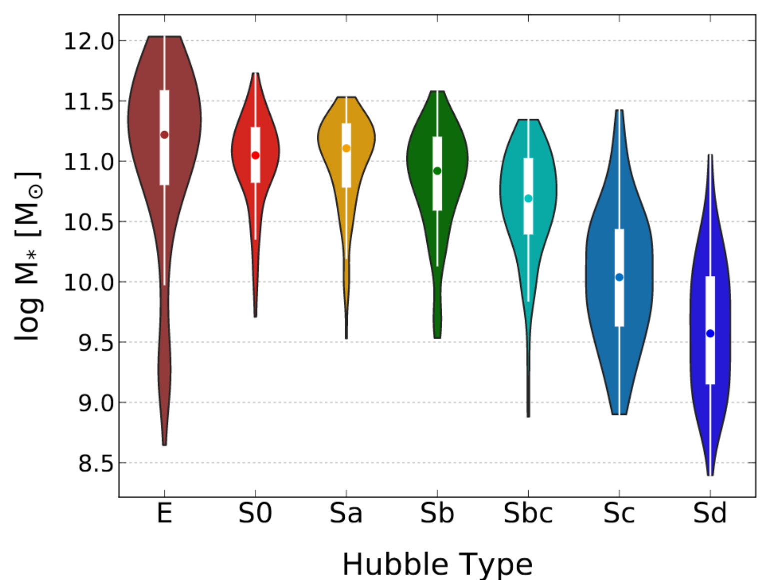


Absolute magnitude

Baldry et al 2004

Galaxy Correlations

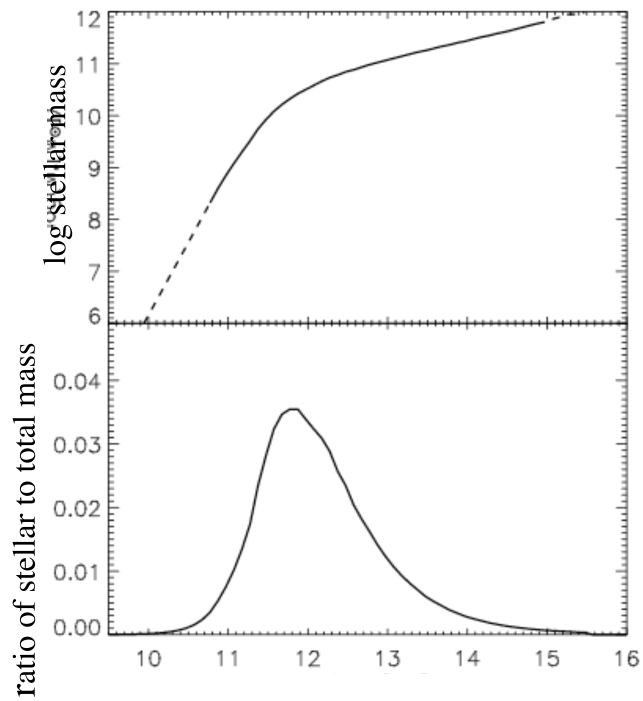
- There is a very strong correlation between galaxy morphological type and its stellar mass (García-Benito et al 2017)
  - but there is strong overlap, such that a given mass may be obtained for a wide range of Hubble types



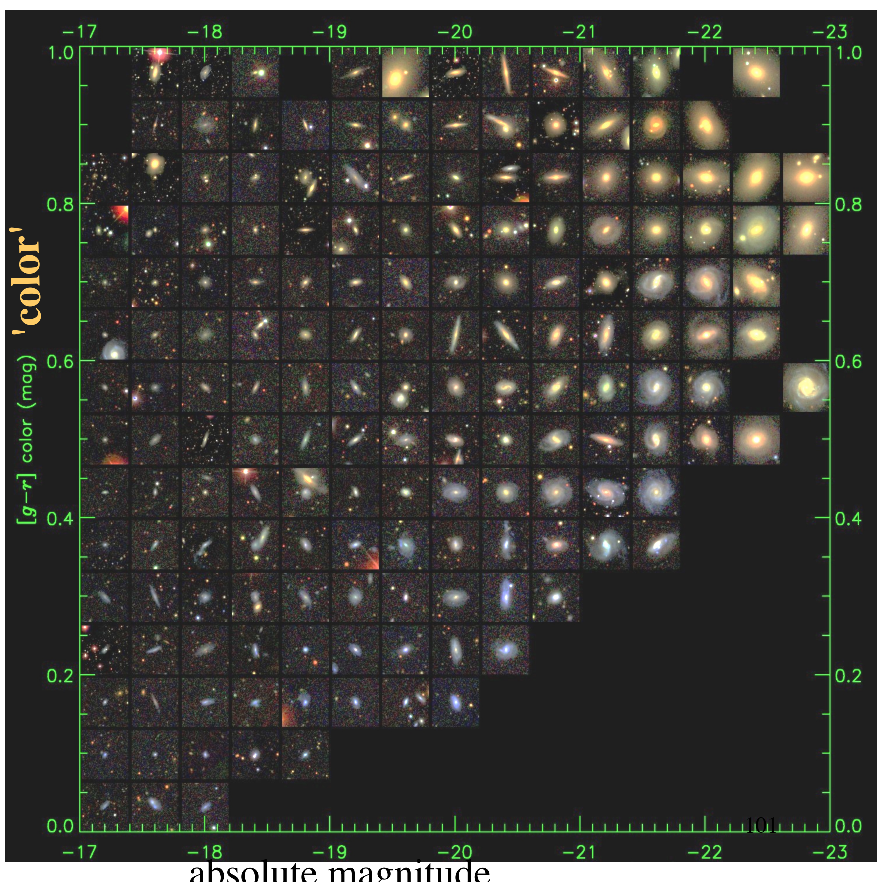
the dots represent the median value the width the relative number of galaxies of a given type at a given mass

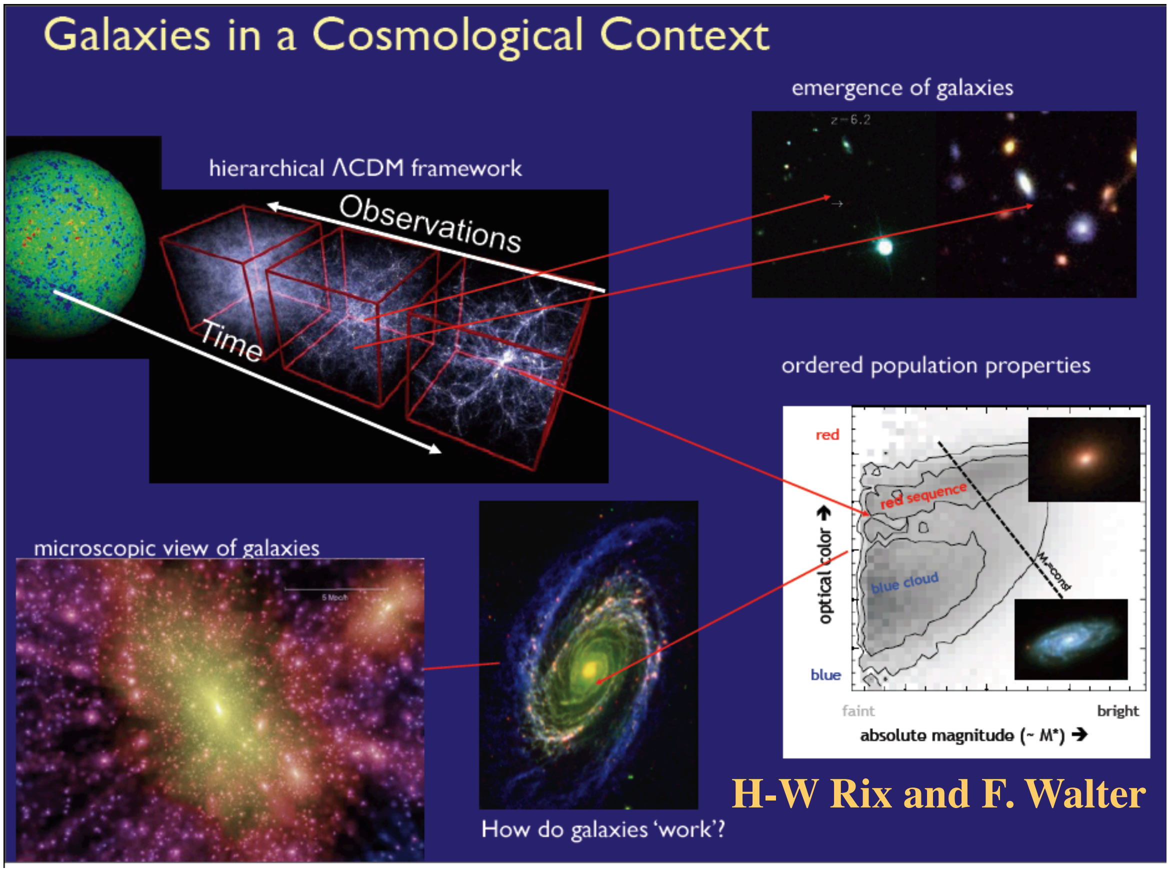
Dark Matter and Baryons

- 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



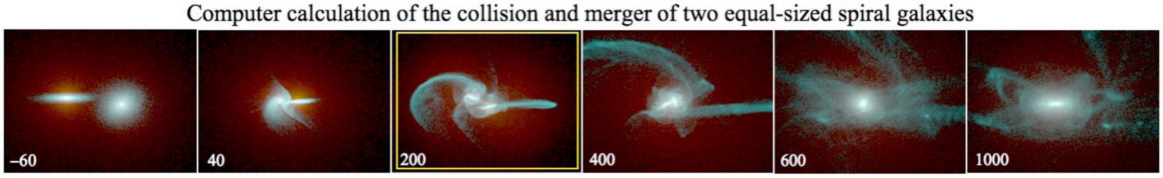
The present day population of galaxies only occupies a small region of phase space mass, size, age of stellar population, shape, are all correlated





Galaxies Change Over Cosmic Time

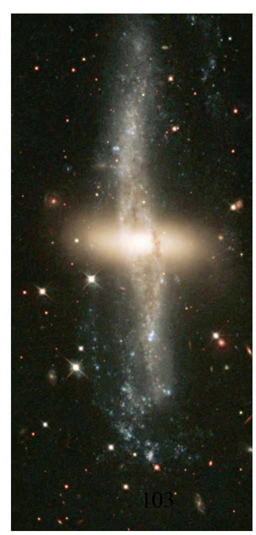
Computer calculation of the collision and merger of two equal-sized spiral galaxies



The Mice: Hubble Space Telescope

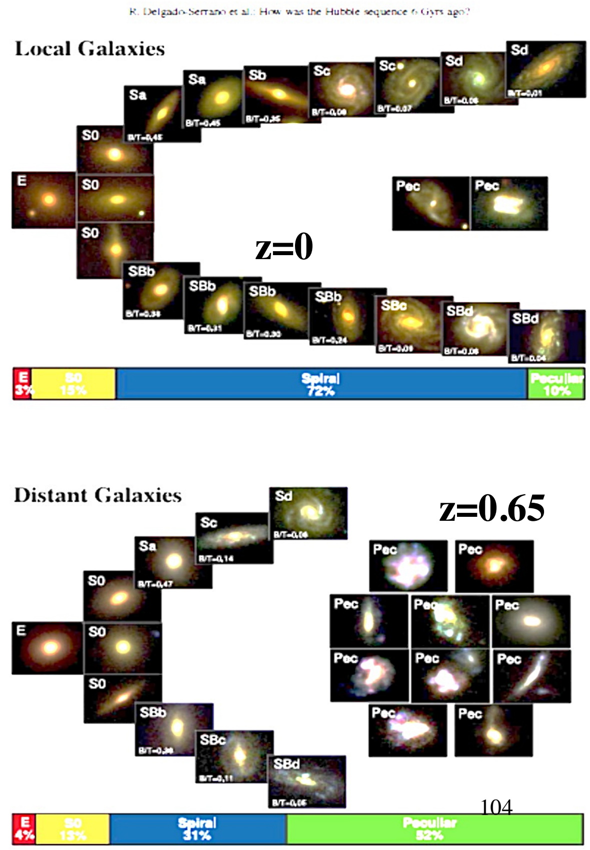
- Galaxies can grow via mergers and acquisition of gas. Mergers can be major or minor

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

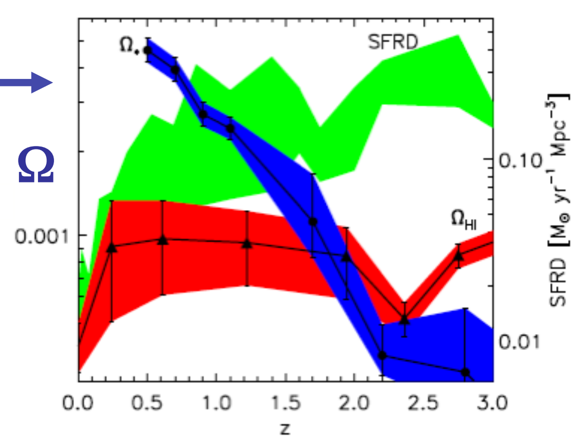


Patterns Change over Cosmic time

- 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 SFR (**green**) rate since z~1

- 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

$\Omega_{\text{star is}}$ ~10% of the cosmic baryon density



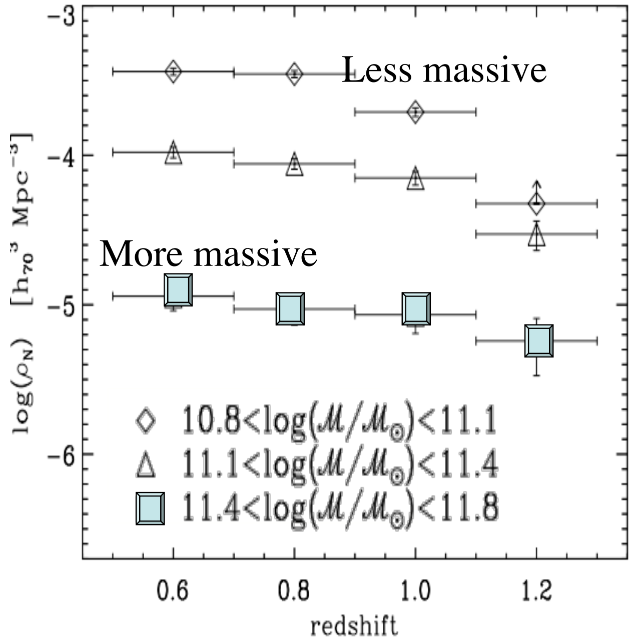
Putnam et al 2010

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-

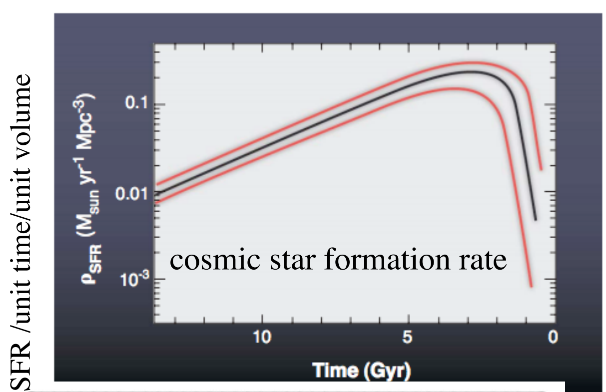
thus while dark halos assemble hierarchically, ***in stellar mass this trend is inverted*** in the sense that <u>the less massive the galaxy, the later is its stellar mass assembly on average.</u>

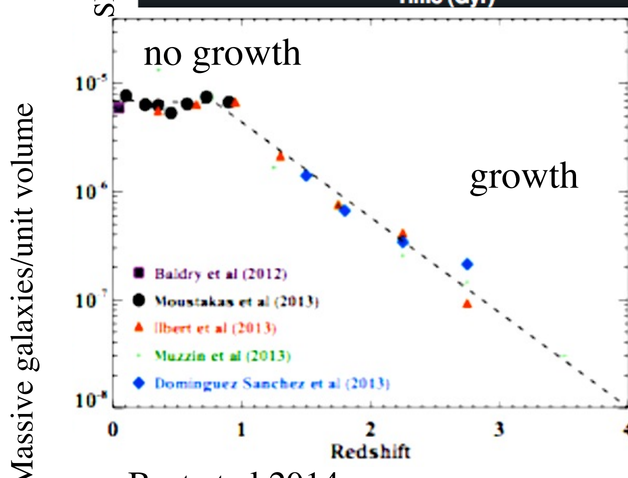
Space Density of Galaxies of Different Mass vs redshift



Things Change Over Cosmic Time

- Over the age of the universe the cosmic star formation rate (solar masses/yr/Mpc^3) has changed 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 todays luminous red galaxies,
- since z~1 SFR occurs mostly in the galaxies that became todays spirals.
- Massive galaxies apparently stopped growing at z~1





Best et al 2014

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?

Summary of 3rd 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

Next Lecture

- Stars and why we should study them