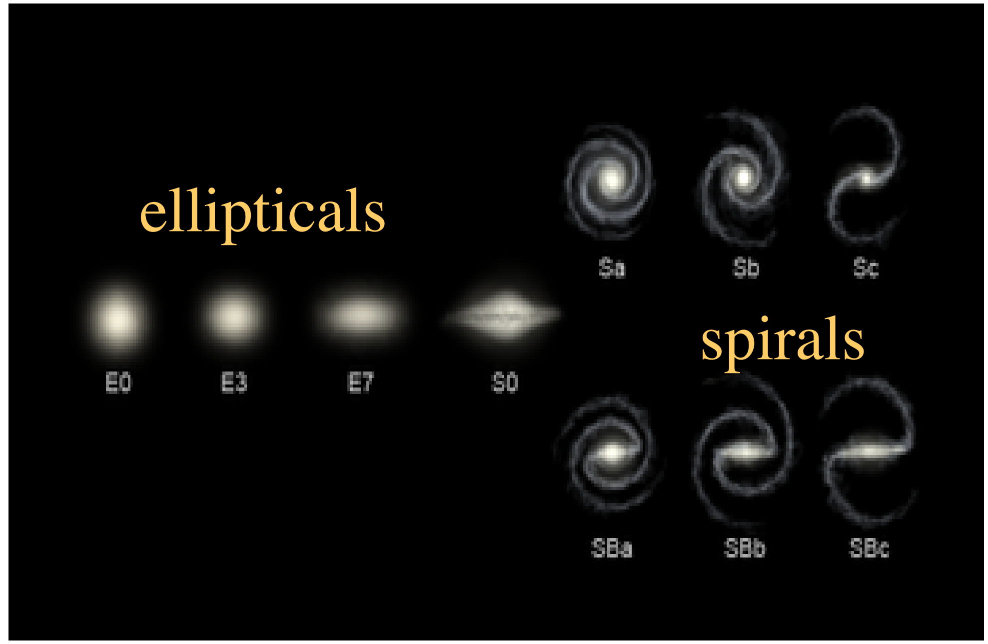
Galaxies

- What is a galaxy?
  - Observationally
  - Theoretically
- Observationally
  - A lot of matter in 'one' place
    - historically matter was traced by optical light (due mostly to stars)
    - Now can find and study galaxies by radio and mm emission from ionized gas and by emission in x-rays from their ISM+ black holes
- Theoretically
  - A bound system with a mass between that of a globular cluster (~$10^6\ M_\odot$ and a group of galaxies ~$10^{13}\ M_\odot$)
  - Most of the mass (>65%) is dark matter (>20x more DM than stars)
    - **e,g compact condensation of baryons near the center of dark matter halos.**



Galaxies come in a huge range of shapes and sizes

Generically divided into two generalized morphologies

spirals

ellipticals

Welcome!

- What is this course about?
- Logistics
  - Textbook, web pages
  - Pre-requisites
  - Assignments, exams, grading
  - Academic integrity
  - Semester plan
- Discussion
  - galaxies the big picture

Textbook & web pages

- Required text: Galaxies in the Universe: An Introduction (2nd Edition) by L. Sparke & J. Gallagher
- Authors' web page:

http://www.astro.wisc.edu/~sparke/book/galaxybook.html

secondary book

Galaxy Formation & Evolution by H. Mo, F. van den Bosch & S. White

- Course web page:

http://www.astro.umd.edu/~richard/teaching/ASTR421.html
  - Information, syllabus, lecture schedule
  - Assignments
  - Past lectures
- Lectures will be posted on the web page *after* they are given

Pre-requisites

- Mathematics
  - High-school algebra, trigometry , geometry calculus
- Familiarity with astronomy at ASTR300 level
  - Course will be fairly self-contained
  - I will use basic astronomy terms freely (e.g. star, planet, galaxy), and will cover some topics quickly
  - We will try to follow the text, but ...
  - Please ask about anything when you are unsure or I am not clear !
- ASTR 100 Introduction to Astronomy (3)
- ASTR 101 General Astronomy (4)
- ASTR 220 Collisions in Space: The Threat of Asteroid Impacts (3)
- ASTR 300 Stars and Stellar Systems (3)
- ASTR 330 Solar-System Astronomy (3)
- ASTR 340 Origin of the Universe (3)
- ASTR 380 Life in the Universe (3)
- ASTR 120 Introductory Astrophysics -- Solar System (3)
- ASTR 121 Introductory Astrophysics II -- Stars and Beyond (4)
- ASTR 288 Special Projects in Astronomy (1-3)
- ASTR 310 Observational Astronomy (3)
- ASTR 320 Theoretical Astrophysics (3)

Astronomy Classes

- ASTR 100 Introduction to Astronomy (3)
- ASTR 101 General Astronomy (4)
- ASTR 220 Collisions in Space: The Threat of Asteroid Impacts (3)
- ASTR 300 Stars and Stellar Systems (3) *
- ASTR 330 Solar-System Astronomy (3)
- ASTR 340 Origin of the Universe (3) *
- ASTR 380 Life in the Universe (3)
- ASTR 120 Introductory Astrophysics -- Solar System (3)
- ASTR 121 Introductory Astrophysics II -- Stars and Beyond (4)*
- ASTR 288 Special Projects in Astronomy (1-3)
- ASTR 310 Observational Astronomy (3) *
- ASTR 320 Theoretical Astrophysics (3)*
- ASTR 410 Radio Astronomy (3)
- ASTR 415 Computational Astrophysics (3)*
- ASTR 421 Galaxies (3)
- ASTR 422 Cosmology (3) *
- ASTR 430 The Solar System (3)
- ASTR 450 Orbital Dynamics (3) *
- ASTR 480 High-Energy Astrophysics (3) *

Letter grades

- Grading by:

Letter grade	Percentage
A	86-100
B	70-85
C	60-69
D	40-59
F	0-39

- I will adjust exam scores for a median of ~75% (low B) *if necessary*
- This means that homework is important!

Exams+ Other Info- Academic calendar

http://www.testudo.umd.edu/acad_cal/fall_2012.html

- One mid-term, date to be fixed next week
- Final exam
- Project/term paper due next to last week of semester
- In event of a REAL EMERGENCY which forces you to miss an exam
    - Contact me prior to the exam- or as soon as possible
    - Document the emergency
- Nov 7 is last date to drop with a W
- Thanksgiving November 22-25 (Thursday-Sunday)
    - Religious Holidays
        - Rosh Hashanah 9//16
        - Yom Kippur 9/25

Emergencies
Based on University Policy

- Regular attendance and participation in this class is best. However, if a class must be missed due to an illness, or other valid reason, the policy is:
  - For every necessary absence from class, a reasonable effort should be made to notify me or the TA in advance of the class. When returning to class, students must e-mail me or bring a note identifying the date of and reason for the absence.
- If a student is absent more than 5 time(s), documentation signed by a health care professional may be requested.
- If a student is absent on days when **tests are scheduled**, they should notify me in advance (if possible), and upon returning to class, bring documentation of the illness or personal reason.
- Please inform me of any other issue requiring special attention

Homework

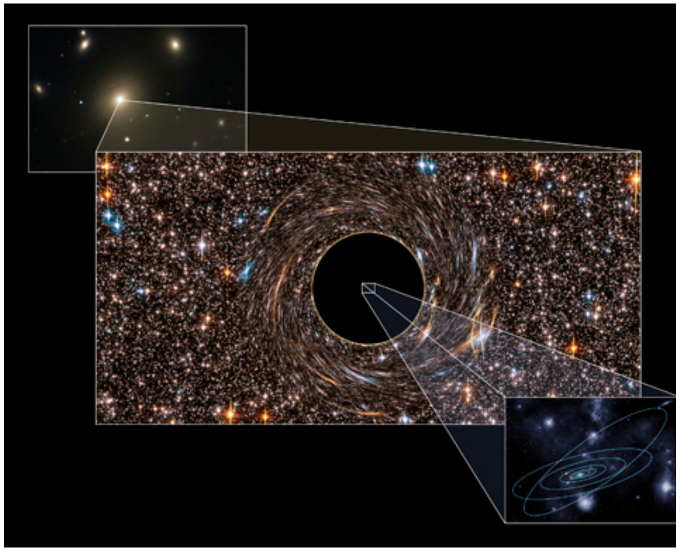
- Homework assigned approx. once every two weeks
- HW is collected *at the start of class* on the due date (a week later)
  - **Please hand in on time**, or document the valid reason why it is late.
  - No credit after the day on which it is due, unless there is a justifiable reason.

Academic integrity

- **Always:**
  - Present your own thoughts in your own words
  - Cite any references that you use
- **Never**:
  - Copy from another student
  - Directly quote any published article unless you also give full credit to that article.
  - Allow other students to copy from you.
- Per campus policy, please write the honor pledge on each assignment

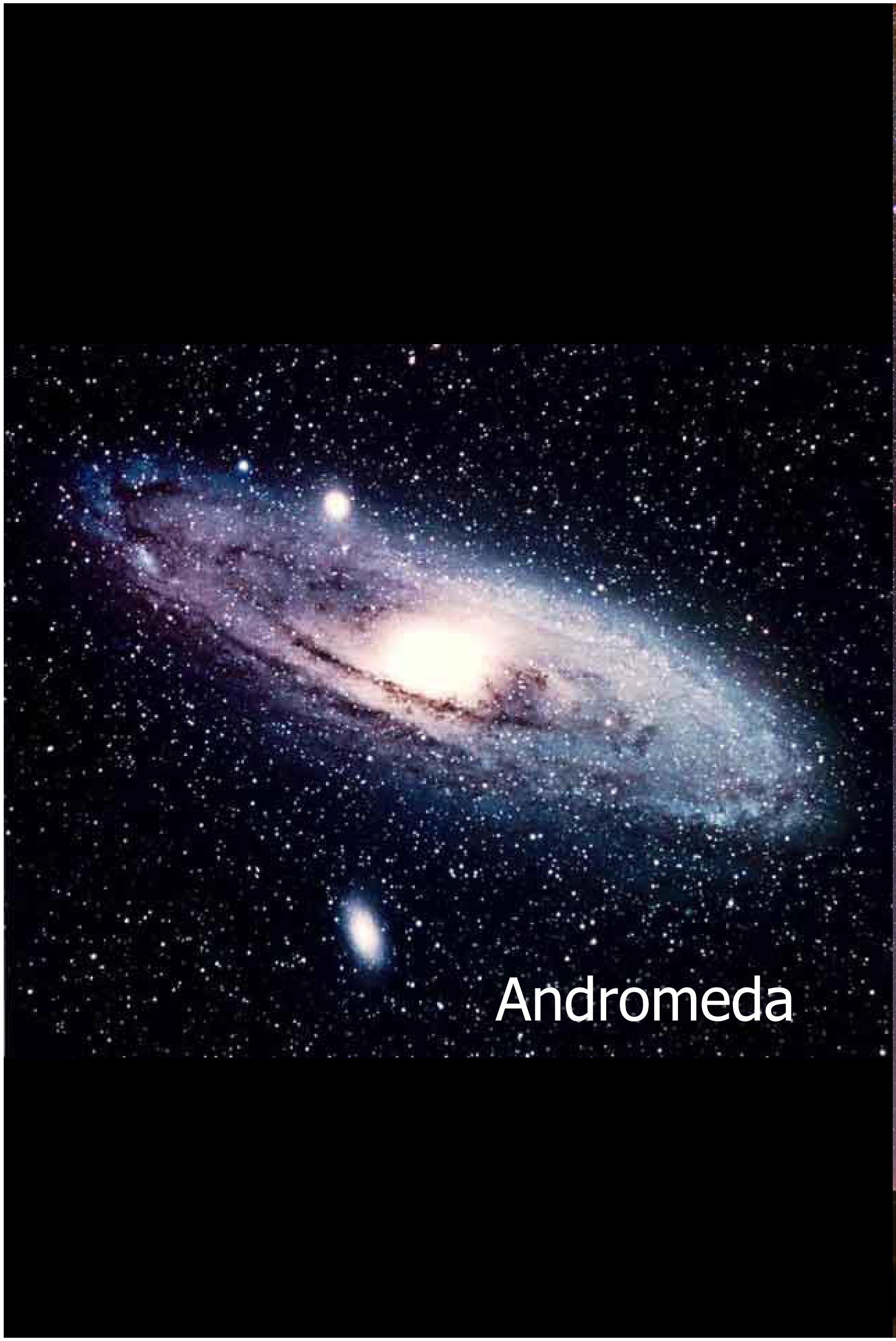
Topics we will cover

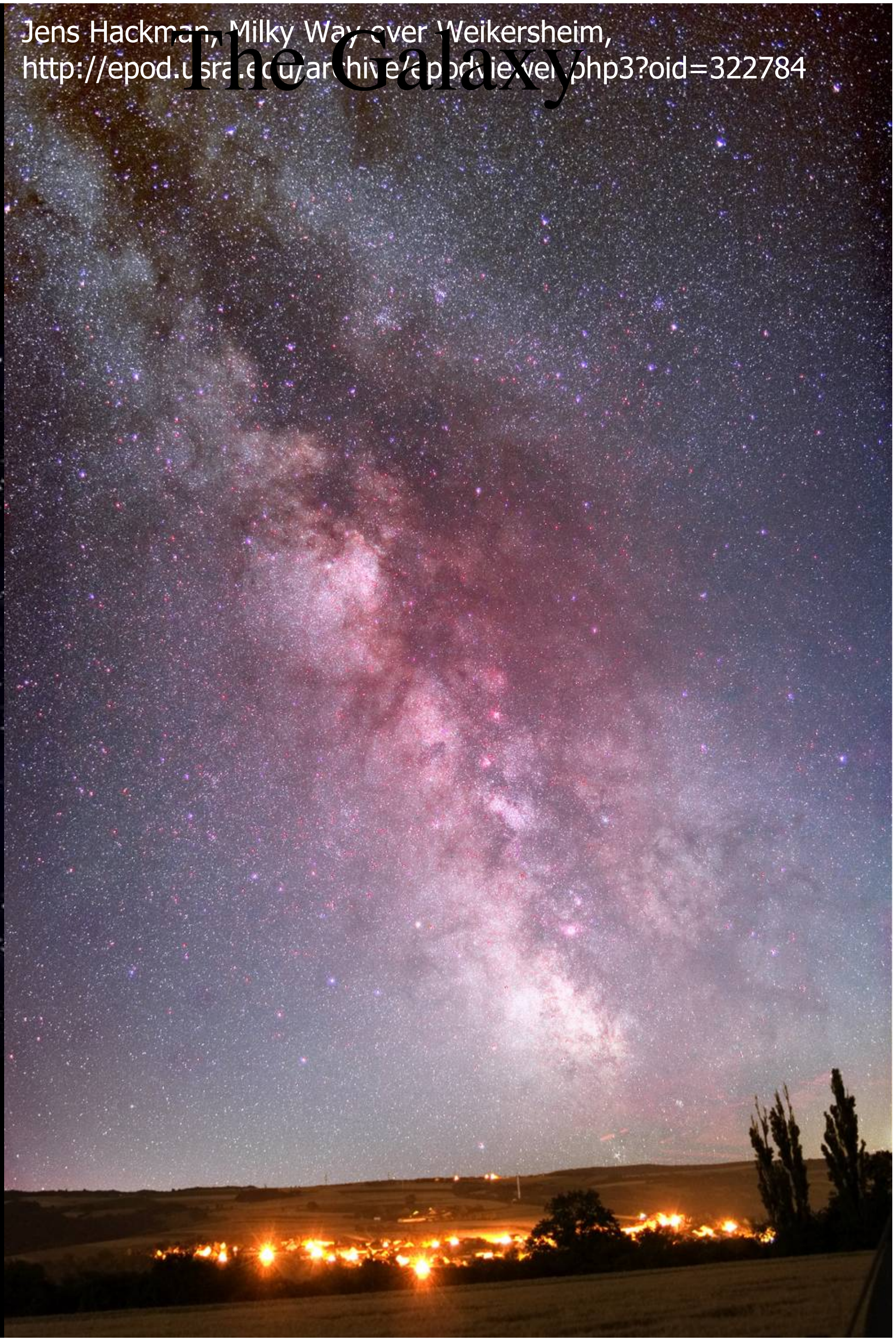
- Broad description of galaxies
- Stellar populations/star formation
- Gas and Dust in galaxies
- Milky Way as a detailed example of a galaxy
- Galactic dynamics/need for dark matter (lensing)
- Spiral galaxies
- Elliptical galaxies
- Galactic evolution/formation and cosmological implications
- Active Galactic nuclei -galactic centers



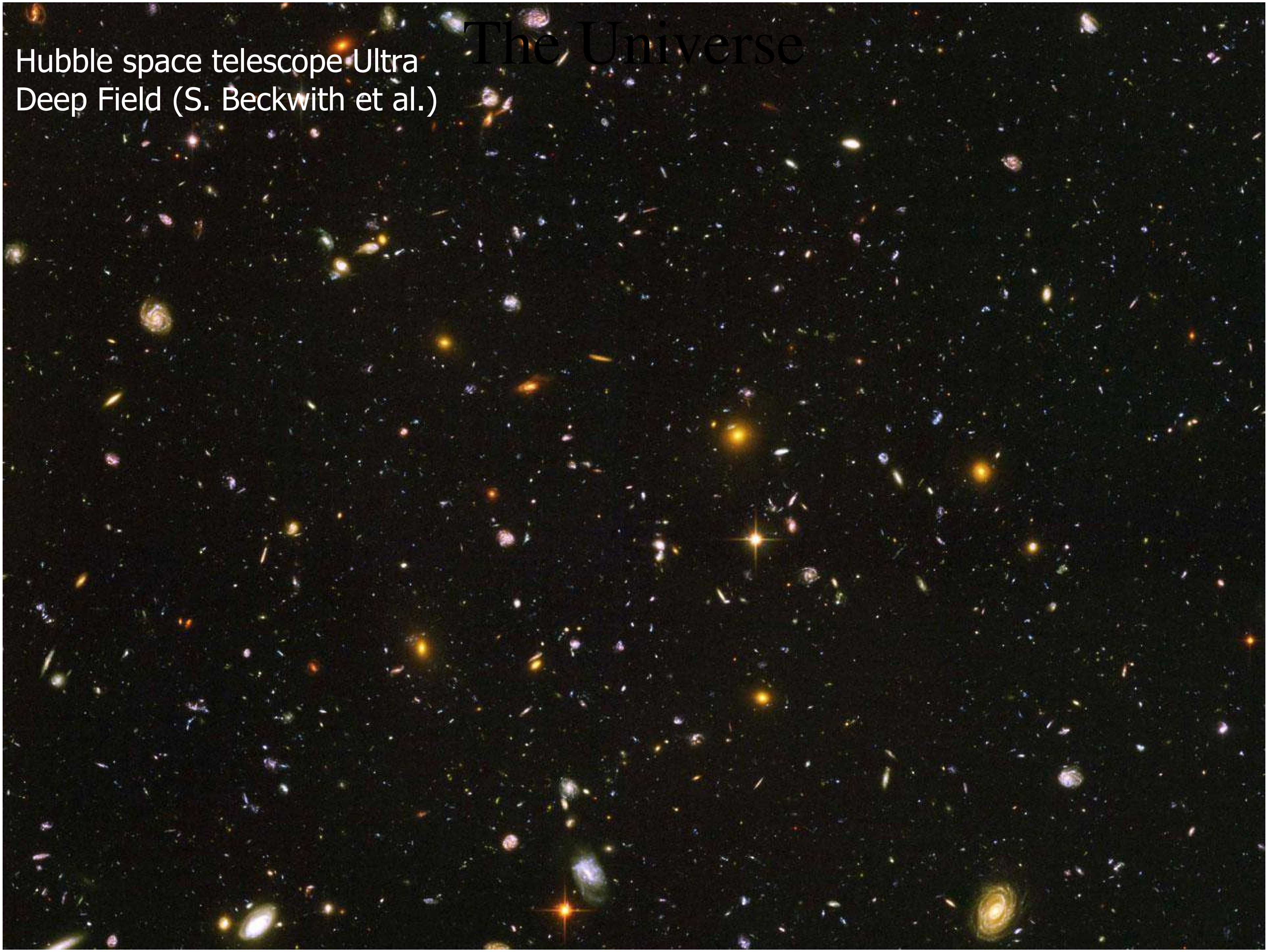
- This is an **enormous** range of material; the level of detail will vary greatly from section to section

The Galaxy


Andromeda


Jens Hackman, Milky Way over Weikersheim,
http://epod.usra.edu/archive/epodviewer.php3?oid=322784

The Universe



Hubble space telescope Ultra Deep Field (S. Beckwith et al.)

Next Time…

- *Please read Chapter 1 of the book*
- First HW assigned Thursday next week
- Syllabus ... next week

The BIG Picture

- Essentially, all research on galaxies aims at answering how galaxies form and evolve
- Steps include understanding the role of the different galactic structural components in this history, and how they relate with each other..
- We need to link structural analysis, kinematics and dynamics, stellar population properties and evolution, multi-wavelength observations, ample redshift coverage, and theory.
- It is only with such a holistic approach that the physics can be obtained (adapted from Gadotti 2012)

- From a theoretical point of view Galaxies reside in dark matter halos, but, are biased tracers of the underlying matter distribution: that is the observable galaxy properties such as luminosity are not *simple* tracers of dark matter.
- Different kinds of galaxies reside in different mass halos and massive halos can host *multiple* galaxies (pairs, groups, clusters)

Modern galaxy research

- Explain the observed galaxy population and its changes over cosmic time
- Understand why galaxies show the extreme regularity of various parameters
- Try to use galaxies to understand cosmology and vv.
- Cosmic laboratories for all the details of astrophysics
  - star formation
  - interaction of baryons with dark matter
  - formation of the chemical elements
  - the relationship of black holes to their host galaxies

What is galaxy research about?

- Explain galaxy population as consequence of initial conditions (+ stability arguments + feedback)
- Understand astonishing regularity of galaxy population
- Understand galaxies well enough to make them (even better) cosmological diagnostics
- Test of galaxy formation
- Have fun!

A Brief History

- Discovery of 'nebulae' in late 1700's (Messier) and their cataloging in the late 1800's (NGC catalog)
- Realization (Hubble etc) that the nebular were outside the Milky Way- island universes(originally due to Kant)
- Expansion of the universe 1920's (Hubble)
- Dark matter- Zwicky 1930's Rubin 1970's
- Cosmic Microwave Background and Big Bang Nucleosyntheis established the Big Bang
- 1980's - the development of Cold Dark Matter (CDM) and post 1998- ΛCDM

http://www.astr.ua.edu/keel/galaxies/history.html

Galaxies: From J. Dalcanton

Ellipticals

$M_{halo}>10^{11}M_\odot$

V~350km/s

Highly Clustered

Old stars

little star formation now

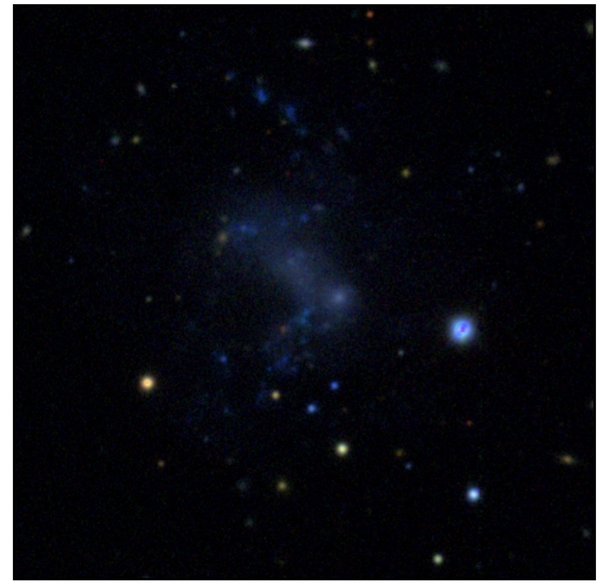
Spirals

$M_{halo}>10^{10}\ M_\odot$

V~200km/s

wide range of stellar ages

star forming



Dwarfs

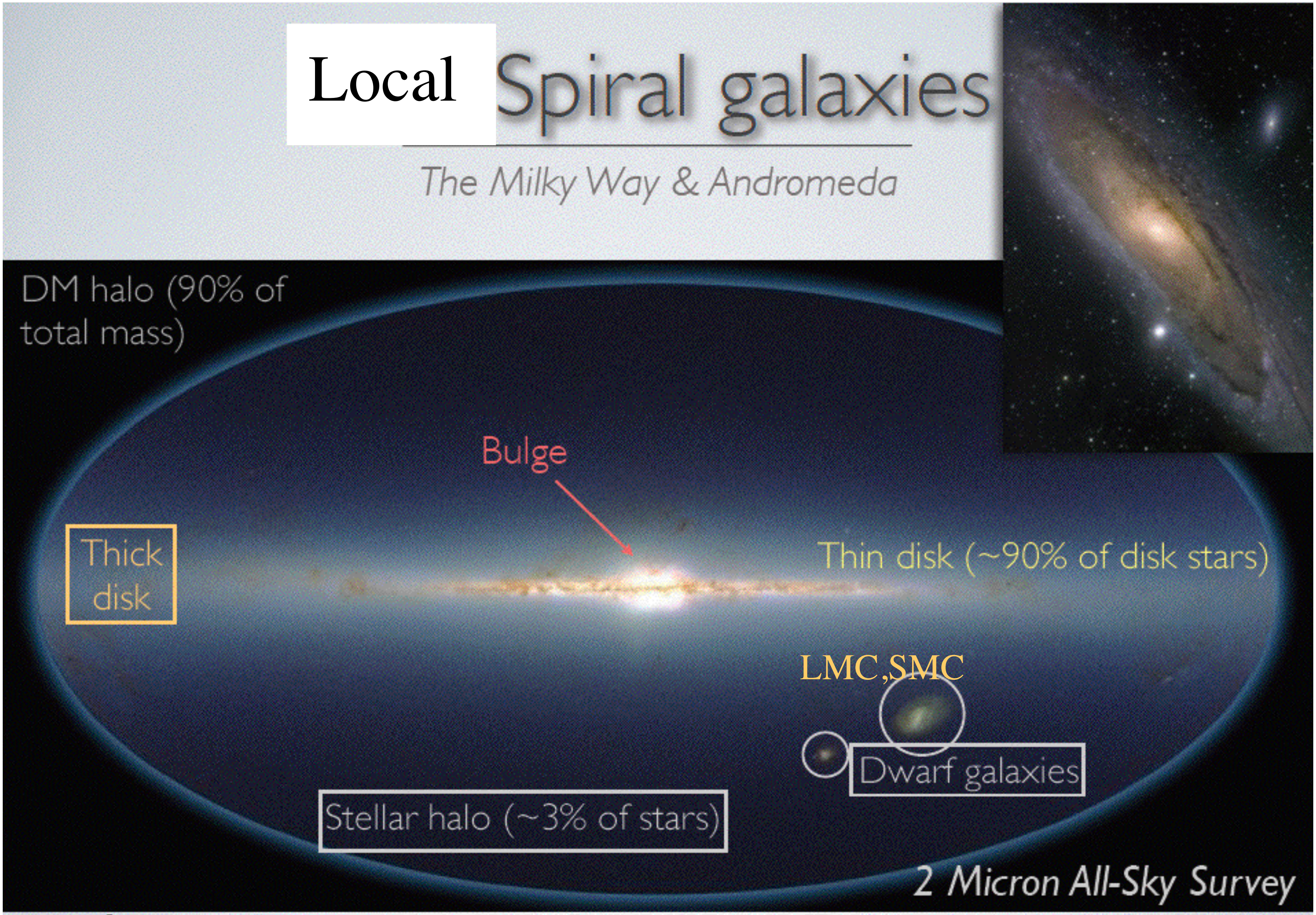
$M_{halo}>10^{8}M_\odot$

V~30km/s

Weakly Clustered

Young stars

Numerous


Local Spiral galaxies
The Milky Way & Andromeda
DM halo (90% of total mass)
Bulge
Thick disk
Thin disk (~90% of disk stars)
LMC,SMC
Dwarf galaxies
Stellar halo (~3% of stars)
2 Micron All-Sky Survey

ASTR421: Galaxies

Prof. Richard Mushotzky

Room: CSS 1104 Phone: 301-405-6853

Email: richard@astro.umd.edu

Office hours: 10:00-11:00am Tues/Thurs

TA: Qian Wang: qw@astro.umd.edu

Room: CSS 0224A

Office hours Monday 15:30-17:00
Wednesday 10:00-12:00 or by appointment

Textbook: Galaxies in the Universe: Sparke and Gallagher- Supplementary text Galaxy Formation and Evolution H. Mo, F. van den Bosch, S. White

75 min class

Mid-term Oct 16

Term paper Nov 27

NO OPEN LAPTOPS or USE of Cell Phones DURING LECTURES

Assignments & Grading

- Assignments:
  - Homework: 25%
  - Midterm : 20%
  - Final : 35%
  - Project/term paper 20%
  - TOTAL : 100%
  - *Class participation is encouraged*

  - *Mid-term date Oct 16*

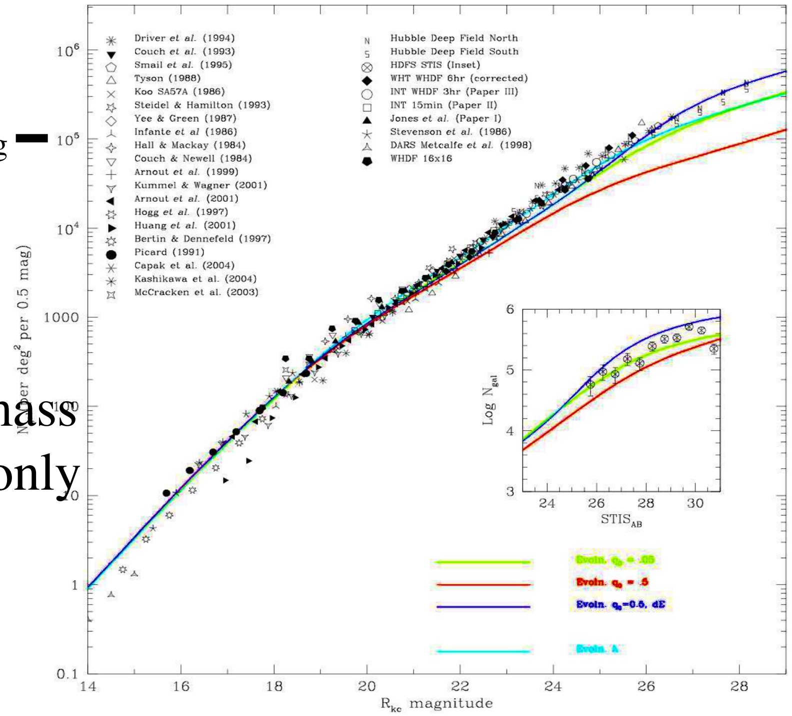
How Many Galaxies are There

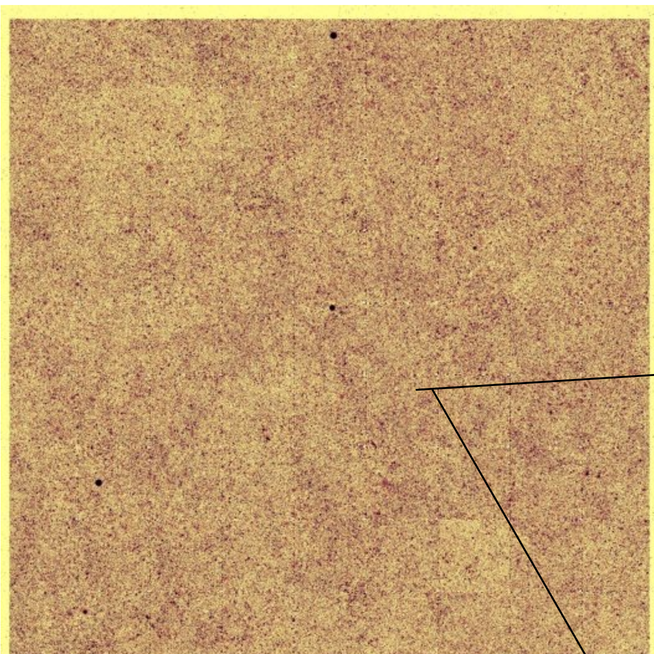
- There are ~50galaxies/sq arc min at m~25.5, rising slowly to ~175 at m~29

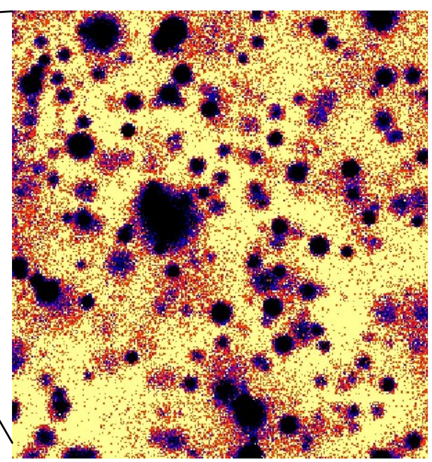
The median redshift at a given magnitude increases slowly

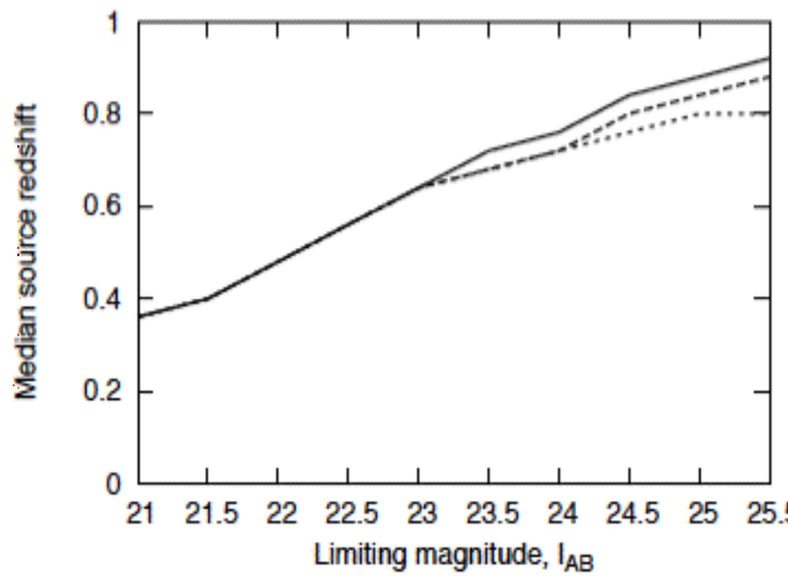
~40% of stellar mass in ellipticals but only 5% by number

10^5/deg^2/0.5mag



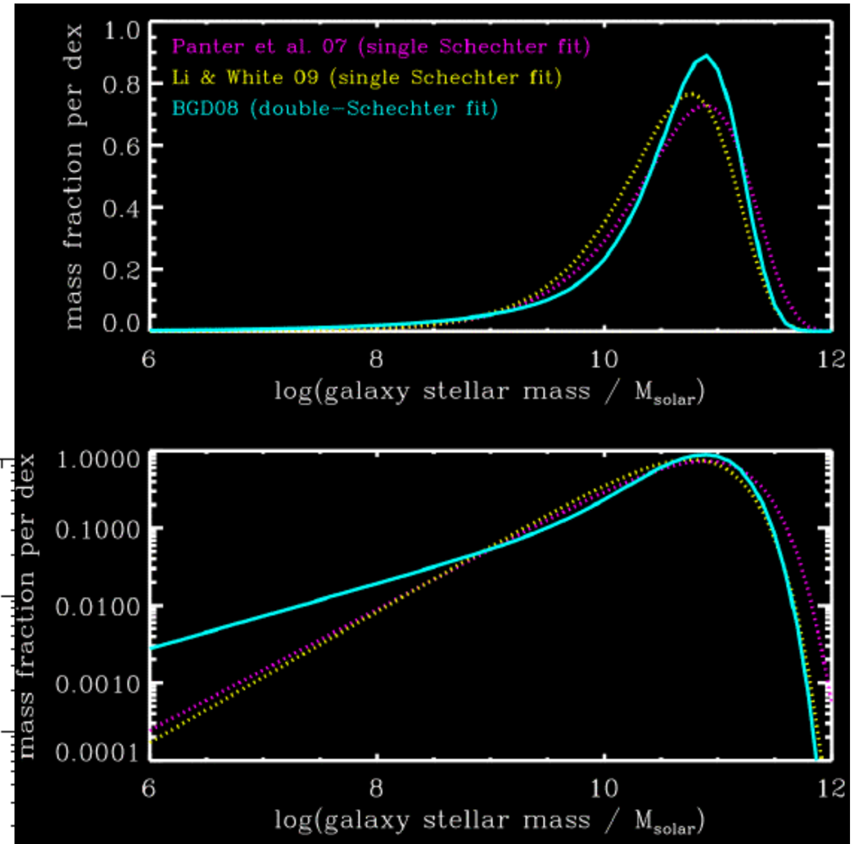


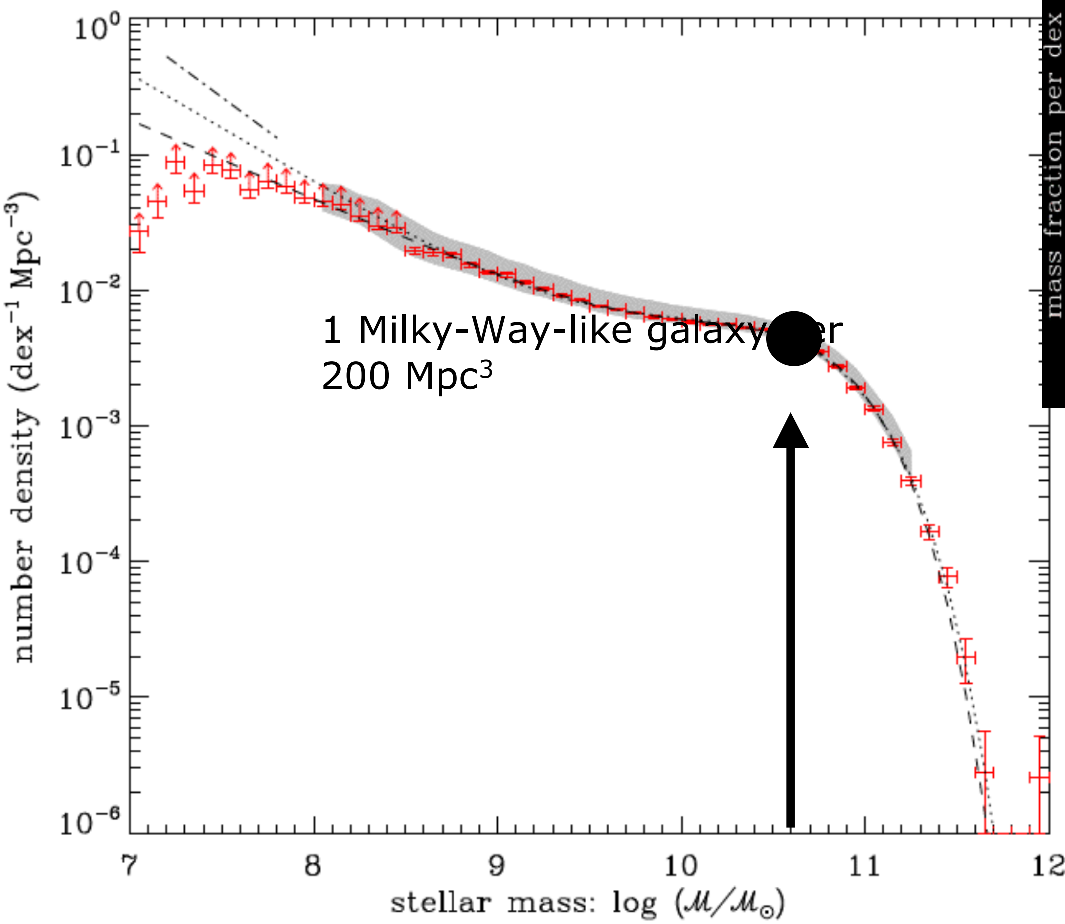




How Many Galaxies are There

- The mass function of galaxies (#/volume)





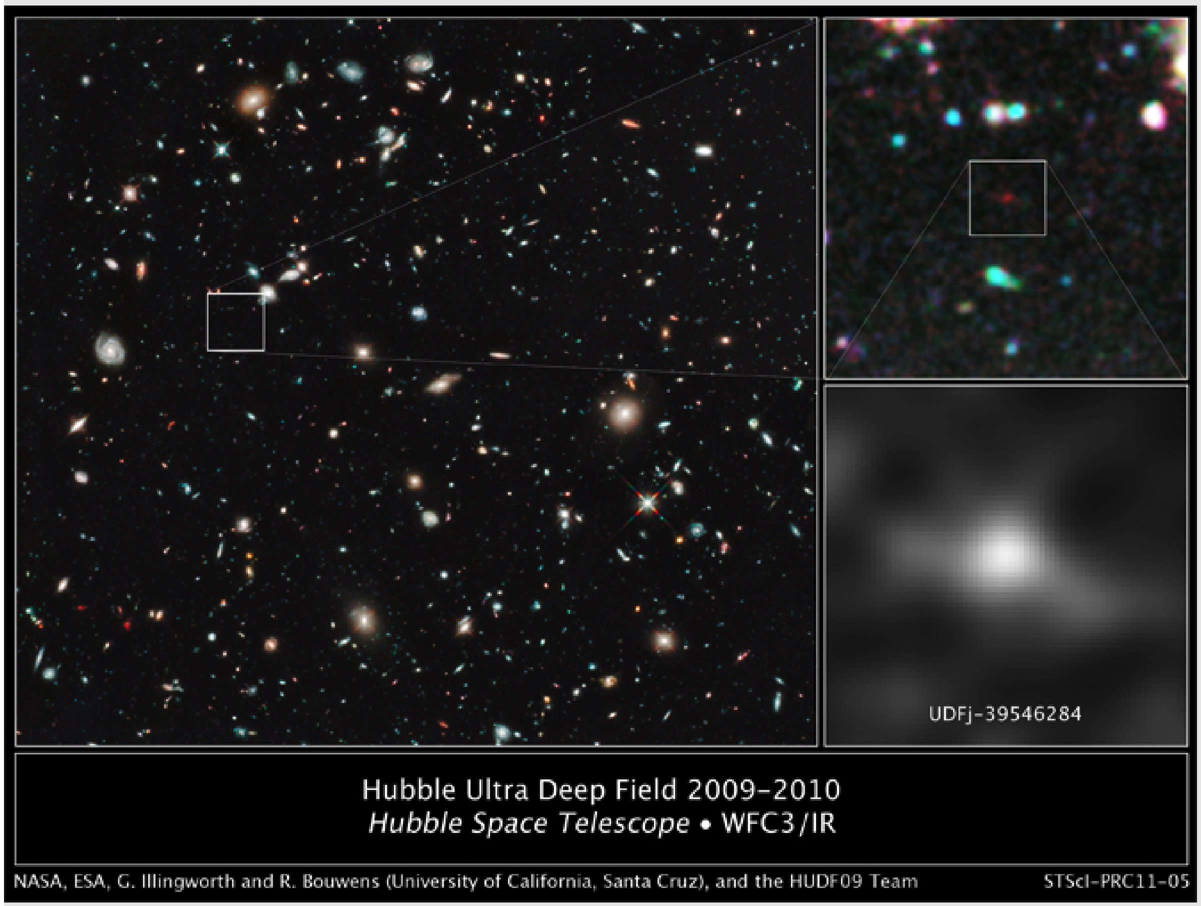
where is the mass- narrow distribution around log M~10.5$M_\odot$.

In mass MW is typical

Rix 2009)

How Old are Galaxies

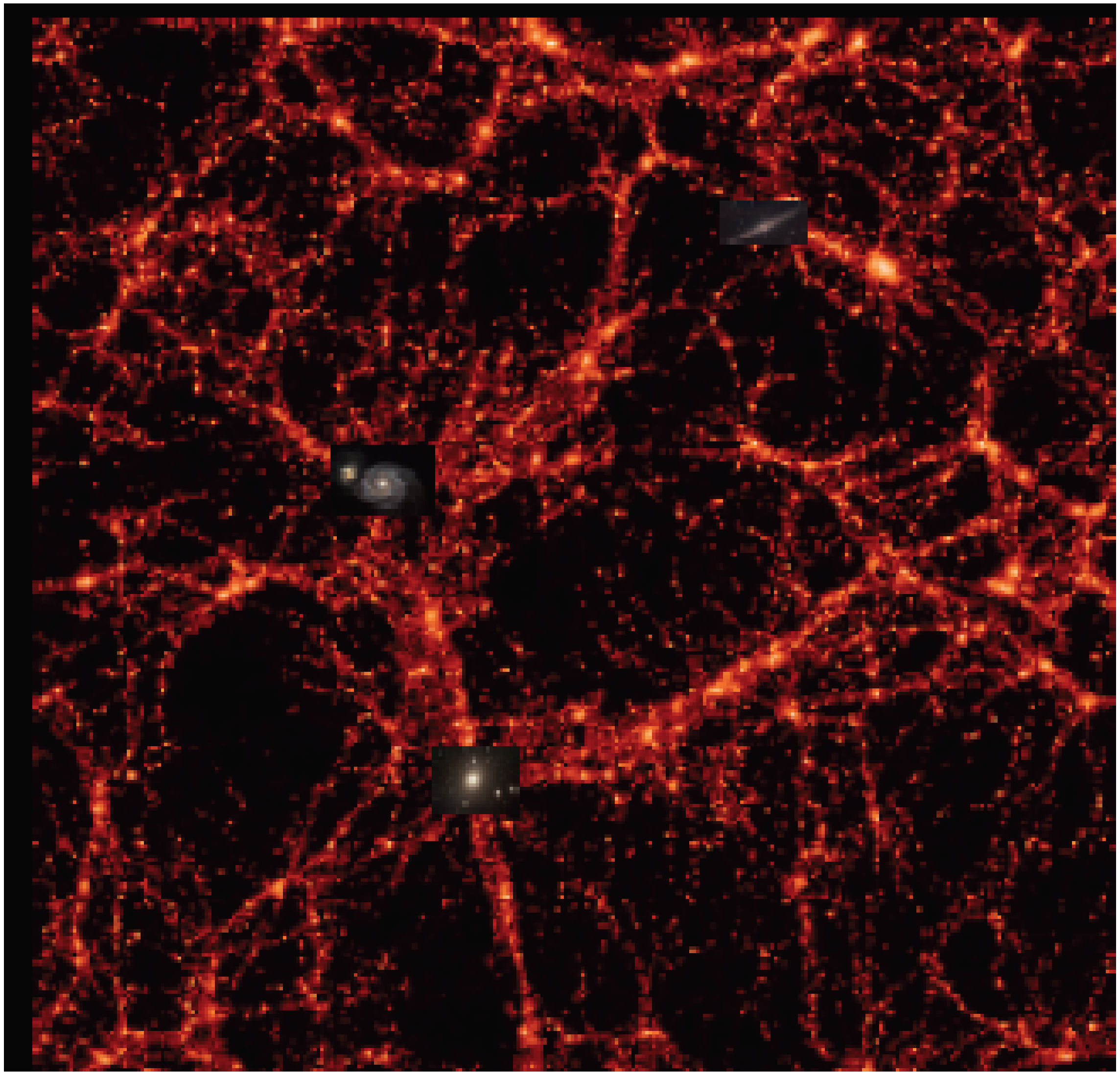
- Direct imaging by HST has shown the existence of galaxies at z~8 (13Gyrs age, for an age of the universe model of 13.7Gyrs)
- Stellar ages: in the MW oldest stars are ~13.2Gyrs old (error of +/-2 Gyrs) (Physics Today, vol. 65, issue 4, p. 49)
- However galaxies have changed enormously over cosmic time
- The present day pattern of galaxies emerged at z~1



The farthest and one of the very earliest galaxies ever seen in the universe appears as a faint red blob in this ultra-deep–field exposure taken with NASA's Hubble Space Telescope. This is the deepest infrared image taken of the universe. Based on the object's color, astronomers believe it is 13.2 billion light-years away. (Credit: NASA, ESA, G. Illingworth (University of California, Santa Cruz), R. Bouwens (University of California, Santa Cruz, and Leiden University), and the HUDF09 Team)

Galaxies Do Not Live Alone

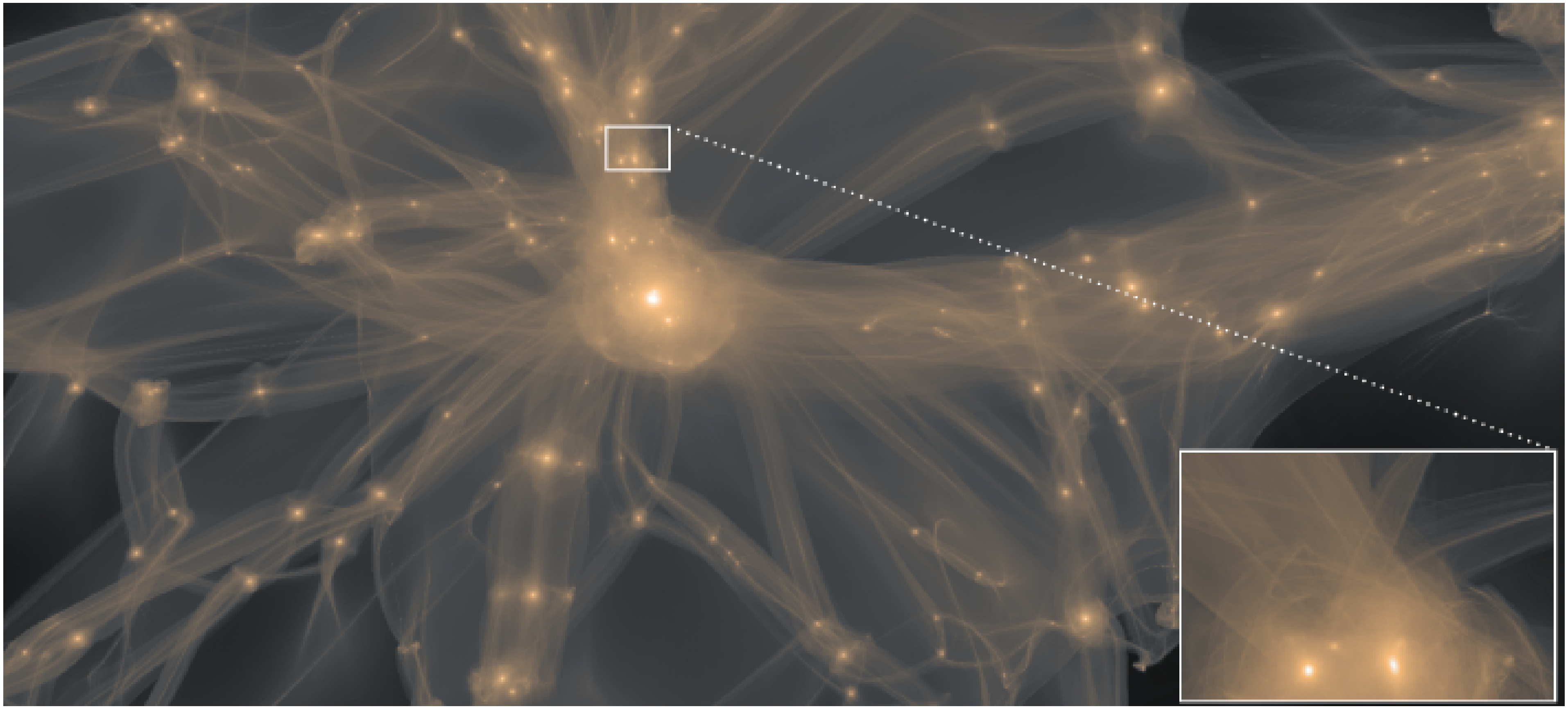
- Galaxies are part of the 'cosmic web'- representing overdense regions of both baryons and dark matter
- The effective size of the dark matter is much larger than the apparent stellar size



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

Eric Bell

Cosmic Web

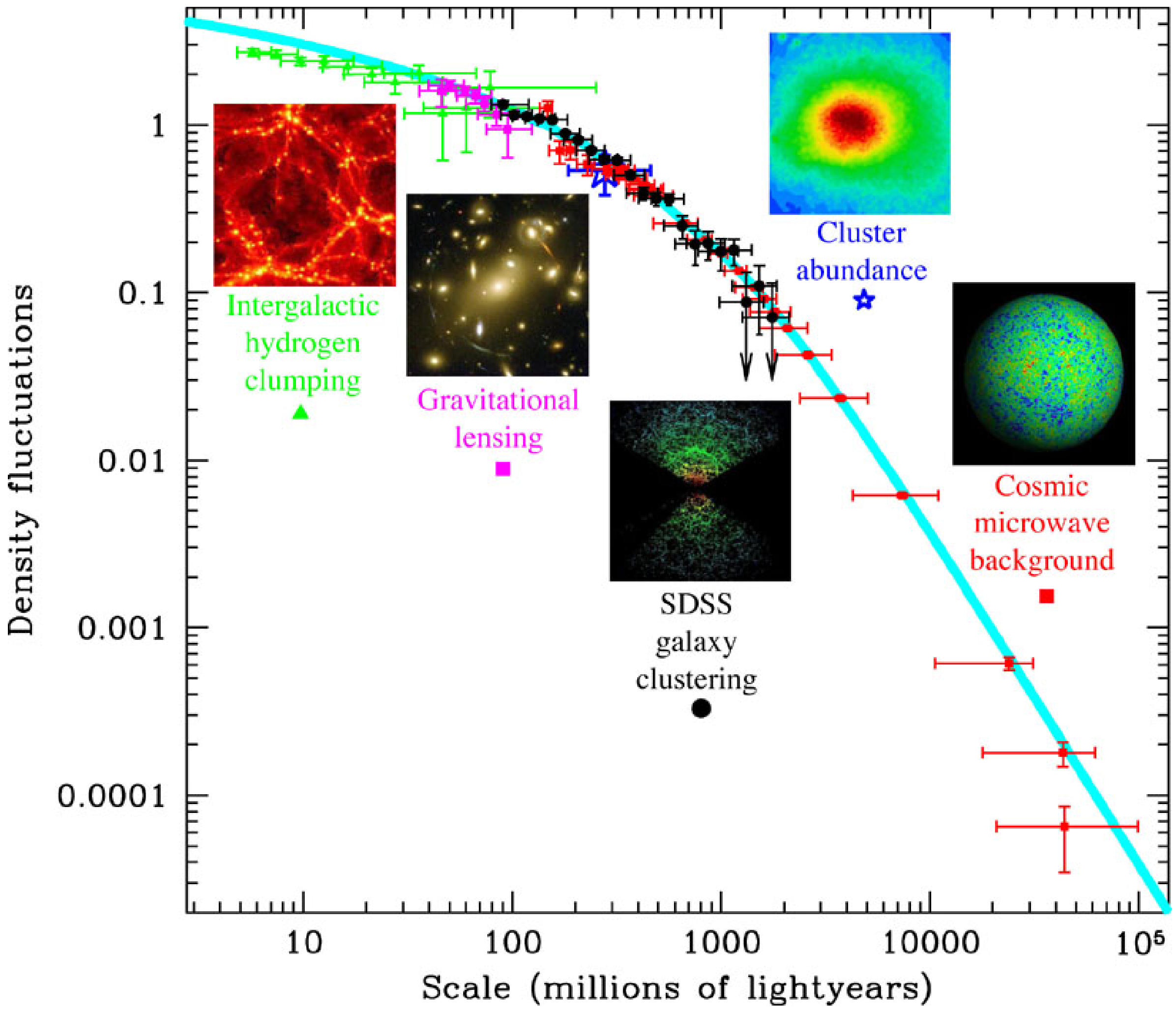


In this rendering the large scale sheets and filaments are more easily seen- galaxies tend to reside in these sheets and filaments and are rare in voids.

Power Spectrum of Fluctuations

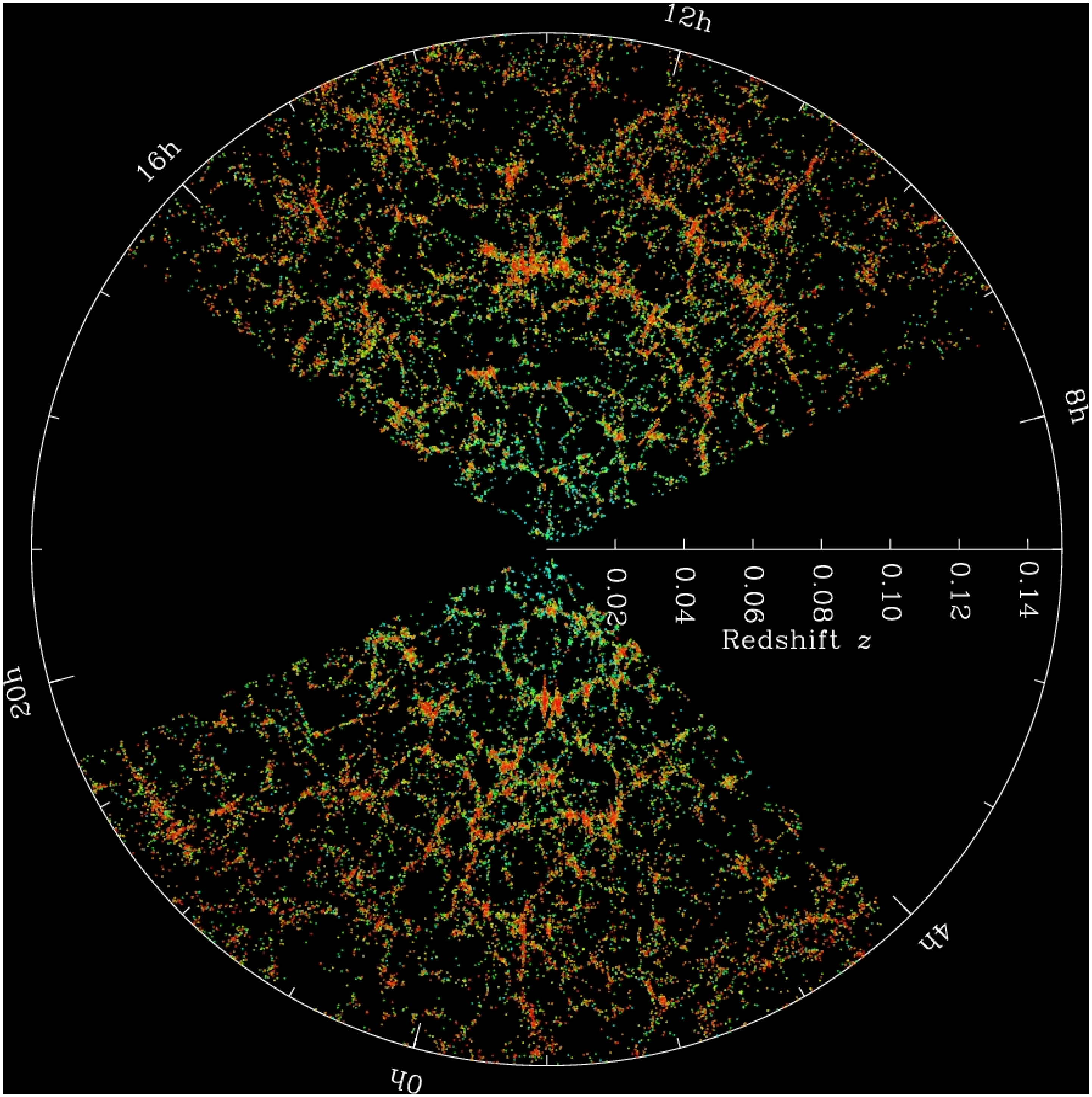
- As one goes to larger scales the universe gets less lumpy (on average)

Lumpiness of universe



Tegmark 2004

size of box



Sloan Digital Sky Survey

Galaxies color coded by the age of their stars

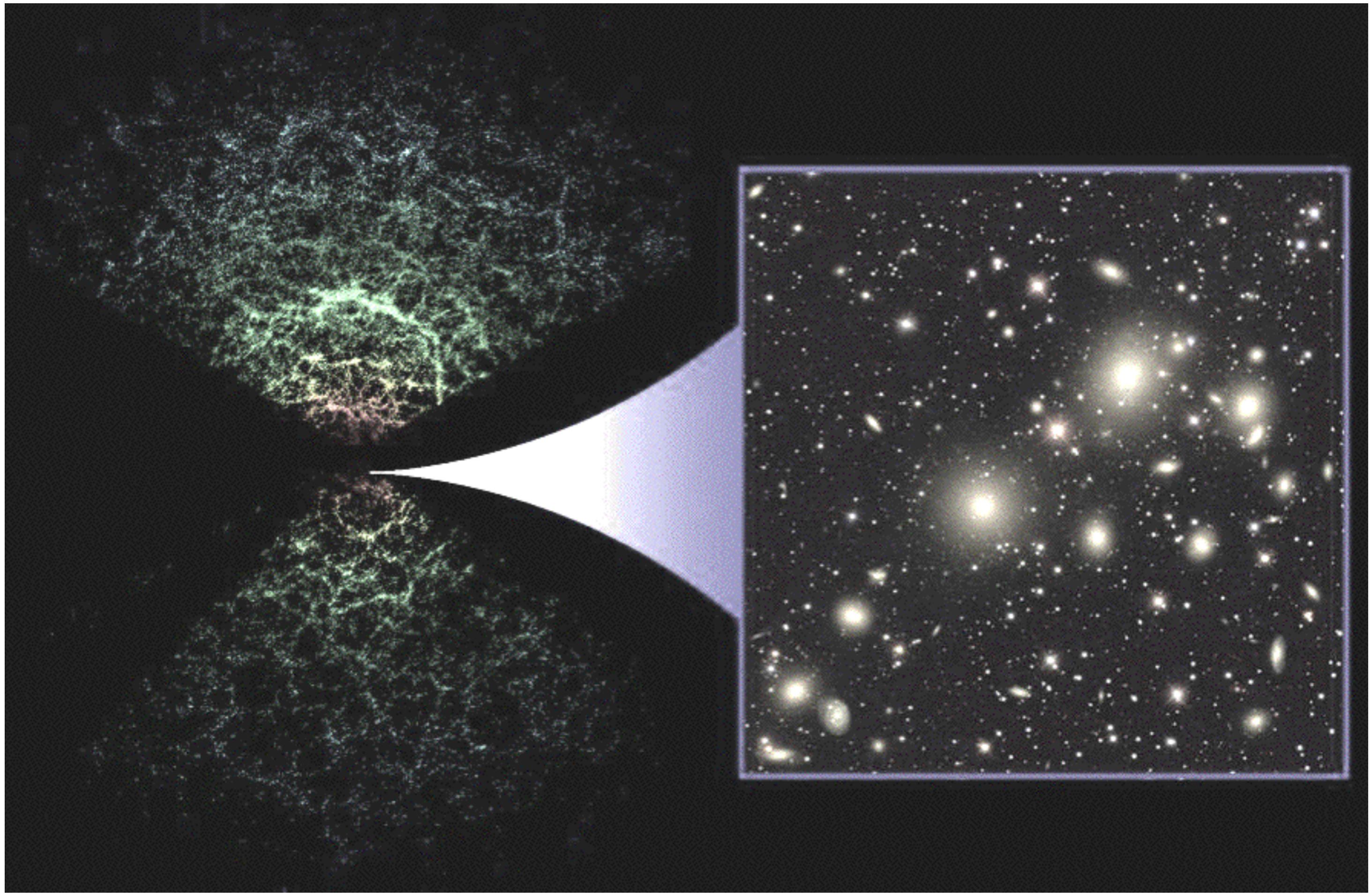
http://www.sdss.org

2MASS view of galaxies selected by infrared flux

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

Large Scale distribution of normal galaxies

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

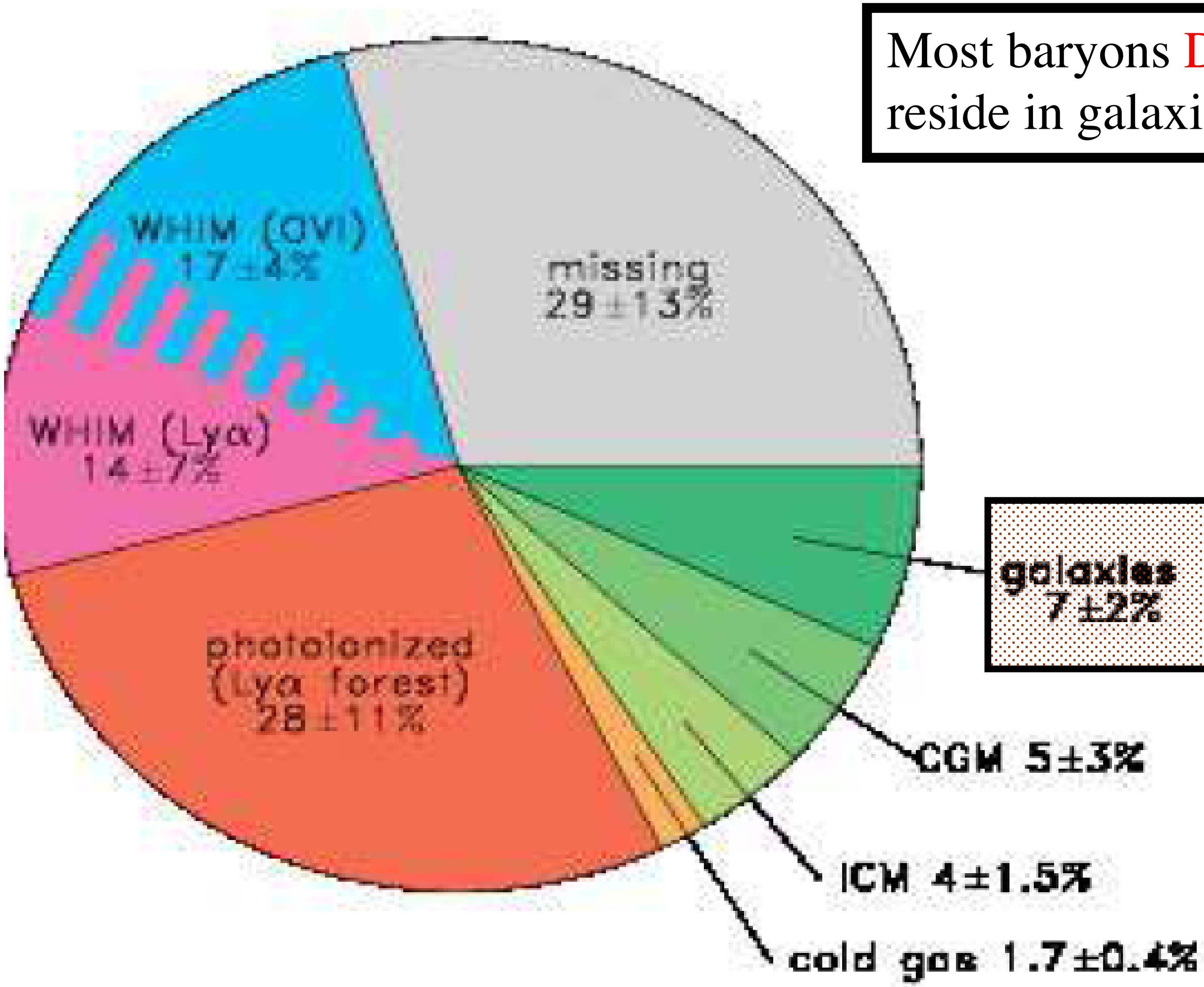


Sloan Digital Sky Survey- http://skyserver.sdss3.org/dr8/en/

Where are the Baryons

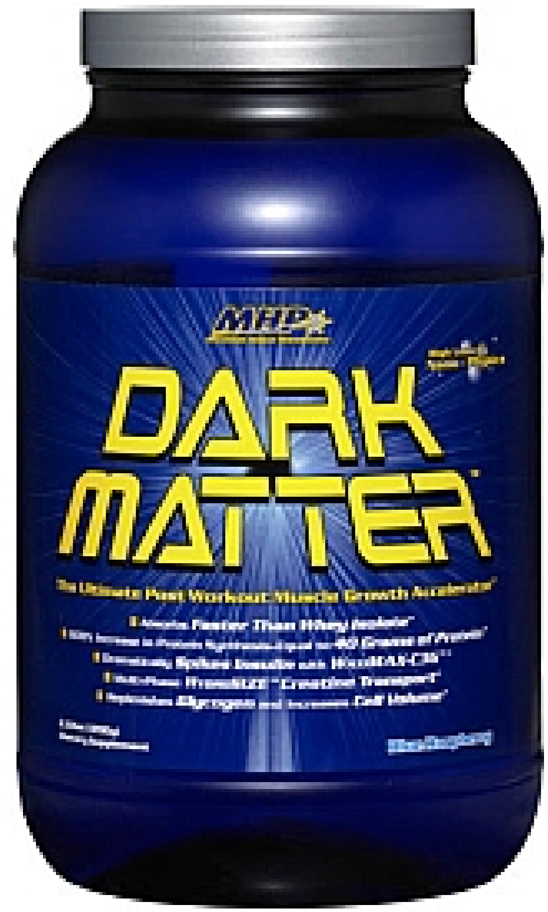
Shull Danforth 2012

Most baryons DO NOT reside in galaxies



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 does 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.
- (seehttp://astro.berkeley.edu/~mwhite/darkmatter/essay.html) for a nice essay on dark matter



Dark Matter Dominates Gravity

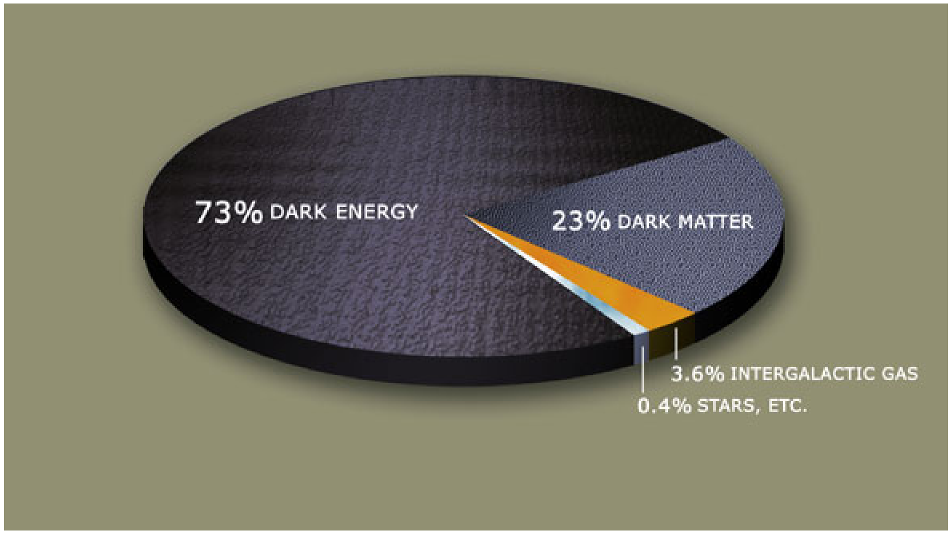
- The cosmic ratio of dark matter to baryons is 6:1

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

$\Omega_{baryons} = 0.042 \pm 0.003$

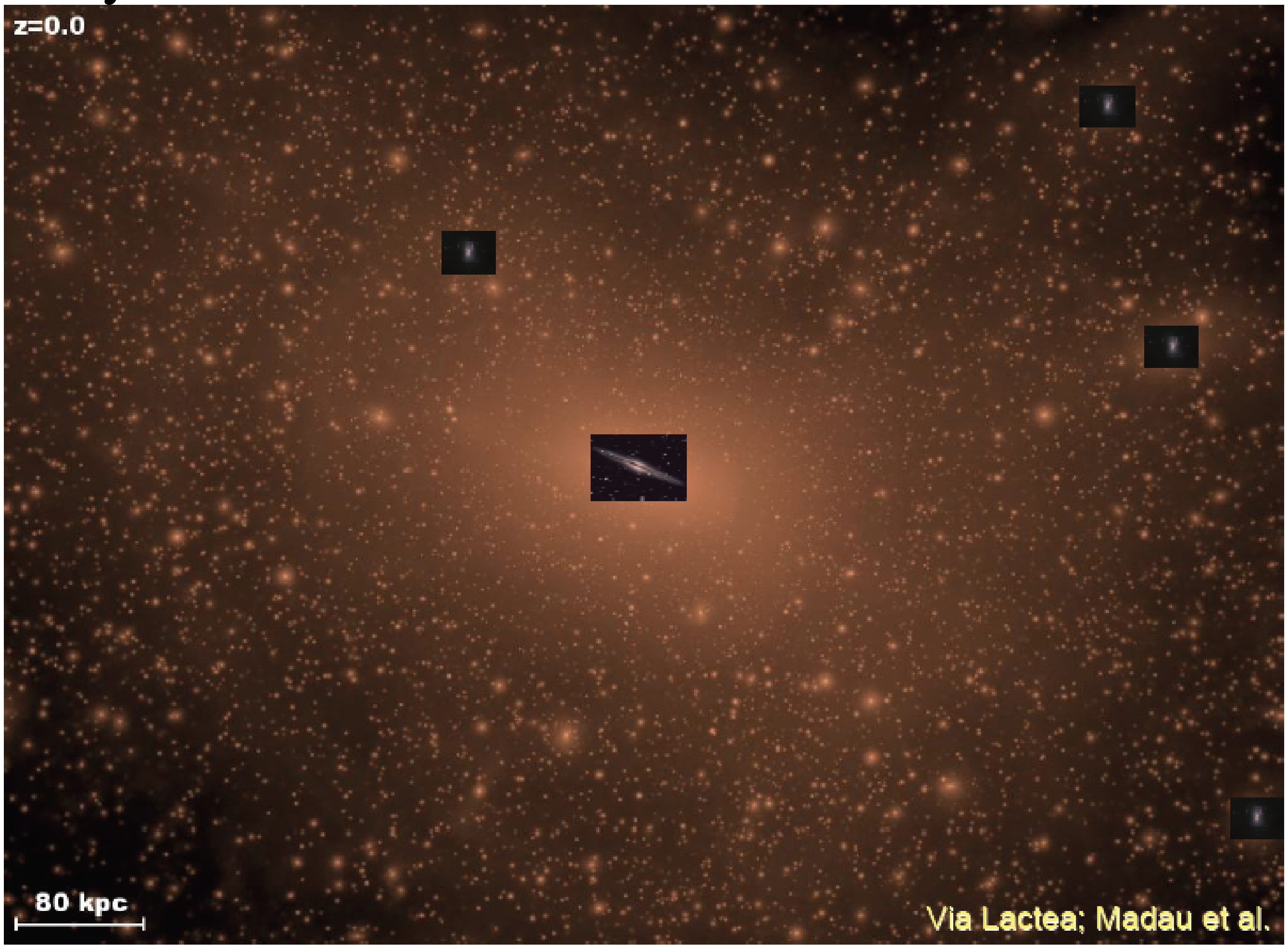
$\Omega_{dark\ matter} = 0.23$

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



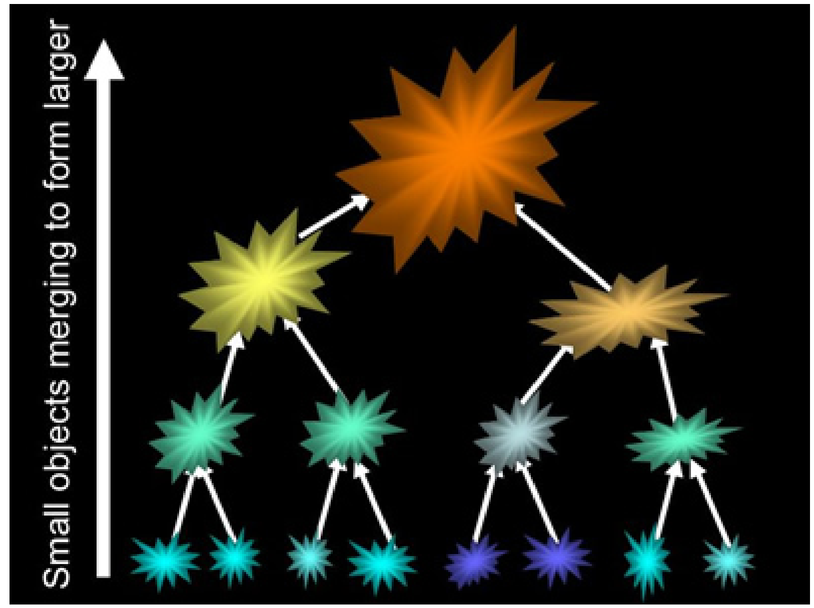
Dark Matter Distribution and Galaxies

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



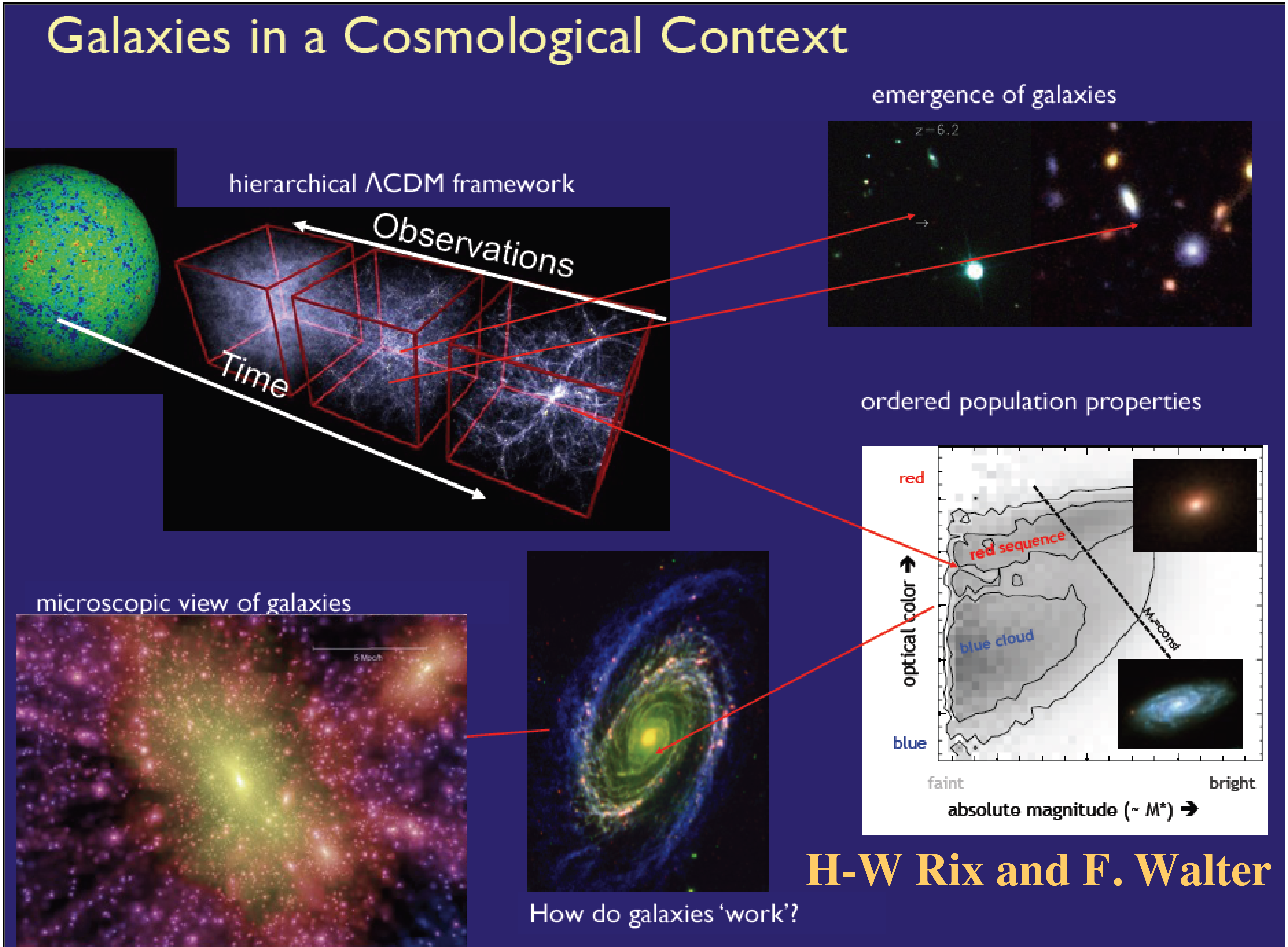
How Things Form

- 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).


Galaxies in a Cosmological Context
emergence of galaxies
z~6.2
hierarchical ΛCDM framework
Observations
Time
ordered population properties
red
red sequence
optical color
blue cloud
blue
faint
bright
absolute magnitude (~ M*)
microscopic view of galaxies
5 Mpc/h
How do galaxies 'work'?
H-W Rix and F. Walter

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

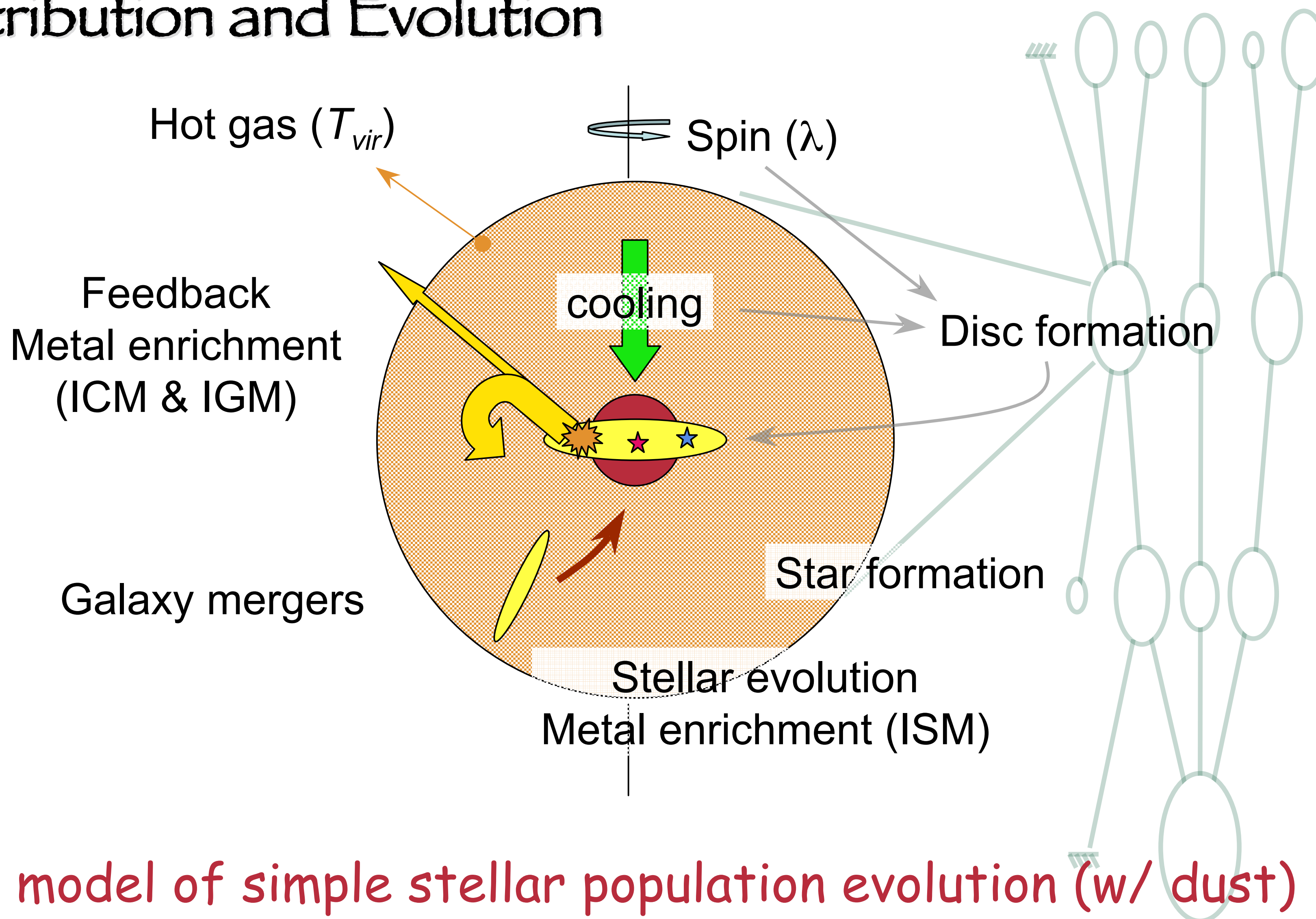
Galaxy interactions (morphological transformations, starbursts, intracluster stars, ...

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

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

taken from **J. Blaizot** presentation

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



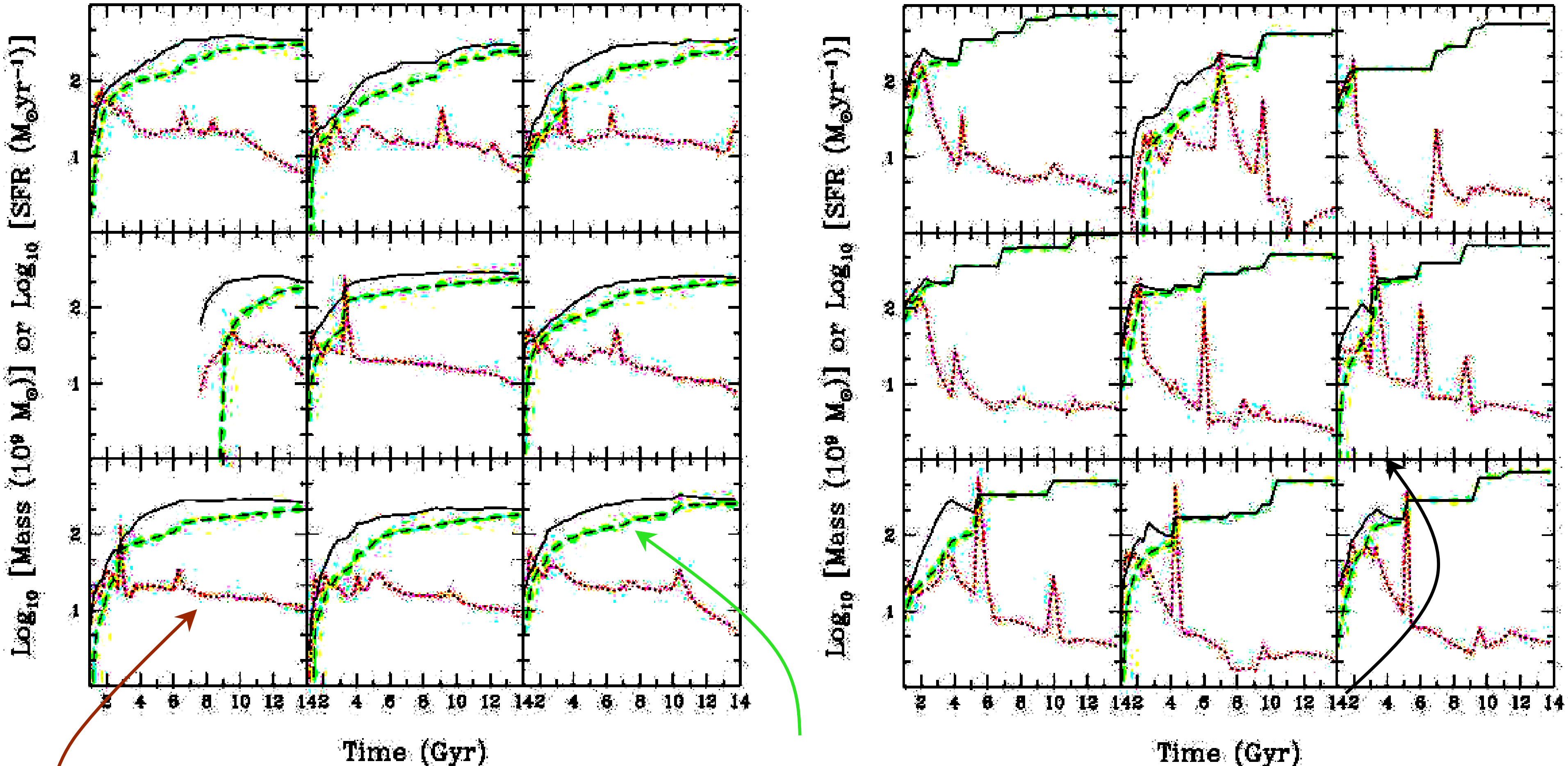
+ model of simple stellar population evolution (w/ dust)

taken from J. Blaizot presentation

A set of results from numerical simulations

spirals

ellipticals



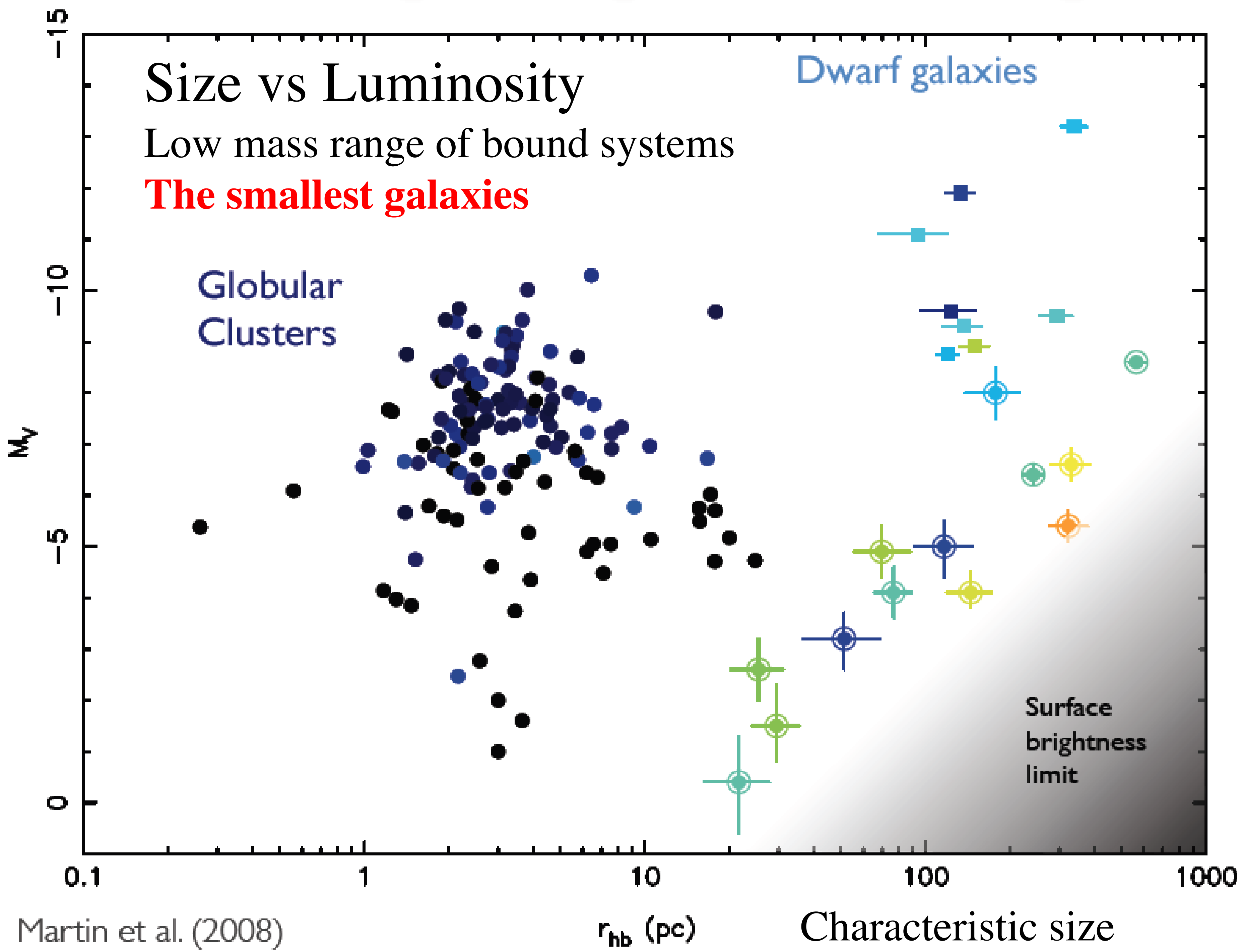
Stellar mass

Gas+stars

SFR

notice SFR not constant

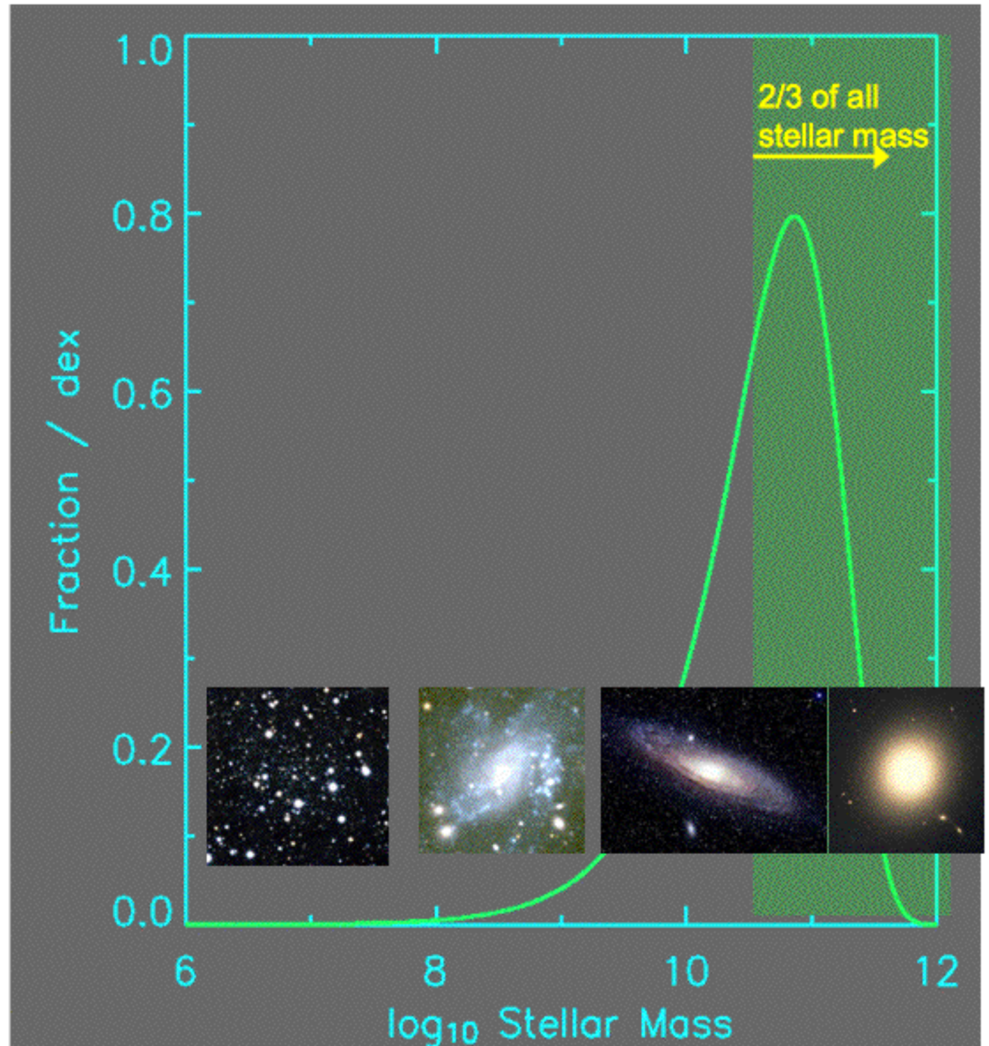
mass growth has 'jumps' - mergers J. Blaizot-



Size vs Luminosity
Low mass range of bound systems
The smallest galaxies
Dwarf galaxies
Globular
Clusters
Surface
brightness
limit
M_V
−15
−10
−5
0
0.1
1
10
100
1000
Martin et al. (2008)
r_{hb} (pc)
Characteristic size

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+/-$3x10^{10}M_\odot$ (in stars)
- The baryons are distributed in gas, stars and dust; wide range in gas/stars, relatively narrow range in dust/gas.



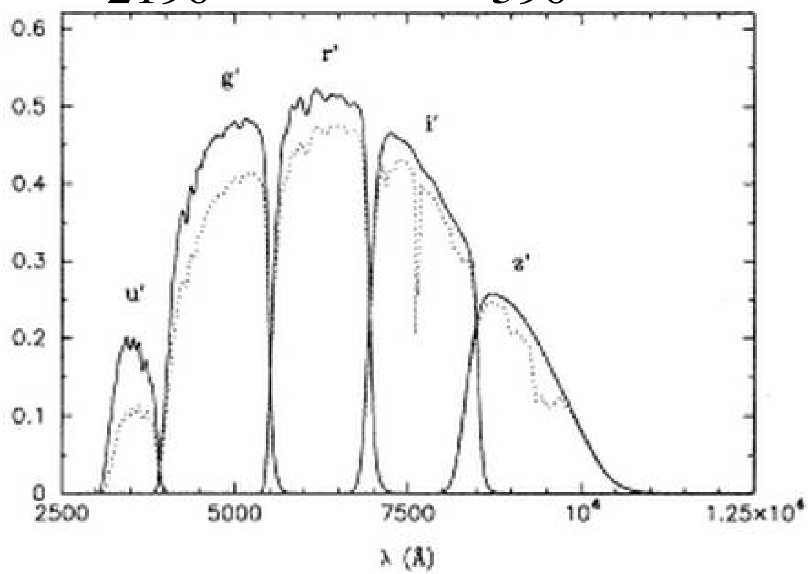
Bell et al. 2003

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

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

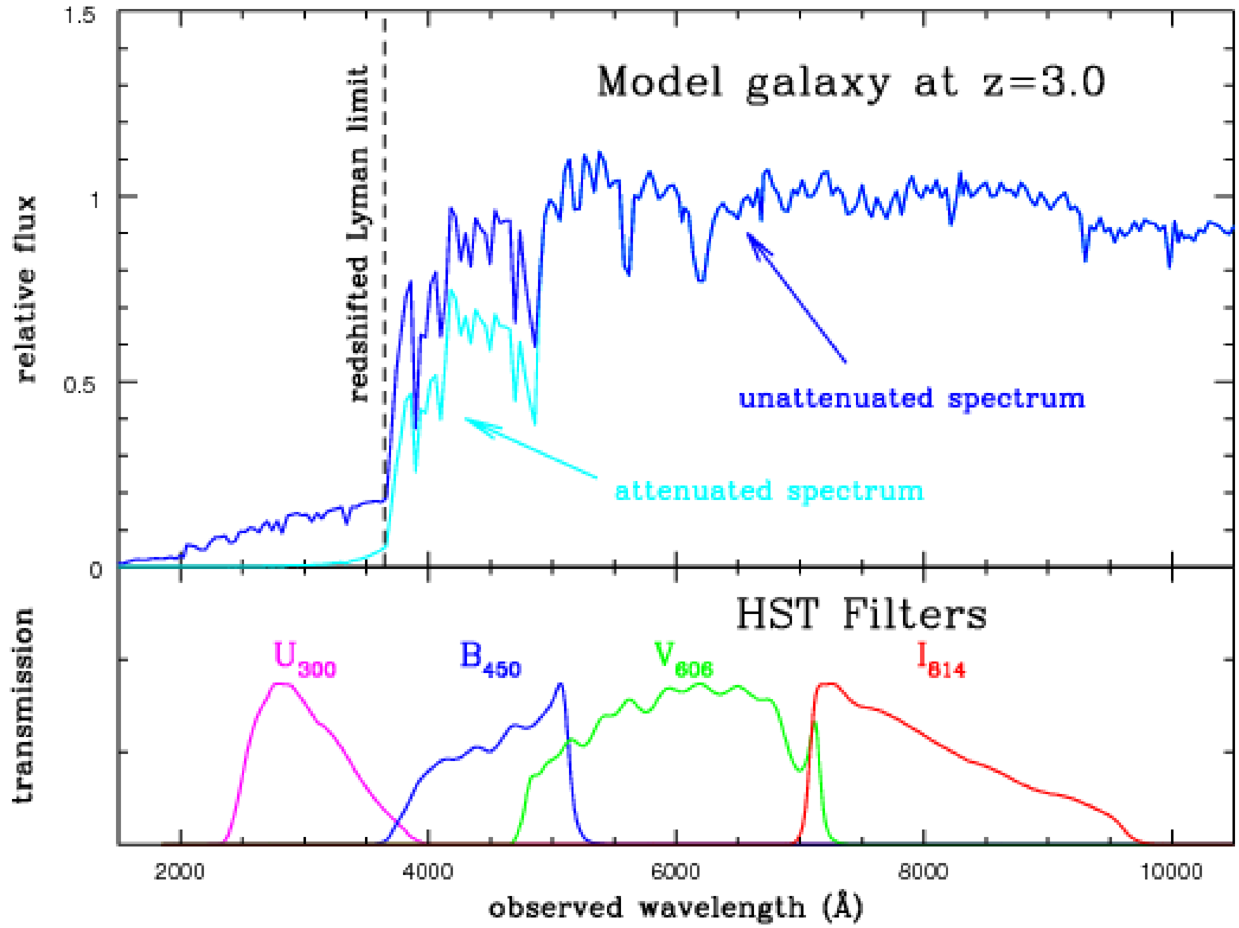
AB system (Oke & Gunn 1983), magnitude 0 object in all bands has the same flux F_ν = 3631 Jy
a object with a flat energy distribution (F_ν=constant) has the same mag in all colors; 3631 Jy is how bright Vega is in the V band!
Absolue mag of sun in SDSS filter set
u;g;r;i;z 5 lg h = 6:80; 5:45; 4:76; 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, uses
(the UBV data set was developed for use with photographic plates, the SDSS set for use with CCDs circa 1995 technology

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 MilkyWay

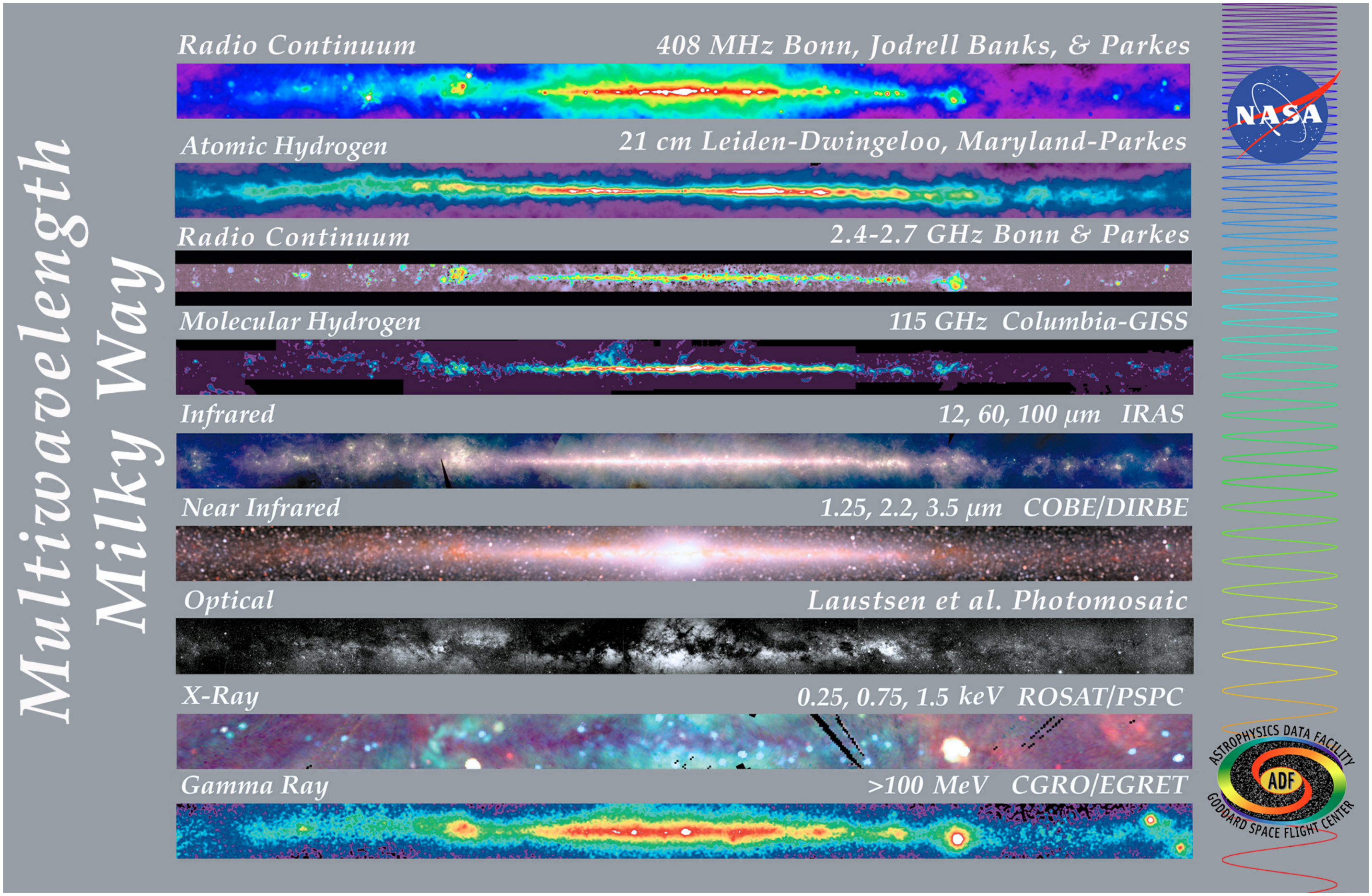
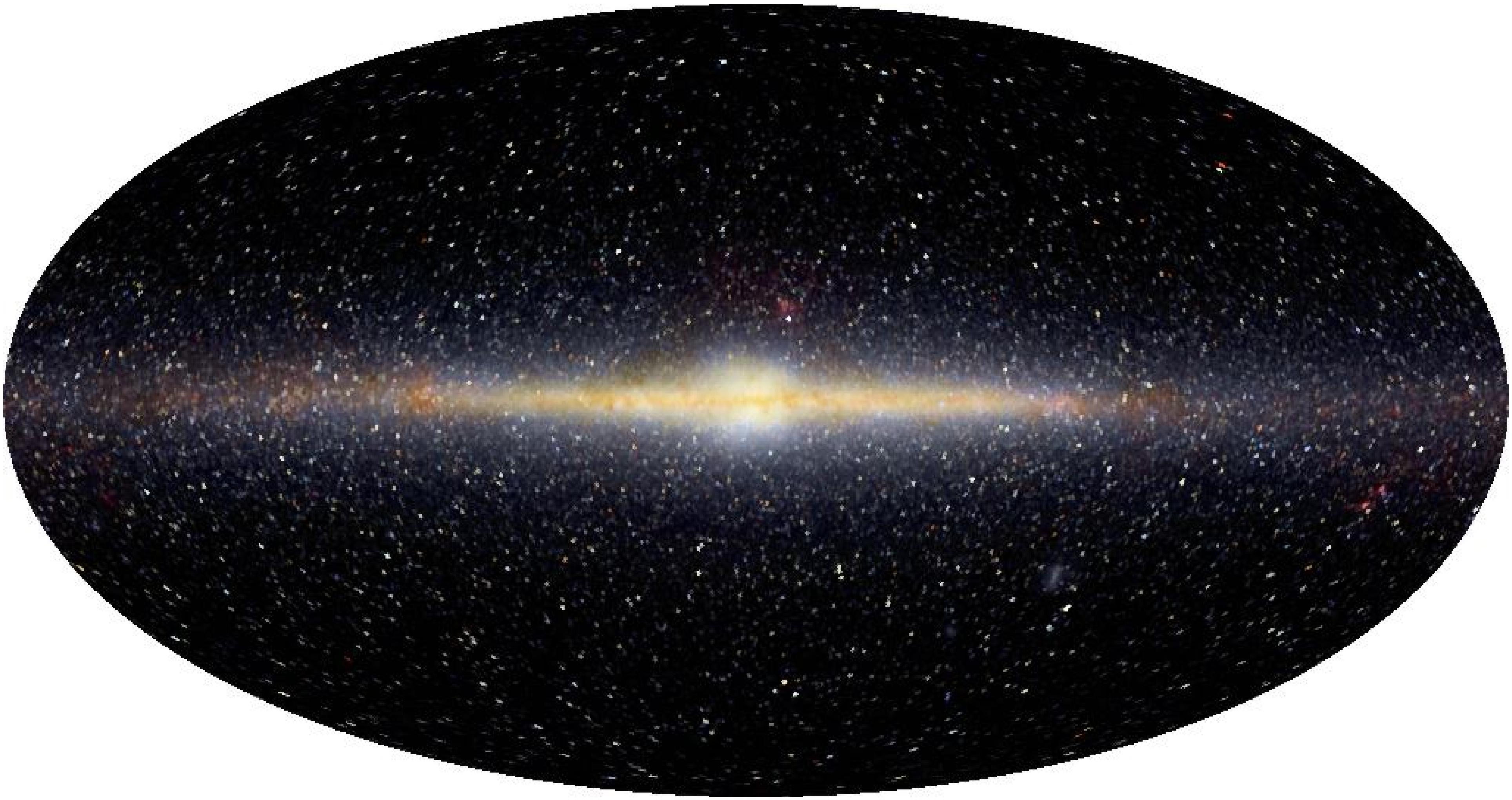


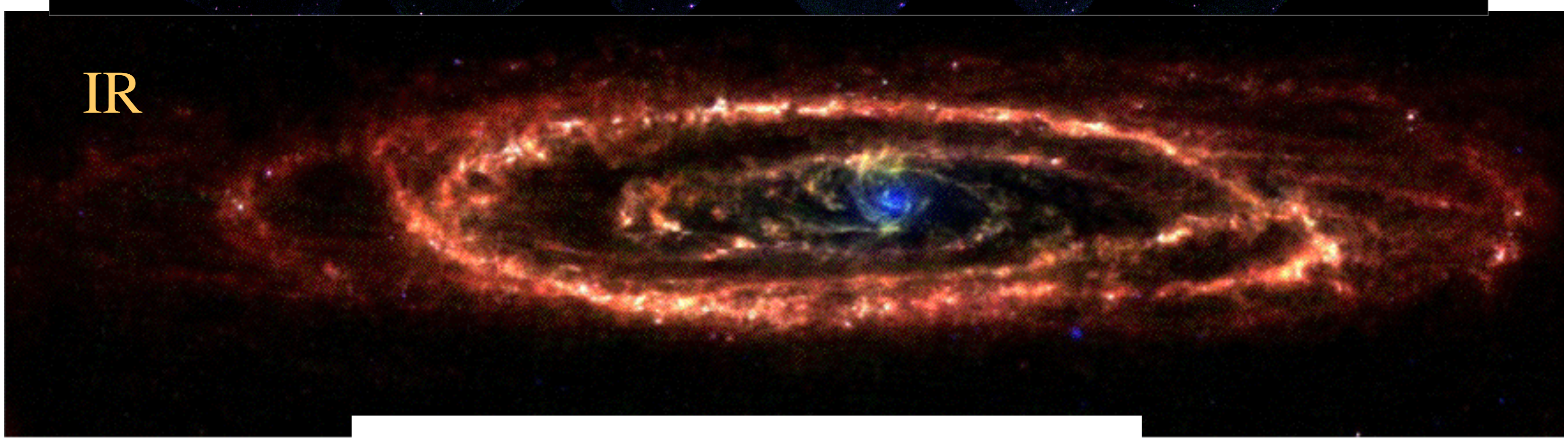
Image of MW galactic plane from radio through γ-rays

Image of MW in IR From COBE



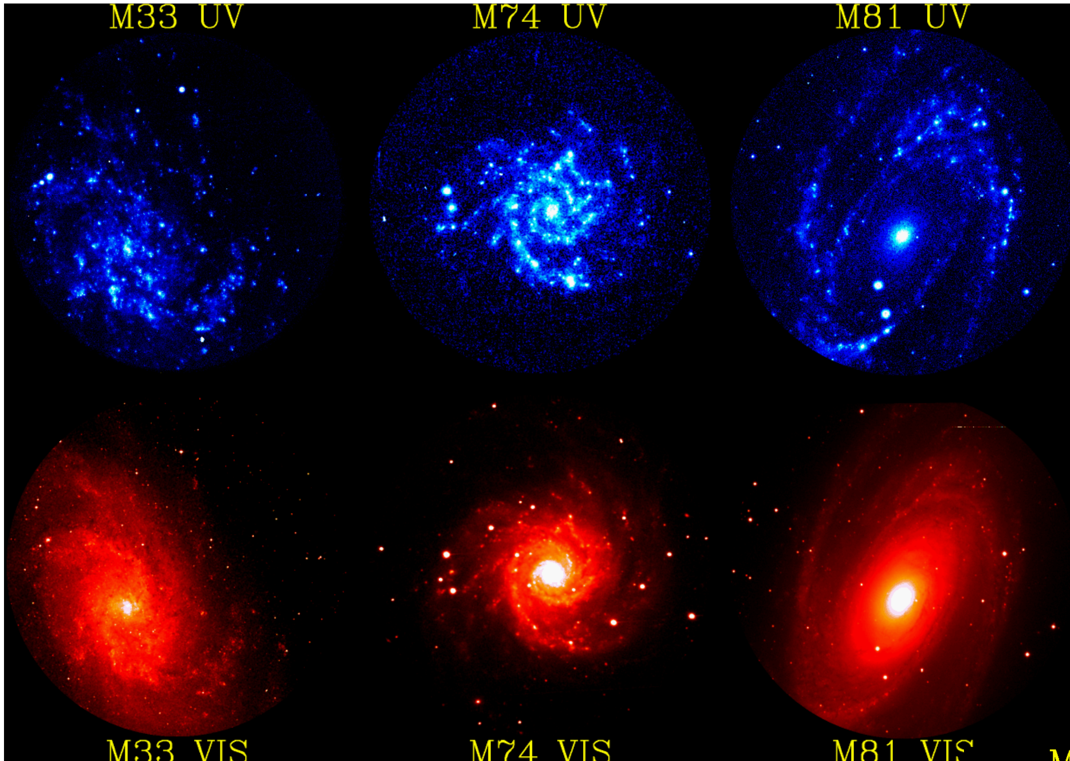
In the IR the effects of dust are minimized and one can see the true distribution of emitted radiation. In this wavelength band the emission is due mostly to old low mass stars

Different Appearances at Different Wavelengths



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

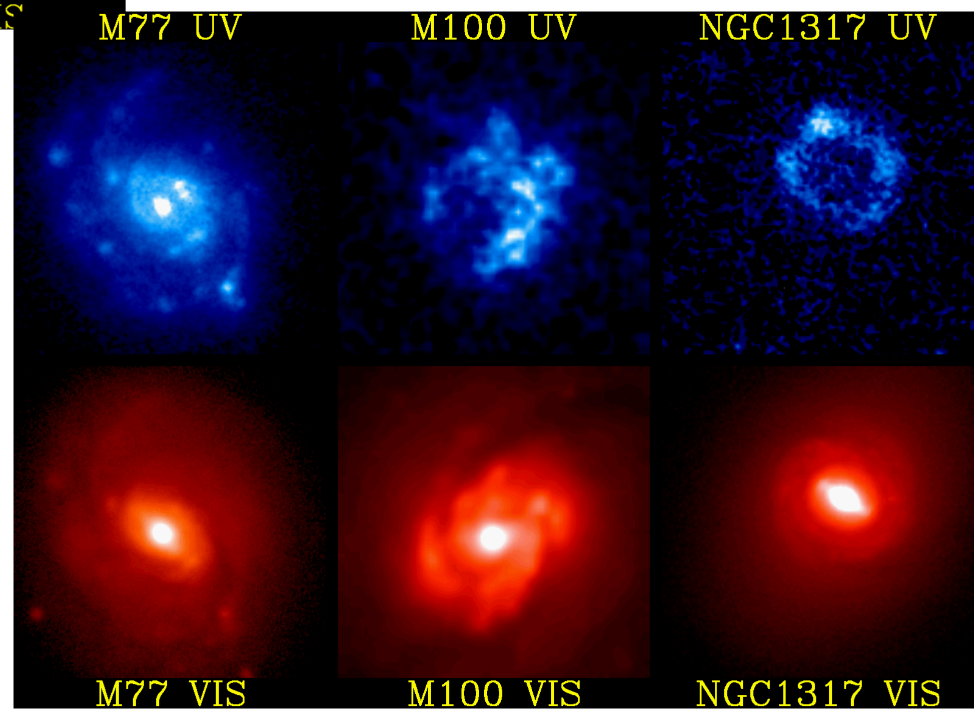
at long IR wavelengths the emission is due to dust which has reprocessed optical/UV light



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

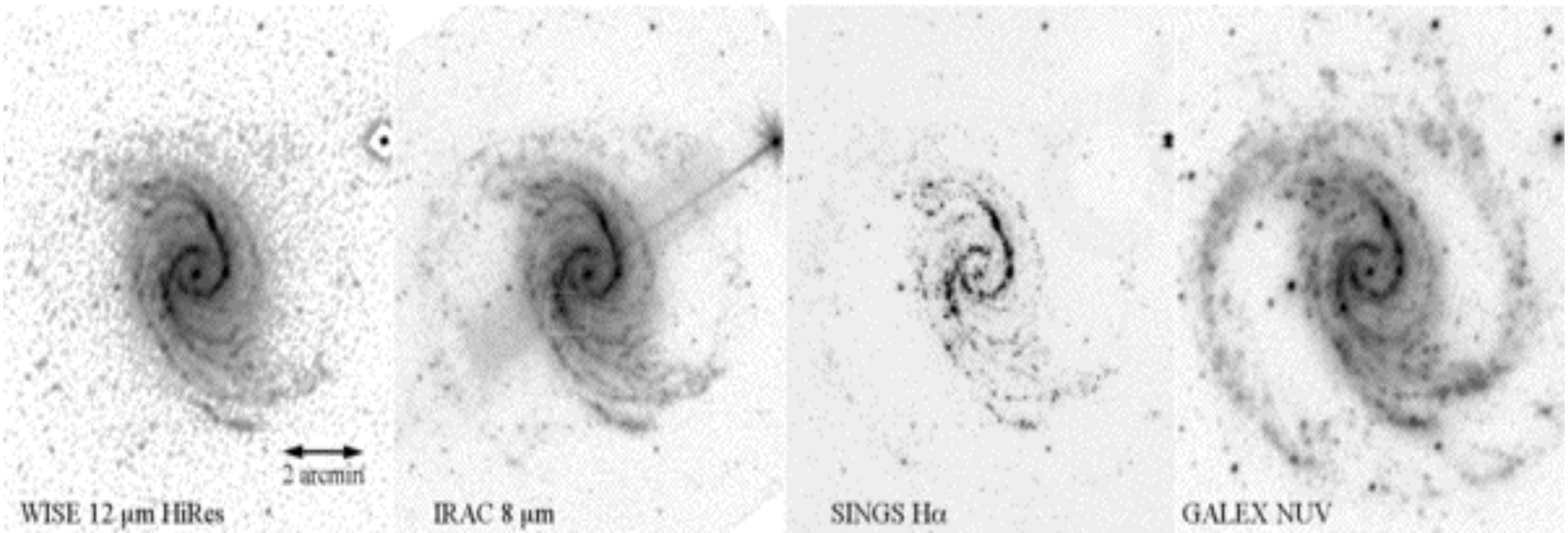
From UIT team



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

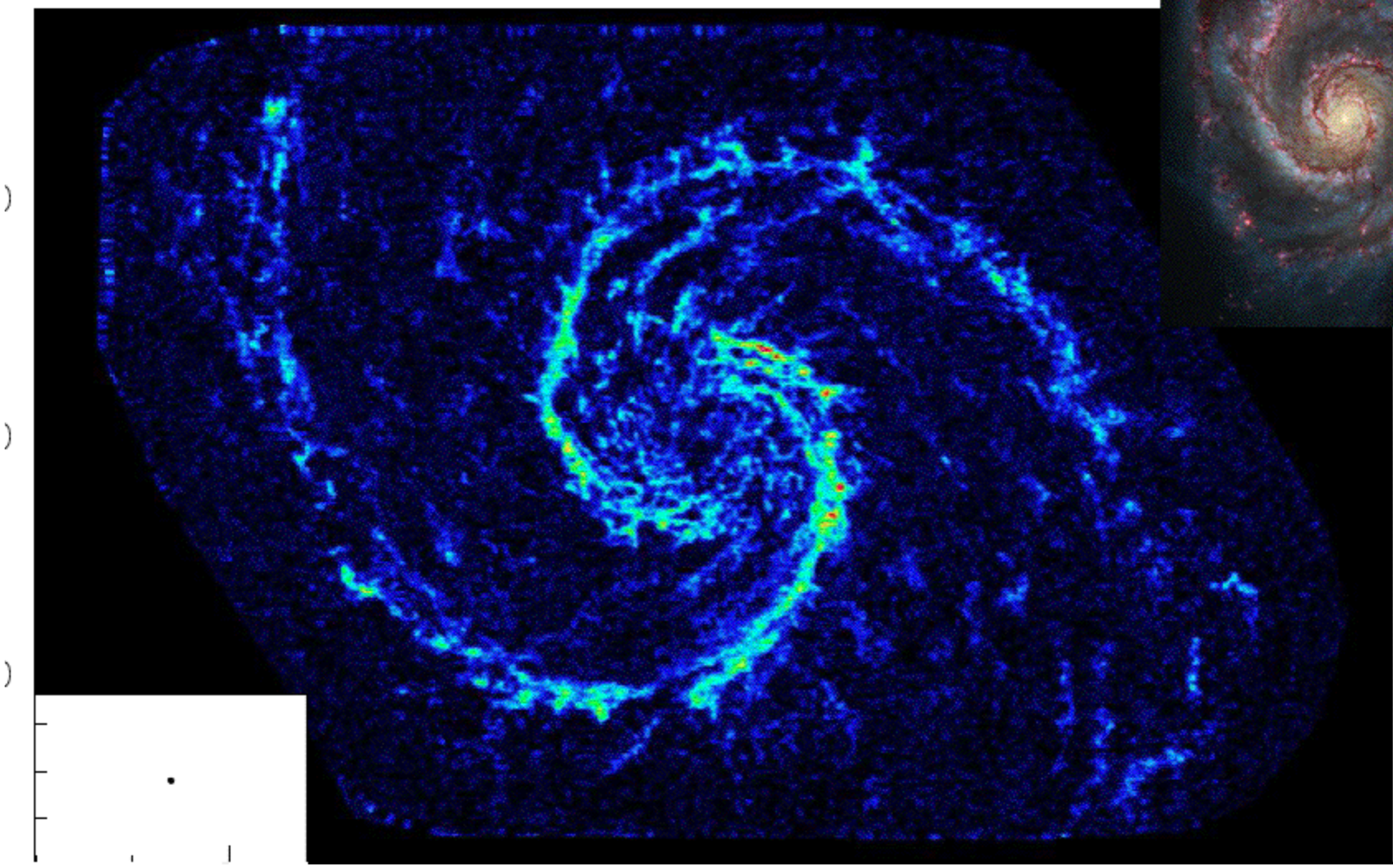
NGC1566 in 4 Bands

- 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

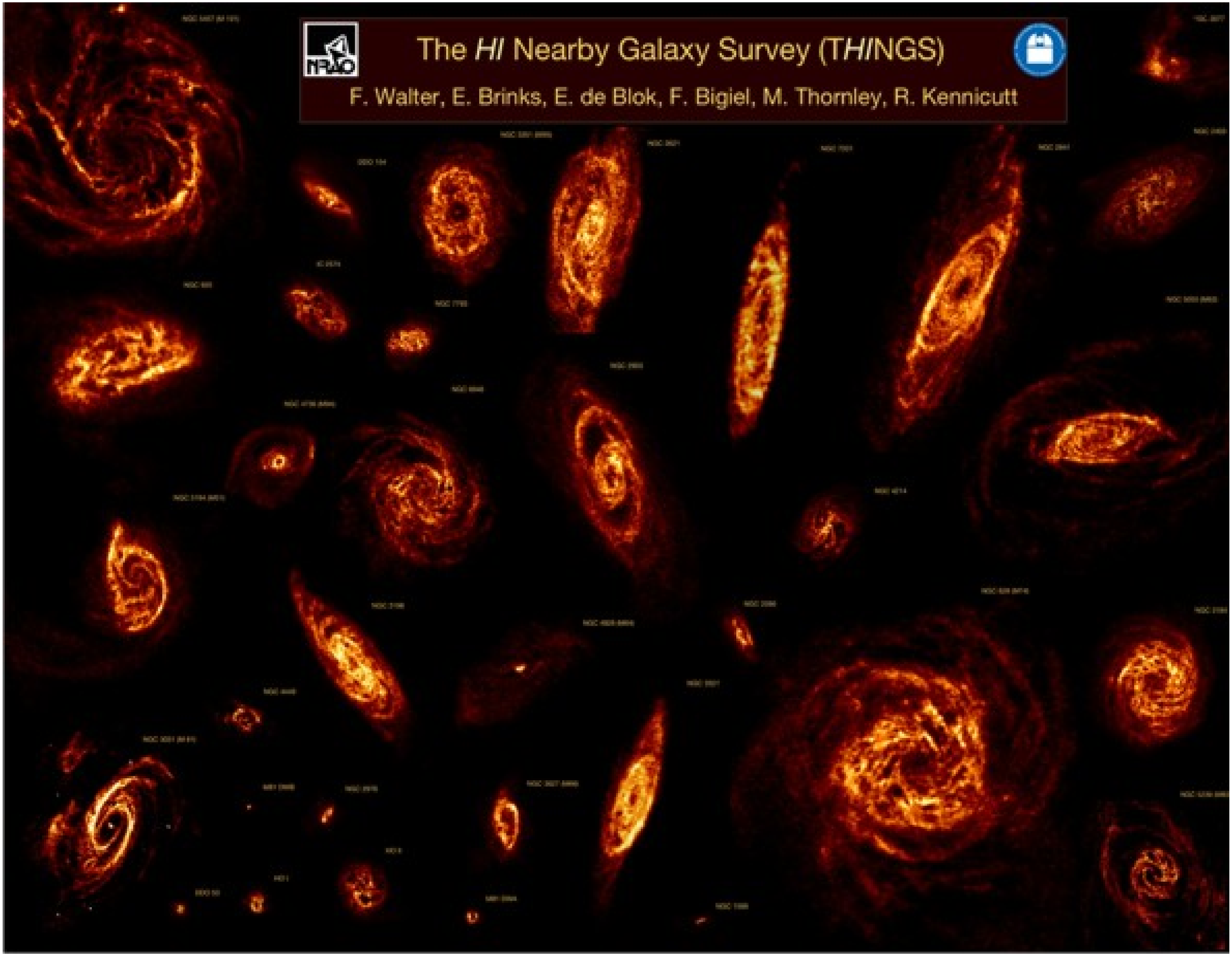


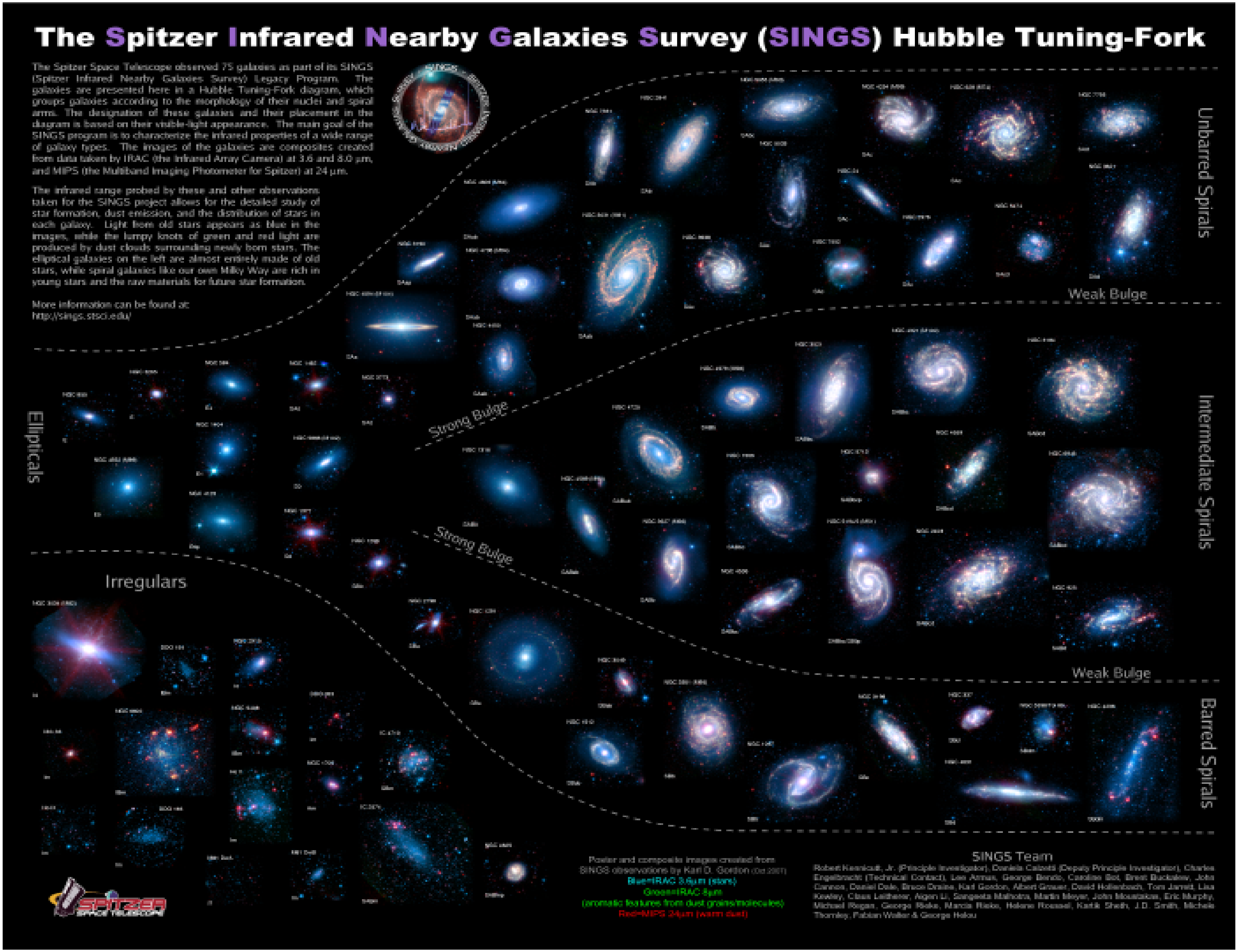
Dust PAH Hα NUV

'Cool gas' (HI-hydrogen) and color coded light (red is warmer hydrogen, blue is young stars reddish color is dust absorption)

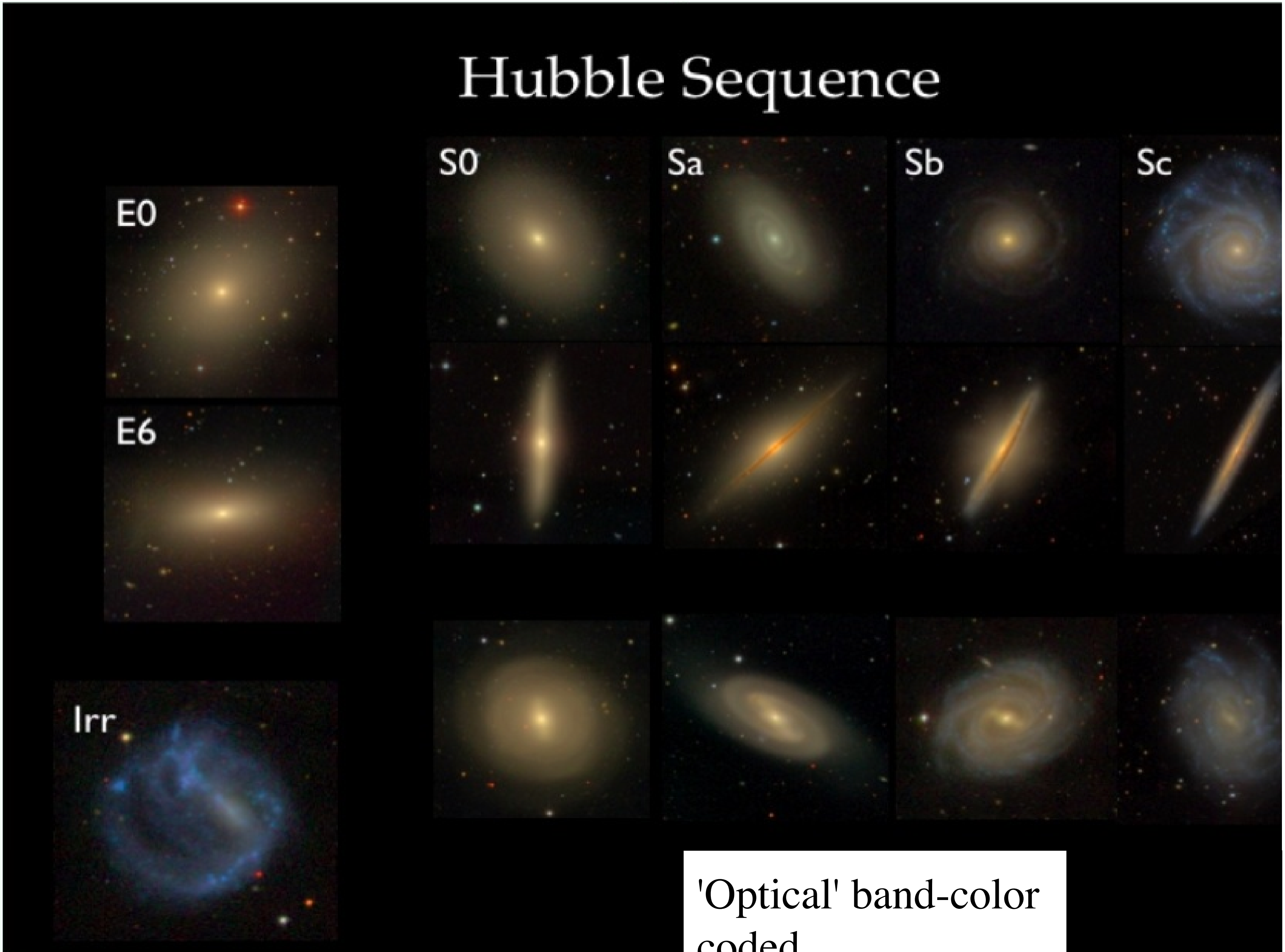


Schinnerer et al 2011


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
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



'Optical' band-color coded


ESO594-G004 Sagittarius Dwarf Irregular Galaxy (in background)
NGC 4676B
UGC 10214 "Tadpole Galaxy"
"The Mice"
NGC 4676A
NGC 634
NGC 5775
M102 "Spindle Galaxy"
ESO 243-49
IC 755
NGC 4452
NGC 4710
M104 "Sombrero Galaxy"
M81 "Bode's Galaxy"

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

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

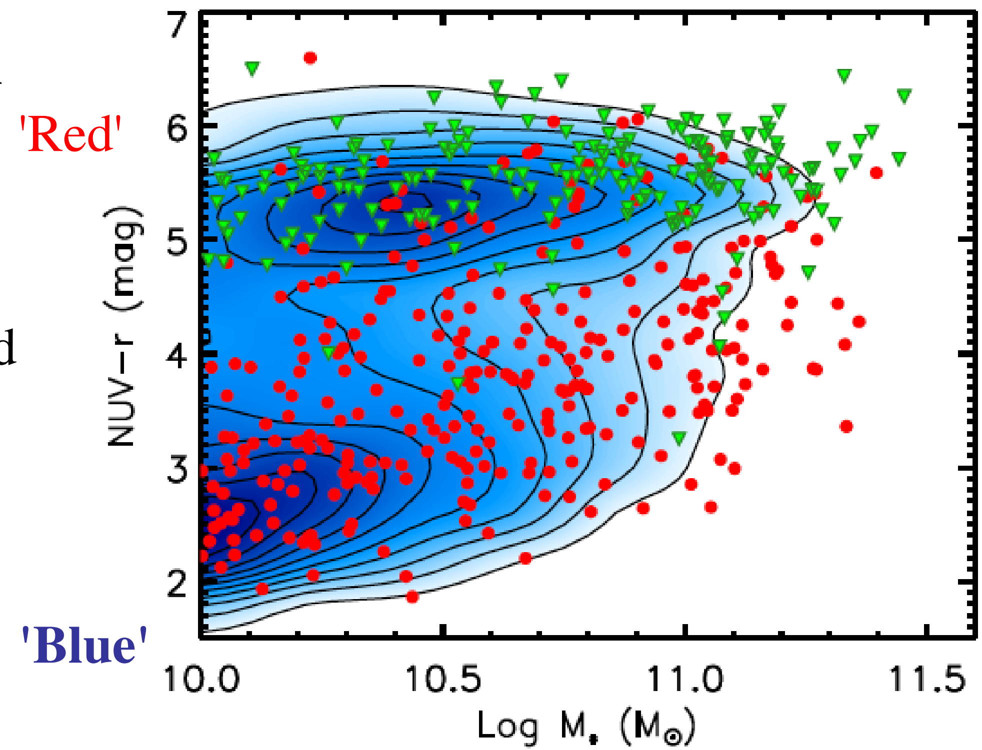


Fig. 4. Color-stellar mass diagram for the GASS *parent sample*, the super-set of ~12,000 galaxies that meet the survey criteria (grayscales). Red circles and green upside-down triangles indicate HI detections and non-detections, respectively, from the representative sample.

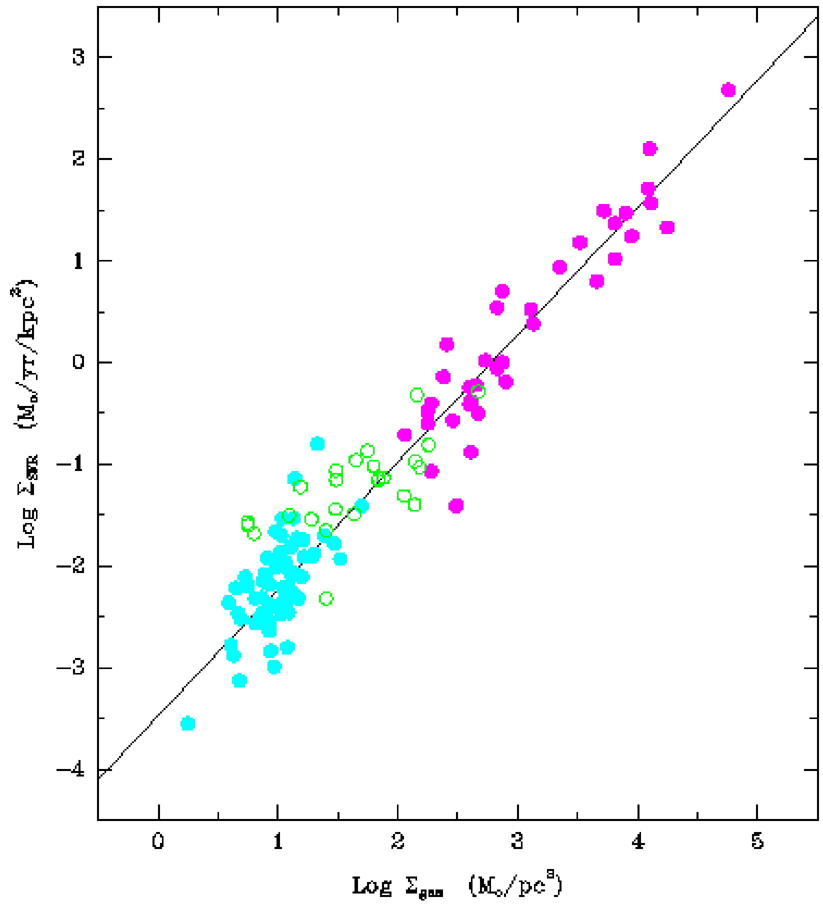
Catinella et al 2012

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

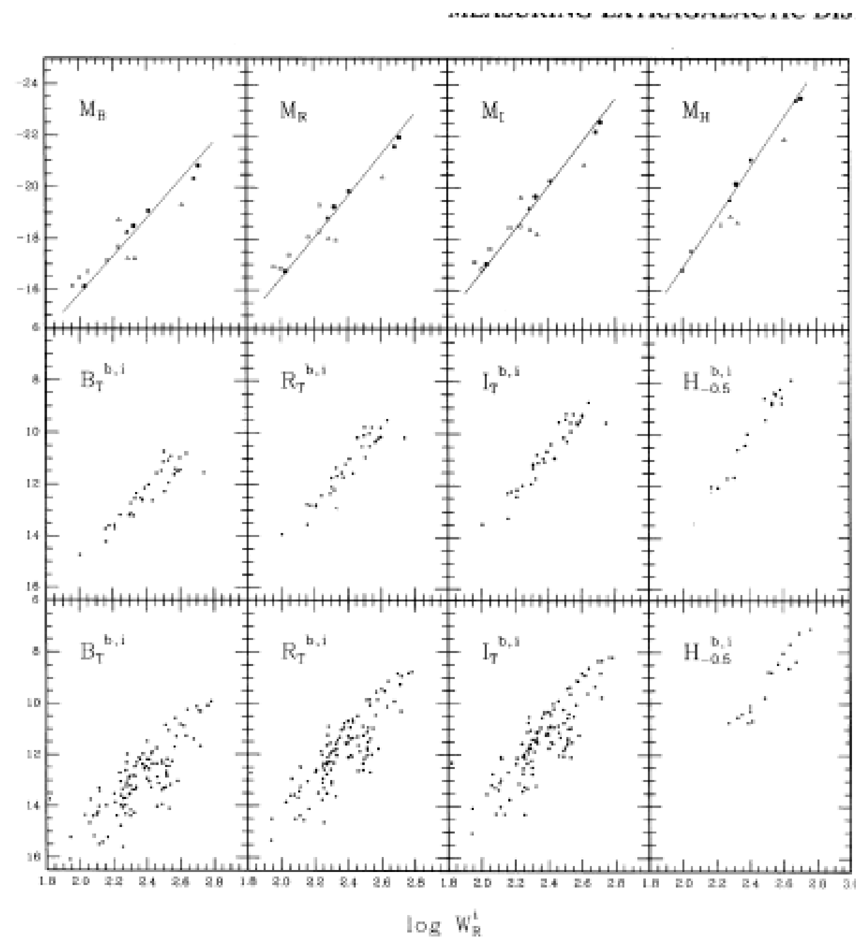
Galaxy Patterns- Continues

- 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

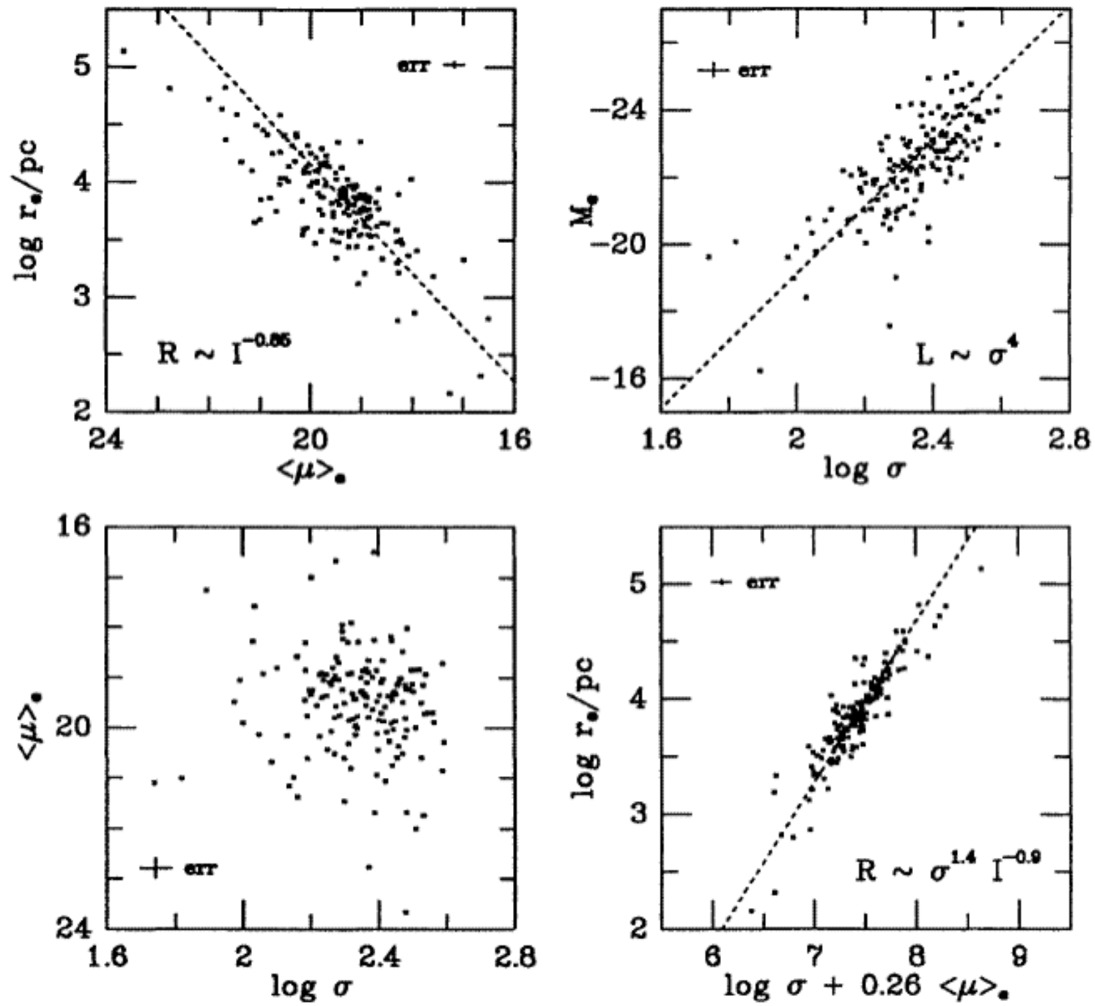


log rotational velocity

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*

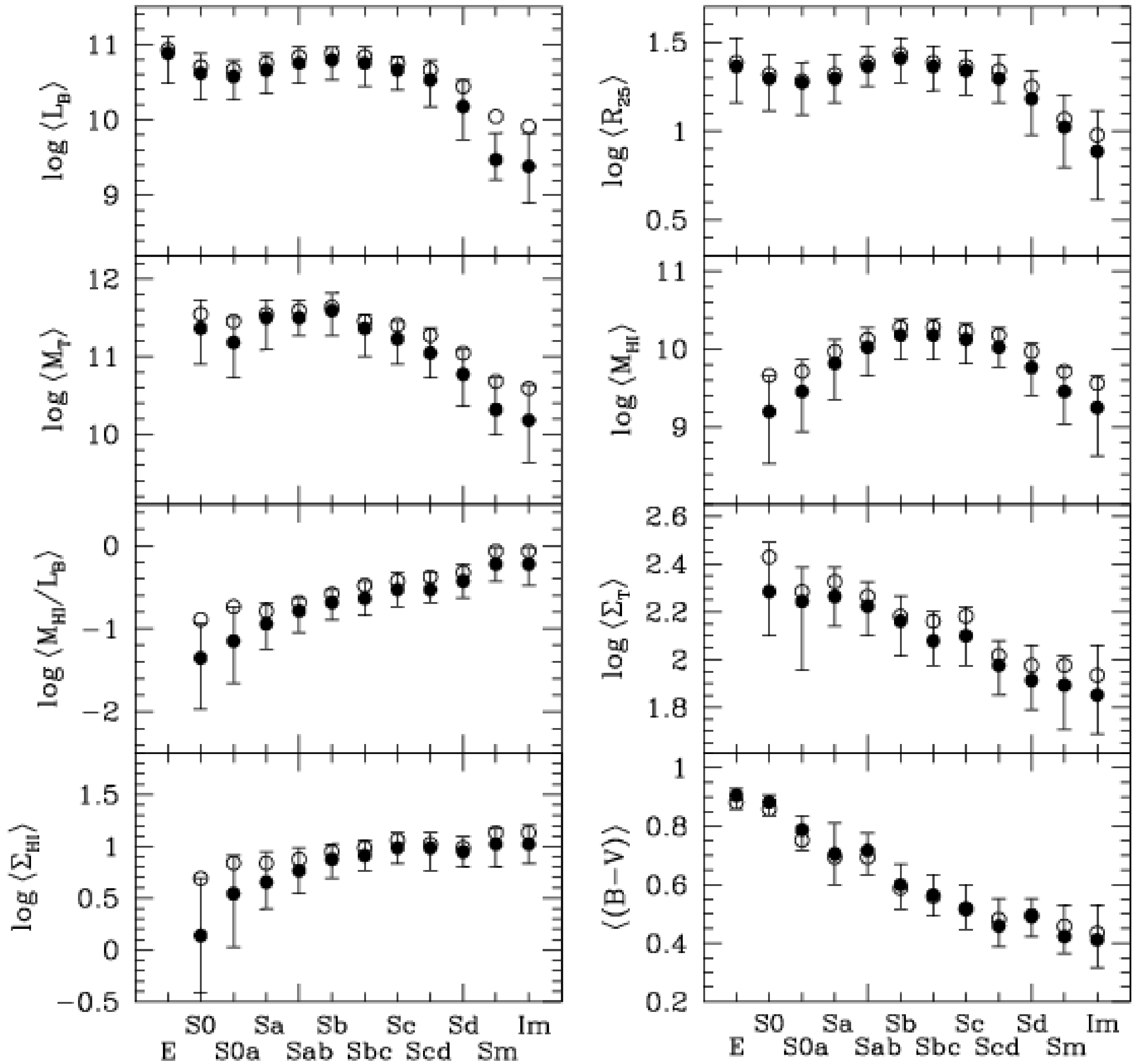
r_e= scale length
μ= surface brightness
σ= velocity dispersion
M=absolute magnitude

A Physical Meaning to Morphology?

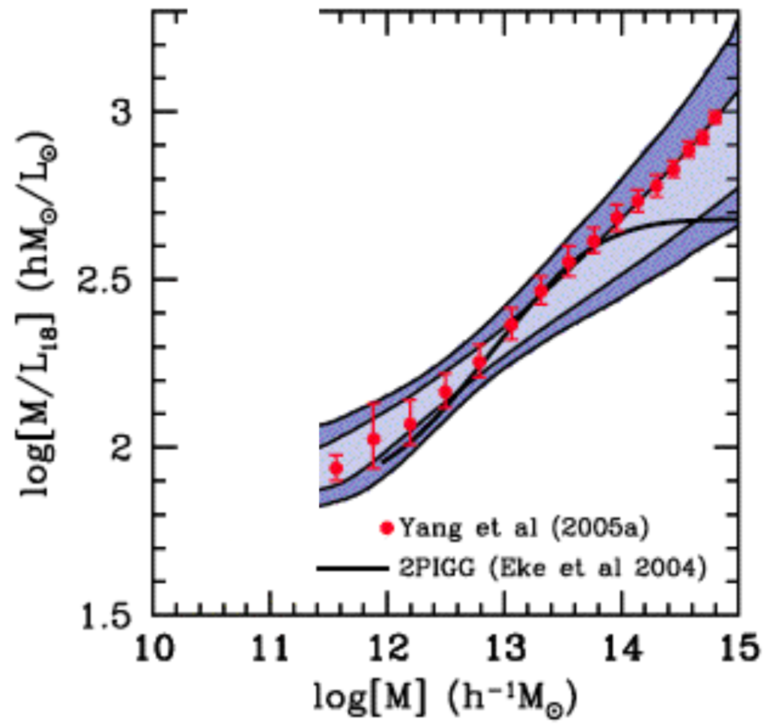
- Specific Star formation rate and Hubble type are strongly correlated (very little to none in E's highest in Sc's and irregulars)
- Lot of other correlations particularly with the amount of cold gas, color and surface brightness

the morphological types have some 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 decisive parameter in setting properties
  - M_* or M_{halo}
  - $10^5\ M_\odot < M_*$ (galaxy) $< 10^{12}\ M_\odot$ exist
  - Most stars live in massive galaxies ($10^{10.5}\ M_o$)
  - Most massive galaxies don't form stars anymore ('early types')



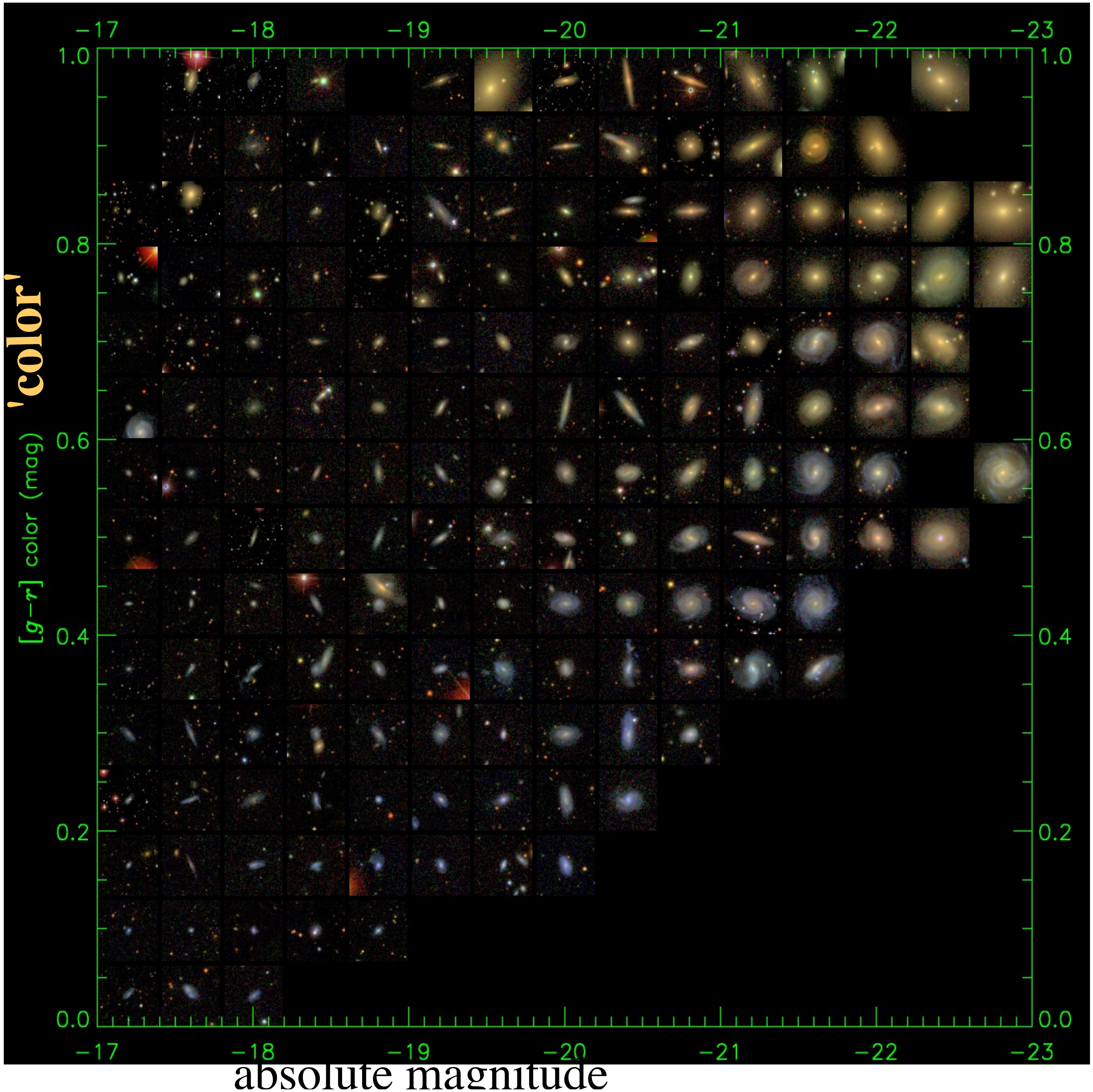
Mass to light ratio vs mass of DM halo
Red pts are data- blue is theory

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

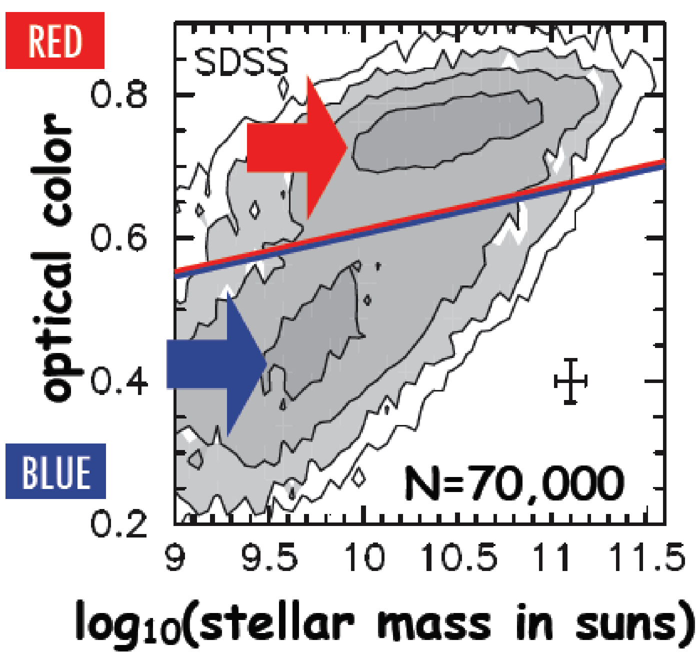
Which of these are meaningful? What do they tell us about the physical conditions in the galaxy and its history, Star formation rate dynamics etc etc

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

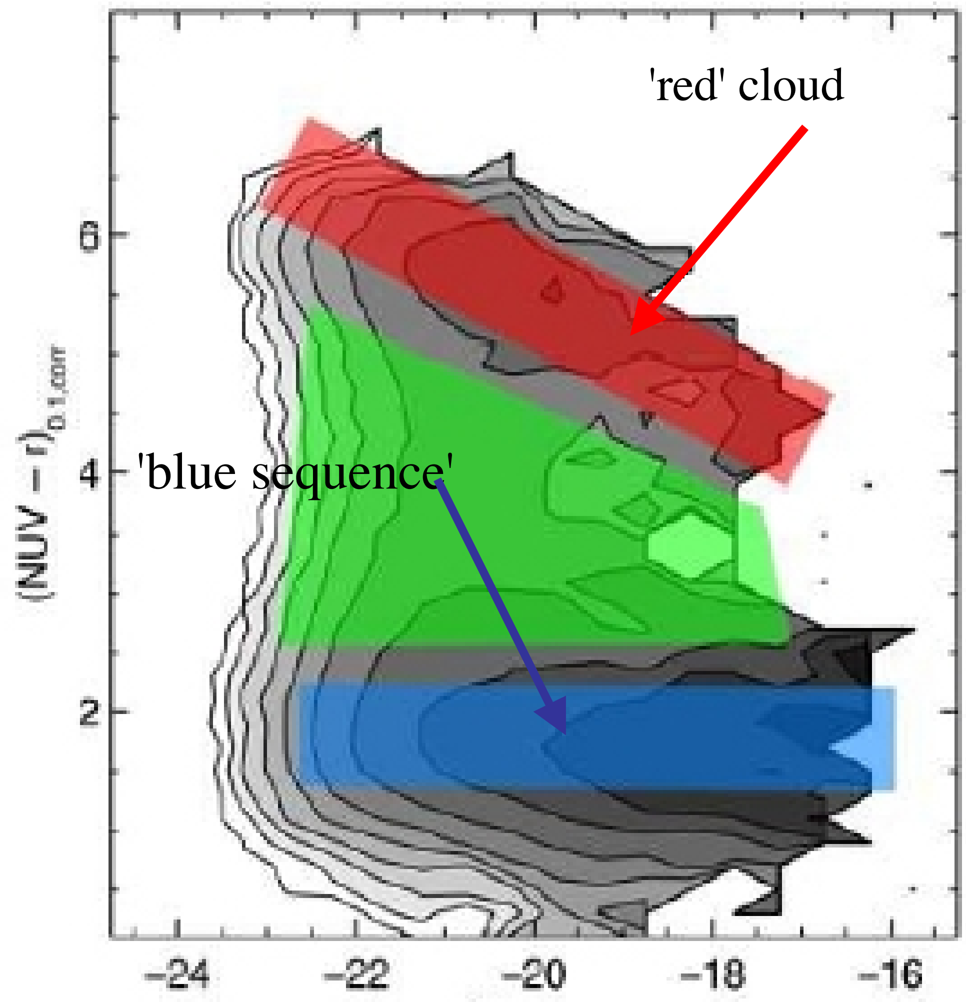


Galaxy Relations

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



Isoplths- lines of constant galaxy density

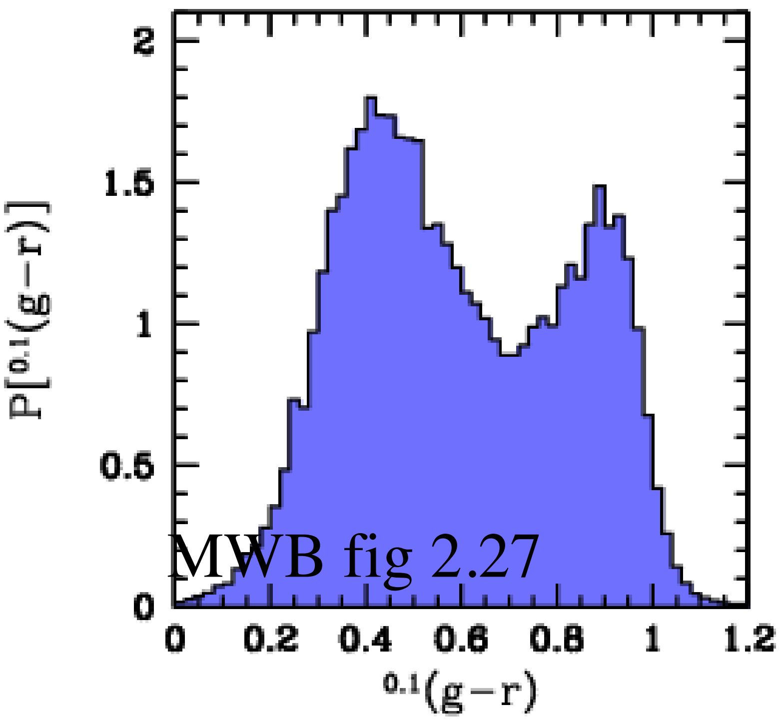


Absolute magnitude

Baldry et al 2004

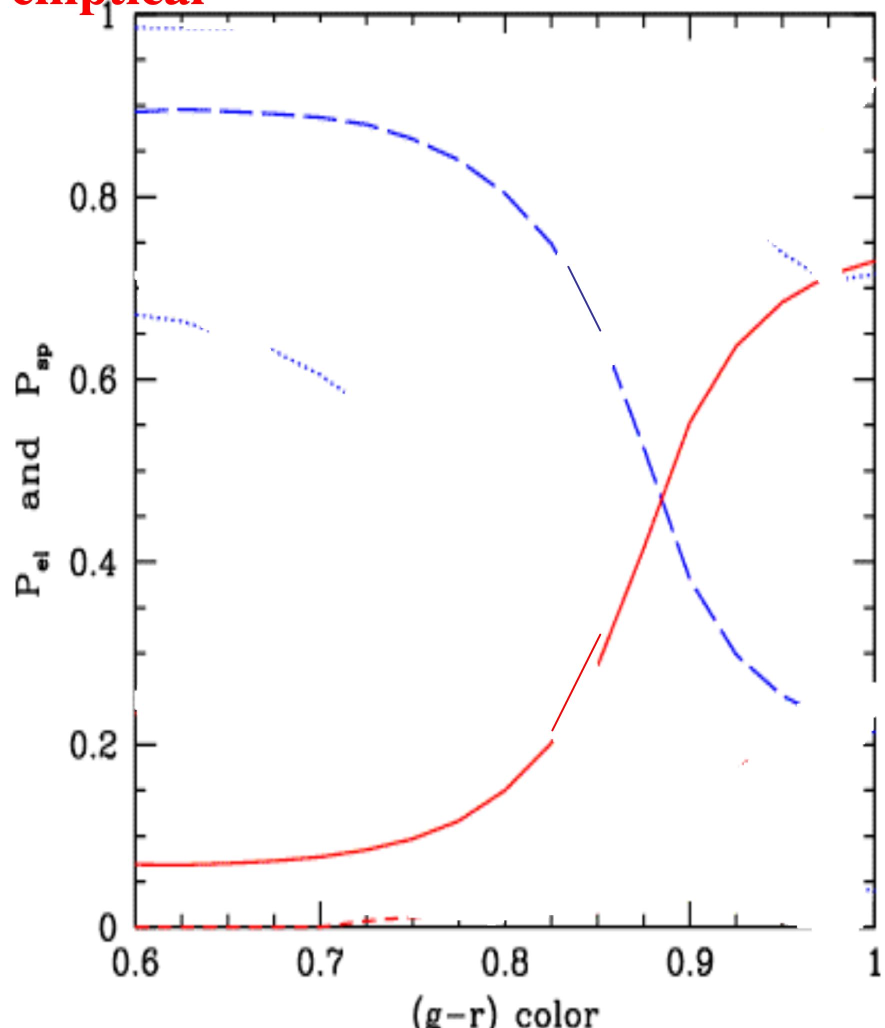
Other Projections of This Plane

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



MWB fig 2.27

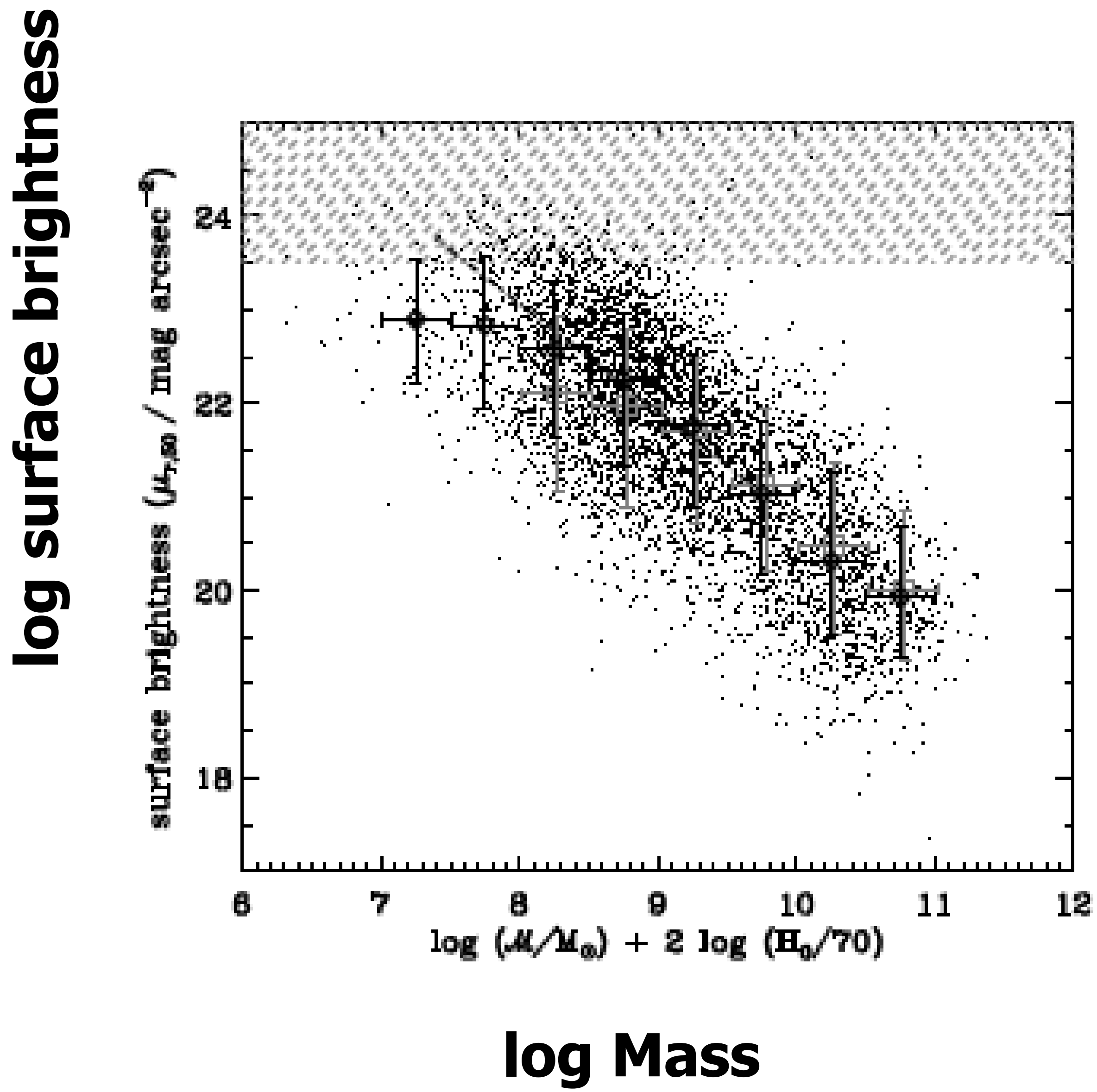
Probability that a given galaxy is a
spiral
elliptical



Skibba et al

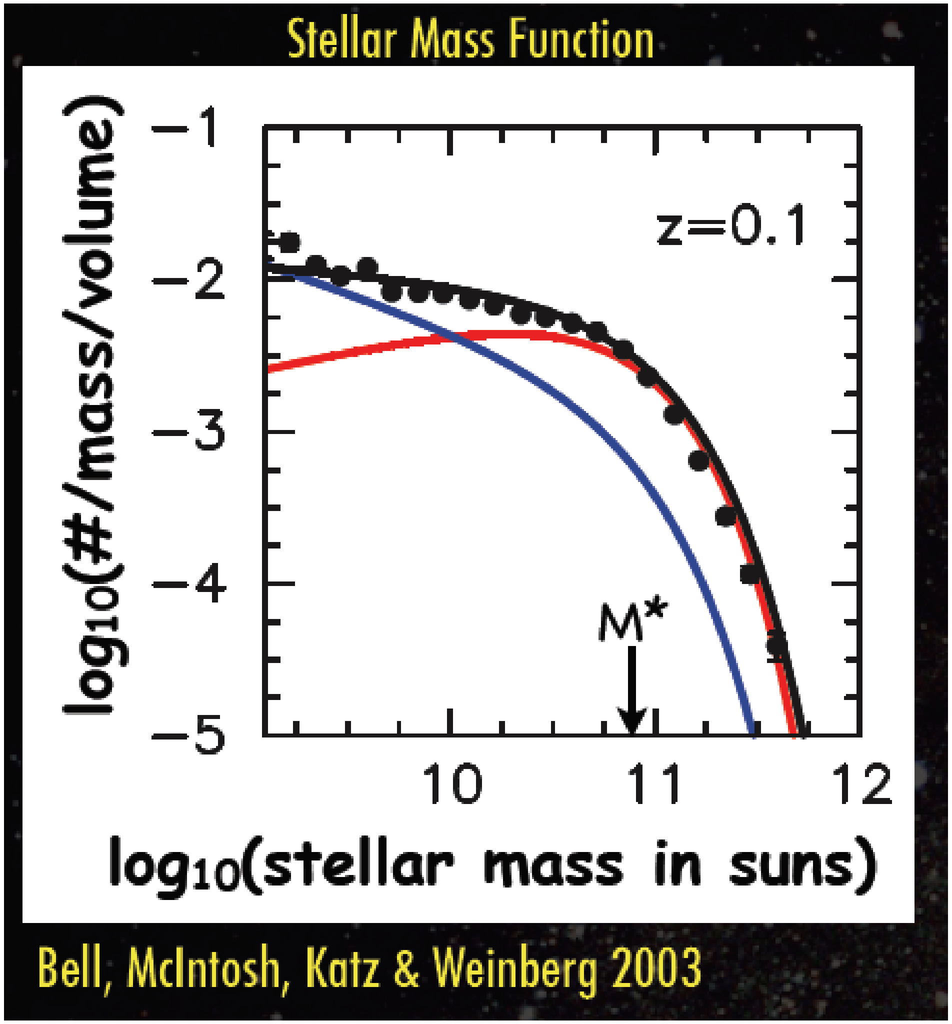
Relationship of Optical Surface Brightness to Mass

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



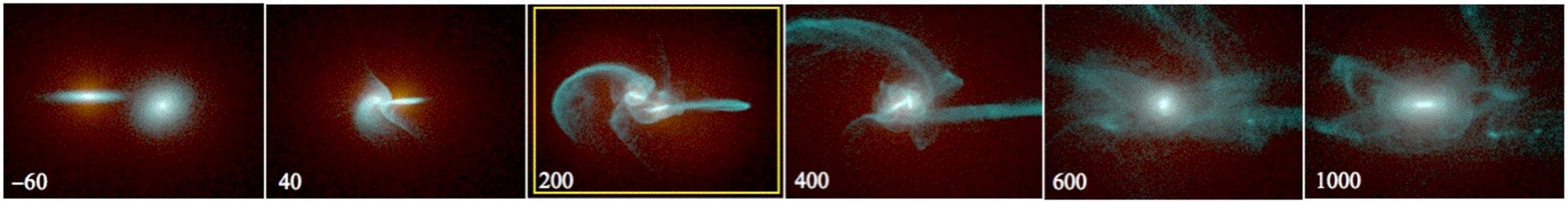
Mass Function of Galaxies

- 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 'Can' Change Over Cosmic Time

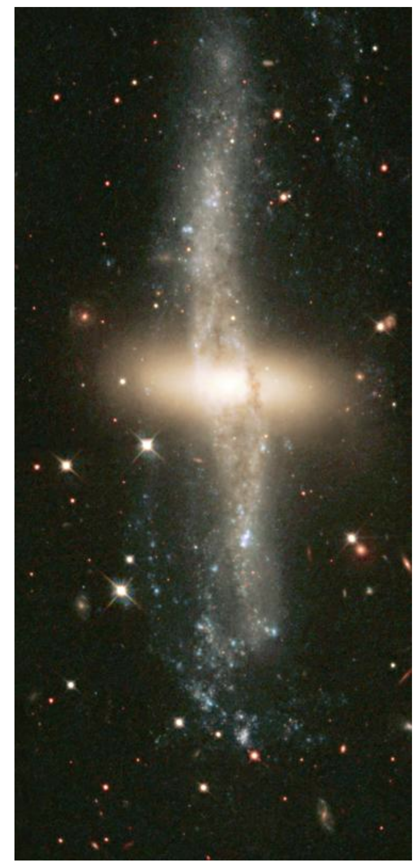
Computer calculation of the collision and merger of two equal-sized spiral galaxies



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?

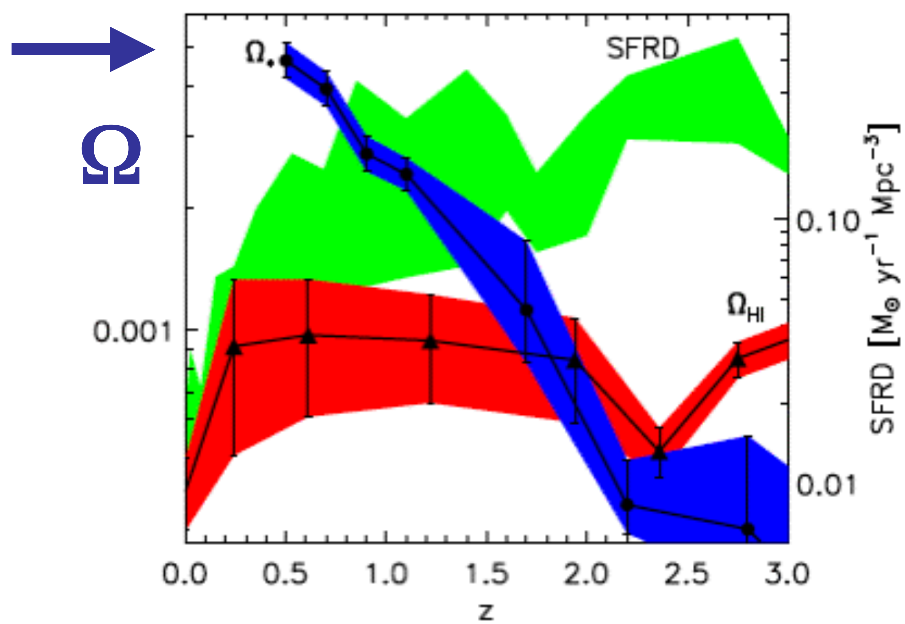


Patterns Change over Cosmic time

- The cosmological mass density of 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 (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

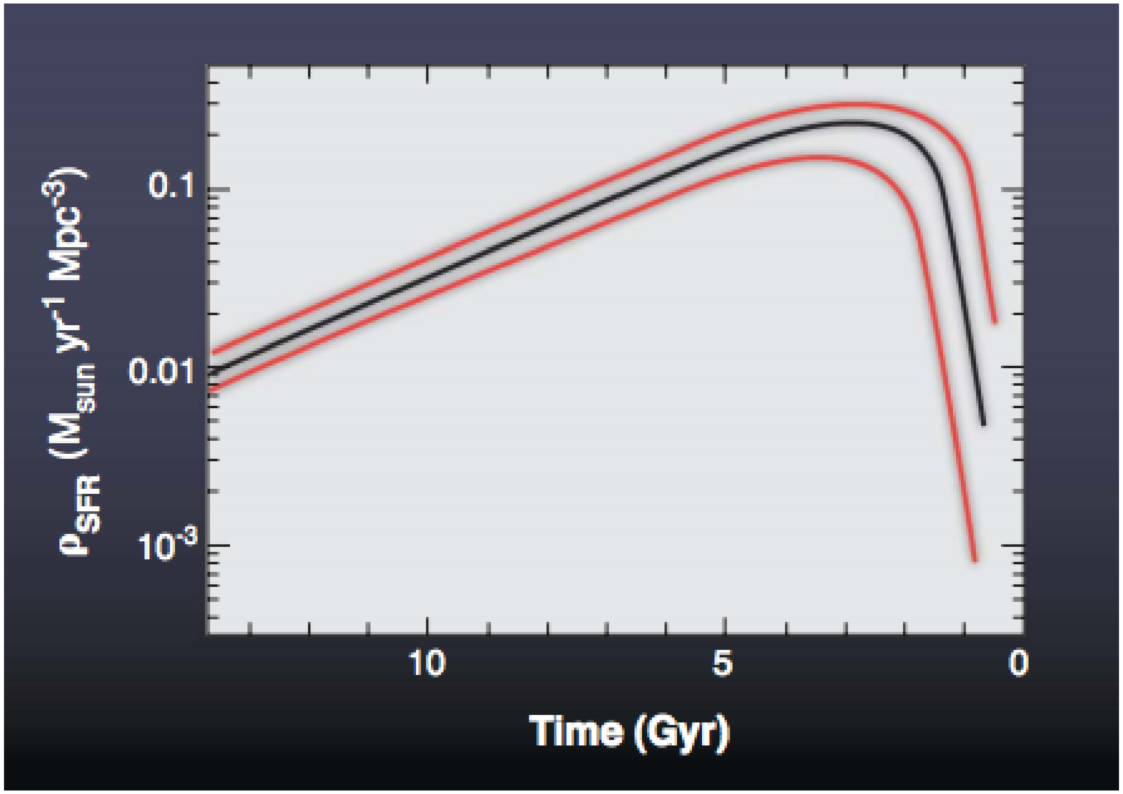
$\Omega_{star\ is}$ ~10% of the cosmic baryon density



Putnam et al 2010

Things Change Over Cosmic Time

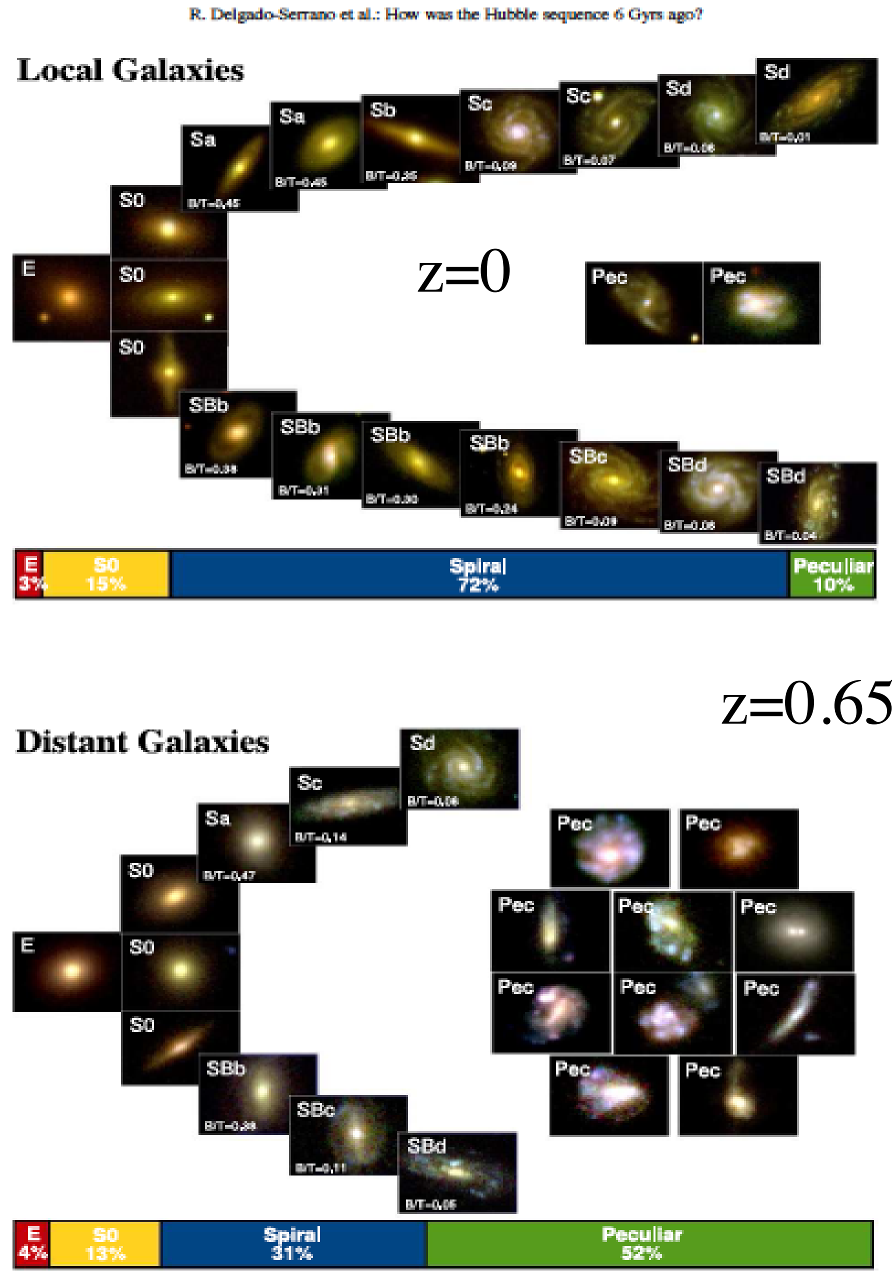
- Over the age of the universe the cosmic star formation rate (solar masses/yr/Mpc3) has change by over a factor of 30- dropping rapidly over the last 7 Gurs (since z~1)
- At high redshifts most star formation occured in the progenitors of todays luminous red galaxies, since z~1 it has occured in the galaxies that became todays spirals.



Dunlop 2011

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 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



Our text :

- Galaxies in the Universe: An Introduction (2nd Edition) by L. Sparke & J. Gallagher

Secondary source

- Galaxy Formation & Evolution by H. Mo, F. van den Bosch & S. White

  upper-level textbook which presents an in-depth discussion on all topics of relevance for the formation and evolution of galaxies. (Cambridge University Press, 2010)

- Other useful books
- Extragalactic Astronomy and Cosmology: An Introduction by P. Schneider

  A good reference, contains a good and up-to-date description of all key concepts in extragalactic astronomy and cosmology, but does not delve too deeply into mathematical formalisms and proofs. The book is very well illustrated (Springer 2006; ISBN 978-3-540-33174-2, hardcover).

- Higher level texts

  Galactic Dynamics (2nd Edition) by J. Binney & S. Tremaine

  An excellent textbook for topics related to the collisionless dynamics of galaxies, galaxy clusters, globular clusters and dark matter haloes (Princeton University Press, 2008)

- Galactic Astronomy by J. Binney & M. Merrifield

  This textbook focuses on observational aspects of galaxies (Princeton University Press,1998; ISBN 9780691025650, paperback)- a bit out of date

- The Structure and Evolution of Galaxies by S. Phillipps
- textbook at the introductory level (John Wiley & Sons,Ltd, 2005; ISBN 978-0-470-85507-X, paperback).

Next Time

- Please read ch 1 of Sparke and Gallagher
- Lecture will be a continuation of general galaxy properties