A Brief History- see B&M Ch 1

- 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) (for historical interest see 'The Great Debate' http://apod.nasa.gov/diamond_jubilee/debate20.html
- Expansion of the universe 1920's (Hubble)
- Dark matter- Zwicky 1930's Rubin 1970's
- Cosmic Microwave Background and Big Bang Nucleosynthesis established the Big Bang
- 1980's - the development of Cold Dark Matter (CDM) and post 1998- ΛCDM
- 1990's The mass function of galaxies (#/volume)
- 2000's Realization that the distribution of dark matter and baryons is complex and time dependent
- 2010- vast increase in surveys of galaxies, stars in the Milky Way

See **http://www.astr.ua.edu/keel/galaxies** for a nice observationally oriented introduction to the subject

Galaxies: From J. Dalcanton

Ellipticals

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

$V_c \sim 350$km/s

Highly Clustered

Old stars

little star formation now; lots at high z

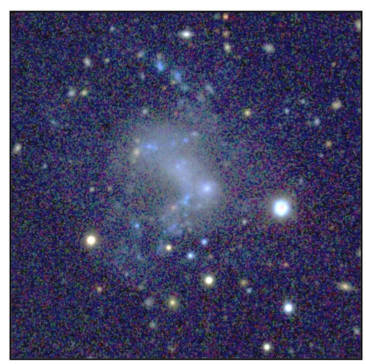
Spirals

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

$V_c \sim 200$km/s

wide range of stellar ages

star forming all time



Dwarfs

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

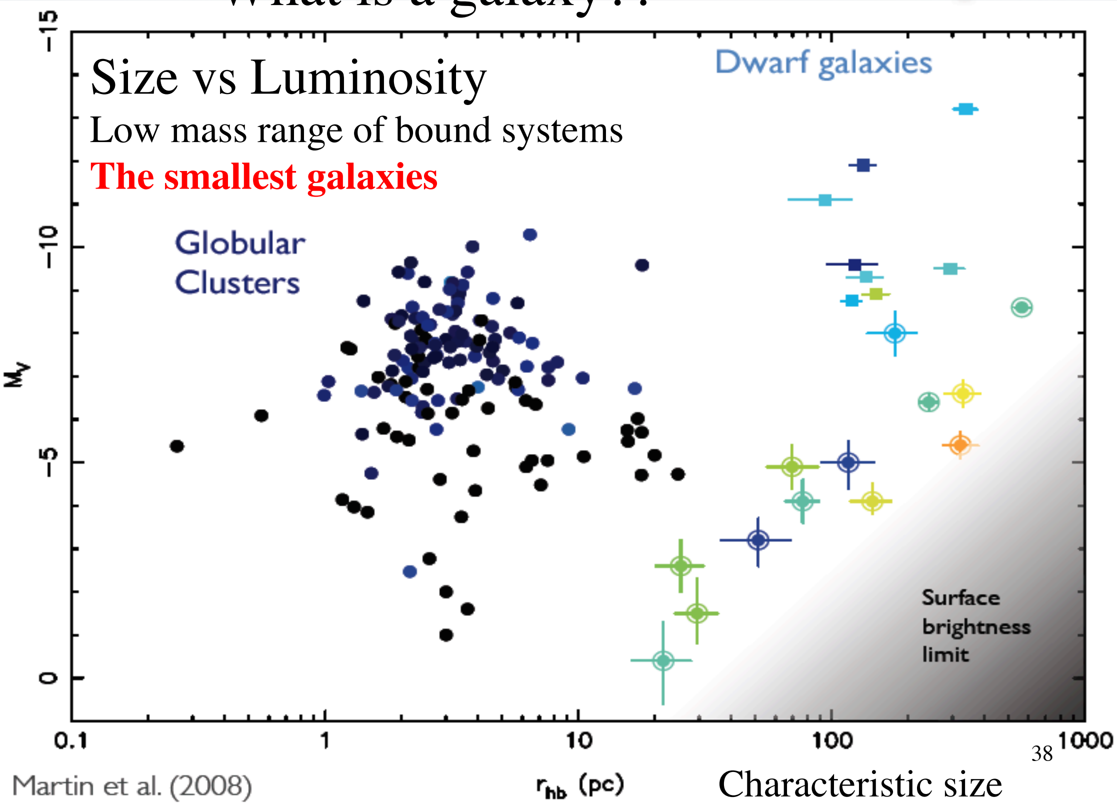
$V_c \sim 30$km/s

Weakly Clustered

Young stars

Numerous

What is a galaxy??



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Characteristic size

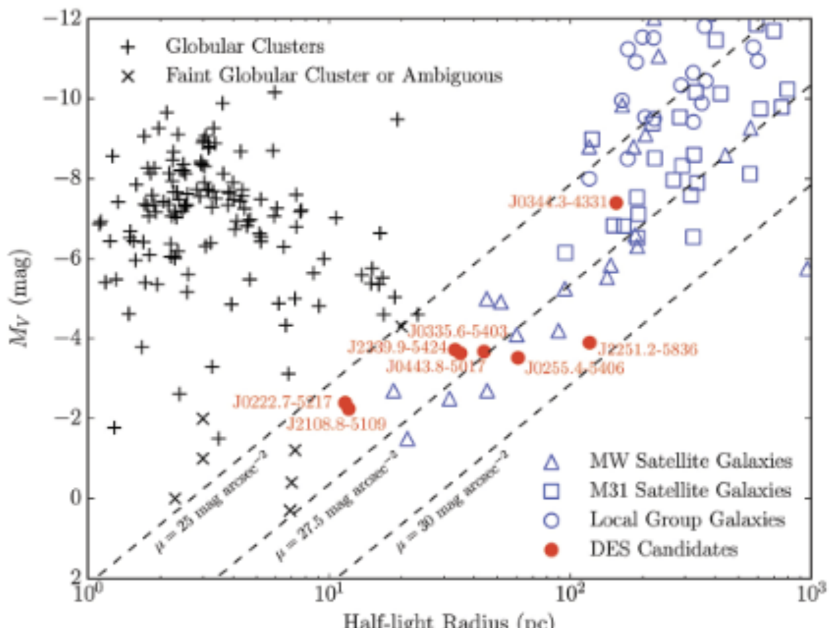
Size vs Luminosity

Low luminosity range of bound systems

The smallest galaxies

The latest result from DEC

http://www.noao.edu/noao/noaonews/sep15/pdf/112science_highlights.pdf



Characteristic size

Figure 2: Local Group satellite galaxies are generally larger and have lower surface brightness than Milky Way globular clusters. Most of the new systems found in the DES Y1 data have structural parameters similar to known ultra-faint satellite galaxies. Follow-up spectroscopic observations are needed to definitively classify the new systems. (Image credit: DES Collaboration.)

The Limit of being a Dwarf- The Reticulum Dwarf as seen by the DES
Left panel full field- right panel- identified stars with right properties

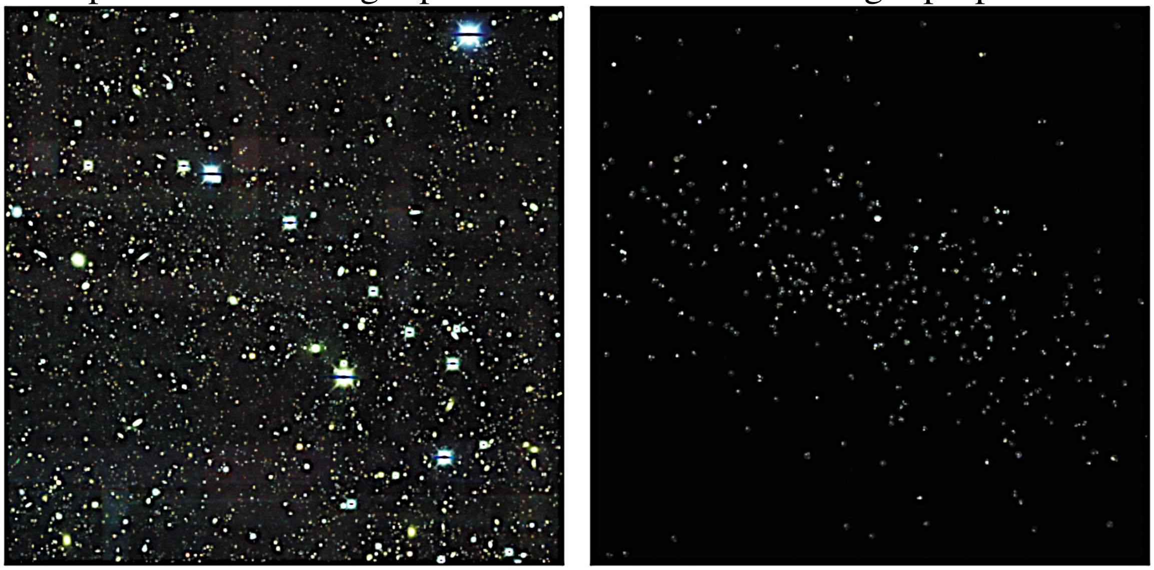


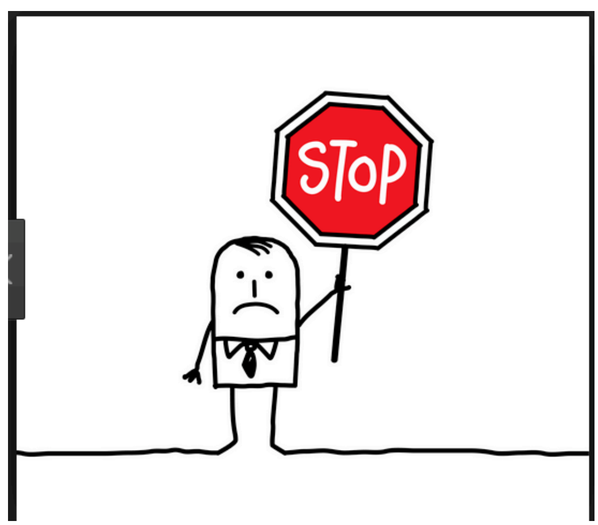
Figure 3: These two images show the most conspicuous new dwarf galaxy found in the first year of Dark Energy Survey data. The first image is a false-color coadd image of the 0.3 deg x 0.3 deg region centered on Reticulum II. The second image shows the detectable stars that likely belong to this object, with all other visible matter blacked out. Reticulum II sits roughly 100,000 light-years from Earth and contains very few stars — only about 300 could be detected in the DES data. Dwarf satellite galaxies are so faint that it takes an extremely sensitive instrument like the Dark Energy Camera to find them. (Image credit: Fermilab/Dark Energy Survey.)

Wait a Moment!

We are about to get a large number of seemingly unrelated and confusing facts about galaxies

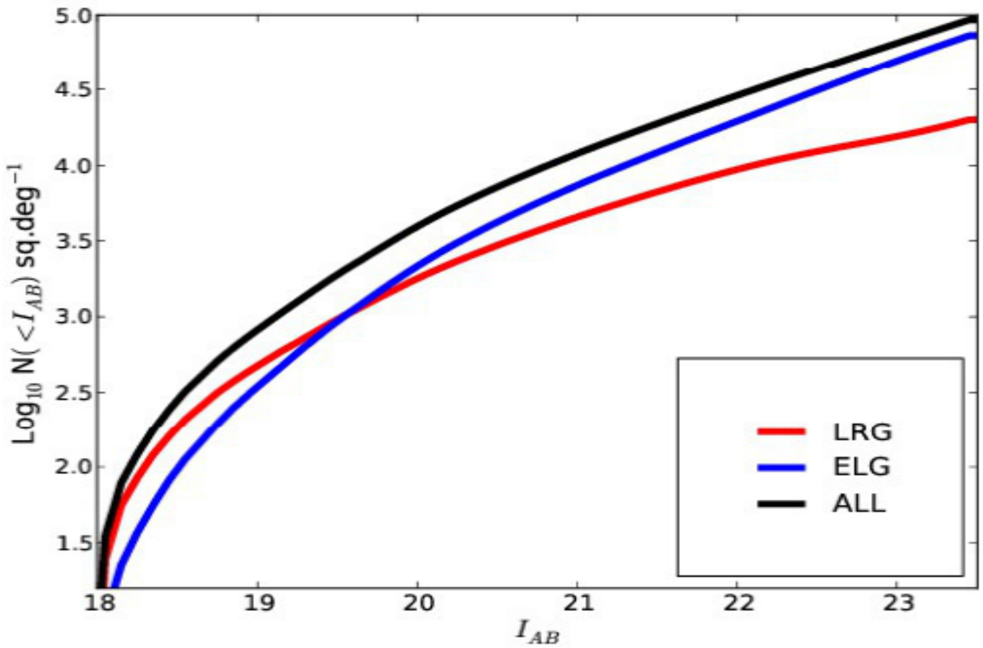
What am I supposed to get out of this?

A big picture look at galaxies and a 'feel' for the subject.

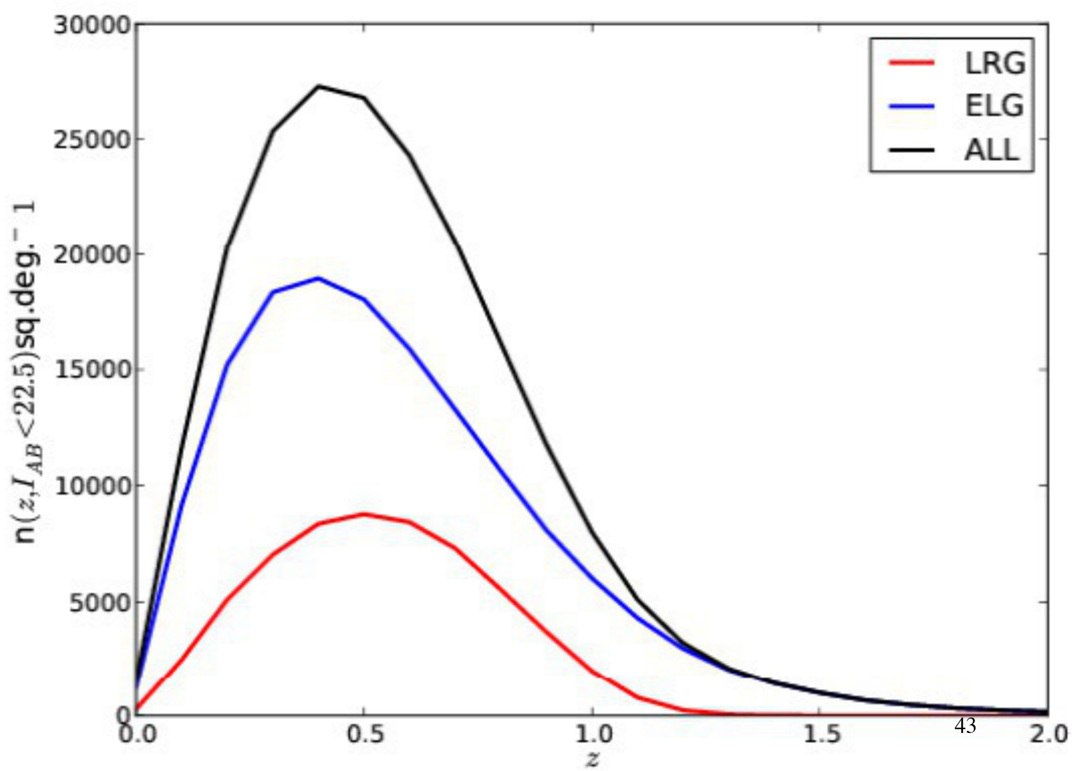


How Many Galaxies ?
Number of Galaxies of "Each' type

- LRG= red galaxies, ELG= **blue** galaxies- this is an *integral* plot



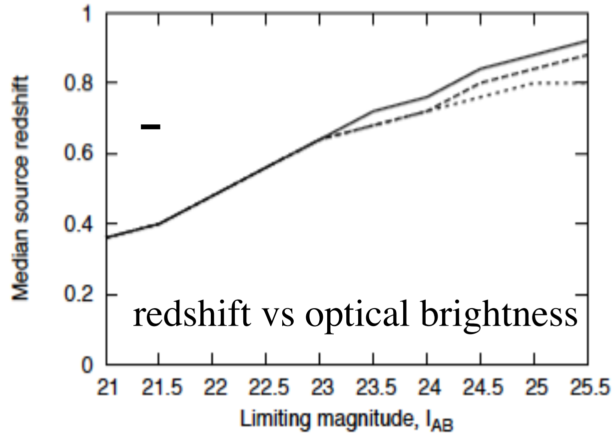
Redshift Distribution at a Given Brightness

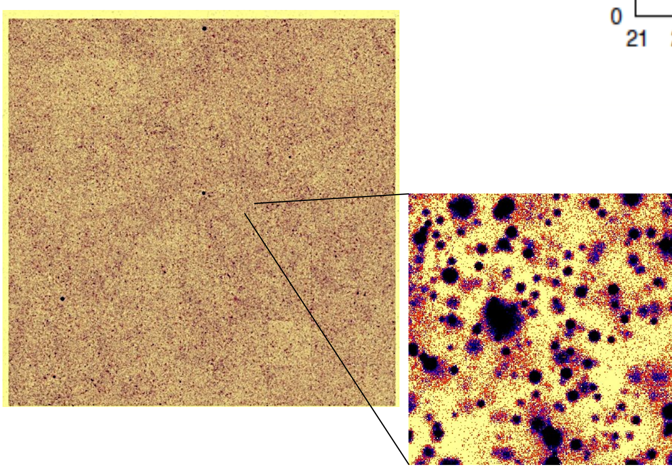


How Many Galaxies are There?

- There are ~50 galaxies/min^2 at m~25.5, rising slowly to ~175 at m~29

The median redshift at a given magnitude increases slowly

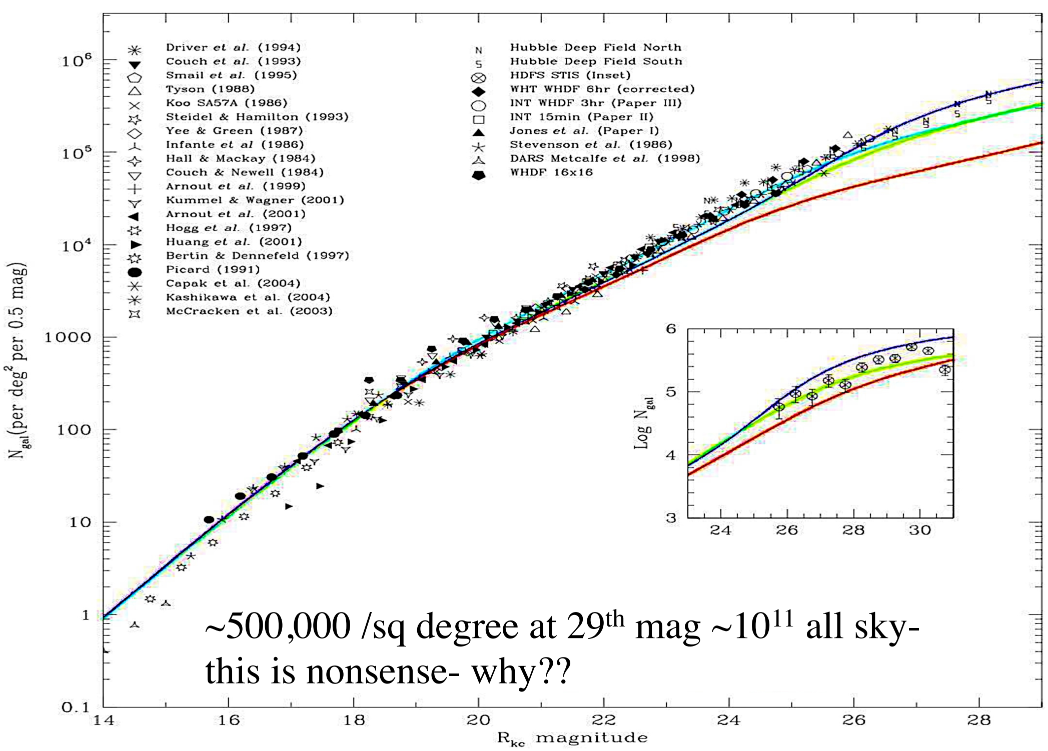




~40% of stellar mass in ellipticals (at z=0) but only 5% by number

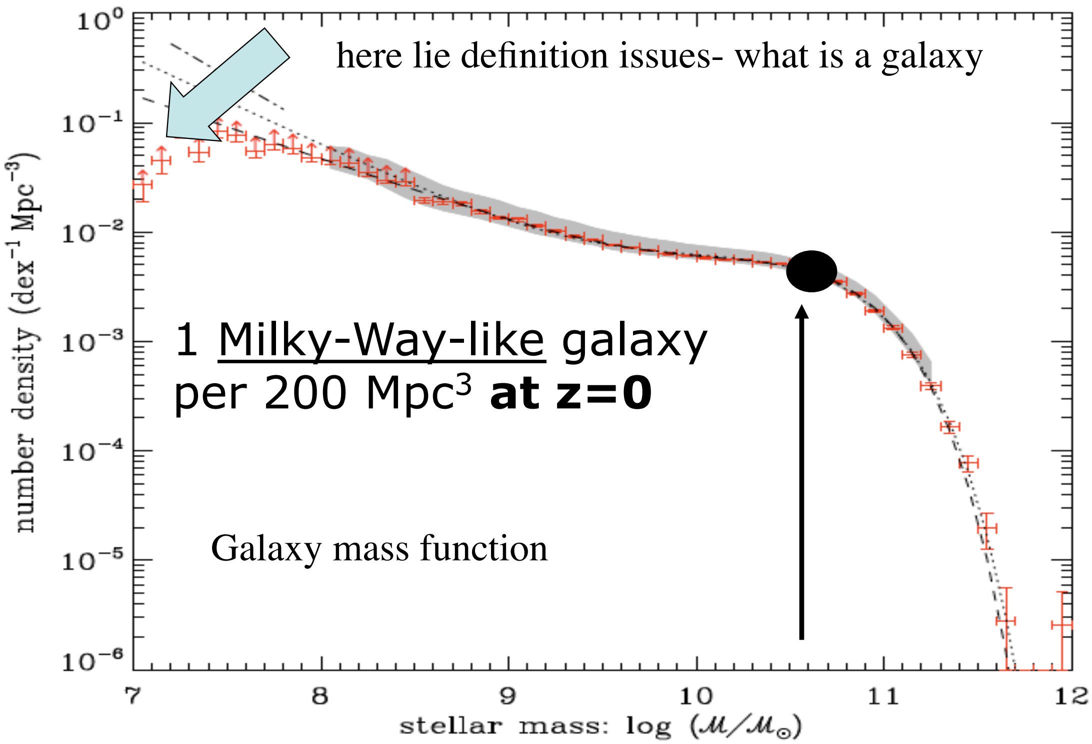
Differential Plot

Number per unit volume/mag

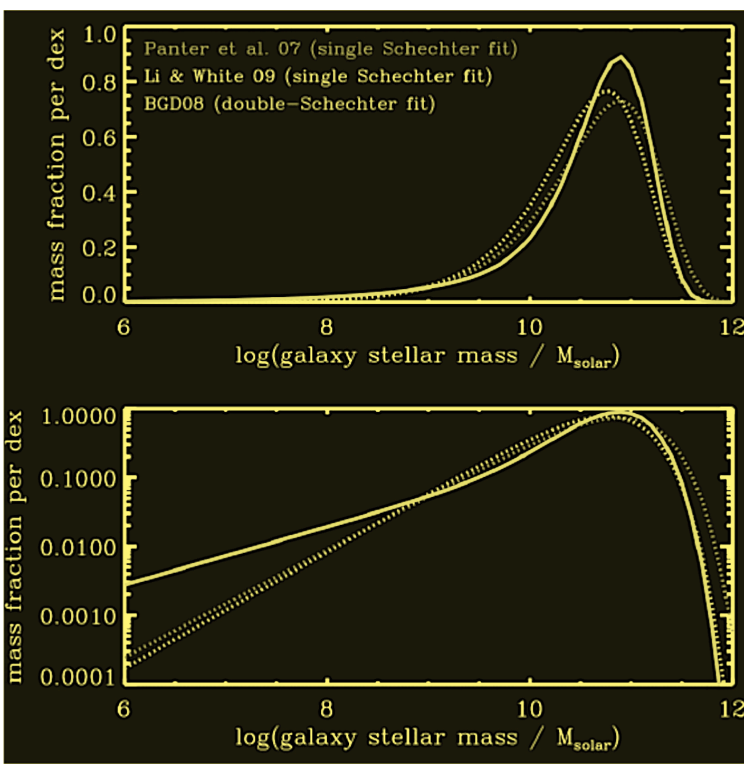


~500,000 /sq degree at 29th mag ~10^{11} all sky- this is nonsense- why??

How Many Galaxies are There ?



Where is the Mass ?



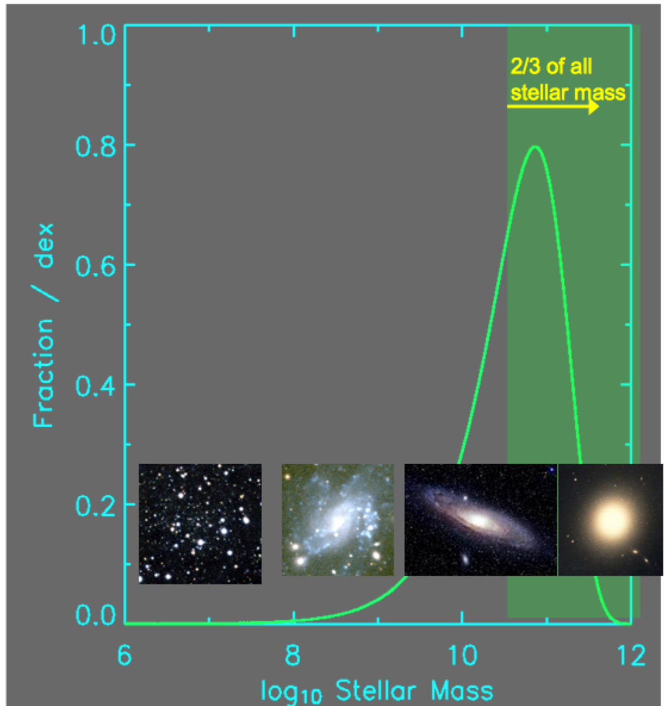
Narrow distribution peaks at log M~10.5M$_\odot$

In mass MW is typical

Galaxies Have a Wide Range in Mass

- There is a range of ~10^8 in galaxy masses- but most stars reside in galaxies in a narrow mass range ~6+/-3x$10^{10}$$M_\odot$ (in stars)
- The baryons are distributed in gas, stars and dust; wide range in gas/stars, relatively narrow range in dust/gas.

Please listen carefully… I often jump back and forth between total mass and stellar mass

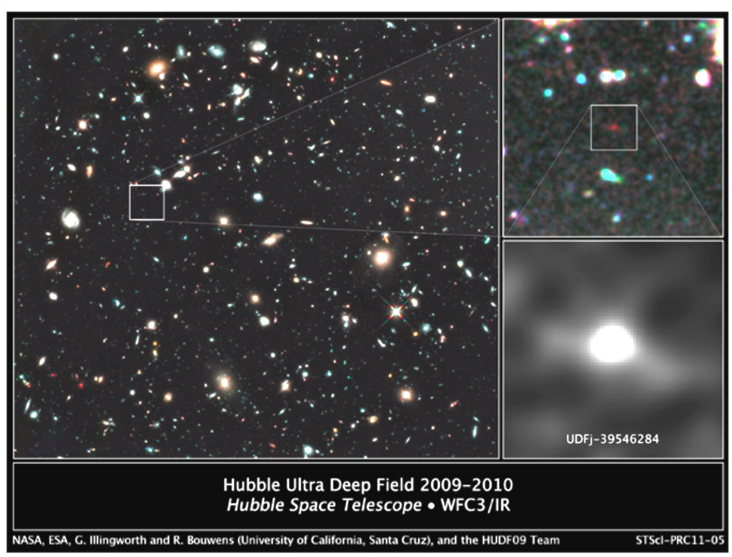


Bell et al. 2003

How Old are Galaxies

- HST imaging of galaxies at z~9 (13.17 Gyrs age, for an age of the universe of 13.72 Gyrs)
- Stellar ages: in MW oldest stars are ~13.2 Gyrs 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

(z is the redshift and for a given cosmology there is a straightforward relation between distance, age and z)

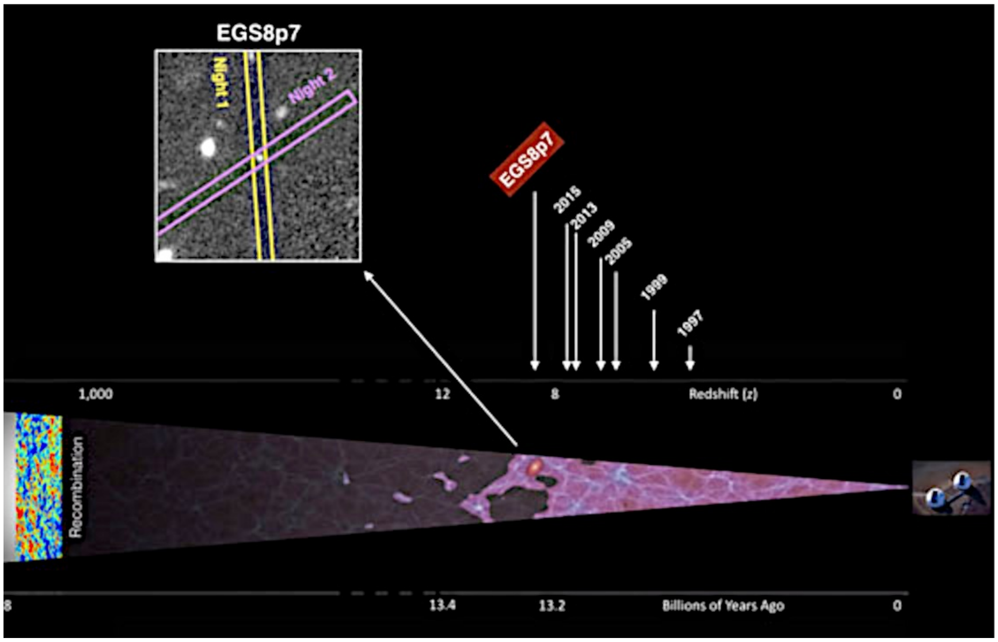


The farthest and one of the very earliest galaxies ever seen in the universe appears as a faint red blob in this ultra-deep–field exposure taken with NASA's Hubble Space Telescope. This is the deepest infrared image taken of the universe. Based on the object's color, astronomers believe it is 13.2 billion 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)

http://www.astro.ucla.edu/~wright/CosmoCalc.html

In the Beginning

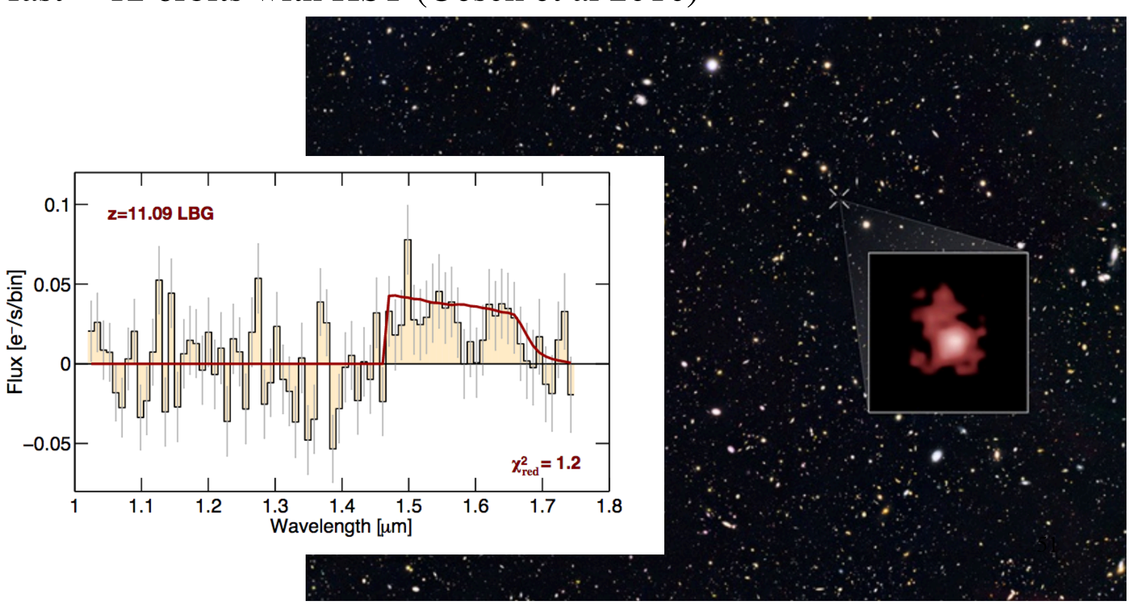
- Galaxy detected at a redshift of 8.68
- http://scitechdaily.com/caltech-astronomers-detect-the-farthest-galaxy-to-date/



GN-z11 spectroscopic redshift of $z = 11.09$

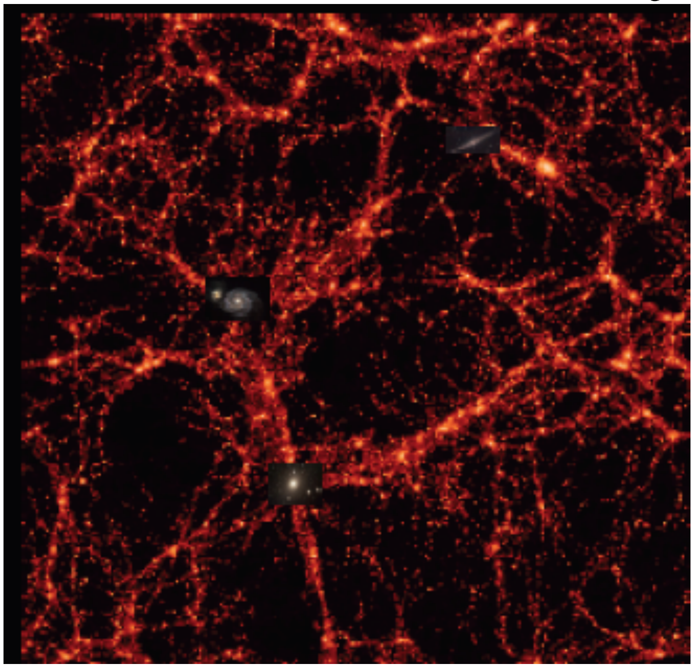
13.4 billion years ago, just 400 million years after the Big Bang

Compared with the Milky Way galaxy, GN-z11 is 1/25 of the size, has 1% of the mass, and is forming new stars approximately twenty times as fast- ~12 orbits with HST (Oesch et al 2016)



Galaxies Do Not Live Alone

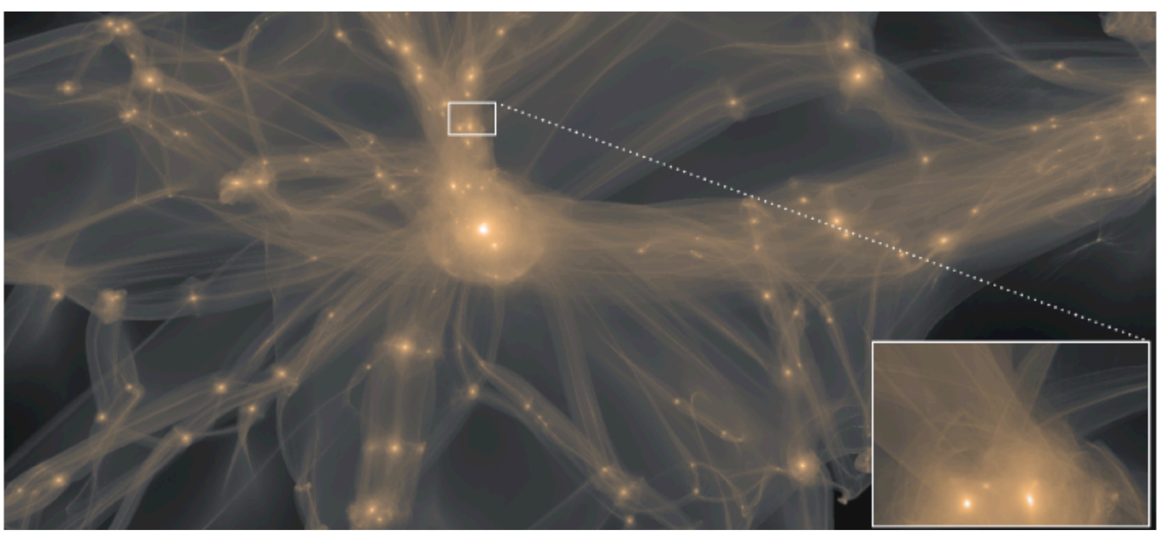
- Galaxies are part of the 'cosmic web'- representing overdense regions of both baryons and dark matter
- The effective size of the dark matter is much larger than the apparent stellar size



The cosmic web has structure at all scales but eventually becomes homogenous at R>70Mpc (sec 2.7 MBW)

Eric Bell

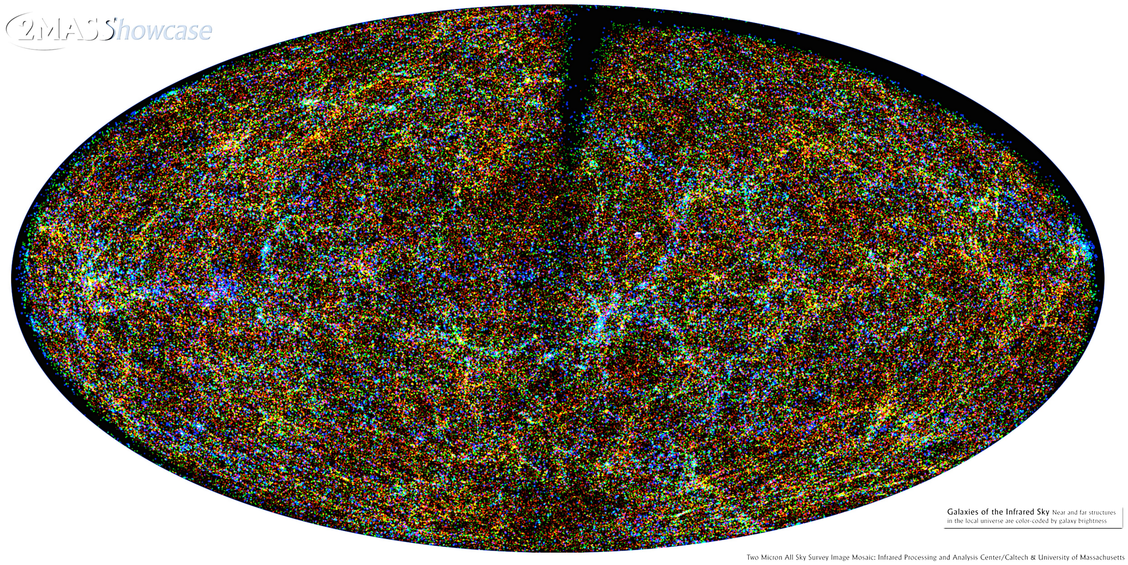
Cosmic Web



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

2MASS all sky galaxy survey

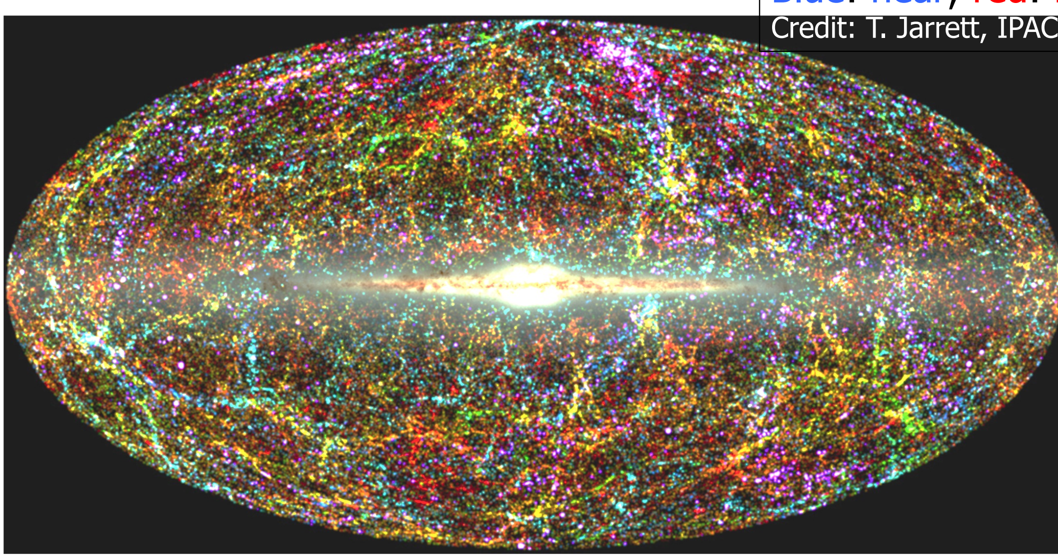
Notice the filaments



Color coded by brightness- Ra and Dec coordinates

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

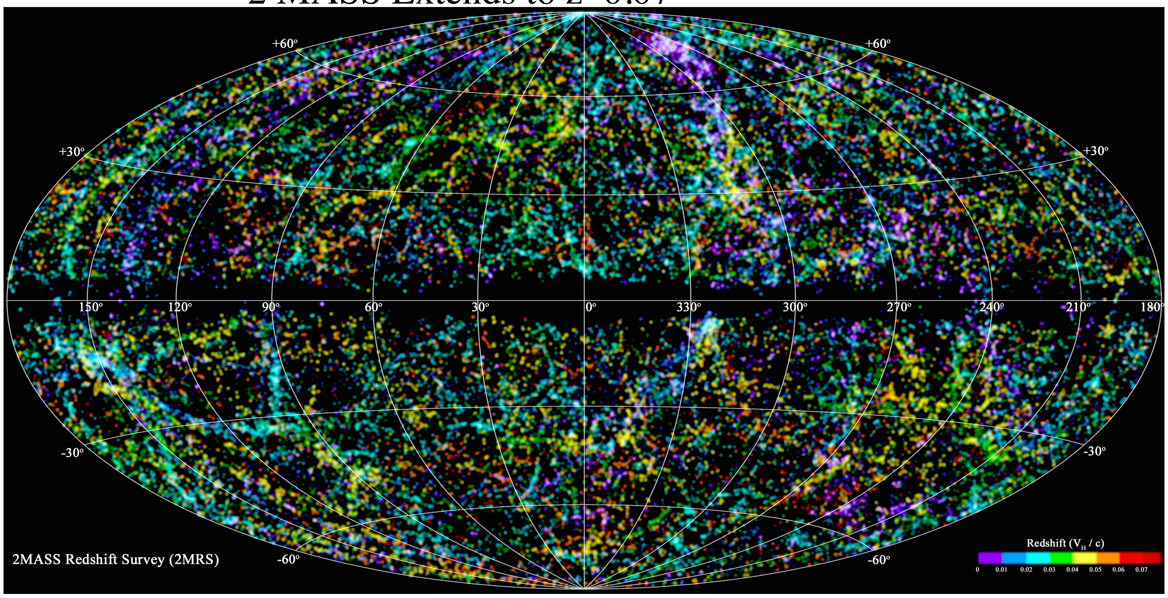
Blue: near; red: far
Credit: T. Jarrett, IPAC

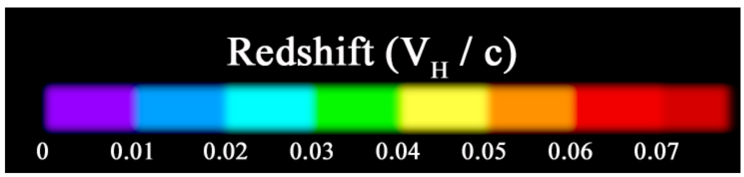


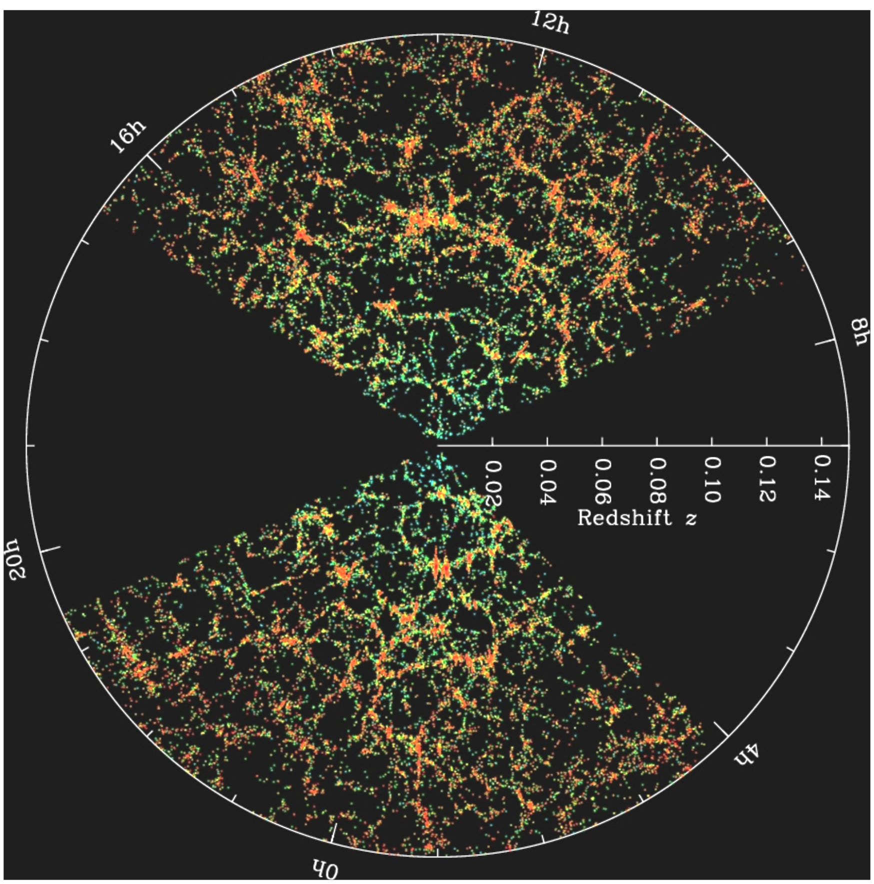
Nearby universe

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

2 MASS Extends to z~0.07-







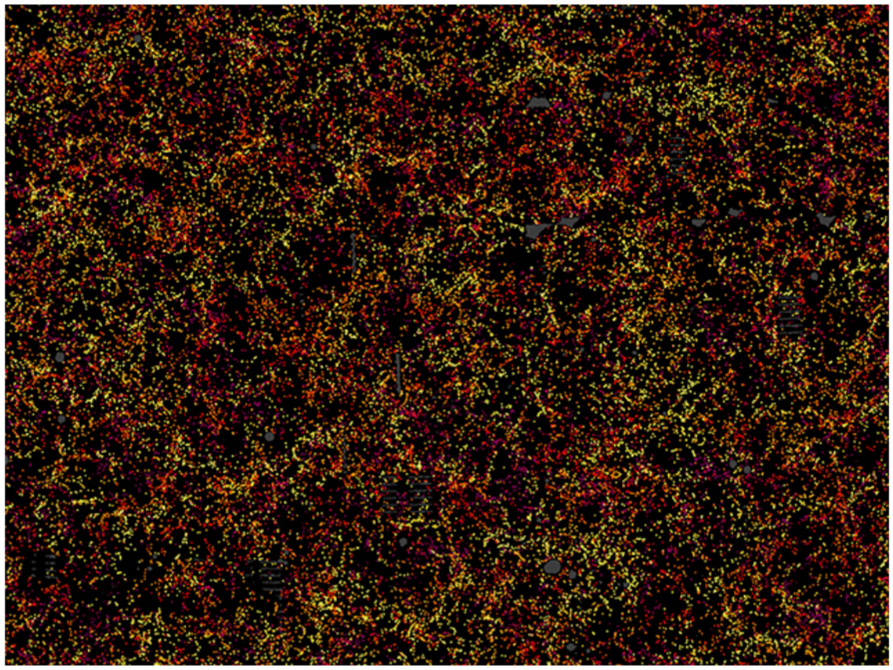
Sloan Digital Sky Survey

Galaxies color coded by the age of their stars
red= old
blue=young

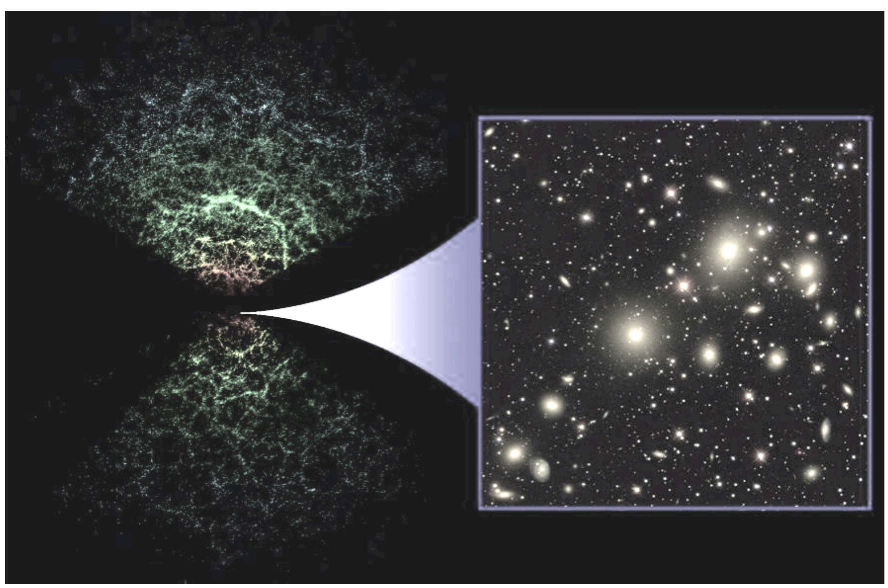
http://classic.sdss.org/includes/sideimages/sdss_pie2.html

Latest SDSS ~2,000 sq degrees

color coded by distance yellow to purple



Large Scale distribution of normal galaxies

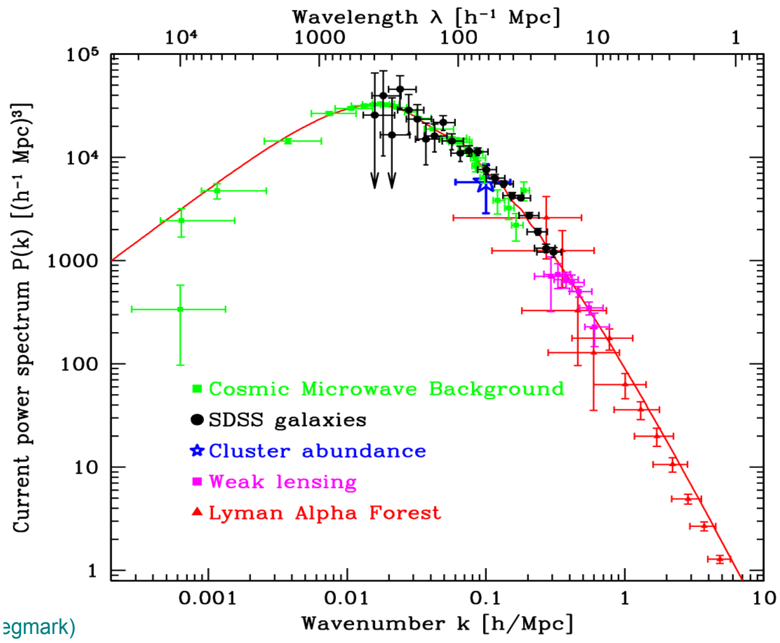


- On scales $<10^8$pc the universe is 'lumpy'- e.g. non-homogenous
- On larger scales it is homogenous- and isotropic

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

Power Spectrum of Fluctuations

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



egmark)

Tegmark 2004

Dark Matter Dominates Gravity

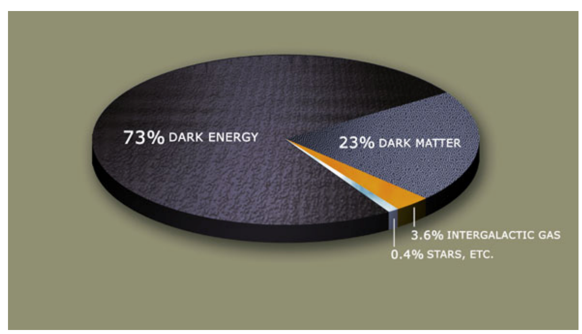
- **The cosmic ratio of dark matter to baryons is ~6:1**

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

$\Omega_{\mathbf{baryons}}$ = 0.042 ± 0.003

$\Omega_{dark\ matter}$ = 0.23

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



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

h=0.67

Taken from the WMAP7 results-

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

h=H_0/100

Ω_m=0.3156+/-0.0091

H_0=67.27+/-0.66

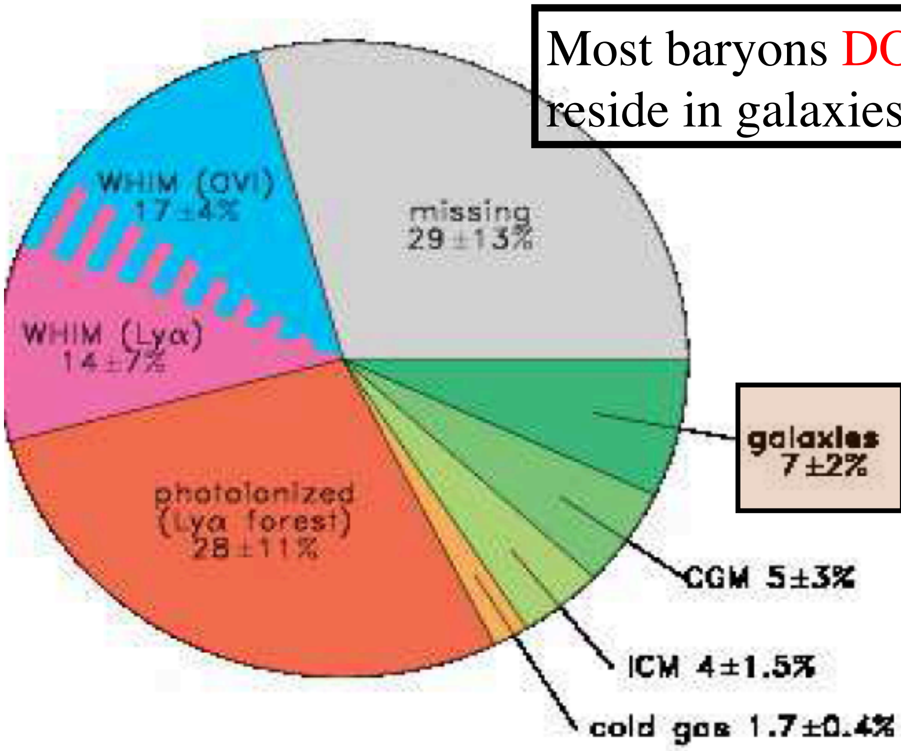
Ω_Λ=0.6844+/-0.0091 (dark energy)

Age 13.813**+/-0.026** Gyrs

Where are the Baryons ?

Shull Danforth 2012

Most baryons DO NOT reside in galaxies



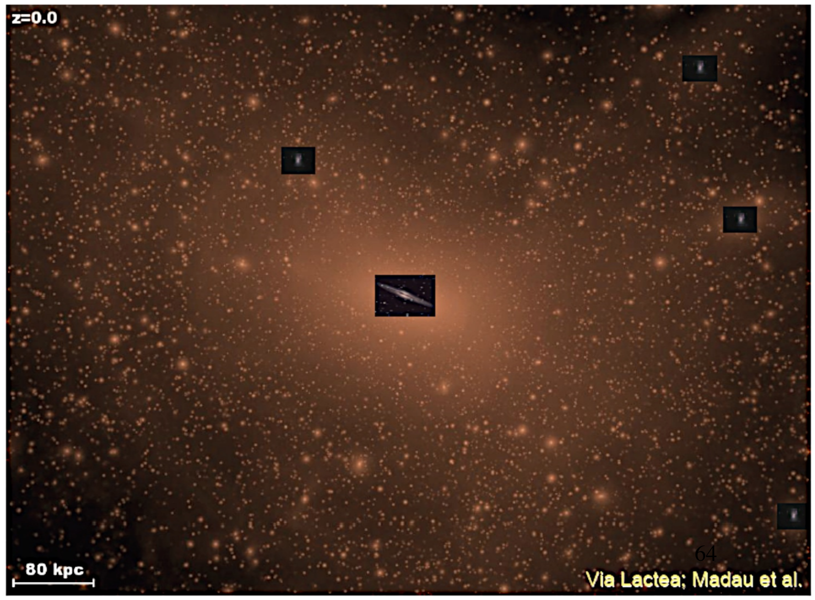
Dark Matter

- Baryons are only 4.9% of all the "matter" (including "dark energy")
- Dark matter is the rest and provides the dynamic skeleton on which galaxies reside and grow
- There is a very complex relation between how the dark matter and baryons (gas and stars) are related and distributed on a wide variety of scales
  - baryons are more concentrated than dark matter
  - 'light' may not trace mass well
- The fundamental difference is that dark matter can only interact via gravity while baryons can interact with photons, shocks, cosmic rays, be heated and cooled.
- http://astro.berkeley.edu/~mwhite/darkmatter/essay.html) for a nice essay on dark matter

Dark Matter Distribution and Galaxies

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

Dark matter is the 'beige' material

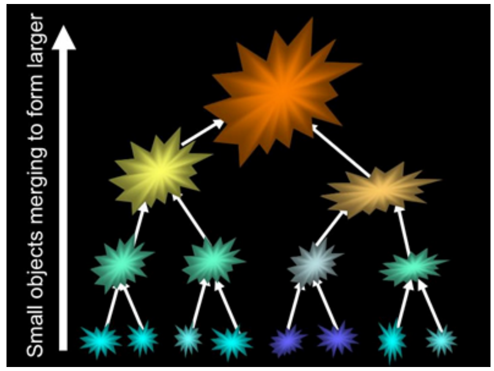


Deep Breath... What Did we cover?

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

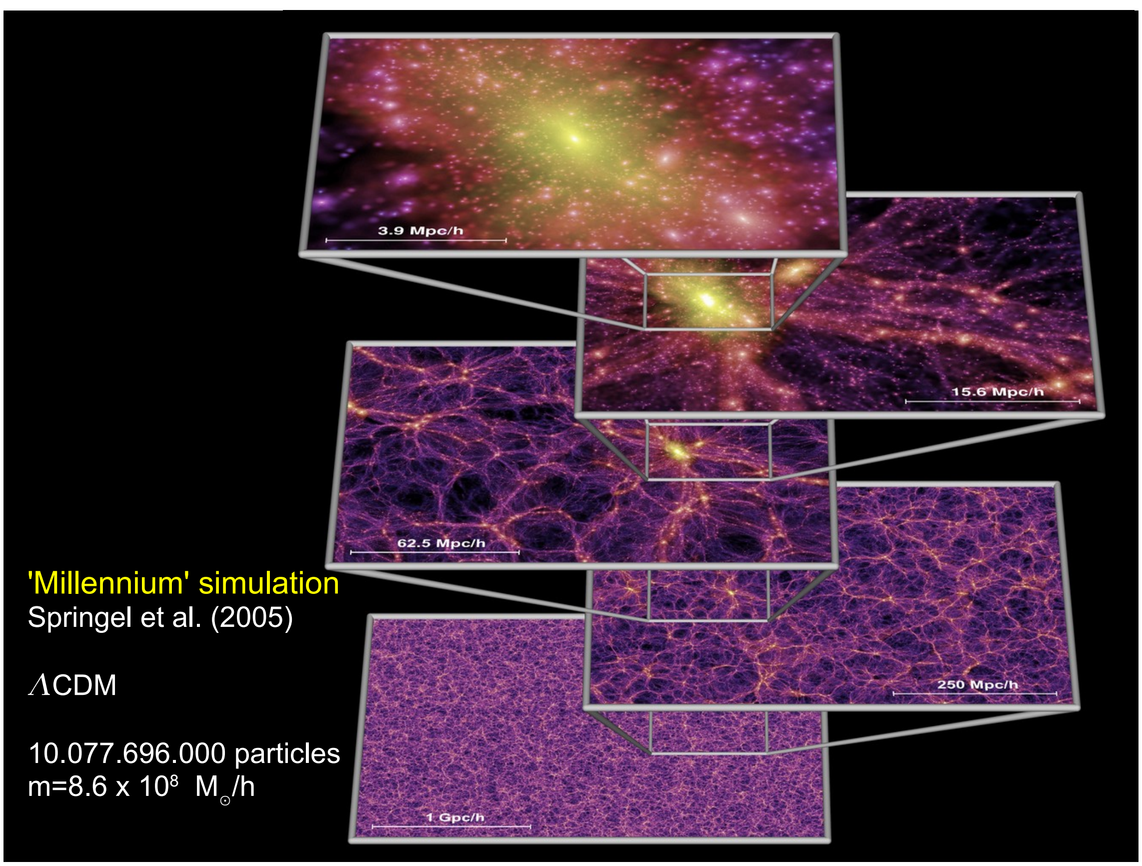
How Things Form (MBW sec. 5.6.1)

- Gravity acts on overdensities in the early universe making them collapse.
- As time goes on these collapsed regions grow and merge with others to make bigger things



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

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

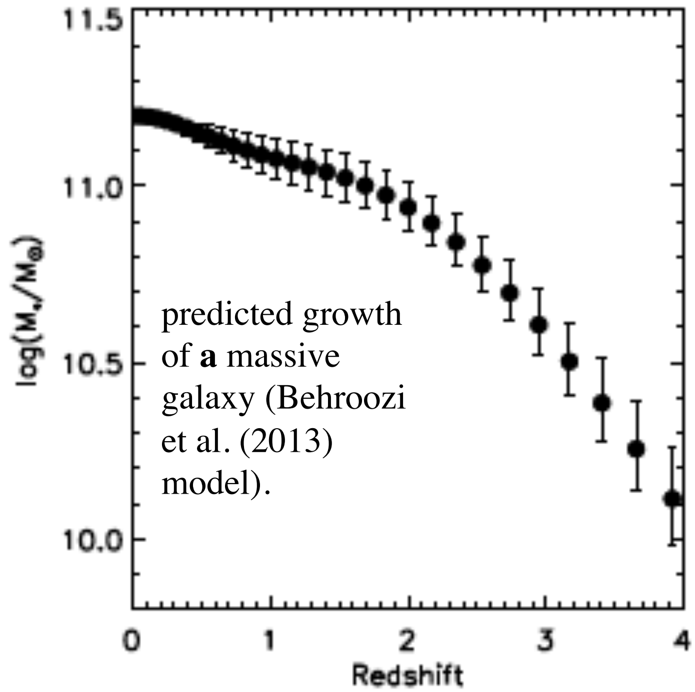


Galaxy growth and changes over cosmic time

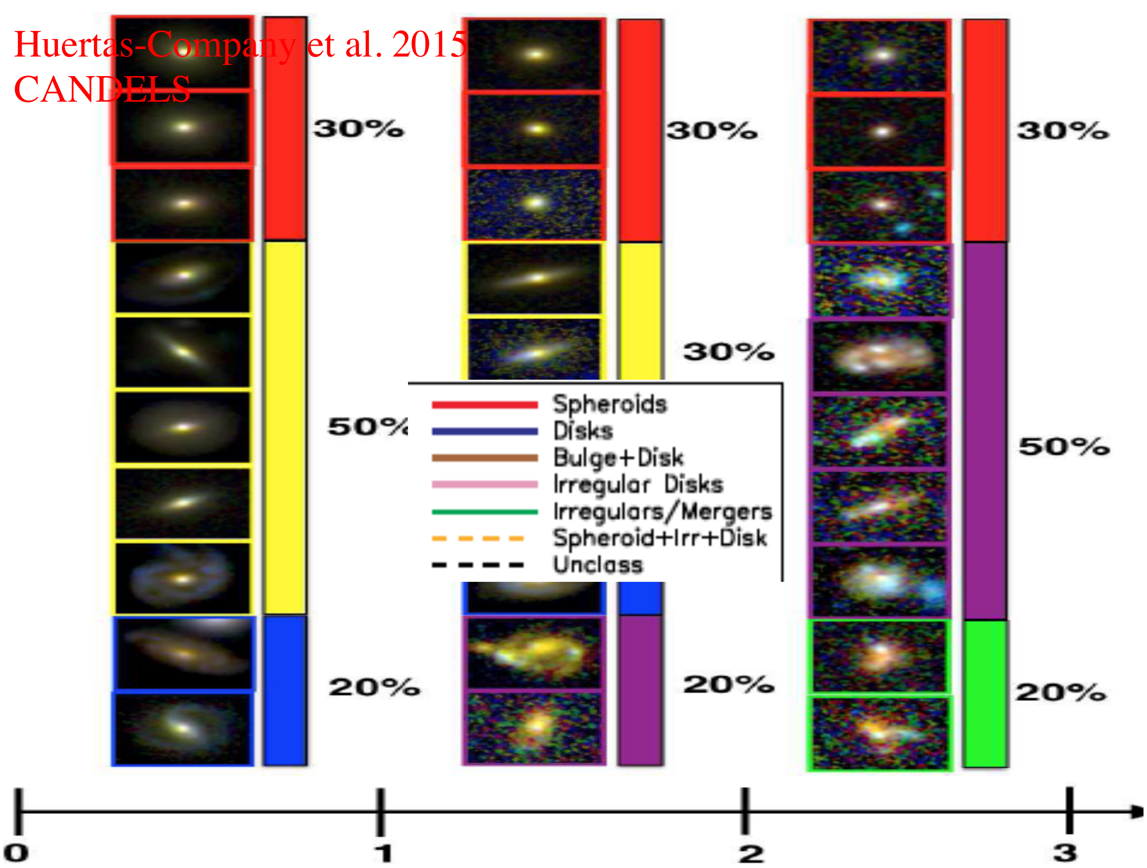
However the *nature* of a given galaxy can change strongly over cosmic time

mass may increase, morphology can change

Galaxies are NOT stationary objects



Huertas-Company et al. 2015
CANDELS



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. 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