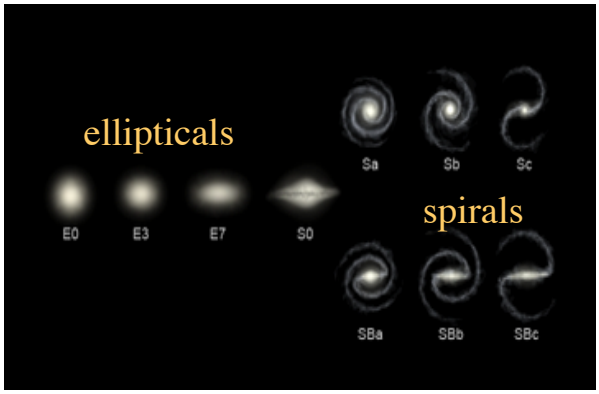
# Galaxies- Please Read CH 1 in S+G

- 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, IR emission from dust and by x-ray emission 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 (>10x 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 3 generalized morphologies

spirals
ellipticals
irregulars



# 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 Mo, van den Bosch and White

http://www.physics.utah.edu/~vdbosch/astro5580.html

- the first two chapters of MBW are on-line at

**http://www.astro.umass.edu/~hjmo/astro330/htmldir/reading.pdf**

For reference

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

Course web page:

- Information, syllabus, lecture schedule
- Assignments
- Past lectures
- Lectures will be posted on the web page *after* they are given



Other books

Extragalactic Astronomy and Cosmology: An Introduction by P. Schneider

A good second reference for this course. The book 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

Secondary books

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

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

Galactic Astronomy by J. Binney & M. Merrifield

This textbook focuses mostly on observational aspects of galaxies and is out of date

The Structure and Evolution of Galaxies by S. Phillipps

Excellent textbook at the introductory level (John Wiley & Sons,Ltd, 2005; ISBN 978-0-470-85507-X, paperback).

# 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 !



# 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!

# Assignments & Grading

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

  - *Mid-term date Oct 16*



# 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.

# ASTR421:Galaxies

Prof. Richard Mushotzky
Room PSC 1111Phone: 301-405-6853
Email: richard@astro.umd.edu
Office hours: 10:00-11:00am Tues/Thurs- TBD by appointment

75 min class

web pages

Mid-term Oct 16

Term paper Nov 25

**Please No open laptops Or Use Of Cell Phones During lectures**



# Other Info- Academic calendar http://www.provost.umd.edu/calendar/14.cfm

- 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 11 is last date to drop with a W
- Thanksgiving November 27-30 (Thursday-Sunday)
  - Religious Holidays
    - Rosh Hashanah 9/24
    - Yom Kippur 10/3

# 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



# 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

# Syllabus

Lecture 1 Introduction: Overview
Lecture 2 Introduction (continued): Overview
Lecture 3 Introduction (continued): Overview
Lecture 4 Basic Galaxy Properties
Lecture 5-6 Properties of Stars
Lecture 7-8 Gas in Galaxies
Lecture 9 Dust in Galaxies
Lecture 10-11 Milky Way Ch 2 in S+G
Lecture 12 Galactic Rotation



Lecture 13-15 Dynamics I-III Chap 3 of S&G
Lectures 16,17 Local group Ch 4 of S&G
Lecture 18 Chemical Evolution
Lecture 19 Star Formation
Lecture 20-22 Spiral Galaxies Ch 5 of S&G
Lecture 23-25 Elliptical galaxies Ch 6 of S&G
Lecture 26-28 AGN I-III Ch9 of S&G

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

# 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
- 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

## Recent Reviews:

Physical Properties and Environments of Nearby Galaxies
ARA&A 47: 159 M Blanton and J Moustakas

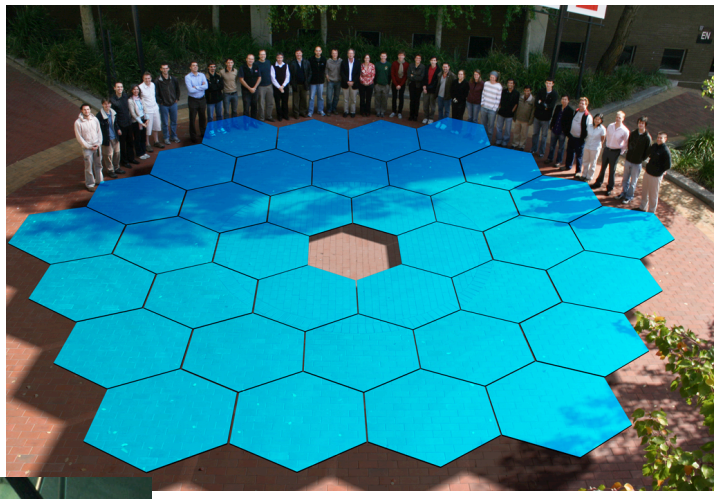
Physical Properties of Galaxies from z = 2–4 ARA&A 49: 525 2011
Alice E. Shapley

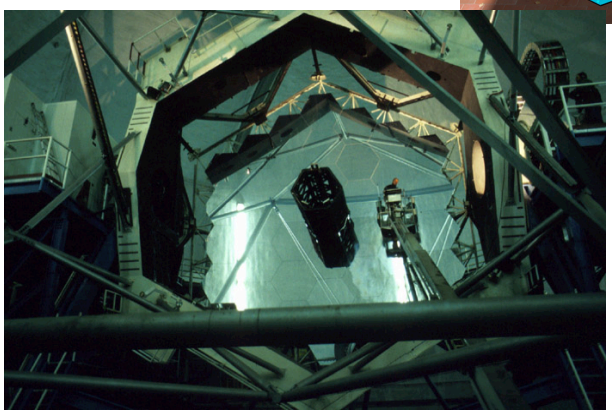
Physical Parameters Along the Hubble Sequence: M Roberts and M. Haynes
ARA&A Vol. 32 (1994): 115-152

Star Formation In Galaxies Along The Hubble Sequence R. Kennicutt, Jr.
ARA&A Vol. 36 (1998): 189 - 231

Galaxy Formation: Where Do We Stand? Christopher J. Conselice arXiv: 1212.5641

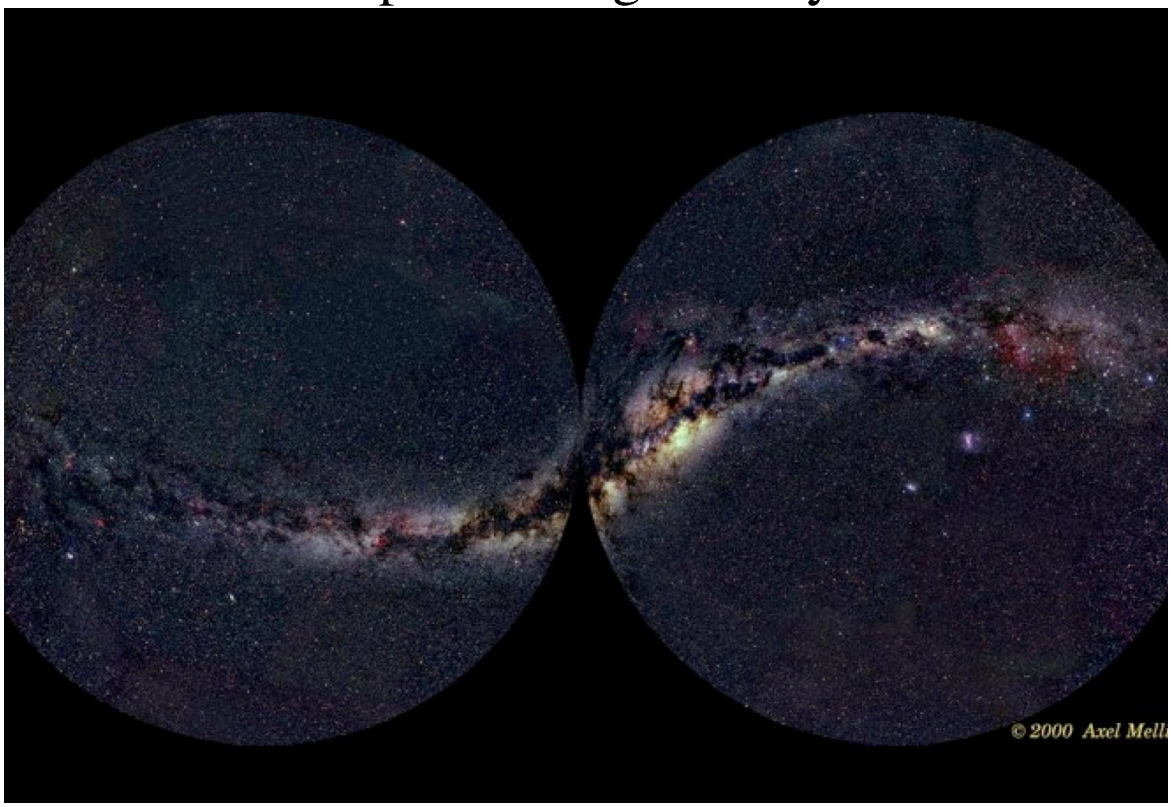




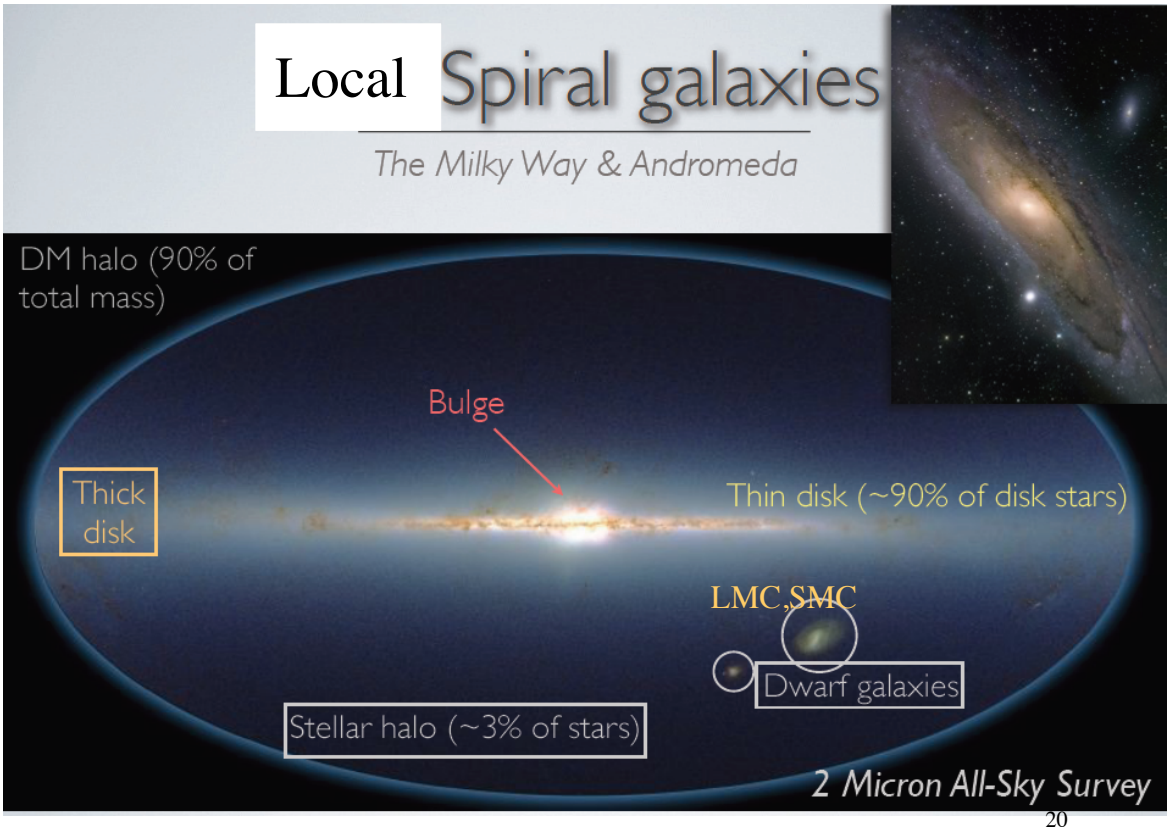


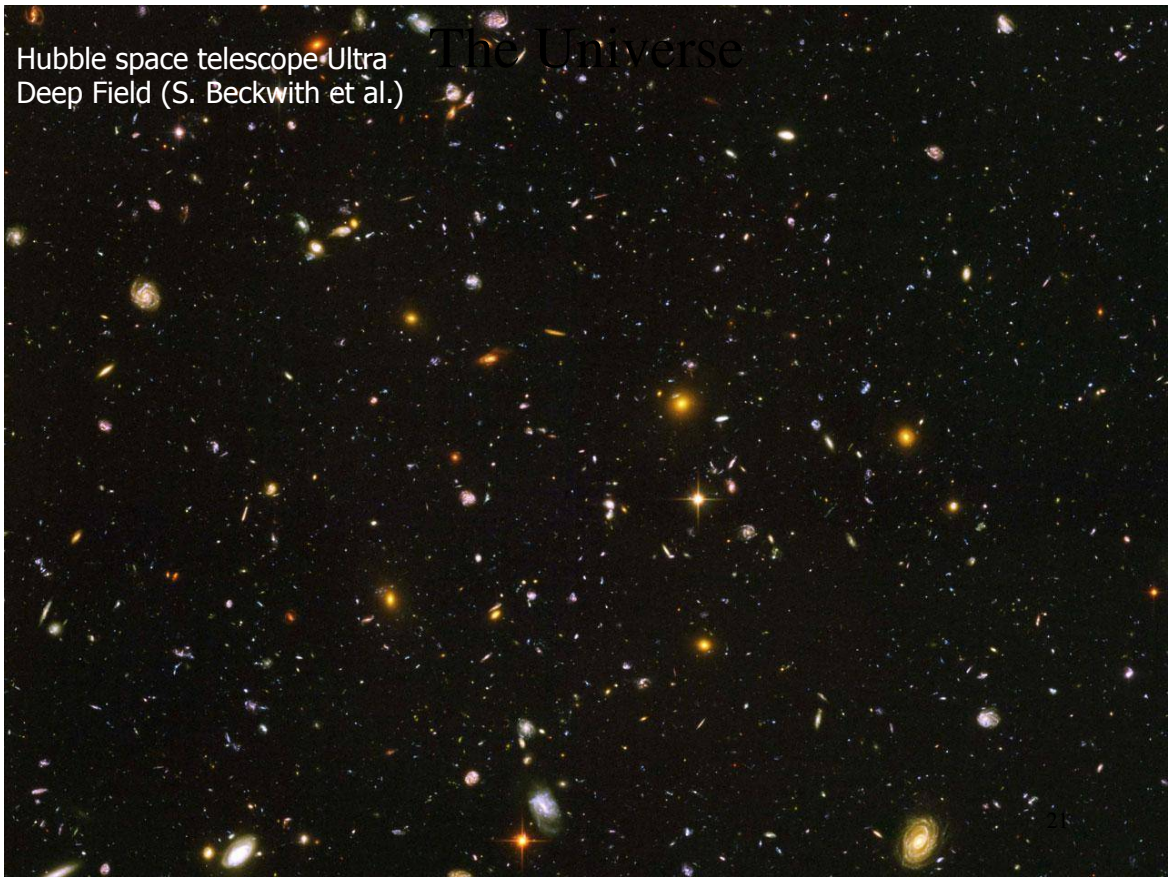


# Optical Image of Sky




Andromeda
Jens Hackman. Milky Way over Weikersheim, http://
The Galaxy


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




# The BIG Picture

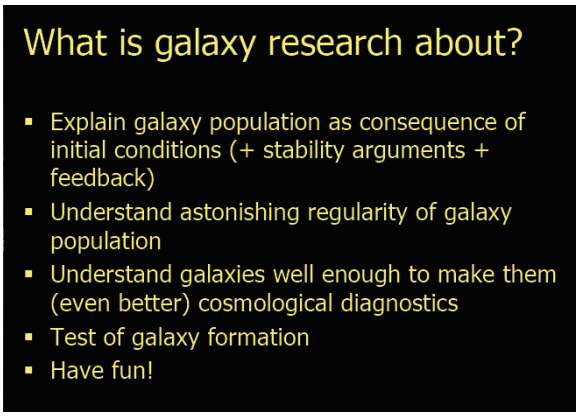
- Essentially, all research on galaxies aims at answering how galaxies form and evolve and the connection between dark matter and baryons
- Steps include understanding the role of the different galactic structural components (e.g. gas, dust, stars, dark matter) in this history, and how they relate with 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)

*** jargon warning**

# 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
  - Nature and distribution of dark matter






# A Brief History

http://en.wikipedia.org/wiki/Galaxy#Observation_history

- Discovery of 'nebulae' in late 1700's (Messier) and their cataloging in the late 1800's (NGC catalog)
- Realization (Great Debate, Shapley, Hubble etc) that the nebula 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

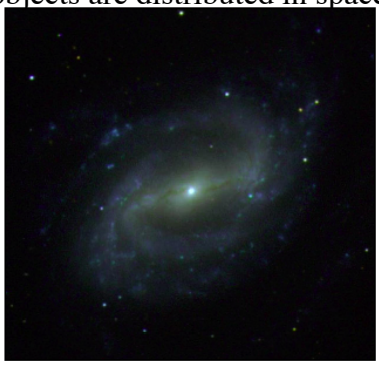
http://www.astr.ua.edu/keel/galaxies/history.html

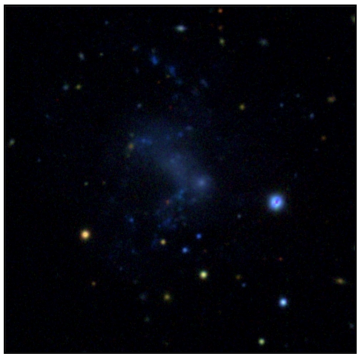
# Galaxies: From J. Dalcanton

The velocity (V) is characteristic of the the motion of stars/gas in these systems

$M_{halo}$ is the mass of the dark matter potential well in which the galaxy resides

Clustering refers to how the objects are distributed in space





## 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 now

## Dwarfs

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

V~30km/s

Weakly Clustered

Young stars

Numerous



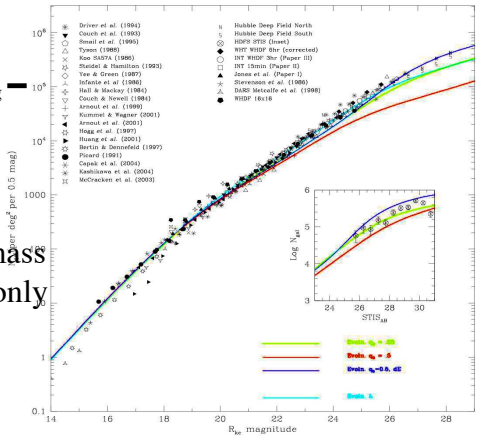
# How Many Galaxies are There?

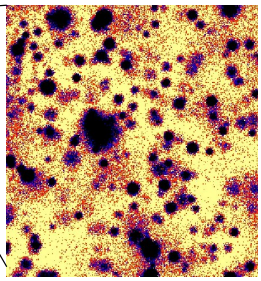
- There are ~50 galaxies/sq arc min at $10^5$/deg$^2$/0.5mag – m~25.5, rising slowly to ~175 at m~29

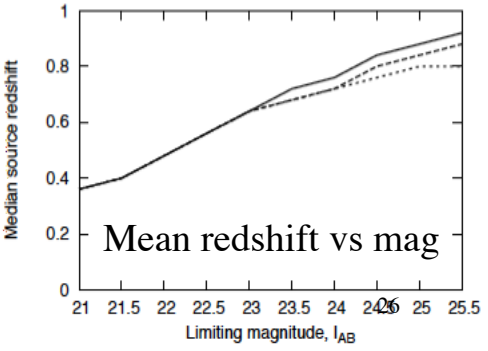
The median redshift at a given magnitude increases slowly

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

Galaxy surface density vs mag

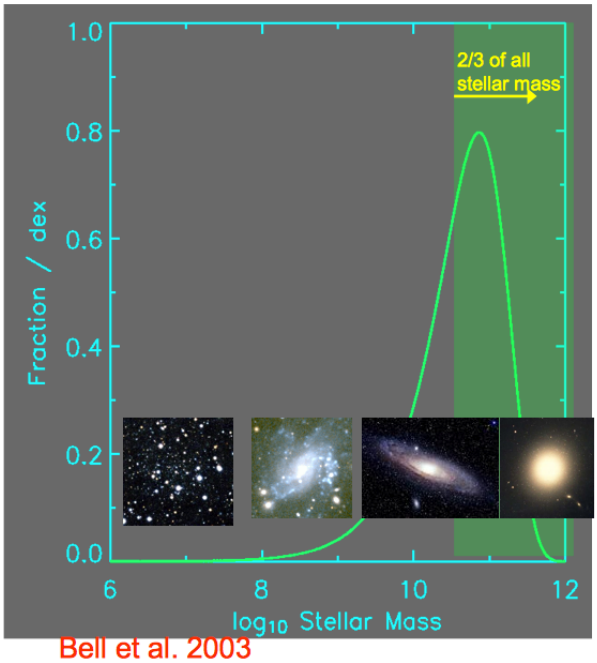






# Galaxies Have a Wide Range in Mass

- 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)- certain types of galaxies tend to live in certain mass ranges.
- The baryons are distributed in gas, stars and dust; wide range in gas/stars, relatively narrow range in dust/gas.

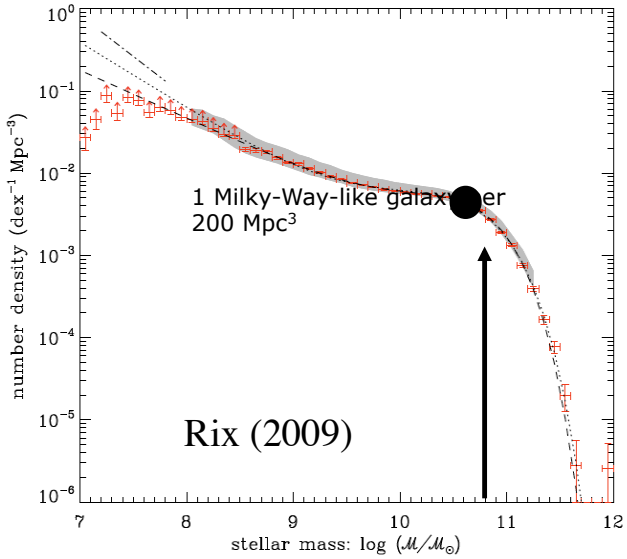


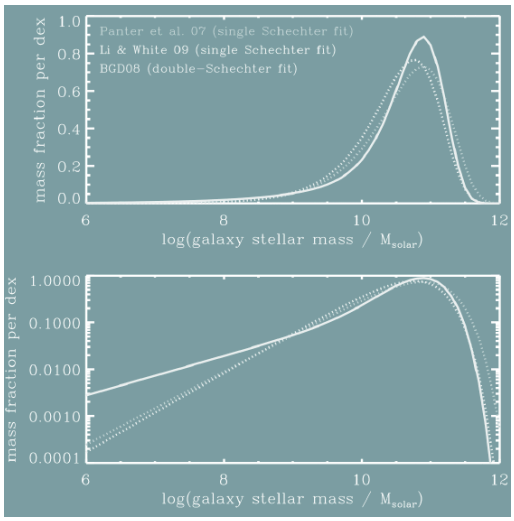

Bell et al. 2003



# Mass Distribution

- The mass function of galaxies (#/volume)



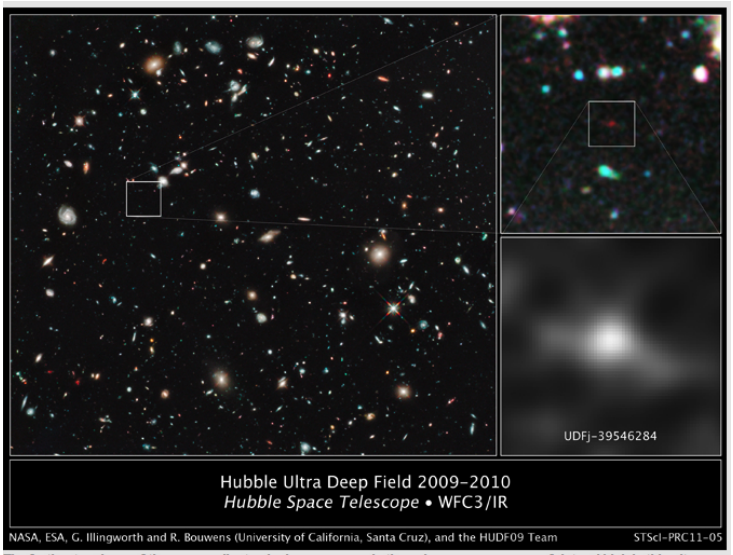




where is the mass-narrow distribution around log $M_{star}$~10.5$M_\odot$
In mass MW is typical

# How Old are Galaxies

- Direct imaging by HST has shown the existence of galaxies at z~9 (13.17 Gyrs age, for an age of the universe of 13.72 Gyrs)
- Stellar ages: in the 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)



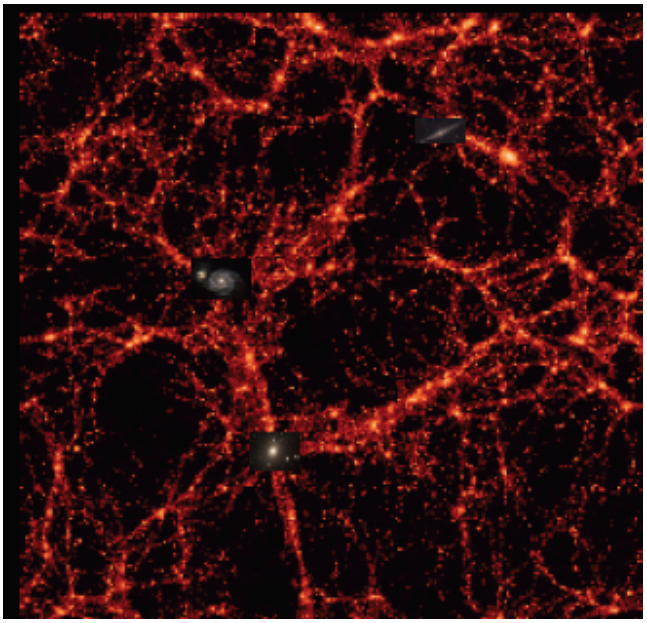

*The farthest and one of the very earliest galaxies ever seen in the universe appears as a faint red blob in this ultra-deep-field exposure taken with NASA's Hubble Space Telescope. This is the deepest infrared image taken of the universe. Based on the object's color, astronomers believe it is 13.2 billion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



# Galaxies Do Not Live Alone

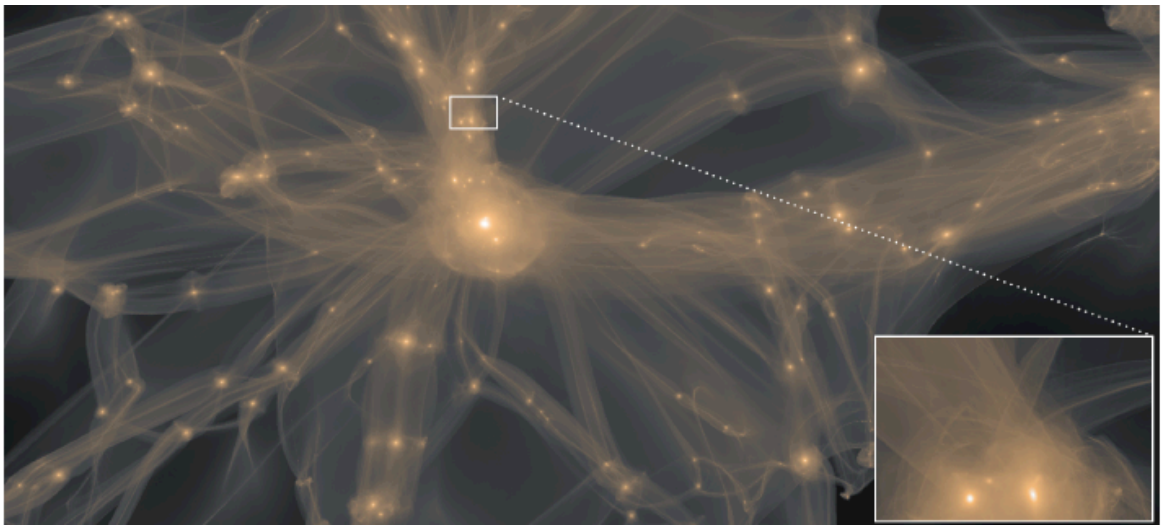
- Galaxies are part of the 'cosmic web'- representing overdense regions of both baryons and dark matter
- The effective size of the **dark matter halo** is much larger than the apparent stellar size of the galaxy



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

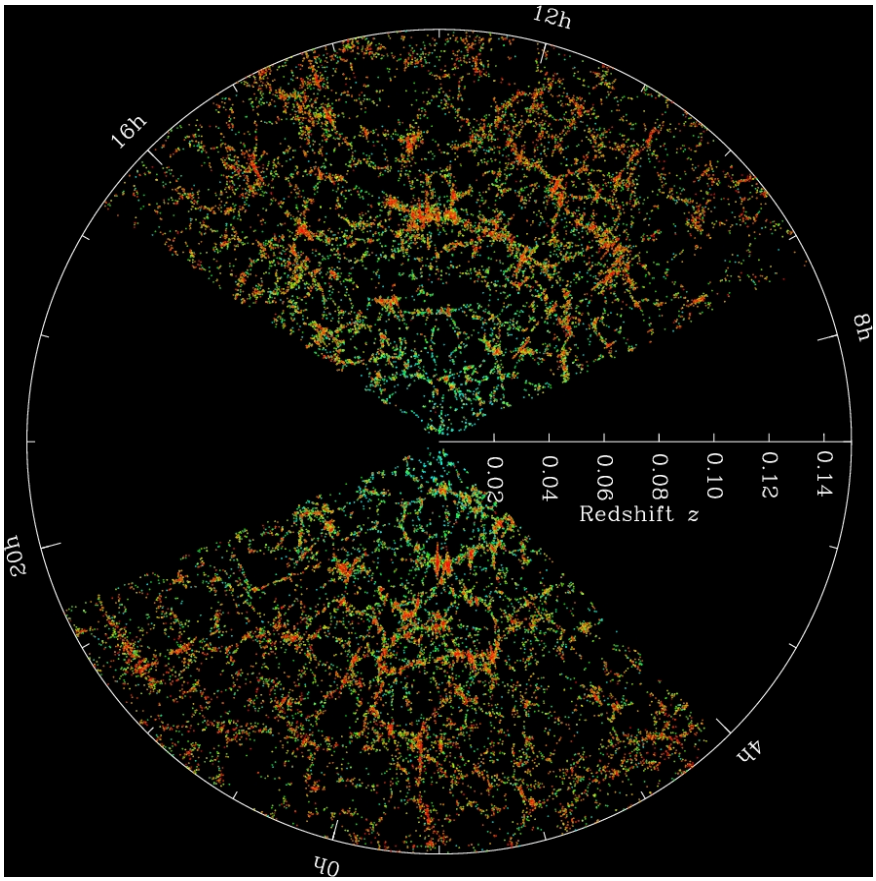
Eric Bell

# Cosmic Web- Numerical Simulation



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.



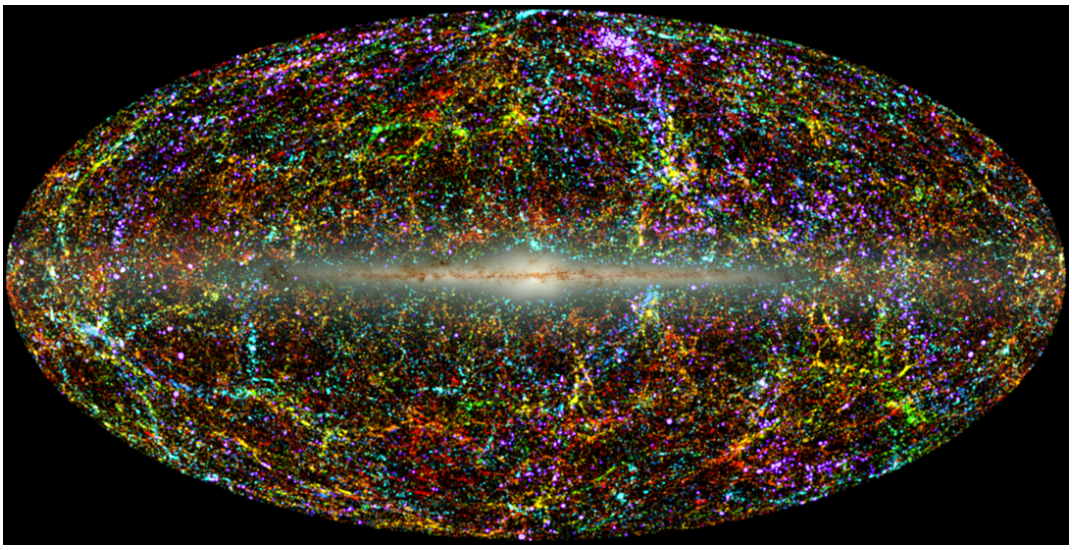



Sloan Digital Sky Survey

Galaxies color coded by the age of their stars

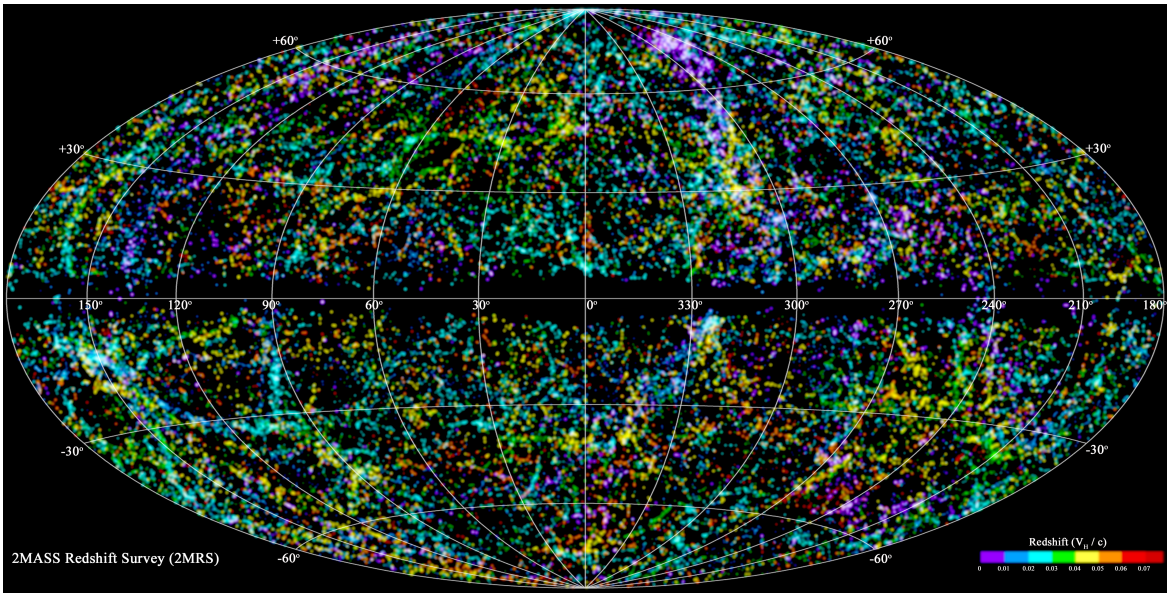
http://www.sdss.org

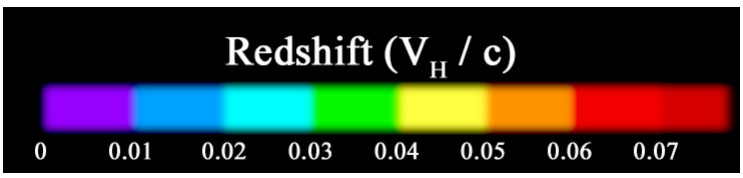
# 2MASS view of galaxies selected by infrared flux notice filamentary structure



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

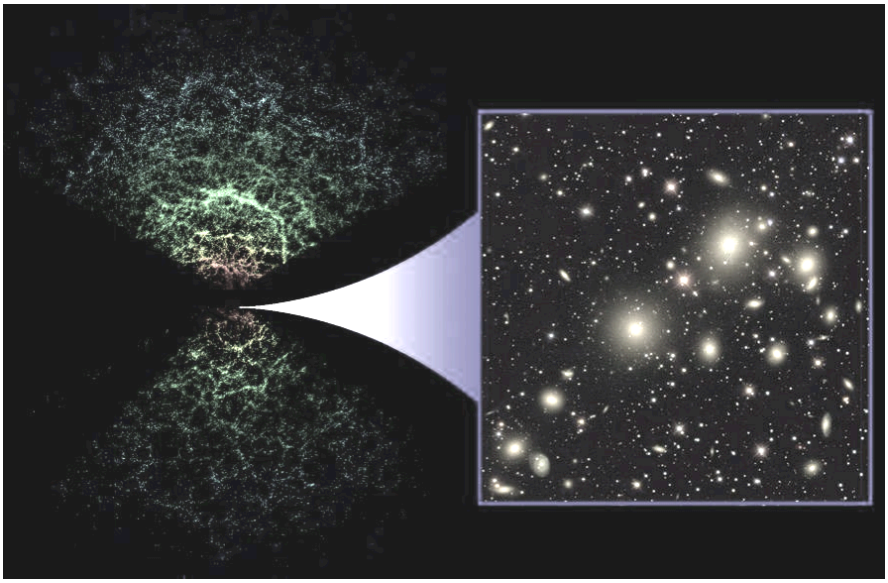




## Large Scale distribution of normal galaxies

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

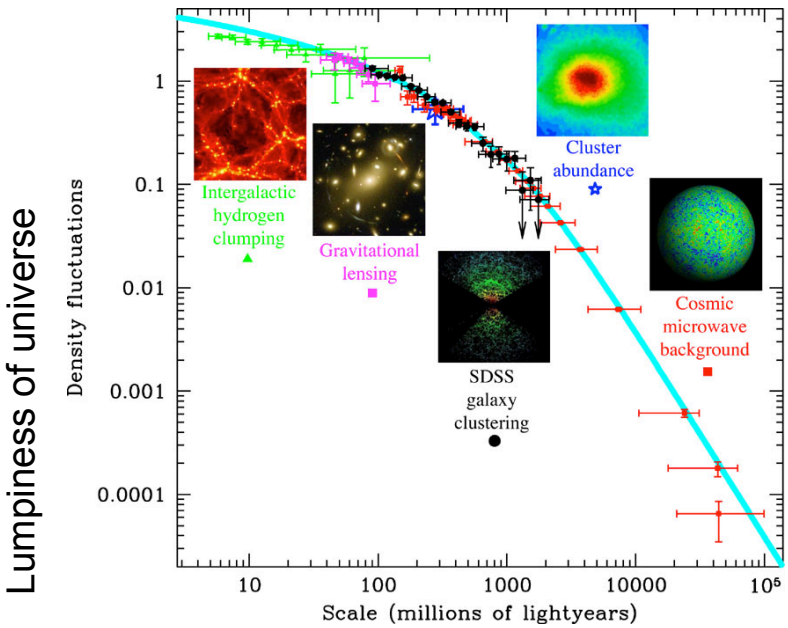


Sloan Digital Sky Survey- http://skyserver.sdss3.org/dr8/en/



# Power Spectrum of Fluctuations

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



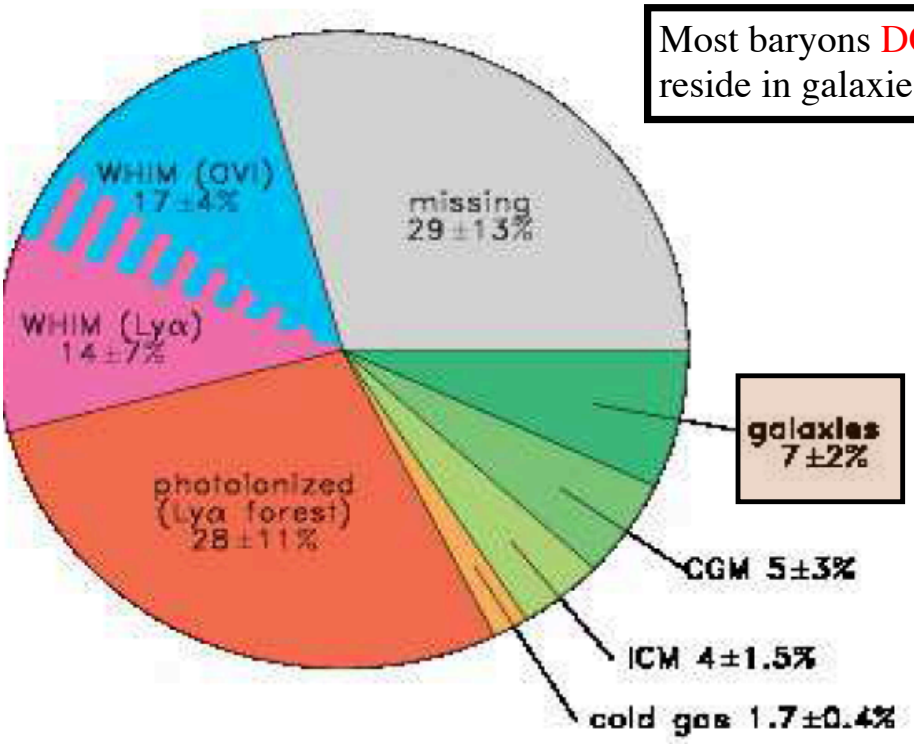

Tegmark 2004

size of box

# Where are the Baryons

Shull Danforth 2012

Most baryons DO NOT reside in galaxies




37

# 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


38

# Dark Matter Dominates Gravity

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

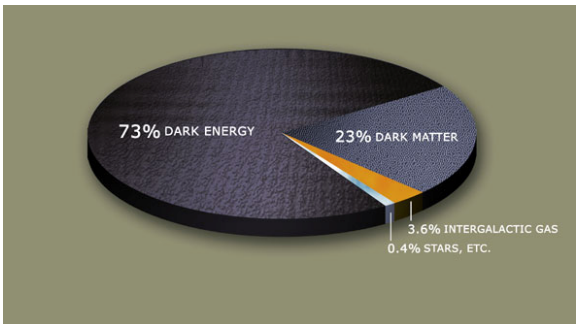
$\Omega_{baryons}/\Omega_{dark\ matter} = 0.167$

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

$\Omega_{dark\ matter} = 0.28$

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

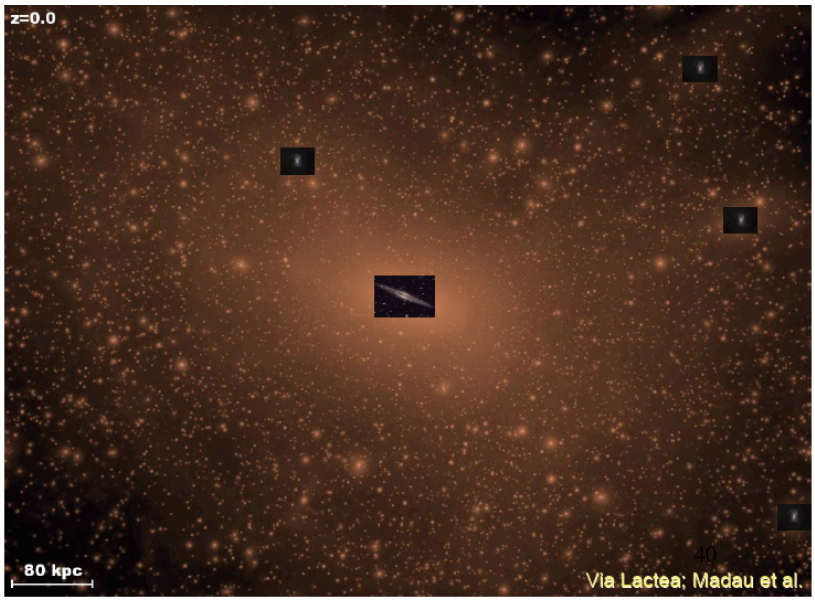
$\Omega_{stuff}$ is the ratio of the mass of the component to the closure density





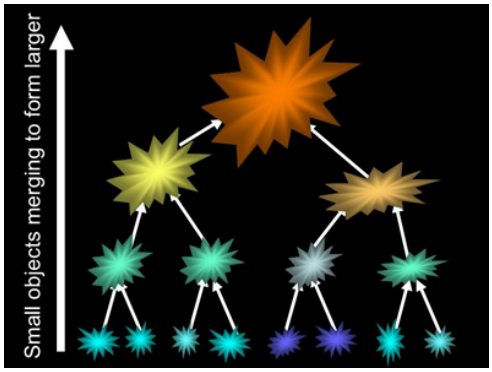

# Dark Matter Distribution and Galaxies

- 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).