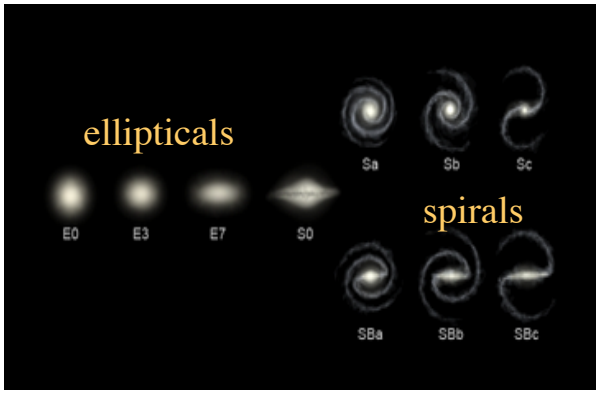
Galaxies- **Please Read CH 1 in S+G**

- 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(https://en.wikipedia.org/wiki/Dark_matter_halo)**



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 (very complete but dense) 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; ISBN978-0-470-85507-X, paperback).

See From the Realm of the Nebulae to Populations of Galaxies pp 243-379
The Anatomy of Galaxies for an interesting intro

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 !

Assignments & Grading

- Assignments:
  - Homework: 25%
  - mid-term : 20%
  - Final : 35%
  - Project/term paper 20%; **Due Dec 4**
  - TOTAL : 100%
  - *Class participation is encouraged*

  - *Mid-term date Oct 11*

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!

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 1158 Phone: 301-405-6853

Email: richard@astro.umd.edu

Office hours: 10:00-11:00am Tues/Thurs- TBD by appointment

75 min class

web pages see YY

Mid-term Oct 11

Term paper Dec 4

Please No open laptops Or Use Of Cell Phones During lectures

Other Info- Academic calendar http://www.provost.umd.edu/calendar/17.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

- -Labor Day Holiday: Monday, Sep. 3
  -Last day for students to add a course or drop a course without a W: Monday, Sep. 10
  -Last day for students to drop a course with a W: Monday, Nov. 5
  -Thanksgiving Holiday: Wednesday, Nov. 21 - Friday, Nov. 23
  -Last day of classes: Monday, Dec. 10
  -Final exam Dec 17

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

Lectures for the Semester

- Lecture 1 Introduction: Some Galaxy Properties
- Lecture 2 Introduction (continued): Some Galaxy Properties
- Lecture 3 Introduction (continued): Some Galaxy Properties
- Lecture 4 Basic Galaxy Properties
- Lecture 5 Properties of Stars I
- Lecture 6 Properties of Stars II
- Lecture 7 Gas in Galaxies Lec I
- Lecture 8 Gas in Galaxies Lec II
- Lecture 9 Dust in Galaxies
- Lecture 10-11 Milky Way Lec
- Lecture 12 Galactic Rotation
- Lecture 13 Dynamics I
- Lecture 14 Dynamics II
- Lecture 15 Dynamics III
- Lectures 16,17 Local group
- Lecture 18 Chemical Evolution
- Lecture 19 Star Formation
- Lecture 20-21-22 Spiral Galaxies
- Lecture 23-24-25 Elliptical galaxies
- Lecture 26 AGN I
- Lecture 27-28 AGN II-III

Syllabus

Lecture #	TOPIC	Text Chapter
Lec 1	**INTRODUCTION**	
Lec 2	Continuation of introduction	Ch 1
Lec 3	Basic Galaxy Properties	Ch 1
Lec 4,5	Relevant Properties of stars	
Lecs 6,7,8	Properties of Gas and Dust	
Lecture 9, 10	Milky Way	Ch 2 in S+G
Lecture 11	Galactic Rotation	
Lecture 12---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
Lec 29	Summary	

Unfortunately we do not have time to cover clusters of galaxies, large scale structure and cosmology

Assignment for Next Week

- *Read Chapter 1, sections **1.1-1.3** of the book-*
  - *for those of you who do not have the book, I will print out the first chapter. You can pick it up Friday or before the next class*
- 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:Advanced Stuff

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

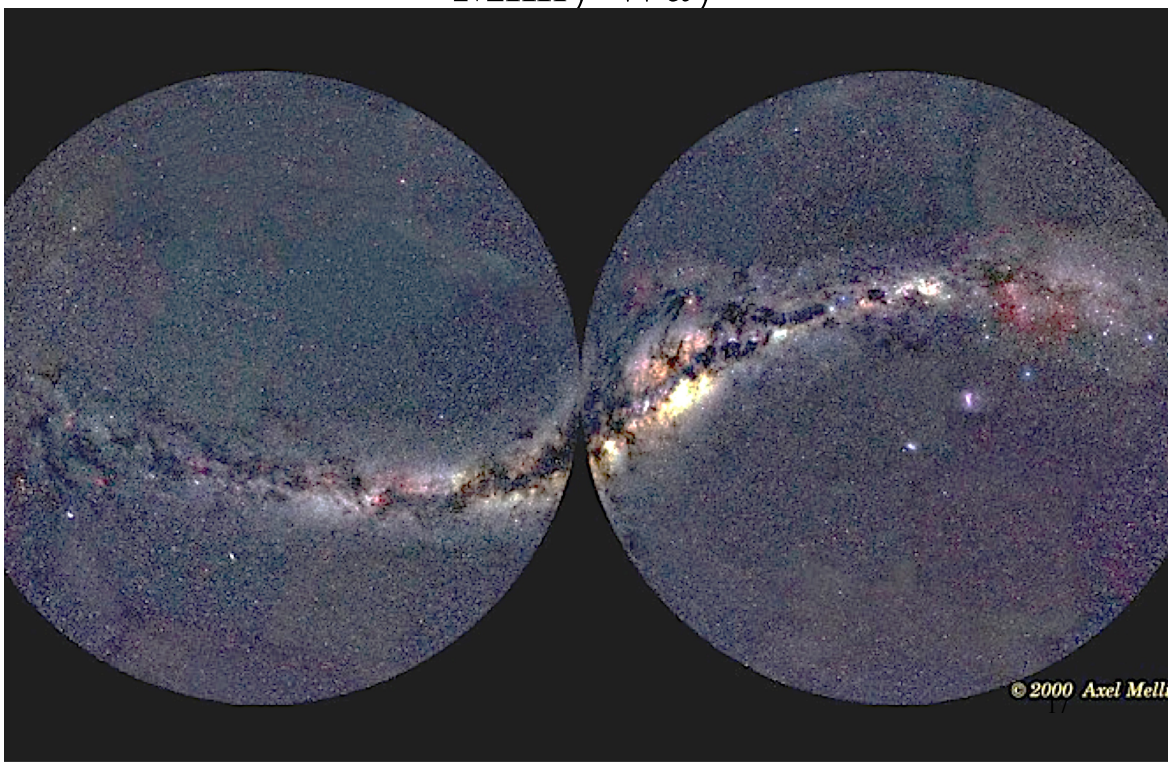
Physical Properties of Galaxies from z = 2–4 ARA&A 49: 525 2011
Alice E. Shapley

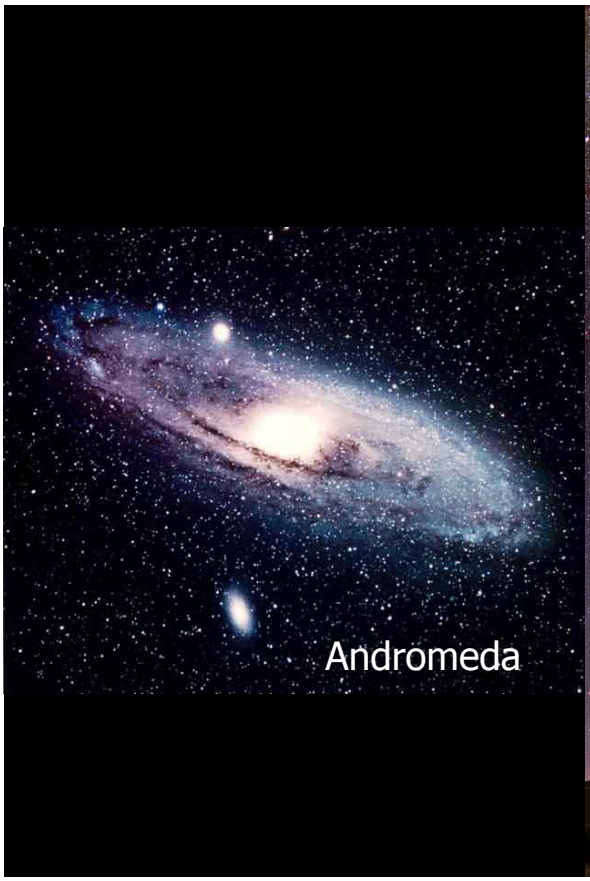
Physical Parameters Along the Hubble Sequence: M Roberts and M. Haynes
ARA&A Vol. 32 (1994): 115-152

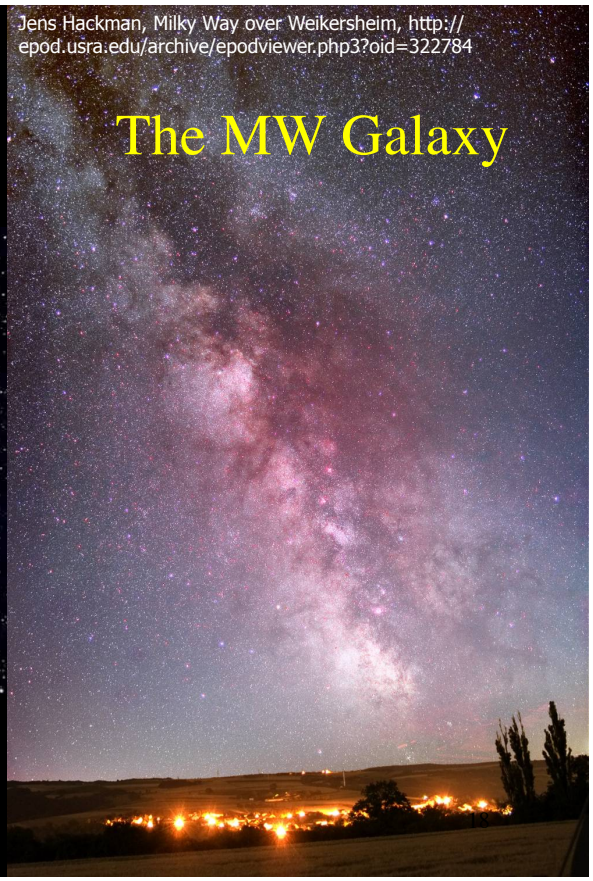
Star Formation In Galaxies Along The Hubble Sequence R. Kennicutt, Jr.
ARA&A Vol. 36 (1998): 189 - 231

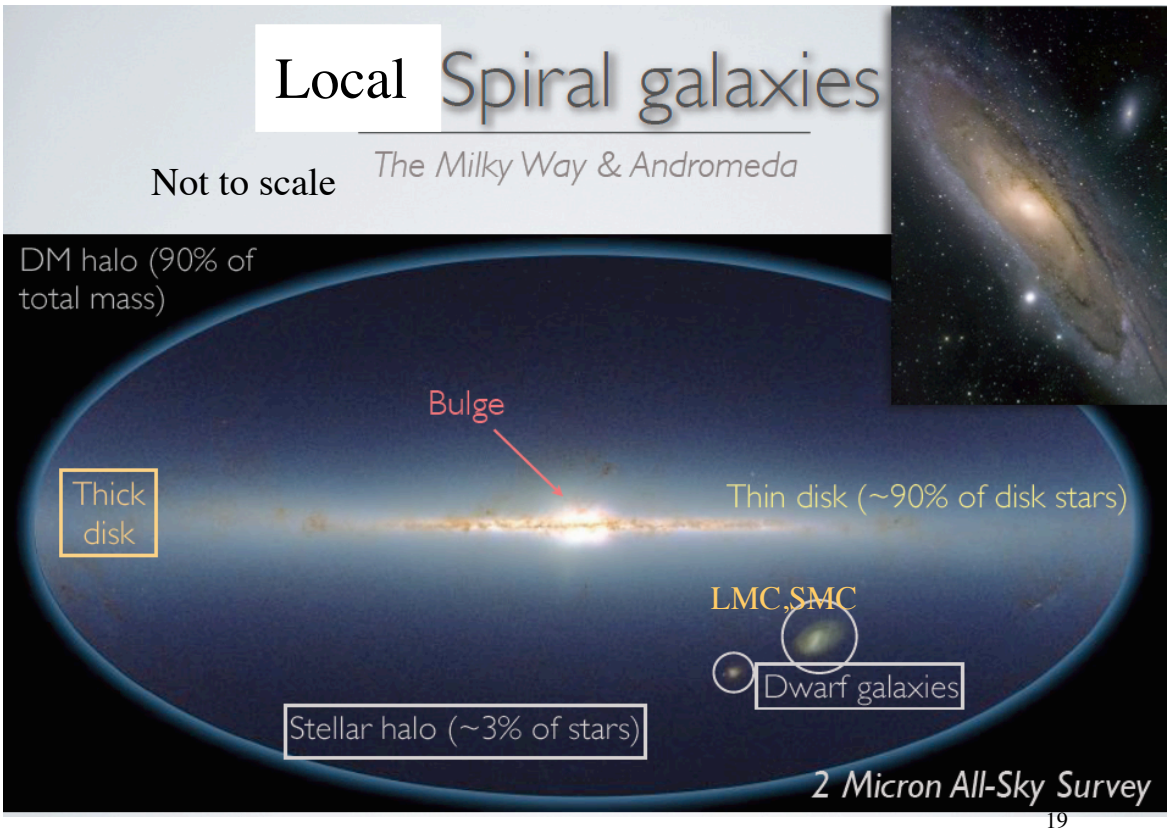
Galaxy Formation: Where Do We Stand? Christopher J. Conselice arXiv: 1212.5641

Optical Image of Sky- Dominated by the Milky Way

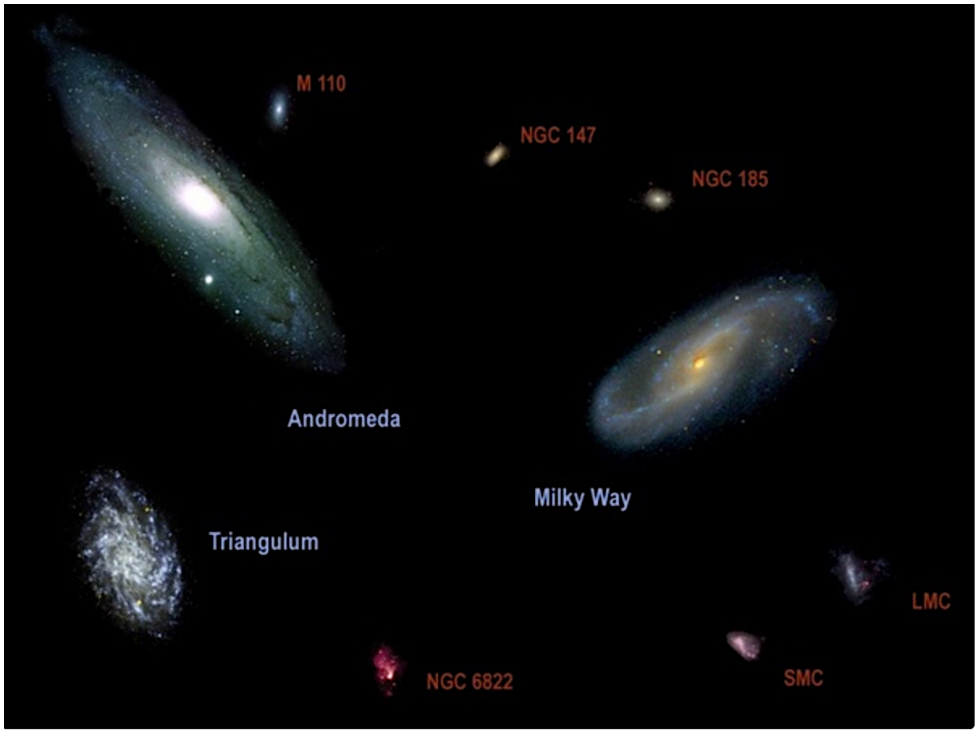






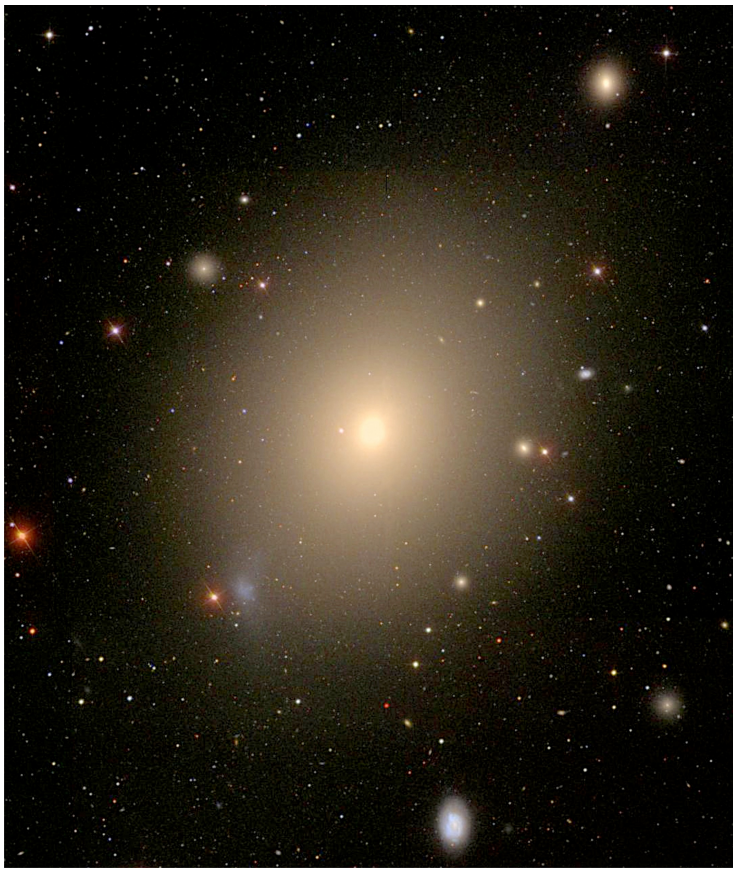


Nearby Galaxies to Scale

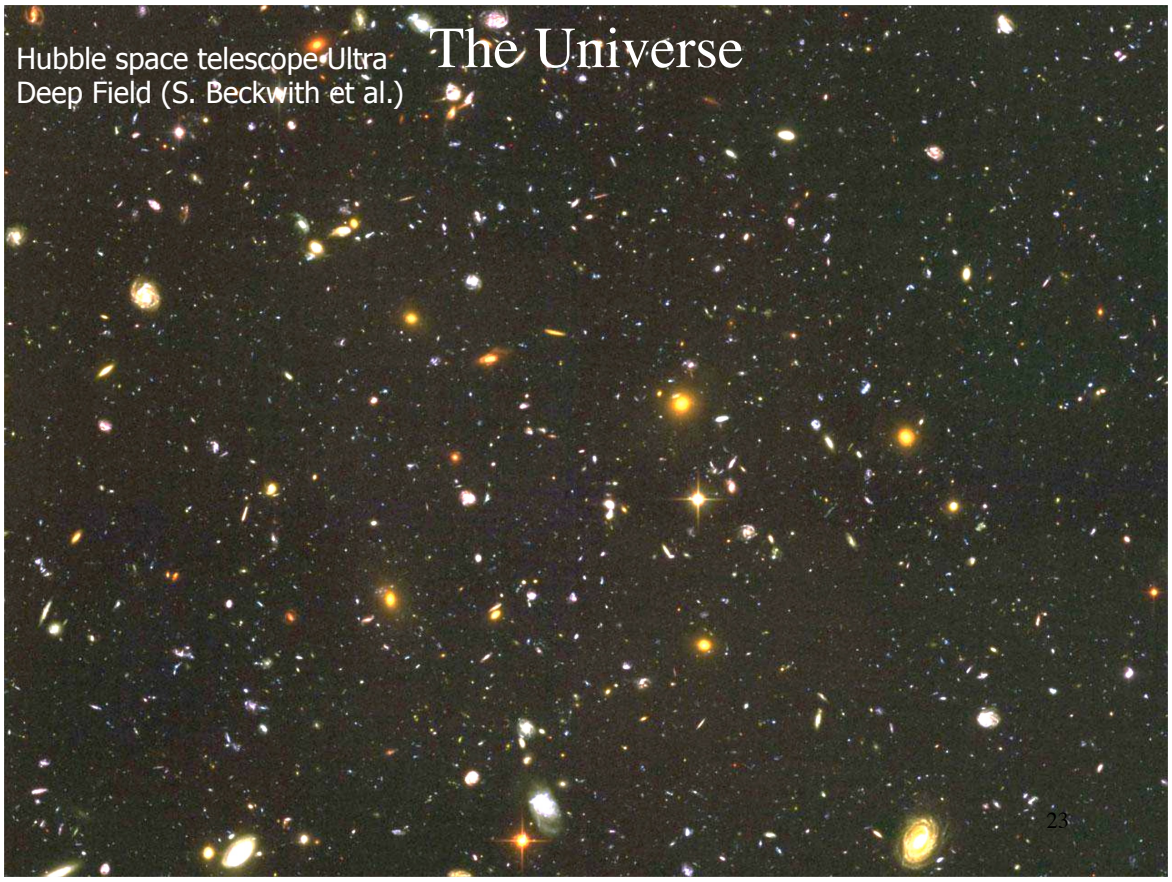


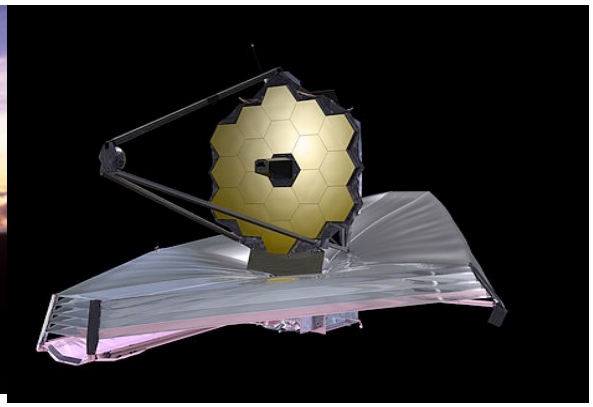
https://www.quora.com/How-big-is-Andromeda-compared-to-the-Milky-Way

NGC 4472 in the Virgo Cluster
D~16Mpc
A 'giant' elliptical galaxy

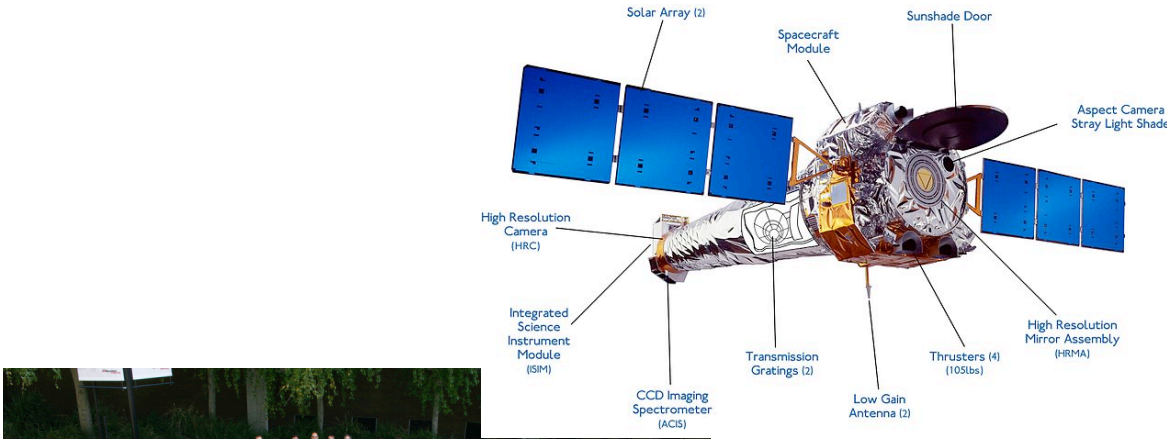


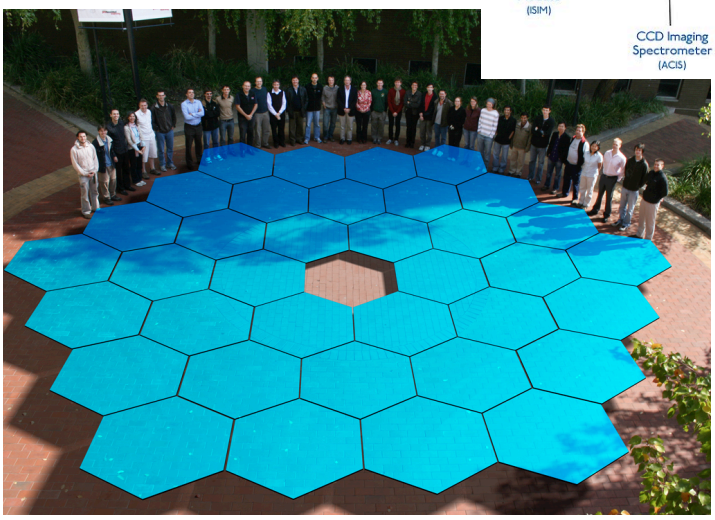
Sloan Digital Sky Survey


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




SOME OF THE TOOLS OF THE TRADE





25

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.

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!

Cosmic laboratories for **all the details of astrophysics**

- star formation
- formation of the chemical elements
- the relationship of black holes to their host galaxies
- nature and distribution of dark matter

26

The BIG Picture

- Essentially, all research on galaxies aims at answering how galaxies form and evolve
- Need to understand
  - the role of the different galactic structural components (baryons (gas, stars and dust), black holes and dark matter), and how they relate with each other.
- Link structural analysis, kinematics and dynamics, stellar population properties and evolution, multi-wavelength observations, redshift coverage, and theory.

It is only with such a holistic approach that galaxies can be 'understood'

The BIG Picture

- From a theoretical point of view Galaxies reside in dark matter halos (see fig 1.8 and pg 27*), but are biased tracers of the underlying matter distribution : the observable galaxy properties such as luminosity are not *simple* tracers of dark matter.

- Different kinds of galaxies reside in different mass halos: (ellipticals tend to be more massive, spirals intermediate, irregulars low mass)

- Massive halos can host *multiple* galaxies (pairs, groups, clusters)- like Russian dolls

*S&G are not correct in saying that "usually assume, without a compelling reason, that it lies in a roughly spherical dark halo"-

Galaxies the Big Picture

- What are galaxies? What are their constituents?
  - Galaxies: gravitationally bound collections of baryons (stars, gas/dust), dark matter, black holes) and **dark matter**
- **Galaxies as intersection of much of of astronomy**: stellar physics, gas physics, cosmology, dynamics
  - ***if you are bored by galaxies, you are bored by astronomy***
- Understanding galaxy formation is one of the current largest problems in astronomy; almost all fields can be regarded as important for understanding galaxy formation!
- Galaxies are luminous tracers of large scale structure, act as cosmological probes
  - MUCH recent efforts have gone into using the distribution of galaxies in space and time as detailed cosmological probes (see arXiv:1708.01530 Dark Energy Survey Year 1 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing)

Goals of Course

- Understand general current picture of galaxy properties and galaxy evolution
- Basic understanding of "how" galaxies are observed – e.g. multiwavelength data
- Review statistical properties of the galaxy population, and specific properties of different types of galaxies
- Understand physical tools by which we learn and characterize different components of galaxies

Some Relevant Timescales/Values

- Lifetime of universe; e.g Hubble time $t \sim H_0^{-1} \sim 14$Gyrs

- dynamical times $t_{orb}=(3\pi/16G\rho)^{1/2}$; G is gravitational constant, ρ is density in gm/cm^3 (eq 2.25 and Equation 3.23 in Section 3.1):
  - free fall time scale for a gas cloud $t_{orb}=(3\pi/32\ G\rho)^{1/2}$
  - ***all dynamical times scale as $\sim(G\rho)^{-1/2}$***
- Cooling time of gas $t_{cool}=[(3/2nkT)/n^2\Lambda(T)]$ (eq 7.12, see text page 298) ; Λ(T) is the cooling function (a lot more later in the class); n is density in particles/cm^3
  - remember that the universe starts as gas, so it has to 'fall into' dark matter halos and cool to form stars
- Virial equilibrium (gas heated by collapse, conversion of potential energy into heat) $T_{vir} \sim (mv^2/3) \sim 3.6 \times 10^5 (v_C/100\text{km/sec})^2$ (problem 7.2)
  - where $v_c=\text{sqrt}(GM/R)$; so v_c is a measure of the mass of a system. For a typical galaxy with $M \sim 10^{11} M_\odot$ and R~10kpc this gives v~300 km/sec (velocity of sun around GC is ~250 km/sec) and T= 3x10^{6}k (BOE calculation)

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)

https://ned.ipac.caltech.edu/level5/March02/Gordon/Gordon2.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

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

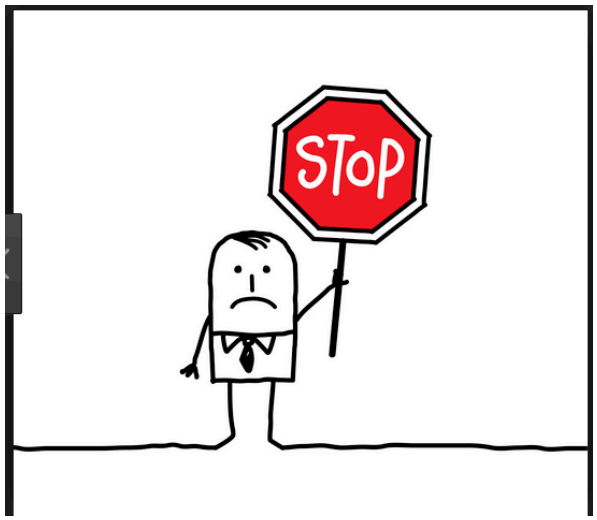
https://science.howstuffworks.com/dictionary/astronomy-terms/galaxy2.htm

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.

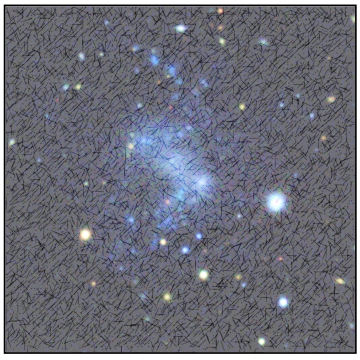


Galaxies: From J. Dalcanton

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

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

V~350km/s

Highly Clustered

Old stars

little star formation *now*

Spirals

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

V~200km/s

wide range of stellar ages

star forming *now*

Dwarfs

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

V~30km/s

Weakly Clustered

Young stars

Numerous

Browse the Sky

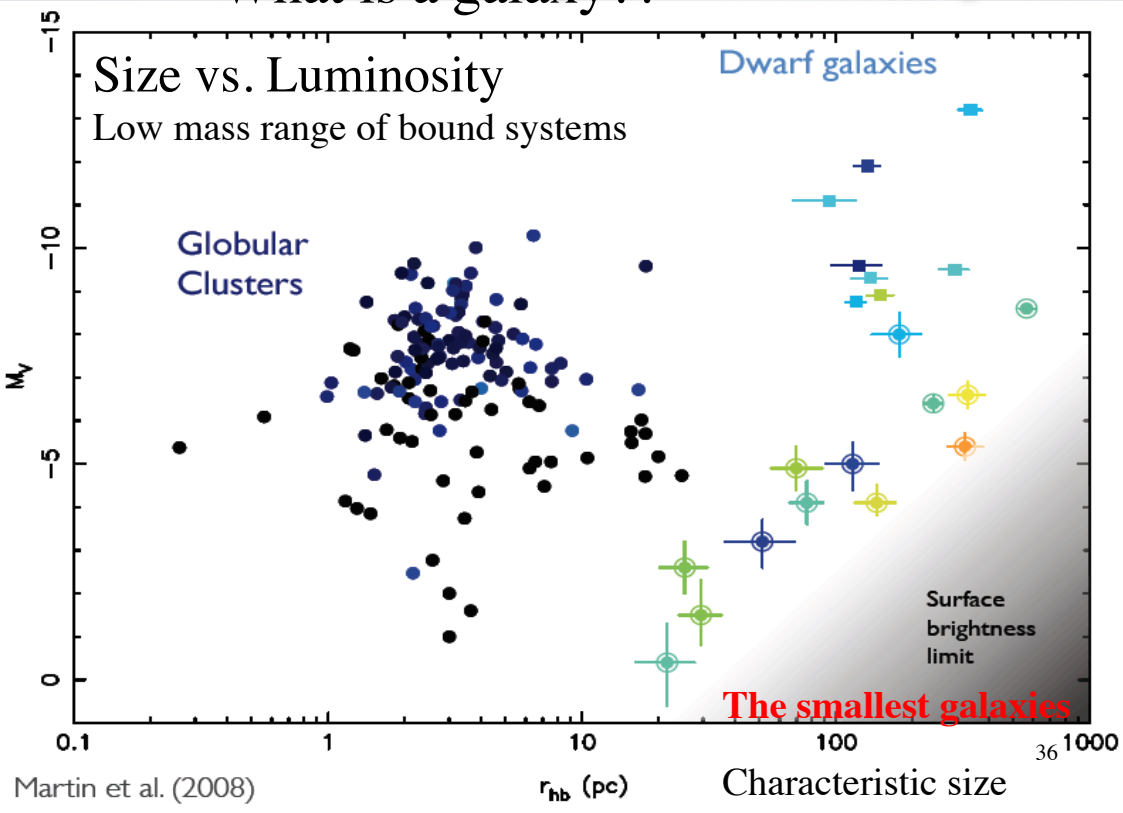
A great site to see how the sky looks from a large telescope:legacysurvey.org

http://legacysurvey.org/viewer ra=147.45674&dec=1.09255&zoom=14&layer=decals-dr5

or
http://legacysurvey.org/viewer#NGC 5614

and the Hubble web site
https://www.spacetelescope.org/images/archive/category/galaxies/

What is a galaxy??



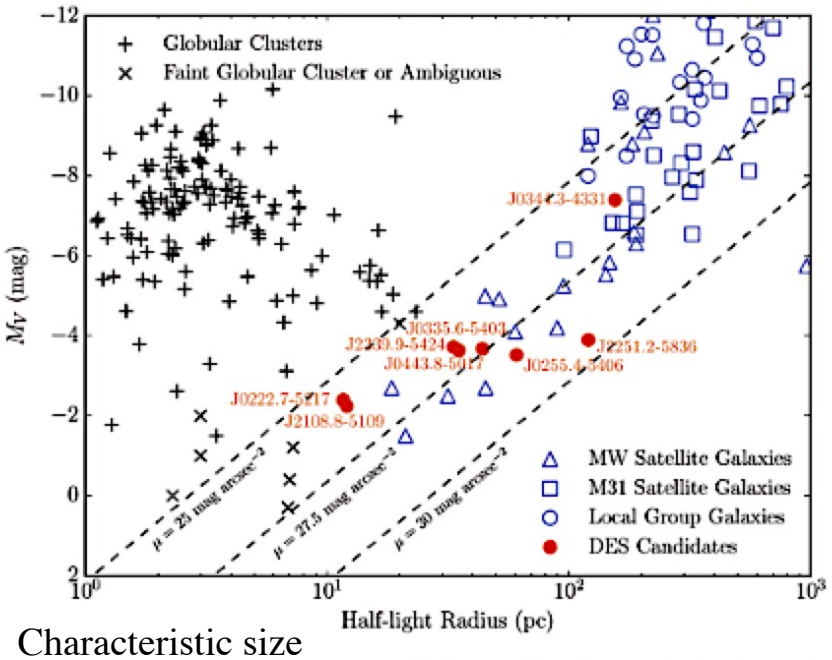
Size vs. Luminosity

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.

Yes we did cover all that last lecture