Welcome!

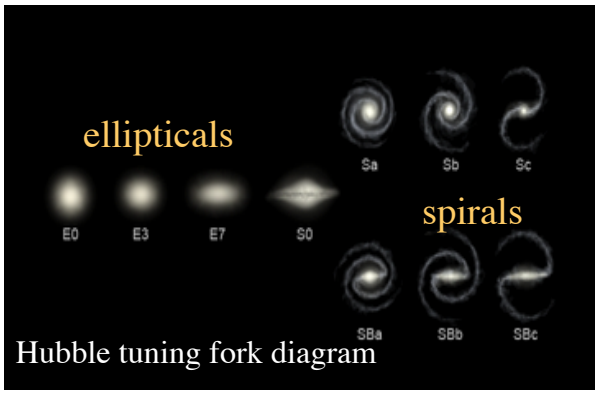
- What is this course about?
- Logistics
  - Textbook, web pages
  - Assignments, exams, grading
  - Academic integrity
  - Semester plan
- Discussion
  - galaxies the big picture

  - The students in the class have a wide range of knowledge about astrophysical objects... I hope to hit a middle level so that the students with the least background are not overwhelmed and the students with the most are not bored.
  - If I miss this middle ground please tell me as soon as possible !!

Galaxies in the Universe

Galaxies- **Please Read Ch 1 and sec 2.1-2.4 in MBW**

- 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, IR and mm emission from ionized gas and dust 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
    - **e,g compact condensation of baryons near the center of dark matter halos.**



Hubble tuning fork diagram

Galaxies come in a huge range of shapes and sizes

Generically divided into 3 generalized morphologies

spirals
ellipticals
irregulars

Textbook & web pages

Required text: Galaxy Formation & Evolution by H. Mo, F. van den Bosch & S. White
Authors' web page:
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

secondary books

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

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

- Galactic Dynamics (2nd Edition) by J. Binney & S. Tremaine
- Galactic Astronomy Binney and Merrifield (no online version)

- Course web page:

http://www.astro.umd.edu/~richard/teaching/ASTR620.html

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

Assignments & Grading

- Assignments:
  - Homework: 30%- including research reports
  - Midterm : 20%
  - Final : 30%
  - Project/term paper 20%
  - TOTAL : 100%
  - *Class participation is strongly encouraged*

Mid-term date Oct 11

Pre-requisites

- I will assume that you are familiar with basic astronomical terms and usage.
- If there is stuff you are not familiar with STOP ME and ASK QUESTIONS- this field is jargon rich !!!
- I will try and introduce the needed physics- Binney and Tremaine is a fairly formidable book in which the reader is assumed to be familiar with advanced dynamics.
- Binney and Merrifield is an excellent book, but out of date.
- Sparke and Gallagher is aimed at both undergraduates and grad classes

The Different Takes

- Galaxies- ch 1 and sec 2.1-2.4 in MBW will give you a crash course in galaxies - lots of material quickly presented.
- A very different take on this material is in B&T ch1 pgs 1-29
  - ch 1 presents a lot of NECESSARY to know stuff about stars (can't study galaxies without some knowledge of stars) and general astronomy stuff and then in pgs 27-49 an eclectic overview of galaxies.
- B&M chap 1 presents a historical introduction
- I will try and present a summary of all of this material in quasi-coherent fashion in the next 3 lectures

Read MBW- please take a look at B&M and S&G

I will often refer to these 2 other books ; copies in the library

The *field is changing rapidly (e.g GAIA results coming out last month)* and even MBW is getting outdated. **I will often use figures from recent papers**...

Its necessary to read and know the literature. There were > 400 papers per month in the last year about galaxies.

Reading

- *Please read Chapter 1, 2.1-2.3 of MBW by next week*
- ***Please develop 1 question from this reading and prepare to discuss next Wednesday (Monday is a holiday).***
- First HW assigned Monday Sept 11
- Web page up by this Wednesday
- I will 'assign' reading of a paper each week, each student will have to present a summary of a research paper twice during the semester – I will ask for volunteers (!) – this is graded as homework.
- Student contributions should summarize the methods and results from the journal/review article and explain the importance of the work and its relevance to broader research on galaxies. The presentations should be pedagogical — focus on explaining rather than summarizing

Exams+ Other Info- Academic calendar

http://www.provost.umd.edu/calendar/15.cfm

- One mid-term, likely Oct 11
- Final exam
- **Project/term paper due *next to last week* of semester (Dec 4)**
- 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
- See http://www.registrar.umd.edu/deadlines.html for deadlines
- Thanksgiving November 23-26 (Thursday-Sunday)
  - Religious Holidays
    - Rosh Hashanah 9/20-22 (since it starts at sun down no impact on class)
    - Yom Kippur 9/30- no impact

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 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
- **None of this should be necessary in a graduate school class**

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
- 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

- I will focus on 'recent' research – to the detriment of 'classical' galaxy material (mostly dynamics of the Milkyway)
- **The goal is that, if you wish, you can understand the recent research literature and start research projects of interest.**

Where is the Material

- We will cover sections of MBW chapters- this text has 3 sections (see page 1), we will only cover PARTS of the third section: Physical processes. *We will not cover cosmology or initial conditions*.
  - 1-2 Introduction and Observational facts
  - 8 Formation and Evolution of Gaseous Halos (only a small part)
  - 9 Star Formation in Galaxies
  - 10 Stellar Populations and Chemical Evolution
  - 11 Disk Galaxies
  - 13 Elliptical Galaxies
  - 14 Active Galaxies
  - 15 Statistical Properties of the Galaxy Population

This is an enormous amount of material and the depth of coverage will vary a lot.

We will not cover the material in the same order as the chapters in MBW (e.g. we will discuss Stellar Populations before Star Formation)

A Warning

- To quote from MBW
- "As in many other branches of applied physics, the phenomena to be studied are diverse and interact in many different ways. Furthermore, the physical processes involved in galaxy formation cover some 23 orders of magnitude in physical size, from the scale of the Universe itself down to the scale of individual stars, and about four orders of magnitude in time scales, from the age of the Universe to that of the lifetime of individual, massive stars.

Put together, it makes the formation and evolution of galaxies a subject of great complexity. From an empirical point of view, the study of galaxy formation and evolution is very different from most other areas of experimental physics. "

Tentative Lecture Order

Lecture #	TOPIC	Text Chapter
Lec 1	INTRODUCTION	MBW Ch 1-2
Lec 2	Continuation of introduction	MBW Ch 1-2
Lec 3	Basic Galaxy Properties	MBW Ch 1-2
Lec 4,5	Relevant Properties of stars	MBW Ch 9,10
Lecs 6,7,8	Properties of Gas and Dust	MBW Ch 10.3
Lecture 9, 10	Milky Way	Not in MBW Ch 2 in S+G and B&M
Lecture 11	Galactic Rotation	MBW Ch 11
Lecture 12-15	Dynamics I---III	MBW Ch 11, B&MChap 3 of S&G
Lectures 16,17	Local group	Ch 4 of S&G
Lecture 18	Chemical Evolution	Ch 11.8 of MBW
Lecture 19	Star Formation	Ch 9.5 of MBW
Lecture 20---22	Spiral Galaxies	Ch 11 of MBW
Lecture 23---25	Elliptical galaxies	Ch 13 of MBW
Lecture 26---28	AGN I---III	Ch 14 of MBW
Lec 29	Summary	
Lec 30	Question	

Some 'Recent' Reviews: There is a longer list on the web page

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

Theoretical Challenges in Galaxy Formation
Thorsten Naab and Jeremiah P. Ostriker ARA&A Vol. 55, 2017, pp. 59–109

Physical Models of Galaxy Formation in a Cosmological Framework Rachel S. Somerville and Romeel Davé ARA&A Vol. 53, 2015, pp. 51–113

Physical Parameters Along the Hubble Sequence: M Roberts and M. Haynes
ARA&A Vol. 32 (1994): 115-15

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

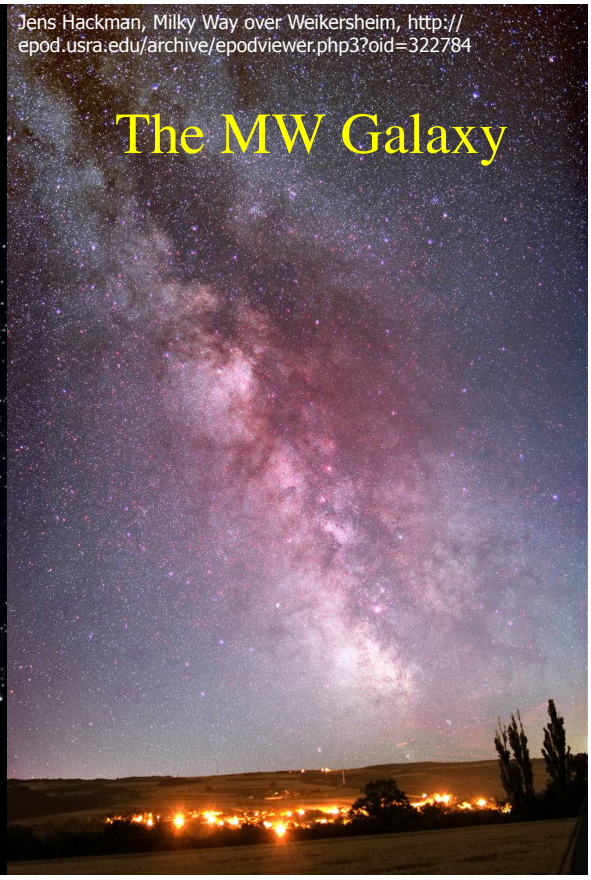
Galaxy Formation: Where Do We Stand? Christopher J. Conselice arXiv:1212.5641

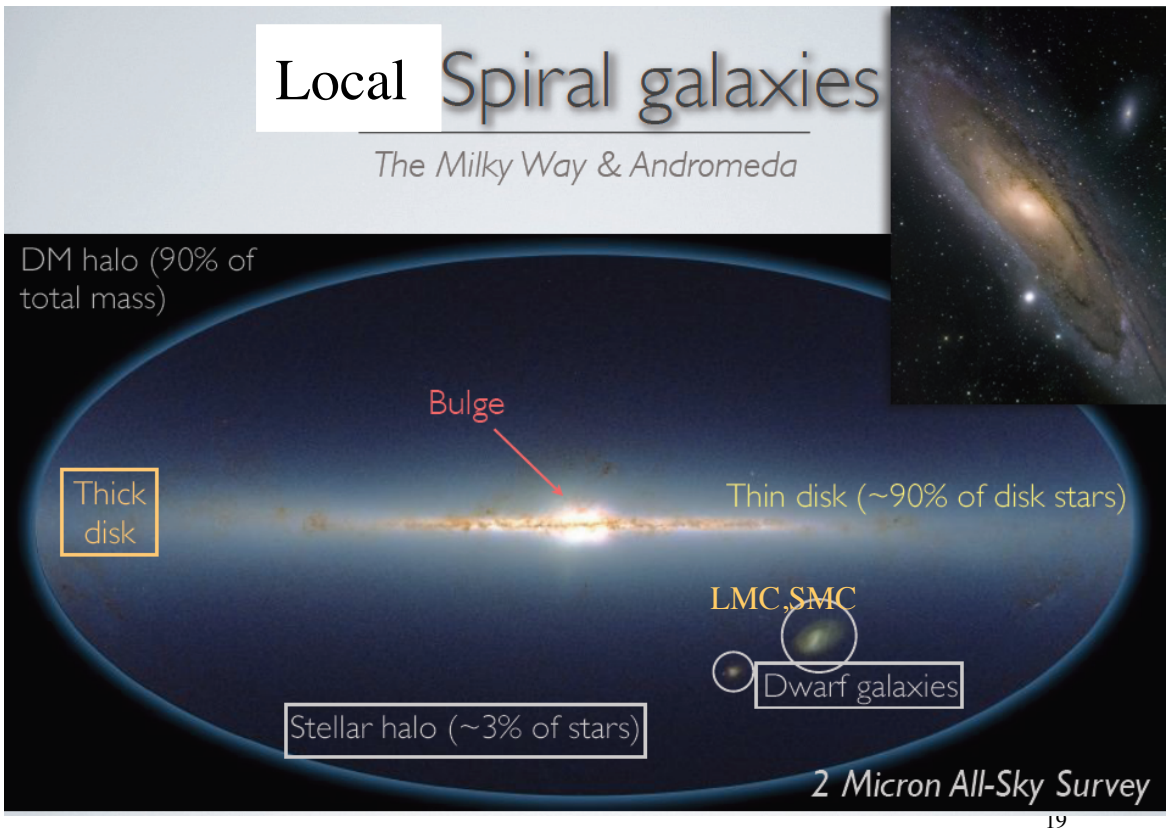
Modeling the Panchromatic Spectral Energy Distributions of Galaxies
Charlie Conroy ARA&A 2013. 51:393–455

The Galaxy in Context: Structural, Kinematic, and Integrated Properties Joss Bland-Hawthorn and Ortwin Gerhard Vol. 54, 2016, pp. 529–596

While I do not expect you to read ALL the reviews in DETAIL, they are good refreshers for the material I will present and are a good introduction to the scientific literature-

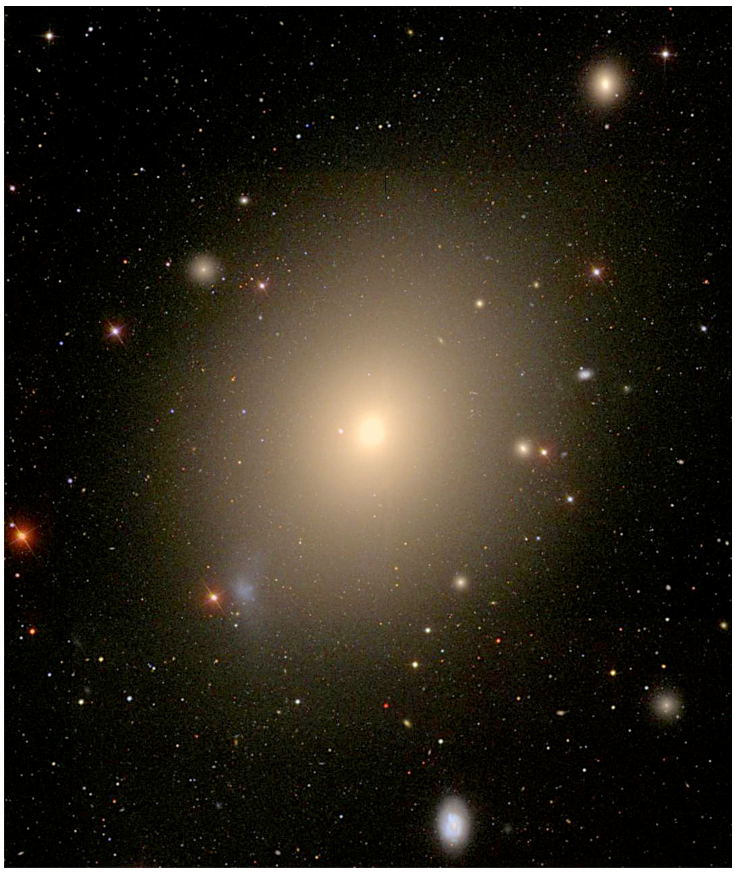
Something you all will need to learn to read and understand... no time like the present.



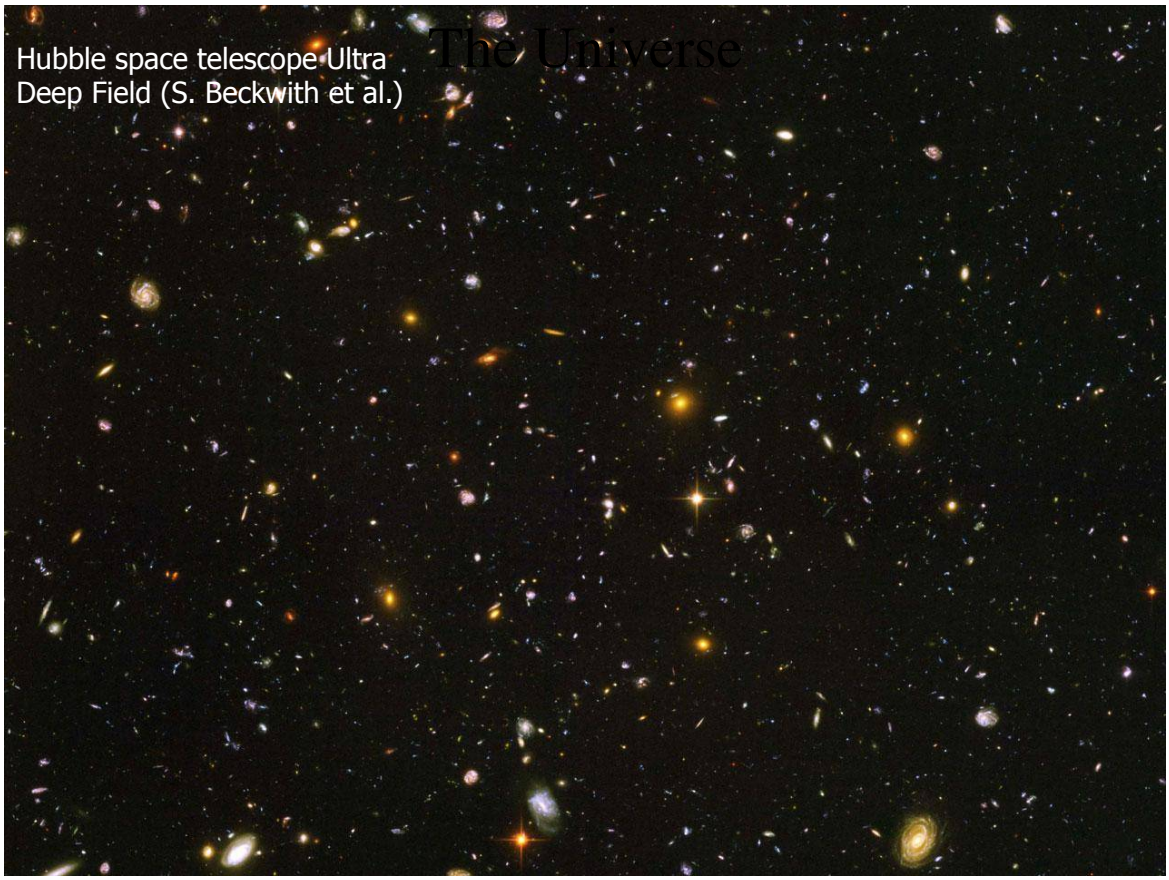

Local Spiral galaxies
The Milky Way & Andromeda
DM halo (90% of total mass)
Bulge
Thick disk
Thin disk (~90% of disk stars)
LMC, SMC
Dwarf galaxies
Stellar halo (~3% of stars)
2 Micron All-Sky Survey


Large Magellanic Cloud- an "Irregular" dwarf galaxy
KIKO FAIRBAIRN • Luziânia, GO, Brasil, 08/2015

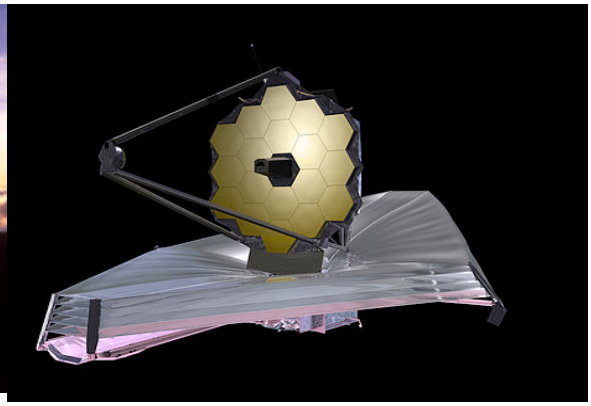
NGC 4472 in the Virgo Cluster
D~16Mpc
A 'giant' elliptical galaxy



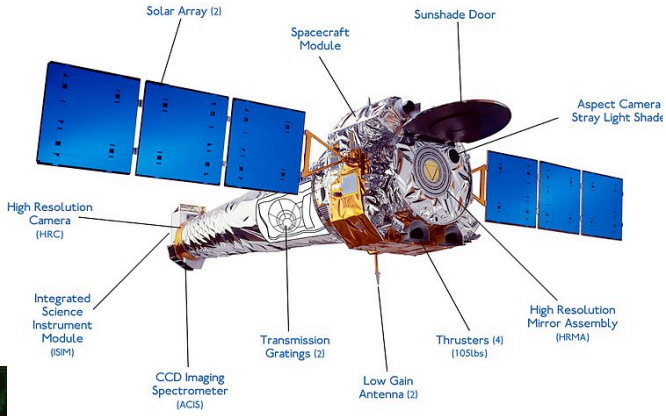
Sloan Digital Sky Survey

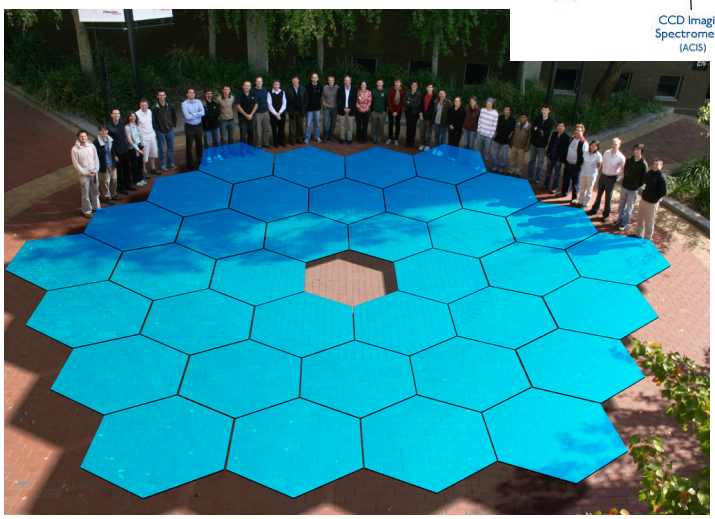


The Universe



SOME OF THE TOOLS OF THE TRADE





The BIG Picture

- Essentially, all research on galaxies aims at answering how galaxies form and evolve (MBW 1.4.5)
- 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 (MBW 1.2.3), but are biased tracers of the underlying matter distribution (MBW sec 1.4.4): 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: (ellipticals tend to be more massive, spirals intermediate, irregulars low mass)

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

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 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

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 of dark matter and its distribution

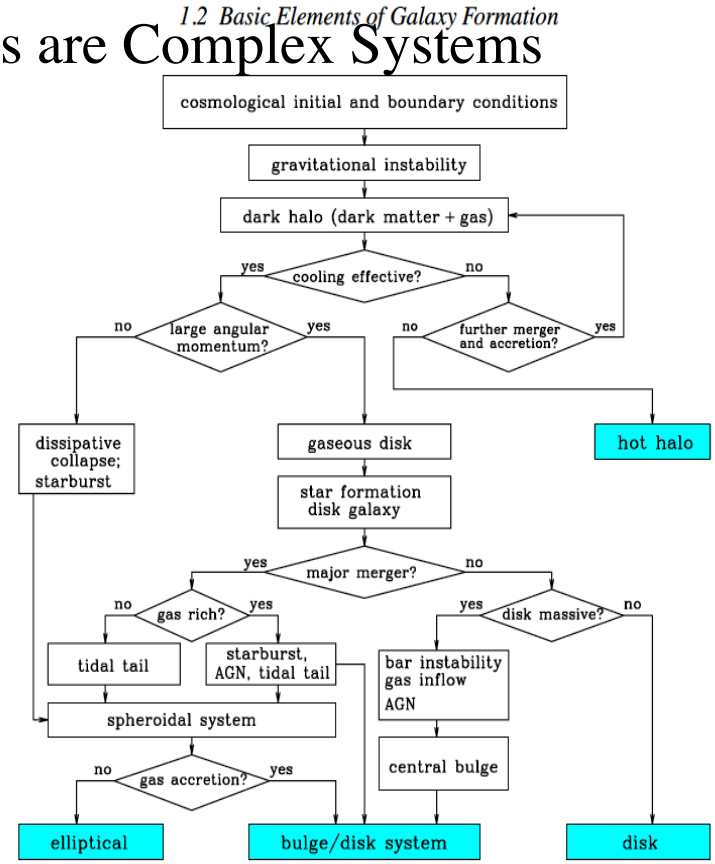
What is galaxy research about?

- 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!

The Evolution of Galaxy Structure Over Cosmic Time
Christopher J. Conselice
ARA&A. 52 (2014): 291-337 –
read sec 1 of this paper (4 pages)

Galaxies are Complex Systems

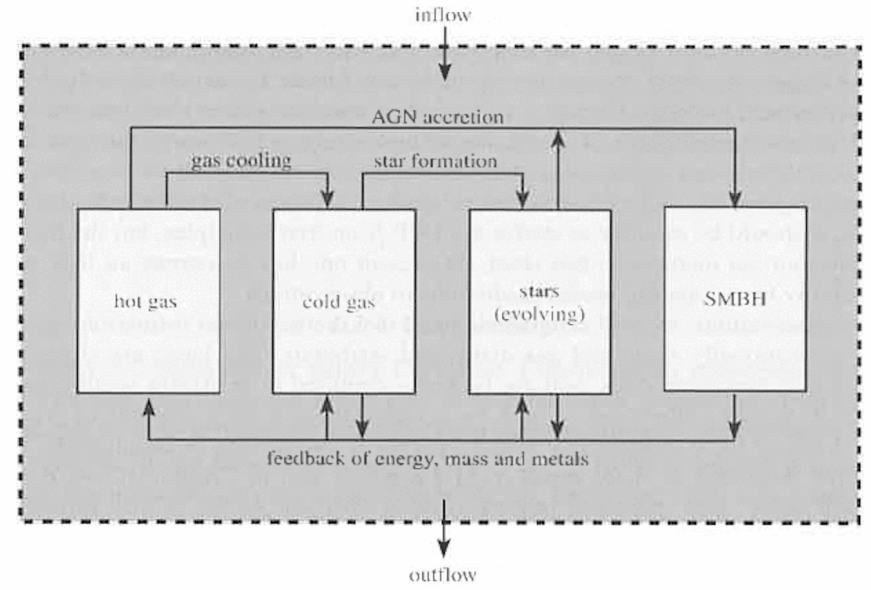
MBW fig 1.1
Notice the vast range of physical mechanisms and interconnectivity
Example- flow chart for galaxy formation (Mo et al)
Notice the large number of physical processes!



A lot of the Processes Are NOT separable

Is there observational evidence for the processes in this graph? What is it?

when do each of these steps happen and what are their relative importance



- Each process has characteristic scales, and the relation between these scales influence how galaxies form, evolve, and appear (MBW fig 1.2)

Mergers

- The present conventional wisdom is that the universe is dominated by "cold dark matter" (CDM)
- In such a universe dark matter halos grow via hierarchical mergering (small things form first and then merge into bigger things)

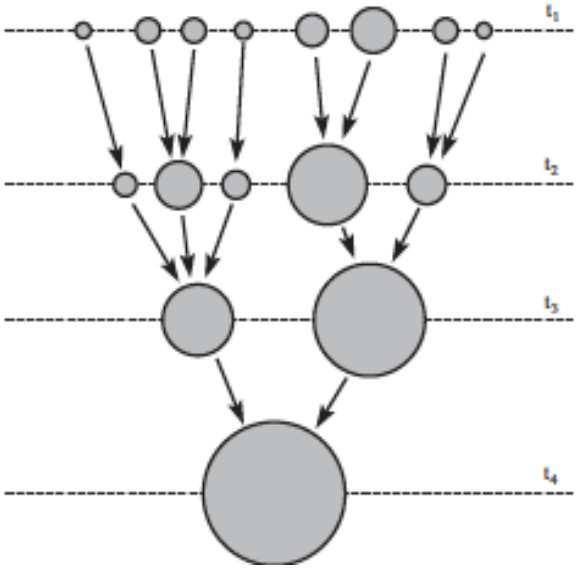


Fig 1.3 MBW

Detailed Questions- taken from Holz

- what sets the masses of galaxies? sizes? luminosities?
- what sets the distributions of number of galaxies as a function of mass/luminosity?
- is the ratio of baryonic mass/total mass different for different galaxies?
  - is the ratio of different baryonic components (e.g stellar mass, gas mass) mass different for different galaxies?
- what triggers star formation in galaxies? how can we parameterize star formation?
  - (how do we measure star formation?)
- what is responsible for the range of galaxy morphology?
- how much of present structure is determined by initial conditions, e.g. initial overdensity, angular momentum and what are initial conditions?
- how much does present appearance depend on basic physics within galaxies, e.g. dynamics and chemical evolution?
- how much depends on environment, e.g. mergers and interactions, local density?
- Does the relative importance of these effects (initial conditions, internal evolution, environment) vary for different galaxies?
- Can we identify the impact of different processes through observations?

Goal #1 of Class

- Know what the main components of galaxies are and how they are related
- Understand the different process involved in galaxy formation
- Understand and describe the characteristic timescales of the processes and where and why they are important

Some Relevant Timescales

- Lifetime of universe; e.g Hubble time $t \sim H_0^{-1}$
- orbital/free-fall times $t_{orb}=(3\pi/G\rho)^{1/2}$; G is gravitational constant, ρ is density in gm/cm^3
  - 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 $t_{cool}=[(3/2nkT)/n^2\Lambda(T)]$; 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) $T_{vir} \sim (mv^2/3) \sim 3.6 \times 10^5 (v_C/100\text{km/sec})^2$
  - where v_c=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= 3×10^6k (BOE calculation)

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

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