Galaxies: Structure, formation and evolution

Lecture 1

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Jan-Feb 2024

Galaxies are a very active field of research today!

Just over 32% of the refereed papers published in 2023 had the word *galaxies* in keyword/abstract, 9287 refereed papers in 2023 alone.
Most things covered in this course were discovered in the last 25 years.

Course Website

http://www.ncra.tifr.res.in/∼yogesh/galaxies_2024/

Best way to reach me is by email at *yogesh@ncra.tifr.res.in*
The PDF file for each lecture will be put on the website immediately after it is given. So, don't bother copying stuff that is already on the slide.

Course will be in classroom mode

Lectures will be live in the NCRA Lecture Hall. There will be a total of 14 lectures over 7 weeks, each of 1.5 hours duration.

Introductions

Assessment

- 25% weightage for a mid-term exam (open notes) to be given at the end of the fourth week and end-term exam (again open notes) with 35% weightage at the end of the course.
- 25% weightage for paper presentation at the end of the course
- 15% for class participation. Asking and answering questions in class

Exams

Mid-term exam will be based on material covered in the first 3 weeks and the end-term exam will be based on material covered in the following 4 weeks.

Paper review

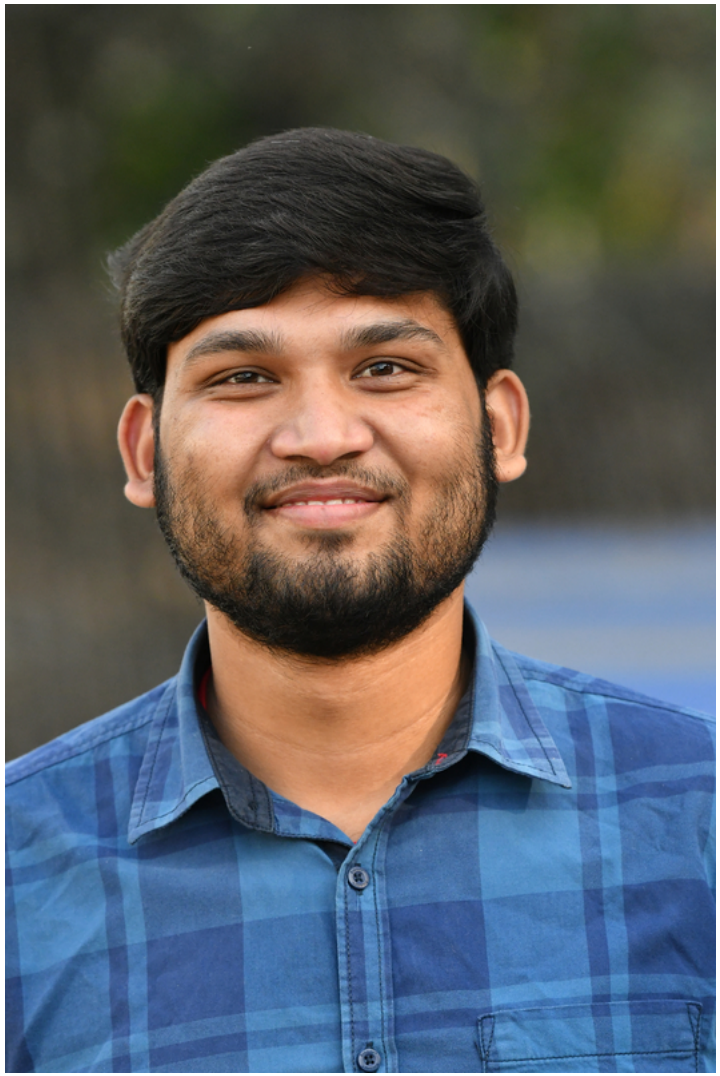
Each one of you chooses a paper to study thoroughly and then gives a presentation on it at the end of the course.
Do discuss amongst yourselves, choose a paper no one else has chosen and let me know via email. If multiple people want to cover the same paper, we will need to resolve this amicably; get in touch with me.
You should present the paper as if you wrote it yourself!

Seminar papers to be selected from a long list

http://www.gama-survey.org/pubs/

Discuss amongst yourselves, choose a paper and let me know by 23 Jan 2024.
Choose a **refereed paper** from the list. You should make sure you choose a paper that is not too long or complicated to explain in the time available to you.

Course tutor - Pralay Biswas of NCRA



He will evaluate the exam papers and also help me evaluate the paper review seminars.

The official syllabus and why I don't like it!

Galaxies : Structure, Dynamics and Evolution
Galaxies as self gravitating objects, virial equilibrium - Estimates of collision times - Collisionless Boltzmann equation and some steady state solutions - Globular clusters - stability - Spiral structure, bars and disc dynamics - Ellipticals - Galaxy morphology - Chemical evolution - Galaxy formation and evolution.
Many active research topics not covered in any other course are missing - e.g. star formation, stellar population synthesis, high redshift (emission/absorption line) galaxies, particularly the new populations discovered by JWST.

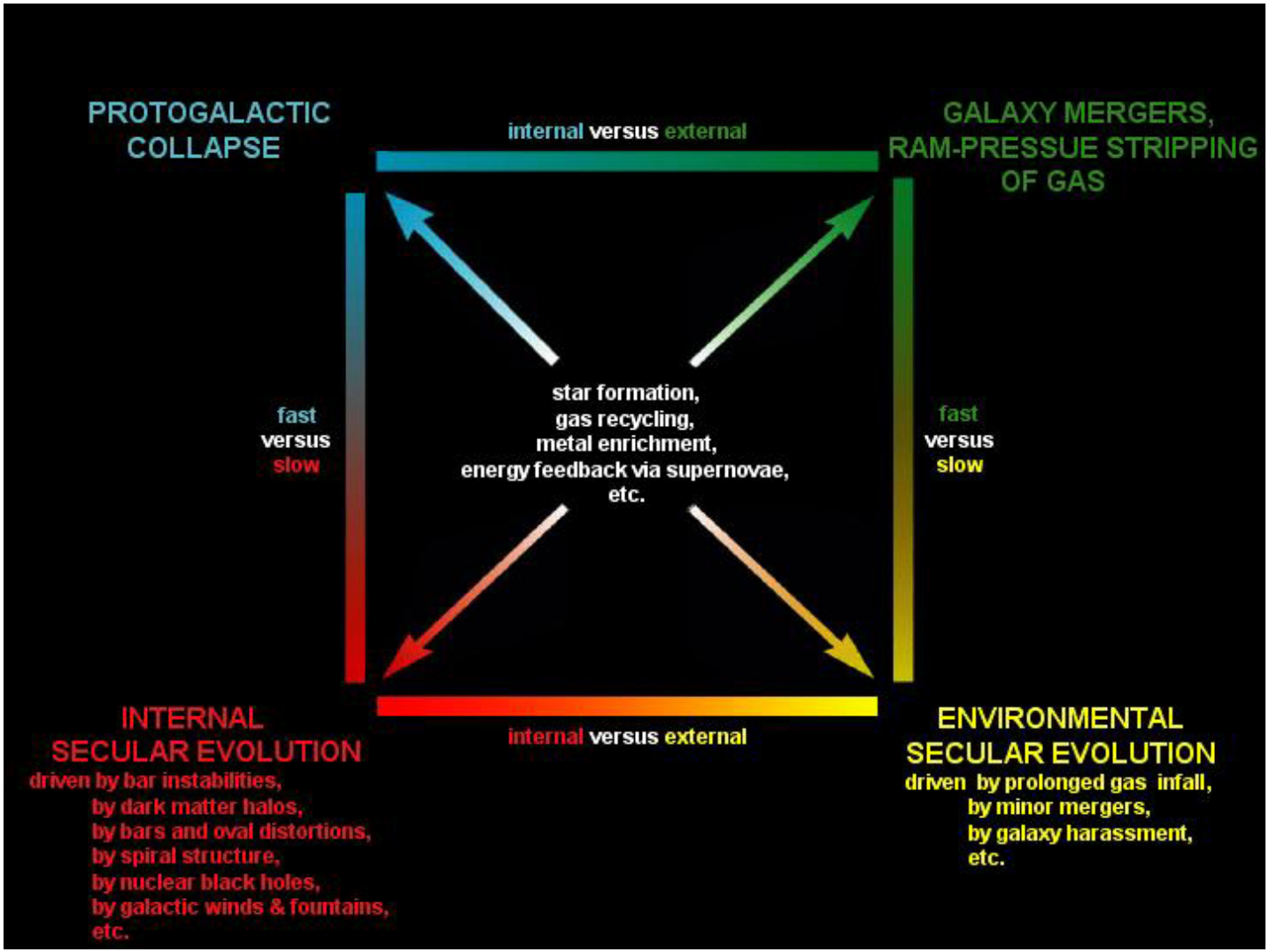
This course has linkages to many other courses

- Extragalactic Astronomy I (Cosmology): quasar absorption systems - high redshift galaxies in absorption
- Interstellar Medium: Extinction and reddening of star light, dust - Ionised gas - HII regions - Molecular clouds and star formation.
- Extragalactic Astronomy II (Radio Galaxies and Quasars): Phenomenology of AGNs

My course on galaxies will cover

- Background material and Overview
  1 A brief History of extragalactic research 2 **Morphological Classification** 3 **Surveys & Quantitative morphology** 4 Galaxy Luminosity Functions
- Normal galaxies
  5 Spiral and Irregular Galaxies 6 Stellar Kinematics I : Disks 7 Elliptical and Lenticular Galaxies 8 **Stellar Kinematics II : 3-D Systems** 9 Gas & Dust in Galaxies 10 **Stellar Population Synthesis**
- Interactions & activity
  11 **Star Formation & Starburst Galaxies** 12 Galaxy Interactions & Mergers 13 Galaxy Groups & Clusters 14 Galaxy Nuclei & Nuclear Black Holes 15 Active Galaxies & Quasars
- Formation and evolution 16 The Cosmological Framework 17 Growth of Large Scale Structure 18 Galaxy Formation, **high** z **galaxies& Evolution in JWST Era** 19 Reionization & the IGM 20 Dark Matter & Gravitational Lenses

The big picture



Textbooks and reference material

Unfortunately, I cannot find one textbook that is both comprehensive and current for our purposes. We will use material from different textbooks for different topics. I have put up a list of books that I am refering to that you may also find useful, on the website.
I have put in a lot of effort to make good slides for my talks. Use these as your primary reference material and remember to stop me and ask questions if you don't understand something. Some of the slides will cite papers which you are encouraged to read to know more.

Questions about the course content and organisation?

Three ubiqitous structures in the Universe

- Atoms
- Stars
- Galaxies

Kant's "Island Universes"

In 1755 he wrote a book called *General Natural History & Theory of the Heavens* in which he said:

1. MW like huge solar system, rotating; origin from rotating cloud.
2. stars far from disk plane on different orbits
3. disks (like MW) project to ellipses
4. oval nebulae (seen by de Maupertius) = "Island Universe"

Major milestones since Kant

- 1755: Kant's Island Universes
- 1912: Slipher discovered that nebulae are rotating
- 1920: Shapley-Curtis debate "Are Spiral Nebulae Island Universes" - 30 minute presentations by each - Shapley "won" the debate, although Curtis was right.
- 1925: Hubble discovered Cepheids in the Andromeda galaxy

Extragalactic astrophysics $<$ 100 years old

What are galaxies?

- agglomerations of stars, dust, gas, dark matter.
- Average Mass ratio Gas:Stars:Dark Matter - 1:10:100
- they are the basic building blocks of the Universe on large scales
- they show a **broad range in their physical properties**
- Understanding of galaxy formation and evolution is one of the main outstanding problems in modern cosmology
- there are $> 10^{11}$ galaxies in the observable universe
- stellar mass of $10^7 - 10^{12}\ M_\odot$

Counting and cataloging galaxies

- In late 1700s,Messier made a catalog of 109 nebulae so that comet hunters wouldn't mistake them for comets! About 40 of these were galaxies.
- NGC New General Catalogue (Dreyer 1888) had 7840 objects, of which about 50% were galaxies. e.g. NGC 4993, 40 Mpc away where the first GW neutron star– neutron star merger was detected in 2017.
- In the 20th century, many catalogs were produced UGC, RC3 etc.
- Nowadays we have automated digital surveys, e.g., DPOSS, SDSS, with tens to hundreds of millions of galaxies. How should we label them?
- Coming very soon are large surveys like Rubin/LSST which will provide 6-band photometry and shape measurements for 1.9×10^{10} galaxies, from the local group to redshifts $z > 6$

First step census, second step classification

third step understanding are common steps in any empirical science.
Hubble proposed a scheme for classifying galaxies (the ”tuning fork” diagram) in his 1936 book, *The Realm of the Nebulae*. This scheme survives in its essence to the present day.
ellipticals, lenticulars, spirals and irregulars (very diverse!) are the main types.
A better approach may be to look at the properties of kinematic subsystems within galaxies (e.g., disks, spheroids, halos, etc.), and deduce their origins and evolution.

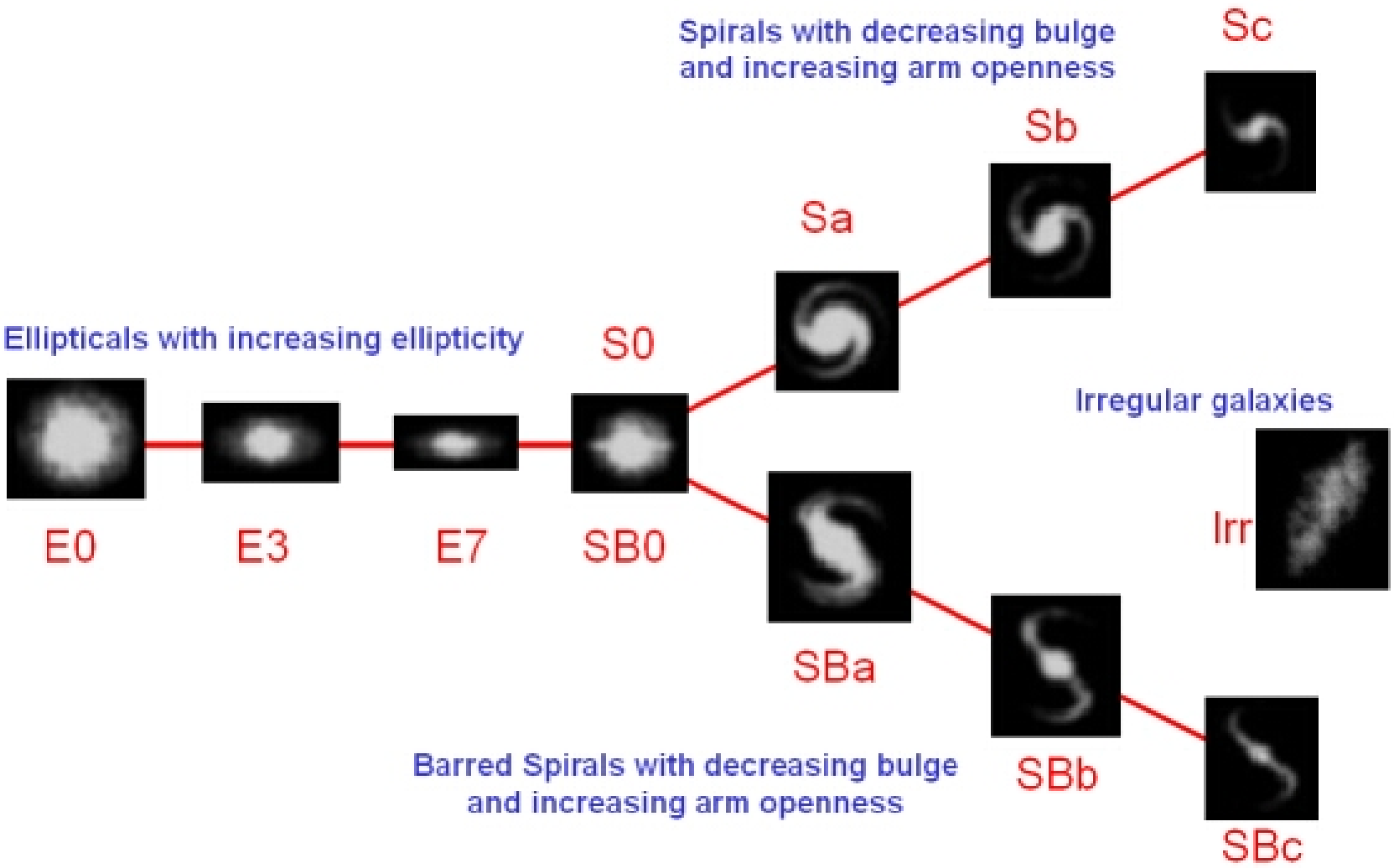
Why is galaxy classification useful?

- Classes bring order to diversity of galaxy forms
- Span/include majority of galaxies
- Unambiguous & easily identified criteria
- Relate to important physical properties $\rightarrow$ provide insight into internal processes, formation, & evolution

Why classify galaxies in the optical band?

Historically, optical imaging was the method used to observe galaxies. Hence Hubble's classification is most widely used. Also, optical light is the best way to trace stars and dust (in absorption).
Today, many other criteria such as color indices, spectroscopic parameters (based on emission or absorption lines), the broad-band spectral energy distribution (galaxies with/without radio- and/or X-ray emission) are also used to group galaxies together.

Hubble tuning fork diagram



Elliptical

Elliptical Galaxies

- About 20% of field galaxies are Ellipticals, but most E's are in clusters
- There are a number of different subtypes:E's (normal ellipticals), cD's (massive bright ellipticals at the centers of galaxy clusters), dE's (dwarf ellipticals) dSph's (dwarf spheroidals - like extremely faint dEs, small size, spherical)
- Smooth and almost featureless. no disc, no spiral arms nor dust lanes. Generally lacking in cool gas, and hence few young blue stars
- Elliptical galaxies are denoted En where:$b/a = 1 - n/10$ i.e. an E4 galaxy has an axis ratio of $b/a = 0.6$, and E0's have circular isophotes.

Lenticular

Lenticular

- are characterised by the presence of a central bulge and disk and the absence of spiral arms i.e. little or no ongoing star formation
- intermediate in many of their properties between ellipticals and spirals.

Grand Design Spiral

What is the diameter of the Milky Way Galaxy?

Flocculent Spirals - NGC 2775

Spiral

Named for their bright spiral arms, which are prominent due to emission from bright O and B stars (evidence for recent star formation) and due to absorption from dust lanes.

Which are more massive, O or B type stars?

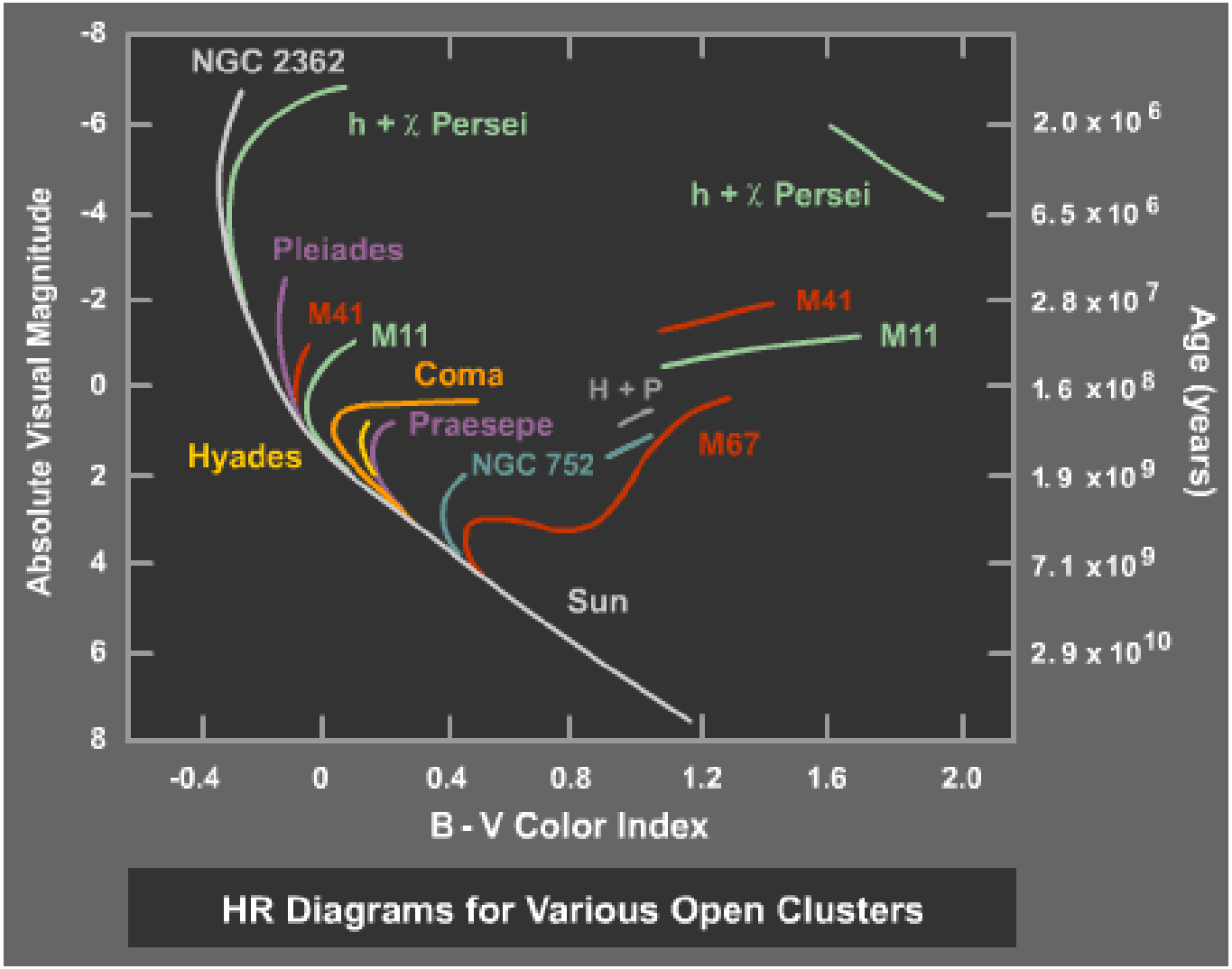
Distance to Andromeda galaxy

If the Andromeda galaxy subtends an angle of 4.96 degrees on the sky and is 67 kpc in diameter what is its distance?

Distance to Andromeda galaxy

If the Andromeda galaxy subtends an angle of 4.96 degrees on the sky and is 67 kpc in diameter what is its distance? Ans: 780 kpc

Age of open clusters via main sequence turnoff



How to use the HR diagram to find age of open cluster?

M/L ratio for stars

For main sequence stars, we have $L \propto M^{3.5}$, giving : $(M/L) \propto M^{-2.5} \propto L^{-0.71}$ showing, as one expects, later spectral types have higher M/L. eg K stars : $M \sim 0.4 M_{\odot} \rightarrow M/L \sim 10$; A stars : $M \sim 2.5 M_{\odot} \rightarrow M/L \sim 0.1$

Mass to light ratio M/L of a galaxy

M/L defined in units of $M_\odot/L_\odot$
For galaxies, M/L reflects the average M/L over the population
Pop I (young) : massive stars dominate light; low mass stars dominate mass Pop II (old) : giants dominate light; M.S. stars dominate mass
Typical spiral galaxy (& solar neighborhood) has $M/L_V \sim 6$, $M/L_B \sim 10$ In general : M/L increases with age and metallicity
Maximum range : $2 < M/L_B < 20$.
What are Pop III stars?

Initial Mass Function IMF

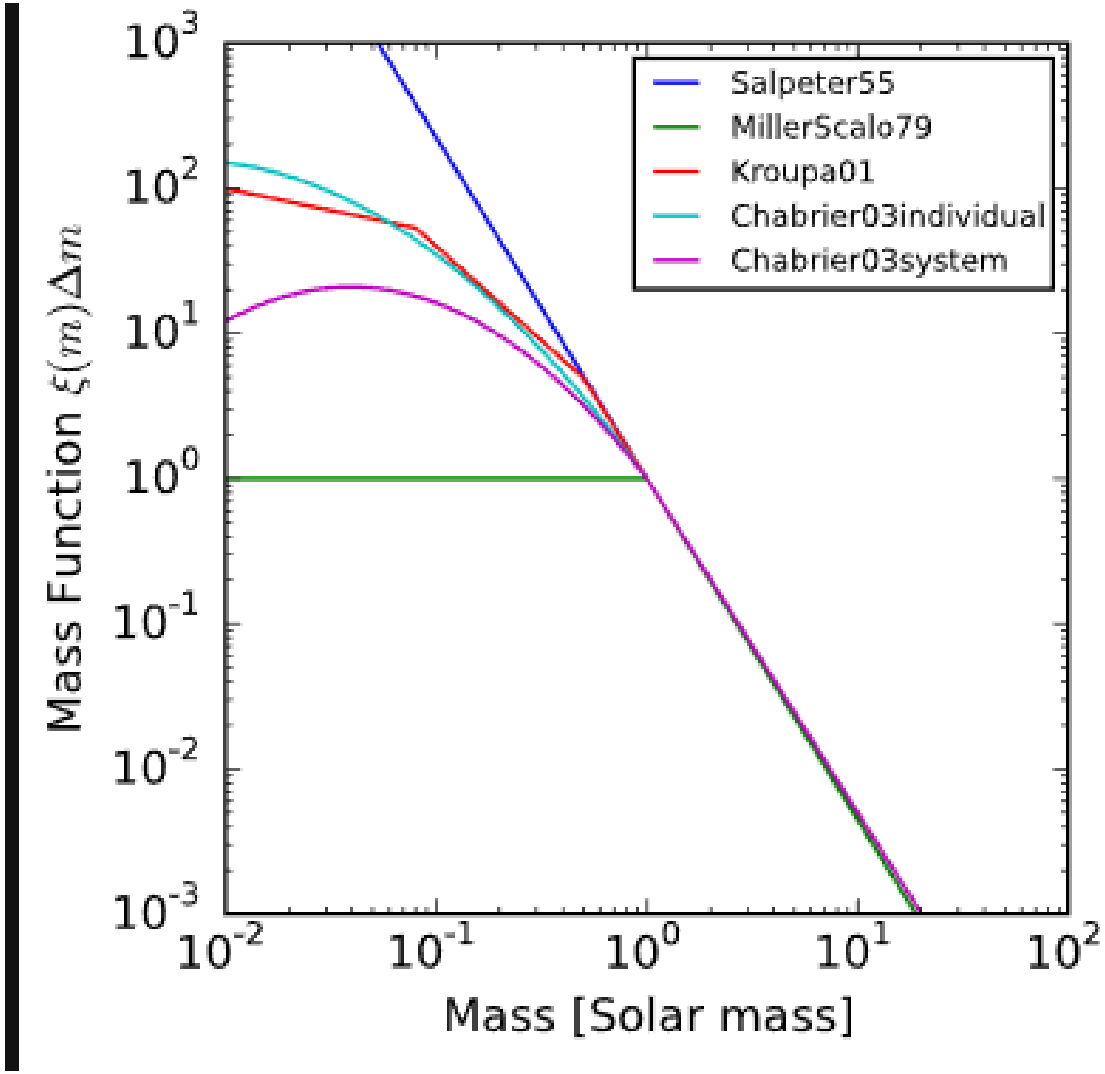
The IMF $\xi(M)$ specifies the distribution in mass of a newly formed stellar population and it is frequently assumed to be a simple power law: $\xi(M) = c\,M^{-(1+x)}$. In general, $\xi(M)$ is assumed to extend from a lower (M_1) to an upper cutoff (M_2).

Initial Mass Function

IMF	M_1	M_2	x
Salpeter	0.10	125.	1.35
Scalo	0.10	0.18	-2.60
	0.18	0.42	0.01
	0.42	0.62	1.75
	0.62	1.18	1.08
	1.18	3.50	2.50
	3.50	125.	1.63
Miller & Scalo	0.10	1.00	0.25
	1.00	2.00	1.00
	2.00	10.0	1.30
	10.0	125.	2.30

Other IMFs in use include Chabrier (2003) and Kroupa (2001). See review by: Bastian et al. (2010).

The various IMFs in common use

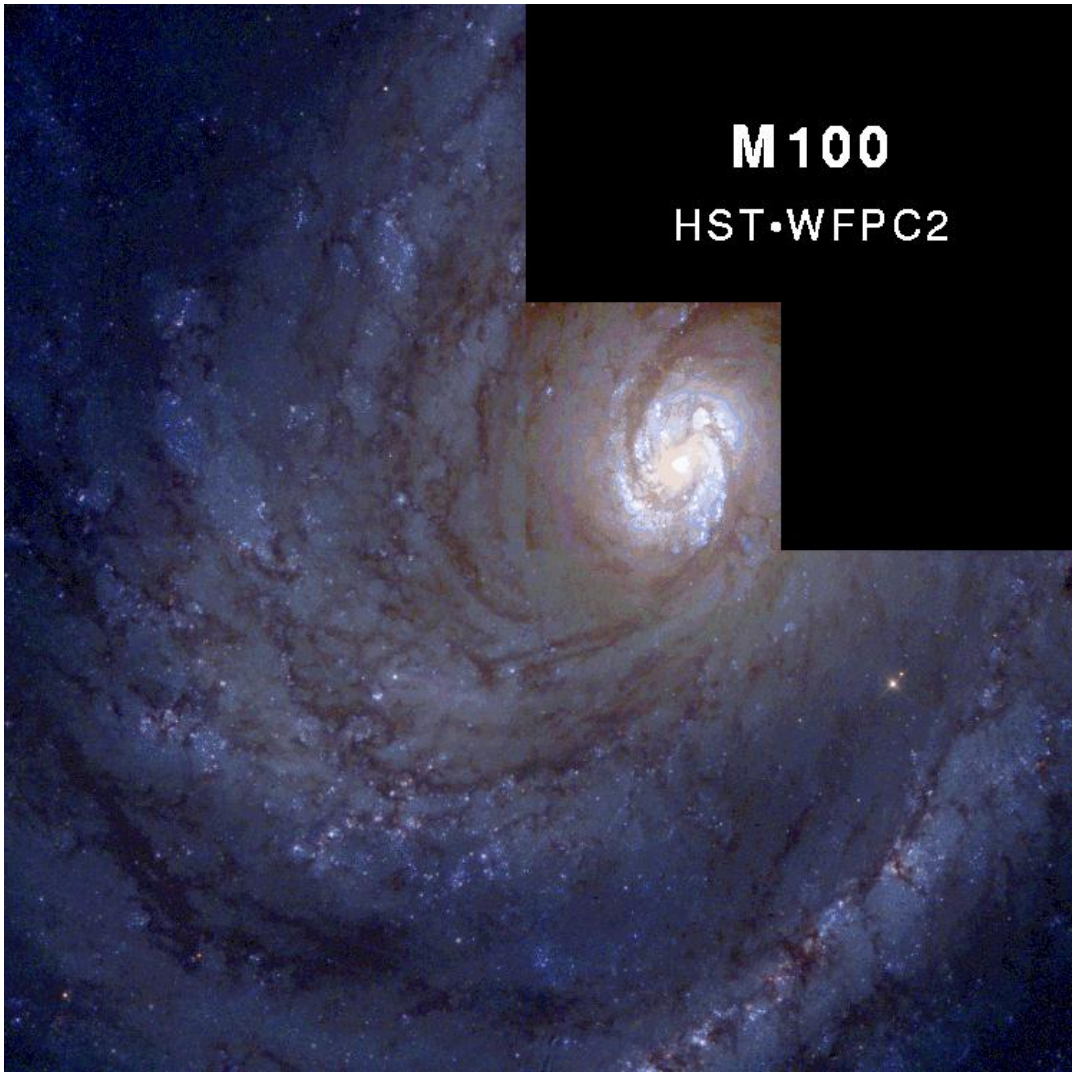


The Chabrier IMF is most commonly used nowadays.

Problem

For a Salpeter IMF, what is the relative number of K and A stars in a cluster *that has just formed?*

M100 nucleus



Barred galaxies

- Roughly half of all disk galaxies - Milky Way included - show a central bar which contains up to 1/3 of the total light Bars are a form of dynamical instability in differentially rotating stellar disks
- S0 galaxies also have bars – a bar can persist in the absence of gas
- Bar patterns are not static, they rotate with a pattern speed, but unlike spiral arms they are not density waves. Stars in the bar stay in the bar
- The asymmetric gravitational forces of a disk allow gas to lose angular momentum (via shocks) compressing the gas along the edge of the bar. The gas loses energy (dissipation) and moves closer to the center of the galaxy.

Barred Spiral NGC 1300