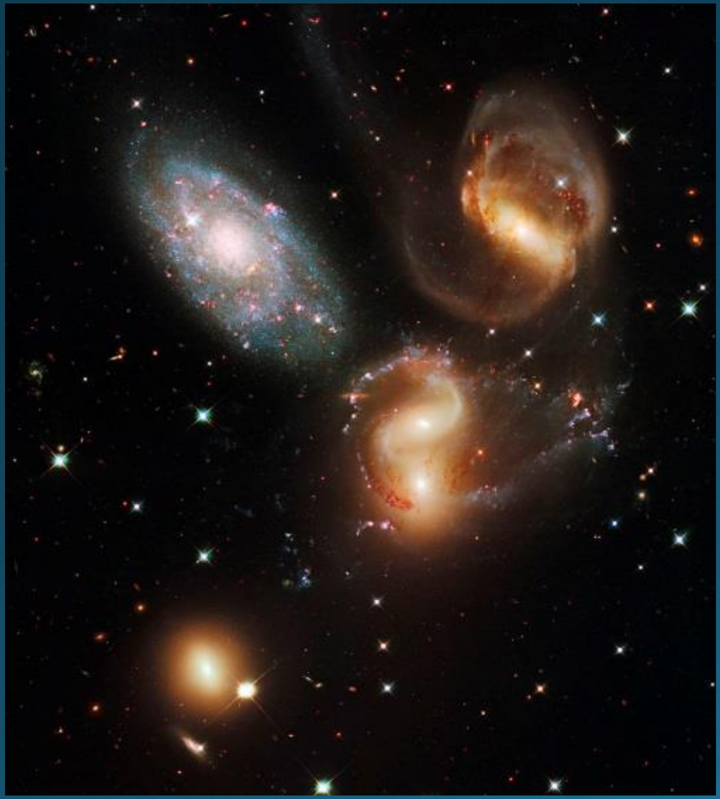
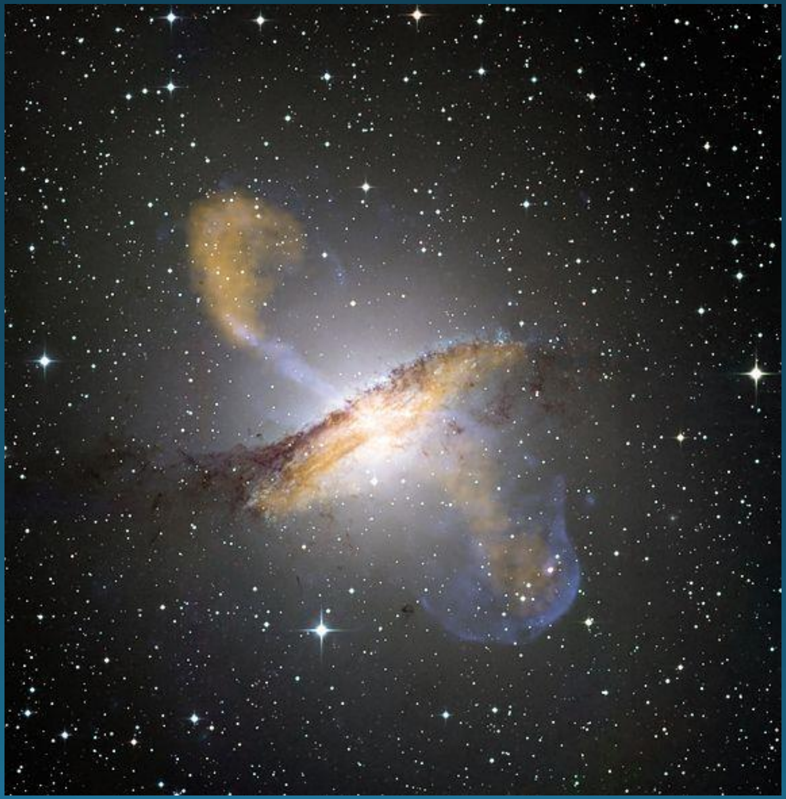
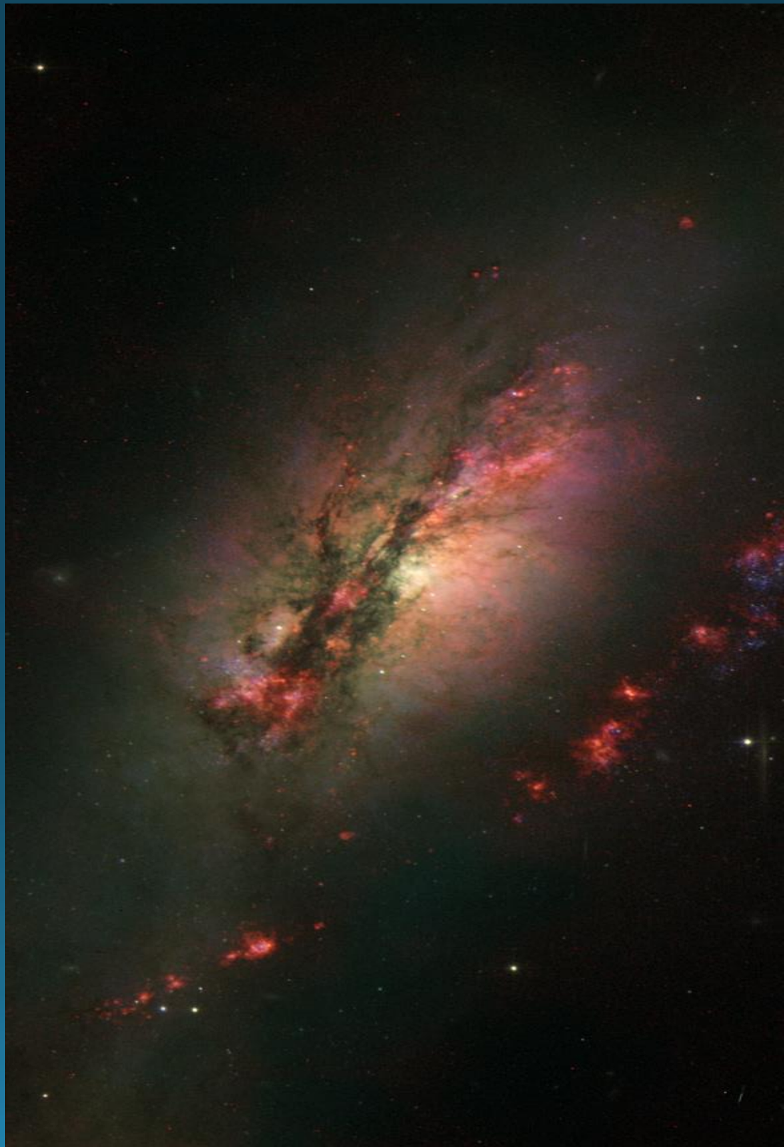
Physics of Galaxies 2019
Lecture 1: Introduction

Outline for today I

- Formal Stuff:
  - Course literature
  - Examination
  - Schedule
- Course outline



Outline for today II

- What is a Galaxy?
- Historical Background
- Galaxy Classification
- The Cosmological Framework

Teacher

- Erik Zackrisson
  - Email: erik.zackrisson@physics.uu.se
  - Room 63103
    In astronomy corridor on floor 3 in house 6 – just ring the bell to get in!

Course homepage

- Link: www.astro.uu.se/~ez/kurs/Galaxies19.html

UPPSALA UNIVERSITET

The Physics of Galaxies, 10 ECTS (hp), Spring 2019

Literature:	Peter Schneider, 2015, "Extragalactic Astronomy and Cosmology", Springer, ISBN 978-3-642-54082-0 (hardback) or 978-3-642-54083-7 (eBook) Please note that students of Uppsala University have free access to the eBook version of this title through the Uppsala University Library
Contents:	Extragalactic astronomy, with emphasis on the properties, evolution and origin of galaxies
Prerequisites:	Knowledge corresponding to a Bachelor's degree in physics, or similar. In addition, basic knowledge about spectra, stellar physics, galaxies and cosmology corresponding to the course Astrophysics I is required.
Examination:	Seminars, literature report, hand-in exercises, laboratory exercise
Teacher:	Erik Zackrisson, erik.zackrisson(at)physics.uu.se
Time:	March-June 2019

If you are interested in participating, please notify Erik Zackrisson as soon as possible!

Schedule

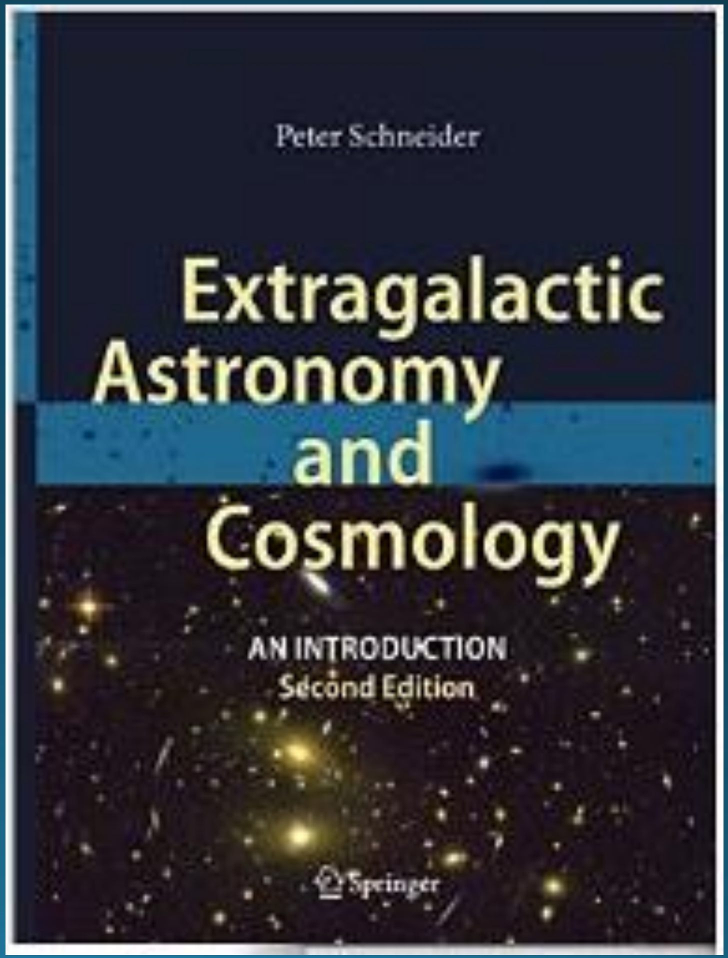
Recent changes are marked in red
Sessions for which attendance is mandatory are marked in blue

Course literature

Extragalactic Astronomy and Cosmology
Peter Schneider
2014/2015, Springer
Hardback:
ISBN 978-3-642-54082-0
eBook:
ISBN 978-3-642-54083-7

Around 700-800 SEK

Note: E-version available from UU library (for free)



Intermission: What is this?

Examination

- Three exercise sessions
- Hand-in exercises
- Four seminars
- One database/laboratory exercise
- Written essay (minimum 3 pages) + oral presentation (10 minutes)

But no written test!

Exercise sessions

- **Session 1:** April 24, 15-17
- **Session 2:** May 9, 13-15
- **Session 3:** May 15, 13-15
- **Objective:** Solve problems *together* in class

Exercise sessions

- **Preparation:**
  - Bring pen, paper, calculator/computer, preferably textbook
  - Session I: No preparation required
  - Session II/III: Study exercises and solutions posted on course homepage
- **Grade:** Pass/Fail

No-show or not actively participating → Need to complete more hand-in exercises

Exercise session I: Fermi problems

Objective: Gain skill in making back-of-the-envelope calculations

Examples:

- How much gold is there in the Milky Way?
- How many galaxies are there in the Observable Universe?

Compete in teams - win marvelous prizes!

Exercises and solutions on the course homepage

Make sure you understand the solutions before coming to exercise session II & III!

The problems we solve in class will be similar.

2. *Brightness and colours of unresolved stellar systems.* Two stars in a close binary system have $m_{\mathrm{B}} = 18.2$ and $m_{\mathrm{B}} = 19.6$, respectively. The first star has a colour $B-V = -0.2$ and the second $B-V = 0.5$. If this system is observed in a telescope which cannot resolve the two components, what would the integrated m_{B} and $(B-V)$ of this object be?

Solution: At large distances, it becomes increasingly difficult to study the individual stars of stellar populations. There are basically two reasons for this:

1. The flux sensitivity of your telescope may be insufficient to allow the detection of a single, very distant star, whereas the combined light from large numbers of stars at the same distance may push them above the detection limit
2. Limitations in angular resolution of your telescope may blend the light from nearby stars, thereby making distant stellar populations appear as single objects.

Much of contemporary extragalactic astronomy is therefore devoted to the study of the *integrated* light from large numbers of stars. To illustrate this point, Figure. 1 shows the appearance of stellar populations at increasing distances, when observed with current telescopes.

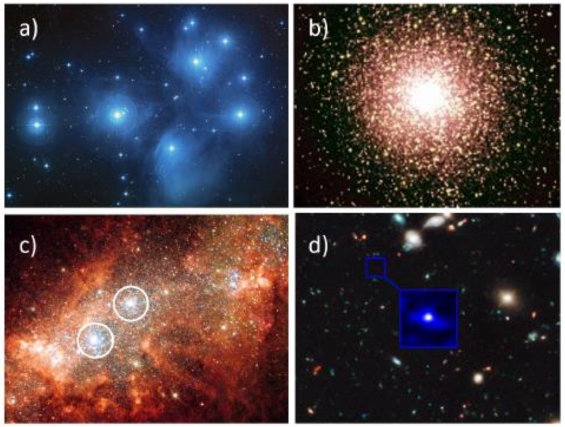


Figure 1: Resolved versus unresolved stellar populations. **a)** A nearby star cluster (the Pleiades, distance 440 ly) in which individual stars can be resolved; **b)** a Milky Way globular cluster (47

Hand-in exercises

- 3 exercises downloadable from the course homepage
- Submit by email
  Deadline: June 7
- **Grade:** Fail, 3, 4, 5
- Collaboration OK, but please don't turn in identical solutions!

Physics of Galaxies

Hand-in exercises 2019

Instructions: These are the three problems you need to solve to pass the course if you have already actively participated in the three exercise sessions. In case you failed to participate in either of these, you should contact the teacher for additional problems to solve in order to pass the course. Hand-written solutions are quite acceptable, but submission via email is highly encouraged (and will allow for a swifter evaluation), so please consider scanning your solutions (or taking photos of them) and submitting them in electronic format. The deadline for handing in solutions to these problems is **June 7, 2019**.

1. *Cosmic star formation.* How many stars are there in the observable Universe? Make an order-of-magnitude estimate of this, quantify the uncertainty and make a top-3 list of the most important shortcomings/simplifications that are likely to affect your estimate (and clearly explain why this is so).

2. *Population synthesis.* Use the table of stellar parameters below to generate a simple population synthesis model. Assume that the stellar population of your model galaxy only consists of three types of stars (O5, A0 and M0), all formed at the same time, and that the relative number of stars of each type is given by the Salpeter IMF.

a) What is the (B-V) colour and M/L_V ratio of this population at an age of 1 Myr?

b) Assuming that the population has aged sufficiently for all the O stars to die (and no longer contribute to the light emitted), what is the (B-V) colour and the M/L_V ratio (where M is defined

Note: If you didn't actively participate in the exercise sessions, you need to hand in additional exercises – please contact me if this situation should arise

Intermission: What is this?

Literature exercise

- Choose subject individually
- Find suitable articles
  - Published papers (ADS abstract service) http://adsabs.harvard.edu/abstract_service.html Preprints: http://www.arxiv.org
- Written report (≥ 3 pages), deadline May 17
  - **Grade:** Fail, 3, 4, 5
- Oral presentation (≈ 10 minutes), May 28
  - **Grade:** Fail, 3, 4, 5


Required format of written report

- Abstract
- Introduction
- Main text (with references)
- Reference list
  - Should be mostly research or review papers
  - Please avoid using the textbook, popular science papers or homepages as references
    Exception: Links to project pages of upcoming telescopes, surveys etc. may be necessary if there is no proper paper out yet

Suggested topics

- The first stars
- 21 cm cosmology
- Origin of supermassive black holes
- Ultrafaint dwarfs
- Extragalactic background radiation
- Galactic archeology
- Conditions for life on galactic scales
- Science cases of future telescopes (pick one!):
    - James Webb Space Telescope
    - The Extremely Large Telescope
    - Square Kilometer Array

But please feel free to suggest other topics!

Seminars

- Small “simulations” of what working as a scientist is really like
- Four seminars:
  - 1. May 13,13-15
  - 2. May 16, 13-16 or May 17, 13-16 (two groups)
  - 3. May 20, 15-17
  - 4. May 22, 15-17

Soft
Soft
Soft
Tough!

Instructions available from course homepage

Seminars

- Purpose:
  - Practice finding and reading relevant research papers
  - Practice critical thinking
  - Practice analyzing astronomical data
  - Practice scientific creativity
  - Practice communication skills
  - Practice working in a team
- What if you cannot attend the seminars?
  - Have to hand in written report instead

  (→ more work!)

Seminar I: An amazing discovery / Crackpot?

- **Grade:** Pass/fail
- Role-playing exercise
- Preparation:
  - Study the two scenarios in the instructions
  - Read the material available in the student portal

Seminar I: An amazing discovery / Crackpot?

General instructions

This document provides instructions for the first of the four seminars forming part of the examination for the course *Physics of Galaxies* in 2019. This is a role-playing exercise that will cast you into situations that scientists (and especially astronomers) frequently encounter, yet in general tend to be rather poorly prepared for.

The point of this exercise is to:

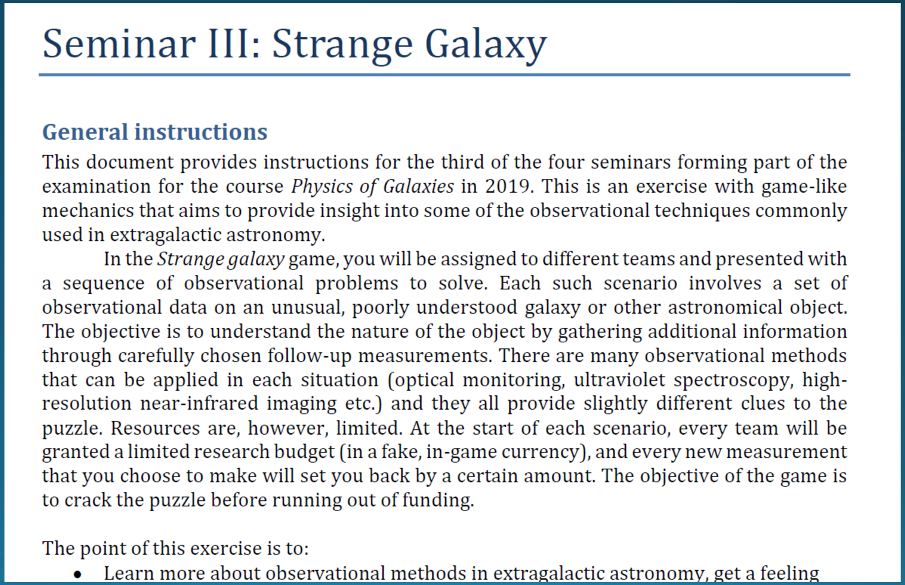
- Practice reading research papers, press releases and other scientific texts in the field of extragalactic astronomy
- Practice critical thinking
- Practice interacting with the public and with journalists in a professional manner, and also to get some feeling for what it may feel like to be on the other side of this conversation.

Seminar II: Virtual Reality Exercise

- **Grade:** Pass/fail
- Title: The black hole at the centre of the Milky Way

Seminar III: Strange galaxy

- **Grade:** Pass/fail
- Puzzle-solving game aiming to teach you about observational techniques in extragalactic astronomy
- Preparation: Read section 1.3-1.4 in textbook



Seminar III: Strange Galaxy

General instructions

This document provides instructions for the third of the four seminars forming part of the examination for the course *Physics of Galaxies* in 2019. This is an exercise with game-like mechanics that aims to provide insight into some of the observational techniques commonly used in extragalactic astronomy.

In the *Strange galaxy* game, you will be assigned to different teams and presented with a sequence of observational problems to solve. Each such scenario involves a set of observational data on an unusual, poorly understood galaxy or other astronomical object. The objective is to understand the nature of the object by gathering additional information through carefully chosen follow-up measurements. There are many observational methods that can be applied in each situation (optical monitoring, ultraviolet spectroscopy, high-resolution near-infrared imaging etc.) and they all provide slightly different clues to the puzzle. Resources are, however, limited. At the start of each scenario, every team will be granted a limited research budget (in a fake, in-game currency), and every new measurement that you choose to make will set you back by a certain amount. The objective of the game is to crack the puzzle before running out of funding.

The point of this exercise is to:

- Learn more about observational methods in extragalactic astronomy, get a feeling

Seminar IV: The most distant galaxies

- **Grade:** Fail, 3, 4, 5
- Preparation:
  - Read suggested papers + others
  - Answer questions + analyze dataset
  - Prepare to present answers and results in class

Seminar IV: The most distant galaxies

General instructions

This document provides preparation instructions for last of the four seminars forming part of the examination for the course *Physics of Galaxies* in 2019. The topic of this seminar is *The most distant galaxies*.

Galaxies are being detected at ever-increasing redshifts, and as of 2019, a number of photometric galaxy candidates have been claimed at $z \approx 10$–12, i.e. at about 300-500 Myr after the Big Bang. So far, only one such object has been confirmed through spectroscopy (at $z \approx 11.1$), but the race to detect even more of these primordial galaxies is on.

The point of this exercise is to:

- Practice reading technical research papers (as opposed to popular articles, review papers or textbooks). As a professional astronomer, most of the stuff you will read is likely to be of this variety.
- Practice critical thinking (for this purpose, speculative and controversial seminar topics have deliberately been chosen).

Database exercise ("lab")

- Introduction to exercise in lecture 6
- Complete individually and hand in report no later than June 3
- **Grade:** Fail, 3, 4, 5

Intermission: What is this?

Schedule I

Complete schedule on course homepage!

- 8 Lectures:
  - March 26, 15—17
  - March 27, 15—17
  - April 1, 13—15
  - April 3, 15—17
  - April 5, 15—17
  - April 26, 15—17 ← **Includes introduction to database exercise**
  - May 6, 13—15
  - May 7, 13—15

- 3 Exercise sessions:
  - April 24, 15—17
  - May 9, 13—15
  - May 15, 13—15

Schedule II

Oral presentations of literature exercises:

- May 28, 15—17 + additional date if required

Grades

- Final grade will be the mean grade from:
  - Seminar 4
  - Written report on literature exercise
  - Oral presentation of literature exercise
  - Report from database exercise
  - Hand-in exercises

- No final grade will be computed until you have a reached a passing grade (3 or higher) for each of these
- Please note that you also need a passing grade from the three exercise sessions and seminar 1, 2 & 3 to complete the course

Grades – example

1) Seminar 4
   Grade: 4
2) Written report on literature exercise
   Grade: 4
3) Oral presentation on literature exercise
   Grade: 3
4) Report on computer exercise
   Grade: 5
5) Hand-in exercises
   Grade: 3

Calculate mean grade: $(4+ 4+ 3 + 5 +3) /5 = 3.8 \approx 4$
Final grade: 4:

How much time will I have to spend on this course?

My estimates:

- Attending lectures, exercise sessions, seminars etc. ≈ 0.75 week
- Studying the textbook ≈ 1.25 weeks
- Preparing for exercise sessions ≈ 0.5 week
- Preparing for seminars ≈ 1.25 week
  Note: Prepare to spend most of this on seminar 4!
- Computer exercise ≈ 0.75 week
- Literature exercise
  (written report + oral presentation) ≈ 1.5 weeks
- Hand-in problems ≈ 0.5 week

Sum: 6.5 weeks, i.e. ≈ 10 hp

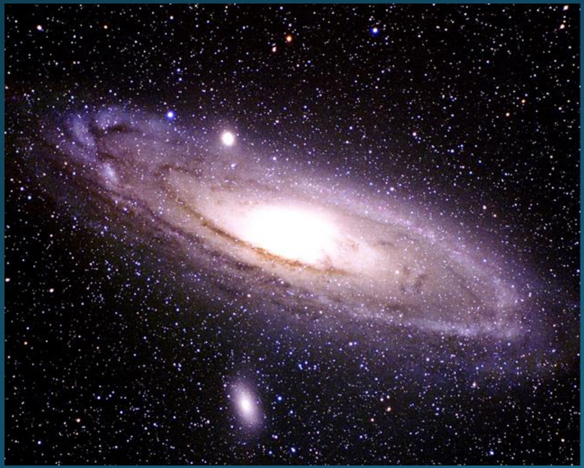
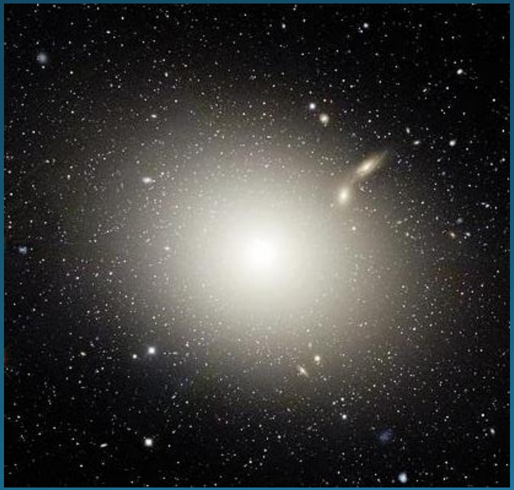
Pro tip

Notice how there is a gap in the schedule (nothing scheduled between April 5 and April 24)?

Friendly advice: Decide on a topic for the literature exercise early and use this time to work on the written report – otherwise things will become very hectic in the last two weeks of May

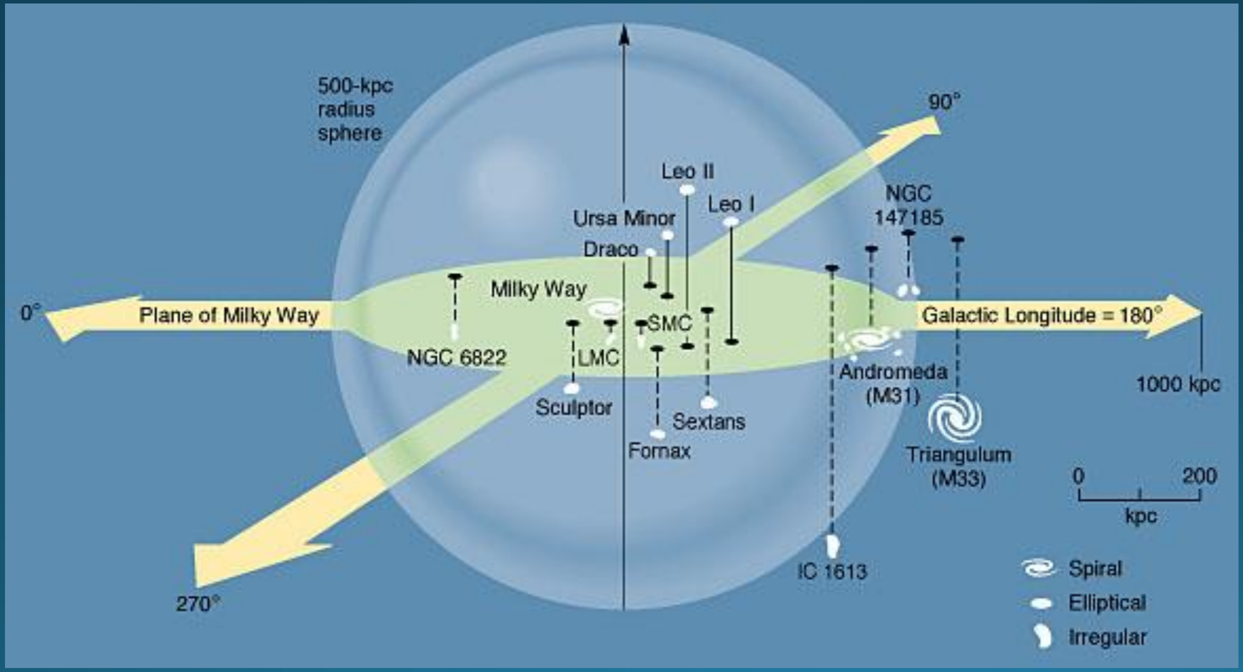
Course Outline

- Lecture 1:
  - Introduction
  - Historical Background
  - Galaxy Classification
  - The Cosmological Framework


Course Outline

- Lecture 2:
  - The Astronomical Distance Scale
  - The Milky Way
  - The Local Group

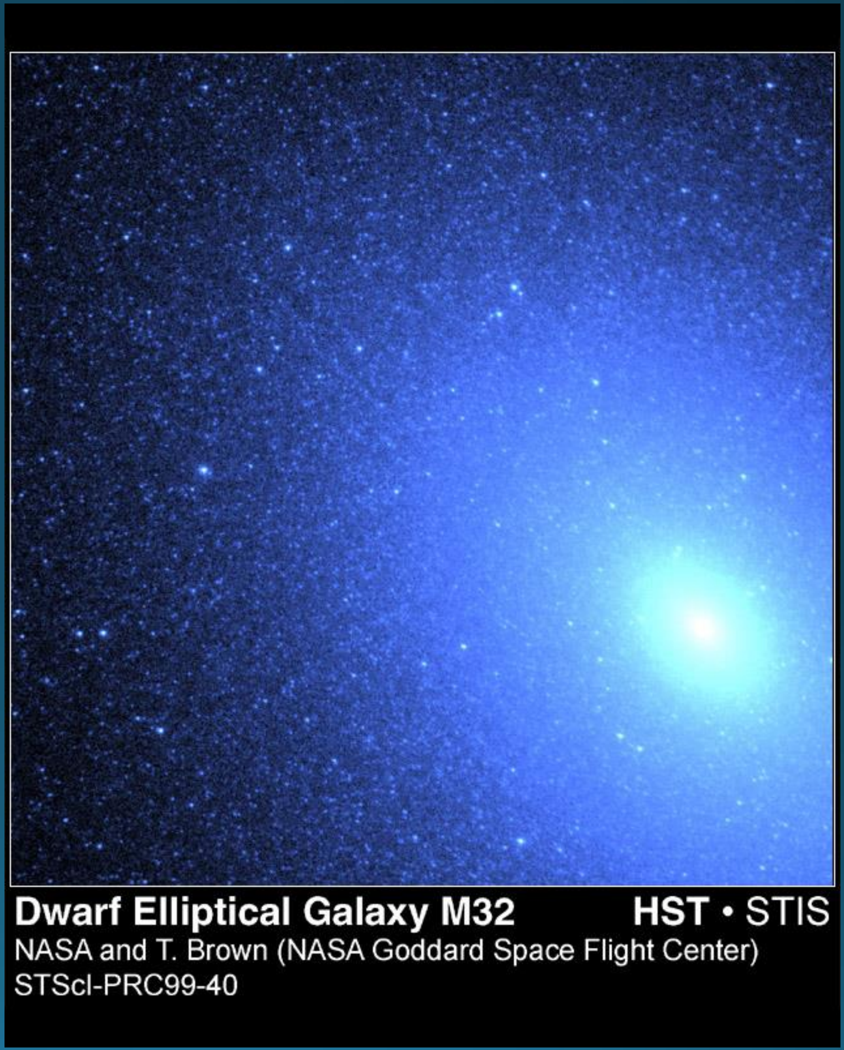


Course Outline

- Lecture 3:
  - Dark matter in galaxies
  - The dark halo
  - Subhalos
  - Mass-to-light ratios
  - Baryon fractions

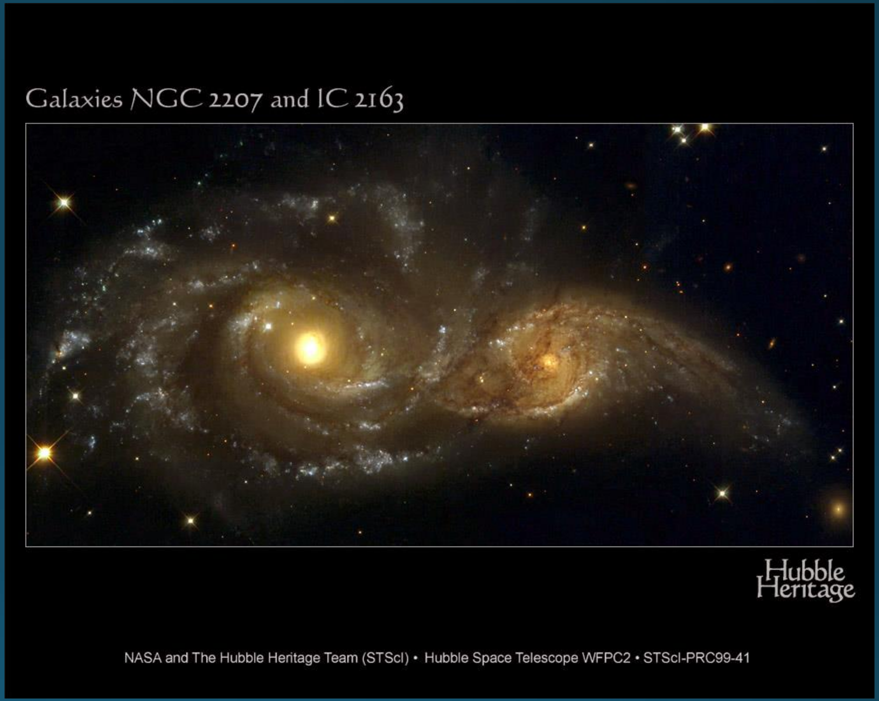
Course Outline

- Lecture 4:
  - Disk galaxies
  - Elliptical galaxies



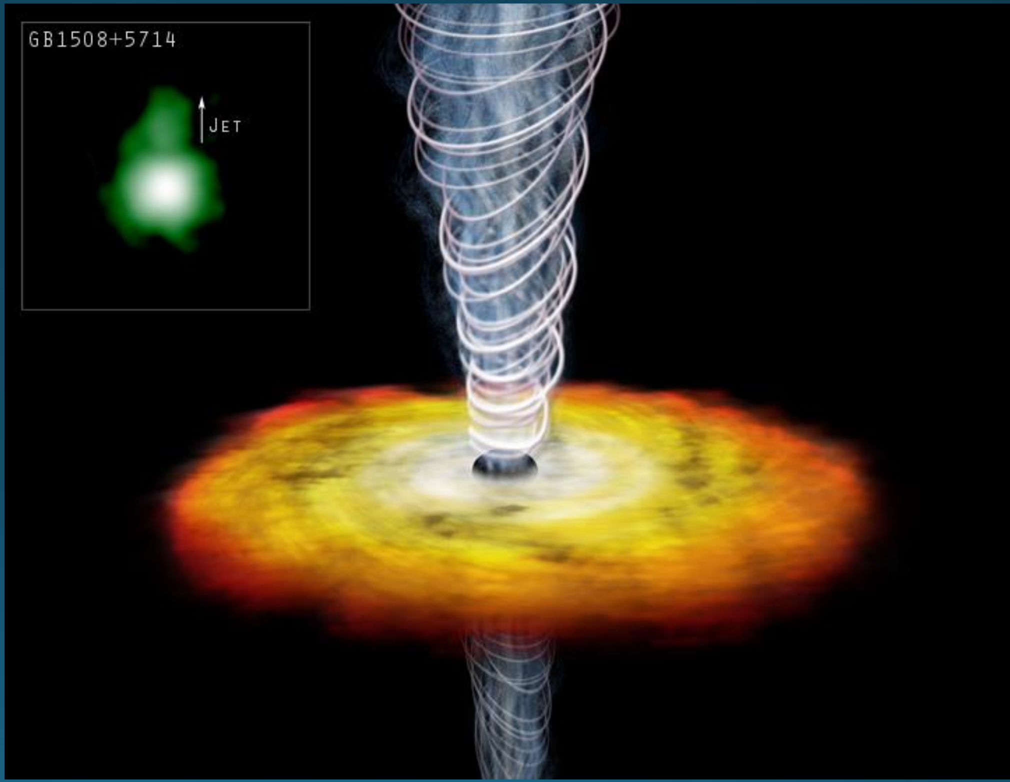
Course Outline

- Lecture 5:
  - Star formation
  - Population synthesis
  - Galaxy spectra
  - The interstellar medium
  - The cosmic star formation history



Course Outline

- Lecture 6:
  - Black holes
  - Active galaxies:
    - Quasars
    - Blazars
    - Seyfert Galaxies
    - Radio Galaxies
  - Introduction to database exercise



Course Outline

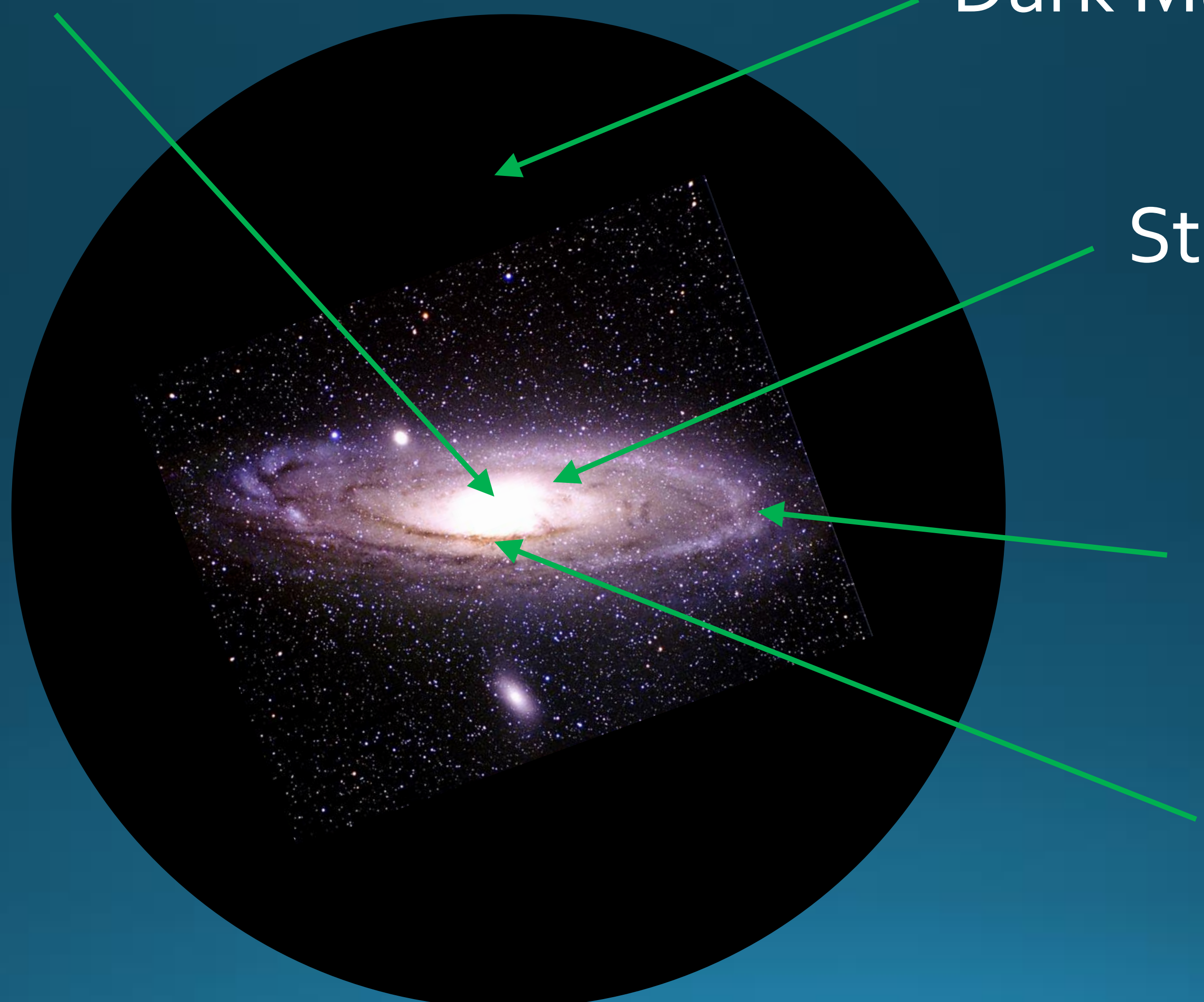
- Lecture 7:
  - Galaxy groups
  - Galaxy clusters
  - Gravitational lensing

Course Outline

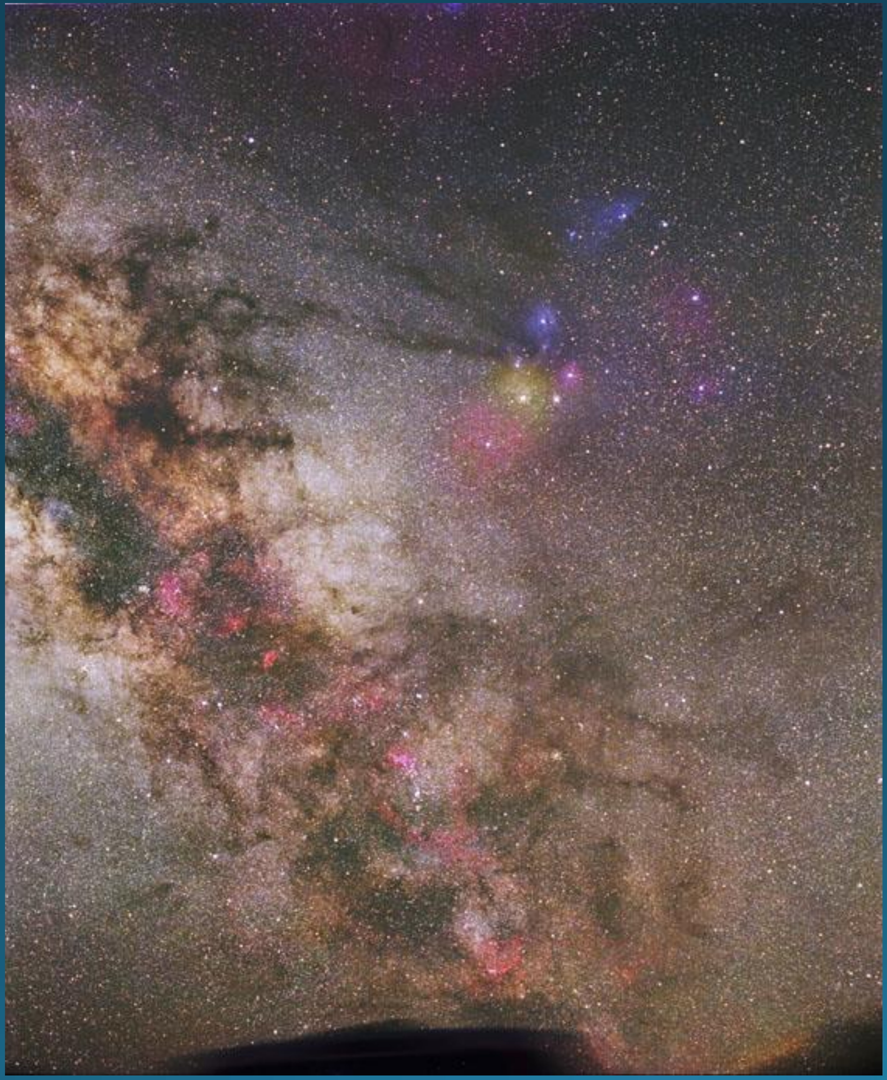
- Lecture 8:
  - The high-redshift Universe
  - Cosmic reionization
  - The first stars and galaxies

Intermission: What is this?

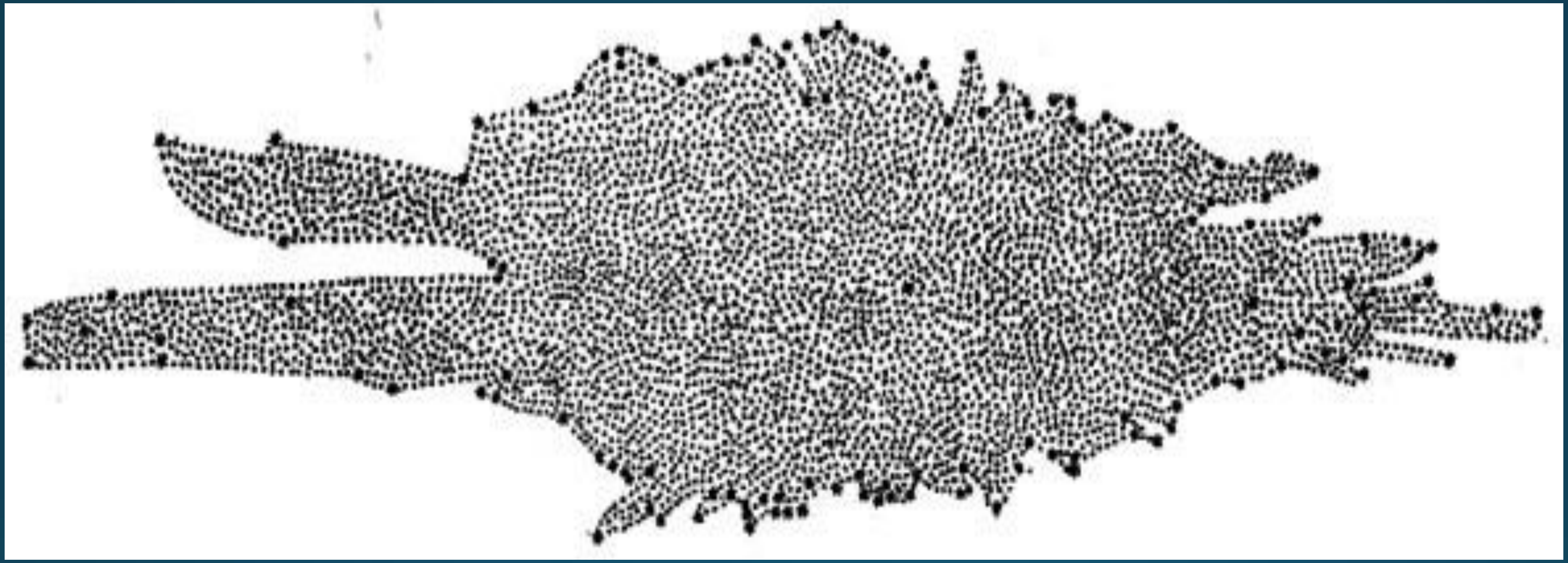
The Anatomy of Galaxies



Historical Background: The Milky Way

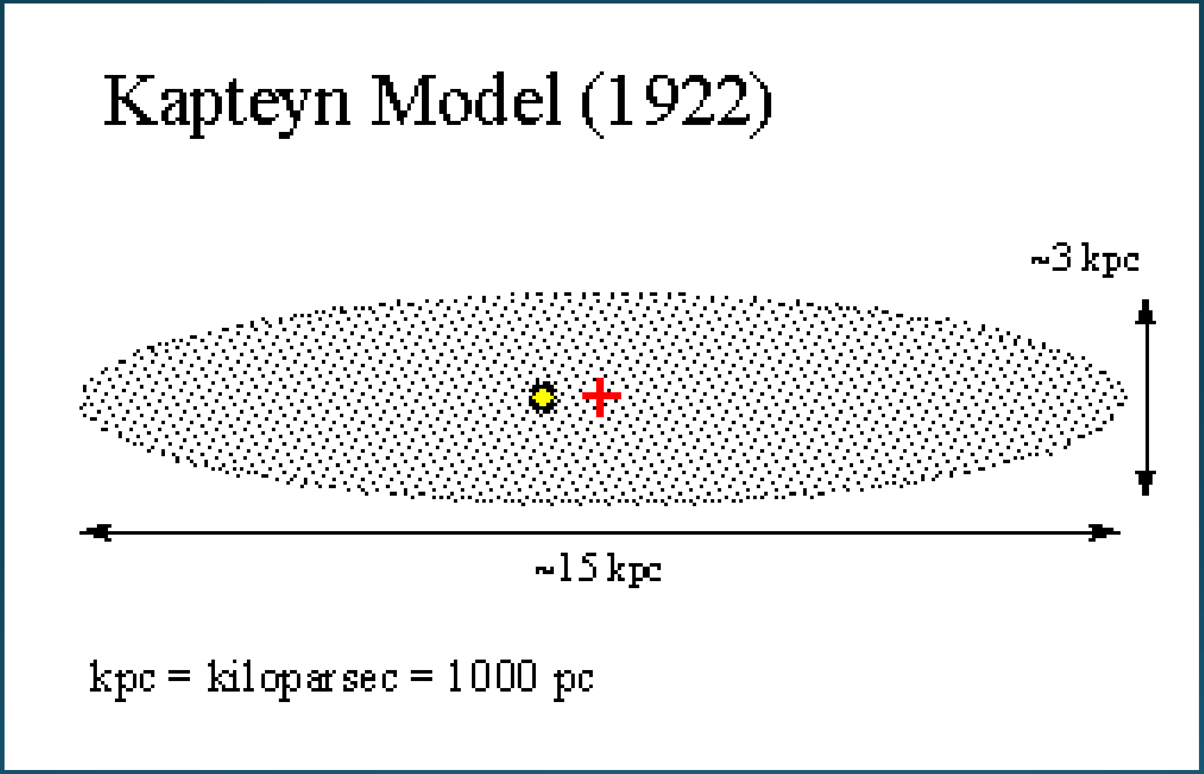


Historical Background: The Milky Way



- The "Herschel Universe" (late 1700s): Sun almost in the centre of Milky way
- Dust obscuration towards centre of the Milky Way (left side of figure) not accounted for

Historical Background: The Milky Way

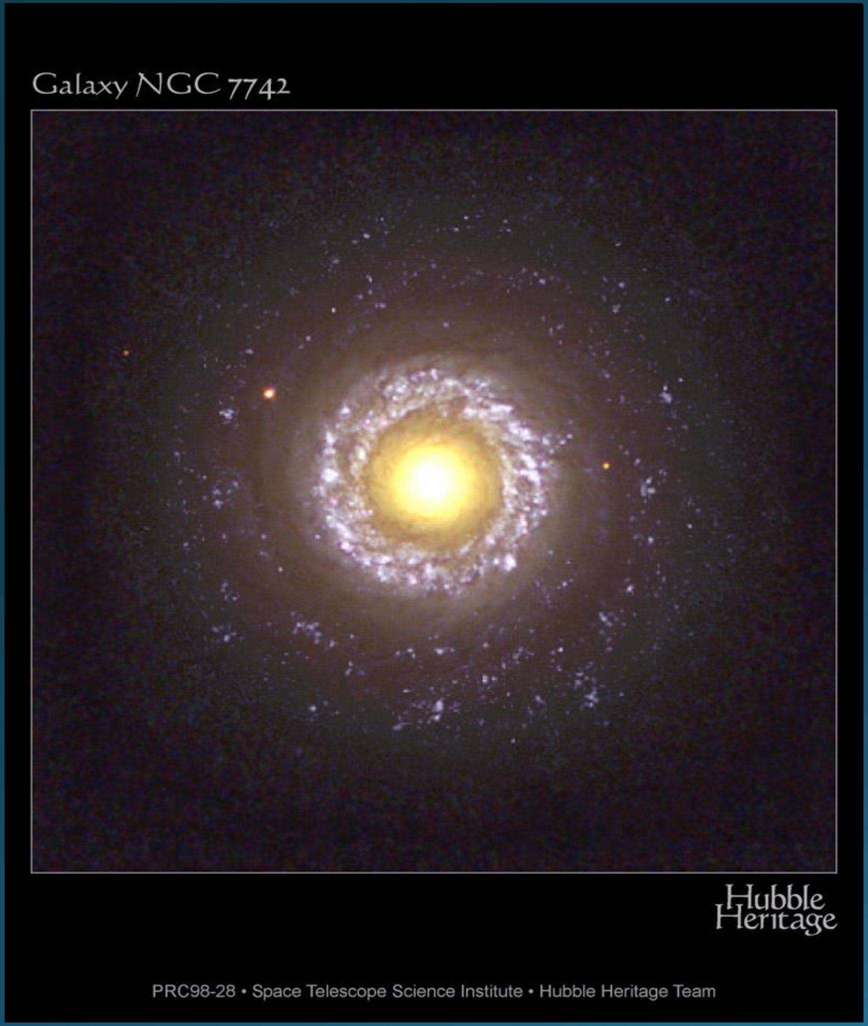


- Sun offset from centre
- Dust obscuration still not accounted for → wrong scale

Historical Background: Other Galaxies

- Mid-1800s: William Parsons (Lord Rosse) discovers spiral structure in nebulae
- 1912: Henrietta Leavitt discovers period-luminosity relation for Cepheids
- 1920s – The Great Debate
  - Shapley (local objects) VS Curtis (outside Milky Way)
  - Outcome: Spiral Nebulae are external galaxies
- 1929 – Expansion of the Universe (Hubble´s law)

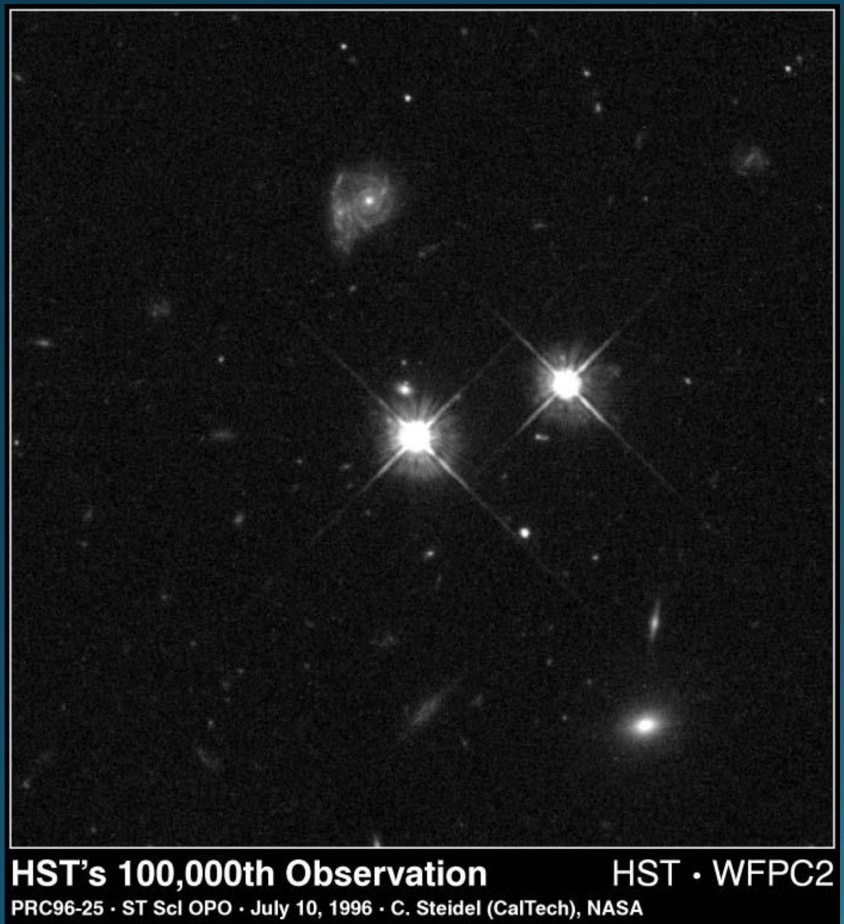
Historical Background: Active Galaxies

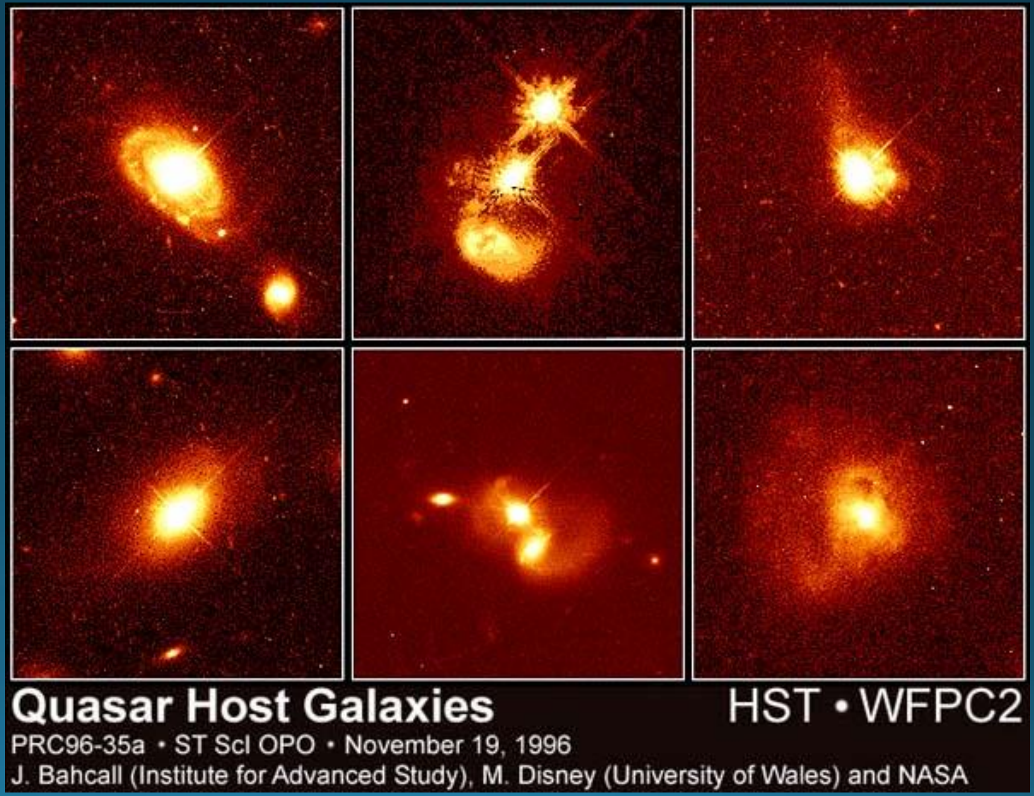


- 1943 - Seyfert Galaxies

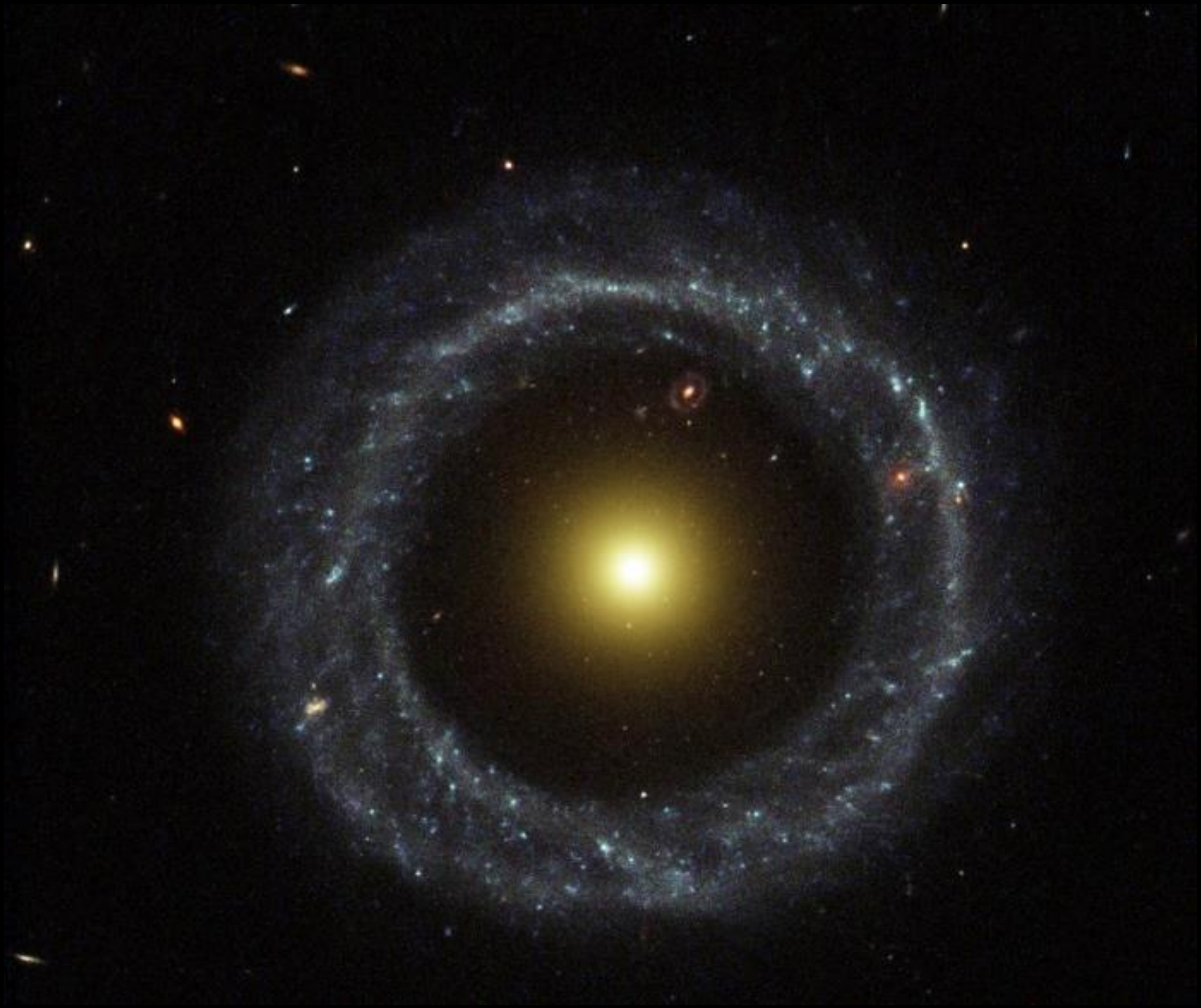
Historical Background: Quasars/QSO

- 1960s – Radio Galaxies, Quasars
- Quasi-Stellar Object: QSO, Quasar

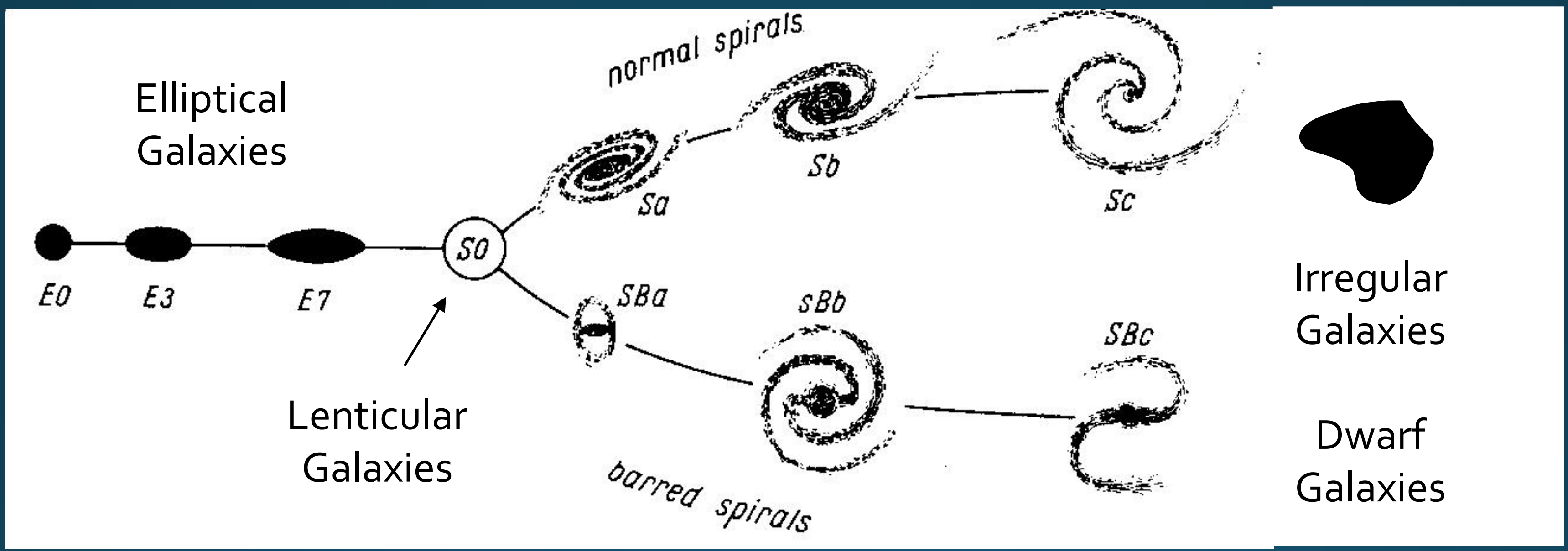




Intermission: What is this?



Galaxy Classification
The Hubble Tuning Fork



Other famous classification schemes:

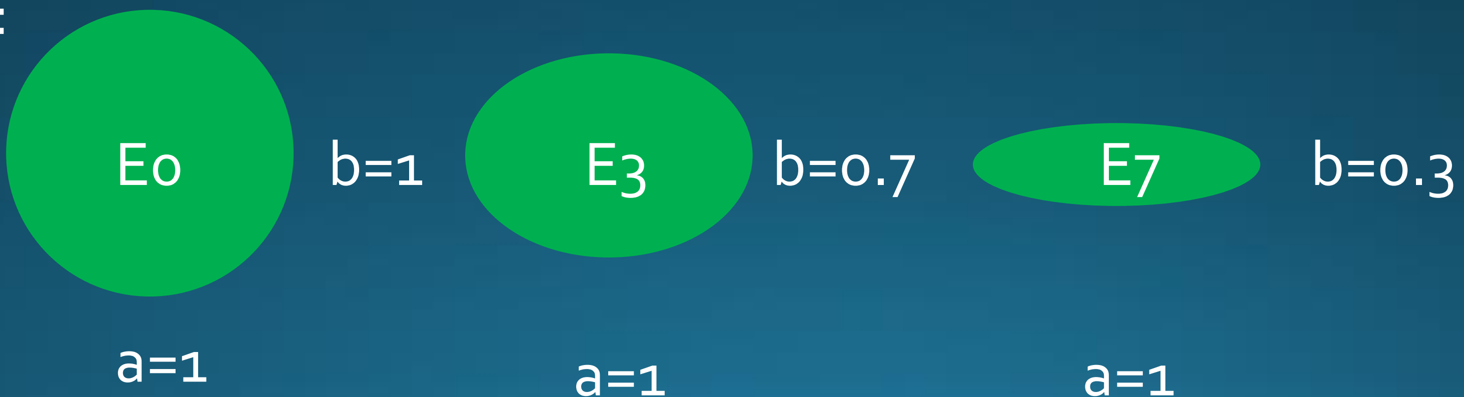
- de Vaucoleur
- van den Bergh
- Vorontsov-Velyaminov

Galaxy Classification

Elliptical galaxies

- Type: En, $n = 10\,(a - b) / a$.
- Major and minor axes: a and b
- $\rightarrow$ E0 circular, E7 galaxies the most flattened.

Examples:

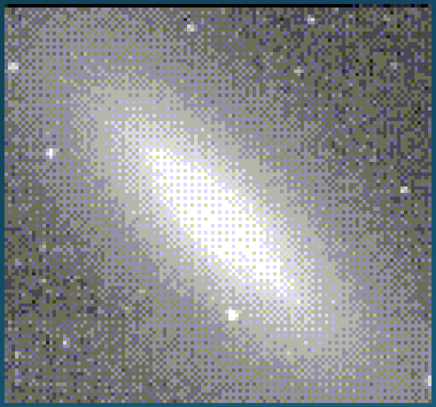


Galaxy Classification

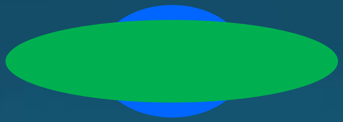
Lenticular galaxies

- Disk and central bulge, but no spiral arms
- SBo if barred, So otherwise

Examples:



So



Edge-on

Face-on

Galaxy Classification

Normal Spirals

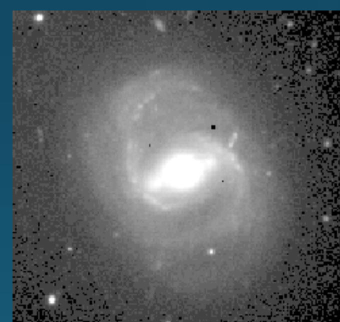
Sa

Sb

Sc

Barred Spirals

SBa



SBb

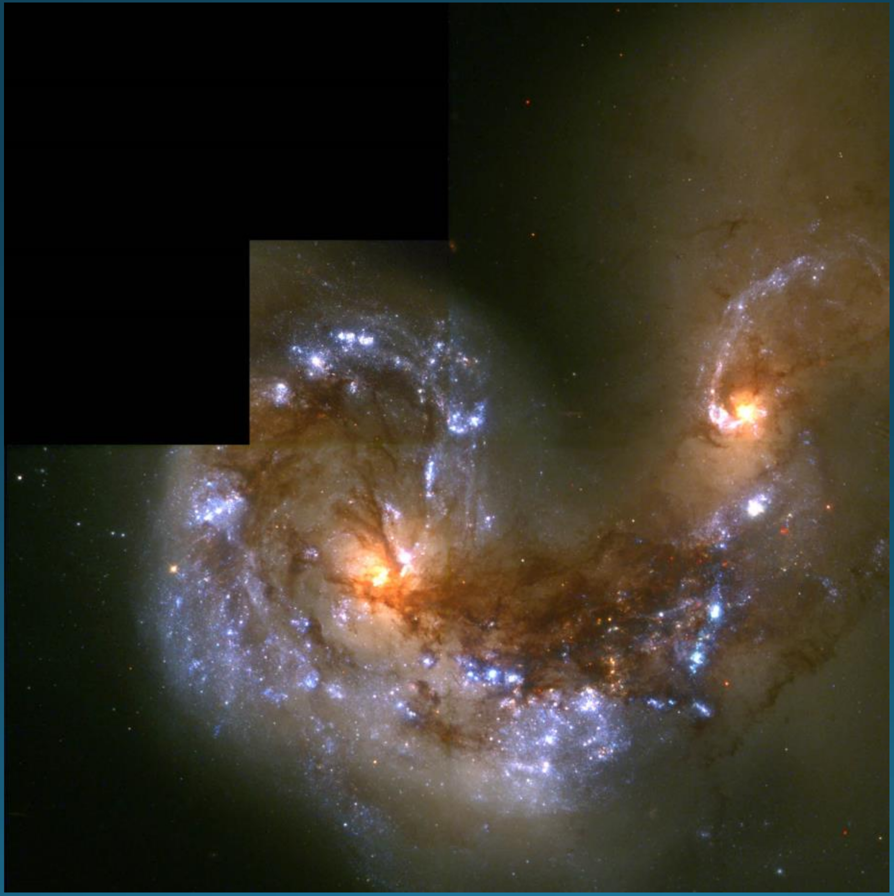
SBc

- Large bulges
- Tightly wound spiral arms
- Few star-forming regions in arms

- Small bulges
- Loosely wound spiral arms
- Many star-forming regions in arms

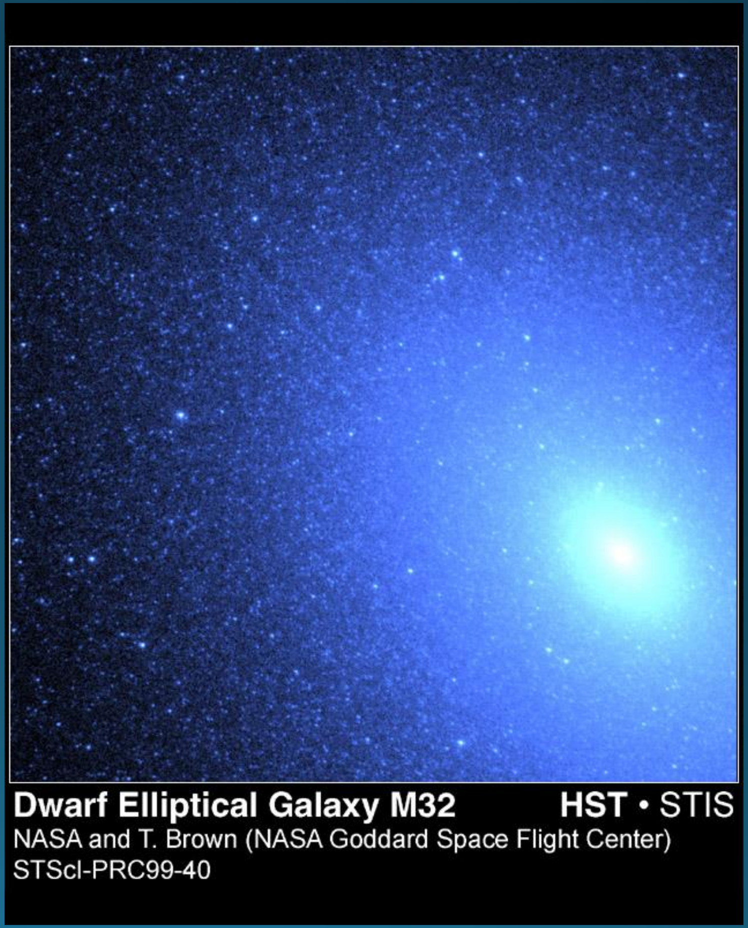
Galaxy Classification

Irregular galaxies (I)

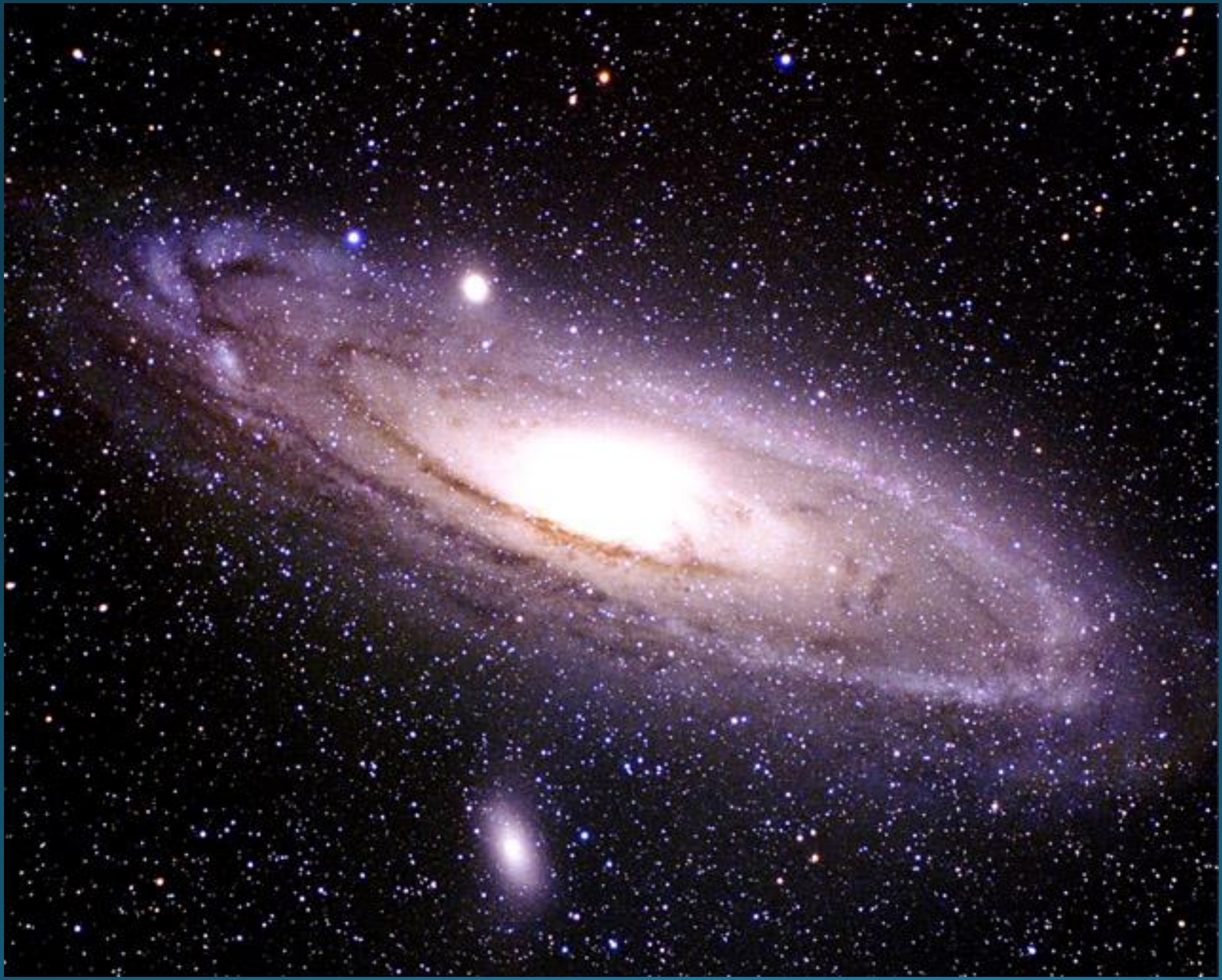


Galaxy Classification

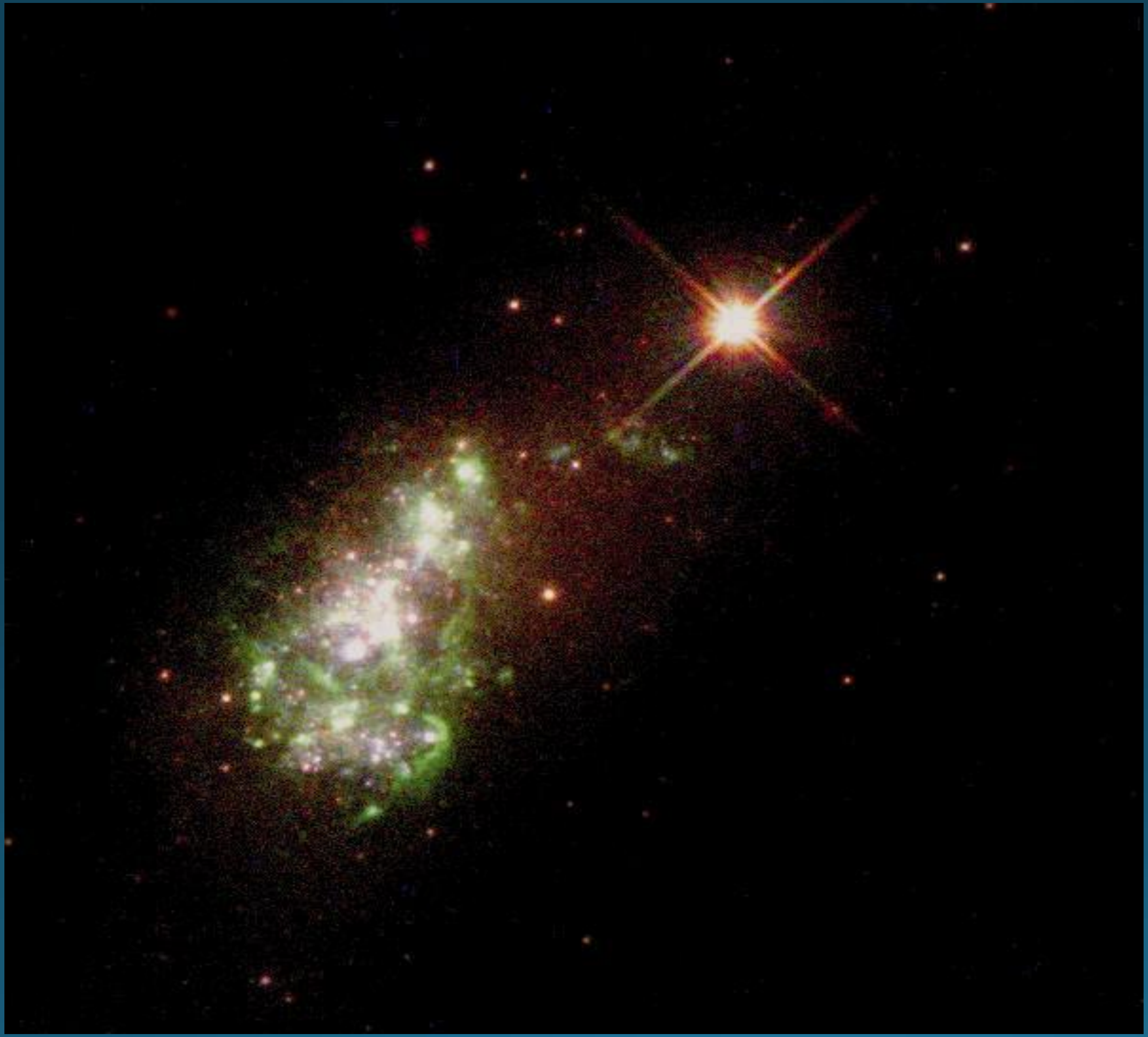
Dwarf galaxies (dE, dSph, dI…) – Low-luminosity objects



Morphological Type?



Morphological Type?

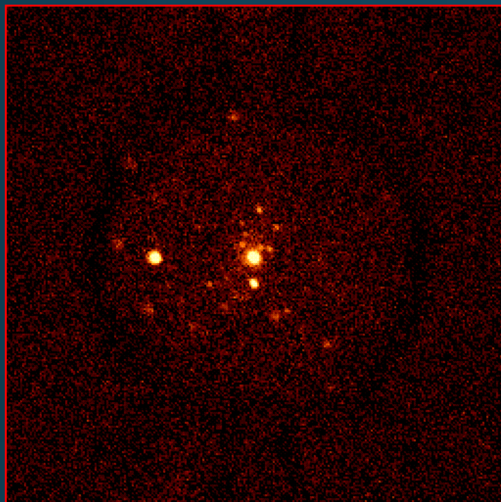


What is the Point of Morphological Classification?

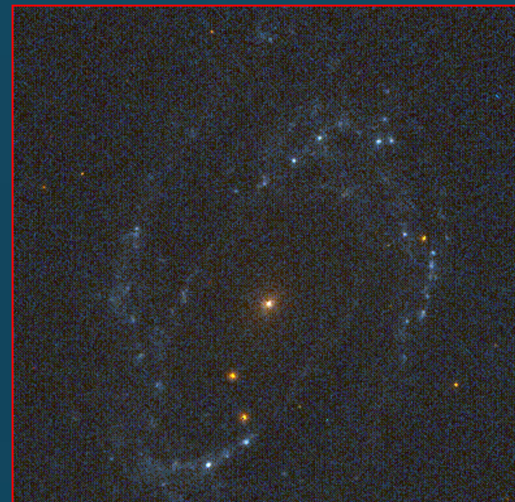
Hubble class correlates with:

- Gas content
- Dust content
- Star-forming properties
- Spectrum
- Metallicity

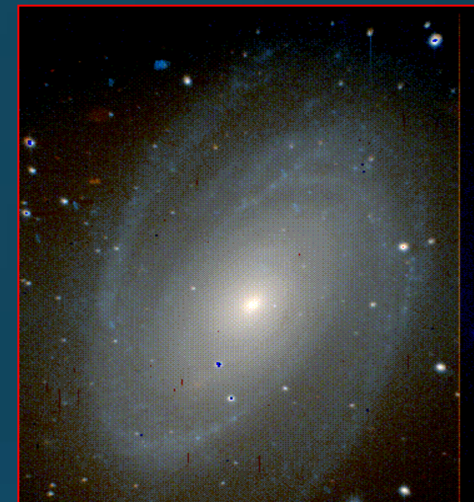
Morphological Complications



X-rays

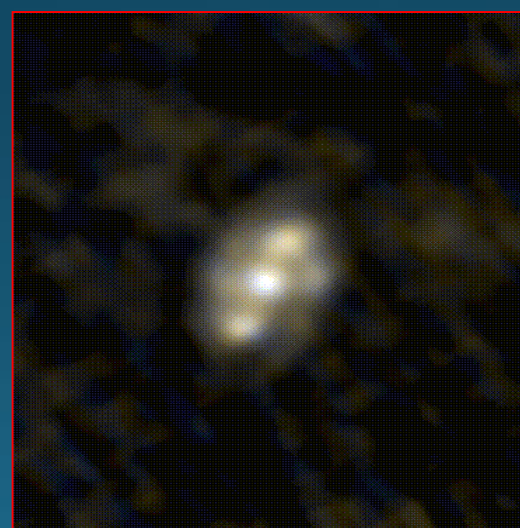


UV



Optical

Near-IR



Far-IR

Same galaxy (M81) at different wavelengths!

Morphological Complications

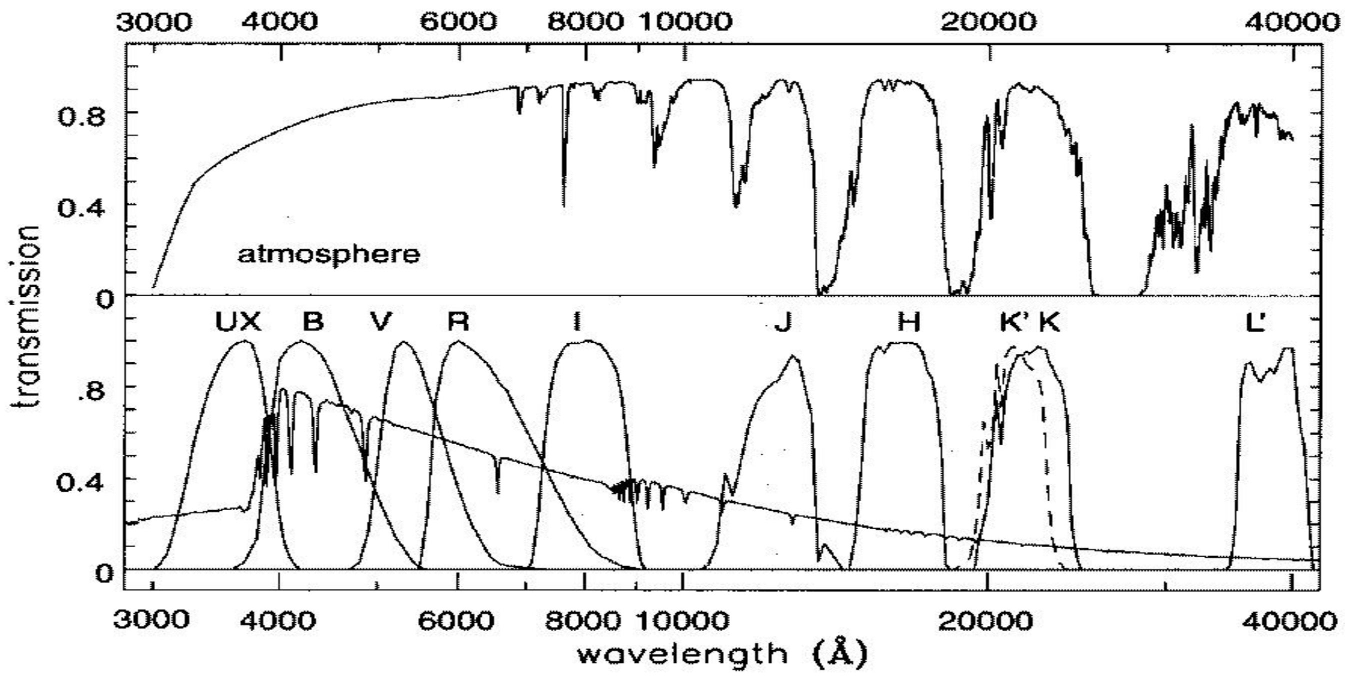
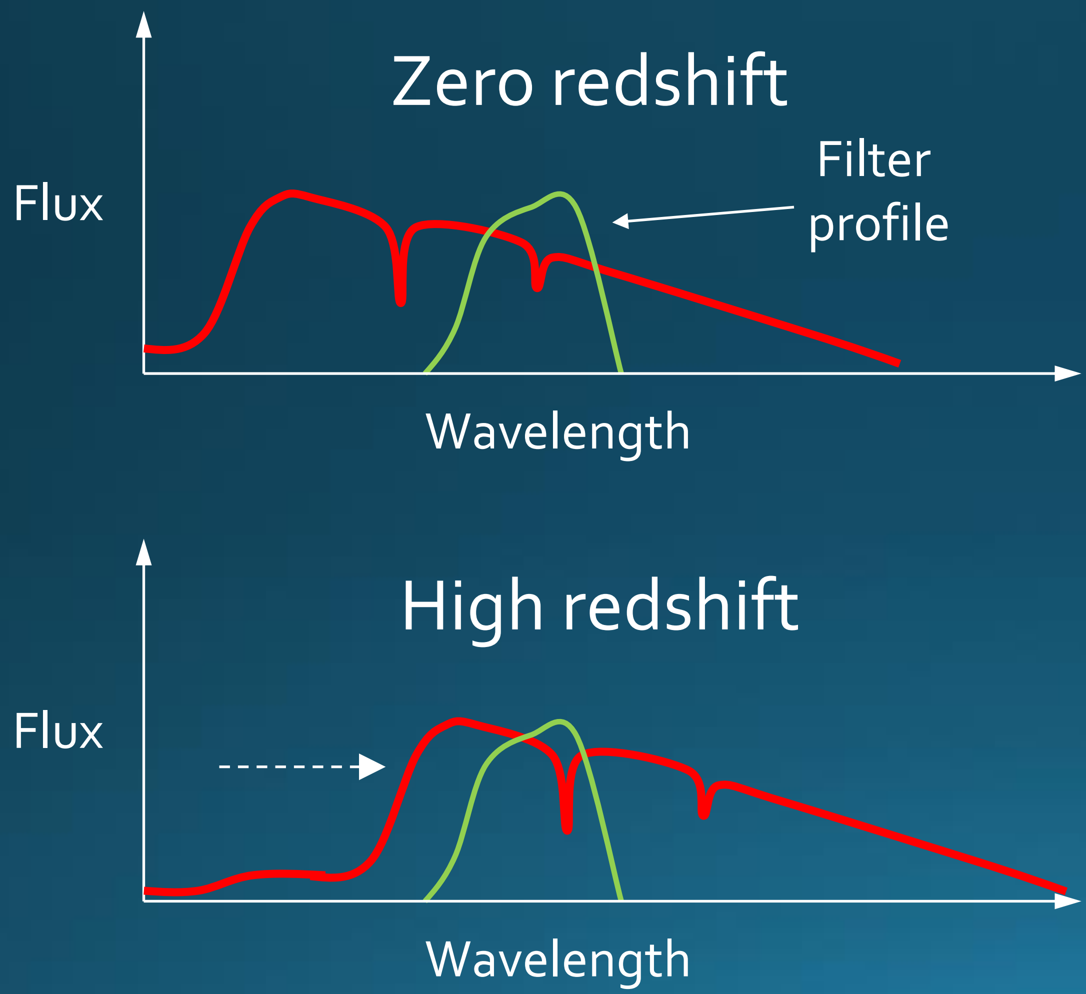


Figure 1.7 Above, atmospheric transmission in the optical and near-infrared. Below, flux F_λ of a model A0 star, with transmission curves $\mathcal{T}(\lambda)$ for standard filters from Bessell, PASP 102, 1181; 1990. UX is a version of the U filter that takes account of atmospheric absorption. For $JHK'KL'$, $\mathcal{T}(\lambda)$ is for transmission through the atmosphere and subsequently through the filter.

Morphological Complications



- Same filter probe different parts of spectrum at high and low redshifts
- Two galaxies with identical morphologies at a given rest wavelength may appear to have different morphologies

Intermission: What is this?

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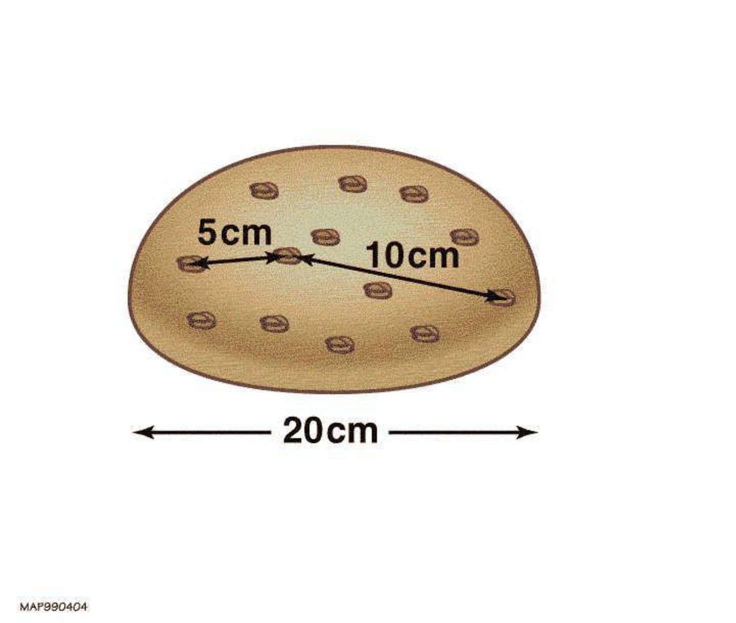
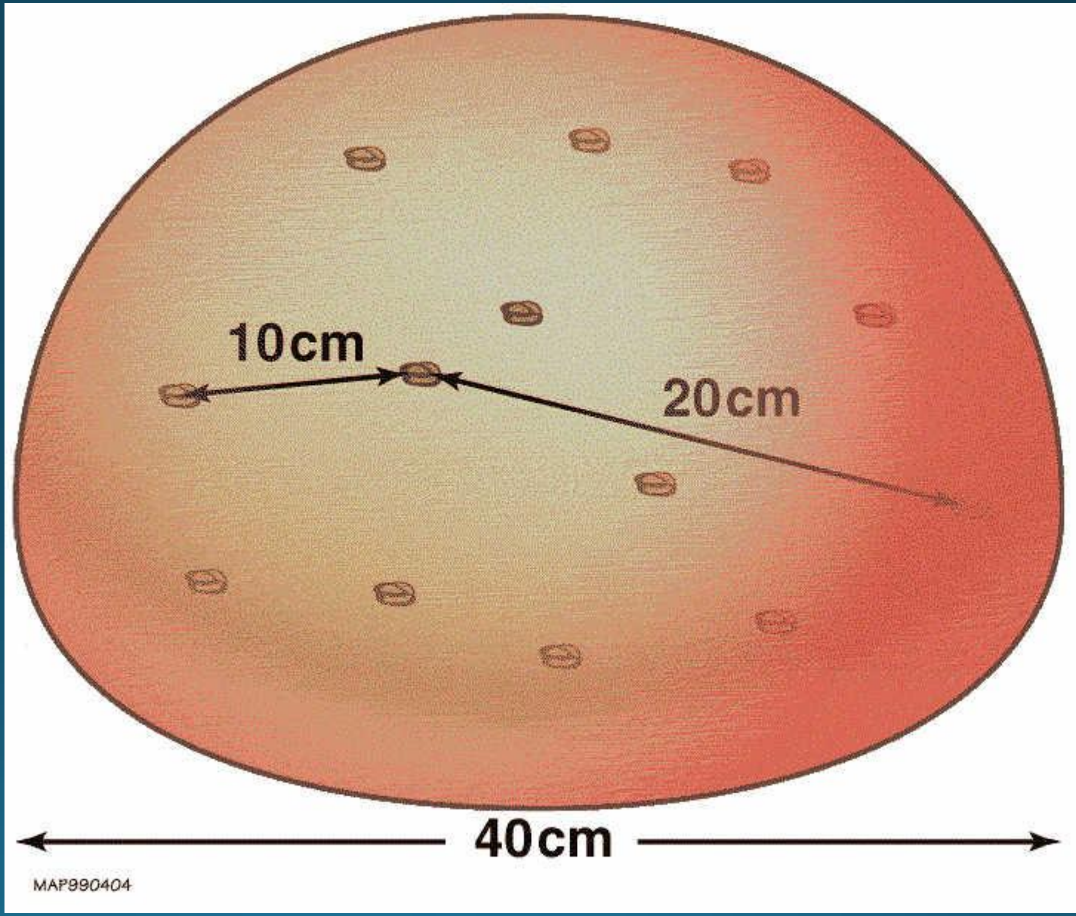
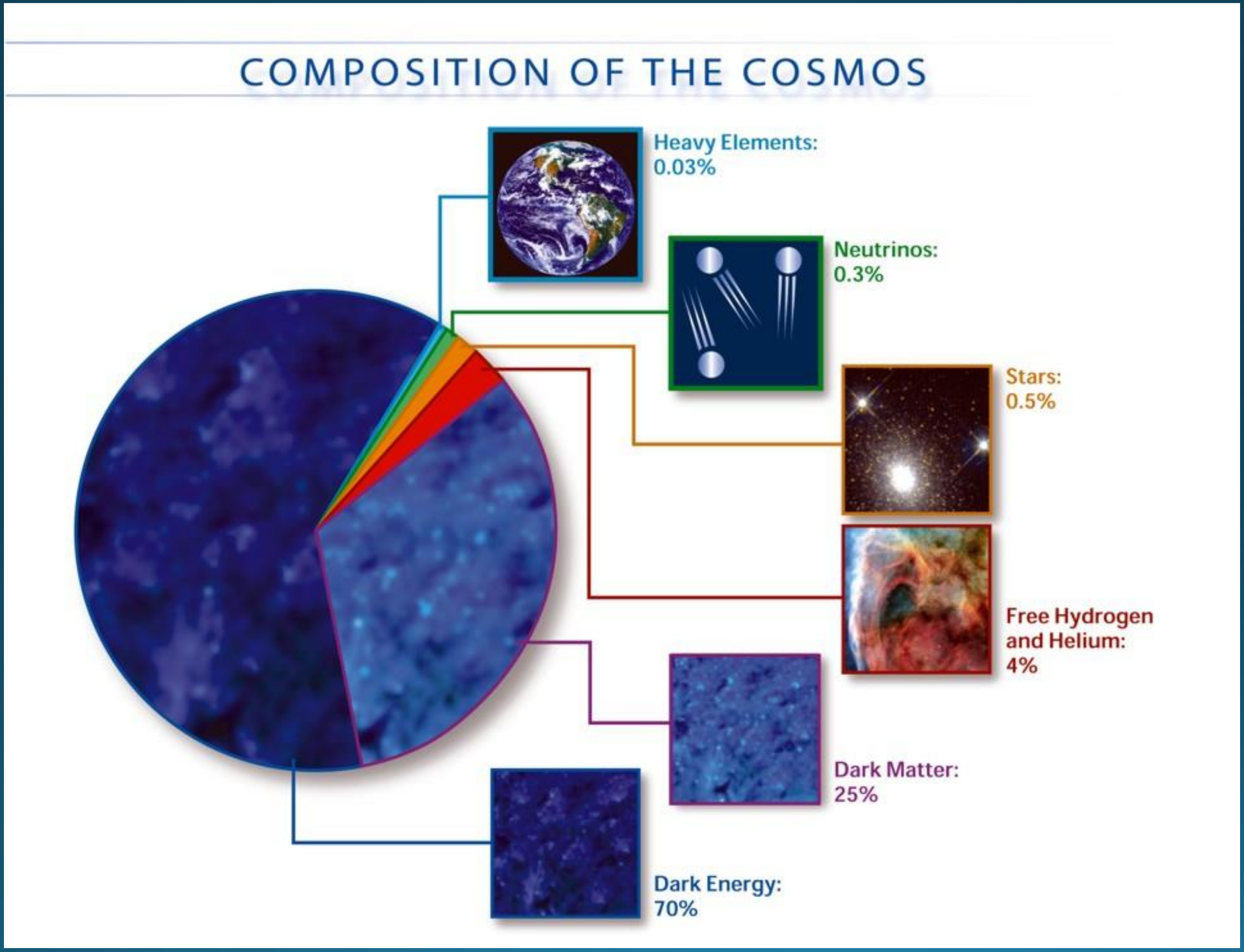
The Cosmological Framework I

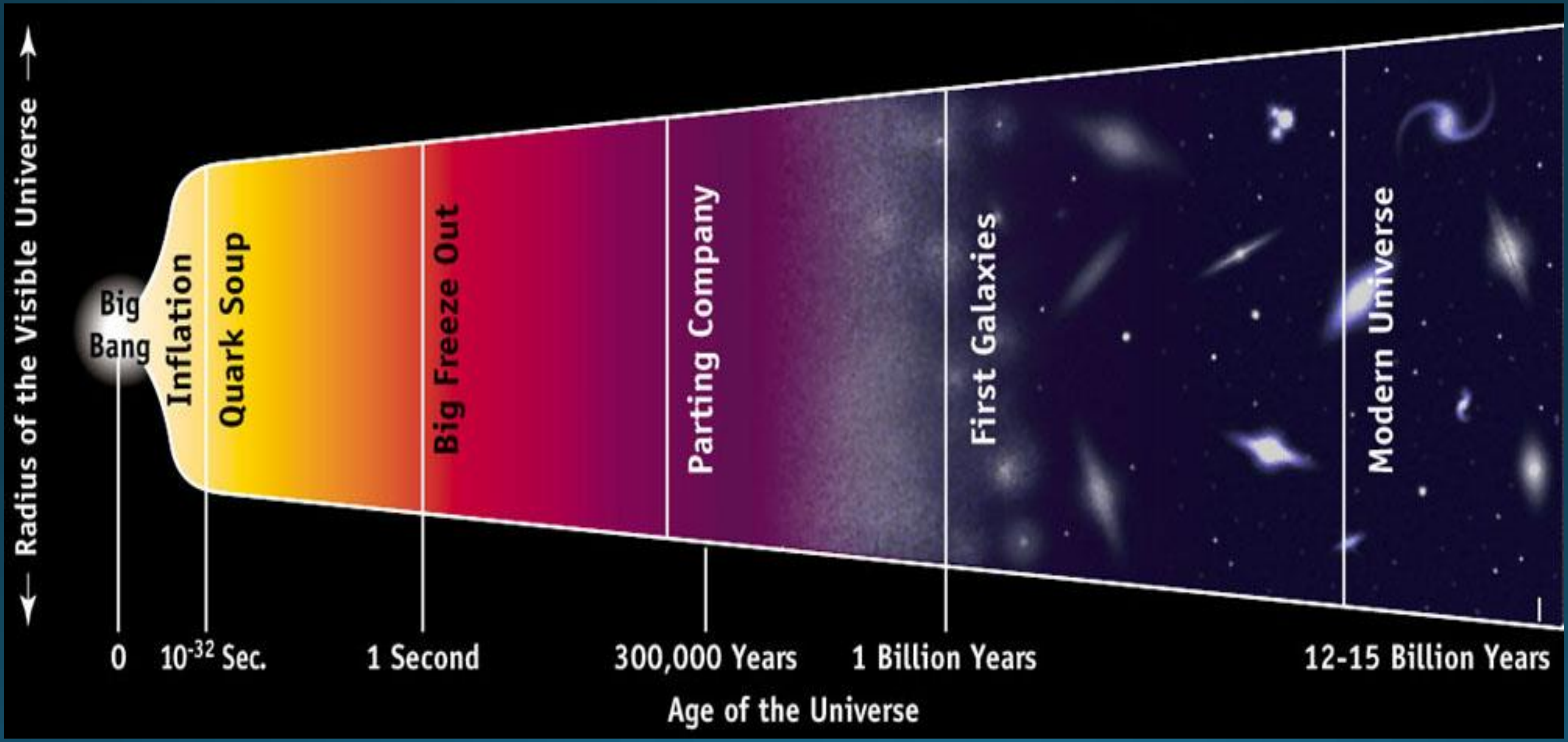




The Cosmological Framework II



The Cosmological Framework III



The Cosmological Framework IV

- $\Omega_i = \rho_i / \rho_c$
- ρ_c = critical density of the Universe
- $\Omega_{Tot} \approx 1.0$
- $\Omega_{Baryons} \approx 0.04$
- $\Omega_M \approx 0.3$
- $\Omega_\Lambda \approx 0.7$