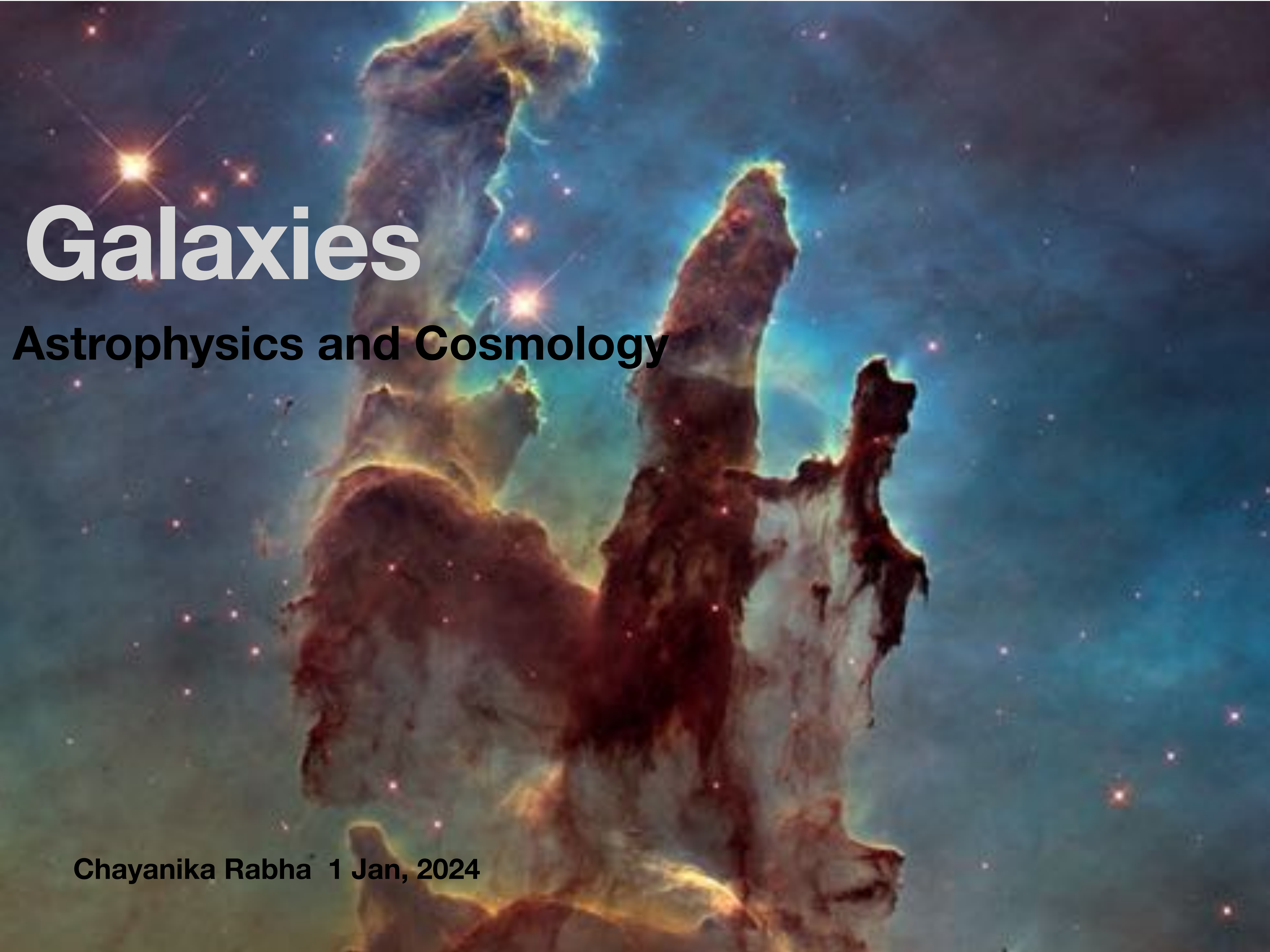


Galaxies

Astrophysics and Cosmology

Chayanika Rabha 1 Jan, 2024

What is Astrophysics?

- Astrophysics is the science that studies the physics of the stars, other celestial bodies, galaxies and the Universe.
- Astronomy: qualitative study of the object whereas Astrophysics describe the physics-oriented version of the subject (as defined by Frank Shu, *The Physical Universe*)
- Cosmology: evolution of the universe, the origin of the universe, present state and future..

Units of measurements:

- Cgs or SI units: appropriate for everyday life
- Inconvenient for astrophysical measurements. Hence we define some basic units in astrophysics.

Unit of mass

- $M_{\odot}$: mass of Sun. Used as the unit of mass in astrophysics

$$1M_{\odot} = 1.99 \times 10^{30}\ \text{kg}$$

Mass of stars usually ranges from $0.1M_{\odot} - 20M_{\odot}$

Mass of galaxy : $10^{11}M_{\odot}$

Unit of length

- Astronomical unit (AU) : average distance of the Earth from the Sun.
- Used as the unit of length in astrophysics

$$1AU = 1.50 \times 10^{11} \text{ m.}$$

- Useful for measuring distances within solar system. Small to express the distances to stars and galaxies.
- Parsec: 1pc=3.26 light years. (What is light year?)
- $1pc = 3.09 \times 10^{16}$ m

Nearest star: Proxima Centauri $\approx$ 1.31 pc
Nearest Galaxy $\approx$ 0.74 Mpc (Mega parsec)

Thumb rule:

- pc: measure of interstellar distance
- Kpc: measure of galactic sizes
- Mpc: measure of intergalactic distances
- Gpc: measure of the visible universe.

$$K = 10^3$$

$$\text{Mega} = 10^6$$

$$\text{Giga} = 10^9$$

Andromeda Galaxy
Source: sky and telescope

The Andromeda Galaxy (M31) is indeed approaching us, by about 300 kilometers (190 miles) per second measured with respect to the Sun.

Unit of time

- Astrophysicists deal with different time scales.
- Age of the universe is of the order of a few billion years
- Pulsars emit pulses periodically after intervals of fractions of seconds
- No special unit of time :- years for large time scales
  Seconds for small time scales
- $1 year = 3.16 \times 10^7$ s

Task: Convert year to seconds!

Age of sun ≈ 4.5 Gyr

Magnitude Scale

- Human eye is more sensitive to geometric progression of intensity than arithmetic progression
- Magnitude scale for describing brightness is based on this fact.
- Hipparchus (second century BC): naked eye observation of stars, classified stars into **six** classes based on their apparent brightness.
- Apparent magnitude 1 being the brightest and 6 being the faintest.
- Oldest classification of stars.

Astronomical Nomenclature

- Needed to identify astrophysical objects
- Several catalogues of astronomical objects
- *Henry Draper Catalogue:* stars down to ninth magnitude were listed, published during 1918-1924
- Gives celestial coordinates and spectroscopic classification.
- Indicated by HD, followed by its listing number

Example: Sirius, the brighter star in the sky is referred as HD48915.

(It is listed as object number 48915 in the HD catalogue)

- Modern astrophysicists were very much interested in objects other than visible stars.

- 1774-1781: French astronomer *Charles Messier* compiled famous list of more than 100 non-stellar objects that was visible through a small telescope.

- List includes: widely studied galaxies, star clusters, supernova and nebulae of various types

- Objects are indicated by 'M' followed by the number in the Messier catalogue.

Example: Andromeda galaxy - M31.
Crab Nebula - M1
(remnant of supernova seen from earth in 1054)

Crab Nebula, Credit: NASA

- Much bigger catalogue, 8000 entries of non-stellar objects
- Compiled by *Dreyer (1888)*, based primarily on observations by Hershel.
- Known as **New General Catalogue (NGC)**
- Objects are indicated by 'NGC' followed by the number in the NGC catalogue.

Example: Cat's eye - NGC 6543 (NGC 6543)

Cat's eye nebula. Image credit: nasa.gov

- Development of radio and X-ray led to identification of objects in the radio and X-ray wavelengths.
- Initially only a few objects emitting radio and X-rays were known, hence they were often named after the constellation in which they were found.
- For example: Cygnus A, strongest radio source. Cygnus X-1, strongest x-ray source. Both in the constellation Cygnus
- *Third Cambridge Catalogue of Radio Sources*, known as 3C (Edge et al.,1959)
- Object 3C 273, brightest quasar in the catalogue.

- Lastly, some astrophysical objects are named by their celestial coordinates.

- Example: PSR 1913+16 is the name of the pulsar having the Right Ascension (R.A.) 19 hours 13minutes and the declination +16.

(Will study in the upcoming classes)

Unit V: Galaxies

JWST image of galaxies: Pandora of galaxies.

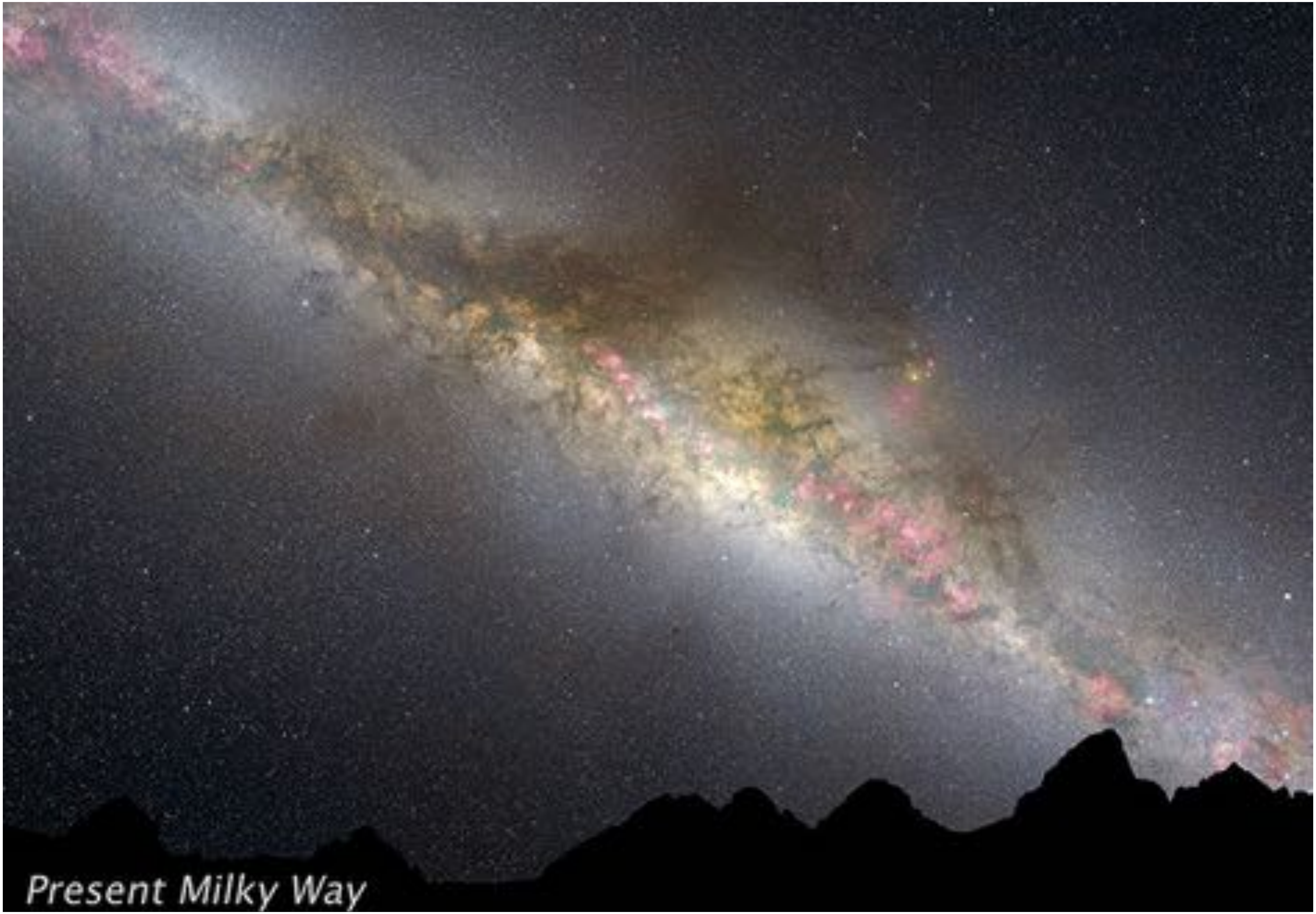
What is a Galaxy?

- Huge collection of stars and inter-stellar matter
- Bounded by gravity
- There are thought to be about 100 billion galaxies in the universe, mainly residing in clusters and groups
- Most well known galaxy: our home- the milky way galaxy, residing in a group called local group.

Our Home: The Milky Way Galaxy
Image credit: NASA

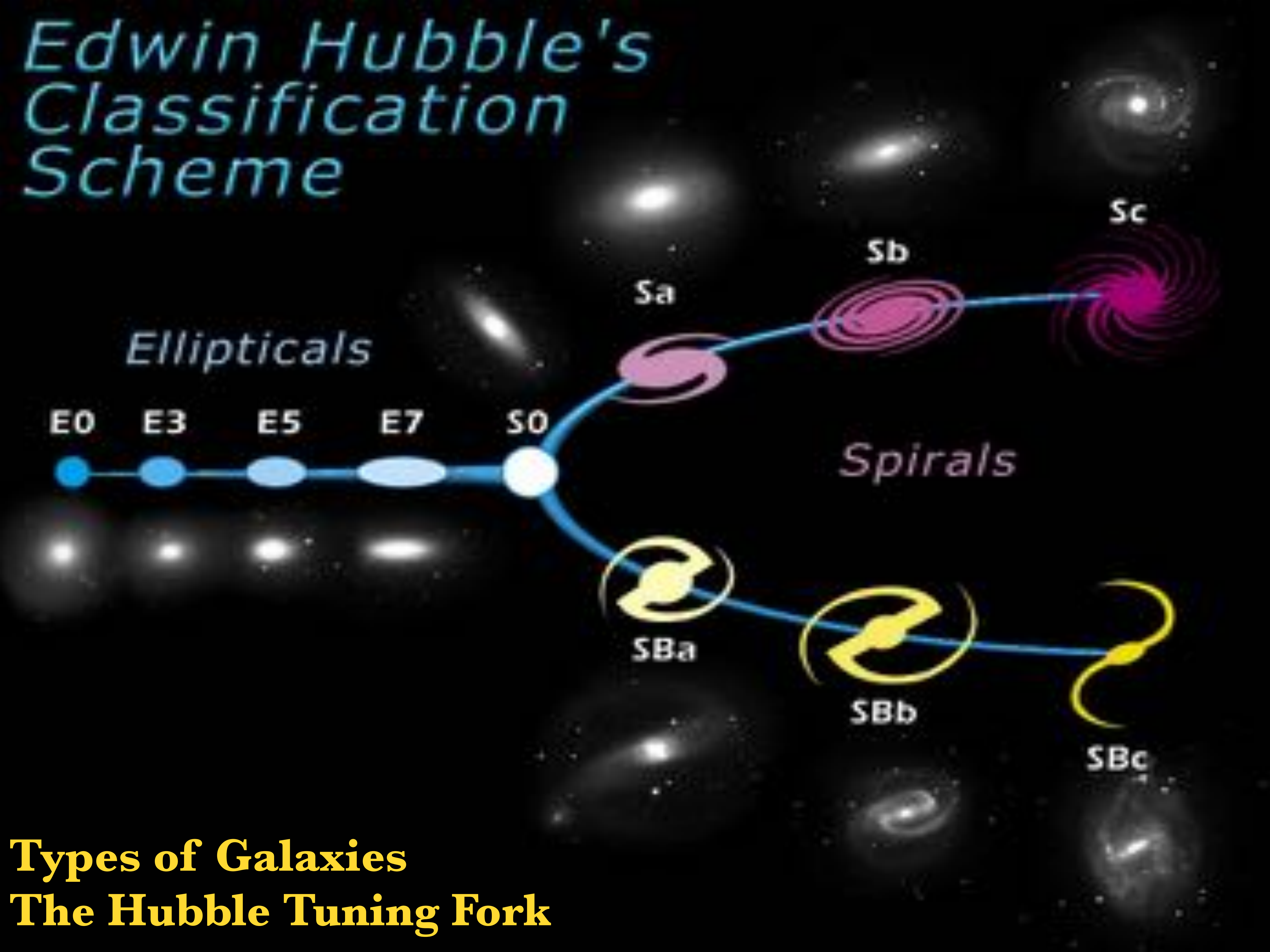
The Milky Way as seen from Earth

- The Milky Way is a highly flattened, disk shaped galaxy comprising about 200 billion (2×10^{11}) stars and other objects like molecular clouds, globular clusters etc.
- Very Huge,would require 100,000 years to travel from one end to another
- Diameter: 30 kpc



The Milky Way as seen from the Earth.

- Solar system is located at a distance of about 8.5 kpc from the centre of the galaxy
- Mass of Milky Way: $2 \times 10^{11} M_{\odot}$
- Galaxy can be divided into three different parts: (a) a central bulge (b) the flattened galactic disk (c) a Halo
- Belongs to the Local Group: a group of 3 big and 30 small odd galaxies.
- Nearest galaxy: Andromeda Galaxy (M31).
- Few dwarf galaxies as satellites or companions: The Large and Small Magellanic Clouds



Types of Galaxies
The Hubble Tuning Fork

The Hubble Tuning Fork

- Galaxies are classified according to their shapes in optical (visible-light) images

- The most common classification scheme in use today is the Hubble classification scheme, or *Hubble tuning fork*

- In this scheme, galaxies are classified into the following broad categories: ***ellipticals, spirals, and irregulars.***

- The ellipticals are smooth and round or elliptical. The ellipticals are sub-divided by how round they are (E0 to E7). E0 is almost round and E7 the most elliptical
- S0: Lenticular galaxies, transition between ellipticals and Spirals.

- The spirals are flat with a spiral pattern in their disk. Spirals are further classified into ***two types: regular spirals*****,** where the arms come right out of the galaxy centre, or ***barred spirals,*** with the arms starting from the ends of a bar of gas and stars going through the centre. Again sub-divided by how loose their arms are and how big their bulge is.

- The irregulars have stars and gas in random patches.

The Hubble Tuning Fork

- The spiral galaxies are flat with a spiral pattern in their disk. They were assigned letters from ***"a" to "c".*** **The letters denote the compactness of the spiral arms. "a" being the most compact/tightly wound and "c" being more loosely wound.**

- Spirals are further classified into ***two types: regular spirals (Sa, Sb..)***, where the arms come right out of the galaxy centre, or ***barred spirals (SBa, SBb),*** with the arms starting from the ends of a bar of gas and stars going through the centre.

- Some galaxies did not fit any of the kinds mentioned: odd shapes, dwarf galaxies and others. Those were categorised under Irregular galaxies.

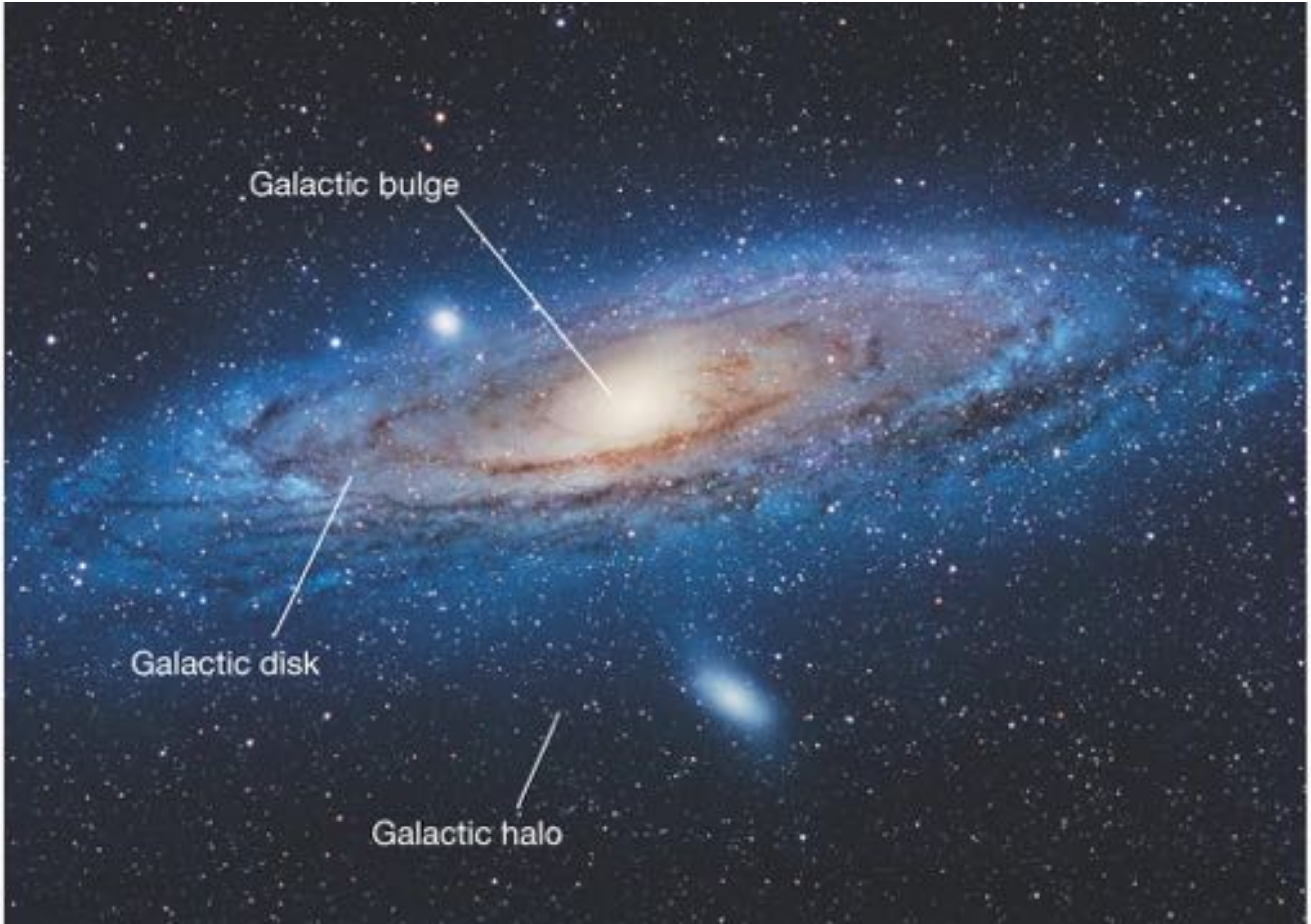
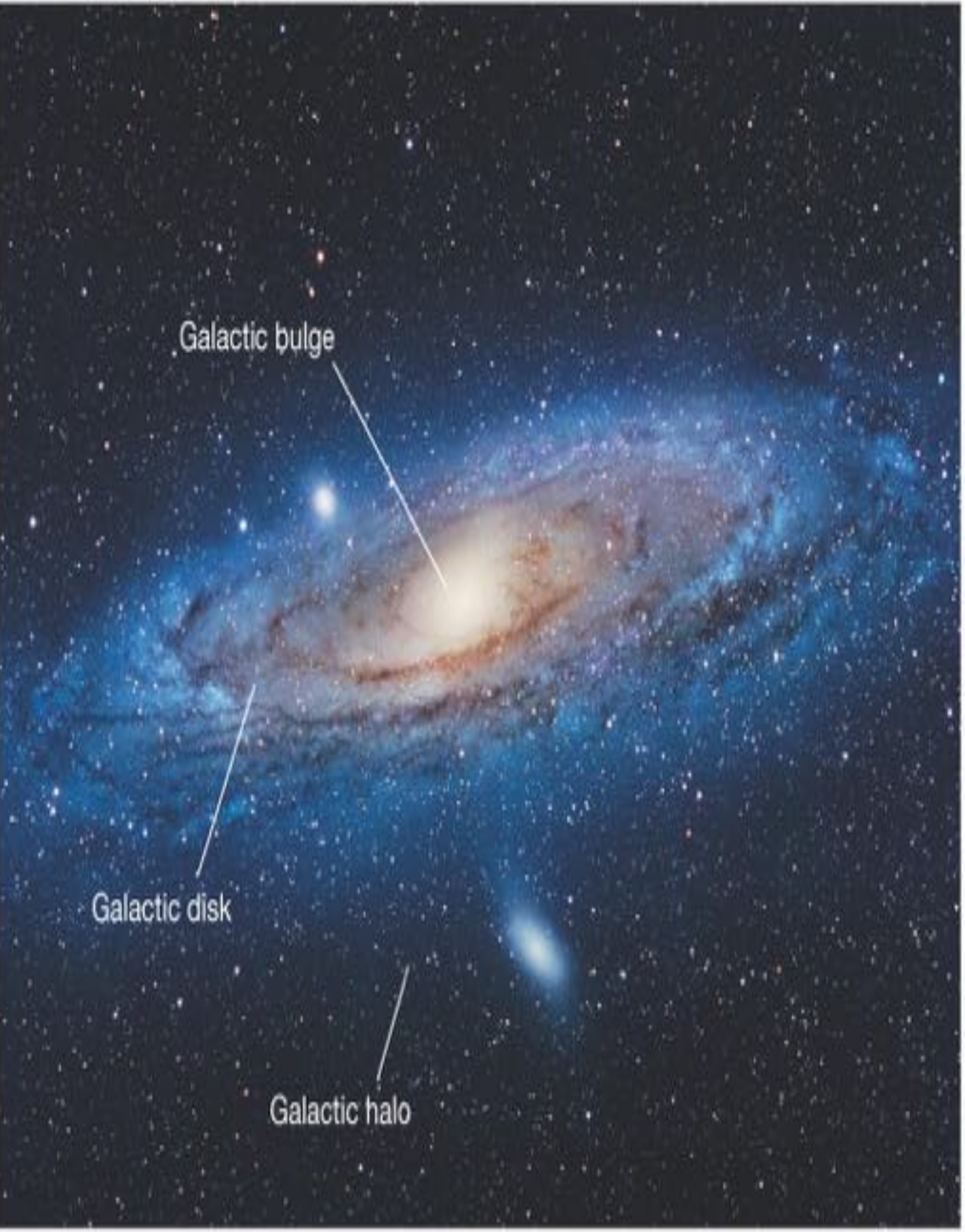


Image Credit: Pearson Education Inc.



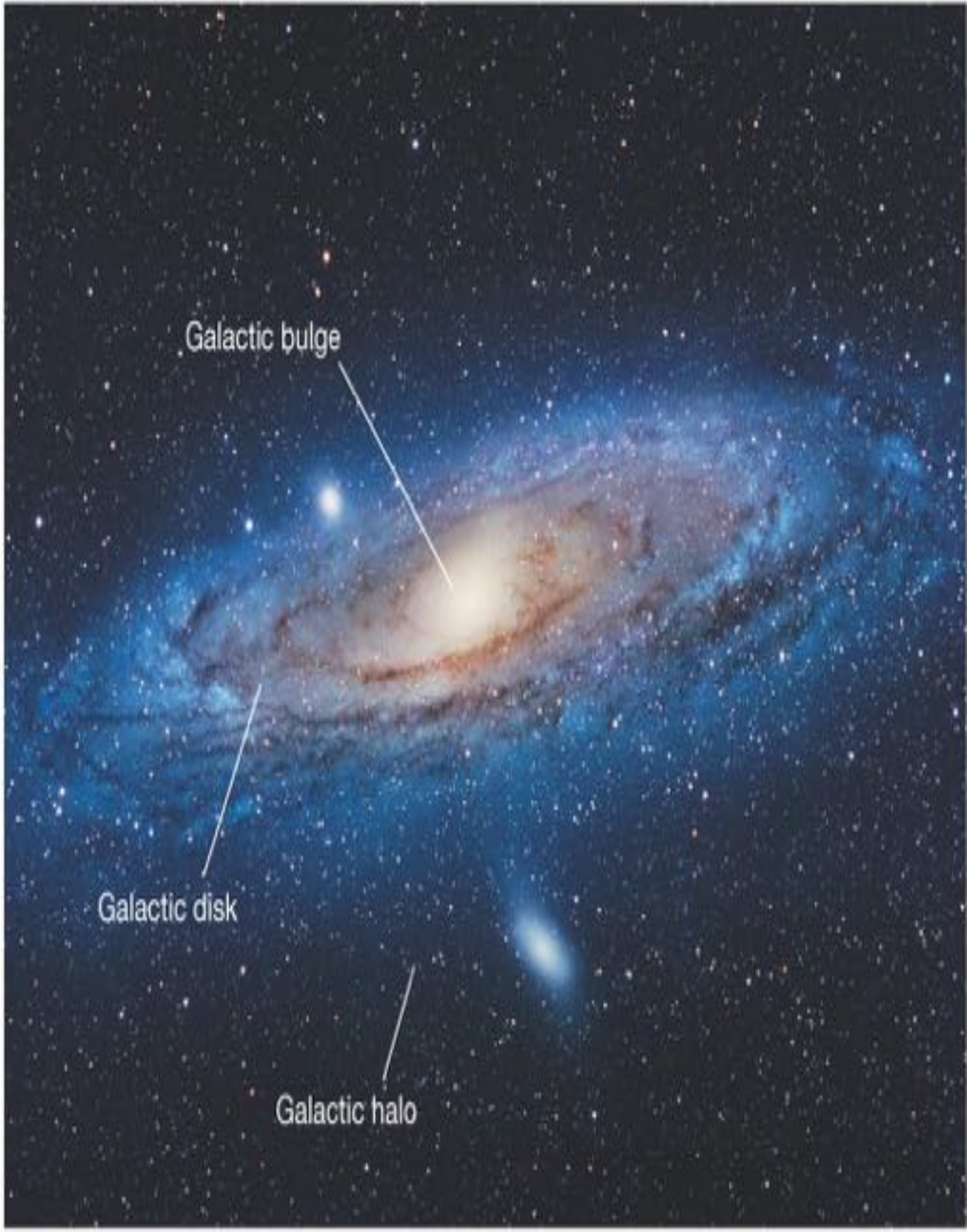
Parts of a Spiral Galaxy

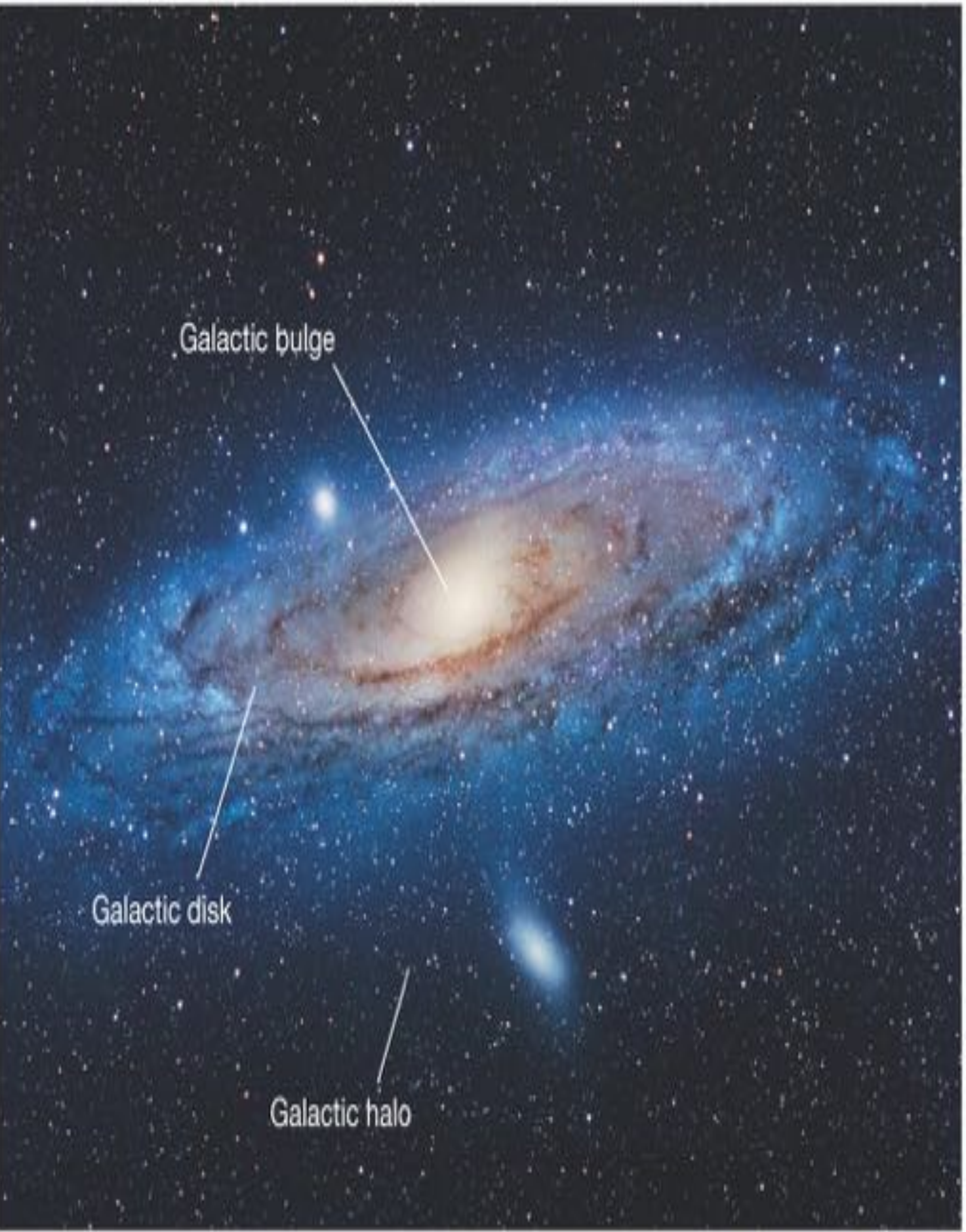
The Central Bulge

- More or less spherical cloud of stars
- Located in the disk region, Cannot see in optical wavelengths
- Because disk region consists of gas and dust: absorbs optical wavelengths
- Total mass of the bulge: $10^{10} M_{\odot}$
- Region consists of gas in the form of molecular clouds and ionised hydrogen.
- Motion of the stars and gas near the centre of the bulge suggests that there could be massive black hole at the centre

The Disk Component

- Flattened disk component has radius of about 15,000 pc.
- Thickness is very small
- Most of the stars are located along the central plane of the disk
- Farther from this plane, density of stars decreases.
- Significant feature: existence of spiral arms
- Spiral arms have: stars called Population I stars, star forming nebulae, and star clusters.





The Halo Component

- Bulge and Disk component surrounded by not so well defined, not so well understood spherical component: Halo component
- Made up of gas and older population of stars.
- These stars exists in vey dense clusters: each cluster having 10^5 to 10^6 stars: Globular clusters.

Thank You……

Active Galaxies

- Normal galaxies: made up of stars and interstellar matter.

- Sometimes, galaxy may additionally have a compact nucleus at its centre giving out abundant amounts of radiation in several bands of electromagnetic spectrum from radio to X-rays.

- Such a galaxy is called an *active galaxy* and its nucleus is called an *active galactic nucleus*, abbreviated as *AGN*.

- Seyfert (1943) noted that some spiral galaxies had unusually bright nuclei.

- Spectra of these nuclei were found to be totally different from the spectra of stars and had strong emission lines.

- So a typical galactic nucleus of this kind could not simply be a dense collection of stars.

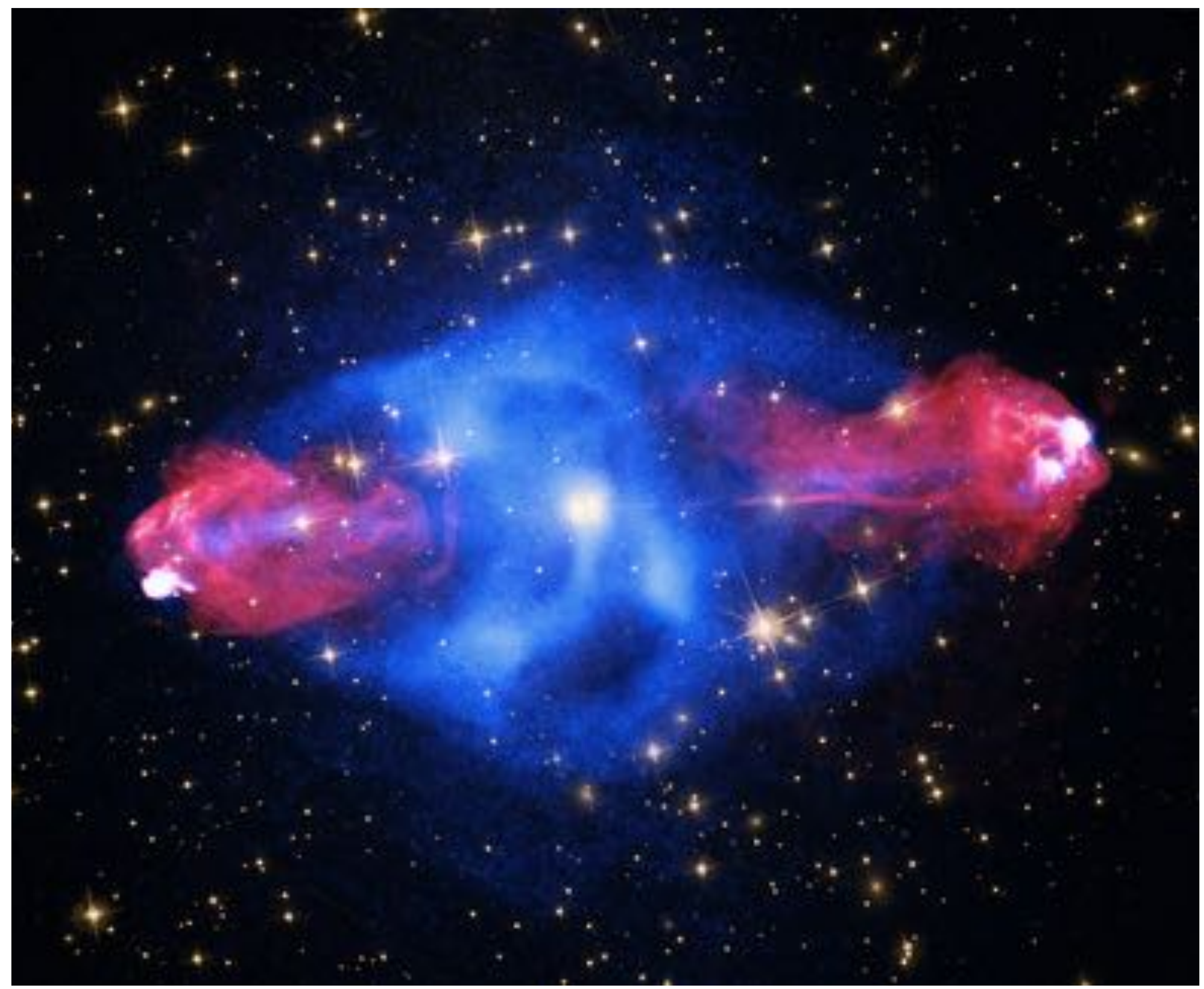
- Depending on whether the emission lines were broad or narrow, these galaxies are now put in two classes.

- Galaxies with nuclei emitting very **broad lines** are called *Seyfert 1* galaxies. On the other hand, if the **emission lines are narrow**, then the galaxies are called *Seyfert 2* galaxies.

NGC 6814, Type I Seyfert galaxy

Circius Galaxy, A type II Seyfert

- Next, it was found that some galaxies emitted radio waves.
- As resolutions of radio telescopes improved, it became possible to study the detailed natures of these so-called *radio galaxies*.
- In 1953, Jennison and Das Gupta discovered that the radio emission of the galaxy Cygnus A comes from two lobes located on two sides of the galaxy lying quite a bit outside the optical image of the galaxy.



Radio lobes of Cygnus A.
Image Source: Wikipedia

- Common in radio galaxies.

Question: What is the source of energy for powering radio emission from these lobes lying so far outside the galaxies?

- At first sight, radio galaxies seemed to have nothing in common with Seyfert galaxies

- Seyfert galaxies are spiral galaxies with bright nuclei.

- On the other hand, the radio galaxies, which were *mostly found to be elliptical galaxies*, have the radio emissions coming from lobes lying outside the galaxies.

- When astronomers started probing the lobes of the radio galaxies, it occurred to them that they do have something in common with the Seyfert galaxies.
- It was found that often oppositely directed radio-emitting jets were squirted out of the central regions of radio galaxies
- These jets, which are presumably made of plasma flowing out at very high speed, made their ways by pushing away the intergalactic medium surrounding the galaxies,
- The lobes are located where the jets are finally stopped by the intergalactic medium.
- It appears that the ultimate source of energy of a radio galaxy lies in its nucleus that produces the jets.

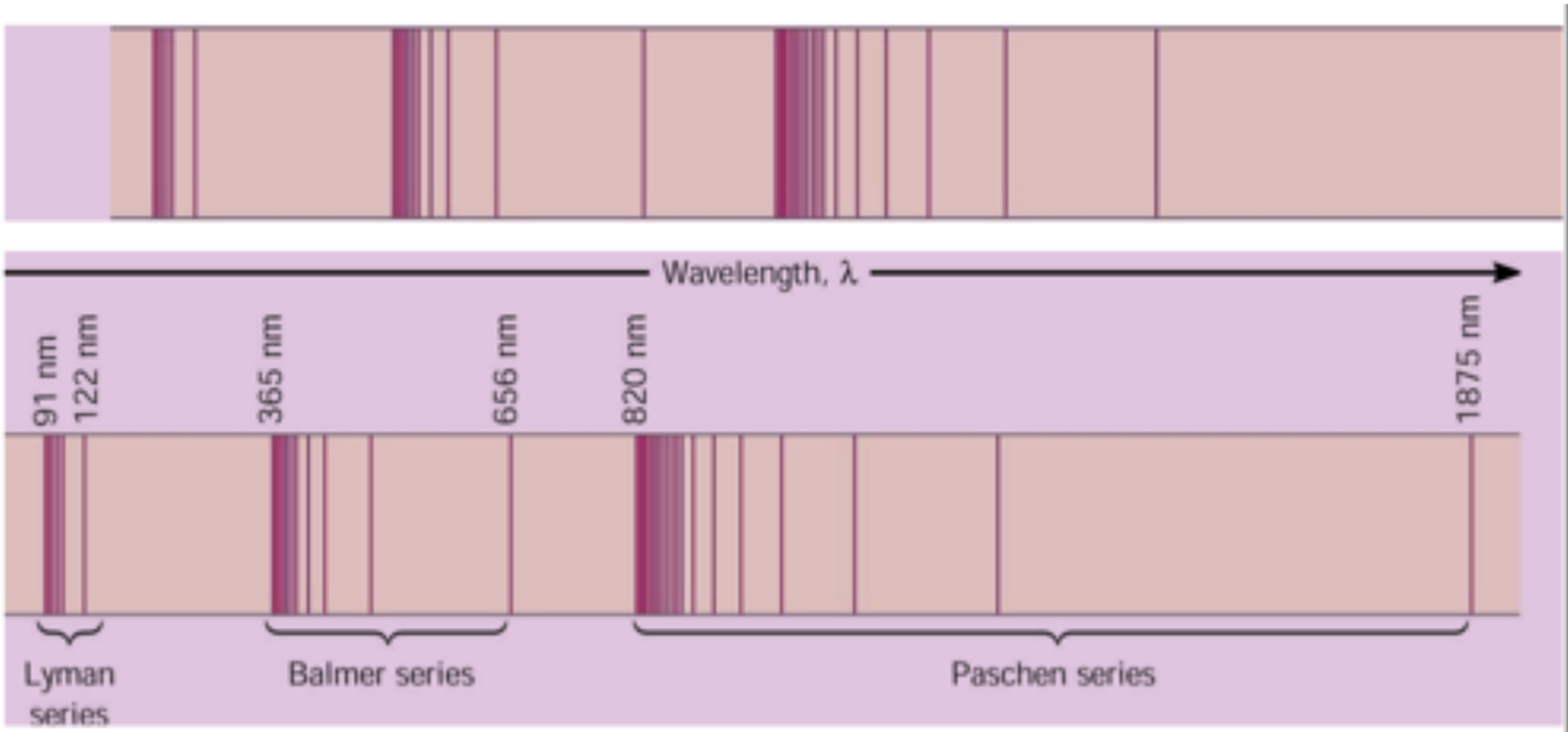
- Like Seyfert galaxies, **radio galaxies are also galaxies which have active nuclei.**

- *Quasars*, which are the most extreme examples of active galaxies, came to the attention of astronomers in a dramatic fashion.

- These are radio sources of very compact size, some of which could be identified with optical sources looking very much like stars.

- However, these optical sources were found to have broad emission lines in the spectra, which seemed mysterious and non- identifiable at first.

- Finally Schmidt (1963) identified the spectral lines of the quasar 3C 273 to be nothing other than the ordinary spectral lines of hydrogen redshifted by an amount $z = 0.158$, which was considered an unbelievably large redshift at that time.



Redshifted spectral lines

SDSS image of Quasar 3C273
Image source: Wikipedia

Artist's concept of quasar J0313-1806, currently the most distant quasar known.
Image source: earthsky.org

- Spectral lines of many other quasars were soon identified to be ordinary lines which had undergone even larger redshifts

- Implied that these quasars must be lying at enormous distances – beyond the distances of most ordinary galaxies known at that time.

- If the quasars were really at such distances and still appeared so bright, then the typical luminosity of a quasar should be of order 10^{39} W, making it more than 100 times brighter than an ordinary galaxy.

"Stars" are now much farther compared to Seyferts!

- Gradually, over several years, astronomers came to accept the fact that quasars are really far-away objects and must be awesome energy-producing machines.

- In the case of at least a few nearby quasars, it became possible to show that they reside inside galaxies and must be nuclei of galaxies.

- It may be noted that the spectra of central regions of Seyfert 1 galaxies look very similar, whereas the emission lines in the spectra of Seyfert 2 galaxies are narrower

- The similarity in spectra suggests that *Seyfert galaxies and quasars may be similar kinds of active galaxies,* the Seyfert galaxies being the **milder form** of such active galaxies, whereas the **quasars are the more extreme and rarer form** which can be detected at very large distances where Seyfert galaxies would not be observable.

Summary till now:

- Galaxies are of two types: **Normal and Active Galaxies**
- Active Galaxies are: **Seyfert Galaxies, Radio galaxies and Quasars**
- All these galaxies have a Active Nuclei known as Active Galactic Nuclei
- Arrived at the question: What Powers an Active Galactic Nuclei………

Main question: What powers an active galactic nucleus, making it able to produce huge amounts of energy in a very small volume?

Supermassive Blackhole: Sagittarius A* (Sgr A*)

- Sagittarius A is a complex radio source located at the centre of the Milky Way.
- The radio source consists of the *supernova remnant Sagittarius A East*, *the spiral structure Sagittarius A West,* and the ***bright compact radio source at the centre of the spiral structure, called Sagittarius A*.***
- ***Sagittarius A* (pronounced "Sagittarius A-star") is the supermassive black hole at the centre of our galaxy.***
- Cannot be seen in optical wavelengths
- Source is hidden from view by large dust clouds in the Milky Way's spiral arms

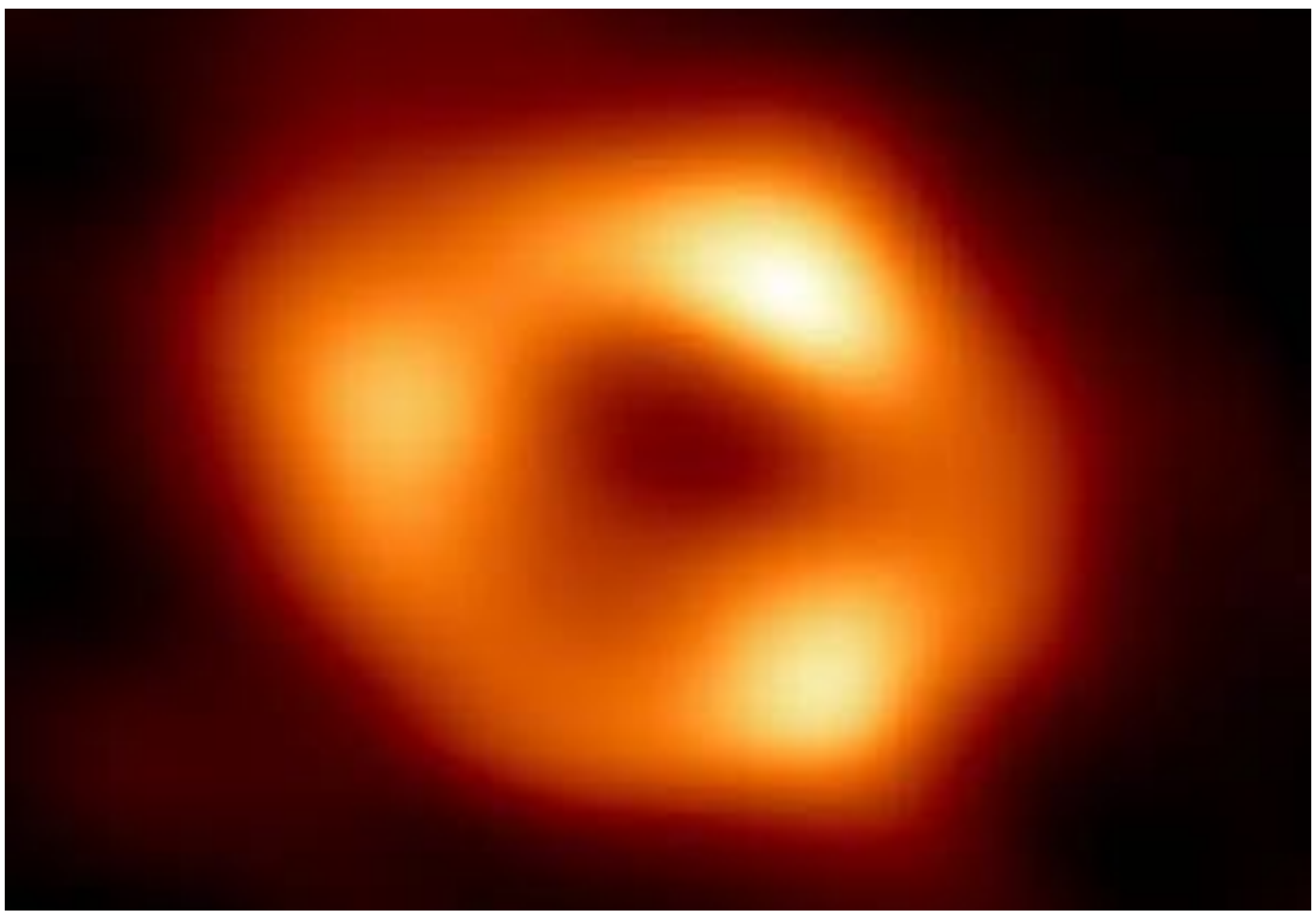
Supermassive Blackhole: Sagittarius A* (Sgr A*)

- Best observed in the **Infrared and Radio Bands.**
- These radio and infrared emissions come from dust and gas being heated to millions of degrees as they fall into the central black hole.
- It has a mass of 4.154 million Suns packed within a diameter of 51.8 million kilometres (32.2 million miles).
- Sagittarius A name was given by John D. Kraus, Hsien-Ching Ko, and Sean Matt (Ohio State University), who listed all the radio sources they detected in the sky and arranged them by constellation in 1954.
- The letter A denoted the brightest radio source in Sagittarius, the Archer.

Supermassive Blackhole: Sagittarius A* (Sgr A*)

- The asterisk (*), pronounced "star," was added by Robert L. Brown in 1982 because the source was considered "exciting."

- The first image of Sagittarius A* was revealed at a press conference held on May 12, 2022. Produced by the Event Horizon Telescope (EHT) Collaboration.



First image of Sgr A*. Image Source: EHT

- The Event Horizon Telescope (EHT), an array which linked together **eight existing radio observatories across the planet to form a single "Earth-sized"** virtual telescope.

- The telescope is named after the event horizon, the boundary of the black hole beyond which no light can escape.

- Although we cannot see the event horizon itself, because it cannot emit light, **glowing gas orbiting around the black hole reveals a telltale signature: a dark central region (called a shadow) surrounded by a bright ring-like structure.**

- The new view captures light bent by the powerful gravity of the black hole, which is four million times more massive than our Sun. The image of the Sgr A* black hole is an average of the different images the EHT Collaboration has extracted from its 2017 observations.

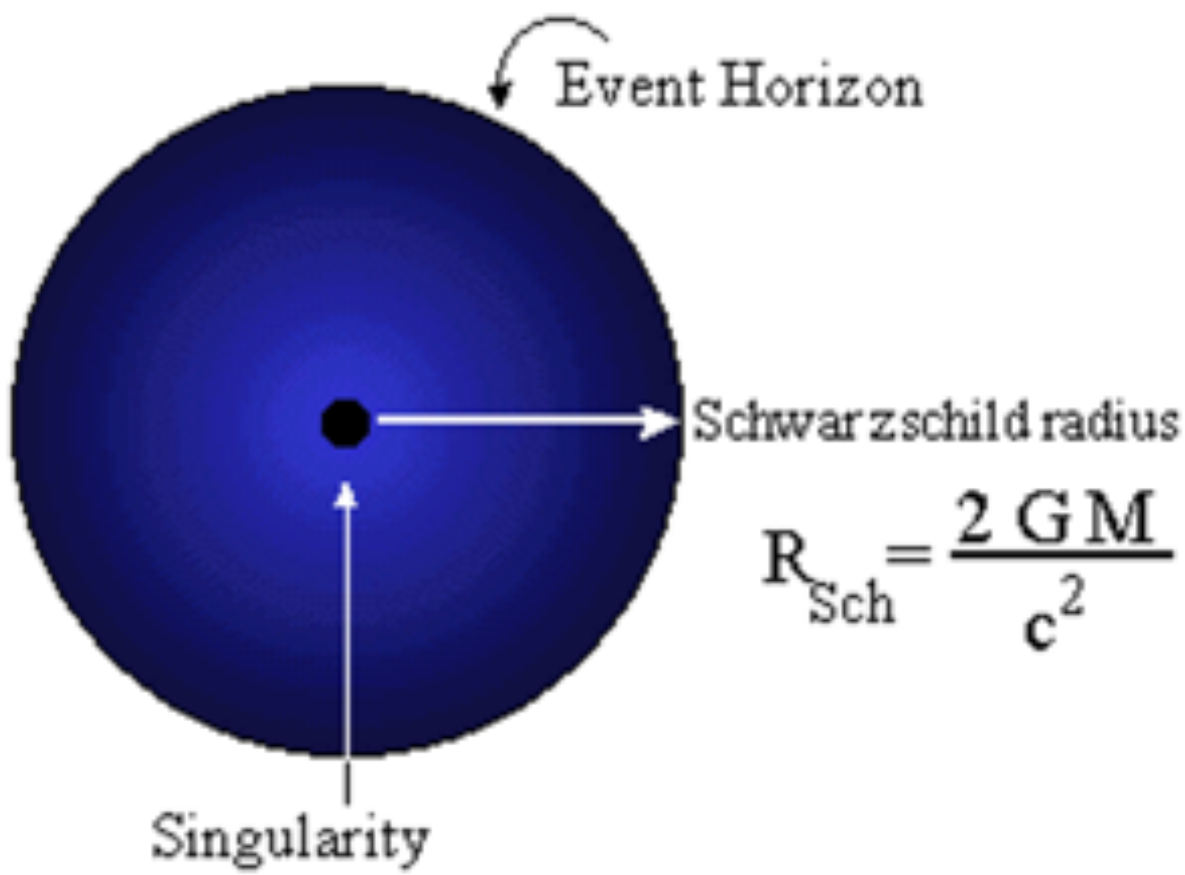
Black Holes: A Theoretical Definition (A Review)

- An area of space-time with a gravitational field so intense that its escape velocity is equal to or exceeds the speed of light.
- The important thing is that this area can be of any size
- As you all know that the speed of light is a finite value in a vacuum.

- In terms of gravitational force, every object has an escape velocity as

$$v_{esc} = \sqrt{\frac{2GM}{r}}$$

- From that Schwarzschild Radius can be easily found (radius of the event horizon).
- All comes down to a matter of density.



Types of Black Holes:

- "Normal Sized" Black Holes
- Microscopic (Primordial) Sized
- Super-Massive Black Holes (On the order of millions to billions of Solar Masses)
- (Estimated 3 million solar masses for Milky Way Black Hole)

- Most Black Holes are believed to come about from the death of massive stars.

Stellar Evolution (Brief)

- Star (Mass of Hydrogen) is massive enough (M > 0.1 Msun) to ignite fusion
- Star performs stable core fusion (first H->HE)
- Cycle repeats if star is big enough until the core is Fe.
- Star is in a kind of onion peel structure of elemental layers

- After fusion cycles through and star's core is Fe, if the star now is M < 1.4 Msun , the star will supernova as a Type II supernova. Otherwise, it becomes a white dwarf, supported by degenerate electron pressure.

- This mass limit for supernovas is the Chandrasekhar limit.

- If the star the went supernova was between 1.4 and 3 Msun , then the remnant will be a Neutron Star supported by degenerate neutron pressure (Pulsar).

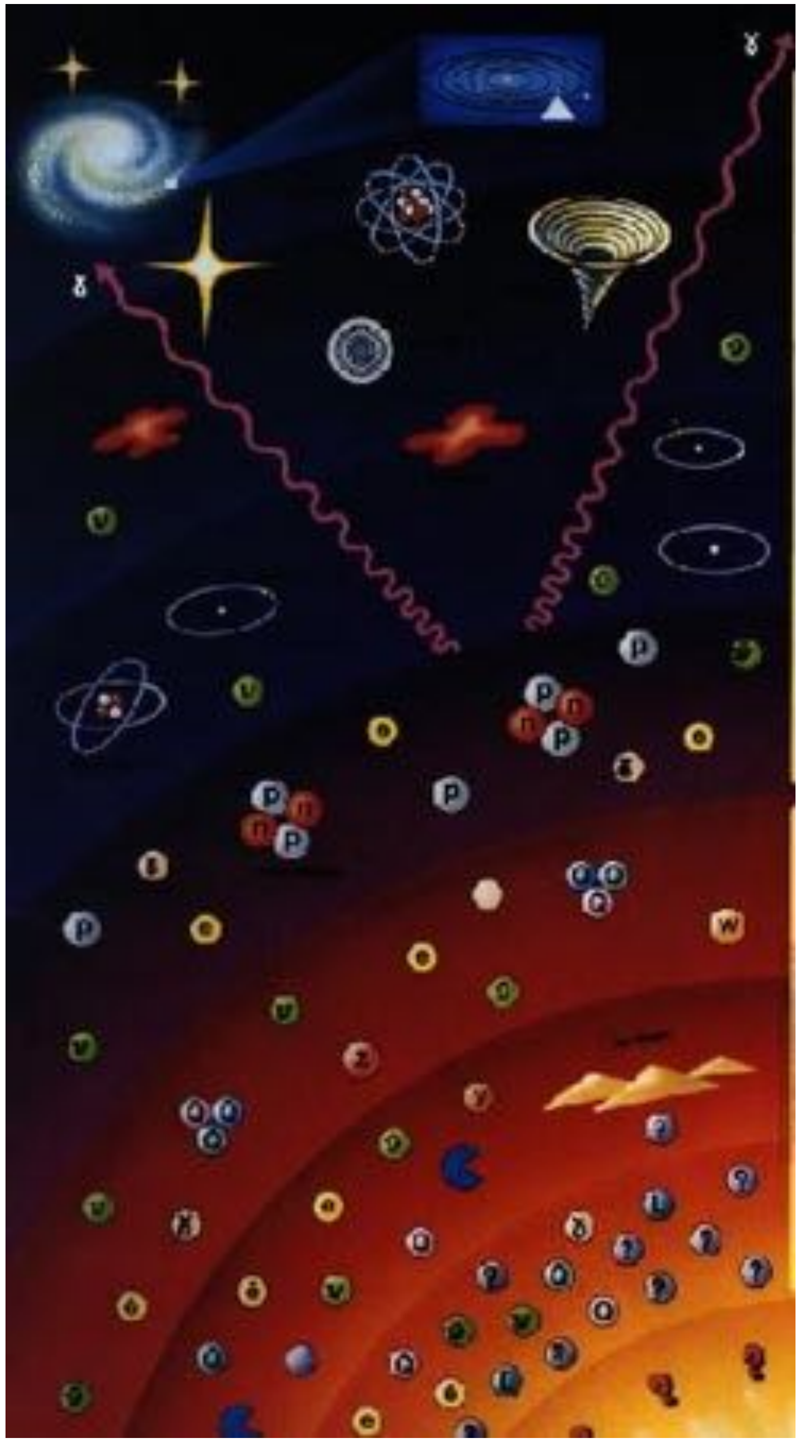
- Otherwise, $M_{final} > 3M_{\odot}$, and the result is a black hole because the is no source of outward pressure

How did Super-Massive Black Holes come about?--theories

- From “Lumps” in the early universe
- The “Stellar Seed” Model
- Collapse of a whole star cluster

Lumps from the early Universe

- In the “Big Bang” the whole universe was in a really dense state. So much that perhaps lumps could have formed and of matter dense enough that a black hole was formed.
- There was enough surrounding matter that galaxies formed around the lumps
- Could explain why pockets of interstellar gas never became galaxies



The Stellar Seed Model

Provided that the surrounding environment is sufficiently rich in matter, a giant black hole could result in an initial "stellar seed" of 10 $M_\odot$ produced during a supernova.

Collapse of a whole cluster

If the stars of a tight knit cluster of the moderately young Universe had all relatively the same size stars (above the Chandrasekhar Limit), there would be quite a few Black Holes forming simultaneously causing smaller stars to be absorbed, and black holes to combine.