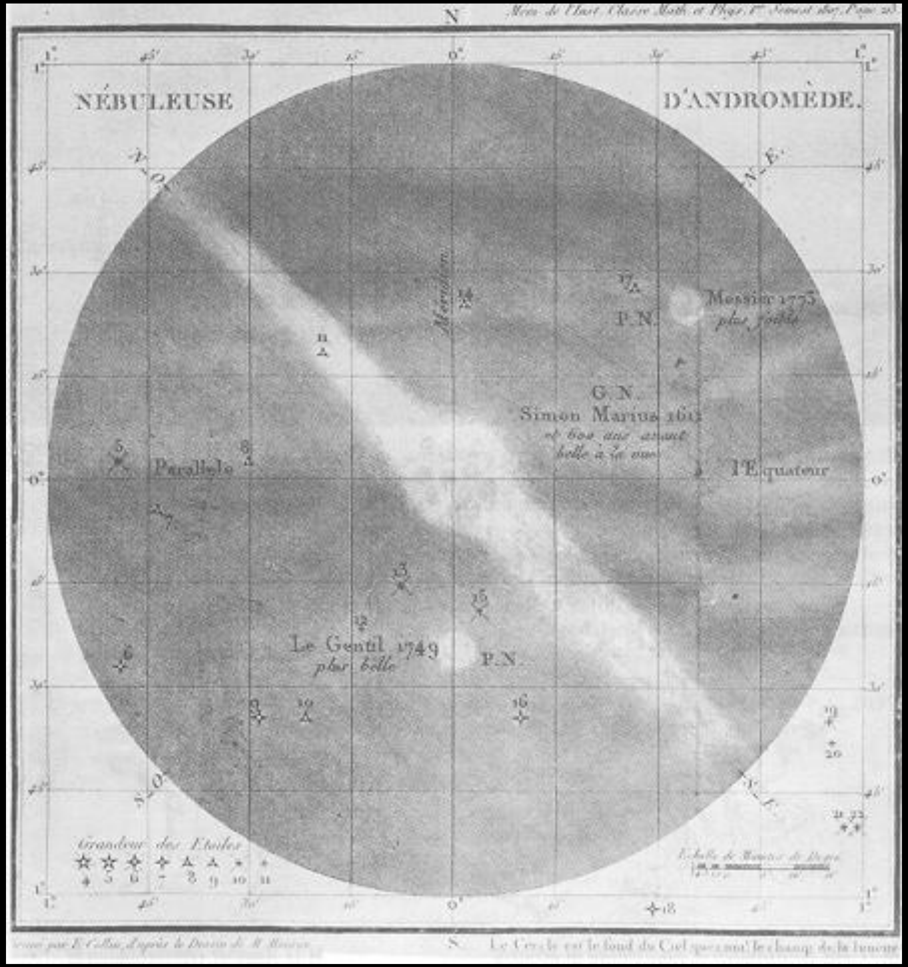
Galaxy Classification

1. Historical Origins of Galaxy Classification

Early Observations

Before the twentieth century, galaxies were generally referred to as "nebulae." Through small telescopes they appeared as faint cloudy patches in the night sky. Astronomers debated whether these objects were nearby gas clouds within the Milky Way or distant stellar systems far beyond it.

The limitations of nineteenth-century telescopes prevented astronomers from resolving individual stars within these objects. Some spiral nebulae showed visible structure in long photographic exposures, but their true nature remained uncertain.



Messier's Andromeda Nebula M31 drawing was published in 1807 in the *Recueil de l'Institute*

2. Historical Origins of Galaxy Classification

The "Great Debate"

A major turning point occurred during the 1920 Shapley–Curtis debate between the two American astronomers.

Harlow Shapley argued that the Milky Way was so enormous that all nebulae existed within it.

Heber Curtis argued instead that spiral nebulae were separate "island universes" — galaxies in their own right.

The debate was ultimately resolved through distance measurements.

Harlow Shapley

Heber D. Curtis

3. Historical Origins of Galaxy Classification

Edwin Hubble and the Discovery of External Galaxies

American astronomer Edwin Hubble used the Cepheid variables to determine distances to stars in the Andromeda Nebula. Henrietta Swan Leavitt discovered that Cepheid variable stars have a predictable relationship between brightness and pulsation period, they can be used as “standard candles.”

Hubble demonstrated that Andromeda lay far beyond the Milky Way, proving it was an entirely separate galaxy. This discovery dramatically expanded humanity’s understanding of the universe.

In 1926 Hubble introduced the first major galaxy classification system.

Edwin Hubble

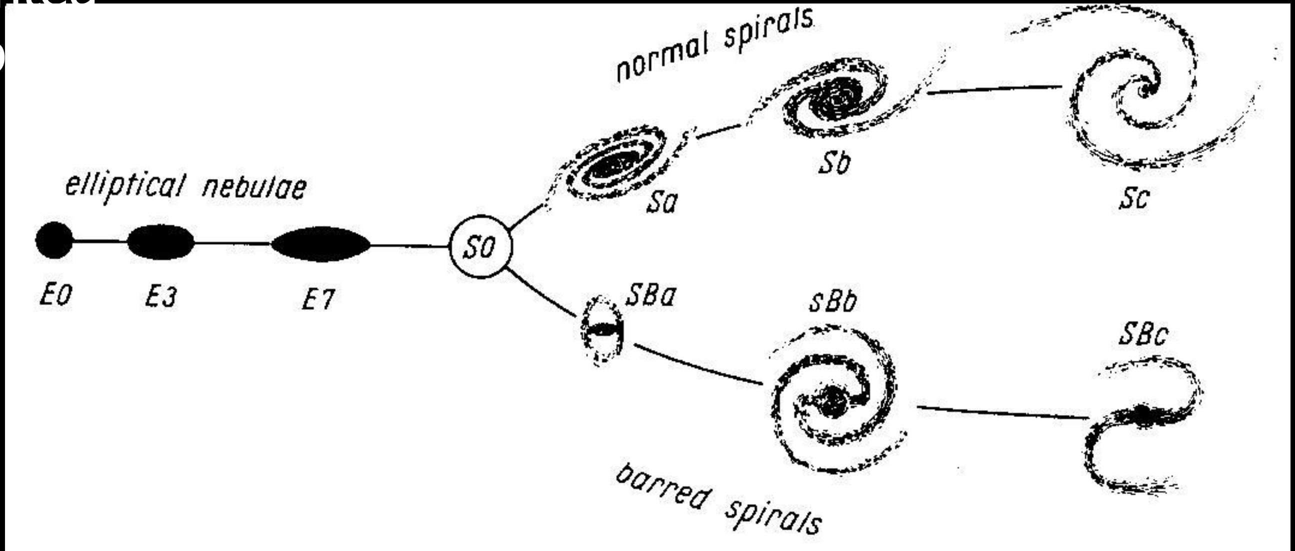
Henrietta Swan Leavitt

4. The Hubble Sequence

The Tuning Fork Diagram

Hubble's classification system is often represented as a tuning fork diagram. Galaxies were group according to visible morphology into:

- Elliptical galaxies (E)
- Spiral galaxies (S)
- Barred spiral galaxies (SB)
- Irregular galaxies (Irr)



The Hubble sequence remains one of the most widely recognized systems in astronomy.

5. Importance of Morphology

Morphology is the study of form, structure, and configuration, to analyze systems (shape, size, structure)

The Hubble sequence remains one of the most widely recognized systems in astronomy.

Although early astronomers sometimes interpreted the sequence as an evolutionary path, modern astronomy shows galaxy evolution is considerably more complex.

Galaxy shape reveals:

- Distribution of stars
- Presence of gas and dust
- Degree of star formation
- Rotational dynamics
- Interaction history

Morphology therefore provides insight into galactic evolution.

6. Elliptical Galaxies

Structure and Appearance

Elliptical galaxies are smooth, featureless systems with approximately ellipsoidal shapes. Unlike spiral galaxies, they lack visible arms or dust lanes.

Their stellar populations are dominated by older, redder stars.

Classification System

Ellipticals are classified from E0 to E7 according to their apparent elongation.

- E0 galaxies are nearly spherical
- E7 galaxies appear highly elongated

The classification is based on the ratio of the major and minor axes.

Messier 87 Galaxy Profile

Designation:	M87 or NGC 4486
Type:	Elliptical
Diameter:	120,000 ly
Distance:	53 Mly
Mass:	2,400 billion M⊙
Number of Stars:	1 trillion
Constellation:	Virgo
Group:	Virgo Cluster

7. Elliptical Galaxies

Physical Characteristics

Elliptical galaxies generally contain:

- Little cold gas
- Minimal dust
- Low star formation rates
- Old stellar populations

Because they lack large reservoirs of gas, few new stars form within them.

Formation

Modern evidence suggests many elliptical galaxies form through mergers between spiral galaxies. Gravitational interactions randomize stellar orbits and disrupt disk structures.

Large elliptical galaxies are common in dense galaxy clusters.

8. Spiral Galaxies

General Structure

Spiral galaxies contain:

- A rotating stellar disk
- Spiral arms
- A central bulge
- A surrounding dark matter halo

The Whirlpool Galaxy, shown in this image from the Hubble Space Telescope, is an example of a grand design spiral galaxy.

Spiral Arms

The spiral arms are regions of active star formation. Massive young blue stars illuminate these arms, while dark dust lanes trace cold interstellar gas.

The arms are not rigid structures. Instead, they are thought to result from density waves moving through the galactic disk.

9. Spiral Galaxies

Spiral Classification

Spiral galaxies are classified as:

Sa, Sb, Sc

Sa galaxies have:

Large central bulges, Tightly wound arms, Less active star formation

Sc galaxies have:

Small bulges, Loosely wound arms, Significant gas content, Strong star formation

Star Formation

Spiral galaxies are often rich in gas and dust, making them active stellar nurseries.

Star formation occurs when gas clouds collapse under gravity, often triggered by compression in spiral density waves.

10. Spiral Galaxies - rotation

11. Barred Spiral Galaxies

Bar Structures

Barred spiral galaxies contain elongated stellar bars crossing their central regions. The spiral arms emerge from the ends of these bars. Observations suggest that roughly two-thirds of spiral galaxies possess bars.

Dynamical Importance

Bars play a major role in galactic evolution by transporting gas inward toward the galactic center. This inward flow can:

- Trigger central star formation
- Feed supermassive black holes
- Reshape galactic structure over time

Bars are therefore important drivers of secular evolution, acting as catalysts for the slow, internal restructuring of galaxies over billions of years.

The Hubble telescope captured a display of starlight, glowing gas, and silhouetted dark clouds of interstellar dust in this image of the barred spiral galaxy NGC 1300. NGC 1300 is considered to be prototypical of barred spiral galaxies

12. Lenticular Galaxies

Transitional Systems

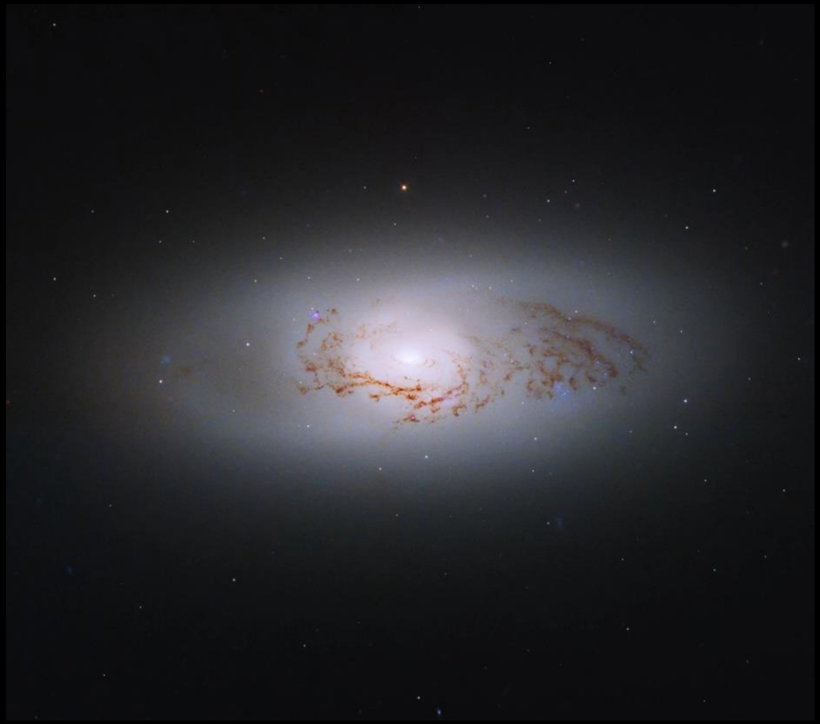
Lenticular galaxies, designated S0 galaxies, occupy an intermediate position between elliptical and spiral galaxies.

They possess:

- A disk structure
- A central bulge
- Little visible gas
- No obvious spiral arms

Environmental Effects

Many astronomers believe lenticular galaxies may form when spiral galaxies lose their gas through interactions within galaxy clusters. Without gas, star formation declines and spiral structure fades.



NASA's Hubble Space Telescope captured this image of the lenticular galaxy NGC 3489. Lenticular galaxies aren't quite spiral galaxies or elliptical galaxies.

13. Irregular Galaxies

Chaotic Structure

Irregular galaxies lack clear organization or symmetry. Unlike spirals and ellipticals, they show no dominant structural pattern.

Causes

Irregular structure often results from:

- Gravitational interactions
- Tidal distortions
- Galaxy collisions
- Gas dynamics

Star Formation

Despite their chaotic appearance, many irregular galaxies experience intense star formation.

The Large Magellanic Cloud (LMC) is a dwarf irregular galaxy that is close to the Milky Way.

14. Dwarf Galaxies

The Most Common Galaxy Type

Dwarf galaxies are small galaxies containing from a few million to several billion stars. Although individually faint, dwarf galaxies are believed to be the most numerous galaxy type in the universe.

Types of Dwarf Galaxies

Major subclasses include:

- Dwarf ellipticals
- Dwarf irregulars
- Dwarf spheroidals

Galactic Interactions

Many dwarf galaxies orbit larger galaxies and can be disrupted through tidal interactions. The Milky Way itself is surrounded by numerous dwarf satellite galaxies.

15. Ring Galaxies

Formation Through Collisions

Ring galaxies possess prominent ring-like structures often filled with bright young stars.These systems are believed to form when one galaxy passes directly through another.

The resulting gravitational disturbance creates outward-moving density waves.
The Cartwheel Galaxy is one of the most famous examples.

Its ring contains intense star formation triggered by the collision.

The Cartwheel Galaxy (catalogue ESO 350-40 and PGC 2248) is a lenticular ring galaxy about 500 million light-years away in the constellation Sculptor. It has a D25 isophotal diameter of 57.69 kiloparsecs (188,200 light-years), and a mass of about 2.9–4.8 billion solar masses; its outer ring has a circular velocity of 217 km/s

16. Polar Ring Galaxies

Unusual Geometry

Polar ring galaxies are among the rarest known galaxy types.

They contain:
- A central host galaxy
- A ring of stars and gas orbiting nearly perpendicular to the host galaxy’s plane

Formation Mechanisms

The polar ring likely forms through:
- Accretion of material from another galaxy
- Galactic mergers
- Tidal capture

This picture is based on data on the polar ring galaxy NGC 4650A that were obtained soon after the MUSE instrument achieved firs light in early 2014. This colour view was created by collapsing the 3D MUSE data into three sections that were coloured blue, green and red. This approximates the natural colours of the object.

17. Active Galaxies

Active Galactic Nuclei

Some galaxies contain extremely energetic centers powered by accretion onto supermassive black holes. These are known as active galactic nuclei (AGN).

Types of Active Galaxies

Examples include:

- Seyfert galaxies
- Radio galaxies
- Quasars
- Blazars

Jets and Energy Output

AGN can produce enormous jets extending far beyond the galaxy itself. The energy released can strongly influence star formation and galactic evolution.

This luminous image from the NASA/ESA Hubble Space Telescope shows Z 229-15, that lies about 390 million light-years from Earth in the constellation Lyra. Z 229-15 is one of those interesting objects defined as several different things: sometimes as an active galactic nucleus (an AGN); sometimes as a quasar; and sometimes as a Seyfert galaxy. Which of these is Z 229-15 really? The answer is that it is all these things all at once, because these three definitions have significant overlap.

18. Galaxy Interactions and Mergers

Galaxies do not evolve in isolation.

Interactions can:

- Distort structure
- Trigger star formation
- Transfer gas
- Produce mergers

Major Mergers

When galaxies merge, their structures can change dramatically. Spiral galaxies may merge to form ellipticals.

The Antennae Galaxies

Antennae Galaxies are a well-known merger system showing long tidal tails and intense starburst activity.

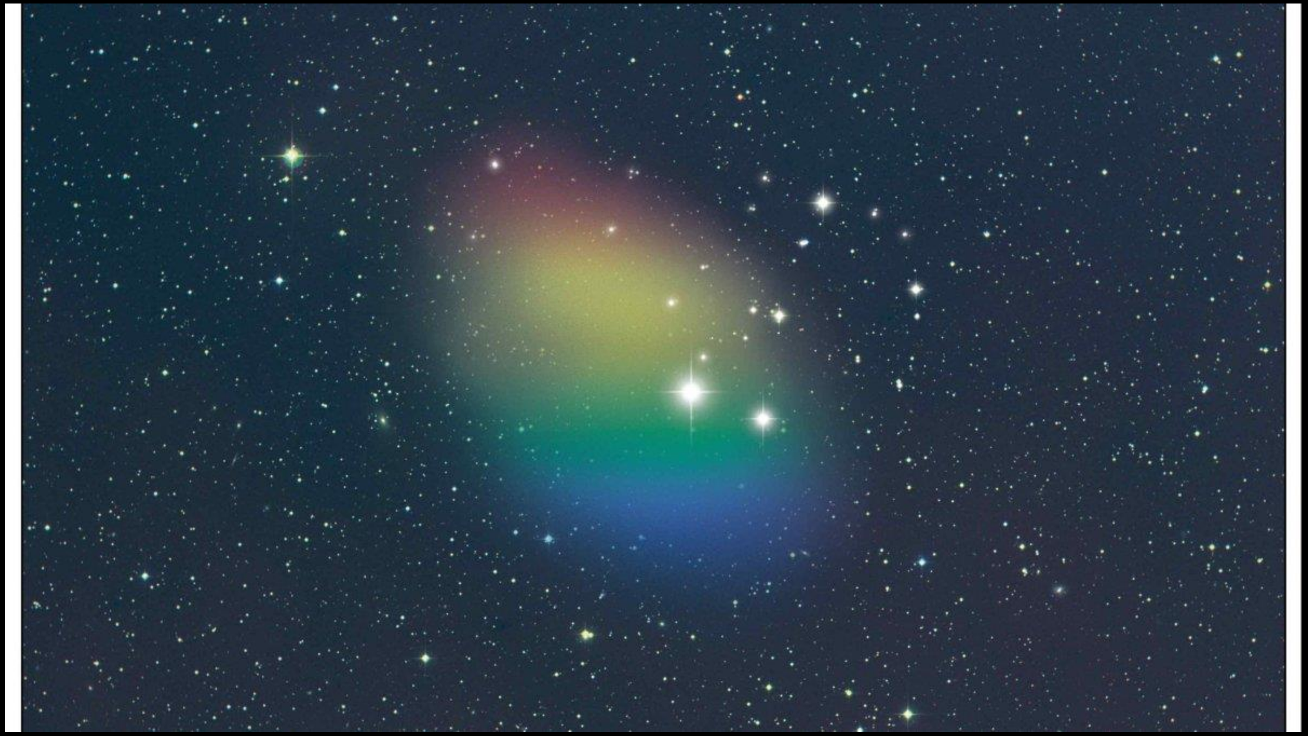
NGC 4038 & NGC 4039. Spiral galaxies that combine as the Antennae are doing will most likely ultimately end up as elliptical galaxies.The merger will erase all traces of their spiral arms. It is likely that when the Milky Way and the Andromeda Galaxies combine, they will look similar to the Antennae during at least one point of their interaction.

19. Dark Galaxies

Gas-only galaxies, often referred to as "dark galaxies" or "starless gas clouds," are isolated, rotating structures composed primarily of dark matter and hydrogen gas with little to no active star formation

Key Characteristics:

These systems are largely invisible to traditional optical telescopes because they lack starlight. Instead, they are detected via radio waves 21cm emission from neutral hydrogen or by observing how their gravity affects nearby visible galaxies.



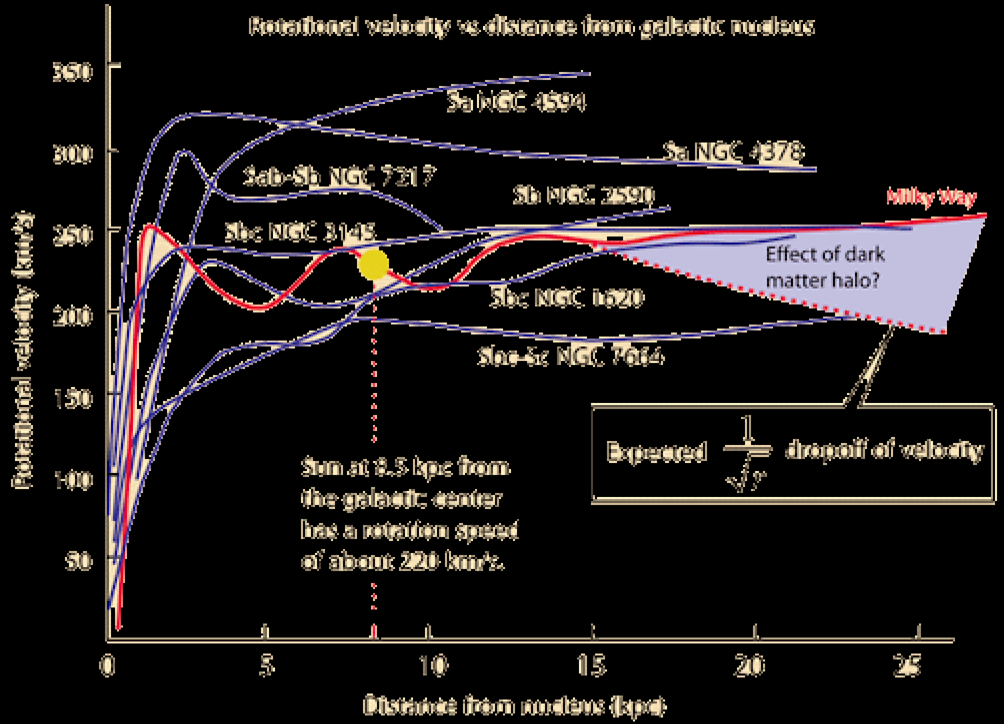
This star field shows a region of space with no known extragalactic sources in it, but where the Green Bank Telescope observed evidence for a large amount of neutral gas in motion, illustrated with the visible colors shown here (red/blue indicates motion away from/toward us). This might be the first dark, primordial galaxy ever discovered.

20. Dark Matter and Galactic Structure

Evidence for Dark Matter

Galaxy rotation curves reveal that visible matter alone cannot explain galactic dynamics.

Stars in outer galactic regions orbit much faster than expected.



Dark Matter Halos

Galaxies are embedded in massive dark matter halos that dominate their gravitational structure.

Dark matter strongly influences:

- Galaxy formation
- Galaxy stability
- Cluster dynamics

The Sun lies about 8.5 kpc from the galactic center of the Milky Way galaxy, and the visible spiral arms and globular clusters extend out to about 15 kpc. But the rotational velocity does not drop off, as shown in the above illustration. This indicates the presence of gravitational mass beyond 15 kpc, but it cannot be detected by any mechanism which has been tried.

21. Modern Classification Systems

Beyond Visual Morphology

Modern astronomy uses many methods beyond visual appearance.

These include:

- Spectroscopy
- Infrared imaging
- Radio observations
- Stellar population analysis
- Kinematic measurements

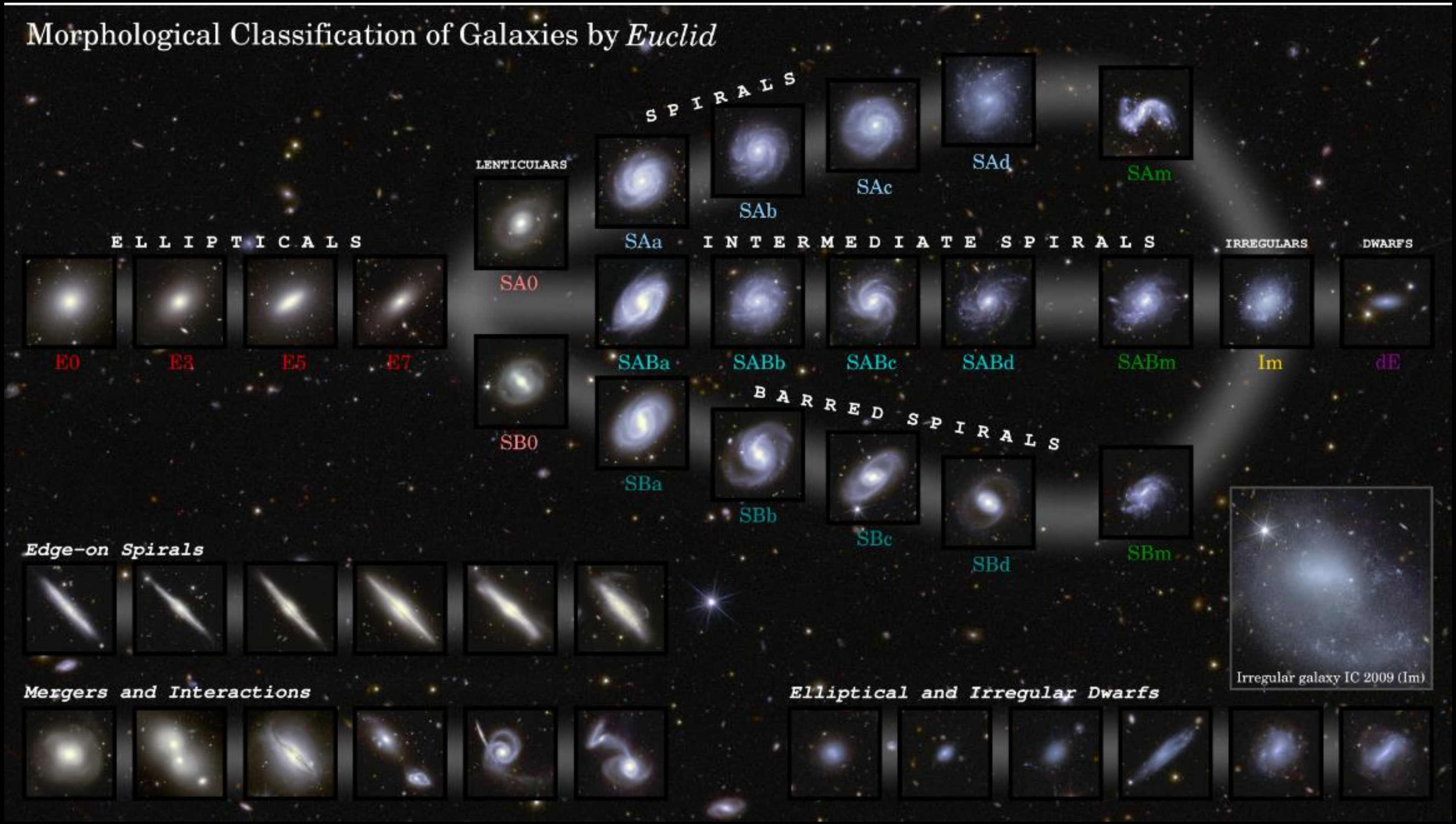
Large Surveys

Projects such as the Sloan Digital Sky Survey have cataloged millions of galaxies. These massive datasets allow statistical analysis of galactic populations.

Machine Learning

Artificial intelligence and machine learning are increasingly used to classify galaxies automatically. These methods are essential for handling the enormous volume of modern astronomical data.

22. Modern Classification Systems



The "Morphological Tuning Fork" of galaxy classifications, re-created using Euclid's high-resolution images from data release Q1

23. Galaxy Evolution

The Cosmic Story

Galaxy classification ultimately helps astronomers understand how galaxies evolve over billions of years.

Evolution depends on:

- Environment
- Gas content
- Dark matter
- Interactions
- Star formation history

Colour and Stellar Populations

Galaxies are often divided into:

- Blue star-forming galaxies
- Red passive galaxies
- Transitional “green valley” galaxies

This colour classification reflects evolutionary state.