Introduction to Astrophysics and Cosmology

Extragalactic astrophysics

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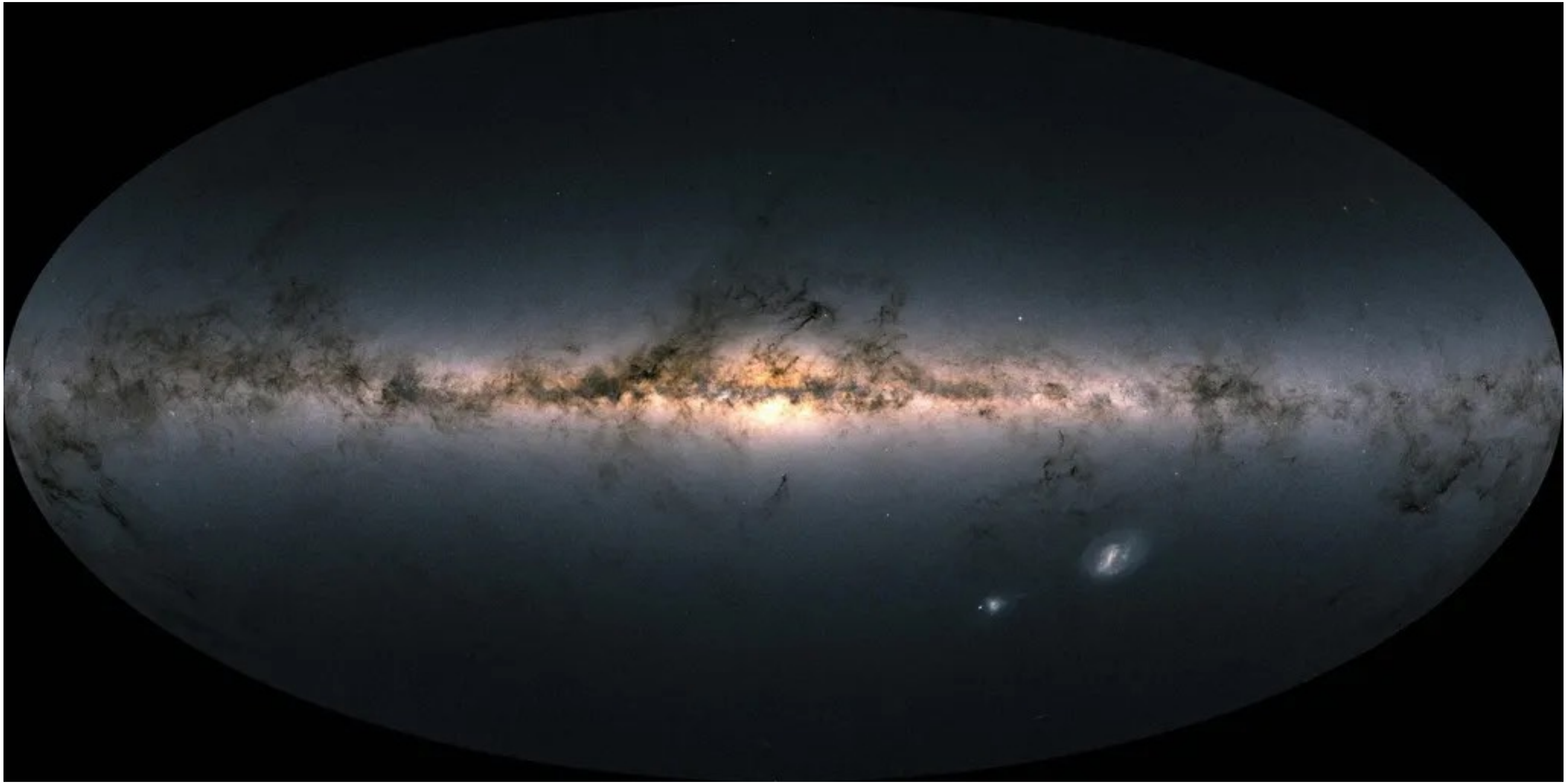
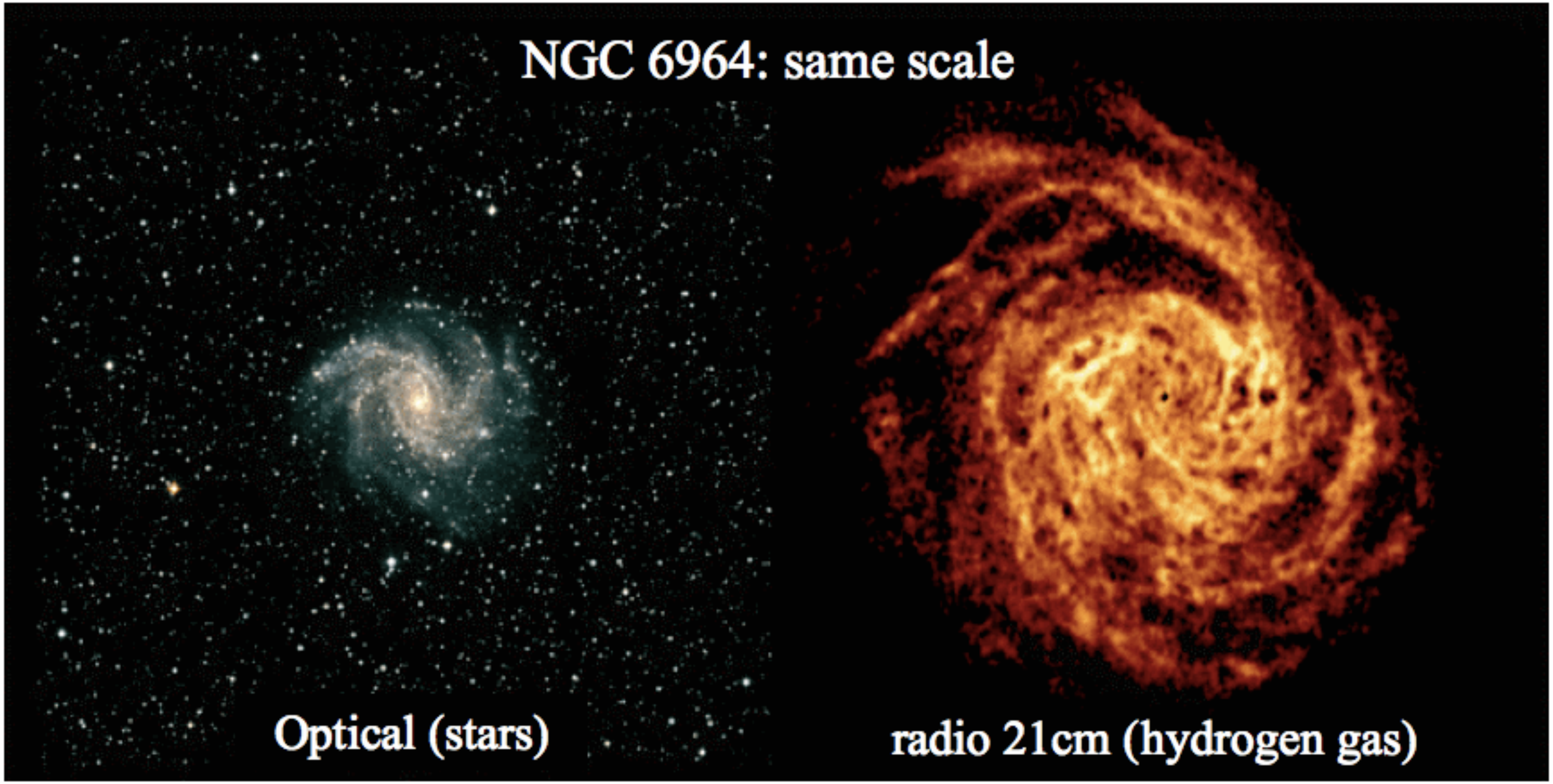
The Milky Way

Stars and dust in the Milky Way
The dust is part of the interstellar medium



A typical spiral galaxy

Face-on view of a spiral galaxy



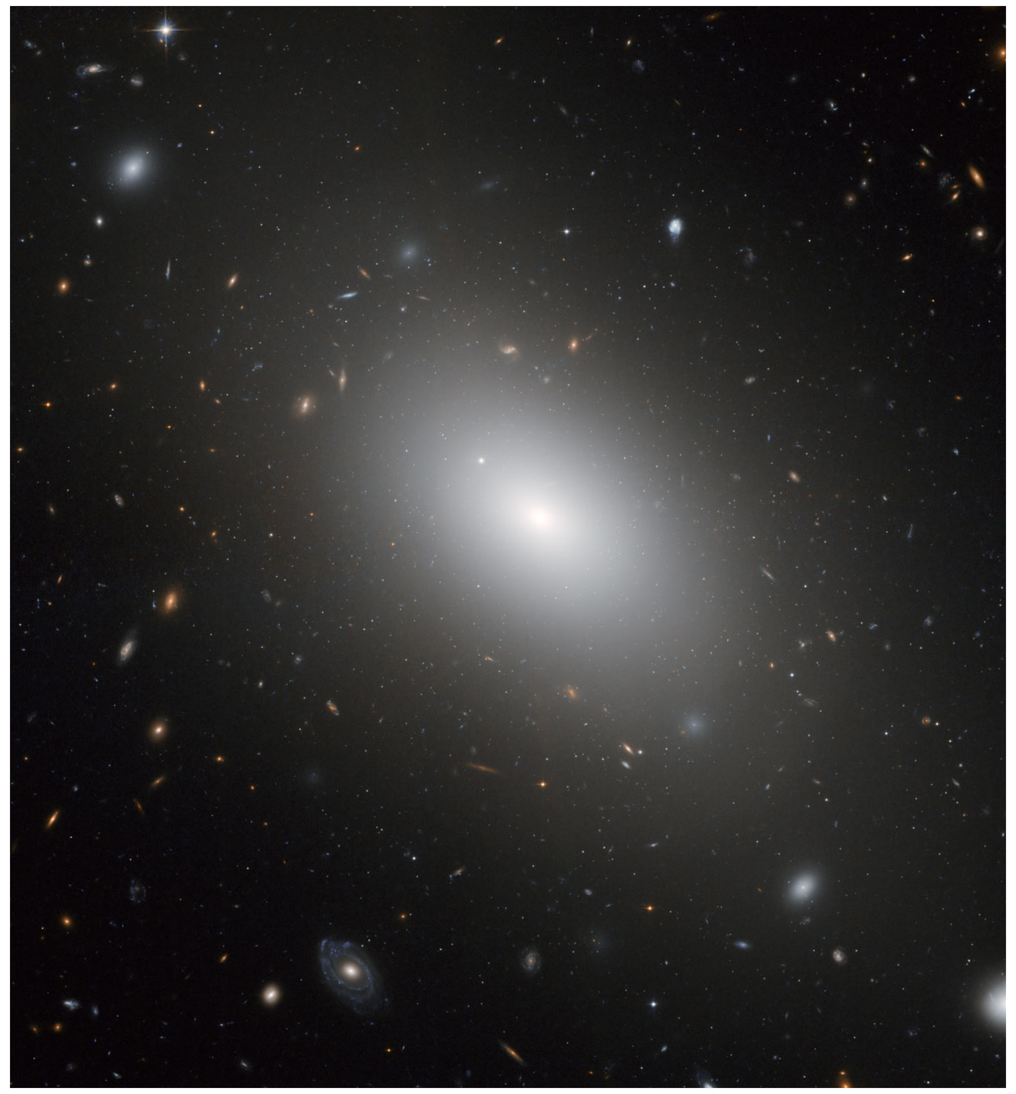
What other type of galaxies are there?

What other type of galaxies are there?

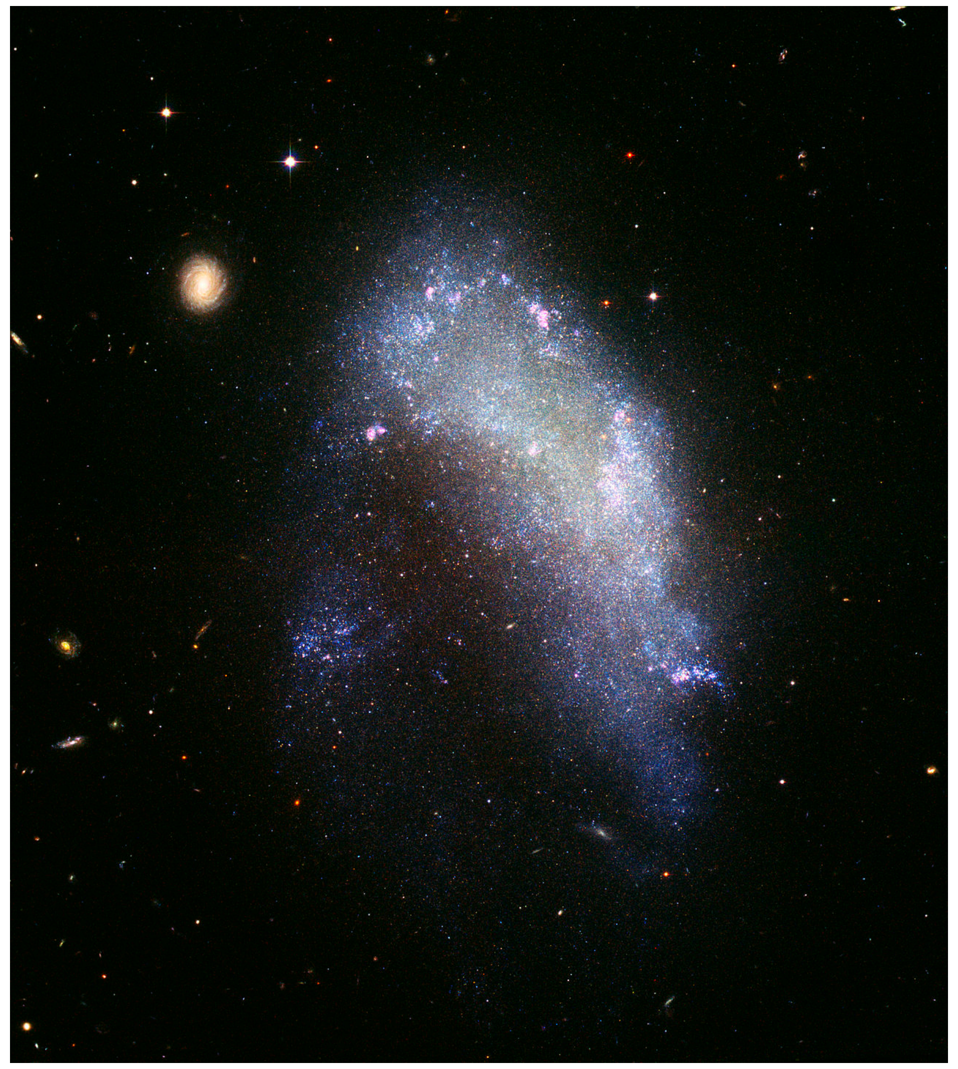
- Galaxies were first classified in the 1920s depending on their appearances through optical telescopes. Some galaxies appear to have beautiful spiral structures. They are called ***spiral galaxies*.**
- On the other hand, many galaxies seem to have featureless elliptical shapes. They are known as ***elliptical galaxies*.**
- Apart from spiral and elliptical galaxies, there are some galaxies with irregular shapes which do not fit into either of these categories. They are simply called ***irregular galaxies*.**

Spiral galaxy M51

Elliptical galaxy NGC 1132

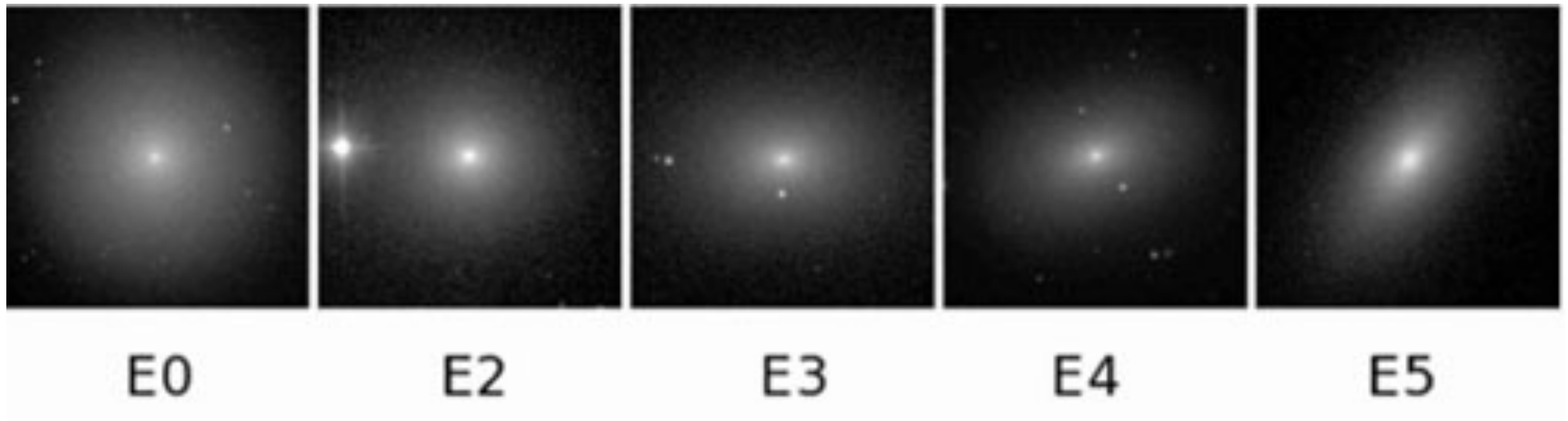


Irregular galaxy NGC 1427A



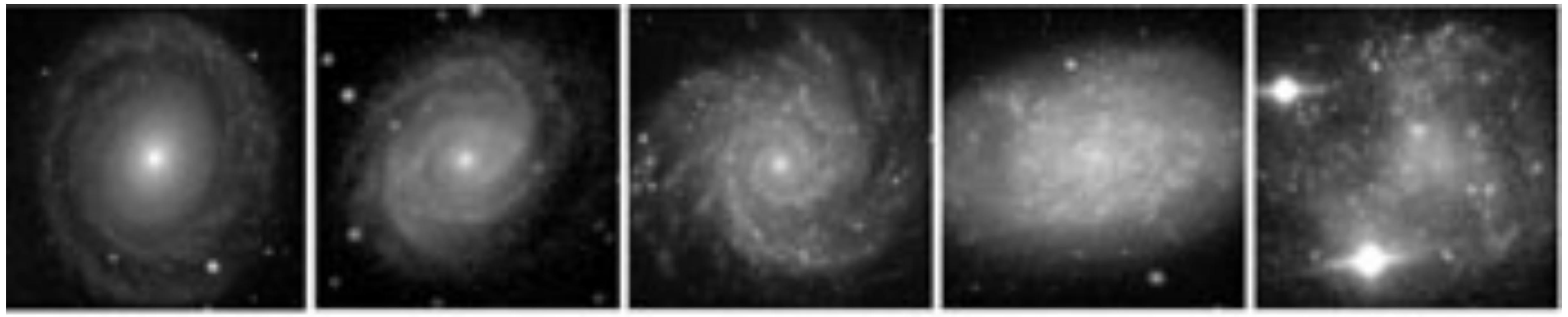
What other type of galaxies are there?

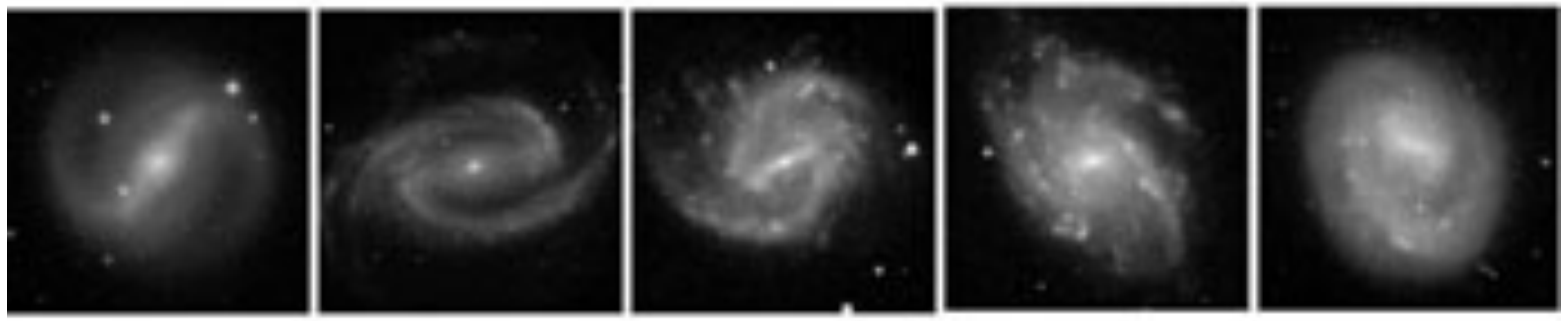
- Since all spiral galaxies are believed to be intrinsically shaped like circular disks, the apparent shape of a spiral galaxy in the sky gives an indication of its inclination with respect to the line of sight.
- On the other hand, different elliptical galaxies have different ellipticities, and their intrinsic ellipticities cannot be deduced easily from apparent shapes.
- For example, a highly flattened elliptical galaxy may appear fairly round in the sky if its short axis is turned towards us.
- Still elliptical galaxies are customarily classified according to their apparent shapes. The circular-looking elliptical galaxies are classified as E0. Then we go through a sequence of E1, E2, E3...in order of increasing ellipticity, ultimately ending with E7 which are fairly flattened elliptical galaxies.
- Hubble developed a famous scheme of classifying galaxies, in which E7 elliptical galaxies are taken to be similar to spiral galaxies with very closely wound spirals.



What other type of galaxies are there?

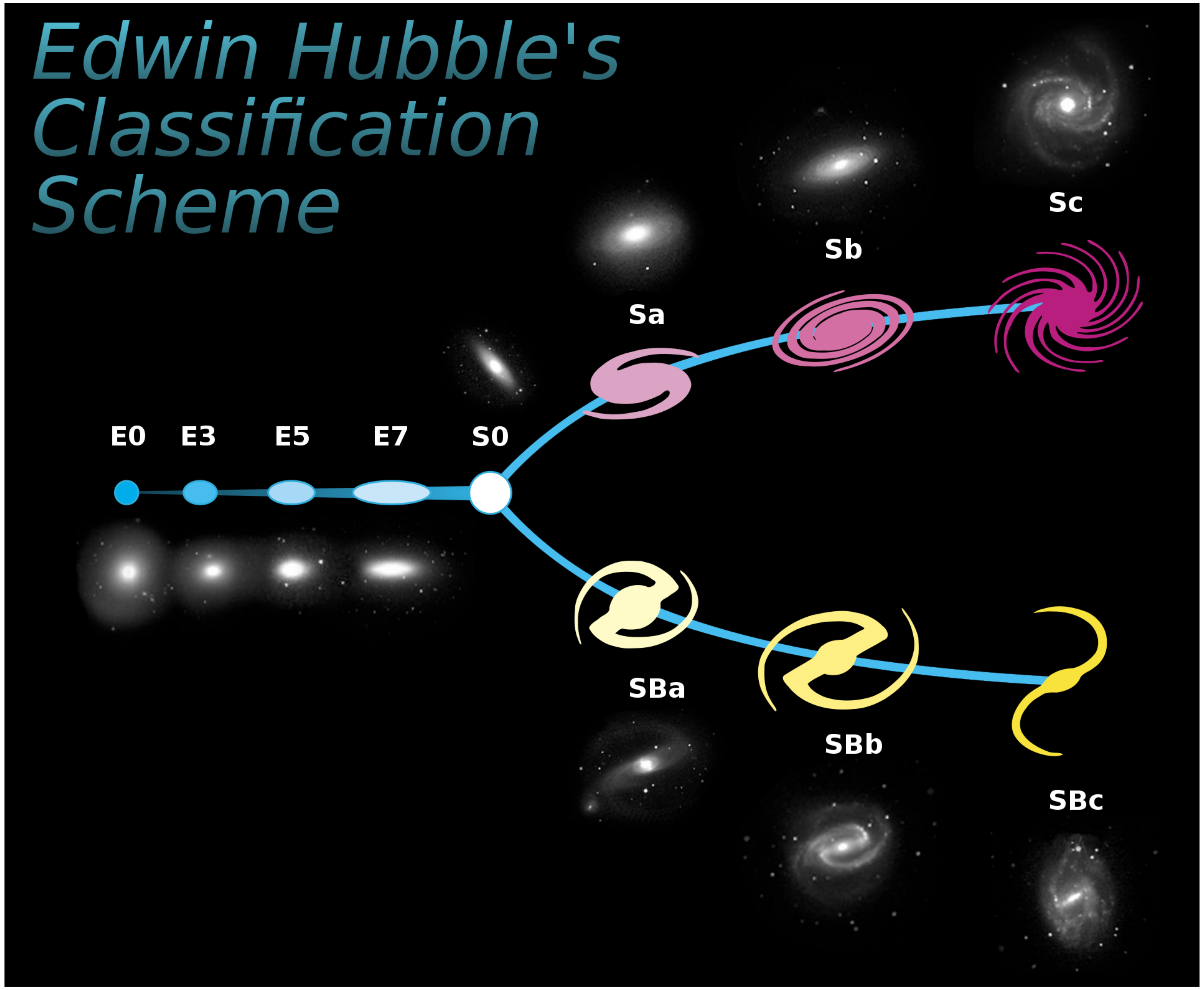
- There are some spiral galaxies with bars in the central regions, such as the galaxy shown in the Figure.
- Hubble divided the spiral galaxies into ordinary spirals and barred spirals.
- Ordinary and barred spirals with very closely wound spirals are classified as S0 and SB0.
- Spiral galaxies with increasingly looser spiral structures are classified in the sequence Sa, Sb, Sc.
- Barred spirals are similarly classified in the sequence SBa, SBb, SBc.





The Hubble classification system

- Also called the **Hubble tuning fork**
- This is the sequentially arranged Hubble classification
- **Elliptical are also called early type galaxies**
- **Spirals are called late type galaxies**
- The early and late type classification is a historical scheme and is evolutionary actually the other way around:
- late type spirals are actually younger galaxies compared to the early type ellipticals, which are the older galaxies.



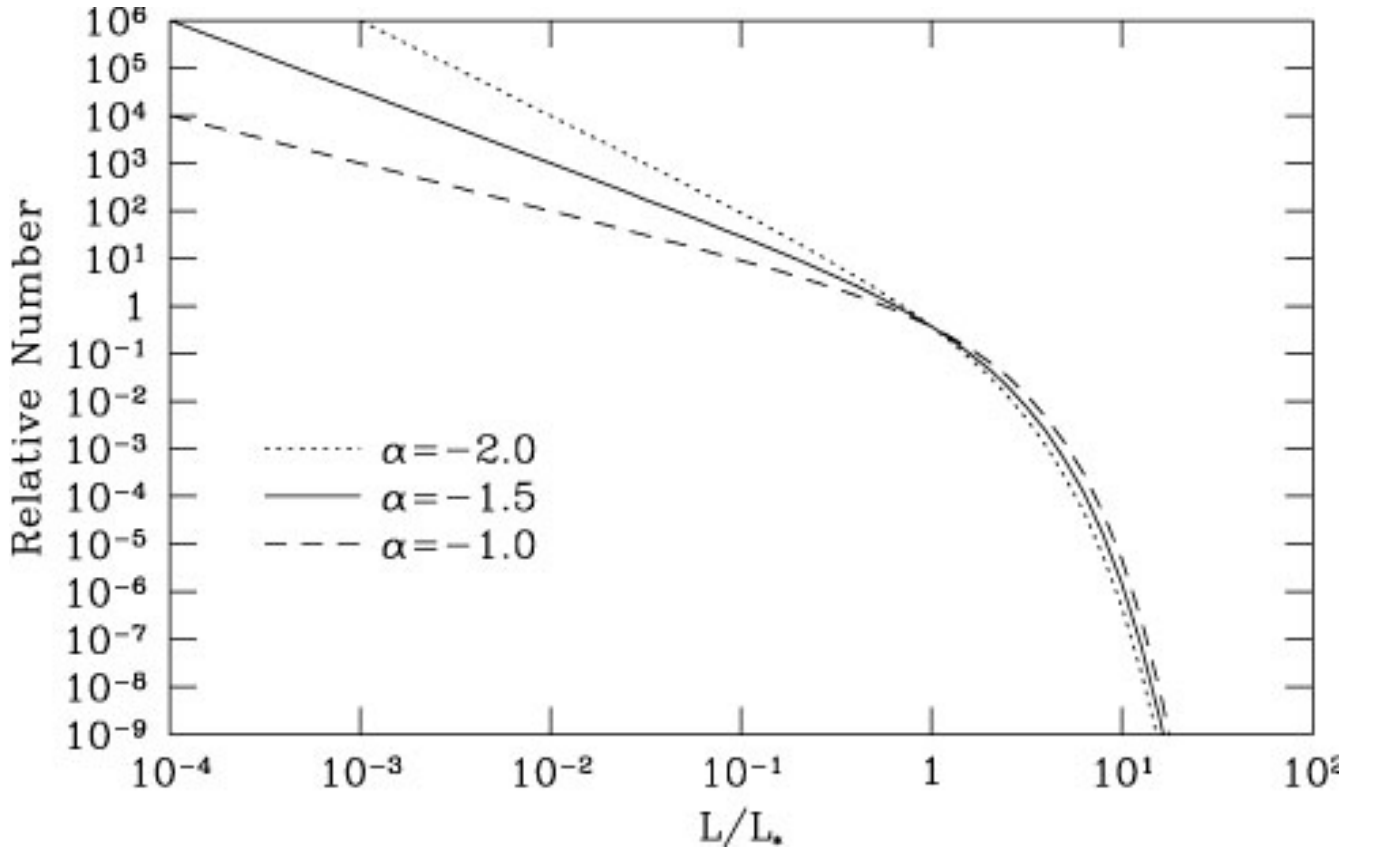
Luminosity function

Galaxies vary widely in luminosity – from very luminous giant galaxies to dwarf galaxies. The number density of galaxies with luminosity in the range L to $L + dL$ is approximately given by ***Schechter's law***

$$\phi(L)\,dL \approx N_0 \left(\frac{L}{L_*}\right)^{\alpha} \exp(-L/L_*) \frac{dL}{L_*},$$

where $N_0 = 1.2 \times 10^{-2} h^3\ \mathrm{Mpc}^{-3}$, $\alpha = -1.25$ and $L_* = 1.0 \times 10^{10} h^{-2} L_\odot$.

- Here h appearing in the expressions of N_0 and L_* is not Planck's constant but called the **Hubble constant.**
- The Hubble constant has a value ~ 70 km/s/Mpc.
- **Dwarf galaxies greatly outnumber the giants.**



Environment

The typical **fractions of spirals and ellipticals in a population of galaxies depend on the environment**.

In the central regions of rich clusters of galaxies, only about 10% of the galaxies may be spirals. In contrast, the spirals may constitute nearly 80% of the bright galaxies in the low-density regions of the Universe. This is called the morphology-density relation.

Environment: galaxies can be found in galaxy clusters, galaxy groups and in the field.

Galaxy cluster: is a structure that consists of anywhere from hundreds to thousands of galaxies that are bound together by gravity, with typical masses ranging from 10^{14} to 10^{15} solar masses.

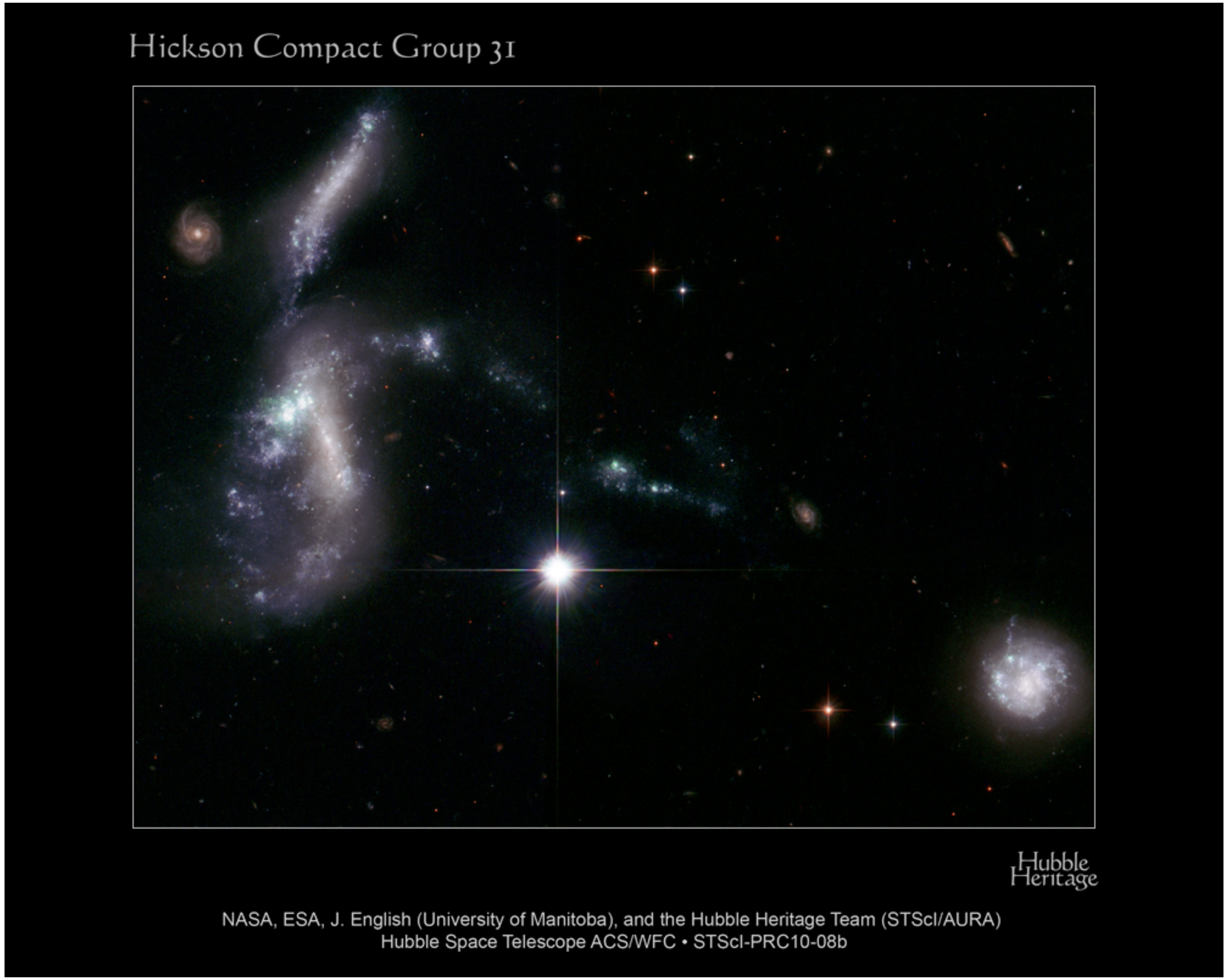
Environment

Galaxy groups: is a structure of galaxies comprising about 50 or fewer gravitationally bound members. The groups and clusters of galaxies can themselves be clustered, into superclusters of galaxies.

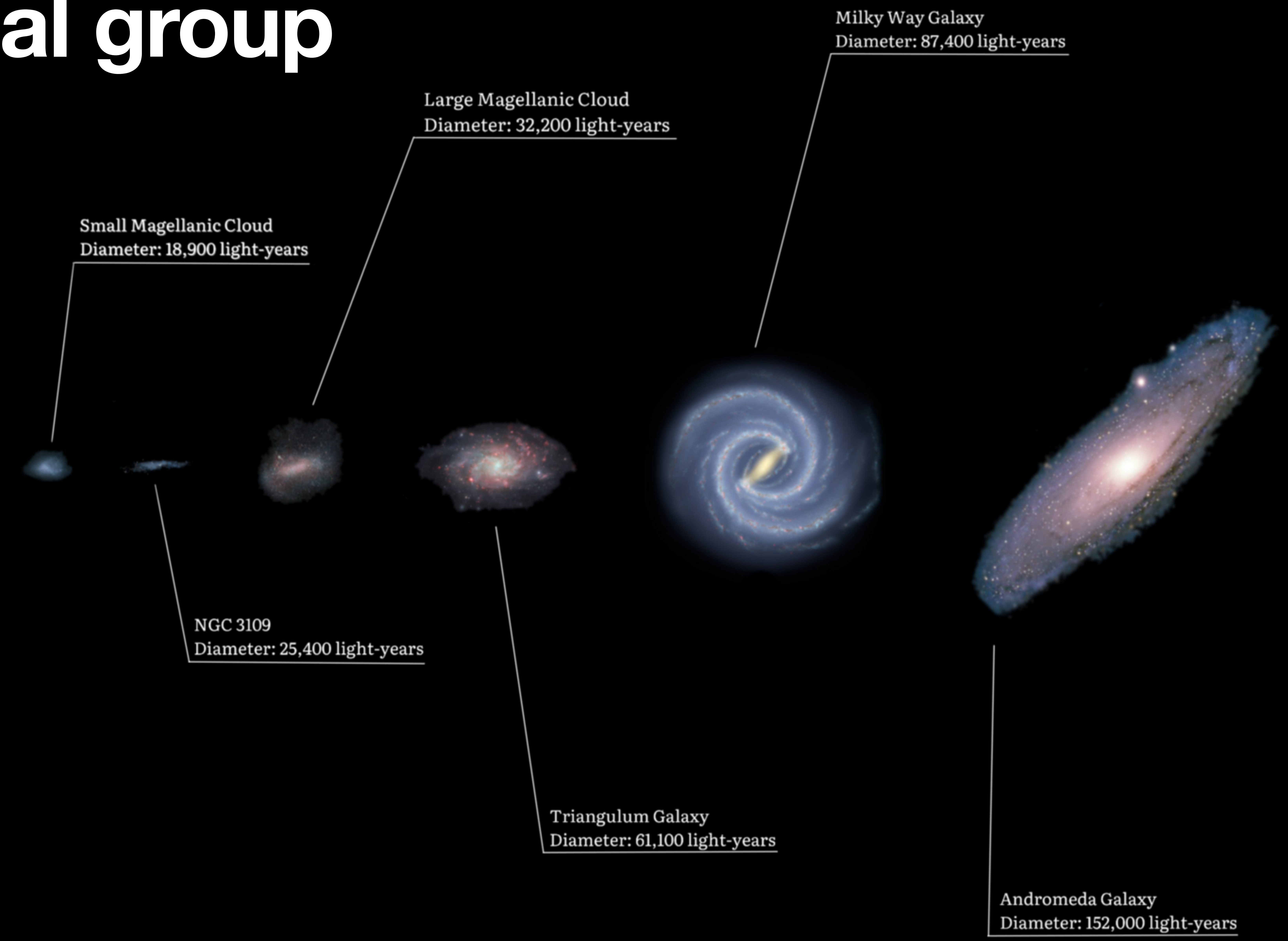
The Milky Way galaxy is part of a group of galaxies called the Local Group, which is part of the Virgo Supercluster.

Field: galaxies that are not gravitationally bound in a group or a cluster

Void: large regions of space with practically no galaxies.

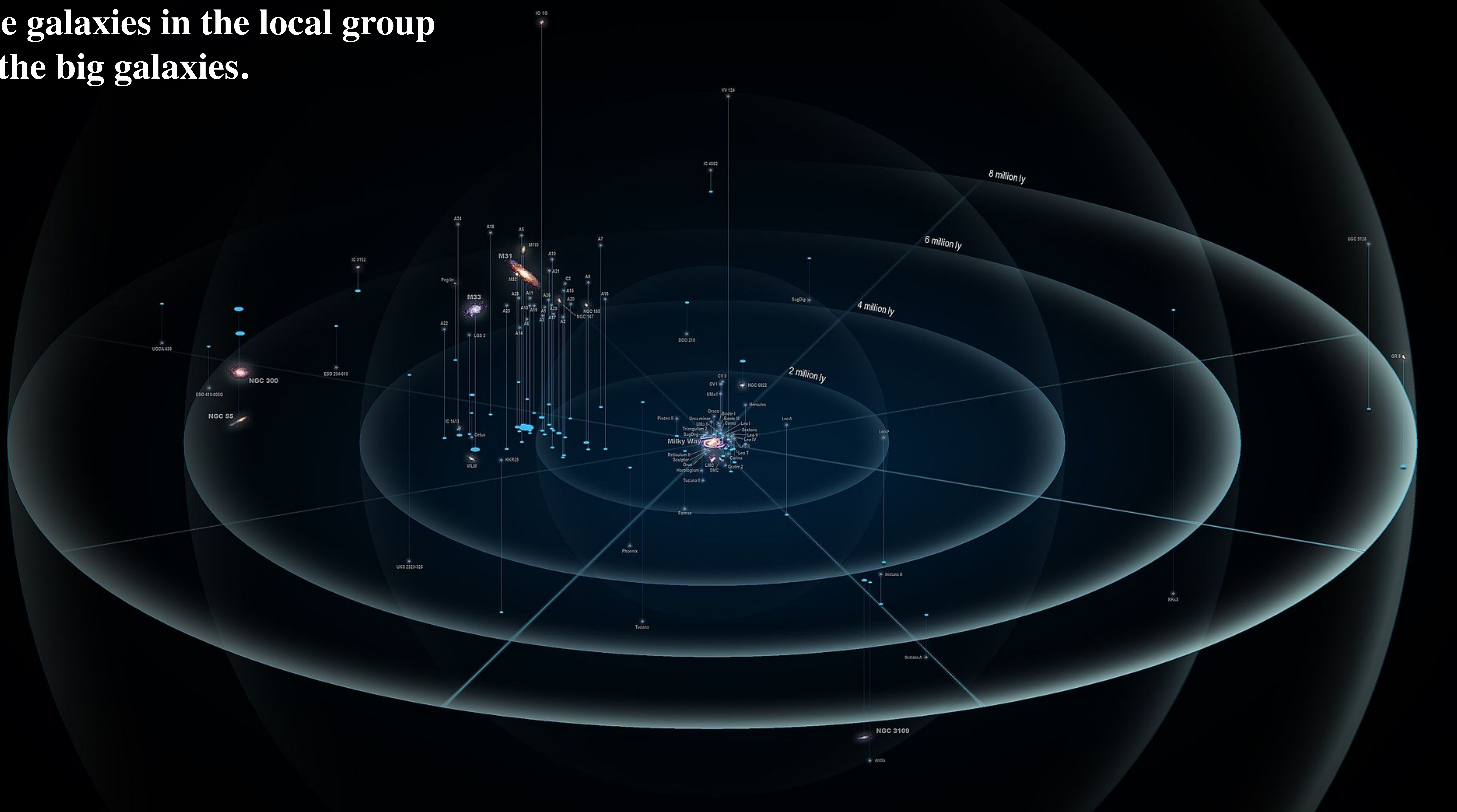


The Local group



Local Group and nearest galaxies

In addition to the big galaxies, there are also many tiny satellite galaxies in the local group that are orbiting the big galaxies.



Surface brightness

The surface brightness of a galaxy is naturally the maximum at the centre and falls off as we go towards the outer edge. In the case of elliptical galaxies, the fall of surface brightness with distance from the centre can be fitted fairly well by the ***de Vaucouleurs law***

$$I(r) = I_e \exp\left\{-7.67\left[\left(\frac{r}{r_e}\right)^{0.25} - 1\right]\right\}$$

where r_e is called the ***effective radius*** **within which half of the luminosity is contained** (if the image of the galaxy happens to be circular), whereas $I_e = I(r_e)$.

For the **disk of a spiral galaxy, an exponential law** gives a reasonably good fit.

Physical characteristics

Apart from the overall appearances, the physical characteristics of elliptical and spiral galaxies are also very different.

A **typical elliptical galaxy is very much like a Population II object.** There is very **little interstellar matter** in an elliptical galaxy and **star formation no longer takes place**. So **most of the stars are fairly old,** giving a **yellowish colour** to the galaxy, in the absence of young bluish stars.

Another property of Population II objects in our Galaxy, is that they have very little rotational velocity and are supported against gravity by random motions. Exactly similar considerations hold for elliptical galaxies as well.

There is usually very **little systematic rotation in an elliptical galaxy**. The stars do not all collapse to the centre because of the **random motions**.

The larger or the more luminous the elliptical galaxy is, the stronger is its gravity and the stars need to have more random motions in order to maintain a steady state. **The velocity dispersion σ of an elliptical galaxy is related to its intrinsic luminosity by the *Faber–Jackson relation*.**

$$\sigma \approx 220 \left(\frac{L}{L_*}\right)^{0.25} \ \mathrm{km\ s^{-1}}$$

Physical characteristics

σ is larger for elliptical galaxies with higher luminosity L .

The Figure shows velocity dispersions of several elliptical galaxies plotted against their luminosities.

The observational data show a reasonably tight correlation corresponding to the **Faber–Jackson relation,** without too much scatter.

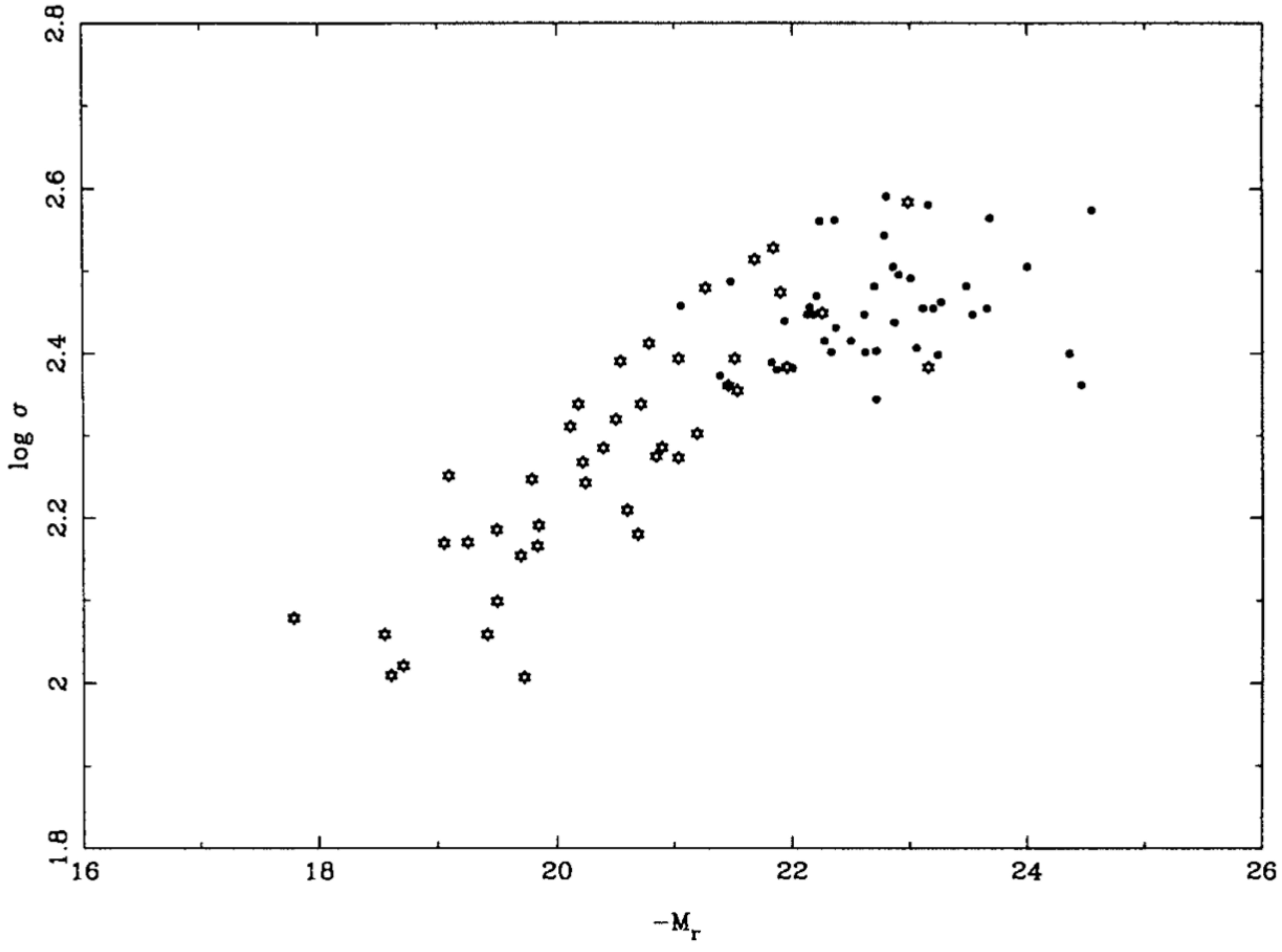


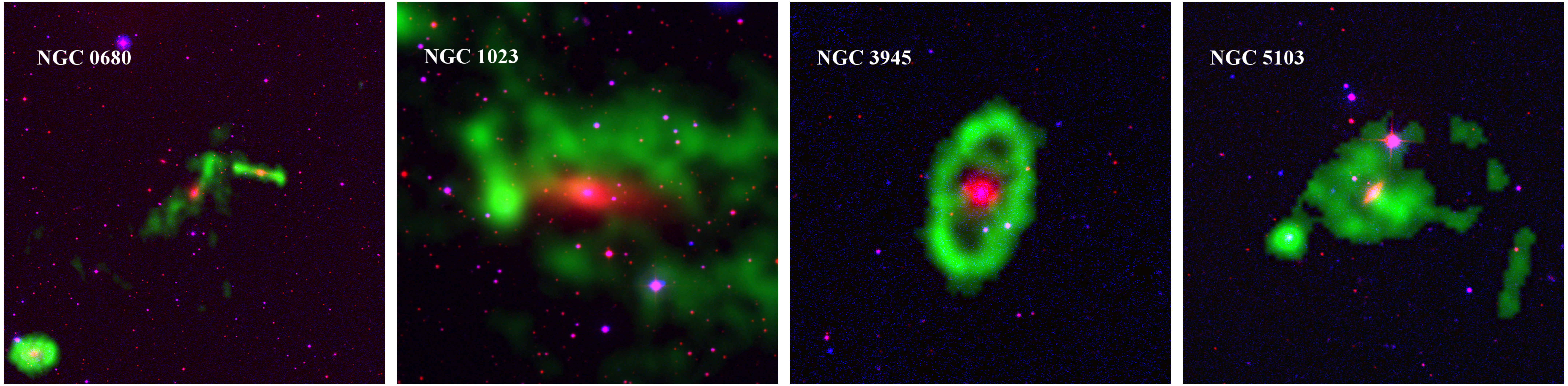
Fig. 9.5 The velocity dispersion σ of elliptical galaxies plotted against their absolute magnitudes. Remembering that the absolute magnitude is 2.5 times the logarithm of luminosity, one obtains the Faber–Jackson relation from this plot. From Oegerle and Hoessel (1991). (©American Astronomical Society. Reproduced with permission from *Astrophysical Journal*.)

Physical characteristics

In addition to the differences in appearance and morphology, spiral galaxies differ from elliptical galaxies in the following basic characteristics:

- **spiral galaxies contain** considerable amounts of **interstellar matter** (ISM); and
- both **stars and the ISM move in roughly circular orbits around the centre of a spiral galaxy** such that the gravitational attraction towards the centre is balanced by the centrifugal force. Because of the presence of ISM, **star formation goes on inside the disks** of spiral galaxies, making them appear **bluer** than elliptical galaxies.
- We also receive synchrotron radiation from the disks of spiral galaxies, which shows that spiral galaxies have **magnetic fields** as well as cosmic ray particles spiralling around them as in our Galaxy.
- Note: elliptical galaxies likely also have some magnetic fields, but they are weaker and more difficult to measure compared to spiral galaxies.

Physical characteristics



- Elliptical galaxies typically do not have much ISM
- In some cases they can acquired from another galaxy (e.g. gas rich merger or tidal interaction)
- In this case they have various HI morphologies from regular disks to rings and unsettled clouds.

Physical characteristics

- Spiral galaxies have HI distributed in a disk, similar to the Milky Way

Physical characteristics

- The emission at the 21-cm line helped in mapping the distribution and kinematics of the ISM in our Galaxy.
- The ISMs of external spiral galaxies can also be studied by analysing the emission at the 21-cm line.
- If the galaxy is moving with respect to us, then we will of course find this line Doppler shifted.
- Additionally, in the case of a rotating disk, we expect the ISM to be moving towards us on one side of the galaxy and moving away from us on the other side (unless the line of sight is exactly perpendicular to the disk). The Doppler shifts of the 21-cm line should accordingly be different on the opposite sides of the spiral galaxy. This is indeed seen and one can use this variation of Doppler shift to determine how the circular speed v_c of the ISM varies with distance from the centre of the galaxy.

Physical characteristics

- The Figure shows the contours of constant Doppler shift in a spiral galaxy superposed on the optical image of the galaxy.
- The contour lines go well beyond the optical image, since the 21-cm emission of a typical spiral galaxy usually comes from a region much larger than the optical image. -> HI disk is typically about 2 times larger than the stellar disk.
- From the velocity field, one can determine how the rotation speed v_c varies with the distance from the centre inside a galaxy.
- A plot of the circular speed v_c as a function of the radius of a galaxy is known as a *rotation curve*.

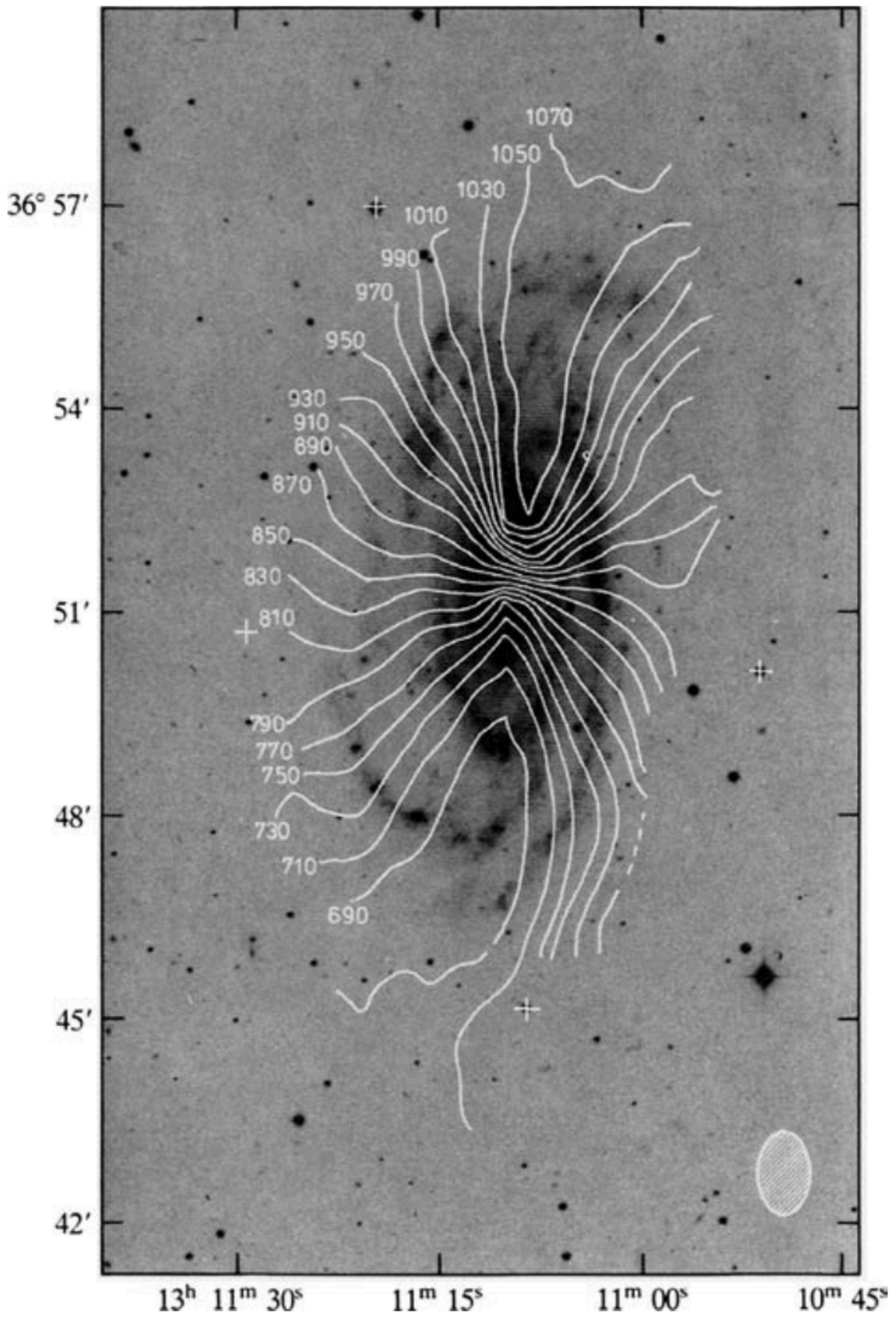
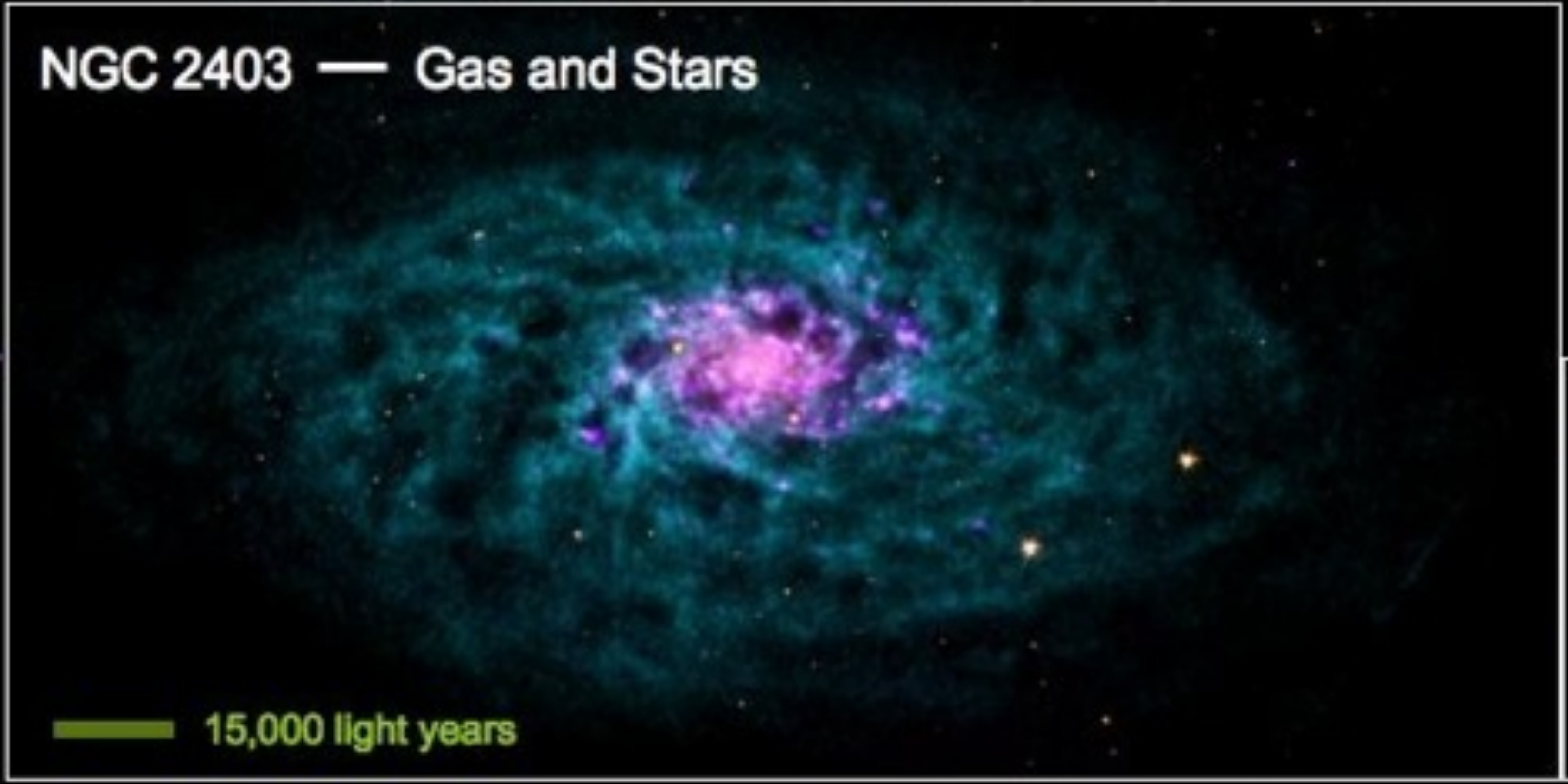


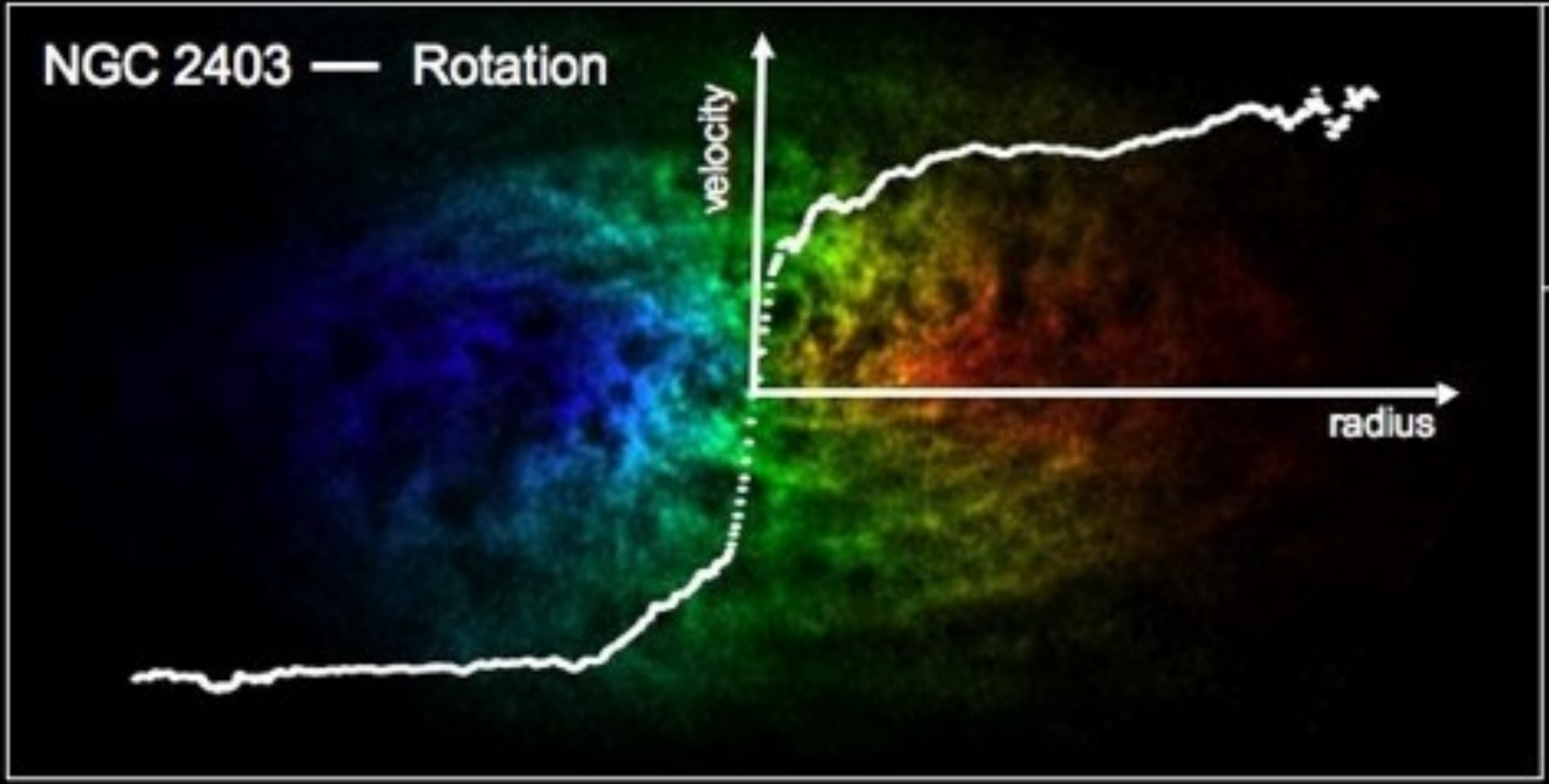
Fig. 9.6 The contours of constant Doppler shift (given in km s^{-1}) in the 21-cm line emission superposed on the negative optical image (i.e. the galaxy is shown in black against a light background) of the galaxy NGC 5033. From Bosma (1978). Courtesy: A. Bosma.

Galaxy Dynamics in THINGS — The HI Nearby Galaxy Survey



THINGS
The HI Nearby Galaxy Survey

Color Coding:
THINGS Atomic Hydrogen
(Very Large Array)
Old stars
(Spitzer Space Telescope)
Star Formation
(GALEX & Spitzer)



Color coding:
THINGS HI distribution:
Red-shifted (receding)
Blue-shifted (approaching)
Rotation Curve

NRAO

Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07
Rotation Curve: de Blok et al. 08

Physical characteristics

- If v_c is the circular speed at a radial distance r from the centre, then equating the centrifugal force with the gravitational force gives

$$\frac{v_c^2}{r} = \frac{GM(r)}{r^2}$$

where $M(r)$ is the mass within the radius r.

We should point out that this is strictly valid only for a spherically symmetric distribution of matter. In the case of a spiral galaxy, we expect this equation to give only an approximate qualitative idea of how v_c varies with r.

If we take $M(r) \propto r^3$ **in the central region of the galaxy,** as we would expect in the **case of a uniform spherical distribution**. Then in the central region of the galaxy:

$$v_c \propto r$$

Physical characteristics

If most of the mass is confined within a certain region, then the circular speed beyond that region, on the other hand, must be given by

$$v_c = \sqrt{\frac{GM_{\rm total}}{r}}$$

where M_{total} is the total mass. In other words, we **expect vc to fall as $r^{-1/2}$ in the outer regions of the galaxy.**

The Figure shows the rotation curves of several spiral galaxies determined from the Doppler shift of the 21-cm line.

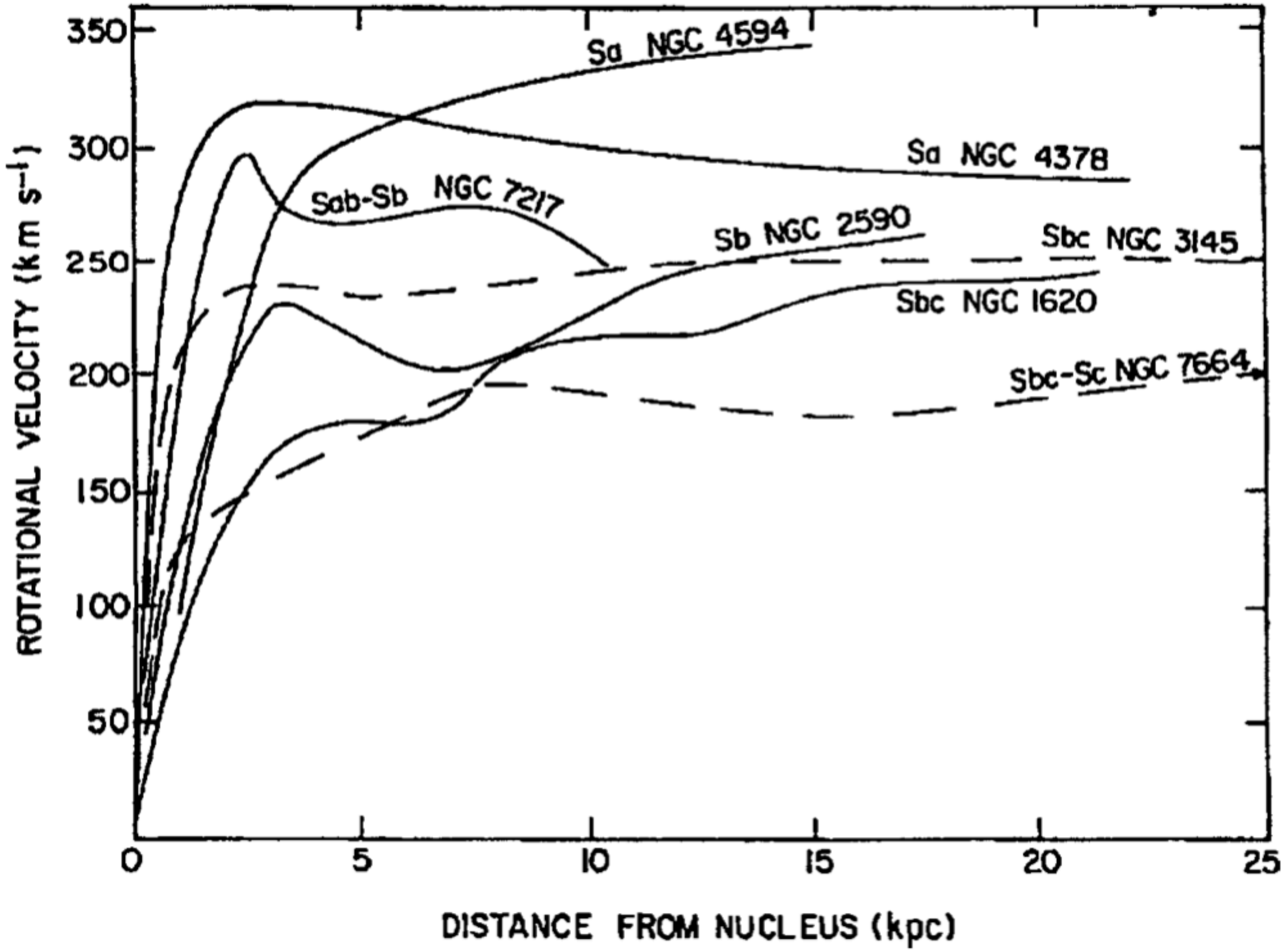


Fig. 9.7 The rotation curves of several galaxies showing how v_c varies with radius. From Rubin, Ford and Thonnard (1978). (©American Astronomical Society. Reproduced with permission from *Astrophysical Journal Letters*.)

Physical characteristics

It seems that v_c rises in the central regions of galaxies roughly as we expect.

However, the **rotation curves become asymptotically flat** and the values of v_c thereafter remain nearly constant with increasing radial distance.

This came as a very big surprise to astronomers when rotation curves of a few spiral galaxies were determined for the first time.

Since the 21-cm emission is detected from regions of galaxies beyond the visible disk, it could be ascertained that **the ISM keeps on going in circular orbits with constant v_c well beyond the regions emitting visible light in the galaxies.**

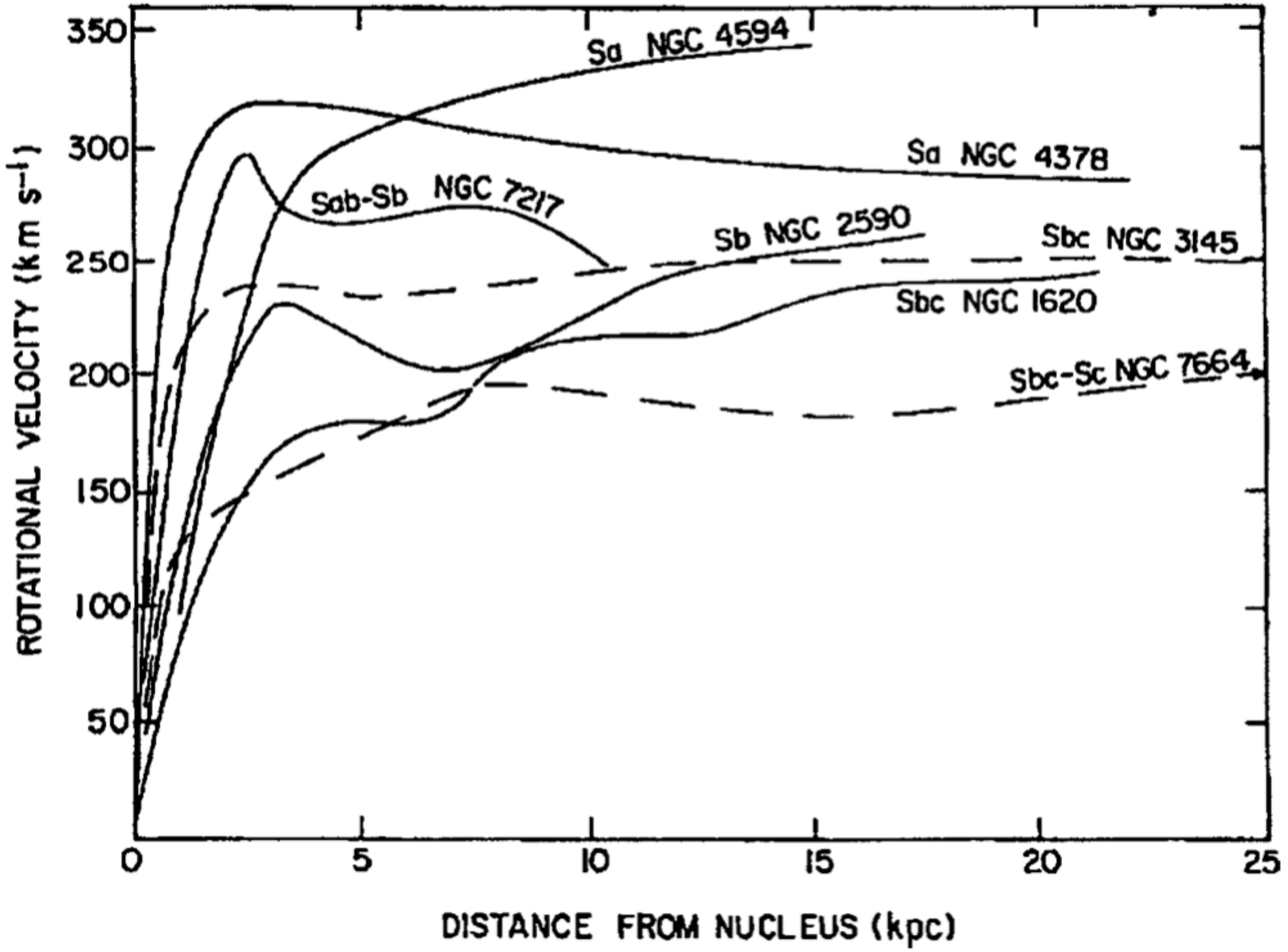


Fig. 9.7 The rotation curves of several galaxies showing how v_c varies with radius. From Rubin, Ford and Thonnard (1978). (©American Astronomical Society. Reproduced with permission from *Astrophysical Journal Letters*.)

Physical characteristics

What is the reason?

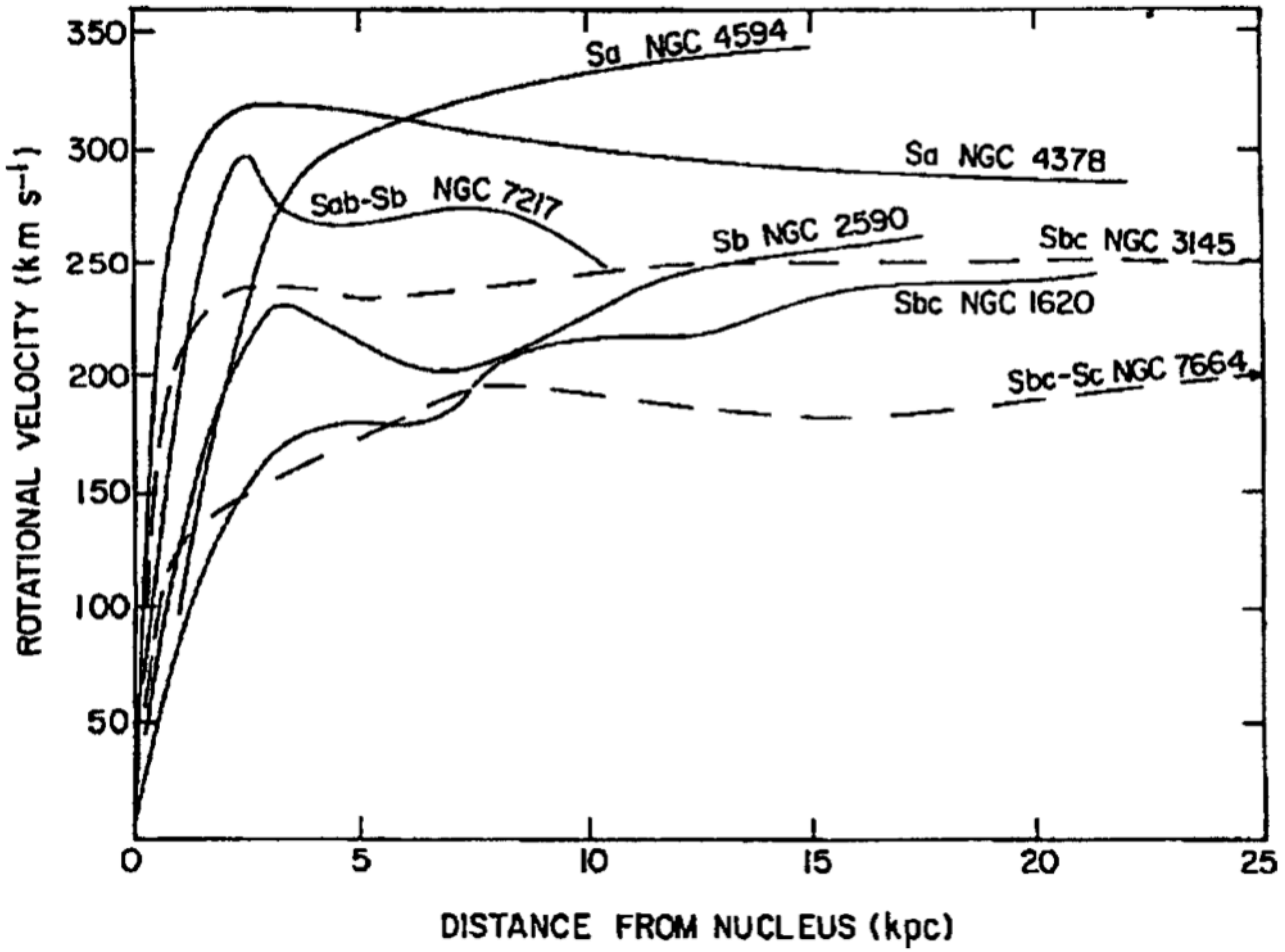


Fig. 9.7 The rotation curves of several galaxies showing how v_c varies with radius. From Rubin, Ford and Thonnard (1978). (©American Astronomical Society. Reproduced with permission from *Astrophysical Journal Letters*.)

Physical characteristics

What is the reason?

The mass distribution continues beyond the visible stellar disk of the galaxy and even beyond the regions from where we receive 21-cm emission.

It appears that the total mass of a typical spiral galaxy is at least a few times the total mass of stars emitting light. -> most of the matter in a spiral galaxy does not emit light and is usually referred to as *dark matter*.

Determining the nature of dark matter is one of the major challenges of modern astronomy.

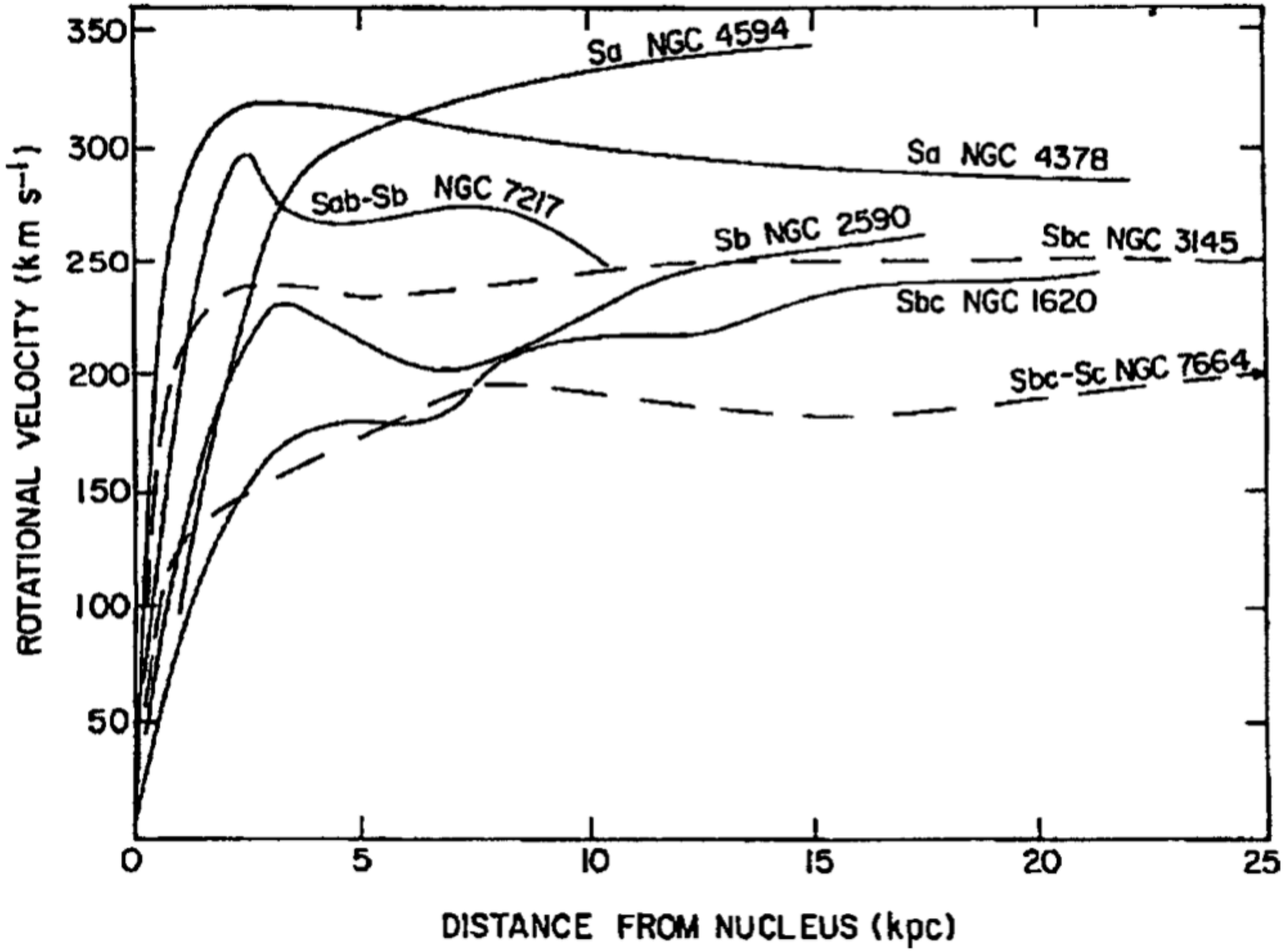


Fig. 9.7 The rotation curves of several galaxies showing how v_c varies with radius. From Rubin, Ford and Thonnard (1978). (©American Astronomical Society. Reproduced with permission from *Astrophysical Journal Letters*.)

Physical characteristics

The asymptotic circular speed v_c in the flat portion of the rotation curve would certainly depend on the mass of the spiral galaxy.

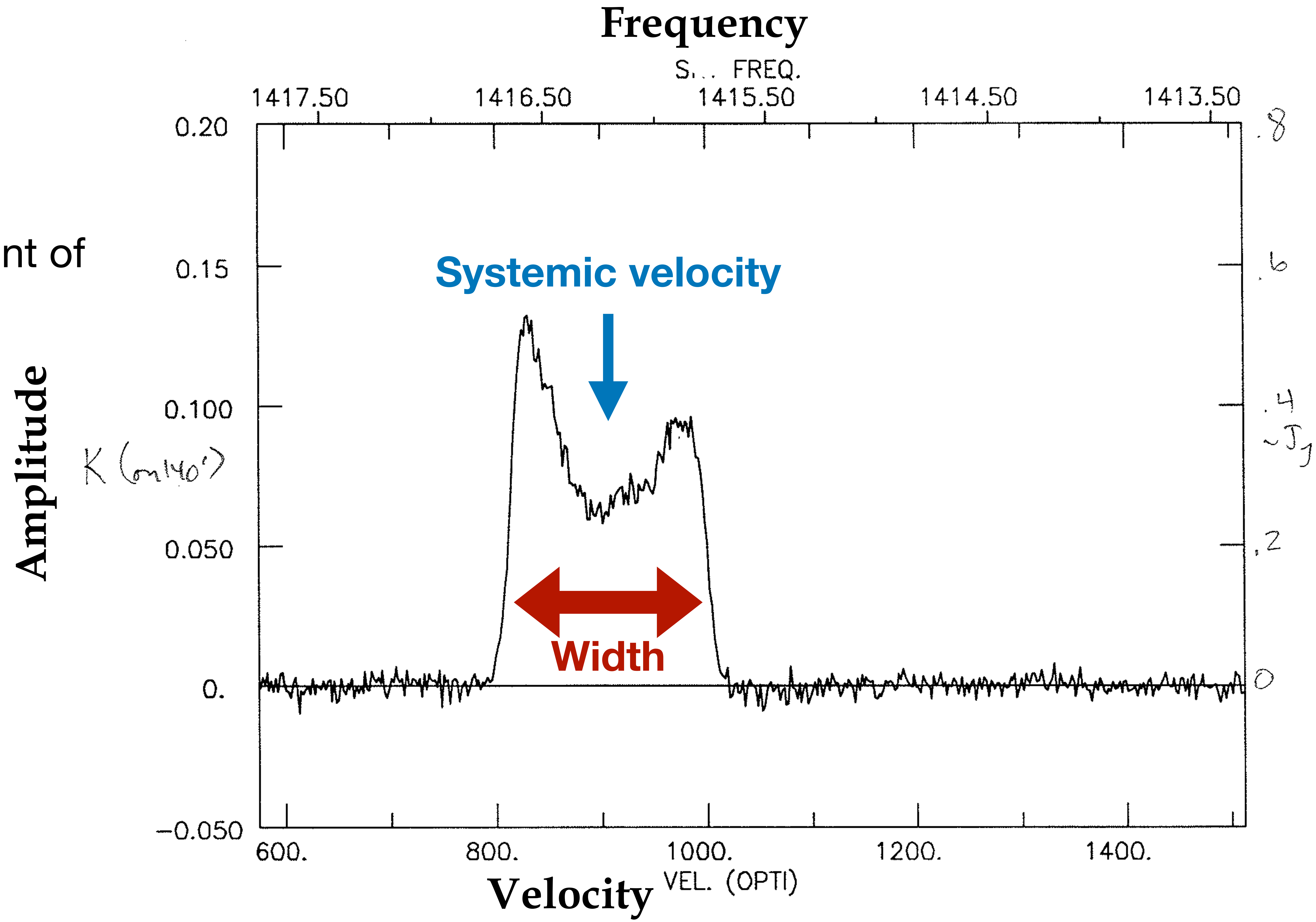
We expect a higher v_c for a more massive galaxy. Since a more massive galaxy is expected to be more luminous as well, we anticipate a **correlation between the asymptotic v_c and the intrinsic brightness of a spiral galaxy.** This is called the ***Tully–Fisher relation*** can be written as

$$v_{\mathrm{c}} \approx 220 \left(\frac{L}{L_*} \right)^{0.22} \ \mathrm{km\ s^{-1}}$$

This is similar to the Faber–Jackson relation of elliptical galaxies.

HI in spiral galaxies

UGC 11707 is a very blue spiral galaxy, indicative of a large amount of HI in the galaxy

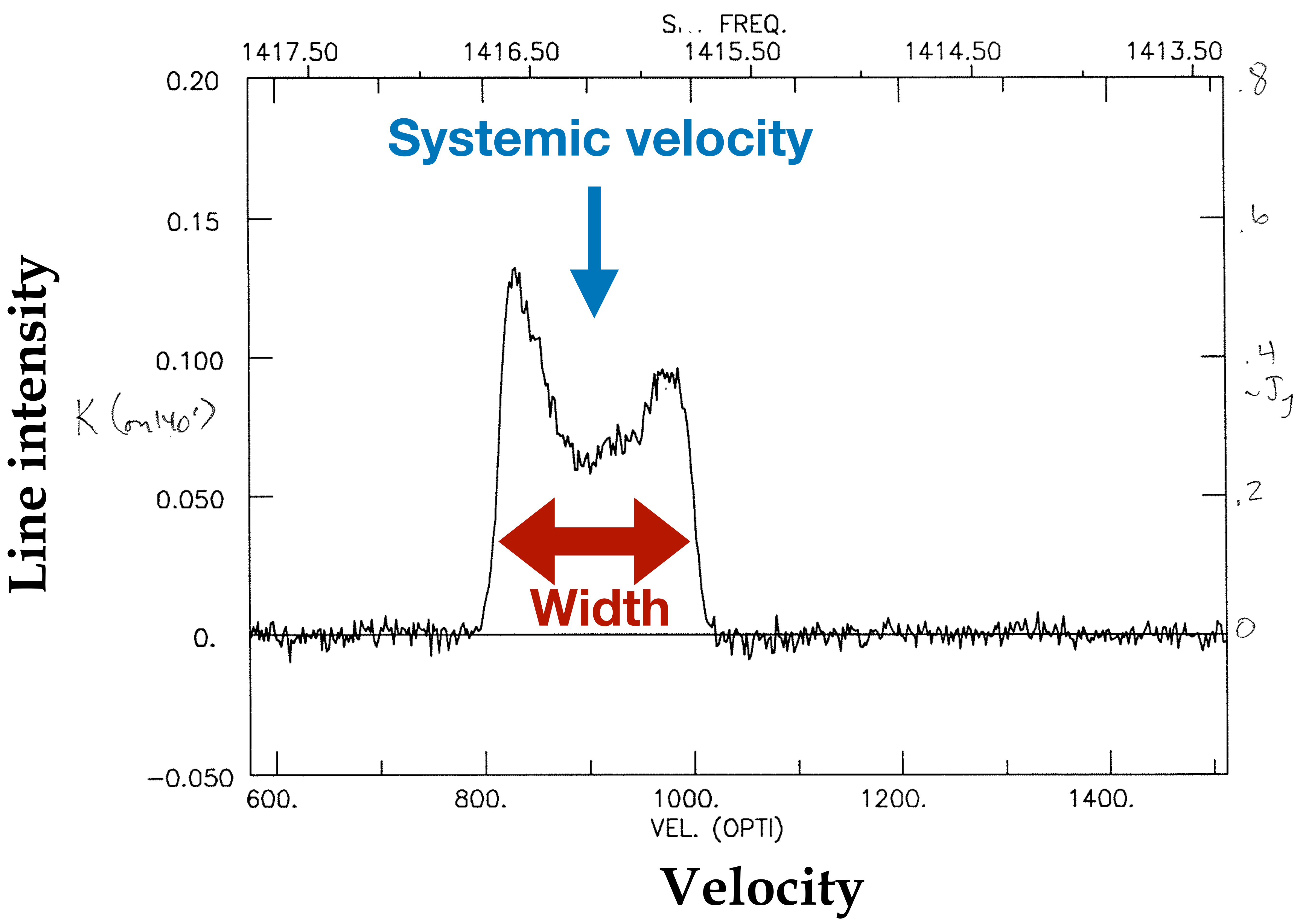


HI profile of UGC 11707
https://www.cv.nrao.edu/~sransom/web/Ch7.html

HI in spiral galaxies

We use the HI profiles of galaxies to calculate the following parameters:

1. The midpoint of the emission profile in km/s, yields the **systemic velocity** of the galaxy. This can be used to make an estimate of the redshift-**distance** using Hubble's law.
2. The **total HI line flux**, can be used to derive the total **HI mass**, using the estimated distance.
3. The observed width of the HI line profile, in km/s, gives the **observed Doppler broadening** due to the galaxy's **rotation**. In combination with an estimate of the galaxy's size and inclination on the plane of the sky, the width parameter can be used to make an estimate of the galaxy's total **dynamical mass**.



HI in spiral galaxies

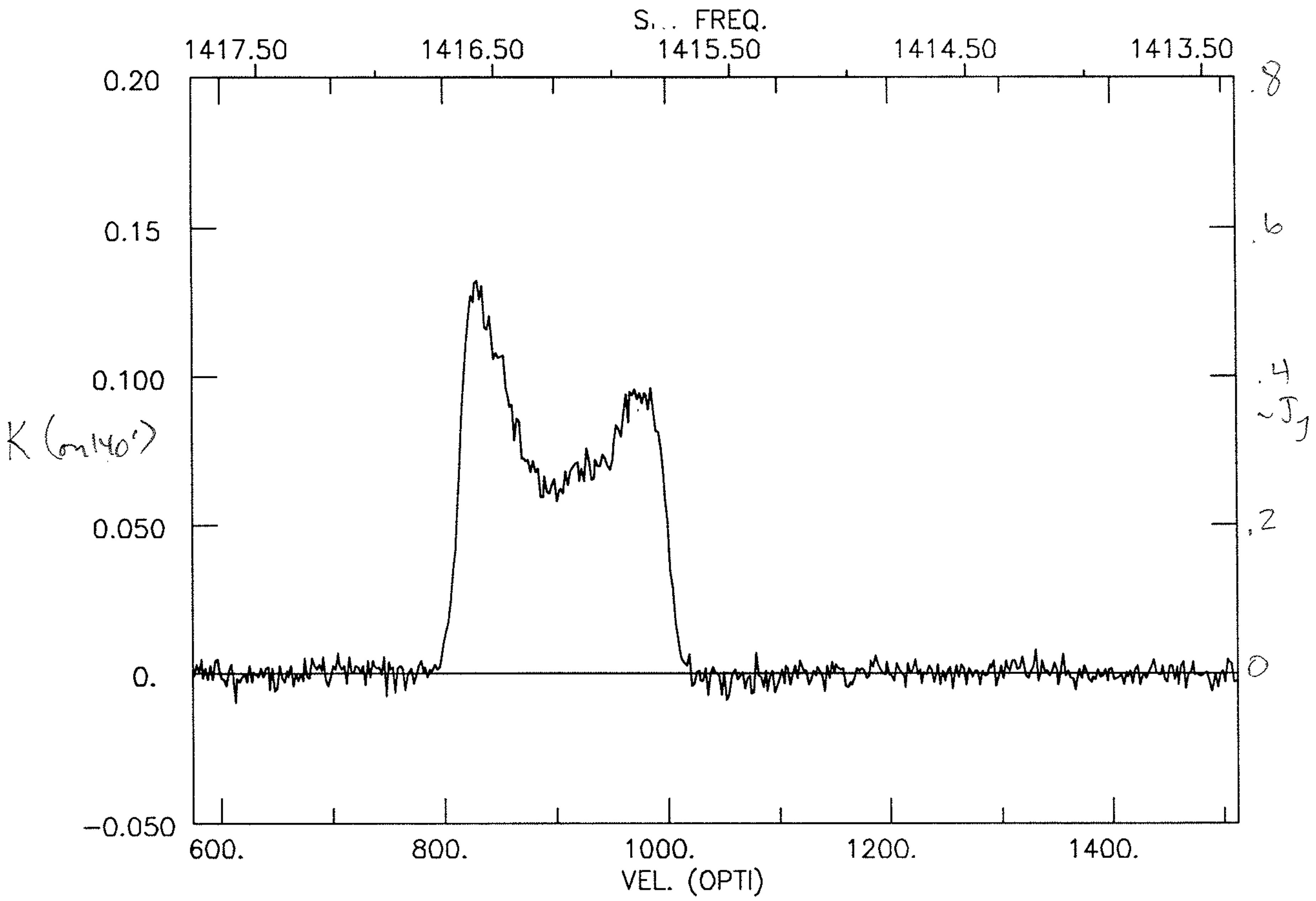
Line intensity is proportional to HI mass, if the gas is optically thin $\tau << 1$

$$\left(\frac{M_{\rm H}}{M_\odot}\right) \approx 2.36 \times 10^5 \left(\frac{D}{\rm Mpc}\right)^2 \int \left[\frac{S(v)}{\rm Jy}\right]\left(\frac{dv}{\rm km\ s^{-1}}\right)$$

HI mass of a galaxy **Distance** **Integrated intensity**

Hubble flow distance to the galaxy, based on the redshift of the line: $D = v/H_0$

Where v is the velocity of the line centre (recession velocity) and H_0 is the Hubble constant.



HI profile of UGC 11707
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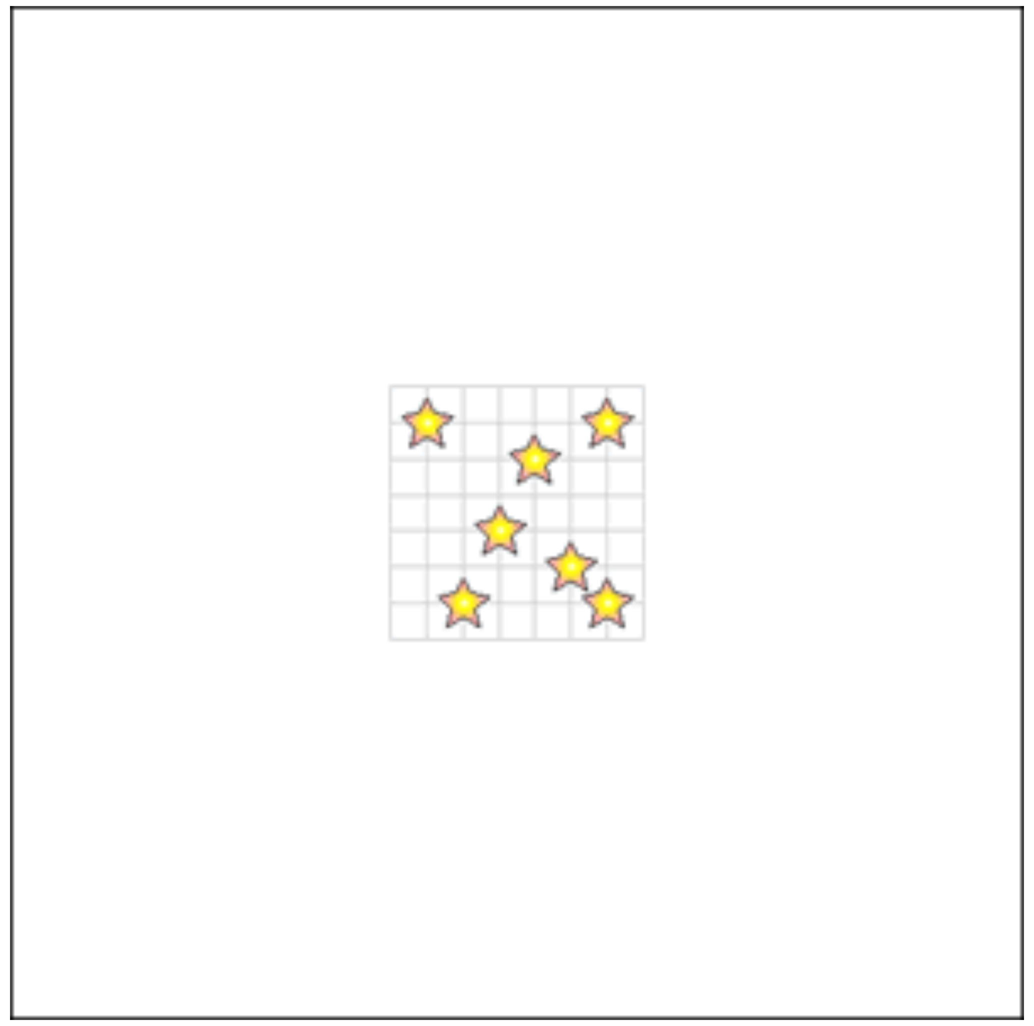
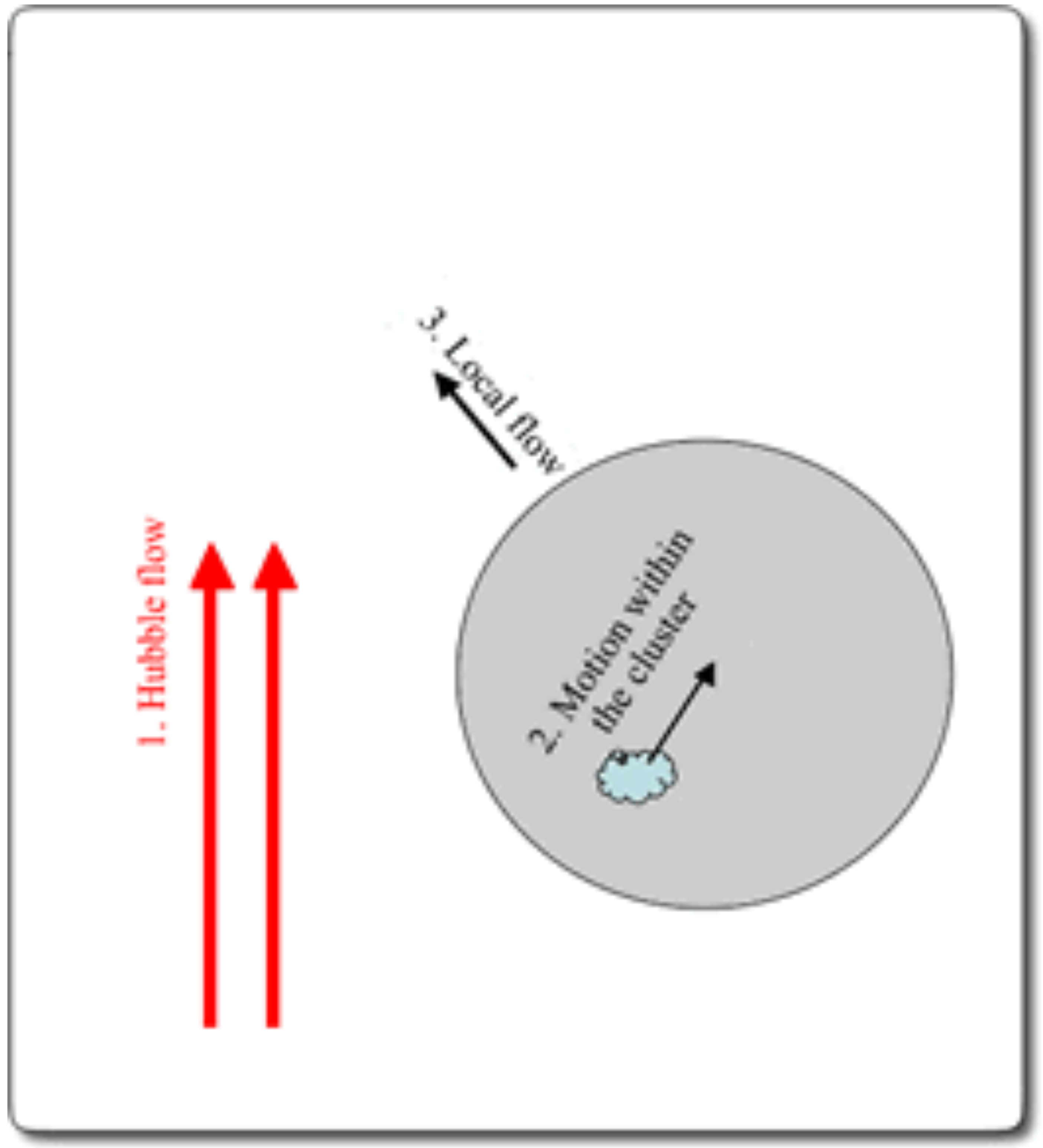
Hubble flow

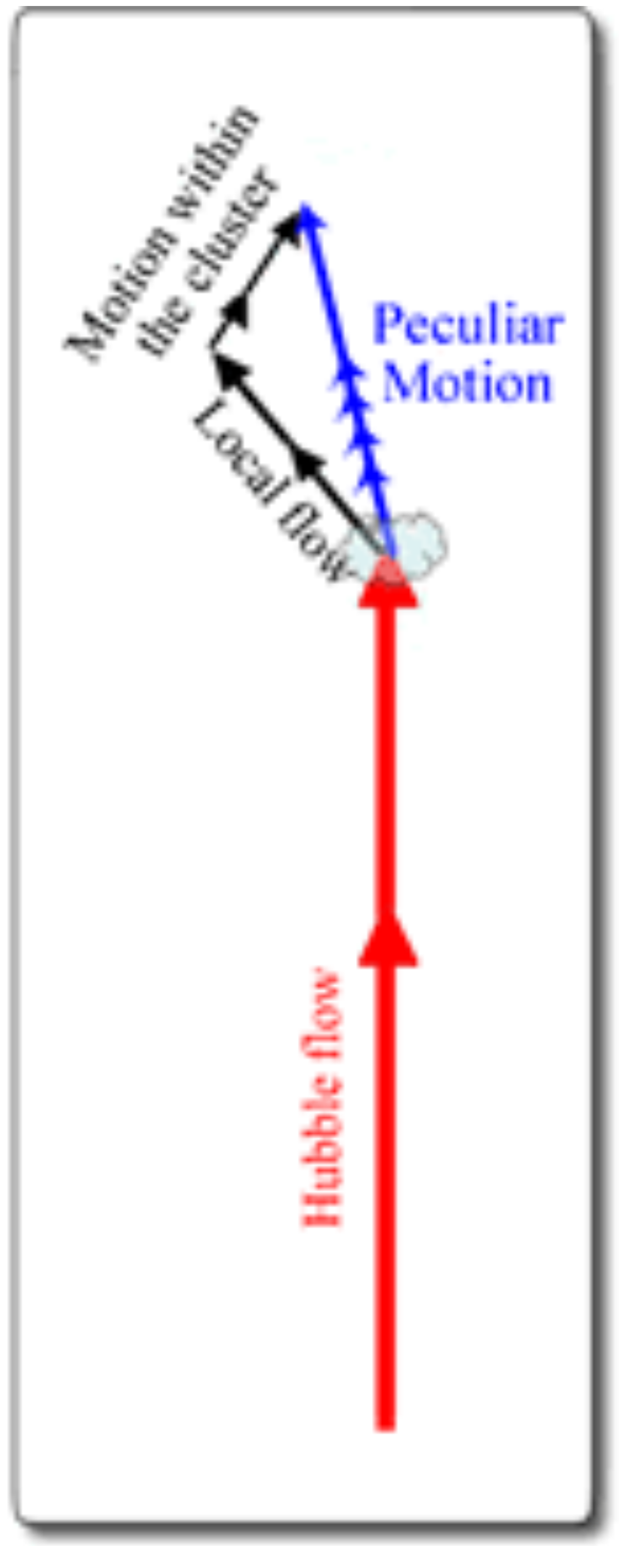


The **'Hubble flow' describes the motion of galaxies due solely to the expansion of the Universe.** The idea of the expanding Universe was first put forward by Edwin Hubble in 1929, after observing a **correlation between the redshifts of galaxies and their distances measured** using the period-luminosity relationship for Cepheid variable stars. Hubble found that all galaxies were moving away from us, and that the velocity of their recession was proportional to their distance from us, this is called the **Hubble Law:**

$v = H_0 \times D$

The motions of galaxies are influenced by more than just the Hubble flow. The net motions of galaxies are comprised of the Hubble flow, the local flow, and the motion of the galaxy within its cluster and/or group environment. These deviations from the pure Hubble flow are referred to as **peculiar motions**.

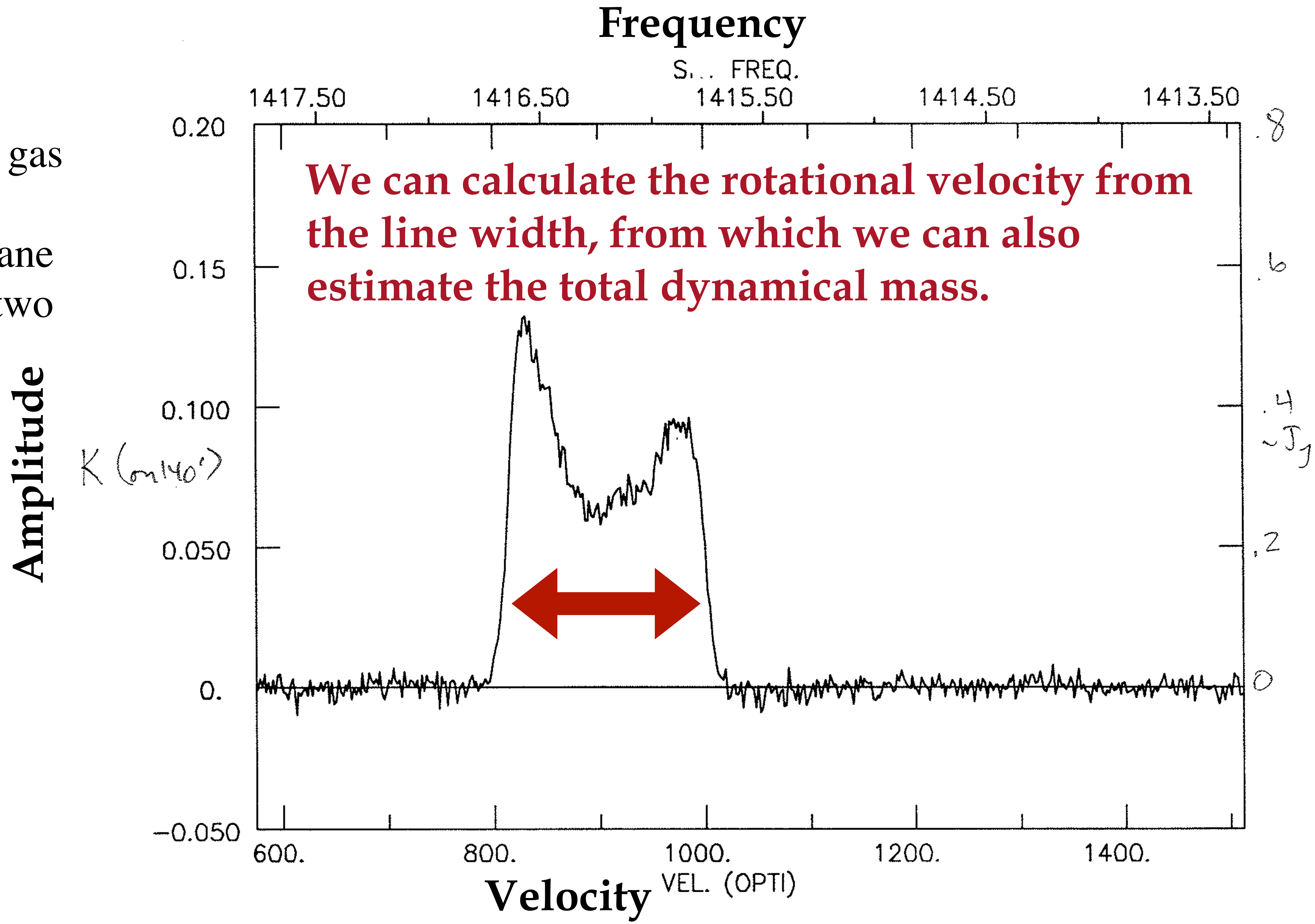




https://astronomy.swin.edu.au/cosmos/h/hubble+flow

HI in spiral galaxies

The shape of the HI line is due to the gas rotating in the disk of the galaxy. If a galaxy is inclined compared to the plane of the sky, we see a line profile with two peaks.



HI profile of UGC 11707
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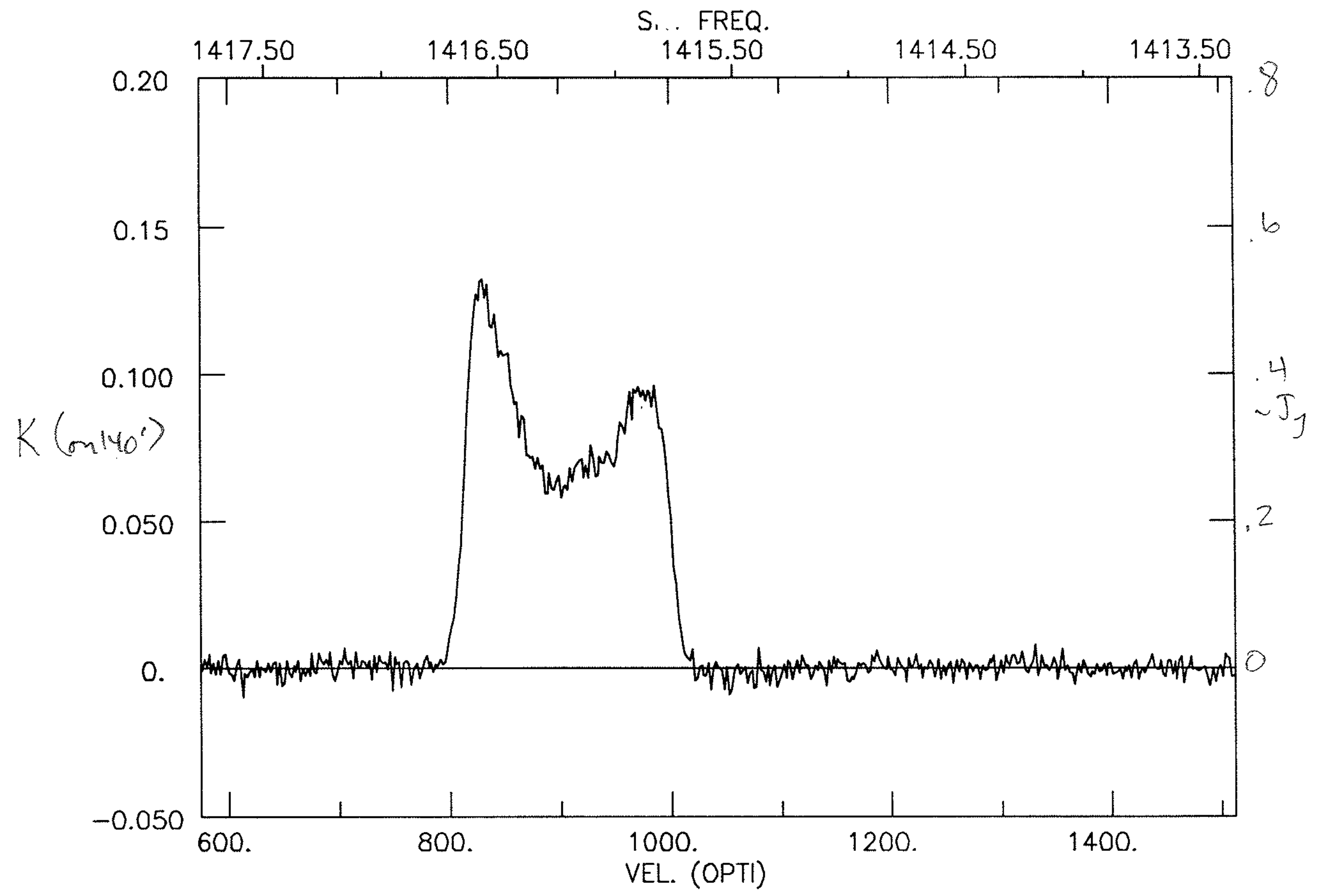
HI in spiral galaxies



$$v(r) = \frac{v_r(r)}{\sin i}$$

Where $v(r)$ is the rotational velocity at radius r,
$v_r(r)$ is the tangential component of the rotational velocity, contributing to the width of the line profile,
And i is the inclination of the galaxy. The inclination is proportional to the axis ratio of the galaxy.

The galaxies dynamical mass inside a radius r is:

$$\left(\frac{M}{M_\odot}\right) \approx 2.3 \times 10^5 \left(\frac{v}{\mathrm{km\ s^{-1}}}\right)^2 \left(\frac{r}{\mathrm{kpc}}\right)$$

Here v is the rotational velocity at radius r.

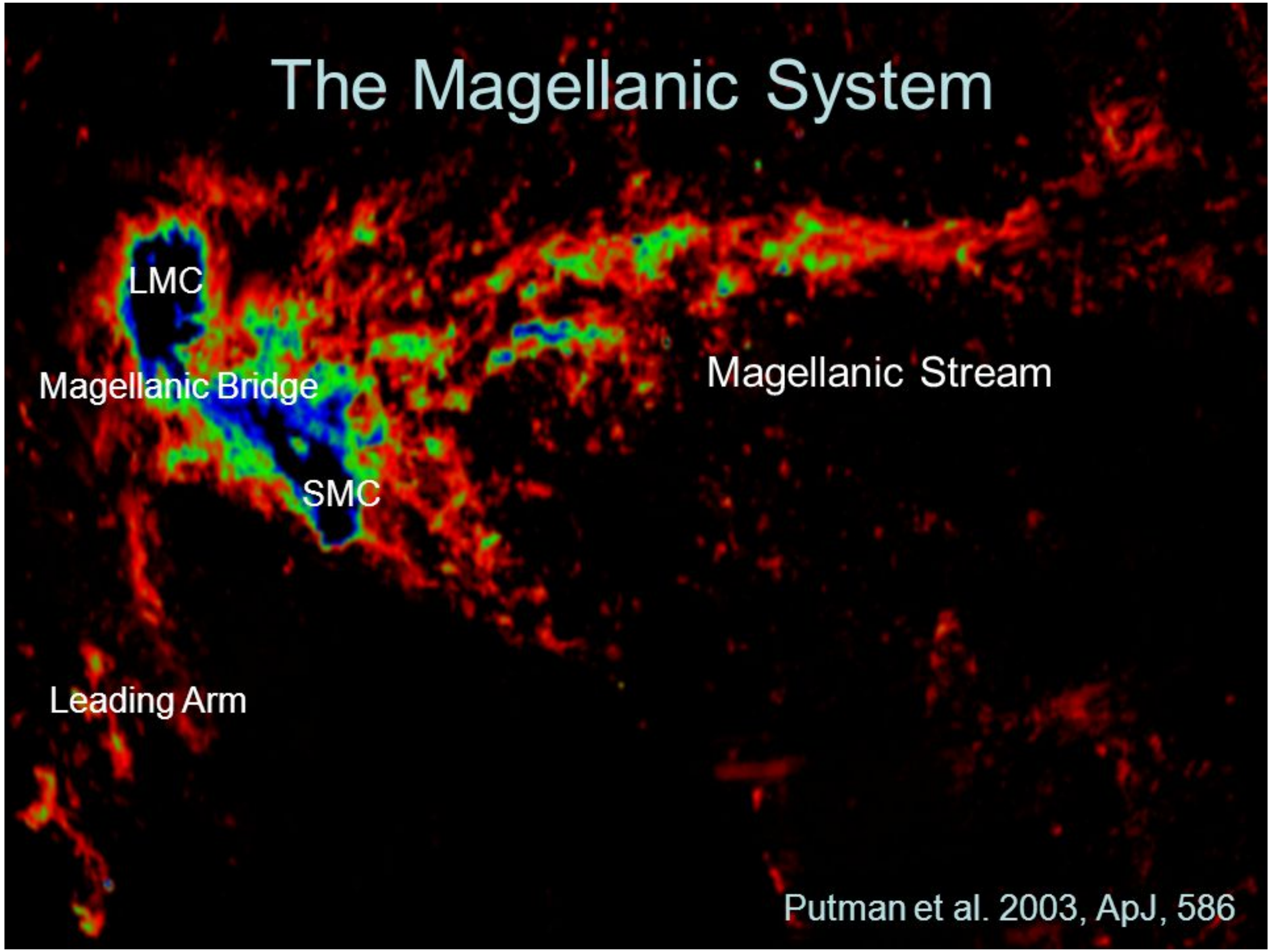
Environmental effects of HI

Tidal interactions between the galaxies are removing gas from the galaxies.

M81 galaxy group

Tidal interactions

HI image



Optical image

More extreme tidal interactions

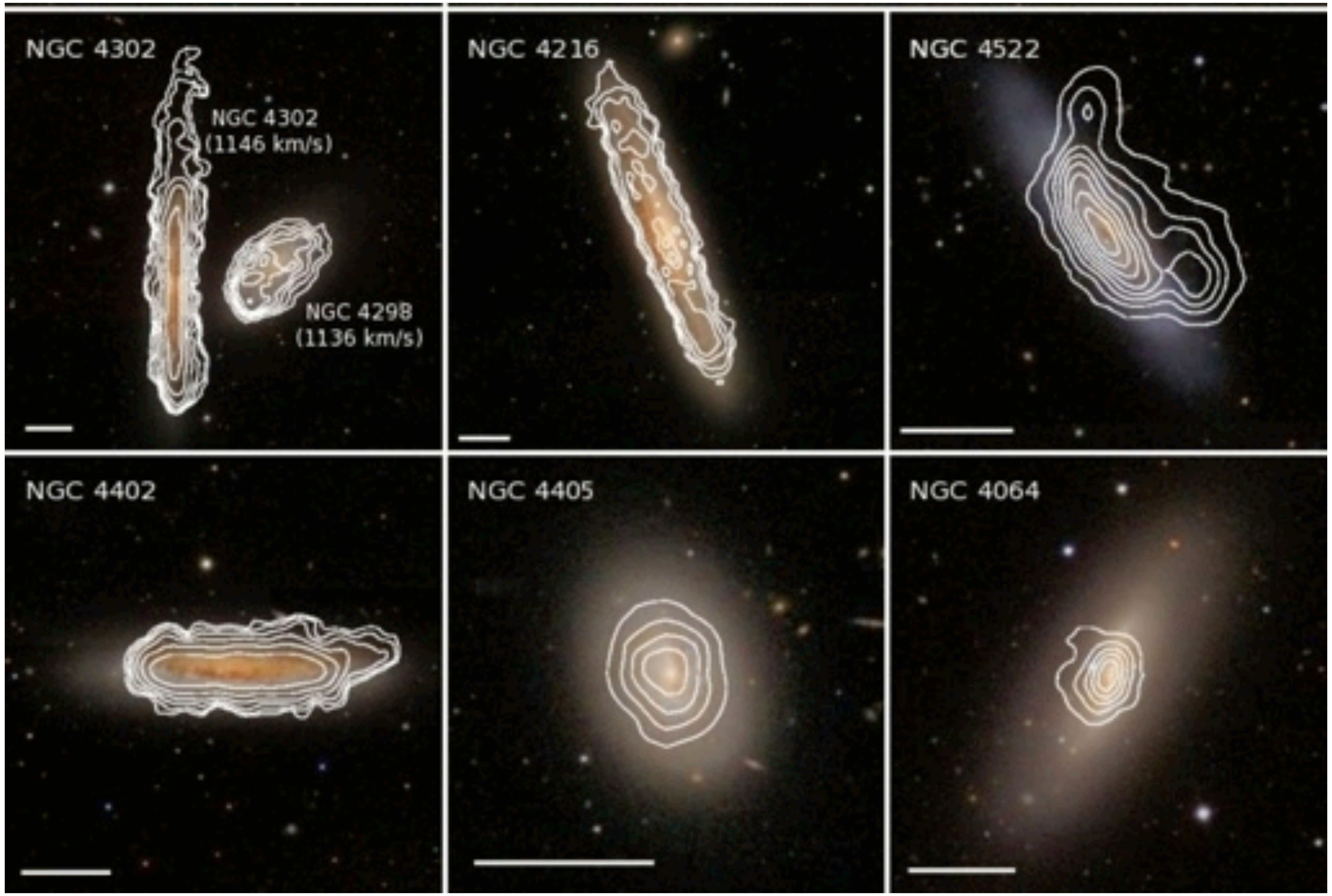
The antenna galaxy is two **merging spiral galaxies** with tails of stars created by the tidal interaction.

Optical image - gas and stars

Zoom in to the central region

Gas removal in galaxy clusters

Galaxies in the Virgo cluster, optical image + HI contours.
They have significantly smaller HI disks compared to galaxies not in clusters.



Gas removal processes in galaxy clusters:

- Tidal interactions
- Ram pressure stripping
- Starvation

Extreme gas removal can eventually transform a spiral galaxy into an elliptical galaxy. -> reason for morphology - density relation in galaxy clusters.

Ram pressure stripping

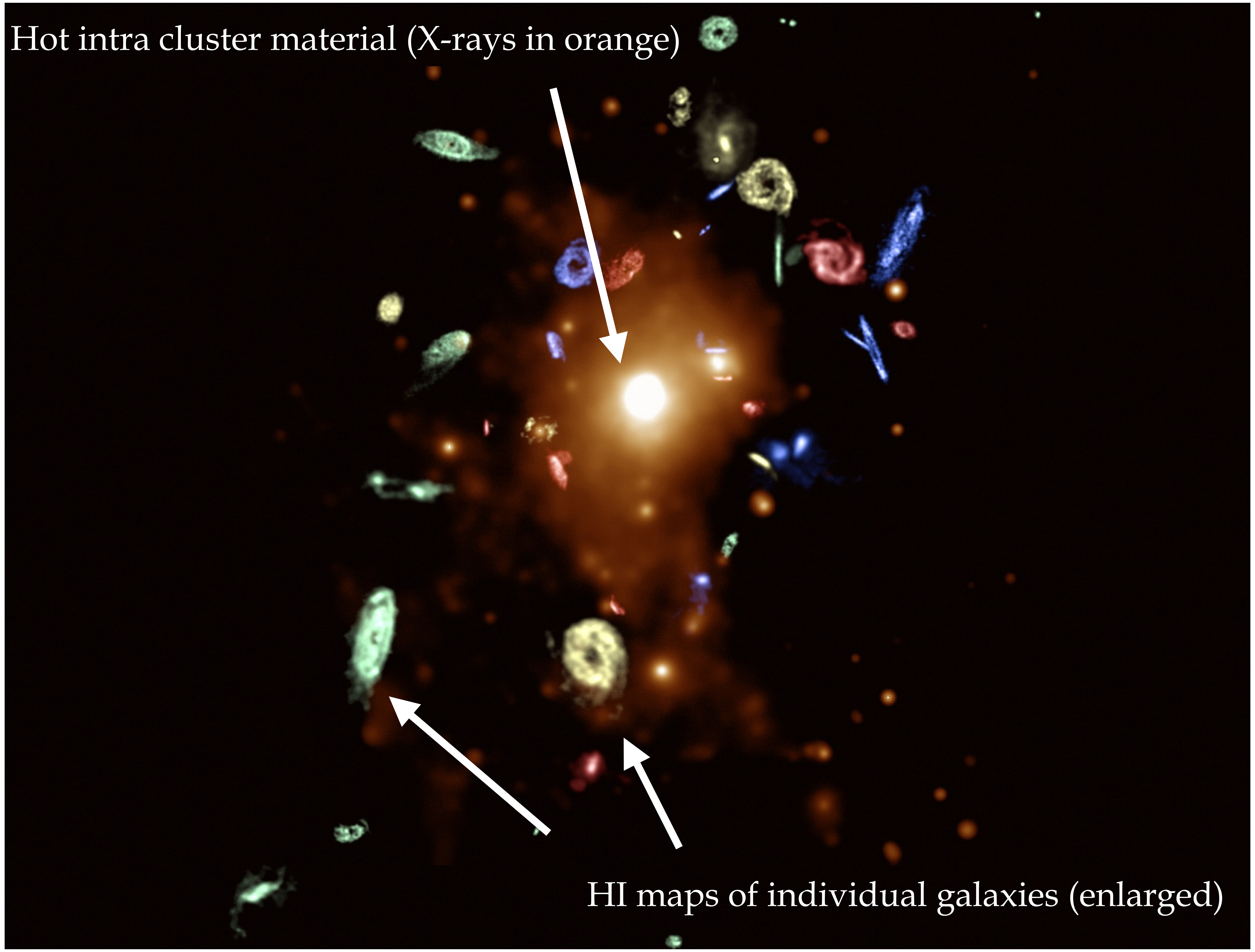
Galaxy **clusters contain hot ionised gas between the individual galaxies.** The density of this gas is typically the highest in the centre of the clusters. -> This gas can be observed trough X-ray observations.
As galaxies move trough the cluster they interact hydrodynamical with the hot cluster gas. -> this can **remove gas and dust from the galaxies.**

$$\rho_{\mathrm{ICM}} v^2 = \gtrsim 2\pi G \sigma_\star(r) \sigma_{\mathrm{g}}(r)$$

ram pressure

disk's gravitational potential

Galaxies in the Virgo cluster



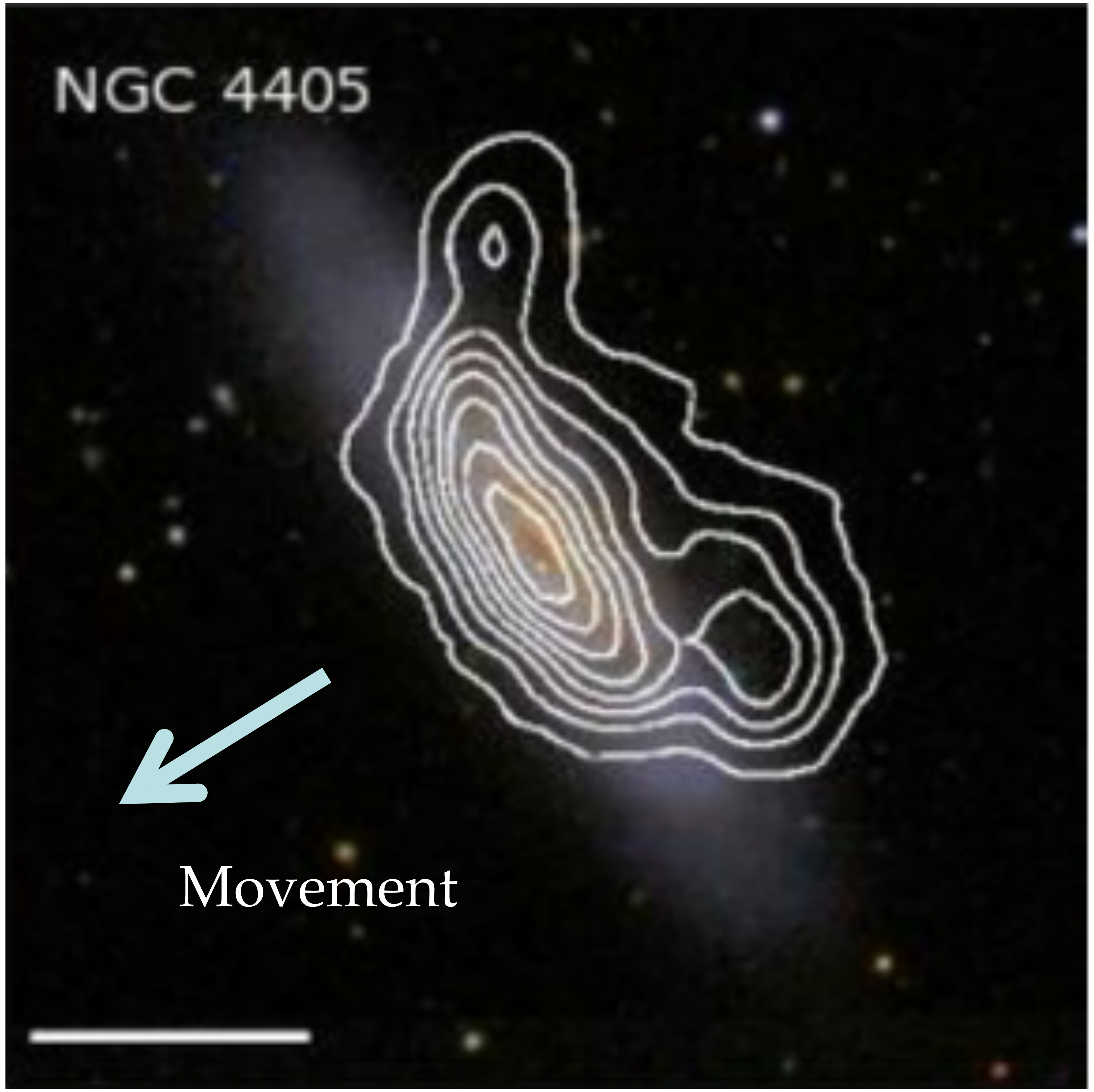
HI maps of Virgo galaxies, Chung et al. 2009

Ram pressure stripping

$$\rho_{\mathrm{ICM}} v^2 => 2\pi G \sigma_\star(r) \sigma_{\mathrm{g}}(r)$$

ram pressure

disk's gravitational potential

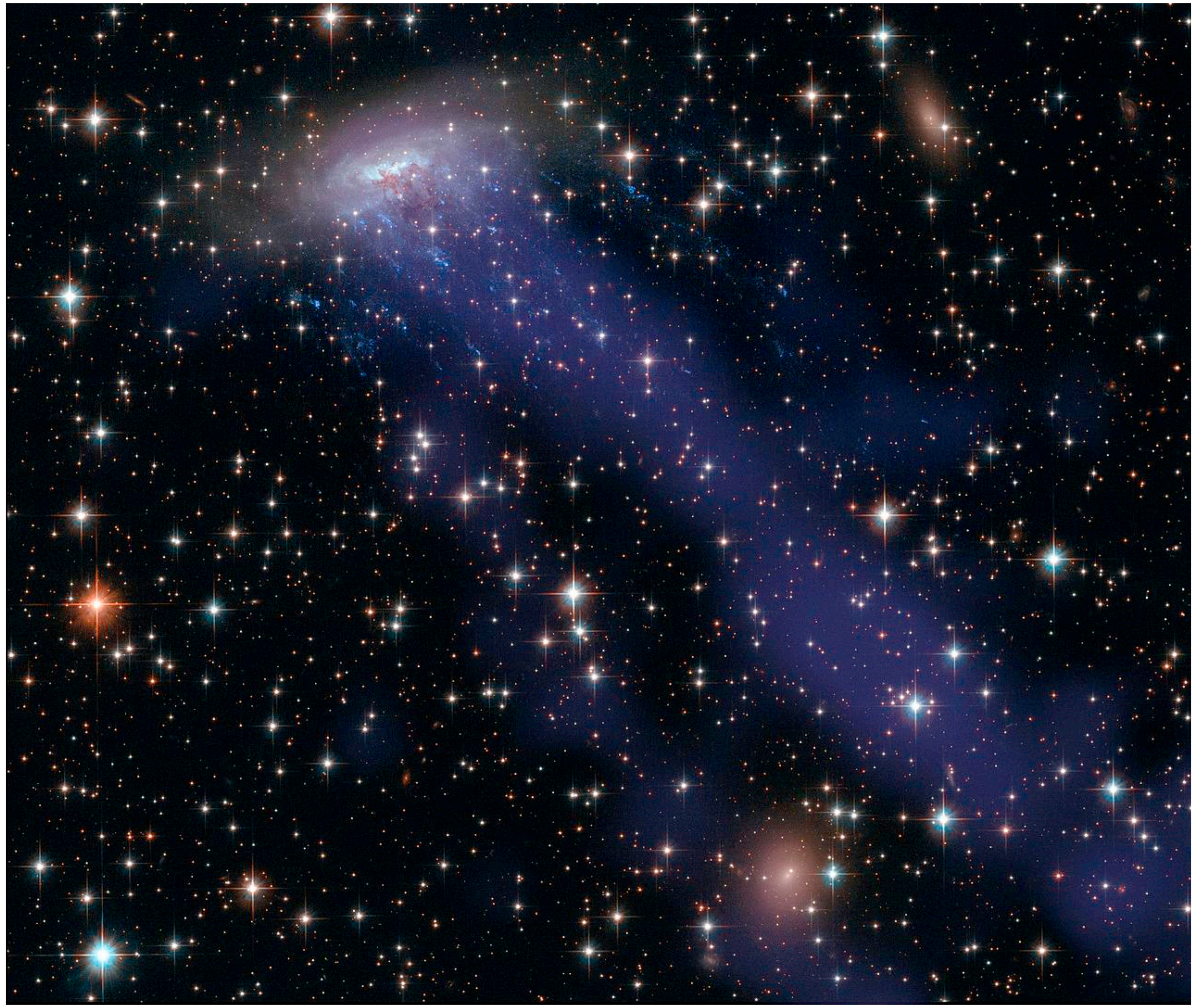


ρ_{ICM} is the density of the intra cluster medium,
v is the velocity of the galaxy inside the cluster,
G is the gravitational constant,
$\sigma_\star(r)$ is the surface density of stars inside radius r,
$\sigma_g(r)$ is the surface density of gas inside radius r

Extreme ram pressure stripping

Jellyfish galaxies

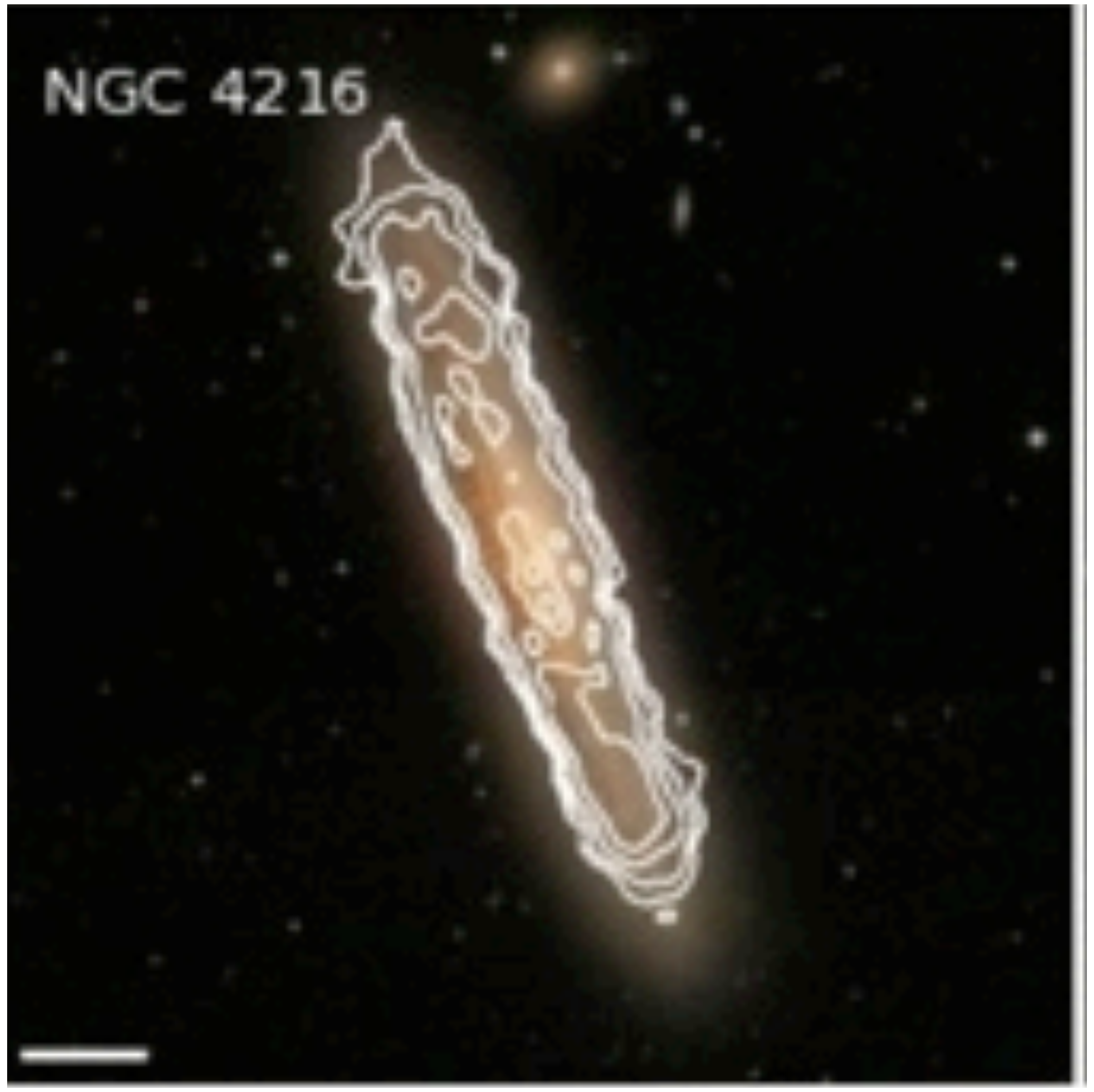
As the dust and gas gets pushed out of the galaxy new stars form in the tail.



Optical image of **ESO 137-001**

Starvation

Starvation is the process when a galaxy can not replenish its HI from its hot halo (e.g. the hot halo can get removed in a cluster) or the cosmic web (there is very diffuse HI gas between the galaxies). If there is no new HI accreted onto the disk of a galaxy, the galaxy will form stars from its HI disk until there is no more gas left for star formation.



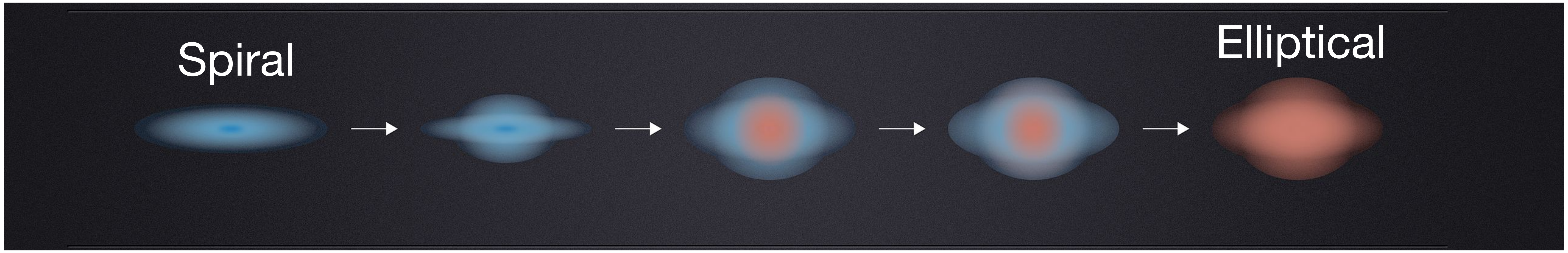
NGC 4216 is a possible example galaxy from the Virgo cluster with a small, regular shaped HI disk.

Galaxy formation

What determines whether a galaxy will turn out to be a spiral galaxy or an elliptical galaxy?

This can be best explained by the hierarchical galaxy formation:

- Since the spiral galaxies are younger we can take them as a first step.
- Stars are in a disk shape because of the angular momentum of the gas when a galaxy is forming.
- As the galaxy runs out of fuel it will not produce new stars and the already present stars will relax into a spherical shape.
- In addition, galaxies often merge. If two spiral galaxies with similar size merge the outcome will be a large elliptical galaxy.



Note: the open questions section in the book is now actually much better understood. Galaxy formation and evolution is a rapidly evolving field in astrophysics.

Galaxy formation

Galaxies can grow trough mergers.

We distinguish two types of mergers based on the size ratio of the galaxies involved:

Major merger (both galaxies have similar mass) - the result is almost always an elliptical galaxy. Stellar streams in the Milky Way are remnants of minor mergers, where the Milky Way consumed some small galaxies.

Minor merger (one galaxy is much larger compared to the other galaxy) - the result is usually the same type of galaxy as the larger galaxy in the merger.