# Part 3: Galaxies and the Universe

Tuesday, March 22 — Reading: Chapter 12.1 — 12.3
- Our Galaxy = The Milky Way

Thursday, March 24 — Reading: Chapter 13.1 — 13.2
- Galaxies: types, properties, clusters of galaxies, dark matter

Tuesday, March 29 — Reading: Chapters 13.3, 15
- Galaxies: formation, evolution; distance scales; expansion of the Universe

Thursday, March 31 — Reading: Chapter 12.4, 14
- Galaxies: active galaxies and quasars; supermassive black holes

Monday, April 4 — TA's help session for HW3: 3 to 5 PM in WCH 1.120

Tuesday, April 5 — Reading: Chapter 15; HW 3 due
- Cosmology: Big Bang ➡ background radiation; formation of structure

Wednesday, April 6 — Help session: 4 to 6 PM in Welch 2.224

Thursday, April 7 — Exam 4

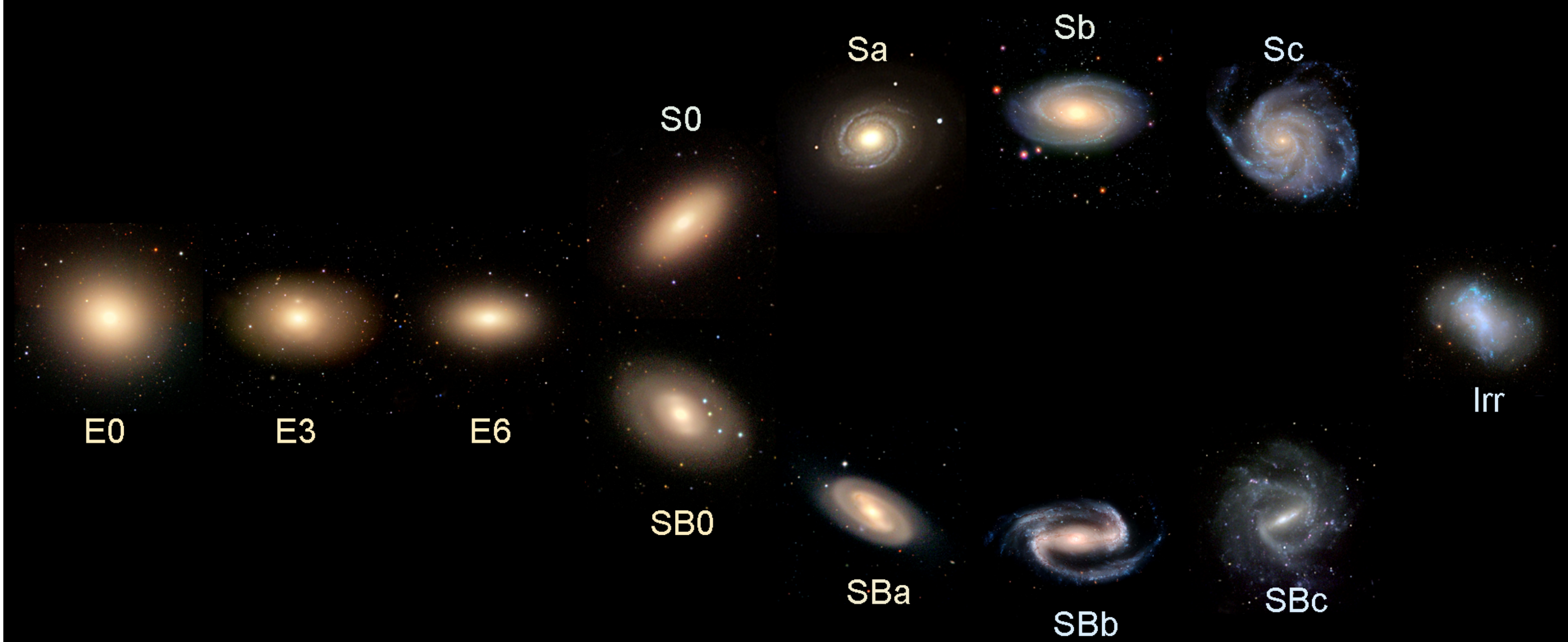

# Review:

## Kinds of Galaxies

The most fundamental distinction is
the one between elliptical galaxies
(shaped like flattened footballs)
and
galaxies with a disk
(like a spinning frisbee).

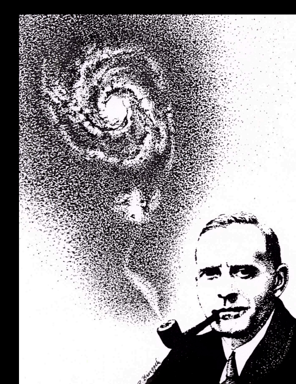
The disks of many galaxies
show beautiful spiral structure.

# Hubble's Galaxy Classification Scheme




Along the sequence Sa → Sc,

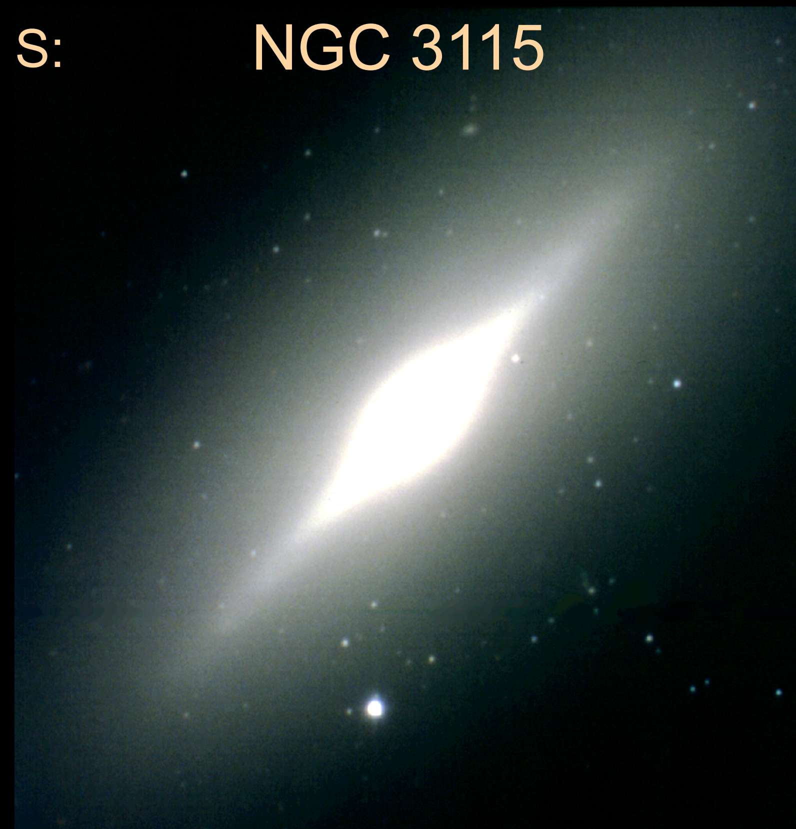
- the contribution of the bulge decreases,
- the fractional amount of gas increases,
- the contribution of young stars increases, so
- the disk looks more patchy, and
- the spiral arms become more open.



Our Milky Way is a typical spiral, intermediate between Sb and Sc. It has a weak bar.

# Types of Galaxies: The Hubble Sequence

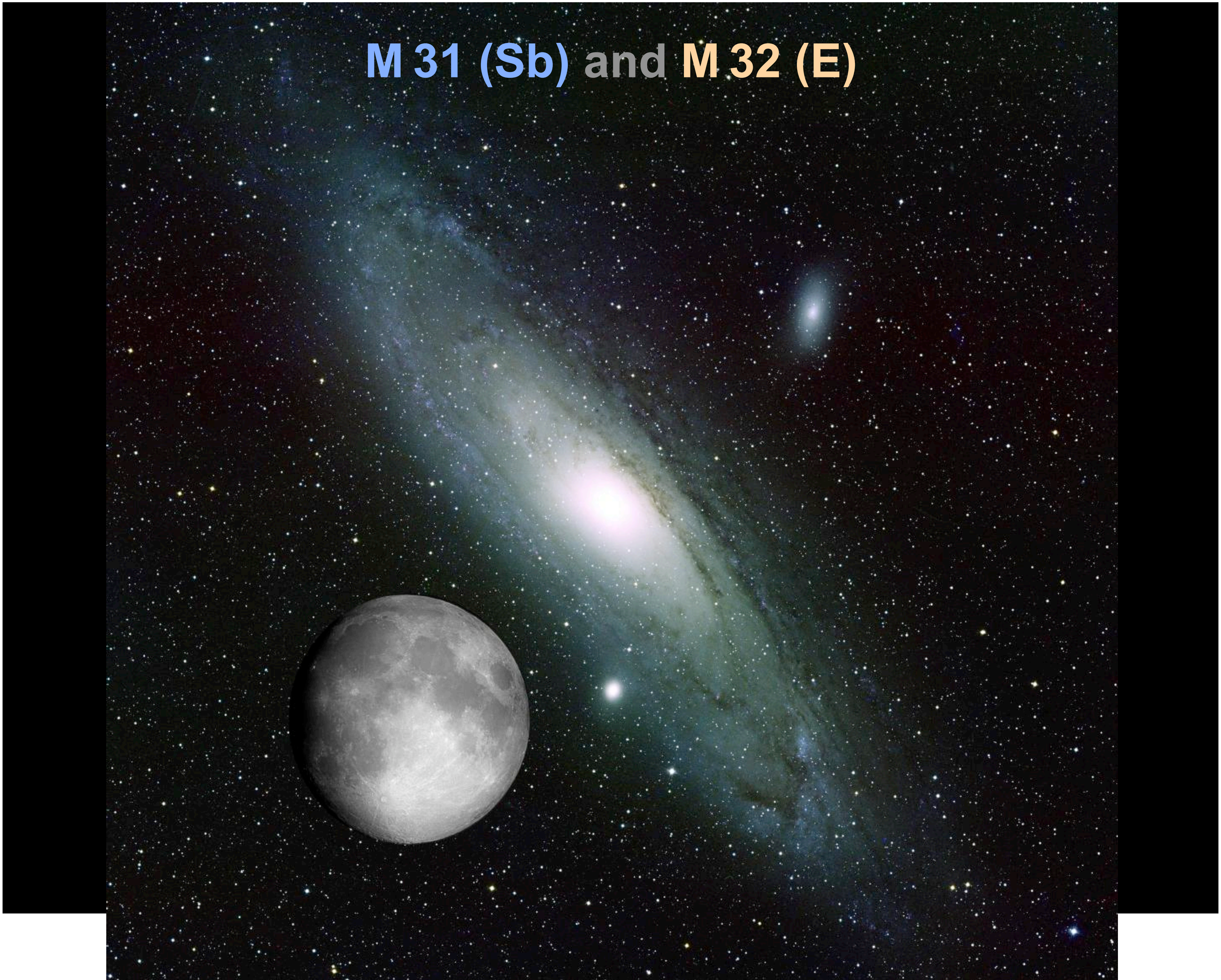
**S0 galaxies** are intermediate between E and S: they have disks, but no spiral structure.

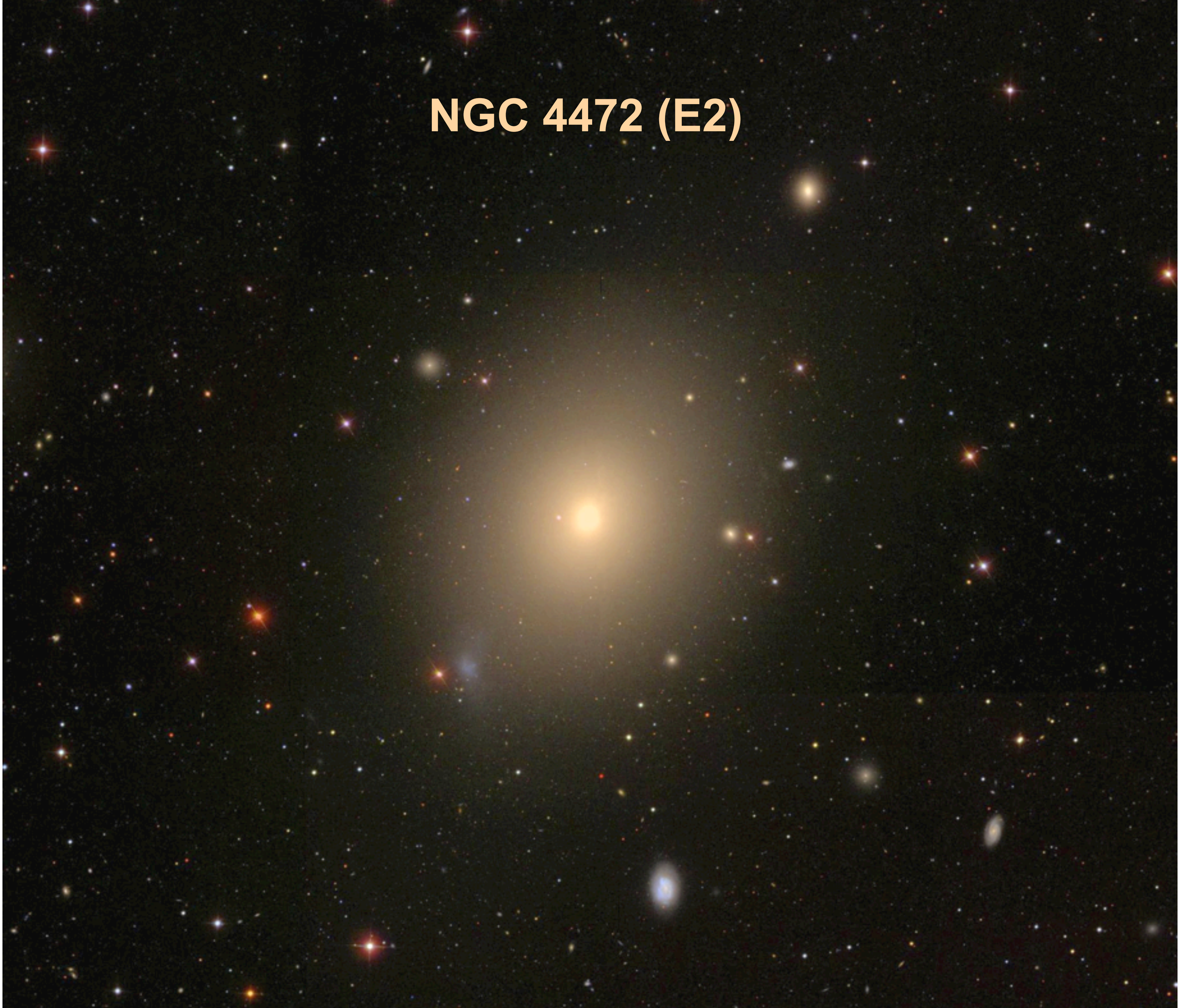


NGC 3115

Sextans A

**Irregular galaxies** are asymmetric and messy. They contain no bulge. They are made mostly of Population I (i. e., young) stars, and so they also must contain large amounts of cold gas.


M 31 (Sb) and M 32 (E)


NGC 4472 (E2)

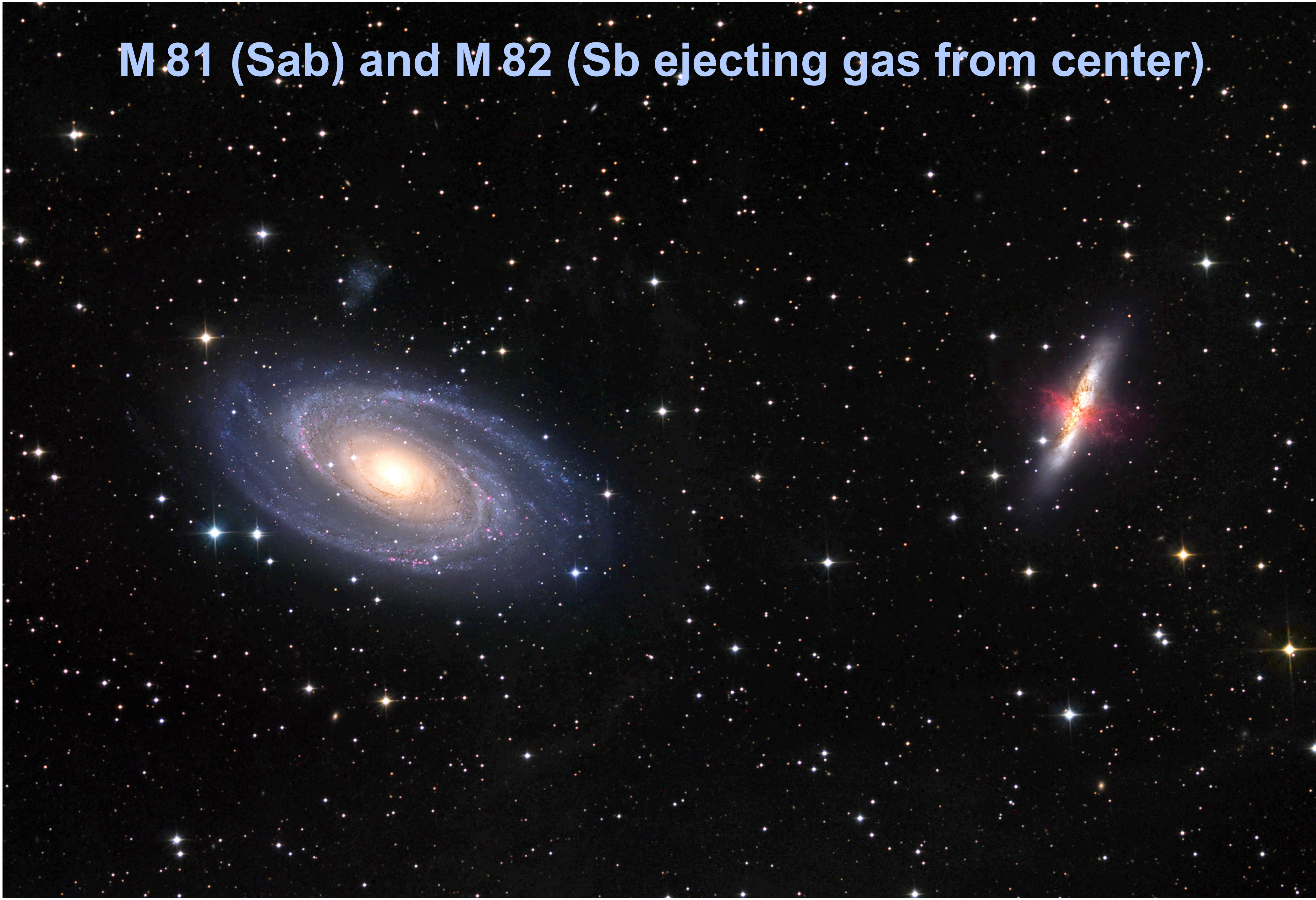
# NGC 4594 (Sa)

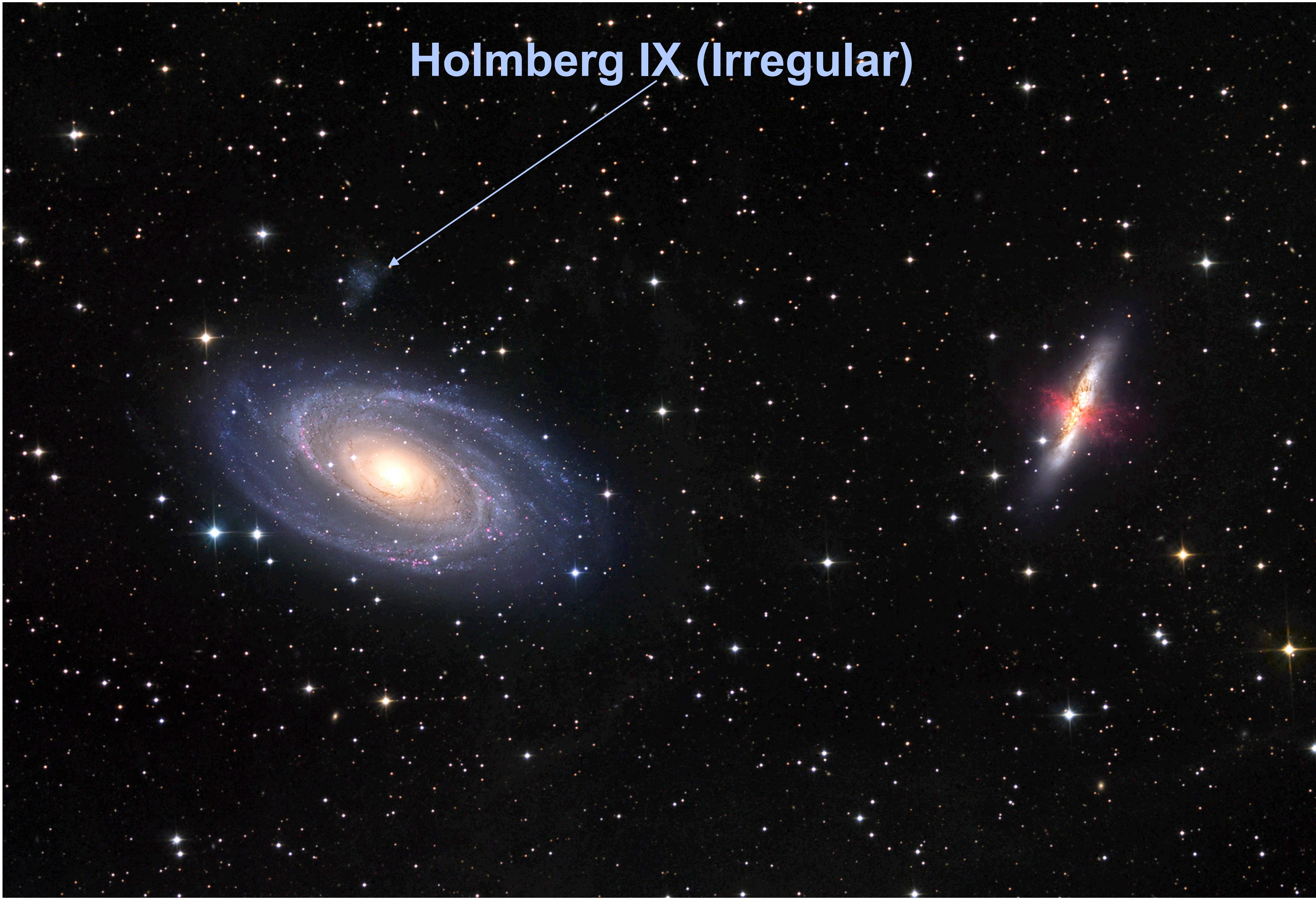
Sombrero Galaxy • M104

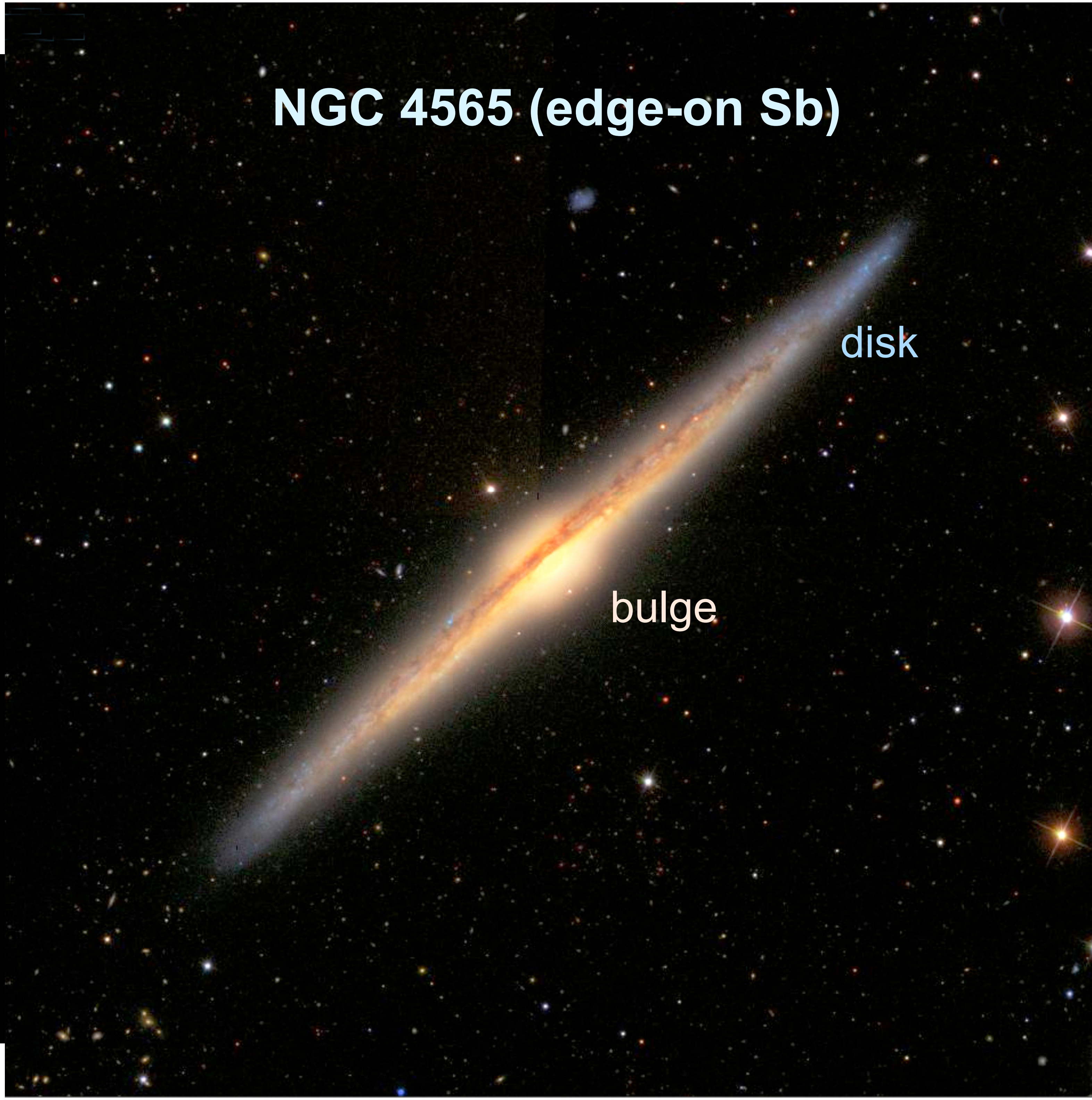
Hubble Heritage

NASA and The Hubble Heritage Team (AURA/STScI) • Hubble Space Telescope ACS • STScI-PRC03-28

# M 81 (Sab) and M 82 (Sb ejecting gas from center)



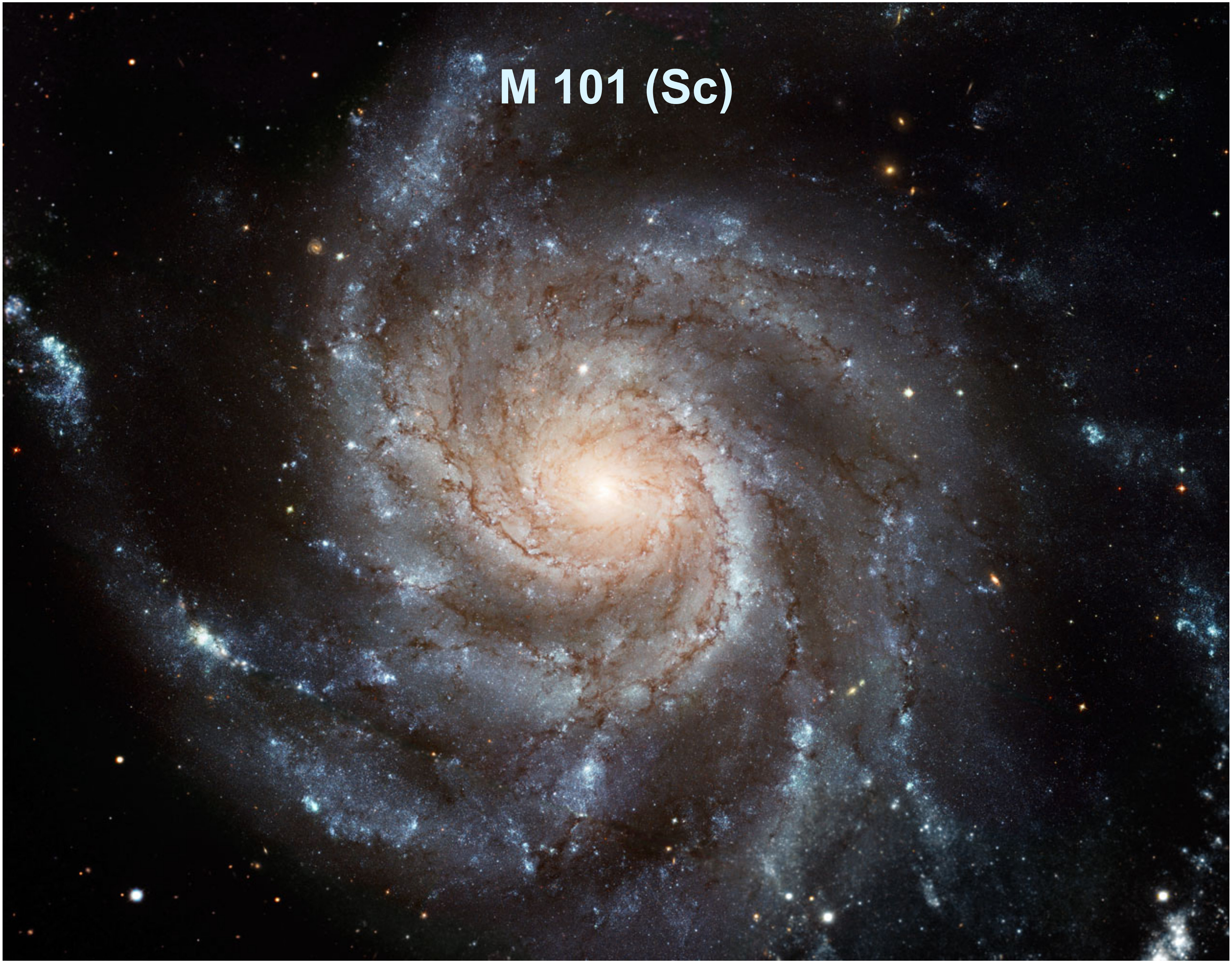

Holmberg IX (Irregular)

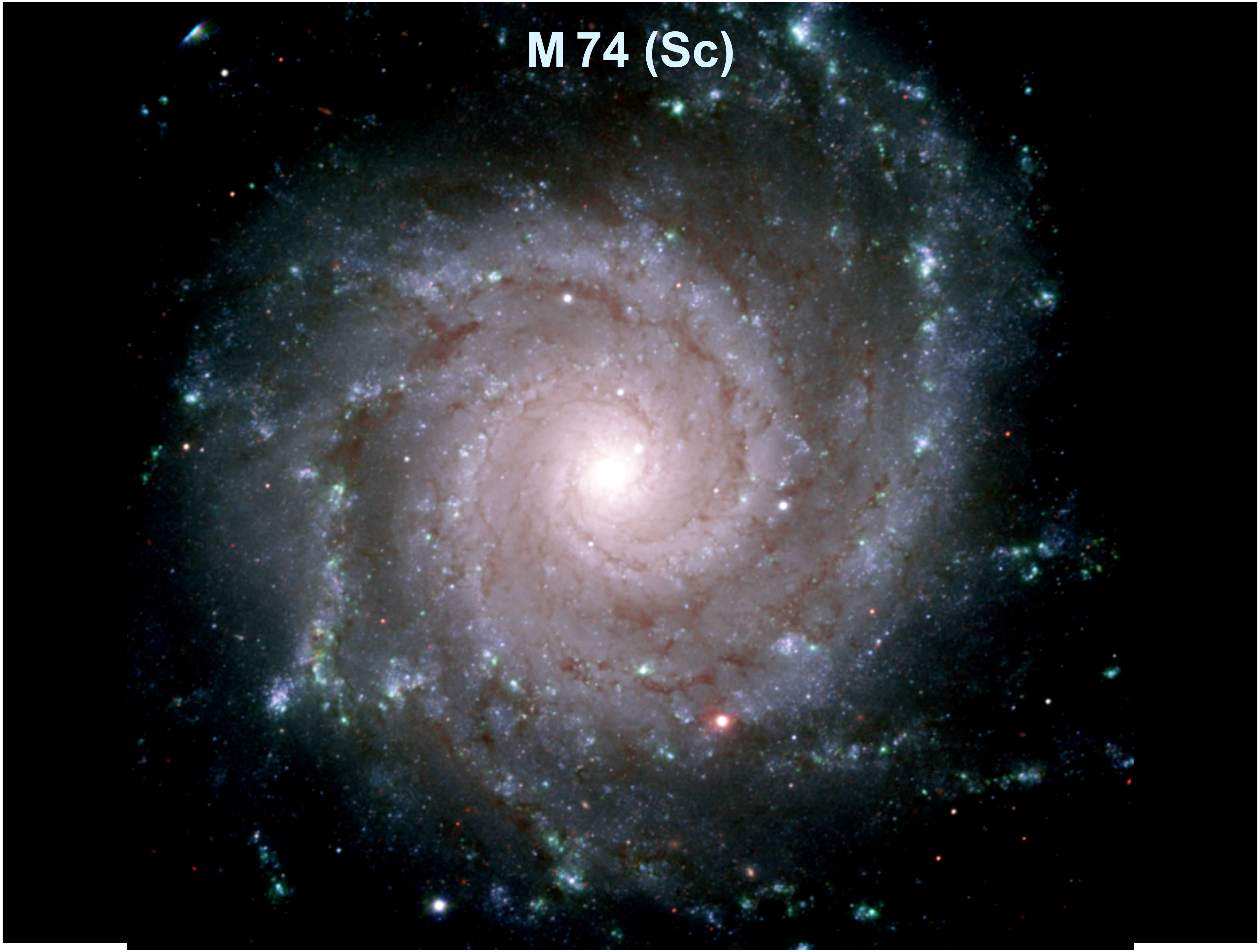

NGC 4565 (edge-on Sb)
disk
bulge

# NGC 891 (edge-on Sbc)

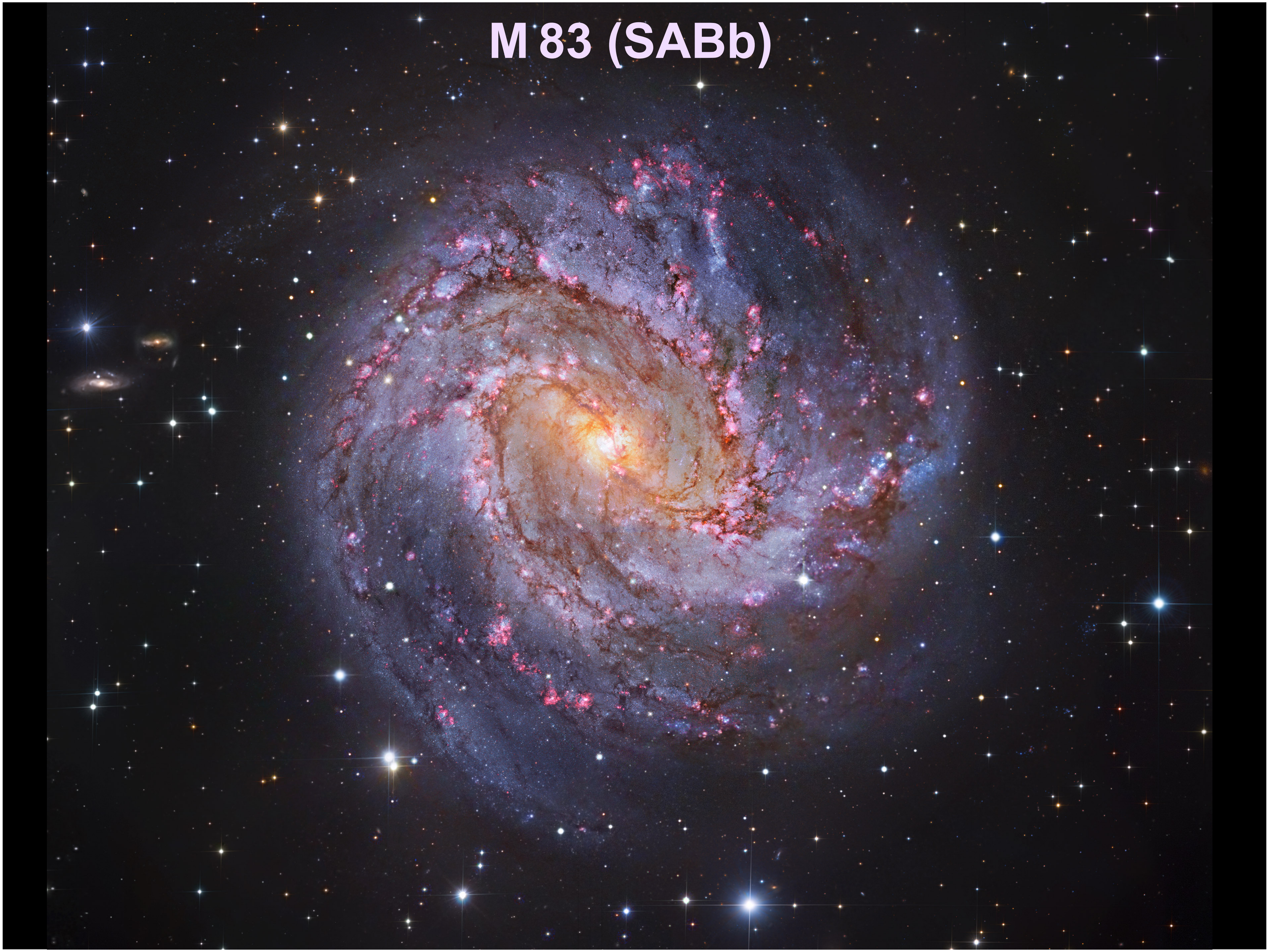
# M 33 (Sc)

M33 © IAC/RGO/Malin
Photo from Isaac Newton Telescope plates by David Malin


M 101 (Sc)

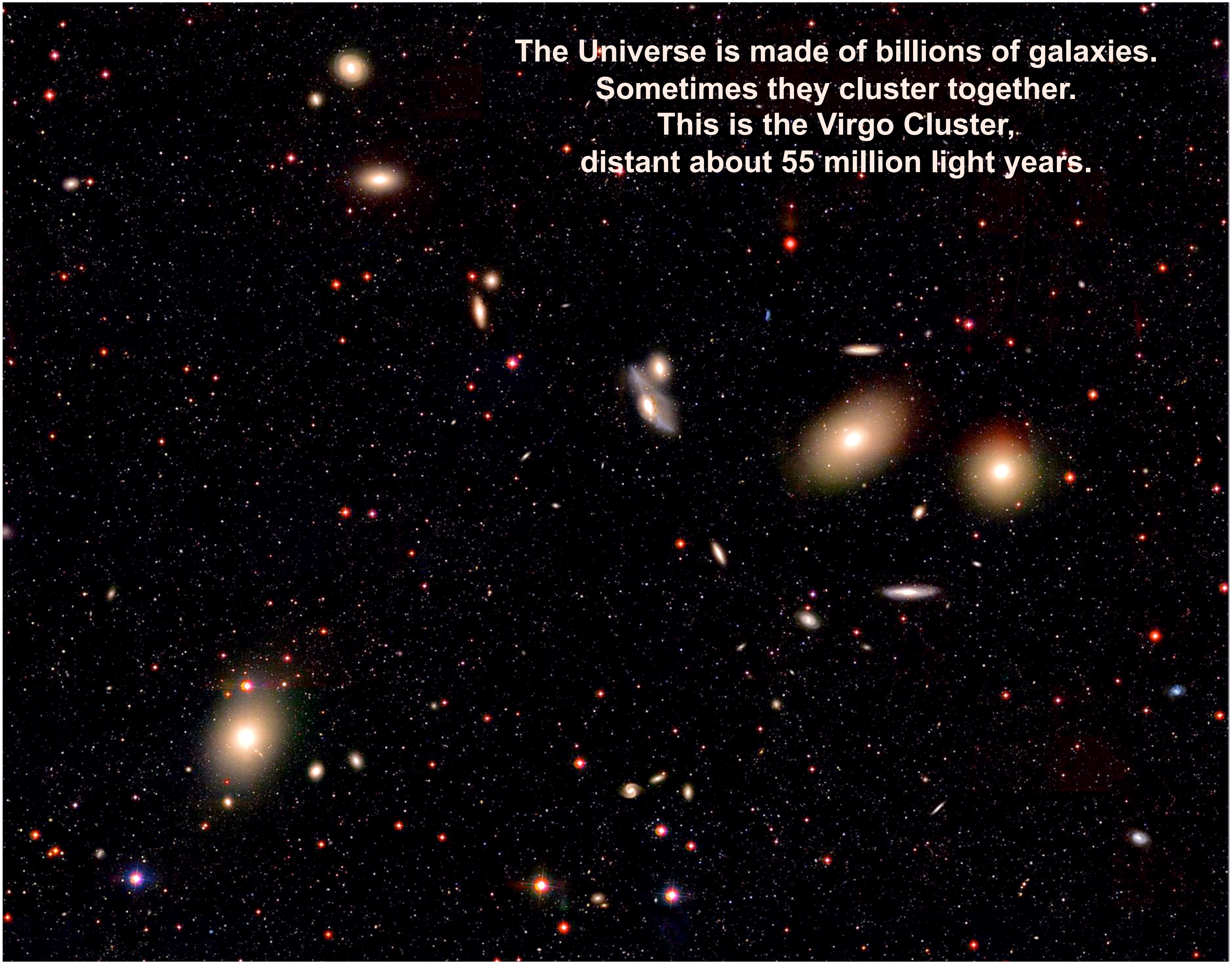

M 74 (Sc)

# NGC 4449 (Irregular)


M 83 (SABb)

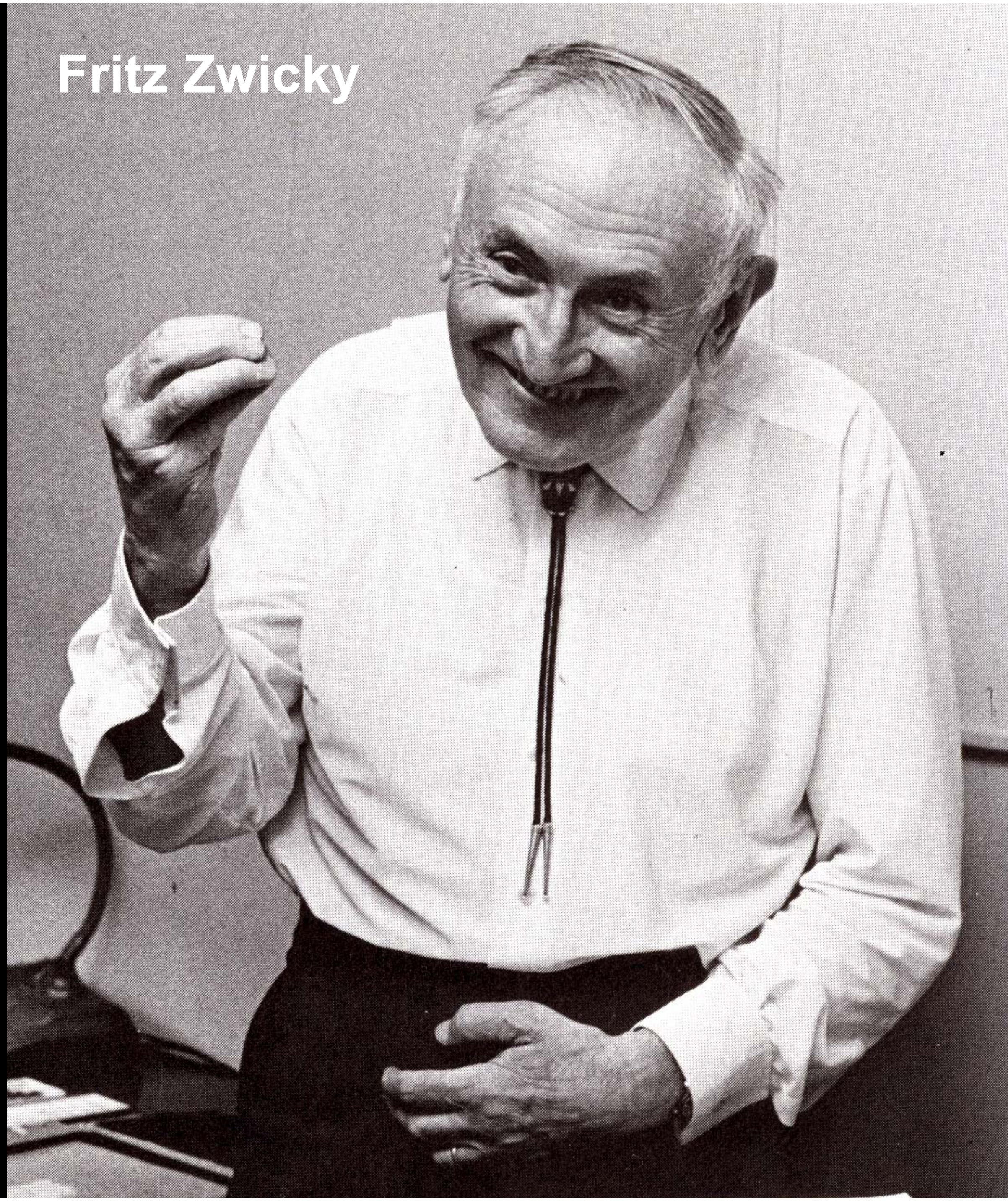
# NGC 1300 (SBbc)

Seyfert's Sextet


The Universe is made of billions of galaxies.
Sometimes they cluster together.
This is the Virgo Cluster,
distant about 55 million light years.


Abell 68 cluster
(distance 2 billion light years)

# Dark Matter in the Universe


Fritz Zwicky

## Visible Matter

Everything that we can see with any kind of telescope — everything that we have talked about in this course — makes up 5 % of the mass of the Universe.

## Dark Matter

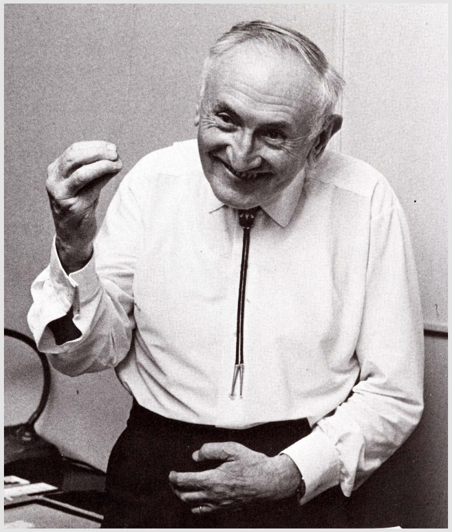
Dark matter of unknown composition makes up 95 % of the mass of the Universe.

Dark matter is detected only via its gravitational attraction on visible objects.

# Dark Matter in Clusters of Galaxies

Galaxies in clusters do not move in circular orbits.
Some galaxies are close to the center and moving at high speed.
Others drift slowly in the outskirts of the cluster.

Because orbits are not circular, we can't measure cluster masses as accurately as we measure masses of disk galaxies. But:
Galaxies in rich clusters typically move faster than 1000 km / s.
To keep these galaxies from flying out of the cluster, the total mass must be 100 times greater than the mass in visible galaxies.



**This result was first discovered for the Coma Cluster in 1933 by Fritz Zwicky.**

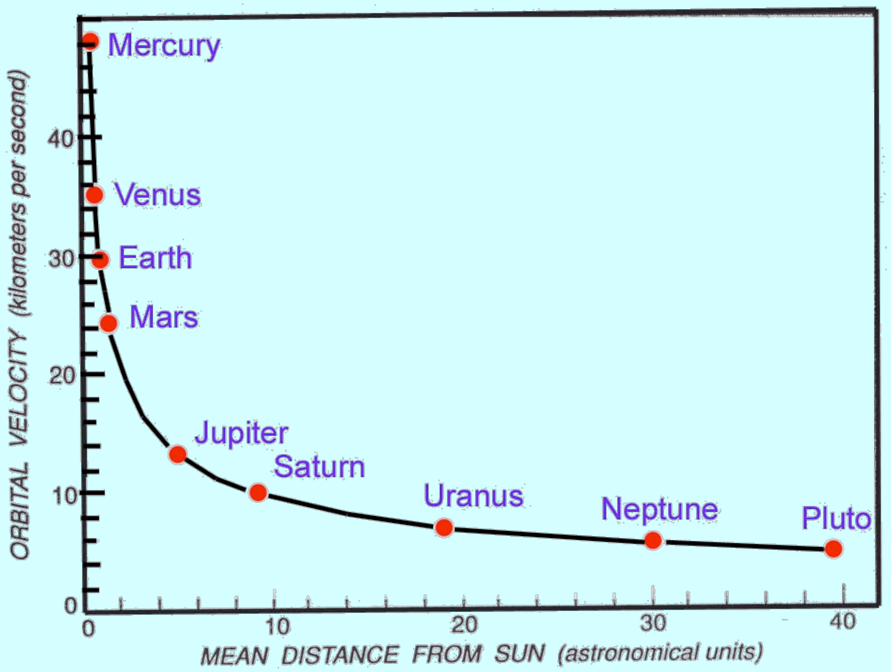
# Evidence for Dark Matter

Evidence for dark matter includes:

- – Galaxies in clusters of galaxies move so quickly that the clusters would fly apart if they didn’t contain a lot more mass than we see.
- – Galaxies rotate quickly even far from the center, where there is no visible matter. Therefore they are surrounded by massive halos of dark matter. If there were no dark matter, the galaxies would rotate more slowly at larger radii, like in the Solar System, where planets revolve around the Sun more slowly at larger radii.

# Masses of Individual Galaxies: Rotation Curves

How fast an object moves in its orbit depends on the mass interior to the object. For example, in the Solar System, almost all of the mass is in the Sun − the masses of the planets are almost negligible. So the outer planets move much more slowly than the inner planets. Reason: the gravitational attraction of the Sun decreases outward as $1/r^2$, where r is the radius of the planet's orbit. As a result, a planet's velocity V around the Sun satisfies $V^2 \propto 1/r$ or $V \propto 1/\sqrt{r}$ :

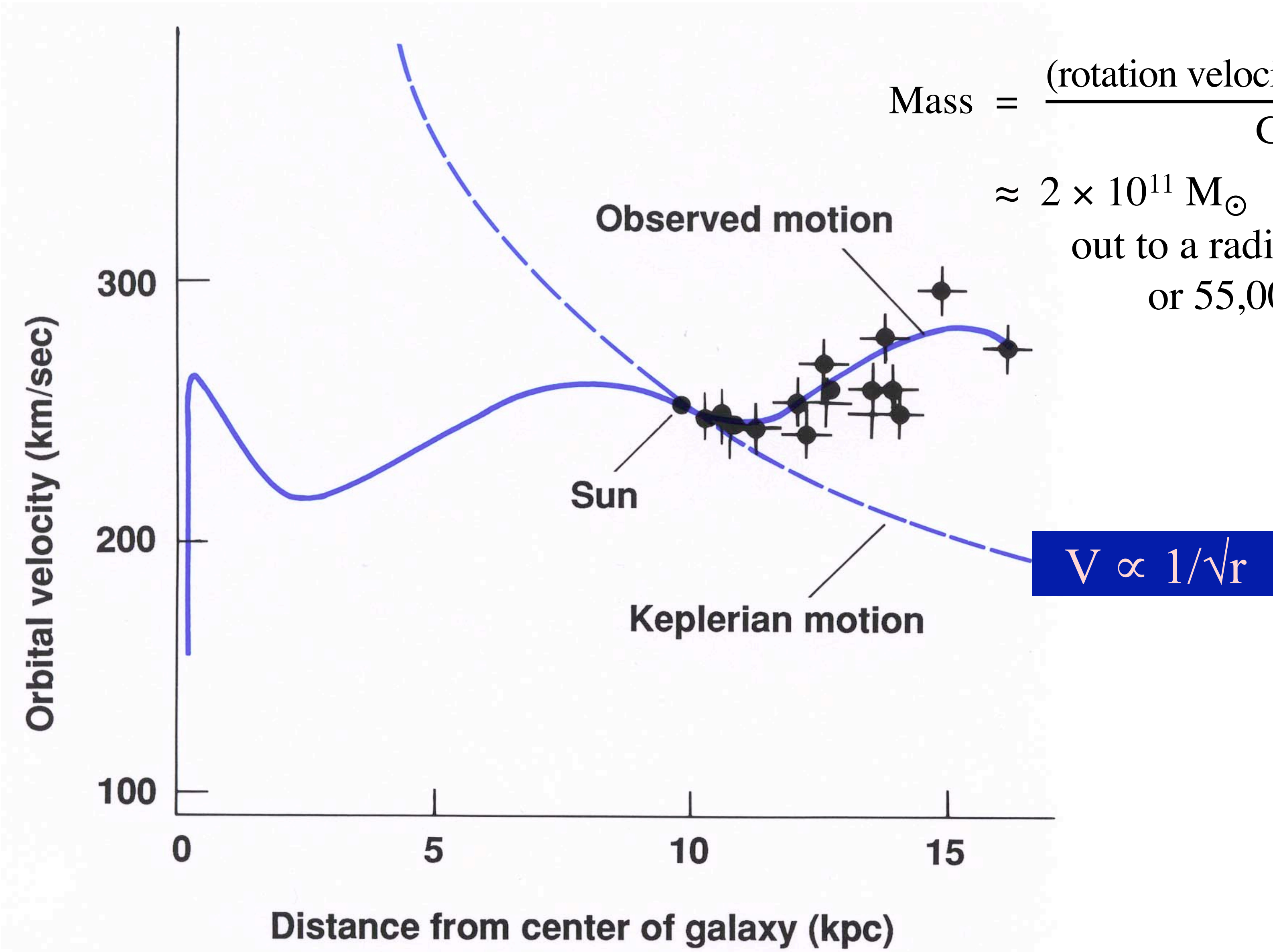



Therefore:

$$(\text{Total mass out to radius r}) = \frac{V^2 r}{G}$$

Similarly, outside (most of) the mass of a galaxy, we would expect that the rotation velocity of what little stuff is left would decrease as $1/\sqrt{r}$ .

# The Mass of Our Galaxy



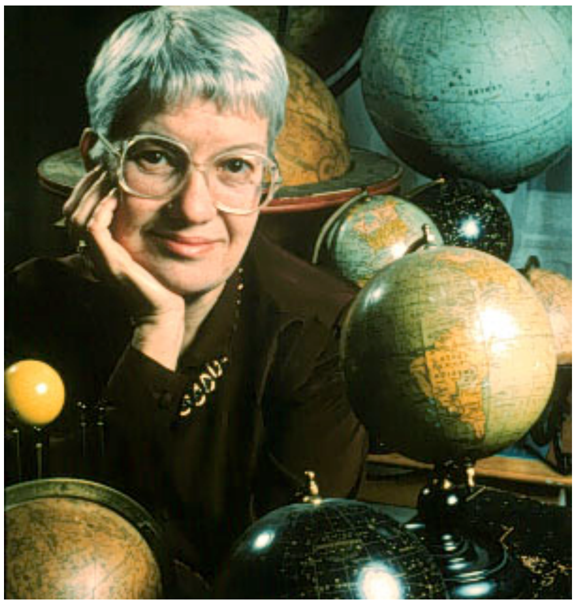

$$\text{Mass} = \frac{(\text{rotation velocity})^2 (\text{radius})}{G}$$

$$\approx 2 \times 10^{11} M_\odot$$

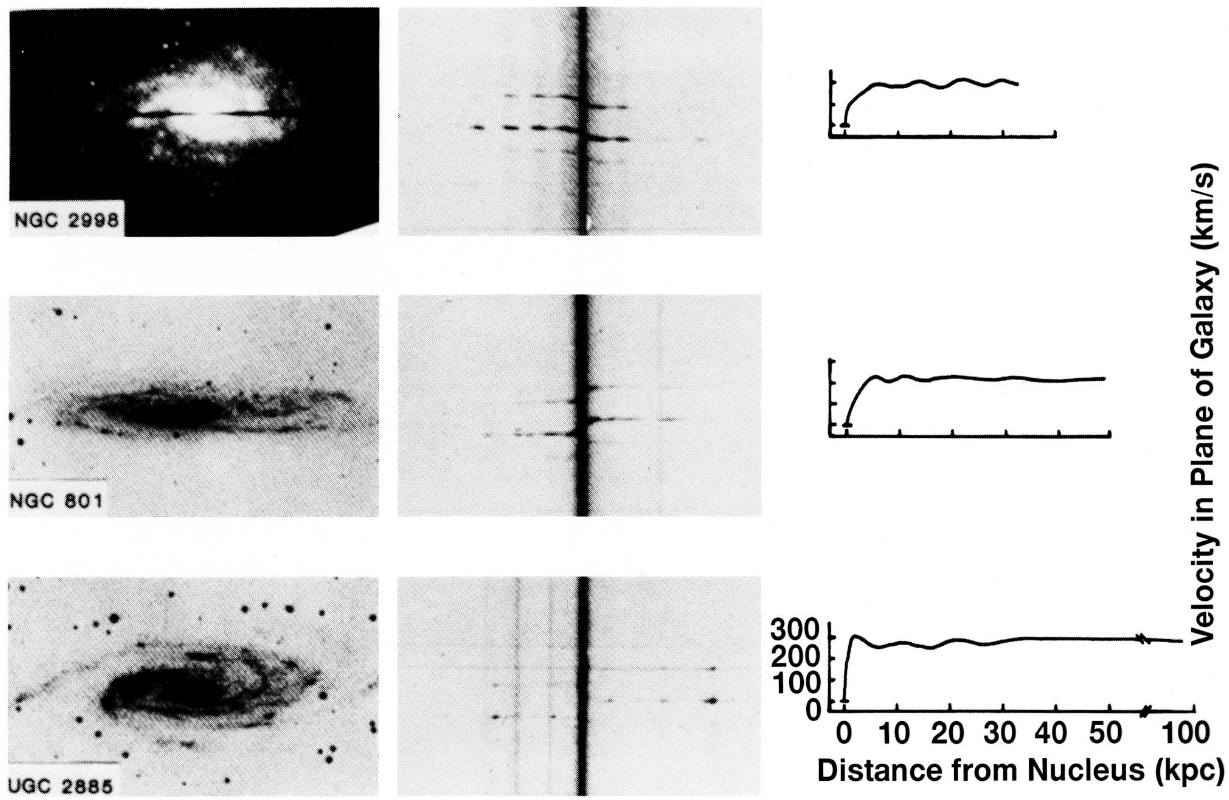
out to a radius of 17 kpc or 55,000 ly.

# Dark Matter Halos of Galaxies

The expected decrease in orbital velocities in the outer parts of galaxies is not seen! Instead, the orbital velocities stay constant out past the visible edges of galaxies.



Vera Rubin




Since rotation velocities stay large at large radii, where there are no stars, **there must be dark matter there that we cannot see – more dark matter than all of the visible matter in the galaxies.**

# Evidence for Dark Matter

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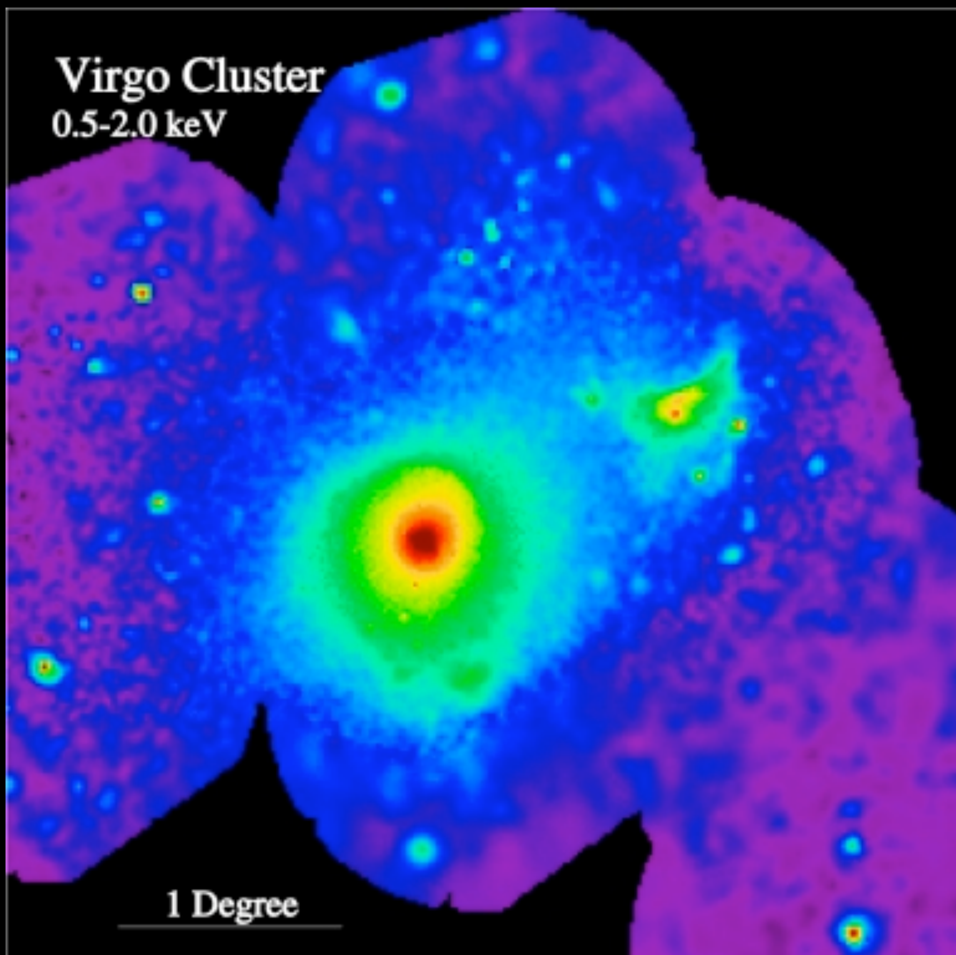
- Individual galaxies rotate quickly even far from the center, where there is no visible matter. This means that they are surrounded by massive halos of dark matter. If there were no dark matter, the galaxies would rotate more slowly at larger radii, exactly as in the Solar System, where planets revolve around the Sun more slowly at larger radii.
- Some clusters of galaxies and some individual galaxies contain halos of hot, x-ray-emitting gas. To hold this gas gravitationally, much more mass must be present than we see. Otherwise the gas would fly away.

# X-Ray Image of the Virgo Cluster of Galaxies




X-ray observations show that rich clusters contain gas with temperatures of about 100 million K.

This hot gas would escape from the cluster unless it is held by a stronger gravitational field than the visible galaxies can explain.

The amount of mass that is required to hold the gas agrees with the amount that is implied by the fast motion of the galaxies.

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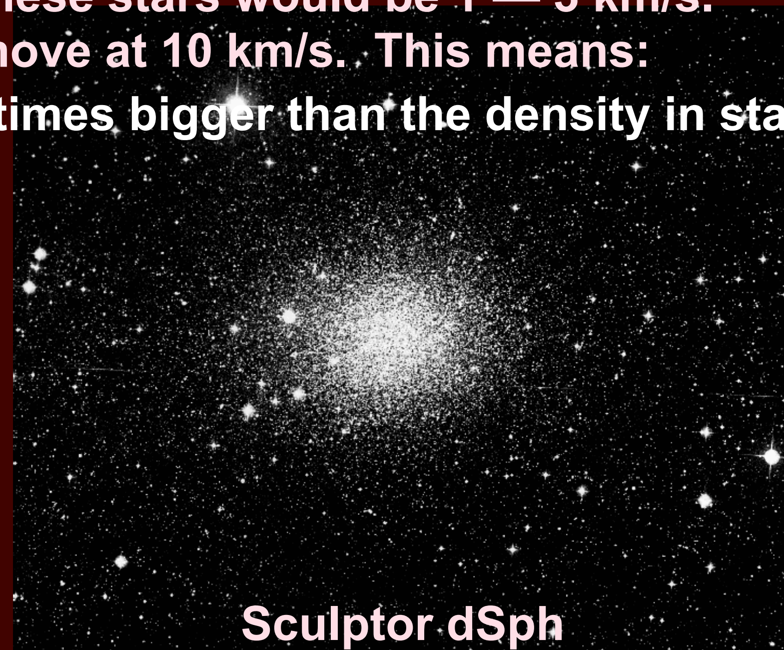
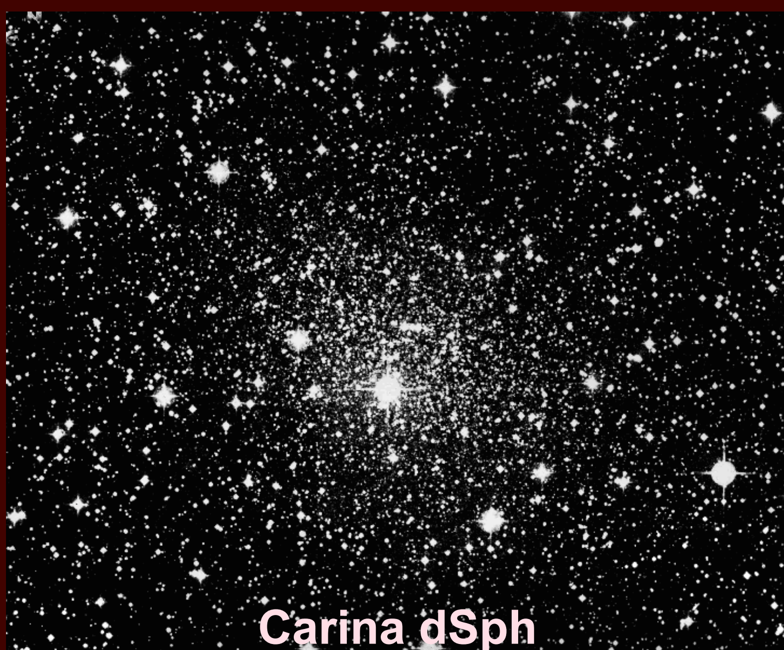
- Some clusters of galaxies and some individual galaxies contain halos of hot, x-ray-emitting gas. To hold this gas gravitationally, much more mass must be present than we see. Otherwise the gas would fly away.
- Stars in the tiniest dwarf galaxies move so quickly that the galaxies would fly apart if they didn't contain a lot more mass than we see.

# The Tiniest Galaxies Contain Almost No Stars But Lots Of Dark Matter

If these galaxies (except Fornax) contained only the stars we see, then the random velocities of these stars would be 1 — 3 km/s. Instead, the stars typically move at 10 km/s. This means:

**The density of dark matter is 5 — 50 times bigger than the density in stars.**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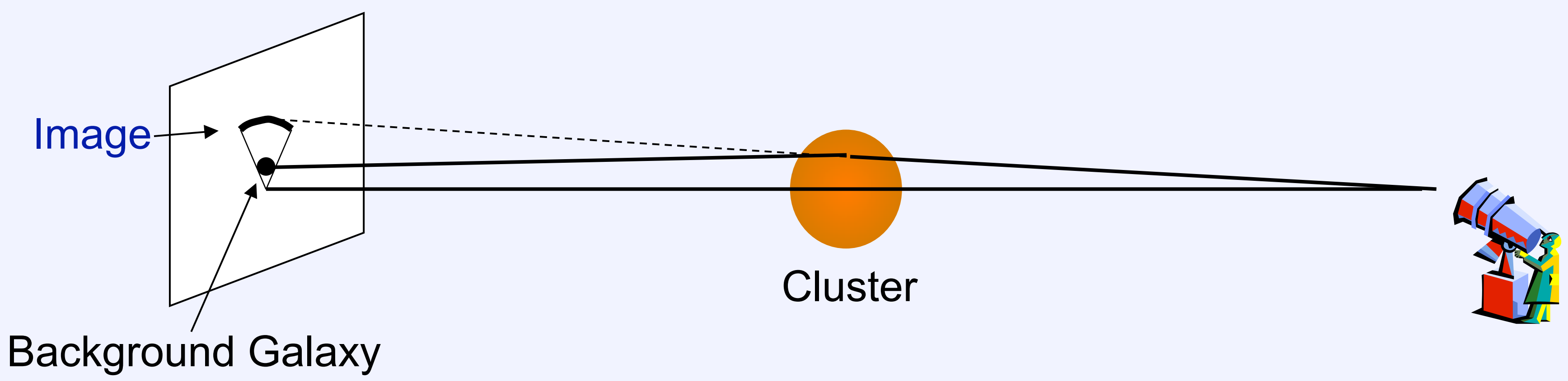
- Some clusters of galaxies and some individual galaxies contain halos of hot, x-ray-emitting gas. To hold this gas gravitationally, much more mass must be present than we see. Otherwise the gas would fly away.
- Stars in the tiniest dwarf galaxies move so quickly that the galaxies would fly apart if they didn't contain a lot more mass than we see.
- In some clusters of galaxies, we see faint arcs of light concentric with the cluster center. They are distorted images of background galaxies that are gravitationally lensed by the cluster mass distribution. They imply that the clusters contain much more mass than we see. The amount of dark matter agrees with results from galaxy motions and from x-ray gas.

# Gravity Bends Light Rays

Dark and visible matter do not only effect the objects that are near them. Their gravitational pull also bends light from very distant objects.

## Gravitational Lensing By Clusters of Galaxies

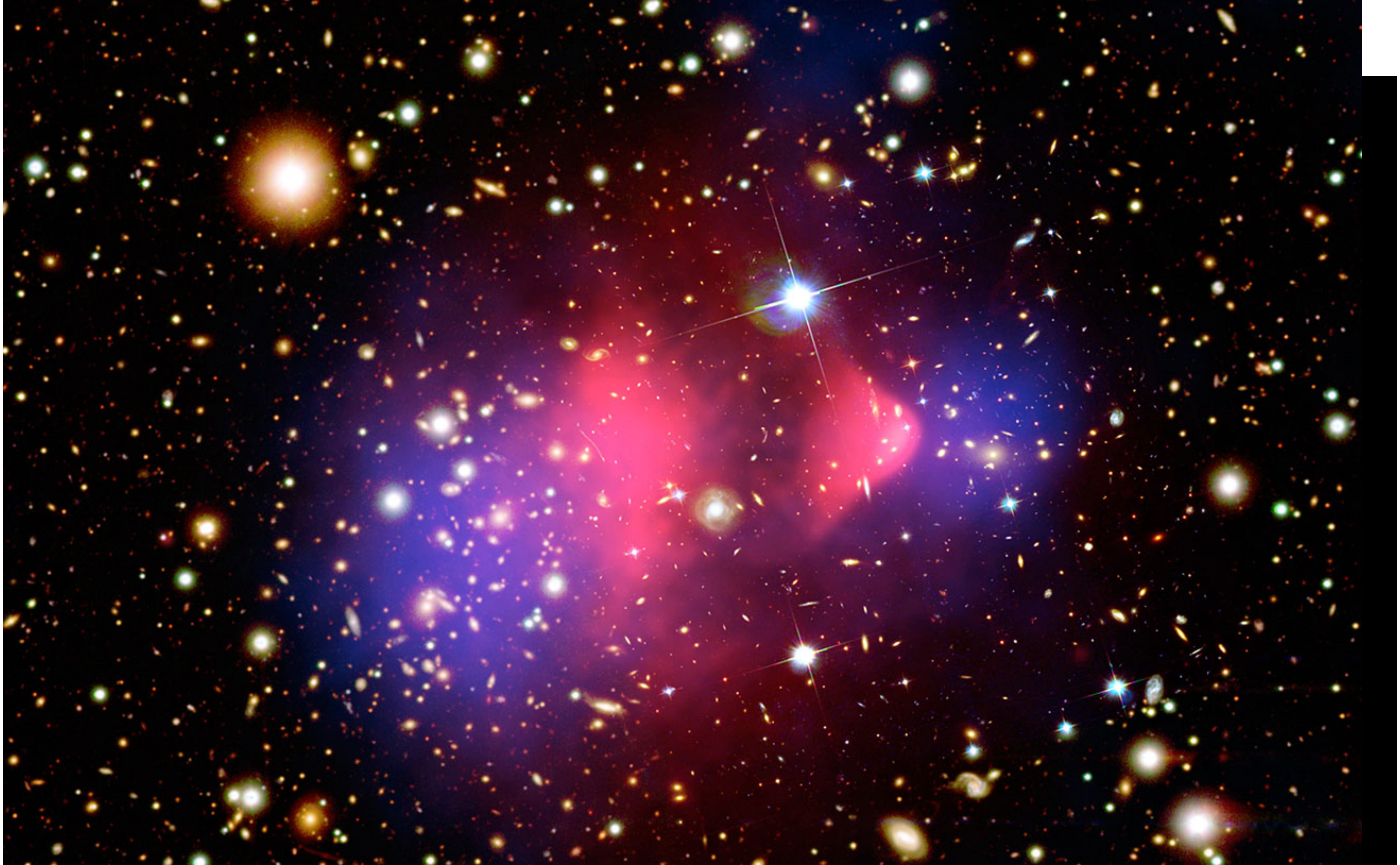
The gravity of a galaxy cluster acts like a lens, distorting images of background galaxies. In many rich clusters, we see bright arcs that are background galaxies stretched and magnified by the cluster's gravity. The amount of distortion implies that there is much more dark matter than visible matter. This dark matter is usually distributed like the galaxies.



# Gravitational Lensing in Abell 2218

**Galaxy Cluster Abell 2218** **HST** • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08



The “Bullet Cluster” is a collision of two galaxy clusters.
The X-rays are separated from dark matter mass (via gravitational lensing) and the optical galaxies. Reason: X-ray gas in the two clusters collides, whereas the galaxies and dark matter particles don’t collide and “overshoot” the hot gas. This “nails” the idea that dark matter is separate from X-ray gas.

# What is Dark Matter?

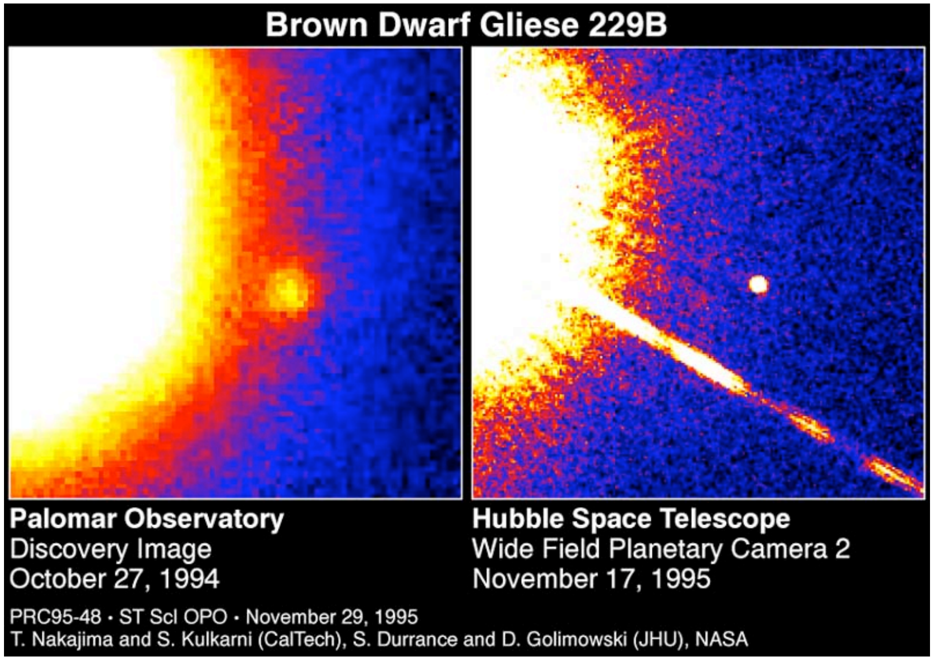
Mostly, we know what it isn't:

**Diffuse gas**

The gas seen in rich clusters accounts for as much as 30% of the total mass of these clusters, but it does not account for all of the dark mass. And there is no evidence for enough gas around individual galaxies.

**Brown dwarfs? White dwarfs?**

"Stars" that have masses smaller than 0.08 $M_\odot$ never get hot enough to burn hydrogen. Microlensing observations suggest that some dark matter is made up of such objects. The same is true of white dwarfs. But we know now that most of the dark halos of galaxies is not made of such ordinary stuff.



# What is Dark Matter?

**Subatomic particles?**

Dark matter may be subatomic particles. For example, neutrinos could make up the dark matter if they have masses 100,000 times smaller than the mass of an electron. But we now know that neutrino masses are too small. Other particles have been proposed and may be viable. None has been detected.

**Black holes?**

Black holes with masses of $10^6\ M_\odot$ could be a component of dark matter.

**What is Dark Matter?**

Lord Martin Rees:

"The mass of a particle of dark matter is unknown to 70 factors of 10."

# Importance of Dark Matter

The nature of dark matter is the most important unsolved problem in astronomy. What we can learn about the Universe is fundamentally limited if we don't understand the main form of matter in it.

- The amount of dark matter determines the fate of the Universe — whether it will expand forever or eventually recollapse in a Big Crunch.

- The dark matter problem is a scientific revolution in progress. We don't know whether the solution will be
  - more stuff that we know about, or
  - different stuff that we don't know about yet, or
  - new laws of physics.

# Dark Matter: A Historical Perspective

(George Lake 1990, STScI Colloquium)

In 1845 there were three dark matter problems based on dynamical perturbations:

- Uranus predicted Neptune
- Mercury predicted Vulcan
- Sirius predicted Sirius B

The solutions required very different amounts of time and took very different forms:

- Solution 1 required ~ 1 year ⇒ more stuff
- Solution 2 required ~ 70 years ⇒ new physics
- Solution 3 required ~ 20 years ⇒ different stuff

**The present dark matter problem has been acute for about 40 years.**

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**With the discovery of dark energy in the 1990s, it is now certain that all three of the above are needed.**

# THE PRINCIPLE OF COSMIC HUMILITY

WE LIVE IN NO SPECIAL PLACE.

– Our home is not the center of the world — it is a typical place among the many that make up the surface of the Earth.

– The Earth is not the center of the Solar System — the Sun is the center of the Solar System, and the Earth is a typical[1] planet revolving around it.

– The Sun is not special — it is a typical star among billions in the Milky Way.

– The Sun is not at the center of the Milky Way — we are in the suburbs, about 30,000 ly from the center.

– The Milky Way is not special — it is a typical galaxy among billions in the Universe.

– Our Galaxy is not special — it is 2nd biggest in the Local Group of ~ 2 dozen galaxies. The Local Group is in the suburbs of the Virgo Cluster of galaxies. Virgo is made of hundreds of bright galaxies and thousands of dwarfs; it is centered about 55 million light years from us. Virgo is embedded in the Local Supercluster of clusters of galaxies.

– None of the above are at the center of the Universe. The Universe has no center!

[1]This is becoming clear as we find lots of more-and-more Earth-like planets. Earth may be especially suitable for life, but it is not unusual in mass or composition or parent star.

# THE PRINCIPLE OF COSMIC HUMILITY

**WE LIVE IN NO SPECIAL PLACE.**

**The existence of dark matter**
**implies an ultimate point in the Principle of Cosmic Humility:**

**We and everything that we see around us**
**are not even made of the main form of matter in the Universe.**

**We do not know what the main form of matter in the Universe is.**

**The mass of the individual particle of dark matter is**
**unknown to 70 factors of 10.**