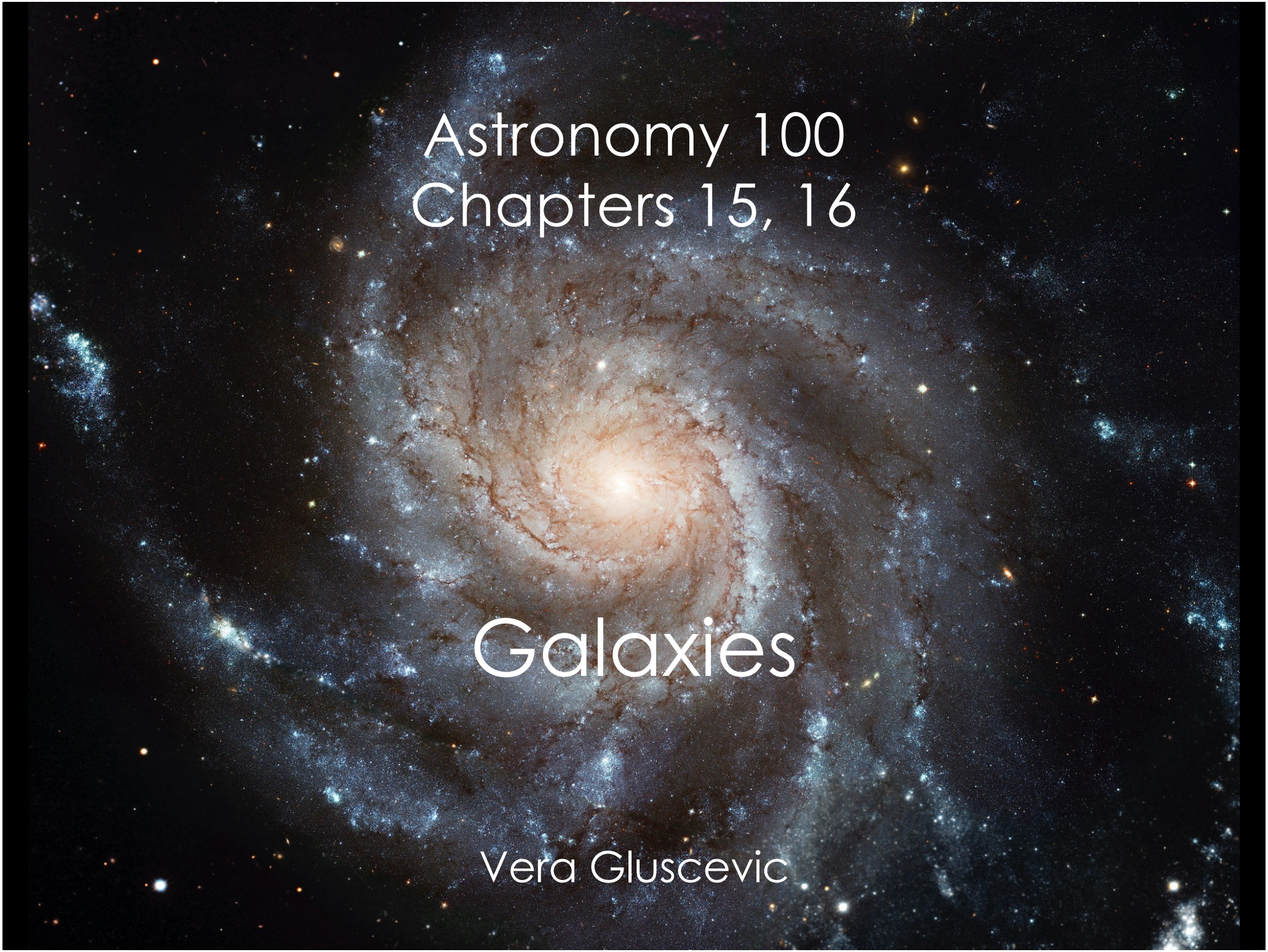
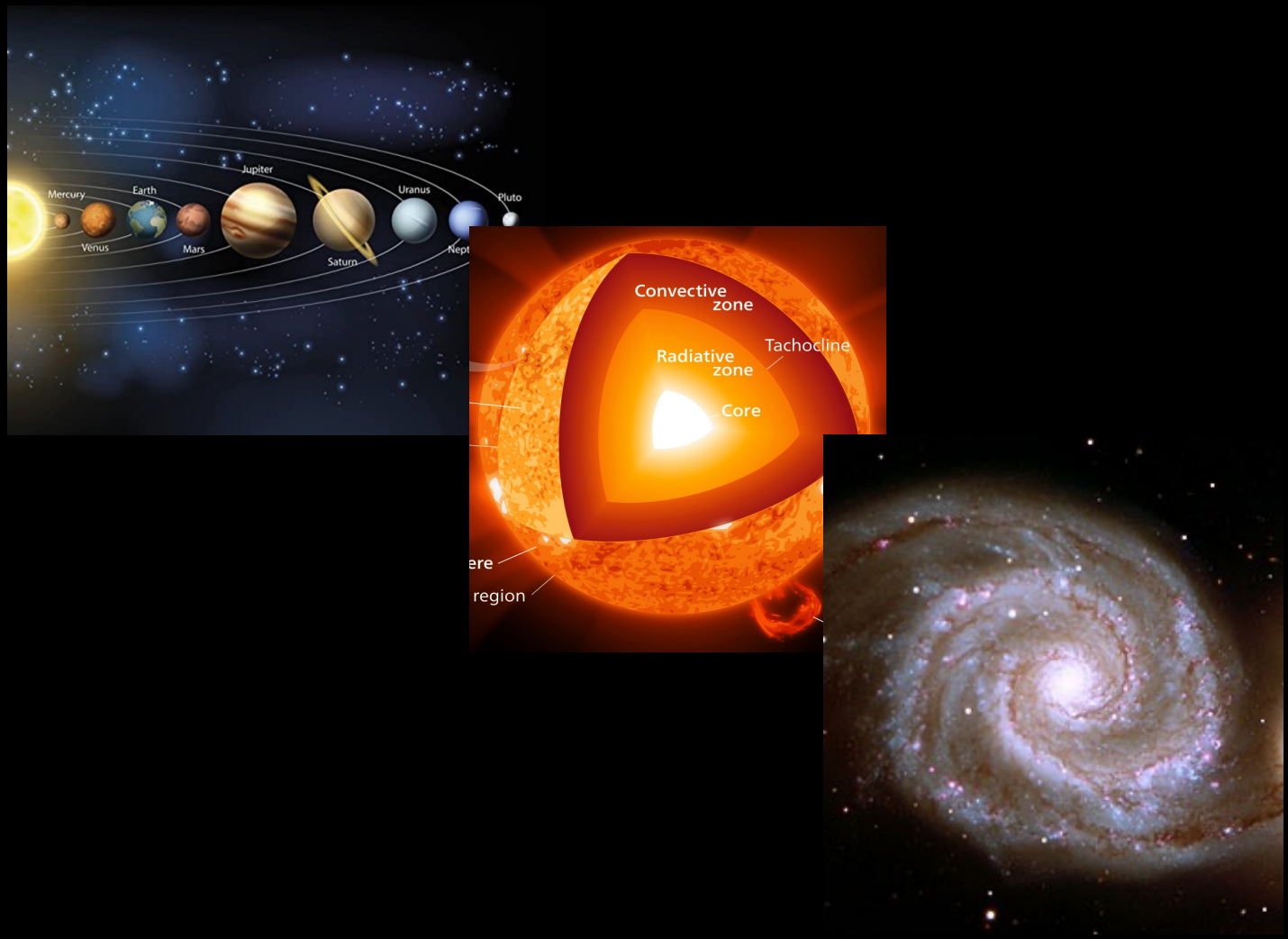


Astronomy 100
Chapters 15, 16

Galaxies

Vera Gluscevic

Content of this course, zooming out:



There is more than stars and the Moon in the night sky:

Fuzzy objects in the sky (nebulae)

Charles Messier (XVIII century) cataloged and published a list of 109 nebulae, objects that appeared fuzzy in telescopes.

M2: Globular Cluster in Aquarius

M42: Orion Nebula

M51: Whirlpool Galaxy

There is more than stars and the Moon in the night sky:

M51: Whirlpool Galaxy

Where are we?

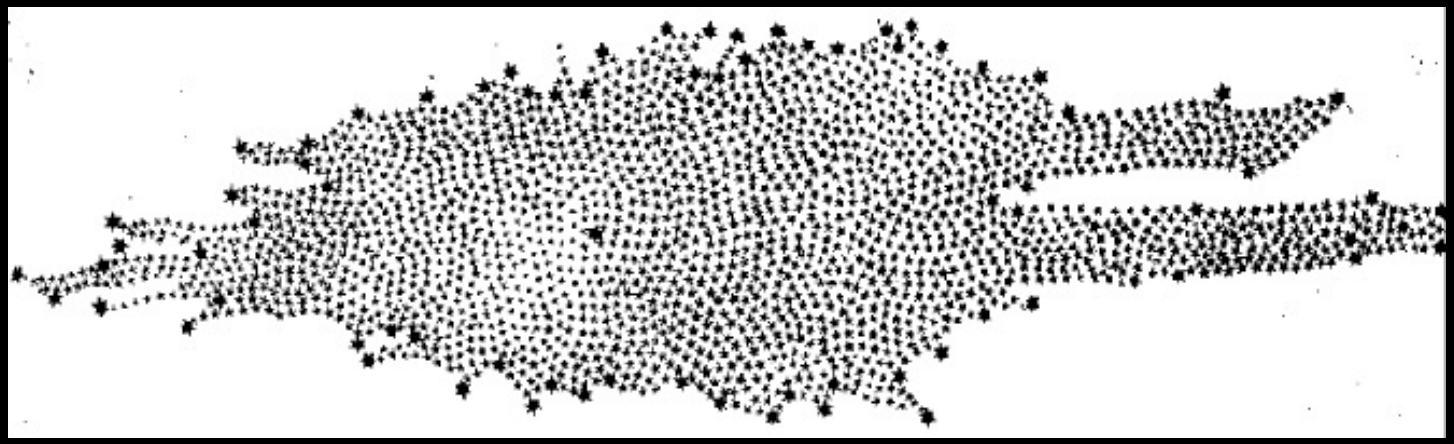
Where are we?

View of the Milky Way from Earth

- 1600s: Galileo: "The Milky Way is nothing else but a mass of innumerable stars planted together in clusters."
- In 1755: Kant coined the term **island universe**, for what we now call a **galaxy**.

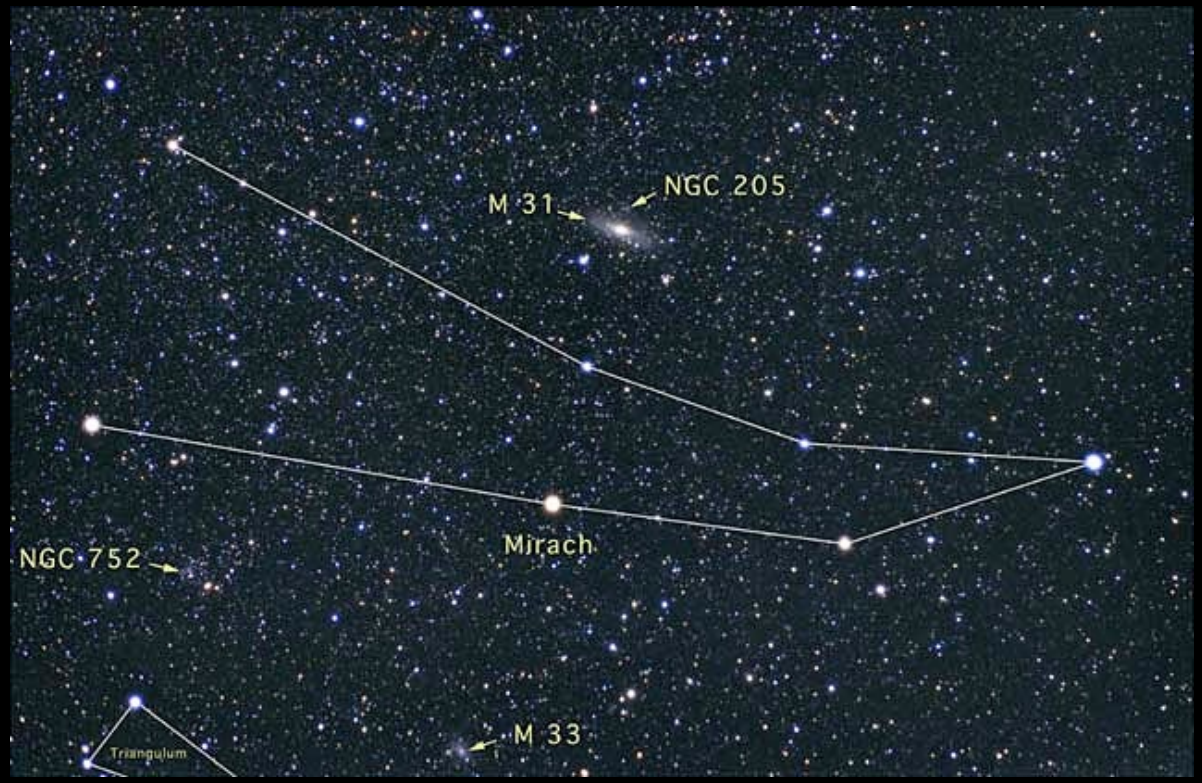
What are Messier's nebulae? Where are we?

- In 1785: The Herschels counted stars in every direction to try to discern the shape of the Milky Way.
- They erroneously concluded that the Solar System was near the center…



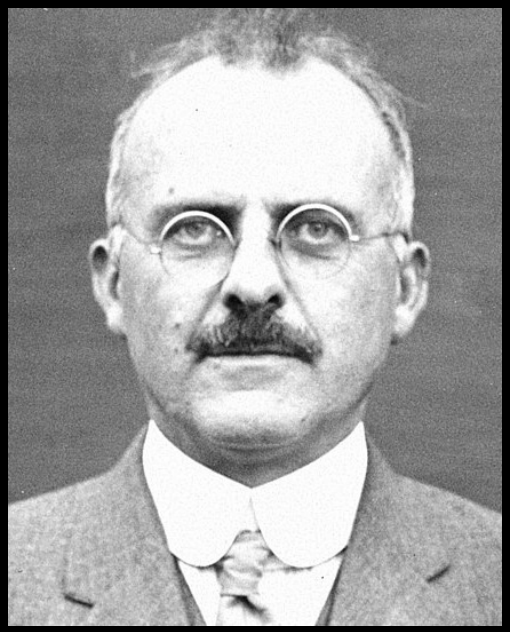
XX century: nebulae are galaxies?

- Observations had eventually shown some "spiral nebulae" are moving away from the Milky Way faster than its escape velocity and are NOT bound to the Milky Way.
- **Nova** explosions in the Andromeda "nebula" showed that it was more distant than any other object ever observed.



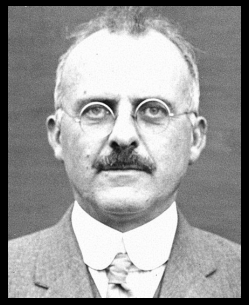
1920: Curtis vs. Shapley:
The Great Debate on nature of "spiral nebulae"

- Shapley: nebulae are within the Milky Way, as is everything else we see; argument based on famous Van Maanen's reported measurement of rotation in the Pinwheel nebula.
- Curtis: Andromeda (M31) is a galaxy of its own, far outside the Milky Way; argument based on seeing novae stars within it.



question for you

Who would you trust?



A) Curtis:
Andromeda is a galaxy.

- We see many novae in it.
- It has dark stripes, like the Milky Way.
- It must be millions of ly away!

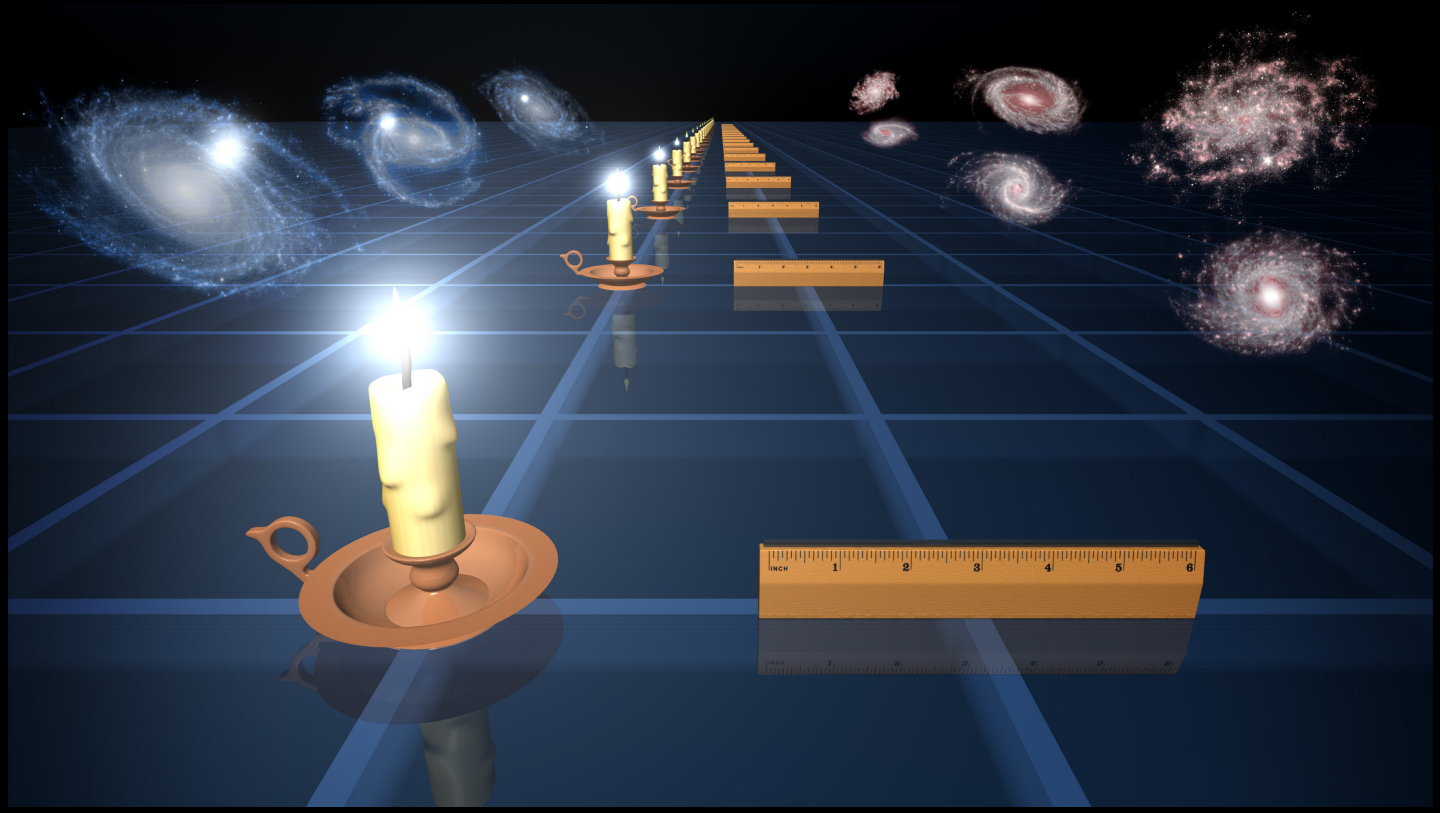
B) Shapley:
Andromeda is in the Milky Way.

- Van Maneen measured its rotation.
- The rotation speed would be **superluminal**.
- Nothing can be that far.

Measuring (large) distances

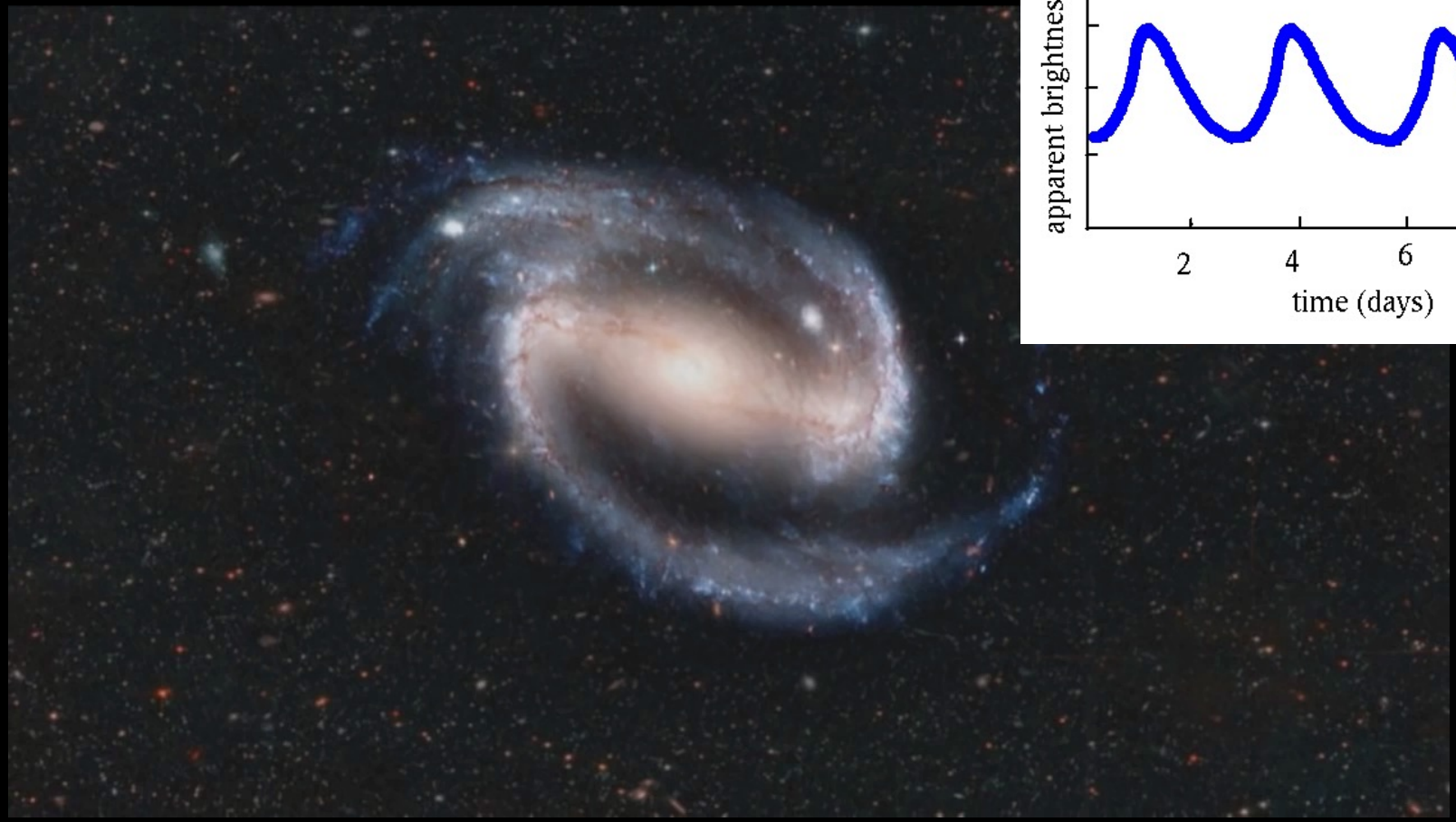
How do we measure extra-galactic distances?

- **Standard rulers** are objects with known size.
- **Standard candles** are objects with known luminosity.
  - Cepheid variables (period-luminosity relationship).
  - Type Ia supernovae (roughly the same absolute luminosity).



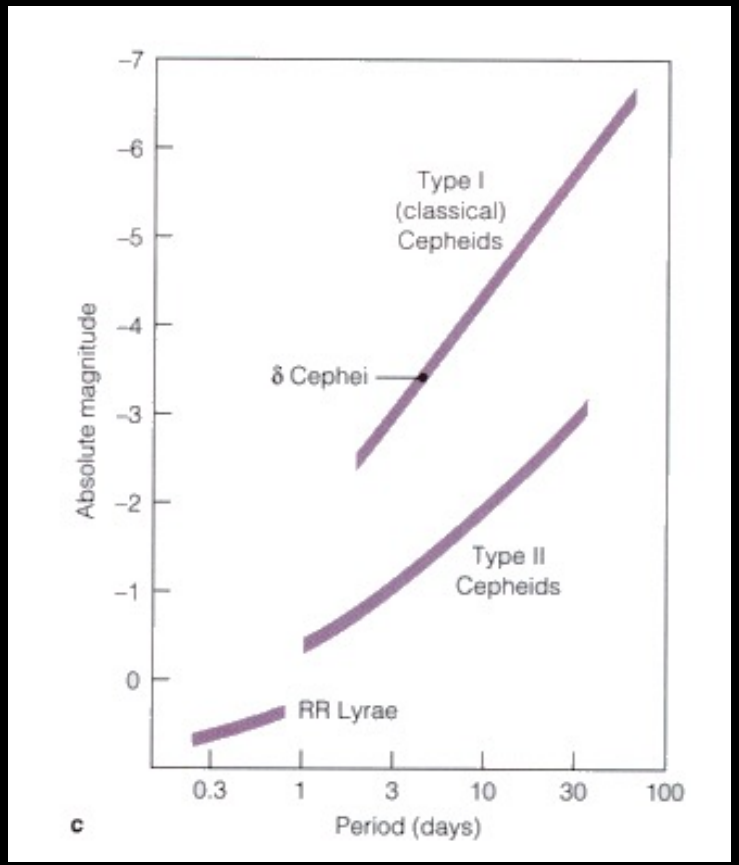
Cepheid variables: standard candles

Cepheid variable is a type of massive, evolved star whose luminosity varies on a period of several days (because its temperature and size changes periodically).



Cepheid variables: standard candles

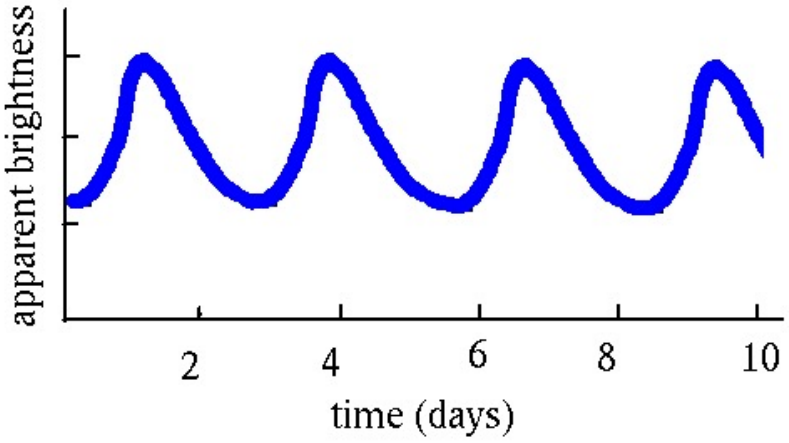
- 1908: **Henrietta Swan Leavitt** discovers the relationship between the period and peak absolute magnitude of **Cepheid variable stars**, allowing us to determine the distance to Cepheids up to 20 Mly.

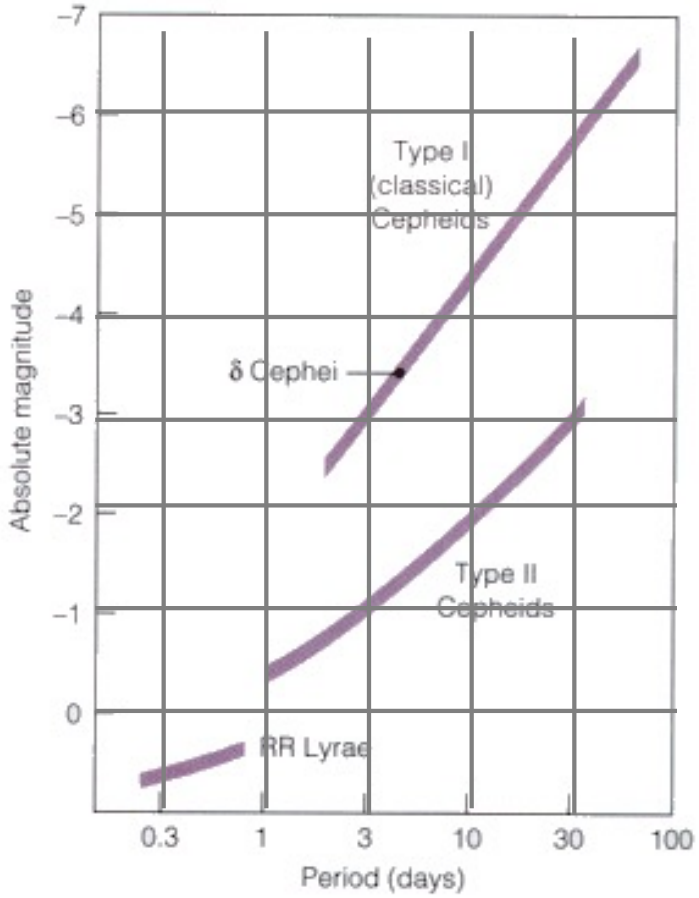


question for you

What is the peak absolute magnitude of a classical Cepheid whose light curve is shown here?

A. -1
B. -2
C. -3
D. -4





Type Ia supernova explosions: standard candles

- White dwarf (or Type Ia) supernovae arise from white dwarfs in binary systems.
- They all have the same absolute magnitude of –19.6 and can be used to measure distances to other galaxies.

question for you

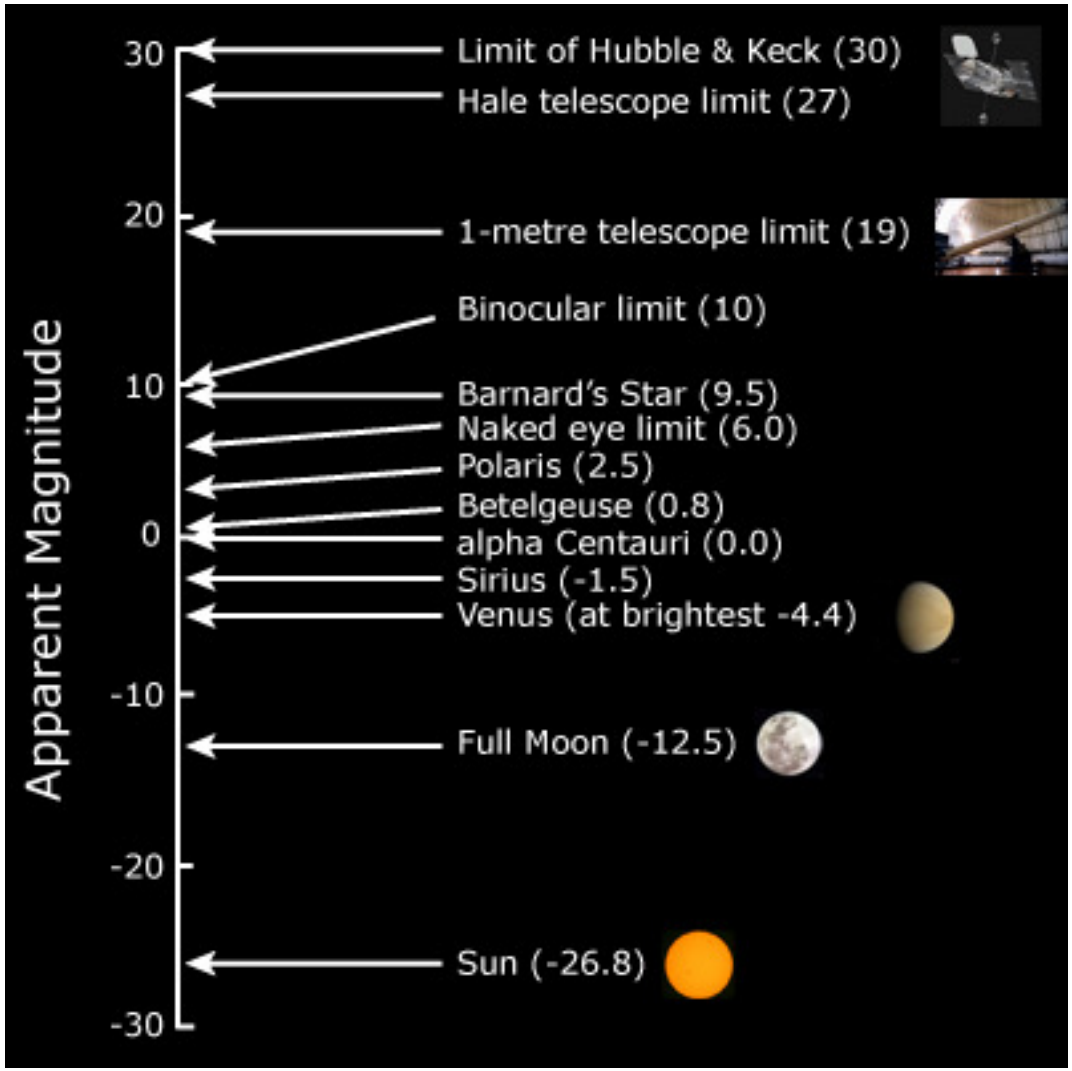
If a star located 10 pc away from the Earth explodes in a Type Ia supernova, how bright will it appear in the sky, compared to other objecs? Remember that the absolute magnitude of a Type Ia supernova is -19.6.

A. Brighter than Polaris and dimmer than Sirius

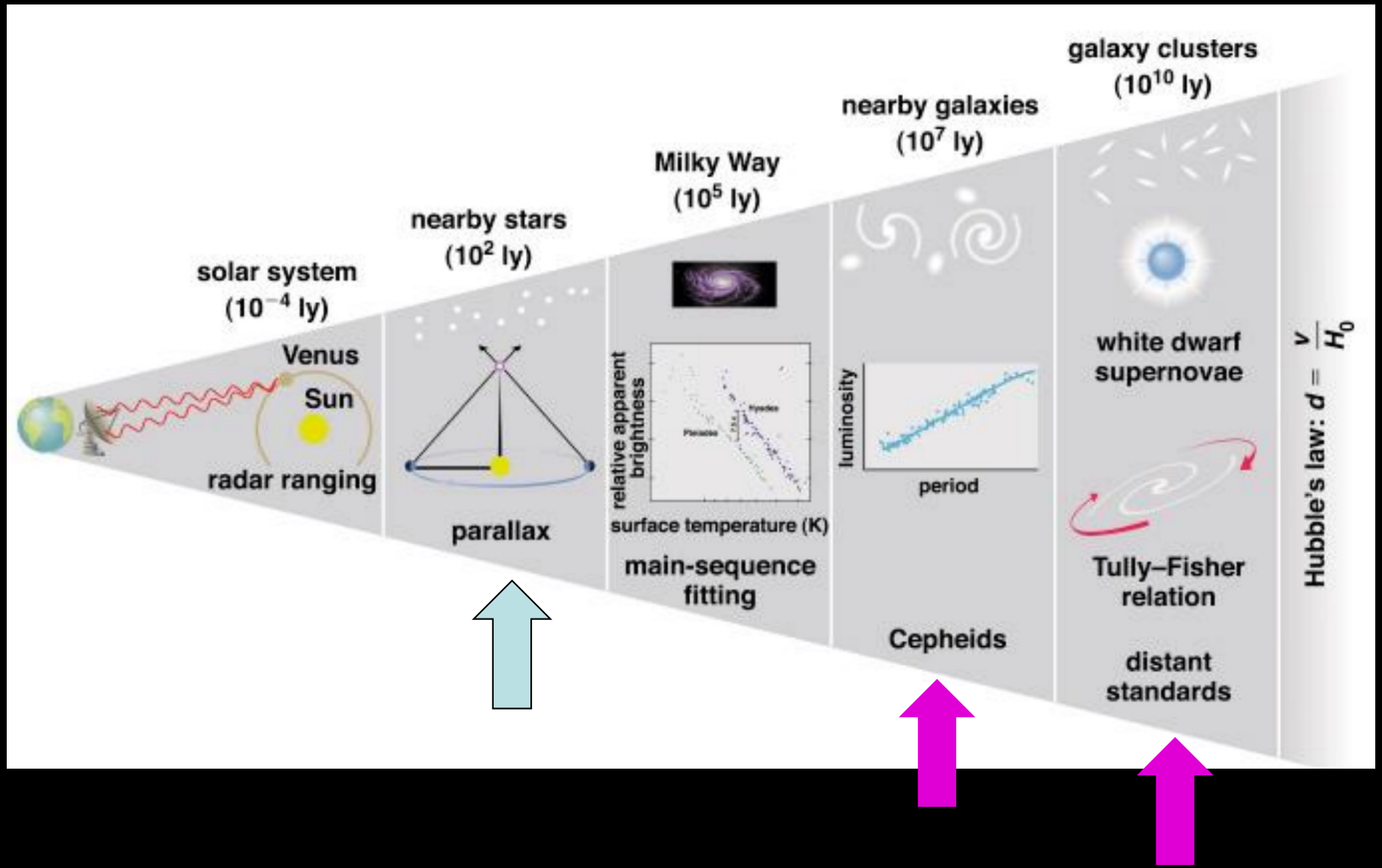
B. Brighter than Sirius and dimmer than the Moon

C. Brighter than the Moon and dimmer than the Sun

D. Brighter than the Sun

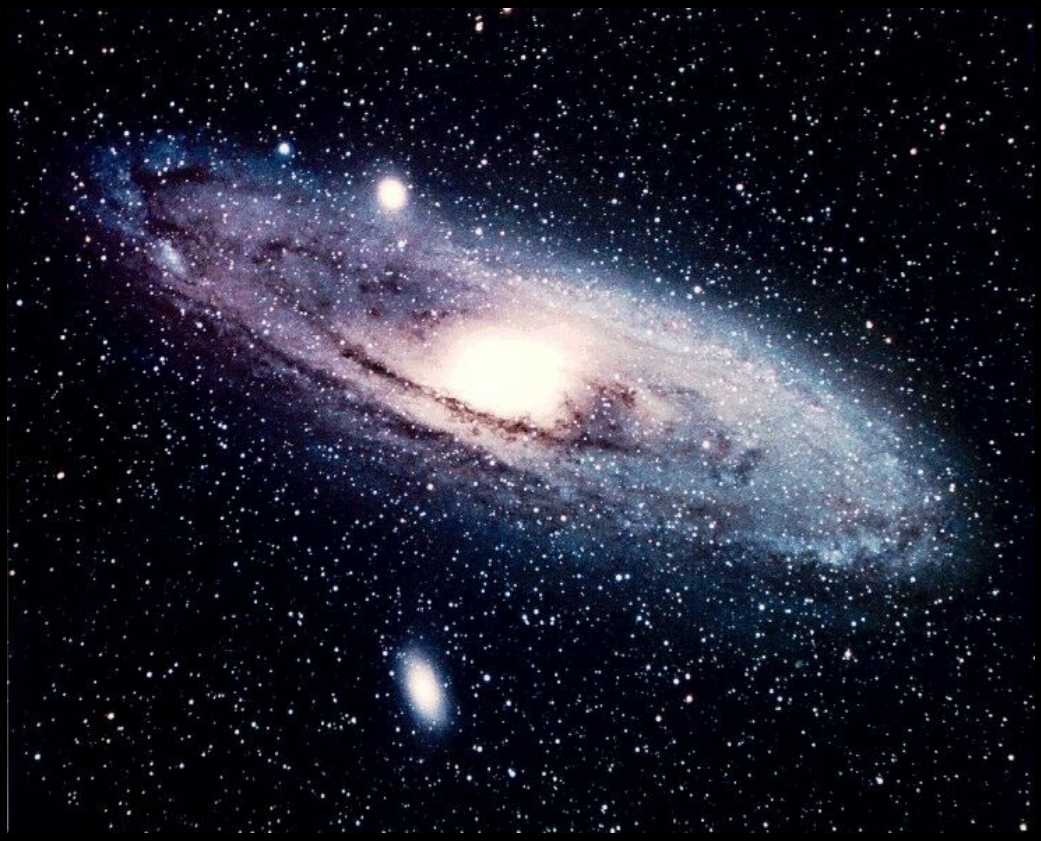


Cosmic distance ladder



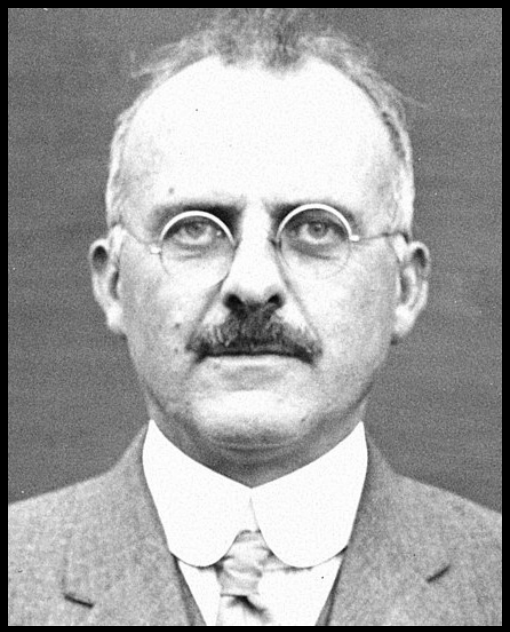
Hubble's Observations

- **Edwin Hubble** spent years classifying galaxies and measuring their distances with Mt Wilson100-inch telescope in San Gabriel Valley.
- Hubble's first target was the Andromeda Galaxy.
- Using Cepheid Variables, Hubble showed that the Andromeda Galaxy was **millions of light years away**.



1920: Curtis vs. Shapley:
The Great Debate on nature of "spiral nebulae"

- Shapley→ **driven by PRIOR KNOWLEDGE.**
- The Debate resolved in favor of Curtis by **Hubble's observations of Cepheid stars** and distance measurements to other island universes.



Milky Way is a **galaxy** full of stars…

Every star we see in the night sky is within our own Galaxy!

The Universe is full of galaxies…

A galaxy is a large system of stars, gas, and dark matter, bound together by mutual gravity.

Our home galaxy, the Milky Way


View of the Milky Way from Earth, inside the Galaxy

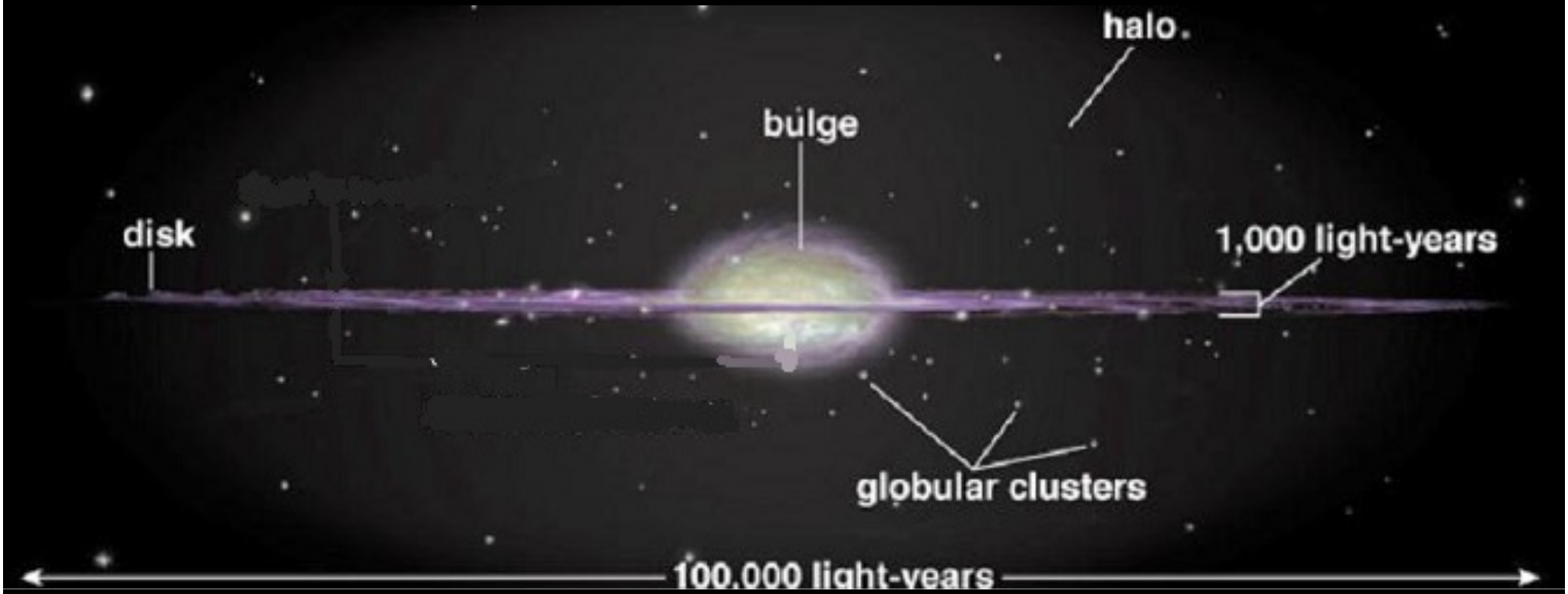
Zooming out of the Milky Way (to get a better view)

https://www.youtube.com/watch?v=DgqAAE9Aagc

The Milky Way

The Milky Way is made of gas, dust, and stars.

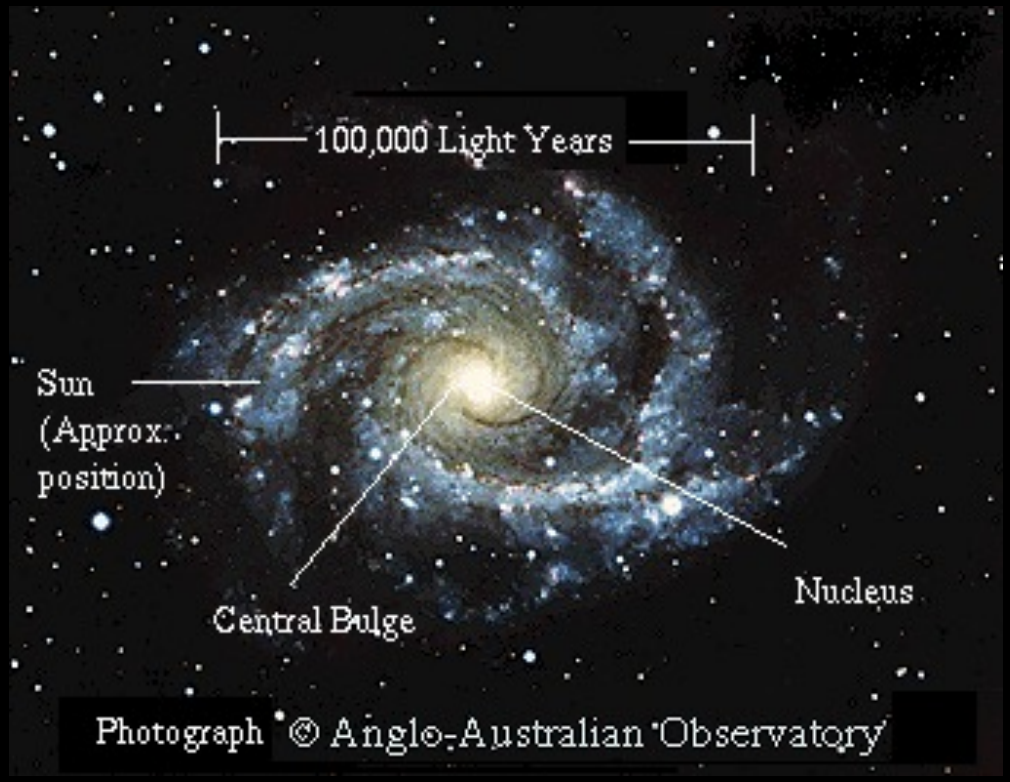
Most of it is located in the disk.



- **Bulge** – Center of the galaxy (tightly packed old stars, Population II)
- **Disk** – Thin disk around bulge (young star, Population I, 2% heavy elements)
- **Halo** – Spherical distribution of stars surrounding the galaxy (thousands of ly)

The Milky Way

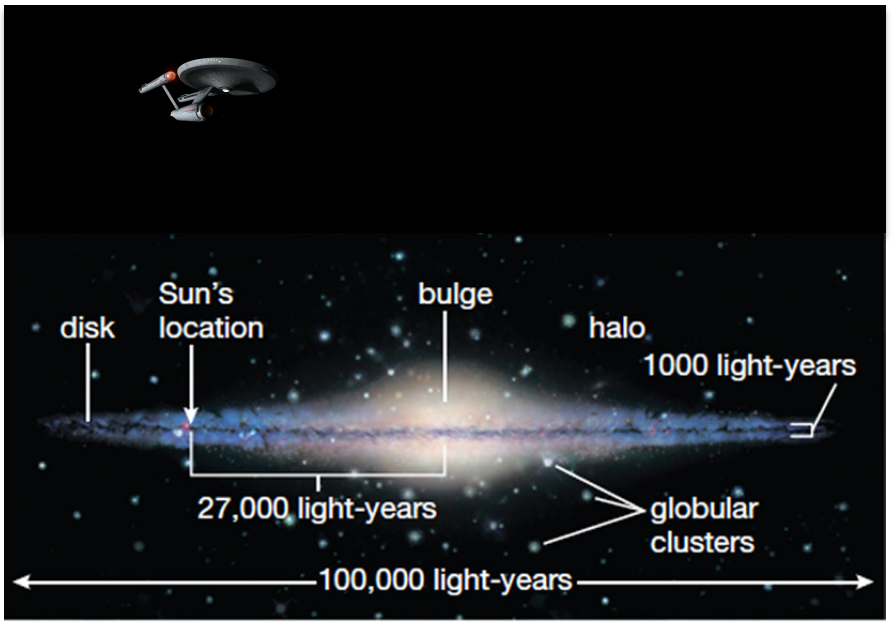
The Milky Way is made of gas, dust and stars. Most of the gas, dust, and stars are located in the disk.



- Milky Way has **400 billion stars**, with a total mass of about **one trillion solar masses**.
- The Sun is about **2/3** of the distance out from the center of the galaxy, with in a spiral arm, within the disk.

question for you

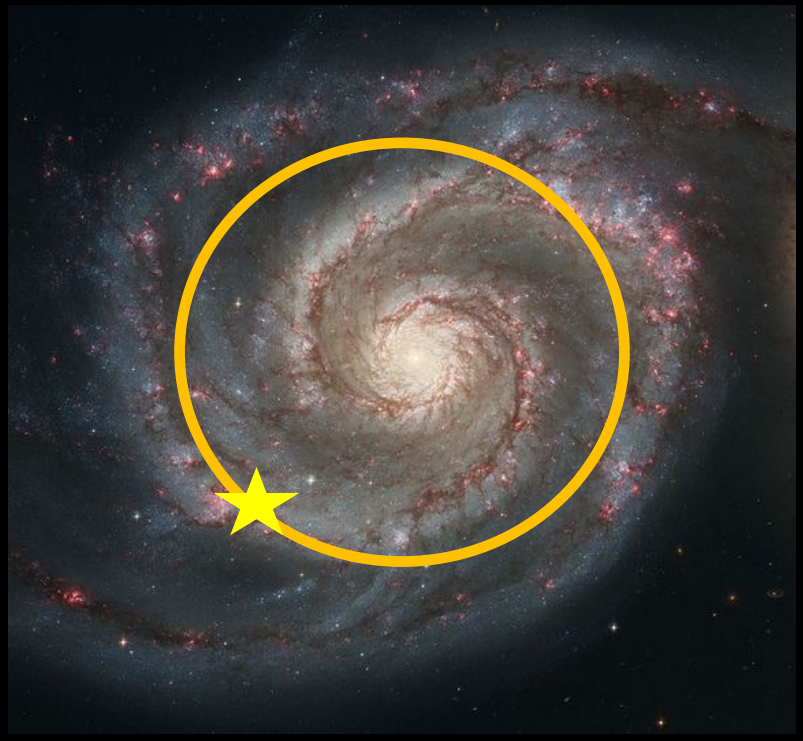
An astronaut decides that she wants a clear view of the Milky Way, from outside of its disk. She decides that she needs to get up to a height at least as large as the Earth's distance to the galactic center. Her ship can travel at 3000 km/sec (1% of the speed of light). How long will this excursion take her, just to get up to that "height"?



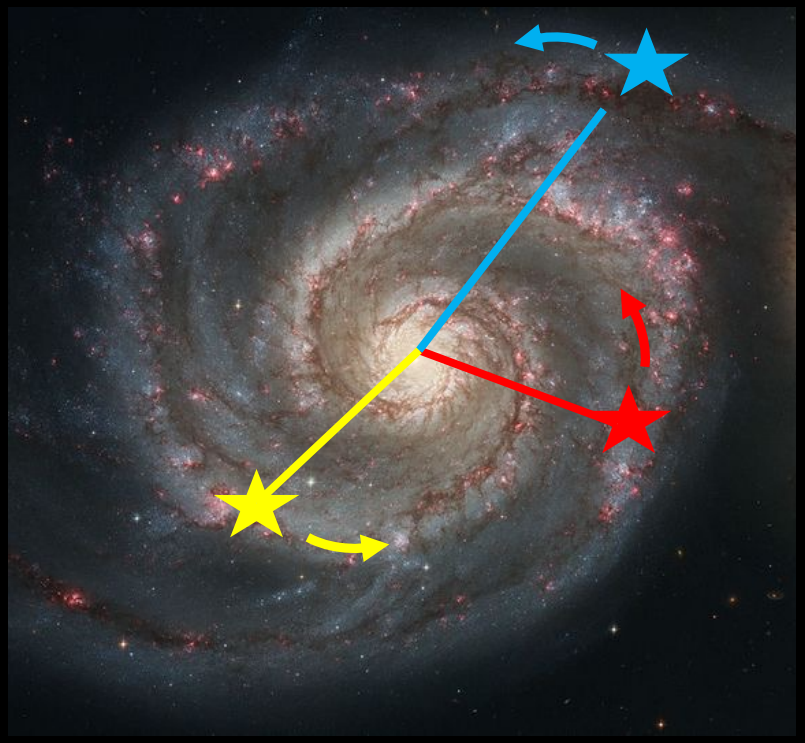
A. 270 years
B. 2700 years
C. 270,000 years
D. 2.7 million years

What holds a star within a galaxy?

Gravity of all the mass within that star's orbit!



What holds a star within a galaxy?



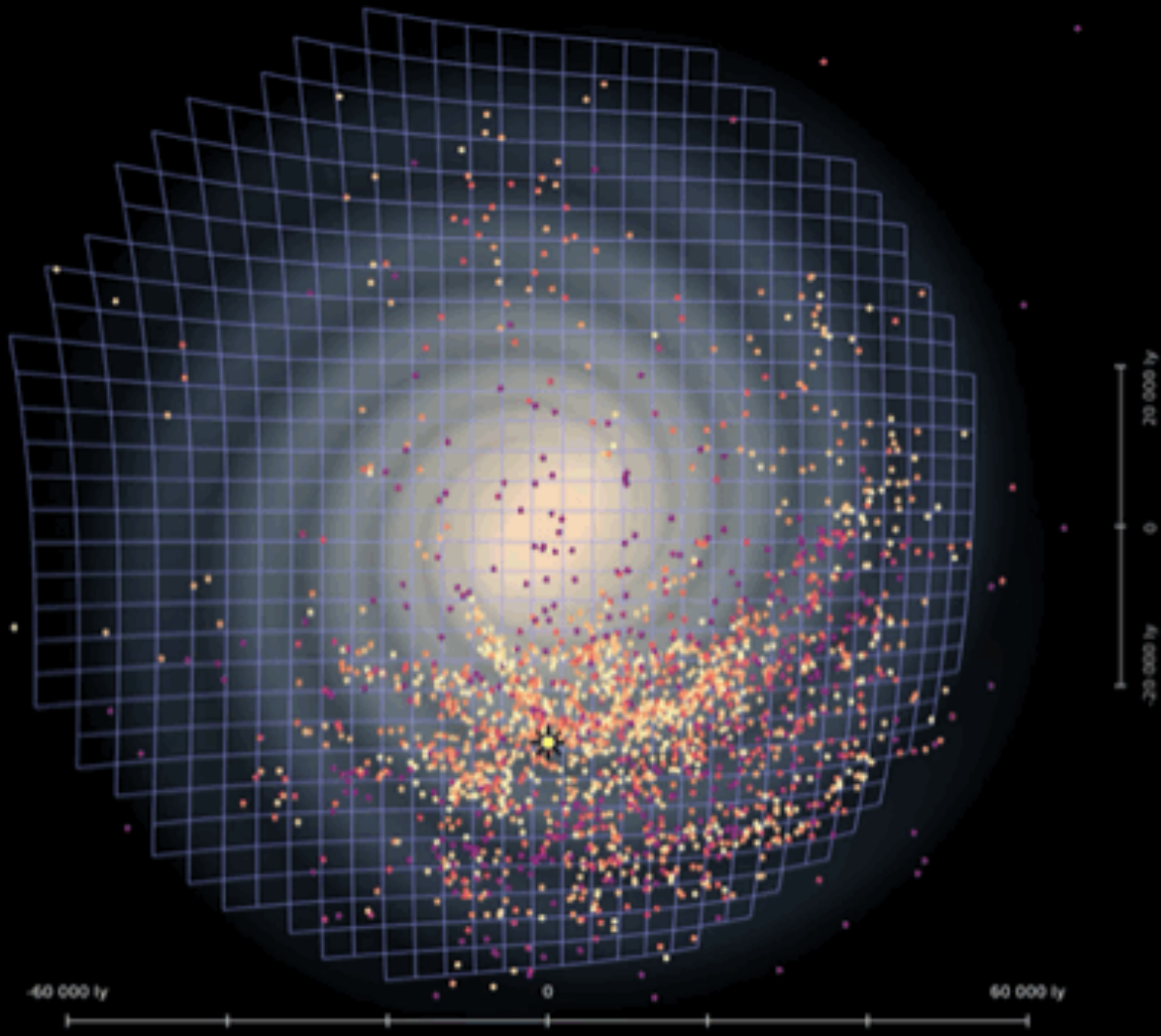
Measuring the mass of the Milky Way

- Orbital velocity of the Sun allows us to determine mass of the Galaxy within the Solar Circle:

$$M_r = \frac{r \times v^2}{G}$$

- Answer is 100 billion solar masses within the Solar Circle.

Measuring the shape of the Milky Way: map of Cepheids

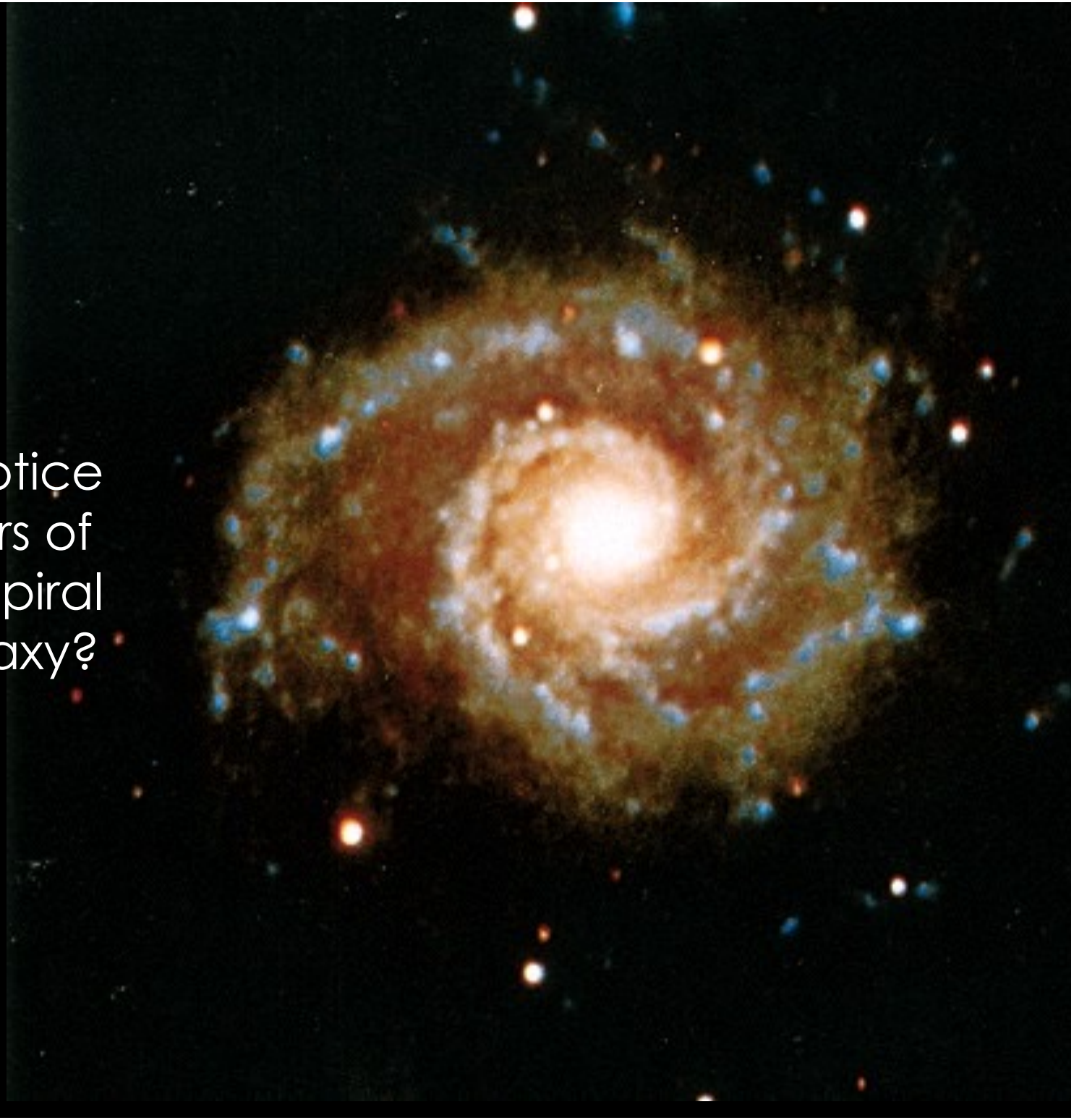


Types of galaxies: **spiral and elliptical**

Whirlpool galaxy

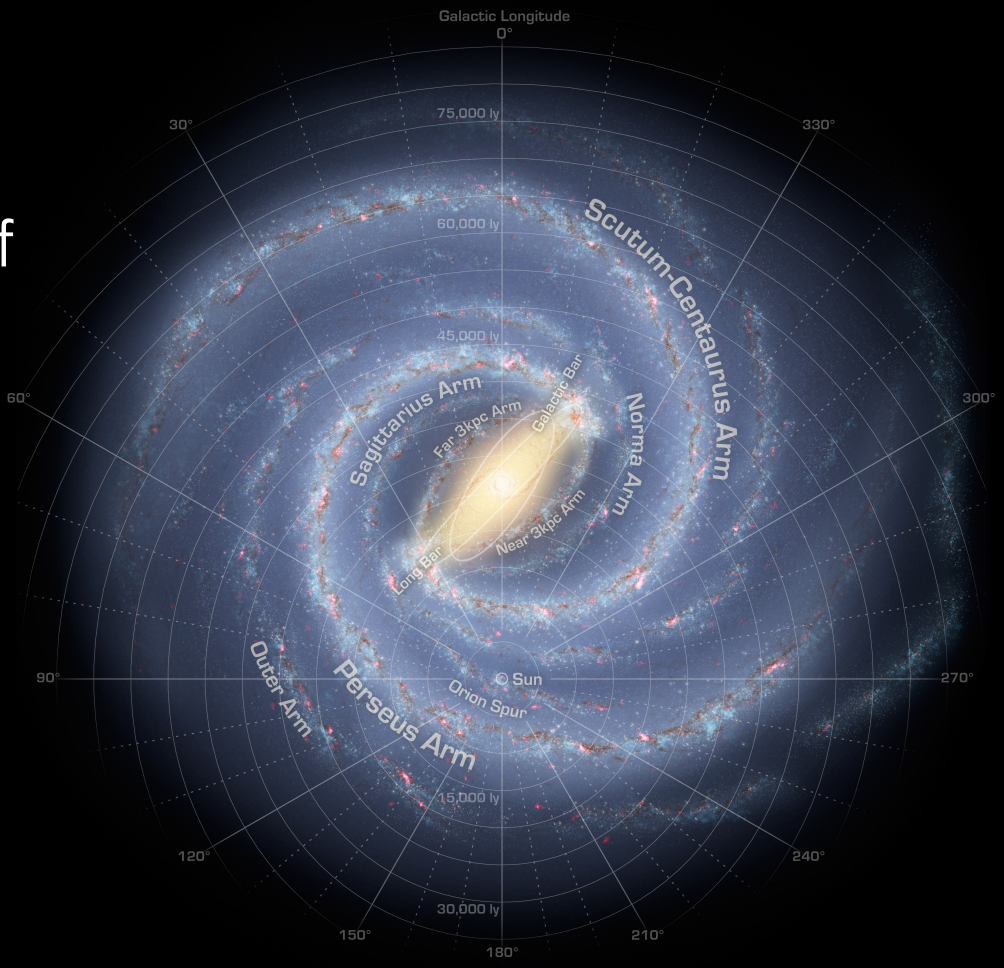
M87 © Anglo-Australian Observatory
Photo by David Malin

What do you notice about the colors of the stars in the spiral arms of this galaxy?

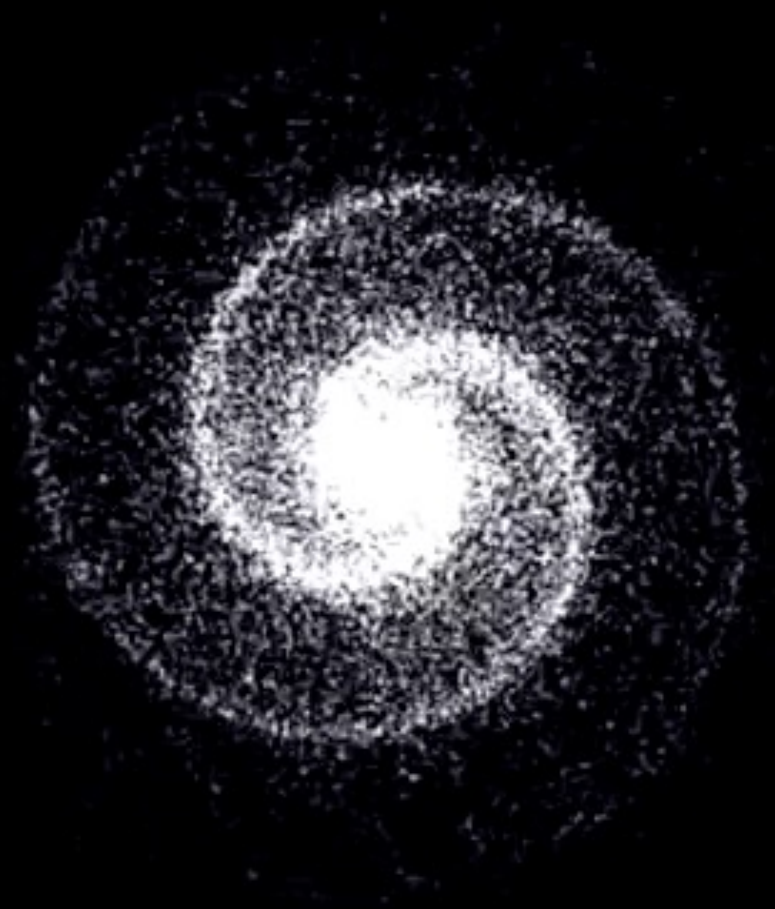


Spiral arms

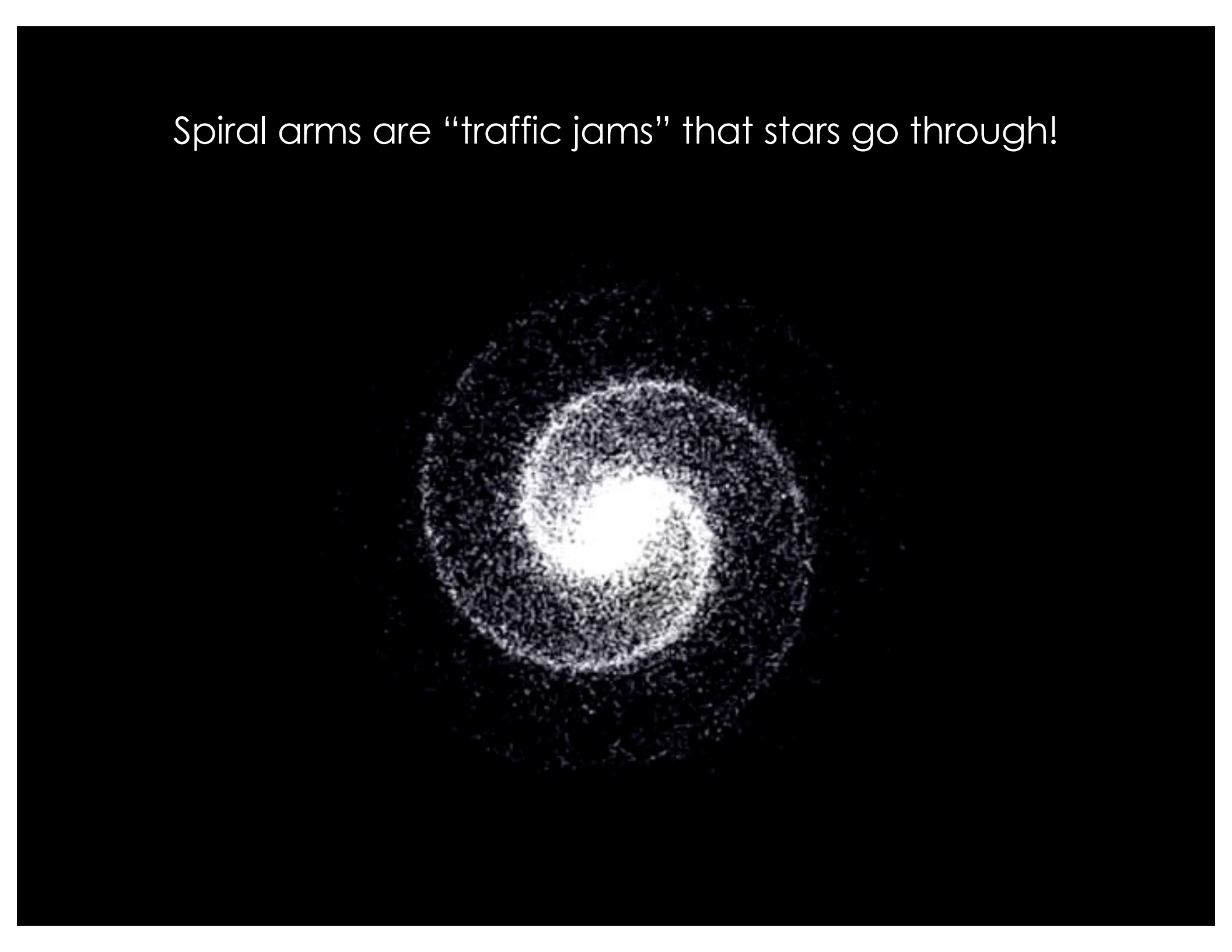
- Spiral arms are ”crests” of density waves.
- They appear bright because of hot young blue stars (type O and B) are forming inside of them (while the bulge and halo harbor old stars).
- Stars can go in and out of the spiral arms.



Spiral arms are NOT like this…

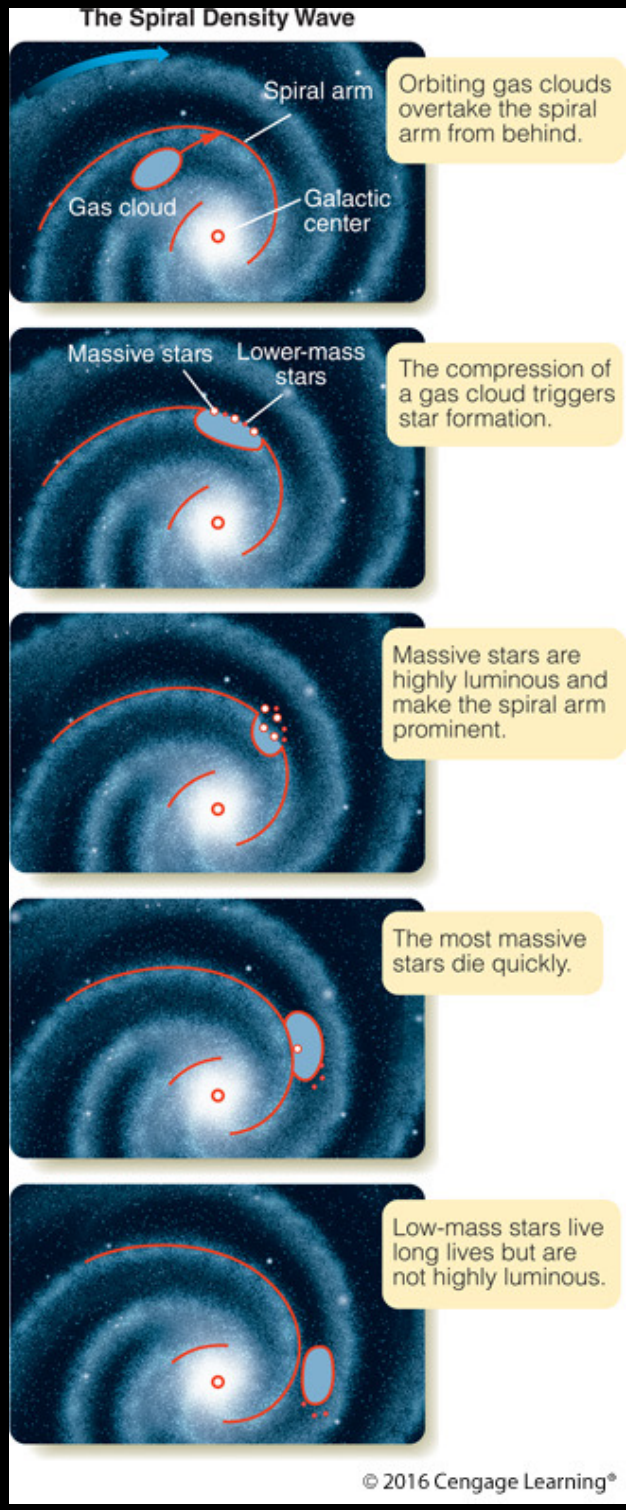


Spiral arms are “traffic jams” that stars go through!



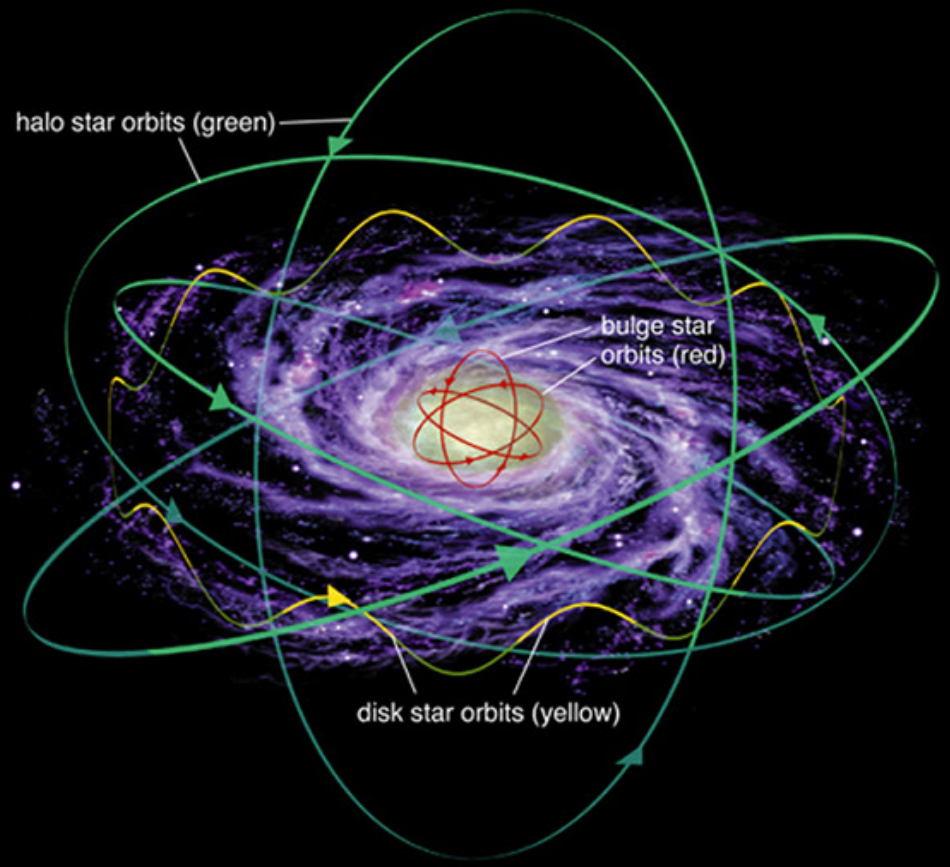
Spiral arms

- **Spiral arms are places where stars form.**
- Molecular clouds (where stars form) are concentrated in the spiral arms of the Milky Way.
- Molecular clouds overtake the slow-moving spiral arms, compressing the gas in the spiral arms and initiating star formation.
- Atomic hydrogen can be mapped throughout the galaxy.



Stellar orbits

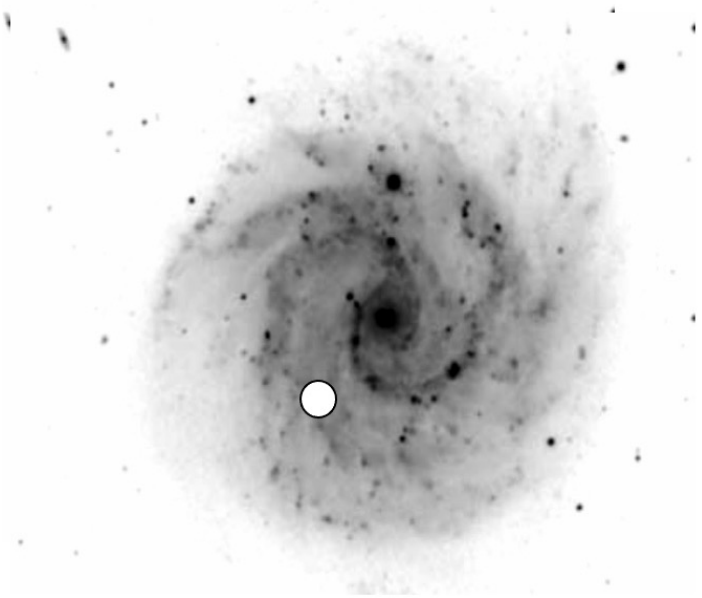
- Stars in Galactic disk bob up and down during their orbit.
- Halo orbits disorganized.
- Bulge orbits also random.
- It takes Sun **230 million years** to complete 1 orbit.
- Sun plunges through the disc every ~**35 Myr.**



question for you

Assuming that this image represents the Milky Way galaxy, approximately how large is the diameter of the white dot?

A. 1,000 light years
B. 10,000 light years
C. 25,000 light years
D. 100,000 light years



Galactic center

The center of the Galaxy

- The center of the Milky Way is in the direction of **Sagittarius**.
- **Sagittarius A*** is a radio source.
- In visible light, the galactic center is obscured by interstellar clouds, but it can be seen in infrared, radio, and x-rays.

Non-visible light allows us to “observe” the Galactic center...

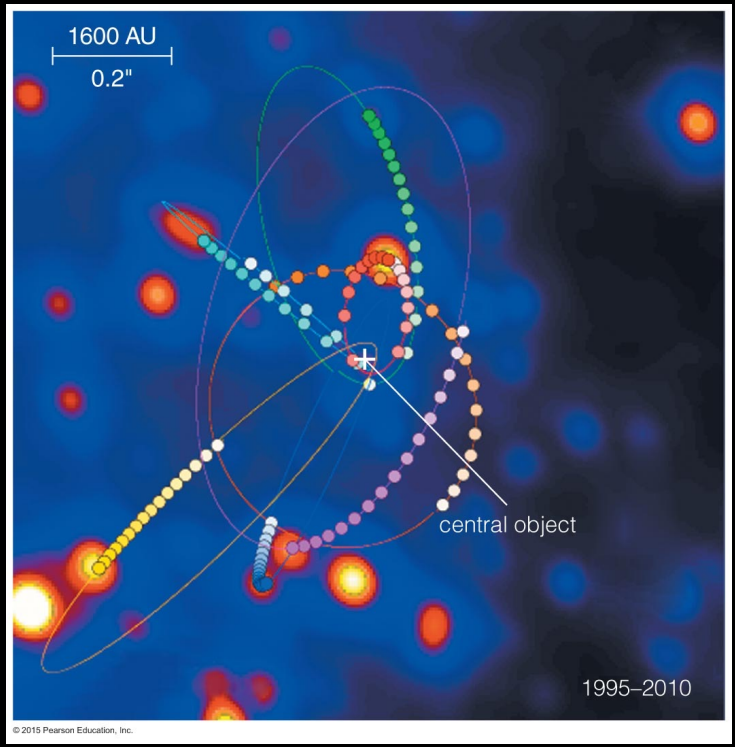
Galactic center is a crowded, active place!

A supermassive black hole at the center of the Milky Way

- 2020 Nobel Prize: **Andrea Ghez and Reinhard Genzel**: discovery of a supermassive compact object at the heart of the Milky Way.
- Orbits of nearby stars have been used to estimate the mass and the size of Sgr A*.
- Sagitarius A* is a **supermassive black hole**, with the mass of 4 million suns, and the Schwarzchild radius of 0.08 AU.

Zooming into Sagittarius A*

What do you need to tell that there is a black hole there, rather than just a very massive object of another kind?



Measurement of the size of the orbits AND the speed of the stars orbiting it!

→ It is <u>too dense</u> *not to be a black hole.*

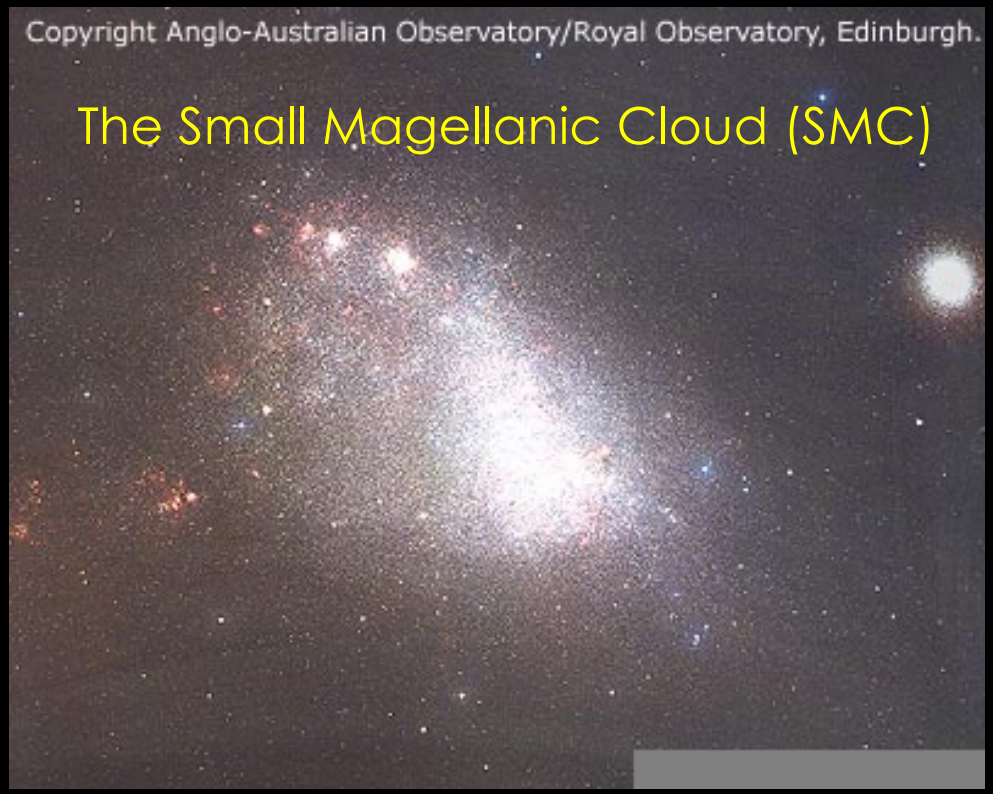
Our galactic neighbourhood

The Milky Way, Large Magellanic Cloud (LMC), and Small Magellanic Cloud (SMC), in the southern hemisphere

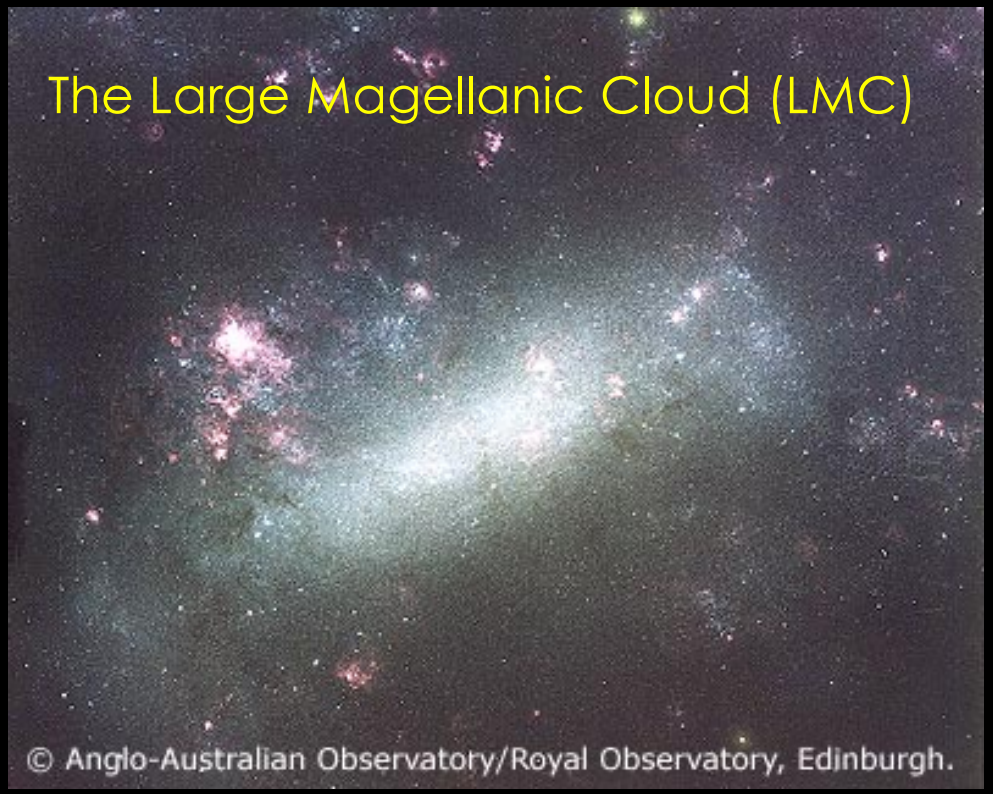
Dwarf galaxies (satellites of the Milky Way)

- Many are **irregular**, small, and faint.
- Distance to LMC & SMC is about 150,000 ly.

Fornax dwarf galaxy

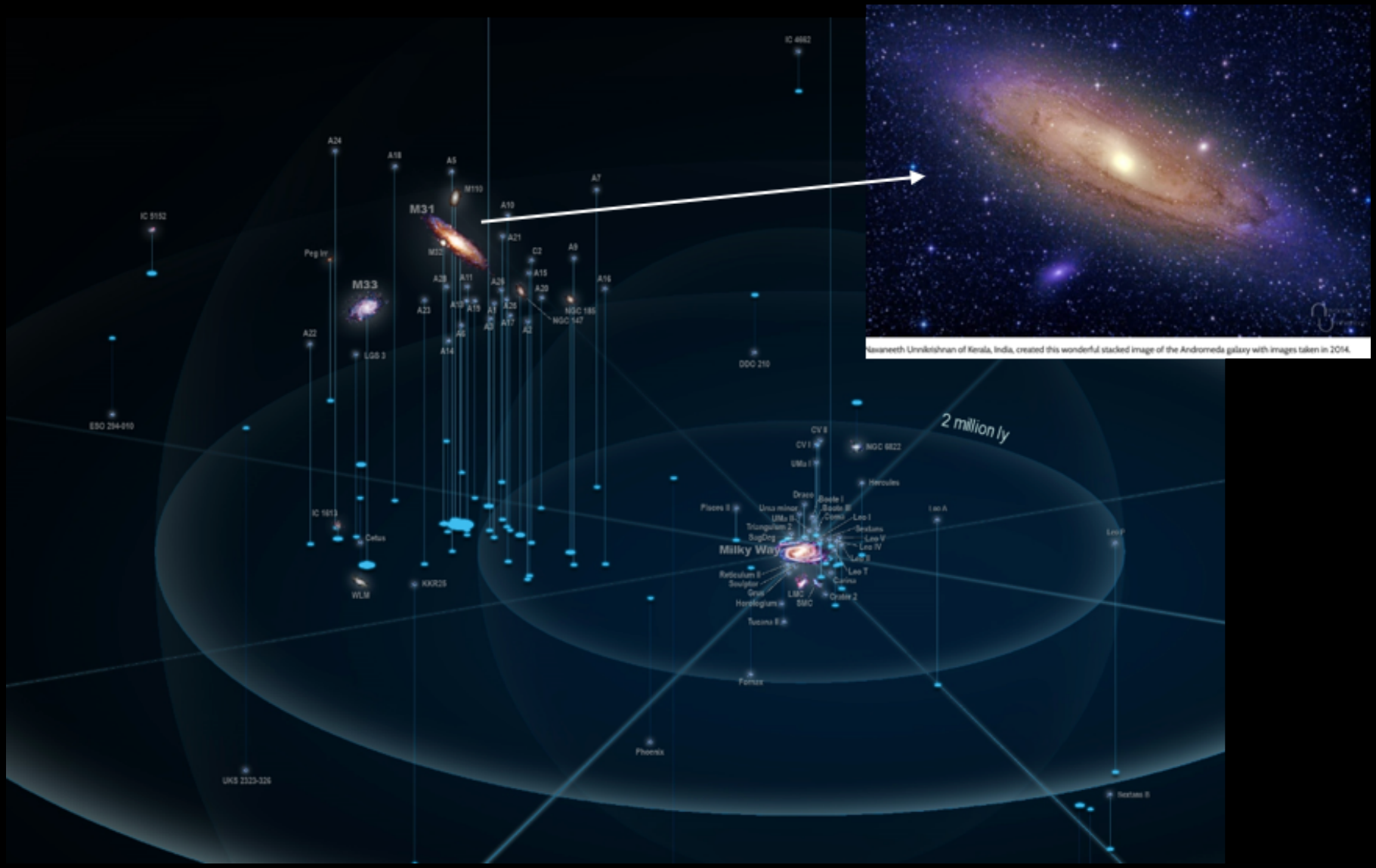


The Small Magellanic Cloud (SMC)



The Large Magellanic Cloud (LMC)

Let's zoom out more…



The Local Group: about 50 galaxies, the largest is Andromeda, 2.5 million light years away from us.

Andromeda is on a collision course with the Milky Way!

question for you

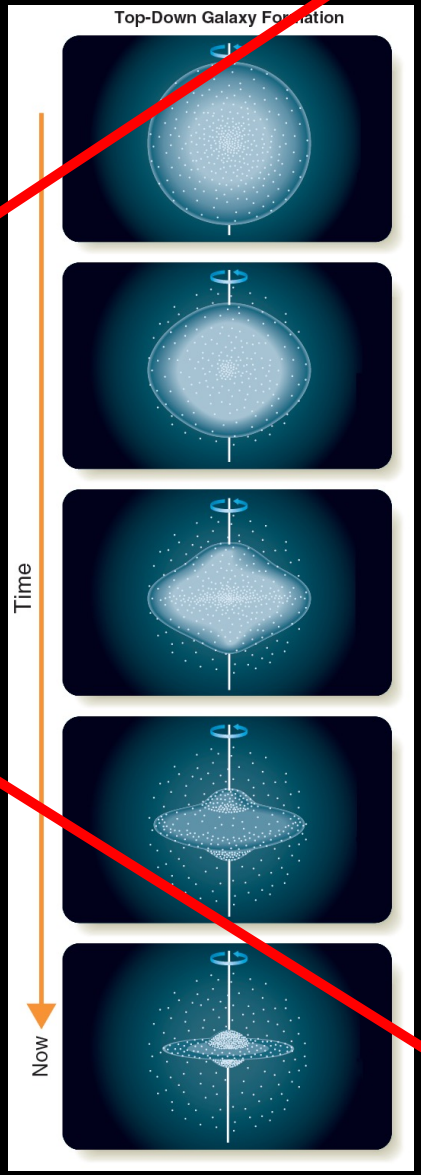
Why does Andromeda appear so still, if it is indeed rotating?

A. Because Andromeda is rotating very, very slowly, and the velocities of its individual stars are very low.
B. Because Andromeda is big, one rotation takes a long time.
C. It's an optical illusion, because we see the light coming from Andromeda to us from a distant past.
D. It's actually still, not rotating.

Lives of galaxies

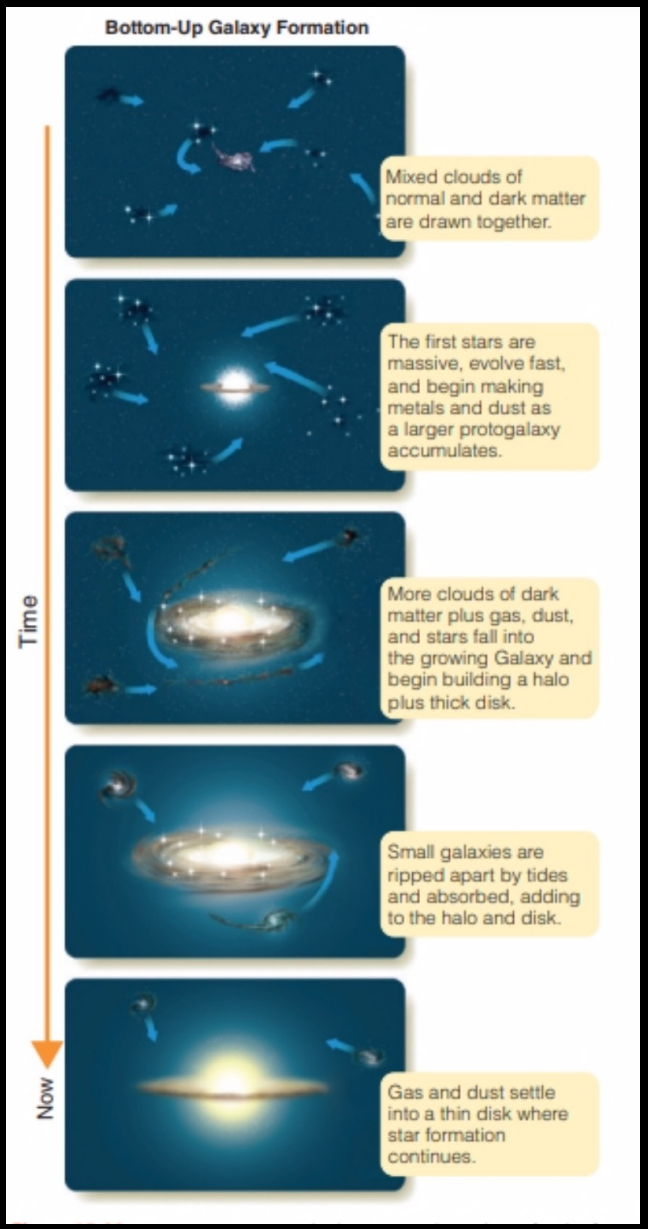
How did the Milky Way form?

- **Old idea: top-down hypothesis**: a single proto-galactic cloud collapsed to form the Milky Way 12 – 13 billion years ago.



How did the Milky Way form?

- **New idea: bottom-up hypothesis**: Milky Way was partly assembled from smaller units, by **mergers** of other galaxies and infalling gas clouds.



Galaxy Formation Simulation

https://www.youtube.com/watch?v=s-25dEcY-WU

What did we learn in Chapter 15?

- Galileo's observations of the Milky Way showed that it was comprised of stars.
- As telescopes grew more powerful, more and more "nebulae" were discovered, and eventually these were identified as islands of stars.
- Shapley vs. Curtis: the Great Debate on the nature of nebulae was resolved by Hubble's observations of Cepheid variables.
- Distances in the Universe can be determined by stellar parallax (up to ~1000 ly), main sequence fitting (for star clusters), by standard candles, and by standard rules.

What did we learn in Chapter 15?

- Two types of standard candles:
  - Cepheid variable stars: luminosity and period of brightness oscillations directly related.
  - White dwarf supernovae, with the same luminosity every time.
- Edwin Hubble used Cepheid variables to show that the Andromeda nebula was a galaxy of its own and not part of the Milky Way.
- The Milky Way is a spiral galaxy100,000 ly across, with a disk 1,000 ly in thickness and a central bulge that is ~3,000 ly thick.

What did we learn in Chapter 15?

- The Milky Way has satellite galaxies, the most prominent of which are the Large and Small Magellanic Clouds.
- Two populations of stars in the Milky Way:
  - Population 1: Disk stars that can be young or old, with an average 2% heavy elements. These stars orbit around the center of the Milky Way, bobbing up and down as they do so.
  - Population 2: Halo stars with random orbits, usually very old and containing very little heavy elements.
- Spiral arms are density waves and stars go in and out of them.

What did we learn in Chapter 15?

- Sagittarius A* is a supermassive black hole at the center of the Milky Way 4 million times more massive than our Sun.
- Most spiral galaxies are observed to have supermassive black holes at their center.
- Large galaxies formed by the merger of smaller galaxies, which accreted much in the same way as solar systems do.
- The star-gas-star cycle is the recycling and enrichment of interstellar matter by successive generations of stars.

What did we learn in Chapter 15?

- In the star-gas-star cycle, a star forms from an interstellar cloud, then returns some of the gas from which it forms back into interstellar space when it ejects a planetary nebula or explodes in a supernova.
- The returned gas is rich in heavy elements, leading to an increase in the abundance of heavy elements in interstellar clouds from which the next generation of stars forms.
- Over time, the star-gas-star cycle leads to less gas available for star formation, but a higher abundance of heavy elements.