

Today's Topics

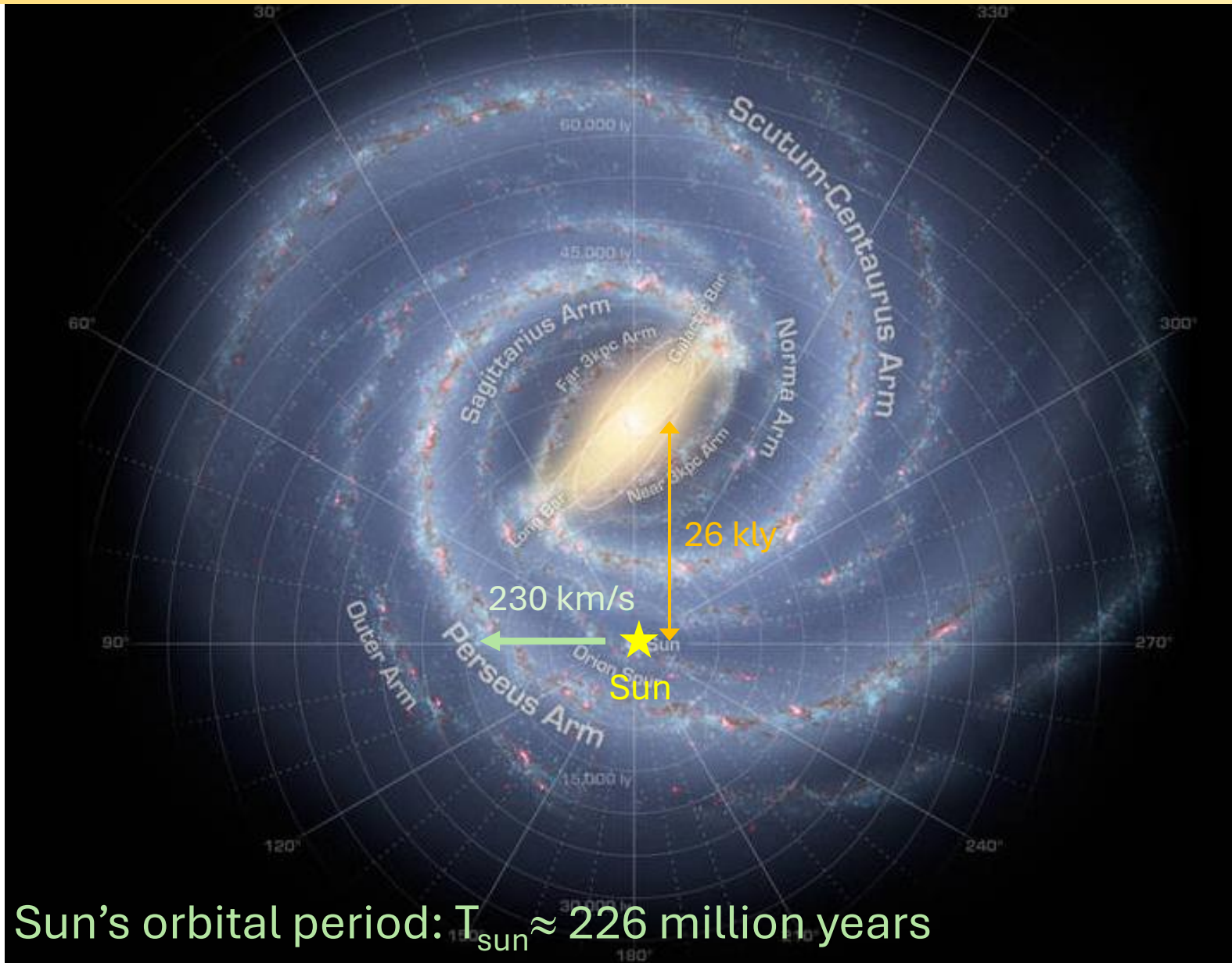
Wednesday, April 15, 2026 (Week 11, Lecture 30) – Chapter 25, 26.

1. **Dark matter**
2. **Stellar population types**
3. **Evolution of the Milky Way**

Problem Set #9 is due on ExpertTA on Friday, April 17, 2026, by 9:00 AM

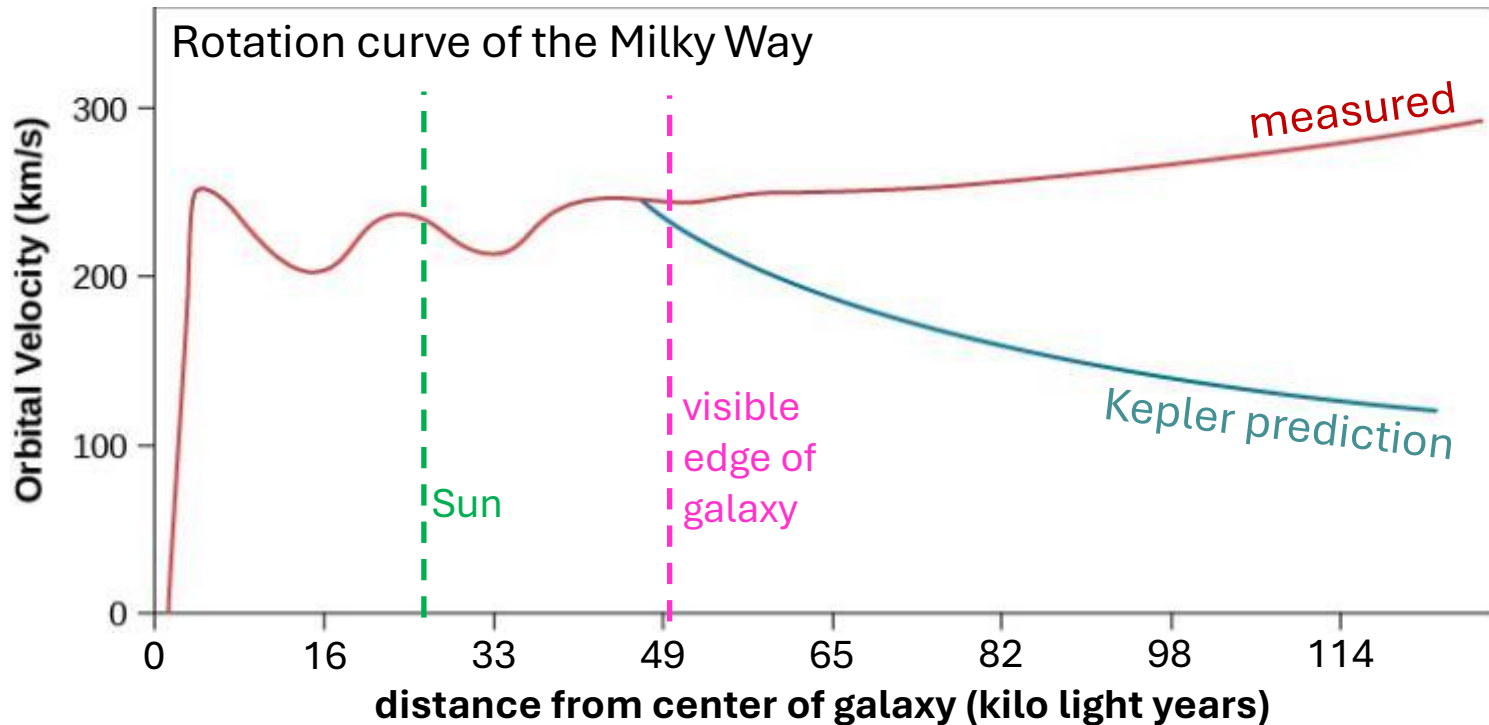
Interlude 2 essay is due on Gradescope on Monday, April 27, 2026

Sun's Orbital Speed



Sun's orbital period: $T_{\text{sun}} \approx 226$ million years

Rotation Curve for Milky Way

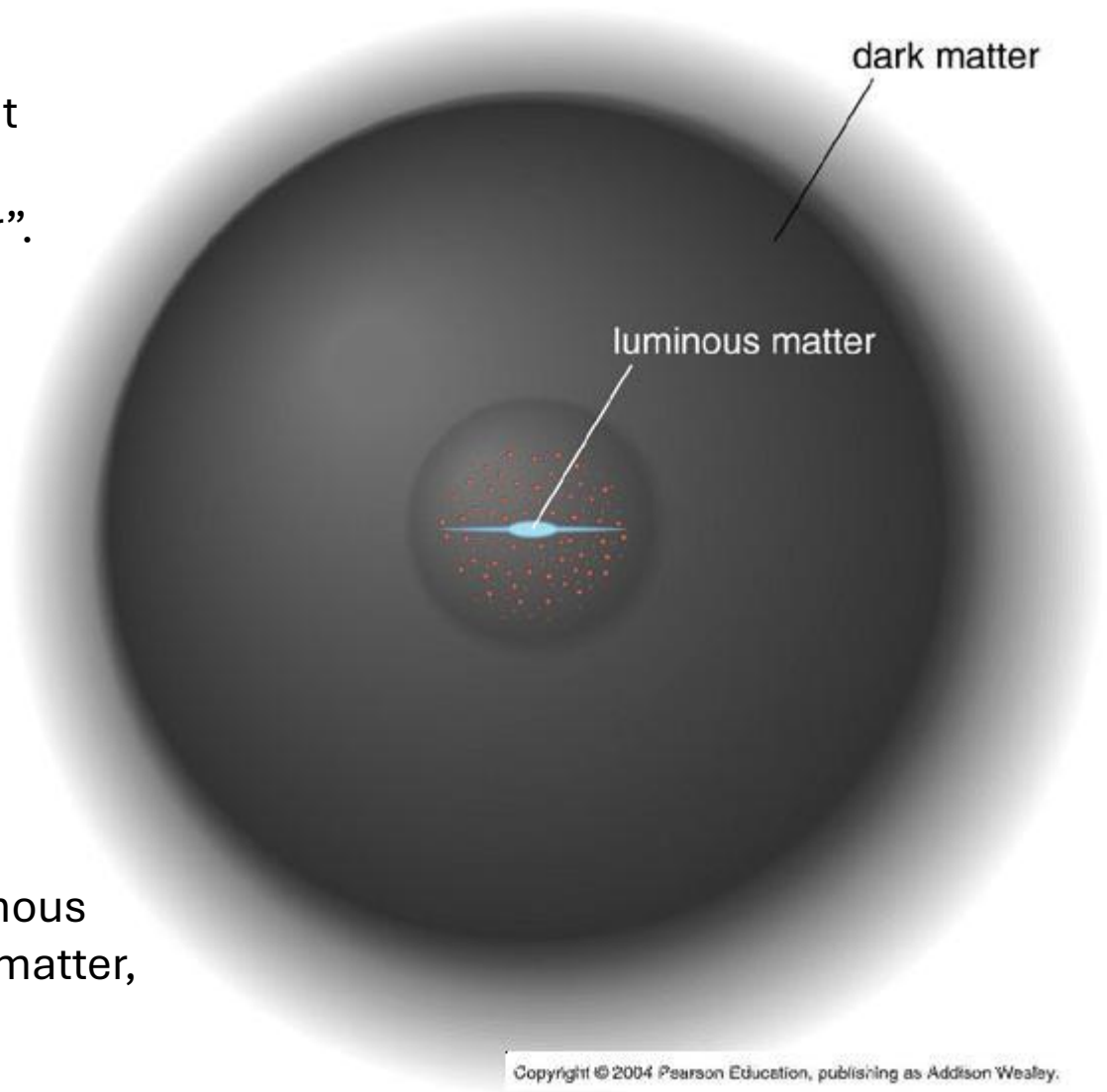


- The orbital speed of carbon monoxide (CO) and hydrogen (H) gas at different distances from the center of the Milky Way Galaxy (red).
- The blue curve shows what the rotation curve would look like if all the matter in the Galaxy were located inside a radius of 30,000 light-years.

→ Instead of going down, the speed of gas clouds farther out remains high, indicating a great deal of mass beyond the Sun's orbit... Indicator of **dark matter**.

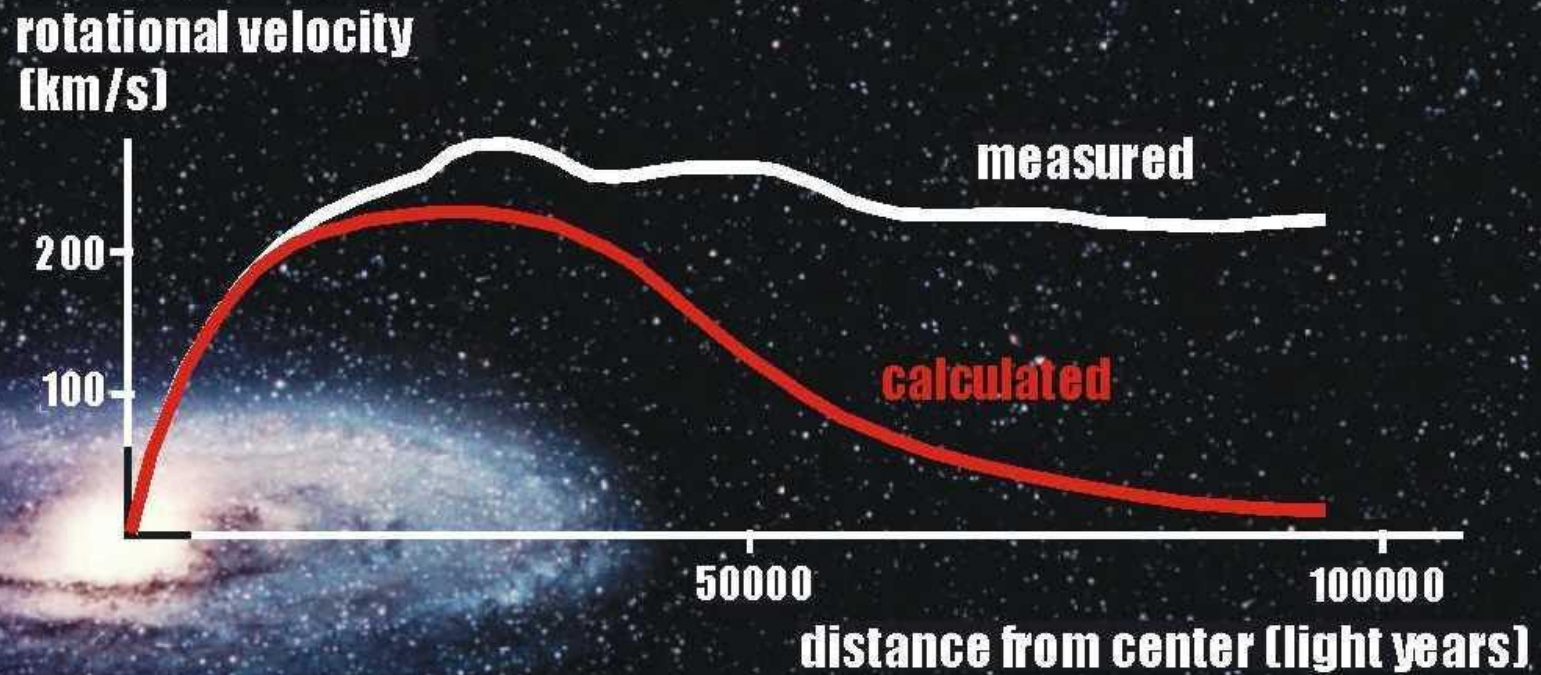
Basic Layout of Dark Matter vs Luminous Matter

- The rotation curve indicates that there is a significant amount of unseen matter, i.e. “dark matter”.
- The basic idea is that the galaxy sits at the center of a large diffuse halo of dark matter.
- The ratio of dark matter to luminous matter is 20-to-1, i.e. 95% dark matter, 5 % luminous matter.



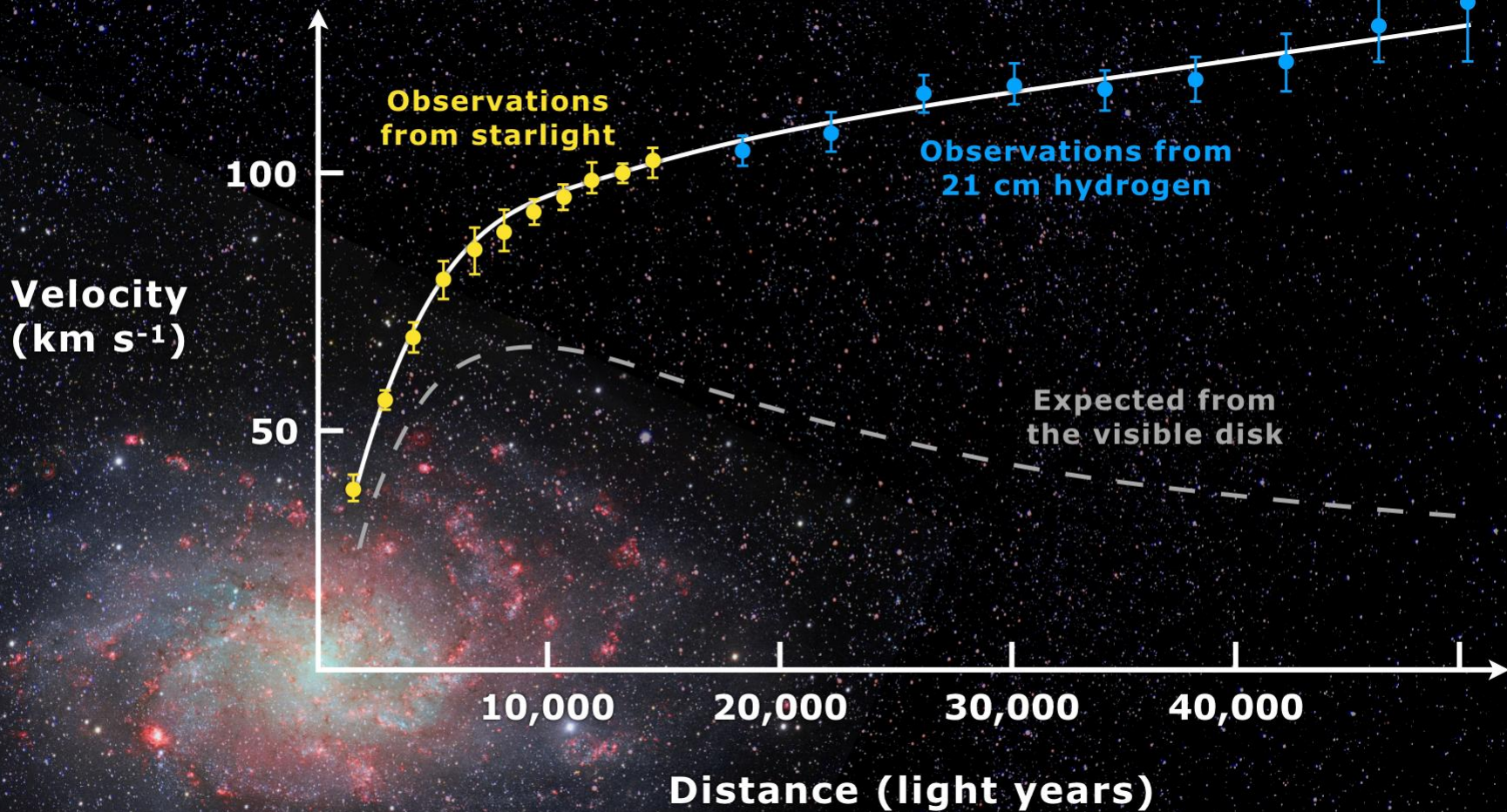
Rotation Curve for M31

M31 Andromeda Galaxy



Rotation Curve for M33

M33 Triangulum Galaxy



[by M. De Leo, Wikipedia (2025), based on Cobelli & Salucci, *Monthly Notices of the Royal Astronomical Society*. 311 (2): 441–447 (2000).]

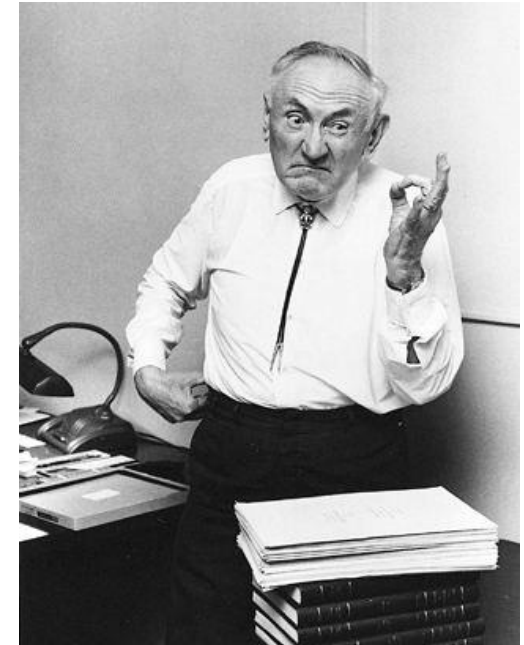
Dark Matter – Coma Cluster



Dark Matter – Coma Cluster

- Coma Berenices constellation.
- Over 1000 galaxies.
- 320 million light years away.
- In 1933, Fritz Zwicky showed that the galaxies of the Coma Cluster were moving too fast for the cluster to be gravitationally bound together by the visible matter of its galaxies.
- Zwicky proposed that the galaxies were held together by "dunkle materie" **dark matter**.
- It took 50 years for the idea of **dark matter** to be widely accepted.

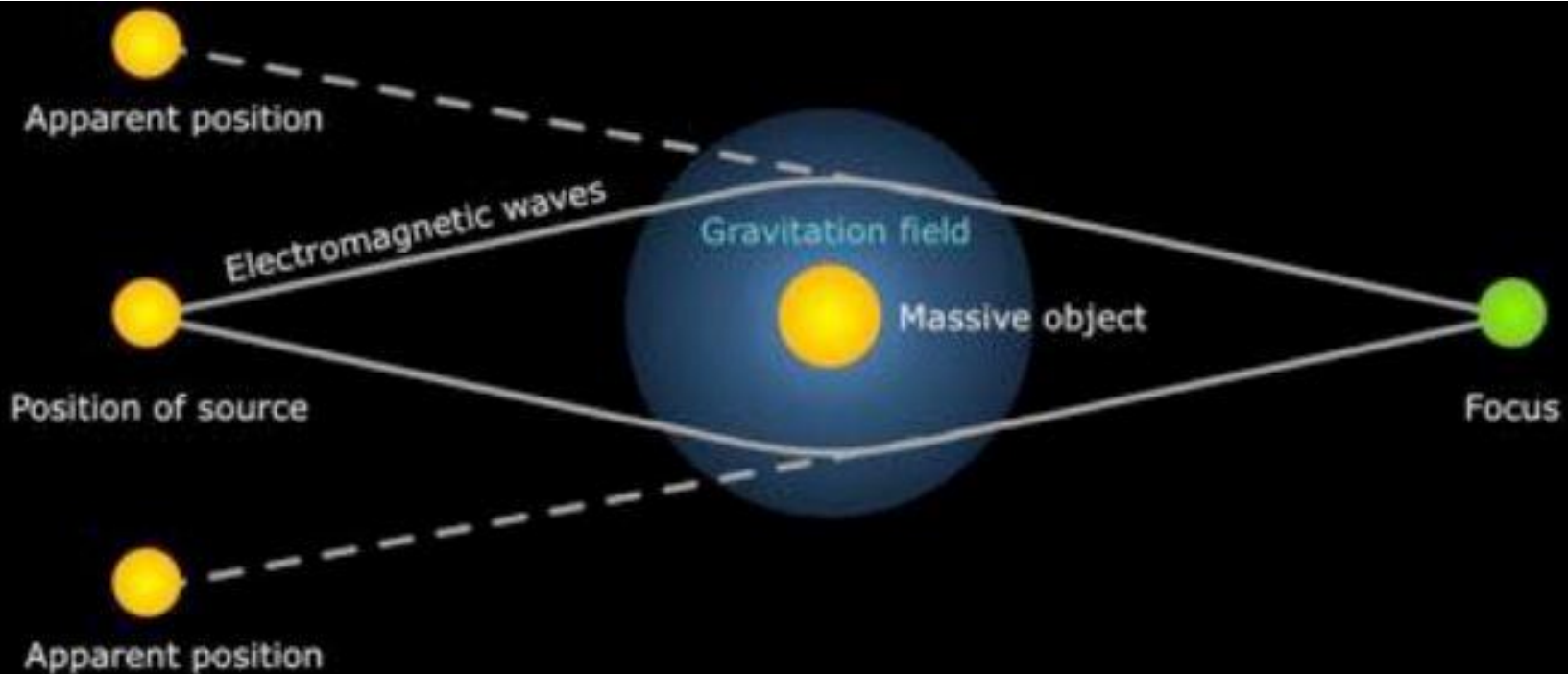
... There are many other examples of such galaxy clusters whose velocities cannot be explained by the luminous matter.



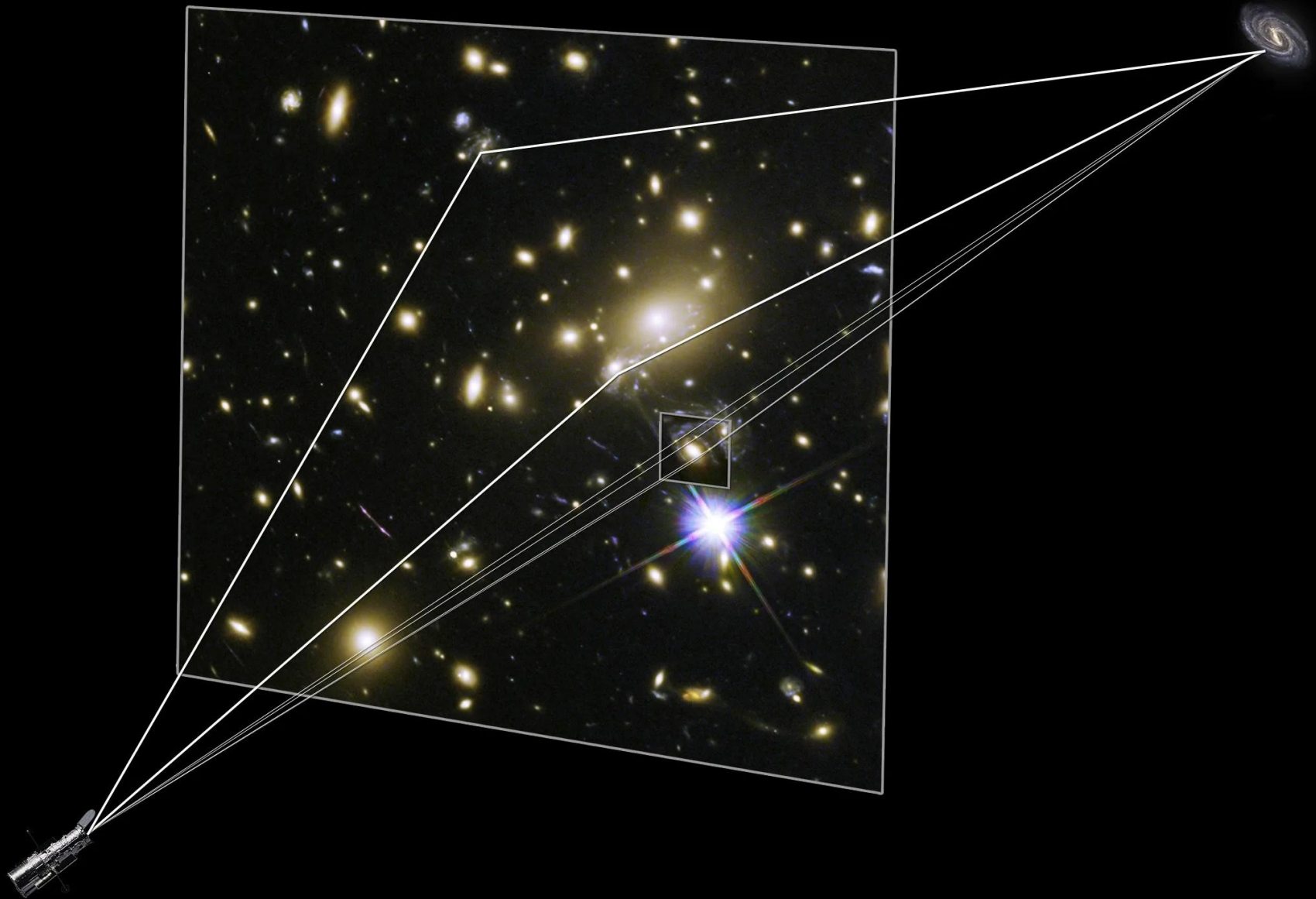
Fritz Zwicky 1898-1974

Dark Matter – Gravitational Lensing

- A large mass can curve the path of light around it and act as a lens.
- Objects behind the large mass can be seen enlarged and in multiple “images”.
- If the “large mass” is unseen (e.g., dark matter), then the “images” can be used to back out the dark matter distribution.



Dark Matter – Gravitational Lensing



Gravitational Lensing -- Example

- A galaxy behind the two elliptical galaxies (yellow) act as a gravitational lens for “blue” galaxy behind them.
- The multiple elongated smears are of the same galaxy and are referred to as “Einstein rings”.

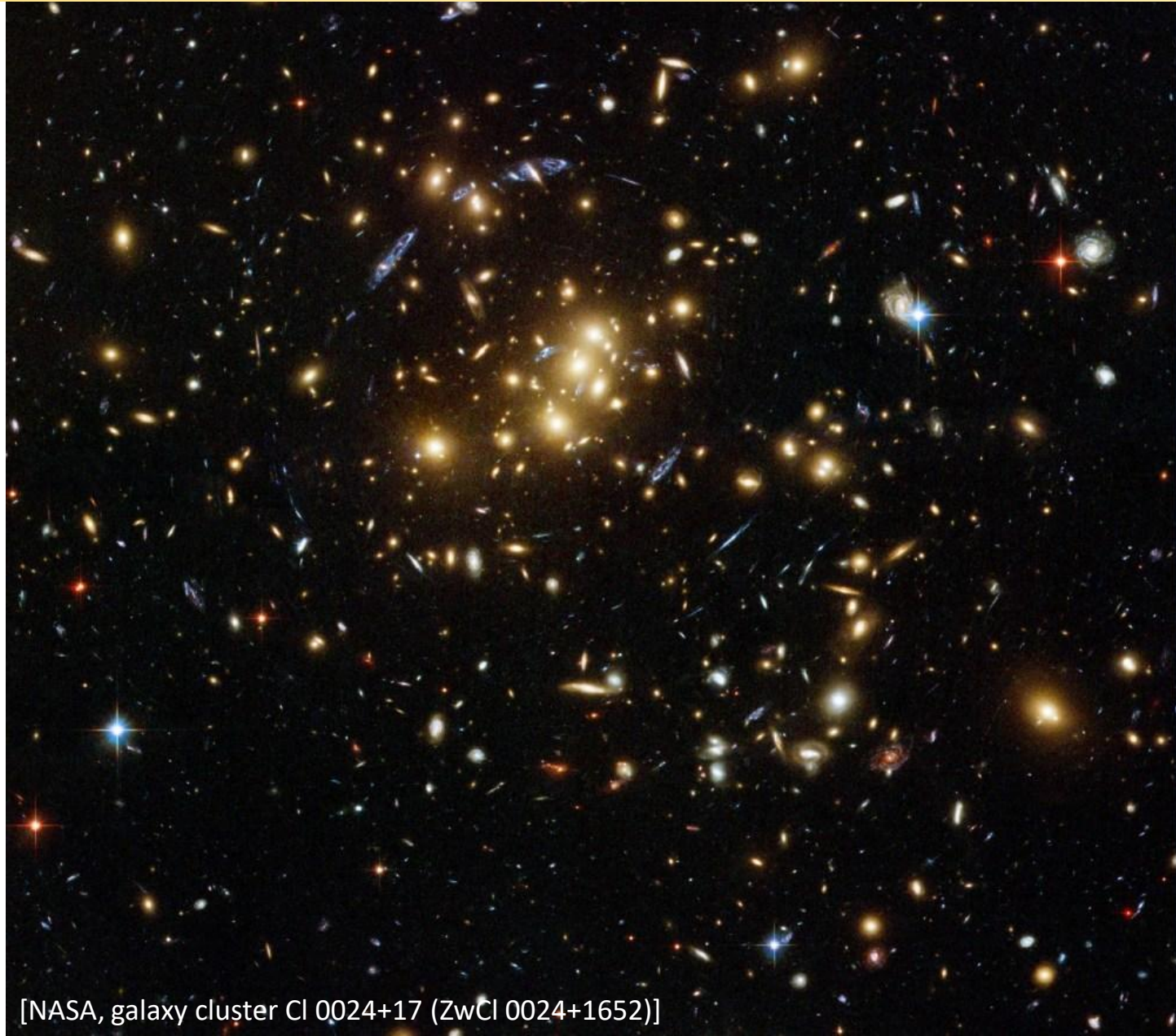


[NASA]

galaxy cluster SDSS J1038+4849

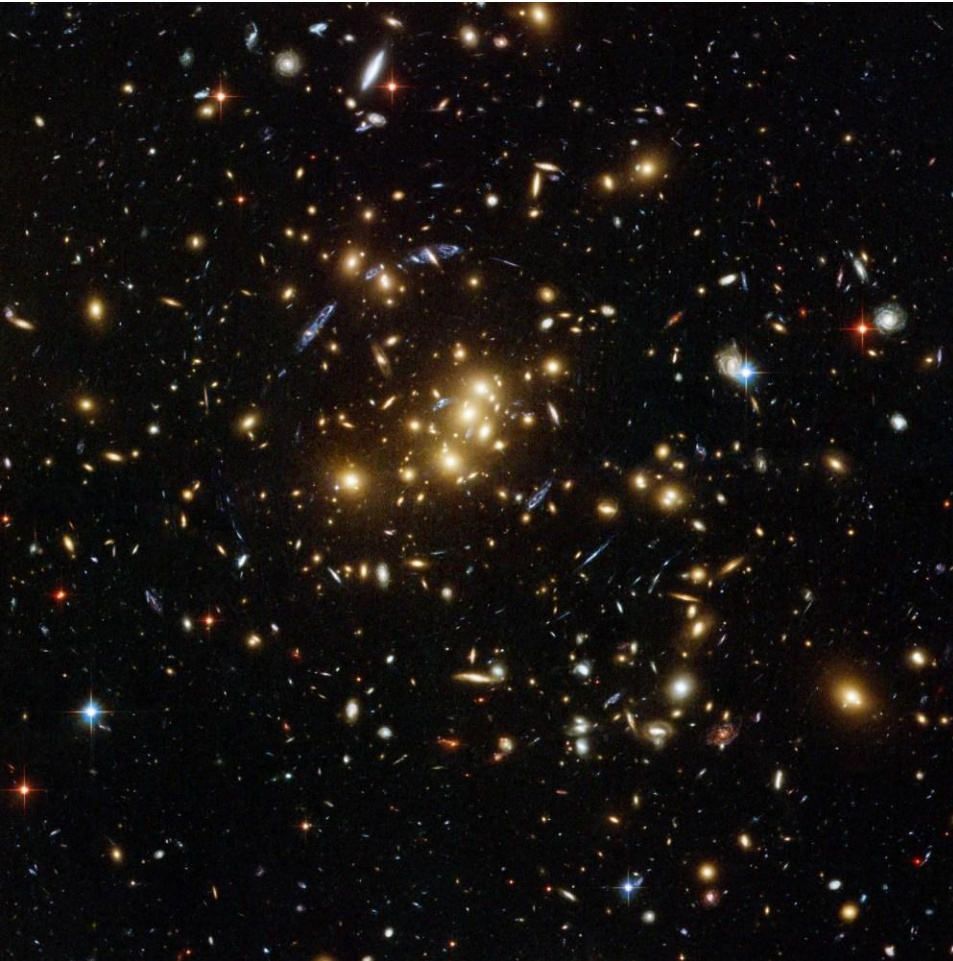
Dark Matter – Gravitational Lensing

Galaxy cluster shows gravitational lensing of multiple background galaxies.

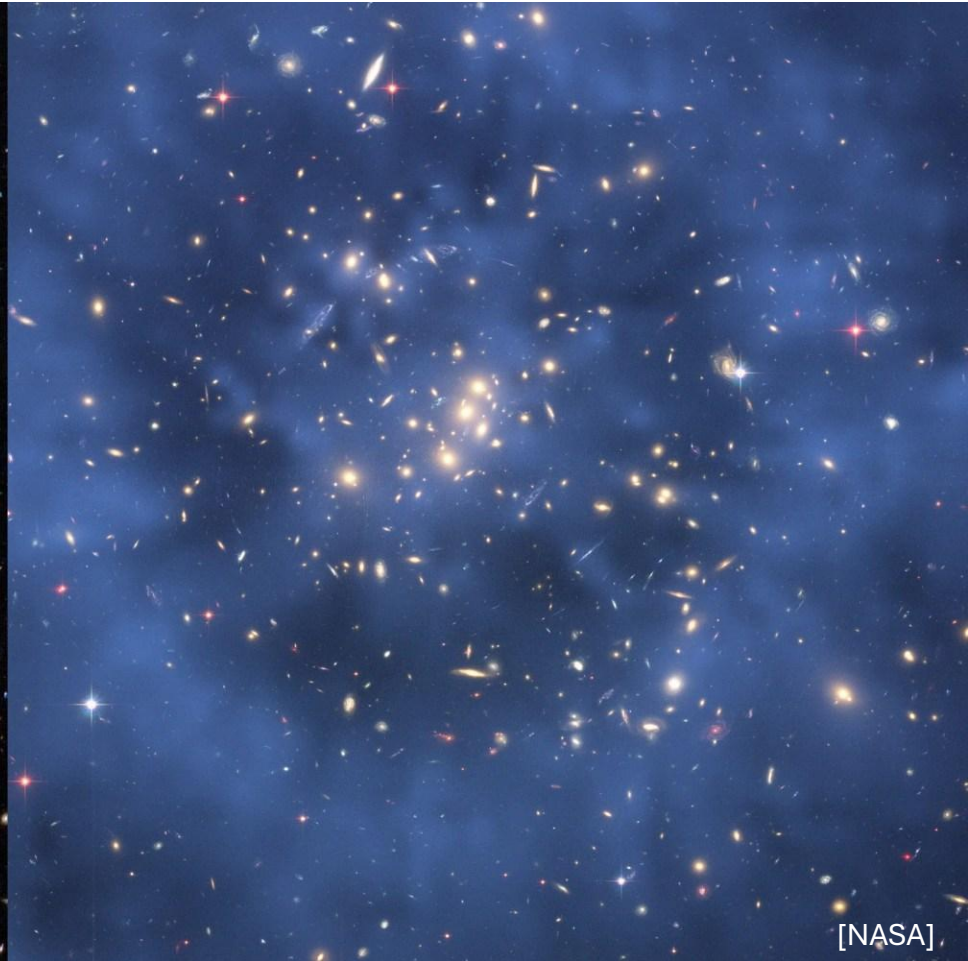


[NASA, galaxy cluster Cl 0024+17 (ZwCl 0024+1652)]

Dark Matter – Gravitational Lensing



original image



Dark matter distribution (blue haze)
inferred from gravitational lensing.

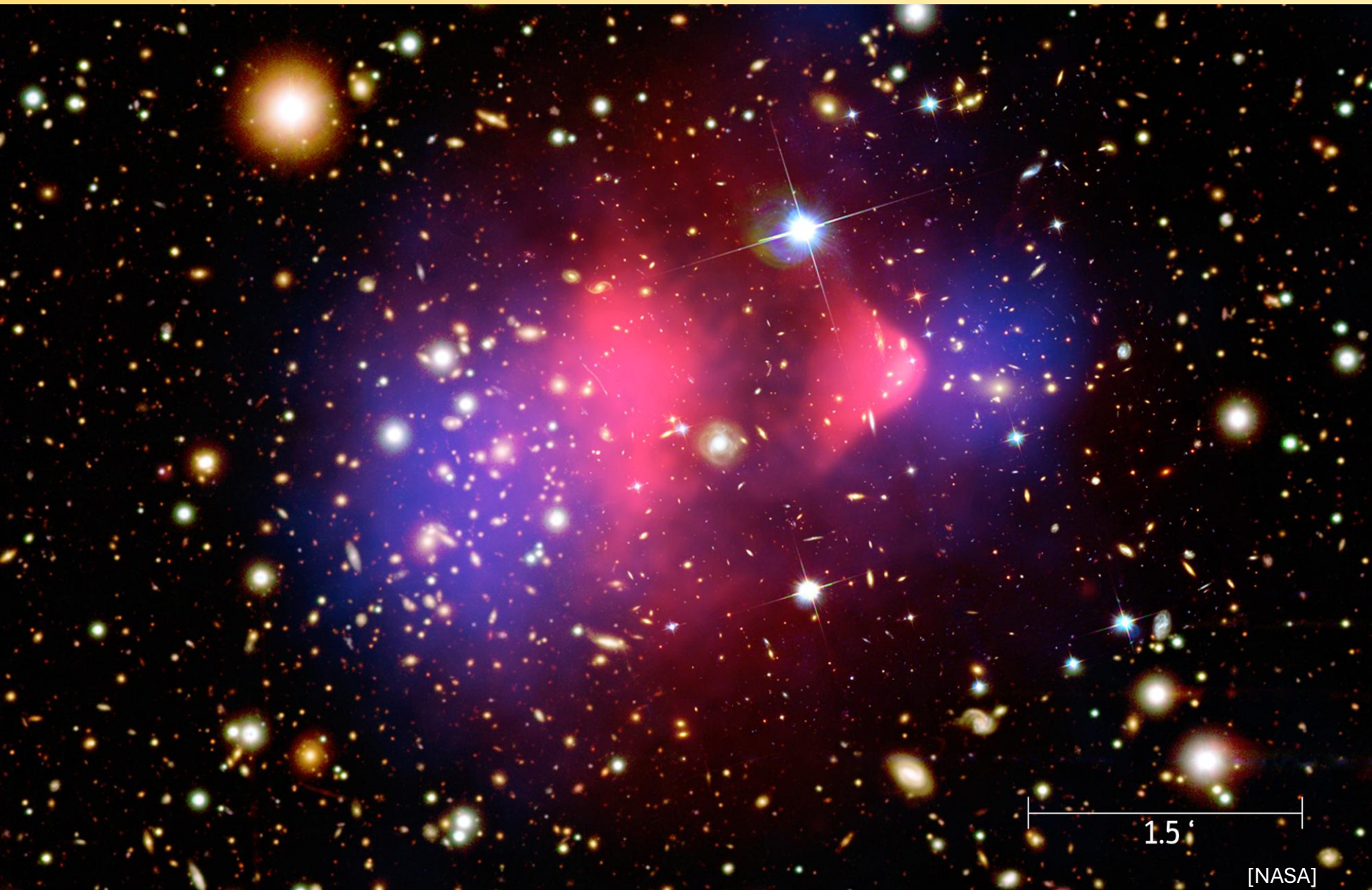
Dark Matter – Pandora Cluster

Red: X-ray data from Chandra Space Telescope.

Blue: Matter lensing map constructed from gravitational lensing data



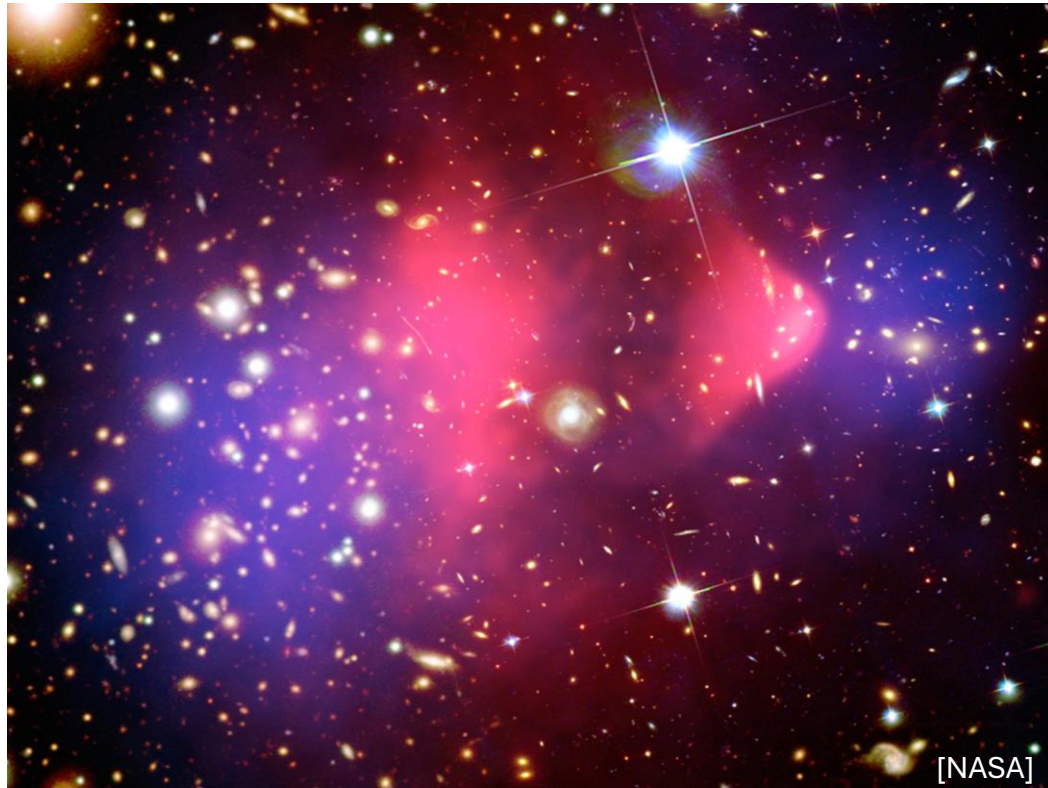
Dark Matter – Bullet Cluster (colliding clusters)



1.5'

[NASA]

Dark Matter – Bullet Cluster (colliding clusters)



Strong evidence for **dark matter** and against modifications of Newton's gravity.

- Two clusters of colliding galaxies
- 3.7 billion light years away
- Superimposed:
 - Chandra X-Ray image (**pink**): mainly hot gas.
 - Visible light (galaxies).
 - Inferred dark matter distribution from gravitational lensing (**blue**).
- Gas (ordinary matter) stayed in the region of the collision (it interacted with the other gases).
- Dark matter followed the galaxies (i.e., it did not interact with itself).

Dark Matter: What is it?

We don't know !!

Could it be:

- **Neutral hydrogen atoms?** Nope. Would see via the 21-cm line.
- **Ionized hydrogen gas?** Nope. Would see in visible light
- **Neutral hydrogen molecules?** Nope. Would see in UV light
- **Interstellar dust?** Nope. Would see block visible light
- **Black holes?** Nope. Would glow in x-rays and gravitational lensing
- **Brown dwarfs or lone Jupiter-like gas giant planets?** Nope.
 - Would see in variation of gravitational lensing of light from Magellanic clouds.

It is not “visible” – don’t see it in the light from galaxies.

Conclusion: Must be a new, **exotic form of matter** – not atoms.

→ In fact, we will see that many precise predictions of cosmology require that dark matter not be made of protons/neutrons/electrons.

Dark Matter: What is it?

Could it be neutrinos?

- After all, they don't interact via strong or electromagnetic interactions, only via weak interaction, and, presumably, gravity, because they have some (tiny) mass.
- **We don't think so:** in order for galaxies to form, dark matter must be **cold**, *i.e.*, it must be moving slowly (not near c) when galaxies were formed.
- However, neutrinos are **hot**: they have so little mass that they are all travelling at very close to the speed of light.

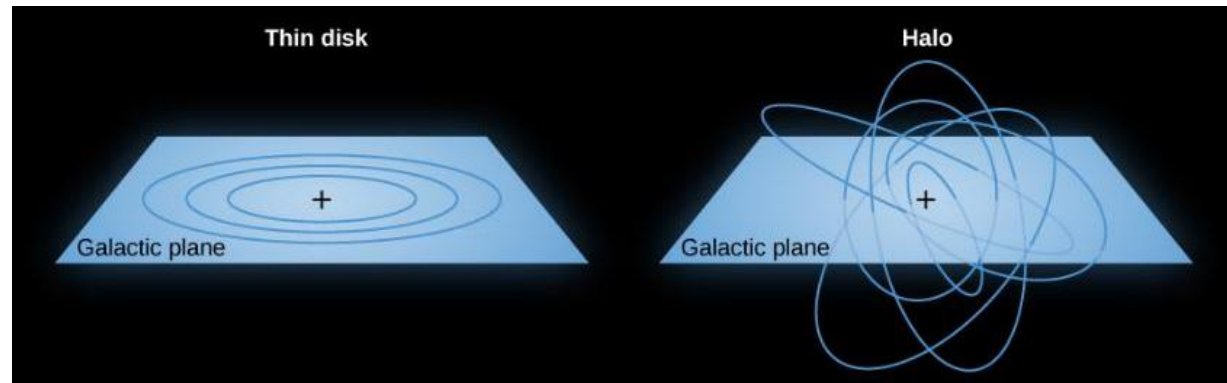
Physicists have looked hard (and are still looking) for **neutrino-like** dark matter particles that are **heavier** and **much slower**, but still interact via the weak force (WIMPS=Weakly Interacting Massive ParticleS).

... so far nothing has been detected yet!!

PolleEv Quiz: PolleEv.com/sethaubin

Stellar Population Types

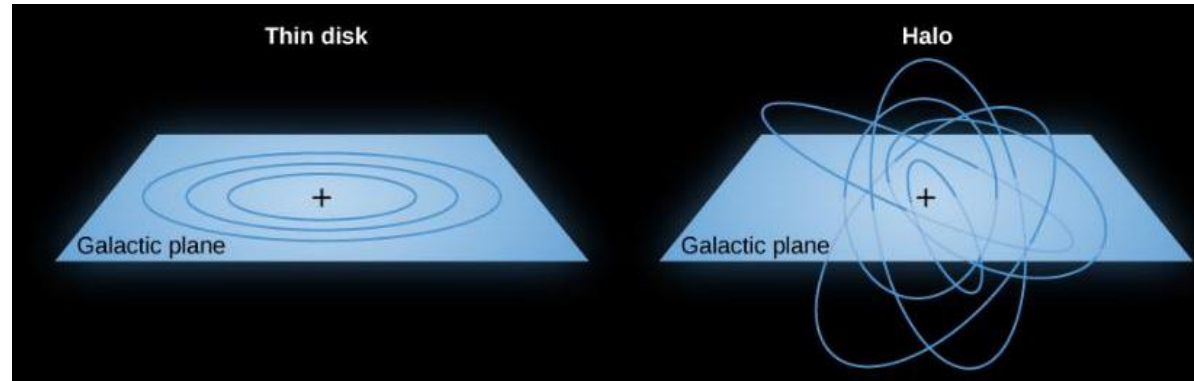
Studies of Milky Way & Andromeda reveal **two** stellar population types.



Stellar population types provide clues to galactic formation process

Stellar Population Types

Studies of Milky Way & Andromeda reveal **two** stellar population types.

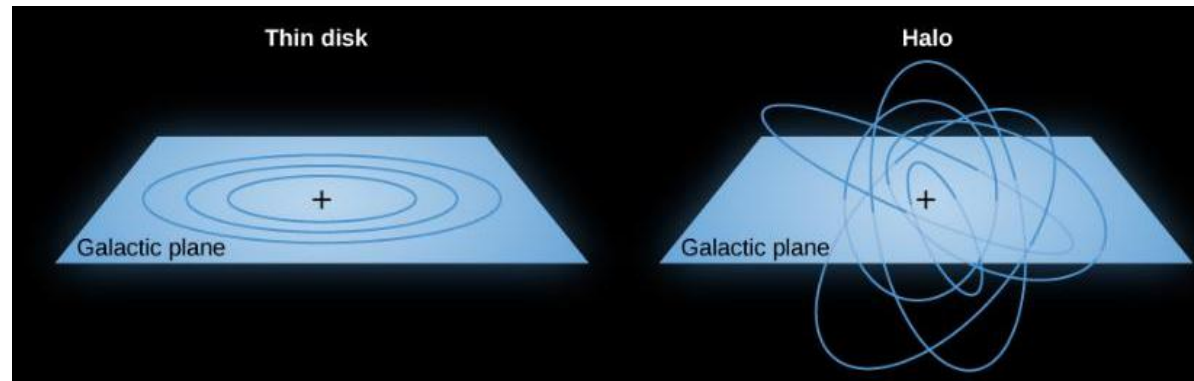


Population I stars

- **In the disk**, orbiting the galactic center. Bright supergiants and O and B spectral class.
- Typically members of young, open (100-1000 stars) clusters. Wide range of ages.
- They are composed of relatively large fractions of heavy elements
 - 1-4% of the mass is neither H nor He = High **metallicity**
- Accompanied by molecular clouds near these stars.

Stellar Population Types

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Population II stars

- **Mainly in the halo**, follow elliptical orbits.
- Typically, they are very old (11-13 billion years).
- Almost entirely H or He. Not surprising – heavy elements are produced in stars.
 - When these stars were formed long ago, there was only H and He in the interstellar gas.

Stellar population types provide clues to galactic formation process

Milky Way Formation-Evolution

Rough timeline of the formation of the Milky Way

1. **Proto-galaxy**: Initial clump of material (possibly two clumps), no spiral structure.
→ *Roughly 12-13 billion years ago.*
2. 0-2 billion years: **central bulge** develops, fuzzy spiral arms develop.
3. 3-4 billion years: Two well-defined **spiral arms form**
4. 8+ billion years: **multiple spiral arms**
5. More recently: **central bar** develops.

Milky Way Formation-Evolution

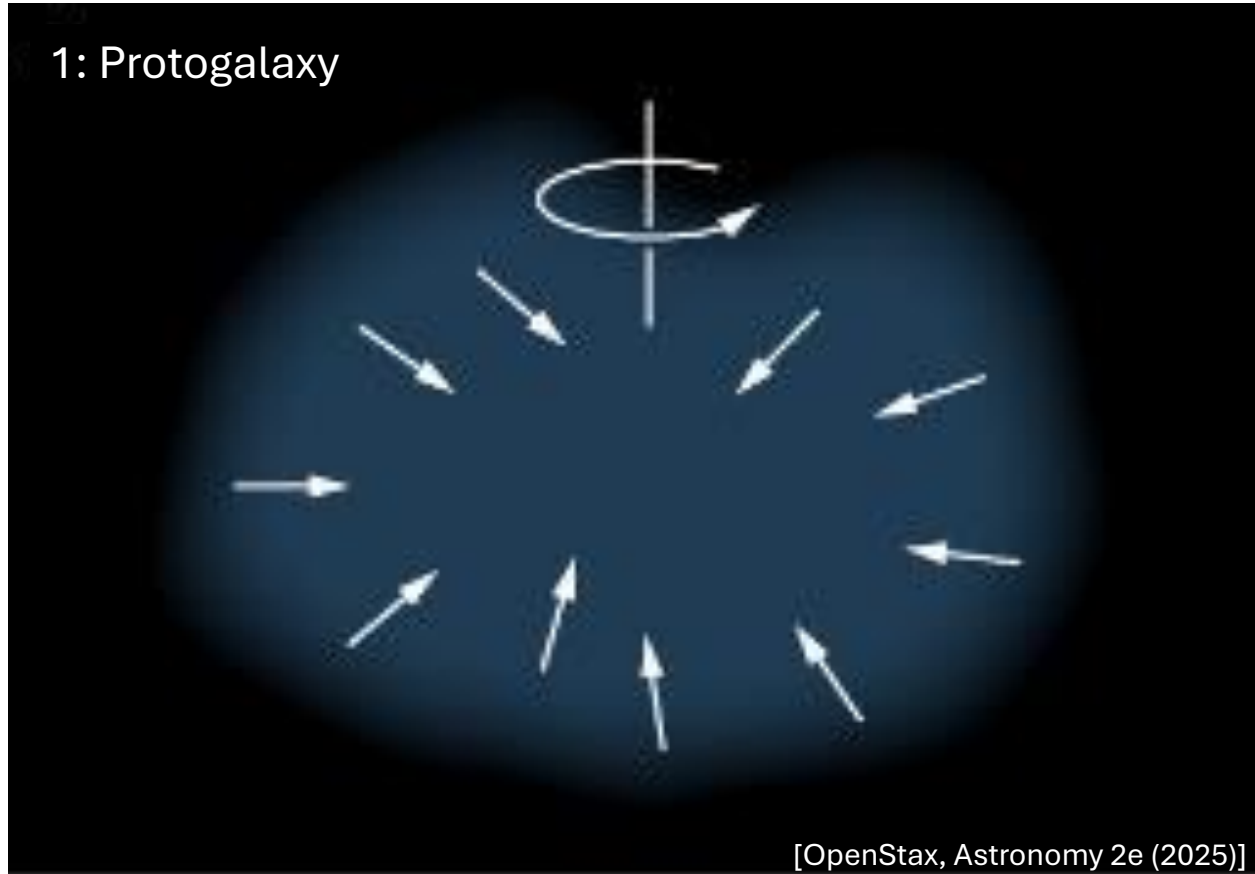
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Additional facts:

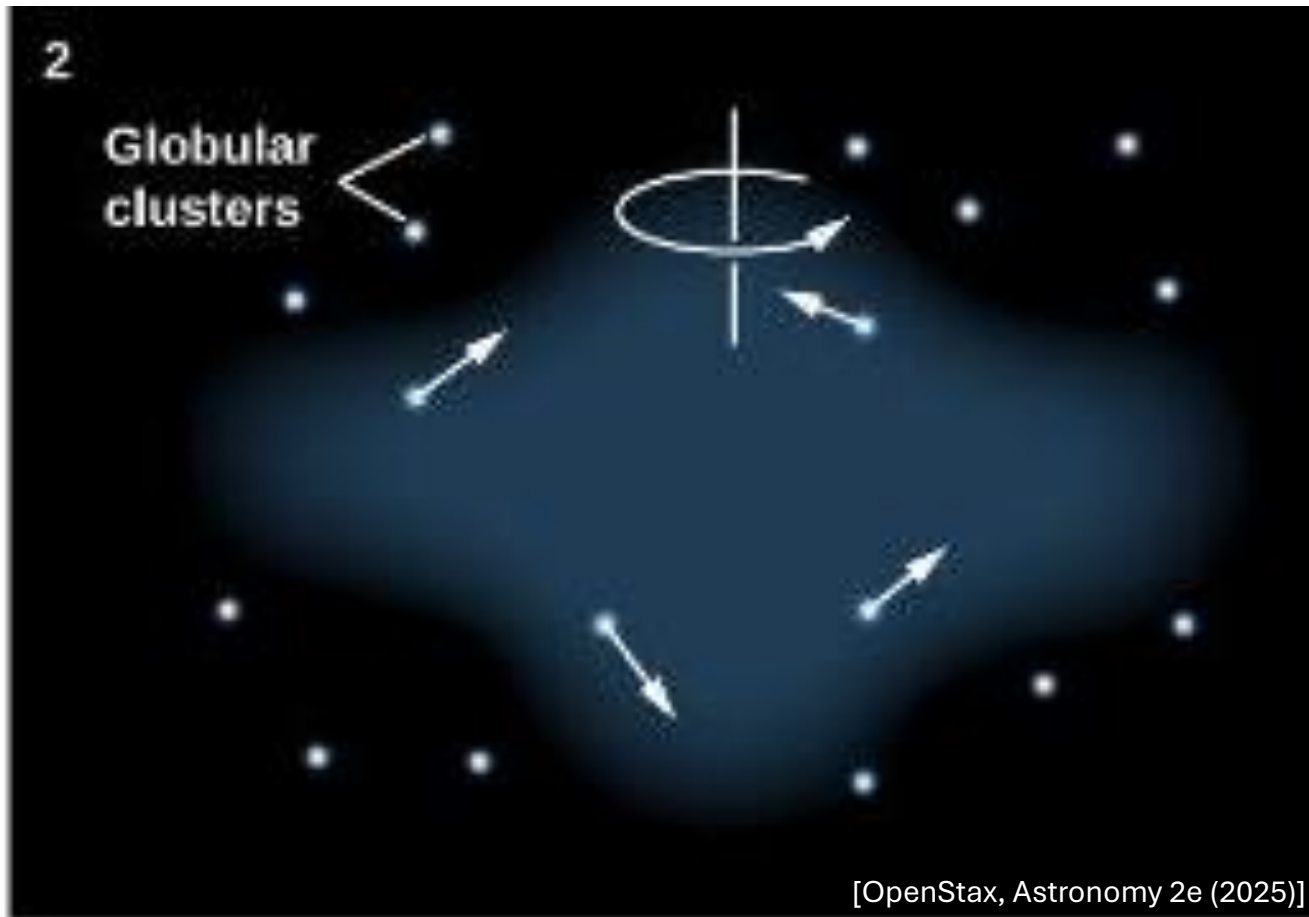
- It is likely that in the early stages the Milky Way **merged** with other large galaxies.
- At present, the Milky Way is **accreting** material from nearby **dwarf galaxies**.
→ e.g. Large and Small Magellanic Clouds, Sagittarius Dwarf.
- The Milky Way is expected to **merge** with Andromeda (M31) in about 4 billion years.

Monolithic Collapse Model: Galaxy formation



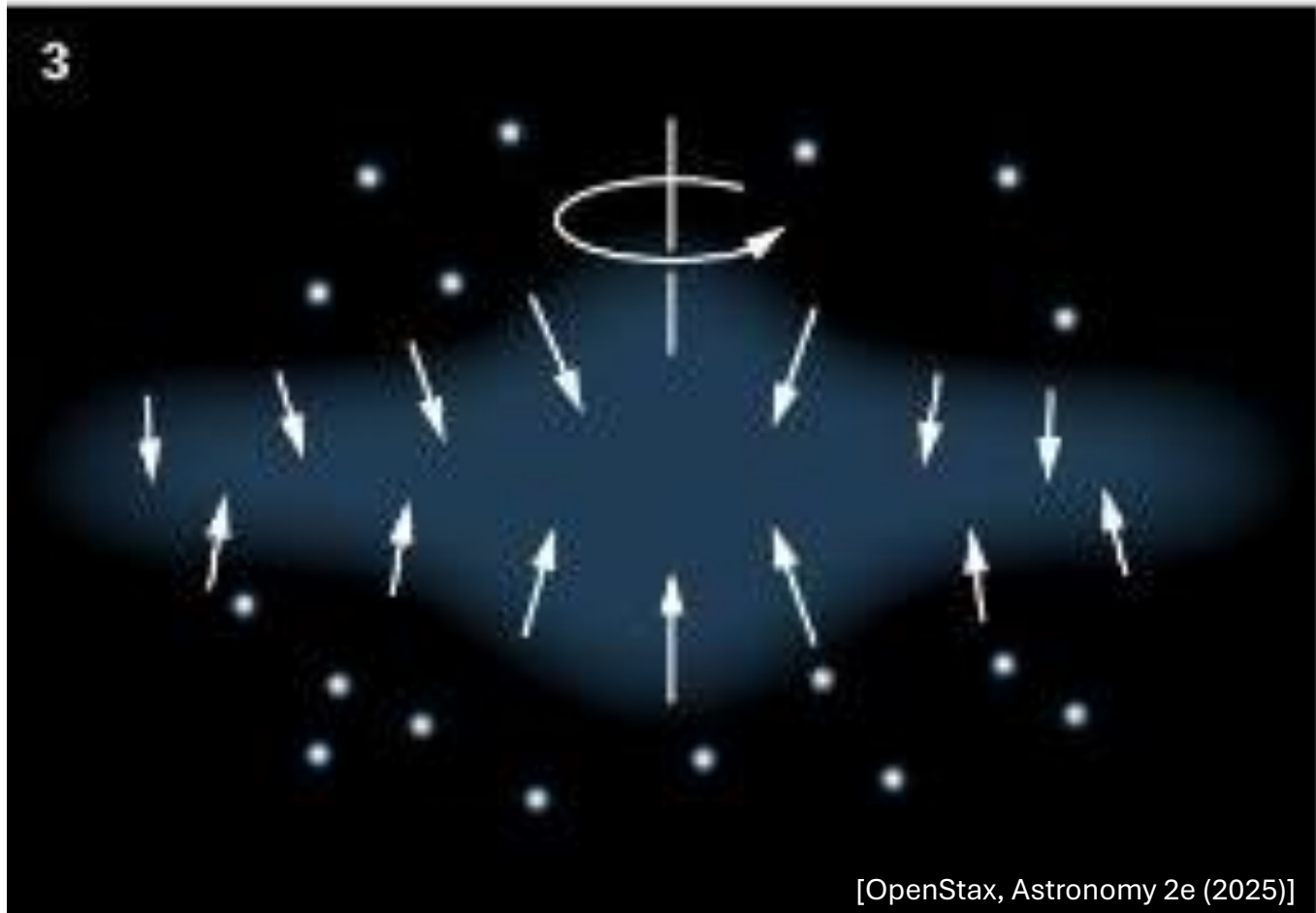
- An initial cloud of gas and dust collapses under its own gravity.
- As it collapses, its initial angular momentum is conserved, and the cloud rotates faster.

Monolithic Collapse Model: Galaxy formation



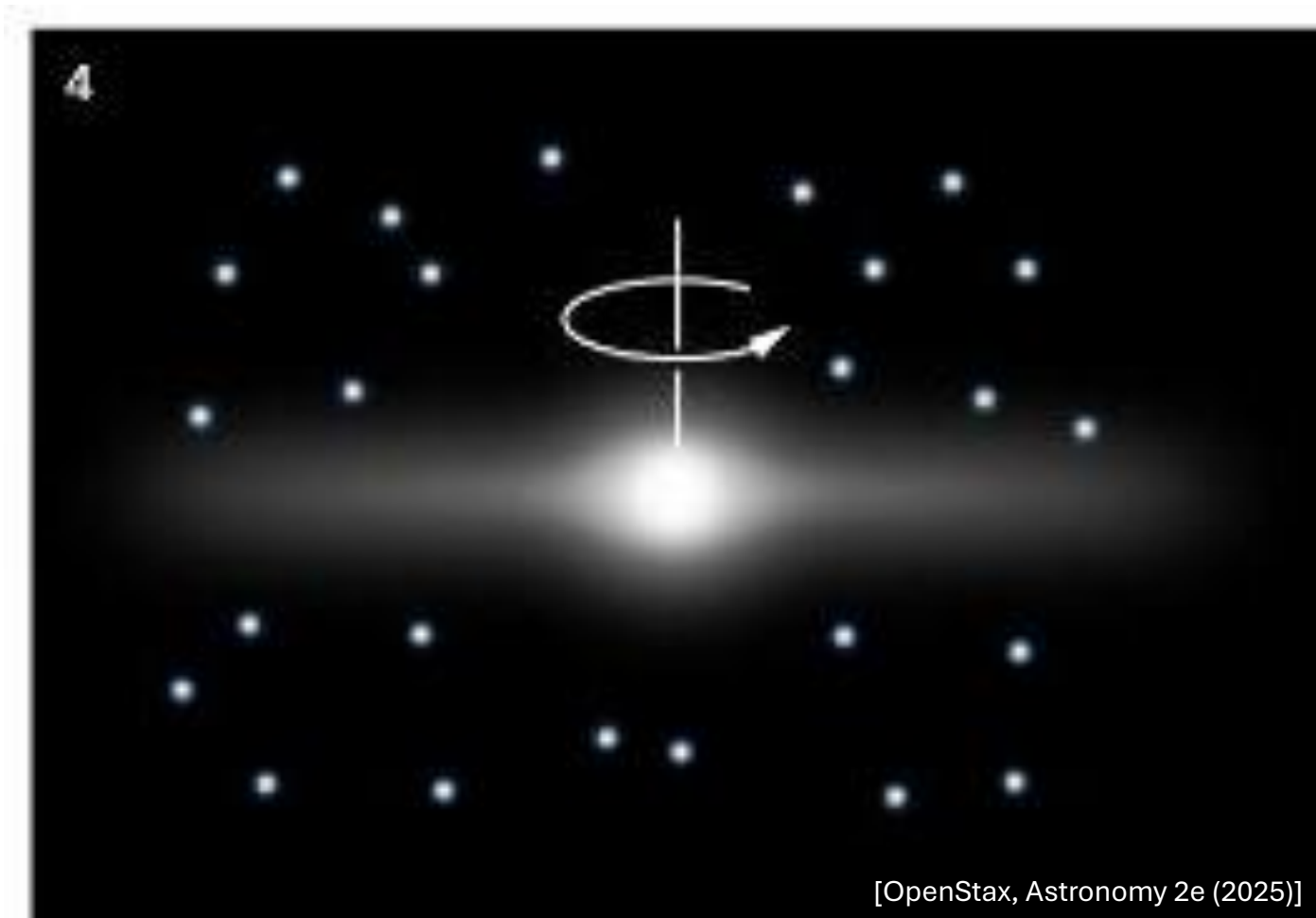
- The globular clusters were formed prior to collapse or were formed elsewhere.
- As it collapses, stars begin to form in regions of higher density.

Monolithic Collapse Model: Galaxy formation



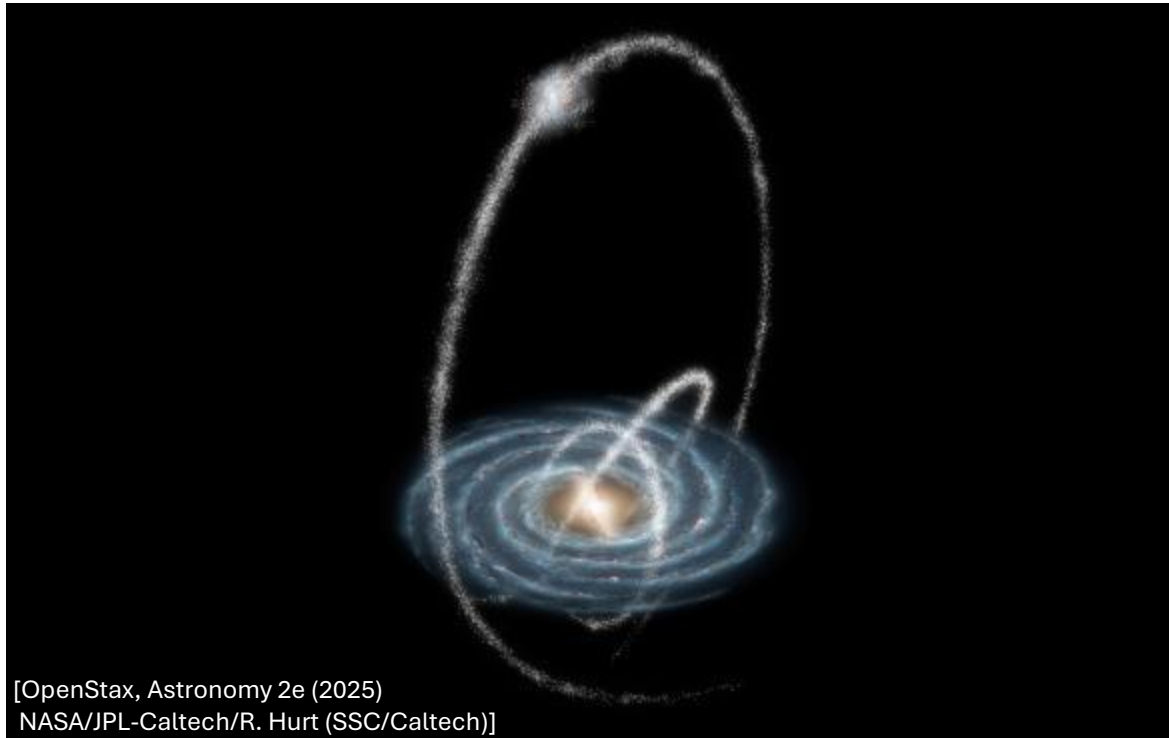
- Interactions between the gas/dust and stars pulls the cloud into a disk (angular momentum is conserved).

Monolithic Collapse Model: Galaxy formation



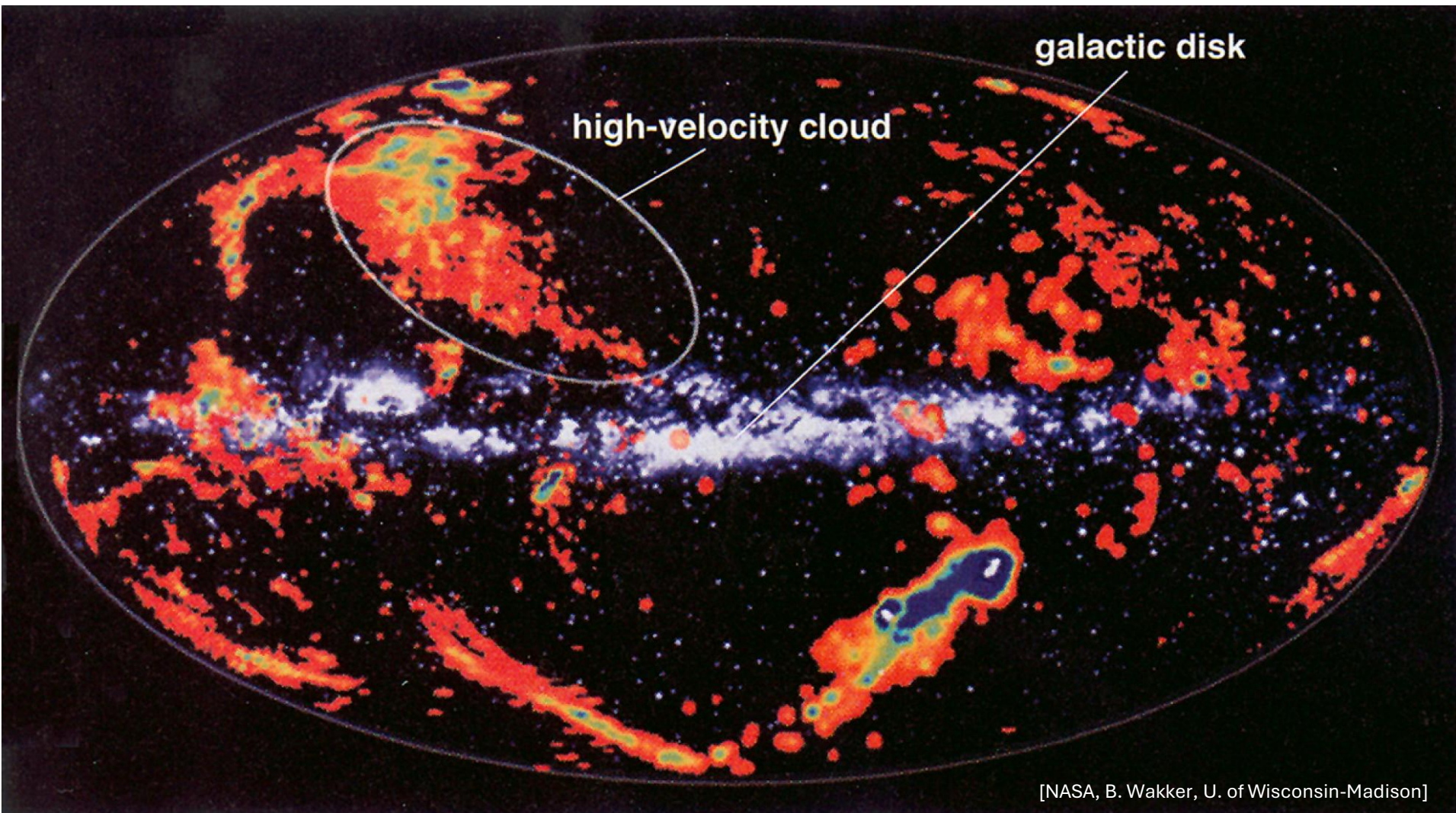
- The densest region centered on the center of mass has the most stars, and bulge emerges with somewhat random orbits (out-of-plane).

Dwarf Galaxy Merger-Accretion



- **Streams in the Galactic Halo:** When a small galaxy is swallowed by the Milky Way, its member stars are stripped away and form streams of stars in the galactic halo.
- This image is based on calculations of what some of these tidal streams might look like if the Milky Way swallowed 50 dwarf galaxies over the past 10 billion years.

Dwarf Galaxy Merger-Accretion



[NASA, B. Wakker, U. of Wisconsin-Madison]