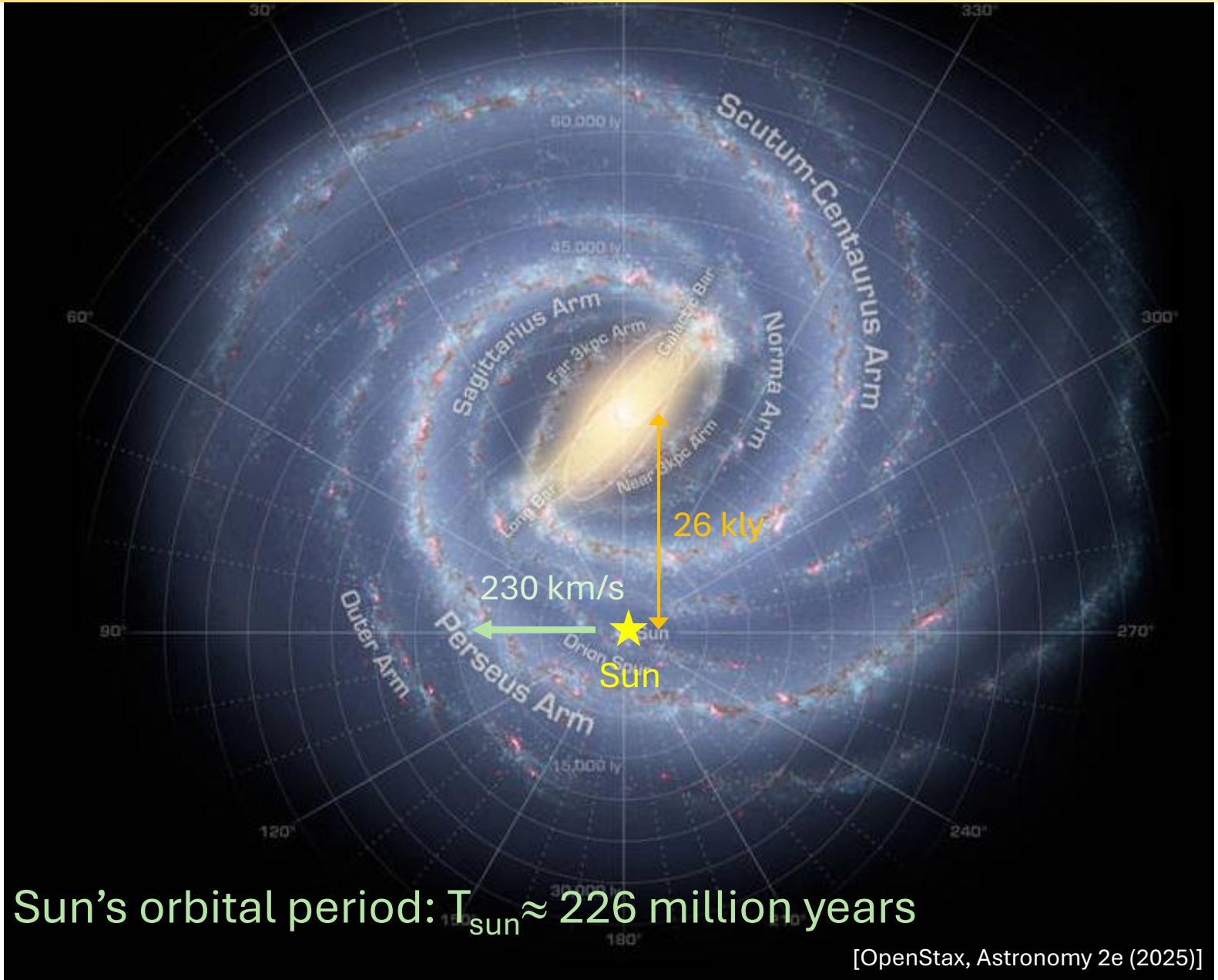
Today's Topics

Wednesday, April 16, 2025 (Week 11, Lecture 29) – Chapter 25, 26.

1. Dark matter
2. Formation of the galaxy

Problem Set #9 is due on ExpertTA on Friday, April 18, 2025, by 9:00 AM

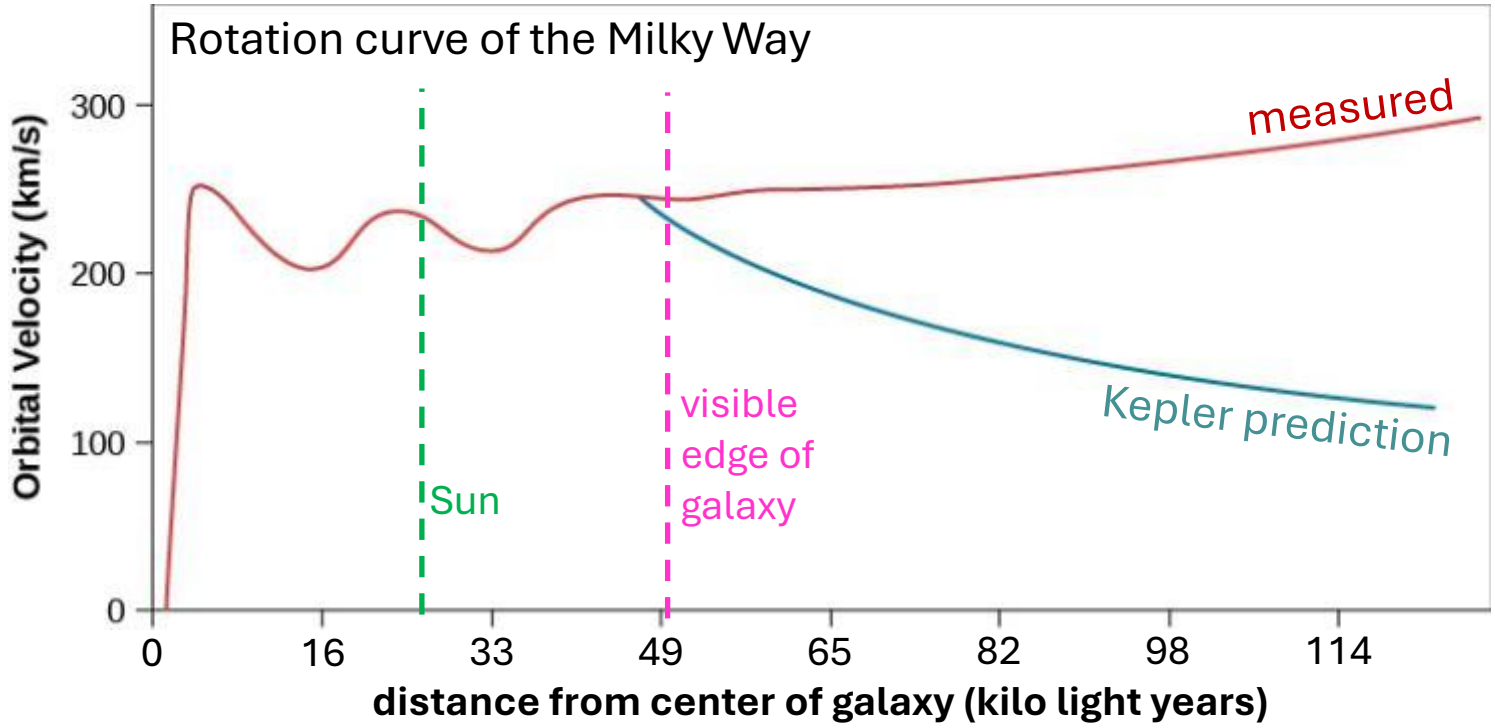
Sun's Orbital Speed



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

[OpenStax, Astronomy 2e (2025)]

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**.

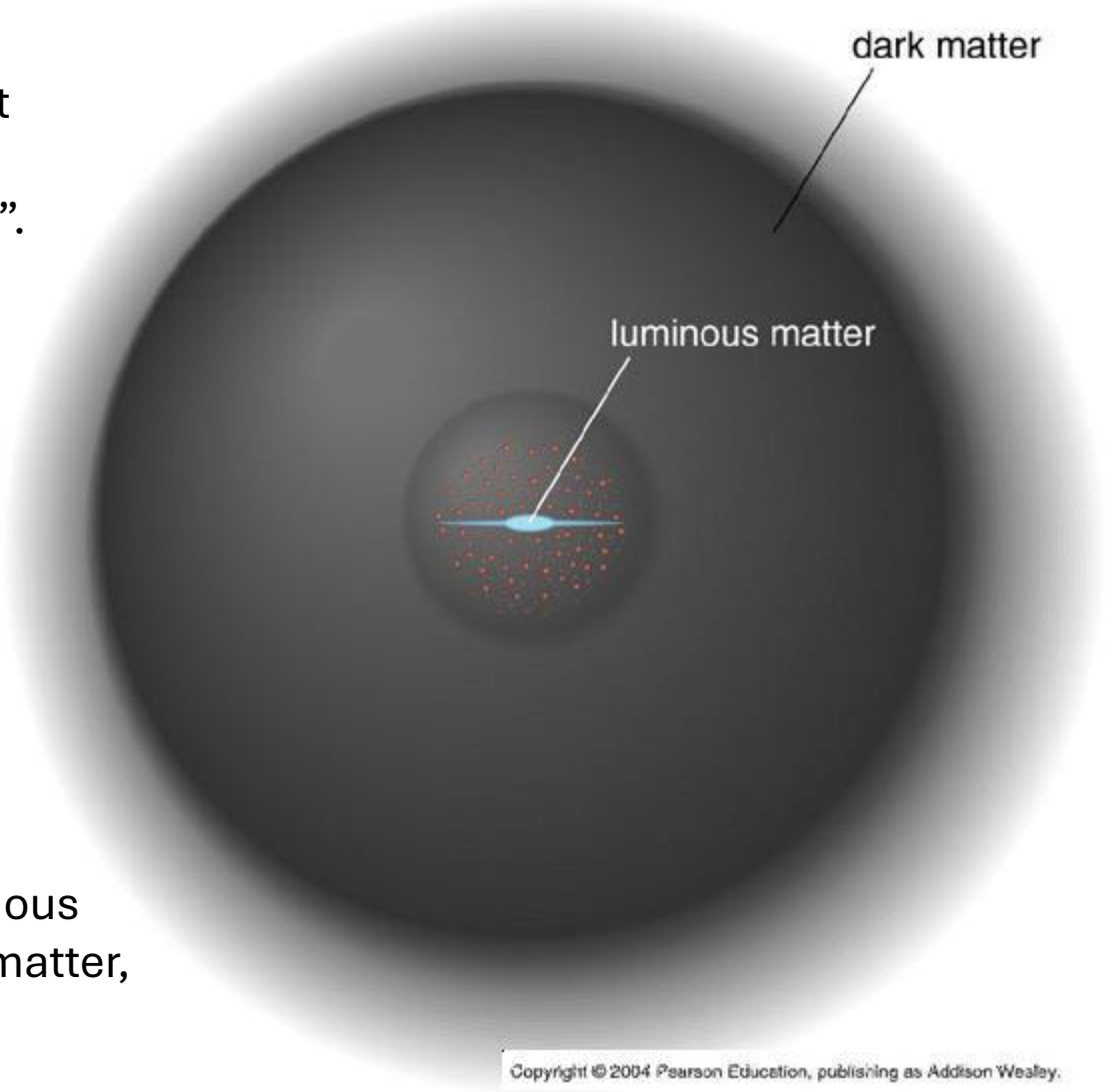
[OpenStax, Astronomy 2e (2025)]

Basic Layout of Dark Matter vs Luminous Matter

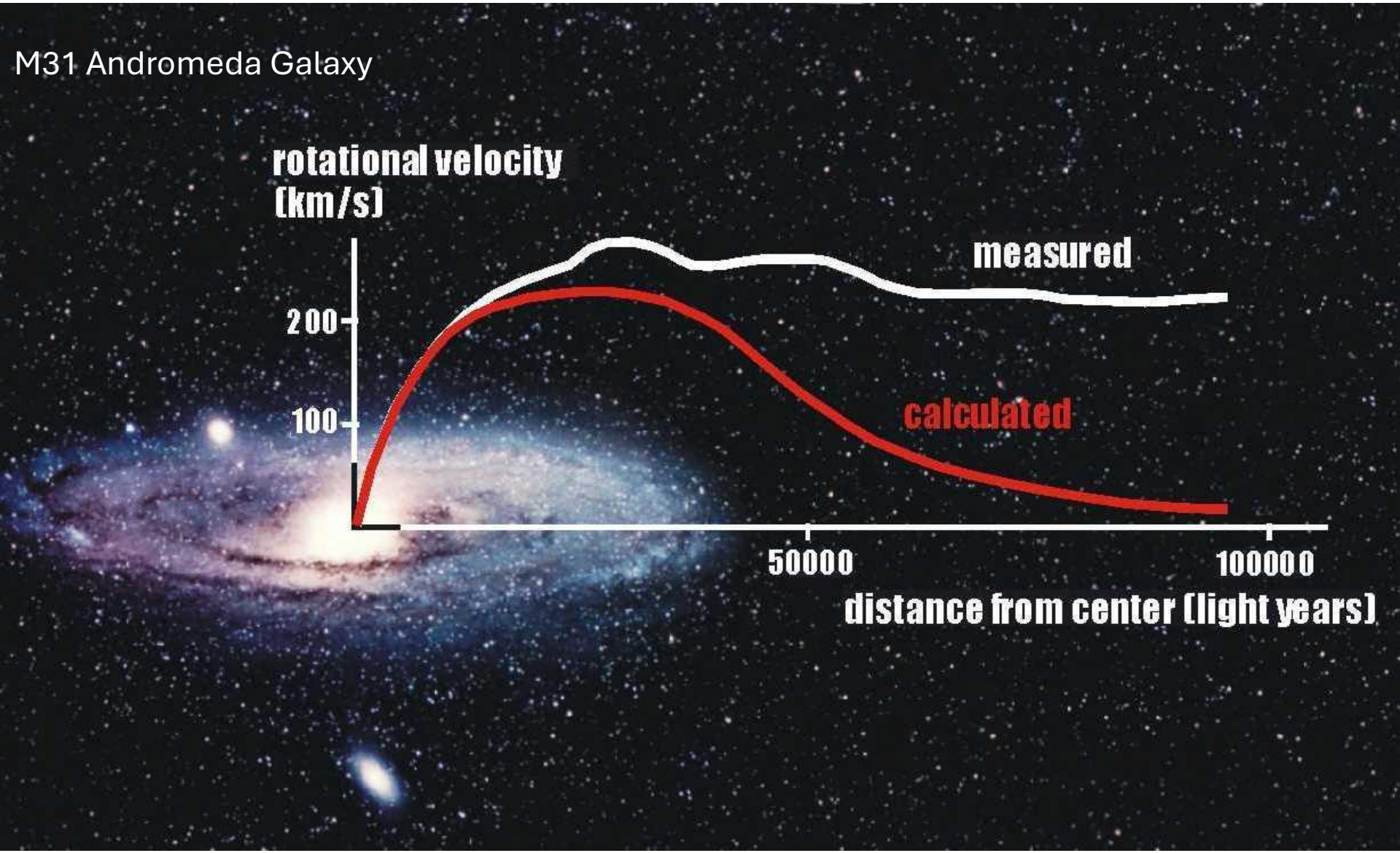
- The rotation curve indicates that there is a significant amount of unseen matter, i.e. “dark matter”.

- 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.

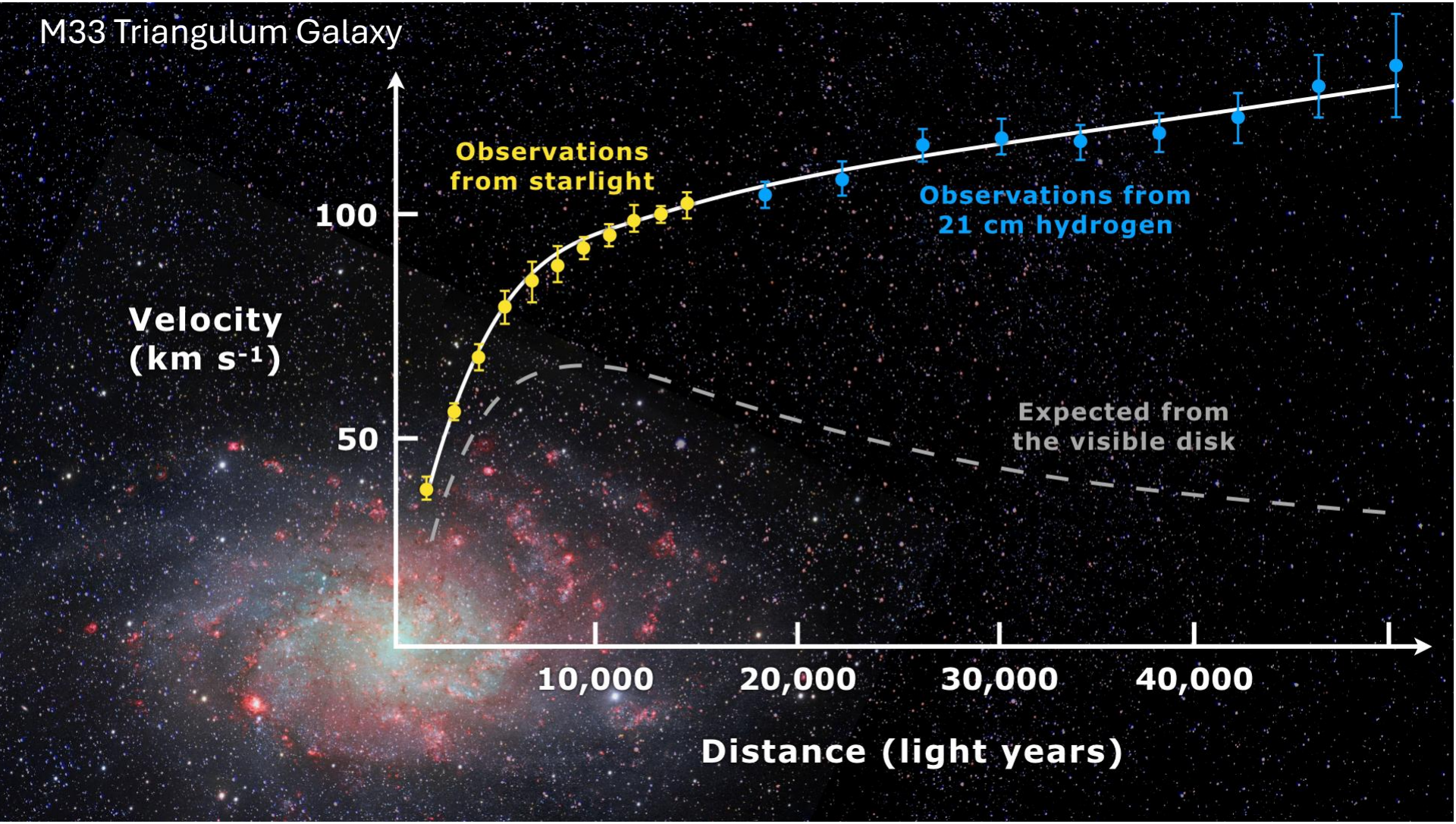


Rotation Curve for M31



[Phys.org (2011), A. R. Parry, Queens U.]

Rotation Curve for M33



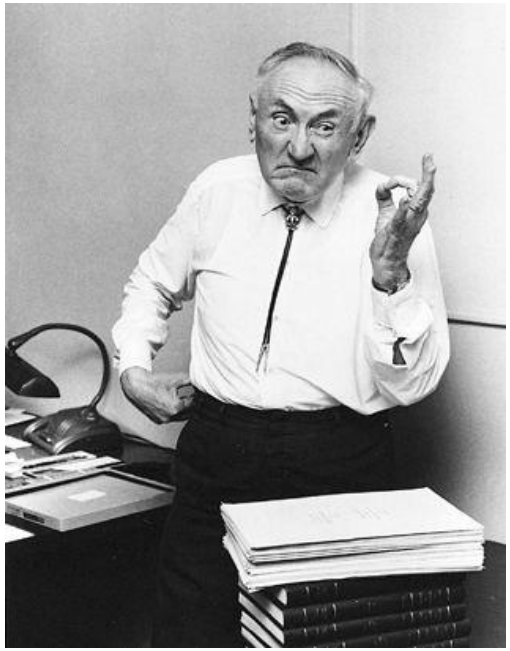
[by M. De Leo, Wikipedia (2025), based on Cobelli & Salucci, *Monthly Notices of the Royal Astronomical Society*. **311** (2): 441–447 (2000).]

Dark Matter – Coma Cluster

[Nielander, Wikipedia (2025)]

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.

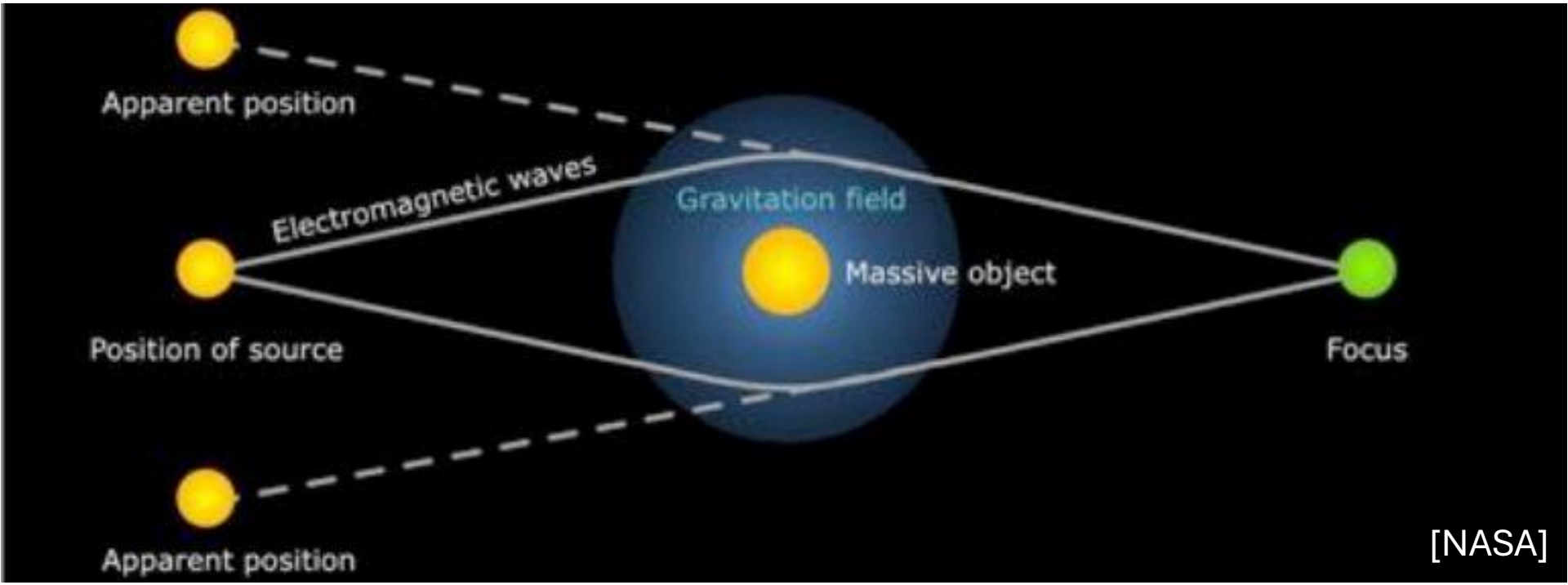


Fritz Zwicky 1898-1974

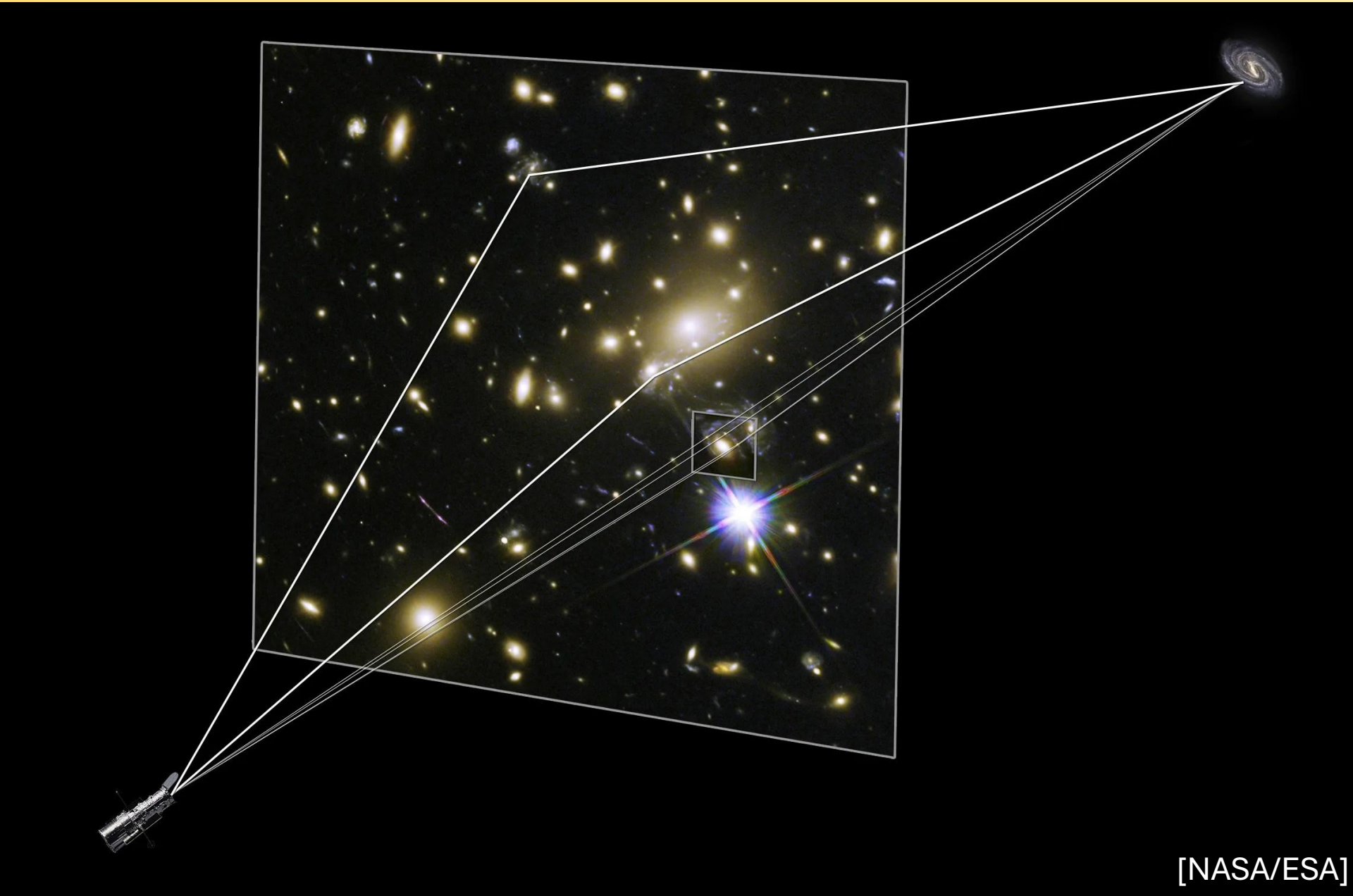
... <u>There are many other examples</u> of such galaxy clusters whose velocities cannot be explained by the luminous matter.

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



[NASA/ESA]

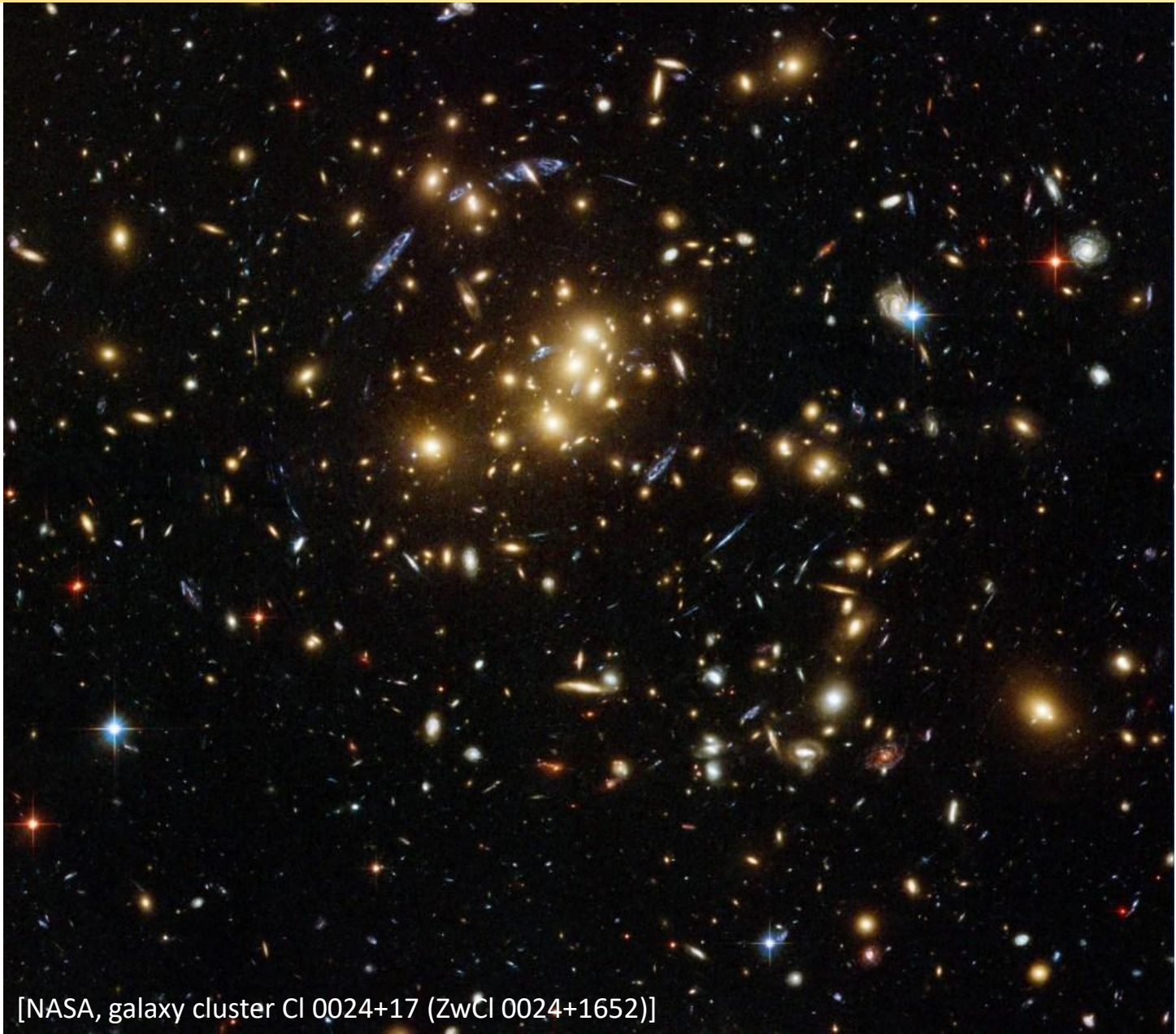
Gravitational Lensing -- Example

- 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”.

galaxy cluster SDSS J1038+4849

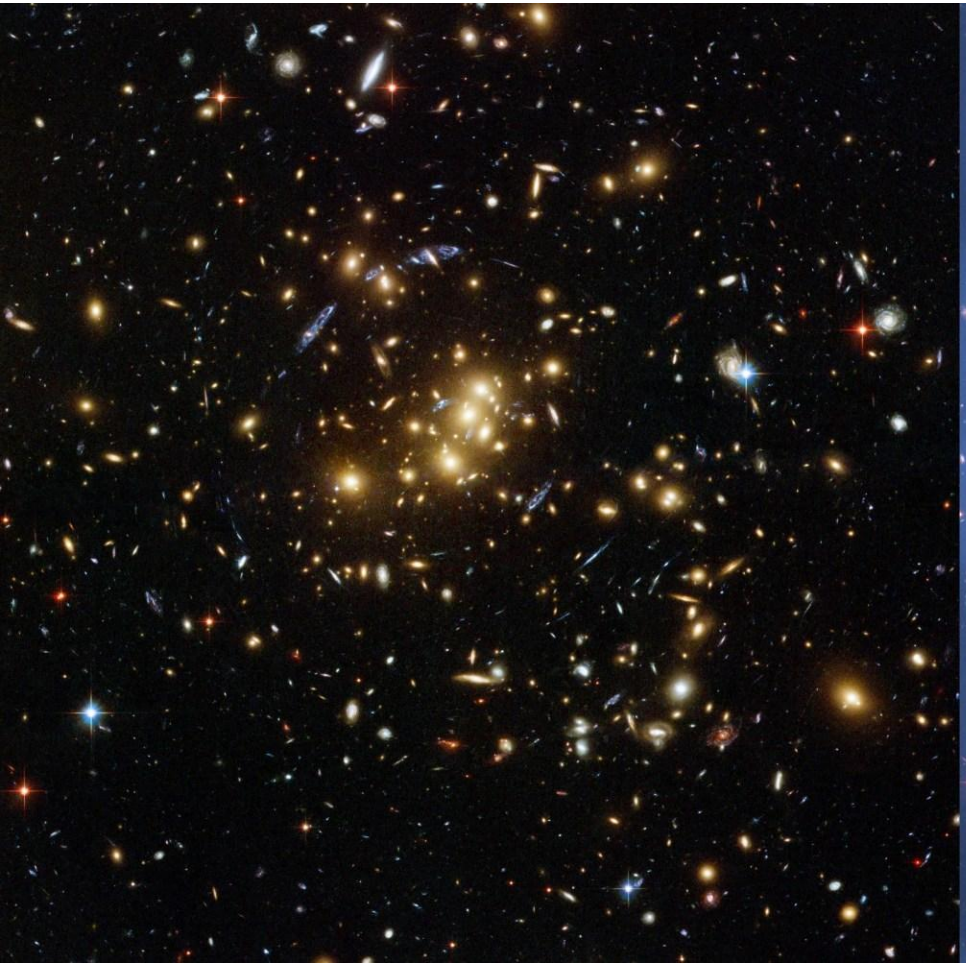
Dark Matter – Gravitational Lensing

Galaxy cluster shows gravitational lensing of multiple background galaxies.

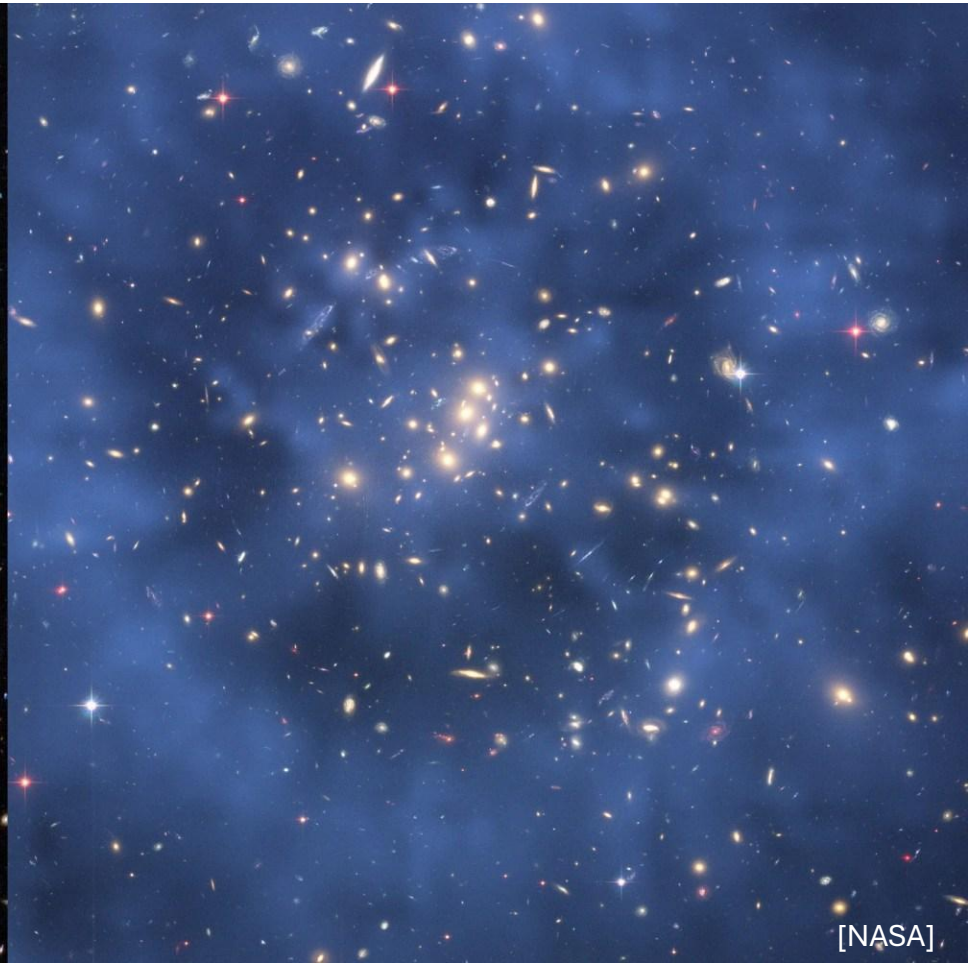


[NASA, galaxy cluster Cl 0024+17 (ZwCl 0024+1652)]

Dark Matter – Gravitational Lensing



original image



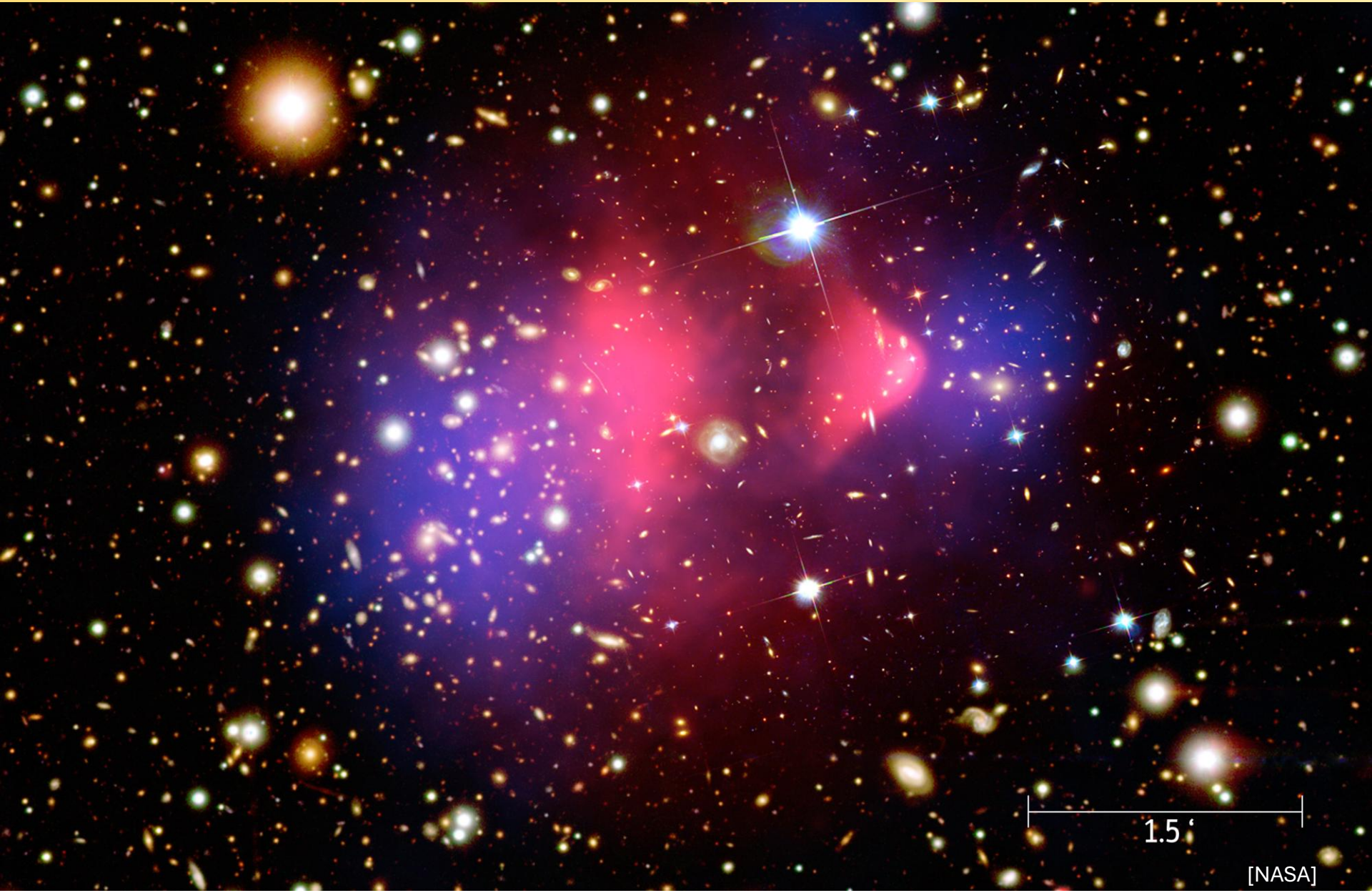
Dark matter distribution (blue haze) inferred from gravitational lensing.

Dark Matter – Pandora Cluster

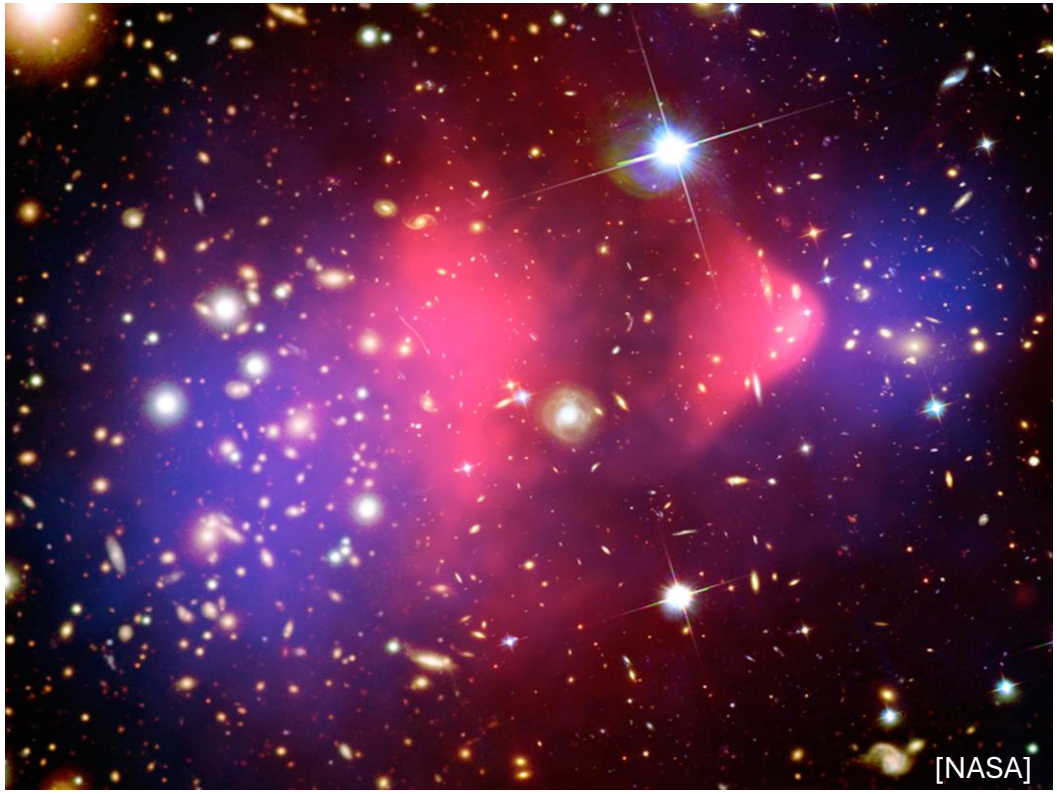
Red: X-ray data from Chandra Space Telescope.

Blue: Matter lensing map constructed from gravitational lensing data

Dark Matter – Bullet Cluster (colliding clusters)



Dark Matter – Bullet Cluster (colliding clusters)



- 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).

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

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?

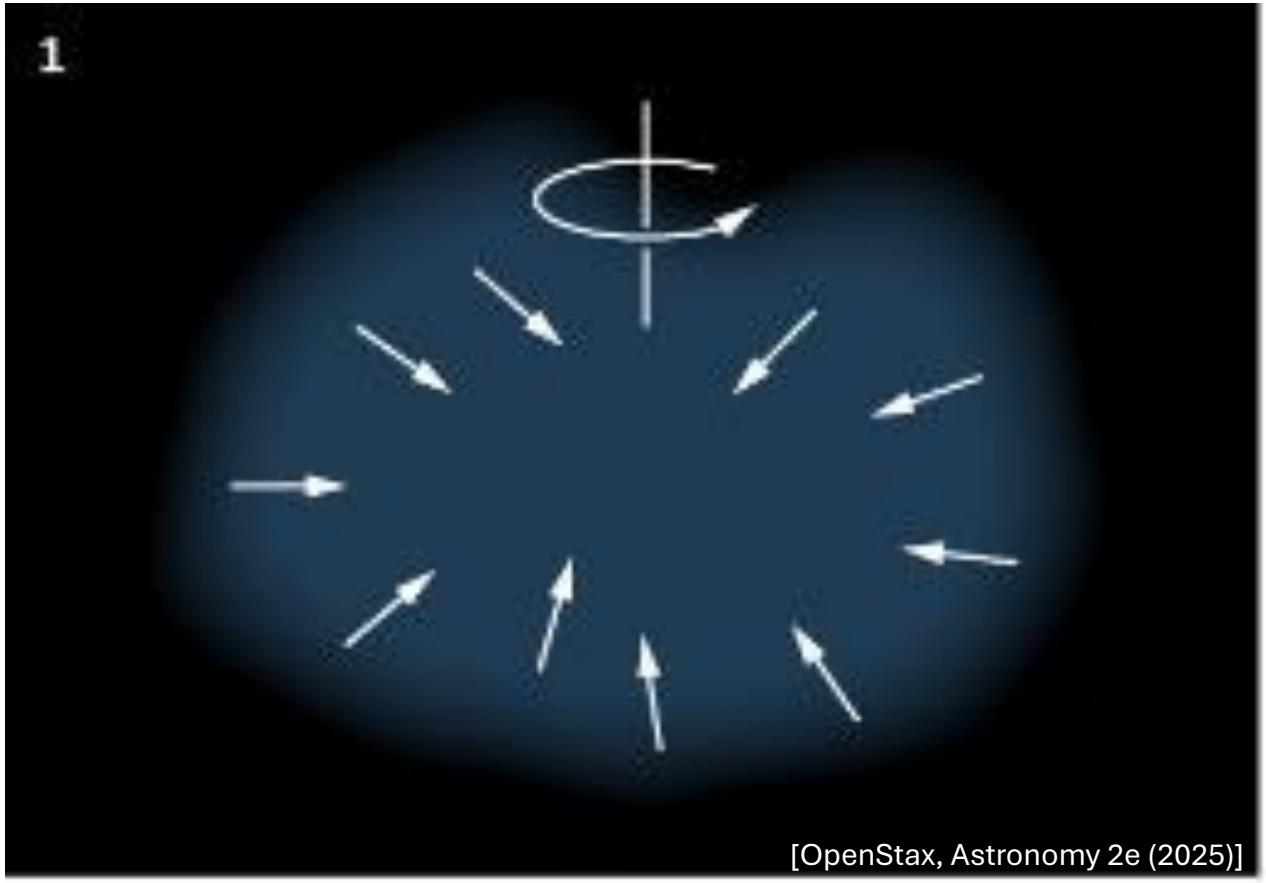
- After all, they don't interact via strong or electromagnetic interactions, only via weak interaction, and, presumably, gravity, because they have some (tiny) mass.
- **We don't think so:** in order for galaxies to form, dark matter must be **cold**, *i.e.,* it must be moving slowly (not near +) when 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!!

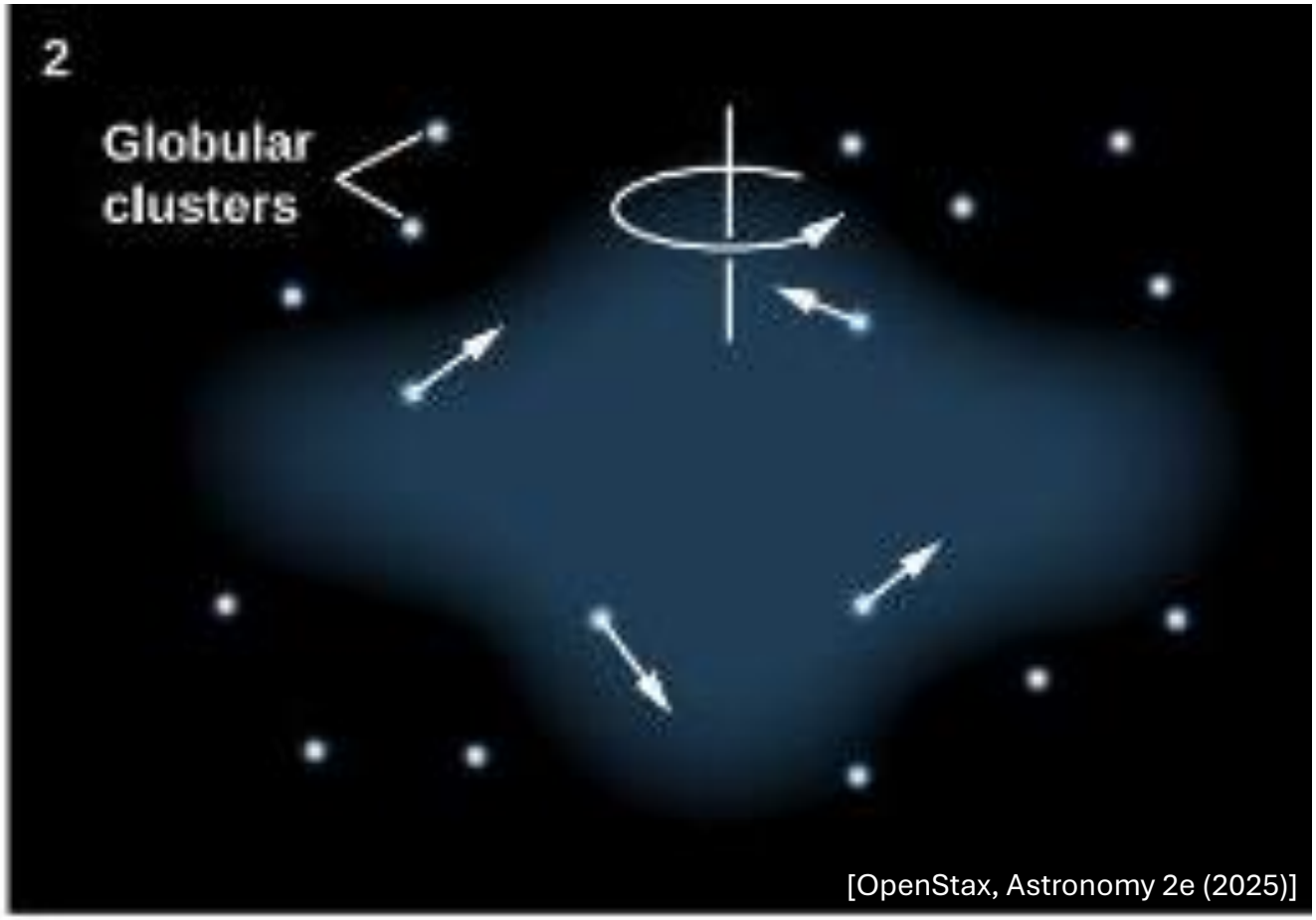
PollEv Quiz: PollEv.com/sethaubin

Monolithic Collapse Model: Galaxy formation



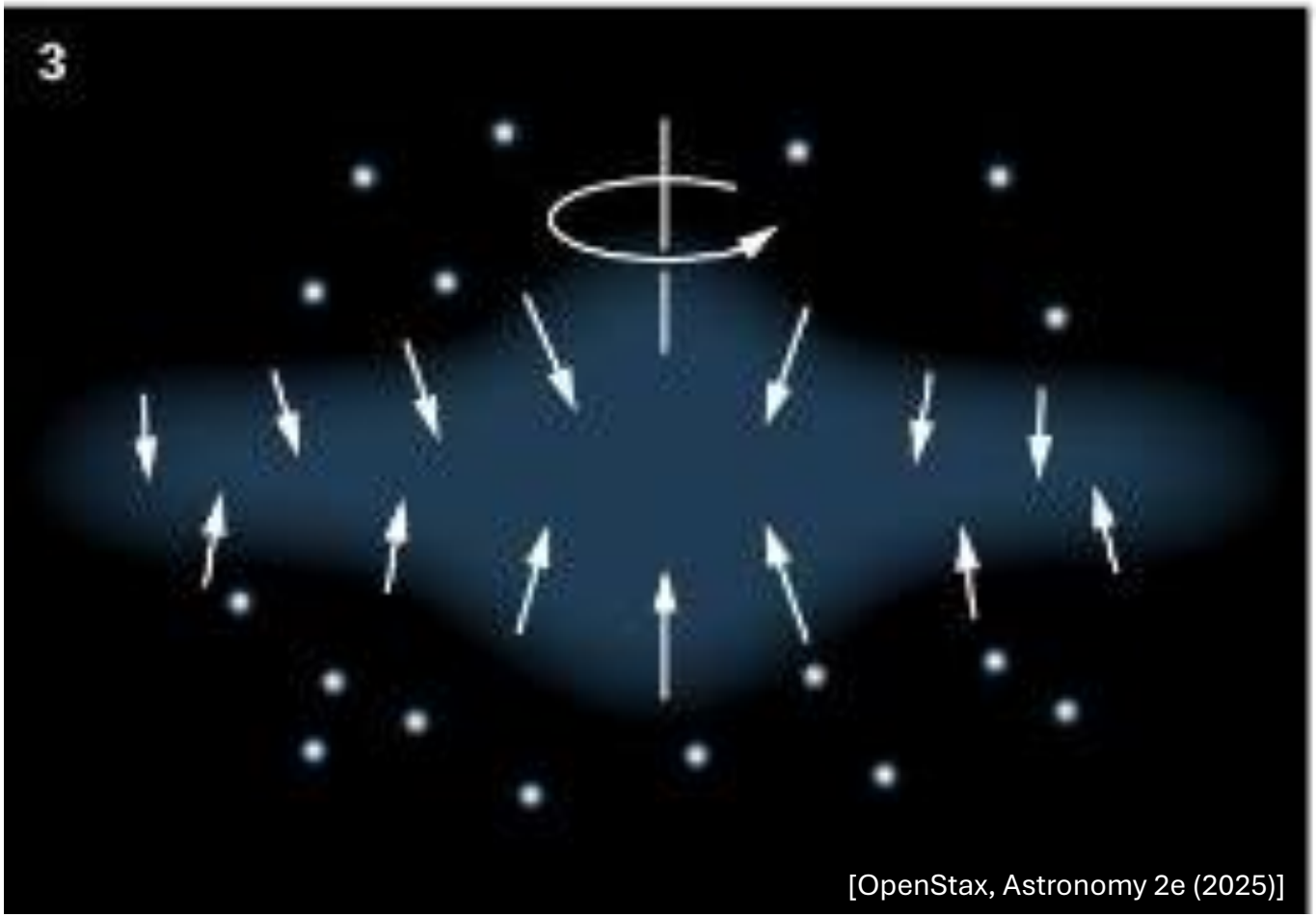
- An initial cloud of gas and dust collapses under its own gravity.
- As it collapses, its initial angular momentum is conserved, and the cloud rotates faster.

Monolithic Collapse Model: Galaxy formation



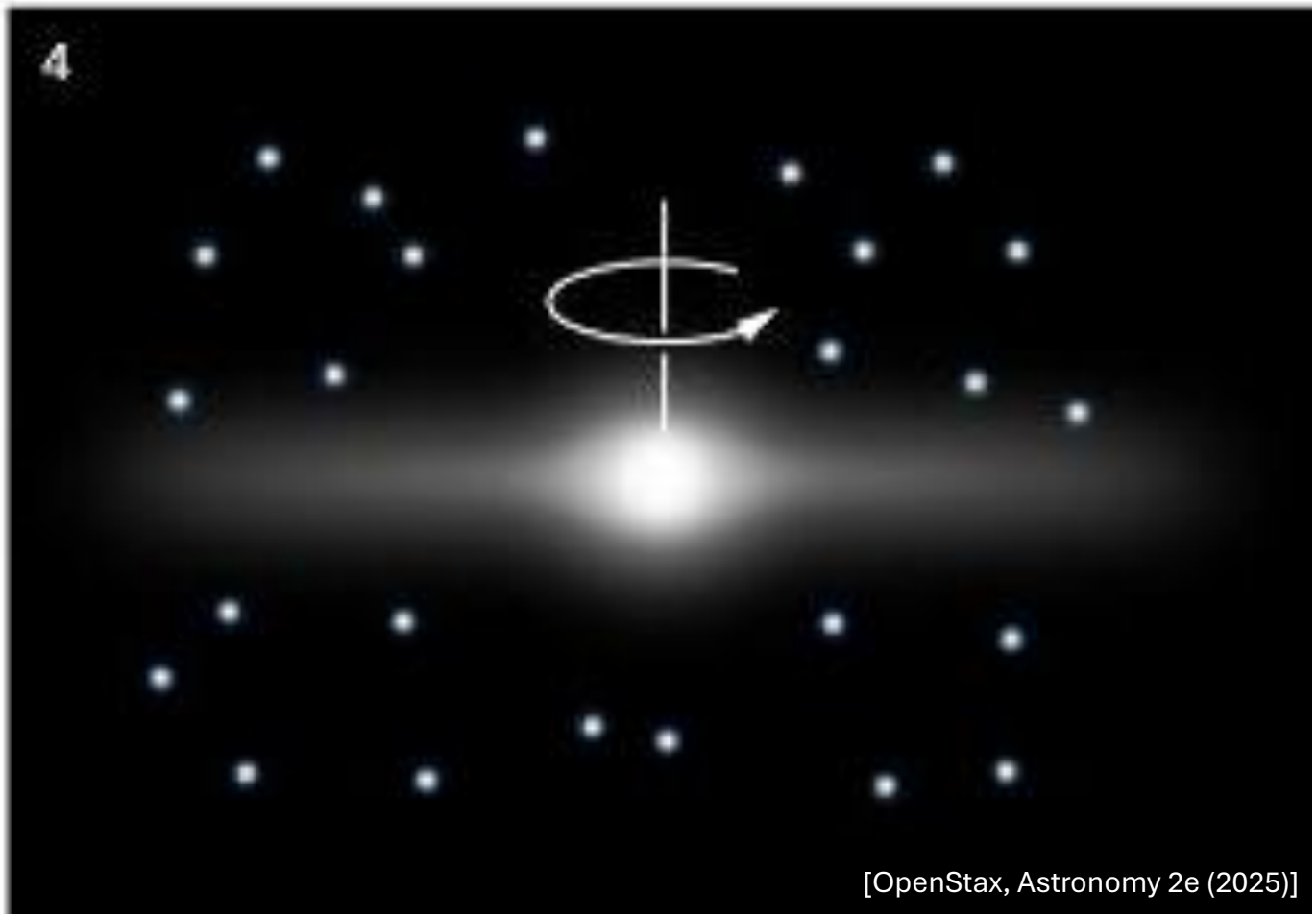
- The globular clusters were formed prior to collapse or were formed elsewhere.
- As it collapses, stars begin to form in regions of higher density.

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).