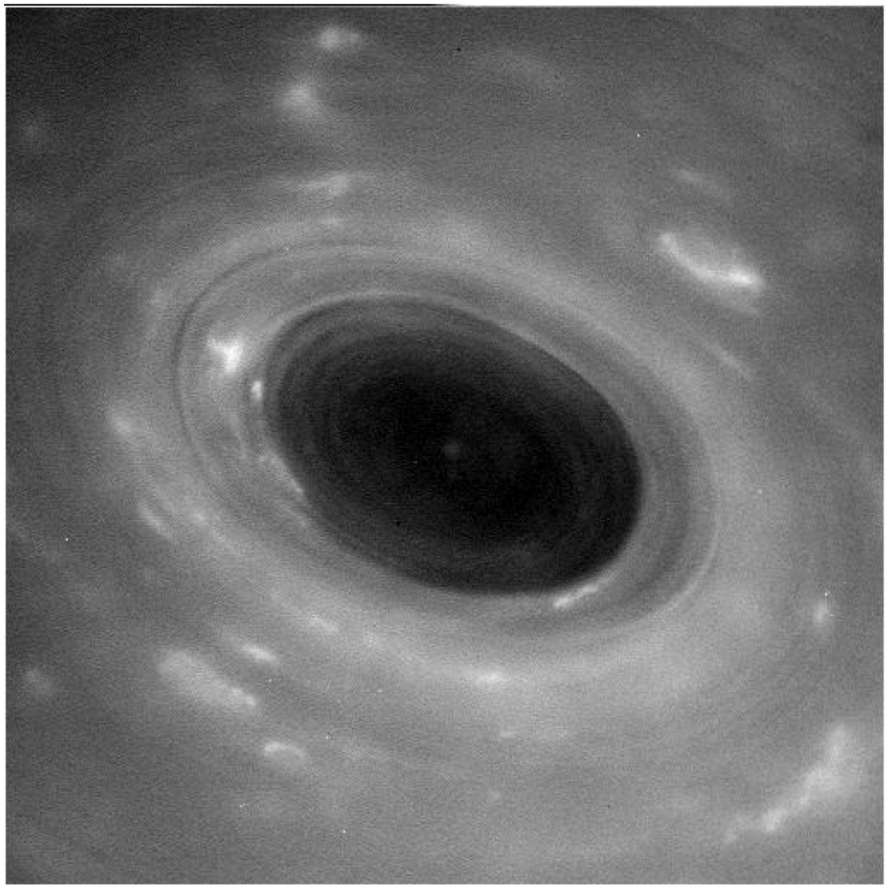
[25] The Case for Dark Matter (5/3/18)

Upcoming Items

1. Homework #6 due next class.
2. Read Ch. 23.3 for next class and do the self-study quizzes

Cassini Raw Image 4/27/17



LEARNING GOALS

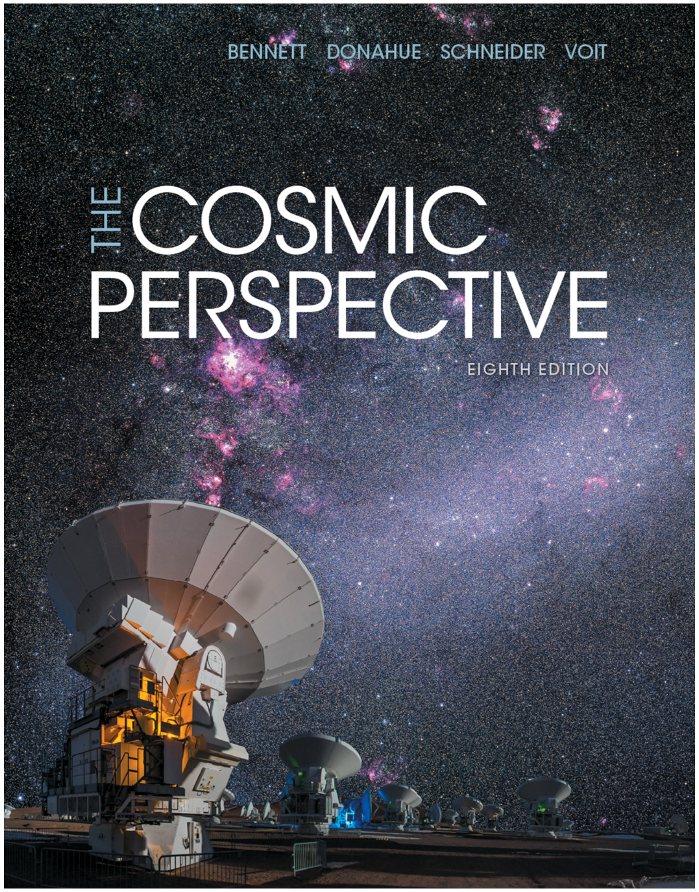
Ch. 23.1–23.2

For this class, you should be able to…

… *explain the various ways astronomers infer the presence of dark matter in galaxies and galaxy clusters;*

… *estimate the total mass of a galaxy or cluster using the orbital-speed law or other appropriate approximations;*

… *based on observations, explain how the properties of theoretical dark matter candidates can be constrained.*



Any astro questions?

The Case for Dark Matter

- The presence of dark matter is revealed in many ways:
  - Rotation curves of spiral galaxies (flat or rising beyond visible disk).
  - Velocity dispersion of ellipticals (faster stars ➔ hidden mass).
  - Motion of galaxies in clusters (faster galaxies ➔ hidden mass).
  - Temperature of intracluster gas (higher temp. ➔ hidden mass).
  - Gravitational lensing of background galaxies (distortion ⬄ mass).
- Simple estimates of total mass can be made by balancing gravitational forces or energy ($M \sim v^2 R/G$, or, in the case of gas, $M \sim k_B TR/Gm_H$).
- Dark matter candidates include unseen "normal" matter (but there are strong constraints on this) or mysterious "dark" matter (which is the favored option—why?).

Unseen Influences

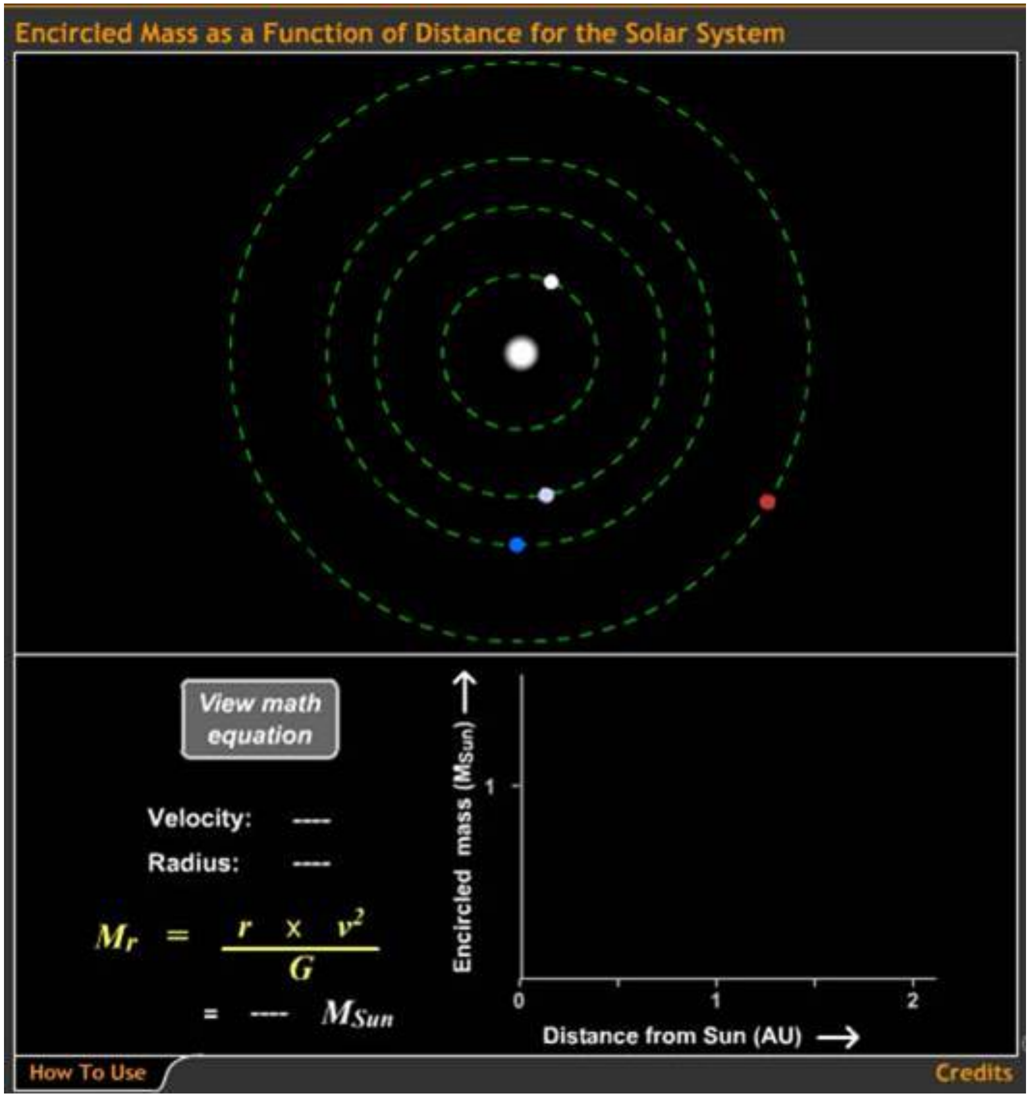
- ***Dark Matter:*** An undetected form of mass that emits little or no light, but whose existence we infer from its gravitational influence.

- ***Dark Energy:*** An unknown form of energy that seems to be the source of a repulsive force causing the expansion of the universe to accelerate. (Next week's lecture.)

Contents of Universe

- “Ordinary” matter: ~5%
  - Ordinary matter inside stars: ~0.5%
  - Ordinary matter outside stars: ~4.5%
- Dark matter: ~26%
- Dark energy: ~69%

Review: Rotation Curves

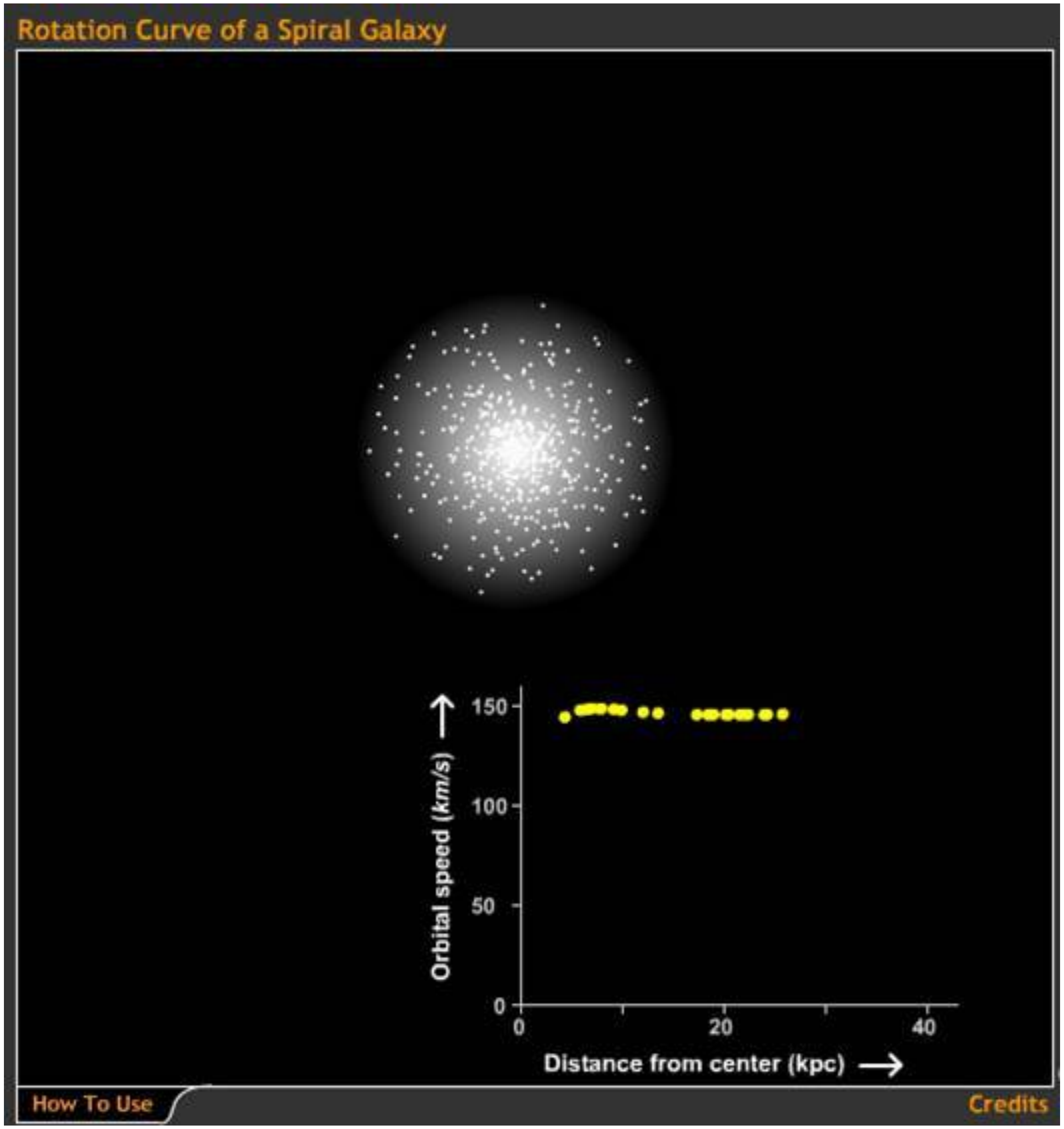


We measure the mass of the solar system using the orbits of planets:

- Orbital period.
- Average distance.

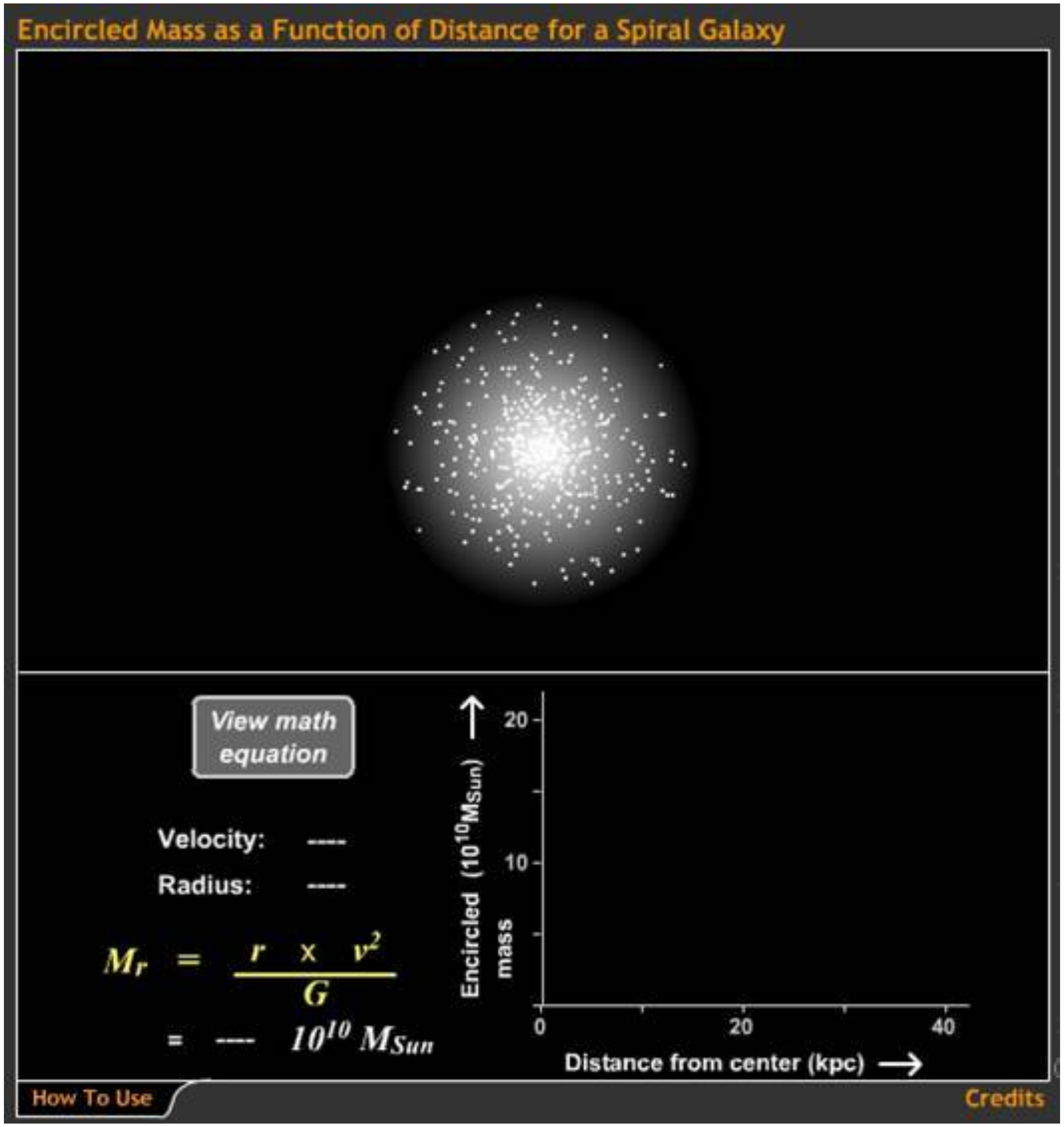
For circles:

- Orbital speed.
- Orbital radius.



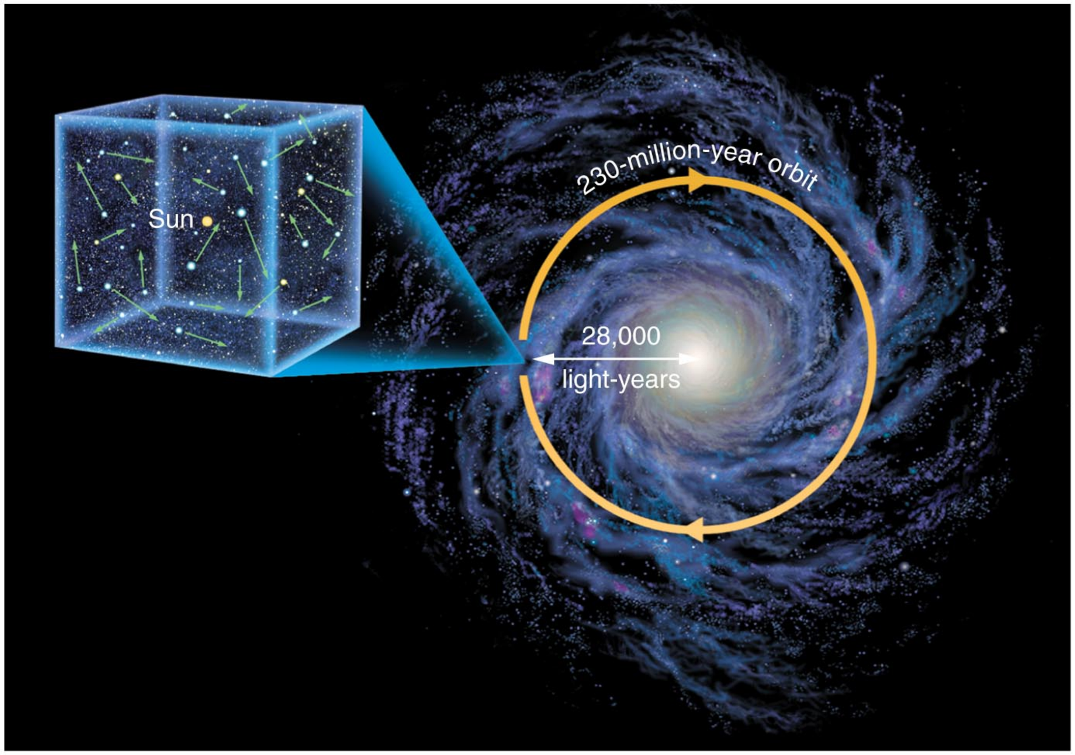
The rotation curve of the Milky Way stays flat with distance.

Mass must be more spread out than in the solar system.



Mass in the Milky Way is spread out over a larger region than its stars.

Most of the Milky Way's mass seems to be ***dark matter***!

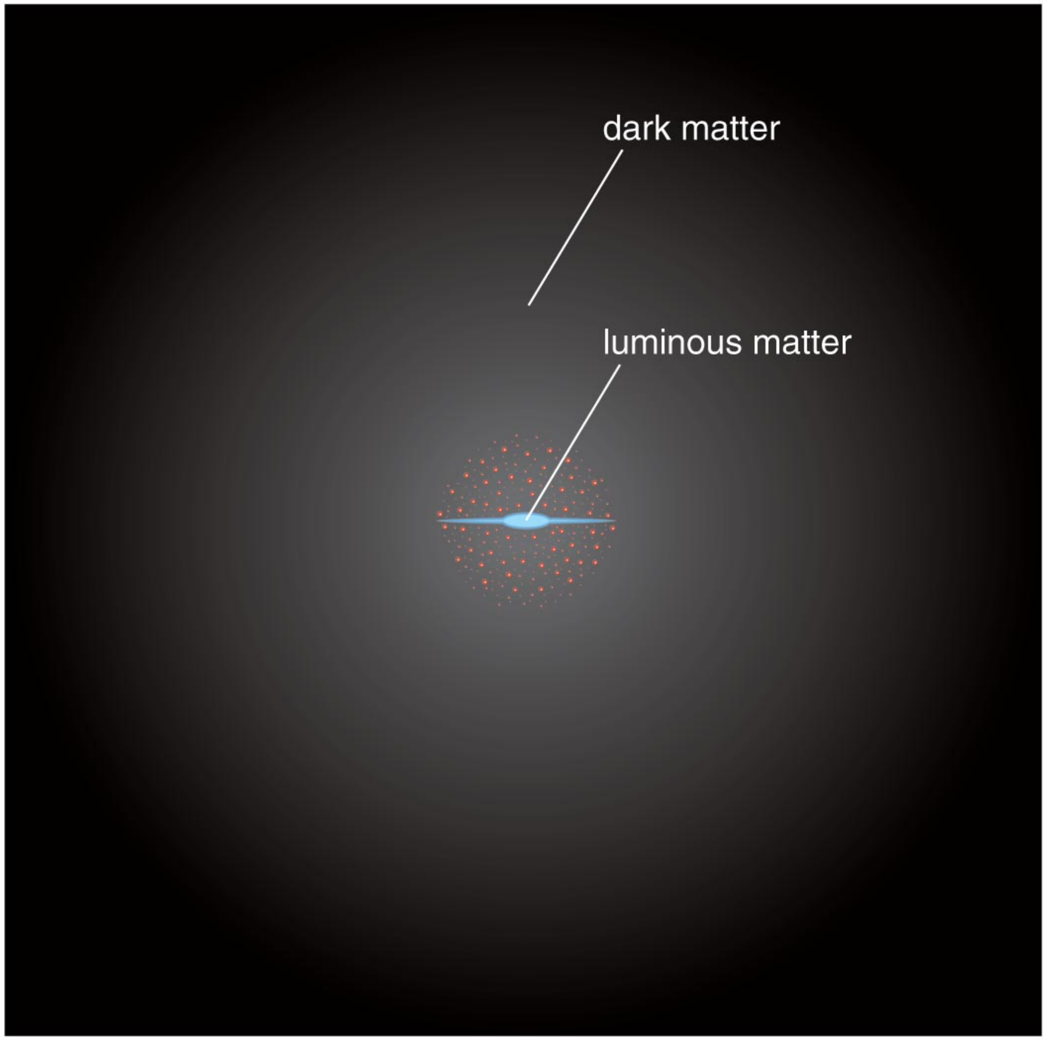


Mass within the Sun's orbit:

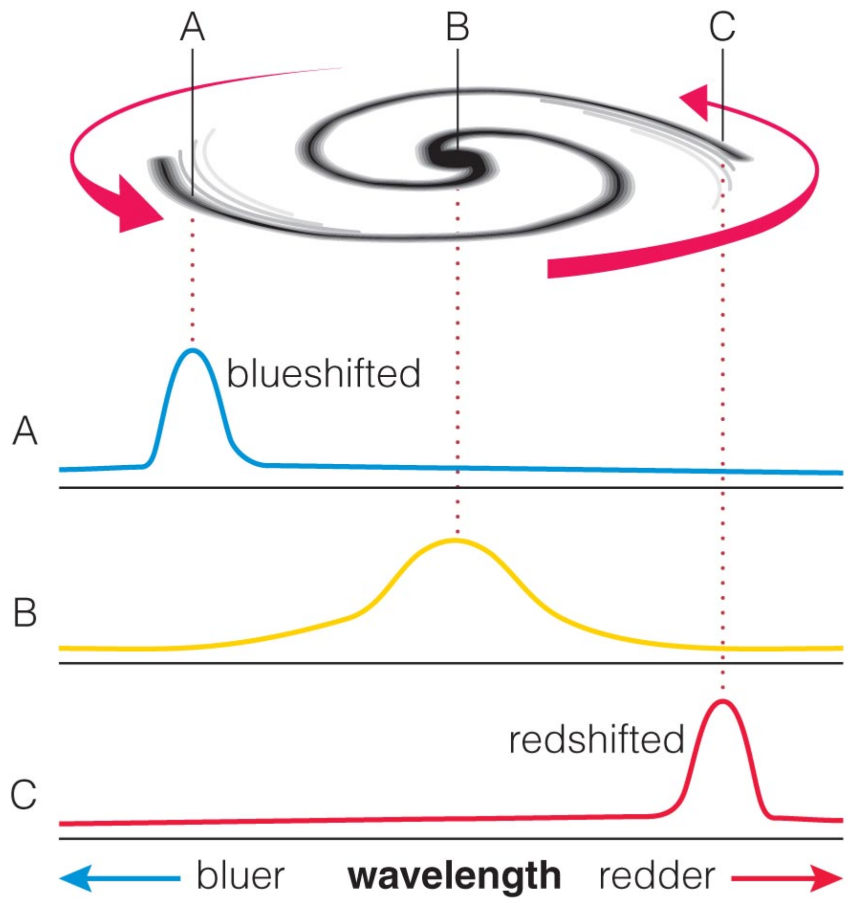
$$1.0 \times 10^{11}\ M_{\odot}.$$

Total mass:

$$\sim 10^{12}\ M_{\odot}.$$

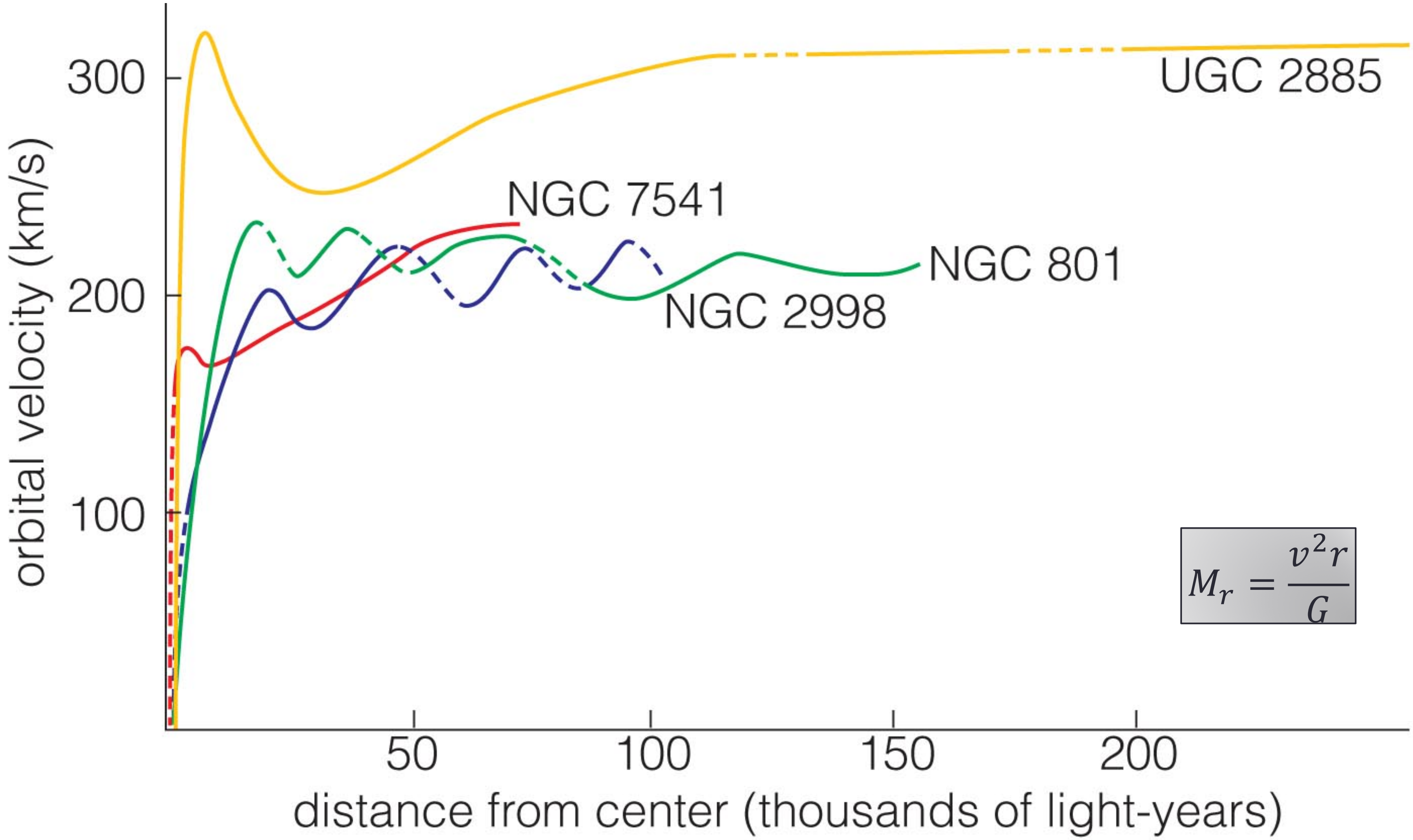


The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.



Recall: we can measure the rotation curves of other spiral galaxies using the Doppler shift of the 21-cm line of atomic hydrogen.

Vera Rubin (DTM/Carnegie)



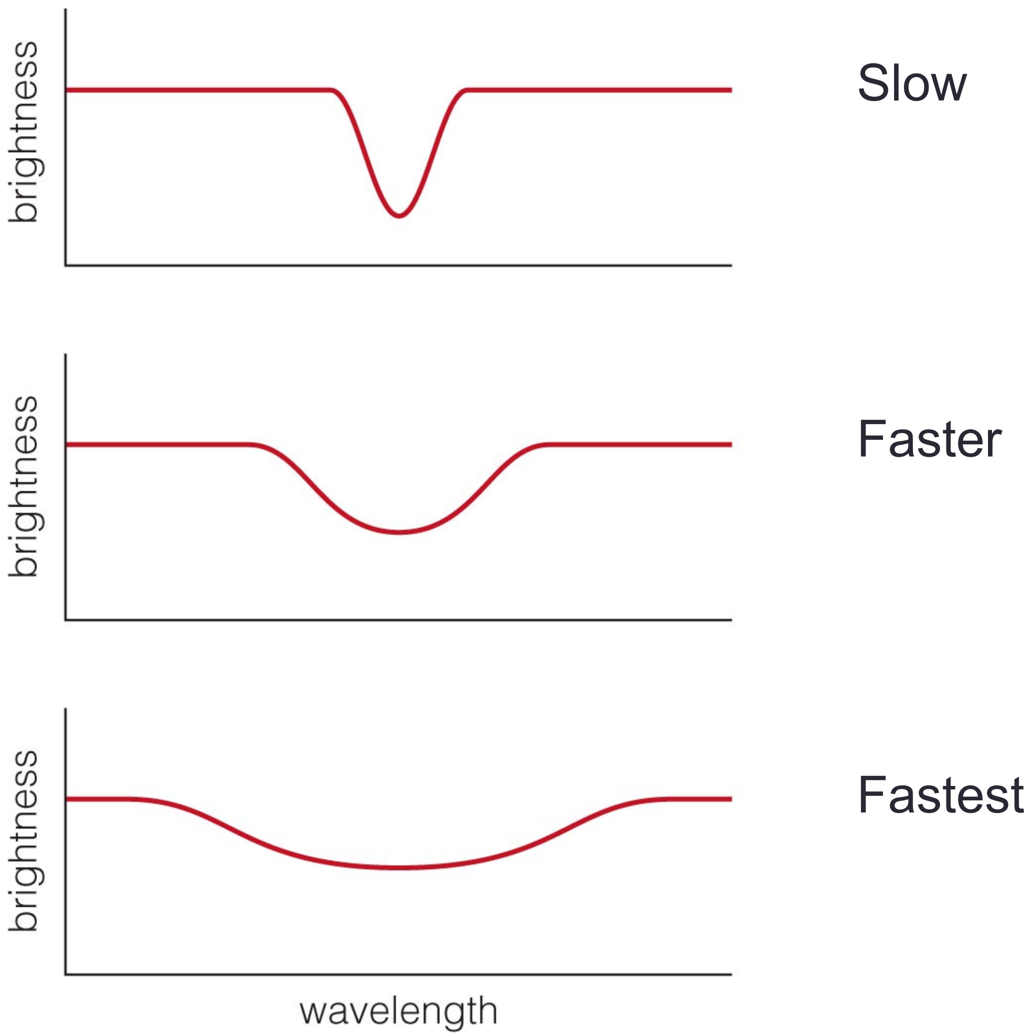
$$M_r = \frac{v^2 r}{G}$$

- Spiral galaxies all tend to have flat rotation curves, indicating large amounts of dark matter.

Details: Dark Matter Profiles

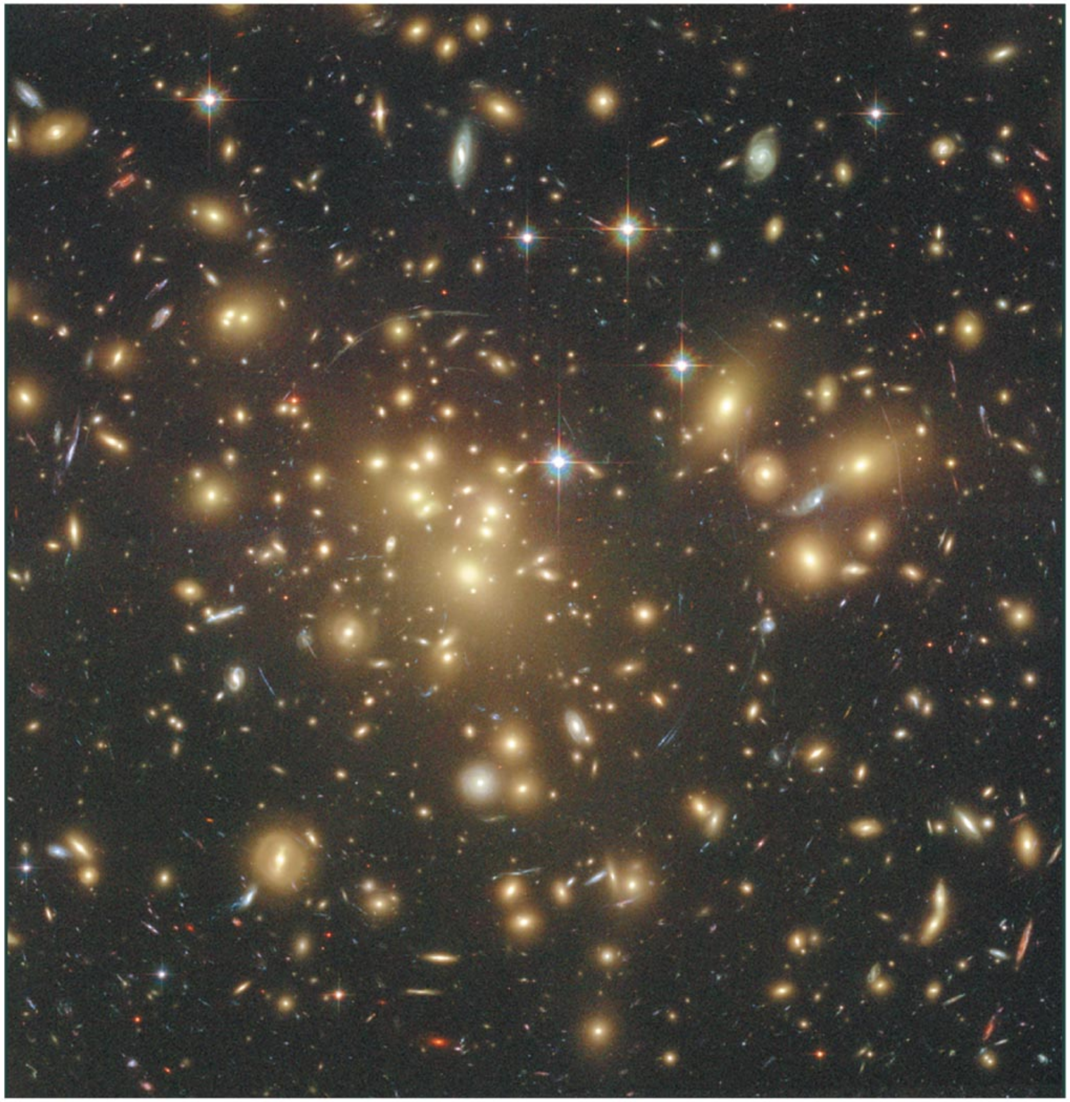
- If $M_r = v^2 r/G \propto r$ if v constant, how do we expect the dark matter density to behave far from the galactic center?
  - Recall density $\rho = 3M/4\pi r^3$, so $M \propto \rho r^3$.
  - Therefore predict $\rho(r) \propto 1/r^2$ far from the center, if v constant.
  - Might expect “cuspy” inner profile (as $r \rightarrow 0$).
- In classic “cold dark matter” N-body simulations, find cuspy profile, but this is *not* seen in actual observations.
  - Supernovae from massive stars, or AGN feedback, may prevent formation of cuspy centers.

Elliptical galaxies have dark matter too…



Broadening of spectral lines in elliptical galaxies tells us how fast the stars move (expect $M_{tot} = \langle v^2 \rangle R/G$, where R is observed radius of galaxy and $\langle v^2 \rangle$ is the stars' mean square speed).

These galaxies also have dark matter.



We can estimate the speeds of galaxies in a cluster from their Doppler shifts: $M_{\mathrm{tot}} = v^2 R/G$, where R is the cluster radius and v is the mean galaxy speed.

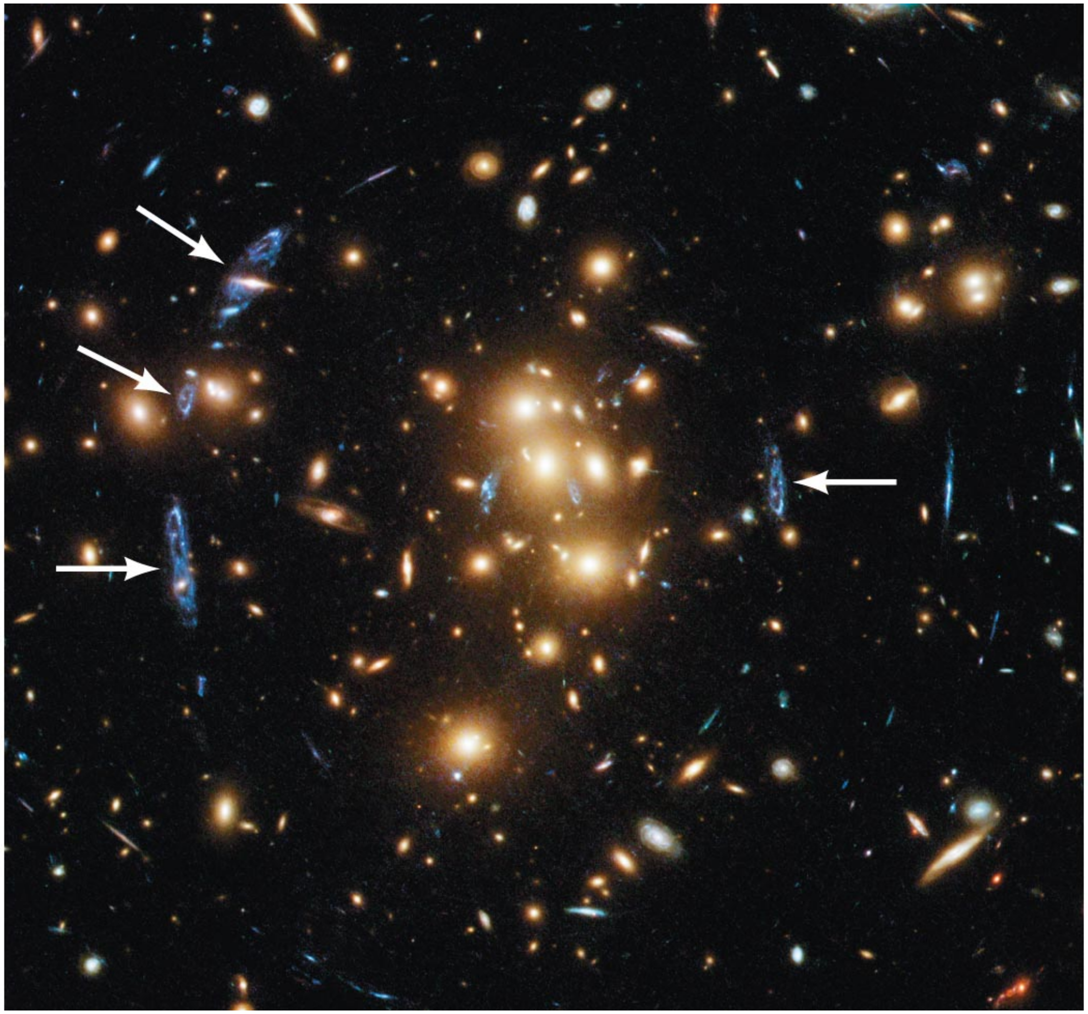
The mass found from galaxy motions in a cluster is about ***50 times*** larger than the mass in stars!

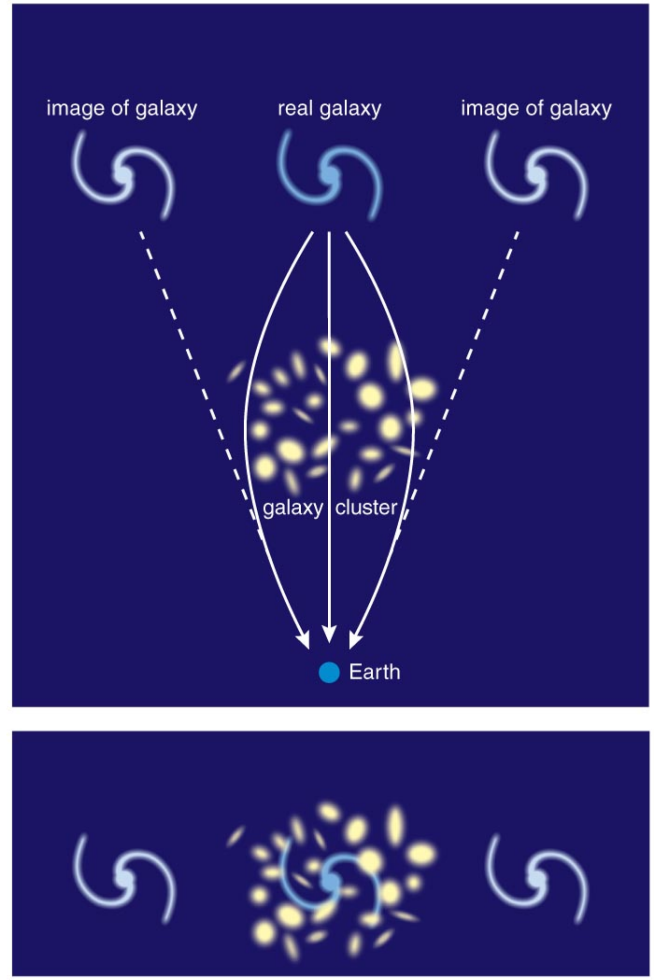
$T \sim GMm_H / k_B R$

Clusters contain large amounts of hot X ray-emitting gas.

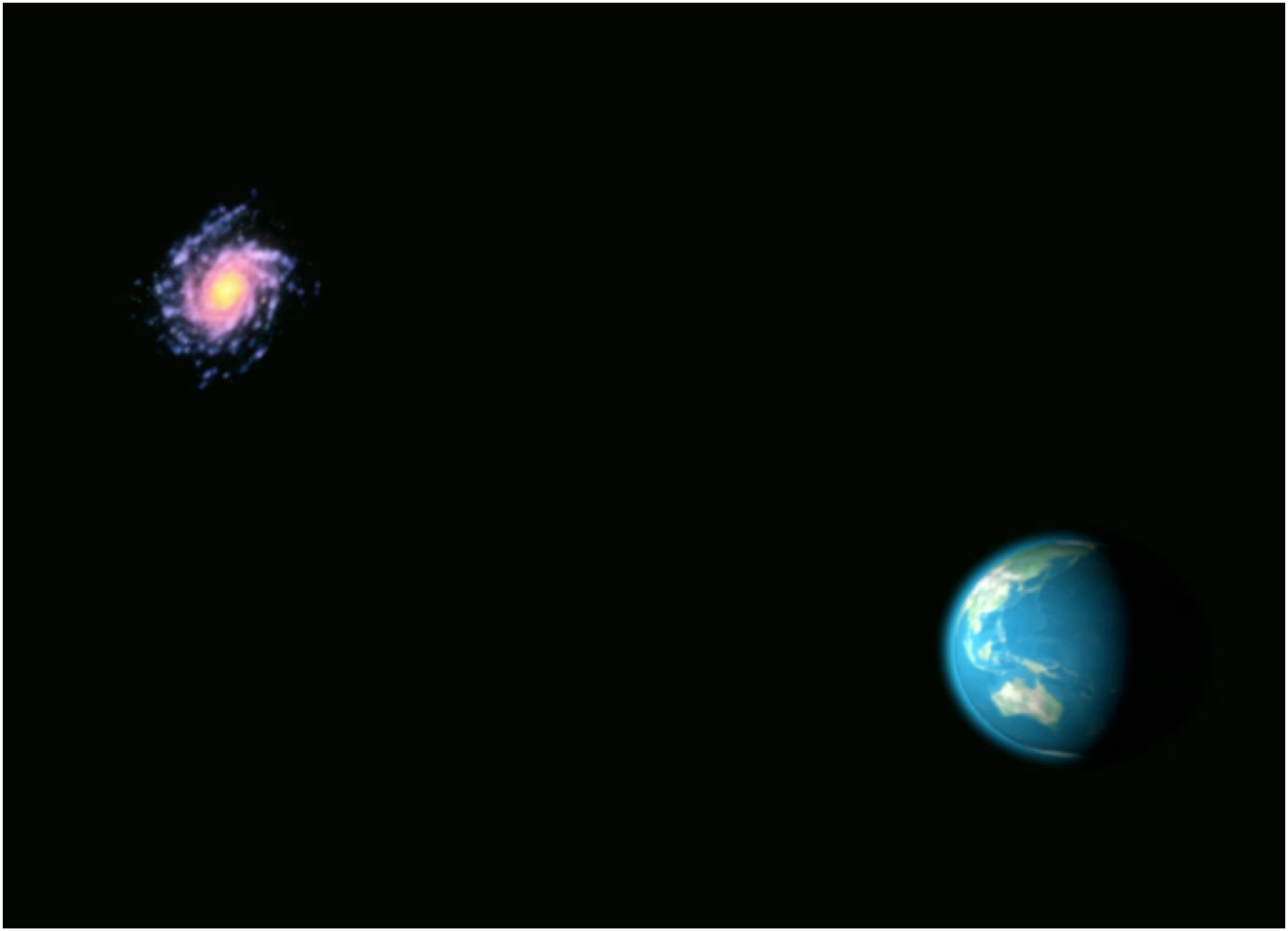
Temperature of hot gas (particle motions) tells us cluster mass:

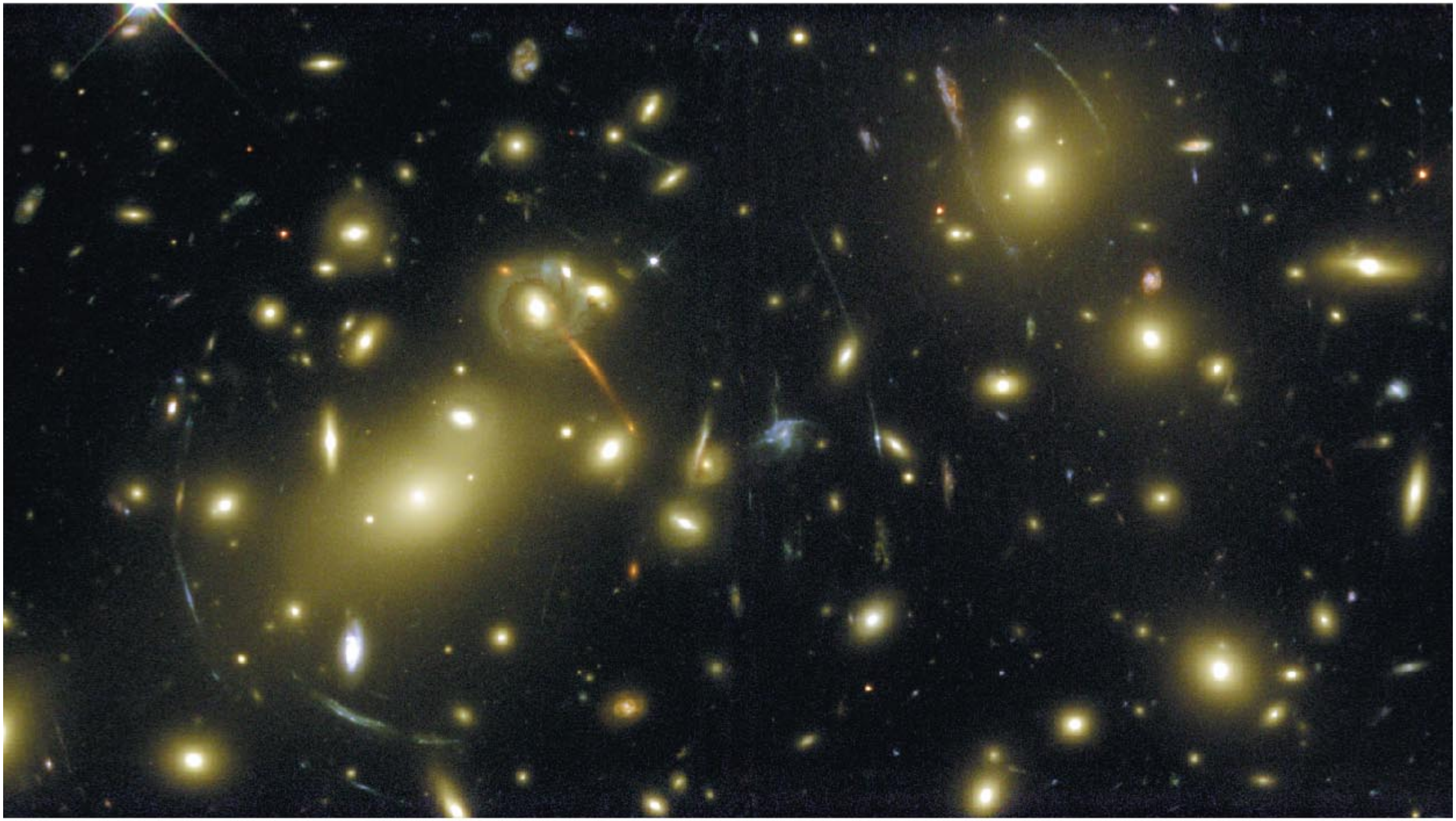
- 85% dark matter.
- 13% hot gas.
- 2% stars.





Gravitational lensing, the bending of light rays by gravity, can also tell us a cluster's mass.





All three methods of measuring cluster mass find similar amounts of dark matter in galaxy clusters.

Details: Gravitational Lensing

- In the weak-gravity limit, can treat intervening mass as a "thin lens" from optics. In the Schwarzschild metric, for an impact parameter (miss distance) b, bending angle α is

$$\alpha = \frac{4GM}{c^2 b} = \frac{2R_S}{b}.$$

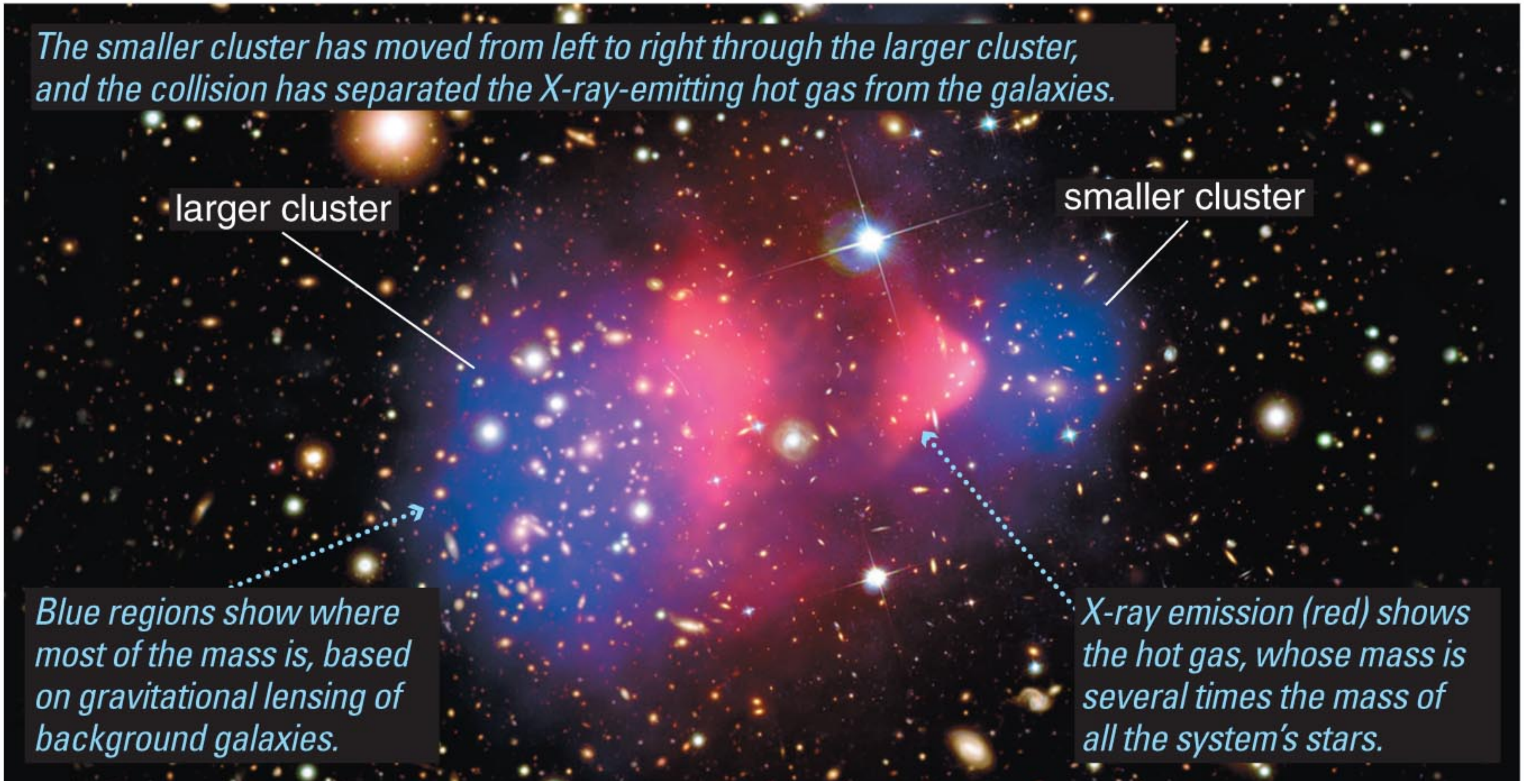
- E.g., for starlight near the Sun's limb, $b \approx R_\odot = 7\times 10^8$ m; since $R_S \sim 3$ km, we get $\alpha \approx 1.8$ arcsec.
  - This was confirmed in 1919 during a total solar eclipse.
  - First experimental confirmation of GR—made Einstein a celebrity!

Dark Matter: Our Options

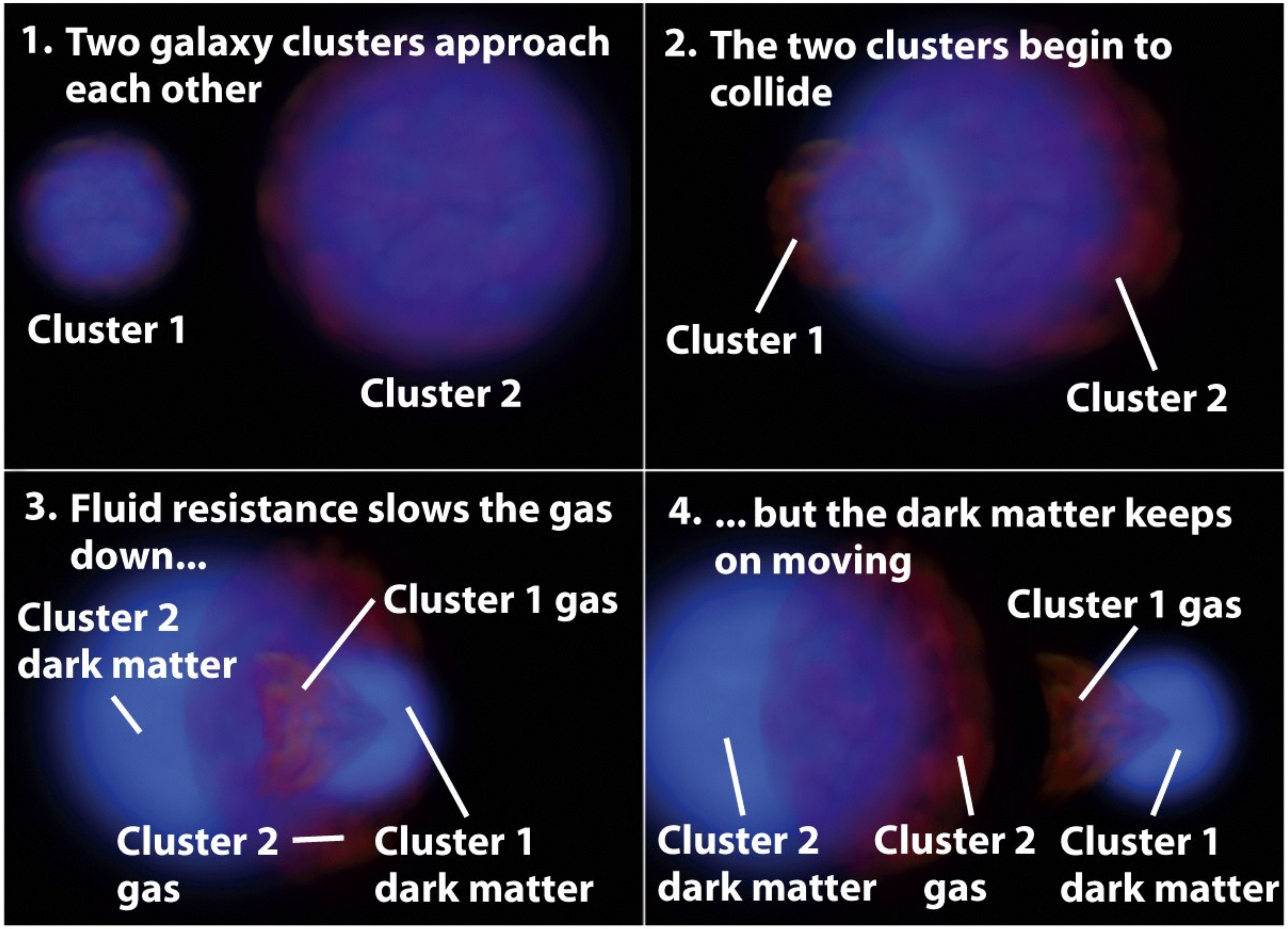
1. Dark matter really exists, and we are observing the effects of its gravitational attraction.

2. Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter.
   - E.g., “MoND”: Modified Newtonian Dynamics.

Because gravity is so well tested, and #1 fits most of the data from galaxies to the CMB, that is the option chosen by most astronomers.



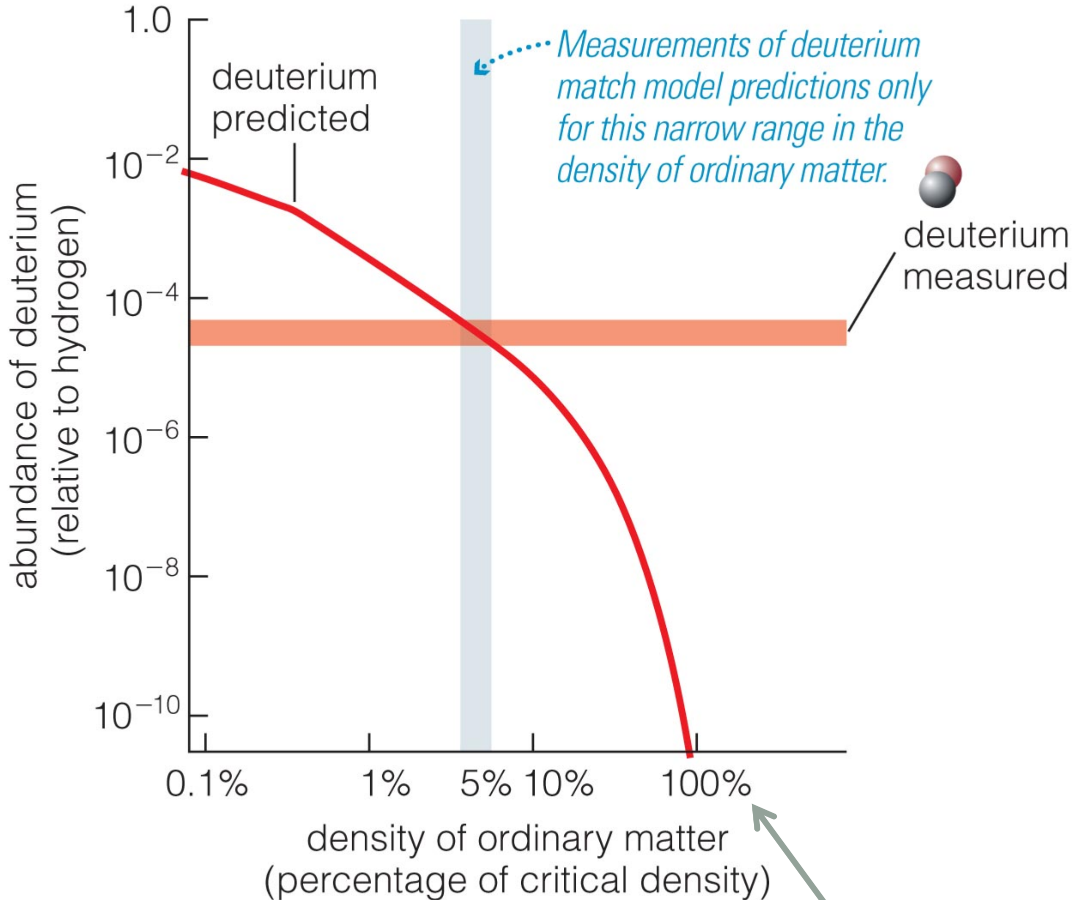
Some observations of the universe are very difficult to explain without dark matter.



A model of how the gas and dark matter in 1E0657-56 could have become separated

Could DM be Ordinary Matter?

- Lots of things in the universe don't emit much light
- Planets and asteroids
- White dwarfs
- Neutron stars



- Measurements of light element abundances indicate that ordinary matter cannot account for more than a small fraction of the dark matter.

Higher matter density uses up more deuterium early on.

What is Dark Matter? Two Basic Options.

1. Primordial black holes
   - Formed before the era of Big Bang nucleosynthesis, these would not interfere with light element abundances

2. Extraordinary dark matter (e.g., WIMPs).
   - Can't be anything we've detected in accelerators! Would have to be pretty stable, otherwise would decay into something else. Also has to have enough mass. Rules out everything!
   - Weakly Interacting Massive Particles: postulated but not yet detected neutrino-like particles. Limits are getting tight...

The best bet???