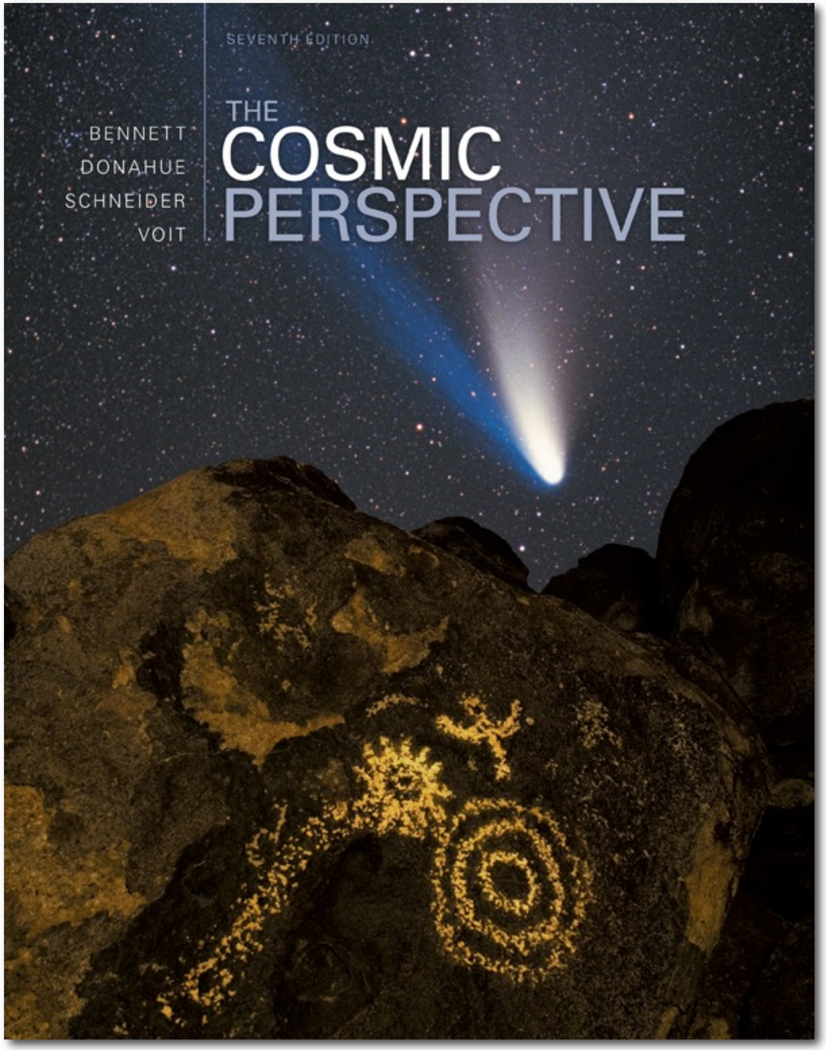
The Cosmic Perspective

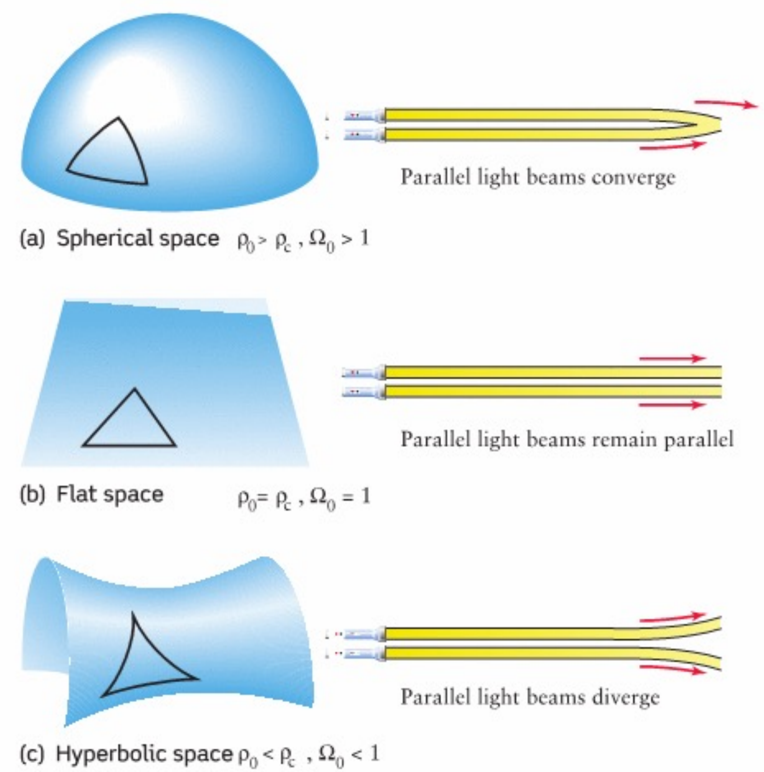
Seventh Edition



Dark Matter, Dark Energy, and the Fate of the Universe

Curvature of the Universe

The total density ρ_0 of the Universe compared to the critical ρ_c density determines the geometry of our Universe.



$$\rho_c = \frac{3H_0^2}{8\pi G}$$

ρ_c = critical density of the Universe

For $H_0 = 68$ km/s/Mpc $\rho_c = 1.0 \times 10^{-26}$ kg/m^3

Curvature of the Universe

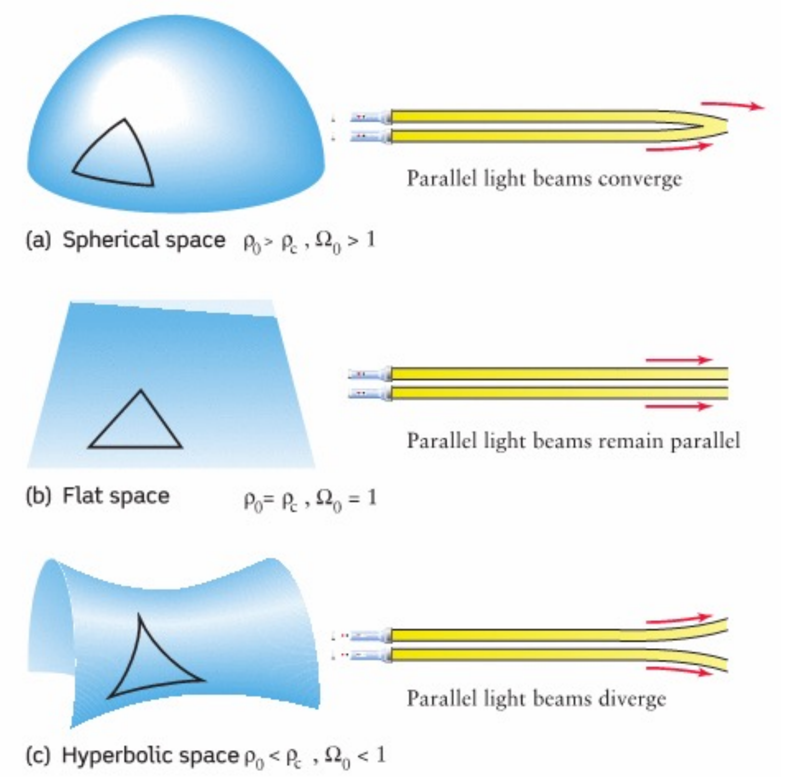
The **Density Parameter of the Universe Ω_0** is defined as the ratio of the combined mass density ρ_0 to the critical mass density ρ_c:

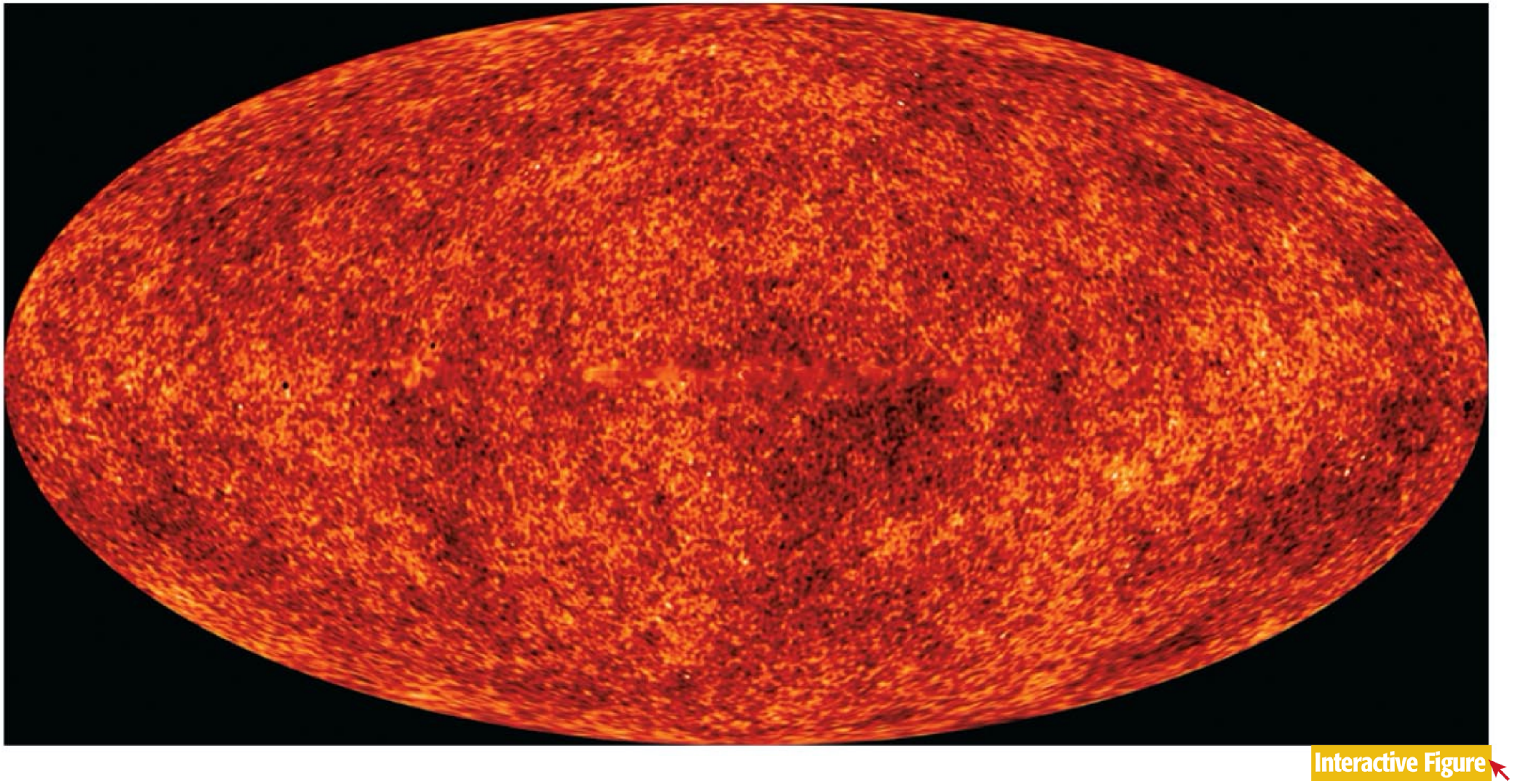
$\Omega_0 = \rho_0/\rho_c$

Closed Universe: $\rho_0 > \rho_c \rightarrow \Omega_0 > 1$

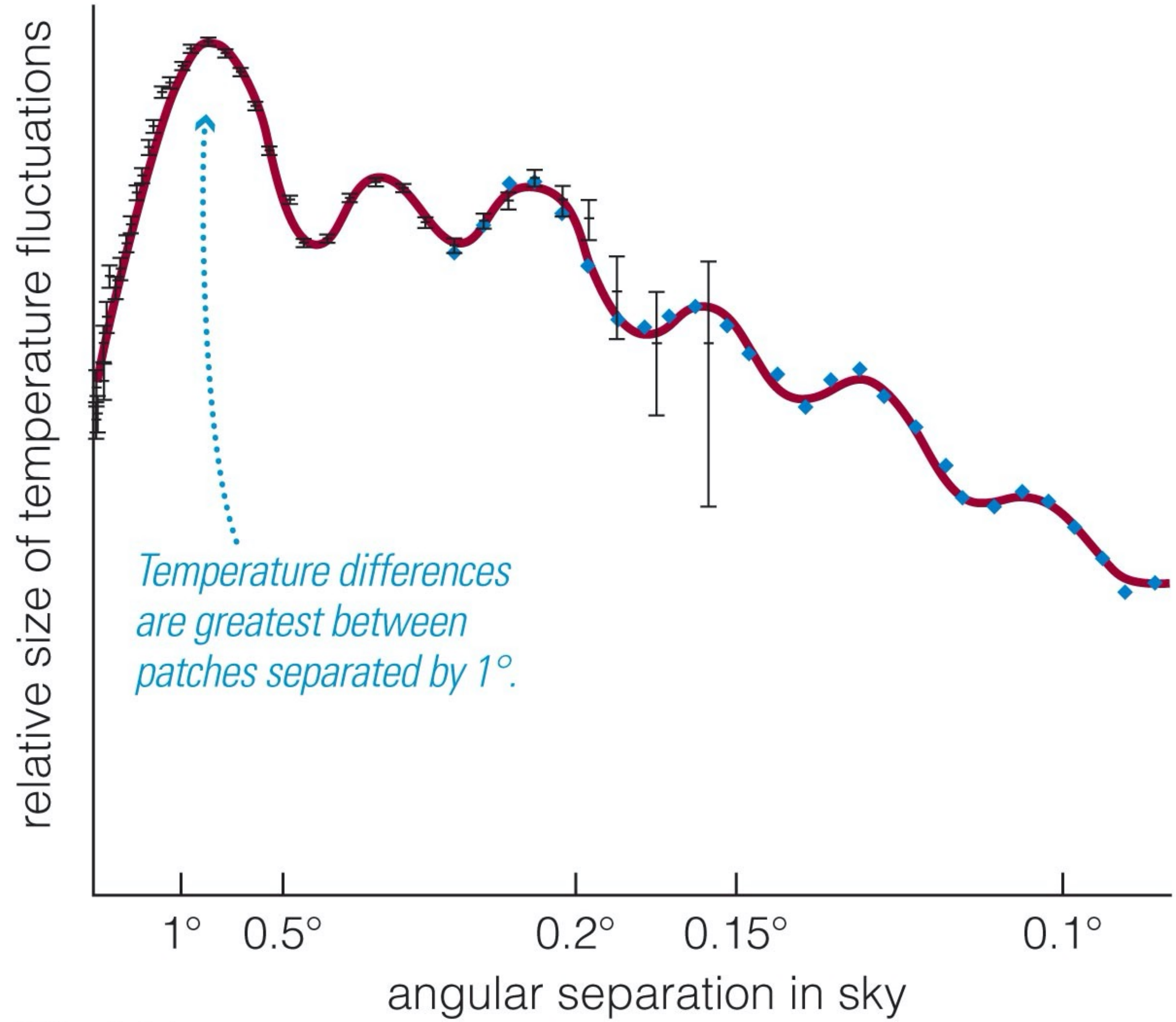
Flat Universe: $\rho_0 = \rho_c \rightarrow \Omega_0 = 1$

Open Universe: $\rho_0 < \rho_c \rightarrow \Omega_0 < 1$



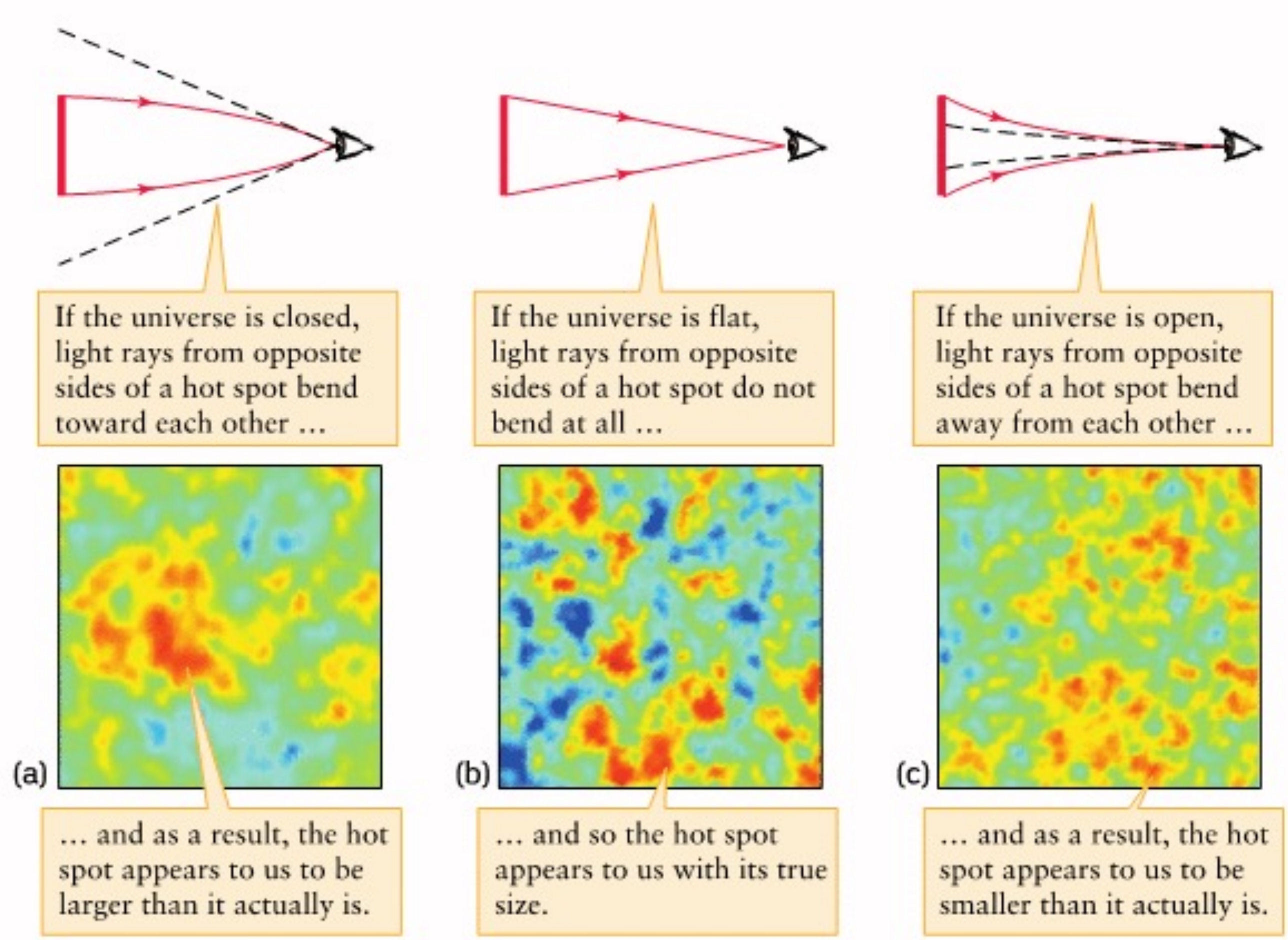


- WMAP gives us detailed baby pictures of structure in the universe.



- Most "hot spots" have a size of about 1° .

Measuring the Curvature of the Universe



The method relies on finding a distant object with a known size and estimating how its angular size would appear in an open, flat and closed Universe. This can be done by looking at hot spots in the CMB. For a flat Universe the angular size of a hot spot is expected to be about 1° and that's what we find!

Dark Energy

The total Density Parameter: $\Omega_0 = \rho_0/\rho_c = 1$ **(we know from CMB hot spots)**

Matter Density Parameter : $\Omega_m = \rho_m/\rho_c = 2.4 \times 10^{-27}/1 \times 10^{-26} = 0.31$
(we know from the observed masses of galaxies and clusters)

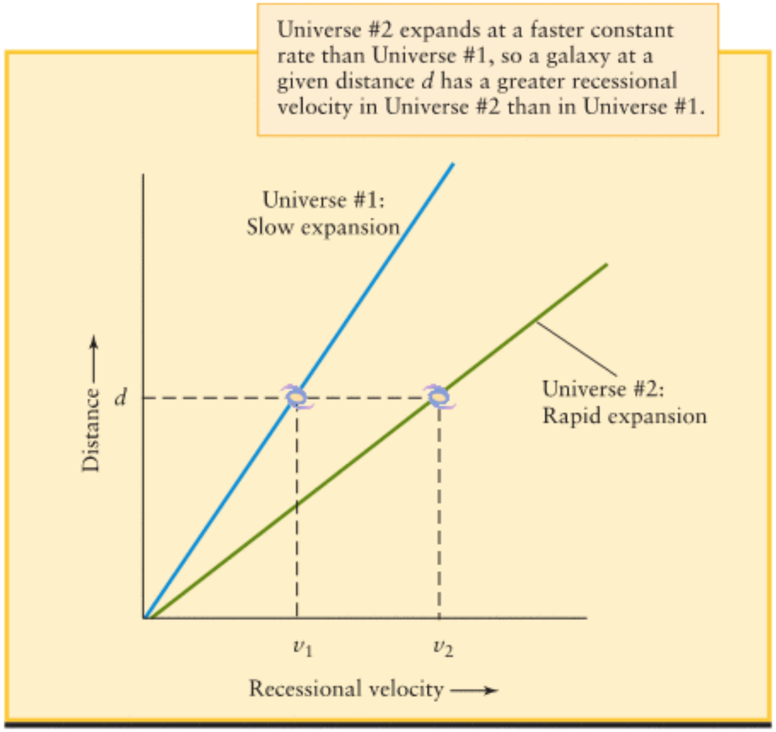
By taking into account all the mass (visible and dark) and radiation in the Universe we obtain a matter Density Parameter of 0.31.
This means that there must be some additional energy source in the Universe to make up for a density parameter equal to 1. This mysterious energy source is called Dark Energy. With this dark energy we associate an average mass density of dark energy of ρ_Λ and a dark energy density parameter Ω_Λ.

Dark Energy Density Parameter: $\Omega_\Lambda = \rho_\Lambda/\rho_c$

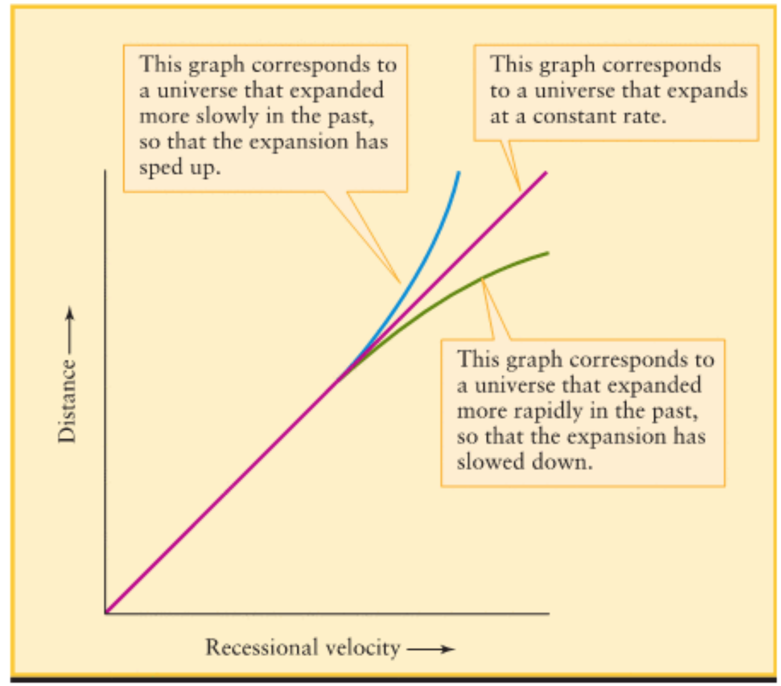
$$\Omega_0 = \Omega_m + \Omega_\Lambda = 1 \text{ (from CMB hot spots)}$$

This implies that the dark energy density parameter is $\Omega_\Lambda = 0.69$ (Planck 2015)

Does The Expansion Rate Change With Time?

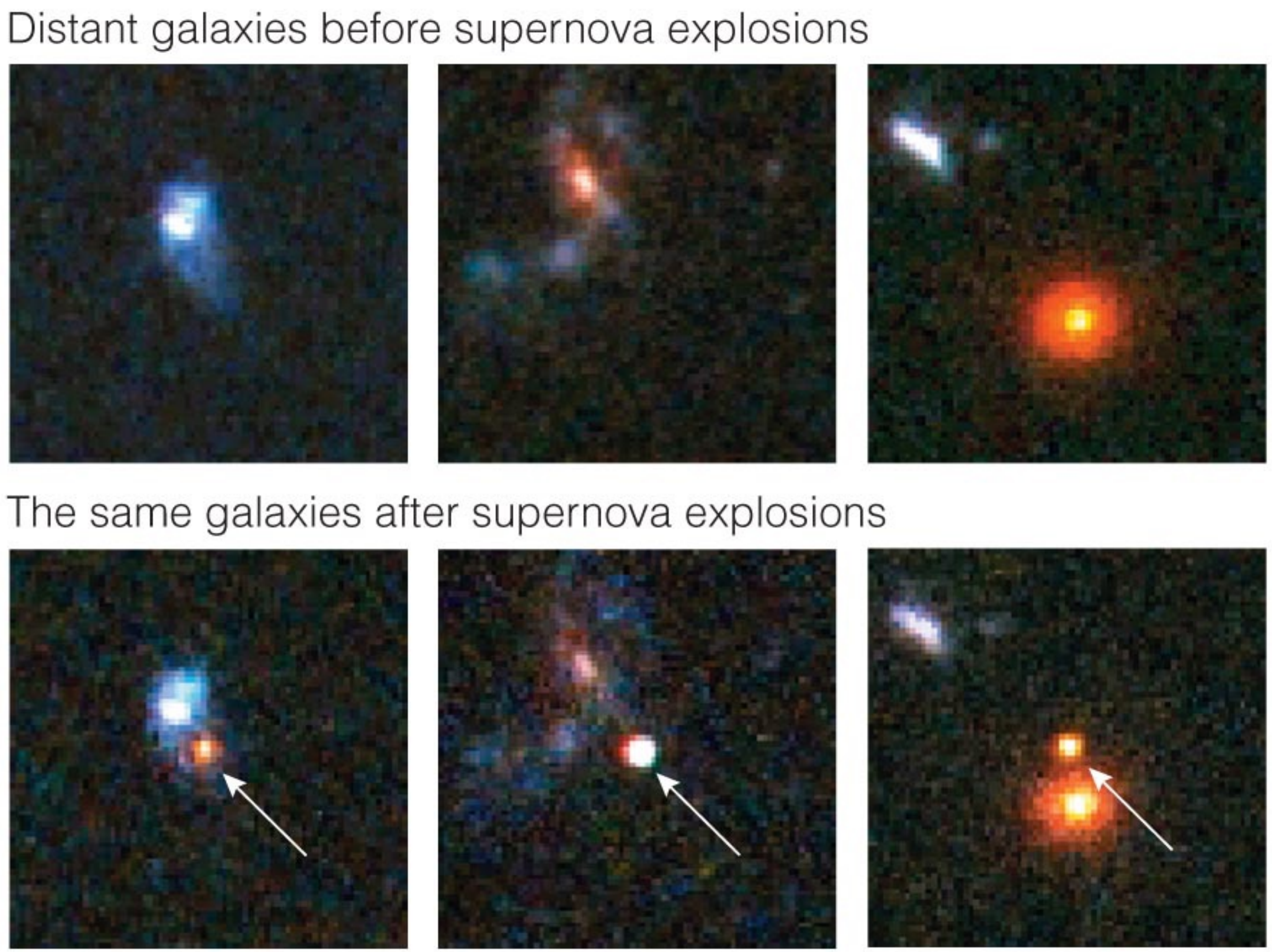


(a) Two universes with different expansion rates



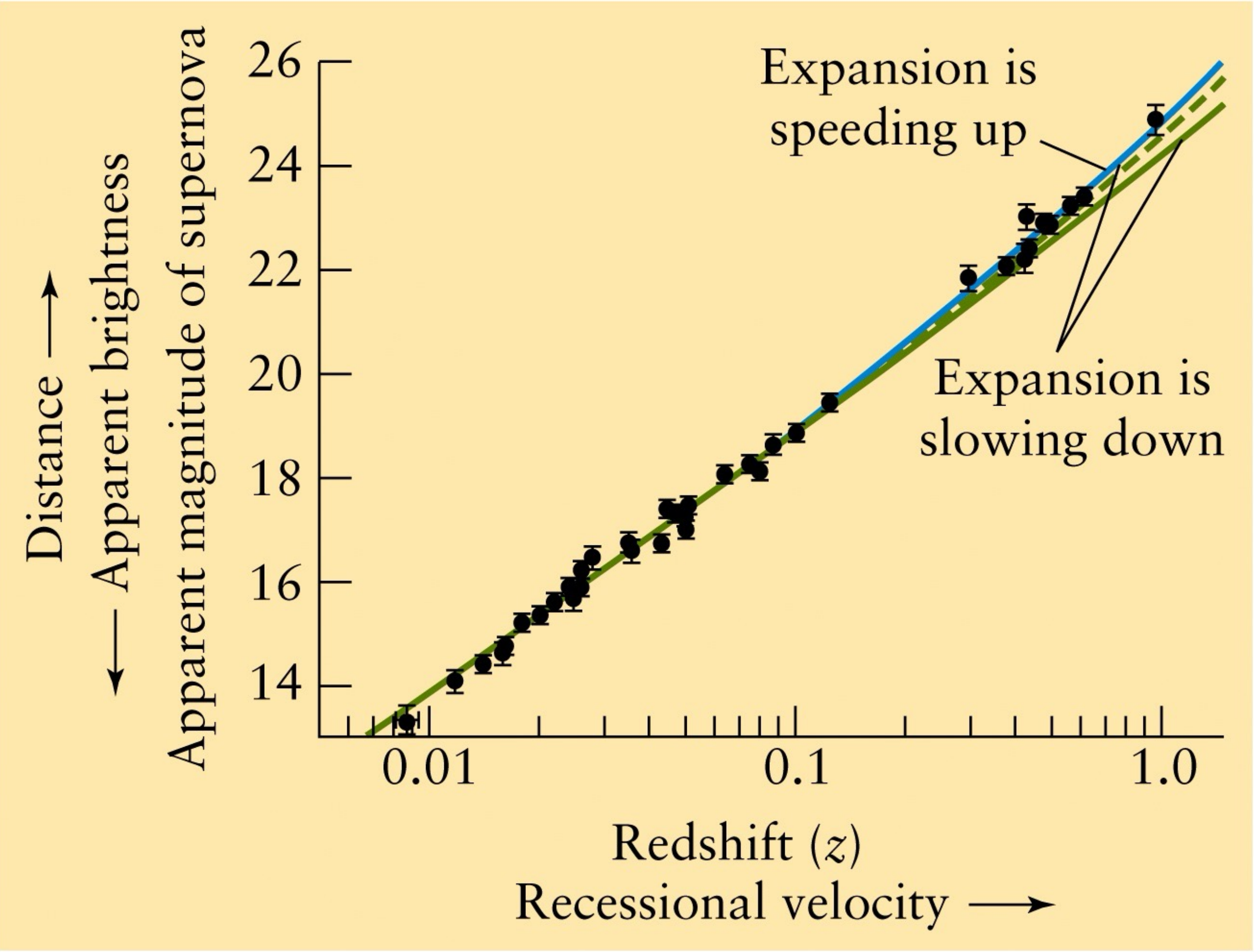
(b) Possible expansion histories of the universe

To address this question, we need to look at the distances versus recessional velocities of objects and see if the expansion rate changes with redshift. If the expansion rate is faster today than in the past, we expect the slope in the Distance versus Velocity plot to increase with velocity.



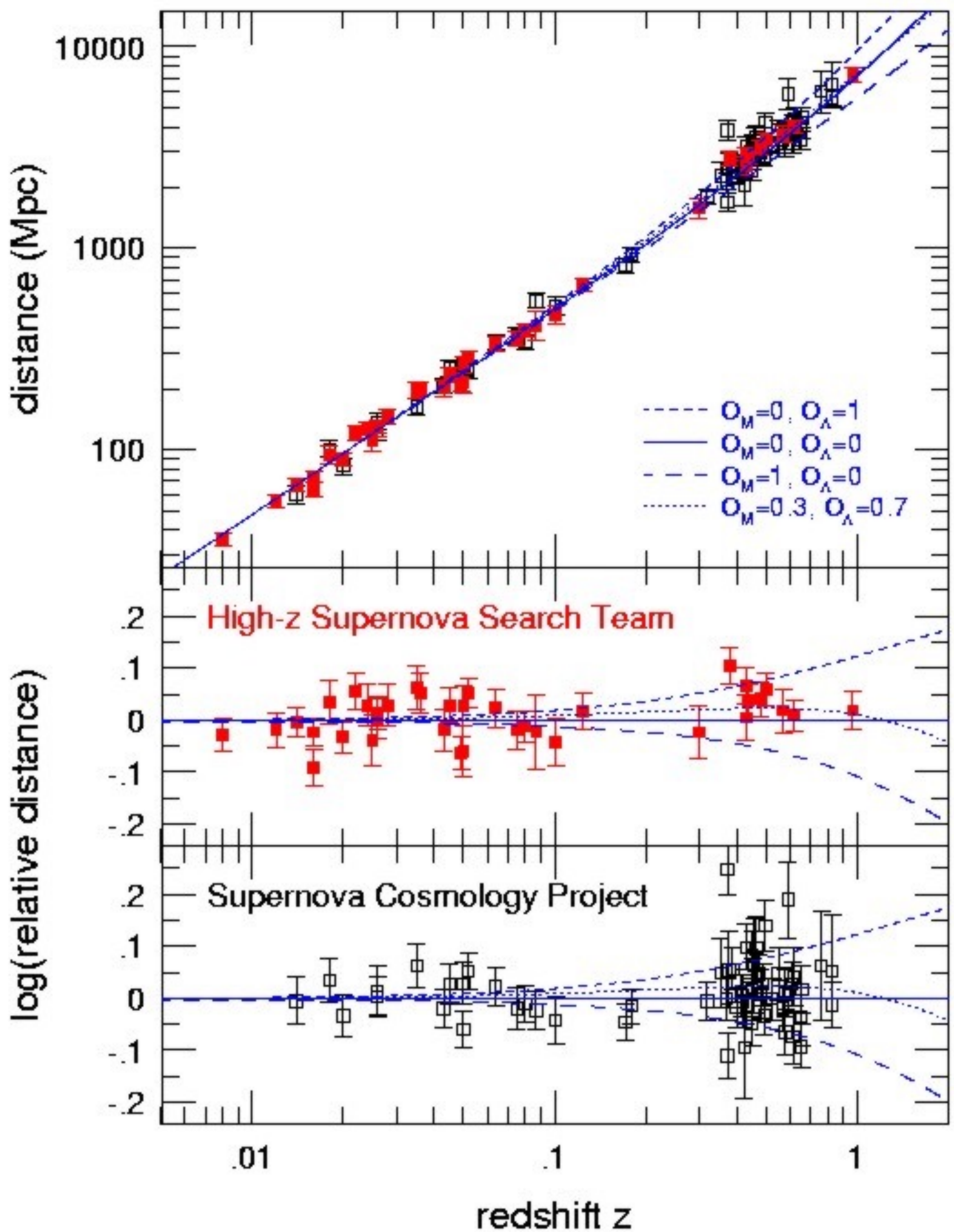
- We use data from distant white dwarf supernovae to make plots of their distances versus their recessional velocities.

Does The Expansion Rate Change With Time?



The data from SN Ia follow the blue curve and show that the Universe was expanding at a slower rate in the past. The expansion of the Universe is now speeding up!

Does The Expansion Rate Change With Time?

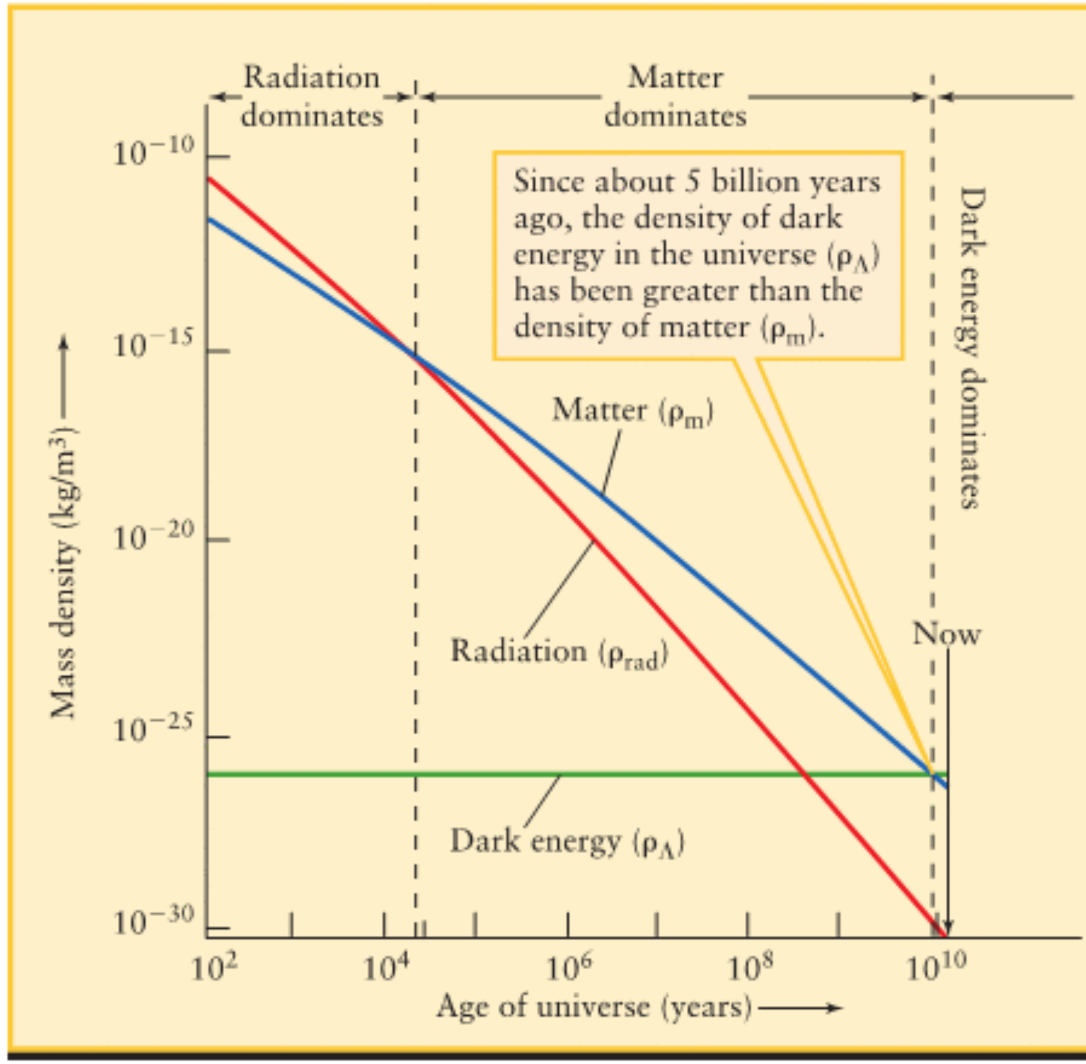


Why Me Why Now?

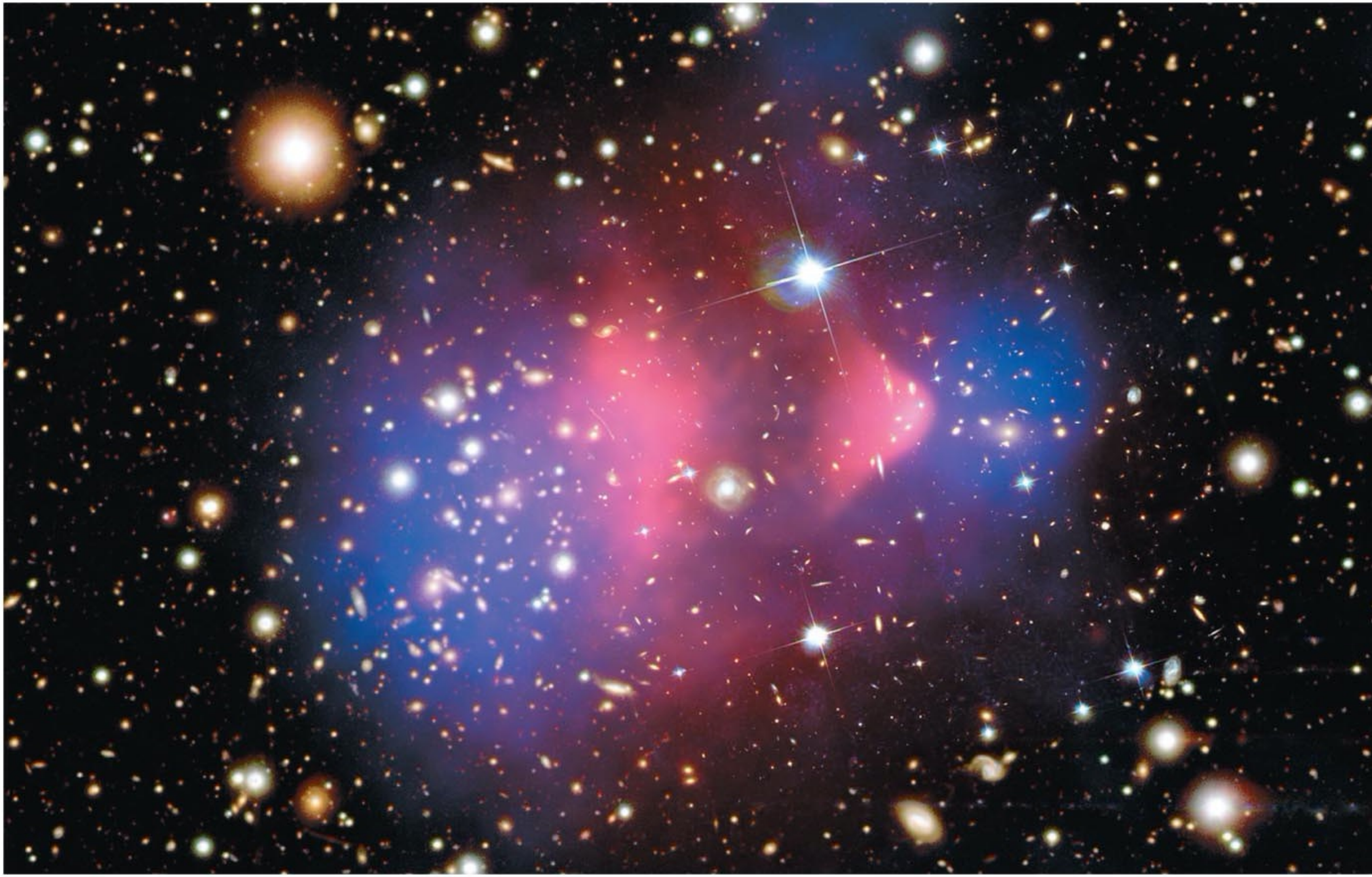
In the past dark energy was unimportant and in the future it will be dominant!

We just happen to live at the time when dark matter and dark energy have comparable densities.

In the words of Olympic skater Nancy Kerrigan, " Why me? Why now?



What do we mean by dark matter and dark energy?



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*

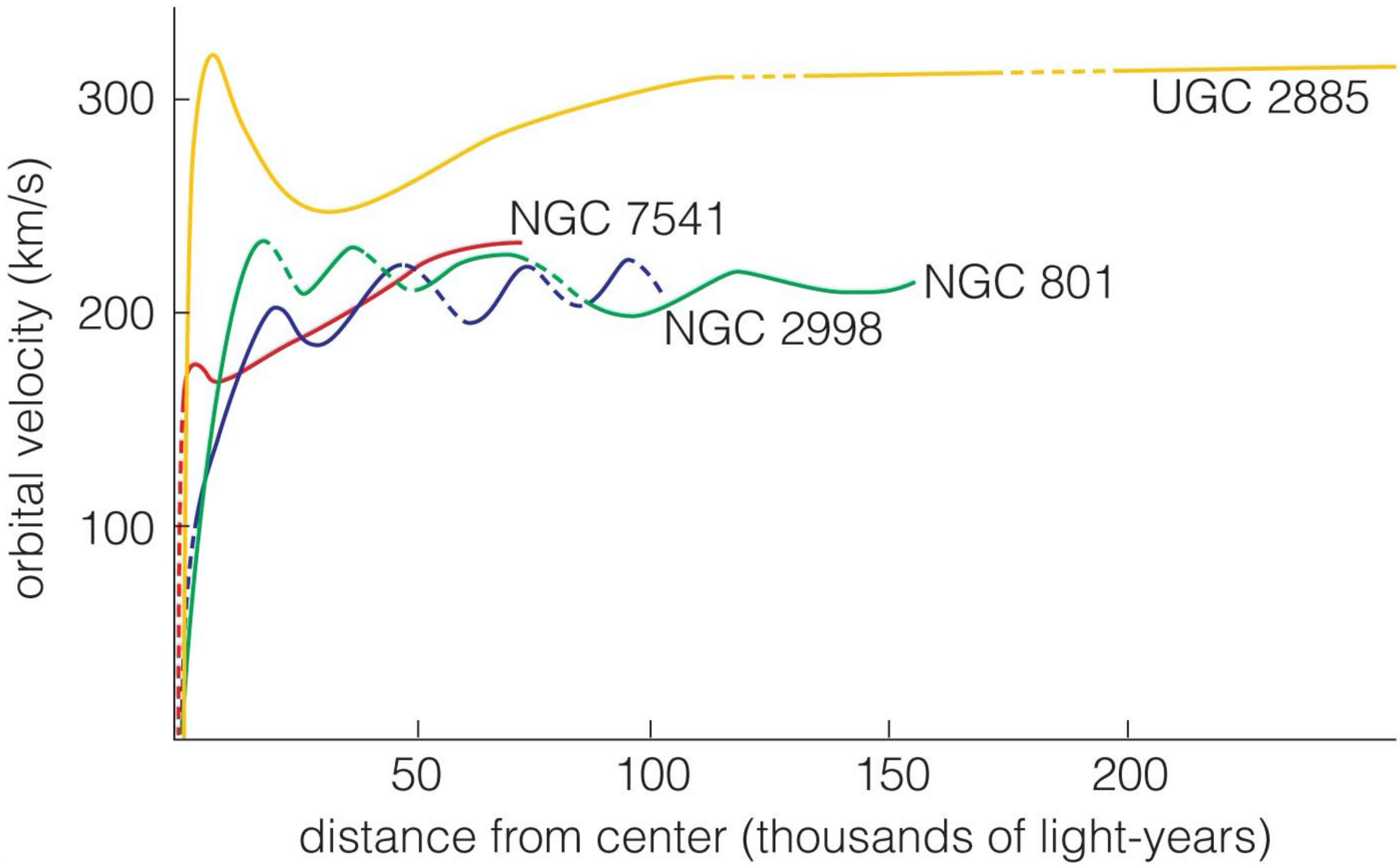
Contents of Universe (Planck 2015)

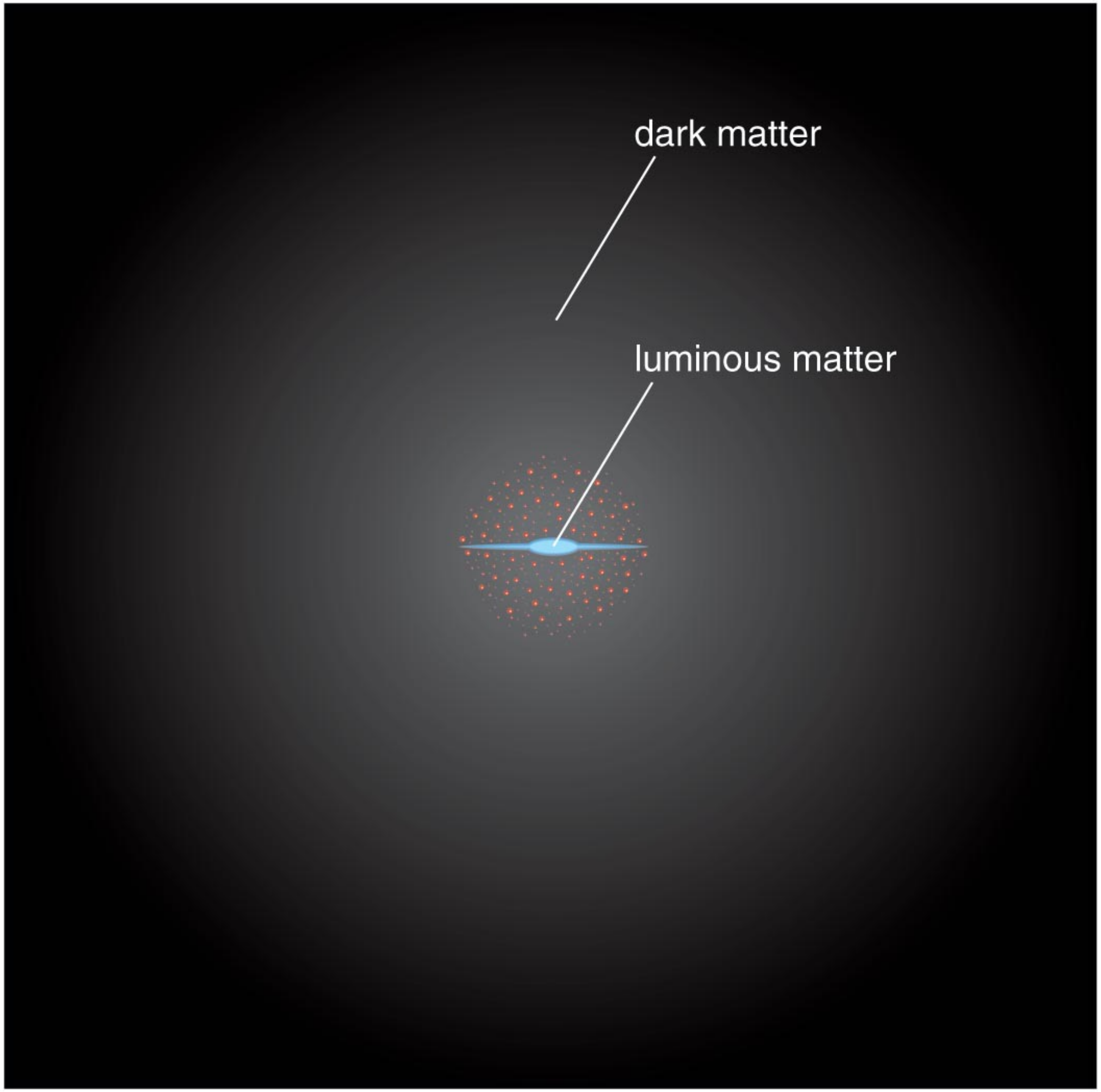
- "Ordinary" matter: ~ 4.9%
  - Ordinary matter inside stars: ~ 0.6%
  - Ordinary matter outside stars: ~ 4.3%
- Dark matter: ~ 26%
- Dark energy: ~ 69%

23.2 Evidence for Dark Matter

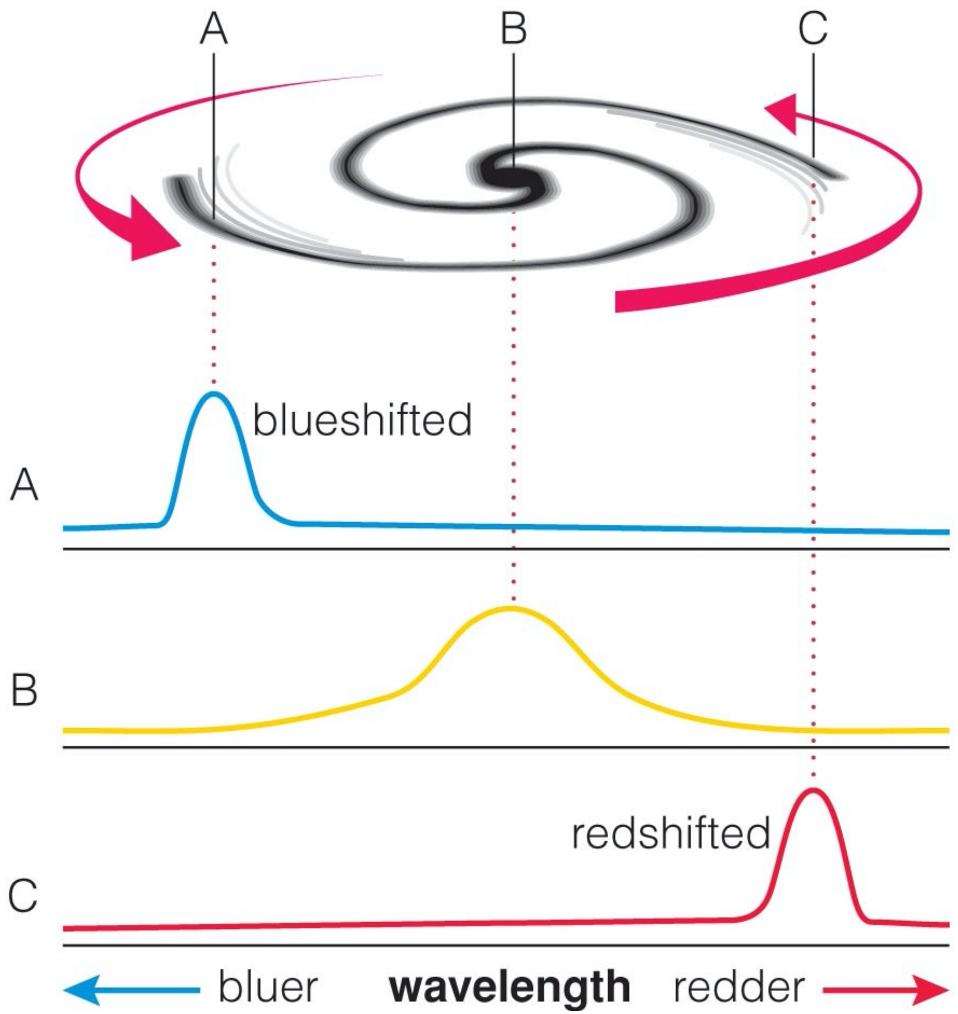
- Our goals for learning:
  - **What is the evidence for dark matter in galaxies?**
  - **What is the evidence for dark matter in clusters of galaxies?**
  - **Does dark matter really exist?**
  - **What might dark matter be made of?**

What is the evidence for dark matter in galaxies?

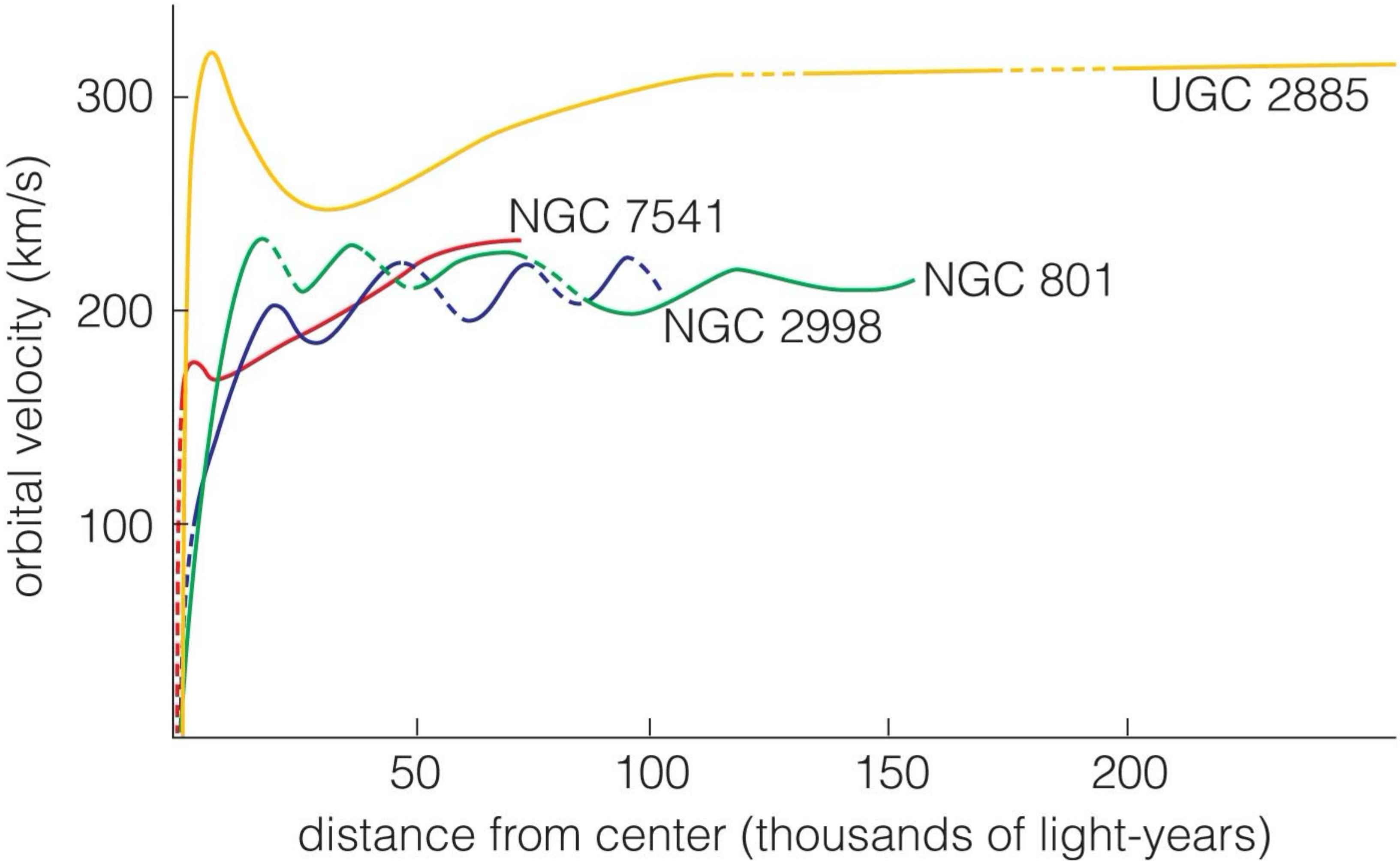




- The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.

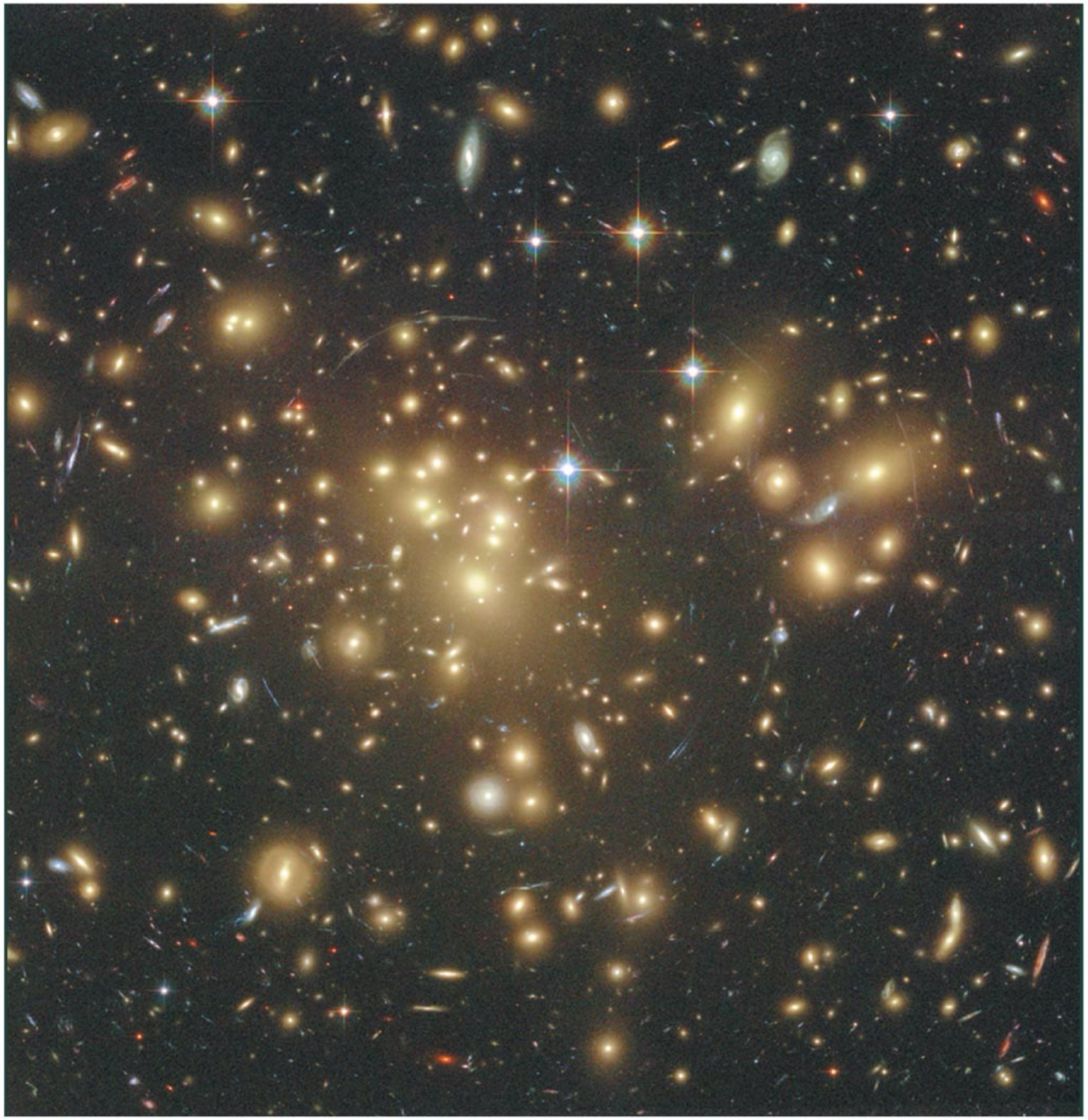


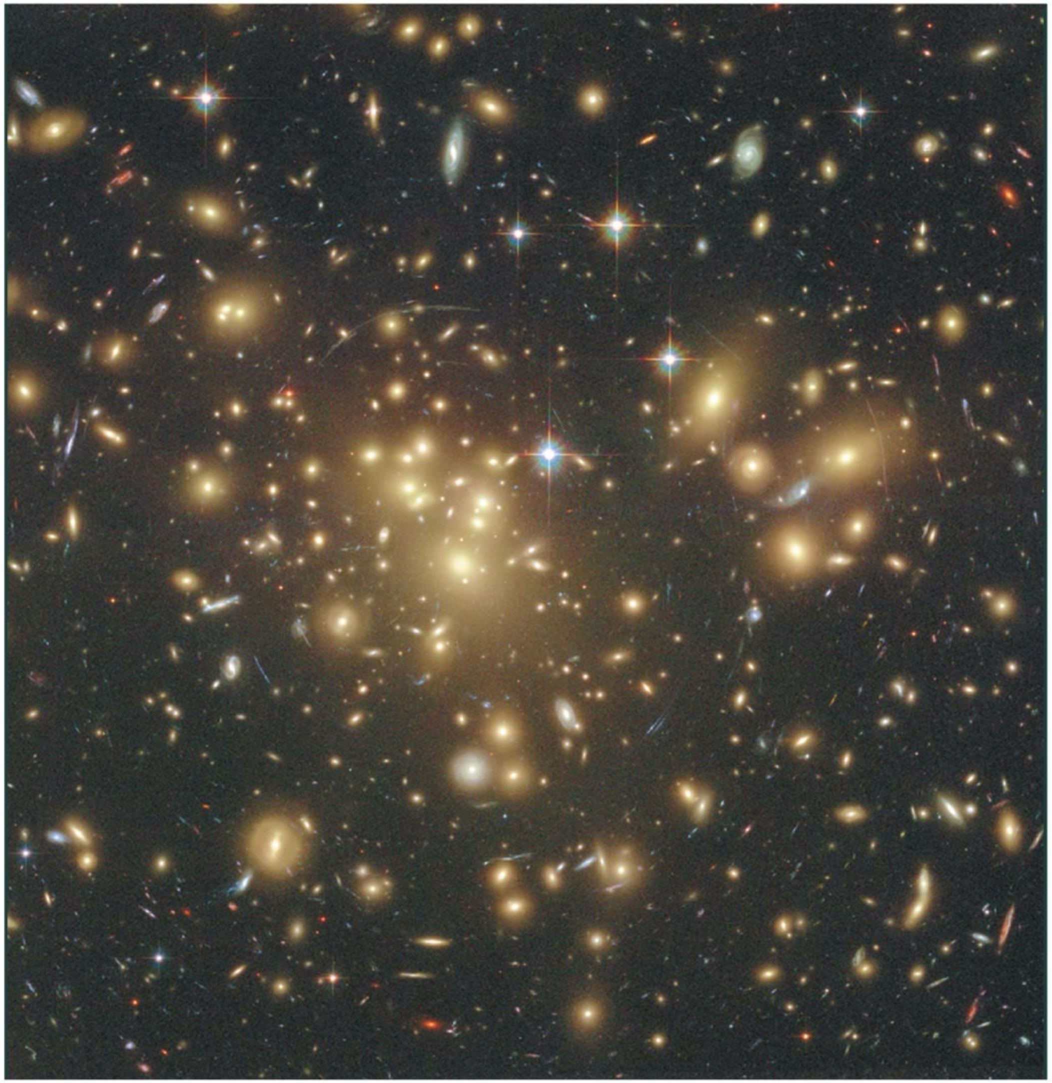
- We can measure the rotation curves of other spiral galaxies using the Doppler shift of the 21-cm line of atomic hydrogen.



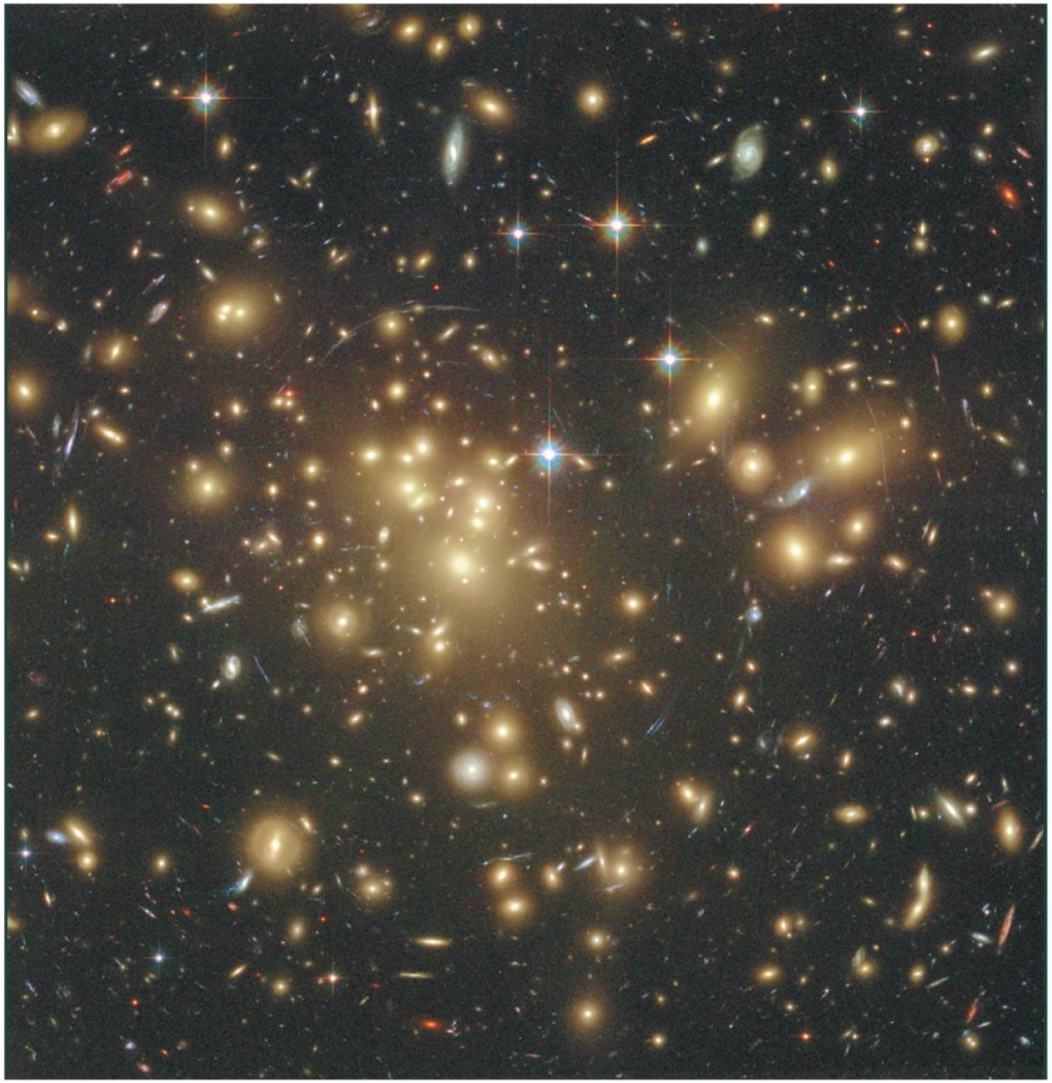
- Spiral galaxies all tend to have flat rotation curves, indicating large amounts of dark matter.

What is the evidence for dark matter in clusters of galaxies?

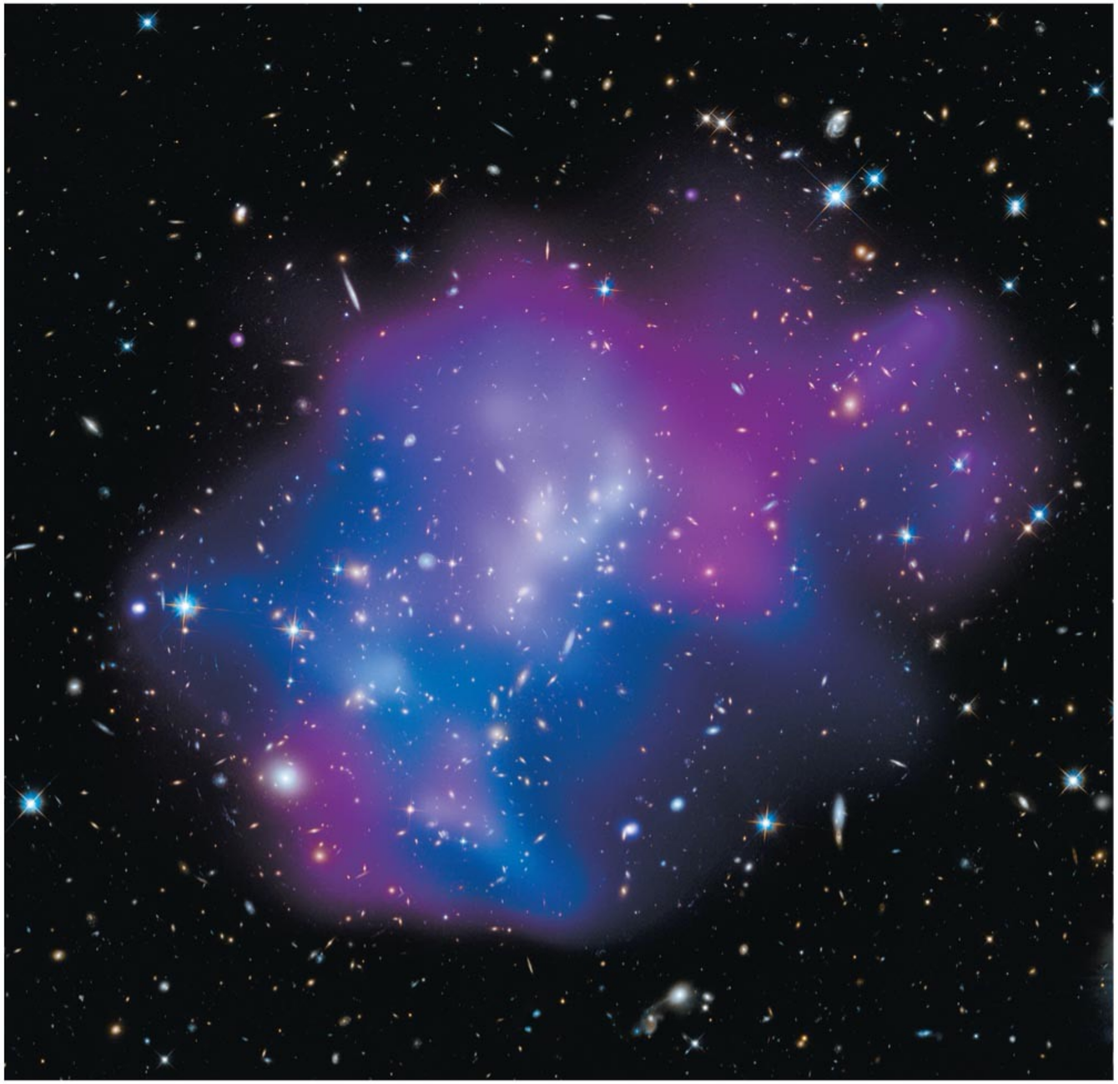




- We can measure the velocities of galaxies in a cluster from their Doppler shifts.

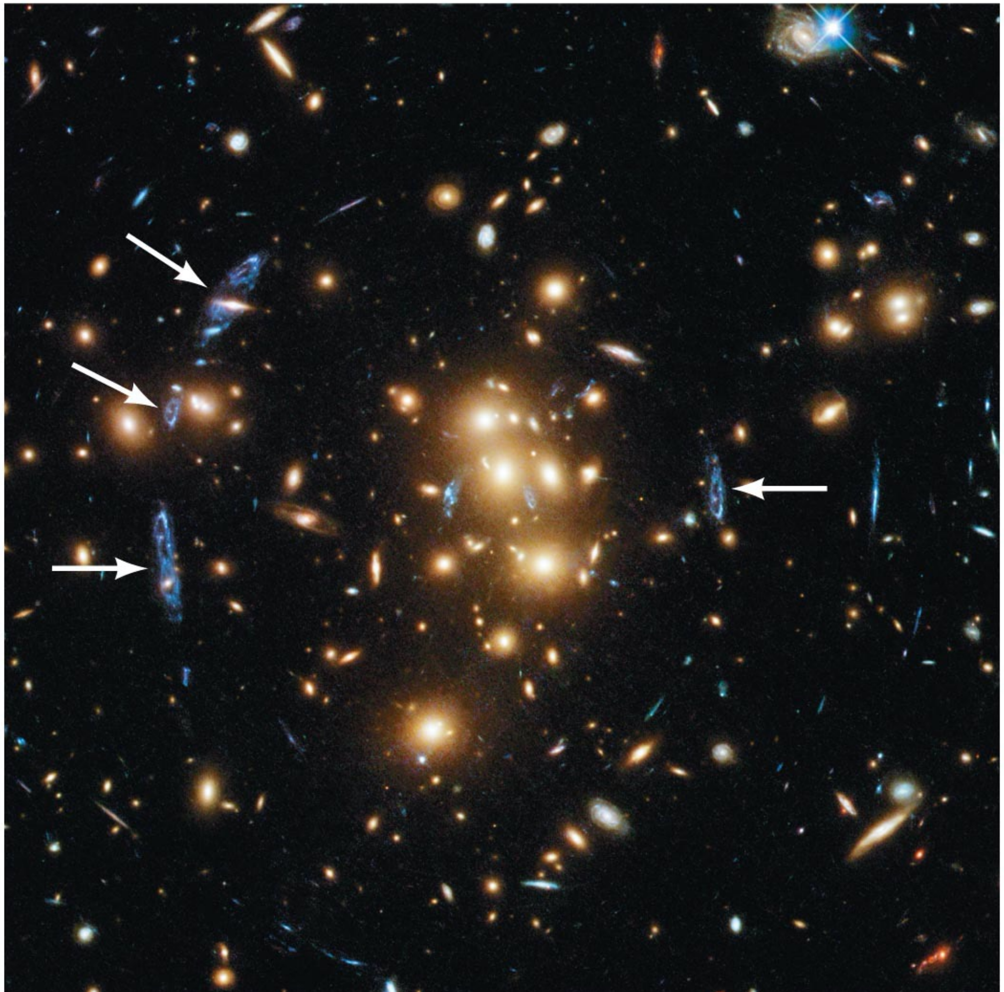


- The total cluster mass we find from galaxy velocities in a cluster is about ***50 times*** larger than the mass in stars!

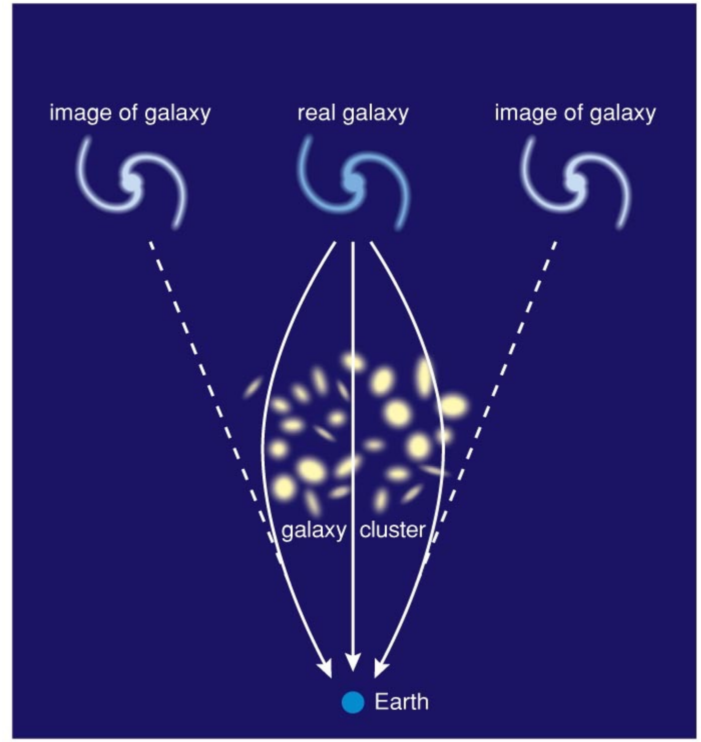


- Clusters contain large amounts of X ray-emitting hot gas.
- *Temperature of hot gas (particle motions) tells us cluster mass*:

85% dark matter
13% hot gas
2% stars

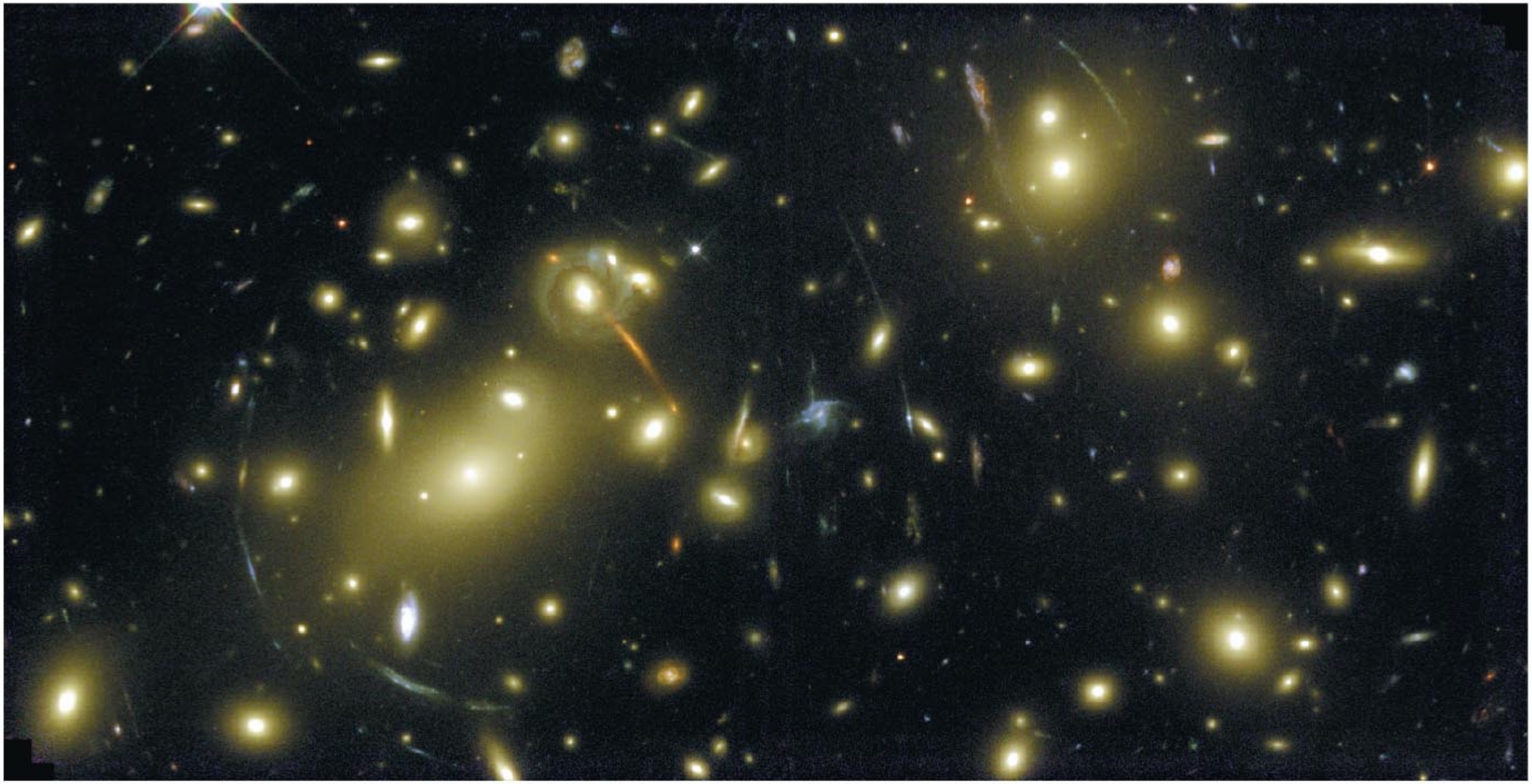


Interactive Figure



Interactive Figure

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



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

Thought Question

What kind of measurement does not tell us the mass of a cluster of galaxies?

A. measuring velocities of cluster galaxies
B. measuring the total mass of cluster's stars
C. measuring the temperature of its hot gas
D. measuring distorted images of background galaxies

Thought Question

What kind of measurement does not tell us the mass of a cluster of galaxies?

A. measuring velocities of cluster galaxies
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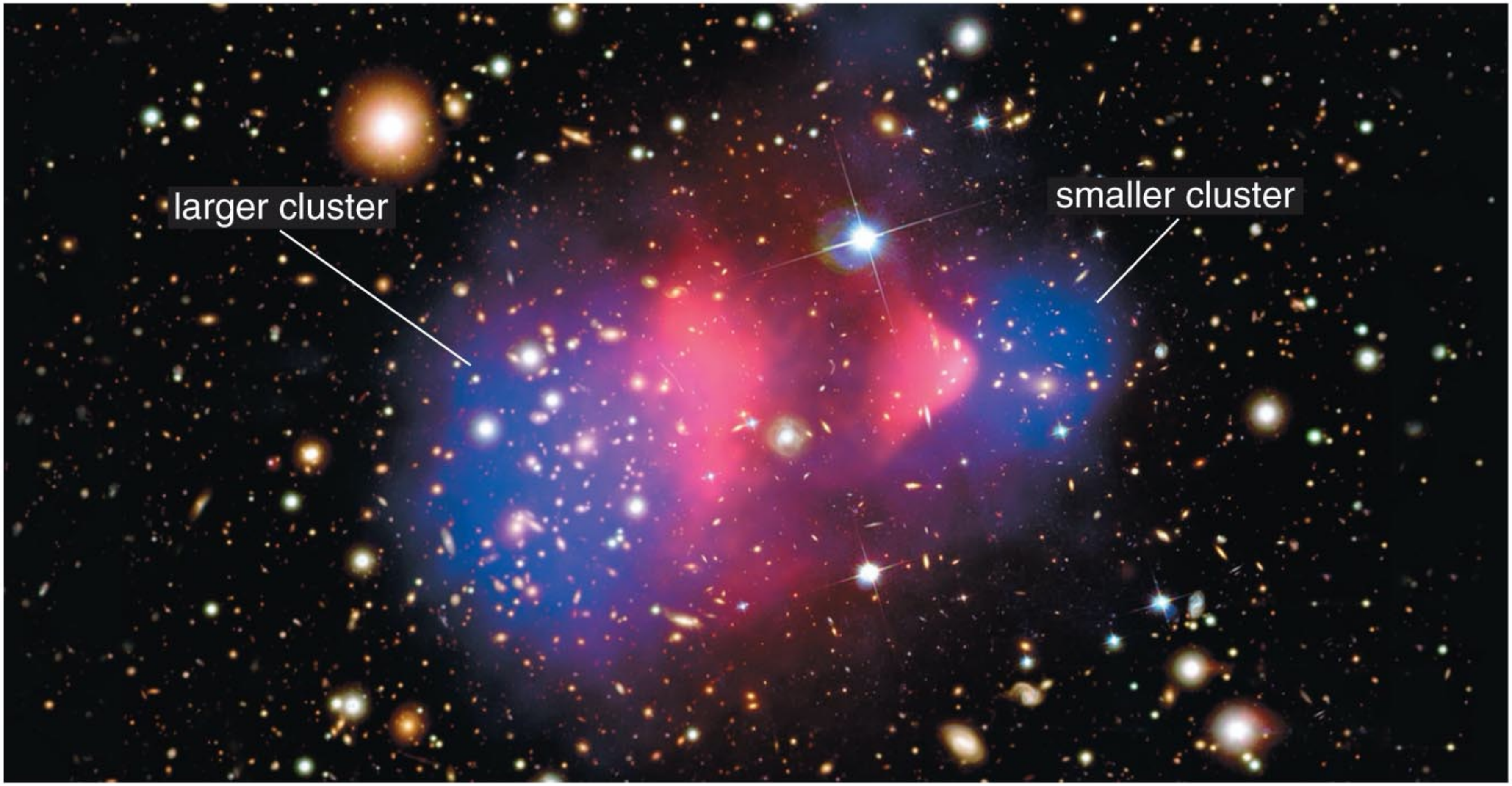
Does dark matter really exist?



What might dark matter be made of? Two Basic Options

- Ordinary Dark Matter
  - Matter made of protons, neutrons, electrons, but too dark to detect with current instruments

- Extraordinary Dark Matter
  - Weakly Interacting Massive Particles: mysterious neutrino-like particles

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The best bet

Why Believe in WIMPs?

- There's not enough ordinary matter.
- WIMPs could be left over from Big Bang.
- Models involving WIMPs explain how galaxy formation works.

What have we learned?

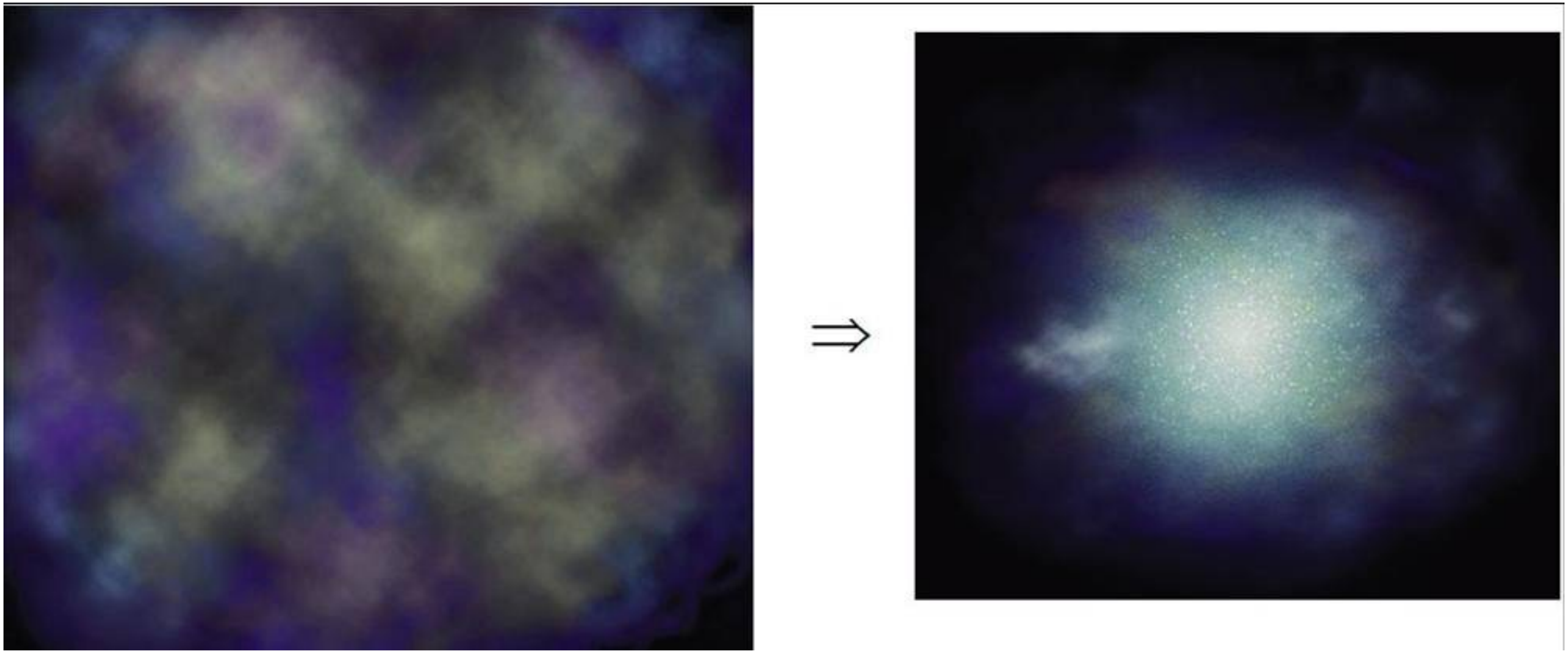
- **What is the evidence for dark matter in galaxies?**
  - Rotation curves of galaxies are flat, indicating that most of their matter lies outside their visible regions.
- **What is the evidence for dark matter in clusters of galaxies?**
  - Masses measured from galaxy motions, temperature of hot gas, and gravitational lensing all indicate that the vast majority of matter in clusters is dark.

What have we learned?

- **Does dark matter really exist?**
  - Either dark matter exists or our understanding of our gravity must be revised.
- **What might dark matter be made of?**
  - There does not seem to be enough normal (baryonic) matter to account for all the dark matter, so most astronomers suspect that dark matter is made of (non-baryonic) particles that have not yet been discovered.

23.3 Dark Matter and Galaxy Formation

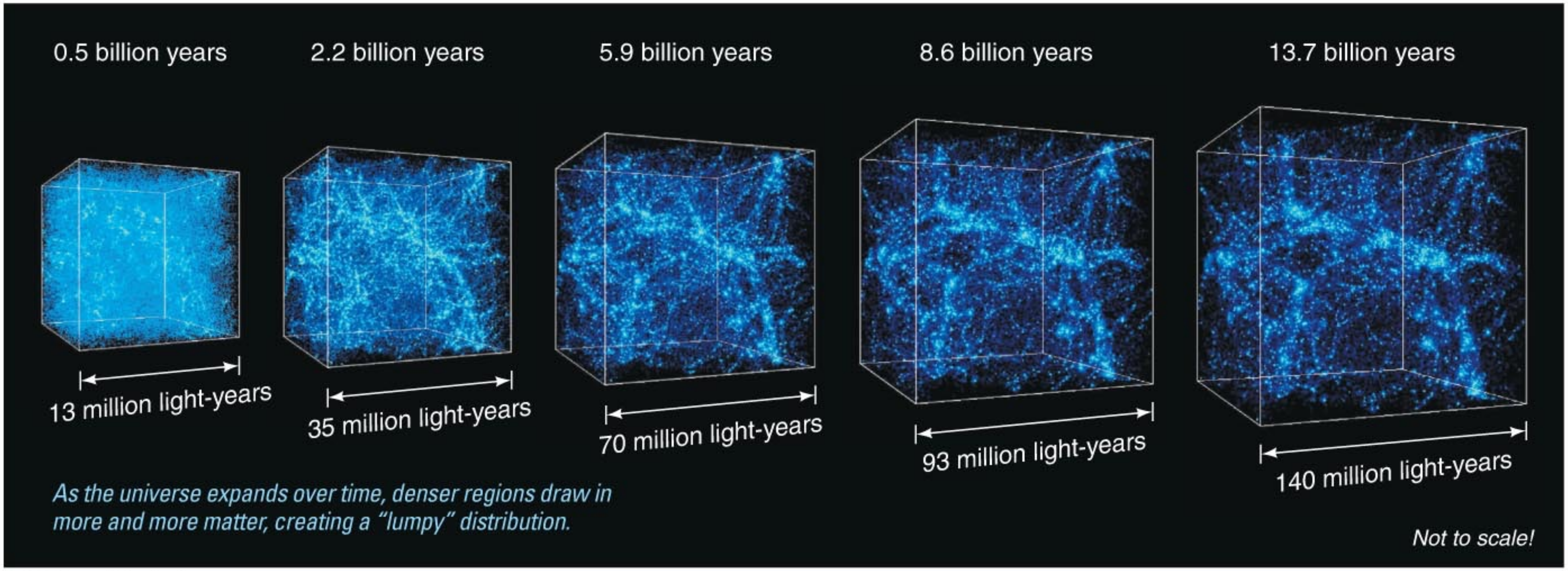
- Our goals for learning:
  - **What is the role of dark matter in galaxy formation?**
  - **What are the largest structures in the universe?**



- Gravity of dark matter is what caused protogalactic clouds to contract early in time.

Time in billions of years

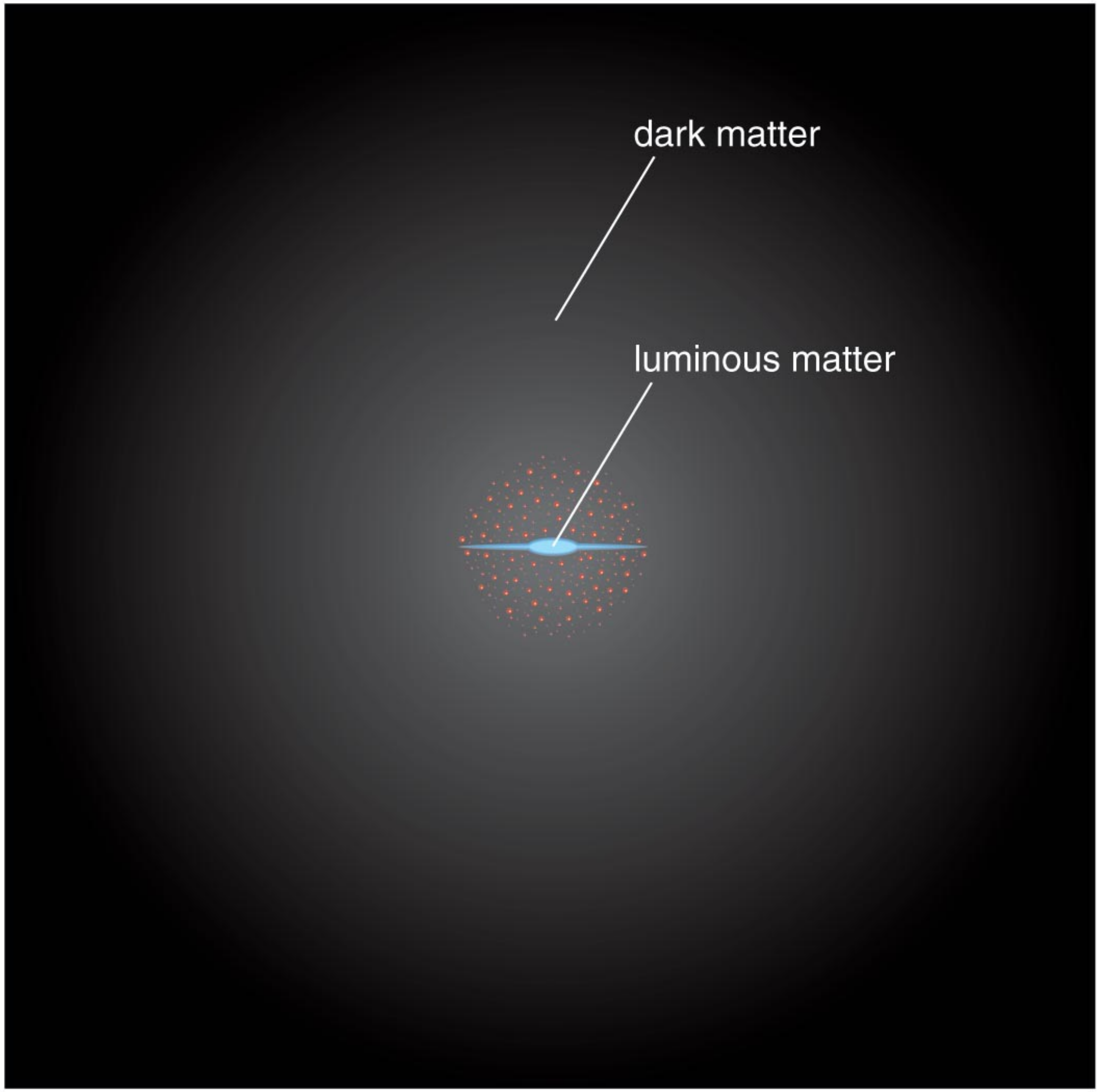
0.5 2.2 5.9 8.6 13.7



13 35 70 93 140

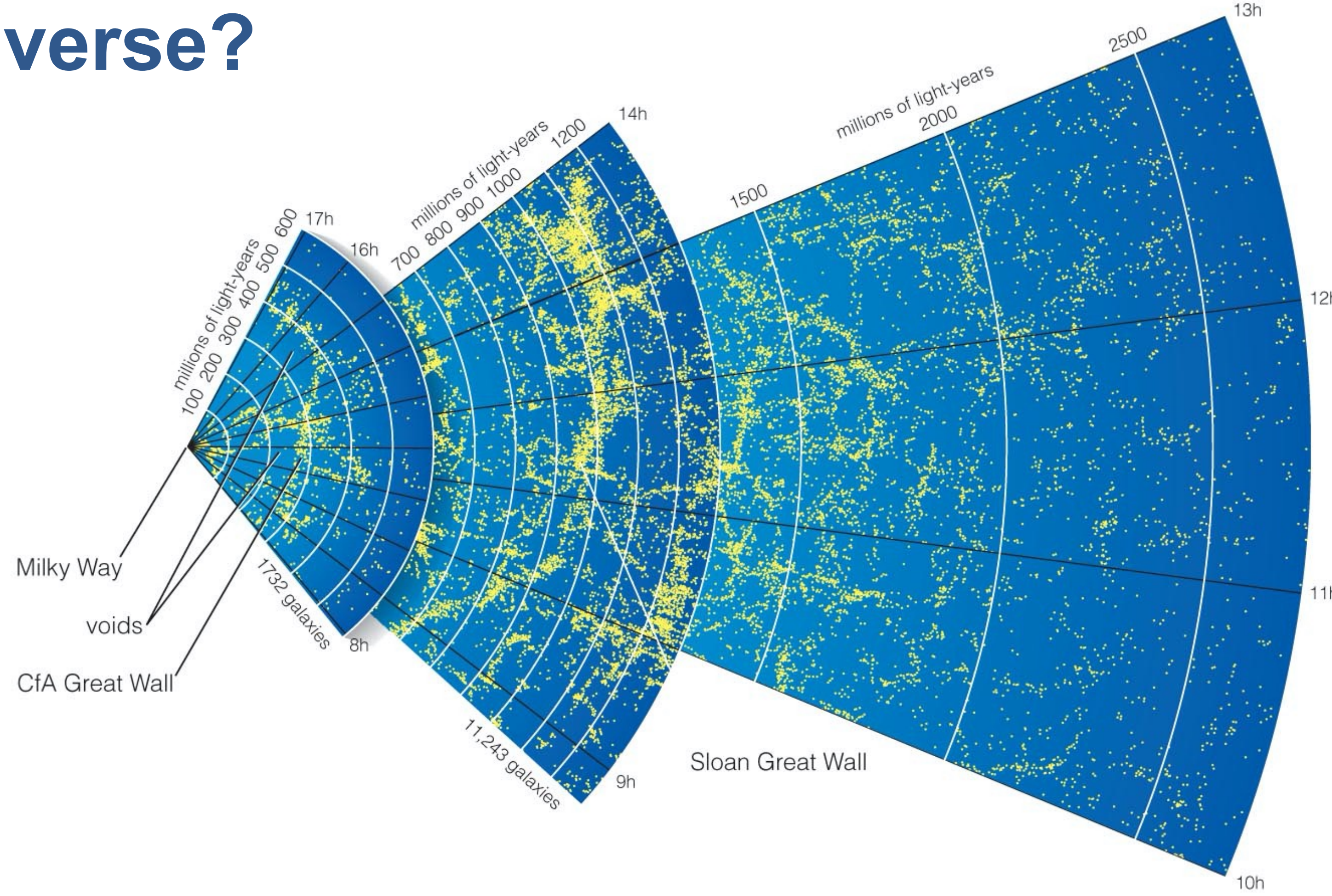
Size of expanding box in millions of light-years

- Models show that gravity of dark matter pulls mass into denser regions—the universe grows lumpier with time.



- WIMPs can't collapse to the center because they don't radiate away their orbital energy.

What are the largest structures in the universe?



- Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids***.

What have we learned?

- **What is the role of dark matter in galaxy formation?**
  - The gravity of dark matter seems to be what drew gas together into protogalactic clouds, initiating the process of galaxy formation.
- **What are the largest structures in the universe?**
  - Galaxies appear to be distributed in gigantic chains and sheets that surround great voids.

23.4 Dark Energy and the Fate of the Universe

- The eventual fate of the universe depends upon the rate of the acceleration of the expansion.
- If the universe does not end in a Big Rip, it should keep expanding for a **very** long time. (Forever?)
- All matter will eventually end up as part of black holes, which will, if Stephen Hawking is right, will eventually evaporate.

What have we learned?

- **Why is accelerating expansion evidence for dark energy?**
  - In the absence of the repulsive force of dark energy the expansion of the universe should not be accelerating.
- **Why is flat geometry evidence for dark energy?**
  - Evidence from the CMB indicates that the universe is very near critical density, requiring an additional contribution to the mass-energy of the universe.

What have we learned?

- **What is the fate of the universe?**
  - The universe should keep expanding indefinitely, the universe eventually consisting of a dilute sea of fundamental particles.

Extra Slides

Finding Cluster Masses from Velocities

- The virial theorem states that $2E_k = -E_p$ where is the average total kinetic energy and Ep is the average total potential energy

$$2E_K = -E_P \Rightarrow 2\frac{1}{2}mv^2 = G\frac{Mm}{R} \Rightarrow$$

$$M(< R) = \frac{v^2 \times R}{G}$$

where $M(< R)$ is the total mass (baryonic and dark matter) within a radius of R and v is the average velocity of a galaxy.

Finding Cluster Masses from Gas Temperatures

- The relation between the hot gas temperature and average speed of an individual particle in the gas (which is mostly hydrogen) is:

$$v_H = (140\text{m/s}) \times \sqrt{T}$$

where T is the temperature of the gas in Kelvins.

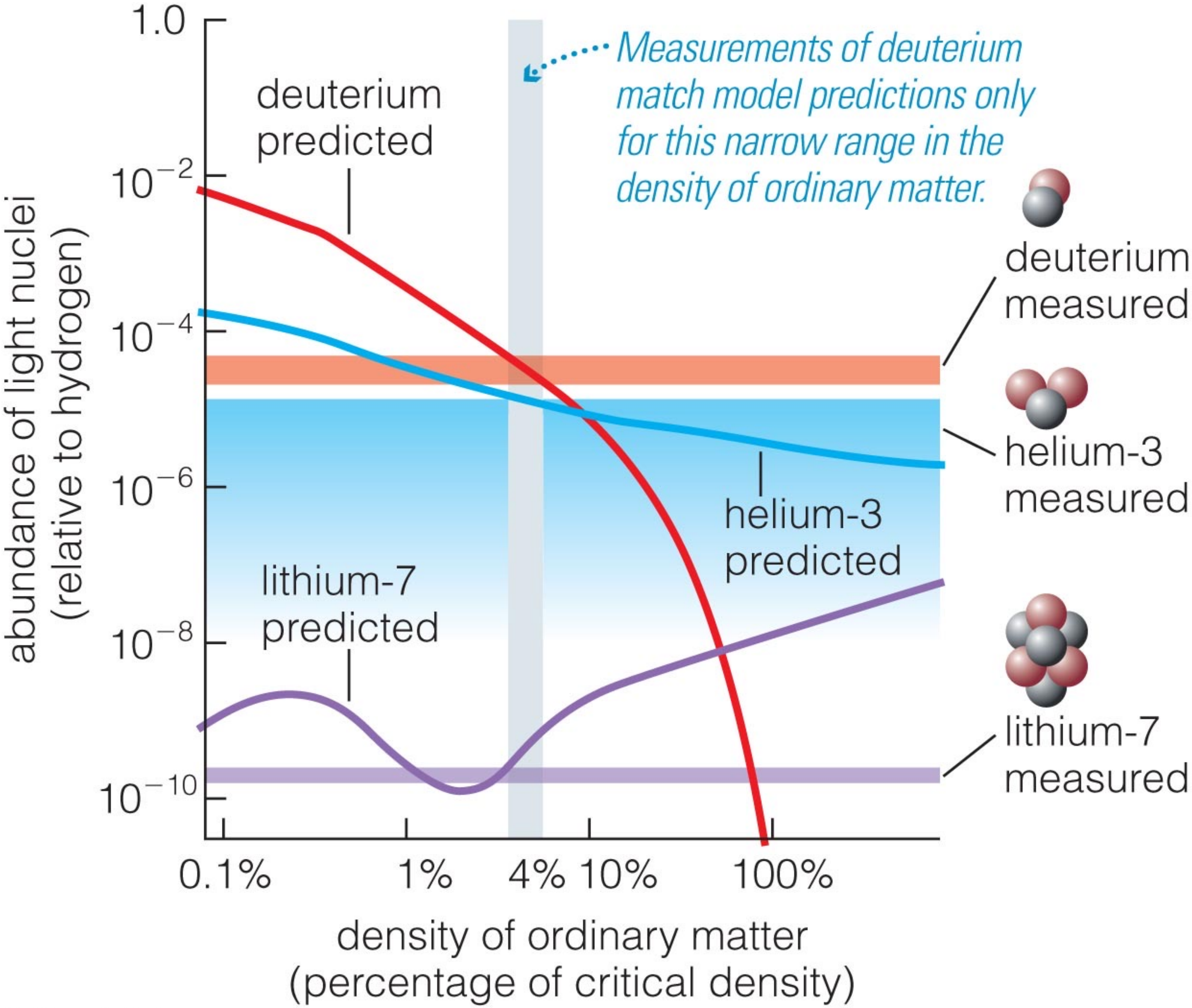
Estimate the mass of a cluster with a temperature of $\text{T} = 9\times10^{7}\text{K}$ and a radius of 6.2 million light years

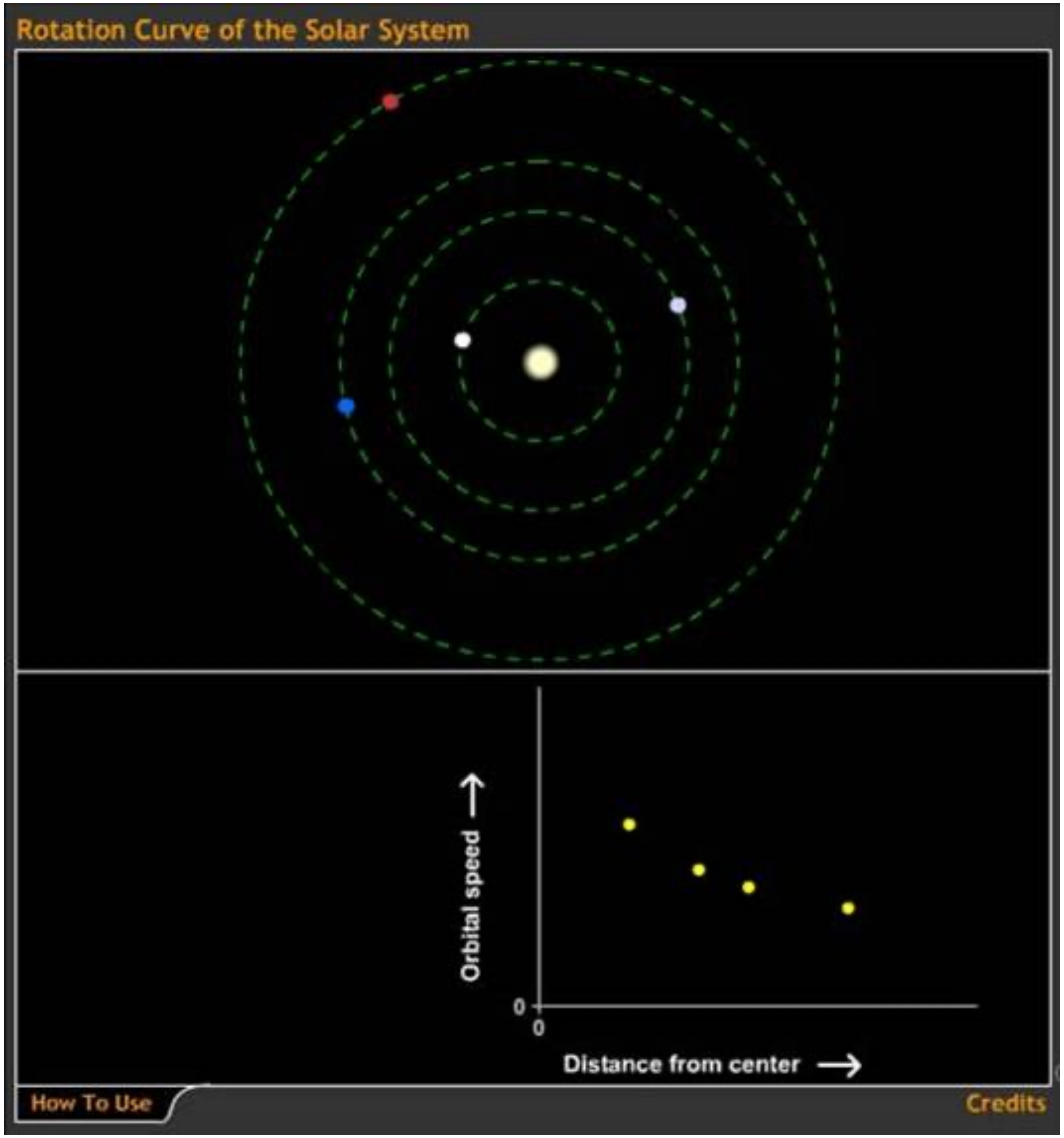
$$v_H = (140\text{m/s}) \times \sqrt{9\times10^{7}\text{K}} = 1.33\times10^{6}\text{m/s}$$

$$M(<R) = \frac{\left(1.33\times10^{6}\text{m/s}\right)^{2} \times R}{G} = \frac{\left(1.33\times10^{6}\text{m/s}\right)^{2} \times \left(6.2\times10^{6}\right) \times \left(9.461\times10^{15}\,m\right)}{6.67408\times10^{-11}\ \text{m}^{3}\ \text{kg}^{-1}\ \text{s}^{-2}} \Rightarrow$$

$$M(<R) = 1.55\times10^{45}\text{kg}$$

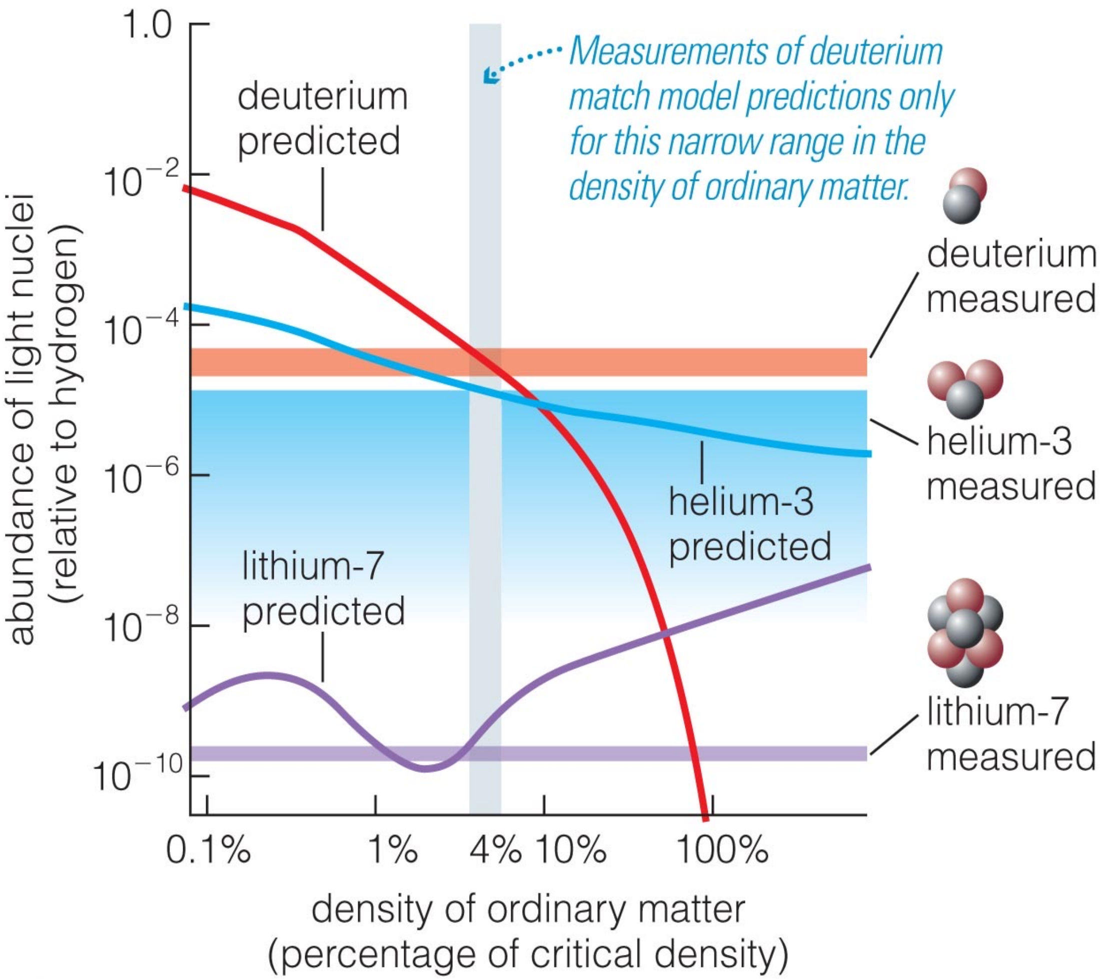
What might dark matter be made of?





Rotation curve

- A plot of orbital velocity versus orbital radius
- The solar system's rotation curve declines because the Sun has almost all the mass.



- Measurements of light element abundances indicate that ordinary matter cannot account for all of the dark matter.

Mass-to-Light Ratio

- An object's mass-to-light ratio (M/L) is its total mass in solar mass units divided by its visible luminosity in units of solar luminosity.

M/L of Sun

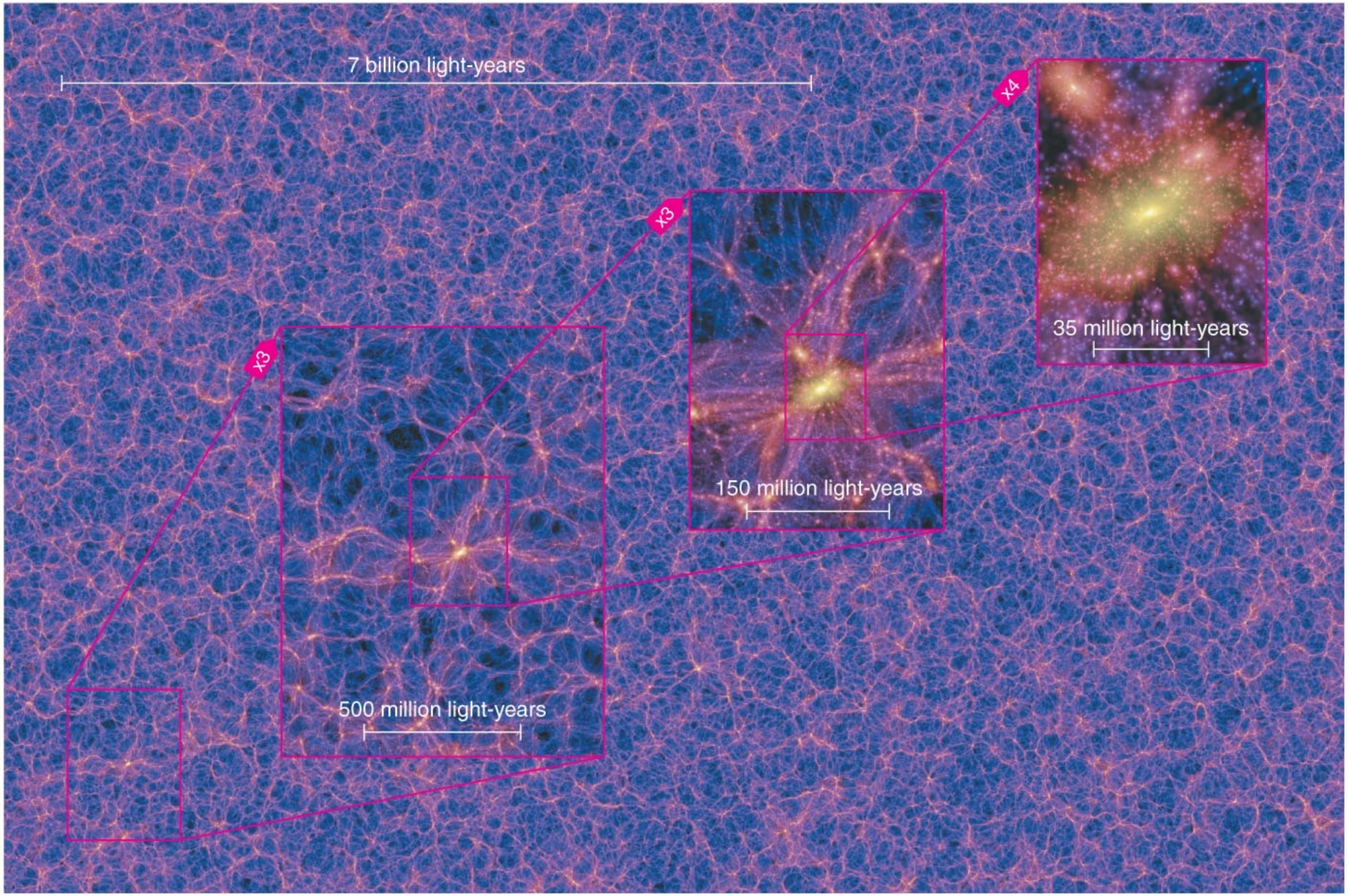
$$\frac{M}{L} = \frac{M_{solar}}{L_{Solar}} = 1\frac{M_{solar}}{L_{Solar}}$$

M/L of Milky Way Galaxy

$$\frac{M}{L} = \frac{9\times 10^{12} M_{solar}}{15\times 10^{9} L_{Solar}} = 6\frac{M_{solar}}{L_{Solar}}$$

Most mass in our galaxy is dimmer per unit mass than the Sun

A galaxy with a large M/L ratio may imply the presence of a significant dark matter component.



- Structures in galaxy maps look very similar to the ones found in models in which dark matter is WIMPs.