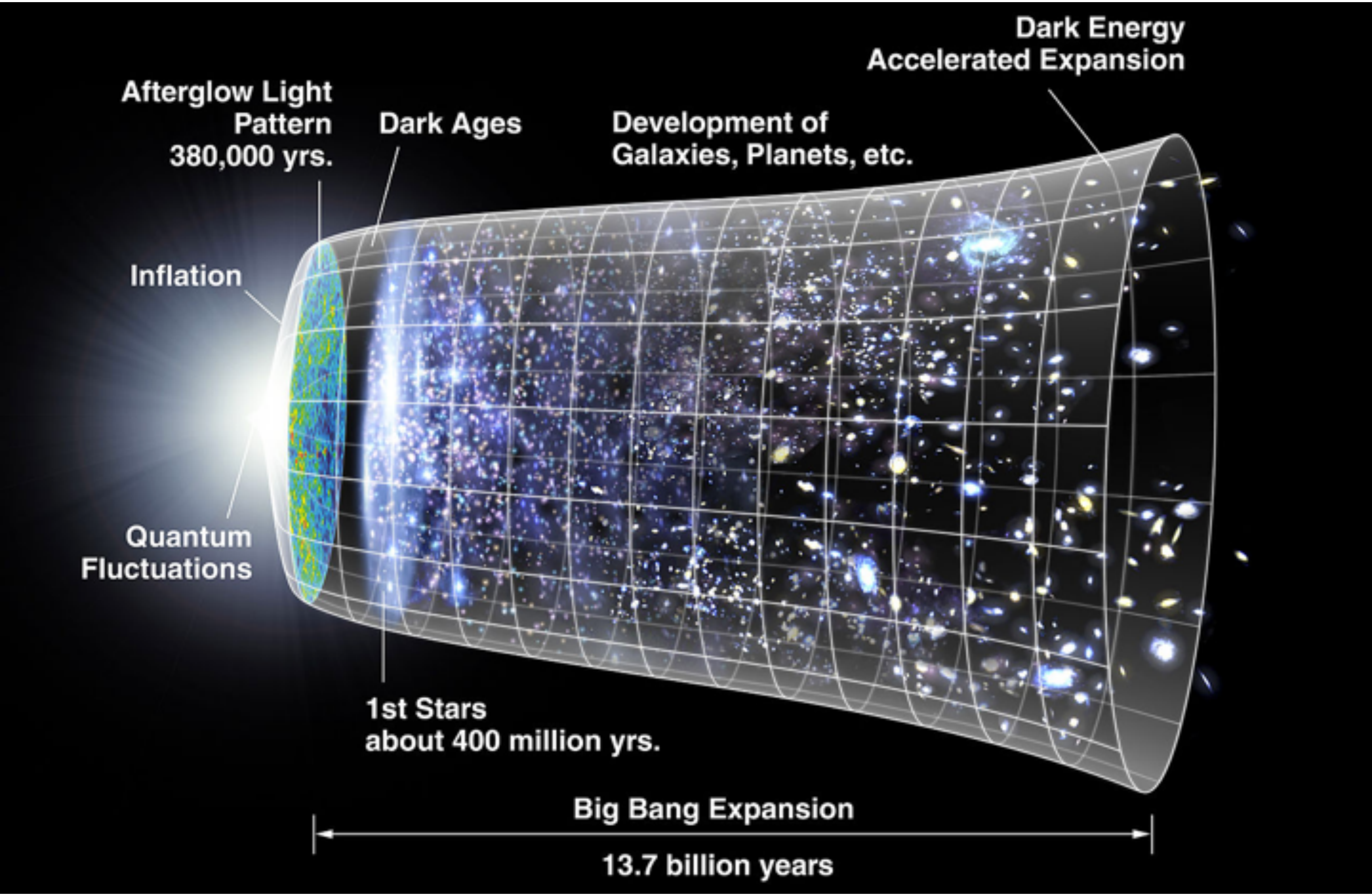
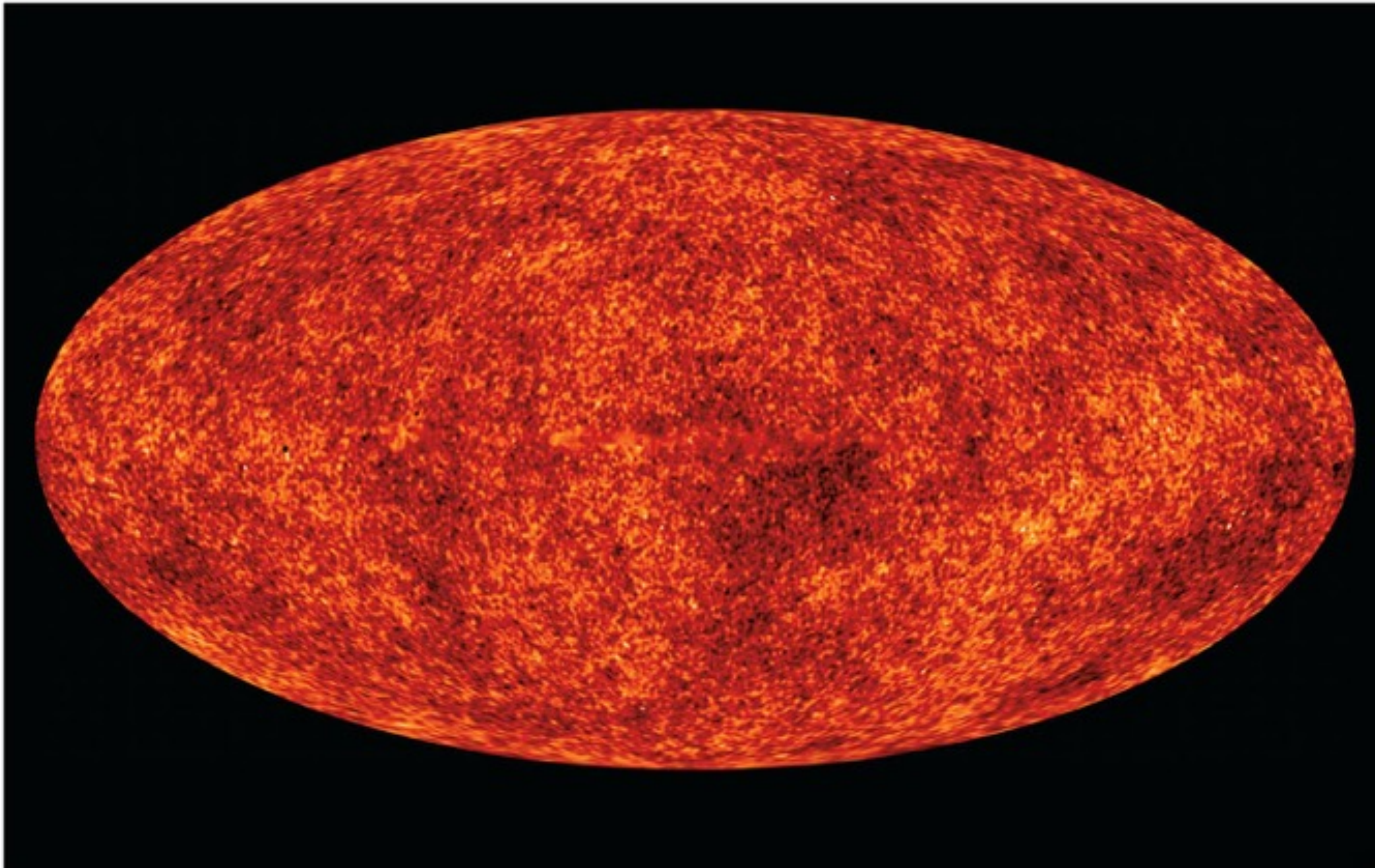
The Birth of the Universe

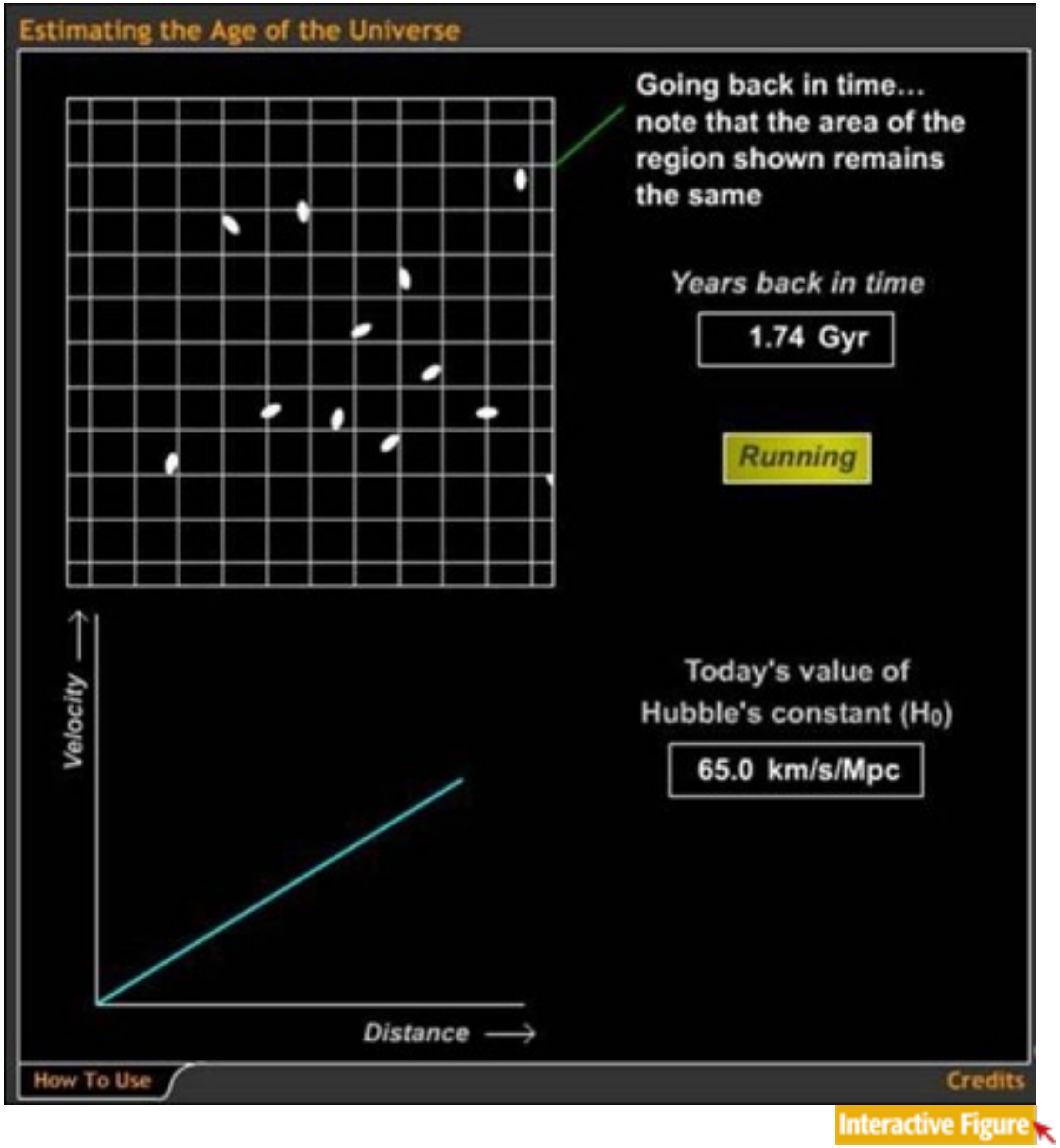


22.1 The Big Bang Theory

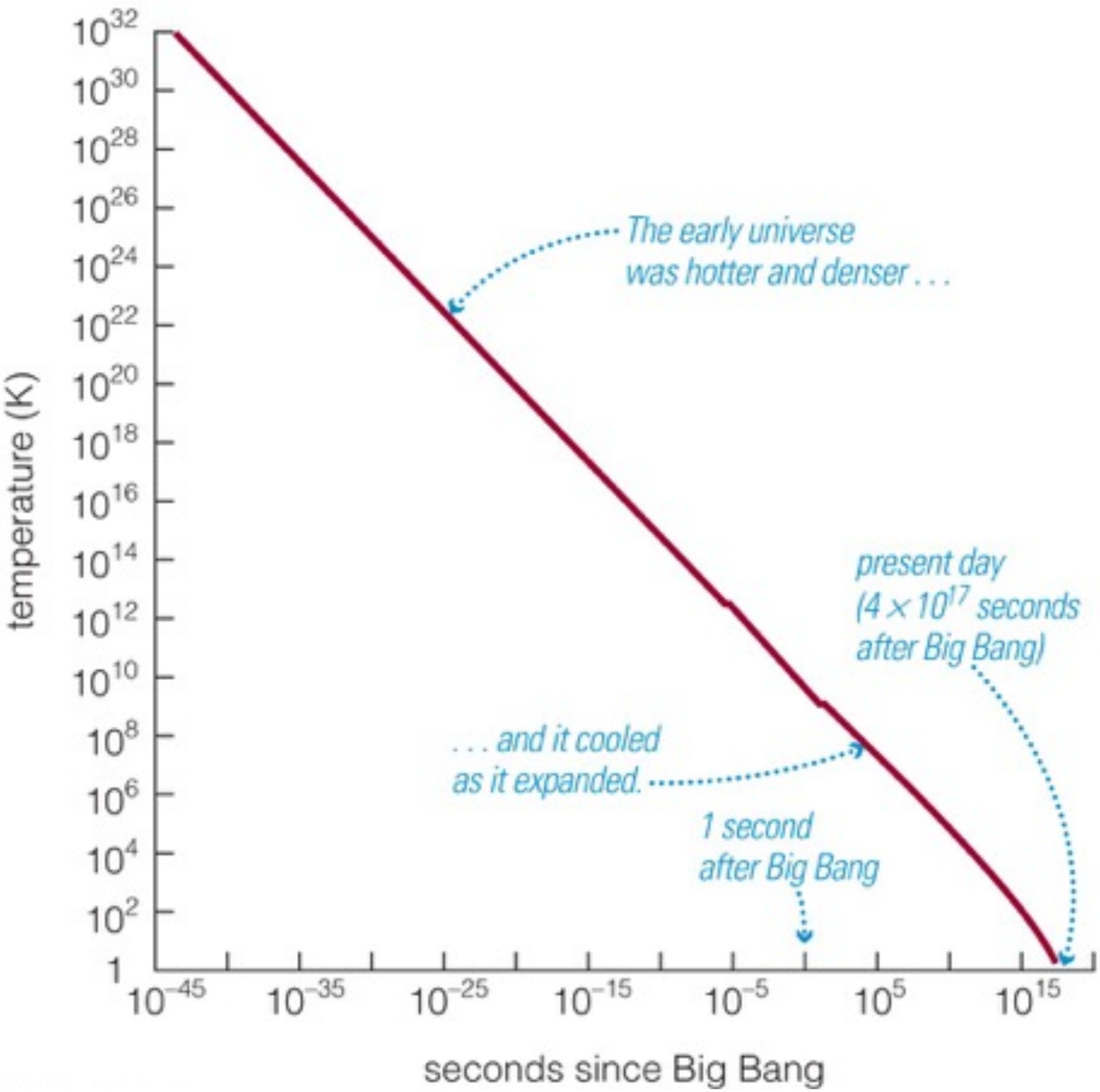
- Our goals for learning:
  - **What were conditions like in the early universe?**
  - **How did the early universe change with time?**

What were conditions like in the early universe?

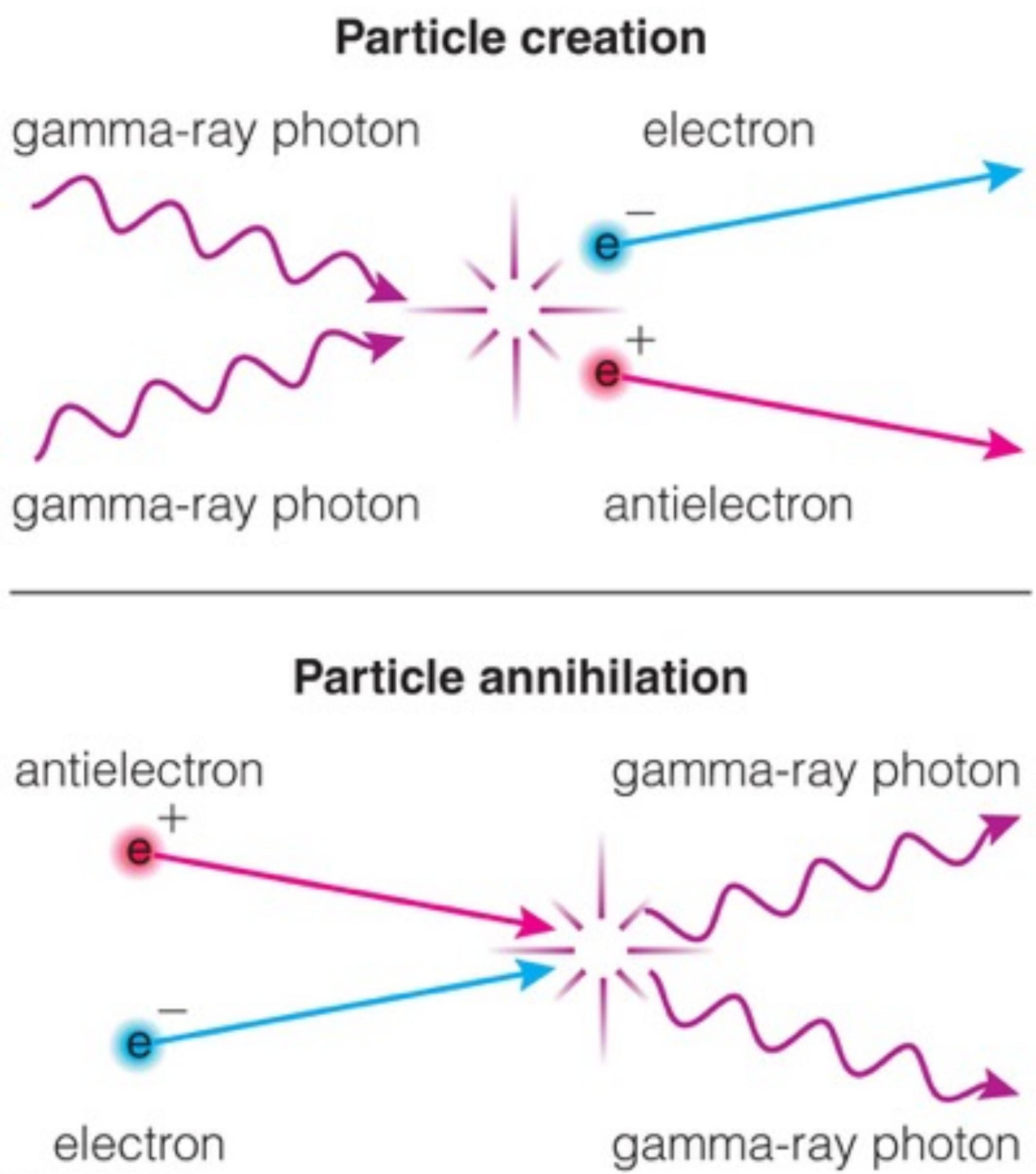




- The universe must have been much hotter and denser early in time.



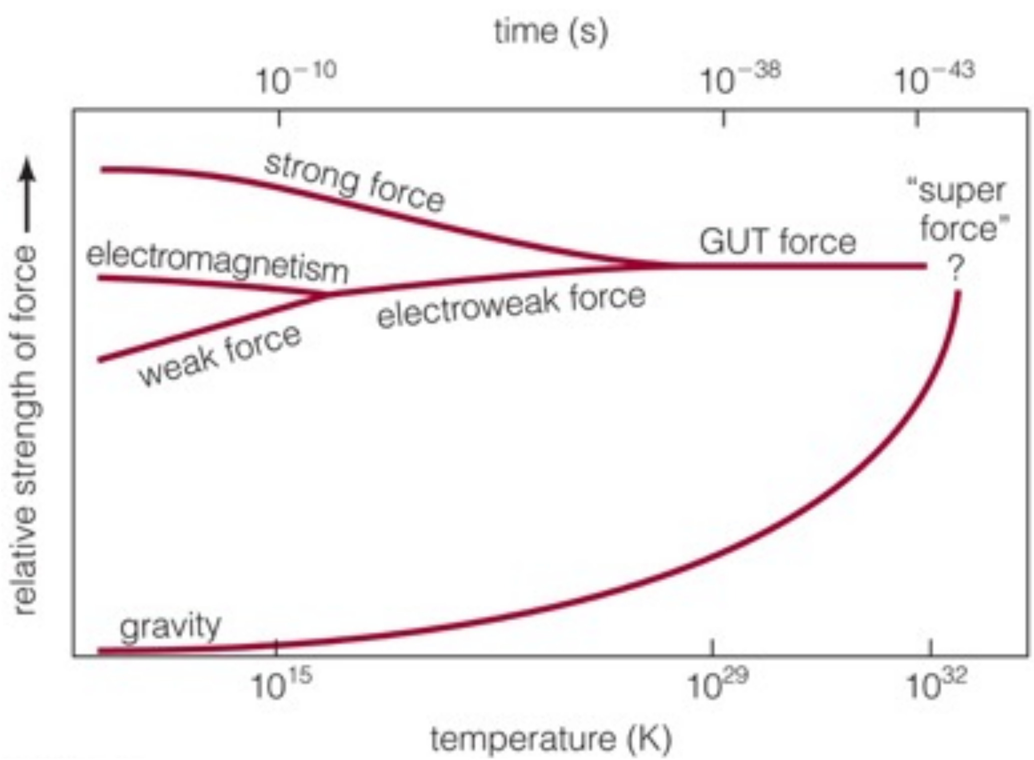
- The early universe must have been extremely hot and dense.



- Photons converted into particle–antiparticle pairs and vice versa.

$$E = mc^2$$

- The early universe was full of particles and radiation because of its high temperature.



- Four known forces in universe:

  Strong force

  Electromagnetism

  Weak force

  Gravity

Thought Question

Which of the four forces keeps you from sinking to the center of Earth?

A. gravity
B. electromagnetism
C. strong force
D. weak force

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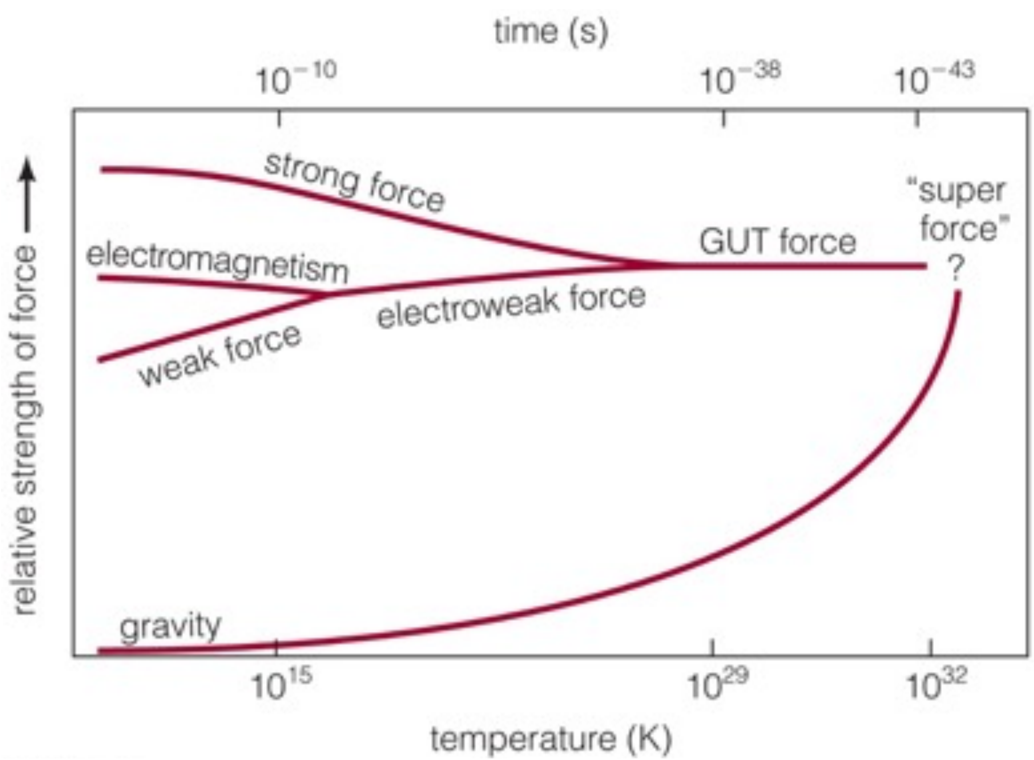
Do forces unify at high temperatures?



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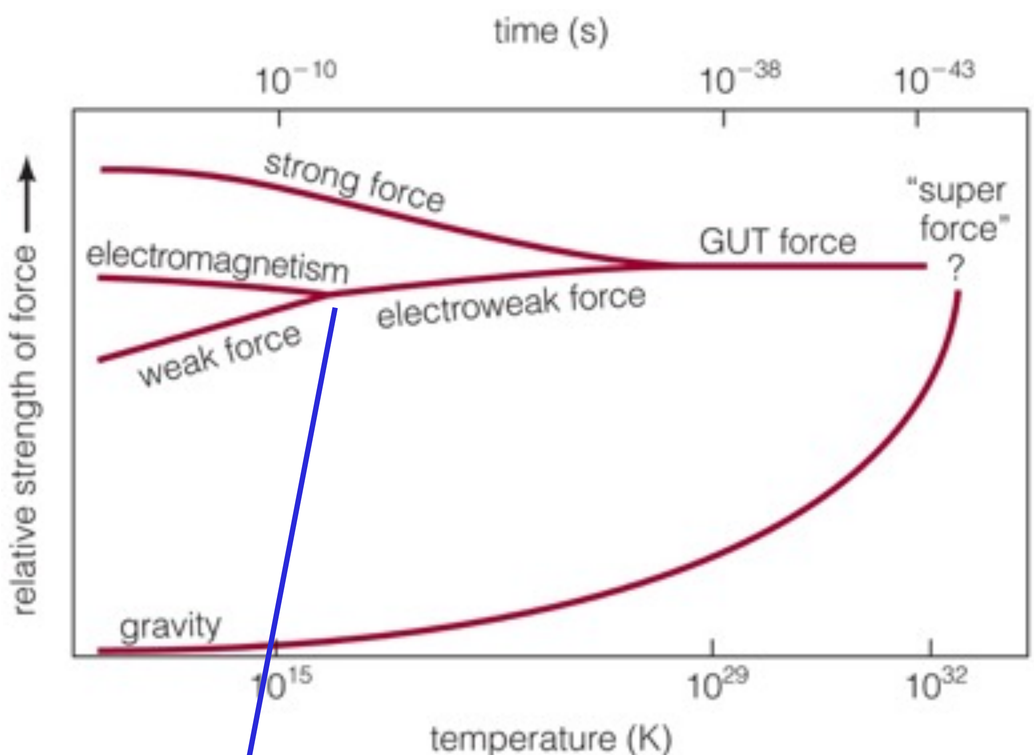

Yes!
(Electroweak)

- Four known forces in universe:

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Electromagnetism

Weak force

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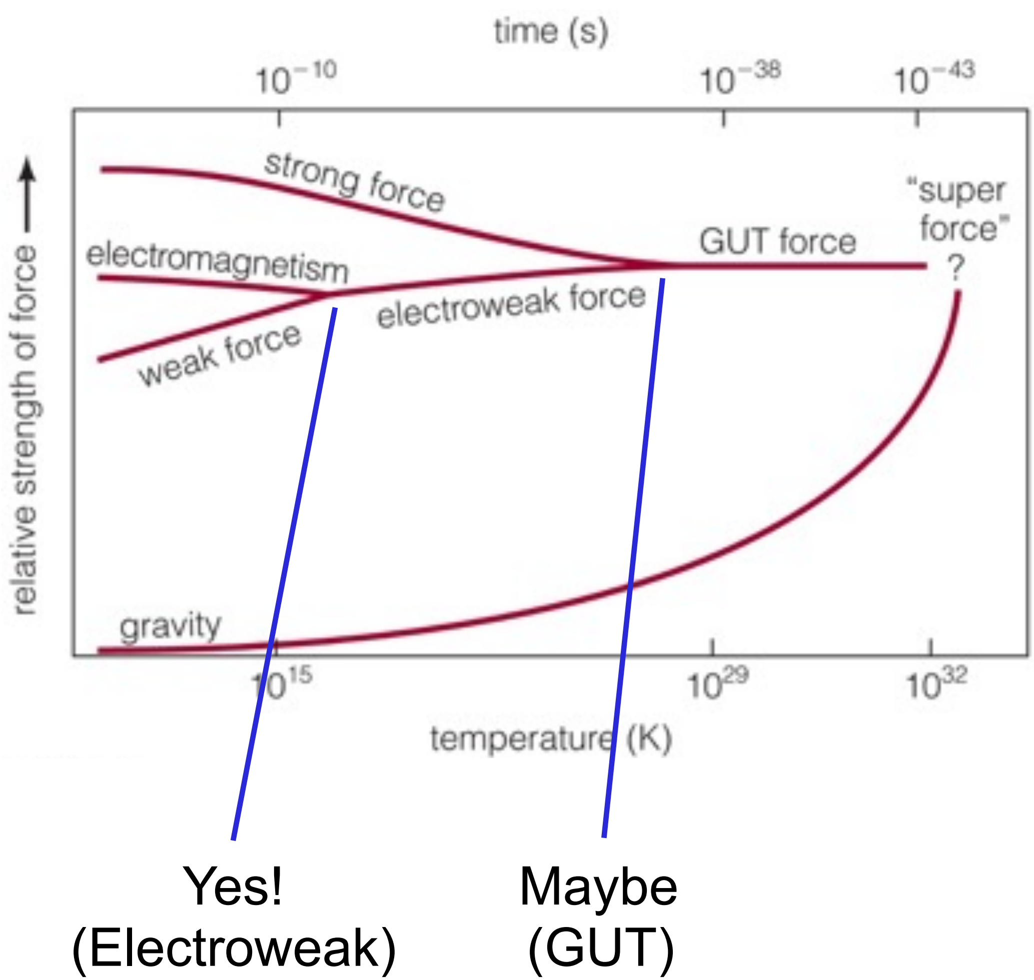
Do forces unify at high temperatures?



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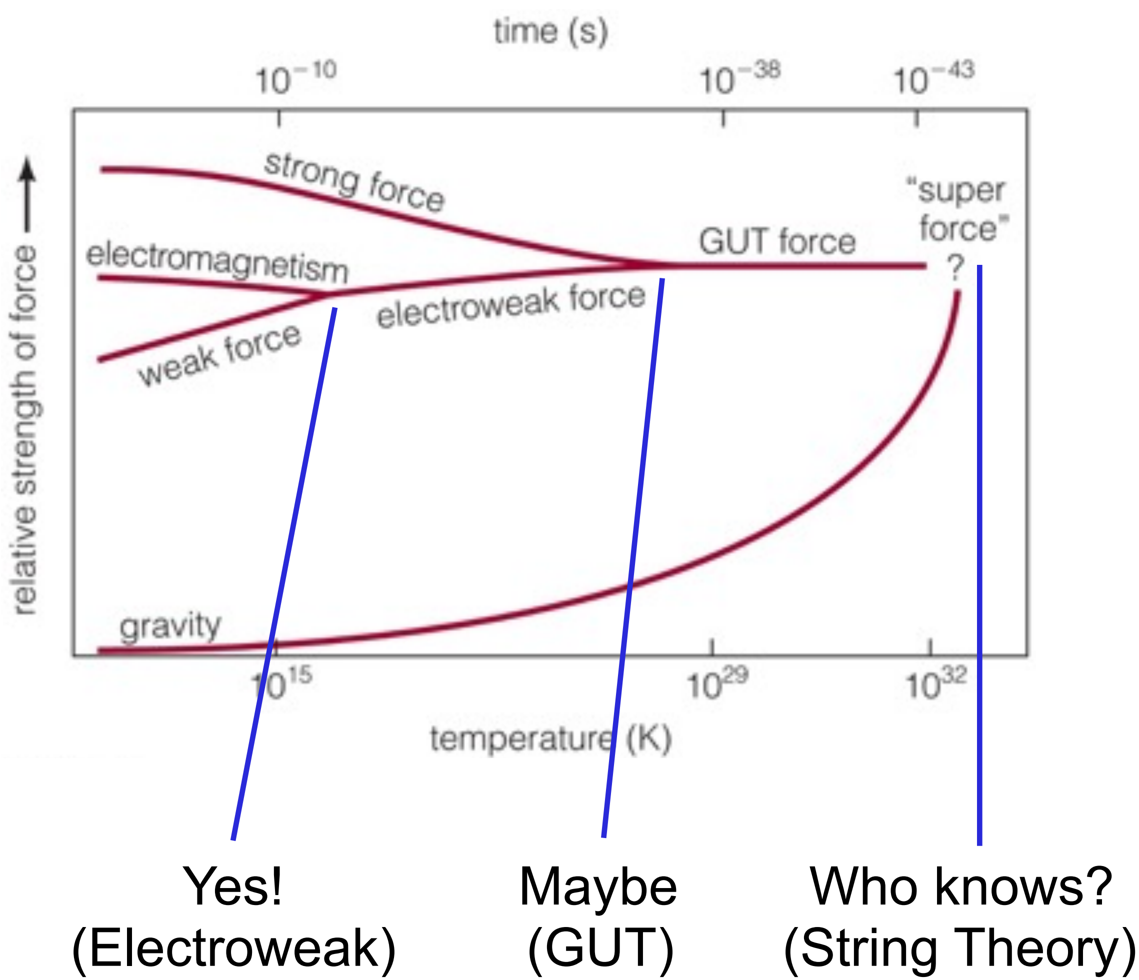


- Four known forces in universe:

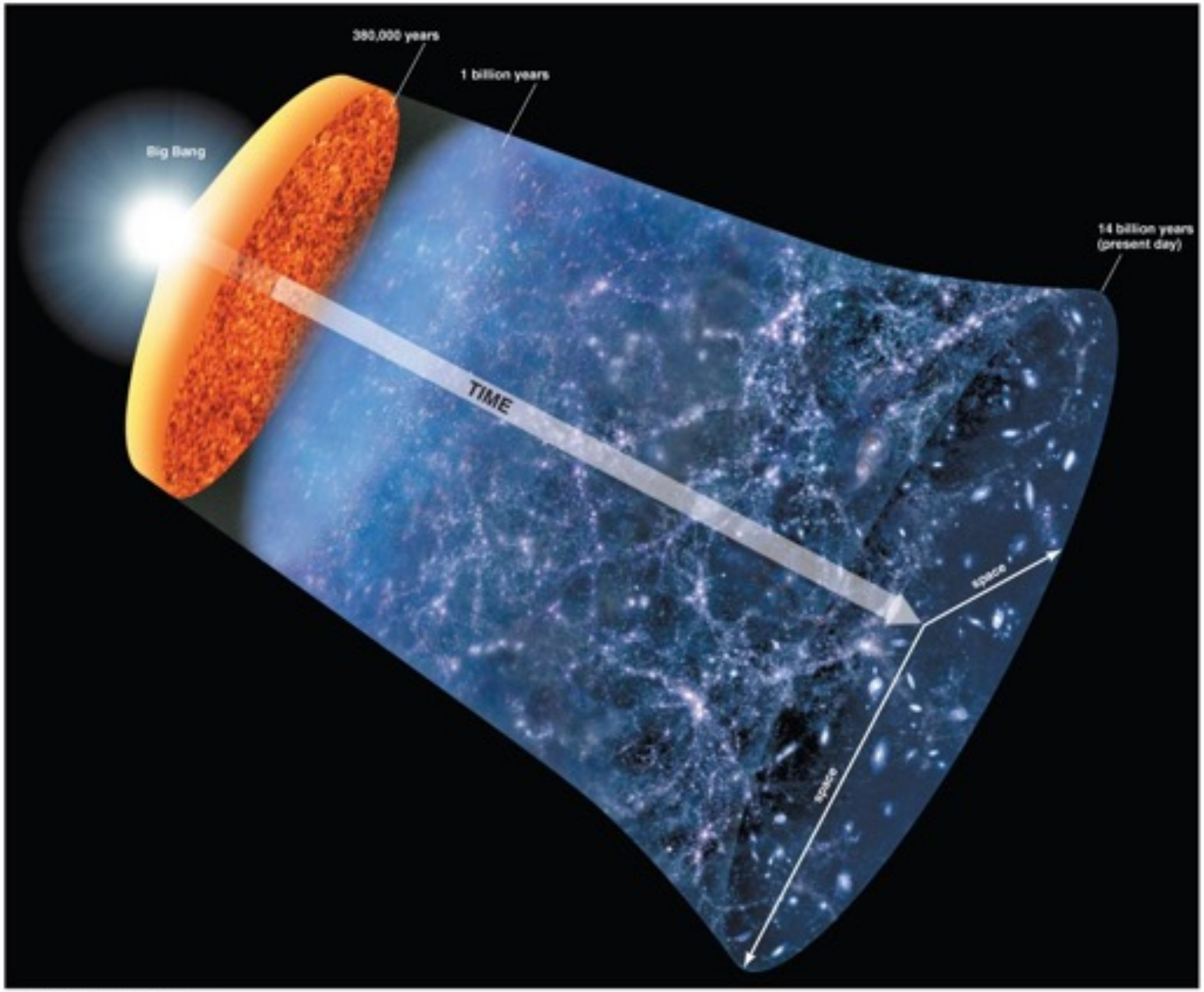
Strong force

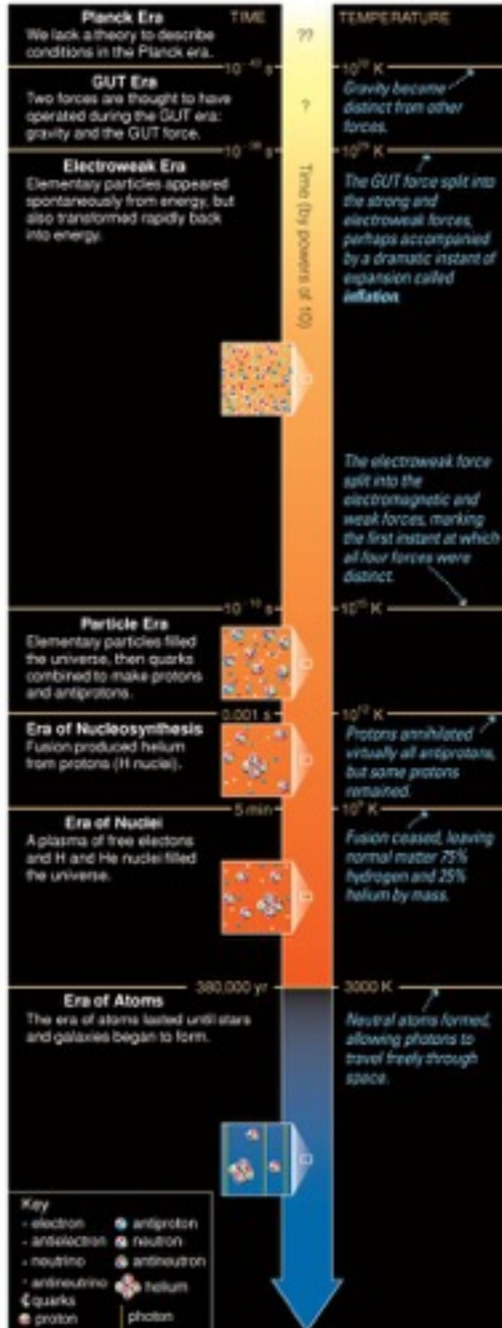
Electromagnetism

Weak force

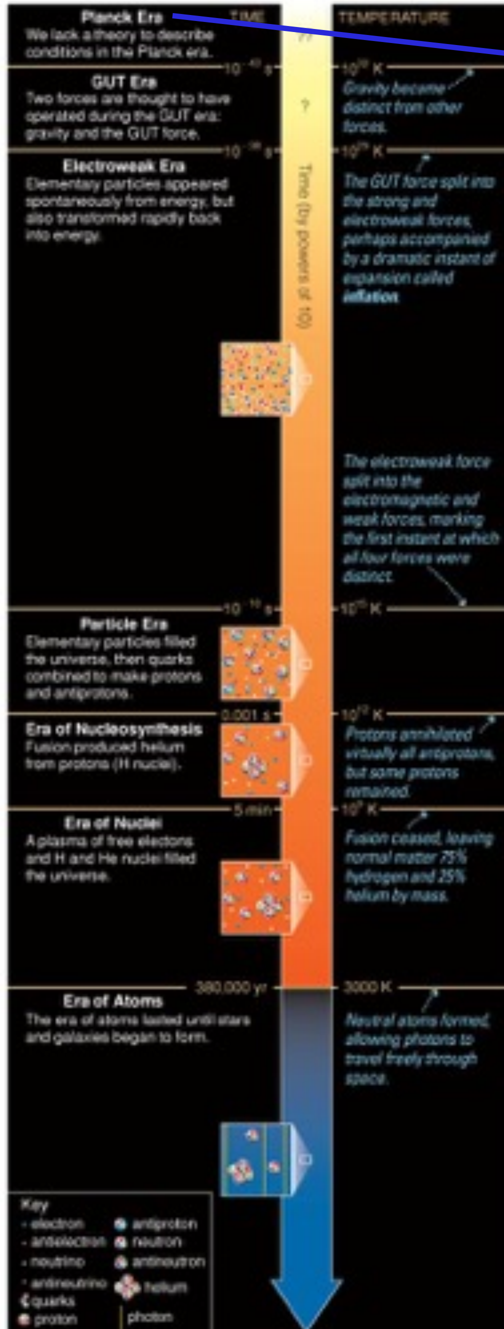
Gravity

How did the early universe change with time?



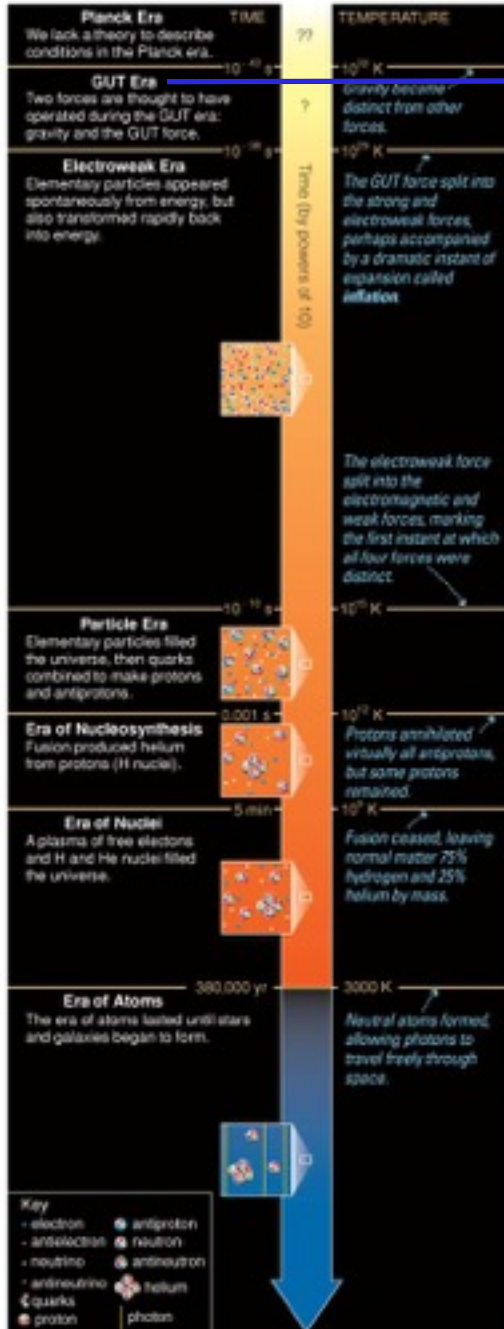


Interactive Figure



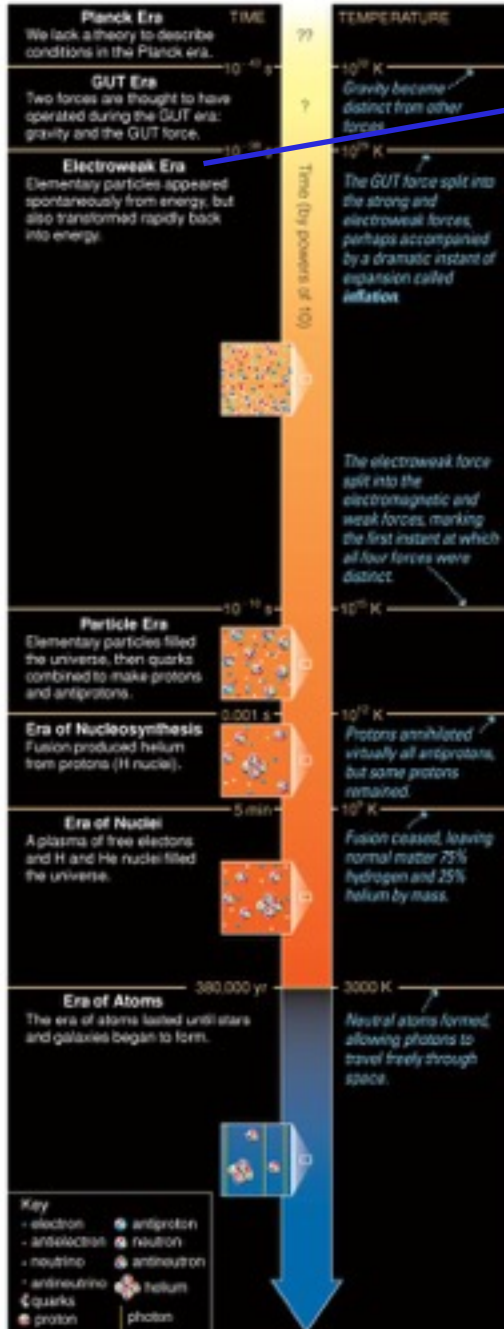
Planck era

- Before Planck time ($\sim 10^{-43}$ second)
- No theory of quantum gravity



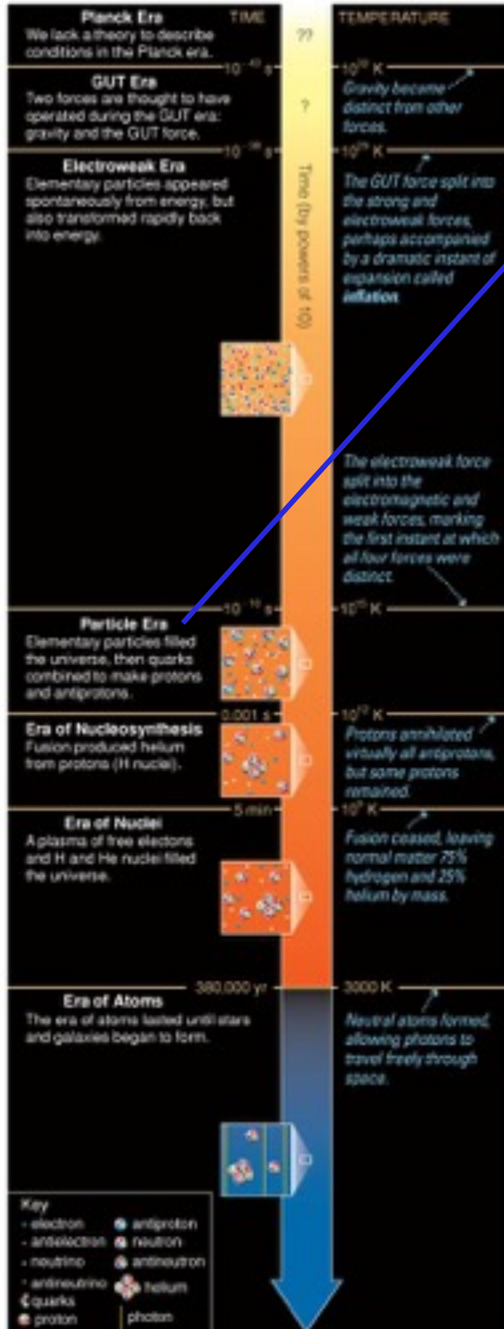
GUT era

- Lasts from Planck time ($\sim 10^{-43}$ second) to end of GUT force ($\sim 10^{-38}$ second)



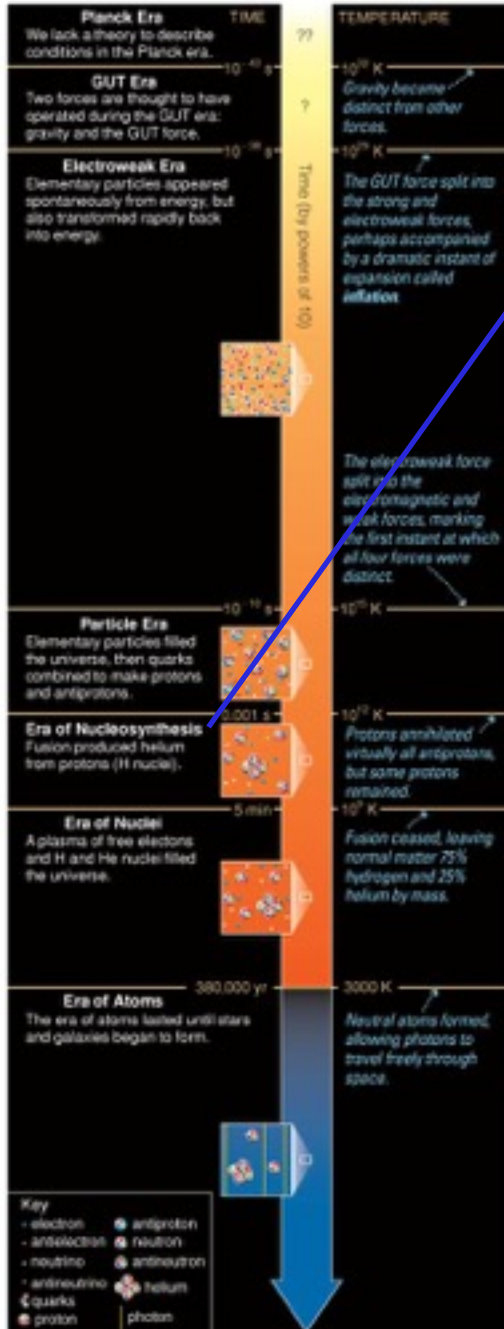
Electroweak era

- Lasts from end of GUT force (~10^{-38} second) to end of electroweak force (~10^{-10} second).



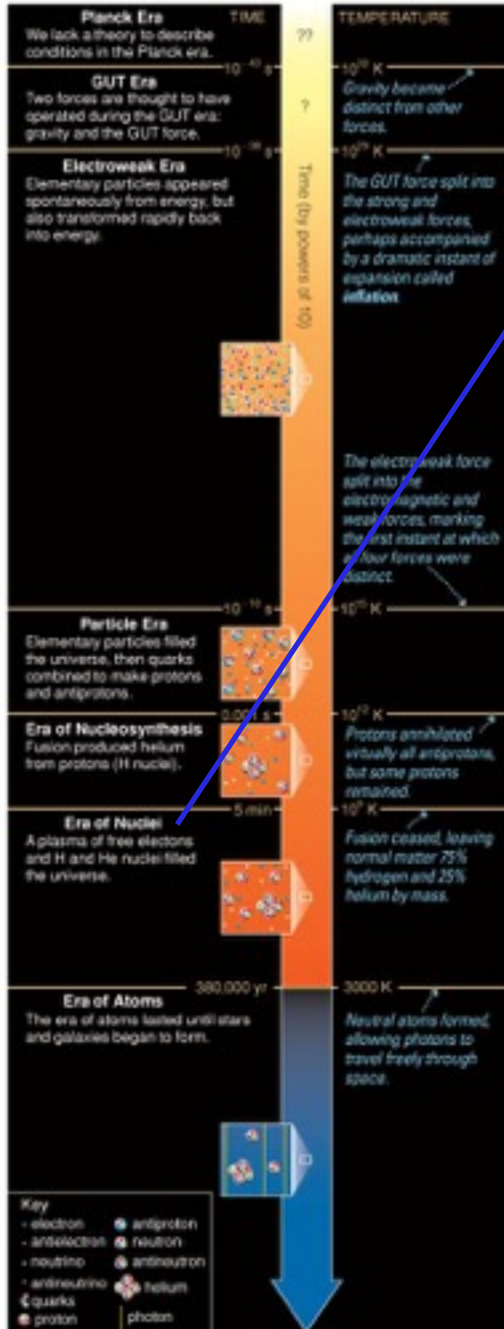
Particle era

- Amounts of matter and antimatter nearly equal (roughly 1 extra proton for every 10^9 proton–antiproton pairs!)



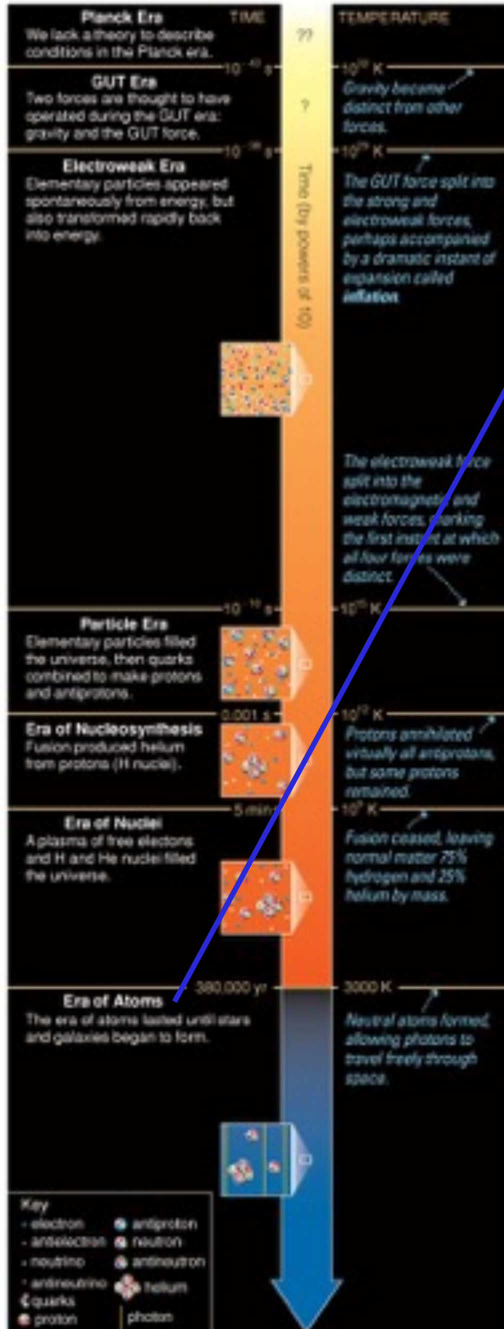
Era of nucleosynthesis

- Begins when matter annihilates remaining antimatter at ~ 0.001 second.
- Nuclei begin to fuse.



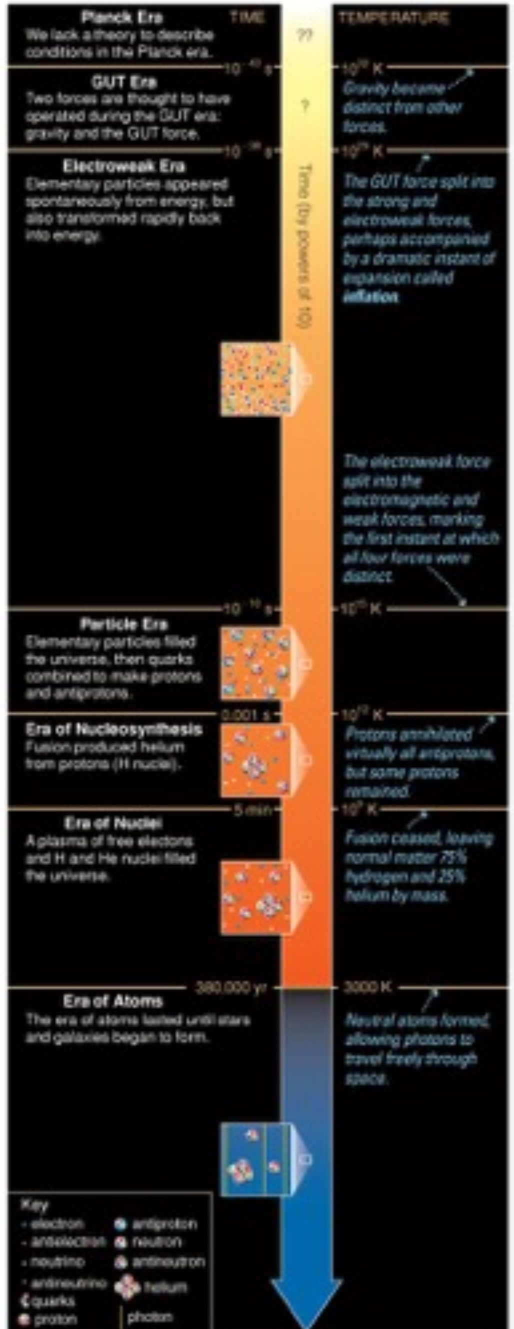
Era of nuclei

- Helium nuclei form at age ~ 3 minutes.
- Universe became too cool to blast helium apart.



Era of atoms

- Atoms form at age ~ 380,000 years.
- Background radiation released.



Era of galaxies

- Galaxies form at age ~ 1 billion years.

What have we learned?

- **What were conditions like in the early universe?**
  - The early universe was so hot and so dense that radiation was constantly producing particle–antiparticle pairs and vice versa.
- **How did the early universe change with time?**
  - As the universe cooled, particle production stopped, leaving matter instead of antimatter.
  - Fusion turned remaining neutrons into helium.
  - Radiation traveled freely after formation of atoms.

22.2 Evidence for the Big Bang

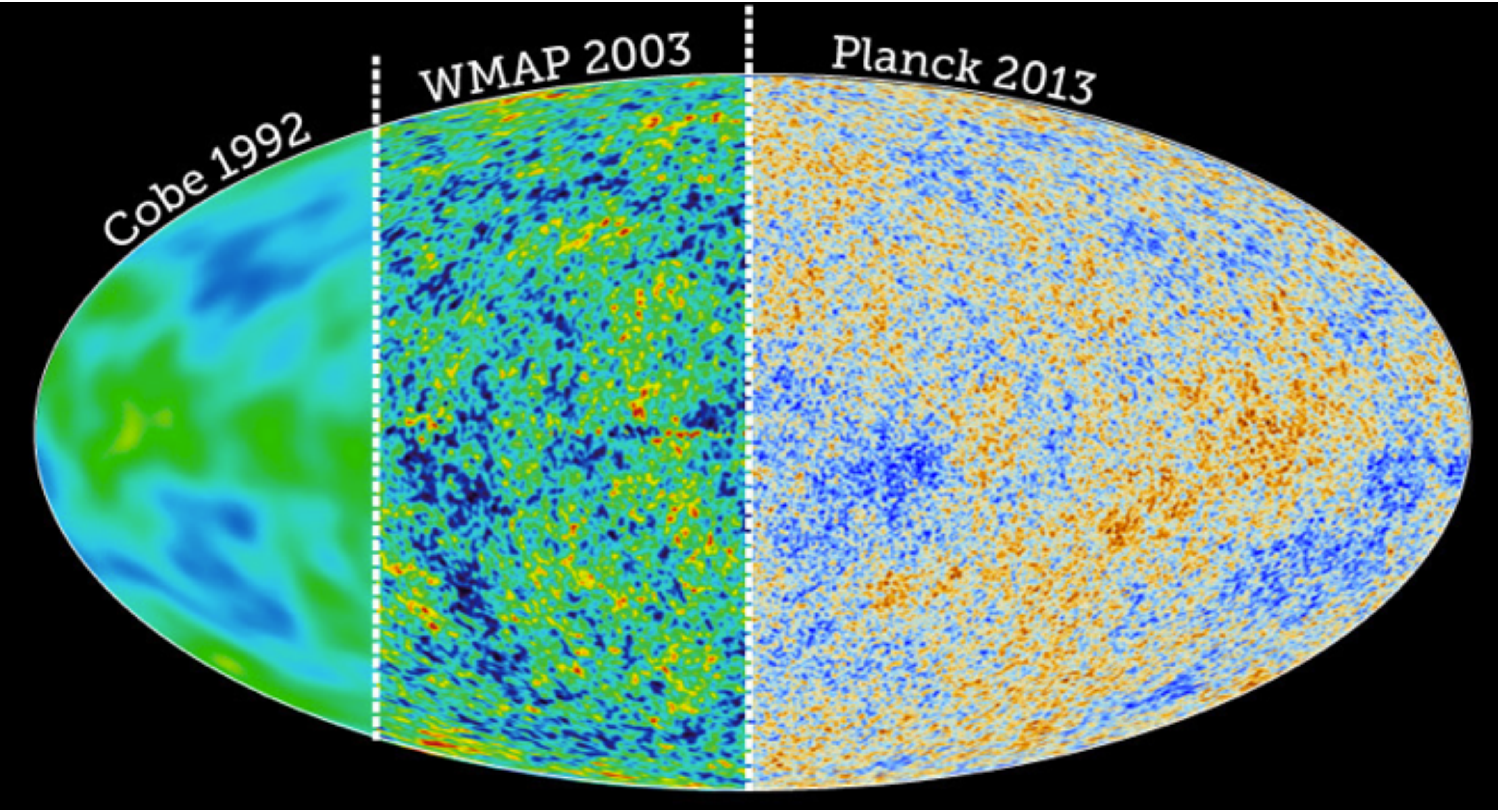
- Our goals for learning:
  - **How do observations of the cosmic microwave background support the Big Bang theory?**
  - **How do the abundances of elements support the Big Bang theory?**

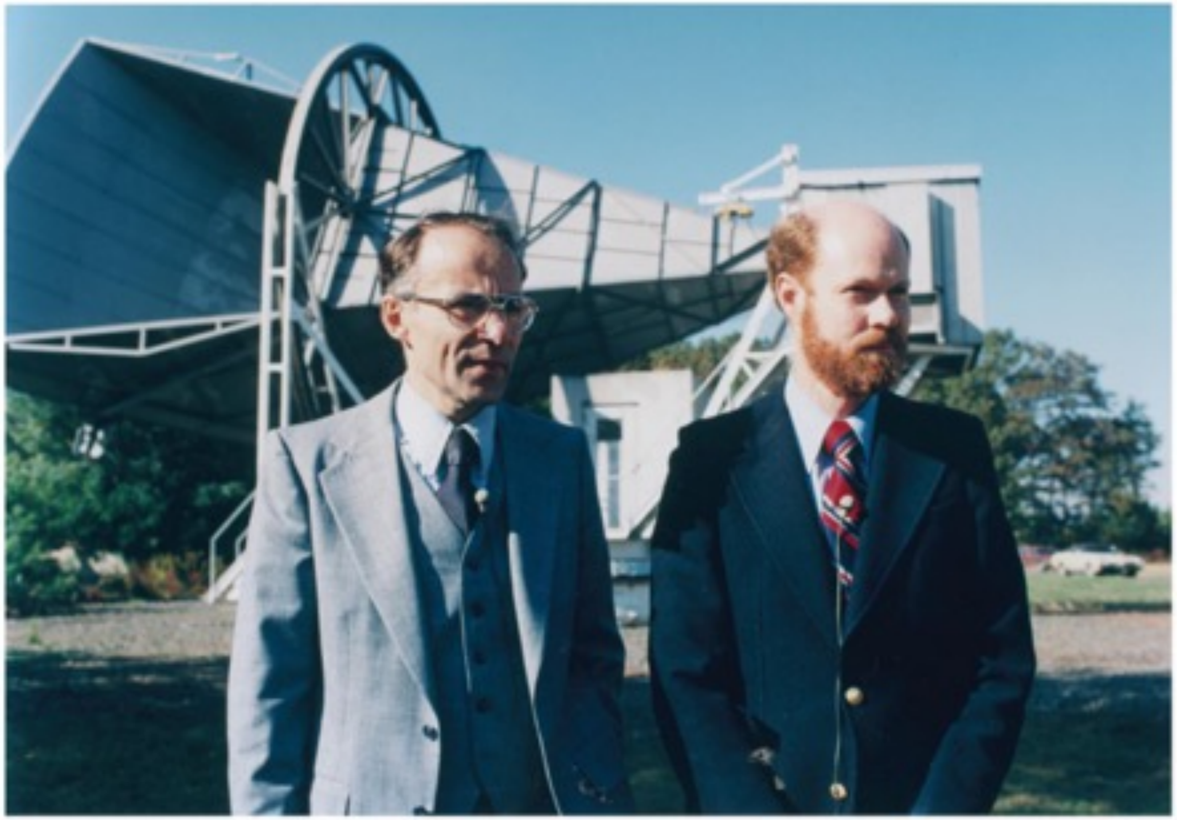
Primary Evidence

1) We have detected the leftover radiation from the Big Bang.

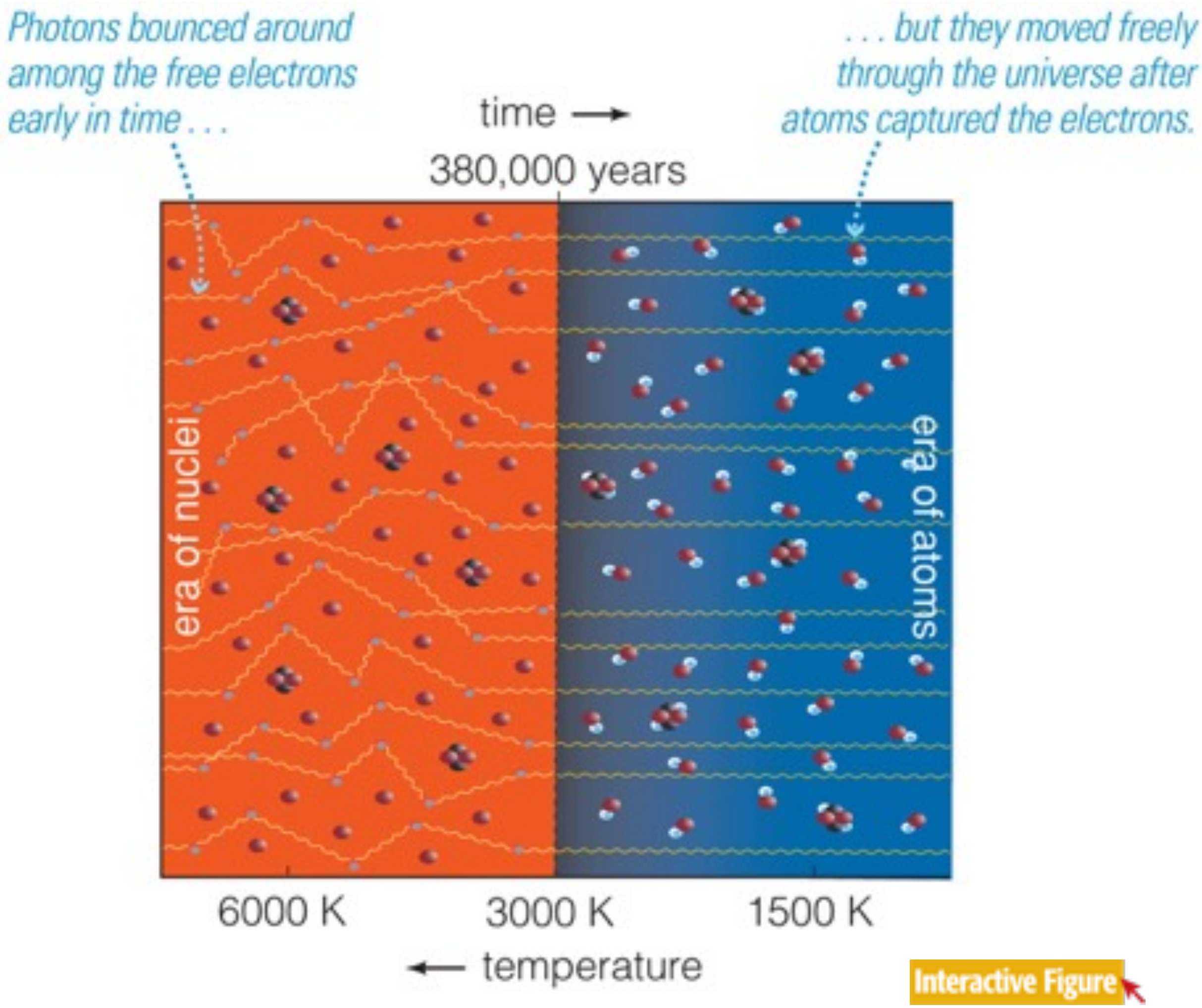
2) The Big Bang theory correctly predicts the abundance of helium and other light elements.

How do observations of the cosmic microwave background support the Big Bang theory?



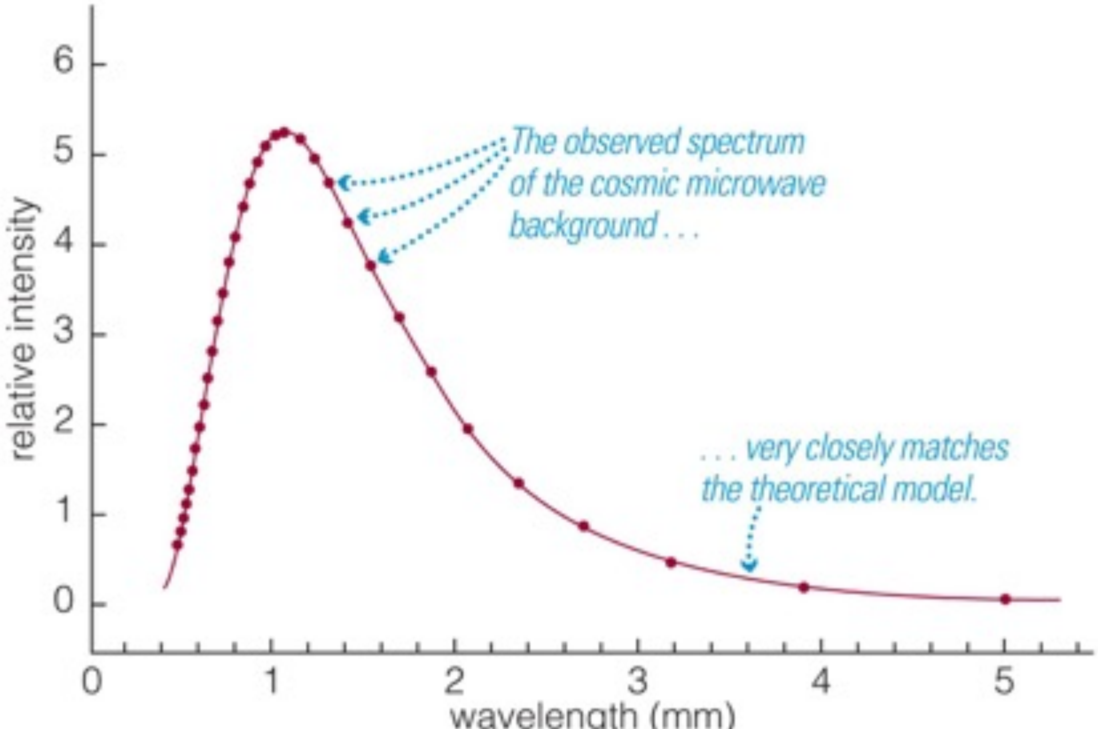


- The ***cosmic microwave background***—the radiation left over from the Big Bang—was detected by Penzias and Wilson in 1965.

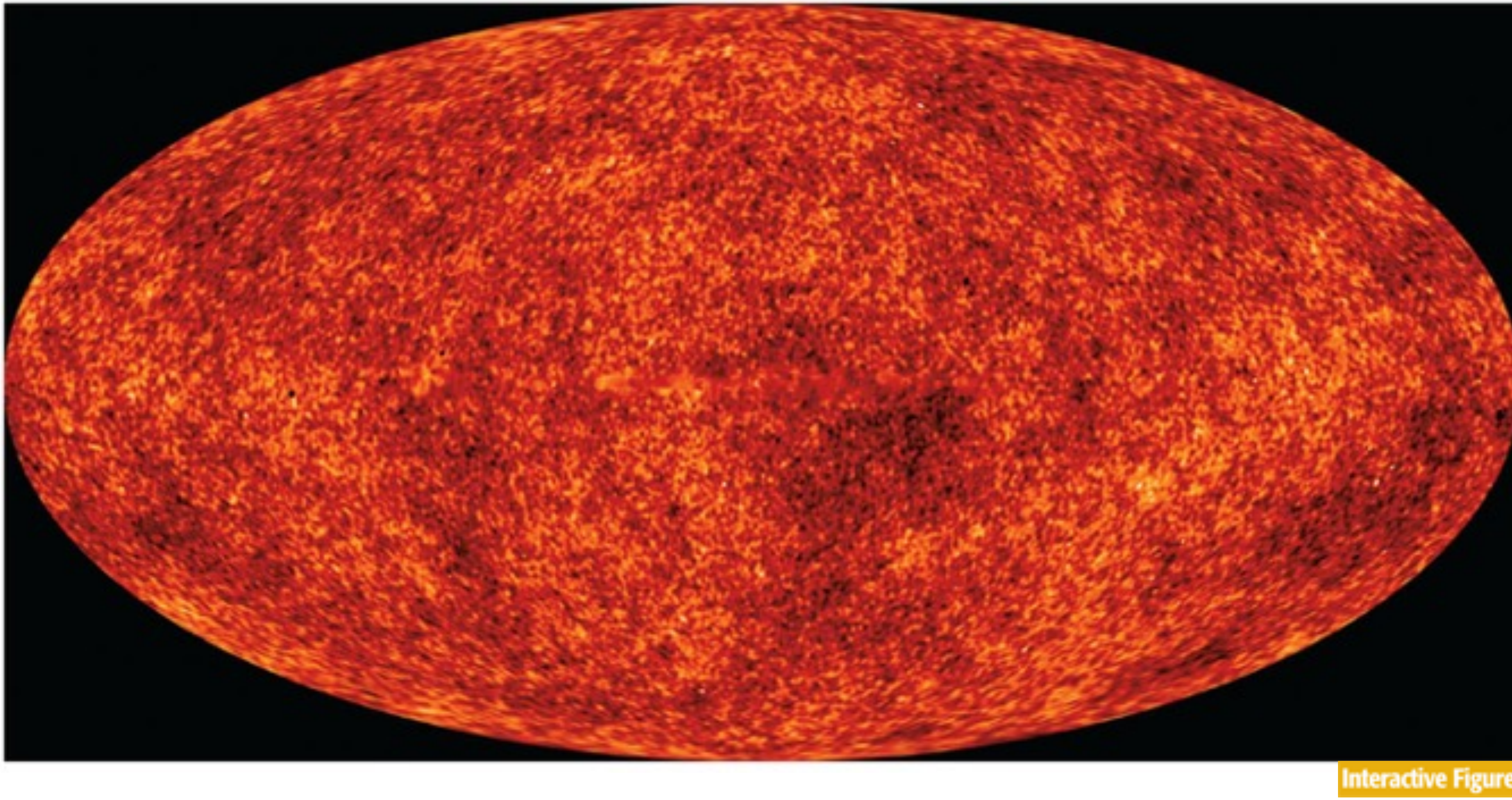


- Background radiation from Big Bang has been freely streaming across universe since atoms formed at temperature ~ 3000 K: *visible/IR.*

- Background has perfect thermal radiation spectrum at temperature 2.73 K.

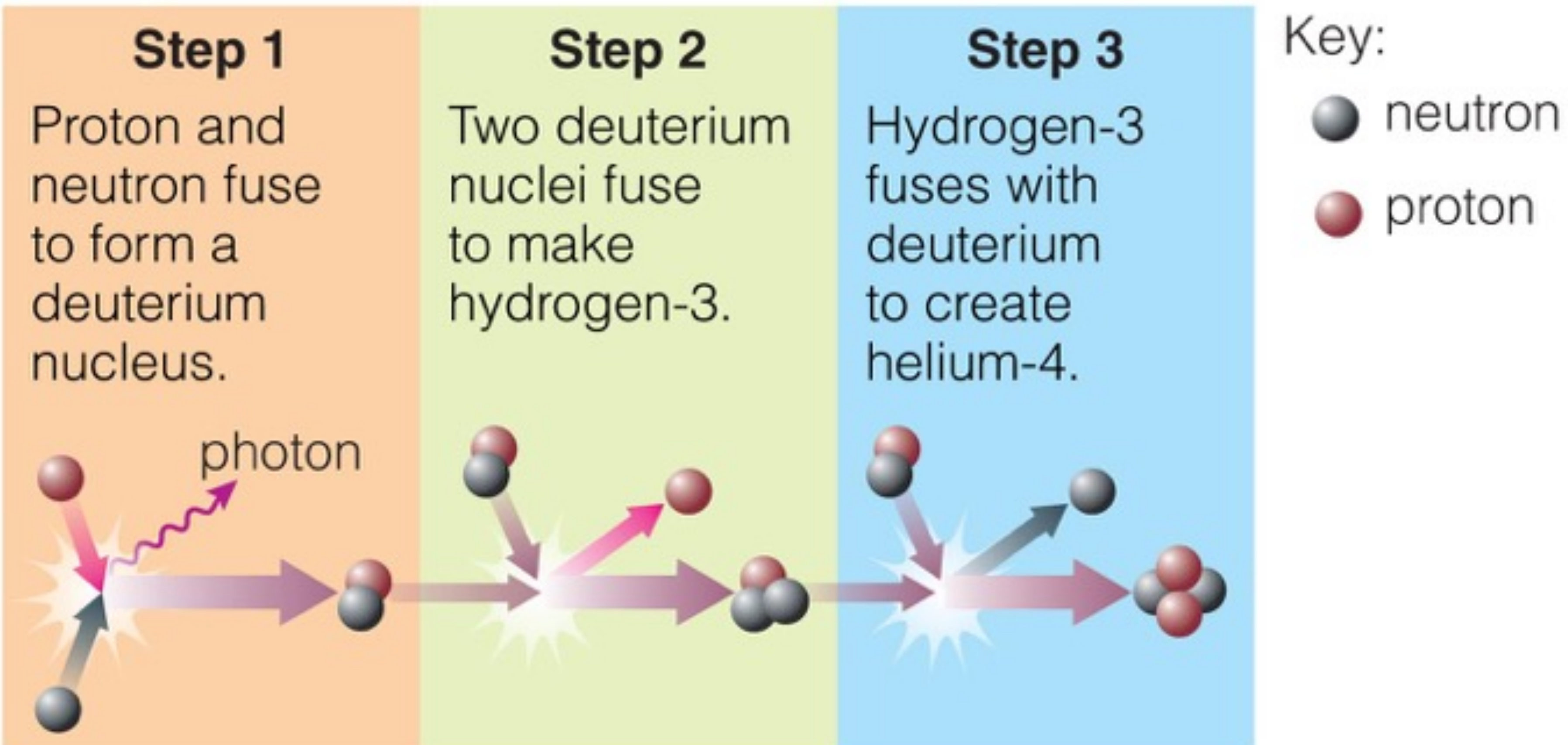


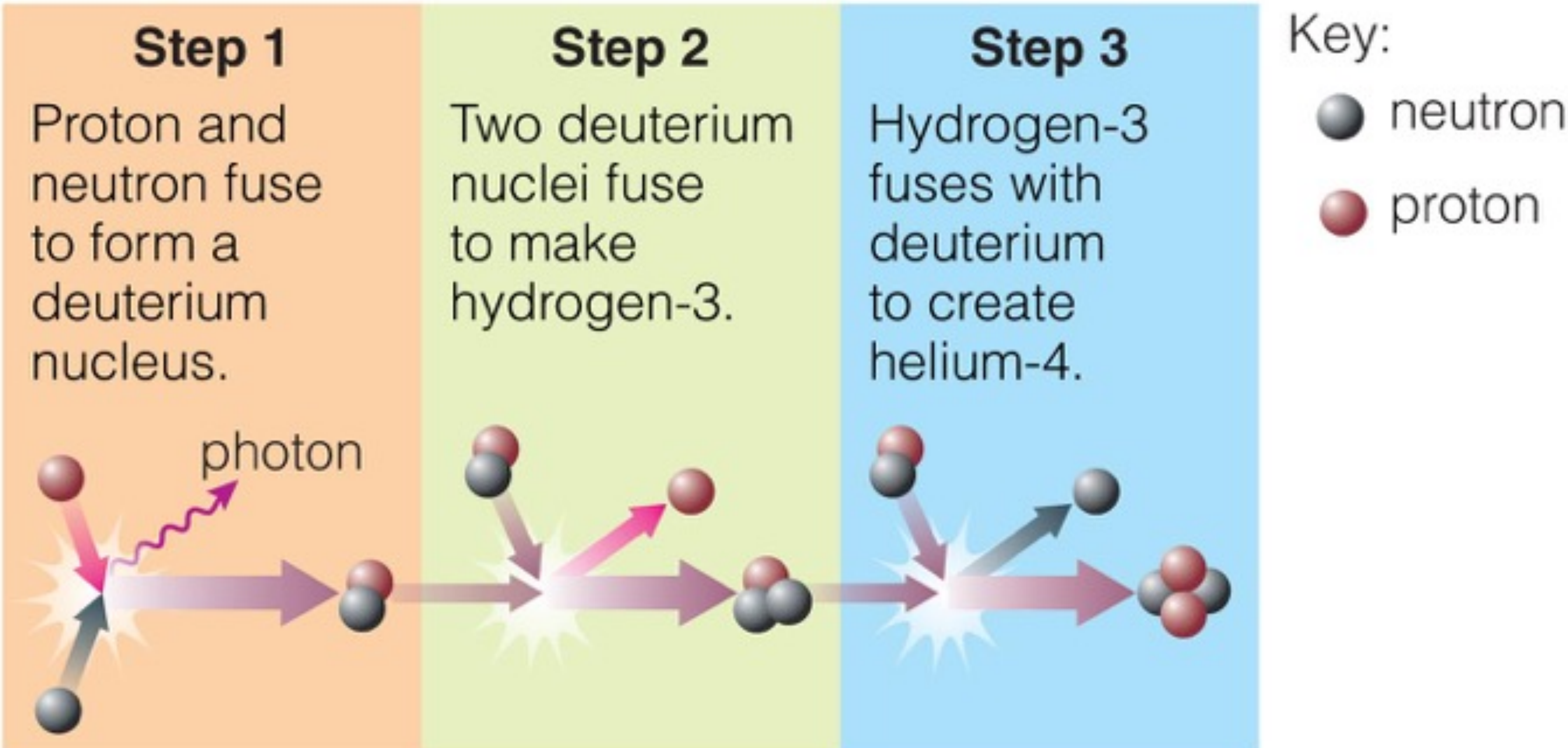
- Expansion of universe has redshifted thermal radiation from that time to ~1000 times longer wavelength: *microwaves.*



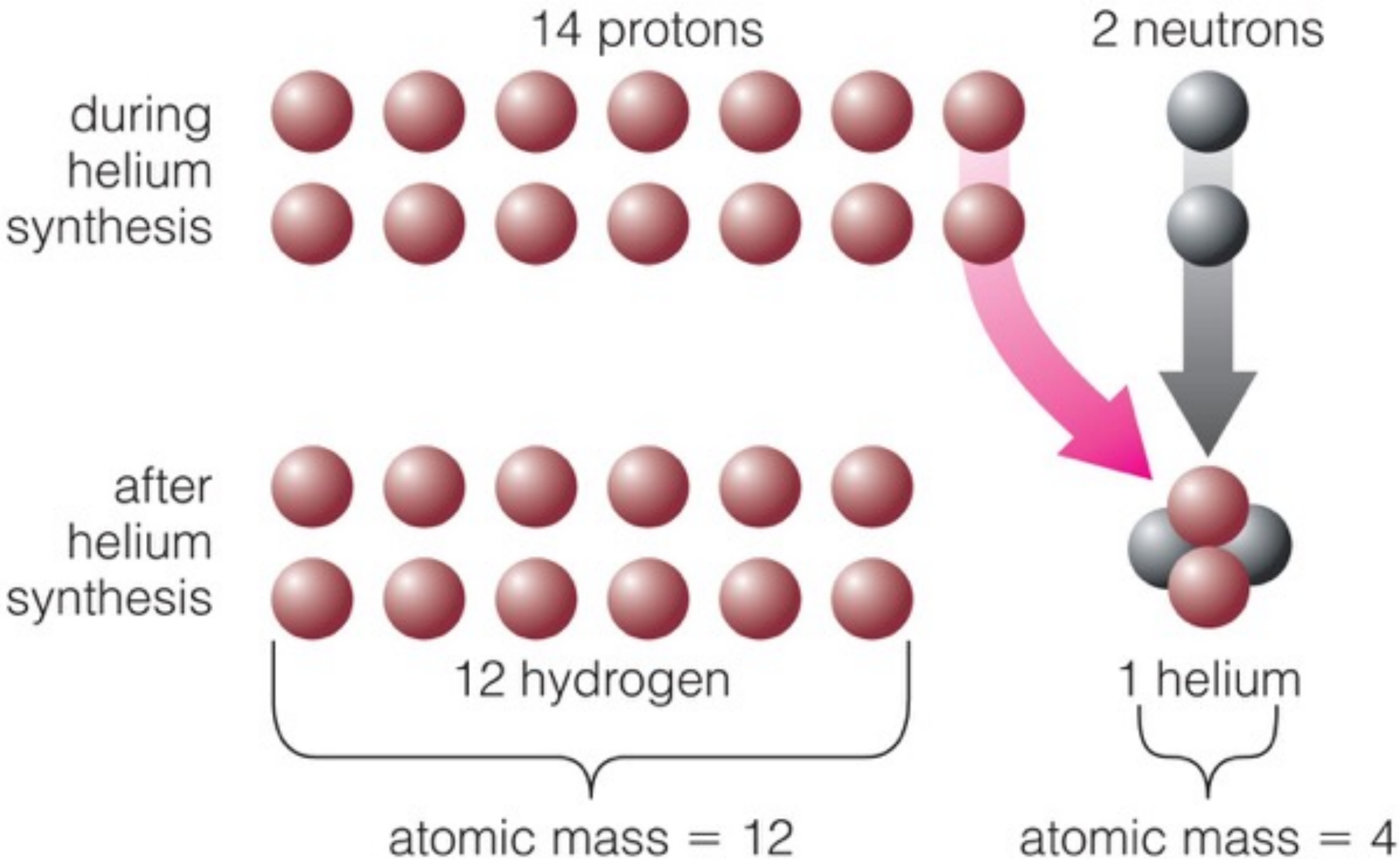
- WMAP gives us detailed baby pictures of structure in the universe.

How do the abundances of elements support the Big Bang theory?





- Protons and neutrons combined to make long-lasting helium nuclei when universe was ~ 3 minutes old.



- Big Bang theory prediction: 75% H, 25% He (by mass). This prediction matches observations of primordial gases.

Thought Question

Which of these abundance patterns is an unrealistic chemical composition for a star?

A. 70% H, 28% He, 2% other
B. 95% H, 5% He, less than 0.02% other
C. 75% H, 25% He, less than 0.02% other
D. 72% H, 27% He, 1% other

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D. 72% H, 27% He, 1% other

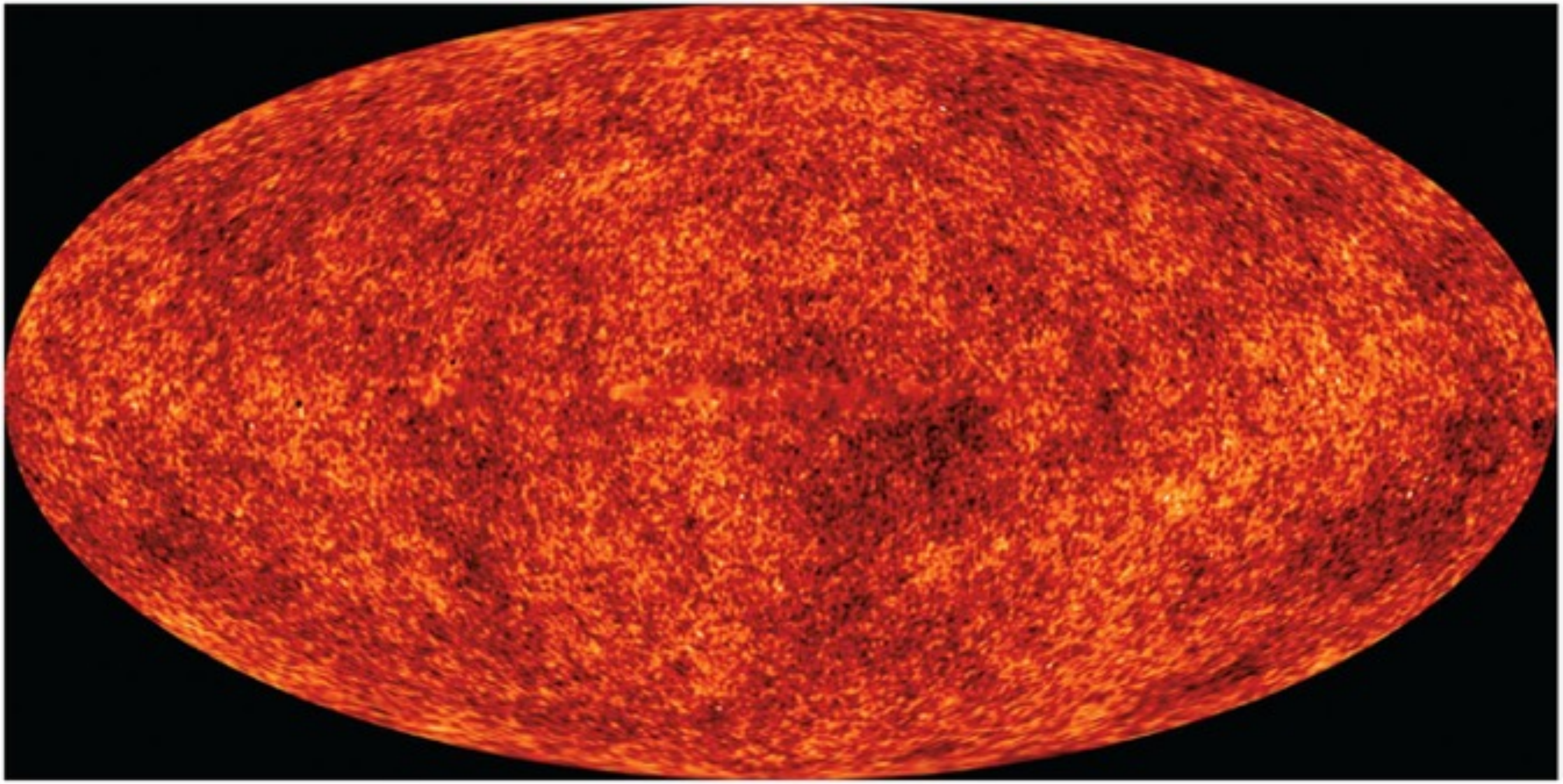
What have we learned?

- **How do observations of the cosmic microwave background support the Big Bang theory?**
  – Radiation left over from the Big Bang is now in the form of microwaves—the cosmic microwave background—which we can observe with a radio telescope.
- **How do the abundances of elements support the Big Bang theory?**
  – Observations of helium and other light elements agree with the predictions for fusion in the Big Bang theory.

22.3 The Big Bang and Inflation

- Our goals for learning:
  - **What key features of the universe are explained by inflation?**
  - **Did inflation really occur?**

What key features of the universe are explained by inflation?



Mysteries Needing Explanation

1) Where does structure come from?

2) Why is the overall distribution of matter so uniform?

3) Why is the density of the universe so close to the critical density?

Mysteries Needing Explanation

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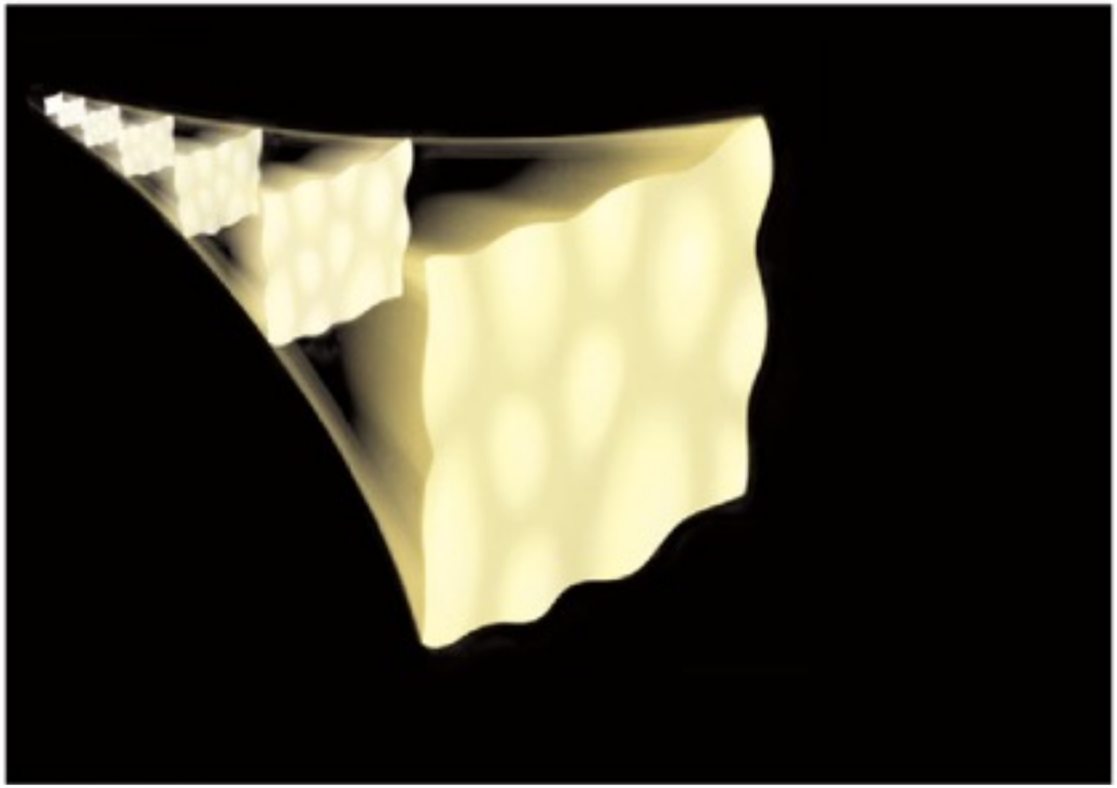
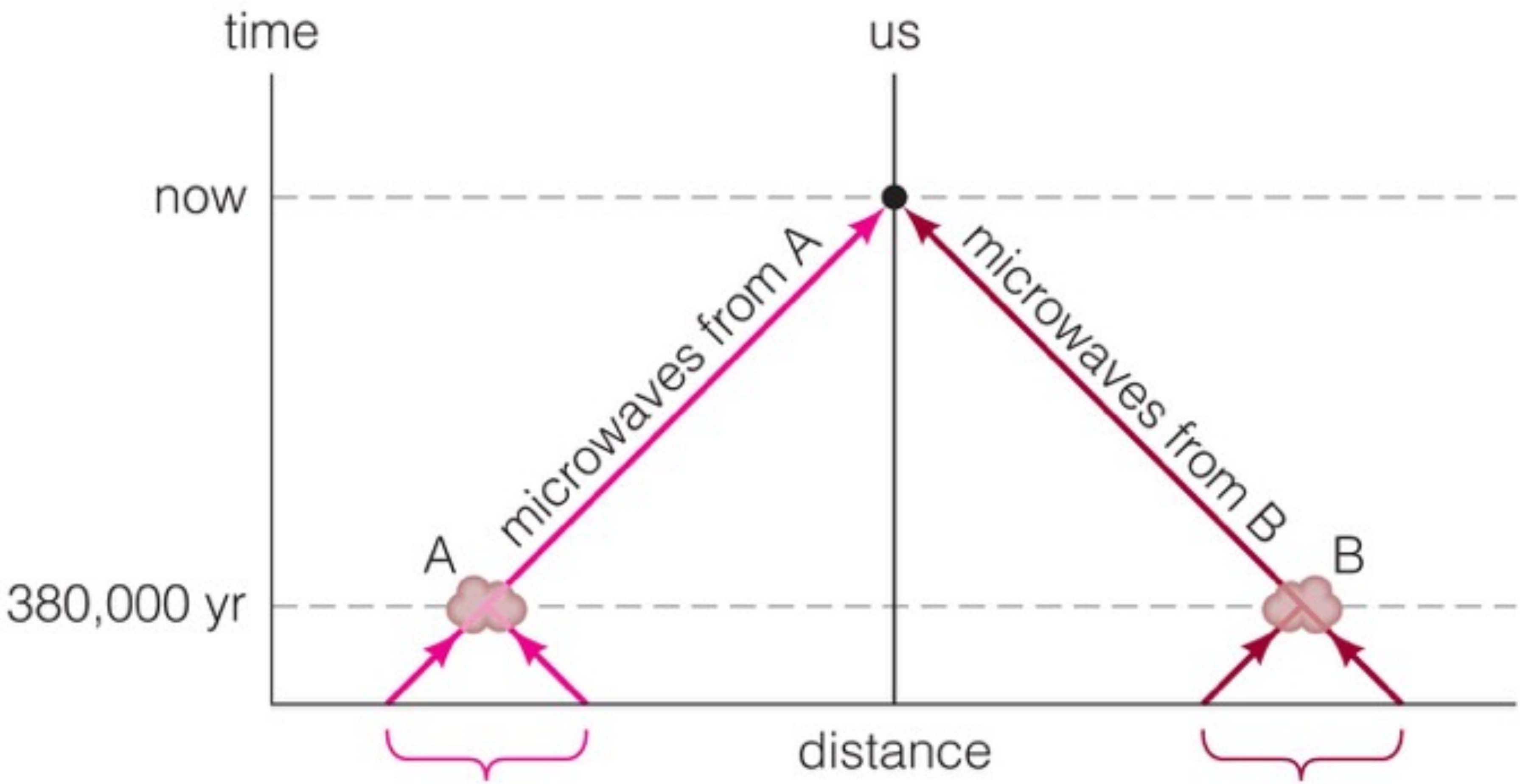
2) Why is the overall distribution of matter so uniform?

3) Why is the density of the universe so close to the critical density?

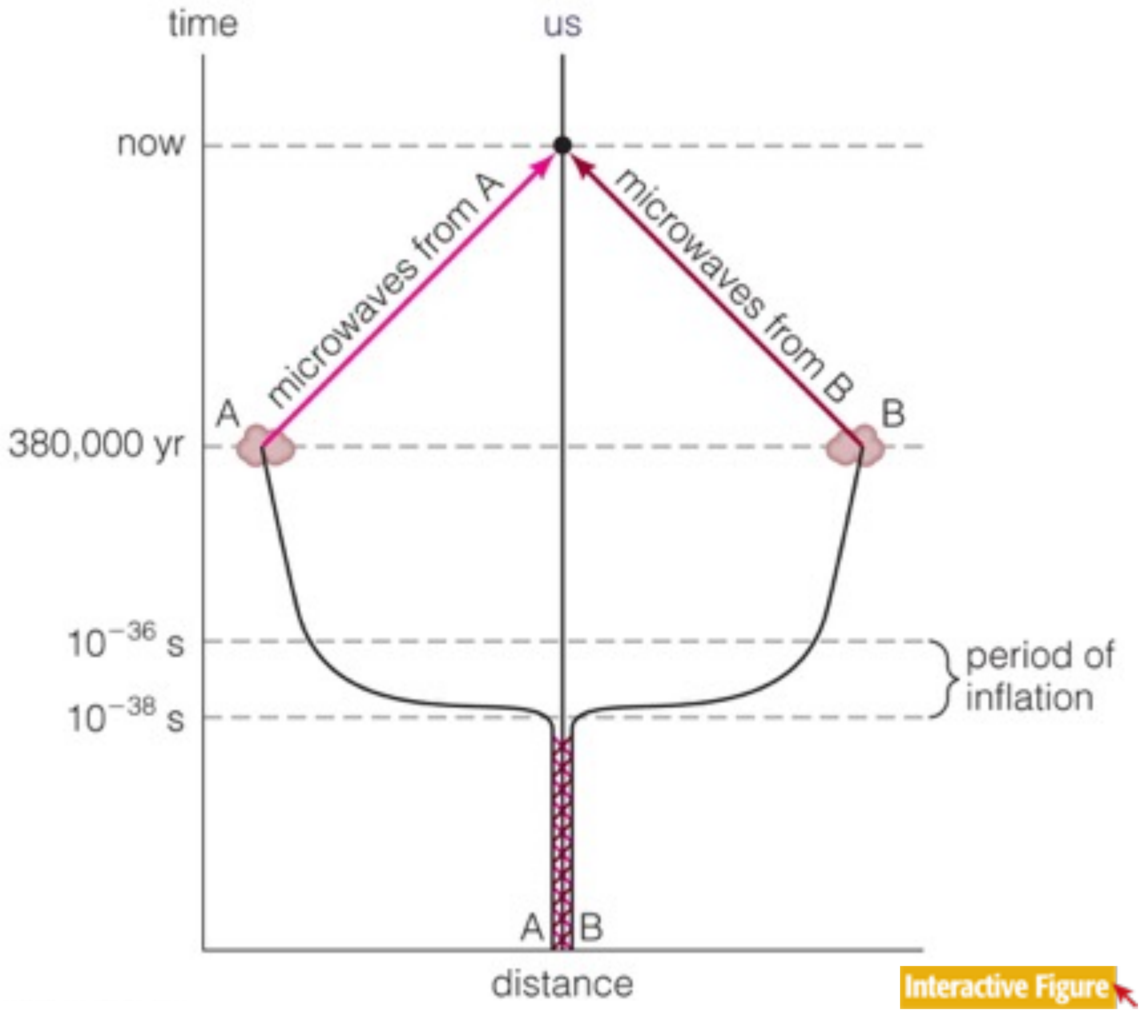
An early episode of rapid inflation can solve all three mysteries!



- Inflation can make all the structure by stretching tiny quantum ripples to enormous size.
- These ripples in density then become the seeds for all structures in the universe.

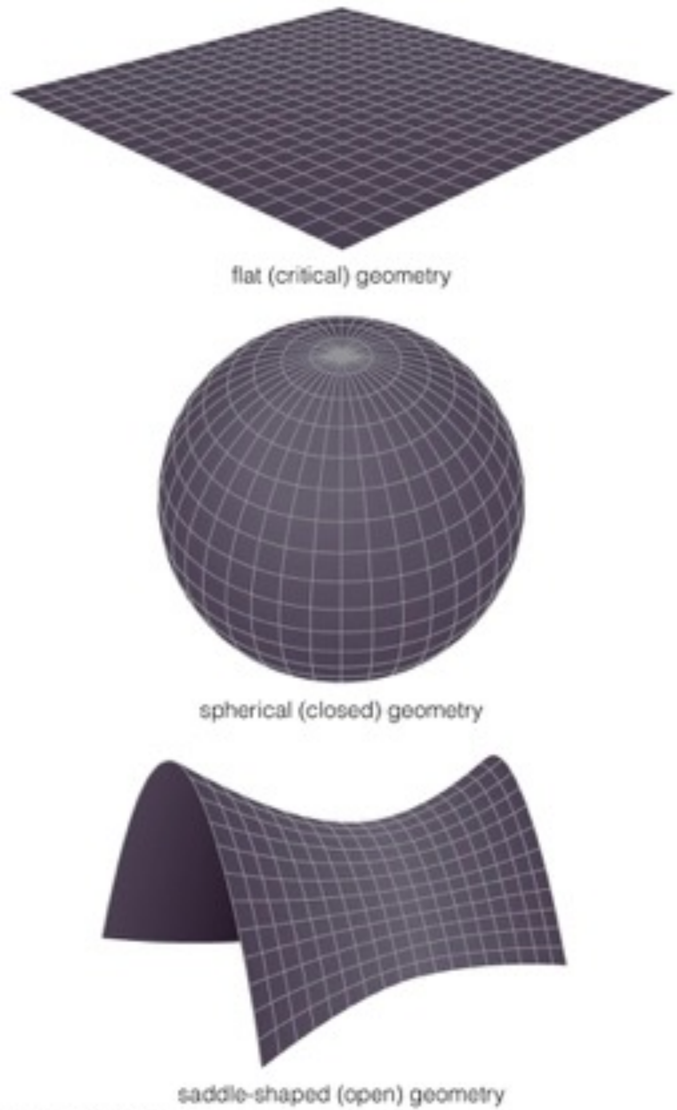


- How can microwave temperature be nearly identical on opposite sides of the sky?

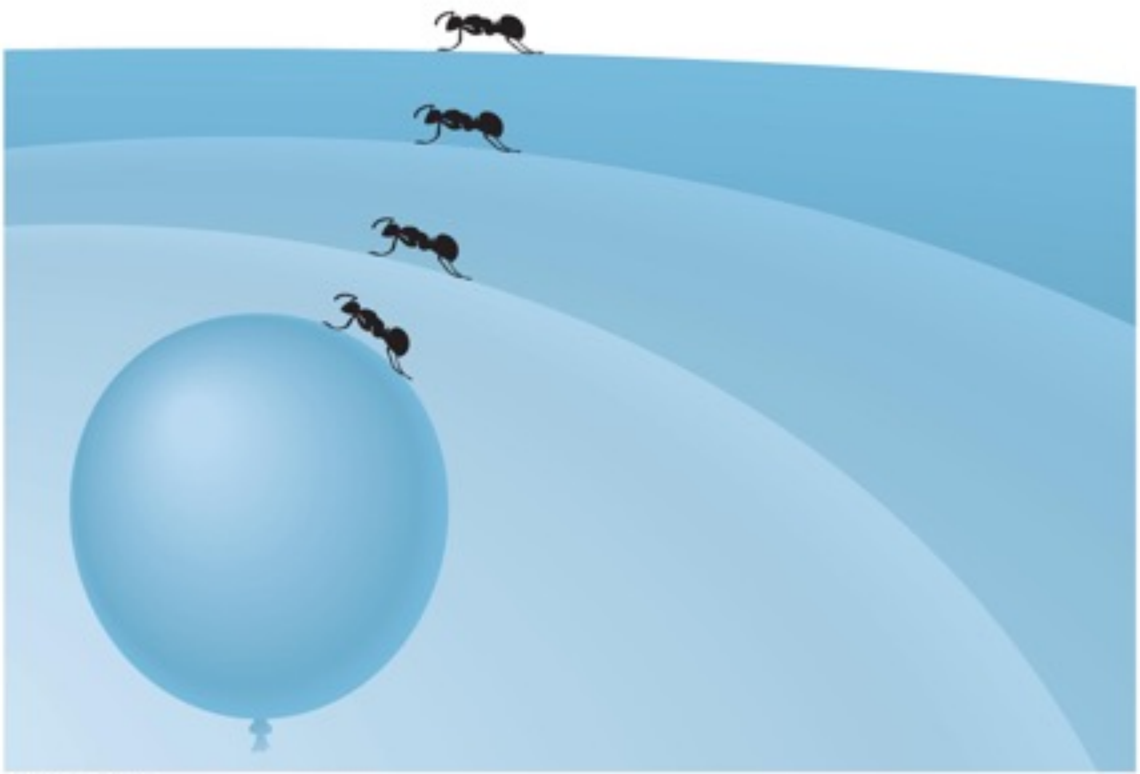


- Regions now on opposite sides of the sky were close together before inflation pushed them far apart.

- Density = Critical
- Density > Critical
- Density < Critical

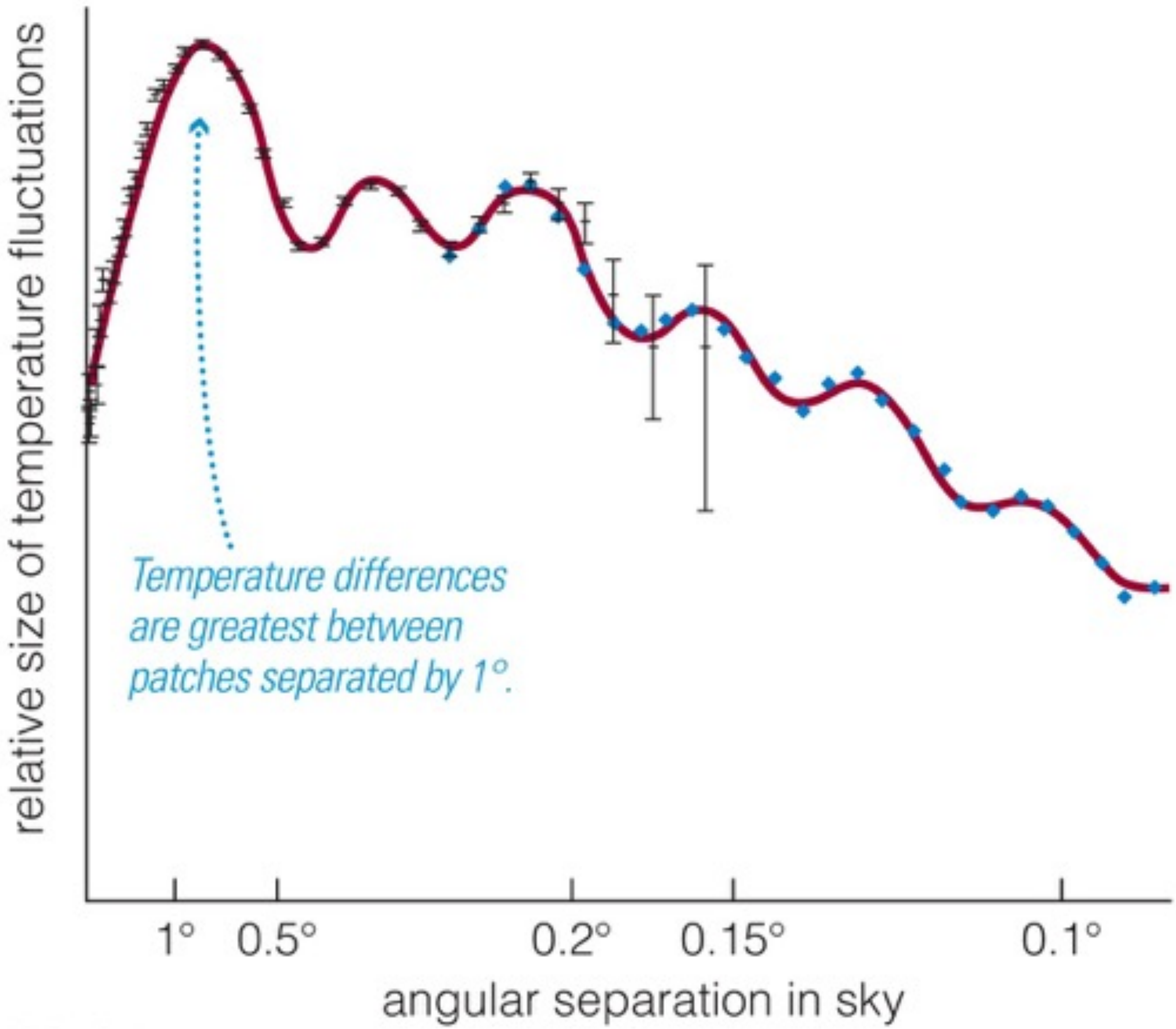


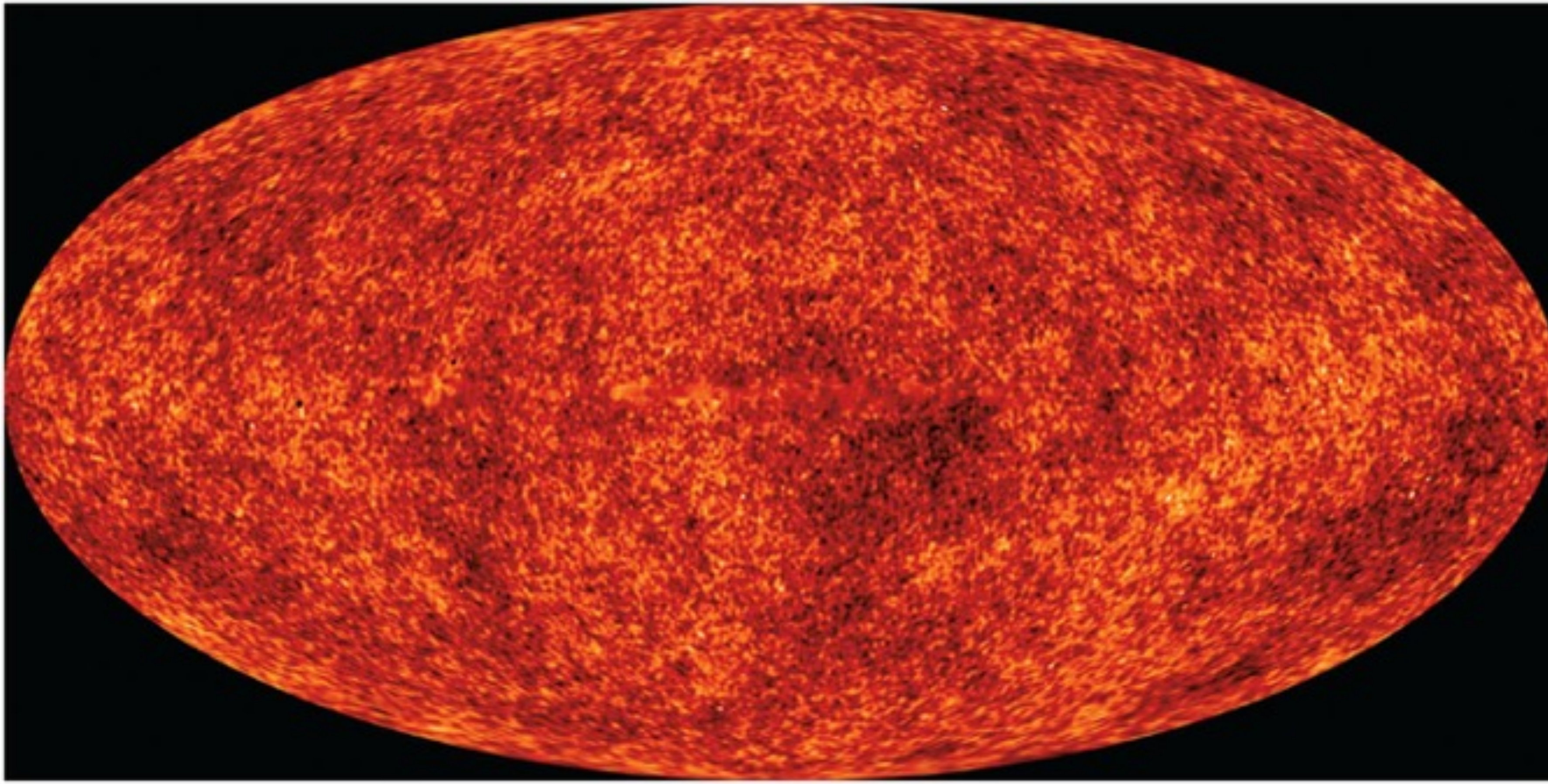
- Overall geometry of the universe is closely related to total density of matter and energy.



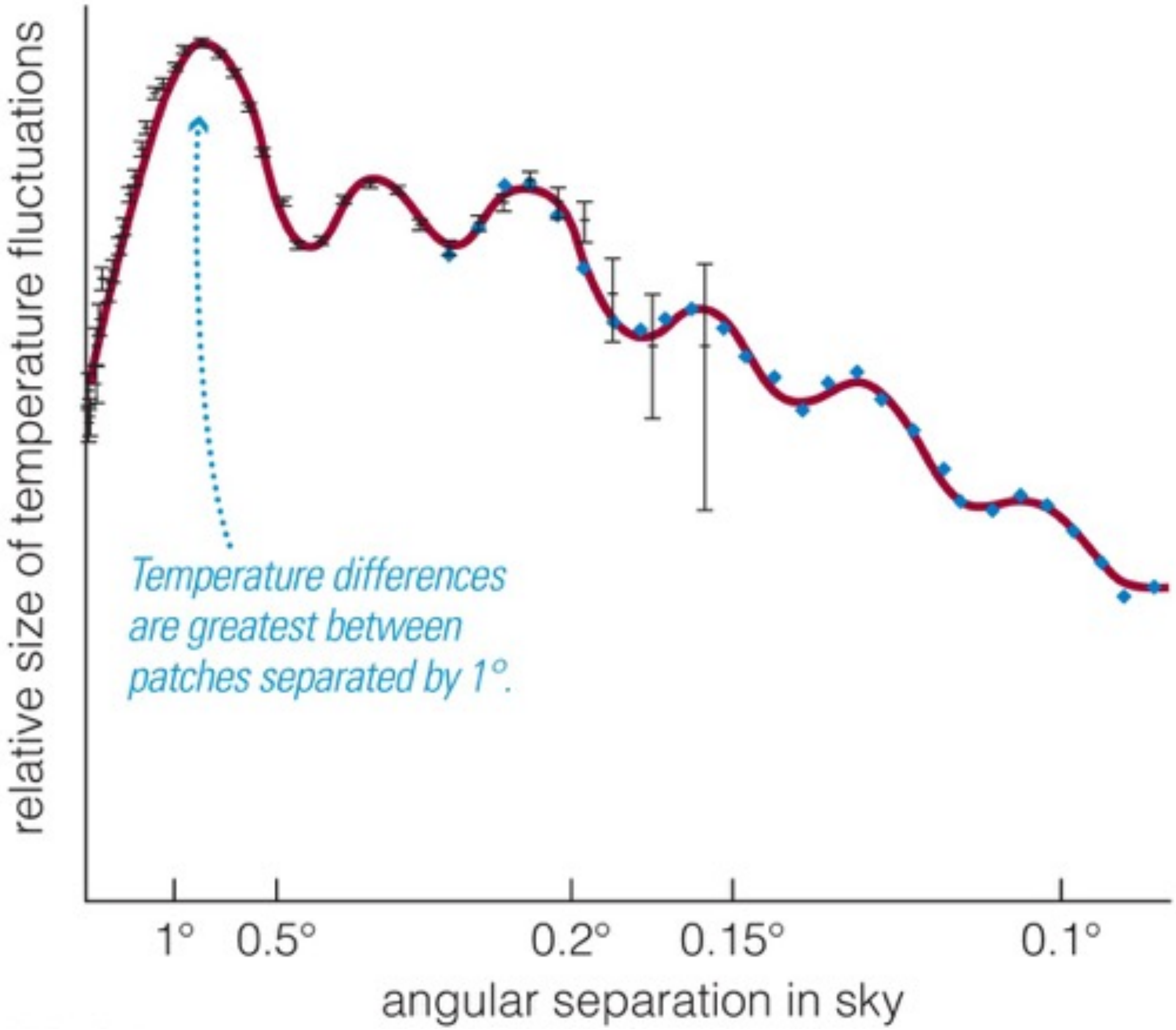
- Inflation of the universe flattens its overall geometry like the inflation of a balloon, causing the overall density of matter plus energy to be very close to the critical density.

Did inflation really occur?





- Patterns observed by WMAP show us the "seeds" of structure in the universe.



- Observed patterns of structure in universe agree (so far) with the "seeds" that inflation would produce.

"Seeds" Inferred from CMB

- Overall geometry is flat.
  - Total mass + energy has critical density.
- Ordinary matter is ~ 4.4% of total.
- Total matter is ~ 27% of total.
  - Dark matter is ~ 23% of total.
  - Dark energy is ~ 73% of total.
- Age is 13.7 billion years.

"Seeds" Inferred from CMB

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  - Dark energy is ~ 73% of total.
- Age is 13.7 billion years.

In excellent agreement with observations of present-day universe and models involving inflation and WIMPs!

What have we learned?

- **What key features of the universe are explained by inflation?**
  - The origin of structure, the smoothness of the universe on large scales, the nearly critical density of the universe.
  - Structure comes from inflated quantum ripples.
  - Observable universe became smooth before inflation, when it was very tiny.
  - Inflation flattened the curvature of space, bringing expansion rate into balance with the overall density of mass-energy.

What have we learned?

- **Did inflation really occur?**
  - We can compare the structures we see in detailed observations of the microwave background with predictions for the "seeds" that should have been planted by inflation.
  - So far, our observations of the universe agree well with models in which inflation planted the "seeds."

22.4 Observing the Big Bang for Yourself

- Our goals for learning:
  - **Why is the darkness of the night sky evidence for the Big Bang?**

Why is the darkness of the night sky evidence for the Big Bang?

Olbers' Paradox

- If universe were

  1) infinite

  2) unchanging

  3) everywhere the same

  then stars would cover the night sky.

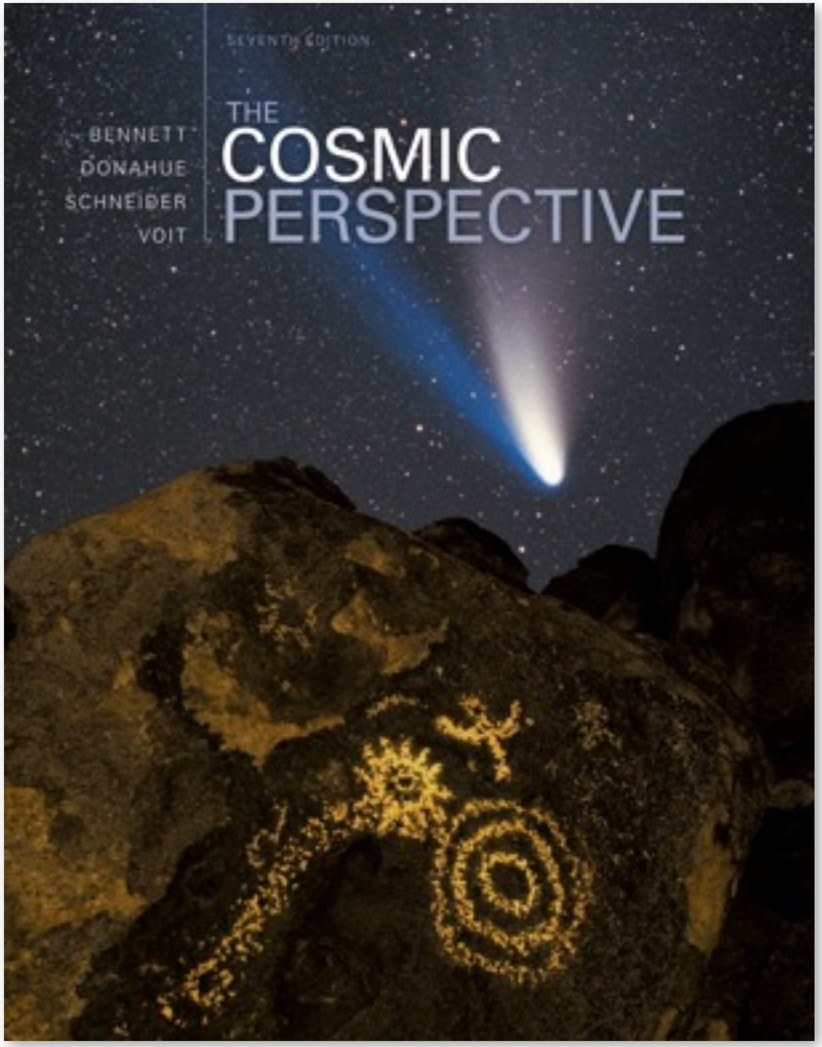
- The night sky is dark because the universe changes with time. As we look out in space, we can look back to a time when there were no stars.

What have we learned?

- **Why is the darkness of the night sky evidence for the Big Bang?**
  - If the universe were eternal, unchanging, and everywhere the same, the entire night sky would be covered with stars.
  - The night sky is dark because we can see back to a time when there were no stars.

The Cosmic Perspective

Seventh Edition



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

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

23.1 Unseen Influences in the Cosmos

- Our goals for learning:
  - **What do we mean by dark matter and dark energy?**

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

- "Ordinary" matter: ~ 4.4%
  - Ordinary matter inside stars: ~ 0.6%
  - Ordinary matter outside stars: ~ 3.8%
- Dark matter: ~ 23%
- Dark energy: ~ 73%

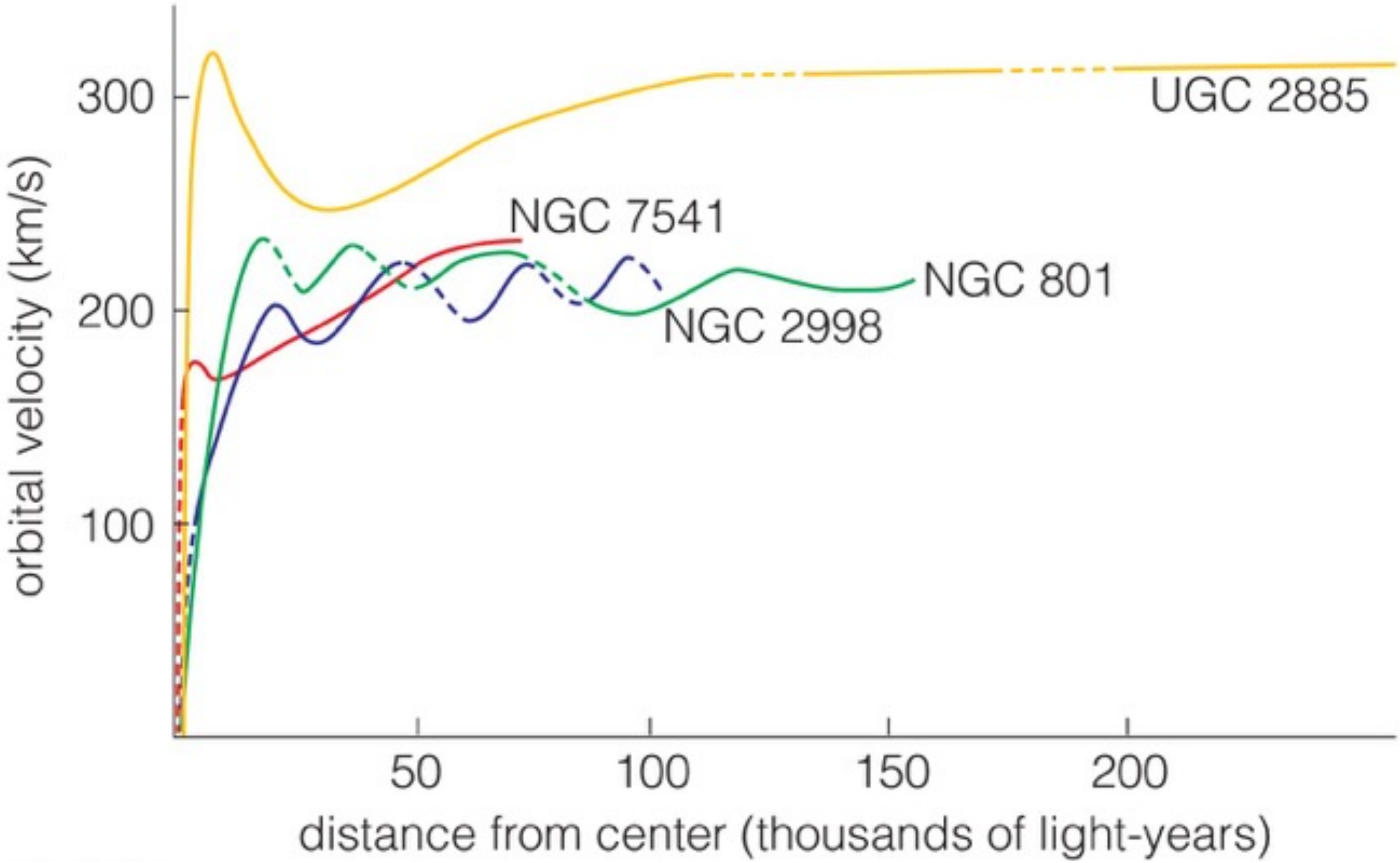
What have we learned?

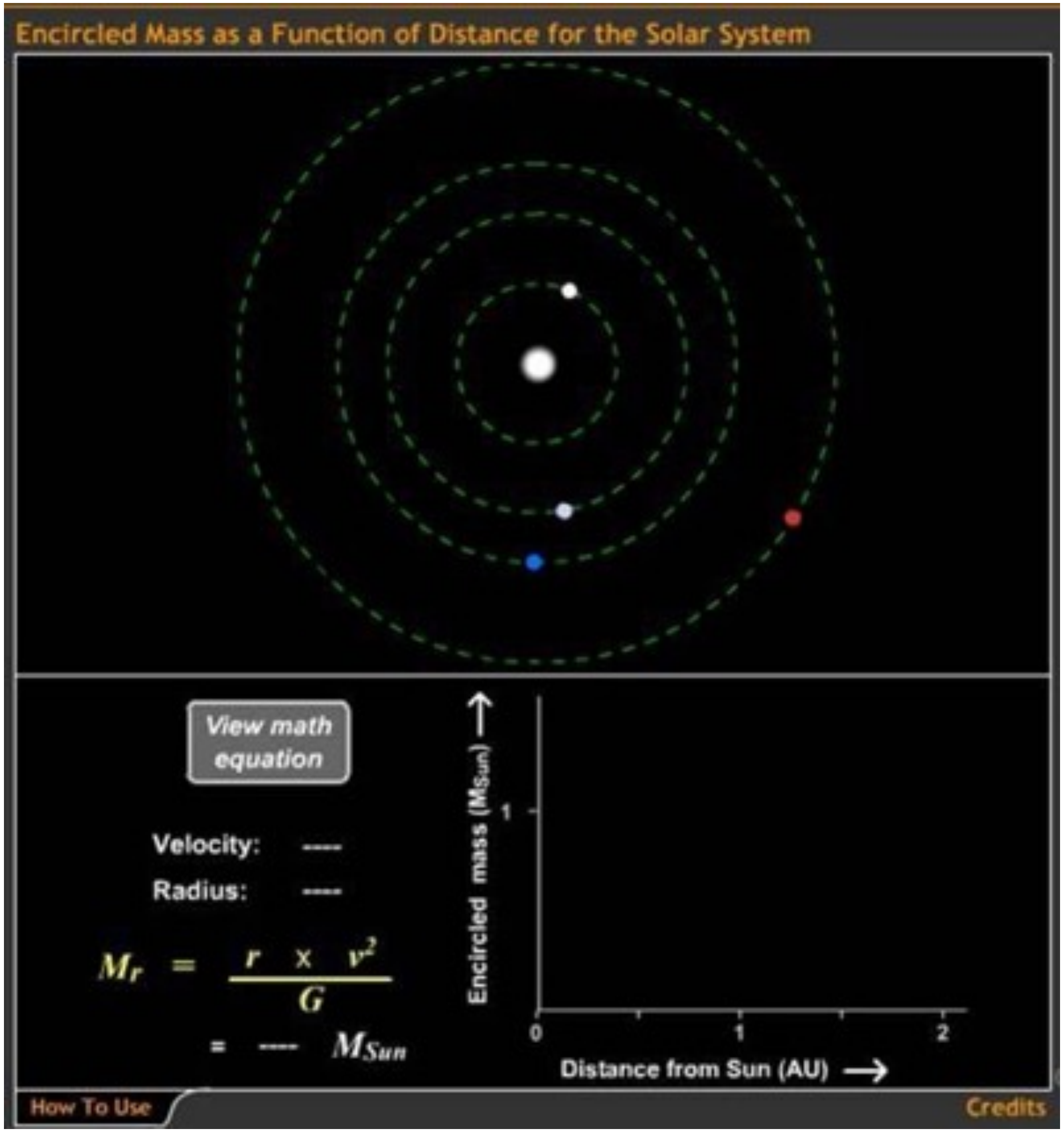
- **What do we mean by dark matter and dark energy?**
  - *Dark matter* is the name given to the unseen mass whose gravity governs the observed motions of stars and gas clouds.
  - *Dark energy* is the name given to whatever might be causing the expansion of the universe to accelerate.

23.2 Evidence for Dark Matter

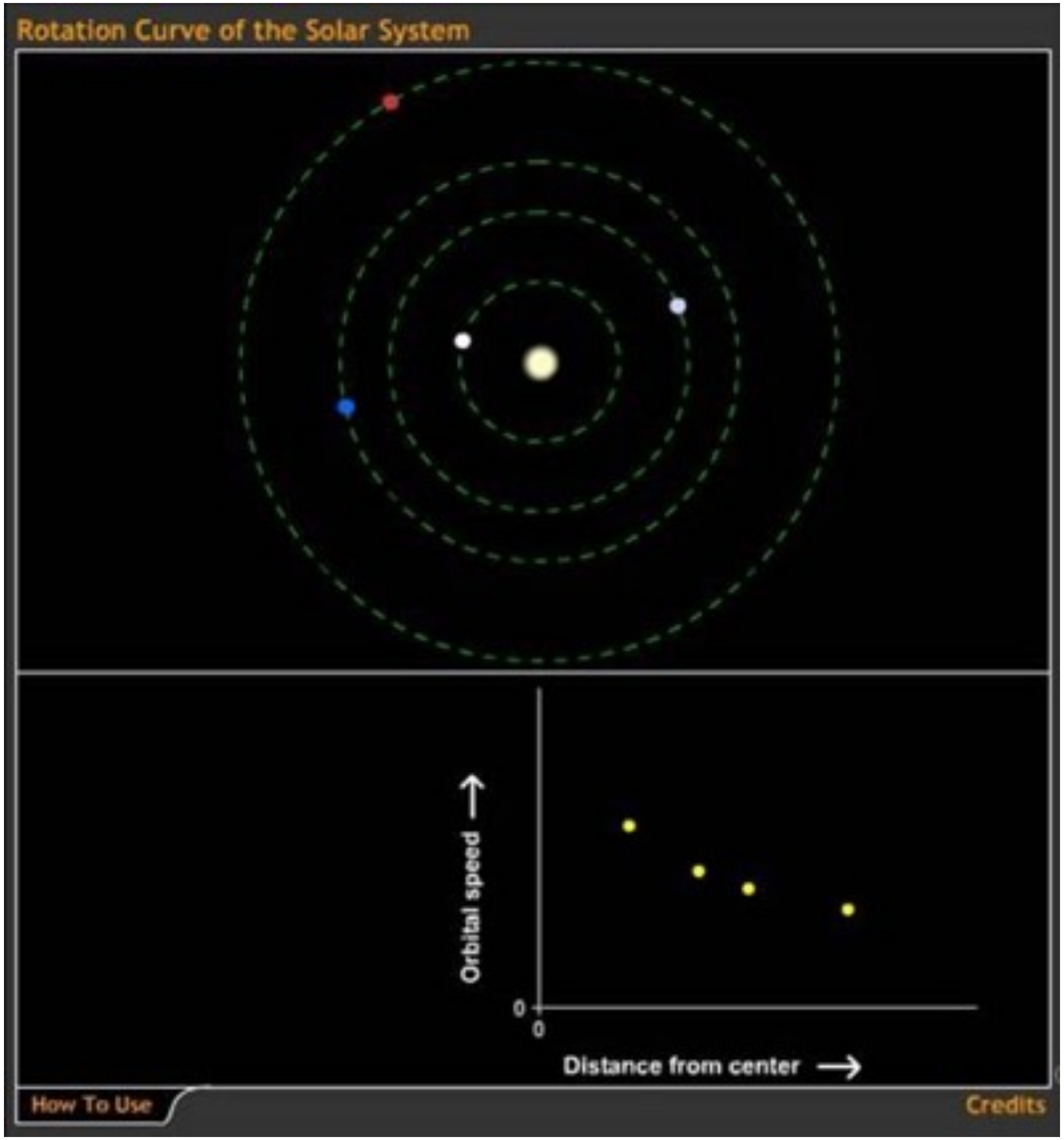
- Our goals for learning:
  - **What is the evidence for dark matter in galaxies?**
  - **What is the evidence for dark matter in clusters of galaxies?**
  - **Does dark matter really exist?**
  - **What might dark matter be made of?**

What is the evidence for dark matter in galaxies?



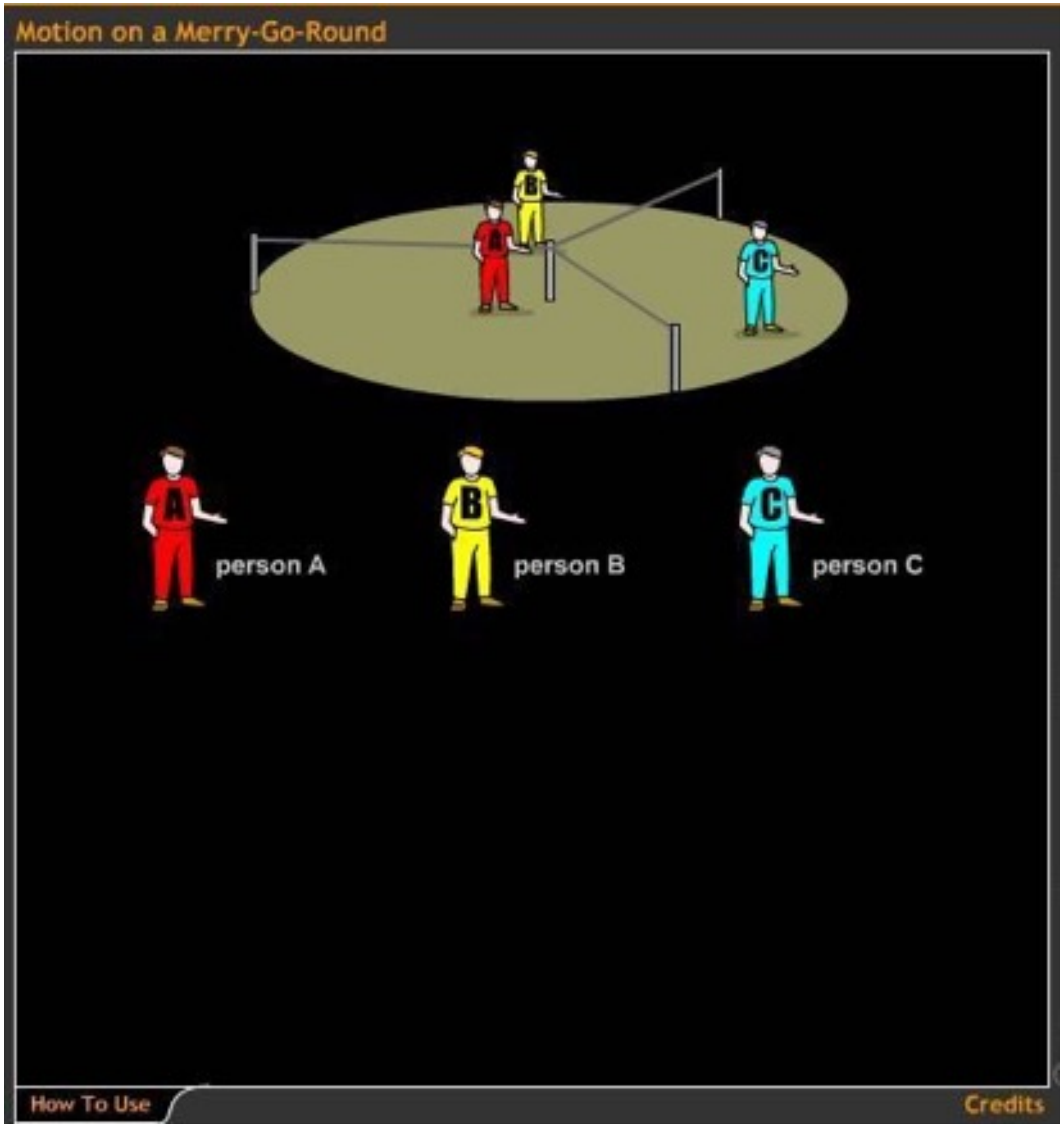


- We measure the mass of the solar system using the orbits of planets:
  - orbital period
  - Average distance
- For circles:
  - orbital velocity
  - orbital radius



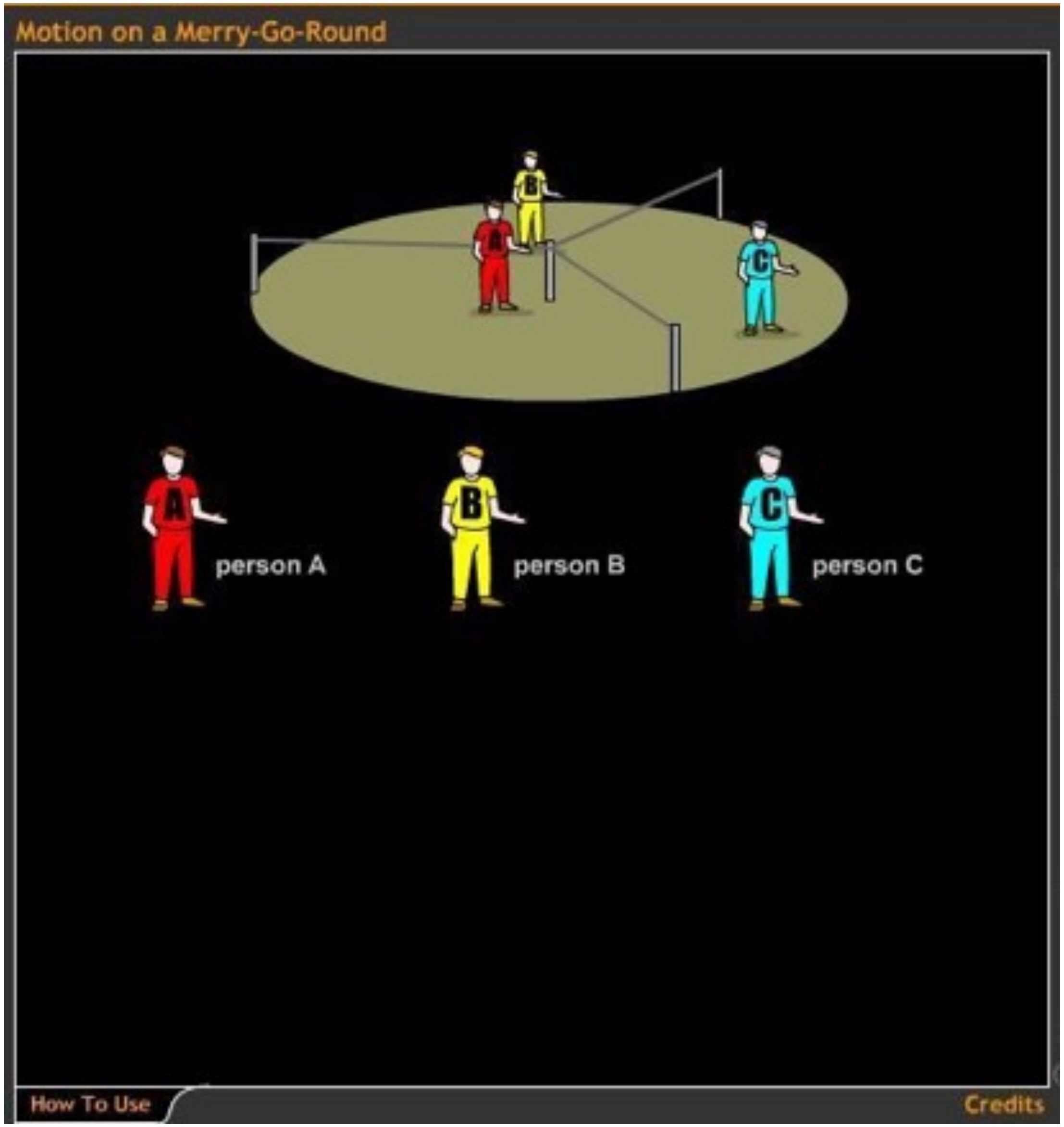
Rotation curve

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



Who has the largest orbital velocity?

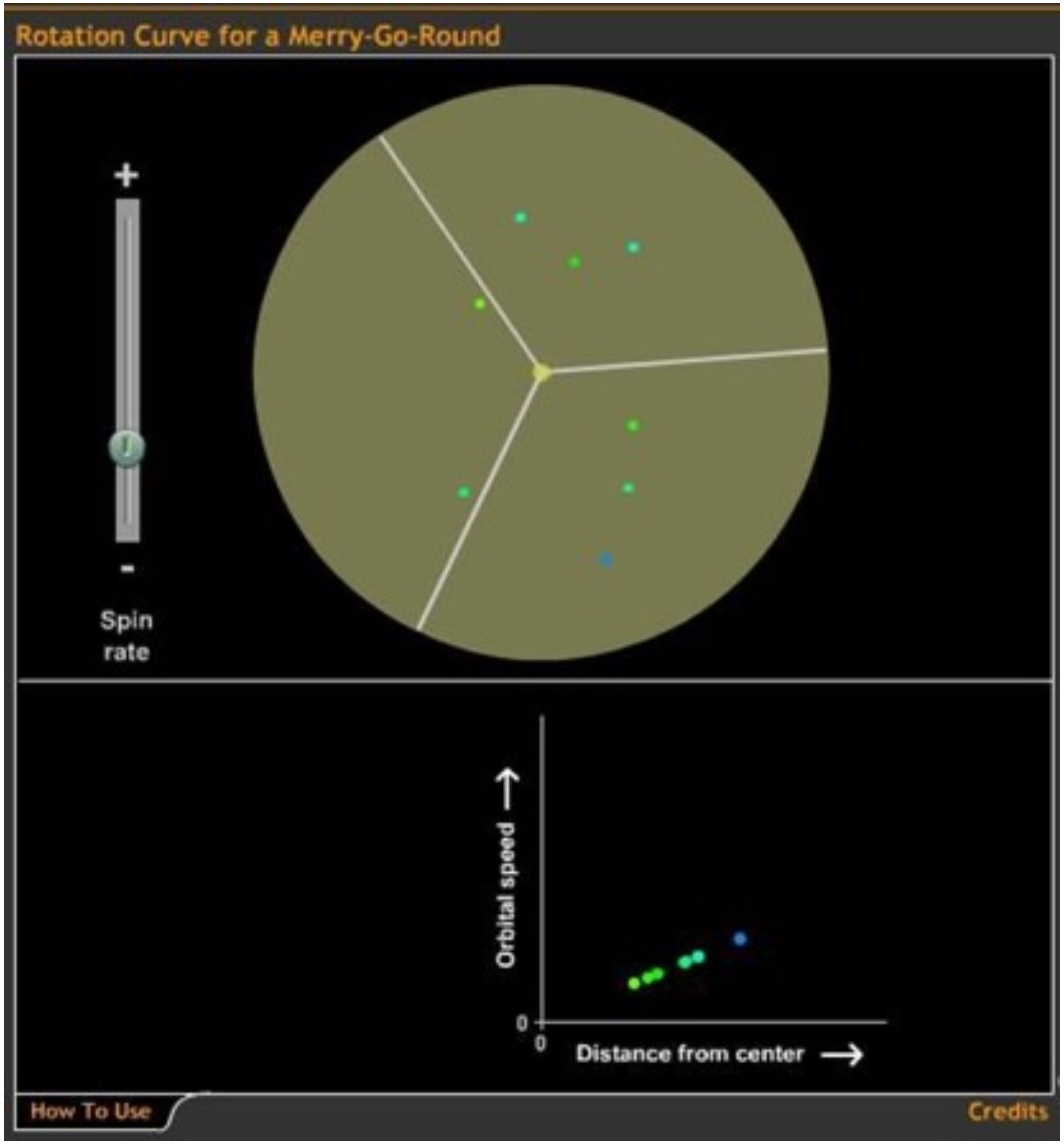
A, B, or C?



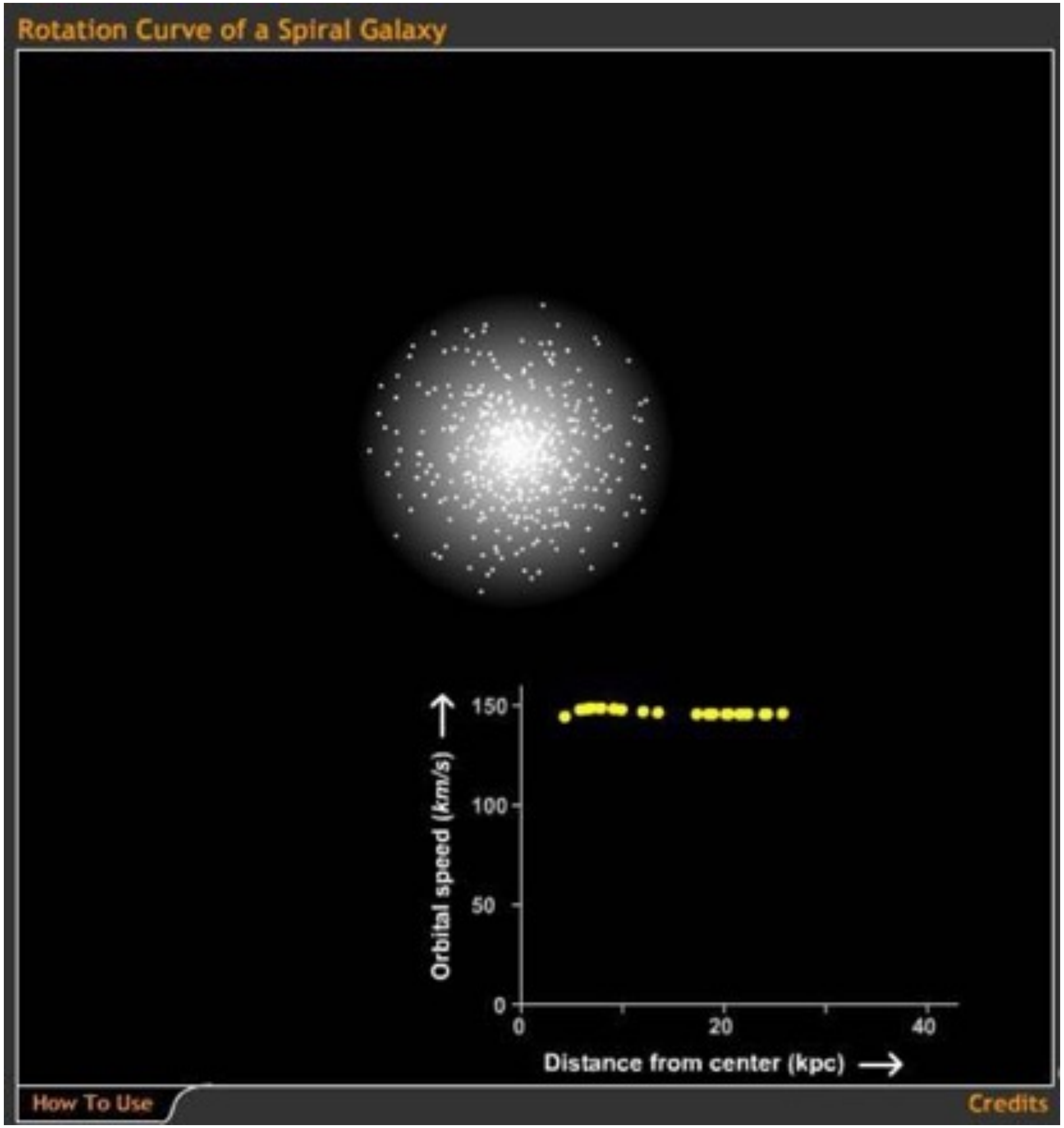
Who has the largest orbital velocity?

A, B, or C?

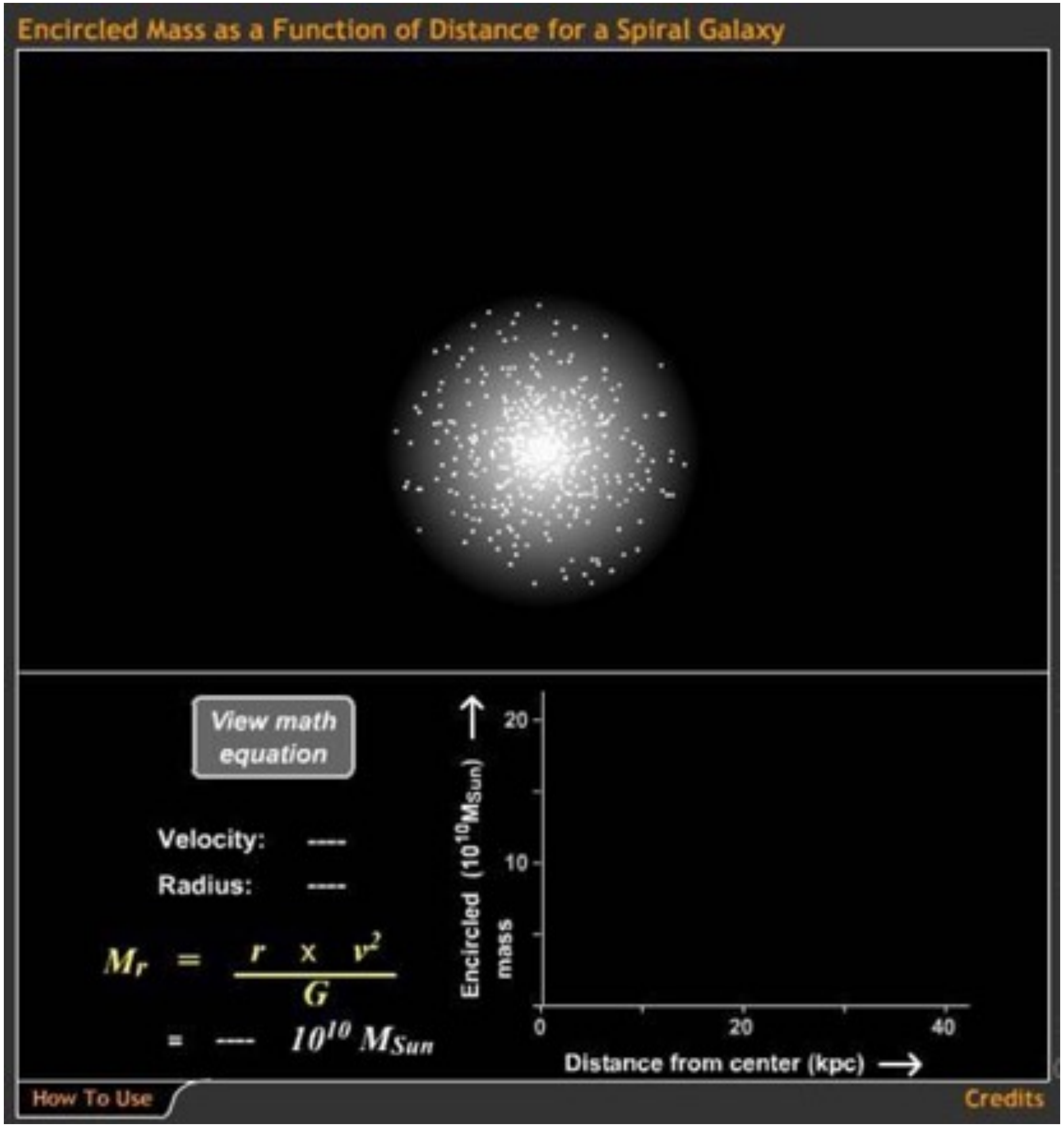
Answer: C



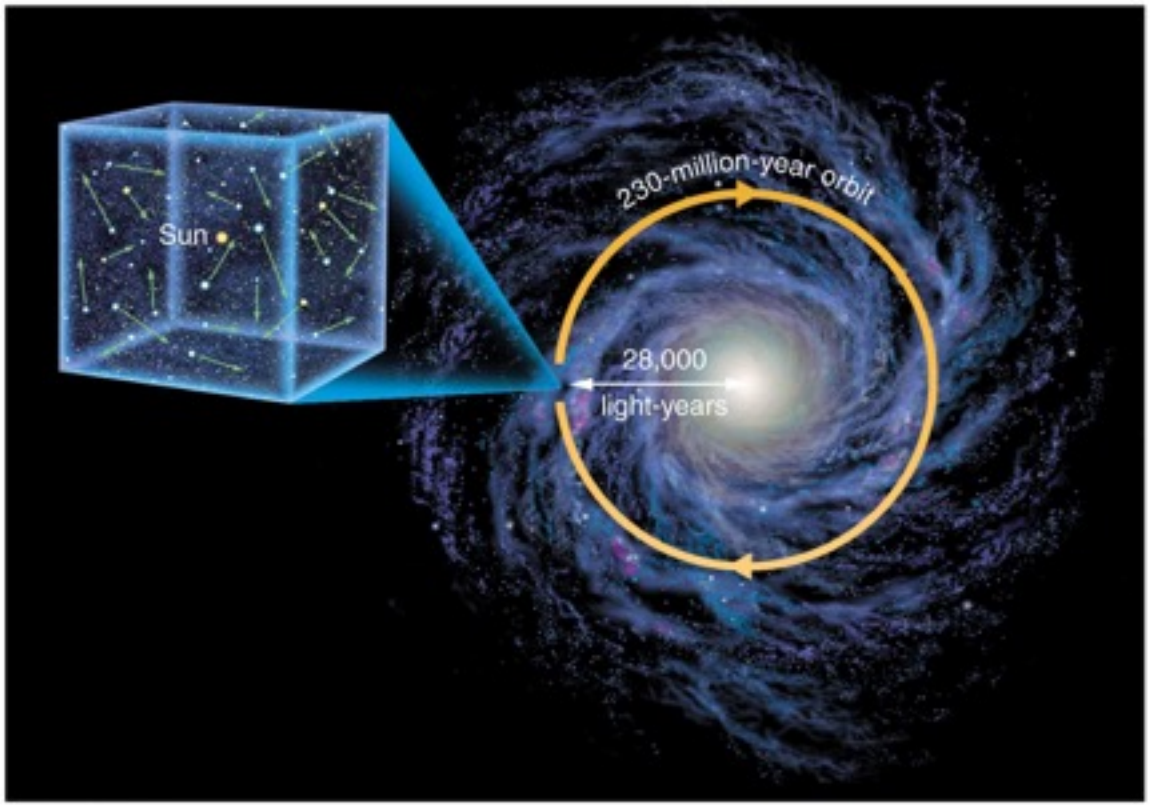
- The rotation curve of a merry-go-round rises with radius.



- 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!***

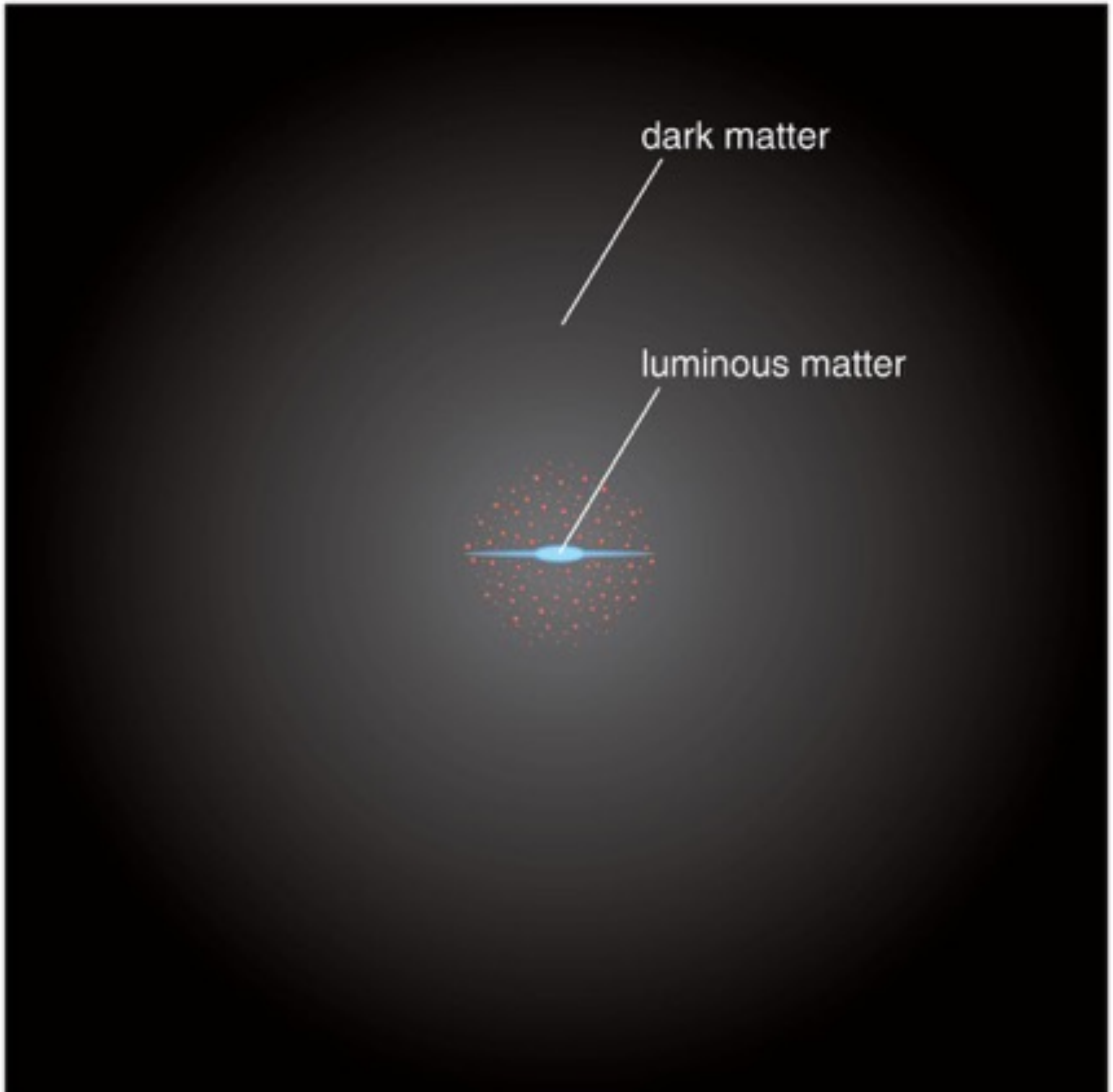


- Mass within the Sun's orbit:

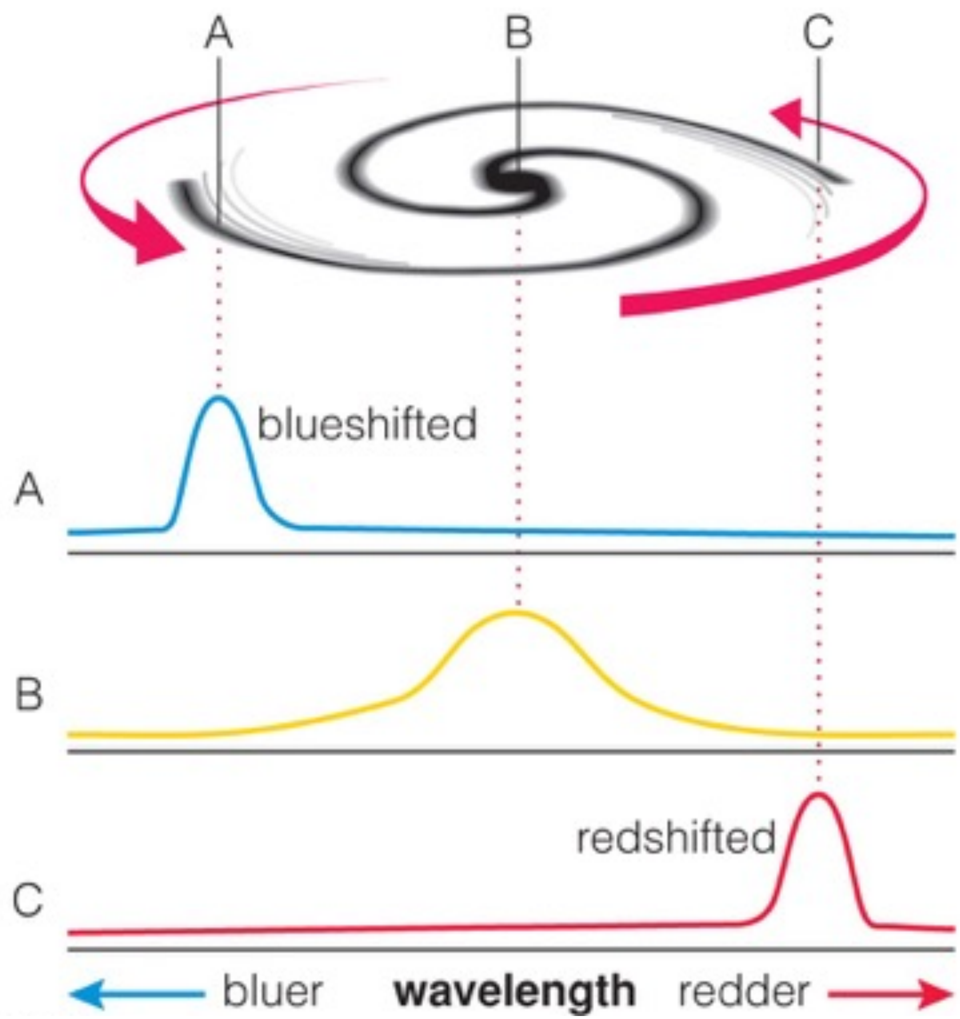
  $1.0 \times 10^{11} M_{Sun}$

Total mass:

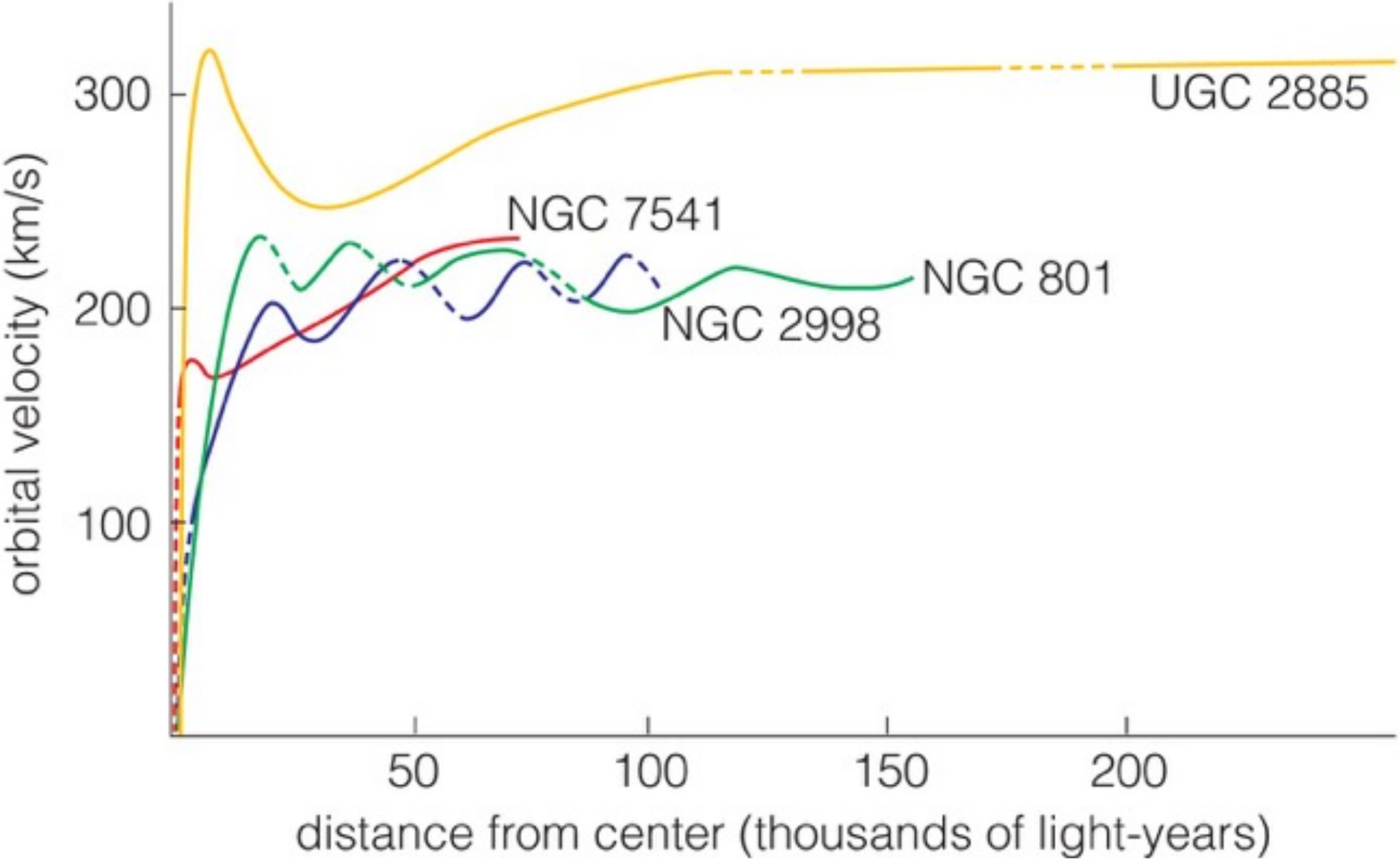
  $\sim 10^{12} M_{Sun}$



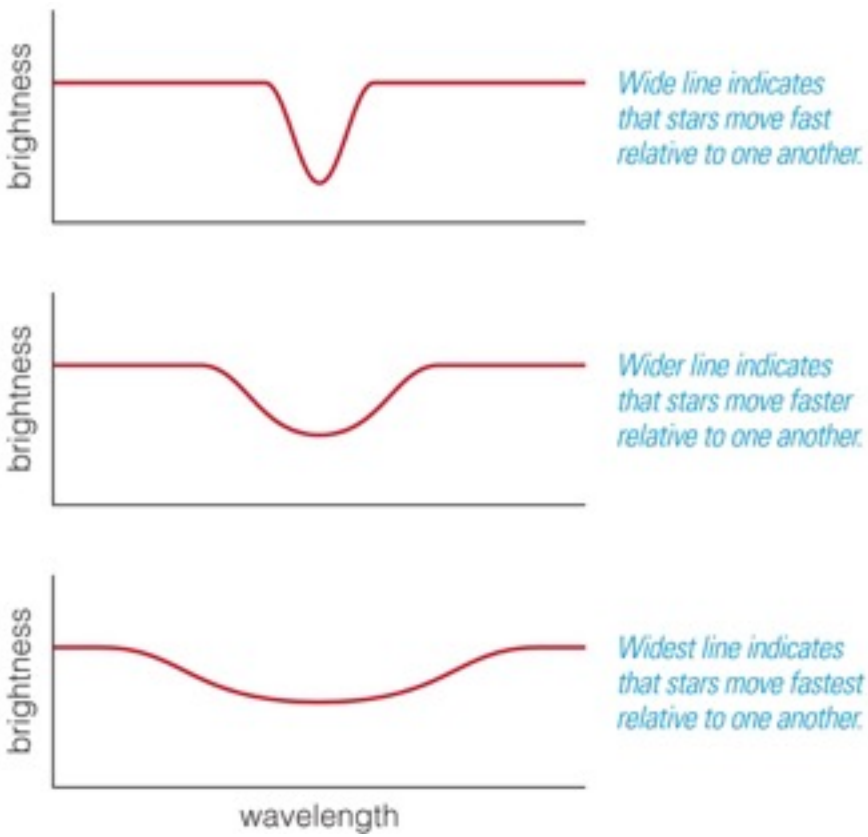
- The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.



- 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.



- Broadening of spectral lines in elliptical galaxies tells us how fast the stars are orbiting.
- These galaxies also have dark matter.

Thought Question

What would you conclude about a galaxy whose rotational velocity rises steadily with distance beyond the visible part of its disk?

A. Its mass is concentrated at the center.
B. It rotates like the solar system.
C. It's especially rich in dark matter.
D. It's just like the Milky Way.

Thought Question

What would you conclude about a galaxy whose rotational velocity rises steadily with distance beyond the visible part of its disk?

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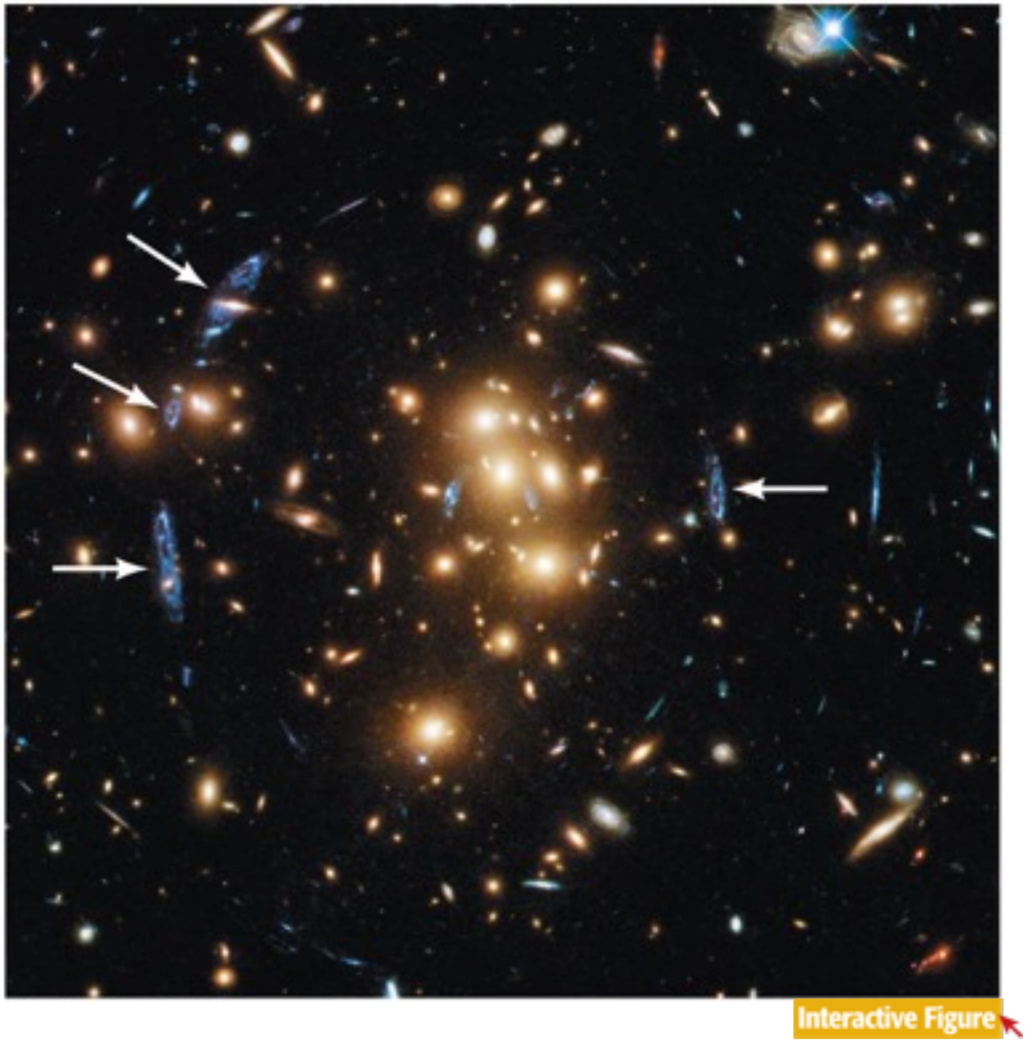
What is the evidence for dark matter in clusters of galaxies?

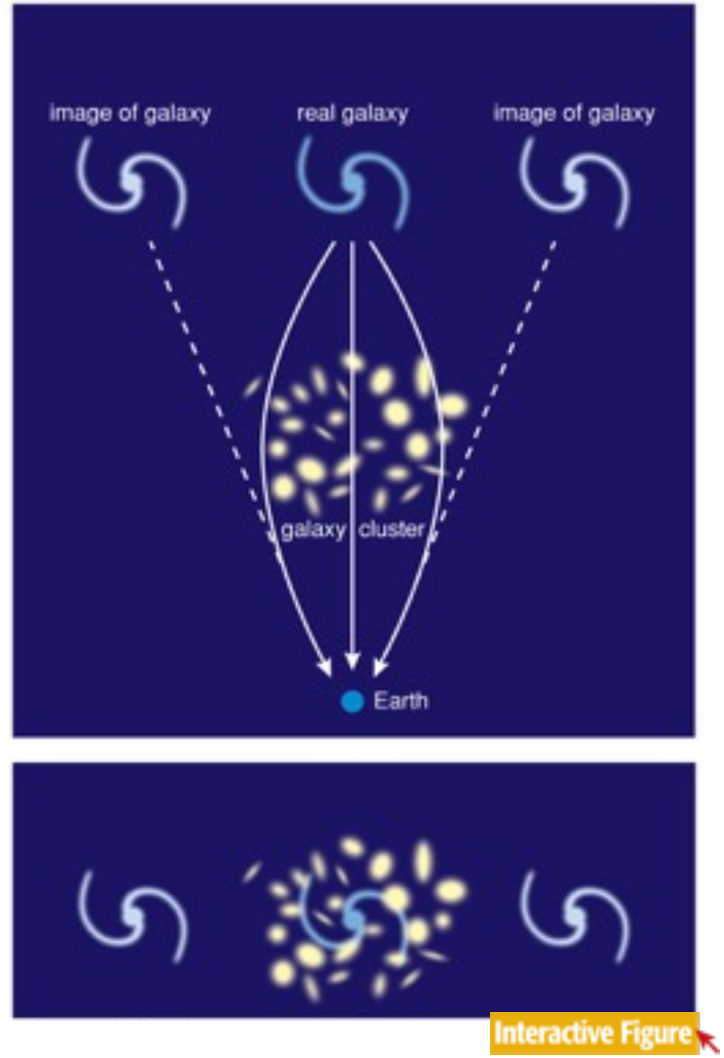
- We can measure the velocities of galaxies in a cluster from their Doppler shifts.

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

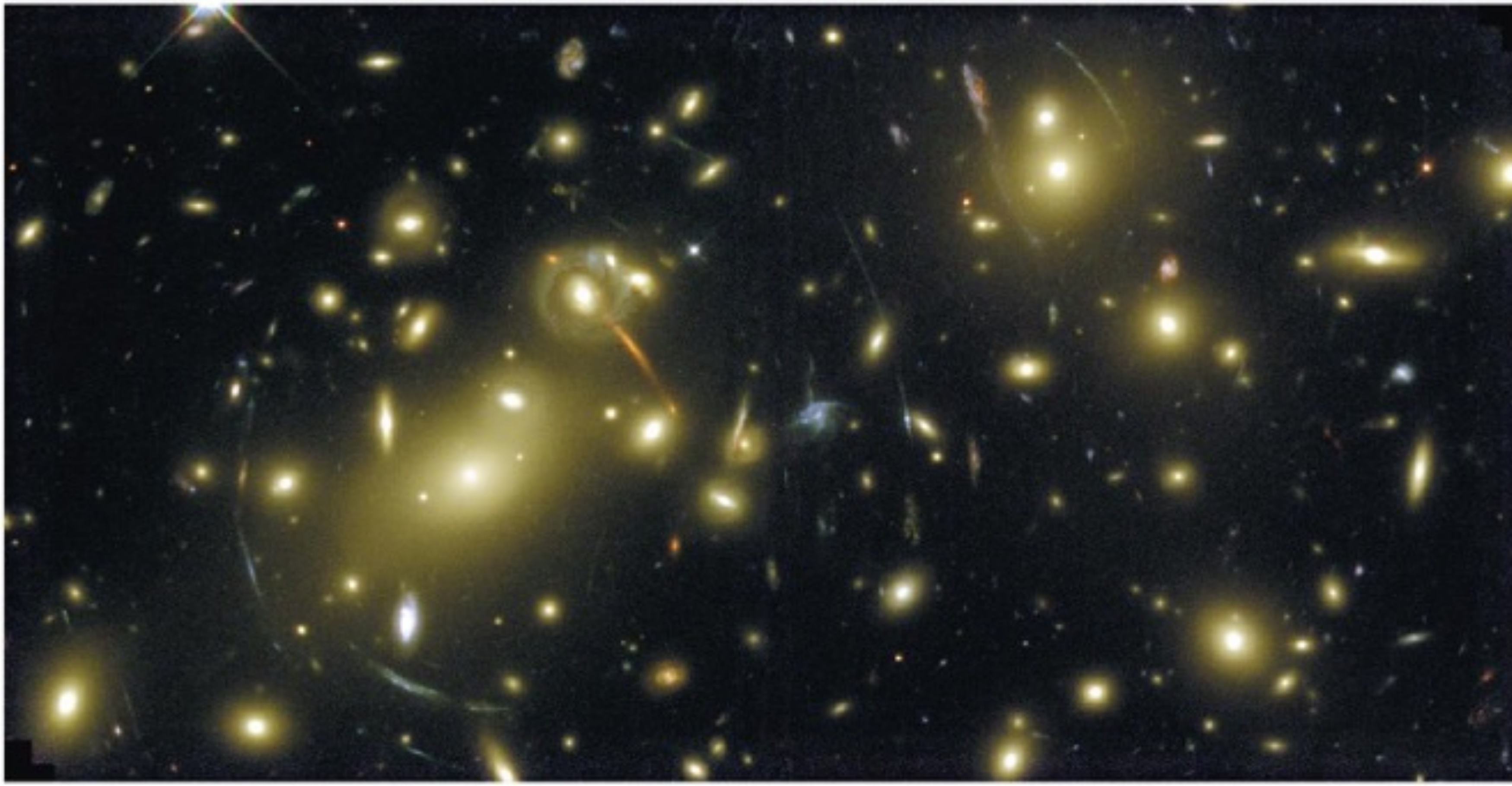
- Clusters contain large amounts of X ray-emitting hot gas.
- Temperature of hot gas (particle motions) tells us cluster mass:

  85% dark matter
  13% hot gas
  2% stars





- ***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?

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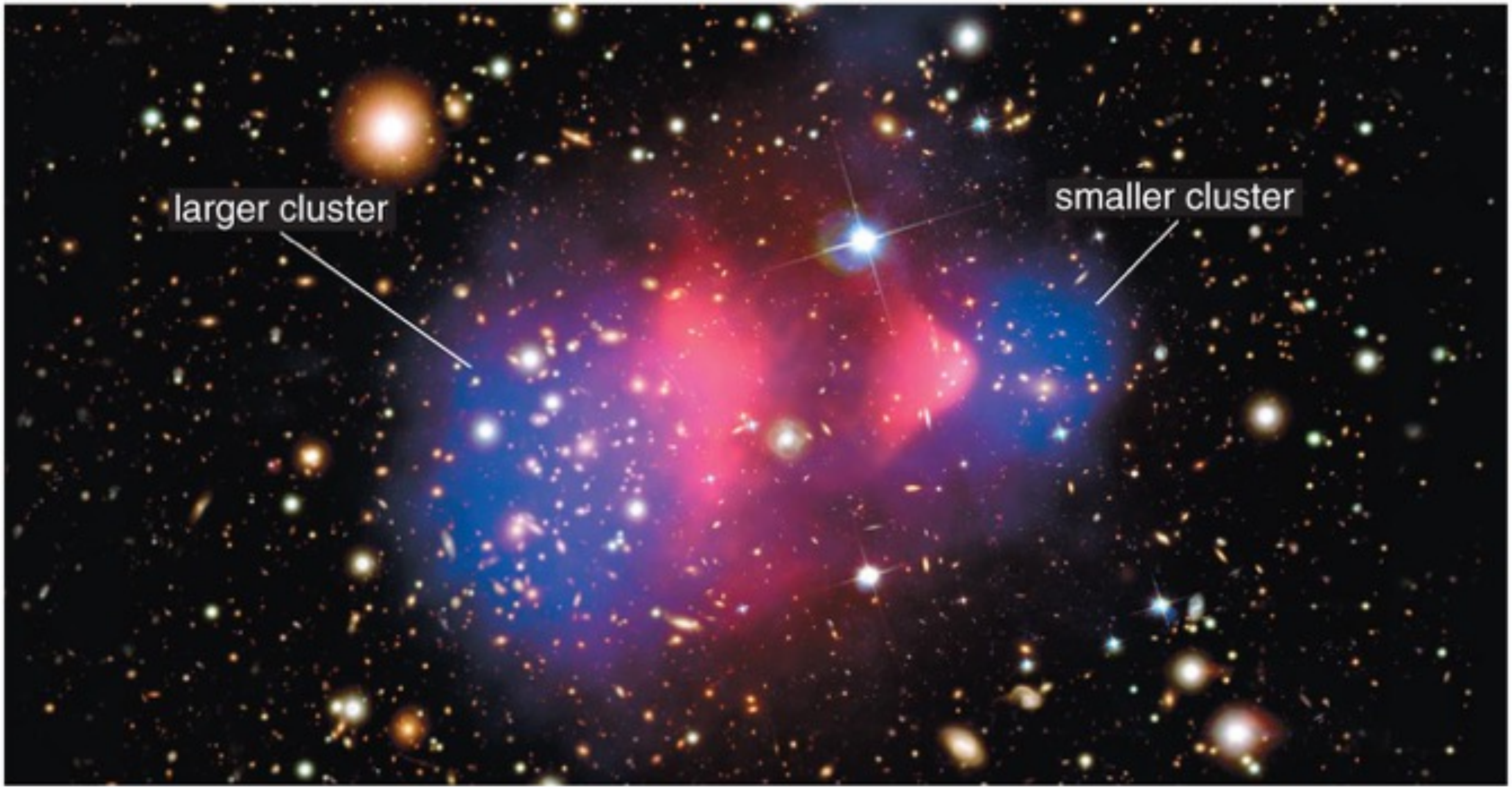
Does dark matter really exist?



Our Options

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

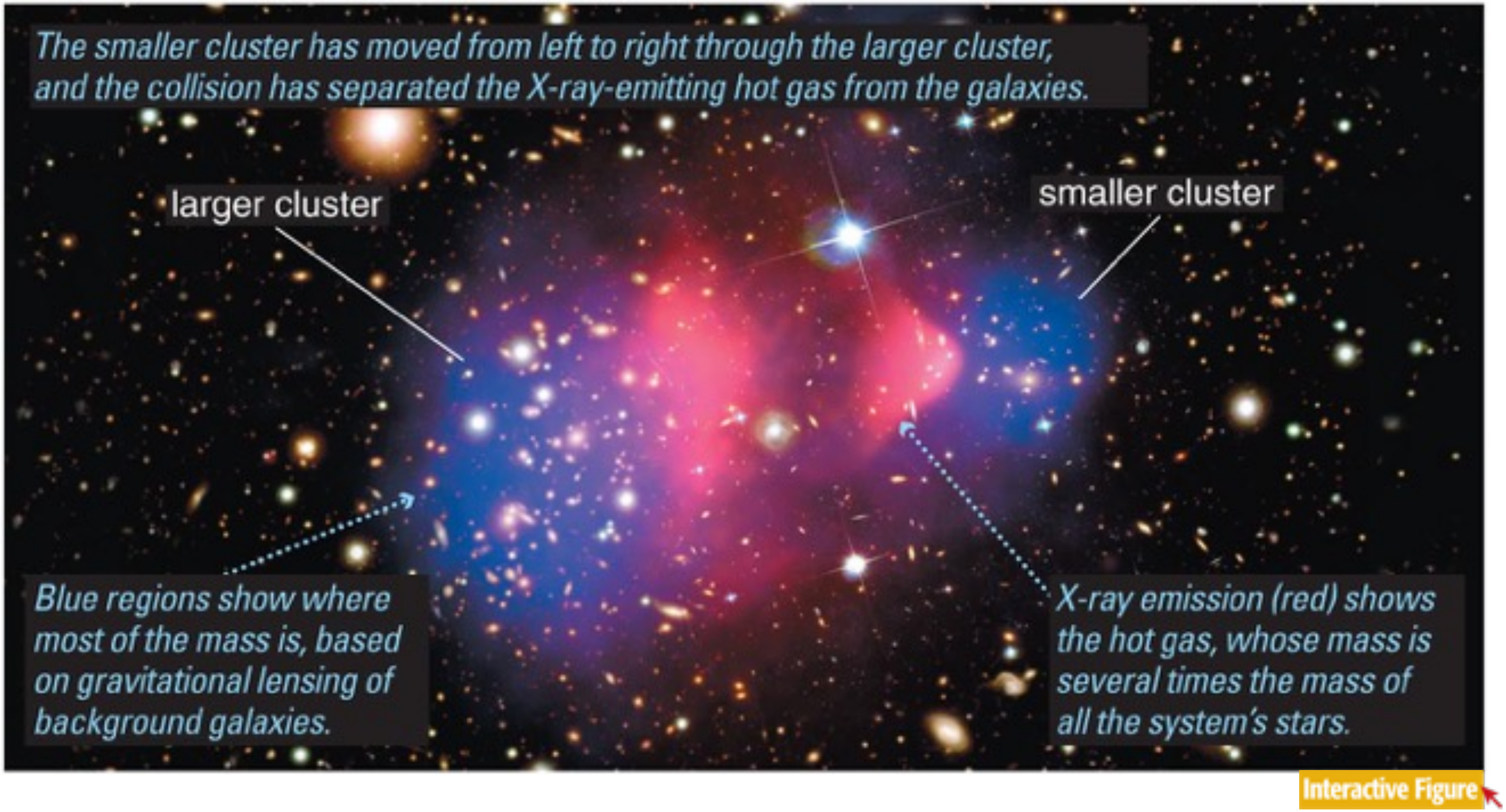
2. Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter.

Our Options

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

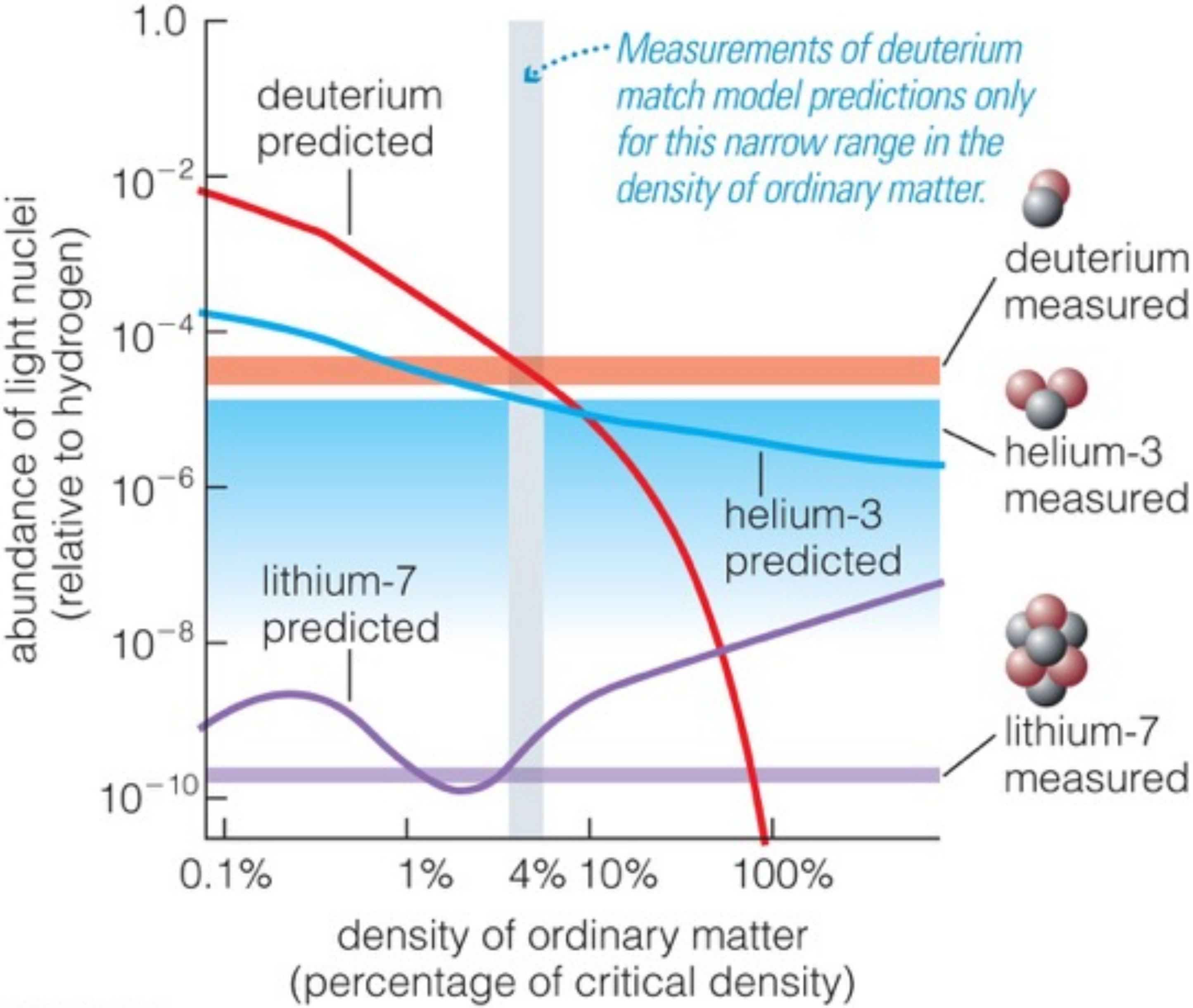
2. Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter.

- ***Because gravity is so well tested, most astronomers prefer option #1.***



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

What might dark matter be made of?



- How dark is dark matter?

  … not as bright as a star.

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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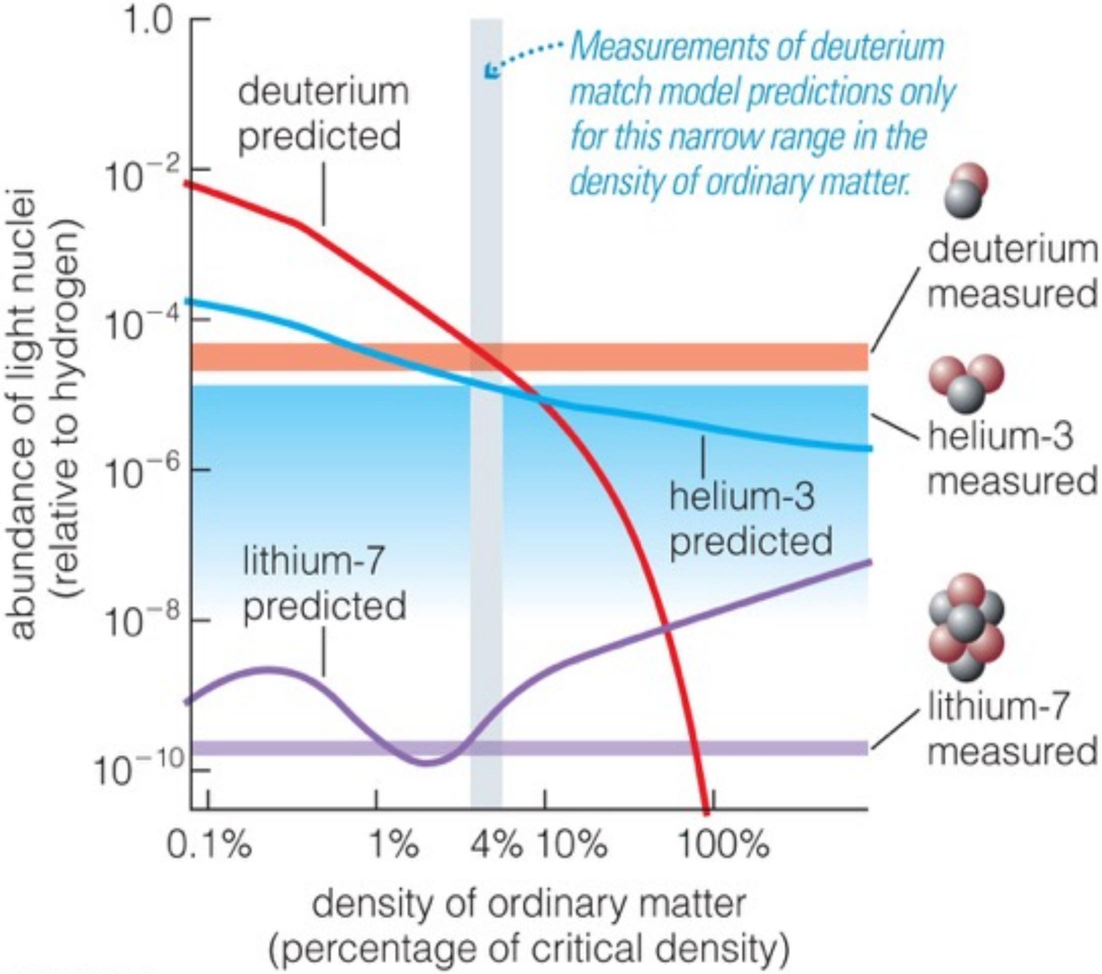
The best bet



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

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.

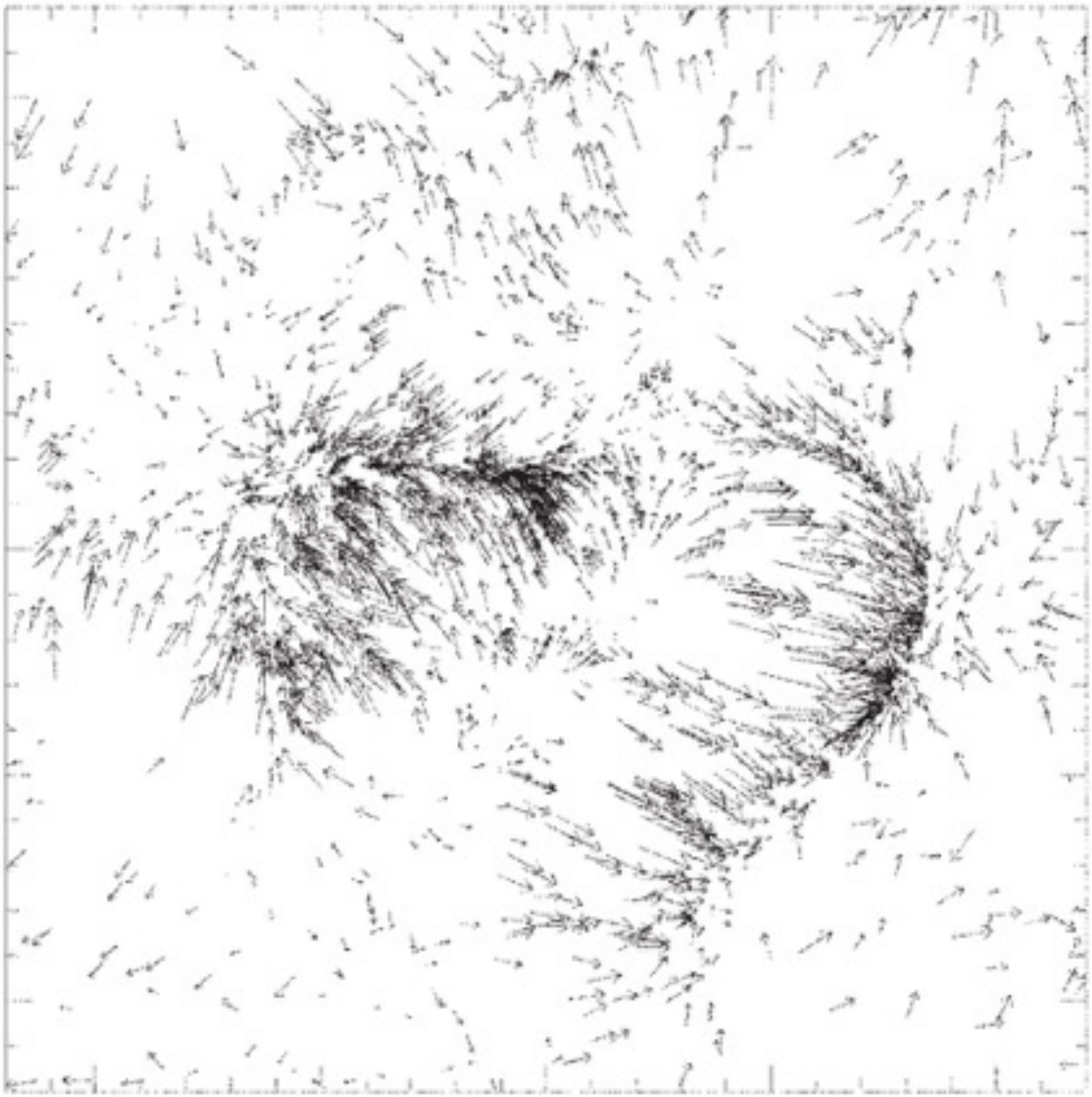
What have we learned?

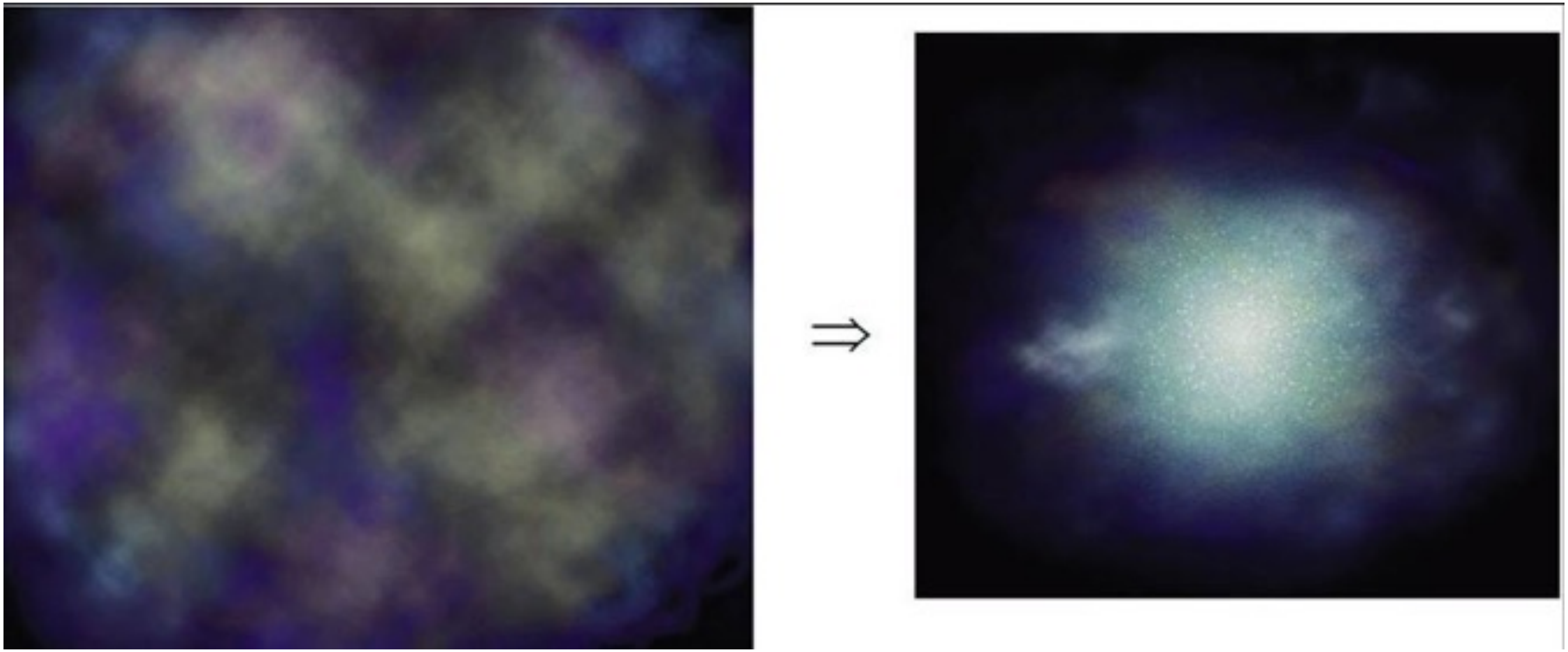
- **Does dark matter really exist?**
  – Either dark matter exists or our understanding of our gravity must be revised.
- **What might dark matter be made of?**
  – There does not seem to be enough normal (baryonic) matter to account for all the dark matter, so most astronomers suspect that dark matter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

23.3 Dark Matter and Galaxy Formation

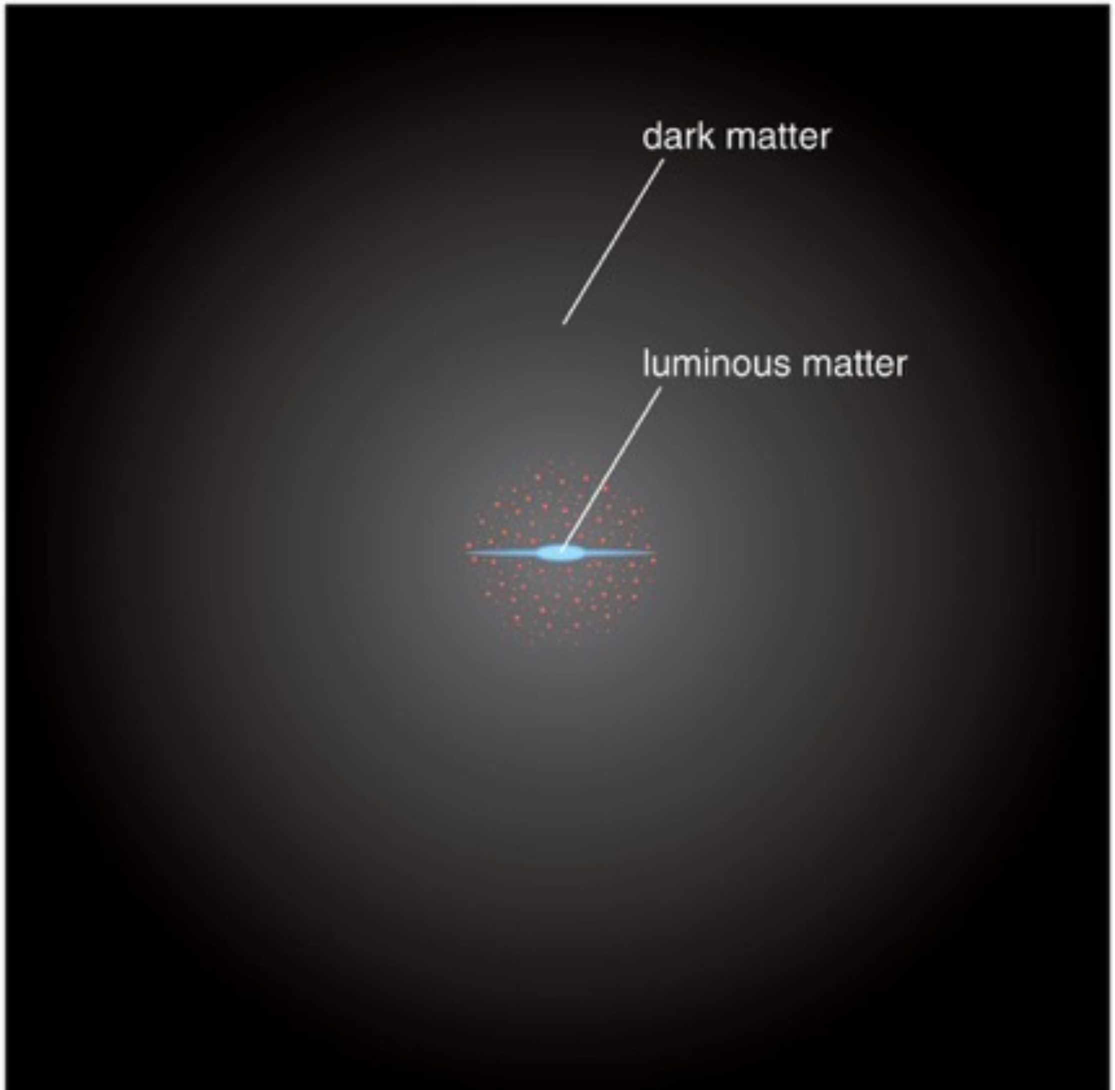
- Our goals for learning:
  - **What is the role of dark matter in galaxy formation?**
  - **What are the largest structures in the universe?**

What is the role of dark matter in galaxy formation?

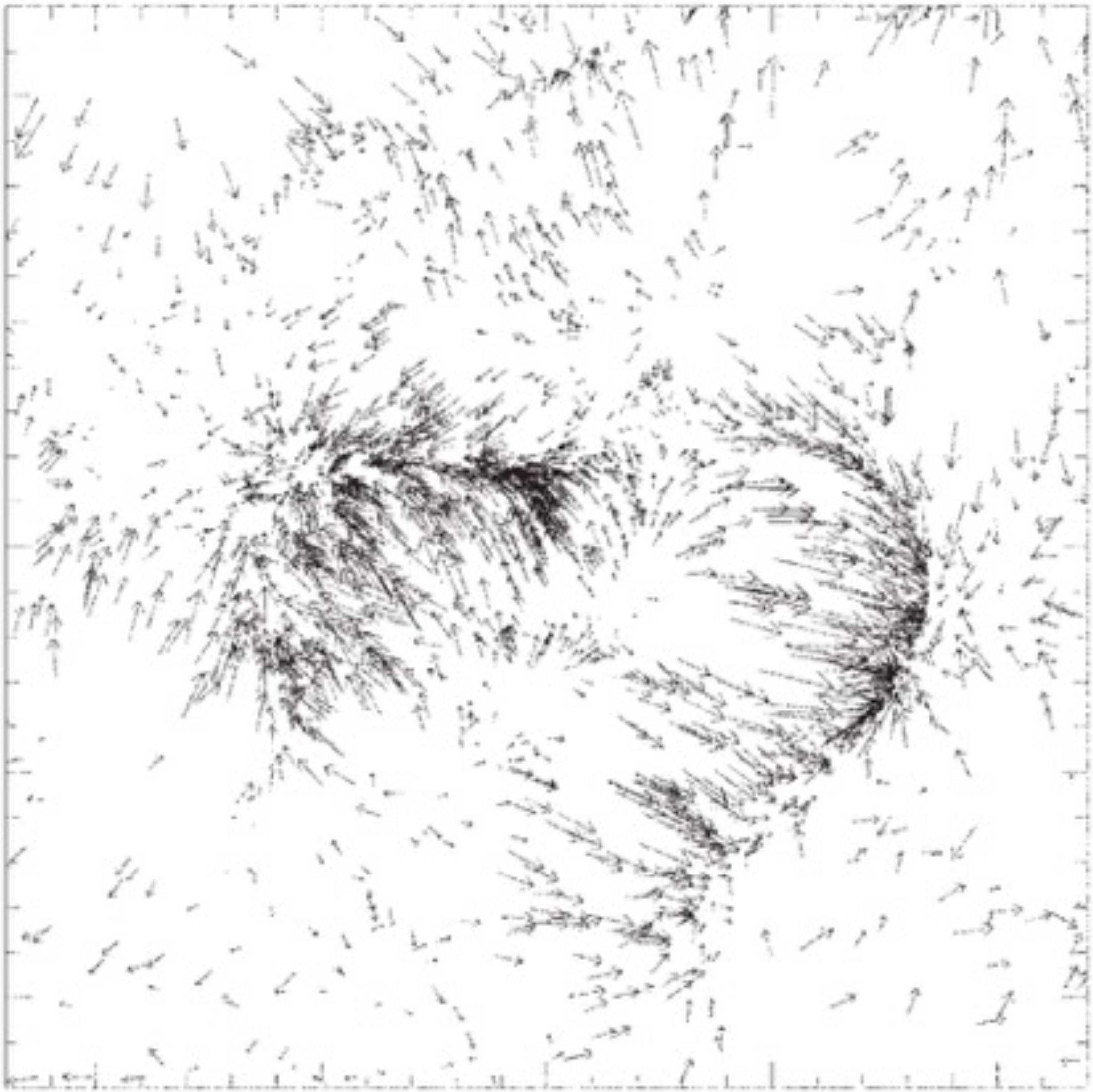




- Gravity of dark matter is what caused protogalactic clouds to contract early in time.

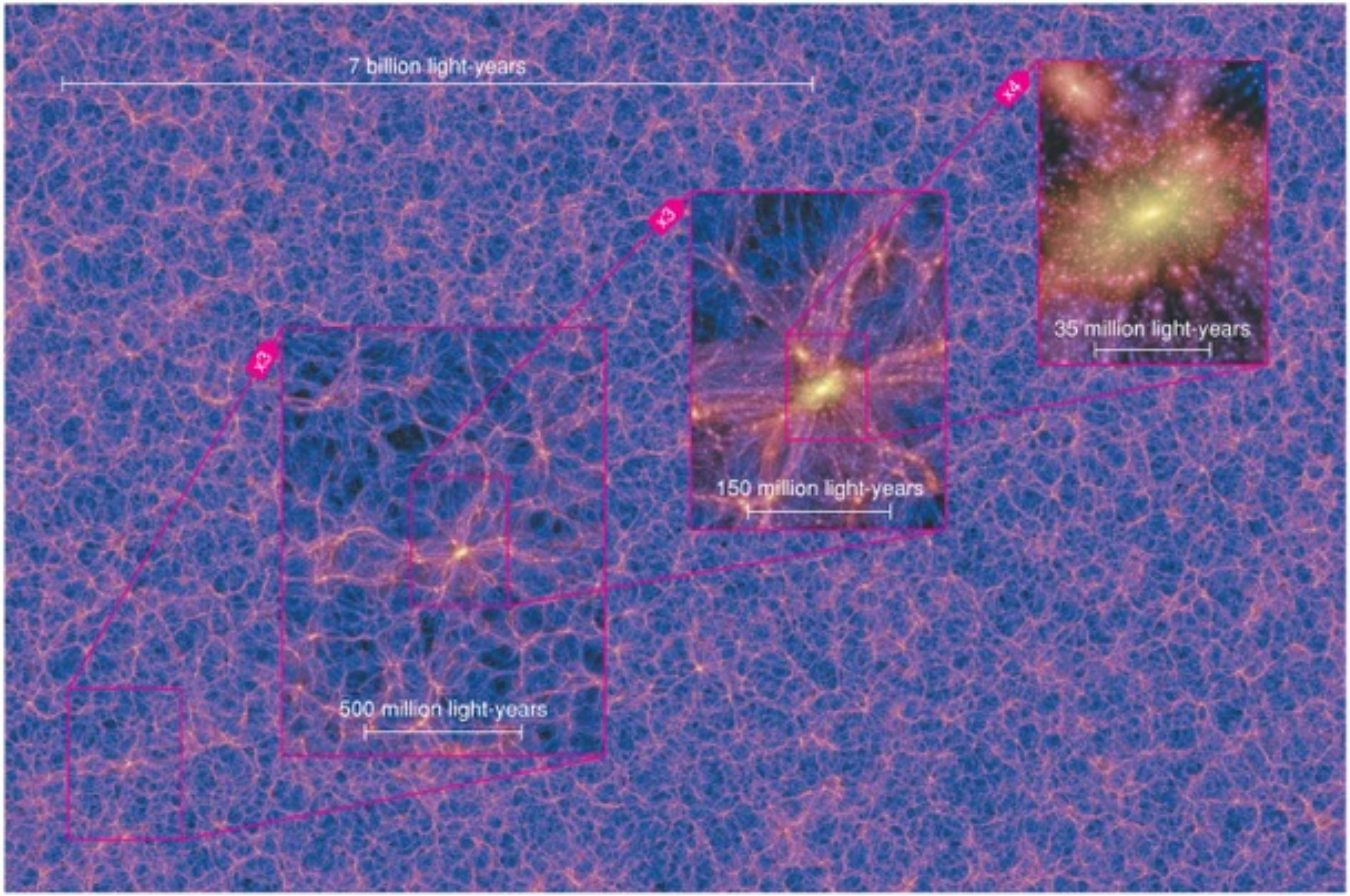


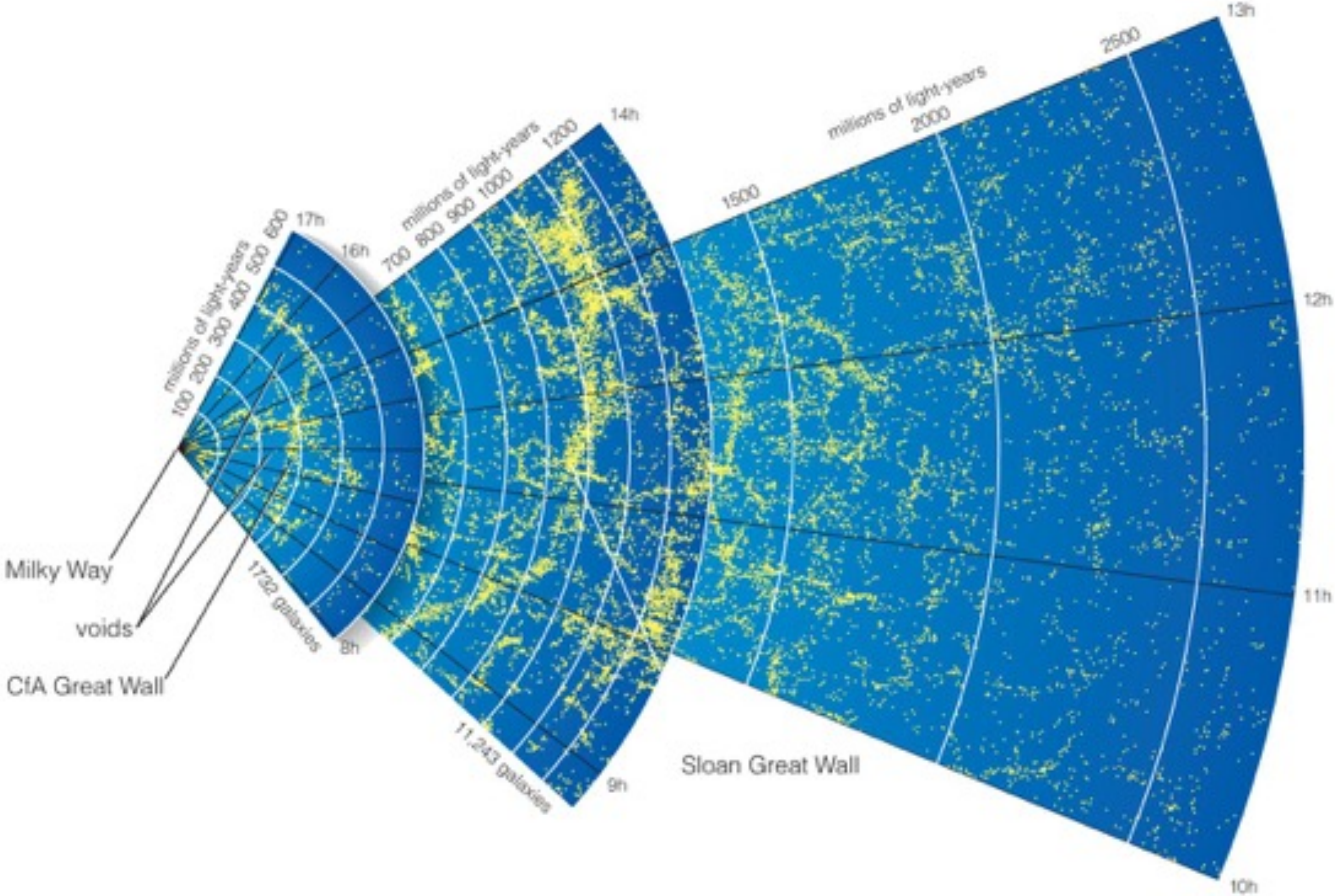
- WIMPs can't collapse to the center because they don't radiate away their orbital energy.



- Dark matter is still pulling things together.
- After correcting for Hubble's law, we can see that galaxies are flowing toward the densest regions of space.

What are the largest structures in the universe?

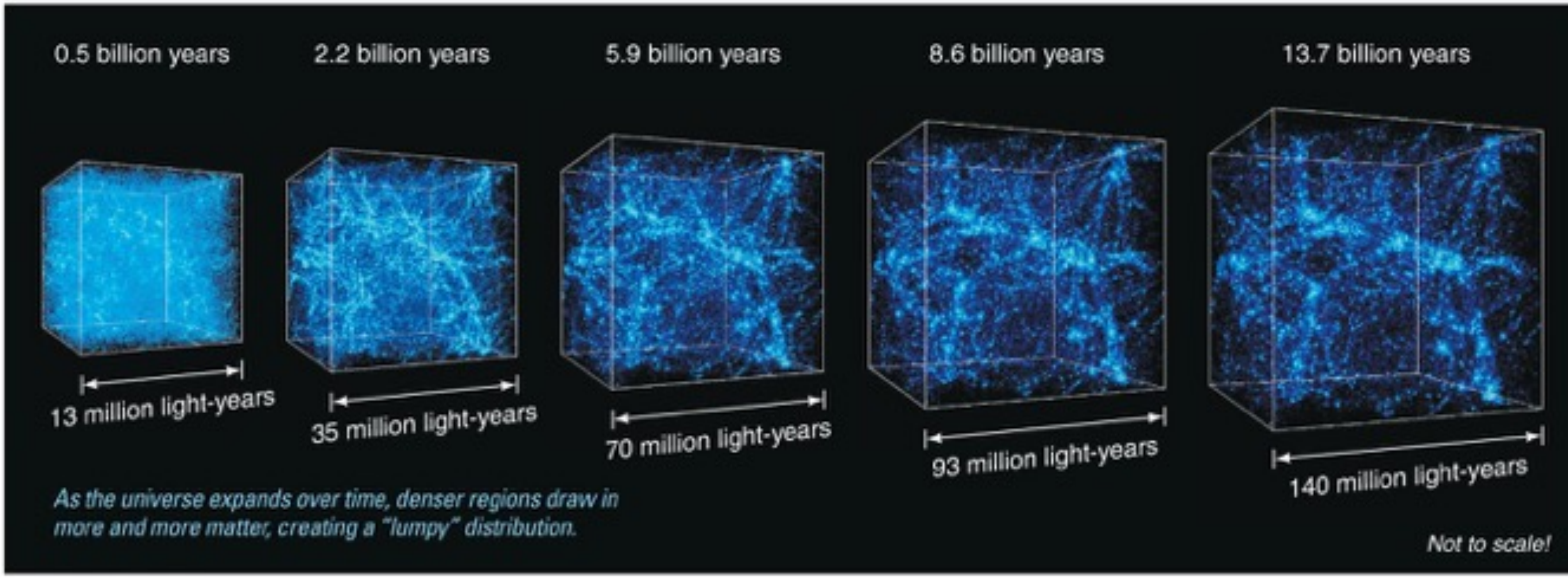




- Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids***.

Time in billions of years

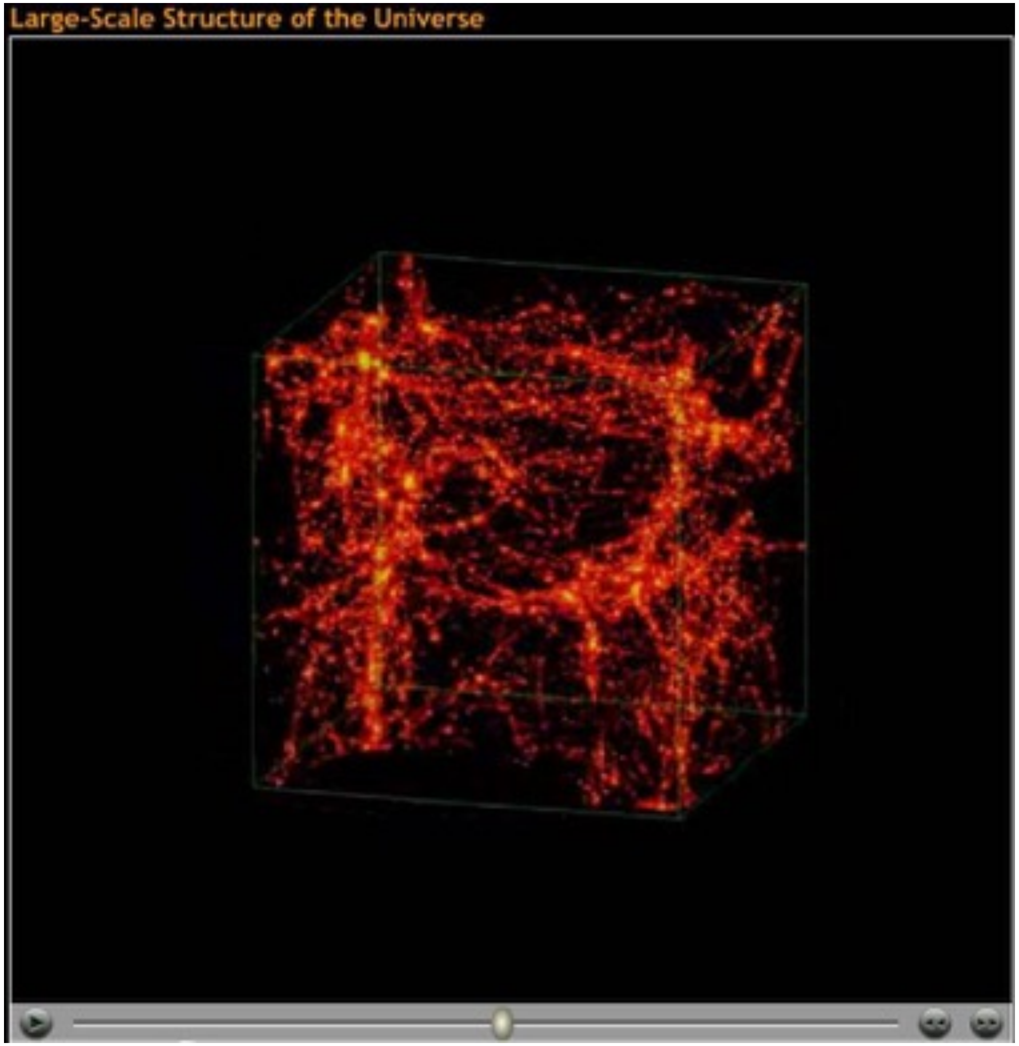
0.5 2.2 5.9 8.6 13.7



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.



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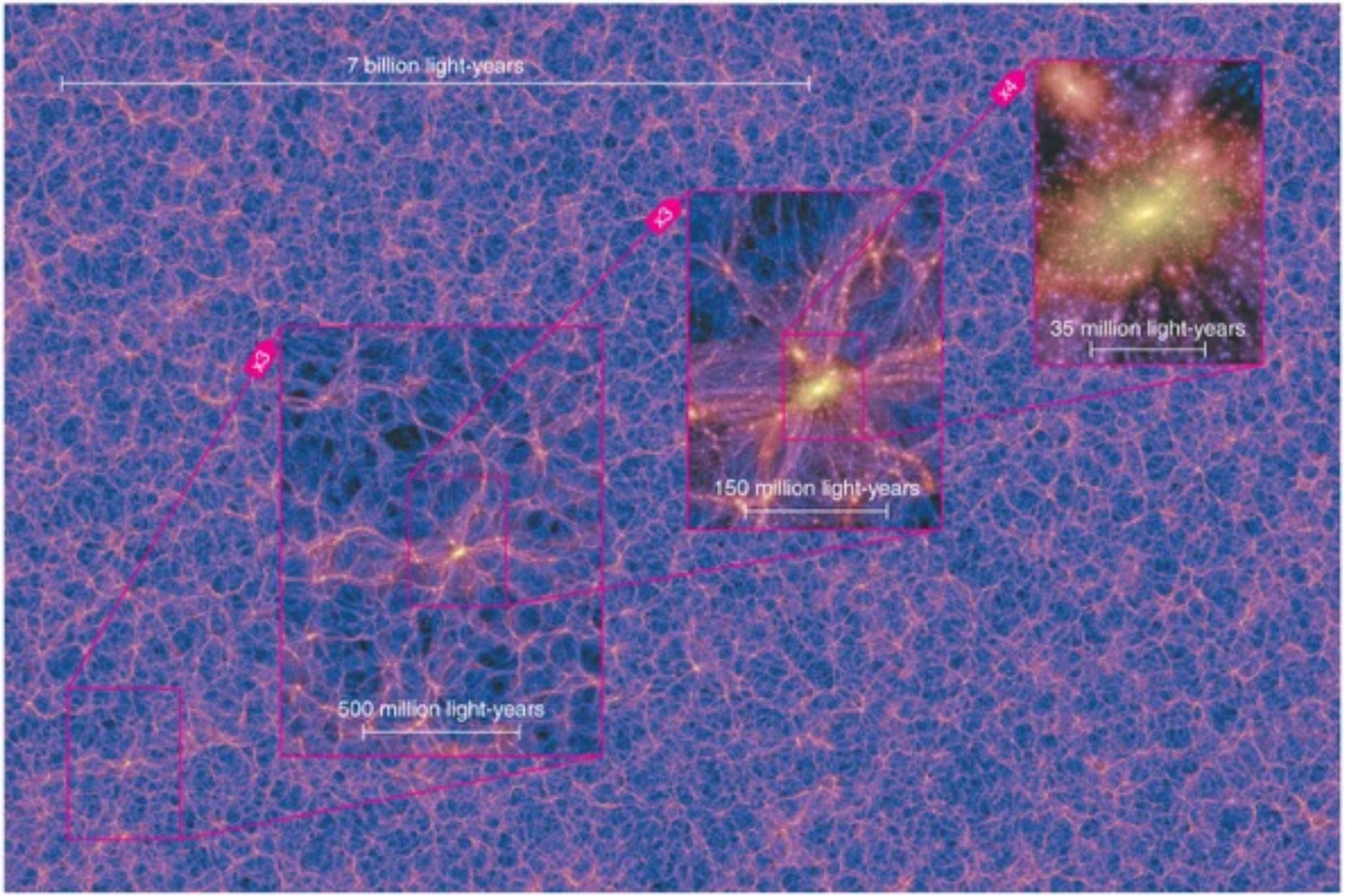


- Structures in galaxy maps look very similar to the ones found in models in which dark matter is WIMPs.

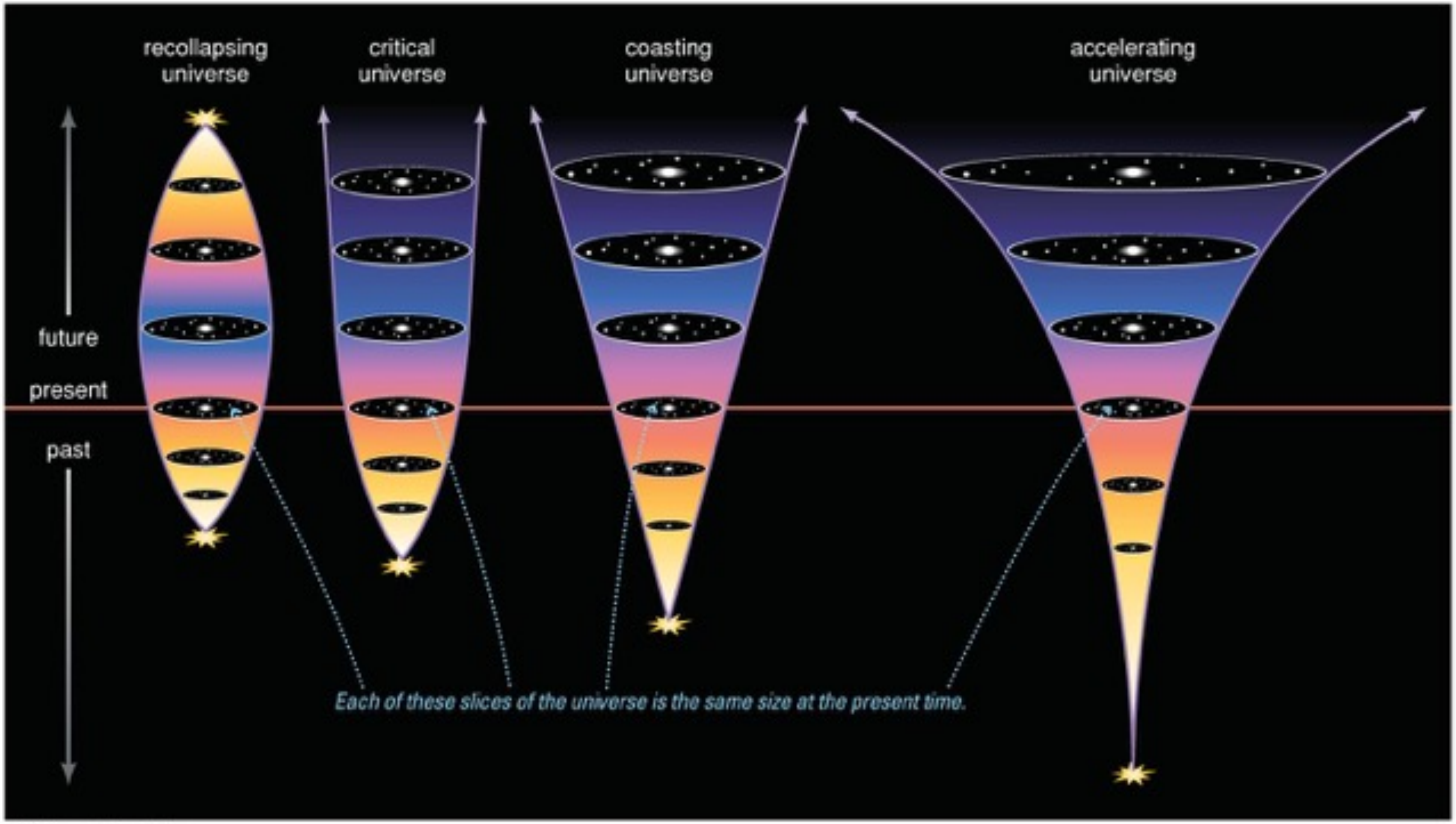
What have we learned?

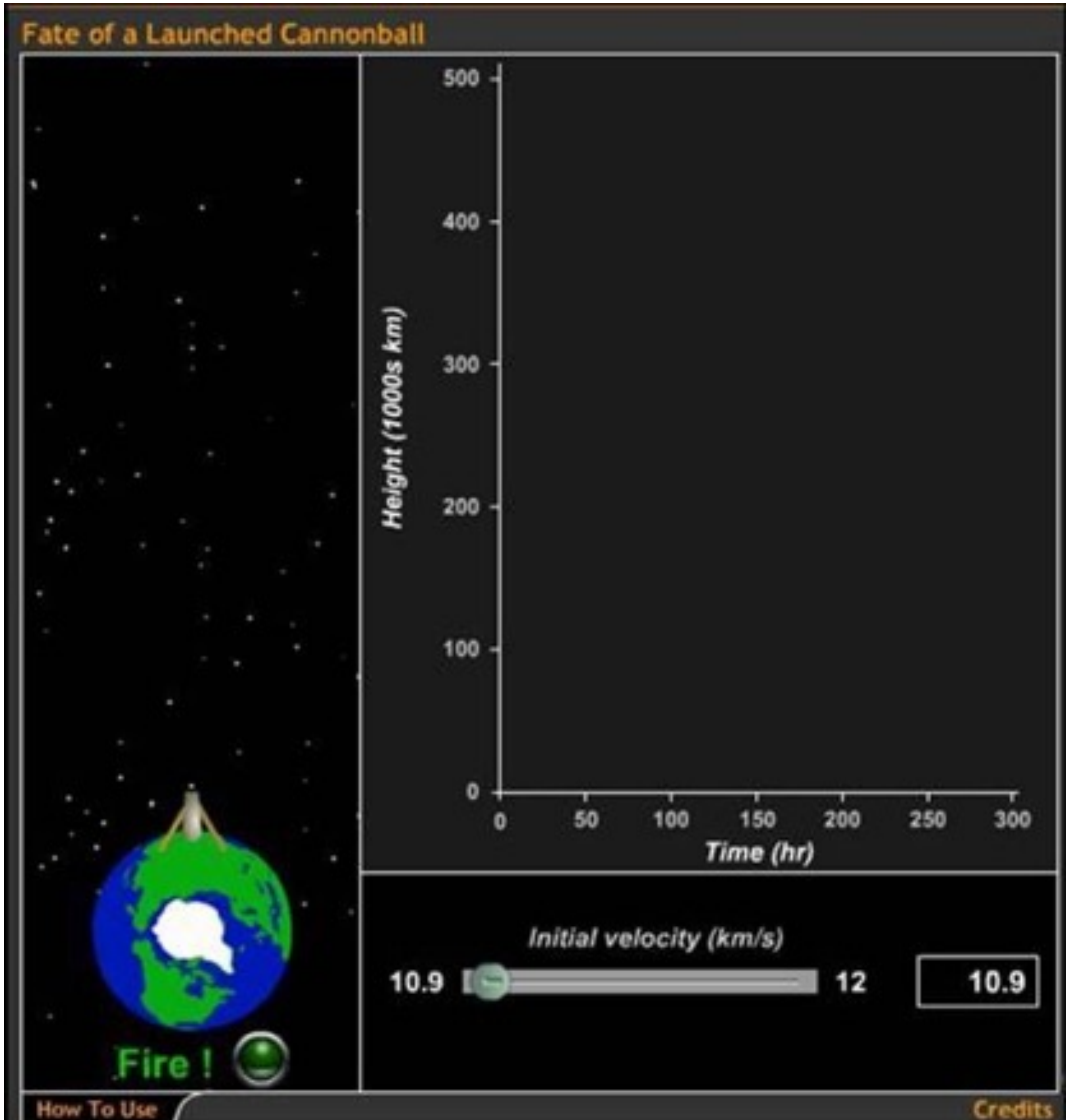
- **What is the role of dark matter in galaxy formation?**
  - The gravity of dark matter seems to be what drew gas together into protogalactic clouds, initiating the process of galaxy formation.
- **What are the largest structures in the universe?**
  - Galaxies appear to be distributed in gigantic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

23.4 Dark Energy and the Fate of the Universe

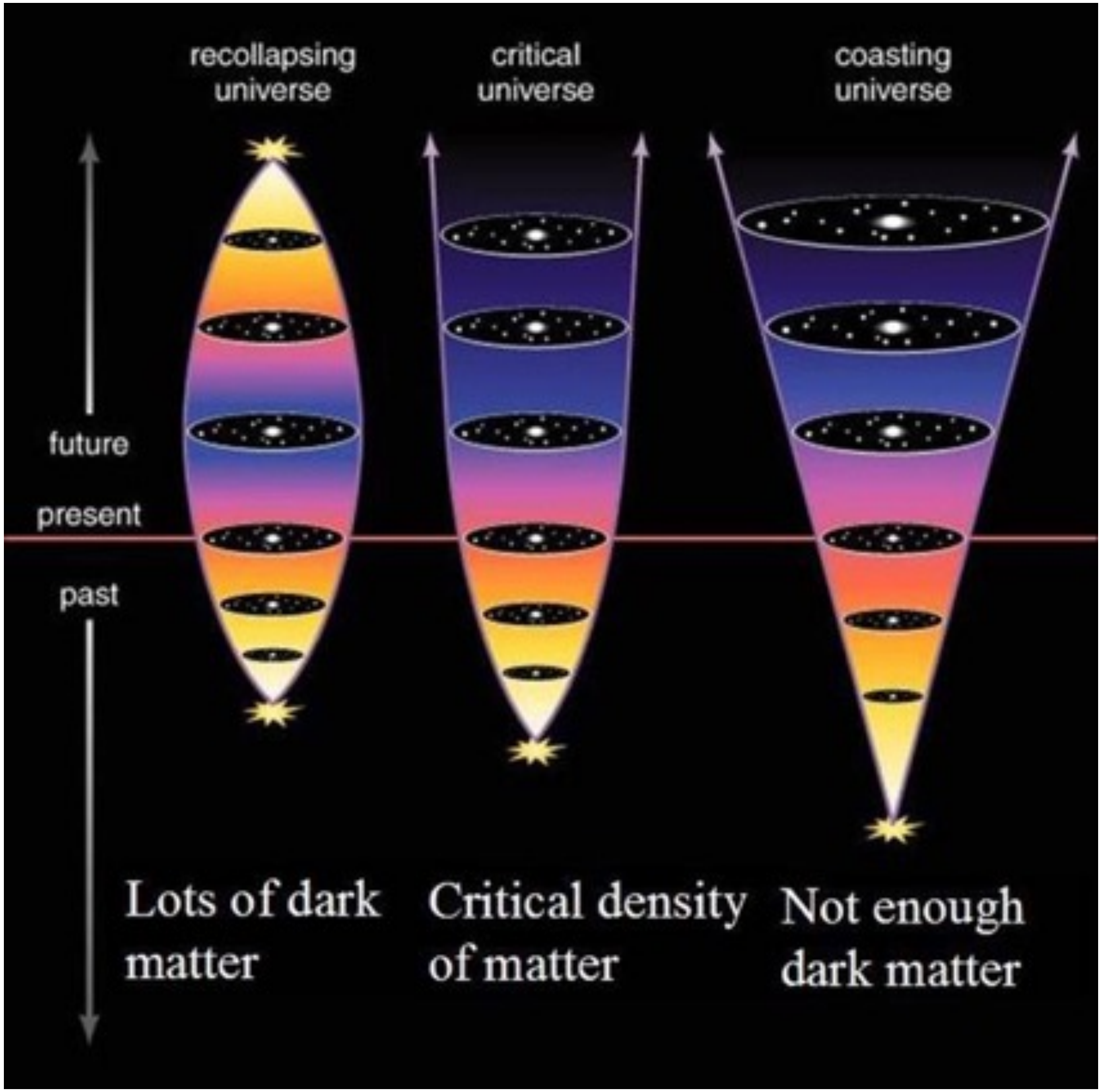
- Our goals for learning:
  - **Why is accelerating expansion evidence for dark energy?**
  - **Why is flat geometry evidence for dark energy?**
  - **What is the fate of the universe?**

Why is accelerating expansion evidence for dark energy?



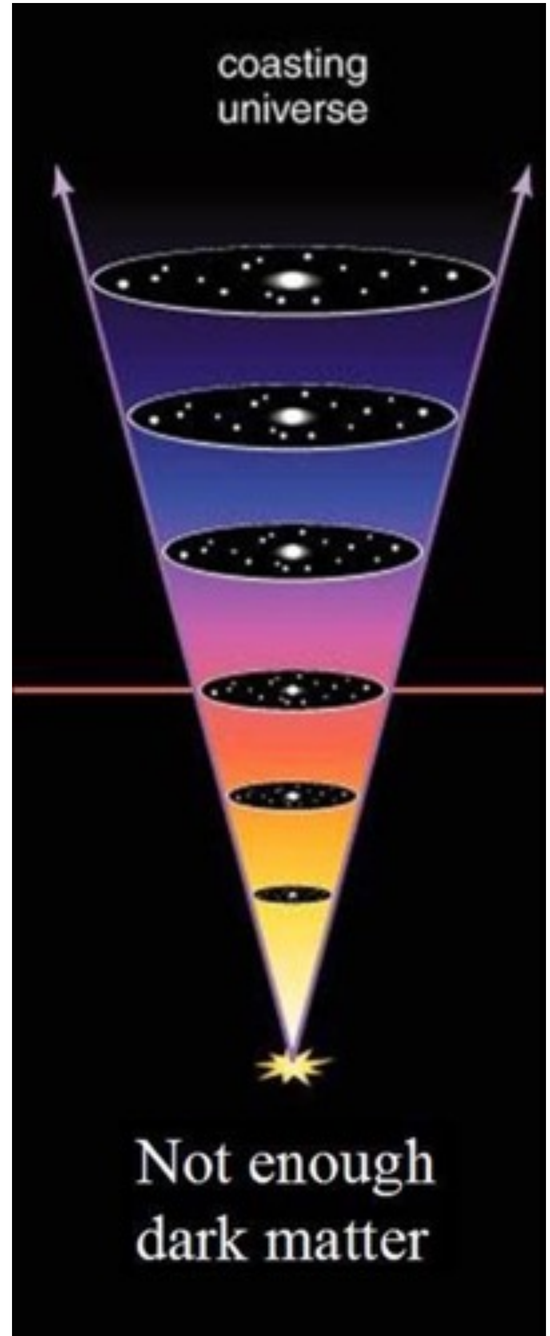


- Does the universe have enough kinetic energy to escape its own gravitational pull?

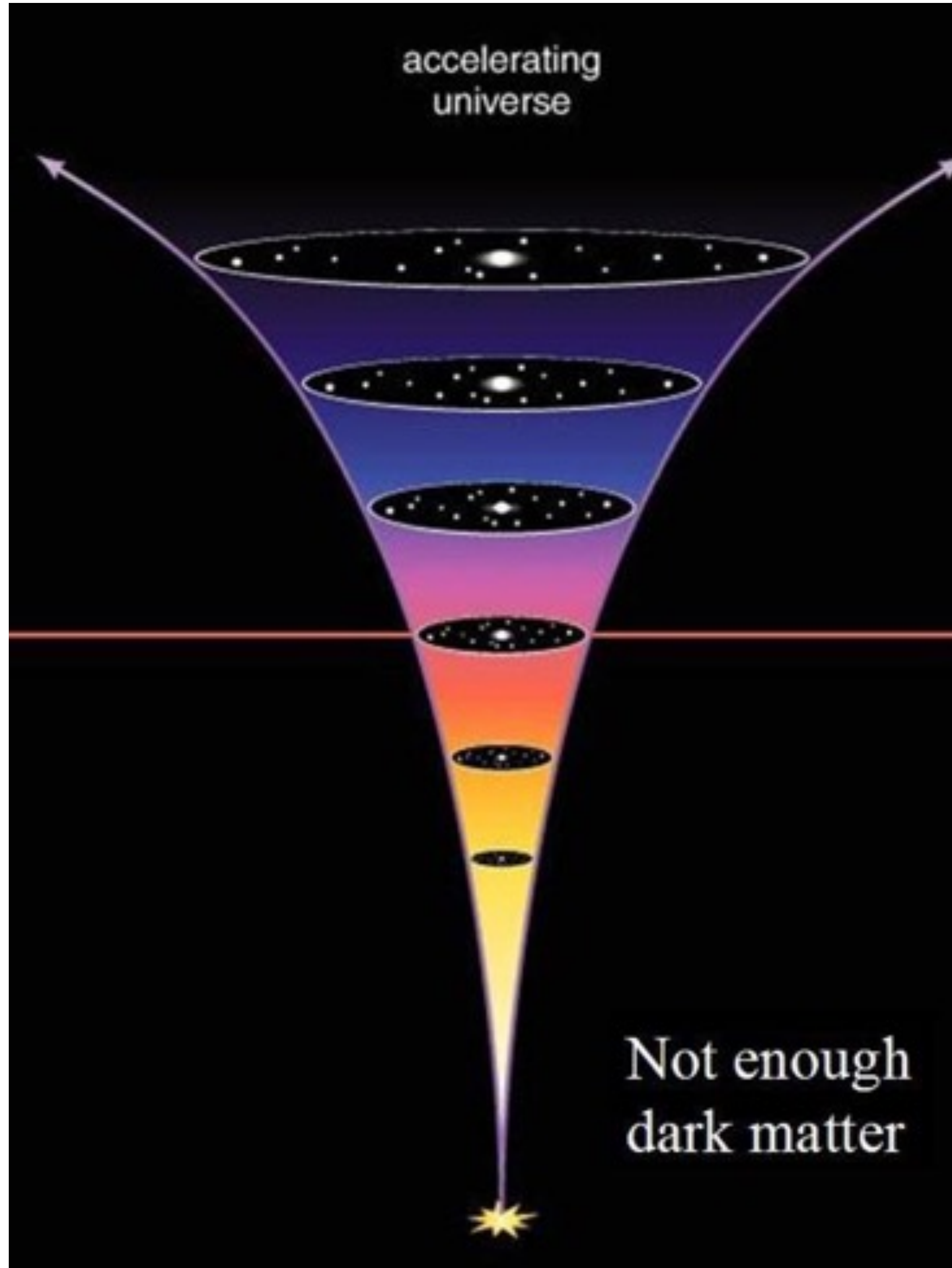


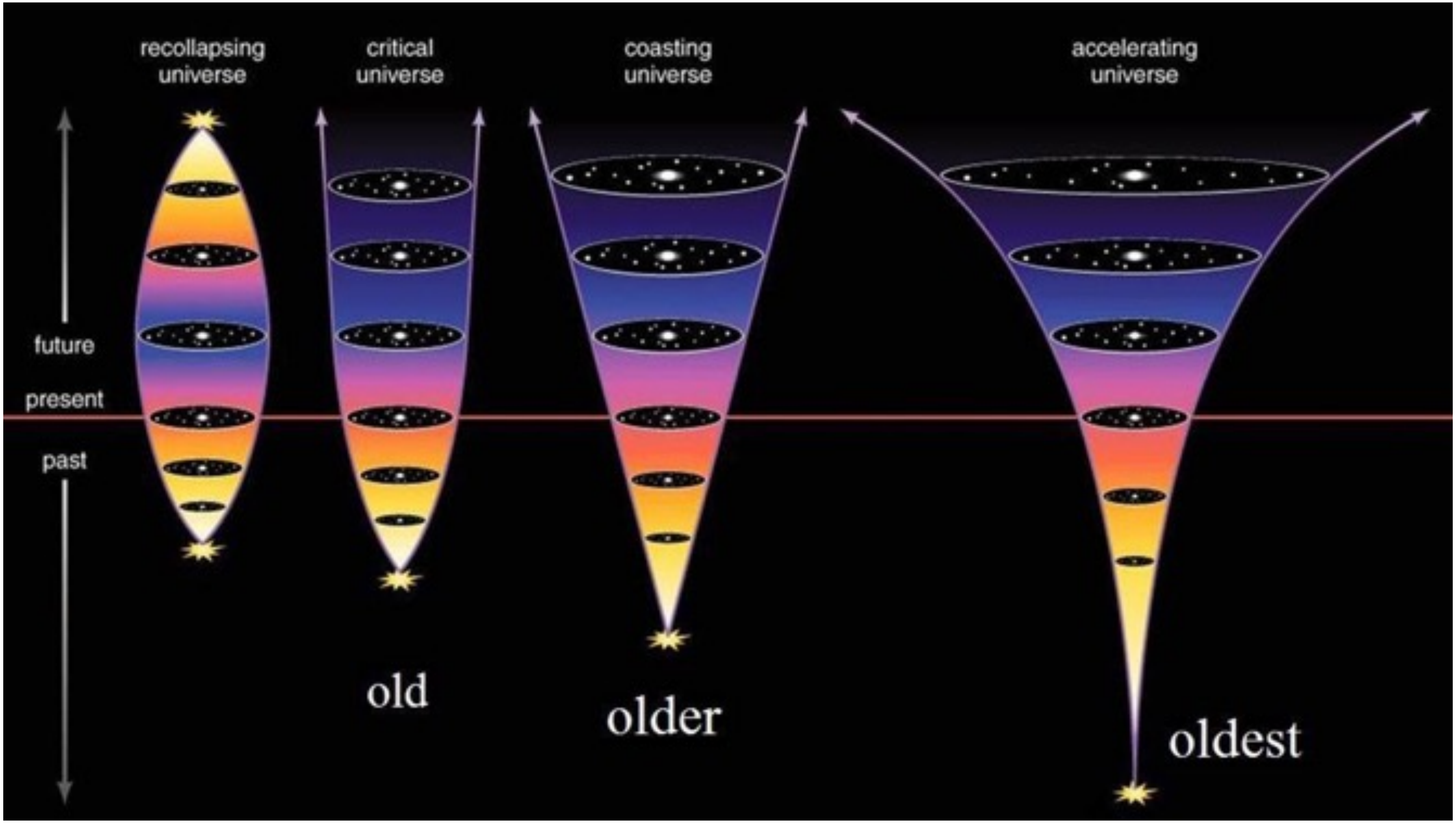
- The fate of the universe depends on the amount of dark matter.

- Since the amount of dark matter is ~25% of the critical density, we expect the expansion of the universe to overcome its gravitational pull.



- In fact, the expansion appears to be speeding up!
- Dark energy?





- Estimated age depends on the amount of both dark matter and dark energy.

Thought Question

Suppose that the universe has more dark matter than we think there is today. How would this change the age we estimate from the expansion rate?

A. The estimated age would be larger.
B. The estimated age would be the same.
C. The estimated age would be smaller.

Thought Question

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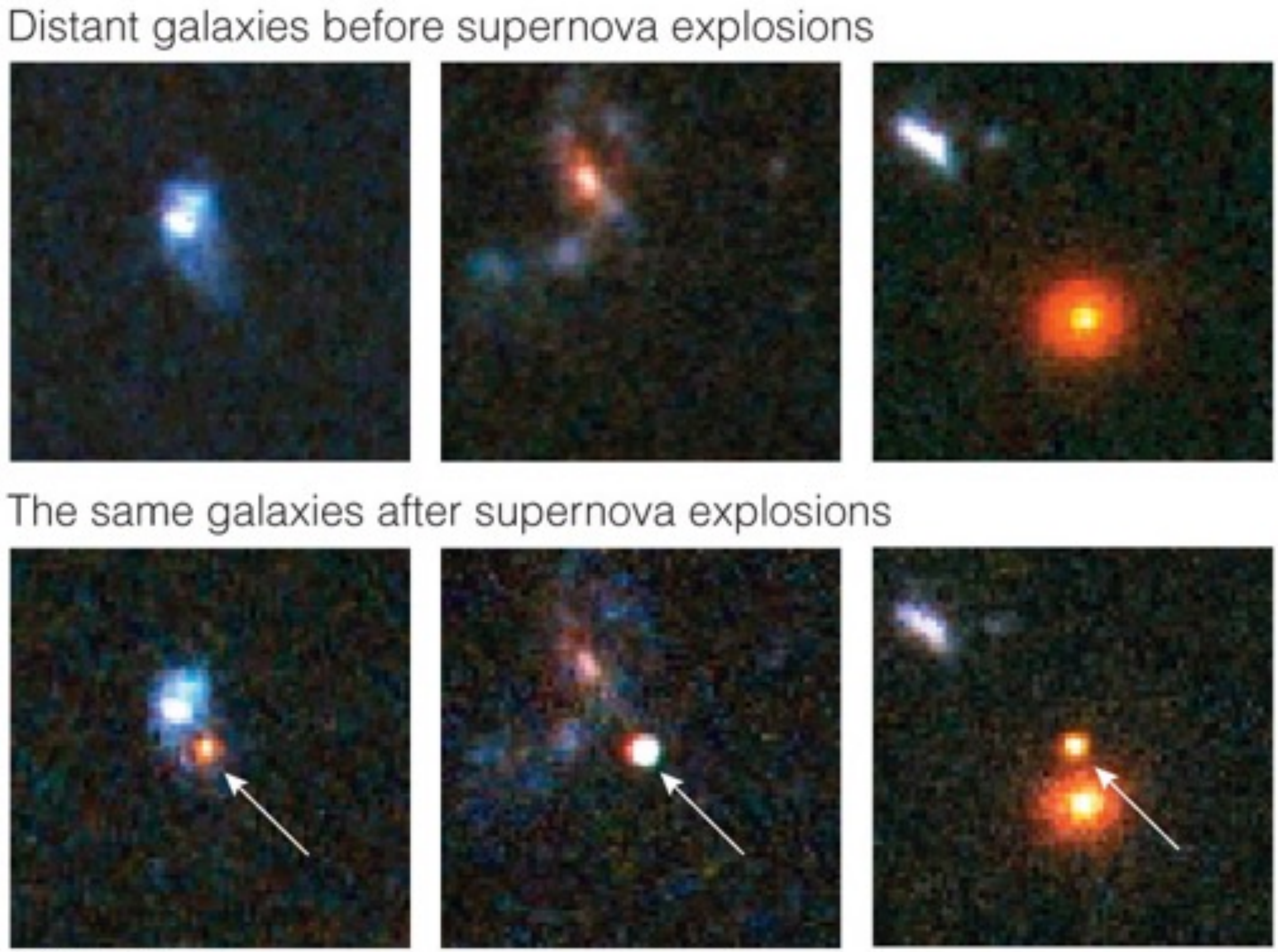
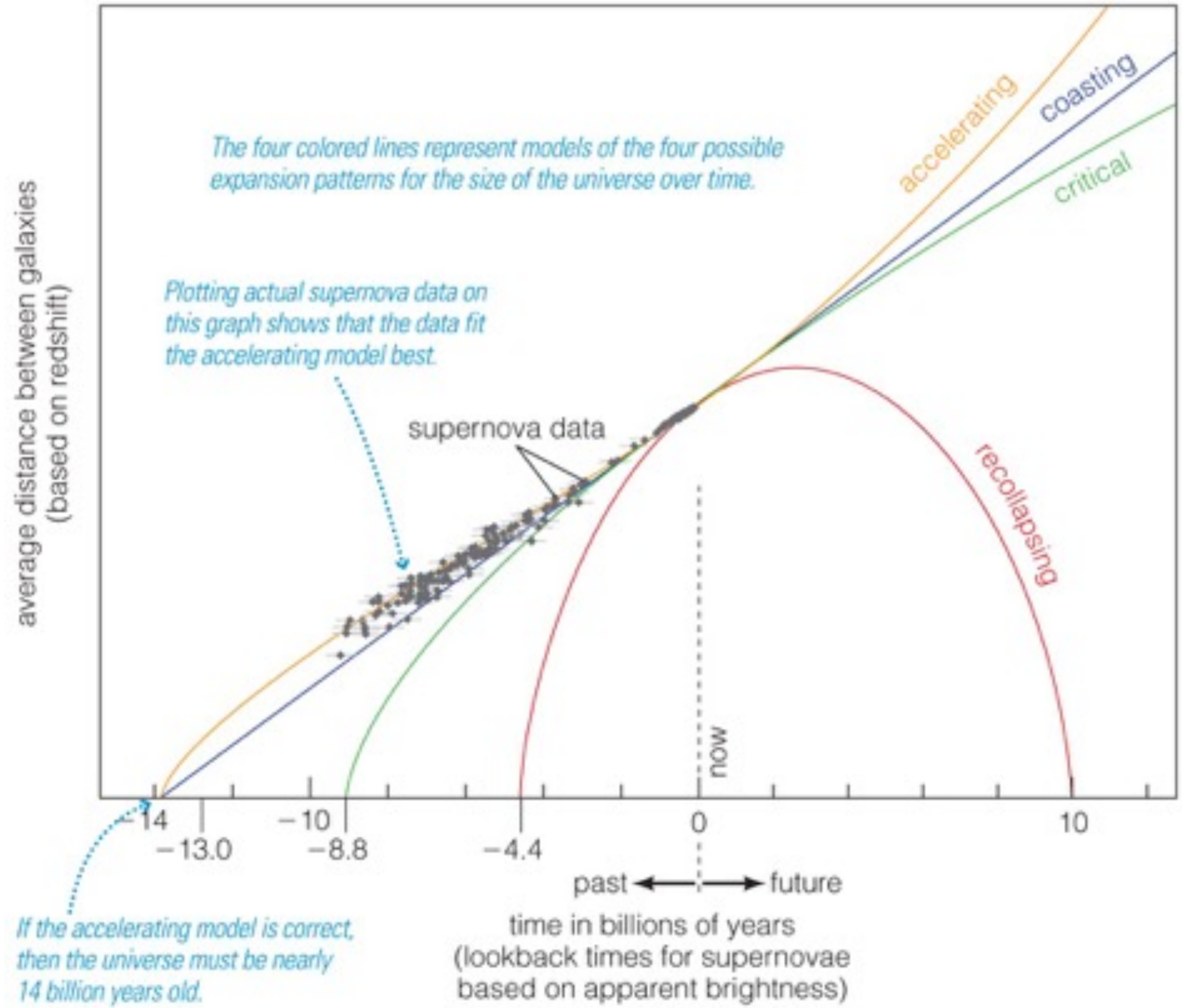
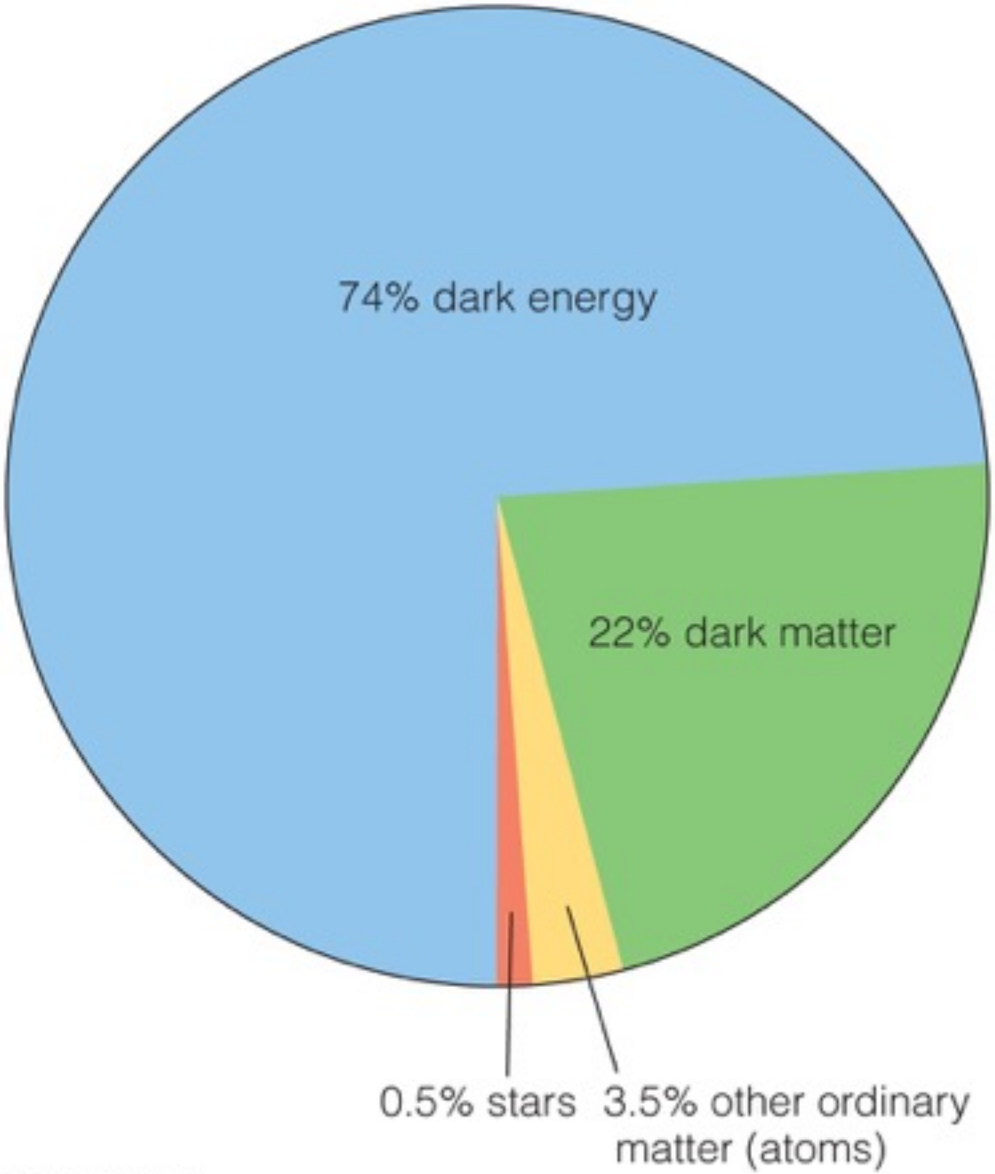


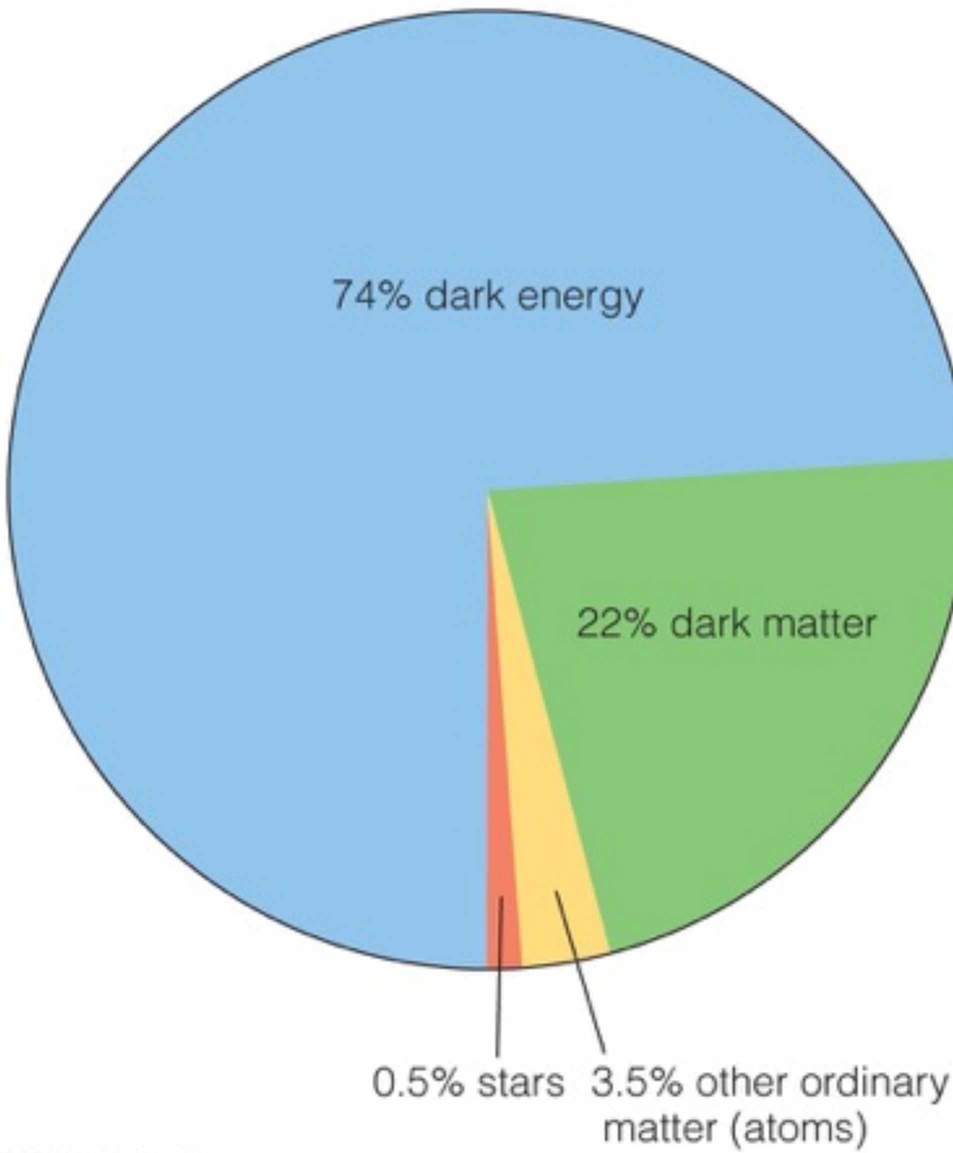
- The brightness of distant white dwarf supernovae tells us how much the universe has expanded since they exploded.



- An accelerating universe best fits the supernova data.

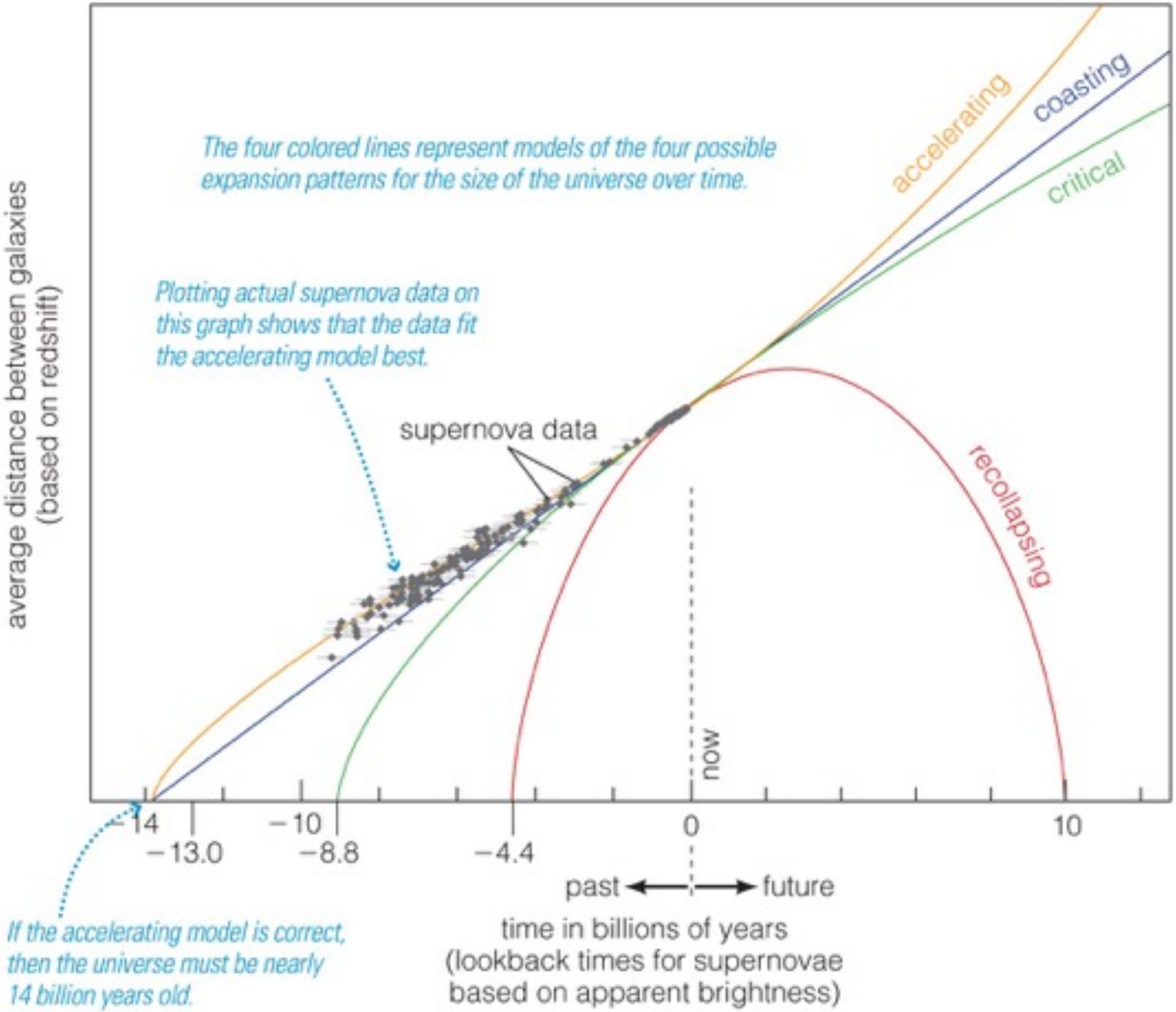
Why is flat geometry evidence for dark energy?





- Measurements of the cosmic microwave background indicate that the universe has a flat geometry, thus dark energy is needed to fill out the remaining mass-energy.

What is 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 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.