Chapter 16
Dark Matter, Dark Energy, and the Fate of the Universe

16.1 Unseen Influences in the Cosmos

Our goals for learning:

- What do we mean by dark matter and dark energy?

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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

- Normal matter: ~ 4.6%
  - Normal matter inside stars: ~ 0.7%
  - Normal matter outside stars: ~ 3.9%
- Dark matter: ~ 23%
- Dark energy: ~ 72%

What have we learned?

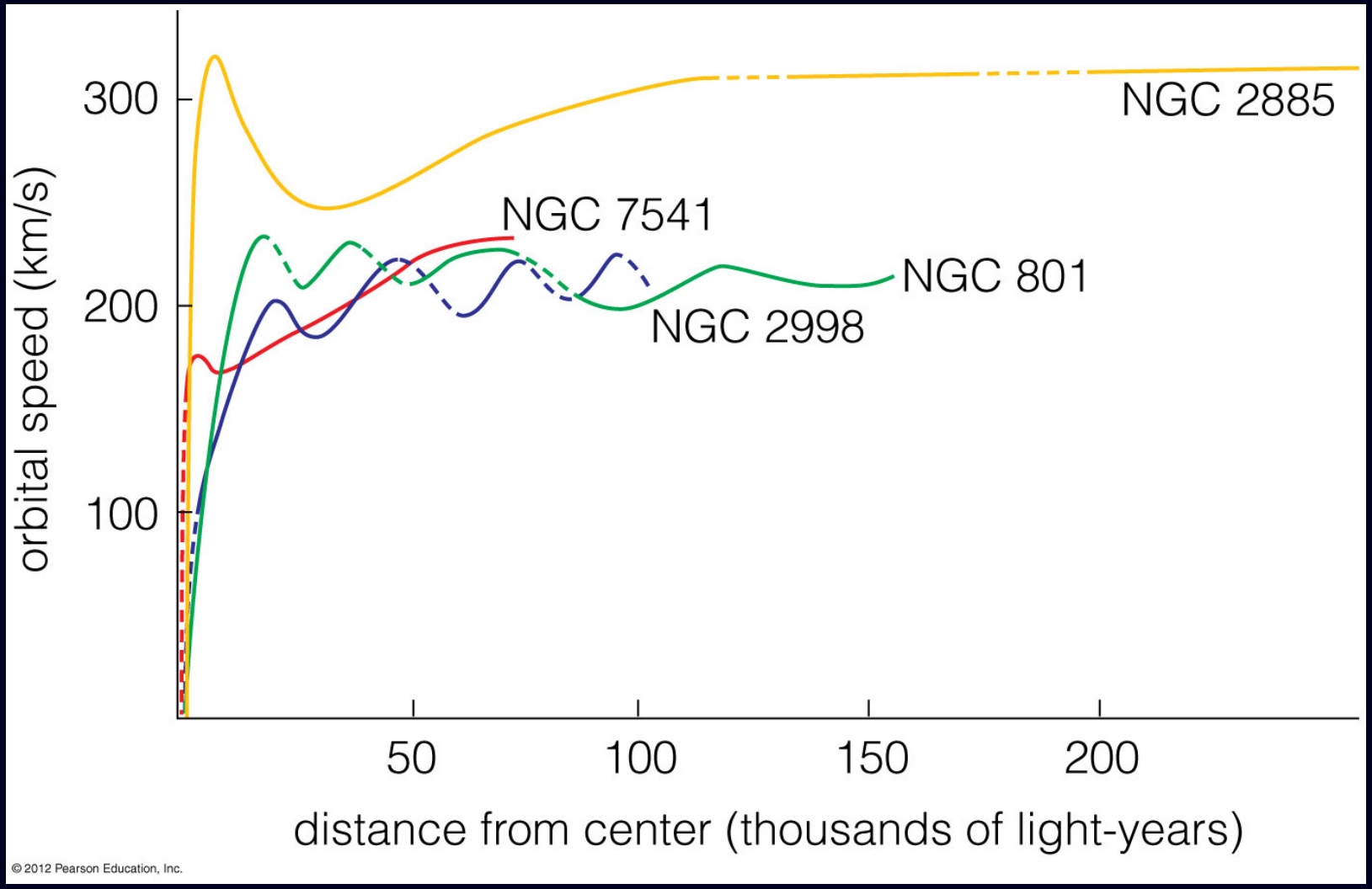
- What do we mean by dark matter and dark energy?
  - Dark matter is the name given to the unseen mass whose gravity governs the observed motions of stars and gas clouds.
  - Dark energy is the name given to whatever might be causing the expansion of the universe to accelerate.

16.2 Evidence for Dark Matter

Our goals for learning:

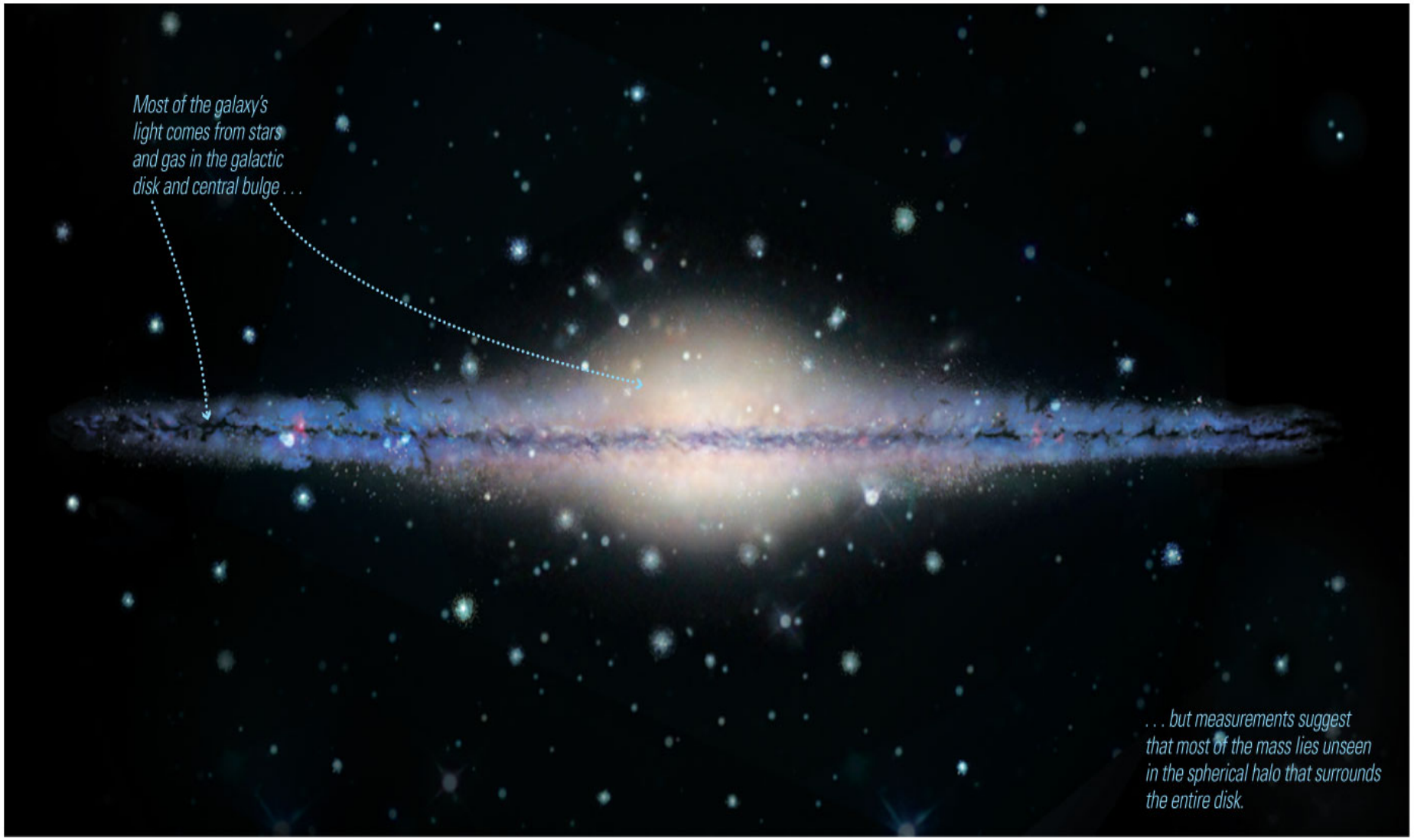
- What is the evidence for dark matter in galaxies?
- What is the evidence for dark matter in clusters of galaxies?
- Does dark matter really exist?
- What might dark matter be made of?

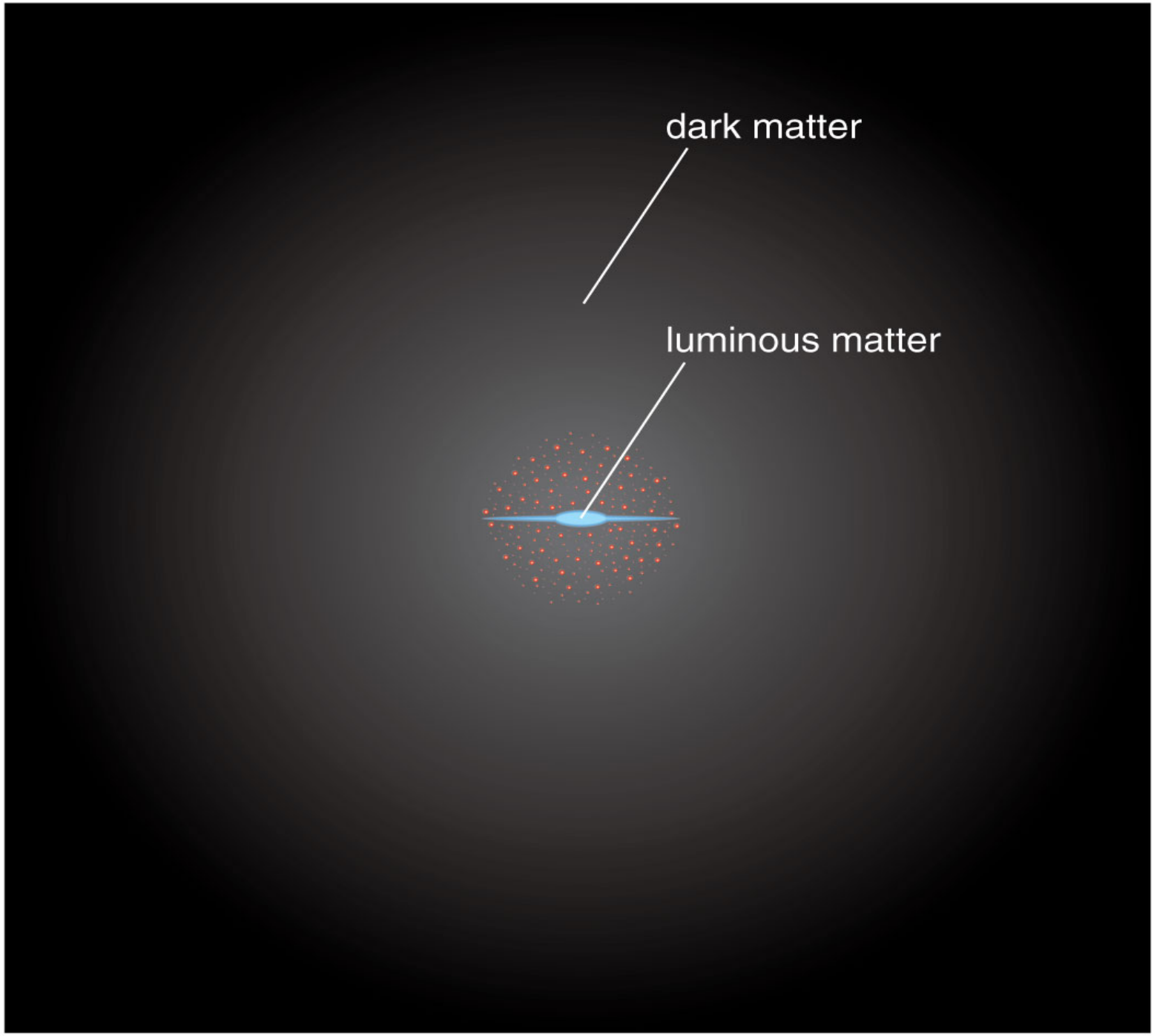
What is the evidence for dark matter in galaxies?



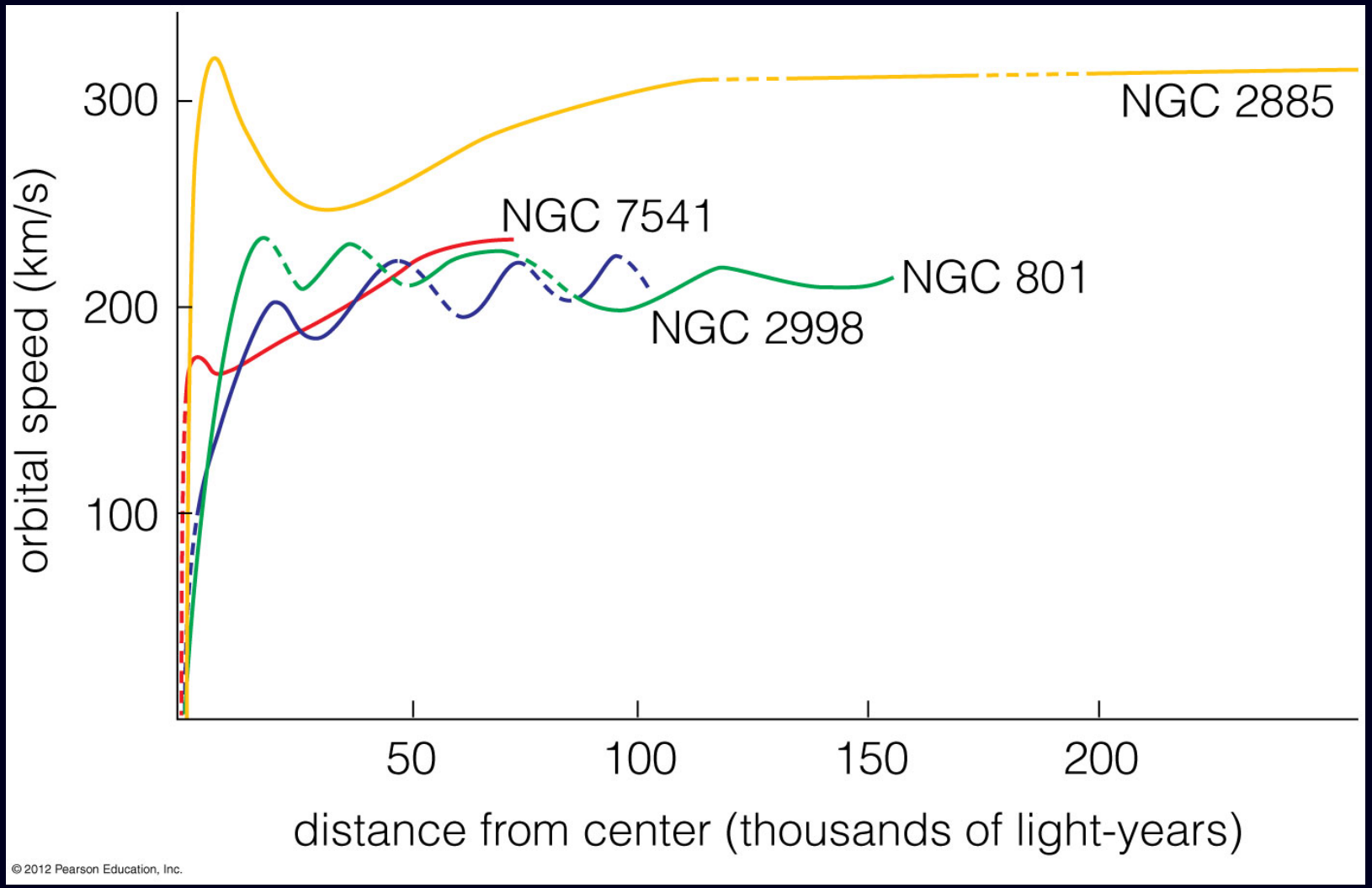
Mass within Sun's orbit:
$1.0 \times 10^{11} M_{\text{Sun}}$

Total mass:
$\sim 10^{12} M_{\text{Sun}}$





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



Spiral galaxies all tend to have orbital velocities that remain constant at large radii, indicating large amounts of dark matter.

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

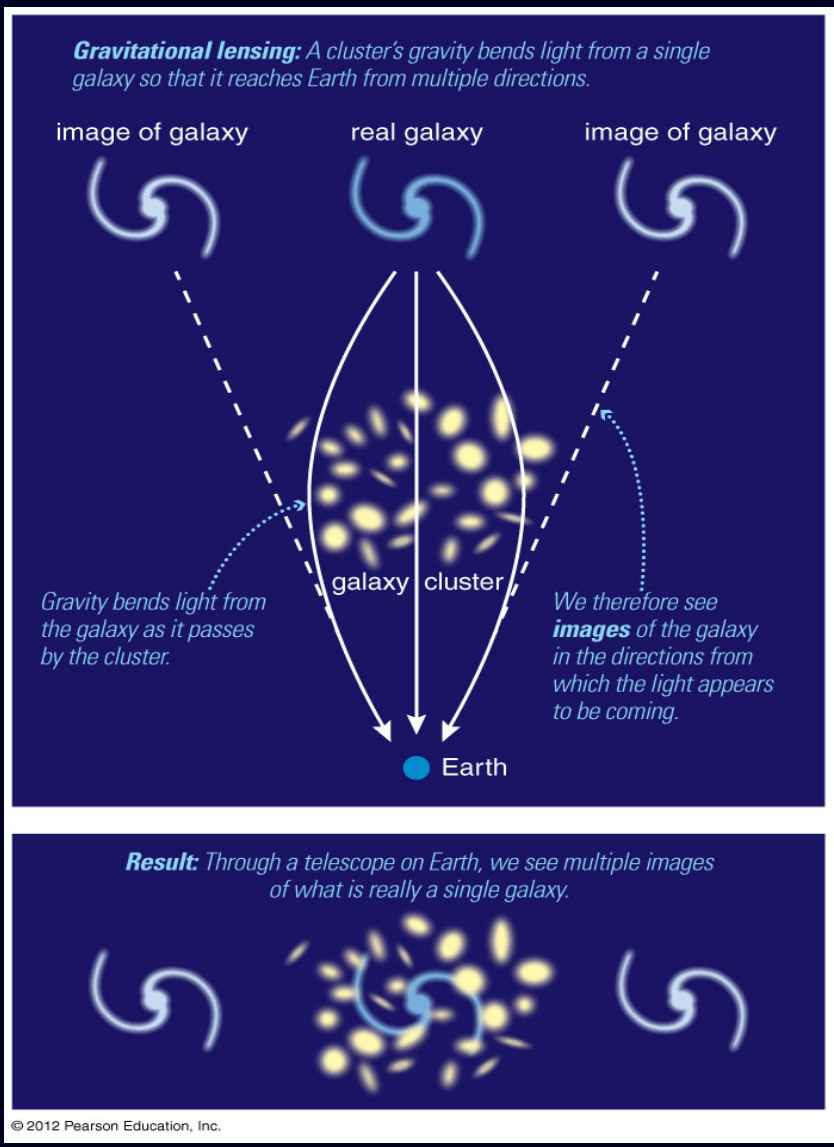
We can measure the velocities of galaxies in a cluster from their Doppler shifts.

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

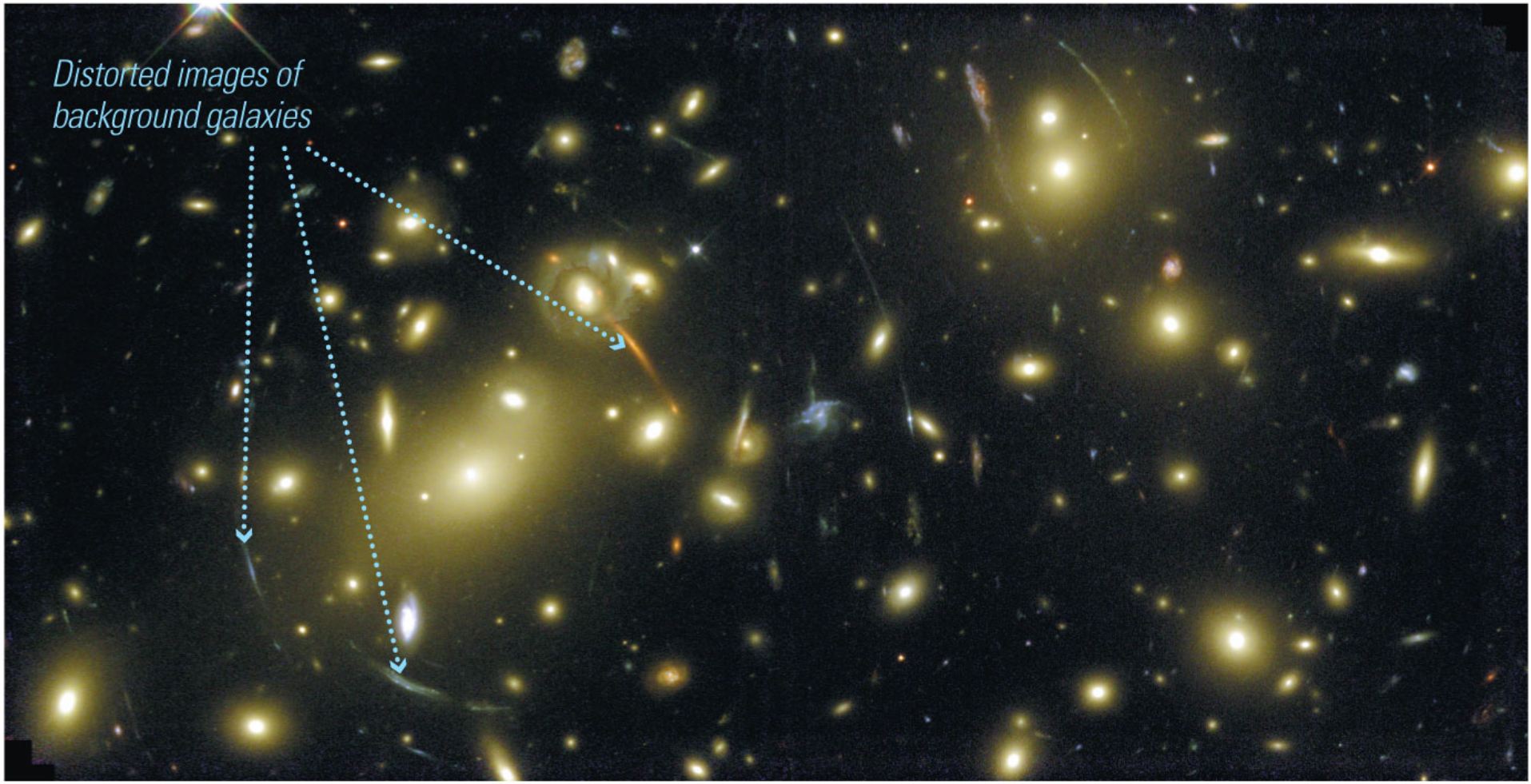
Clusters contain large amounts of X ray–emitting hot gas.

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

85% dark matter
13% hot gas
2% stars

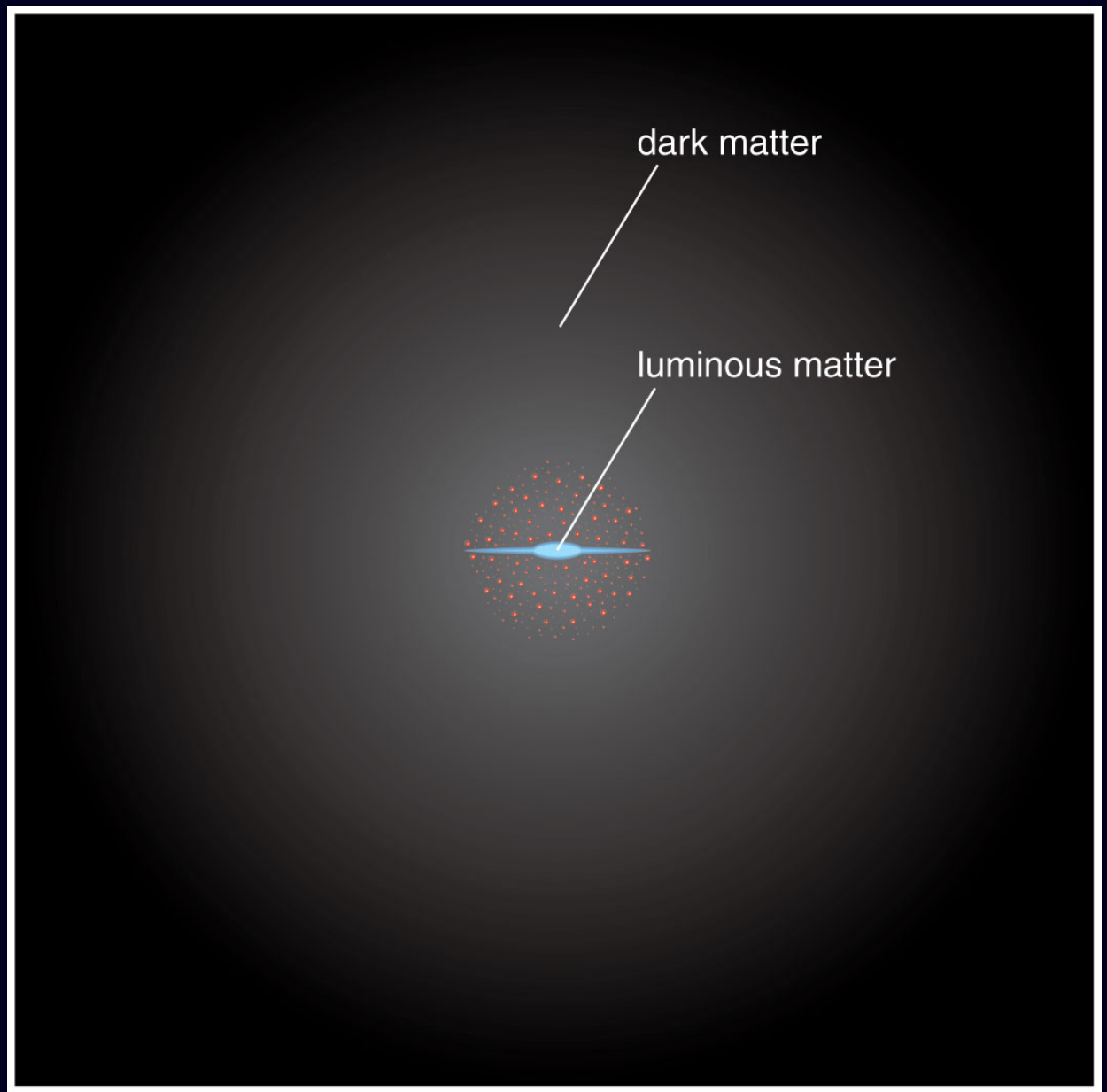


Gravitational lensing, the bending of light rays by gravity, can also tell us a cluster's mass.



All three methods of measuring cluster mass indicate similar amounts of dark matter.

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.

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

What might dark matter be made of?

Two Basic Options

- Ordinary Matter (MACHOs)
  - Massive Compact Halo Objects: dead or failed stars in halos of galaxies
- Exotic Particles (WIMPs)
  - Weakly Interacting Massive Particles: mysterious neutrino-like particles

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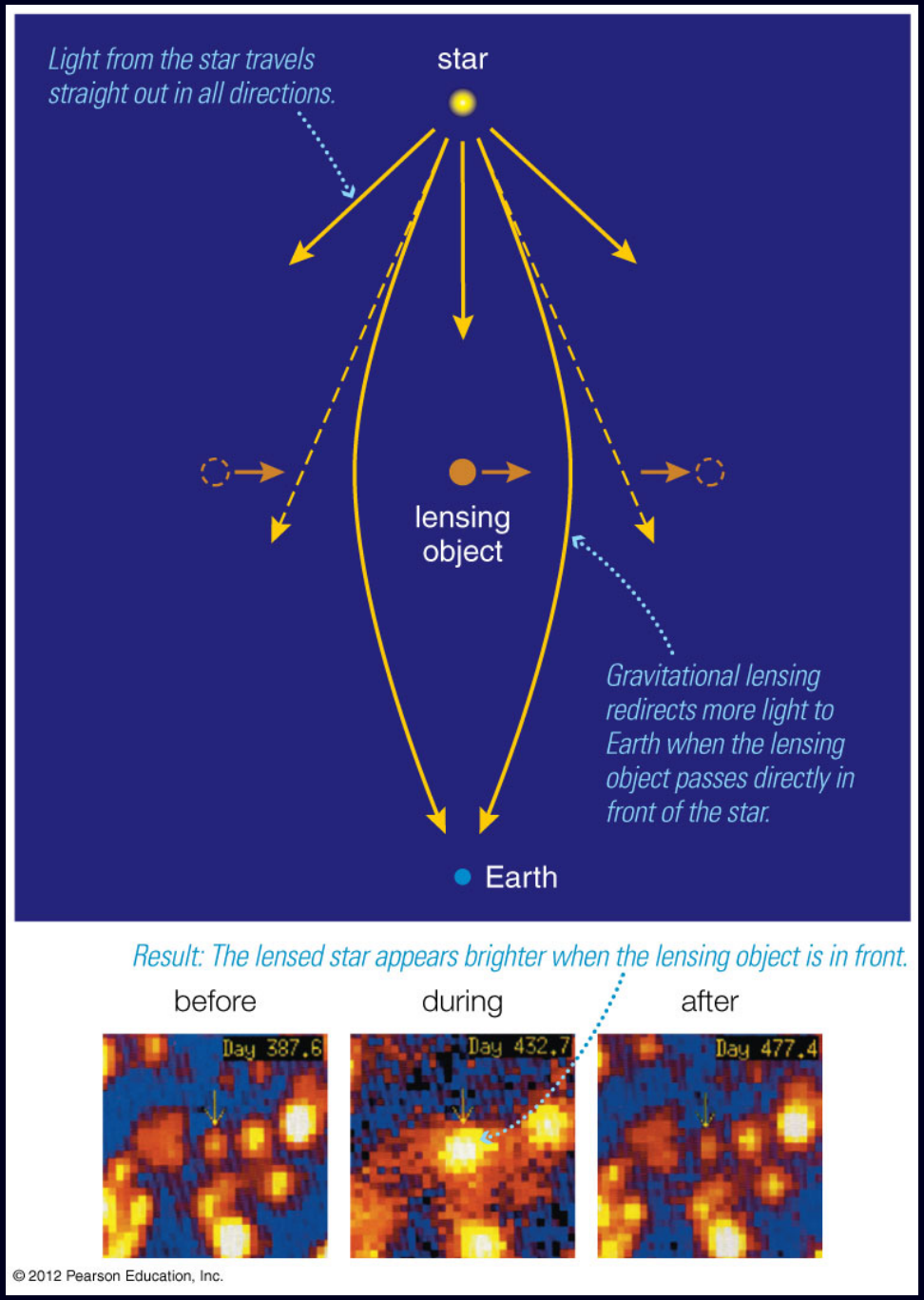
The Best Bet



Compact starlike objects occasionally make other stars appear brighter through lensing…

… but there are not enough lensing events to explain all the dark matter.

Why WIMPs?

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

What have we learned?

- What is the evidence for dark matter in galaxies?
  - Orbital velocities within galaxies remain nearly constant at large radii, indicating that most of the matter lies outside the 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?

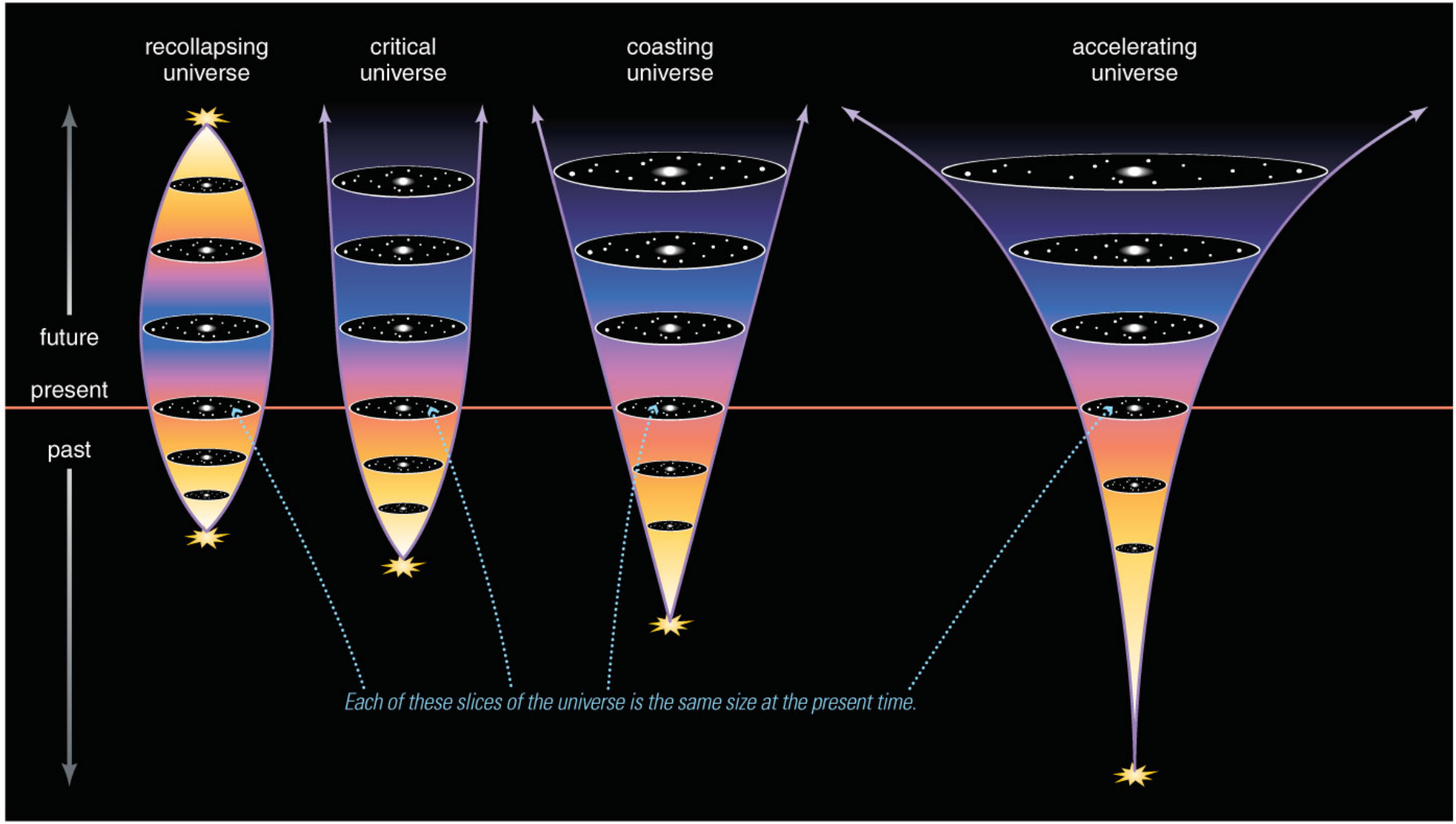
- Does dark matter really exist?
  - Either dark matter exists or our understanding of our gravity must be revised.
- What might dark matter be made of?
  - There does not seem to be enough normal (baryonic) matter to account for all the dark matter, so most astronomers suspect that dark matter is made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

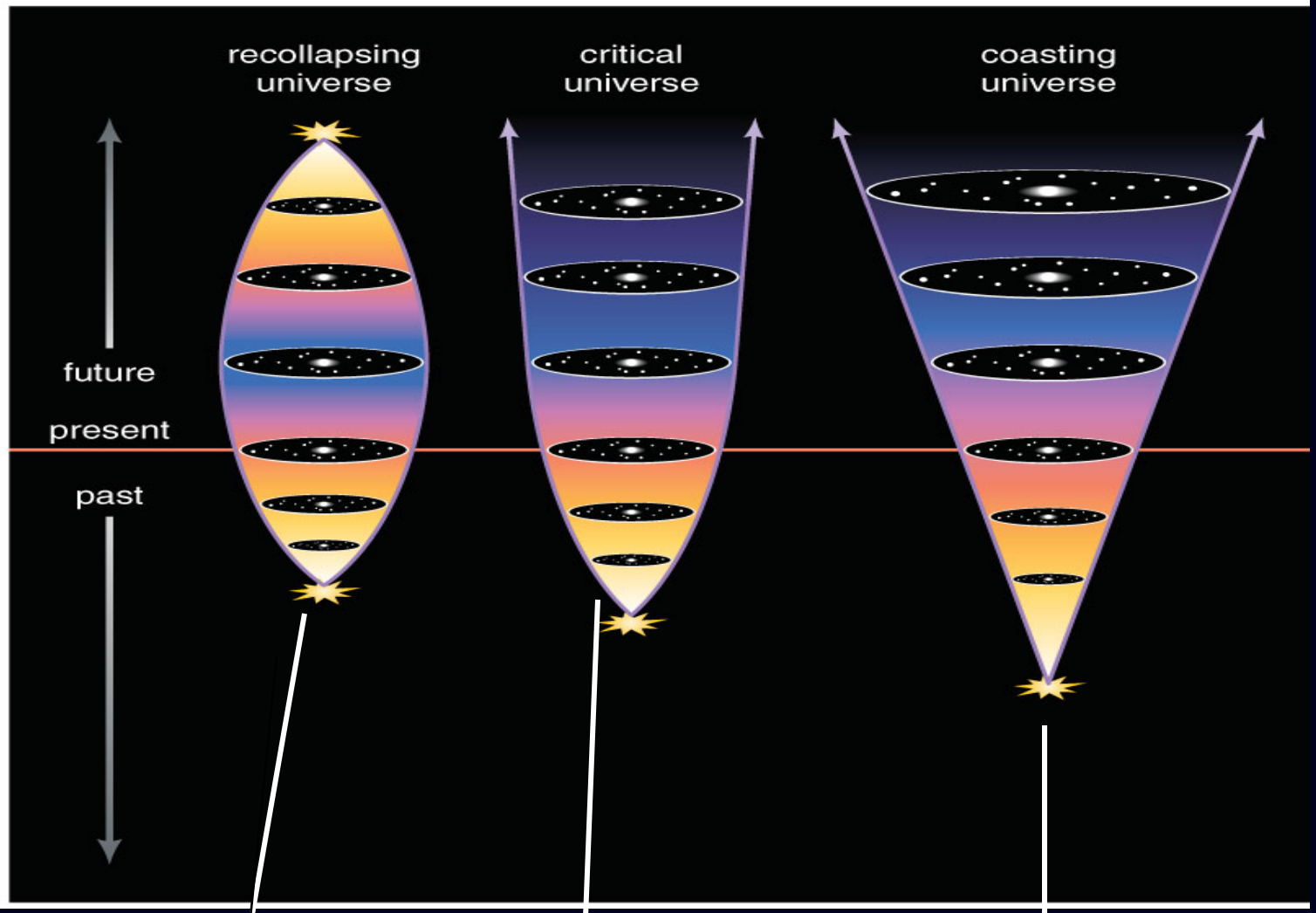
16.4 The Fate of the Universe

Our goals for learning:

- Will the universe continue expanding forever?
- Is the expansion of the universe accelerating?

Will the universe continue expanding forever?





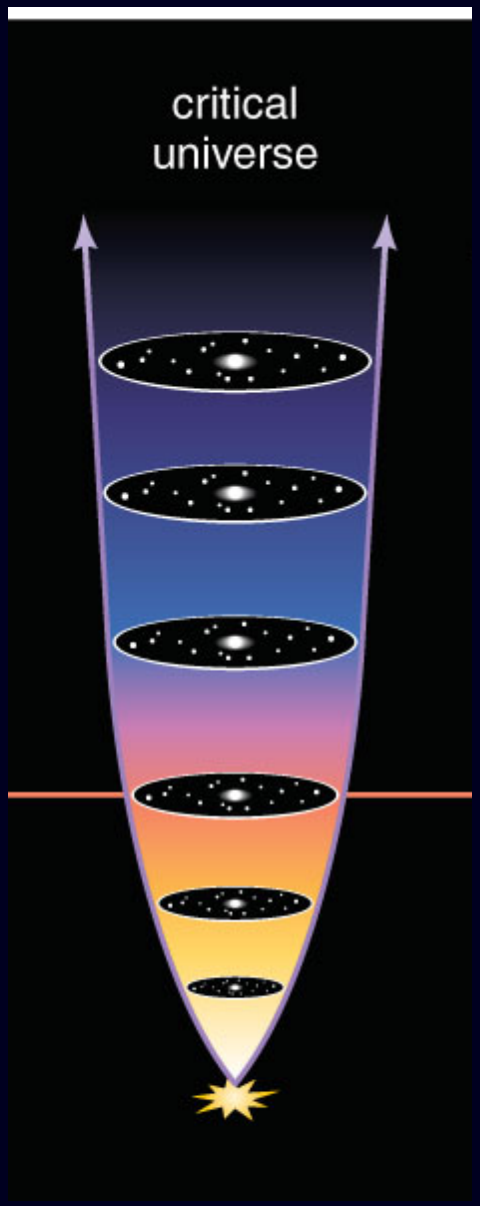
Fate of universe depends on the amount of dark matter.

Lots of dark matter

Critical density of matter

Not enough dark matter

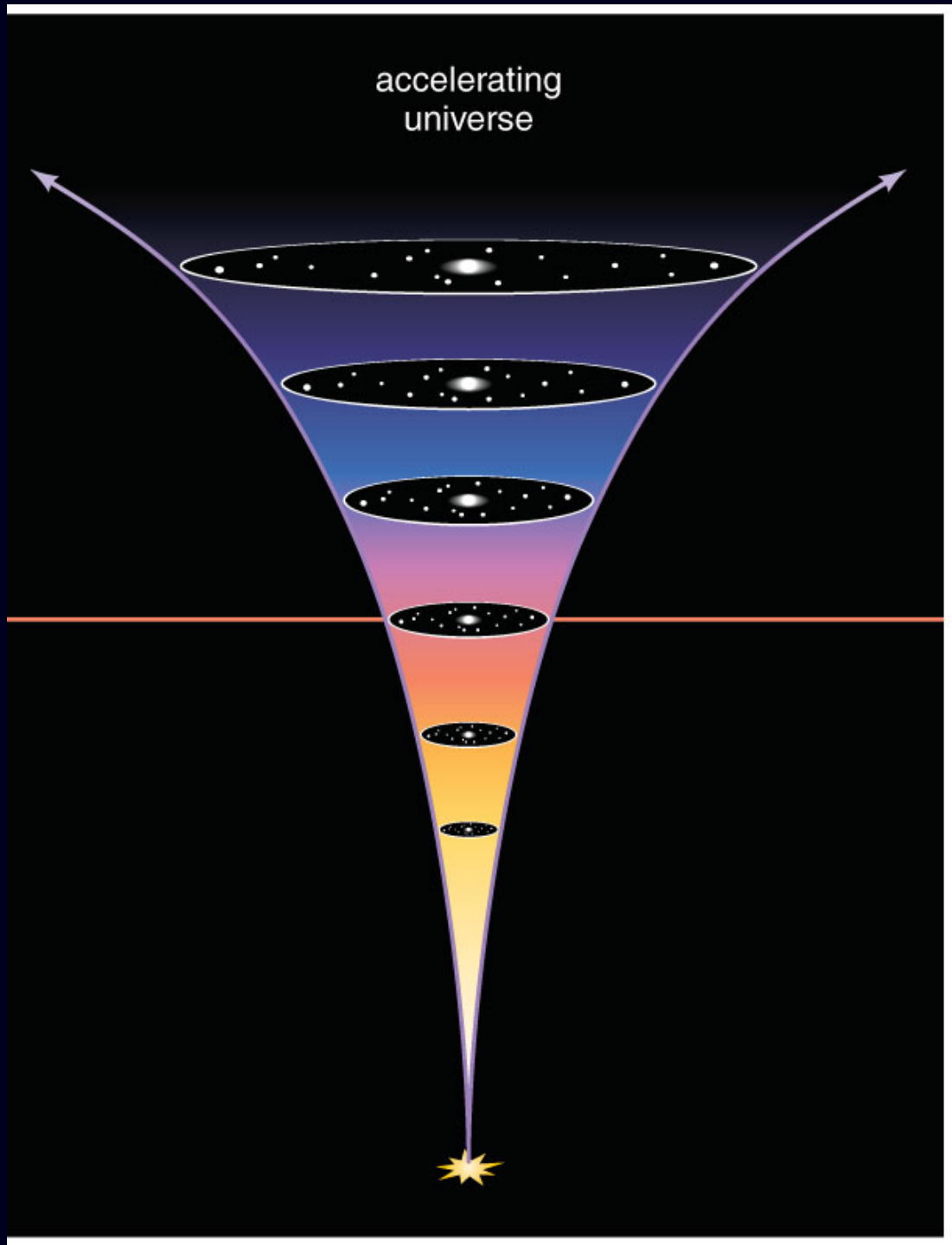
Amount of matter is ~25% of the critical density, suggesting fate is eternal expansion.



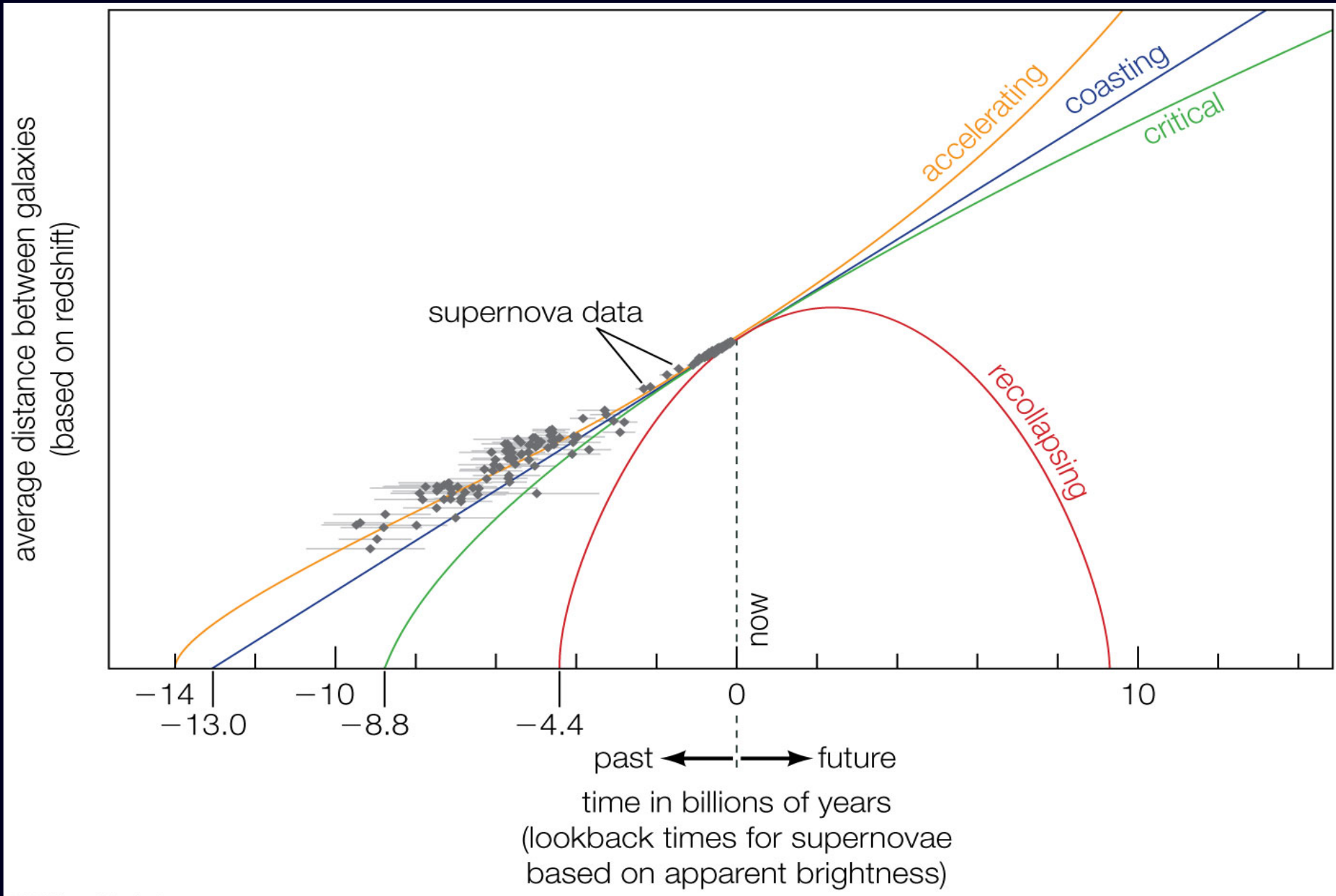
Not enough dark matter

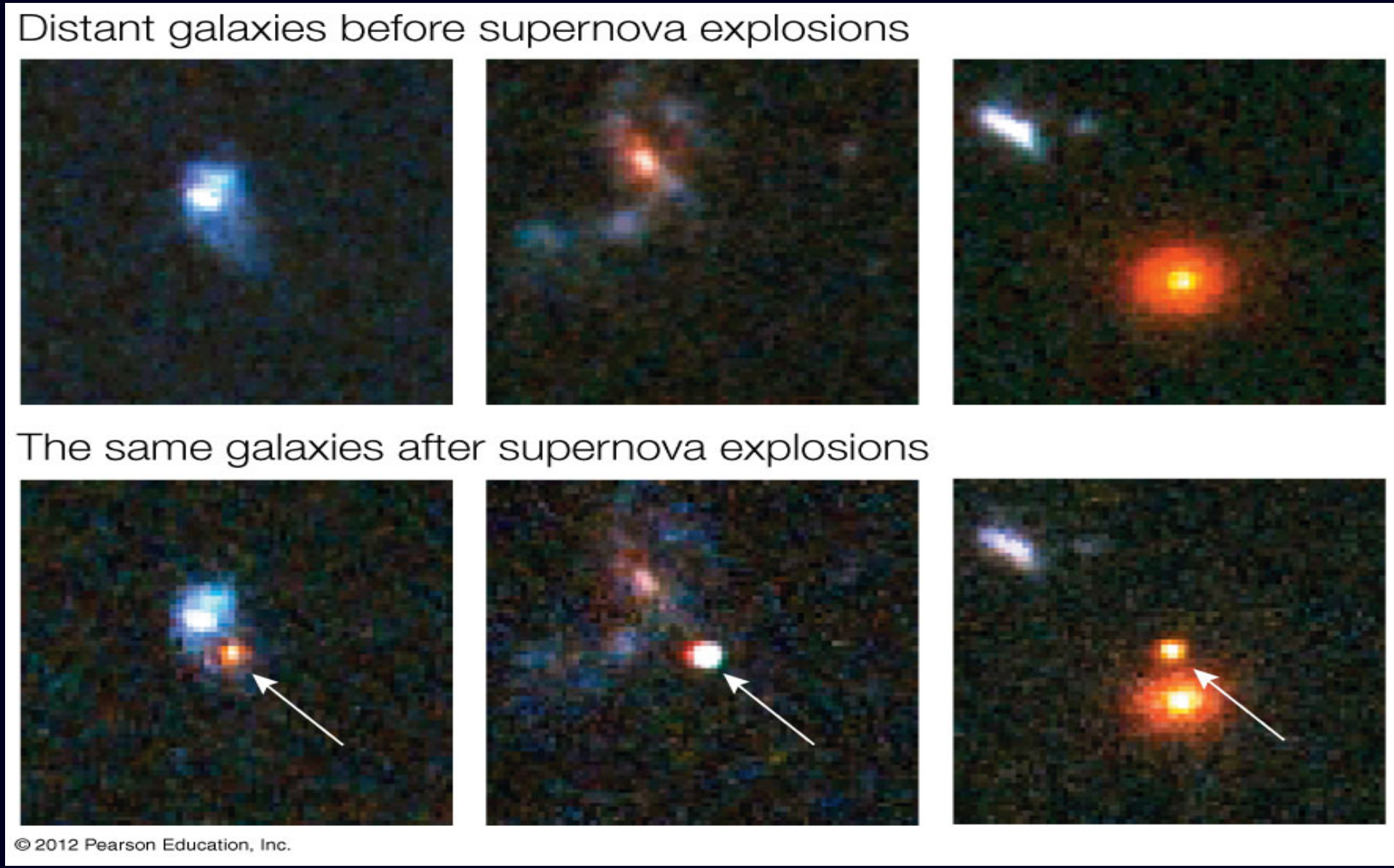
But expansion appears to be speeding up!

Dark energy?

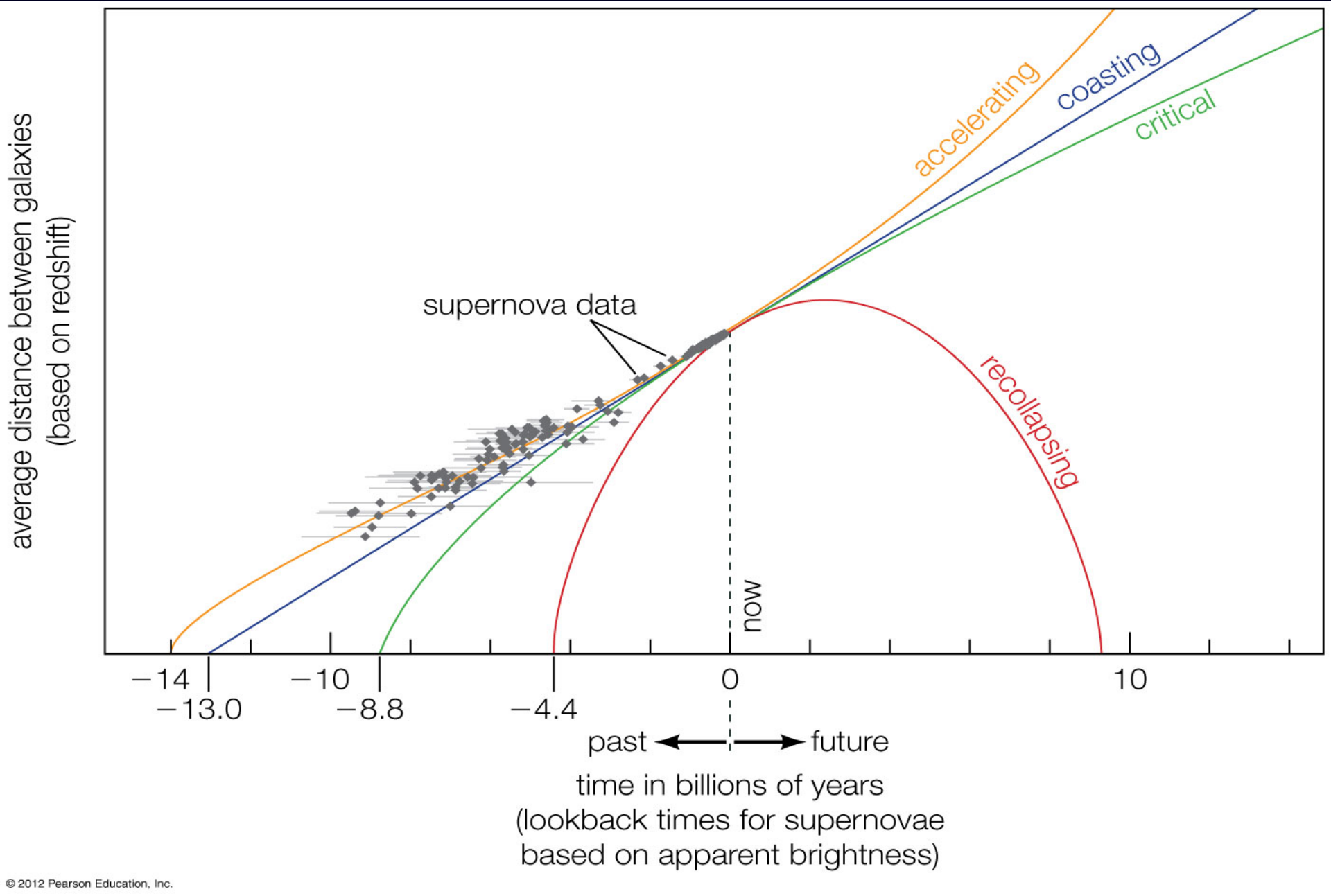


Is the expansion of the universe accelerating?





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



An accelerating universe is the best fit to supernova data.

What have we learned?

- Will the universe continue expanding forever?
  - Current measurements indicate that there is not enough dark matter to prevent the universe from expanding forever.
- Is the expansion of the universe accelerating?
  - An accelerating universe is the best explanation for the distances we measure when using white dwarf supernovae as standard candles.