Quick Memos

- New Mastering Astronomy assignment for Week 5 is up
- This Friday’s exam will be a combination of this week’s material and cumulative material from the entire term
  - Study guide will be posted soon
- Friday will be last chance to finish any missing work
- We will be doing FCQs on Thursday (8/5)
- Pizza on Thursday!

ASTR 1120

:: Stars and Galaxies ::

Inflation,
Fate of the Universe,
Dark Energy

But first, Tutorial!

- The Big Bang (not in book, a handout)
  - Should review the concepts you learned yesterday

Tutorial follow-up: which is most accurate?

A) In the beginning, all the matter in the universe was confined to an extremely small region in the universe which then expanded into empty space.

B) In the beginning, all the matter in the universe was confined to an extremely small region. The universe itself then began to expand.

C) In the beginning, the universe was composed of pure energy confined to an extremely small region in the universe which then began to expand into empty space.

D) In the beginning, the universe was composed of pure energy confined to an extremely small region. The universe itself then began to expand.

Learning goals

- Is there anything the Big Bang Theory doesn't quite explain?
- What is inflation? What does it explain?
- What will be the fate of our Universe?
- What is dark energy? What is it doing? What told us it exists?

Big Bang Basics (Review)

- The Universe started out very hot and very dense
- As the universe expanded it cooled off and matter spread out
- The Big Bang Theory predicts the following:
  - After ~380,000 years the universe should have cooled enough to allow for radiation to begin streaming freely through the universe

    ➡ Cosmic Microwave Background (CMB)
  - Under Big Bang Nucleosynthesis (BBN) some of the original hydrogen should have fused into helium

    ➡ Observations agree!

Anything left unanswered?

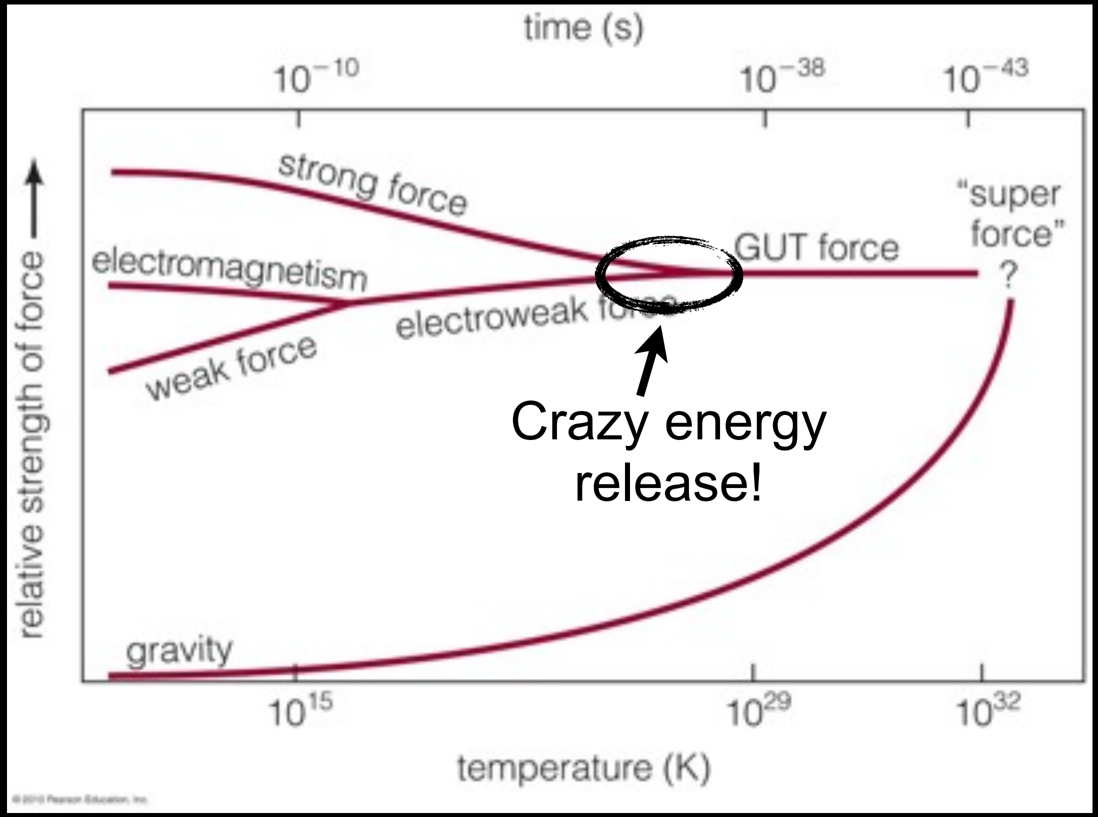
- Where does the large scale structure come from?
  - We know it came from small density fluctuations in the early universe, but where did those come from?
- Why is the large-scale universe so uniform?
  - Distant reaches of the universe look very, very similar. How is that possible if separated by such vast distances?
- Why is the density of the universe so close to the "critical density"?
  - Couldn't any density be possible?

The answer:

INFLATION

What is inflation?

- Separation of the strong force from the GUT force should have released an enormous amount of energy



- Could have resulted in dramatic expansion of the universe
  - a factor of 10^{30} in 10^{-36} second (trillionth-trillionth-trillionth of a second)

Review: Why is gravity important on large scales, even though it is the weakest force?

A) There is no repulsive force to counter gravity

B) The strong force counters electromagnetism

C) On large scales, gravity is the GUT force

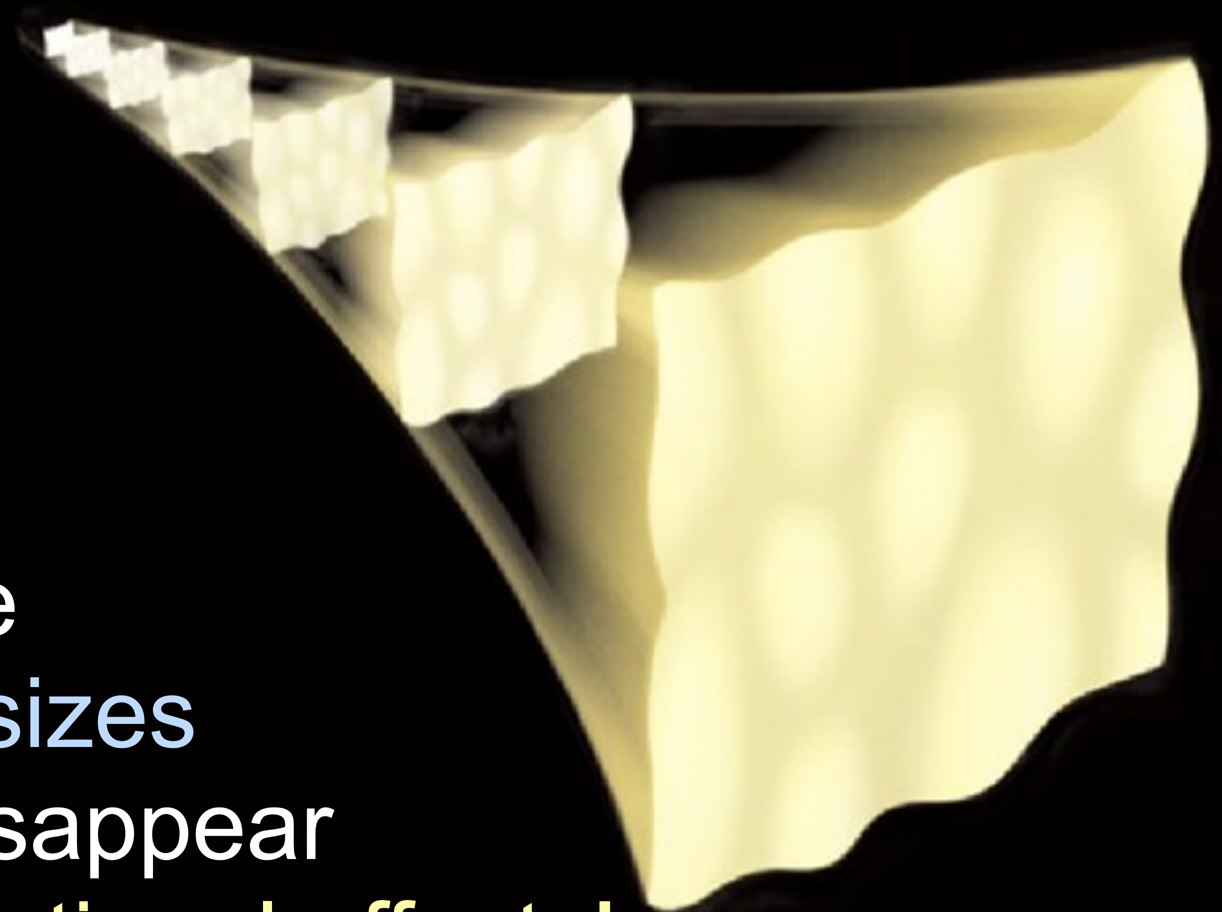
D) Because when Fig met Newton, magic happened

What caused large-scale structure?

- Quantum mechanics suggests that there are always "quantum fluctuations" present in energy fields
  - These fluctuations are generally tiny, couldn't cause gravitational collapse
  - Fluctuations have short lifetimes, constantly changing
- If the Universe expanded "normally", these fluctuations would continue to be formed on the quantum scale
- But...

What caused large-scale structure?

- Quantum mechanics suggests that there are always "quantum fluctuations" present in energy fields
  - These fluctuations are generally tiny, couldn't cause gravitational collapse
  - Fluctuations have short lifetimes, constantly changing
- If the Universe expanded "normally", these fluctuations would continue to be formed on the quantum scale
- But... Inflation could blow these fluctuations up to much larger sizes before they had a chance to disappear -- large enough to cause gravitational effects!

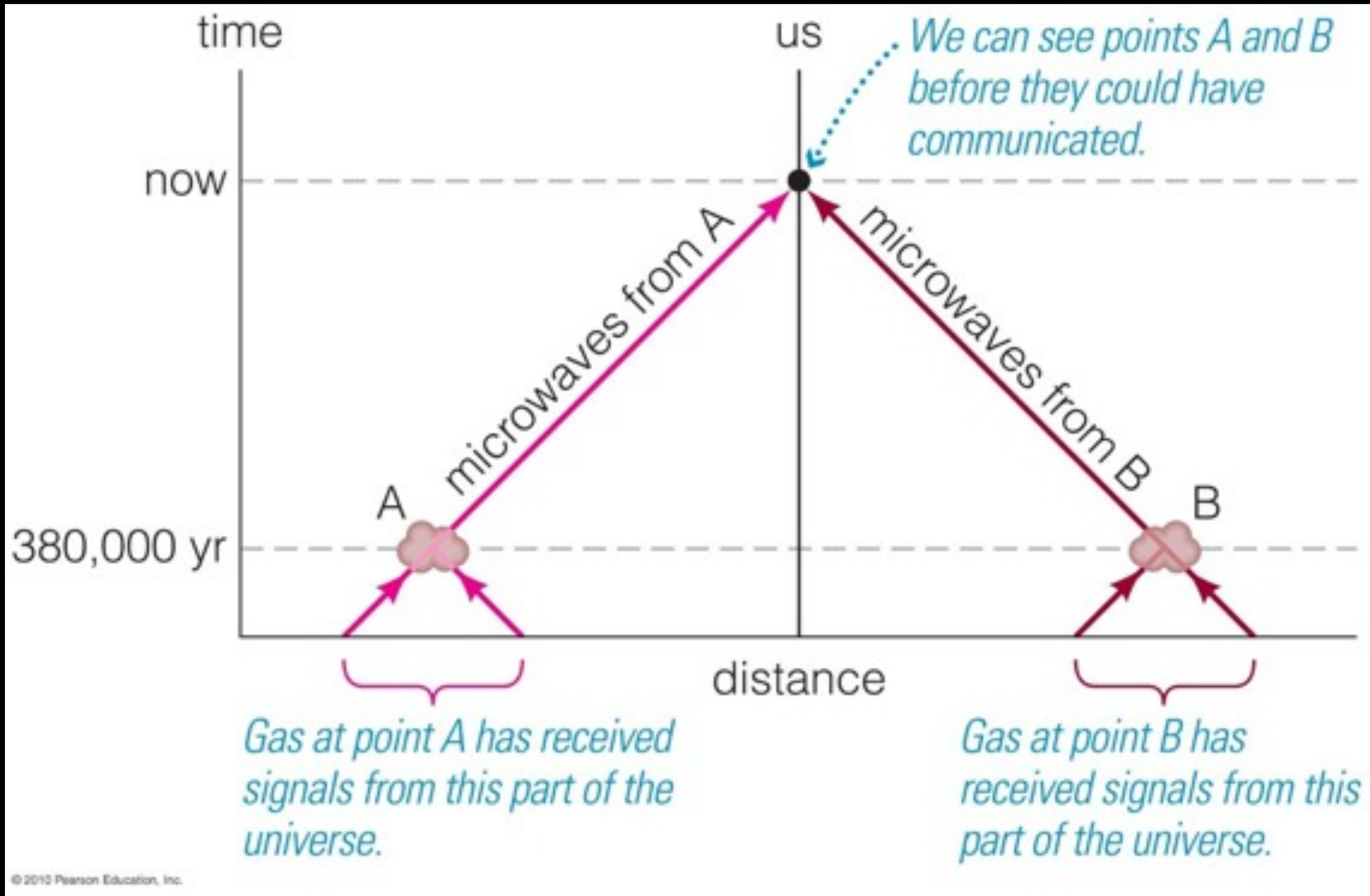


Why is the universe so darn uniform?

- The CMB shows remarkable smoothness in all directions
  - Variations on the order of 1 part in 100,000
- Why is this puzzling? Does it make sense for the universe to look nearly the same everywhere?

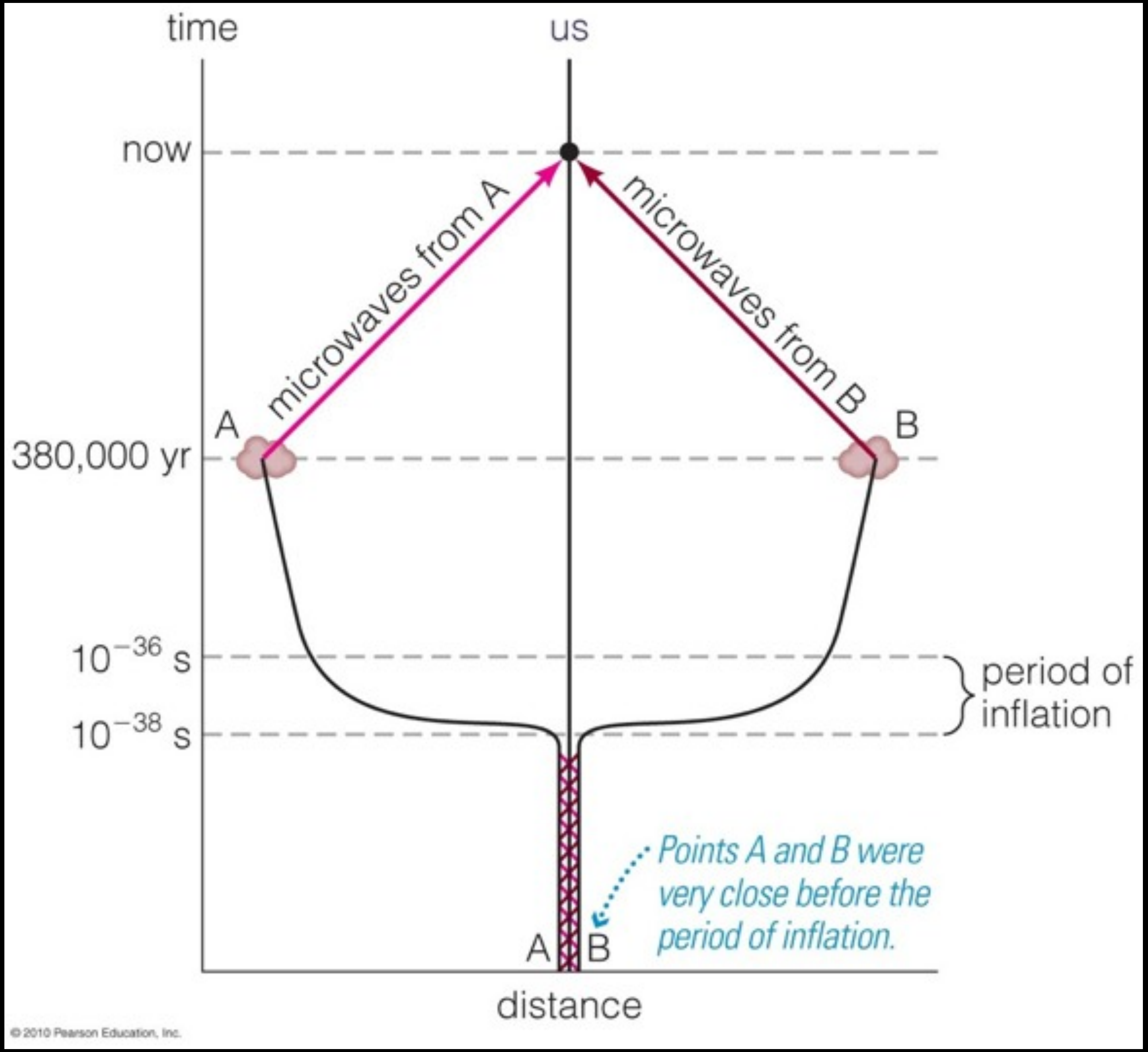
Let's think for a moment about the nature of our CMB observations

- If we look out in one direction, we see CMB photons that have been traveling for ~14 billion years and tell us about what the universe was like when it was ~380,000 years old
- If we look in the opposite direction, we see more CMB photons that have also been traveling for ~14 billion years that tell us the same thing
- There is no way that these two sides of the universe could have communicated to figure out what their densities and temperature should be, right?



Inflation strikes again!

- In order for the Universe to be so uniform, the opposite sides must have been in close contact (causal contact) at some point in the past
- Then inflation came along and ripped in them apart in the less than the blink of an eye



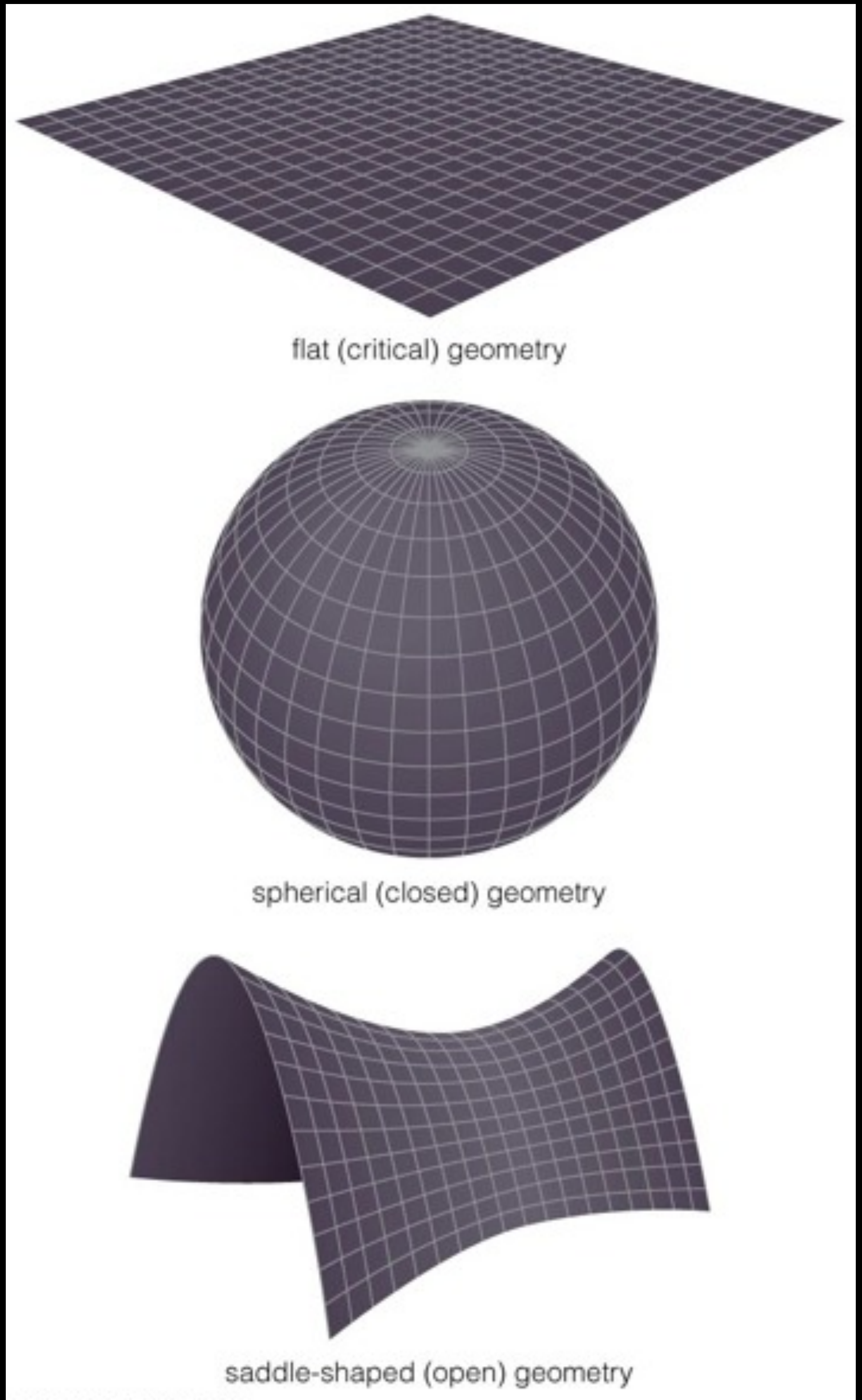
True or False?: Inflation couldn’t have happened because it means that matter would have moved faster than the speed of light, and relativity says this is impossible.

A) True

B) False -- matter isn’t moving through space, space itself is expanding

How can the universe be so close to the critical density?

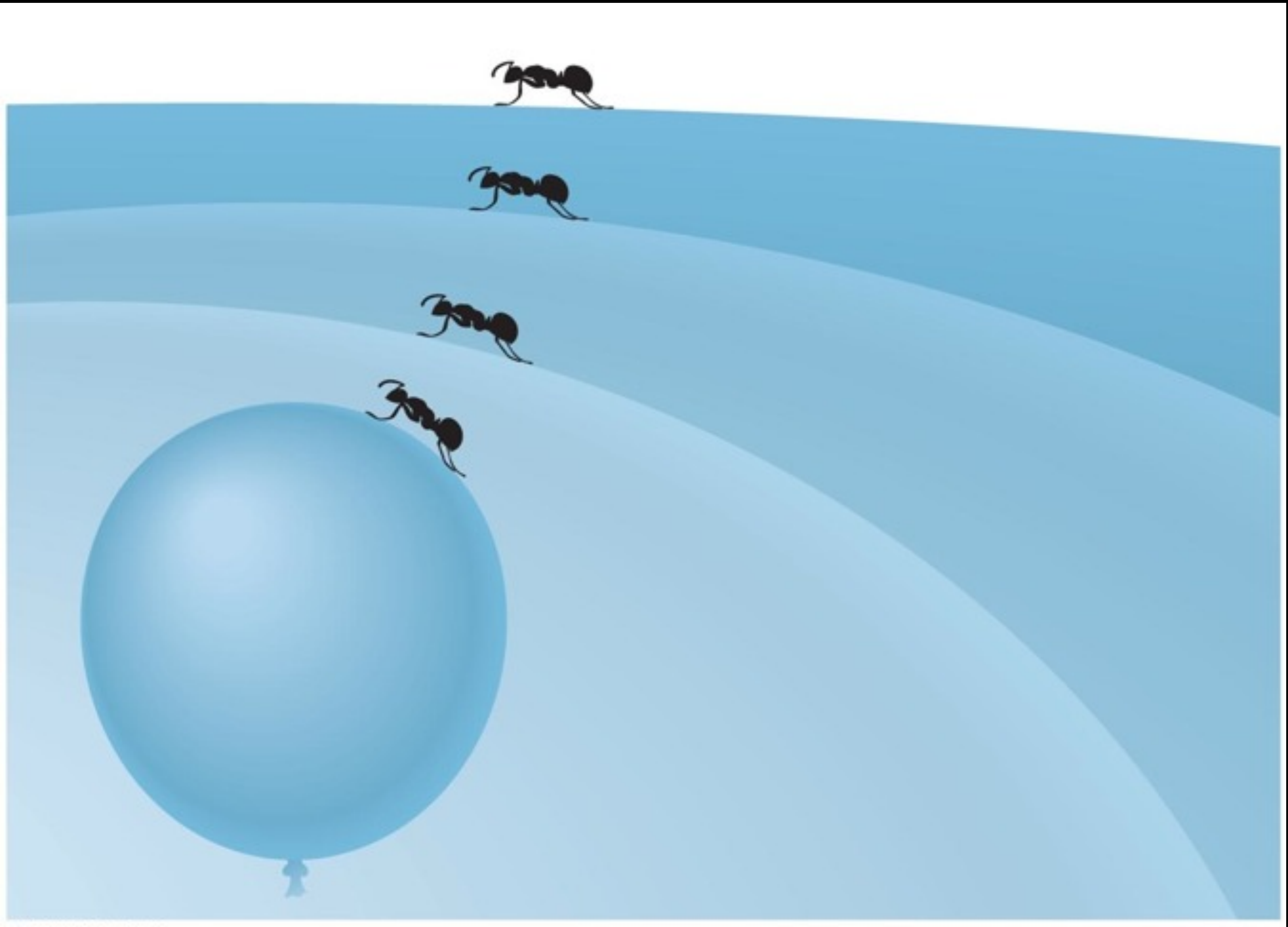
- Critical Density = The matter density at which the overall inward pull of gravity precisely balances the kinetic energy of expansion
- In this case the geometry of the universe is “flat” (other options are “spherical” and “saddle-shaped”)
- Any deviations in this imbalance would become more severe as the universe evolved -- how does inflation prevent this from happening?



Inflation flattened the Universe

- Inflation is like expanding the surface of a balloon and imaging what it would be like to be an observer on that surface

Any curvature that might have existed before inflation would only be noticeable on size scales much larger than the observable universe



We’ve talked about the beginning, but what about the end?

"Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice."

-Robert Frost, *Fire and Ice*

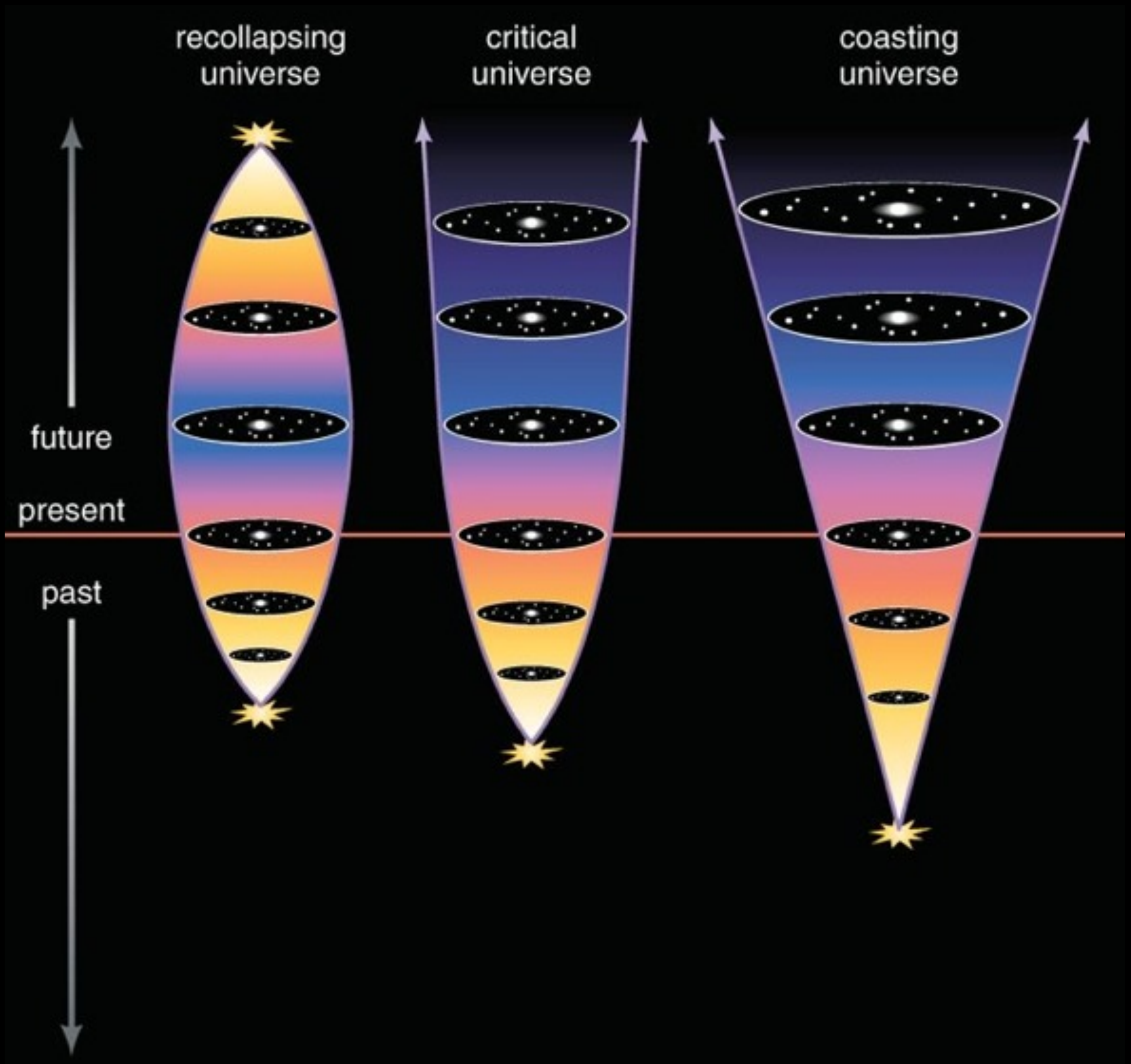
The Fate of the Universe

- Predictions from General Theory of Relativity
  - Einstein (1917) realized GTR predicted a collapsing universe, but he didn't like that idea – added 'cosmological constant' (CC) as repulsive force in space-time to counteract attractive force of gravity (A fudge factor!)
  - Willem de Sitter (Dutch, 1917) solves GTR equations with no CC and low density of matter: showed universe must expand
  - Alexander Friedmann (Russian, 1920) solves GTR with no CC but any density of matter: universes can expand forever, or collapse again, depending on mean matter density
  - Georges Lemaitre (Belgian, 1927) rediscovers Friedmann solutions, told Hubble (observing redshifts since 1924) that cosmic expansion suggests more distant galaxies should have greater redshifts (Hubble publishes $V = H_0 d$ in 1929)
  - Einstein visited Hubble in 1932, said CC was "the greatest blunder" of his career

Quick question about escape velocity: Assuming I'm standing on the earth and I throw a ball straight up, other than velocity, what else most affects whether the ball escapes?

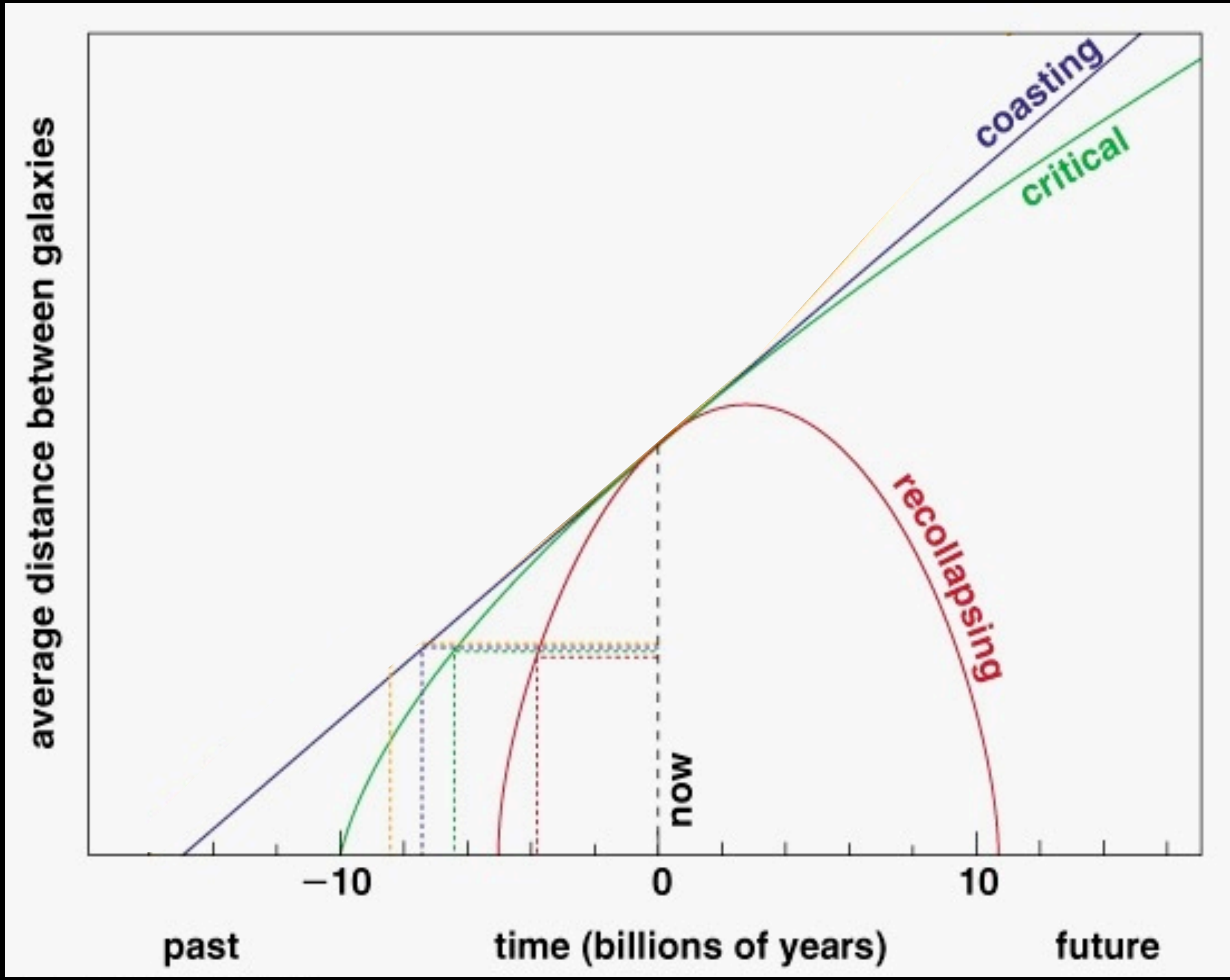
A) Mass of the ball
B) Mass of the Earth
C) Height that I throw it to
D) The shape of the ball
E) Watch out! It's coming back down!

Three original models



Possible histories/futures

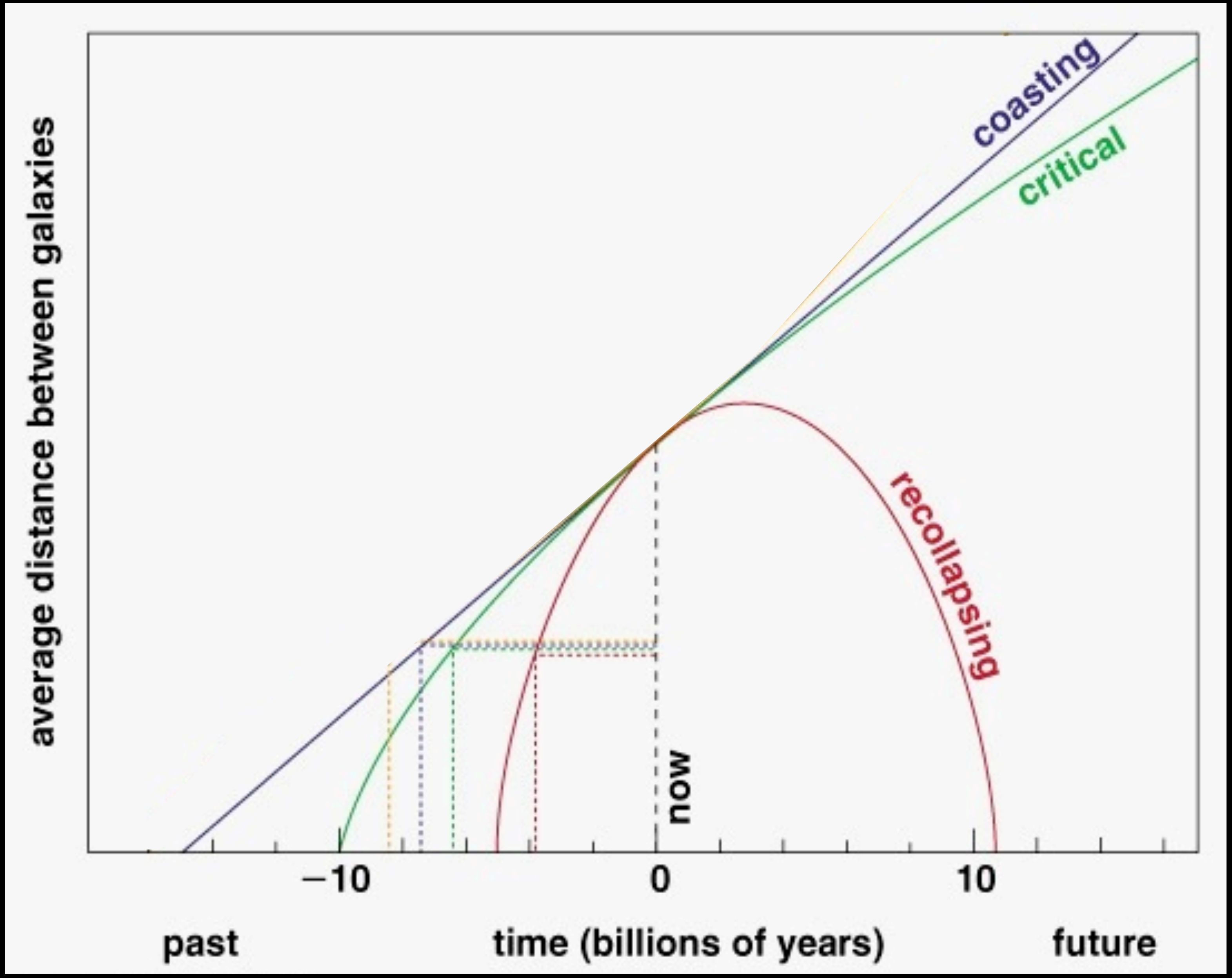
- "Average distance between galaxies" is an indicator of the size of the universe
- Hubble's constant defines how fast the Universe is expanding right now



Big Bang is when distance is zero!

Expansion rate doesn't have to be constant

- "What goes up, must come down"
  - Gravity should slow the rate of expansion
- Different models account for different amounts of matter in the Universe

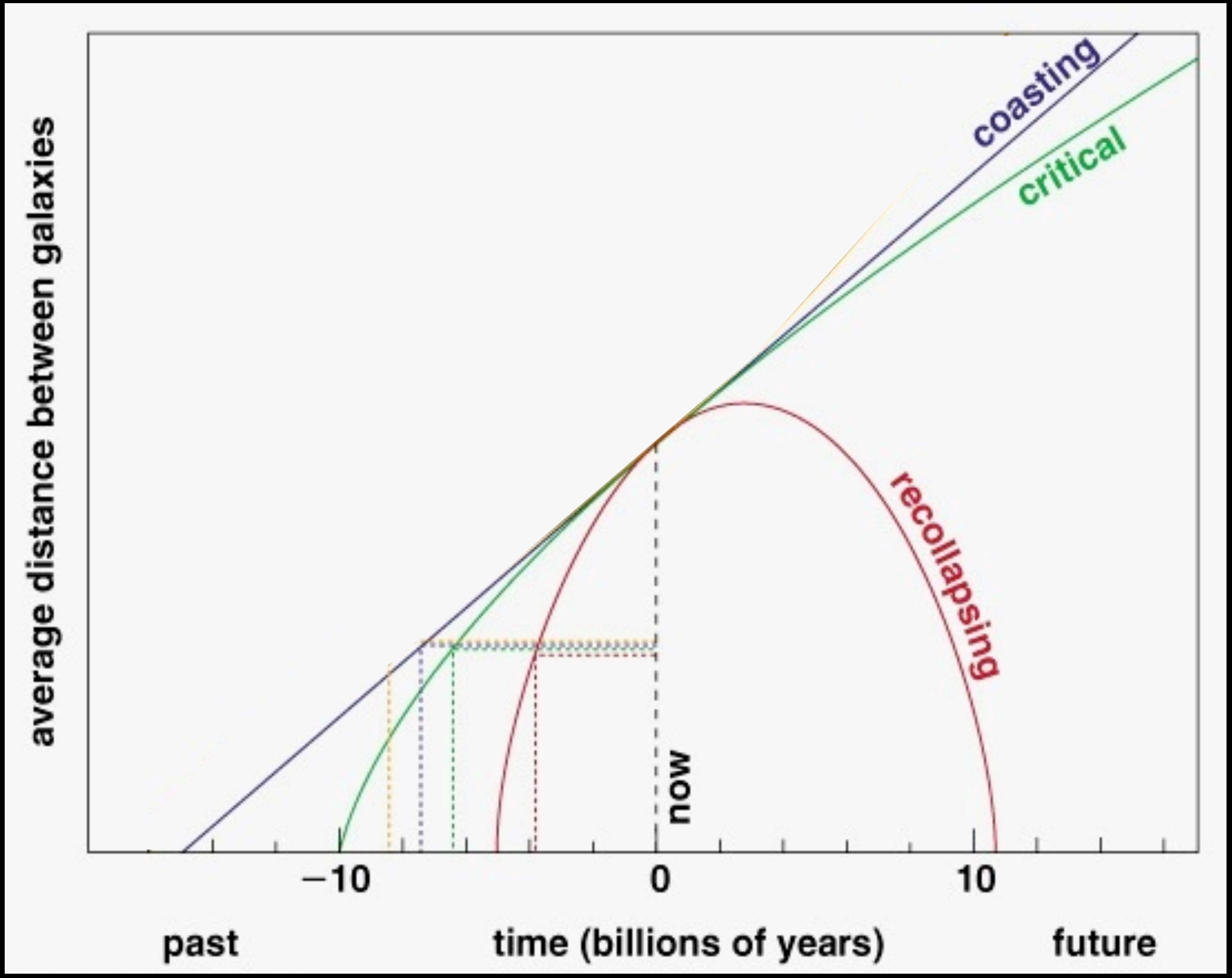


Critical Density, the gravitational "magic number"

- If you have just right right amount of matter in the Universe, then you can perfectly balance expansion
- The Universe will expand more and more slowly as time progress
- After an infinite amount of time, the universe will stop expanding
- Critical Density ~ 10^{-29} grams/cm^3 (a few atoms in a closet)

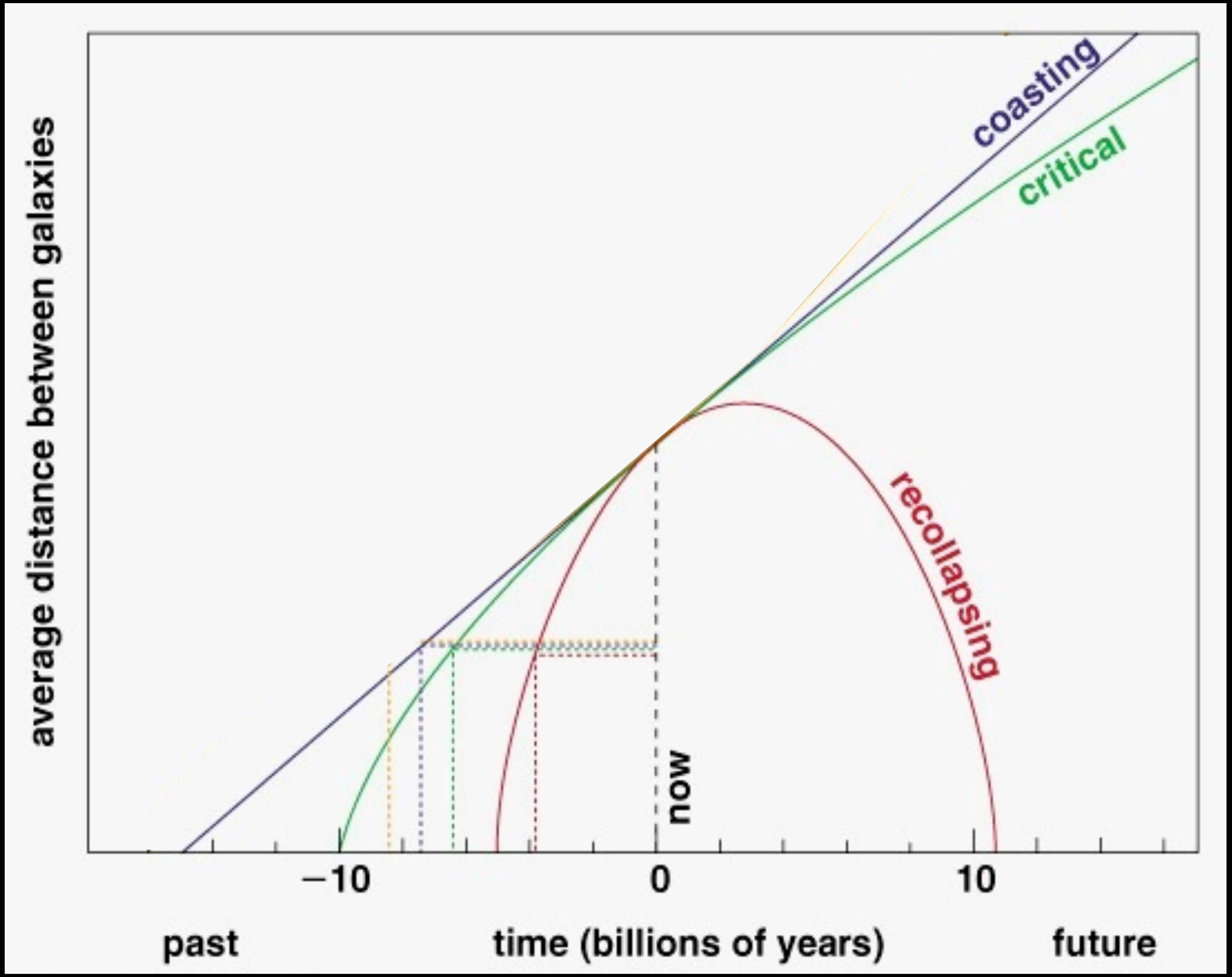
Critical Universe

- Density of matter is equal to the Critical Density
- Decelerating Universe
  - The Universe will expand “forever”, but just barely



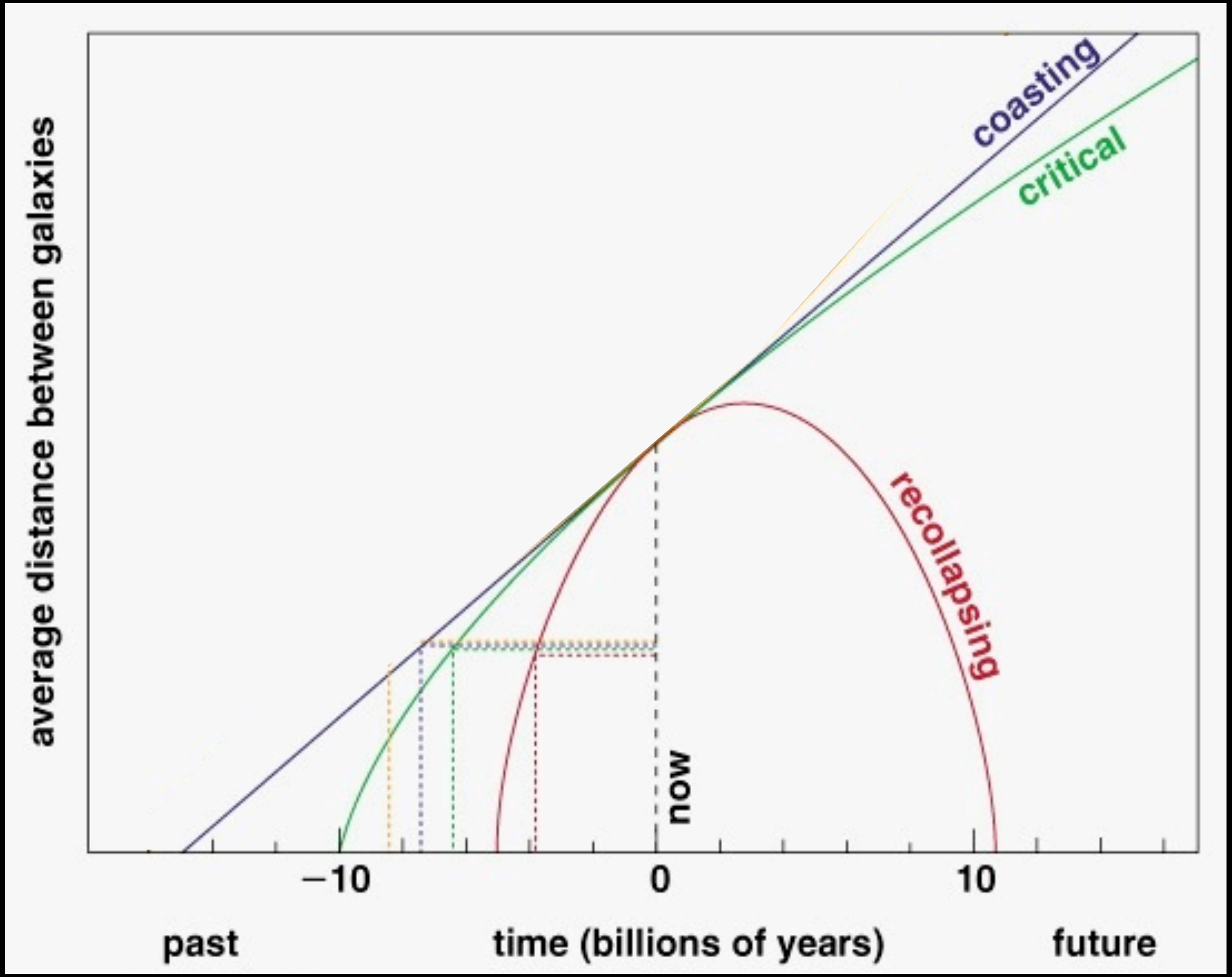
Recollapsing Universe

- Density of matter is greater than the Critical Density
- Decelerating Universe
    - Expansion will eventually stop, then collapse occurs
        - Big Crunch
        - Oscillations?



Coasting Universe

- Density of matter is less than the Critical Density
- Constant rate of expansion
  - Effect of gravity is not enough to slow the Universe down



Which model should predict the largest age for the universe today?

(Hint: In all cases, the "size" of the universe and Hubble constant must match what we measure today)

A) Recollapsing

(high deceleration)

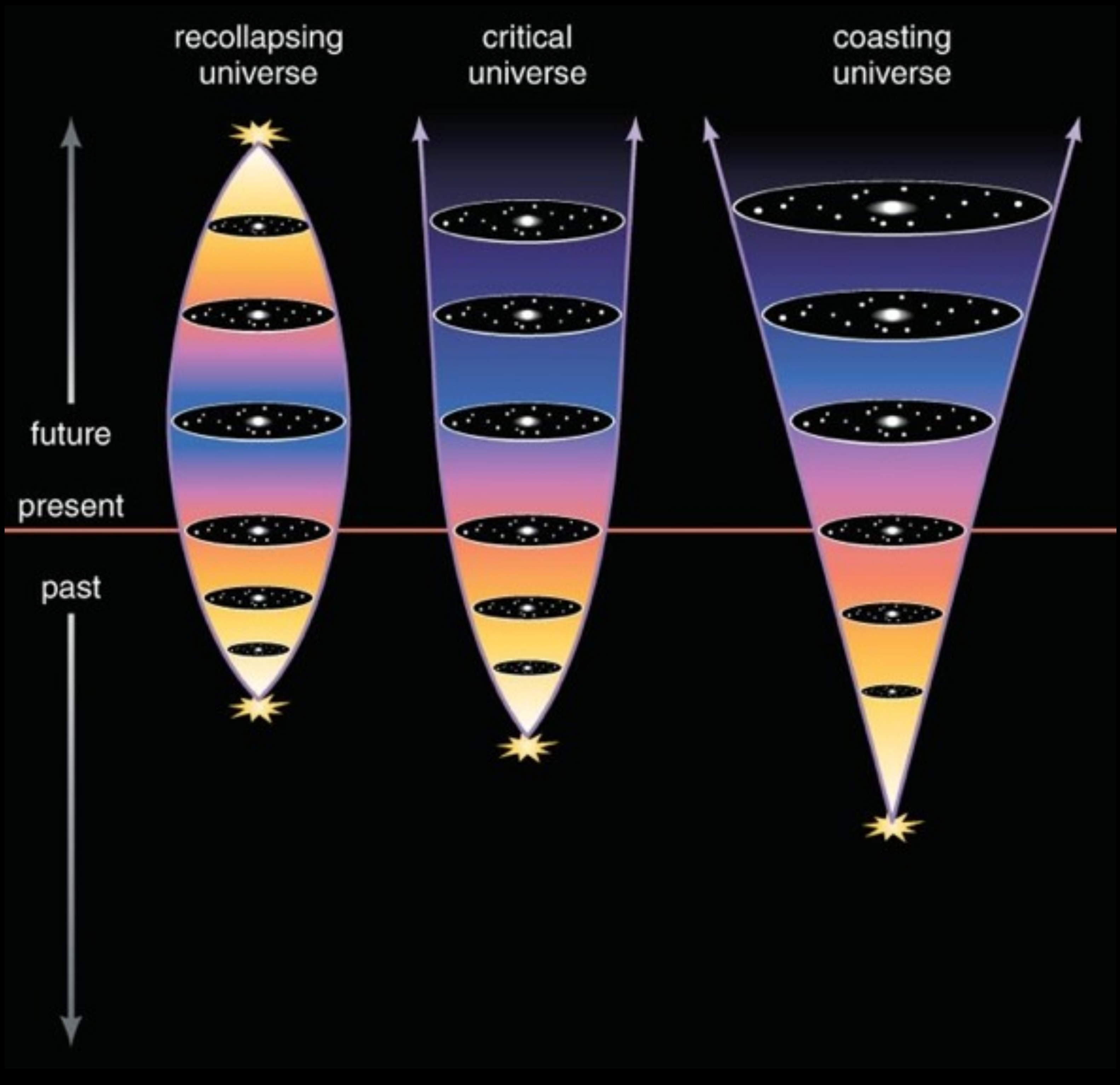
B) Critical

(minimum deceleration)

C) Coasting

(no deceleration)

Review:
Three original models



The end game?

- Recollapse to Big Crunch (Death by Fire)
  - Crushing heat
  - Destruction of all matter
  - Rebirth?
- Eternal expansion (Death by Ice)
  - Things get cold, galaxies dim
  - Star formations slows
  - Everything ends up as a brown dwarf, black dwarf, neutron star, or black hole

So, which is it?

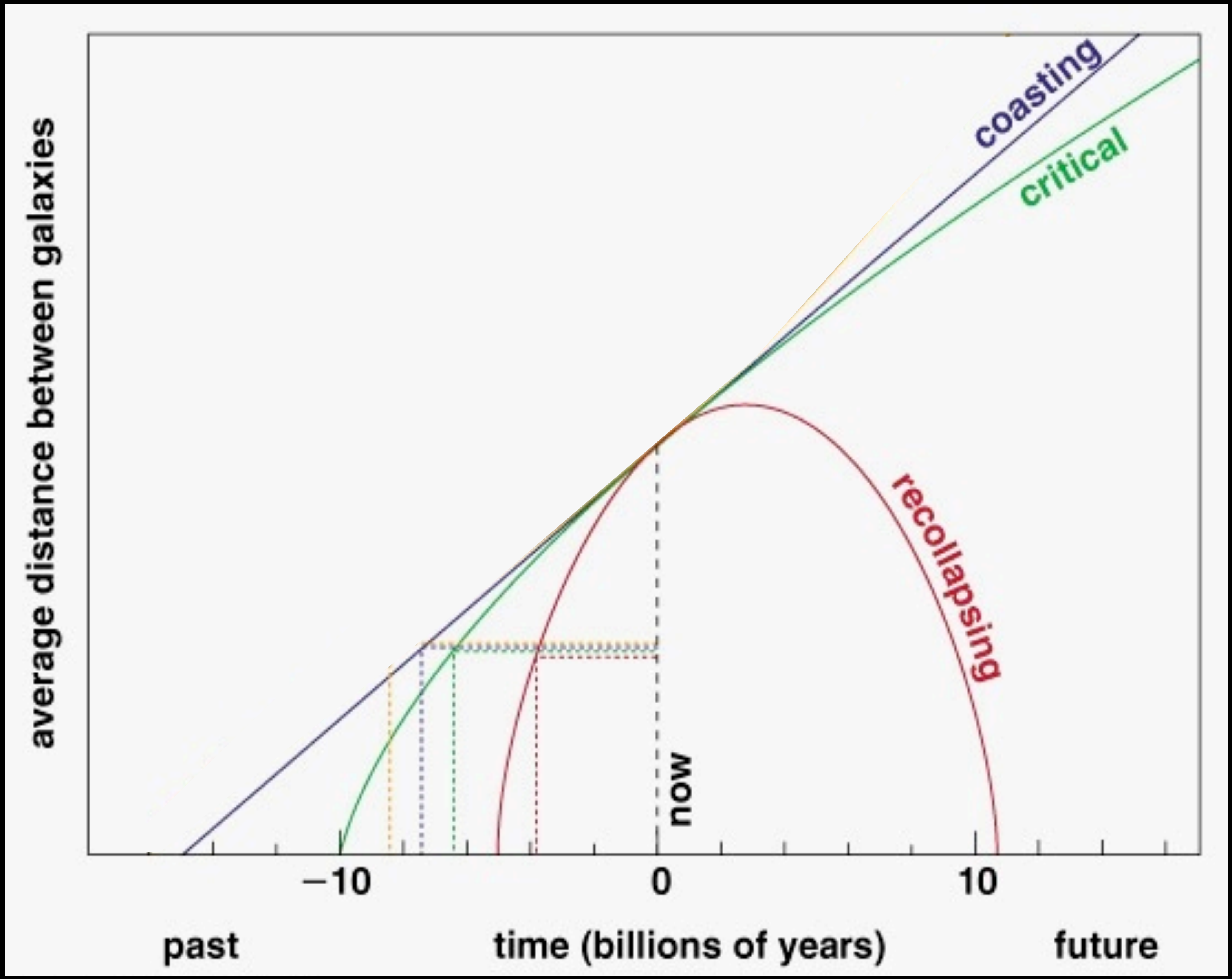
- Is there enough matter to recollapse the Universe?
    - Normal matter: only a few percent of the critical density

If there was really ZERO dark matter in the universe, which model would we expect to be the closest to reality?

A) Recollapsing

B) Critical

C) Coasting



So, which is it?

- Is there enough matter to recollapse the Universe?
  - Normal matter: only a few percent of the critical density
  - Dark matter: only about 30% of what would be needed
- Universe should be somewhere between critical and coasting

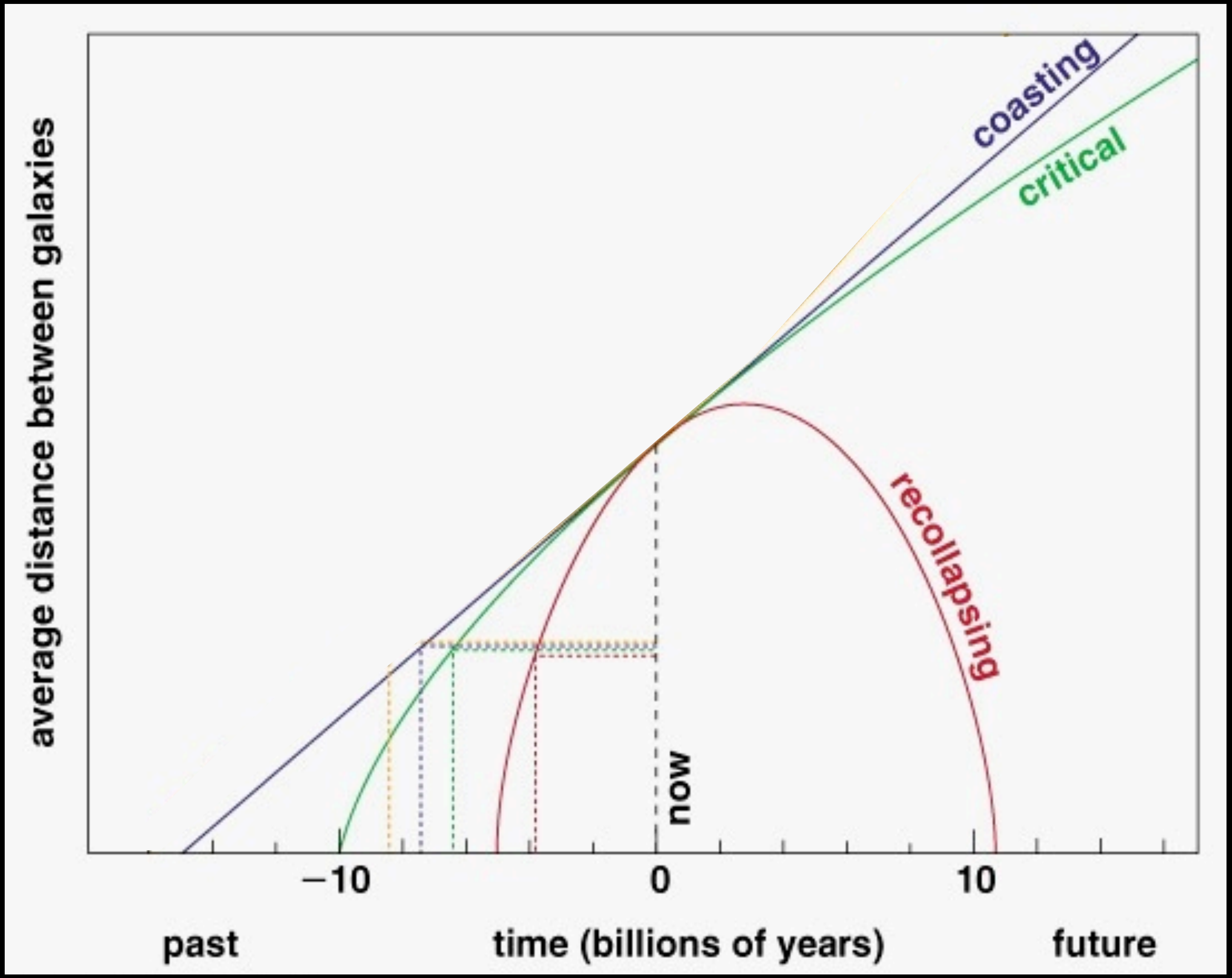
The Universe will expand forever!

Measuring the expansion history

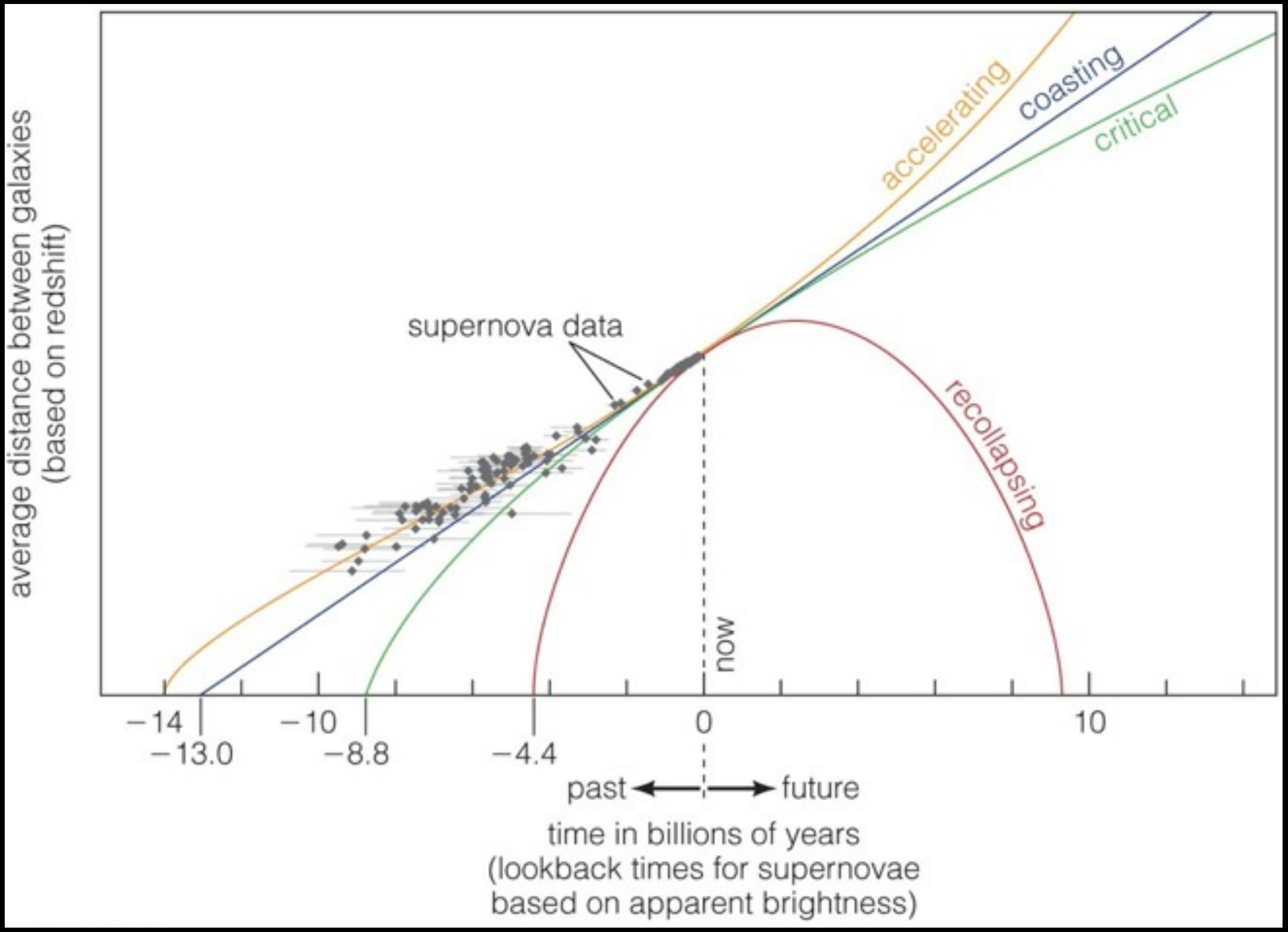
Saul Perlmutter
Supernova Cosmology Project

Adam Riess
High-z Supernova Search Team

- Early 1990s, two teams were competing to use WD supernovae to measure the Hubble Constant in the past
- They expected to see a decelerating universe



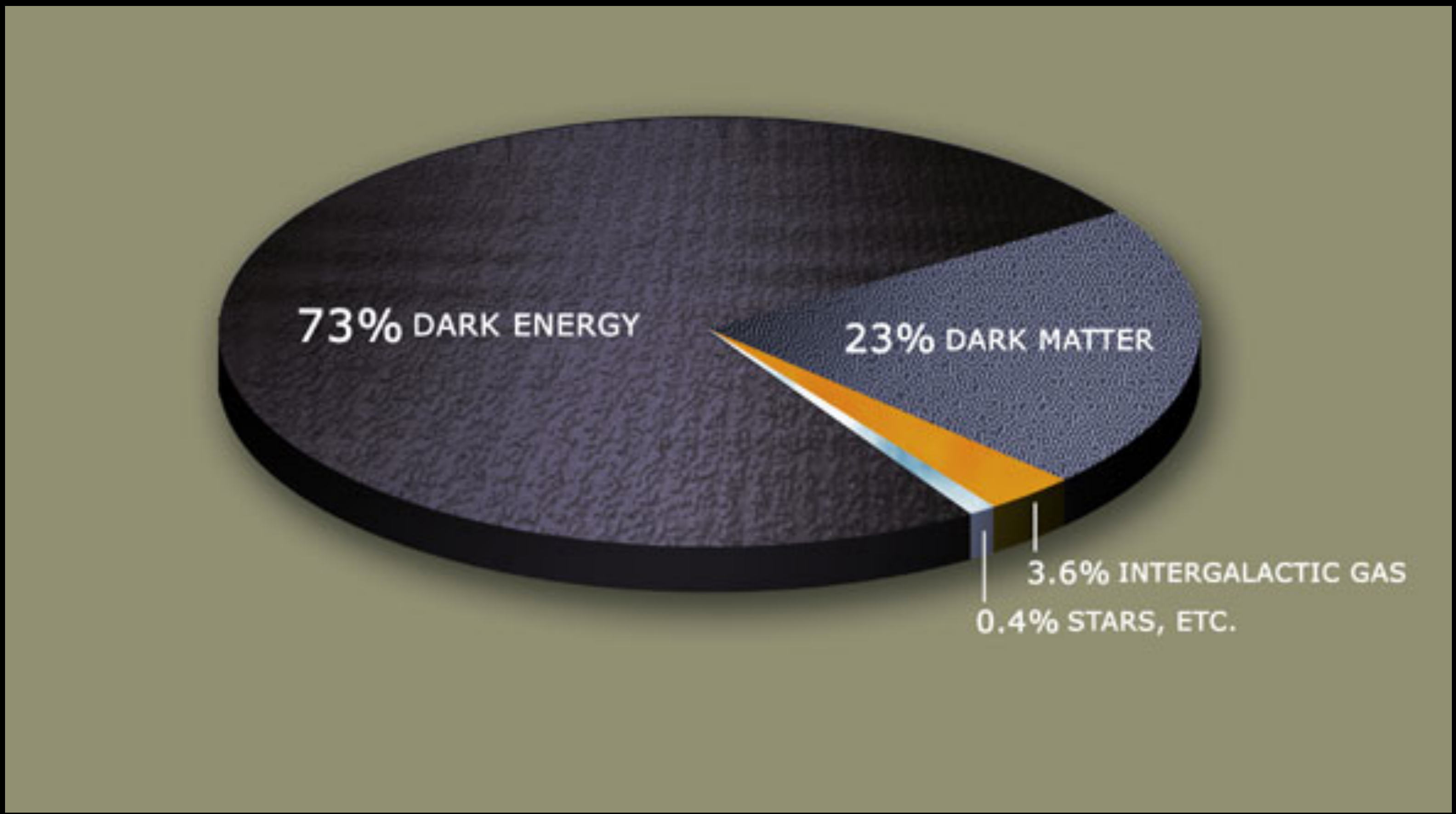
Surprise!

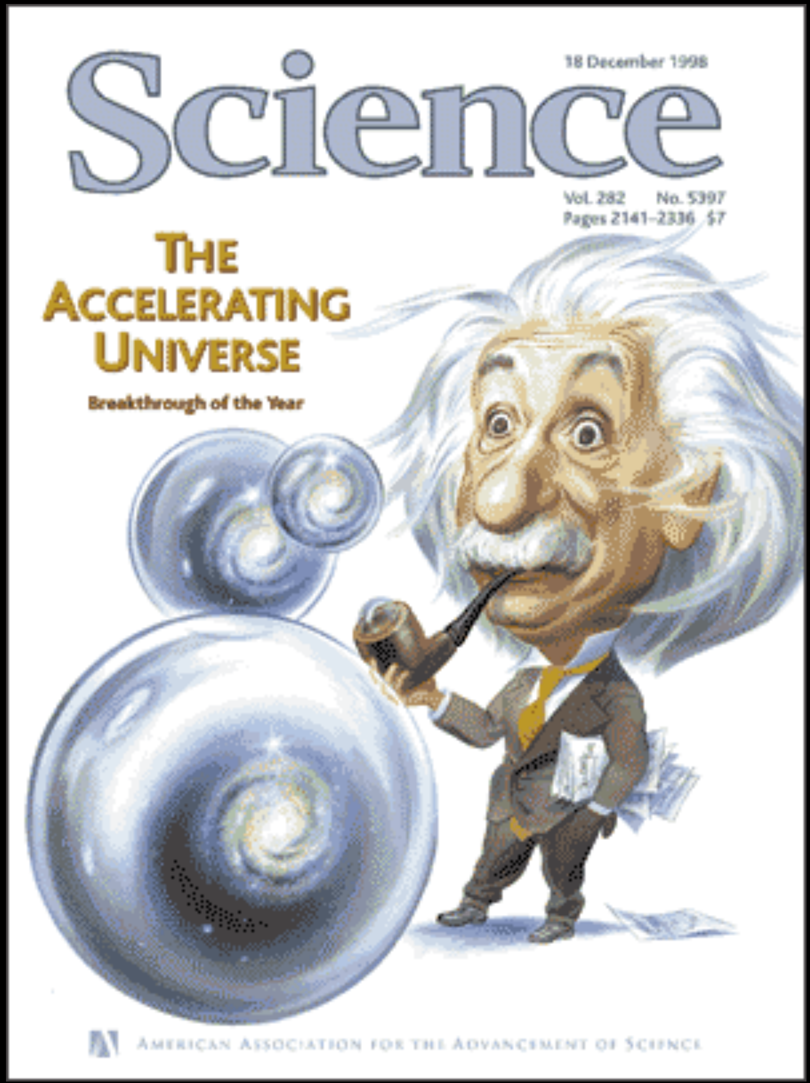


- The Universe is accelerating!
- The cause of this acceleration has been termed “dark energy”, but we have no idea what it is!

An *accelerating* universe?

- Dark energy makes up more of the universe than any other matter/energy
- It counteracts gravity, how is that possible?
- Einstein wasn't wrong! phew.
    - Cosmological constant does exist

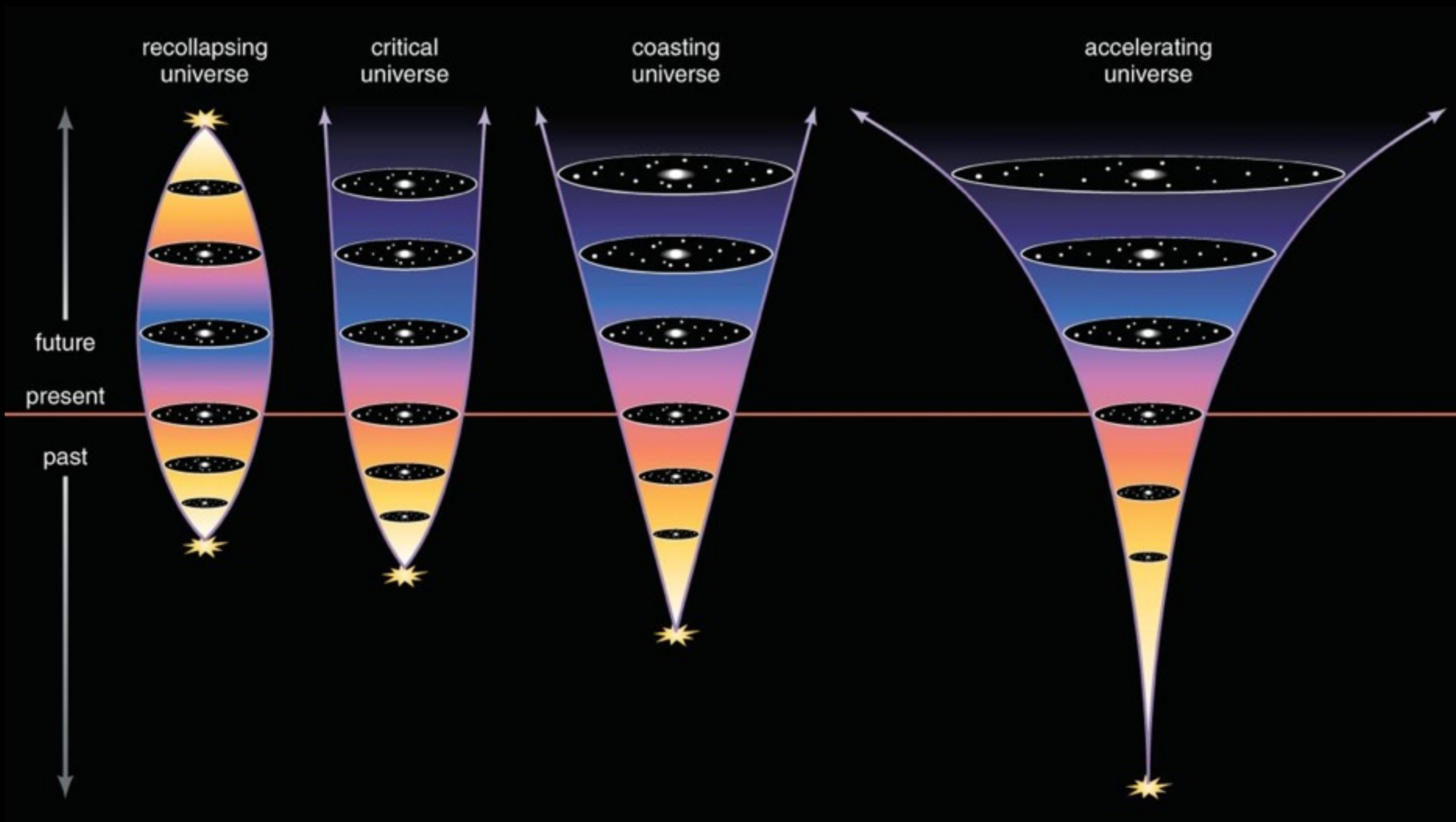




Could have something to do with vacuum energy

- The background energy that exists even when space is devoid of matter
- 1 cubic centimeter of empty space is though to have ~1 trillionth of an erg worth of energy
  - 1 erg is roughly equivalent to an ant doing a pushup
- Can think of it as virtual particles (particle/anti-particle pairs) popping in an out of existence and leaking away some energy before they disappear

Correction: Four models



Searching for evidence in Antarctica

- 10-meter telescope at the South Pole!
- Observing at millimeter and sub-millimeter wavelengths
- Intended to map the primary and secondary anisotropies in the CMB
- Location is great, low water vapor, stable atmosphere

Summary

- Early in the history of the Universe, inflation occurred.
- Inflation addresses observations that the Big Bang Theory didn’t address on its own
- The Universe appears to be on track to expand forever
- Not only is it expanding, but its accelerating thanks to dark energy