The End of the Universe: Dark Energy and Accelerating Expansion

Chapter 23.4

Midterm 3 is June 12

- Midterm on June 12 2025
- 3:30pm-5:00pm
- multi-choice and text questions

- Covers material through (lectures 19-26)
  - **Special Relativity** (S2), **General Relativity** (S3),
  - **Milky Way, Galaxies and Galaxies evolution** (Ch 19-20-21)
  - **The Big Bang** (Ch 22) **Dark Energy, Dark matter and acceleration** (Ch 23)
- Exam is not cumulative, but much of this material builds on what we learned in the first 1/3rd of the course

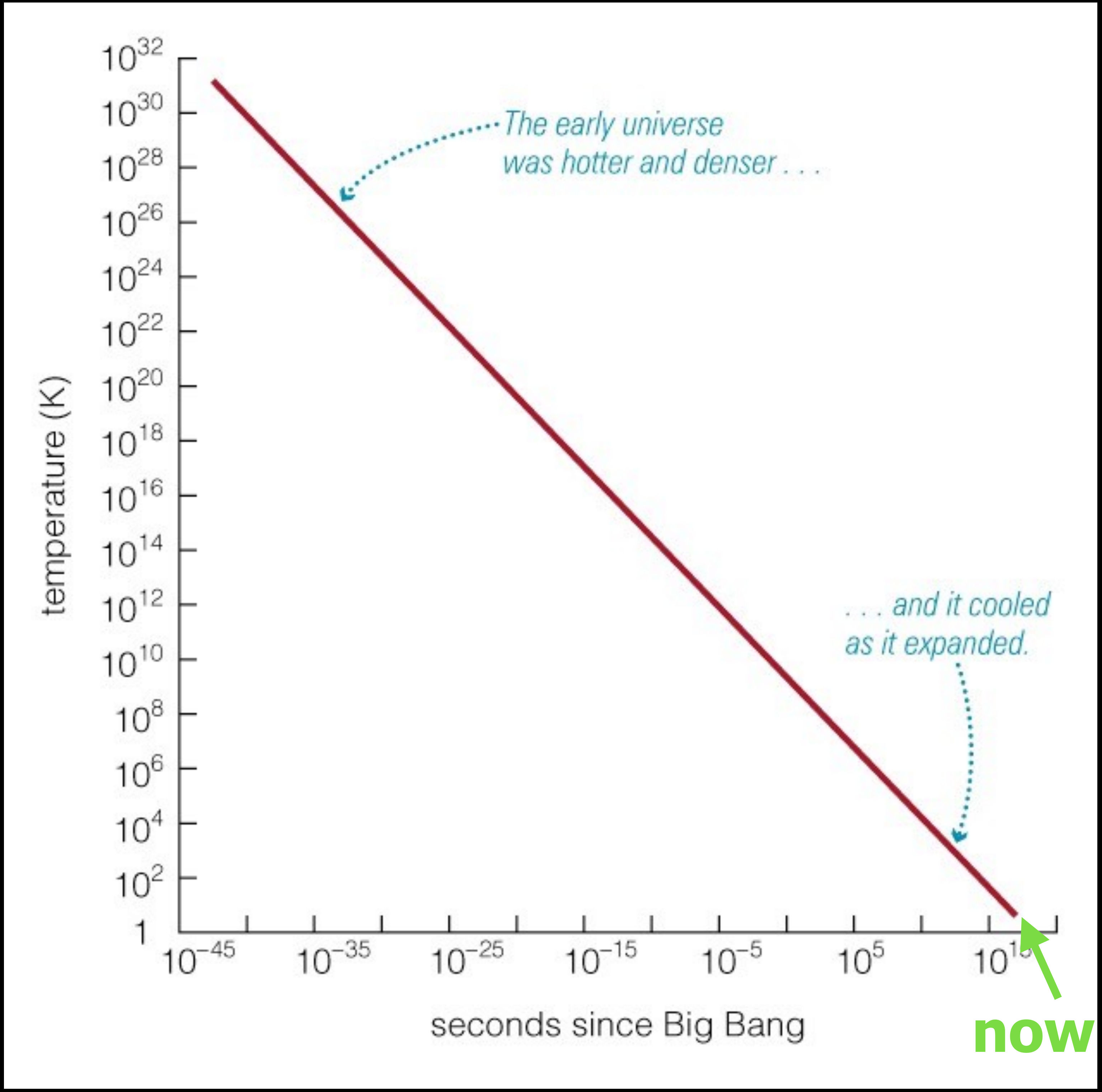
The End of the Universe: Dark Energy and Accelerating Expansion

Chapter 23.4

Recap: the Big Bang

The Universe is expanding, so it was smaller in the past.

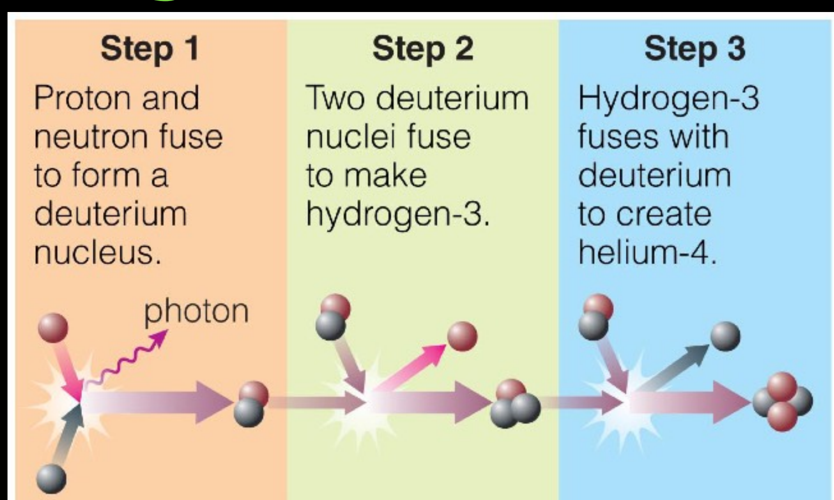
In the beginning the Universe was very small, dense, and **HOT**, and expanding rapidly:
the "**Big Bang**"!



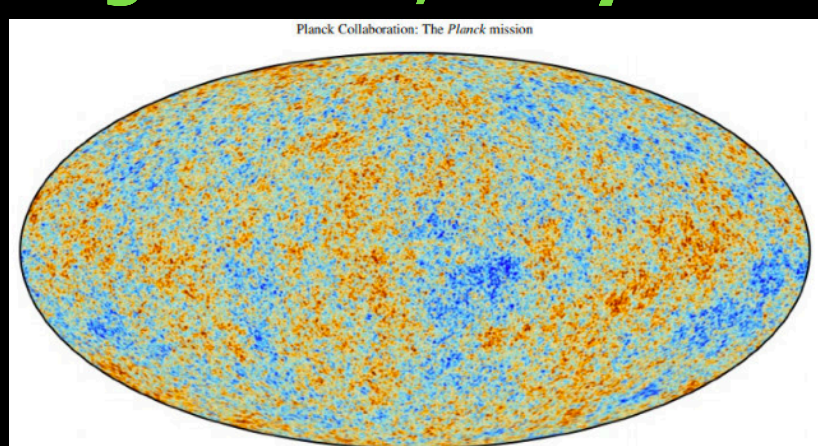
Evidence from the Big Bang: two clear predictions

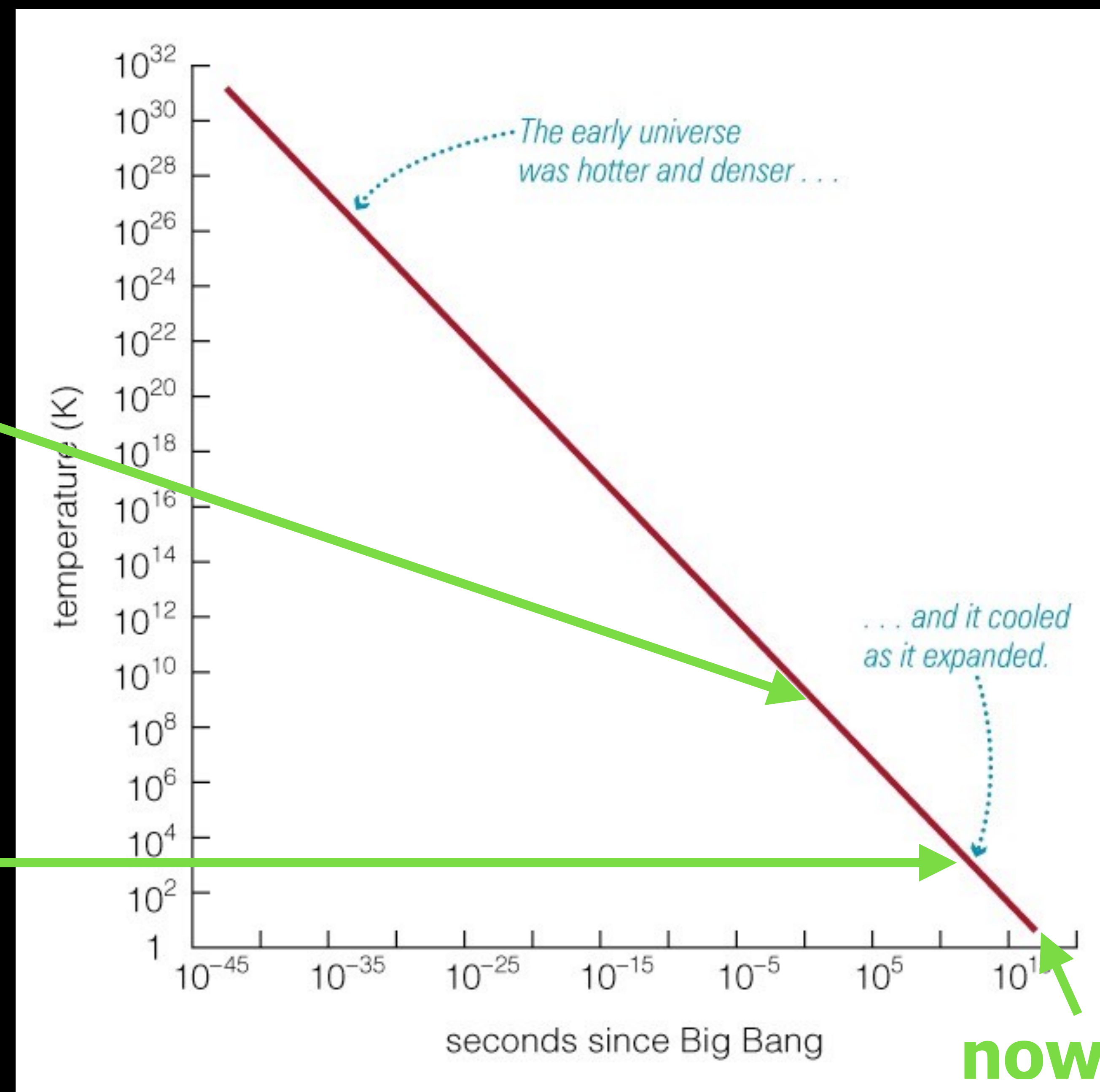
1. **Cosmic Microwave Background (CMB)**: thermal radiation leftover from when the Universe was 380,000 years old
2. **Big Bang Nucleosynthesis (BBN)**: creation of light elements (H, He, Li) when the Universe was ~1-3 minutes old

BBN: T ~ 10^9 K
Age ~ 1-3 minutes



CMB: T ~ 3000 K
Age ~ 380,000 years



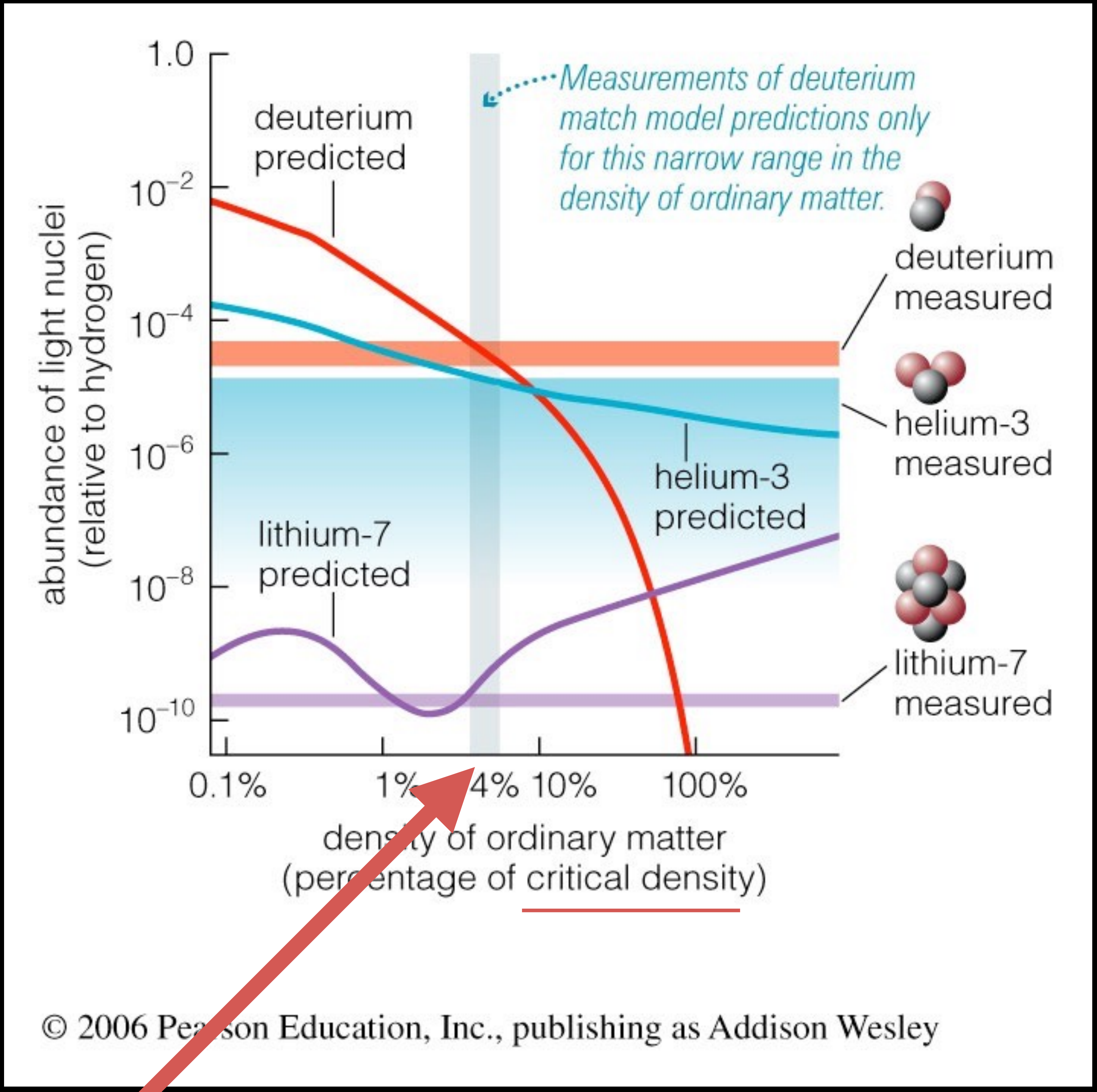


Recap: what have we learned?

- **What evidence do we have to support the Hot Big Bang theory?**
  - **The Cosmic Microwave Background (CMB)**
  - Radiation left over from the Big Bang is now in the form of microwaves (millimeter wavelengths), which we observe with radio telescopes
  - Near-perfect thermal spectrum matches predictions of Big Bang theory

  - **Big Bang Nucleosynthesis (BBN)**
  - Nuclear fusion created large amounts of Helium (age ~1-3 minutes) and small amounts of other light elements
  - Measurements of Helium and other elements agree with the predictions for fusion in the Big Bang theory

Big Bang Nucleosynthesis (BBN)



Prediction of Big Bang theory: 75% H-1, 25% He-4 (by mass), + tiny amounts of other nuclei

Data agree very well with predictions of theory!

- Deuterium (H-2)
- He-3
- Li-7

Theory predicts the number of CMB photons for every Hydrogen atom… and measurements agree!

- More photons → fewer heavy atoms (they would be broken apart)

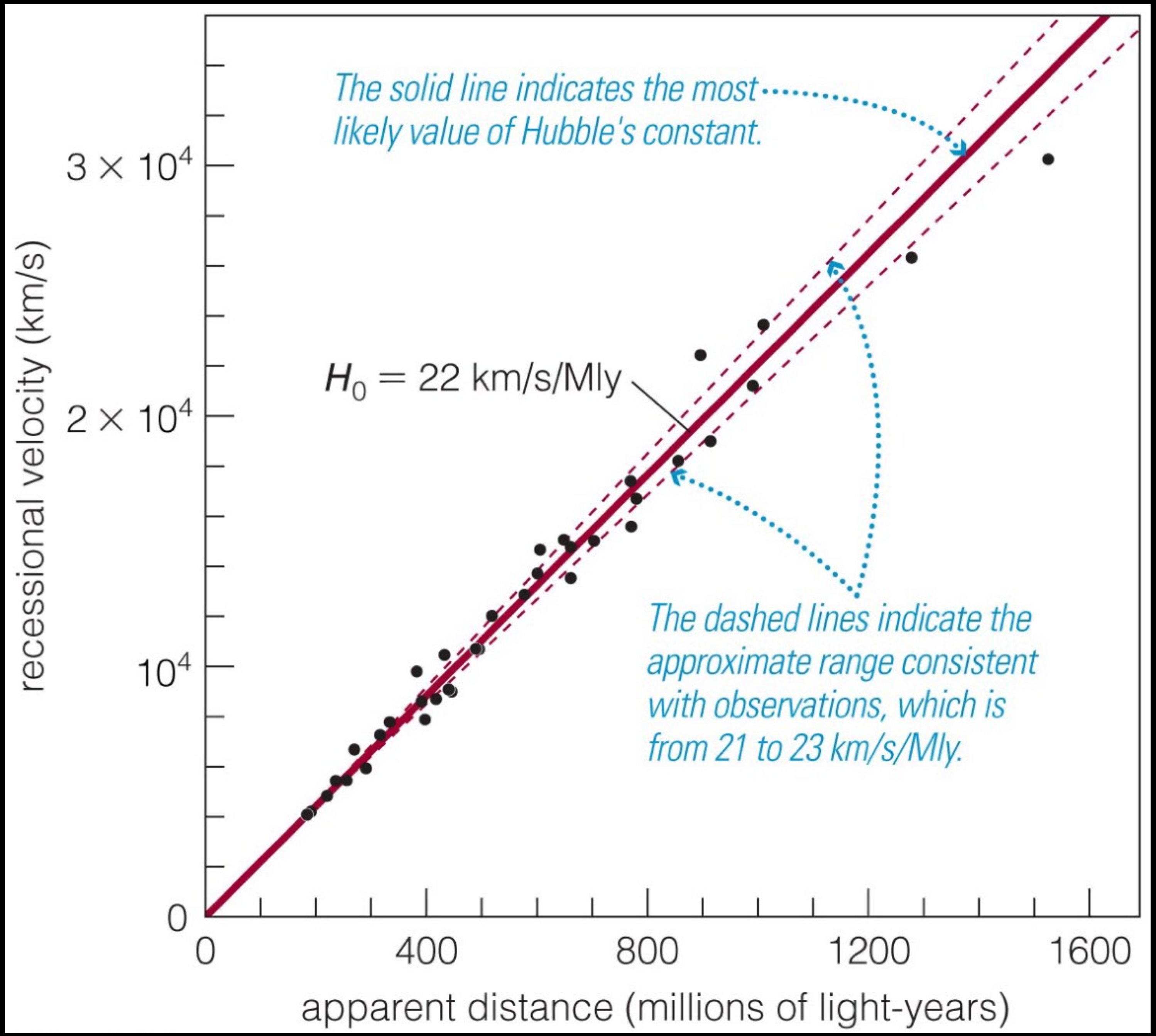
Dark Energy

Chapter 23.4

Questions of the day

- How is the expansion rate of the Universe changing over time?
- What is “Dark Energy”?
- What is the ultimate fate of the Universe?

Hubble's Law: current expansion rate of the Universe



Distant galaxies appear to be moving away from us:
$v = H_0 \times D$

We understand this as an expansion of space.

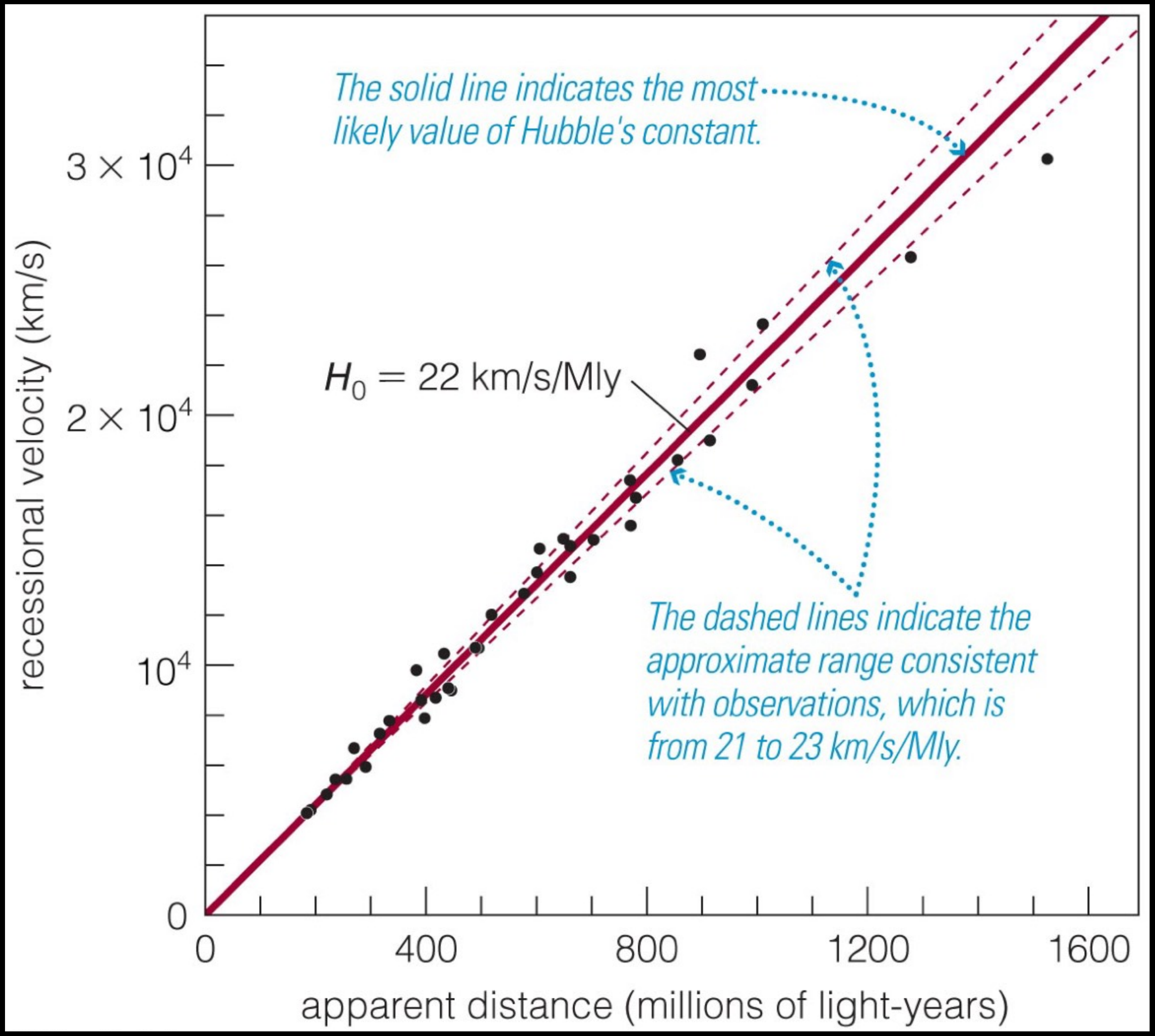
- The Universe was smaller in the past

"Hubble's Constant" H_0 tells us the rate of expansion: 22 km/s / Mly

A region of space 1 Million light-years in size is growing by 22 km every second.

- A region of 2 Mly is growing by 44 km every second. Etc…

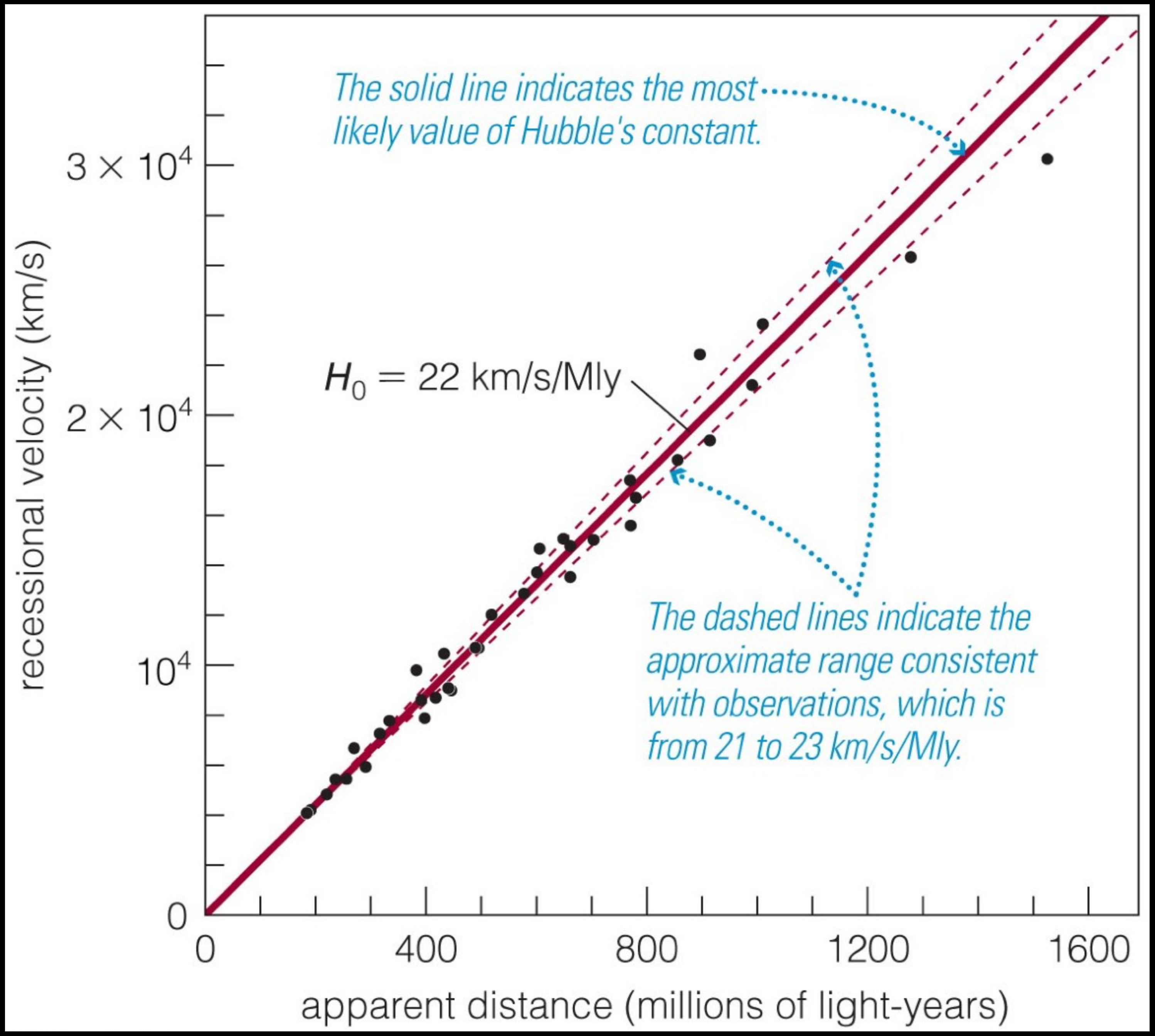
Hubble's Law: current expansion rate of the Universe



"Hubble's Constant" H_0 tells us the rate of expansion **currently**:
22 km/s / Mly

It could have been a smaller rate in the past!
Or larger!

Hubble's Law: current expansion rate of the Universe



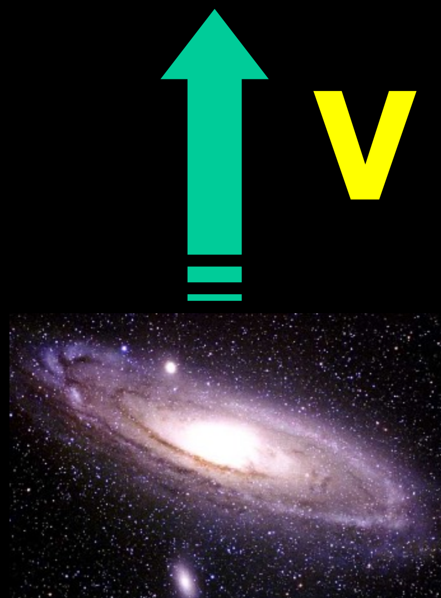
"Hubble's Constant" H_0 tells us the rate of expansion **currently**:
22 km/s / Mly

It could have been a smaller rate in the past! Or larger!

If expansion rate was constant, we can find the time when size = 0. This is the beginning of the Universe — the Big Bang!

- Time = $(1/H_0)$ ≈ 14 billion years ago

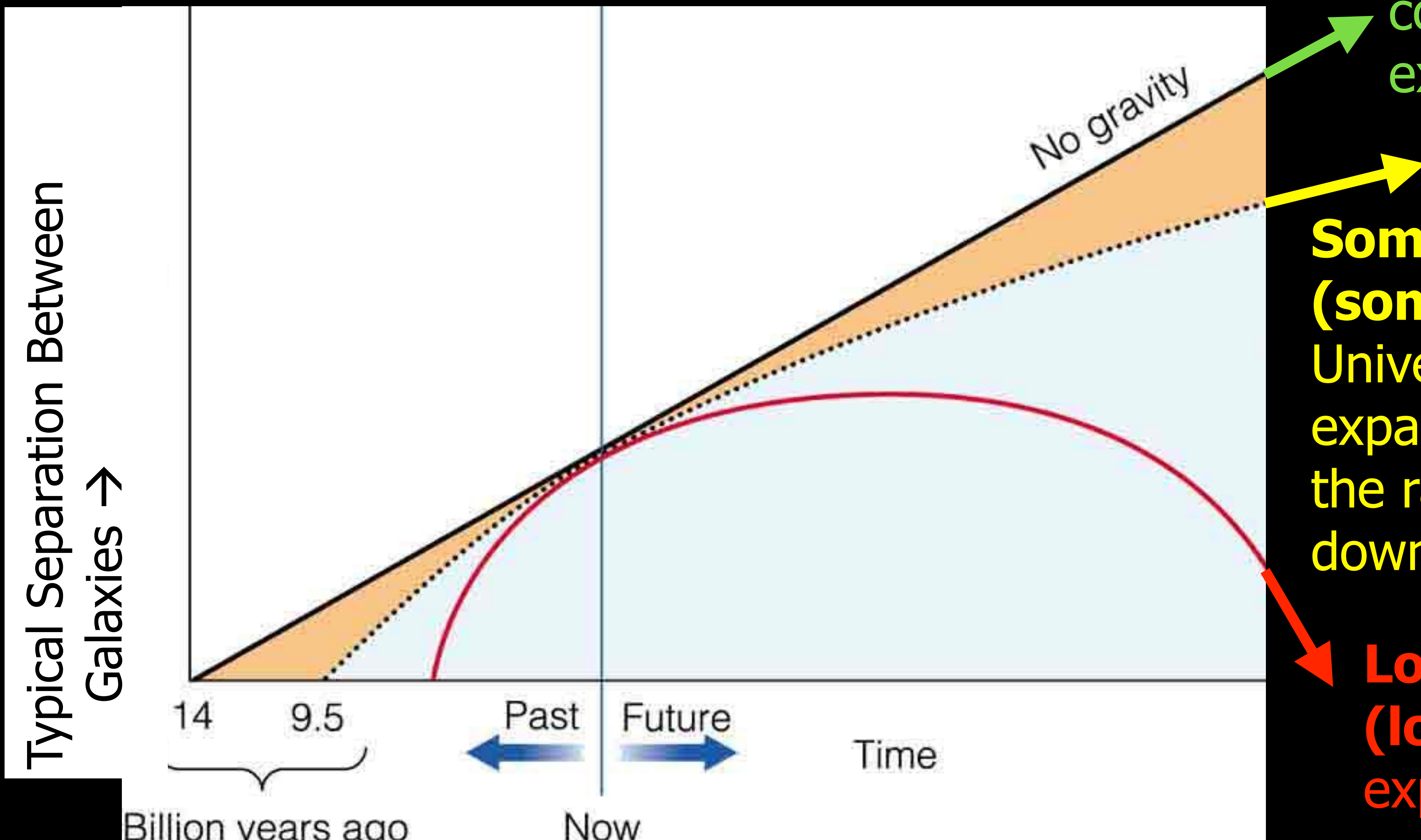
Expansion versus Gravity



M

- Consider a distant galaxy
- The space between us and that galaxy is expanding
  - We observe the galaxy moving away from us
- Our galaxy has a lot of mass, and so does this distant galaxy
- Gravitational attraction!
  - Force $F_G = G\frac{M_1 M_2}{D^2}$
  - Gravity tries to pull galaxies **closer together**, opposing the expansion of space

Expansion versus Gravity



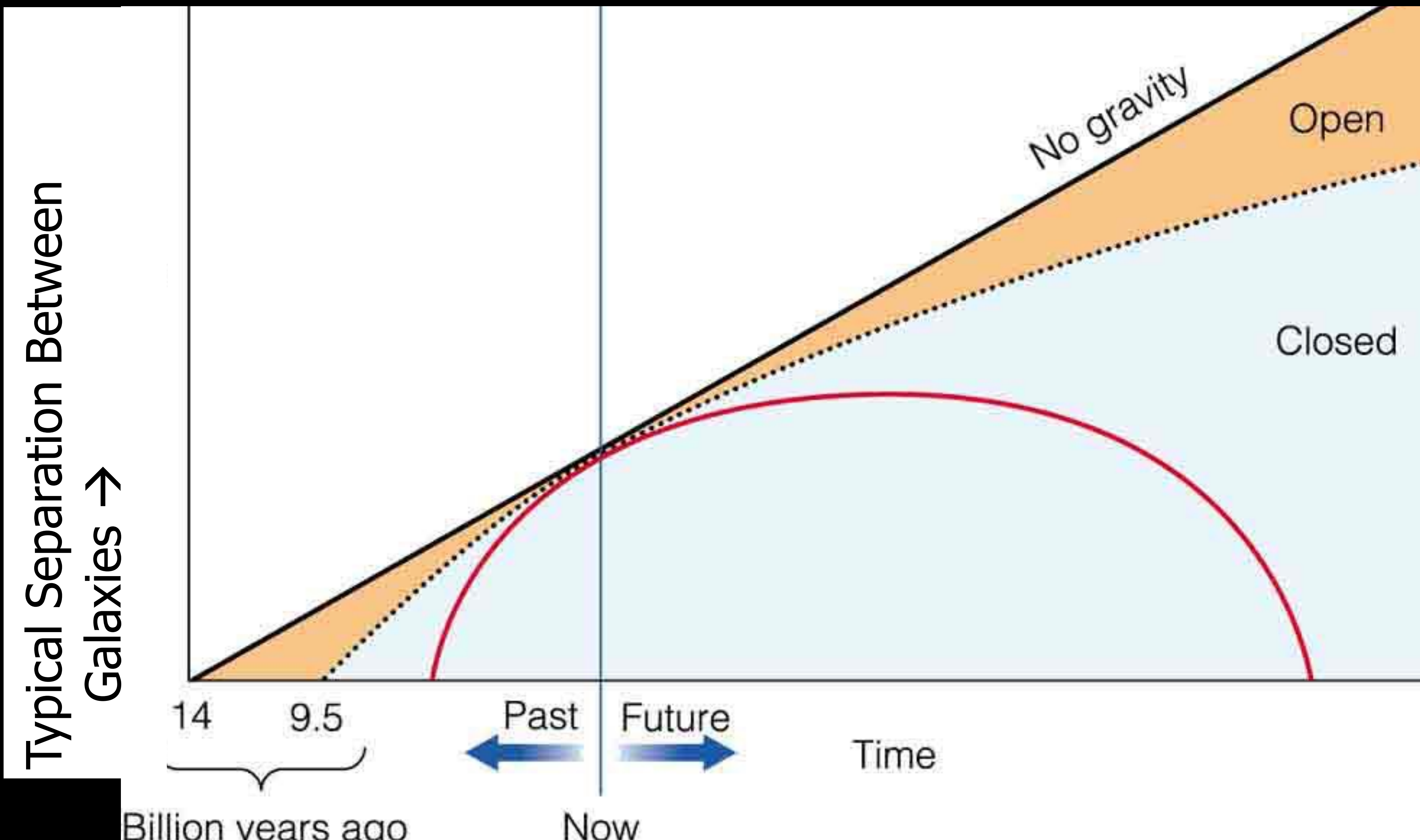
No gravity: constant expansion rate

Some gravity (some mass): Universe keeps expanding, but the rate slows down

Lots of gravity (lots of mass): expansion stops, reverses, and the Universe collapses!

Expansion versus Gravity

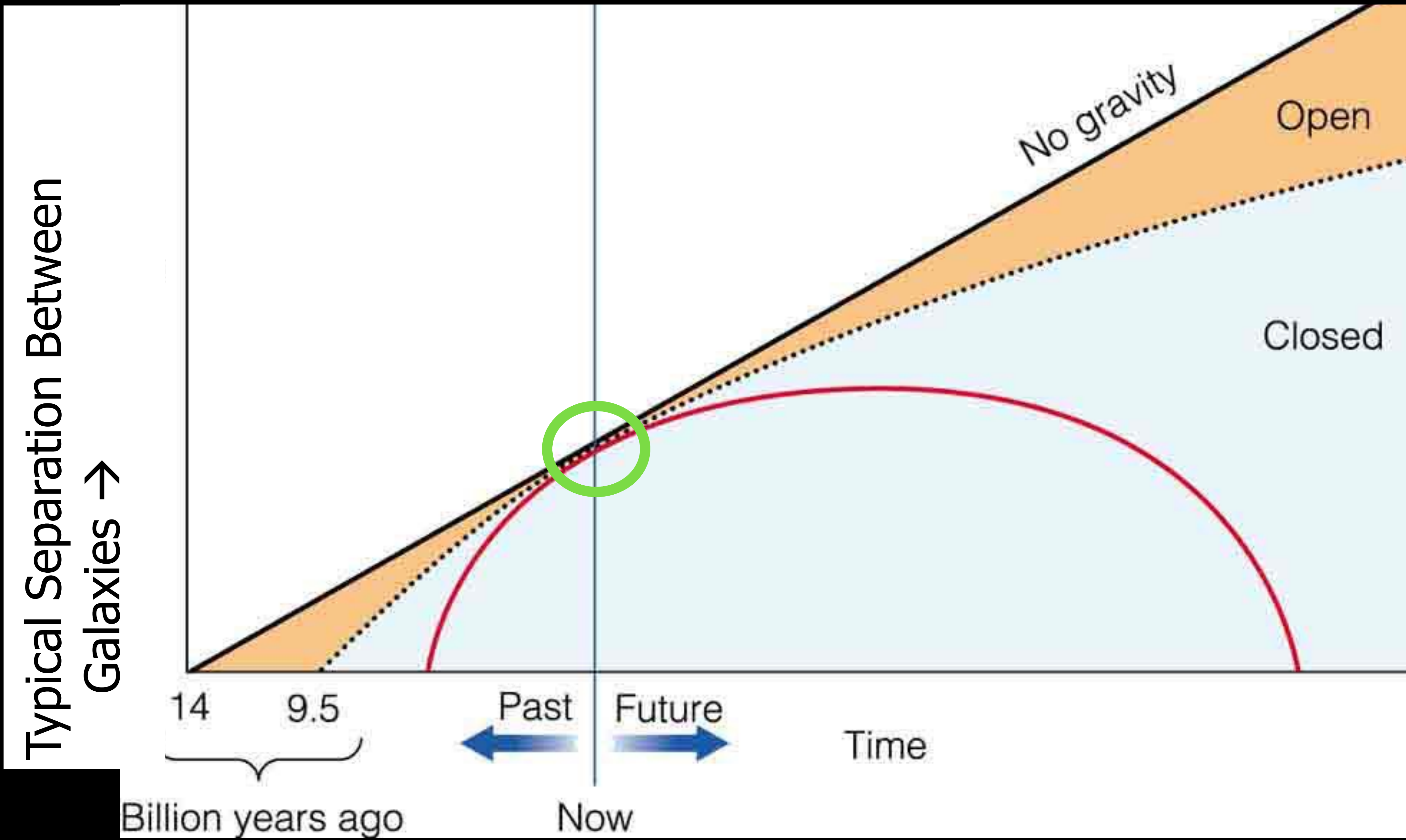
If there is too much mass in the Universe, eventually the expansion will stop and the Universe will collapse (Big Crunch)!



If there is less mass, the Universe will keep expanding forever.

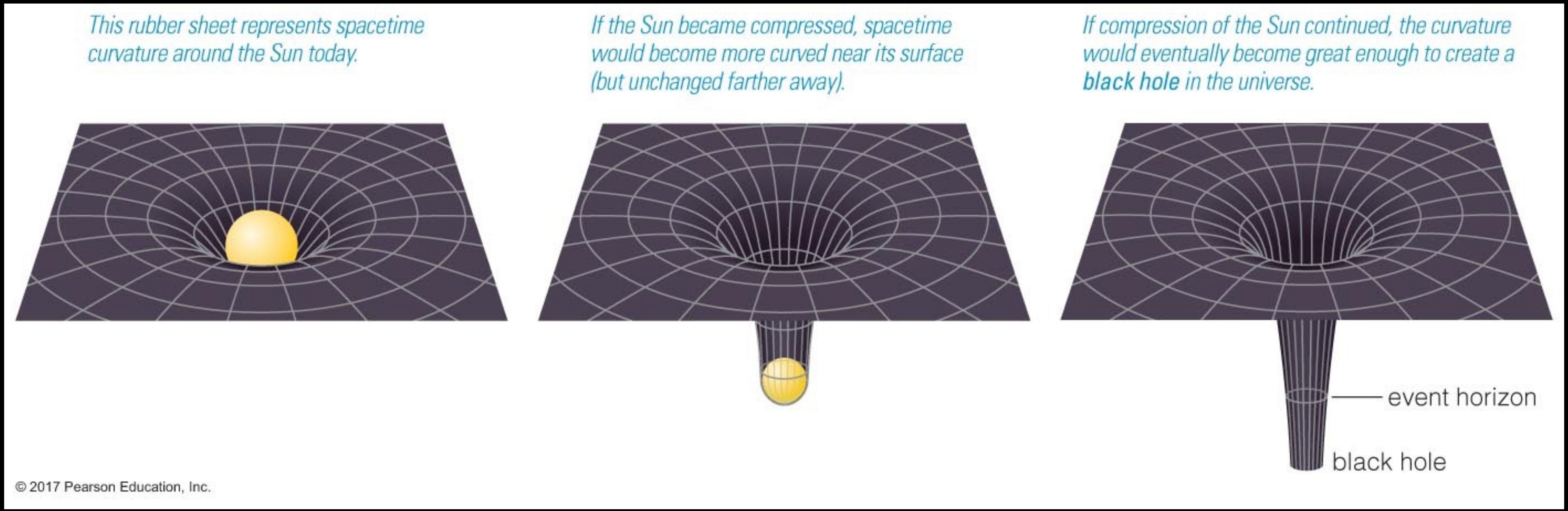
Expansion versus Gravity

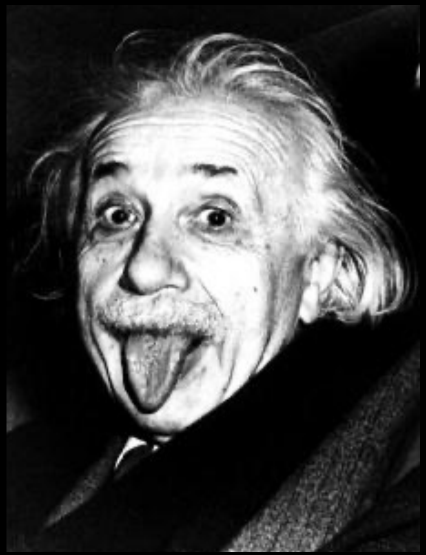
All three cases can explain the same current expansion rate & size of the Universe. How do we tell which is happening?



1. Measure the amount of mass (gravity) in the Universe
2. Measure how expansion rate has changed in the past

Recall: gravity = distortion of space (& time)



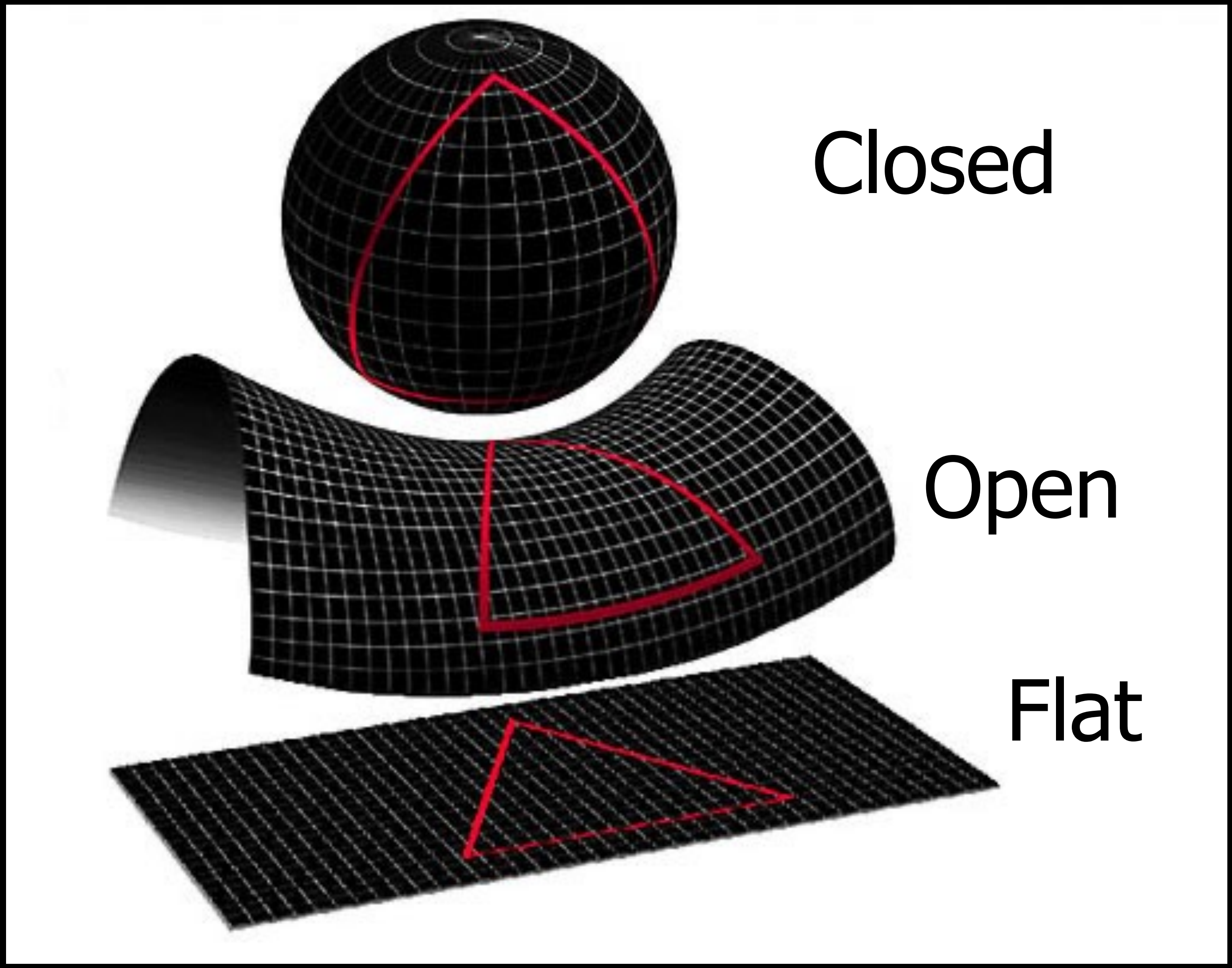


- Einstein's theory of General Relativity says that gravity is actually a "curvature" of space-time
- More mass = more curvature
  - $E = mc^2$ means that mass and energy are equivalent
  - Any form of mass or energy will create curvature

Recall: gravity = distortion of space (& time)

Three general ways for space to be curved:

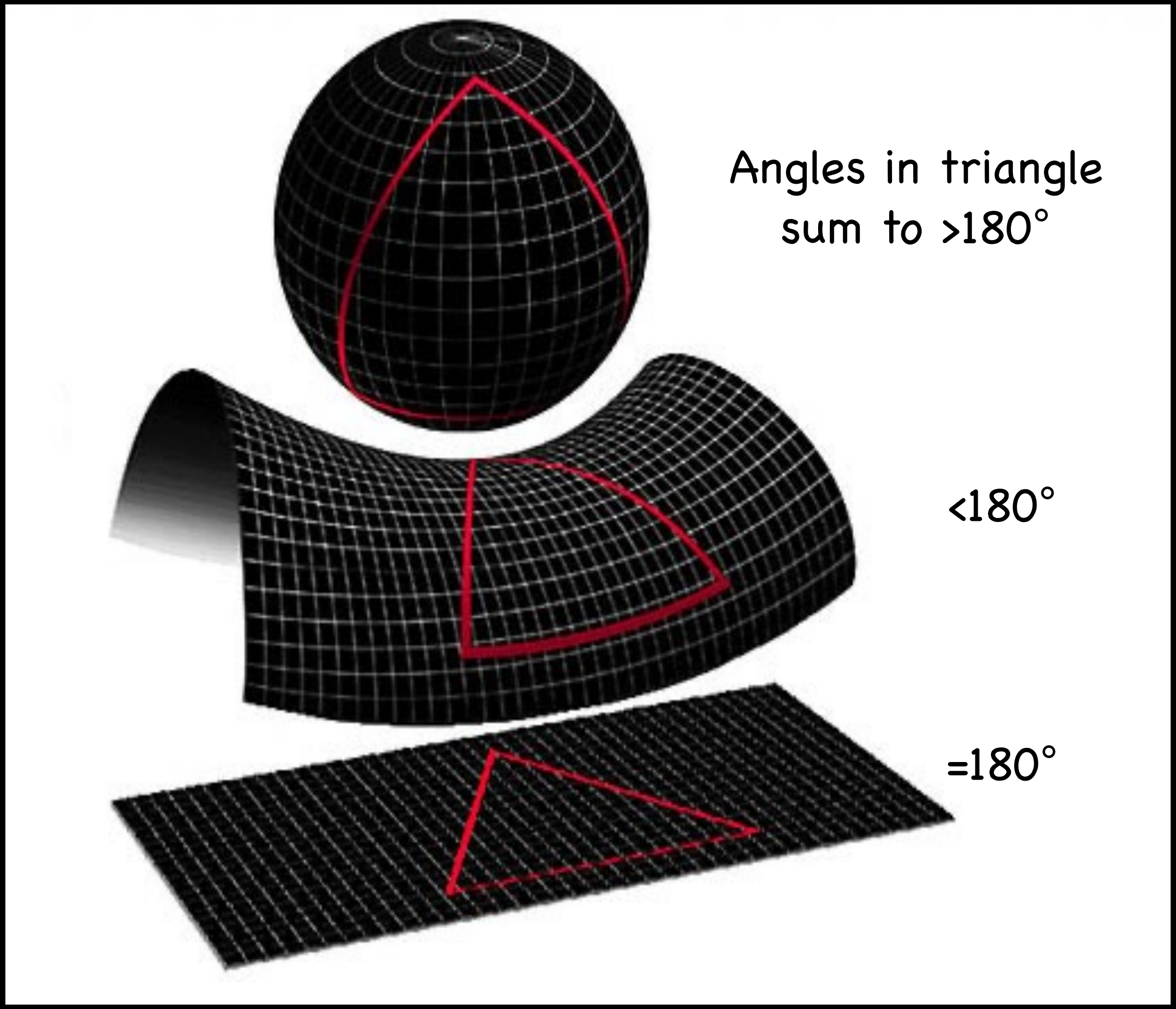
- Closed: lots of mass (high density)
- Open: less mass (low density)
- Flat: intermediate (“critical density”)



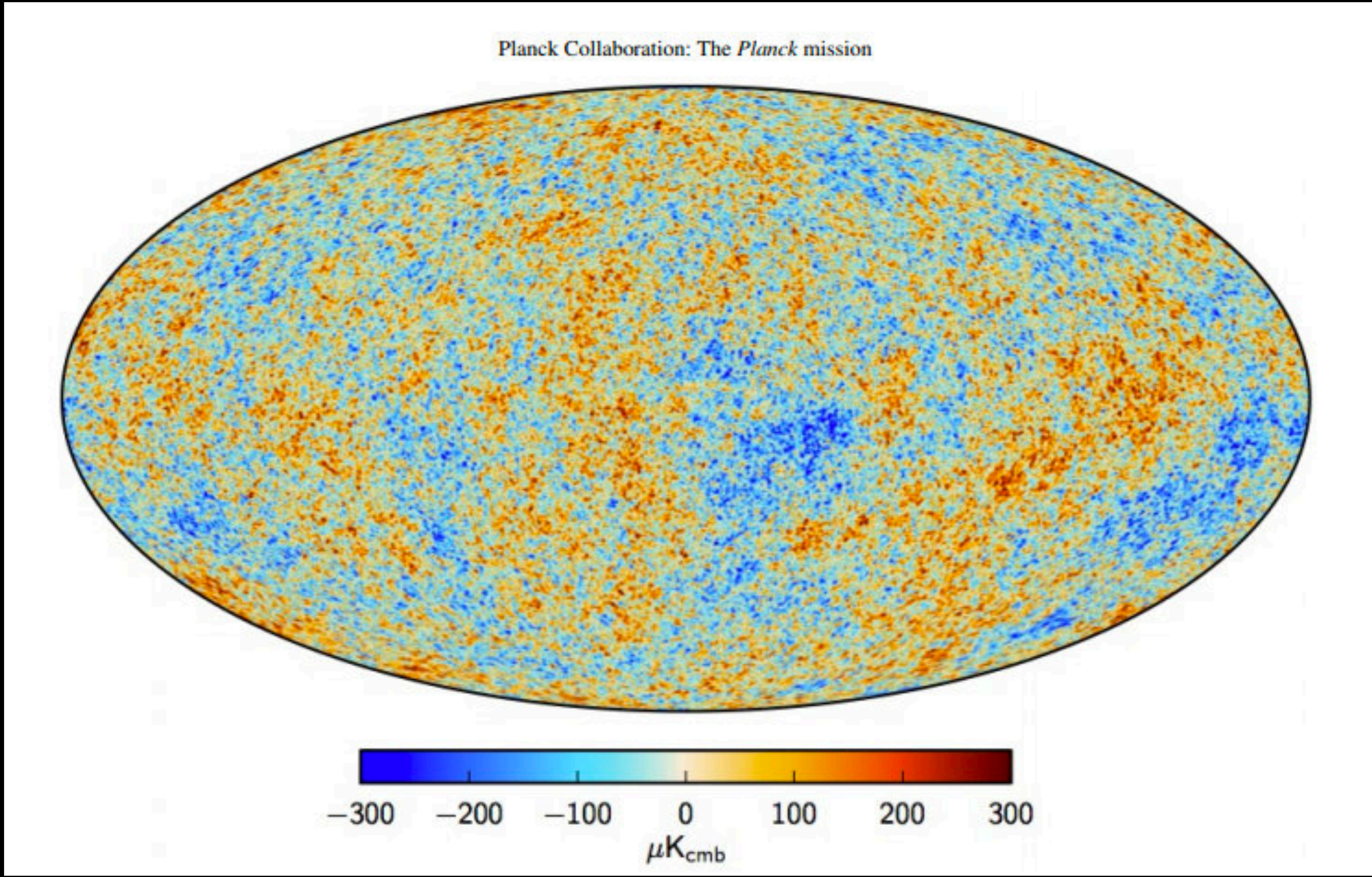
How to measure curvature of space

Look at the angles in a triangle!

- Closed: angles are larger (sum to >180 degrees)
- Open: angles are smaller (sum to <180 degrees)
- Flat: angles sum to exactly 180 degrees



Recall: map of the Cosmic Microwave Background



Small fluctuations in temperature

- T = 2.73, with variations of ~0.0001 K
- The hotter & denser regions are where galaxies and galaxy clusters will eventually start to form!

Size of hot & cold spots in the CMB

Closed:
more gravity

Open:
less gravity

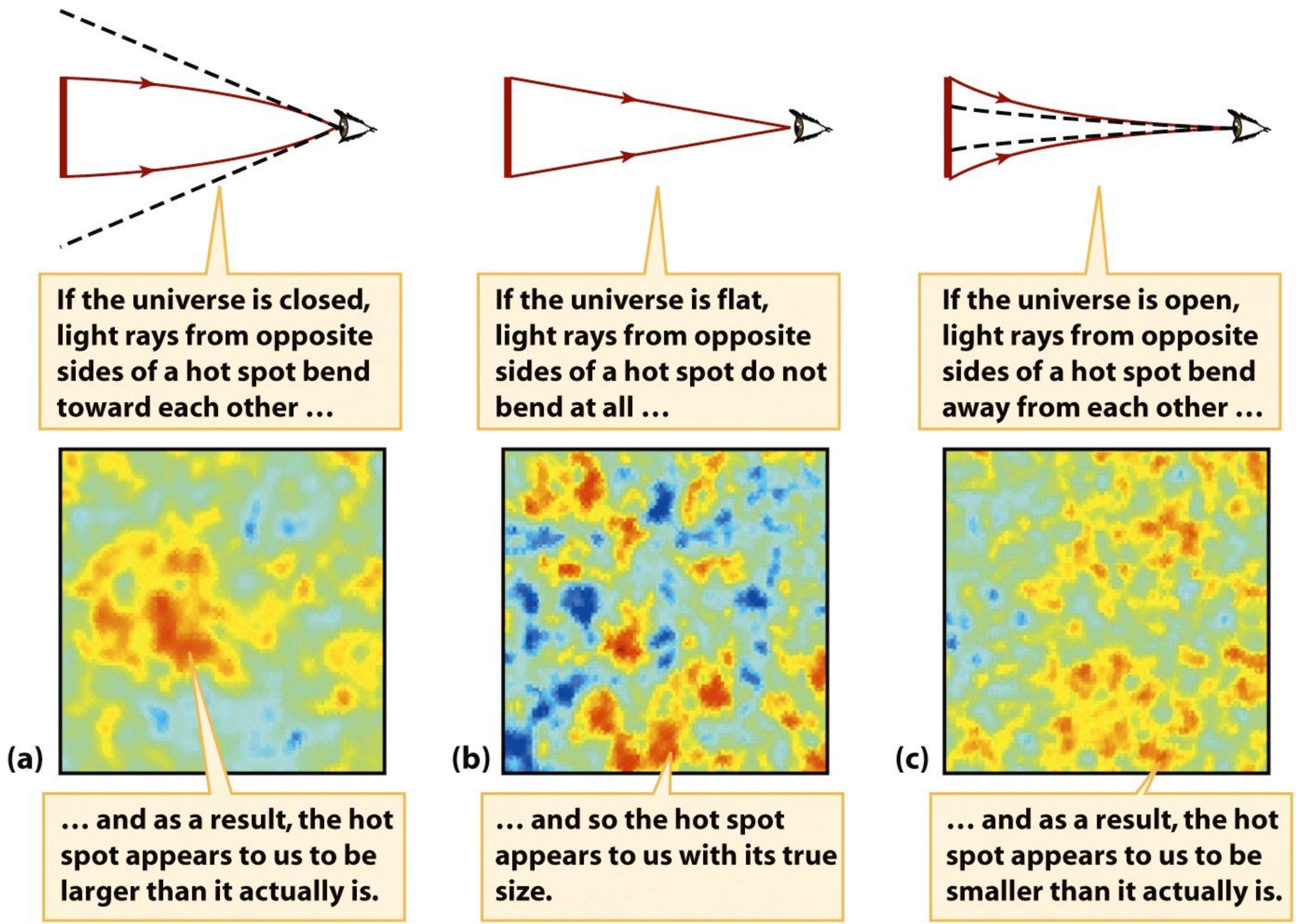
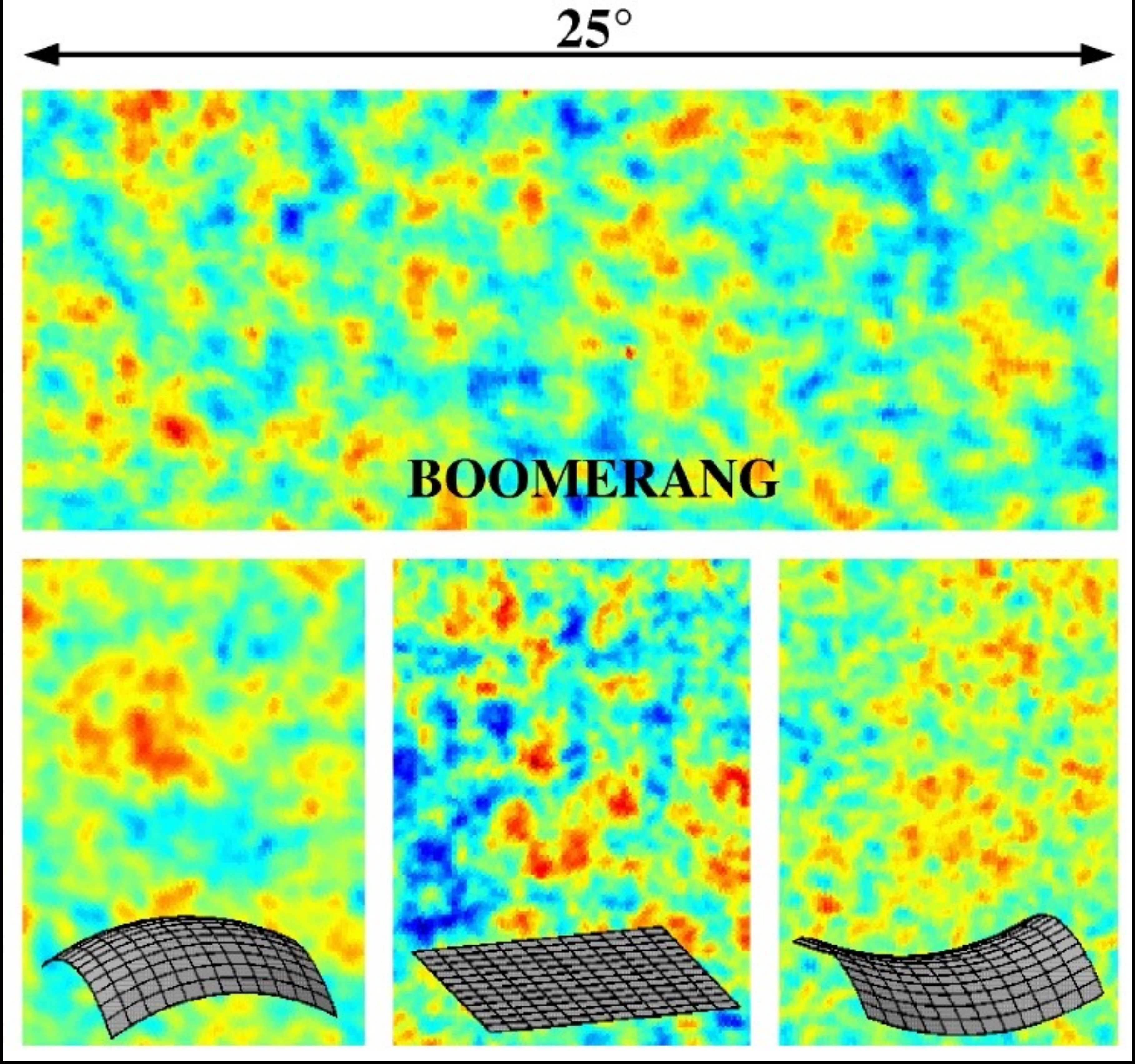


Figure 26-16
Universe, Eighth Edition

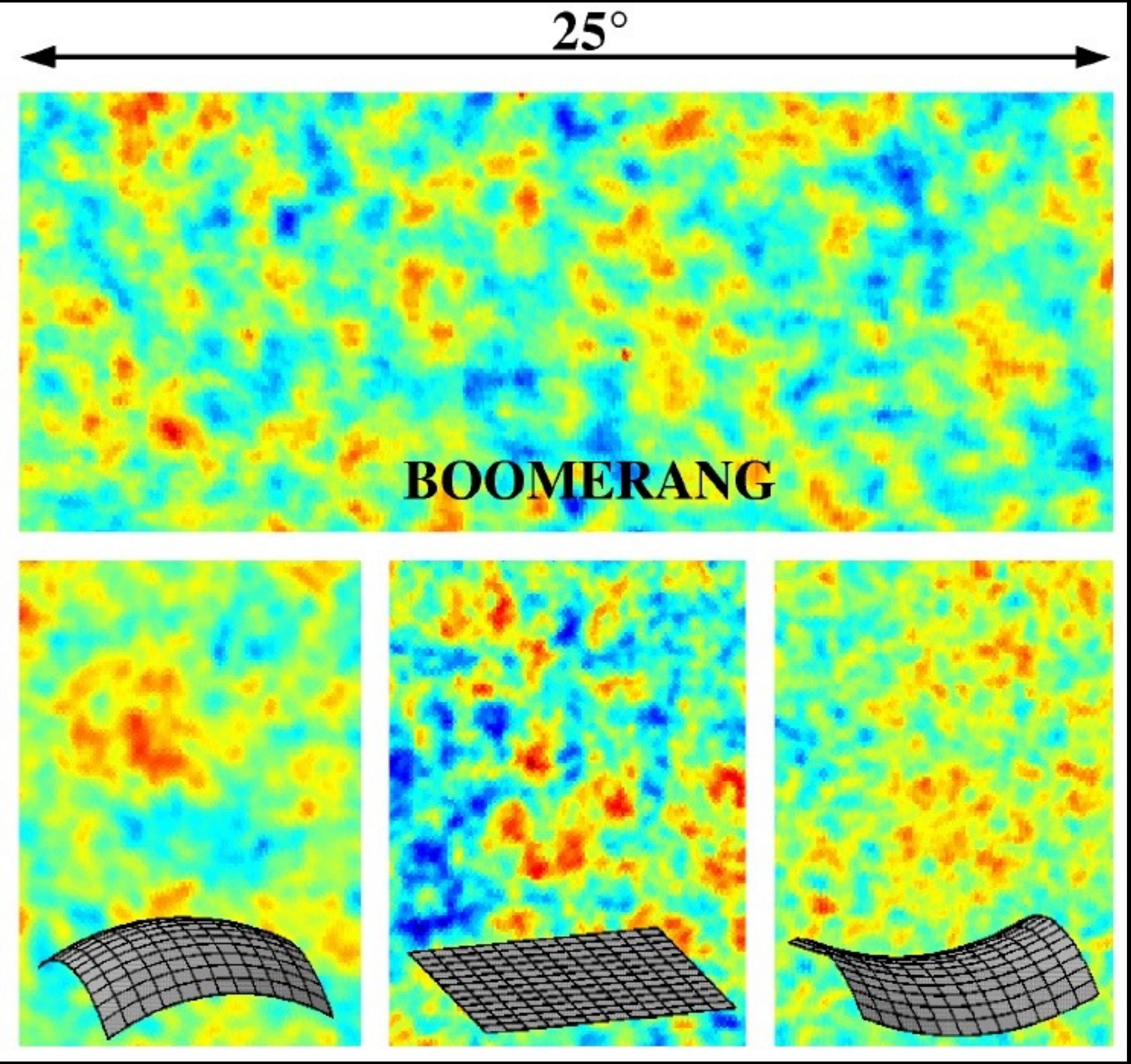
Measurements:



←Real Data

←Prediction for closed, flat, and open universes

Measurements: the Universe is flat!



←Real Data

←Prediction for closed, flat, and open universes

What is the Universe made of?

- Curvature of space tells us the total amount of mass + energy in the Universe
- "Flat" curvature corresponds to a specific density: equivalent to 5 H atoms per m^3
- Can we account for all of this mass + energy?

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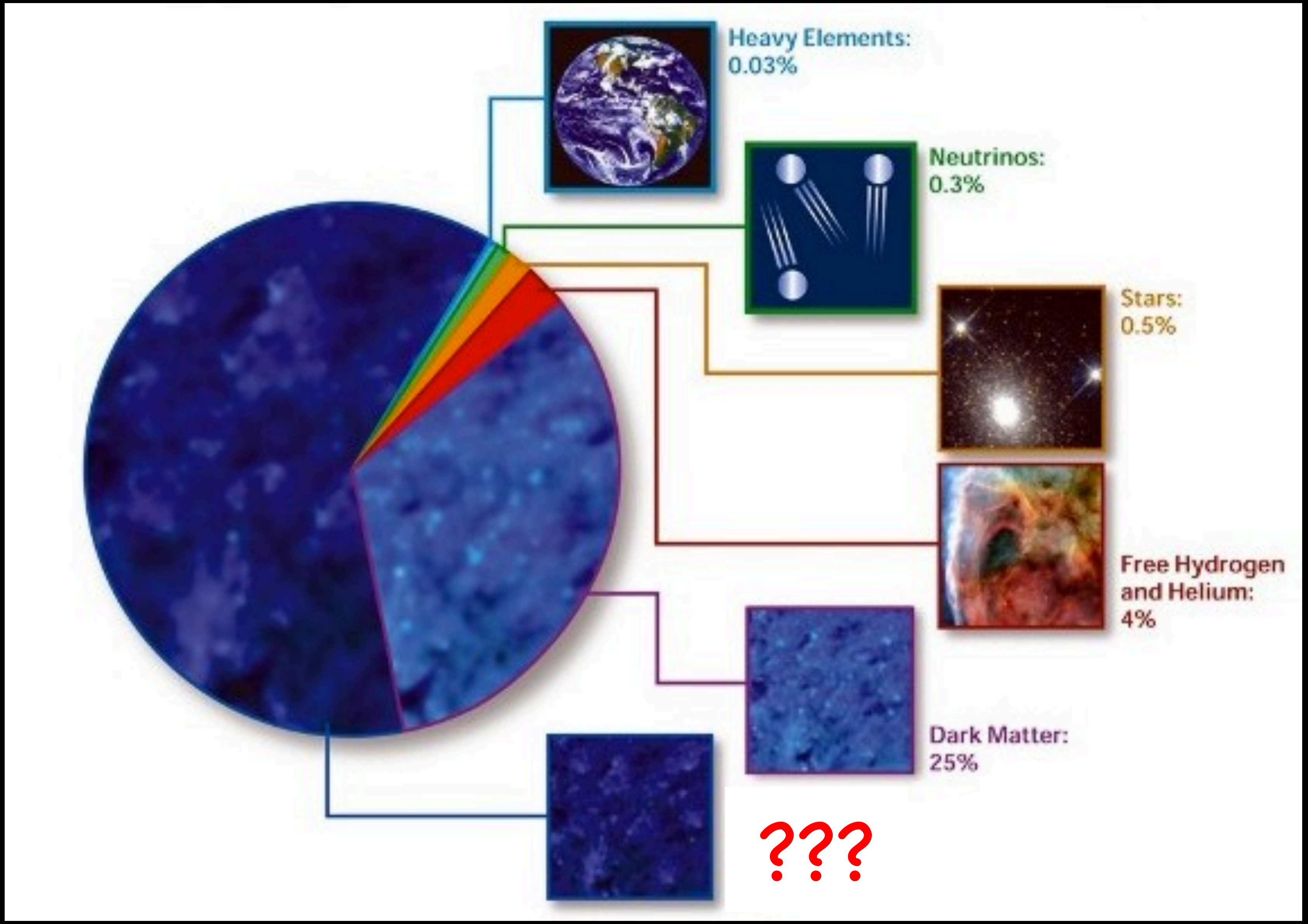
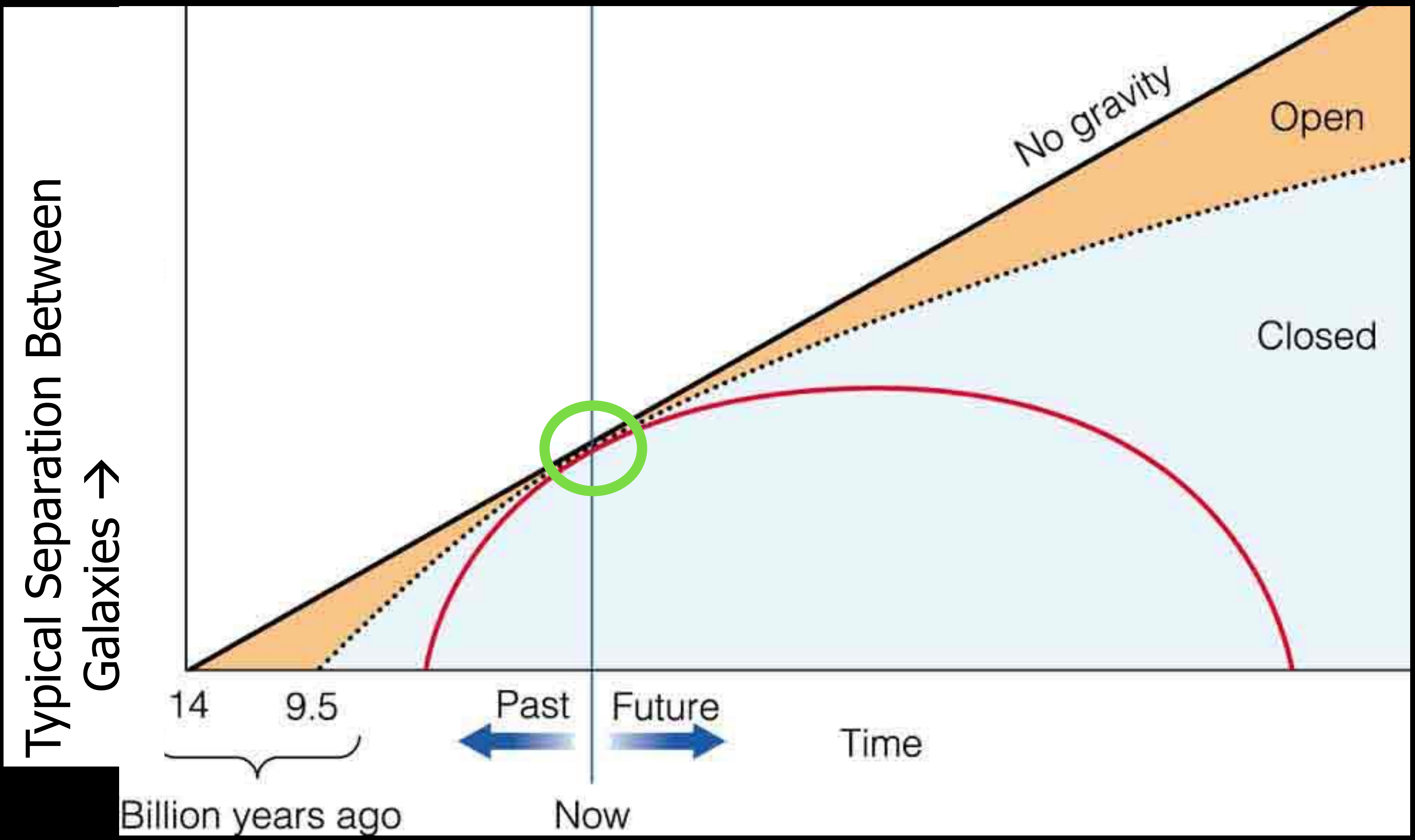


No!!!!

- We can only account for ~30%
- (and most of that 30% is "Dark Matter")
- The rest we call "Dark Energy"

Back to Expansion versus Gravity

All three cases can explain the same current expansion rate & size of the Universe. How do we tell which is correct?

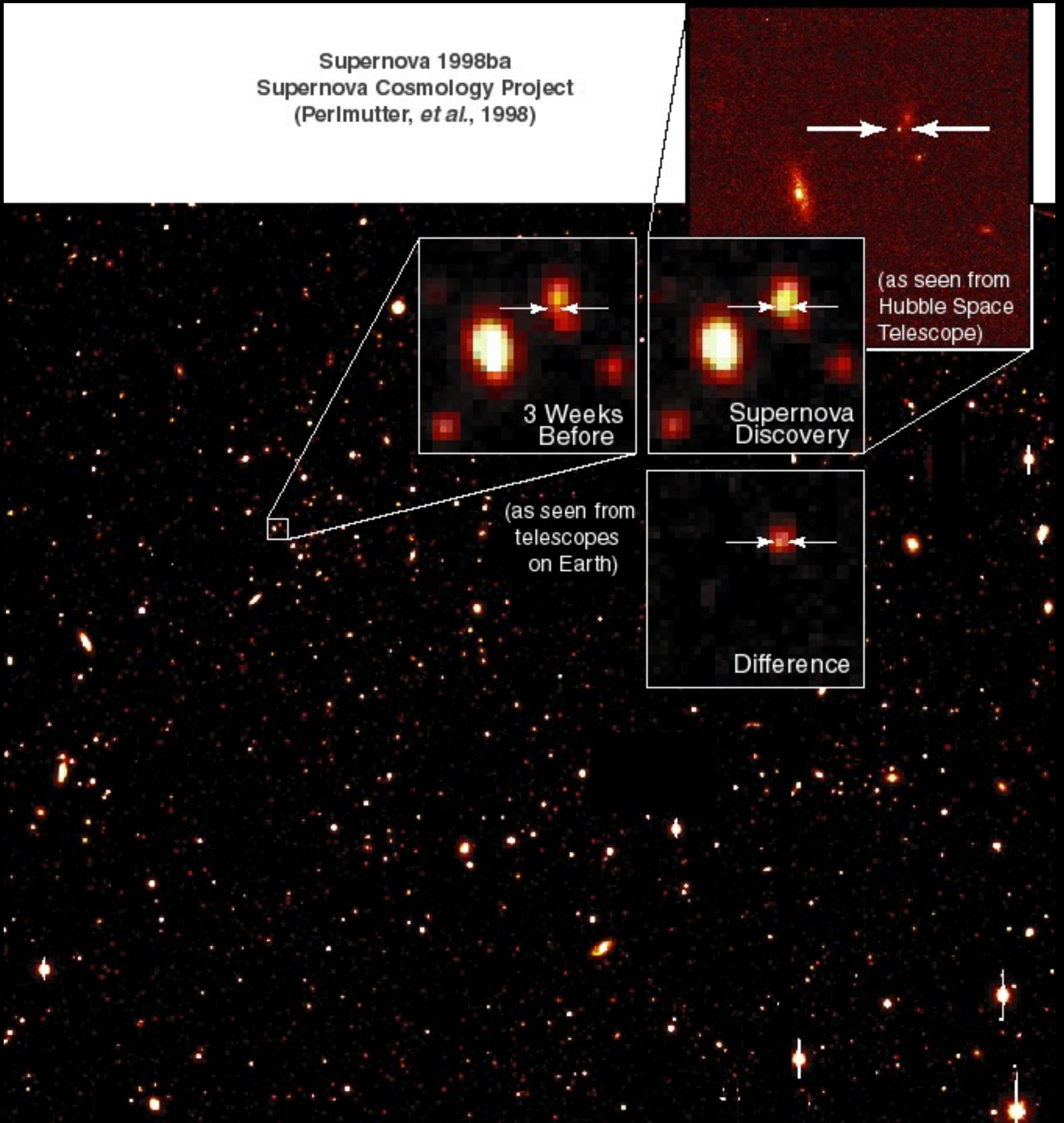


1. Measure the amount of mass (gravity) in the Universe
2. Measure how expansion rate has changed in the past

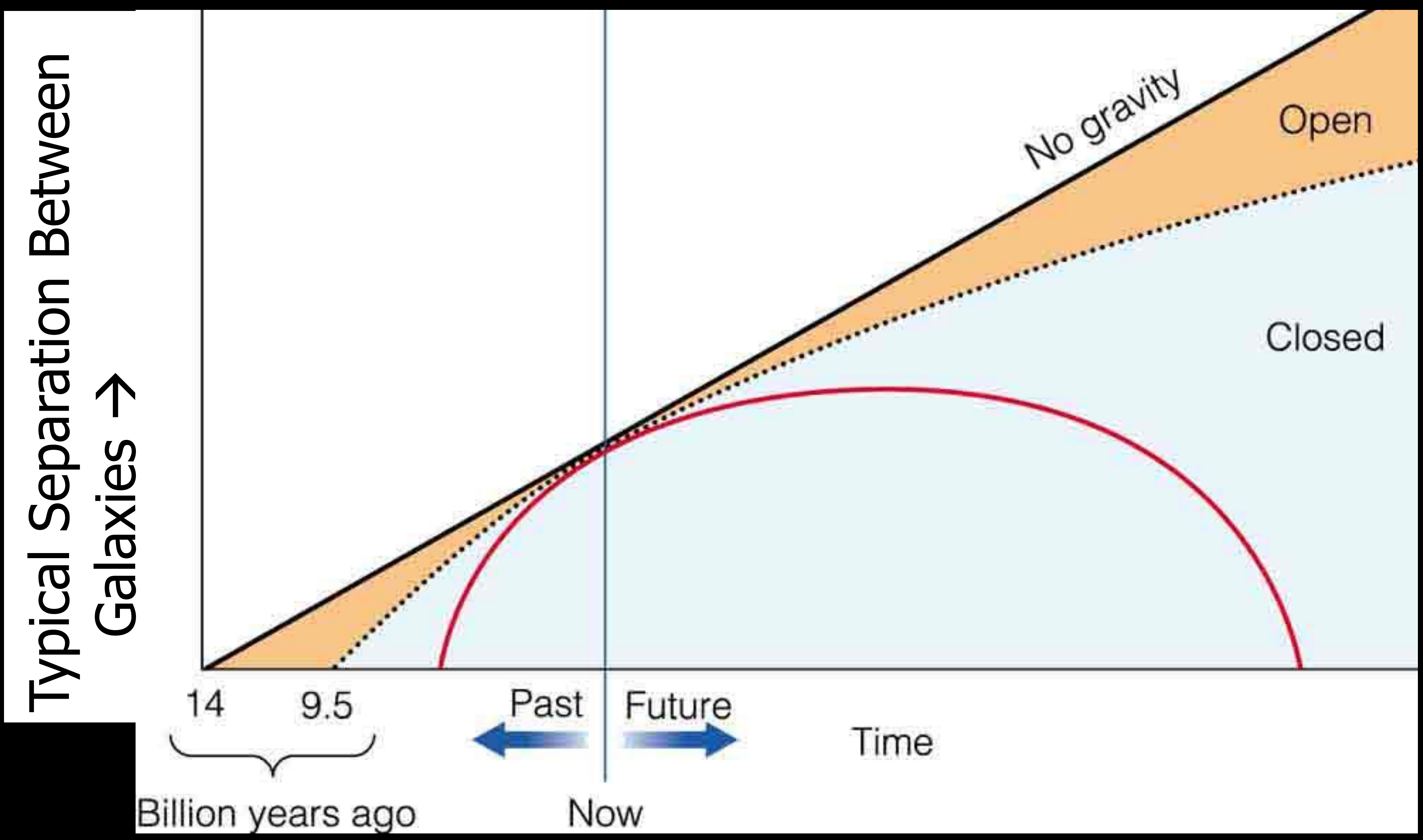
How has expansion rate changed in the past?

Search for **white dwarf supernova (standard candles!)** in distant galaxies

- Measure their distances, compared to redshift (amount of expansion of space)
- Farther away would mean faster expansion in the past

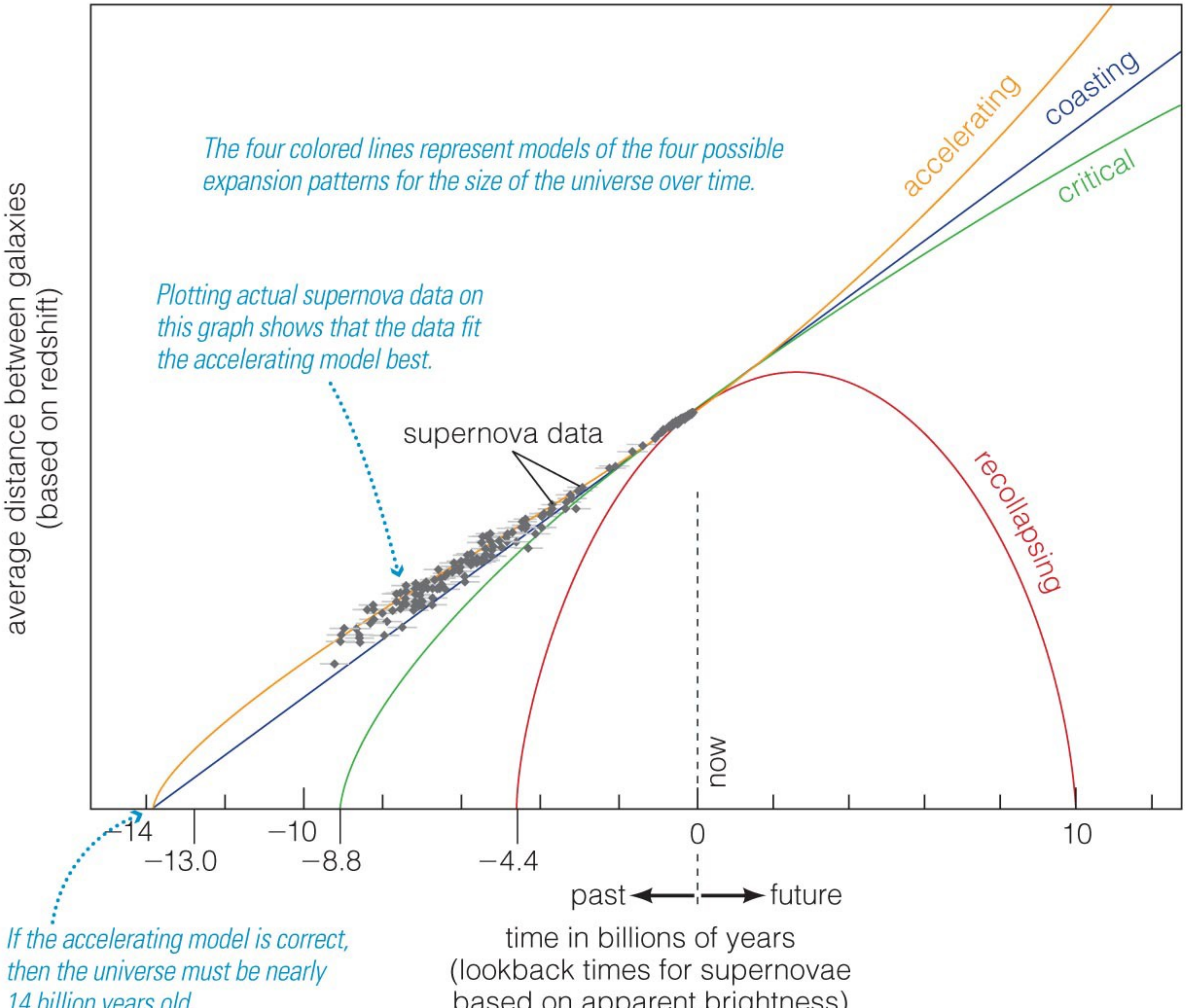


How has expansion rate changed in the past?



Expansion rate expected from the density of **matter** (mass) in a **“flat” Universe**

Measure expansion rate at earlier times using Standard Candles (white dwarf supernovae), and see if it agrees!



The four colored lines represent models of the four possible expansion patterns for the size of the universe over time.
accelerating
coasting
critical
recollapsing
Plotting actual supernova data on this graph shows that the data fit the accelerating model best.
supernova data
now
average distance between galaxies (based on redshift)
−14
−13.0
−10
−8.8
−4.4
0
10
past
future
time in billions of years (lookback times for supernovae based on apparent brightness)
If the accelerating model is correct, then the universe must be nearly 14 billion years old.

Expansion rate is **increasing!!!**

- The expansion of the Universe is **accelerating**: rate of expansion increases!
- Totally unexpected! Gravity should cause expansion rate to slow down!!
- What is going on???

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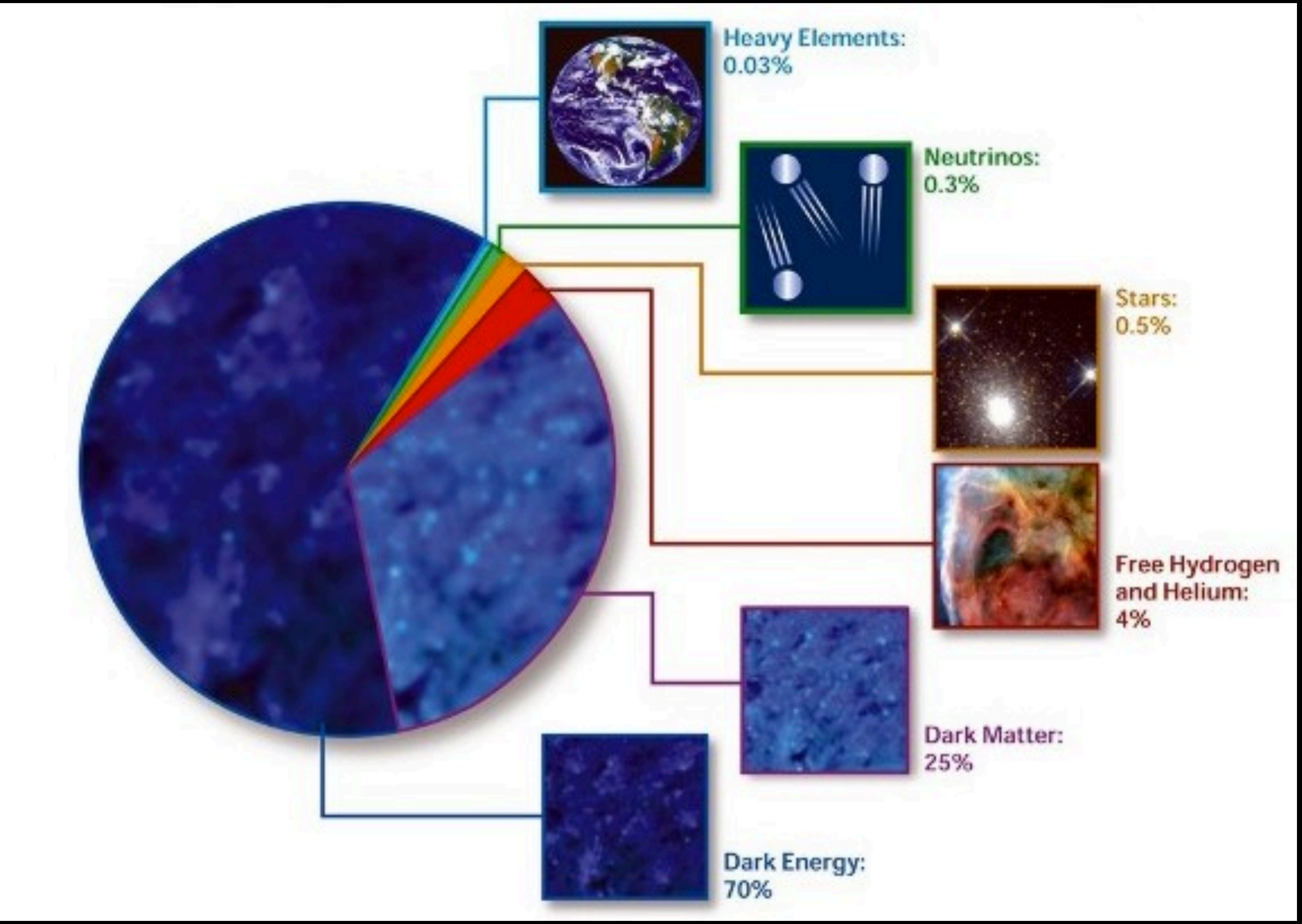
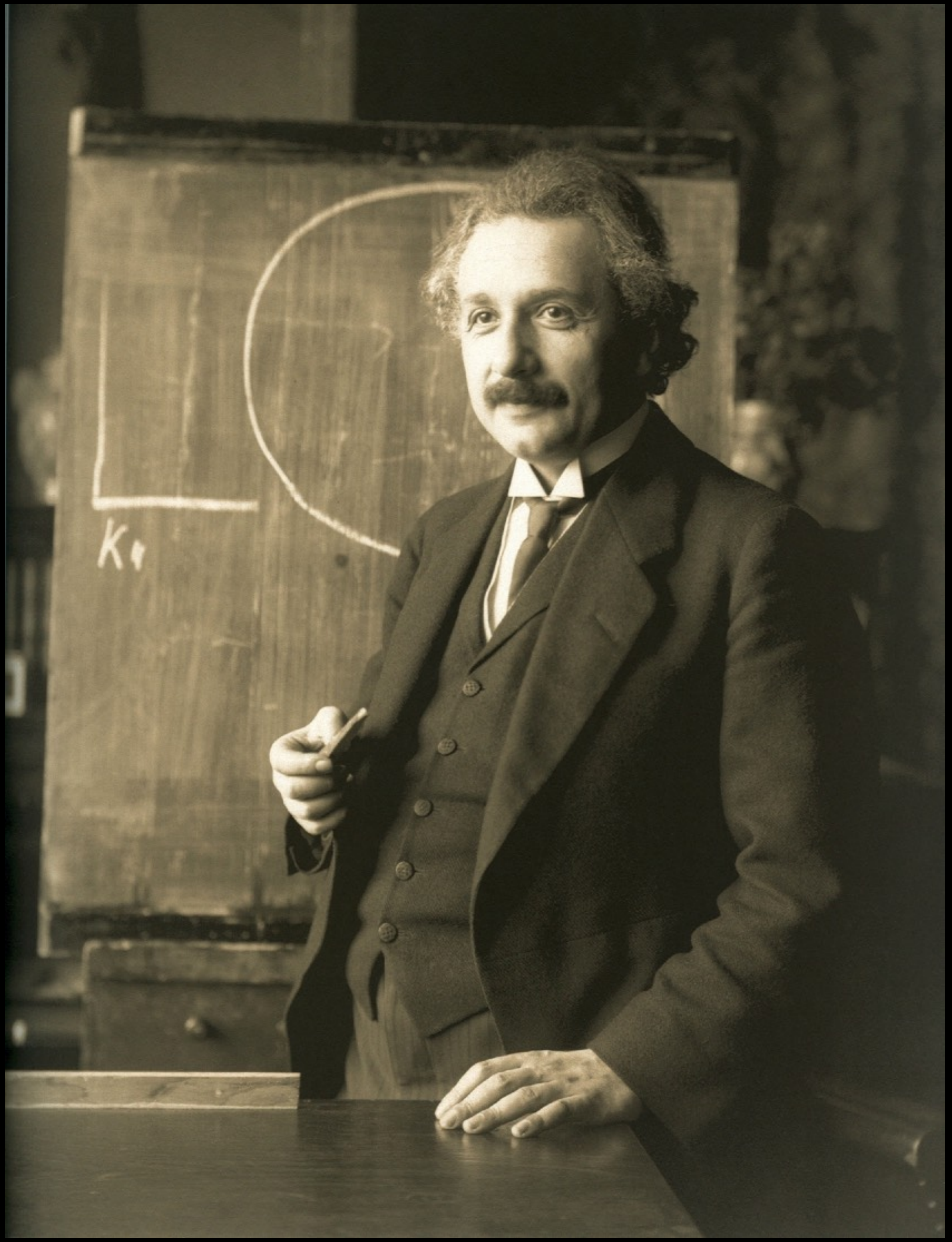


- ~70% of the "density" of the Universe is **Dark Energy**
- It does not have mass. No attraction from gravity!
- It opposes gravity — pushes galaxies apart!

Back to Einstein and Relativity

- 1915: Einstein develops the general theory of relativity, which suggests that the Universe should either be expanding or contracting
- Expansion of the Universe was not yet known
  - not known that other galaxies existed beyond the Milky Way!
- Einstein introduces a "cosmological constant" Λ to his equations, which **accelerates the expansion of space (in opposition to gravity)!**
  - He was trying to explain a non-expanding Universe…



The "Dark Energy" could be Einstein's "cosmological constant"

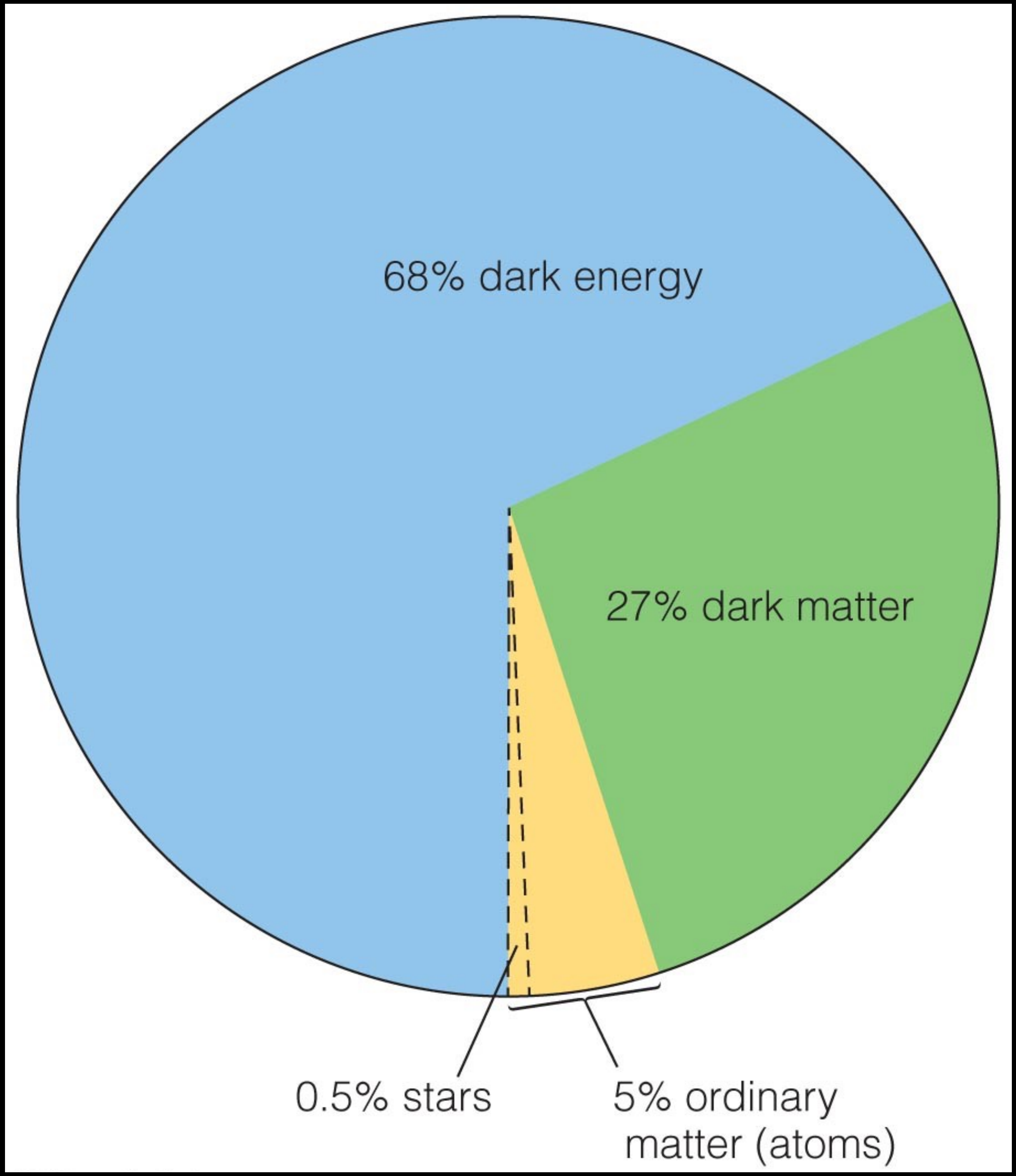
- It behaves exactly as we would expect

Contents of the Universe

- Ordinary matter: ~ 5%
  - Ordinary matter inside stars: ~ 0.5%
  - Ordinary matter outside stars: ~ 4.5%
- Dark matter: ~ 27%
- Dark energy: ~ 68%

Total mass + energy is exactly the right amount for a "flat" Universe.

Mass decreases the expansion rate, but Dark Energy increases it. Dark Energy is winning!



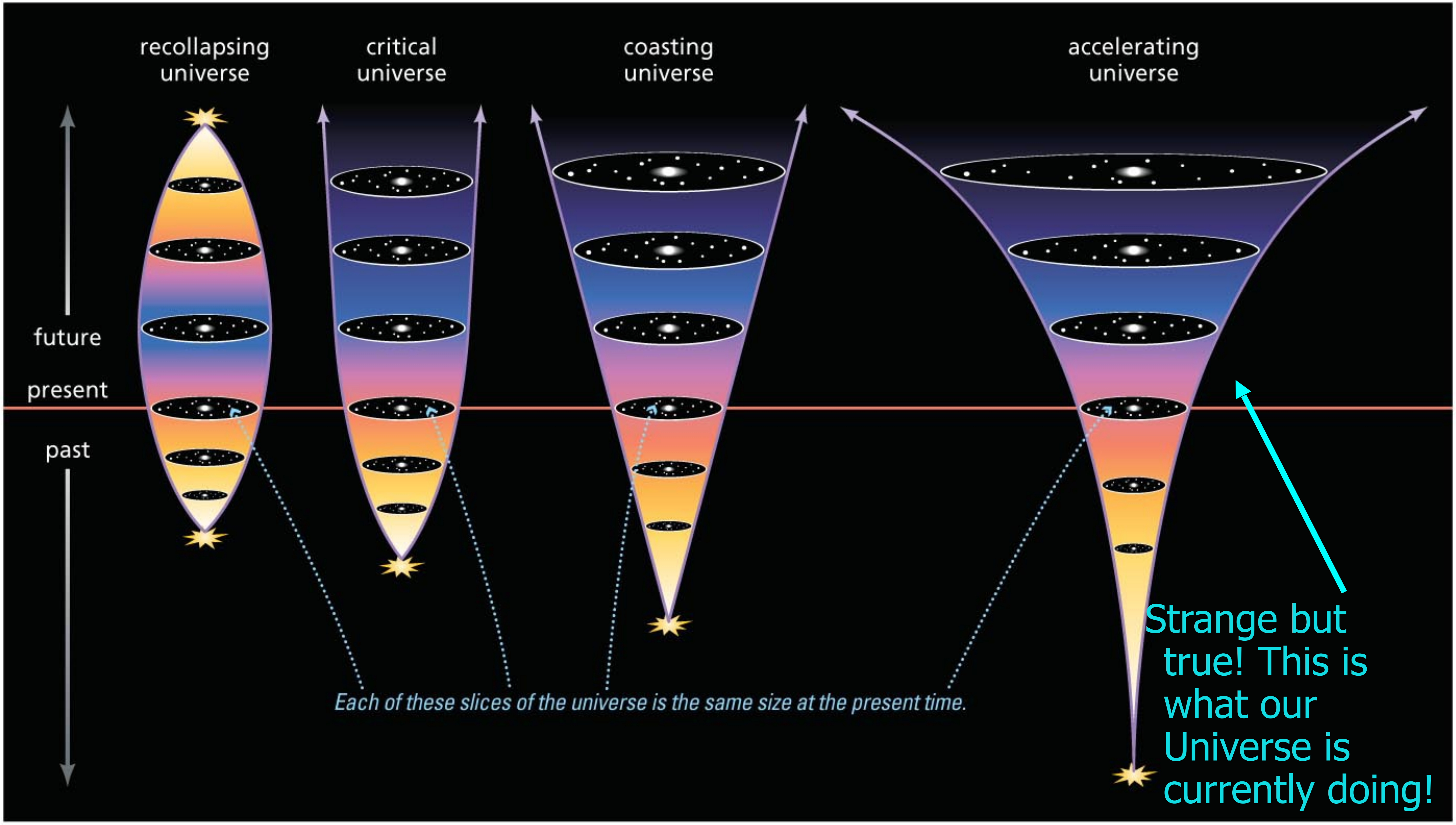
“Dark Matter” vs “Dark Energy”

What do we mean by Dark Matter and Dark Energy?

- **Dark Matter** is what we call a form of matter which does not interact with light, but which has mass
  - It slows down the expansion of the Universe, due to gravitational attraction

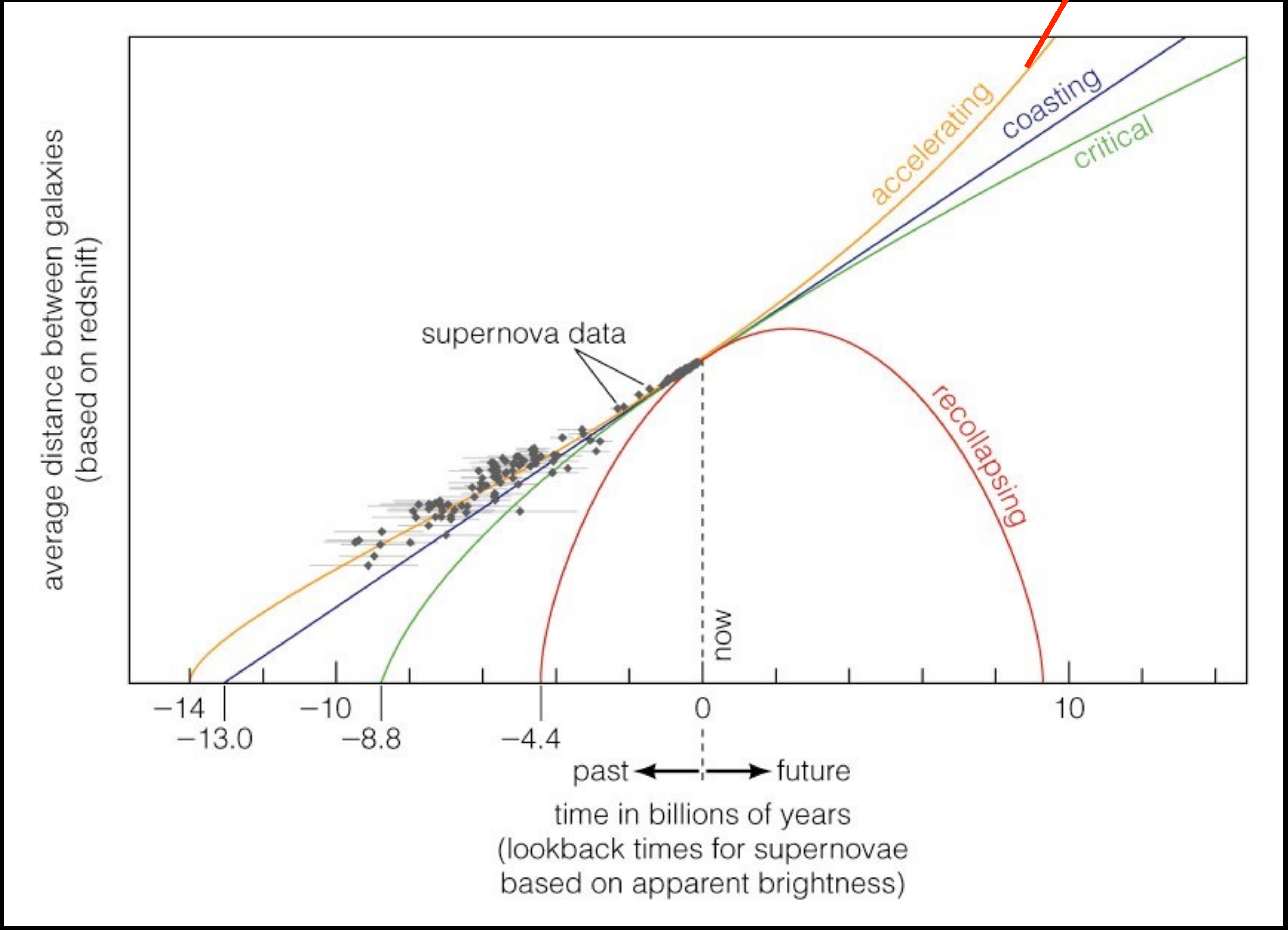
- **Dark energy** is what we call the stuff that causes the expansion rate of the Universe to accelerate
  - It does not have mass. We don’t really know what it is.

Possible models of the expanding Universe



The future fate of the Universe

Universe expands forever!
"Dark Energy" takes over and the expansion rate keeps accelerating.



What will happen in the future?

- The Universe will continue to expand at an ever-faster rate
- It will cool as it expands, getting colder and colder
  - A "cold death"
- In ~5 billion years, the Sun will turn into a Red Giant star and envelop the Earth
- Eventually the galaxy will run out of gas to form new stars, and old stars will fade away…
  - …leaving black holes, neutron stars, white dwarfs, and brown dwarfs
- In 1 trillion+ years, much (most?) of the matter will fall into black holes
  - Galaxies will turn into graveyards of black holes and dark matter, being pushed farther and farther apart by expansion of space

Recap: what have we learned?

- **How is the expansion rate of the Universe changing?**
  - It is speeding up — accelerating! Even though gravity should cause the expansion rate to slow down.
  - We know this from measurements of distant Standard Candles (white dwarf supernovae)
- **What is Dark Energy?**
  - Dark Energy is what we call the form of energy that causes the expansion rate of the Universe to accelerate
  - We don’t know what it actually is
- **What is the ultimate fate of the Universe?**
  - It will expand forever, getting colder and less dense
  - A slow, cold death

Summary: past and future

- The Universe is huge, but it used to be tiny and very dense
  - It started with a (Hot) Big Bang!
- The Universe is flat
  - This tells us the total mass + energy density
- Most of the density content of the Universe is Dark Energy
  - We don't know what it is. Could be a cosmological constant.
- The second most abundant type of stuff is Dark Matter
  - We don't really know what it is, but we have some ideas
- Space is expanding, the expansion rate is accelerating, and it appears that the universe will keep expanding forever

The End…