Announcements

- Please fill out an on-line course evaluation, available today (and sending you annoying email daily!)
- Final Exam: Wednesday, 3/22, 7:30pm, this room
  - 3 hours, same format, rules as midterm: multiple choice with formula sheet, closed book and notes
  - Bring a #2 pencil and a non-internet-enabled calculator. I'll provide the scantrons
- Cumulative: study the midterm material, too. A version of the midterm with the answer key is posted on the course web page
- Review sessions:
  - Marie: Friday, 3/17, 4-5 pm, NatSci2 Annex 101
  - Plato: Sunday, 3/19, 3-4pm, NatSci2 Annex 101

Hubble’s Constant and the Age of the Universe

Hubble’s Law: $v = H_0 \times D$

Hubble’s Constant $H_0 = 21$ (km/s)/Mly

$\frac{1}{H_0}$ has units of seconds = time!

What time? Time since the expansion started!

If everyone is moving with speed 5 m/s and they have run 5 m, how long ago did the race start?

A) 5 seconds
B) 1 second
C) 10 seconds
D) 0.5 seconds

Hubble's Constant and the Age of the Universe

$H_0 = \dfrac{21\ \text{(km/s)}}{\text{million light-years}}$ tells us the time since the expansion started: the age of the universe.

Speed of light (c) = 300,000 km/s
1 million light-years: $(1\text{x}10^6\ \text{years})\times(300{,}000\ \text{km/s})$

$= (1\text{x}10^6\ \text{years})\times(300{,}000\ \text{km/s}) = 3\text{x}10^{11}\ \text{(km/s)years}$ (yes, that is units of distance, just weird)

So: $H_0 = \dfrac{21\ \text{(km/s)}}{3\text{x}10^{11}\ \text{(km/s)years}} = \dfrac{21}{3\text{x}10^{11}\ \text{years}}$

$\dfrac{1}{H_0}$ = time since expansion started

$= \dfrac{3\text{x}10^{11}\ \text{years}}{21} = 14.3\text{x}10^9$ or about 14 billion years

The true best value is 13.8 billion years. The difference has to do with the accounting between dark matter, dark energy and regular atoms. But this is basically how we measure the age of the universe: $\dfrac{1}{H_0}$

Hubble's Constant and the Age of the Universe

Hubble's Law: $v = H_0 \times D$ in units: $v = \frac{D}{t}$

If v is constant, then when t is small (near the beginning), D must be small, too.

What is D? the distance between any two galaxies, any two places in the universe.

Since space is what is really expanding, D is a measurement of the size of the universe.

So, what was the universe like when t was small?

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A) bigger
B) smaller
C) It's finally sunny and warm outside!

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Smaller! Everything is has been expanding since the Big Bang, so it must have been smaller at early times.

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A) more irregular
B) less massive
C) more massive
D) more dense

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Denser! Same amount of matter as today, but in a smaller volume.

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Hotter!
Different and very weird!

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So, what was the universe like when t was small?

Smaller!
Denser!
Hotter!
Different and very weird!

The term "Big Bang" was initially a sarcastic way to refer to the state of the universe just before expansion began.

First used by people who thought this whole idea of expanding space was crazy.

But there turns out to be lots of evidence for it...

Evidence for the Big Bang

Universe was hotter, denser, smaller at early time (small t, small D)

Another hot, dense place in the universe that we've thought about:
The cores of stars

That leads us to some predictions:
1) Nuclear fusion should have been happening.
This is why we think the universe starts out with some Helium (and a tiny amount of Beryllium, Lithium and Boron), not just Hydrogen.

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2) Thermal radiation: the universe was dense enough to be opaque, so light interacts with lots of atoms before it can escape. Makes a thermal spectrum.

- “Escape” in this case means that the universe expands enough that the density goes down. Atoms recombine (protons and electrons stick together). Photons stop interacting with atoms so easily.

- Like photons escaping from the outer layers of a star when the density finally is low enough that there are not so many atoms to interact with.

Big Bang Nucleosynthesis

The early universe was hot and dense, just like the core of a star.

→ fuse hydrogen into helium, other light elements

Just like in a star, nuclear fusion is more efficient at higher density.
Density of ***atoms*** is the only thing that matters.
"baryons": normal matter. Protons, neutrons, electrons, atoms, easy chairs, banana slugs, etc.

So this can tell us the total amount of baryonic matter (atoms, normal matter) in the universe.
Gravity: works on ***all*** matter, baryons + dark matter.
Early universe nucleosynthesis: how much baryonic (normal) matter (atoms)

Universe today: 70% Hydrogen, 28% Helium, 2% everything else
But all the stars that have ever lived could have made only 3% Helium.
Where did the rest come from?
The Big Bang!

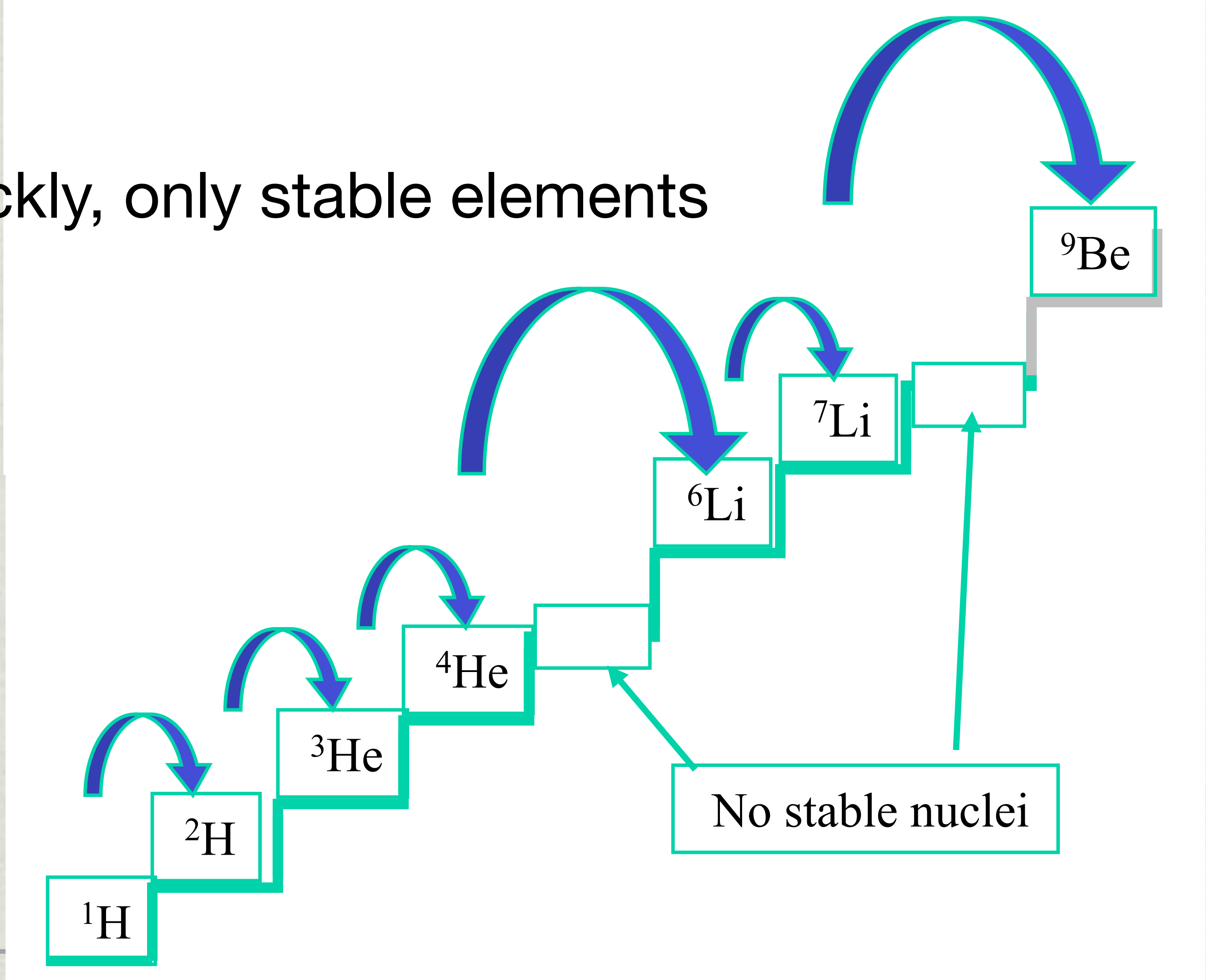
Big Bang Nucleosynthesis

Conditions in the early universe hot and dense enough for nucleosynthesis:

When the universe was 0.001 seconds to 3 minutes old

Protons, neutrons, electrons bouncing around with ***lots*** of kinetic energy
Lots of very energetic photons.

Nuclei form and break apart very quickly, only stable elements survive.



Big Bang Nucleosynthesis

As the universe expands, the temperature and density go down.

Eventually, temperature and density are too low and nucleosynthesis stops.

The number of atoms of each element stays stable: "freeze-out"

75% Hydrogen

25% Helium

tiny traces of Deuterium (Hydrogen plus one neutron), Lithium, Boron, Beryllium

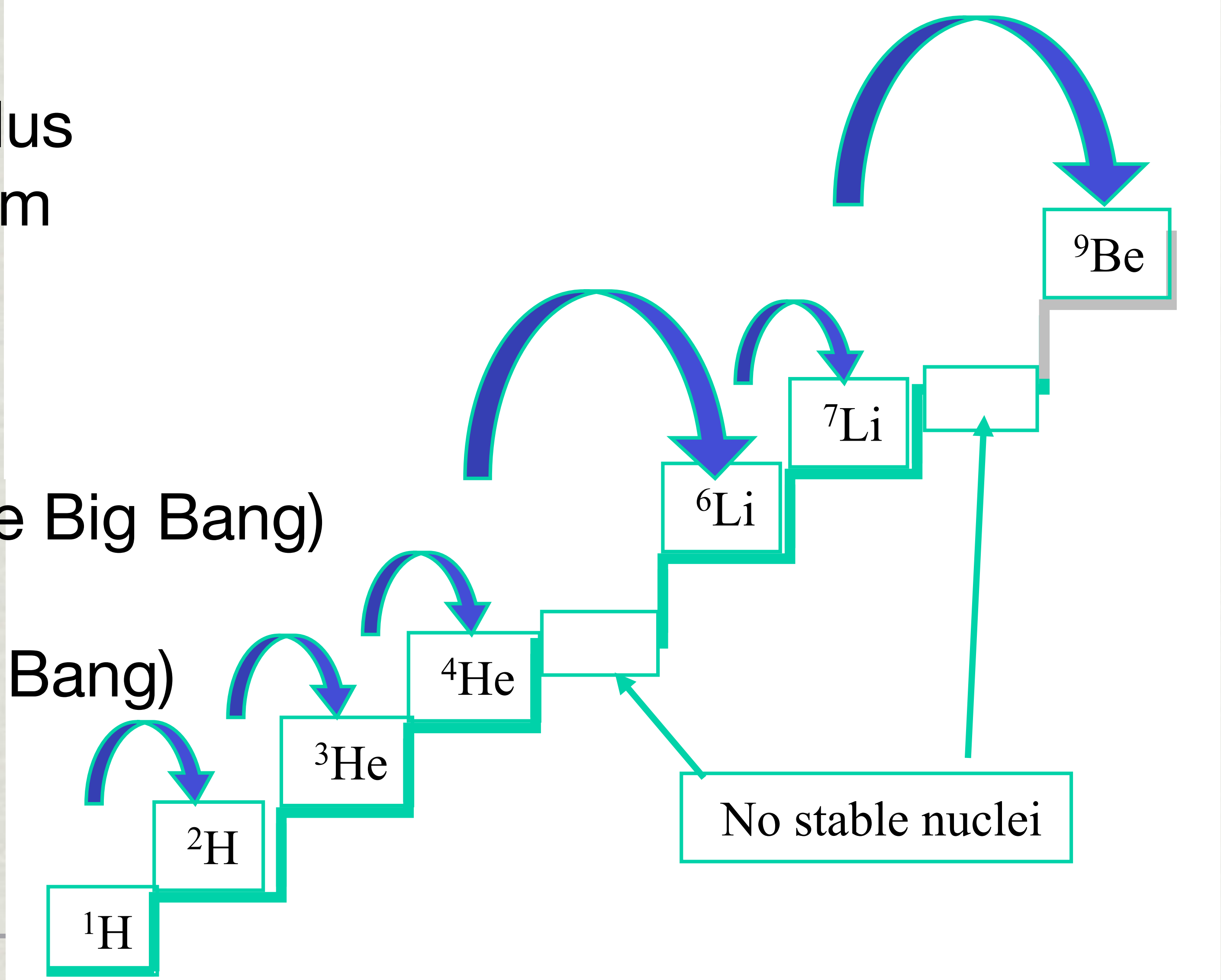
Universe today:

70% Hydrogen

28% Helium (3% from stars since the Big Bang)

2% everything else

(all made in stars since the Big Bang)



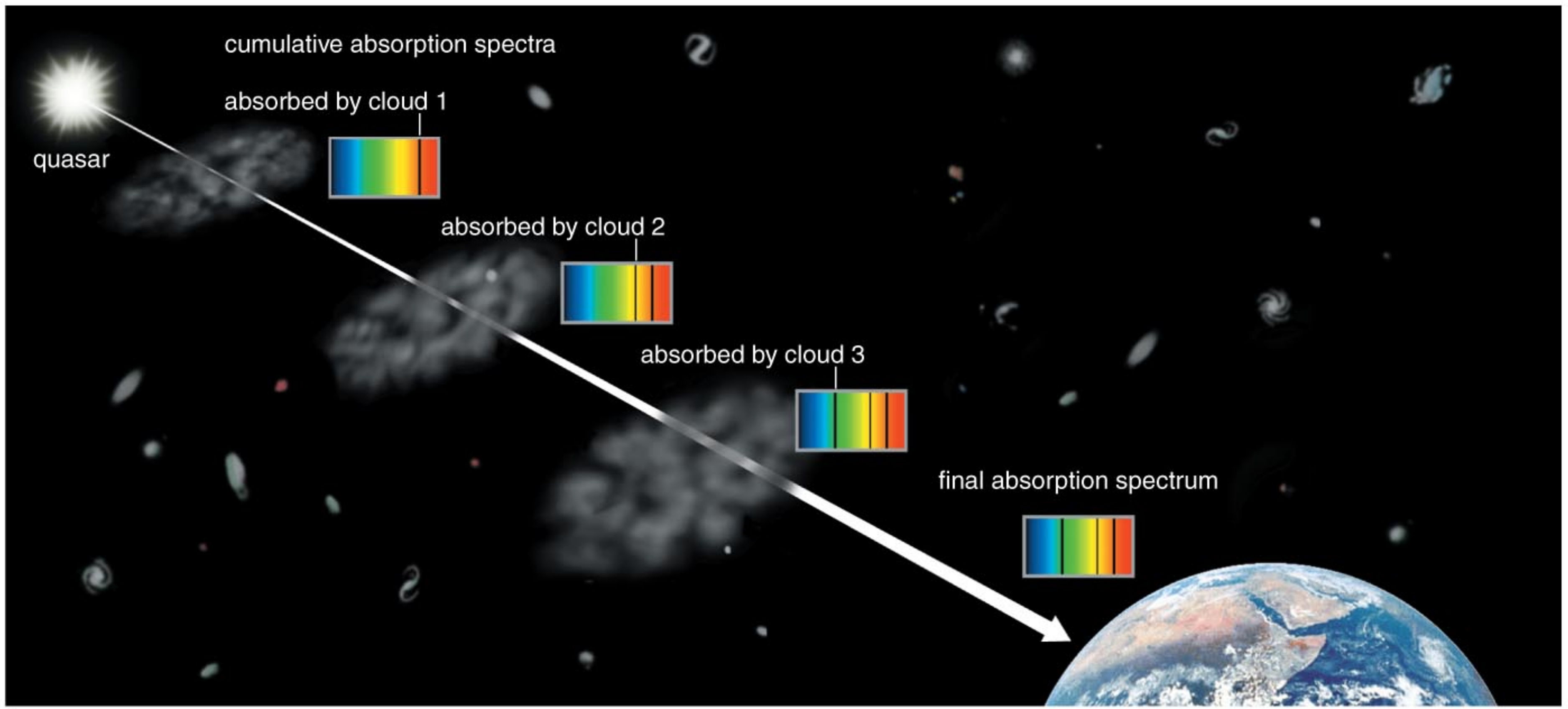
Big Bang Nucleosynthesis

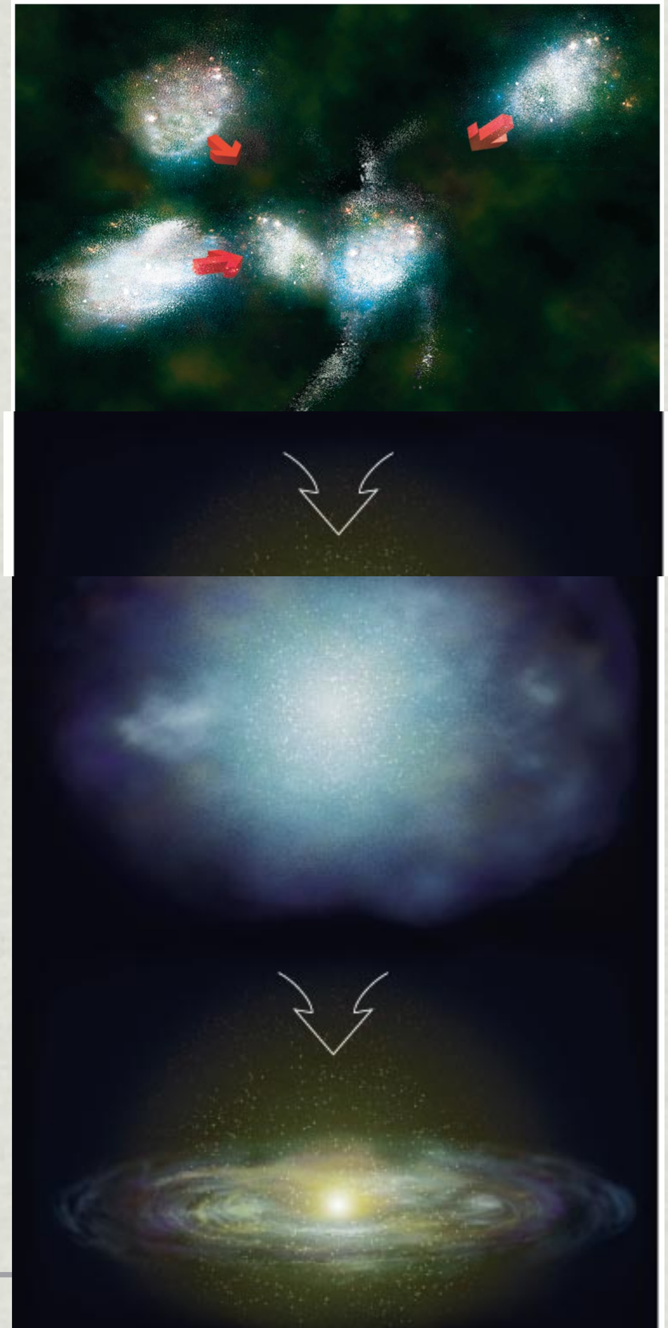
How do we measure the helium and deuterium content of the universe to compare to predictions?

Gas clouds in the distant universe.

These are young overdensities, like the first blobs of gas that we think made the Milky Way.

Not much time for star formation (ideally, no star formation at all) to make helium in stars.





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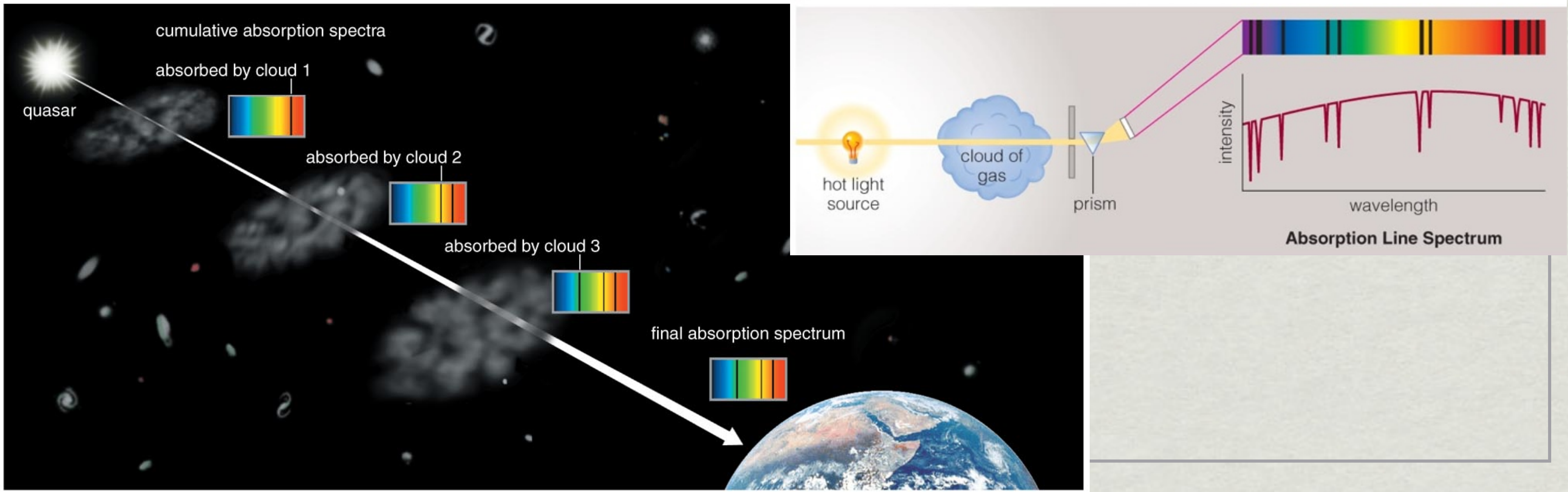
Quasar: hot source behind cool gas. Get an absorption spectrum, look for the fingerprints of deuterium and helium.



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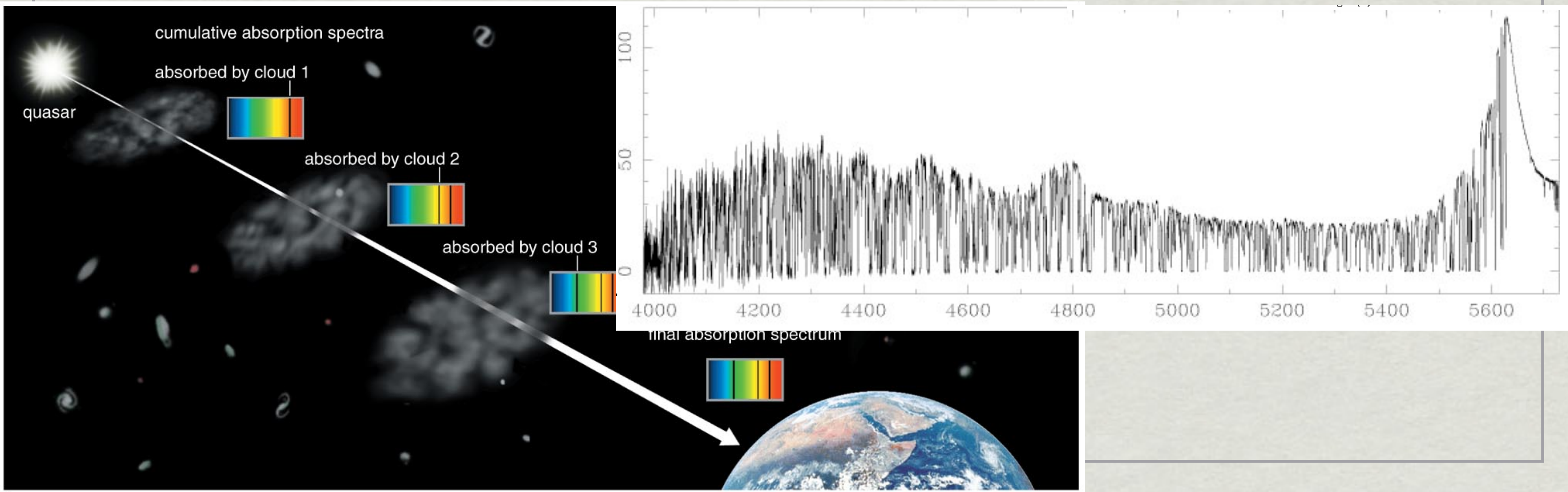
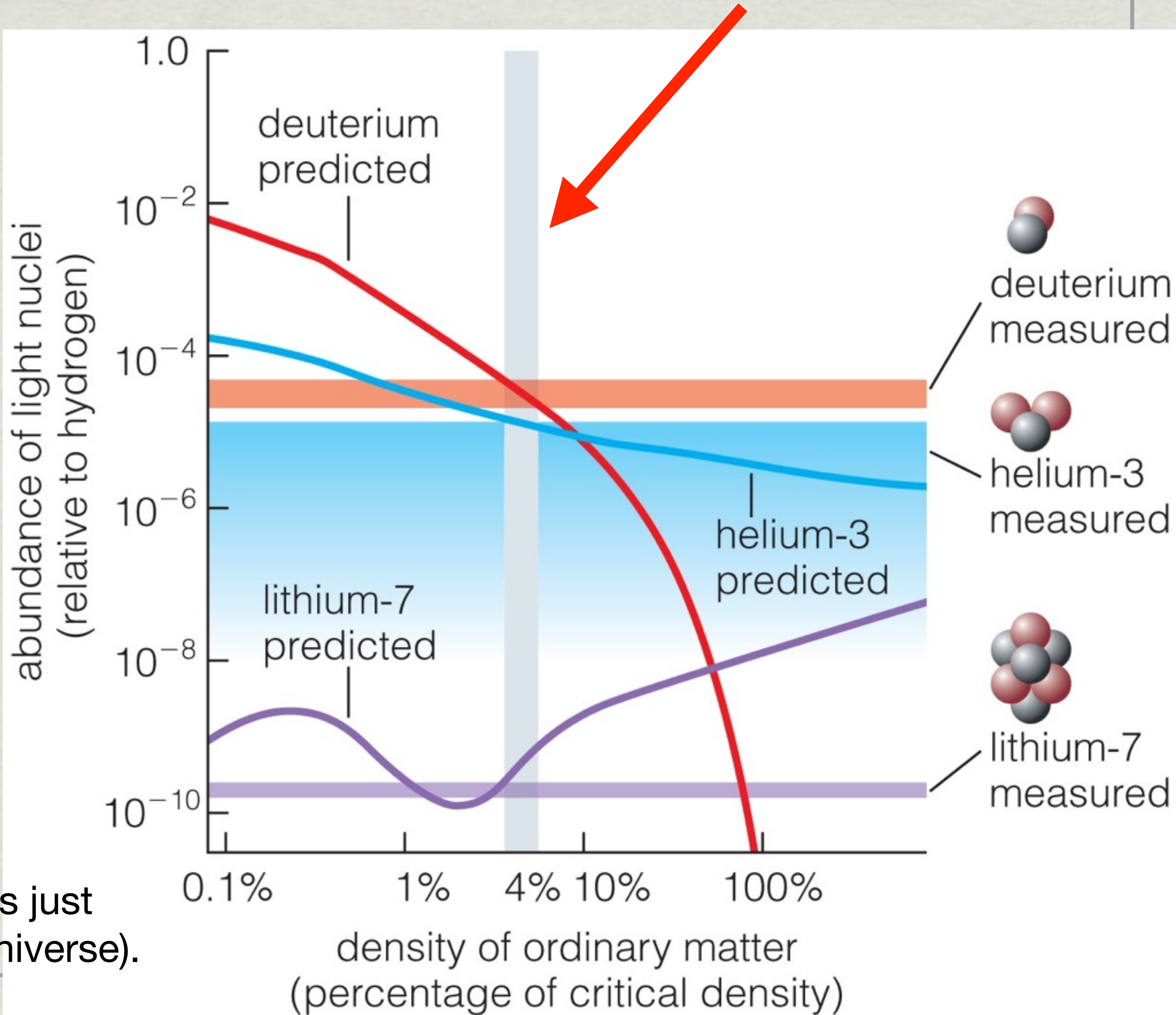


Big Bang Nucleosynthesis

Measurements agree with predictions for a density of baryons about 4% of the critical density.

Y-axis of this plot: Predicted fraction of the total mass-energy budget of the universe that is Helium, Deuterium and Lithium made in early-universe nucleosynthesis.

X-axis: element fractions (D are calculated for different fractions of the "critical density" required for gravity to just stop expansion of the universe.



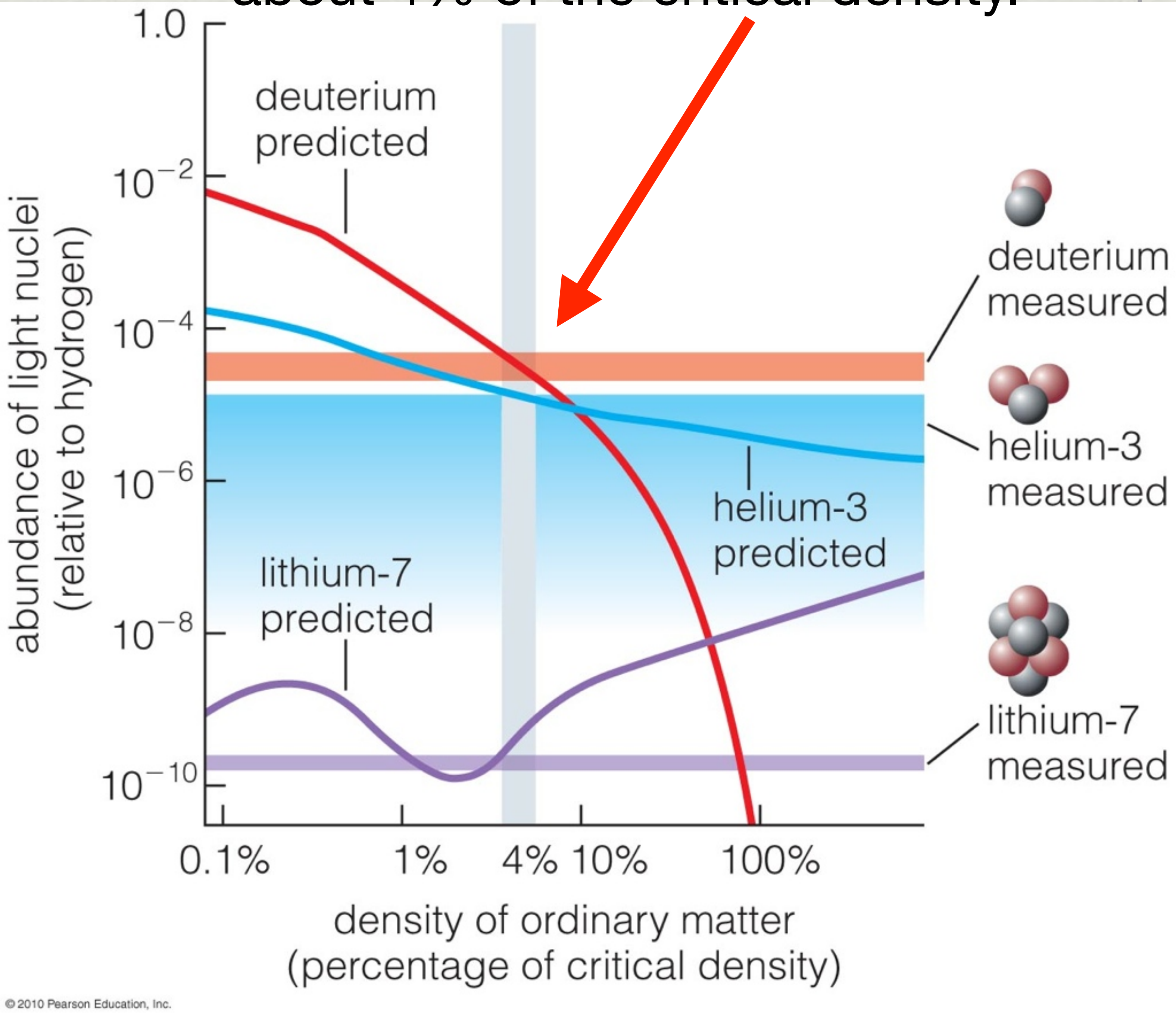
(We'll get to "critical density" later. For now it is just way to scale to the total mass-energy in the universe).

Big Bang Nucleosynthesis

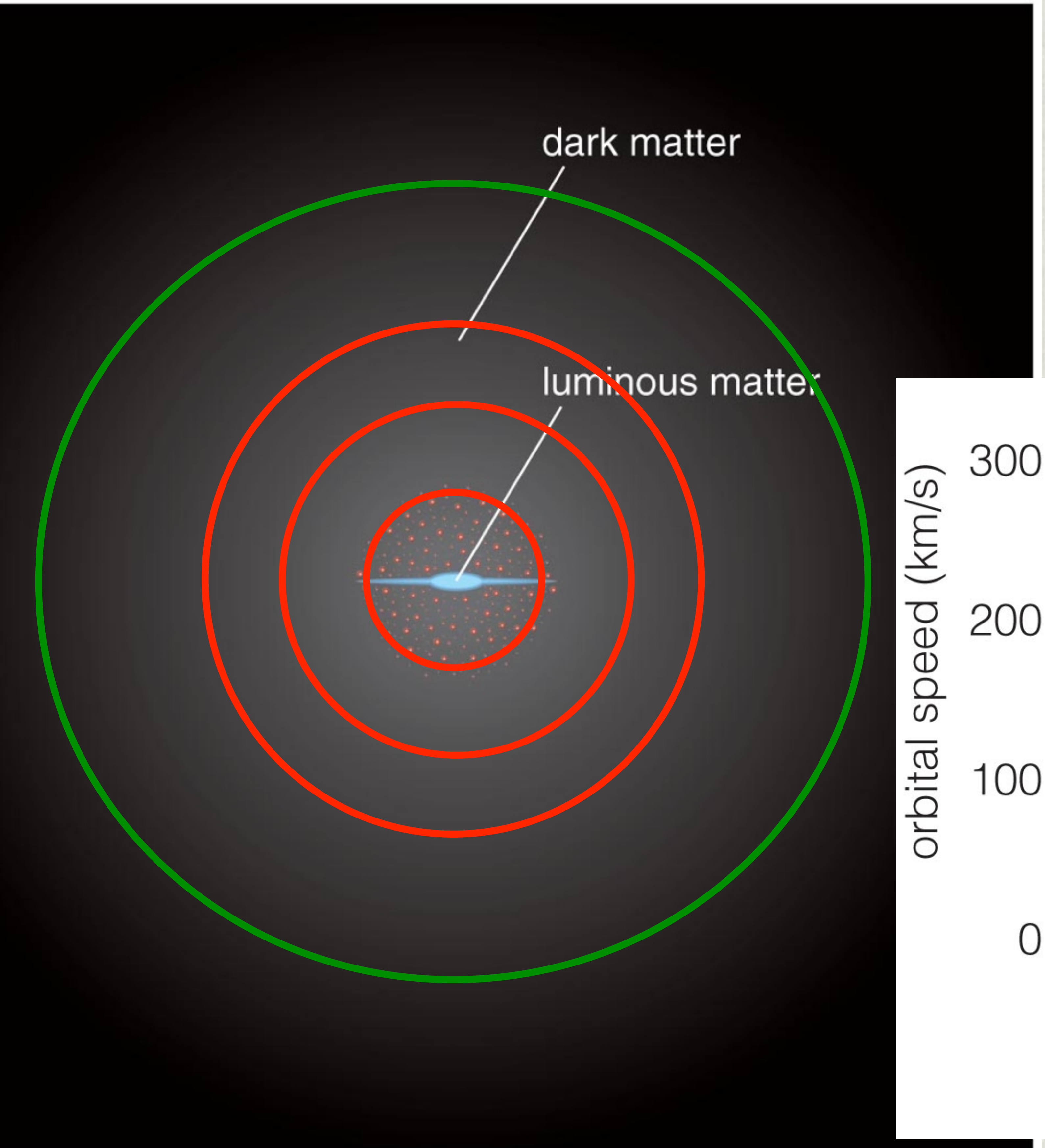
Early universe nucleosynthesis tells us **baryon** density.

Baryons: normal atoms. You, me, rocks, planets, stars, hamburgers, broccoli, …

Measurements agree with predictions of density of baryons is about 4% of the critical density.

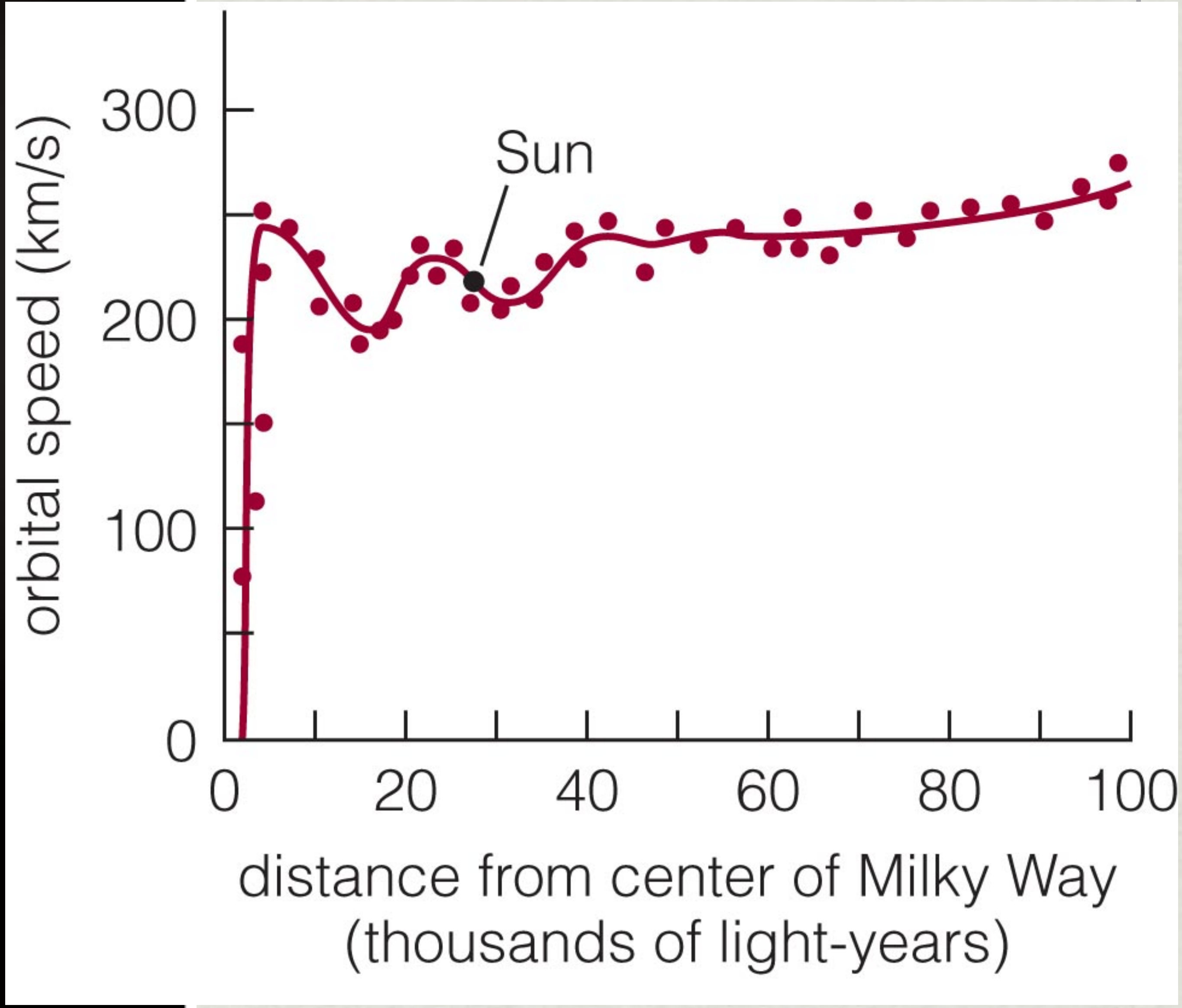


Milky Way: Mass



$$M = \frac{v^2 r}{G}$$

We can’t see it, but the velocity measurements tell us there is mass at larger distances than all the mass we can see

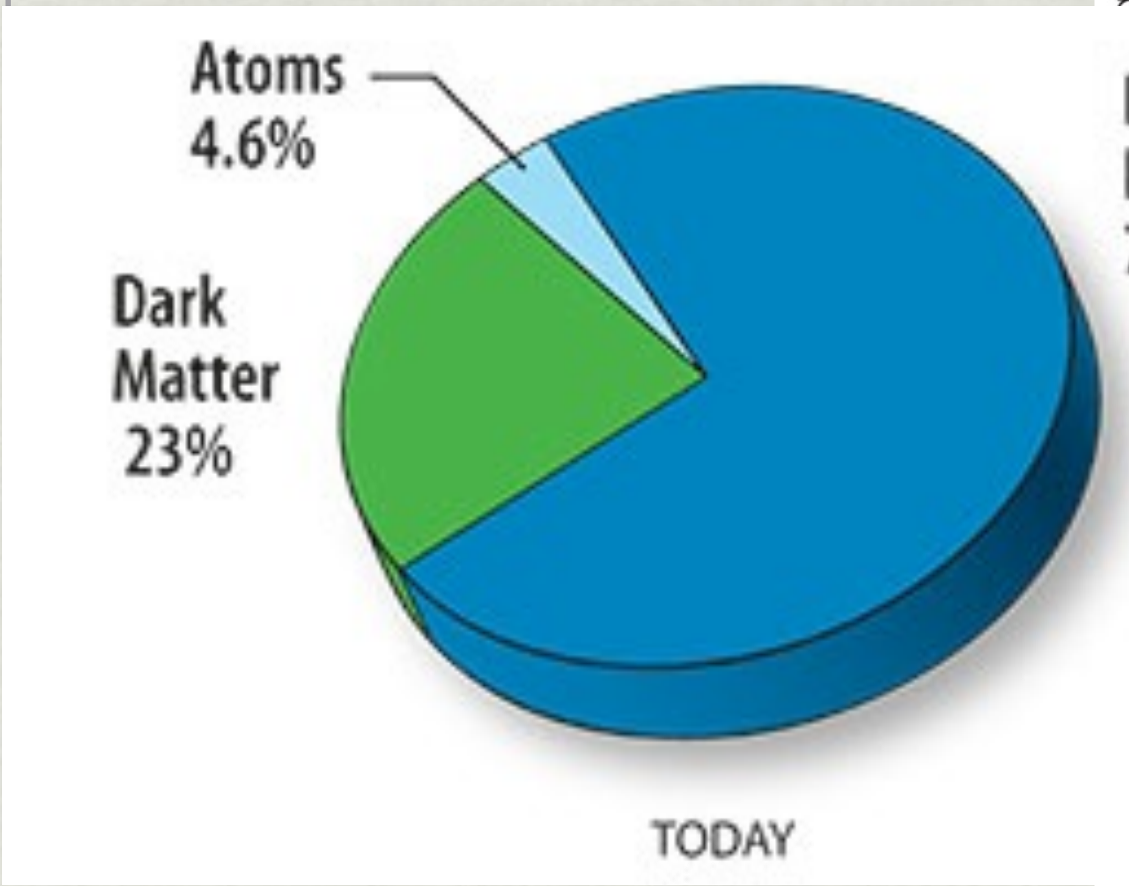


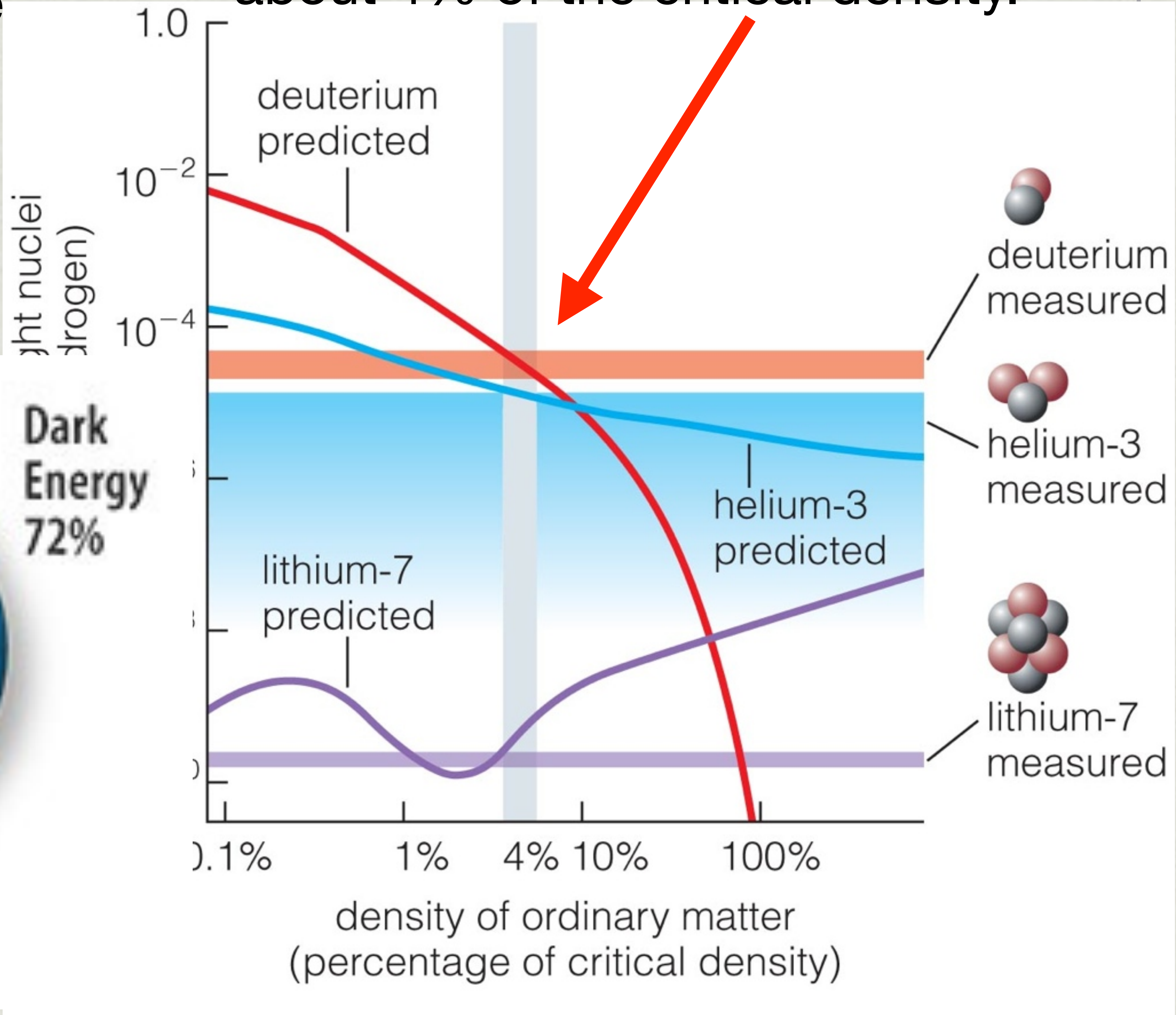
Big Bang Nucleosynthesis

Early universe nucleosynthesis tells us **baryon** density.

This is how we know that all the gravitating matter in the universe is not atoms. We measure more gravitating matter than we measure atoms.

Measurements agree with predictions of density of baryons is about 4% of the critical density.



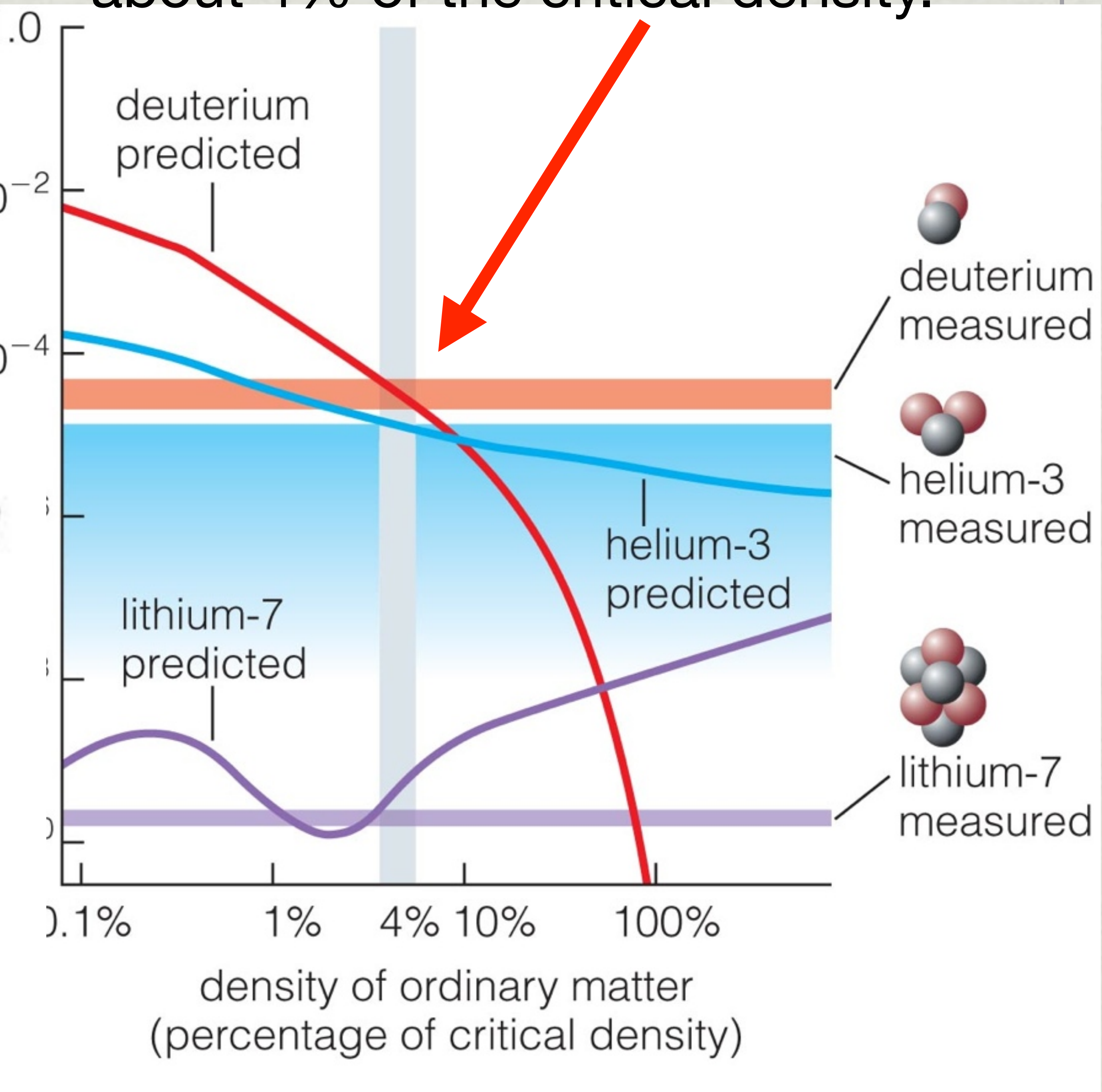


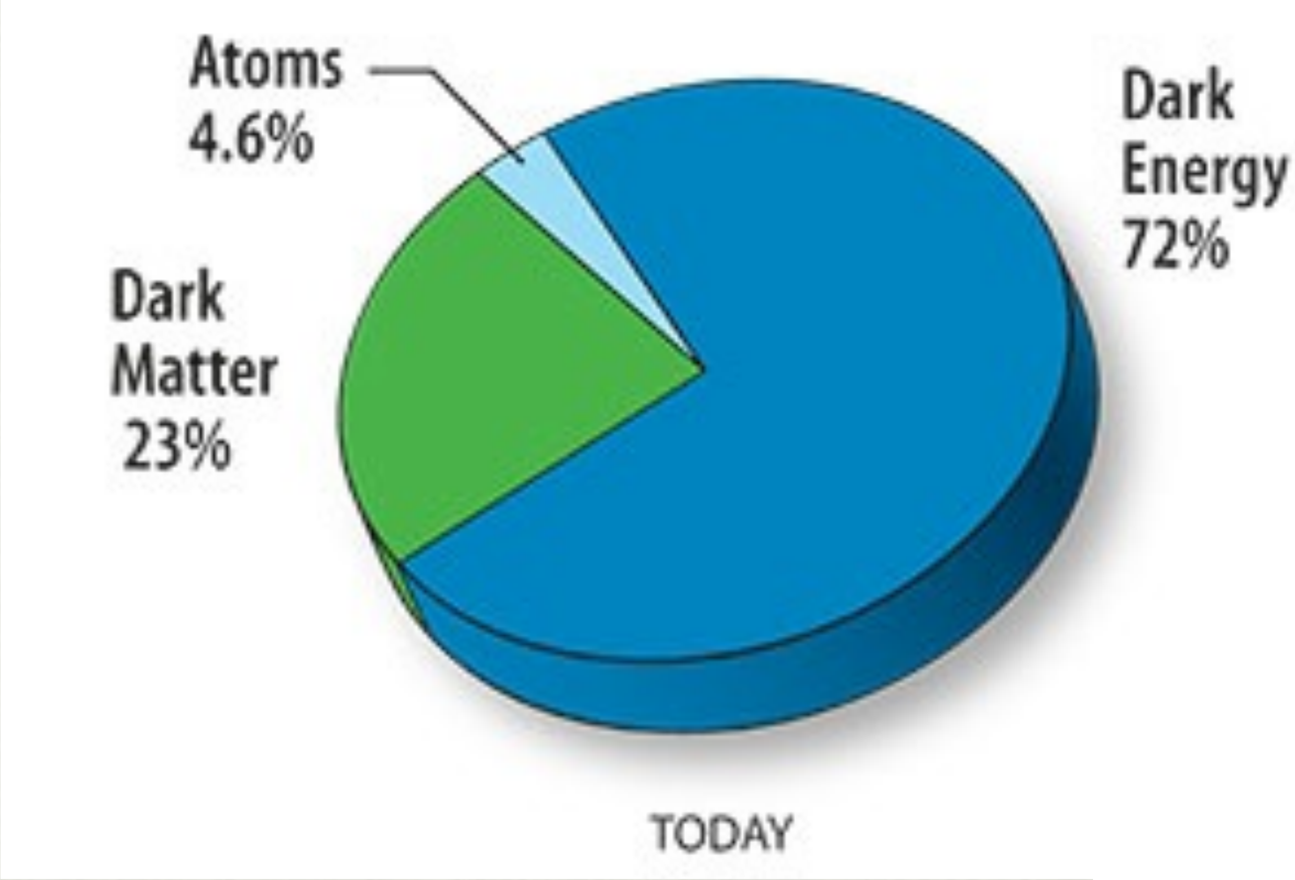
Big Bang Nucleosynthesis

Early universe nucleosynthesis tells us **baryon** density.

It also means that big bang nucleosynthesis doesn't tell us whether the universe is more or less dense than the "critical" value

Measurements agree with predictions of density of baryons is about 4% of the critical density.





Evidence for the Big Bang

Universe was hotter, denser, smaller at early time (small t, small D)

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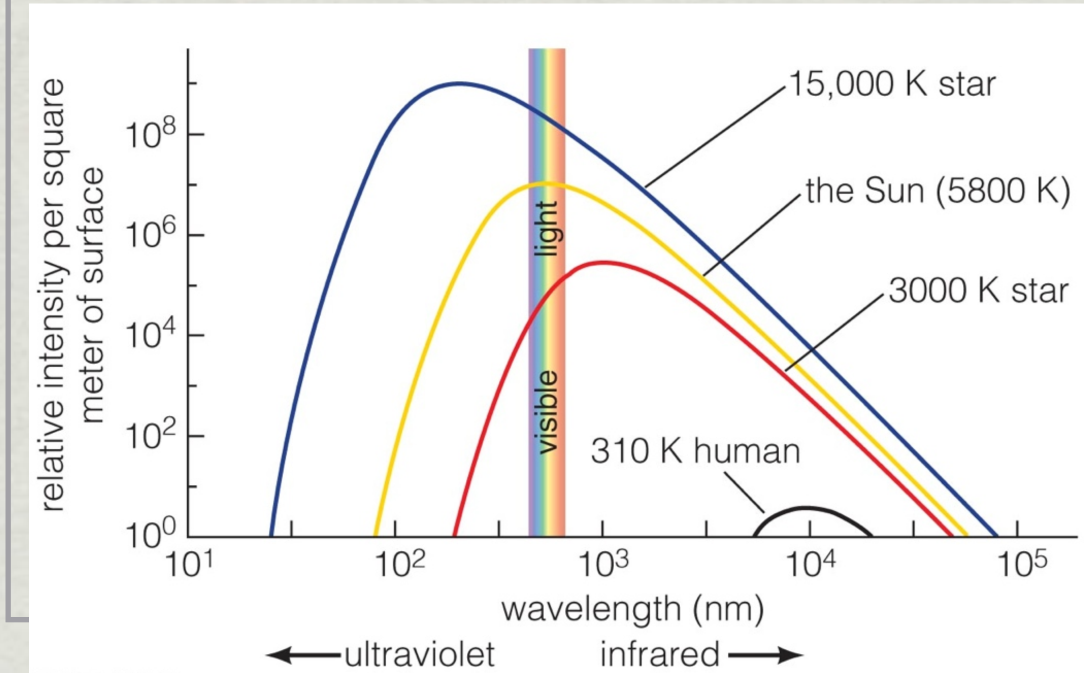
Cosmic Microwave Background

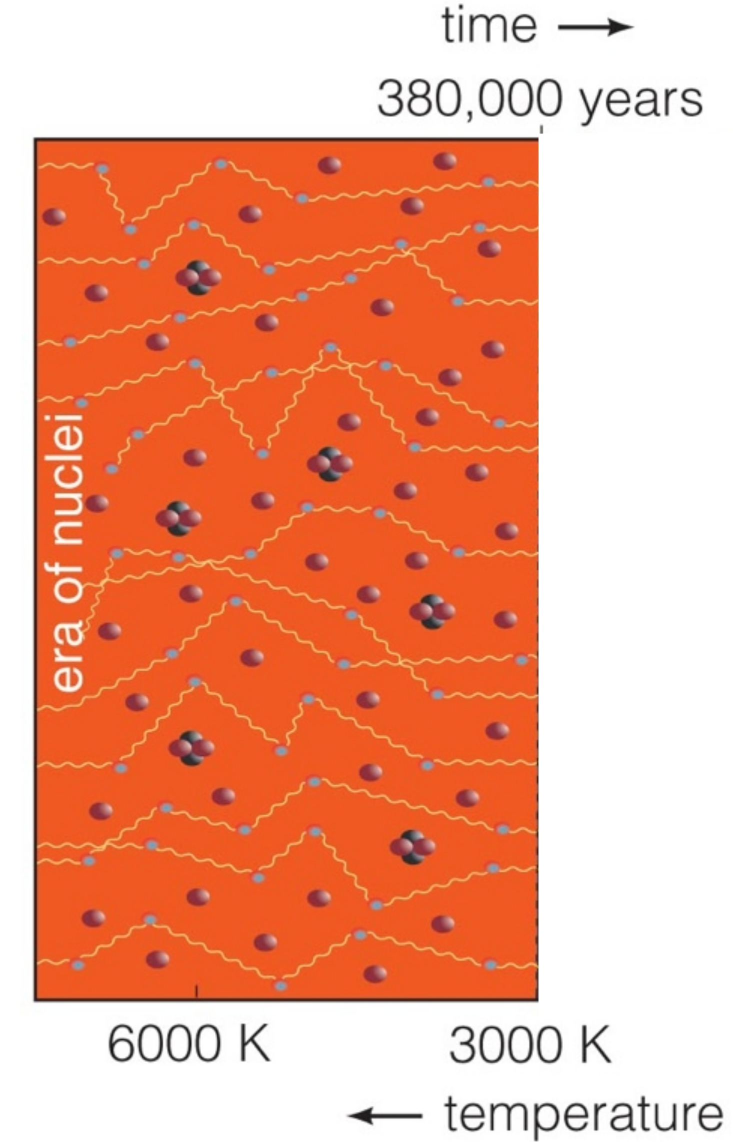
Prediction of the Big Bang:

2) Thermal radiation: dense, opaque matter. Light interacts with lots of atoms before it can escape.

Early universe is hot and dense. Atoms separated into protons and electrons. It is ionized — too hot (too much kinetic energy) for electromagnetic force to keep them together.

Photons interact with electrons even more readily than with atoms, so dense gas with free electrons is very opaque





Cosmic Microwave Background

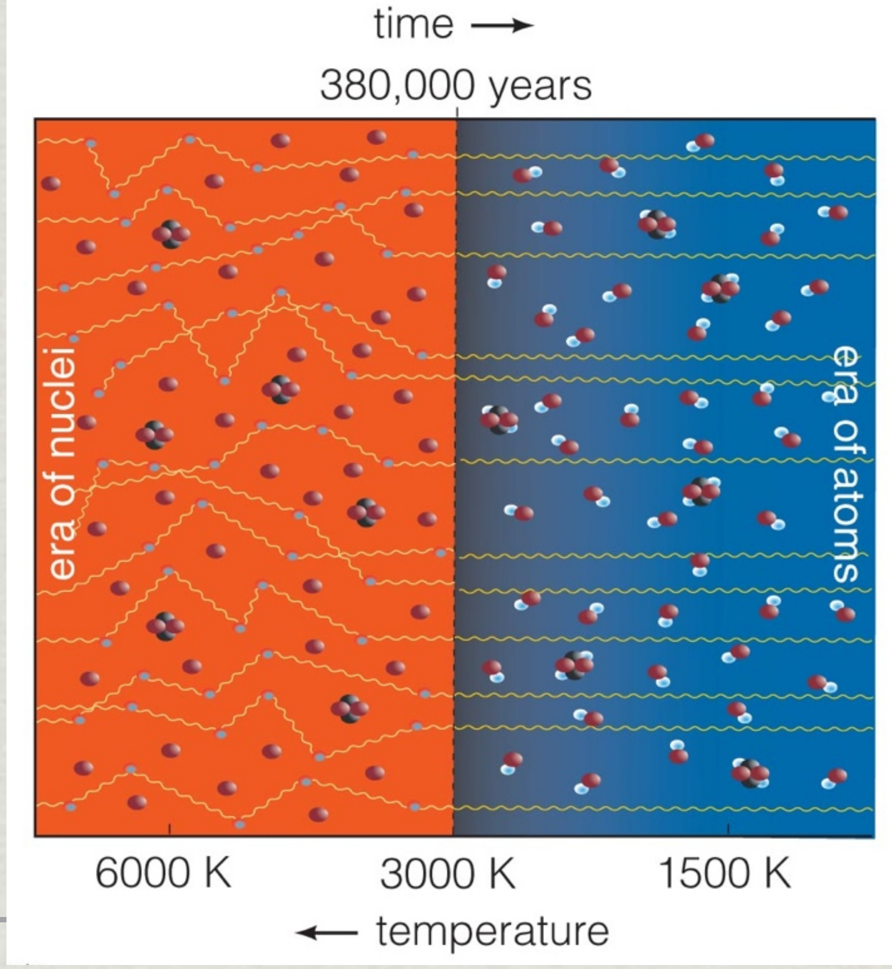
Prediction of the Big Bang:

2) Thermal radiation: dense, opaque matter. Light interacts with lots of atoms, protons and electrons before it can escape.

What do we mean by “Escape” ?

As the universe expands the density goes down and it cools. Atoms recombine, protons and electrons stick together. Photons stop interacting (very much) with atoms.

Universe becomes transparent, photons can move through space uninterrupted.



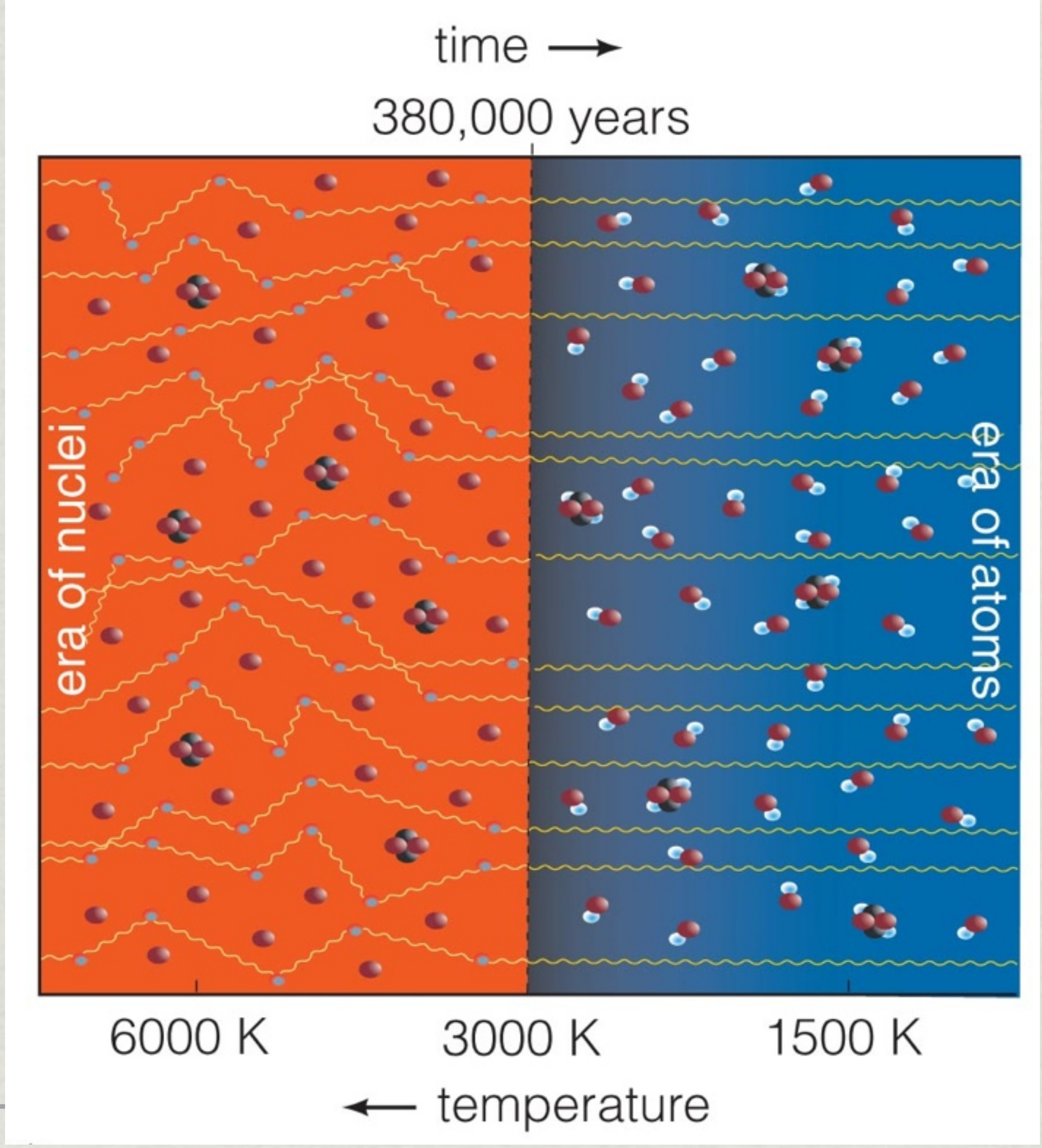
Cosmic Microwave Background

Prediction of the Big Bang:

2) Thermal radiation: dense, opaque matter. Light interacts with lots of atoms, protons and electrons before it can escape.

- Like the sun, we see the "surface" where that density drops so photons can escape. Where do they escape to? Into the expanding universe, where we eventually see them.

- Rate of photon interaction with atoms depends on pressure and density. Higher density, more trapped photons, brighter. The thermal radiation gives us a record of the density and temperature in the universe at the time the photons escape.



Cosmic Microwave Background

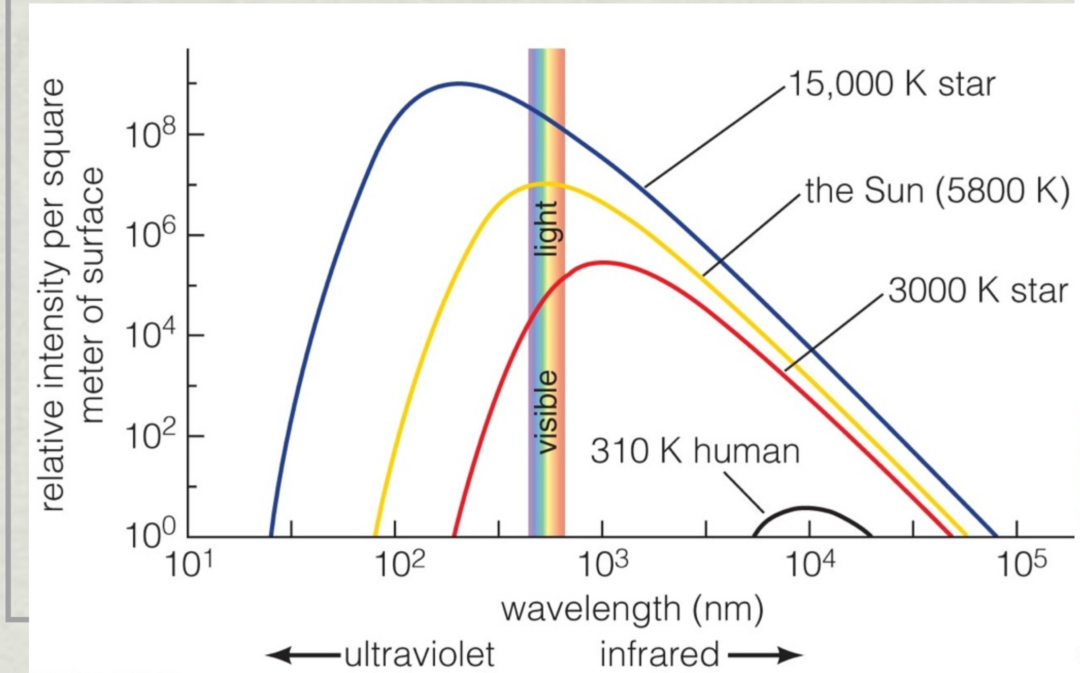
What happens to this thermal spectrum as the universe expands?

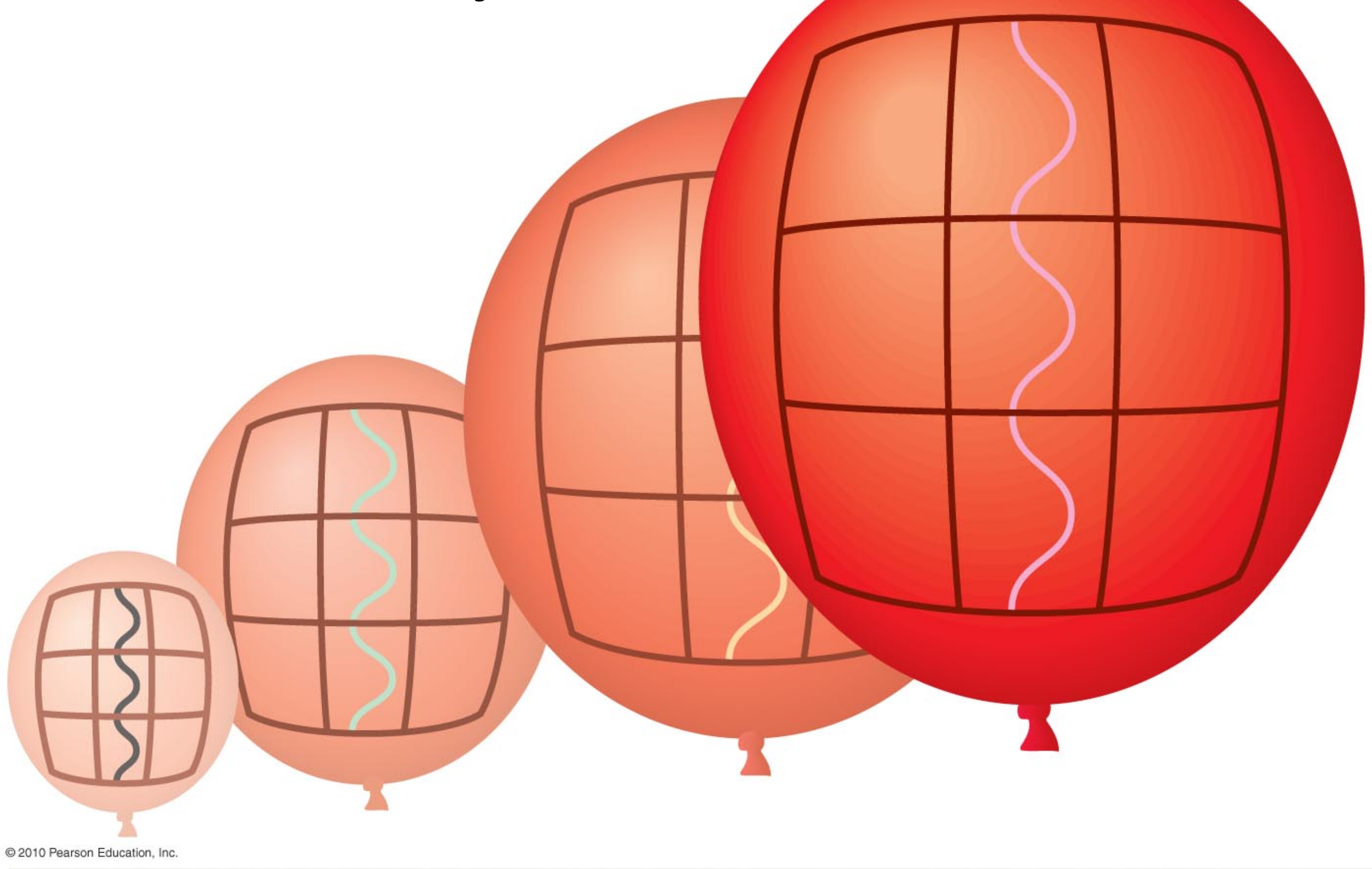
A) the peak wavelength gets redder

B) the peak wavelength gets bluer

C) the total luminosity gets larger

D) did you get that? Warm and sunny!

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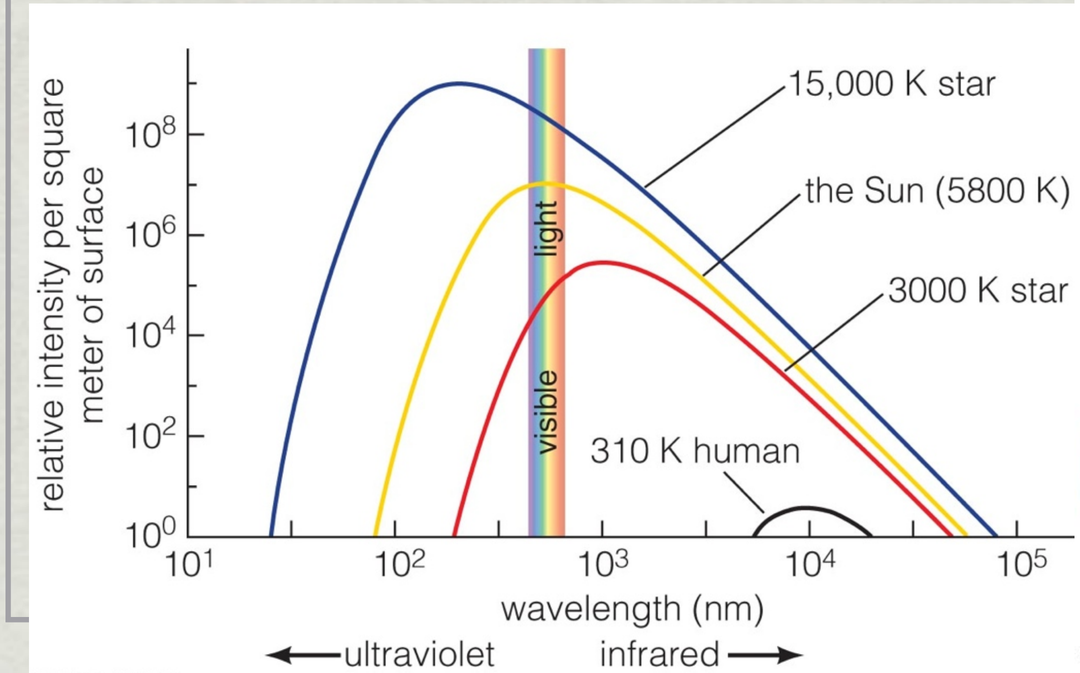
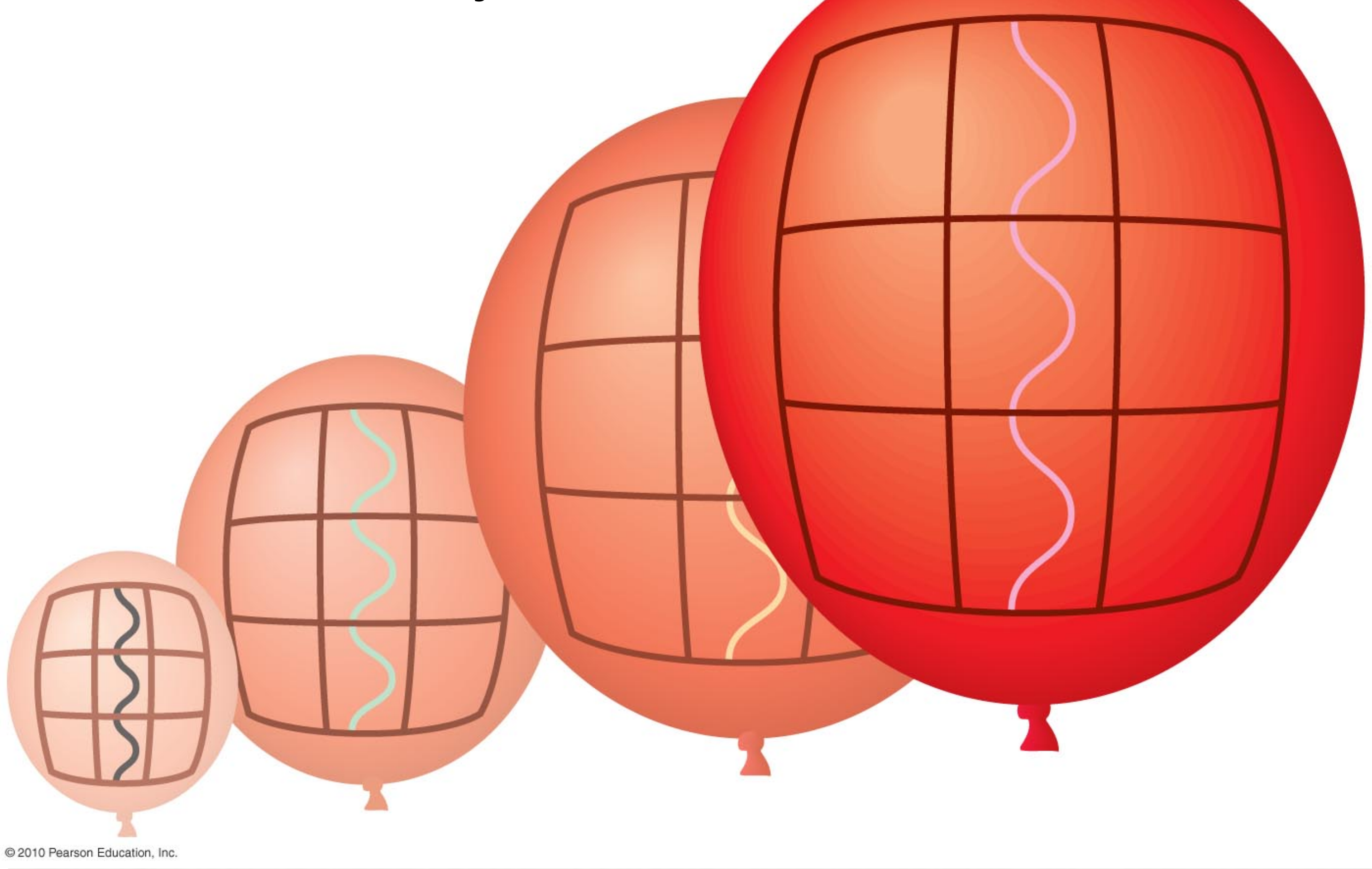




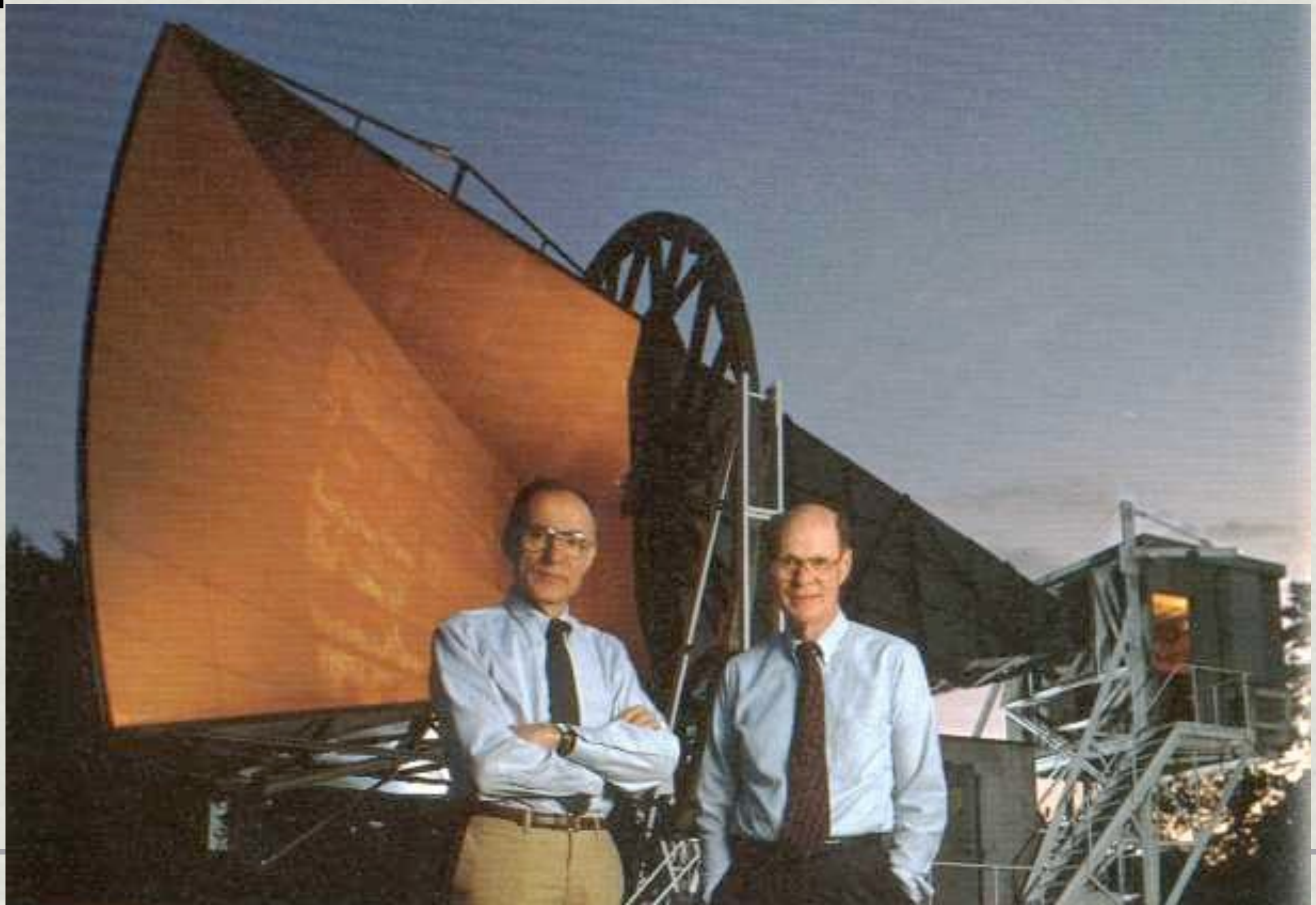
Cosmic Microwave Background

Observation: Penzias and Wilson, 1964, AT&T Bell Laboratories in New Jersey

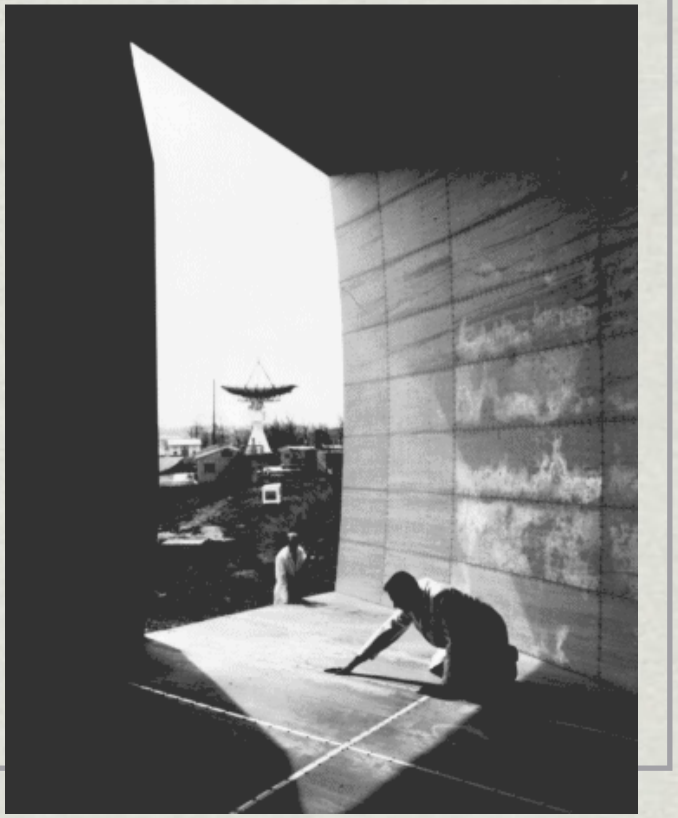
Trying to receive very faint signals from the first communication satellites

Found an annoying radiation background with a thermal spectrum at a temperature of 3° K

With a little help from Peebles and Dickie at Princeton, who had calculated what T should be at the time the photons escape, it was identified as that thermal radiation spectrum from the Big Bang at exactly the expected temperature.



Bird poop?

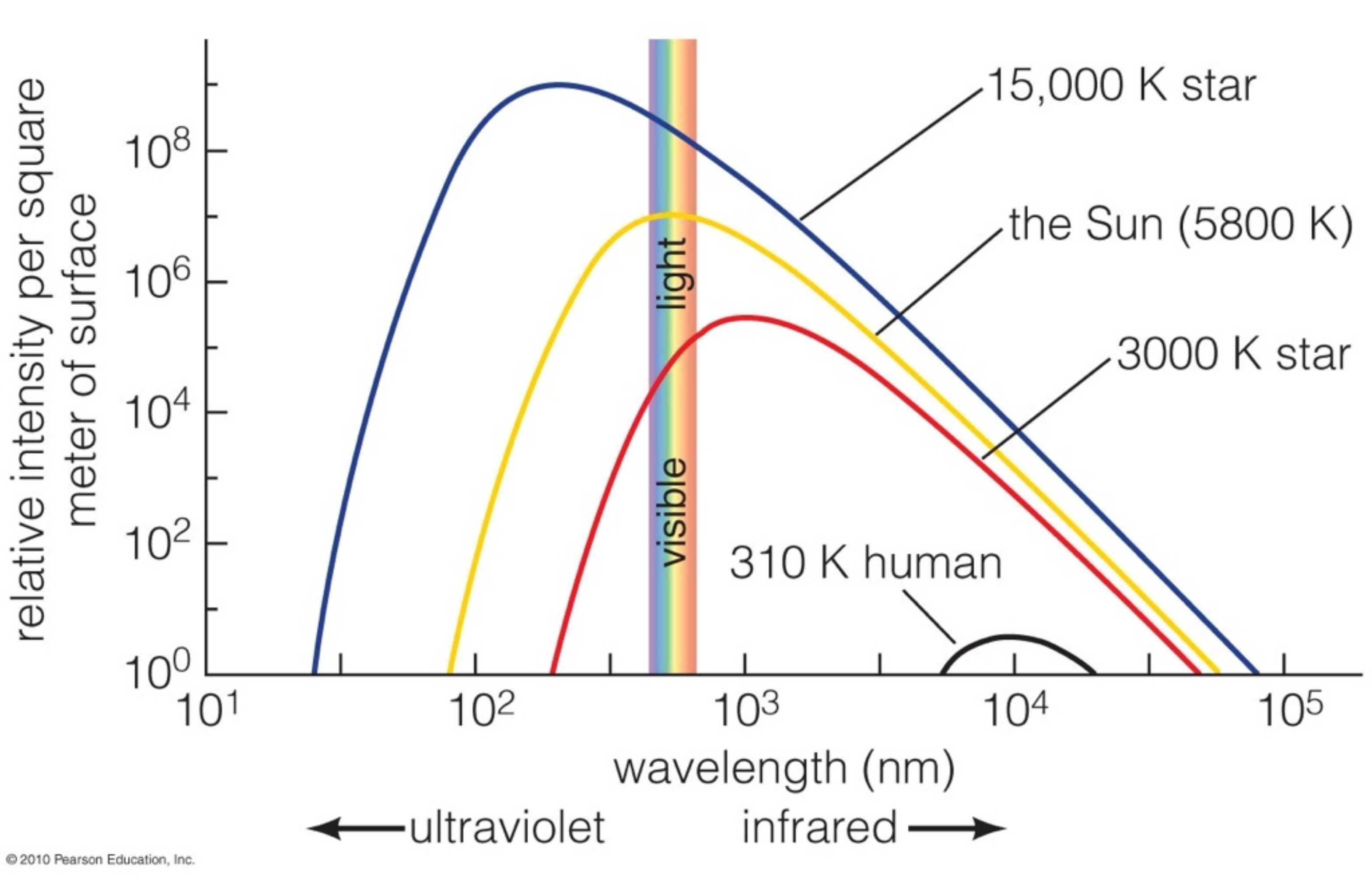


Cosmic Microwave Background

Penzias and Wilson found that the spectrum matched a Stefan-Boltzmann law perfectly, as well as they could measure, with peak wavelength of about 1 mm (Wein’s Law) or 3° K

This is true in every direction.

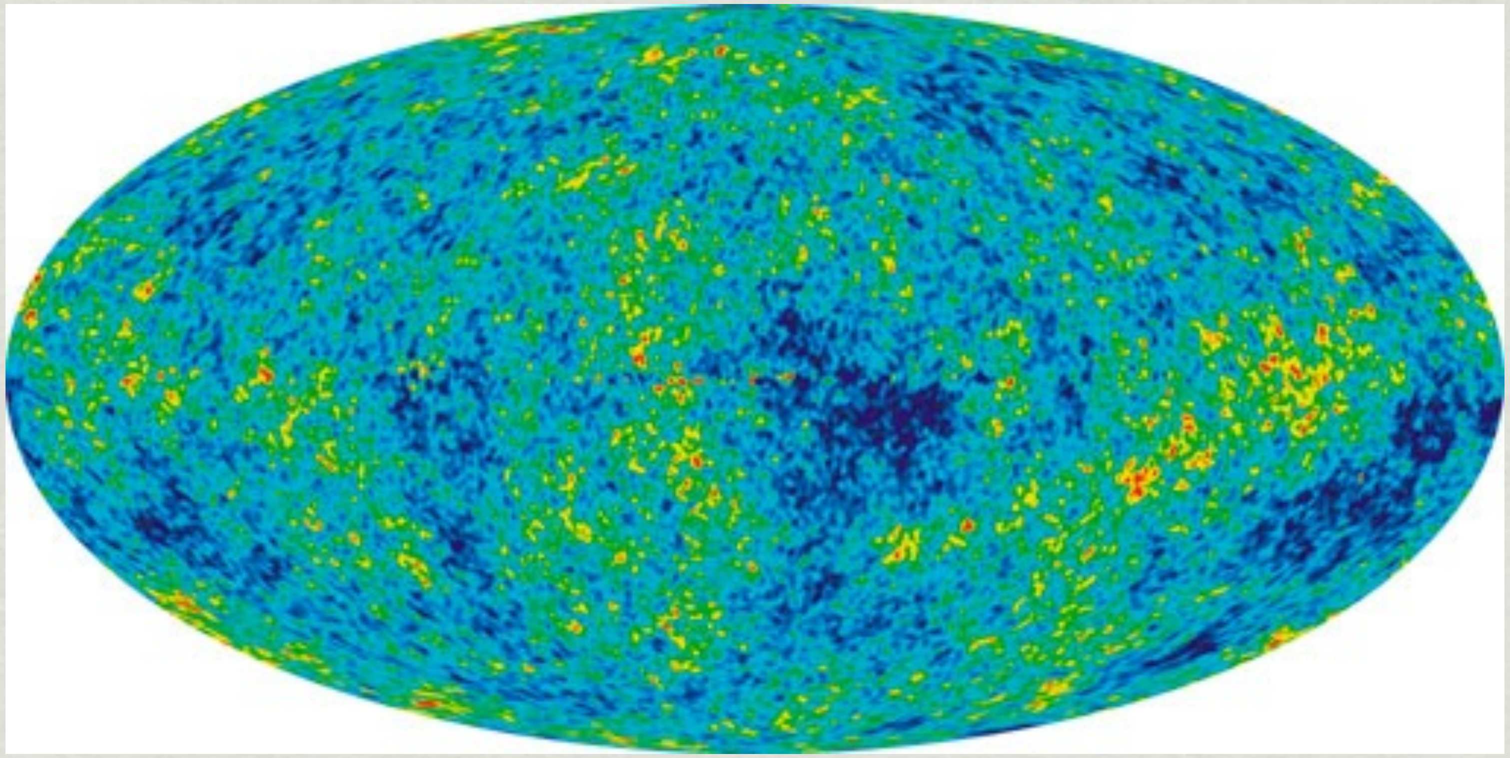
“Cosmic Microwave Background” (CMB)



Penzias and Wilson’s discovery:
Nobel prize in physics, 1978

Cosmic Microwave Background

as seen by WMAP



Variations are temperature are ***tiny*** changes of ± 200 microKelvin

$\pm 200 \times 10^{-6}$ Kelvin!

Density and temperature are related (remember the ideal gas law!)

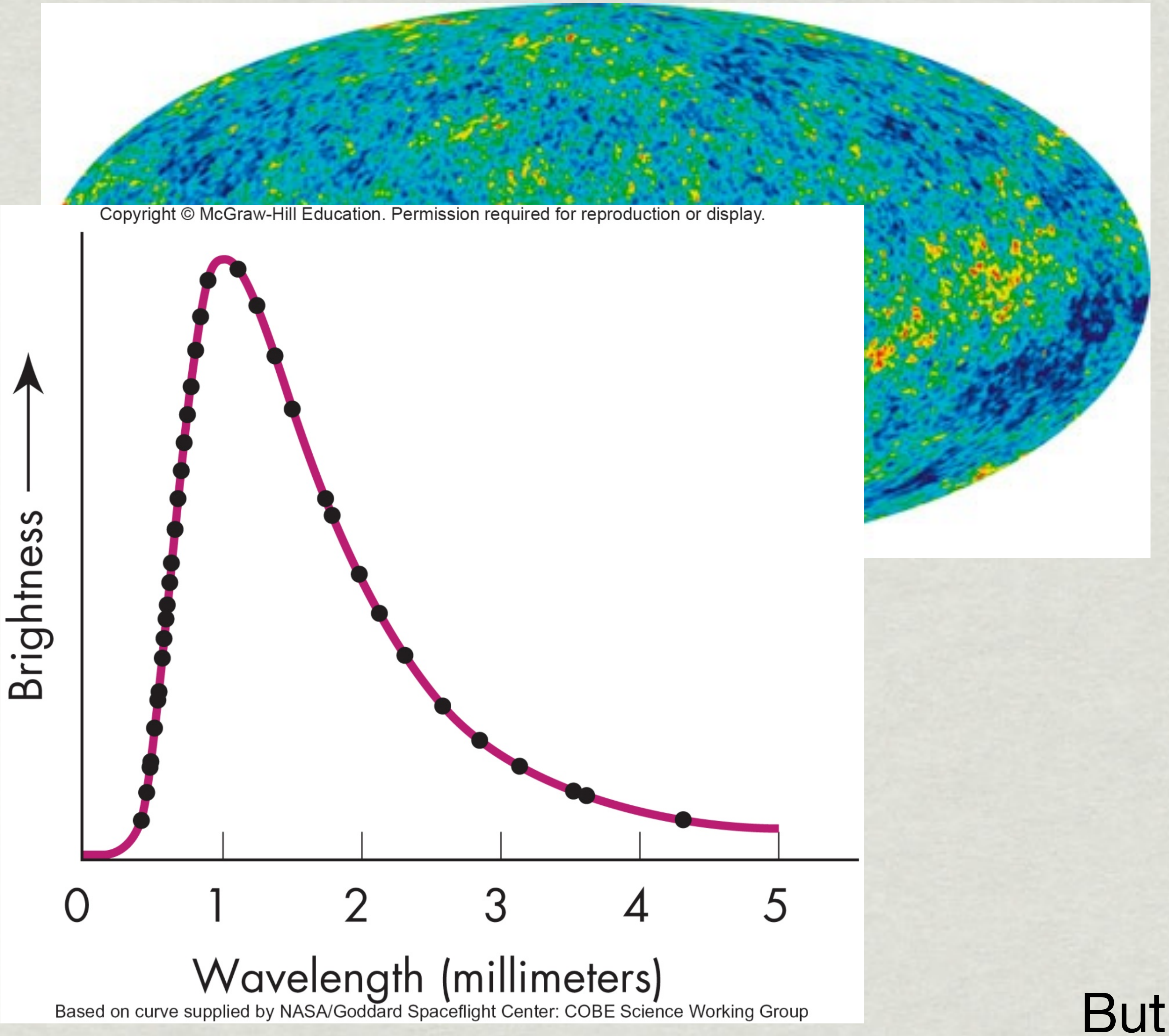
These patches are small density variations, too.

Red: hot, more dense spot
Blue: cool, less dense spot

But mostly the background looks like a thermal spectrum at 3 K

Cosmic Microwave Background

as seen by WMAP



Based on curve supplied by NASA/Goddard Spaceflight Center: COBE Science Working Group

note really long peak wavelength — cold!

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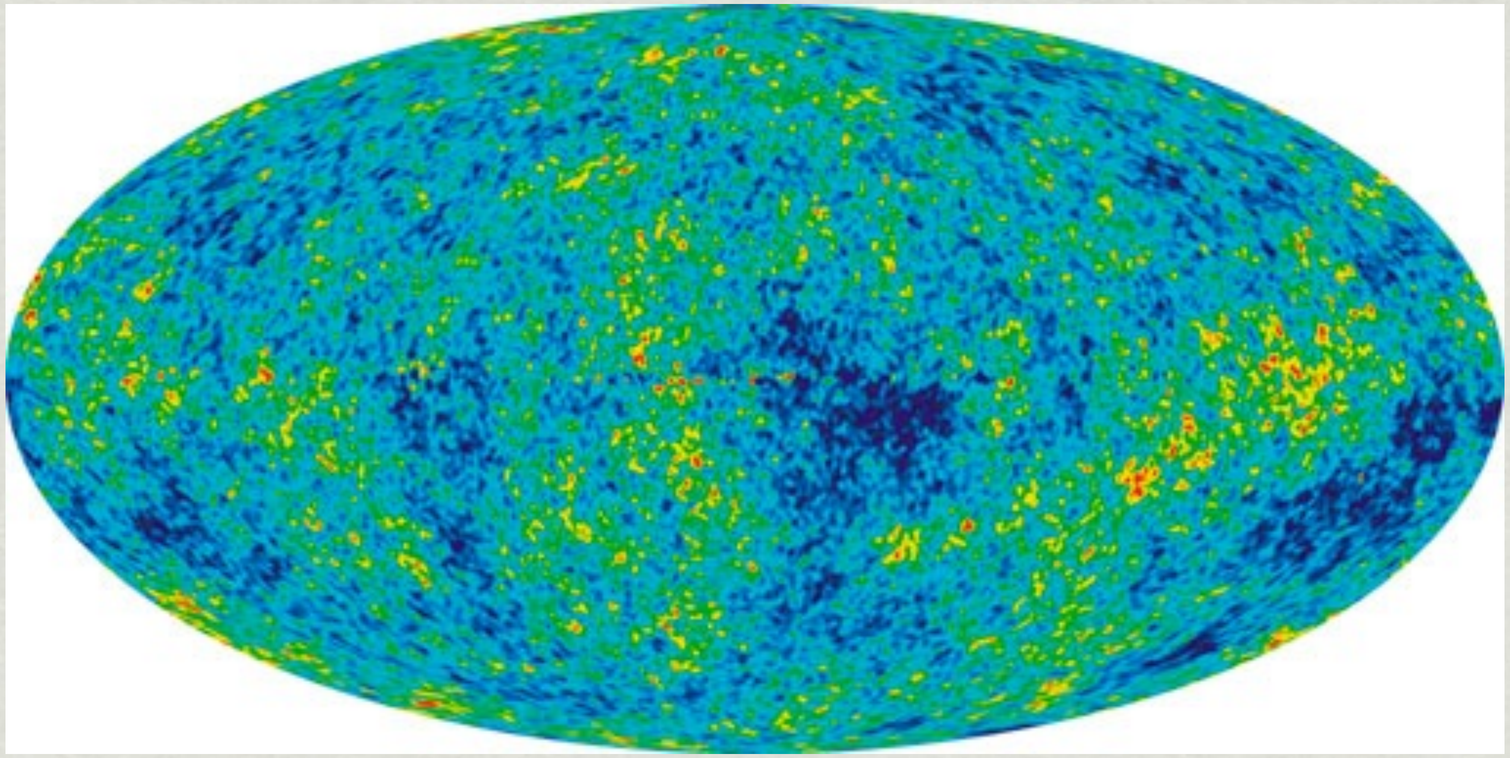

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Density and temperature are related (remember the ideal gas law!)

These patches are small density variations, too.

Red: hot, more dense spot
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Another prediction: temperature should not follow a Stefan-Boltzmann law perfectly.

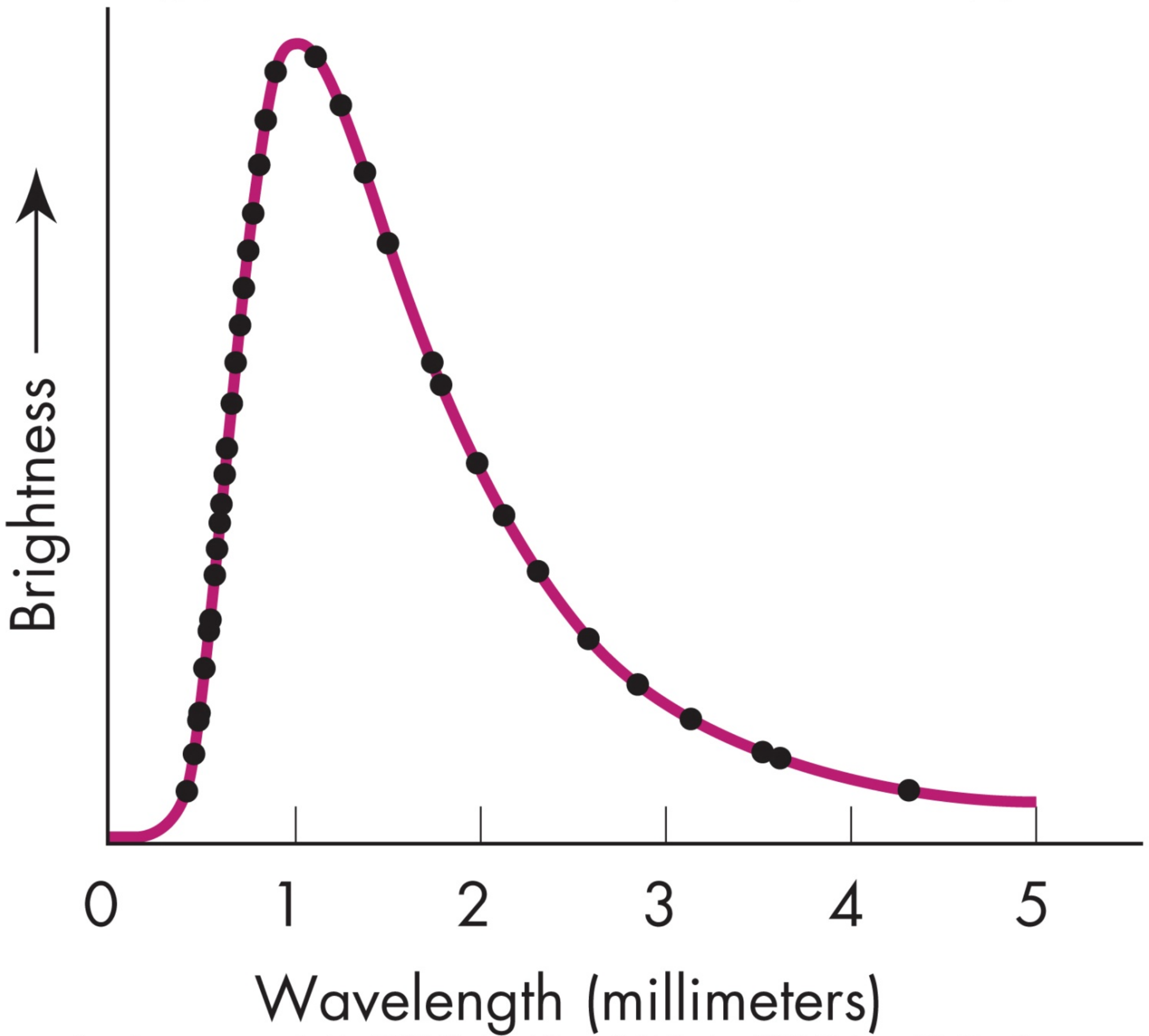
Expect small variations in density and temperature.

Dense patches are what grow by gravity into galaxies!

But mostly the background looks like a thermal spectrum at 3 K

Cosmic Microwave Background

Two spectacular satellite experiments from NASA and one from ESA: COBE (COsmic Background Explorer) and the Wilkinson Microwave Anisotropy Probe (WMAP) both measured the themal spectrum shape and detected small measured deviations from that perfect thermal spectrum. Whew!



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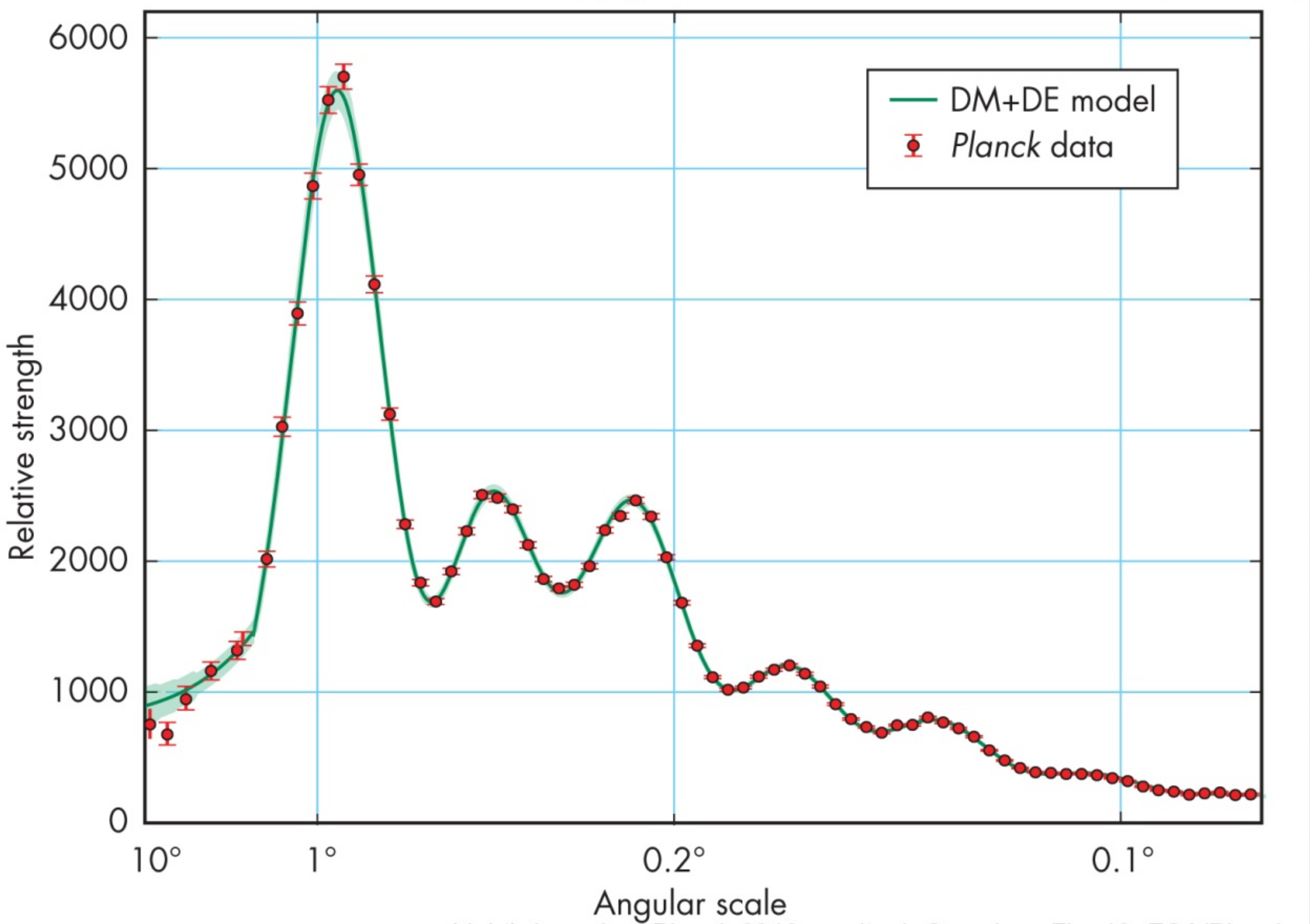
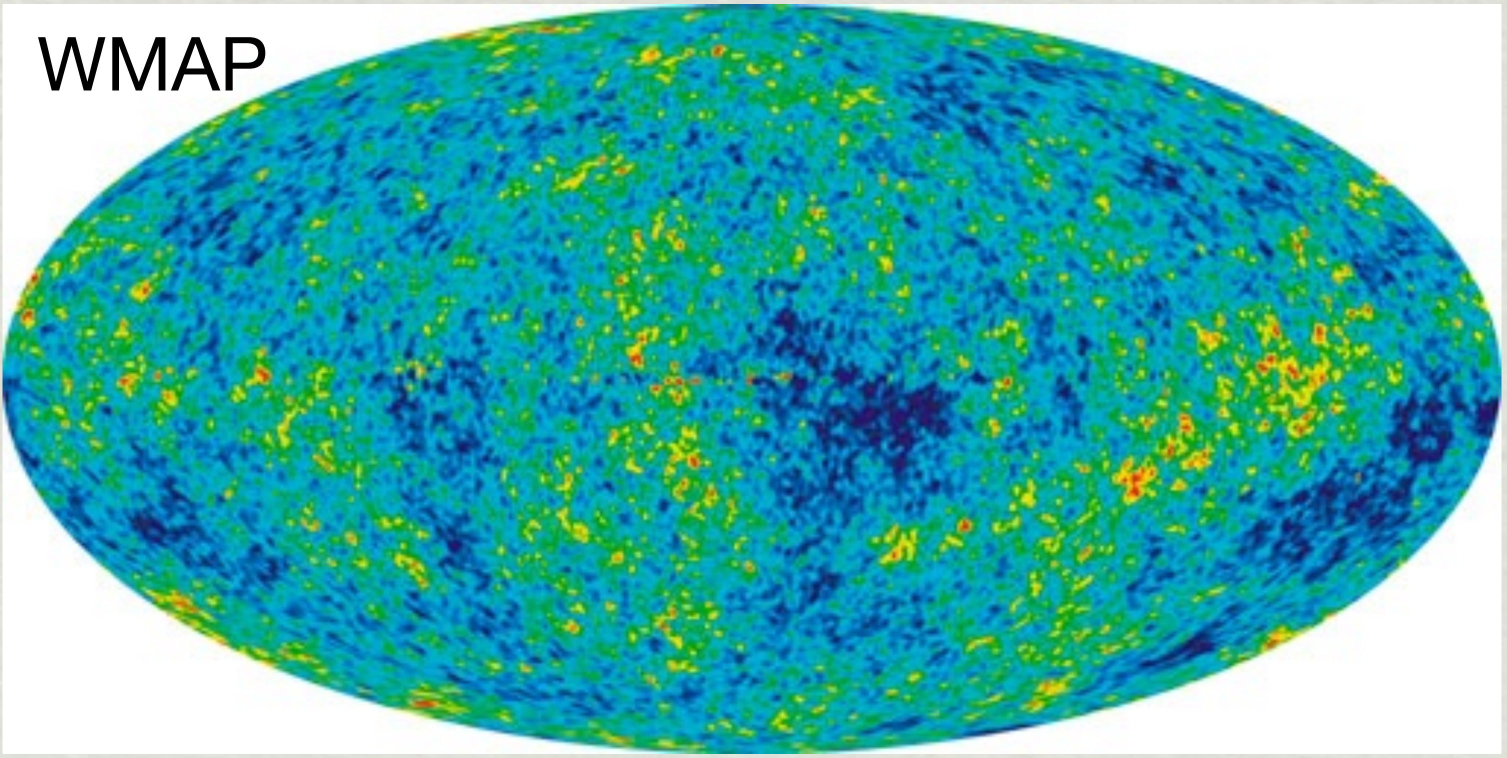


(right): based on Planck 2013 results. I. Overview: Fig. 19, ESA/Planck, a

Evolution of Density



temperature variations:
±200 x 10^{-6} Kelvin

Density variations are similar.

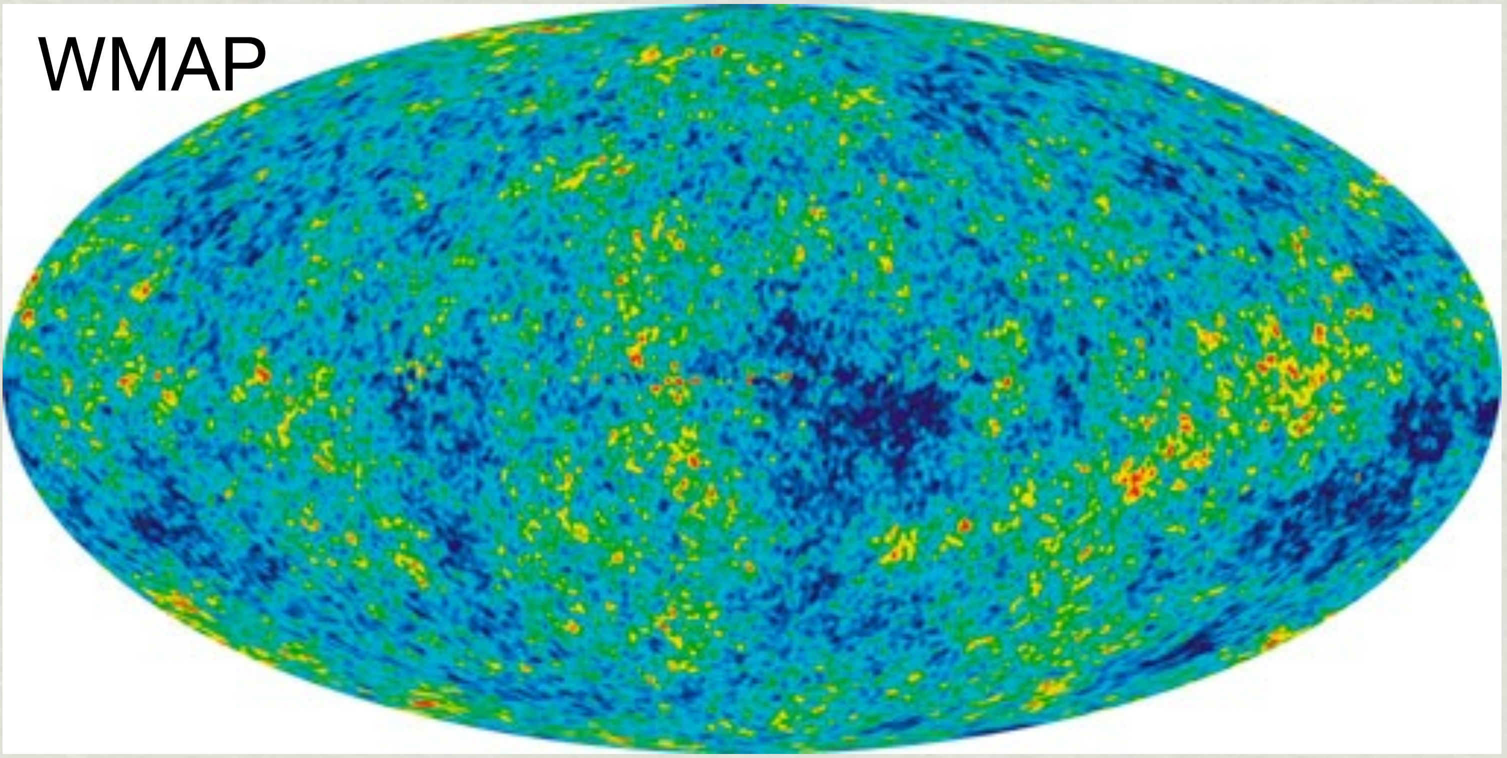
How do we get from (almost) smooth to the lumpy universe we see today?

Gravity!

Hubble Deep Field:
Galaxies in the universe

Much lumpier!
1×10^{6} over-dense compared to average density in universe.

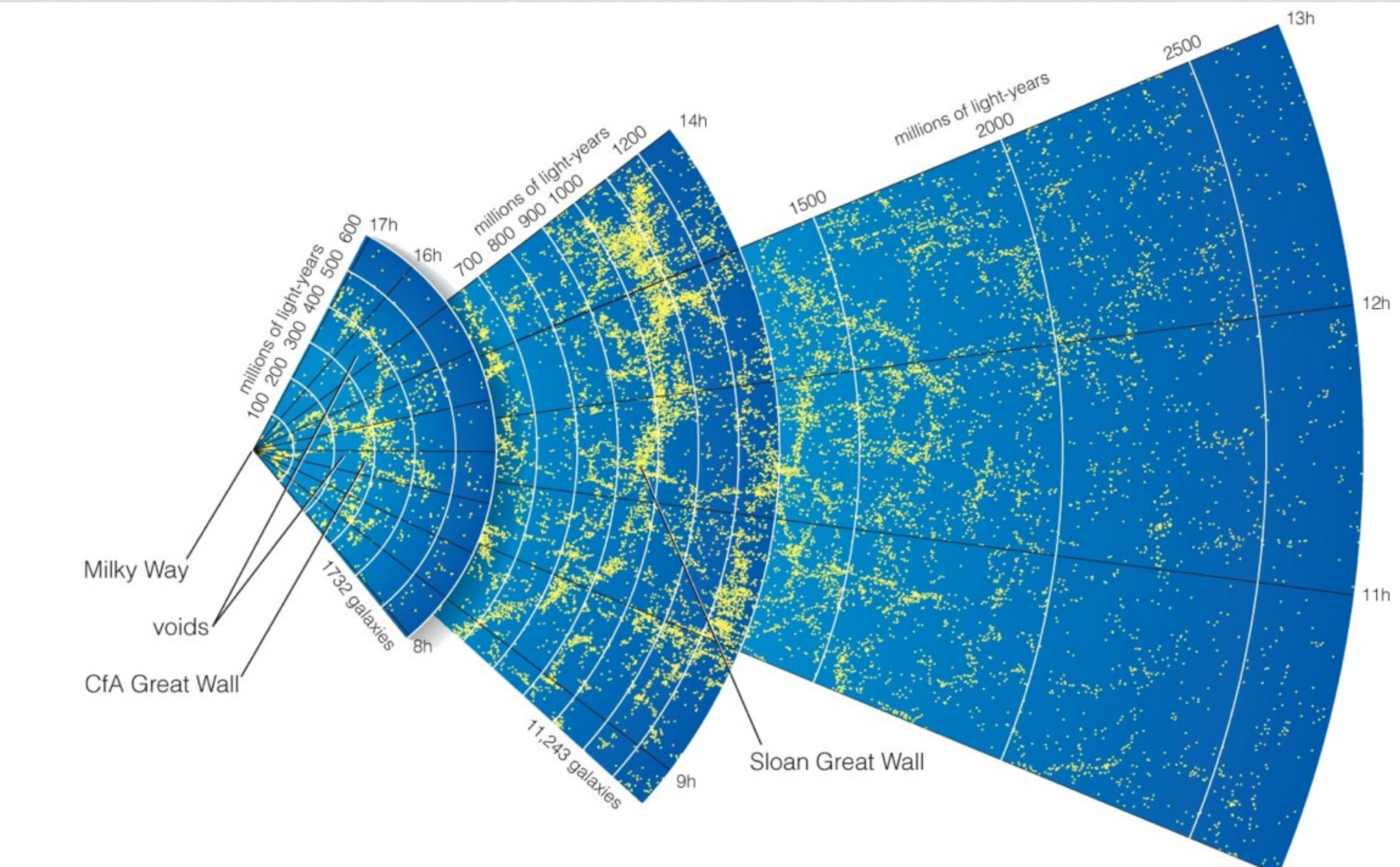
Evolution of Density



How do we get from smooth to lumpy?

Gravity!

The density variations in the Cosmic Microwave Background are the “seeds” of the structure we see today:
Galaxies, groups of galaxies



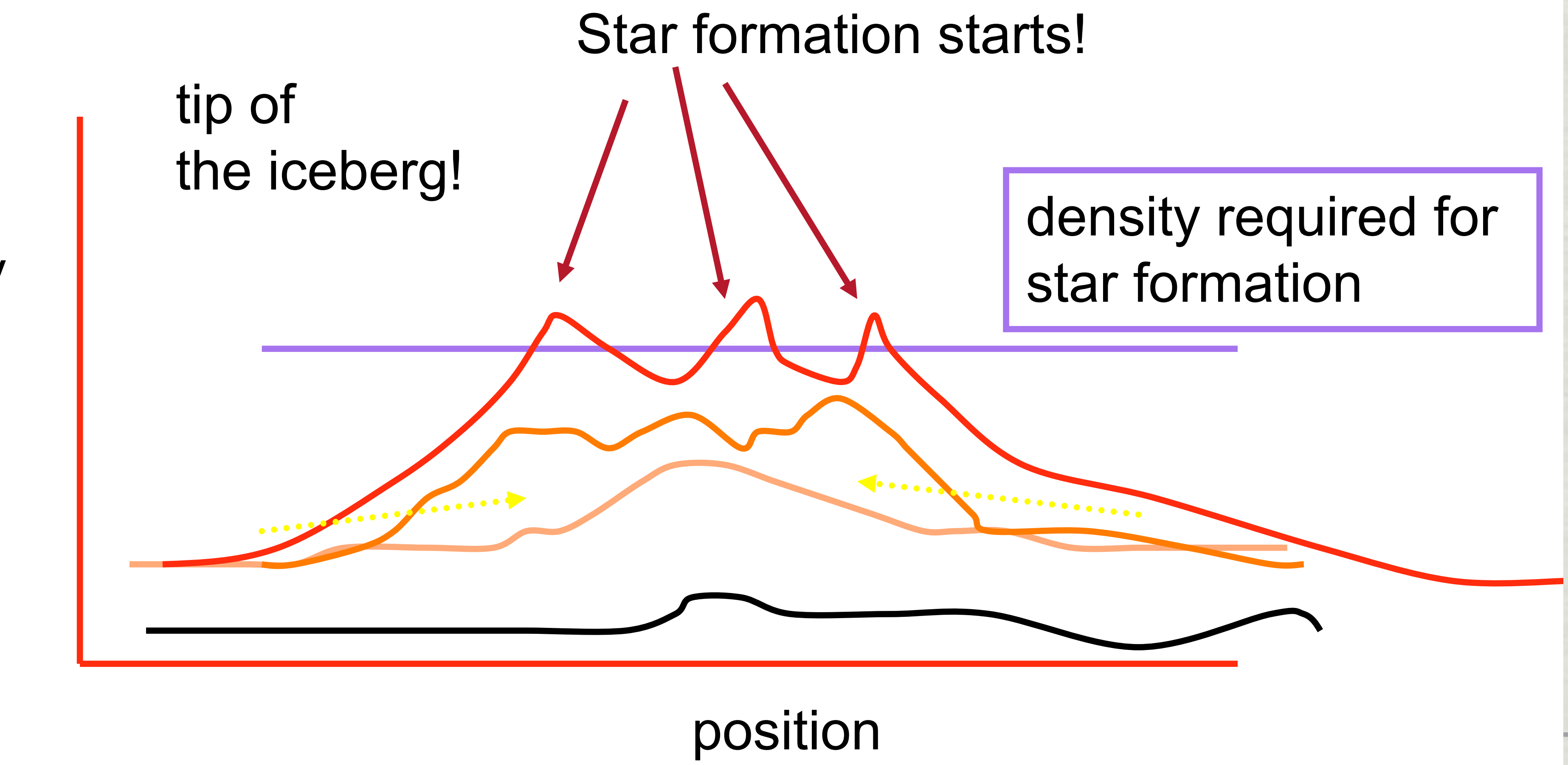
Observed distribution of galaxies seen today: a slice in distance and position along a circle in the sky.

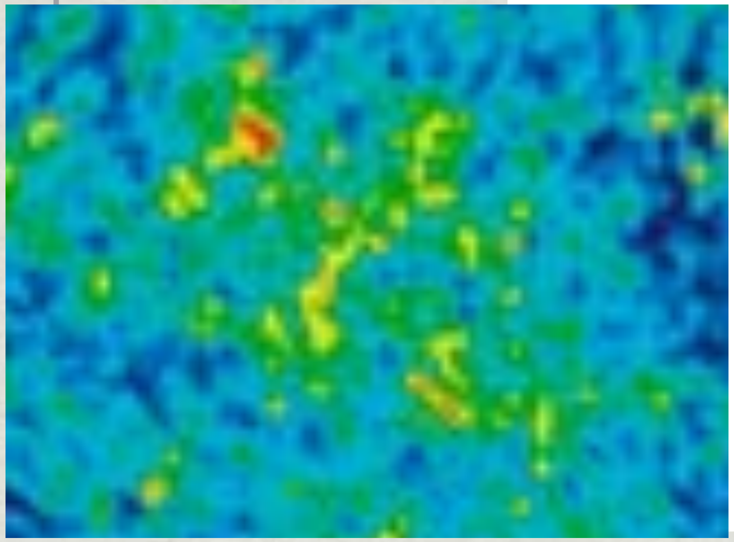
Evolution of Density

How do we get from smooth
to lumpy?   Gravity!

Very small overdensities grow: gravitational attraction of stuff in a dense patch to itself is stronger than pull of gravity from the less-dense stuff outside the patch.

Stuff in the over-dense patch get closer together.
Patch becomes more over-dense.



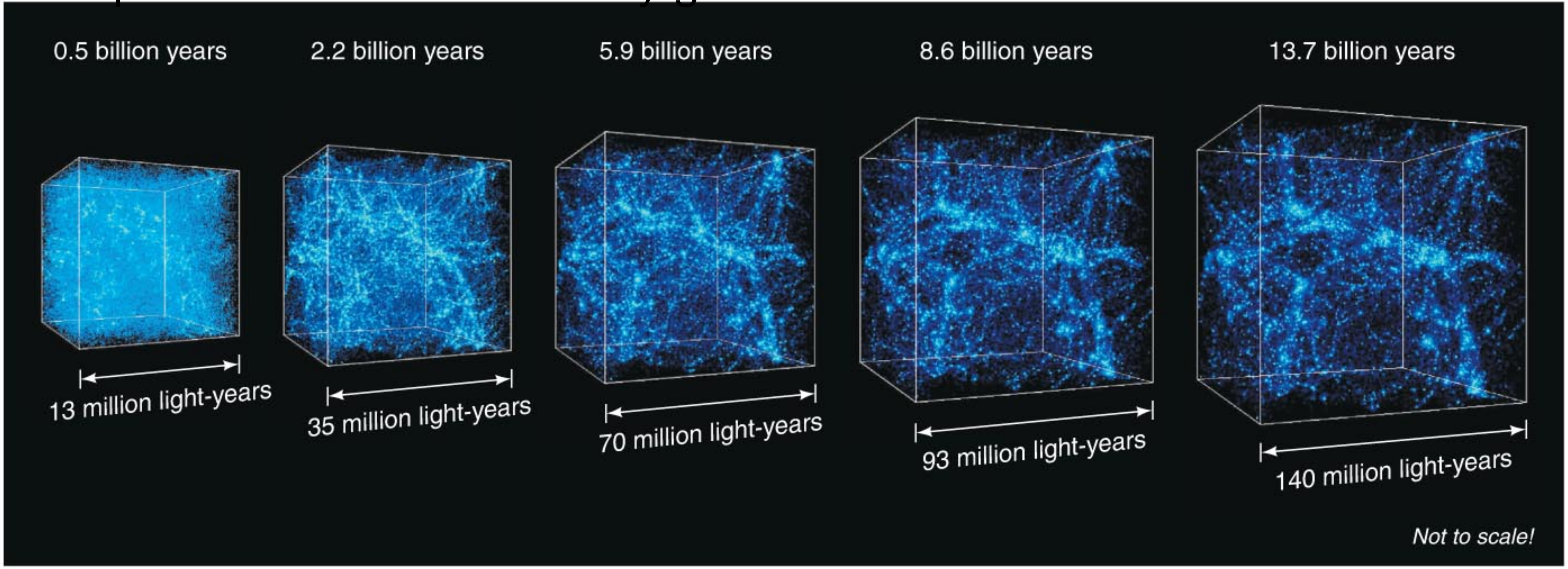


Evolution of Density

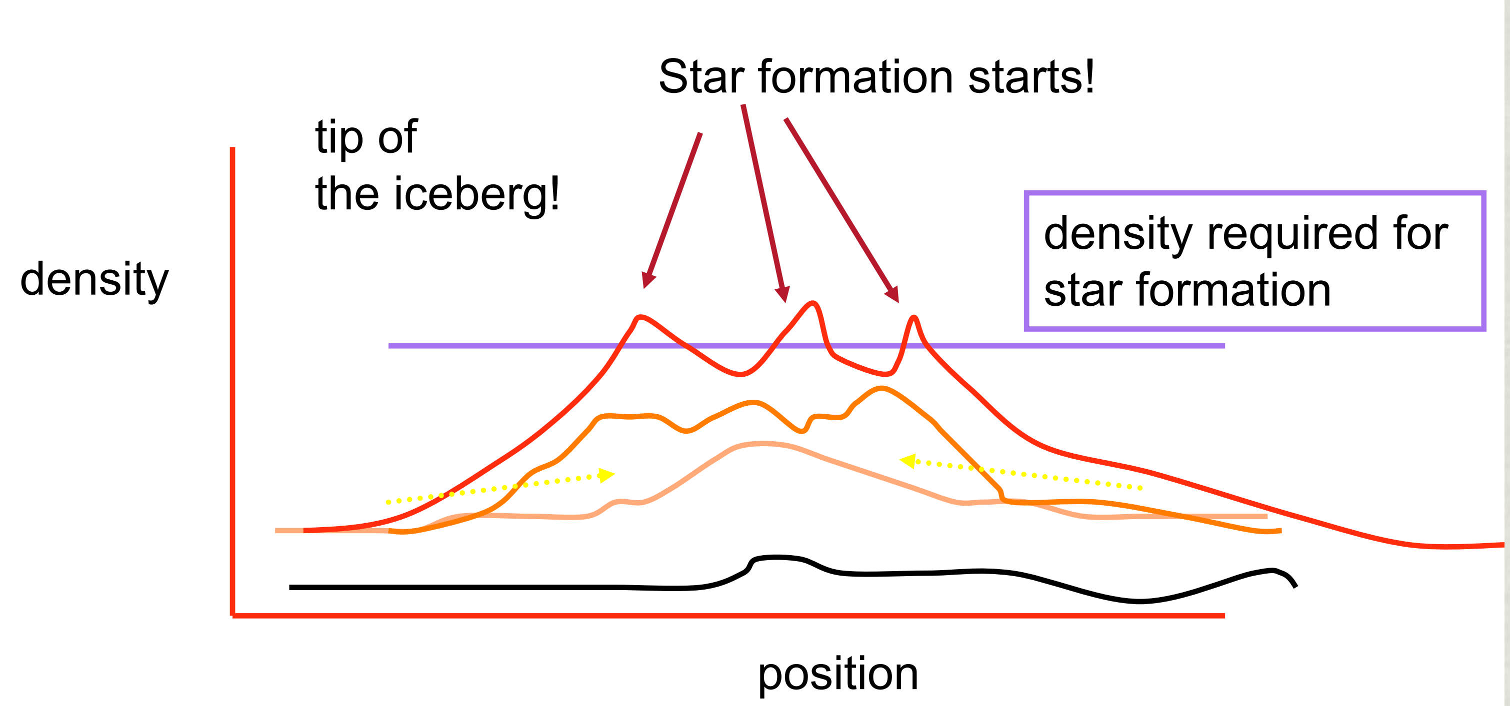
Overdensities grow due to gravity.

The rate at which an overdensity grows depends on the amount of gravitating stuff (normal atoms + dark matter) in the universe.

Computer simulation of density growth in the universe



Evolution of Density

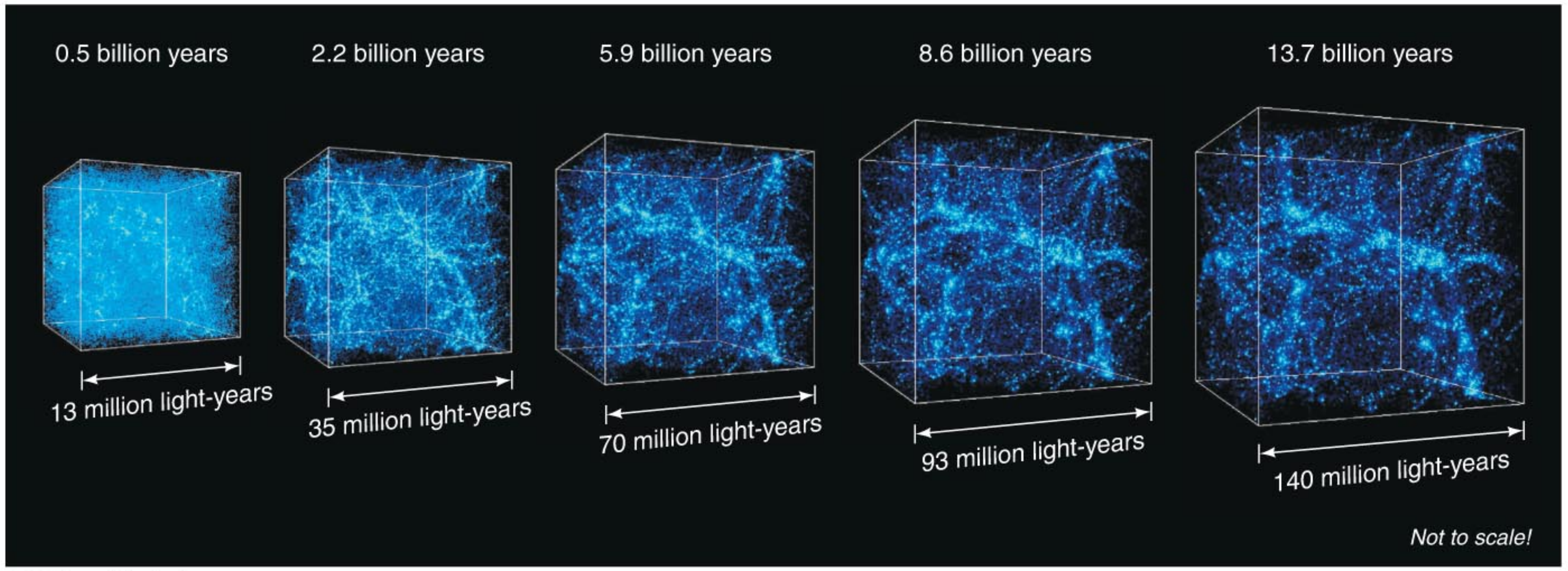


In regions that are dense enough, gravity wins over the expansion of the universe.

Example: Andromeda and the Milky Way are moving toward each other. Someday will crash!

Over-dense patches live in bigger over-dense regions: this is why galaxies live near each other in the present day.

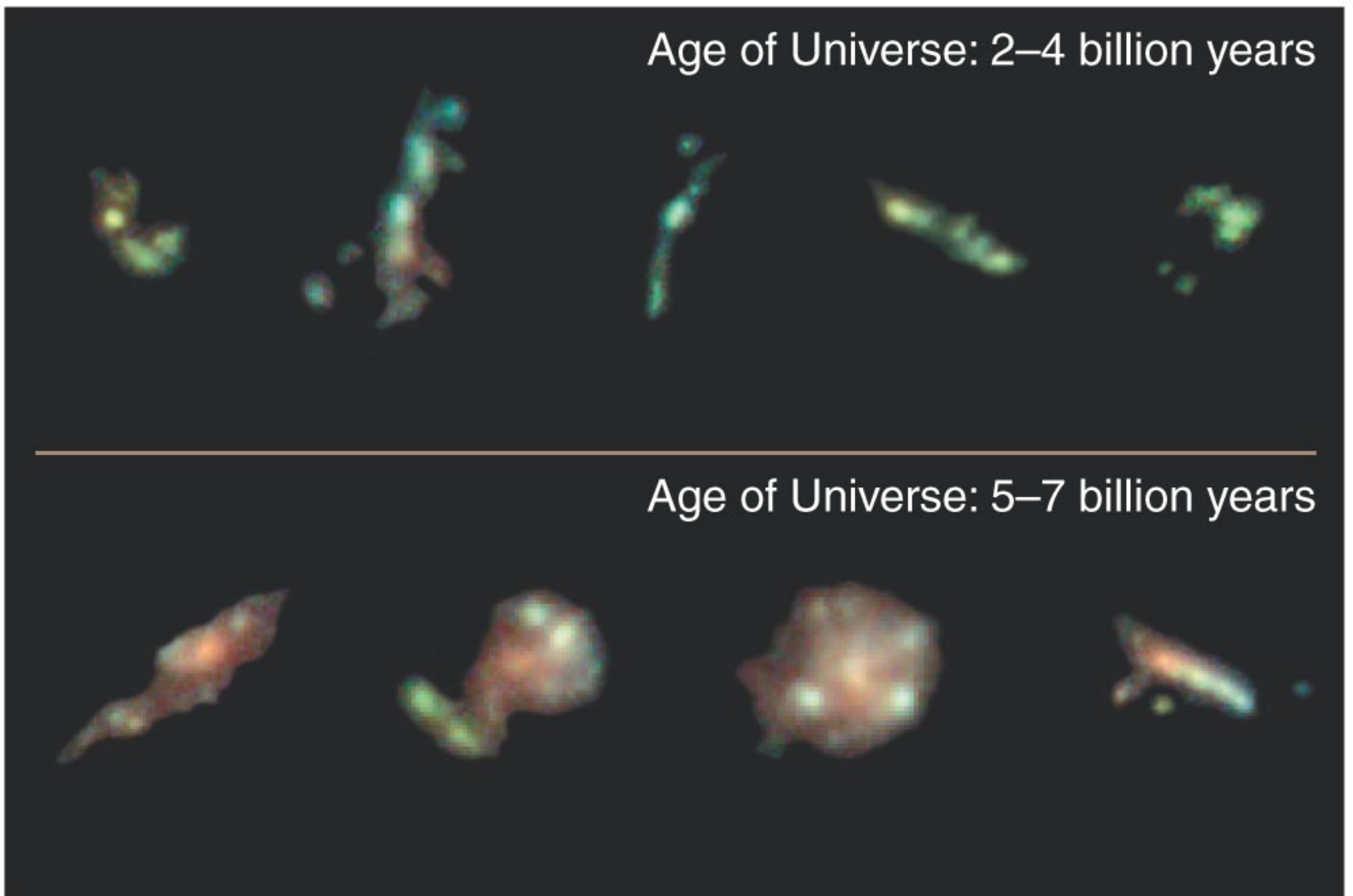
Gravity pulls over-dense patches together until they merge:

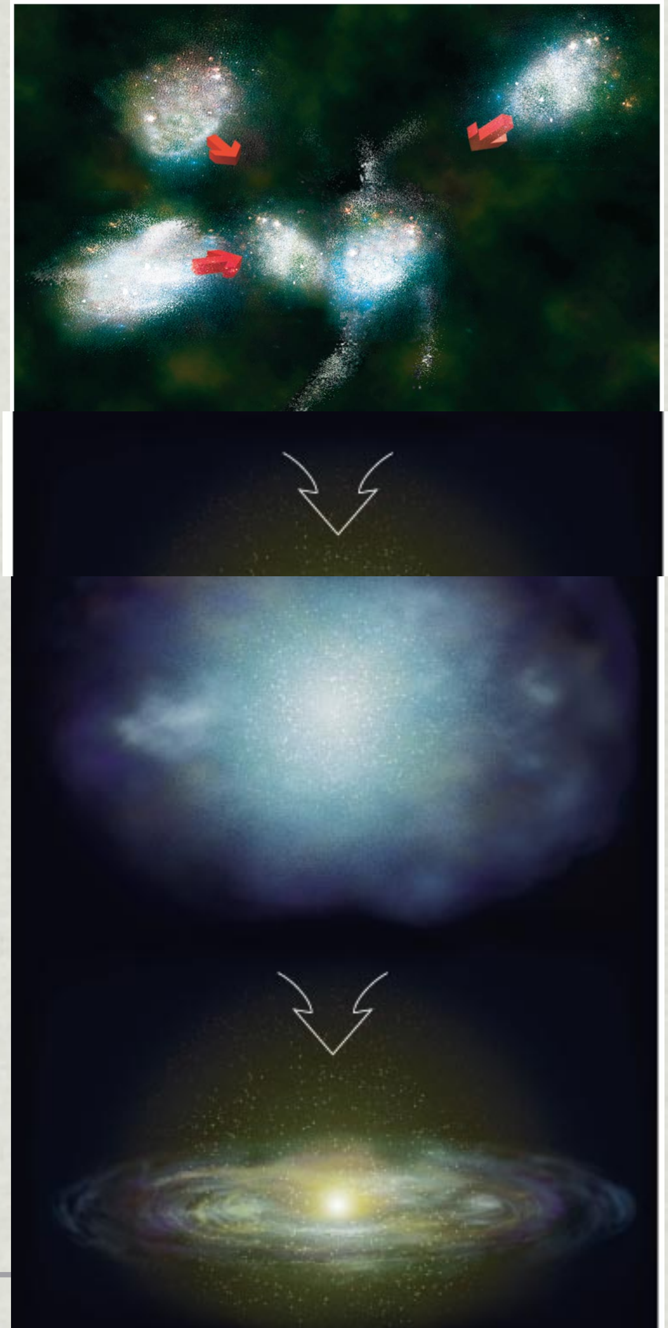


This is why we think galaxies and clusters of galaxies grow from smaller

Evolution of Density and Galaxy Growth

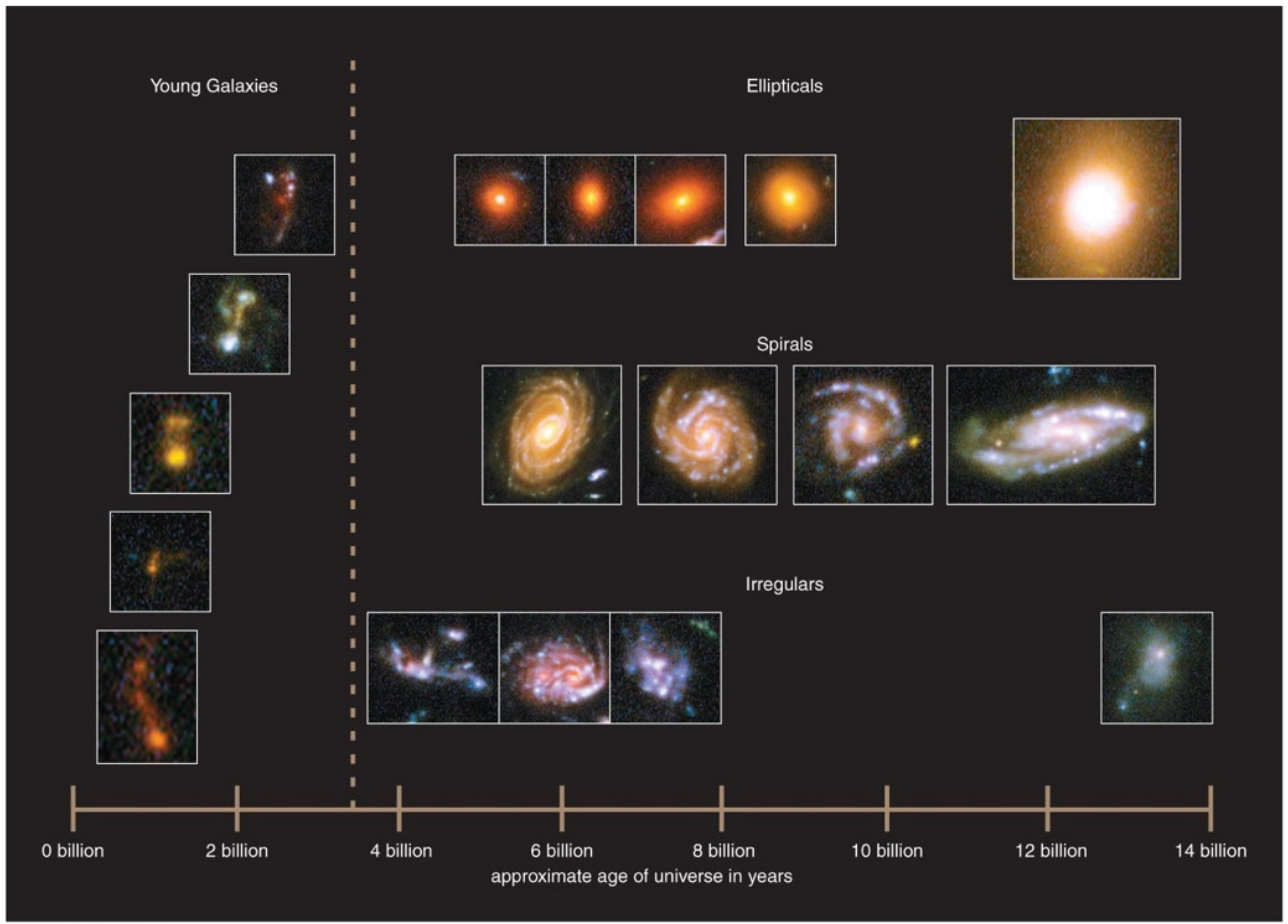
Young galaxies: lumpier, more evidence of individual overdensities that merge together to make galaxies

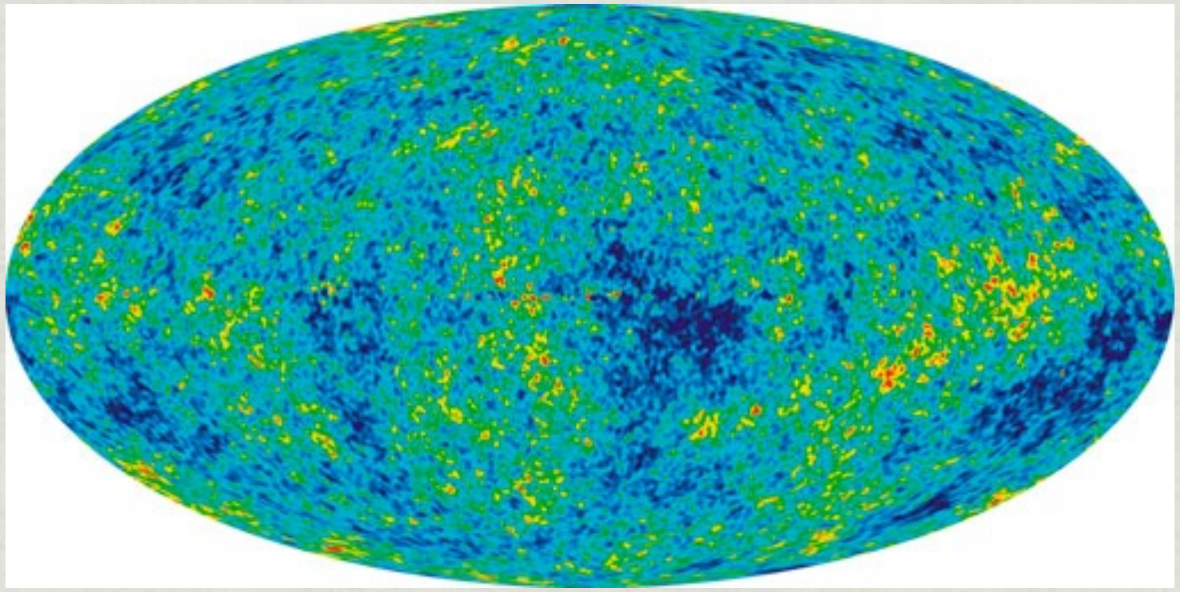




Evolution of Density and Galaxy Growth

Timeline of Galaxy growth





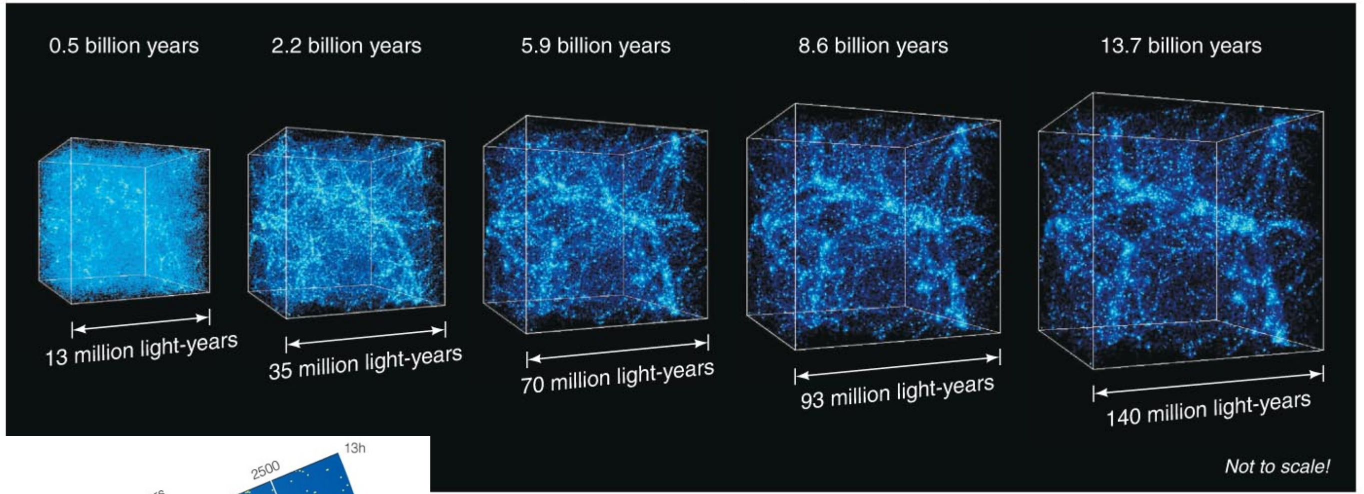
Goal of Observational Cosmology:

Understand how initial density perturbations grow in the expanding universe.

Predict how density variations in the CMB become the observed distribution of galaxies today.

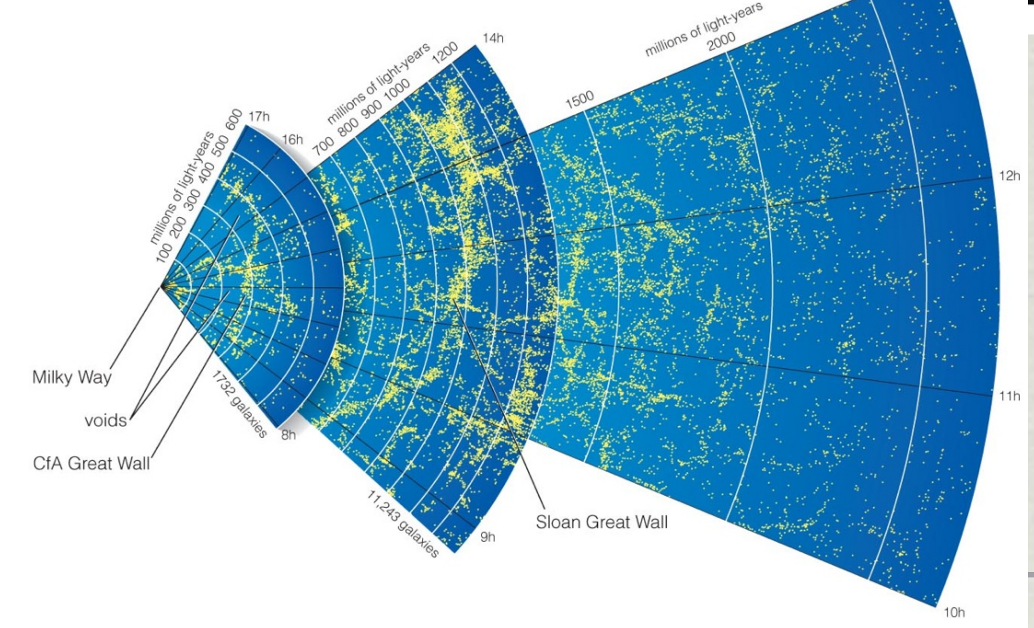
Extra challenge: explain galaxy shapes, sizes, colors, star formation rates, ...

Computer simulation of density growth in the universe



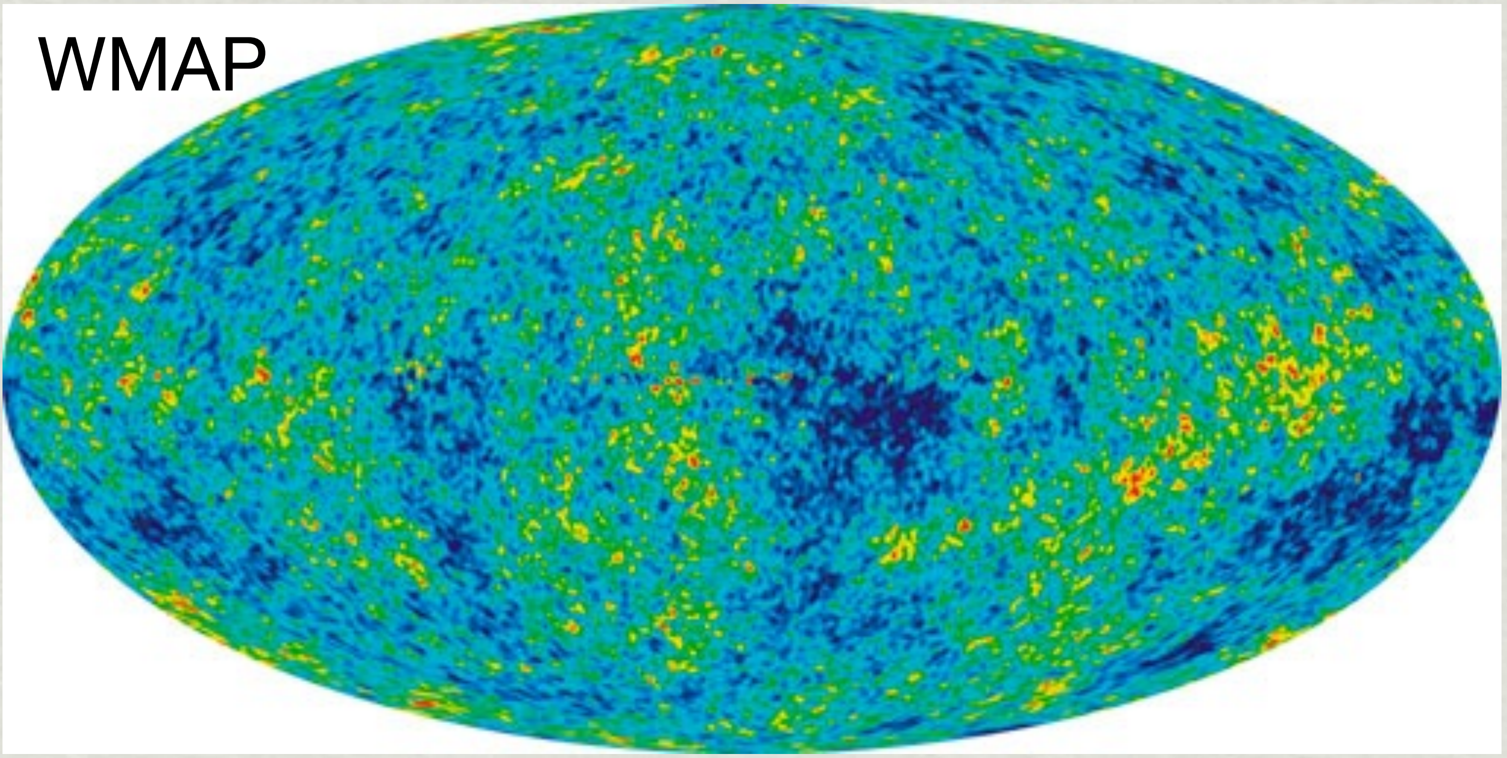
Do we have the whole story yet?

Hubble Deep Field: Galaxies



Observed distribution of galaxies seen today

Evolution of Density



Key factors that determine how fast overdensities grow:

1) How large the density variations are at the time of the CMB. Gravity has less work to do to grow the overdensity if it starts out very dense.

2) Rate of expansion (Hubble's Constant). Gravity takes longer to win against a fast expansion.

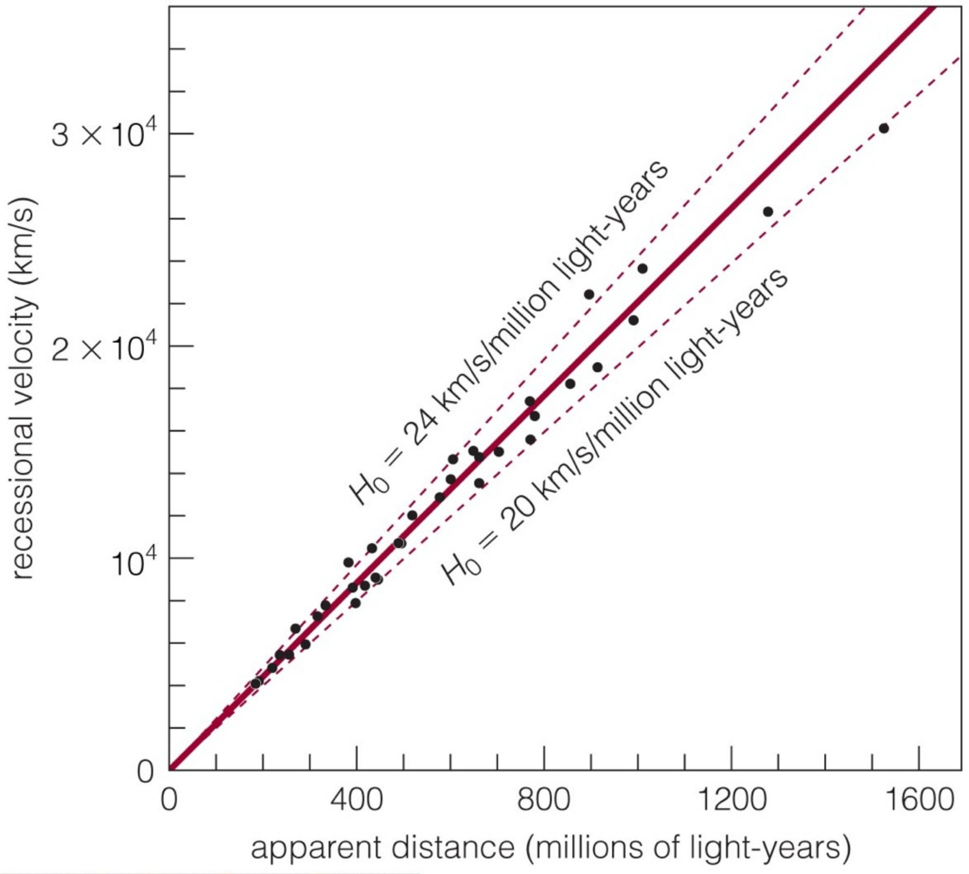
3) Total density in the universe: More dense, gravity has more mass to work on in any volume to slow down the expansion.

Hubble Deep Field: Galaxies in the universe

Expansion and Fate of the Universe

Hubble's Law:

- Galaxies appear to be rushing away from us as space expands.
- Larger velocity (redshift) measured for galaxies at larger distances.
- Interpret redshift as stretching of photons as space expands.



Gravity works against expansion:

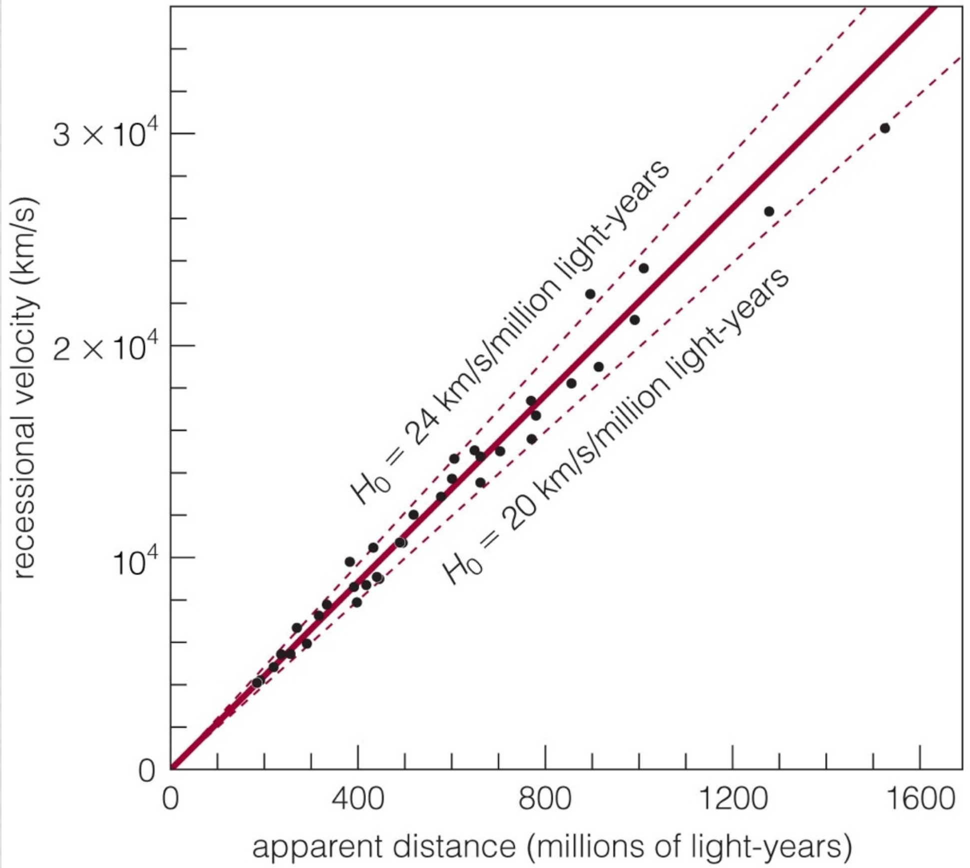
- Dense regions of the universe (like galaxies) are attracted to each other by gravity. Gravity pulls them closer together.

What happens? Options:

Expansion and Fate of the Universe

Hubble's Law:

- Galaxies appear to be rushing away from us as space expands.
- Larger velocity (redshift) measured for galaxies at larger distances.
- Interpret redshift as stretching of photons as space expands.



Gravity works against expansion:

- Dense regions of the universe (like galaxies) are attracted to each other by gravity. Gravity pulls them closer together.

What happens? Options:

1) Gravity wins
2) Expansion wins
3) Tie

Expansion and Fate of the Universe

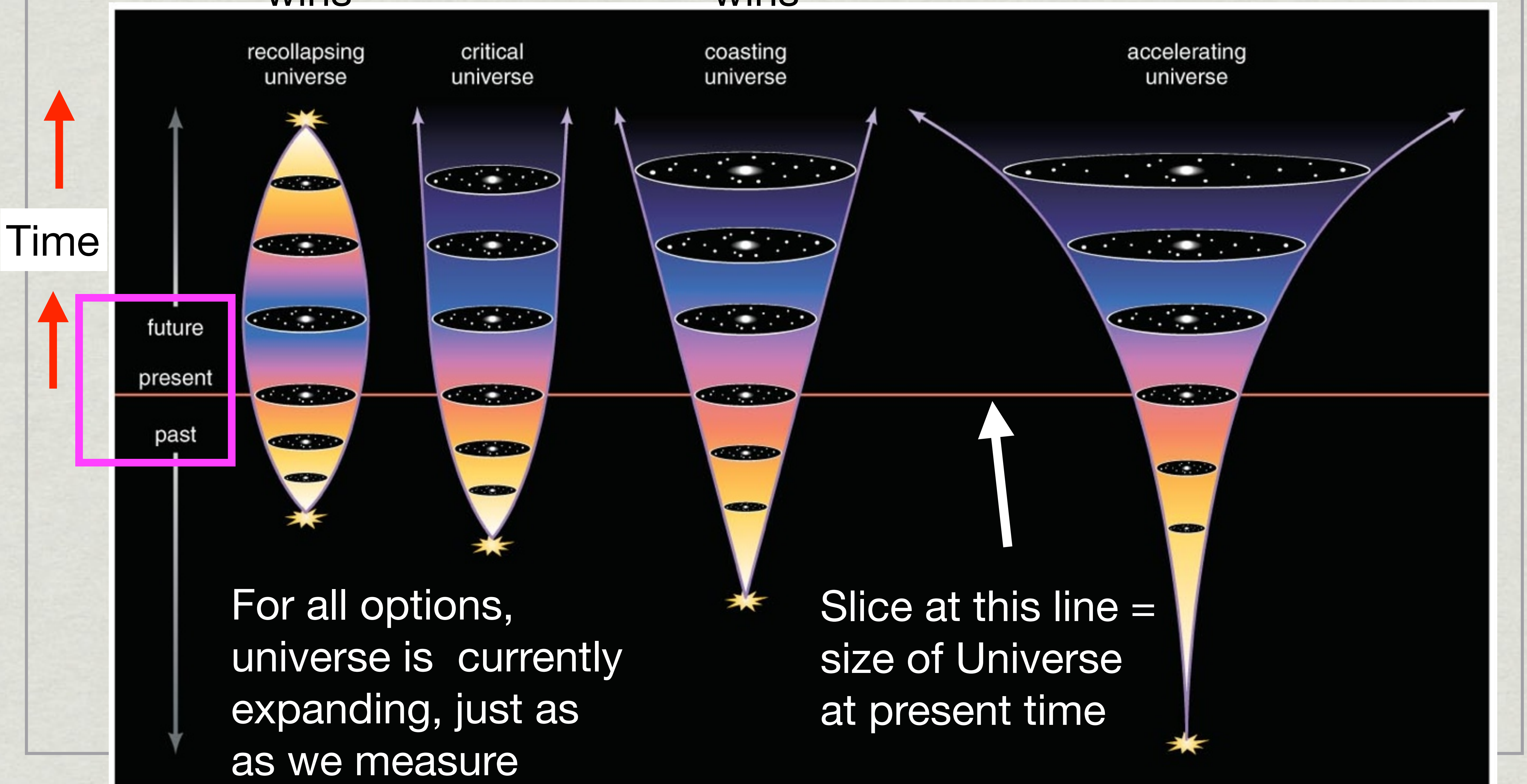
Options:

Gravity wins

Tie

Expansion wins

Accelerating: expansion increases



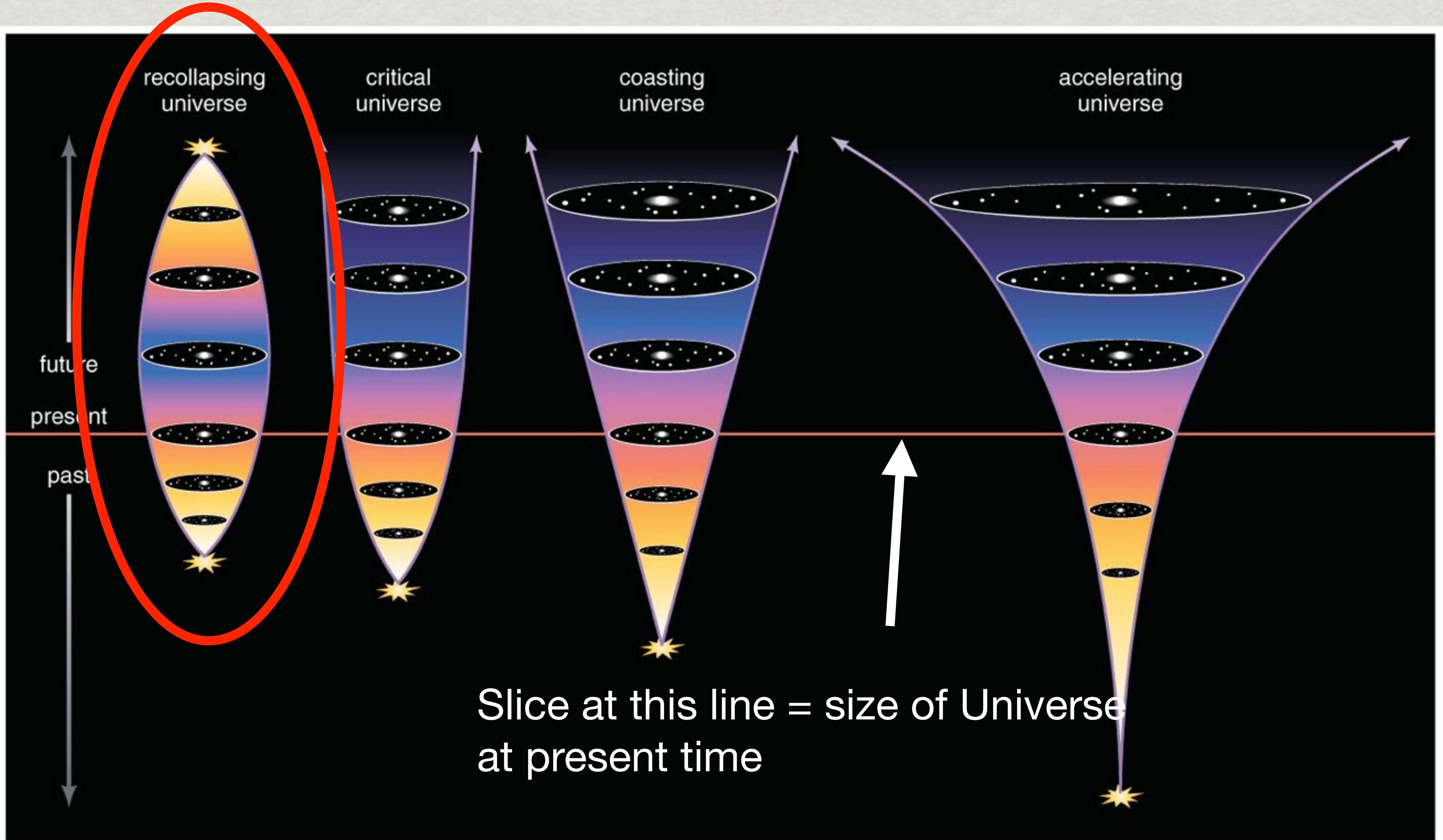
Time

For all options, universe is currently expanding, just as as we measure

Slice at this line = size of Universe at present time

Expansion and Fate of the Universe

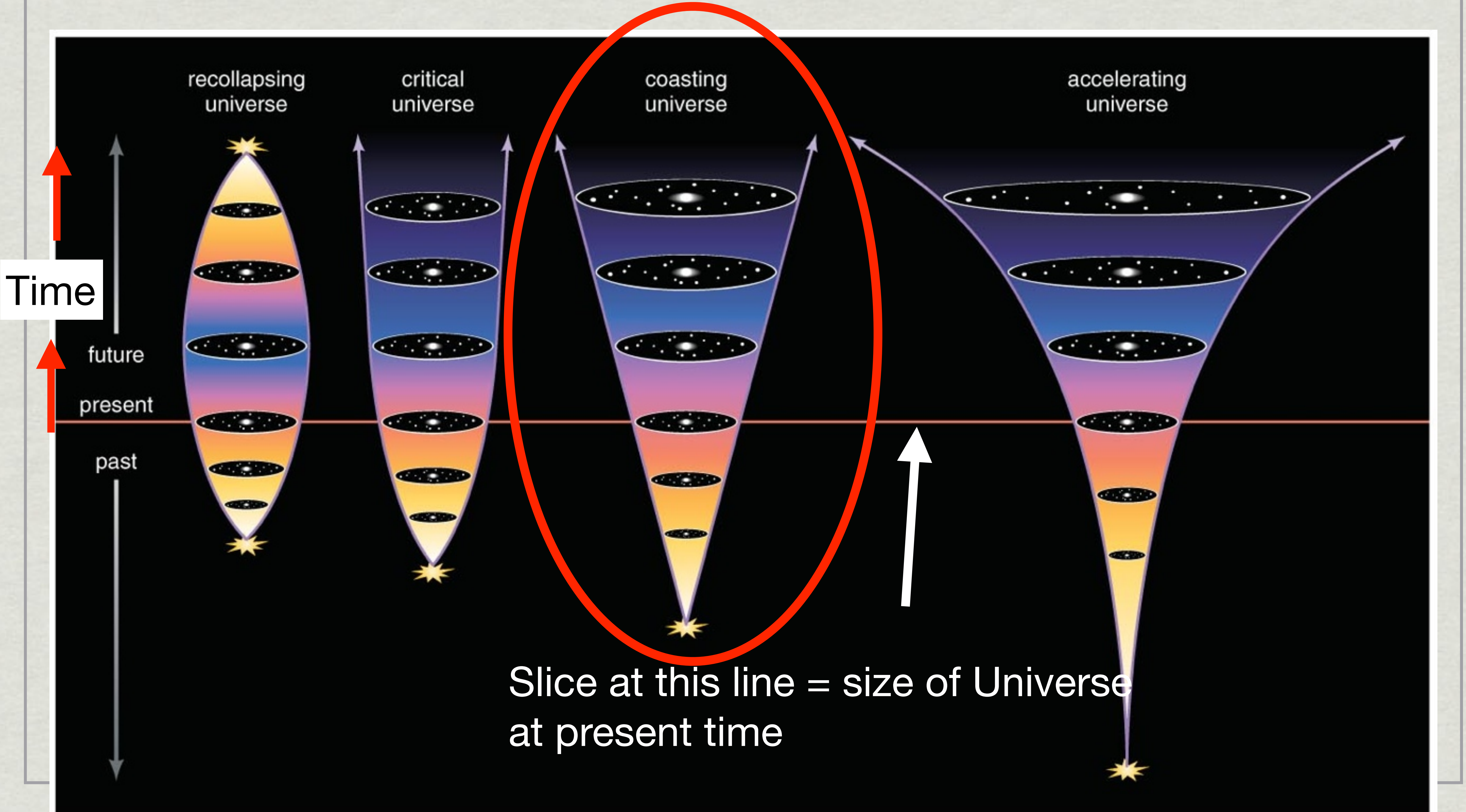
Recollapsing universe: gravity stops the expansion



Slice at this line = size of Universe at present time

Expansion and Fate of the Universe

Coasting universe: expansion continues to expand at about the same rate

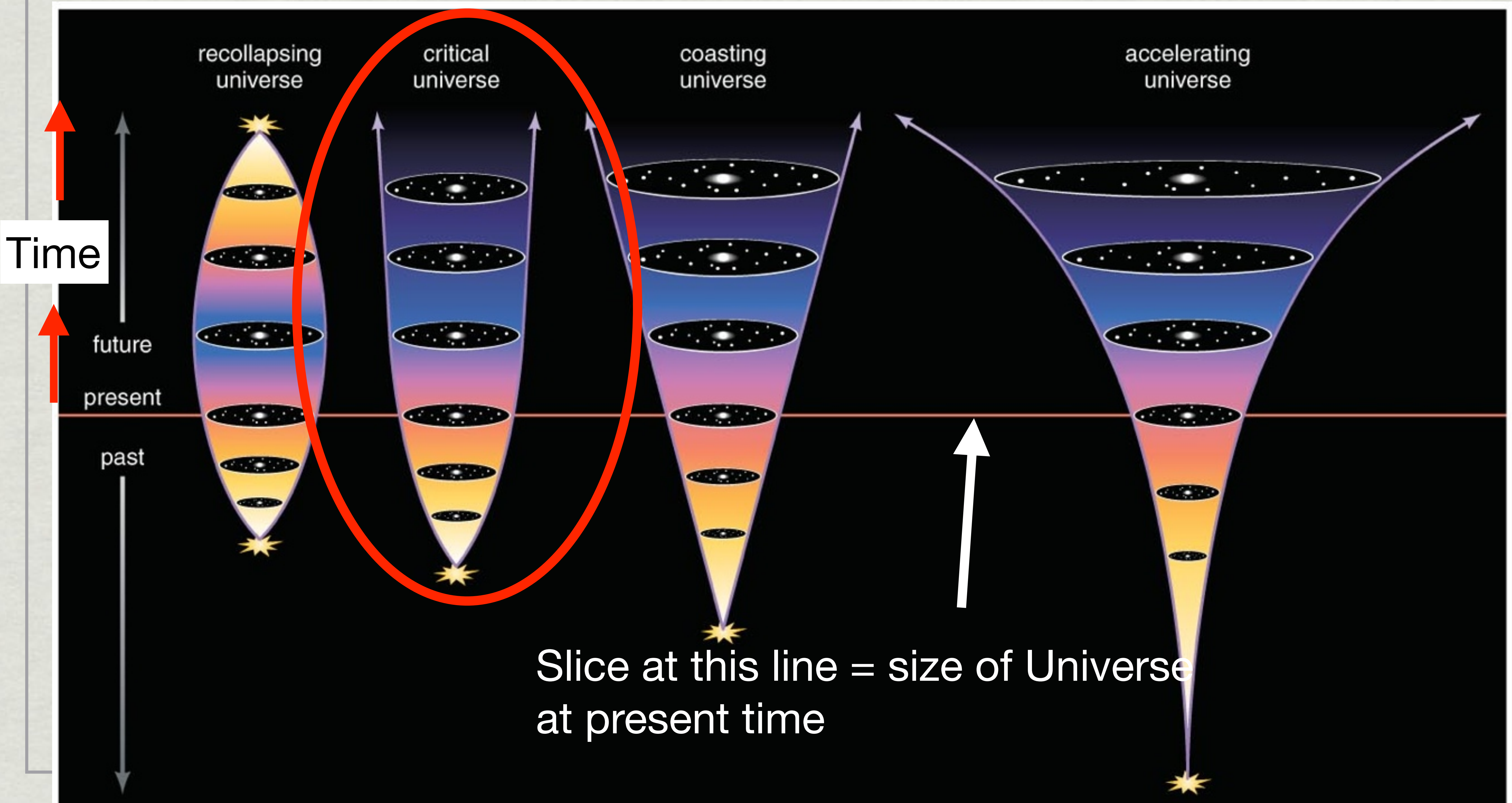


Slice at this line = size of Universe at present time

Expansion and Fate of the Universe

Critical universe: gravity and expansion just balance. Expansion slows gradually, will stop at an infinitely long time in the future.

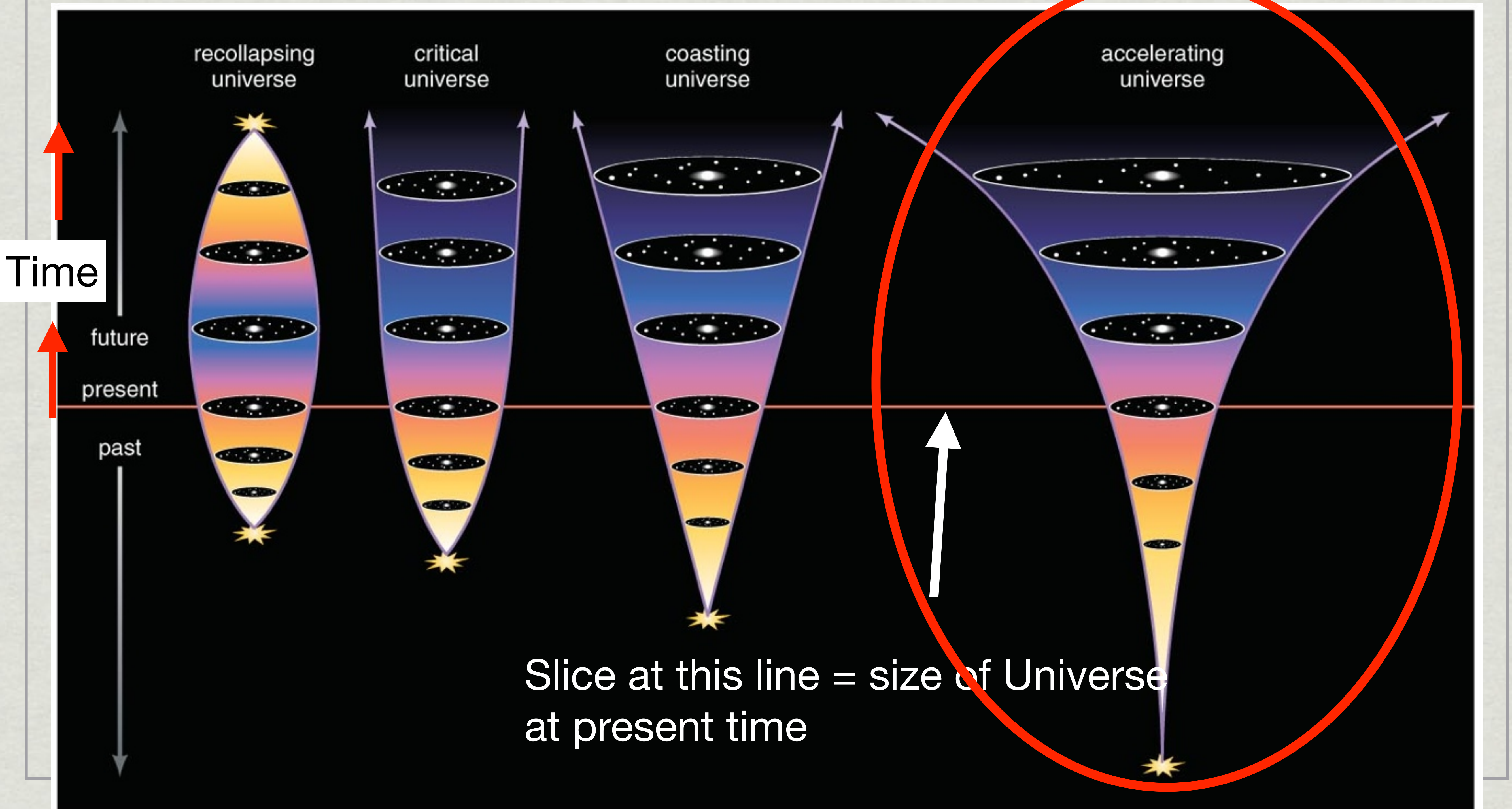
Critical density - mass density (dark + baryons) required to balance gravity and expansion.



Slice at this line = size of Universe at present time

Expansion and Fate of the Universe

Accelerating universe: expansion rate increases. (How? later…)



Slice at this line = size of Universe at present time

Expansion and Fate of the Universe

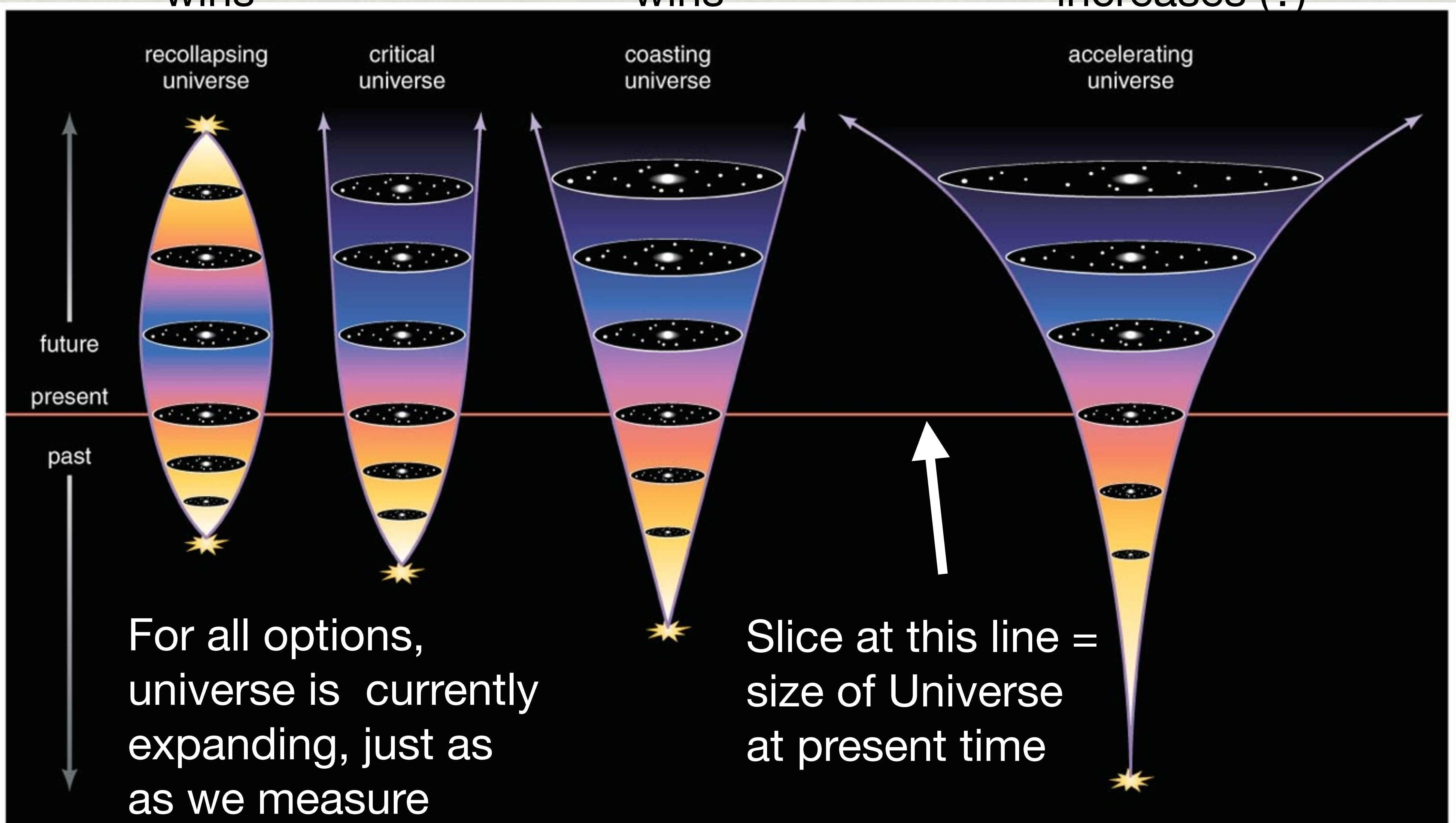
What determines the outcome? Amount of mass in the universe.

Gravity wins

Tie

Expansion wins

Expansion increases (?)



Time

For all options, universe is currently expanding, just as as we measure

Slice at this line = size of Universe at present time

Expansion and Fate of the Universe

What determines the outcome? Amount of mass-energy in the universe (remember: $E = mc^2$)

Use data from white dwarf supernovae to measure the expansion rate at different distances.

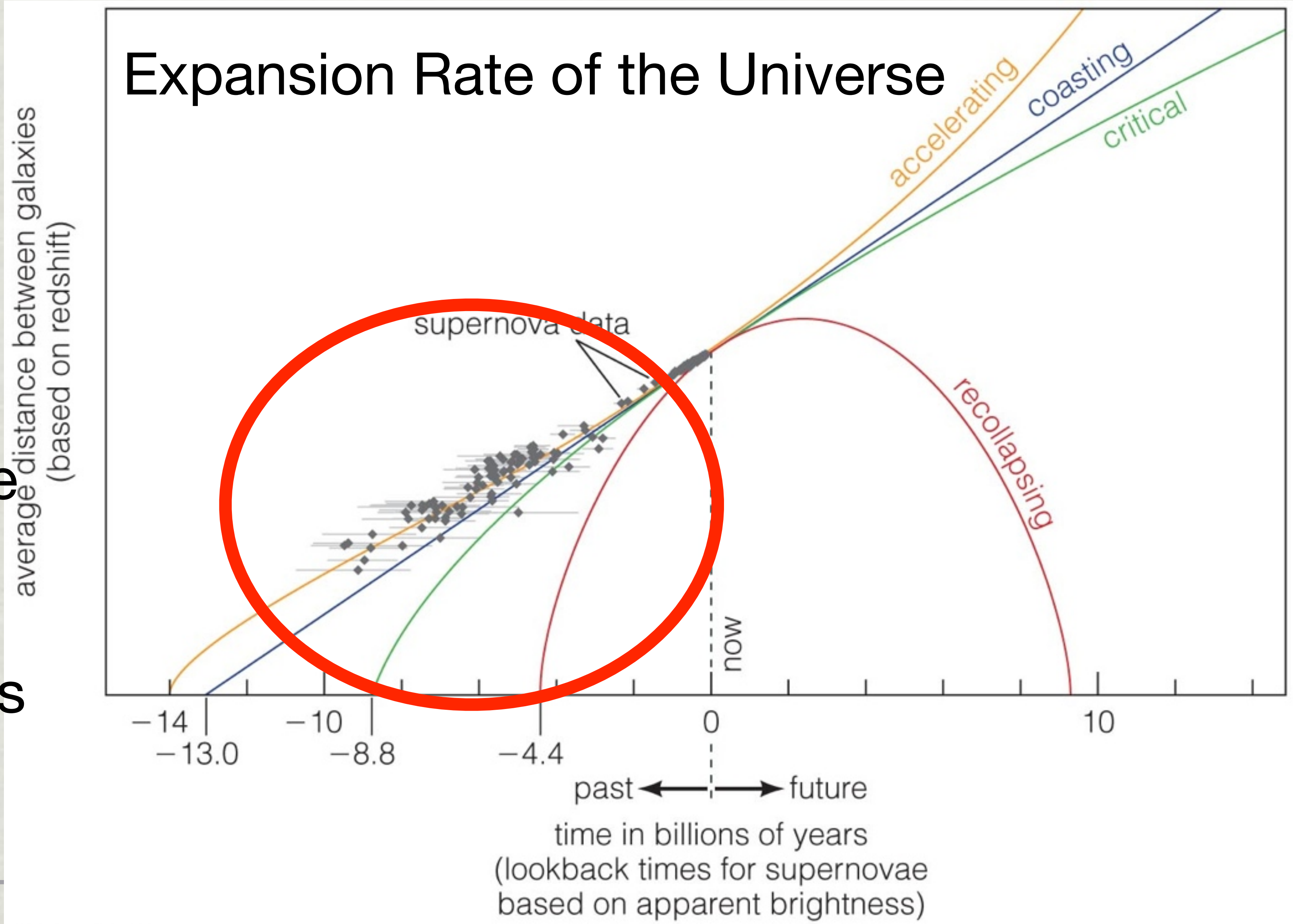
Remember: measurements at larger distances = measurements earlier in time

Y-axis: average distance between galaxies

X-axis: time

“Now” is in the middle of the plot, time = 0

We can make measurements in the past by looking at large distances.



Distances to Galaxies

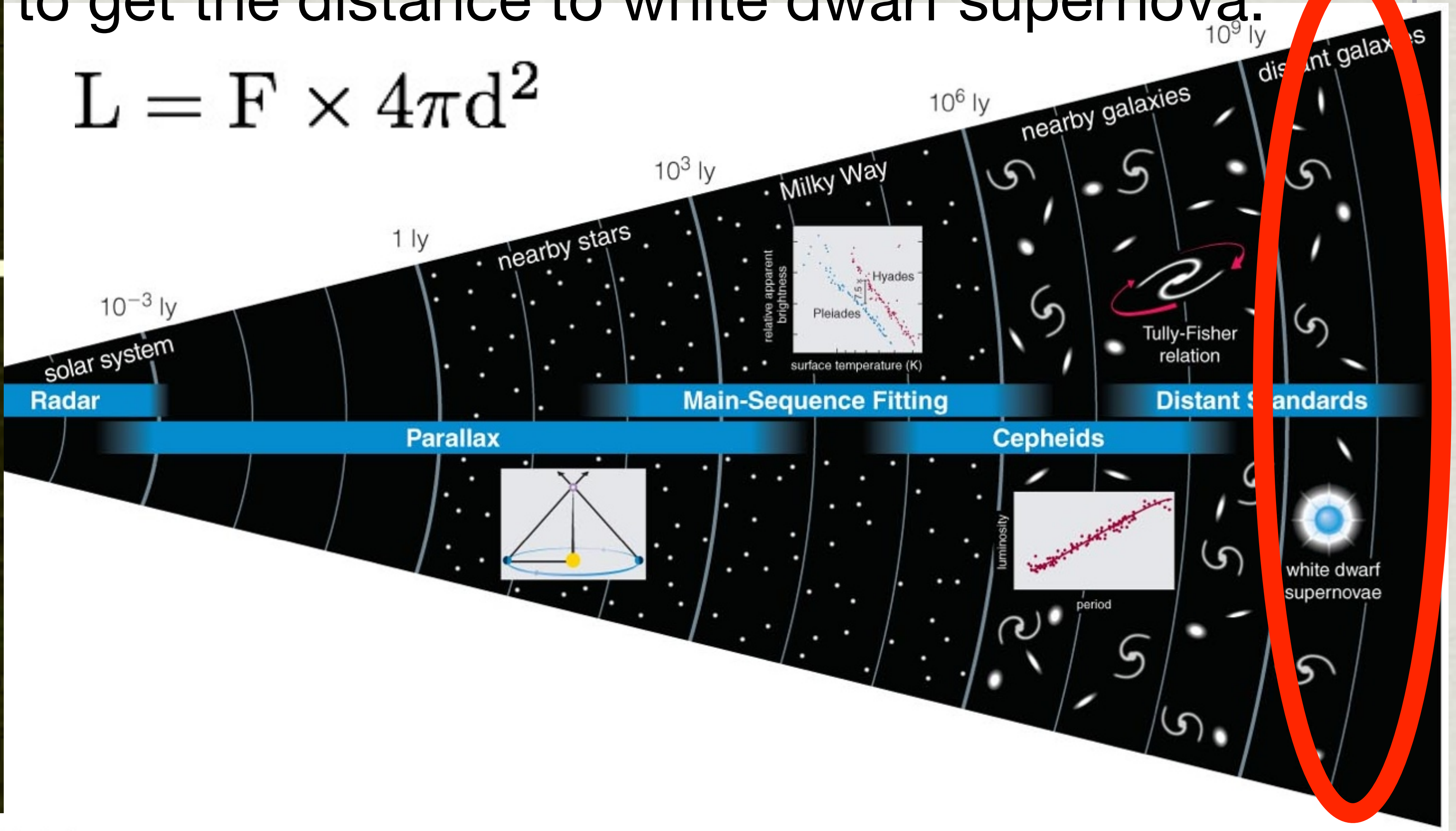
Reminder:

White dwarf supernovae: 1.4 M_{sun} → Fe by nuclear fusion, so we know how much energy is released.

This means we know the luminosity:
10 billion L_{sun}, about the luminosity of our Galaxy.
Can see these much farther away that Cepheids

Can use the measured flux (apparent brightness) to get the distance to white dwarf supernova:

$$L = F \times 4\pi d^2$$



Expansion and Fate of the Universe

What determines the outcome?   Amount of mass-energy in the universe.

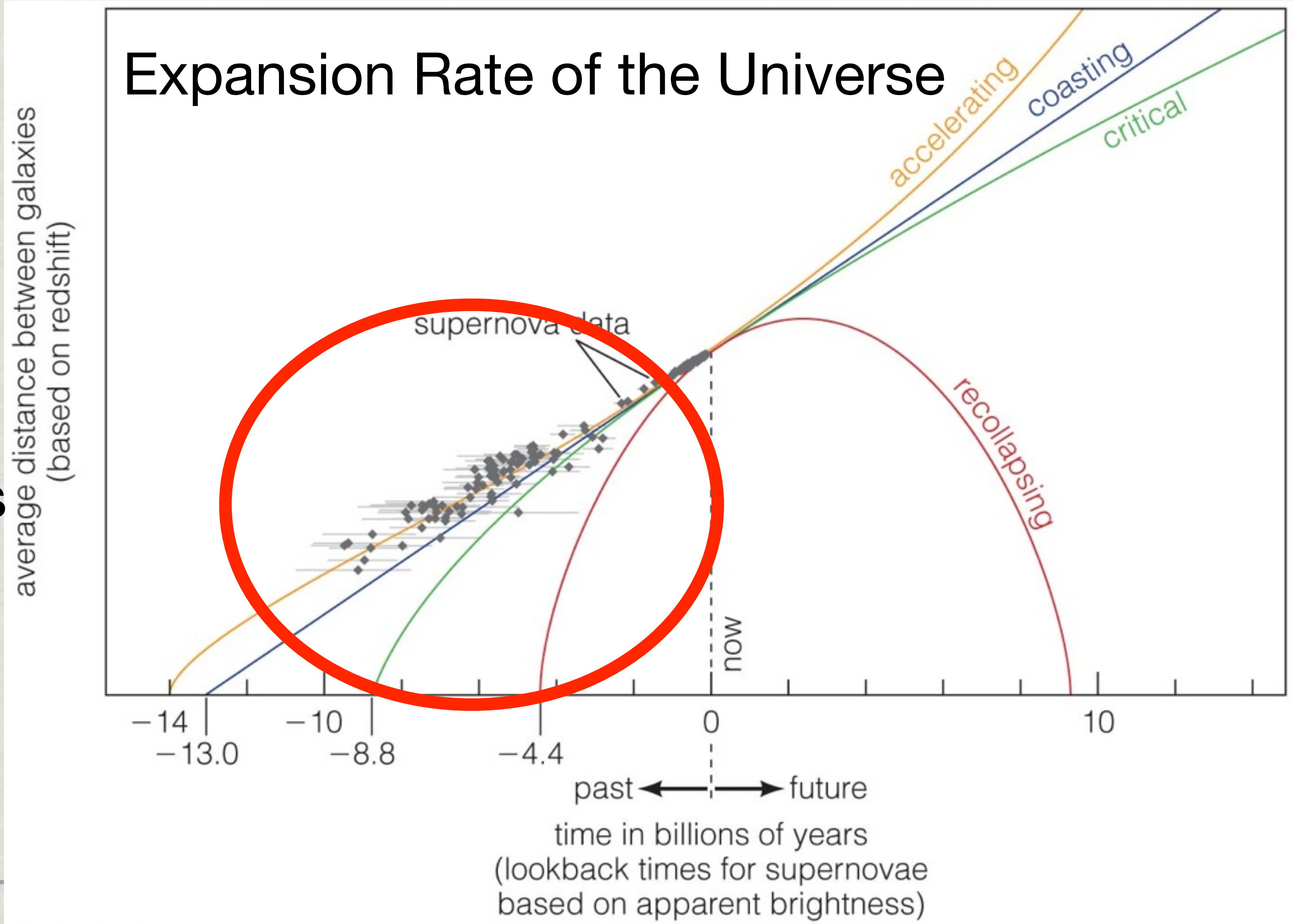
Use data from white dwarf supernovae to measure the expansion rate at different distances.

Remember: measurements at larger distances = measurements earlier in time

Y-axis: average distance between galaxies
X-axis: time

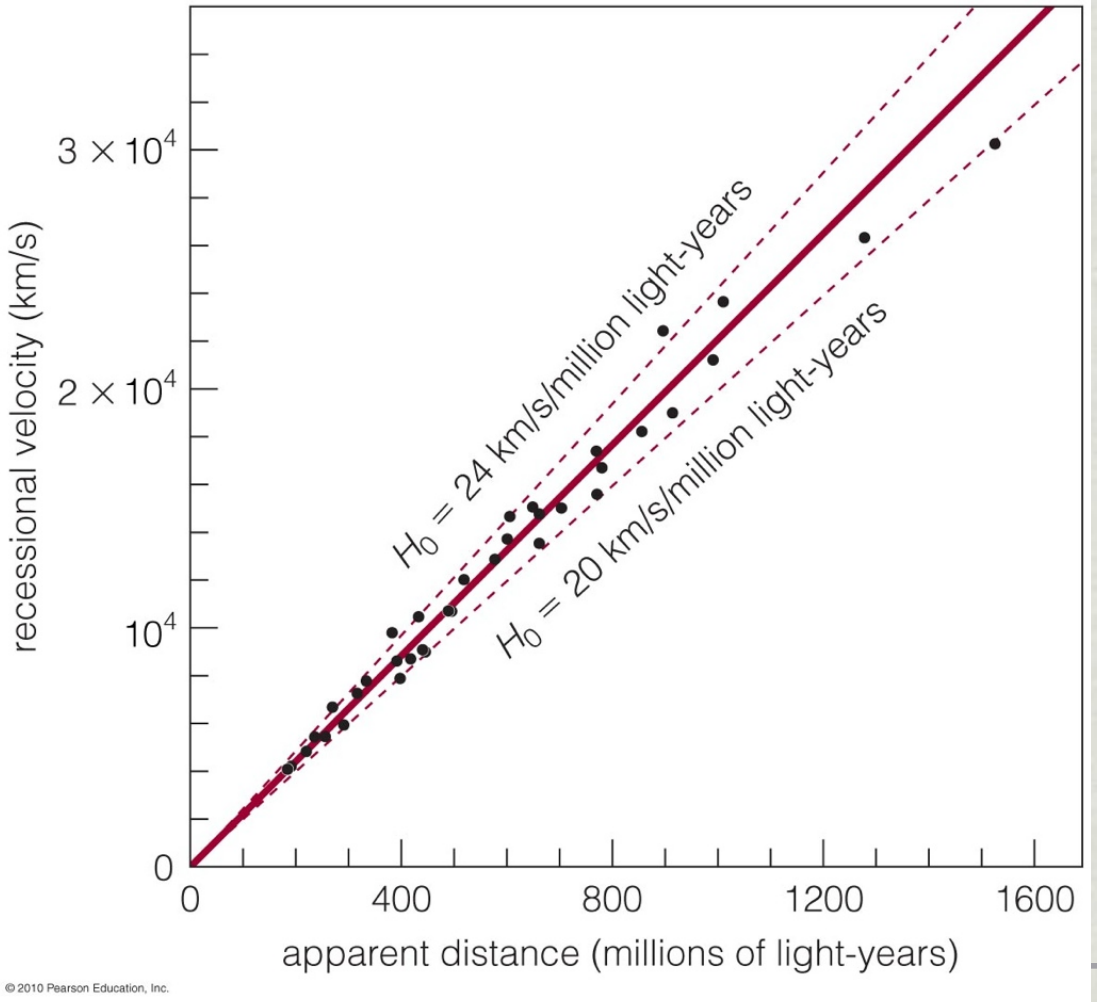
Slope of lines: how quickly distance between galaxies is changing with time.

That's the expansion rate!



Hubble’s Law and the Expanding Universe

This plot that gave us Hubble’s Law measures the expansion rate at **one** time in the history of the universe. The straight line tells us the expansion is the same everywhere.



Expansion and Fate of the Universe

What determines the outcome? Amount of mass-energy in the universe.

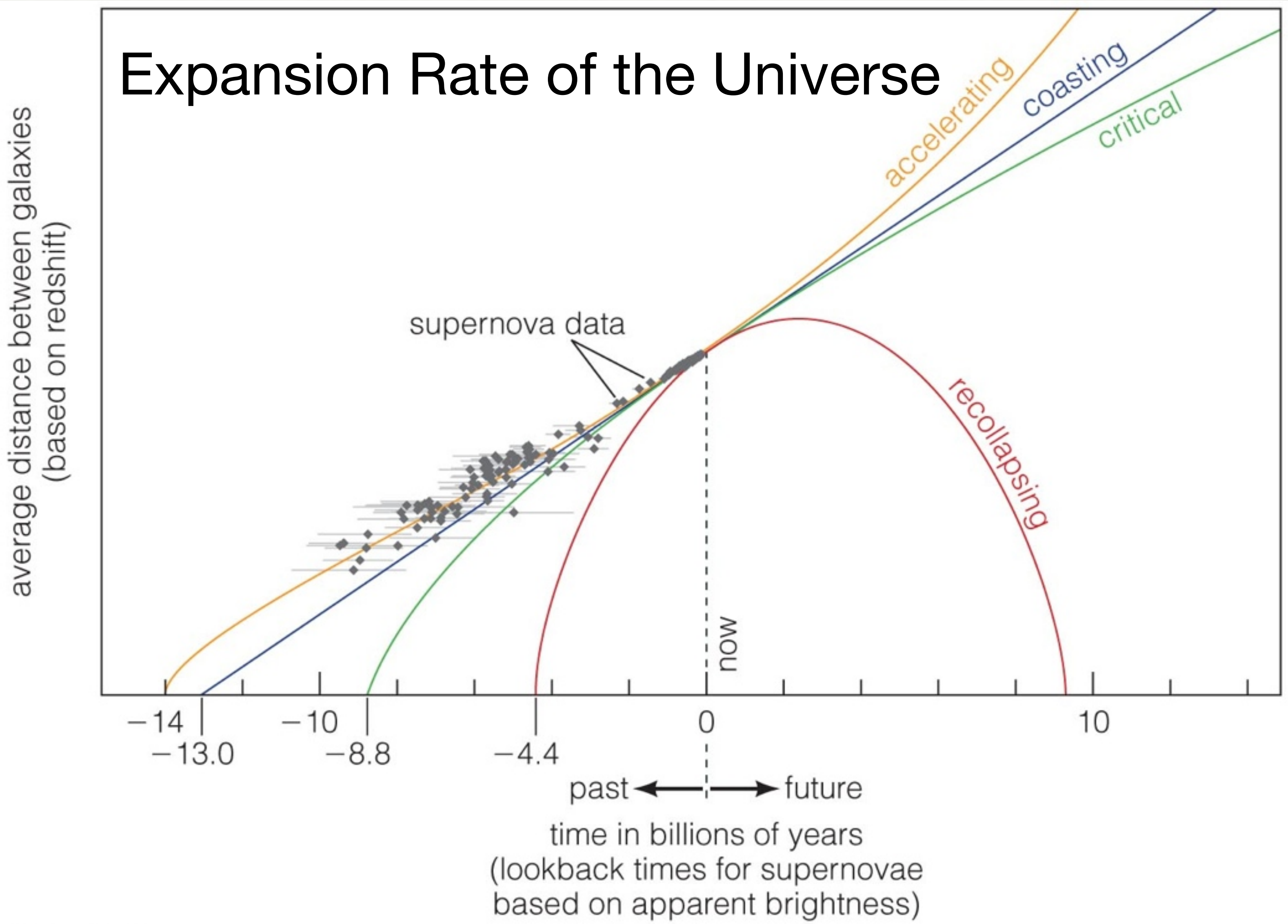
Use data from white dwarf supernovae to measure the expansion rate at different distances.

Recall: measurements at larger distances = measurements earlier in time

Y-axis: average distance between galaxies
X-axis: time

If the slope stays the same, the distance between galaxies always changes the same amount for each step on the X-axis.

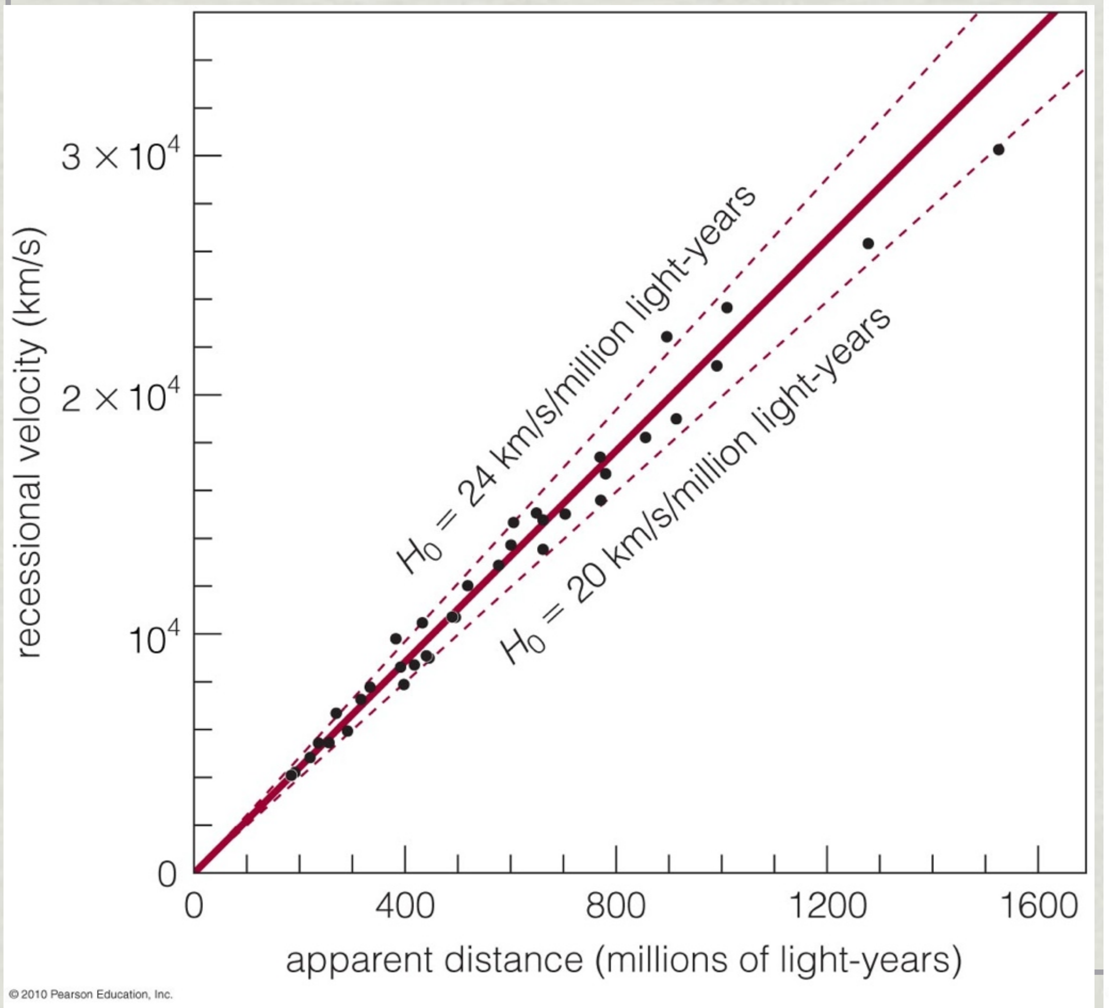
→The expansion rate stays the same over the history of the universe.



Hubble’s Law and the Expanding Universe

This plot that gave us Hubble’s Law measures the expansion rate at **one** time in the history of the universe. The straight line tells us the expansion is the same everywhere.

A straight line in this plot says that the expansion rate is constant with time: the slope of the Hubble Diagram was always the same.



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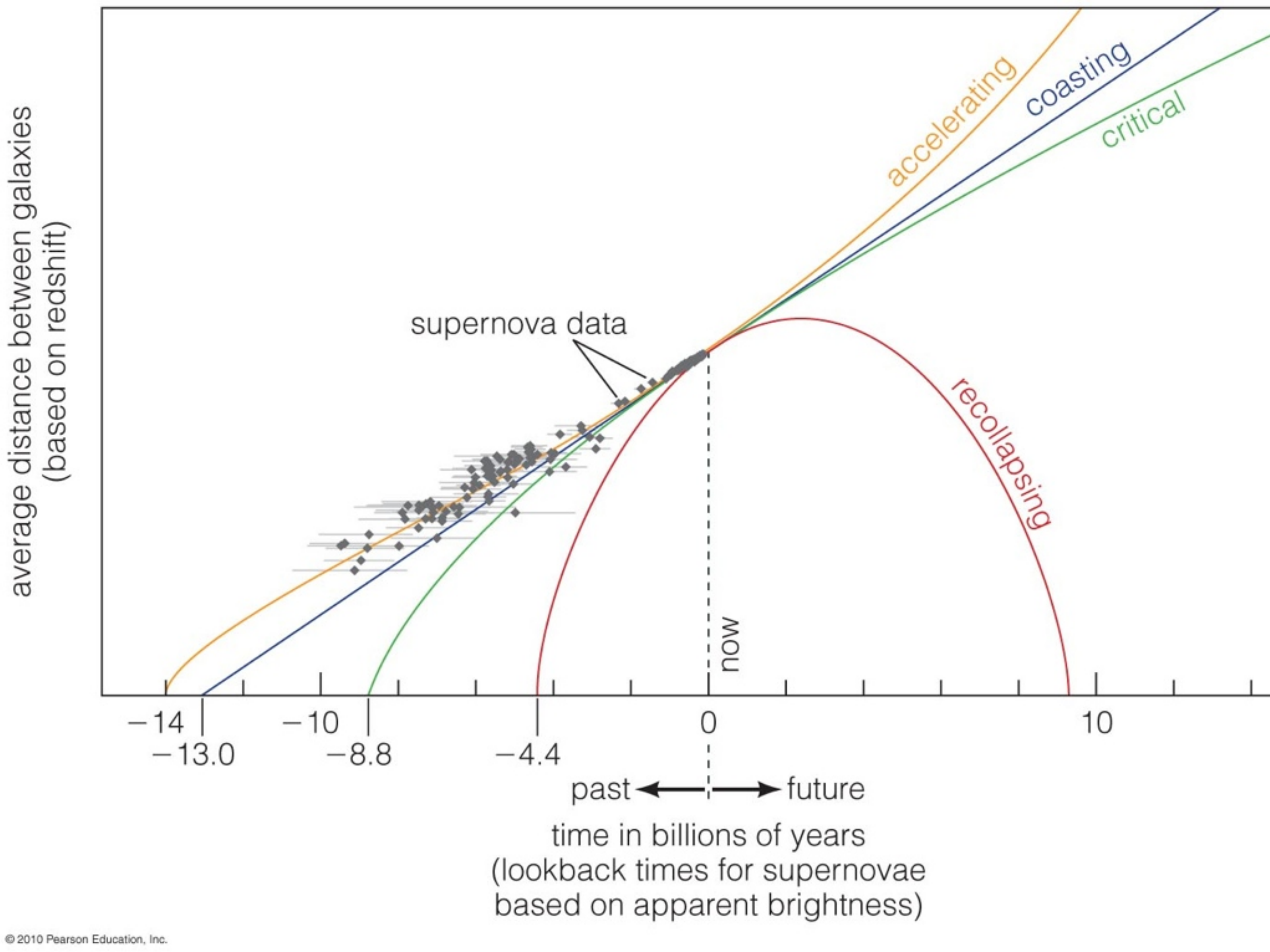

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Expansion and Fate of the Universe

What determines the outcome? Amount of mass-energy in the universe.

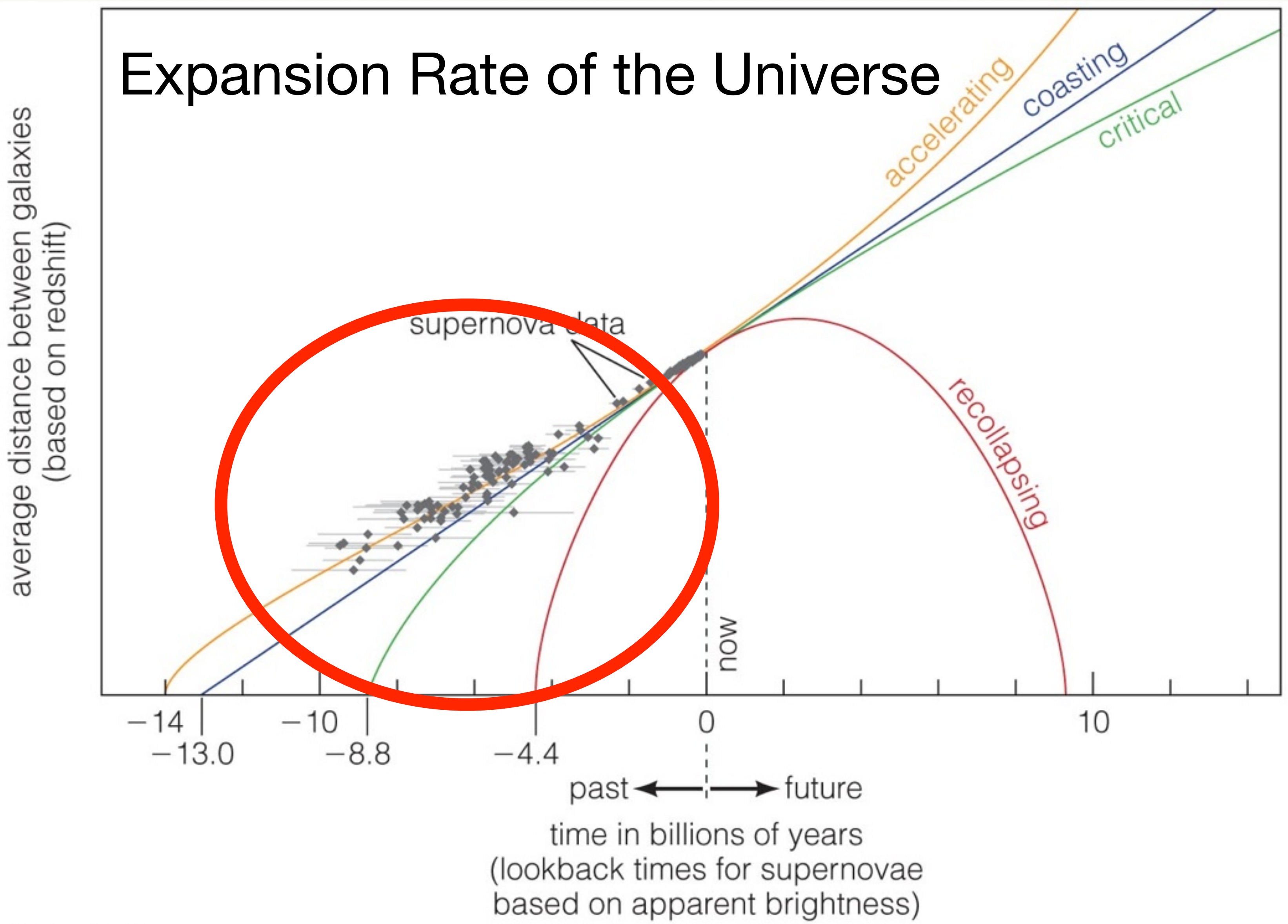
Use data from white dwarf supernovae to measure the expansion rate at different distances.

Recall: measurements at larger distances = measurements earlier in time

Y-axis: average distance between galaxies
X-axis: time

Steep slope: means the distance between galaxies is getting bigger very quickly = fast expansion = large expansion rate

Shallow slope: small expansion rate



Expansion and Fate of the Universe

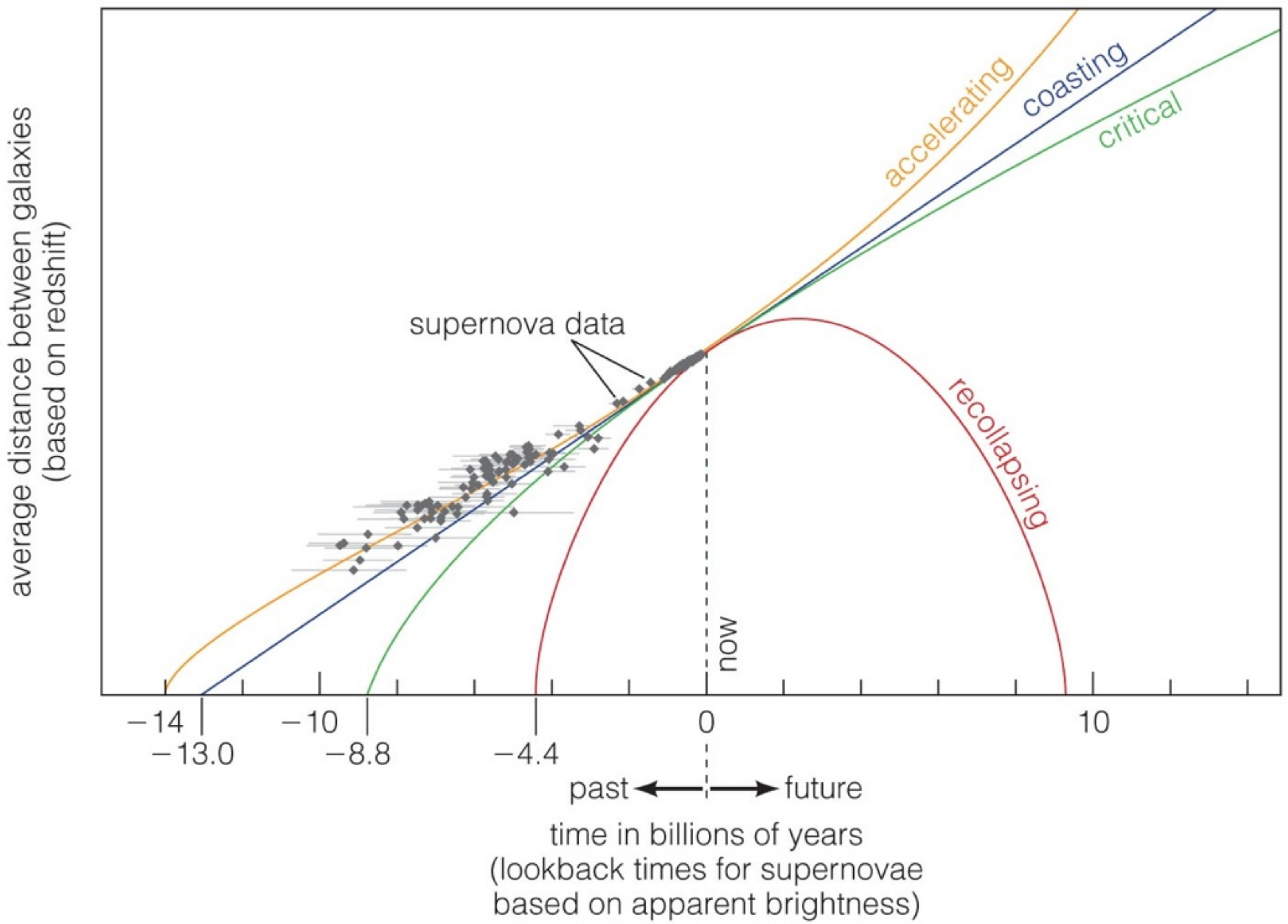
What determines the outcome?   Amount of mass-energy in the universe.

Use data from white dwarf supernovae to measure the expansion rate at different distances.

Recall: measurements at larger distances = measurements earlier in time

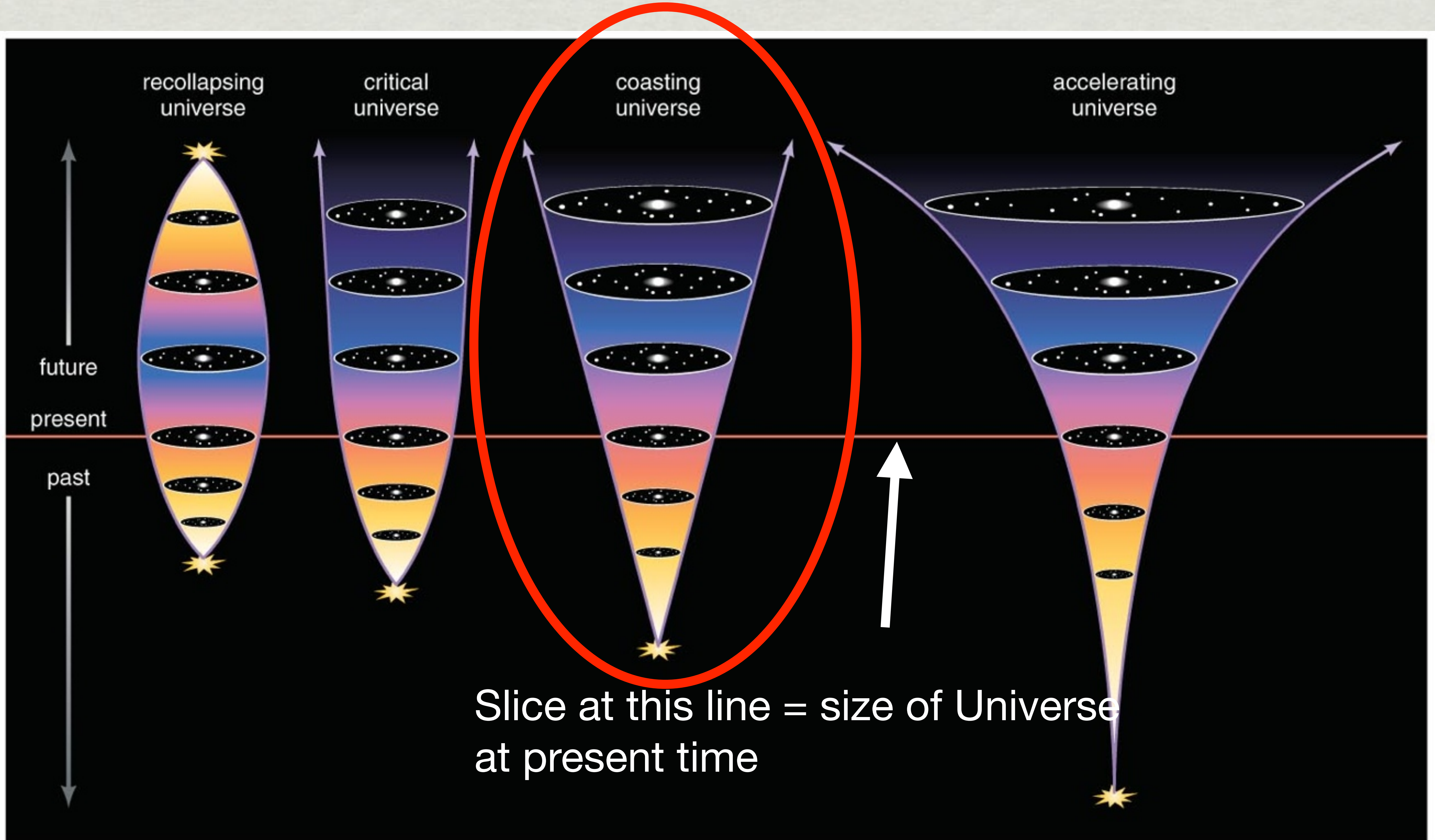
Notice: expansion rate is only constant (or close to constant) if the universe is coasting.

Why? Gravity doesn't have much mass to work with, so can't do much to slow the expansion rate.



Expansion and Fate of the Universe

Coasting universe: expansion continues to expand at about the same rate



Slice at this line = size of Universe at present time

Expansion and Fate of the Universe

Surprisingly, the data fit the accelerating model best (yellow line).
The expansion has been speeding up.
The universe will expand ***faster*** in the future.

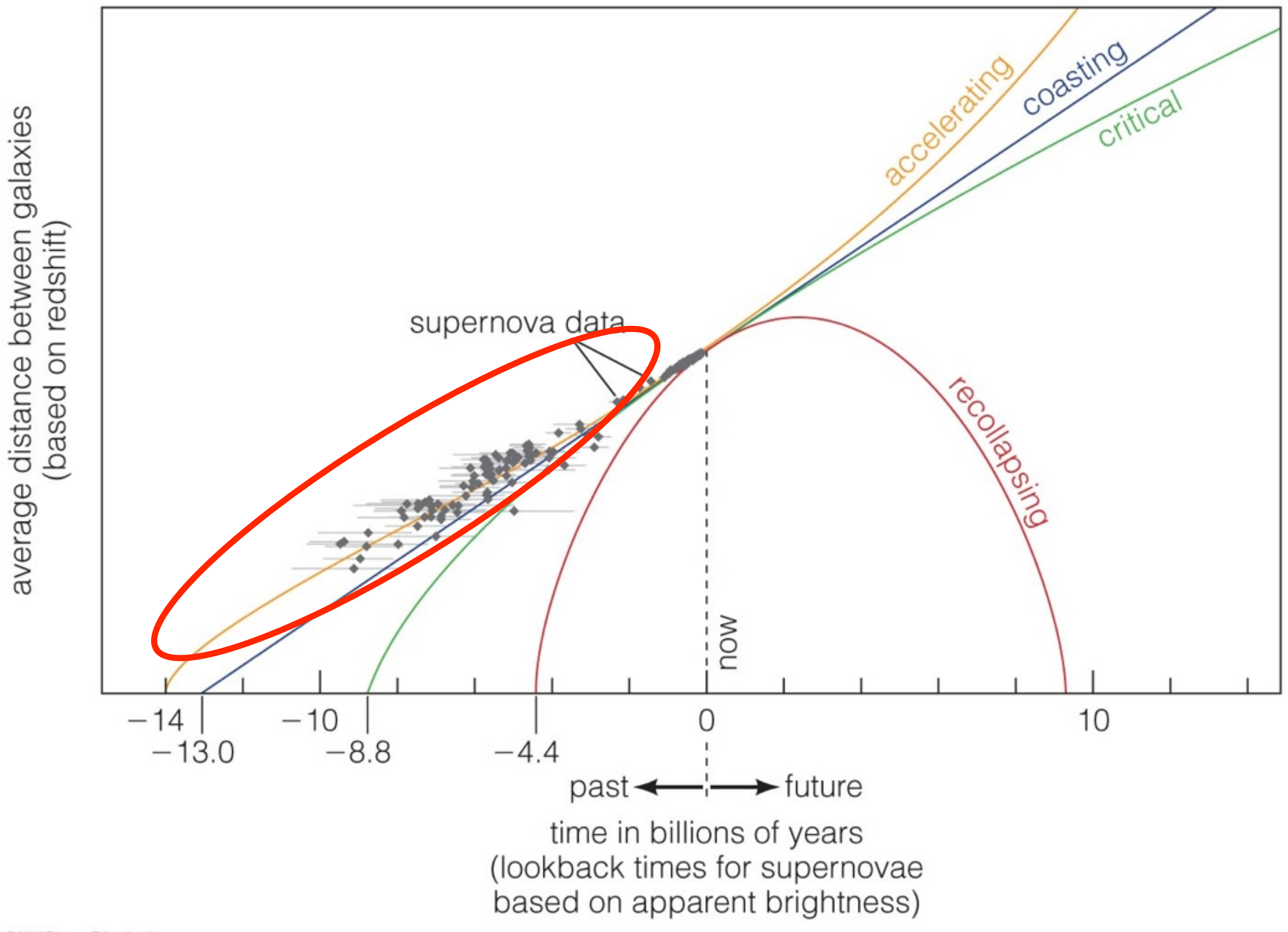
We know gravity acting on lots of matter (dark or baryonic) can slow expansion down.

What can speed it up?

We have ***no idea*** !

Call it “Dark Energy”

“Dark” because we can’t see it. Like dark matter, it doesn’t interact with light.



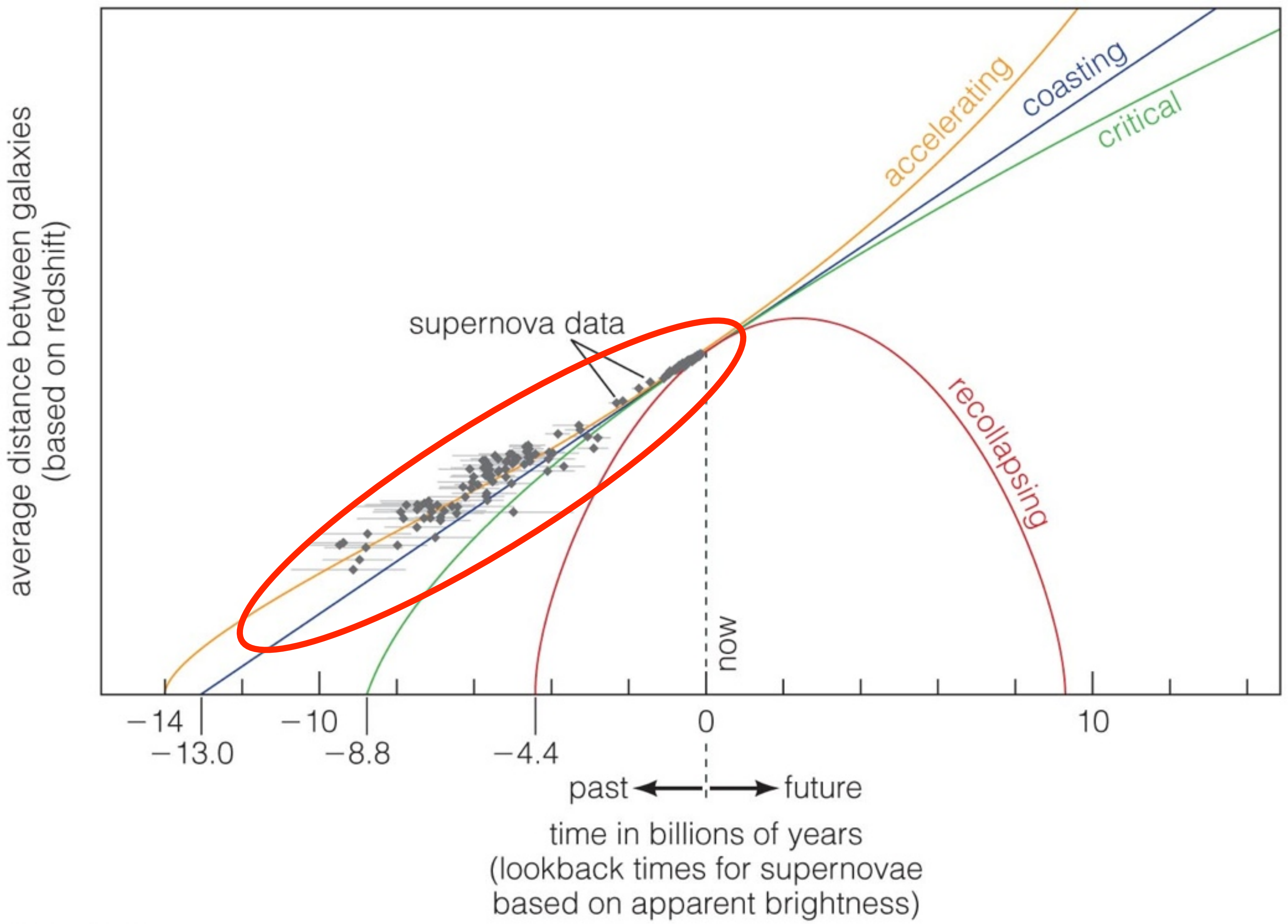
Dark Energy

“Dark” because we can’t see it. Like dark matter, it doesn’t interact with light.

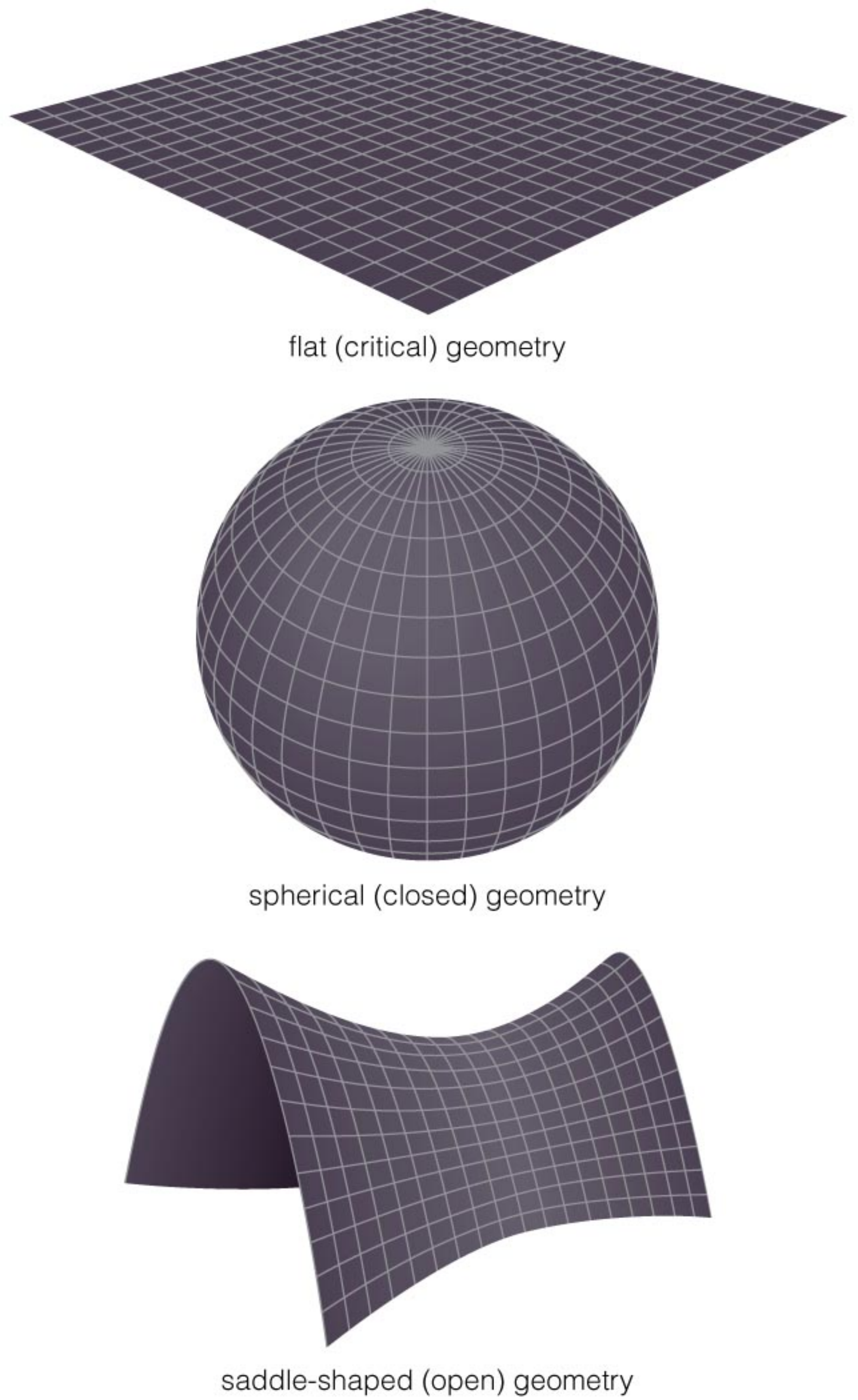
It’s not mass: gravity doesn’t work on it.

But it does contribute to the mass-energy of the universe.

Remember mass and energy are equivalent: $E=mc^2$



Expansion and Fate of the Universe



flat (critical) geometry

spherical (closed) geometry

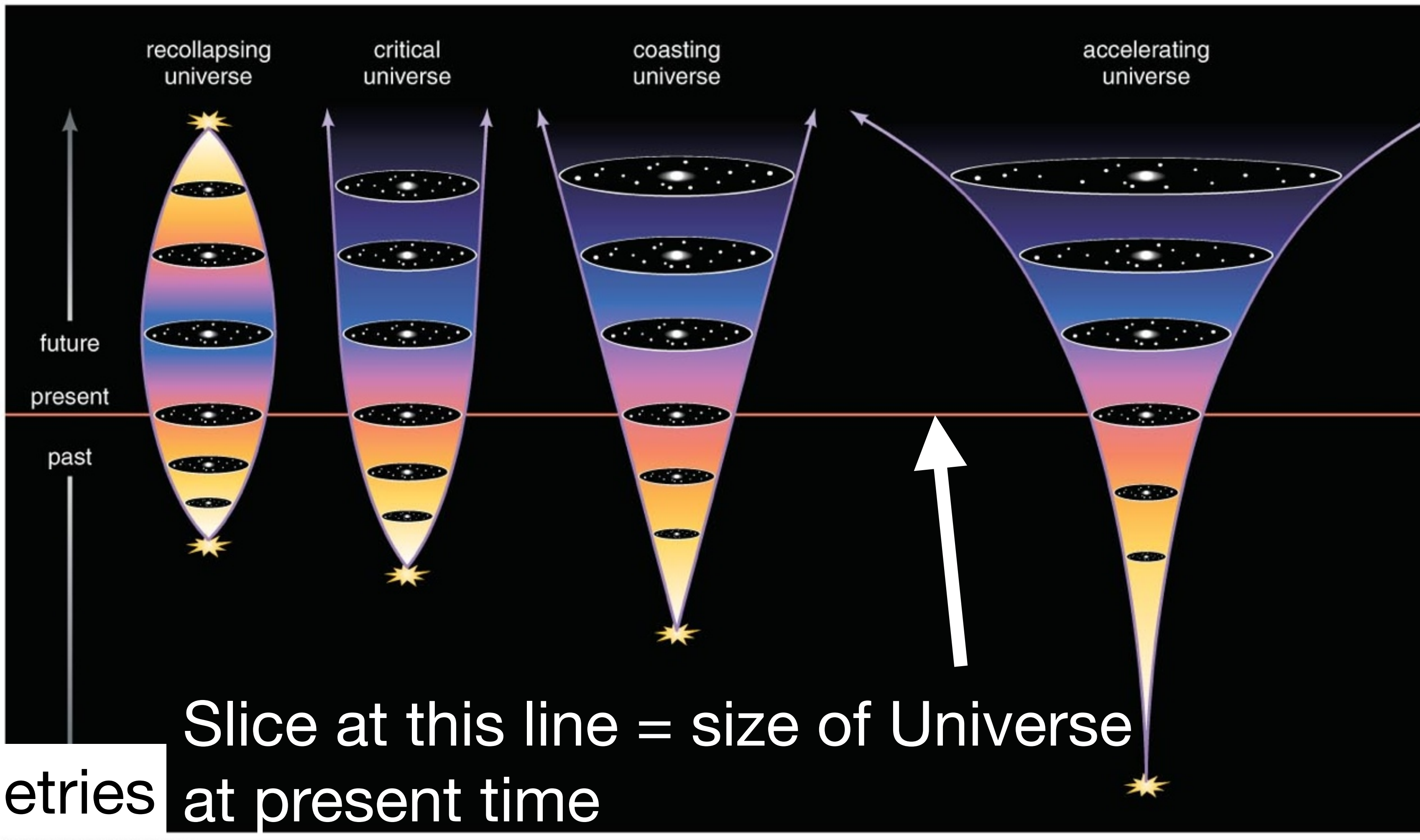
saddle-shaped (open) geometry

3D analogies of universe geometries

Mass curves space-time.

The mass-energy density of the universe determines its overall curvature.

How do we measure the mass-energy density of the universe?



Slice at this line = size of Universe at present time

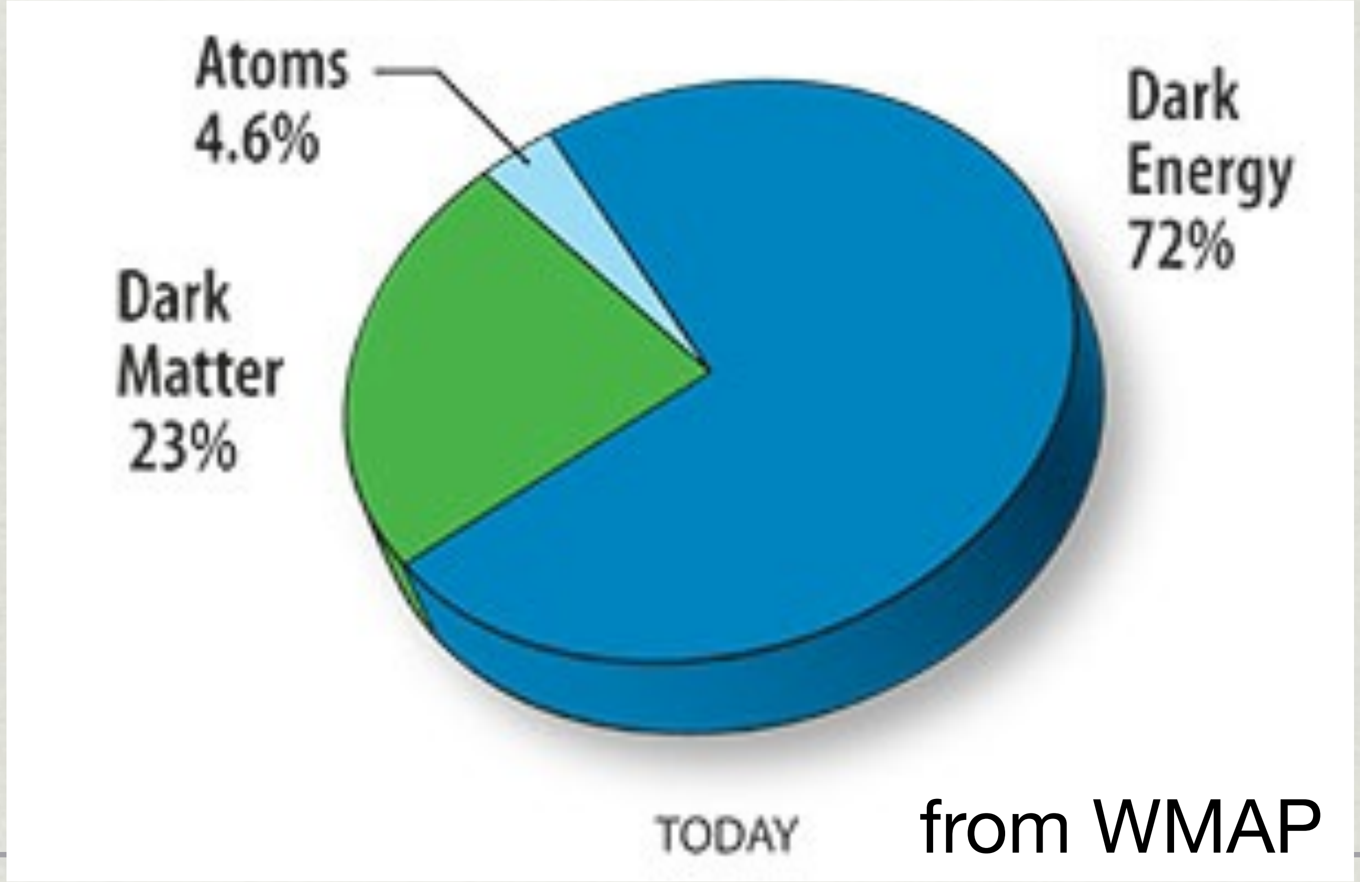
Embarrassing Accounting

We don’t know what dark matter is.

We don’t know what dark energy is.

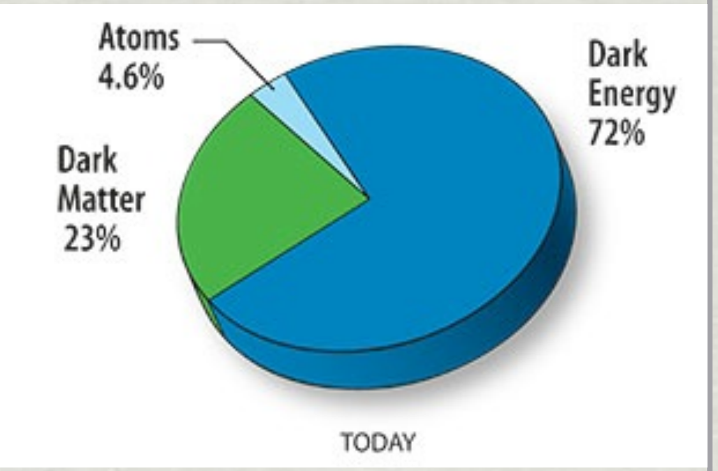
But those are all but 95.4% of what the universe is made of!

How do we measure the contents of the universe?



from WMAP

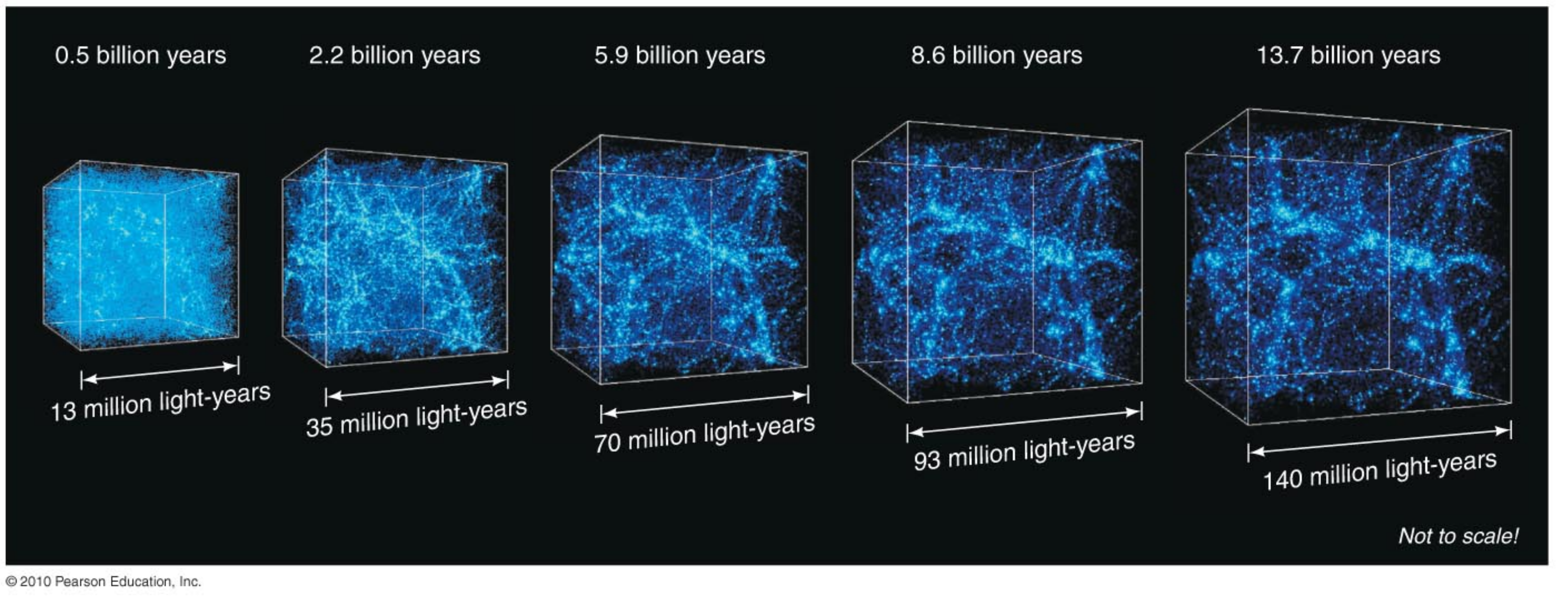
Contents of the Universe



How do we measure the contents of the universe?

1) Mass density (dark matter + baryons): use gravity. Measure how rapidly density variations in the CMB grow into galaxies and groups of galaxies.

Map galaxies at large distances (= far back in time), compare to measurements today (nearby galaxies).



How fast gravity can grow structure depends on how much mass there is for it to work on.

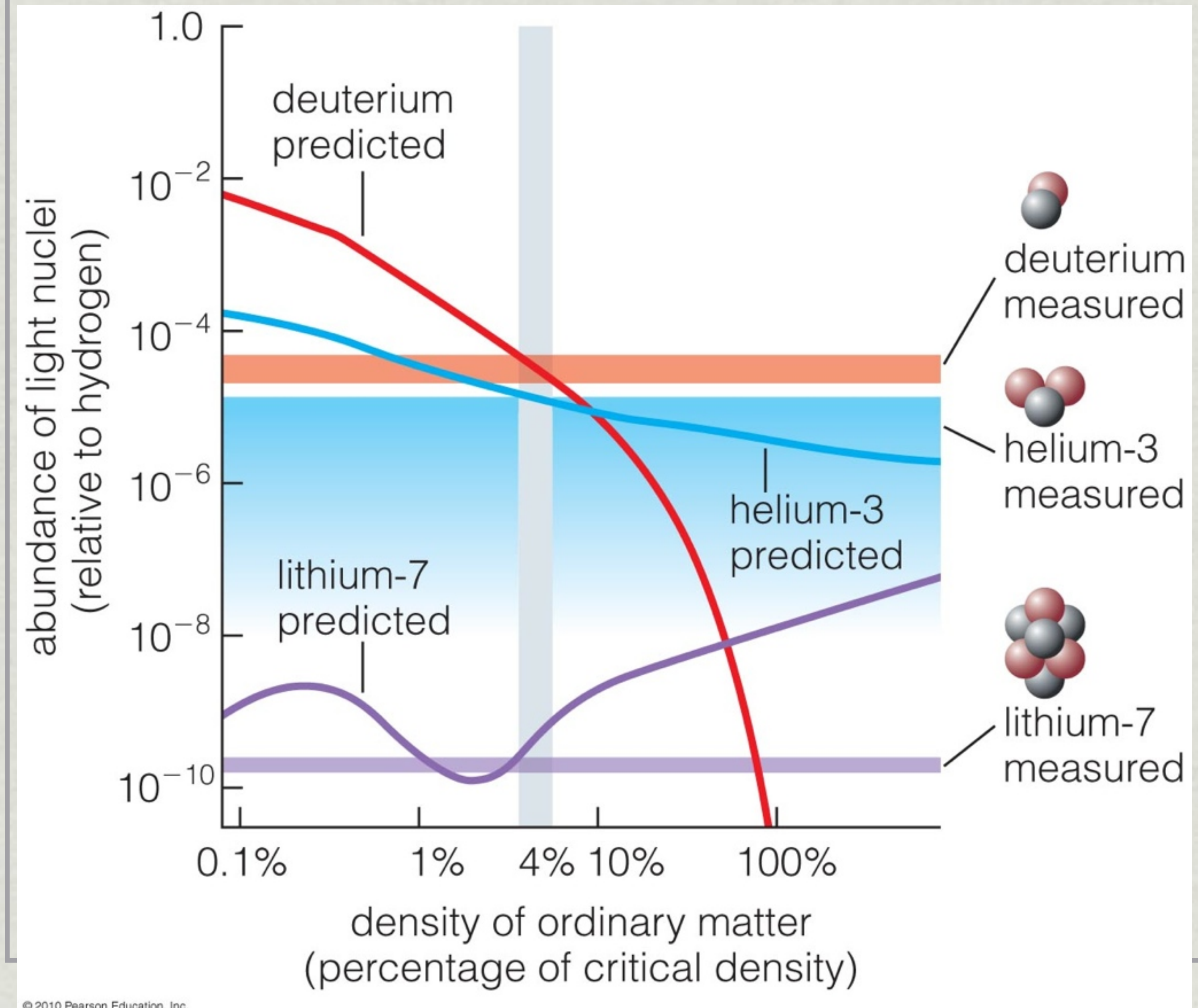
Computer simulation of density evolution.
Simulations with different mass content can be compared with data to find the best match.

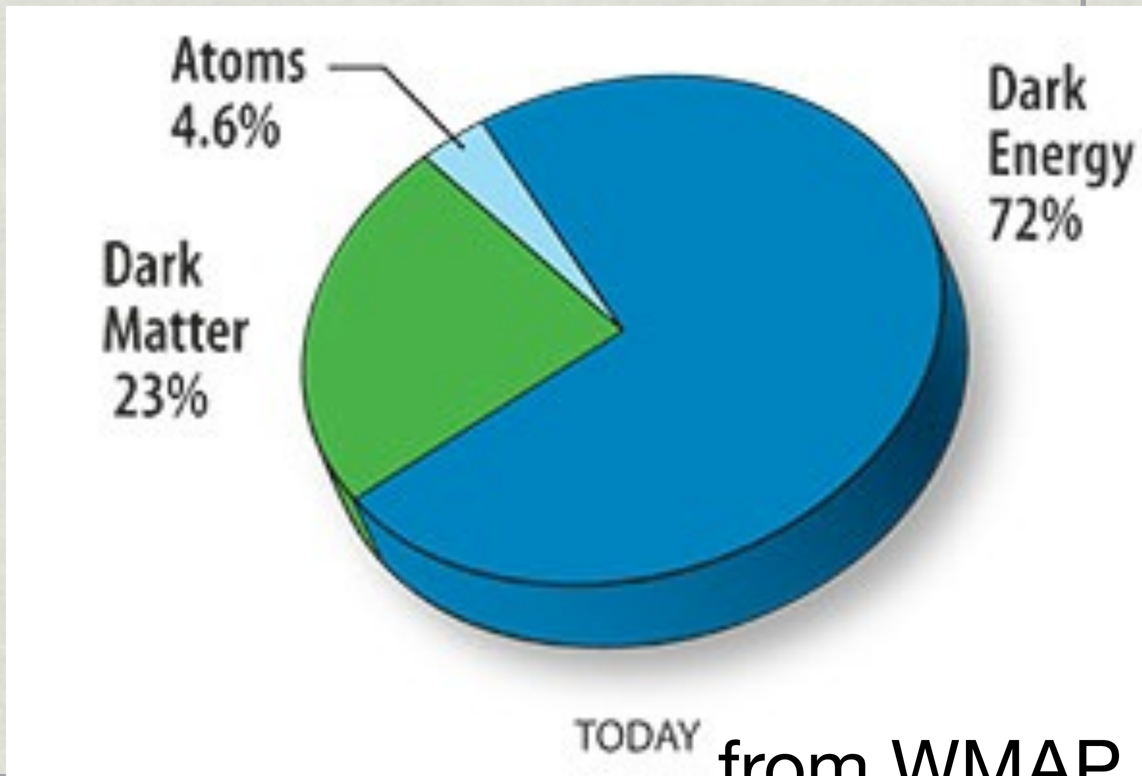
Contents of the Universe

How do we measure the contents of the universe?

2) Mass in baryons only: measure amount of Helium and other elements made in the early universe. Nucleosynthesis depends on density of baryons.

Then use: total mass - mass in baryons = dark matter mass





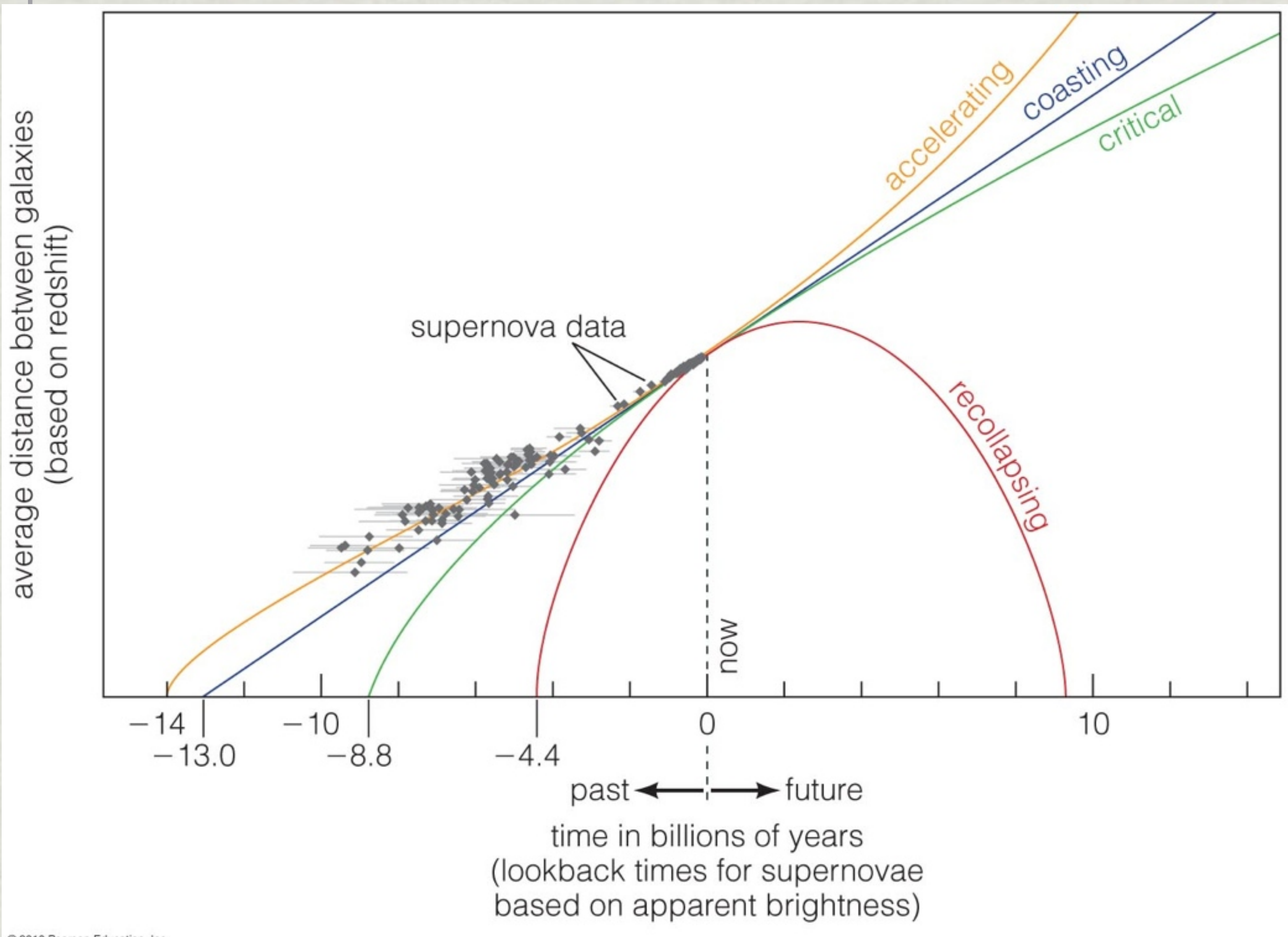
from WMAP

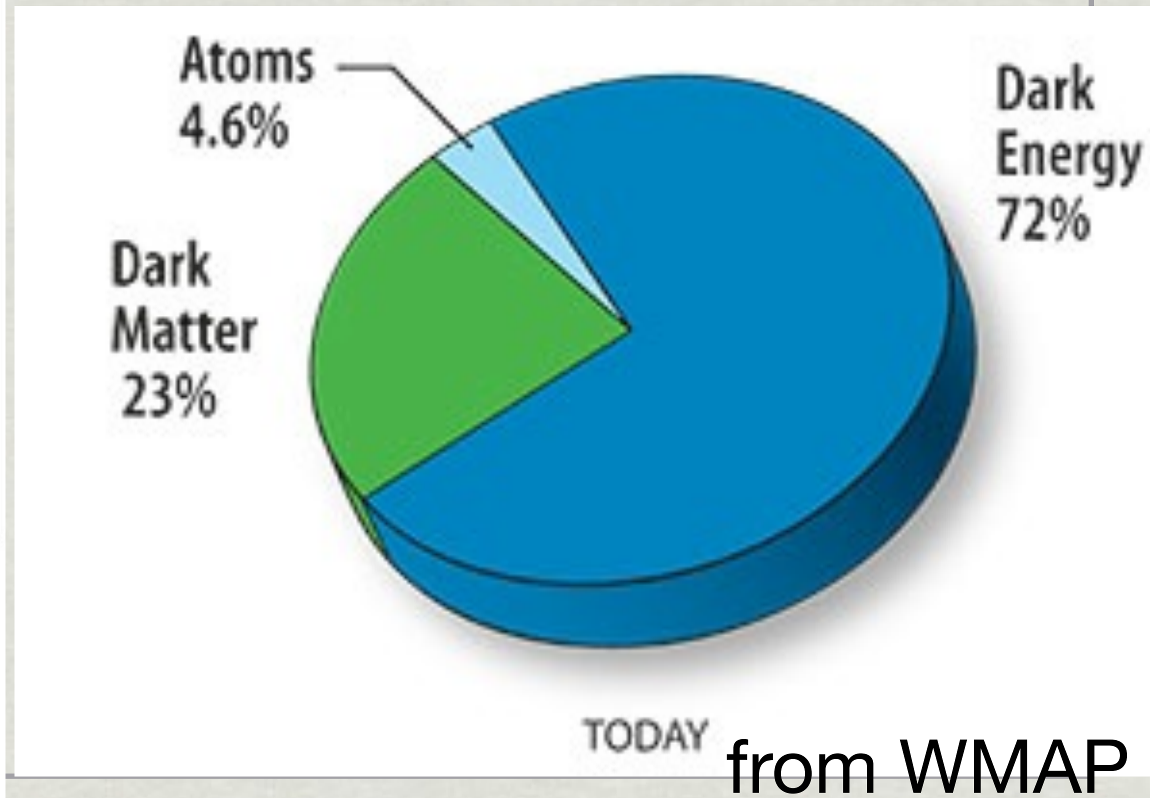
Contents of the Universe

How do we measure the contents of the universe?

3) Dark energy: from the acceleration of the universe.

More dark energy = faster acceleration.





from WMAP

Contents of the Universe

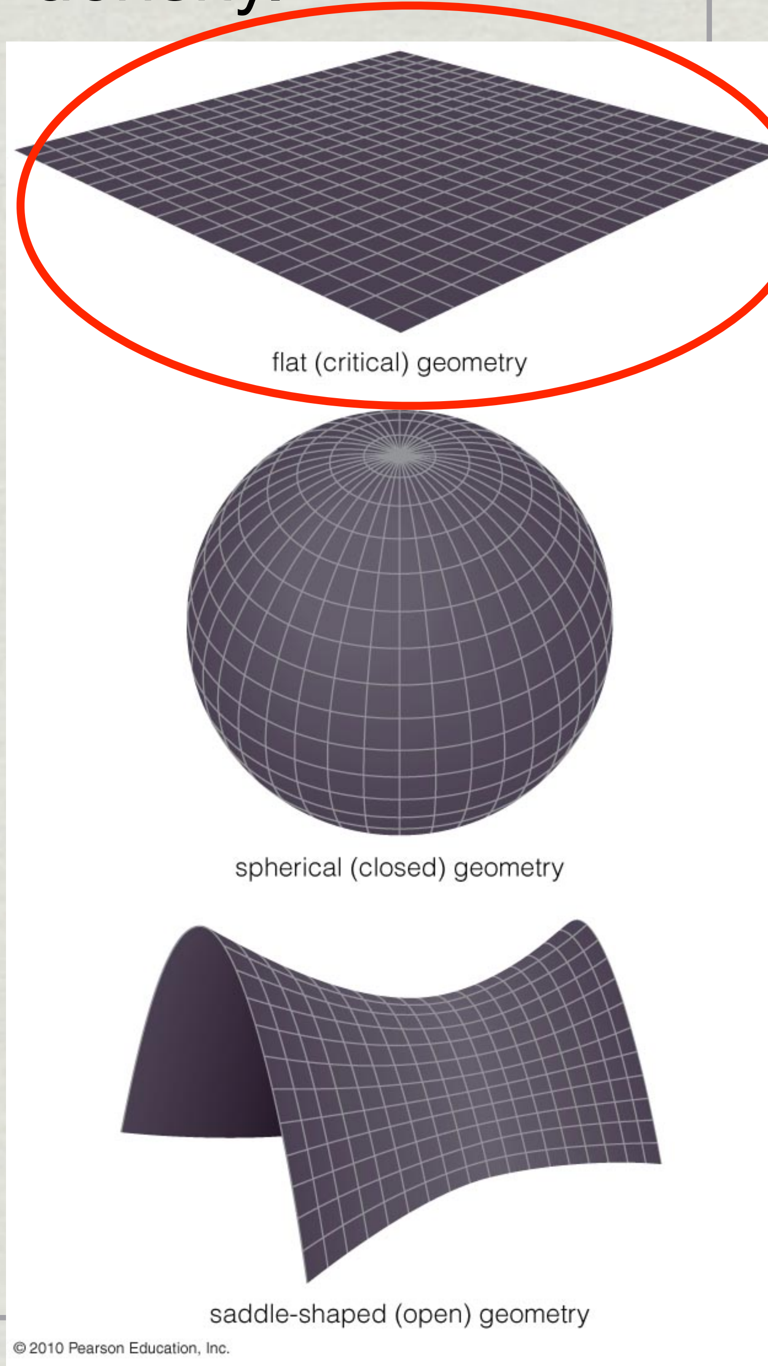
Density of baryons + dark matter + dark energy = total mass-energy density of the universe.

Remarkably, that total mass-energy density = the critical density.

That tells us that the curvature of space is flat.

On average! We know it is not flat locally: gravity keeps the planets in orbit around the sun, the galaxy together, the Milky Way and Andromeda on an collision course, …

Though we don't know whether the expansion will keep accelerating: that depends on what Dark Energy is and if it changes with time.



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Expansion and Fate of the Universe

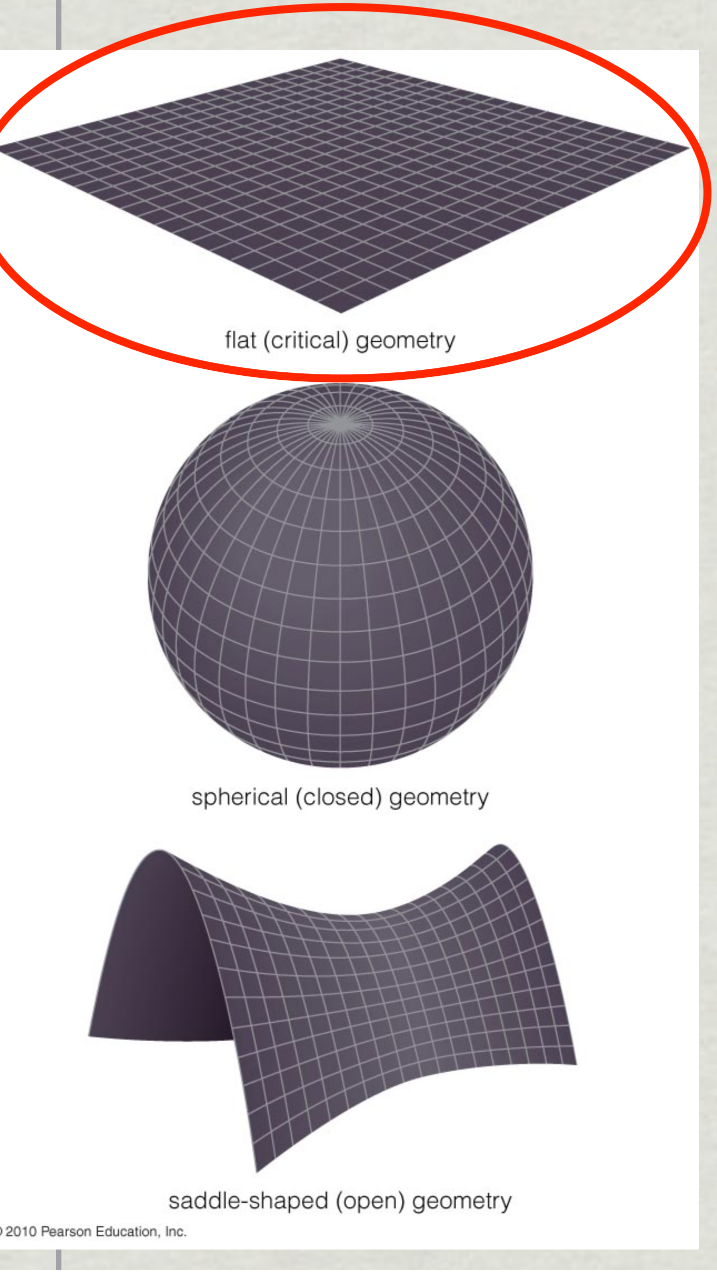
The total mass-energy density in the universe = the critical density.

That tells us that the curvature of space is flat.

But gravity doesn't work on Dark Energy, so the fate of the universe is not set by the curvature.

Our Universe is flat with critical density, but Dark Energy is causing the expansion to accelerate

We don't know if it will continue to accelerate: depends on what Dark Energy is and whether it changes with time



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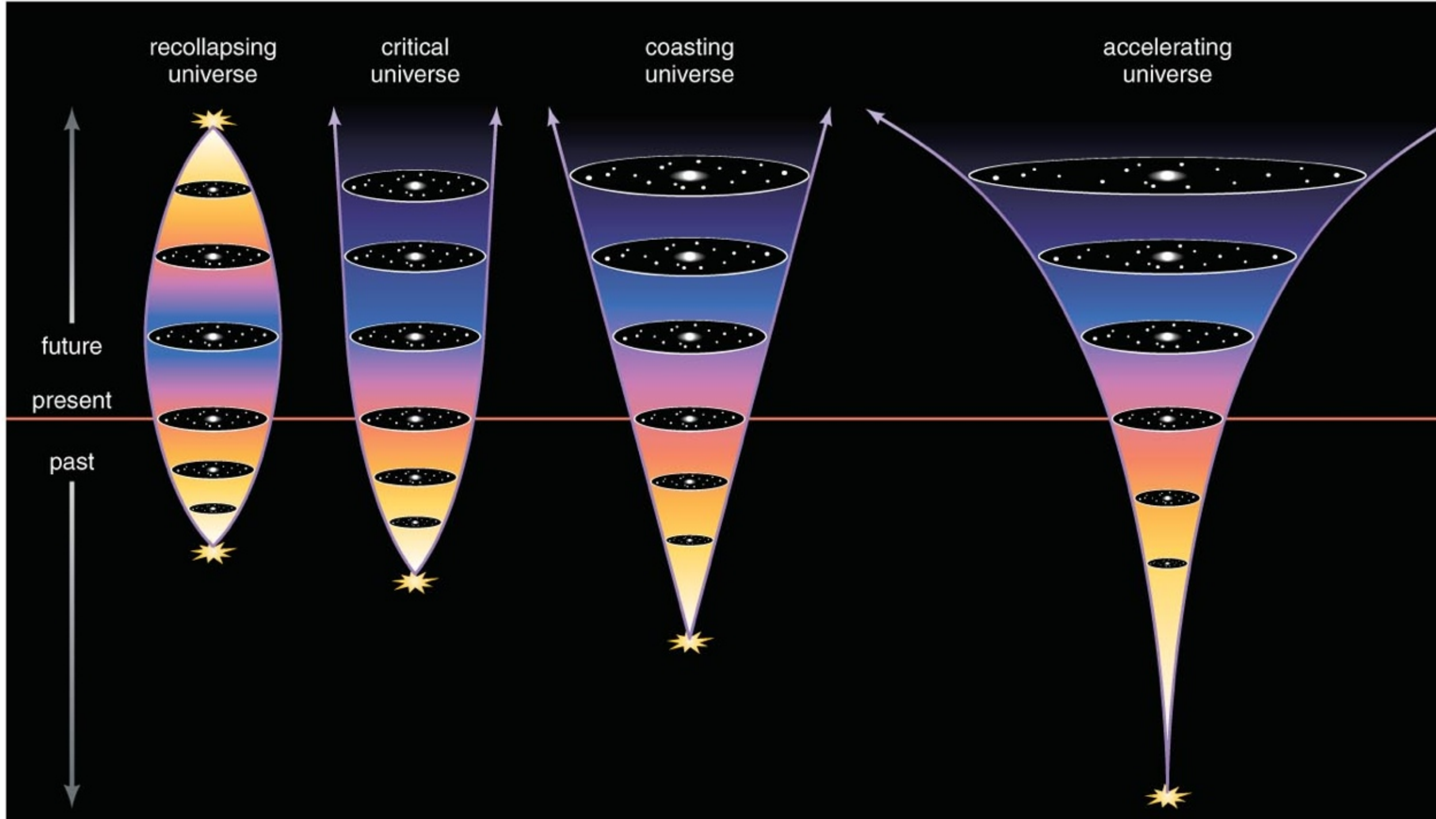
3D analogies of universe geometries



How Big is the Universe?

Horizon: farthest distance you can see

If you are looking out over the ocean, set by the curvature of the earth

The Cosmic Horizon

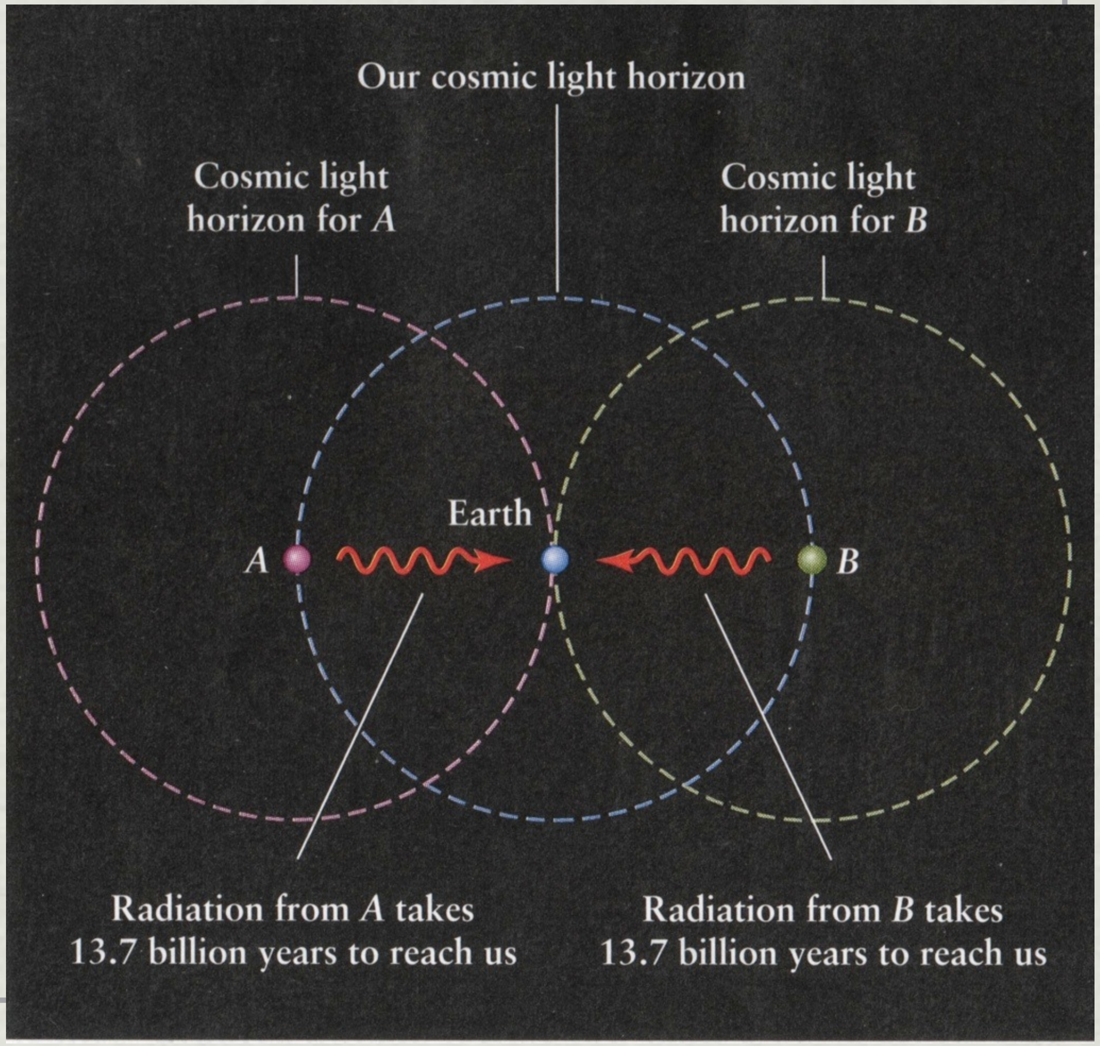
The cosmic horizon is the edge of the universe that we can see.

This is just the distance that light can travel in the time available.

Time available: age of the universe since the Big Bang = 13.8 billion years.

The cosmic horizon is
________ light-years away!

Think about this for
a few seconds...



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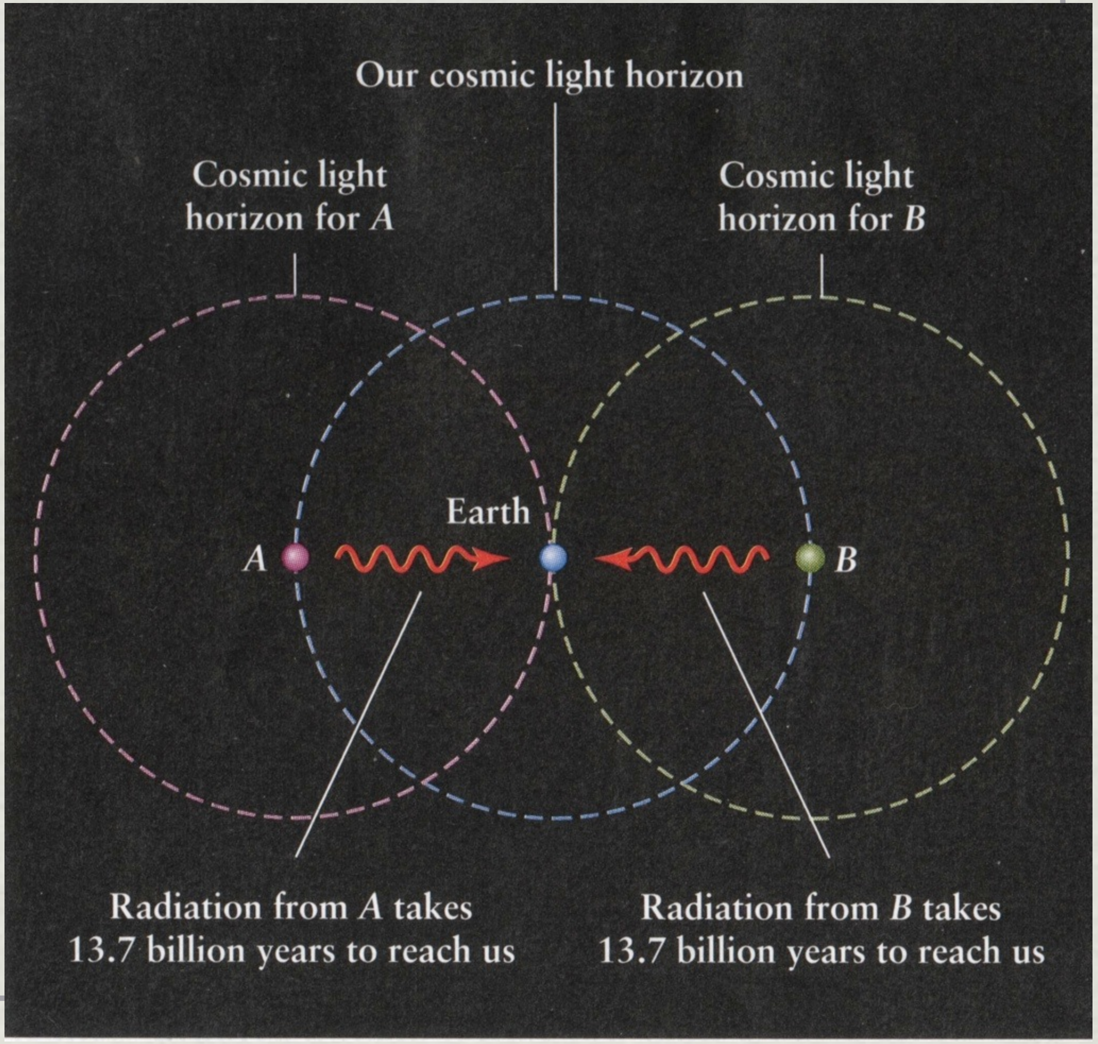
Time available: age of the universe since the Big Bang = 13.8 billion years.

The cosmic horizon is
________ light-years away!

A) 5 billion light-years
B) 13.7 billion light-years
C) 22 million light-years



The Cosmic Horizon

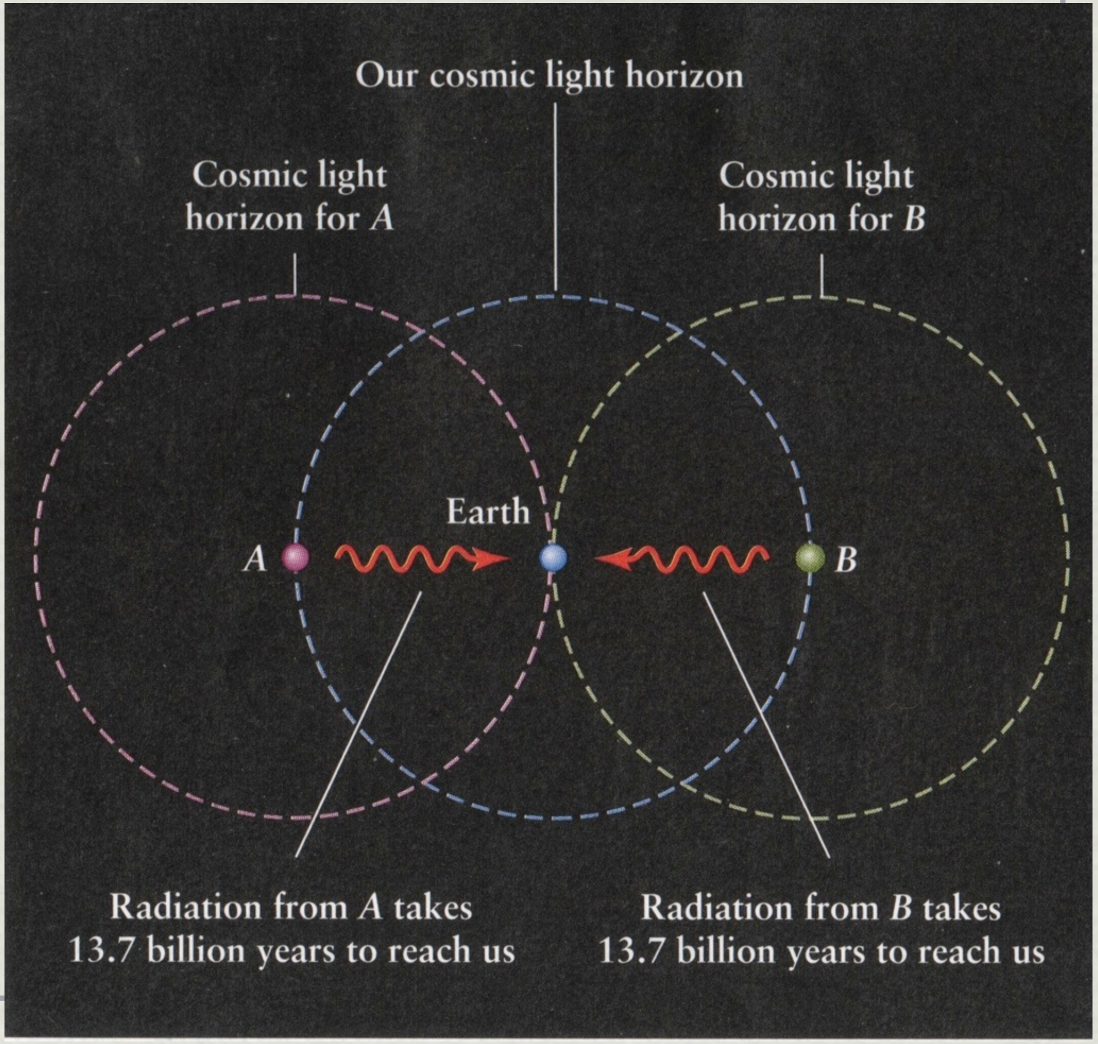
The cosmic horizon is the edge of the universe that we can see.

This is just the distance that light can travel in the time available.

Time available: age of the universe since the Big Bang = 13.7 billion years.

The cosmic horizon is
13.8 billion light-years away!

A) 5 billion light-years
B) 13.8 billion light-years
C) 22 million light-years



The Cosmic Horizon

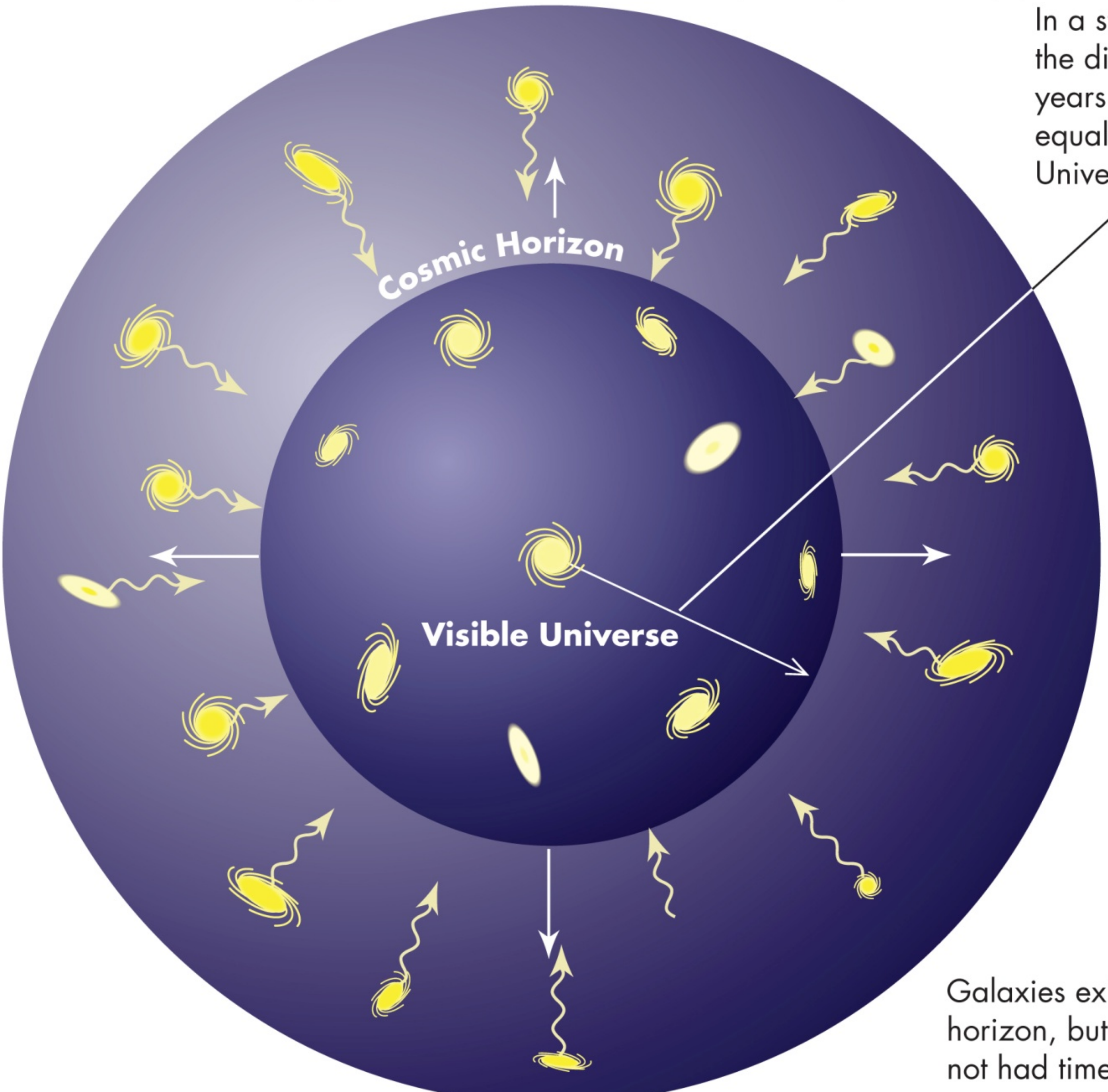
Horizon: farthest distance you can see

If a galaxy is more than 13.8 billion light years away, light from that galaxy takes more than 13.8 billion light years to reach us

There hasn't been enough time in the universe for it to get here.

So we can't see it.

It is outside our cosmic horizon.



In a static Universe, the distance in light-years to the horizon equals age of Universe in years.

Galaxies exist beyond horizon, but their light has not had time to reach us.

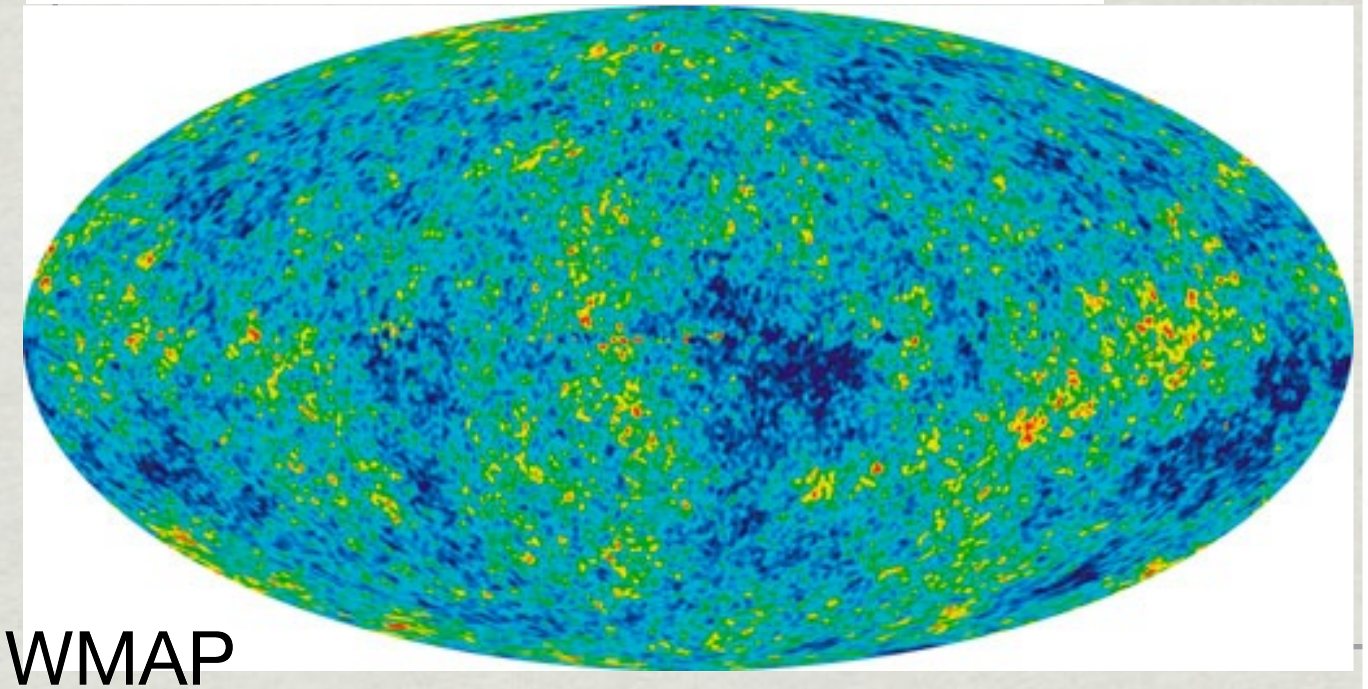
The Cosmic Horizon

Photons from the CMB: when the universe expanded and cooled enough to allow thermal radiation to stream freely throughout the universe.

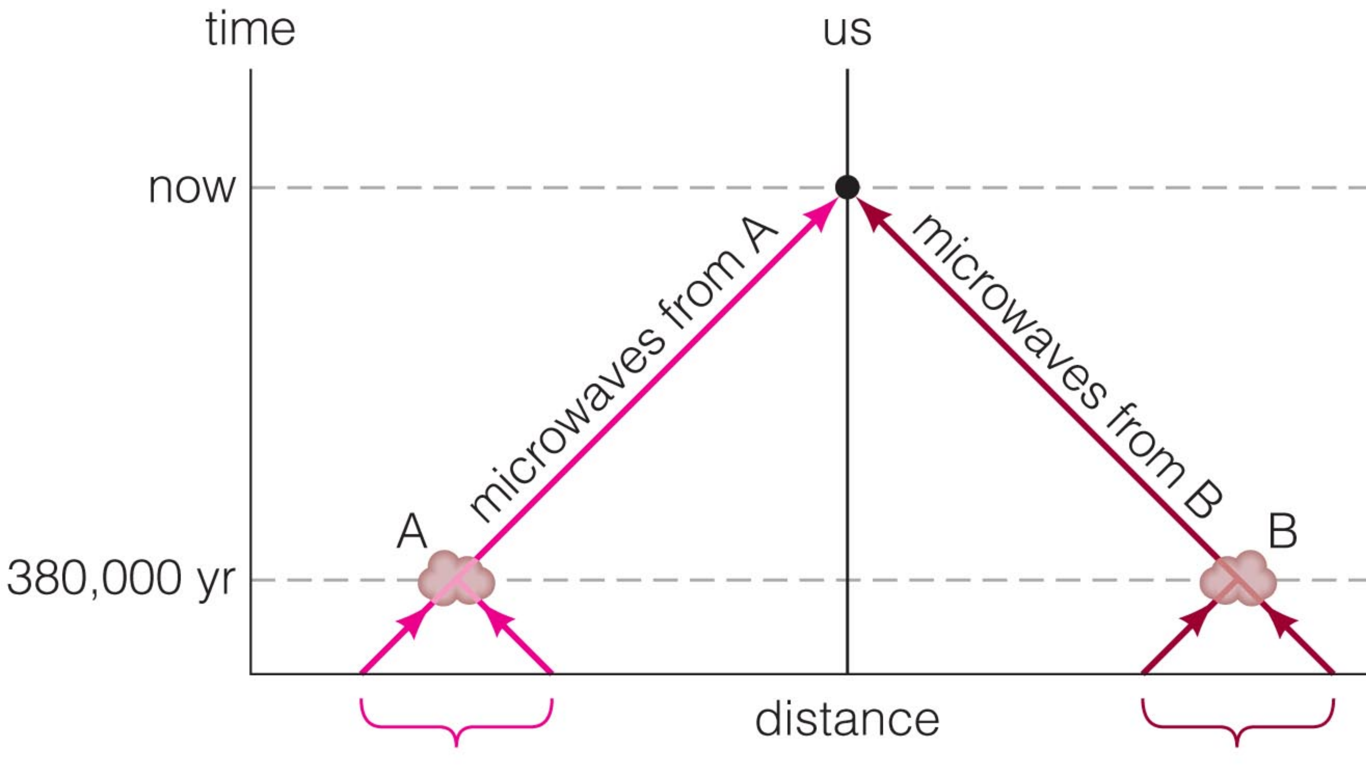
Those photons are just reaching us now, 13.8 billion years later.

So CMB photons from opposite directions on the sky cannot have been “in contact” with each other yet. **Ever.**

Variations: ±200 microKelvins

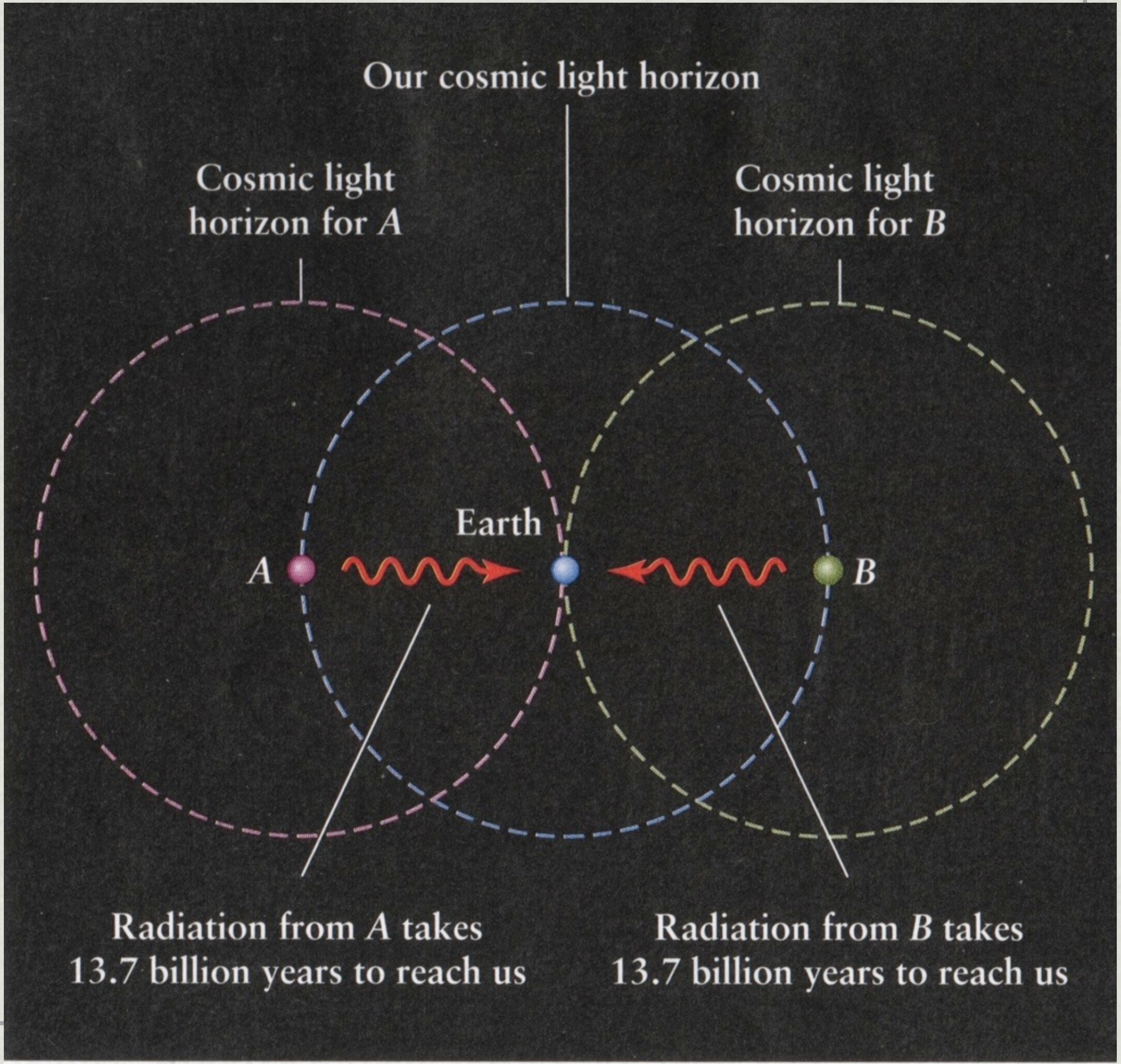


WMAP



The Cosmic Horizon

What does it mean for photons to be “in contact”? Collide, share energy, all the things that happen when radiation interacts with dense, opaque matter to make a thermal spectrum.



The Horizon Problem

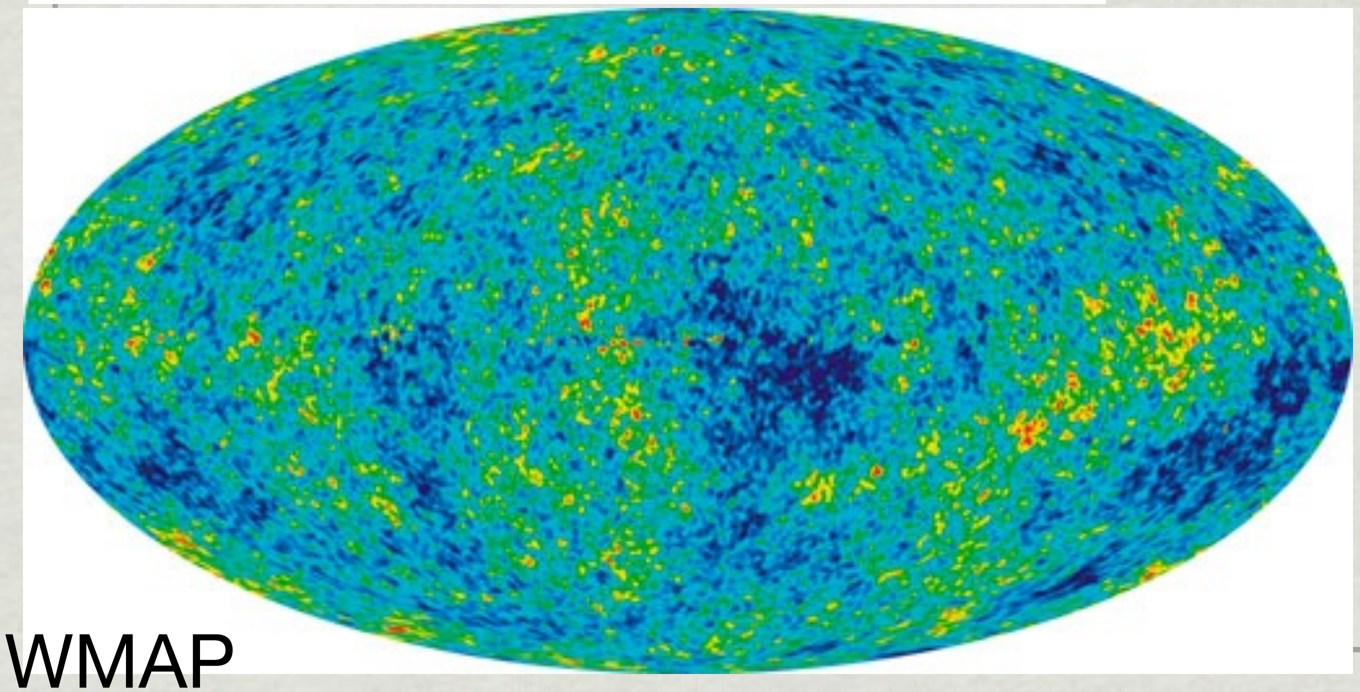
Photons from the CMB are just reaching us now, 13.8 billion years later.

So CMB photons from opposite directions on the sky cannot have been "in contact" with each other yet. **Ever.**

Including early on, when the universe was still opaque and photons were interacting with matter.

But the thermal spectrum of the CMB is incredibly uniform.

Variations: ±200 microKelvins



WMAP

So how did the universe become so uniform, so close to the same temperature everywhere?

We need to go back to what the universe was like when it was still dense and opaque, before it became transparent to the CMB