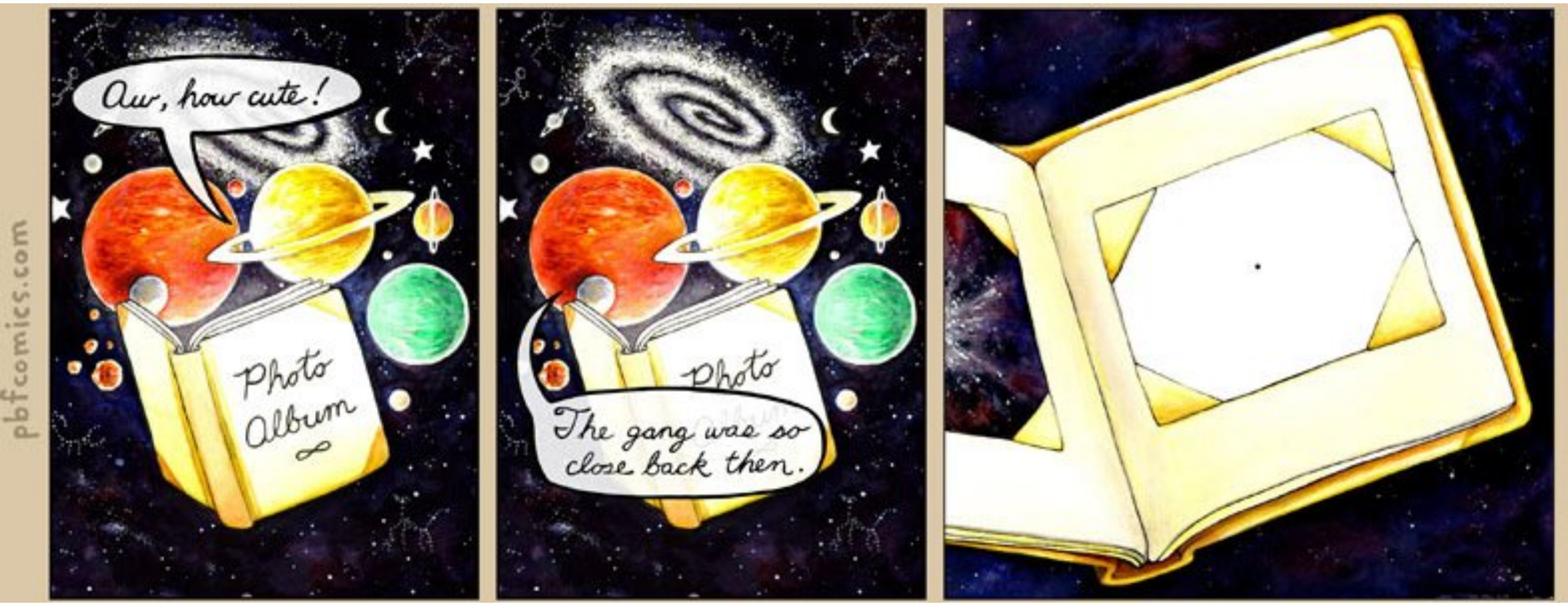
Killer Skies



- **HW 11** due next Monday
- Exam 3, Dec 11
- Last time: Hubble's Law
- Today: Big Bang

Music: *Rocket Man* – Elton John

Hour Exam 3

Hour Exam 3 Wed, Dec 11th, in class

- information on course website
- 40 questions (cover material from Nov 4 to Dec 9: Lect 25-36)

May bring 1-page of notes

- both sides
- printed, handwritten, whatever

Most useful study materials

- class notes
- iClicker questions
- study guide
- homework questions
- old exam

Focus on concepts, main ideas

The Big Bang Theory

- The early Universe was filled with energy – hot and dense
- It then began to expand
- As space expanded, it became less dense and cooler
- Eventually forming the stars and galaxies we see today

An idea proposed by Georges Lamaître, a Belgian priest. The early Universe was filled with energy – hot and dense
It then began to expand. As spacetime expanded, the Universe became less dense and cooler. Eventually forming the stars and galaxies we see today. In 1949, Sir Fred Hoyle called this theory the "Big Bang". He was actually trying to ridicule it. But the name stuck.

The Age of the Universe

Imagine: "switch off" gravity (!?)

- then galaxies are free bodies
- each coasts with its own constant speed v

if Universe today has age t_0

- then a galaxy with constant speed v has gone
- distance: $d = v\, t_0$

Combine with Hubble's law

- which says $v = H_0\, d$
- with H_0 a measured constant (Hubble's constant)

Math:

- $d = v\, t_0 = H_0\, d\, t_0$
- distance cancels! $H_0\, t_0 = 1$

solve: age of Universe **$t_0 = 1/H_0 = 13.6$ billion years**

In reality: gravity not switched off!

- our analysis too simple
- but more careful job gives similar answer! -- 13.8 billion is the correct age.

Context:

- age of Sun & Earth: 4.55 billion years -- good!
- age of oldest stars 13 billion years -- good!

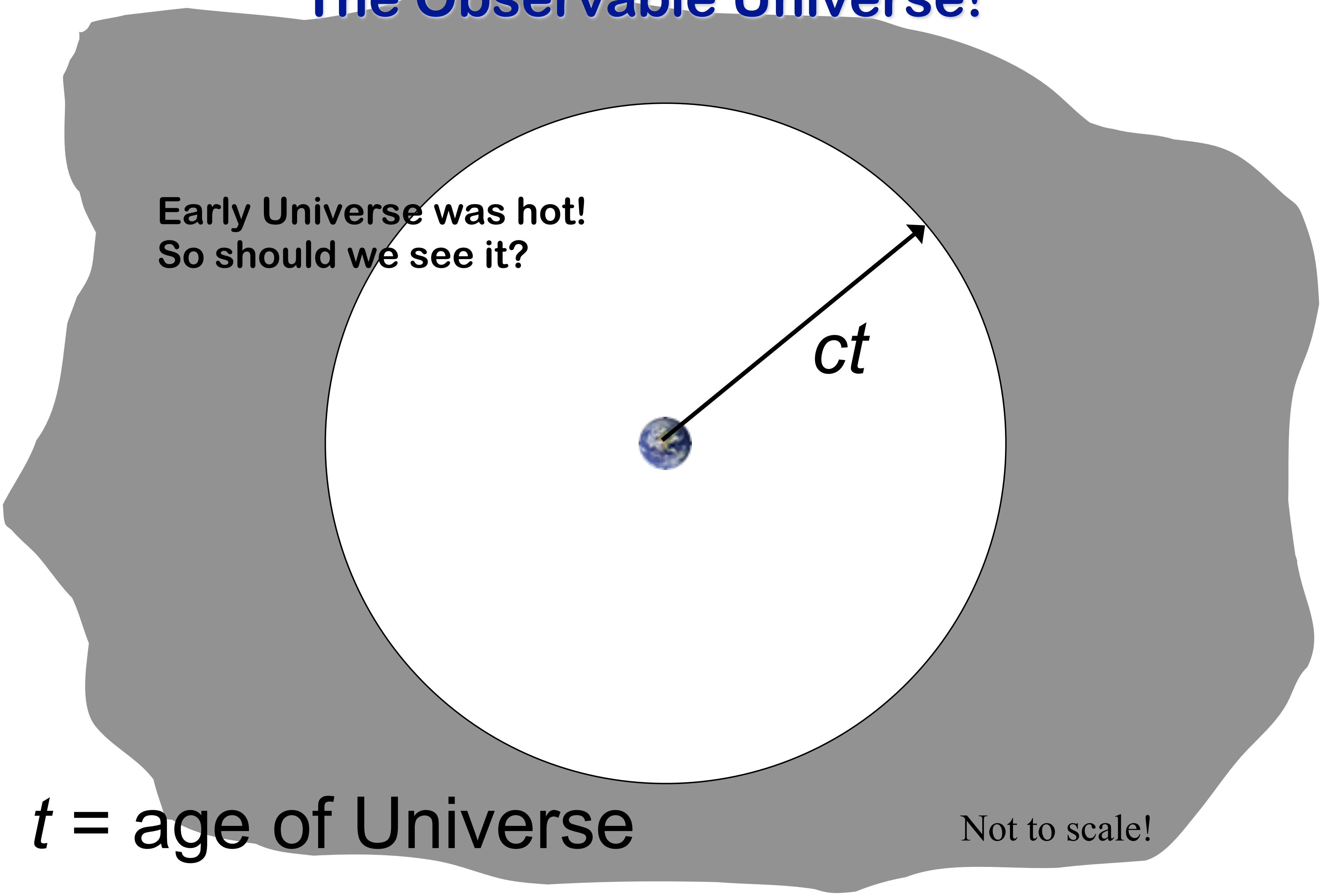
Thought Question

Over time, the Universe has gotten...

A. smaller, cooler, and more dense
B. bigger, hotter, and more dense
C. bigger, hotter, and less dense
D. bigger, cooler, and more dense
E. bigger, cooler, and less dense

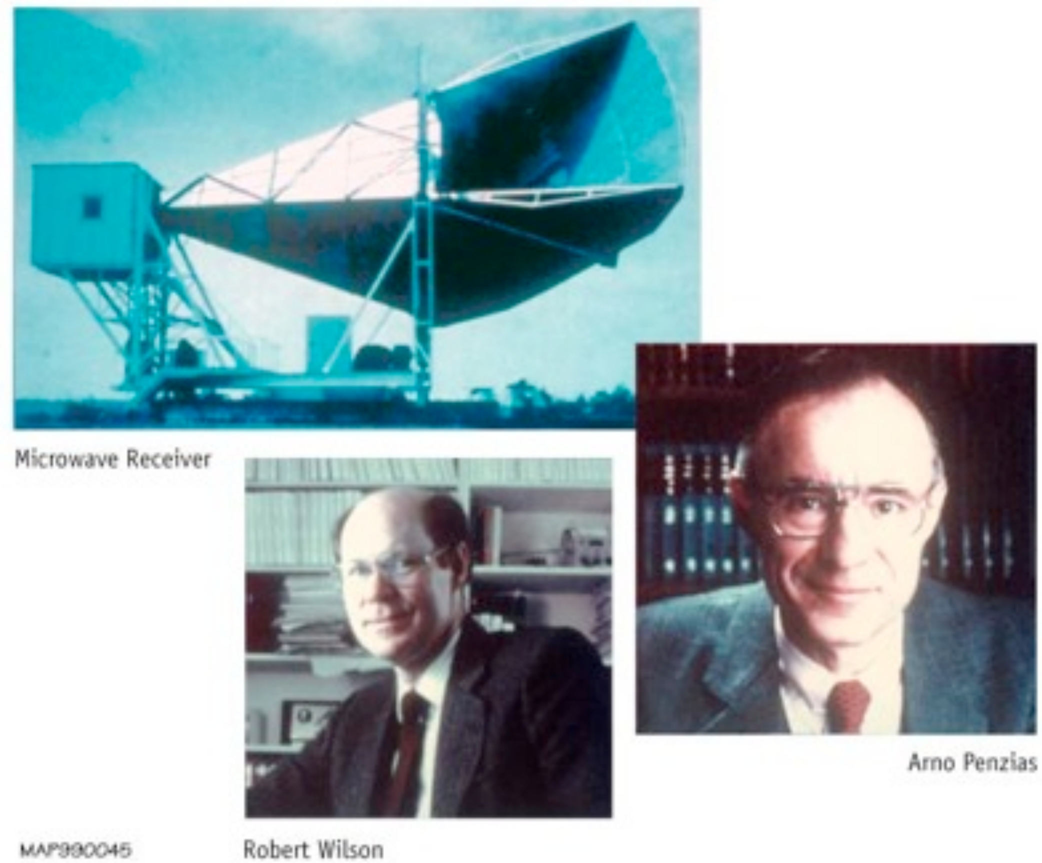
Answer: E. Universe is expanding, Because of that, it is getting cooler and less dense.

Looking Back in Time: The Observable Universe!



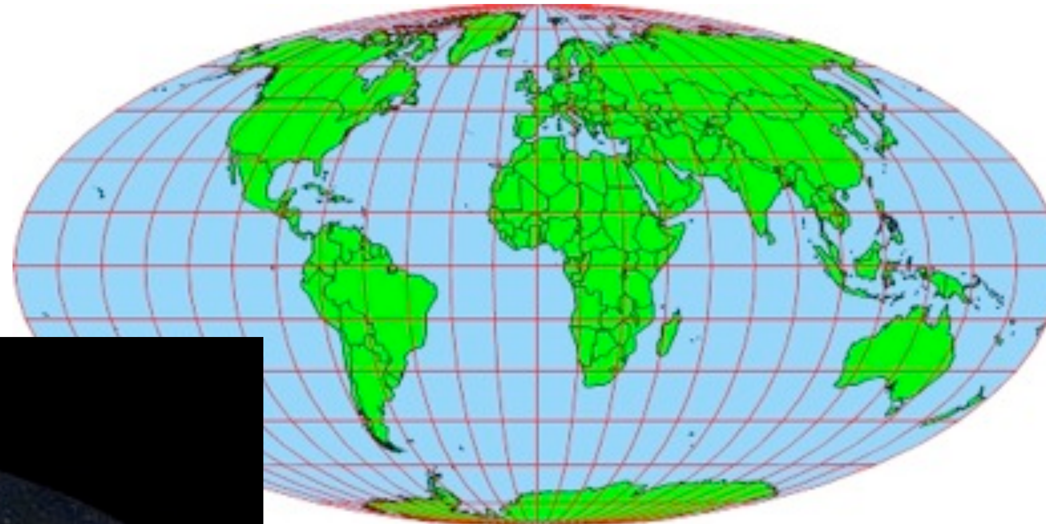
The Early Universe was HOT!

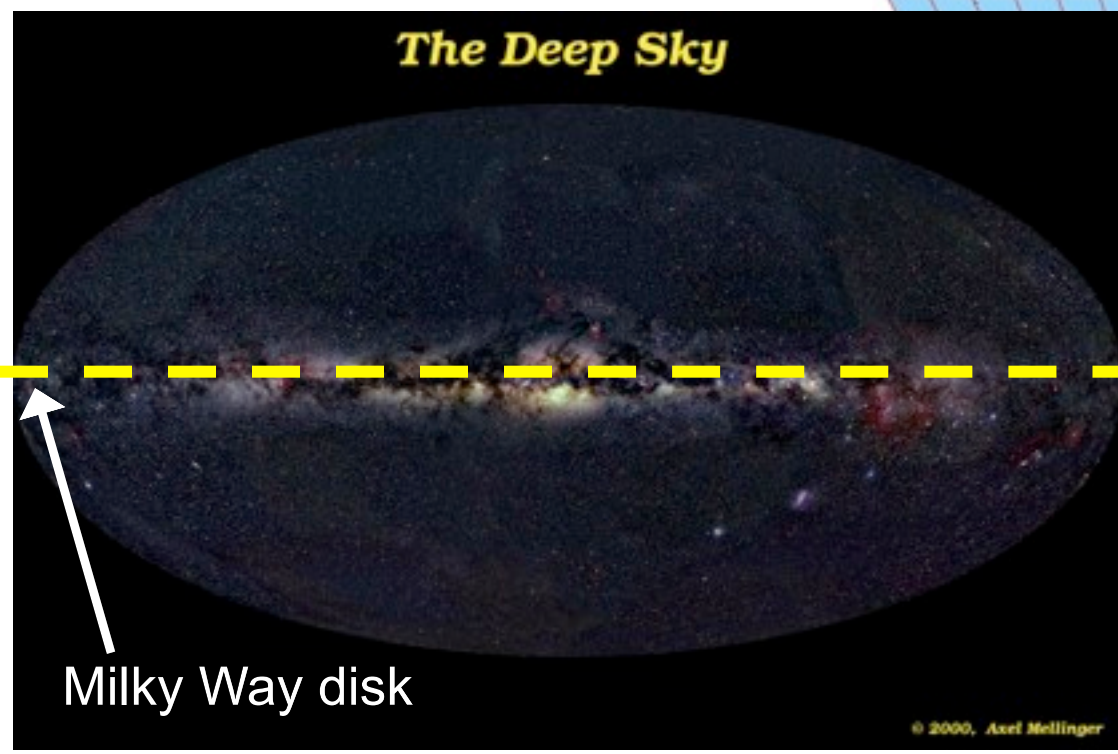
- Recall: hot objects glow!
- If the early Universe was so hot, we should be able to see it glowing too. Right?
- Yep, we do! But, as the Universe expanded, the glow redshifted down to the microwave--invisible to our eyes.
- Now, it is called the Cosmic Microwave Background (CMB).



First detected by Robert Wilson and Arno Penzias. Won the Nobel Prize-- short paper with amazing result and changed the world

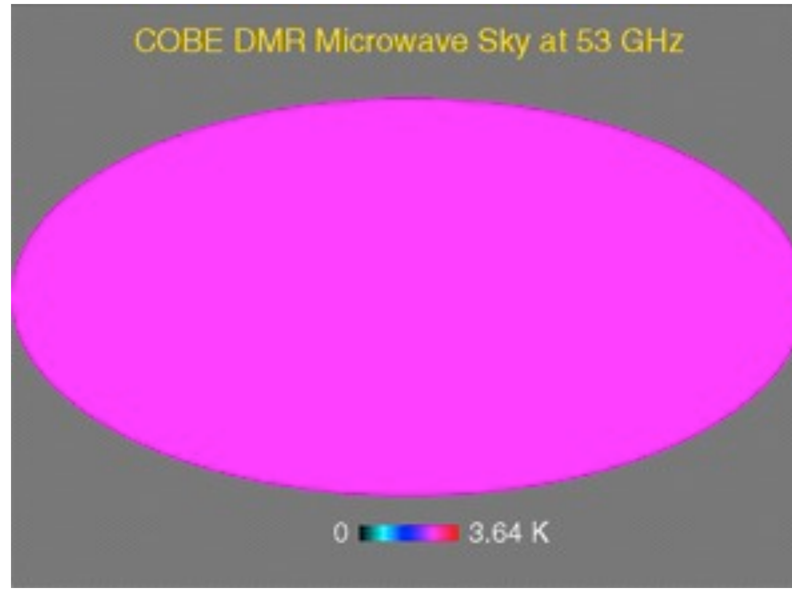
How to Understand Sky Maps

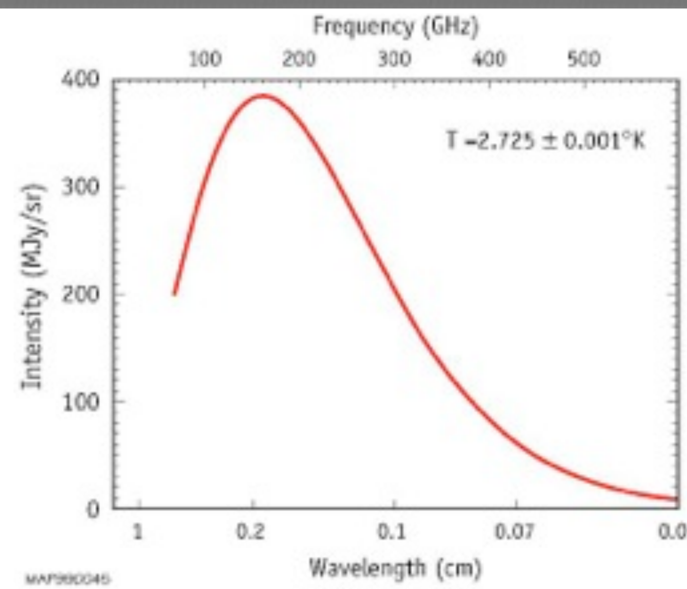




Fantastically Uniform Thermal Emission

- **All over the sky, we see thermal radiation**
  - the Universe has a temperature!
  - in fact: T = 2.73 K today
    - cold! barely above absolute zero!
- **Provides compelling evidence for the Big Bang Theory**
- **Temperature nearly the same in all directions**



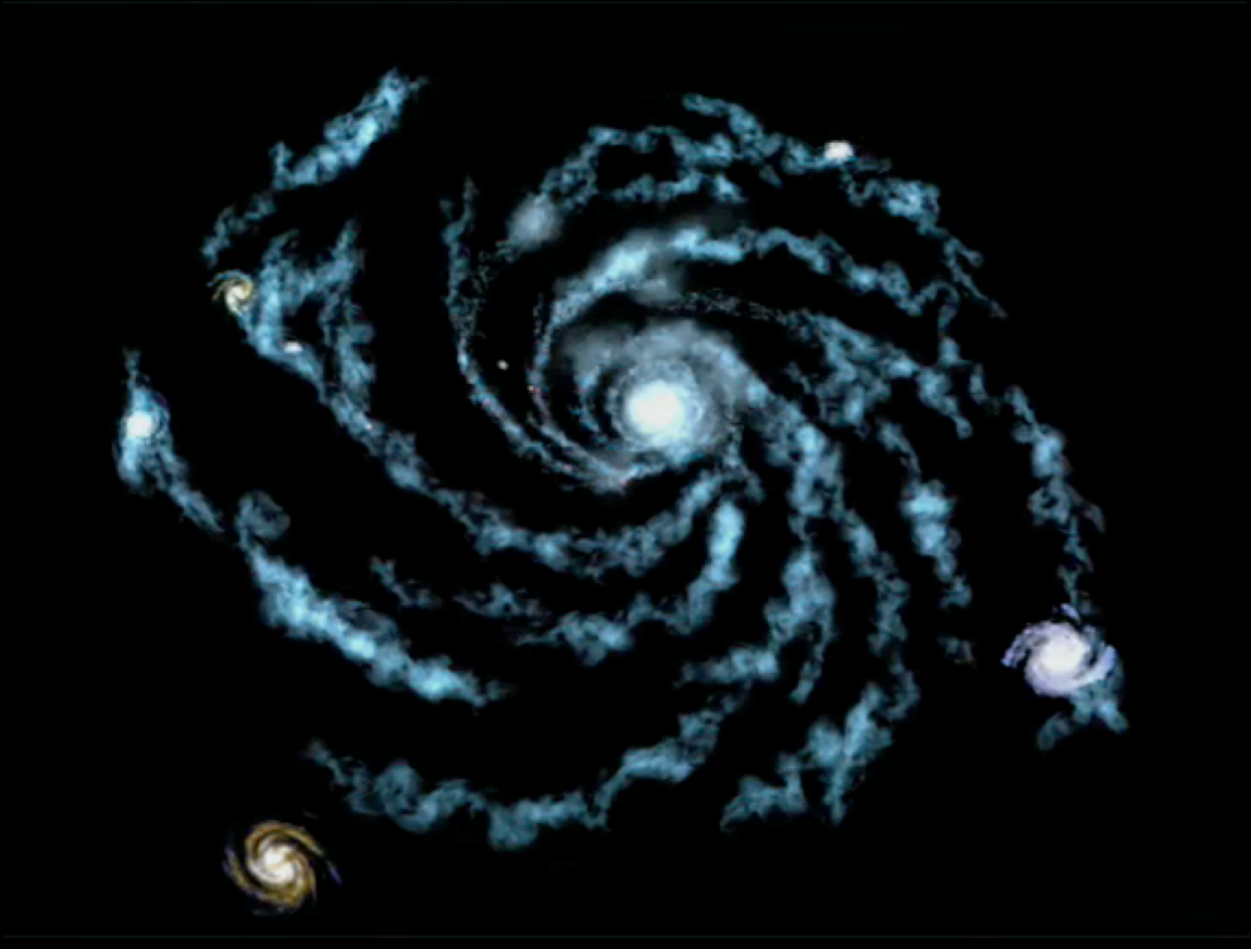


Cosmic Background Explorer
(COBE) satellite
(launched 1989)

very isotropic! Indicates that, over large scales, the Universe is indeed smoothly filled with matter: homogeneous

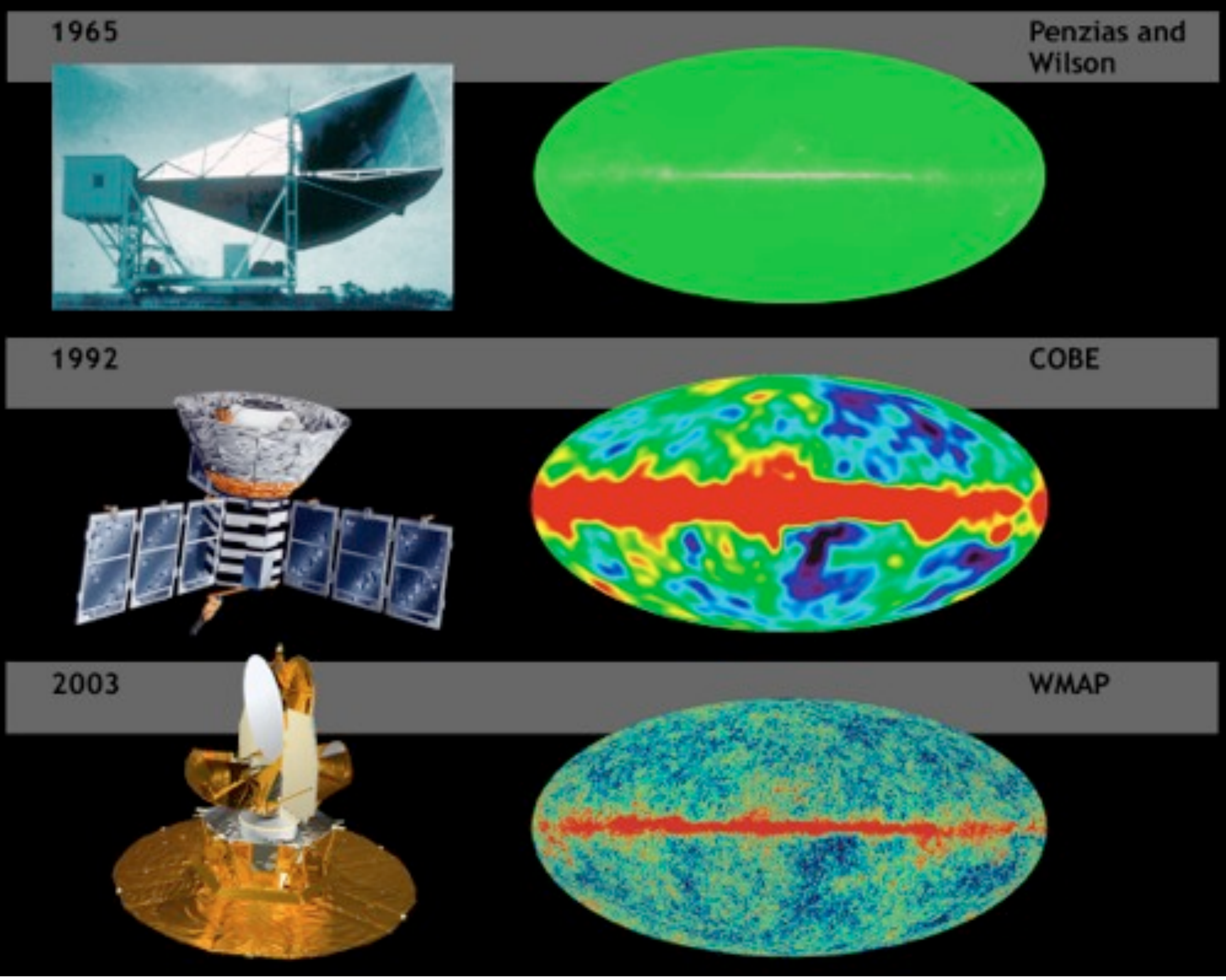
Turning Up the Contrast
Is the CMB temperature perfectly uniform?

http://map.gsfc.nasa.gov/media/030640/index.html



Turning Up the Contrast
Is the CMB temperature perfectly uniform?

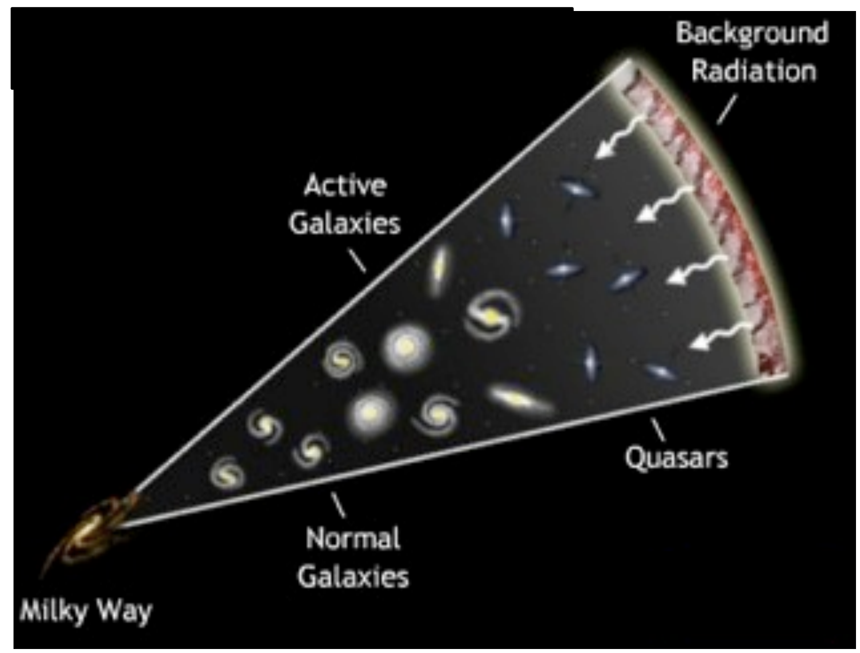
No! T fluctuates across sky: differences in 5th decimal place!



Where is this from exactly? Remember the early Universe was too dense to see light from, so this is some time after the big bang. How long?

What is the history of the Universe according to the Big Bang theory?

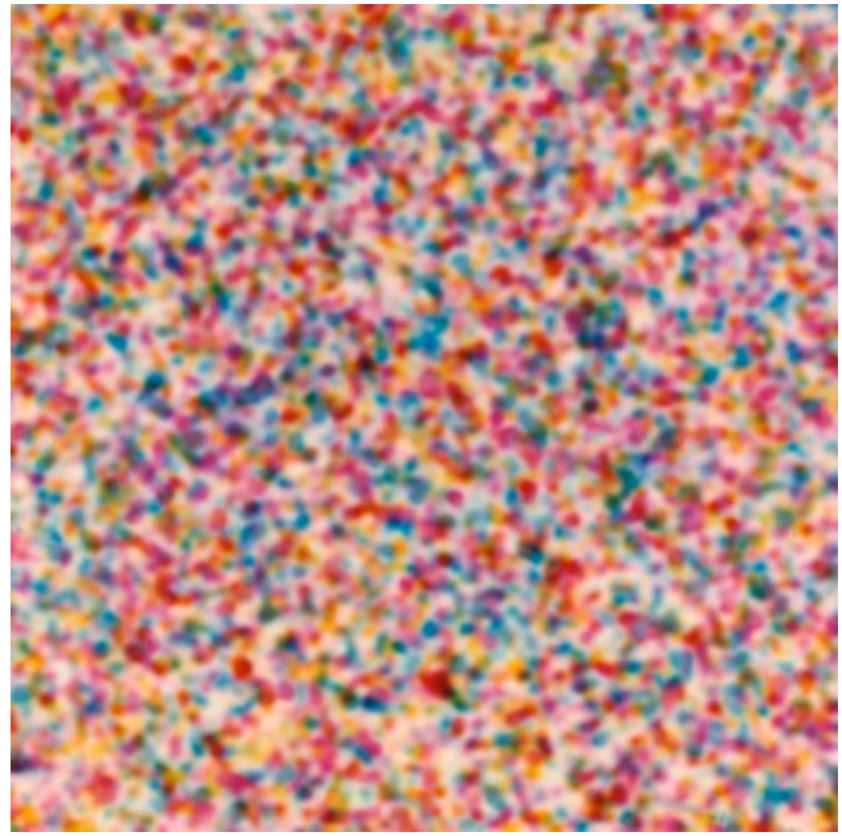
- Cannot begin the history of the Big Bang at time zero
  - Physics not understood
- At the moment of the Big Bang
  - Observable Universe was smaller than an atomic nucleus
  - Compact Universe = freaky high density, freaky high temperature



At the moment of the Big Bang. Our current observable universe was smaller than an atomic nucleus. Compact universe = high density, high temperature. Universe cooled as it expanded. Cosmologists cannot begin their history of the big bang at time zero. No one understands the physics of matter and energy under such extreme conditions. Nevertheless, they can come amazingly close.

The Universe at 0.0000001 seconds

- Average temperature well over 1 trillion K (10^{12} K)!
- Filled with high-energy gamma-ray photons and exotic particles
- As the universe expanded and cooled, protons and neutrons then began to form

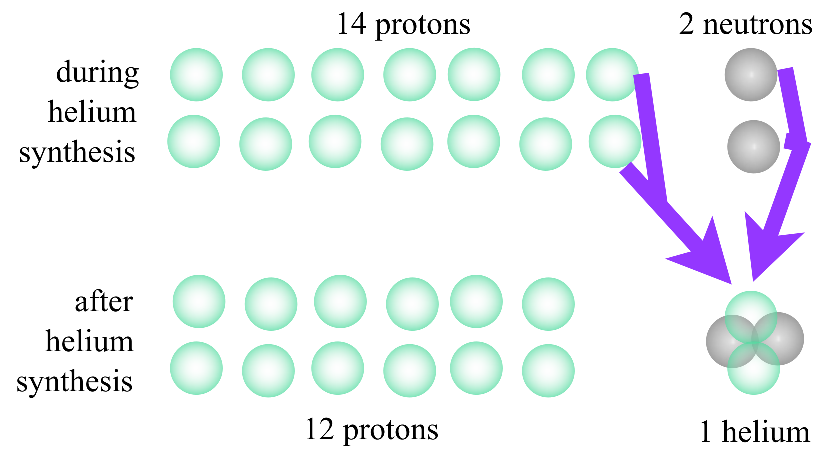


Early Universe was a 'soup' of energetic particles and radiation

At the moment after the Big Bang (<1 sec old), the entire observable universe was smaller than an atom
It inflated in size an enormous amount, over a million trillion trillion times in less than a second!

3 minutes old: The first non-H elements!

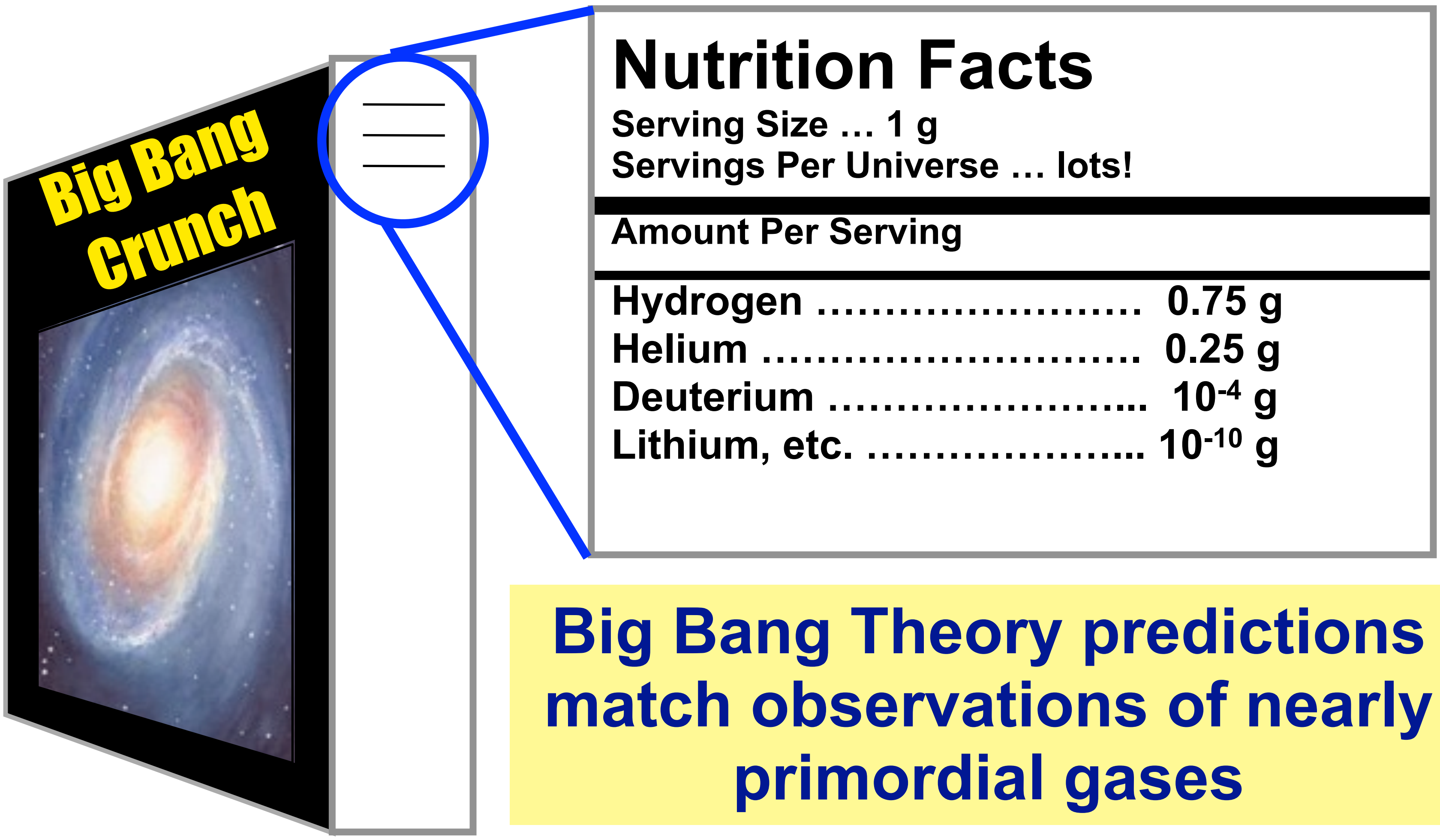
- Temperature ~ 10^9 K
- Protons and neutrons undergo fusion to form heavier atomic nuclei
- Fusion only lasts a few minutes - Universe is cooling as it expands
- Ratio of hydrogen to helium: 75% to 25%
- Very few atoms made heavier than helium



As the Universe cools, some protons and neutrons fuse to form helium nuclei

By the time the universe was 3 minutes old, it had become so cool that most nuclear reactions had stopped. About 25 percent of the mass was in the form of helium nuclei. The rest was in the form of hydrogen nuclei (protons). Astronomers can calculate that the big bang produced a tiny amount of lithium but no elements heavier than that. Heavier elements were built by nuclear processes inside later generations of massive stars.

How do the abundances of elements support the Big Bang?

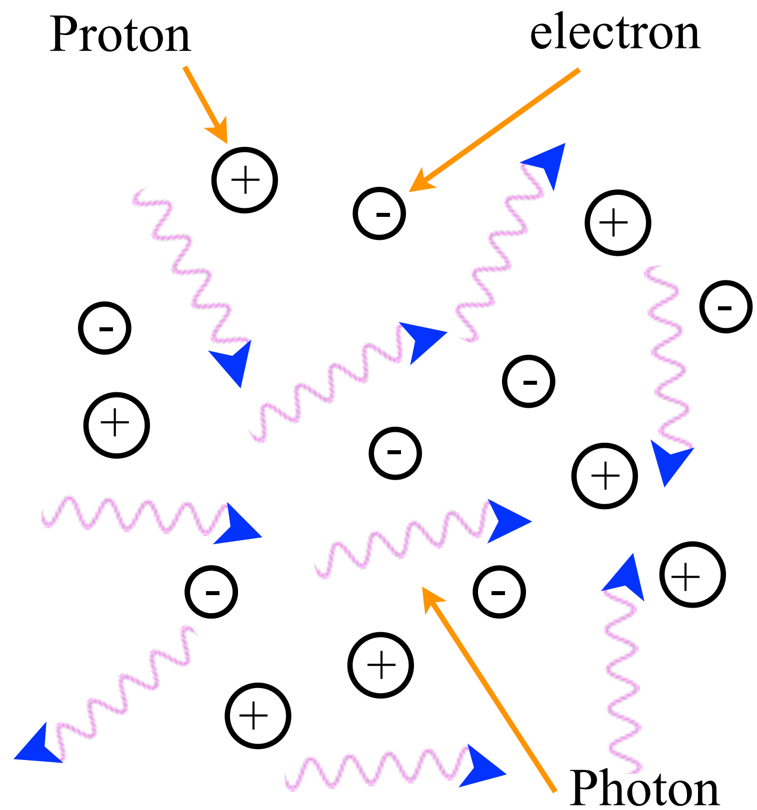


Big Bang Theory predictions match observations of nearly primordial gases

Protons and neutrons combined to make helium (and a little bit of other heavy elements) when universe was ~1-3 minutes old. Big Bang Theory predicts primordial proton-neutron ratio should be 7 to 1. So, H-He ratio should be 75% to 25%, which matches observations.

Radiation and Matter in the Early Universe

- In the young Universe gas was *ionized*
- Free atomic nuclei and electrons
- Photons and matter interact continuously with each other and cool together as the Universe expands
- Matter can't clump together

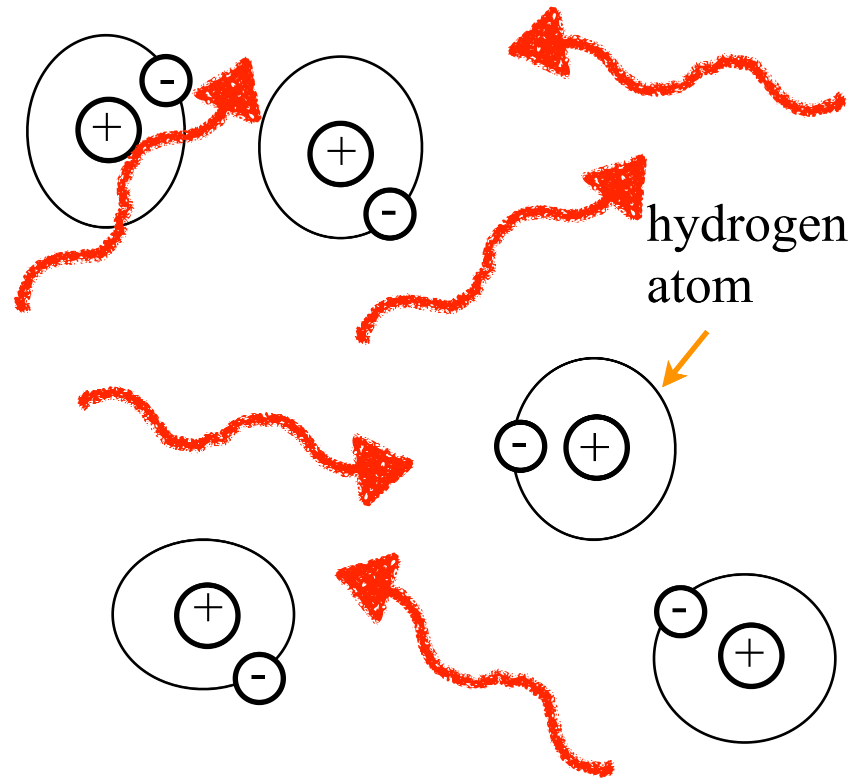


The young Universe was filled with hot, dense, *ionized* gas

ionized: The electrons were not attached to atomic nuclei. Free electrons interact with photons so easily that a photon could not travel very far before it encountered an electron and was deflected. Matter could not clump together because the intense sea of photons smoothed the gas out. As the young universe expanded, it went through three important changes.

380,000 years old: The first atoms!

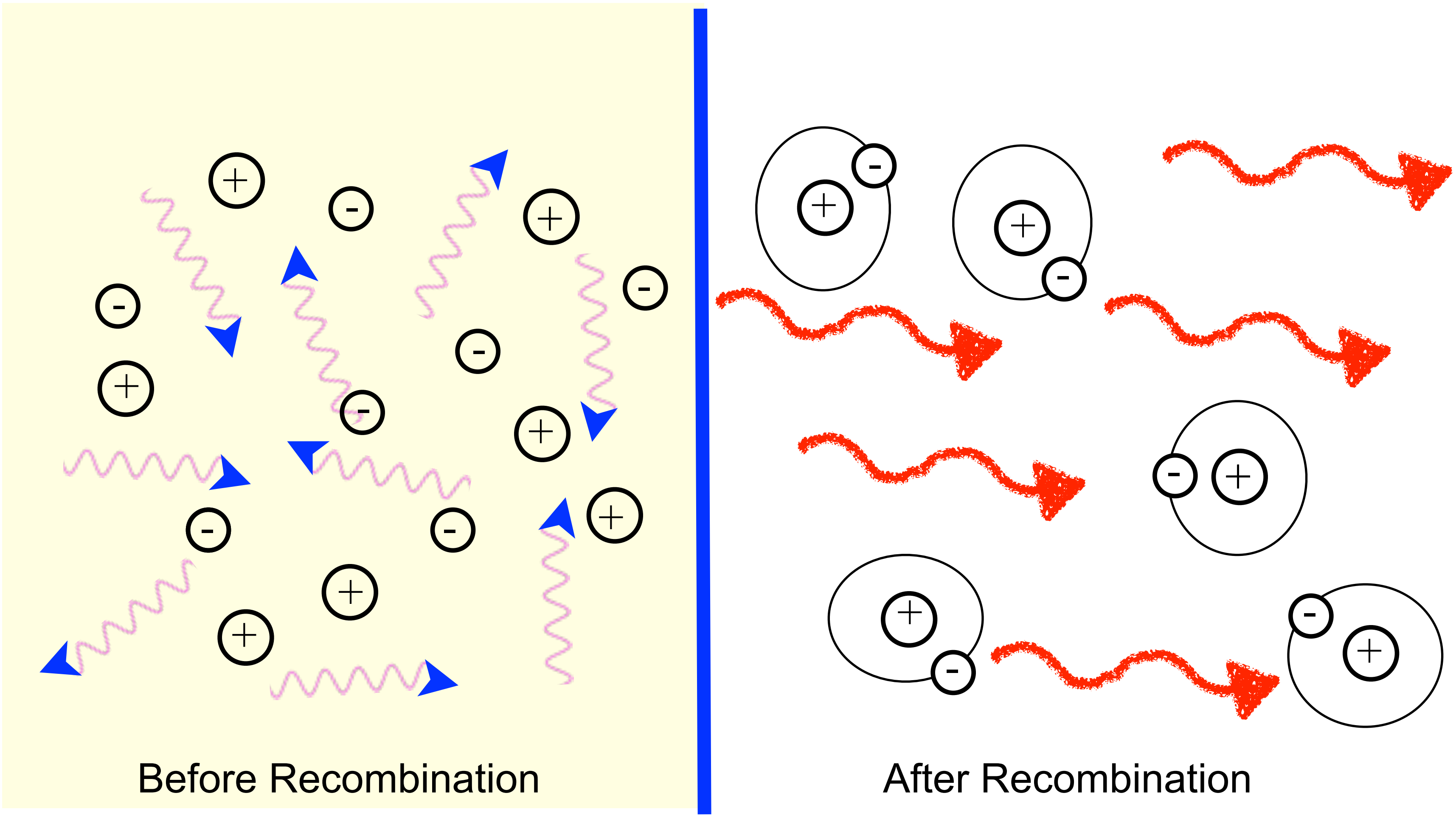
- The Universe cools to ~3,000 K
- Hydrogen & helium nuclei capture electrons and form neutral atoms
  - This is called "recombination"
- This neutral gas is transparent to light
- Matter and radiation are no longer at the same temperature



After atoms formed, the Universe was filled with hot, dense, *neutral* gas

As the density decreased and the falling temperature of the universe reached 3,000 K, protons were able to capture and hold free electrons to form neutral hydrogen. This process is called recombination—although 'combination' (for the first time) would be more accurate. As the free electrons were gobbled up into atoms, they could no longer deflect photons. The photons could travel easily through the gas. So, the gas became transparent. Also, the photons retained the blackbody temperature of 3,000 K that the gas and photons together had at the time of recombination.

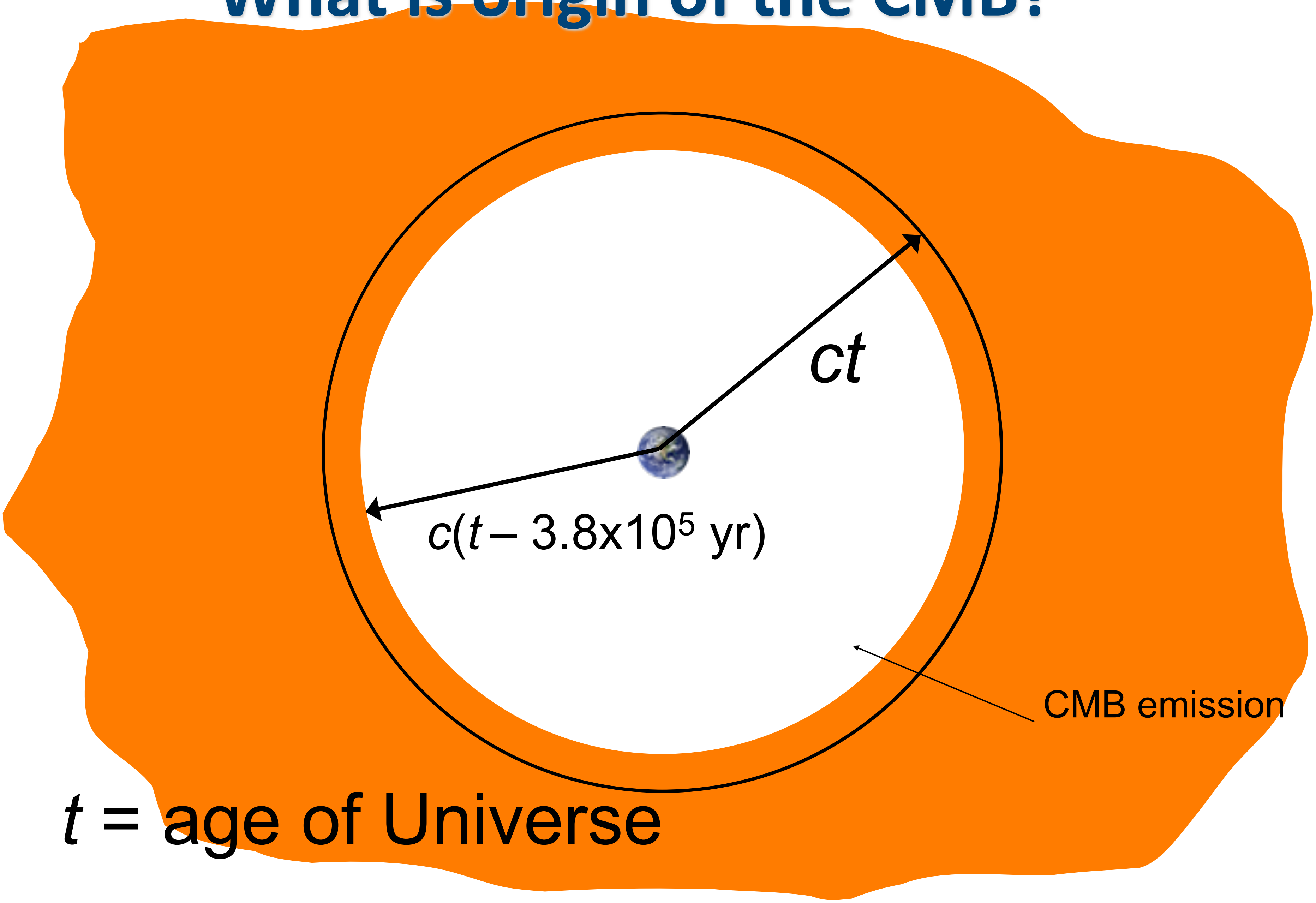
Looking Back in Time to the CMB



The CMB is light from the Era of Recombination!

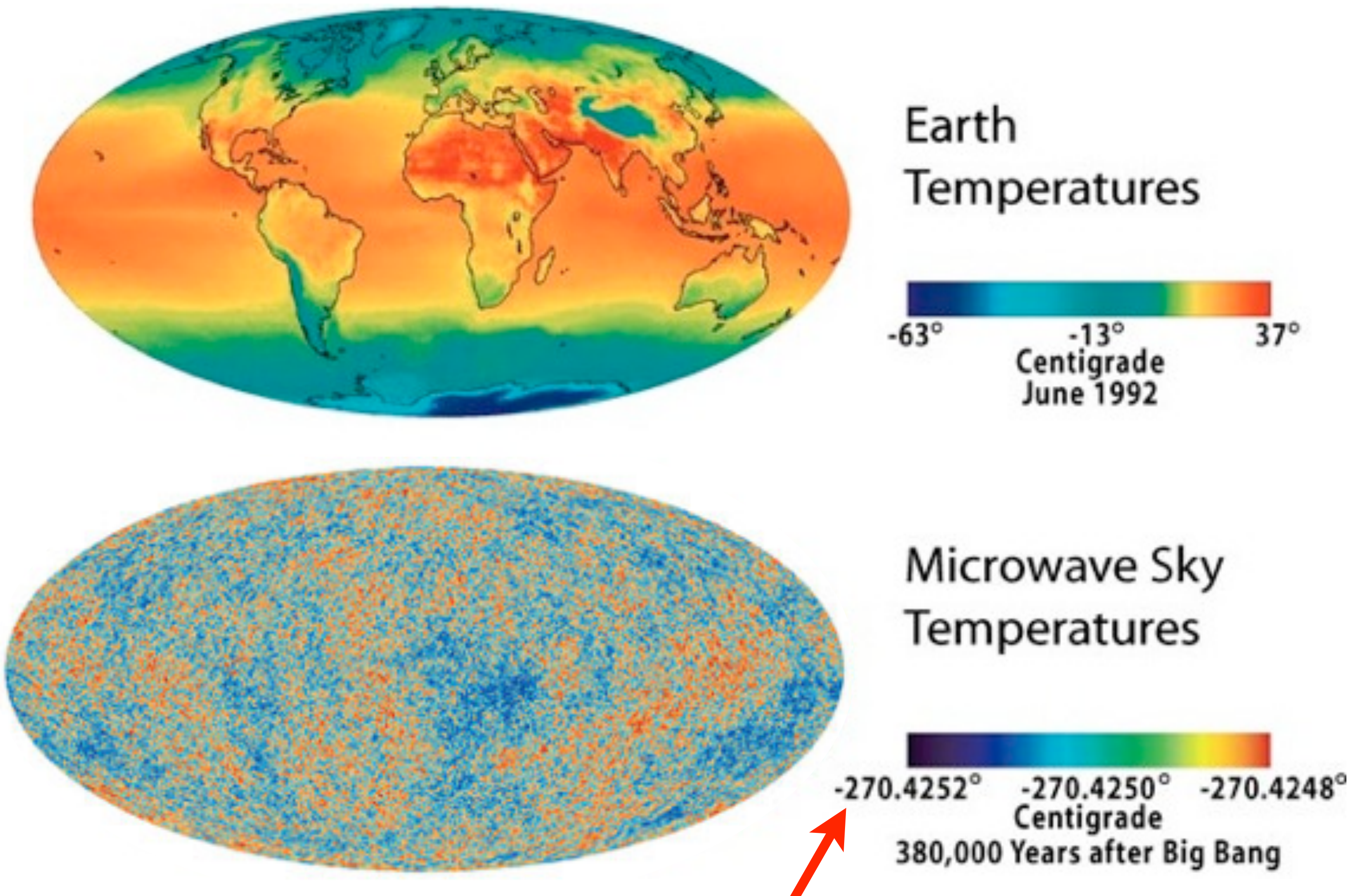
The CMB comes from the era of recombination. Before that, photons were stuck ionizing any hydrogen atoms that formed and they could not travel very far, but when the Universe cooled down enough, the photons did not have enough energy to ionize hydrogen and the Universe became transparent to the light, allowing the light to travel all the way to us. This is the CMB.

What is origin of the CMB?



Remember – the farther away we look in distance, the further back we look in time. So, when we look out to a distance of 13.8 billion light years, we are seeing the Universe as it was just after the Big Bang. But we can not see before the era of recombination

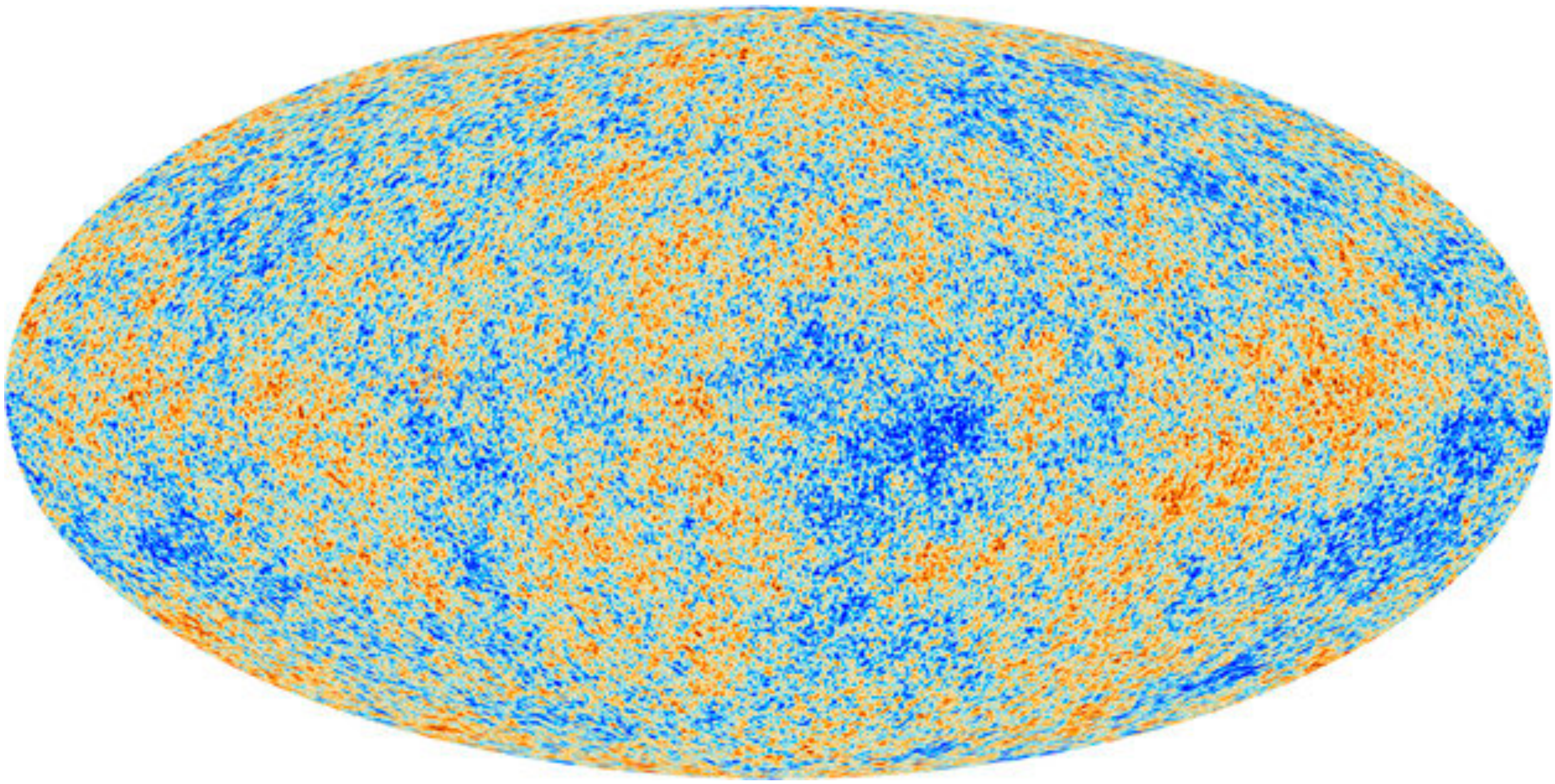
A "baby picture" of the Universe– only 400000 yrs old.



note tiny temperature range
lesson: temperature very nearly isotropic!

New Planck
image.

The beginnings of structure...



Cosmological variations in the CMB are less than 1 part in 100,000!!!

Planck 2013

Red regions are 0.0001 K hotter, denser lumps in the Universe at the beginning of the era of atoms – 1 part in 100,000! The beginnings of structure formation – lumps became superclusters. But, lumps aren't dense enough to cause galaxy formation. We need extra gravity of dark matter – dark matter wouldn't affect temperature of CMB (don't interact). Small density enhancements echo larger enhancements of dark matter.

Thought Question

When we look at the cosmic microwave background radiation we are looking farther into space – further back in time – than when we look at the farthest galaxies.

A. True

B. False

Answer A. The CMB is the farthest back we can observe. That is the first time in the Universe when space was transparent. Before that, it was like looking at a wall. You can not see inside a wall.

Thought Question

As we look outward from our vantage point in the universe, we see normal galaxies nearby, many active galaxies farther away, distant quasars, and ultimately the microwave background radiation. An observer in a distant galaxy looking outward would see…

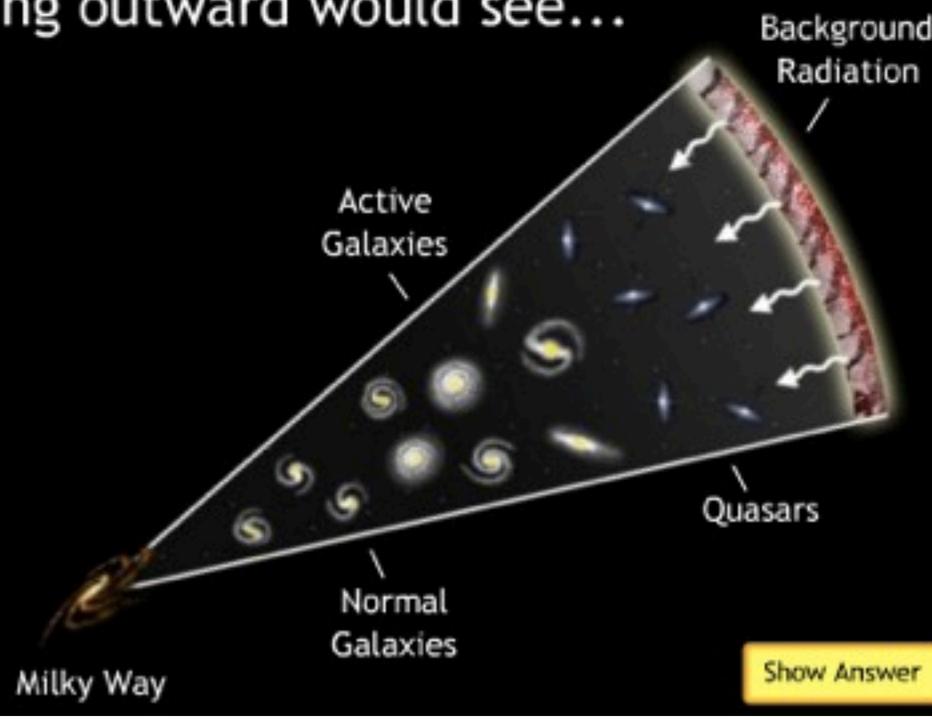
(A) nearby quasars

(B) many active galaxies nearby

(C) normal galaxies far away

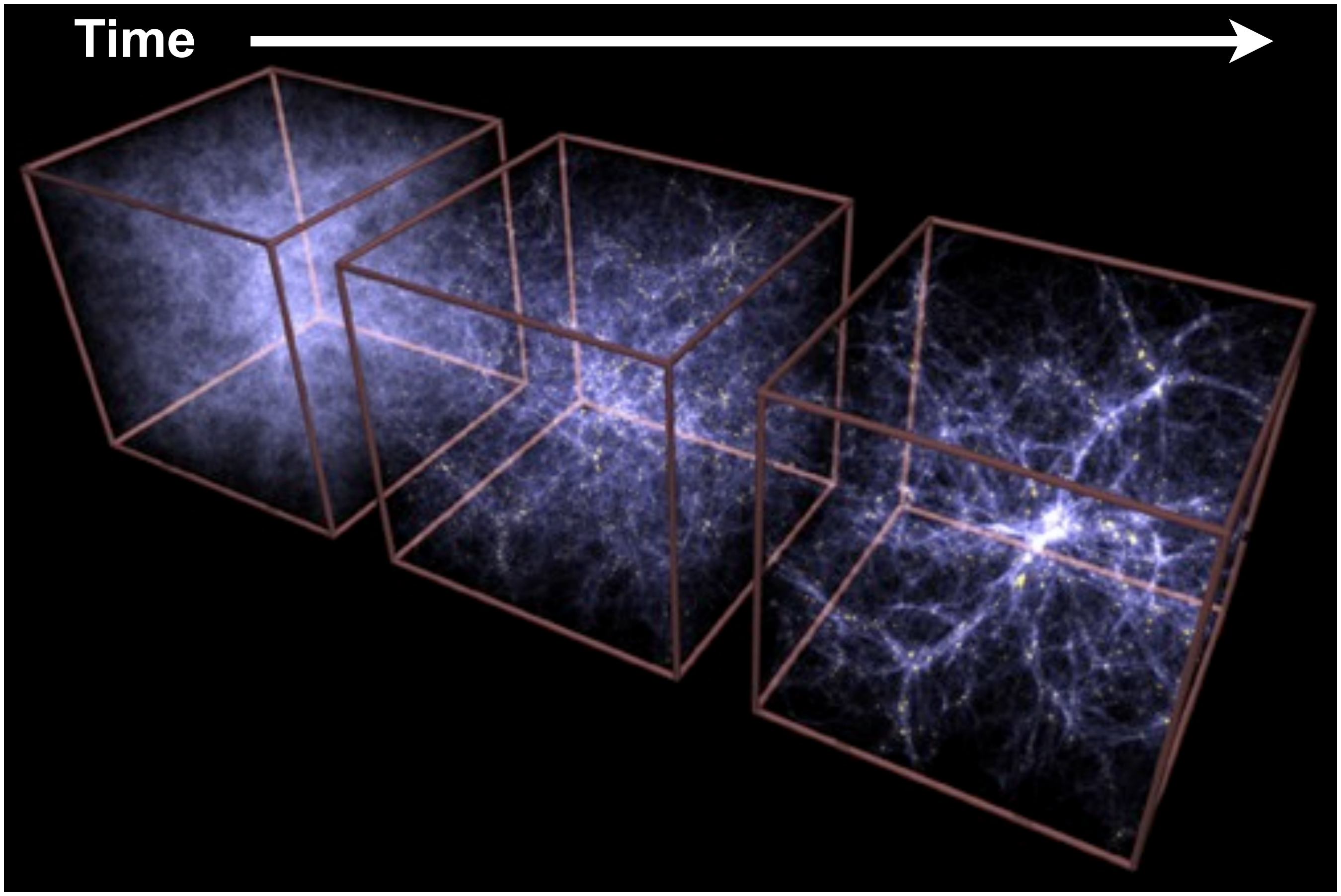
(D) all of the above

(E) the same view that we see



Answer E. As they look out, they are also looking back in time and will observe the exact same structure, although their view is different.

The Dark Age: Universe in darkness

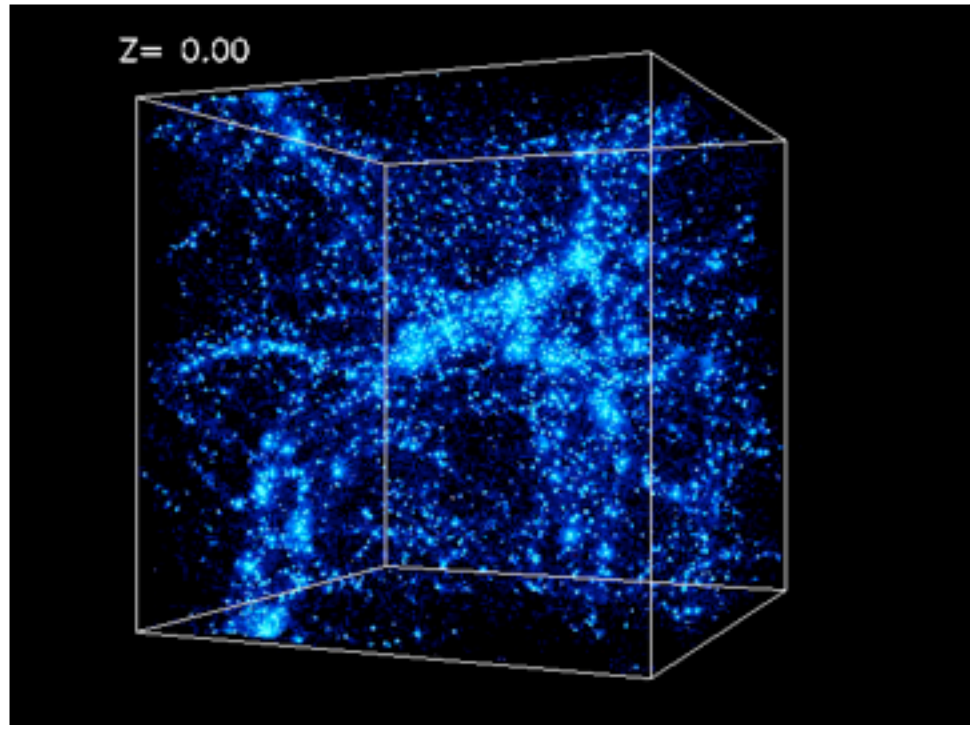


There were a few regions with slightly more material than others. So, as the Universe expands, denser regions draw in more matter, creating a 'lumpy' distribution

Recombination left the gas of the Big Bang neutral, hot, dense, and transparent. The universe entered what cosmologists call the dark age. This was a period lasting hundreds of millions of years until the formation of the first stars. During the dark age, the universe expanded in darkness. There were denser regions, with slightly more gravitational pull than the less dense regions. The extra gravitational pull meant that these regions accumulated more matter, and so got denser. But overall, the Universe is expanding, spreading out. Other than this, the Universe was a fairly dull place, with nothing particularly exciting going on.

What is the role of dark matter in galaxy formation?

- Gravity of dark matter draws in gas
- Creates a "lumpy" distribution, proto-galactic clouds
- Without dark matter, models show galaxies don't form
- No dark matter = no galaxies = no us!

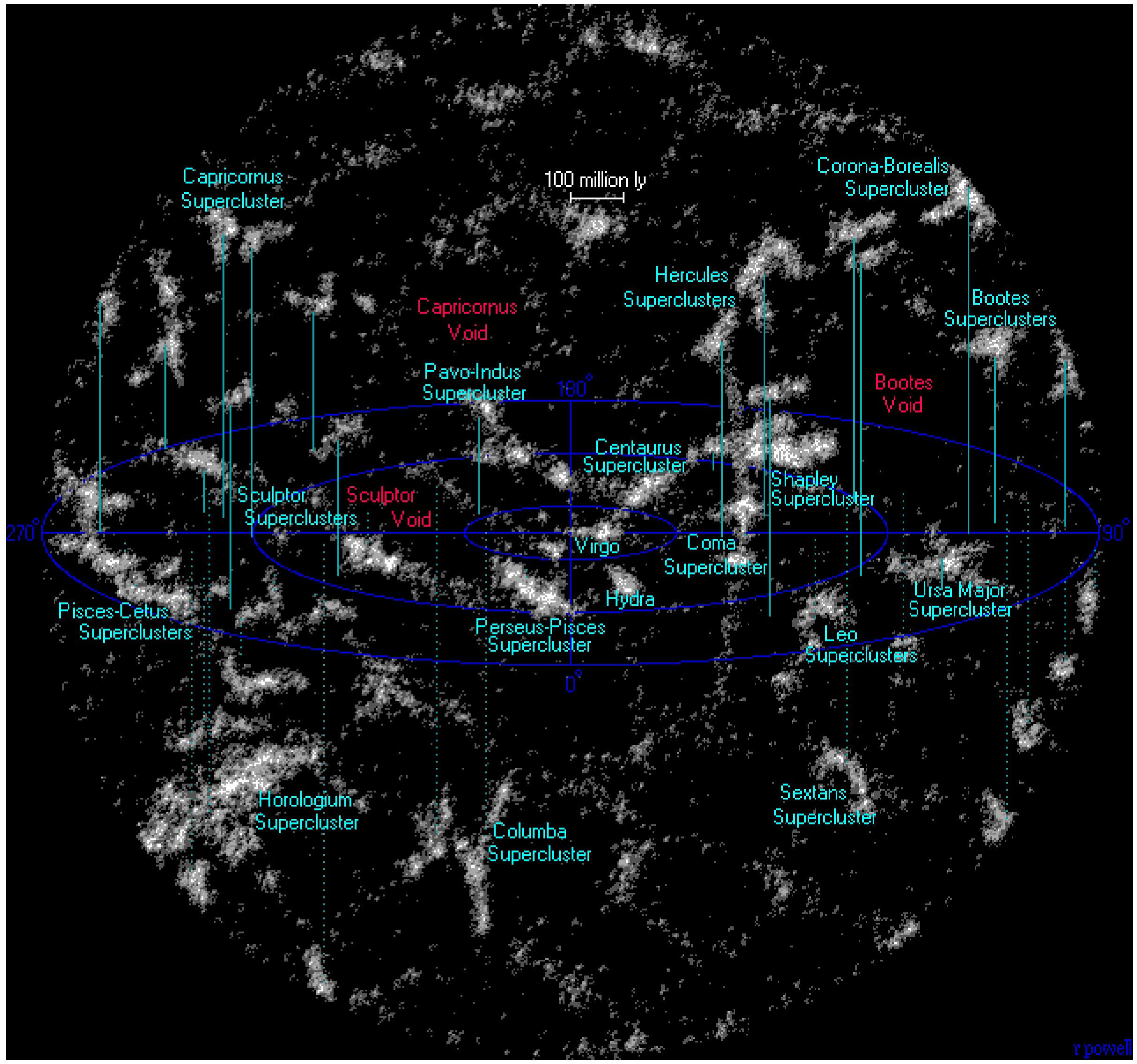


Over time, denser regions draw in more and more matter

Models show that gravity of dark matter pulls mass into denser regions. As the universe expands (note the increasing size of the box as time moves forward), that the matter in the universe grows "lumpier". Even as the whole universe spreads out, the regions that had higher concentrations of dark matter continue to grow denser. The gravity of dark matter seems to be what drew gas together into protogalactic clouds, initiating the process of galaxy formation

Dark matter created the large-scale structure of the Universe

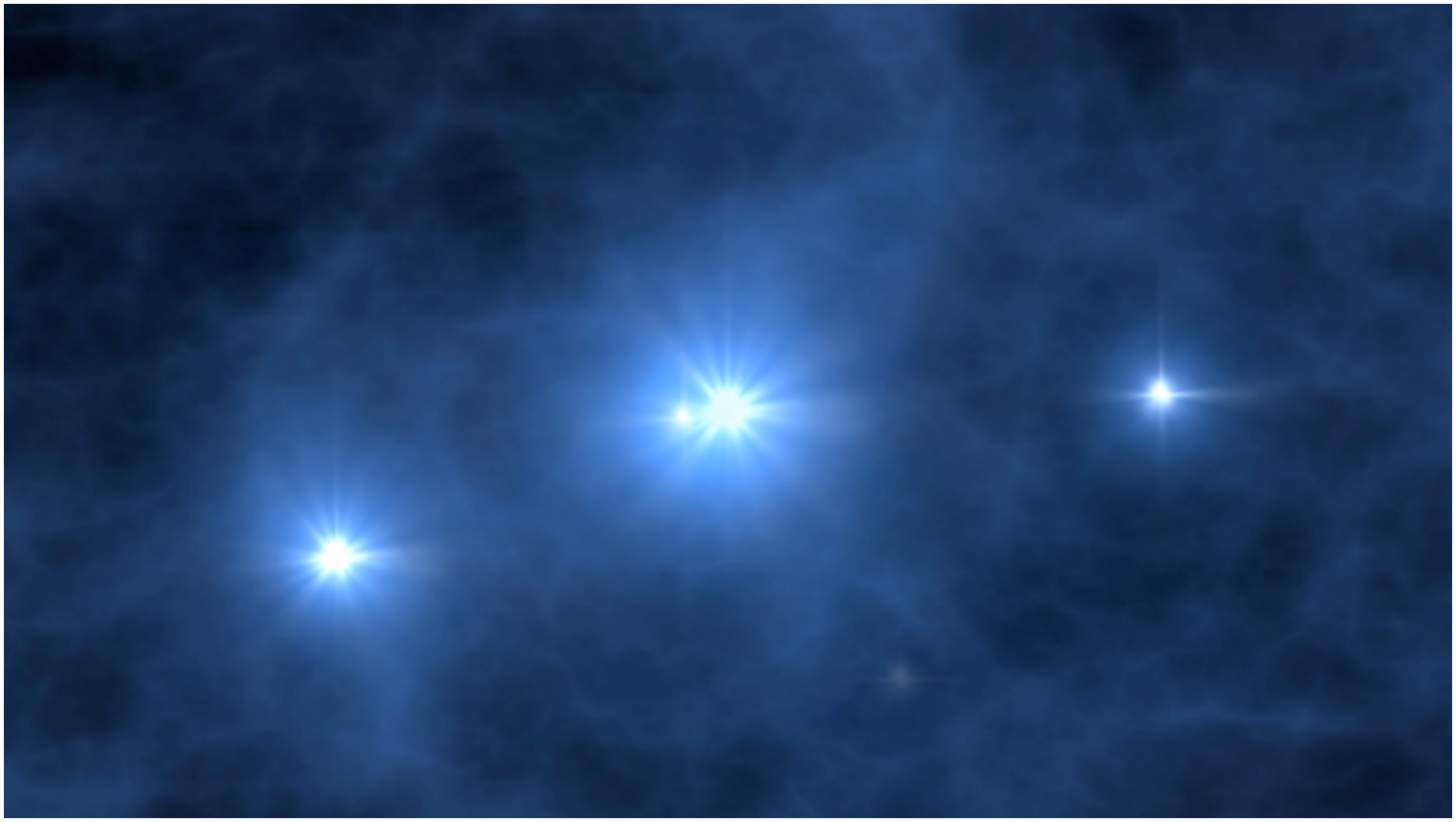
Maps of galaxy positions reveal extremely large structures: *superclusters* and *voids*



Galaxies and clusters of galaxies are not uniformly distributed in the Universe, instead they collect into vast clusters and sheets and walls of galaxies interspersed with large voids in which very few galaxies seem to exist. The map above shows many of these superclusters including the Virgo supercluster – the minor supercluster of which our galaxy is just a minor member. The entire map is approximately 7 percent of the diameter of the entire visible Universe.

- Number of galaxy groups within 1 billion light years = 240 000
- Number of large galaxies within 1 billion light years = 3 million
- Number of dwarf galaxies within 1 billion light years = 60 million
- Number of stars within 1 billion light years = 250 quadrillion

400 million years old: The first stars!



The dark age ended as the first stars began to form

Gravity draws gas in, forming the first stars after 400 million years. The gas from which these first stars formed contained almost no elements heavier than hydrogen and helium. Mathematical models show that the first stars formed from this gas would have been very massive, very luminous, and very short-lived. These stars gave the Universe it first supply of heavy elements.

What is the primary evidence for the Big Bang?

1. The expansion of the Universe.
2. The detection of the “leftover radiation” from the Big Bang
3. The Big Bang theory correctly predicts the abundance of helium and other light elements

No other theory can explain these three pieces of evidence.

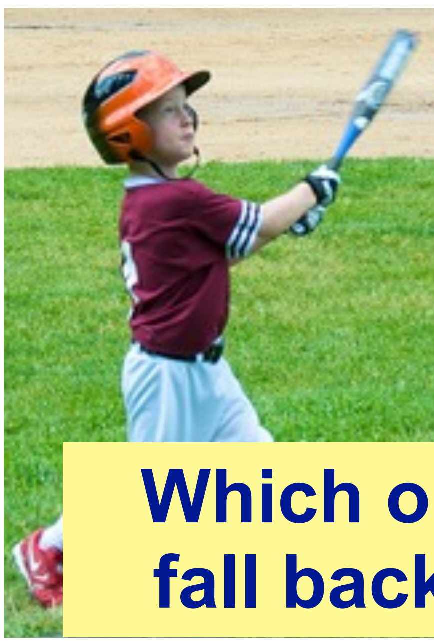

The Future

What is the Universe's Fate?

Today: Universe is expanding. What do you expect to happen next?

Competition: gravity vs inertia of expansion

Compare: Pop fly and rocket!
Quantitative question: Launch speed vs speed to escape Earth



or

Which one do you expect to fall back to Earth and why?

What is the Universe's Fate?

For the Universe it is still gravity vs speed.

- Gravity acts on mass of Universe (pulling back)
- The speed is the speed of expansion

Both are observable!

Our fate is a **quantitative** question :

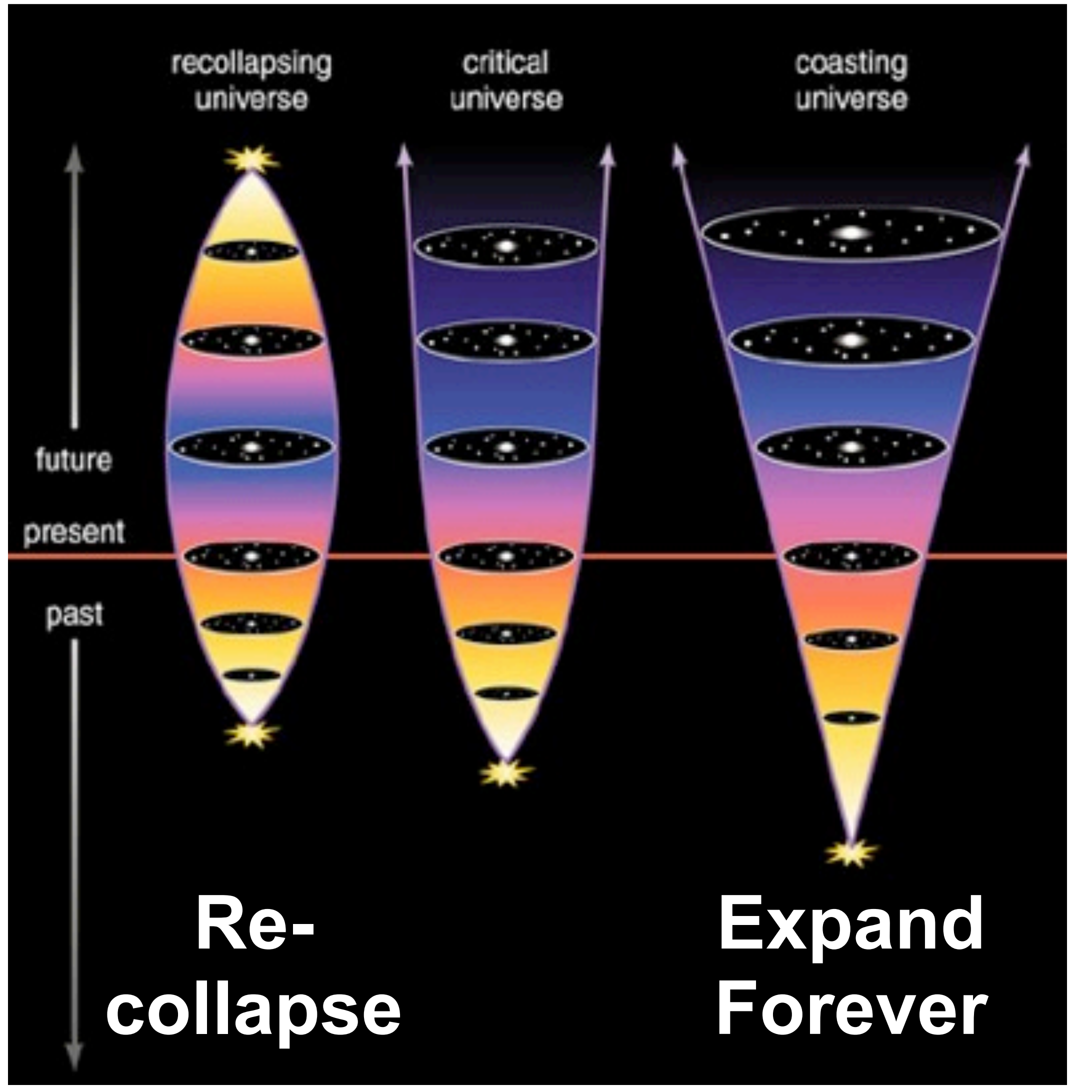
- **If our mass (or better density) is small enough we expand forever.**
- **If our density is large enough expansion halts, and we collapse back.**

or

Which case is the Big Bang?

The fate of the Universe depends on the density of matter in it

- High density
  - Enough gravity to stop expansion
  - Space is finite
  - **Closed Universe**
- Low density
  - Not enough gravity to stop the expansion
  - Space is infinite
  - **Open Universe**



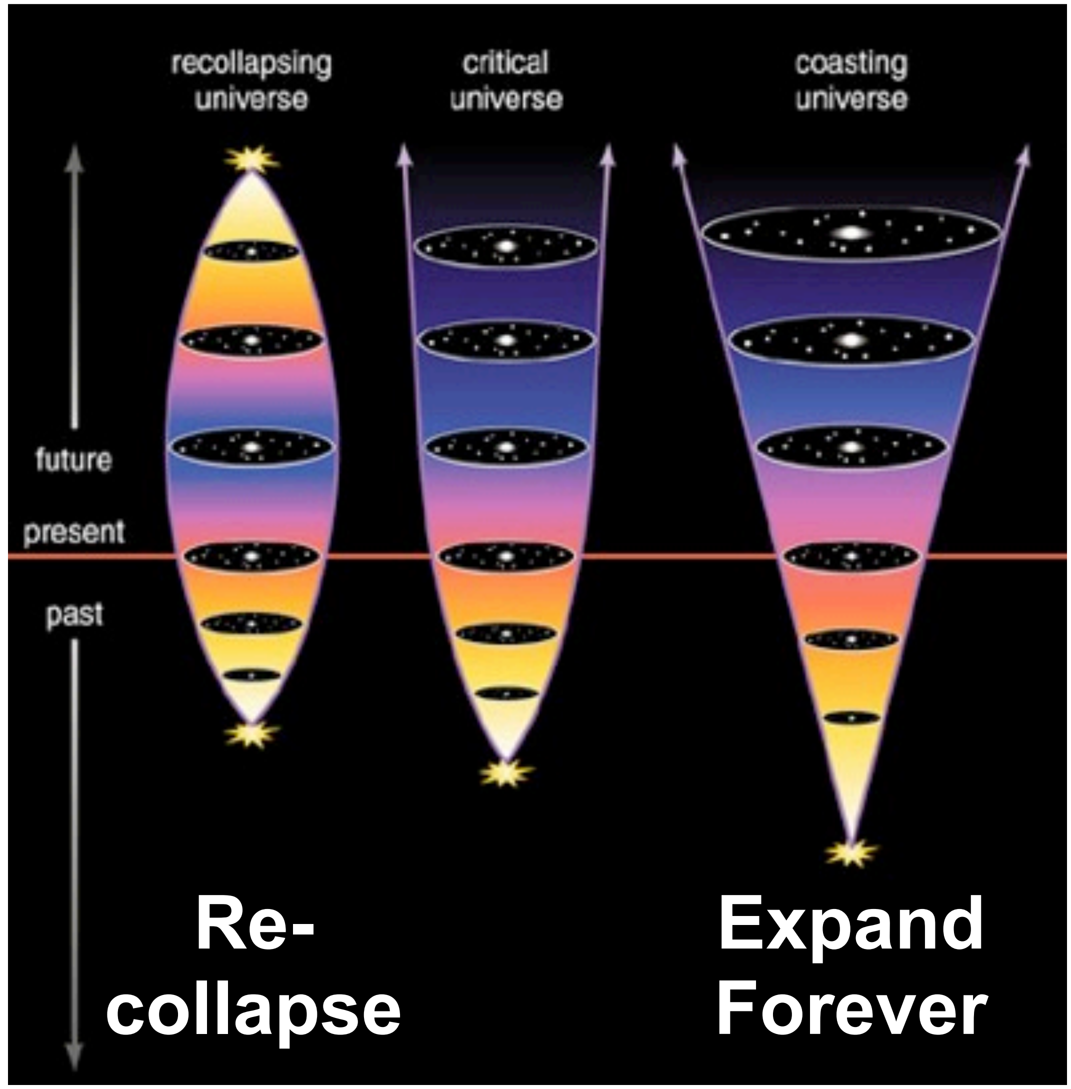
If the total density of matter is high enough, the Universe will recollapse under its own gravity – Big Crunch or Recollapsing Universe (left).

If the total density of matter is too small, the Universe will expand forever – Big Chill or Coasting Universe (right).

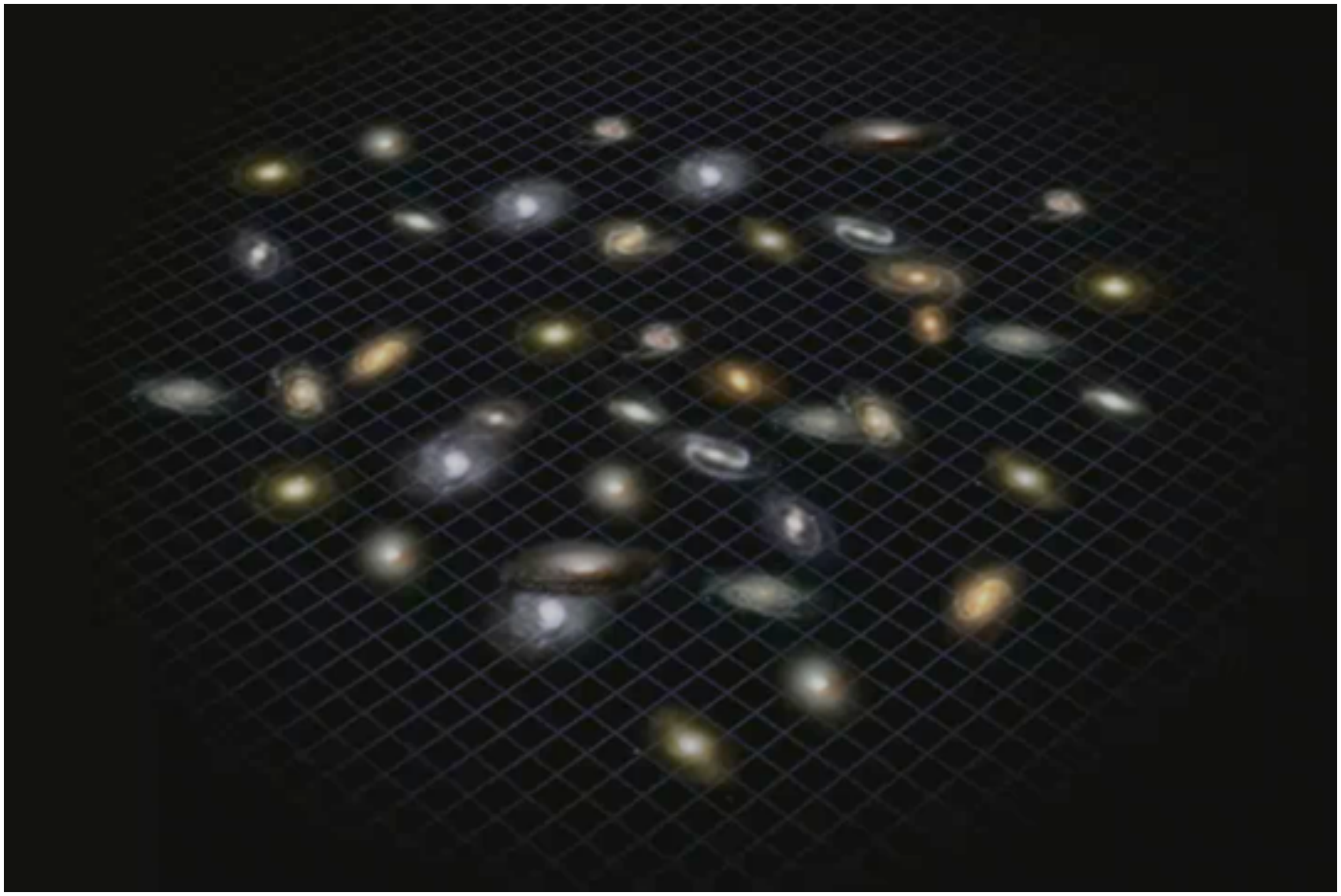
If the total density is just right, expansion will slow to zero as time goes to infinity – Critical Universe. Goldilocks Universe..

The fate of the Universe depends on the density of matter in it

- High density
  - Closed Universe
  - **Big Crunch**, Universe re-collapses
- Low density
  - Open Universe
  - **Big Chill**, expands forever
- Just Right
  - Universe barely expands forever with expansion going to zero at infinite time



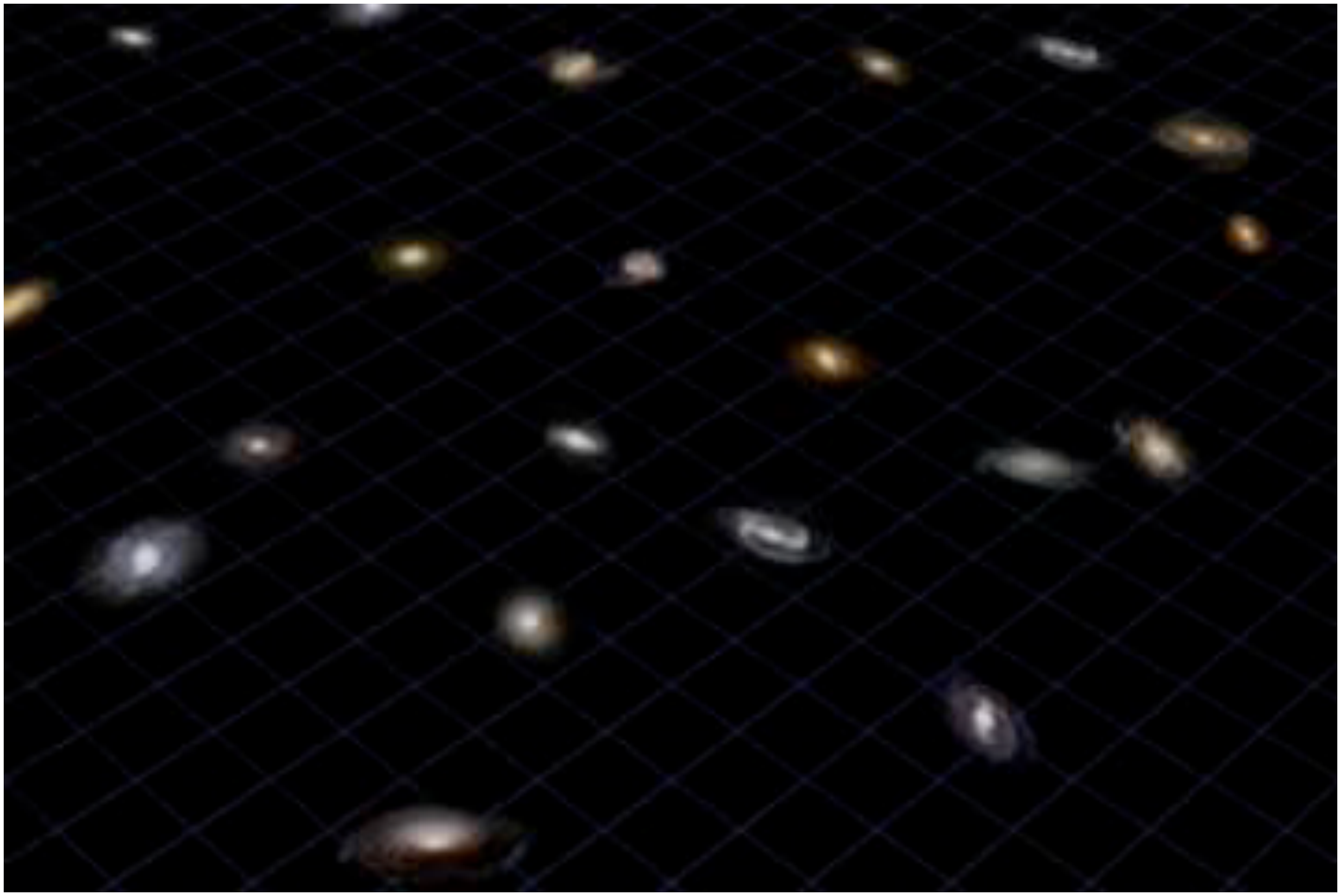
Recollapsing Universe



If there is enough matter in the Universe to halt the expansion, it will eventually recollapse

A contracting universe would become increasingly dense. Eventually all matter would collapse into black holes, which would then coalesce producing a unified black hole or Big Crunch singularity.

Expanding Forever

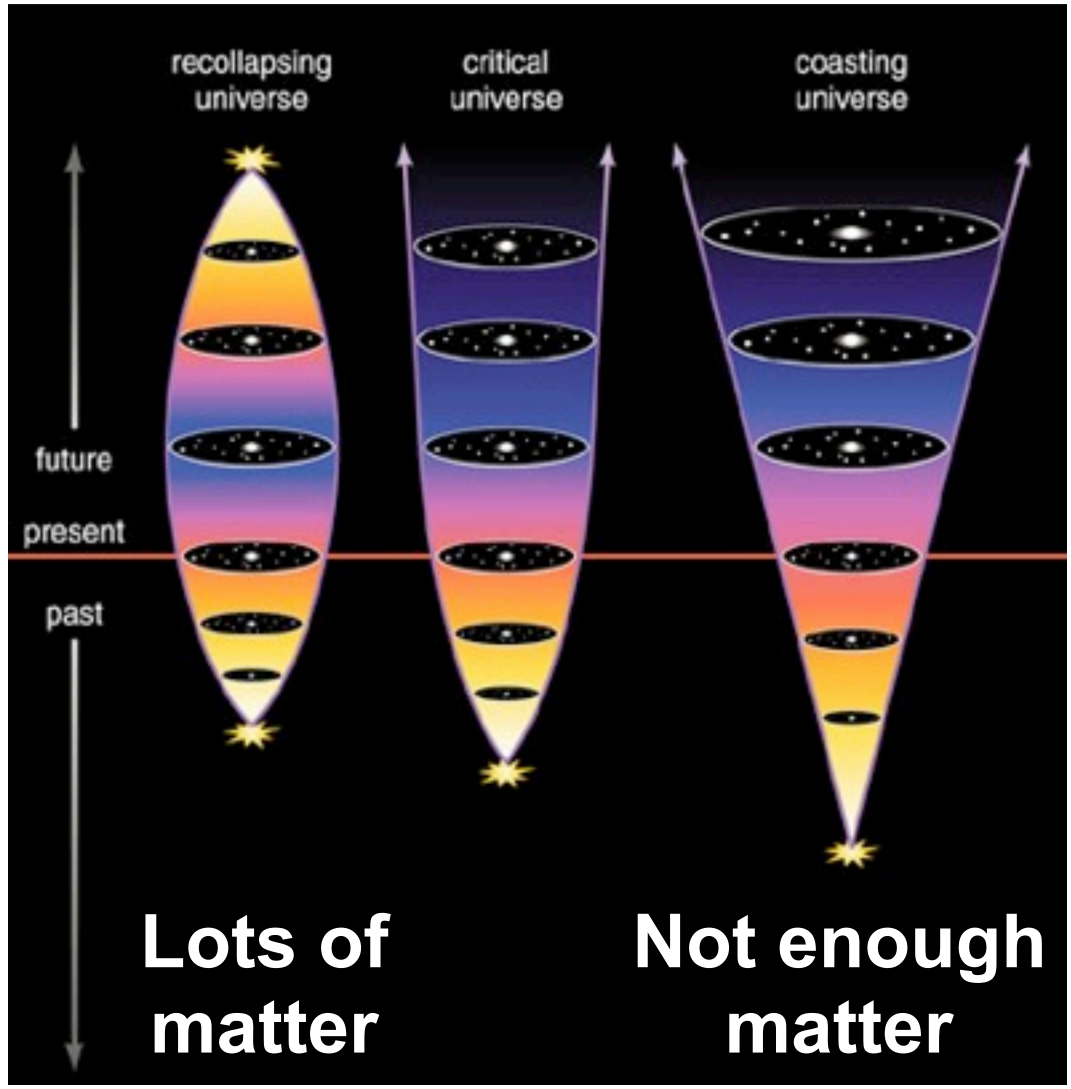


If there is not enough matter in the Universe to halt the expansion, it will continue forever

The galaxies will get farther and farther apart. They will use up their gas and dust making stars. Ultimately, the stars will all die. Each galaxy will be isolated, burnt out, dark, and alone.

Is there enough matter?

- Density of normal matter is only ~5% of “critical density”
- Even dark matter is just ~25% of the critical density
- Suggests a fate of eternal expansion

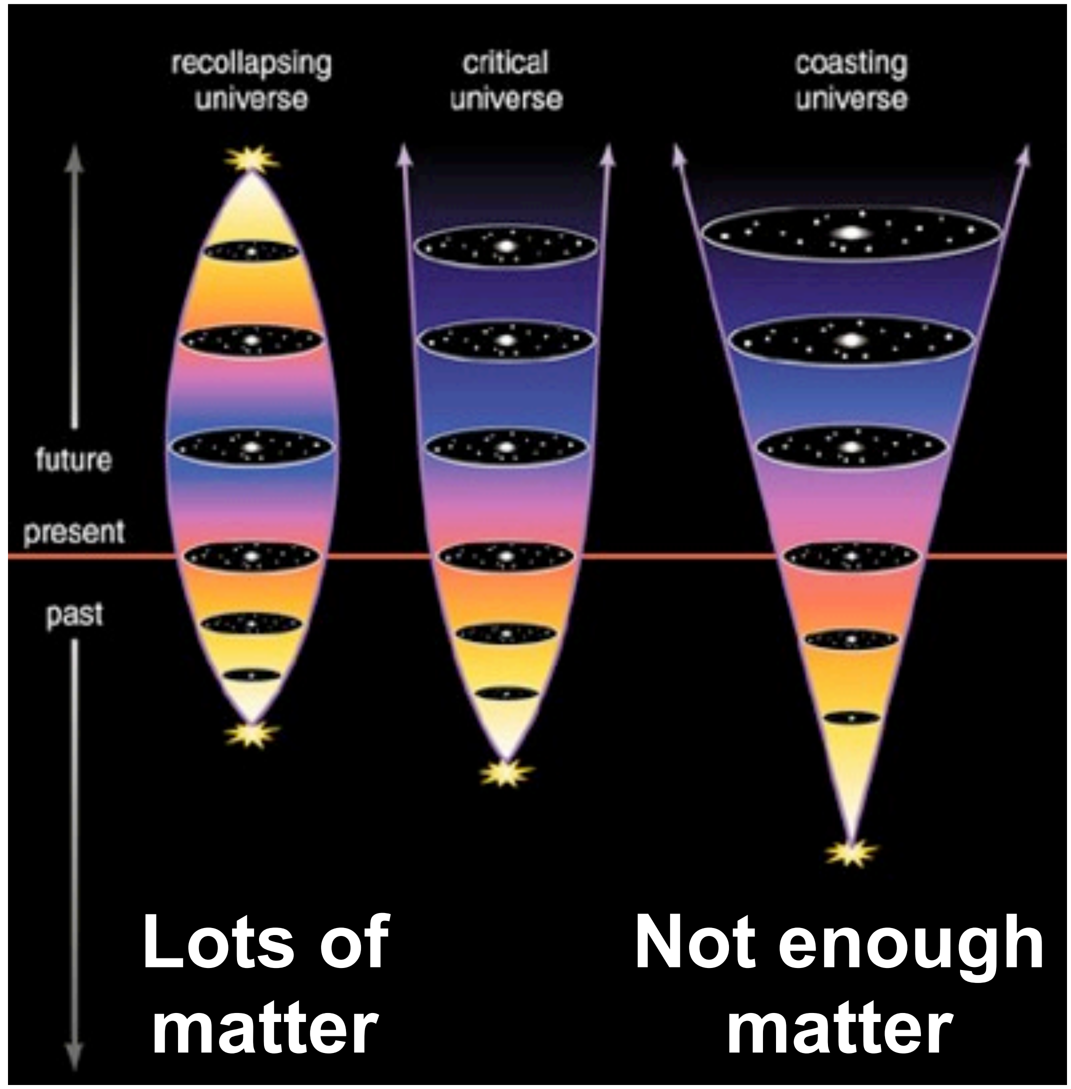


Critical Universe is the density needed to slow the expansion to zero as time goes to infinity.

If density < critical density: Expand forever
If density > critical density: Recollapse

Is there enough matter?

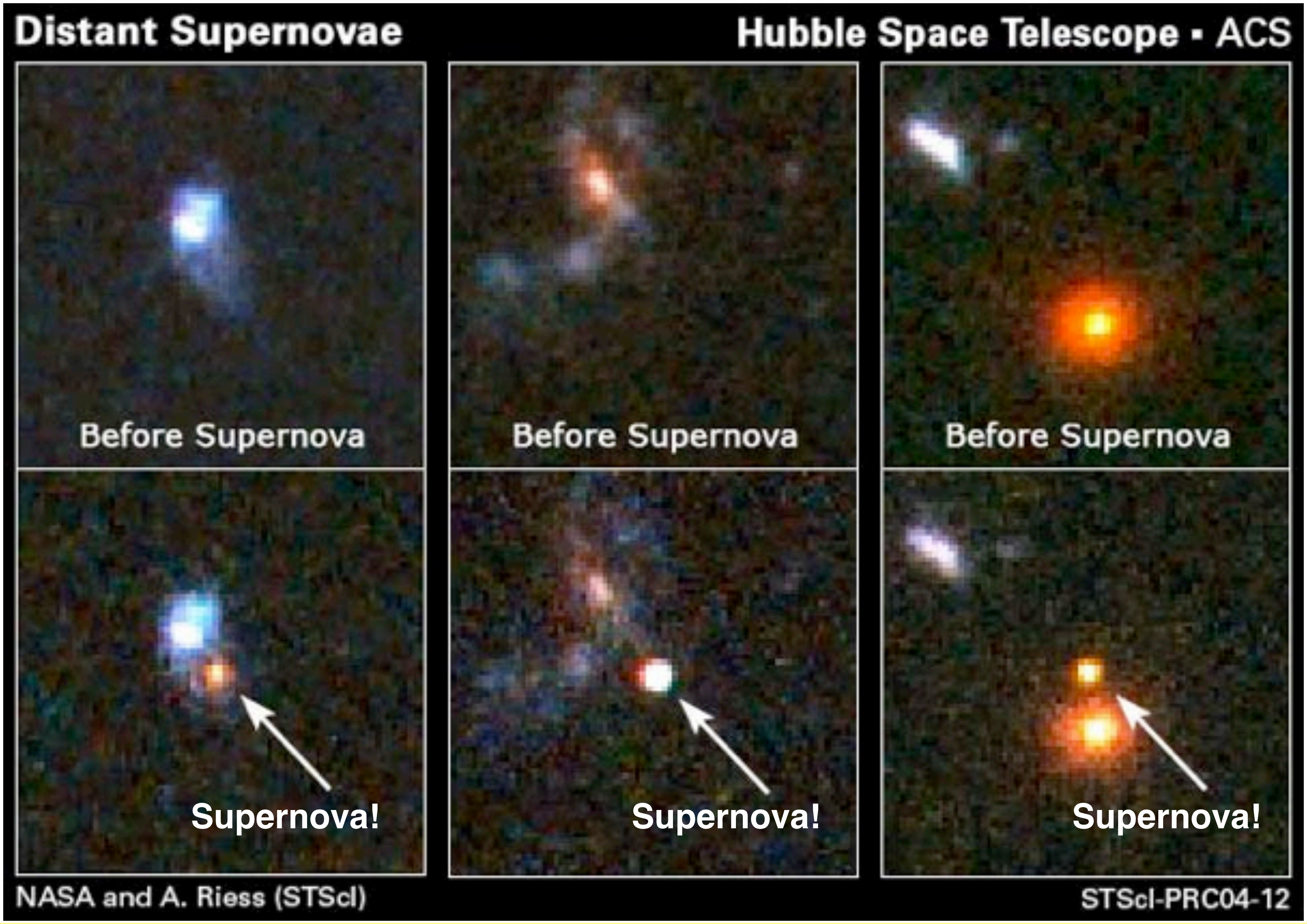
- In other words, the Universe does not weigh enough to bring the Universe back on itself
- In our analogy, the rocket keeps going.



Measuring changes in the expansion of the Universe

- **Step 1**: measure the distances to many galaxies, from nearby to billions of light years away
- **Step 2**: measure the cosmic redshifts of those galaxies
- **Step 3**: compare distances with redshifts to measure changes in the expansion rate of the Universe

Expectation: The gravity of the matter (normal and dark) in the Universe is slowing down the expansion - even if its not enough to stop it.



Astronomers measure distances to very distant galaxies using supernova explosions

For decades, astronomers struggled to measure the distance to very distant galaxies directly, compare distances with redshifts, and thereby detect the slowing of the expansion. Measure distances to far galaxies using a certain class of supernovas. Type 1a supernovae have a known intrinsic luminosity and so bright they are visible billions of light years away. This makes them excellent standard candles for determining distances. This study won the Nobel Prize in 2011!