AST 301
Introduction to Astronomy

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Topics for this week

Is the rate of expansion of the Universe changing?

What could make the expansion slow down? What could make it speed up?

How did the temperature of the gas in the Universe change with time since the big bang?

What caused the temperature to change?

What particles and atoms were made at different times in the early Universe?

What is the cosmic microwave background? How was it emitted and why is it seen at the wavelengths it is?

What do the fluctuations in the microwave background tell us about the early Universe?

Schedule for this week

I will be gone tomorrow and Wednesday. (Prof. Jaffe will be here for class on Wednesday.)

The TAs will have their usual office hours and review session this week.

I will have office hours Thursday 10-12.

We will try hard to have the tests graded by Monday.

The scores will be posted with the formulas to calculate your final grade if you don't take the final.

Tests will be available in my office.

We will have multiple office hours Monday and Tuesday.

The final is on Wednesday of next week.

The interpretation of Hubble's law

The best way to look at the motion of the other galaxies away from us is not to say that the galaxies are flying through space.

Instead, we think that space is stretching.

It's like the stretching surface of a balloon.

The writing on the balloon isn't moving on the rubber.

But the distance between letters increases as the rubber stretches.

It's easier to understand the stretching of a balloon since as the 2-D surface of the balloon stretches it moves into a different place in 3-D space.

It's hard to understand how 3-D space can be stretching.

Maybe it is moving into a different place in a 4^{th} dimension that we aren't aware of.

Stretching photons

Saying that space is expanding does not mean that galaxies are expanding or the solar system is expanding.

Gravity keeps the stars orbiting in a galaxy and the planets orbiting in the solar system. The sizes of their orbits don't change.

But the expansion of space does affect photons as they travel to us across space from distant galaxies.

As they travel through expanding space, the wavelength of the light in a photon is stretched.

If space stretches by a factor of 2 while a photon is traveling, the wavelength of the light also stretches by a factor of 2.

This is another way of looking at the redshifts of distant galaxies.

What is the Universe made of?

Stars and planets are made of protons, neutrons, and electrons. These particles are called baryonic matter [although strictly speaking only protons and neutrons are baryons (heavy particles); electrons are leptons (light particles)].

But we have reasons to believe that there are other unseen kinds of matter in the Universe.

One is dark matter, which seems to dominate the mass of the Milky Way and other galaxies.

The first evidence for dark matter was the motions of galaxies in clusters, observed by Fritz Zwicky.

Although galaxies don't move on circular orbits, we can us a form of Kepler's 3rd law to calculate the mass that they orbit around, and it appears to be larger than the mass of the stars we can see in the galaxies.

Flat rotation curves

About 30 years ago, Vera Rubin found that stars orbit around galaxies at about the same speed at all distances from the center.

Kepler's 3rd law says that this means that there is as much mass in a 1000 pc wide ring at the outer edge of a galaxy as within 1000 pc of the center, even though there are many fewer stars near the outer edge.

Especially in the outskirts of galaxies, most of the mass in galaxies must be in something other than stars.

Fritz Zwicky's measurements indicate that even more dark matter is found in clusters of galaxies, in between the galaxies.

Dark Matter in galaxies and galaxy clusters

The dark matter could be in many small black holes, or conceivably even in rocks in space, but we now think it is in some unknown form of matter which doesn't respond to either the electromagnetic force or the strong force.

Neutrinos fit this description, but we don't think they have enough mass to be the dark matter.

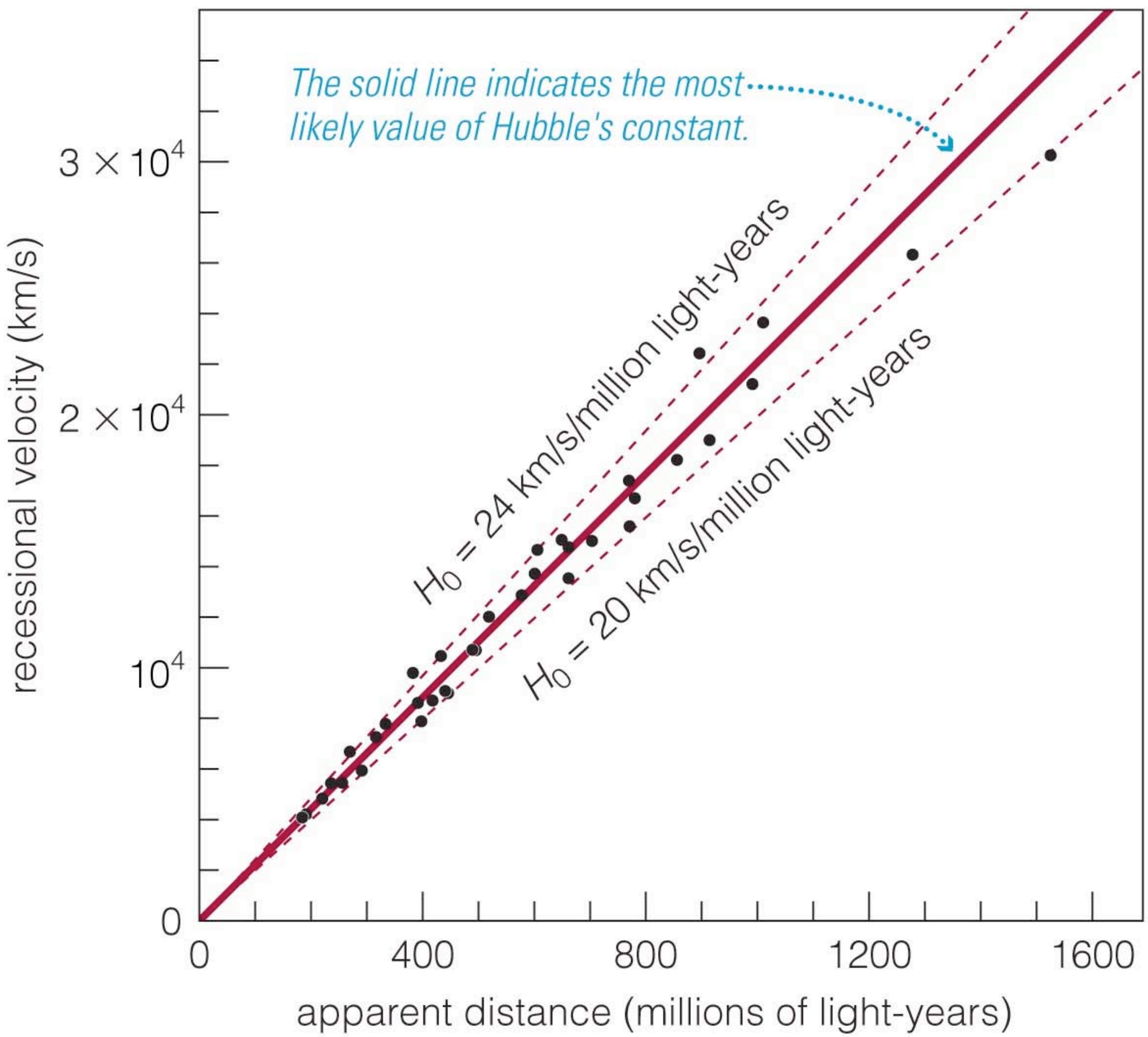
Maybe there is some kind of a particle like the neutrino, but with much more mass.

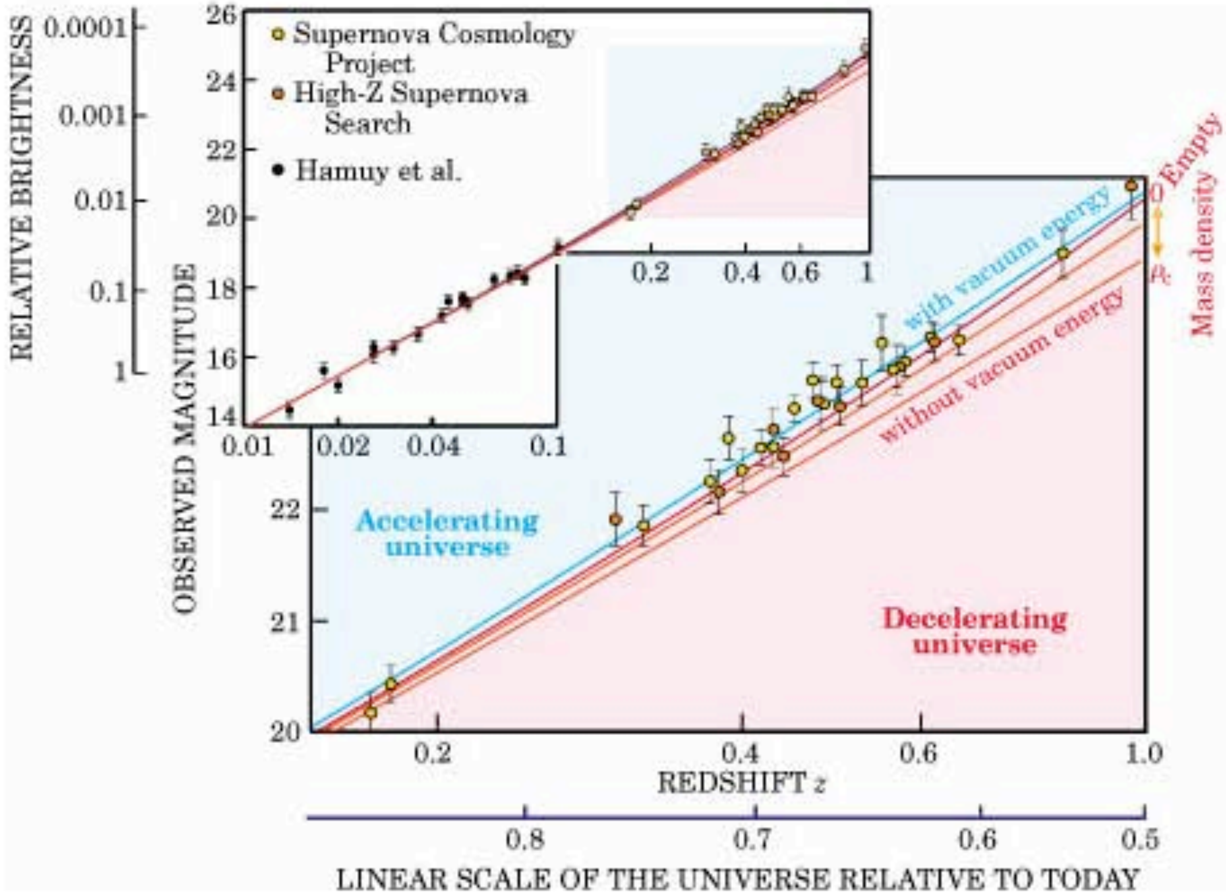
These hypothesized particles are often called WIMPs, or weakly interacting massive particles.

We can also ask how much matter is in the Universe by asking how it affects the expansion of the Universe.

We would expect gravity to slow the expansion.

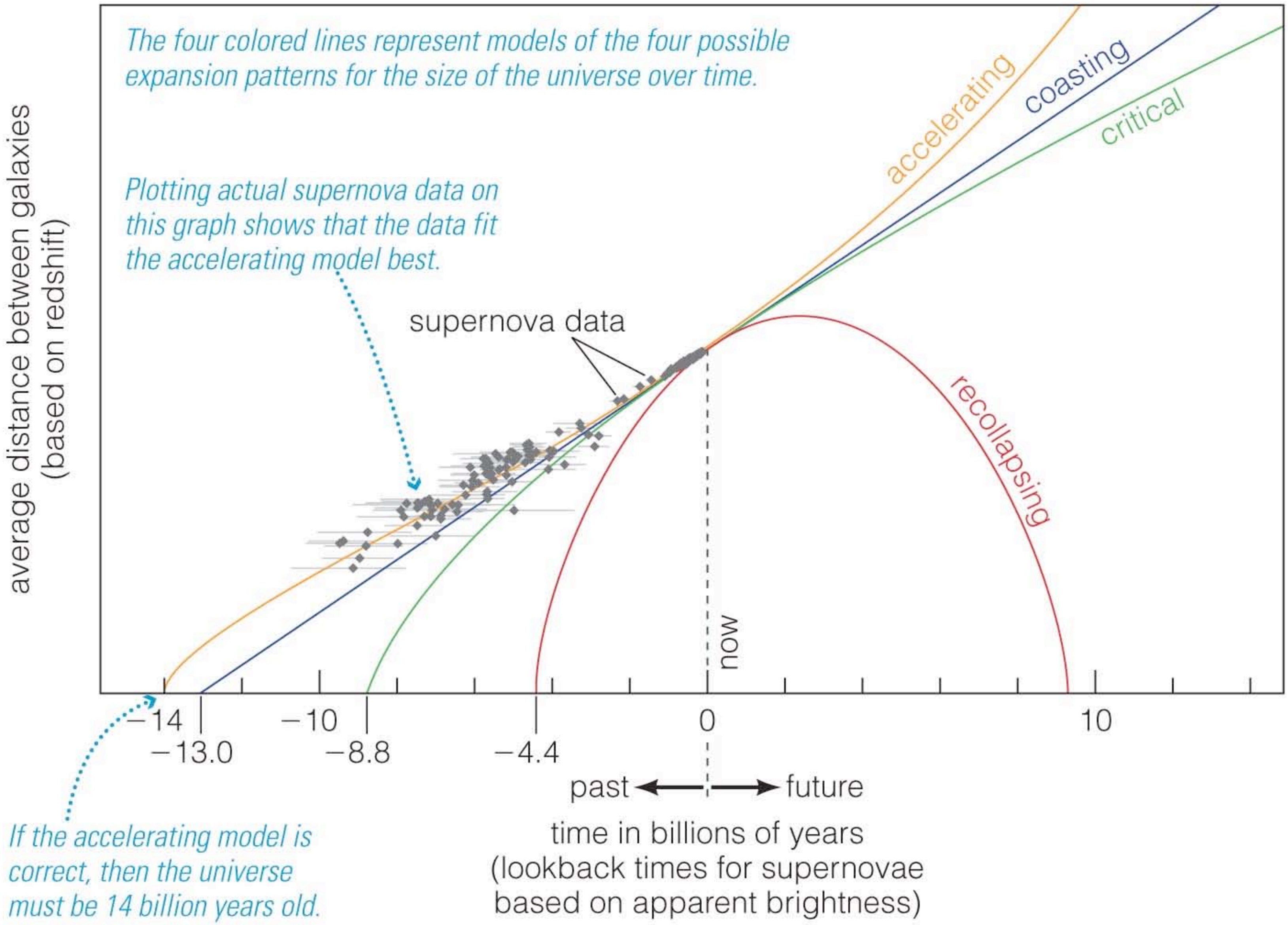
Hubble diagram for not too distant galaxies





Observed magnitude versus redshift is plotted for well-measured distant[12,13] and (in the inset) nearby[7] type Ia supernovae. For clarity, measurements at the same redshift are combined. At redshifts beyond $z = 0.1$ (distances greater than about 10^9 light-years), the cosmological predictions (indicated by the curves) begin to diverge, depending on the assumed cosmic densities of mass and vacuum energy. The red curves represent models with zero vacuum energy and mass densities ranging from the critical density ρ_c down to zero (an empty cosmos). The best fit (blue line) assumes a mass density of about $\rho_c/3$ plus a vacuum energy density twice that large--implying an accelerating cosmic expansion.

Expansion of Universe vs. time



The measured acceleration

Instead of greater speeds in the past, as would be expected if gravity is causing the expansion of the Universe to decelerate, smaller speed were observed.

Apparently the expansion is accelerating.

There seems to be some sort of negative gravity affecting the expansion of the Universe.

According to general relativity this could happen if creation and destruction of particles in a vacuum gives the vacuum a negative pressure (like a stretched piece of rubber).

The cause of this negative pressure is called dark energy (although vacuum energy may be a better name).

There are theories about its cause, but we really don’t know which (if any) are right.

The inventory

As a fraction of the critical density, which would have enough gravity to stop the expansion:

visible stars: 1%

unseen normal matter: 2%

dark matter: 24%

vacuum energy 73%

(Note: vacuum energy accelerates, rather than slows the expansion, but we include it in the inventory since the sum of these four stays constant as the Universe expands.)

What is the Universe made of?

Content of the Universe

WMAP measures the composition of the universe. The top chart shows a pie chart of the relative constituents today. A similar chart (bottom) shows the composition at 380,000 years old (13.7 billion years ago) when the light WMAP observes emanated. The composition varies as the universe expands: the dark matter and atoms become less dense as the universe expands, like an ordinary gas, but the photon and neutrino particles also lose energy as the universe expands, so their energy density decreases faster than the matter. They formed a larger fraction of the universe 13.7 billion years ago. It appears that the dark energy density does not decrease at all, so it now dominates the universe even though it was a tiny contributor 13.7 billion years ago.

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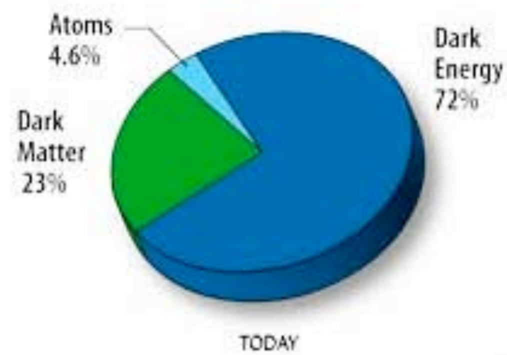
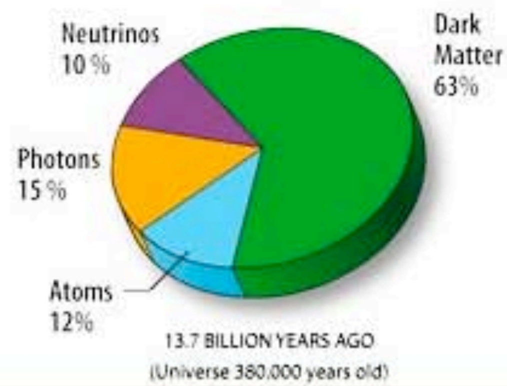




Hubble's Law and the Big Bang Theory

Distant galaxies are moving away from us with speeds proportional to their distances from us.

Our favored interpretation is that the Universe is expanding, so the space between the galaxies is expanding.

But other ideas have been suggested.

Do we have other evidence that the Universe actually began with an explosion?

Our best evidence involves microwave radiation discovered 45 years ago.

Radiation from the Early Universe

In ~1950 George Gamow predicted that there should be radiation left over from the early Universe.

About 400,000 years after the big bang, the Universe was filled with ionized gas at a temperature of 3000 K, and was 1000 times smaller than it now is.

The ionized gas emitted black body radiation like a glowing solid at 3000 K, or a red giant star.

As the Universe cooled below 3000 K, protons and electrons combined to make hydrogen atoms.

The Universe then became transparent, and the photons emitted by the ionized gas could fly across space, and should still be around.

Why don’t we see a 3000 K glow in all directions?

The Background Radiation

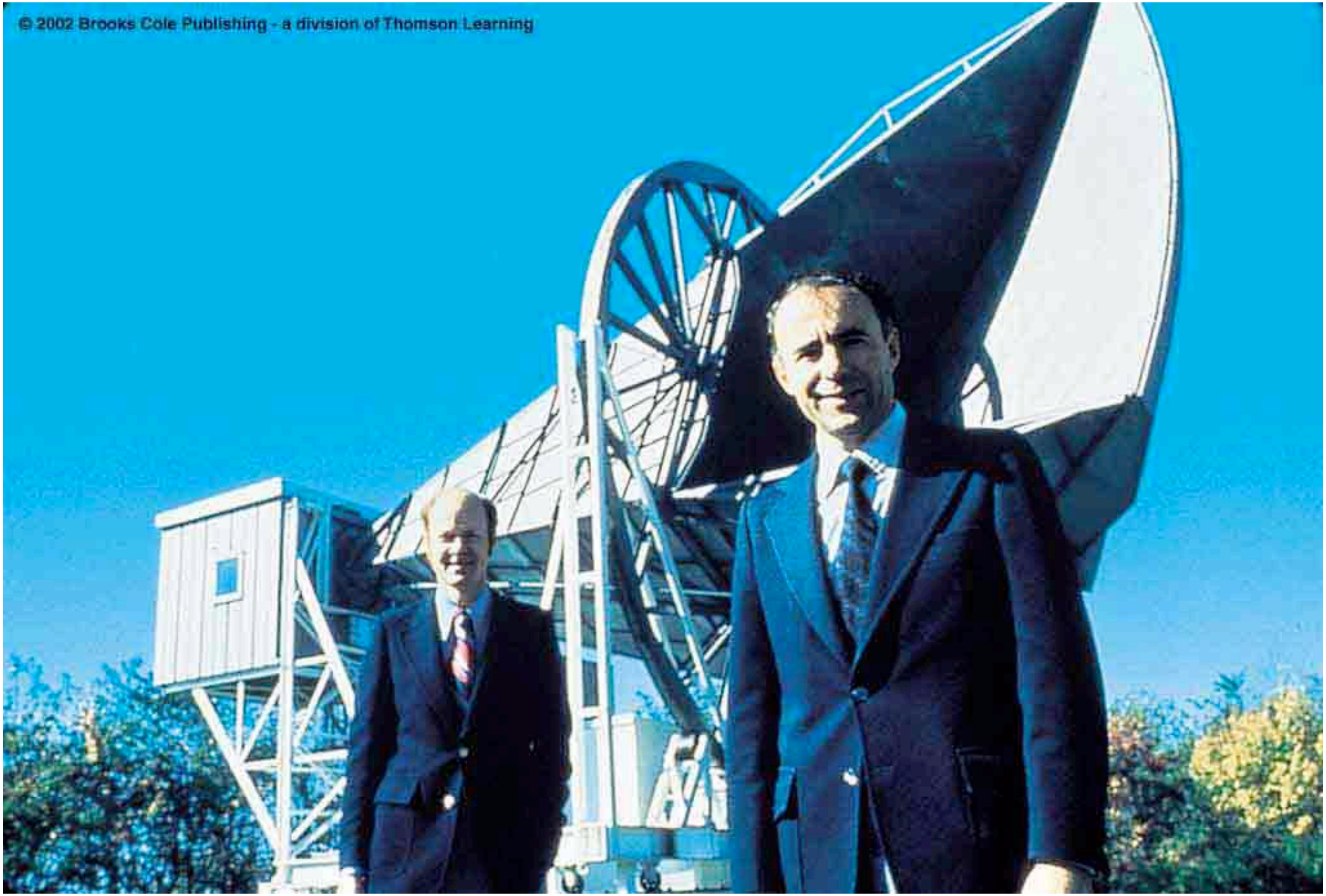
The light that is reaching us now has had its wavelengths Doppler shifted by the expansion of the Universe.

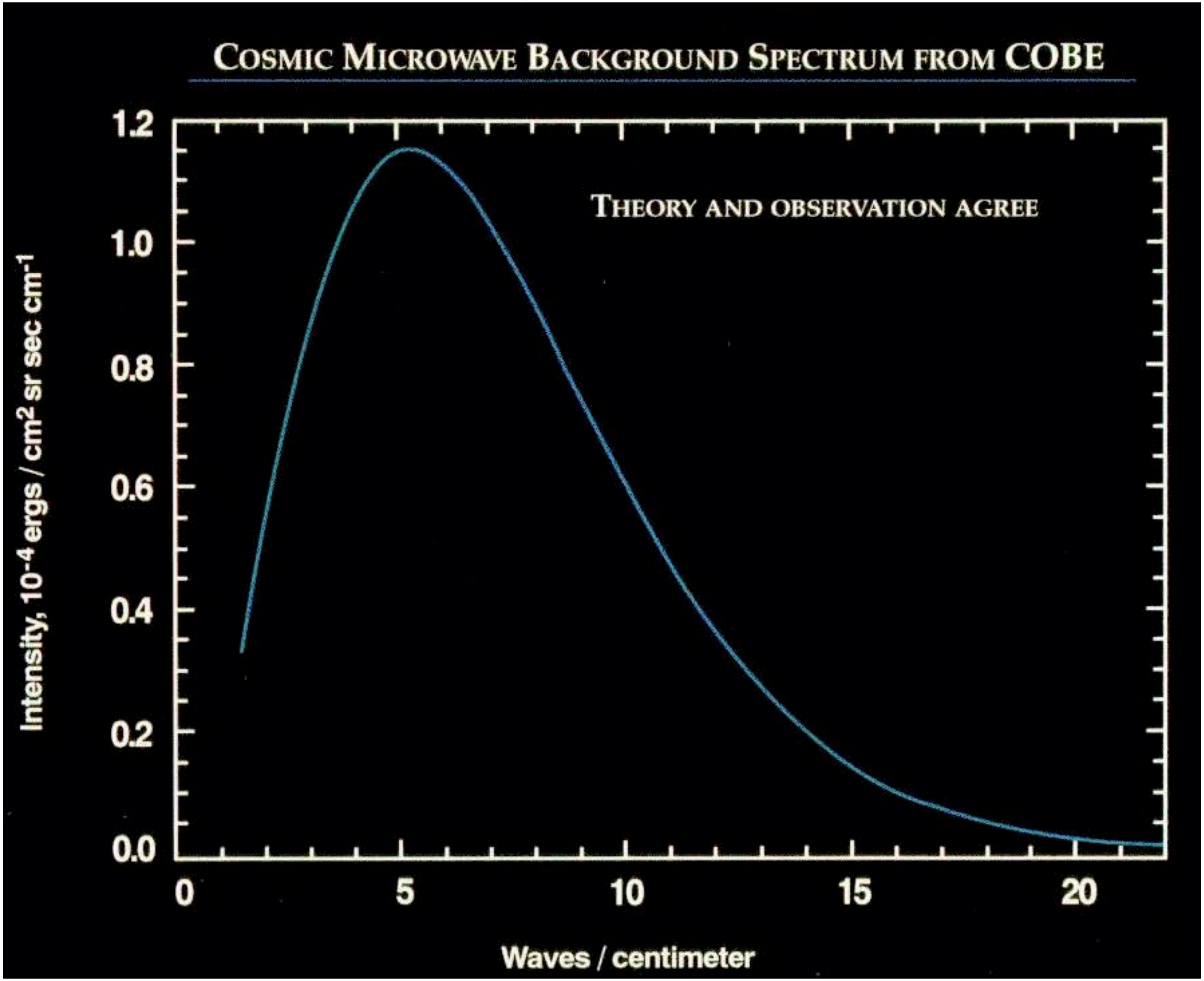
For this purpose it is easiest to look at the Doppler shift as being a stretching of wavelengths of light by the same factor as distances in the Universe have been stretched.

For 3000 K, $\lambda_{max} = 1\ \mu m$.

Stretched by a factor of 1000, this light appears now with $\lambda_{max} = 1$ mm.

It has the spectrum expected for an object at a temperature of 3 K, which would have its peak emission at 1 mm.



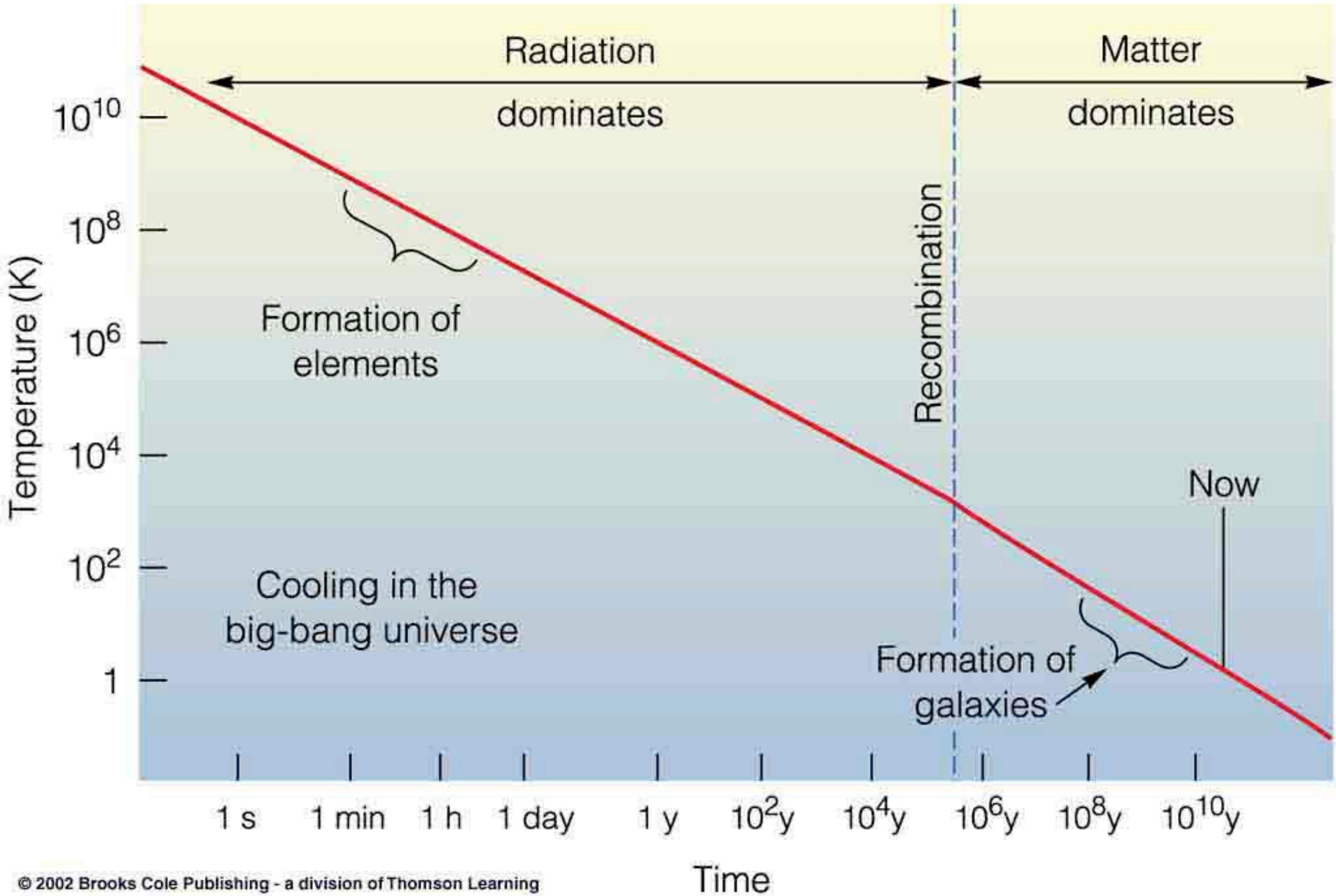


COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE
THEORY AND OBSERVATION AGREE
Intensity, 10^-4 ergs / cm^2 sr sec cm^-1
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Waves / centimeter

Thinking farther back

If the Universe has been cooling as it expanded, and it was at a temperature of 3000K 400,000 yr after the big bang, it should have been even hotter earlier.

We can ask what the temperature was at different times and what should have been happening then.



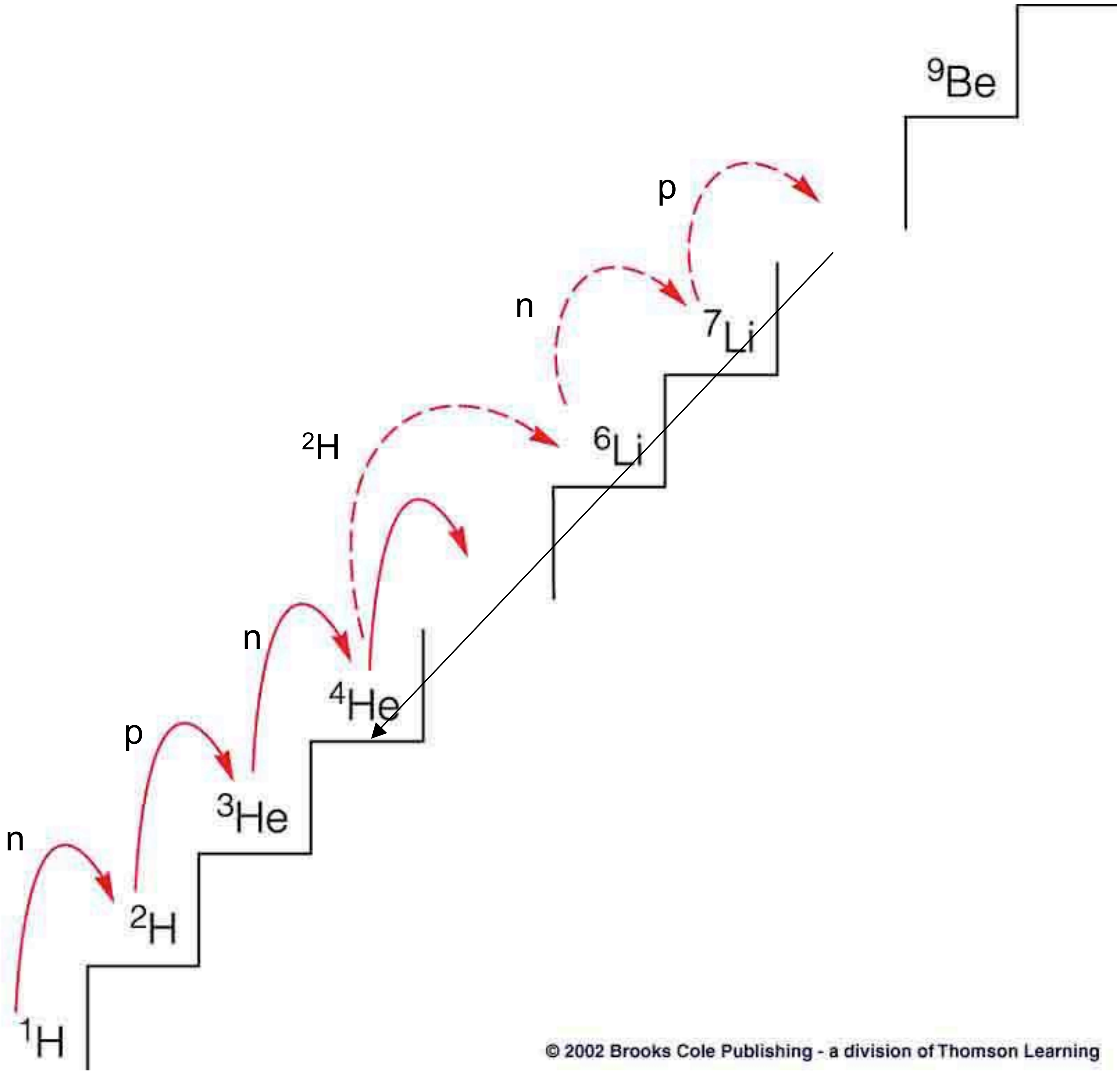
Radiation
dominates
Matter
dominates
Recombination
Temperature (K)
10^10
10^8
10^6
10^4
10^2
1
Formation of
elements
Cooling in the
big-bang universe
Now
Formation of
galaxies
1 s
1 min
1 h
1 day
1 y
10^2y
10^4y
10^6y
10^8y
10^10y
Time

Before 400,000ABB

$t = 10^{-6}$ sec	$T \sim 10^{13}$ K	$\gamma + \gamma \leftrightarrow p^+ + p^-$
$t = 1$ sec	$T \sim 10^{10}$ K	$\gamma + \gamma \leftrightarrow e^- + e^+$
		$p^+ + e^- \leftrightarrow n + \nu$
$t = 2$ min	$T \sim 10^{9}$ K	$p^+ + n \leftrightarrow d^+$
		$d^+ + d^+ \leftrightarrow He^{++}$
		$n \rightarrow p^+ + e^- + \nu$

Heavier elements weren't formed because $^8Be \rightarrow 2\ ^4He$

Where did the elements other than hydrogen in your body come from?



^9Be
p
n
^7Li
^2H
^6Li
n
^4He
p
^3He
n
^2H
^1H