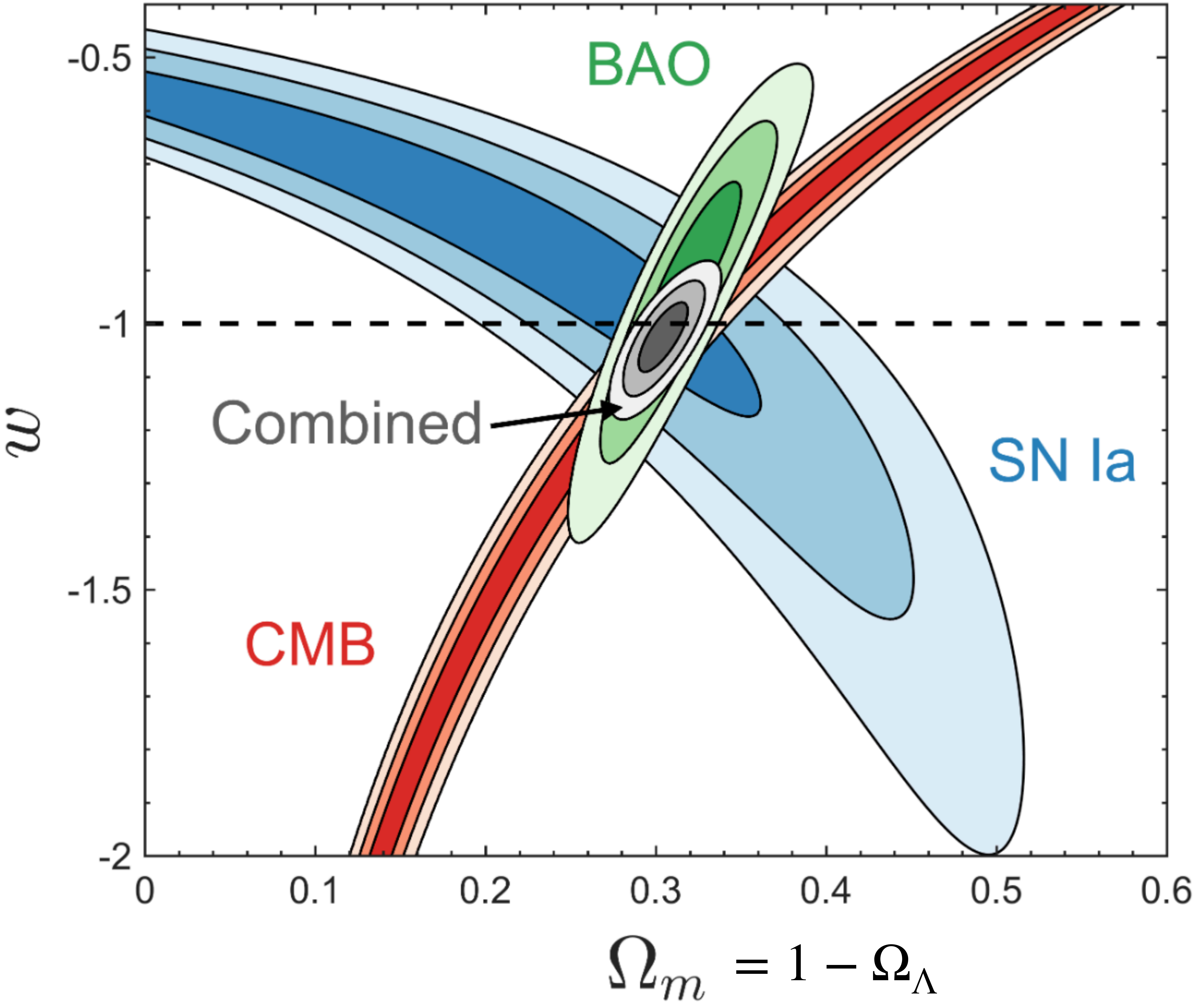


$$w = \frac{\textbf{pressure}}{\textbf{density}}$$

$$\rho = R^{-3(1+w)}$$

matter	$w = 0$
radiation	$w = 1/3$
dark energy	$w = -1$

The flatness problem

Why is Ω_{total} ~ 1? Why not 106? Why not 42? Why not 0.0021034011031?

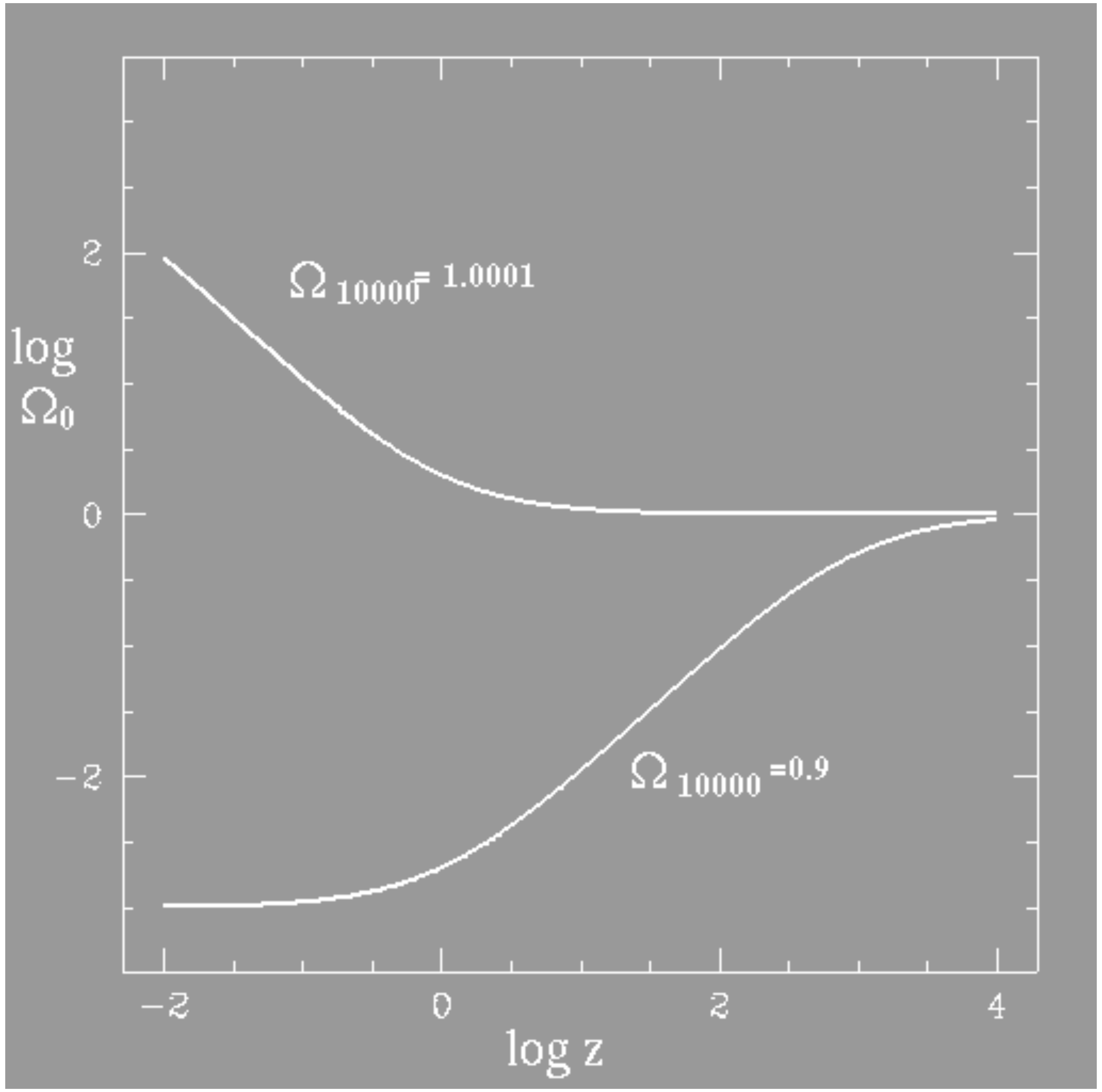
The density of the Universe changes with time, as the Universe expands. So Ω_M, the ratio of the actual density to the critical density also changes:

$$\Omega(z) = \Omega_0 \left[\frac{1+z}{1+\Omega_0 z}\right]$$

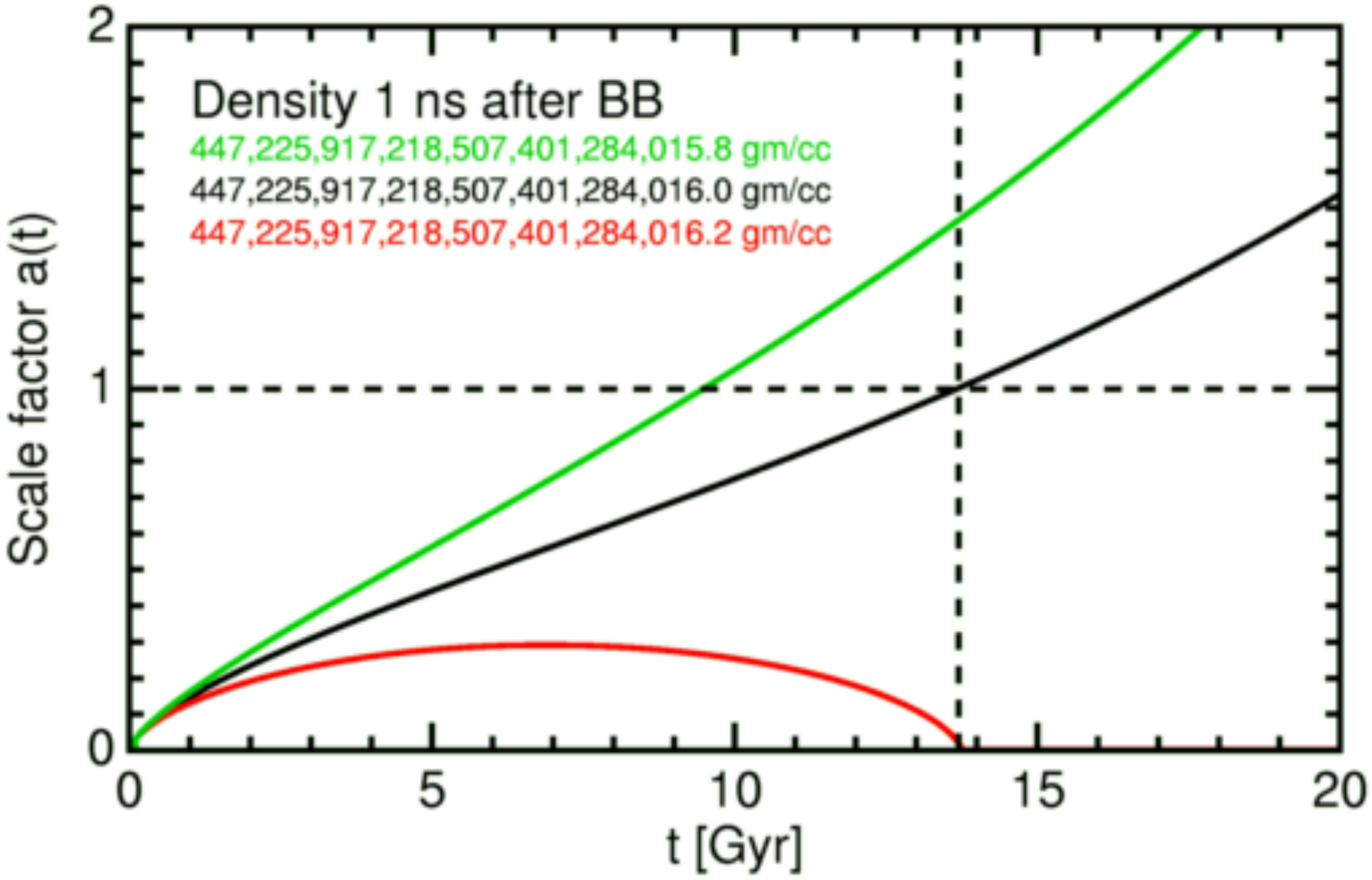
Let's look at two examples.

- **At a redshift of z=10,000 (ie when the universe was 10^4 times smaller than now), it had a density parameter of 1.0001**
- **At a redshift of z=10,000, it had a density parameter of 0.9**

In the universe that is slightly overdense at z=10^4, the density parameter today (at z=0) would be 100. In the universe that is slightly underdense at early times, we ought to measure a density parameter today of 0.001. Omega very quickly diverges from 1, unless it is equal to 1.

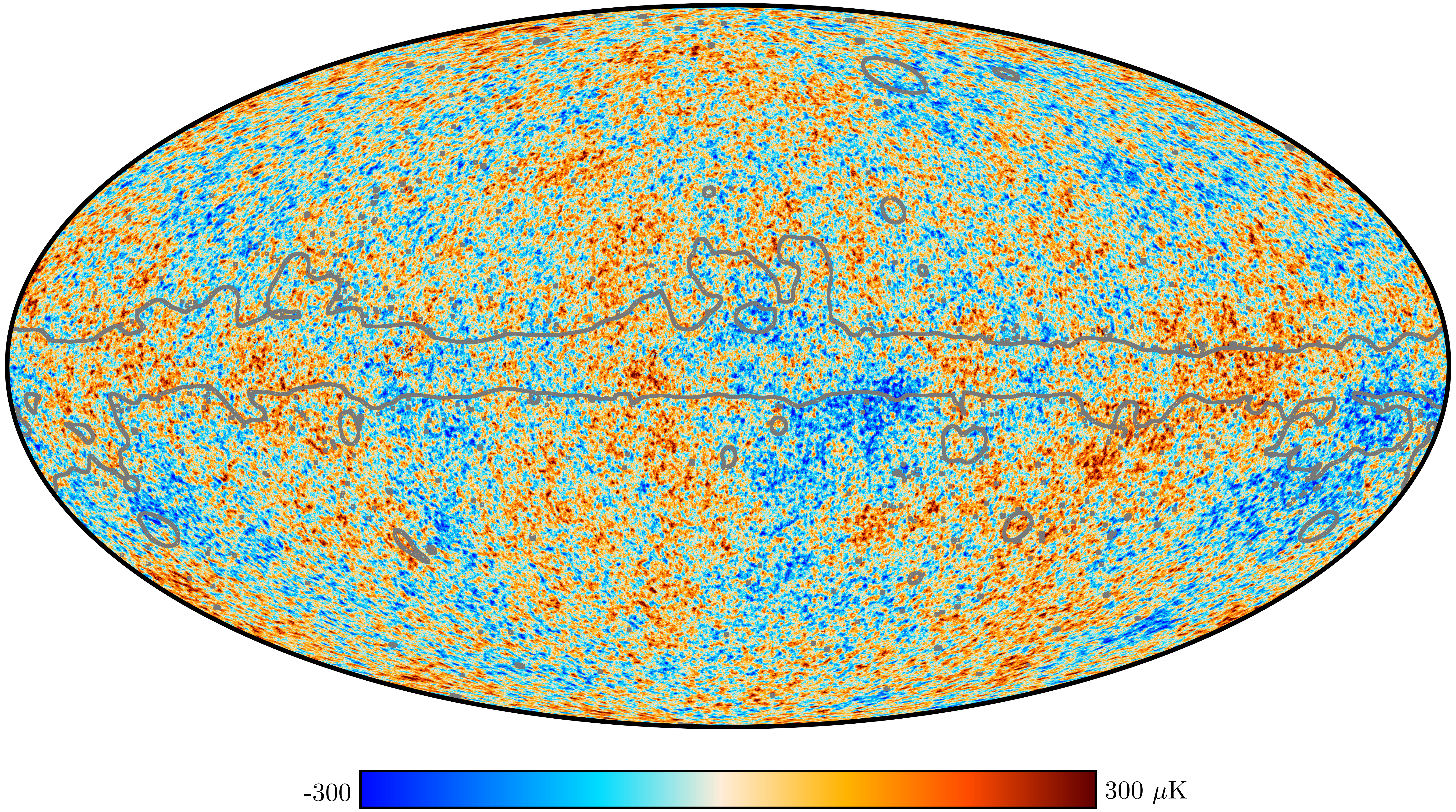


It gets worse. Look at this figure (from [Ned Wright's Cosmology Tutorial]): if the density of the universe had been ever so slightly non-critical 1 nanosecond after the big bang, we would have a drastically different universe:



The Smoothness Problem

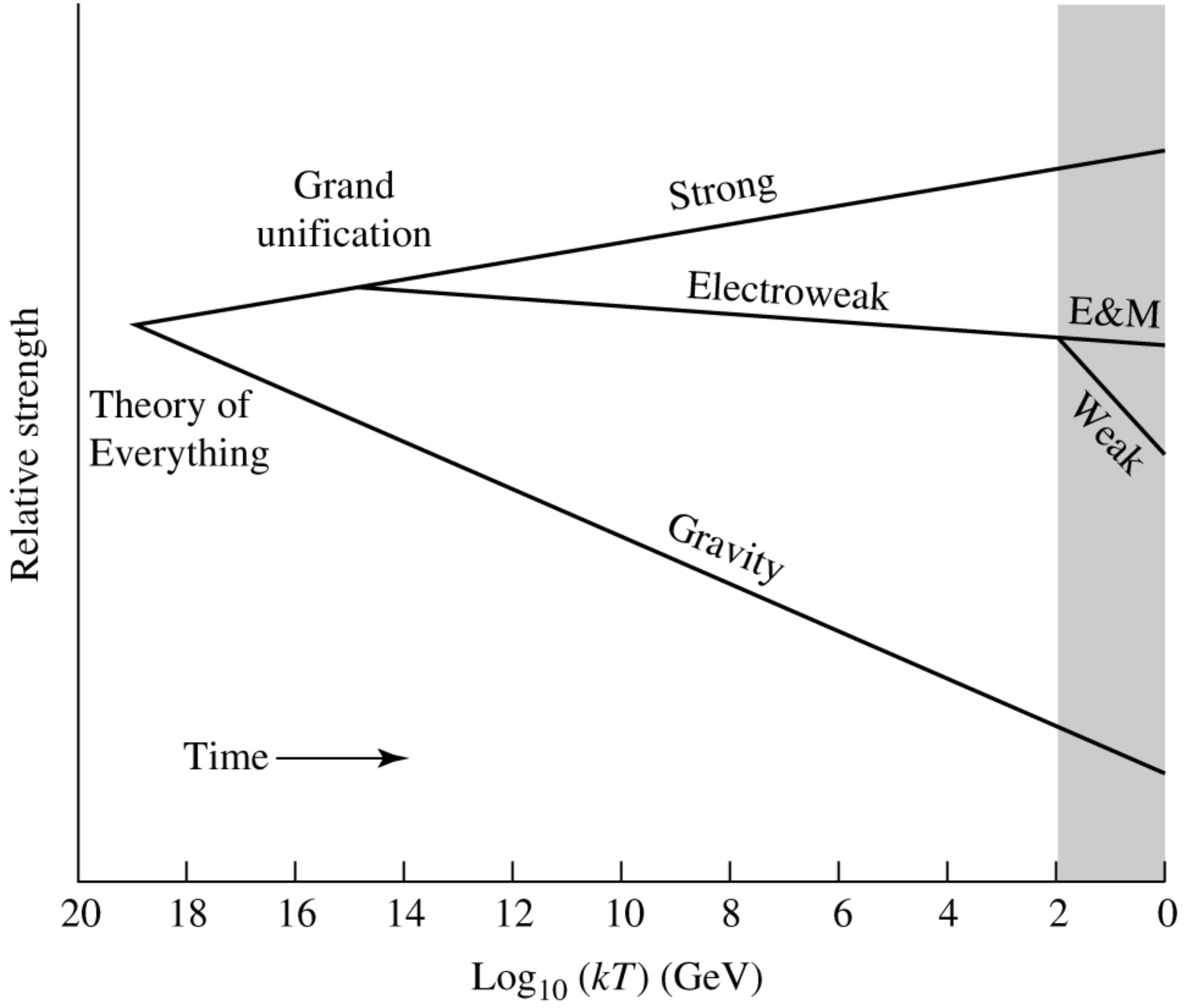
Looking at the microwave background, it is very smooth to 1 part in 10^5. Everywhere. But at the time of recombination, regions of the universe which are now separated by more than 2 degrees on the sky were never in causal contact. How did all these regions of space "know" that they should all be at exactly the same temperature?



Why is the universe flat? Why is the universe smooth?

1980: Alan Guth dreams up inflation.

- **Let's say in the very early history of the universe it went through a phase of exponential expansion: in 10^{-24} seconds it expanded by a factor of 10^{50}. How would this fix the flatness and smoothness problems?**
  - **flatness: imagining blowing up space by a factor of 10^{50}. Any curvature it had would be instantly "flattened".**
  - **smoothness: originally the universe was smaller than the extrapolation of the standard expansion history to early epochs. So before inflation, everything was causally connected, then inflation drove things apart.**
- ***But what drives inflation?***
  We don't know.
  Inflation is thought to have occurred when the Universe was only ~ 10^{-34} seconds old, when the temperature was ~ 10^{27} K. One possibility is that at this point the vacuum energy universe underwent a phase transition, at which point the strong nuclear force differentiated from the electroweak force. ***This phase transition may have released the energy which drove inflation.***



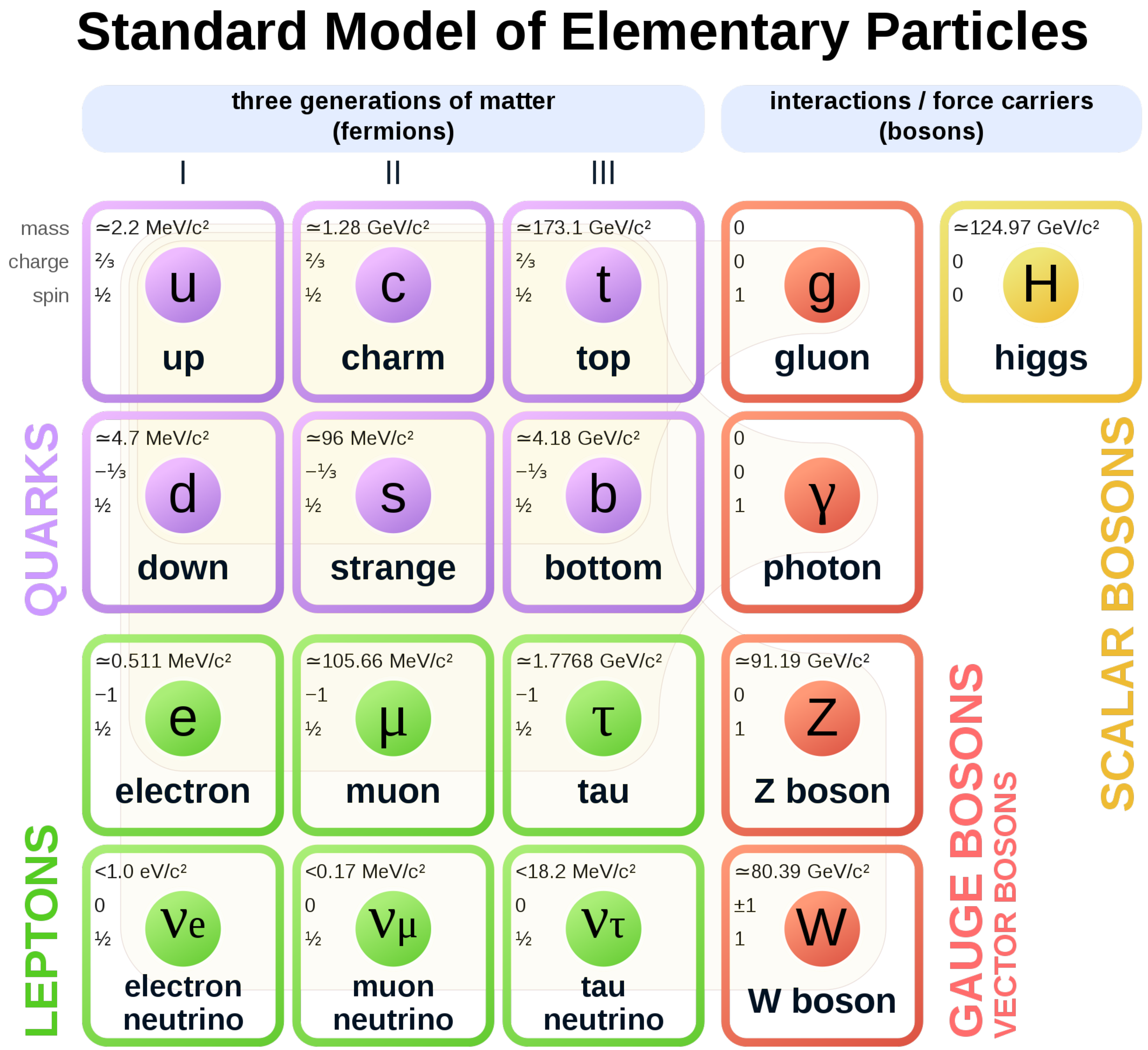
Making particles

Remember the **Heisenberg Uncertainty Principle**: $\Delta E \Delta t = \hbar$

And since E=mc^2, we can rewrite this as $\Delta m \Delta t = \hbar / c^2$

In other words, over a small enough timescales, there is some uncertainty as to how much mass there is in a vacuum. This is the source of virtual particles: matter can spontaneously appear. But it must do so in particle pairs -- matter and antimatter (ie a positron and an electron). So they will annihilate almost instantly, in a time *Δt*, which for electron-positron pairs is ~ 6x10^{-22} seconds.

Particles that were present before inflation would be "diluted out" -- the density of particles would be essentially zero after inflation. So particles today are thought to have been produced by the energy released during inflation.

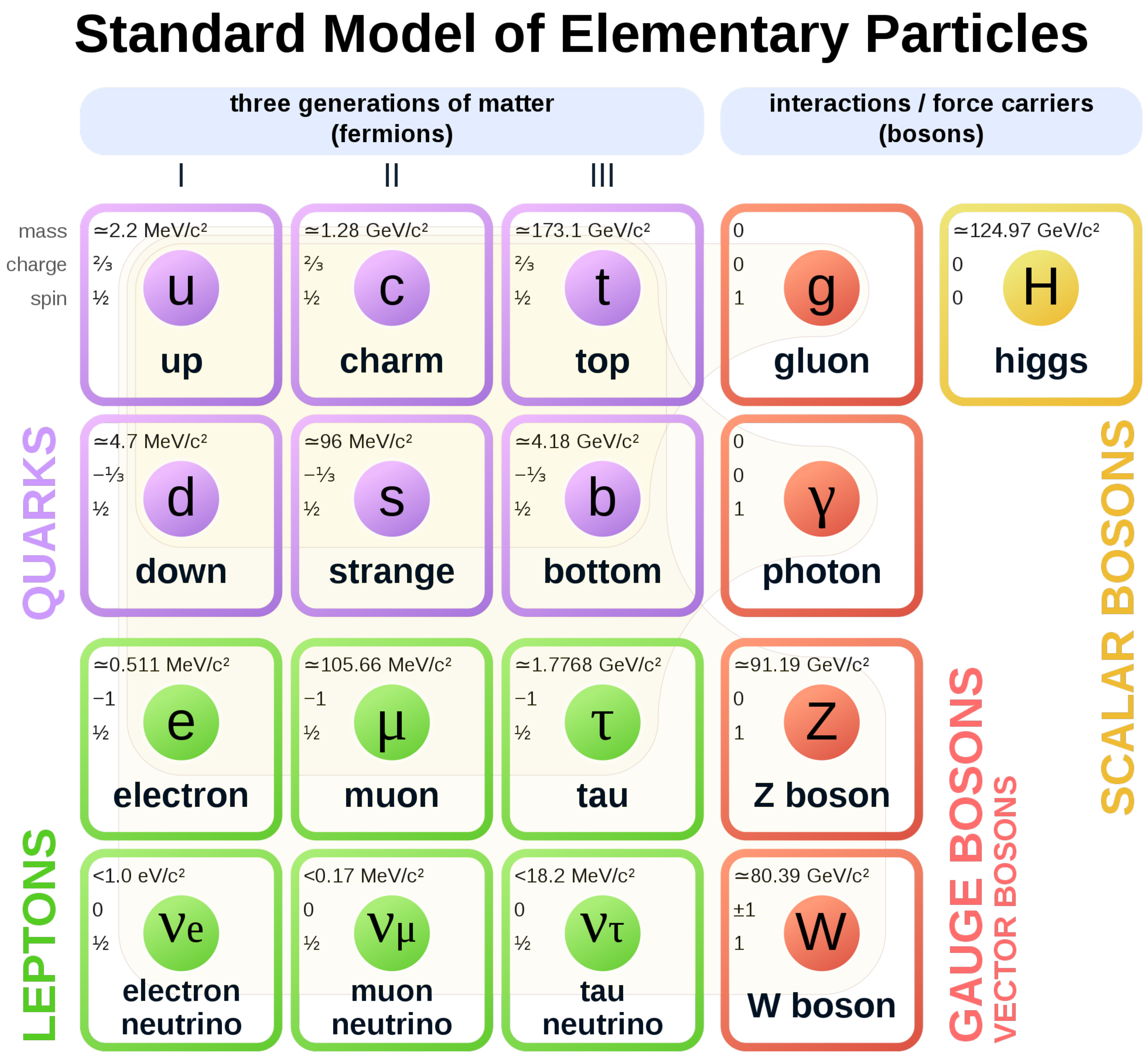


So after inflation we have a Universe filled with elementary particles and photons. But normal pair production means that they are still going back and forth between gamma rays and particles, for example:

$$e^+ + e^- \rightarrow \gamma + \gamma$$

$$\gamma + \gamma \rightarrow e^+ + e^-$$

But the universe is expanding (normally, now, not inflating), so the **gamma rays are getting redshifted and losing energy**. When the universe was 0.0001 seconds old, the energy of the gamma rays had dropped to the point where they could not create protons and neutrons. You could still lose neutrons when they collided with antineutrons, but you couldn't make any more: **the matter content of the universe dropped, and the radiation density went up**. A similar thing happens with electrons and positrons at t=1 second.



Standard Model of Elementary Particles

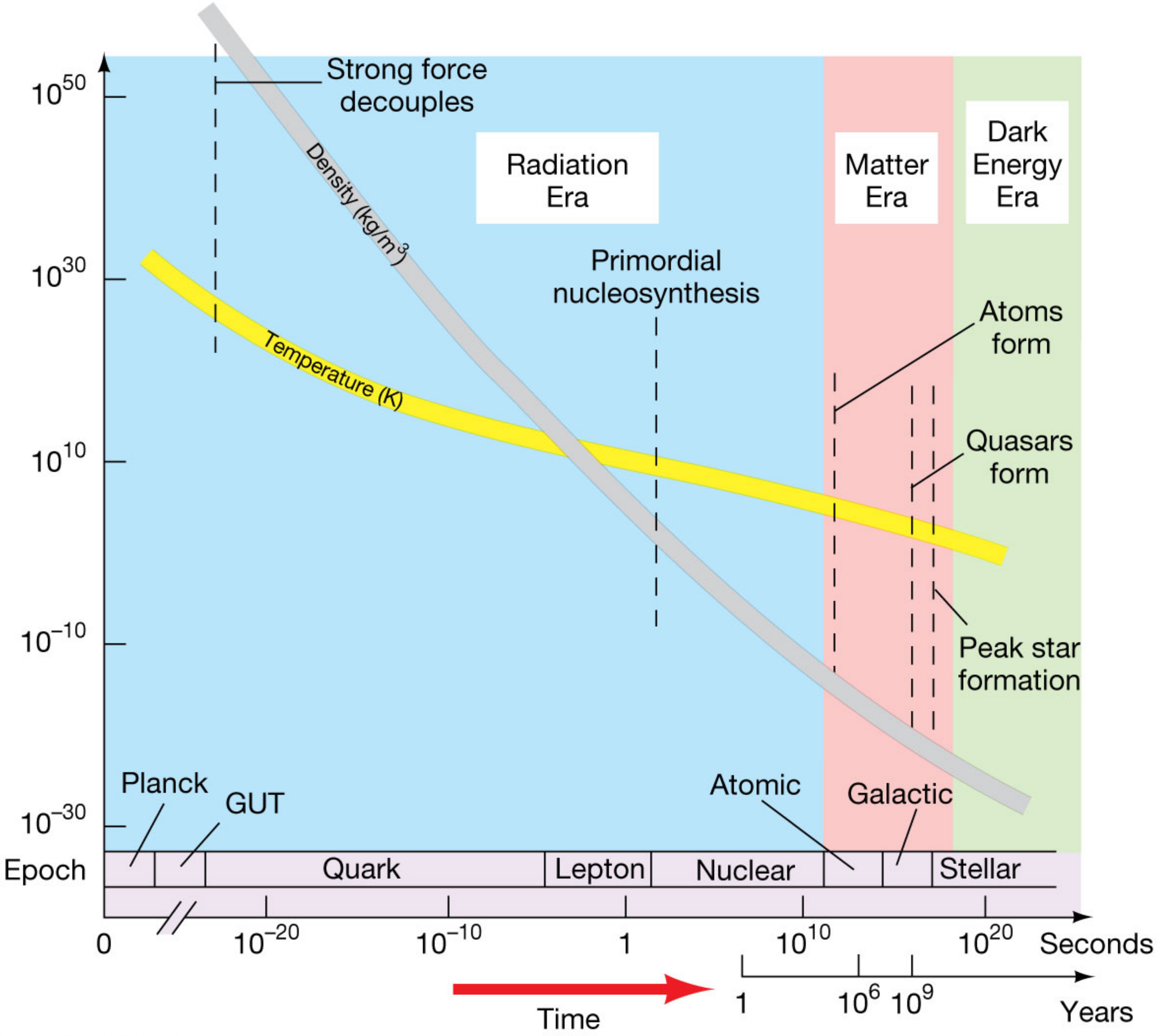
		three generations of matter (fermions)			interactions / force carriers (bosons)	
		I	II	III		
QUARKS	mass charge spin	≃2.2 MeV/c^2 ⅔ ½ u up	≃1.28 GeV/c^2 ⅔ ½ c charm	≃173.1 GeV/c^2 ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c^2 0 0 H higgs
		≃4.7 MeV/c^2 −⅓ ½ d down	≃96 MeV/c^2 −⅓ ½ s strange	≃4.18 GeV/c^2 −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
LEPTONS		≃0.511 MeV/c^2 −1 ½ e electron	≃105.66 MeV/c^2 −1 ½ μ muon	≃1.7768 GeV/c^2 −1 ½ τ tau	≃91.19 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS VECTOR BOSONS
		<1.0 eV/c^2 0 ½ νe electron neutrino	<0.17 MeV/c^2 0 ½ νμ muon neutrino	<18.2 MeV/c^2 0 ½ ντ tau neutrino	≃80.39 GeV/c^2 ±1 1 W W boson	

So did we just lose all our matter? Why are we here?

There must have been an **initial asymmetry in the amount of matter and antimatter** in the Universe: for every 10^9 antiparticles there must have been 10^9+1 particles. Wow. Ask the physicists about that one...
So we are left with lots and lots of photons and very little matter. Welcome to the radiation era.

After about 2 seconds, the density of the universe dropped enough that neutrinos stopped interacting with the matter, and "decoupled" from the thermal history of the Universe. There should be lots of primordial neutrinos running around in the Universe...

Now we have a hot universe which is a few seconds old. The energy budget is dominated by radiation, with a small mixture of protons, neutrons, and electrons. Time to start making elements: Big Bang Nucleosynthesis



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Big Bang Nucleosynthesis

So we have the building blocks of the elements: protons, neutrons, electrons. The temperature is high, but dropping fast; the density is also pretty high, but also dropping fast. If we act quick, we might be able to have nuclear fusion. This happens when the Universe is a few minutes old.

Step 1: Initial mix of particles

When the Universe is a few seconds old, at T=10^{10} K, protons and neutrons are in thermal equilibrium, and their ratio is given by the Boltzmann equation:

$$\frac{n_n}{n_p} = e^{-(m_p - m_n)c^2/kT}$$

which gives n/p = 0.223. Below 10^{10} K, no new neutrons are formed, so that ratio is frozen in. Yet it is too hot for nuclear fusion to happen, so the mix of protons and neutrons is maintained. So for every 1000 protons, there are 223 neutrons.

Step 2: Beta decay changes the balance

But free neutrons undergo beta decay, which converts neutrons into protons with a half life of 617 seconds. When the universe was about four minutes old, the time the temperature had dropped to 10^9 K, and particles can begin to fuse together in nuclear reactions. At the point in time when this happens, neutron decay has rebalanced the neutron to proton ratio to n/p=0.164.

So our proton/neutron mix above has changed to 1051 protons and 172 neutrons.

Step 3: Nucleosynthesis

Now we are are ready for nucleosynthesis. At 10^9 K, fusion of particles can create deuterium, tritium, and helium:

$$p^+ + n \rightleftharpoons {}^2H + \gamma$$

$${}^2H + {}^2H \rightleftharpoons {}^3H + p$$

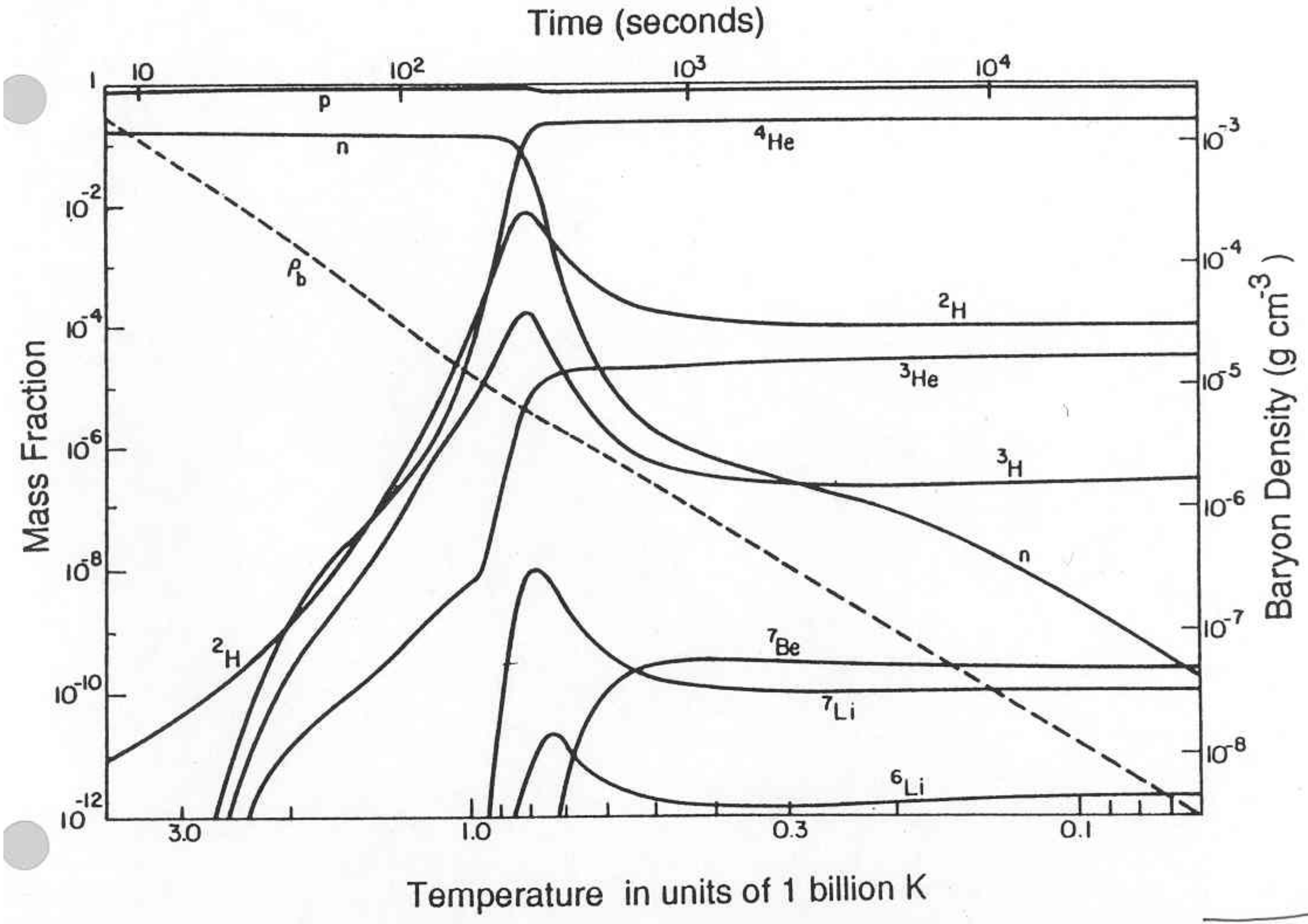
$${}^3H + {}^2H \rightleftharpoons {}^4He + n$$

(note that these are different reactions from pp chain that powers the Sun!)

These reactions happen so efficiently that we make as much helium as possible. If we have 172 neutrons, we can make a total of 86 ^{4}He nuclei, with 879 protons (H nuclei) left over. So the mass fraction of helium in the Universe was

$$\mathrm{Y} = \frac{4(86)}{879 + 4(86)} = 0.28$$

Which is not too far off the observed value of the primordial helium content of the Universe: ~ 23-24%.


Time (seconds)
1
10
10^2
10^3
10^4
p
n
^{4}He
10^{-2}
ρ_b
10^{-4}
^{2}H
^{3}He
10^{-6}
^{3}H
10^{-8}
n
^{2}H
^{7}Be
10^{-10}
^{7}Li
^{6}Li
10^{-12}
Mass Fraction
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Baryon Density (g cm^{-3})
3.0
1.0
0.3
0.1
Temperature in units of 1 billion K

Some of the less massive nuclei are also produced: deuterium (^{2}H), ^{3}He, ^{7}Li.

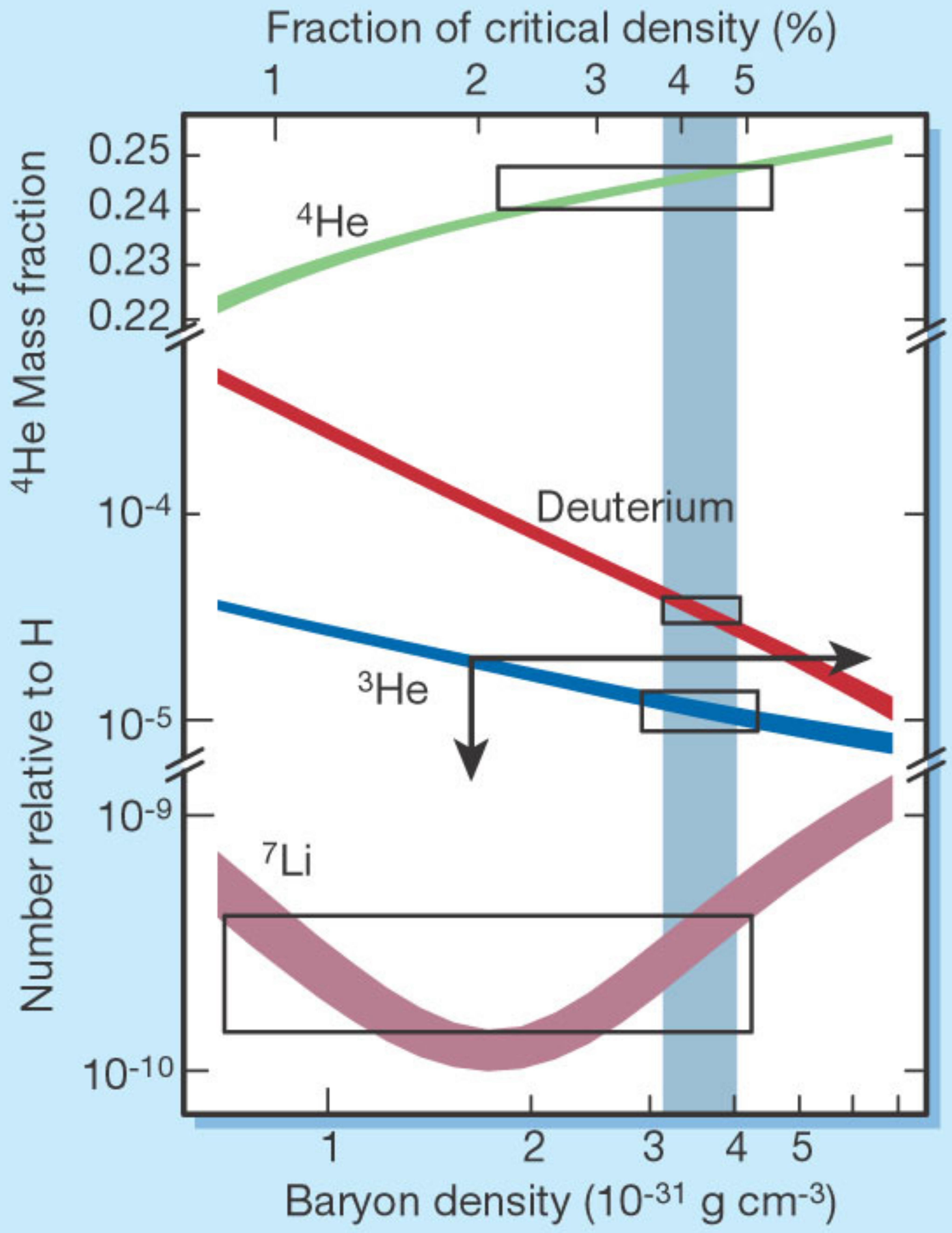
The abundances of these elements can be used to constrain the baryonic density of the universe at the time of BBN.

If the baryon density is high, the reactions are more efficient, more ^{4}He is created, and fewer intermediate nuclei like ^{2}H are left over.

If the density is low, the reactions happen more slowly, and don't create as much ^{4}He before the temperatures drop too low. More intermediate nuclei are left over.

The plot at the left shows the abundances of these light elements as a function of the present baryon density of the universe. Based on the observed abundances of these elements (particularly deuterium — ^{2}H), we infer that *the baryonic density of the universe is only a few percent of the critical density*.

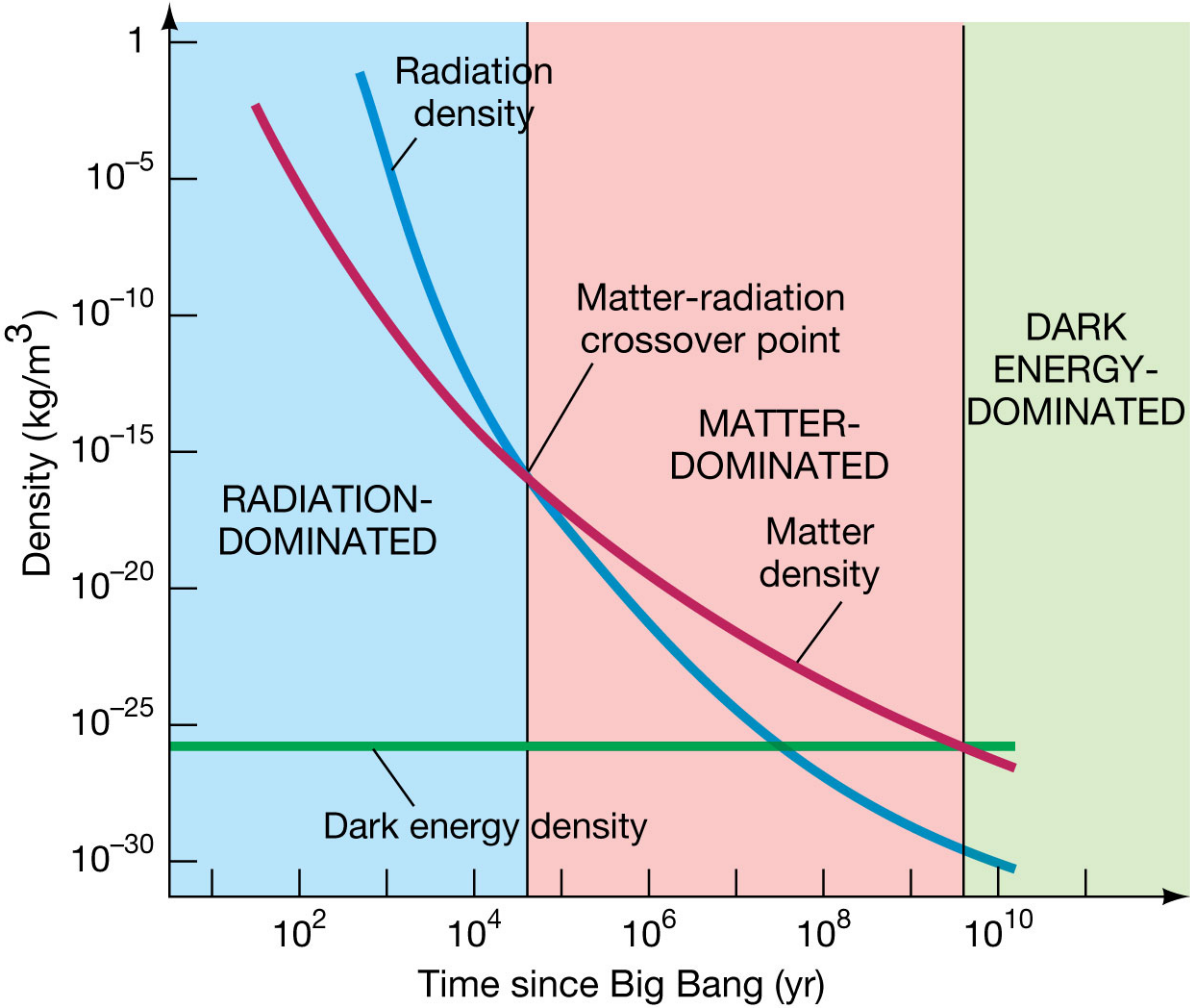
Dark matter cannot be normal baryonic material!



The Epoch of Recombination

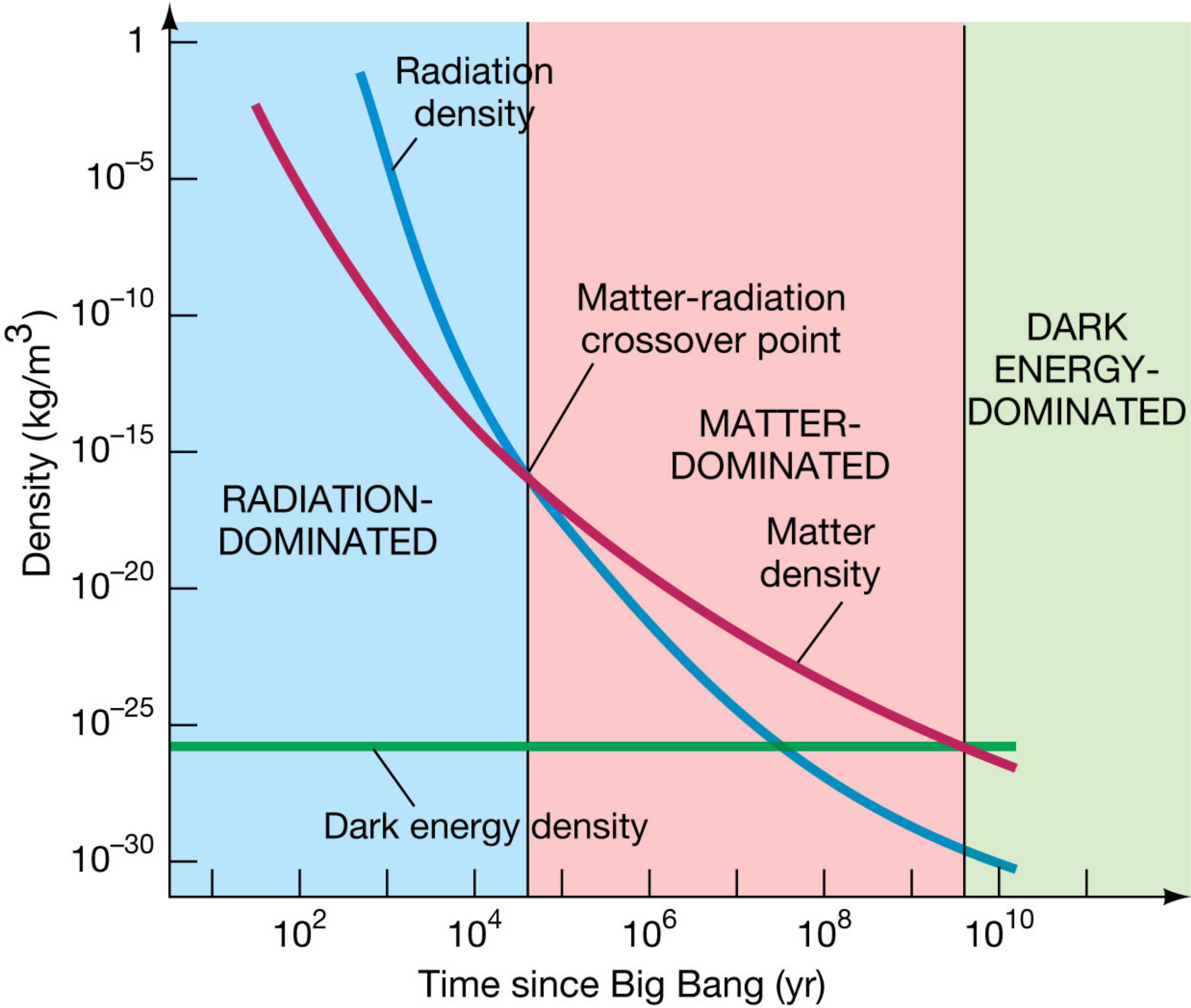
After BBN, the universe is a hot soup of protons, electrons, helium nuclei, and photons. Initially, the energy density of radiation was greater than the energy density of matter and we were in the radiation era. During the radiation era, the energy from the radiation governs the expansion of the Universe But the energy density of radiation drops faster than that of matter:
Matter: energy density proportional to R^{-3} (volume effect)
Radiation: energy density proportional R^{-3} (volume effect) times another R^{-1} (redshift effect), so R^{-4}.

After about 55,000 years, T ~ 9000 K and the energy density of radiation falls below that of matter: we enter the matter era. Now, photons and particles are still closely coupled, due to all the free electrons running around. Electrons scatter photons through Thomson scattering, so that photons cannot free stream. *The Universe is opaque, and matter and radiation behave as a single fluid.*



Imagine a little piece of the Universe, which has an excess amount of matter. It will want to start collapsing under its own gravity. But it can't: the photons are coupled to the particles and keep them from collapsing. *So structure (galaxies, stars, clusters, etc) cannot form!*

When the temperature of the universe drops below 3000 K or so, when the Universe is ~ 200,000 years old, the electrons and nuclei combine to form atoms. No free electrons are running around, so photons can free stream and matter decouples from radiation. This is a fundamentally important time in the Universe's history: called the epoch of recombination. The Universe becomes transparent, we see it as the microwave background, and structure can start to form...



Think of the early universe -- there are fluctuations in the matter density on all scales, big and small. Look back at the microwave background, which shows large scale fluctuations:

These fluctuations continue down at smaller scales not visible in the CMB maps.

We characterize those fluctuations by a power spectrum:

Density fluctuations on small scales are stronger than on large scales. We can think of this as each region of the universe being characterized by its own set of cosmological parameters due to differences in Ω_M. So some regions will recollapse quickly and form galaxies and galaxy clusters, while others will have low Ω_M and not collapse at all (voids)