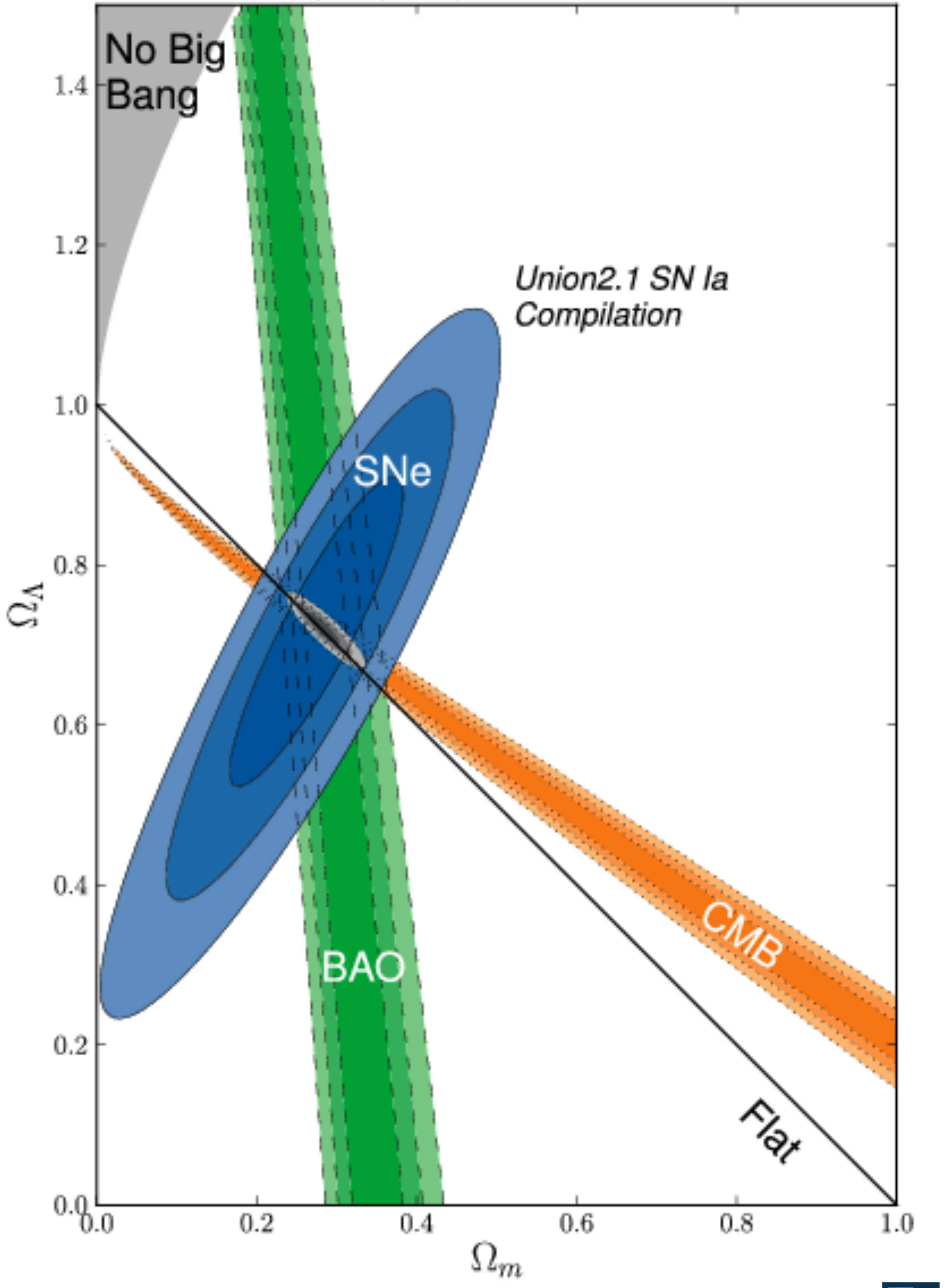
A "union" plot-- multiple datasets, multiple methods

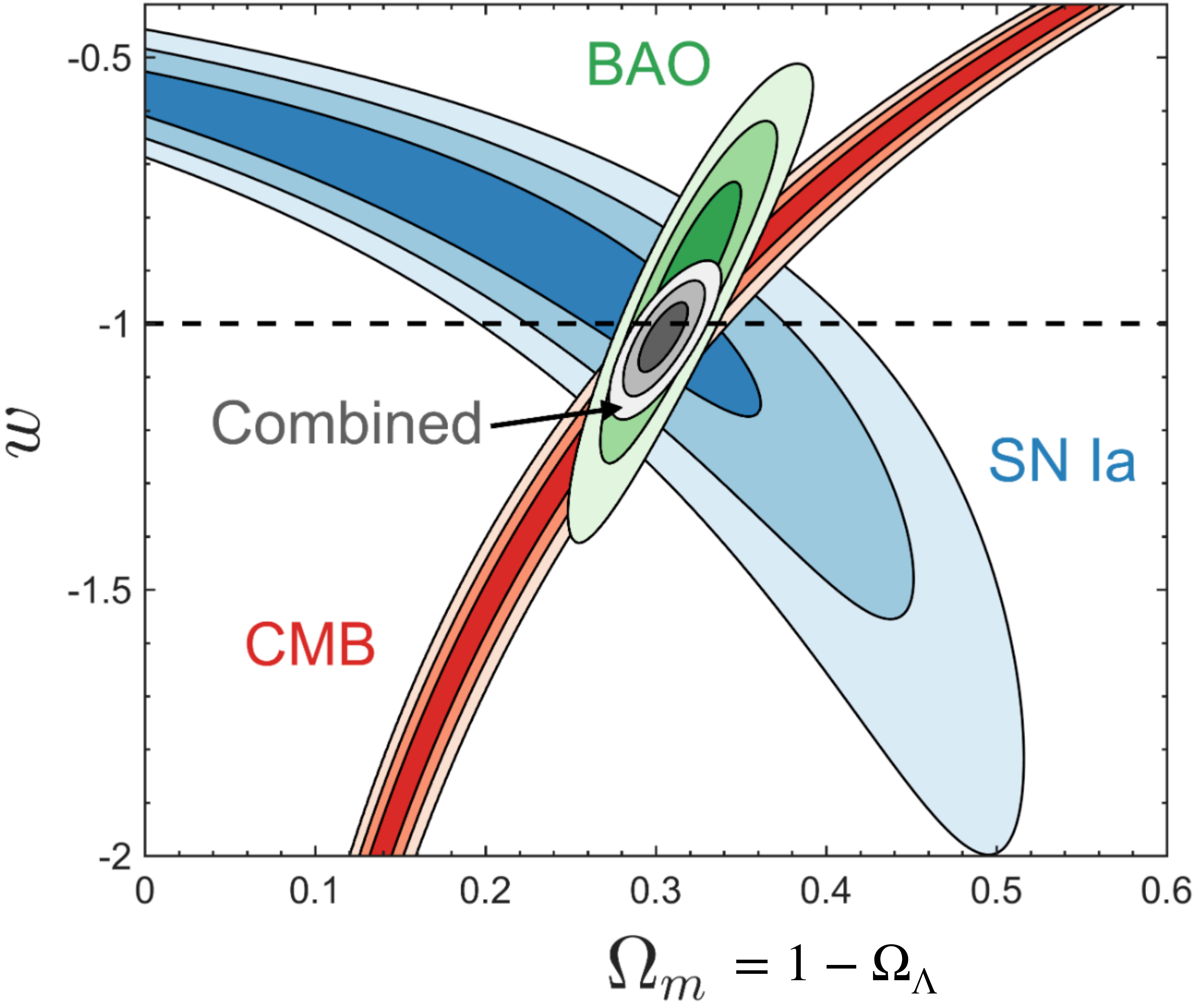
CMB = microwave background, sensitive to shape of space
SNe = supernovae, sensitive to R(t), the rate of expansion of the universe
BAO = tracing large scale structure of galaxies, sensitive to matter density parameter.

Working together, they suggest we live in a universe with:

- **Ω_M ~ 0.25**
- **Ω_Λ ~ 0.75**
- **Other observations give H_0 ~ 69-72 km/s/Mpc**
- **Results in t_0 ~ 13.8 Gyr**

Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)





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

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

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?

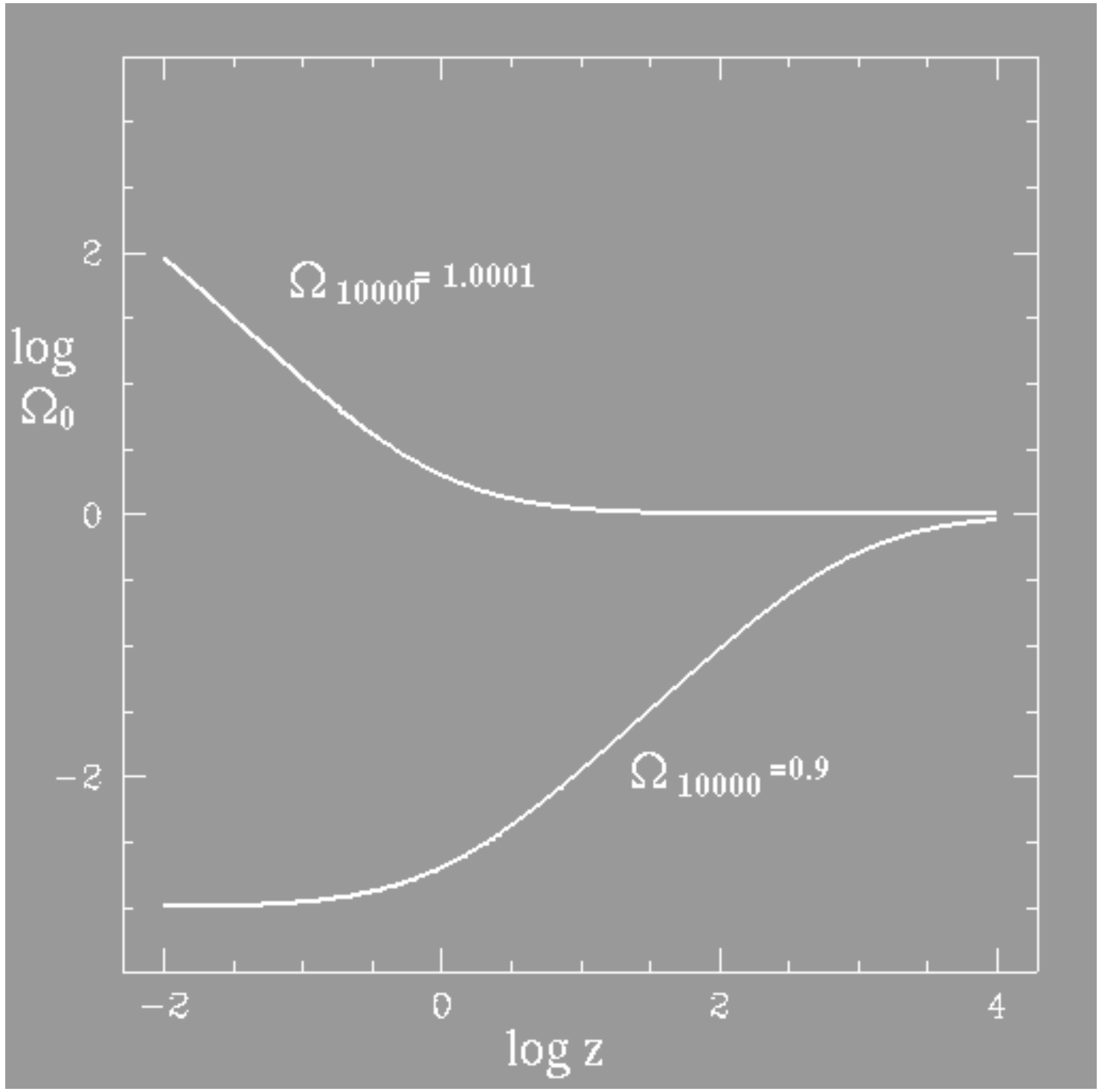
The density of the Universe changes with time, as the Universe expands. So Ω_M, the ratio of the actual density to the critical density also changes:

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

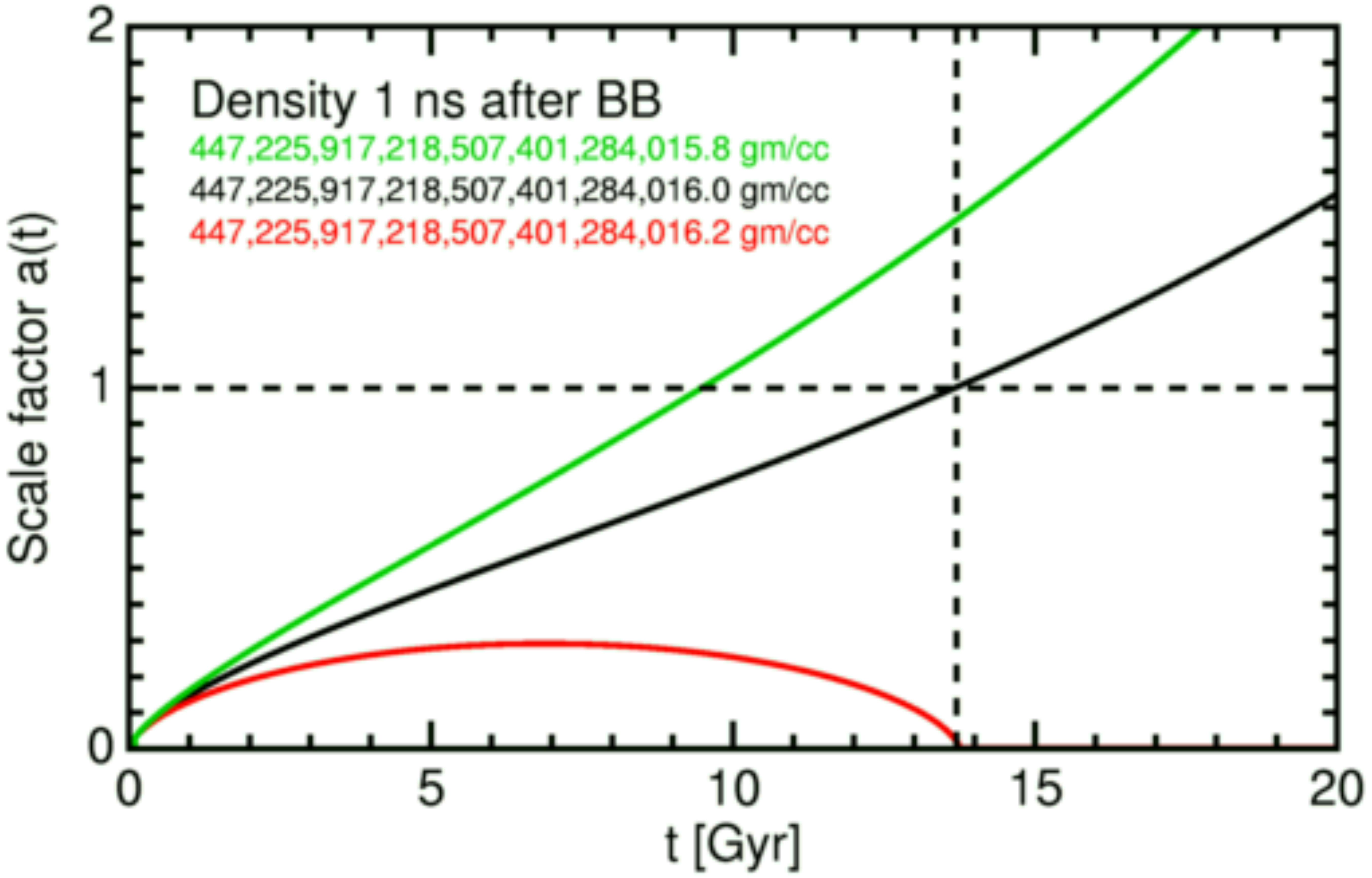
Let's look at two examples.

- **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.

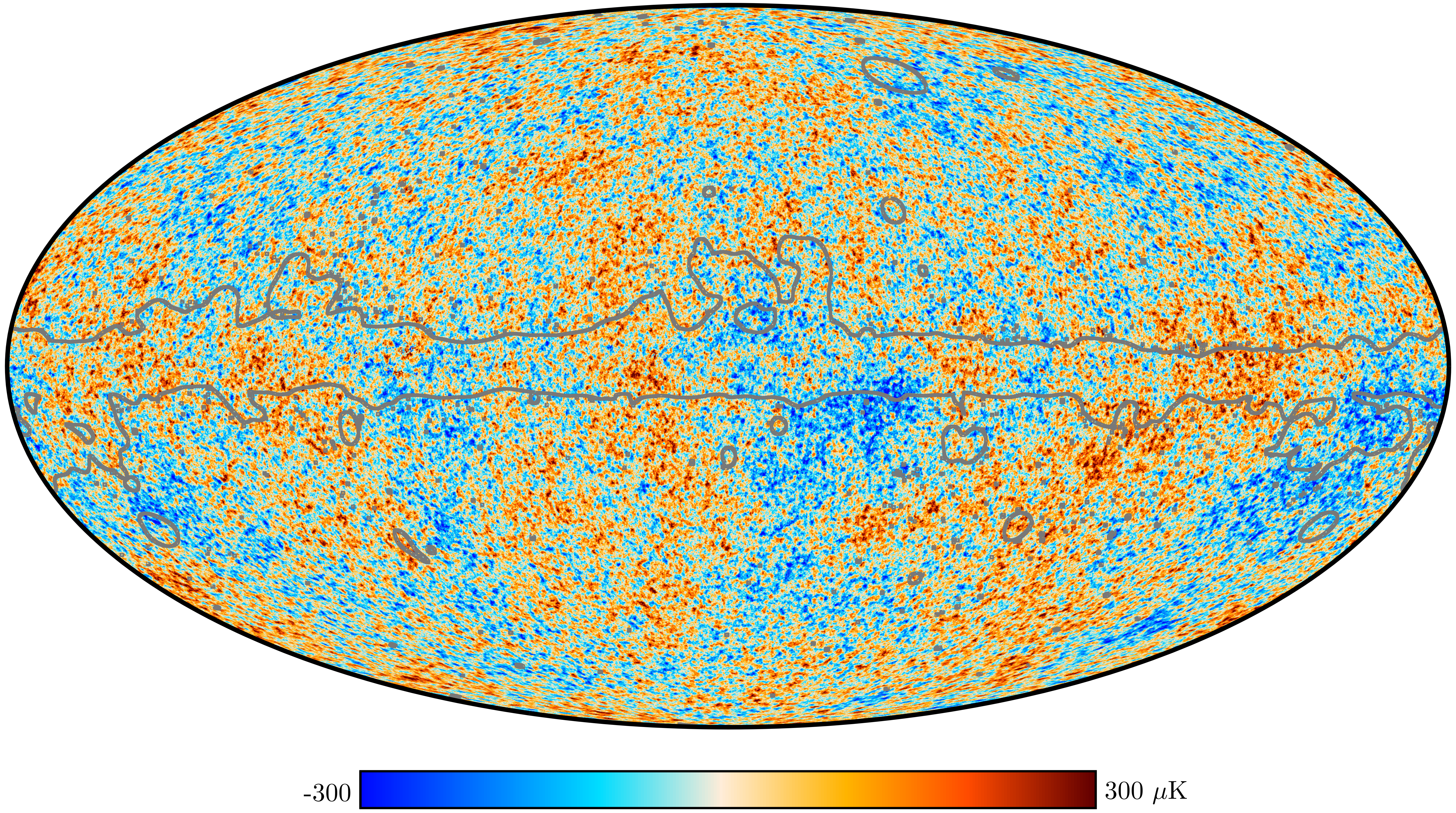


It gets worse. Look at this figure (from Ned Wright's Cosmology Tutorial): if the density of the universe had been ever so slightly non-critical 1 nanosecond after the big bang, we would have a drastically different universe:



The Smoothness Problem

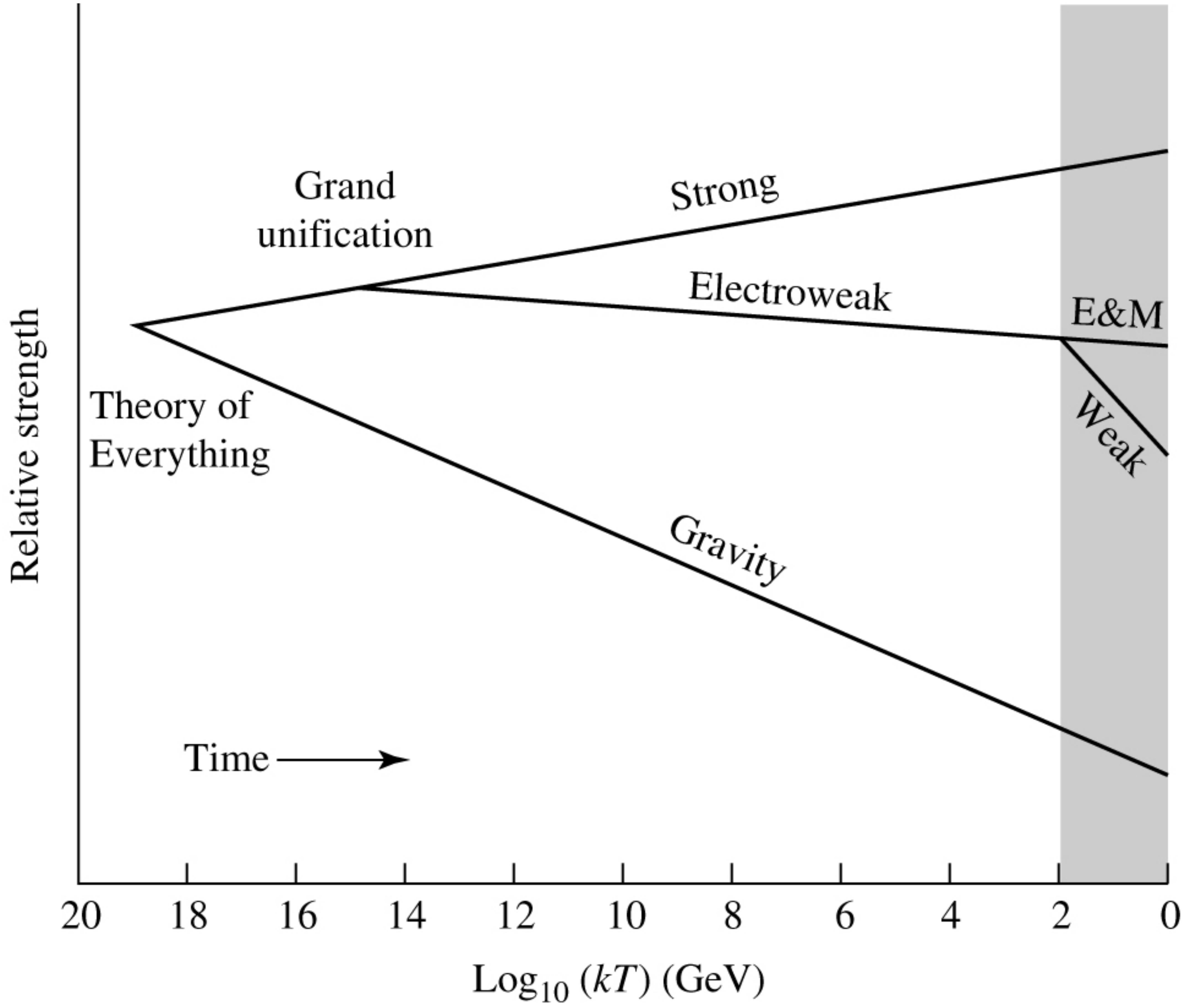
Looking at the microwave background, it is very smooth to 1 part in 10^5. Everywhere. But at the time of recombination, regions of the universe which are now separated by more than 2 degrees on the sky were never in causal contact. How did all these regions of space "know" that they should all be at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



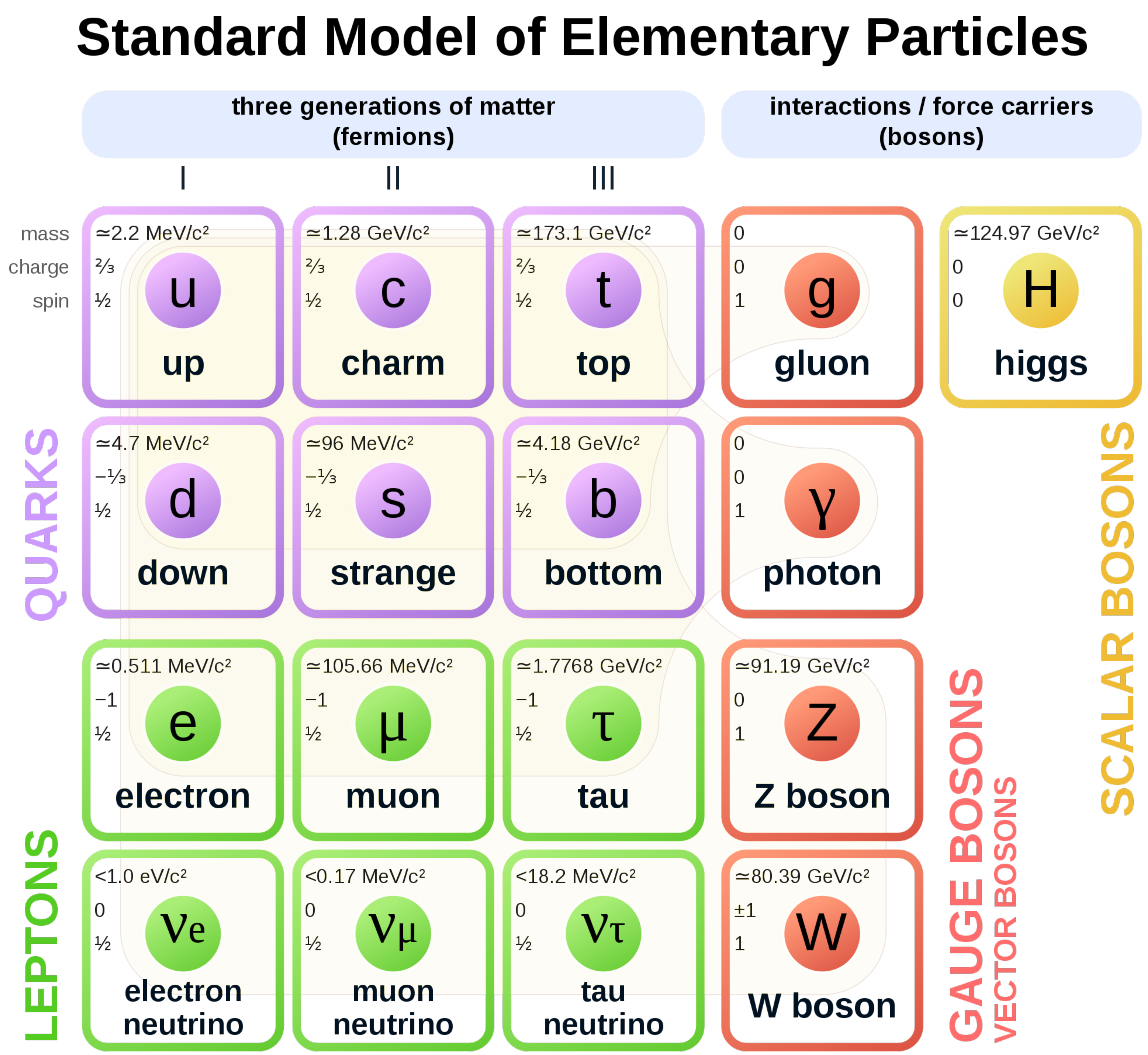
Making particles

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 ~ 6×10^{-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.



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	
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	
		<1.0 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<18.2 MeV/c^2 0 ½ ν_τ tau neutrino	≃80.39 GeV/c^2 ±1 1 W W boson	

SCALAR BOSONS

GAUGE BOSONS

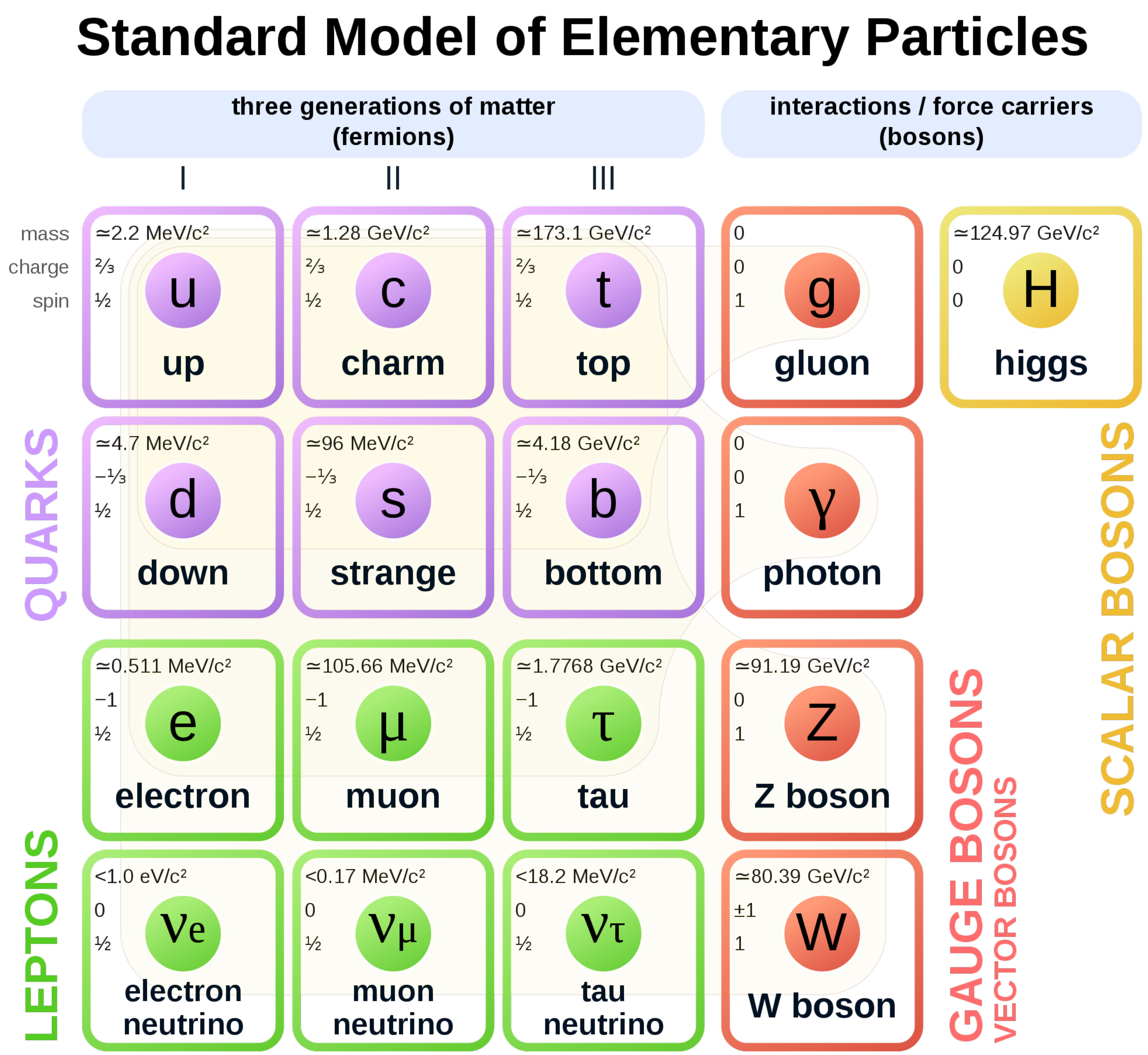
VECTOR BOSONS

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.



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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