

Timetable of the Universe

- $< 10^{-43}$ s: *unknown* – quantum gravity required; all forces unified
- $\sim 10^{-43}$ s: Gravity separates out; electromagnetism, weak and strong forces still unified (Grand Unified Theories – GUTs)
- $\rightarrow 10^{-35}$ s: **inflation**, universe expands by $\sim 10^{50}$ in radius, driven by energy of spontaneous symmetry breaking; strong force separates out
- $\sim 10^{-10}$ s: electromagnetic and weak forces separate, making the 4 forces we know today
- ~ 0.1 s: $T \sim 10^{11}$ K; all particles and radiation still in thermal equilibrium

Main constituents: e^-, e^+, μ, τ, ν with relatively few p, n .

T is below the threshold temperature ($=m_{\text{particle}}c^2/k$) for p, n , and most of them have annihilated with their antiparticles. There are $\sim 10^9$ ν for every baryon.

~ 1 s: $T \sim 10^{10}$ K

Lower T means more $n \rightarrow p$ than the reverse, so the p/n ratio increases.

T now falls below threshold for e^-, e^+ production.

ν decouple and stream outward.

~ 10 s: $T \sim 3 \times 10^9 \text{K}$

e^-, e^+ disappearing due to annihilation

p/n ratio still rising

DEUTERIUM BOTTLENECK: ${}^4\text{He}$ could survive, but the first step in making ${}^4\text{He}$ is $p + n \rightarrow {}^2\text{D} + \gamma$. Because ${}^2\text{D}$ is fragile and is broken apart by energetic photons before the next step can occur, we have a bottleneck.

~ 10 s – 3 min: $T \sim 10^9 \text{K}$

Most antiparticles are gone.

The universe consists of γ and γ , except for the $1/10^9$ excess of matter over antimatter.

~3.75 min: $T < 10^9$

T is now low enough that ${}^2\text{D}$ can form! Most of the ${}^2\text{D}$ is rapidly transformed into ${}^4\text{He}$, but *no farther*, because of the bottlenecks at nuclei with masses 5 and 8.

All n have been incorporated into ${}^4\text{He}$, which is now ~25% by mass, or 9% by number, of all the nuclei in the universe, with the remainder being ${}^1\text{H}$ (i.e., p).

~35 min: $T \sim 3 \times 10^8 \text{K}$

All nucleosynthesis ends.

All particles are ${}^4\text{He}$ or free p and e^- .

It's still too hot for neutral atoms to form.

$\sim 10^6$ yr: $T \sim 3000\text{K}$

Matter and radiation now *decouple*, and are no longer in thermal equilibrium. Neutral hydrogen and helium atoms can form, capturing the electrons that prevented the photons from expanding freely. Photons now stream across the universe with a spectrum characteristic of a blackbody at 3000K. These photons provide the oldest, earliest possible look at the universe since nothing prior to decoupling will ever be directly visible.

$\sim 10^{10}$ yr: $T \sim 3\text{K}$

The blackbody photons at 3000K have been redshifted to $T \sim 3\text{K}$, yielding $z \sim 1000$ for the era of decoupling. That means the universe was 1000 times smaller in scale than it is now.