

Cosmology

and Large Scale Structure



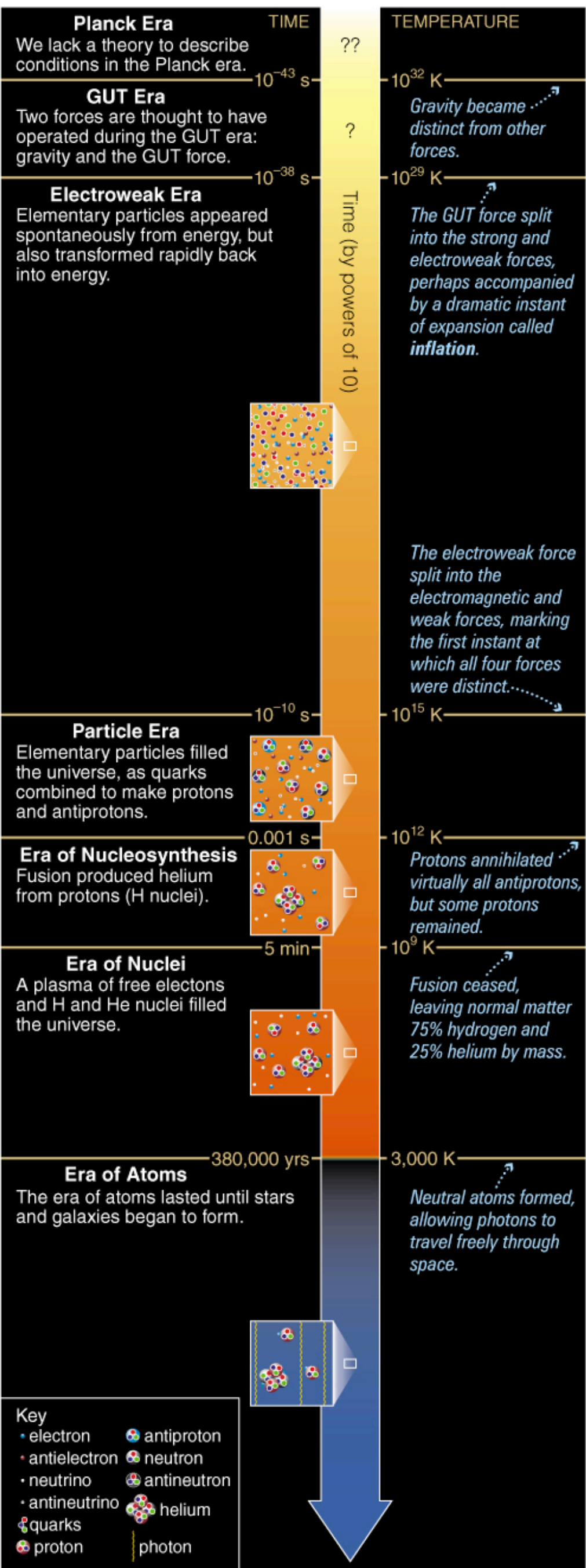
Today
Early Universe

History of the Universe



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Time	Event
$t \sim 10^{-43}$ s	Planck scale (<i>speculative</i>)
$t \sim 10^{-38}$ s	GUT scale (<i>speculative</i>)
$t \sim 10^{-35}$ s	Inflation (<i>speculative</i>)
$t \sim 10^{-12}$ s	Standard Model forces emerge
$t \sim 10^{-8}$ s	WIMPs decouple (<i>speculative</i>)
$t \sim 10^{-5}$ s	quarks condense into baryons (<i>baryogenesis</i>)
$t \sim 10^{-4}$ s	proton-antiproton annihilation ends
$t \sim 1$ s	neutrinos decouple
$t \sim 4$ s	electron-positron annihilation ends
$t \sim 10^2$ s	Big Bang Nucleosynthesis
$t \sim 10^5$ yr	Matter-radiation equality
$t \sim 4 \times 10^5$ yr	Atoms form, CMB emerges
$t \sim 5 \times 10^6$ yr	Gas temperature decouples from radiation
$t \sim 10^7$ yr	Dark Ages
$t \sim 5 \times 10^8$ yr	Cosmic dawn (first stars)
$t \sim 10^9$ yr	Galaxies form
$t \sim 4 \times 10^9$ yr	Peak star formation
$t \sim 9 \times 10^9$ yr	Sun forms
$t \sim 13 \times 10^9$ yr	Life on earth



time

Temp

Cosmic Timeline

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Early U radiation dominated

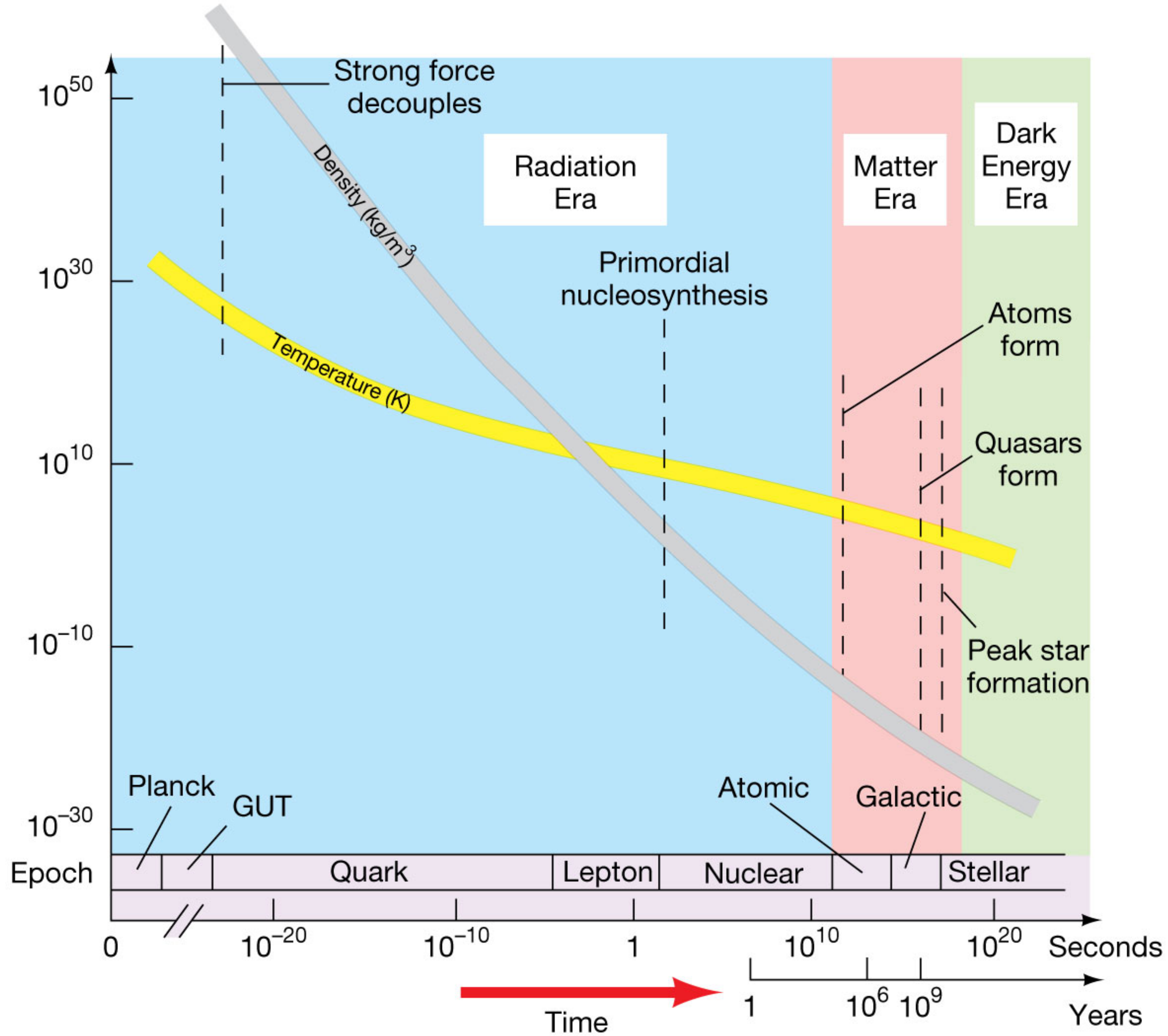
$$t \lesssim 10^5 \text{ yr}$$

$$a \sim t^{1/2}$$

$$T \sim a^{-1}$$

$$Tt^2 \sim \text{constant}$$

Figure 17.4 This timeline summarizes conditions and transitions that marked the early eras of the universe.



Time
 $t \sim 10^{-43}$ s Event
 Planck scale (*speculative*)

Known physics breaks down at the Planck scale

$$m_P = \sqrt{\frac{\hbar c}{G}} = 1.22 \text{ GeV } c^{-2} \approx 2 \times 10^{-5} \text{ g}$$

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}} = 1.6 \times 10^{-35} \text{ m}$$

$$t_P = \frac{\ell_P}{c}; \text{ need a theory of quantum gravity.}$$

$t \sim 10^{-38}$ s GUT scale (*speculative*)

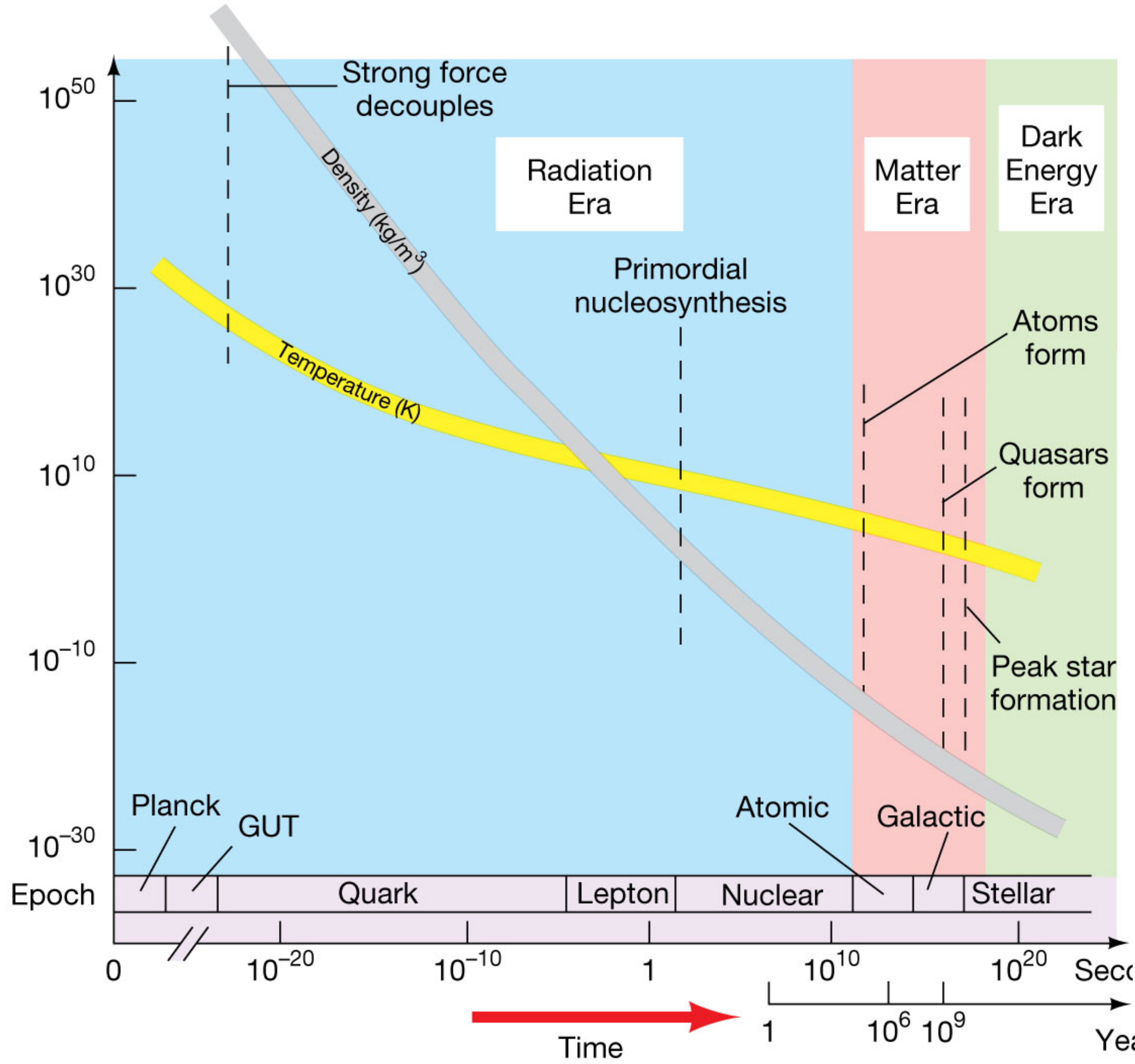
GUT stands for Grand Unified Theory; this is the hypothetical scale at which the strong nuclear force becomes indistinguishable from the electroweak force.

$t \sim 10^{-35}$ s Inflation (*speculative*)

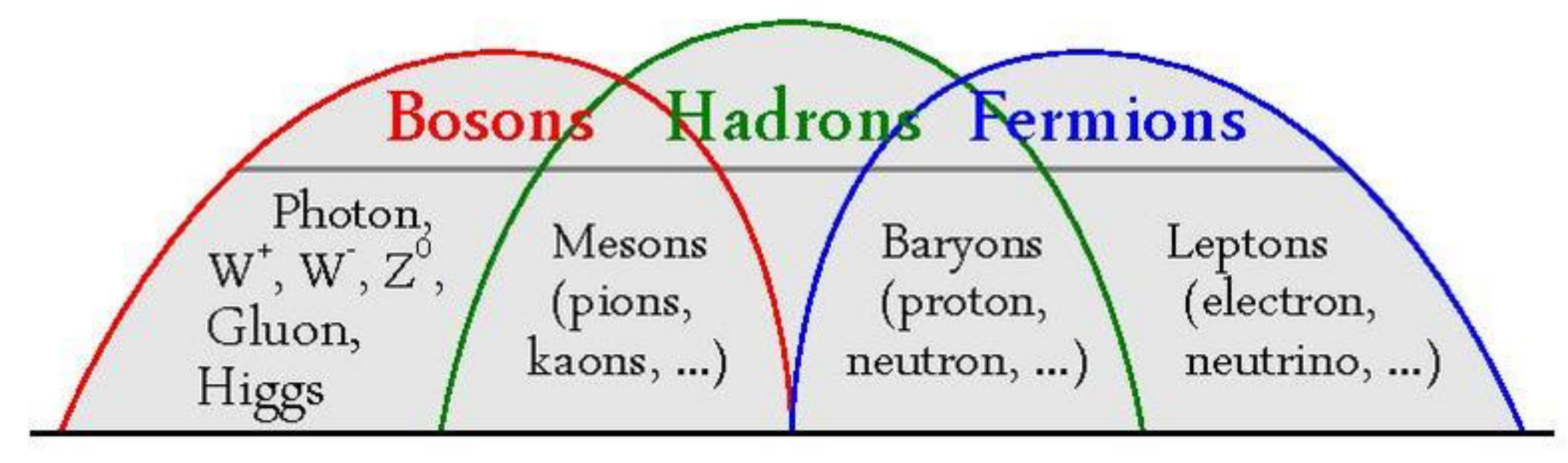
Period of exponential growth: $a \sim e^{Ht}$

$t \sim 10^{-12}$ s Standard Model forces emerge

The four forces become distinct; one can begin to recognize "ordinary" particles that one might find in high energy particle accelerators: $T \sim 10^{15} \text{ K} \sim 150 \text{ GeV}$.



Time	Event
$t \sim 10^{-8}$ s	WIMPs decouple (<i>speculative</i>)
	Weakly Interacting Massive Particles (WIMPs) freeze out around this time, depending on their mass ($M_\chi \sim 100$ GeV with huge uncertainty). <i>It is not clear that these supersymmetric particles exist.</i>
$t \sim 10^{-5}$ s	quarks condense into baryons (<i>baryogenesis</i>)
	The quark-gluon plasma coalesces into hadrons (baryons and mesons); no more free quarks. This must have happened, but we do not understand the resulting matter-antimatter asymmetry.
	Baryons have an odd number of quarks (usually 3: e.g., protons & neutrons) Mesons have an even number of quarks (usually 2: e.g., pions)



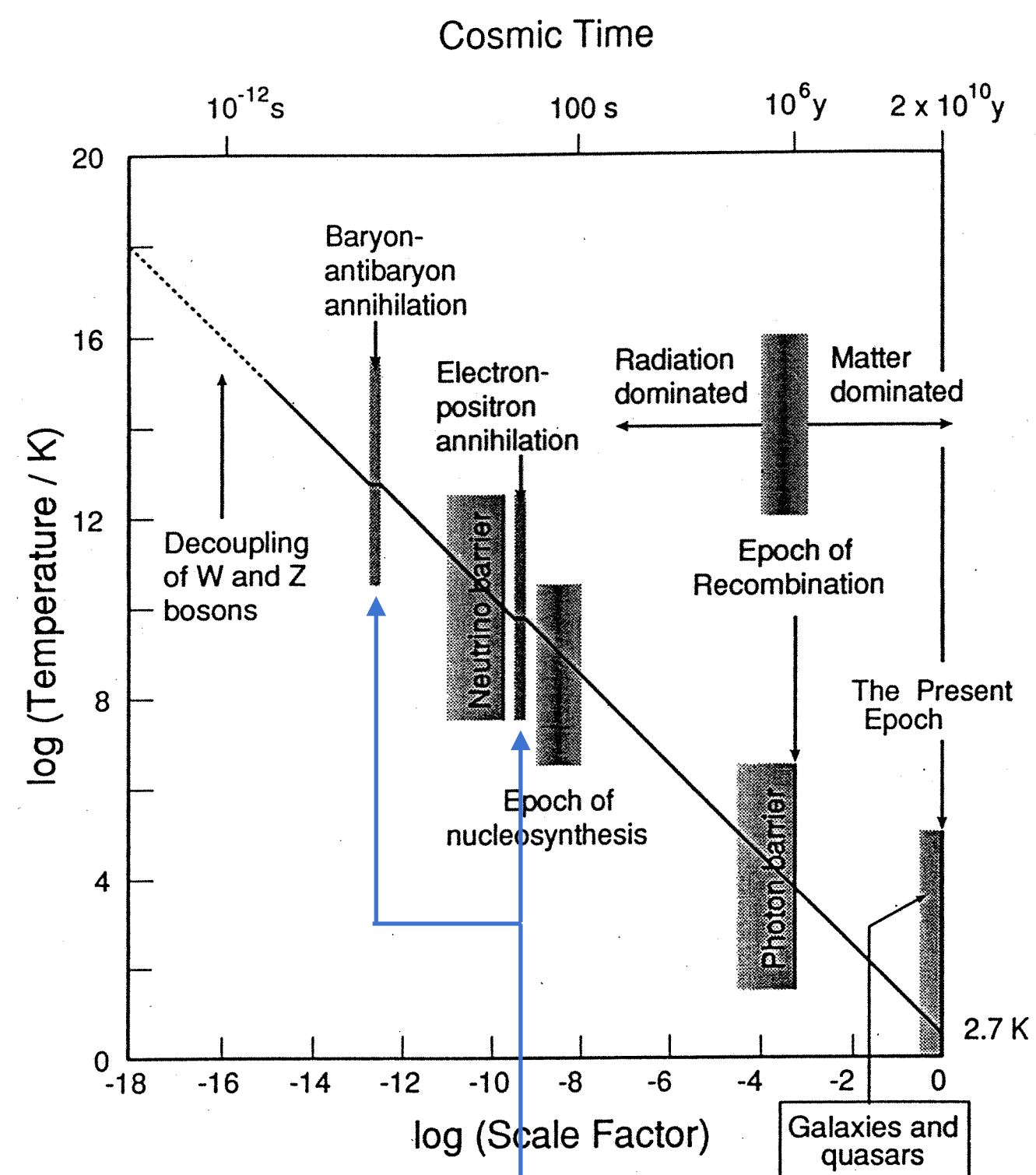


Fig. 6.1 The thermal history of the standard Hot Big Bang. The radiation temperature decreases as $T_r \propto R^{-1}$ except for abrupt jumps as different particle-antiparticle pairs annihilate at $kT \approx mc^2$. Various important epochs in the standard model are indicated. An approximate time scale is indicated along the top of the diagram. The neutrino and photon barriers are indicated. In the standard model, the Universe is optically thick to neutrinos and photons prior to these epochs.

Note the brief pause in the decline of the temperature of the radiation field as first proton-antiproton annihilation, then later electron-positron annihilation dump energy into radiation.

Time Event
 $t \sim 10^{-4}$ s proton-antiproton annihilation ends

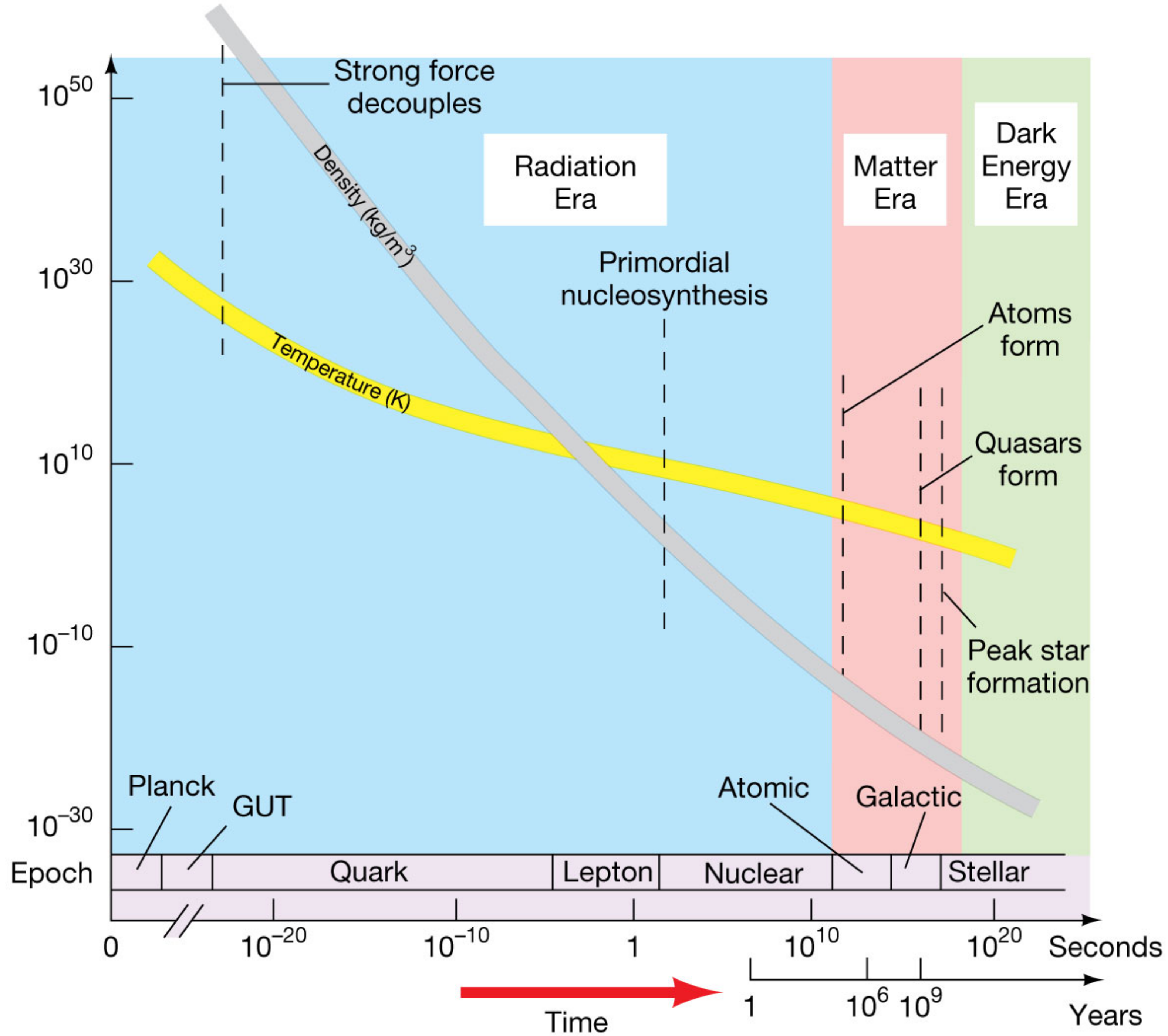
This energy is deposited in the radiation field (which becomes the CMB). Only about one proton is left over for every billion proton-antiproton pairs.

$t \sim 1$ s neutrinos decouple

neutrinos drop out of equilibrium as photons will later do. They lose energy with expansion the same as the radiation field, $T_\nu \sim a^{-1}$, with an initial energy density $\epsilon_\nu \sim T_\nu^4$ fixed at this point.

$t \sim 4$ s electron-positron annihilation ends

Being less massive than protons, electrons freeze out from positrons at this later time. The excess energy feeds the radiation background but not the neutrino background.



Time	Event
$t \sim 10^2$ s	Big Bang Nucleosynthesis

Surviving neutrons fuse with protons to make the isotopes of hydrogen, helium, and lithium. These exist as free nuclei in an opaque plasma until recombination.

$t \sim 10^5$ yr	Matter-radiation equality
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Must happen at some point since $\epsilon_r \sim a^{-4}$ while $\rho_m \sim a^{-3}$. Exactly when depends sensitively on the matter density.

$t \sim 4 \times 10^5$ yr	Atoms form, CMB emerges
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Electrons and protons combine to form hydrogen. The opacity drops to near zero; the photons of the radiation field propagate freely without further interactions.

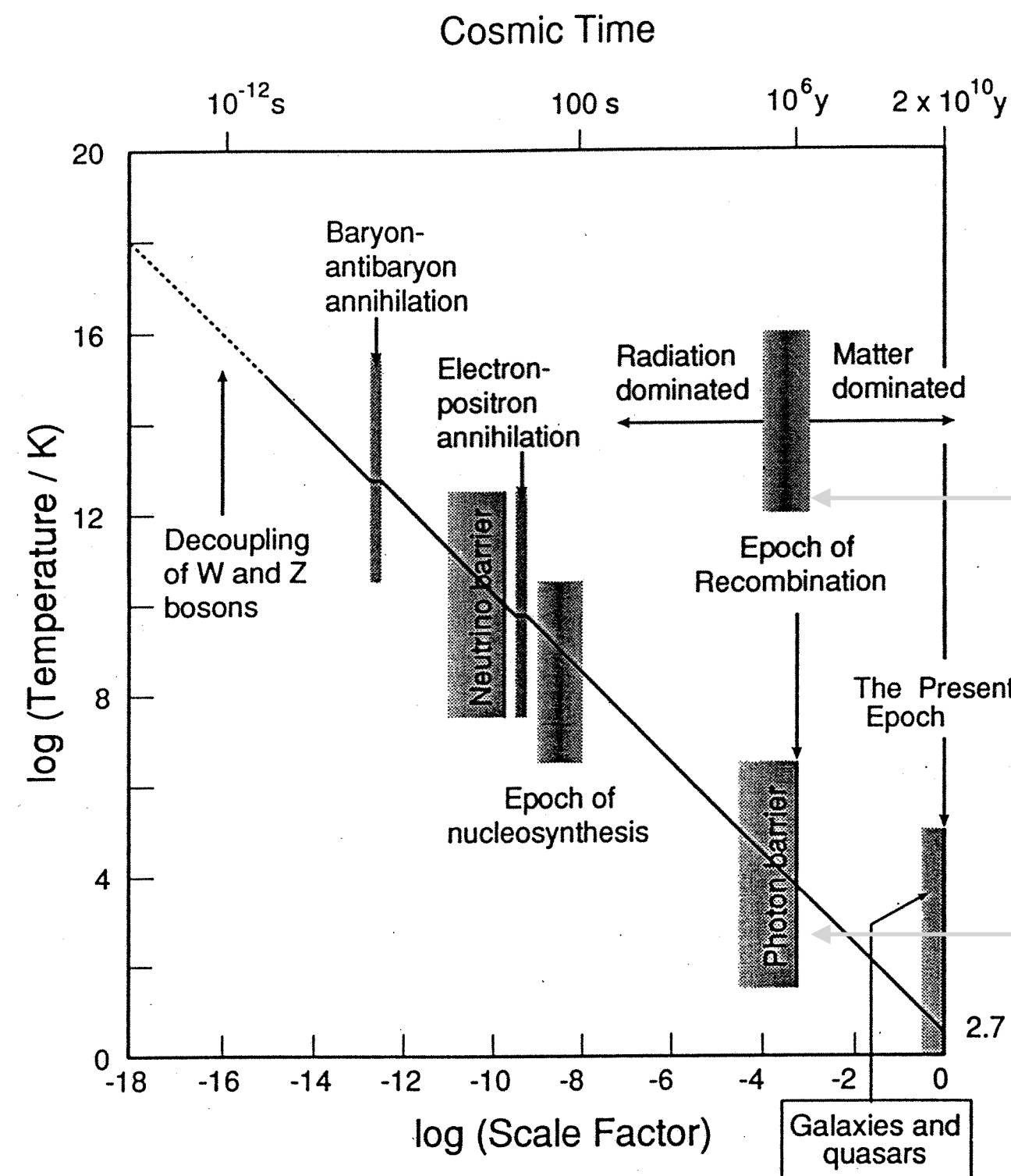


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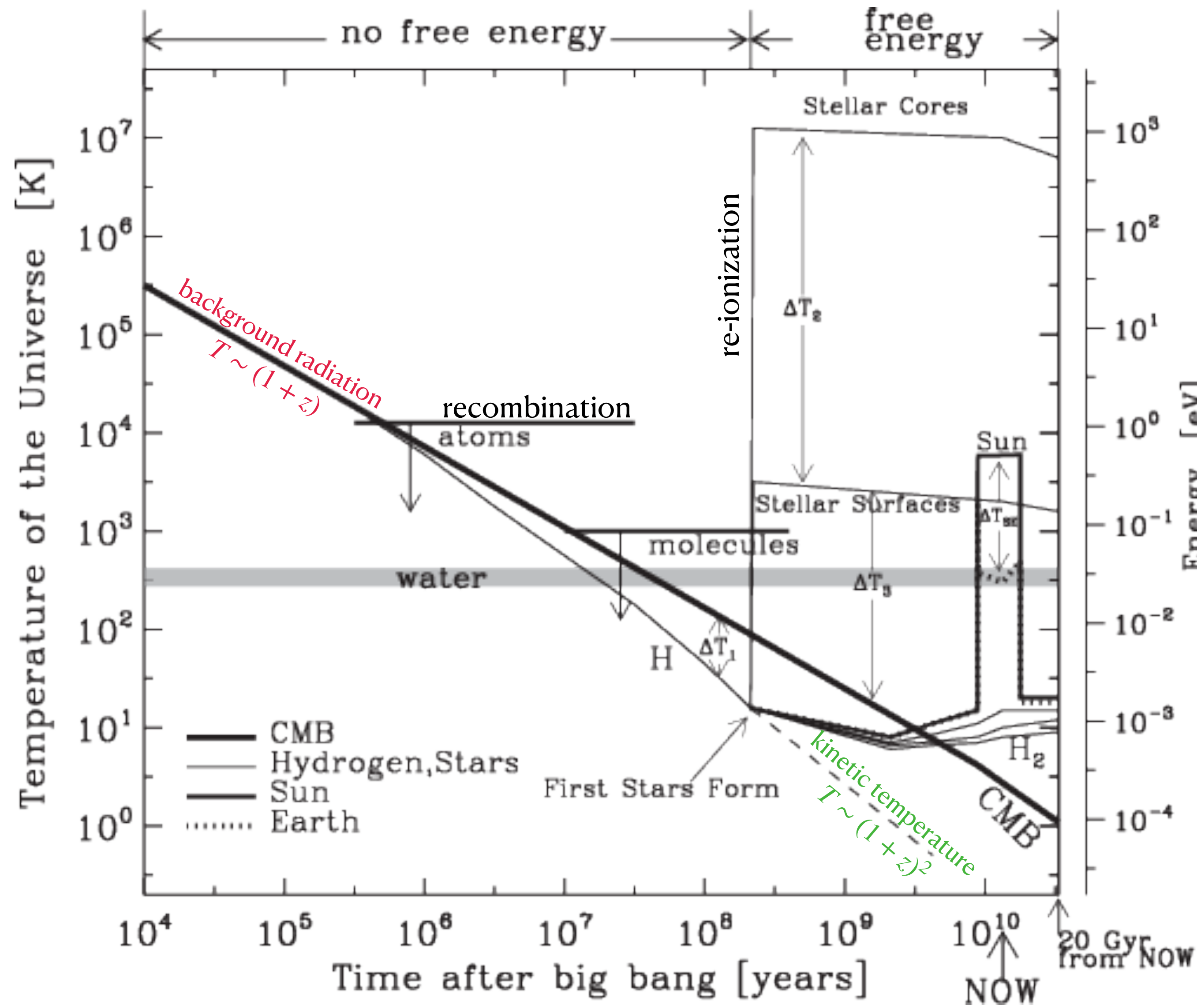
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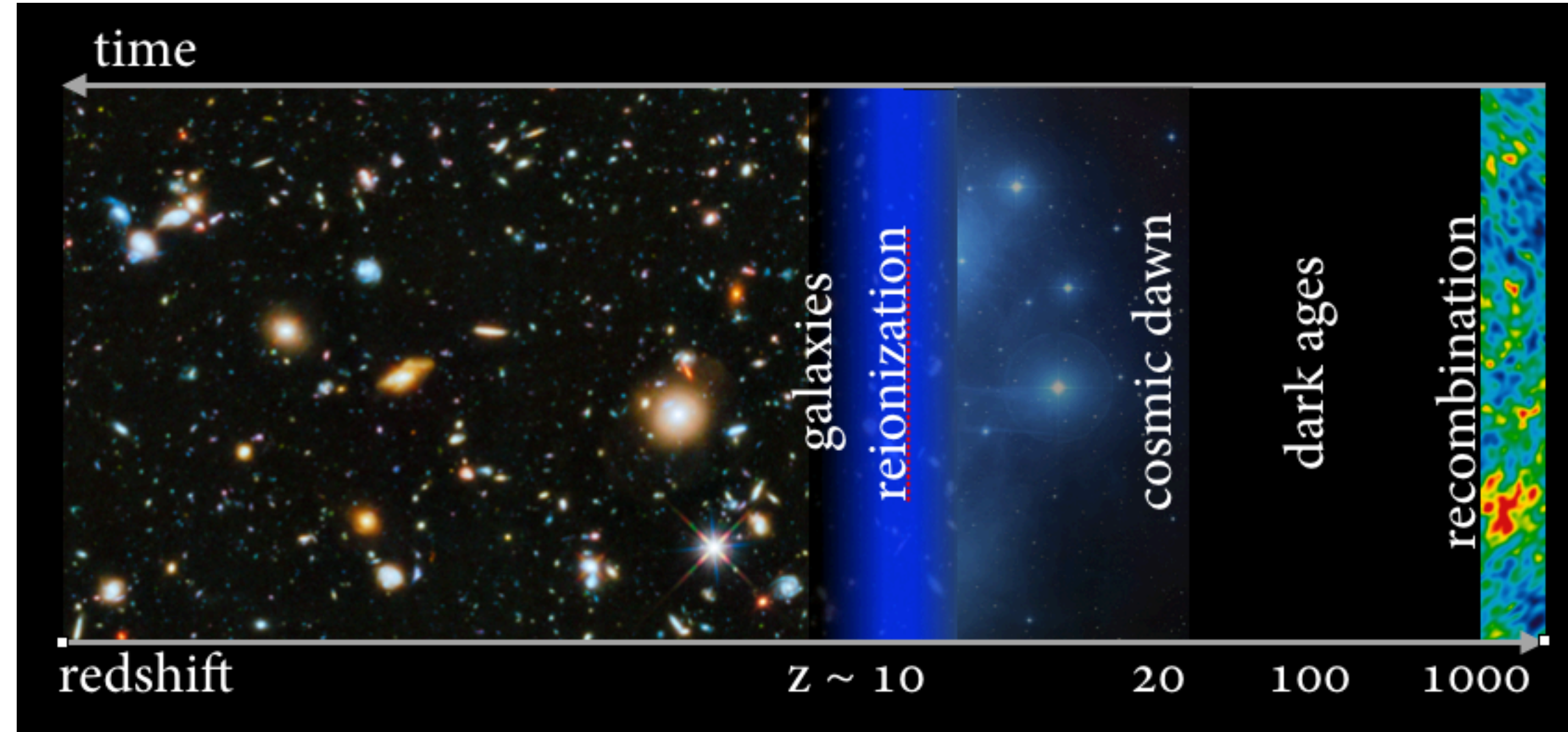
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Called the "photon barrier" here because of the sudden change in opacity.

Electrons and protons combine to form hydrogen. The opacity drops to near zero; the photons of the radiation field propagate freely without further interactions.



<u>Time</u>	<u>Event</u>
$t \sim 5 \times 10^6$ yr	Gas temperature decouples from radiation
	After recombination, the kinetic temperature of matter departs from that of the radiation field. They start out identical, and it takes a while for the matter to relax to fall as $T_{mat} \sim a^{-2} \sim (1+z)^2$ after $z \approx 200$.
$t \sim 10^7$ yr	Dark Ages (no stars)
	From $z \approx 1000$ to $z \approx 20$, the universe is composed of neutral, primordial gas. Sources of light have yet to form, so this period is known as the Dark Ages.
$t \sim 5 \times 10^8$ yr	Cosmic dawn / re-ionization
	Formation of the first stars (and maybe quasars?) These flood the universe with UV radiation that re-ionizes the universe. The gas in the intergalactic medium remains hot and highly ionized to this day.



Time	Event
$t \sim 4 \times 10^5$ yr	Atoms form, CMB emerges
$t \sim 5 \times 10^6$ yr	Gas temperature decouples from radiation

Baryons can only begin to gather together and form structures after decoupling from the radiation

$t \sim 10^7$ yr	Dark Ages
$t \sim 5 \times 10^8$ yr	Cosmic dawn / re-ionization
$t \sim 10^9$ yr	Galaxies form

Free fall time for Milky Way mass ~ 1 Gyr
Probably a messy process involving the merger of smaller protogalactic fragments that can collapse more quickly.

$t \sim 4 \times 10^9$ yr Peak star formation

The star formation rate of the universe peaked at $z \approx 2$; declines precipitously after $z < 1$

$t \sim 9 \times 10^9$ yr Sun forms

A relative late comer, merely 4.5 Gyr old.

$t \sim 13 \times 10^9$ yr multicellular life on earth

Singe-celled life appeared fairly early, but the Cambrian explosion didn't occur until 0.6 Gyr ago