Physics of the earliest Universe: from quantum gravity to primordial nucleosynthesis

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Physics Horizon

If we talk about the earliest eras of the Universe we encounter *Physics Horizon*: because the energies we can attain in particle accelerators are limited by technology (no larger than the Solar System), there are limits to our ability to experimentally determine the nature of physical interactions dominating at earliest times. This is the Physics Horizon:
it prevents us from experimentally testing the physical theories which we expect that should be relevant at these eras.

Definition:

Physics Horizon is a curtain that separates those aspects of physics we can hope to test by high energy experiments in future, from those where it is reasonable to expect no such test will ever be possible.

At least two earliest eras of the U., Quantum Gravity Era and Grand Unified theories (GUT) Era are hidden under the PH.

Physics of the processes occurring at these eras is not directly verifiable and we can only test it by searching for its far-going consequences appearing in the well known and confirmed physics: for instance if a ,,fundamental theory" generates and simplifies the phenomenological Standard Particle Model (SPM). Would it be a quantum theory of gravity (QG)?

Singularities and the origin of the U.

Why at all high energies and the PH?
These arise from famous *Hawking–Penrose singularity theorems*:
under generic and physically reasonable conditions a spacetime filled with matter contains a spacetime singularity, usually a curvature singularity.
In the case of FLRW spacetime (or perturbed) the singularity is a spacelike singular boundary (3–dim. hypersurface) located in the *past* of any regular point $\Rightarrow$ this is ,,simultaneous" origin of the spacetime. The singular boundary is metrically shrunk to a point $\Rightarrow$ all distances are 0 $\Rightarrow$ entire space is a point.
The singularity is an origin of the spacetime: space and time emerge from it - the Big Bang (BB), Fred Hoyle 1949.

The spacetime interval ds in FLRW:

$$ds^2 = c^2\,dt^2 - R^2(t)[dr^2 + f_k^2(r)(d\theta^2 + \sin^2\theta\,d\phi^2)],$$

$$f_k(r) = \begin{cases} r & \text{for } k = 0 \\ \sin r & \text{for } k = +1 \\ \sinh r & \text{for } k = -1. \end{cases}$$

$R(t)$ — *the cosmic scale factor*,
$t = 0$ — the origin of time (BB),
$R(0) = 0 \Rightarrow ds^2 = 0$ for *all* points at the singular boundary $\Rightarrow$ space is contracted to a single point.
$t > 0$ soon after BB $\Rightarrow$ R is small $\Rightarrow$ all volumes are small $\Rightarrow$ matter has extreme high density.
The early U.: divided into 3 to 7 eras, from BB to the *recombination epoch* $\approx$ 500.000 years. Its history — *thermal history* of the U.
I will discuss its *first 1 hour*.

First Era: Quantum Gravity

Einstein's GR: for all $t > 0$ there is classical regular spacetime with FLRW geometry.
Actually this not so. Current viewpoint: from initial singularity there emerges not a regular spacetime but a *quantum version* of gravitational field.
Motivation.
1. If for $t > 0$ there is regular spacetime with FLRW geometry, then $R \approx 0 \Rightarrow$ matter energy density $\rho \to \infty$, very intensive interactions, gravit. field $[R(t)]$ is very rapidly varying in time $\Rightarrow$ conditions for quantum effects of gravitation.
2. Planck system of units.
A universal scale of units for *fundamental* processes must be based on fundamental constants of the nature:
$\hbar$ — all matter (and fields) have quantum nature,
c — all matter is relativistic (in the sense of special relativity),
G — all matter interacts gravitationally (the *universal* interaction).

Units of all dimensional physical quantities:

$$
\begin{aligned}
l_P &= \sqrt{\frac{\hbar G}{c^3}} = 1,6 \cdot 10^{-33}\mathrm{cm}, \\
t_P &= \frac{l_P}{c} = \sqrt{\frac{\hbar G}{c^5}} = 5,4 \cdot 10^{-44}\mathrm{s}, \\
m_P &= \sqrt{\frac{\hbar c}{G}} = 2,2 \cdot 10^{-5}\mathrm{g}, \\
E_P &= m_P c^2 = 1,2 \cdot 10^{19}\mathrm{GeV}, \\
T_P &= \frac{E_P}{k_B} = 1,4 \cdot 10^{32}\mathrm{K}, \\
\rho_P &= \frac{m_P}{l_p^3} = \frac{c^5}{\hbar G^2} = 5,1 \cdot 10^{93}\mathrm{g\,cm}^{-3} \ldots .
\end{aligned}
$$

(Max Planck, 1900)

These units are either *huge* or *extremely small* — do not fit known fundam. processes for element. particles.

Conjecture:
these units are relevant for QG processes.
Only QG needs both $\hbar$, c and G. Soon after BB: ρ, $T \to \infty \Rightarrow$ the scale of all processes at these times is expressed in Planck units.
Fundamental difficulty:
— we see (observationally or experimentally) NO QG effects,
— we have NO quantum theory of gravity.
We *do believe* that QG effects exist, though we know none of them:
all matter is quantum and gravitation is the universal interaction $\Rightarrow$ *gravitation should have quantum nature*.
On physical grounds we believe that QG Era should occur for extremely high ρ and T when we go back to $t \approx 0$, but
reliably we know nothing about this epoch.
All attempts to construct a quantum theory of gravity encounter fundamental conceptual problems.

Conjecture:
in QG Era the regular spacetime is replaced by ,,quantum spacetime" — nobody knows what it is (both mathematically and physically).
There is no space and time.
Maybe QG effects cancel or ,,smooth out" the initial singularity (BB).
QG Era is hidden under the Physics Horizon.

Second Era: Grand Unified Theories

For unknown (but necessarily effective!) reasons QG Era ends up in a logical rather than a temporal order (there was no time) and a regular spacetime (differential manifold) emerges subject to Einstein's GR.
The simplest (not necessary) conjecture: it has FLRW geometry.
Conventionally: one assigns time $t \cong O(t_P) \cong 10^{-42}$ s to the emergence of the spacetime („earlier" no time).
At this moment: matter comprises all particles of Standard Particle Model (SPM).
Particles are ultrarelativistic with $\rho_P > \rho \approx 10^{93} \mathrm{g\,cm}^{-3}$.
Particle interactions at extreme densities are governed by Grand Unified Theories (GUT): hypothetical unification of Electroweak (Weinberg–Salam) Theory and QCD (strong interactions).
These theories are in initial stage of construction yet $\Rightarrow$ reliably we know very little about physical processes in this era.
Conjecture: GUT Era ended at $t \approx 10^{-32} - 10^{-30}$ s.

Conjecture:
in GUT Era two important processes occurred:
— short period of very rapid — inflationary — evolution (,,inflation"),
— baryogenesis.

1. Inflation.

Conjecture based on general principles of QFT in flat Minkowski spacetime:
in GUT Era there was a specific physical field, INFLATON, (scalar, vector or tensor) with energy density $\rho_V \cong const > 0$.

Initially ultrarelativistic matter (all SPM particles) was dominating,
$\rho_M \gg \rho_V \Rightarrow$ standard evolution, $R \propto \sqrt{t}$.
But $\rho_M \propto R^{-4} \Rightarrow$ as R increases, ρ_M quickly decreases while $\rho_V \cong \mathrm{const}$.
Inflaton energy in any comoving volume $V \propto R^3$ grows as R^3 — a spectacular case of *energy non–conservation*.
At $t_1 \cong 10^{-36} - 10^{-34}$ s (model dependent) $\rho_V = \rho_M$ and for $t > t_1$:
$\rho_V \cong \mathrm{const} > \rho_M$ — *inflationary epoch* occurred with $\rho \cong \rho_V$.
Friedmann eq.

$$\dot{R}^2 + k = \frac{8\pi G}{3}\rho\, R^2 \Rightarrow R(t) = Ae^{H(t-t_1)},$$

$H = \left(\frac{8\pi G}{3}\,\rho_V\right)^{1/2} = \mathrm{const}$ — Hubble constant.

Rapid exponential expansion $\Rightarrow$ all distances and volumes enormously grow in short time. U. becomes huge $\Rightarrow$ all matter gets extremely diluted (practically disappears), the space gets empty and expands at constant H.
The inflationary epoch must come to an end, otherwise we get a universe radically different from ours.
Conjecture:
the inflation ends at $t_2 \approx 10^{-32} - 10^{-30}$ s (model dependent).
The inflaton field *decays* and its huge energy is transformed into all particles of SPM $\Rightarrow$ space is again full of ultrarelativistic particles, the primordial particles are negligible.
Intensive interactions (electroweak and strong) $\Rightarrow$ particles attain thermal equilibrium and form hot and dense ultrarelat. plasma.

During inflationary epoch, $\Delta t \approx 10^{-32} - 10^{-30}$ s, the size of the U. grows Z times,
$R(t_2) = Z\, R(t_1)$, $Z \geq 10^{28}$.
Originally it was believed that inflation might have solved almost all problems of cosmology. Now it is clear that it may solve two problems.
1) Spatial flatness.
If spacetime has FLRW geometry, then there is actually
— infinite number of spacetimes with spaces being 3–spheres ($k = +1$),
— infinite number of spacetimes with spaces being hyperbolic open ones ($k = -1$),
— one spacetime forming a border line between these 2 classes, with euclidean space, $k = 0$.

These spacetimes are characterized by the *density parameter* Ω.

$$H(t) = \frac{\dot{R}}{R}, \quad \text{critical density} \quad \rho_c = \frac{3H^2(t)}{8\pi G},$$

all forms of matter have together

$$\Omega(t) = \frac{\rho(t)}{\rho_c(t)}.$$

Open universes ($k = -1$): $\Omega(t) < 1$,
closed universes ($k = +1$): $\Omega(t) > 1$,
spatially flat universe: $\Omega(t) = 1$.
Observations: $|\Omega_0 - 1| < 0,005$ today.
We are very close to the border. Why?
In the standard cosmol. model the difference $|\Omega(t) - 1|$ grows in time.

Friedmann eq. $\Rightarrow \Omega - 1 = k\dot{R}^{-2} \Rightarrow$

$$\frac{d}{dt}|\Omega - 1| = -\frac{2\ddot{R}}{\dot{R}^3}.$$

Standard cosmology: $\dot{R} > 0$, $\ddot{R} < 0 \Rightarrow \frac{d}{dt}|\Omega - 1| > 0$.
If now $|\Omega_0 - 1| < 0,005$, then at the recombination epoch and earlier Ω was extremely close to 1.
Typical universe: $\Omega \approx 10^5$ (close), $\Omega \approx 10^{-6}$ (open). We live in a non-typical, very specific U. Why?

During inflation: $\dot{R} > 0$ and $\ddot{R} > 0 \Rightarrow \frac{d}{dt}|\Omega - 1| = -\frac{2\ddot{R}}{\dot{R}^3} < 0$ — the difference decreases.

Let at the outset of inflation: $\Omega(t_1) \gg 1$ or $\ll 1$ — typical FLRW universe.

$$R = Ae^{H(t-t_1)} \Rightarrow \Omega = 1 + \frac{k}{A^2 H^2}\, e^{-2H(t-t_1)} \to 1 \quad \text{for large } t.$$

Due to inflation Ω at the recombination epoch was indeed very close to 1 and now it is still close to 1.

Inflation made our world very homogeneous and almost spatially flat.

2) Origin of structure.
FLRW world is perfectly homogeneous and isotropic — our real U. contains stars and galaxies („structures").
Current theory: all structures developed from small density perturbations in the primordial hot dense plasma due to gravitational instability. What was the physical mechanism generating these density inhomogeneities?
The best explanation: the decaying inflaton field, while creating all particles of SPM, was subject to strong quantum fluctuations and these generated almost scale-invariant density perturbations of the plasma.
These are two main advantages of the inflationary scenario.
Inflation strongly influences our knowledge of the earliest U.

Inflation, if occurred, rendered the earlier evolution unavailable to us — it swept away all traces of previous events.
There might have been no BB singularity, no Quantum Gravity Era, the primordial matter (before inflation) might have been different from SPM particles, it might have been even non-existent. ,,At the origin" there might have been only inflaton filling various spatial domains (,,bubbles"), each with different energy density ρ_M.
One of these domains, with a large inflaton ρ_M, has developed into our U. and its boudaries are far beyond the observable part. Outside it there are other domains which evolve in distinct ways (,,multiverse").

The scenario is plagued by hard problems.

— The inflaton field does NOT fit the SPM and must be artificially added by hand to it. It cannot represent a swarm of specific particles since it requires pressure< 0.

— There is experimentally no trace of inflaton field in the present world. Physics does NOT need it.

— There is no well-grounded description in the framework of QFT of the decay of inflaton into fundamental particles — this is the ,,graceful exit" problem.

— The fundamental problem: inflaton evolves and finally decays as a quantum field, but there is NO QFT in strong rapidly varying gravit. fields $\Leftarrow$ current QFT is consistent and reliable only in flat spacetime.

There is a multitude of various inflationary models and none of them is a ,,standard" one.

There is growing strong opposition against the ,,inflationary paradigm".

Cosmology requires 3 kinds of exotic matter unknown to physics:
— inflaton field with $p_V \approx -\rho_V$,
— dark matter (stable massive particles),
— dark energy: a field with $p_X \approx -\rho_X$, phenomenologically identified with the cosmol. constant Λ.
Λ *cannot* be identified with the inflaton: it represents energy density $\rho_\Lambda = \Omega_{\Lambda 0}\,\rho_{c0} \cong 0,7 \cdot 1,88 \cdot 10^{-29} h^2\,\mathrm{g\,cm}^{-3} \approx 6 \cdot 10^{-30}\mathrm{g\,cm}^{-3}$,
far smaller than matter density in GUT Era, $\rho_M \gg 10^{15}\mathrm{g\,cm}^{-3}$.

2. Baryogenesis and leptogenesis

Fundamental physics (SPM) is exactly *matter–antimatter symmetric*. Yet U. appears to be populated exclusively with matter. Antiprotons are observed only in cosmic rays and arise in collisions of high energy protons in the interstellar medium. If there existed macroscopic lumps of antimatter („antistars"), they would have arisen from macroscopic lumps of antiprotons already existing in the hot plasma long before the recombination epoch.

But we know of NO processes separating macroscopically antiprotons from protons in a dense hot plasma ⇒ antiprotons quickly annihilate wherever they appear.

Fundamental physics ⇒ symmetric universe: equal numbers of p, $\bar{p}$ and e^+ and e^- in relat. plasma ⇒ when $k_B T \leq m_e c^2$ all pairs annihilate and later such universe contains only photons.

In our U.: $\eta \equiv \frac{n_B}{n_\gamma} \approx 6 \cdot 10^{-10}$ ⇒ in the primordial hot plasma there was 1 excessive p per 10^9 $p\bar{p}$ pairs ⇒ later all pairs annihilated in photons and only the excessive p's survived and now form the entire baryonic U.

What was the origin of this matter excess?

Most models:
after the inflationary epoch some Grand Unified Theories provided conditions necessary for generating this matter-over-antimatter excess in the ultradense plasma of newly created (by the inflaton decay) particles and antiparticles.
There are also models which postpone this baryo- and leptogenesis (excess of e^- over e^+) to later times, but they are less reliable.
Conclusions.
1. Most of the matter contents and properties of our U. = *initial conditions for the entire future evolution* were determined in GUT Era.
2. GUT Era is hidden under the Physics Horizon ⇒ physical theories establishing these initial conditions for our U. are beyond our experimental control. We can reconstruct the initial conditions from the current U., but we cannot reliably verify of how they were generated.

Third Era: Quark-Gluon Plasma

Approximately from 10^{-30} s to 10^{-10} s.

Spacetime is regular and governed by GR, ultrarelat. and ultradense plasma has been thermalized on the turn of the 2 eras by particle interactions.

$k_B T < 10^{14}$ GeV $\Rightarrow$ Grand Unified Theories are replaced by QCD and Electroweak theory. U. enters evolution driven by well-developed and reliable theories.

Hot dense plasma comprises all fundamental particles of SPM:

— 6 quarks, 8 gluons (massless carriers of strong interactions),

— 6 leptons (electrons e^-, muons μ^-, tauons τ^-, 3 neutrinos ν_e, ν_μ and ν_τ), 3 massless bosons carrying electroweak interactions (γ, W^-, Z^0)

— antiparticles of all these plus *Higgs particles*.

There is small excess of matter over antimatter of order 10^{-9}.

All particles are ultrarelativistic with average energy $\bar{E} \approx k_B T \gg mc^2 \Rightarrow$ plasma behaves like the photon gas (black-body radiation with the Planck spectrum).

Photons have 2 polarizations (2 spin states) $\Rightarrow \rho_\gamma = 2 \cdot \frac{\pi^2}{30} (k_B T)^4$, $\hbar = 1 = c$.
Total plasma energy density is

$$\rho = N(T) \cdot \frac{\pi^2}{30} (K_B T)^4,$$

$$N(T) = \sum_B g_B + \frac{7}{8} \sum_F g_F \qquad \text{— \textit{effective number of spin states}},$$

g_B — number of spin states of the given species of bosons (spin $= 1$),
g_F — number of spin states of the given species of fermions (spin $= 1/2$).
Total ρ is $N/2$ times larger than ρ_γ.
$N(T)$ is temperature dependent since it includes only ultrarelat. particles, $mc^2 \ll k_B T$.
Initially $N = 106\frac{3}{4}$ and plasma is dominated by *free* quarks and gluons: their contribution to N is 79 $\Rightarrow$ their energy is 74% of ρ.

The plasma is so dense, $\rho \gg 10^{30}\mathrm{g\,cm}^{-3}$, that there are NO hadrons, only their constituents, *free* quarks (and antiquarks) and gluons, there is no ,,quark confinement".

Though very dense, plasma is well descibed as *perfect gas*.

U. expands very quickly, $H(t) \approx 1/t$, strong and electroweak interactions maintain thermal equilibrium in cooling plasma at $TR =$const.

U. is almost perfectly homogeneous (with small perturbations coming from inflation) and physically extremely simple.

$T \equiv k_B T$ — in GeV.

Near the end of this era, for $t \geq 10^{-12}$ s, at $T \approx T_{WS} \approx 100 - 300$ GeV, a kind of *phase transition* occurs:

electroweak interaction is broken into 2 well known from laboratory interactions,

— electroweak interactions carried by massless photons,

— weak interactions with short range $\approx 10^{-13}$ cm, carried by massive $W^{\pm}$ and Z^0, $m_W = 80$ GeV, $m_Z = 91$ GeV, almost 100 m_p.

This is a very exotic process from the viewpoint of the physics we are familiar with:

originally massless particles acquire rest masses $\Rightarrow$ rest mass of a fundamental particle is NOT its inherent feature and it depends on physical conditions.

At the end of this era, $T \approx 50$ GeV, there appear first nonrelativistic particles:

$W^{\pm}$, Z^0, Higgs particles, quark t ($m_t \approx 170$ GeV).

These particles are unstable and either decay into lighter particles or their pairs annihilate $\Rightarrow$ N decreases to $N(T) = 86\frac{1}{4}$.

Fourth Era: Hadron Era

From 10^{-10} s to 10^{-4} s, or from $T \approx 50$ GeV to 100 Mev.
Interactions: long range (electromagnetic) and short range (strong and weak, $\approx 10^{-13}$ cm).
Plasma is still like a perfect gas with $N = 86\frac{1}{4}$, quarks and gluons still dominate yielding $79,4\%$ of ρ. U. is still simple: homogeneous thermal plasma diluting (expansion) and cooling as $T \propto 1/R$.
For $T < 5$ GeV further particles become nonrelativistic:
quarks $b\bar{b}(m_b \approx 4,5$ GeV), quarks $c\bar{c}(m_c \approx 1,3$ GeV), tauons ($m_\tau \approx 1,777$ GeV) $\Rightarrow$ pairs annihilate, unpaired particles decay $\Rightarrow N$ decreases.
For $T < 1$ GeV the ideal gas approximation gets worse and worse: plasma is more akin to a liquid than to a gas. Plasma is so diluted that strong interactions are so powerful that quarks and gluons no more behave as free, they gradually get mutually bound.

For QCD *critical temperature* $T \approx T_{QCD} \approx 150$ MeV there begins very important process — *plasma hadronization*. Quark-gluon plasma disappears since quarks and gluons *get confined in hadrons*. There are formed most hadrons known from laboratory particle physics:
nucleons (p, n), mesons (mainly pions $\pi^{\pm}$, π^0),hyperons (baryons heavier than p and n).
Experimental physics knows hundreds mesons and baryons, probably only lightest of them were formed in larger amounts in the hadronization process.
It is very hard to describe this process in detail since calculations in QCD are extremely complicated. We know that hadrons and antihadrons were formed in almost equal quantities: hadrons in 10^{-9} excess.
Hadronization process — thermodynamically it was a *phase transition*.
It lasted from $10 \cdot 10^{-6}$ s to approx. $20 \cdot 10^{-6}$ s after BB.

Most newly formed hadrons and antihadrons are *unstable* and quickly decay or pairs $h\bar{h}$ annihilate, final products are mainly photons.
Only proton is stable. Neutron is practically stable: lifetime $\tau_n = 880$ s.
Close to end of hadron era, $t \geq 10^{-4}$ s, most pairs $p\bar{p}$ and $n\bar{n}$ annihilate there survive only 1 p and 1 n per 10^9 pairs.
Nucleons (p, n) become nonrelativistic.

Fifth Era: Lepton Era

From $T \approx 100$ MeV to ≈ 1 MeV, or from $t \approx 10^{-4}$ s to ≈ 1 s.
Plasma energy density falls down from $10^{16}\mathrm{g\,cm}^{-3}$ to $10^{6}\mathrm{g\,cm}^{-3}$.
In the first part of this era decays and annihilations continue.
At $T \approx 30$ MeV ($t \approx 10^{-3}$ s) annihilations of baryons terminate.
At beginning of the era pions $\pi^{\pm}$ and π^{0} start to annihilate and decay, also leptons (muons $\mu^{\pm}$) decay and annihilate. Annihilations and decays of pions and muons end at $T \approx 10$ MeV.
Relativistic particles (are numerous and dominate in ρ):
γ, $e^{\pm}$, 3 species of neutrinos.
These particles drive the expansion of U. Few surviving nonrelat. protons and neutrons form a negligible admixture and are *dynamically* irrelevant. They will become important 10^{5} years later.
Effective number of spin states: $N(T) = 10\frac{3}{4}$ — diminished 10 times since Q-G Era.
Main contribution to energy density comes from leptons ($e^{\pm}$, 3 neutrinos): 81,4% $\Rightarrow$ Lepton Era.

Thermal equilibrium of relativist. plasma is maintained in the rapidly expanding U. by electromagn. (EM) and weak interactions. EM interactions are effective for all times.

Weak interactions are so weak (or ,,slow") that at $T \approx 1$ MeV (end of the era) they become *ineffective*: $e^{\pm}$, neutrinos and photons stop to interact weakly.

$e^{\pm}$ and γ interact EM,

ν_e, ν_μ and ν_τ interact only weakly $\Rightarrow$ below $T \approx 1$ MeV they do not interact — neutrinos *decouple* from $e^{\pm}\gamma$ plasma and from nucleons and become free particles $\Rightarrow$ U. is *transparent* to neutrinos.

At the end of Lepton Era there are 4 independent relativ. gases:

— $e^{\pm}\gamma$ plasma of interacting particles (photons are scattered on $e^{\pm}$), in thermal equilibrium with temp. $T_\gamma R =$const,

— 3 independent gases of ν_e, ν_μ and ν_τ separately, each comprising free (non–interacting) particles.

At the moment of decoupling (ν's become free), $T \approx 1$ MeV, the 3 neutrino gases had the same temp. $T_\nu = T_\gamma$ — they formed gases in thermal equilibrium with Planck spectrum.
Neutrinos are almost massless $\Rightarrow$ later each neutrino gas evolves as the EM relic radiation in galalctic era: temperature diminishes as $T_\nu \propto 1/R$ energy of each neutrino (of each type) is $\hbar\omega$ (as for photons) and it falls down according to $\omega R =$ const.

Sixth Era: Radiation-dominated Era

The last era begins at $T \approx 1$ MeV and $t \approx 1$ s, ends for $t > 100.000$ years. At the turn of the two eras neutrinos become free and form 3 independent gases (are decoupled from $e^{\pm}\gamma$ and from each other) with $T_\nu = T_\gamma$.
Relativistic particles:
γ, 3ν — during the entire era,
$e^{\pm}$ — only for first few seconds.
Nonrelativistic: p, n (dark matter?).
At $T \leq 0,5\mathrm{MeV} = m_e c^2 = 6 \cdot 10^9$ K the last annihilation process starts: $e^+e^- \to 2\gamma$. Most annihilations end at $T \approx 0,1\mathrm{MeV} \approx 10^9$ K, last pairs disappear at $T \approx 10$ keV or $t \approx 10^4$ s.
Created photons are scattered by remaining e^- and by protons $\Rightarrow$ after several scatterings photons get ,,thermalized" and join the thermal gas of already existing photons $\Rightarrow$ number density of photons n_γ *increases*.

If the annihilation process of all e^+e^- pairs were immediate, the additional photons would ,,warm up" the photon gas (and the *epn* plasma too).
Annihilation is extended in time up to $T \approx 0,1$ MeV $\Rightarrow$ there is no ,,warming up", but the plasma temp. T_γ *decreases slower* than according to $T_\gamma R =$ const.
The neutrino gases are free $\Rightarrow$ they acquire no annihilation energy $\Rightarrow$ their common temp. always decreases according to $T_\nu R =$const $\Rightarrow$ when the annihilation processes terminate the neutrino gases are *cooler* than γ*epn* plasma.
Entropy of plasma and of each neutrino gas is conserved and from it one computes the temperature difference

$$T_\gamma = \left(\frac{11}{4}\right)^{1/3} T_\nu \cong 1,401\, T_\nu .$$

This ratio is preserved up to today:
$T_{\gamma 0} = 2,725$ K $\Rightarrow T_{\nu 0} \cong 1,95$ K.
This temp. difference is conceptually important, but the effect is *unobservable*.

We are technologically not capable to observe cosmological relic neutrinos due to their tiny energy, we can only register solar neutrinos with much higher energies and fluxes.

After the annihilation $n_e = n_p$ (U. is electrically neutral) and these numbers are very small,

$$\frac{n_p}{n_\gamma} \approx \frac{n_B}{n_\gamma} \equiv \eta \cong 6 \cdot 10^{-10}.$$

Dynamical evolution of U. is for a long time still dominated by relativ. particles: γ and 3ν.

The effective number of spin states is

$$N(T) = 2 + \frac{21}{4}\left(\frac{4}{11}\right)^{4/3} \cong 3,363$$

and the main contribution to ρ comes from photons: 59,5% $\Rightarrow$ Radiation-dominated Era.

Nucleon contribution is negligible, it becomes comparable (smaller) to $\gamma\nu$ only after many thousands years.

Primordial Nucleosynthesis (Big Bang Nucleosynthesis, BBN)

Thermonuclear reactions in the early U. form the last piece of initial conditions that determined the future evolution and shaped U. today. These initial conditions are not independent of the previous ones: BBN was inevitable once U. entered Radiation-dom. Era with the matter contents determined by the initial conditions fixed at the end of GUT Era. What is new here is that products of thermonuclear reactions were determined by details of nuclear forces. We believe that nuclear forces are strictly determined by strong interactions, but at present we are not capable to derive them from first principles of QCD $\Rightarrow$ today these forces and reactions are viewed as independent part of physics and astrophysics. We come back to end of Hadron Era. Most $p\bar{p}$ and $n\bar{n}$ pairs have already annihilated, there have survived 1 p and 1 n per 10^9 pairs.

Lepton Era: protons and neutrons interact by weak forces in 3 reactions: $p + e^- \leftrightarrow n + \nu_e$, $p + \bar{\nu}_e \leftrightarrow n + e^+$, $n \leftrightarrow p + e^- + \bar{\nu}_e$.
These reactions require sufficient energies. Neutron-proton mass difference $\Delta m = m_n - m_p = 1,293$ MeV $\Rightarrow$ in thermal equilibrium there are less heavier neutrons than protons,

$$\frac{n_n}{n_p} = e^{-\Delta m/T}.$$

During Lepton Era weak interactions gradually become ineffective and the first 2 reactions cease, only neutron decays go on.
End of Lepton Era/beginning of Rad.-dom. Era, $T \approx 1$ MeV, $t \approx 1$ s, weak interactions ,,freeze out", neutrinos become free,
$n_n/n_p \approx 0,17 \approx 1/6$.
Rad.-dom. Era: neutrons are free and begin to decay, lifetime $\tau_n = 880$ s, n_n/n_p slowly diminishes.

In hot $pn\gamma$ plasma thermonuclear reactions may go, but at high T there are many high-energy photons ($n_\gamma/n_p \approx 10^9$) and they photo-dissociate complex nuclei $\Rightarrow$ synthesis becomes effective when T drops below T_N — temp. at which most stable nuclei may survive.
T_N depends on nucleus binding energy B and relative number of high energy photons.
$B = Zm_p + (A - Z)m_n - m(Z, A) > 0$ — binding energy.
The number of photons per nucleon having energy above B is $\frac{1}{\eta}\, e^{-B/T}$.
Nuclei may survive if $T < T_N$ where T_N is given by

$$\frac{1}{\eta}\, e^{-B/T_N} = 1 \quad \Rightarrow \quad T_N = \frac{B}{\ln \frac{1}{\eta}}.$$

$B = 28,2$ MeV for ^{4}He, strongly bound light nucleus,
$B = 2,23$ MeV for D=^{2}H, weakly bound simplest nucleus.

Photo-dissociation ⇒ first ^{4}He nuclei should be formed and much later (at lower T) D.
This was NOT so. If first formed, ^{4}He would require *4–body reaction* $2p + 2n \to {}^4\text{He}$ — plasma density far too *low*.
For ^{4}He: $T_N \cong 1,34$ MeV $\cong 1,5 \cdot 10^{10}$ K ⇒ at that time baryon (nucleon) density was

$$\rho_b(T_N) = (1+z)^3\,\rho_{b0} = \left(\frac{T_N}{T_0}\right)^3 \rho_{b0} \approx 7 \cdot 10^{-2}\mathrm{g\,cm}^{-3}$$

— below water density ($\rho_{b0} \approx 4 \cdot 10^{-31}\mathrm{g\,cm}^{-3}$).
Center of Sun: $\rho \cong 150\,\mathrm{g\,cm}^{-3}$ — 3- and 4-body reactions are very rare ⇒ in diluted primordial plasma they were impossible.
Conclusion:
BBN could not first produce strongly bound ^{4}He, it must have been postponed until weakly bound D could have been synthesized in 2-body reactions („narrow deuterium bottleneck").
For D: $T_N \approx 0,1$ MeV $\approx 1,2 \cdot 10^9$ K — the outset of BBN, plasma density was

$$\rho_b(T_N) = (1+z)^3\,\rho_{b0} = \left(\frac{T_N}{T_0}\right)^3 \rho_{b0} \approx 3 \cdot 10^{-5}\mathrm{g\,cm}^{-3}$$ — below air density.

$t_N \approx 130$ s — „the third minute" (S. Weinberg).

First reaction $p + n \to D + \gamma$.
When T falls to $T \approx 8 \cdot 10^8$ K, $t \approx 280$ s, abundance of D is sufficiently large to make further reactions efficient:
$D + D \to^3$He$+n$ or $D + D \to^3$H$+p$,
then ^{3}He$+D \to^4$He$+p$, ^{3}H$+D \to^4$He$+n$ and others.
Reactions are effective $\Rightarrow$ nearly all neutrons end up bound in ^{4}He.
In the period between neutrons become free, $T \approx 1$ MeV at $t \approx 1$ s and $T_N \approx 0,1$ MeV at $t \approx 130$ s, the ratio n_n/n_p falls from $0,17$ to $\approx 0,14$ due to decays and then, once neutrons enter various nuclei, it remains constant up to now $\Rightarrow$ the mass abundance of ^{4}He is today

$$Y = \frac{2\frac{n_n}{n_p}}{1 + \frac{n_n}{n_p}} \cong \frac{2 \cdot 0,14}{1 + 0,14} \cong 0,25$$

in a good agreement with current observations.

BBN was practically terminated on ^{4}He —*NO heavier nuclei* besides tiny amount of ^{7}Li, by number of nuclei $^7Li/H \approx 10^{-10}$.
Products of BBN besides ^{4}He and ^{7}Li: D and ^{3}He, by number of nuclei:

$$\frac{D}{H} \approx \frac{^3He}{H} \approx 10^{-5}.$$

All other nuclei are synthesized in stars, supernovae explosions and neutron star collisions.
Why was BBN ineffective in synthesizing heavier nuclei?

1. Helium has only 2 isotopes, ^{3}He and ^{4}He, there are NO ^{2}He and ^{5}He. Isotope ^{2}He (,,diproton") has extremely short lifetime and decays very rapidly after formation, $^2He \rightarrow 2p$. Diproton plays fundamental role in hydrogen burning stars (pp cycle) $\Rightarrow$ this is why the Sun shines uniformly for billions years. Physical conditions during BBN $\Rightarrow$ diproton played no role in it.

2. There are NO long-lifetime isotopes with atomic mass $A = 5$ and 8. Reactions
$^4He + p$, $^4He + n$ or $^4He +^4 He$ produce unstable nuclei which immediately decay.
(In helium burning heavy stars the unstable ^{8}Be nuclei are essential.)

3. Large Coulomb barrier (electrostatic repulsion) impeded reactions of the type
$^4He +^3 He \rightarrow^6 Li + p$, $^4He +^3 He \rightarrow^7 Be + \gamma$.
Too small intensity of nuclear forces caused that BBN could not cross two ,,gaps": $A = 5$ and 8.

Alternative.
Were nuclear forces slightly stronger $\Rightarrow$ there would be long-lifetime diproton and nuclei with $A = 5$ and 8.
BBN would produce heavier nuclei up to ^{26}Fe $\Rightarrow$ today there would be no H- or He-burning stars, no sources of energy $\Rightarrow$ no life. U. would be filled with macroscopic lumps of matter, dark and cold, $T \approx 3$K.
The facts from nuclear physics: NO ^{2}He, NO $A = 5$, NO $A = 8$ do shape our U.

The isotopes D and ^{3}He are remnants of the nuclear fuel which are left-over from BBN. They were intermediate steps in nuclear burning of protons and neutrons to ^{4}He. The synthesis lasted up to $t \approx 10^3$ s and these isotopes were not burnt up since the plasma was then *too diluted*. These isotopes are not formed in stars, but destroyed in stars and their recent abundances show upper limits of their abundance as left-over remnants of BBN.

In the structure of the present U. D and ^{3}He are not abundant and insignificant, but they play a significant role in our discovering the matter contents of U.

D and ^{3}He abundances are *very sensitive* (unlike ^{4}He) to the value of

$$\eta = \frac{n_B}{n_\gamma}.$$

Best observations concern D: $D/H \cong 2,6 \cdot 10^{-5} \Rightarrow$ this gives number densities of protons and neutrons during BBN $\Rightarrow$ present (and constant) value of η,

$$5,8 \cdot 10^{-10} < \eta < 6,6 \cdot 10^{-10}$$

and this gives us the number density of ,,dark baryons" contained in unobservable objects.