when g_* is constant $a(t) \propto t^{1/2}$ & $T(a) \propto a^{-1}$

entropy density: $s(T) = \frac{\rho(T) + P(T)}{T} = \frac{2\pi^2}{45} g_{*,s}(T)\, T^3$

entropic D.F : $g_{*,s}(T) \equiv \sum_{\text{bose}} g_i \left(\frac{T_i}{T_\gamma}\right)^3 + \frac{7}{8} \sum_{\text{fermion}} g_i \left(\frac{T_i}{T_\gamma}\right)^3$

Cosmic Inventory & Timeline

Big Bang Nucleosynthesis (BBN)

light nuclei formed during first few minutes

theory / measurement agree if universe is radiation dominated (Temp > 1MeV)

caveat: anything hotter/earlier is speculative

but good reason for it

assumed that Temp >> 100s GeV initially

Time / Temp Intuition

back to Friedmann eqn $H = \frac{1}{a} \cdot \frac{da}{dt} = \left(\frac{4\pi^2 G \cdot g_*}{45}\right)^{1/2} T^2 \equiv KT^2$

define $a(T_{BBN}) \equiv 1$ $T_{BBN} = 1\,\text{MeV} = 10^6\,\text{eV}$

$\rightarrow T(a) = \frac{T_{BBN}}{a}$ $H(a) = \frac{1}{a} \cdot \frac{da}{dt} = K \cdot \frac{T^2_{BBN}}{a^2}$

age of universe: $dt = \frac{da}{a \cdot H(a)} = \frac{a \cdot da}{K \cdot T^2_{BBN}}$

$$t = \int_0^a \frac{1}{KT^2_{BBN}} \cdot a\,da = \frac{a^2}{2KT^2_{BBN}} = \frac{1}{2K+2} \simeq 1.2\ \text{sec} \left(\frac{\text{MeV}}{T}\right)^2$$

recover $T = \text{MeV}$ in 1 second → hotter temps cooldown?

Cosmic Inventory

Quarks : spin 1/2 fermions, strong force (QCD)

charge +2/3: $\underset{1}{\underline{u\ (\text{up})}}$, $\underset{2}{\underline{c\ (\text{charm})}}$, $\underset{3}{\underline{t\ (\text{top})}}$

charge −1/3 : $\underset{1}{\underline{d\ (\text{down})}}$, $\underset{2}{\underline{s\ (\text{strange})}}$, $\underset{3}{\underline{b\ (\text{bottom})}}$

temp >> 200 MeV → free
temp << 200 MeV → "hadrons" protons/neutrons/... $\hookleftarrow \Lambda_{QCD}$

12 degeneracy = 2 spin · 2 matter/antimatter · 3 colors

hadrons bind for neutral color

Gluons : "force carriers" for QCD, spin 1 bosons

2 polarizations, 8 colors

Leptons : spin 1/2 fermions, no QCD

2 spin, antiparticles

neutrinos (neutral), basically massless, only 1 polarization

Gauge Bosons: big photons, mediate short-range Weak Force

own antiparticle

Photon: spin 1/2

Higgs Boson: gives mass :), 1 polarization
(to elementary particles)

Inflation?

Where did radiation density come from

E12D volume

widely accepted rapid inflation.

universe locally flat/smooth & explains correlations on scales beyond causal contact

like zooming in on iPad faster than c

dilutes density of preexisting stuff

"it's been 13.7 Gyr since inflation"

density responsible for "inflating" converted into particles quickly thermalizing

Baryogenesis

Today, particles > antiparticles
asymmetry in quarks & antiquarks

Standard Model predicts symmetry :(

need some asymmetry for light nuclei

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.1 \cdot 10^{-10}$$

Neutrino Decoupling

scattering rate >> H

at temp >> MeV, neutrinos maintain equilibrium w/ visible particles

scattering rate: $$\Gamma_{\nu e \to \nu e} \equiv n_\nu \langle \underset{\uparrow}{\sigma} v \rangle \approx G_F^2 \cdot T^5$$

cross section
$\propto G_F^2 T^2$

$$G_F \equiv 1.16 \cdot 10^{-5}\ \text{GeV}^{-2}$$

gravitational constant but for weak force