FIZIKALNA

KOZMOLOGIJA

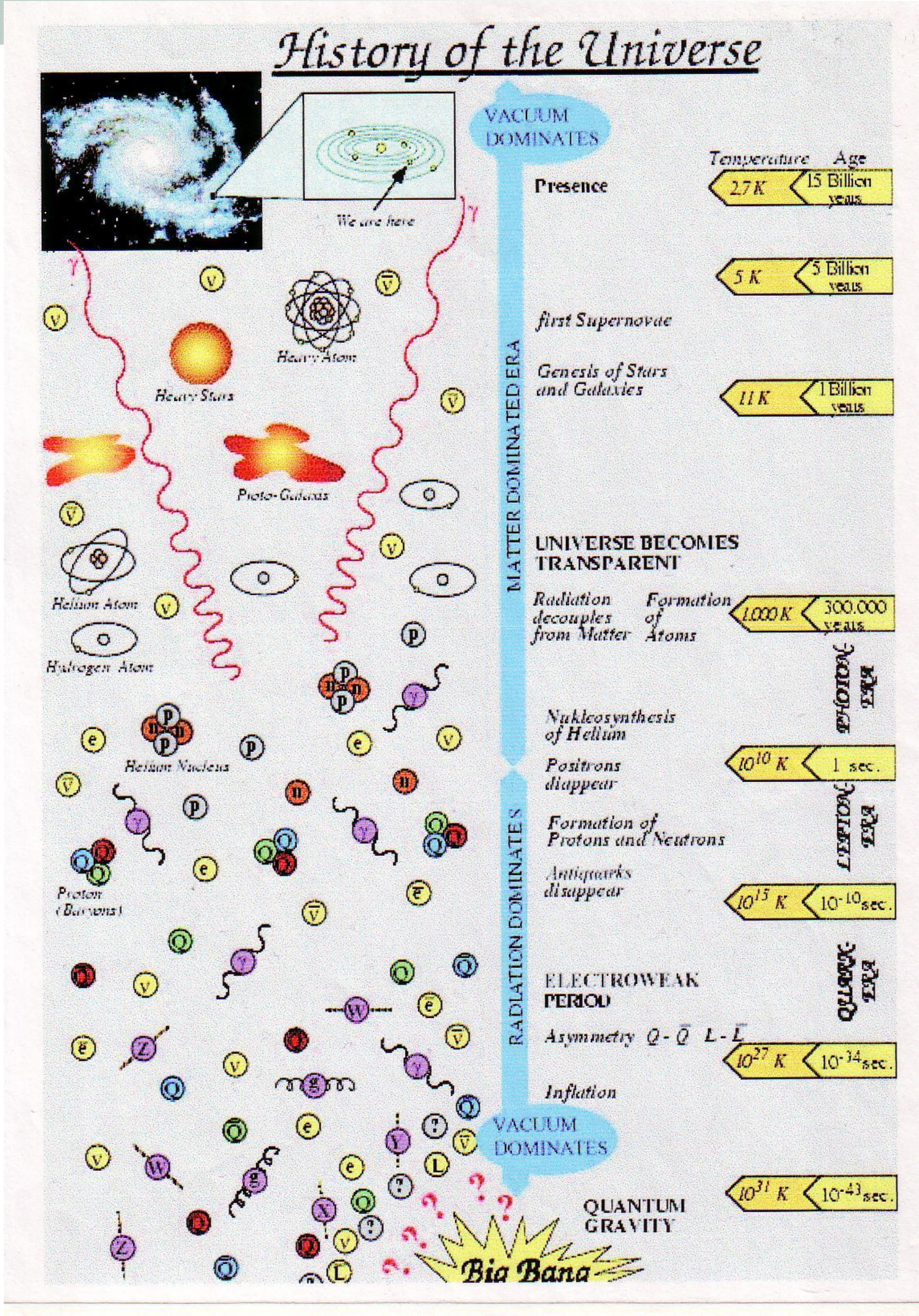
VI. TERMIČKA POVIJEST RANOG SVEMIRA

Počinjemo na 10^{13} K

~ 900 MeV

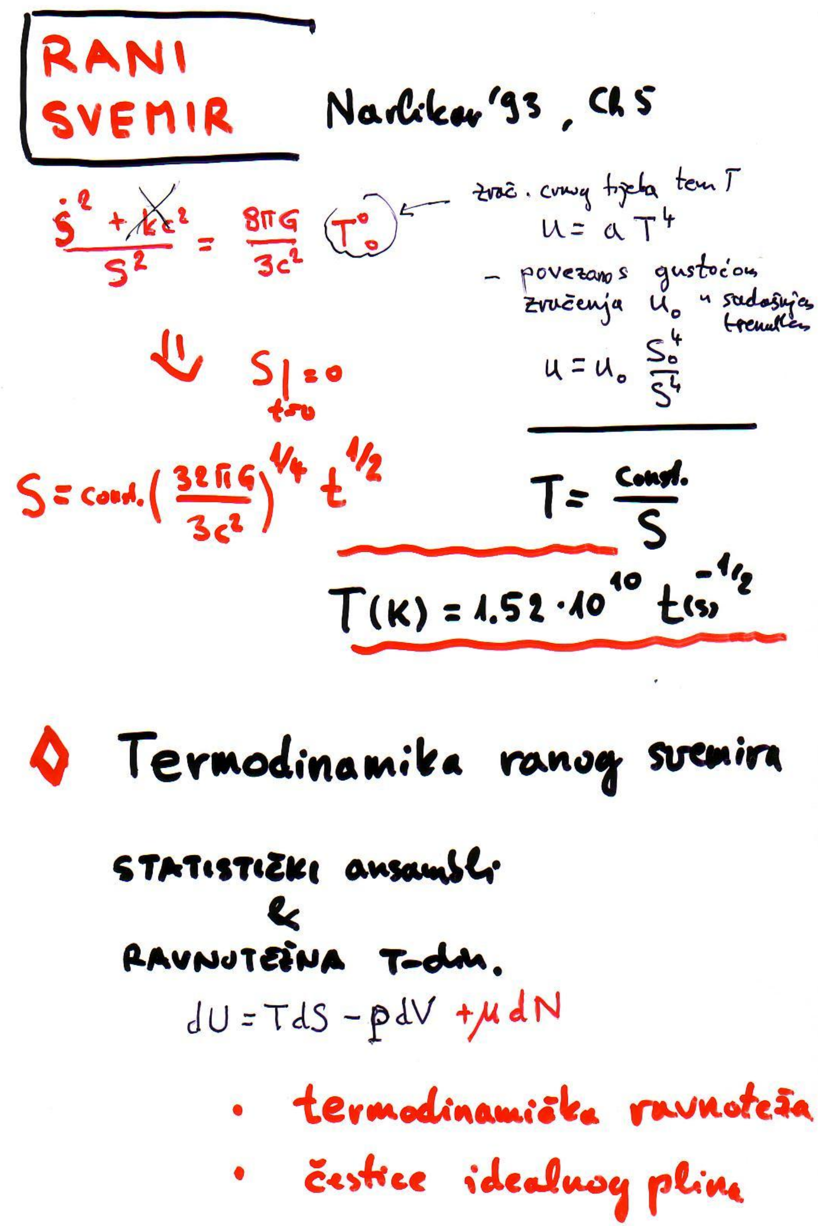
ispod praga produkcije

$e^+ + e^- \to \gamma^* \to p + \bar{p}$



SVEMIR U ERI ZRAČENJA

UKAZUJE NA VRUĆI VELIKI PRASAK



RANI SVEMIR

Narlikar '93, Ch 5

$$\frac{\dot{S}^2 + kc^2}{S^2} = \frac{8\pi G}{3c^2}\left(T^0_0\right)$$

← zrač. crnog tijela tem T

$u = aT^4$

– povezano s gustoćom zračenja u_0 u sadašnjem trenutku

$u = u_0 \frac{S_0^4}{S^4}$

⇓ $S|_{t=0} = 0$

$$S = \text{const.}\left(\frac{32\pi G}{3c^2}\right)^{1/4} t^{1/2}$$

$$T = \frac{\text{const.}}{S}$$

$$T(K) = 1.52 \cdot 10^{10}\, t_{(s)}^{-1/2}$$

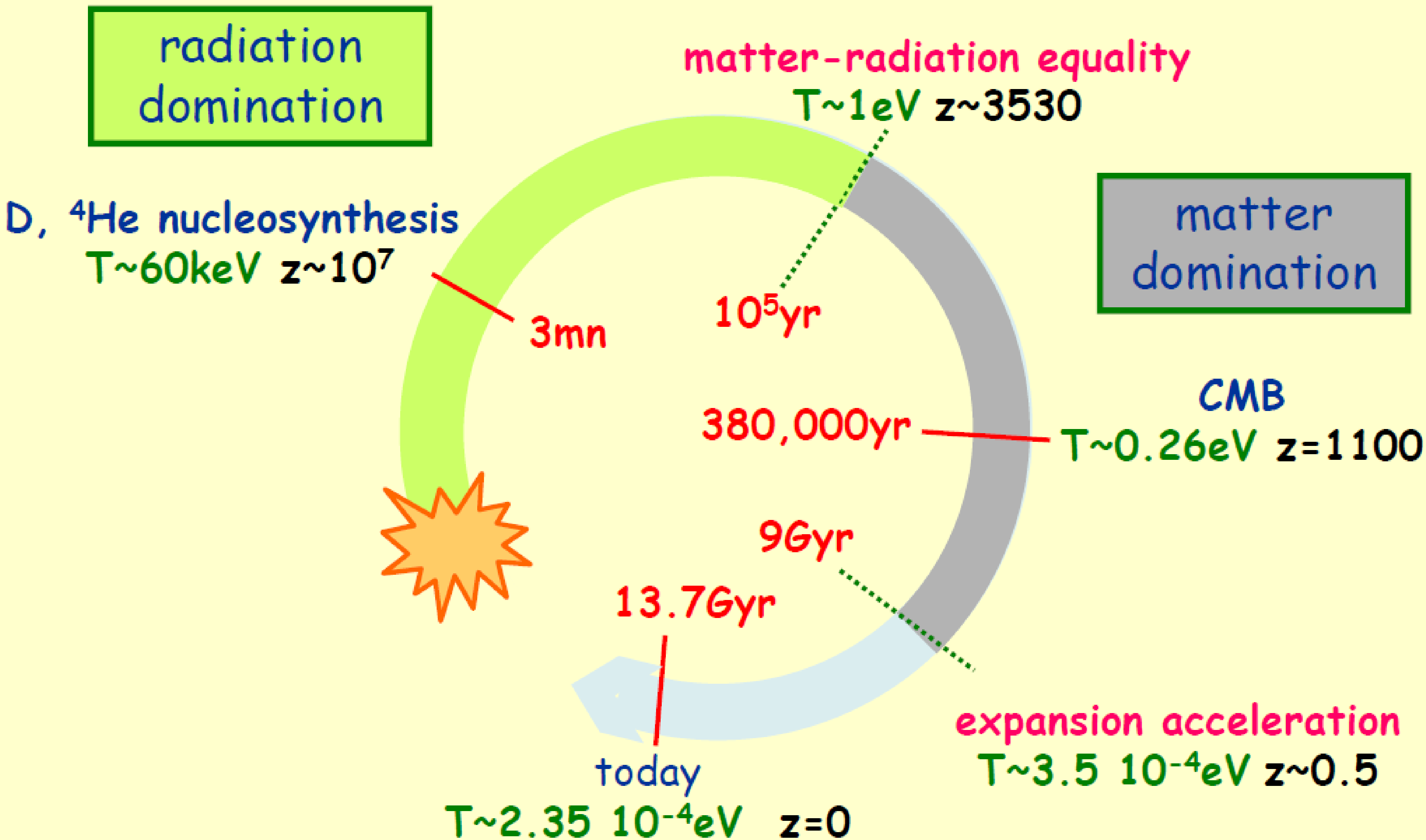
◊ Termodinamika ranog svemira

STATISTIČKI ansambli & RAVNOTEŽNA T-dm.

$$dU = TdS - pdV + \mu dN$$

- termodinamička ravnoteža
- čestice idealnog plina

"KOZMIČKI SAT"



TERMODINAMIKA RANOG SVEMIRA

Mala gustoća bariona

$N_B / N_\gamma \sim 10^{-9}$

i jednako mala gustoću leptona

⇓

opravdanje

$\mu_A = 0$ za sve A

Gustoće (uz $\mu_A = 0$)

- broja čestica $$N_A = \frac{g_A}{2\pi^2\hbar^3}\int_0^\infty \frac{p^2\,dp}{e^{E_A(p)/k_BT} \pm 1}$$
- energije $$\varepsilon_A = \frac{g_A}{2\pi^2\hbar^3}\int_0^\infty \frac{p^2 E_A(p)\,dp}{e^{E_A(p)/k_BT} \pm 1}$$
- tlaka $$p_A = \frac{g_A}{2\pi^2\hbar^3}\int_0^\infty \frac{\left[\frac{c^2p^2}{E_A(p)}\right] p^2\,dp}{e^{E_A(p)/k_BT} \pm 1}$$
- entropije $$s_A = \frac{p_A + \varepsilon_A}{T}$$

Visoko-temperaturna granica
(relativist. č. $E_A \simeq pc$)

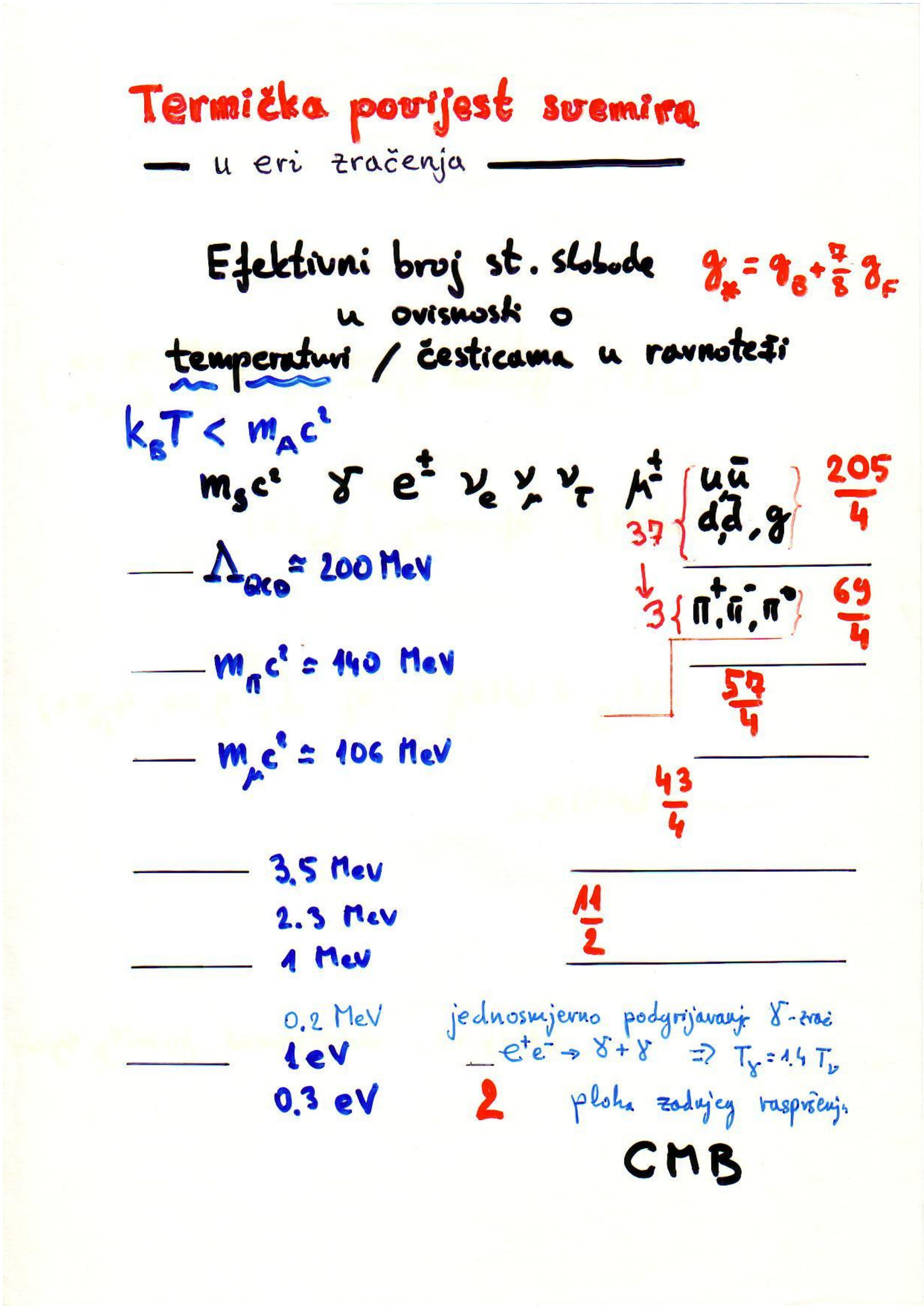
$$\rho_B c^2 = \frac{g_B}{2} a T^4$$
$$\rho_F c^2 = \frac{7}{16} g_F a T^4$$

ukup.

$$\rho c^2 = \frac{1}{2} g_* a T^4$$
$$g_* = g_B + \frac{7}{8} g_F$$

Jednoznačna veza temperature i vremena:

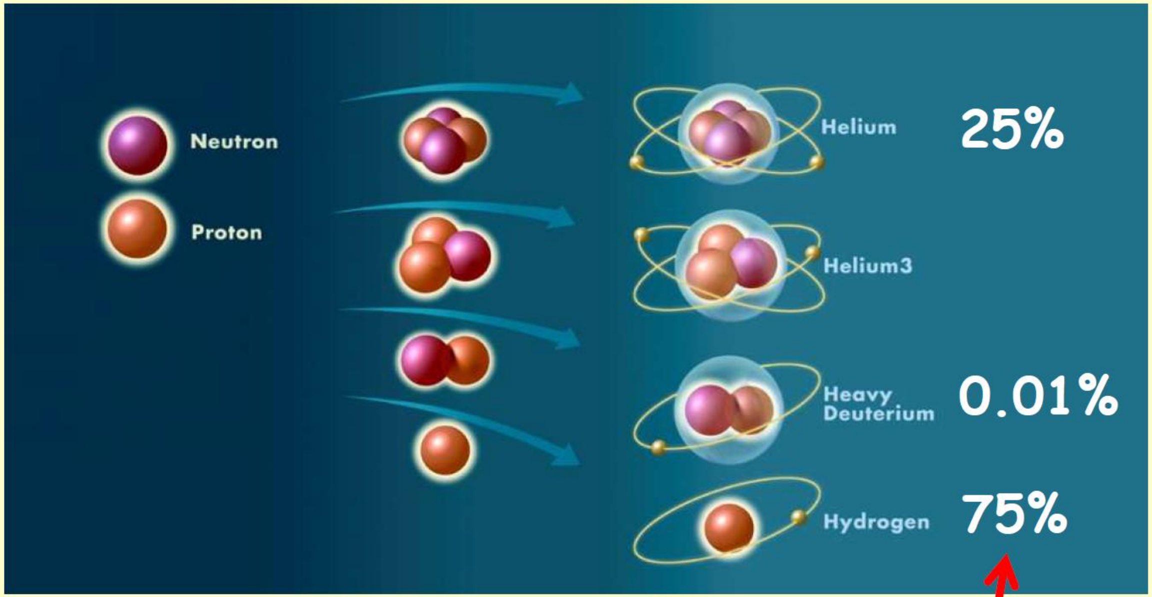
$$\sqrt{t(s)} = \frac{1.8 \cdot 10^{10}}{g_*^{1/4}\, T(K)}$$



PRVOTNA NUKLEOSINTEZA

- 1948: G.Gamow, R.Alpher "The origin of Chemical Elements"

Expanding universe : deuterium and helium nuclei are formed b nuclear reactions inside the primordial plasma of p,n,e,γ whe temperature and densities are adequate, leading to ligh elemer abundances as measured.



measured primordial abundances

PRVOTNA NUKLEOSINTEZA

- Seminarske teme

Prvotna nukleosinteza

– zahtijeva spuštanje temperature ispod en. vezanja deuterona (2,22 MeV)

ekv. temp. 2.58×10^{10} K

1,29 MeV ali koliko ?

$$r = \frac{N_n}{N_p} = e^{-(m_n-m_p)c^2/k_B T} = e^{-\frac{1.5\cdot 10^{10}\,K}{T(K)}} \rightarrow 1/6 \quad \text{za } T \approx (0.7\text{–}0.8)\,\text{MeV}$$

dopunjeno s $n \rightarrow p + e^- + \bar{\nu}_e$ ⇒ 1/7 (prije formiranja deut.)

– lanac reakcija vodi na jezgre ^4He kao dominantni produkt;

jednostavno brojanje daje udio $Y = \frac{^4He}{^4He + p} = \frac{4(r/2)}{4(r/2)+1-r} = \frac{2r}{1+r} \simeq \frac{2}{8} = 25\%$

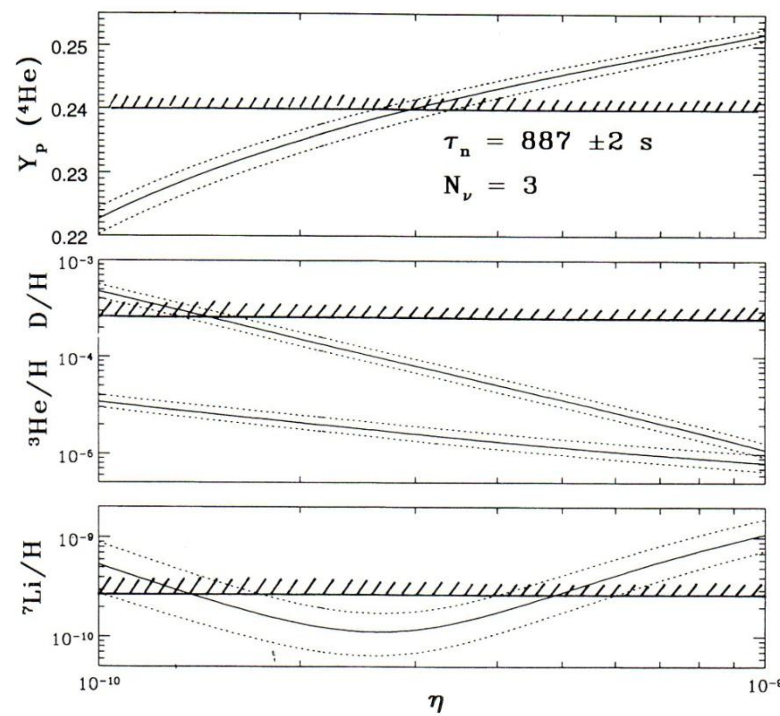
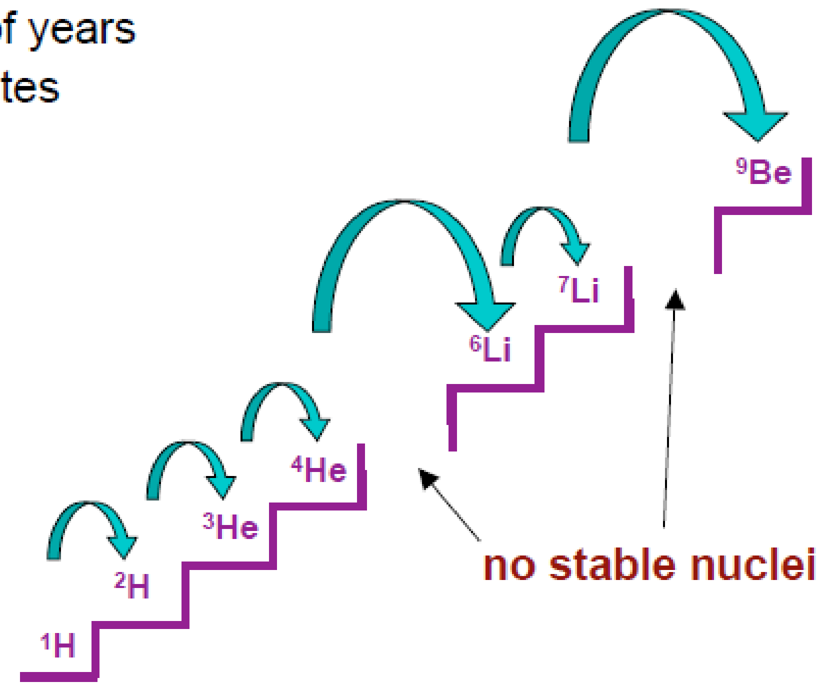


Fig. 35 Mass abundances of the nuclei ^{4}He, ^{3}He, D and ^{7}Li relative to ^{1}H, as functions of the baryon to photon ratio η. The curves are the predicted primordial nucleosynthesis abundances; the shaded regions are excluded by observations. Reproduced by permission of S. Sarkar [10]
Rep. Prog. in Phys. 59 ('96) 1493

USPOREDBA PRVOTNE I STELARNE NUKLEOSINTEZE

- **Timescale**
  - » Stellar Nucleosynthesis (SN): billions of years
  - » Primordial Nucleosynthesis (PN): minutes
- **Temperature evolution**
  - » SN: slow increase over time
  - » PN: rapid cooling
- **Density**
  - » SN: 100 g/cm^3
  - » PN: 10^{-5} g/cm^3 (like air!)
- **Photon to baryon ratio**
  - » SN: less than 1 photon per baryon
  - » PN: billions of photons per baryon



The lack of stable elements with masses 5 and 8 make it hard for primordial nucleosynthesis to synthesise elements beyond Helium

UVJETI U RANOM SVEMIRU

$$T \gtrsim 1 \text{ MeV}$$

$$\rho = \frac{\pi^2}{30}\left(2 + \frac{7}{2} + \frac{7}{4}N_\nu\right)T^4$$

$$\eta = n_B/n_\gamma \sim 10^{-10}$$

β-Equilibrium maintained by weak interactions

Freeze-out at ~ 1 MeV determined by the competition of expansion rate $H \sim T^2/M_p$ and the weak interaction rate $\Gamma \sim G_F^2 T^5$

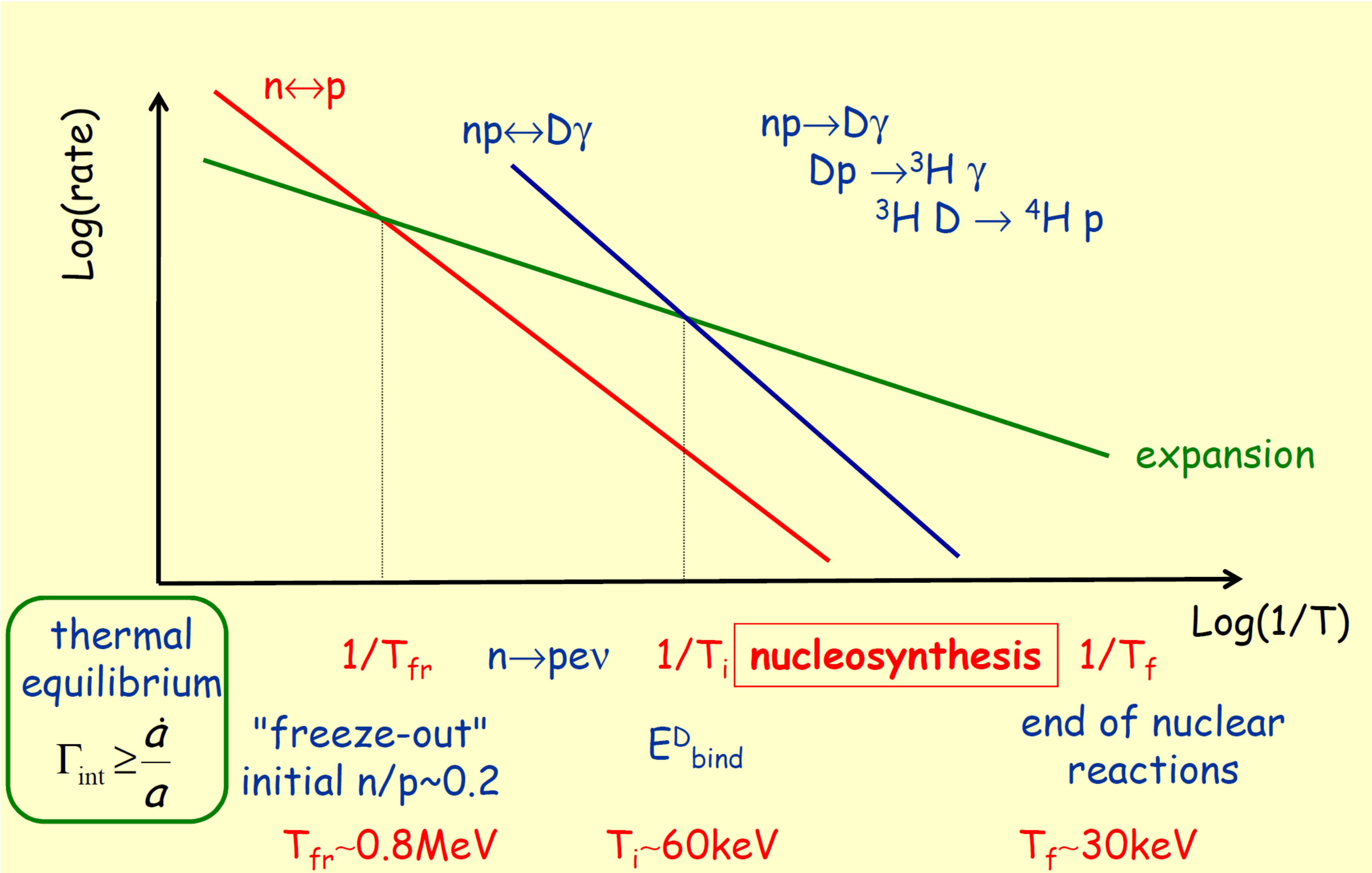
$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

$$n + \nu_e \leftrightarrow p + e^-$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

At freezeout n/p fixed modulo free neutron decay, $(n/p) \simeq 1/6 \rightarrow 1/7$

3 KORAKA NUKLEOSINTEZE



"BROJANJE NEUTRINA"

Light element abundances are sensitive to expansion history during BBN

$$H^2 \sim G\rho_{rel}$$

⇒ observed values constrain relativistic energy density

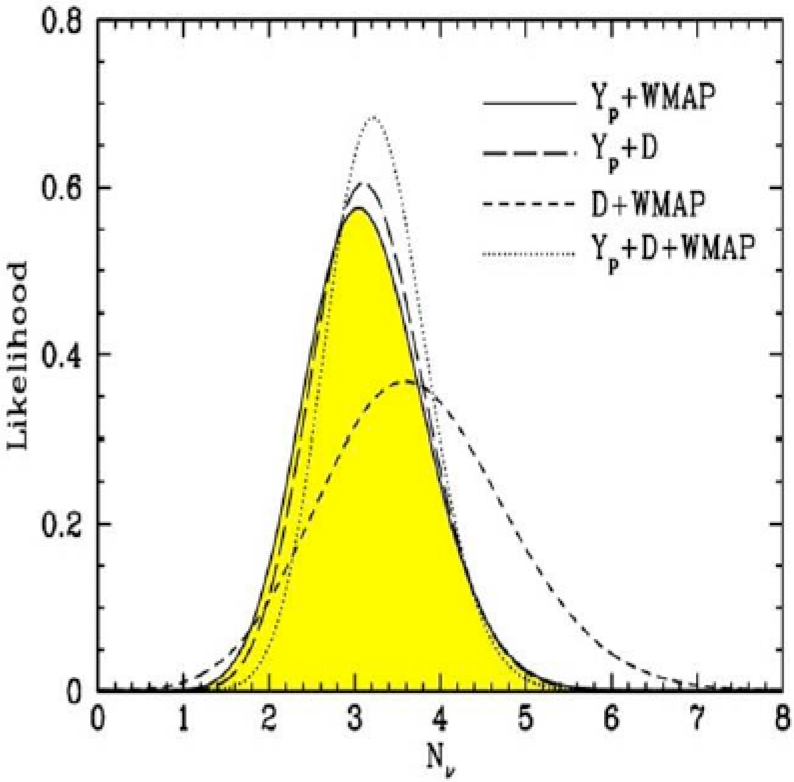
$$\rho_{rel} \equiv \rho_{EM} + N_{\nu,eff}\, \rho_{\nu\bar{\nu}}$$

Pre-CMB:

^{4}He as probe, other elements give η

With η from CMB:

- All abundances can be used
- ^{4}He still sharpest probe
- D competitive if measured to 3%



This constrains sterile neutrinos (and other hypothetical particles) which do *not* couple to the Z^0 … *complementary* to laboratory bounds e.g from LEP

Step 1: n, p in thermal equilibrium via reactions

$$\nu_e n \leftrightarrow e^- p \qquad \bar{\nu}_e p \leftrightarrow e^+ n$$

but easier to produce p than n (mass difference), hence

$$\frac{n}{p} \approx \exp(-\Delta m / T) \qquad \Delta m = m_n - m_p = 1.293 MeV$$

We have

$$\Gamma_{n\leftrightarrow p} \approx G_F^2 T^5 \qquad H \approx \sqrt{g_*(T) G_N} T^2$$

effective number of spin states of relativistic particles :

SM: $\gamma, e, \nu \Rightarrow g_*(1MeV) = 2 + 3.5 + 7/4\, N_\nu$

End of equilibrium ("freeze-out"):

$$\boxed{\Gamma_{n\leftrightarrow p} = H} \Rightarrow T_{fr} \approx (g_*(T_{fr}) G_N / G_F^4)^{1/6} \approx 0.8 MeV$$

hence: $\frac{n}{p} \approx 0.2$

step 1: T> 0.8 MeV (t<1s)

Step 2: n→pev and first phase of D formation

$$np \leftrightarrow D\gamma$$

Deuterium binding energy: $\Delta_D = 2.23 MeV$

- deuterium formation ↔ photodissociation : n,p,γ,D in thermal equilibrium
- end of equilibrium: no longer enough photons with $E_\gamma > \Delta_D$ ⇒ T~60keV (for $\eta = (n_B - n_{\bar{B}})/n_\gamma \sim 5.10^{-10}$)

then:

$$\Delta t = t(60kev) - t(0.8MeV) \approx 3mn$$

$$\left(\frac{n}{p}\right)_0 \approx 0.2\exp(-\Delta t/\tau_n) \approx 0.1$$

$$\tau_n = 885.7 \pm 0.8s \quad (PDG \quad 2008)$$

step 2: 0.8 MeV>T>60keV

Step 3: nucleosynthesis

$$n\ p \rightarrow D\ \gamma \qquad D\ p \rightarrow {}^3H\ \gamma \qquad {}^3H\ D \rightarrow {}^4He\ p \quad \ldots\ldots$$

Production of D, followed by ^{3}H and ^{4}He

- heavier nuclei: unstable (A=5,8) or too difficult to produce (^{7}Li,^{7}Be: large Coulomb barriers)
- end of photosynthesis at T~30keV (densities are too weak due to expansion)

hence:

$$Y_p \equiv {}^4He/H \approx \frac{2(n/p)_0}{1-(n/p)_0} \approx 0.25$$

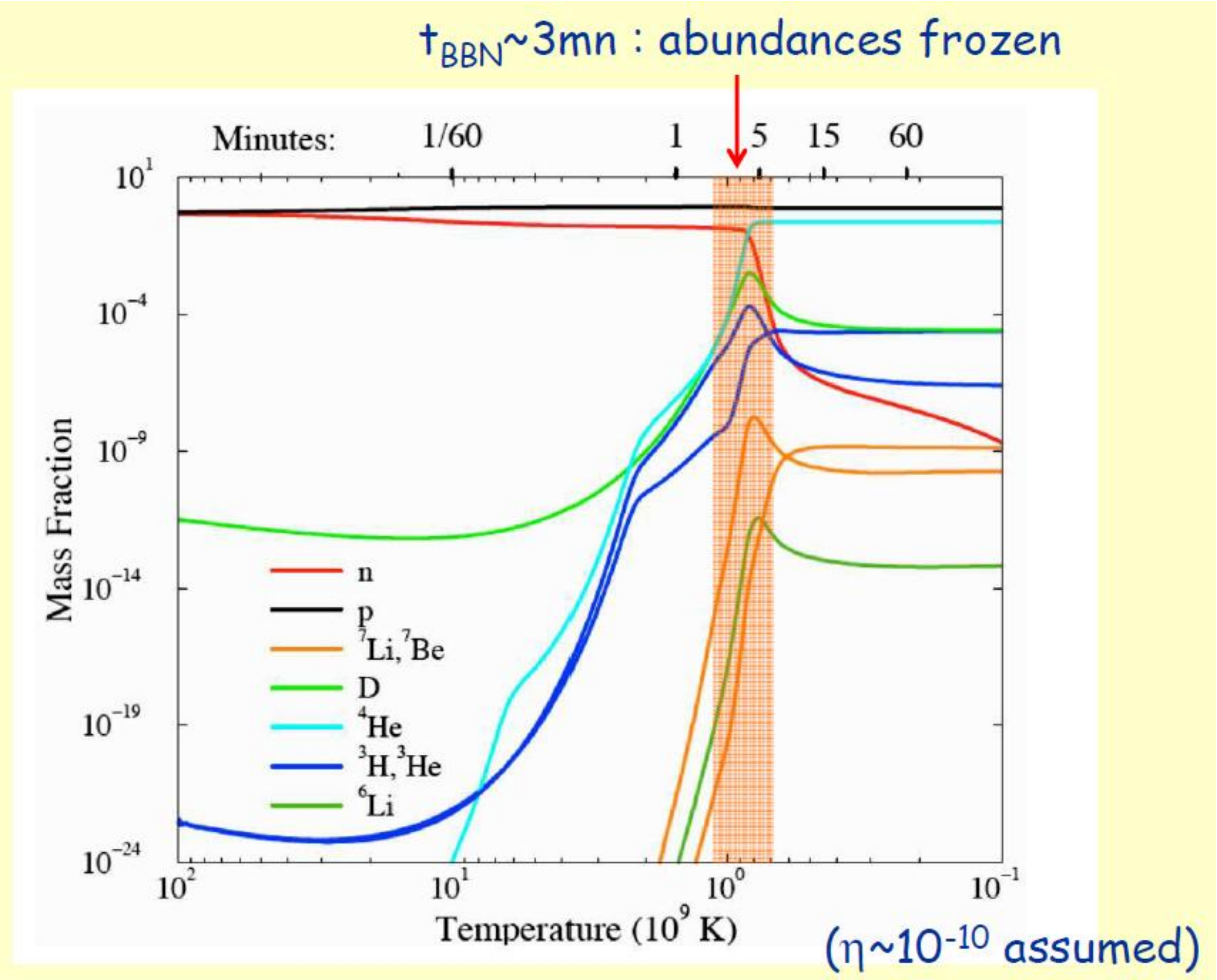
depends primarily on τ_n

other abundances: depend on initial conditions (baryon-to-photon ratio, η) and on nuclear reaction rates

Note: nearly all neutrons end up bound in ^{4}He

step 3: 60 keV>T>30keV; end of nucleosynthesis ~3mn

EVOLUCIJA OBILJA



BEZ RAČUNALA

$$\frac{dX}{dt} = J(t) - \Gamma(t)X \qquad \Rightarrow \qquad X^{eq} = \frac{J(t)}{\Gamma(t)}$$

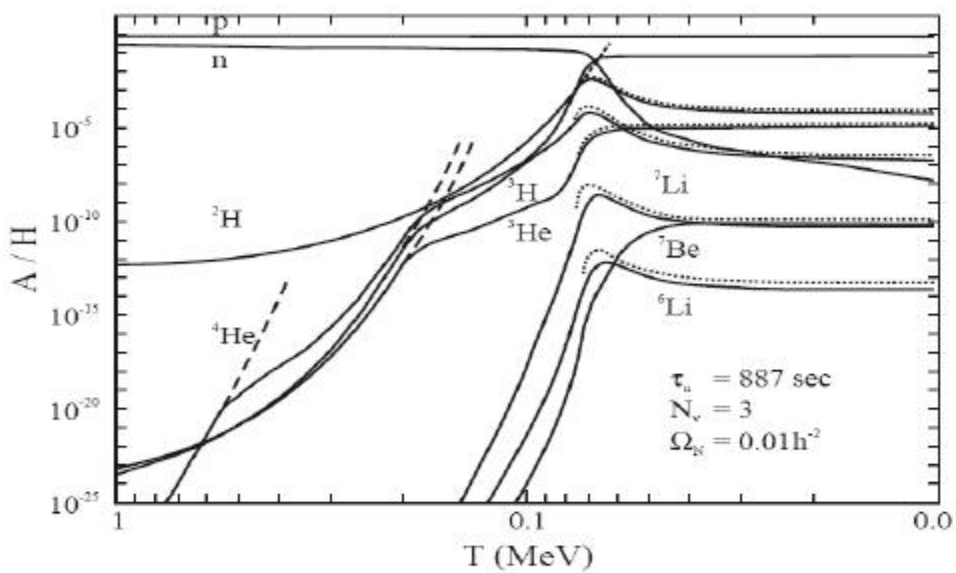
source ($J(t)$) … sink ($\Gamma(t)X$)

… but general solution is:

$$X(t) = \exp\left(-\int_{t_i}^{t} dt'\, \Gamma(t')\right)\left[X(t_i) + \int_{t_i}^{t} dt'\, J(t')\, \exp\left(-\int_{t_i}^{t} dt''\, \Gamma(t'')\right)\right]$$

If $\left|\frac{\dot{J}}{J} - \frac{\dot{\Gamma}}{\Gamma}\right| \ll \Gamma$ … then abundances approach equilibrium values

Freeze-out occurs when: $\Gamma \simeq H \quad \Rightarrow \quad X(t \to \infty) \simeq X^{eq}(t_{fr}) = \frac{J(t_{fr})}{\Gamma(t_{fr})}$



analytic solution

TERMIČKA POVIJEST

- Photons emitted at t (e.g. CMB), received today:

$$1+z \equiv \frac{\lambda_{observed}}{\lambda_{emitted}} = \frac{a_0}{a(t)} = \frac{E_\gamma(t)}{E_\gamma(t_0)} = \frac{T(t)}{T_0}$$

- Temperature was hotter in the past, expansion implies cooling down
- CMB: $T_{CMB}^{now} \approx 2.725 K \Rightarrow T_0 \approx 2.35\ 10^{-4}\ eV$

  $(k = 8.617\ 10^{-5}\ eV.K^{-1})$
- CMB anisotropy measurements:

  $z_{CMB}^{emission} \approx 1100 \Rightarrow T_{CMB}(t_{emission}) \approx 0.26 eV \approx 3{,}000 K$
- matter-radiation equality:

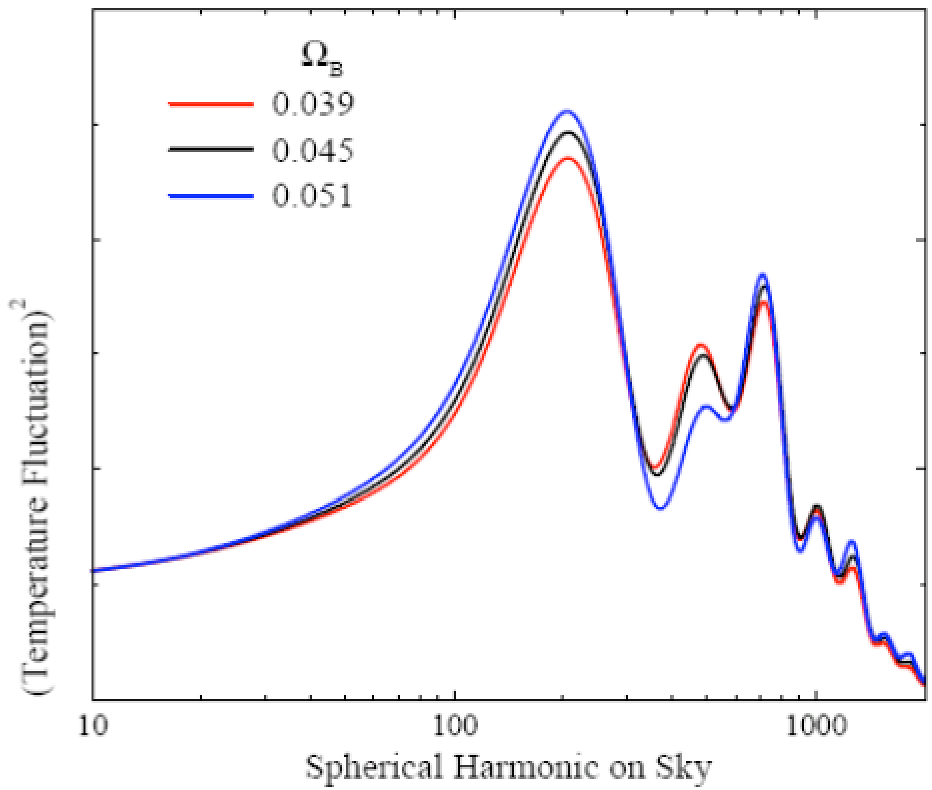
  $\rho_r(t_{eq}) = \rho_m(t_{eq}) \Rightarrow a_0 / a(t_{eq}) \Rightarrow T_{eq} \approx 1 eV \quad z \approx 3530$

CMB KAO "BARYOMETAR"

ΔT_ℓ provide *independent* measure of $\Omega_B h^2$

Acoustic oscillations in (coupled photon-baryon fluids Imprint features at < 1^o in angular power spectrum

Peak positions and heights sensitive to cosmological parameters e.g.
Ratio of 2nd peak/1st peak
⇒ baryon density



BBN vs CMB determinations of baryon density → fundamental test of cosmology and thermal history at z ~ 10^3 - 10^{10}