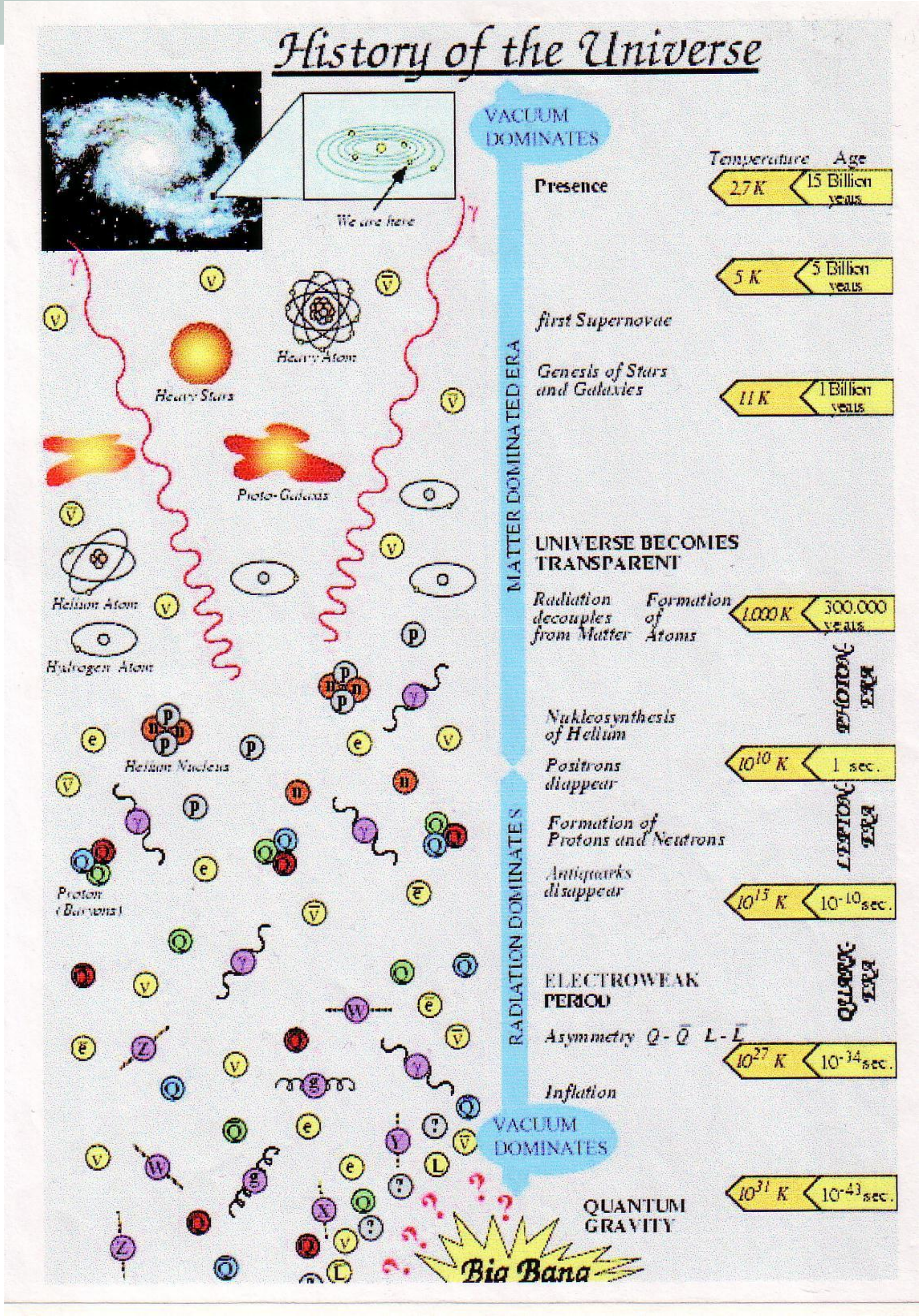
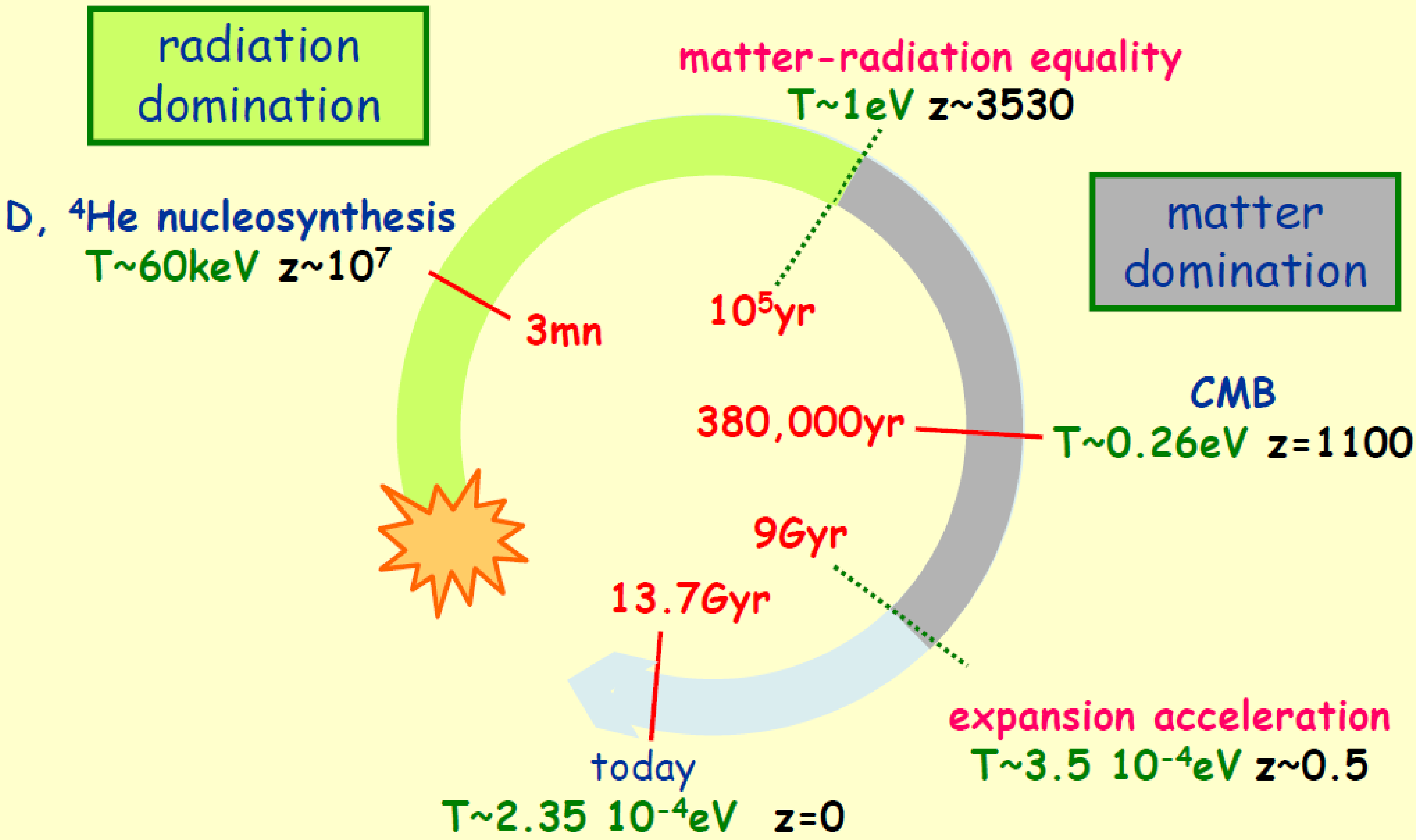
FIZIKALNA

KOZMOLOGIJA

VII. VRLO RANI SVEMIR & INFLACIJA



“KOZMIČKI SAT” ranog svemira



Ekstra zračenje u mjerenju CMB

$$\rho_r = \rho_\gamma + \rho_\nu \qquad \rho_\gamma = \frac{\pi^2}{15} T_\gamma^4,$$

$$\rho_\nu + \rho_{\rm er} \equiv \frac{\pi^2}{15} T_\nu^4 \cdot \frac{7}{8} N_{\rm eff}$$

$$\rho_r = \rho_\gamma \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\rm eff} \right] \qquad N_{\rm eff} = 3.30 \pm 0.27$$

- Usporedba s rezultatima LEP-a

$$N_\nu = 2.984 \pm 0.008$$

Usporedba CMB i neutrina

- Vj.: Pozadinsko zračenje neutrina u svjetlu činjenice masivnih neutrina

$$m(\nu_\mu)^2 - m(\nu_e)^2 = 5 \cdot 10^{-5}\ \mathrm{eV}^2$$

$$m(\nu_\tau)^2 - m(\nu_\mu)^2 = 3 \cdot 10^{-3}\ \mathrm{eV}^2$$

Termička povijest svemira

— u eri zračenja —

Efektivni broj st. slobode $g_* = g_B + \frac{7}{8} g_F$

u ovisnosti o

temperaturi / česticama u ravnoteži

$k_B T < m_A c^2$

$m_s c^2$ γ $e^\pm$ ν_e ν_μ ν_τ $\mu^\pm$ 37 $\{u\bar{u}, d\bar{d}, g\}$ $\frac{205}{4}$

— $\Lambda_{QCD} \simeq 200$ MeV

↓ 3 $\{\pi^+, \pi^-, \pi^0\}$ $\frac{69}{4}$

— $m_\pi c^2 \simeq 140$ MeV $\frac{57}{4}$

— $m_\mu c^2 \simeq 106$ MeV

$\frac{43}{4}$

— 3.5 MeV

2.3 MeV $\frac{11}{2}$

— 1 MeV

0.2 MeV jednosmjerno podgrijavanje γ-zrač.

— 1 eV $e^+ e^- \to \gamma + \gamma$ ⇒ $T_\gamma = 1.4\, T_\nu$

0.3 eV 2 ploha zadnjeg raspršenja

CMB

VRLO RANI SVEMIR

Vraćanje u prošlost **prije** $g_* = 69/4$

~ 10^5 god (formir. CMB) → 10^4 god (dominac. zrač. → tvar) → 3 min (formiranje jezgri ^4He) → 10^{-4} s / 10^{12} K plin mezona, leptona i γ u t-din. ravn.

γ, ν_e, ν_μ, ν_τ, $e^\pm, \mu^\pm$, $u\bar{u}, d\bar{d}, g$ $g_* = \frac{205}{4}$

$m_s c^2$ - - - - - - -

+ $s, \bar{s}$ $2 \cdot (3 \cdot 2 \cdot \frac{7}{8}) = \frac{42}{4}$ ⇒ $\frac{247}{4}$

$m_c c^2$ - - - - - - -

+ $c, \bar{c}$ $\frac{289}{4}$

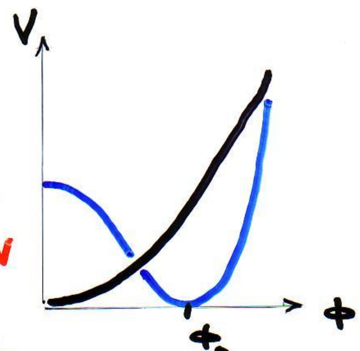
$m_\tau c^2$ / $m_b c^2$ / $M_{W,Z} c^2$ - - - - - - - + $\tau, \bar{\tau}$ / $b, \bar{b}$ / W^+, W^-, Z

◊ Fermijeva skala SSB

$V(\phi) = \frac{1}{2} m^2 \phi^2 + \frac{\lambda}{4} \phi^4$, $m^2 \to -\mu^2$

$\langle \phi \rangle = 0 \to \phi_0 = \pm \mu / \sqrt{\lambda}$

$\simeq 250$ GeV



◊ "GUT" skala velikog ujedinjenja ~ 10^{15} GeV / 10^{-36} s

◊ Planckova skala ~ 10^{19} GeV / $5 \cdot 10^{-44}$ s

Svemir u vrlo ranoj fazi je BARIONSKI ASIMETRIČAN

- Vj.: Barionsko simetričan svemirna temp. 1 TeV vodio bi na omjer broja nukleona i fotona daleko ispod opaženog

$$\frac{n_N}{n_\gamma} = \frac{g_N \left(\frac{m_N T}{2\pi}\right)^{3/2} e^{-m_N/T}}{2\frac{1.2022T^3}{\pi^2}} = 7.3 \times 10^{-27}$$

puno manji od opaženog 6×10^{-10}.

Bariogeneza

- očuvani barionski broj je prije formiranja hadrona (na 200 MeV) nošen kvarkovima

opažene gustoće broja $n_B = n_q - n_{\bar{q}}$

→ bezdimenzionalni omjeri :

$$\eta_B = \frac{n_B}{n_\gamma}$$

n_γ = gustoća br. fotona

$$Y_B = \frac{n_B}{s}$$

s = gustoća entropije

Na niskim temperaturama $(T < m_e)$

$$\eta_B \simeq 7\, Y_B$$

→ mjerene vrijednosti svode se na sadašnje vrijeme (t_0):

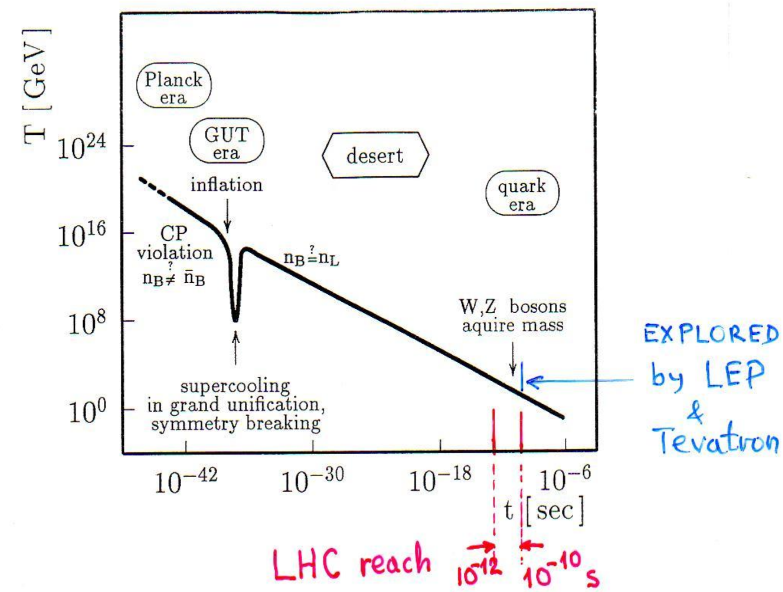
$$\eta_B = 6.1(3) \cdot 10^{-10}$$

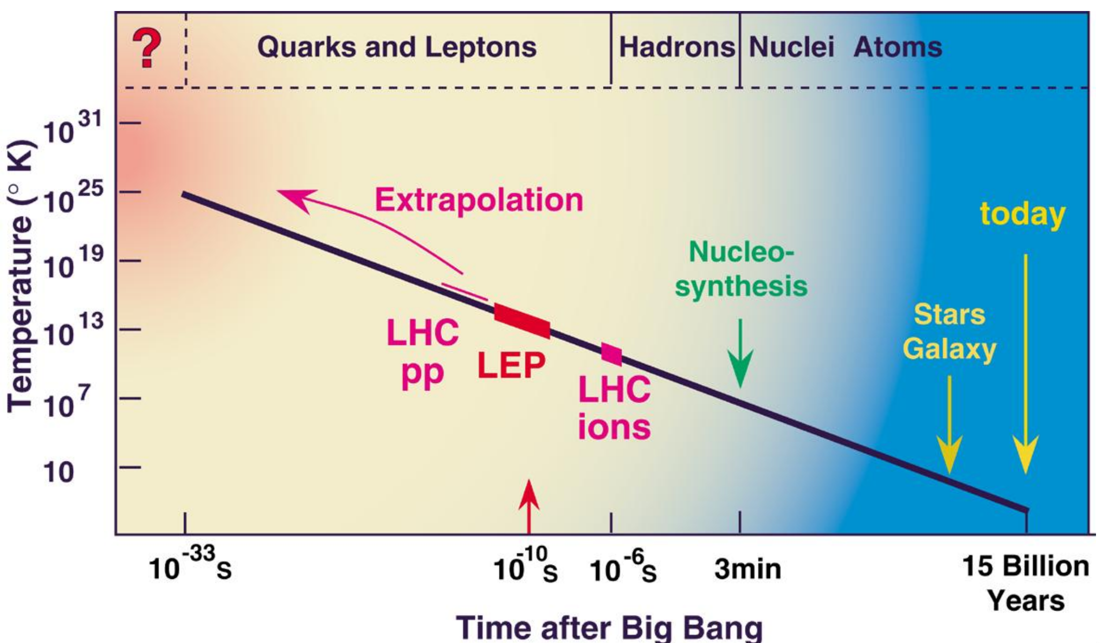
(iz CMB-a
WMAP)

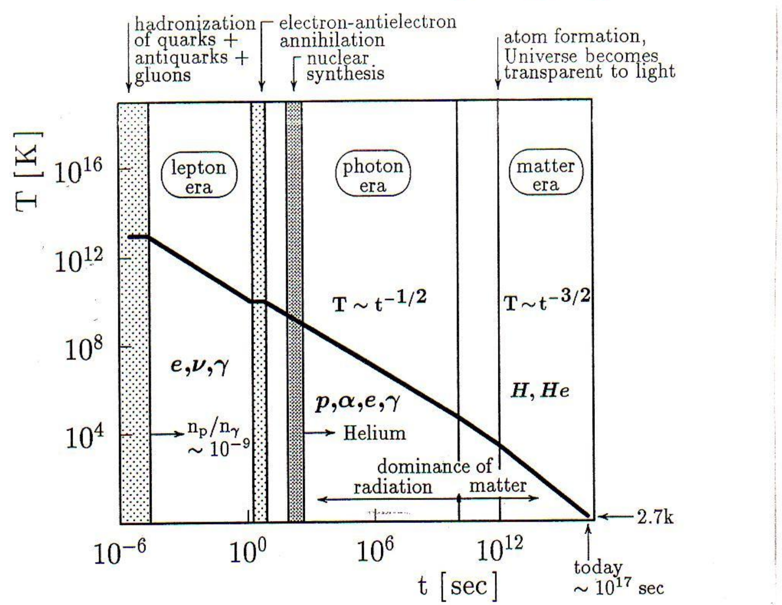
$$Y_B = 0.8 \cdot 10^{-10}$$

upravo vrijednosti potrebne za nastanak galaktika!

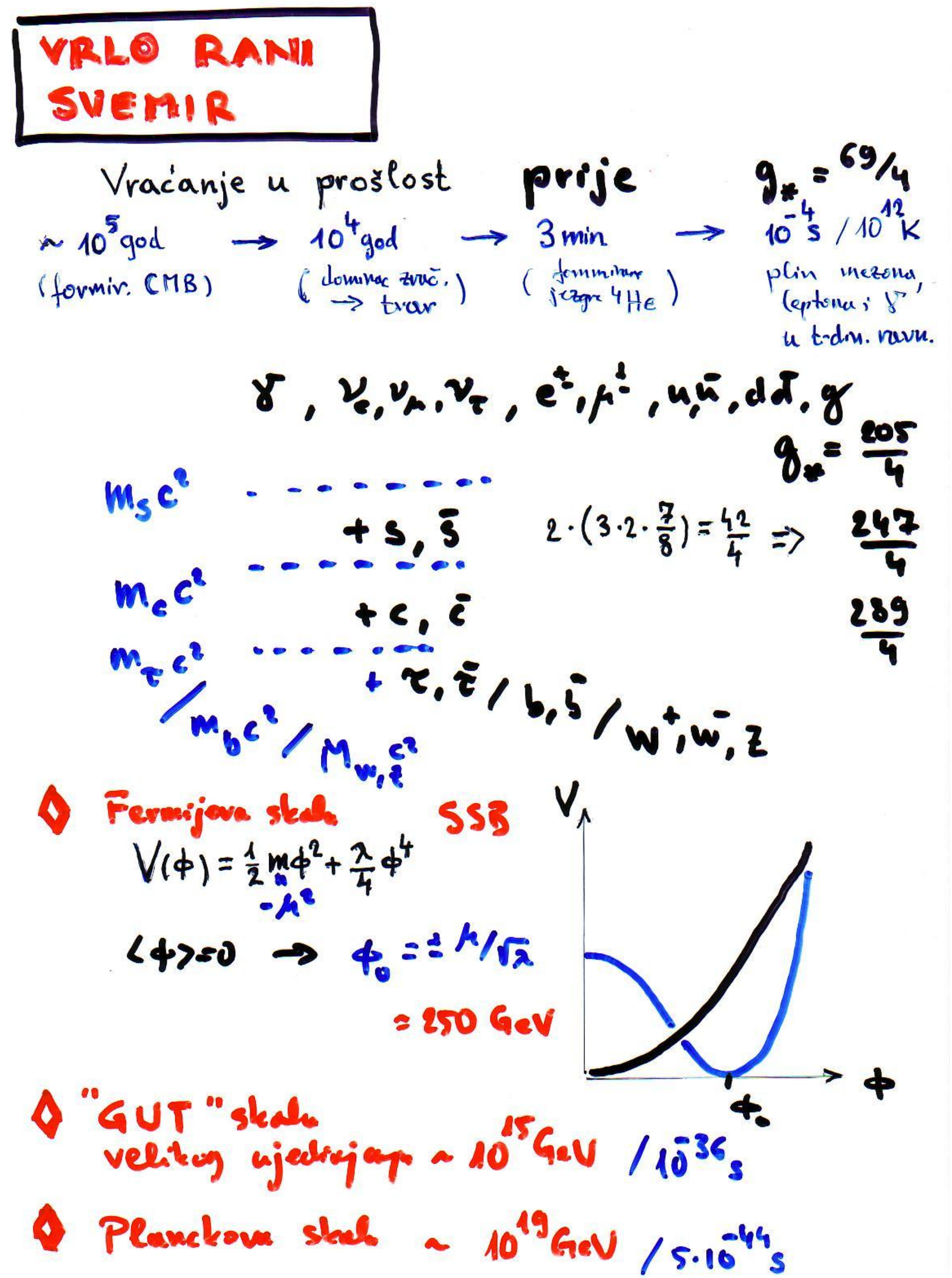
VRLO RANI SVEMIR







NIZ PROBLEMA STANDARDNE (FRW) KOZMOLOGIJE ZAHTIJEVA DA ERI ZRAČENJA PRETHODI INFLATORNA ERA



0-ti PROBLEM:
PROBLEM EKSPANZIJE SVEMIRA
(ekspanzija sada, jer je bila i u prošlosti) - 2 pristupa:

- za sve probleme vezane uz “početne uvjete svemira”, kriva je kvantna gravitacija
- kozmologija 80-tih potražila je odgovore na “GUT skali” – na tragu problema magnetnih monopola

Spuštanje sa skale

KVANTNE GRAVITACIJE $\sim 10^{19}$ GeV

na skalu

VELIKE UNIFIKACIJE, GUT $\sim 10^{15}$–10^{16} GeV

vodi na opću sliku VRLO RANOG SVEMIRA, koju treba provjeriti opažanjima, primjerice <u>PROBLEM MAGNETNIH MONOPOLA</u>

- mase $\gtrsim 10^{-9}$ gr
- veličine $\sim 10^{-29}$ cm

kojih bi trebalo biti koliko i fotona CMB-a

◇ "Normalnom" ekspanzijom

jezgre monopola udaljene $\sim 10^{-29}$ cm

na $T_{GUT} \simeq 10^{28}$ K

za faktor $\frac{T_{GUT}}{T_0 = 3K} \simeq 3 \cdot 10^{27}$ $\Rightarrow$ $3 \cdot 10^{-2}$ cm

danas bi bili dominantni sastojak svemira

◇ Inflacija poveća separaciju

za $e^{\eta} \frac{T_{GUT}}{T_0}$

- za $\eta = 60$ 1 mon/galakt.
- za $\eta = 67$ 1 mon/Hubble sfera

Koncept inflacije

The idea (A. Guth and A. Linde, 1981): Shortly after the Big Bang, the Universe went through a phase of rapid (exponential) expansion. In this phase the energy and thus the dynamics of the Universe was determined by a term similar to the cosmological constant (vacuum energy).

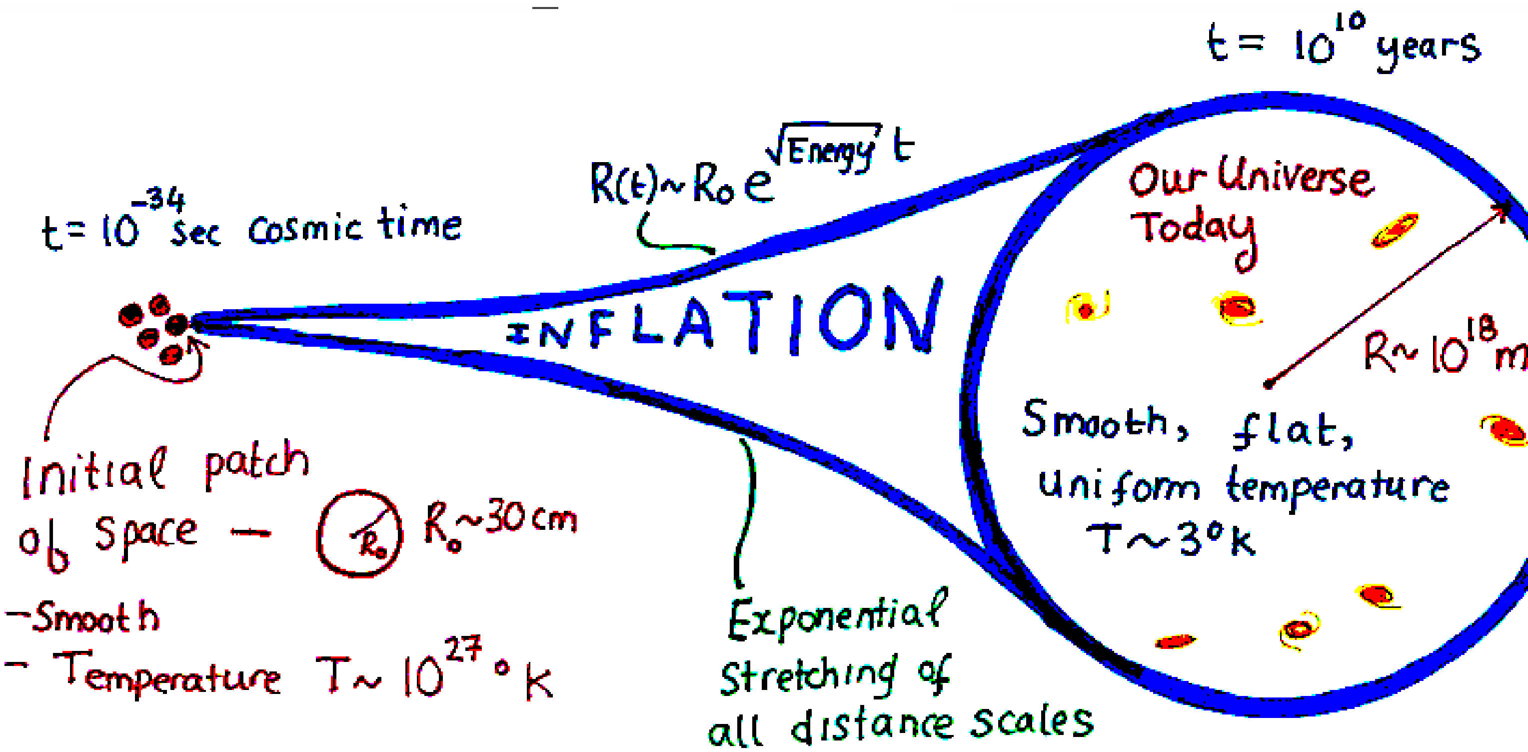
Why would the Universe do that ?

Why does it help ?

Problem relikta

- The monopole problem
  - big issue in early 1980s
    - Grand Unified Theories of particle physics → at high energies the strong, electromagnetic and weak forces are unified
    - the symmetry between strong and electroweak forces 'breaks' at an energy of $\sim 10^{15}$ GeV ($T \sim 10^{28}$ K, $t \sim 10^{-36}$ s)
      - this is a phase transition similar to freezing
      - expect to form 'topological defects' (like defects in crystals)
      - point defects act as magnetic monopoles and have mass $\sim 10^{15}$ GeV/c^2 (10^{-12} kg)
      - expect one per horizon volume at $t \sim 10^{-36}$ s, i.e. a number density of 10^{82} m^{-3} at 10^{-36} s
      - result: universe today completely dominated by monopoles (not!)

Inflacija i problem relikta



1. PROBLEM:

PROBLEM HORIZONTA

(područja koja nisu bila u kauzalnom kontaktu nalazimo s istom temperaturom)

Udalj. najudaljenijih objekata u čas t

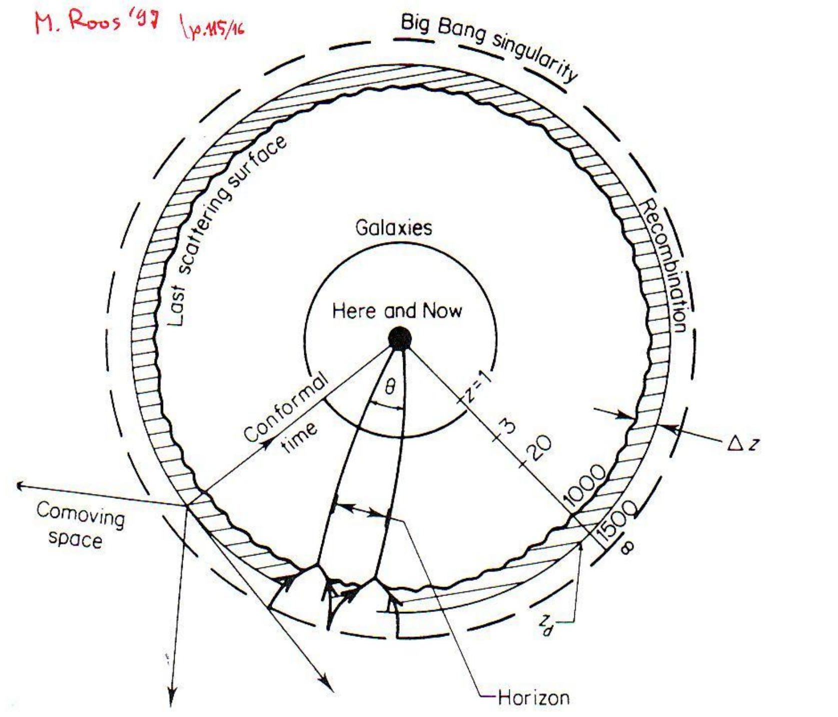
$$d_{Horiz.}(t) = S(t) \times (\text{svjetlosna koor. udalj.})$$

$$\text{svjetlosna koor. udalj.} = \int_0^t \frac{c\,dt'}{S(t')}$$

$$\int_0^{t_{odvez}} \frac{dt'}{S(t')} \ll \int_{t_{odvez}}^{t_0} \frac{dt'}{S(t')}$$

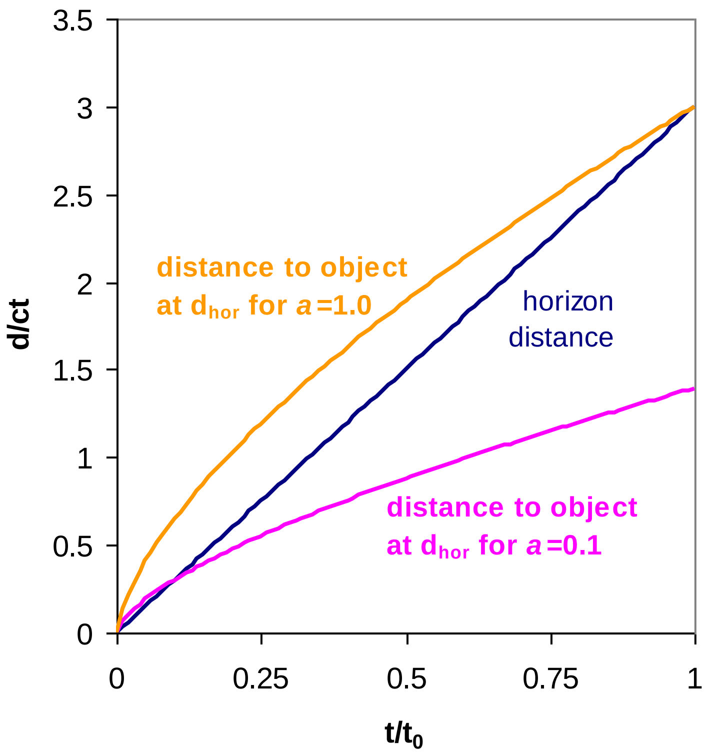
Udaljenost koju je svjetlost mogla prevaliti prije odvezivanja CMB (danas unutar = 1.12°) $\ll$ sadašnjeg horizonta

M. Roos '97 (p. 115/116)



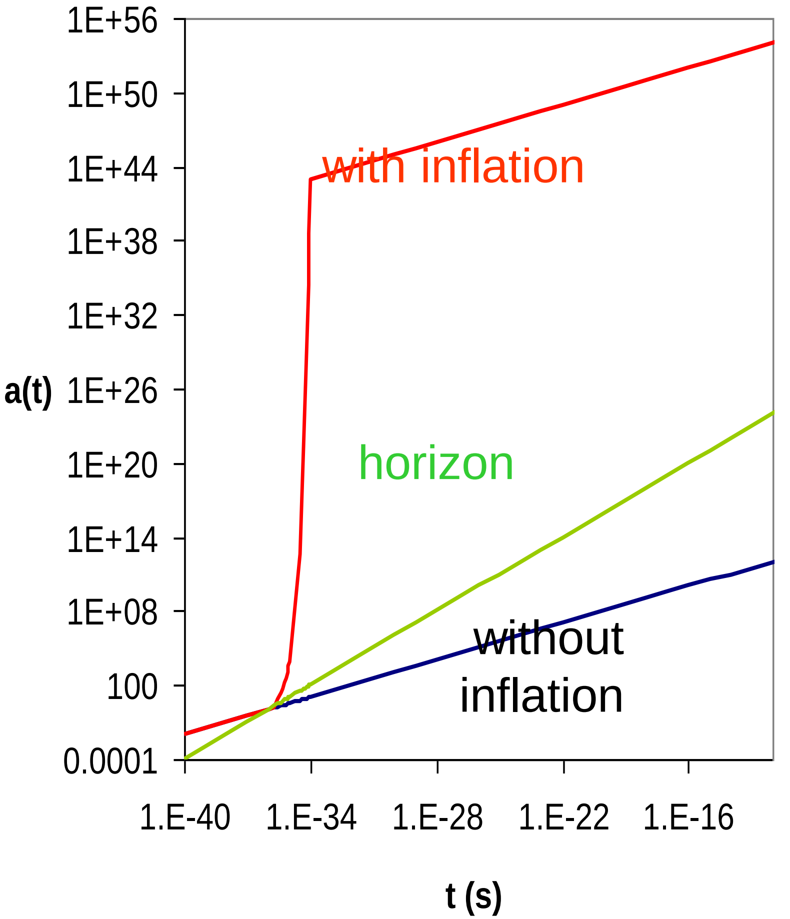
Horizon Problem

- Why is the CMB so isotropic?
  - consider matter-only universe:
    - horizon distance $d_H(t) = 3ct$
    - scale factor $a(t) = (t/t_0)^{2/3}$
    - therefore horizon expands faster than the universe
      - "new" objects constantly coming into view
  - CMB decouples at $1+z \sim 1000$
    - i.e. $t_{CMB} = t_0/10^{4.5}$
    - $d_H(t_{CMB}) = 3ct_0/10^{4.5}$
    - now this has expanded by a factor of 1000 to $3ct_0/10^{1.5}$
    - but horizon distance now is $3ct_0$
    - so angle subtended on sky by one CMB horizon distance is only $10^{-1.5}$ rad ~ 2°
  - patches of CMB sky >2° apart should not be causally connected



Inflation and the horizon

- Assume large positive cosmological constant Λ acting from t_{inf} to t_{end}
- then for $t_{inf} < t < t_{end}$
  $a(t) = a(t_{inf}) \exp[H_i(t - t_{inf})]$
  - $H_i = (\frac{1}{3}\Lambda)^{1/2}$
  - if Λ large a can increase by many orders of magnitude in a very short time
- Exponential inflation is the usual assumption but a power law $a = a_{inf}(t/t_{inf})^n$ works if $n > 1$



2. PROBLEM: PROBLEM RAVNOSTI

1. predviđanje inflacije – ravni svemir (Friedmannova jedn. daje de Sitterovo rješ. za k=0)

Zanemarimo Λ i "kozmološki član", u okolini $\Omega=1$ Friedmannova j-ba ima oblik

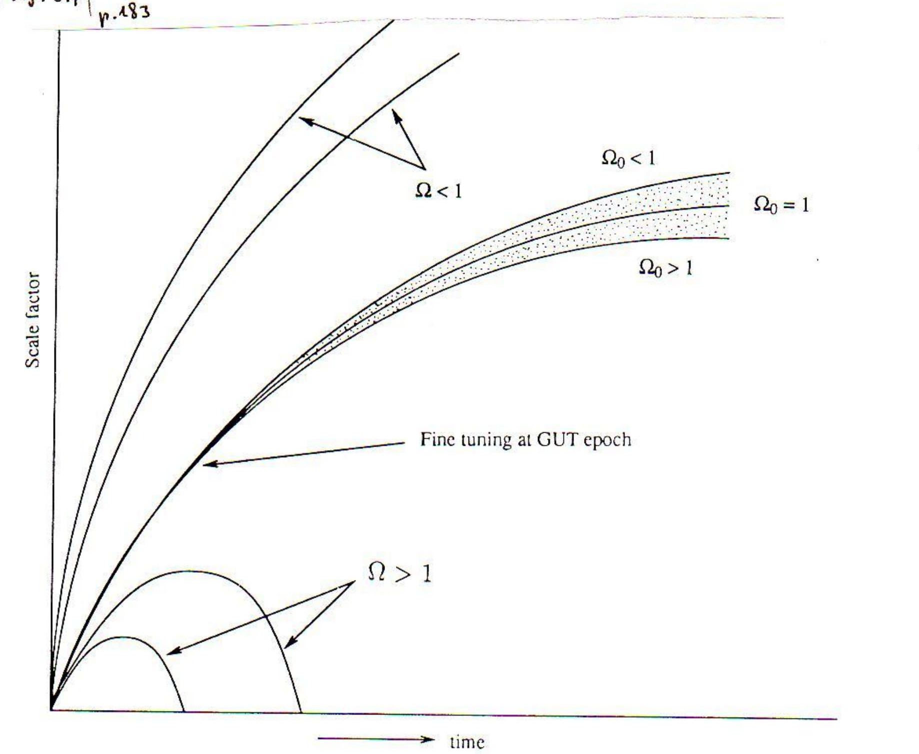
$$|\Omega-1| = \frac{|k|}{S^2H^2} \propto \begin{cases} t^{2/3} & \text{dominacija tvari} \\ t^{1/2} & \text{dominac. zračenja} \end{cases}$$

(opada u stand. evoluc. velikog praska)

pokazuje da Ω u prošlosti mora biti fino podešen

$$|\Omega-1| < \begin{cases} O(10^{-16}) & \text{u eri nukleosinteze } (t\sim1\,s) \\ O(10^{-27}) & \text{e-w skala } (t\sim10^{-11}\,s) \\ O(10^{-53}) & \text{GUT skala } (t\sim10^{-35}\,s) \\ O(10^{-61}) & \text{Planck skala } (t\sim10^{-44}\,s) \end{cases}$$

Narlikar Fig. 6.7 | p.183



3. PROBLEM:
PROBLEM STRUKTURA

- **Problem porijekla svega opaženog!**

  Modeli hladne tamne tvari (CDM) objašnjavaju kako fluktuacije u CMB rastu do formiranja galaktika
- **Preostaje objasniti odakle fluktuacije opažene u CMB-u**

Inflatorno rješenje problema struktura

- Prije inflacije: postoje kvantne fluktuacije
- Inflacija pojačava kvantne fluktuacije na makroskopske skale
- Nakon inflacije makroskopske fluktuacije (kakve su opažene u CMB zračenju) daju sjeme formiranja galaktika

JOŠ O INFLACIJI

- Da bi očuvali uspjehe modela velikog praska, epohu inflacije treba ograničiti na dovoljno ranu fazu svemira - povratak na normalnu jedn. stanja je kozmološki FAZNI PRIJELAZ
- 2. predviđanje inflacije – pozadinski gravitacijski valovi kao RELIKT dostupan misiji PLANCK-ova mjerenja
- Kandidati za pogonitelja inflacije?