

# Inflation, baryosynthesis and dark matter/energy

Lecture from the course  
« Introduction to  
cosmoparticle physics »

# Structure of visible Universe

$$1 \text{ pc} = 3.26 \text{ l.y.} = 3.086 \times 10^{18} \text{ cm}$$

$$M_{\text{Gal}} \sim 10^{11} M_{\text{Sun}}$$

Length scales:

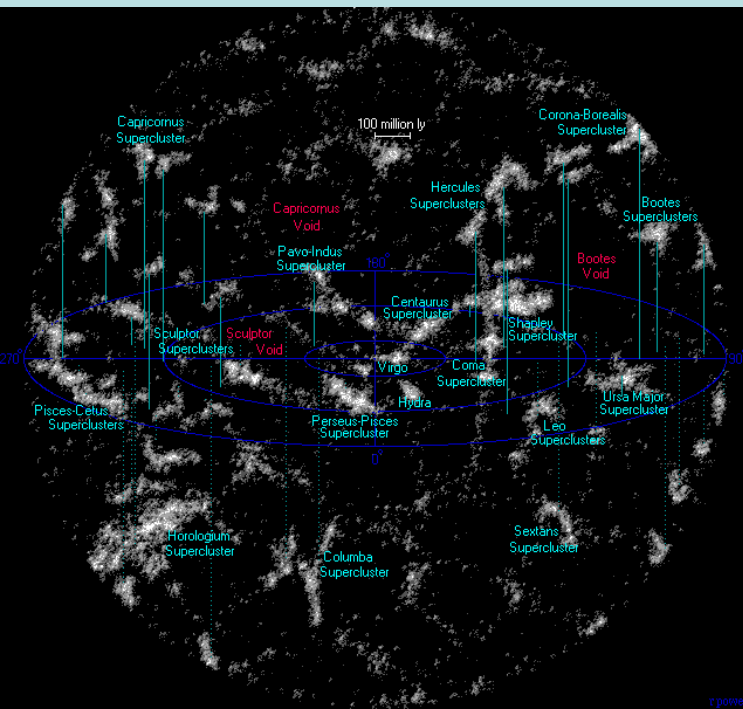
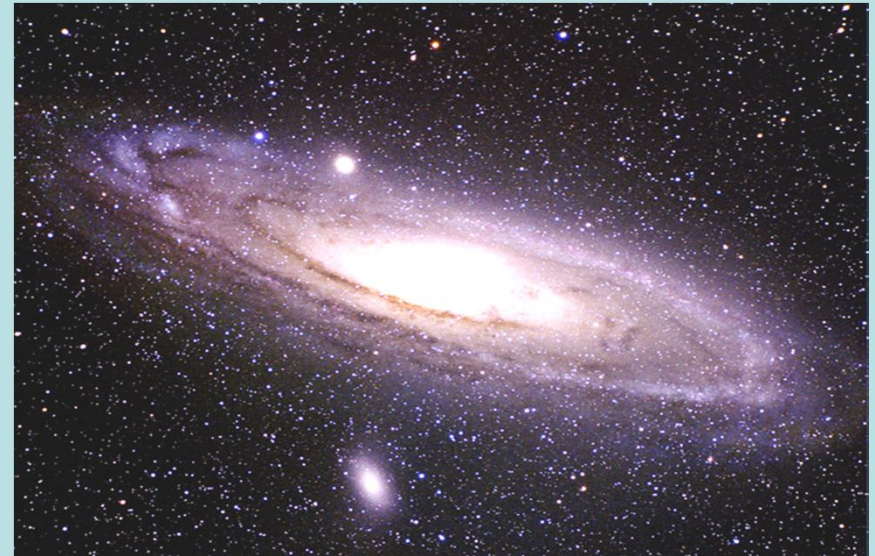
Galaxy -----  $\sim 30 \text{ kpc}$

Local group -----  $\sim 1\text{-}10 \text{ Mpc}$

Cluster -----  $\sim 100 \text{ Mpc}$

Universe\* -----  $\sim 5000 \text{ Mpc}$

\*) the size of visible part of Universe



At the scales  $\gg 100 \text{ Mpc}$ , the Universe looks **homogenous** and **isotropic**.

# The Hubble law

Galaxies have systematic **red shifts** of spectral lines, what can be interpreted due to Doppler effect as a recessional velocity (Vesto Slipher, 1912-1917):

$$z = \Delta\lambda/\lambda \cong v/c \quad (\text{for } v \ll c)$$

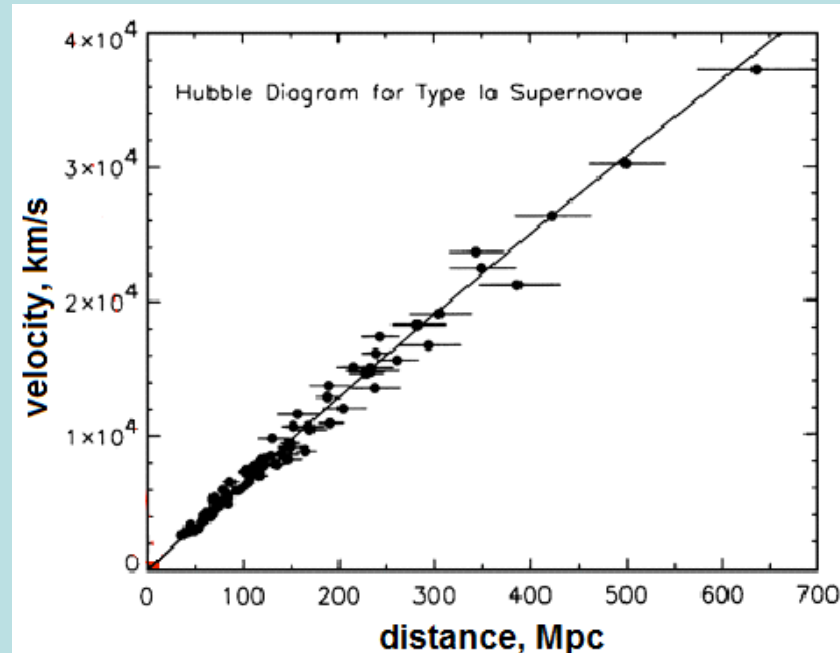
In 1929, **Edwin Hubble**, having determined the distances to the galaxies (“extra-Galactic nebulae”), revealed the law of galaxies recession:

$$v = H \cdot R$$

Modern measurements give

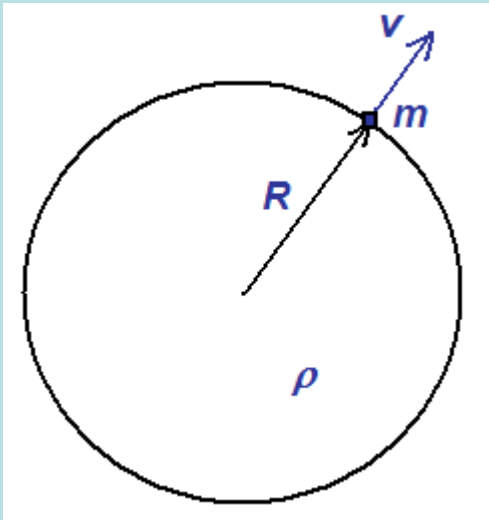
$$H = 74.2 \pm 3.6 \text{ (km/s)/Mpc}$$

Hubble's result was  $H = 576 \pm 6 \text{ (km/s)/Mpc}$



# The Critical Density

To understand an ultimate fate of Universe (whether or not expansion is infinite), let us determine the density, at which recession tends to zero at infinity



$$\begin{cases} \frac{mv^2}{2} = \frac{GMm}{R} \\ v = HR \\ M = \frac{4}{3}\pi R^3 \cdot \rho \end{cases}$$



$$\rho_{cr} = \frac{3H^2}{8\pi G}$$

$\rho > \rho_{cr}$  – expansion is finite, it must change by contraction (closed world)

$\rho < \rho_{cr}$  – expansion is infinite (open world)

$\rho = \rho_{cr}$  – expansion is infinite, but its rate tends asymptotically to zero (flat world)

# Expansion in General Relativity

GR (Einstein) equations

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

**Alexander Friedmann** obtained the equations of evolution of Universe from GR under suppositions of homogeneity and isotropy of Universe.

$$\begin{cases} \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left( \varepsilon + \frac{3p}{c^2} \right) + \frac{\Lambda c^2}{3} \\ \left( \frac{\dot{a}}{a} \right)^2 - \frac{8\pi G \varepsilon}{3} = -\frac{K c^2}{a^2} + \frac{2\Lambda c^2}{3} \end{cases} \quad H \equiv \frac{\dot{a}}{a}$$

Here  $a$  is the scale factor,  $\varepsilon$  and  $p$  are the energy density and pressure of matter respectively,  $K$  is the parameter of curvature.

# Equation of state

$$p = 0 \quad \text{- non-relativistic ("dust"-like) matter}$$

Compare  $p = nkT \sim \varepsilon_{kin} \ll mc^2 \cdot n = \varepsilon$

$$p = \frac{\varepsilon}{3} \quad \text{- (ultra)relativistic (radiation-like) matter}$$

$$p = -\varepsilon \quad \text{- vacuum-like matter (vacuum energy)}$$

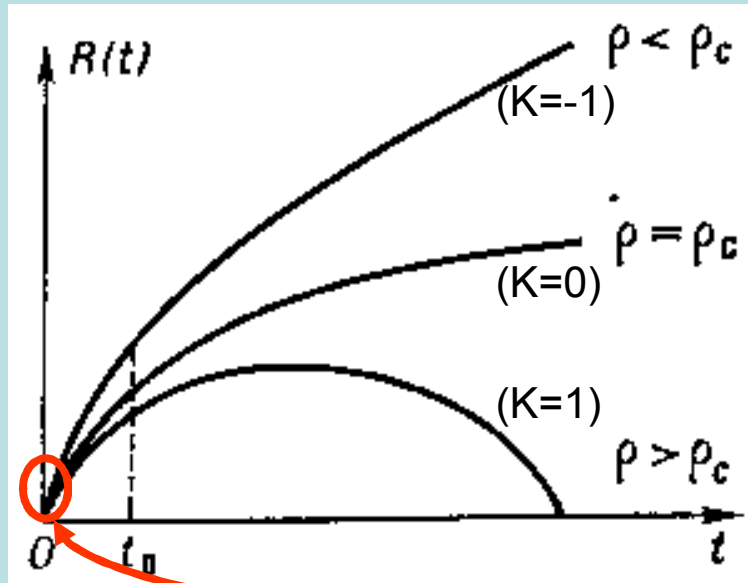
Here and further we use the units

$$\hbar = c = k = 1$$

# The Beginning of Expansion

$t \sim 1/H$  defines the age of the Universe – time from the beginning of expansion

$\Lambda=0$



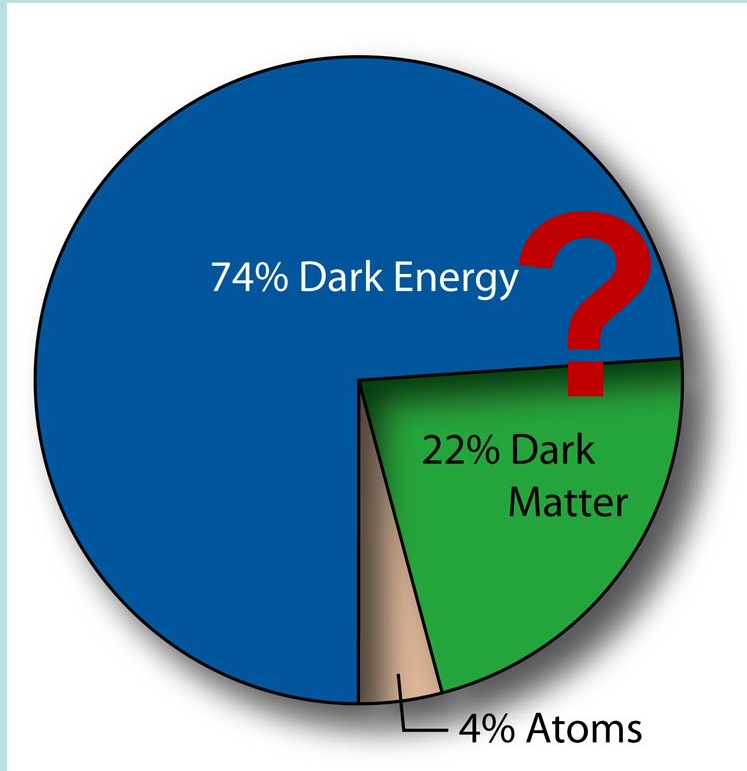
$$m_{Pl} = \sqrt{\frac{\hbar c}{G}} \approx 2 \cdot 10^{-5} \text{ g} \approx 1.2 \cdot 10^{19} \text{ GeV}$$

$$l_{Pl} = \sqrt{\frac{G \hbar}{c^3}} \approx 1.6 \cdot 10^{-33} \text{ cm}$$

$$t_{Pl} = \sqrt{\frac{G \hbar}{c^5}} \approx 0.5 \cdot 10^{-43} \text{ s}$$

$K=-1$  corresponds to open world,  $K=0$  to flat world and  $K=1$  to closed world. In the early Universe effects of curvature were negligible and the expansion was very close to flat model. Formally, the model is singular at  $t=0$ , but the classical description of space time is limited by Planck scales, at which quantum effects of gravity should be taken into account.

# The Modern Composition



$$\Omega \equiv \frac{\rho}{\rho_{cr}}$$

$$\Omega_b \approx 0.044 \quad \Omega_{\text{CMB}} \approx 0.5 \cdot 10^{-4}$$

$$\Omega_{\text{DM}} \approx 0.20$$

$$\Omega_{\Lambda} \approx 0.7$$

$$\Omega_{\text{tot}} \approx 1.0$$

In the modern Universe dominate dark energy and dark matter – their nature will be the subject of our analysis, which strongly involves the important role of a tiny component of CMB.

# Relic Radiation

Cosmic microwave background (CMB):

Planckian black body spectrum with

$$T=2.73 \text{ K}$$

$$n_\gamma=411 \text{ cm}^{-3}$$

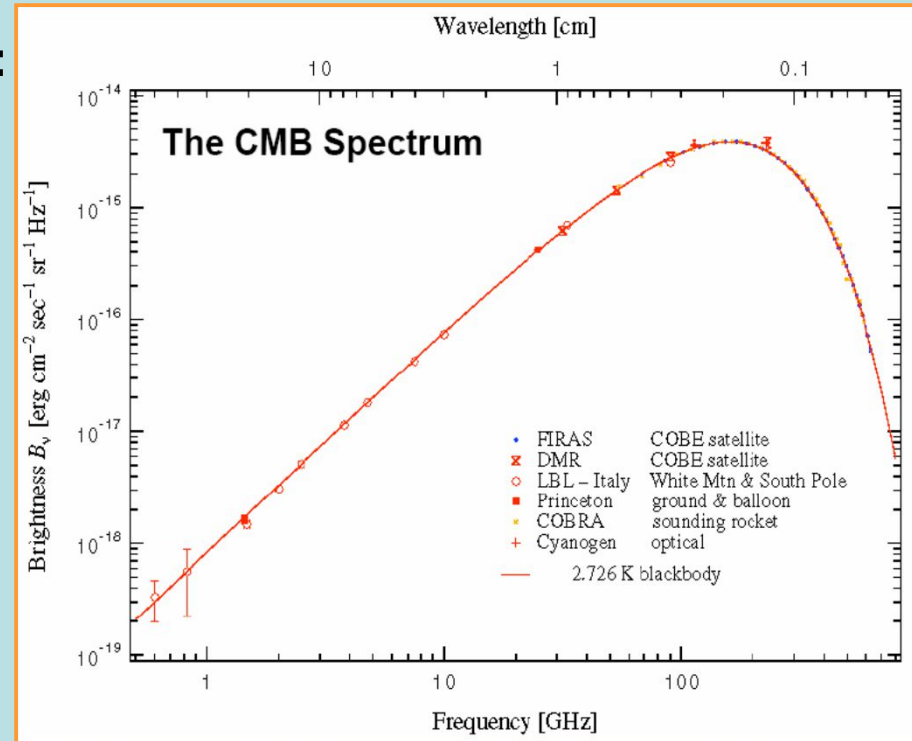
$$\delta T/T \sim 10^{-4}$$

$T$  is proportional to  $1/a$ .

Energy density of this radiation  $\sim 3Tn_\gamma$  was much larger in the early Universe.

For the fixed ratio of number densities of baryons (nucleons) and photons :

$n_b/n_\gamma \sim 0.6 \times 10^{-9}$  it means inevitable dominance of radiation over the baryonic matter in the early Universe



# Adiabatic Law of Expansion

From Friedmann's equations one can get

$$\dot{\varepsilon} = -3H(\varepsilon + p)$$

$$d(\varepsilon \cdot V) + p \cdot dV = 0 \quad \text{where } dV = d(a^3)/a^3 \cdot V = 3Hdt \cdot V$$

This means that expansion can be interpreted like adiabatic process ( $dQ=dU+dA=0$ ), what justifies application of respective laws of thermodynamics.

Going back in time, we come to denser and hotter matter. This trend can be followed up to Planck scales.

It was just this trend that made people to think about the early Universe as on a natural laboratory for super high energy physics.

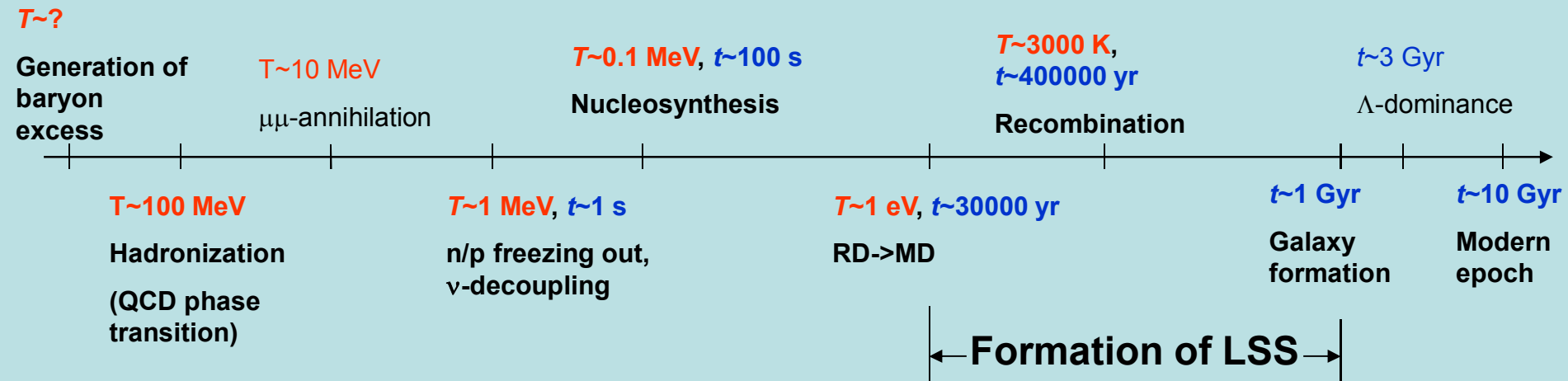
However, it turned out that the history of the Universe was much more complicated and inevitably involved super high energy physics as the basic elements of this history.

# Thermal History of Universe

The modern expansion of the Universe with relic radiation corresponds to the thermal history of its early hot stages, including:

- very early Universe ( $t < 1\text{s}$ ),
- Big Bang Nucleosynthesis (first three minutes),
- beginning of matter dominance and formation of Large Scale structure of Universe and galaxies

# Cosmochronology



# Freezing out of n/p ratio

The ratio between the numbers of  $n$  and  $p$  (of two energetic states of nucleon) is defined by thermodynamic relation while  $T > T_*$ .

$$\frac{n_n}{n_p} = \exp\left(-\frac{\Delta m}{T}\right), \quad \Delta m \equiv m_n - m_p = 1.29 \text{ MeV}$$

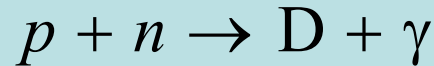
After  $T = T_*$  this ratio is frozen out at the magnitude

$$\frac{n_n}{n_p} = \exp\left(-\frac{\Delta m}{T_*}\right) \sim \frac{1}{6}$$

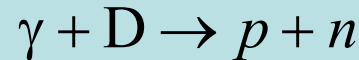
Afterwards, neutrons decay gradually until they are combined with protons into nuclei.

# Formation of deuterium

In order a simplest composite nucleus (deuteron) were synthesized in primordial plasma, the rate of reaction



might become higher than that of back reaction (photo-disintegration of deuteron)



The last rate exponentially falls down when the temperature becomes below the binding energy of deuteron,  $E_D = 2.2 \text{ MeV}$ , because photons from only a tiny tail of thermal distribution can do it.

So

$$n_\gamma(> E_D) \sim n_\gamma \cdot (E_D / T)^2 \exp(-E_D / T) \equiv n_\gamma \cdot f(> E_D)$$

$$\Gamma_{np \rightarrow D\gamma} = \Gamma_{D\gamma \rightarrow np},$$

$$\Gamma_{np \rightarrow D\gamma} = n_{n,p} \langle \sigma_{np \rightarrow D\gamma} v_{np} \rangle \sim \eta_B n_\gamma \cdot \langle \sigma v \rangle,$$

$$\Gamma_{D\gamma \rightarrow np} = n_\gamma(> E_D) \langle \sigma_{D\gamma \rightarrow np} v_{D\gamma} \rangle \sim f(> E_D) n_\gamma \cdot \langle \sigma v \rangle.$$



$$T \equiv T_D \sim E_D / \ln \left( \frac{400}{\eta_B} \right) \approx 0.1 \text{ MeV}$$

$$t_D \sim 100 \text{ s}$$

Here  $\eta_B = n_B / n_\gamma \sim 0.6 \times 10^{-9}$ .

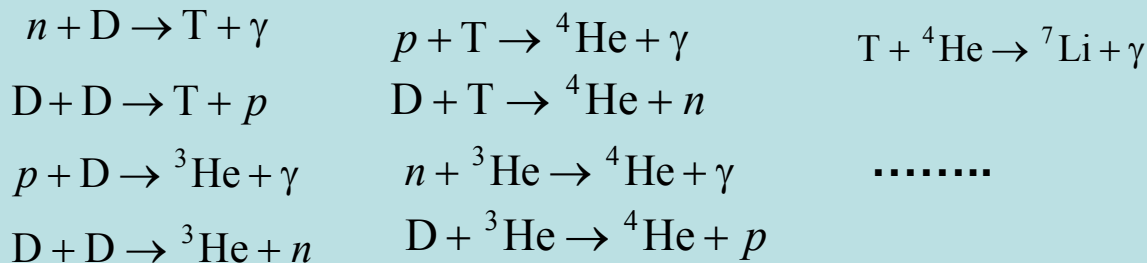
# Big Bang nucleosynthesis

During period between  $t_*$

$$\frac{n_n}{n_p} \equiv \frac{n}{p} \sim \frac{1}{7}$$

This ratio defines **total modern number of neutrons**.

Virtually all the neutrons hit into **helium-4** nuclei in the result of the successive chain of nuclei reactions (**BBN**)



Formation of heavier nuclei is suppressed because of **big Coulomb barrier**.

# Primordial chemical elements

All reactions had been going during  $\sim 100$  s, in the result of which a **primordial chemical composition** has been established, where the majority of **protons** and **neutrons** are distributed between **helium-4** and **hydrogen**:

$$\frac{\rho_{\text{H}}}{\rho_{\text{B}}} \approx \frac{1 - n/p}{1 + n/p} \approx 0.75$$

$$\frac{\rho_{\text{He}}}{\rho_{\text{B}}} \equiv Y_p \approx \frac{2(n/p)}{1 + n/p} \approx 0.25$$

$$\frac{n(\text{D})}{n(\text{H})} \sim 3 \cdot 10^{-5}; \quad \frac{n(\text{He}^3)}{n(\text{H})} \sim 10^{-5}$$

$$\frac{n(\text{Li}^7)}{n(\text{H})} \sim 10^{-10}; \quad \frac{n(\text{Li}^6)}{n(\text{H})} \sim 10^{-13}; \quad \frac{n(\text{Be}^9)}{n(\text{H})} < 10^{-17}$$

# Formation of LSS and galaxies (1)

**Large Scale Structure (LSS)** is supposed to form from small initial perturbations of density (inhomogeneities).

According to the theory of LSS formation,

- inhomogeneities, if they are, are preserved in form of sound waves at **RD-stage** (for particles being in equilibrium)

$$\frac{\delta\rho}{\rho} \approx \text{const}$$

- inhomogeneities grow at **MD-stage** (for non-relativistic particles), according to Lifshits's theory for **expanding Universe**, following to a linear law

$$\frac{\delta\rho}{\rho} \propto a \propto t^{2/3} \quad \text{until} \quad \frac{\delta\rho}{\rho} \ll 1$$

# Formation of LSS and galaxies (2)

- when  $\delta\rho/\rho \sim 1$  is reached, evolution of inhomogeneity separates from common cosmological expansion and follows to a non-linear law (“object has been formed”);
- no inhomogeneity of the size  $>$  horizon  $= ct$ , if it is, changes;
- no inhomogeneity of the size  $<$  length of free streaming path of particles survives (they are washed out).

Before **recombination**, no baryon inhomogeneities could grow since this process is prevented by the pressure of relativistic gas of photons (they exist in form of “sound”).

From observational data on an **anisotropy** of CMB we have

$$\left. \frac{\delta\rho_B}{\rho_B} \right|_{\text{at recombination}} \sim 3 \frac{\delta T}{T} \sim 10^{-4}$$

# The problems of the old Big Bang Cosmology

- Magnetic Monopole overproduction has instigated critical analysis of the old Big Bang scenario.
- The problems of initial state, horizon, flattness, of the origin of primordial fluctuations and of the origin of baryon excess appealed to the change of scenario of very early Universe.
- Problems of « virial paradox » in galaxy clusters, of « hidden mass » of galaxies and of galaxy formation together with the observed deficit of baryons imply the existence of nonbaryonic dark matter.
- The data on SNIa, LSS and CMB together with the measured value of Hubble constant favour the existence of dark energy – dominance of vacuum energy in the modern Unvierse, leading to its accelerated expansion.
- The solution of these problems lead to the modern cosmology

# Magnetic monopoles in GUTs

Dirac suggested an existence of magnetic monopole with magnetic charge

$$g = (2e)^{-1}$$

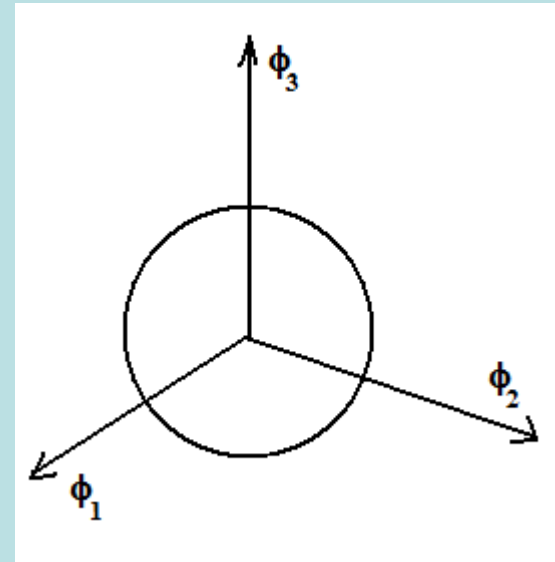
as condition of quantization of electric charge.

T'Hooft and Polyakov have shown, that in GUT models, where  $U(1)_{e/m}$  symmetry is included to  $SU(3)$  or wider symmetry, magnetic monopole must appear in the result of spontaneous breaking of GUT symmetry as a topological defect of respective Higgs' field. The mass of monopole are predicted to be

$$m_M \sim \Lambda_{\text{GUT}} / \sqrt{\alpha} \quad (\Lambda_{\text{GUT}} \sim 10^{15} \text{ GeV})$$

# Formation of magnetic monopoles

In the isotopic space of Higgs' field, the minimum of potential corresponds to sphere. At the sphere, Higgs' field can be defined by angles  $\theta$  and  $\varphi$ .



After phase transition (violation of  $SO(3)$  symmetry), at  $T < T_{cr} \sim v$ , Higgs' field acquires vacuum expectation value. In all (coordinate) space  $\phi$  gets the value  $v$  and different magnitudes of  $\theta$  and  $\varphi$ , which vary within the length scale

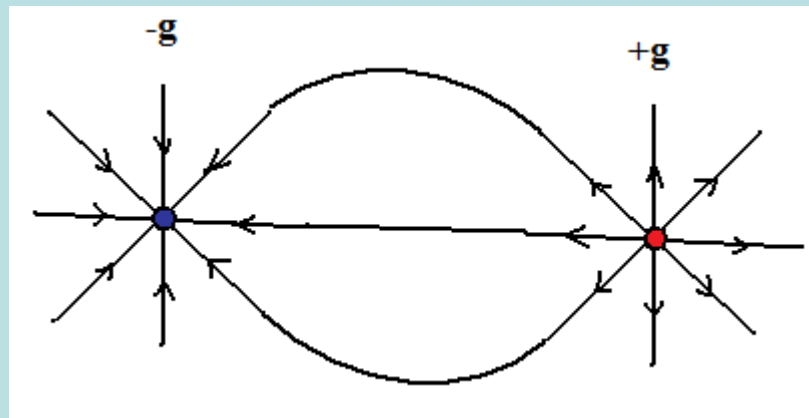
$$\Delta l \sim \frac{1}{ev}$$

However, it is not possible for  $\theta$  and  $\varphi$  to vary continuously over  $2\pi$  and not to get a singularity – the point where  $\theta$  and  $\varphi$  are indefinite (like a pole on globe, “one cannot brush a hedgehog”).

# Magnetic monopole pairs

Such a singularity is topological defect – monopole. Its size is defined by  $\Delta l$ . In its center  $\phi=0$ , it corresponds to non-zero energy density of  $\phi$  (outside of minimum) – mass, pointed previously.

Gradients of  $\theta(\mathbf{x})$  and  $\phi(\mathbf{x})$ , issuing from singularity, define intensity of magnetic field. This is accounted for by the fact that the field  $\phi$  is connected with gauging of electromagnetic field. Singularity, where gradients of  $\theta(\mathbf{x})$  and  $\phi(\mathbf{x})$  come to, corresponds to an antimonopole.



# Diffusion of magnetic monopoles

Two charge particles (with magnetic charge  $g$ ) feel each other in plasma at distance when

$$\frac{g^2}{r} \sim E \sim T \quad \longrightarrow \quad r \sim r_0 \equiv \frac{g^2}{T}$$

Diffusive approximation is proved by condition

where  $\lambda \sim \frac{1}{n_a \sigma} \sim \frac{1}{T^3} \frac{Tm}{(ge)^2} \sim \frac{m}{T^2 (ge)^2}$  is the scattering length.  $\lambda \ll r_0$

In this case annihilation rate is defined as

$$\frac{dn_M}{dt} = -n_M^2 4\pi D r_0$$

where  $D = \frac{1}{3} \lambda v$  is diffusion coefficient.

# Magnetic monopole overproduction

Finally, for monopole relic density one finds

$$\Omega_M \sim m \frac{m}{g^5 (eg) m_{Pl}} \frac{n_\gamma^{(\text{mod})}}{\varepsilon_{cr}} \sim 10^{15} \left( \frac{\Lambda_{GUT}}{10^{15} \text{ GeV}} \right)^2$$

That is conclusion does not change in principle, the [problem of overproduction](#) of magnetic monopoles remains. In fact, diffusion slows down annihilation rate with respect to direct annihilation (in approximation of free monopole motion) and more monopoles should survive.

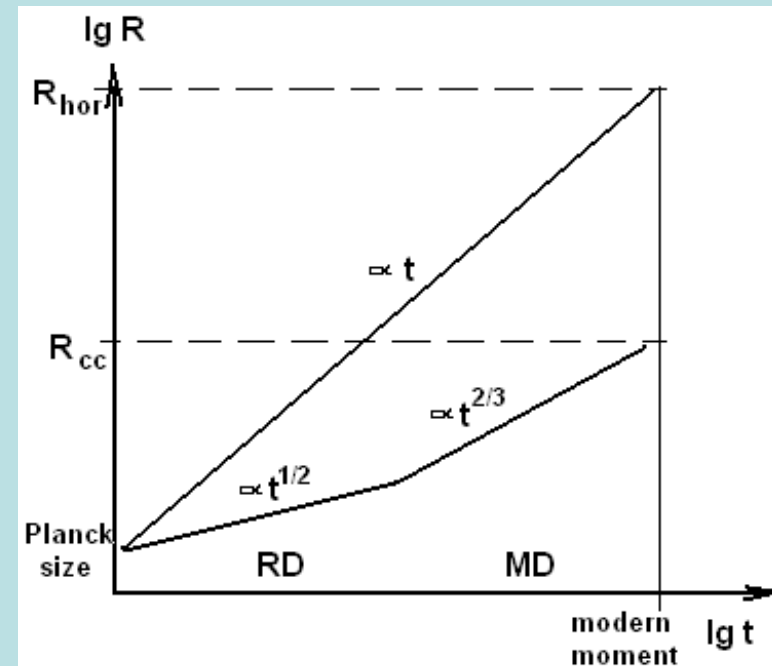
**This problem either excludes magnetic monopole with given properties, or implies completely different conditions in very early Universe.**

# The horizon problem

- Initially causally-connected region grows slower (as scale factor being  $\sim t^{1/2}$  at RD stage,  $\sim t^{2/3}$  at MD-stage) than horizon  $R_{\text{hor}} \sim ct$ . So  $10^{88}$  regions, initially causally-disconnected at Planck time, are inside modern horizon, while the observed conditions in them are very similar.

$$\left( \frac{R_{\text{hor}}^{(\text{mod})}}{R_{\text{cc}}^{(\text{mod})}} \right)^3 = \left( \frac{l_{\text{Pl}} \cdot t_{\text{mod}} / t_{\text{Pl}}}{l_{\text{Pl}} \cdot a_{\text{mod}} / a_{\text{Pl}}} \right)^3 \sim \left( \frac{t_{\text{mod}} / t_{\text{Pl}}}{T_{\text{Pl}} / T_{\text{mod}}} \right)^3 \sim$$

$$\sim \left( \frac{5 \cdot 10^{17} \text{s} / 0.5 \cdot 10^{-43} \text{s}}{1.2 \cdot 10^{19} \text{GeV} / 2.7 \text{K}} \right)^3 \sim 10^{88}$$



# The flatness problem

**Flatness:** the curved Universe initially must be extremely close to flat. At Planck time  $\Omega$  should be as close to unit as  $10^{-59}$ .

In fact, from Friedman's equations for total density one can get

$$\Omega - 1 = \frac{K}{\dot{a}^2} \propto K \cdot \begin{cases} t \propto a^2 & \text{at RD-stage,} \\ t^{2/3} \propto a & \text{at MD-stage.} \end{cases}$$

$$\Omega \equiv \frac{\mathcal{E}}{\mathcal{E}_{cr}}$$

$$\Omega_{Pl} - 1 \approx (\Omega_{mod} - 1) \left( \frac{T_{Pl}}{T_{RD}} \right)^2 \frac{T_{RD}}{T_{mod}} \sim 10^{-59} (\Omega_{mod} - 1)$$

Note: closeness of Universe to flat in the past justifies the use of adopted approximation ( $K=0$ ) in description of its evolution (for RD- and MD-stages).

# The problem of initial fluctuations

- **Initial inhomogeneities:** the amplitude of density fluctuations cannot be explained stochastically and should be put “by hands” in old cosmology framework.
- In fact, data on anisotropy of CMB tells that initial fluctuations (of baryonic matter) were of the order of

$$\frac{\delta\varepsilon}{\varepsilon} \sim 10^{-4}$$

While, statistical fluctuations for galactic cluster are of the order of

$$\frac{1}{\sqrt{N_{\text{atoms}}}} \sim \frac{1}{\sqrt{10^{68}}} \sim 10^{-34}$$

# The problem of baryon excess

If there were equality between baryons (nucleons) and antibaryons then we had (roughly)

$$n_B^* = \frac{H^*}{\langle \sigma_{\text{ann}} v \rangle}$$

$$T_* \sim m_N / 10 \approx 100 \text{ GeV}$$

$$n_B^{\text{mod}} = n_B^* \left( \frac{a_*}{a_{\text{mod}}} \right)^3 = \frac{H^*}{\langle \sigma_{\text{ann}} v \rangle} \cdot \frac{n_\gamma^{\text{mod}}}{n_\gamma^*} \frac{\kappa_s^{\text{mod}}}{\kappa_s^*} \sim \left( \begin{array}{l} H^* \sim m_{\text{Pl}}^{-1} T_*^2 \\ n_\gamma^* \sim T_*^3 \\ \langle \sigma_{\text{ann}} v \rangle \sim m_\pi^{-2} \end{array} \right) \sim 10^{-20} n_\gamma^{\text{mod}}$$

More accurate estimation gives  $10^{-18}$ .

While we observe  $n_B^{\text{mod}} \approx 0.6 \cdot 10^{-9} n_\gamma^{\text{mod}}$

Approximately the same takes place for leptons (electrons).

# The problem of baryons' deficit

**Estimation of baryonic density:** estimations of the modern density of baryons (ordinary matter) show that visible baryons correspond to about  $\frac{1}{4}$  of total baryon density. The total baryon density does not exceed 0.04 of critical density.

In fact, observations give for visible baryons

$$\Omega_{B \text{ visible}} \sim 0.01$$

Cosmological analysis of chemical composition and of CMB anisotropy give for total baryon density

$$\Omega_{B \text{ tot}} \sim 0.044(4)$$

# The problem of dark matter

Estimation of density of matter in galaxies: the matter concentrated in galaxies (referred below to as “matter”) composes

$$\Omega_m \sim 0.22(3)$$



The hidden mass of galaxy clusters.

In fact, as early as 1933, F.Zwicky observed Coma cluster of galaxies and concluded according virial theorem that  $M/L \sim 100 M_{\text{Sun}}/L_{\text{Sun}}$ .

It cannot be ascribed to intergalactic gas. Temperature of this gas confirms the “virial paradox”.

Gravitational lensing measures the total mass of clusters.

# The bedrocks of modern cosmology

Our current understanding of structure and evolution of the Universe implies three necessary elements of Big Bang cosmology that can not find physical grounds in the standard model of electroweak and strong interactions. They are:

- Inflation
- Baryosynthesis
- Dark matter/energy

# Friedman's equations

$$\left\{ \begin{array}{l} \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left( \varepsilon + \frac{3p}{c^2} \right) \\ \left( \frac{\dot{a}}{a} \right)^2 - \frac{8\pi G \varepsilon}{3} = -\frac{Kc^2}{a^2} + \frac{\Lambda c^2}{3} \end{array} \right.$$

$\Lambda$ -term is equivalent to the matter with vacuum-like equation of state (E.Glinner 1965, Ya.Zeldovich 1968):

$$p = -\varepsilon = -\frac{\Lambda}{8\pi G}$$

$$m_{\text{Pl}} = \sqrt{\frac{\hbar c}{G}} \approx 2 \cdot 10^{-5} \text{ g}$$

$$l_{\text{Pl}} = \sqrt{\frac{G \hbar}{c^3}} \approx 1,6 \cdot 10^{-33} \text{ cm}$$

$$t_{\text{Pl}} = \sqrt{\frac{G \hbar}{c^5}} \approx 0,5 \cdot 10^{-43} \text{ s}$$

$$\hbar = c = 1$$

$$\varepsilon_{\text{cr}} = \frac{3H^2}{8\pi G} \quad H \equiv \frac{\dot{a}}{a}$$

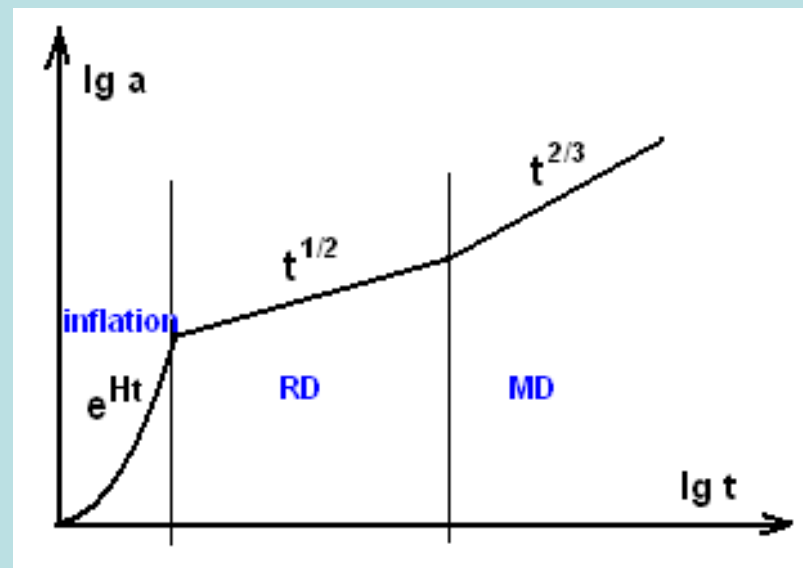
$$\text{If } p < -\frac{\varepsilon}{3} \quad \Rightarrow \quad \ddot{a} > 0$$

# Prerequisites for inflation

From Friedman's equations we have:

$$a(t) \propto \exp\left(\int H dt\right)$$

$$H = \sqrt{8\pi G \varepsilon / 3}$$



E.Gliner, I.Dymnikova 1965, 1975: vacuum-like state of matter ( $p=-\varepsilon$ )

A.Bugrii and A.Trushevsky (1976) indicated the possibility of an exponential stage of expansion at the hadronic stage,

A.Starobinsky 1979, 1980: realization due to quantum corrections in  $R$

A.Guth 1981: realization due to scalar field and solution of cosmological problems (introduction of term "inflation")

# Solution for cosmological problems

Exponential expansion provides solution for the problems of singularity:

In the period of inflation  $\varepsilon \neq \infty$

initial state:

$$H_0 = (8\pi G\varepsilon/3)^{1/2}$$

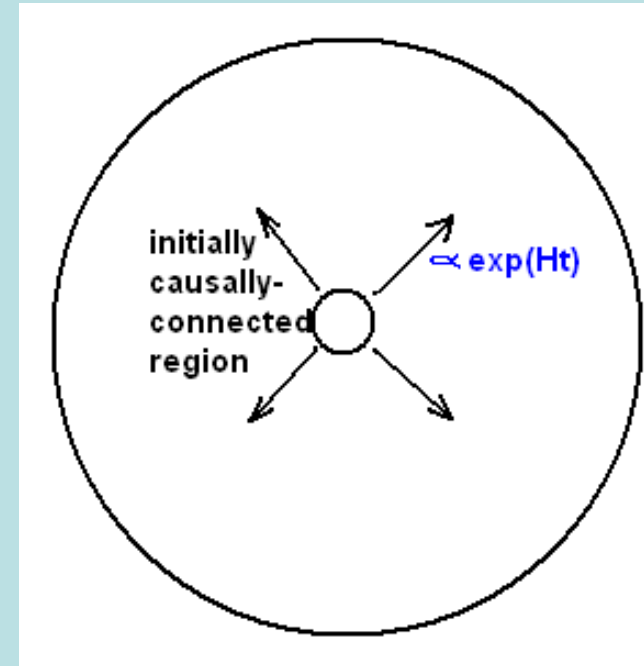
For instance, if inflation began at Planck time and finished in GUT era

$$\begin{aligned} \varepsilon &\sim m_{\text{Pl}}^4 & t_{\text{оконч. инфляц.}} &\sim t_{\text{GUT}} \sim \Lambda_{\text{GUT}}^{-1} \\ a(t_{\text{GUT}}) / a(t_{\text{Pl}}) &\propto \exp(H \cdot \Delta t) \sim \exp\left(\sqrt{8\pi G\varepsilon/3} \cdot t_{\text{GUT}}\right) \sim \exp(m_{\text{Pl}} / \Lambda_{\text{GUT}}) \sim e^{10000} \end{aligned}$$

# Solution for problem of magnetic monopoles

Problem of magnetic monopole overproduction:

if monopoles are produced before the end of inflationary stage  
 $\Rightarrow n \sim 1/a^3 \sim \exp(-3Ht) \rightarrow 0$



# Inflation

Scalar field

$$L = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi)$$



$$\begin{cases} \cancel{\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0} \\ H^2 = \frac{8\pi G}{3} \left( \cancel{\frac{\dot{\phi}^2}{2}} + V \right) - \cancel{\frac{K}{a^2}} \end{cases}$$

$$\varepsilon = \frac{\dot{\phi}^2}{2} + V, \quad p = \frac{\dot{\phi}^2}{2} - V$$

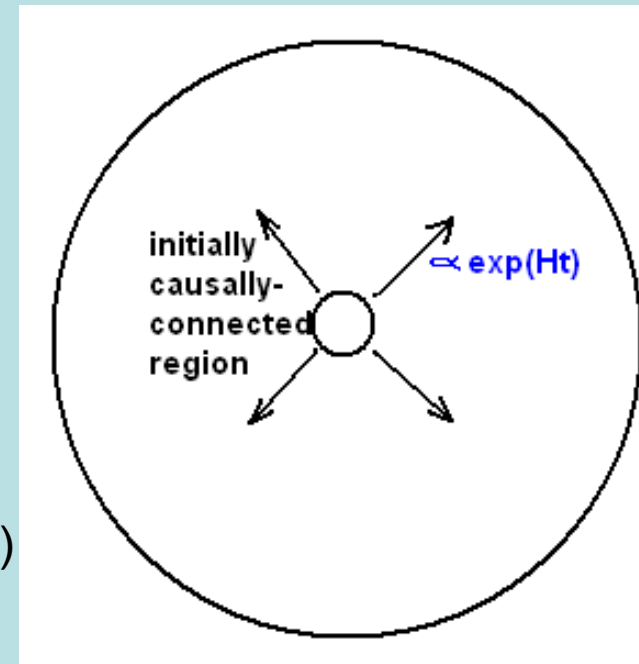
If  $\dot{\phi}^2 \ll V \Rightarrow p \cong -\varepsilon$

Exponential expansion, accounted for by this equation of state, would resolve the problems of

*horizon*

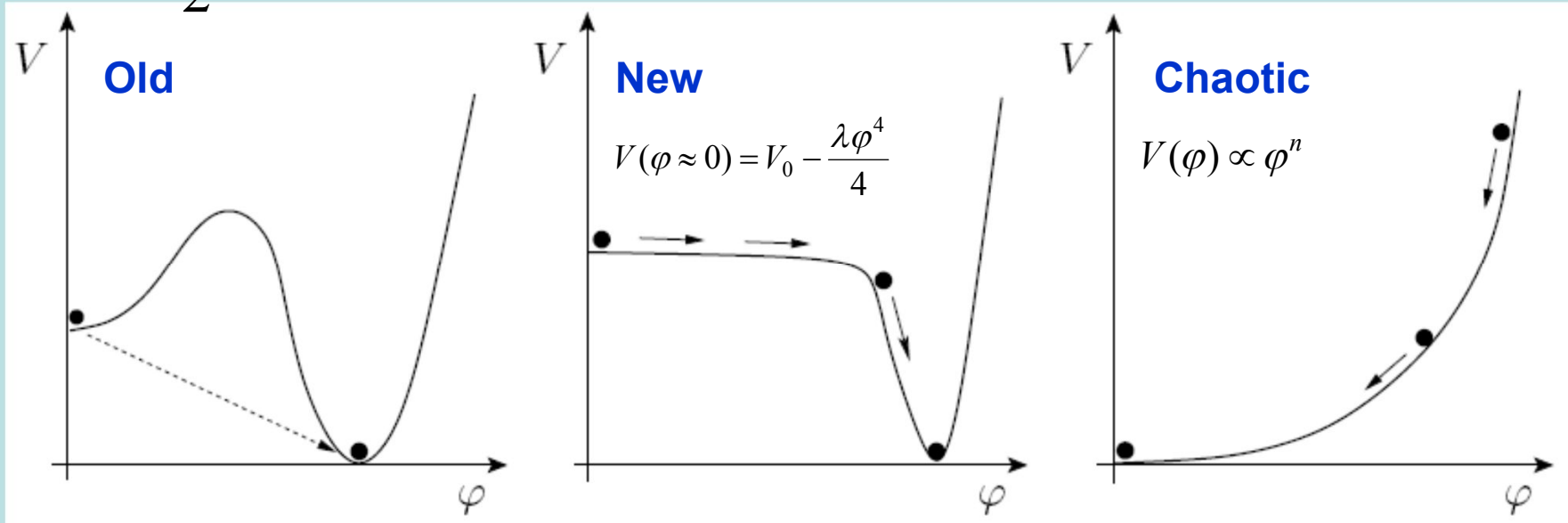
*flatness.*

$$\left( \frac{\dot{a}}{a} \right)^2 - \frac{8\pi G \varepsilon}{3} = -\frac{Kc^2}{a^2} \quad (\text{or } \Omega - 1 = \frac{K}{\dot{a}^2} \rightarrow 0)$$



# "Old", "New" and Chaotic Inflation

$$L = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi)$$



A.Guth (1981)

- Phase transition of GUT (**due to tunneling**)
- Too large inhomogeneities
- Problem of before-inflation conditions

A.Albrecht, P.Steinhardt (1982),  
A.Linde (1982)

- Phase transition of GUT (**slow rolling down**)
- Fine-tuning of parameters:  $\lambda \sim 10^{-12}$
- Problem of before-inflation conditions

A.Linde (1983)

\*Quantum fluctuations

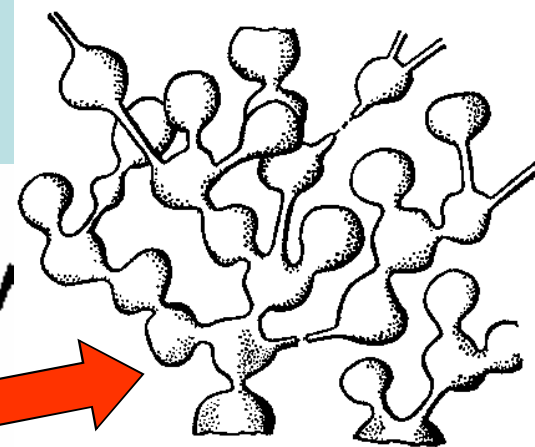
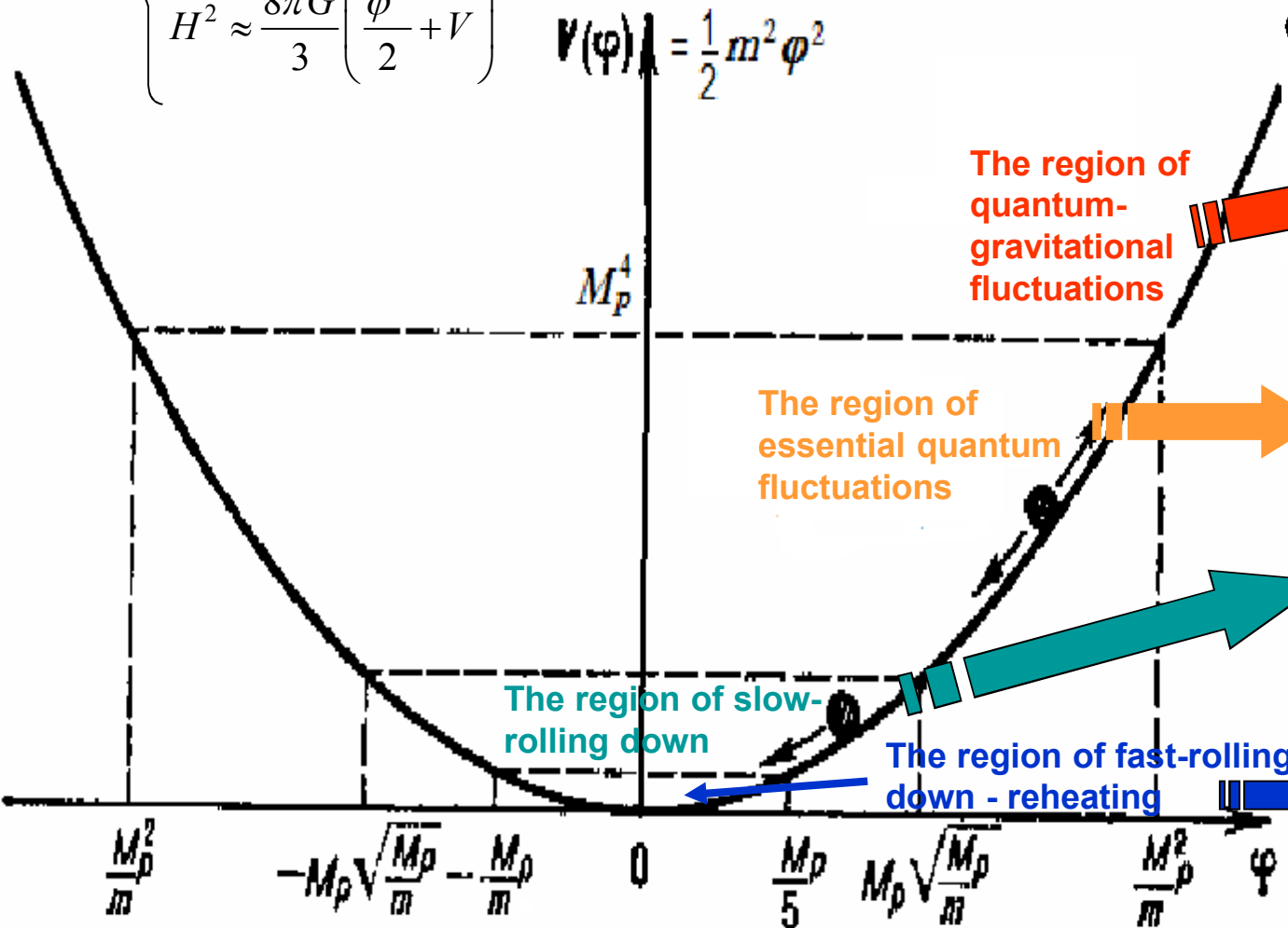
# Chaotic/eternal inflation

“friction” provides slow rolling down

$$\begin{cases} \ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0 \\ H^2 \approx \frac{8\pi G}{3} \left( \frac{\dot{\phi}^2}{2} + V \right) \end{cases}$$

$$a \propto \exp(2\pi\phi^2 / m_{\text{Pl}}^2)$$

$$V(\phi) = \frac{1}{2} m^2 \phi^2$$



“Multiverse”

“Eternal” inflation

LSS requires:

$$m \sim 10^{-6} m_{\text{Pl}}$$

$$\begin{aligned} \kappa\sigma T_R^4 &= V(\phi \sim m_{\text{Pl}}/5) \\ T_R &\sim 10^{10-16} \text{ GeV} \end{aligned}$$

# The bedrocks of modern cosmology

Our current understanding of structure and evolution of the Universe implies three necessary elements of Big Bang cosmology that can not find physical grounds in the standard model of electroweak and strong interactions. They are:

- Inflation
- Dark matter/energy
- Baryosynthesis

The latter (Baryosynthesis) is the topic of our discussion today

# Baryosynthesis

To explain the origin of the observed baryonic matter together with the absence of the symmetric amount of antimatter in the Universe one should assume an initial excess of baryons, which is retained after baryon-antibaryon annihilation (at  $\sim 1$  ms).

Excess of baryons, as A.D.Sakharov (1967) and then V.A.Kuzmin (1970) supposed, was generated from baryon-symmetric matter in early Universe due to processes, satisfying conditions:

- 1)  $\Delta B \neq 0$
- 2)  $CP \neq 1$
- 3) out of equilibrium

# Baryosynthesis: GUT

In the framework of **GUT** the following scenario is possible.

Let us assume existence of superheavy particles and antiparticles (leptoquarks) which had been present in the early Universe in the equal amounts:

$$X, \quad \bar{X}$$

Let us assume that their decay was out of equilibrium, i.e. was irreversible (for this one needs  $\Gamma_X \ll H$ ), with violation of baryon/lepton number and CP-parity:

$$\begin{array}{ll} X \rightarrow qq, & r \\ X \rightarrow \bar{q}l, & 1-r \end{array} \quad \begin{array}{ll} \bar{X} \rightarrow \bar{q}\bar{q}, & \bar{r} \\ \bar{X} \rightarrow q\bar{l}, & 1-\bar{r} \end{array}$$

Here  $r$  is branching ratio of respective decay channels. Inequality  $r \neq \bar{r}$  is provided by CP-violation, while the total width of particle and antiparticles should be equal due to CPT theorem.

# Baryosynthesis: GUT

In the result of decays of leptoquarks we get baryon asymmetry as large as

$$n_B - n_{\bar{B}} \propto (r - \bar{r})n_X$$

In SU(5) GUT model there is a rule for baryon and lepton numbers:

$$\mathbf{B - L=0}$$

It turns out that the conservation of baryon and lepton numbers can be also violated in the Standard model at high temperatures.

# Baryosynthesis: electroweak model

In the framework of electroweak model the following scenario is possible (V.Kuzmin,V.Rubakov, M.Shaposhnikov, 1985).

Baryon and lepton numbers are not conserved at high temperature ( $T > 175$  GeV) due to so call sphaleron processes. These processes satisfy condition

$$B+L=0$$

Under condition of non-homogeneity of EW phase transition (in space), a non-equilibrium conditions are realized at boundary region of different phases. CP-violation is introduced in theory explicitly, on the base of experimental data. So all Sakharov's conditions can be satisfied in the Standard model too.

**However**, 1) degree of CP-violation is too small, 2) for realization of necessary non-equilibrium conditions, the mass of Higgs boson is required to be too small (about 50 GeV), being inconsistent with modern data.

**Baryosynthesis in Universe can not be realized without going beyond the standard electroweak model,**

\* **Note**: electroweak physics prevents to create baryon excess by the mechanism of SU(5) GUT model.

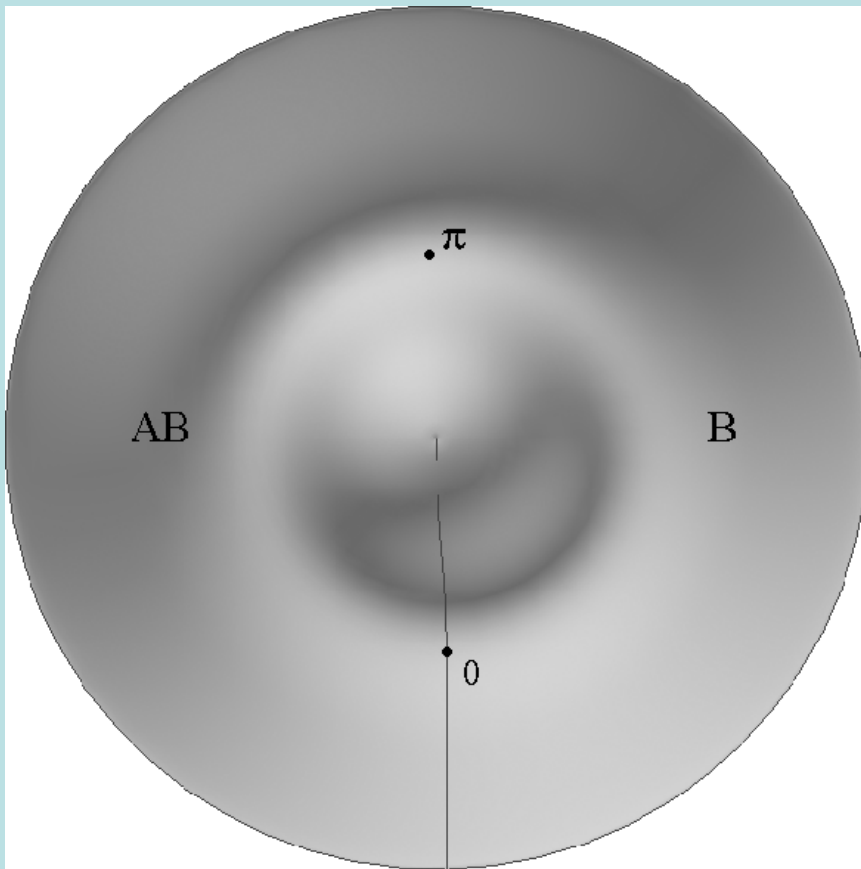
# Baryosynthesis: SUSY model

In the framework of supersymmetry (SUSY) the following scenario is possible (I.Affleck, M.Dine 1985, Linde 1985).

Conservation of baryon and lepton numbers are not required in supersymmetry as well as in electroweak model. Moreover, some superpositions of scalar fields (of SUSY partners of ordinary quarks and leptons) that possess non-zero baryon/lepton numbers can have a wide range of energetically equivalent nonzero amplitudes (their potential is flat until supersymmetry is not broken). So, these fields can get arbitrary initial amplitudes with nonzero B and L. After SUSY breaking, a condensate of respective scalar particles appears. It decays afterwards, producing baryon (and lepton) excess.

This mechanism is analogous to one of the mechanisms of axion production in early Universe. Two stages take place: violation of  $U(1)_{PQ}$  and axion field gets energetically equivalent, arbitrary magnitudes; then QCD phase transition removes energetic degeneracy [ $\sim$ SUSY breaking] and condensate appears. If the first step of symmetry breaking takes place on inflationary stage and the B and L non-conserving channels of decay for the field are possible, **spontaneous baryosynthesis** can take place.

# Spontaneous baryosynthesis



Model of spontaneous baryosynthesis

$$L = -\frac{f^2}{2}\partial_\mu\theta\partial^\mu\theta + i\bar{Q}\gamma^\mu\partial_\mu Q + i\bar{L}\gamma^\mu\partial_\mu L \\ -m_Q\bar{Q}Q - m_L\bar{L}L + \left(\frac{g}{\sqrt{2}}f\bar{Q}L + h.c.\right) + \partial_\mu\theta\bar{Q}\gamma^\mu Q$$

leads to generation of baryon excess in the rolling of the field to the state of minimum of its potential

Sufficiently large domains of antimatter survive to the present time

# Baryosynthesis from leptogenesis: in model of Majorana neutrino mass

In see-saw mechanism of Majorana neutrino mass we have two neutrino states: light left-handed Majorana neutrino, and heavy right-handed one ( $N_R$ ).

Baryosynthesis can be realized with the help of  $N_R$  analogously to mechanism in GUT model in combination with mechanism in electroweak model.

- 1)  $N_R$  decays with violation of  $L$  and  $CP \Rightarrow L$ -synthesis (like  $B$ -synthesis in GUT)
- 2) Synthesized lepton number is re-distributed between  $B$  and  $L$  due to sphaleron processes (with  $B+L=0$ )

# Baryosynthesis from transitions between ordinary and mirror particles

- If there are transitions between ordinary and mirror particles  $O \leftrightarrow M$ , nonequilibrium character of such transitions can lead to generation of excess of baryons, which is related with excess of mirror « antibaryons » (Berezghiani et al).

It is not the complete list of models for possible origin of baryon asymmetry of the Universe. The problem is to make a choice between them and special methods of cosmoparticle physics are developed to probe these ideas.

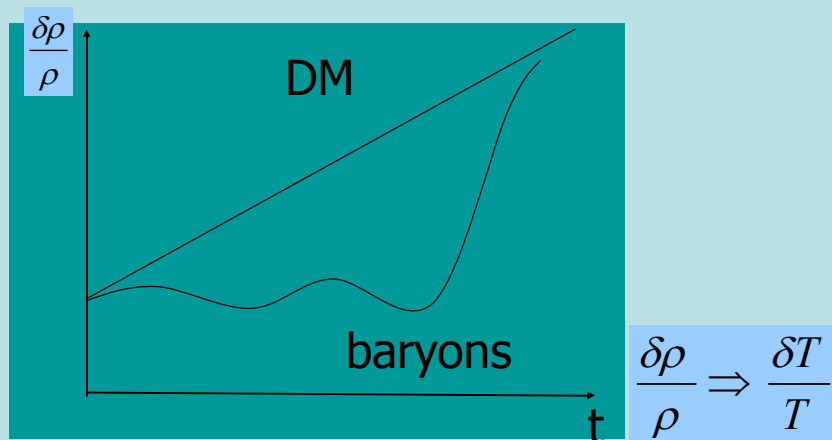
# The bedrocks of modern cosmology

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- Dark matter/energy

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# Cosmological Dark Matter



**Cosmological Dark Matter explains:**

- virial paradox in galaxy clusters,
- rotation curves of galaxies
- dark halos of galaxies
- effects of macro-lensing

**But first of all it provides formation of galaxies from small density fluctuations, corresponding to the observed fluctuations of CMB**

To fulfil these duties Dark Matter should interact sufficiently weakly with baryonic matter and radiation and it should be sufficiently stable on cosmological timescale.

Baryon density estimated from the results of BBN (mainly from Primordial deuterium) is not sufficient to explain the matter content of the modern Universe

# **Dark Matter – Cosmological Reflection of Microworld Structure**

**Dark Matter should be present in the modern Universe, and thus is stable on cosmological scale.**

**This stability reflects some Conservation Law, which prohibits DM decay.**

**Following Noether's theorem this conservation law should correspond to a (nearly) strict symmetry of microworld.**

# Dark Matter from Elementary Particles

By definition Dark Matter is non-luminous, while charged particles are the source of electromagnetic radiation. Therefore, neutral weakly interacting elementary particles are usually considered as Dark Matter candidates. If such neutral particles with mass  $m$  are stable, they freeze out in early Universe and form structure of inhomogeneities with the minimal characteristic scale

$$M = m_{Pl} \left( \frac{m_{Pl}}{m} \right)^2$$

- However, if charged particles are heavy, stable and bound within neutral « atomic » states they can also play the role of specific composite Dark matter (Dark atoms).
- Physical models, underlying dark matter scenarios, their problems and nontrivial solutions as well as the possibilities for their test will be the subject of the successive talks.

# Stable DM models

For weakly interacting particles that were in equilibrium, the scale of structure is in the inverse dependence on mass of particles:

- Hot Dark Matter (HDM) – particles with mass of tens eV (scale of superclusters)
- Cold Dark Matter (CDM) – particles with mass, exceeding GeVs (planet scale – biasing)
- Warm Dark Matter (WDM) – particles with mass few keV (scale of galaxies)

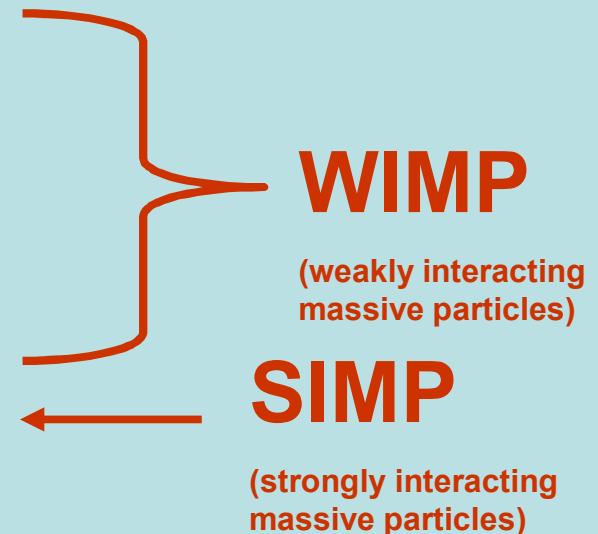
# Unstable DM models

For metastable particles the necessary condition to form the structure is to have lifetime, exceeding the time of structure formation :

- Unstable Dark Matter (UDM) – particles with lifetime, less than the age of the Universe. Modern dark matter is explained by primordial particles and/or their decay products.
- Decaying Dark Matter (DDM) – particles with lifetime, exceeding the age of the Universe. Their decays can be a source of CR anomalies.

# The list of some physical candidates for DM

- Sterile neutrinos – physics of neutrino mass
- Axions – problem of CP violation in QCD
- Axinos - SUSY
- Gravitinos - SUGRA
- Neutralinos - SUSY
- KK-particles:  $B_{KK1}$
- Anomalous hadrons, O-helium
- Supermassive particles...
- Mirror and shadow particles, PBHs...



# Physical candidates for DM

## Axions and axinos

Peccei-Quinn model resolves the problem of strong CP-violation:

$$\Delta L_{\text{QCD}} = \frac{\alpha_s^2}{16\pi} \theta \cdot \varepsilon_{\alpha\beta\mu\nu} G^{a\alpha\beta} G^{a\mu\nu}$$

$$d_n \approx e\theta m_u / m_n^2 \sim \theta \cdot 10^{-16} e \cdot \text{cm} \quad \text{From experiment one has } |\theta| < 10^{-9}$$

Solution comes from adding extra  $U(1)_{\text{PQ}}$  symmetry. Scalar field, associated with spontaneous  $U(1)_{\text{PQ}}$  violation at energy scale  $f_a$ , provides mechanism of dynamical suppression of  $\theta$  (due to its Nambu-Goldstone boson – axion).

Axion interacts with quarks as

$$L_{\text{aff}} = ic_{\text{aff}} \frac{m_f}{f_a} a \bar{f} \gamma_5 f$$

and have potential  $V_{\text{eff}} \sim m_u \Lambda_{\text{QCD}}^3 (1 - \cos(\theta + a / f_a))$

minimizing at  $a = \langle a \rangle = -\theta f_a$

# Physical candidates for DM

## Axions and axinos

The axion has the mass

$$m_a \approx 0,6 M_{\text{Pl}} \frac{10^{10} \Gamma_{\text{QCD}}}{f_a}$$

According existing constraints its mass and energy scale must be

$$f_a > 2 \cdot 10^9 \text{ GeV}, m_a < 0,5 \cdot 10^{-2} \text{ eV}$$

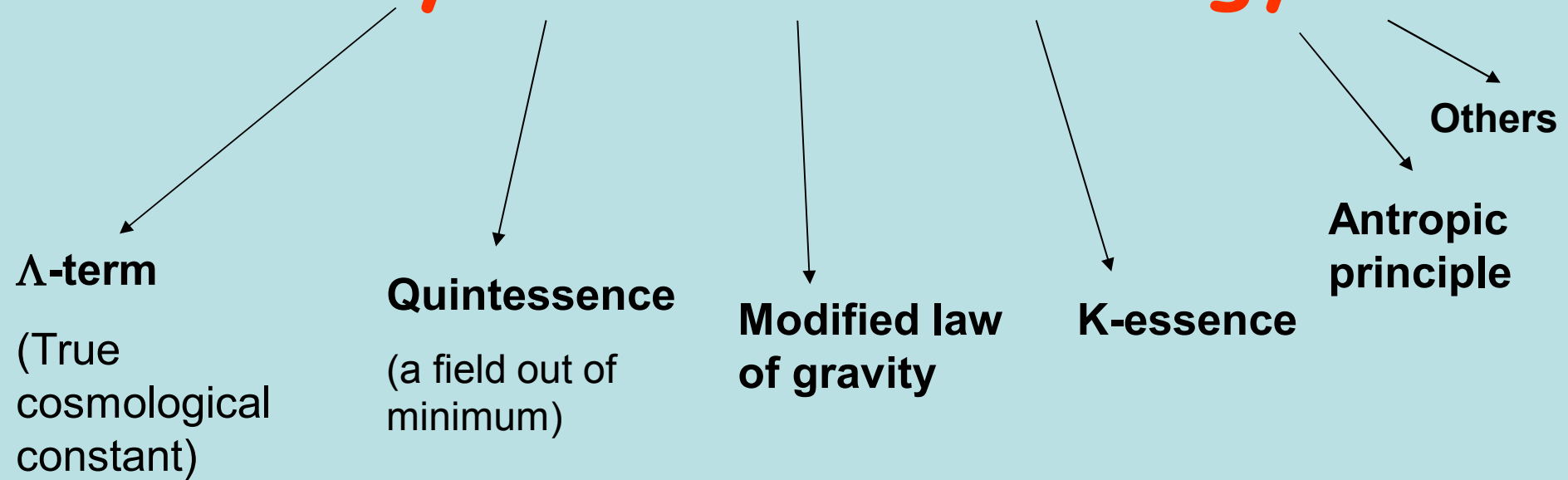
At early Universe axions might be born as Bose-condensate after succession of PQ- and QCD-phase transitions. So, its density could be

$$\Omega_a \approx 0,2 \cdot \left( \frac{f_a}{10^{12} \Gamma_{\text{QCD}}} \right)^{7/6} \approx 0,1 \left( \frac{10^{-5} \text{ eV}}{m_a} \right)^{7/6}$$

It restricts axion parameter as

$$2 \cdot 10^9 \Gamma_{\text{QCD}} < f_a < 10^{12} \Gamma_{\text{QCD}}$$

# Physics of dark Energy



$$\Lambda \sim 10^{-120} G^{-1} !!!$$

# Evidences for Standard LCDM

- $H > 50$ , age of Universe needs Lambda term
- LSS evolution slows down **relative** to accelerated expansion
- SN data are interpreted in terms of **accelerated** expansion

Homogeneous dark energy is provided by Lambda-term, quintessence...

# UDM versus LCDM

- **UDM:**
- $H < 50$ , age of Universe does not need  $\Lambda$
- LSS evolution slows down **absolutely** due to decrease of density in it
- Homogeneously distributed dark matter – products of decay of unstable dark matter
- SN data are interpreted in terms of **non-accelerated** expansion
- **LCDM:**
- $H > 50$ , age of Universe needs  $\Lambda$
- LSS evolution slows down **relative** to accelerated expansion
- Homogeneous dark energy is provided by  $\Lambda$ -term, quintessence...
- SN data are interpreted in terms of **accelerated** expansion

# Conclusions

- Inflation, Baryosynthesis and Dark matter/energy are the cornerstones of modern cosmology. They relate the observed structure of the Universe to physical processes in the early Universe.
- Magnetic Monopole overproduction has instigated critical analysis of the old Big Bang scenario. It found solution in the framework of inflational models, in which the problems of initial state, horizon, flatness and of the origin of primordial fluctuations also find solutions. Inflation involves hypothetical inflaton field.
- Baryosynthesis relates the observed baryon asymmetry of the Universe to physical processes in the early Universe.
- These cornerstones of the modern cosmology are involve physics Beyond the Standard model.