Inflation, baryosynthesis dark matter/energy and BSM Physics

Lecture from the course
« Cosmoparticle physics »

Structure of visible Universe

1 pc = 3.26 l.y. = 3.086×10^{18} cm

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

Length scales:

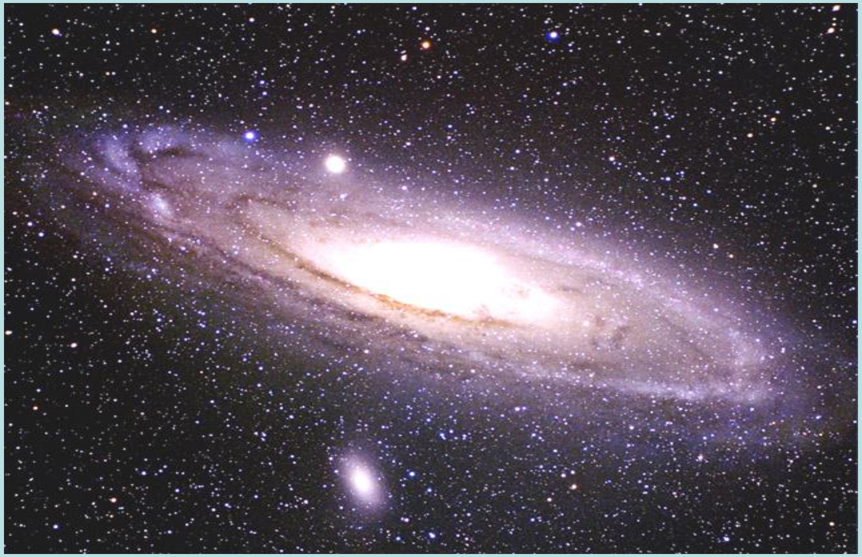
Galaxy --------------- ~30 kpc

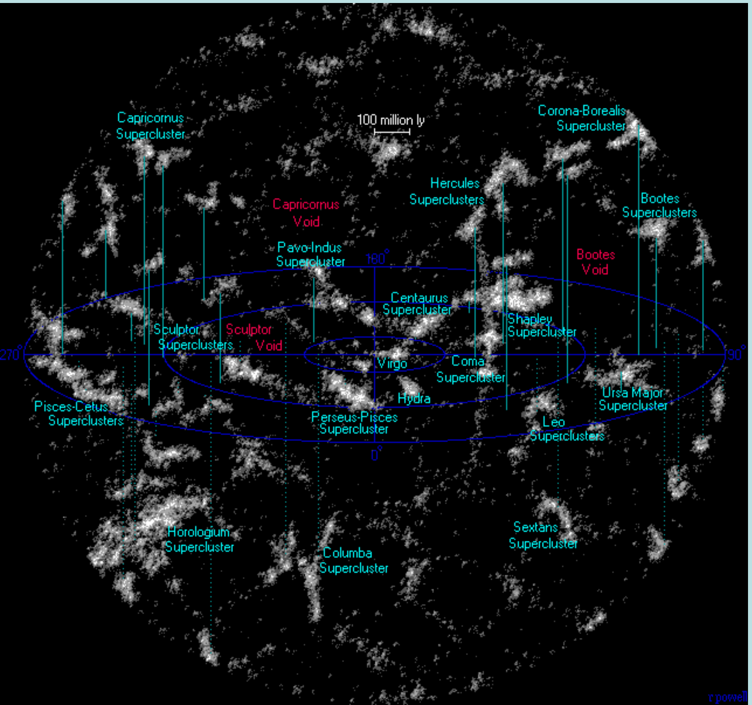
Local group ---------- ~1-10 Mpc

Cluster ---------------- ~100 Mpc

Universe* ------------- ~ 5000 Mpc

*) the size of visible part of Universe





At the scales >> 100 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):

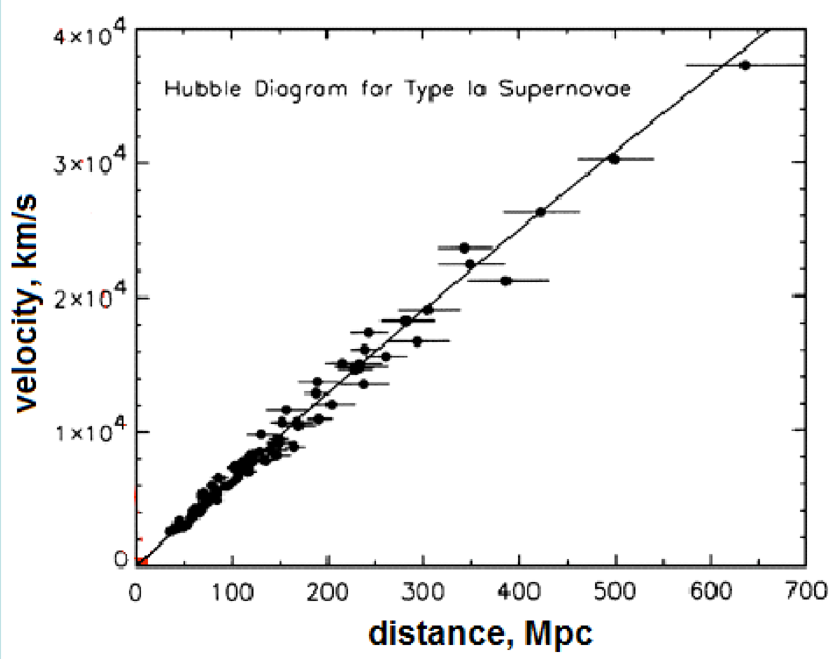
$$z=\Delta\lambda/\lambda \cong v/c \quad \text{(for } v<<c\text{)}$$

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

$$v = H*R$$

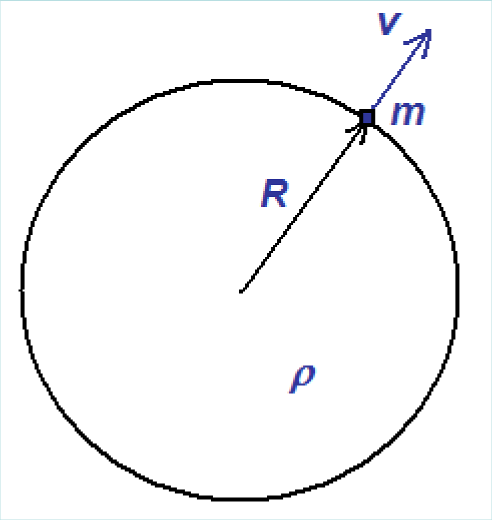
Modern measurements give
H = 74.2 ± 3.6 (km/s)/Mpc

Hubble's result was H=576±6 (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



$$\begin{cases} \dfrac{mv^2}{2} = \dfrac{GMm}{R} \\ v = HR \\ M = \dfrac{4}{3}\pi R^3 \cdot \rho \end{cases} \Rightarrow \boxed{\rho_{cr} = \dfrac{3H^2}{8\pi G}}$$

$\rho > \rho_{cr}$ – 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.

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

$$H \equiv \frac{\dot{a}}{a}$$

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

Equation of state

$$p = 0$$ **- non-relativistic ("dust"-like) matter**

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

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

$$p = -\varepsilon$$ **- vacuum-like matter (vacuum energy)**

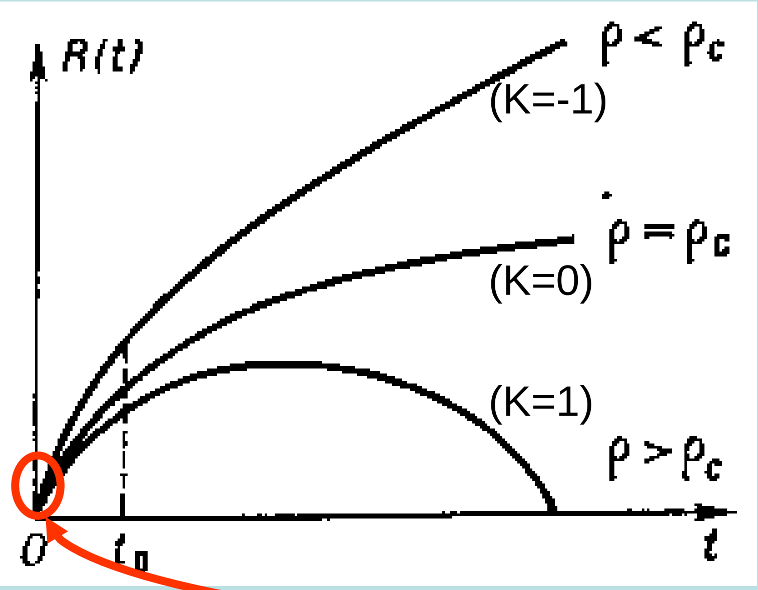
Here and further we use the units

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

The Beginning of Expansion

t ~1/*H* defines the age of the Universe – time from the beginning of expansion

Λ=0



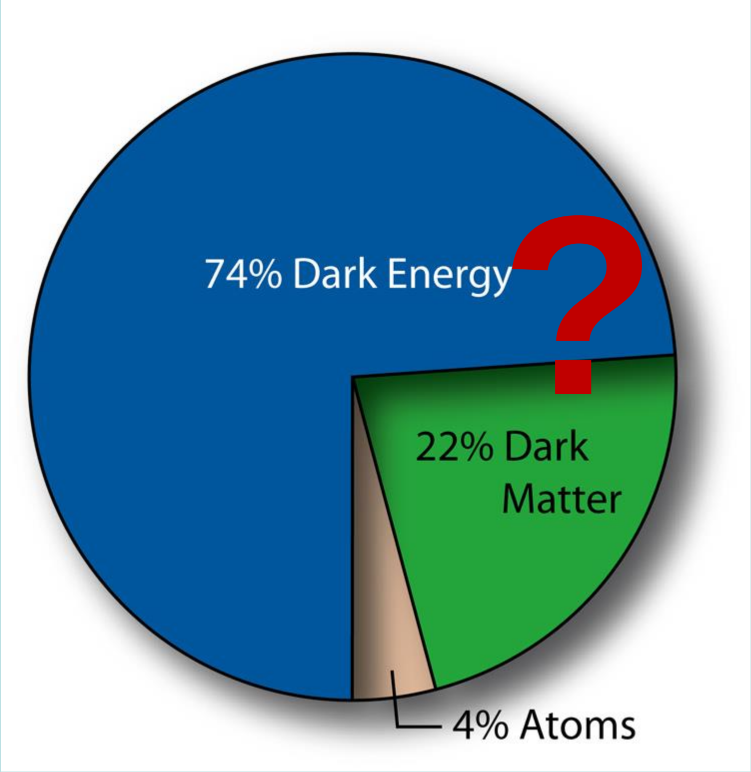
$$m_{\rm Pl} = \sqrt{\frac{\hbar c}{G}} \approx 2\cdot10^{-5}\,{\rm g} \approx 1.2\cdot10^{19}\,{\rm GeV}$$

$$l_{\rm Pl} = \sqrt{\frac{G\hbar}{c^3}} \approx 1.6\cdot10^{-33}\,{\rm cm}$$

$$t_{\rm Pl} = \sqrt{\frac{G\hbar}{c^5}} \approx 0.5\cdot10^{-43}\,{\rm s}$$

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 negligeble 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



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

$$\Omega_{\mathrm{b}} \approx 0.044 \qquad \Omega_{\mathrm{CMB}} \approx 0.5 \cdot 10^{-4}$$

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

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

$$\boxed{\Omega_{\mathrm{tot}} \approx 1.0}$$

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

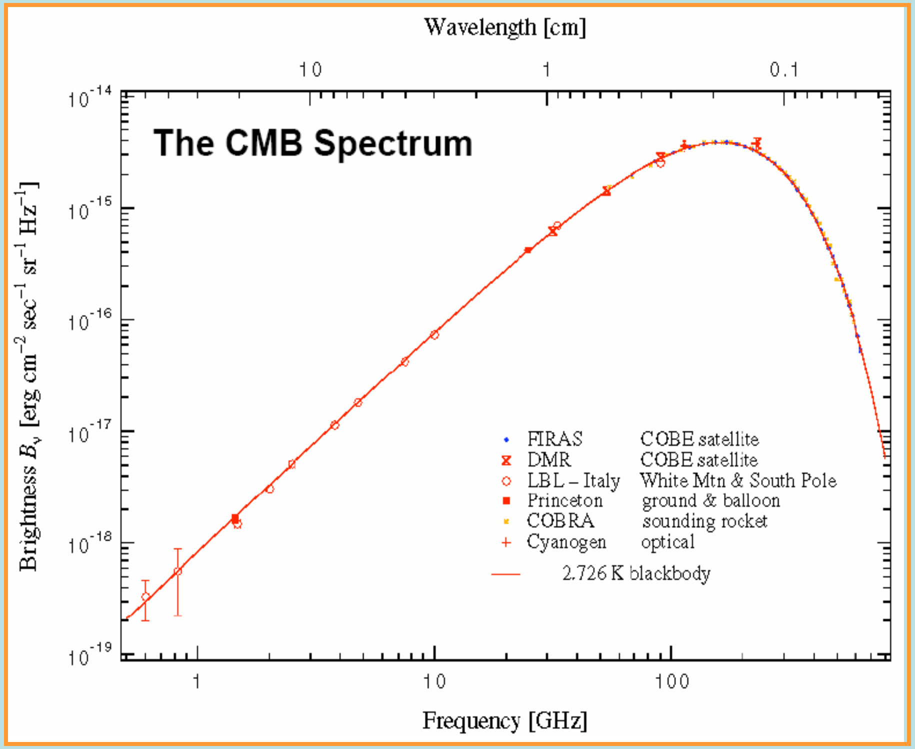
Cosmic microwave background (CMB):

Planckian black body spectrum with

T=2.73 K

n_γ=411 cm^{-3}

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



T is proportional to $1/a$.

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

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

n_b/n_γ ~ 0.6x10^{-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

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

$d(\varepsilon \cdot V) + p \cdot dV = 0$ 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.

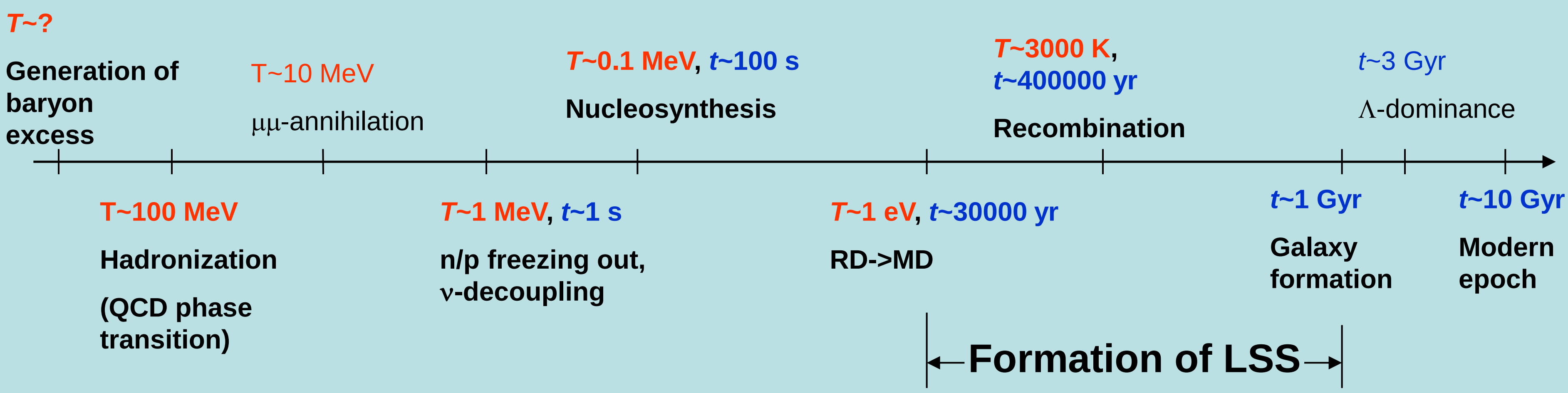
However, it turned out that the history of the Universe was much more complicated and inevitably involved super high energy physics as the basic elements of this history.

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<1s),
- 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 $T>T_*$

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

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

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

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

$$p + n \rightarrow \mathrm{D} + \gamma$$

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

$$\gamma + \mathrm{D} \rightarrow p + n$$

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

So

$$n_\gamma(>E_{\mathrm{D}}) \sim n_\gamma \cdot (E_{\mathrm{D}}/T)^2 \exp(-E_{\mathrm{D}}/T) \equiv n_\gamma \cdot f(>E_{\mathrm{D}})$$

$$\Gamma_{np\to\mathrm{D}\gamma} = \Gamma_{\mathrm{D}\gamma\to np},$$

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

$$\Gamma_{\mathrm{D}\gamma\to np} = n_\gamma(>E_{\mathrm{D}})\left\langle \sigma_{\mathrm{D}\gamma\to np} v_{\mathrm{D}\gamma} \right\rangle \sim f(>E_{\mathrm{D}}) n_\gamma \cdot \langle \sigma v \rangle.$$

$$\Rightarrow \quad T \equiv T_{\mathrm{D}} \sim E_{\mathrm{D}} / \ln\left(\frac{400}{\eta_B}\right) \approx 0.1\,\mathrm{MeV}$$

t_{D}~100 s

Here $\eta_B = n_B/n_\gamma \sim 0.6\times10^{-9}$.

Big Bang nucleosynthesis

During period between $t_* \div t_D$, about 10% of neutrons decay, so

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

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)

$$n + \mathrm{D} \to \mathrm{T} + \gamma \qquad p + \mathrm{T} \to {}^4\mathrm{He} + \gamma \qquad \mathrm{T} + {}^4\mathrm{He} \to {}^7\mathrm{Li} + \gamma$$

$$\mathrm{D} + \mathrm{D} \to \mathrm{T} + p \qquad \mathrm{D} + \mathrm{T} \to {}^4\mathrm{He} + n$$

$$p + \mathrm{D} \to {}^3\mathrm{He} + \gamma \qquad n + {}^3\mathrm{He} \to {}^4\mathrm{He} + \gamma \qquad \ldots\ldots\ldots$$

$$\mathrm{D} + \mathrm{D} \to {}^3\mathrm{He} + n \qquad \mathrm{D} + {}^3\mathrm{He} \to {}^4\mathrm{He} + p$$

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

Primordial chemical elements

All reactions had been going during ~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:

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

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

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

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

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)

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

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

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

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

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

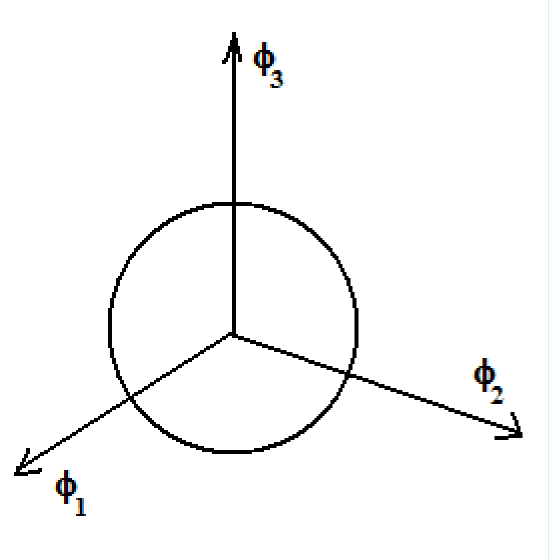
as condition of quantization of electric charge.

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

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

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 θ and φ.



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

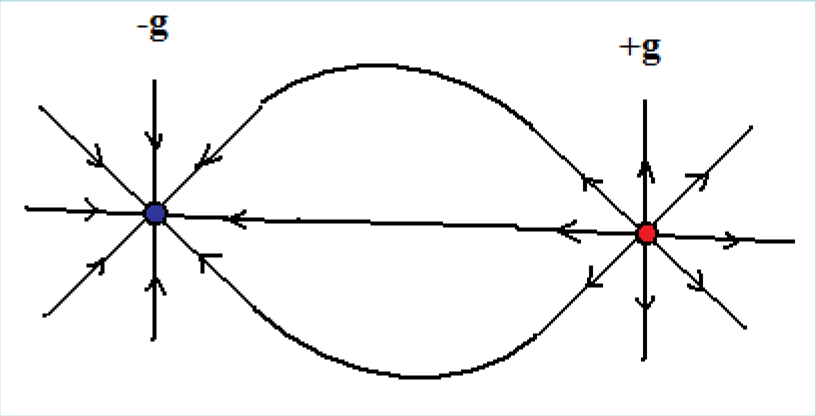
$$\Delta l \sim \frac{1}{ev}$$

However, it is not possible for θ and φ to vary continuously over 2π and not to get a singularity – the point where θ and φ 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 **Δl**. In its center **ϕ=0,** it corresponds to non-zero energy density of ϕ (outside of minimum) – mass, pointed previously.

Gradients of **$\theta(x)$** and **$\varphi(x)$**, issuing from singularity, define intensity of magnetic filed. This is accounted for by the fact that the field ϕ is connected with gauging of electromagnetic field. Singularity, where gradients of **$\theta(x)$** and **$\varphi(x)$** 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

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

Diffusive approximation is proved by condition

$$\lambda \ll r_0$$

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.

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

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

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.

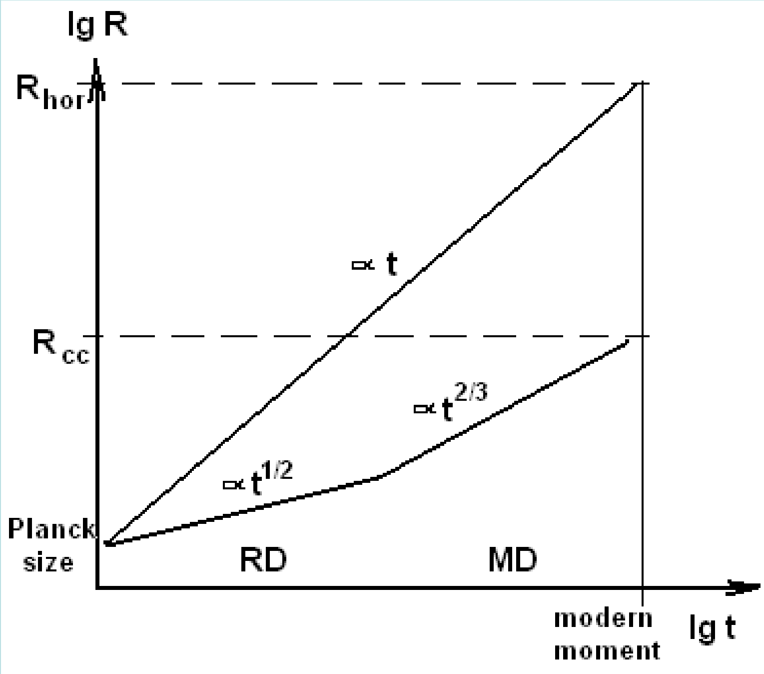
This problem either excludes magnetic monopole with given properties, or implies completely different conditions in very early Universe.

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 $R_{hor}\sim ct$. So 10^{88} regions, initially causally-disconnected at Planck time, are inside modern horizon, while the observed conditions in them are very similar.

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

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



The flatness problem

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

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

$$\Omega \equiv \frac{\varepsilon}{\varepsilon_{cr}}$$

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

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

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

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

The problem of baryon excess

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

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

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

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

More accurate estimation gives 10^{-18}.

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

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 ¼ of total baryon density. The total baryon density does not exceed 0.04 of critical density.

In fact, observations give for visible baryons

$$\Omega_{B\,\mathrm{visible}} \sim 0.01$$

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

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

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 $M/L \sim 100\ M_{Sun}/L_{Sun}$.

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

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

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

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

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

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

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

$$\hbar = c = 1$$

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

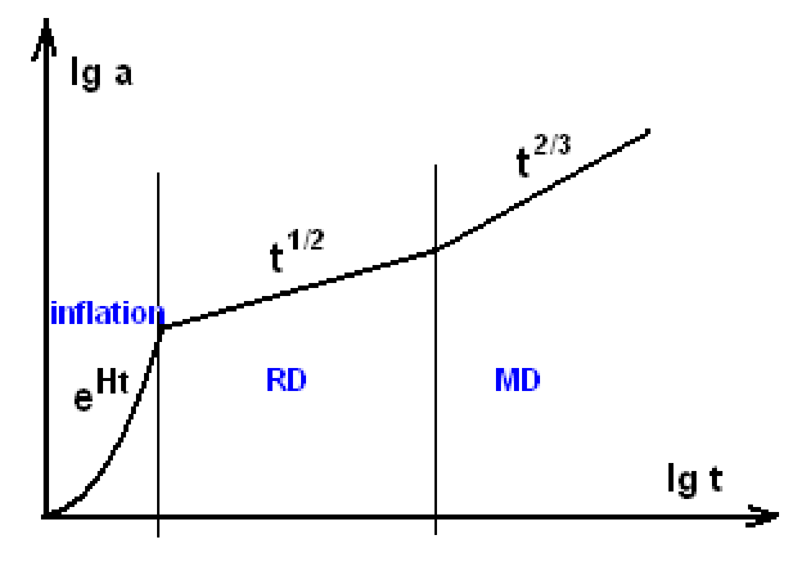
$$\text{If } p < -\frac{\varepsilon}{3} \quad \Rightarrow \quad \ddot{a} > 0$$

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=-ε)

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

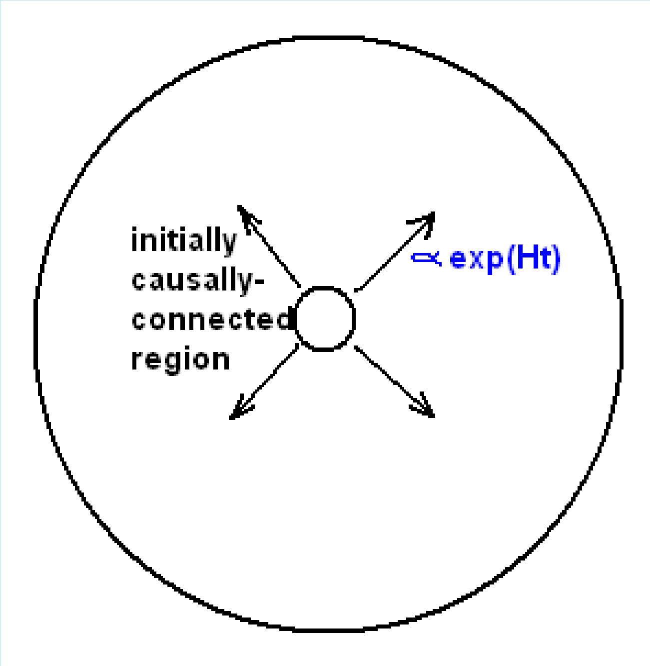
$$\varepsilon \sim m_{\mathrm{Pl}}^4 \qquad t_{\text{оконч.инфляц.}} \sim t_{\mathrm{GUT}} \sim \Lambda_{\mathrm{GUT}}^{-1}$$

$$a(t_{\mathrm{GUT}})/a(t_{\mathrm{Pl}}) \propto \exp\left(H \cdot \Delta t\right) \sim \exp\left(\sqrt{8\pi G\varepsilon/3} \cdot t_{\mathrm{GUT}}\right) \sim \exp\left(m_{\mathrm{Pl}}/\Lambda_{\mathrm{GUT}}\right) \sim e^{10000}$$

Solution for problem of magnetic monopoles

Problem of magnetic monopole overproduction:

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



Inflation

Scalar field

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

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

$$\varepsilon = \frac{\dot{\varphi}^2}{2} + V, \qquad p = \frac{\dot{\varphi}^2}{2} - V$$

$$\text{If} \quad \dot{\varphi}^2 << V \quad \Rightarrow \quad \boxed{p \cong -\varepsilon}$$

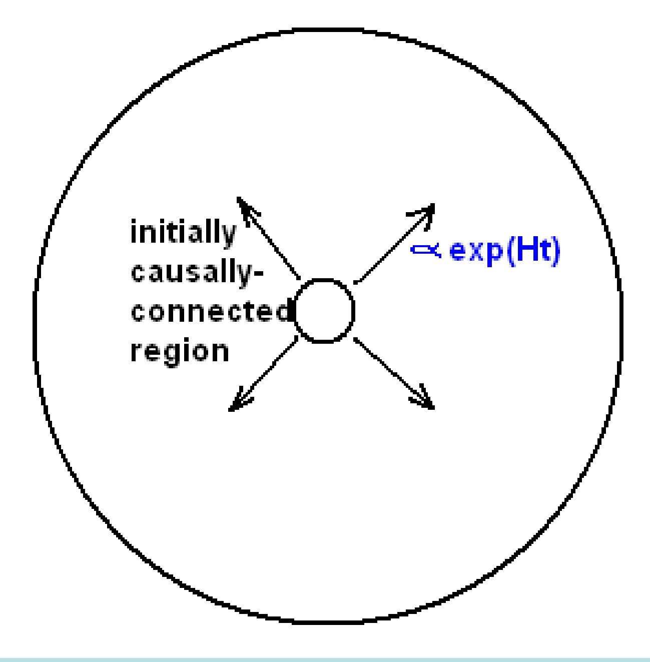
Exponential expansion, accounted for by this equation of state, would resolve the problems of

horizon

flatness.

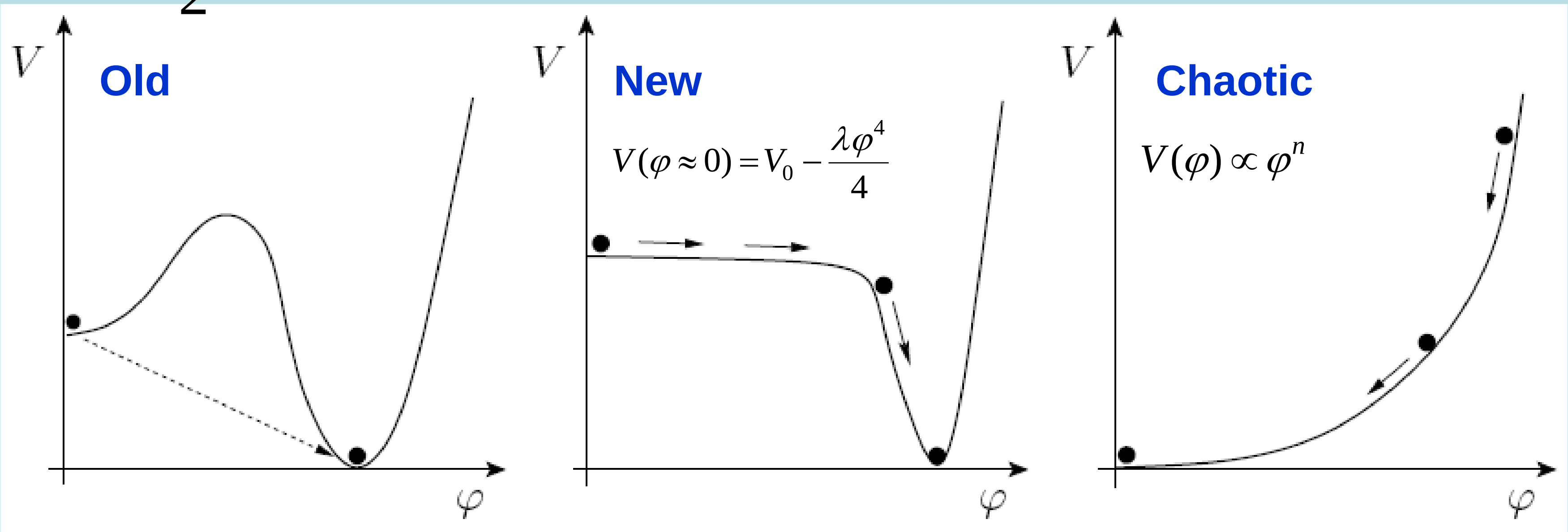
$$\left(\frac{\dot{a}}{a}\right)^2 - \frac{8\pi G\varepsilon}{3} = -\frac{Kc^2}{a^2}$$

(or $\Omega - 1 = \frac{K}{\dot{a}^2} \rightarrow 0$)



"Old", "New" and Chaotic Inflation

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



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)

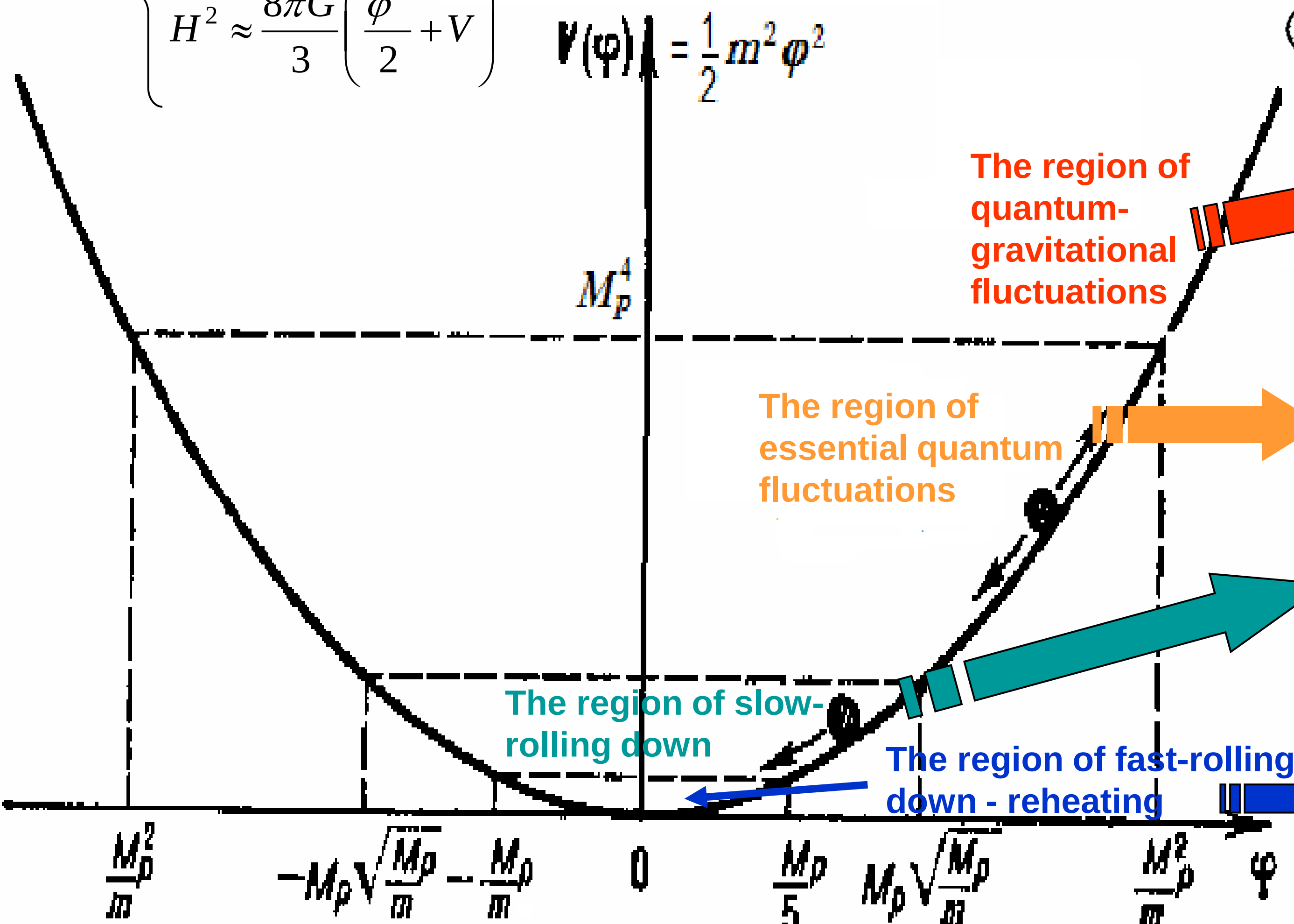
*Quantum fluctuations

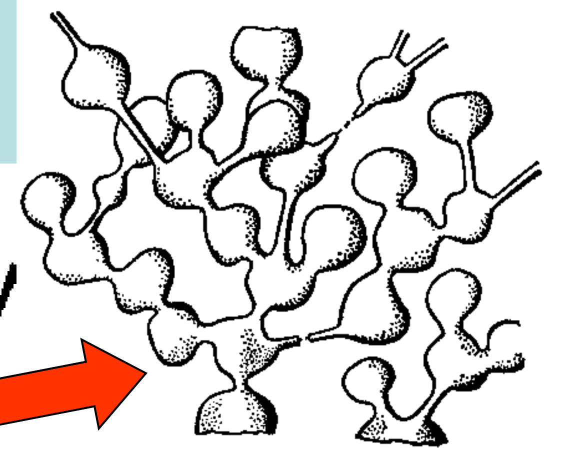
Chaotic/eternal inflation

"friction" provides slow rolling down

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

$$a \propto \exp\left(2\pi\varphi^2 / m_{\rm Pl}^2\right)$$





"Multiverse"

"Eternal" inflation

LSS requires:

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

$$\kappa\sigma T_R^4 = V(\varphi \sim m_{\rm Pl}/5)$$

$$T_R \sim 10^{10-16}\,{\rm GeV}$$

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 ~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:

$$X \to qq, \; r \qquad \bar{X} \to \overline{qq}, \; \bar{r}$$

$$X \to \bar{q}l, \; 1-r \qquad \bar{X} \to q\bar{l}, \; 1-\bar{r}$$

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:

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.

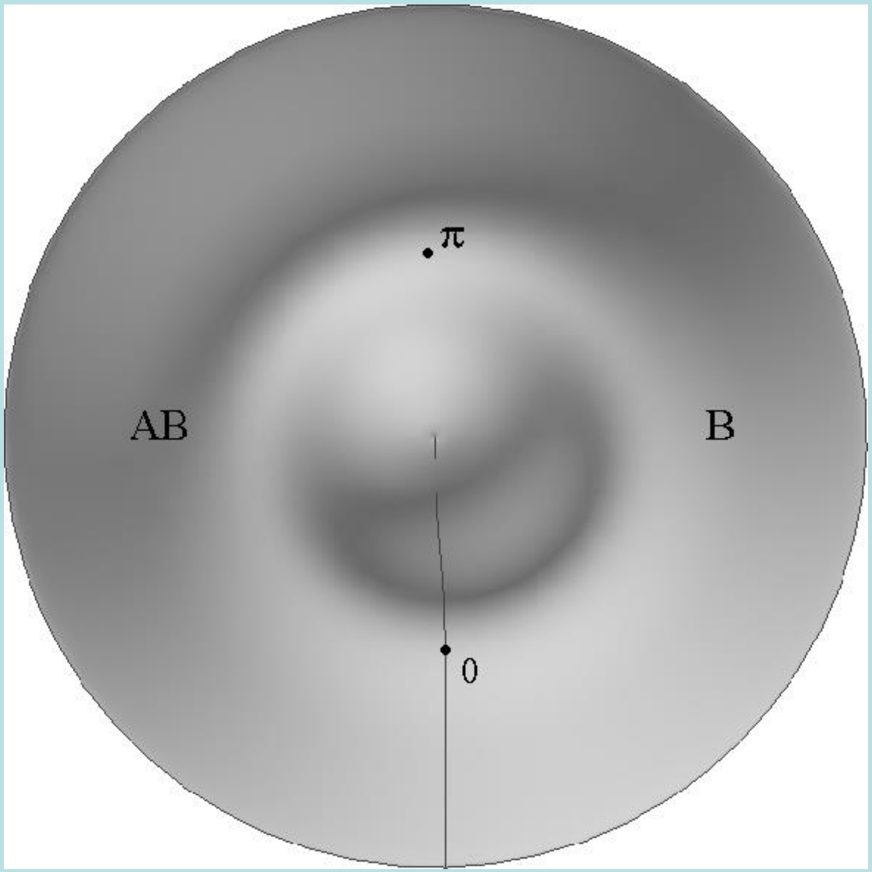
Baryosynthesis: SUSY model

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 mechanisms is analogous to one of the mechanism 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 [~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 => 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< -- >M, nonequilibrium character of such transitions can lead to generation of excess of baryons, which is related with excess of mirror « antibaryons » (Berezhiani 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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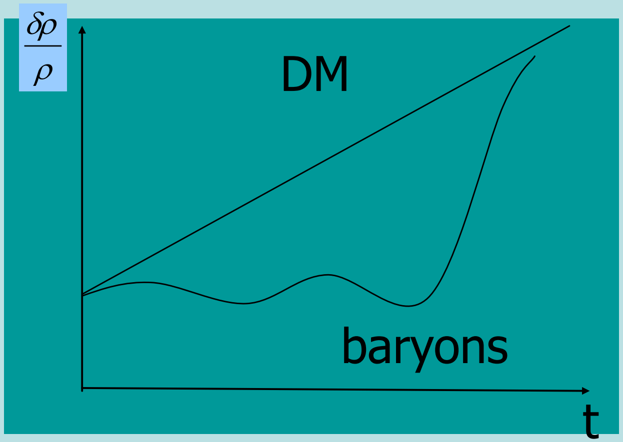
- Dark matter/energy

The latter (Dark matter and dark energy) is the topic of our discussion today

Cosmological Dark Matter



$$\frac{\delta\rho}{\rho} \Rightarrow \frac{\delta T}{T}$$

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 stabilty 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 characterstic 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…

WIMP

(weakly interacting massive particles)

SIMP

(strongly interacting massive particles)

Physical candidates for DM

Axions and axinos

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

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

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

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

Axion interacts with quarks as

$$L_{aff} = i c_{aff} \frac{m_f}{f_a} a \bar{f} \gamma_5 f$$

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

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

Physical candidates for DM

Axions and axinos

The axion has the mass

$$m_a \approx 0{,}6\,\text{мэВ}\,\frac{10^{10}\ \text{ГэВ}}{f_a}$$

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

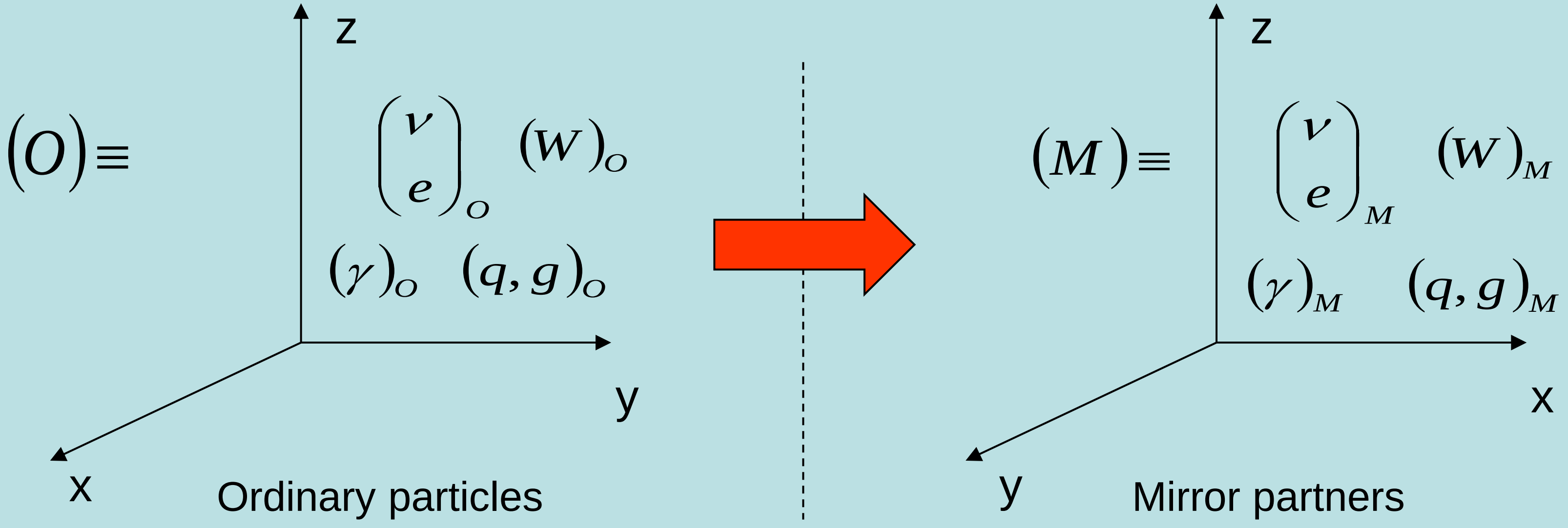
$$\Omega_a \approx 0{,}2 \cdot \left(\frac{f_a}{10^{12}\,\text{ГэВ}}\right)^{7/6} \approx 0{,}1 \left(\frac{10^{-5}\,\text{эВ}}{m_a}\right)^{7/6}$$

It restricts axion parameter as

$$2 \cdot 10^9\,\text{ГэВ} < f_a < 10^{12}\,\text{ГэВ}$$

Mirror world

Blinnikov,Khlopov(1980,1982,1984)



Assume that there is no common interaction between ordinary particles and their mirror partners, except for gravity. All the masses and coupling constants of mirror particles are strictly symmetric to the ordinary ones.The initial conditions are also assumed strictly symmetric.

Strictly symmetric evolution of mirror particles in the Universe

- Strict symmetry in physics and initial conditions leads to

$$n_O^i(x) = n_M^i(x)$$

for $i = \gamma, e, q, \ldots$ and to equality in the amount and spatial distribution for ordinary and mirror baryon excess

$$\Delta n_{B,O}^i(x) = \Delta n_{B,M}^i(x)$$

Primordial He and mirror particles

The frozen out n/p ratio is

$$\frac{n}{p} = \exp\left\{-\frac{\Delta m}{T_f}\right\}$$

and the freezing out temperature is

$$T_f \propto \left(\frac{\kappa}{\kappa_0}\right)^{1/6}$$

Any new species of relativistic particles increases the abundance of primordial He-4. Strict (but model dependent) constraints give

$$Y_{prim} = 0.25 \Rightarrow \Delta n_\nu < 1$$

Mirror particles double the number of relativistic species. It leads to

$$Y_{prim} \geq 0.28$$

which formally does not contradicts to the observed He abundance

$$Y_{obs} = 0.28\text{-}0.40$$

But it is only the first trouble of symmetric cosmology of mirror world

Separation of ordinary and mirror objects in Galaxy

- Strict symmetry in physics and initial conditions leads to symmetry in distributions

$$f_O^i(M) = f_M^i(M); \quad f_O^i(v) = f_M^i(v); \ \langle n_O^i(x) \rangle = \langle n_M^i(x) \rangle$$

but ordinary and mirror matter is separated on scales $M < M_{th} \sim 10^6 M_{sun}$ at which formation of objects involves development of thermal instability. Cold gas clouds are pressed by hot gas. It results in separate evolution of ordinary and mirror clouds, and formation of objects (e.g. stars) with definite mirrority.

Mirror objects in Galaxy

- Strict symmetry in physics should result in symmetry in forms of astronomical objects of mirror matter and their evolution. There should be mirror stars, planets and interstellar gas of mirror matter.
- Mirror stars in halo can play the role of MACHOs and observed by effect of microlensing.
- Mirror gas can be accreted by ordinary stars and ordinary gas can be accreted by mirror stars.
- Mirror gas accreted by Sun can form a mirror planet inside the Sun, giving rise to Solar surface oscillations with T=160min.
- Ordinary gas, accreted by mirror neutron star, can form a dense visible core $R_c \sim 100m$, giving rise to time variations $\tau \sim R_c/c$ more rapid, than in ordinary neutron stars and black holes.
- Galactic disc should contain equal amount of ordinary and mirror stars.

Local Dark Matter

- In vicinity of Solar system the density should be two times larger due to invisible mirror stars and gas:

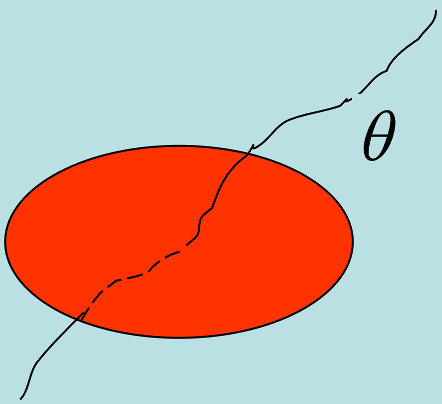
$$\rho_{dyn} \geq 2\rho_{vis}$$

- Such increase of local density can not be due to collisionless dark matter, and evidences for it could be considered as favoring mirror matter.
- HIPPARCOS data (1999) gave

$\rho_{dyn} = 0.098 \pm 0.011 \frac{M_{Sun}}{pc^3}$ for the estimated

$$\rho_{vis} = 0.095 \frac{M_{Sun}}{pc^3}$$

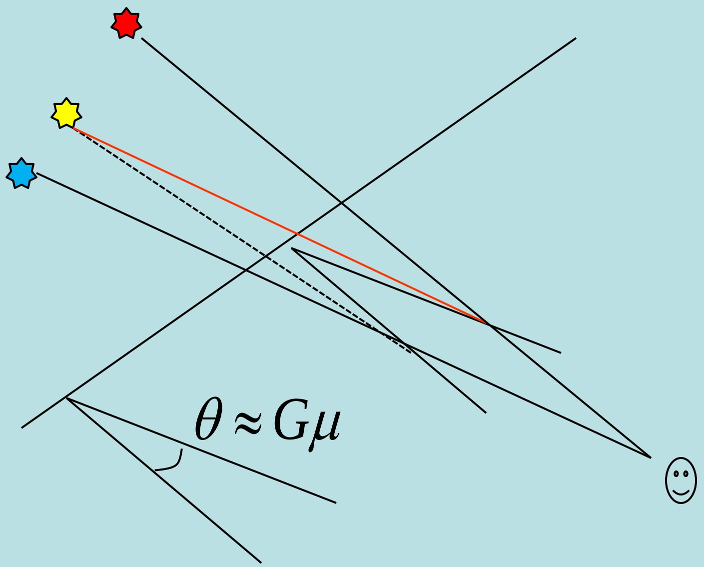
Alice strings



- If $GUT \supset M \otimes O$ due to strict symmetry $M \Leftrightarrow O$ multi-component Higgs fields play the role of imaginary and real parts of a single complex field. Corresponding cosmic string changes mirrority of particle circulating around it. Alice could go « Through the looking glass » around such Alice string.

- Spontaneous breaking of U(1) symmetry results in the continuous degeneracy of vacua. In the early Universe the transition to phase with broken symmetry leads to formation of cosmic string network.
- Alice string crossing a line of sight to a visible object changes its relative mirrority and makes it mirror and invisible. On the contrary, mirror object becomes visible, if Alice string crosses the line of sight to it.

Gravitational lens on Alice string



- If Alice string crosses the line of sight to QSO, it converts ordinary radiation into mirror radiation and vice versa. Rapid variation of QSO luminocity is then possible.

- Cosmic string cuts a piece of space along its line, and it leads to effect of gravitational lens. One sees two images instead of the lensed object.
- Alice string separates ordinary and mirror light. The light, which is ordinary to the left of the string is mirror to the right of the string.
- If the object is the source of ordinary and mirror light (as e.g. QSO) one sees its ordinary radiation in the left image, while the mirror radiation becomes ordinary and visible in the right image.

Fractons

- Mixed states, having mirror and ordinary charges, have unusual properties.
- Mirror hadron, having ordinary electroweak charges, behaves as fractionally charged lepton.
- Ordinary quarks, having mirror electroweak charges, are neutral relative to ordinary electromagnetism and, bound with ordinary quarks, give rise to a colorless fractionally charged particles.
- While negatively charged « leptonic » fractons should be bound with nuclei and thus excape annihilation with their positively charged antiparticles, « hadronic » fractons possess mirror electromagnetic charges and owing to mirror Coulomb attraction diffuse to their antiparticles and annihilate in dense matter bodies.
- Recombination of hadronic fractons in matter makes their exitence compatible with stringent experimental upper limits on abundance of fractionally charged particles in terrestrial matter.

Asymmetric initial conditions

- Problems of strictly symmetrical cosmology of mirror matter can be avoided, if initial cosmological conditions were different for ordinary and mirror matter (Berezhiani et al).
- If temperature of mirror matter after reheating of Universe was few times smaller, than for ordinary matter, symmetric mechanism of baryogenesis should lead to mirror baryon excess, larger than for ordinary matter.
- Smaller temperature of relativistic mirror species in the period of SBBN reduces their influence on He abundance.
- Larger mirror baryon excess can provide mirror baryonic matter as the dominant form of Dark Matter.
- However, constraints on MACHOs and on Local Dark Matter put forward a question about the dominant form of mirror baryons in the Galaxy.

Shadow world

- Asymmetry in physics of ordinary and mirror matter (e.g. by a scale factor in their masses – Mohapatra, Senjanovich), Okun's y-matter, 248 fundamental particles and 248 fundamental interactions of E'_8 symmetry in $E'_8 \otimes E_6$ GUT model of $E'_8 \otimes E_8$ heterotic string give examples of shadow world.
- As shadow deforms an image of the original, properties of shadow particles and their interactions may strongly differ from the ones of the ordinary matter, even if shadow world results from breaking of initially strict mirror symmetry.
- Qualitative features of shadow world can be analyzed with the use of methods of cosmoarcheology, while quantitative description of the Universe with shadow matter is strongly model dependent.
- This model dependence provides good example of relationship between cosmological scenarios and particle models, on which these scenarios are based.

Physics of dark Energy

Λ-term

(True cosmological constant)

Quintessence

(a field out of minimum)

Modified law of gravity

K-essence

Antropic principle

Others

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

Evidences for Standard LCDM

- H>50, age of Universe needs Lamda 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 Lamda
- 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 Lamda
- 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.

Cosmological Reflections of Microworld Structure

- **(Meta-)stability of new particles reflects some Conservation Law, which prohibits their rapid decay. Following Noether's theorem this Conservation Law should correspond to a (nearly) strict symmetry of microworld. Indeed, all the particles - candidates for DM reflect the extension of particle symmetry beyond the Standard Model.**
- **In the early Universe at high temperature particle symmetry was restored. Transition to phase of broken symmetry in the course of expansion is the source of topological defects (monopoles, strings, walls…).**
- **Structures, arising from dominance of superheavy metastable particles and phase transitions in early Universe, can give rise to Black Holes, retaining in the Universe after these structures decay.**