Antimatter regions in the baryon-dominated Universe

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OUTLINE

- Big Bang reminder
- Constraints on the existence of antimatter
- Scenario of antimatter regions generation
- An antimatter region with high interior density
- Observational signature

The expansion of the Universe

The scale factor $a(t)$ gives **physical size** to the spatial coordinates $\vec{x}$, and the expansion is nothing but a change of scale with time

$$\boxed{ds^2 = dt^2 - a^2(t)d\vec{x}^2}$$

The observed wavelength of photons coming from distant objects is greater than when they were emitted by a factor precisely equal to the **ratio of scale factors**

$$\boxed{\frac{\lambda_{obs}}{\lambda_{em}} = \frac{a_0}{a} = 1 + z}$$

The **expansion of the Universe** is characterized by the Hubble rate, $H(t) = \dot{a}(t)/a(t)$.

The physical distance d_L and the present rate of expansion, in terms of **redshift** parameter

$$\boxed{H_0 d_L = z + \frac{1}{2}(1 - q_0)z^2 + \mathcal{O}(z^3)}$$

At small distances from us, i.e. at $z \ll 1$, the recession velocity becomes proportional to the distance

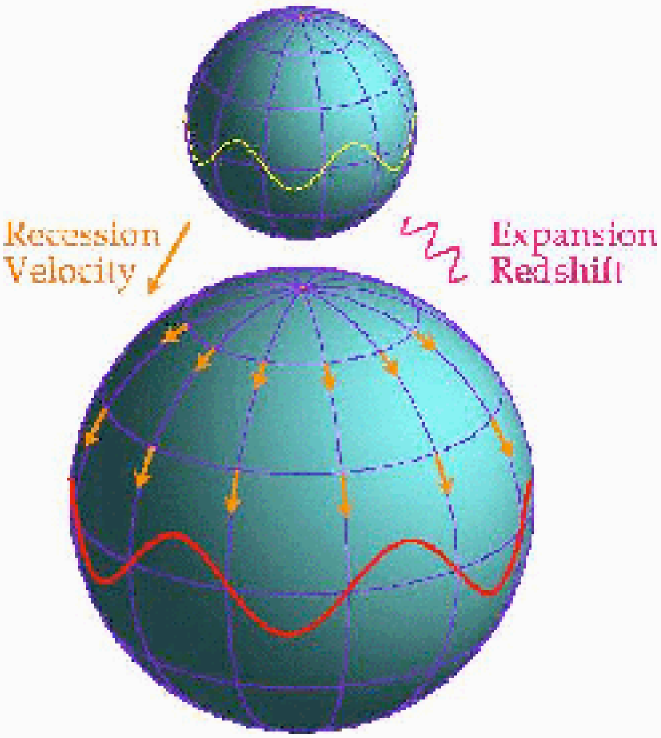
$$\boxed{v = cz = H_0 d_L}$$

$$\boxed{H_0 = 100\mathrm{h}\ \ \mathrm{km \cdot s^{-1} \cdot Mpc^{-1}} \quad h_{MAP} = 0.71^{+0.04}_{-0.03}}$$

$$\boxed{cH_0^{-1} = 3000\mathrm{h}^{-1}\ \ \mathrm{Mpc}}$$

$$\boxed{H_0^{-1} = 9.773\mathrm{h}^{-1}\ \ \mathrm{Gyr}}$$

The scale factor



For some massive body moving relative to the expansion, the momentum also "redshifts"

$$\boxed{p \propto \frac{1}{a(t)}}$$

So freely moving bodies in an expanding universe eventually come to rest relative to the expanding coordinat system s.c. comoving frame.

The expansion of the universe creates a kind of dynamical friction for everything moving in it.

For a gas in thermal equilibrium

$$\boxed{T \propto \frac{1}{a(t)}}$$

The matter content

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

The critical density

$$\rho_c = \frac{3H_0^2}{8\pi G}$$

$$\Omega \equiv \frac{\rho}{\rho_c} \qquad \begin{array}{ll} <1: & \text{Open} \\ =1: & \text{Flat} \\ >1: & \text{Closed.} \end{array}$$

A flat universe with presureless matter, $\rho \propto a^{-3}$.

$$a(t) \propto t^{2/3}; \quad H = \frac{\dot{a}}{a} = \frac{2}{3}t^{-1}$$

$$t_0 = \frac{2}{3}H_0^{-1}$$

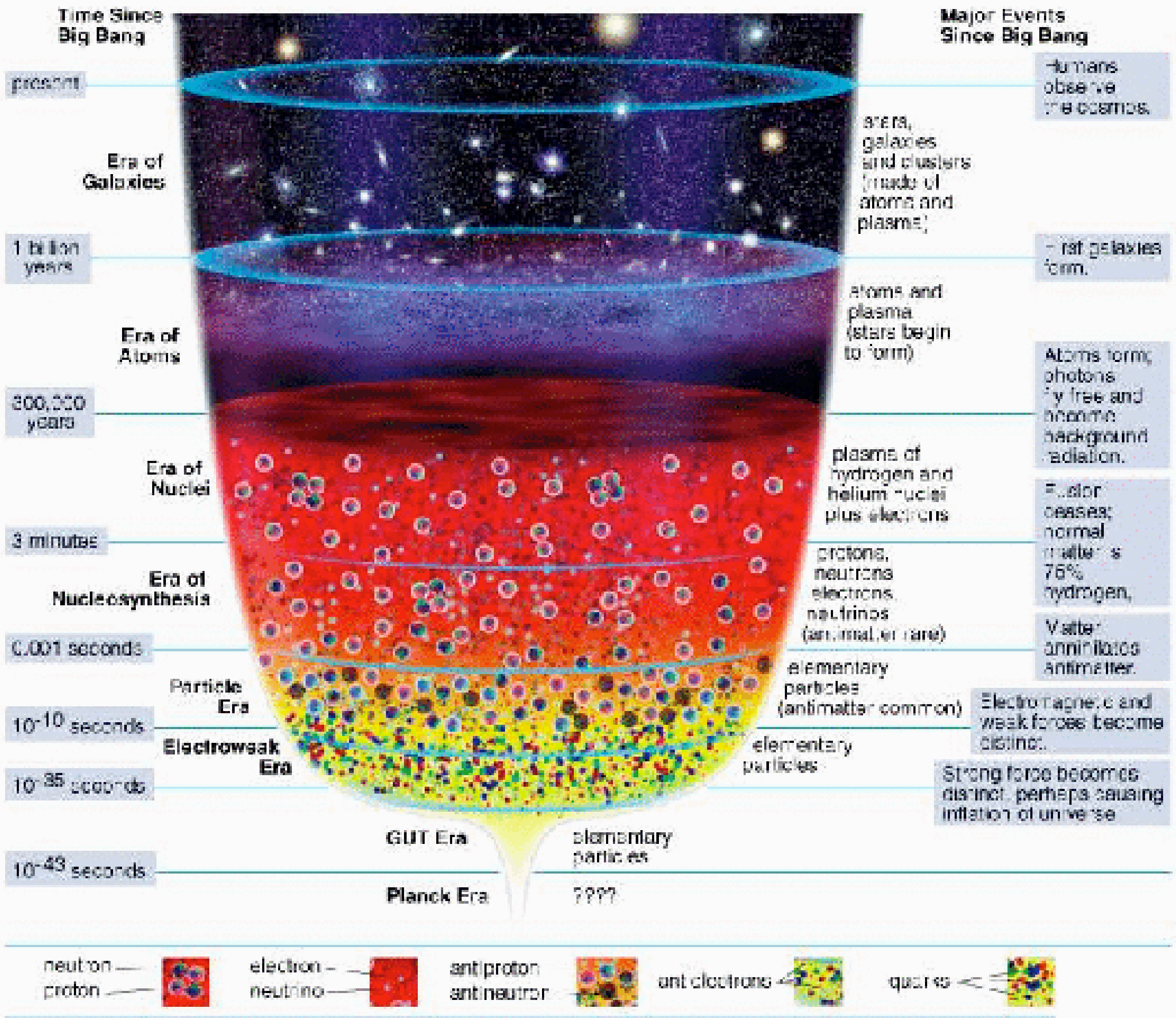
In therms of critical density $\Omega_i = \rho_i/\rho_c$

$$\rho_c = 1.88 \cdot h^2 \cdot 10^{-29}\,\mathrm{g/cm^3}$$

$$\Omega_R = 2.4 \cdot 10^{-5} h^{-2} \qquad \Omega_\Lambda = 0.72$$

$$\Omega_M = \Omega_B + \Omega_{DM} = 0.28$$

Big Bang history



Recombination, CMB

- $T \sim 10^{15}\ K$, $t \sim 10^{-12}$ sec: **Primordial soup of fundamental particles.**
- $T \sim 10^{13}\ K$, $t \sim 10^{-6}$ sec: **Protons and neutrons form.**
- $T \sim 10^{10}\ K$, $t \sim 3$ min: **Nucleosynthesis: nuclei form.**
- $T \sim 3000\ K$, $t \sim 300,000$ years: **Atoms form.**
- $T \sim 10\ K$, $t \sim 10^{9}$ years: **Galaxies form.**
- $T \sim 3\ K$, $t \sim 10^{10}$ years: **Today.**

Once the gas in the universe is in a neutral state, the mean free path for a photon rises to much larger than the Hubble distance. The universe is then full of a background of freely propagating photons with a blackbody distribution of frequencies.

As the universe expands the photons redshift, so that the temperature of the photons drops with the increase of the scale factor, $T \propto a(t)^{-1}$.

We can detect these photons today. Looking at the sky, this background of photons comes to us evenly from all directions, with an observed temperature of $T_0 \sim 2.73$ K.

The shape of CMB power cpectrum

The simplest contribution to the CMB temperature anisotropy is due to the slightly varying Newtonian potential Φ from density fluctuations at the surface of last scattering

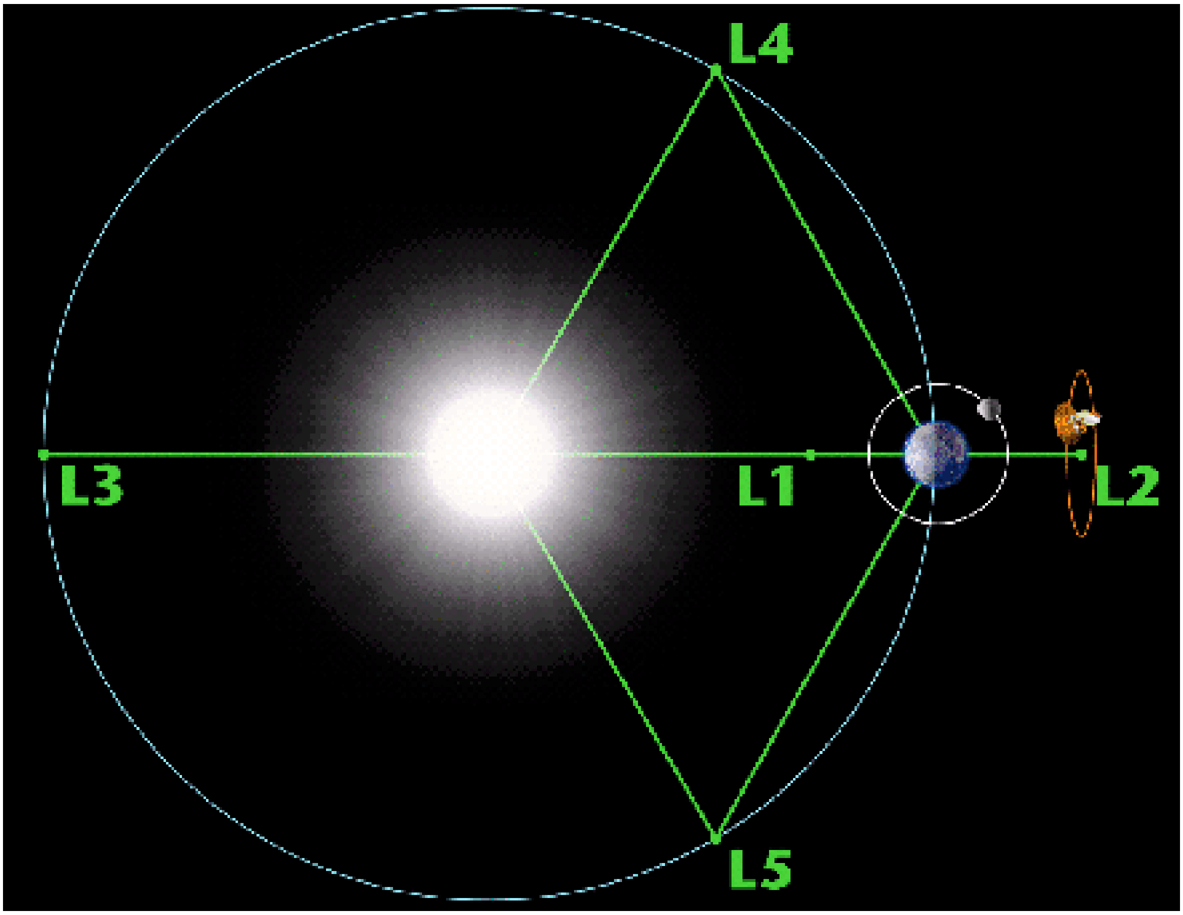
$$\boxed{\left(\frac{\Delta T}{T}\right) = \frac{1}{3}\Phi}$$

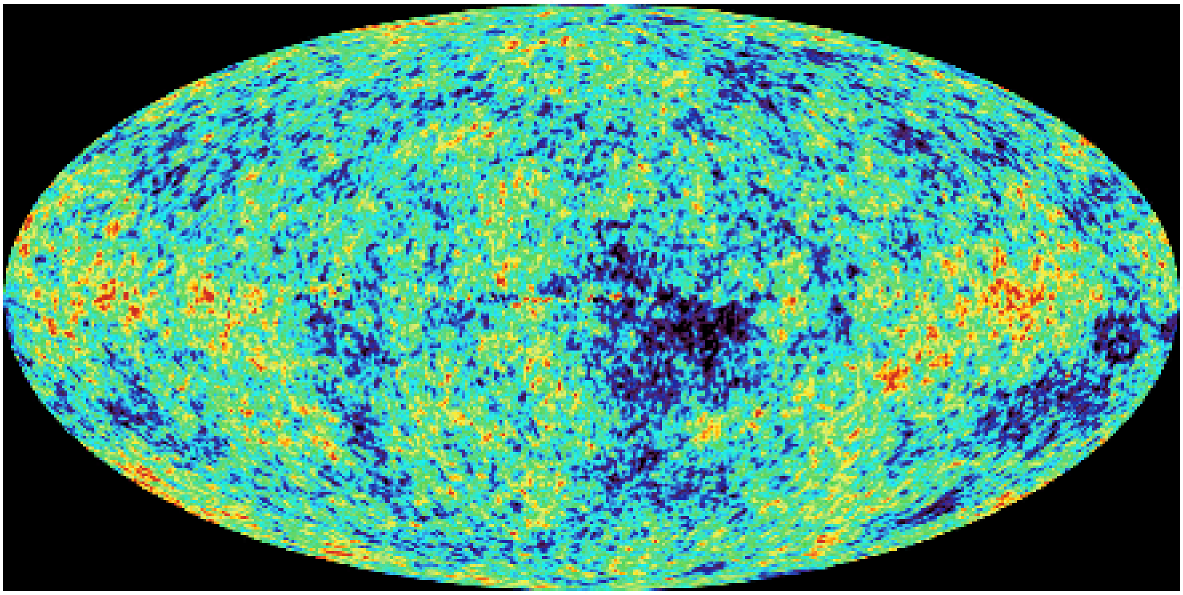
There are acoustic oscillations in the baryon/photon plasma. Matter tends to collapse due to gravity onto regions where the density is higher than average. However, since the baryons and the photons are still strongly coupled, the photons tend to resist this collapse and push the baryons outward.

The gas heats as it compresses and cools as it expands, and this creates fluctuations in the temperature of the CMB. This manifests itself in the C_ℓ spectrum as a series of bumps. The specific shape and location of the bumps is created by complicated, although well-understood physics, involving a large number of cosmological parameters.

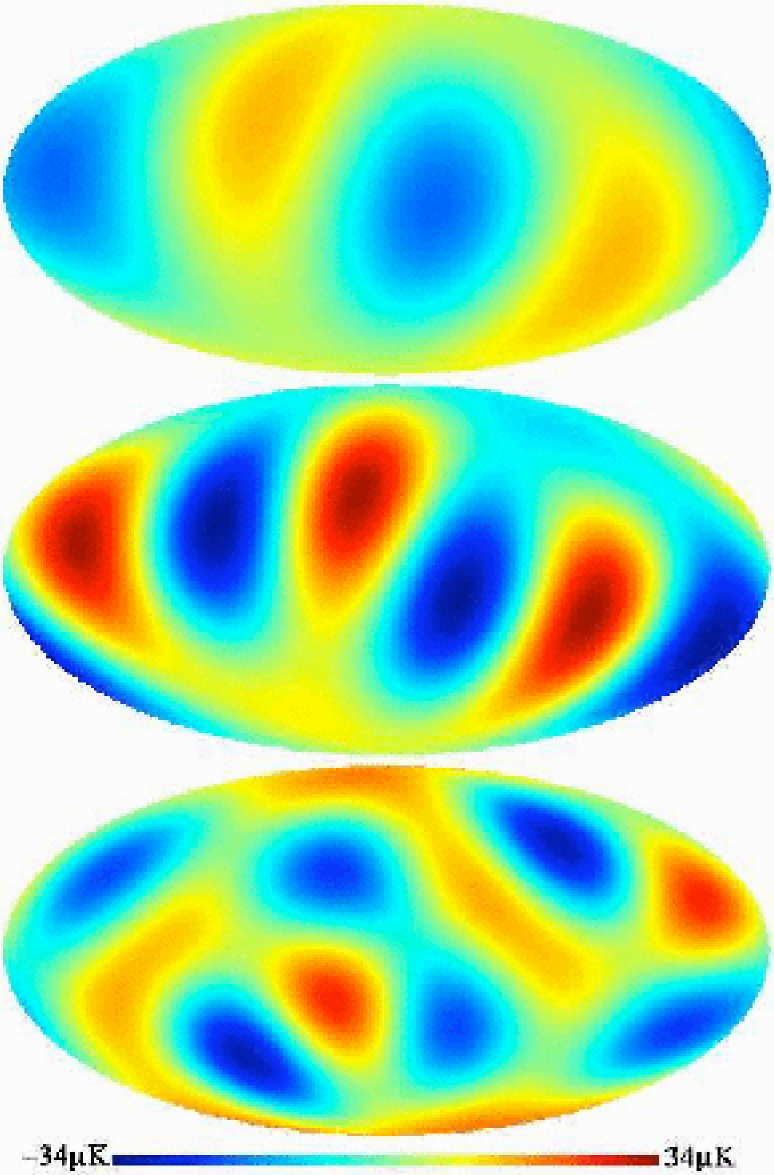
The shape of the CMB multipole spectrum depends, for example, on the baryon density Ω_b, the Hubble constant H_0, the densities of matter Ω_M and cosmological constant Ω_Λ.........

CMB-WMAP



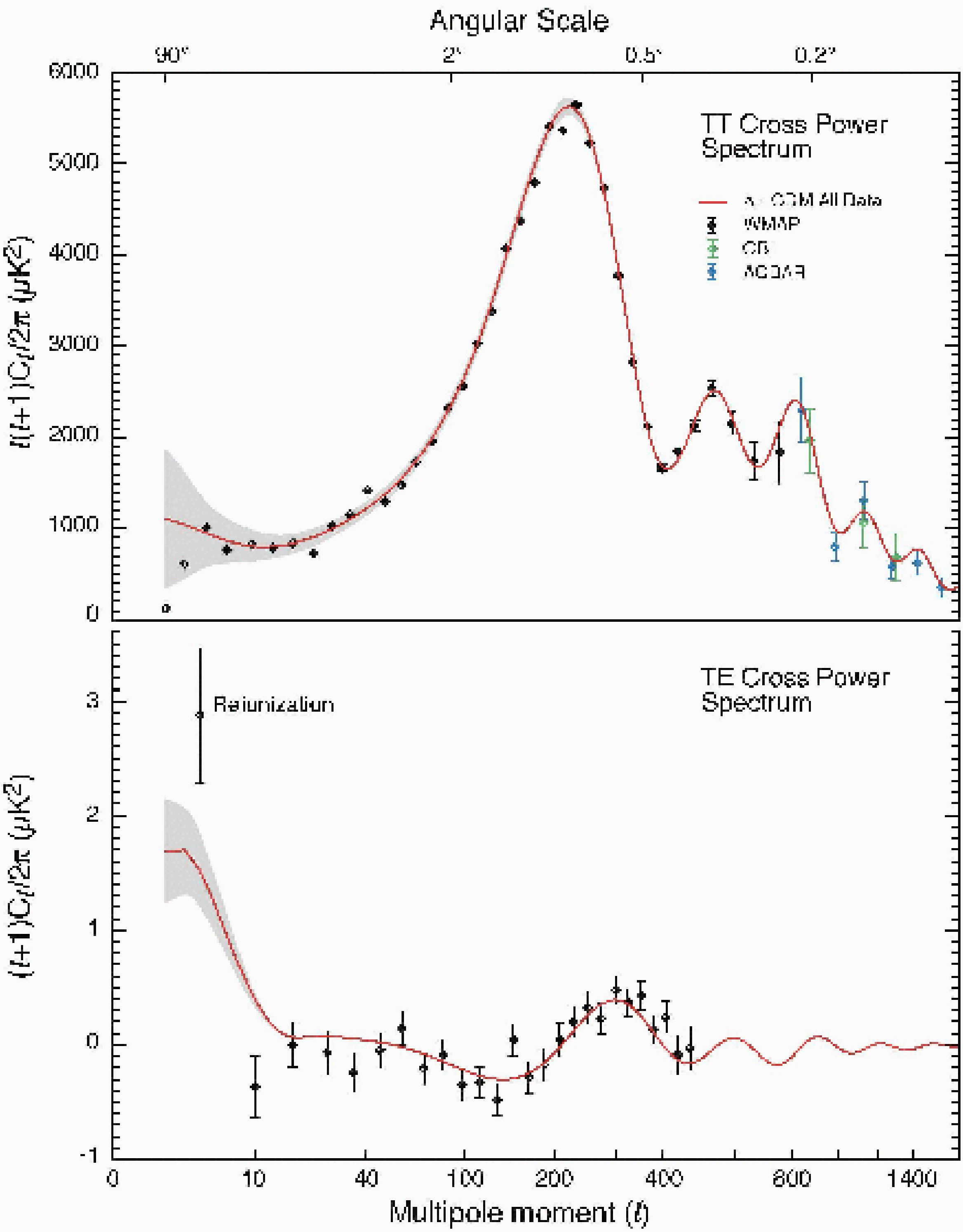


Low WMAP multipoles



The quadrupole (top), octopole (middle) and hexadecapole (bottom) components of CMB map from Figure 1 are shown on a common temperature scale (Tegmark et. all. 2003).

CMB power spectrum



The homogeneity problem

An expanding Universe has a particle horizon, that is, spatial region beyond which causal communication cannot occur.

$$\boxed{d_H(t) = a(t)\int_0^t \frac{dt'}{a(t')} \simeq H^{-1}(t)}$$

The fact that the causal horizon grows faster, $d_H \propto t$, than the scale factor, $a \propto t^{1/2}$, implies that at any given time the Universe contains regions within itself that, where never in causal contact.

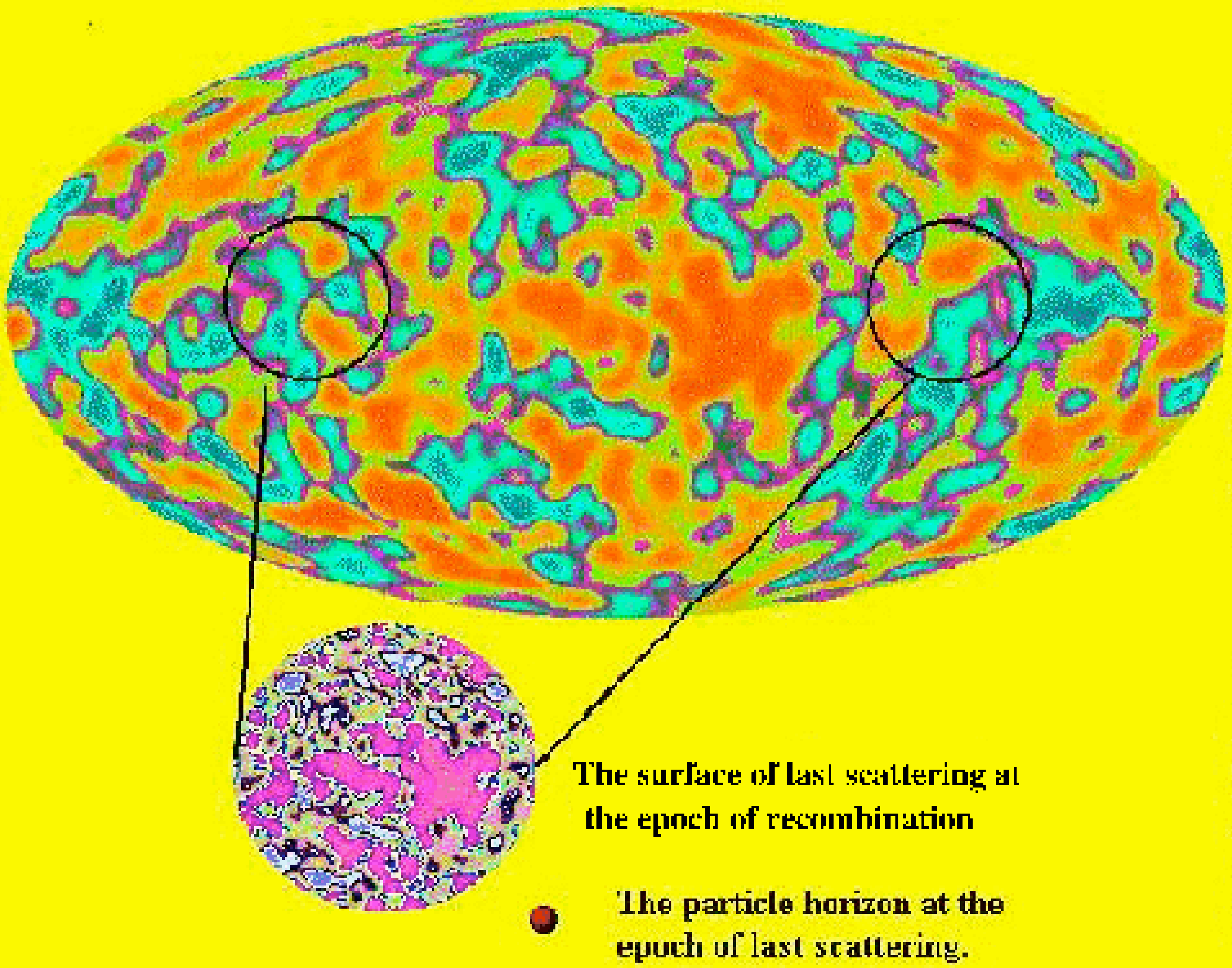
The number of causal disconnected regions at a given redshift z present in our causal volume today, $d_H(t_0) = a_0$, is

$$\boxed{N_{CD}(t_{dec}) \propto \left(\frac{a(t_{dec})}{d_H(t_{dec})}\right)^3 \simeq 10^5 >> 1}$$

The causal region at the time of photon decoupling could not be larger than $d_H(t_{dec}) \simeq 3 \cdot 10^5$ light years across, or about 1^0 projected in the sky today.

Why should regions that are separated by more then 1^0 in the sky today have exactly the same temperature? The photons that come from those two distant regions could not have been in causal contact when they were emitted.

The homogeneity problem



The cosmic microwave background radiation implies that the radiation on the surface of last scattering was homogeneous and isotropic to a very high degree. The temperature fluctuations at left are on the order of one part in 10^{-5}.

The radiation on the last scattering surface displayed this level of uniformity on a surface of radius 10 times the radius of the particle horizon at that epoch.

Cosmological inflation

The Universe went through a period of exponential expansion, driven by the approximately constant energy density of a scalar field called inflaton

This superluminal expansion is capable of explaining the large scale homogeneity of our observable universe and, in particular, why the microwave bacground looks so isotropic: regions separated today by more than 1^0 in the sky were, in fact, in causal contact before inflation, but they were stretched to cosmological distances by the expansion.

If the energy density of the scalar field dominates the kinetic energy, $V(\phi) >> \dot{\phi}^2$

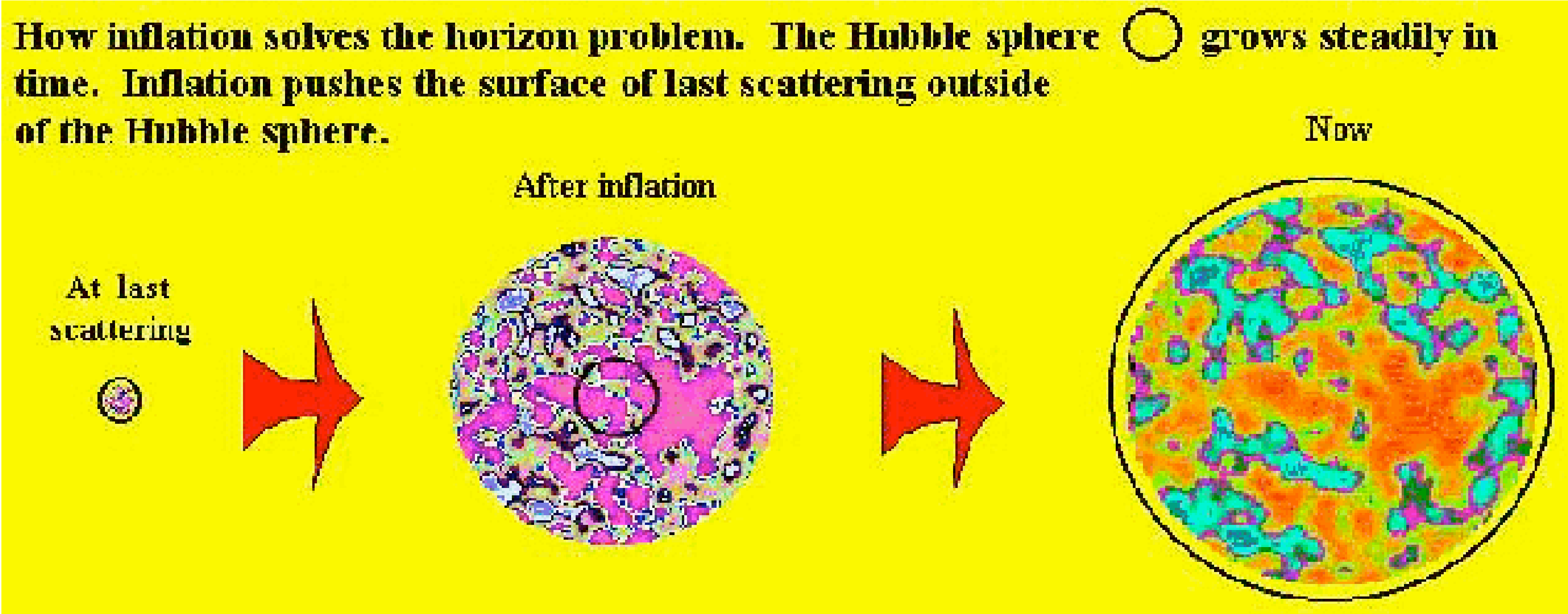
$$p \simeq -\rho \quad \Rightarrow \quad \rho \simeq const \quad \Rightarrow \quad H(\phi) \simeq const$$

$$a(t) = a_i \exp(Ht) = a_i \exp(N) \quad \Rightarrow \quad \frac{\ddot{a}}{a} > 0$$

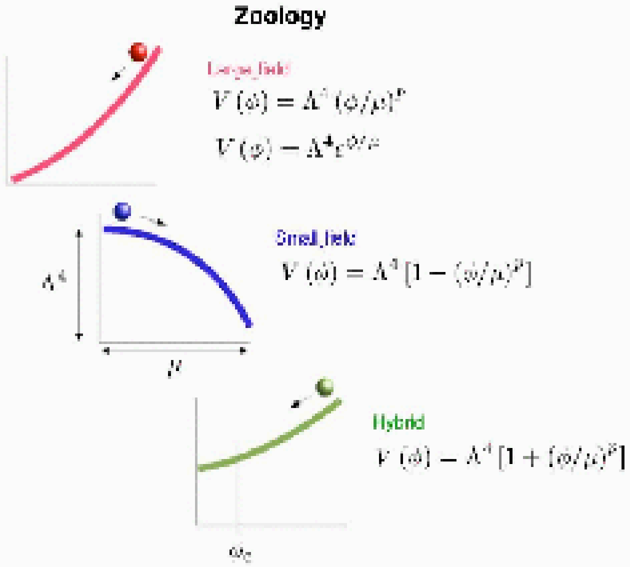
The scale factor grows exponentially, while the horizon distance remains essentially constant $d_H \simeq H^{-1} = const$, any scale within the horizon during inflation will be stretched by the superluminal expansion to enormous distances, in such a way that at photon decoupling all the causally disconnected regions that encompass our present horizon actually come from a single region during inflation.

$$N \approx 60$$

The inflation



Inflation from scalar field



$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)\,; \quad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3m_{\rm Pl}^2}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right]; \quad a(t) \propto e^{Ht}$$

If the potential is sufficiently flat, $V'(\phi) \ll V(\phi)$.

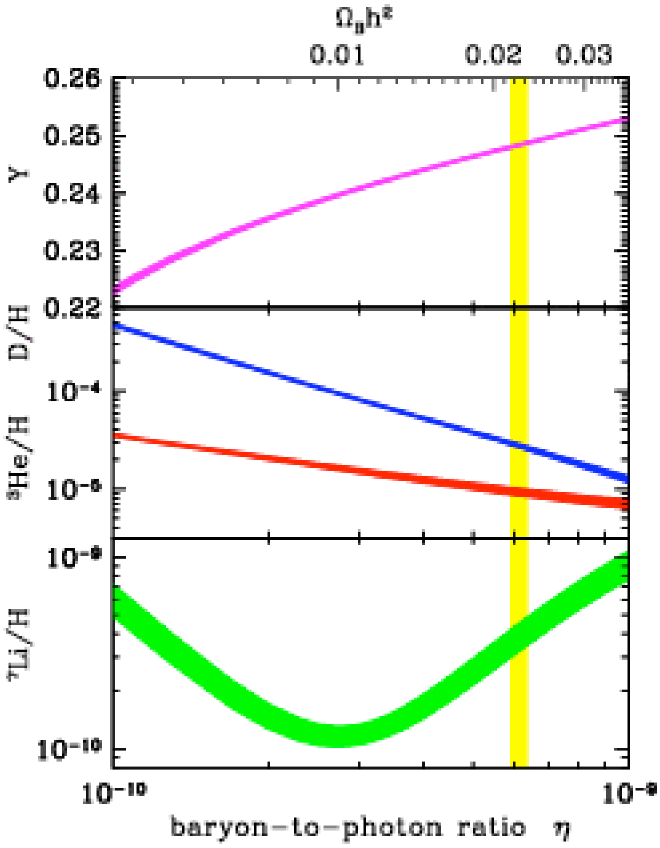
$$3H\dot{\phi} + V'(\phi) \simeq 0$$

BBN baryometer

The baryon number density $n_B \propto a^{-3}$.

$$\eta = \frac{n_B}{s} = \frac{n_b - n_{\bar{b}}}{n_\gamma} = \frac{n_B}{n_\gamma}; \quad \eta \equiv \eta_{10}/10^{10}$$

The BBN method for determining the baryon density of Universe is the concordance of the BBN predictions and the observations of the light element abundances of D, ^{3}He, ^{4}He, and ^{7}Li



The likelihood analyses using the combined ^{4}He, ^{7}Li and D/H observations gives a 95 % CL range of $5.1 < \eta_{10} < 6.7$ with a most likely value of $\eta_{10} = 5.7$ corresponding to $\Omega_B h^2 = 0.021$.

The baryon symmetric Universe?

How do we observe that our Universe is matter-antimatter asymmetric as a whole?

What is, if the dominance of matter over antimatter is only local up to a certain scale L_B

- **Direct observations exclude the macroscopic amount of antimatter within the distance up to 20Mpc, because the reaction of annihilation** $p\bar{p} \to \pi^0 \to \gamma$ (*G.Steigman 1976, F.M.Stecker et all 1971, 1985*)

- **Annihilation is unavoidable. The larger then 20Mpc matter and antimatter regions must be in contact, because of uniformity of CMBR.** (*W.H.Kinney, E.W.Kolb, M.S.Turner 1997*)

- **The annihilation, which would take place at the border between matter and antimatter region, during the early stages, disturbs the observable diffuse γ − ray background. It does not happen if $L_B > 10^3$Mpc.** (*A.G.Cohen, A.De Rujula, S.L.Glashow 1998*)

We are living in the Universe, which does not contain any significant amount of antimatter.

$$\boxed{\frac{V_{matter}}{V_{antimatter}} >> 1}$$

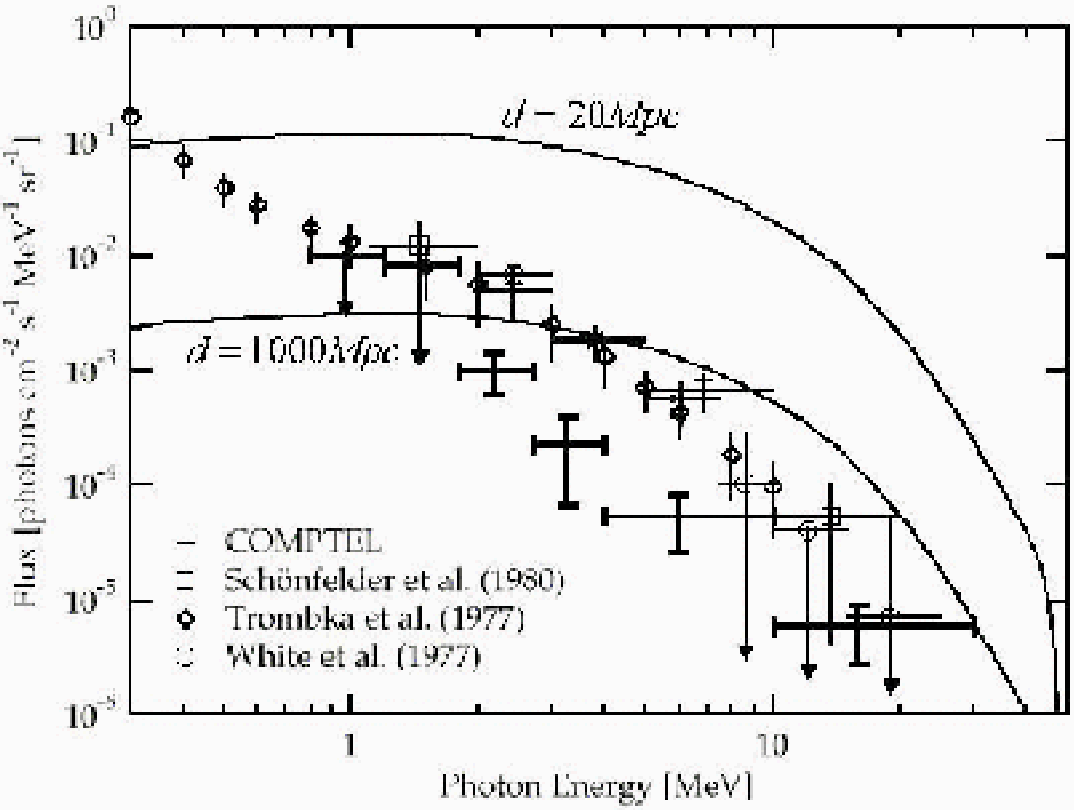
The experimental constraints

Experimental constraints on the existence of antimatter

- **According to direct observations from X-ray emitting clusters** (G. Steigman 1976, F.W Stecker 1985)

Clusters of galaxies of typical size $d \approx 20 Mpc$ are the largest objects that cannot contain significant ($\nu_{\bar{B}} \approx \nu_B$) admixture of antimatter

- **Indirect constraints** (A.G.Cohen, A.De.Rujula, S.L.Glashow 1997)



In the B=0 Universe it is impossible to avoid annihilation near the borders between matter and antimatter regions during the epoch $1100 > z > 20$.

The critical surviving size

The primordial antimatter domains to be formed in the early Universe, must be astronomically large but not too large and sufficiently rare

Astronomicaly large antimatter regions get formed out of primordial antimatter region which are not caten up by diffusion of surrounding matter.

$$\frac{\partial r}{\partial t} = D(t)\frac{\partial^2 r}{\partial l^2}; \quad r = \frac{n_B}{n_\gamma}; \quad \frac{\partial n_\gamma}{\partial t} = -\alpha n_\gamma$$

$$D(t) \approx \frac{3T_\gamma c}{2\rho_\gamma \sigma_T} \approx 0.61 \cdot 10^{32} z^{-3} cm^2/s$$

A primordial antimatter region which grows up to 1pc or more at the end of RD epoch remains unaffected by the diffusion

Without any evolution the contemporary physical surviving size of antimatter region

$$L_{antimatter} > l_c = 8h^2 kpc$$

The basic conditions for baryogenesis

The three Sakharov conditions should be valid simultaneously in the early Universe

1. Baryon number violation

2. No symmetry between particles and antiparticles C and CP violation

3. Departure from thermal equilibrium

If all the particles in the Universe remained in thermal equilibrium, then no preferred direction for time evolution can be defined and the CPT invariance would prevent the appearance of any baryon excess, making the presence of CP violating interactions irrelevant

Inhomogeneous baryogenesis requires that CP violation has different sign in different space regions

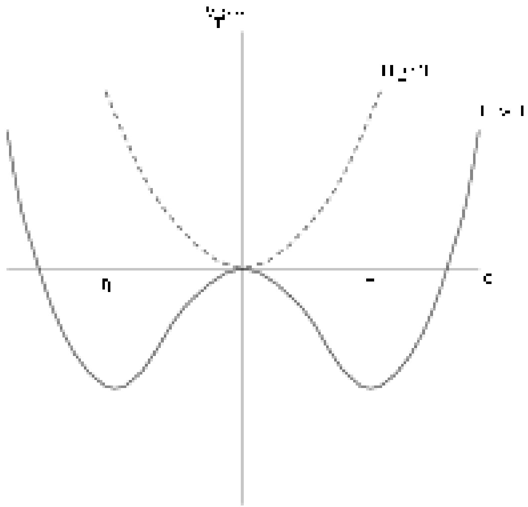
globaly CP is $+ \rightarrow$ matter

somewhere CP is $- \rightarrow$ antimatter

The thermal corrections

A thermal bath, in the early Universe, represents the thermal distribution of particles.

$$\boxed{V_{eff,T}(\phi) = \left[-\frac{\mu^2}{2} + \frac{3\lambda T^2}{4\pi} b(T)\right]\phi^2 + \frac{\lambda^4}{4}\phi^4}$$



Critical temperature

$$\boxed{T_c \simeq \eta}$$

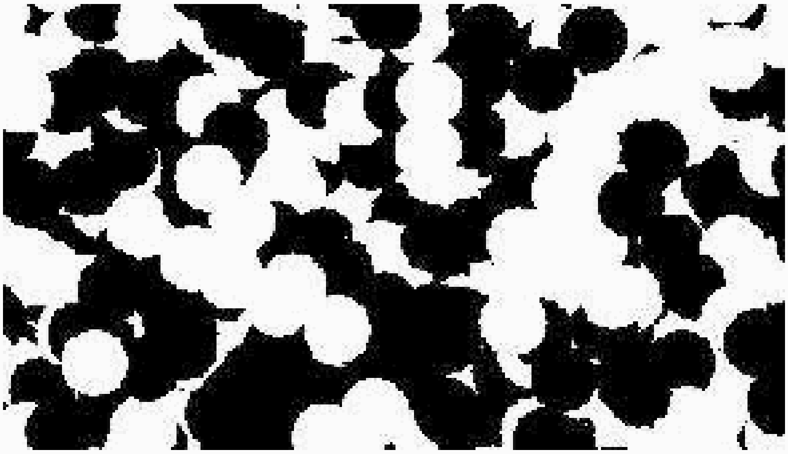
By causality the characteristic length is bounded from above by $H(t_c)^{-1}$, however the typical length is

$$\boxed{\xi(t_c) \simeq \lambda^{-1}\eta^{-1}}$$

$$\boxed{-\eta \rightarrow \mathrm{CP} \text{ is } +}$$

$$\boxed{-\eta \rightarrow \mathrm{CP} \text{ is } -}$$

Scales



The correlation length defines the maximal possible size of domain with wrong sign (antimatter) of CP violation

$$\xi \simeq \frac{1}{\lambda T_0} \simeq 10^{-21} \frac{pc}{\lambda} \qquad 1 > \lambda > 10^{-14}$$

The critical surviving scale

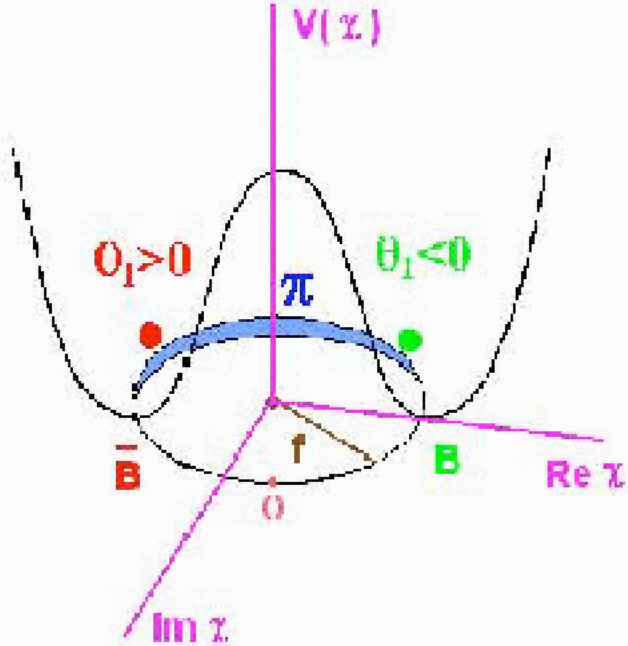
$$l_c \approx 2kpc$$

The inflation is the mechanism, which could blow-up the scale of correlation length.

$$l_{infl} \propto H_{infl}^{-1} e^{N_e}$$

$$l_{infl}(H_{infl} \approx 10^{13} GeV; N_e = 45) \to l_c$$

Spontaneous baryogenesis



Complex, baryon charged scalar field $\chi = \frac{f}{\sqrt{2}}\exp(i\theta)$

$$\boxed{V(\chi) = -m_{\chi}^2\chi^*\chi + \lambda_\chi(\chi^*\chi)^2 + V(\theta) + V_0}$$

$$\boxed{V(\theta) = \Lambda^4(1 - \cos\theta)}$$

The lepton number violation (*A.D.Dolgov et all 1996*)

$$\boxed{\mathcal{L}_{\Delta L} = g\chi QL + \text{h.c.}}$$

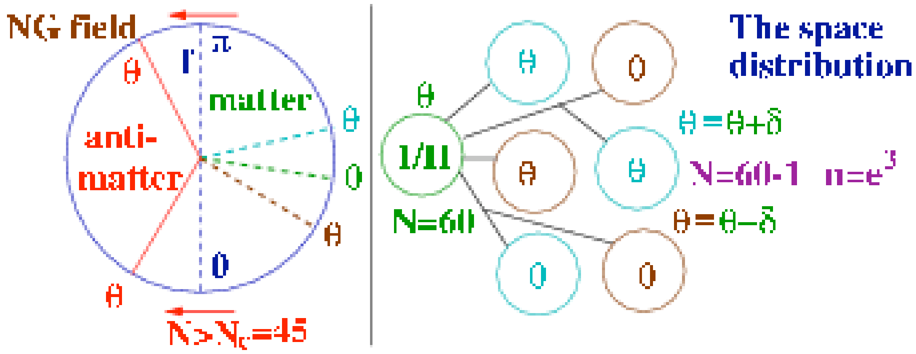
$$\boxed{\mathrm{U}(1): \quad \chi; Q \to \exp(i\beta)\chi; Q \qquad L \to L}$$

The number density of produced

$\theta_I < 0 \to$ baryons/$\theta_I > 0 \to$ antibaryons

$$\boxed{n_{B(\bar{B})} = \frac{g^2 f^2 m_0}{4\pi^2}\theta_I \int_{+\frac{\theta_I}{2}}^{\infty} d\omega \frac{\sin^2\omega}{\omega^2}}$$

Quantum fluctuations



During inflation the bottom is flat $m_\theta = \frac{\Lambda^2}{f} << H$

Since θ field is effectively massless, every e-fold it makes a quantum step with the lenght $\delta\theta = \frac{H}{2\pi f}$

During the time interval Δt the number of steps is $N = H\Delta t$ (e-fold)

$$N_{max} \approx 60 \rightarrow 3000h^{-1}\mathrm{Mpc} \text{ (size of the Universe)}$$

$$N_c = 45 \rightarrow l_c \text{ (critical surviving size)}$$

Astronomically large antimatter regions get formed before the 45th e-fold

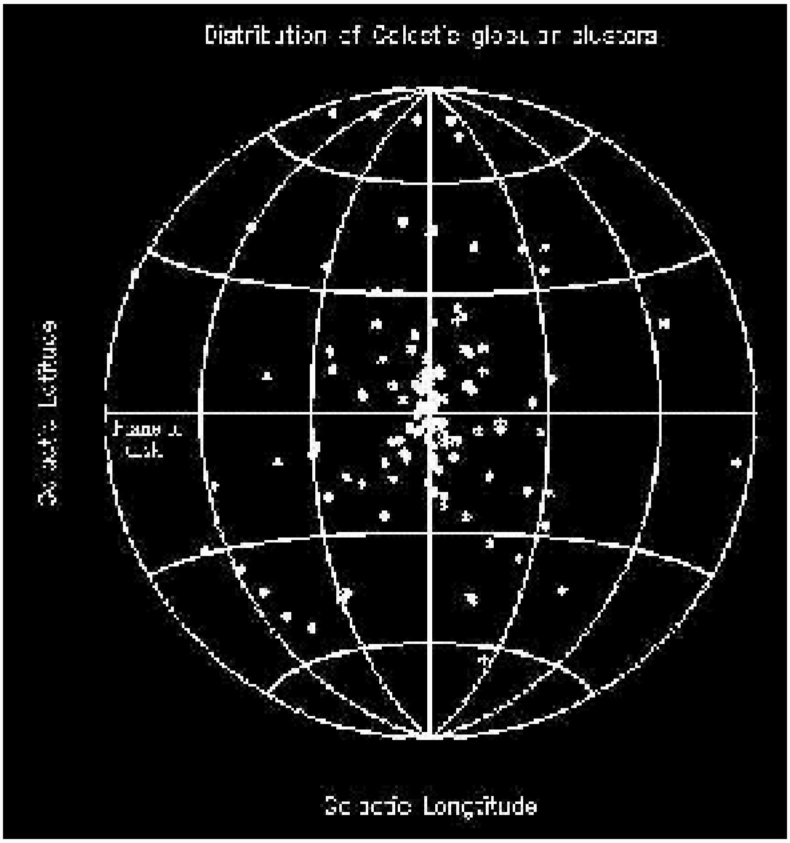
$\theta_{60} = \frac{\pi}{6}$; $\delta\theta = 0.026$

e-fold	n_{anti}	Size$\cdot h^{-1}$
50	74	255 kpc
49	$9 \cdot 10^3$	94 kpc
48	$8 \cdot 10^5$	35 kpc
47	$5.6 \cdot 10^7$	12 kpc
46	$3.34 \cdot 10^9$	4.7 kpc
45	$1.7 \cdot 10^{11}$	1.7 kpc

The total number of galaxies $\approx 10^{11}$

$$\boxed{\frac{V_{antimatter}}{V_{matter}} = 7.6 \cdot 10^{-9} << 1}$$

Globular clusters

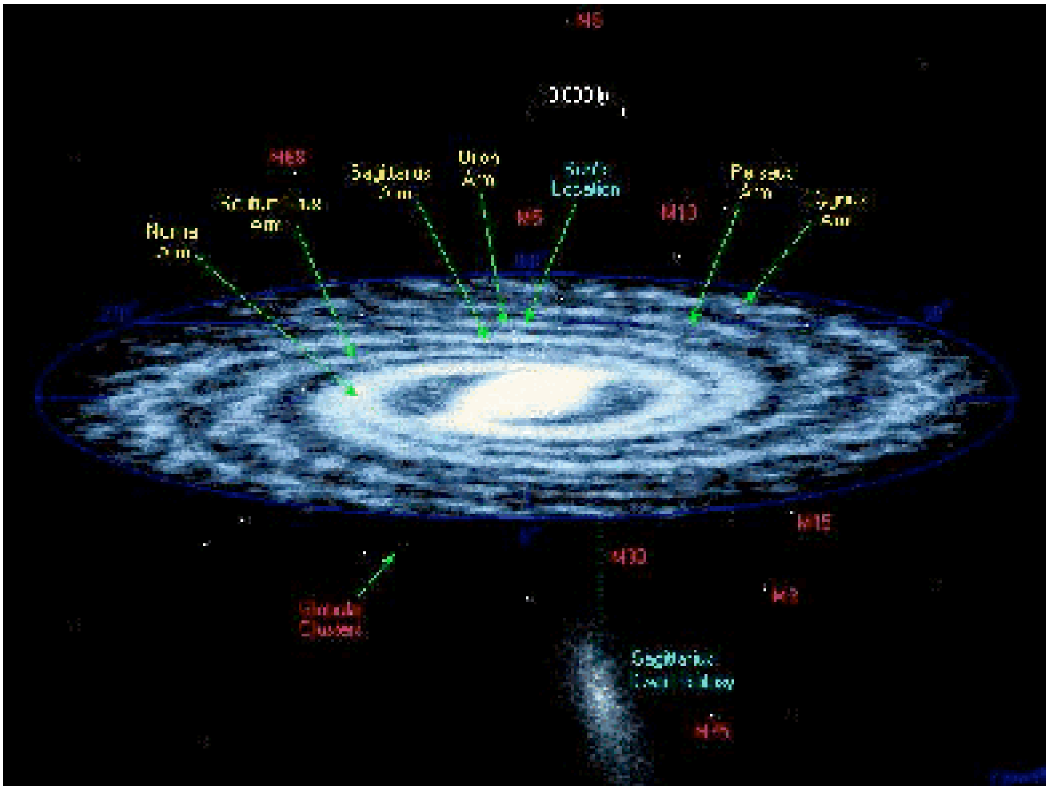


- l_c at the recombination epoch coincide with the scale of protoglobular clusters
- The volume box coming with every galaxy can contain up to 10 antimatter regions
- In a half of regions the density of the antimatter can be several times higher then the density of sorrounding matter. What makes them gravitationaly unstable.

If the high density antimatter region has been formed in our Galaxy, it survives in the form of globular cluster at large galactocentric distance.

Globular cluster population in our Galaxy consists of 147 confirmed globular clusters. One of them could be made out of antistars.

Globular Clusters



Annihilation on anti-stars

The γ radiation from from annihilation of antimatter with galactic matter gas should not exceed the observed γ-ray background

$$\boxed{\mathrm{v}_{\mathrm{disp}} \simeq 300\ \mathtt{km/s;}\ \ < r > \simeq 20\mathrm{pc}\,;\ \ D \simeq 100\mathrm{pc}}$$

$$\boxed{t_{orb} \simeq 2 \cdot 10^{15}\mathtt{s};\ \ t_{cross} \simeq 10^{13}\mathtt{s}}$$

The cluster spends not more than 1% of the time in the dense region.

The annihilation of matter gas captured by the antimatter stars

$$\boxed{\sigma_{capture} \simeq \pi R \left(R + \frac{2GM}{v^2}\right) \approx 4 \cdot 10^{22}\mathrm{cm}^2}$$

The γ luminosity of a cluster of 10^5 $(M_5 - 10^3 M_\odot)$ stars

$$\boxed{L_\gamma \ \le\ M_5 \cdot 10^{29}\, erg/s}$$

$$\boxed{F^\gamma_{\mathrm{GeV}} \ \le\ 10^{-13}\ \mathtt{(ster\cdot\ cm^2\cdot\ s)}^{-1}}$$

This explains why the antimatter star itself can be rather faint gamma source elusive for gamma astronomy

$$\boxed{\Phi^\gamma_{\mathrm{GeV}} \ \le\ 10^{-6}\ \mathtt{(ster\cdot\ cm^2\cdot\ s)}^{-1}}$$

The annihilation model

There are two sources of an antimatter pollution from the (anti-)cluster: the (anti-)stellar wind and the antimatter Supernova explosions.

The annihilation cross section of the antiprotons

$$\sigma_{ann}(P < 300\mathrm{MeV}/c) = (160\mathrm{mb})\, C(v^*)/v^*$$

$$C(v^*) = \frac{2\,\pi\, v_c/v^*}{1-\exp(-2\,\pi\, v_c/v^*)}$$

The spherical model for halo with z axis directed to North Pole and x axis directed to the Solar system

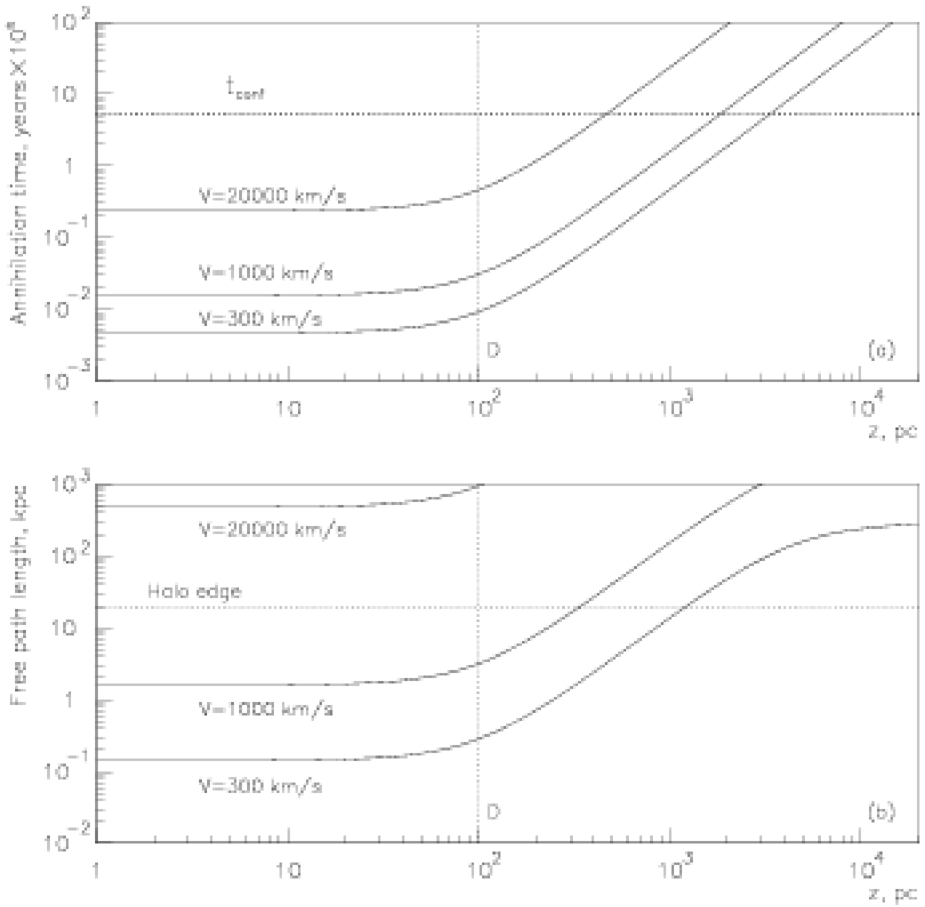
$$n_H(z) = n_H^{halo} + \Delta_H(z); \quad \Delta_H(z) = \frac{n_H^{disk}}{1+(z/D)^2}$$

$$n_H^{halo} = 5 \cdot 10^{-4}\mathrm{cm}^{-3}; \quad n_H^{halo} = 1\mathrm{cm}^{-3}$$

The validity of the stationary approximation depends on the interplay of the life-time of the antiprotons to the annihilation and their confinement time in the Galaxy.

$$\frac{dn_{\bar{p}}}{dE} = I_p(E)\, t_{ann}(E)\left(1 - e^{-t/t_{ann}}\right)$$

Confinement versus annihilation



For antiprotons with velocities 10^3 km/s (stellar wind) the confinement time in the halo, starting from distancies $z \sim 2$ kpc, is less than their annihilation time

$$n(E) \approx I_{\bar{p}}(E) T_{conf}$$

During large confinement time $\approx 5 \cdot 10^8$ yrs the antiprotons are being spread over the halo with constant number density not depending on the position of the antistars cluster and under usual acceleration mechanisms in the halo their energy spectrum comes to the stationary form.

The upper mass limits

We chose the antiproton spectrum in the halo to be similar to the galactic cosmic-rays proton spectrum

$$n_p(E, z >> D) \sim \left(\frac{1\,\mathrm{GeV}}{E_{kin}}\right)^{2.7}$$

$$\int_{E_{min}}^{\infty} n_{\bar{p}}(E, z >> D)\, dE = n_0$$

We choose the minimal velocity of antiprotons v_{min}, one can obtain the necessary integral number density of the antiprotons n_0 to be not above the Galactic North Pole EGRET data.

Stelar wind

$v \approx 10^3 \mathrm{km/s};\ n_0 \approx 5.0 \cdot 10^{-12} \mathrm{cm}^{-3};$

$\dot{M}^{SW} \approx 8.5 \cdot 10^{-9}\ M_{\odot}/yr$

Eliptical galaxies $10^{-12} M_{\odot}$ per $M_{\odot}$

$\mathrm{M}_{\mathrm{GC}}^{\mathrm{max}} \approx 2 \cdot 10^4 \mathrm{M}_{\odot}$

Dispersion velocity

$v \approx 300 \mathrm{km/s};\ n_0 \approx 2.0 \cdot 10^{-12} \mathrm{cm}^{-3};$

$\dot{M}^{disp} \approx 3.0 \cdot 10^{-9}\ M_{\odot}/yr$

$\mathrm{M}_{\mathrm{GC}}^{\mathrm{max}} \approx 7 \cdot 10^3 \mathrm{M}_{\odot}$

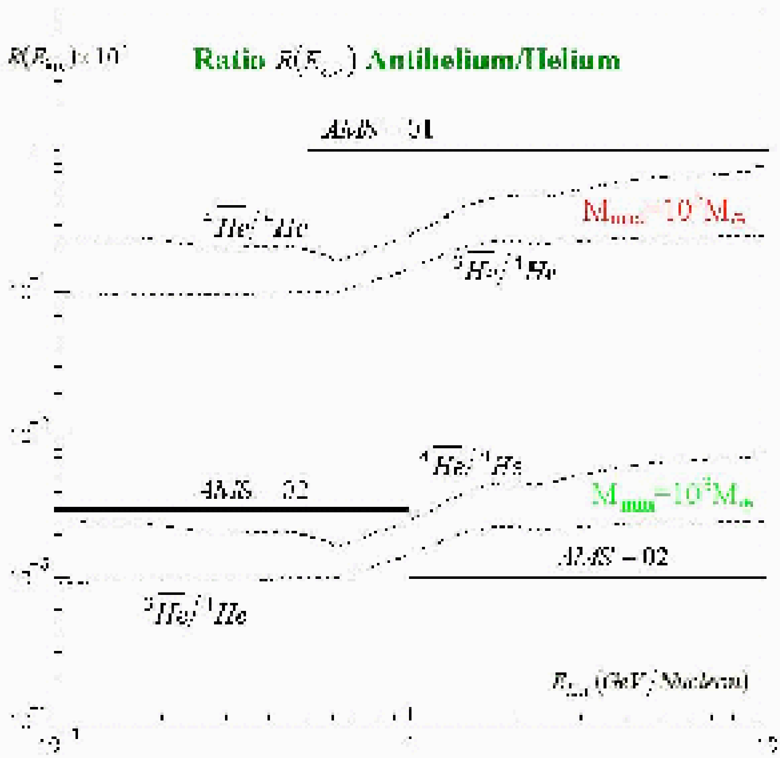
Supernova explosions

$v \approx 2 \cdot 10^4 \mathrm{km/s};\ n_0 \approx 6.0 \cdot 10^{-11} \mathrm{cm}^{-3};$

$\dot{M}^{SN} \approx 1.0 \cdot 10^{-7}\ M_{\odot}/yr$

$\mathrm{M}_{\mathrm{GC}}^{\mathrm{max}} \approx 4 \cdot 10^5 \mathrm{M}_{\odot}$

Experimental signature



The integral effect of "anticluster" in our galaxy is estimated by the analysis of antimatter pollution.

The main source is the stelar wind.

The main content of pollution is $\bar{p}$ and ^4He

$\bar{p}$'s are collecting in the galaxy $\to \gamma$ flux.

EGRET normalization $\to M_{max} = 10^5 M_{\odot}$

$l_c \to M_{min} = 10^3 M_{\odot}$

Expected flux of $^4\bar{He}$ in cosmic rays

$$\frac{N_{\bar{He}}}{N_{He}} \approx 10^{-8} - 10^{-6} \qquad E > 0.5\ \text{GeV/nucleon}$$

$^4He + p \to {}^3He + \text{all}$, **inelastic nuclei destruction, ionization and excitation of H atoms**

The uncertainty

The actual distribution of magnetic field in our Galaxy.

The mechanism of cosmic ray acceleration

The relative contribution of disc and halo particles into the cosmic ray spectrum

The acceleration of matter and antimatter cosmic rays are similar

The contribution of antinuclei into the cosmic ray fluxes is proportional to the mass ratio of globular cluster and Galaxy.

Conclusions

- The existence of a small number of primordial antimatter regions in the matter/antimatter asymmetric Universe does not contradict to direct and indirect observations of diffuse γ–ray background

- A considerable number of antimatter domains is found in the inflationary model with spontaneous baryogenesis

- The comming up AMS 02 and PAMELA experiment provide the test of the hypothesis of the existence of antimatter globular cluster in our galaxy, in the mass range $10^5 M_\odot - 10^3 M_\odot$