Baryon-dominated Universe with macroscopically large antimater regions

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OUTLINE

- **Constraints on the existence of antimatter in the Universe**
- **Inhomogeneous baryogenesis**
- **Possible evolution and experimental signature of antimatter regions**
- **Isocurvature issues**
- **Conclusions**

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 $\gamma -$ 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.

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

The critical surviving size

The Universe with observable antimatter domains can be created if a certain phase transition occurred at inflationary stage leaving behind astronomically large regions with different physical conditions.

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 eaten up by diffusion of surrounding matter.

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

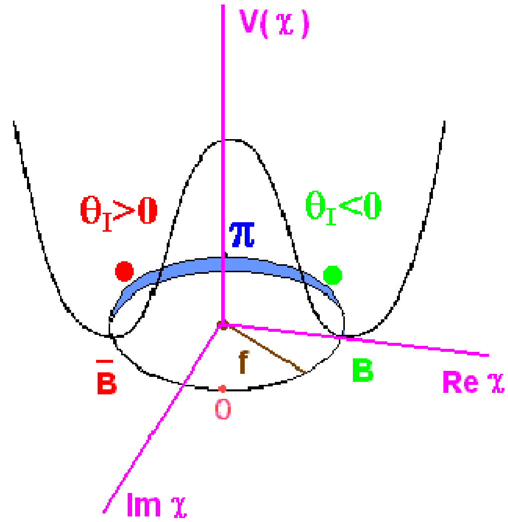
$$\boxed{D(t) \approx \frac{3T_\gamma c}{2\rho_\gamma \sigma_T} \approx 0.61 \cdot 10^{32} z^{-3} cm^2/s}$$

A primordial antimatter region which grows up to 1pc or more at the end of RD epoch remains unaffected by the diffusion (*M.Yu.Khlopov, R.V.Konoplich, R.Mignani, S.G.Rubin, A.Sakharov 1999*)

The contemporary physical surviving size of antimatter region

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

Spontaneous baryogenesis



Complex, baryon charged scalar field $\chi = \frac{f}{\sqrt{2}} \exp(i\theta)$ (*A.Cohen & D.Kaplan 1987*)

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

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

The lepton number violation (*A.Cohen & D.Kaplan 1987; A.D.Dolgov et all 1996*)

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

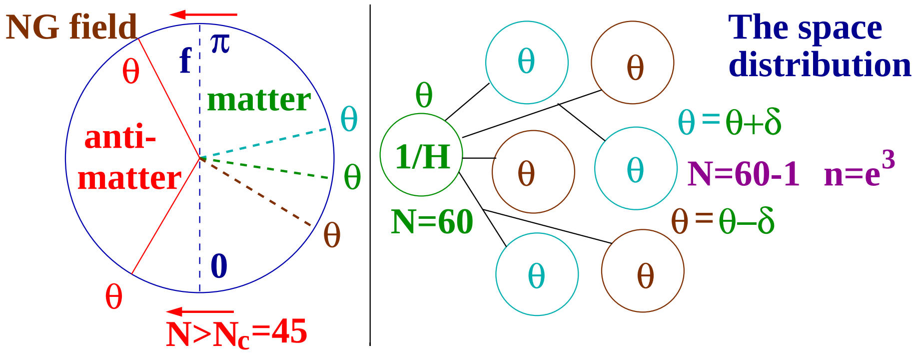
$$\mathrm{U}(1): \qquad \chi; Q \to \exp(i\beta)\chi; Q \qquad L \to L$$

The number density of produced

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

$$n_{B(\bar{B})} = \frac{g^2 f^2 m_\theta}{4\pi^2}\theta_I \int_{\mp\frac{\theta_I}{2}}^{\infty} d\omega \frac{\sin^2\omega}{\omega^2}$$

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)**

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

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

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 $\approx 10^{11}$

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

Baryon/Antibaryon Density

The reheating takes place due to the decays of inflaton ϕ, when the PNG potential is still flat

$$\boxed{\Gamma^{\phi}_{tot} >> m_{\theta}}$$

The relaxation of θ along the angular direction starts at the condition

$$\boxed{H \simeq m_{\theta} \simeq \sqrt{g_*}\frac{T^2}{M_{Pl}}}$$

The baryon/antibaryon – number density

$$\boxed{\frac{n_{B(\bar{B})}}{s} \approx 10^{-2} g^2 \left(\frac{f}{M_{Pl}}\right)^{3/2} \frac{f}{\Lambda} F(\theta_i)}$$

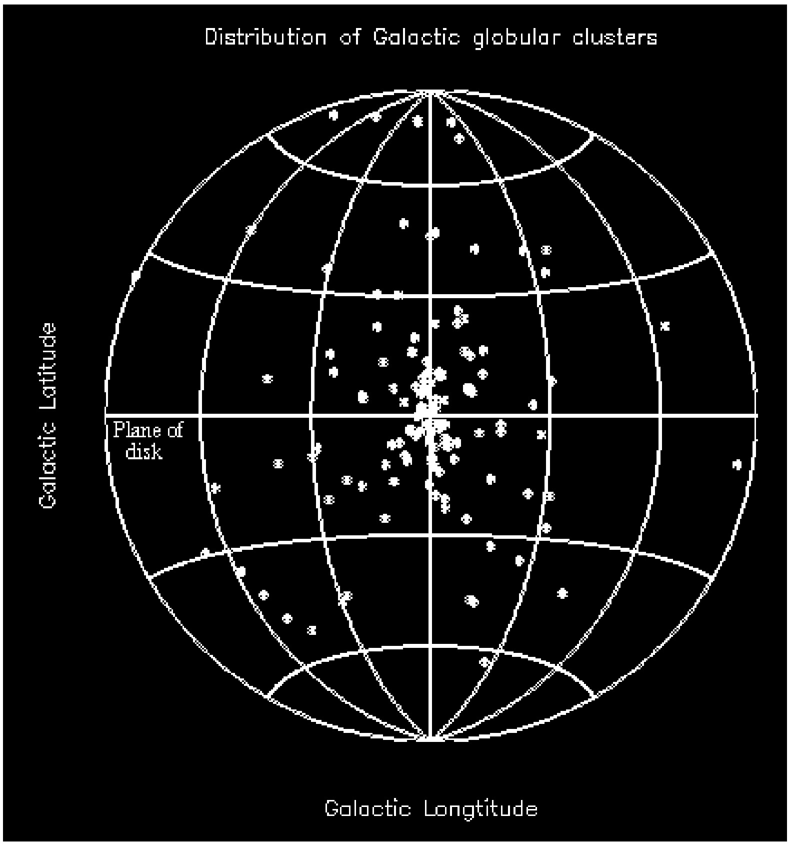
Normalization on the observable baryon asymmetry

$$\boxed{f \geq H \approx 10^{-6} M_{Pl}; \qquad g \simeq 10^{-2}; \qquad \frac{f}{\Lambda} \geq 10^5}$$

At small $\theta_i << 1$

$$\boxed{\frac{n_{B(\bar{B})}}{s} \propto \theta_i^3}$$

Globular clusters

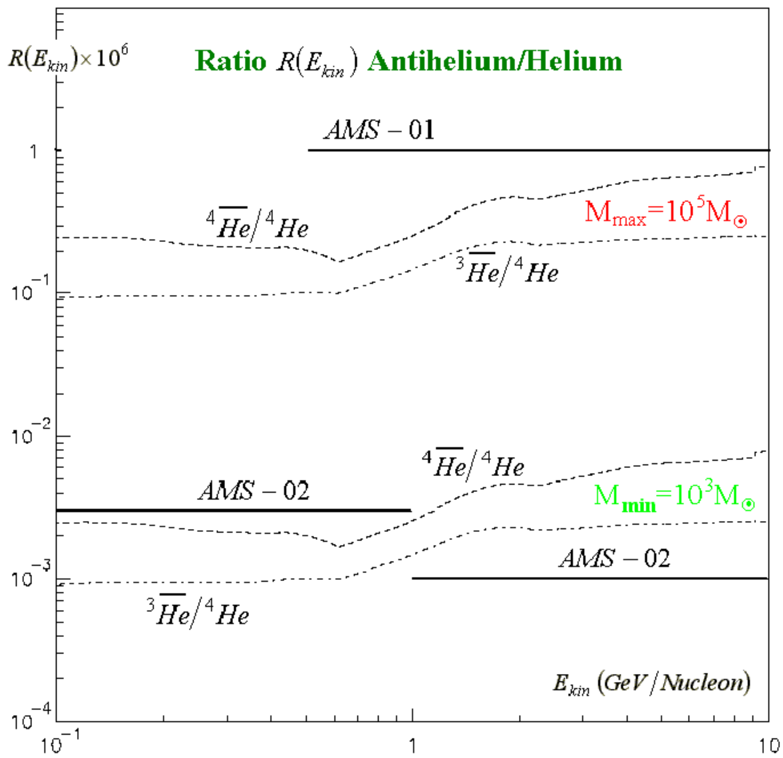


- l_c at the recombination epoch coincide with the scale of protoglobular clusters
- The volume box coming with every galaxy can contain up to 10 antimatter regions
- In a half of regions the density of the antimatter can be several times higher then the density of sorrounding matter. What makes them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

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 $^4\bar{H}e$

$\bar{p}$'s are collecting in the galaxy$\rightarrow$ γ flux.

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

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

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

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

$^4\bar{H}e + p \rightarrow {}^3\bar{H}e + \mathrm{all}$, **inelastic nuclei destruction, ionization and excitation of H atoms**

Isocurvature fluctuations

Baryogenesis models with antimatter regions is a radical limit of models with local baryon number density fluctuations δ_B

$$\boxed{\delta_B \rightarrow \text{ Isocurvature fluct}}$$

$$\boxed{\text{Isocurvature fluctuations} \rightarrow \text{CMB}}$$

$$\boxed{\frac{\Delta T_{CMB}}{T_{CMB}} \approx -\frac{\Omega_B}{\Omega_{tot}}\delta_B \qquad \left(\frac{\Delta T_{CMB}}{T_{CMB}}\right)_{COBE} \simeq 10^{-5}}$$

$$\boxed{\frac{\Omega_B}{\Omega_{tot}} \simeq 10^{-2}}$$

$$\boxed{\delta_B < 10^{-3}}$$

We need

$$\boxed{\delta\theta = \delta_B \simeq 10^{-2}}$$

To obtain a small CMBR anisotropy and still be able to generate astronomically large antimatter regions one should strongly suppress the isocurvature fluctuation on the horizon scale while keeping them suffisiently large on the $\simeq$kpc scales.

Varying dispersion

$$V(\phi,\chi) = \frac{1}{2}m_\phi\phi^2 + V(\chi) + V_{\phi\chi}(\phi\chi)$$

$$\lambda(\chi\chi^* - \frac{f^2}{2})^2 - g_{\phi\chi}\chi\chi^*(\phi - cM_{Pl})^2$$

$$H^2 = \frac{4\pi m_\phi^2\phi^2}{3M_{Pl}^2}$$

$$\sqrt{\frac{3}{4\pi}}g\frac{HM_{Pl}}{m_\phi}\chi\chi^*(H - \sqrt{\frac{4\pi}{3}}m_\phi)^2$$

In SUSY & SUGRA $\propto \alpha H^2$**;** $\propto \beta H$

$$f_{eff} = \sqrt{f^2 + \frac{g}{\lambda}(\phi - cM_{Pl})^2}$$

$$f_{eff} = f\sqrt{1 + \frac{g}{\lambda}\frac{M_{Pl}^2}{f^2}(N_f - N)^2}$$

The dispersion depends on e-folds

$$\delta\theta = \frac{H}{2\pi f_{eff}}$$

Cutoff

Mean-square density perturbation

$$\boxed{\frac{<(\delta\theta)^2>}{\theta^2} = \left(\frac{H}{2\pi f}\right)^2 \ln\frac{k_{max}}{k_{min}} \simeq \left(\frac{H}{f}\right)^2}$$

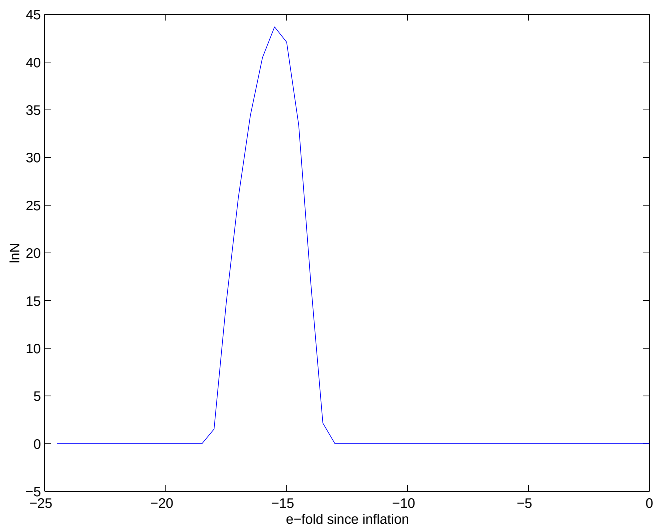
If $H << f$, the field perturbations is small.
Spectrum is time independent Gaussian

$$\boxed{\Delta = 2\frac{\delta\theta}{\theta}; \qquad P_\delta^{1/2} = \frac{H}{\pi f} << 1}$$

In the opposite regime $H \geq f$, the perturbations can be bigger than unperturb value. Spectrum is time independent nonGaussian

$$\boxed{\Delta = \frac{(\delta\theta)^2}{<(\delta\theta)^2>}; \quad P_\delta(k) = 4\ln(k/k_{min})\frac{P_\theta(k_{min})^2}{<(\delta\theta)^2>} \simeq 1}$$

After $N \approx f/H$ e-folds, the local value of θ jumps to the antimatter production region in vacuum manifold



Numerical example: $n_{anti} \approx 10^{11}$; $l \approx 3kpc$;
$\delta\theta = 0.05; 1.59; 0.05$; $V_{antimatter}/V_{matter} = 10^{-3}$

Conclusions

- **The existence of small number of primordial antimatter regions in the matter/antimatter asymmetric Universe does not contradict to observations of diffuse γ-ray background.**

- **The appropriate number of antimatter domains can be found in the inflationary model with spontaneous baryogenesis. Isocurvature fluctuations on large scales can be suppresed.**

- **The comming up AMS-02 experiment provides the test of antimatter globular cluster hypothesis in the mass range $10^5 M_\odot - 10^3 M_\odot$.**