

Asymmetric antimatter evolution in a baryon asymmetrical Universe

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What are we studying?

Non-homogeneous baryosynthesis scenario describes the mechanisms of local formation of **antimatter domains**

Mass limitations

- Mass of the domain must be large enough to survive to the modern era
- Gamma background from annihilation at the boundaries should correspond to the observed one

$$10^3 M_{\odot} < M < 10^5 M_{\odot}$$

AMS-02 experiment



The experiment is searching for antihelium nuclei, which would indicate the existence of significant amounts of antimatter in the universe

Antibaryon density

Antimatter domain was formed before the primary nucleosynthesis, so it should contain zero metallicity

$$3 \times 10^{-12} \leq \eta \leq 1 \times 10^{-6}$$

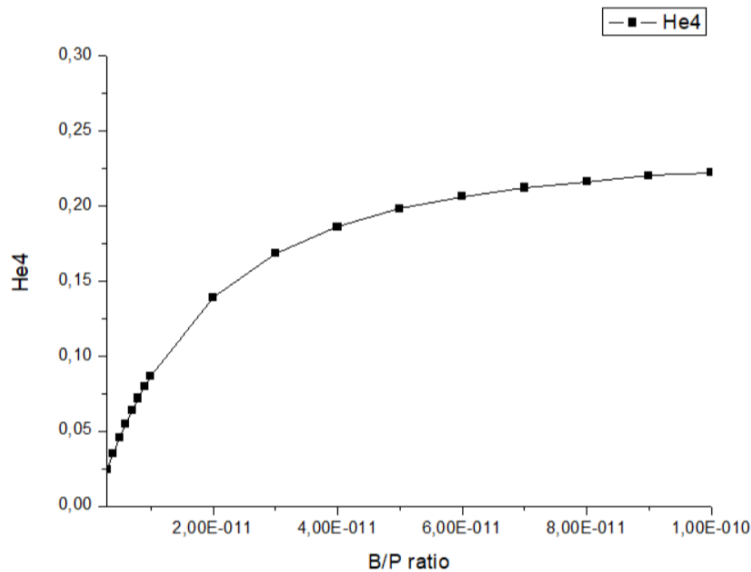


Figure 1. Dependence of the 4He's mass fraction on baryon/photon ratio

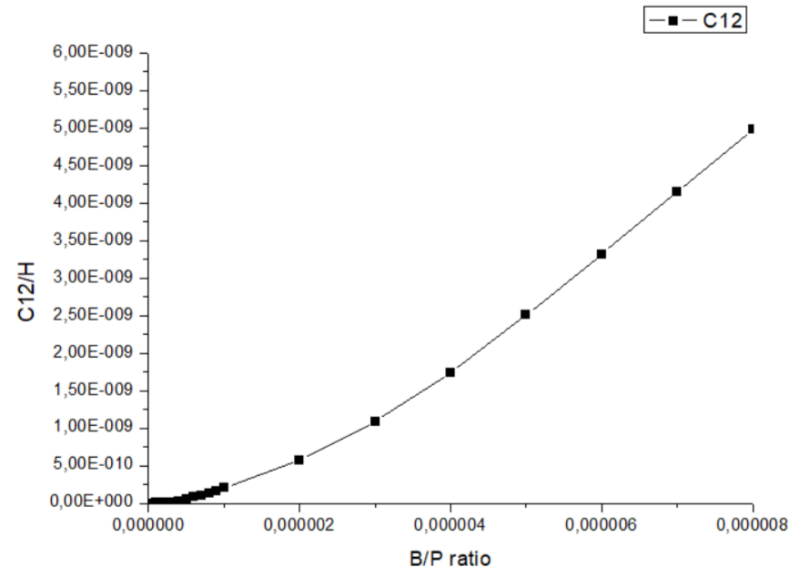


Figure 2. Dependence of the 12C's mass fraction on baryon/photon ratio

Processes at the border

Assuming spherical symmetry, size of the domain might be estimated:

$$R \sim \left(\frac{M}{m_p \eta T^3} \right)^{\frac{1}{3}}$$

Domain enters the horizon

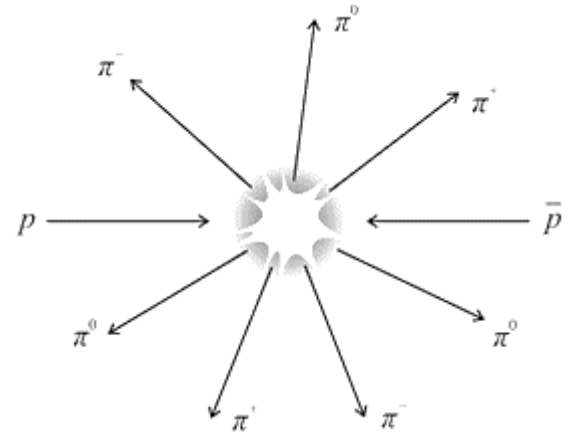
$$t_{\text{form}} = \frac{1}{4c^2} \left(\frac{M}{0.24 m_p \eta T_0^3} \right)^{2/3} \cdot \frac{1}{t_0}$$

At the border of the domain baryon-antibaryon annihilation will occur

Main channels:

- Production of photons due to neutral pion decay

- Production of electrons and positrons due to charged pion decay involving muon production



What is coming inside?

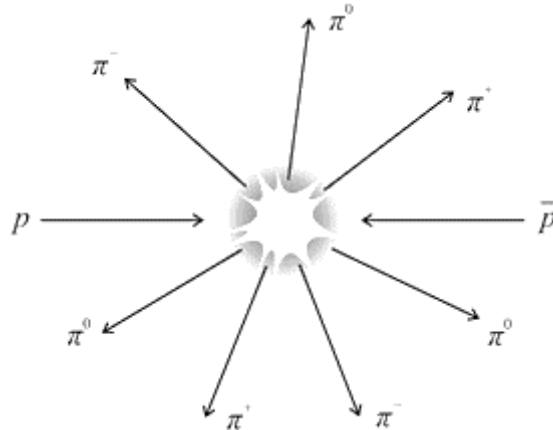
As a result of the processes discussed earlier, annihilation products will penetrate into the interior of the domain. Different processes can take place within the domain

$$T > 10^7 \text{K}$$

Dominant process:
pair production

$$\sigma_{pp} \approx 2,1 \times 10^{-28} \text{cm}^2$$

$$\lambda_{pp} = \frac{1}{0,24T^3\sigma_{pp}}$$



$$T \leq 10^7 \text{K}$$

Dominant process:
multiple Compton scattering

$$\sigma_{eff} \geq 8.4 \times 10^{-22} \text{cm}^2$$

$$\lambda_k = \frac{1}{0,24T^3\eta Z\sigma_{eff}}$$

The mean free path is significantly smaller than the radius of the domain

Diffusion

$$\frac{\partial \bar{n}_b}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 D(t) \frac{\partial \bar{n}_b}{\partial r} \right) - f_m(r, t) \langle \sigma v \rangle_{\text{int}} n_b^{(\text{inc})}(r, t) \bar{n}_b - 3H(t) \bar{n}_b$$

The transport of baryons and antibaryons toward domain boundaries is governed by elastic scattering processes

$$D(t) = \frac{1}{3} \frac{1}{n\sigma} v$$

Radiation-dominant era

Matter-dominant era

Dominant process: Compton scattering

$$D_{RD}(t) \propto \frac{t^{\frac{3}{2}}}{\sigma_{\text{eff}}} \propto t^{\frac{3}{2}}$$

Dominant process: radiation drag

$$D(t) \propto \frac{t^2}{\sigma_{\tau}} \propto t^2$$

Ionization



If the ionization of matter is sufficiently high, it must be taken into consideration when describing the evolution of the domain

Mean free path of electrons

$$L_e(z) \approx \frac{m_e c^2}{K_{\gamma}(z)} \arcsin \beta_0$$

Mean free path for photons

$$\lambda_{\text{UV}} = \frac{1}{n_H \sigma_{\text{ion}}}$$

Flux of UV-photons

$$F_{\text{UV}}(r) \approx \frac{J \bar{g} \kappa_{\text{UV}} L_e}{4} \cdot \frac{R^2}{r^2} \exp\left(-\frac{R-r}{L_e}\right) \cdot \left[1 - \exp\left(-\frac{L_e}{\lambda_{\text{UV}}}\right)\right]$$

$$\frac{\partial x_e}{\partial t} = \bar{\sigma}_{\text{ion}} F_{\text{UV}}(r, t) n_H (1 - x_e) - \alpha_B(T) n_H x_e^2$$

Ionization

Applicability of the model:

1. Annihilation rate
2. Weak ionization
3. Photon mean free path

$$\eta \lesssim 10^{-9}$$

The volume-averaged degree of ionization: $\langle x_e \rangle \approx \frac{6\lambda_{y\Phi}}{R} x_e(R) \approx \frac{6\lambda_{y\Phi}}{R} \propto \eta^{-\frac{2}{3}} M^{-\frac{1}{3}} T^{-2}$

Temperature criterion: $T \geq \left(\frac{m_p}{\sigma_{ion}^3} \right)^{\frac{1}{6}} \left(\frac{1}{0,24\eta^2 M} \right)^{\frac{1}{6}}$

High-density domains require more careful treatment and are described by the model only in a very limited high-temperature region near recombination

Obtained results:

At the border: 1

Inside the ionized layer: 0,22

Inside the domain: decreases exponentially to zero

Averaged over the volume, the domain can be considered neutral

Swiss-cheese model

In the non-homogeneous model short-lived subdomains consisting of matter may form

New source term must be added to the ionization balance:

$$\frac{\partial x_e}{\partial t} = \bar{\sigma}_{\text{ion}} F_{\text{UV}}(r, t) n_H (1 - x_e) - \alpha_B(T) n_H x_e^2 + \boxed{\xi_{\text{ion}} \frac{Q_{\text{ann}}(r, t)}{\Delta E_{\text{ion}} n_H}}$$

Different scenarios

Many small subdomains
uniformly distributed

The ionisation source is uniform
in the interior

$$x_e^{(\text{int})} = \sqrt{\frac{\xi_{\text{ion}} \bar{f}_m \langle \sigma v \rangle_{\text{int}} n_b^{(\text{inc})} \bar{n}_b \varepsilon_{\text{ann}}}{\alpha_B \Delta E_{\text{ion}} n_H^2}}$$

One large subdomain
at the centre

The ionisation source is
localised near the centre

$$x_e(r) \approx \sqrt{\frac{\xi_{\text{ion}} Q_{\text{ann}}(r)}{\alpha_B \Delta E_{\text{ion}} n_H^2}}$$

Survival criterion

$$\int_{t_i}^{t_{\text{now}}} \bar{f}_m(t) \langle \sigma v \rangle_{\text{int}}(t) \bar{n}_b^{(\text{inc})}(t) dt \lesssim 1$$

What about outside?

$$T > 10^7 \text{K}$$

Processes:

1. **Electron–positron pair production**
2. Compton scattering of an annihilation photon on an electron
3. Bremsstrahlung of an annihilation electron/positron on a thermal photon (inverse scattering)
4. Positron annihilation with electrons

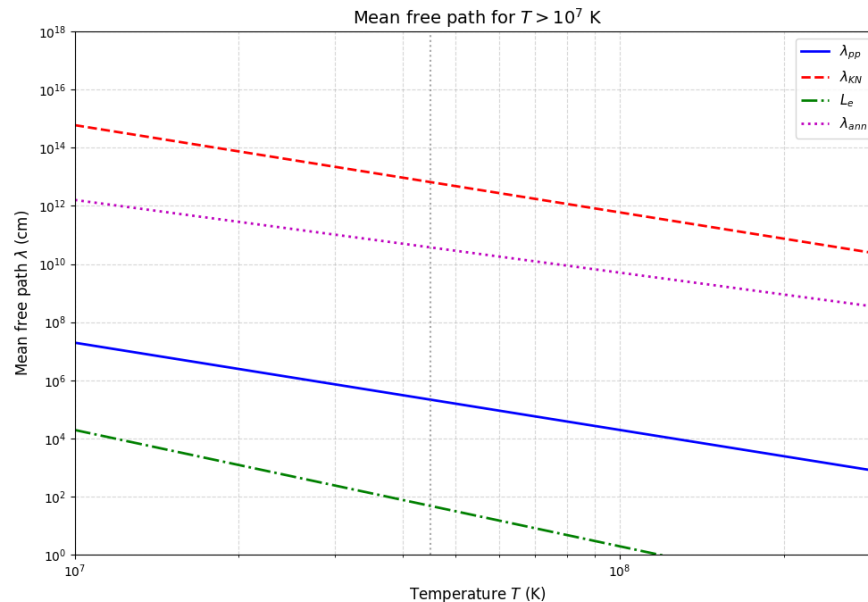


Figure 3. Dependence of the mean free path on various processes

$$R_{glow} \leq 2 \times 10^4 \text{ cm}$$

What about outside?

$$T \in [10^7, 3 \times 10^3] K$$

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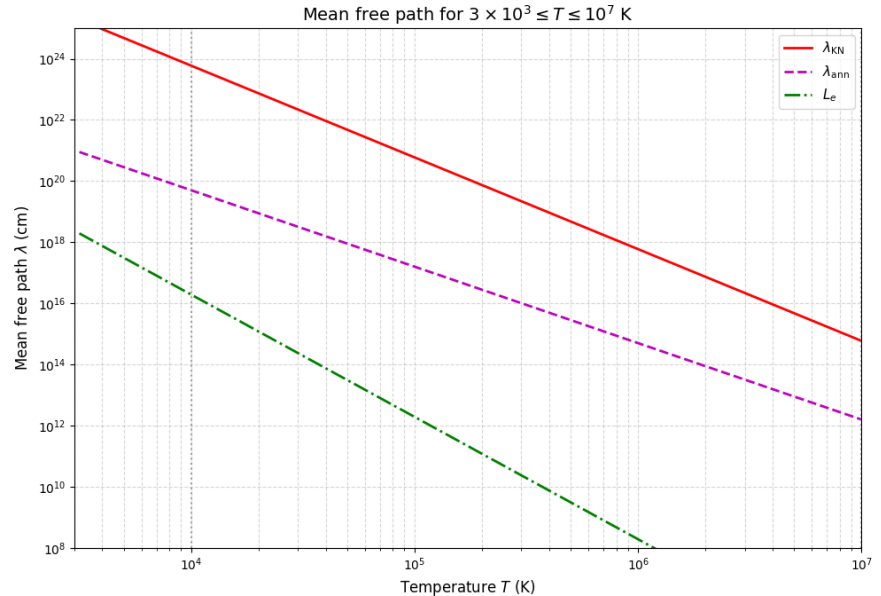


Figure 4. Dependence of the mean free path on various processes

$$R_{glow} \in [2 \times 10^4, 6 \times 10^{16}] \text{cm}$$

Energy release

The annihilation of a domain of mass M releases an observable amount of energy

$$Q_{\text{obs}} \approx 1.15 \times 10^{57} \left(\frac{M}{10^3 M_{\odot}} \right) \text{erg}$$

$$\frac{dQ}{dt} = 0,32 \cdot M^{2/3} \cdot \eta^{1/3} \cdot t$$

Size of the main glow region

$$R_{\text{exp}}(t) = a(t) \frac{R_0}{a(\tau_{\text{death}})}$$

Size of the halo

$$R_{\text{halo}}(t) = R_{\text{direct}}(t) + \langle \lambda_{\text{mfp}} \rangle \cdot \frac{a(t)}{a(\tau_{\text{death}})}$$

$$T > 10^7 \text{K}$$

The size of the halo is comparable to the main glow region

$$T \in [10^7, 3 \times 10^3] \text{K}$$

The size of the halo is larger than the main glow region

Conclusion

- Antimatter domains can form in a baryon-asymmetric Universe via non-homogeneous baryosynthesis
- The volume-averaged ionization degree inside a domain is negligible, so the domain can be considered neutral on average
- Annihilation at domain boundaries leads to a glow region and an extended halo; their sizes depend on temperature

Future plans:

- Description of domain evolution within the Swiss-cheese model
- Investigation of energy release processes from non-surviving domains in order to estimate the possibility of their observation

Thank you for your attention!

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