Evolution and Possible Forms of Primordial Antimatter and Dark Matter celestial objects

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Abstract
The structure and evolution of Primordial Antimatter domains and Dark matter objects are analysed. Relativistic low- density antimatter domains are described. The Relativistic FRW perfect-fluid solution is found for the characterization of i) ultra-high density antimatter domains, ii) high-density antimatter domains, and iii) dense antimatter domains. The possible sub-domains structures is analyzed. The structures evolved to the time of galaxy formation are outlined. Comparison is given with other primordial celestial objects. The features of antistars are outlined. In the case of WIMP dark matter clumps, the mechanisms of their survival to the present time are discussed. The cosmological features of neutrino clumping due to fifth force are examined.

Keywords: perfect-fluid plasma solution; nonhomogeneous baryosynthesis, antimatter; cosmology, celestial bodies.
1 Introduction

The formation of antimatter regions and antimatter domains in a matter/antimatter asymmetric Universe has long been studied according to the properties of the pertinent celestial objects, as well as to the observational signatures expected, i.e. the energetic gamma rays descending from the matter-antimatter interaction at the boundaries of the antimatter domains. Several scenarios can be envisaged, i.e. also ones in which strong antimatter inhomogeneities interact with the surrounding medium (see [1, 2, 3, 4, 5] for review and references).

The mechanisms of survival for the antimatter domains can be analyzed. Comparison with other celestial bodies enables one to extrapolate the properties of both the formation and evolution of such celestial bodies, as well as the interactions under which the celestial bodies are formed.

In the present paper, low-density antimatter domains will be revised in the non-relativistic description, under the suitable hypotheses. The Relativistic diffusion equation of low-density antimatter domains will be solved; the Relativistic radius and the Relativistic spherical shell interaction width will be calculated.

Dense antimatter domains will be introduced and classified according to the density, i.e. ultra-high density antimatter domains, very-high density ones and high-density ones. The Relativistic FRW diffusion equation of dense antimatter domains will be solved in the perfect-fluid FRW plasma solution. The Relativistic radius of the dense antimatter domains in the FRW symmetry and the Relativistic spherical shell interaction width in the FRW symmetry will be calculated; the calculated expressions will be shown to depend on the Relativistic quantities in a non-trivial manner.

Baryon subdomains inside the antimatter domains will be investigated; in particular, the analysis will be conducted in the cases pertinent to the epoch before the second phase transition and that after the second phase transition. This way, the formation of non-trivial structures will be assessed; more in detail, 'Swiss-cheese' structures and 'Chinese-boxes' structures will be reconducted to the analytical quantification.

Antimatter-excess regions will be explored wrt the diffusion process taking place at the boundary regions.

The density of antimatter domains at the time of galaxy formation will be written down.

Experimental-verification methods will be recapitulated for antimatter domains in a matter/antimatter asymmetric Universe within the framework of inhomogeneous baryosynthesis. The investigation methods for these purposes will be specialized to the study of the $\gamma$-ray background and of the expected anti-Helium. Further experimental purposes will be recalled.
Comparison with other celestial bodies will be brought. The features of antimatter celestial bodies in the Galaxy, WIMP dark-matter clumps and Fifth-Force neutrino lumps will be revised for the sake of the study of the formation mechanisms, the Universe-evolution survival models, and of the interaction ruling the structure of the celestial bodies.

2 Low-density antimatter domain: diffusion equation

The Relativistic diffusion equation of

\[ \frac{dn_b}{dt} = -\frac{3d}{R} <\sigma v> n_b - \beta n_b \] (1)

being \( R \) the antimatter domain non-Relativistic radius, and \( d \) the antimatter domain spherical shell boundary interaction width; furthermore, \(<\sigma v>\) antibaryon-baryon annihilation cross-section within the interaction region is defined, and \( \beta \) the FRW Relativistic factor is introduced.

Being \( \bar{r} \) the antibaryon-to-photon ratio and \( r \) baryon-to-photon ratio the Relativistic FRW diffusion equation of low-density domains rewrites

\[ \hat{\bar{r}} = -\frac{3d}{R} <\sigma v> rn_\gamma \bar{r} - \beta \bar{r} \] (2)

2.1 Low-density antimatter domains: non-Relativistic approximation

The non-Relativistic diffusion equation of low-density antimatter domains can be approximated after neglecting \( \beta \bar{r} \), and posing \(<\sigma v>rn_\gamma \Delta t \sim 1\), and solved as

\[ \frac{\hat{\bar{r}}}{\bar{r}_0} = \exp[-\frac{3d}{R} \int_{t_0}^{t_r} <\sigma v> rn_\gamma dt] \] (3)

2.2 Low-density antimatter domains: Relativistic solution

The Relativistic diffusion equation of low-density antimatter domains under the assumption \( \beta \bar{r} \ll 1 \) can be solved as

\[ \frac{d}{dt_r} (\ln \left( \frac{r_r}{r_0} - \hat{\beta}(t_r - t_0) \right)) = -\frac{1}{3} \left( \frac{4\pi}{3} \right)^{1/3} \delta(t_r) \frac{a(t_r)^{1/3}}{a(t_0)^{1/3}} \] (4)
with $\tilde{\beta} = -\beta$.

The Relativistic quantities $d \rightarrow \delta(t)$ Relativistic spherical-shell width interaction region, and $a(t) = \frac{4\pi R(t)^3}{3}$ FRW volume have been upgraded.

3 General implementation- Relativistic

After hypothesizing $-\beta n \equiv \tilde{\beta}$ small but not negligible, and $\tilde{\beta} \simeq \text{const}$, the following solution is found

$$\ln \left[ \frac{\bar{r}_f}{\bar{r}_0} - \tilde{\beta} \Delta t \right] \simeq -\frac{\delta}{3a} \Delta t$$

(5)

in the case of perturbed Minkowski space-time.

In the case of an FRW symmetry, the following solution is written

$$\frac{d}{dt} \ln \left[ \frac{\bar{r}_f}{\bar{r}_0} - \tilde{\beta} \Delta t \right] \simeq -\frac{\delta(t_\tau)}{3a(t_\tau)}$$

(6)

4 Perfect-fluid Relativistic FRW equation of dense antimatter domains

The perfect-fluid FRW diffusion equation of the antibaryon number density writes

$$\frac{d n_{\bar{b}}}{dt} = -\frac{3d}{R} < \sigma v >_{ext} n_{\bar{b}} n_b - \beta n_{\bar{b}} + Q(\bar{r}, p, t) - \frac{n_{\bar{b}}}{t_d} + \sum_i F_i(p, \dot{p}; ...) - f(\rho_E, \bar{p}; R_d, l_d; \bar{v}_T, v_f; \bar{v}; i) - \mu \nabla^2 n_{\bar{b}}$$

(7)

Here, $< \sigma v >_{ext}$ is cross-section of the antibaryon-baryon annihilation process at the boundary of the antimatter domain, $Q(\bar{r}, p, t)$ is a source term (can be neglected), $F_i(p, \dot{p}; ...)$ are further terms depending on the momentum (can be neglected), $f(\rho_E, \bar{p}; R_d, l_d; \bar{v}_T, v_f; v_f; i)$ is plasma characterization in terms of the viscosity properties and of the turbulent velocity (can be neglected), $\frac{n_{\bar{b}}}{t_d} \simeq < \sigma \bar{v} >_{int} n_{\bar{b}} n_b$ is the decay rate inside the interior of the domain, $t_d = \text{const}$? is the time scale of annihilation, $< \sigma v >_{int}$ is cross-section of the antibaryon-baryon annihilation process in the interior of the antimatter domain, $\beta n_b$ accounts for the FRW homogeneous Relativistic expansion of the universe, and $\mu$ is the chemical potential, i.e. $\tilde{\mu} n_{\bar{b}} = -\mu \nabla^2 n_{\bar{b}}$ for the self-similarity properties of the equation.
5 Dense antimatter domains

By construction, both the antibaryon density and the baryon one are much higher than average baryon density in all the Universe; several cases can be distinguished:

i) **ultra-high densities**

the antibaryon excess and baryon ones start to exceed the contribution of thermal quark-antiquark pairs before QCD phase transition

ii) **very-high densities** the antibaryon density and the baryon ones exceed the contribution of plasma and radiation after the QCD phase transition

iii) **high densities** the antibaryon densities and the baryon ones exceed the DM density

5.1 i) **ultra-high density antimatter domains**

Let $n_{\bar{b}}$ be the number density of antibaryons. The following diffusion equation is outlined

$$\frac{dn_{\bar{b}}}{dt} = -\frac{3d}{R} <\sigma v>_{ext} n_{\bar{b}} n_b - \beta n_{\bar{b}} - \mu \nabla^2 n_{\bar{b}} \equiv -\frac{m_b}{t_s} - \beta n_{\bar{b}} + \beta + \mu$$ (8)

and solved as

$$\ln \left( \frac{\bar{r}_\tau}{\bar{r}_0} - (\beta + \mu)(t_\tau - t_0) \right) = -\frac{1}{3} \left( \frac{4\pi}{3} \right)^{1/3} <\sigma v>_{ext} r n_{\gamma} \int_{t_i}^{t_\tau} \frac{\delta(t)}{(a(t))^{1/3}} dt$$ (9)

with $a(t) = 4\pi R(t)^3/3$ the Relativistic FRW volume, and $d \to \delta(t)$ the Relativistic interaction spherical-shell width, which simplifies as

$$\frac{d}{dt_\tau} \left( \ln \left( \frac{\bar{r}_\tau}{\bar{r}_0} - (\beta + \mu)(t_\tau - t_0) \right) \right) = -\frac{1}{3} \left( \frac{4\pi}{3} \right)^{1/3} <\sigma v>_{ext} r n_{\gamma} \frac{\delta(t_\tau)}{(a(t_\tau))^{1/3}}$$ (10)

5.1.1 Relativistic expression for the radius of the antimatter domain

Relativistic expression for the radius of the antimatter domain reads

$$\left( a(t_\tau) \right)^{1/3} = -\left( \frac{3}{4\pi} \right)^{1/3} <\sigma v>_{ext} r n_{\gamma} \frac{\delta(t_\tau)}{3} \frac{\left[ \bar{r}_\tau - (\beta + \mu)(t_\tau - t_0) \right]}{\frac{d}{dt_\tau} \left[ \bar{r}_\tau - (\beta + \mu)(t_\tau - t_0) \right]}$$ (11)
5.1.2 Relativistic expression for the interaction width

Relativistic expression for the interaction width is obtained as

\[
\delta(t_r) \sim - \left( \frac{3}{4\pi} \right)^{1/3} \frac{3(a(t_r))^{1/3}}{< \sigma v >_{\text{ext}} \frac{d}{dt_r} \left[ \frac{t_r}{t_0} - (\bar{\beta} + \bar{\mu})(t_r - t_0) \right]}
\]

(12)

The relativistic expression of the interaction width of the antimatter domain depends therefore also on the Relativistic radius in a non-trivial manner, i.e. as a prefactor.

5.2 (ii) very-high-density antimatter domains

In the case of very-high-density antimatter domains, the diffusion equation of the baryon number density becomes

\[
\frac{dn_b}{dt} = - \frac{3d}{R} < \sigma v >_{\text{ext}} n_b - n_b - n_b - \frac{n_b}{t_d} - \beta n_b - \frac{n_b}{t_s} - \mu \nabla^2 n_b = \frac{n_b}{t_d} - \beta n_b - \frac{n_b}{t_s} - \mu \nabla^2 n_b
\]

(13)

solved as

\[
\ln \left[ \frac{\bar{r}}{t_0} + < \bar{\sigma} \bar{\mu} >_{\text{int}} \frac{n_b}{t_0} - (\bar{\beta} + \bar{\mu})(t_r - t_0) \right] = - \frac{1}{3} \left( \frac{4\pi}{3} \right)^{1/3} \int_{t_i}^{t_r} \frac{\delta(t)}{(a(t))^{1/3}} dt
\]

(14)

with \(a(t) = 4\pi R(t)^3/3\) Relativistic FRW volume, and \(d \rightarrow \delta(t)\) Relativistic interaction spherical-shell width

\[
\frac{d}{dt_r} \left( \ln \left[ \frac{\bar{r}}{t_0} + < \bar{\sigma} \bar{\mu} >_{\text{int}} \frac{n_b}{t_0} - (\bar{\beta} + \bar{\mu})(t_r - t_0) \right] \right) = - \frac{1}{3} \left( \frac{4\pi}{3} \right)^{1/3} \frac{\delta(t_r)}{(a(t_r))^{1/3}}
\]

(15)

5.2.1 Relativistic expression of the radius of the antimatter domain

The Relativistic expression of the radius of very-high-density antimatter domains is obtained as

\[
(a(t_r))^{1/3} = - \left( \frac{3}{4\pi} \right)^{1/3} \frac{< \sigma v >_{\text{ext}} \frac{d}{dt_r} \left[ \frac{t_r}{t_0} - (\bar{\beta} + \bar{\mu})(t_r - t_0) \right]}{3}
\]

(16)

5.2.2 Relativistic expression of the spherical shell interaction width

The Relativistic expression of the spherical shell interaction width of very-high-density antimatter domains is

\[
\delta(t_r) \sim - \left( \frac{3}{4\pi} \right)^{1/3} \frac{3(a(t_r))^{1/3}}{< \sigma v >_{\text{ext}} \frac{d}{dt_r} \left[ \frac{t_r}{t_0} + < \bar{\sigma} \bar{\mu} >_{\text{int}} \frac{n_b}{t_0} - (\bar{\beta} + \bar{\mu})(t_r - t_0) \right]}
\]

(17)
The Relativistic expression of the interaction width of the antimatter domain depends therefore also on the Relativistic radius in a non-trivial manner, i.e. as a prefactor.

5.3 iii) high-density antimatter domains

The diffusion equation of the antibaryon number density of high-density antimatter domains is characterized as

\[
\frac{dn_b}{dt} = -\frac{3d}{R} < \sigma v >_{ext} n_b n_\bar{b} \equiv \frac{3d}{R} < \sigma v >_{ext} n_b n_\bar{b} - \frac{n_b}{t_d} - \frac{n_\bar{b}}{t_s} - \mu \nabla^2 n_b
\]

and solved as

\[
\ln \left[ \bar{r}_\tau / \bar{r}_0 - (\bar{\mu})(t_\tau - t_0) \right] = -\frac{1}{3} \left( \frac{4\pi}{3} \right)^{1/3} < \sigma v >_{ext} r n_\gamma \int_{t_i}^{t_\tau} \frac{\delta(t)}{(a(t))^{1/3}} dt
\]

Here, \(a(t) = 4\pi R(t)^3 / 3\) is the Relativistic FRW volume, and \(d \to \delta(t)\) is the Relativistic interaction spherical-shell width.

Eq. (19) rewrites

\[
\frac{d}{dt_\tau} \left( \ln \left[ \frac{\bar{r}_\tau}{\bar{r}_0} - (\bar{\mu})(t_\tau - t_0) \right] \right) = -\frac{1}{3} \left( \frac{4\pi}{3} \right)^{1/3} < \sigma v >_{ext} r n_\gamma \frac{\delta(t_\tau)}{(a(t_\tau))^{1/3}}
\]

5.3.1 Relativistic expression for the radius of the antimatter domain

In the case of high-density antimatter domains, the Relativistic expression for the radius of the antimatter domain is expressed as

\[
(a(t_\tau))^{1/3} = - \left( \frac{3}{4\pi} \right)^{1/3} < \sigma v >_{ext} r n_\gamma \left[ \frac{\bar{r}_\tau}{\bar{r}_0} - \bar{\mu}(t_\tau - t_0) \right] \frac{d}{dt_\tau} \left( \frac{\bar{r}_\tau}{\bar{r}_0} - \bar{\mu}(t_\tau - t_0) \right)
\]

5.3.2 Relativistic expression for the spherical shell interaction width

The Relativistic expression for the spherical shell interaction width of high-density antimatter domains is solved as

\[
\delta(t_\tau) \sim - \left( \frac{3}{4\pi} \right)^{1/3} 3(a(t_\tau))^{1/3} \frac{d}{dt_\tau} \left[ \frac{\bar{r}_\tau}{\bar{r}_0} - \bar{\mu}(t_\tau - t_0) \right] < \sigma v >_{ext} r n_\gamma \left[ \frac{\bar{r}_\tau}{\bar{r}_0} - \bar{\mu}(t_\tau - t_0) \right]
\]

The Relativistic expression of the spherical-shell interaction width of the antimatter domain depends therefore also on the Relativistic radius in a non-trivial manner, i.e. as a prefactor.
6 Conditions and evolution of different types of strong primordial inhomogeneities in non-homogeneous baryosynthesis

In the case of non-homogeneous primordial baryosynthesis, various types of scenarios can accomplish: antimatter consisting of axion-like particles; closed walls for baryogenesis with excess of antibaryons, and phase fluctuations such that a baryon excess is created everywhere and with non-homogeneous distribution. To avoid large-scale fluctuations, the fluctuations have to be imposed to be small.

In the latter cases of small fluctuations, the following inequality holds

\[ \frac{3B}{4\pi R(t)^3} \gg \rho_B \]  

(23)

The diffusion process of the model is described as follows.

Three Regions can be outlined:

1) the **dense antimatter domain** of radius \( R \leq R_1 \) of antibaryon number density \( n_{b_1} \), and of chemical potential \( \mu_1 \),

2) the **outer spherical shell** region of radius \( R_1 \leq R \leq R_2 \) of antibaryon number density \( n_{b_2} \), and of chemical potential \( \mu_2 \),

where the diffusion process happens, and 3) the outmost region of radius \( R_3 \geq R_2 \) of antibaryon number density \( n_{b_3} \) of low antimatter density.

The chemical potentials of related to the three regions are assumed to be small but not negligible, i.e.

\[ |\tilde{\mu}_1| << 1, \quad |\tilde{\mu}_2| << 1, \quad \text{and} \quad |\tilde{\mu}_3| << 1. \]

The differential equation of the antibaryon number density in Region 1) is

\[ \frac{d n_{b_1}}{dt} = -\mu_1 \nabla^2 n_{b_1} \sim \tilde{\mu}_1 n_{b_1} \]  

(24)

The differential equation of the antibaryon number density in Region 2) is

\[ \frac{d n_{b_2}}{dt} = -\mu_2 \nabla^2 n_{b_2} \sim \tilde{\mu}_2 n_{b_2} \]  

(25)

The differential equation of the antibaryon number density in Region 3) is

\[ \frac{d n_{b_3}}{dt} = -\mu_3 \nabla^2 n_{b_3} \sim \tilde{\mu}_3 n_{b_3} \]  

(26)

The solutions of Eq. (24), Eq. (25), and Eq. (26) must satisfy the continuity conditions

\[ n_{b_1}(t, R_1) = n_{b_2}(t, R_1) \]  

(27)

on the boundary of Region 1), and

\[ n_{b_2}(t, R_2) = n_{b_3}(t, R_2) \]  

(28)

on the boundary of Region 2).
7 Dense Baryon subdomains

It is possible to hypothesize the presence of antibaryons inside the baryon subdomains, which exceed the survival size of volume $V_j = 4\pi R_j^3/3$; such a possibility is dependent on the second phase transition.

For axion-like particles, it is dependent on the QCD phase transition.

Two possibilities are outlined, i.e. according to whether the description is taken before the $\Lambda_{QCD}$ phase transition, or after it.

I) In the case $\Lambda < \Lambda_{QCD}$, the baryon number density $n_b$ in a baryon subdomain filled with (grazing) antibaryons obey the following plasma characterization

$$\frac{dn_b}{dt} = - \langle \sigma v \rangle_j \text{ext} n_b n_b - \langle \sigma v \rangle_j \text{int} n_b n_b - \mu \nabla^2 n_b \quad (29)$$

The following perfect-fluid Relativistic FRW solution is found

$$- \sqrt{\frac{4\pi}{3}} \frac{\delta(t)}{3a(t)} r_{\text{int}} r_{\text{int}} n_{\gamma} < \sigma v >_j \text{ext} =$$

$$= \frac{d}{dt \tau} \ln[r_{\text{int}} r_{\text{int}} n_{\gamma}] + \bar{\mu}(t_{\tau} - t_0) + ]$$

In the case II) $\Lambda > \Lambda_{QCD}$ the baryon number density $n_b$ in a baryon subdomain without free antibaryons inside

is described by the following plasma characterization

$$\frac{dn_b}{dt} = - \langle \sigma v \rangle_j \text{ext} n_b n_b - \mu \nabla^2 n_b \quad (31)$$

The following perfect-fluid Relativistic FRW solution is found

$$- \sqrt{\frac{4\pi}{3}} \frac{\delta(t)}{3a(t)} r_{\text{int}} r_{\text{int}} n_{\gamma} < \sigma v >_j \text{ext} = \frac{d}{dt \tau} \ln[\bar{\mu}(t_{\tau} - t_0)]$$

8 Further structures

Further structures can be analysed, according to the presence of baryon subdomain(s) inside the antibaryon domain.

8.1 'Swiss-cheese' structures

A description of 'Swiss-cheese' structures can be hypothesized as an antimatter domain containing one matter domain, in the simplest instance, and more complicated 'Swiss-cheese' structures, such as an antimatter domain containing several matter subdomains.
8.1.1 Antibaryon domain containing one baryon subdomain

In the case of an antibaryon domain containing one baryon subdomain, the antibaryon number density obeys the differential equation

\[
\frac{dn_b}{dt} = - \frac{3d}{R} \left< \tilde{\sigma} \tilde{v} >_{ext} n_b n_b + Q(\vec{r}, p) - \frac{n_b}{t_d} \right> + F_i(p, \dot{p}; \ldots) + \mu \nabla^2 n_b - \frac{3d_i}{R_i} \left< \tilde{\sigma} \tilde{v} >_i n_i n_i - \mu_i \nabla^2 n_i \right>
\]  

(33)

8.1.2 Swiss-cheese structure: baryon domain containing several baryon subdomains

\[
\frac{dn_b}{dt} = - \frac{3d}{R} \left< \tilde{\sigma} \tilde{v} >_{ext} n_b n_b + Q(\vec{r}, p) - \frac{n_b}{t_d} \right> + \sum_{i=1}^{i=I} \left( F_i(p, \dot{p}; \ldots) - \mu \nabla^2 n_b - \frac{3d_i}{R_i} \left< \tilde{\sigma} \tilde{v} >_i n_i n_i - \mu_i \nabla^2 n_i \right> \right)
\]  

(34)

8.1.3 Chinese-boxes structures

‘Chinese-boxes’ structures are described as

\[
\frac{dn_b}{dt} = - \frac{3d}{R} \left< \sigma v >_{ext} n_b n_b - \beta n_b + Q(\vec{r}, p, t) - \frac{n_b}{t_d} - \mu \nabla^2 n_b \right> - \sum_{i=1}^{i=I} \left[ F_i(p, \dot{p}; \ldots) - \mu \nabla^2 n_i - \frac{3d_i}{R_i} \left< \sigma_v >_i n_i n_i \right> \right] + \sum_{j=1}^{j=J} \left[ F_j(p, \dot{p}; \ldots) - \mu \nabla^2 n_j - \frac{3d_j}{R_j} \left< \sigma_v >_j n_j n_j \right> \right]
\]  

(35)

9 Galaxy formation: Relativistic density of the surviving domains

The present section is aimed at studying the density of the antimatter domains at the time of galaxy formation.
9.1 Plasma characterization

The plasma characterization of the antimatter domains at the time of galaxy formation is given after the condition

\[ < \sigma v >_{\text{int}} r = 0, \]  

(36)
i.e. after the antibaryon/baryon interactions in the interior of the antimatter domains have exhausted.

The following conditions are taken into account:

\[ \tilde{\mu}(t_\tau - t_0)n_\gamma \ll 1, \]  

(37)
and

\[ \tilde{\beta}(t_\tau - t_0)n_\gamma \ll 1, \]  

(38)
with

\[ (\tilde{\mu} + \tilde{\beta})(t_\tau - t_0)n_\gamma \ll 1, \]  

(39)
i.e. that the chemical-potential terms and the Relativistic FWR terms be small but not negligible.

9.1.1 i) ultra-high-density antimatter domains

In the case of ultra-high-density antimatter domains, the antimatter-domain density at the time of galaxy formation reads

\[
\frac{\bar{r}_\tau n_\gamma}{a(t_\tau)} = \frac{1}{a(t_\tau)} \frac{n_\gamma}{\bar{r}_0 + (\bar{\beta} + \bar{\mu})(t_\tau - t_0)n_\gamma} \nonumber \cdot \exp \left[ \frac{1}{3} \left( \frac{4\pi}{3} \right)^{1/3} < \sigma v >_{\text{ext}} r_0 n_\gamma \int_{t_0}^{t_\tau} \frac{\delta t}{a(t)} \right] \]  

(40)

9.1.2 ii) very-high-density antimatter domains

In the case of very-high density antimatter domains, the antimatter-domain density at the time of galaxy formation is

\[
\frac{\bar{r}_\tau n_\gamma}{a(\tau)} = \frac{1}{a(\tau)} \frac{n_\gamma}{\bar{r}_0 n_\gamma + (\bar{\beta} + \bar{\mu})(t_\tau - t_0)n_\gamma} \nonumber \cdot \exp \left[ \frac{1}{3} \left( \frac{4\pi}{3} \right)^{1/3} < \sigma v >_{\text{ext}} r_0 n_\gamma \int_{t_0}^{t_\tau} \frac{\delta t}{a(t)} \right] \]  

(41)
9.1.3  iii) high-density antimatter domains

In the case of high-density antimatter domains, the antimatter-domain density at the time of galaxy formation becomes

$$\frac{\bar{r}_\tau n_\gamma}{a(\tau)} = \frac{1}{a(t_\tau)} \frac{r_\tau}{\bar{r}_\tau} + \mu(t_\tau - t_0) n_\gamma \varepsilon^* \left( \frac{4\pi^{1/3}}{3} \right) < \sigma v >_{\text{ext}} r_0 n_\gamma \int_{t_0}^{t_\tau} \frac{\delta t}{a(t)} dt \quad (42)$$

10  Experimental verification

The signatures of the experimental verification of the existence of antimatter domains have to be analysed. In particular, the $\gamma$-ray background is expected to be modified after the baryon/antibaryon interaction within the boundary interaction region of the antimatter domains. Furthermore, the detection of anti-Helium flux after the AMS2 experiment is awaited. The properties of $pp$ atoms have been studied in [7]. In [8], the $\gamma$-ray spectrum originated after the $p\bar{p}$ annihilation in liquid Hydrogen is analysed by means of two spectrometers. As a result, no exotic narrow peaks are evidenced, and the upper limit is calculated.

The $\gamma$-ray signal due to matter-antimatter annihilation on the boundary of an antimatter domain can therefore be analyzed [9]; the hypotheses of a matter/antimatter symmetric Universe and of a matter/antimatter asymmetric Universe can be scrutinized and compared.

In the case of a matter/antimatter-symmetric Universe: more $\gamma$-rays than the observed quantities are predicted; therefore, a matter/antimatter-symmetric Universe is possible iff the present Universe is one consisting of the matter quantity.

The $p\bar{p}$ interaction process is studied as resolving in photons after the $\pi^0$ decay. Be

$\bar{g}$ the mean photon multiplicity;

each $p\bar{p}$ annihilation process is estimated to produce $\bar{g} \simeq 3.8$ electrons and positrons, and an approximate similar number of photons.

The annihilation electrons are described at a redshift $y$ s.t. $20 < y < 1100$.

The mechanisms that control the electrons motion must therefore be studied. Such mechanisms are evaluated to be the cosmological redshift, the collision with CBR photons, and the collision with ambient plasma electrons.

At the considered values of the redshift, the collisions with CBR photons are considered the most important control mechanism of the electron trajectory.

For initially-Relativistic electrons of energy $E_0 = \gamma_0 m_e$, the dependence of
the width of the reheated zone where the electrons produced after the annihilation directly deposit energy into the fluid, i.e. the electron range, on $\gamma_0$ is negligible.

The inclusive photon spectrum in the $p\bar{p}$ process is normalized to $\bar{g}$; the average number of photons made per unit volume is calculated: the transport equation of the photons scatter and redshift, (which lead to a spectral flux of annihilation photons), is therefore assessed. A conservative lower limit for the $\gamma$-ray signal can this way estimated.

The $\gamma$-rays energy is expected to be of order $100\text{MeV} - 10\text{MeV}$ at modern times; a different value can be expected for the opaque universe at the early stages).

The results are awaited after the experiment AMS2 as far as the presence of the anti-Helium flux is concerned.

## 11 Further experimental verifications

Further experimental verifications of a matter/antimatter Universe can be expected.

As an example [10], annihilation and transformation of annihilating matter’s rest mass into energy particles and radiation with 100% efficiency can be looked for at different length scales.

A substantial lack of antimatter on the Earth is evidentiated within the due limits.

A lack of antimatter in the vicinity of the Earth is found.

Matter asymmetry in the Solar System can be revealed within the study of the:

Solar wind, i.e. the continuous outflow of particles from the Sun. For antiplanets of radius $r$ and distance $d$ from the Earth intercepting the Solar wind, the expected annihilation flux is

$$F(\gamma = 100\text{MeV}) \sim 10^8(r/d)^2 \text{photons cm}^{-2} \text{s}^{-1}.$$  

At scales larger than the Solar System, i.e. at the Galaxy scales, the $\gamma$-ray analysis must be investigated ($\gamma$-ray detectors have better detection capabilities and localization ones at $E \sim 100 \text{ MeV}$ than neutrino detectors). Antimatter mixed in with matter inside our Galaxy’s gas at $E \sim 100 \text{ MeV}$ is expected to be present in a matter/antimatter-symmetric Universe.

Models can be postulated [11], such that SUSY-condensate baryogenesis models motivate the possibilities of antimatter domains in the Universe.

In this case, vast antimatter structures in Early-Universe evolution possible after initial space distribution at the inflationary stage of the quantum fluc-
tuation field $\phi(r, t_0)$, unharmonic potential of the field carrying the baryon charge, and inflationary expansion of the initially microscopic baryon distribution. The vast antimatter regions are calculated to be separated at distances larger than $10\, \text{Mpc}$ from the Earth, and separated from the matter ones by baryonically-empty voids.

Such models are not ruled out after cosmic rays data, $\gamma$-rays ones, and CMB anisotropy ones.

Antimatter in a matter/antimatter-symmetric Universe can be further verified after the presence of antimatter at the Galactic scale and above. As far as hydrogen in "clouds" is concerned, the experimental verification is based on the observation of $\gamma$-rays from their directions, compatible with $\pi^0$ decay, and non-observation of a $\gamma$ excess. In this case, form the observational data, the antibaryon presence in the media is calculated not to exceed one part in $10^{15}$.

The instance of galaxy-antigalaxy collisions can be studied. Such events have not been verified after devices s.t. Antennae pair NGC4038(9). Clusters of certain galaxies, dense enough and active in order to allow for intergalactic hot plasma in the central parts (at temperatures of order $\sim 10\, \text{keV}$) it is therefore possible to verify the presence of antimatter as a few parts per million from the observation of absence of enough $\gamma$-ray excess on the thermal spectral tail.

Large antimatter regions with sizes larger than the critical surviving size can be verified in different observational proofs. The absence of anti-Helium in the cosmic rays and annihilation signals can be consistent as an indicator: their fraction in the Galaxy is smaller than $10^{-4}$. The antimatter islands must be separated from a space filled with matter at least by the distance of about $1\, \text{Mpc}$.

For this, the possibility for antimatter islands (antistars) in the Galaxy still allowed. Large antimatter regions with high antimatter density evolve to single galaxies. They are detected after particular content of anti-Helium and anti-deuterium.

Further Cosmic antimatter searches can be pursued. The presence of antistars in our Galaxy can be verified after the possibility to detect antinuclei with $Z \geq 2$. Domain sizes of the scale of galaxies or scales of galaxy clusters can be testified after antimatter cosmic rays (CR) originating from the nearest domain for uniform domains, non-uniform domains, and condensed antimatter bodies (i.e. antistars, antiplanetoids). The upper limit of antistars in the Milky Way has been estimated as $10^7$ (i.e. ...
$10^{-4}$ of the total number of stars). Antistars can be described as confined into compact structures separated from the matter environment and able to survive for a longer period rather than in gas clouds. Antistars are not expected to be strong $\gamma$-ray emitters, unless they at least cross a galactic cloud or impact on other condensed bodies.

The lower limit on the distance of the nearest antistar [17] has been set as $\sim 30$ pc. The upper limit on the fraction of antistars in the Andromeda Galaxy has been estimated as $\sim 10^{-3}$.

Experimental verification of presence of matter regions and antimatter ones in a matter/antimatter-symmetric universe should be studied after the pre-recombinational signals and the post-recombinational ones. The prerecombination signal [18] allows one for the verification of the presence of domains of larger size. The assumption that matter domains and antimatter ones were in contact before the last scattering exhibits such effects after which contact and annihilation significantly distort the radiation from the last-scattering surface: a single domain boundary, or a fraction, can be detectable; differently, the absence of such signatures rules out a matter/antimatter-symmetric universe.

The postrecombination signal [18] would consists of the observable unobserved $\gamma$-ray flux, due to nuclear annihilation rate of matter/antimatter near domain boundaries; the a resulting relic diffuse $\gamma$-ray flux exceeds the observed cosmic diffuse $\gamma$ spectrum, so that a matter/antimatter-symmetric Universe is ruled out unless the matter region consists of almost the entire Universe.

### 12 Antistars

The analysis of the mean free path of the cross section of the matter/antimatter annihilation products in the interaction spherical shell boundary of the antistars is consistent for the comparison with the $\gamma$-ray-background constraints [19].

After the compilation of the 10-years Fermi Large Area Telescope (LAT) $\gamma$-ray-sources catalog, constraints on the abundance of antistars around the Sun are obtained: 14 antistar candidates are present around the Sun. In particular, they have been chosen as they are not associated with any objects belonging to established $\gamma$-ray source classes, and exhibit a spectrum compatible with baryon-antibaryon annihilation [20].
13 **Antimatter celestial objects in the Galaxy**

The exist observational evidences of the existence of antimatter celestial objects in the Milky Way; more in detail [21], they are point-like sources of gamma radiation, and diffuse galactic $\gamma$-ray background, where the latter possible antimatter sources are to be verified after an anomalous abundance of chemical (anti-)elements around it possibly measured by spectroscopy, anti-nuclei in cosmic rays, and more exotic events, where large amounts of matter and antimatter interact. In the latter case, star-antistar annihilation can be considered: huge energy produced, even though their total destruction is prevented by the radiation pressure produced in the collision; and collision of a star and an anti-star with similar masses is calculated to provoke a peculiar result.

13.1 **Antistars**

The creation of stellar-like objects in the very early universe [22], from the QCD phase transition until the BBN and later, can be witnessed as the presence of some of the celestial objects created which can consist of antimatter. The $\alpha$ cosmological baryon asymmetry $\alpha = \frac{N_B}{N_\gamma}$ can be close to unity, i.e. much larger than the observed value $\alpha \simeq 6 \cdot 10^{-10}$. The ratio $\alpha$ can also be negative: this way, the amount of antimatter constituting compact objects in the Galaxy is expected.

14 **WIMP’s clumps**

14.1 **Neutralino clumps**

Within the standard cosmological scenario (FRW with its thermal history, inflationary-produced primordial fluctuation spectrum and with a hierarchical clustering), the neutralino clumps [23] undergo tidal destruction in the hierarchical clustering (i.e. the smaller clumps are captured by the larger clumps) at early stages of the structure-formation process, starting from a time of clump detachment from the Universe expansion. In the case of small-scale dark-matter clumps, a mass function can be calculated for the survived clumps: the tidal destruction of clumps by the Galactic disk, the life-time of clumps in the central stellar bulge, and the life-time of clumps in the stellar halo spheroid can be calculated; as a result, the minimal mass is the evaluated as the Moon-scale mass.
14.2 Neutralino annihilation in the Galaxy

Within the standard cosmological scenario, neutralino annihilation of small-scale neutralino clumps [24] would produce a signal from the galactic halo: the clump destruction is due to larger-scale clumps, gravitational field of the galactic disk, stars in the galactic bulge, and stars in the galactic halo. The mutual tidal clumps interactions would become important at early stages of hierarchical clustering, and for the galactic halo formation. The hierarchical clustering implies clumps surviving the hierarchical clustering to be continuously destroyed by interactions with the galactic disk and stars. This way, 20% of neutralino clumps surviving the hierarchical clustering between the Earth and the Moon can 'survive the Sun position' because of tidal destruction due to Galactic disk. Furthermore, the diminishing of the expected DM annihilation signal from the galactic halo would be awaited.

14.3 Small-scale DM clumps

The clumps scenarios comprehend spherical models, non-spherical models, and clumps around topological defects [25]. The possible observational verifications are established DM-particles direct detection, record of clumps in gravitational-wave detectors, neutralino stars, baryons in clumps, and clump motion in the Sky sphere.

15 Fifth-Force neutrino lumps

15.1 Fifth-Force codifications

The Fifth Force potential can be codified as [26], [27]

\[ V(r) = \frac{\tilde{G} m_1}{r} \left(1 + \alpha e^{-r/\lambda}\right) = G \frac{m_1 m_2}{r} \left(1 + e^{-\beta \phi}\right) = \frac{m_1 m_2}{r} \left(G + \frac{G}{\Delta G}\right). \] (43)

Such a codification allows for the description of dark-matter gravitational clustering.

15.2 Modellizations for neutrino cosmology

The parameter \( \beta \) is intended as the Fifth-Force parameter, and \( \phi - \nu \) coupling is postulated.
The fifth force is requested to be subdominant with respect to the gravitational force \[28, 29\]. As an example, the request can be expressed as

\[
\beta = - \frac{d \ln m_\nu}{d \phi}.
\]  

(44)

Is is also possible to set a \( \lambda \) comoving length scale larger than the typical lump sizes, but smaller than their typical distances, such that the mean distance between neighboring lumps be of order \( 100 h^{-1} \text{Mpc} \).

\( l \) lumps of masses \( M_l \) are expressed via smoothed fields \( \hat{\phi} \). The effective coupling

\[
\beta_l = - \frac{d \ln M_l}{d \hat{\phi}}
\]  

(45)

is worked out.

### 15.3 Applications for fluids of composite objects

Neutrino lumps are described within a hydrodynamic framework, i.e. endowed with a balance equation \[29\], and a stability equation \[30\] based on the Tolman-Oppenheimer-Volkoff equation.

Within the framework of the \( \phi - \nu \) coupled fluid, neutrino fluctuations are hypothesized to grow under the effect of the Fifth-Force \[31\]. Non-Relativistic neutrino clusters under the effect of the fifth-force are hypothesized at scales estimated to be around a few \( 10-100 \text{Mpc} \). A statistical distribution of neutrino lumps is expressed as a function of the mass at different redshifts \( z \geq 1 \).

The oscillating structure formation is described as at the time a large number of neutrinos were staying in gravitationally-bounded lumps at \( z = 1.3 \).

### 15.4 Formation of large-scale neutrino lumps in a recent cosmological epoch

Within the framework of a \( \phi - \nu \) interaction, the non-linear features of the Fifth-Force can be outlined \[32\].

The averaged interaction strength \( < \beta > \) of the neutrinos in a neutrino lump reads

\[
< \beta > = -M \frac{d \ln < m_\nu >}{d \phi}.
\]  

(46)

The effective suppression of the \( \phi \)-mediated attractive force between neutrino lumps is proportional to \( 2\beta \). In particular, the attraction between...
two equal lumps is reduced by a factor \( \left( \frac{\beta}{\langle \beta \rangle} \right)^2 \). Furthermore, the characteristic time scale for the infall increased by a factor \( \frac{\beta}{\langle \beta \rangle} \) compared to the consideration excluding non-linear effects and thus results in a slow down of the infall: the time scale for the clumping of lumps to larger lumps enhanced by a factor \( \left( \frac{\beta}{\langle \beta \rangle} \right)^2 \).

In the interior of the lump, the possibility of a time variation of fundamental constants results much smaller than the cosmological evolution; therefore, it is possible to reconcile the cosmological variations of the fine structure constant with geophysical bounds.

### 15.5 CMB verification for neutrino lumps

Within the framework of a \( \phi - \nu \) interaction, the integrated Sachs-Wolfe effect of CMB \(^{33}\) can be considered. The size of the gravitational potential induced by the neutrino lumps, and the time evolution of the gravitational potential induced by the neutrino lumps have to be analyzed. As a result, a proportionality between the scalar potential and the neutrino-induced gravitational potential is found as

\[
\beta \delta \phi = 2\beta^2 \Phi_\nu
\]  

for the local potential and the cosmological-averaged potential.

The population of lumps of size \( \geq 100 \text{Mpc} \) can lead to observable effects from the CMB anisotropies for low angular momenta.

### 16 Outlook and perspectives

Evolution of antimatter domains have been studied: an analysis of low-density antimatter domains and dense antimatter domains has been performed. More in detail, ultra-high density antimatter domains, very-high density antimatter domains, and high-density antimatter domains.

Experimental verification of their signatures consists of the search for confirmation in the observed \( \gamma \)-ray background, and for the expected anti-Helium flux in \( AM\!/S02 \) experiment.

Comparison with other celestial objects has been accomplished: study of formation mechanisms, Universe-evolution survival models, and comparison of interactions characterizing the structure of the celestial bodies has been performed.
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