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Studies of baryon-antibaryon annihilation in the evolution of antimatter domains in baryon-asymmetric Universe.

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Abstract

Non-trivial baryosynthesis scenarios can lead to the existence of antimatter domains in a baryon-asymmetrical Universe.
The consequences of antibaryon-baryon annihilations interactions within antimatter domains will be investigated.
Boundary interactions are studied. Low-density antimatter domains are further classified according to the boundary interactions.
Differently, a similar classification scheme is also proposed for higher-densities antimatter domains.
Antimatter domains containing antiprotons and different types of antinuclei are studied.
The antiproton-proton annihilation interactions are therefore schematized and evaluated.
The antinuclei-nuclei-interaction-patterns are investigated.
The two-point correlation functions for antimatter domains are studied in the case of baryon-antibaryon boundary interactions, for which the spacial evolution and the time evolution are considered.

The space-time evolution of antimatter domains after the photon thermalization epoch is analyzed.

Summary

- classification of antimatter domains according to the densities, and to the type(s) of antimatter involved within the *non-trivial baryosyntheses processes* considered

- definition of boundary interactions for antimatter domains

- further estimations:
  - space-time evolution of antimatter domains
  - two-point correlation functions

- outlook

Introduction

In several cosmological scenarios, the appearance of domains with antibaryon excess can be predicted.
Within the framework of non-trivial baryosynthesis scenarios, the formation of antimatter domains containing antibaryons, such as antiprotons, antinuclei, and both possibilities are studied according to their dependence on their antimatter densities within the domains.
The boundary conditions for antimatter domains are determined through the interaction with the surrounding baryonic medium.
Within the analysis, new classifications for antibaryon domains, which can evolve in antimatter globular clusters, are in order.

Differences must be discussed within the relativistic framework chosen, the nucleosynthesis processes, the description of the surrounding matter medium, the confrontation with the experimental data within the observational framework. The spacetime-evolution of antimatter domains and the two-point correlation functions are described within the nucleon-antinucleon boundary interactions.

Introductory statements

If the density is so low that nucleosynthesis is not possible, low density antimatter domains contain only antiprotons (and positrons).
High density antimatter domains contain antiprotons and antihelium.
Heavy elements can appear in stellar nucleosynthesis, or in the high-density antimatter domains.
Strong non-homogeneity in antibaryons might imply (probably as a necessary condition) strong non-homogeneity for baryons, and produce some exotic results in nucleosynthesis.

Antimatter domains and antibaryons interactions

radiation-dominated era

within the cosmological evolution, the dominant contribution to the total energy is due to photons.

low density antimatter domains:
the contribution of the density of antibaryons $\rho_{\overline{B}}$ is smaller than the contribution due to the radiation ρ_γ even at the matter-dominated stage

in a FRW Universe, within its thermal history, for $T < 100keV$ only photons as a dominant components are considered

matter-dominated era and following

within a *non-homogeneous* scenario,
$\rho_{DM} > \rho_B$, with $\rho \equiv \rho(x)$

the creation of high density antibaryon domains can be accompanied by similar increase in baryon density in the surrounding medium. Therefore outside high density antimatter domain baryonic density may be also higher than DM density

$\rho_B(x) > \rho_{DM}(x)$

low density antimatter domains:

total density $\rho_{\overline{B}} + \rho_\gamma$

$\rho_{\overline{B}} < \rho_\gamma$

$\rho_{dm} > \rho_B$

Boundary interactions

boundary interaction examples:
The amount of annihilated antibaryons $\Delta\tilde{N}$ should not exceed the total amount $\tilde{N}$ of antibaryons in domain.
Therefore, the domain can survive if $\tilde{N} > \Delta\tilde{N}$.

Nucleon-antinucleon interaction studies

a study: **proton-antiproton annihilation probability: limiting process- theoretical formulation**

- $P(\bar{p})$ probability of existence of one antiproton of mass m_p, m_p being the proton mass, in the spherical shell, of section r_I, of (antimatter)-density ρ_I, delimiting the antimatter domain, in which the interaction takes place $P(\bar{p}) \equiv 3Nm_p/(r_I\rho_I)$ according to the Fisher's hypergeometrical non-central modified distribution;
- $\tilde{P}_i \equiv \tilde{P}_{\bar{p}\rightarrow(d.c._i)}$ probability of antiproton $\bar{p}$ interaction with a proton p in a chosen i annihilation channel $a.c.$, possibly also depending on the chemical potential;
- Δt time interval considered,

under the most general hypotheses (most stringent constraint), $\Delta t \pm \delta t$,
$\Delta t \simeq t_U \simeq 4 \cdot 10^{17} s$
t_U age of the universe, δt to be set according to the particular phenomena considered;
$\bar{P}_{\bar{p},i}(t, \Delta t)$ probability of antiproton interaction, i.e. antiproton-proton annihilation (density)

$$\bar{P}_{\bar{p},i} \simeq \frac{1}{\Delta t} P_{\bar{p}} \tilde{P}_i$$

a study: **nucleon-antinucleon interaction (annihilation) probabilities**
antinucleus $\bar{M}$ interaction probability $\bar{P}_{\bar{M},j}(t, \Delta t)$ through the annihilation channel(s) k
$\bar{P}_{\bar{M},k}(t, \Delta t) \simeq \frac{1}{\Delta t} P_{\bar{A}} \tilde{P}_{\bar{A},k}$ [t^{-1}]

to be further specified for:

- non-trivial Relativistic scenarioes

such as perturbed FRW
with the thermal history of the Universe
i.e., also, according to the Standard Cosmological Principle

at large scales asymptotically isotropic and homogeneous;

- non-trivial nucleosyntheses;
- possibilities of surrounding media;
- antibaryon-baryon annihilation:

most stringent constraint: $\bar{P}$ evaluated for present times in the description of reducing density in the limiting process of a low-density antimatter domain.

An example

Low-density antimatter domains:
- non-interacting antiprotons;
- boundary interactions;
- interaction with surrounding medium.

Low-density antimatter domains can be surrounded by low-density matter regions.

observational evidences
existence of low-density antimatter domains
-*to be compared with the experimental data and numerical simulation of existence and non-disappearing of antimatter domains* based on the hypothesis that the examined antimatter domain has not undergone disappearance in the limiting process
- in the case of higher densities antimatter domains, further schematizations allow one to describe processes.

further analyses: antinuclei antimatter domains
non-trivial baryosyntheses products
further constraints
further studies

Symmetry-breaking scenario

Ya. B. Zeldovich, L. B. Okun, L.Yu. Kobzarev, Cosmological Consequences of the Spontaneous Breakdown of Discrete Symmetry, Zh. Eksp. Teor. Fiz. 40,1 (1974);
V.M. Chechetkin, M.G. Sapozhnikov, M.Yu. Khlopov, Ya.B. Zeldovich, Astrophysical aspects of antiproton interaction with ^{4}He (antimatter in the universe) Phys. Lett. B 118, 329 (1982);
V.M. Chechetkin, M.G. Sapozhnikov, M.Yu. Khlopov, Antiproton interactions with light elements as a test of GUT cosmology, Riv. N. Cim. 5, 1 (1982);
V.A. Kuzmin, I.I. Tkachev, M.E. Shaposhnikov, Are There Domains of Antimatter in the Universe?, Zh. Eksp. Teor. Fiz. Lett. 33, 557 (1981).
spontaneous CP violation

$$\begin{aligned}V(\phi_1,\phi_2,\chi) = &-\mu_1^2(\phi_1^+\phi_1+\phi_2^+\phi_2)+\lambda_1[(\phi_1^+\phi_1)^2+(\phi_2^+\phi_2)^2]+2\lambda_3(\phi_1^+\\ &\phi_1)(\phi_2^+\phi_2)(\phi_1^+\phi_2)+2\lambda_4(\phi_1^+\phi_2)(\phi_2^+\phi_1)+\lambda_5[(\phi_1^+\phi_2)^2+h.c.]+\\ &\lambda_6(\phi_1^+\phi_1+\phi_2^+\phi_2)(\phi_1^+\phi_2+\phi_2^+\phi_1)-\mu_2^2\chi^+\chi+\delta(\chi^+\\ &\chi)^2+2\alpha(\chi^+\chi)(\phi_1^+\phi_1+\phi_2^+\phi_2)+2\beta[(\phi_1^+\chi)(\chi^+\phi_1)+(\phi_2^+\chi)(\chi^+\phi_2)]\end{aligned}$$

effective low-energy electroweak $SU(2)\otimes U(1)$ theory.
GUT spontaneous CP violation

formation of vacuum structures separated from the rest of the matter universe by

domain walls,

- whose size is calculated to grow with the evolution of the Universe. behavior calculated not to affect the evolution of the Universe if the volume energy $\rho(\tilde{V})$ density of the walls for
$\rho(\tilde{V}) \sim \sigma_\phi^2 T^4/\tilde{h}$,
$\tilde{h}$ value of the scalar coupling constant.

CP-invariant Lagrangean

$$L = (\partial\phi)^2 - \lambda^2(\phi^2 - \chi^2)^2 + \bar{\psi}(i\partial - m - ig\gamma_5\phi)\psi$$

vacuum characterized by $<\phi>=\sigma\eta$, with $\sigma = \pm 1$.

$$L = (\partial\chi)^2 - \frac{1}{2}m_\chi^2\chi^2 - 4\sigma\lambda 2\chi\eta^3 - \lambda^2\chi^4 + \bar{\psi}(i\hat{\partial} - M - i\frac{gm}{M}\gamma_5\chi - \frac{g^2\sigma\eta}{M}\chi)\psi.$$

CP violation can be achieved after the substitution $\phi = \chi + \sigma\eta$.

the domain wall problem can be solved after the Kuzmin-Sapozhnikov-Tkachev mechanism.

- research for antinuclei in cosmic rays;
- research for annihilation products;

- annihilation at rest on Relativistic background;
- annihilation of small-scale domains
  - thin-boundary approximation;
  - at different times, the diffusion of the baryon charge is determined after different processes.

Spontaneous baryosynthesis

allowing for the possibility of sufficiently large domains through proper combination of effects of inflation and baryosynthesis

$\chi \equiv \frac{f}{\sqrt{2}} e^{\theta}$

variance

$< \delta\theta >= \frac{H^3 t}{4\pi^2 f^2}$

$\tilde{N}(t) - \tilde{N}(t_0) \equiv \int_{t_0}^{t_\iota} P(\chi) \ln \chi d\chi(t), \quad P(\chi)$ including variance

$\tilde{H}$ Hubble-radius function,

Δf_{eff} effective (time-dependent) phase function

$f_{eff} = f\sqrt{1 + \frac{g_{\phi\chi} M_{Pl}}{12\pi\lambda}(N_c - N)}$

N e-foldings at inflation

M.Yu. Khlopov, S.G. Rubin, A.S. Sakharov, Possible origin of antimatter regions in the baryon dominated universe, Phys. Rev. D 62, 083505 (2000);

M.Yu. Khlopov, S.G. Rubin, A.S. Sakharov, Antimatter regions in the baryon dominated universe, 14th Rencontres de Blois on Matter- Anti-matter Asymmetry [hep-ph/0210012].

Poisson space-time antimatter statistical distribution

antibaryon gas with positrons in the FRW Universe within the thermal history
low density domains: neither nucleosynthesis, nor recombination takes place

k Poisson probability of the existence of two neighboring domains with antibaryons
$\tilde{N}$ number of antibaryons

$$\tilde{N}(k) - \tilde{N}_0(k)(\Delta t) \simeq \sum_n \sum_k \frac{k^n e^k}{n!} \frac{\chi_{t_a}}{\chi_{t_0}} \frac{2}{\Delta f_{eff}(t; t_a, t_i, t_0)} \cdot \left(\frac{(-2)}{4\pi^2} \left[ln \frac{L_u e^{\tilde{H}_c(t_c - t_0)} - e^{\tilde{H}_0 t_0}}{l} \right] \right)^k (t)^{k-3},$$

Two-point correlation functions

two-point correlation functions $\tilde{C}_2$ for two antimatter domains α_1 and α_2 of size $> 10^3 M_\odot$ each
- on (homogenous, isotropic) Minkowski-flat background
- antimatter densities $\rho \equiv \tilde{N}/V$ following a Poisson space-time statistical distribution

$d\tilde{C}_2(\alpha_1, \alpha_2) \equiv \rho^2(1 + \xi(\mid \vec{r}_{\alpha_1\alpha_2} \mid))dV_1 dV_2$

estimator $\xi(\mid \vec{r}_{\alpha_1\alpha_2} \mid) \equiv \mid \vec{r}_{\alpha_1\alpha_2} \mid$

$\vec{r}_{\alpha_1\alpha_2}$ distance of the two antimatter domains

for the two antimatter domains
of volume $V_{\alpha_l} \equiv \frac{4}{3}\pi r_l^3$
separated of a distance $\mid \vec{r}_{\alpha_1\alpha_2} \mid$

analytical solution for the two-point correlation functions for two antimatter domains

analytically integrated:

$$\tilde{C}_2(\alpha_1, \alpha_2) = 2\pi\tilde{n}(n, k; \Delta f_{eff}, \tilde{H}; \Delta t) \mid \vec{r}_{\alpha_1\alpha_2} \mid \left(\frac{1}{r_2} + \frac{1}{r_1}\right) \tilde{H_c}^{2k} t^{4k-4}$$

evaluated at the present time t

$\tilde{H}_c$ effective Hubble-radius function

Low-density antimatter domains described by a Binomial space-time statistical distribution

k binomial probability of the limiting process (approximation) of existence of a domain containing only two antibaryons,
p^k binomial probability of the limiting process of existence of a domain containing $k-1$ neighbouring antibaryons,
Relativistic expression for the antimatter domain density, $\tilde{N}(k) - \tilde{N}_0(k)$

$$\tilde{N}_{bin}(k) - \tilde{N}_{bin0}(k) \simeq \sum_k \frac{1}{(k!)(1-k)!} \frac{\chi_{t_a}}{\chi_{t_0}} \frac{2}{\Delta f_{eff}(t; t_a, t_i, t_0)} \Big(\frac{(-2)}{4\pi^2} \cdot \cdot \big[ln \frac{L_u e^{H_c(t_c - t_0)} - e^{H_0 t_0}}{l} \big] \Big)^k (t)^{k-3}$$

$2\hat{n}$ antibaryon (and/or antinuclei) density (at least considered for the neighbouring antibaryon-antibaryon interaction),
expressed by the effective expression of H for $\hat{n}$ antibaryons;
n the number of antibaryons surrounding the domain,
i.e. $n-k$ relates the number of antibaryons neighbouring with a baryon;
$(1-p)^{n-k}$ binomial probability that a baryon is neighbouring with an antibaryon, i.e. at the domain boundary.

an example: **two-point correlation functions for an antimatter domain and another object**

limiting example:

correlation function between an antimatter domain α_1 and an antibaryon α_3

Davies-Peebles estimator

for the macroscopic objects described in terms of density distribution and temperature distribution

$\xi_{l,l'} \equiv \frac{\tilde{N}_{bin}}{\tilde{N}}\frac{D_l(|\vec{r}|)}{D_{l'}(|\vec{r}|)} - 1$

$\tilde{N}$ number of antibaryons in a low-density antimatter domain

$\tilde{N}_{bin}$ number of antibaryons in a low-density antimatter domain where the antimatter is distributed according to a binomial space-time statistical distribution,

$D_l(|\vec{r}|)$ number of pairs of low-density appropriate-mass antimatter domains

within the geodesics (coordinate) interval distance $\left[r-\frac{dr}{2}, r+\frac{dr}{2}\right]$

$D_l'(|\vec{r}|)$ number of pairs of objects between an antimatter domain and an (*Poisson-distributed*) antibaryon on the coordinate geodesics

$$\xi_{l,l'} \equiv \frac{\tilde{n}_{bin}(n,k;\Delta f_{eff},\tilde{H};\Delta t)}{\tilde{n}(n,k;\Delta f_{eff},\tilde{H};\Delta t)} \frac{D_l(|\vec{r}|)}{D_l'(|\vec{r}|)} - 1$$

within the use of statistical estimators, the time dependence $\tilde{H_c}^{2k} t^{4k-4}$ is suppressed, and
the *time dependence* is expressed after the ratio $\frac{\tilde{n}_{bin}(n,k;\Delta f_{eff},\tilde{H};\Delta t)}{\tilde{n}(n,k;\Delta f_{eff},\tilde{H};\Delta t)}$, i.e. on the different statistical antimatter space-time distributions and on their dependence on the
- $\tilde{H}$ Hubble-radius function, and on
- Δf_{eff} effective (time-dependent) phase function.

Hamilton estimator
the Hamilton estimator
$\tilde{\xi}_{l,l'}$ takes into account the difference in distances among the Binomial distribution and the Poisson distribution

Time evolution of antimatter domains

the baryon/photon ratio s
$s \equiv n_b/n_{\tilde{\gamma}}$

$$\frac{\partial s}{\partial t} = D(t)\frac{\partial^2 s}{\partial x^2}, \tag{1}$$

$s(\mathbf{R}, t_0) = s_0, x < 0, \quad s(\mathbf{R}, t_0) = 0, x > 0,$
to compute the geodesics coordinate distance run accross by atoms after the recombination age until the present time
within a suitable photon thermalization process with s_0 the initial condition n_0/n_γ

M.Yu. Khlopov, R.V. Konoplich, R. Mignani, S.G. Rubin, Evolution and observational signature of diffused antiworld, Astrop. Phys. 12, 367 (2000).

equation for the number density of antiprotons

antiprotons which takes into account both the annihilation and the expansion of the Universe

- study at a temperature T, $4 \cdot 10^4 K < T < 10^9 K$; - low-density antimatter domains: density of antimatter within a domain 3 orders of magnitude less than the baryon density;
- study of the interaction $\overline{n} + \overline{p} \rightarrow \overline{d} + \gamma$:

  its cross section $< \sigma v >$ does not depend on the temperature if below $1 MeV$ and implies the antideuterium production in the reaction only if the reaction rate exceeds the expansion rate of the Universe;
- the (integrated) Thomson cross section is studied through the diffusion coefficient $D(t)$;
- *analytical solution of the equation for the number density of antiprotons as a function of annihilation and expansion of the Universe*

Bernoulli distribution

$$\tilde{N}(k) - \tilde{N}_0(k) \simeq \frac{1}{(k!)(1-k)!}\frac{\chi_{t_a}}{\chi_{t_0}}\frac{2}{\Delta f_{eff}(t; t_a, t_i, t_0)}\left(\frac{(-2)}{4\pi^2}\cdot\right.$$
$$\left.\left[ln\frac{L_u e^{H_c(t_c - t_0)} - e^{H_0 t_0}}{l}\right]^k (t)^{k-3}\right.$$

Binomial distribution

$$\tilde{N}(k) - \tilde{N}_0(k) \simeq \sum_k \frac{1}{(k!)(1-k)!} \frac{\chi_{t_a}}{\chi_{t_0}} \frac{2}{\Delta f_{eff}(t; t_a, t_i, t_0)} \left(\frac{(-2)}{4\pi^2}\right. \cdot$$

$$\left[ln \frac{L_u e^{H_c(t_c - t_0)} - e^{H_0 t_0}}{l}\right]^k (t)^{k-3}$$

J. Bernoulli, Ars Conjectandi, Opus Posthumum. Accedit Tractatus de Seriebus infinitis, et Epistola Gallice scripta de ludo Pilae recticularis; Impensis Thurnisiorum, Fratrum, Basel (1713).

number of antibaryons in the boundary spherical shell in which the antibaryon-baryon interaction takes place

$\frac{dn_{\bar{b}}}{dt} \simeq -\frac{R_d}{3} n_{\bar{b}} \left(< \sigma v > n_b - \beta\right)$

R_d radius of the spherical antimatter domain

$\beta > 0$ growth rate of the photon density

formally it can be taken into account but
almost negligible at the RD stage and very small contribution of antimatter in the total density
allows for the solution

Bernoulli space-time statistical distribution of antimatter

$\ln n_{\bar{b}\ \ Ber} \simeq \ln n_{\bar{b}\ \ Ber\ \ 0} - \frac{R_d}{3} \tilde{n}_{Ber}(k; \Delta f_{eff}, \tilde{H}; \Delta t) \frac{1}{k-2} t^{k-1} \mid_{t_0}^{t} (< \sigma v > n_b - \beta)$

Poisson space-time statistical distribution of antimatter

$\ln n_{\bar{b}\ \ Poiss} \simeq \ln n_{\bar{b}\ \ Poiss\ \ 0} - \frac{R_d}{3} \tilde{n}_{Poiss}(n, k; \Delta f_{eff}, \tilde{H}; \Delta t) \frac{1}{k-2} t^{k-1} \mid_{t_0}^{t} (< \sigma v > n_b - \beta)$

Binomial space-time statistical distribution of antimatter

$\ln n_{b\ \ \bar{b}in} \simeq \ln n_{\bar{b}\ \ bin\ \ 0} - \frac{R_d}{3} \tilde{n}_{bin}(n, k; \Delta f_{eff}, \tilde{H}; \Delta t) \cdot \cdot \frac{1}{k-2} t^{k-1} \mid_{t_0}^{t} (< \sigma v > n_b - \beta)$

Gaussian space-time statistical distribution of antimatter

$\ln n_{\bar{b}\ \ Gauss} \simeq - \ln n_{\bar{b}\ \ Gauss\ \ 0} \frac{R_d}{3} \tilde{n}_{Gauss}(\Delta t - 1) e^{\Delta t} (\Delta f_{eff}, \tilde{H}; \Delta t) \left(< \sigma v > n_b - \beta\right)$

after treating the number of baryons n_b as not changing with respect to the number of antibaryons $n_{\bar{b}}$,
it is possible to evaluate the boundary of the antimatter domain as a spherical shell in which the baryon-antibaryon annihilation takes place as depending on
- whether the antibaryons in the low-density antimatter domains are not interacting.

Matter domains can be of interest only, if we take into account that high density antimatter domains are associated with surrounding high density baryonic matter.

Further characterizations of the number of antibaryons in the boundary spherical shell in which the antibaryon-baryon interaction takes place

perfect-fluid solution

perfect-fluid $(\rho_E, \vec{p})$

$\frac{dn_{\bar{b}}}{dt} \simeq -\frac{R_d}{3} n_{\bar{b}} (<\sigma v> n_b - \beta) - F(\rho_E, \vec{p})$

F function which encodes the properties of the perfect-fluid solution on a Relativistic background at the time at which the number of baryons is evaluated under the hypotheses that annihilation products should induce isotropic pressure that stops the limiting process of the disappearance of the domain

at very small scales (smaller than the non-disappearance scale) the radiation pressure is not sufficient

$\frac{dn_{\bar{b}}}{dt} \simeq -\frac{R_d}{3} n_{\bar{b}} (< \sigma v > n_b - \beta) - \tilde{F}(\rho_E, \vec{p}; R_d, l_d; \vec{v}_T, v_f)$

plasma epoch

the plasma behaves as a single fluid,

$\Rightarrow$ fluid viscosity determined by the radiation field

annihilation region: antibaryons migrating to the boundary of the antimatter domain

as density increases, the annihilation interactions become rapid, and the products of annihilation can express an isotropic pressure

the annihilation interactions cannot provide with the energy required to let the turbulent regime start
(and induce galaxy formation)

$\Rightarrow$ differently, the radiation spectrum is modified

ΔE_T *energy dissipated* per unit density per unit time at the effect of fluid viscosity

within the interaction region of width ΔR

$\Delta E_T \simeq \frac{{v_T}^3}{l_d} \frac{3(R_d^2 - \Delta R^2)}{R_D^3}$

v_T turbulent velocity

F.W. Stecker, J.L. Puget, Astrophys. J. 178,57 (1972).

characteristic size of the emulsion region

turbulence scale determined by the coefficient of viscosity v

$\Delta E_v \simeq \frac{3(R_d^2 - \Delta R^2)}{R_D^3} n$

$\Delta R \sim v_f(z) t(z)$

study redshift of the thermal photons

v_f determined by the mass of the fluid moving

$t(z) = t_0 (1+z)^{-3/2}$, with t_0 present age of the Universe

$0.1d \leq \Delta R \leq d$ larger than the mean-free path of π-decay γ rays

G.A. Steigman, Annu. Rev. Astron. and Astrophys. 14, 339 (1976).

$\frac{dn_{\bar{b}}}{dt} \simeq -\frac{R_d}{3} n_{\bar{b}} \left(< \sigma v > n_b - \beta \right) - f(\rho_E, \vec{p}) \equiv$
$\equiv -\frac{R_d}{3} n_{\bar{b}} \left(< \sigma v > n_b - \beta \right) - \left(\Delta E_T + \Delta E_v \right) \frac{dn_{\bar{b}}}{dt}$
Bernoulli space-time statistical distribution of antimatter
$\ln n_{\bar{b}\ \ Ber} \simeq \ln n_{\bar{b}Ber\ \ 0} -$
$\frac{R_d}{3} \tilde{n}(k; \Delta f_{eff}(\rho_E(b), \rho_E(\bar{b})), \tilde{H}(\rho_E(b), \rho_E(\bar{b})); \Delta t) \frac{1}{k-2} t^{k-1} \left(< \sigma v > n_b - \beta \right) -$
$(\Delta E_T + \Delta E_v) n \Delta t$

in this case the effective-phase function $\Delta f_{eff}(\rho_E(b), \rho_E(\bar{b}))$ and the Hubble-radius function from the F equation $\tilde{H}(\rho_E(b), \rho_E(\bar{b}))$ are modified by the interaction between radiation and antibaryons

the thermal radiation implies separation of nucleons and antinucleons through
$\frac{dn_{\bar{b}}}{dt} \simeq -\frac{R_d}{3} n_{\bar{b}} \left(< \sigma v > n_b - \beta \right) - \left(\Delta E_T + \Delta E_v \right) \frac{dn_{\bar{b}}}{dt} - \mu \nabla^2 n$

solution found at the radiation-dominated era,

at which the antimatter space-time statistical distributions are defined,

solution expanded after the time of last scattering

according to the effective quantities

Bernoulli space-time statistical distribution of antimatter

$$\ln n_{\bar{b}} \quad \leq$$
$$-\ln n_{\bar{b}} \quad {}_{Ber} \quad {}_{0}\frac{R_d}{3}\tilde{n}(k; \Delta f_{eff}(\rho_E(b), \rho_E(\bar{b})), \tilde{H}(\rho_E(b), \rho_E(\bar{b})); \Delta t)\frac{1}{k-2}t^{k-1}\,(< \sigma v > n_b - \beta)$$
$$-(\Delta E_T + \Delta E_v + \tilde{\mu})n\Delta t$$

with $\tilde{\mu} < \Delta E_T + \Delta E_v$

Outlook

- comparison with dm objects of different/smaller mass/ limiting processes

V. Berezinsky, V. Dokuchaev, Y. Eroshenko, Small-scale clumps of dark matter, Usp. Fiz. Nauk 184, 3 (2014);
V. Berezinsky, V. Dokuchaev, Y. Eroshenko, Destruction of small-scale dark matter clumps in the hierarchical structures and galaxies, Phys.Rev. D 77, 083519 (2008); V. Berezinsky, V. Dokuchaev, Y. Eroshenko, Dark Matter Annihilation in the Galaxy, Phys. Atom. Nucl. 69,2068077 (2006).

- analyses of the limiting processes and characterization of the results

Newlin C. Weatherford, G. Fragione et al., Black Hole Mergers from Star Clusters with Top-Heavy Initial Mass Functions, arXiv:2101.02217;
A.A. Abdujabbarov, B.J. Ahmedov, V.G. Kagramanova, Particle Motion and Electromagnetic Fields of Rotating Compact Gravitating Objects with Gravitomagnetic Charge, Gen. Rel. Grav. 40 (2008).

- antimatter domains separated in a small angular distance
  - Rubin-Limber correlation functions for small angles

V.C. Rubin, Fluctuations in the space distribution of galaxies, Proc. Natl. Acad. Sci. USA 40, 541 (1954);
D.N. Limber, The Analysis of Counts of the Extragalactic Nebulae in Terms of a Fluctuating Density Field. II., Astrophys. J. 119, 655 (1954).

- analysis of the metric requiring a time evaluation after the time of the surface of last scattering A. Pontzen, A. Challinor, Linearization of homogeneous, nearly-isotropic cosmological models, Class. Quant. Grav. 28, 185007 (2011), Eq. (52).

Thank You for Your attention