29th Workshop
“What Comes Beyond the Standard Models”
7 July 2026

Energy release from non-surviving antimatter domains

Dembitskaia A.I.[1,] Khlopov M.Yu.[1,2]

1.National Research Nuclear University MEPhI, Moscow, Russia

2.Virtual Institute of Astroparticle Physics, Paris, France

Antimatter domains

Current understanding of the Universe assumes its baryon asymmetry, which implies the absence of macroscopic antimatter in quantities comparable to that of matter. Nevertheless, under certain conditions, the local generation of antimatter domains is possible, caused by strong small-scale **inhomogeneity of baryosynthesis**

Size of the spherical symmetrical domain:

$$\mathrm{R} = \left(\frac{Mt^{\frac{3}{2}}}{0,24 m_p \eta 10^{30}}\right)^{\frac{1}{3}}$$

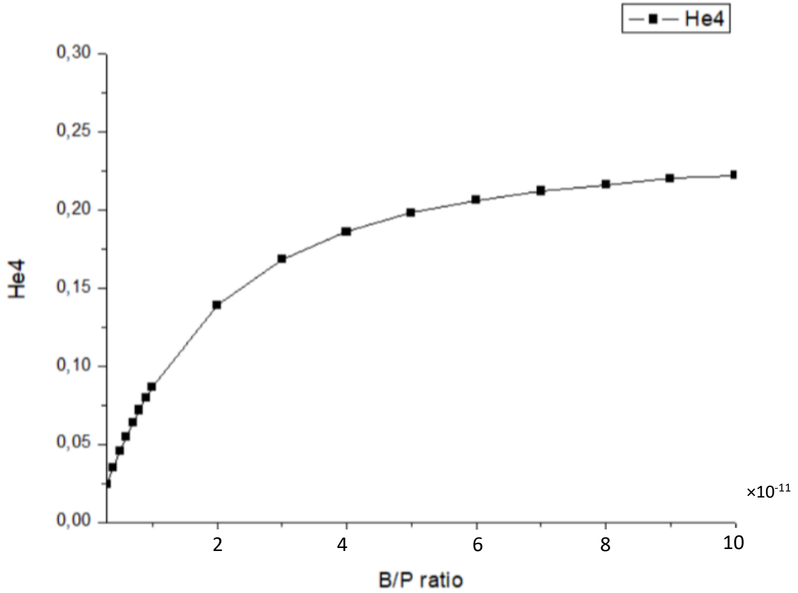
Moment of entering the horizon:

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

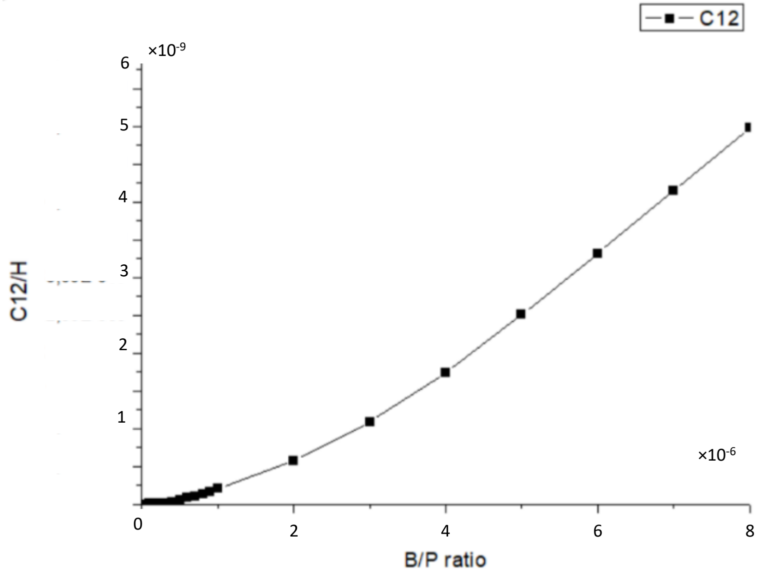
The domain must satisfy two conditions:

1. Sufficient 4He production to allow cooling and collapse into Population III objects;
2. No significant 12C production, since carbon and heavier elements would trigger observable annihilation signatures.

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



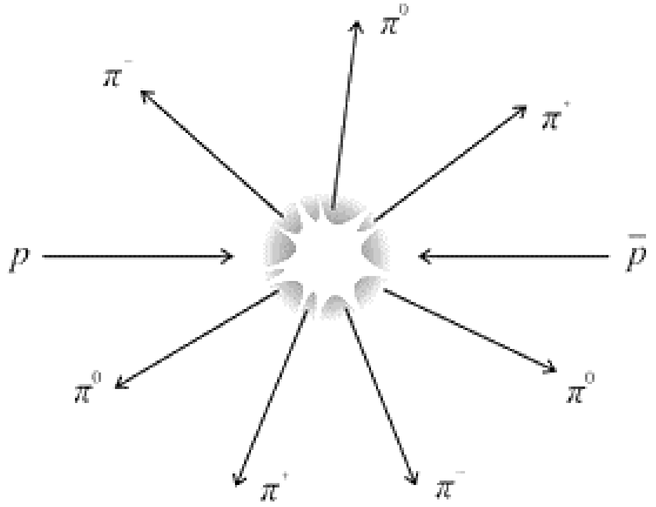
Dependence of the mass fraction of 4He on baryon/photon ratio



Dependence of the mass fraction of 12C on baryon/photon ratio

Processes inside the domain

After the domain enters the horizon, annihilation will occur at the border



The products of proton-antiproton annihilation:

1. Photons (from the decay of neutral pions)
2. Electrons/positrons (from the decay of charged pions)

$T > 10^7 K$

Dominant process:
electron-positron pair production

$$n_{\gamma\_high} \approx n_\gamma \left(\frac{E_{min}}{kT}\right)^2 e^{\frac{-E_{min}}{kT}}$$

$$\sigma_{pp} \approx \frac{2\pi\alpha^2}{s}\left[2\ln\frac{s}{m_e^2} - \frac{3}{2}\right] \approx 2,1 \times 10^{-28}\text{cm}^2$$

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

$T \leq 10^7 K$

Dominant process:
Multiple Compton scattering

σ_τ -Thomson scattering cross section,
$f(x)$-correction factor accounting for relativistic effects,
x-the dimensionless photon energy.

$$\sigma_{KN} = \sigma_\tau f(x)$$

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

Diffusion at the border

The diffusion process in the domain in the spherical approximation is described by a modified Fick's equation:

$$\frac{\partial n_b}{\partial t} = \frac{D(t)}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial n_b}{\partial r}\right) - \boxed{\Gamma_{\text{ann}}(r)\, n_b} - \boxed{\beta n_b}$$

Annihilation term

Expansion term

Diffusion coefficient: $\boxed{D(t) = \frac{1}{3}\frac{1}{n\sigma}v}$

Radiation-dominated era

Dominant process:
Compton scattering

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

Matter-dominated era

Dominant process:
radiation drag

$$\boxed{D(t) \propto \frac{t^2}{\sigma_T} \propto t^2}$$

Ionization of the domain

The next process that must be taken into account to describe the evolution of the antimatter domain over time is the ionization of antimatter, which will be caused by the products of proton-antiproton annihilation at the boundary. If the ionization of matter is sufficiently high, it must be taken into consideration in describing the evolution of the domain

Ionization

Boundary region

Ionization will occur due to high-energy electrons produced as a result of annihilation

Inner region

UV photons produced by inverse Compton scattering of relativistic electrons ionize neutral antihydrogen in a thin near-boundary layer of the domain

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

The thickness of the ionized layer δ is defined as the distance from the surface at which mean ionization drops by a factor of 100 relative to its value at the surface.

$$\exp\left(-\frac{\delta}{2\lambda_{UV}}\right) = 0.01$$

$$\delta \approx 9.2 L_e \approx 9 L_e$$

Ionization degree

Electron mean free path

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

where $\beta_0 \approx 1$ for initially relativistic electrons;
$K_\gamma(z) \approx 0.7\,(1+z)^4$ eV/Mpc -loss coefficient.

Flux density of UV photons

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

$$\langle x_e \rangle \approx \frac{6 L_e}{R} \propto T^{-3}$$

Absorption length of an UV-photon

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

Applicability of the model:

1. Annihilation rate
2. Photon mean free path should be less than the size of the domain
3. Ionization over the volume must be weak

$$T \geq \left(\frac{m_p}{\sigma_{ion}^3}\right)^{\frac{1}{6}} \left(\frac{1}{\eta^2 M}\right)^{\frac{1}{6}}$$

Ionization fraction:

1. At the boundary: 1
2. In the ionized layer: 0.22
3. In the bulk volume: exponentially decreases to zero

On average over the volume, the domain can be considered neutral

Differential equation for the evolution of the antimatter domain

The evolution of primordial antimatter domain is governed by the competition between the cosmological expansion and the local erosion at this boundary due to annihilation

$$\dot{R}(t) = H(t)R(t) - v_{\text{ann}}(t)$$

Expansion term

Annihilation term

The annihilation velocity is obtained from dynamic balance at the boundary, known as Stefan-Type boundary condition :

$$v_{\text{ann}}(t) = v_0(t)\sqrt{1 + \frac{P_{ann}(t)}{k_{\text{B}}T(t)n_{\text{eff}}(t)}}$$

$$v_0(t) \equiv \sqrt{D(t)\langle\sigma v\rangle n_b(t)}$$

If the expansion term dominates, the domain grows with the Hubble flow, however if the annihilation term dominates, the boundary recedes and the domain disappears

$$\dot{R}(t) = H(t)R(t) - v_0(t)\sqrt{1 + \frac{P_{ann}(t)}{k_{\text{B}}T(t)n_{\text{eff}}(t)}}$$

Non-surviving antimatter domains

For a domain to survive to the present epoch, its mass must be greater than M_{crit}. Meanwhile, less massive domains can form, which will eventually be destroyed over time

The survival condition for an antimatter domain can be obtained by comparing the physical radius of the domain with the critical radius derived from the balance of cosmic expansion and annihilation-driven erosion

The criteria of surviving of domains

1. If the actual mass $M > M_{crit}(t)$, the expansion term dominates over annihilation-the domain survives and grows with the Hubble flow.
2. If the actual mass $M < M_{crit}(t)$, the annihilation overtakes the expansion, the domain is rapidly destroyed

$$M_{\rm crit}(t) = m_p \eta T(t)^3 \left[\frac{v_0(t)}{H(t)} \sqrt{1 + \frac{P_{ann}(t)}{k_{\rm B} T(t) n_{\rm eff}(t)}} \right]^3$$

$$R_{\rm crit}(t) = \frac{v_0(t)}{H(t)} \sqrt{1 + \frac{P_{ann}(t)}{k_{\rm B} T(t) n_{\rm eff}(t)}}$$

The energy release will occur near the border

Dynamics of energy release

We consider the domain that die before the recombination era

50% of annihilation energy is carried by neutrinos → Observed energy: $Q_{obs} = Mc^2$

Lifetime of the domain: $\tau_{\text{death}} = t_{\text{form}} + \frac{R(t_{\text{form}})}{v_{\text{ann}}} \approx \frac{2ct_{\text{form}}}{v_{\text{ann}}}$

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

This energy will not be released instantaneously, but over time.
It is necessary to investigate the dynamics of the energy release.

The rate of energy release: $\frac{\mathrm{d}Q}{\mathrm{d}t} = 4\pi R^2(t) n_{\bar{b}} v_{\text{ann}} \epsilon_{\text{ann}} \Phi(T)$

$$\mathrm{R} = \left(\frac{Mt^{\frac{3}{2}}}{0,24 m_p \eta 10^{30}}\right)^{\frac{1}{3}}$$

For the radiation-dominant era: $\frac{dQ}{dt} \propto \left(\frac{M}{m_p}\right)^{2/3} \eta^{1/3} \cdot t^{-1/2}\ \mathrm{erg/c}$

Size of the energy release region

The annihilation products will be ejected outward, forming a glow region around the domain. The size of this region will be determined by the mean free path of the annihilation products.

Main processes:

1. Electron-positron pair production

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

2. Compton scattering of an annihilation photon on an electron

3. Drag of annihilation electrons/positrons on thermal photons (inverse scattering)

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

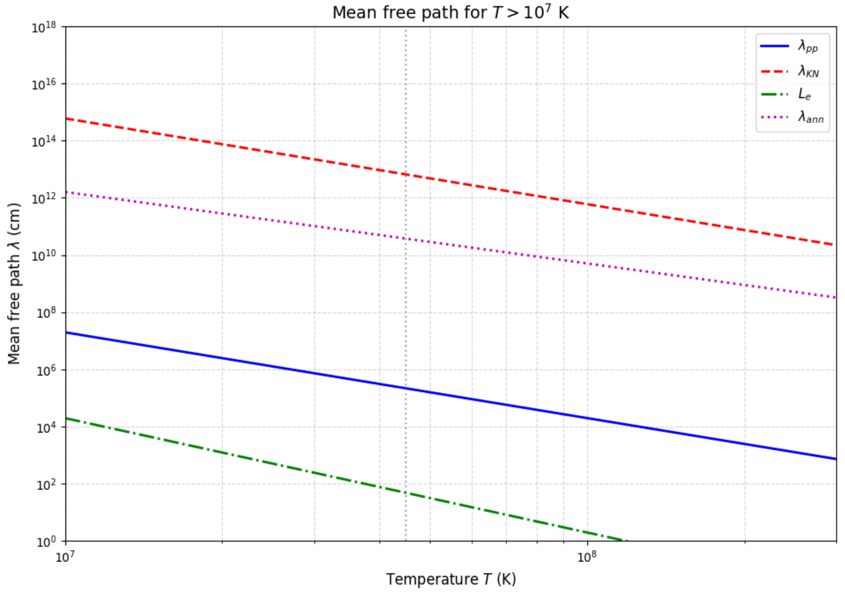
4. Positron annihilation with electrons

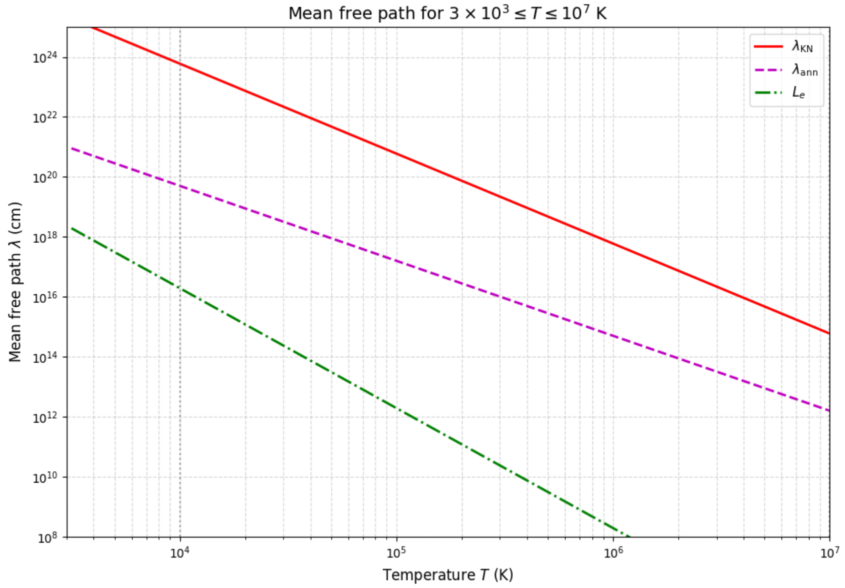
$T > 10^7\text{K}$

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

$10^3 K \leq T \leq 10^7\text{K}$

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





Evolution of the emission region size

$$R_{\mathrm{obs}}(t) = a(t)\sqrt{x_0^2 + 2d\int_{\tau_{\mathrm{death}}}^{t} \frac{D_x(t')}{a^2(t')}\,dt'}$$

Main glow region

-ballistic regime with no scattering

-is determined by the expansion of the Universe

$$R_{\mathrm{direct}}(t) = R_0 \frac{a(t)}{a(\tau_{\mathrm{death}})}$$

Halo

-diffusion regime taking into account single photon scattering

-is determined by the mean free path of photons

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

$$\frac{R_{\mathrm{halo}}(t)}{R_{\mathrm{direct}}(t)} = 1 + \frac{\langle \lambda_{\mathrm{mfp}} \rangle}{R_0}$$

Radiation-dominant era

sizes of the halo and the main glow region can be considered equal

Matter-dominant era

size of the halo significantly exceeds the size of the main emission region

Non-homogeneous scenario

The mechanism of inhomogeneous baryosynthesis does not prohibit the formation of inclusions consisting of matter inside the antimatter domain

Various scenarios

One large subdomain at the centre

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

Many small subdomains uniformly distributed

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

Additional source of annihilation and ionization:

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

Survival criterion of the antimatter domain:

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

Conclusion

- Antimatter domains are a natural consequence of inhomogeneous baryosynthesis and remain cosmologically viable within a narrow range of internal baryon-to-photon ratio.
- Annihilation at the domain boundary proceeds through distinct regimes: pair production at high temperatures and Compton scattering at lower temperatures, with diffusion properties evolving differently in the radiation and matter eras.
- Ionization is strongly stratified: fully ionized at the boundary, partially ionized in an intermediate layer, and neutral in the bulk, so the domain remains neutral on average.
- Domain survival is determined by the competition between Hubble expansion and annihilation-driven erosion. Domains above a critical mass survive; those below are destroyed before recombination.
- Energy release is not instantaneous but extended over time. Half of the annihilation energy escapes with neutrinos; the remainder is deposited into the surrounding plasma.
- The emission region consists of a direct component and a diffuse halo. The halo becomes dominant in the matter-dominated era, significantly enlarging the region affected by energy deposition.
- Matter inclusions inside antimatter domains provide additional annihilation channels and can destroy the domain internally even if the outer boundary remains stable.

Thank you for your attention!