High energy Gamma-Ray Bursts as a result of the collapse and total annihilation of neutralino clumps

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Abstract

Rare astrophysical events – cosmological gamma-ray bursts with energies over GeV – are considered as an origin of information about some SUSY parameters. The model of generation of the powerful gamma-ray bursts is proposed. According to this model the gamma-ray burst represents as a result of the collapse and the total annihilation of the neutralino clump. About 80% of the clump mass radiates during \( \sim 100\) second at the final stage of annihilation. The annihilation spectrum and its characteristic energies are calculated in the framework of Split Higgsino model.

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I. INTRODUCTION

Since the direct experimental information about structure of SUSY model and values of SUSY particles’ masses are absent now we try to extract any possible data from the cosmology. From the recent WMAP data \( \rho_{\text{crit}} \approx 0.54 \cdot 10^{-5} \text{GeV/cm}^3 \), the structured Dark Matter (DM) and the isotropic and homogeneous Dark Energy (DE) contribute to this density \( \approx 23\% \) and \( \approx 73\% \), correspondingly. As it is known, baryons give \( \approx 4\% \) of the total Universe’s mass. In our Galaxy \( \approx 50\% \) of total mass is the mass of DM which forms the Halo. The Lightest Supersymmetric Particles (LSP) – neutralino – are supposed to be the main contributors to the cold (and hot) DM. The physics of LSP is discussed intensively in various aspects \[2\].

To observe the neutralino appearance in space or land experiments one can use of the different ways. For example, the high energy antiprotons, positrons or neutrino flux due to neutralino annihilation in the Dark Halo or in the center of the Sun or the Earth. In our work we have concentrated on the specific gamma-radiation \[3\] which can be diffuse (due to annihilation into fermions and bosons) or monochromatic (due to annihilation into \( \gamma\gamma \) or \( Z\gamma \)) \[4\]). To measure characteristics of these specific gamma-fluxes the special experimental programs have been elaborated with space telescopes (EGRET, GLAST) \[3\], \[5\].

Now we have from the collider experiments only low restriction for the neutralino mass \( m_\chi > 32.5 \text{ GeV} \). ATLAS and CMS collaborations (LHC) will say something else only after 2007. But the absolute stability of neutralino (or metastability) cannot be checked in collider experiments. Moreover, some details of the standard cosmological scenario, which are based on the neutralino as the CDM, should be changed if neutralino’s and other superparticles’ characteristics do not agree with the scenario. Thus we need in combined analysis of the LHC and astrophysical data to verify our ideas on cosmological and cosmogonic evolution \[6\].

Neutralino in our Galaxy or in other galaxies up to \( z = 8 \div 10 \) at the gravity separation stage can form massive dense clumps of different sizes \[7\], \[8\], \[9\]. Due to the inner gravitational instability clumps can collapse and intensively annihilate. Our basic supposition is that the nature and origin of the rare high-energy GRB can be understood as a result of the neutralino clump total annihilation. We have shown that at the final stage of the process the powerful gamma-ray burst (GRB) with photon energies over GeV will occur. In the standard GRB the energies of photons are only fractions of MeV (see \[10\]). The specific energy and time distribution of this hard \( \gamma \)-radiation can be related with the parameters of superparticles (neutralino, in particular) and give an important information on the SUSY model details and its compatibility with cosmology. As an interesting example we have considered the Split Higgsino scenario \[11\] in the framework of famous Split Supersymmetry model \[12\] and obtained the values of annihilation time of the neutralino clump, characteristic photon energies of the GRB and the annihilation spectrum.

II. THE COLLAPSE OF THE HOMOGENEOUS NEUTRALINO CLUMP

Consideration of neutralino as a carrier of DM mass in the Universe generates questions about their evolution and about astrophysical phenomenons which prove both the existence of neutralino and the reality of the evolution process with neutralino participation.

According to high resolution cold dark matter simulations in the framework of the hierarchical principle of structure formation the large virilized halos are formed through the
constant merging of smaller halos produced at earlier times. Neutrino at the gravitational isolation stage \( z = 8 \div 10 \) formed dense massive clumps of different scales \[8\], \[13\]. It is naturally that DM clumps are in the state of dynamical equilibrium as a result of compensation of own gravitational forces by forces of tidal interactions with each other. In consequence of inner instability the clump can turn into irreversible collapse state. The growth of density provides the growth of annihilation rate. So neutralino clouds become more and more intense sources of relativistic particles. At final stage of this process there is a gamma-ray burst. Specific energy and time distribution of the gamma radiation are connected with neutralino parameters and give an important information about structure of the MSSM and about its correspondence with cosmology. Therefore our main statement consist in the nature of rare powerful cosmological gamma ray bursts is a result of the total annihilation of neutralino clumps.

We have analyzed the qualitative and quantitative descriptions of this process in the spherically symmetric collapse model with two assumptions. First, annihilation products leave a clump during a time substantially smaller than the time of its macroscopic evolution. And second, an annihilating clump is spatially homogeneous and isotropic since more dense regions annihilate faster than the rest and heterogeneities are vanishing.

The model, defined by equations of mass and momentum balance and the equation of non-relativistic gravitation theory, is:

\[
\frac{d}{dt} \int \rho_\chi dV = - \int \rho_\chi v_i dS_i - \int \frac{2(\sigma v)_{ann}\rho_\chi^2}{M_\chi} dV, \]

\[
\frac{d}{dt} \int \rho_\chi v_i dV = - \int (\rho_\chi v_i v_k + P_{ik}) dS_k - \int \rho_\chi \nabla_i \phi dV - \int \nu_{dis} \rho_\chi v_i dV - \int \frac{2(\sigma v)_{ann}\rho_\chi^2}{M_\chi} v_i dV, \tag{2.1}
\]

\[
\Delta \phi = 4\pi G \rho_\chi,
\]

where \( P_{ik} \) is the pressure tensor for neutralino gas. It is absent in consequence of the second assumption. Last terms in the balance equations describe the momentary going away of annihilation products from the collapsing clump. We have taken into account that annihilation and scattering are cross-channels. In the local form we have the simple system:

\[
\frac{dM}{dt} = -\frac{3(\sigma v)_{ann}}{2\pi M_\chi} \cdot \frac{M^2}{R^3}, \quad \left( \frac{dR}{dt} \right)^2 = \frac{2GM}{R} \left( 1 - \beta^2 \frac{R}{R_0} \right), \tag{2.2}
\]

which integrates elementary. Here \( R \) is the clump radius; \( M = 4\pi \rho_\chi R^3/3 \) is the clump mass; \( R_0 = \text{const} \) is the initial radius; \( \beta^2 \leq 1 \) is the constant which fixed by initial velocity of the surface clump compression. The results are in the parametric form

\[
M(\zeta) = M(\ast) \left[ 1 + \frac{(\sigma v)_{ann}}{M_\chi} \left( 3\rho_{\chi(\ast)} \frac{3}{2\pi G} \right)^{1/2} \left( \frac{\zeta^2}{3} + \beta^2 \zeta \right) \right]^{-2},
\]

\[
R(\zeta) = R_0 (\zeta^2 + \beta^2)^{-1},
\]

\[
\left( \frac{8\pi G \rho_{\chi(\ast)}}{3} \right)^{1/2} t(\zeta) = \frac{1}{\beta^2} \left( \frac{\zeta}{\zeta^2 + \beta^2} - (1 - \beta^2)^{1/2} \right) + \frac{1}{\beta^3} \left( \arctan \frac{\zeta}{\beta} - \arctan \frac{(1 - \beta^2)^{1/2}}{\beta} \right) +
\]

\[
+ \frac{(\sigma v)_{ann}}{3M_\chi} \left( 3\rho_{\chi(\ast)} \frac{3}{2\pi G} \right)^{1/2} \left( \ln(\zeta^2 + \beta^2) + \frac{2\beta^2(\zeta^2 + \beta^2 - 1)}{\zeta^2 + \beta^2} \right), \tag{2.3}
\]
where \( M_{(s)} \sim M_\odot = 4 \cdot 10^{33} \text{g}, \rho_{\chi(s)} \sim 10^{-4} \text{g/cm}^3 \) are the initial clump mass and density. As we see \( M(t) \to 0, R(t) \to 0 \) for \( t \to \infty \).

The annihilation rate is

\[
- \frac{dM}{dt} \equiv \dot{E}_{\text{ann}} = M_{(s)}\rho_{\chi(s)} \cdot \frac{2(\sigma v)_{\text{ann}}}{M_\chi} \cdot \frac{(\zeta^2 + \beta^2)^3}{\left[ 1 + \frac{(\sigma v)_{\text{ann}}}{M_\chi} \left( \frac{3\rho_{\chi(s)}}{2\pi G} \right)^{1/2} \left( \frac{\zeta^3}{3} + \beta^2\zeta \right) \right]^4}. \tag{2.4}
\]

Generally behavior of this function is that a slow growth at small times changes into quick evolution around narrow peak after that there is an exponential drop to zero. This behavior explains by changing of the parameter hierarchy during the collapse. We use the convenient time scale

\[
\dot{E}_{\text{ann}} = \frac{M_{(s)}}{4} \left( 1 - \frac{(t - t_0)^2}{2\tau_0^2} \right), \quad \tau_0 = \frac{(\sigma v)_{\text{ann}}}{3\pi G M_\chi}. \tag{2.5}
\]

Here \( t_0 \) is the time of the maximum. Since we have

\[
g = \frac{(\sigma v)_{\text{ann}}}{M_\chi} \left( \frac{3\rho_{\chi(s)}}{2\pi G} \right)^{1/2} \ll 1
\]

then the annihilation rate doesn’t depend on initial conditions and expresses through the fundamental constants only. The functions \( E_{\text{ann}}/M_{(s)} \) and \( M/M_{(s)} \) of dimensionless time \( \eta = (t - t_0)/\tau_0 \) are shown at the Fig. [1].

![Graph](image)

**FIG. 1:** Annihilation rate \( \dot{E}_A/M_{(s)} \) (right) and relative mass \( M/M_{(s)} \) (left) of neutralino clump as a function of dimensionless time \( \eta \).

About 80% of clump mass annihilates during the time

\[
t_{\text{ann}} = 6\tau_0 = \frac{2(\sigma v)_{\text{ann}}}{\pi G M_\chi}. \tag{2.6}
\]

Effectively the annihilation takes place between \( t_{A}^{(-)} = 4\tau_0 \) (before maximum) and \( t_{A}^{(+) = 2\tau_0} \) (after maximum). Such event represents as a powerful gamma-ray burst with total energy about clump mass. Kinetic cross section can be parameterized in the form: \( (\sigma v)_{\text{ann}} = \)
\(\alpha^2/8\pi M_c^2, M_c\) – some parameter with the dimension of mass. So the decay time of collapsing neutralino clump expresses through SUSY parameters \(M_c, M_\chi\) and gravitational constant but it is absolutely independent from initial density and initial velocity of clump compressing.

Deeper analysis is possible only in the framework of concrete SUSY model. So there exits a possibility to extract of the SUSY parameters from observable characteristics of the bursts and to find constraints on the SUSY model. In the framework of Split Higgsino scenario \(\text{[11]}\) the neutralino mass \(M_\chi \simeq 3\) TeV is estimated from the statement that the Dark Matter in the Universe has formed at the high symmetry phase of the cosmological plasma. Neutralino of such type in the halo annihilate into \(W\)- and \(Z\)-bosons and fermions (see Fig. 2).

\[ \bar{\chi}\chi \rightarrow W^+ W^- \quad \bar{\chi}\chi \rightarrow Z^0 \]

\[ \bar{\chi}\chi \rightarrow Z^0 f \quad \bar{\chi}\chi \rightarrow Z^0 f \]

FIG. 2: Diagrams of neutralino annihilation in the framework of Split Higgsino scenario.

Total kinetic cross section is

\[ (\sigma v)_{\text{ann}} = \frac{g_2^4 (21 - 40 \cos^2 \theta_W + 34 \cos^4 \theta_W)}{256 \pi M_\chi^2 \cos^4 \theta_W}. \]  

(2.7)

The clump annihilation time in this model is \(t_{\text{ann}} \simeq 30\) s.

III. CALCULATION OF CHARACTERISTIC PHOTON ENERGIES AND ANNIHILATION SPECTRUM

The energy spectrum \(dN_\gamma(E_\gamma) / dE_\gamma\) is determined by the distribution in multiplicity of the secondary hadrons resulted from the neutralino annihilation. We use of the fact that the total secondary hadrons multiplicity is nearly twice larger than the charged hadrons multiplicity \(\text{[14]}\). The average multiplicity of secondary charged hadrons \(\langle \bar{n}_{\text{ch}} \rangle (\sqrt{s})\) was studied in \(e^+e^-, pp, p\bar{p}, e^\pm p\) processes \(\text{[15]}\). It was established that this quantity is some universal function of energy

\[ \bar{n}_{\text{ch}}(\sqrt{s}) = A + B \ln \sqrt{s} + C \ln^2 \sqrt{s}, \quad \bar{n}_{\text{ch}} \equiv \langle n_{\text{ch}} \rangle (\sqrt{s}/q_0) - n_0 \]

with experimentally fixed parameters

\[ A = 3.11 \pm 0.08, \quad B = -0.49 \pm 0.09, \quad C = 0.98 \pm 0.02. \]

To choice a specific channel it is necessary to fix parameters \(q_0, n_0\). For neutralino annihilation \(q_0(\chi\chi) = 1, n_0(\chi\chi) = 0\).

Further it is supposed that the part of charged hadrons \(\kappa \equiv \langle n_{\text{ch}} \rangle / \langle n_h \rangle\) doesn’t depend on energy and has the value \(\kappa \simeq 0.49\), which is extracted from \(Z\)-peak data \(\text{[14]}\).
For characteristic photon energies generation the following processes are most important $\pi^0 \rightarrow 2\gamma$, $\eta^0 \rightarrow 3\gamma$, $\eta^0 \rightarrow 3\pi^0 \rightarrow 6\gamma$. In the fermion annihilation channel (Fig. 2) the total hadron multiplicity is described by following logarithmic function with good accuracy:

\[
\langle n_{h}^{ff} \rangle = \kappa^{-1}(A + B \ln 2M_\chi + C \ln^2 2M_\chi) \simeq 149 \quad \text{for} \quad M_\chi \simeq 3 \text{ TeV}. \tag{3.1}
\]

An average energy of neutral pions in neutralino annihilation secondaries is $\bar{E}_{\pi^0} \simeq \bar{E}_{\eta^0} \simeq 2M_\chi/\langle n_{h}^{ff} \rangle$. Then in the $\pi^0 \rightarrow 2\gamma$ decay maximal characteristic energy of photon is equal:

\[
\bar{E}_{\gamma(\pi^0 \rightarrow 2\gamma)} \simeq \bar{E}_{\pi^0}/2 = 20 \text{ GeV}. \tag{3.2}
\]

Analogously, for reactions $\eta^0 \rightarrow 3\gamma$ and $\eta^0 \rightarrow 3\pi^0 \rightarrow 6\gamma$ energies of photons are:

\[
\bar{E}_{\gamma(\eta^0 \rightarrow 3\gamma)} \simeq \bar{E}_{\eta^0}/3 = 13.5 \text{ GeV}, \quad \bar{E}_{\gamma(\eta^0 \rightarrow 6\gamma)} \simeq \bar{E}_{\eta^0}/6 = 6.7 \text{ GeV}. \tag{3.3}
\]

In the boson annihilation channel (Fig. 2) the total hadron multiplicity of $W$- and $Z$-bosons decays is:

\[
\langle n_{h}^{WZ} \rangle \simeq 42.9. \tag{3.4}
\]

Here neutral pion average energy is $\bar{E}_{\pi^0} \simeq \bar{E}_{\eta^0} \simeq M_\chi/\langle n_{h}^{WZ} \rangle$ and maximal characteristic photon energies are:

\[
\bar{E}_{\gamma(\pi^0 \rightarrow 2\gamma)} \simeq \bar{E}_{\pi^0}/2 \simeq 35 \text{ GeV}, \quad \bar{E}_{\gamma(\eta^0 \rightarrow 3\gamma)} \simeq \bar{E}_{\eta^0}/3 = 23.3 \text{ GeV}, \quad \bar{E}_{\gamma(\eta^0 \rightarrow 6\gamma)} \simeq \bar{E}_{\eta^0}/6 = 12 \text{ GeV}. \tag{3.5}
\]

In a wide energy region the multiplicity distribution can be described with a good accuracy by the Negative Binomial Distribution (NBD) that depends on energy very weakly (logarithmically) [14]:

\[
P(n; \bar{n}, k) = \frac{k(k+1)(k+n-1)}{n!} \cdot \frac{(\bar{n}/k)^n}{[1+(\bar{n}/k)]^{n+k}}, \tag{3.6}
\]

\[
k^{-1}(\sqrt{s}) = a + b \ln \sqrt{s},
\]

where $n \equiv n_{ch}$, $\bar{n} \equiv \bar{n}_{ch}$. For various channels the coefficients in the function $k^{-1}(\sqrt{s})$ are different:

\[
a_{e^+e^-} = -0.064 \pm 0.003, \quad b_{e^+e^-} = 0.023 \pm 0.002; \tag{3.7}
\]

\[
a_{pp/\bar{p}p} = -0.104 \pm 0.004, \quad b_{pp/\bar{p}p} = 0.058 \pm 0.001. \tag{3.8}
\]

Using the NBD it is possible to find the approximate energy distribution of photons. For example, in the hadronic channel with $Br(h) \simeq 0.58$ it is supposed that the branching ratios for various hadrons $Br(i/h) \equiv \langle n_i \rangle/\langle n_h \rangle$ are nearly constants and equal to the corresponding branching ratios extracted from $e^+e^-$-annihilation [14]. Each annihilating neutralino pair gives a number of neutral pions $Br(\pi^0/h) \cdot 2n_{h}^{0}P(n; \bar{n}, k)$ with the probability $Br(h)$. These pions generate the following distribution of photons $\Delta n_{\gamma} \simeq 2 \cdot Br(h)Br(\pi^0/h) \cdot 2n_{h}^{0}P(n; \bar{n}, k)\Delta n$ with energy $E_{\gamma} = M_\chi/2n$ in the multiplicity interval $\Delta n$, which is connected with energy
interval $\Delta n = M_\chi \Delta E_\gamma / 2E_\gamma^2$. For $\eta^0$-mesons and boson annihilation channel considerations are analogous. Then the number of photons with energy $E_\gamma$ per one annihilation act is:

$$\frac{dN_\gamma}{dE_\gamma} \approx \frac{2M_\chi}{E_\gamma^2} \left\{ \left[ Br(\pi^0/h) + Br(\eta^0/h) \cdot Br(\eta^0 \rightarrow 2\gamma) \right] \times 
\right.$$

$$\times \left[ Br(h) \langle n_{ch}^{ff} \rangle P \left( \frac{M_\chi}{2E_\gamma}; \langle n_{ch}^{ff} \rangle, k_{ff} \right) + \frac{1}{2} Br(WZ) \langle n_{ch}^{WZ} \rangle P \left( \frac{M_\chi}{4E_\gamma}; \langle n_{ch}^{WZ} \rangle, k_{WZ} \right) \right] + 
$$

$$+ Br(\eta^0/h) \left[ Br(\eta^0 \rightarrow 3\pi^0) + \frac{1}{3} Br(\eta^0 \rightarrow \pi^+\pi^-\pi^0) \right] \times 
\right.$$

$$\times \left[ Br(h) \langle n_{ch}^{ff} \rangle P \left( \frac{M_\chi}{6E_\gamma}; \langle n_{ch}^{ff} \rangle, k_{ff} \right) + \frac{1}{2} Br(WZ) \langle n_{ch}^{WZ} \rangle P \left( \frac{M_\chi}{12E_\gamma}; \langle n_{ch}^{WZ} \rangle, k_{WZ} \right) \right] + 
$$

$$+ \frac{1}{3} Br(\eta^0/h) Br(\eta^0 \rightarrow \pi^+\pi^-\gamma) \times 
\right.$$

$$\times \left[ Br(h) \langle n_{ch}^{ff} \rangle P \left( \frac{M_\chi}{3E_\gamma}; \langle n_{ch}^{ff} \rangle, k_{ff} \right) + \frac{1}{2} Br(WZ) \langle n_{ch}^{WZ} \rangle P \left( \frac{M_\chi}{6E_\gamma}; \langle n_{ch}^{WZ} \rangle, k_{WZ} \right) \right]\}.
$$

(3.9)

Here $Br(WZ) \approx 0.2$ is the total branching ratio for neutralino annihilation into $W$- and $Z$-bosons; charge hadron multiplicities $\langle n_{ch}^{ff} \rangle$ and $\langle n_{ch}^{WZ} \rangle$ are defined in (3.1) and (3.4); parameters $k_{ff}^{-1} = k^{-1}(2M_\chi) = 0.4$ and $k_{WZ}^{-1} = k^{-1}(M_\chi) = 0.12$ were determined with coefficients from (3.8) and (3.7), respectively. The spectrum is shown in Fig. 3.

![Gamma ray annihilation spectrum](image_url)

FIG. 3: Gamma ray annihilation spectrum.

The particular duration of the GRB and the specific shape of its energy spectrum are the characteristic features of considering astrophysical event – the collapse and total annihilation of the neutralino clump. Calculated values of characteristic photon energies are close to the threshold of sensitivity for the satellite detector GLAST. Possibility of neutralino annihilation spectrum registration at this apparatus will be clarified when the GLAST will be put into operation.
IV. CONCLUSION

We have proposed the new production mechanism of the cosmological gamma-ray bursts. In the framework of this mechanism the gamma-ray burst represents as a result of collapse and total annihilation of the neutralino clump. The GRB signal when registered should contain an information on SUSY parameters and the details of the annihilation process. We have calculated the characteristic photon energies and annihilation spectrum for $M_\chi = 3 \text{ TeV}$ in the framework of Split Higgsino scenario. The particular duration of the GRBs and specific shape of its energy spectrum are the characteristic features which can help to separate considering astrophysical events from the radiation background. From astrophysical data on GRBs with high-energy photons it is possible to extract an information about SUSY parameters in different models. It can help to investigate compatibility of the SUSY model with cosmology, cosmogony and high-energy collider data.

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