Neutralino clump annihilation, GRB and SUSY parameters

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Abstract

A rare astrophysical events – Gamma Ray Bursts with energies up to GeV and more – are considered as an origin of information about some SUSY parameters in the model of total neutralino clump annihilation. Compatibility of neutralino structure, following from limiting MSSM cases, with the GRB model is analyzed.

1 Introduction

Because direct experimental information about structure of SUSY model and values of SUSY particles' masses is absent, now we try to extract any possible data from the cosmology. From the recent WMAP data the mass density in the Universe is equal to its critical value $\rho_{crit} \simeq 0.54 \cdot 10^{-5}\, GeV/cm^3$; the structured dark matter (DM) and the isotropic and homogeneous dark energy (DE) contribute to this density $\simeq 23\%$ and $\simeq 73\%$, 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. Neutralino – heavy, electrically neutral and absolutely stable (if R parity is conserved)particles, which are the LSP in the various SUSY models – are the main contributors to the cold (and hot) DM, so the neutralino physics is discussed intensively in various aspects [1, 2, 3, 4].

To observe neutralino manifestations in space or land experiments can be used different channels. For example: antiprotons, positrons or neutrino fluxes due to neutralino annihilation in the halo CDM or in the center of the Sun or the Earth. Here we concentrate on the specific gamma – radiation [5] which can be diffuse (due to annihilation into fermions and bosons) and monochromatic (due to annihilation into $\gamma\gamma$ or $Z\gamma$ [6, 7]). To measure characteristics of specific gamma - fluxes special experimental program had been elaborated with space telescopes (EGRET, AGILE, GLAST) [5, 8].

Now we have from the collider experiments only low restriction for the neutralino mass $m_\chi > 32.5GeV$. ATLAS and CMS collaborations (LHC) will say something more 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 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 [19].

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 [9, 10, 11, 12, 13, 15, 16]. Due to inner instability clumps can collapse and intensively annihilate. At the final stage of the process GRB with energies $\sim 1\, GeV$ will occur accompanying by fluxes of other particles, in the known EGRET GRB 940217 event energies of photons lie between $50\,MeV$ and $3\,GeV$. In the standard GRB energies of photons are only fractions of MeV (see [17]). Specific energy and time distributions of this hard γ - radiation can be linked with the parameters of superparticles (neutralino, in particular) and give an important information on the MSSM details and its compatibility with cosmology. Thus, our basic supposition is that the nature and origin of the rare high – energy GRB can be understood as the result of neutralino clump total annihilation.

2 Neutralino annihilation at the different stages of the clump evolution

Annihilating clump can be considered as homogeneous and isotropic because the larger is its density, the higher is intensity of annihilation. For the period $t_G = (4\pi G\rho_\chi^{-1/2})$ gravitational instability arises, so the total annihilation time is estimated as $t_A = (2n_\chi(\sigma v)_A)^{-1}$, where $\rho_\chi = m_\chi n_\chi$ and M_χ are mass density and total clump mass, respectively. Annihilation intensity grows rapidly when $t_G = t_A$. Using following functions: $\rho_\chi = \rho_\chi(t)$, $v_i = H(t)x_i$, we have in the hydrodynamic approximation with account of dissipation the system:

$$\frac{d\rho_\chi}{dt} + 3H\rho_\chi = -\frac{2(\sigma v)_A\rho_\chi^2}{m_\chi}, \quad \frac{dH}{dt} + H^2 = -\frac{4\pi G\rho_\chi}{3} - bH\frac{(\sigma v)_A\rho_\chi}{m_\chi}. \tag{1}$$

These equations can be integrated exactly with the functions $M_\chi(t)$, $R(t)$ which are defined parametrically as $M_\chi(\zeta)$, $R(\zeta)$, $t(\zeta)$

$$M_\chi(\zeta) = M_{\chi(*)}\left[1 + \frac{(\sigma v)_A}{m_\chi}\left(\frac{3\rho_{\chi(*)}}{2\pi G}\right)^{1/2}\left(\frac{\zeta^3}{3} + \beta^2\zeta\right)\right]^{-2}, \ R(\zeta) = R_0(\zeta^2+\beta^2)^{-1},$$
$$\left(\frac{8\pi G\rho_{\chi(*)}}{3}\right)^{1/2} t(\zeta) = \frac{1}{\beta^2}\left(\frac{\zeta}{\zeta^2+\beta^2} - (1-\beta^2)^{1/2}\right) + \frac{1}{\beta^3}\left(\arctan\frac{\zeta}{\beta} - \arctan\frac{(1-\beta^2)^{1/2}}{\beta}\right) +$$
$$+\frac{(\sigma v)_A}{3m_\chi}\left(\frac{3\rho_{\chi(*)}}{2\pi G}\right)^{1/2}\left(\ln(\zeta^2+\beta^2) + \frac{2\beta^2(\zeta^2+\beta^2-1)}{\zeta^2+\beta^2}\right). \tag{2}$$

Here $M_{\chi(*)} \sim 2M_\odot = 4\cdot 10^{33}\mathrm{g}$, $\rho_{\chi(*)} \sim 10^{-4}\mathrm{g/cm^3}$ are initial values of the clump mass and density. Then for the relative rate of radiation we get:

$$-\frac{dM_\chi}{dt} \equiv \dot{E}_A = M_{\chi(*)}\rho_{\chi(*)}\cdot\frac{2(\sigma v)_A}{m_\chi}\cdot\frac{(\zeta^2+\beta^2)^3}{\left[1 + \frac{(\sigma v)_A}{m_\chi}\left(\frac{3\rho_{\chi(*)}}{2\pi G}\right)^{1/2}\left(\frac{\zeta^3}{3}+\beta^2\zeta\right)\right]^4}; \tag{3}$$

Parameter $\beta^2 \le 1$ is defined by the initial rate of the clump compression. With the dimensionless time of radiation maximum reaching $\eta = (t-t_0)/\tau_0$, where t_0 is the time when the maximum of radiation is reached; $\tau_0^{-1} = 24\pi^2 G m_\chi M^2\alpha^{-2}$ depends on the fundamental constants only, annihilation rate (see Fig. 1) initially rises slowly, then sharply changes near the peak and exponentially goes to zero. This behavior corresponds to hierarchy of different characteristic periods of clump collapse. At the Fig. 2 relative rate of radiation $\dot{\epsilon}_A \equiv M^{-1}_{\chi(*)} \cdot |\frac{dM_\chi}{dt}|$ demonstrates sharp asymmetry and $\approx M_{\chi(*)}/2$ annihilates for the time $t_A = 3\tau_0 = \frac{2(\sigma v)_A}{\pi G m_\chi}\, s$. More exact result is $t_A \simeq 80 \cdot (\frac{m_Z^3}{m_\chi M^2})\, s$. Most effectively neutralino annihilate in the periods $2\tau_0$ before and τ_0 after the maximum reaching. It is of interest that all features of the curve are determined by the fundamental parameters only.

3 Energy spectrum of GRB

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. Because energy is taken out of the vacuum in the universal manner, it is naturally to believe that in this process multiplicity distribution, as for e^+e^-, pp, $\bar{p}p$ channels at $\sqrt{s} \sim m_\chi \sim 100\, GeV$, is well described by the negative binomial distribution, which depends on the energy only as logarithm.

Photons are mainly generated in the decays $\pi^0 \longrightarrow 2\gamma$, $\eta^0 \longrightarrow 3\pi^0 \longrightarrow 6\gamma$. For the neutralino annihilation channels there are experimentally known branchings $Br(i/h) \equiv < n_i > / < n_h >$ and parameter $\kappa \equiv < n_{ch} > / < n_h >$. Then for the differential photon spectrum we have:

$$dN_\gamma/dE_\gamma \simeq \frac{N_\chi m_\chi}{E_\gamma^2} Br(h)\bar{n} \sum_{h_0 \longrightarrow \gamma} Br(h_0/h) \cdot P(m_\chi/k_0 E_\gamma; \bar{n}; k).$$

Here $Br(h)$ – is the branching of the annihilation hadron channel; $Br(h_0/h)$ – is the combination of branchings like the following: $Br(\eta^0/h)Br(\eta^0 \longrightarrow 3\pi^0)$ etc. So in the sum there are contributions from all channels with π^0 and η^0 production and decay. $P(m_\chi/k_0 E_\gamma; \bar{n}; k)$ – is the negative binomial distribution where the numerical coefficient k_0 depends on the channel, $\bar{n}$ – is the total average multiplicity, and k is defined as $k^{-1}(s) = a + b \ln \sqrt{s}$ (coefficients a and b depend on the channel).

Each annihilating neutralino pair with the probability $Br(h)$ gives the number of neutral pions $Br(\pi^0/h) \cdot 2\bar{n}P(n, \bar{n}, k)$ which generate the number of photons $\triangle n_\gamma \simeq 2Br(h) \cdot Br(\pi^0/h) \cdot 2\bar{n}P(n, \bar{n}, k) \triangle n$ with the energy $E_\gamma = m_\chi/2n$. The multiplicity interval $\triangle n$ is connected with the E_γ in the following way: $\triangle n = m_\chi \triangle E_\gamma/2E_\gamma^2$. For η^0 mesons there are analogous formulas.

So, there is specific double peaked (due to contributions from π^0 and η^0 decays) differential photon spectrum (Fig. 3). Maxima in the spectrum depend on m_χ; the ratio of characteristic peak energies is $\bar{E}_{\gamma(\pi^0)}/\bar{E}_{\gamma(\eta^0)} \simeq 3$. When $E_\gamma \gg \bar{E}_{\gamma(\pi^0)}$ the spectra decrease rapidly. Photons take away up to 10% of the total clump mass.

Predictions for the spectra hold only for multiparticle production channels. Due to account for the photons from the η decays the spectrum differs from the known spectra which are generated mainly by heavy states production and decays and exponentially fall in this energy region.

4 What are annihilating neutralino?

Physics of neutralino annihilation is well known [3, 18, 19, 20, 21, 23, 22, 24] for different SUSY models (MSSM, CMMSSM, mSUGRA,AMSSM) and parameter spaces with all physical constraints.

In a general case neutralino is a mixture of gauginos and higgsinos, but, as it follows from the relic abundance analysis, in particular, bino is most proper candidate for CDM [25, 26]. We propose here the limiting case of MSSM with hierarchy of scales that minimized SUSY effects near the SM scale. We denote the MSSM variant as mMSSM. For example, first case of the model, where neutralino is practically pure higgsino, occurs in the limit of small $\mu \ll M_{1/2}$. In this case two lowest neutralino can be nearly degenerate with the nearest chargino, and scalar sparticles have masses near the TeV scale. Moreover, near the SM scale there is only one neutral Higgs boson, other higgses lie near few TeV scale. In the opposite limiting case neutralino is almost pure gaugino, namely, bino. The whole set of various neutralino structures lies between these two limiting cases.

Thermally averaged nonrelativistic (because of large neutralino mass) annihilation cross sections have the form ([18, 19, 21, 23] and others): $(\sigma v)_A^{(q,l)} = \sum_{i=l,q} \sum_k (\tilde{a}_{q,l} + \tilde{b}_{q,l} \cdot T_f/m_\chi)$, here v - a relative velocity of annihilating particles, $\tilde{a} \sim m_{q,l}^2$ and $\tilde{b} \sim m_\chi^2$,$x = T_f/m_\chi$ and T_f – a freeze-out temperature, when $T > T_f$ the number density is approximately equal to its equilibrium value, $x \approx 1/20 - 1/25$. Cross sections depend on the intermediate masses which we approximately parametrize as m_S – some typical value of intermediate sfermion mass. For the gauge bosons production there is an additional parameter - an average chargino mass m_C, in our case of higgsino $m_S \approx m_C$.

Cross section of the total clump annihilation is parametrized in the form: $(\sigma v)_A = \dfrac{\alpha^2}{8\pi M^2}$, M – some parameter with the dimension of mass. To evaluate it we consider for the neutralino density n_χ a kinetic equation with parameters depending on cosmological scale factor and statistical weight for the cosmological plasma which consists of photons, gluons, leptons of all types and quarks for the corresponding number of flavors. For the asymptotic of the kinetic equation solution (when the annihilation of the dense clump has finished and the remaining density is approximately equal to the average CDM density)we have:

$$\rho_\chi \simeq \frac{m_\chi}{3.15 \cdot T_0} \frac{M^2}{m_Z^2} \cdot 4.8 \times 10^{-6}\, GeV/cm^3,$$

here T_0 - is an average temperature of cosmological plasma when the neutralino begin intensively annihilate in a clump. From the comparison with the experimentally fixed CDM density(we suppose that the CDM totally consists of neutralinos) $\rho_{DM} \simeq 0.23\rho_{crit} \simeq 1.23 \cdot 10^{-6}\, GeV/cm^3$ we find that $M \simeq 45.6\, GeV$. Thus we have for the neutralino annihilation cross section two expressions: the first one is computed in the nonrelativistic approximation and depends on the SUSY model parameters, and the second one is fixed in the framework of cosmological model of the clump total annihilation. Comparing these formulas we fix a region for SUSY parameters (in particular, m_χ and an average masses of sparticles) which is compatible with cosmological clump annihilation model for high-energy GRB explaining.

Fig. 4 and 5 demonstrate that in the mMSSM model it is possible to get reasonable values of neutralino and squark and sfermion masses. Their possible values are manifested through projection of intersection lines to the coordinate axes. The obtained values are in agreement with known results for the SUSY parameter space analysis [2, 4, 26, 27]. Bino mass is in the interval $100 - 250\, GeV$ and it corresponds to the parameter $m_{1/2} \simeq 250 - 600\, GeV$. Accordingly the $m_S \simeq 150 - 350\, GeV$. Higgsino mass, in principle, is unlimited: from our estimation $m_\chi \simeq 100 - 500\, GeV$, nearest chargino has the mass close to this value, and squark mass rapidly goes to the stable value $\sim 1\, TeV$, which is practically independent on the neutralino mass in the above interval up to $500\, GeV$. Note, that in our consideration $m_\chi \neq M$, and these parameters are independent.

Due to almost degeneracy of neutralino and chargino there should be additional contribution from coannihilation, which together with other contributions – annihilation to two gluons and photons (see also [21, 25, 28])– leads to increase of the total cross section. So SUSY parameters can be changed within the range $15 - 20\%$.

One photon with the energy $\sim 18\, GeV$ may be associated with the annihilation to monochromatic photons, $E_\gamma \simeq m_\chi$ or with $\chi\chi \to Z\gamma$. For $z = 6 \div 8$ we get $m_\chi \simeq 100\, GeV$. Combining total annihilation time of the neutralino clump t_A and the characteristic energy of photons $\bar{E}_\gamma$, we find the combination:

$$t_A \cdot \bar{E}_\gamma \simeq k_h \frac{m_Z^3}{M^2} \cdot \frac{1}{A + B \ln(2m_\chi) + C \ln^2(2m_\chi)},$$

which depends on the m_χ only as logarithm. So it is a suitable criterion for the selection of astrophysical events (k_h – is a numerical factor).

5 Conclusions

1. The model of neutralino clump collapse and total annihilation predicts that in the process γ – quanta with two characteristic energies $\bar{E}_{\gamma(\pi^0)} \sim 1.0\, GeV$ and $\bar{E}_{\gamma(\eta^0)} \sim 0.3\, GeV$ can be radiated. Energy spectra of these GRB have two maxima, their positions depend on the neutralino mass.

2. The GRB signal when registered should contain an information on the details of the total annihilation. With the rise of cosmological time the product of characteristic radiation energy and the value of the annihilation time is nearly constant. Due to this fact such events can be separated from the radiation background.

3. Parameters of the EGRET GRB 940217 event(1994) are close to the above criteria. But statistics is too low and we know in fact the existence of such specific events only. It is evident that the events are very rare, nevertheless some details of SUSY parameters can be extracted from the experimental astrophysical data. In particular, bino is preferable as the CDM and there is an agreement between astrophysics and SUSY models.

4. The proposed mMSSM model, when near the SM scale there are a few extra SUSY degrees of freedom, is compatible with astrophysical data on GRB and the model of its generation from total clump annihilation process. Higgsino (and chargino) mass in this case is in sufficiently wide interval, but the squark has a stable mass near $1\, TeV$. Thus, this limiting variant of MSSM has interesting peculiarities that should be verified in collider experiments.

5. From astrophysical data on GRB with high-energy photons it is possible to extract information about SUSY parameters in different models. It can help to investigate compatibility of the model with cosmology, cosmogony and high-energy collider data.

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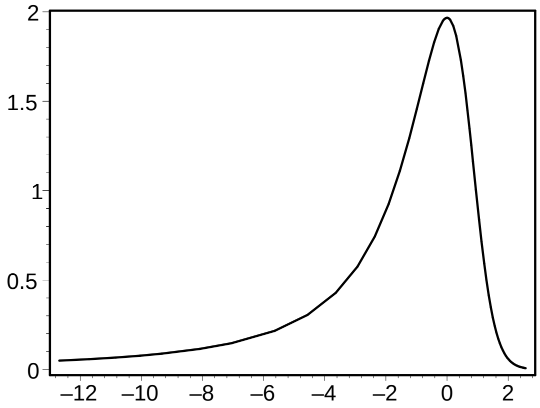

Figure 1: Annihilation rate $\dot{E}_A/M_{\chi(*)}$ as function of dimensionless time η.

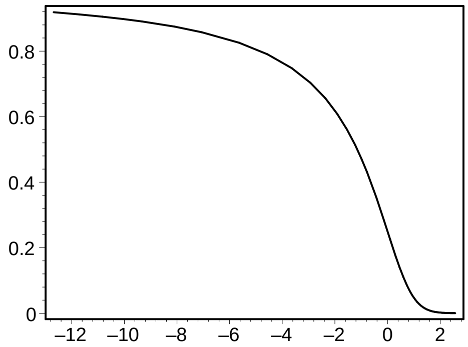

Figure 2: Mass $M_\chi/M\chi(*)$ of the annihilating neutralino clump as function of dimensionless time η.

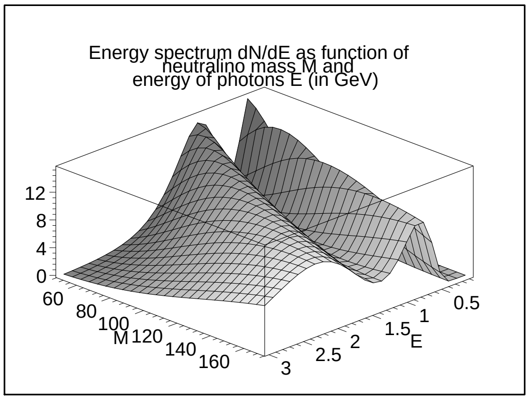

Figure 3: Energy spectrum dN/dE as function of neutralino mass m_χ and energy of photons E (in GeV).

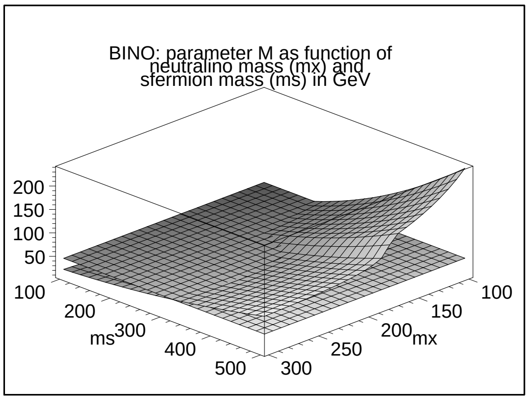

Figure 4: BINO: parameter M as function of neutralino mass m_χ and sfermion mass m_S in GeV.

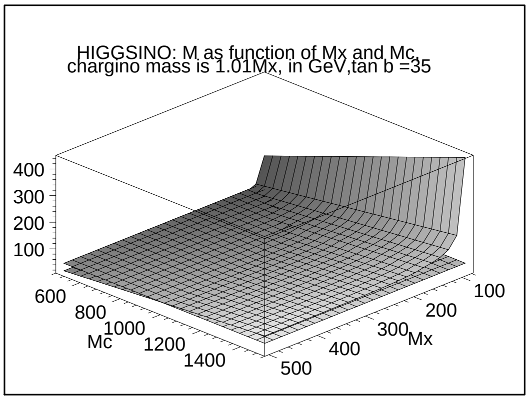

Figure 5: HIGGSINO: parameter M as function of neutralino mass m_χ and sfermion mass m_S in GeV (chargino mass is $\approx 1.01 m_\chi$.