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Neutralino relic density including coannihilations

Paolo Gondolo
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
Föhringer Ring 6, 80805 München, Germany
`gondolo@mppmu.mpg.de`

Joakim Edsjö
Department of Theoretical Physics, Uppsala University
P.O. Box 803, SE-751 08 Uppsala, Sweden
`edsjo@teorfys.uu.se`

Abstract

We give an overview of our precise calculation of the relic density of the lightest neutralino, in which we included relativistic Boltzmann averaging, subthreshold and resonant annihilations, and coannihilation processes with charginos and neutralinos.

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Neutralino relic density including coannihilations*

P. Gondolo[a] and J. Edsjö[b†]

[a]Max Planck Institute for Physics, Föhringer Ring 6, 80805 München, Germany

[b]Department of Theoretical Physics, Uppsala University, P.O. Box 803, SE-751 08 Uppsala, Sweden

We give an overview of our precise calculation of the relic density of the lightest neutralino, in which we included relativistic Boltzmann averaging, subthreshold and resonant annihilations, and coannihilation processes with charginos and neutralinos.

1. INTRODUCTION

The lightest neutralino is one of the most promising candidates for the dark matter in the Universe. A linear combination of the superpartners of the neutral gauge and Higgs bosons, it is believed to be the lightest stable supersymmetric particle in the Minimal Supersymmetric extension of the Standard Model (MSSM).

In the near future, high precision measurements of the dark matter density may become possible from high resolution maps of the cosmic microwave background, and this may constrain supersymmetry. It is therefore of great interest to calculate the relic density of the lightest neutralino as accurately as possible.

As a major step towards a complete and precise calculation valid for all neutralino masses and compositions, we included for the first time [1] all concomitant annihilations (coannihilations) between neutralinos and charginos, properly treating thermal averaging in presence of thresholds and resonances in the annihilation cross sections.

2. FORMALISM

Consider coannihilation of N supersymmetric particles with masses m_i and statistical weights g_i (first studied in ref. [2]). Normally, all heavy particles have time to decay into the lightest one, which we assume stable. Its final abundance is then simply described by the sum of the densities $n = \sum n_i$. When the scattering rate of supersymmetric particles off the thermal background is much faster than their annihilation rate, n obeys the evolution equation [3]

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\rm eff} v \rangle \left(n^2 - n_{\rm eq}^2 \right) \tag{1}$$

with effective annihilation cross section

$$\langle \sigma_{\rm eff} v \rangle = \frac{A}{n_{\rm eq}^2} \, . \tag{2}$$

The numerator A is the total annihilation rate per unit volume at temperature T, and $n_{\rm eq}$ is the total equilibrium density. Under the assumption of Boltzmann statistics (a good approximation for $T \lesssim m_i$), we obtain [1]

$$n_{\rm eq} = \frac{T}{2\pi^2} \sum_i g_i m_i^2 K_2\!\left(\frac{m_i}{T}\right) \tag{3}$$

and

$$A = \frac{T}{16\pi^4} \int_{4m_\chi^2}^{\infty} ds \sqrt{s - 4m_\chi^2}\, K_1\!\left(\frac{\sqrt{s}}{T}\right) W(s). \tag{4}$$

Here $K_i(x)$ is the modified Bessel function of the second kind of order i, and

$$W(s) = \sum_{ij} \frac{\lambda(s, m_i^2, m_j^2)}{2\sqrt{\lambda(s, m_\chi^2, m_\chi^2)}}\, g_i g_j \sigma_{ij} \tag{5}$$

where $\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$.

$W(s)$ is a Lorentz invariant annihilation rate per unit volume in which coannihilations appear

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[*] Presented by P. Gondolo.

[†] Present address: Center for Particle Astrophysics, University of California, Berkeley, 301 Le Conte Hall, Berkeley, CA 94720-7304, U.S.A.

as thresholds at $\sqrt{s}$ equal to the sum of the masses of the coannihilating particles. The independence of $W(s)$ on temperature is a remarkable calculational advantage in presence of coannihilations: in fact it can be tabulated in advance, before taking the thermal average and solving the density evolution equation.

Eqs. (2-5) generalize the result of Gondolo and Gelmini [4] to coannihilations.

3. RESULTS

To explore a significant fraction of the MSSM parameter space [5], we keep the number of theoretical relations among the parameters to a minimum. We assume GUT relations for gaugino masses, keep only the top and bottom trilinear soft supersymmetry-breaking parameters, and use a single mass parameter for the diagonal entries in the sfermion mass matrices at the weak scale. We perform many different scans in parameter space, some general and some specialized to interesting regions. We keep only models that satisfy the experimental constraints on the Z^0 width, on the $b \to s\gamma$ branching ratio, and on superpartner and Higgs boson masses.

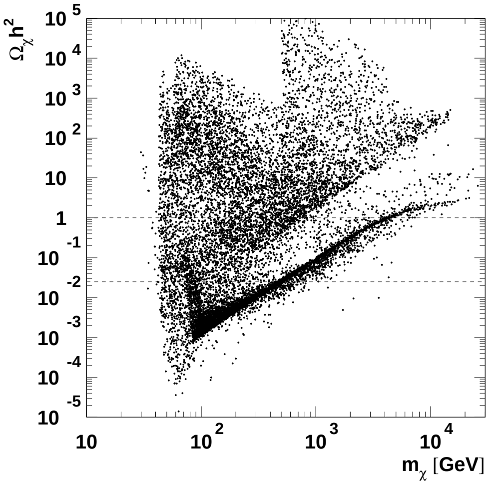

Figure 1. Neutralino relic density including neutralino and chargino coannihilations versus neutralino mass. The horizontal lines bound the cosmologically interesting region $0.025 < \Omega_\chi h^2 < 1$.

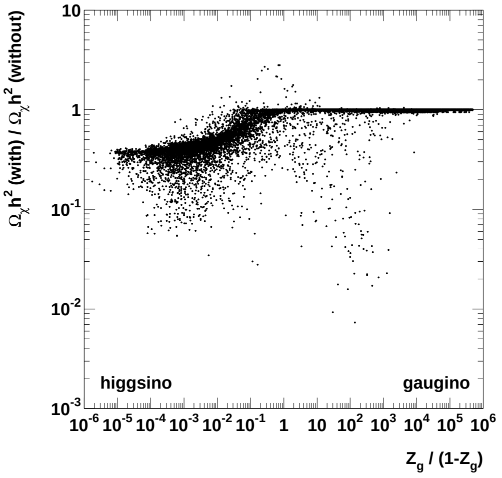

Figure 2. Ratio of the neutralino relic density with and without neutralino and chargino coannihilations versus neutralino composition.

We obtain analytic expressions for the many Feynman diagrams contributing to the two-body cross sections at tree level for neutralino-neutralino, neutralino-chargino and chargino-chargino annihilation. Then for each set of model parameters, we sum over particle polarizations and over initial and final states numerically and tabulate the annihilation rate $W(s)$. Thermal averaging and integration of the density equation finally give the neutralino relic density $\Omega_\chi h^2 = m_\chi n_0/\rho_{\rm crit}$ in units of the critical density $\rho_{\rm crit}$.

Fig. 1 shows the neutralino relic density $\Omega_\chi h^2$ versus the neutralino mass m_χ. Each point represents a set of model parameters. It should be kept in mind that bands and holes in the point distributions are mere artifacts of our sampling in parameter space.

The horizontal lines limit the cosmologically interesting region where the neutralino can constitute most of the dark matter in galaxies without violating the constraint on the age of the Universe. We take it to be $0.025 < \Omega_\chi h^2 < 1$.

The effect of coannihilations on the neutralino relic density is summarized in Fig. 2, which shows the ratio of the neutralino relic density with and without coannihilations versus the neutralino composition $Z_g/(1-Z_g)$ (here Z_g is the gaugino fraction).

Coannihilation processes are important not only for light higgsino-like neutralinos, as pointed out before in approximate calculations [6], but also for heavy higgsinos and for mixed and gaugino-like neutralinos. Indeed, coannihilations should be included whenever $|\mu| \lesssim 2|M_1|$, independently of the neutralino composition. When $|\mu| \sim |M_1|$, coannihilations can increase or decrease the relic density in and out of the cosmologically interesting region.

Fig. 3 shows the cosmologically interesting region in the neutralino mass–composition plane, before and after including coannihilations. This region is limited to the left by accelerator constraints, to the right by $\Omega_\chi h^2 < 1$, and below and above by incompleteness in our survey of parameter space, except for the hole at 85–450 GeV where $\Omega_\chi h^2 < 0.025$.

The main effect of coannihilations is to shift the higgsino region to higher masses. In particular the cosmological upper bound on the neutralino mass changes from 3 to 7 TeV. Differently from previous approximate results [6], there is a cosmologically interesting window of light higgsino-like neutralinos with masses around 75 GeV.

We conclude that if coannihilations are properly included, the neutralino is a good dark matter candidate whether it is light or heavy, and whether it is higgsino-like, mixed or gaugino-like.

P. Gondolo thanks P. Salati for bringing ref. [2] to his attention.

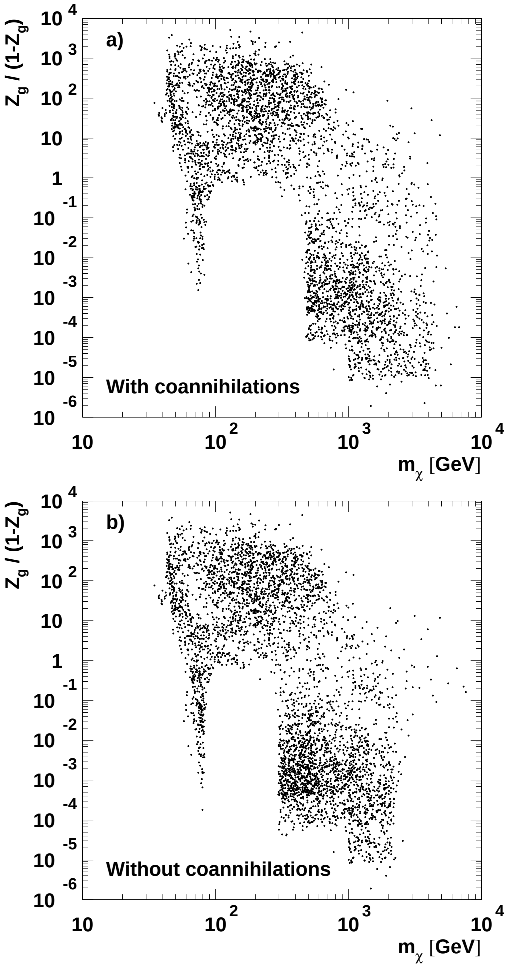

Figure 3. Neutralino masses m_χ and compositions $Z_g/(1-Z_g)$ for cosmologically interesting models (a) with and (b) without coannihilations.

REFERENCES

1. J. Edsjö and P. Gondolo, Phys. Rev. D56 (1997) 1879.
2. P. Binetruy, G. Girardi, P. Salati, Nucl. Phys. B237 (1984) 285.
3. K. Griest and D. Seckel, Phys. Rev. D43 (1991) 3191.
4. P. Gondolo and G. Gelmini, Nucl. Phys. B360 (1991) 145.
5. H.E. Haber and G.L. Kane, Phys. Rep. 117 (1985) 75; J.F. Gunion and H.E. Haber, Nucl. Phys. B272 (1986) 1 [Erratum: ibid. B402 (1993) 567].
6. S. Mizuta and M. Yamaguchi, Phys. Lett. B298 (1993) 120; M. Drees and M. Nojiri, Phys. Rev. D47 (1993) 376; M. Drees, M.M. Nojiri, D.P. Roy and Y. Yamada, Phys. Rev. D56 (1997) 276.