DARKSUSY – A NUMERICAL PACKAGE FOR SUPERSYMMETRIC DARK MATTER CALCULATIONS

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The question of the nature of dark matter in the Universe remains one of the most outstanding unsolved problems in basic science. One of the best motivated particle physics candidates is the lightest supersymmetric particle, assumed to be the lightest neutralino. We here describe DarkSUSY, an advanced numerical FORTRAN package for supersymmetric dark matter calculations. With DarkSUSY one can: (i) compute masses and compositions of various supersymmetric particles; (ii) compute the relic density of the lightest neutralino, using accurate methods which include the effects of resonances, pair production thresholds and coannihilations; (iii) check accelerator bounds to identify allowed supersymmetric models; and (iv) obtain neutralino detection rates for a variety of detection methods, including direct detection and indirect detection through antiprotons, gamma-rays and positrons from the Galactic halo or neutrinos from the center of the Earth or the Sun.

1. Introduction

One of the favourite candidates for the dark matter is a Weakly Interacting Massive Particle, a WIMP. In supersymmetric extensions of the standard

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model, the neutralino emerges as a natural WIMP candidate for the dark matter of the universe.

Over several years, we have developed analytical and numerical tools for dealing with the sometimes complex calculations necessary to go from given supersymmetric input parameters to actual quantitative predictions of the neutralino relic density in the Universe, and of the direct and indirect detection rates of neutralino dark matter. In 2000, we made available the first public release of DarkSUSY \(^1\). Here we outline the different components of DarkSUSY, and comment on the updates and improvements in the coming release. The latest version of DarkSUSY can be downloaded from the official DarkSUSY website, [http://www.physto.se/~edsjo/darksusy/](http://www.physto.se/~edsjo/darksusy/).

2. Supersymmetric model in DarkSUSY

DarkSUSY implements the general structure of the Minimal Supersymmetric Standard Model (MSSM), with R-parity and CP conservation (except in the quarks CKM matrix). The parameter space of the MSSM is specified by 124 a priori free parameters\(^2\).

Most of the DarkSUSY code does not make any specific assumption about the 124 parameters (except for R-parity and CP conservation, as mentioned). However, in the version of DarkSUSY soon to be released, the supersymmetric mass spectrum and the particle mixing matrices are computed under one of two classes of restrictions on the choice of supersymmetric parameters: (1) seven input parameters at the electroweak scale, as was available in the previous release (see \(^3,4\) for details), or (2) five parameters at the GUT scale, in the context of minimal supergravity (mSUGRA) implemented via an interface to ISASUGRA\(^5\). Beyond these two possibilities, the user can in principle implement his own flavor of MSSM.

DarkSUSY calculates all masses, mixings, and most of the vertices entering the Feynman rules. All of these are available to the user. DarkSUSY includes several options for the loop corrections to the Higgs masses\(^6,7,8,9\), and for the loop corrections to the neutralino and chargino masses\(^10,11\).

3. Accelerator bounds

Accelerator bounds can be checked by a call to a subroutine. By modifying an option, the user can impose bounds as of different moments in time. The default option in the coming public release adopts the 2002 limits by the Particle Data Group\(^12\). The user is also free to use his own routine to check for experimental bounds, in which case he or she would only need to
provide an interface to DarkSUSY.

4. Calculation of the relic density

DarkSUSY calculates the neutralino relic density by fully computing the thermal average of the effective neutralino annihilation cross section, including all resonances, thresholds and coannihilations, and then solves the Boltzmann equation numerically with the methods given in \cite{13,14}.

A major update in the next public release is the inclusion of coannihilations with squarks and sleptons. Coannihilations are important in the computation of the relic density when other particles the neutralino can convert to are close in mass to the lightest neutralino. These other particles are abundant at the time of neutralino freeze-out in the early Universe, and their annihilation rate must be included in the calculation. The current public release of DarkSUSY includes coannihilation processes between all neutralinos and charginos; the next release includes coannihilations between all the above and also squarks and sleptons.

DarkSUSY includes all two-body final states that occur at tree level, and neutralino annihilation into $gg$, $\gamma\gamma$ and $Z\gamma$ that occur at the 1-loop level.

5. Detection rates

The different detection rates for neutralino dark matter have been calculated by many authors in the past. We will here only give a brief review about what is included in DarkSUSY, and which calculations they are based on. For a more extensive list of references, we refer to \cite{3}.

5.1. Halo models

Currently implemented in DarkSUSY is the spherical family of halo profiles $\rho(r) \propto 1/\left((r/a)^\alpha [1 + (r/a)^\alpha]^{(\beta-\gamma)/\alpha}\right)$ where e.g. the Navarro, Frenk and White profile\cite{15} is given by $(\alpha, \beta, \gamma) = (1, 3, 1)$ and the isothermal sphere is given by $(\alpha, \beta, \gamma) = (2, 2, 0)$. The velocity distribution is assumed to be a standard isotropic gaussian distribution.

5.2. Direct detection

These routines calculate the spin-dependent and spin-independent scattering cross sections on protons and neutrons assuming the quark contributions to the nucleon spin from \cite{16}. The older set of data from \cite{17} is also available as an option, and the user can set his/her own values if desired.
5.3. *Monte Carlo simulations*

In several of the indirect detection processes described below we need the yield of different particles per neutralino annihilation. The hadronization and/or decay of the annihilation products have been simulated with PYTHIA\(^\text{18}\) and the results have been tabulated. These tables are incorporated in DarkSUSY.

5.4. *Neutrinos from the Sun and Earth*

Neutralinos can accumulate in the Earth and the Sun where they can annihilate pair-wise producing high energy muon neutrinos. The branching ratios for different annihilation channels are calculated and the PYTHIA simulations are used to evaluate the yield of neutrinos. Neutrino interactions in the Sun as well as the charged current neutrino-nucleon interaction near the detector are also simulated with PYTHIA.

There are routines to calculate a) the neutrino flux, b) the neutrino-to-muon conversion rate and c) the neutrino-induced muon flux either differential in energy and angle or integrated within an angular cone and above a given threshold. The new population of neutralinos in the solar system described in \(^\text{19,20,21}\) (arising from neutralinos that have scattered in the outskirts of the Sun) can optionally be included as well.

5.5. *Antiprotons from halo annihilations*

Neutralinos can also annihilate in the Milky Way halo producing e.g. antiprotons. These propagate in the galaxy before reaching us. We have implemented the propagation method described in \(^\text{22}\). Optionally, the antiproton fluxes can also be solar modulated with the spherically symmetric model of \(^\text{23}\). There are also other propagation models\(^\text{24}\) available as options. The antiproton fluxes are given differential in energy.

5.6. *Positrons from halo annihilations*

Neutralino annihilations in the halo can also produce positrons. The flux of positrons is calculated with the propagation model in \(^\text{25}\) (with two choices of the energy dependence of the diffusion constant). The models in \(^\text{26}\) or \(^\text{27}\) can also be used as an option. The positron fluxes are given differential in energy.
5.7. Gamma rays from halo annihilations

Halo annihilations can also produce gamma rays. These are either monochromatic (produced from 1-loop annihilation into $\gamma\gamma$ and $Z\gamma$) or have a continuous energy spectrum (produced from $\pi^0$ decays in quark jets).

The flux of gamma rays can be obtained in any given direction on the sky for the user’s choice of $(\alpha, \beta, \gamma)$ in the halo profile. There are also routines to average the flux over a chosen angular resolution. The continuous gamma rays use Pythia simulations to calculate the gamma ray flux (differential in energy, or integrated above an energy threshold).

5.8. Neutrinos from halo annihilations

Neutralino annihilations in the halo can also produce neutrinos. Although the neutrino fluxes are small, DarkSUSY contains routines to calculate (a) the neutrino flux, (b) the neutrino-to-muon conversion rate, and (c) the neutrino-induced muon flux either differential in energy and angle or integrated within an angular cone and above a given energy threshold.

6. Conclusions

Over the years we have developed a numerical package, DarkSUSY, for neutralino dark matter calculations in the Minimal Supersymmetric Standard Model, MSSM. Since the initial public release in 2000, the main improvements to the code are the inclusion of mSUGRA models via an interface to ISASUGRA and the inclusion of all squark and slepton coannihilations. These additions will be available in the next public release.

We have here presented an overview of what the program can do, and refer the reader to the upcoming paper and manual, where the details will be given. A test program, provided with the distribution, shows in more detail how DarkSUSY is used.

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References

1. P. Gondolo, J. Edsjö, L. Bergström, P. Ullio and E. Baltz, proceedings of the 4rd International Workshop on the Identification of Dark Matter (idm2000), York, September, 2000, astro-ph/0012294.
2. S. Dimopoulos and D. Sutter, Nucl. Phys. B465 (1995) 23.
3. P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke and E.A. Baltz, in preparation.
4. L. Bergström and P. Gondolo, Astrop. Phys. 5 (1996) 263.
5. H. Baer, F.E. Paige, S.D. Protopopescu and X. Tata, hep-ph/0001086.
6. S. Heinemeyer, W. Hollik and G. Weiglein, Comp. Phys. Comm. 124 (2000) 76; hep-ph/0002213.
7. M. Drees, M. Nojiri, Phys. Rev. D45 (1992) 2482.
8. M. Carena, Espinosa, M. Quirós, and C. Wagner, Phys. Lett. B355 (1995) 209.
9. M. Carena, M. Quirós, and C. Wagner, Nucl. Phys. B461 (1996) 407.
10. M. Drees, M.M. Nojiri, D.P. Roy and Y. Yamada, Phys. Rev. D56 (1997) 276.
11. D. Pierce and A. Papadopoulos, Phys. Rev. D50 (1994) 565, Nucl. Phys. B430 (1994) 278; A.B. Lahanas, K. Tamvakis and N.D. Tracas, Phys. Lett. B324 (1994) 387.
12. Particle Data Group, K. Hagiwara et al., Phys. Rev. D66 (2002) 010001.
13. P. Gondolo and G. Gelmini, Nucl. Phys. B360 (1991) 145.
14. J. Edsjö and P. Gondolo, Phys. Rev. D56 (1997) 1879.
15. J.F. Navarro, C.S. Frenk and S.D.M. White, Ap. J. 462 (1996) 563.
16. D. Adams et al, Phys. Lett. B357 (1995) 248.
17. R.L. Jaffe and A. Manohar, Nucl. Phys. B337 (1990) 509.
18. T. Sjöstrand, Comm. Phys. Comm. 82 (1994) 74.
19. T. Damour and L.M. Krauss, Phys. Rev. Lett. 81 (1998) 5726.
20. T. Damour and L.M. Krauss, Phys. Rev. D59 (1999) 063509.
21. L. Bergström, T. Damour, J. Edsjö, L. M. Krauss and P. Ullio, JHEP 08 (1999) 010.
22. L. Bergström, J. Edsjö and P. Ullio, Astrophys. J. 526 (1999) 215.
23. L.J. Gleeson and W.I. Axford, ApJ 149 (1967) L115.
24. P. Chardonnet, G. Mignola, P. Salati and R. Taillet, Phys. Lett. B384 (1996) 161; A. Bottino, F. Donato, N. Fornengo and P. Salati, Phys. Rev. D58 (1998) 123503.
25. E.A. Baltz and J. Edsjö, Phys. Rev. D59 (1999) 023511.
26. M. Kamionkowski and M. S. Turner, Phys. Rev. D43 (1991) 1774.
27. I.V. Moskalenko and A.W. Strong, Phys. Rev. D60 (1999) 063003.
28. L. Bergström and P. Ullio, Nucl. Phys. B504 (1997) 27; see also Z. Bern, P. Gondolo and M. Perelstein, Phys. Lett. B411 (1997) 86.
29. P. Ullio and L. Bergström Phys. Rev. D57 (1998) 1962.
30. L. Bergström, J. Edsjö and P. Ullio, Phys. Rev. D58 (1998) 083507.
31. P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke and E.A. Baltz, DarkSUSY manual to be included with the next public release of DarkSUSY.