Review of Dark Matter computational tools

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In this short summary we provide a brief overview of different existing numerical tools that can be used in order to compute dark matter observables. Emphasis is given to numerical codes which allow the user to calculate the predicted dark matter abundance in the Universe in different extensions of the Standard Model and/or cosmological frameworks.

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1. Introduction

Understanding the nature of dark matter constitutes one of the key questions in contemporary high-energy physics and cosmology. Among all of the potential properties of dark matter, most of which remain unknown, the measurement of its cosmic abundance within ΛCDM cosmology [1] occupies a pivotal point. Indeed, providing an explanation for this measurement arguably constitutes a defining point for most of the (numerous!) dark matter models that have been proposed during the past few decades and which invoke different (thermo)dynamical mechanisms in order to explain how dark matter came to acquire its observed abundance.

At the same time, and in close relation to the different proposals about how dark matter came to be, a huge experimental effort has been developed in order to detect dark matter through its potential non-gravitational interactions. Much like the different dark matter generation mechanisms, each dark matter detection technique necessitates different theoretical input and, eventually, analytical and numerical computations.

Public numerical codes for the automatic calculation of different dark matter properties have been available since more than two decades. Starting off, for the most, as tools in order to automatize the calculation of the predicted relic abundance of neutralino dark matter in the Minimal Supersymmetric Standard Model (MSSM), they have since developed and expanded enormously driven, among other factors, by

- Evolutions on the experimental side, and the need to efficiently compute an ever-increasing number of dark matter observables, often with an increasing level of sophistication.

- The exploration of different dark matter models and generation mechanisms.

- The drive to study dark matter phenomenology going beyond some of the most minimal cosmological and astrophysical assumptions.

- The realisation that there are models which may predict somehow "unconventional" effects and which require special treatment, both analytically and numerically.

Today there exists a large number of dark matter-related numerical tools, covering different aspects of dark matter phenomenology[1] and which broadly fall into one of two categories: firstly, "all-purpose" numerical codes (`SuperIso Relic` [3], `DarkSUSY` [4], `MadDM` [5], `microMEGAs` [6]) that allow the user to compute the dark matter abundance in the Universe and which also offer some capabilities for the computation of different dark matter observables, the latter typically within a relatively limited set of assumptions and approximations. Secondly, "specialized" codes (some of which will be discussed in Section 2.5) that serve more specific tasks and which are mostly concerned with offering the possibility to perform some computations with an increased level of sophistication[2]. In many cases, the latter can be (or have been) promptly linked to the former, in order to create comprehensive frameworks for the study of different facets of dark matter

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[1]For another review *cf e.g.* [2].

[2]Note that this division by no means imples that specialized tools are developed just in order to improve upon the treatment included in all-purpose codes. In fact, some of them *preceeded* the development of multi-purpose ones! This division is made here just for reasons of methodology of the subsequent presentation.

phenomenology. In what follows, we will try to provide a brief overview of (some of) these tools, focusing mostly on all-purpose dark matter numerical codes.

2. Status of dark matter tools

As we already mentioned, public codes which allow users to compute the predicted dark matter abundance in the Universe have been in continuous development since more than two decades. All of them have, in one way or another, gradually incorporated additional features – most notably related with the possibility of handling different dark matter candidates and/or generation mechanisms, with the computation of dark matter observables for direct, indirect detection and the LHC, with the linking to external numerical packages performing additional computations or with the comparison against existing experimental results.

Some basic functionalities, in particular as far as standard WIMP phenomenology is concerned, are more or less common to all of these codes, which has allowed for extensive comparison between them. This has helped to understand their strengths and weaknesses, to debug them and to improve the features that they offer. Below we will sketch some of the main characteristics of each one of these "all-purpose" codes and highlight some of their features which we consider to be among their strongest points. In the end, we will also mention some notable examples of more "task-specific" codes which can be used in order to perform more specialized computations.

2.1 SuperIso Relic

`SuperIso Relic` [7, 8] is a mixed C/Fortran code that offers the possibility to compute dark matter observables in the MSSM and in the NMSSM. The User can choose which of the two models he/she wishes to work with, input different parameter values, compute the physical particle spectrum, the predicted dark matter abundance in the Universe according to thermal freeze-out, numerous direct and indirect detection signals under different astrophysical assumptions and, eventually, compare to some of the existing corresponding experimental limits.

In passing, `SuperIso Relic` is also readily linked with `SuperIso` [9], which allows the User to compute flavour observables as predicted by the two models, as well as with `AlterBBN` [10, 11] which offers the possibility to compute observables related to primordial nucleosynthesis.

Among the main stand-out characteristics of `SuperIso Relic` we should mention the fact that it indeed constitutes a very comprehensive framework for the study of neutralino dark matter in the (N)MSSM. The possibility to compute a large number of flavour observables is, to the best of our knowledge, a fairly unique feature within the realm of dark matter tools. Moreover, it offers the possibility to modify several cosmological assumptions by adopting, *e.g.*, a modified expansion rate for the Universe, as predicted in scenarios of non-standard cosmology. Lastly, it is the only dark matter code with a quasi-built-in capability of computing BBN observables and extract relevant constraints.

2.2 DarkSUSY

Until recently, `DarkSUSY` [12] was a Fortran code that was also mostly dedicated to the MSSM. However, a few years ago it underwent a *major* upgrade [13], with radical changes both in its

structure and in its general philosophy and is now capable of computing observables for general dark matter candidates.

The User can implement his/her favourite model by providing a set of quantities (*e.g.* the dark matter mass and its self-annihilation cross-sections) and `DarkSUSY` can solve the relevant freeze-out Boltzmann equation in order to calculate the predicted dark matter abundance in the Universe[3] as well as compute a broad array of observables related to direct or indirect detection under different astrophysical assumptions. It also offers the possibility to link the code to external, model-specific packages, *e.g.* SUSY-related. The input quantities have to be computed independently by the User, although a set of pre-implemented models is also provided by the developers (*e.g.* the MSSM or the Silveira-Zee model).

One of the main highlights of `DarkSUSY` is its highly modular philosophy and structure: the User is offered a great amount of freedom to easily single-out the precise functions and routines he/she wishes to employ according to the goals of his/her study or to simply replace some of them altogether. On the physics side, it provides numerous options to employ different astrophysical assumptions and it offers the possibility to study phenomenological aspects of decaying dark matter. Moreover, to the best of our knowledge, for the moment it is the only code which can perform dark freeze-out computations assuming different temperatures in each sector, it incorporates the option to account for late kinetic decoupling and Sommerfeld enhancement, whereas it also provides the possibility to compute self-interaction effects.

2.3 MadDM

`MadDM` [15, 16] is a mixed Fortran/Python code to compute dark matter observables in generic extensions of the Standard Model and the most recent addition to the arsenal of public dark matter tools available in the high-energy physics community.

In order to implement a new model, the User must provide the relevant information (particle content, interactions, parameter relations) in the `UFO` file format [17] and import it. `MadDM`, then, relies on `MG5_ AMC` [18] in order to calculate on-the-fly all the quantities that are necessary to compute the predicted dark matter abundance in the Universe according to the thermal freeze-out picture, along with different observables related to direct and indirect detection under different astrophysical assumptions. Possibilities for comparison against existing experimental limits are also offered.

One of the strongest features of `MadDM` is, undoubtedly, the fact that it automatically computes all necessary cross-sections through `MG5_ AMC` thus saving the User the task of computing them by hand. Moreover, `MG5_ AMC` is one of the most extensively used computational frameworks in collider physics, which is extremely convenient when incorporating collider constraints in dark matter studies. Lastly, `MadDM` offers the possibility to compute $2 \rightarrow n$ and some loop-induced processes through `MadLoop` [19], a feature which can be highly relevant for indirect detection studies.

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[3]Recently, a further extension of `DarkSUSY` appeared which offers the possibility to also perform computations according to the freeze-in picture [14].

2.4 MicrOMEGAs

`MicrOMEGAs` [20] is a C code[4] to compute dark matter observables in generic extensions of the Standard Model of particle physics. Historically, it was the first publicly available dark matter numerical code [21] and by far the first to incorporate the possibility to implement new models [22].

In `micrOMEGAs`, the User must define his/her model in the `CalcHEP` [23, 24] file format, import it and the code automatically calculates on-the-fly all the quantities that are necessary for the computation of the predicted dark matter abundance in the Universe according to different dark matter generation mechanisms as well as a large variety of observables related to direct and indirect detection, under different astrophysical assumptions. Possibilities for comparison against existing experimental limits and linking with external packages are also provided.

Among the main highlights of `micrOMEGAs` we should note the fact that although it computes automatically all the matrix elements and cross-sections that are needed for all computations, it also offers the possibility of easily replacing some of the internally computed quantities, *e.g.*, if the User wishes to include 1-loop corrections to the relic density calculation. On the physics side, among its strongest points are the possibility to work with models of multi-component dark matter, the fact that it can properly handle scenarios involving dark matter semi-annihilation processes and the fact that it can compute the predicted dark matter abundance in models with FIMP dark matter candidates, according to the freeze-in mechanism.

2.5 Specialized tools

The numerical packages that we described are capable of performing an extremely diversified set of dark matter-related computations. The price to pay is that, in many cases, they are forced to operate within a limited set of assumptions and/or approximations. Additional computational tools exist which allow Users to overcome some of these limitations.

In the case of direct detection, it is known that the full set of non-relativistic effective operators describing WIMP-nucleon scattering is much more extended with respect to the usual spin-independent and spin-dependent ones and that in several well-motivated New Physics scenarios the effects of these additional operators can be of crucial importance in order to extract reliable predictions. `DirectDM` [25] is a tool which allows the User to study the full set of these operators by matching the Wilson coefficients of relativistic effective field theories onto Gallilean-invariant non-relativistic ones, while also incorporating renormalization group evolution effects which can have an important impact on direct detection observables. Renormalization group effects can also be quantified by means of the `runDM` [26] code, which performs the RGE evolution from the UV scale of the theory down to the scale which is relevant for direct detection. Finally, `RAPIDD` [27] and `DDCalc` [28] can be used in order to efficiently evaluate signals in direct detection experiments while `DaMaSCUS` [29] enables the User to quantify the impact of underground dark matter scattering on the expected signals.

On the side of indirect detection, there exist numerical packages which allow for a much more detailed description of cosmic-ray propagation effects, be they dark matter annihilation-induced or produced in astrophysical sources. Concretely, `GALPROP` [30] and `DRAGON` [31] perform a fully numerical resolution of a 3-dimensional version of the diffusion equation, whereas `USINE` [32] opts

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[4]Interface to some Fortran code is also provided but the full Fortran version is not maintained anymore.

for semi-analytical methods. The CLUMPY [33] numerical package allows the User to compute the impact of halo substructres on the dark matter annihilation-induced cosmic-ray signals, whereas PPPC4DMID [34], besides tabulating numerous astrophysical quantities which are relevant for indirect detection, also provides detailed dark matter annihilation spectra including electroweak corrections. Most all-purpose dark matter codes have drawn heavily from these dedicated tools, although the latter certainly offer more flexibility to explore different astrophysical configurations.

3. Summary

Hopefully, through this short presentation it has become clear that dark matter-related computational tools have evolved enormously during the last decade – and are continuing to do so.

At present, all of the existing dark matter tools can treat, in a fairly comprehensive manner, most of the basic facets of WIMP phenomenology: relic abundance, direct and indirect detection. Moreover, many of them have expanded in order to treat effects as diversified as the evolution of dark matter within generalized cosmological settings, different astrophysical phenomena, dark matter self-interactions, different dark matter generation mechanisms, multi-component dark matter, generic dark matter candidates and higher-order quantum effects.

It is very difficult to predict the future of each one of these numerical packages: their evolution goes hand-in-hand both with developments on the experimental and on the theoretical side. After all, much like all "tools" in high-energy physics and cosmology, dark matter tools are developed by colleagues *from* the community and evolve thanks to the (direct and/or indirect) feedback *from* the community. What is certain is that, under one form or another, as long as the nature of dark matter remains unknown, dark matter tools will continue to develop and expand.

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