MICROMEGAS a package for calculation of of Dark Matter properties in generic model of particle interaction.

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These lecture notes describe the micrOMEGAs package for the calculation of Dark Matter observables in extensions of the standard model.

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1. Introduction

Since the 1930's, with the pioneering work of Zwicky[1] on the dynamics of the Coma galaxy and the observation[2] thirty years later of the flatness of the rotation curves of spiral galaxies, evidence for the existence of some missing non luminous matter has been steadily gathering. The last two decades or so have witnessed spectacular advances in cosmology and astrophysics confirming that ordinary matter is a minute part of what constitutes the Universe at large. Most spectacular has been the study of the Cosmic Microwave Background (CMB), in particular combining the results of the 7-year WMAP data[3] on the 6-parameter ΛCDM model, the baryon acoustic oscillations from SDSS[4] and the most recent determination of the Hubble constant[5] one[6] arrives at a measurement of the relic density to better than 3%. Yet the exact nature of this dark matter and its microscopic properties remain mysterious. At the same time the field of high energy

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physics has been rich in discoveries of a large number of particles. All these particles can in fact fit very neatly with a modicum of elementary building blocks within the much successful standard model (**SM**). Were it not for the masses of these particles the dynamics of the standard model would require less than a handful of parameters which makes the theory very predictive. Yet, none of the particles of the SM contributes much to the weight of the Universe, therefore Dark Matter (**DM**) is certainly New Physics. Moreover, the problem of mass in the SM is also still mysterious. Electroweak symmetry breaking and the mechanism behind the generation of mass need elucidation. The SM description poses serious conceptual problems having to do with the missing scalar particle of the SM: the Higgs particle. At the heart of the problem, the naturalness problem, is the observation that there is no symmetry to protect the mass of a lone elementary scalar like the SM Higgs. This fact has been behind the intense activity in the construction of New Physics models. Until a few years ago, the epitome of this New Physics has been supersymmetry which when endowed with a discrete symmetry, called R-parity, furnishes a good dark matter candidate. Recently, a few alternatives for the New Physics have been put forward. Originally, they were confined to solving the Higgs problem, but it has been discovered that, generically, their most viable implementation (in accord with electroweak precision data, proton decay, *etc.*) fares far better if a discrete symmetry is embedded in the model. The discrete symmetry is behind the existence of a possible dark matter candidate. We will call *even* the particles which are neutral with respect to the symmetry and *odd* the ones which get non-trivial factors[a]. All the SM particles share the same quantum number (even) which sets them apart from most of the New Physics particles which have a non even quantum number. This makes the lightest New Physics particle with this non even quantum number a stable particle which is, beside its electrically neutral character, a potentially good dark matter candidate. Among the most popular possibilities, let us mention some of the candidates and the discrete symmetry behind each of these candidates.

- R-parity (a Z_2 symmetry)[7] with the DM in Supersymmetry which is a Majorana fermion
- KK parity (a Z_2 symmetry with $x_5 \to -x_5$)[8] and the DM in Universal Extra Dimension which is a gauge boson
- T-parity (a Z_2 symmetry)[9] in Little Higgs model with the DM which is a gauge boson

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[a]This terminology comes from the widely used Z_2 case

- Z_3 symmetry in warped GUTs with the DM[10] which is a fermion

Models with Z_n symmetry and $n > 3$ have interesting phenomenology[11] since there can be more than one stable Dark Matter particle.

Therefore, with the fact that a very large class of models for the New Physics whose primary aim is a better description of the Higgs sector of the SM provide, as a bonus, a candidate for DM, it is fair to say that we are witnessing the emergence of a strong cross breeding between high energy collider physics on the one hand and cosmology and astrophysics on the other to unravel the mystery of DM. This should be set in the new landscape where a wealth of data and analyses are being conducted at the colliders, in particular the LHC, as well as important non collider experiments in astrophysics and cosmology. At the *cosmological level*, weighing the Universe will be achieved with even higher precision with Planck.[12] *Direct detection* of Dark Matter in underground experiments, where one measures the recoil of a nucleus due to the Dark Matter particle impinging on it is being carried out by many collaboration using complementary techniques and nuclear material DAMA,[13] CDMS,[14] XENON.[15] Many *indirect detection* experiments are also at work gathering signals from the annihilation of Dark Matter that takes place for example in the galactic halo. These result in fluxes of γ, $e^{\pm}$, $p^{\pm}$ and neutrinos which can reach the Earth. Photons and neutrinos propagate directly, but the charged particles path and their energy spectra get distorted by the magnetic fields. These signals would be detected by satellites and ground experiments such as Pamela,[16,17] HEAT,[18] Fermi,[19,20] ATIC,[21] HESS,[22–24] EGRET,[25] INTEGRAL.[23] New data on $\gamma, e^{\pm}, p^{\pm}$ from AMS02[26] experiment are expected soon. Other types of experiments are dedicated to analysing the Dark Matter neutrinos as they get accumulated in the core of the Sun or the Earth. Super-Kamiokande[27,28] and IceCube[29] are two such neutrino observatories. Reconstructing the microscopic properties of Dark Matter at the LHC and future linear colliders could provide invaluable input for direct and indirect experiments as well as cosmology since this will allow access to a better understanding of the density distribution of dark matter as well as their velocity distribution.

Simulation and Monte Carlo codes for BSM physics at colliders have been around for quite some time. Automatic codes for the generation of matrix elements and cross sections for the colliders are now also numerous. At the colliders the initial state consisting of SM particles is well defined even if in the case of hadronic machines one needs a convolution over struc-

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ture functions. Predictions are then made for a specific channel or a BSM particle in the final state. The task of a DM code that returns the value of the relic density requires the calculation of a very large number of channels and processes. First of all one needs to identify what could be a potentially valid DM candidate (neutrality and stability are a first requirement). Once this is set one generally needs to calculate a large number of processes corresponding to the annihilation of this candidate to all possible SM final states. In general, since the BSM model has not been constrained and its parameters not measured one has to allow for the calculation of a very large number of processes depending on the properties of the DM particle. In the MSSM for example, one has to be ready to calculate the rates for some 3000 processes. Early codes for the calculations of the relic density listed only a few processes that were, at some stage, of a particular interest. Whenever a new mechanism was deemed interesting new calculations were added. Indirect detection codes require the decay and fragmentation products of the SM produced in annihilation of DM particles. Furthermore sophisticated modeling of the propagation of charged particles is needed. In direct detection the rates have to be parametrized and evaluated at very small recoil energy, interaction with nuclei require elements from nuclear physics for instance (form factors,..). All these different observables need to be "convoluted" with different DM density distributions and call for a knowledge of the velocity distribution. For the relic density a model of cosmology has to be invoked to take into account the evolution of the Universe, the dilution of the DM and its decoupling.

micrOMEGAs has been developed with the aim of providing the value the relic density, the fluxes of photons, antiprotons, and positrons for indirect DM searches; cross sections of DM interactions with nuclei and energy distribution of recoil nuclei; neutrino and the corresponding muon flux from DM particles captured by the Sun; collider cross sections and partial decay widths of particles within a BSM that provides a possible WIMP (weakly Interacting Massive Particle) DM candidate. What sets micrOMEGAs apart from other codes is its ability, once given a *Model File* that encodes a BSM model, to output, for any set of parameters of the model, all the observables we have just listed. All the needed cross sections are built up on the fly. There are several packages which calculate different properties of DM within the very popular minimal supersymmetric standard model (MSSM): DarkSUSY[30] SuperIso[31] and Isared.[32] The modular structure of micrOMEGAs with the (self) automatic generation of all the needed ma-

trix elements and cross sections allows `micrOMEGAs` to tackle practically any model. The package has been developed within a French-Russian collaboration by G.Bélanger, F.Boudjema (LAPTh), A. Pukhov (SINP), and A.Semenov (JINR). The various features of the `micrOMEGAs` code are described in a series of papers.[33–37] In these lectures we describe the micrOMEGAs package, give the main formulas related to the calculation of DM relic density and DM signals and present some examples of `micrOMEGAs` output. The `micrOMEGAs` package is accompanied with an on-line manual which provides a detailed description of all functions included in the package. The user can refer to this manual for a complete specification of the functions and more detailed information on the program.

For a review on Dark Matter see.[38–40]

2. An overview of the modules of `micrOMEGAs`

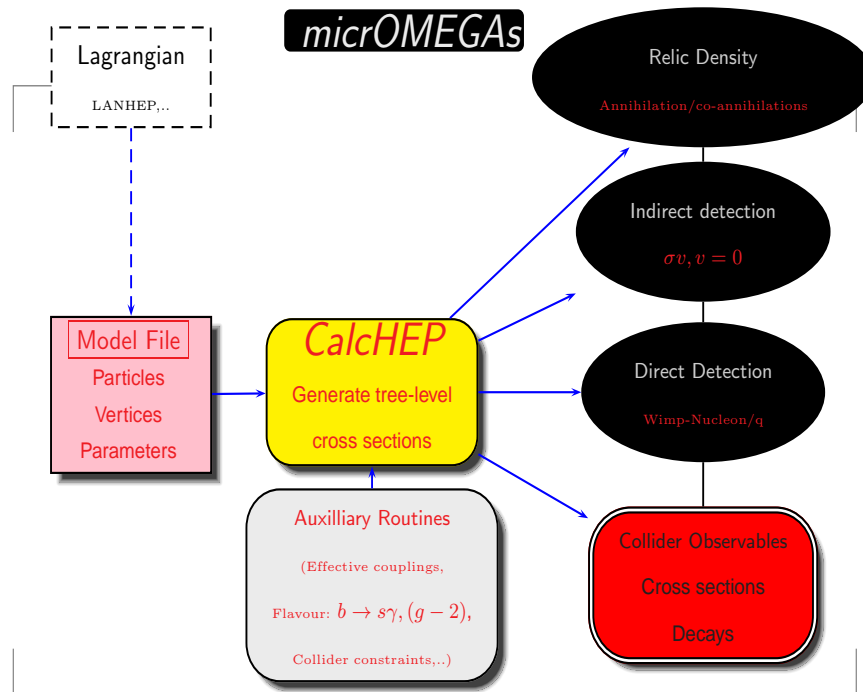The chart flow of `micrOMEGAs`[33–37] is displayed in Fig. 1

Fig. 1.   The micrOMEGAs flow chart.

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All the observables we have pointed at require the computation of interaction rates. The calculation of the cross sections in different kinematical regimes is at the heart of the system. We rely on `CalcHEP`[41,42] for the generation of all tree-level cross sections. Naturally a model must be defined. `CalcHEP` requires therefore a model file which defines the nature of all particles in the model (spin, charges,..), parameters (masses, couplings) as well as the interaction vertices or in other words the Feynman rules. Once this is specified in the proper format, `CalcHEP` proceeds to the identification of the DM particle. The Z_n assignment is therefore crucial as is of course the mass ordering and the electric neutral character of the WIMP candidate. The current public version of micrOMEGAs can only treat models with Z_2 and Z_3 discrete symmetries. The code is then ready to process any needed cross section. For some models, for example the MSSM, deriving the Feynman rules is a horrendous task. Traditionally `micrOMEGAs` has relied on `LanHEP`[43] which is a code that outputs the model file once given the Lagrangian. `FEYNRULES`[44] is another recent code that can achieve the same effect. From the cross sections which are model specific, the code calls different shared libraries (common to all models) to output the value of

- the relic density
- the rates for indirect detection of $e^+, \bar{p}, \gamma, \nu$. For the case of ν this includes capture by the Sun and the Earth.
- direct detection for specific targets in large-scale underground experiments.
- cross sections at colliders and branching ratios for various particles of the model.

This sequence of calls and computations is automated. The code includes also many auxiliary routines which are model specific. Since `CalcHEP` is a tree level cross section generator some important radiative corrections must be introduced through the auxiliary routines. This is the case of the MSSM where the mass of the lightest Higgs must be corrected in a coherent way through an effective Lagrangian that can be interfaced to some spectrum calculator, for example `FeynHiggs`[45] or corrections to Higgs couplings (`HDECAY`[46]). Input of the MSSM mass spectrum is also implemented through SLHA.[47,48] Other routines include computations such as $(g-2)$, $b \rightarrow s\gamma$, $B_s \rightarrow \mu + \mu-$,..Bounds on some masses and parameters can be easily input by the user with sometimes the help of external codes such as `HiggsBounds`.[49,50] The code is "open source" and allows to add a large number of models and also different external codes for some of the auxiliary

routines.

3. Downloading and compilation of micrOMEGAs.

To download micrOMEGAs, go to
>   `http://lapth.in2p3.fr/micromegas`

and unpack the file received, `micromegas_`2.6.X`.tgz`, with the command
>   `tar -xvzf micromegas_`2.6.X`.tgz`

This should create the directory `micromegas_`2.6.X`/` which occupies about 40 Mb of disk space. You will need more disk space after compilation of specific models and generation of matrix elements. In case of problems and questions
>   `email: micro.omegas@lapp.in2p3.fr`

3.1. *File structure of micrOMEGAs.*

`Makefile`	to compile the kernel of the package
manual2.6.X`.tex`	the manual: description of micrOMEGAs routines
`CalcHEP_src/`	generator of matrix elements for micrOMEGAs
`sources/`	micrOMEGAs code
`newProject`	to create a new model directory structure
MSSM model directory	
`MSSM/`	
`Makefile`	to compile the code and executable for this model
`main.c[pp] main.F`	files with sample *main* programs
`lib/`	directory for routines specific to this model
`Makefile`	to compile auxiliary code library *lib/aLib.a*
`*.c *.f`	source codes of auxiliary functions
`work/`	CalcHEP working directory for thegeneration of matrix elements
`Makefile`	to compile library *work/work_aux.a*
`models/`	directory for files which specifies the model
`vars1.mdl`	free variables
`func1.mdl`	constrained variables
`prtcls1.mdl`	particles
`lgrng1.mdl`	Feynman rules
`tmp/`	auxiliary directories for CalcHEP sessions
`results/`	
`so_generated/`	storage of matrix elements generated by CalcHEP

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`calchep/`	directory for interactive CalcHEP sessions

Directories of other models which have the same structure as `MSSM/`

`NMSSM/`	Next-to-Minimal SUSY Model[51,52]
`CPVMSSM/`	MSSM with complex parameters[53,54]
`IDM/`	Inert Doublet Model[55]
`LHM/`	Little Higgs Model[56]
`RHNM/`	Right-handed Neutrino Model[57]
`etc/`	for testing

3.2. *Compilation of CalcHEP and micrOMEGAs routines.*

CalcHEP and micrOMEGAs are compiled by *gmake*. Go to the micrOMEGAs directory and launch

   `gmake`

If `gmake` is absent, then `make` should work like `gmake`. In principle micrOMEGAs defines automatically the names of *C* and *Fortran* compilers and the flags for compilation. If you meet a problem, open the file which contain the compiler specifications, `CalcHEP_src/FlagsForSh`, improve it, and launch `[g]make` again. The file is written is **sh** script format and looks like

```
# C compiler
CC="gcc"
# Flags for C compiler
CFLAGS="-g -fsigned-char"
# Disposition of header files for X11
HX11=
# Disposition of lX11
LX11="-lX11"
# Fortran compiler
FC="gfortran"
FFLAGS="-fno-automatic"
........
```

After a successful definition of compilers and their flags, micrOMEGAs rewrites the file *FlagsForSh* into *FlagsForMake* and substitutes its contents in all *Makefile*s of the package.

   `[g]make clean` deletes all generated files, but asks permission to delete *FlagsForSh*.

[g]`make flags` only generates FlagsForSh. It allows to check and change flags before compilation of codes.

3.3. *Module structure of main programs.*

Each model included in micrOMEGAs is accompanied with sample files for C and Fortran programs which call micrOMEGAs routines, the *main.c*, *main.F* files. These files consist of several modules enclosed between the instructions

```
#ifdef XXXXX
  ...................
#endif
```

Each of these blocks contains some code for a specific problem

```
#define MASSES_INFO        //Displays information about mass spectrum
#define CONSTRAINTS        //Displays B_>sgamma, Bs->mumu, etc
#define OMEGA              //Calculates the relic density
#define INDIRECT_DETECTION //Signals of DM annihilation in galactic halo
#define RESET_FORMFACTORS //Redefinition of Form Factors and other
                          //parameters
#define CDM_NUCLEON        //Calculates amplitudes and cross-sections
                           //for DM-nucleon collisions
#define CDM_NUCLEUS         //Calculates number of events for 1kg*day
                          //and recoil energy distribution for various nuclei
#define NEUTRINO          //Calculates flux of solar neutrinos and
                          //the corresponding muon flux
#define DECAYS            //Calculate decay widths and branching ratios
#define CROSS_SECTIONS    //Calculate cross sections
```

All these modules are completely independent. The user can comment or uncomment any set of *define* instructions to suit his/her need.

3.4. *Compilation of codes for specific models.*

After compilation of micrOMEGAs one has to compile the executable to compute DM related observables in a specific model. To do this, go to the model directory, say MSSM, and launch

[g]`make main=main.c`

It should generate the executable `main`. In the same manner

gmake main=*filename.ext*

generates the executable `filename` based on the source file *filename.ext*. For *ext* we support 3 options: *'c'*, *'F'*, *'cpp'* which correspond to `C`, `FORTRAN` and

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C++ sources. `[g]make` called in the model directory automatically launches `[g]make` in subdirectories *lib* and *work* to compile

    `lib/aLib.a` - library of auxiliary model functions, e.g. constraints,

    `work/work_aux.a` - library of model particles, free and dependent parameters.

3.5. *Command line parameters of main programs.*

Default versions of *main.c/F* programs need some arguments which have to be specified in command lines. If launched without arguments *main* explains which parameter are needed. As a rule *main* needs the name of a file containing the numerical values of the free parameters of the file. The structure of a file record should be

`Name        Value # comment ( optional)`

For instance, an Inert Doublet model (IDM) input file, see section4.1, contains

```
 Mh    125   # mass of SM Higgs
 MHC   200   # mass of charged Higgs ~H+
 MH3   200   # mass of odd Higgs ~H3
 MHX    63.2 # mass of ~X particle
 la2  0.01   # \lambda_2  coupling
 laL  0.01   # 0.5*(\lambda_3+\lambda_4+\lambda_5)
```

In other cases, different inputs can be required. For example, in the MSSM with input parameters defined at the GUT scale, the parameters have to be provide in a command line. Launching `./main` will return

```
   This program needs 4 parameters:
  m0      common scalar mass at GUT scale
  mhf common gaugino mass at GUT scale
  a0     trilinear soft breaking parameter at GUT scale
  tb    tan(beta)
Auxiliary parameters are:
  sgn +/-1, sign of Higgsino mass term (default 1)
  Mtp top quark pole mass
  MbMb Mb(Mb) scale independent b-quark mass
  alfSMZ strong coupling at MZ
Example: ./main 120 500 -350 10 1 173.1
```

4. Structure of model files in CalcHEP

micrOMEGAs uses CalcHEP[41,42] to generate automatically the code for the computation of matrix elements. It makes micrOMEGAs flexible for new model implementation. The complete manual for CalcHEP and in particular a description of the structure of CalcHEP model files can be found at

> http://theory.sinp.msu.ru/~/pukhov/calchep.html

Here we present only the information about model files needed for understanding and using micrOMEGAs. As an example, we will use here the Inert Doublet model.

4.1. *A simple example, the Inert Doublet Model.*

The IDM[58] contains two $SU(2) \times U(1)$ scalar doublets. In the unitary gauge

$$H_1 = \begin{pmatrix} 0 \\ \langle v \rangle + h/\sqrt{2} \end{pmatrix} \quad, \quad H_2 = \begin{pmatrix} \widetilde{H}^+ \\ (\widetilde{X} + i\widetilde{H}_3)/\sqrt{2} \end{pmatrix}$$

where H_1 is the SM Higgs doublet and H_2 is a new *inert* doublet which does not couple to quarks and leptons and is odd under a new Z_2 symmetry. Unlike the SM scalar doublet it does not develop a vacuum expectation value. $\widetilde{H}^+$, $\widetilde{X}$, and $\widetilde{H}_3$ are the new fields of the model. The IDM Lagrangian contains only even powers of the doublet H_2

$$\mathcal{L} = (SM\ terms) + D^\mu H_2^* D_\mu H_2 - \mu^2 |H_2^2|^2 \tag{1}$$
$$-\lambda_2 H_2^2 - \lambda_3 H_1^2 H_2^2 - \lambda_4 |H_1^* H_2|^2 - \lambda_5 Re[(H_1^* H_2)^2]$$

Because of the $H_2 \rightarrow -H_2$ symmetry, the lightest new particle is stable. In the following example we will use the masses of new particles as well as λ_2 and $\lambda_L = (\lambda_3 + \lambda_4 + \lambda_5)/2$ as independent parameters, The couplings μ, λ_3, λ_4, λ_5 can be expressed in terms of the independent parameters. For details of IDM and further references see Ref.[55]

4.2. *Particles of the model.*

The list of particles is given in the file *models/prtcls1.mdl*, for example

```
Inert Doublet
Full    Name | P | aP|number|spin2|mass|width|color|aux|> LaTeX(A)
photon       |A  |A  |22     |2    |0   |0    |1    |G  |A
Z boson      |Z  |Z  |23     |2    |MZ  |wZ   |1    |G  |Z
gluon        |G  |G  |21     |2    |0   |0    |8    |G  |G
```

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```
W boson       |W+ |W- |24   |2   |MW  |wW   |1   |G  |W^+
neutrino      |n1 |N1 |12   |1   |0   |0    |1   |L  |\nu^e
electron      |e1 |E1 |11   |1   |0   |0    |1   |   |e
mu-neutrino   |n2 |N2 |14   |1   |0   |0    |1   |L  |\nu^\mu
muon          |e2 |E2 |13   |1   |Mm  |0    |1   |   |\mu
tau-neutrino  |n3 |N3 |16   |1   |0   |0    |1   |L  |\nu^\tau
tau-lepton    |e3 |E3 |15   |1   |Mt  |0    |1   |   |\tau
u-quark       |u  |U  |2    |1   |0   |0    |3   |   |u
d-quark       |d  |D  |1    |1   |0   |0    |3   |   |d
c-quark       |c  |C  |4    |1   |Mc  |0    |3   |   |c
s-quark       |s  |S  |3    |1   |Ms  |0    |3   |   |s
t-quark       |t  |T  |6    |1   |Mtop|wtop |3   |   |t
b-quark       |b  |B  |5    |1   |Mb  |0    |3   |   |b
Higgs         |h  |h  |25   |0   |Mh  |!wh  |1   |   |h
odd Higgs     |~H3|~H3|36   |0   |MH3 |!wH3 |1   |   |H_3
Charged Higgs|~H+|~H-|37   |0   |MHC |!wHC |1   |   |H^+
second Higgs |~X |~X |35   |0   |MHX |!wHX |1   |   |X
```

The columns of this table have the following meaning:

- **P, aP -** names of particle and antiparticle used in interaction vertices.
- **number -** Particle number according to the Monte Carlo numbering scheme[59] (PDG code). For new particles not listed in PDG, one can use any number as long as it is not already used for some particle. In order to recognize which name corresponds to a given particle, micrOMEGAs uses PDG numbers. Interface with other packages is also based on these codes.
- spin2 - twice the particle spin
- mass - mass identifier
- width - width identifier, when an exclamation mark precedes the width symbol, this width will be calculated automatically.
- color - dimension of representation of color group.
- aux - 'G' means that this particle is a gauge boson which is treated in the t'Hooft-Feynman gauge. Interactions of ghost fields have to be specified in the file for vertices and the sum over ghost fields will be taken into account automatically. 'L/R' denotes massless fermions which exist only in left/right states. A number written in this column means $3Q$ where Q is the electric charge. This charge is usually detected by CalcHEP automatically from the interaction vertices, in cases where it is not possible, the number should be specified in this column.

- Latex(A) Particle names in LaTex format (optional)

Note that the names of particles in the odd sector should started with tilde ~.

4.3. *Free parameters of the model.*

The independent (free) parameters of the model are listed in the file *models/vars1.mdl* [b]. For example,

```
Inert Doublet Model
 Variables
  Name | Value     | Comment                                |
EE     |0.31333    |Electromagnetic coupling constant
SW     |0.474      |sin of the Weinberg angle
MZ     |91.187     |Mass of Z
MHX    |63.2       |Mass of Inert Doublet Higgs
MH3    |200        |Mass of CP-odd Higgs
MHC    |200        |Mass of charged Higgs
Mh     |125        |Mass of standard Higgs
LaL    |0.01       |Coupling in Inert Sector
La2    |0.01       |Coupling in Inert Sector
.................................
```

Three functions can be used to extract or set the values of the free parameters:

`findValW(char*name)` - returns the numerical value of parameter *name*.

`assignValW(char*name,double value)` - assigns new value to parameter *name*. It gives a warning if *name* does not correspond to any parameter.

`readVar(fileName)` - allows to download a set of parameters, e.g. from a file. The structure of the file is explained in section 3.5. `readVar` returns zero when the file has been read successfully or a positive value corresponding to the line in the file which contained an error.

4.4. *Constrained parameter of the model.*

Constrained parameters are stored in the file *models/func1.mdl*. For example

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[b]See micrOMEGAs file structures in section 3.1

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```
Inert Doublet Model
 Constraints
 Name |> Expression
CW    |sqrt(1-SW^2)              % cosine of Weinberg angle
MW    |MZ*CW                     % W+ mass
Mb    |MbEff(Q)                  % b-quark effective mass
Mc    |McEff(Q)
mu2   |MHX^2-laL*(2*MW/EE*SW)^2      % mu^2
la3   |2*(MHC^2-mu2)/(2*MW/EE*SW)^2  % \lambda_3
la5   |(MHX^2-MH3^2)/(2*MW/EE*SW)^2  % \lambda_5
la4   |2*laL-la3-la5                 % \lambda_4
%Local!|
 .................
```

The constrained parameters are divided into two parts. The *public* parameters listed at the top of the file and the *local* parameters at the bottom of the file. The splitting of parameters into two sets is constructed using the following rules: *public* parameters include **i)** all parameters involved in the calculation of particle masses and **ii)** all parameters which call external functions for calculations. The value of *public* parameters can be obtained via the function `findValW(name)`.

Local parameters appear only inside the matrix elements codes and can not be accessed with micrOMEGAs. The user can enlarge the list of *public* parameters by writing a record in func1.mdl which starts with `%Local!`. Then all parameters disposed above this record become *public*. This separation of parameters into two classes is needed for optimization of calculations in models where there is a large number of constrained parameters.

The calculation of all *public* model constraints and of the particle spectrum is done with

$\qquad$ `sortOddParticles(text)` ,

which computes all constraints, sorts the odd particles with increasing masses, writes the name of the lightest odd particle in *text* and assigns its mass to the global parameter `Mcdm`. This routine returns a non zero error code if some constraint cannot be calculated. The name of the corresponding constraint is written in *text*. This routine has to be called before any other functions when starting to work with a model, furthermore it has to be called after a reassignment of any input parameter.

The properties of particles can be tested with the two functions

$\qquad$ `pMass(pName)`, which gives the mass of particle *pName*.

$\qquad$ `qNumbers(pName, &spin2,&charge3,&cdim)`, which calculates the

quantum numbers of a particle and returns directly its *PDG* code. This function allows to check that the Dark Matter candidate has no electric or color charges.

The table of Feynman rules for each model is rather long. For example, one can check the *IDM/work/models/lgrng1.mdl* file to see how the interactions of SM and Inert doublet particles are presented in CalcHEP/micrOMEGAs.

4.5. *Example: MSSM mass spectrum.*

As an example we present here the code used for finding the properties of the DM candidate in the MSSM model with parameters defined at GUT scale. This option is specified by

```
#define SUGRA
```

at the top of the main file in the MSSM directory.

```
// CODE
err=sortOddParticles(cdmName);
if(err){ printf("Can't calculate %s\n",cdmName); return 1;}
qNumbers(cdmName,&spin2, &charge3, &cdim);
printf("\nDark matter candidate is '%s' with spin=%d/2  mass=%.2E\n",
   cdmName,spin2,Mcdm);
```

With the following input parameters (in GeV for dimensionful variables)

$M_0 = 120$, $M_{1/2} = 500$, $A_0 = -350$, $\tan\beta = 10$, $sign(\mu) = 1$, $M_{top} = 173.1$;

the micrOMEGAs output is

```
Dark matter candidate is '~o1' with spin=1/2  mass=2.06E+02
```

One can print the masses of particles included in the model with the commands

printHiggs(FD)- prints masses and widths of scalar (Higgs) particles in open file *FD*.

printMasses(FD,sort)- prints masses of *odd* sector particles. If $sort \neq 0$ particles are sorted with respect to their masses. The corresponding micrOMEGAs output for these two functions is

```
Higgs masses and widths
    h   115.99 3.07E03
    H   766.59 1.65E+00
   H3   766.34 1.68E+00
   H+   770.85 1.61E+00
Masses of odd sector Particles:
~o1  : MNE1 =    205.9  || ~l1  : MSl1  =    212.3  || ~eR  : MSeR  =223.7
~mR  : MSmR  =   223.7  || ~nl  : MSnl  =    344.8  || ~ne  : MSne  =346.8
```

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```
~nm  : MSnm  =    346.8  || ~eL  : MSeL  =    355.4   || ~mL  : MSmL  =355.4
~l2  : MSl2  =    356.5  || ~1+  : MC1   =    389.6   || ~o2  : MNE2  =389.7
~o3  : MNE3  =    692.7  || ~2+  : MC2   =    704.2   || ~o4  : MNE4  =704.3
~t1  : MSt1  =    767.9  || ~b1  : MSb1  =    959.3   || ~b2  : MSb2  =1005.7
~t2  : MSt2  =   1006.1  || ~dR  : MSdR  =   1009.9   || ~sR  : MSsR  =1009.9
~uR  : MSuR  =   1013.4  || ~cR  : MScR  =   1013.4   || ~uL  : MSuL  =1050.2
~cL  : MScL  =   1050.2  || ~dL  : MSdL  =   1053.1   || ~sL  : MSsL  =1053.1
~g   : MSG   =   1146.4  ||
```

5. Runtime generation of matrix elements by CalcHEP.

5.1. *Running CalcHEP in blind mode.*

In general the CalcHEP version used in micrOMEGAs for generating matrix elements is a menu driven package. micrOMEGAs users can go to *./calchep* subdirectory found in any *MODEL* directory and launch the *./calchep* command script to see how CalcHEP works and to check different matrix elements of the DM model used. However CalcHEP also works in *blind* mode when special keys passed in command line are interpreted as keyboard hits. For example, the command

    CalcHEP_src/bin/s_calchep -blind "{{~dm,~dm>2*x{{{[{[{{0"
generates C-code for annihilation of two DM particles (~dm) into 2 arbitrary particles of the model. Here { simulates hit of the Enter key, } simulates Esc, [and] are used for down and up arrow keys respectively.

5.2. *Dynamic linking and generation of shared libraries of matrix elements.*

micrOMEGAs transfers the C-code of matrix elements into shared library. The general form for such command is

    gcc -shared -o library_name.so matrix_element_files.c
All shared libraries of matrix elements for a given MODEL are stored in the directory

    MODEL/work/so_generated/
They are recompiled automatically if the model is changed. Shared library can be linked dynamically in runtime[c]. A simple example of such code is presented below

```
* =========== file dltest.c =========*/
#include <stdio.h>
```

---

[c]See output of *man* unix command for *dlopen*, *dlsym*

```
#include <dlfcn.h>
int main(void)
{ void *handle; double (*arcsin)(double);
  handle = dlopen("libm.so",RTLD_NOW);
  arcsin = dlsym(handle,"asin");
  printf ("%f\n", 2*(*arcsin)(1));
}
```

Here we open in runtime the standard library of mathematical functions which was not linked to the code from the beginning, find an address of the *arcsine* function and calculate $2\arcsin(1)$ which should be equal to π. To compile the function presented above use

```
    gcc dtest.c -ldl
```

The general scheme for matrix element generation in micrOMEGAs is the following. The downloaded package does not contain any code for matrix elements. When micrOMEGAs needs some matrix element it first checks the existence of the corresponding library in the directory `MODELS/work/so_generation`. If such library already exists, it is linked dynamically. If not, micrOMEGAs calls CalcHEP to generate the C-code for the requested matrix element, transforms it to a shared library, moves this library to the `so_generated` directory and loads it dynamically. Because of this set-up the first call to micrOMEGAs can take some time. However further calls, even with new parameters, are executed rather fast.

6.   Calculation of Relic Density.

Density of DM in the Universe is extracted from measurements of fluctuations of CMB temperature by the WMAP[60,61] experiment.

$$\Omega_{dm}h^2 = \rho_{dm}/\rho_c = 0.105(8)$$

where h =0.73(3) defines the present day Hubble expansion rate

$$H_0 = h \cdot 100 km/s/Mpc \quad ,$$

$\rho_c = 10.537h^2 GeV/m^3$ is a critical density corresponding to H_0. Thus $\rho_{dm} \approx 1.11 GeV/m^3$. The DM density is usually given by the value $\Omega_{dm}h^2$ to avoid the uncertainty associated with the Hubble rate.

We assume that at large temperatures DM particles are in thermal equilibrium with SM particles, so that DM self-annihilation is compensated by DM production in collisions of SM particles. Thus the DM density reaches its equilibrium value, N_{eq}, described by the Boltzmann formula,

$$N \approx N_{eq} \approx e^{-\frac{M_{cdm}}{T}} \quad .$$

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When the DM density becomes small and self-annihilation stops, the DM density is driven by the expansion of the Universe and decreases slowly while N_{eq} drops rapidly to zero. So, some *relic* DM can be observed.

If the DM is a WIMP with a mass scale from 1-1000GeV and which interact weakly with SM particles, then its *relic* density is in agreement with the value observed, $\Omega h^2 \approx 0.1$. It is usually called the *WIMP miracle*. The temperature where self annihilation stops is called the *freeze-out* temperature.

6.1. *Equations of thermal evolution of DM density*

Here we present the equations used for the calculation of Ωh^2 using the `darkOmega` function in micrOMEGAs, see section 6.5. Let N designate the total number density of *odd* particles. Then the time evolution of the DM density reads

$$\frac{dN}{dt} = -3HN - \langle \sigma v \rangle_T (N^2 - N_{eq}^2)$$

The first term is caused by Hubble expansion which is a function of the current matter density ρ

$$H = \frac{1}{M_{Planck}} \sqrt{\frac{8\pi}{3}\rho}$$

The second term describes two processes, DM annihilation into SM particles and its reverse. If $N = N_{eq}$, these two processes are in thermal equilibrium. In general, the rate of a reaction is defined by the product of the particle velocity with the cross section, $\sigma \cdot v$. Because the DM velocity follows a Boltzmann distribution, one has to compute the thermally average cross section, $\langle \sigma v \rangle_T$. The equilibrium density N_{eq} equals the sum of contributions of different *odd* particles

$$N_{eq} = \sum_{i \in oddParticles} N_{eq}^i \ ,$$

where

$$N_{eq}^i = n^i \int \frac{dp^3}{(2\pi)^3} \left(e^{\frac{\sqrt{p^2+M_i^2}}{T}} \pm 1 \right)^{-1} \approx n^i \int \frac{dp^3}{(2\pi)^3} e^{-\frac{\sqrt{p^2+M_i^2}}{T}} \ ,$$

where n^i denotes the number of degrees of freedom of particle i.

The total DM number density is obtained after summing on all different odd particles, $N = \sum N_i$, since all odd particles eventually decay into the

DM. One can assume a chemical equilibrium between different components N_i because of the decays of all odd particles into the lightest one. Thus,

$$N_i(T)/N_j(T) = N_{eq}^i(T)/N_{eq}^j(T) \approx e^{-\frac{M_i - M_j}{T}}$$

Consequently the formula for $\langle \sigma v \rangle_T$ should contain averaging over different particle of the *odd* sector. One can find explicit formulas for $\langle \sigma v \rangle_T$ in the papers.[35,62]

Let us define s as the entropy density. Because of entropy conservation

$$\frac{ds}{dt} = -3H \cdot s$$

and we can replace the equation for the number density by a simpler equation for the abundance $Y = N/s$

$$\frac{dY}{ds} = \frac{1}{3H} \langle \sigma v \rangle_T (Y^2 - Y_{eq}(T)^2) = \frac{M_{Planck}}{\sqrt{24\pi\rho}} \langle \sigma v \rangle_T (Y^2 - Y_{eq}(T)^2) \qquad (2)$$

6.2. *Thermodynamics of Universe*

The formulas that give the contribution of one relativistic degree of freedom to the entropy density and energy density of the Universe are rather simple. For bosons

$$\rho_b = \frac{\pi^2}{30} T^4 \ , \quad s_b = \frac{2\pi^2}{45} T^3 \qquad (3)$$

The corresponding functions for fermions have an additional factor $\frac{7}{8}$. In the generic case one can write

$$\rho(T) = \frac{\pi^2}{30} T^4 g_{eff}(T) \ , \quad s(T) = \frac{2\pi^2}{45} T^3 h_{eff}(T) \qquad (4)$$

where $g_{eff}(T)/h_{eff}(T)$ count the effective numbers of degrees of freedom[d]. At freeze-out temperatures, the contribution of Dark Matter should be strongly suppressed, only Standard Model particles contribute to g_{eff} and h_{eff}.[e] At low temperature ($T \ll 100 MeV$), the effective number of degree of freedom is defined by photons, neutrinos, light leptons. As the temperature increases, one has to add the quarks degrees of freedom. There is a problem of correct matching between these two regions. micrOMEGAs uses the tabulated functions for $g_{eff}(T)/h_{eff}(T)$ obtained in.[63,64] They are displayed in Fig.2.

---

[d]$g_{eff}(T)$ and $h_{eff}(T)$ are related via condition $\frac{d\rho(T)}{dT} = T \frac{ds(T)}{dT}$
[e]We assume that at low temperatures when DM contributes significantly to ρ the formation of Dark Matter is finished and $Y(T) = Const$.
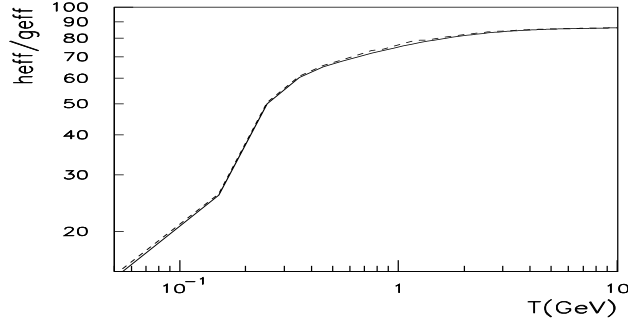
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Fig. 2. h_{eff} (solid) and g_{eff}(dashed) as functions of temperature.

In order to convert the abundance Y_0 obtained by solving Eq.(2) into the DM number density one has to know the value of the entropy today. The present day entropy is stored in photons and neutrinos. Photons have a temperature $T = 2.725K = 2.348 \cdot 10^{-4}eV = 1196m^{-1}$. When $e^{\pm}$ pairs annihilate, their entropy is transformed into entropy of photons which leads to a temperature of photons larger than the temperature of neutrinos. After electrons decouple we have independent gases of photons and neutrinos. Counting the degrees of freedom leads to the entropy density ratio

$$\frac{s_\nu}{s_\gamma} = \frac{6(7/8)}{2 + 4(7/8)} = \frac{21}{22}$$

which allows to calculate the present day entropy. As a result we get for the relic density

$$\Omega h^2 = \frac{M_{cdm}[GeV]}{10.57[GeV/m^3]} \cdot Y_0 \cdot 2.889 \cdot 10^9 m^{-3}$$

where $2.889 \cdot 10^9 m^{-3}$ is the present day entropy[59] and $10.57 GeV/m^3$ is the critical density for $H = 100\frac{km}{sMpc}$

6.3.   *Numerical solution of DM thermal evolution equation.*

6.3.1. *High temperature region*

Equation (2) can be solved numerically by means of the Runge-Kutta method. The only problem with this method is to find a starting point at

high temperature. Let $\Delta Y = Y - Y_{eq}$. Assuming that at high temperature

$$\Delta Y \ll Y_{eq} \ , \quad \frac{d\Delta Y}{ds} \ll \frac{dY_{eq}}{ds} \tag{5}$$

we estimate

$$\Delta Y = \frac{d\log Y_{eq}(s)}{ds} \frac{\sqrt{6\pi\rho}}{M_{Planck}\langle\sigma v\rangle_T} \quad . \tag{6}$$

The function Y_{eq} drops rapidly, nevertheless our initial assumption (5) is satisfied because the dependence on Y_{eq} is only logarithmic. This gives us a rather simple picture of freeze-out. We have an almost constant ΔY on the background of a fast dropping Y_{eq} as the temperature decreases. At some temperature ΔY becomes comparable with Y_{eq} and we have the freezing-out of $Y \approx \Delta Y$.

micrOMEGAs uses Eq.(6) to find the starting point for the Runge-Kutta procedure looking for a point where $\Delta Y \approx 0.1 Y_{eq}$.

6.3.2. *Freeze-out approximation*

One can use Eq.(6) to find s_f (or the corresponding T_f) where $Y(T_f) \gg Y_{eq}(T)$. micrOMEGAs defines T_f by condition

$$Y(T_f) = 2.5 Y_{eq}(T_f) \ . \tag{7}$$

Below T_f one can neglect the Y_{eq}^2 term in Eq.(2) and get the explicit solution

$$\frac{1}{Y(s_0)} = \frac{1}{2.5 Y_{eq}(s_f)} + \int_{s_0}^{s_f} ds \frac{M_{Planck}\langle\sigma v\rangle_T}{\sqrt{24\pi\rho}} \tag{8}$$

This solution is called *freeze-out approximation* and as a rule works with $\approx 2\%$ accuracy.

One can make further approximations and discard the first term in the right side of (8). This approximation corresponds to an infinite DM density at T_f and works with $\approx 20\%$ accuracy

$$\frac{1}{Y(s_0)} = \int_{s_0}^{s_f} ds \frac{M_{Planck}\langle\sigma v\rangle_T}{\sqrt{24\pi\rho}} \tag{9}$$

micrOMEGAs uses this to calculate the relative contributions of different channels to Ω^{-1}. It gives an understanding of the physical reactions responsible for relic DM formation.

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6.4. *The Z_3 case.*

The Z_3 internal charge of particles can be zero, 1, or -1, which corresponds to phases $\{0, \frac{2\pi}{3}, \frac{-2\pi}{3}\}$. The lightest particle with non-zero charge has to be stable. Particles with charge -1 are the antiparticles of those with charge 1. Thus, only one DM candidate is expected. We have 2 types of reactions which change the DM density

$$\widetilde{X}, \widetilde{Y} \to SM, SM \quad \widetilde{X}, \widetilde{Y} \to \widetilde{Z}, SM \tag{10}$$

The second type of reactions modify the abundance equation, Eq.(2),

$$\frac{dY}{ds} = \frac{M_{Planck}}{\sqrt{24\pi\rho}}(\langle\sigma v\rangle_T^{11\to00}(Y^2 - Y_{eq}(T)^2) + 0.5\langle\sigma v\rangle_T^{11\to10}Y \cdot (Y - Y_{eq}(T))$$

where $\langle\sigma v\rangle_T^{11\to00}$, $\langle\sigma v\rangle_T^{11\to10}$ define the thermally average cross section for 2 particles with charge ±1 annihilating into particles with charge 0 and into a charge 1 and a charge 0 respectively. The modified abundance equation can be solved by the same method as Eq.(2) and is included in micrOMEGAs. The case of Z_4 discrete symmetry which leads to two stable particles with Z_4 charges $\{1,-1\}$ and $\{2,-2\}$ is not treated in the current version of micrOMEGAs, however see Ref.[11] for an application.

6.5. *The micrOMEGAs routines.*

Ωh^2 can be calculated by the function

    omega= darkOmega(&Xf, fast,Beps);

where *fast* and *Beps* are input parameters. $fast \neq 0$ leads to an optimized fast calculation. The parameter *Besp* allows to change the number of channels taken into account for the evaluation of Ωh^2. The contribution of channels for which the sum of the mass of incoming or outgoing particles, M_s, is large is suppressed by the Boltzmann factor

$$e^{\frac{2M_{cdm}-M_s}{T_f}}$$

where T_f is the freeze-out temperature (7). micrOMEGAs discards all channels for which this factor is smaller then *Beps*. The default value $Beps = 10^{-4}$ leads to a robust evaluation of the relic density. In some special cases, for example, in models with extra dimensions, there are too many co-annihilation channels and it is reasonable to set $Beps = 10^{-2}$ to have a fast calculation. The output parameter

$$X_f = M_{cdm}/T_f$$

characterizes the freeze-out temperature T_f. To get a reasonable value of the DM density, the parameter X_f should be about 25.

The micrOMEGAs package contains two routines which are useful for understanding of relic density formation.

- `printChannels(Xf,cut,Beps,prcnt,FD)`
writes into opened file `FD` the contributions of different channels to $(\Omega h^2)^{-1}$. Here `Xf` is an input parameter which should be first evaluated in `darkOmega`. Only the channels whose relative contribution is larger than `cut` will be displayed. `Beps` plays the same role as the `darkOmega` routine. If $prcnt \neq 0$ the contributions are given in percent. Note that for this specific purpose we use the freeze-out approximation (9).

- `vSigma(T,Beps,fast)`
calculates the thermally averaged cross section for DM annihilation times velocity at a temperature T [GeV], see formula (2.6) in Ref.[33] The value for σ_v is expressed in [pb]. The parameters $Beps$ and $fast$ work in the same way as in the `darkOmega` function. In the Z_3 case, `vSigma` returns

$$\langle \sigma v \rangle_T^{DM,DM->SM,SM} + 0.5 \langle \sigma v \rangle_T^{DM,DM->DM,SM}$$

The micrOMEGAs code contains the obsolete `darkOmegaFO` function which calculates Ωh^2 in freeze-out approximation (8).

6.6. *Example of output*

The output of `darkOmega`, `vSigma` and `printChannels` commands for the MSSM point of section 4.5 is presented below,

```
==== Calculation of relic density =====
Xf=2.65e+01 Omega=1.10e01
Channels which contribute to 1/(omega) more than 1%.
Relative contributions in % are displyed
 29% ~o1 ~l1 >A l
 21% ~l1 ~l1 >l l
  8% ~o1 ~l1 >Z l
  6% ~l1 ~L1 >A A
  4% ~o1 ~o1 >l L
  3% ~o1 ~o1 >m M
  3% ~o1 ~o1 >e E
  3% ~o1 ~eR >A e
```

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```
3% ~o1 ~mR >A m
3% ~l1 ~L1 >A Z
3% ~eR ~l1 >e l
3% ~mR ~l1 >m l
```

One can use the `vSigma` function to study the dependence of $\langle \sigma v \rangle$ on the temperature, see Fig.3.
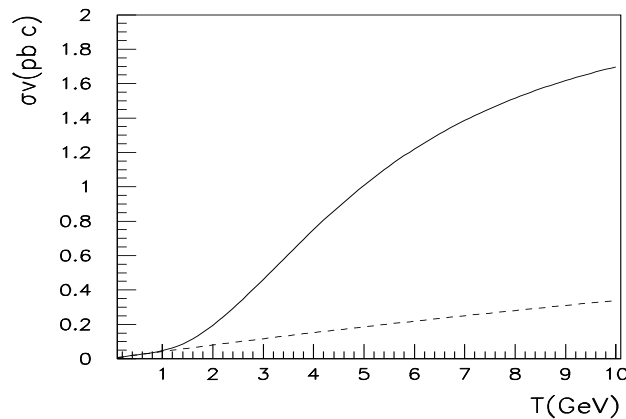

Fig. 3. $\sigma_v(T)$ for the MSSM point of section 4.5 including all coannihilation channes(solid) and the same for only neutralino self-annihilation(dashed).

For this test point, the contribution of DM (the neutralino - `~o1`) self-annihilation to Ω^{-1} is about 10%. The spectrum also contains the *stau* particle (`~l1` - superpartner of τ) which has a large self-annihilation cross section as well as a large annihilation cross section with DM. Furthermore the *stau* has a small mass difference with the DM (≈ 6 GeV). At the freeze-out temperature ($T_f \approx 8$GeV) the *stau* density is hardly suppressed by the Boltzmann factor, therefore this particle give a large contribution to $\langle \sigma_v \rangle_T$. Fig.3 shows that at low temperatures where the *stau* contribution is suppressed, the total cross section is small, but at $T = T_f$ it increases to the [pb] level, this is sufficient to get a reasonable value for the relic density.

7. Dark Matter distribution in Milky Way.

Fluctuations of CMB temperatures provide crucial information about DM in the early Universe before recombination. Other observables are related to DM in the galaxies. To make predictions for these observables, one has to

know the DM density in the region of our Galaxy where the Sun is located as well as the velocity distribution for DM particles. The more impressive evidence of DM is the flatness of galactic rotation curves at large distances r from the galactic center

$$v(r) \approx Const$$

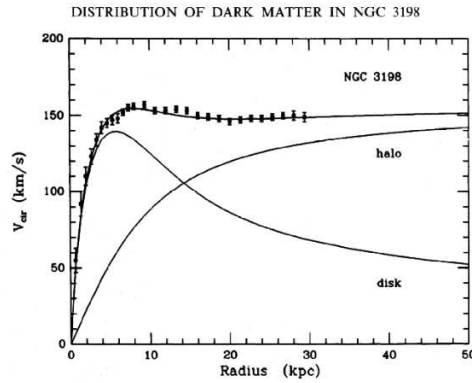which is established from observations of a large set of spiral galaxies. See, for instance, Fig.4.

Fig. 4.   Rotation curve for spiral galaxy NGC 3198.[65]

For the rotation velocity to be constant at all distances, assuming that the DM contribution dominates, the density has to be

$$\rho(r) = \frac{v_{rot}^2}{4\pi G r^2} \quad , \tag{11}$$

where G is the gravitational constant. DM velocity distribution is related to the spatial distribution. In the simplest case one can assume the micro-canonical DM phase space distribution[f]

$$f(E_{tot}/M_{cdm})d^3vd^3x = f(v^2/2 - v_{rot}^2 log(r))d^3vd^3x \quad ,$$

where $v_{rot}^2 log(r)$ is the gravitational potential of unit mass. This phase space distribution has to reproduce the DM density Eq.(11)

$$\int f(v^2/2 - v_{rot}^2 log(r))d^3v = \frac{v_{rot}^2}{4\pi G r^2}$$

[f]In general, the equilibrium phase space distribution could also depend on angular momentum.

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which leads to

$$f(\mathcal{E}) = \frac{exp(-2\mathcal{E}/v_{rot}^2)}{4\pi^{5/2}Gv_{rot}^2}$$

and in particular to the Maxwell isothermal DM velocity distribution

$$\frac{e^{-(v/v_{rot})^2}d^3v}{\pi^{3/2}v_{rot}^3} \tag{12}$$

For remote galaxies, the rotation curve is well measured via the Doppler shift of the 21.1 cm line of hydrogen radiation. For the Milky Way, the rotation curve is not known as well as for other galaxies, see Fig.5
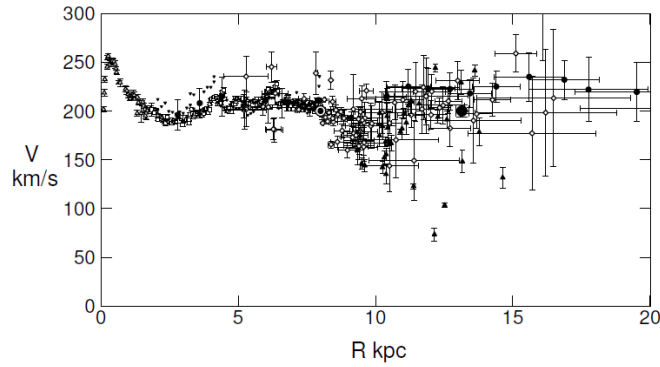

Fig. 5.   Rotation curve for the Milky Way. Compilation of different experiments presented in Ref[66] and normalized for $R_\odot = 8$kps, $v_{rot}(R_\odot = 200$km/s.

The Sun is located at a distance $R_\odot = 8.4 kpc$ from the galactic center, where the rotation curve becomes flat, with[59]

$$v_{rot} \approx 240(10)\text{km/s} \ .$$

For this value of the rotation velocity, Eq.(11) gives an estimation $\rho \approx 0.58 GeV/cm^3$. A more precise estimation of the DM density at the Sun orbit is

$$\rho_\odot = 0.3\text{GeV/cm}^3$$

within a factor $2-3$ uncertainty.[59] Because the Galaxy has a finite gravitational potential, there is some escape velocity corresponding to Sun orbit. Observations of fast stars in the Milky Way give the limits of[59]

$$498\text{km/s} < v_{esc} < 608\text{km/s}.$$

The Maxwell velocity distribution is truncated at v_{esc}.

micrOMEGAs has several global parameters which describe the Dm distribution in the Galaxy, see Tab.1.

Table 1.   Galaxy parameters

Name	default value	units	Symbol	Comment
Rsun	8.5	kpc	$R_{\odot}$	Distance from Sun to center of Galaxy
rhoDM	0.3	GeV/cm^3	$\rho_{\odot}$	Dark Matter density at Rsun
Vesc	600	km/s	v_{esc}	galactic escape velocity
Vearth	225.2	km/s	v_{Earth}	Galaxy velocity of Earth
Vrot	220	km/s	v_{rot}	rotation velocity at Sun orbit

Note: We keep the old recommended 1985 IAU value for v_{rot} because it is used for comparing results of Direct Detection experiments

In general different DM spatial and velocity distributions in the Milky Way are considered and micrOMEGAs can work with any distribution implemented as external functions. But the formulas presented above characterize the DM distribution and contain all important features of distributions used in real calculations of direct and indirect DM signals.

The DM spatial mass density in micrOMEGAs is given as a product of the local density at the Sun orbit with the halo profile function.

$$\rho(r) = \rho_{\odot} F_{halo}(r) \ .$$

By default micrOMEGAs uses the Zhao[67] profile

$$F_{halo}(r) = \left(\frac{R_{\odot}}{r} \right)^{\gamma} \left(\frac{r_c^{\alpha} + R_{\odot}^{\alpha}}{r_c^{\alpha} + r^{\alpha}} \right)^{\frac{\beta - \gamma}{\alpha}}$$

with parameters $\alpha = 1, \beta = 3, \gamma = 1, rc = 20[kpc]$ which corresponds to the NFW[68] profile. These values can be changed by the command

setProfileZhao(α,β,γ,r_c) ,

for example,

setProfileZhao(2,2,0,3.5)

sets isothermal profile with a core.[69] micrOMEGAs can work with any external function that describes a spherically symmetric halo profile. For this, call

setHaloProfile($myHaloProfile$)

with the name of external functions as argument. To restore the default Zhao profile use

setHaloProfiles(hProfileZhao).

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8. Direct Detection in micrOMEGAs.

8.1.   *Amplitudes in the $v = 0$ limit.*

To predict the Direct Detection rate one has to calculate the differential cross section for elastic scattering of a DM particle on atomic nuclei. The velocities of DM particles near the Earth are close to the orbital velocity of the Sun, $v \approx 0.001c$. Since elastic cross sections are finite in the $v \to 0$ limit, we can compute the DM nucleon cross sections in this limit thus simplifying the computation. However the transfer momenta are large as compared with the inverse size of a nucleus, so nuclei elastic form factors have to be taken into account. In the non-relativistic limit the DM-nucleon elastic amplitudes can be divided into two classes, the scalar or spin independent (SI) interaction and the axial-vector or spin dependent (SD) interaction. For a spin 1/2 nucleon interactions corresponding to higher spin exchange will clearly vanish in the zero momentum limit. When the DM particle is not self-conjugate the amplitudes can be further divided in two classes *even* and *odd* with respect to swapping $DM \leftrightarrow \overline{DM}$.

   DM-nucleon amplitudes are related to the DM-quark amplitudes after introducing form factors that describe the quark content of the nucleon. These form factors are different for different quark current. The general scheme for calculating DM nuclei cross sections is the following:

   (i) we expand the DM-quark amplitudes over basic operators in the $v = 0$ limit;
  (ii) using information about nucleon quark form factors we transform DM-quark amplitudes into DM-nucleon amplitudes;
 (iii) we use the nucleon form factors in nuclei to calculate the DM-nuclei differential cross sections.

8.2. *DM-quark operators.*

The independent set of DM-quark operators in the $v = 0$ limit are presented in Tab.2,

   To compute the amplitudes for DM -quark scattering at low energy, micrOMEGAs expands the Lagrangian of the model in terms of local operators and extracts the coefficients of the low energy effective DM quark Lagrangian numerically. To do this we need to add to the model Lagrangian the projection operators defined in Table 1. The interference between one projection operator and the effective vertices will single out either the spin dependent or spin independent contribution, since the effective Lagrangian

Table 2.   Operators for DM(χ) - quark interactions.

	DM Spin	$\hat{\mathcal{O}}_e$ Even operators	$\hat{\mathcal{O}}_o$ Odd operators
SI	0	$2M_\chi \phi_\chi \phi_\chi^* \overline{\psi}_q \psi_q$	$i(\partial_\mu \phi_\chi \phi_\chi^* - \phi_\chi \partial_\mu \phi_\chi^*)\overline{\psi}_q \gamma^\mu \psi_q$
	1/2	$\overline{\psi}_\chi \psi_\chi \overline{\psi}_q \psi_q$	$\overline{\psi}_\chi \gamma_\mu \psi_\chi \overline{\psi}_q \gamma^\mu \psi_q$
	1	$2M_\chi A_{\chi\mu}^* A_\chi^\mu \overline{\psi}_q \psi_q$	$+i\lambda_{q,o}(A_\chi^{*\alpha}\partial_\mu A_{\chi,\alpha} - A_\chi{}^\alpha \partial_\mu - A_{\chi\alpha}^*)$ $\overline{\psi}_q \gamma_\mu \psi_q$
SD	1/2	$\overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_q \gamma_\mu \gamma_5 \psi_q$	$-\frac{1}{2}\overline{\psi}_\chi \sigma_{\mu\nu}\psi_\chi \overline{\psi}_q \sigma^{\mu\nu}\psi_q$
	1	$\sqrt{6}(\partial_\alpha A_{\chi\beta}^* A_{\chi\nu} - A_{\chi\beta}^* \partial_\alpha A_{\chi\nu})$ $\epsilon^{\alpha\beta\nu\mu}\overline{\psi}_q \gamma_5 \gamma_\mu \psi_q$	$i\frac{\sqrt{3}}{2}(A_{\chi\mu}A_{\chi\nu}^* - A_{\chi\mu}^* A_{\chi\nu})\overline{\psi}_q \sigma^{\mu\nu}\psi_q$

is written in an orthogonal basis. The matrix element

$$\langle q(p_1), \chi(p_2)|\hat{S}\hat{\mathcal{O}}_{e,o}|q(p_1), \chi(p_2)\rangle \tag{13}$$

is then evaluated numerically at zero momentum transfer. Here $\hat{S}$ is the S-matrix obtained from the complete Lagrangian at the quark level.

In the general case, there are other operators with higher order derivatives which contribute in the $v = 0$ limit, in particular *twist=2* operators. The contribution of twist=2 operator is however suppressed by a factor $\frac{M_N}{M_{\widetilde{q}}-M_{cdm}}$ where M_N is the nucleon mass, $M_{\widetilde{q}}$ is the mass of the lightest odd particle which couples to DM and quarks. To extract the contribution of twist=2 operators, micrOMEGAs calculates the matrix element (13) for non-zero collision momenta.

8.3. *Nucleon form factors.*

Each operator describing DM-quark interaction is related to a similar operator for DM-nucleon interactions with a coefficient called the *nucleon form factor*. Some of the form factors of light quarks are determined experimentally, other can be obtained by lattice calculations. micrOMEGAs uses global parameters to store the form factors of light quarks thus allowing the user to change them easily. The list of nucleon form factors is presented in Tab.3.

8.3.1. *Even nucleon form factors*

Even form factors give the same contribution to DM and $\overline{DM}$ scattering, they include

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- **Scalar (SI) even form factor for light quarks.** These form factors, f_q^N, which relate quark and nucleon operators are defined by

$$\langle N|m_q\overline{\psi}_q\psi_q|N\rangle = f_q^N M_N \tag{14}$$

where N means nucleon and M_N its mass. The scalar form factor actually counts the contribution of each quark to the nucleon mass. If, for instance, the DM interacts with light quarks via Higgs exchange, then the matrix element will contain a quark mass. This mass will cancel with the quark mass in the scalar form factor so that the final answer will be independent of the quark mass, a quantity which depends strongly on the QCD scale. This also means that despite the very small coupling of light quarks with the Higgs, they give a finite contribution to DM-nucleon scattering.

Scalar form factors are known from hadron spectroscopy, data of πN scattering[70] and lattice calculations of s quark contribution to the nucleon mass. Still there is some uncertainty in the form factors especially for the s-quark contribution.

- **Axial-vector(SD) even form factors.** The axial-vector current $\overline{\psi}_q\gamma_\mu\gamma_5\psi_q$ counts the total spin of quarks and anti-quarks q in the nucleon. The axial-vector interactions in the nucleon are related to those involving quarks, with

$$2s_\mu\Delta q^N = \langle N|\overline{\psi}_q\gamma_\mu\gamma_5\psi_q|N\rangle \tag{15}$$

where s_μ is the nucleon spin. The coefficients Δq^N are extracted from HERMES[71] and COMPASS[72] experiments, they are defined as `pVectorFFPq` in micrOMEGAs, see Tab.3.

- **Form factors for heavy quarks.**

The nucleon consists of light quarks and gluons, nevertheless one can also consider interactions of DM with heavy quarks inside the nucleon. These effectively come into play since heavy quark loops contribute to the interactions of DM with gluons, see for example the diagrams in Fig. 6. Heavy quarks, Q, give a large contribution to the SI amplitude. Their form factor can be calculated in QCD.

When the contribution of the triangle diagram in Fig.6 is dominant one can use the anomaly of the trace of the QCD energy-momentum tensor[73] to calculate the heavy quark form factor. The leading order result is

$$f_Q = \frac{2}{27} \tag{16}$$

which is about twice as large than the form factor of light quarks. If the mass of $\widetilde{q}$, the new particle that couples to the DM and a quark, is not
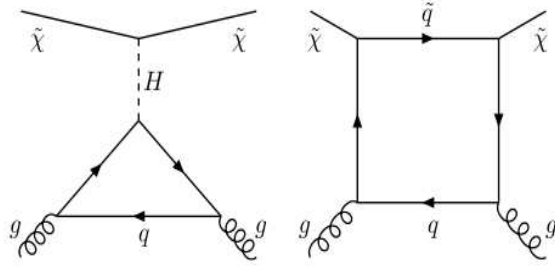
Fig. 6.   Diagrams that contribute to DM-gluon interaction via heavy quark loops

large then this simple formula cannot be used and one has to include the contribution of box diagrams. The box diagrams in the MSSM were computed by Drees&Nojiri.[74] Because QCD interaction is universal these formulas can be used in any model with spin $1/2$ DM and spin 0 $\widetilde{q}$. The contribution of heavy quarks to SD amplitudes is negligible.

Table 3.   Nucleon form factors.

Quark	Even		Odd
	SI	SD	SD
	Proton		
	ScalarFFPq	pVectorFFPq	SigmaFFPq
d	0.0253	-0.427	-0.23
u	0.0205	0.842	0.84
s	0.0277	-0.085	-0.046
	Neutron		
	ScalarFFNq	pVectorFFNq	SigmaFFNq
d	0.0370	0.842	0.84
u	0.0140	-0.427	-0.23
s	0.0277	-0.085	-0.046

Note: Names of global parameters for form factor can be obtained by replacing q with the quark name.

8.3.2. *Odd nucleon form factors*

Odd form factors are needed to calculate the difference between $DM - N$ and $\overline{DM} - N$ amplitudes.

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- **Scalar (SI) odd form factors**. The $\overline{\psi_q}\gamma_\mu\psi_q$ quark current gives rise to scalar interactions. Since the vector current is conserved, the associated nucleon form factor just counts the number of quark minus the number of antiquarks in the nucleon. Thus the $\{u\,,d\}$ quarks have form factors $\{2,1\}$ in proton and $\{1,2\}$ in neutron while the form factor is zero for heavy quarks .

- **Pseudo-vector (SD) odd form factors.** The $\langle N|\overline{\psi}\sigma_{\mu\nu}\psi|N\rangle$ current can be interpreted as the difference between the spin of quarks and the spin of anti-quarks in nucleons. Measurements by COMPASS and HERMES indicate that the antiquark contribution to nucleon spin is compatible with zero. Thus these form factors should be close to the even SD axial-vector form factors. QCD lattice calculations[75,76] confirm this expectation, the lattice results are used as default values for the form factors `SigmaFFPq` listed in Tab.3.

Form factors for twist=2 operators are calculated via parton distribution functions

$$f_q^{twist=2} = \frac{1}{2}\int_0^1 dx\, x f_q^{pdf}(x, Q = M_q)$$

8.4. *Nucleon amplitudes: example.*

In micrOMEGAs the amplitudes for DM-nucleon scattering at rest can be computed using the routine

        `nucleonAmplitudes(qBOX,pAsi,pAsd,nAsi,nAsd)`

where *pAsi, pAsd, nAsi, nAsd* are output parameters which contain proton/neutron SI/SD amplitudes. Each of these parameters is a two dimensional array which contains amplitudes for DM and $\overline{DM}$ scattering. Amplitudes are normalized so that the total cross section for DM-nucleon scattering reads

$$\sigma_{tot} = \frac{4M_{cdm}^2 M_N^2}{\pi(M_{cdm} + M_N)^2}(|pAsi[0]|^2 + 3|pAsd[0]|^2)$$

The parameter `qBOX` specifies the name of the function which calculates the box diagram of Fig.6. The option `qBOX=FeScLoop` includes the calculation of the box diagram with a spin $1/2$ DM and a scalar $\widetilde{q}$ particle. When `qBOX=NULL`, the form factors for heavy quarks (6) with QCD NLO correction are used. This approximation works well when the masses of $\widetilde{q}$ particles included in vertices $DM \cdot q \cdot \widetilde{q}$ are large.

For the MSSM test point of section 4.5 we have

```
//          CODE                              OUTPUT
nucleonAmplitudes(FeScLoop, pA0,pA5,nA0,nA5);   |
printf("CDM-nucleon micrOMEGAs amplitudes:\n"); |CDM-nucleon micrOMEGAs amplitudes:
printf("proton: SI=%.2E SD=%.2E\n",pA0[0],pA5[0]); |proton: SI=-1.33E-09 SD=-1.58E-08
printf("neutron:SI=%.2E SD=%.2E\n",nA0[0],nA5[0]); |neutron:SI=-1.33E-09 SD= 1.98E-08
                                                |
coef=4/M_PI*3.8938E8*pow(Nmass*Mcdm/(Nmass+Mcdm),2);|
printf("CDM-nucleon cross sections[pb]:\n");    |CDM-nucleon cross sections[pb]:
printf(" proton  SI %.3E  SD%.3E\n",            |
    coeff*pA0[0]*pA0[0],3*SCcoeff*pA5[0]*pA5[0]); |proton  SI 2.177E-10  SD 3.223E-07
printf(" neutron SI %.3E  SD %.3E\n",           |
    coeff*nA0[0]*nA0[0],3*SCcoeff*nA5[0]*nA5[0]); |neutron SI 2.696E-10  SD 5.113E-07
```

[A The cross section for SI interactions on protons in this example,

$$\sigma^{SI} \approx 2.2 \cdot 10^{-10}[pb] = 2.2 \cdot 10^{-46}[cm^2]$$

is well below the current Xenon100[15] upper limit $\sigma^{SI} < 2 \cdot 10^{-44}[cm^2]$, but within reach of the next generation of direct detection experiments such as Xenon1T.

8.5. *Dark matter nucleus scattering.*

For zero DM velocity, the cross section for DM-nucleus SI interaction reads

$$\sigma_0^{SI} = \frac{4\mu^2}{\pi} \left(\lambda_p Z + \lambda_n (A - Z)\right)^2 \ , \quad \mu = \frac{M_{cdm} M_A}{M_{cdm} + M_A} \qquad (17)$$

where λ_p, λ_n are amplitudes for DM scattering on nucleons; M_A, Z, A are the nucleus mass, charge, and atomic number respectively. For a small DM velocity, $v \approx 10^{-3}c$, we neglect the dependence on the small momentum transfer in the cross section but include this dependence in the nucleus form factor, the differential cross section is

$$\frac{d\sigma^{SI}}{dE} = \frac{\sigma_0^{SI}}{E_{max}} F_A^2(q) \ , \quad 0 < E < E_{max} = 2 \left(\frac{v^2\mu^2}{M_A}\right) \qquad (18)$$

where E is the nucleus recoil energy and $q = \sqrt{2EM_A}$ the transfer momentum. The form factors $F_A(q)$ are well known from experiments of μ scattering on atomic nuclei. Note that Eq. 18 predicts an A^2 enhancement of the SI cross section at large A. Such enhancement does not occur for SD interactions due to a strong compensation of the proton/neutron spins with the same orbital state.

For SD scattering on nucleus, three form factors are introduced

$$\frac{d\sigma_A^{SD}}{dE} = \frac{16\pi\mu^2}{(2J_A + 1)E_{max}} (S_{00}(q)a_0^2 + S_{01}(q)a_0 a_1 - S_{11}(q)a_1^2) \qquad (19)$$

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where $a_0 = \xi_p + \xi_n$, $a_1 = \xi_p - \xi_n$, ξ_p, ξ_n are proton and neutron SD amplitudes, J_A is a total angular momentum of nucleus. The S_{ij} form factors are obtained by computation. The list of available form factors is presented in the review.[77,78]

8.6. *Calculation of Direct Detection signal in micrOMEGAs.*

The distribution of the number of events over the recoil energy is obtained after integrating Eq. (18, 19) over the DM velocity distribution. In the resulting formulas, the DM local density enters as a total factor. In the micrOMEGAs package this density is a global parameter `rhoDM` whose default value is $0.3 GeV/cm^3$. The recoil energy distribution is calculated by the routine

    nucleusRecoil(f,A,Z,J,Sxx,qBOX,dNdE)

Here the input parameters are

$\diamond$ `f` - the DM velocity distribution normalized such that

$$\int_0^\infty v f(v) dv = 1 \tag{20}$$

   The units are km/s for v and s^2/km^2 for f(v).
$\diamond$ `A` - atomic number of nucleus;
$\diamond$ `Z` - number of protons in the nucleus;
$\diamond$ `J` - nucleus spin;
$\diamond$ `Sxx` - routine which calculates SD nucleus form factors, Eq.(19), for spin-dependent interactions.
$\diamond$ `qBOX` - a parameter needed by `nucleonAmplitudes`, see the description above.

The micrOMEGAs package contains the predefined constants $Z\_\{Name\}$, $J\_\{Name\}\{atomic\_number\}$ for the electric charges and spins for a large set of isotopes, for instance, `Z_Xe`, `J_Xe129`, `J_Xe131`. Furthermore all SD form factors presented in the Review[77,78] are included. Their generic name is $Sxx\_\{Name\}\{atomic\_number\}$, for instance `SxxXe129`. The isotopes whose charges, spins and form factors are included in micrOMEGAs are

`F19 Na23 Na23A Al27 Si29 K39 Ge73 Ge73A Nb92 Te125 I127 Xe129 Xe131`

For the velocity distribution, the user can substitute any function. The

default function included in micrOMEGAs is

$$\text{Maxwell(v)} = \frac{c_{\text{norm}}}{\text{v}} \int\limits_{|\vec{v}|<v_{esc}} d^3\vec{v} \exp\left(-\frac{(\vec{v}-V_{Earth})^2}{v_{rot}^2}\right) \delta(\text{v}-|\vec{v}|)$$

which corresponds to the velocity distribution of the isothermal model. Here V_{Earth}, v_{rot}, and v_{esc} a global parameter presented in Tab.1.

nucleusRecoil returns the total number of events per day and per kilogram of detector material. In general the result is averaged over DM and $\overline{DM}$. The energy spectrum of recoil nuclei is stored in dNdE array which contains 200 elements. The value in the ith element corresponds to

$$dNdE[i] = \frac{dN}{dE}|_{E=i*keV}$$

in units of (1/keV/kg/day). The recoil energy distribution can be displayed on the screen with

       displayRecoilPlot(dNdE,title,E1,E2)
where title is a character string specifying the title of the plot and E1,E2 are minimal and maximal values for the displayed energy in keV. The function

       cutRecoilResult(dNdE,E1,E2) calculates the number of events in an energy interval defined by the values E1,E2 in keV, each experiment normally gives an energy interval for their result.

8.7. *Example.*

For the MSSM test point of section 4.5, to obtain the recoil energy corresponding to the Xenon100 experiment, we call

```
double E1=8.4 /*KeV*/, E2=44.6/*KeV*/, Exposure=1471/*day*kg*/;
double nEvents, dNdE[200]; /* output */
int i;
nucleusRecoil(Maxwell,131,Z_Xe,J_Xe131,SxxXe131,FeScLoop,dNdE);
nEvent=Exposur*cutRecoilResult(dNdE,E1,E2);
printf("Expected number of events %.2E\n",nEvents);
for(i=0;i<200;i++) dNdE[i]*=Exposure;
displayRecoilPlot(dNdE,"Recoil energy distribution for Xe",E1,E2);
```

The number of events given in output is 0.07, this means that this point can be tested by XENON if one increases the exposure by roughly a factor 50, in agreement with the estimate obtained in section 8.4. The resulting distribution is displayed in Fig.7. Here we see that the number of events

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decrease rapidly with the recoil energy. This is due to the nucleus form factor and to the DM velocity distribution.
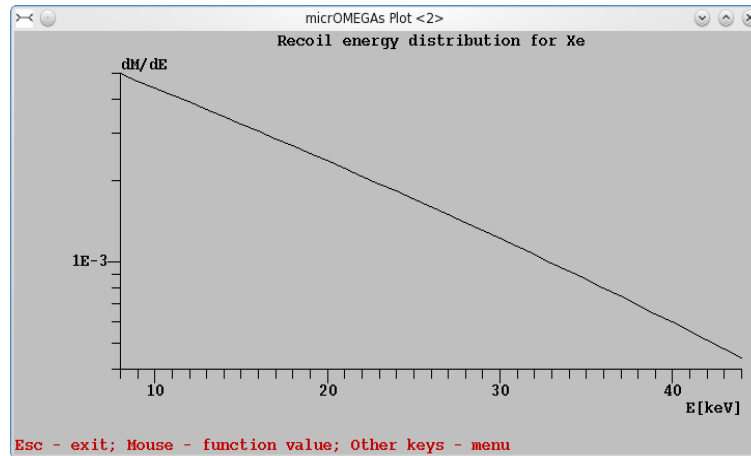

Fig. 7.   Recoil energy distribution for neutralino-Xenon collisions.

8.8. *Nuclei event rates for arbitrary DM-nucleon cross-sections.*

The function
$$\text{nucleusRecoilAux(f,A,Z,J,Sxx,csIp,csIn,csDp,csDn,dNdE)}$$
is similar to nucleusRecoil except that csIp(csIn), the SI cross sections for DM scattering on protons(neutrons) and csDp(csDn), the SD cross sections on protons(neutrons) are specified as input parameters (in pb units). A negative value for one of these cross sections is interpreted as a destructive interference between the proton and the neutron amplitudes. Note that the rate of recoil energy depends implicitly on the Mcdm and rhoDM parameters.

The etc/ subdirectory contains the *DD_ALL.c* program which can be compiled by the standard procedure
$$\text{make main=DD\_ALL.c}$$
giving the executable DD_ALL which needs the following command line arguments
$$\text{./DD\_ALL   Mcdm   csSIp   csSIn   csSDp csSDn}$$
This call writes the prediction for DM detection in DAMA_NAI, Xenon,

CDMS, CoGent and COUPP. Some experimental input data used in this program (exposures, energy cuts, efficiency) can be obsolete. The user can improve this code easily to take into account new experimental data.

9. Neutrino signals of DM captured by Sun and Earth.

9.1. *Neutrino fluxes*

Dark Matter particles captured by the Sun/Earth accumulate in the center of the Sun/Earth and annihilate into standard model particles. The neutrinos that escape the Sun/Earth can then be detected. When the capture and annihilation rates reach an equilibrium (we assume that equilibrium can be reached within the lifetime of the Sun/Earth), the rate of DM annihilation is defined by the capture rate. This rate depends on the cross sections for elastic scattering of DM on nuclei in the Sun/Earth. The larger the atomic weight, the larger the DM energy loss. Knowing the chemical contents of the Sun/Earth is important for the calculation of the capture rate. The $DM(\overline{DM})$ capture rates C_χ ($C_{\bar{\chi}}$) depend also on the DM density and velocity distribution at the Sun galactic orbit. To calculate the capture rate we use the simplified formula found in the review of Jungman *et.al.*[40]

$$C_\chi = 4.8 \times 10^{28}\,\mathrm{s}^{-1}\left(\frac{\rho_\chi}{0.3\,\mathrm{GeV/cm^3}}\right)\left(\frac{270\,\mathrm{km/s}}{\bar{v}}\right)$$
$$\times \sum_i \left(\frac{\sigma_{\chi i}}{pb}\right)\frac{f_i\phi_i}{m_\chi m_{N_i}}F_i(m_\chi)S(m_\chi/m_{N_i})$$

where m_{N_i}, the mass of the nuclear specie i, and m_χ are given in GeV. $\bar{v}$ is the DM velocity dispersion, f_i is the mass fraction of element i in the Sun, and ϕ_i its distribution. $F_i(m)$ is a form factor suppression and S a kinetic suppression factor.

Let $\Gamma_{\chi\chi}$, $\Gamma_{\bar{\chi}\bar{\chi}}$ and $\Gamma_{\chi\bar{\chi}}$ be the annihilation rates for $DM(\overline{DM})$ processes in the Sun/Earth and $N_\chi/N_{\bar{\chi}}$ the $DM/\overline{DM}$ densities in the Sun/Earth. For a self-conjugate DM,

$$C_\chi = 2\Gamma_{\chi\chi},$$

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while in general we have the following equations

$$C_\chi = 2\Gamma_{\chi\chi} + \Gamma_{\chi\bar{\chi}}$$

$$C_{\bar{\chi}} = 2\Gamma_{\bar{\chi}\bar{\chi}} + \Gamma_{\chi\bar{\chi}}$$

$$\frac{\Gamma_{\chi\chi}}{\Gamma_{\bar{\chi}\bar{\chi}}} = \frac{\langle\sigma_v^{\chi\chi}\rangle}{\langle\sigma_v^{\bar{\chi}\bar{\chi}}\rangle}\left(\frac{N_\chi}{N_{\bar{\chi}}}\right)^2$$

$$\frac{\Gamma_{\chi\chi}}{\Gamma_{\chi\bar{\chi}}} = \frac{\langle\sigma_v^{\chi\chi}\rangle/2}{\langle\sigma_v^{\chi\bar{\chi}}\rangle}\left(\frac{N_\chi}{N_{\bar{\chi}}}\right)$$

which can be solved to obtain the annihilation rates $\Gamma_{\chi\chi}$, $\Gamma_{\bar{\chi}\bar{\chi}}$, $\Gamma_{\chi\bar{\chi}}$.

The neutrino spectrum that result from DM annihilation inside the Sun is different from annihilation in the vacuum because some long-lived particles can interact with the Sun medium before decaying. Furthermore the neutrino spectrum is deformed by attenuation and oscillation processes that occur during propagation inside the Sun/Earth. In Ref[79] all these factors where taken into account and the neutrino spectra after propagation were tabulated for different DM masses. To get the neutrino flux at the surface of the Earth micrOMEGAs calculates for each SM final state the relative contribution of the $\chi\chi \to SMSM$ channel and multiplies this by the annihilation rate $\Gamma_{\chi\chi}$ and the tabulated neutrino spectra functions[79] prepared for this channel for the relevant M_{cdm}.

        neutrinoFlux(forSun,nu_flux, Nu_flux)

calculates ν_μ and $\nu_{\bar{\mu}}$ fluxes close to the Earth surface. If forSun==0 then the flux of neutrinos from the Earth is calculated, otherwise this function computes the flux of neutrinos from the Sun. The velocity distribution is assumed to be Maxwellian and its parameters can be changed by SetfMaxwell function. The calculated fluxes are stored in nu_flux, Nu_flux arrays of dimension NZ=250. For neutrino fluxes we use units [1/Year/km^2].

9.2. *micrOMEGAs tools to work with particle spectra.*

Various particle spectra and fluxes relevant to neutrino signals and to indirect detection ones (see next section) are stored in arrays with **NZ=250** elements. The ith element of an array corresponds to dN/dz_i where $z_i = log(E_i/Mcdm)$[g]. Spectra interpolation can be done by one of the two functions

        zInterp(z,flux) which returns d(flux)/dz and
        SpectdNdE(E,flux) which returns d(flux)/dE[GeV]

---

[g]The z_i grid can be obtained with the function $Zi(i)$.

where `flux` means the array where tabulated data are stored. To display the function on the screen one can use

```
displaySpectrum(flux,title,Emin,Emax,Units) ,
```

where `title` is a text string which gives a title to the plot. `Emin` and `Emax` define plot limits. If `Units=0` the flux is displayed as a function of $z_{10} = log_{10}(E/\text{Mcdm})$ otherwise one gets the dN/dE plot as a function of the energy `E` in GeV units.

The integrated spectra/fluxes can be obtained by

`spectrInfo(Xmin,flux,&Ntot,&Xtot)` where $X_{min} = E_{min}/M_{cdm}$

and

$$N_{tot} = \int_{X_{min}}^{1} \frac{d(flux)}{dx} dx$$

$$X_{tot} = \int_{X_{min}}^{1} x \frac{d(flux)}{dx} dx$$

.

9.3. *Muon fluxes*

A detector measures the muon flux that results from interactions of neutrinos with rocks below the detector or water within the detector. The routines which calculate such μ fluxes are based on the formulas of Ref.[80]

```
muonUpward(nu_flux,Nu_flux, mu)
```

calculates the muon flux which result from interactions of neutrinos with rocks. Here `nu_flux` and `Nu_flux` are input parameters which designate the neutrino/anti-neutrino fluxes calculated by `neutrinoFlux`. `mu` is an array which stores the sum of μ^+ and μ^- fluxes.

`muonContained(nu,Nu,rho, mu)` calculates the flux of muon which are produced in a given (detector) volume. It has the same parameters as the function for the calculation of upward events. `rho` is the density of detector material in g/cm^3 units. For instance, `rho=1` for water. The array `mu` gives the muon flux in `1/Year/`km^3 units representing the number of neutrinos converted to muons in a km^3 volume.

9.4. *Example*

As an example we calculate the muon flux for the CMSSM with parameters

$M_0 = 3200,\ M_{1/2} = 315,\ A_0 = 0,\ \tan\beta = 10,\ sign(\mu) = 1,\ M_{top} = 173.2;$

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The commands

```
double nu_flux[NZ],Nu_flux[NZ],mu_flux[NZ];
double Ntot, Emin=1;
neutrinoFlux(1/* for Sun*/,nu_flux, Nu_flux);
neutrinoUpward(nu_flax,Nu_flux, mu_flux);
displaySpectrum(mu,"Upward muons[1/Year/km^2/GeV]",Emin,Mcdm/2,1);
spectrInfo(Emin/Mcdm,mu, &Ntot,NULL);
printf("Upward muon flux for   1GeV threshold %.2E /Year/km^2\n",Ntot);
spectrInfo(50/*GeV*//Mcdm,mu, &Ntot,NULL);
printf("Upward muon flux for  50GeV threshold %.2E /Year/km^2\n",Ntot);
```

will generate the muon spectrum displayed in Fig.8. and print integrated flux in 1/Year/km^2 units

```
Upward muon flux for   1GeV threshold=2.50E+03
Upward muon flux for  50GeV threshold=2.51E+02
```
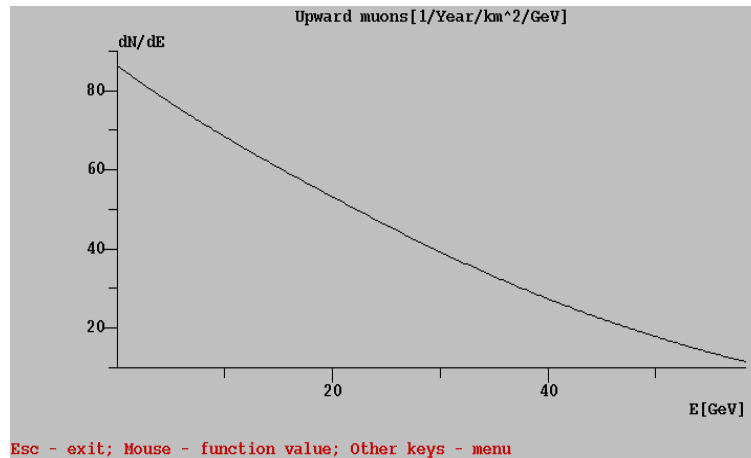

Fig. 8.   Solar muon flux.

10. Indirect Detection in micrOMEGAs

10.1. *Initial annihilation spectra.*

Should primordial self-annihilations take place in the early Universe, the same process would take place nowadays in the denser regions of the Galac-

tic DM halo. DM annihilation in the Galactic halo produces pairs of Standard Model particles that hadronize and decay into stable particles. The final states with γ, e^+, $\bar{p}$, and ν_μ are particularly interesting as they are the subject of indirect searches. The production rate of particles from DM annihilation at location $\mathbf{x}$ reads

$$Q_a(\mathbf{x}, E) \;\; = \;\; \frac{1}{2}\langle\sigma v\rangle\frac{\langle\rho(\mathbf{x})^2\rangle}{M_{cdm}^2}f_a(E) \;\; , \tag{21}$$

where $\langle\sigma v\rangle$ is the annihilation cross-section times the relative velocity of incoming DM particles which we evaluate in the limit $v = 0$ (this is a good approximation since $v = 10^{-3}c$). Note that $\langle\sigma v\rangle$ includes averaging over incoming particles/antiparticles. Thus, for a Dirac DM particle χ for which $\sigma_{\chi\chi} = 0$, $\langle\sigma v\rangle = 1/2\langle\sigma_{\chi\bar{\chi}}v\rangle$. $\rho(\mathbf{x})$ is the DM mass density at the location $\mathbf{x}$ and $f_a(E) = dN_a/dE$ is the energy distribution of the particle a produced in one reaction. micrOMEGAs first calculates the cross sections for all basic processes with two body final states. The tabulated fragmentation functions obtained by Pythia are then used to generate spectra for each final stable particle. The routine to compute the spectra f_a and $\langle\sigma v\rangle$ is

```
calcSpectrum(key,Sg,Se,Sp,Sne,Snm,Snl,&err)
```

which returns $\langle\sigma v\rangle$ in cm^3/s units. The calculated spectra for γ, e^+, $\bar{p}$, and neutrinos, are stored in arrays `Sg`, `Se`, `Sp`, `Sne`, `Snm`, `Snl` of dimension **NZ**(See section 9.2). Note that the spectra of particles and anti-particles are identical. **key** is a switch, depending on its value micrOMEGAs

1 takes into account the polarization of W,Z bosons. It can be important for MSSM-like models where W,Z are transversely polarized;
2 calculates $2 \to 2 + \gamma$ processes to improve spectrum of high energy photons.
4 prints on the screen the calculated cross sections.

More than one option can be switched on simultaneously by adding the corresponding values for `key`. A problem in the spectrum calculation will produce a non zero error code, $err \neq 0$.

The annihilation processes $DM, \overline{DM} \to 2\gamma$ and $DM, \overline{DM} \to \gamma, Z$ are loop suppressed but lead to a very distinctive signature, a monochromatic gamma-ray line. micrOMEGAs can calculate the corresponding cross section only for specific models, for example the MSSM. The routine to do this is

```
loopGamma(&vcs_gz,&vcs_gg)
```
which calculates $\langle\sigma v\rangle$ for $\gamma\gamma$ and γZ processes in cm^3/s units.

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10.2. *Propagation of photons and neutrinos*

The flux of photons (neutrinos) can be evaluated as

$$\Phi_\gamma(E, \phi) = \frac{\langle \sigma v \rangle}{M_{cdm}^2} f_\gamma(E) H(\phi) \tag{22}$$

where the factor H includes the integral over the line of sight,

$$H(\phi) = \frac{1}{8\pi} \int_0^\infty dr \overline{\rho^2} \left(\sqrt{r^2 + r_\odot^2 - 2rr_\odot \cos\phi} \right) \tag{23}$$

and ϕ is the angle in the direction of observation. This flux can be calculated by the routine

```
gammaFluxTab(fi,dfi,sigmav,Sg,Sobs)
```

where `fi` is the angle between the line of sight and the center of the galaxy, `dfi` is half the cone angle which characterizes the detector resolution (the solid angle is $2\pi(1 - cos(\text{dfi}))$, `sigmav` and `Sg` are the annihilation cross section and the photon spectrum calculated previously by `calcSpectrum`. `Sobs` is the flux observed in $[(cm^2 s)^{-1}]$ units.

Note that the neutrino spectra obtained by `calcSpectrum` do not take into account neutrino oscillation. One expects the muon neutrino flux at the Earth

$$f_{\nu_\mu}^{Earth} = 0.22 f_{\nu_e}^0 + 0.39(f_{\nu_\mu}^0 + f_{\nu_\tau}^0) \ ,$$

where numerical coefficients are defined by neutrino flavour mixing[29] and f_ν^0 fluxes are calculated by `calcSpectrum`.

10.3. *Propagation of charged particles*

The propagation of charged particles depends on the structure of the galactic magnetic field and is characterized by the diffusion equations. We assume that the region of diffusion of cosmic rays is represented by a thick disk of thickness $2L$ and radius $R \approx 20$ kpc, with a thin galactic disk in the middle of the thick disk. The parameters entering this equation are not well known, but they are constrained by observations of the B/C ratio in cosmic rays.[81] Table 4 lists the default values for the propagation parameters, together with the MIN/MAX variations which are compatible with the B/C observations.

The energy spectrum of positrons is obtained by solving the diffusion-loss equation keeping only the two dominant contributions: space diffusion and energy losses,

$$-\nabla \cdot (K(E)\nabla\psi_{e^+}) - \frac{\partial}{\partial E}(b(E)\psi_{e^+}) = Q_{e^+}(\mathbf{x}, E) \tag{24}$$

Table 4.   Global parameters of micrOMEGAs responsible for propagation of charged particles.

Name	MIN	MED Default	MAX	Units	Comments
Rdisk	20	20	20	kpc	Radius of the galactic diffusion disk, R
K_dif	0.0016	0.0112	0.0765	$\frac{kpc^2}{Myr}$	Diffusion coefficient K_0
L_dif	1	4	15	kpc	Half height of the galactic diffusion zone L
Delta_dif	0.85	0.7	0.46		Slope of diffusion coefficient, δ
Tau_dif	10^{16}	10^{16}	10^{16}	s	Positron energy loss, τ_E
Vc_dif	13.5	12	5	km/s	Convective velocity of galactic vind , V_C

Here

$$K(E) = K_0 \beta(E) \left(\mathcal{R}/1 \text{ GV} \right)^{\delta}$$

where β is the particle velocity and $\mathcal{R} = p/q$ its rigidity. The positron loss rate $b(E)$ is dominated by synchrotron radiation in the galactic magnetic field and inverse Compton scattering on stellar light and CMB photons,

$$b(E) = \frac{E^2}{E_0 \tau_E} \tag{25}$$

where $\tau_E = 10^{16}$ s is the typical energy loss time. Subdominant contributions from diffusive reacceleration and galactic convection were shown to have an impact only below a few GeV's and are not included in our treatment. The function

        posiFluxTab(Emin,sigmav,Se,Sobs)

computes the positron flux at the Earth. Here `sigmav` and `Se` are values obtained by `calcSpectrum`. `Sobs` is the positron spectrum after propagation in units $(\text{s cm}^2\text{sr})^{-1}$). `Emin` is the energy cut to be defined by the user. Note that a low value for `Emin` increases the computation time.

The energy spectrum of antiprotons is obtained by solving the diffusion equation

$$\left[-K(E)\nabla^2 + V_c \frac{\partial}{\partial z} + 2(V_c + h\Gamma_{tot}(E))\delta(z) \right] \psi_{\bar{p}}(E, r, z) = Q_{\bar{p}}(\mathbf{x}, E) \tag{26}$$

An important difference with the positron case is that energy loss of antiprotons is negligible, while the convective galactic wind and annihilation of anti-protons in the interstellar medium should be taken into account. The function

        pbarFluxTab(Emin,sigmav, Sp, Sobs) computes the antiproton

flux and works like `posiFluxTab`.

The spectra calculated above are interstellar ones. The spectra measured close to the Earth can be calculated by

```
solarModulation(Phi, mass, stellarTab, earthTab)
```

Here `Phi` is the effective Fisk potential in MeV, `mass` is the particle mass, `stellarTab` describes the interstellar flux, `earthTab` is the calculated particle flux at the Earth orbit.

10.4. *Example*

Recent PAMELA[82] results on the antiproton flux are in good agreement with background calculations.[83] It means that antiprotons are mainly produced by collision of protons[h] with the interstellar gas. micrOMEGAs has a routine which provides the interstellar antiproton flux tabulated in Ref[84]

```
pBarBackgroundTab(pBarBgTab) .
```

In order to compare this flux with PAMELA, one has first to apply the `solarModulation` routine.

The antiproton flux resulting from DM annihilation in the MSSM is generally small unless one assumes a large clump factor. Thus the MSSM generally agree with the PAMELA antiproton data. As an example of a model that leads to a large antiproton flux, we consider the IDM point presented in section 3.5. This point corresponds to $\Omega h^2 = 0.102$ and gives a nucleon cross section $\sigma = 1.4 \cdot 10^{-45} \text{cm}^2$ compatible with direct detection experiments. This point also features a DM mass which very slightly exceeds the half of Higgs mass. Thus, the annihilation cross section at rest (in the galactic halo) which is enhanced by the exchange of a Higgs near resonance, is much larger than the annihilation cross section at freeze-out temperatures, see Fig.9. The resulting antiproton flux for two sets of propagation parameters is displayed in Fig.10. With the MED parameters, the antiproton flux is excluded by PAMELA results.

Below we present the list of micrOMEGAs commands which generate the data for the fluxes displayed in Fig.10

```
pBarBackgroundTab(BG);
solarModulation(560,1, BG,BG);
displaySpectrum(BG,"Background",Emin,Mcdm/2,1);
sigmaV=calcSpectrum(4,SpA,SpE,SpP,SpNe,SpNm,SpNl,&err);
pbarFluxTab(Emin, sigmaV, SpP,FluxP);
solarModulation(560,1, FluxP,FluxP);
```

---

[h]Proton spectrum is about four order of magnitudes exceeds the antiproton one.
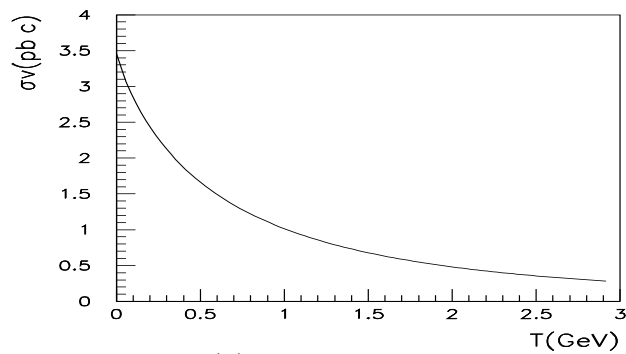
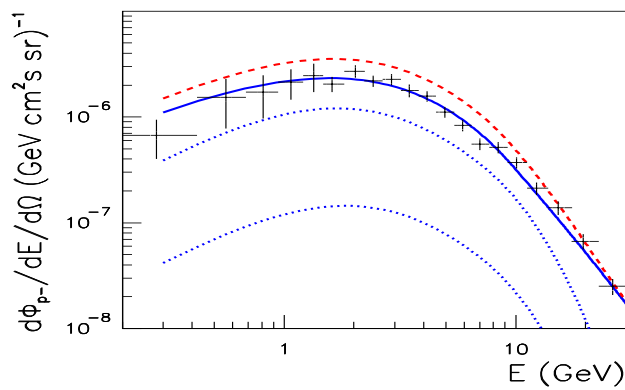Fig. 9. $\sigma_v(T)$ for the sample IDM point of section 4.3

Fig. 10.   Differential flux of anti-protons in the IDM model point of section 3.5 assuming MIN (lower dot) and MED (upper dot) propagation parameters as compared to the background only (full line) and to the measurement of PAMELA (crosses). The signal plus background for MED parameters is also displayed (dash).

```
displaySpectrum(FluxP,"antiproton flux(MED)" ,Emin,Mcdm/2,1);
K_dif=0.0016; L_dif=1; Delta_dif=0.85; Vc_dif=13.5;
  Rdisk=20; // MIN parameters
pbarFluxTab(Emin, sigmaV, SpP,FluxP);
solarModulation(560,1, FluxP,FluxP);
displaySpectrum(FluxP,"antiproton flux(MIN",Emin,Mcdm/2,1);
```

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11. Calculation of cross sections in micrOMEGAs.

The functions presented in this section are activated in micrOMEGAs template files *main.c[F]* by uncommenting the instruction

```
#define CROSS_SECTIONS
```
micrOMEGAS uses the function
```
numout*cc=newProcess(ProcessName);
```
for generating codes of matrix elements for processes defined by the textual variable *ProcessesName*. `numout` is a special type to store process code and auxiliary information. The variable `cc` contains the computer address of the corresponding code. For instance
```
cc = newProcess("e,E->2*x");
```
returns a code for the matrix elements of all processes with e^+e^- annihilation into two arbitrary particles. `newProcess` can generate the code for processes with more than two particles in the final state, however the current version of micrOMEGAs contains integration tools only for $2 \rightarrow 2$ processes. The function:
```
cs22(cc,L,Pcm,cos_min,cos_max,&err);
```
calculates the cross section for L^{th} subprocess where

`Pcm` - momentum in center of Mass reference frame;
`cos_min`, `cos_max` - cuts for cosine of scattering angle in the same frame;
L numerates subprocesses. $1 \leq L \leq ntot$, the total number of subprocess.

The number of the subprocess as well as the numbers of incoming (nin) and outgoing ($nout$) particles for the compiled set of processes cc can be obtained by
```
procInfo1(cc,&ntot,&nin,&nout)
```

The names of incoming/outgoing particles of a given process and their masses can be obtained by the function
```
procInfo2(cc,L,Names,Masses);
```
where the variable `char**Names` is an output parameter used for the array of particle names, and the variable `double*Masses` is an array of numerical values for masses.

For proton-[anti]proton collisions we have to apply convolution of matrix element with structure functions and perform summation over all types on incoming partons. This calculation can be performed with the function
```
hCollider( Pcm, pp, scale,  pName1, pName2)
```
which compiles the needed matrix elements and calculates the cross section for production of two heavy particles at a hadron collider. Here *Pcm*

is the beam energy in the center-of-mass frame. If $pp > 0$ then proton-proton collision is considered, otherwise a proton-antiproton collision. If `scale=0` the largest mass of outgoing particles is used to set the QCD scale. It is well known that tree level calculations with such scale for *squarks* and *gluinos* production (in the MSSM) need a *K-factor* about 1.5. If `scale!=0` micrOMEGAs decreases the QCD scale to simulate loop corrections. `hCollider` uses the CTEQ6L set of parton distributions. The return value is the cross section in [`pb`] units.

For example, for the MSSM test point of section 4.5 a call of

```
hCollider(3500.,1 ,1, "~uL","~UL" );
```

gives the production cross section for super-partners of left-handed u-quark of 0.0082pb at the LHC. The total cross section for all channels which contain *squarks* and *gluinos* gives 0.113pb. Note that this point has recently been excluded by SUSY searches in the jets plus missing E_T channel by ATLAS and CMS.

12. Calculation of particle widths in micrOMEGAs.

The functions presented in this section are activated in micrOMEGAs template *main.c[F]* files with the instruction

```
#define DECAYS
```

Calculation of particle widths and decay branchings in micrOMEGAs can be done by the functions

`pWidth( pName, &L)` where *pName* is name of particle and `txtList L;` is a variable of special type intended to store list of decay channels.

`findBr(txtList L, pattern)` allows to find the branching ratio of a specific channel. Here *pattern* is a text variable which contains a list of decay particles separated by commas. If two particle decays are kinematically forbidden, micrOMEGAs automatically calculates 3-body decays.

The list of decay channels can be printed with the function

```
printTxtList(txtList*L,FILE*f)
```

Example:

```
          CODE                       |      OUTPUT
txtList L;                           |
double width;                        |
width=pWidth("l",&L); // tau lepton  |
printf("tau width=%.3E[GeV]\n",width); |  tau width=2.052E-12[Gev]
```

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```
printf( "Branchings:\n");                  |  Branchings:
printTxtList(L,stdout);                     |  5.998536E-01 l-> nl,U,d
                                            |  2.000733E-01 l-> m,Nm,nl
                                            |  2.000733E-01 l-> e,Ne,nl
printf("Br(e,Ne,nl)=%E\n",findBr(L,         |
      "nl,Ne,e"));                          |  Br(e,Ne,nl)= 2.000733E-01
```

13.   Implementation of new models in micrOMEGAs

To implement new models in micrOMEGAs the user has to

(i) create the model file structure presented in section 3.1 for the MSSM. It can be done by one command launched in micrOMEGAs root directory
   ./newProject *myDarkMatter*
It creates the directory *myDarkMatter* with all needed subdirectories.

(ii) put CalcHEP model files into subdirectory
   myDarkMatter/work/models/.
Recall that the names of odd sector particles have to started with the \~ symbol.

(iii) Launch ./calchep in myDarkMatter/ directory and use the *Check Models* menu line to test the model. In case CalcHEP returns an error message all mistakes should be corrected before starting the micrOMEGAs session.

(iv) If the model constraints or user's files *main.c*, *main.F* need external functions, then the codes for these functions has to be put in the lib/ subdirectory. The file lib/Makefile should compile them and create the library *aLib.a*. The default Makefile will work properly only if your functions are written in *C*. In general, the default Makefile has to be adapted.

(v) Write function prototypes of *C* and/or *Fortran* functions in lib/pmodel.h and lib/pmodel.fh to use them subsequently in *main.c* and *main.F*.

(vi) Create an input file with the values of the free parameters of the model.

General tools are available to make it easier to generate model files. The LanHEP,[43] FeynRules[44] and SARAH[85] packages allow automatic generation of model files in CalcHEP format. The former will be described briefly below as it was used to generate micrOMEGAs model files. Furthermore the SLHAplus package facilitates the implementation of complicated models.

13.1. *The SLHAplus package.*

In several models of elementary particles we have noticeable loop corrections to particle masses. There are several packages which allow to perform such calculations for MSSM-like models: Isajet, SoftSusy,[86] Spheno,[87] SuSpect,[88] NMSSMTools[51] [i] . There is an agreement to pass the calculated particles spectra and mixing matrices via text file in a special format SLHA.[47,48] CalcHEP/micrOMEGAs contain the package *SLHAplus*[89] intended for reading SLHA files. An SLHA file also can contain information about particle widths and decays channels. If such information is downloaded, CalcHEP/micrOMEGAs will use the downloaded values for particle widths instead of its automatic calculation. Below is an example of a SLHA file record and of the SLHAplus instructions to read them

```
          File records                     SLHAPlus reading

BLOCK STOPmix # stop mixing matrix
1 1 5.37975095e-01 # O_{11}        Zt11=slhaVal("STOPmix",MZ,2,1,1);
1 2 8.42960733e-01 # O_{12}        Zt12=slhaVal("STOPmix",MZ,2,1,2);
2 1 8.42960733e-01 # O_{21}        Zt21=slhaVal("STOPmix",MZ,2,2,1);
2 2 -5.37975095e-01 # O_{22}       Zt22=slhaVal("STOPmix",MZ,2,2,2);
```

Here the first argument of slhaVal is the name of *block*, the second one is the *scale* parameter (in this example the scale parameter is not specified in BLOCK), the third parameter fixes the number of *key* parameters, the key parameters themselves follow.

Another important option of the *SLHAplus* package is a tool for diagonalizing mass matrices which occur in models with complicated multiplet structure.

13.2. *Generation of model files by LanHEP.*

The LanHEP[43] package allows automatic generation of CalcHEP model files. It starts from model definition in terms of particle multiplets and performs substitution of physical particle fields in multiplets. LanHEP also checks at the symbolic level the absence of linear terms and at the numerical level the absence of off-diagonal terms in the quadratic part of Lagrangian. Also LanHEP compares diagonal quadratic terms with declared particle masses. Using LanHEP allows to avoid a large number of mistakes which could appear in the derivation of Feynman rules by hand.

---

[i]SuSpect and NMSSMTools packages are included in micrOMEGAs

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We present here part of a LanHEP input file for the IDM model describing only new particles and new interactions beyond the Standard Model.

```
parameter MHX=111,MH3=222,MHC=333.  % Declaration of new masses
parameter laL=0.01, la2=0.01.        % Declaration of new couplings

%mu^2 as a function of masses
parameter mu2=MHX**2-laL*(2*MW/EE*SW)**2.
% constraints for couplings
parameter la3=2*(MHC**2-mu2)/(2*MW/EE*SW)**2.
parameter la5=(MHX**2-MH3**2)/(2*MW/EE*SW)**2.
parameter la4=2*laL-la3-la5.
% Declaration of new particles
scalar '~H3'/'~H3':('odd Higgs',pdg 36, mass MH3, width wH3 = auto).
scalar '~H+'/'~H-':('Charged Higgs',pdg 37,mass MHC,width wHC=auto).
scalar '~X'/'~X':('second Higgs',pdg 35,mass MHX,width wHX=auto).
% second Higgs doublet
let h2 = { -i*'~H+',  ('~X'+i*'~H3')/Sqrt2 },
    H2 = {  i*'~H-',  ('~X'-i*'~H3')/Sqrt2 }.
% covariant derivative.
% Here B1 -U(1)  gauge field,
% WW={W-,W3,W+} SU(2) triplet
let Dh2^mu^a = (deriv^mu+i*g1/2*B1^mu)*h2^a +
        i*g/2*taupm^a^b^c*WW^mu^c*h2^b.
let DH2^mu^a = (deriv^mu-i*g1/2*B1^mu)*H2^a
        -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*H2^b.


lterm DH2*Dh2.                     % Kinematic and other terms.
% Below  h1 is standard Higgs doublet.
lterm -mu2*h2*H2.
lterm -la2*(h2*H2)**2.
lterm -la3*(h1*H1)*(h2*H2).
lterm -la4*(h1*H2)*(H1*h2).
lterm -la5/2*(h1*H2)**2 + AddHermConj.
```

The complete LanHEP input file for the IDM can be found in the directory IDM/lanhep. Indeed all models treated by micrOMEGAs were constructed with LanHEP. Compilation of models by LanHEP can be done by the command

```
    lhep  <source file>  -ca -evl 2
```

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