Quantum Field Theory, High-Energy Physics, and Cosmology.

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MicrOMEGAs,
A package for calculation of Dark Matter observables

https://lapth.cnrs.fr/micromegas

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General features and purposes

- MicrOMEGAs is based on CalcHEP package

  https://theory.sinp.msu.ru/~pukhov/calchep.html

  which is intended for calculation of cross sections and particle decay widths in generic model of particle interaction.
- MicrOMEGAs is able to calculates relic density of DM, signals of direct and indirect DM detection.
- Micromegas contains/imports external packages for model construction, calculation of particle spectra, testing of collider signals.
- Operation system Lunux or Darwin (Mac)
- User’s code language is C or C++

MicrOMEGAs works with generic model of particle interaction presented in CalcHEP format:

vars1.mdl: **Free parameters of the model.**

```
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   |111         |Mass of Inert Doublet Higgs
MH3   |222         |Mass of CP-odd Higgs
MHC   |333         |Mass of charged Higgs
LaL   |0.01        |Coupling in Inert Sector
```

………………………………

func1.mdl: Constrained parameter of the model.

```
Inert Doublet
 Constraints
 Name  |> Expression
CW     |sqrt(1-SW^2)
MW     |MZ*CW
Mb     |MbEff(Q)
Mc     |McEff(Q)
mu2    |MHX^2-laL*(2*MW/EE*SW)^2
la3    |2*(MHC^2-mu2)/(2*MW/EE*SW)^2
la5    |(MHX^2-MH3^2)/(2*MW/EE*SW)^2
```

prtcls1.mdl: Particles of the model

List fo particles presented in file MODEL/work/models/prtcls1.mdl

```
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
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    |   |(H3)
Charged Higgs      |~H+|~H-|37          |0    |MHC |!wHC |1    |   |(H+)
second Higgs       |~X |~X |35          |0    |MHX |!wHX |1    |   |(X)
```

Names of particles of odd sector start with tilde ~

lgrng1.mdl: Feynman rules

```
Inert Dublet
 Lagrangian
P1 |P2 |P3 |P4 |>   Factor        <|> dLagrangian/ dA(p1) dA(p2)dA(p3)
A  |W+ |W- |   |-EE                |m3.p2*m1.m2-m1.p2*m2.m3- …....
A  |~H+|~H-|   |EE                 |m1.p3-m1.p2
B  |b  |A  |   |EE/3               |G(m3)
B  |b  |G  |   |GG                 |G(m3)
B  |b  |Z  |   |-EE/(12*CW*SW)     |4*SW^2*G(m3)-3*G(m3)*(1-G5)
B  |b  |h  |   |-EE*Mb/(2*MW*SW)   |1
B  |t  |W- |   |-EE*Sqrt2/(4*SW)   |G(m3)*(1-G5)
W+ |W- |~X |~X |EE^2/(2*SW^2)      |m1.m2
h  |~X |~X |   |-2*MW*SW/EE        |la3+la4+la5
Z  |Z  |~X |~X |EE^2/(2*CW2*SW^2)  |m1.m2
   …...............
```

p – momentum,   m – Lorentz index

Model files can be generated by **LanHEP** (included in MO), **FeynRules**, **Sarah**

Runtime compilation of external packages and generation of matrix elements.

When micrOMEGAs needs matrix element, it calls CalcHEP for runtime generation of shared library for matrix element and its dynamic linking:

```
numout *cc =newProcess("~X,~X→b,B);
double cs = cs22(cc,1, pcm, cos1, cos2,&err);
```

External packages are downloaded and compiled when user try to call them.

More information:

There is complete manual included in the package:
man/manual,_5.3.pdf

There is tutorial for beginners:
https://theory.sinp.msu.ru/~pukhov/microLyon.pdf

Resent development: Recasting of direct Detection experiments:

Direct Detection experiments: underground experiments with massive detector which have a goal to find ionization trace of DM collision with detector body.

DD experiments presents 90% exclusion limit on DM-nucleon cross section assuming
a) point-like collision of DM with nuclei,
b) fixed Maxwell velocity distribution of DM with parameters Vrot=220km/s, Vearth=232kv/s Vesc=544km/s
c) form factors of spin-depended interaction.

We have done recasting of the following DD experiments DarkSide, PICO, CRESST, Xenon1T to include in micrOMEGAs limits imposed by direct detection and to check how the mentioned above assumptions work.

MicrOMEGAs calculates recoil energy distribution of events. Then we take into account efficiency of detection of event, background, statistical method used in the experiment and try to reproduce experimental exclusion. We get a help of DarkSide, PICO, CRESST teams to understand details of experiments.

PICO-60 – bubble chamber low background experiment. Main background – neutrons. Multiple events caused by neutrons, Number of multiple events leads to estimation of number of single neutron events. Statistical method – Feldman-Cousins. Neyman.

DarkSide-50 large background argon experiment. Theoretical estimation of background. Profile likelihood.

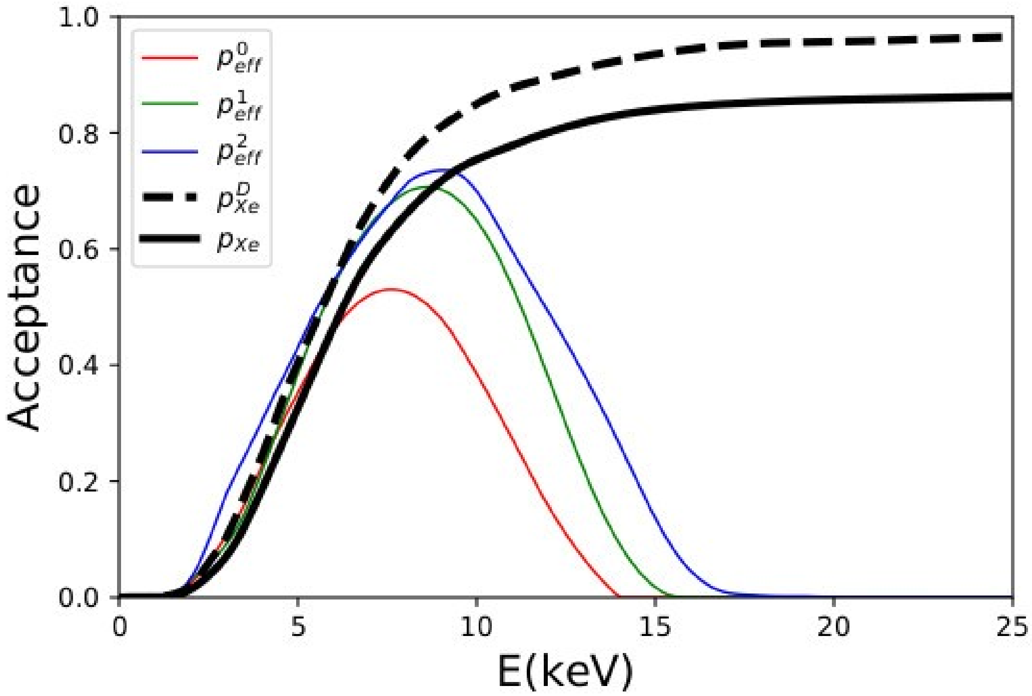
CRESST-III - $CaWO_4$ no background estimation. Yellin Optimal Interval Method is used.

Xenon1T - Liquid Xenon. Primary S1 and secondary S2 gamma signals allow to distinguish electromagnetic events from DM+neutron ones. Then they choose internal volume 0.9t (of 1.3t) to exclude neutrons. Profile likelihood. Data are close. Black box.

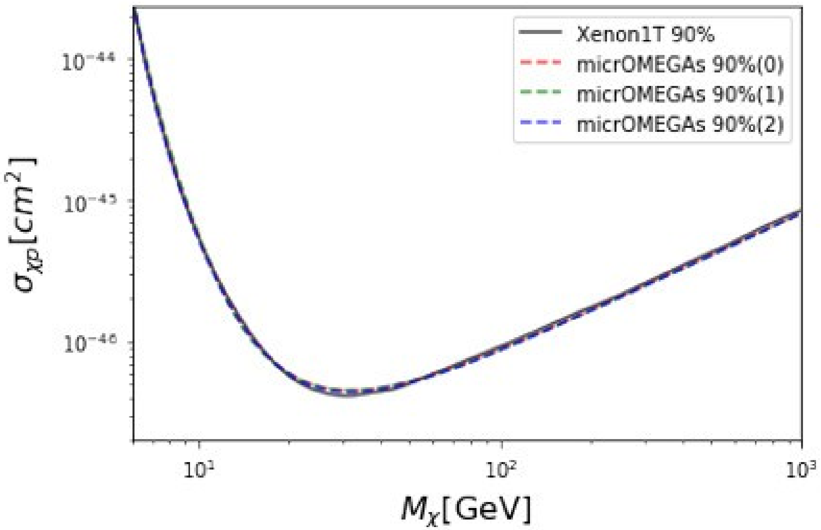
Xenon1T

To extract efficiency of Xenon1T we solve Fredholm equation.

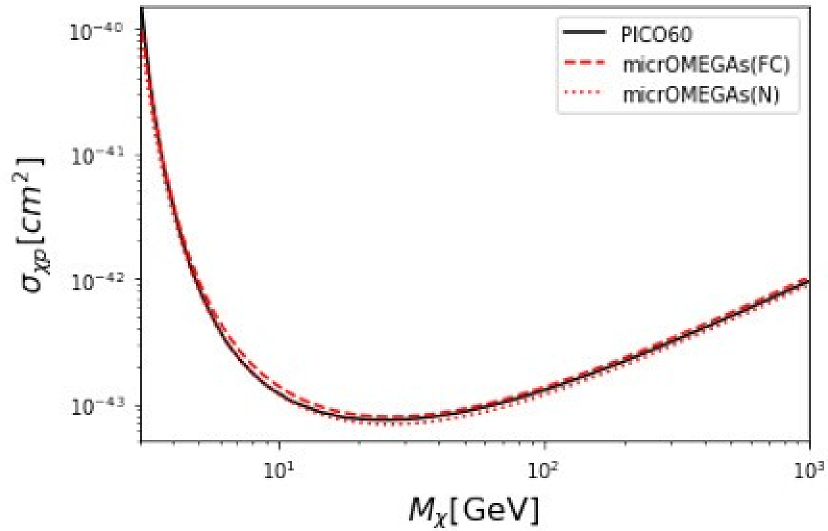
$$\mathcal{L}\int p^0_{eff}(E)\frac{dN(M_\chi,\sigma^{90}(M_\chi))}{dE}dE = -\log(\alpha) = \log(0.1)$$



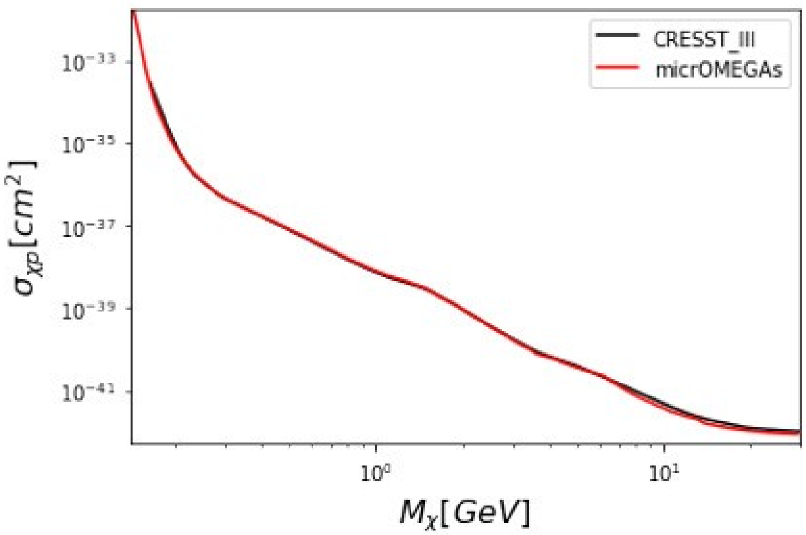
Xenon1T



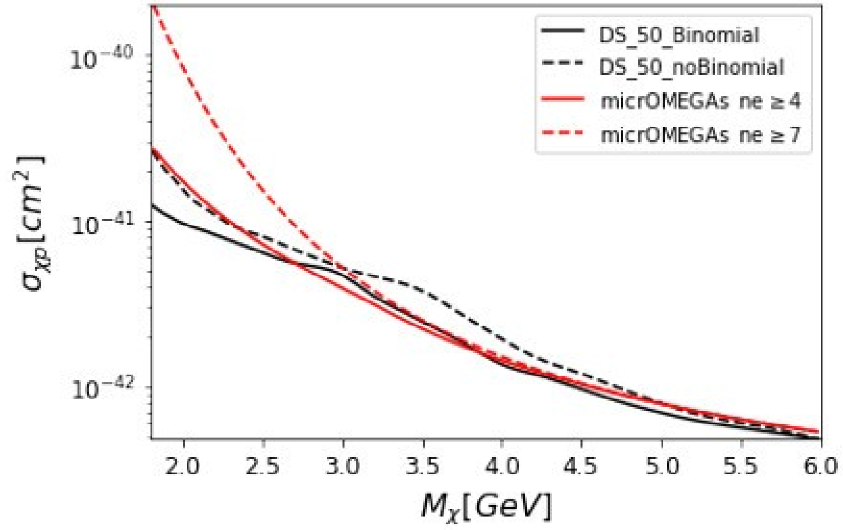
PICO



CRESST



DarkSide



Spin Depended interaction

When we successfully finished recasting of PICO and CRESST for scalar interaction, we find a disagreements for spin-flip one. It was caused by mistake in experiments.

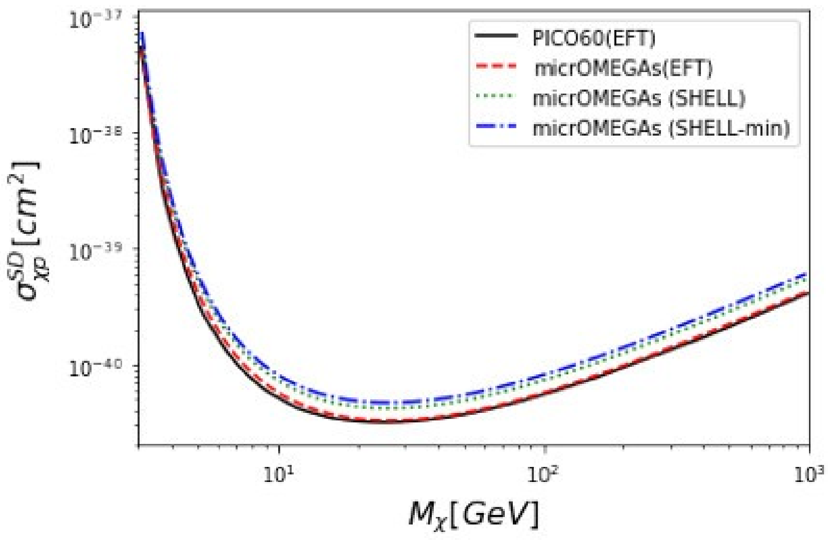
PICO had lost a factor which define fraction of nuclei sencitive to spin-flip interactions.

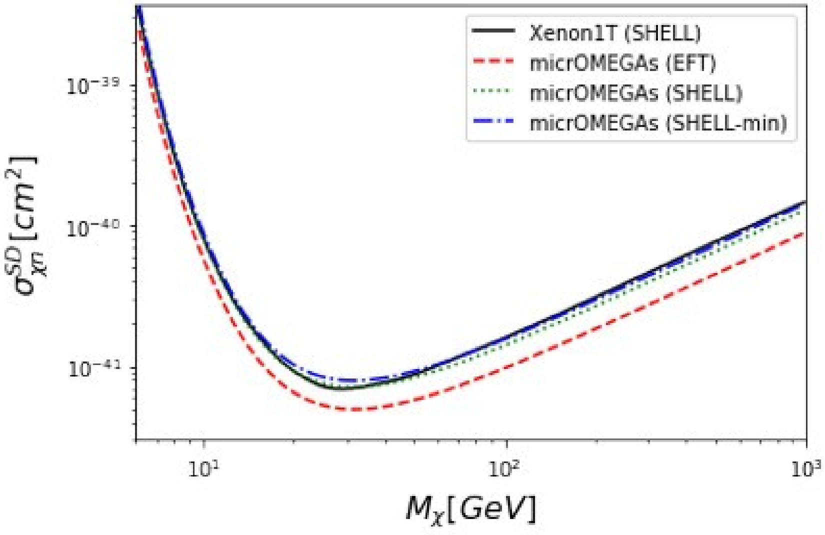
CRESST had a mistake caused by simulation of work of detector close to detector threshold.

Dependence on Form Factor

SHELL - P. Klos, J. Menéndez, D. Gazit, and A. SchwenkP. 2014

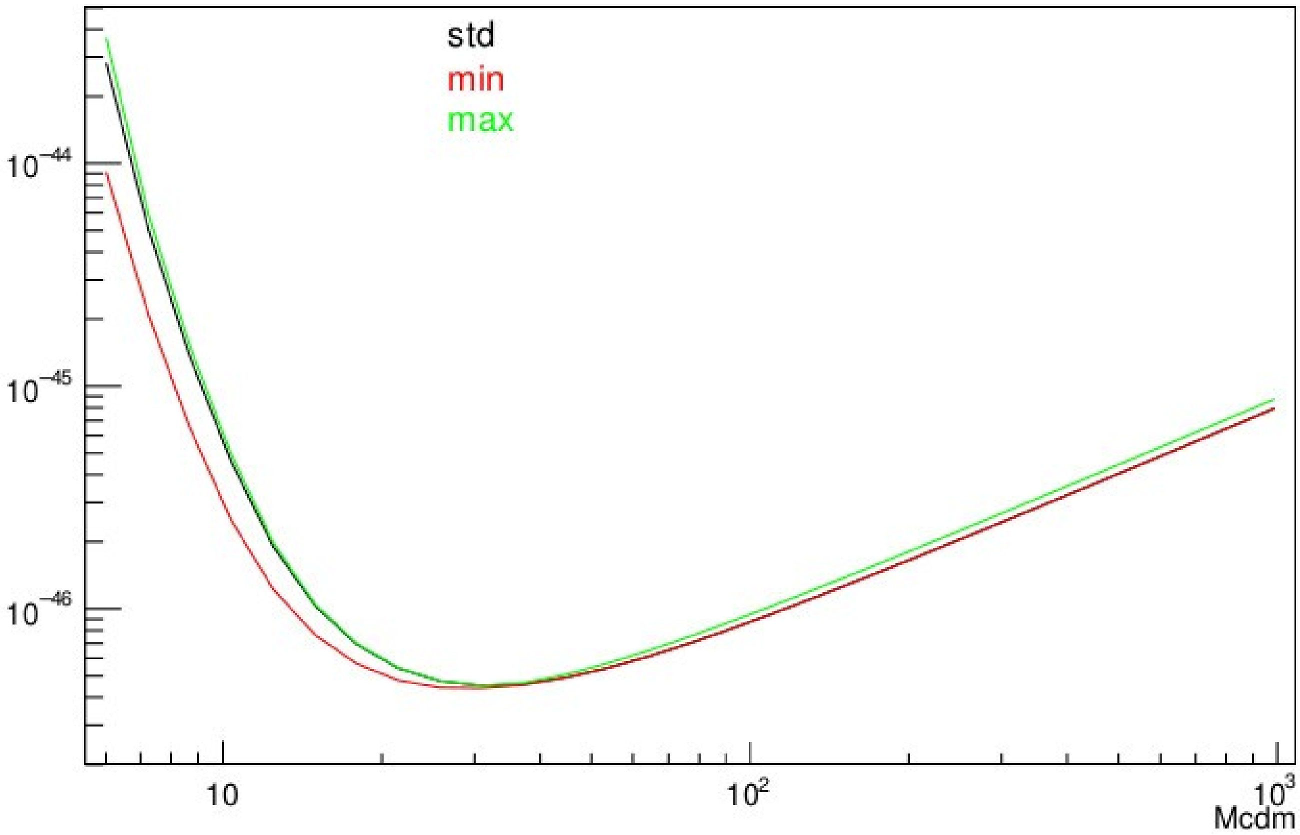
EFT - A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers, and Y. Xu. 2013





Dependence on velocity distribution.

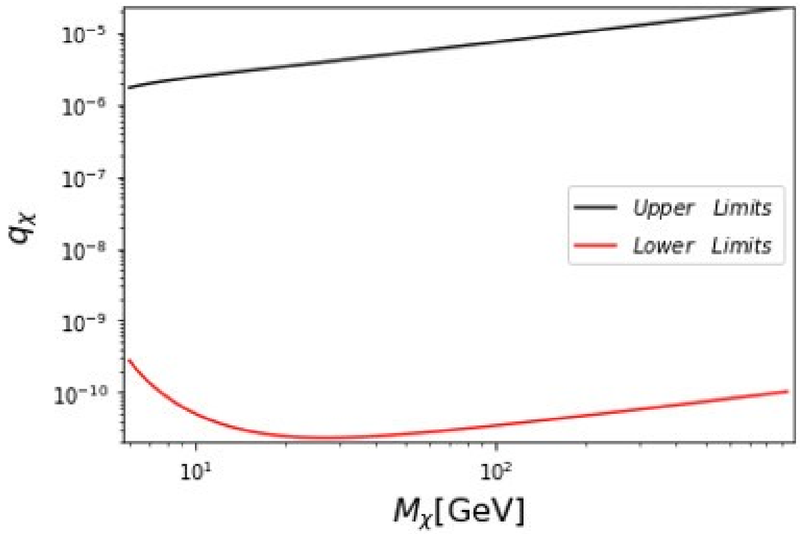
Maxwell: vRot +/- 18 km/s: vEarth=232-252 km/s: vEsc=580+/-63 km/s



vEsk_DD – 544 km/s

RhoDM_DD=0.3GeV/cm^3   rhoDM=(0.39+/-0.03)(1.2+/-0.2)(1 +/- 0,2)

Light mediator and milli-charge DM



Main function of micrOMEGAs package for testing Derect Detection:

pval=DD_pval(Experiment, f(v), bestExp)

Experiment =XENON1T_2018 | DarkSide_2018| PICO_2019|CRESST_2019
f(v) - DM velocity distribution
bestExp - experiment which leads to the best exclusion

Chemical equilibrium, decays and co-scattering for calculation relic density

In general we solve equation for evolution of DM density assuming chemical equilibrium between DM particles in case of one DM component DM or assuming chemical equilibrium inside of each DM sector in case of multicomponent DM :

$$n_i/n_j = \bar{n}_i/\bar{n}_j$$

were n – number density, \bar{n} – equilibrium number density. It is assumed that there are fast decay processes which support chemical equilibrium:

$$\omega(DM_i \to DM_j, SM) \gg Hubble$$

Chemical equilibrium allows to solve equations for

$$n_\alpha = \sum_{i \in \alpha} n_i$$

were α is a set of particles which are in chemical equilibrium. For instance, in case of Z4 symmetry α is 1 or 2.

In last version of micrOMEGAs we have routines which check chemical equilibrium and if need solve equation for evolution of DM density taking into account processes responsible for chemical equilibrium : decay processes and co-scattering processes.

Co-scattering are the processes of type

$$DM_i, SM \to DM_j, SM'$$

For small temperatures decay processes are more important, but for large temperatures co-scattering increases like T^2 and becomes more important.

We solve the following task: to write automatically evolution equation for N-component DM taking into account decays and co-scattering.

$$\frac{dn_\mu}{dt} = -\sum_{\alpha\le\beta;\ \gamma\le\delta} n_\alpha n_\beta < v\sigma >_{\alpha\beta\to\gamma\delta} (\delta_{\mu\alpha} + \delta_{\mu\beta} - \delta_{\mu\gamma} - \delta_{\mu\delta})$$

$$-\sum_{\gamma\le\delta}(n_\mu - \frac{n_\gamma n_\delta}{\bar{n}_\gamma \bar{n}_\delta}\bar{n}_\mu) < \omega >_{\mu\to\gamma\delta} (1 - \delta_{\mu\gamma} - \delta_{\mu\delta}) - 3H(T)n_\mu$$

Were n0 is a number density of SM bath particles

New micrOMEGAs functions for calculation of relic abundance

checkTE(nSector , T, mode, Beps) returns w_eff/H

w_eff/H >> Xf = Mdm/Tf

proposes how to split sector nSector

defThermalSet(n_set, particle list)

printThermalSets()

darkOmegaN(Y, Beps, &error); calculate relic density for N-component DM.