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MicrOMEGAs - a tool for calculating Dark Matter signals.

https://lapth.in2p3.fr/micromegas

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Main publictions (CPC) and steps of development:

1.MicrOMEGAs: A Program for calculating the **relic density in the MSSM**
with F.Boudjema(LapTH) A.Semenov (JINR) *hep-ph/0112278*

2.MicrOMEGAs 2.0: A Program to calculate the **relic density of dark matter in a generic model** *hep-ph/0607059*

3.Dark matter **direct detection rate** in a generic model with micrOMEGAs 2.2 *arXiv:0803.2360*

4.**Indirect search** for dark matter with micrOMEGAs2.4 *arXiv:1004.1092*
with P.Brun, S.Rosier-Lees, P.Salati

5. micrOMEGAs_3: A program for calculating dark matter observables arXiv:*1305.0237*

6. Limits on dark matter proton scattering from **neutrino telescopes** using micrOMEGAs *arXiv:1507.07987*

7.**Collider limits** on new physics within micrOMEGAs4.3 *arXiv:1606.03834*
with D.Barducci, J.Bernon, S.Kraml,U.Laa

8.micrOMEGAs5.0 : Freeze-in. *arXiv:1801.03509*
with A.Goudelis, A. Pukhov, B.Zaldivar

9.micrOMEGAs 6.0: N-component dark matter *arXiv:2312.14894*

Cited > 5000

Similar packages: DarkSusy, MadDM

Included models

MSSM/	
NMSSM/	Next-to-Minimal SuSy Model
CPVMSSM/	MSSM with complex parameters
IDM/	Inert dublet model
LHM/	Little Higgs Model
Z3IDM/	Z^3 model
Z4IDMS/	Z^4 model (2 DM paticles)
Z7M	Z^7 (3 DM particles)
ZpPortal	Z`

./newProgect newModelName - *creates new model*

Model is described by 4 files :vars1.mdl, func1.mdl, prtcles1.mdl lgrng1.mdl disposed in newModelName/work/models subdirectory

Model Files: Inert Doublet Model

Inert Doublet model contains two SU(2)*U(1) doublets

$$H_1 = \begin{pmatrix} 0 \\ <v> + h/\sqrt{2} \end{pmatrix} \;,\; H_2 = \begin{pmatrix} \tilde{H}+ \\ (\tilde{X} + i \cdot \tilde{H3})/\sqrt{2} \end{pmatrix}$$

The Lagrangian contains only *even* powers of H_2 doublet

$$L = (SM\ terms) + D^{\mu} H_2^* D_{\mu} H_2$$

$$-\mu^2 H_2^2 - \lambda_2 H_2^4 - \lambda_3 H_1^2 H_2^2 - \lambda_4 |H_1^* H_2|^2 - \lambda_5 Re[(H_1^* H_2)^2]$$

Because of symmetry $H_2 \rightarrow -H_2$ the lightest of $\tilde{H}^+, \tilde{X}, \tilde{H3}$ is stable

Parameters $\mu, \lambda_3, \lambda_4$ can be expressed in terms of masses

New couplings are λ_2 , $\lambda_L = \lambda_3 + \lambda_4 + \lambda_5$

See details **arXiv:1106.1719**

Model Files: **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
...............................
```

Model Files: 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
```

Model Files: Particles of the model

```
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 are started with tilde ~

Model Files: 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
   …...............
```

Generation of new models in micrOMEGAs

./newProgect newModelName *- creates new model*

Model is described by 4 files :vars1.mdl, func1.mdl, prtcles1.mdl lgrng1.mdl disposed in newModelName/work/models subdirectory

Model files can be created by mean of
LanHEP, FeynRules, Sarah

```
let B1= -SW*Z+CW*A, W3=CW*Z+SW*A, W1=('W+'+'W-')/Sqrt2,  W2 =
i*('W+'-'W-')/Sqrt2.
let WW = {W1,  W2 , W3}.
lterm -F**2/4  where F=deriv^mu*WW^nu^a-deriv^nu*WW^mu^a
g*eps^a^b^c*WW^mu^b*WW^nu^c.
```

```
Let  hi= {-i*W+.f,  (h+ vev(2*MW/EE*SW)+i*Z.f)/Sqrt2).
let hh = { -i*'~H+',  ('~X'+i*'~H3')/Sqrt2 }.
%                              Hi and HH – conjugated doublets
lterm -la2*(hh*HH)**2. -la3*(hi*H)*(hh*HH). -la4*(hi*HH)*(Hi*hh).
lterm  -la5/2*(hi*HH)**2 + AddHermConj.vv
```

Generation of matrix elements

numout *cc ; // numout – is a type for matrix element in micrOMEGAs.

cc = newProcess(char*Process); // call CalcHEP to calculate symbolically and compile matrix element for given process. For instance

cc = newProcess(“e,E->m,M”);

Matrix element is presented as a shared library and stored in directory

MODEL**/work/so_generated**

Name of library is related to names of particles in the process.

If model library already was generated and the model was not changed, then library is not recompiled.

For example, cross sections of 2->2 processes can be calculated by

cs= cs22(cc,L,Pcm,cos_min,cos_max,&err);

Pcm – momentum in Center of Mass reference frame

cos_min, cos_max - cuts for cosine of scattering angle in the same frame

L=1 in case you have generated codes only for one process. For general case L numerates subprocesses.

So, micrOMEGAs works with a matrix element which is compiled by CalcHEP for given model and passed to micrOMEGAs

Loop induced vertices

micrOMEGAs is able to get numerical coefficients at vertex implemented in Lagrangian and use them to construct loop induced vertexes.
It is implemented for construction of Higgs-gamma-gamma and Higgs-glue-glue vertices which are needed for interface with HIGGSBOUNDS and LILITH for applying LHC constrains on Higgs particle
Also it need for correct calculation of Higgs width.

MicrOMEGAs fuctions

double complex lAAhiggs(Q, HiggsName);
double complex lGGhiggs(Q, HiggsName);

$$\lambda F_{\mu\nu}F^{\mu\nu}$$

double complex lAA5higgs(Q,HiggsName);
double complex lGG5higgs(Q,HiggsName);

$$\lambda F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Q is reserved for the case of off-shell vertex.

For example in IDM Lagrangian

```
func1.mdl                                        lgrgn1.mdl
 LAAH  |-cabs(lAAhiggs(Mh,"h"))      A |A |h |  |-4*LAAH |p1.p2*m1.m2-m2.p1*m1.p2
```

Problem I – breaking of gauge invariance.

Increase of cross sections in unitary gauge and appearance of negative cross sections in Feynman one.

a) Loop correction if mass spectrum in MSSM.

We add corrections to potential according to
M. Carena, M. Quiros and C.E.M. Wagner, "Effective potential methods and the Higgs mass spectrum in the MSSM", Nucl. Phys. B461 (1996) 407.
But it is not enough.

b) Implementation of particle widths breaks gauge invariance.

Calculation of DM relic density (Freeze out)

Ωh^2 = darkOmega(&Xf,fast,Beps,&err)   *fast =1 for for fast* calculation

We assume that all decays in odd sectors are fast and,so, in odd sector

$$\frac{N_i}{N_j} = \frac{N_i^{eq}}{N_j^{eq}} \approx exp(-(M_i - M_j)/T) \qquad (1)$$

And solve equation for total abundance $Y=N_{odd}/s$, where s – entropy density,

$$\frac{dY}{ds} = \frac{< v\sigma >}{3H}(Y^2 - Y_{eq}^2)$$

H – Hubble rate

Beps excludes   co-annihilation if $exp(\frac{2M_{cdm} - M_1 - M_2}{T}) < Beps$

Co-annihilation: (annihilation of non-DM odd particles)
Problem: double counting caused by t-channel pole: ~m,~χ → m, h

Ωh^2 = darkOmegaN(fast, Beps, &err)   calculates relic density for N-component DM.
By default DM sectors defined by the number of “~” symbols, But also can be defined by the used. So, one can split a DM thermal sector on 2 and   check Eq,(1) ! Here we take into account decay and processes of co-scattering :

Dm1, SM1 → Dm2,SM2

Co-scattering and decays

1) As a rule decay plus co-scattering restore thermal equilibrium inside of DM sector with fixed charge of group of symmetry.

2) Decays are responsible for low temperatures, co-scattering is responsible for thermal equilibrium at high temperatures.

3) Infrared divergent processes with photon and gluon

g, ~b → b, ~χ *(gluon + s-botom decay)*

does not contribute to co-scattering

Width calculation in plasma:

arXiv:1110.2171, 1607.03910, 1207.6082

Kinetic equilibrium.

We assume kinetic equilibrium between DM particles and SM bath.

Indeed massive DM cools faster than SM particles, but kinetic equilibrium is supported by

reactions ~χ,SM->~χ,SM

It can be important when double DM mass is a little bit smaller than (Higgs) resonance.

Not solved in micrOMEGAs. (See darkSUSY)

Feebly interacting Dark Matter. Freeze-in

For DM which has nether been in thermal equilibrium with SM bath.

We get explicitly integrable equation

$$\frac{dY}{ds} = \frac{< v\sigma >}{3H}(\qquad -Y_{eq}^2)$$

Problem with quantum statistics. A proper account of it breaks Lorentz invarience and requires multi-dimension integration.
But the corresponding correction is small (<= 20%) and there is a fast way of approximate solution.

Vev(T) dependence. One can implement dependence of Lagrangian from temperature via parameter “T”

Problem of implementation of thermal masses. At high temperatures particle density is about T^3, the distance between particles is about 1/T, Debye mass are about gT. Thermal masses are taken into account via cut for small (-t) contribution of matrix matrix element.

T-cut

$$\int_{t_{max}}^{0} \frac{dt}{m(T)^2 - t} \approx \int_{t_{max}}^{-m(T)^2 - m_0^2} \frac{dt}{m_0^2 - t}$$

Y = darkOmegaFi(TR, *feebleParticle*, &err);

calculates the DM abundance after summing over all 2 → 2 processes involving particles in the bath B in the initial state and at least one *feebleParticle* in the final state.

Low-Temperature Reheating

During cosmic reheating, the inflaton ϕ decays into SM radiation with a total decay width Γϕ. The dynamics of the background is driven by the set of Boltzmann equations for the inflaton energy density ρ_ϕ and the SM entropy density s

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

$$\frac{ds}{dt} + 3Hs = \frac{\Gamma_\phi}{\rho}\ {}_{\phi}\ T$$

$$H^2 = \frac{\rho_\phi + \rho_R}{3M_P}$$

The evolution of the DM number density n can be tracked by the Boltzmann equation

$$\frac{dn}{dt} + 3Hn = - < \sigma v > (n^2 - n_{eq}^2)$$

darkOmegaInflDecay(HI ,Γ, Beps,&aend , &err)

Direct Detection

To predict results of direct detection experiment in the given model of elementary particles interaction we have to calculate cross sections of DM – nuclei elastic scattering.

So, we have in the model

DM - quarks interaction

Then we have to calculate

DM - nucleon scattering cross section

And at next step

DM -nuclei scattering cross section

Velocities of DM particles in halo of Milky Way are about orbital velocities of stars

$$v \approx 220km/s \approx 10^{-3}c$$

We can treat such scattering as scattering at v → 0 limit, taking into account that elastic cross section can be finite in this limit.

DM – fermion interaction in the v → 0 limit

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

SI – Spin independent (scalar) – interactions without spin flip.
SD – Spin dependent – interactions with spin flip.
Even - DM and DM* have the same amplitude.
Odd   - DM and DM* amplitudes have different signs.

Operator expansion

SI and SD operators have the following normalization conditions for scattering at rest:

SI : $|A^{SI}|^2 = 64 M_{DM}^2 M_f^2$
SD: $|A^{SD}|^2 = 192 M_{DM}^2 M_f^2$

Assuming effective Lagrangian

$$\hat{\mathcal{L}}_{eff}(x) = \sum_{q,s=(even,odd)} \lambda_{q,s}\hat{\mathcal{O}}_{q,s}(x) + \xi_{q,s}\hat{\mathcal{O}}'_{q,s}(x)$$

micrOMEGAs creates new model with effective operators and finds coefficients λ and ξ calculating amplitudes for collision at rest

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

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

Twist-2 operators

One exeption: to select contribution of twist-2 operators

$$\mathcal{O}_{q,t} = \frac{1}{2}(\bar{\chi}\gamma_\mu\partial_\nu\chi)\bar{q}(\gamma^\mu\overrightarrow{\partial}^\nu - \gamma^\mu\overleftarrow{\partial}^\nu + \gamma^\nu\overrightarrow{\partial}^\mu - \gamma^\nu\overleftarrow{\partial}^\mu + im_q g^{\mu\nu})q$$

micrOMEGAs tests forward scattering amplitudes for finite momentum

$$< q(p_1),\chi(p_2)|\mathcal{O}_{q,t}\mathcal{O}_{q,e}|q(p_1),\chi(p_2) >= -32 m_q M_\chi(4(p_1.p_2)^2 - m_q^2 M_\chi^2)$$

Even vector form factor $\gamma_5\gamma_\mu$

Describe contribution of quarks and and anti-quarks to nucleon spin

Odd vector form factor $\sigma_{\mu\nu}$

Describe difference of contribution of quarks and antiquarks to nucleon spin.

Form factors of light quarks are presented by global parameters

Proton		Neutron		
Name	value	Name	value	comments
ScalarFFPd	0.0191	ScalarFFNd	0.0273	Scalar form factor
ScalarFFPu	0.0153	ScalarFFNu	0.011	
ScalarFFPs	0.0447	ScalarFFNs	0.0447	
pVectorFFPd	-0.427	pVectorFFNd	0.842	Axial-vector form factor
pVectorFFPu	0.842	pVectorFFNu	-0.427	
pVectorFFPs	-0.085	pVectorFFNs	-0.085	
SigmaFFPd	-0.23	SigmaFFNd	0.84	Tensor form factor
SigmaFFPu	0.84	SigmaFFNu	-0.23	
SigmaFFPs	-0.046	SigmaFFNs	-0.046	

Twist-2 form factors

are obtained via integration of structure functions.

$$< N(p)|\mathcal{O}^{\mu\nu}_{q,t}|N(p) >= (p^\mu p^\nu/M_N - g^{\mu\nu}M_N/4)\int_0^1 (q(x)+\bar{q}(x))x dx$$

Heavy quark form factors

are obtained by QCD calculations. No contribution to SD part and odd SI.

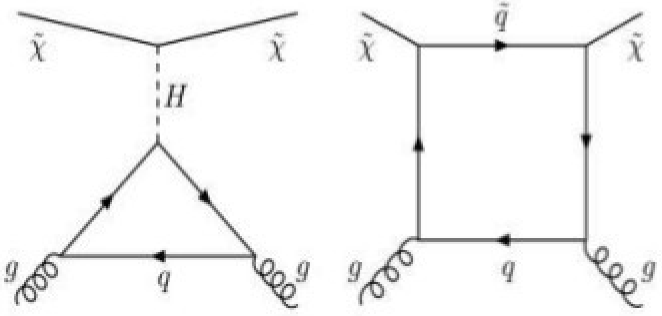
The anomaly of the trace of energy-momentum tensor in QCD implies (Wanstein,Zakharov, Shifman)

$$M_N\langle N|N\rangle = \langle N|\sum_{q\le n_f} m_q\overline{\psi}_q\psi_q(1+\gamma) + (\frac{\beta^{n_f}}{2\alpha_s^2})\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle$$

where $\beta^{n_f} = -\alpha_s^2/4\pi(11-2n_f/3+\alpha_s/4\pi(102-38n_f/3))$.

$$\langle N|m_Q\bar{\psi}_Q\psi_Q|N\rangle = -\frac{\Delta\beta}{2\alpha_s^2(1+\gamma)}\langle N|\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle \approx \frac{2}{27}\langle N|M_N\bar{\psi}_N\psi_N|N\rangle$$

Heavy quark loops



Diagrams that contribute to DM-gluon interaction via heavy quark loops

Heavy quarks interact with nucleon via gluon condensate. For triangle (Higgs) heavy quark condensate is a good approximation. For box diagrams one needs loop calculation.

For renormalizable interactions corresponding boxes where presented in

DM spin 1/2	M.Drees & M.Nojiri	hep-ph/9307208
DM spin 0 and 1	Hisano,Junji,Nagai,Ryo,Nagata,Natsumi	arXiv:1502.02244

MicrOmegas replaces propagators on corresponding loop functions without testing type of interaction arXiv 0803.2360

Nucleon amplitudes and cross sections in micrOMEGAs

nucleonAmplitudes(name_of_DM ,pA0,pA5,nA0,nA5);

Output: *pA0,pA5,nA0,nA5* – 2 dimension arrays

Proton

pA0[even SI, odd SI]   pA5[even SD, odd SD]

Neutron

nA0[even SI, odd SI]   nA5[even SD, odd SD]

Then DM-nucleon cross section in [pb] units are

$\sigma_{SI}= C*A^2$ $\sigma_{SD}= 3*C*A^2$ where $C=4/\pi*3.89E8*(M_N*M_{dm}/(M_N+ M_{dm}))^2$

Nuclei interactions

Nuclei form factors

For zero DM velocity DM-nucleus SI cross section reads

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

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

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

For SI interactions, $F(q)$ is a Fourier transform of the nucleus distribution function,

$$F_A(q) = \int e^{-iqx} \rho_A(x) d^3x$$

micrOMEGAs use the Fermi distribution function

$$\rho_A(r) = \frac{c_{norm}}{1 + exp((r - R_A)/a)}$$

where $a = 0.52fm$ nuclei surface thickness, and
$R_A = 1.23A^{\frac{1}{3}} - 0.6\text{fm}$ nuclei radius

There are similar but more complicated formulas for SI nucleus cross section which depends on 3 form factors, proportion to nucleus momentum J and does not lead to A enhancement.

micrOMEGAs function for nuclei

nucleusRecoil(
f, - velocity distribution f(v[km/s]) normalized by

$$\int_0^\infty v f(v) dv = 1$$

A, - atomic number
Z, - nucleus charge
J, - number of spin states
Sxx, - SD formfactors
dNdE - recoil energy distribution stored in array
)

dNdERecoil(E[keV],dNdE) interpolates dNdE table and gives spectrum in 1/keV/kg/day units

For example:
nEvents=nucleusRecoil(Maxwell,73,Z_Ge,J_Ge73,SxxGe73,dNdE);

```
          Result depends on global parameter
  rhoDM     0.3[GeV/cm^3] Dark Matter density at Rsun
```

How to get plot for dNdE ontained by nucleusRecoil?

displayPlot(title,xName,xMin,xMax,lScale, N, ...)
displays several curves/histograms on one plot. Here title presents title of plot,

xName Is a name of variable,
xMin,xMax are the lower and upper limits for x
lScale is a logarithmic scale flag for x-axis,
N is a number of curves/histograms to display.

After the parameter N displayPlot expects N*4 parameters, where each tetrad can contain

textual	Dim	array of data	array of error
label	Dim	array of data	NULL
	0	(double* f)(double x)	NULL
	0	(double* f)(double x, void*arg)}	arg

For linear scale lScale=0 , the arrays of data and errors should correspond to a grid

x[i]=xMin+(i+0.5)(xMax-xMin)/Dim

For Log scale lScale=1

x[i]=xMin (xMax/xMin)^((i+0.5)/Dim)

For Recoil energy

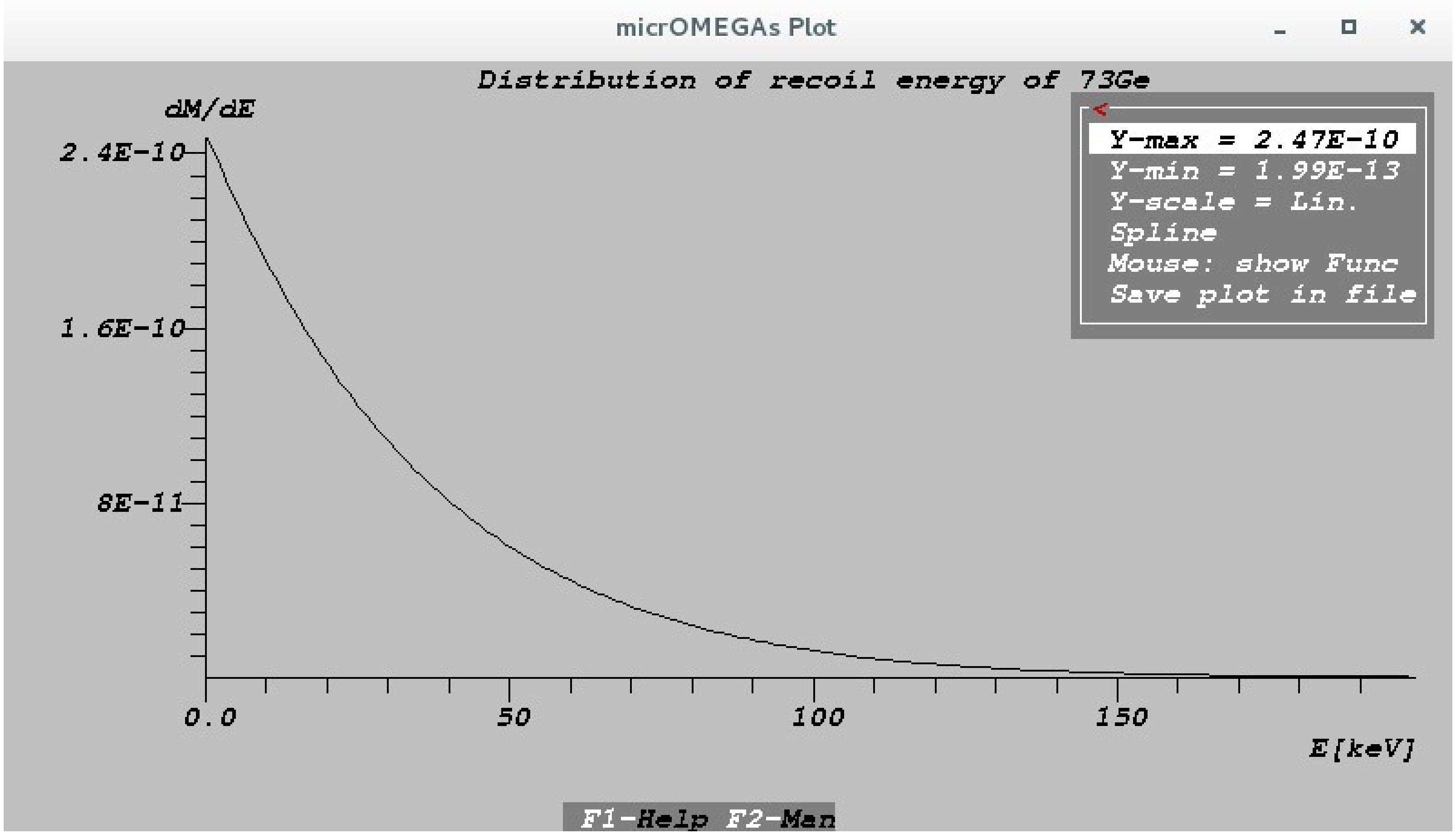
displayPlot("Distribution of recoil energy of 131Xe","E[KeV]",0,200,0,1, "
“dN/dE",0,dNdERecoil,dNdE);

One has to uncomment

#define SHOWPLOTS

to see different plots for distribution produced by micrOMEAGs.

There is an menu driving option to save plot in Root, PAW, and GnuPlot formats.



Y-max = 2.47E-10
Y-min = 1.99E-13
Y-scale = Lin.
Spline
Mouse: show Func
Save plot in file

Neutrino telescope

micrOMEGAs uses direct detection module to calculate number of DM captured by Sun/Earth.

Captured DM is concentrated in the center of Sun/Earth and neutrino produced in result of DM annihilation can be detected by neutrino telescope experiment (IceCube, Super-Kamiokande, Baksan).

DM annihilation inside of Sun/Earth is different from annihilation in vacuum. Also there are effects of propagation and oscilation.

For flux of resulting muon neutrinos micrOMEGAs uses tables obtained by
WimpSim package: J. Edso et.al arXiv 0709.3898
Or
PPPC4DMnu: M. Cirelli, et.al. arXiv 1312.6408

Agreement between two sets is not very good.

MicrOMEGAs routine basicNuSpectra reads these tables depending on
WIMPSIM flag
WIMPSIM=1 for WimpSIm
WIMPSIN=0 for PPPC4DMnu

basicNuSpectra(*forSun,Mcdm,pdg, pol, nu, nu_bar*)
where

forSun is 1 or 0,

pdg - is PDG number of annihilation channel.

pol=-1(1) corresponds to longitudinal (trans-verse) polarisation of vector bosons or to left-handed (right-handed) fermions, pol=0 is used for unpolarized spectra.

Arrays **nu, nu_bar** contains spectra.

SpectdNdE(E,spect) interpolates arrays.

Combining DM capture rate and annihilation spectra micrOMEGAs calculates muon neutrino fluxes at Earth surface

neutrinoFlux(Maxwell,forSun, nu,nu_bar);

After that one can apply iceCude22 limits for neutrino spectra: iceCube22 arXiv 0902.2460

exLevIC22(nu,nu_bar,NULL) exclusion level.

MicrOMEGAs is able to calculate muon spectra produced to neutrinos, but we have not now angular resulution for muon flax. It should be improved to apply micrOMEGAs to other neutrino telescope experiments

Indirect detection in micrOMEGAs

Indirect detection -detection of photons, positrons and antiprotons signal obtained in result of DM annihilation in Galactic Hallo.

For various spectra we use NZ=250 dimention arrays and interpolation function for them is SpectdNdE(E,spectArr)
One can use displayPlot to see and compare difference spectra.

vsigma=calcSpectrum(key,Sg,Se,Sp,Sne,Snm,Snl,&err)
Calculates vσ cross section in cm^3/sec units of DM annihilation and photon Sg, positron Se, antiprotons Sp, and 3 neutrino spectra at one collision of DM particles.
Here the avarage over Dm,Dm/antiDm is done. dmAssym is taken into account, In case of 2 DM particles we have an average over all types of collisions. PITHIA was used for hadronisation of primary annihilation channels.
Meaning of key parameter: 1-takes into account W/Z polarization
2-include gammas from 2->2+gamma
4-print cross sections

Check CMB re-ionization (Slatyer 2017)

Photon flux

gammaFluxTab(fi,dfi,sigmav,Sg,Sobs)
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 2π(1 − cos(df i)) ,
sigmav is the annihilation cross section,
Sg - photo spectrum at point of annihilation
Sobs is resulting photon flux in [1/(GeV cm^2 s)] units.

For all implemented models we have
Dm,Dm -> photon, photon and Dm,Dm -> photon, Z
loop induced signals. This signals are not compiled automatically in run-time but generated in advance by means of FormCalc.

One has to uncomment
//#define LoopGAMMA
to force micrOMEGAs to work with point like gamma signal.
Function   loopGamma(&vcs_gz,&vcs_gg) calculates annihilation calculates annihilation rates vcs_gz and vcs_gg [cm^3/s]

Signal from Dwarf galaxies.

Antiproton and positron fluxes

- **posiFluxTab**(Emin,sigmav, Se, Sobs)

- **pbarFluxTab**(Emin,sigmav, Sp, Sobs)

The same style as for photons. But depends on propagation parameters

```
K_dif     | 0.0112| kpc^2/Myr |The normalized diffusion coefficient
L_dif     |  4    | kpc       | Vertical size of the Halo diffu
Delta_dif| 0.7    |           |Slope of the diffusion coefficient
Tau_dif   | 10^16 |   s       |Electron energy loss time
Vc_dif    | 0     |  km/s     |Convective Galactic wind
```

And finally
  solarModulation(Phi, mass, stellarTab, earthTab)
allows to take into account solar modulation effect.
  Here Phi potential [MeV], mass is mass of particle,
  stellarTab flux before modulation
  earthTab flux after modulation.

LHC limits

Check of LHC limits is realized via interface with SMODELS. (S. Kraml)
MicrOMEGAs creates a table of cross sections

$$\bar{q}, q \to BSM, BSM$$

$$\bar{q}, q \to BSM, SM$$

and passes it to SMADELS.

Future development

1) Kinematic decoupling

2) Direct detection signals in case of DM elecromagnetic form factor

3) Model exclusion based on anti-proton signals of indirect detection experiments.

4) Indirect detection signal for models with light DM.

5) Investigation of models with right handed neutrino as DM candidate.