MicrOMEGAs: current status and new development

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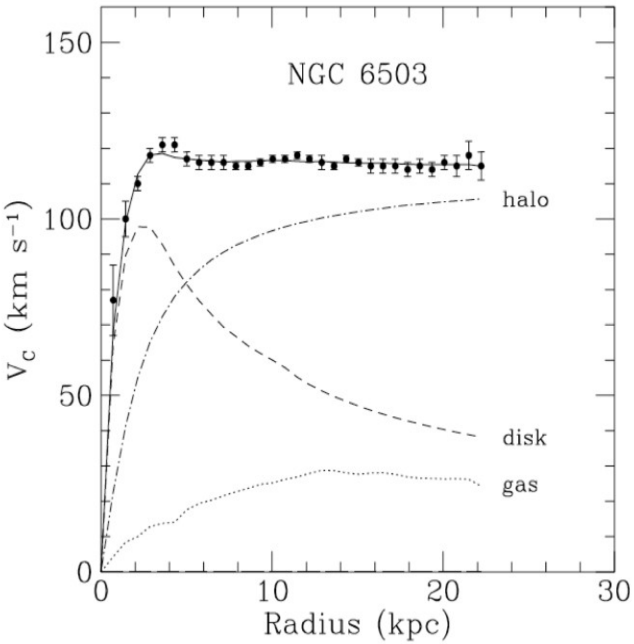
arXiv: 1001.0181

http:://lappweb.in2p3.fr/lapth/micromegas

Motivation

- Strong evidence for dark matter
  a) Rotation curves
  b) Structures formation
  c) CMB (WMAP+SDSS) gives precise
- information on the amount of dark matter
- and constrains models of cold dark matter



- Direct Detection experiments:
  CDMS, Xenon100, DAMA .....
- Indirect detection experiments:
  PAMELA, Fermi, ATIC ....

Standard Model explains all experimental results of particle physics. But

1) SM needs Higgs particle which still is not observed.

2) SM has not a candidate for Dark Matter

which should be a stable neutral massive particle.

Dark matter is a trace of BSM physics which we explicitly observe now.

- Most attractive explanation for dark matter: new weakly interacting particle which is stable because of new Z_2 or Z_3 symmetry

- Many models for new physics whose main motivation is to solve the hierarchy problem also have a R-parity like symmetry introduced to avoid rapid proton decay or guarantee agreement with electroweak precision
- Examples:
  - MSSM and extensions, UED, Warped Xtra-Dim, Little Higgs,
  - Extended Higgs.

- There are public codes that compute relic density and other observables in MSSM DarkSUSY, Isatools, SuperIso(2009). But we need such tool for generic model which is able to predict both *astroparticle and colliders* experiments

- micOMEGAs is based on CalcHEP (A.Pukhov, A.Belyaev, N.Christensen)
  http:theory.sinp.msu.ru/~pukhov/calchep.html
  a code for calculation of cross sections in generic model of particle interactions.

Model Files: variables

```
 Name | Value          |>  Comment                                  <|
alfEMZ|0.0078180608 |MS-BAR electromagnetic alpha(MZ)
alfSMZ|0.1172       |Srtong  alpha at MZ
SW    |0.481        |MS-BAR sin of the Weinberg angle
MZ    |91.1884      |Z mass
Ml    |1.777        |mass of tau lepton
MbMb  |4.23         |b-quark mass
Mtp   |171.4        |top quark mass
tb    |7            |Tangent beta
MG1   |39           |
MG2   |75.0         |
MG3   |252          |
Am    |-166         |
Al    |-166         |
At    |-232         |
Ab    |-405         |
MH3   |192          |
```

Model file: particles

ewsbMSSM

Particles

Full name	P	antiP	number	2*spin	mass	width	color	aux
gluon	G	G	21	2	0	0	8	G
photon	A	A	22	2	0	0	1	G
Z boson	Z	Z	23	2	MZ	wZ	1	G
W boson	W+	W-	24	2	MW	wW	1	G
electron	e	E	11	1	0		1	L
muon	m	M	13	1	0	0	1	
mu-neutrino	nm	Nm	14	0	1	0	1	
e-neutrino	ne	Ne	12	1	0	0	1	L
muon	m	M	13	1	0	0	1	
mu-neutrino	nm	Nm	14	1	0	0	1	L
tau-lepton	l	L	15	1	Ml	0	1	
tau-neutrino	nl	Nl	16	1	0	0	1	L
s-quark	s	S	3	1	0	0	3	
c-quark	c	C	4	1	0	0	3	
b-quark	b	B	5	1	Mb	0	3	
t-quark	t	T	6	1	Mt	wt	3	
Light Higgs	h	h	25	0	Mh	!wh	1	
chargino 2	~2+	~2-	1000037	1	MC2	!wC2	1	
neutralino 1	~o1	~o1	1000022	1	MNE1	!wNE1	1	

Model files: Feynman rules

```
ewsbMSSM
 Lagrangian
P1 |P2 |P3 |P4|>   Factor                <|> dLagrangian/dA(p1dA(p2)
A  |H+ |H- |  |-EE                        |m1.p2-m1.p3
A  |W+ |W- |  |-EE                        |m1.p3*m2.m3-m2.p3*m1.m3-
             m3.p1*m1.m2+m2.p1*m1.m3+m3.p2*m1.m2-m1.p2*m2.m3
B  |b  |A  |  |EE/3                       |G(m3)
B  |b  |G  |  |GG                         |G(m3)
B  |b  |H  |  |(-ca*EE*MbH)/(2*cb*MW*SW)  |1
B  |b  |H3 |  |(EE*i*MbH3*tb)/(2*MW*SW)   |G5
```

There are software tools to create CalcHEP model files:

LanHEP : (A.Semenov)
http://theory.sinp.msu.ru/~semenov/lanhep.html

FeynRules:(Neil D. Christensen, Claude Du,hr)
http://feynrules.phys.ucl.ac.be

SLHAplus package for model interface

There are many models realisation based on SLHA agreement betweem particle spectrum calculator (SuSpect, SoftSUSY, SPHENO, Isajet) and programs which calculate particle cross sections.

```
BLOCK MASS   # Mass spectrum
#  PDG Code     mass             particle
      25     1.15137179E+02   # lightest neutral scalar
      37     1.48428409E+03   # charged Higgs

BLOCK NMIX  # Neutralino Mixing Matrix
  1  1     9.98499129E-01   # Zn11
  1  2    -1.54392008E-02   # Zn12

BLOCK Au Q=  4.42653237E+02  # The trilinear couplings
  1  1    -8.22783075E+02   # A_u(Q) DRbar
  2  2    -8.22783075E+02   # A_c(Q) DRbar
```

SLHAplus tools for SLHA interface

SUGRA MSSM

```
Name  | Function
Open   | openAppend("suspect2_lha.in")
Input1 | aPrintF("Block MODSEL  # Select model\n  1  1   # SUGRA\n")
Input2 | aPrintF("Block SMINPUTS\n 5 %E#mb(mb)\n 6   %E#mt \n",
                                                     MbMb,Mtp)
Input3 | aPrintF("BLOCK MINPAR\n 1 %E #m0\n 2 %E #m1/2\n”
                                                     ,Mzero,Mhalf)
Input4|  aPrintF("3 %E #tb\n 4 %E #sign(mu)\n 5 %E #A0\n",tb,sgn,A0)
Sys    | System("%s/suspect2.exe",path())
Rd     | slhaRead("suspect2_lha.out",0)
Mh     | slhaVal("MASS",   0.,1,  25)         % light Higgs
Mhc    | slhaVal("MASS",   0.,1,  37)         %  charged Higgs
Zn12   | slhaVal("NMIX",0., 2, 1, 2 )         % neutralino mixing
```

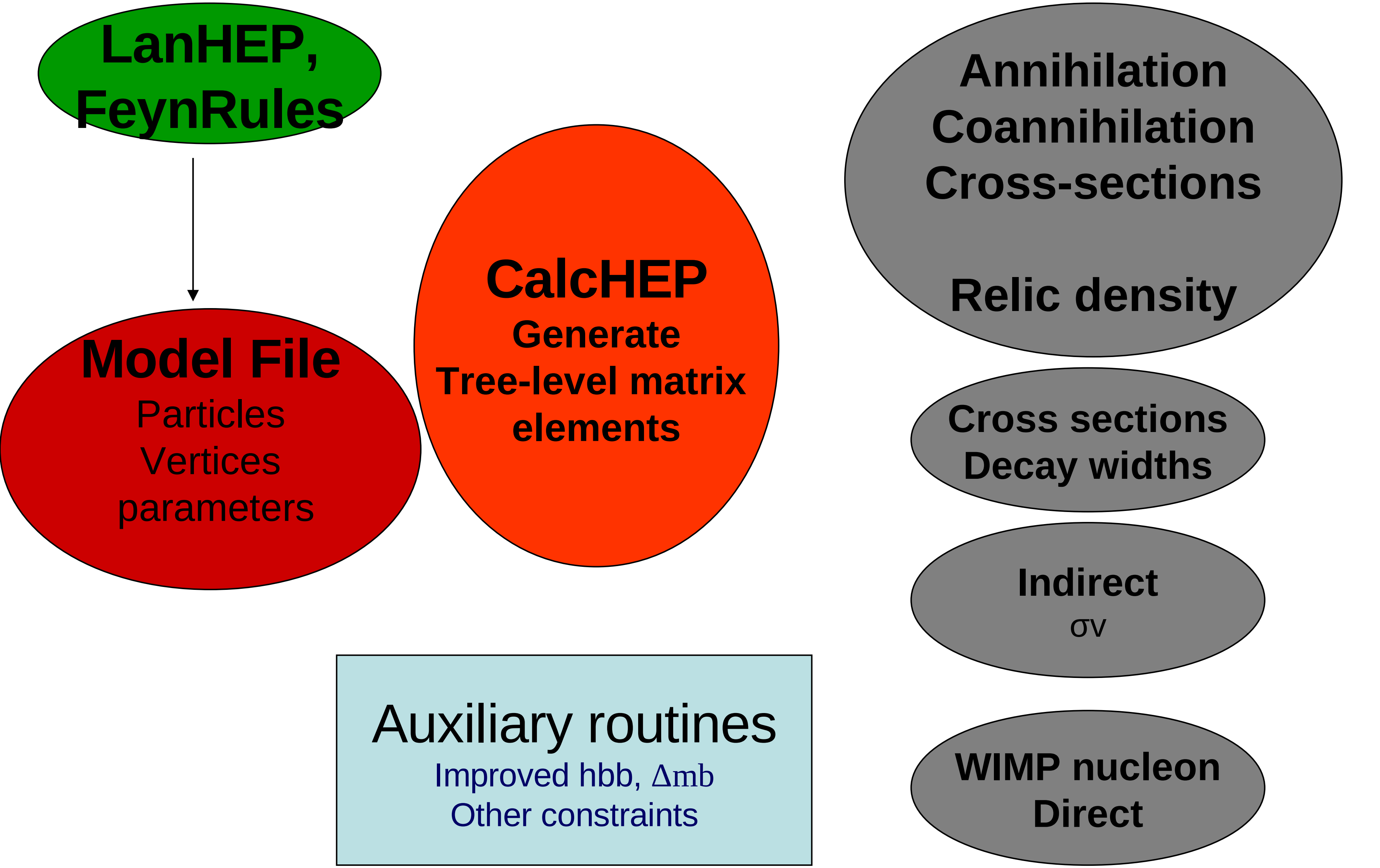
Other tool included in SLHAplus is routines for diagonalizing mass matrices. We have routines for diagonalizing all types of mass matrices which appears in particle physica

id | rDiagonal(2,M11,M12,M22)
M1 | MassArray(id,1)
Zt12 | MixMatrix(id,1,2)

Now all these options are supported by LanHEP (A.Semenov), a code for automatic generation of CalcHEP model files from model definition in terms of field multiplets.

SLHAplus makes implementation of new models very simple.

micrOMEGAs


LanHEP,
FeynRules
Model File
Particles
Vertices
parameters
CalcHEP
Generate
Tree-level matrix
elements
Annihilation
Coannihilation
Cross-sections
Relic density
Cross sections
Decay widths
Indirect
σv
WIMP nucleon
Direct
Auxiliary routines
Improved hbb, Δmb
Other constraints

Dark matter models

- Models distributed
  - MSSM
  - NMSSM (with C. Hugonie, hep-ph/0505142)
  - CPV-MSSM (with S. Kraml, hep-ph/0604150)
  - Right-handed neutrino (with G. Servant, arXiv:0706.0526)
  - Little Higgs (A. Belyaev)
- Other models
  - SUSY N=2 (with K. Benakli et al arXiv:0905.1043)
  - Mixed sneutrino (with M. Kakizaki, S. Kraml, E.K. Park arXiv:1008.0580)
  - UED (with M. Kakizaki, in progress)
- From other groups
  - Scalar DM (Lopez-Honorez et al., S. Su)
  - …..

Runtime matrix element generation.

Any time when some new matrix element needs micrOMEGAs, launches CalcHEP for matrix element generation.

Generated shared libraries are stored on the disk and are linked dynamically.

```
#include <dlfcn.h>
 handle=dlopen(libName, flag);
      returns handre for the library
 void *dlsym(handle,  symbol);
        give address of symbol.
```

Works fine for all UNIX platforms including Linux ,Mac and Cygwin

The idea of dynamic code generation was implemented in CaclHEP itself for calculation of particle widths and branchings.

Asymmetry Dark Matter

In case DM is presented by a particle with internal charge we foresee an option of DM – antiDM abundance difference cause by CP violation.

Density calculation, direct and inderect signals are sensitive to this difference.

Relic density of wimps

- In early universe WIMPs are in thermal equilibrium with SM
- As the universe expanded and cooled their density is reduced.
- Because this reduction is realized through pair annihilation, DM decouples at low temperature.
- There is thermal equilibrium between different kinds of odd particles at all temperatures.
- All co-annihilation processes are included automatically.

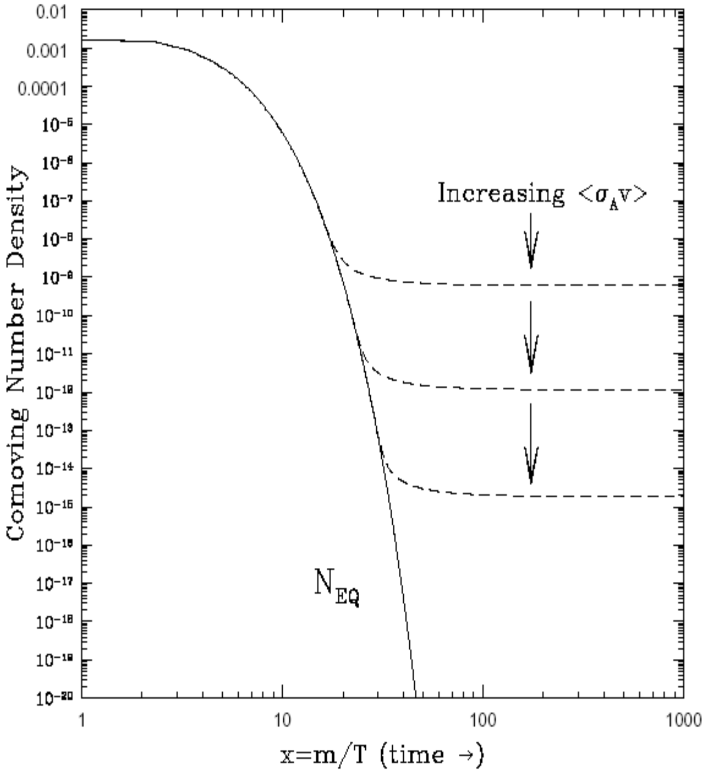
$$< \sigma v >= \frac{\sum\limits_{i,j} g_i g_j \int\limits_{(m_i+m_j)^2} ds\sqrt{s} K_1(\sqrt{s}/T) p_{ij}^2 \sigma_{ij}(s)}{2T\left(\sum\limits_i g_i m_i^2 K_2(m_i/T)\right)^2}$$

$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

$$Y = n/s$$

S is entropy

$$\frac{dY}{dT} = \sqrt{\frac{\pi g_*(T)}{45}} M_p <\sigma v> (Y(T)^2 - Y_{eq}(T)^2)$$



$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle} .$$

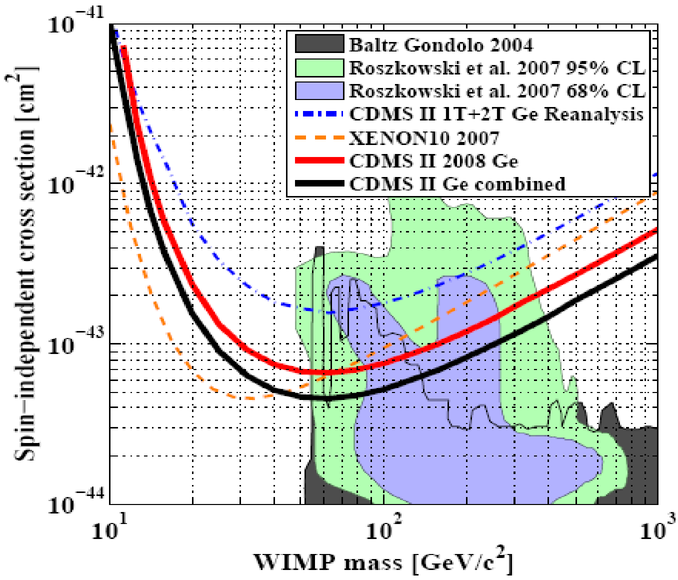
Typical annihilation cross-section at FO

$$<\sigma v> = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$

Direct detection

- Elastic scattering of WIMPs off nuclei in a large detector
- Measure nuclear recoil energy, E_R
- Would give best evidence that WIMPs form DM

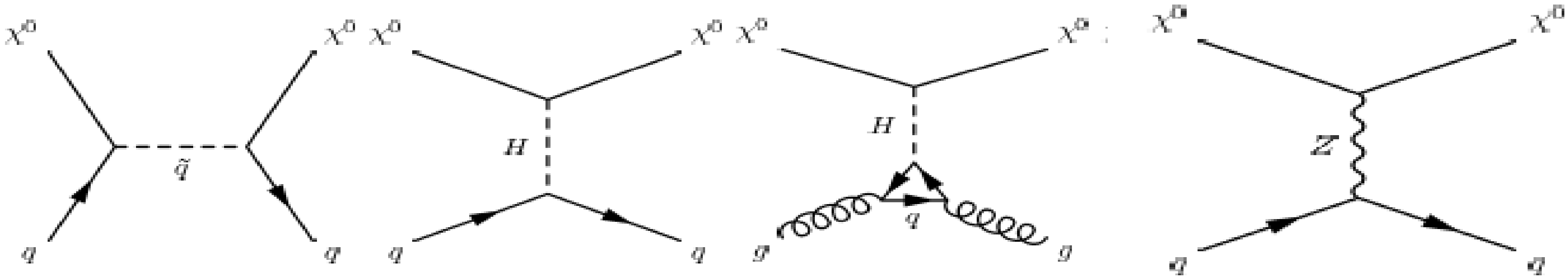
- Two types of scattering
  - Coherent scattering on A nucleons in nucleus, for spin independent interactions
    - Dominant for heavy nuclei
  - Spin dependent interactions – only on one unpaired nucleon
    - Dominant for light nuclei



Direct detection

- Typical diagrams

- Higgs exchange often dominates



For Dirac fermions Z exchange contributes to SI and SD

WIMP quark effective Lagrangian

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

- Operators for WIMP quark Lagrangian, extract automatically the coefficients for SI and SD –

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

- In micrOMEGAs: evaluate coefficients numerically using projection operators
- Add all projection operators as new vertices in the model
- Compute χq-χq scattering element at zero momentum transfer
- Interference between one projection operator and effective vertex- single out SI or SD contribution

$$\lambda_{q,e} + \lambda_{q,o} = \frac{-i\langle q(p_1), \chi(p_2)|\hat{S}\hat{O}_{q,e}|q(p_1), \chi(p_2)\rangle}{\langle q(p_1), \chi(p_2)|\hat{O}_{q,e}\hat{O}_{q,e}|q(p_1), \chi(p_2)\rangle}$$

- Use quark and anti-quark scattering elements to split even/odd contributions
- The projection operators are added to the model file by micrOMEGAs
- Warning: in the model file must include couplings proportional to light quark masses (eg. Hqq coupling)

WIMP-quark to WIMP-nucleon

- Coefficients relate WIMP-quark operators to WIMP nucleon operators
  - Extracted from experiments
  - Source of theoretical uncertainties
- Example , scalar coefficients, contribution of q to nucleon mass

$$\langle N|m_q\overline{\psi}_q\psi_q|N\rangle = f_q^N M_N \qquad \lambda_{N,p} = \sum_{q=1,6} f_q^N \lambda_{q,p}$$

$$f_Q^N = \frac{2}{27}\left(1 - \sum_{q\leq 3} f_q^N\right)$$

- Can be defined by user
- Different coefficients can lead to one order magnitude correction in cross section

- Scalar coefficients extracted from ratios of light quark masses, pion-nucleon sigma term and σ_0 (size of SU(3) breaking effect)

- Large uncertainty in s-quark contribution

Nucleon	f_{Tu}	f_{Td}	f_{Ts} [24]	f_{Ts} [25]	f_{Ts} [20, 26]
n	0.023	0.034	0.08	0.14	0.46
p	0.019	0.041	0.08	0.14	0.46

- Lattice calculations have provide new estimates of those coefficients – soon should help reduce uncertainties

- For example varying coefficients within this range can in the MSSM lead to almost one order of magnitude change in cross section
  - Bottino et al hep-ph/0010203, Ellis et al hep-ph/0502001

WIMP-nucleon to WIMP-nucleus

- Modularity and flexibility: can change velocity distribution, nuclear form factors, quark coefficients in nucleon

$$\frac{dN^{SI}}{dE} = \frac{2M_{det}t}{\pi} \frac{\rho_0}{M_\chi} F_A^2(q) \left(\lambda_p Z + \lambda_n (A-Z)\right)^2 I(E)$$

Particle physics
+ quark content in nucleon

DM velocity distribution

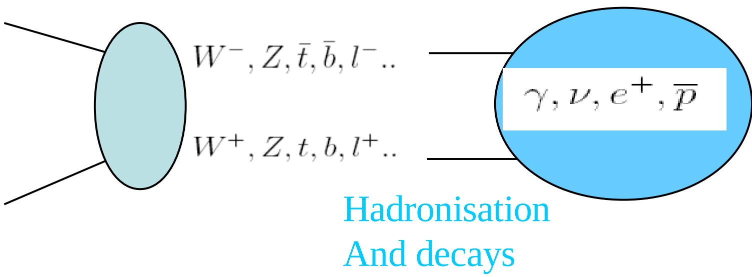
$$\begin{aligned} I(E) &= \int_{v_{min}(E)}^{\infty} \frac{f(v)}{v} dv \\ v_{min}(E) &= \left(\frac{EM_A}{2\mu_\chi^2}\right)^{1/2} \end{aligned}$$

Indirect detection

- Annihilation of pairs of DM particles into SM : decay products observed

- Searches for DM in 4 channels
  - Antiprotons (Pamela)
  - Positrons/electrons from galactic halo/center (Pamela, ATIC, Fermi..)
  - Photons from galactic halo/ center (Egret, Fermi, Hess..)
  - Neutrinos from Sun (IceCube)

- Rate for production of e^+,p,γ
  - Dependence on the DM distribution (ρ) – not well known in center of galaxy



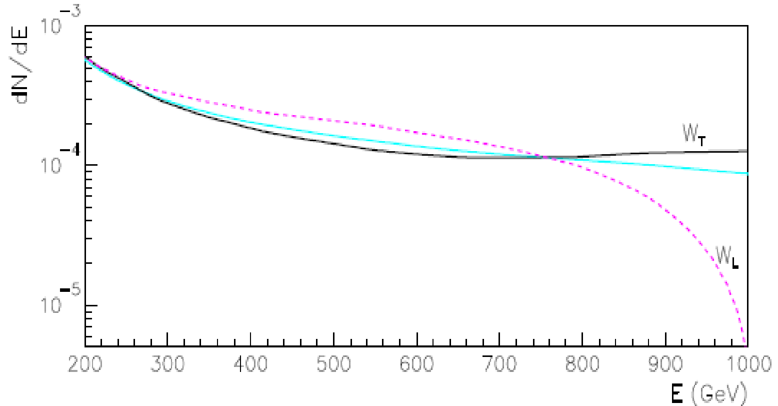
v=0.001c

$$Q(x, \mathrm{E}) = \frac{<\sigma v>}{2} \left(\frac{\rho(\mathbf{x})}{m_\chi} \right)^2 \frac{dN}{dE}$$

Annihilation spectra

- Photon/positron.. production in decay of SM + R-even new particles

- dN/dE : basic channels ff, VV, VH, HH
  - Tables extracted from Pythia6.4 – from 10GeV-5TeV
  - For particles of unknown mass (H,Z'..) compute 1->2 decay recursively until only basic channels
- Vector particle polarisation
  - In MSSM only transverse W's lead to harder positron spectrum
  - Determine degree of polar : reconstruct angular distribution from $\chi\chi \rightarrow We\nu$
  - Decay tables for W_T and W_L



Annihilation spectra

- Radiative emission, 2->3 process
  - FSR included in Pythia, radiation from internal lines also should be included
  - Remove p-wave suppression in MSSM ($\chi\ \chi \to e^+e^-\gamma$)
  - Large enhancement when t-channel mass close to m(LSP), enhancement $m_\chi^2/(m_T^2-m_\chi^2)$
  - Photon spectrum : option to request all 3-body processes
  - Subtraction procedure from Pythia: no double counting

- Monochromatic gamma rays ($\gamma\gamma,\gamma Z$) – loop process but distinctive signature
  - in micromegas_2.4 for MSSM

Dark matter profile

- Integral over line of sight depends strongly on the galactic DM distribution

Halo model	α	β	γ	a (kpc)
Isothermal with core	2	2	0	4
NFW	1	3	1	20
Moore	1.5	3	1.5	28

- DM profile parametrisation

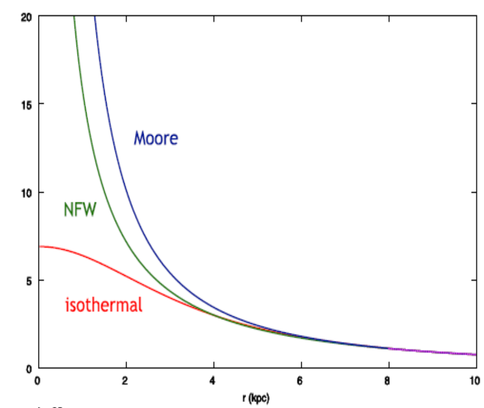
$$\rho_s(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/a)^\alpha}{1+(r/a)^\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}$$

$r_\odot = 8$ kpc

$\rho_\odot = 0.3\ \mathrm{GeV.cm^{-3}}$

- Einasto profile

$$F_{halo}(r) = \exp\left[\frac{-2}{\alpha}\left(\left(\frac{r}{r_\odot}\right)^\alpha - 1\right)\right]$$

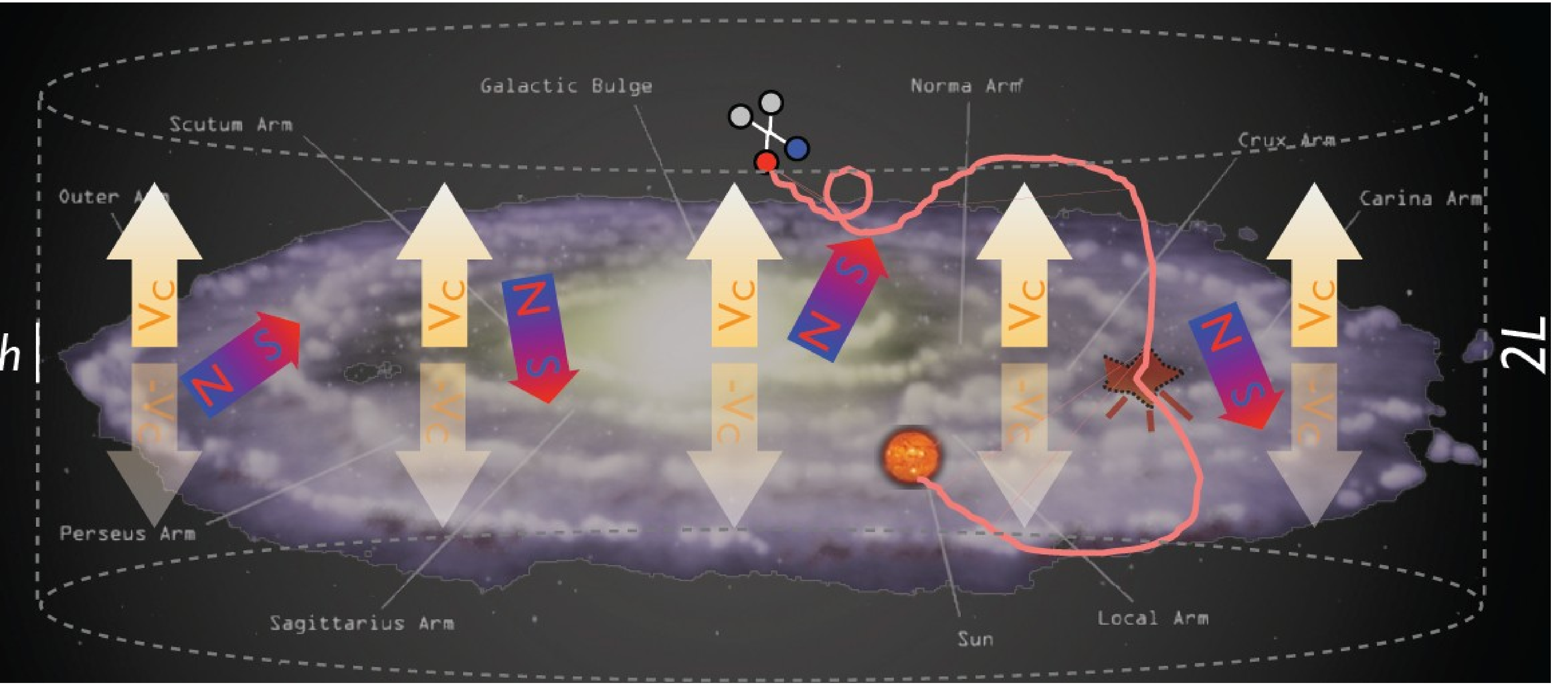


- Clump factor profile
- Different halo profile rather similar except in center of galaxy

micrOMEGAs allows calculation with any user profile

Antiprotons and positrons from DM annihilation in halo

M. Cirelli, Pascos2009



$$\frac{\partial N}{\partial t} - \nabla \cdot [K(\mathbf{x}, E)\, \nabla N] - \frac{\partial}{\partial E}[b(E)\, N] = q(\mathbf{x}, E)$$

diffusion Energy losses Source

Propagation

- Positrons: dominated space diffusion and energy loss (synchroton radiation, Inverse Compton scattering)

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

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

- Antiprotons: energy loss negligible
  - Negative source term (annihilation of antiproton in interstellar medium)
  - Galactic wind, convective velocity: V_c

$$\left[-K(E)\nabla^2 + V_c\frac{\partial}{\partial z} + 2(V_c + h\Gamma_{tot}(E))\delta(z)\right]\psi_{\bar{p}}(E, r, z) = \frac{\sigma v}{2}\frac{\overline{\rho^2}(r, z)}{M_\chi^2} f_{\bar{p}}(E)$$

- Propagation parameters constrained by B/C

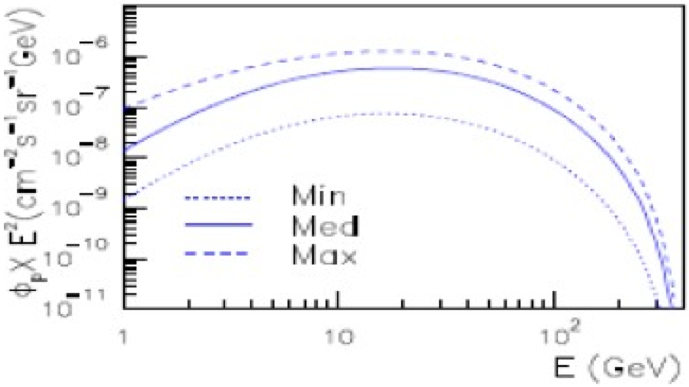
Propagation

- Choice of diffusion parameters

Model	δ	K_0 (kpc^2/Myr)	L (kpc)	V_C(km/s)
MIN	0.85	0.0016	1	13.5
MED	0.7	0.0112	4	12
MAX	0.46	0.0765	15	5

Donato et al

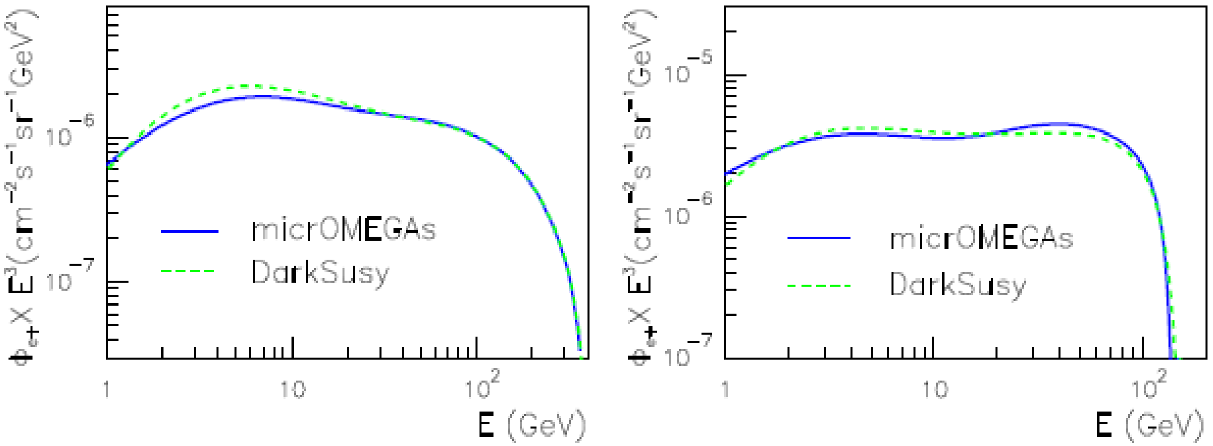
- Strong impact on the predictions



Model 1
$\mu = -440, M_A = 1000$
$M_2 = 800, M_0 = 2500$
$A_t = A_b = 1000$
$\tan\beta = 10$

- At low energies solar modulation effect

Comparison micrOMEGAs/DarkSUSY for positron spectrum



Model 1	Model 2
$\mu = -440, M_A = 1000$	$\mu = -200, M_A = 1000$
$M_2 = 800, M_0 = 2500$	$M_2 = 320, M_0 = 2500$
$A_t = A_b = 1000$	$A_t = -A_b = -2500$
$\tan\beta = 10$	$\tan\beta = 8.$

$\delta = 0.6$, $K_0 = 0.03607$ kpc^2/Myr, $L = 4$ kpc and $V_C = 10$ km/s.

Nearest future development

1)calculation of signal from annihilation of DM captured Sun (almost done)

2) signal from unstable DM (very easy)

3) Other models (always in progress)

4) DM,DM -> A,A/A,Z (almost done)

5) Interface with GalProp