micrOMEGAs :
a tool for dark matter studies

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LAPTH

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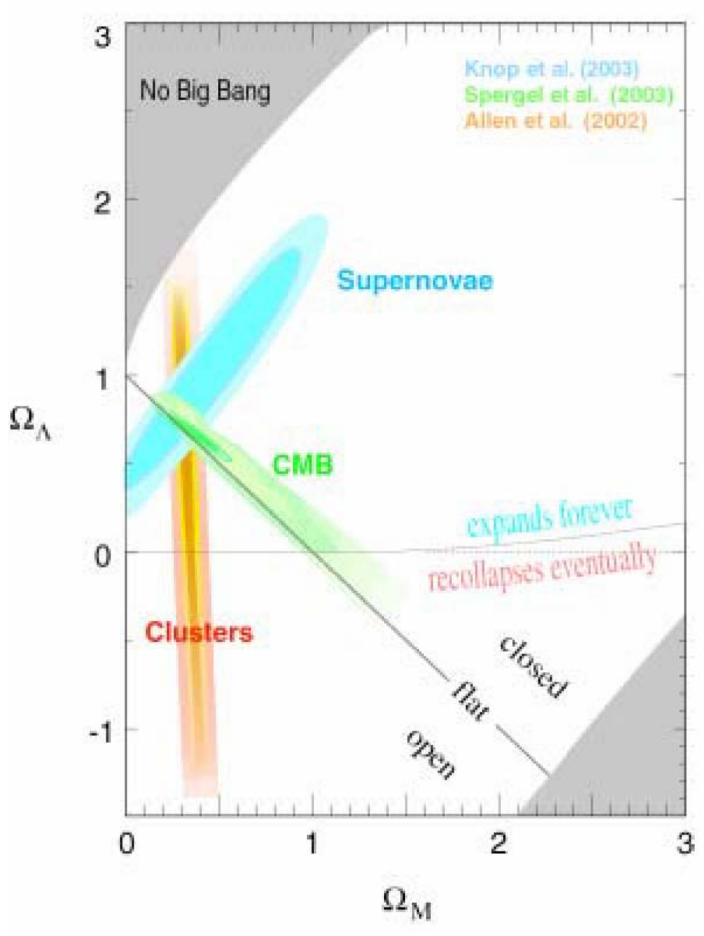
hep-ph/0112278, hep-ph/0405253,
hep-ph/0607059, arXiv:08032360[hep-ph]
arXiv:1004.1092[hep-ph]

Outline

- General description
- Interactive session
  - Running the code
  - New models
- Download
  - http:://wwwlapp.in2p3.fr/lapth/micromegas
- Installation
  - tar –zxvf micromegas_2.4.O.tgz

Motivation

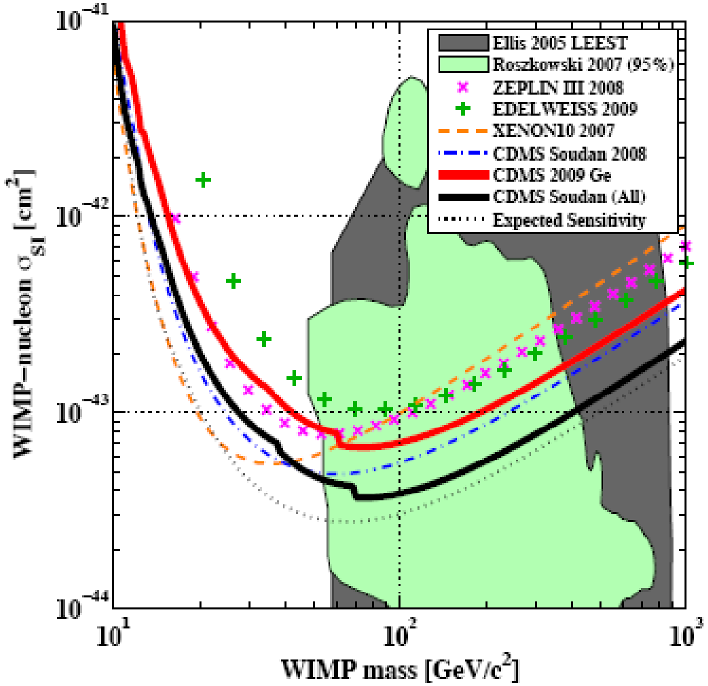
- Strong evidence for dark matter
- CMB (WMAP+SDSS) gives precise information on the amount of dark matter
- Most attractive explanation for dark matter: new weakly interacting particle
- Many models for new physics whose main motivation is to solve the hierarchy problem also have a dark matter candidate – symmetry that ensures that lightest particle is stable
  - MSSM and extensions, UED, warped extra-dim, little Higgs, techinicolour +….
- R-parity like symmetry introduced to avoid rapid proton decay or guarantee agreement with electroweak precision



- Cosmological measurements are strongly constraining dark matter models

- Direct and indirect searches are also probing models of dark matter
  - Xenon, CDMS, Cogent, Picasso, Coupp, DAMA, Fermi, PAMELA …

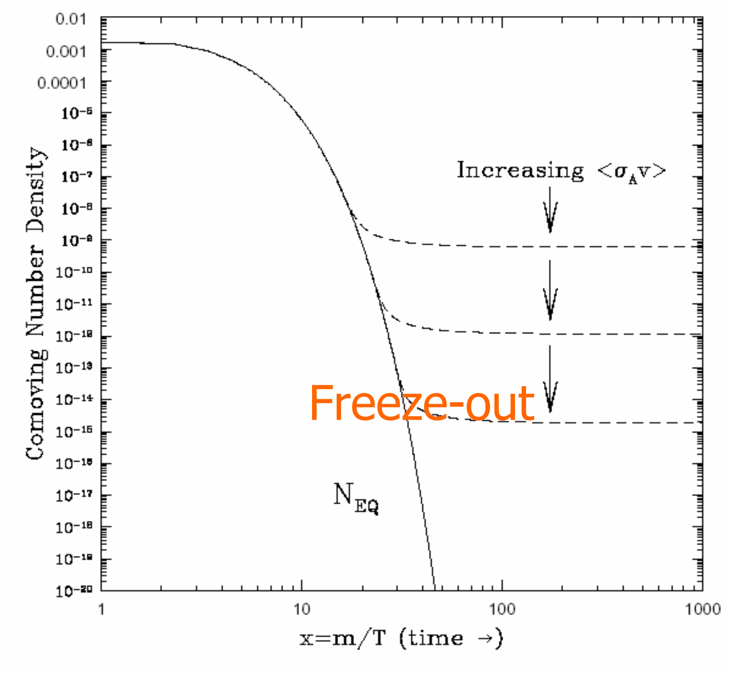
- Public codes for dark matter studies in the MSSM:
  - micrOMEGAs, DarkSUSY, Isatools, superIso



•*Complete tool for dark matter studies : precise calculation of relic density, direct detection, indirect detection, cross section at colliders and decays in a wide variety of models: micrOMEGAs2.4*

Relic density of wimps

- In early universe WIMPs are present in large number and they are in thermal equilibrium
- As the universe expanded and cooled their density is reduced through pair annihilation
- Eventually density is too low for annihilation process to keep up with expansion rate
  - Freeze-out temperature
- LSP decouples from standard model particles, density depends only on expansion rate of the universe



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

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

Solving numerically, get present day abundance $Y(T_0)$ and

$$\Omega_{LOP} h^2 = \frac{8\pi}{3} \frac{s(T_0)}{M_p^2 (100(\mathrm{km/s/Mpc}))^2} M_{LOP} Y(T_0) = 2.742 \times 10^8 \frac{M_{LOP}}{GeV} Y(T_0)$$

Weakly interacting particle gives roughly the right annihilation cross section to have $\Omega h^2 \sim 0.1$ ‘WIMP miracle’

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

Typical annihilation cross-section at FO $\quad < \sigma v >= 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}$

Coannihilation

- If M(NLSP)~M(LSP) then $\chi + X \longrightarrow \chi' + Y$ maintains thermal equilibrium between NLSP-LSP even after non standard particles decouple from standard ones

- Relic density depends on rate for all processes involving LSP/NLSP → SM

- All particles eventually decay into LSP, calculation of relic density requires summing over all possible processes

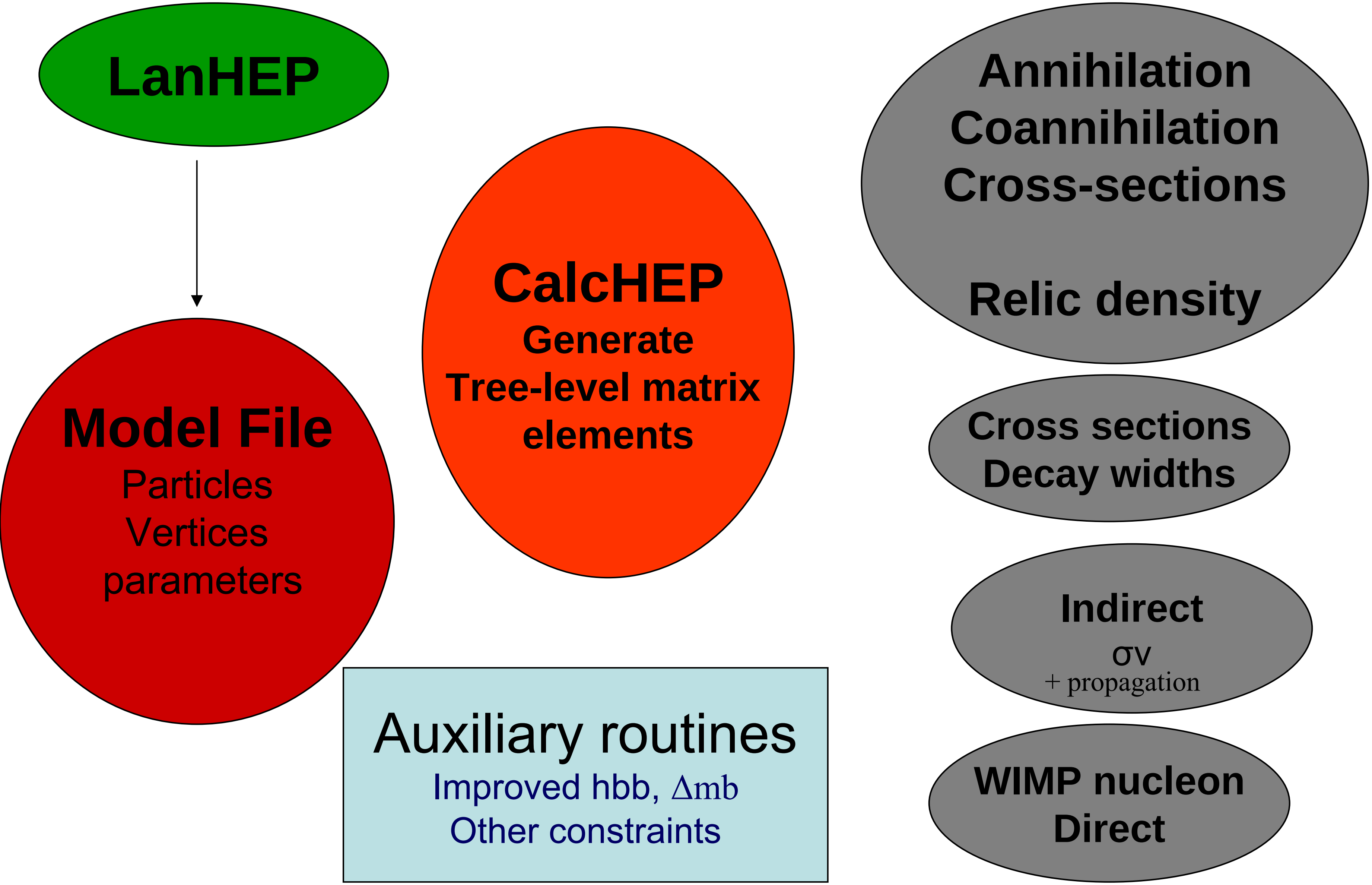
Exp(- ΔM)/T

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

- **Important processes are those involving particles close in mass to LSP, for example up to 3000 processes can contribute in MSSM**

- *Need for automation*

micrOMEGAs



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

micrOMEGAs_2.4

- A generic program to calculate DM properties in any model
- Assume some “ R-parity “, particles odd/even under R (odd particles: ~)
- Need to specify model file in CalcHEP notation : particles, variables, vertices, functions (do by hand or with LanHEP)
- After the model is implemented and checked with CalcHEP
  - Code then automatically looks for “LSP”
  - Computes all annihilation and coannihilation cross-sections
  - Complete tree-level matrix elements for all subprocesses
  - Automatically check for presence of resonances and improves the accuracy near pole
  - Numerical solution of evolution equation and calculation of relic density with non-relativistic thermal averaging and proper treatment of poles and thresholds
    - Gondolo, Gelmini, NPB 360 (1991)145
    - coannihilation : Edsjo, Gondolo PRD56(1997) 1879

- Includes and compiles relevant channels only if needed (Beps)

$$B = \frac{K_1((m_i + m_j)/T)}{K_1(2m_{LOP}/T)} \approx e^{-X\frac{(m_i+m_j-2M_{LOP})}{M_{LOP}}} > B_\epsilon$$

- Calculates the relic density for any LSP (even charged)
- Computes σv, v->0 for LSP,LSP annihilation and signatures for γ and positron/antiproton including propagation
- Automatically compute elastic scattering rate on nucleon/nucleus

- CalcHEP is included: computes all 2->2 processes and 1-> 2,3 decays at tree-level
- Some facilities provided for pp collisions
- Interactive link to CalcHEP

- *For new models : constraints and auxiliary routines must be provided by the user in fortran or C routine*
- C code

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 available
  - Scalar DM (Lopez-Honorez et al., S. Su)

- Models to be distributed
  - SUSY N=2 (with K. Benakli et al arXiv:0905.1043)
  - UED (with M. Kakizaki)
  - MSSM+RHneutrino (with M. Kakizaki, S. Kraml, E.K. Park)

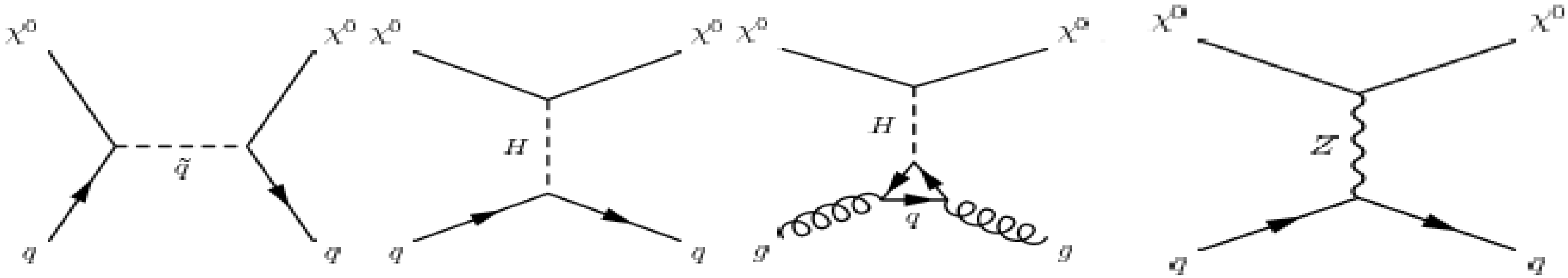
Direct detection

- 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- Nucleon amplitude

- For any WIMP, need effective Lagrangian for WIMP-nucleon amplitude *at small momentum ~100MeV*,
- Generic form for a fermion

$$\mathcal{L}_F = \lambda_N \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + i\kappa_1 \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \gamma_5 \psi_N + i\kappa_2 \bar{\psi}_\chi \gamma_5 \psi_\chi \bar{\psi}_N \psi_N + \kappa_3 \bar{\psi}_\chi \gamma_5 \psi_\chi \bar{\psi}_N \gamma_5 \psi_N$$
$$+ \kappa_4 \bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N + \xi_N \bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_N \gamma^\mu \gamma_5 \psi_N$$

- For Majorana fermion only 2 operators survive at small q^2

- First need to compute the WIMP quark amplitudes
  - normally computed symbolically from Feynman diagrams+ Fierz
  - Automatic approach (works for all models)
- Effective Lagrangian for WIMP-quark scattering has same generic form as WIMP nucleon

WIMP quark effective Lagrangian

	WIMP Spin	Even operators	Odd operators
SI	0 1/2 1	$2M_\chi\phi_\chi\phi_\chi^*\overline{\psi}_q\psi_q$ $\overline{\psi_\chi}\psi_\chi\overline{\psi}_q\psi_q$ $2M_\chi A_{\chi,\mu}A_\chi^\mu\overline{\psi}_q\psi_q$	$i(\partial_\mu\phi_\chi\phi_\chi^* - \phi_\chi\partial_\mu\phi_\chi^*)\overline{\psi}_q\gamma^\mu\psi_q$ $\overline{\psi_\chi}\gamma_\mu\psi_\chi\overline{\psi}_q\gamma^\mu\psi_q$ $+i\lambda_{q,o}(A_\chi^{*\alpha}\partial_\mu A_{\chi,\alpha} - A_\chi{}^\alpha\partial_\mu A_{\chi\alpha}^*)\overline{\psi}_q\gamma_\mu\psi_q$
SD	1/2 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 –

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

- 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

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

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

- 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

- Rates (SI and SD) depends on nuclear form factors and velocity distribution of WIMPs + local density

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

Nuclear form factors

Particle physics + quark content in nucleon

DM velocity distribution

$$I(E) = \int_{v_{min}(E)}^{\infty} \frac{f(v)}{v} dv$$

$$v_{min}(E) = \left(\frac{EM_A}{2\mu_\chi^2}\right)^{1/2}$$

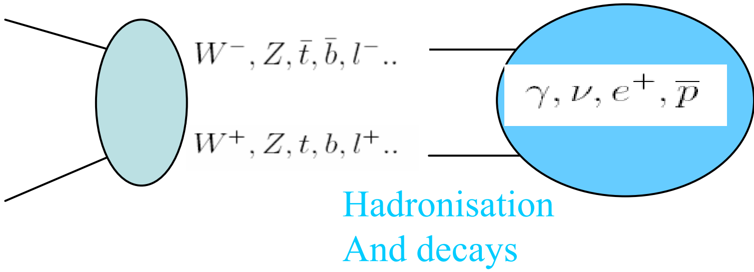
- Modularity and flexibility: can change velocity distribution, nuclear form factors, quark coefficients in nucleon

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

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

Photons

- Flux calculation

$$\Phi_{\gamma,\nu} = \frac{1}{8\pi}\frac{<\sigma_{ann}v>}{m_\chi^2}\sum_{f.s.}\left(\frac{dN_{\gamma,\nu}}{dE}\right)_{f.s.}\int_{l.o.s.}\rho_s^2$$

- Photon production
  - In decay of SM particles + R-even new particles
  - dN/dE : basic channels ff, VV, VH, HH and polarization of gauge bosons
  - For particles of unknown mass (H,Z'..) compute 1->2 decay recursively until only basic channels
  - Monochromatic gamma rays (γγ,γZ) – for MSSM
  - Internal bremsstrahlung ($\chi\,\chi \to e^+e^-\gamma$)

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

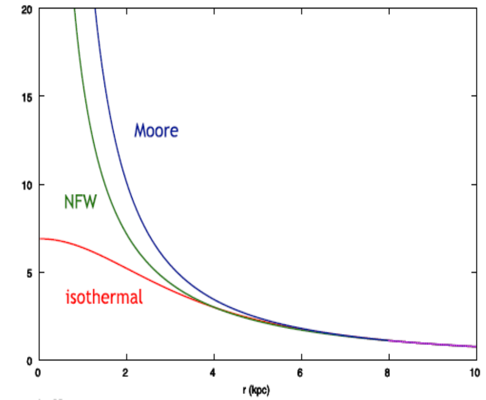
Dark matter profile

- Dark matter 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

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



- Different halo profile rather similar except in center of galaxy

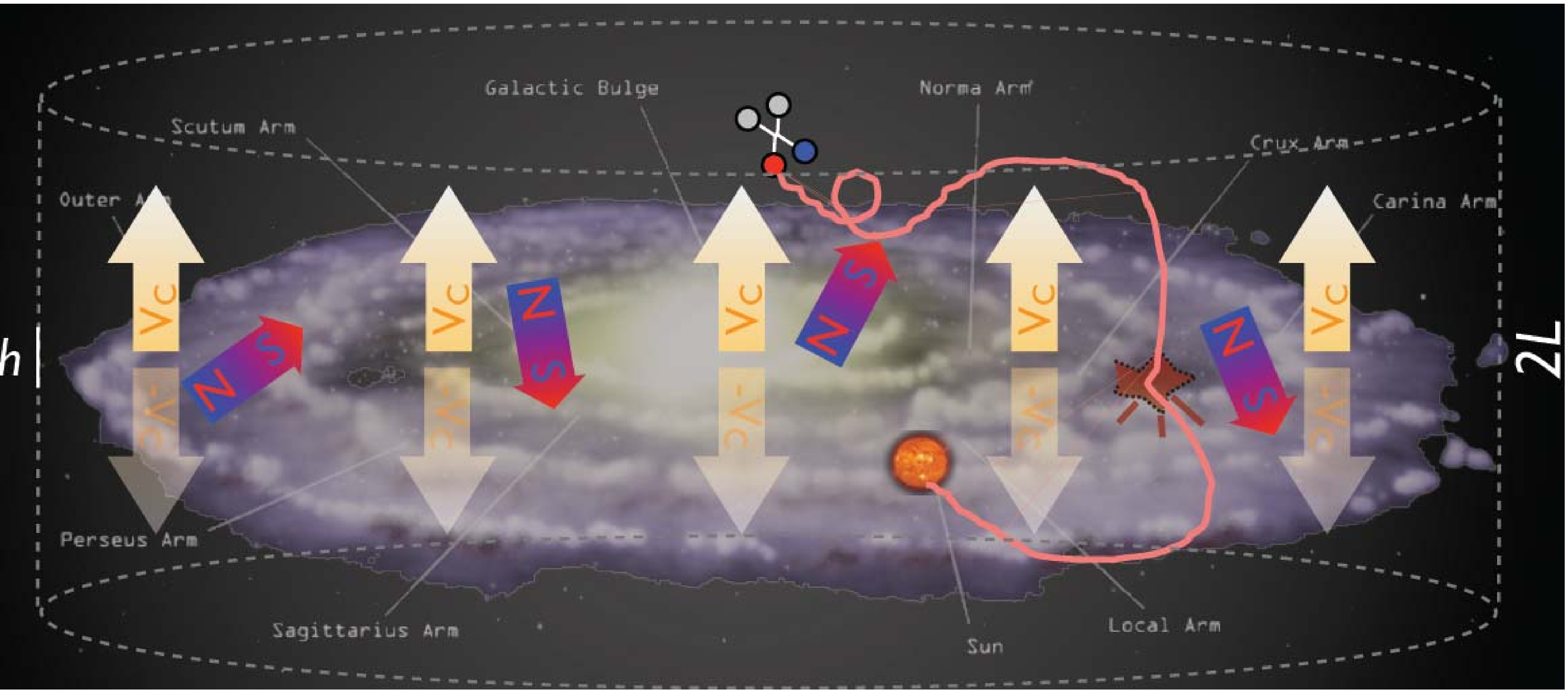
Halo model	α	β	γ	a (kpc)
Isothermal with core	2	2	0	4
NFW	1	3	1	20
Moore	1.5	3	1.5	28

- Also Einasto profile

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

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 of cosmic rays

- *For Charged particle spectrum detected different than spectrum at the source*

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

- Charged cosmic rays deflected by irregularities in galactic magnetic field
  - For strong magnetic turbulence effect similar to space diffusion
- Energy losses due to interactions with interstellar medium
- Convection driven by galactic wind and reacceleration due to interstellar shock wave
- For positron, antiproton : solution propagation equations based on
  - Lavalle, Pochon, Salati, Taillet, astro-ph/0603796

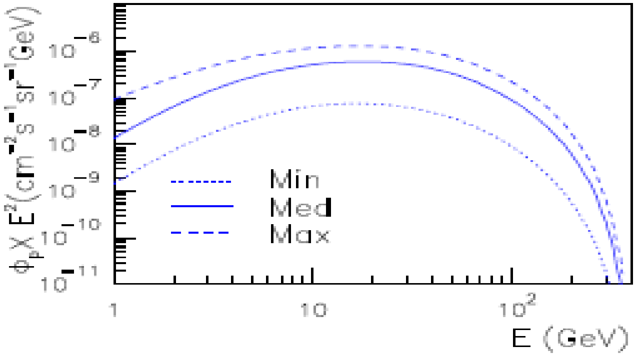
Propagation

- 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

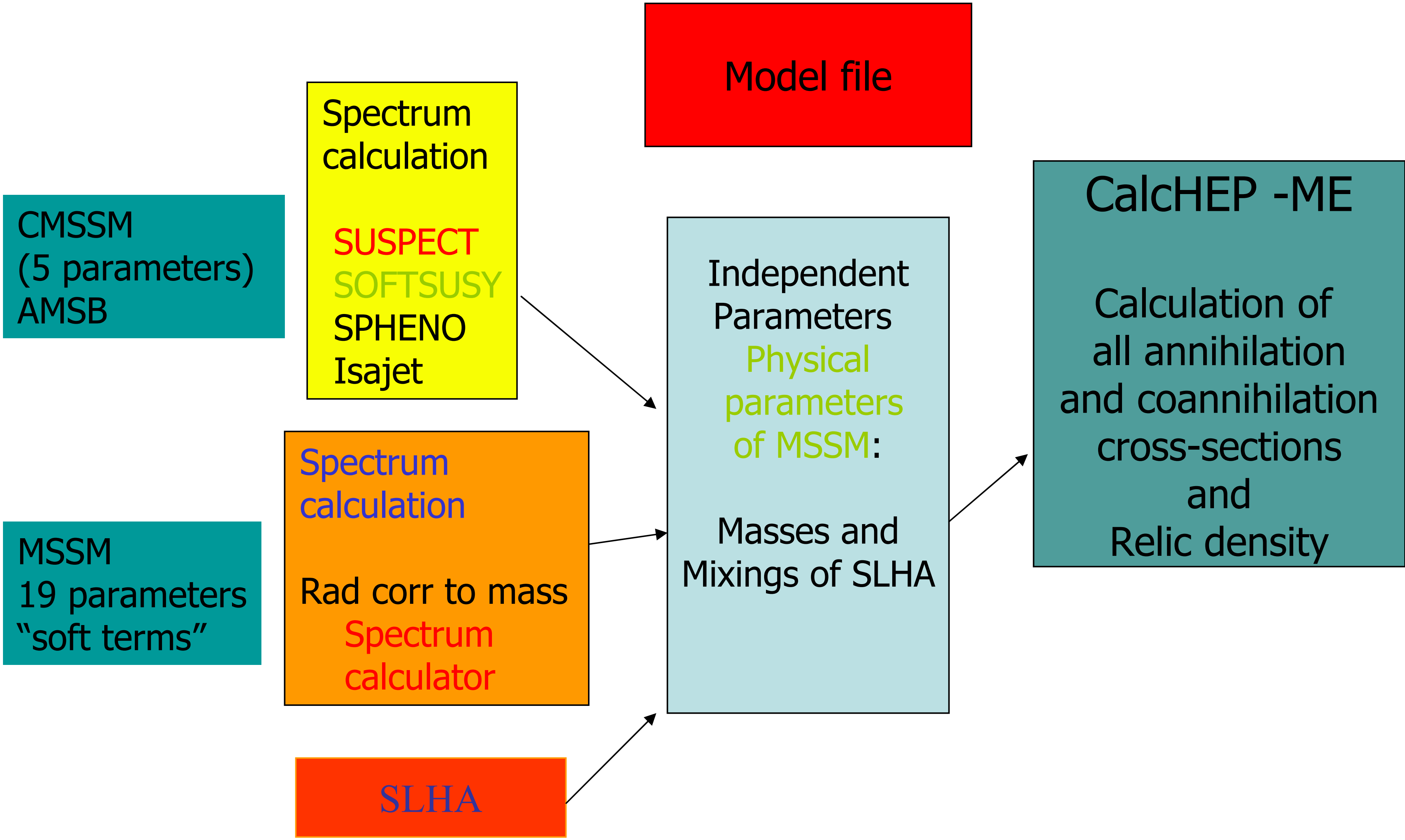


Model 1
$\mu = -440, M_A = 1000$
$M_2 = 800, M_0 = 2500$
$A_t = A_b = 1000$
$\tan\beta = 10$

- At low energies solar modulation effect

MSSM

Parameters of MSSM model file



MSSM-Specific features

- Independent parameters of model are physical parameters of SHLA, flexibility: any model for which the MSSM spectrum can be calculated with an external code can be incorporated easily

- Input parameters to micromegas can be specified at the weak scale or at the GUT scale using some SpectrumCalc program, includes CMSSM, non-univ. SUGRA, AMSB

- ***Uses SUSY Les Houches Accord***

- Radiative corrections to masses can be important – SUSY masses and Higgs masses (via spectrum calculator)

- Package includes other constraints (developed for MSSM) – not automatic

  b->s γ (NLO) , $(g-2)_{\mu}$, B_s->$\mu\mu$, B->$\tau\nu$, $\Delta\rho$

Extensions of MSSM

- Spectrum calculation, constraints on models: make use of existing programs develop independently, when possible interface with SLHA2
  - NMSSM
    - relies on NMSSMTools (NMSPEC and NMHDECAY) for spectrum calculation, indirect constraints (B physics, g-2, Higgs collider constraitns)
    - Ellwanger, Gunion, Hugonie
  - CPVMSSM :
    - interface to CPSuperH (J.S. Lee et al) for spectrum calculation, effective Higgs potential and constraints: edm, Bphysics
    - Interface to Higgs bounds for LEP/Tevatron Higgs constraints (next release)

Interactive session

Download

- New version micromegas_2.4
  - http:://wwwlapp.in2p3.fr/lapth/micromegas
  - For help, bug report : micro.omegas@lapp.in2p3.fr
- Installation

  tar –zxvf micromegas_2.4.O.tgz
- cd micromegas_2.4.O

```
calc         clean    LHM             MSSM        README
CalcHEP_src  CPVMSSM  Makefile        newProject  RHNM
cgwRun       etc      manual240.tex   NMSSM       sources
```

- make
- Go to the directory of model you want to work with
- cd MSSM
  - sample main file main.c – fix switches

Main program - description

```
/*======  Spectrum calculator  =========
   Choose RGE from the list below. SuSpect is included
   in micrOMEGAs, to use another code define the path
   to the corresponding package in lib/Makefile
=======================================*/
#define RGE suspect
     /* choose 'suspect','isajet','softSusy','spheno'*/

/*=========   SUSY scenario  ==========
  One can define SUGRA, AMSB, EWSB (for low scale input).
  By default program reads SLHA data file
=========================================*/
#define SUGRA
/* #define AMSB  */
/*#define EWSB */

/*====== Modules ===============
   Keys to switch on
   various modules of micrOMEGAs
==================================*/

#define MASSES_INFO
      /* Display information about SUSY and Higgs masses
      */
#define CONSTRAINTS
      /* Display  deltarho, B_>sgamma, Bs->mumu, gmuon and
         check LEP mass limits
      */
#define OMEGA
      /* Calculate relic density and display contribution of
         individual channels
      */
```

```
#define INDIRECT_DETECTION
      /* Compute spectra of gamma/positron/neutrinos
         for DM annihilation; calculate <sigma*v> and
         integrate gamma signal over DM galactic squared
         density for given line of sight.
      */

/*#define RESET_FORMFACTORS*/
      /* Modify default nucleus form factors,
         DM velocity distribution,
```

```
#define CDM_NUCLEON
      /* Calculate amplitudes and cross-sections for
         CDM-mucleon collisions
      */
/* #define TEST_Direct_Detection */
      /*
        Compare analytical formula for DD against micrOMEGAS calculation.
        As well as compare tree level and box improved approaches.
       */
#define CDM_NUCLEUS
      /* Calculate number of events for 1kg*day
         and recoil energy distibution for various nuclei
      */
#define DECAYS
      /* Calculate decay widths and branchings  */
/* #define CROSS_SECTIONS */
      /* Calculate cross sections of reactions specified by the user */

/*===== end of Modules  ======*/
```

Choosing options

```
#ifdef INDIRECT_DETECTION
{
  int err,i;
  double Emin=1,SMmev=320;/*Energy cut in GeV and solar potential in MV*/
  double  sigmaV;
  double vcs_gz,vcs_gg;
  char txt[100];
  double SpA[NZ],SpE[NZ],SpP[NZ];
  double SpNe[NZ],SpNm[NZ],SpNl[NZ];
  double Etest=Mcdm/2;

  K_dif=0.036;
  L_dif=4;

  sigmaV=calcSpectrum( 1+2+4,SpA,SpE,SpP,SpNe,SpNm,SpNl ,&err);
    /* Returns sigma*v in cm^3/sec.     SpX - calculated spectra of annihilation.
       Use SpectdNdE(E, SpX) to calculate energy distribution in  1/GeV units.

       First parameter 1-includes W/Z polarization
                       2-includes gammas for 2->2+gamma
                       4-print cross sections
    */
```

Global parameters

Name	Default value	Units	Comments
Mcdm		GeV	Mass of Dark Matter particle, M_χ
Rsun	8.	kpc	Distance from the Sun to the Galactic center, $r_\odot$
rhoDM	0.3	GeV/cm^3	Dark Matter density at Rsun, $\rho_\odot$
Rdisk	20	kpc	Radius of the galactic diffusion disk, R
K_dif	0.0112	kpc^2/Myr	Diffusion coefficient K_0
L_dif	4	kpc	Half height of the galactic diffusion zone L

make main=main.c

./main 120 500 -300 10 1 173.1

```
========= mSUGRA scenario =====
 Spectrum calculator is suspect
Warnings from spectrum calculator:
 .....none

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

~o1 = 0.997*bino -0.015*wino +0.074*higgsino1 -0.029*higgsino2

=== MASSES OF HIGGS AND SUSY PARTICLES: ===
Higgs masses and widths
    h   115.99 2.52E-03
    H   766.59 1.78E+00
   H3   766.34 1.82E+00
   H+   770.85 1.73E+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
~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 ||
```

Relic density

```
==== Physical Constraints: =====
deltartho=1.51E-05
gmuon=9.47E-10
bsgnlo=3.58E-04
bsmumu=3.09E-09
btaunu=9.91E-01
MassLimits OK

==== Calculation of relic density =====
Xf=2.65e+01 Omega=1.10e-01

Channels which contribute to 1/(omega) more than 1%.
Relative contrubutions 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
  3% ~o1 ~mR -> A m
  3% ~l1 ~L1 -> A Z
  3% ~eR ~l1 -> e l
  3% ~mR ~l1 -> m l
The rest 7.79 %
```

Indirect and direct detection

```
==== Indirect detection =======
    Channel            vcs[cs^3/s]
  ~o1,~o1 -> b B          2.25E-29
  ~o1,~o1 -> t T          2.55E-29
  ~o1,~o1 -> l L          5.37E-29
  ~o1,~o1 -> W+ W-        2.95E-31
  ~o1,~o1->e,E,A
  ~o1,~o1->m,M,A
  ~o1,~o1->l,L,A
sigmav=1.02E-28[cm^3/s]
Photon flux  for angle of sight f=0.00[rad]
and spherical region described by cone with angle 0.0349[rad]
Photon flux = 7.51E-16[cm^2 s GeV]^{-1} for E=103.0[GeV]
Executable
 /home/genevieve/tools/micromegas_2.4.0/MSSM/work/../nngg/lGamma.exe
 is not found. Launch 'make -C nngg'
Positron flux  =  3.50E-14[cm^2 sr s GeV]^{-1} for E=103.0[GeV]
Antiproton flux  =  2.06E-15[cm^2 sr s GeV]^{-1} for E=103.0[GeV]

==== Calculation of CDM-nucleons amplitudes  =====
CDM-nucleon micrOMEGAs amplitudes:
proton:  SI  -1.316E-09  SD  -1.575E-08
neutron: SI  -1.332E-09  SD  1.984E-08
CDM-nucleon cross sections[pb]:
 proton  SI 7.497E-10  SD 3.223E-07
 neutron SI 7.691E-10  SD 5.113E-07

======== Direct Detection ========
73Ge: Total number of events=1.74E-04 /day/kg
Number of events in 10 - 50 KeV region=9.40E-05 /day/kg
131Xe: Total number of events=2.87E-04 /day/kg
Number of events in 10 - 50 KeV region=1.43E-04 /day/kg
```

Decays and cross sections

```
~o2->2*x :   total width=3.837725E-01
 and Branchings:
2.128198E-03 ~o2 -> Z,~o1
2.914427E-02 ~o2 -> h,~o1
6.004674E-02 ~o2 -> E,~eL
6.004674E-02 ~o2 -> e,~EL
1.052718E-03 ~o2 -> E,~eR
1.052718E-03 ~o2 -> e,~ER
6.004674E-02 ~o2 -> M,~mL
6.004674E-02 ~o2 -> m,~ML
1.052718E-03 ~o2 -> M,~mR
1.052718E-03 ~o2 -> m,~MR
4.205439E-02 ~o2 -> L,~l1
4.205439E-02 ~o2 -> l,~L1
5.482904E-02 ~o2 -> L,~l2
5.482904E-02 ~o2 -> l,~L2
8.582378E-02 ~o2 -> Ne,~ne
8.582378E-02 ~o2 -> ne,~Ne
8.582378E-02 ~o2 -> Nm,~nm
8.582378E-02 ~o2 -> nm,~Nm
9.363385E-02 ~o2 -> Nl,~nl
9.363385E-02 ~o2 -> nl,~Nl
```

Implementing and working with a new model

micromegas_2.x

- A generic program to calculate the relic density of DM in any model
- Assume some “ R-parity “ particles either odd/even under this parity (odd particles: ~)
- A simple example : RH neutrino
- Create new model
  - ./newProject name
- New directory created with all routines to compute annihilation cross sections find the “LSP’, look for possible resonances, ‘main program’
- User needs to specify model file in CalcHEP notation : particles, variables, vertices, functions in work/models (do by hand or with LanHEP)

Particles : prtcls1.mdl

```
RH neutrino
 Particles
 Full  name    |A   |A+  | number  |2*spin| mass   |width  |color|aux|>LaTex(A)<|>LaTeX(A+)   <|
photon         |A   |A   |22       |2     |0       |0      |1    |G  |\gamma     |\gamma
gluon          |G   |G   |21       |2     |0       |0      |8    |G  |g          |g
electron       |e   |E   |11       |1     |0       |0      |1    |   |e          |\bar{e}
e-neutrino     |ne  |Ne  |12       |1     |0       |0      |1    |L  |\nu_e      |\bar{\nu}_e
muon           |m   |M   |13       |1     |Mm      |0      |1    |   |\mu        |\bar{\mu}
m-neutrino     |nm  |Nm  |14       |1     |0       |0      |1    |L  |\nu_\mu    |\bar{\nu}_\mu
tau-lepton     |l   |L   |15       |1     |Ml      |0      |1    |   |\tau       |\bar{\tau}
t-neutrino     |nl  |Nl  |16       |1     |0       |0      |1    |L  |\nu_\tau   |\bar{\nu}_\tau
u-quark        |u   |U   |2        |1     |Mu      |0      |3    |   |u          |\bar{u}
d-quark        |d   |D   |1        |1     |Md      |0      |3    |   |d          |\bar{d}
c-quark        |c   |C   |4        |1     |Mc      |0      |3    |   |c          |\bar{c}
s-quark        |s   |S   |3        |1     |Ms      |0      |3    |   |s          |\bar{s}
t-quark        |t   |T   |6        |1     |Mtp     |wtp    |3    |   |t          |\bar{t}
b-quark        |b   |B   |5        |1     |Mb      |0      |3    |   |b          |\bar{b}
Higgs          |H   |H   |25       |0     |MH      |!wH    |1    |   |H          |H
W-boson        |W+  |W-  |24       |2     |MW      |wW     |1    |   |W^+        |W^-
Z-boson        |Z   |Z   |23       |2     |MZ      |wZ     |1    |   |Z          |Z
LZP            |~n4|~N4|100000    |1     |MLZP    | wn4   |1    |   |           |
===========================================================================================
```

Vertices (lgrng1.mdl)

```
RH neutrino (RS-inspired)
 Vertices
A1   |A2   |A3   |A4   |>          Factor               <|>  Lorentz part
G    |G    |G    |     |SC                               |m1.m2*(p1-p2).m3+m2.m3*(p2-p3).m1+m3.m1
W+   |W-   |A    |     |-EE                              |m1.m2*(p1-p2).m3+m2.m3*(p2-p3).m1+m3.m1
W+   |W-   |A    |A    |-EE^2                            |2*m1.m2*m3.m4-m1.m3*m2.m4-m1.m4*m2.m3
H    |W+   |W-   |     |EE*MW/SW                         |m2.m3
H    |H    |H    |     |-(3/2)*EE*MH^2/(MW*SW)           |1
H    |H    |H    |H    |(-3/4)*(EE*MH/(MW*SW))^2         |1
U    |u    |H    |     |-EE*Mu/(2*MW*SW)                 |1
T    |t    |H    |     |-EE*Mtp/(2*MW*SW)                |1
Ne   |e    |W+   |     |EE/(2*Sqrt2*SW)                  |G(m3)*(1-G5)
E    |ne   |W-   |     |EE/(2*Sqrt2*SW)                  |G(m3)*(1-G5)
E    |e    |Z    |     |-EE/(4*SW*CW)                    |G(m3)*(1-G5)-4*(SW^2)*G(m3)
T    |t    |A    |     |(2/3)*EE                         |G(m3)
U    |d    |W+   |     |EE*Vud/(2*Sqrt2*SW)              |G(m3)*(1-G5)
~N4  |~n4  |H    |     |gH                               |1
~N4  |~n4  |Z    |     |gZ/2                             |G(m3)*(1+G5)
==============================================================================
```

Parameters (vars1.mdl)

```
RH neutrino
 Parameters
 Name | Value       |> Comment                                                     <|
EE    |0.31223      |Elementary charge (alpha=1/128.9, on-shell, MZ point, PDG96)
alfSMZ|0.1172       |MS-bar Srong coupling at MZ
Q     |100          |QCD SCALE
SW    |0.4730       |sine of the electroweak mixing angle (PDG96)
s12   |0.221        |Parameter of C-K-M matrix  (PDG96)
Ml    |1.777        |tau-lepton mass      (PDG96)
Mu    |0.005        |
Md    |0.007        |
McMc  |1.25         | Mc(Mc) MS-bar  PDG-07
MbMb  |4.20         | Mb(Mb) MS-bar value PDG-07
Mtpole|171.4        |t-quark mass  (pole mass)
MZ    |91.1884      |Z-boson mass         (PDG96)
MH    |300          |higgs mass
wtp   |1.59         |t-quark width        (tree level 1->2x)
wZ    |2.49444      |Z-boson width        (tree level 1->2x)
wW    |2.08895      |W-boson width        (tree level 1->2x)
gH    |0.3          |H-lZP coupling
gZ    |0.3          |Z-lZP coupling
MLZP  |100.         |n4 mass
wn4   |0            |n4 width
==============================================================================================
```

Constraints (func1.mdl)

```
RH neutrino
 Constraints
 Name |> Expression                                                    <|
QCDok |initQCD(alfSMZ,1.4,MbMb,Mtpole)
Mb    |MbEff(Q)*one(QCDok)
Mtp   |MtEff(Q)*one(QCDok)
CW    |sqrt(1-SW^2)                 %     cos of the Weinberg angle
MW    |MZ*CW                        %     W-boson  mass
c12   |sqrt(1-s12^2)                %     parameter  of C-K-M matrix
Vud   |c12*c13                      %     C-K-M matrix element
Vus   |s12*c13                      %     C-K-M matrix element
Vub   |s13                          %     C-K-M matrix element
===========================================================================
```

micromegas_2.x

- After the model is implemented and check with CalcHEP
  - In directory micromegas_2.2.CPC/name/work
  - Launch ./calchep
    - Edit model
    - Check model
    - Correct mistakes until model is OK
- Code then automatically
  - looks for “LSP” and for resonances
  - Computes all annihilation and coannihilation cross-sections
  - Solves the evolution equation and obtains the relic density
  - Gets any 2->2 cross section and 1->2,3 decay
  - Computes σ v (for indirect detection) and direct detection rate

- Note: for direct detection needs coupling of Higgs to light quarks

- *Other constraints must be provided by the user in fortran or C routine*

- Run the code
  - main.c is the default main program – fix switches
  - define input parameters
  - make main=main.c
  - ./main test1.par

Input parameters (test1.par)

```
#   This file is intended for changing of model parameters.
#   While it is empty, default paremeters defined in work/models/vars1.mdl file
#   are used. Format of the input data is
#   variable_name    new_value.
 EE     3.122300E-01
 SW     4.730000E-01
 MbMb   4.20
 Mtpole 171.4
 MZ     9.118840E+01
 MH     200.
 wtp    1.590000E+00
 wZ     2.494440E+00
 wW     2.088950E+00
 gH     0.025
 gZ     0.002
 MLZP  46.
```

Results

```
=== MASSES OF ODD SECTOR: ===

Masses of odd sector Particles: ~n4  : MLZP  =    46.0 ||

==== Physical Constraints: =====

==== Calculation of relic density =====
Dark Matter candidate is ~n4 Xf=2.38e+01 Omega=1.00e-01

Channels which contribute to 1/(omega) more than 1%.
Relative contrubutions in % are displyed
 15% ~n4 ~N4 -> d D
 15% ~n4 ~N4 -> s S
 15% ~n4 ~N4 -> b B
 12% ~n4 ~N4 -> u U
 12% ~n4 ~N4 -> c C
  7% ~n4 ~N4 -> nl Nl
  7% ~n4 ~N4 -> nm Nm
  7% ~n4 ~N4 -> ne Ne
  3% ~n4 ~N4 -> e E
  3% ~n4 ~N4 -> m M
  3% ~n4 ~N4 -> l L
```

```
==== Indirect detection =======
sigma*v=5.49E-26 [cm^3/sec] 1.41E+01 gamma with E > 1.00E-01 are generated at one collision
gamma flux for fi=0.00E+00[rad] is 1.04E-06[ph/cm^2/s/sr]

WIMP annihilation at V_rel=1.0E-03 (Pcm=2.30E-02)

~n4,~N4 ->   b   B  sigma*v=1.66E-26 [cm^3/sec] sigma[pb]=5.55E+02
~n4,~N4 ->   s   S  sigma*v=1.67E-26 [cm^3/sec] sigma[pb]=5.58E+02
~n4,~N4 ->   c   C sigma*v=1.30E-26 [cm^3/sec] sigma[pb]=4.34E+02
~n4,~N4 ->   d   D sigma*v=1.67E-26 [cm^3/sec]sigma[pb]=5.58E+02
~n4,~N4 ->   u   U  sigma*v=1.30E-26 [cm^3/sec] sigma[pb]=4.35E+02
~n4,~N4 ->  nl  Nl sigma*v=7.47E-27 [cm^3/sec] sigma[pb]=2.49E+02
~n4,~N4 ->   l   L  sigma*v=3.77E-27 [cm^3/sec] sigma[pb]=1.26E+02
~n4,~N4 ->  ne  Ne  sigma*v=7.47E-27 [cm^3/sec] sigma[pb]=2.49E+02
~n4,~N4 ->   e   E sigma*v=3.78E-27 [cm^3/sec] sigma[pb]=1.26E+02
```

Outlook

- *Incorporating one-loop for dominant processes in MSSM – beyond improved Higgs vertices*
  - *Sloops (Baro, Boudjema, Chalons, Semenov)*

- *Neutrino signals from capture in Sun,Earth*
- *Pursue implementation of new models*

Conclusion

- *To understand the nature of dark matter clearly need information and cross checks from cosmology, direct and indirect detection as well as from collider physics*

- *micrOMEGAs_2.4 is tool to perform these analyses in a generic model*