

# *micrOMEGAs*

A Tool for Dark Matter and New Physics

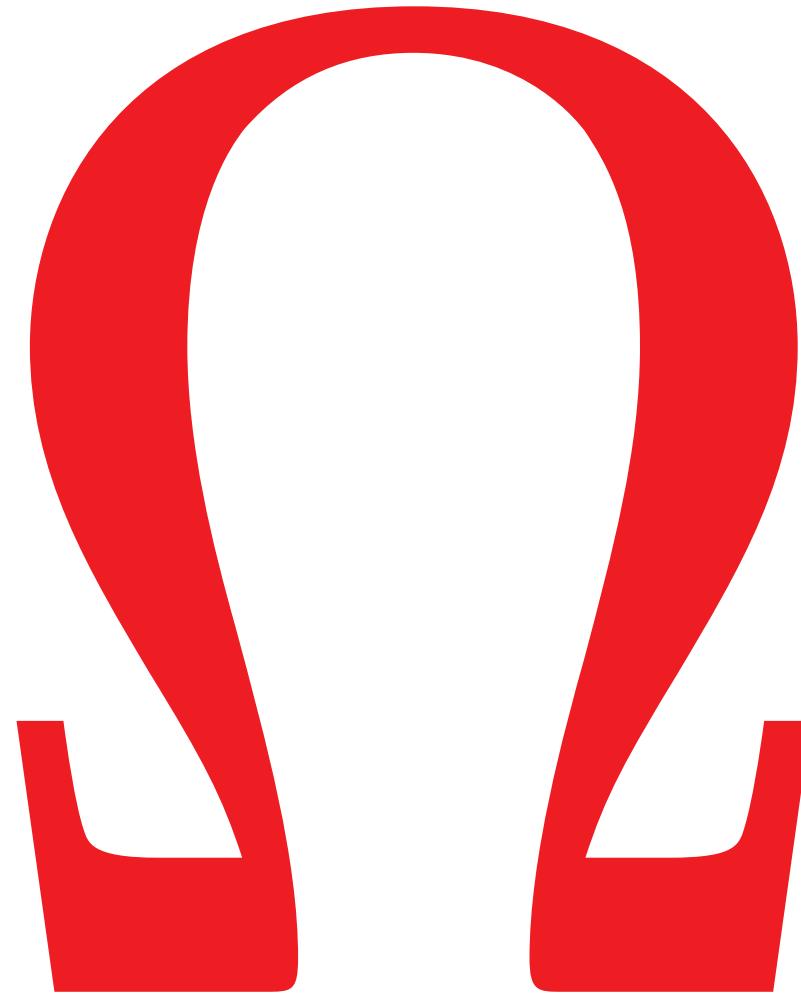
Fawzi BOUDJEMA

in collaboration with Geneviève Bélanger, Sacha Pukhov and Andrei Semenov

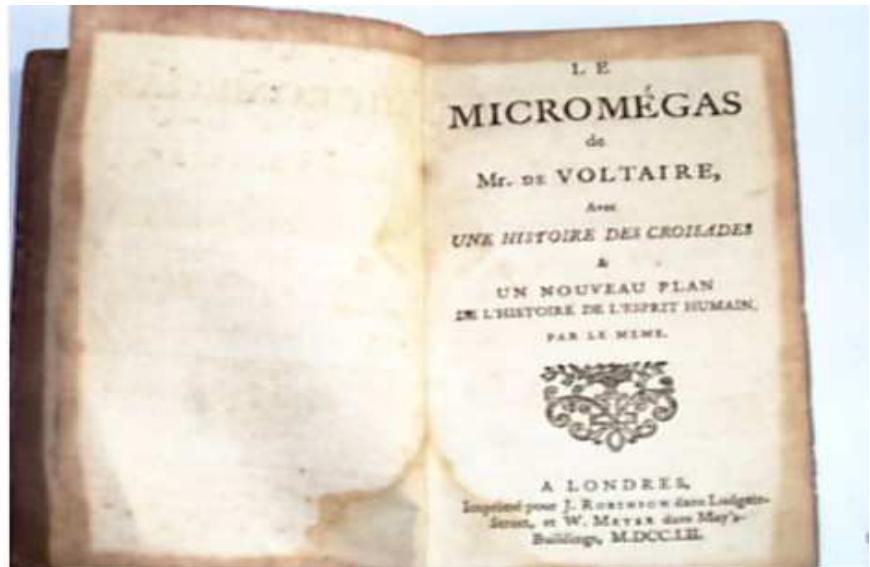
and Pierre Brun, Pierre Salati and Sylvie Rosier

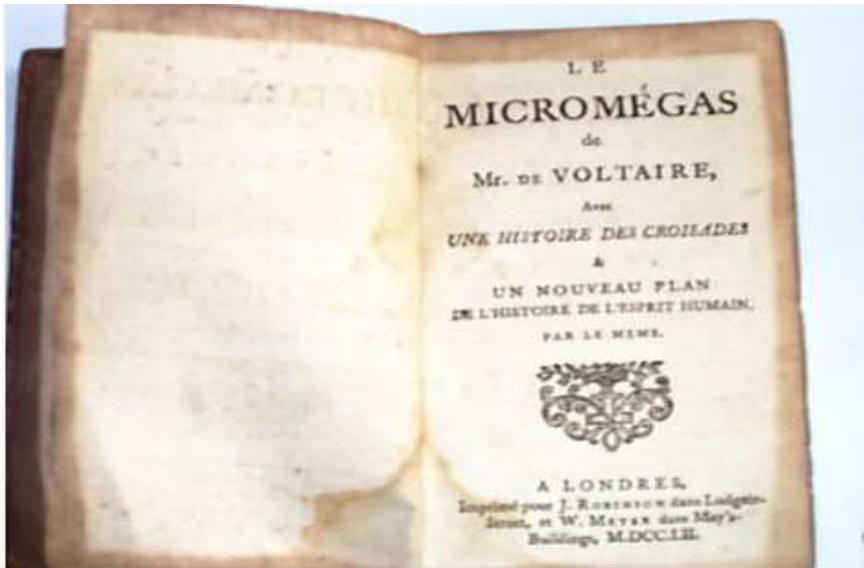
LAPTH, CNRS, Annecy-le-Vieux, France

micrOMEGAs



$\Omega$





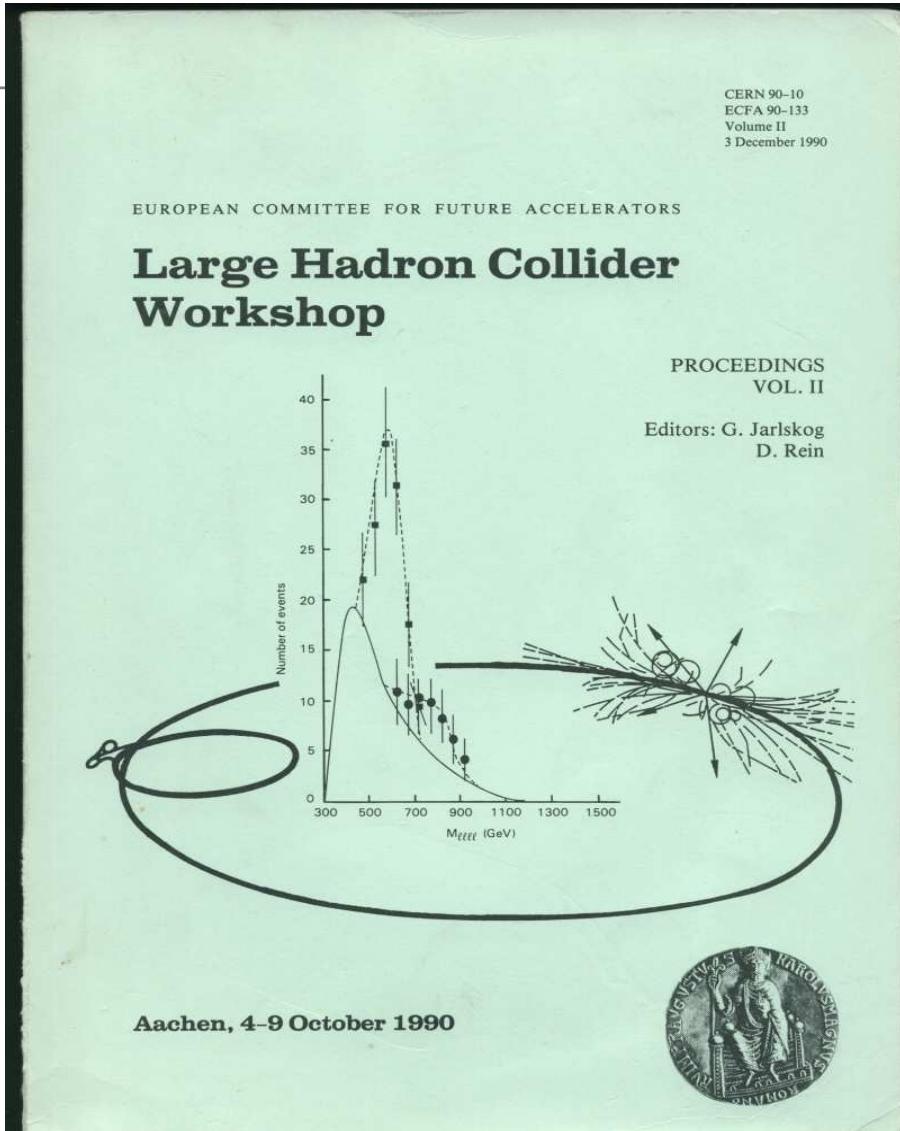
“ O atomes intelligents,  
dans qui l'Etre éternel  
s'est plu à manifester  
son adresse et sa puissance,  
vous devez sans doute  
goûter des joies  
bien pures sur  
votre globe car,  
**ayant si peu de matière....,”**

Voltaire, Micromegas,  
chapitre septième,  
conversation avec les hommes

## LHC Dark Matter Connection



## LHC Dark Matter Connection: The new paradigm



no mention of a connection, despite a SUSY WG

There is a mention of LSP to be stable/neutral because of cosmo reason, but no attempt at identifying it or weighing the universe at the LHC

LHC: Symmetry breaking and Higgs

New Paradigm, Dark Matter is New Physics. Dark Matter is being looked for everywhere

New Paradigm, Particle Physics to match the precision of recent cosmological measurements

**Need powerful, modular and versatile tools**

**micrOMEGAs: Tools for DM/ Collider Physics/  
Flavour for a general NP**

# Models of New Physics: Symmetry breaking and DM

- The SM Higgs naturalness problem has been behind the construction of many models of New Physics: at LHC not enough to see the Higgs need to address electroweak symmetry breaking
- DM is New Physics, most probable that the New Physics of EWSB provides DM candidate, especially that
- All models of NP can be made to have quite easily and naturally a conserved quantum number,  $Z_2$  parity such that all the NP particles have  $Z_2 = -1$  (odd) and the SM part. have  $Z_2$  even ( $Z_3$  can work also)
- Then the lightest New Physics particle is stable. If it is electrically neutral then can be a candidate for DM
- This conserved quantum number is not imposed just to have a DM candidate it has been imposed for the model to survive

# Symmetry breaking and DM

## Survival

evasive proton decay

indirect precision measurements (LEP legacy)

## Examples:

R-parity and LSP in SUSY (majorana fermion)

KK parity and the and LKP in UED (gauge boson)

T-parity in Little Higgs with the LTP (gauge boson)

LZP (warped GUTs) (actually it's a  $Z_3$  here) (Dirac fermion)

even modern technicolour has a DM candidate

LANHEP

micrOMEGAs

LANHEP

micrOMEGAs

Model File  
Particles  
Vertices  
Parameters



LANHEP

micrOMEGAs

Model File  
Particles  
Vertices  
Parameters

*CalcHEP*

Generate tree-level  
cross sections

LANHEP

micrOMEGAs

Model File  
Particles  
Vertices  
Parameters

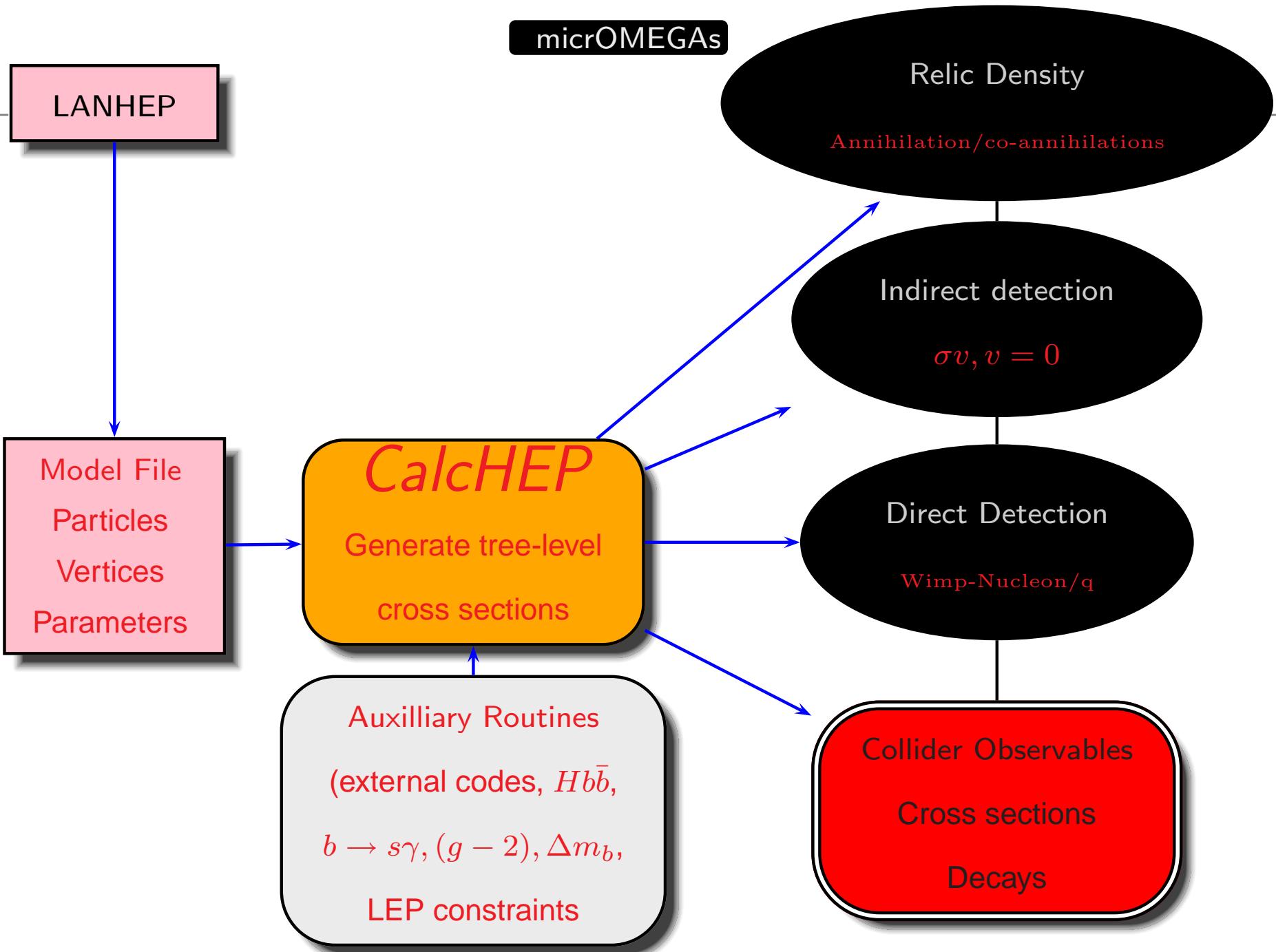
*CalcHEP*

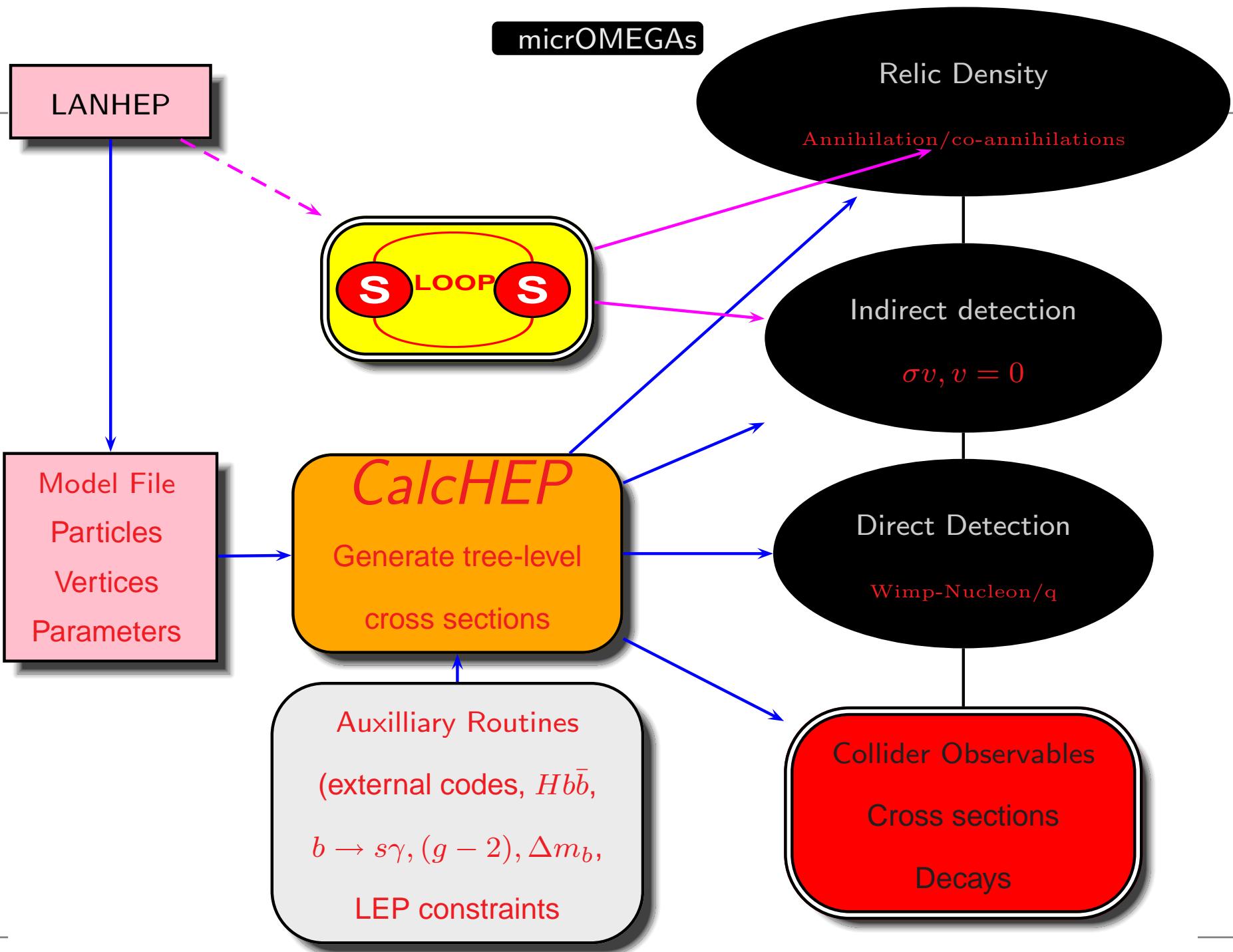
Generate tree-level  
cross sections

Auxilliary Routines

(external codes,  $Hb\bar{b}$ ,  
 $b \rightarrow s\gamma$ ,  $(g - 2)$ ,  $\Delta m_b$ ,

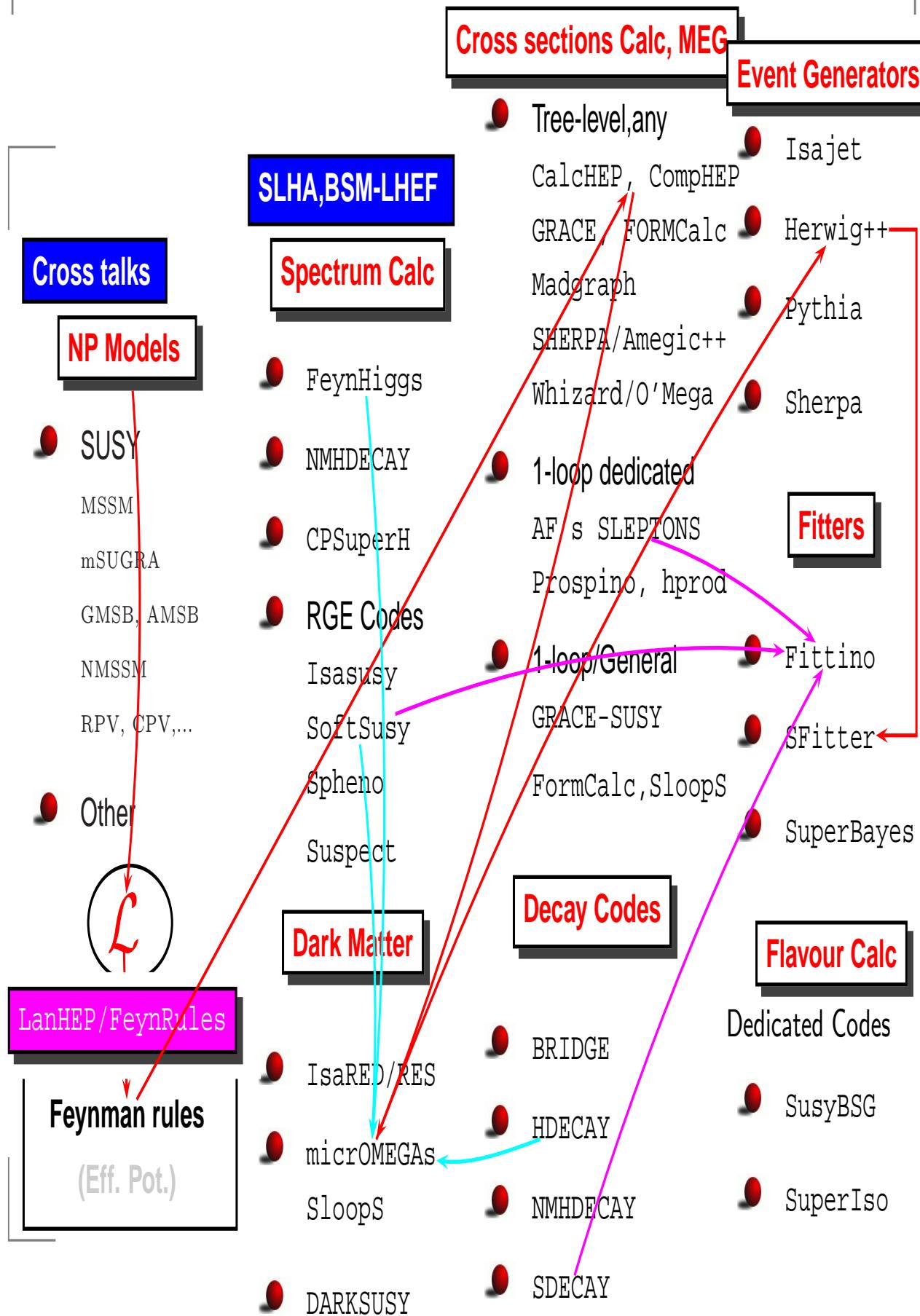
LEP constraints





## micrOMEGAs

- given any set of parameters it can identify LSP, NLSP, generate and calculate  $\Omega h^2$
- Model defined in Lanhep (more later)
- Fed into CalcHEP ....tree-level, some 3000 processes could be needed.
- Higgs sector (SUSY): improved Higgs masses/mixings (read from FeynHiggs, for example) but interpreted in terms of an effective scalar potential (GI), following FB and A. Semenov (PRD 02)
- Effective Lagrangian also includes important RC (Higgs couplings,  $\Delta m_b$  effects,...)
- Interfaced with Isajet, Suspect, SoftSUSY parameters at high scale run down to the ew scale
- $(g - 2)_\mu$ ,  $b \rightarrow s\gamma$ ,  $B_s \rightarrow \mu^-\mu^+$ ...
- NMSSM (with C. Hugonie), CP violation (with S. Kraml), UED, Dirac, host of others
- “open source”: procedure to define your own model
- powerful generalised direct detection module
- indirect detection cross sections, interface with propagation, polarisation completed
- SLHA compliant, MCMC interface for parameter scans

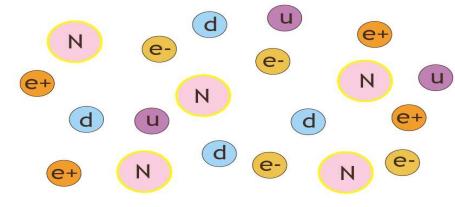


SLHA compliant, talks to other codes easily

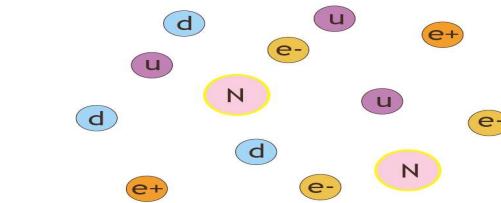
## Relic Density

**Relic Density**

# formation of DM: Very basics of decoupling



the universe expands and cools ...



until today ...



- At first all particles in thermal equilibrium, frequent collisions and particles are trapped in the cosmic soup

- universe cools and expands: interaction rate too small or not efficient to maintain Equil.

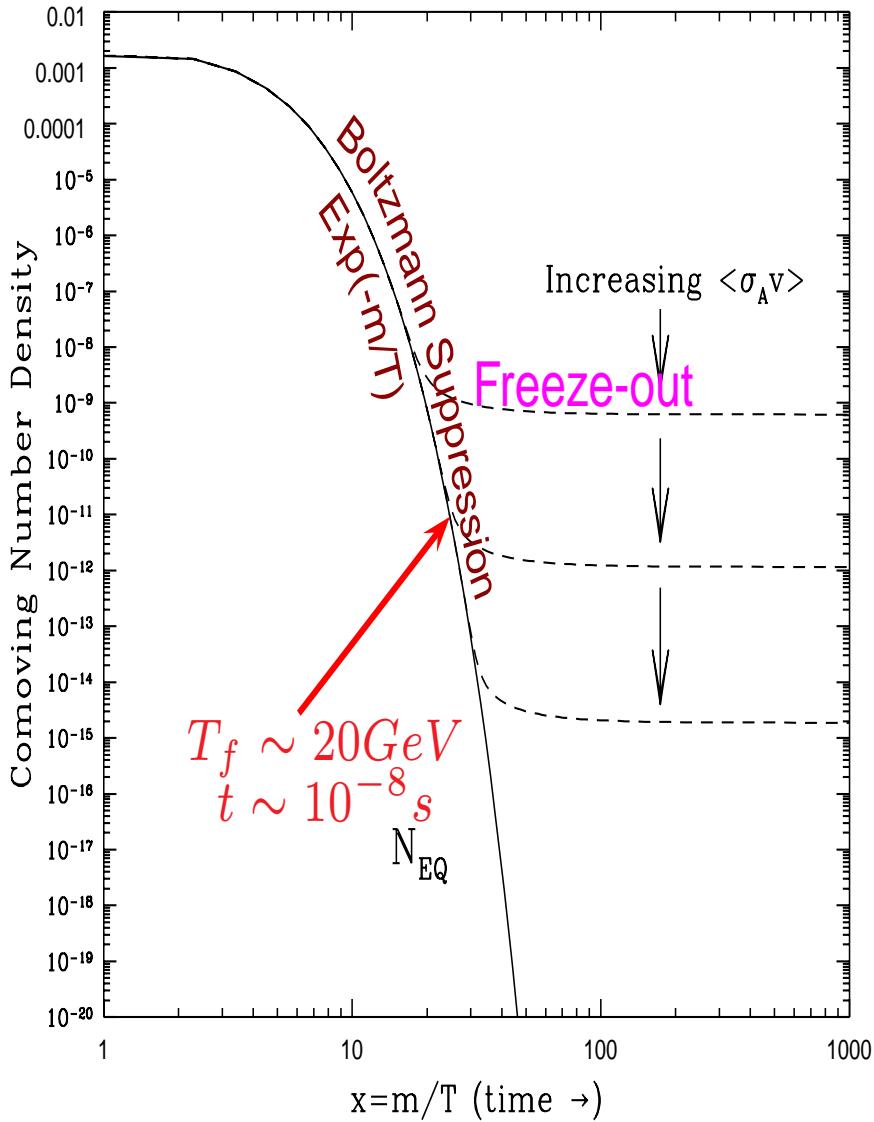
- (stable) particles can not find each other: freeze out and get free and leave the soup, their number density is locked giving the observed relic density

- from then on total number  $(n \times a^3) = cste$

- Condition for equilibrium: mean free path smaller than distance traveled:  $l_{\text{m.f.p}} < vt$     $l_{\text{m.f.p}} = 1/n\sigma$   
 $t \sim 1/H$  or Equilibrium:  $\Gamma = n\sigma v > H$

freeze ou/decoupling occurs at  $T = T_D = T_F : \Gamma = H$    and    $\Omega_{\tilde{\chi}_1^0} h^2 \propto 1/\sigma_{\tilde{\chi}_1^0}$

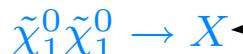
## Relic Density: Boltzman transport equation



based on  $\mathcal{L}[f] = \mathcal{C}[f]$

dilution due to expansion

$$dn/dt = -3Hn - \langle \sigma v \rangle (n^2 - n_{eq}^2)$$



- at early times  $\Gamma \gg H \rightarrow n \sim n_{eq}$

- $T \sim m$   $X$  not enough energy to give

$X \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$   $n$  drops and so does  $\Gamma$

$$T_f \simeq m/25$$

$$\Omega_{\tilde{\chi}_1^0} h^2 \propto 1/\sigma_{\tilde{\chi}_1^0}$$

## Thermal average

must calculate all annihilation, co-annihilation processes. Each annihilation can consist of tens of cross sections...

$$\chi_i^0 \chi_j^0 \rightarrow X_{SM} Y_{SM}, \chi_1^0 \tilde{f}_1 \rightarrow X_{SM} Y_{SM}, \dots$$
$$\langle \sigma v \rangle = \frac{\sum_{i,j} g_i g_j \int ds \sqrt{s} K_1(\sqrt{s}/T) p_{ij}^2 \sigma_{ij}(s)}{2T \left( \sum_i g_i m_i^2 K_2(m_i/T) \right)^2},$$

$p_{ij}$  is the momentum of the incoming particles in their center-of-mass frame.

Origin of Boltzman factor

$$\exp(-\delta M/T)$$

## Thermal average

must calculate all annihilation, co-annihilation processes. Each annihilation can consist of tens of cross sections...

$$\chi_i^0 \chi_j^0 \rightarrow X_{SM} Y_{SM}, \chi_1^0 \tilde{f}_1 \rightarrow X_{SM} Y_{SM}, \dots$$

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

$p_{ij}$  is the momentum of the incoming particles in their center-of-mass frame.

Origin of Boltzman factor

$$\exp(-\delta M/T)$$

$$B_f = \frac{K_1((m_i + m_j)/T_f)}{K_1(2m_{\tilde{\chi}_1^0}/T_f)} \approx e^{-X_f \frac{(m_i + m_j - 2m_{\tilde{\chi}_1^0})}{m_{\tilde{\chi}_1^0}}} \quad \text{if } B_f < B_\epsilon \text{ do not compute}$$

In the code  $B_\epsilon = 10^{-6}$  by default. Most often  $B_\epsilon = 10^{-2}$  enough for 1% accuracy, only a few processes computed.

## Thermal average

must calculate all annihilation, co-annihilation processes. Each annihilation can consist of tens of cross sections...

$$\chi_i^0 \chi_j^0 \rightarrow X_{SM} Y_{SM}, \chi_1^0 \tilde{f}_1 \rightarrow X_{SM} Y_{SM}, \dots$$

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

$p_{ij}$  is the momentum of the incoming particles in their center-of-mass frame.

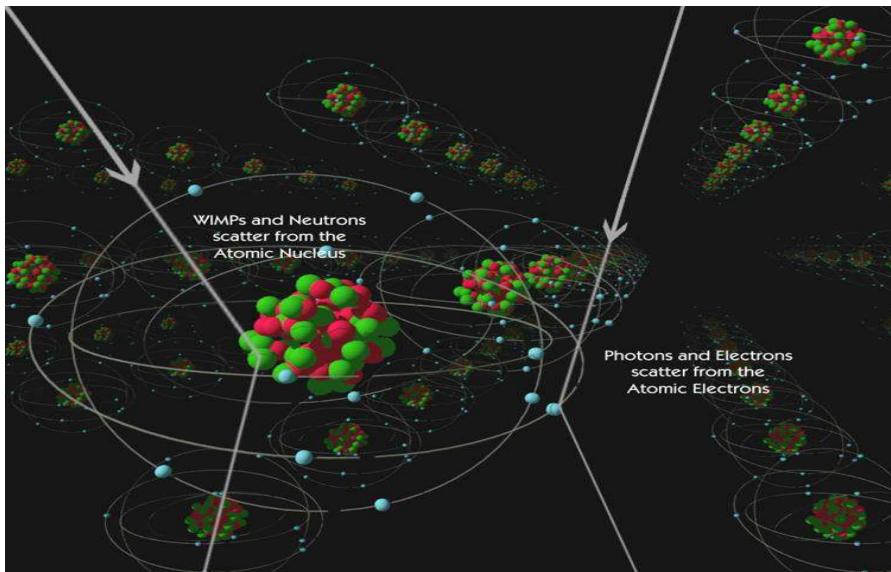
Origin of Boltzman factor

$$\exp(-\delta M/T)$$

In micrOMEGAs  $\langle \sigma v \rangle(T)$  is obtained from direct integration, through adaptive Simpson with two options (fast, default) and accurate (checks for accuracy). Adaptive: looks for poles and thresholds.

in DarkSUSY: tabulation

## Direct detection

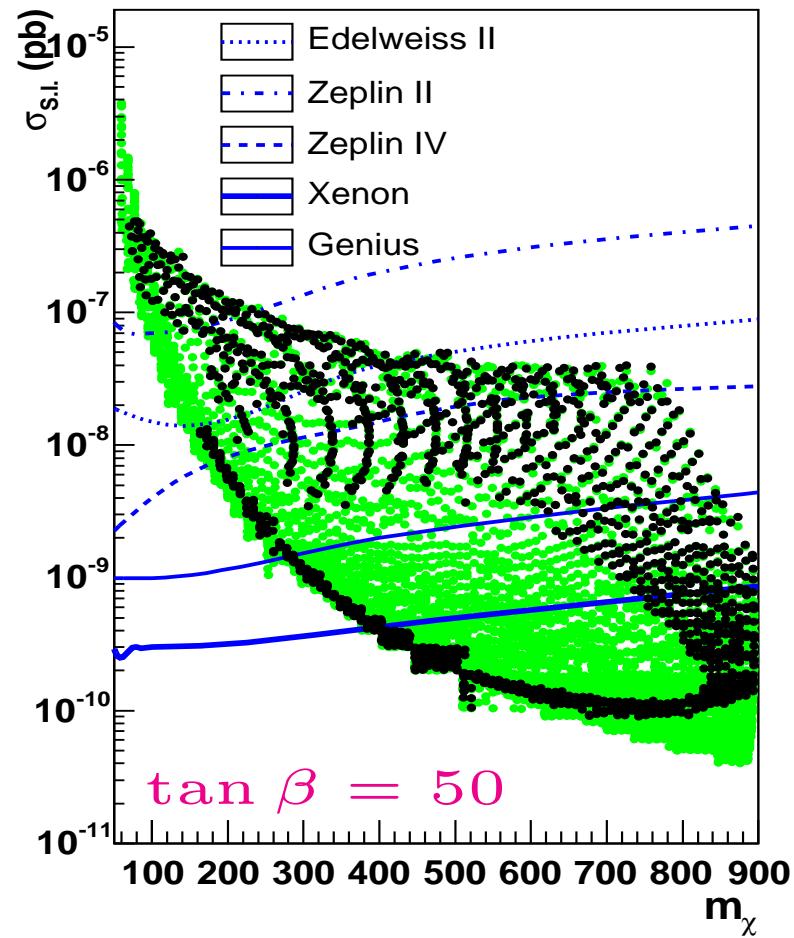
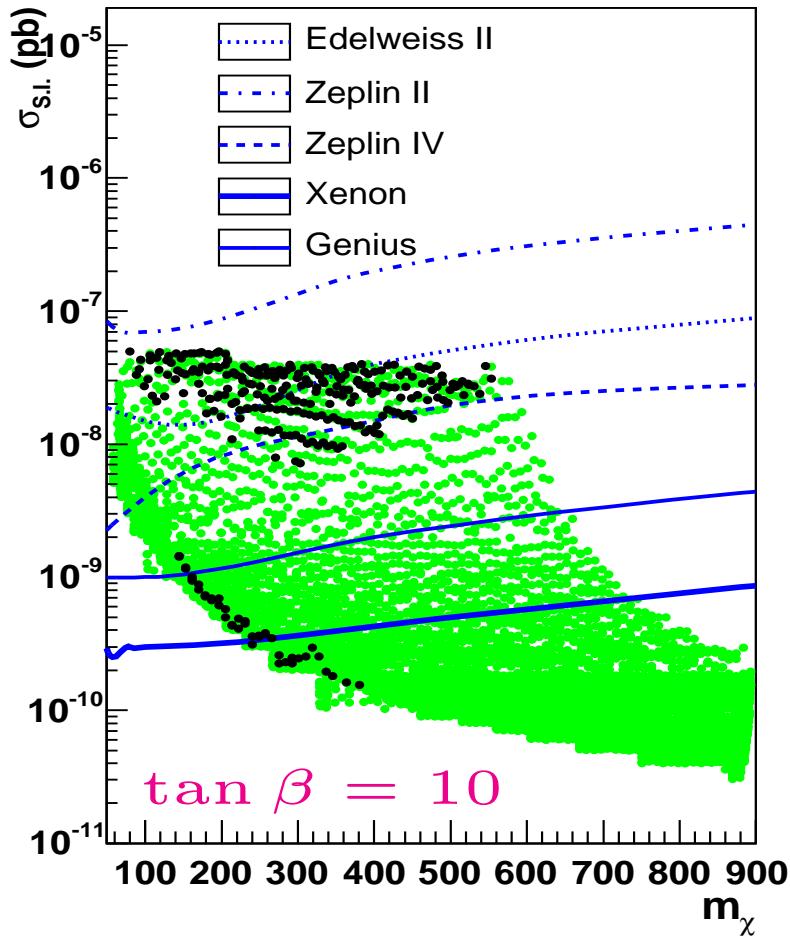


$\chi\mathcal{N} \rightarrow \chi\mathcal{N}$  **to**  $\chi N \rightarrow \chi N$  ( $N = n, p$ )  
**to**  $\chi q \rightarrow \chi q$

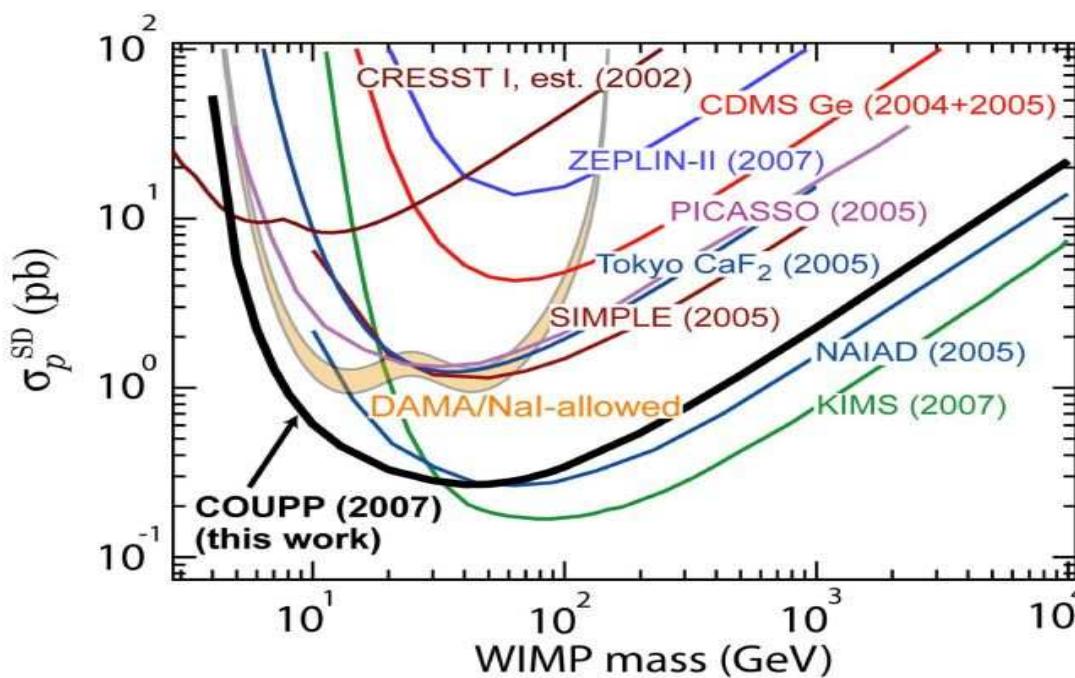
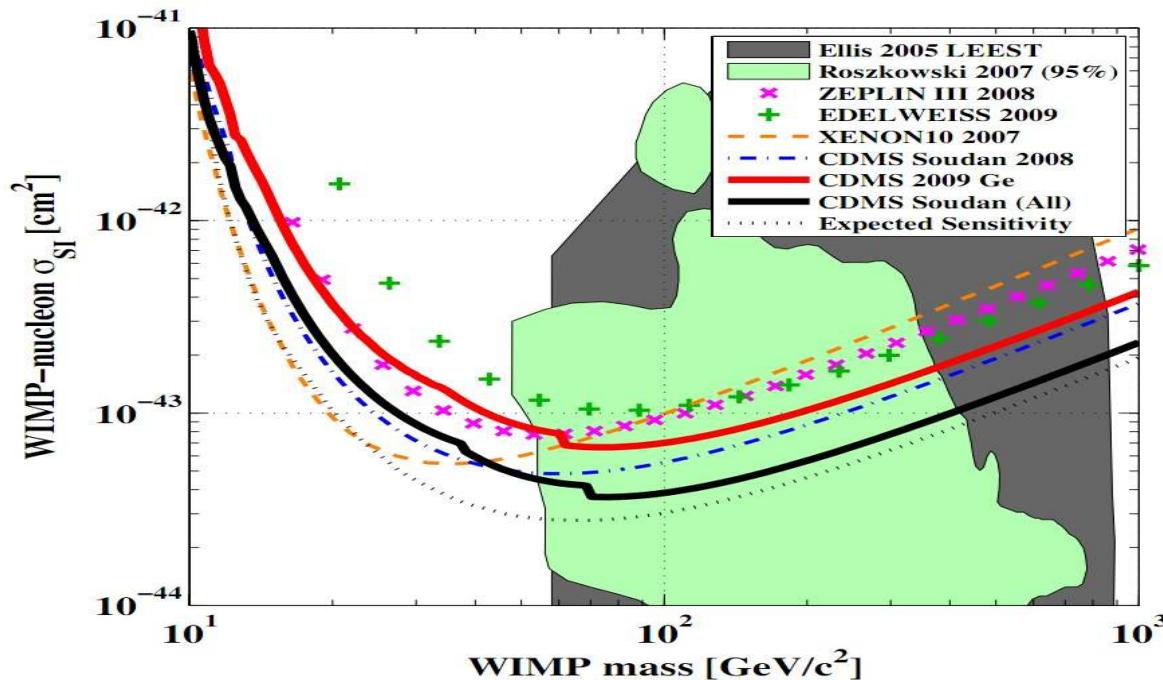
**ingredients/Modules:** dark matter density and modulation, velocity distribution  
quark content in nucleon, Nuclear form factors,.....

# Underground direct detection

• within WMAP



## Limits are improving fast, signals??



## Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}| > v_{\min}} d^3v v \textcolor{green}{f}(\vec{v}, \vec{v}_e) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

## Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}| > v_{\min}} d^3v v f(\vec{v}, \vec{v}_e) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

- $N_T$  is the number of target nuclei per unit mass
- $E_R$  = recoil energy
- $\vec{v}$  is the dark matter velocity in the frame of the Earth,  $\vec{v}_e$  is the velocity of the Earth with respect to the galactic halo, and  $f(\vec{v}, \vec{v}_e)$  is the distribution function of dark matter particle velocities.  
In micrOMEGAs a truncated Maxwellian distribution is implemented by default, with free parameters to allow for study/deviations from the isothermal model.
- $\sigma_{W\mathcal{N}}$  Wimp-Nucleus cross section. Involves: BSM physics, nuclear physics, SM particle physics

## Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}| > v_{\min}} d^3v \, v \, f(\vec{v}, \vec{v}_e) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

$$\frac{d\sigma_{W\mathcal{N}}}{dE_R} = \frac{m_{\mathcal{N}}}{2v^2\mu_{\mathcal{N}}^2} \left( \sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2 \right)$$

## Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}| > v_{\min}} d^3v v \mathbf{f}(\vec{v}, \vec{v}_e) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

$$\frac{d\sigma_{W\mathcal{N}}}{dE_R} = \frac{m_{\mathcal{N}}}{2v^2\mu_{\mathcal{N}}^2} \left( \sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2 \right)$$

$F_{SI,SD}$  = Nuclear Form Factors

$\mu_{\mathcal{N}}^2$  reduced  $\mathcal{N} - \chi$  mass

## Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}| > v_{\min}} d^3v v \textcolor{red}{f}(\vec{v}, \vec{v}_e) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

$$\frac{d\sigma_{W\mathcal{N}}}{dE_R} = \frac{m_{\mathcal{N}}}{2v^2\mu_{\mathcal{N}}^2} \left( \sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2 \right)$$

For SI further factorisation

$$\sigma_0^{SI} = \frac{4\mu_N^2}{\pi} [\lambda_p Z + \lambda_n (A - Z)]^2,$$

(For SD no factorisation but spin structure functions (more involved)).

Nuclear Physics: Fourier transform of the nucleus distribution function, use Fermi distribution (which leads to so called Woods-Saxon FF)

$$F_{SI} = F_{\mathcal{N}}(q) = \int e^{-iqx} \rho_{\mathcal{N}}(x) d^3x, \quad \rho_{\mathcal{N}}(r) = \frac{c_{norm}}{1 + \exp((r - R_{\mathcal{N}})/a)}$$

## Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}| > v_{\min}} d^3v v \textcolor{red}{f}(\vec{v}, \vec{v}_e) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

$$\frac{d\sigma_{W\mathcal{N}}}{dE_R} = \frac{m_{\mathcal{N}}}{2v^2\mu_{\mathcal{N}}^2} \left( \sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2 \right)$$

For SI further factorisation

$$\sigma_0^{SI} = \frac{4\mu_N^2}{\pi} [\lambda_p Z + \lambda_n (A - Z)]^2,$$

(For SD no factorisation but spin structure functions (more involved)).

Nuclear Physics: Fourier transform of the nucleus distribution function, use Fermi distribution (which leads to so called Woods-Saxon FF)

$$F_{SI} = F_{\mathcal{N}}(q) = \int e^{-iqx} \rho_{\mathcal{N}}(x) d^3x, \quad \rho_{\mathcal{N}}(r) = \frac{c_{norm}}{1 + \exp((r - R_{\mathcal{N}})/a)}$$

$\lambda_{p,n}$  coupling of DM but also  
quark content in nucleon

## Wimp-Nucleon (N=n,p) at small momentum transfer (100MeV)

Take for exemple the case of a Majorana Wimp **Majorana**:  $\chi = \bar{\chi}$

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

## Wimp-Nucleon (N=n,p) at small momentum transfer (100MeV)

Majorana  $q^2 \rightarrow 0$

$$\begin{aligned}\mathcal{L}_F &= \lambda_N \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N \Rightarrow \text{scalar spin-independent SI} \\ &+ \xi_N \bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_N \gamma^\mu \gamma_5 \psi_N \Rightarrow \text{spin-dependent SD}\end{aligned}$$

## Wimp-Nucleon (N=n,p) at small momentum transfer (100MeV)

Majorana  $q^2 \rightarrow 0$

$$\begin{aligned}\mathcal{L}_F &= \lambda_N \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N \Rightarrow \text{scalar spin-independent SI} \\ &+ \xi_N \bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_N \gamma^\mu \gamma_5 \psi_N \Rightarrow \text{spin-dependent SD}\end{aligned}$$

Generalisation to other DM particles, Spin-0, 1/2, 1 for  $q^2 \rightarrow 0$

not necessarily of Majorana type :  $\chi \neq \bar{\chi}$

Classify as two types of operators

1)  $_e$ =even under  $\chi \leftrightarrow \bar{\chi}$  interchange

2)  $_o$ =odd under  $\chi \leftrightarrow \bar{\chi}$  interchange, vanish for self-conjugate (Majorana) DM

## Wimp-Nucleon (N=n,p) at small momentum transfer (100MeV)

Majorana  $q^2 \rightarrow 0$

$$\mathcal{L}_F = \lambda_N \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N \Rightarrow \text{scalar spin-independent SI}$$

$$+ \xi_N \bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_N \gamma^\mu \gamma_5 \psi_N \Rightarrow \text{spin-dependent SD}$$

$$\begin{aligned} \mathcal{L}_{s=1/2} &= \lambda_{N,e} \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + \lambda_{N,o} \bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N \\ &+ \xi_{N,e} \bar{\psi}_\chi \gamma_5 \gamma_\mu \psi_\chi \bar{\psi}_N \gamma_5 \gamma^\mu \psi_N - \frac{1}{2} \xi_{N,o} \bar{\psi}_\chi \sigma_{\mu\nu} \psi_\chi \bar{\psi}_N \sigma^{\mu\nu} \psi_N \end{aligned}$$

## Wimp-Nucleon (N=n,p) at small momentum transfer (100MeV)

Majorana  $q^2 \rightarrow 0$

$$\mathcal{L}_F = \lambda_N \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N \Rightarrow \text{scalar spin-independent SI}$$

$$+ \xi_N \bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_N \gamma^\mu \gamma_5 \psi_N \Rightarrow \text{spin-dependent SD}$$

$$\begin{aligned} \mathcal{L}_{s=1/2} &= \lambda_{N,e} \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + \lambda_{N,o} \bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N \\ &+ \xi_{N,e} \bar{\psi}_\chi \gamma_5 \gamma_\mu \psi_\chi \bar{\psi}_N \gamma_5 \gamma^\mu \psi_N - \frac{1}{2} \xi_{N,o} \bar{\psi}_\chi \sigma_{\mu\nu} \psi_\chi \bar{\psi}_N \sigma^{\mu\nu} \psi_N \end{aligned}$$

$$\mathcal{L}_{s=0} = 2\lambda_{N,e} M_\chi \phi_\chi \phi_\chi^* \bar{\psi}_N \psi_N + i\lambda_{N,o} (\partial_\mu \phi_\chi \phi_\chi^* - \phi_\chi \partial_\mu \phi_\chi^*) \bar{\psi}_N \gamma_\mu \psi_N$$

## Wimp-Nucleon (N=n,p) at small momentum transfer (100MeV)

Majorana  $q^2 \rightarrow 0$

$$\begin{aligned} \mathcal{L}_F &= \lambda_N \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N \quad \Rightarrow \text{scalar spin-independent SI} \\ &+ \xi_N \bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_N \gamma^\mu \gamma_5 \psi_N \quad \Rightarrow \text{spin-dependent SD} \end{aligned}$$

$$\begin{aligned} \mathcal{L}_{s=1/2} &= \lambda_{N,e} \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + \lambda_{N,o} \bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N \\ &+ \xi_{N,e} \bar{\psi}_\chi \gamma_5 \gamma_\mu \psi_\chi \bar{\psi}_N \gamma_5 \gamma^\mu \psi_N - \frac{1}{2} \xi_{N,o} \bar{\psi}_\chi \sigma_{\mu\nu} \psi_\chi \bar{\psi}_N \sigma^{\mu\nu} \psi_N \\ \mathcal{L}_{s=0} &= 2\lambda_{N,e} M_\chi \phi_\chi \phi_\chi^* \bar{\psi}_N \psi_N + i\lambda_{N,o} (\partial_\mu \phi_\chi \phi_\chi^* - \phi_\chi \partial_\mu \phi_\chi^*) \bar{\psi}_N \gamma_\mu \psi_N \end{aligned}$$

$$\begin{aligned} \mathcal{L}_{s=1} &= 2\lambda_{N,e} M_\chi A_{\chi\mu} A_\chi^\mu \bar{\psi}_N \psi_N + \lambda_{N,o} i (A_\chi^{*\alpha} \partial_\mu A_{\chi,\alpha} - A_\chi^\alpha \partial_\mu A_{\chi\alpha}^*) \bar{\psi}_N \gamma_\mu \psi_N \\ &+ \sqrt{6} \xi_{N,e} (\partial_\alpha A_{\chi\beta}^* A_{\chi\gamma} - A_{\chi\beta}^* \partial_\alpha A_{\chi\gamma}) \epsilon^{\alpha\beta\gamma\mu} \bar{\psi}_N \gamma_5 \gamma_\mu \psi_N \\ &+ i \frac{\sqrt{3}}{2} \xi_{N,o} (A_{\chi\mu} A_{\chi\nu}^* - A_{\chi\mu}^* A_{\chi\nu}) \bar{\psi}_N \sigma^{\mu\nu} \psi_N \end{aligned}$$

## Wimp-Nucleon (N=n,p) at small momentum transfer (100MeV)

Majorana  $q^2 \rightarrow 0$

$$\begin{aligned} \mathcal{L}_F &= \lambda_N \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N \Rightarrow \text{scalar spin-independent SI} \\ &+ \xi_N \bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_N \gamma^\mu \gamma_5 \psi_N \Rightarrow \text{spin-dependent SD} \end{aligned}$$

$$\begin{aligned} \mathcal{L}_{s=1/2} &= \lambda_{N,e} \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + \lambda_{N,o} \bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N \\ &+ \xi_{N,e} \bar{\psi}_\chi \gamma_5 \gamma_\mu \psi_\chi \bar{\psi}_N \gamma_5 \gamma^\mu \psi_N - \frac{1}{2} \xi_{N,o} \bar{\psi}_\chi \sigma_{\mu\nu} \psi_\chi \bar{\psi}_N \sigma^{\mu\nu} \psi_N \\ \mathcal{L}_{s=0} &= 2\lambda_{N,e} M_\chi \phi_\chi \phi_\chi^* \bar{\psi}_N \psi_N + i\lambda_{N,o} (\partial_\mu \phi_\chi \phi_\chi^* - \phi_\chi \partial_\mu \phi_\chi^*) \bar{\psi}_N \gamma_\mu \psi_N \end{aligned}$$

$$\begin{aligned} \mathcal{L}_{s=1} &= 2\lambda_{N,e} M_\chi A_{\chi\mu} A_\chi^\mu \bar{\psi}_N \psi_N + \lambda_{N,o} i (A_\chi^{*\alpha} \partial_\mu A_{\chi,\alpha} - A_\chi^\alpha \partial_\mu A_{\chi\alpha}^*) \bar{\psi}_N \gamma_\mu \psi_N \\ &+ \sqrt{6} \xi_{N,e} (\partial_\alpha A_{\chi\beta}^* A_{\chi\gamma} - A_{\chi\beta}^* \partial_\alpha A_{\chi\gamma}) \epsilon^{\alpha\beta\gamma\mu} \bar{\psi}_N \gamma_5 \gamma_\mu \psi_N \\ &+ i \frac{\sqrt{3}}{2} \xi_{N,o} (A_{\chi\mu} A_{\chi\nu}^* - A_{\chi\mu}^* A_{\chi\nu}) \bar{\psi}_N \sigma^{\mu\nu} \psi_N \end{aligned}$$

$$\begin{aligned} \lambda_N &= \frac{\lambda_{N,e} \pm \lambda_{N,o}}{2} \quad \text{and} \quad \xi_N = \frac{\xi_{N,e} \pm \xi_{N,o}}{2} \\ &+ \mapsto \text{WIMP} \quad \text{and} \quad - \mapsto \text{anti-WIMP} \end{aligned}$$

## Wimp-quark effective Lagrangian, $\psi_N \rightarrow \psi_q$

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

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

In model files of micrOMEGAs (CalcHEP) these operators are added

## Wimp-quark effective Lagrangian: Automation

- In the usual approach these low energy operators and their coefficients are extracted by computing WIMP-quark *amplitudes* from Feynman diagrams and using Fierz transformations,..

## Wimp-quark effective Lagrangian: Automation

- In the usual approach these low energy operators and their coefficients are extracted by computing WIMP-quark *amplitudes* from Feynman diagrams and using Fierz transformations,..
- in `micrOMEGAs` all operators are defined and only need to extract coefficients automatically

## Wimp-quark effective Lagrangian: Automation

- In the usual approach these low energy operators and their coefficients are extracted by computing WIMP-quark *amplitudes* from Feynman diagrams and using Fierz transformations,..
- in `micrOMEGAs` all operators are defined and only need to extract coefficients automatically
- we compute  $\chi q \rightarrow \chi q$  at  $q^2 = 0$  as a normal cross section but...

## Wimp-quark effective Lagrangian: Automation

- In the usual approach these low energy operators and their coefficients are extracted by computing WIMP-quark *amplitudes* from Feynman diagrams and using Fierz transformations,..
- in `micrOMEGAs` all operators are defined and only need to extract coefficients automatically
- we compute  $\chi q \rightarrow \chi q$  at  $q^2 = 0$  as a normal cross section but...
- Interference between one projection operator and an effective vertex singles out SI or SD

## Wimp-quark effective Lagrangian: Automation

- In the usual approach these low energy operators and their coefficients are extracted by computing WIMP-quark *amplitudes* from Feynman diagrams and using Fierz transformations,..
- in `micrOMEGAs` all operators are defined and only need to extract coefficients automatically
- we compute  $\chi q \rightarrow \chi q$  at  $q^2 = 0$  as a normal cross section but...
- Interference between one projection operator and an effective vertex singles out SI or SD
- The trick is to use also  $\chi q \rightarrow \chi q$  vs  $\chi \bar{q} \rightarrow \chi \bar{q}$

## Wimp-quark effective Lagrangian: Automation

- In the usual approach these low energy operators and their coefficients are extracted by computing WIMP-quark *amplitudes* from Feynman diagrams and using Fierz transformations,..
- in `micrOMEGAs` all operators are defined and only need to extract coefficients automatically
- we compute  $\chi q \rightarrow \chi q$  at  $q^2 = 0$  as a normal cross section but...
- Interference between one projection operator and an effective vertex singles out SI or SD
- The trick is to use also  $\chi q \rightarrow \chi q$  vs  $\chi \bar{q} \rightarrow \chi \bar{q}$
- with the *S*-matrix,  $\hat{S} = 1 - i\mathcal{L}$  obtained from the complete Lagrangian at the quark level

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

## Wimp-quark effective Lagrangian: Automation

- In the usual approach these low energy operators and their coefficients are extracted by computing WIMP-quark *amplitudes* from Feynman diagrams and using Fierz transformations,..
- in `micrOMEGAs` all operators are defined and only need to extract coefficients automatically
- we compute  $\chi q \rightarrow \chi q$  at  $q^2 = 0$  as a normal cross section but...
- Interference between one projection operator and an effective vertex singles out SI or SD
- The trick is to use also  $\chi q \rightarrow \chi q$  vs  $\chi \bar{q} \rightarrow \chi \bar{q}$
- with the *S*-matrix,  $\hat{S} = 1 - i\mathcal{L}$  obtained from the complete Lagrangian at the quark level

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

- warning: couplings proportional to light quark masses must be kept

## $\chi q$ to $\chi N$ : Sandwich within nucleon, Nucleon form factors

$$\langle N | \bar{\psi}_q \psi_q | N \rangle, \langle N | \bar{\psi}_q \gamma_\mu \psi_q | N \rangle, \langle N | \bar{\psi}_q \gamma_\mu \gamma_5 \psi_q | N \rangle, \langle N | \bar{\psi}_q \sigma_{\mu\nu} \psi_q | N \rangle$$

These are extracted from experiments (e.g  $\sigma_{\pi N}$ ), lattice computations, plus a fair deal of theory (trace anomaly, chiral perturbation,...)

Large source of uncertainty, apart from vector (which counts number of quarks minus anti-quarks, valence quarks)

## $\chi q$ to $\chi N$ : Sandwich within nucleon, Nucleon form factors

Scalar, light quarks

$$\langle N | m_q \bar{\psi}_q \psi_q | N \rangle = f_q^N M_N \Rightarrow \lambda_N = \sum_{q=1,6} f_q^N \lambda_q \quad M_N : \text{Nucleon mass}$$

$$f_q^{p,n} = \sigma_{\pi N} G_q^{n,p}(m_u/m_d, m_s/m_d, B_u/B_d, y), \quad B_q = \langle N | \bar{q}q | N \rangle, \quad y = 1 - \sigma_0/\sigma_{\pi N}$$

Large uncertainty in  $\sigma_{\pi N}$  translates into very large range for  $0.08 < f_s^{p,n} < 0.46$  and hence expect variations in detection range within an order of magnitude

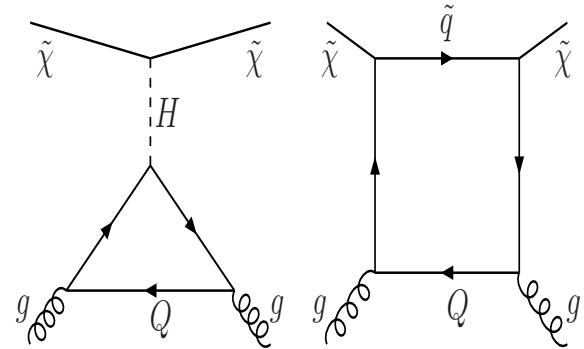
Lattice calculations are providing new estimates that will reduce uncertainty. Tensor coefficients are for example extracted from lattice calculations.

## $\chi q$ to $\chi N$ : Sandwich within nucleon, Nucleon form factors

SI, heavy quarks, Gluons and QCD

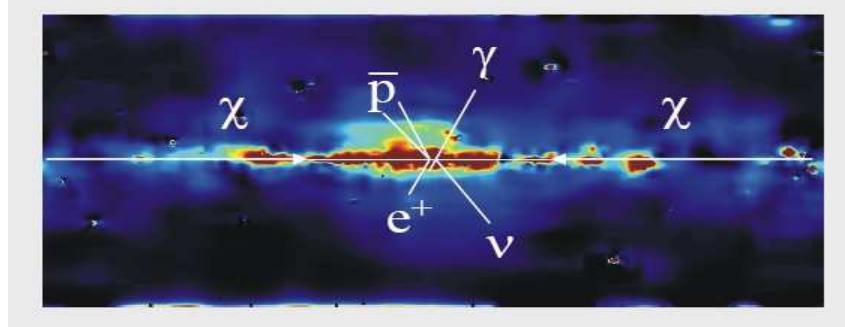
$$\begin{aligned}\langle N | m_Q \bar{\psi}_Q \psi_Q | N \rangle &= -\frac{\Delta \beta^{h.Q}}{2\alpha_s^2(1+\gamma)} \langle N | \alpha_s G_{\mu\nu} G^{\mu\nu} | N \rangle \\ &= -\frac{1}{12\pi} \left(1 + \frac{11\alpha_s(m_Q)}{4\pi}\right) \langle N | \alpha_s G_{\mu\nu} G^{\mu\nu} | N \rangle\end{aligned}$$

Good description of the dominant triangle, Box diagram model dependent, sub-dominant, evaluated for the MSSM only



Diagrams that contribute to WIMP-gluon interaction via quark loops in the MSSM  
Other QCD and SQCD corrections for MSSM

## Indirect Detection

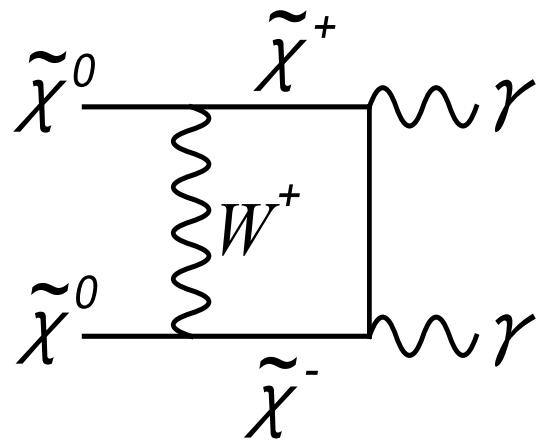


# Annihilation into photons

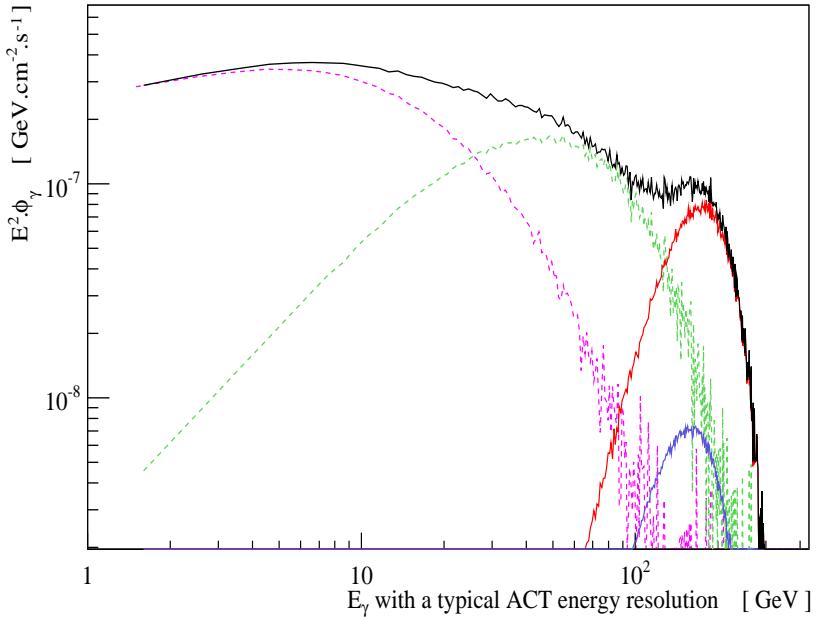
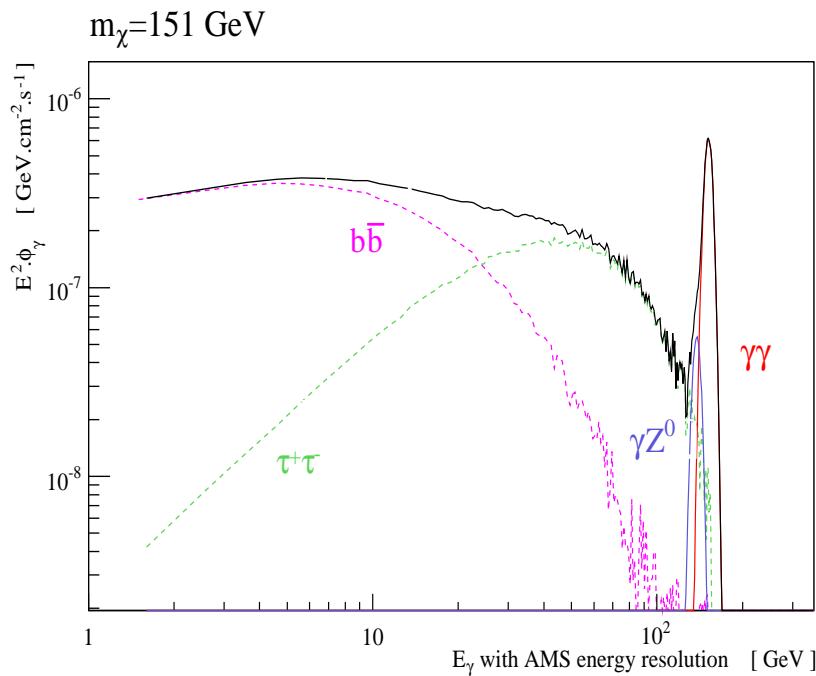
$$\frac{d\Phi_\gamma}{d\Omega dE_\gamma} = \sum_i \underbrace{\frac{dN_\gamma^i}{dE_\gamma} \sigma_i v}_{\text{Particle physics}} \frac{1}{4\pi m_\chi^2} \underbrace{\int (\rho + \delta\rho)^2 dl}_{\text{Astro}}$$

$\gamma'$ s: Point to the source, independent of propagation model(s)

- continuum spectrum from  $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow f\bar{f}, \dots$ , hadronisation/fragmentation ( $\rightarrow \pi^0 \rightarrow \gamma$ ) done through isajet/herwig
- Loop induced mono energetic photons,  $\gamma\gamma$ ,  $Z\gamma$  final states



ACT: HESS,  
 Magic, VERITAS,  
 Cangoroo, ...  
Space-based:  
 AMS, Fermi-LAT,  
 Egret, ...



## SIMULATION: (with/from P. Brun)

Parameterising the halo profile:

$(\alpha, \beta, \gamma) = (1, 3, 1)$ ,  $a = 25 \text{ kpc}$ . (core radius),  $r_0 = 8 \text{ kpc}$  (distance to galactic centre),

$\rho_0 = 0.3 \text{ GeV/cm}^3$  (DM density), opening angle cone  $1^\circ$

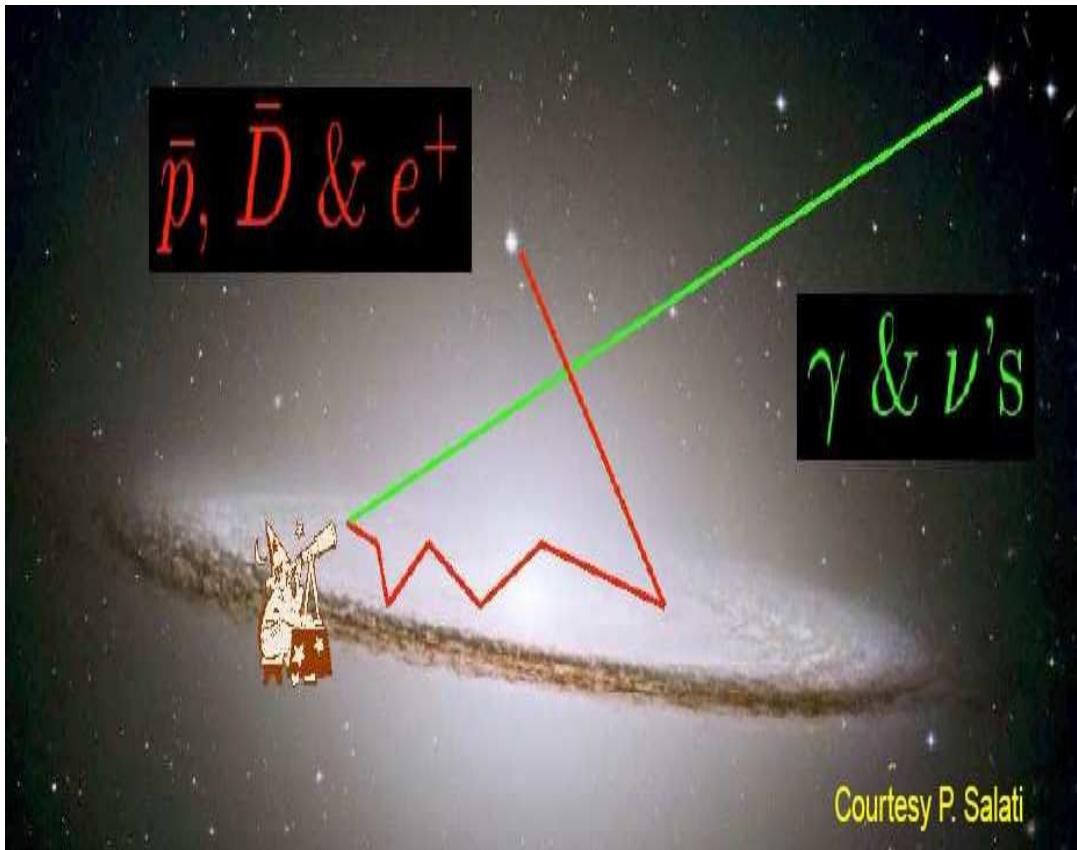
SUSY parameterisation

$m_0 = 113 \text{ GeV}$ ,  $m_{1/2} = 375 \text{ GeV}$ ,  $A = 0$ ,  $\tan \beta = 20$ ,  $\mu > 0$

$\gamma$  lines could be distinguished from diffuse background

# Annihilation into $e^+, \bar{p}, \bar{D}$

$$\frac{d\Phi_{\bar{f}}}{d\Omega dE_{\bar{f}}} = \sum_i \underbrace{\frac{dN_{\bar{f}}^i}{dE_{\bar{f}}} \sigma_i v}_{\text{Particle physics}} \frac{1}{4\pi m_\chi^2} \underbrace{\int (\rho + \delta\rho)^2 P_{prop}}_{\text{Astro}}$$



ACT: HESS,  
Magic, VERITAS,  
Cangoroo, ...  
Space-based:  
AMS, GLAST,  
Egret,...

# Annihilation into $e^+, \bar{p}, \bar{D}$

$$\frac{d\Phi_{\bar{f}}}{d\Omega dE_{\bar{f}}} = \sum_i \underbrace{\frac{dN_{\bar{f}}^i}{dE_{\bar{f}}}}_{\text{Particle physics}} \sigma_i v \frac{1}{4\pi m_\chi^2} \underbrace{\int (\rho + \delta\rho)^2 P_{prop}}_{\text{Astro}}$$



**charged particles:** Model of propagation and background

- Halo Profile modeling, clumps, cusps,..boost factors,...

ACT: HESS,  
Magic, VERITAS,

Cangoroo, ...

Space-based:  
AMS, GLAST,  
Egret,...

## Features in the Indirect Detection Module of micrOMEGAs

- Annihilation cross sections for all 2-body tree-level processes for all models.

## Features in the Indirect Detection Module of micrOMEGAs

- Annihilation cross sections for all 2-body tree-level processes for all models.
- Annihilation cross sections including radiative emission of a photon for all models.

## Features in the Indirect Detection Module of micrOMEGAs

- Annihilation cross sections for all 2-body tree-level processes for all models.
- Annihilation cross sections including radiative emission of a photon for all models.
- Annihilation cross sections into polarized gauge bosons.

## Features in the Indirect Detection Module of micrOMEGAs

- Annihilation cross sections for all 2-body tree-level processes for all models.
- Annihilation cross sections including radiative emission of a photon for all models.
- Annihilation cross sections into polarized gauge bosons.
- Annihilation cross sections for the loop induced processes  $\gamma\gamma$  and  $\gamma Z^0$  in the MSSM.

## Features in the Indirect Detection Module of micrOMEGAs

- Annihilation cross sections for all 2-body tree-level processes for all models.
- Annihilation cross sections including radiative emission of a photon for all models.
- Annihilation cross sections into polarized gauge bosons.
- Annihilation cross sections for the loop induced processes  $\gamma\gamma$  and  $\gamma Z^0$  in the MSSM.
- Modelling of the DM halo with a general parameterization and with the possibility of including DM clumps.

## Features in the Indirect Detection Module of micrOMEGAs

- Annihilation cross sections for all 2-body tree-level processes for all models.
- Annihilation cross sections including radiative emission of a photon for all models.
- Annihilation cross sections into polarized gauge bosons.
- Annihilation cross sections for the loop induced processes  $\gamma\gamma$  and  $\gamma Z^0$  in the MSSM.
- Modelling of the DM halo with a general parameterization and with the possibility of including DM clumps.
- Integrals along lines of sight for  $\gamma$ -ray signals.

## Features in the Indirect Detection Module of micrOMEGAs

- Annihilation cross sections for all 2-body tree-level processes for all models.
- Annihilation cross sections including radiative emission of a photon for all models.
- Annihilation cross sections into polarized gauge bosons.
- Annihilation cross sections for the loop induced processes  $\gamma\gamma$  and  $\gamma Z^0$  in the MSSM.
- Modelling of the DM halo with a general parameterization and with the possibility of including DM clumps.
- Integrals along lines of sight for  $\gamma$ -ray signals.
- Computation of the propagation of charged particles through the Galaxy, including the possibility to modify the propagation parameters.

## Features in the Indirect Detection Module of micrOMEGAs

- Annihilation cross sections for all 2-body tree-level processes for all models.
- Annihilation cross sections including radiative emission of a photon for all models.
- Annihilation cross sections into polarized gauge bosons.
- Annihilation cross sections for the loop induced processes  $\gamma\gamma$  and  $\gamma Z^0$  in the MSSM.
- Modelling of the DM halo with a general parameterization and with the possibility of including DM clumps.
- Integrals along lines of sight for  $\gamma$ -ray signals.
- Computation of the propagation of charged particles through the Galaxy, including the possibility to modify the propagation parameters.
- Effect of solar modulation on the charged particle spectrum.

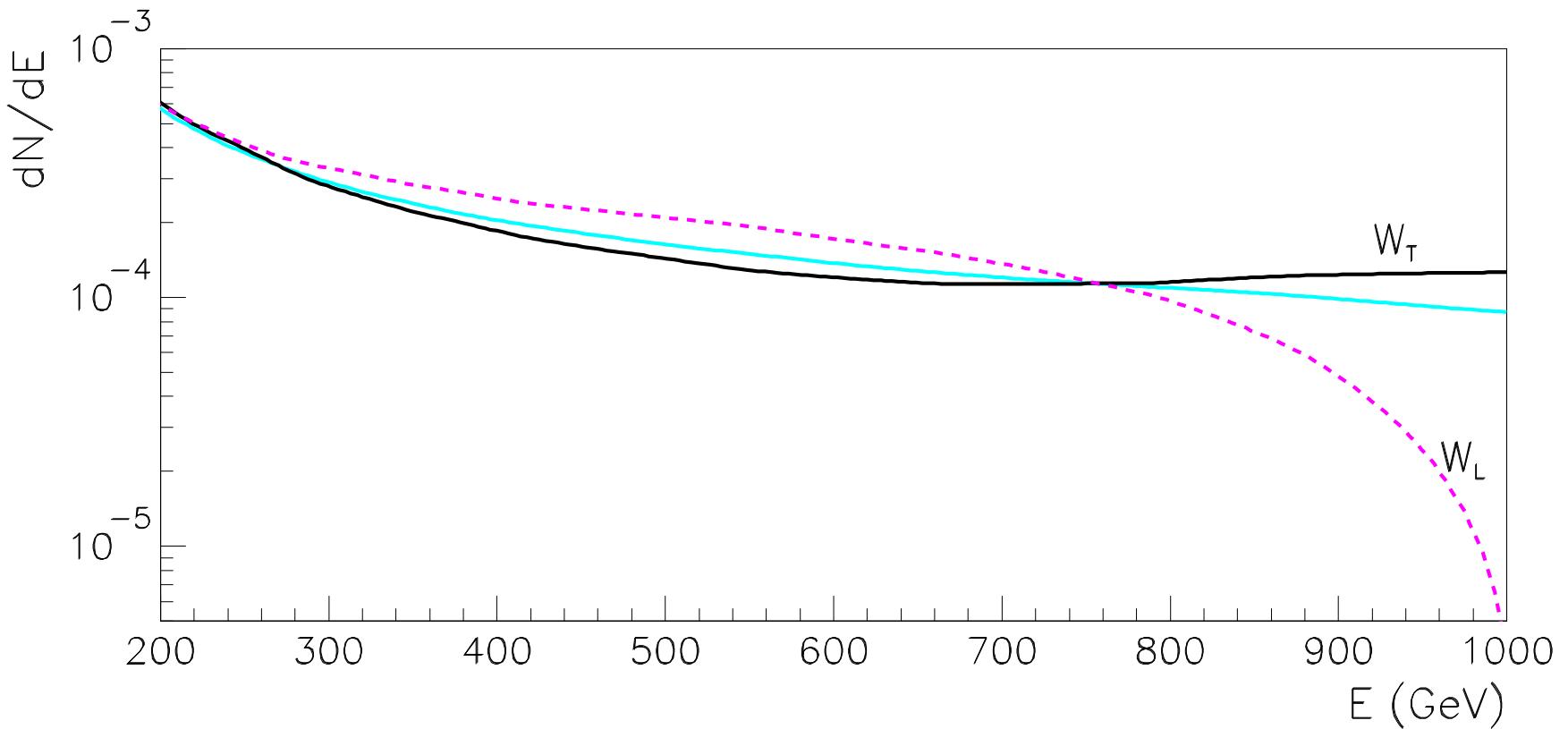
## Features in the Indirect Detection Module of micrOMEGAs

- Annihilation cross sections for all 2-body tree-level processes for all models.
- Annihilation cross sections including radiative emission of a photon for all models.
- Annihilation cross sections into polarized gauge bosons.
- Annihilation cross sections for the loop induced processes  $\gamma\gamma$  and  $\gamma Z^0$  in the MSSM.
- Modelling of the DM halo with a general parameterization and with the possibility of including DM clumps.
- Integrals along lines of sight for  $\gamma$ -ray signals.
- Computation of the propagation of charged particles through the Galaxy, including the possibility to modify the propagation parameters.
- Effect of solar modulation on the charged particle spectrum.
- Model independent predictions of the indirect detection signal

## Features in the Indirect Detection Module of micrOMEGAs

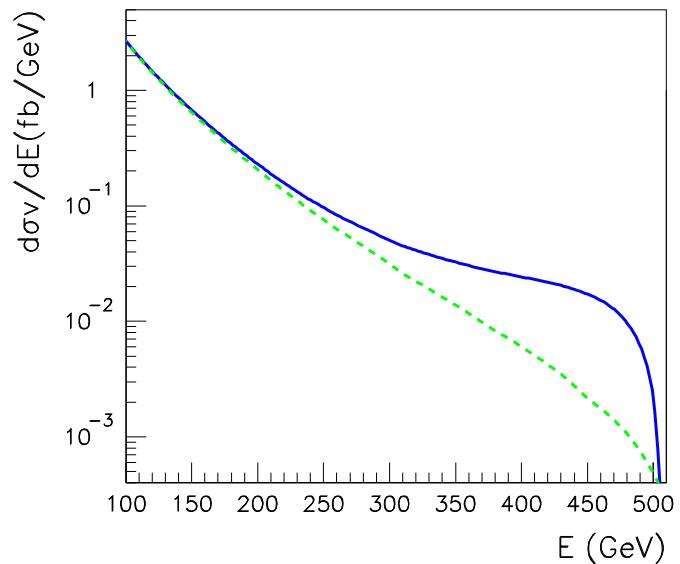
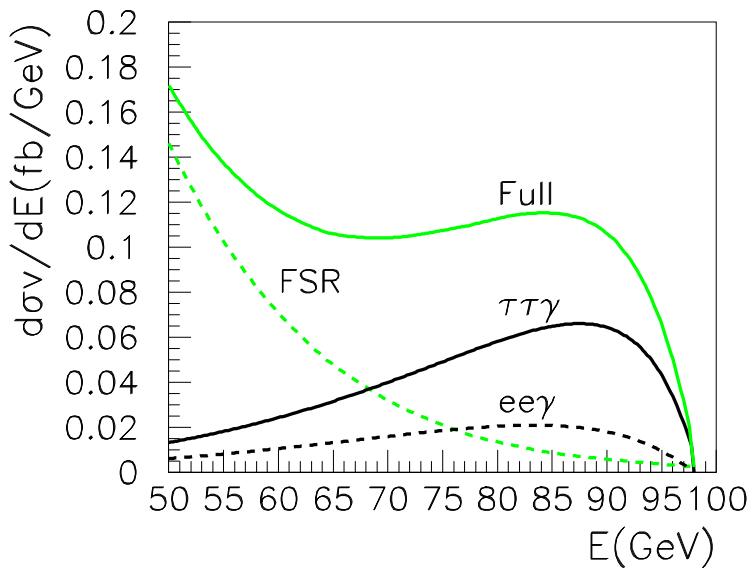
- Annihilation cross sections for all 2-body tree-level processes for all models.
- Annihilation cross sections including radiative emission of a photon for all models.
- Annihilation cross sections into polarized gauge bosons.
- Annihilation cross sections for the loop induced processes  $\gamma\gamma$  and  $\gamma Z^0$  in the MSSM.
- Modelling of the DM halo with a general parameterization and with the possibility of including DM clumps.
- Integrals along lines of sight for  $\gamma$ -ray signals.
- Computation of the propagation of charged particles through the Galaxy, including the possibility to modify the propagation parameters.
- Effect of solar modulation on the charged particle spectrum.
- Model independent predictions of the indirect detection signal
- The neutrino spectrum originating from dark matter annihilation is also computed, however the neutrino signal is usually dominated by neutrinos coming from DM capture in the Sun or the Earth.  
The inclusion of this signature is left for a further upgrade.

## Effect of the polarisation



$dN/dE_{e^+}$  for positrons from  $\chi\chi \rightarrow W^+W^-$ .  $M_\chi = 1$  TeV.

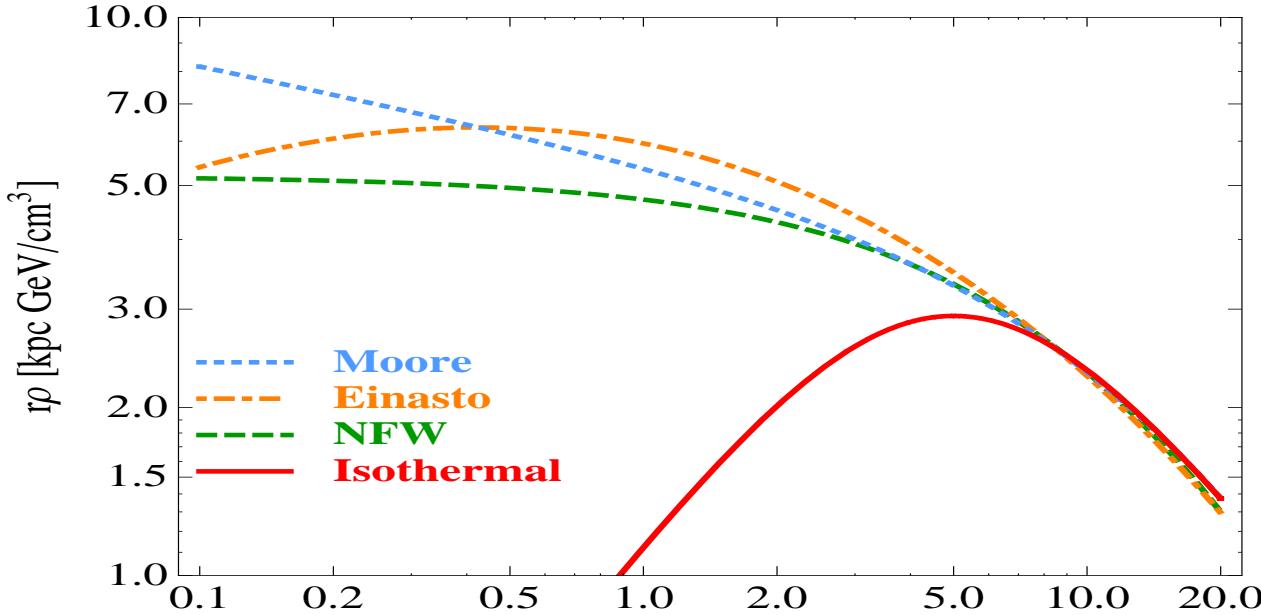
## Effects of non factorisable (non collinear, hard) photons



Photon spectrum within a CMSSM point including the additional photon contribution from  $2 \rightarrow 3 \tau\tau\gamma$ ,  $e^+e^-\gamma$ , and FSR photons from PYTHIA (FSR)

In a model for  $WW$  production, including full  $WW\gamma$  as compared to PYTHIA FSR

## Dark Matter Halo Profiles in micrOMEGAs



$$\rho(r) = \rho_o \left( \frac{r_o}{r} \right)^\gamma \left( \frac{1 + (r_o/a)}{1 + (r/a)} \right)^{\left( \frac{\beta - \gamma}{\alpha} \right)}$$

$(\alpha, \beta, \gamma, a(kpc)) = (2, 2, 0, 4)$  Isothermal

$(\alpha, \beta, \gamma, a(kpc)) = (1, 3, 1, 20)$  NFW cusped

$(\alpha, \beta, \gamma, a(kpc)) = (1.5, 3, 1.5, 28)$  Moore, cusped

$$\rho_o \sim 0.3 \text{GeV/cm}^3 \text{ at } r_o = 8.5 \text{kpc}$$

(1)

Other profiles (provided they are spherically symmetric) are possible. For example **Einasto**  
To avoid central divergence, we set  $r > r_{min} = 10^{-3} \text{pc}$

## indirect detection: modelling propagation 0, Transport

$$\frac{\partial \psi_a}{\partial t} - \nabla \cdot (K(E) \nabla \psi_a) - \frac{\partial}{\partial E} (b(E) \psi_a) + \frac{\partial}{\partial z} (V_C \psi_a) = Q_a(\mathbf{x}, E) + \tilde{\Gamma}_{ann}, \quad \psi_a = dn/dE$$

## indirect detection: modelling propagation 0, Transport

$$\frac{\partial \psi_a}{\partial t} - \nabla \cdot (K(E) \nabla \psi_a) - \frac{\partial}{\partial E} (b(E) \psi_a) + \frac{\partial}{\partial z} (V_C \psi_a) = Q_a(\mathbf{x}, E) + \tilde{\Gamma}_{ann}, \quad \psi_a = dn/dE$$

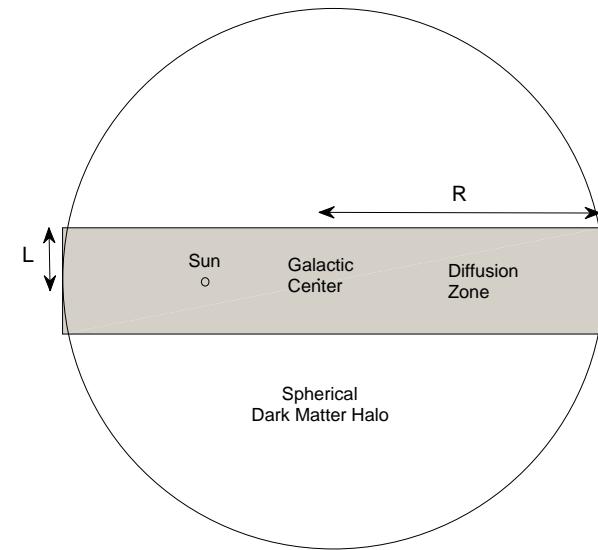
- $K(E) = K_0 \beta(E) (E/E_0)^\delta$  diffusion term, stochastic galactic magnetic fields
- $B$  energy losses due to synchrotron rad., CMB , ICS, negligible for  $\bar{p}$
- $V_C$  convection galactic wind wipes away charged particles from disk (not for e+)
- $\tilde{\Gamma}_{ann.}$  for  $\bar{p}$  disappearance through nuclear reactions ( $H, H_e$ )
- from Sun to earth “rescaling”, due to solar wind and energy loss. (use Fisk pot.)

## indirect detection: modelling propagation 0, Transport

$$\frac{\partial \psi_a}{\partial t} - \nabla \cdot (K(E) \nabla \psi_a) - \frac{\partial}{\partial E} (b(E) \psi_a) + \frac{\partial}{\partial z} (V_C \psi_a) = Q_a(\mathbf{x}, E) + \tilde{\Gamma}_{ann}, \quad \psi_a = dn/dE$$

Model	$\delta$	$K_0$ kpc <sup>2</sup> /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

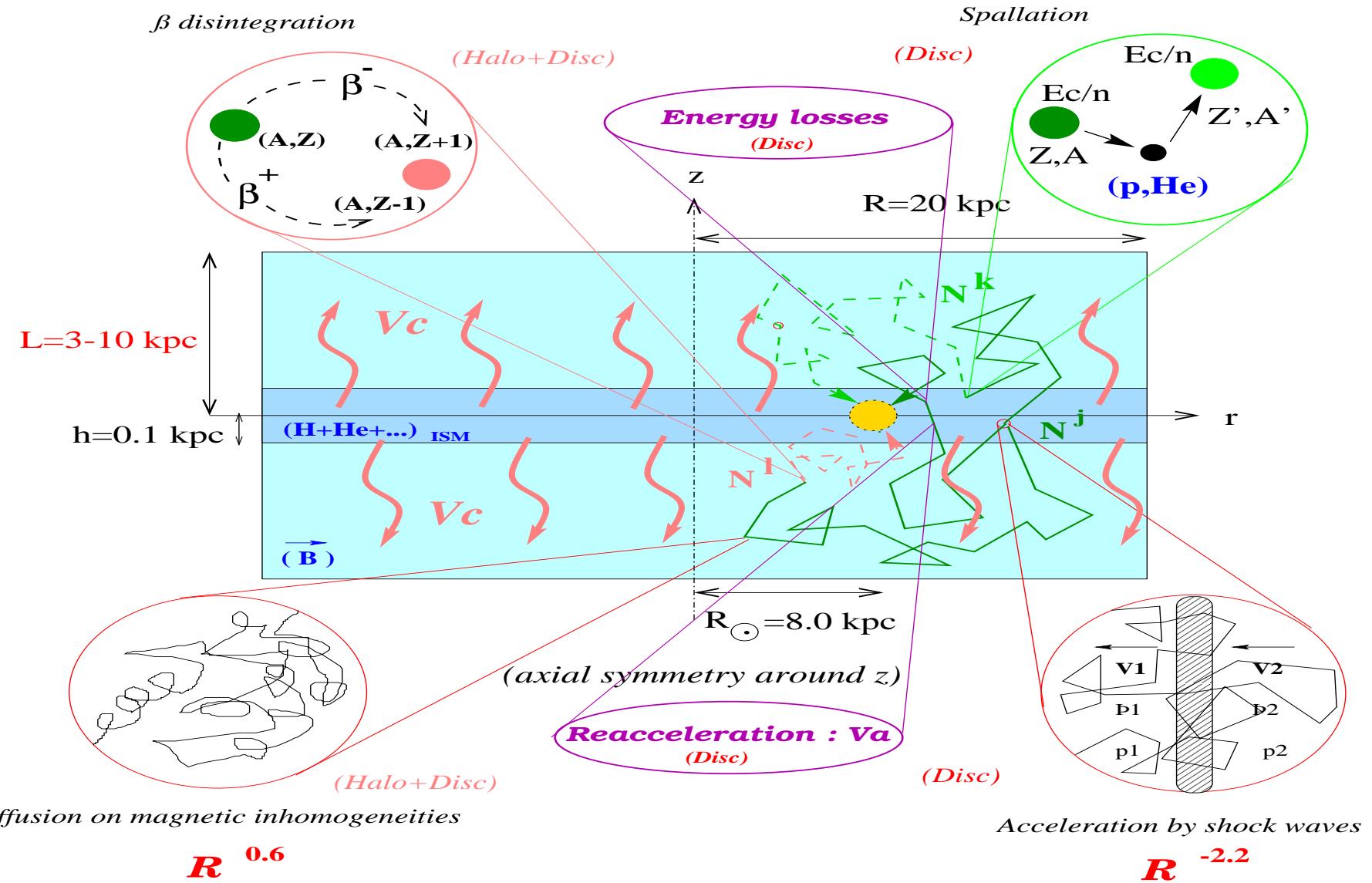
Leaky Box. Typical diffusion parameters that are compatible with the B/C analysis (Maurin et al. 2001)  $E_0 = 1\text{GeV}$ .



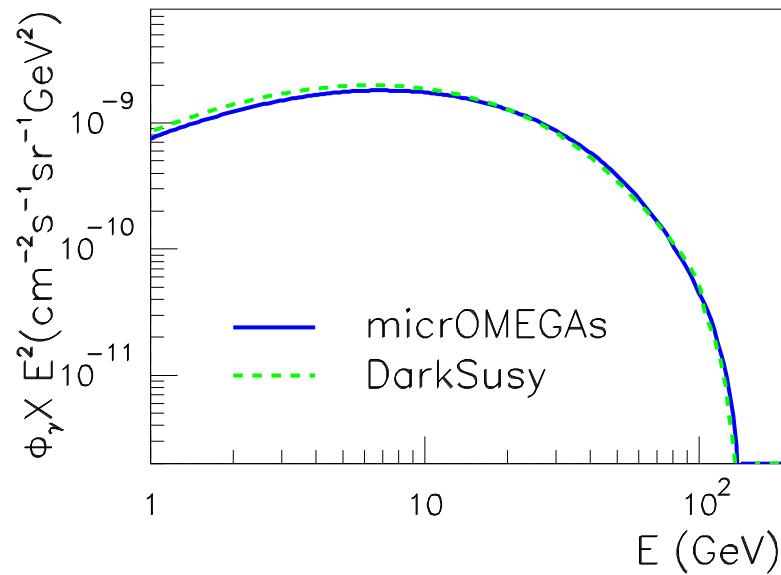
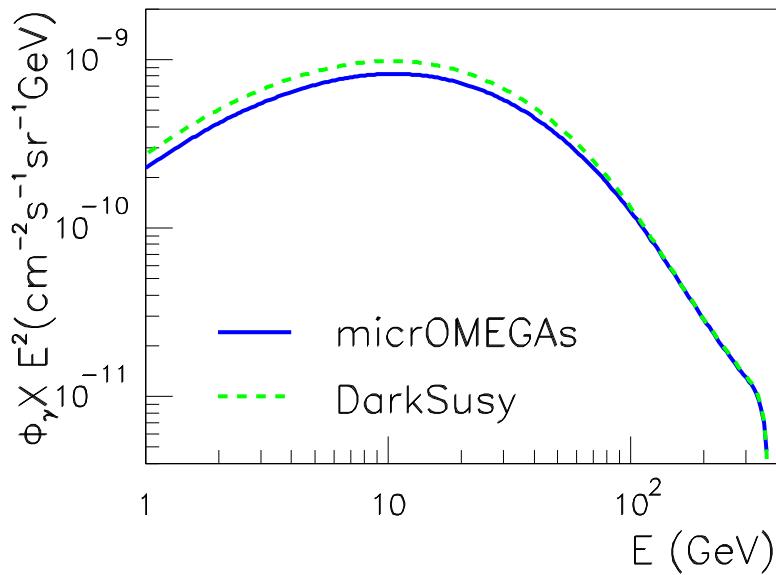
$\frac{\partial \psi_a}{\partial t} = 0$ , steady state, takes  $e^+$   $10^8\text{y}$  to reach the edge.

Equations solved semi-analytically

## indirect detection: modelling propagation 1 (Maurin et al., 2002)



## Results and Comparison, microMEGAs vs DARKSUSY, $\gamma$

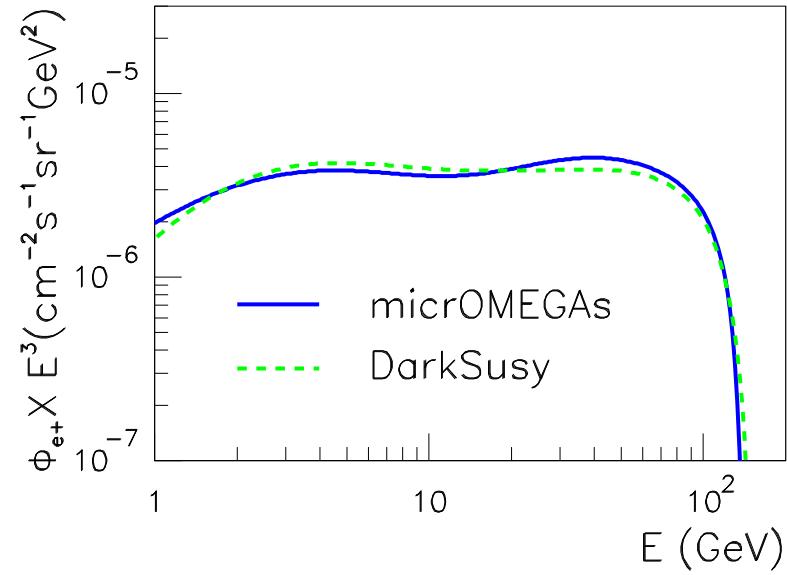
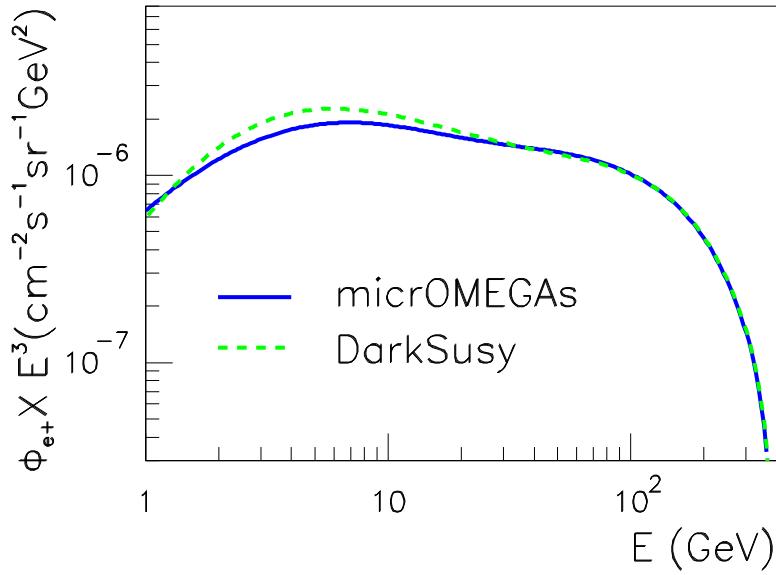


comparisons for  $\gamma$  signal from two CMSSM models, with NFW profile, signal from the GC in a cone of  $1^\circ$  opening angle (corresponding to a solid angle of  $\Delta\Omega = 10^{-3} \text{ sr}$ )

slight difference due to  $\sigma v$

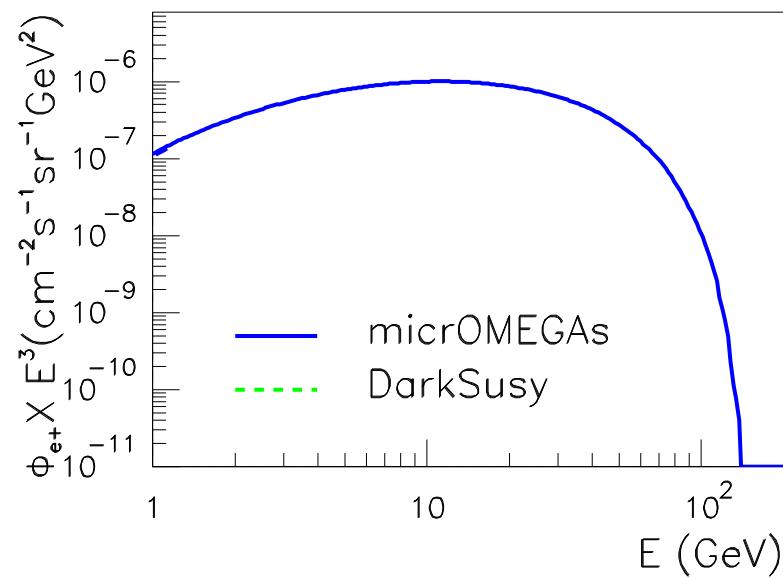
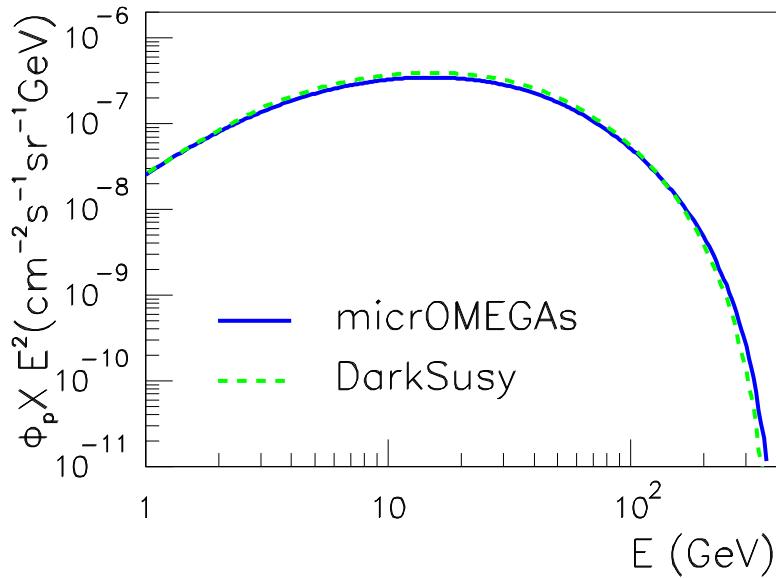
For  $\gamma$  line, good agreement from  $\gamma\gamma$  but not  $Z\gamma$ , DS misses contributions

## Results and Comparison, microMEGAs vs DARKSUSY, $e^+$



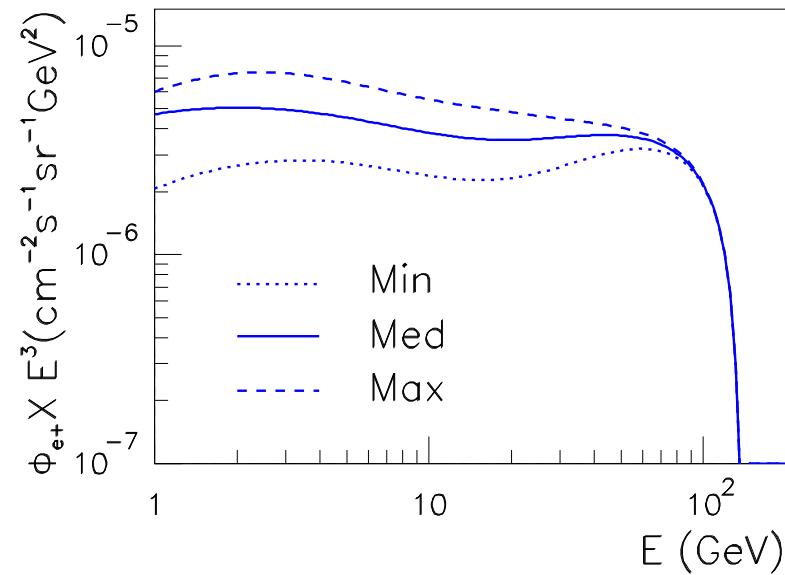
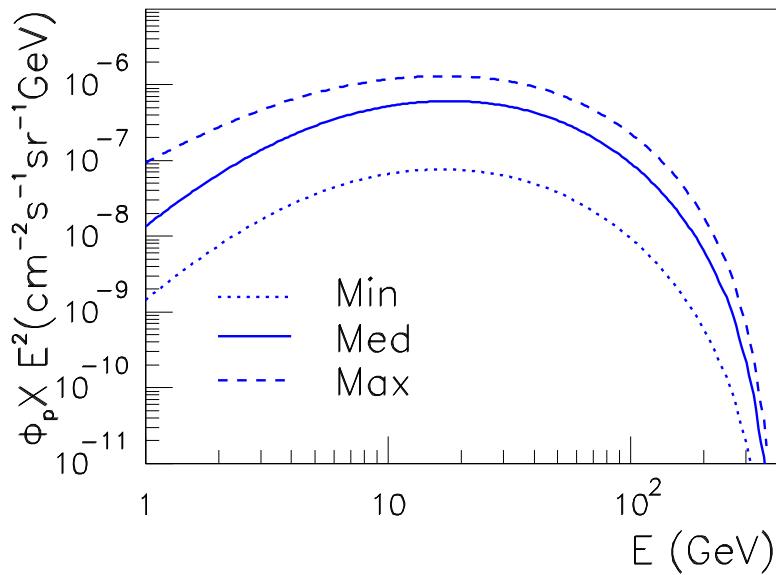
In the same SUSY models, default prop. parameters of microMEGAs tuned.

## Results and Comparison, microMEGAs vs DARKSUSY, $\bar{p}$



In the same SUSY models, default prop. parameters of microMEGAs tuned.

## Uncertainties due to propagation microMEGAs



## 1. Need to go beyond tree-level: Need percent level

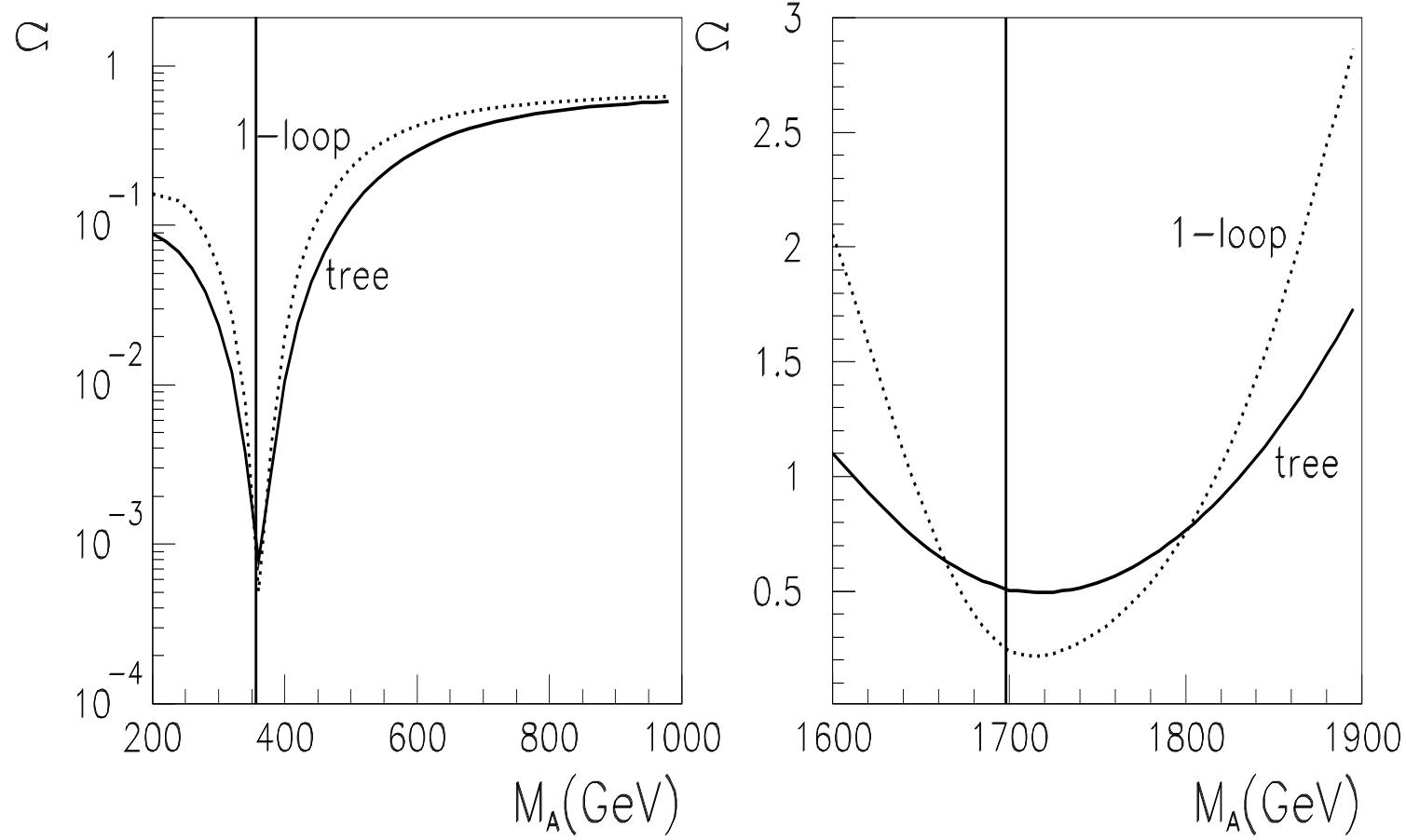
Present measurement at  $2\sigma$   $0.0975 < \omega = \Omega_{\text{DM}} h^2 < 0.1223$  (6%)

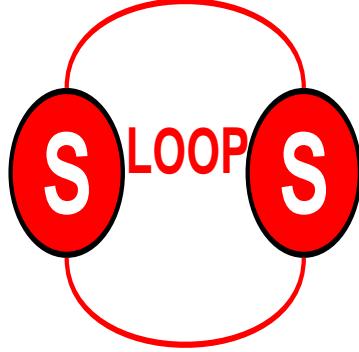
future (SNAP+Planck)  $\rightarrow < 1\%$

Need more Precise Predictions

$\gamma$  *ray-line is a one-loop calc.*

## 2. Need to go beyond tree-level: Need percent level





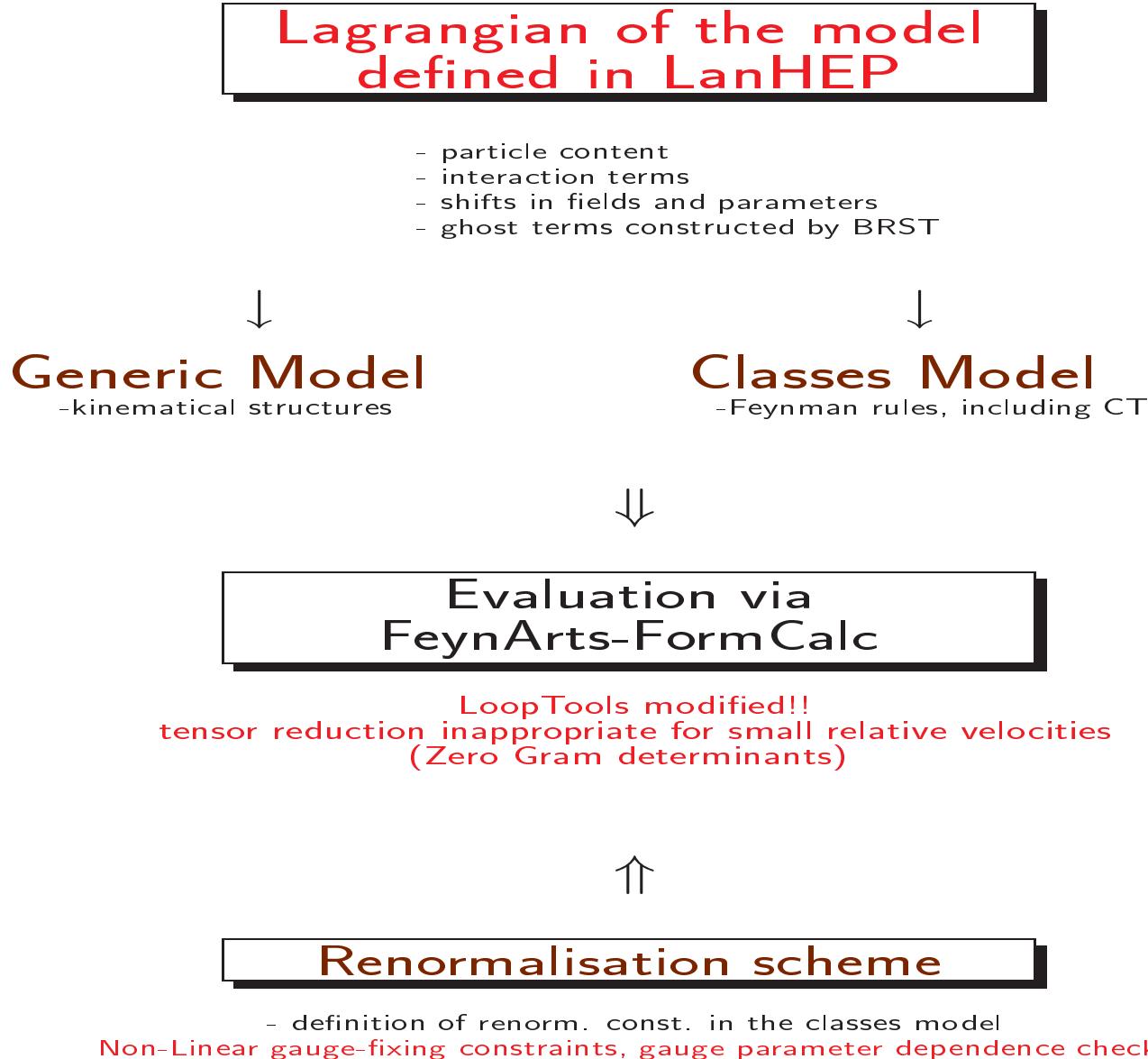
- Need for an automatic tool for susy calculations
- handles large numbers of diagrams both for tree-level
- and loop level
- able to compute loop diagrams at  $v = 0$  : dark matter, LSP, move at galactic velocities,  $v = 10^{-3}$
- ability to check results: UV and IR finiteness but also gauge parameter independence for example
- ability to include different models easily and switch between different renormalisation schemes
- Used for SM one-loop multi-leg: new powerful loop libraries (with Ninh Le Duc, Sun Hao)

## Non-linear gauge implementation

$$\begin{aligned}\mathcal{L}_{GF} = & -\frac{1}{\xi_W} |(\partial_\mu - ie\tilde{\alpha}A_\mu - igc_W\tilde{\beta}Z_\mu)W^\mu + \xi_W \frac{g}{2}(v + \tilde{\delta}_h h + \tilde{\delta}_H H + i\tilde{\kappa}\chi_3)\chi^+|^2 \\ & -\frac{1}{2\xi_Z} (\partial.Z + \xi_Z \frac{g}{2c_W}(v + \tilde{\epsilon}_h h + \tilde{\epsilon}_H H)\chi_3)^2 - \frac{1}{2\xi_\gamma} (\partial.A)^2\end{aligned}$$

- quite a handful of gauge parameters, but with  $\xi_i = 1$ , no “unphysical threshold”
- more important: no need for higher (than the minimal set) for higher rank tensors and tedious algebraic manipulations

# Strategy: Exploiting and interfacing modules from different codes



```
vector
A/A: (photon, gauge),
Z/Z:('Z boson', mass MZ = 91.1875, gauge),
'W+/'W-': ('W boson', mass MW = MZ*CW, gauge).
scalar H/H:(Higgs, mass MH = 115).
```

```
transform A->A*(1+dZAA/2)+dZAZ*Z/2, Z->Z*(1+dZZZ/2)+dZZA*A/2,
'W+'->'W+)*(1+dZW/2), 'W-'->'W-)*(1+dZW/2).
transform H->H*(1+dZH/2), 'Z.f'->'Z.f)*(1+dZZf/2),
'W+.f'->'W+.f)*(1+dZWf/2), 'W-.f'->'W-.f)*(1+dZWf/2).
```

```
let pp = { -i*'W+.f', (vev(2*MW/EE*SW)+H+i*'Z.f')/Sqrt2 },
PP=anti(pp).
```

```
lterm -2*lambda*(pp*anti(pp)-v**2/2)**2
      where
lambda=(EE*MH/MW/SW)**2/16, v=2*MW*SW/EE .
```

```
let Dpp^mu^a = (deriv^mu+i*g1/2*B0^mu)*pp^a +
  i*g/2*taupm^a^b^c*WW^mu^c*pp^b.
let DPP^mu^a = (deriv^mu-i*g1/2*B0^mu)*PP^a
  -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*PP^b.
lterm DPP*Dpp.
```

### Gauge fixing and BRS transformation

```
let G_Z = deriv*Z+(MW/CW+EE/SW/CW/2*nle*H)*'Z.f'.
lterm -G_A**2/2 - G_Wp*G_Wm - G_Z**2/2.
lterm -'Z.C'*brst(G_Z).
```

vector

```
A/A: (photon, gauge),
Z/Z:('Z boson', mass MZ = 91.1875, gauge),
'W+/'W-': ('W boson', mass MW = MZ*CW, gauge).
scalar H/H:(Higgs, mass MH = 115).
```

```
transform A->A*(1+dZAA/2)+dZAZ*Z/2, Z->Z*(1+dZZZ/2)+dZZA*A/2,
'W+'->'W+)*(1+dZW/2), 'W-'->'W-)*(1+dZW/2).
```

```
transform H->H*(1+dZH/2), 'Z.f'->'Z.f'*(1+dZZf/2),
'W+.f'->'W+.f'*(1+dZWf/2), 'W-.f'->'W-.f'*(1+dZWf/2).
```

```
let pp = { -i*'W+.f', (vev(2*MW/EE*SW)+H+i*'Z.f')/Sqrt2 },
PP=anti(pp).
```

```
lterm -2*lambda*(pp*anti(pp)-v**2/2)**2
where
lambda=(EE*MH/MW/SW)**2/16, v=2*MW*SW/EE .
```

```
let Dpp^mu^a = (deriv^mu+i*g1/2*B0^mu)*pp^a +
i*g/2*taupm^a^b^c*WW^mu^c*pp^b.
let DPP^mu^a = (deriv^mu-i*g1/2*B0^mu)*PP^a
-i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*PP^b.
lterm DPP*Dpp.
```

### Gauge fixing and BRS transformation

```
let G_Z = deriv*Z+(MW/CW+EE/SW/CW/2*nle*H)*'Z.f'.
```

```
lterm -G_A**2/2 - G_Wp*G_Wm - G_Z**2/2.
```

```
lterm -'Z.C'*brst(G_Z).
```

```
M$CouplingMatrices = {
```

```
(*----- H H -----*)
C[ S[3], S[3] ] == - I *
```

```
{
{ 0 , dZH },
{ 0 , MH^2 dZH + dMHSq } }
```

```
(*----- W+.f W-.f -----*)
C[ S[2], -S[2] ] == - I *
```

```
{
{ 0 , dZWf },
{ 0 , 0 } }
```

```
(*----- A Z -----*)
C[ V[1], V[2] ] == 1/2 I / CW^2 MW^2 *
```

```
{
{ 0 , 0 },
{ 0 , dZZA },
{ 0 , 0 } }
```

```
(*----- H H H -----*)
C[ S[3], S[3], S[3] ] == -3/4 I EE / MW / SW *
```

```
{
{ 2 MH^2 , 3 MH^2 dZH -2 MH^2 / SW dSW - MH^2 / MW^2 dMWSq + }
```

```
(*----- H W+.f W-.f -----*)
C[ S[3], S[2], -S[2] ] == -1/4 I EE / MW / SW *
```

```
{
{ 2 MH^2 , MH^2 dZH + 2 MH^2 dZWf -2 MH^2 / SW dSW - MH^2 / }
```

```
(*----- W-.C A.c W+ -----*)
C[ -U[3], U[1], V[3] ] == - I EE *
```

```
{
{ 1 },
{ - nla } }
```

```
},
```

vector

```
A/A: (photon, gauge),
Z/Z:('Z boson', mass MZ = 91.1875, gauge),
'W+/'W-': ('W boson', mass MW = MZ*CW, gauge).
scalar H/H:(Higgs, mass MH = 115).
```

```
transform A->A*(1+dZAA/2)+dZAZ*Z/2, Z->Z*(1+dZZZ/2)+dZZA*A/2,
'W+'->'W+)*(1+dZW/2), 'W-'->'W-)*(1+dZW/2).
```

```
transform H->H*(1+dZH/2), 'Z.f'->'Z.f)*(1+dZZf/2),
'W+.f'->'W+.f)*(1+dZWf/2), 'W-.f'->'W-.f)*(1+dZWf/2).
```

```
let pp = { -i*'W+.f', (vev(2*MW/EE*SW)+H+i*'Z.f')/Sqrt2 },
PP=anti(pp).
```

```
lterm -2*lambda*(pp*anti(pp)-v**2/2)**2
where
lambda=(EE*MH/MW/SW)**2/16, v=2*MW*SW/EE .
```

```
let Dpp^mu^a = (deriv^mu+i*g1/2*B0^mu)*pp^a +
i*g/2*taupm^a^b^c*WW^mu^c*pp^b.
let DPP^mu^a = (deriv^mu-i*g1/2*B0^mu)*PP^a
-i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*PP^b.
lterm DPP*Dpp.
```

### Gauge fixing and BRS transformation

```
let G_Z = deriv*Z+(MW/CW+EE/SW/CW/2*nle*H)*'Z.f'.
```

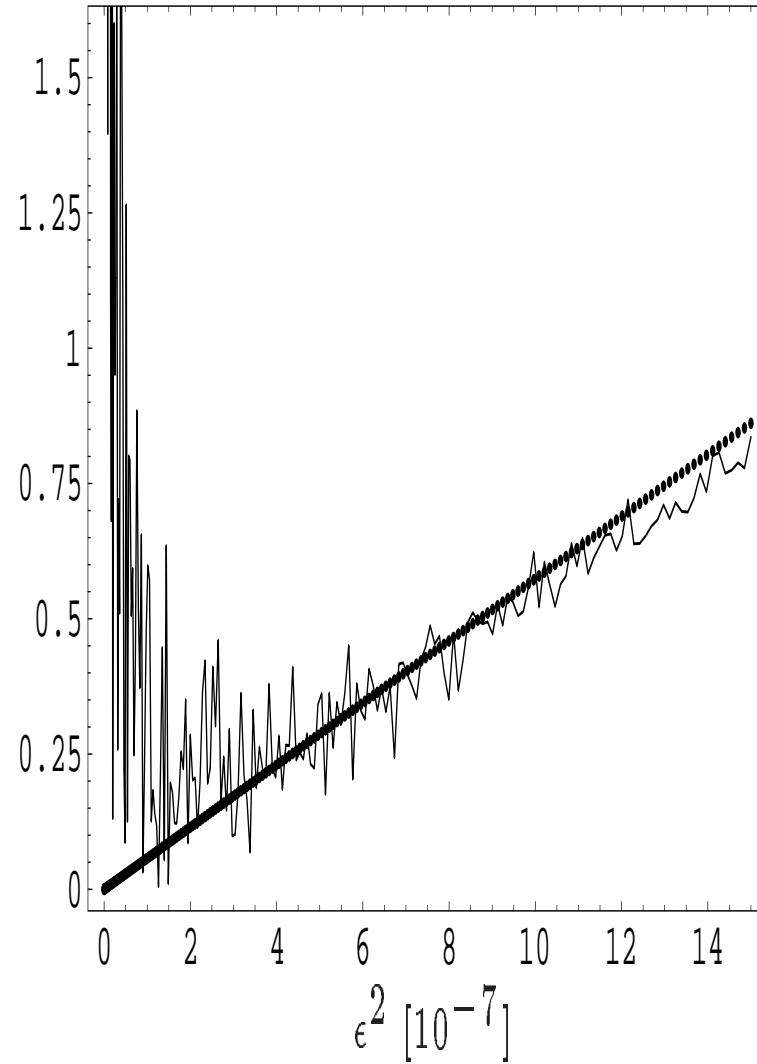
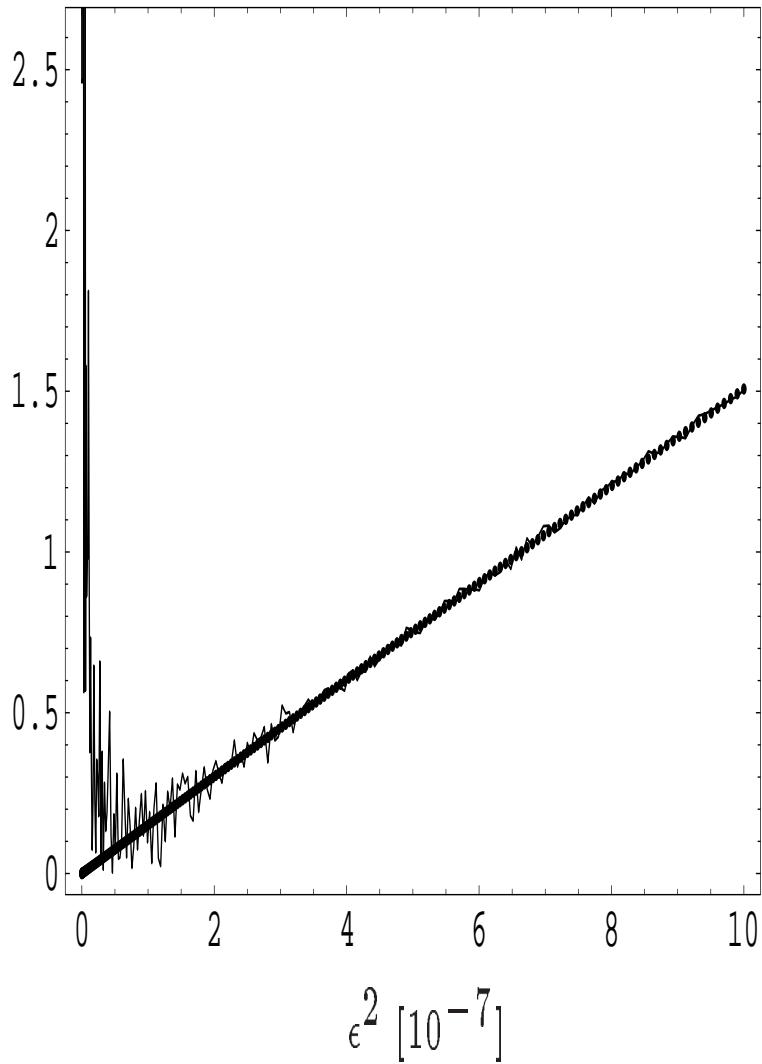
```
lterm -G_A**2/2 - G_Wp*G_Wm - G_Z**2/2.
```

```
lterm -'Z.C'*brst(G_Z).
```

```
RenConst[ dMHSq ] := ReTilde[SelfEnergy[prt["H"] -> prt["H"], MH]]
RenConst[ dZH ] := -ReTilde[DSelfEnergy[prt["H"] -> prt["H"], MH]]
RenConst[ dZZf ] := -ReTilde[DSelfEnergy[prt["Z.f"] -> prt["Z.f"], MZ]]
RenConst[ dZWf ] := -ReTilde[DSelfEnergy[prt["W+.f"] -> prt["W+.f"], MW]]
```

```
M$CouplingMatrices = {
(*----- H H -----*)
C[ S[3], S[3] ] == - I *
{
{ 0 , dZH },
{ 0 , MH^2 dZH + dMHSq }
},
(*----- W+.f W-.f -----*)
C[ S[2], -S[2] ] == - I *
{
{ 0 , dZWf },
{ 0 , 0 }
},
(*----- A Z -----*)
C[ V[1], V[2] ] == 1/2 I / CW^2 MW^2 *
{
{ 0 , 0 },
{ 0 , dZZA },
{ 0 , 0 }
},
(*----- H H H -----*)
C[ S[3], S[3], S[3] ] == -3/4 I EE / MW / SW *
{
{ 2 MH^2 , 3 MH^2 dZH - 2 MH^2 / SW dSW - MH^2 / MW^2 dMHSq +
},
(*----- H W+.f W-.f -----*)
C[ S[3], S[2], -S[2] ] == -1/4 I EE / MW / SW *
{
{ 2 MH^2 , MH^2 dZH + 2 MH^2 dZWf - 2 MH^2 / SW dSW - MH^2 /
},
(*----- W-.C A.c W+ -----*)
C[ -U[3], U[1], V[3] ] == - I EE *
{
{ 1 },
{ - nla }
},
```

## Gram determinant for small velocity



## TREE LEVEL CALCULATIONS

Comparison with public codes: Grace and CompHEP

Cross-section [pb]	SloopS	CompHEP	Grace
$h^0 h^0 \rightarrow h^0 h^0$	$3.932 \times 10^{-2}$	$3.932 \times 10^{-2}$	$3.929 \times 10^{-2}$
$W^+ W^- \rightarrow l_1 \bar{l}_1$	$7.082 \times 10^{-1}$	$7.082 \times 10^{-1}$	$7.083 \times 10^{-1}$
$e^+ e^- \rightarrow \tilde{\tau}_1 \bar{\tilde{\tau}}_2$	$2.854 \times 10^{-3}$	$2.854 \times 10^{-3}$	$2.854 \times 10^{-3}$
$H^+ H^- \rightarrow W^+ W^-$	$6.643 \times 10^{-1}$	$6.643 \times 10^{-1}$	$6.644 \times 10^{-1}$
Decay [GeV]			# 200 processes checked
$A^0 \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$	$1.137 \times 10^0$	$1.137 \times 10^0$	$1.137 \times 10^0$
$\tilde{\chi}_1^+ \rightarrow t \bar{b}_1$	$5.428 \times 10^0$	$5.428 \times 10^0$	$5.428 \times 10^0$
$H^0 \rightarrow \tilde{\tau}_1 \bar{\tilde{\tau}}_1$	$7.579 \times 10^{-3}$	$7.579 \times 10^{-3}$	$7.579 \times 10^{-3}$
$H^+ \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^0$	$1.113 \times 10^{-1}$	$1.113 \times 10^{-1}$	$1.113 \times 10^{-1}$

## A FEW EXAMPLES

### BINO-LIKE NEUTRALINO

$$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow l^+ l^-$$

$M_1$	$M_2$	$\mu$	$M_3$	$M_{\tilde{f}_{L,R}}$	$A_f$	$M_{A^0}$	$t_\beta$
90	200	-600	1000	250/110 800/800	0	500	5

### COANNIHILATION WITH A STAU

$$\tilde{\chi}_1^0 \tilde{\tau}_1^+ \rightarrow \tau^+ \gamma$$

$$\tilde{\chi}_1^0 \tilde{\tau}_1^+ \rightarrow \tau^+ Z^0$$

$$\tilde{\tau}_1^+ \tilde{\tau}_1^+ \rightarrow \tau^+ \tau^+$$

$M_1$	$M_2$	$\mu$	$M_3$	$M_{\tilde{f}_{L,R}}$	$A_f$	$M_{A^0}$	$t_\beta$
166	300	400	1000	290-276/190-166 800/300	0	1000	10

### MIXED-LIKE NEUTRALINO

$$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow W^+ W^-$$

$$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow Z^0 Z^0$$

$M_1$	$M_2$	$\mu$	$M_3$	$M_{\tilde{f}_{L,R}}$	$A_f$	$M_{A^0}$	$t_\beta$
110	150	-163	1000	1000	0	1000	5

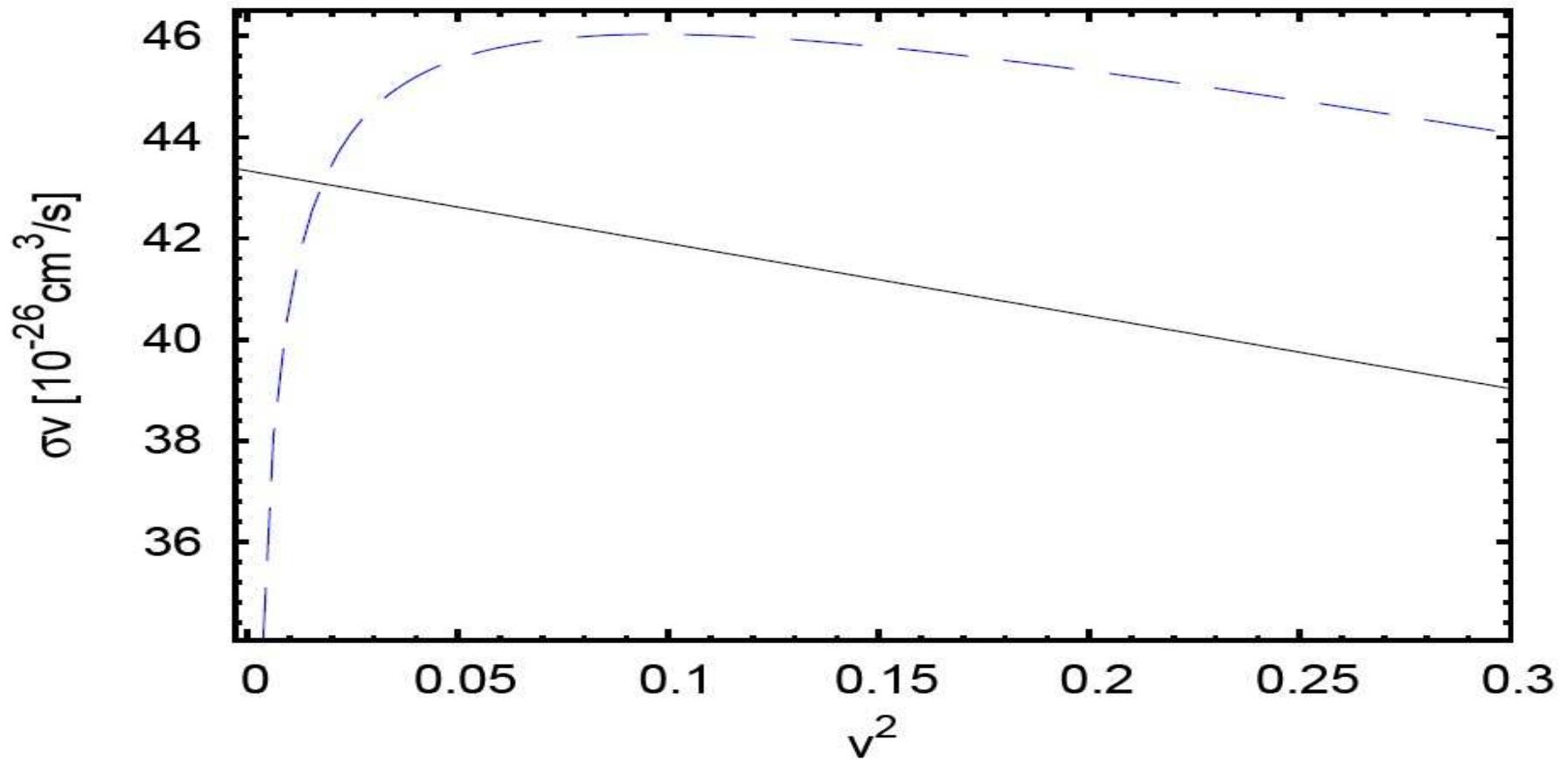
### QCD CORRECTION

$$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow b\bar{b}$$

$M_1$	$M_2$	$\mu$	$M_3$	$M_{\tilde{f}_{L,R}}$	$A_f$	$M_{A^0}$	$t_\beta$
250	150	-180	400	250/200	0	300	5

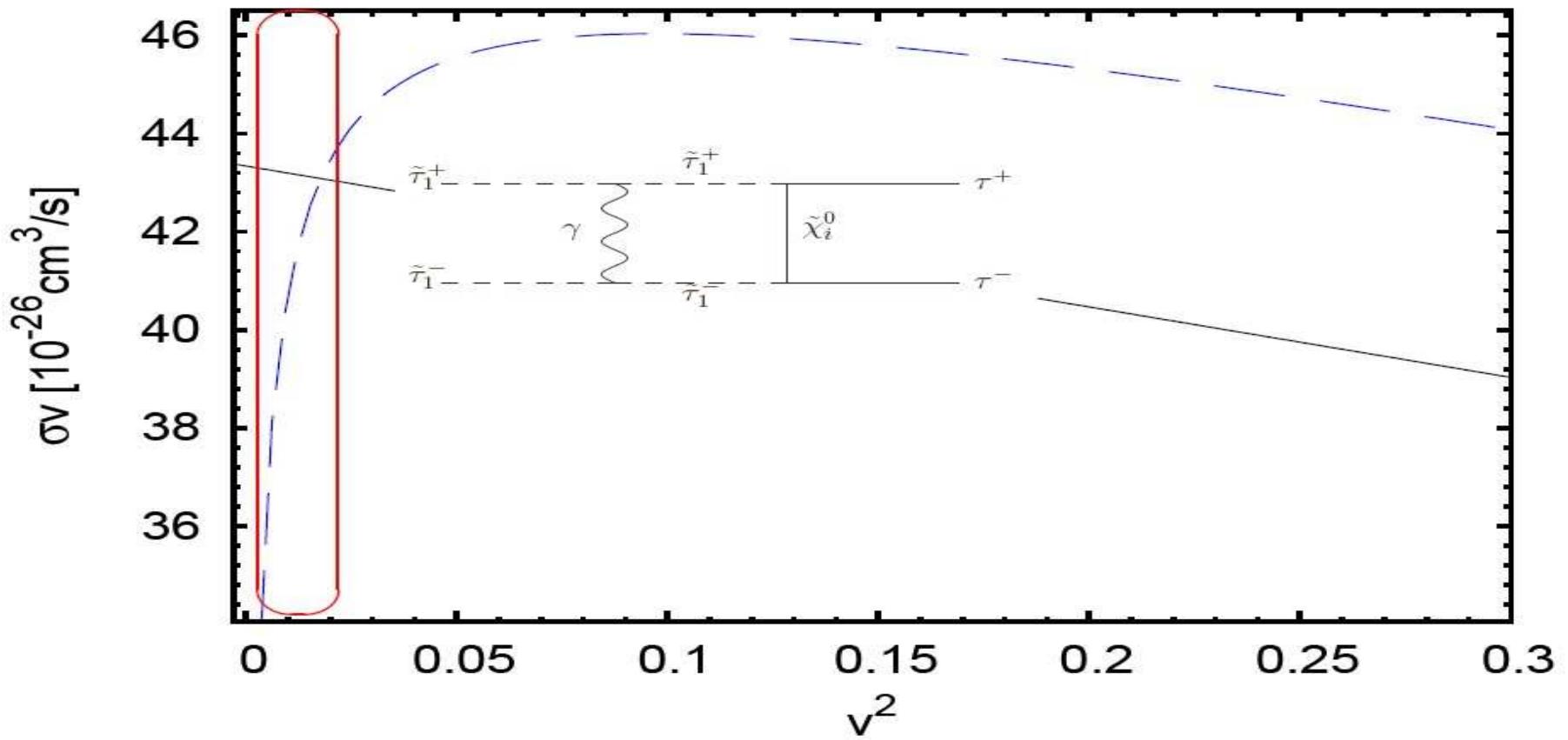
**COANNIHILATION CASE**

$$\tilde{\tau}_1^+ \tilde{\tau}_1^+ \rightarrow \tau^+ \tau^+ \text{ (23\%)}$$



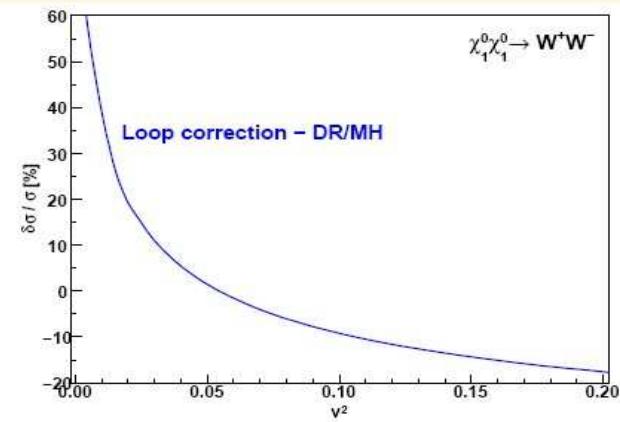
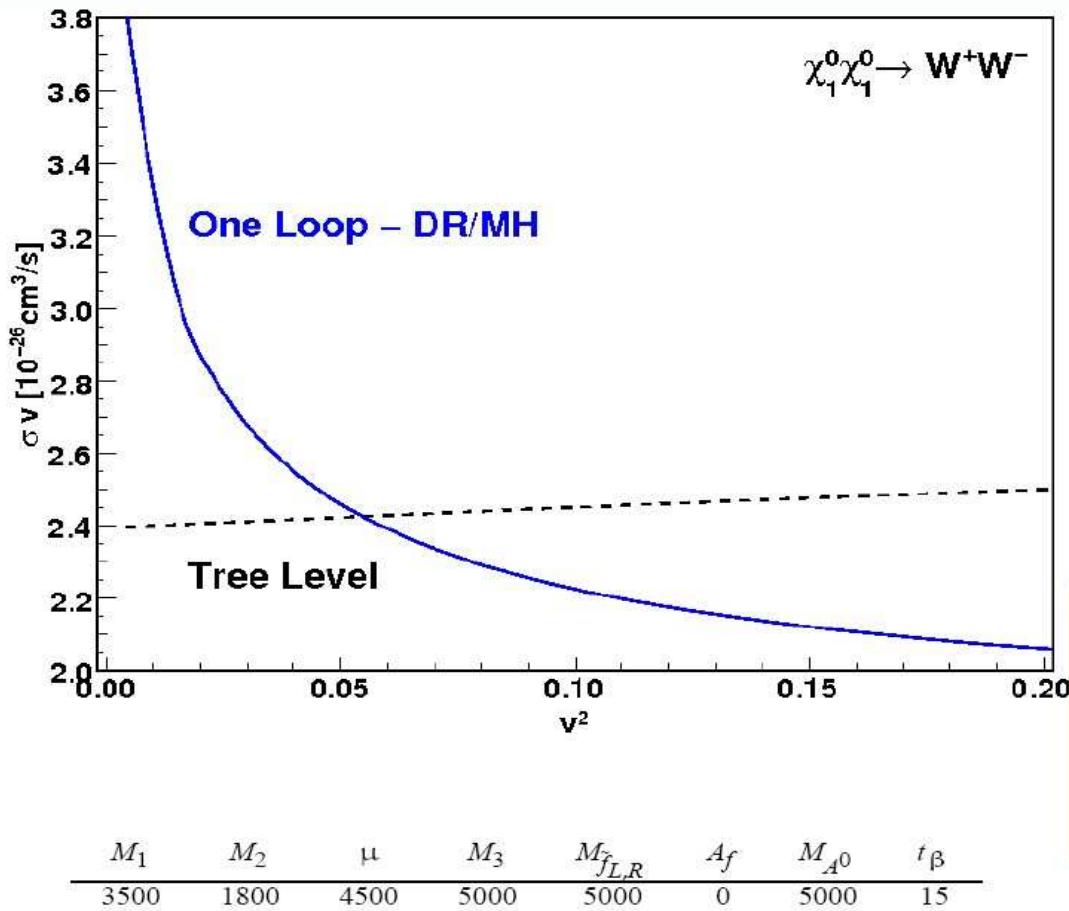
## COANNIHILATION CASE - COULOMB EFFECT

$\tilde{\tau}_1^+ \tilde{\tau}_1^+ \rightarrow \tau^+ \tau^+ (23\%)$



# SloopS, wino co-annihilation

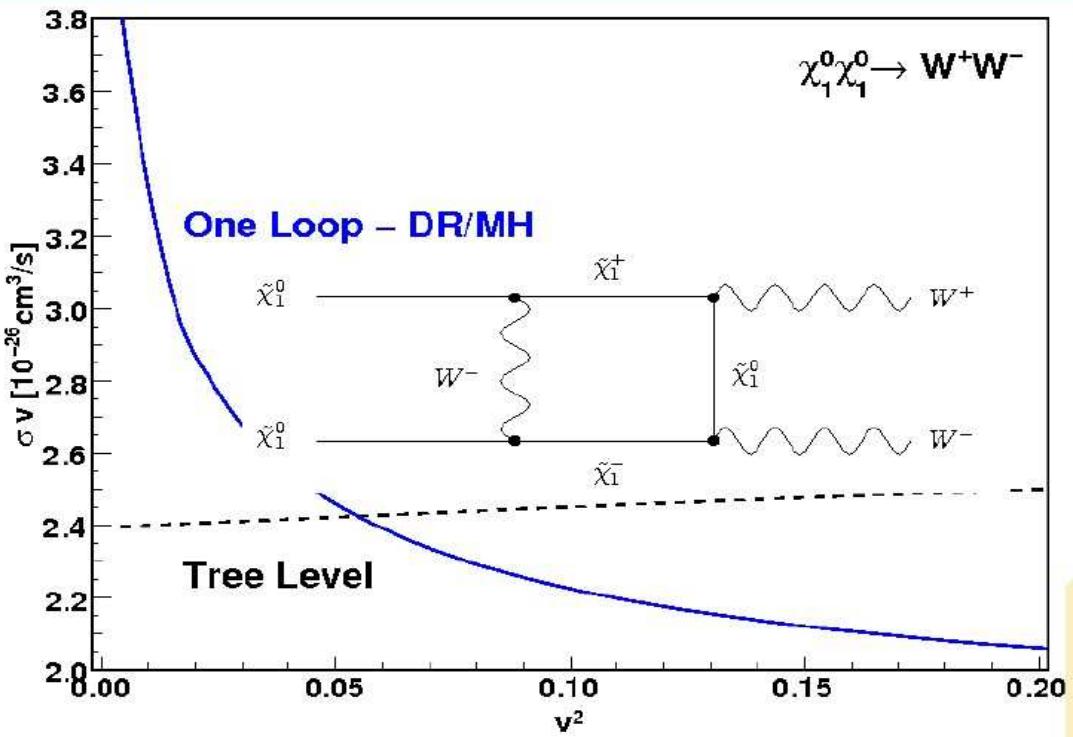
## HEAVY WINO-LIKE CASE



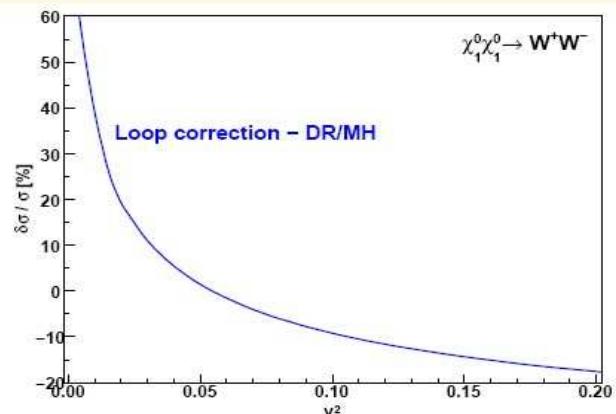
- No  $t_\beta$  scheme dependence
  - Large corrections
  - Sommerfeld effect
- $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^+}$  with TeV masses  
 same effect for  $\tilde{\chi}_1^+ \tilde{\chi}_1^+ \rightarrow W^+ W^+$   
 $\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow W^+ W^-$

# SloopS, wino co-annihilation

## HEAVY WINO-LIKE CASE



$M_1$	$M_2$	$\mu$	$M_3$	$M_{f_{L,R}}$	$A_f$	$M_{A^0}$	$t_\beta$
3500	1800	4500	5000	5000	0	5000	15



- No  $t_\beta$  scheme dependence
  - Large corrections
  - Sommerfeld effect
- $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^+}$  with TeV masses
- same effect for  $\tilde{\chi}_1^+ \tilde{\chi}_1^+ \rightarrow W^+ W^+$
- $\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow W^+ W^-$

## SloopS, examples for relic

$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow$				
$W^+ W^-$	Tree	$A_{\tau\tau}$	$\overline{DR}$	$MH$
a	0.904	-9%	-3%	+34%
b	1.714	-10%	-5%	+30%
$ZZ$	Tree	$A_{\tau\tau}$	$\overline{DR}$	$MH$
a	0.061	+2%	+5%	+31%
b	0.254	-6%	-2%	+24%
$b\bar{b}$	Tree	$A_{\tau\tau}$	$\overline{DR}$	$MH$
a	0.858	-27%	-23%	+5%
b	1.032	-31%	-27%	-1%
$\tau^+ \tau^-$	Tree	$A_{\tau\tau}$	$\overline{DR}$	$MH$
a	0.033	+3%	+9%	+52%
b	0.631	+19%	+18%	+12%

$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow b\bar{b}$	$A_{\tau\tau}$	$\overline{DR}$	$MH$
$\delta a/a$ EW	-1%	+3%	+31%
$\delta a/a$ QCD	-26%	-26%	-26%
$\delta b/b$ EW	-1%	+3%	+29%
$\delta b/b$ QCD	-30%	-30%	-30%

Mixed case 2: As in Table 3 for the array on the left. The array on the right gives the relative corrections to the  $b\bar{b}$  channel for the QCD and EW corrections.

Baro, Semenov, FB, 2007

		Tree	$A_{\tau\tau}$	$\overline{DR}$
$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow W^+ W^- [26\%]$	a	+11.84	+4.3%	+5.1%
	b	+4.17	+12.7%	+13.4%
$\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow ud [12\%]$	a	+15.28	+6.8%	+7.0%
	b	-5.31	+30.4%	+30.7%
$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow Z^0 Z^0 [9\%]$	a	+4.28	+10.4%	+9.6%
	b	+1.83	+12.7%	+12.0%
$\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow Z^0 W^+ [6\%]$	a	+6.99	+1.7%	+2.1%
	b	-0.51	+85.6%	+86.5%
$\Omega_\chi h^2$		0.00931	0.00909	0.00908
$\frac{\delta \Omega_\chi h^2}{\Omega_\chi h^2}$			-2.4%	-2.5%

Tree-level values of the s-wave (a) and p-wave (b) coefficients in units  $10^{-26} \text{cm}^3 \text{s}^{-1}$  in a higgsino scenario

Baro, Chalons, Sun Hao FB 2009

# *Outlook*

- Indirect: Neutrino signals
- Indirect: Improve the propagation code, clumps,...
- finish off  $\bar{D}$
- Link to USINE (then **The DA NNECY CODE(s)**)
- Sommerfeld Effects ?
- Incorporating dominant loop effects (Interface to SloopS)
- Relic: Alternative cosmological scenarios
- Pursue implementation of new models

Table 1: Comparison micrOMEGAs2.4, DarkSUSY5.0 and Isajet7.78 and  
comparison with other DM codes

	micrOMEGAs	DarkSUSY	IsaTools
<b>Relic density resonances</b>	★ ★ ★ ★	★ ★ ★ ★	★ ★ ★ ★
$\sigma_{\chi p}$	★	★	★
$\sigma_{\chi N}$	★	★	★
$\sigma v _{v \approx 0}$	★	★	★
<b>Detection rates</b>	$\gamma, e^+, \bar{p}, \nu$ semi-analytic	$\gamma, e^+, \bar{p}, \nu, \bar{D}$ <b>GALPROP</b> or semi-analytic	
<b>Propagation</b>		Sun, Earth	
<b>Neutrino rates</b>			
<b>Input GUT scale</b>	SusPect, Isajet SoftSUSY, Spheno	Isajet, SuSpect	Isajet
<b>Input EW scale</b>	Suspect, Isajet	SUSY(1loop)+FH	Isajet
<b>SLHA input</b>	Yes	Yes	Yes
<b>Higgs masses</b>	SpectCalc (Susy-)QCD	FH or Isajet QCD not in DD	Isajet (Susy-)QCD
<b>hbb</b>		Tree	
<b>Higgs potential</b>	Effective		Effective
<b>Collider applications</b>	$2 \rightarrow 2, 1 \rightarrow 2, 3$ <b>CalcHEP</b>	No	Isajet
$b \rightarrow s\gamma, B_s \rightarrow \mu^+\mu^-$	+ $B \rightarrow \tau\nu$	yes	yes
$(g - 2)_\mu, \Delta\rho$	yes LEP	yes LEP	yes LEP
<b>GUT scale models</b>	SpectCalc	Isajet, Suspect	Isajet
<b>Other models</b>	CPVMSSM, (C)NMSSM <b>RHNM,LHM</b>	complex(not tested) No	MSSM+ $\nu_R$ No
<b>Speed</b>	**	*	—
<b>Non SUSY Models</b>	** Open Source	—	—

# MicrOMEGAs: a code for the calculation of Dark Matter Properties

including the **relic density**, direct **new** and **indirect rates**  
in a **general supersymmetric model**  
and other models of New Physics **new**

by

Geneviève Bélanger, Fawzi Boudjema, Alexander Pukhov and Andrei Semenov

## MicrOMEGAs 2.2CPC (Generic Model)

[Introduction](#)

[Documentation](#)

[Download and Instal](#)

[Previous versions](#)

[Registration and Mailing list](#)

[History: version 1.1](#)

[Help and Contact](#)

[Feedback: Comparisons](#)

[CalcHEP](#)

[LanHEP for SUSY](#)

## Micromegas v\_2.2 for a generic model for the calculation of Relic density

### **Direct detection rates**

### **Indirect detection rates**

Code to calculate the properties of a stable massive particle in a generic model. First developed to compute the relic density of a stable massive particle, the code also computes the rates for direct and indirect detection rates of dark matter. It is assumed that a discrete symmetry like R-parity ensures the stability of the lightest odd particle. All annihilation and coannihilation channels are included in the computation of the relic density. Specific examples of this general approach include the MSSM and various extensions. Extensions to other models can be implemented by the user. The New Physics model first requires to write a new [CalcHEP](#) model file, a package for the automatic generation of squared matrix elements. This can be done through [LanHEP](#). Once this is done, all annihilation and coannihilation channels are included automatically in any model.

The cross-sections for both spin dependent and spin independent interactions of WIMPs on protons are computed automatically as well as the rates for WIMP scattering on nuclei in a large detector.

Annihilation cross-sections of the dark matter candidate at zero velocity, relevant for indirect detection of dark matter, are also computed automatically.

The package includes the minimal supersymmetric standard model ([MSSM](#)), the [NMSSM](#), the MSSM with complex phases ([CPVMSSM](#)), the little Higgs model ([LHM](#)) and a model with right-handed neutrino DM ([RHNM](#)).

**Present version (December 2008) is [micromegas 2.2.CPC](#)**

A web interface for the computation of the direct detection rates developed by Rachid Lemrani can be found [here](#).

# SloopS Webpage, Code not public...yet

Home | News and Articles | search... | NEWS FLASH



PUBLIC PAGES

- Home
- The Project
- Publications and Talks
- News and Articles
- Events: Workshops,...
- Blog
- Links
- RSS Feeds

INTRANET LOGIN

MEMBERS ONLY

Username

Password

Remember me

**Login** **Lost Password?**

SYNDICATE

RSS 0.91
RSS 1.0
RSS 2.0
ATOM 0.3
OPML SHARE IT!

**SloopS**

is a code for the calculation of cross sections and other observables at one-loop in the MSSM. Renormalisation is performed in the On-Shell Scheme with the possibility of easily switching to other schemes. SloopS has been designed so that it has applications not only for physics at colliders but also for astrophysics and cosmology.

The principle behind the code is **modularity**: Considering the complex structure of the MSSM (large number of parameters) and that no simple complete renormalisation scheme of the MSSM has emerged one should have a code that is flexible enough so that it is simple to define the model file. Moreover since different codes exist already that deal with important ingredients in the calculation of loops it is best to exploit these, combine them together and whenever improve on them.

The model file is implemented in an automatic way both at tree-level and at the one-loop level with the help of **LANHEP** adapted such that it can be interfaced with the **FeynCalc/FormCalc** package. LANHEP has been extended so that it can generate counterterms in a most efficient manner.

- Model file:
  - example** of particle definition, gauge fixing and ghost Lagrangian via BRS in LANHEP.
  - Feynman rules including counterterms (see [here](#)).
  - renormalisation conditions (see [here](#)).
- A powerful feature of the code is the use of a non-linear gauge fixing condition (see [here](#)).
- The aim of the code is also to be used for annihilation of dark matter that is highly non-relativistic, this calls for an added routine in the loop tensor reduction that avoids Gram determinants. Our trick is to do [this](#) and [this](#).
  - Overview of strategy ([here](#))
  - Example** of combining SloopS with **micrOMEGAs** to predict the photon flux from neutralino annihilation.

Home

There are no items to display

LATEST POSTINGS

- Tools of the Project
- Team Members
- The Project
- Summary and Aims

CALENDAR

<< July 09 >>						
Mo	Tu	We	Th	Fr	Sa	Su
					1	2
					3	4
					5	6
					7	8
					9	10
					11	12
					13	14
					15	16
					17	18
					19	
					20	21
					22	23
					24	25
					26	
					27	28
					29	30
					31	

WHO'S ON LINE