Dartmouth

TRIUMF

The lecture will begin shortly. Please mute your microphone until you are ready to speak.

micrOMEGAs

A Tool for Dark Matter

micrOMEGAs Team

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Genevieve Belanger, Sacha Pukhov and Andrei Semenov

and Pierre Brun, Pierre Salati and Sylvie Rosier (Indirect Detection)

D. Barducci, J. Bernon, J. Da Silva, S. Kraml, U. Laa (Collider Limits)

https://lapth.cnrs.fr/micromegas/

ernal tools | micrOMEGAs---Relic Density, Direct and Indirect rates Calculations in SUSY and other Models of new Physics

MicrOMEGAs: a code for the calculation of Dark Matter Properties

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

Geneviève Bélanger, Fawzi Boudjema, Alexander Pukhov and Andrei Semenov

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MicrOMEGAs 4.3 (Generic Model)

- Introduction
- Documentation
- Download and Install
- Previous versions
- Registration and Mailing list
- History: version 1.1
- Help and Contact
- Feedback: Comparisons
- CalcHEP
- LanHEP

«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

Micromegas v_4 for the calculation of
Relic density
Direct detection rates
Indirect detection rates

Code to calculate the properties of one or two stable massive particles 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.
The neutrino flux and the induced muon flux from DM captured in the Sun and the Earth are computed as well as the exclusion from IceCube22.
Annihilation cross-sections of the dark matter candidate at zero velocity, relevant for indirect detection of dark matter, are also computed automatically. The propagation of charged particles in the Galactic halo is handled with a new module.

The decay widths of all particles in the model as well as the cross-sections for production of any pair of new particles at colliders are computed automatically as well as the production of a pair of dark matter particles with a jet.

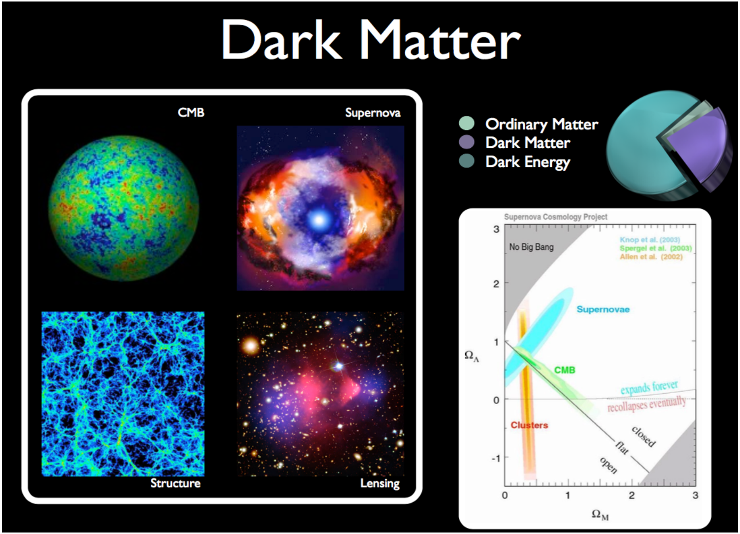
Starting from version 4.2, the relic density of two stable massive particles as well as their direct and indirect detection rates are computed. It is assumed that the model contains two dark sectors, each with different transformation properties under a discrete symmetry.

Version 4.3 includes links to HiggsSignals, Lilith and SmodelS to confront a dark model with LHC results on the Higgs and on searches for new particles. The package includes the minimal supersymmetric standard model (MSSM), the NMSSM, the UMSSM, the MSSM with complex phases (CPVMSSM), the little Higgs model (LHM), the inert doublet model (IDM), a inert doublet model with a Z3 discrete symmetry (Z3IDM), and a model with inert doublet and singlet with a Z4 symmetry (Z4IDSM). Facilities to include an arbitrary model are provided.

Other models available:
- **Z5M** : two scalar singlets and a Z5 symmetry
- **RHNM** : right-handed neutrino dark matter
- **SM4** : SM with a fourth generation of lepton

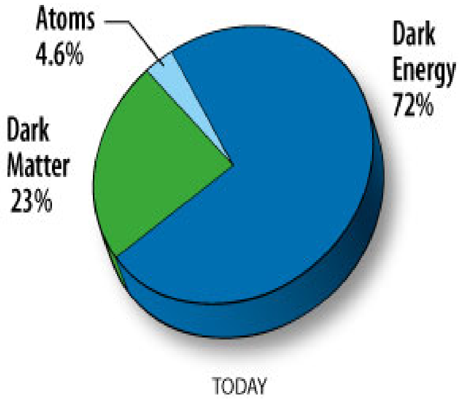
Present version (June 2017) is micromegas 4.3.5

Evidence for Dark Matter



The code covers more than 25% of the matter budget of the Universe

including the SM stuff of course



DM: What is it? Properties

Microscopic Level: interaction, couplings, masses $\Longrightarrow$ We don't know

Macroscopic level: How is it distributed? $\Longrightarrow$ We don't know ***really***

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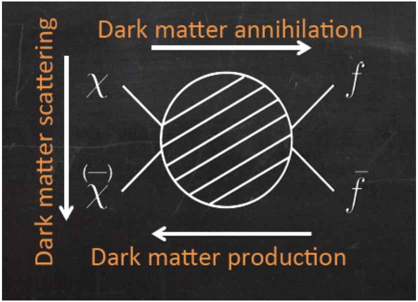
Apart from being

- NEUTRAL
- STABLE
- INTERACTING
  - • WIMP gives the correct abundance
    - with weak scale masses 10GeV - few *TeV* (link to EW symmetry breaking?)

Searches for DM



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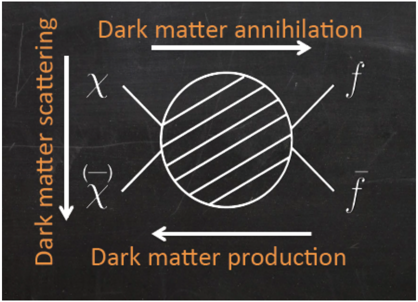
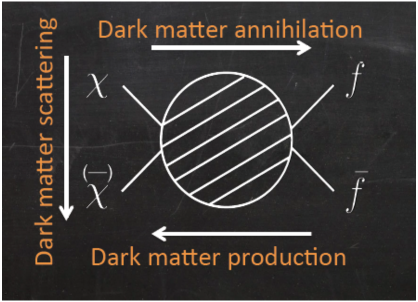


What do we need to know, to predict these observables?

Searches for DM



σv ....first

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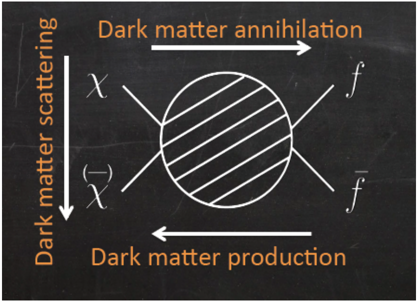
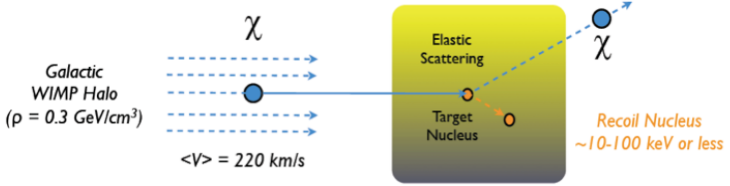


Cross section determines the abundance, rate of direct detection, the rate at which particles from the Galactic halo accrete into the Earth and Sun, it determines the signal in the indirect detection experiments, $\cdots$

Direct Detection: What is it and what's at stake, 1



Elastic Scattering of WIMPs off nuclei in a large underground detector

Measure nuclear recoil energy E_R

Very small teansfer momentum of order $q \sim 100$MeV

$E_R = q^2/2m_{\mathcal{N}}$, so that for a 100 GeV WIMP with mean velocity $v \sim 200 km/s$
$E_R < 10 - 50$ keV.

This affects the design of many detectors

Direct Detection

Need to go from $\chi q \to \chi q$ **TO** $\chi N \to \chi N$ **TO** $\chi \mathcal{N} \to \chi \mathcal{N}$

(N=n,p) Ingredients Factorise

Interaction Rate = [counts/keV/ kg/day]

particle theory | nuclear structure | local properties of DM halo

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \, \frac{F^2(E_R)}{m_r^2} \, \frac{\rho_o \, T(E_R)}{v_o \sqrt{\pi}}$$

$F(E_R) \simeq \exp\left(-E_R \, m_N \, R_o^2/3\right)$ "form factor" (quantum mechanics of interaction with nucleus)

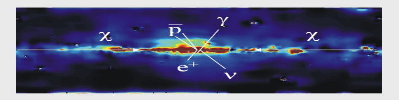
$m_r = \dfrac{m_\chi m_N}{m_\chi + m_N}$ "reduced mass"

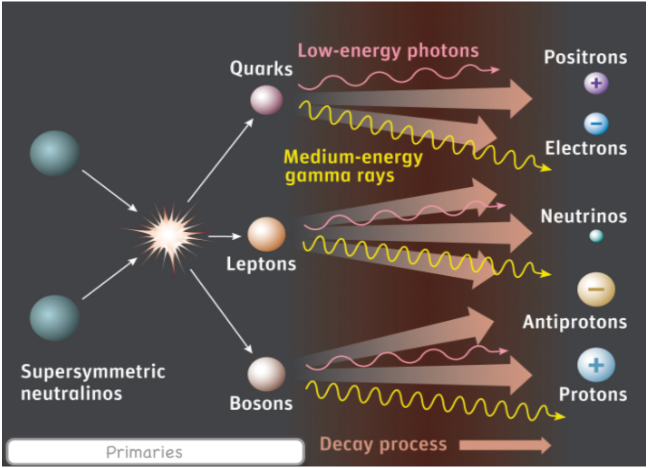
$T(E_R) \simeq \exp(-v_{\rm min}^2/v_o^2)$ integral over local WIMP velocity distribution

$v_{\rm min} = \sqrt{E_R \, m_N/(2m_r^2)}$ minimum WIMP velocity for given E_R

(particle theory includes $q \to N$)

Ingredients for Annihilation of DM in Indirect Detection





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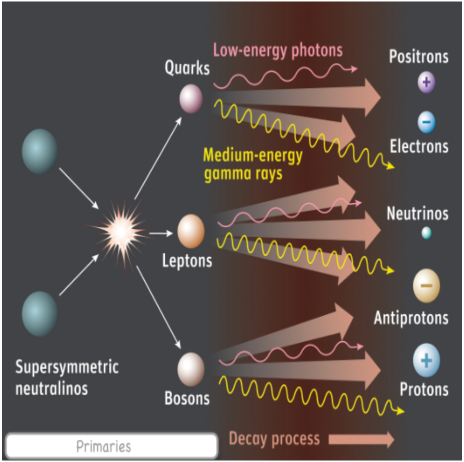

Particle Physics Uncertainties: even at the level of cross section of primaries:

hadronisation/fragmentation at scales outside particle physics energies (extrapolations)

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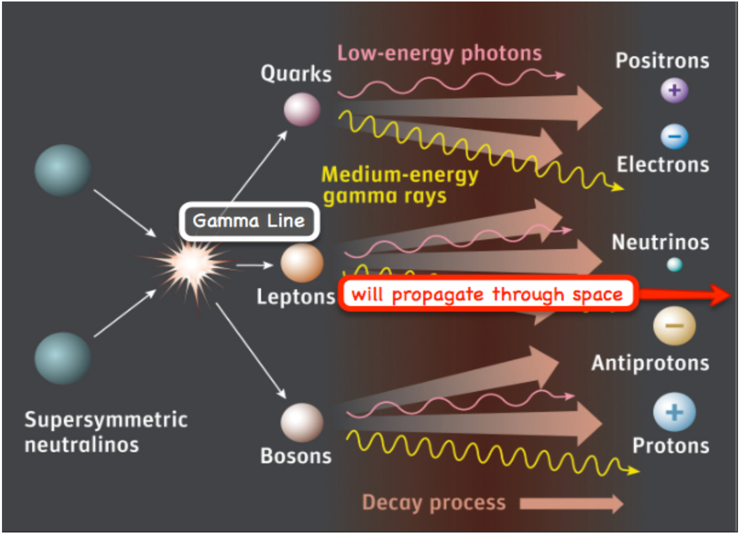

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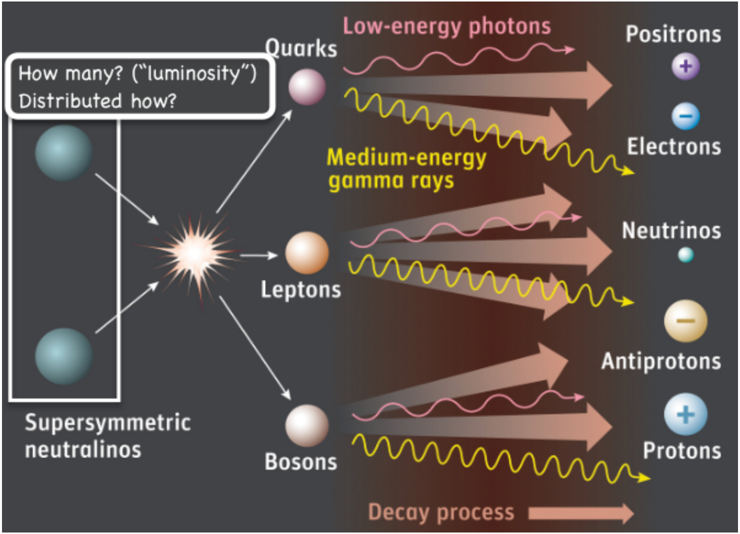
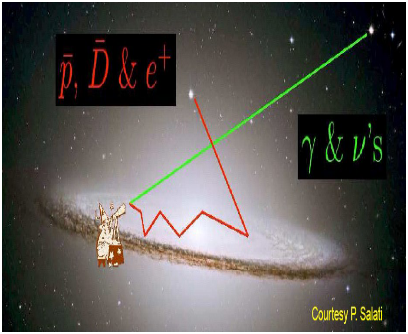


Annihilation into $e^+, \bar{p}, (\bar{D}), \gamma, \nu$

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



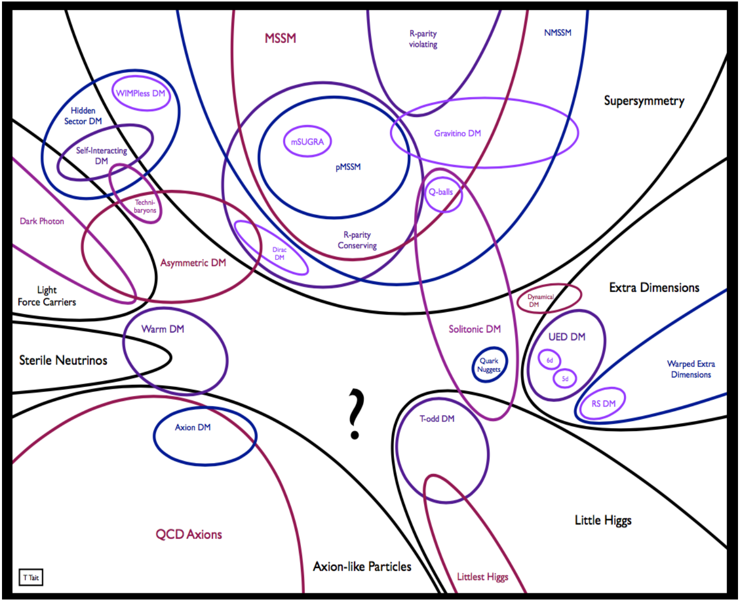
- The density which is what you would need to calculate the flux, ρ, is uncertain, this is like not knowing your PDF at the LHC!
- There might be small regions with over-densities, $\delta\rho$, etc... that may be important in some cases. $(\rho + \delta\rho)^2 \to \rho^2 F_{\text{clump}}$
- **not all particles scan the same portion of the "sky"**

At Colliders

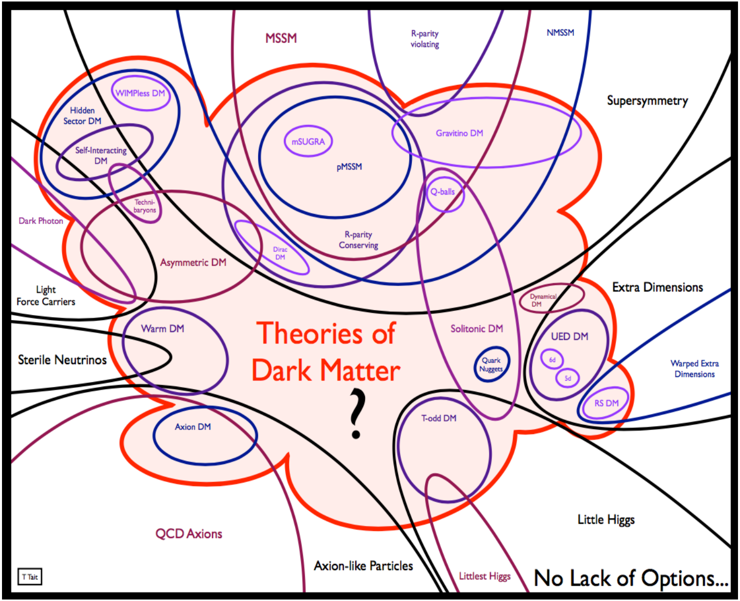
We are more in control !

provided we know

The other big unknown! New Physics Models from Tim Tait



New Physics Models/DM from Tm Tait



micrOMEGAs: a Tool for DM Properties for a generic New Physics Scenario

Ω

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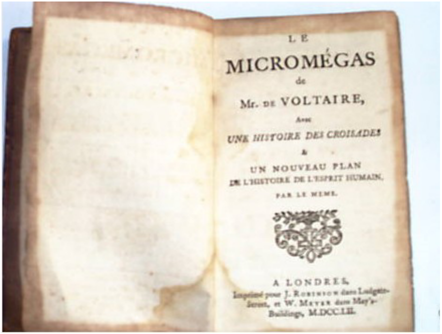
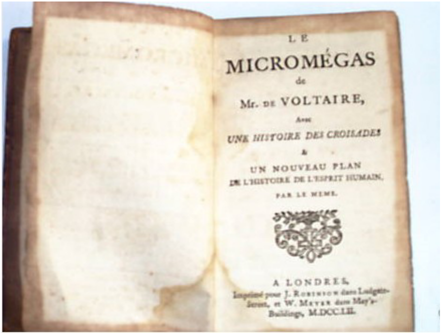
$$\Omega$$

Need powerful, modular and versatile tools


LE
MICROMÉGAS
de
Mr. DE VOLTAIRE,
Avec
UNE HISTOIRE DES CROISADES
&
UN NOUVEAU PLAN
DE L'HISTOIRE DE L'ESPRIT HUMAIN,
PAR LE MEME.
A LONDRES,
Imprimé pour J. ROBINSON dans Ludgate-Street, et W. MEYER dans May's-Buildings, M.DCC.LII.



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Voltaire, Micromegas,
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micrOMEGAs: Guiding Principle

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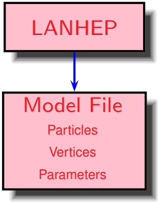
micrOMEGAs

LANHEP

micrOMEGAs



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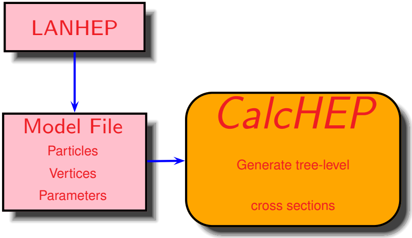
LANHEP
Model File
Particles
Vertices
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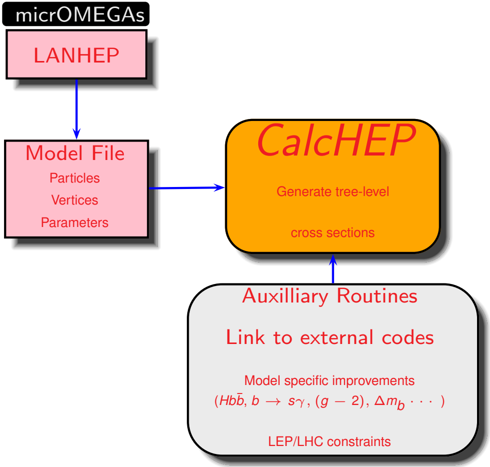
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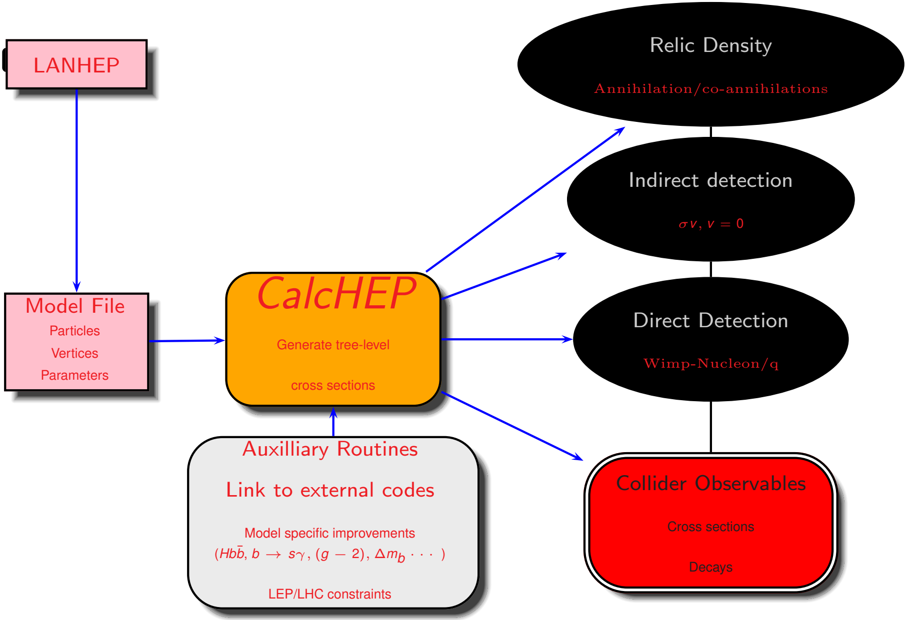
LEP/LHC constraints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σv, $v = 0$
Direct Detection
Wimp-Nucleon/q
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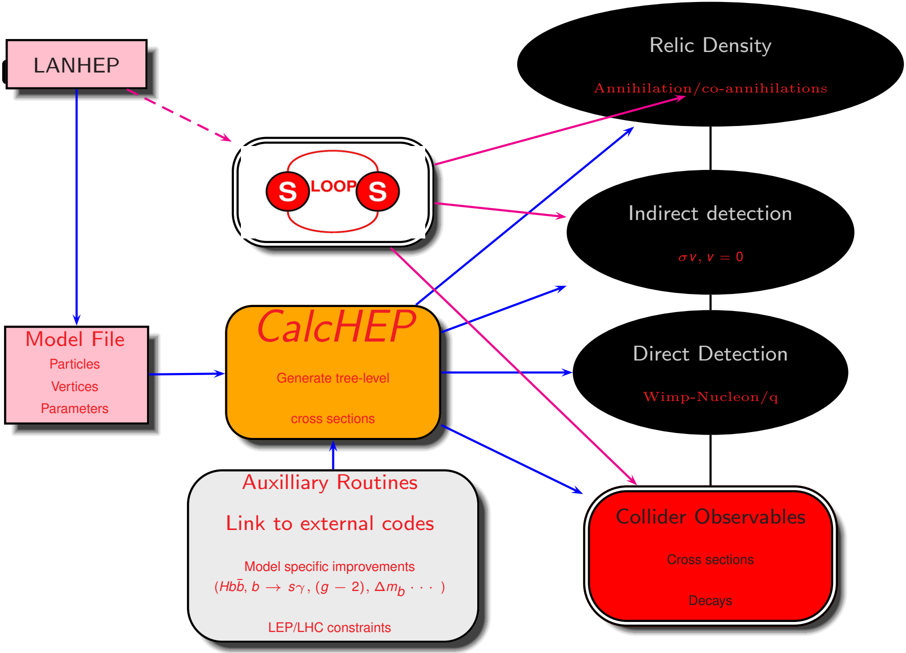
Cross sections
Decays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Stability and Importance of Symmetry: Identification of the DM candidate

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- Odd particles denoted ~ X

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  - Generalisation to other models easy, same principle: Needs a model file and a quantum number based on same Z_N. Classification is then straightforward.
  - set a switch (that can be changed by the user) so that even co-annihilation processes are generated on the fly. The code decides on *its own* when to include these co-annihilations.

Calculation of the relic density for a **Thermal WIMP** (in thermal equilibrium)

Freeze-out. **(universal parameters that govern the thermodynamics, no model dependent thermo parameters)**

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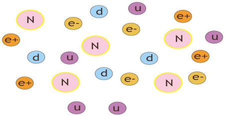
- The critical time scale is set by the expansion of the Universe, Hubble parameter,

$$H$$

Formation of DM: Very basics of decoupling



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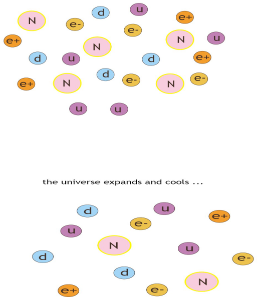

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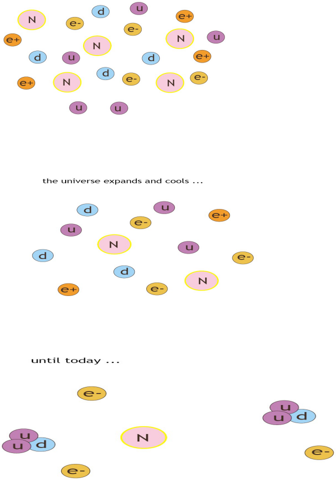
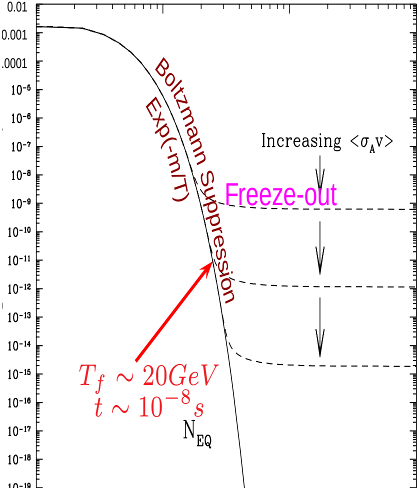


- At first all particles in thermal equilibrium, frequent collisions. Particles are trapped in the cosmic soup
- universe cools and expands: interaction rate too small or not efficient to maintain equilibrium
- (stable) particles can not find each other: freeze out and get free and leave the soup, their 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: $l_{\rm m.f.p} < vt \quad l_{\rm m.f.p} = 1/n\sigma$ $t \sim 1/H$ or Equilibrium: $\Gamma = n\sigma v > H$

freeze out/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

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

$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to X$

$X \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$

- at early times $\Gamma \gg H \to \sim n_{eq}$
- $T \sim m$ X not enough energy to give $X \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ n drops and so does Γ

$T_f \simeq m/25$

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

Calculation of the relic density for a WIMP: Thermodynamics

The thermal eq. nbr density, n, for a particle with $E_i^2 = p_i^2 + m_i^2$ at temp. T

$$n_i = \frac{g_i}{(2\pi)^3} \int f_i(p) d^3p \ , \quad f(p) = \frac{1}{exp(E_i/T) \pm 1} \ , \quad g_i = \text{n.o.d.o.f}$$

- For relativistic particles (radiation) $n_R = s_i g_i \zeta(3) T^3/\pi^2 \quad s_i = 1, 3/4$ (boson, fermion)
- for non relativistic (matter, dust, pressure-less) one has (for $T \ll m_i$)

the Boltzman suppression

$$\mathbf{n_{nr} = g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} exp - (m_i/T)}$$

- The total energy density is $\rho_i = \int E_i f_i(p) d^3p$

$\rho_R = u_i g_i (\pi^2 T^4/30) \quad u_i = 1, 7/8$ (boson, fermion) , $\rho_{nr} \sim n_{nr} = m\, n_{nr}$

- The entropy $\rightarrow s_i(T_i) = \int \frac{3m_i^2 + 4p_i^2}{3E_i T_i} f_i(p) d^3p$

ge recap: Normalised to radiation: ▶

$$\rho = g_{eff}(T) \frac{\pi^2}{30} T^4 \ , \quad s = h_{eff}(T) \frac{2\pi^2}{45} T^3 \quad g_{eff}^{\gamma} = h_{eff}^{\gamma}$$

Thermal average

micrOMEGAs computes <u>ALL</u> $2 \to 2$ processes *which are thermodynamically relevant*

$\chi_i^0 \chi_j^0 \to X_{SM} Y_{SM}$, $\chi_1^0 \tilde{t}_1 \to X_{SM} Y_{SM}$,...

Thermal average

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

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

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

$$p_{ij} = \frac{1}{2}\left[\frac{(s-(m_i+m_j)^2)(s-(m_i-m_j)^2)}{s}\right]^{\frac{1}{2}} \to v$$

$v = 0$

$v \times \sigma v$

co-annihilation, only if particle close thermodynamically to DM particle, close in small otherwise suffers very large Boltzmann suppression

Relic Density: Thermal average

$\chi_i^0\chi_j^0 \to X_{SM} Y_{SM},\ \chi_1^0 \tilde{f}_1 \to X_{SM} Y_{SM}, \ldots$ $v \times \sigma v$

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

Origin of Boltzman factor $exp(-\delta M/T)$

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

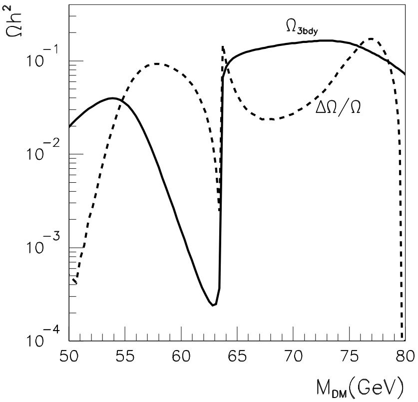
In micrOMEGAs $B_\epsilon = 10^{-6}$ by default. Most often $B_\epsilon = 10^{-2}$ enough for 1% accuracy, only a few processes computed.

micrOMEGAs_3.0: Asymmetric dark matter

Sasha tutorial

micrOMEGAs_3.0: Annihilation into Three-body and Four-body (included with a Flag)

Simple observation: $\chi\chi' \to XV$ (V, W, Z) **closed** but $\chi\chi' \to XV^\star \to Xll'$ **open !**



Ωh^2 as a function of M_{DM} in the MSSM (full) and relative difference between the 3-body and 2-body value (dashed).

micrOMEGAs_3.0: DM with non Z_2 discrete symmetry: $Z_3, \cdots Z_N$

DM stabilized with a larger symmetry than Z_2

Ex: Z_3 custodial $SU(2)$ $W^{+\prime}W^{-\prime} \to Z'H$ semi-annihilation.

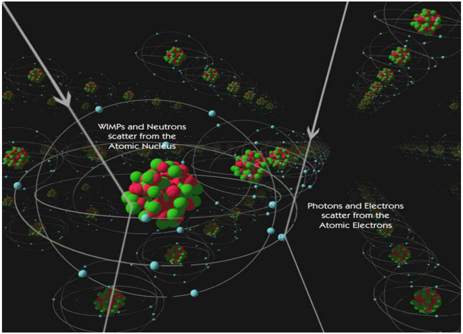
More generally:

$\chi_i\chi_j \to \chi_k A$, χ's stable A unstable (decays eventually to SM).

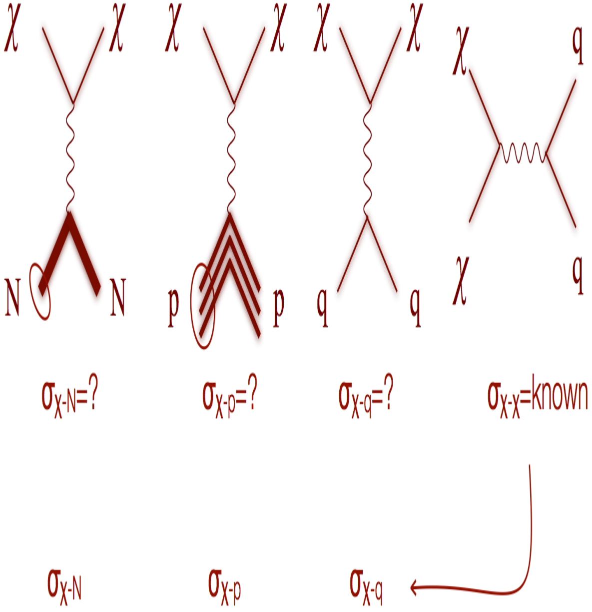
Lead to coupled Boltzman equations.

$$\frac{dn}{dt} = -\langle v\sigma^{\chi\bar{\chi}\to XX}\rangle \left(n^2 - {n_{\rm eq}}^2\right) - \frac{1}{2}\langle v\sigma^{\chi\chi\to\bar{\chi}X}\rangle \left(n^2 - n\, n_{\rm eq}\right) - 3Hn.$$

Direct detection; in micrOMEGAs Elastic Scattering



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



1. $\chi q \to \chi q$ ($\chi g \to \chi g$) $\longrightarrow$

2. $\chi N \to \chi N$, $(N = n, p)$ $\longrightarrow$

3. $\chi \mathcal{N} \to \chi \mathcal{N}$

The ingredients: From quarks, to nucleons (p, n), to Nucleus

Interaction Rate = [counts/keV/ kg/day]		particle theory	nuclear structure	local properties of DM halo
	$\frac{dR}{dE_R} =$	$\frac{\sigma_o}{m_\chi}$	$\frac{F^2(E_R)}{m_r^2}$	$\frac{\rho_o \, T(E_R)}{v_o \sqrt{\pi}}$

$F(E_R) \simeq \exp\left(-E_R \, m_N \, R_o^2/3\right)$	"form factor" (quantum mechanics of interaction with nucleus)
$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$	"reduced mass"
$T(E_R) \simeq \exp(-v_{\rm min}^2/v_o^2)$	integral over local WIMP velocity distribution
$v_{\rm min} = \sqrt{E_R \, m_N/(2m_r^2)}$	minimum WIMP velocity for given E_R

(particle theory includes $q \to N$)

$v \sim 220\mathrm{km/s} \sim 10^{-3}$, momentum transfer $q^2 \to 0$!

Wimp-quark effective Lagrangian at $q^2 \to 0$. micrOMEGAS takes spin-0,1/2,1 DM

Divides into Spin-Indepent (SI) and Spin-Dependent (SD) interactions

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

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

In the 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,..

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- with the S-matrix, $\hat{S} = 1 - i\mathcal{L}$ obtained from the complete Lagrangian at the quark level

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

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

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

Step 2: $\sigma_{\chi p/n}$: χq to χN: Sandwich within nucleon: Nucleon form factors

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

For the light quarks these are extracted from experiments (*e.g* $\sigma_{\pi N}$), lattice computations, plus a fair deal of theory (chiral perturbation,...) (Large source of uncertainty, apart from vector (which counts number of quarks minus anti-quarks, valence quarks)

For the heavy quarks appeal to the trace anomaly

Light quarks, examples

Scalar, light quarks

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

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

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.

Heavy quarks: QCD calculations

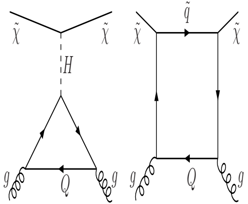
- SI, Scalar Interaction (Trace anomaly)

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

Heavy quarks: QCD calculations

• Heavy quarks interact with nucleon via gluon condensate

Good description of the dominant triangle, Box diagram model dependent (Spin-1/2 DM: Drees and Nojiri 1993. Spin-0, Spin-1, Hisano et al., 2015.)



Diagrams that contribute to WIMP-gluon interaction via quark loops in the MSSM.

Heavy quarks: QCD calculations

Can then get $\sigma_{\chi\, p/n}$

Step 3. From p/n to the Nucleus

The spin and scalar components of the nucleons must now be added coherently. Need nuclear wave functions

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

$F_{SI,SD}$ = Nuclear Form Factors. q^2 dependent

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

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$F_{SI,SD} =$ Nuclear Form Factors. q^2 dependent

Easiest case: SI

For SI further factorisation

$$\sigma_0^{SI} = \frac{4\mu_N^2}{\pi}\left(\lambda_p Z + \lambda_n(A-Z)\right)^2, \quad A: \text{ Atomic Number } \; Z: \text{ nucleus charge}$$

$\lambda_{p/n}$ amplitude for $\chi p/n$ scattering (coupling). Nuclear Physics: Fourier transform of the nucleus distribution function, use Fermi distribution

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

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For SD no factorisation but spin structure functions (more involved), J number of spin-states, nucleus momentum

Step 3. From p/n to the Nucleus : The Rates

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

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- N_T is the number of target nuclei per unit mass
- $\vec{v}$ 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.

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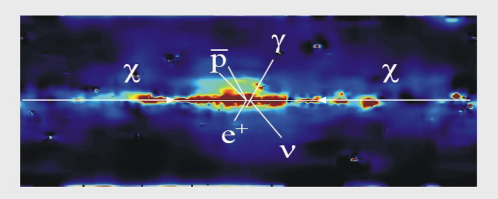
The codes offer different choices for

- form factors
- velocity distributions
- routines for DD rates off composite targets beside nuclei

Indirect Detection in micrOMEGAs



- γ, ν, charged cosmic rays (e^+, $\bar{p}$, $\cdots$) from annihilation in the galactic halo
- ν from the Sun and the Earth

Features in the Indirect Detection Module of micrOMEGAs

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

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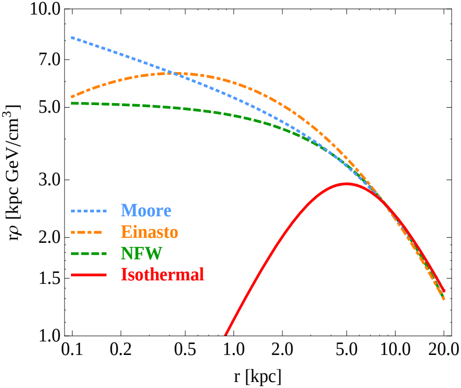
- The neutrino spectrum originating from dark matter annihilation is also computed. With in version 3.0 Capture in the Sun and the Earth

Dark Matter Halo Profiles in micrOMEGAs



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

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

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

Other profiles (provided they are spherically symmetric are possible.

To avoid central divergence, we set $r > r_{min} = 10^{-3}$pc

Annihilation into photons

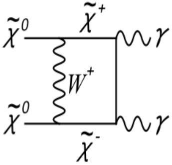
$$\frac{d\Phi_\gamma}{d\Omega dE_\gamma} = \sum_i \underbrace{\frac{dN^i_\gamma}{dE_\gamma}\sigma_i v \frac{1}{4\pi m^2_\chi}}_{\text{Particle physics}} \underbrace{\int \rho^2 dl}_{\text{Astro}}$$

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

- continuum spectrum from $\tilde{\chi}^0_1\tilde{\chi}^0_1 \to f\bar{f}, \ldots,$ hadronisation/fragmentation ($\to \pi^0 \to \gamma$) done through Pythia/Herwig

- Loop induced mono energetic photons,$\gamma\gamma, Z\gamma$ final states

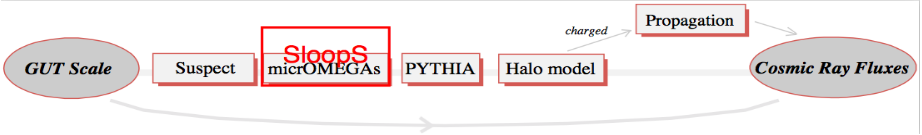
Generated by SloopS (implementation for some models)



ACT: HESS, Magic, VERITAS, Cangoroo, ...

Space-based: AMS, Fermi-LAT, Egret,...

SloopS, micrOMEGAs,AMS/HESS: for CR + γ



SIMULATION: (with/from P. Brun)

Parameterising the halo profile:

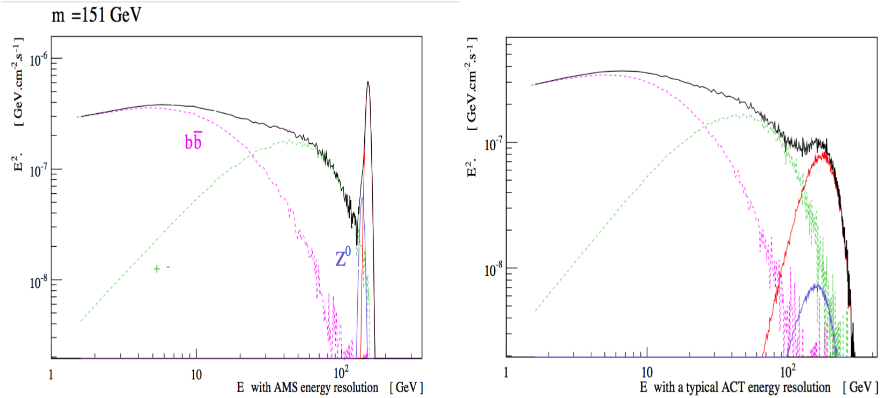
$(\alpha, \beta, \gamma) = (1, 3, 1)$, $a = 25$kpc. (core radius), $r_0 = 8kpc$ (distance to galactic centre),

$\rho_0 = 0.3\, GeV/cm^3$ (DM density), opening angle cone 1^o

SUSY parameterisation

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

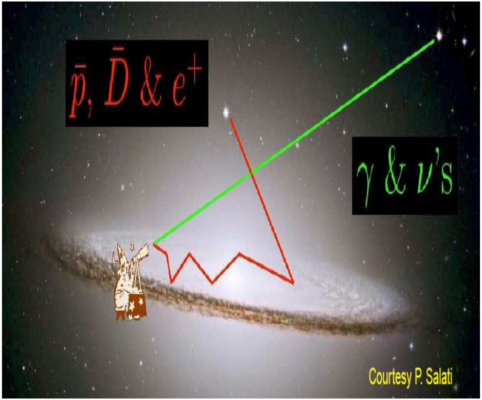
SloopS, micrOMEGAs,AMS/HESS



γ lines could be distinguished from diffuse background

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

$$\frac{d\Phi_{\bar{f}}}{d\Omega dE_{\bar{f}}} = \sum_i \underbrace{\frac{dN^i_{\bar{f}}}{dE_{\bar{f}}} \sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particle physics}} \underbrace{\int \rho^2 F_{\text{clump}} P_{prop}}_{\text{Astro}}$$



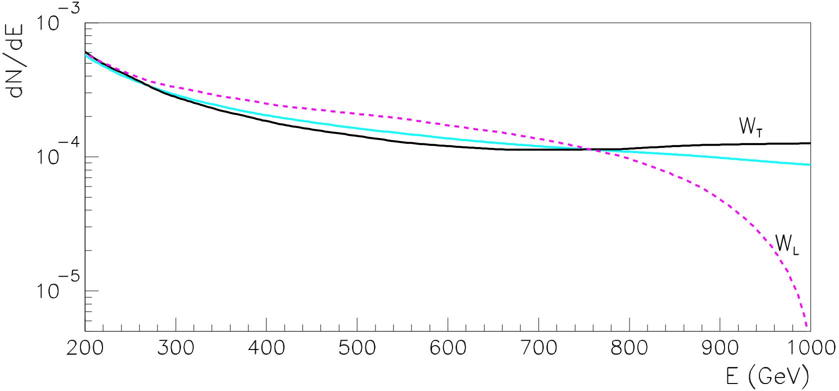
ACT:

HESS, Magic, VERITAS, Cangoroo, ...

Space-based:

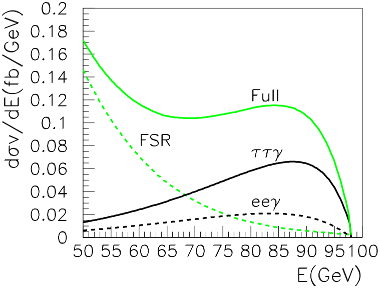
AMS, GLAST, Egret,...

Effect of the polarisation (at injection)

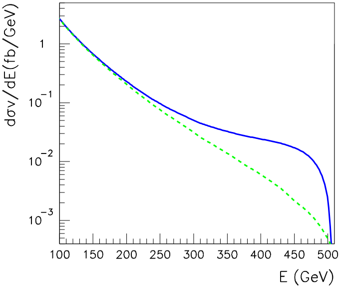


dN/dE_{e^+} for positrons from $\chi\chi \to W^+W^-$. $M_\chi = 1$ TeV.

Effects of non factorisable (non collinear, hard) photons



Photon spectrum within a CMSSM point including the aditional 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*γ as compared to PYTHIA diffusion is assumed to take place in space only: steady state

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

indirect detection: modeling propagation, 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
- $b = E^2/E\tau$energy losses due to synchroton rad., CMB , ICS, negligible for $\bar{p}$
- V_C convection galactic wind wipes away charged particles from disk (not for e+)
- $\Gamma_{ann.}$ 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.)

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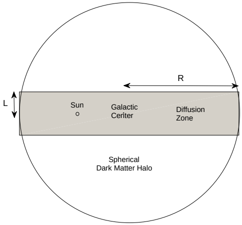
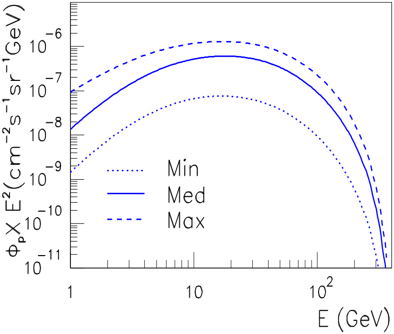
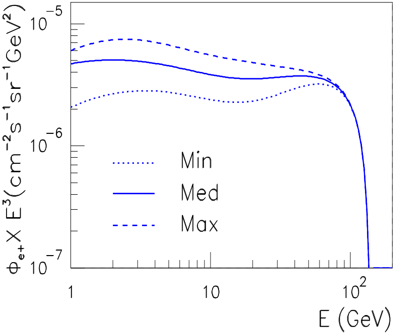
Model	δ	K_0 kpc^2/Myr	L kpc	V_C km/s
MIN	0.85	0.0016	1	13.5
MED	0.7	0.0112	4	12
MAX	0.46	0.0765	15	5

Two-zone diffusion model (Green's function and tabulation). Typical diffusion parameters that are compatible with the B/C analysis (Maurin et al. 2001) $E_0 = 1$GeV.



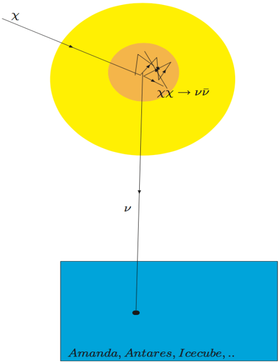
Uncertainties due to propagation micrOMEGAs





Neutrinos from from the Sun and the Earth

- calculates capture rate of neutralinos in Sun/Earth
- solve the evolution equation for capture
- Let neutralinos annihilate in the Centre into neutrinos (tabulation from `WimpSim` module and `PPPC4DMnu`)
- neutrinos propagate to the detector taking into account oscillations (tabulation `WimpSim` module and `PPPC4DMnu`)
- choice of velocity distributions



micrOMEGAs_3.0: Neutrino Signals: Earth, Sun,

- Capture Rate Earth and Sun, C_χ from Gould 1987
- DM-Nucleus cross section (ref. direct detection), form-factor
- DM velocity dist. and local density
- Number density of nucleus (Sun: Asplund, Grevesse, Sauval 2004. Earth: McDonough 2003)
- Annihilation of captured DM: $A_{\chi\chi}$
- Evaporation,E_χ. may be important for light (<5) GeV DM
- Neutrino Flux:

$$\dot{N}_\chi = C_\chi - A_{\chi\chi} N_\chi^2 - E_\chi N_\chi \,,$$

- Neutrino spectra: from decays of fermions, gauge bosons, hadrons,...cascade decays. Effect of neutrino oscillations, from Cirelli *et al.* 2005 (we use their tables).

Conclusion 1: Structure before the hand-on tutorial