Dark matter tools: an overview

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LAPTh - Annecy
Evidence for dark matter

- Evidence from different scales: galaxies (rotation curves), galaxy clusters (M/L, lensing, Xray), CMB
- All point to large dark matter component – also in agreement with light element abundance
- Structure formation: DM is mostly cold (non-relativistic), no electromagnetic interactions
What do we know about dark matter?

- Within $\Lambda$CDM model – precisely know its relic density
  $\Omega_{\text{cdm}} h^2 = 0.1193 \pm 0.0014$ (PLANCK – 1502.01589)
Universe is made of 27% cold dark matter. Can it be a new particle?
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Can it be a new particle?

Early studies on cosmological constraints on new particles:
Dark matter

• Dark matter cannot be baryons nor neutrinos (too hot) – prime candidate since the 80’s – new weakly interacting particle (WIMP)

• At the time – supersymmetry was favourite extension of the SM, with R-parity introduced to avoid rapid proton decay the lightest supersymmetric particle (LSP) is stable and a natural DM candidate (neutralino)

• Nowadays much larger range of dark matter candidates – more extensions of the SM (extra dimensions, extended scalar sector, little Higgs, composite…)

• Only requirement for WIMP is new neutral particle + discrete symmetry + weak interactions

• Explaining dark matter is one of the main motivation for physics beyond the standard model
A wide variety of DM candidates
wide range of interactions/mass scales

- WIMPs
- FIMPs
- SIMPs
- Asymmetric
WIMPs

• In early universe WIMPs are present in large number and they are in thermal equilibrium

• As the universe expanded and cooled their density is reduced through pair annihilation

• Eventually density is too low for annihilation process to keep up with expansion rate
  – Freeze-out temperature

• LSP decouples from SM particles, density depends only on expansion rate of the universe

\[
\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[ n^2 - n_{eq}^2 \right]
\]
WIMPs- relic density

• Write equation in terms of abundance

\[ \frac{dY}{dT} = \sqrt{\frac{\pi g_*(T)}{45}} M_p \langle\sigma v\rangle (Y(T)^2 - Y_{eq}(T)^2) \]

• Numerical solution of evolution equation and calculation of relic density with non-relativistic thermal averaging and proper treatment of poles and thresholds
  • Gondolo, Gelmini, NPB 360 (1991)145

\[ \Omega h^2 \equiv \frac{\rho_X}{\rho_c} = \frac{m_X Y_\infty s_\infty}{1.05 \times 10^{-5} \text{ GeV}^2 \text{ cm}^{-3}}, \]

• Weakly interacting particles have roughly annihilation cross section to obtain \( \Omega h^2 \sim 0.1 \)

\[ \Omega_X h^2 \approx \frac{3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle\sigma v\rangle}. \]
Coannihilation

- If $M(\text{NLSP}) \sim M(\text{LSP})$ then $\chi + \chi \rightarrow \chi' + Y$ maintains thermal equilibrium between NLSP-LSP.

- Relic density depends on all processes involving LSP/NLSP $\rightarrow$ SM.

- All particles eventually decay into LSP, calculation of relic density requires summing over all possible processes - Edsjo, Gondolo PRD56(1997) 1879.

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

\[<\sigma v> = \frac{\sum g_i g_j \int \frac{ds}{m_i + m_j} \sqrt{s} K_1(\sqrt{s}/T)p_{ij}^2 \sigma_{ij}(s)}{2T(\sum g_i m_i^2 K_2(m_i/T))^2}\]

- Need for codes for precise relic density computation.
In the WIMP paradigm, Comprehensive tools for dark matter studies: precise calculation of relic density, direct detection, indirect detection, cross section at colliders and decays.
Public DM tools

• Neutdriver - neutralino in supersymmetry
  – Jungman, Griest, Kamionkowski (1995) – not maintained

• micrOMEGAs
  – GB, Boudjema, Pukhov, Semenov (2001)

• DarkSUSY

• IsaRed and IsaRes in IsaTools
  – Baer, Balazs, Belyaev (2002)

• SuperISORelic
  – Arbey, Mahmoudi (2009)

• MadDM
  • Backovic, Kong, McCaskey (2013)

• And many private codes: K. Olive, M. Drees, L. Roszkowski…
Philosophy

- Modularity and flexibility
  - Possibility to exchange modules, user might want to improve one module
- Models are often complex with huge parameter space
  - Speed of execution
- Ready made, stand-alone package for the non-expert
  - User friendly
- We do not know what DM is made of
  - Possibility to include different DM candidates (only 2)
- Several groups are developing specialized codes
  - Link them
DarkSUSY

MSSM

Model File
Particles
Vertices
Parameters

Hand coding of all relevant cross sections

Auxiliary Routines
(Effective couplings,
Flavour: $b \rightarrow s\gamma, (g-2),$
Collider constraints,..)

Relic Density
Annihilation/co-annihilations

Indirect detection
$\sigma v, v = 0$

Direct Detection
Wimp-Nucleon/q

Collider Observables
Cross sections
Decays

Fortran code
SuperISORelic

Lagrangian

LANHEP, ...

Model File

Particles
Vertices
Parameters

FeynArts, FormCalc

Auxiliary Routines

SuperIso for flavour constraints

Relic Density

Annihilation/co-annihilations

Indirect detection

\( \sigma v, \nu = ? \)

Direct detection

Neutron, pion

Collider Observables

Cross sections
Decays

Automatic generation of cross section in generic Model in progress

C code
Fortran and python
(for Madgraph interface)
Dark matter models

• **MSSM**: included in all codes,
  • Both high scale models (CMSSM, NUHM…) as well as electroweak scale input (pMSSM)
  • Spectrum calculators (Suspect, Isajet, Softsusy, Spheno) – important radiative corrections to masses
  • Interface made easy with Susy Les Houches Accord (SLHA)
  • Various model specific constraints (b->sγ (NLO), (g-2)μ, B_s->μμ, Δρ, LEP, Higgs)

• **NMSSM** (in micrOMEGAs, SuperISO, MadDM) – SLHA2
  • relies on NMSSMTools (NMSPEC and NMHDECAY) for spectrum calculation, indirect constraints (B physics, g-2, Higgs collider constraints) - Ellwanger, Gunion, Hugonie

• Host of other models available and user implementation of generic model possible (micrOMEGAs and MadDM)
Relic density tool

• Define model files (automatically or by hand) as well as routines/tools to compute Spectrum

• After the model is implemented and checked
  – Definition of LSP
  – Computes all annihilation and coannihilation cross-sections
  – Complete tree-level matrix elements for all 2-2 subprocesses
  – Checks for presence of resonances
  – Numerical solution of evolution equation and calculation of relic density with non-relativistic thermal averaging and improved accuracy near poles and thresholds
    • Gondolo, Gelmini, NPB 360 (1991)145
    • coannihilation : Edsjo, Gondolo PRD56 (1997) 1879

• Includes only relevant channels - criteria based on mass difference with LSP

• Some codes calculate the relic density for any LSP (even charged)
  • Relevant when LSP is very weakly coupled, NLSP freeze—out then decay to DM
Reliability of results

- Extensive comparisons between DarkSUSY/micrOMEGAs, SuperISO/micrOMEGAs, MadDM/micrOMEGAs – generally results are in good agreement – few percent
- MadDM/micrOMEGAs – Backovic et al 1308.0955
  - Real singlet model: % level except near Higgs resonance
  - MSSM: 5% level except near Higgs resonance when large $\Delta m_b$ corrections (25%)
Higher-order effects

• Is it enough to include only 2-2 tree-level annihilation?
  • Photon radiation (aka internal bremsstrahlung) can be relevant
  • Annihilation into 3-body final state can be as large as 2-body, eg when annihilation into W pairs kinematically suppressed - C. Yaguna, arXiv: 1003.2730

• MSSM : bino/higgsino LSP, $\mu=150\text{GeV}$, $M_2=2M_1$
• Dominant channels WW,Zh
Higher-order effects

- What about NLO corrections? (example in MSSM)
  - Corrections to masses/couplings, Higgs width through spectrum calculator
  - QCD corrections can be large– worked out for example in DM@NLO and fed into DS or micrΩ (left) – in principle accessible in MadDM through Madgraph@NLO
  - Electroweak corrections – can also be large - some cases treated with SloopS – then fed into micrOMEGAs

Harz et al, 1609.04998

Corrections to ZZ in MSSM, Boudjema et al, 1403.7459
Direct detection
Direct detection

- Elastic scattering of WIMPs off nuclei in a large detector
- Measure nuclear recoil energy, $E_R$
- Would give best evidence that WIMPs form DM
- Two types of scattering
  - Coherent scattering on $A$ nucleons in nucleus, for spin independent interactions (dominant for heavy nuclei)
  - Spin dependent interactions – only on one unpaired nucleon (important for light nuclei)
Limits DM searches

Sensitive enough to probe DM models
Ongoing – Xenon1T
m<10GeV more challenging

SD detector now probe parameter
Space of MSSM
SuperK – IceCube assume
DM annihilation channel (tau)
WIMP- Nucleon amplitude

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

$$\mathcal{L}_F = \lambda_N \bar{\psi}_X \psi_X \bar{\psi}_N \psi_N + i \kappa_1 \bar{\psi}_X \psi_X \bar{\psi}_N \gamma_5 \psi_N + i \kappa_2 \bar{\psi}_X \gamma_5 \psi_X \bar{\psi}_N \psi_N + \kappa_3 \bar{\psi}_X \gamma_5 \psi_X \bar{\psi}_N \gamma_5 \psi_N$$

- For Majorana fermion only 2 operators survive at small $q^2$
- First need to compute the WIMP quark amplitudes
  - Compute symbolically from Feynman diagrams+ Fierz (DS)
  - Automatic approach -works for all models-micrOMEGAs &MadDM
- Effective Lagrangian for WIMP-quark scattering has same generic form as WIMP nucleon
WIMP quark effective Lagrangian

- Implement effective Lagrangian including operators relevant for specific DM spin

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

- Add it to input model to get the interference term between \( \mathcal{L}_{\text{inp}} \) and \( \mathcal{L}_{\text{eff}} \) -> allow to single out SD or SI contribution

<table>
<thead>
<tr>
<th>WIMP Spin</th>
<th>SI</th>
<th>Even operators</th>
<th>Odd operators</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1/2</td>
<td>( 2M_X \phi_X \phi_X^* \bar{\psi}_q \psi_q )</td>
<td>( i(\partial_\mu \phi_X \phi_X^* - \phi_X \partial_\mu \phi_X^*) \bar{\psi}_q \gamma^\mu \psi_q )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 2M_X A_{X,\mu} A_{X}^\mu \bar{\psi}_q \psi_q )</td>
<td>( + i \lambda_{q,o} (A_{X,\alpha}^* \partial_\mu A_{X,\alpha} - A_{X,\alpha} \partial_\mu A_{X,\alpha}^*) \bar{\psi}<em>q \gamma</em>\mu \psi_q )</td>
</tr>
</tbody>
</table>

| SD        | 1/2 | \( \bar{\psi}_X \gamma_\mu \gamma_5 \psi_X \bar{\psi}_q \gamma_\mu \gamma_5 \psi_q \) | \( - \frac{i}{2} \bar{\psi}_X \sigma_{\mu\nu} \psi_X \bar{\psi}_q \sigma^{\mu\nu} \psi_q \) |
|           |     | \( \sqrt{6}(\partial_\alpha A_{X,\alpha}^* A_{X,\nu} - A_{X,\beta} A^*_{X,\beta} A_{X,\nu}) \) | \( i \frac{\sqrt{3}}{2} (A_{X,\mu} A_{X,\nu}^* - A_{X,\mu} A_{X,\nu}) \bar{\psi}_q \sigma^{\mu\nu} \psi_q \) |
WIMP-quark to WIMP-nucleon

- Include coefficients relate WIMP-quark operators to WIMP nucleon operators
  - Extracted from experiments – or from lattice calculations
  - Source of theoretical uncertainties
- Example, scalar coefficients, contribution of q to nucleon mass

\[
\langle N|m_q \bar{\psi}_q \psi_q|N \rangle = f_q^N M_N
\]

\[
\lambda_{N,p} = \sum_{q=1,6} f_q^N \lambda_{q,p}
\]

- Can be defined by user
- Different coefficients can lead to large corrections in cross section
Output

- Amplitudes (protons and neutrons)
- SI and SD cross sections on protons and neutrons
- Rates (SI and SD) for specific nuclei

\[
\frac{dN^{SI}}{dE} = \frac{2M_{det}}{\pi} \frac{\rho_0}{M_X} F_A^2(q) (\lambda_p Z + \lambda_n (A - Z))^2 I(E)
\]

- Nuclear form factors
- Particle physics + quark content in nucleon
- DM velocity distribution

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

\[
v_{\min}(E) = \left( \frac{EMA}{2\mu^2} \right)^{1/2}
\]

- Modularity and flexibility: can change velocity distribution, nuclear form factors...
Beyond the basics

- Larger set of effective operators could be probed
- Not included in any of the tools described
- New tool: DirectDM: mathematica code that provide the link between EFT and effective operators for DM-nucleon within a specific model. Bishara et al 1708.02678

\[
\begin{align*}
\mathcal{O}_5^N &= \vec{s}_x \cdot \left( \vec{v}_\perp \times \frac{i \vec{q}}{m_N} \right) \mathbb{1}_N, \\
\mathcal{O}_7^N &= \mathbb{1}_x \left( \vec{s}_N \cdot \vec{v}_\perp \right), \\
\mathcal{O}_9^N &= \vec{s}_x \cdot \left( \frac{i \vec{q}}{m_N} \times \vec{s}_N \right), \\
\mathcal{O}_{11}^N &= -\left( \frac{i \vec{q}}{m_N} \right) \mathbb{1}_N, \\
\mathcal{O}_6^N &= \left( \vec{s}_x \cdot \frac{\vec{q}}{m_N} \right) \left( \vec{s}_N \cdot \frac{\vec{q}}{m_N} \right), \\
\mathcal{O}_8^N &= \left( \vec{s}_x \cdot \vec{v}_\perp \right) \mathbb{1}_N, \\
\mathcal{O}_{10}^N &= \mathbb{1}_x \left( \vec{s}_N \cdot \frac{i \vec{q}}{m_N} \right), \\
\mathcal{O}_{12}^N &= \vec{s}_x \cdot \left( \vec{s}_N \times \vec{v}_\perp \right),
\end{align*}
\]

- Directional detection (included only in MadDM)
  - If DM discovered, directional detection can be used to extract information on halo property
  - Multi-ton detector will become sensitive to neutrino background – directional detection useful to distinguish from DM
Indirect detection

micrOMEGAs, DarkSUSY
MadDM and SuperISO (in progress)
Indirect detection

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

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

\[ Q(x, E) = \frac{\langle \sigma v \rangle}{2} \left( \frac{\rho(x)}{m_X} \right)^2 \frac{dN}{dE} \]
Limits DM searches - photons

Gamma rays from Dwarfs – robust limits
Probe generic annihilation cross section
for DM below ~70GeV
Results given for many annihilation channels
– simple to recast the limit for specific model
with several annihilation channels

Cross section can be directly compared with output of code
Photons

• Flux calculation

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

• Photon production
  – In decay of SM particles + R-even new particles
  – \( dN/dE \) : basic channels ff, VV, VH, HH and polarization of gauge bosons
  – For particles of unknown mass (Z’,H) compute 1->2 decay recursively until only basic channels
  – Annihilation into 3 body (\( \chi \chi \rightarrow e^+e^-\gamma \)) – can have strong impact on spectrum

• Integral over line of sight depends strongly on the galactic DM distribution – especially in Galactic center
  • NFW, isothermal, Einasto
Monochromatic gamma-rays

- Monochromatic gamma rays ($\gamma\gamma,\gamma Z$) and ($\gamma h$) are loop-induced BUT lead to very distinctive signal

- In micrOMEGAs available for MSSM and NMSSM - in generic models only have the Higgs contribution (through $h\gamma\gamma$ effective vertices)
  - Computed with SloopS, a code for computation of one-loop processes in the SM, MSSM and some extensions
    - F. Boudjema, A. Semenov, D. Temes, hep-ph/0507127
    - G. Chalons, A. Semenov, arXiv:1110.2064

- Included in DarkSusy for MSSM

- No difficulty to include in MadDM for any model provided with NLO model files
Antiprotons and positrons from DM annihilation in halo

M. Cirelli, Pascos2009

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

diffusion Energy losses Source
Propagation of cosmic rays

For Charged particle spectrum detected different than spectrum at the source

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

• Charged cosmic rays deflected by irregularities in galactic magnetic field
  – For strong magnetic turbulence effect similar to space diffusion

• Energy losses due to interactions with interstellar medium

• Convection driven by galactic wind and reacceleration due to interstellar shock wave

• For positron, antiproton : solution propagation equations based on
  – Lavalle, Pochon, Salati, Taillet, astro-ph/0603796 (micrOMEGAs)
  – Semi-empirical diffusion equation in a 2d model with cylindrical symmetry and free escape boundary conditions (DarkSUSY)
Comparison with data

- Large uncertainties on the secondary antiproton spectrum
- Constraints on DM from AMS02 for given annihilation channel and propagation model – can be directly compared with output of DS/micro

Giesen et al, 1504.04276
Neutrinos from DM capture in Sun

• DM particles captured by Sun/Earth, concentrate in center and annihilate into SM, lead to neutrino flux, can be observed at Earth (SuperKamiokande, IceCube)

• Shape of neutrino flux depends on DM annihilation channel

• Capture rate determined by cross section for DM scattering on nuclei --related to DD

\[
\dot{N}_\chi = C_\chi - A_{\chi N}\chi^2 - A_{\chi \bar{\chi}} N_\chi N_{\bar{\chi}} - E N_\chi ,
\]

\[
\dot{N}_{\bar{\chi}} = C_{\bar{\chi}} - A_{\bar{\chi} N\bar{\chi}} N_\chi N_{\bar{\chi}} - A_{\chi \bar{\chi}} N_{\bar{\chi}}^2 - E N_{\bar{\chi}} ,
\]

• When capture/annihilation is large, equilibrium is reached and annih. rate determined by capture rate

\[
\frac{d\phi_{\nu}}{dE_{\nu}} \ = \ \frac{1}{4\pi d^2} \left( \Gamma_{\chi\chi} B r_{\nu\nu} \frac{dN_{\nu\nu}}{dE} + \Gamma_{\chi\bar{\chi}} \sum_f B r_{f\bar{f}} \frac{dN_f}{dE} \right)
\]
• Solve equation for number density numerically and obtain $\nu$ flux at Earth

$$\frac{d\phi_\nu}{dE_\nu} = \frac{1}{4\pi d^2} \left( \Gamma_{\chi \chi} Br_{\nu\nu} \frac{dN_{\nu\nu}}{dE} + \Gamma_{\chi \tilde{\chi}} \sum_f Br_{f\bar{f}} \frac{dN_f}{dE} \right)$$

• Neutrino spectrum originating from different SM decays and including oscillation available in
  – PPPC4DM, M. Cirelli et al, 1012.4515

• Neutrinos that reach the Earth interact with rock below or water/ice in detector -> muon flux

• Both neutrino flux and muon flux are computed (micrOMEGAs and DarkSUSY) – see J. Edsjo’s talk
Dark Matter at colliders
Collider physics

- Higgs sector put strong constraints on BSM: Higgs mass, Higgs signal strengths and searches for new Higgses
  - easy to interface to codes that fit HiggsSignal strengths (Lilith or HiggsSignals)
  - One issue: must provide loop-induced Higgs partial widths (two-photons and two-gluons) - known in MSSM
    - implemented in micrOMEGAs together with tool to extract vertices automatically from the model file
  - Also simple interface to code that provides limits from Higgs searches- HiggsBounds
DM production at LHC

- DM direct production: missing energy (need additional particle to trigger) – monojet, monophoton, mono-X

- DM in Higgs decays

- Production of coloured particles: DM in decay chain (MET+..)

- Charged tracks and displaced vertices (for quasi stable NLDSP – next-lightest dark sector particle)

- Production of mediator (in standard channels)
DM at LHC

• Many searches for new particles at LHC – several tools for reinterpretation – Checkmate, Smodels, MadAnalysis5, Fastlim …

• 3 approaches for DM tools : 1) leave it to specialists (eg fitting codes), 2) interfaces, 3) specific routines
  – micrOMEGAs: interface to SmodelS for simplified models results
    • fast and efficient for scan of parameter space but so far cannot exploit full LHC results in all channels
    • specific routines for Z’ searches and monojet
  – MadDM : interface to MadAnalysis5
  – DarkSUSY – no development beyond LEP limits and Higgs sector but included in Gambit
  – SuperISORelic – no development, to be included in GamBit, also private code for extensive checks of LHC limits
Generalisation of relic density calculation

– WIMPs: Discrete symmetries other than $Z_2$
– Asymmetric dark matter
– Feebly interacting particles and non-thermal production
– Beyond LCDM: Different universe expansion
Other discrete symmetries

- Discrete remnant of some broken gauge group, e.g. $Z_N$
- Impact for dark matter: new processes
  - *semi-annihilation*: processes involving different number of “odd particles” $\chi \chi \rightarrow \chi^* \text{SM}$,
  - T. Hambye, 0811.0172, T. Hambye, M. Tytgat, 0907.1007
  - Modification of Boltzmann equation
    \[
    \frac{dn}{dt} = -n \sigma^{\chi \chi \rightarrow XX} \left( n^2 - \bar{n}^2 \right) - \frac{1}{2} \frac{1}{n} \sigma^{\chi \chi \rightarrow \chi^* X} \left( n^2 - n \bar{n} \right) - 3Hn.
    \]
- More than one WIMP-DM candidate: Assisted freeze-out/DM conversion: interaction between particles from different dark sectors
- Two coupled Boltzmann equations
- Solved numerically in micrOMEGAs4, MadDM
Asymmetric DM

- Motivation: baryon-antibaryon and DM asymmetry related
- The case where DM is not self-conjugate (e.g. Dirac fermion, complex scalar)
- $Y^+(Y^-)$: abundance of DM particle(anti-)
  \[
  \frac{dY^\pm}{ds} = \frac{2}{3H} <\sigma v> (Y^+Y^- - Y_{eq}Y_{eq}^-)
  \]
- $\Delta Y = Y^+ - Y^-$ is constant
- Define $Y = 2(Y^+Y^-)^{1/2}$
- Similar to equation for self-conjugate - solve num.
  \[
  \Omega h^2 = \frac{8\pi}{3H_{100}^2} \frac{m_\chi}{M_{Planck}} \sqrt{\frac{Y_0^2 + \Delta Y^2}{s_0}}
  \]
- Note asymmetry always increase relic abundance
FIMPS (Feebly interacting MP)

- Freeze-in (Hall et al 0911.1120): in early Universe, DM so feebly interacting that decoupled from plasma
- Assume that after inflation abundance DM very small, interactions are very weak but lead to production of DM
- T~M, DM ‘freezes-in’ - yield increase with interaction strength

\[ \dot{n}_\chi + 3Hn_\chi = \langle \sigma v \rangle_{\chi \bar{\chi} \to \chi \bar{\chi}}(T) n_{eq}^2(T) + n_{eq}(T) \Gamma_{Y \to \chi \chi}(T) \]

- Production by annihilation or decay
- Can lead to Long-lived particles

[Equilibrium yield graph]
The case of gravitino

- Gravitinos: alternative DM candidate in SUSY (also RH-sneutrino)
- Despite very weak interactions – can be produced from gaugino scattering - included in SuperISO
- Can also be produced from decay of NLSP – relic density related to that of NLSP - all codes
- LHC can put constraints on reheating temperature
  - Arbey et al, 1505.04595
Beyond $\Lambda$CDM

• Modify parameters of cosmological model (expansion rate, entropy content, non-thermal DM production, effective numbers of $\nu$) – in SuperISO

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

$$H^2 = \frac{8\pi G}{3} (\rho_{rad} + \rho_D)$$

$$\frac{ds}{dt} = -3Hs + \Sigma_D$$

• Impact DM relic density, can match relic density with almost any susy model
  – Gelmini, Gondolo, hep-ph/0602230; Arbey, Mahmoudi, 0906.0368

• Can affect light element abundance, codes to compute light element abundance:
  – PArthENoPE, O. Pisanti et al, 0705.0290
  – AlterBBN, A. Arbey, 1106.1363

• In general: constraints from cosmology on DM – not considered in DM tools so far
Conclusion

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

• Several tools are available for this purpose – just waiting for a confirmed signal!!