SuperIso Relic tutorial

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Code references: arXiv:0906.0369 and 1806.11489

`https://superiso.in2p3.fr/`

Computational Tools for High Energy Physics and Cosmology

IP2I, Lyon, France – November 22nd, 2021

Main purpose

Computing dark matter observables in standard and non-standard cosmological scenarios

Main features

- public and open-source C program
- (hopefully) easy to modify and user-friendly
- includes different cosmological scenarios
- computes dark matter relic density
- computes dark matter direct and indirect detection observables
- computes flavour physics observables
- incorporates supersymmetric models
- no external library needed
- interfaced with `AlterBBN` to constrain cosmological scenarios with BBN

Webpage

Download from

`https://superiso.in2p3.fr/`

A detailed manual is also available.

Compilation instructions

- to uncompress: `tar xjvf superiso_relic_v4.1.tar.bz2`
- enter directory: `cd superiso_relic_v4.1/`
- to set-up compilation: `./configure --with-cc=gcc --with-fc=gfortran`
- to compile the library: `make` → This will take a few minutes...
- to compile the program `xxx.c`: `make xxx`

Let us focus on the observable linking particle physics and cosmology:

Dark matter relic density

Radiation domination true at temperatures below $\sim$ MeV

However, **this may not hold at higher temperatures.**

If the calculated relic density is different from the measured dark matter density, it could be due to novel phenomena in the early Universe.

In the Standard Model of Cosmology:

- before and at nucleosynthesis time, the expansion is dominated by radiation
$$H^2 = 8\pi G/3 \times \rho_{\rm rad}$$
- the evolution of the number density of all NP particles follows the Boltzmann equation
$$\frac{dn}{dt} = -3Hn - \langle\sigma_{\rm eff} v\rangle(n^2 - n_{\rm eq}^2)$$
- the time and temperature are related through the adiabaticity condition:
$$\frac{ds_{\rm rad}}{dt} = -3Hs_{\rm rad}$$

with $s_{\rm rad} \propto h_{\it eff}(T)\, T^3$ ($h_{\it eff}$: radiation entropy degrees of freedom)

$\langle\sigma_{\rm eff} v\rangle$: related to the amplitudes of (co-)annihilations of BSM particles into SM particles

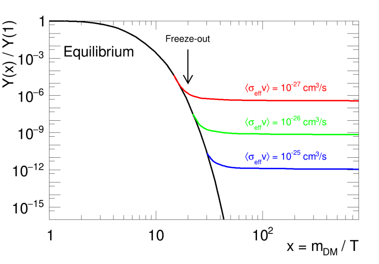
$\langle\sigma_{\text{eff}} v\rangle$: Thermal average of effective cross section ($K_{1,2}$: **modified Bessel functions**):

$$\langle\sigma_{\text{eff}} v\rangle = \frac{\int_0^\infty dp_{\text{eff}}\, p_{\text{eff}}^2\, W_{\text{eff}}\, K_1\left(\frac{\sqrt{s}}{T}\right)}{m_1^4\, T \left[\sum_i \frac{g_i}{g_\chi}\frac{m_i^2}{m_\chi^2} K_2\left(\frac{m_\chi}{T}\right)\right]^2}$$

where: **(ij: coannihilating BSM particles / kl: SM outgoing particles)**

$$\frac{dW_{\text{eff}}}{d\cos\theta} = \sum_{ijkl} \frac{p_{ij}\, p_{kl}}{32\pi\, p_{\text{eff}}\, S_{kl}\sqrt{s}} \sum_{\text{helicities}} \left| \sum_{\text{diagrams}} \mathcal{M}(ij \to kl) \right|^2$$

Dark matter density normalised to radiation entropy density as a function of m_χ/T.



AA & F. Mahmoudi, Prog.Part.Nucl.Phys. 119 (2021) 103865

The moment at which the dark matter density leaves the equilibrium density is called freeze-out.

The differential equations are solved from an initial temperature T_{init} down to the present temperature $T_0 = 2.725$ K

The relic density is then obtained:

$$\Omega_\chi h^2(T_0) \equiv 2.755 \times 10^{-8} \frac{\rho_\chi(T_0)}{s_{rad}(T_0)} \qquad \text{with} \;\; \rho_\chi = m_\chi \, n(T_0)$$

Very precise measurements of cold dark matter density by Planck (+ others):

$$\Omega_c h^2(T_0) = 0.120 \pm 0.001$$

The Planck results lead to very strong constraints on BSM parameters.

For example, the expansion rate can be modified:

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

The entropy content of the Universe can also be altered!

$$\frac{ds_{\rm rad}}{dt} = -3Hs_{\rm rad} + \Sigma_D$$

$\Rightarrow$ Modified relation between time, expansion rate and temperature!

And relics can be generated non-thermally:

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

ρ_D, Σ_D and N_D are model-dependent.

Main programs

- amsb.c, cmssm.c, gmsb.c, hcamsb.c, mmamsb.c, nuhm.c: observable calculation in different MSSM scenarios
- cnmssm.c, ngmsb.c, nnuhm.c, mmamsb.c: observable calculation in different NMSSM scenarios
- test_modeleff.c: effect of QCD eos on relic density
- test_widthcalc.c: effect of Higgs widths on relic density
- test_standmod.c: effect of non-standard cosmological models on relic density
- test_reheating.c: effect of reheating cosmological scenario on relic density
- test_phi.c: effect of decaying scalar field on relic density
- direct.c: calculation of direct detection observables
- indirect.c: calculation of indirect detection observables
- create_propagation.c: calculation of indirect detection observables within user-defined propagation and DM profile models
- blackholes.c: indirect detection constraints for PBH spectra from BlackHawk
- flha.c, modelindep_chi2.c, slha_chi2.c, sm.c, sm_chi2.c, thdm.c: flavour observables only

With which arguments?

Running `./program.x` without argument will show you the possible arguments

Example: `./test_standmod.x`

```
This program assumes that in the early Universe,  during the dark times (before BBN), a dark entropy and/or
a dark density could modify the expansion and thermal properties.
The program consider the presence of a dark density such as
rho_dark(T) = rho_0 T^ndd
and of a dark entropy such as
s_dark(T) = s_0 T^nsd
rho_dark(T) = rho_0 T^ndd
and of non-thermal production of relic particles such as
N_nt(T) = nt0 T^nnt

It needs 5 parameters:
  name    name of the SLHA file
  dd0     dark energy proportion to photon density at BBN time (1 MeV)
  ndd     dark energy decrease exponent (preferentially >4)
  sd0     dark entropy proportion to photon entropy at BBN time (1 MeV)
  nsd     dark entropy decrease exponent
Auxiliary parameters are:
  Td      dark energy cut temperature (in GeV)
  Ts      dark entropy cut temperature (in GeV)
  nt0     Non thermal production rate at BBN time
  nnt     Non thermal production rate decrease exponent
  Tt      Non thermal production rate cut temperature (in GeV)
```

```
./stand_cosmo.x example.lha 3 6 0 0

SuperIso Relic v4.1 - A. Arbey, F. Mahmoudi & G. Robbins
AlterBBN v2.1 - A. Arbey, J. Auffinger, K. Hickerson & E. Jenssen

For the cosmological standard model:
omega=1.429e+01
For the specified model with dark density/entropy/non thermal relics:
omega=1.263e+04
Model excluded by BBN constraints
```

Starting from an SLHA point with a relic density of 14.29, adding a dark density with 3 times the radiation density at BBN time and decrease exponent 6, the relic density becomes 1.263×10^4.

This model is nevertheless excluded by BBN constraints, as tested automatically by AlterBBN.

Three Dark Matter benchmark cases

- CONSERVATIVE: AMS-02 antiprotons with Burkert profile and MED propagation model + local density of 0.2 GeV/cm^3
- STANDARD: Fermi-LAT gamma rays with NFW profile + local density of 0.4 GeV/cm^3
- STRINGENT: AMS-02 antiprotons with NFW profile and MAX propagation model + local density of 0.6 GeV/cm^3

Example of direct detection constraints

./direct.x example.lha

```
/----WIMP-NUCLEON cross-section(pb) at 0-momentum transfer----/

 /-Spin-Independent-/
Conservative             Standard       Stringent
Proton 1.838746e-10     1.838746e-10    1.838746e-10
Neutron 1.907715e-10    1.907715e-10    1.907715e-10

/-Spin-Dependent-/
Conservative             Standard       Stringent
Proton 5.242343e-07     5.242343e-07    5.242343e-07
Neutron 5.332762e-07    5.332762e-07    5.332762e-07

/----PANDAX-2 2017 Poisson delta-loglikelihood (point excluded at 2 sigma if <-4.000000 with 1 d.o.f.)----/
Conservative     Standard        Stringent
 -2.265334e+00   -2.265334e+00    -2.265334e+00

/----XENON1T 2017 Poisson delta-loglikelihood  (point excluded at 2 sigma if <-4.000000 with 1 d.o.f.)----/
Conservative     Standard        Stringent
 -2.076444e+00   -2.076444e+00    -2.076444e+00

/----PICO60 2017 Poisson delta-loglikelihood (point excluded at at 2 sigma if <-4.000000 with 1 d.o.f.)----/
Conservative     Standard        Stringent
 -2.261627e-02   -2.261627e-02    -2.261627e-02
```

Example of indirect detection constraints

./indirect.x example.lha

```
channel           <sigmav>[cm^3/s]
--------------------------------
o1 o1 -> ebar e |   6.50564e-38
o1 o1 -> mbar m |   2.78134e-33
o1 o1 -> lbar l |   5.05824e-31
o1 o1 -> ubar u |   8.04793e-39
o1 o1 -> dbar d |   7.71775e-36
o1 o1 -> sbar s |   3.02177e-33
o1 o1 -> cbar c |   5.86478e-33
o1 o1 -> bbar b |   2.87619e-30
o1 o1 -> tbar t |   1.72962e-31
o1 o1 -> wbar w |   2.33630e-31
o1 o1 -> z z    |   7.58712e-32
o1 o1 -> h z    |   2.05907e-31
--------------------------------
Total annihilation cross section 4.082059e-30 [cm^3/s]
--------------------------------
Fermi-LAT
--------------------------------
delta-loglikelihood : excluded at 2 sigma if <-12.850000 with 6 d.o.f.
--------------------------------
conservative     standard        stringent
--------------------------------
2.905715e-04     2.728380e-04    -2.857854e-04

--------------------------------
AMS-02
--------------------------------
delta-loglikelihood : excluded at 2 sigma % CL if <-12.850000 with 6 d.o.f.
--------------------------------
conservative     standard        stringent
--------------------------------
1.655830e-02     2.213955e-02    7.296463e-02
```

```
./slha.x example.lha
(...)

Relic density Oh2                1.429e+01

SI proton xsection               1.839e-10
SD proton xsection               5.242e-07

excluded_Xenon1T (standard)      0
excluded_PANDAX (standard)       0
excluded_PICO60 (standard)       0

Tot annihilation xsection        4.082e-30

excluded_Fermi (standard)        0
excluded_AMS02 (standard)        0
```

Scenario with a pressureless decaying scalar field (e.g. modulus, late inflaton, dilaton, ...) of energy density ρ_ϕ:

$$H^2 = 8\pi G/3\,(\rho_{rad} + \rho_\phi)$$

We define the scalar field decay width Γ_ϕ, with a large branching fraction to radiation and a (tiny) branching ratio b to WIMPs:

$$\begin{aligned}
\frac{d\rho_\phi}{dt} &= -3H\rho_\phi - \Gamma_\phi\rho_\phi \\
\frac{ds_{rad}}{dt} &= -3Hs_{rad} + \frac{\Gamma_\phi\rho_\phi}{T} \\
\frac{dn}{dt} &= -3Hn - \langle\sigma_{\text{eff}} v\rangle\left(n^2 - n_{eq}^2\right) + \frac{b}{m_\phi}\Gamma_\phi\rho_\phi
\end{aligned}$$

Reheating temperature T_{RH} (at which the scalar field is mostly decayed) defined by:

$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_{eff}(T_{RH})}{45}}\,\frac{T_{RH}^2}{M_P}$$

Non-thermal production parameter:

$$\eta = b\left(\frac{1\ \mathrm{GeV}}{m_\phi}\right)$$

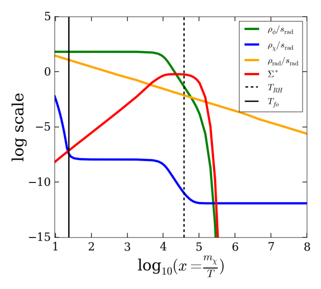
Initial (relative) scalar field density:

$$\kappa_\phi = \frac{\rho_\phi(T_{init})}{\rho_\gamma(T_{init})}$$

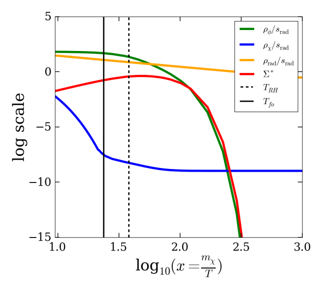
Relic density: decaying scalar field in absence of non-thermal production

AA, J. Ellis, F. Mahmoudi & G. Robbins, arXiv:1807.00554

Evolution of the scalar field density, WIMP density and entropy injection $\tilde{\Sigma}^* \equiv \frac{\Gamma_\phi \rho_\phi}{3HTs_{rad}}$ as a function of $x = m_\chi / T$, in absence of non-thermal production of WIMPs ($\eta = 0$)



(a) $T_{RH} = 0.01$ GeV, $\kappa_\phi^{init} = 100$, $T_{init} = 40$ GeV



(b) $T_{RH} = 10$ GeV, $\kappa_\phi^{init} = 100$, $T_{init} = 40$ GeV

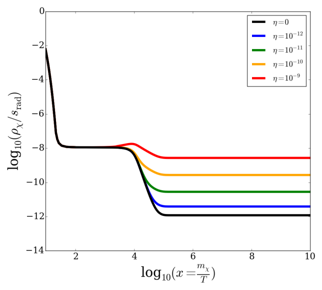
Complex interplay between expansion rate and entropy injection...

In absence of non-thermal WIMP production, results in a decrease of the relic density

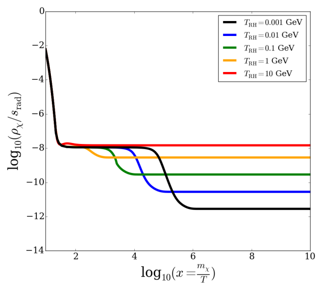
Relic density: decaying scalar field in presence of non-thermal production

AA, J. Ellis, F. Mahmoudi & G. Robbins, arXiv:1807.00554

Evolution of the WIMP density as a function of $x = m_\chi / T$ in presence of non-thermal production of WIMPs



(c) $T_{RH} = 0.01$ GeV, $\kappa_\phi^{init} = 100,\ T_{init} = 40$ GeV

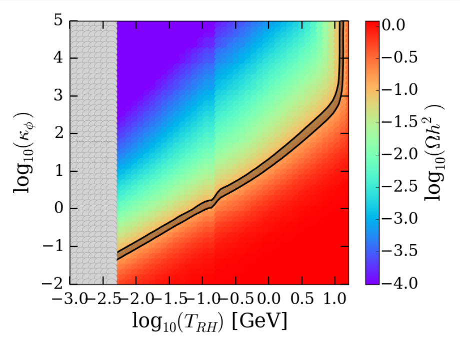


(d) $\eta = 10^{-11}$, $\kappa_\phi^{init} = 100,\ T_{init} = 40$ GeV

Standard scenario can be strongly modified by the non-thermal production of WIMPs.

AA, J. Ellis, F. Mahmoudi & G. Robbins, arXiv:1807.00554

Value of the relic density as a function of T_{RH} and κ_ϕ for a pMSSM example point with $\Omega_{\rm standard} h^2 = 1.27$, in absence of non-thermal production ($\eta = 0$)

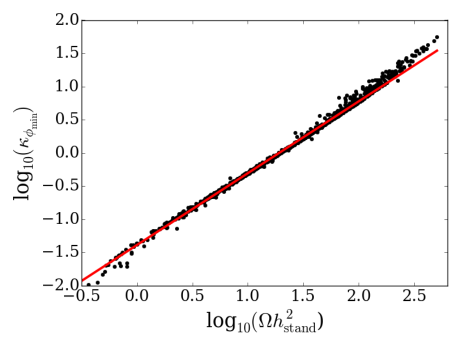


The gray region is excluded by Big-Bang nucleosynthesis constraints

The dark strip is compatible with Planck results

AA, J. Ellis, F. Mahmoudi & G. Robbins, arXiv:1807.00554

Minimal value of κ_ϕ to obtain the observed relic density as a function of original relic density $\Omega_{\rm standard} h^2$ for a sample of pMSSM points, with $T_{RH} = 6$ MeV, $T_{init} = 40$ GeV and in absence of non-thermal production ($\eta = 0$)



This sets constraints on the primordial Universe...

Ongoing developments

- Possibility to input tables of dark density or entropy for non-standard cosmological scenarios.
- Interface with `MARTY` for automatic dark matter observable calculation in any BSM scenario
  - one type of dark matter particles
  - several types of dark matter particles
  - density of each NP particle through time
  - freeze-out and freeze-in scenarios
- Interface with `BlackHawk`
  - NP particles radiated by PBHs
  - DM as PBHs and particles
  - Indirect detection of PBHs through Hawking radiation
- Automatic calculations of Wilson coefficients, flavour physics observables and $(g-2)_\mu$ in any BSM scenario, using `MARTY`