Coscattering in micrOMEGAs : a case study for the singlet-triplet dark matter model

Gaël Alguero

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LPSC Grenoble & LAPTh Annecy

In collaboration with G. Belanger, S. Kraml and A. Pukhov [arXiv:2207.10536]

Overview

Introduction to coscattering *

The Singlet-Triplet model

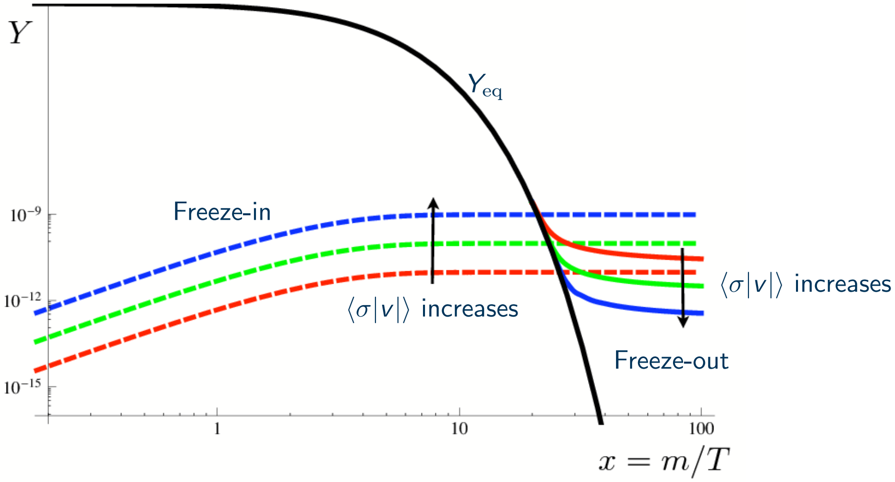
Numerical results

*. M. Garny et al. [1705.09292] and R.T. D'Agnolo et al. [1705.08450]

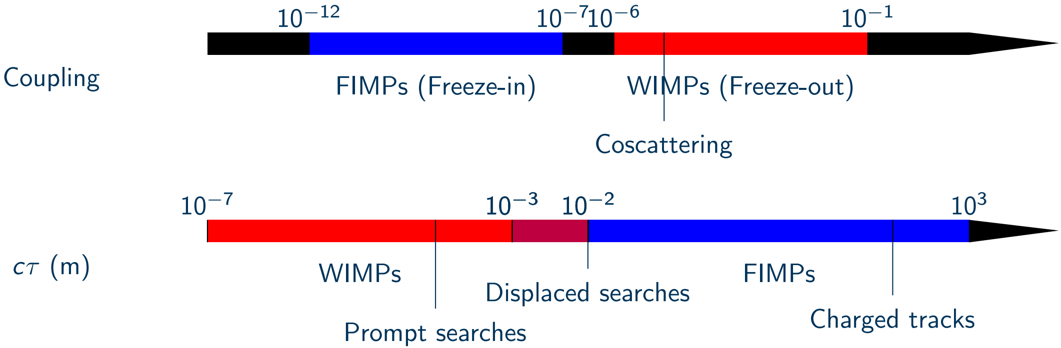
Introduction to coscattering [a]

a. M. Garny et al. [1705.09292] and R.T. D'Agnolo et al. [1705.08450]

Dark matter production in the universe



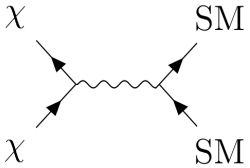
WIMPs, FIMPs and beyond



Freeze-out Boltzmann equation

- freeze-out : all dark particles in equilibrium

$$\frac{dY}{dT} = \frac{1}{3H}\frac{ds}{dT}\left[\langle\sigma_{\mathrm{eff}} v\rangle(Y^2 - Y^{eq\,2})\right]$$



- if dark particles not in equilibrium ⇒ need to solve 2 equations separately

With two thermal sectors

- in the following, 0 : SM, 1 : dark matter, 2 : 2nd dark sector

$$\begin{aligned}
\frac{dY_1}{dT} &= \frac{1}{3H}\frac{ds}{dT}\Bigg[\langle\sigma_{1100}v\rangle(Y_1^2 - Y_1^{eq\,2}) + \langle\sigma_{1122}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_1^{eq\,2}}{Y_2^{eq\,2}}\right) \\
&+ \langle\sigma_{1200}v\rangle(Y_1Y_2 - Y_1^{eq}Y_2^{eq}) + \langle\sigma_{1222}v\rangle\left(Y_1Y_2 - Y_2^2\frac{Y_1^{eq}}{Y_2^{eq}}\right) \\
&- \langle\sigma_{1211}v\rangle\left(Y_1Y_2 - Y_1^2\frac{Y_2^{eq}}{Y_1^{eq}}\right) - \frac{\Gamma_{2\to 1}}{s}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)\Bigg] \\
\frac{dY_2}{dT} &= \frac{1}{3H}\frac{ds}{dT}\Bigg[\langle\sigma_{2200}v\rangle(Y_2^2 - Y_2^{eq\,2}) - \langle\sigma_{1122}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_1^{eq\,2}}{Y_2^{eq\,2}}\right) \\
&+ \langle\sigma_{1200}v\rangle(Y_1Y_2 - Y_1^{eq}Y_2^{eq}) - \langle\sigma_{1222}v\rangle\left(Y_1Y_2 - Y_2^2\frac{Y_1^{eq}}{Y_2^{eq}}\right) \\
&+ \langle\sigma_{1211}v\rangle\left(Y_1Y_2 - Y_1^2\frac{Y_2^{eq}}{Y_1^{eq}}\right) + \frac{\Gamma_{2\to 1}}{s}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)\Bigg]
\end{aligned}$$

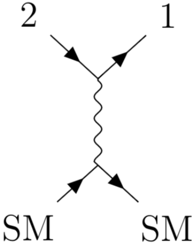
Coscattering equations (conversion-driven freeze-out)

- if DM is very weakly coupled to the SM, DM self-annihilation is negligible

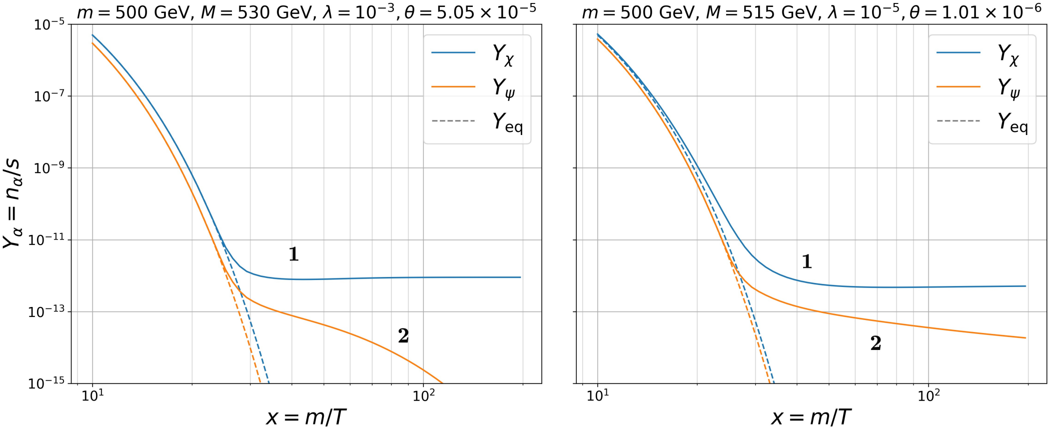
$$\frac{dY_1}{dT} = \frac{-\Gamma_{2\to1}}{HT}\left[Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right]$$

$$\frac{dY_2}{dT} = \frac{s}{HT}\left[\langle\sigma_{2200}v\rangle\left(Y_2^2 - Y_2^{eq\,2}\right) + \frac{\Gamma_{2\to1}}{s}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)\right]$$

$$\Gamma_{2\to1} = \Gamma_{2\to1,0}\frac{K_1\left(\frac{m_2}{T}\right)}{K_2\left(\frac{m_2}{T}\right)} + \langle\sigma_{2010}v\rangle\bar{n}_0$$



Example of density evolution



Implementation in micrOMEGAs

- new `darkOmegaN()` function to compute the relic density for N-component dark matter
  ⇒ allows to include coscattering and decays
- use `defThermalSet()` to define multiple dark sectors
- e.g., `defThermalSet(1, "~o1")` and `defThermalSet(2, "~o2 ~1+ ~1-")`
- processes can be excluded : `ExcludedFor2DM='2010'`

The Singlet-Triplet model

The fermionic Singlet-Triplet model

- Standard Model extended with
  - a $SU(2)$ singlet
  - a $SU(2)$ triplet

$$\chi, \quad \begin{Bmatrix} \psi^{\pm} \\ \psi^{0} \end{Bmatrix}$$

  - odd under a $\mathbb{Z}_2$-symmetry

Field	$\mathrm{SU(2)_L}$	$\mathrm{U(1)_Y}$	$\mathbb{Z}_2$
ℓ_L	**2**	$-1/2$	$+$
e_R	**1**	-1	$+$
H_1	**2**	$1/2$	$+$
χ	**1**	0	$-$
ψ	**3**	0	$-$

$$H_1 \xrightarrow{\mathbb{Z}_2} H_1$$

$$\chi \xrightarrow{\mathbb{Z}_2} -\chi$$

- χ and ψ can be identified to a bino and a wino (Split-SUSY [hep-th/0405159] and [hep-ph/0406088])
- χ very weakly coupled to the SM but two dark sectors coupled to each other

Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{i}{2}\bar{\chi}\gamma^\mu\partial_\mu\chi + \frac{i}{2}\bar{\psi}\gamma^\mu D_\mu\psi - \frac{1}{2}\left(m\bar{\chi}\chi + M\bar{\psi}\psi\right) + \mathcal{L}_5 + \mathcal{L}_{\geq 6}$$

$$\mathcal{L}_5 = -\frac{1}{2}\frac{\kappa}{\Lambda}\bar{\psi}\psi H^\dagger H - \frac{1}{2}\frac{\kappa'}{\Lambda}\bar{\chi}\chi H^\dagger H - \frac{\lambda}{\Lambda}\bar{\chi}\psi^a H^\dagger\tau^a H + \text{h.c.} + \dots$$

Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{i}{2}\bar{\chi}\gamma^\mu\partial_\mu\chi + \frac{i}{2}\bar{\psi}\gamma^\mu D_\mu\psi - \frac{1}{2}\left(m\bar{\chi}\chi + M\bar{\psi}\psi\right) + \mathcal{L}_5 + \mathcal{L}_{\geq 6}$$

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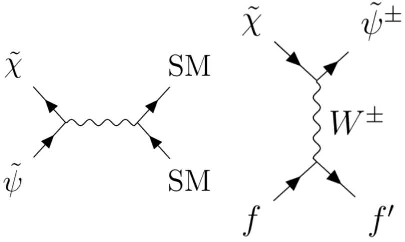
- λ term produces a χ-ψ mixing $\theta \approx \frac{\lambda v^2}{2\Lambda(M-m)}$
- if Δm small $\Rightarrow$ typical bino-wino coannihilation
- $\kappa, \kappa' = 0$ and $\Lambda = 10$ TeV
- physical states
  - dark matter : $\tilde{\chi}$
  - second dark sector : $\tilde{\psi}^0$ and $\tilde{\psi}^\pm$



Numerical results

Coscattering fraction

- when λ and Δm small, coscattering keeps $\tilde{\chi}$ coupled to the $\tilde{\psi}$ sector
- without coscattering, DM freezes out very early $\Rightarrow$ too high relic density
- to quantify when coscattering is necessary to keep $\tilde{\chi}$ coupled with the $\tilde{\psi}$ sector

$$\Delta_{2s}^{\Omega} = 1 - \frac{\Omega h^2(\text{total},\ 2\text{ sectors})}{\Omega h^2(\text{no coscattering},\ 2\text{ sectors})}$$

$$\Delta_{1s}^{\Omega} = 1 - \frac{\Omega h^2(1\text{ sector})}{\Omega h^2(2\text{ sectors})}$$

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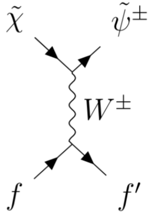
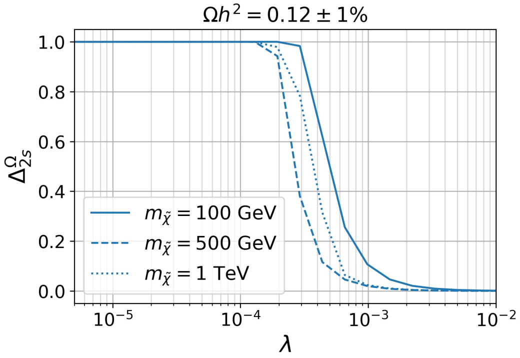
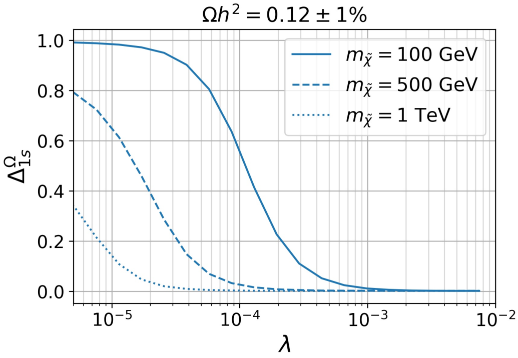


- if coannihilation dominant $\Rightarrow \Delta^{\Omega} = 0$ $(\lambda \gtrsim 10^{-3})$
- if coscattering dominant $\Rightarrow \Delta^{\Omega} = 1$ $(\lambda \lesssim 10^{-3})$

Coscattering fraction





Numerical results

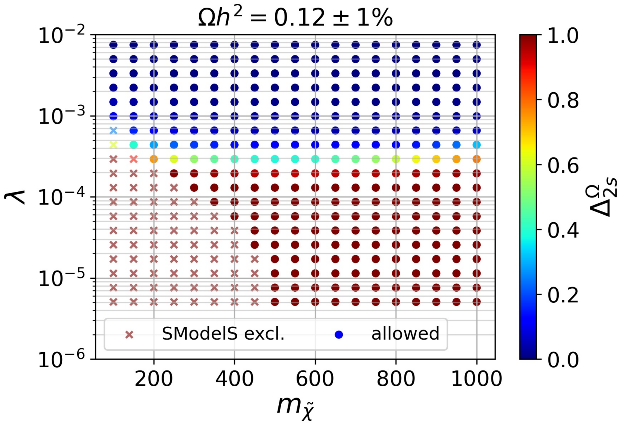
- grid scan over m and λ

  $\kappa, \kappa' = 0$, $\Lambda = 10$ TeV
- $\Delta m\left(\tilde{\psi}^0, \tilde{\chi}\right)$ to get $\Omega h^2 = 0.12$
- radiative corrections to $\Delta m\left(\tilde{\psi}^{\pm}, \tilde{\psi}^0\right)$ from [1712.00968]
- $\tilde{\psi}^{\pm}$ decay into pions

$$\mathcal{L}_{\tilde{\psi}^+\tilde{\psi}^0\pi^-} = \frac{g^2 \cos\theta f_\pi}{2\sqrt{2}m_W^2}\bar{\tilde{\psi}}^0\gamma^\mu\delta_\mu\pi^-\tilde{\psi}^+$$

A.Belyaev [1612.00511]

- disappearing tracks constraints from SModelSv2.1.1 [2112.00769]



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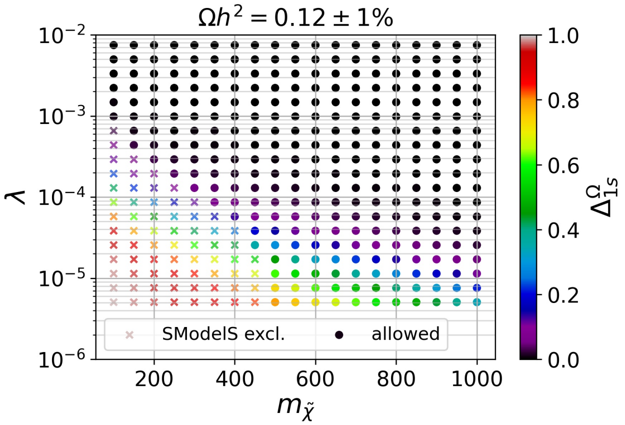
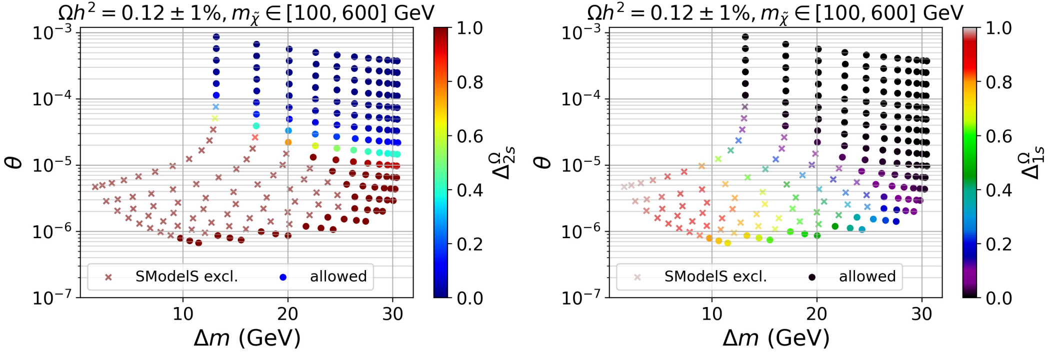
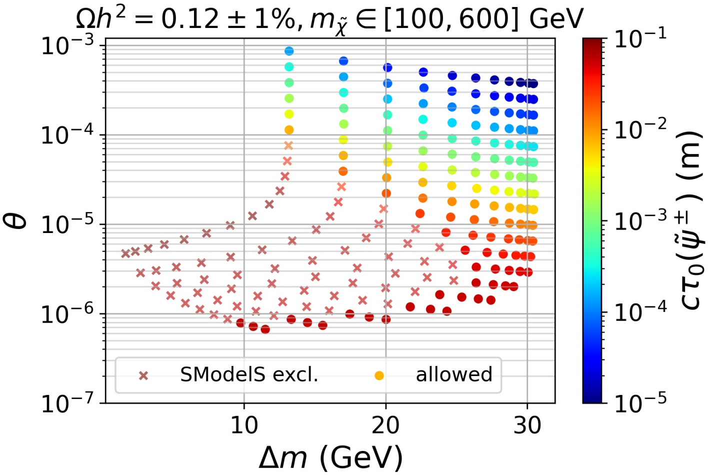


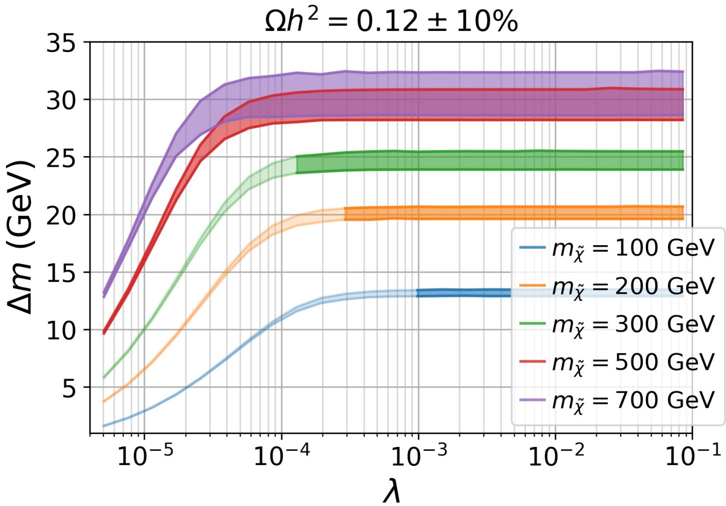
Coannihilation vs coscattering



Coannihilation vs coscattering



Allowing a 10% uncertainty



Conclusions

- micrOMEGAs is now able (since v5.3.34) to include coscattering and decays in the relic density computation
- case study of the Singlet-Triplet model
  - coscattering relevant for $\lambda \lesssim 10^{-3}$ and $\Delta m \lesssim 30$ GeV
    $\Rightarrow$ opens a new region in the parameter space
  - in the coscattering phase, $\tilde{\psi}^{\pm}$ is long-lived
    $\Rightarrow$ disappearing tracks constraints exclude up to $m_{\tilde{\chi}} \sim 450$ GeV
  - caveat : momentum-integrated Boltzmann equation can be a bad approximation when kinetic equilibrium is not maintained for very small coupling as discussed in [1910.01549] by Felix Brümmer $\Rightarrow$ be careful !

micrOMEGAs and SModelS are publicly available
and micrOMEGAs also has an interface to SModelS

Thanks for your attention !

Backups

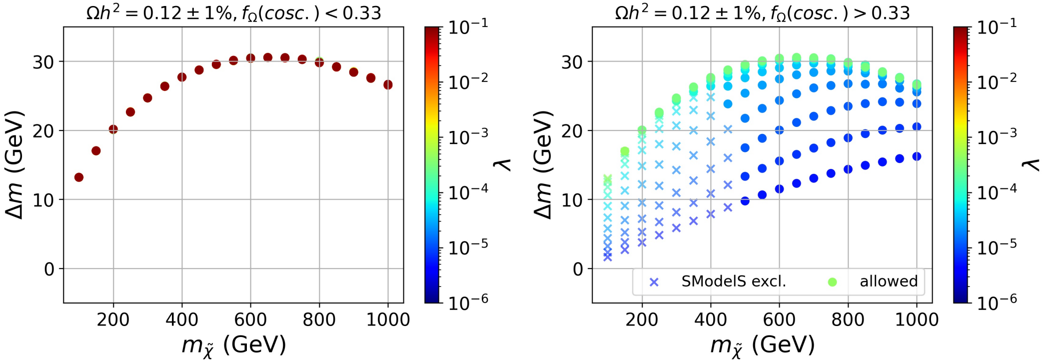
Complete width definition

$$\Gamma_{2\to1} = \frac{\sum_{a\in2} \Gamma_{a\to1,0} g_a m_a^2 K_1\left(\frac{m_a}{T}\right) + \sum_{a\in1} \Gamma_{a\to2,0} g_a m_a^2 K_1\left(\frac{m_a}{T}\right)}{\sum_{a\in2} g_a m_a^2 K_2\left(\frac{m_a}{T}\right)} + \langle\sigma_{2010} v\rangle \bar{n}_0 \tag{1}$$

Mixing angle

$$\sin 2\theta \sim 2\theta = \frac{2a}{\sqrt{(M-m)^2 + 4a^2}} \quad \rightarrow \quad \theta \approx \frac{\lambda v^2}{2\Lambda(M-m)} \tag{2}$$

Mass splitting

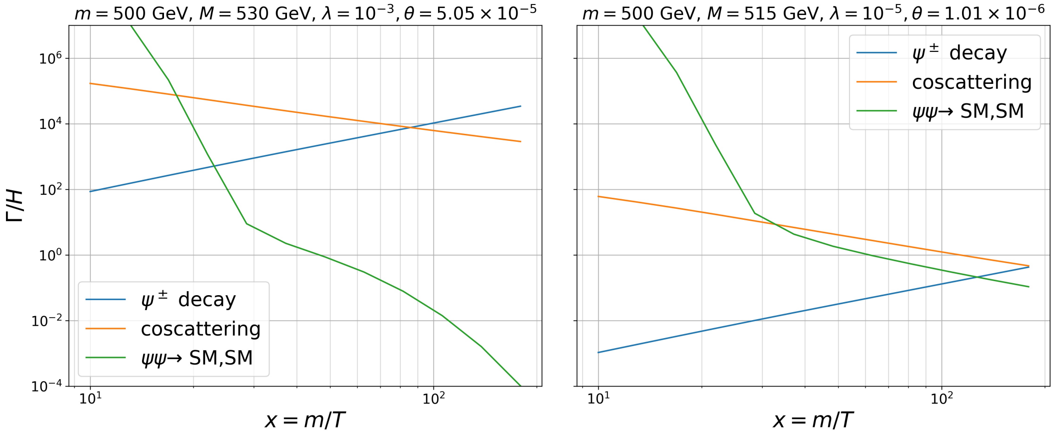


micrOMEGAs code snippet

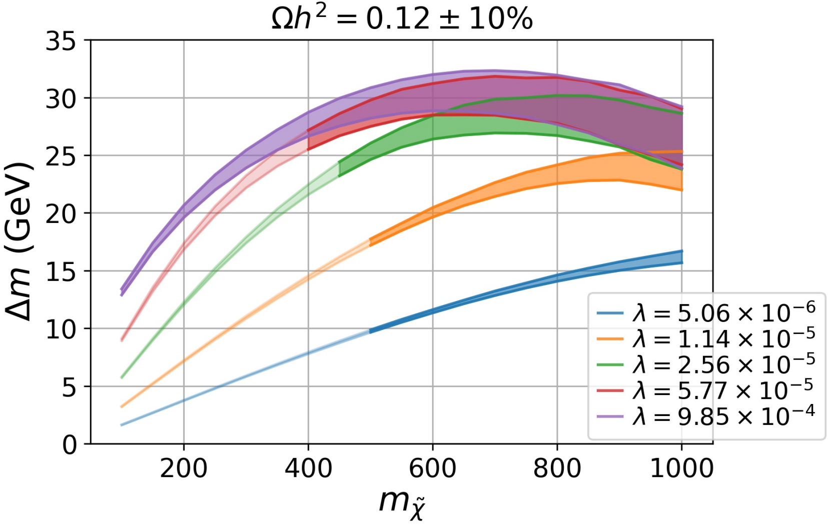
```
double Beps=1.E-4, Omega, Y[2];
int err;
defThermalSet(2, "~o2 ~1+ ~1-");
sortOddParticles(NULL);
printThermalSets();
Omega=darkOmegaN(Y,Beps,&err);
printf("Omega = %.3f\n",Omega);
...
```

```
There are 3 thermal sectors
Sector 2 : ~o2 ~1+ ~1-
Sector 1 : ~o1
Sector 0 : A Z G W+ W- ne Ne e E nm Nm m M nl Nl l L u U d D c C s S t T b
Omega= 0.124
```

Checking equilibrium



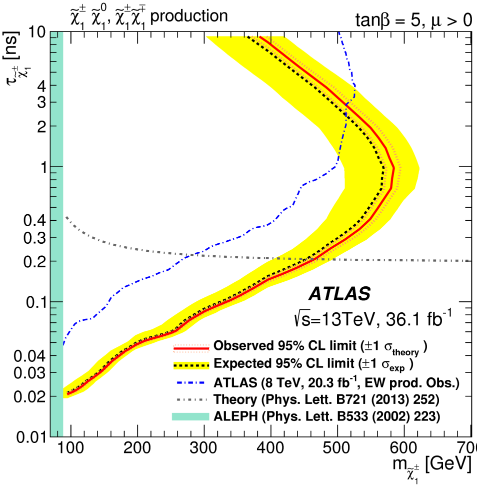
Checking equilibrium



LHC excluding analyses

2 disappearing tracks analyses ($\sqrt{s} = 13$ TeV)

- ATLAS-SUSY-2016-06
- CMS-EXO-19-010



Evolution with λ