

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

Gaël Alguero

ICHEP 2022, Dark Matter Session, July 7, 2022

LPSC Grenoble & LAPTh Annecy

In collaboration with G. Belanger, S. Kraml and A. Pukhov

Overview

Introduction to cospattering *

The Singlet-Triplet model

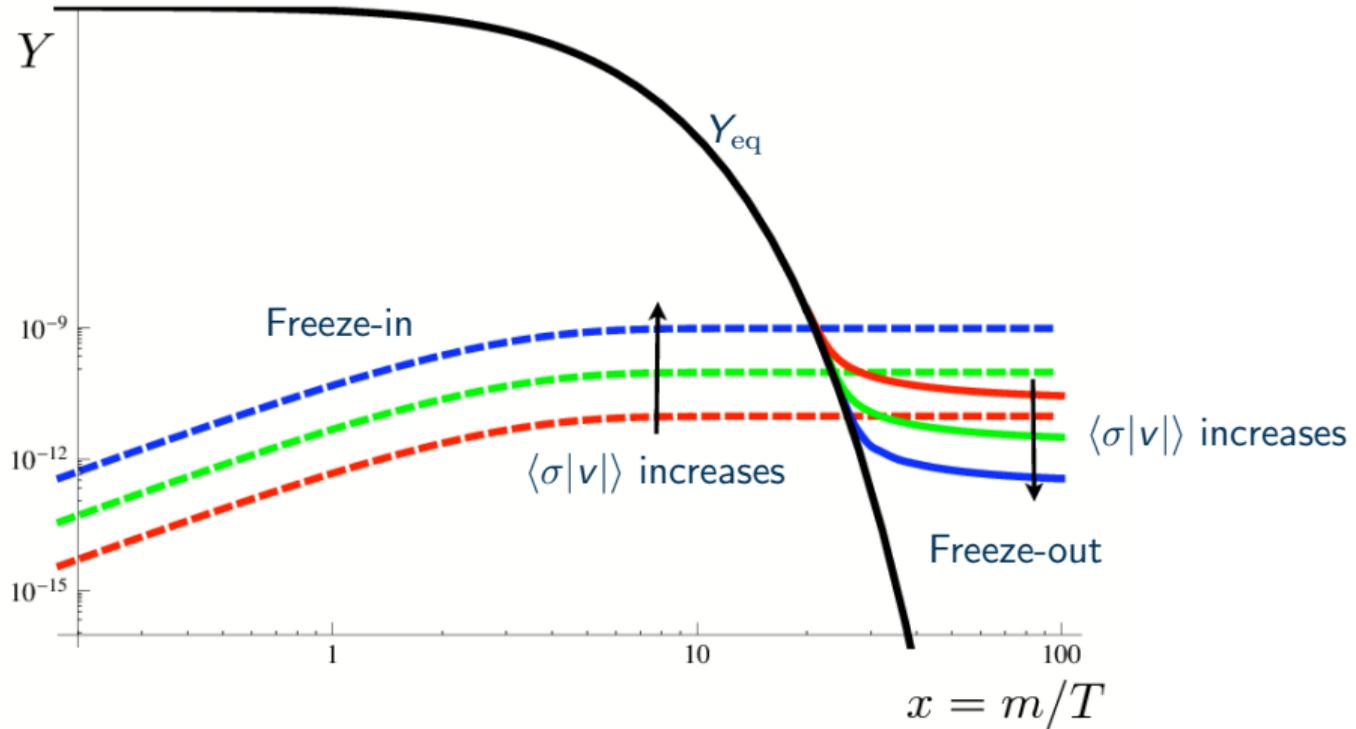
Numerical results

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

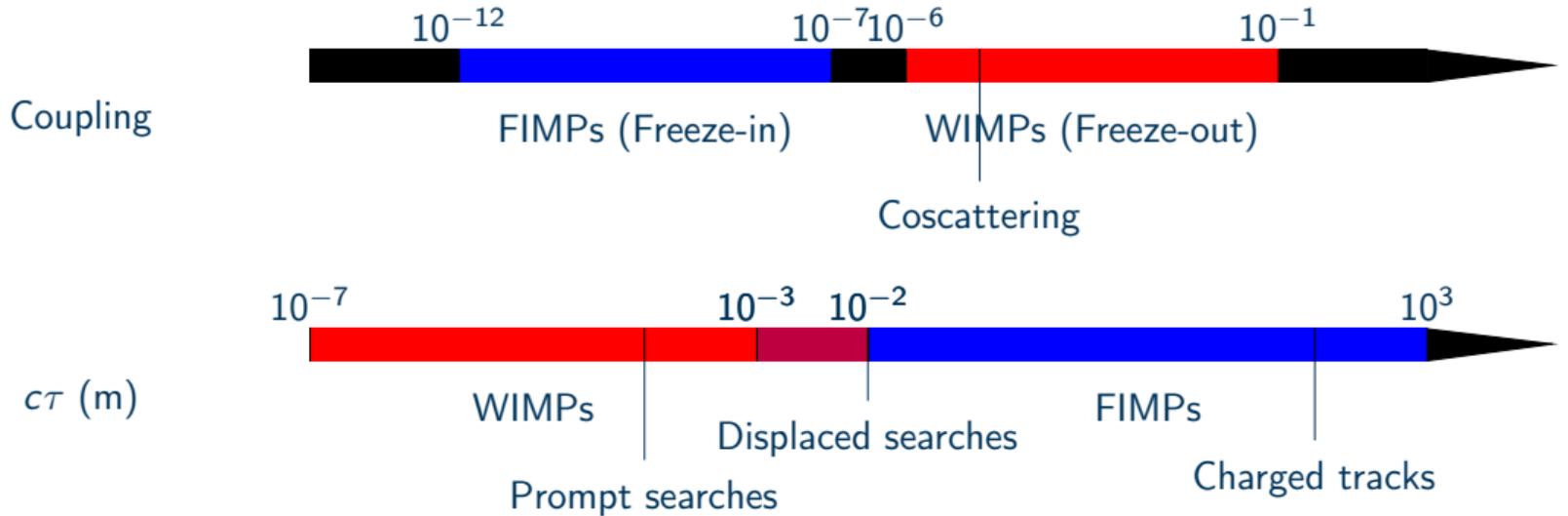
Introduction to coscattering^a

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

Dark matter production in the universe



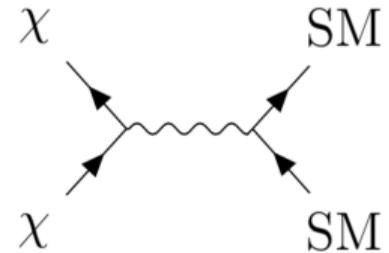
WIMPs, FIMPs and beyond



Freeze-out Boltzmann equation

- freeze-out : all dark particles in equilibrium

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



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

With two thermal sectors

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

$$\begin{aligned}
 \frac{dY_1}{dT} &= \frac{1}{3H} \frac{ds}{dT} \left[\langle \sigma_{1100} v \rangle (Y_1^2 - Y_1^{eq2}) + \langle \sigma_{1122} v \rangle \left(Y_1^2 - Y_2^2 \frac{Y_1^{eq2}}{Y_2^{eq2}} \right) \right. \\
 &\quad + \langle \sigma_{1200} v \rangle (Y_1 Y_2 - Y_1^{eq} Y_2^{eq}) + \langle \sigma_{1222} v \rangle \left(Y_1 Y_2 - Y_2^2 \frac{Y_1^{eq}}{Y_2^{eq}} \right) \\
 &\quad \left. - \langle \sigma_{1211} v \rangle \left(Y_1 Y_2 - Y_1^2 \frac{Y_2^{eq}}{Y_1^{eq}} \right) - \frac{\Gamma_{2 \rightarrow 1}}{s} \left(Y_2 - Y_1 \frac{Y_2^{eq}}{Y_1^{eq}} \right) \right] \\
 \frac{dY_2}{dT} &= \frac{1}{3H} \frac{ds}{dT} \left[\langle \sigma_{2200} v \rangle (Y_2^2 - Y_2^{eq2}) - \langle \sigma_{1122} v \rangle \left(Y_1^2 - Y_2^2 \frac{Y_1^{eq2}}{Y_2^{eq2}} \right) \right. \\
 &\quad + \langle \sigma_{1200} v \rangle (Y_1 Y_2 - Y_1^{eq} Y_2^{eq}) - \langle \sigma_{1222} v \rangle \left(Y_1 Y_2 - Y_2^2 \frac{Y_1^{eq}}{Y_2^{eq}} \right) \\
 &\quad \left. + \langle \sigma_{1211} v \rangle \left(Y_1 Y_2 - Y_1^2 \frac{Y_2^{eq}}{Y_1^{eq}} \right) + \frac{\Gamma_{2 \rightarrow 1}}{s} \left(Y_2 - Y_1 \frac{Y_2^{eq}}{Y_1^{eq}} \right) \right]
 \end{aligned}$$

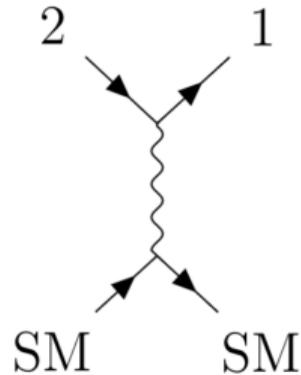
Coscattering equations (conversion-driven freeze-out)

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

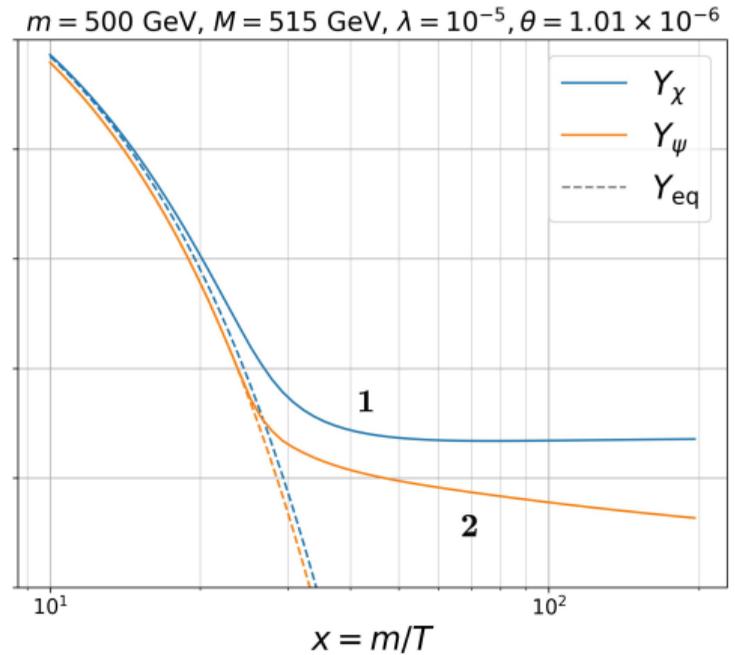
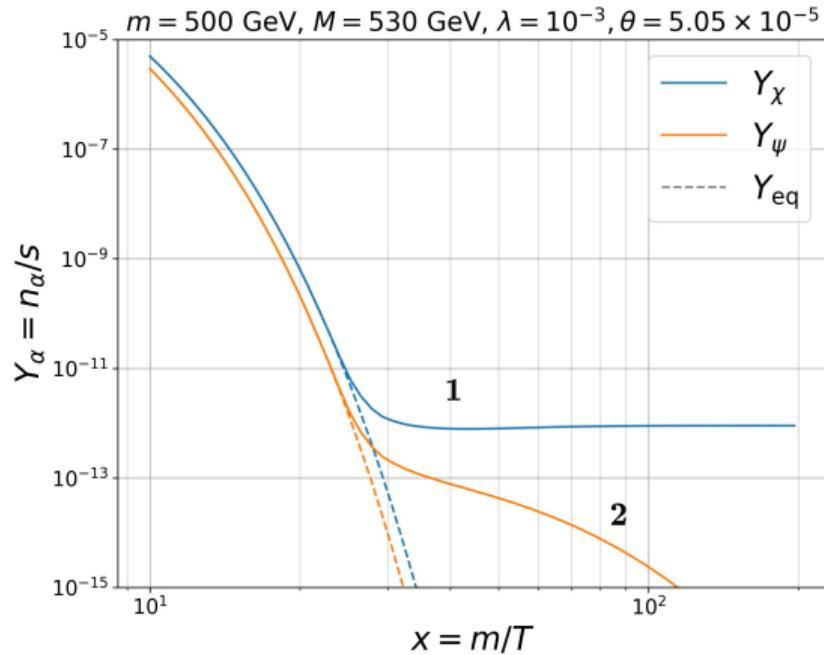
$$\frac{dY_1}{dT} = \frac{-\Gamma_{2 \rightarrow 1}}{HT} \left[Y_2 - Y_1 \frac{Y_2^{eq}}{Y_1^{eq}} \right]$$

$$\frac{dY_2}{dT} = \frac{s}{HT} \left[\langle \sigma_{2200} v \rangle (Y_2^2 - Y_2^{eq2}) + \frac{\Gamma_{2 \rightarrow 1}}{s} \left(Y_2 - Y_1 \frac{Y_2^{eq}}{Y_1^{eq}} \right) \right]$$

$$\Gamma_{2 \rightarrow 1} = \Gamma_{2 \rightarrow 1,0} \frac{K_1 \left(\frac{m_2}{T} \right)}{K_2 \left(\frac{m_2}{T} \right)} + \langle \sigma_{2010} v \rangle \bar{n}_0$$



Example of density evolution



Implementation in micrOMEGAs

- new `darkOmegaN()` function to compute the relic density for N-component dark matter
⇒ allows to include cospattering and decays
- use `defThermalSet()` to define multiple dark sec :newtheories
- 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

Field	SU(2) _L	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	-

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

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

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

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

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

- 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

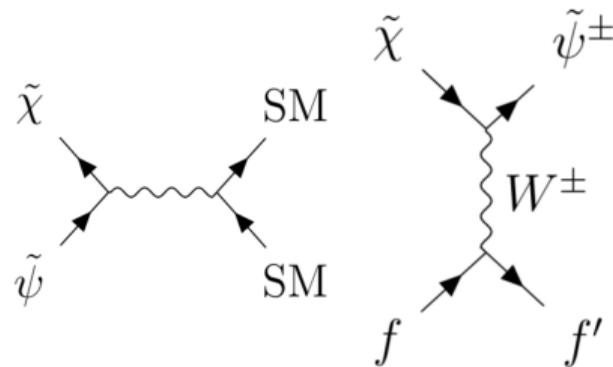
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{i}{2} \bar{\chi} \gamma^\mu \partial_\mu \chi + \frac{i}{2} \bar{\psi} \gamma^\mu D_\mu \psi - \frac{1}{2} (m \bar{\chi} \chi + M \bar{\psi} \psi) + \mathcal{L}_5 + \mathcal{L}_{\geq 6}$$
$$\mathcal{L}_5 = -\frac{1}{2} \frac{\kappa}{\Lambda} \bar{\psi} \psi H^\dagger H - \frac{1}{2} \frac{\kappa'}{\Lambda} \bar{\chi} \chi H^\dagger H - \frac{\lambda}{\Lambda} \bar{\chi} \psi^a H^\dagger \tau^a H + \text{h.c.} + \dots$$

Lagrangian

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

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

- 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

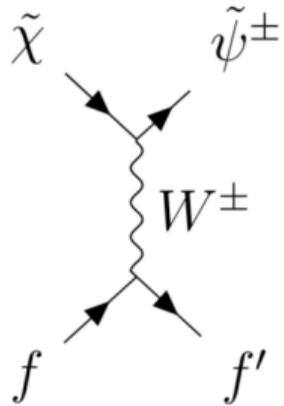
$$f_{\Omega}(\text{cosc.}) = 1 - \frac{\Omega h^2(\text{total})}{\Omega h^2(\text{no coscattering})}$$

Coscattering fraction

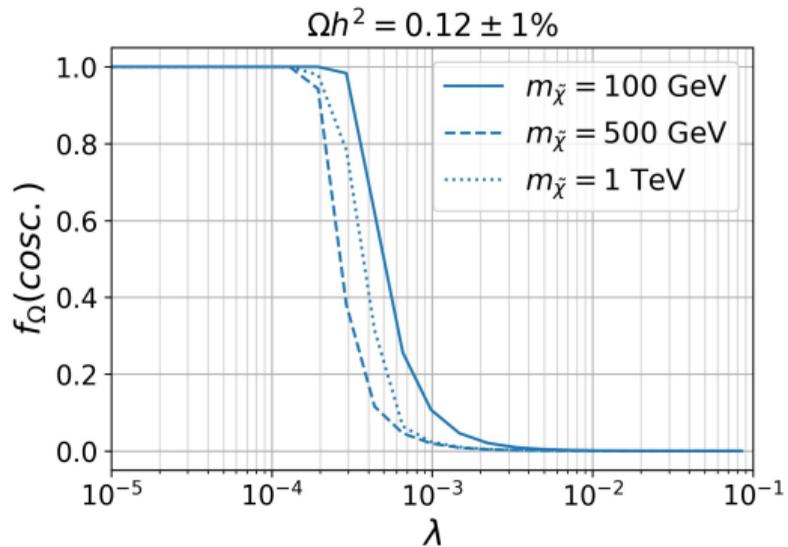
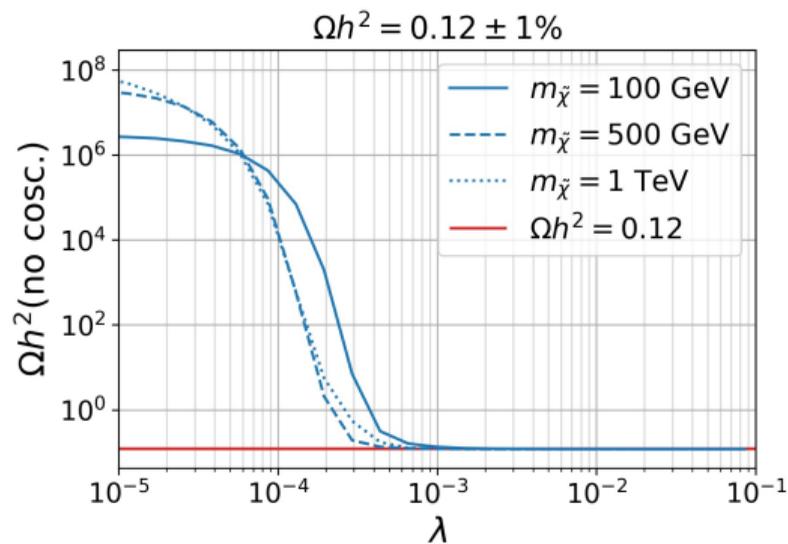
- when λ and Δm small, coscattering keeps $\tilde{\chi}$ coupled to the $\tilde{\psi}$ sector
- without coscattering, DM freezes out very early \Rightarrow too high relic density
- to quantify when coscattering is necessary to keep $\tilde{\chi}$ coupled with the $\tilde{\psi}$ sector

$$f_{\Omega}(\text{cosc.}) = 1 - \frac{\Omega h^2(\text{total})}{\Omega h^2(\text{no coscattering})}$$

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



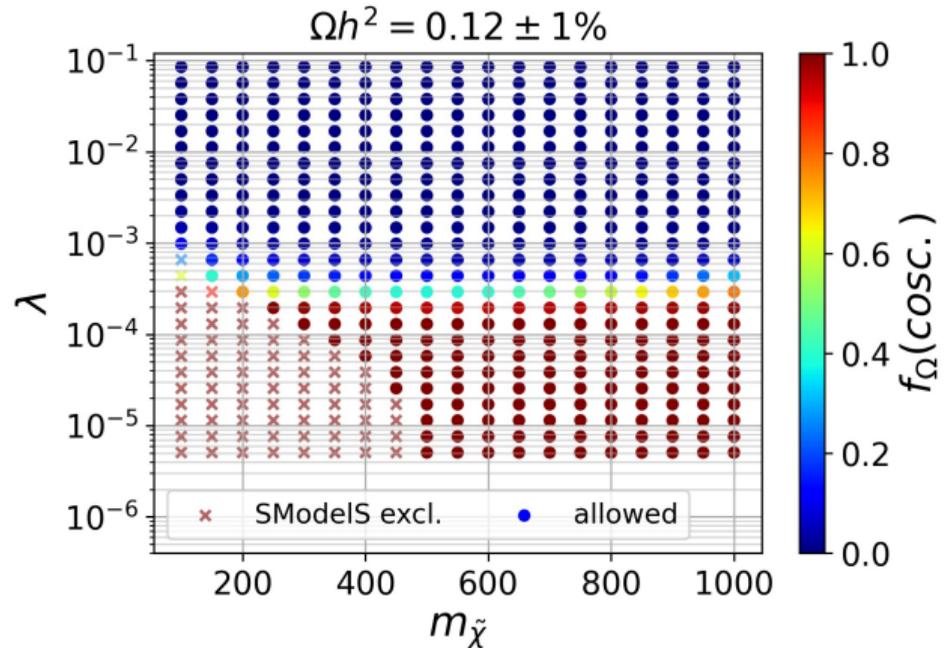
Coscattering fraction



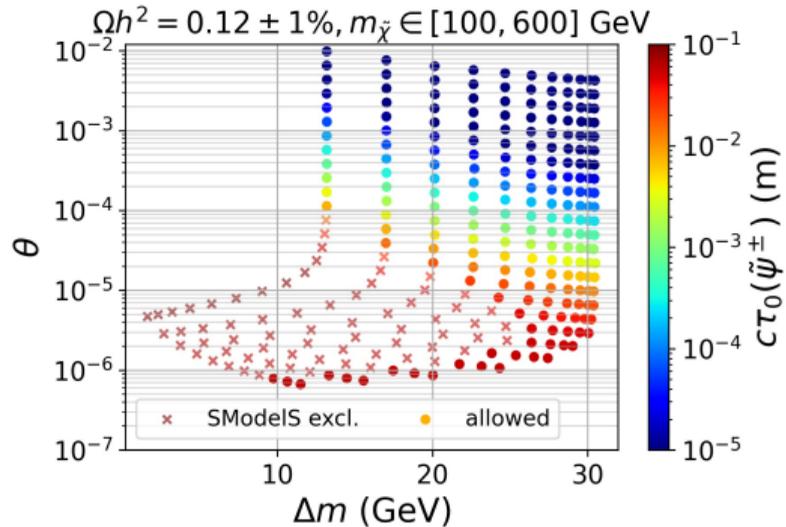
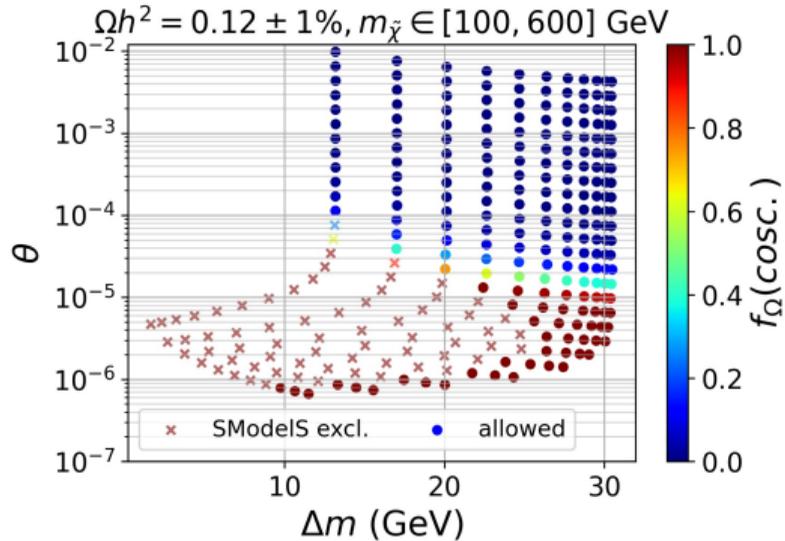
Numerical results

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

$$\mathcal{L}_{\tilde{\psi}^+ \tilde{\psi}^0 \pi^-} = \frac{g^2 \cos \theta f_\pi}{2\sqrt{2} m_W^2} \tilde{\psi}^0 \gamma^\mu \delta_{\mu\nu} \pi^- \tilde{\psi}^+$$
A.Belyaev [1612.00511]
- disappearing tracks constraints
 from SModelSv2.1.1 [2112.00769]

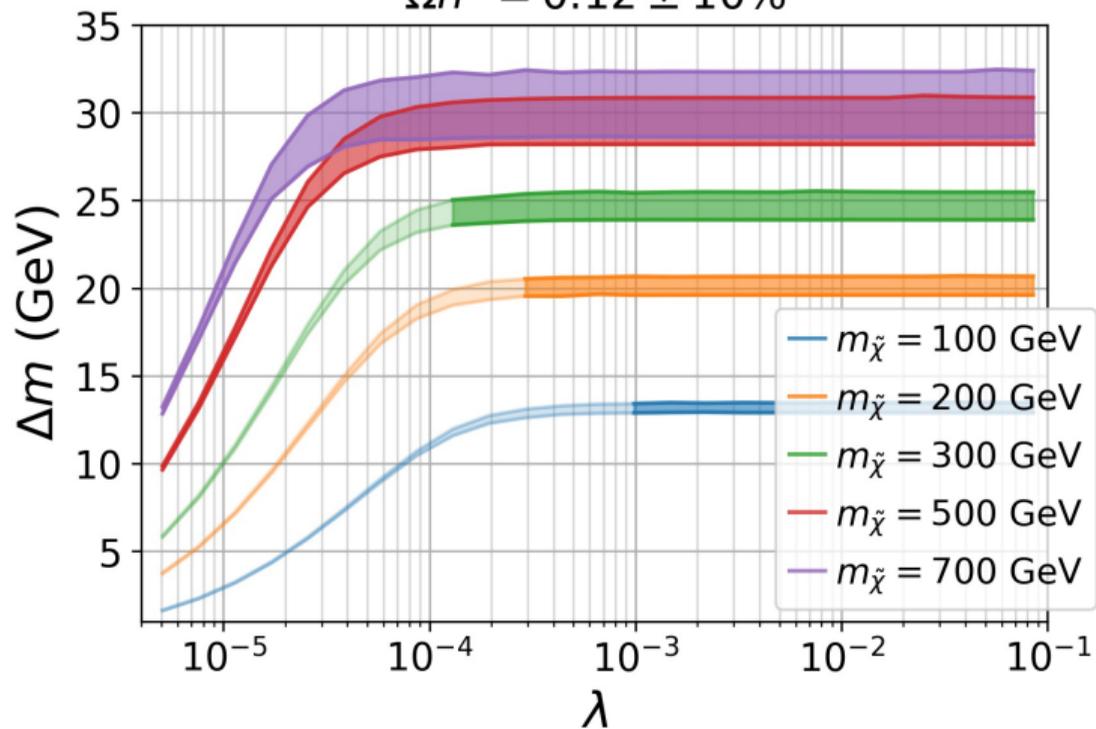


Coannihilation vs cospattering



Allowing a 10% uncertainty

$$\Omega h^2 = 0.12 \pm 10\%$$



Conclusions

- micrOMEGAs will be able (v5.3.34) to include cospattering and decays in the relic density computation
- case study of the Singlet-Triplet model
 - cospattering relevant for $\lambda \lesssim 10^{-3}$ and $\Delta m \lesssim 30$ GeV
⇒ opens a new region in the parameter space
 - in the cospattering phase, $\tilde{\psi}^\pm$ is long-lived
⇒ 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 ⇒ be careful !

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

Thanks for your attention !

Backups

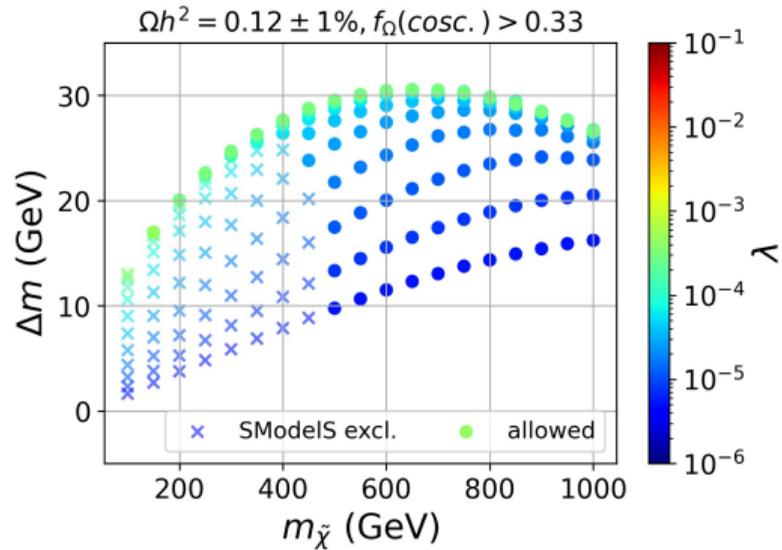
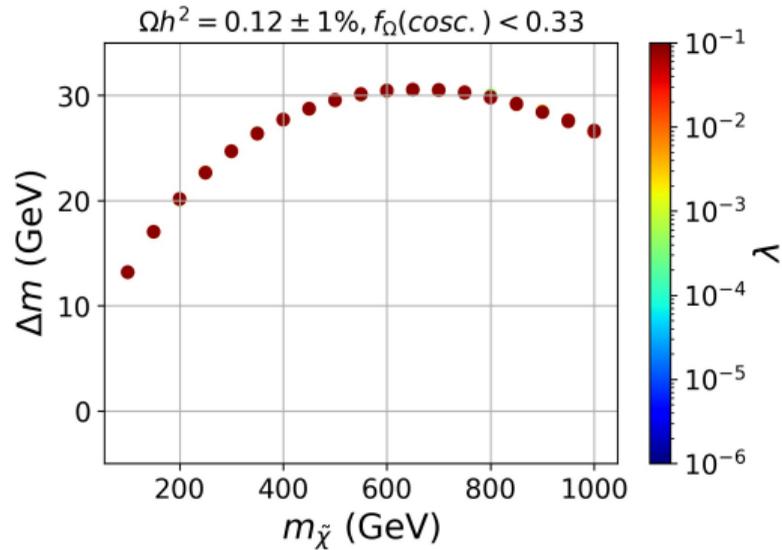
Complete width definition

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

Mixing angle

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

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

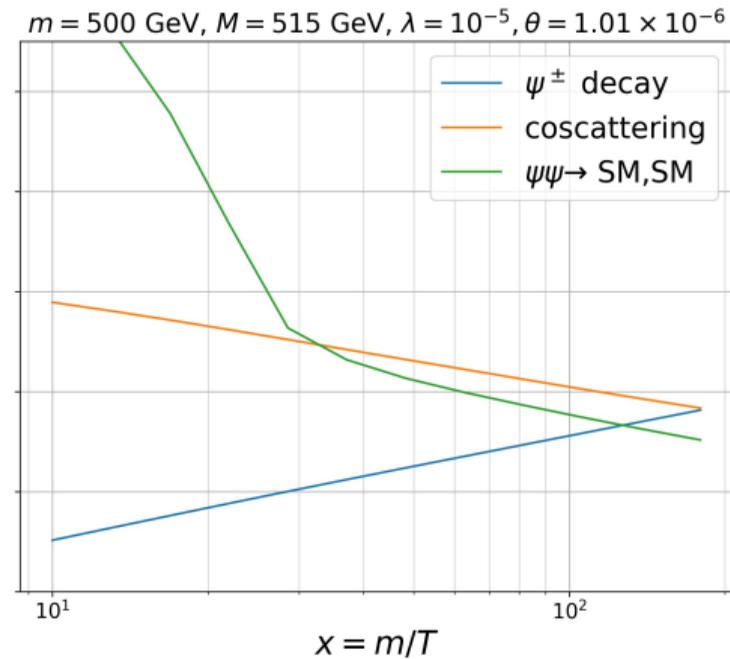
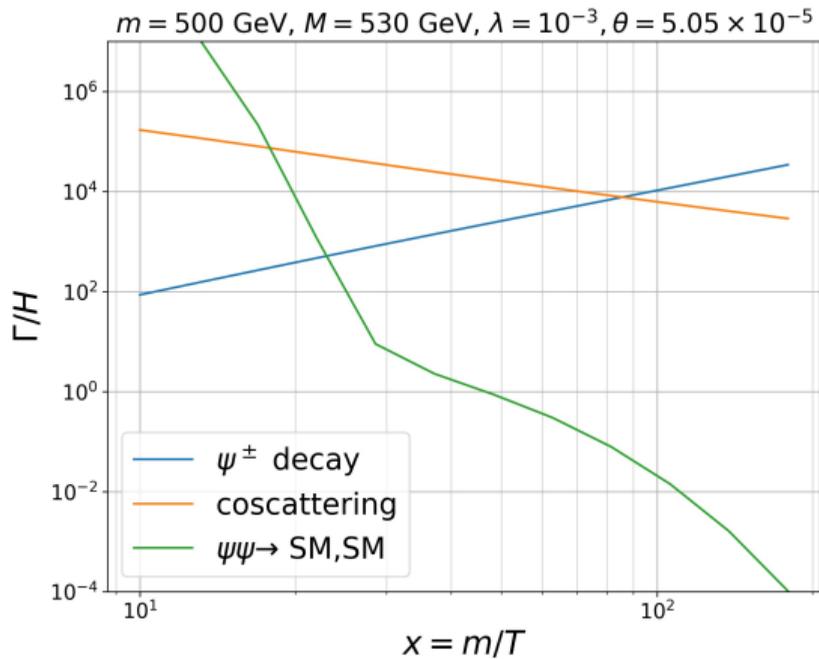
Sector 2 : ~o2 ~1+ ~1-

Sector 1 : ~o1

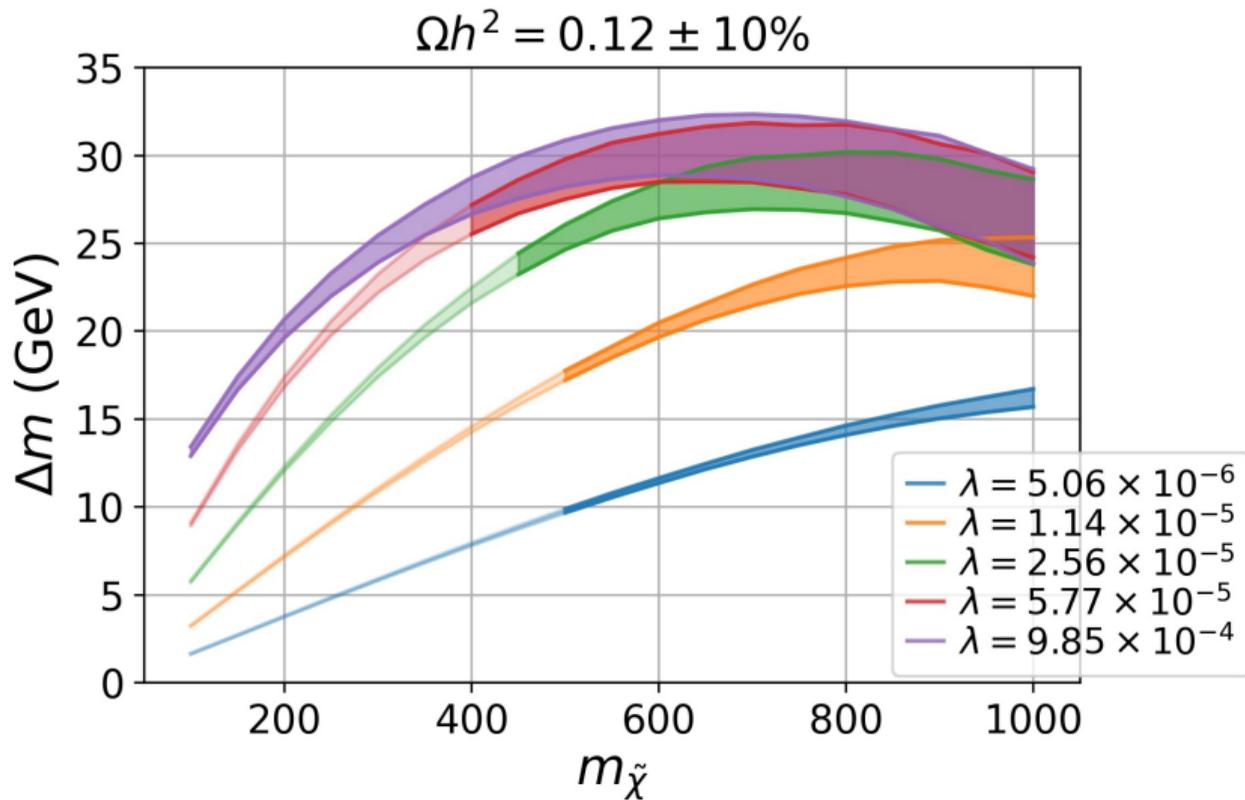
Sector 0 : A Z G W+ W- ne Ne e E nm Nm m M nl Nl l L u U d D c C s S t T b

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

