Long-lived particles and co-scattering

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Based on Alguero, GB, Kraml, Pukhov, 2207.10536, to appear in SciPost Phys

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Outline

- Introduction
- Coscattering
- A case-study: singlet-triplet
- Remarks and conclusions

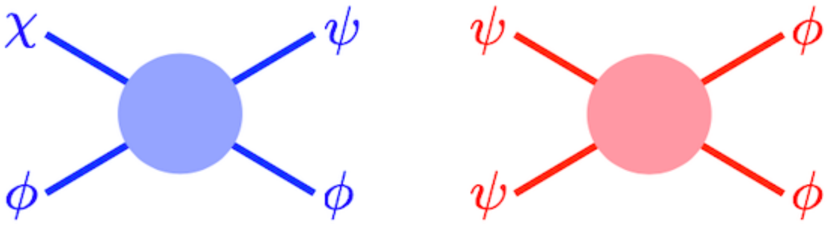
Introduction

- Extensive experimental programs for searches for WIMPs in direct/in-direct searches as well as collider searches
- Many DM production mechanism in early universe: Freeze-out, freeze-in, asymmetric, coscattering…
- Once DM is discovered – can we identify the production mechanism?
- Currently at colliders active searches for long-lived particles
- When DM couplings are very weak and/or spectrum in the dark sector is compressed : possible displaced signatures

Co-scattering - Conversion driven FO

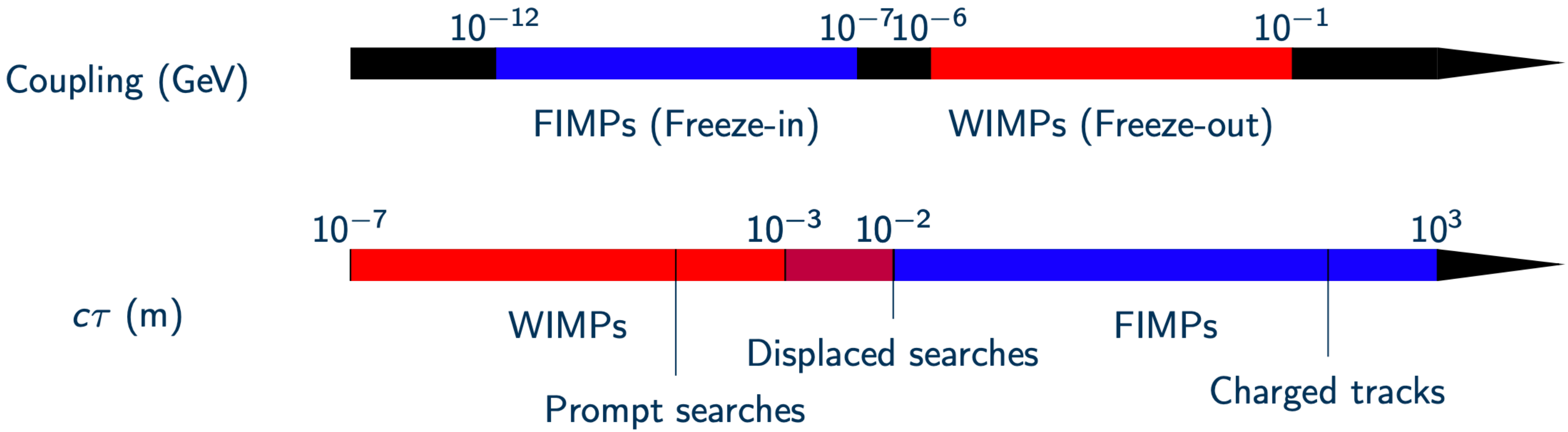
- When interactions of DM with SM are very weak, processes $\chi\chi$-> SMSM($\phi\phi$) are inefficient
- If other particles in the dark sector (ψ), inelastic scattering can dominate DM production

Coscattering Mechanism



- M. Garny et al 1705.09292 (conversion-driven FO)
- R.T D'Agnolo et al 1705.08450 (coscattering)
- Note : When red process decouples before blue process : coannihilation sets the relic abundance
- Otherwise FO of inelastic scattering (blue) sets the relic abundance
- Both coannihilation and coscattering require small mass splitting
- In coscattering typically ψ has long lifetime

Co-scattering - Conversion driven FO



A case study : 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 + SU(2) triplet (ψ)+ SU(2) singlet (χ) both odd under Z_2
- χ, ψ can be identified with bino, wino in split-SUSY with heavy Higgsinos
- couplings of χ (DM) to SM : very weak but couplings to other dark sector states (ψ) not negligible – will drive DM formation

Lagrangian

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

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

- Only H gets a vev, v
- Mass eigenstates: (singlet ~ m; triplet ~M)

$$m_{\tilde{\chi},\tilde{\psi}^0} = \frac{1}{2}\left(m + M \mp \sqrt{(M-m)^2 + 4a^2}\right), \quad \text{where } a = \lambda v^2/(2\Lambda)\,.$$

- Small mixing singlet-triplet: $$\theta \approx \frac{\lambda v^2}{2\Lambda(M-m)}$$

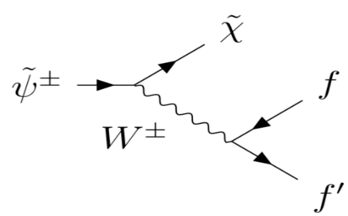
- Mixing also lifts degeneracy between neutral and charged triplet ~160MeV (McKay, Scott, arXiv:1712:00968)

Interactions

$$\mathcal{L}_{W^\pm\tilde{\psi}^\mp\tilde{\chi}} = -g\sin\theta\bar{\tilde{\chi}}\gamma^\mu W^+_\mu\tilde{\psi}^- + g\sin\theta\bar{\tilde{\chi}}\gamma^\mu W^-_\mu\tilde{\psi}^+ + \text{h.c.}$$

$$\mathcal{L}_{W^\pm\tilde{\psi}^\mp\tilde{\psi}^0} = g\cos\theta\bar{\tilde{\psi}}^0\gamma^\mu W^+_\mu\tilde{\psi}^- .$$

- For small mixing with χ, ψ^+ is long-lived, competing decays : 3-body decay $\psi^+ \to \chi$ ff or 2-body decay $\tilde{\psi}^\pm \to \tilde{\psi}^0\pi^\pm$



- Typical lifetime of charged triplet : 1cm- 1 m
- Couplings to Higgs, same order as coupling to gauge bosons:

$$\frac{\lambda v}{\sqrt{2}\Lambda}\bar{\tilde{\chi}}\tilde{\psi}^0 h$$

- Couplings of DM further suppressed: $-\frac{\lambda^2 v^3}{2\sqrt{2}\Lambda^2(M-m)}\bar{\tilde{\chi}}\tilde{\chi}h$

Solving for co-scattering
(as implemented in micrOMEGAs)

- Small couplings → particles in the dark sector might not be in thermal equilibrium with each other -> separate Boltzmann equations
- Assume kinetic equilibrium
- Assign particles to 'dark sectors', within each sector assume that particles are in thermal equilibrium
- Sector 0 : SM; sector 1 : singlet, sector 2 : triplet
- Singlet is lightest, triplet can decay to singlet+SM, triplet has em interacti niverse

$$\frac{dY_1}{dT} = \frac{1}{3H}\frac{ds}{dT}\Bigg[\langle\sigma_{1100}v\rangle(Y_1^2 - Y_1^{eq2}) + \langle\sigma_{1122}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_1^{eq2}}{Y_2^{eq2}}\right) + \langle\sigma_{1200}v\rangle(Y_1Y_2 - Y_1^{eq}Y_2^{eq}) + \langle\sigma_{1222}v\rangle\left(Y_1Y_2 - Y_2^2\frac{Y_1^{eq}}{Y_2^{eq}}\right) - \langle\sigma_{1211}v\rangle\left(Y_1Y_2 - Y_1^2\frac{Y_2^{eq}}{Y_1^{eq}}\right) - \frac{\Gamma_{2\to1}}{s}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)\Bigg],$$

- Similar Eq. For Y_2

- When coupling of singlet (λ) is very small : self-annihilation of singlet negligible

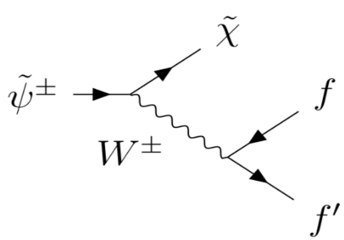
$$\frac{dY_1}{dT} = \frac{-\Gamma_{2\to 1}}{HT}\left[Y_2 - Y_1 \frac{Y_2^{eq}}{Y_1^{eq}}\right] ,$$

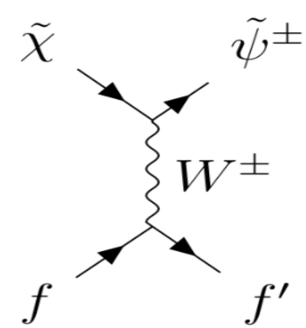
$$\frac{dY_2}{dT} = \frac{s}{HT}\left[\langle\sigma_{2200}v\rangle(Y_2^2 - Y_2^{eq2}) + \frac{\Gamma_{2\to 1}}{s}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)\right] .$$

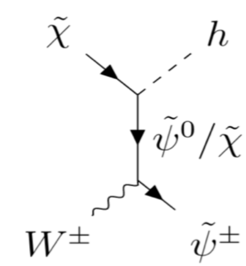
$$\Gamma_{2\to 1} = \frac{\sum_{a\in 2}\Gamma_{a\to 1,0}\, g_a m_a^2 K_1\left(\frac{m_a}{T}\right) + \sum_{a\in 1}\Gamma_{a\to 2,0}\, g_a m_a^2 K_1\left(\frac{m_a}{T}\right)}{\sum_{a\in 2} g_a m_a^2 K_2\left(\frac{m_a}{T}\right)} + \langle\sigma_{2010}v\rangle\bar{n}_0 ,$$

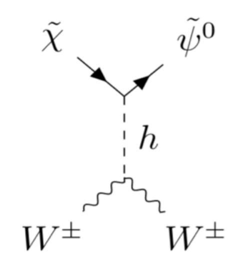
decays

coscattering

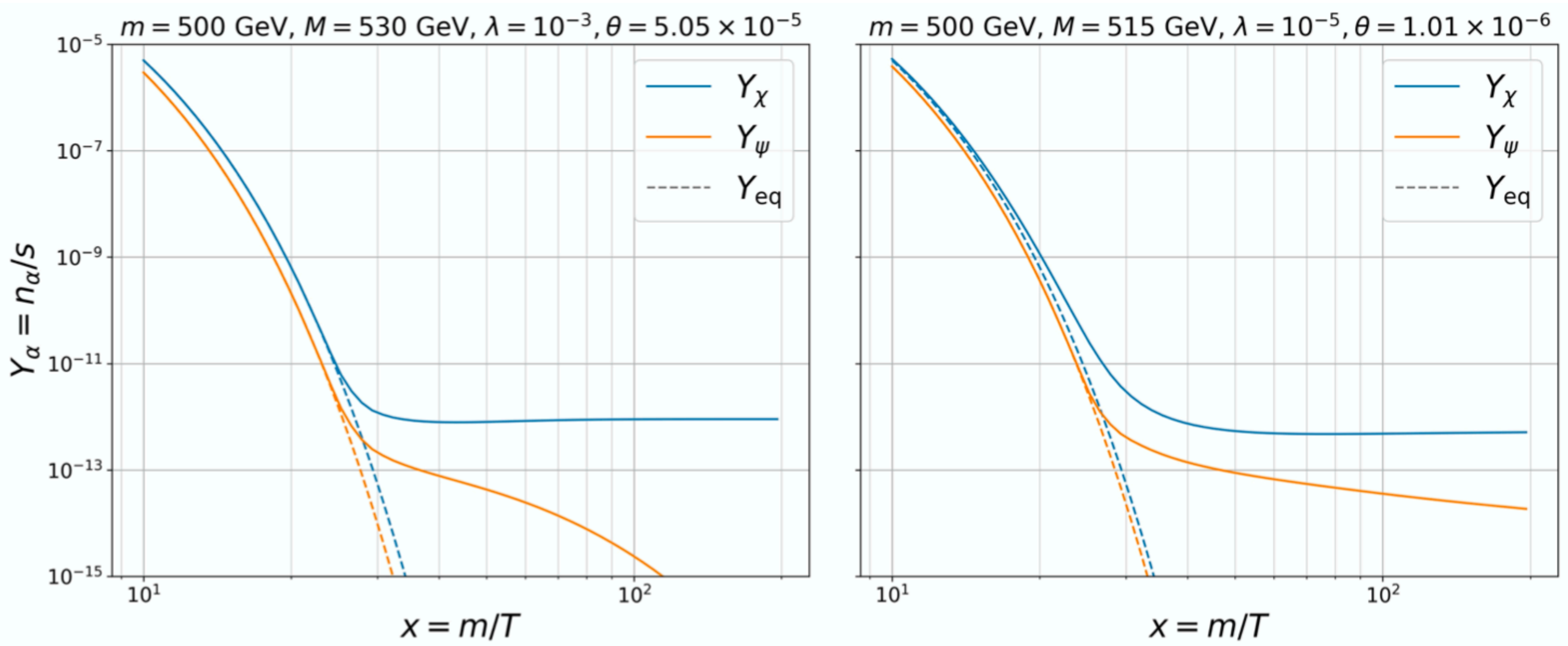






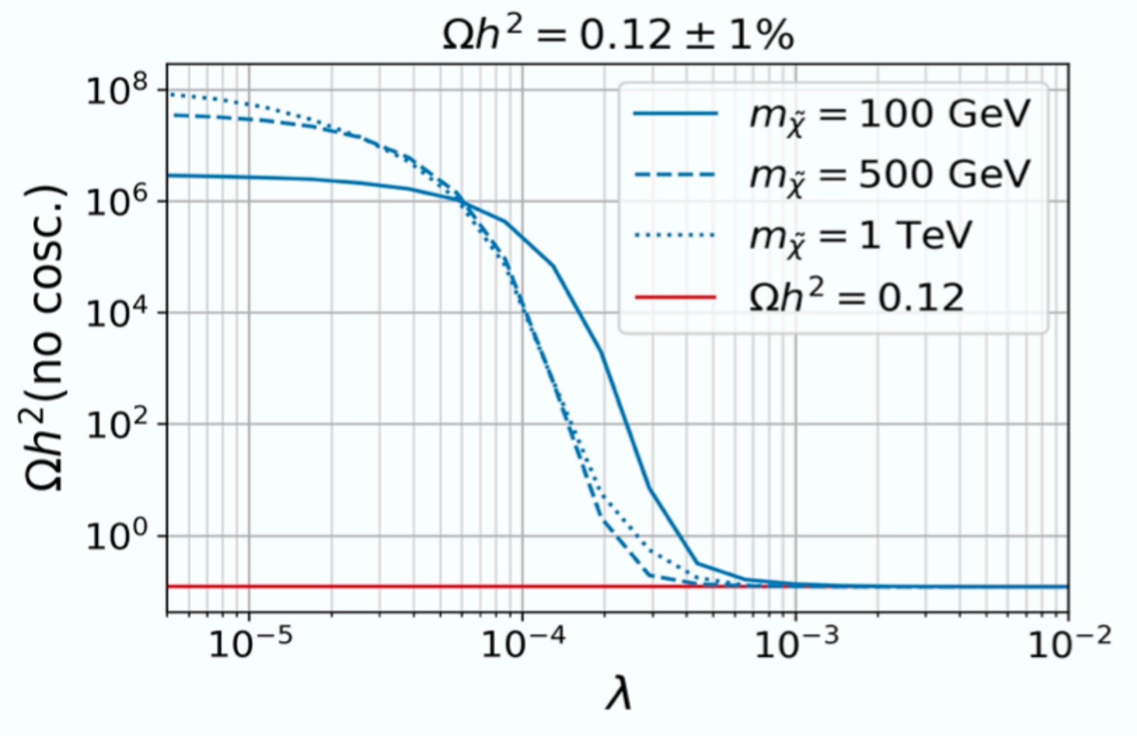


Abundances



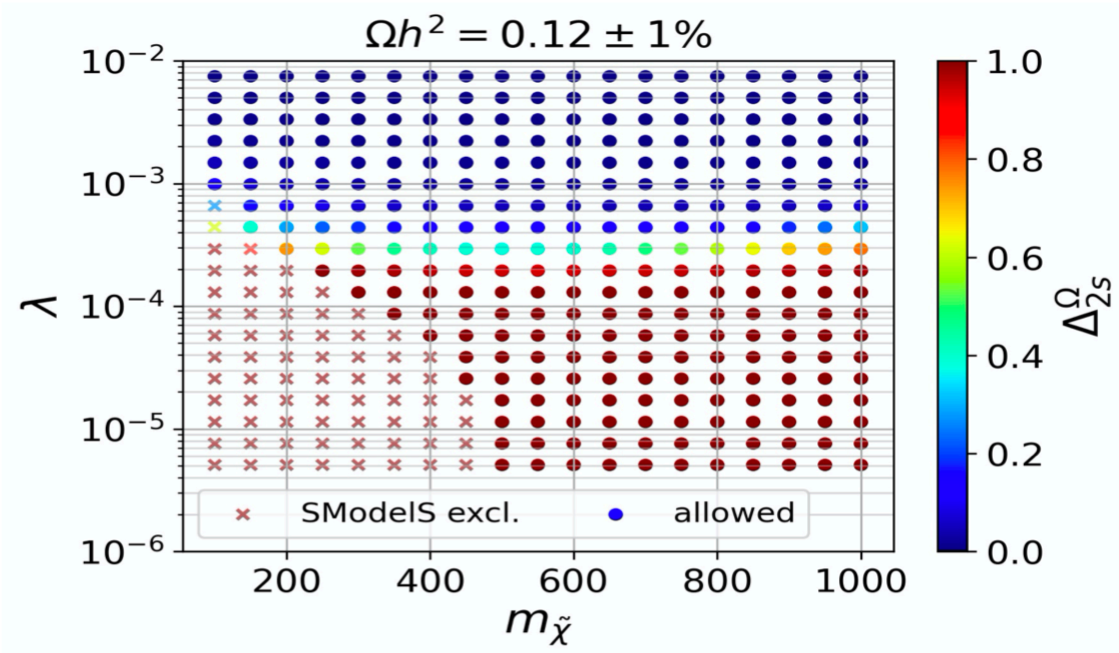
- Solving for relic density: micrOMEGAs5.3 solving momentum integrated Boltzmann eq. including decay/coscattering term
- Small coupling : departure from Y_{eq}

Importance of co-scattering



- $\Delta m \equiv m_{\tilde{\psi}^0} - m_{\tilde{\chi}}$ adjusted to get $\Omega h^2 = 0.12$ when all processes included
- Co-scattering dominant at small $\lambda <$ few 10^{-4}

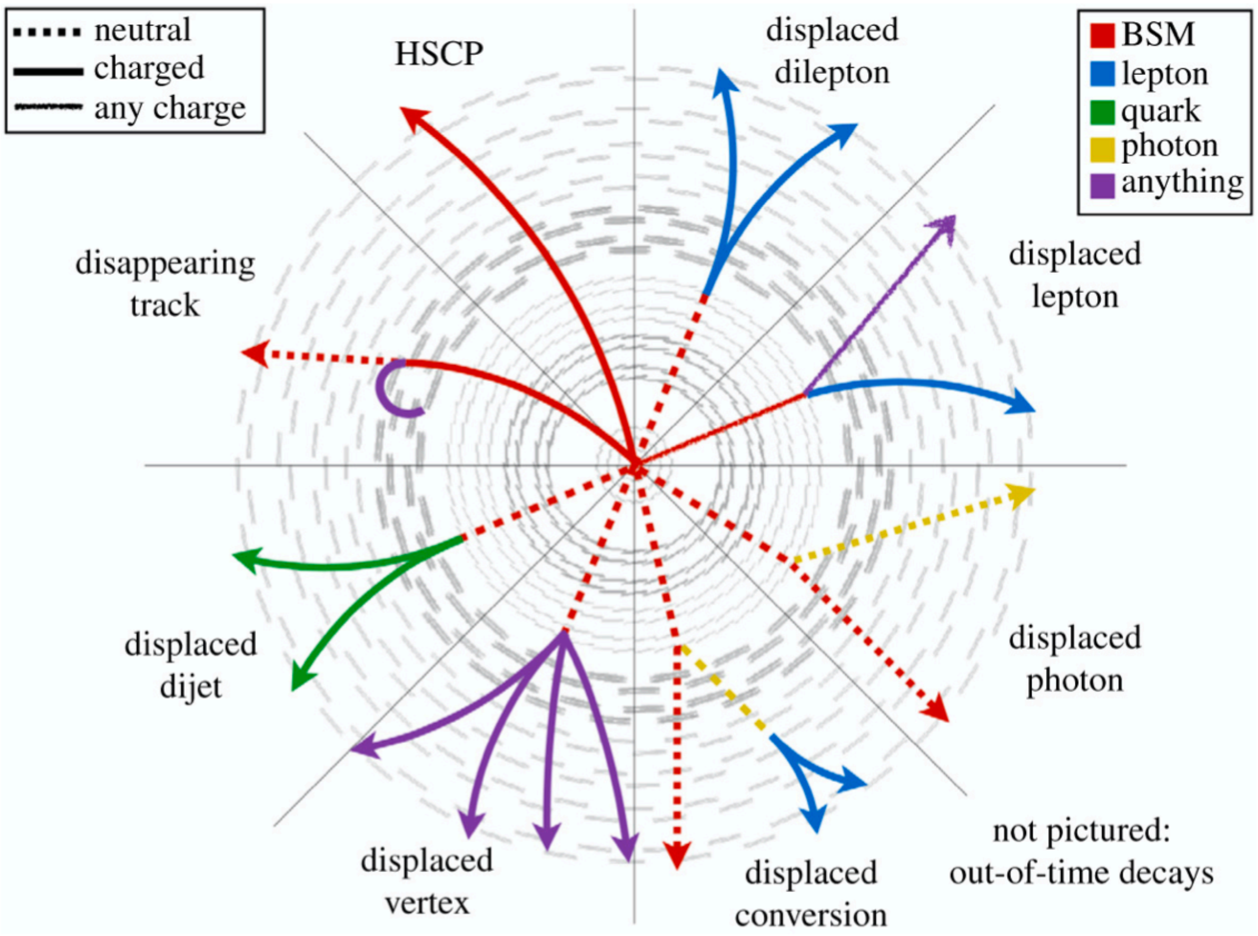
Importance of co-scattering



$$\Delta_{2s}^{\Omega} \equiv 1 - \frac{\Omega h^2(\text{2 sectors})}{\Omega h^2(\text{2 sectors, no co-scattering})}.$$

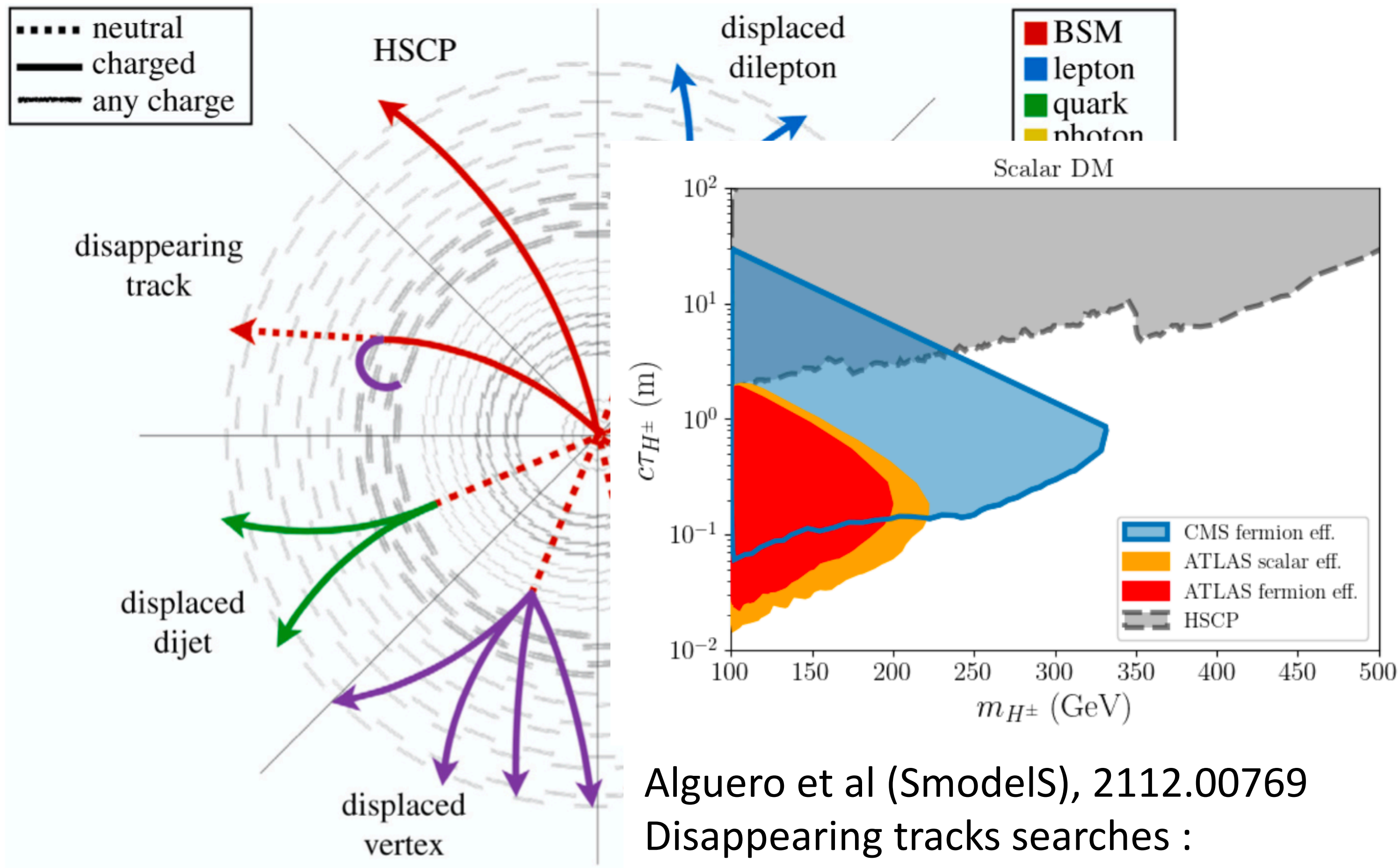
- $\Delta m \equiv m_{\tilde{\psi}^0} - m_{\tilde{\chi}}$ adjusted to get $\Omega h^2=0.12$ when all processes included
- Co-scattering dominant at small $\lambda <$ few 10^{-4}
- $\Delta=0.5$ means Ωh^2 reduced by factor 2 by co-scattering
- Smodels excl : current disappearing track searches

LLP at LHC



neutral
charged
any charge
HSCP
displaced
dilepton
BSM
lepton
quark
photon
anything
disappearing
track
displaced
lepton
displaced
dijet
displaced
photon
displaced
vertex
displaced
conversion
not pictured:
out-of-time decays

LLP at LHC



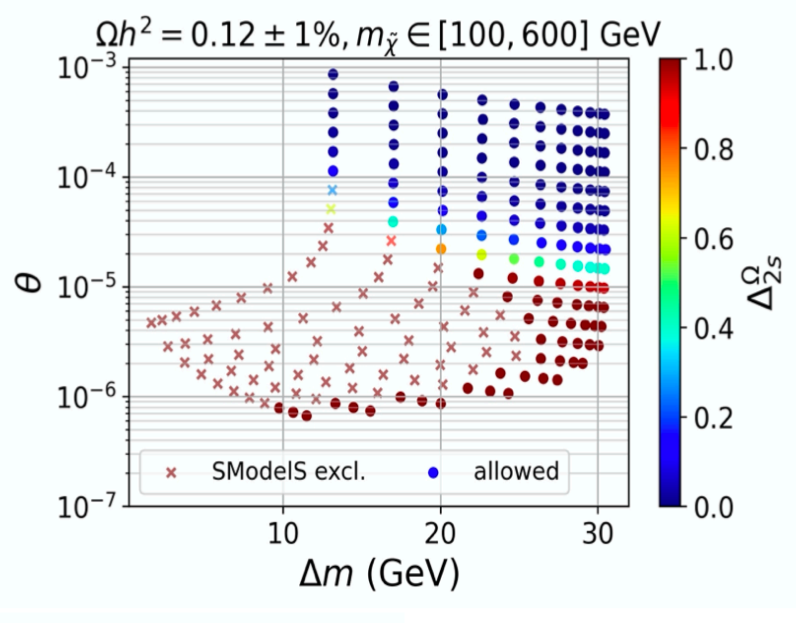
Alguero et al (SmodelS), 2112.00769

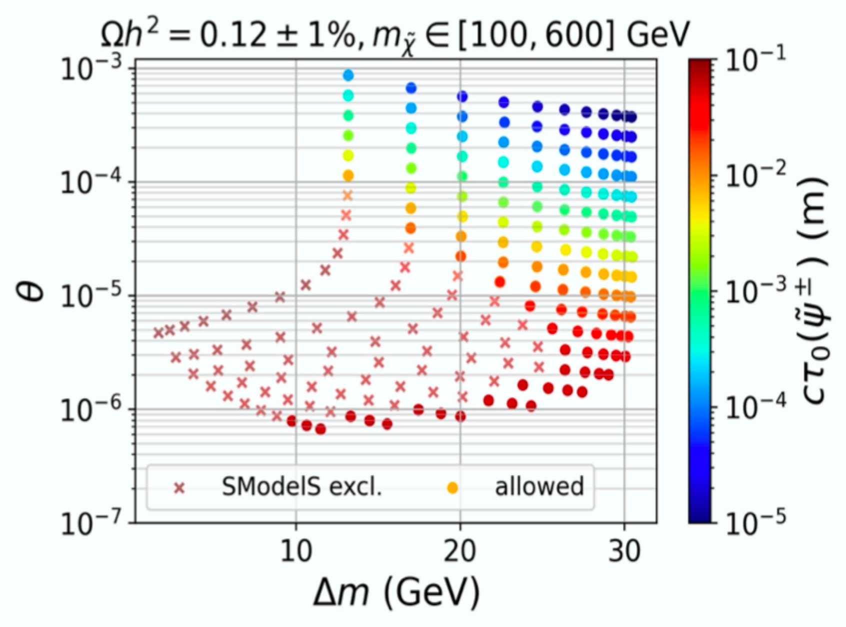
Disappearing tracks searches :

ATLAS ($36fb^{-1}$) , 1712.02118

CMS ($101fb^{-1}$), 2004.05153

Coscattering and disappearing tracks





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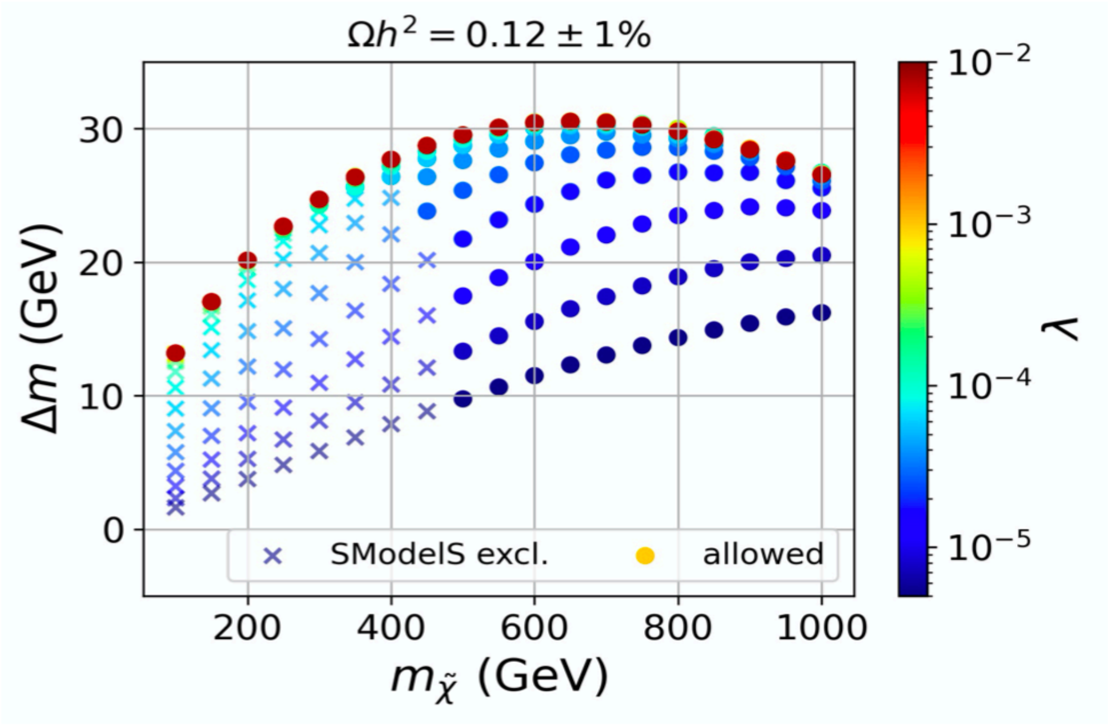
Typical mass splitting



- Singlet –triplet mass splitting : when λ is large (10^{-3}-10^{-2}) coannihilation dominates, Δm ~10-30 GeV (or 13%-3%), smaller mass splitting leads to underabundant DM unless coscattering is included
- When coscattering dominates ($\lambda<10^{-4}$) mass splitting can be much smaller
- -> at LHC important to cover the region at very small mass splitting

Remarks

- Departure from equilibrium for very small couplings – loose accuracy using momentum integrated Boltzmann equation
- For very small couplings, early kinetic decoupling, to include these effects must solve full momentum dependent Boltzmann equations

$$\left(\frac{\partial}{\partial t} - H\mathbf{p}\cdot\nabla_{\mathbf{p}}\right) f_\chi(p,t) = \frac{1}{E}C[f_\chi],$$

- C(f) is collision operator for χ X-> ψ X'

$$\frac{1}{E_\chi}C[f_\chi] = \sum_{\psi,X,X'} \left(f_\chi^{\rm eq}\frac{n_\psi}{n_\psi^{\rm eq}} - f_\chi\right)\frac{1}{2E_\chi}\int \widetilde{{\rm d}p}_X \widetilde{{\rm d}p}_{X'} \widetilde{{\rm d}p}_\psi\, \delta^{(4)}\left(\sum p_i\right) |\overline{M}|^2\, f_X^{\rm eq}$$

- In the singlet-triplet model, F. Brummer arXiv:1910.01549

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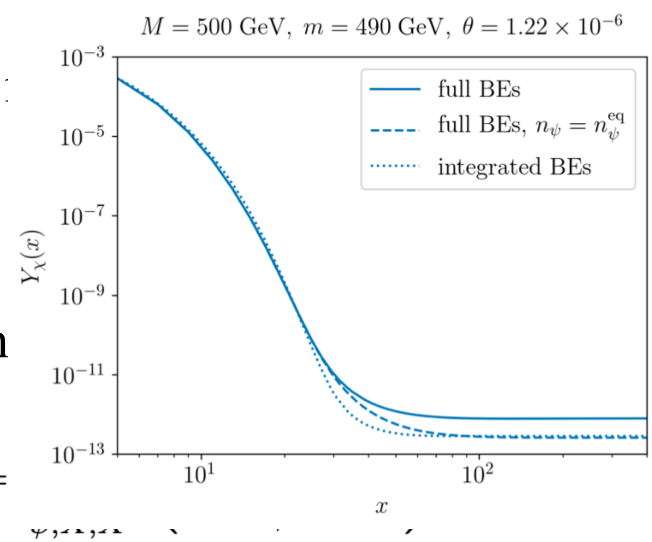

],

- C(f) is collision

$$\frac{1}{E_\chi} C[f_\chi] = \quad \widetilde{p}_{X'} \widetilde{dp}_\psi \; \delta^{(4)} \left(\sum p_i\right) |\overline{M}|^2 \; f_X^{eq}$$

- In the singlet-triplet model, F. Brummer arXiv:1910.01549
- For small couplings correction can be 100%

Conclusion

- Co-scattering can drive DM formation when DM is very weakly coupled to the SM and there exist other dark states with small mass splitting with DM
- General solution of relic abundance implemented in micrOMEGAs assuming kinetic equilibrium
- To probe coscattering mechanism at colliders important to cover the region with very small mass splitting - in conventional coannihilation this region corresponds to underabundant DM.
- Under investigation : full solution to Boltzmann equation (GB, Chakraborti, Hryczuk et al)