Impact of Sommerfeld Effect and Bound State Formation in Simplified t-Channel Dark Matter Models

in collaboration with

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Simplified t-Channel Dark Matter

Universal framework for t-channel DM models [Arina,Fuks,Mantani (2020)]

S3M-uR t-channel Dark Matter

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin,BSM}} + g_{\text{DM}}\overline{\chi}(u_R)_i(X^\dagger)_i + h.c.$$

$$\chi = (\mathbf{1},\mathbf{1})_0 \qquad X_i = (\mathbf{3},\mathbf{1})_{2/3}$$

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- Discrete $\mathcal{Z}_2$: SM fields even, dark sector fields odd
- 3 generation of mediator fields that couple democratically diagonally to the SM quarks
- Parameters: $(m_\chi = m_{\text{DM}}, \Delta m = m_X - m_{\text{DM}}, g_{\text{DM}})$

Dark Matter Freeze-Out

Assumptions during DM freeze-out:

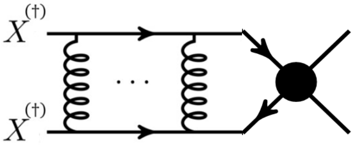
- Dark sector in *kinetic* eq. with the SM.
- Dark sector particles in *chemical* eq. with themselves.

Coannihilation

$$\frac{dn}{dt} + 3Hn = -\langle \sigma_{\text{eff}} v \rangle \left(n^2 - \left(n^{\text{eq}}\right)^2 \right)$$

$$\langle \sigma_{\text{eff}} v \rangle = \sum_{i,j} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{\text{eq}}}{n^{\text{eq}}} \frac{n_j^{\text{eq}}}{n^{\text{eq}}}$$

$n = \sum_i n_i$ and $i,j = \{\chi, X_1, X_2, X_3\}$ and $\Omega_{\text{DM}} \sim \langle \sigma_{\text{eff}} v \rangle^{-1}$

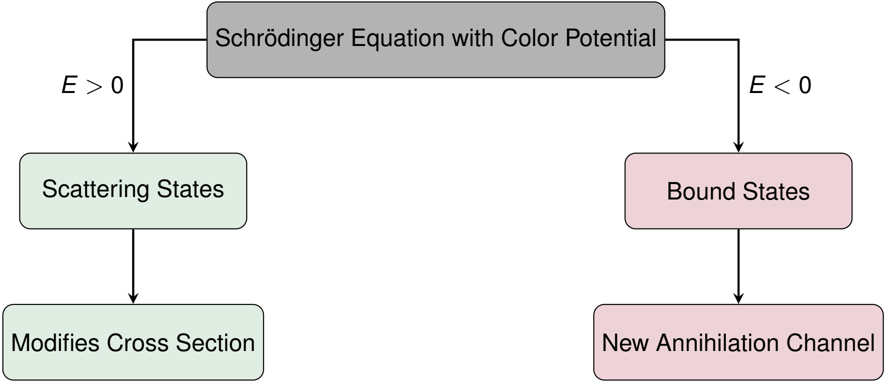


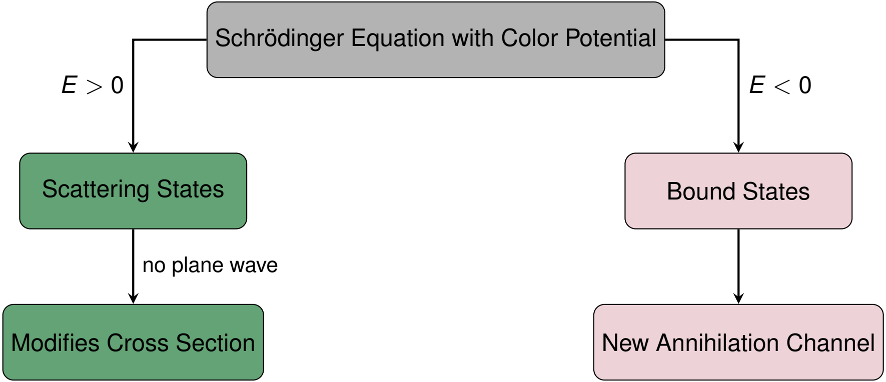
n-gluon exchanges contribute with $\left(\frac{\alpha}{v}\right)^n$ for $\alpha \sim v$

$\rightarrow$ Resummation required since $\alpha \sim v$

$\rightarrow$ Reduces to Schrödinger Equation for $v \ll 1$. For details [Petraki,Postma,Wiechers(2015)]

Figure from Talk by J.Harz @ DM Working Group


Schrödinger Equation with Color Potential
$E > 0$
$E < 0$
Scattering States
Bound States
Modifies Cross Section
New Annihilation Channel


Schrödinger Equation with Color Potential
$E > 0$
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Scattering States
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no plane wave
Modifies Cross Section
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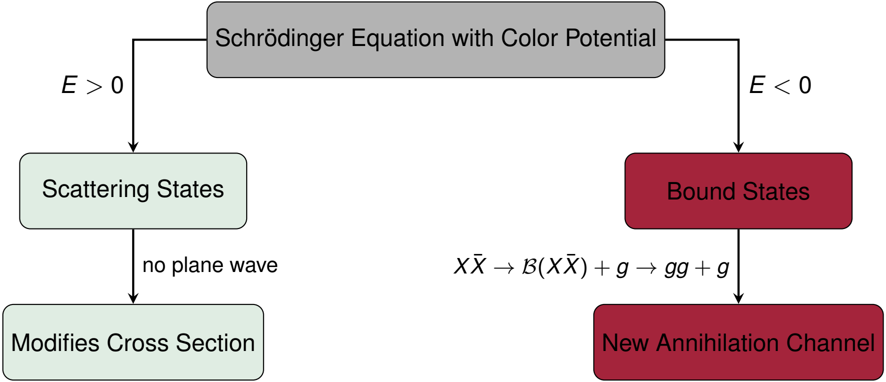
Schrödinger Equation with Color Potential
$E > 0$
$E < 0$
Scattering States
Bound States
no plane wave
$X\bar{X} \to \mathcal{B}(X\bar{X}) + g \to gg + g$
Modifies Cross Section
New Annihilation Channel

SE vs BSF

Modified Coannihilation [Ellis,Luo,Olive(2015)]

$$\langle \sigma_{\rm eff} v \rangle = \sum_{i,j \in \{\chi, X\}} \langle S\left(\alpha / v_{ij}\right) \cdot \sigma_{ij} v_{ij} \rangle \frac{n_i^{\rm eq}}{n^{\rm eq}} \frac{n_j^{\rm eq}}{n^{\rm eq}} + \langle \sigma_{\rm BSF} v \rangle_{\rm eff} \left(\frac{n_X^{\rm eq}}{n^{\rm eq}} \right)^2$$

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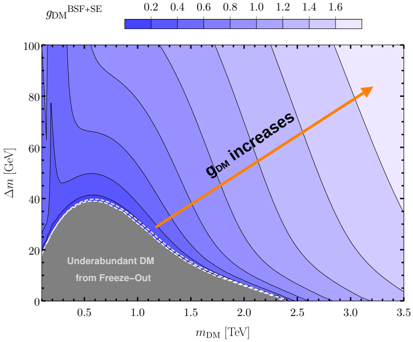
$\langle \sigma_{\text{eff}} v \rangle$	Sommerfeld Effect	Bound State Formation
$g_{\text{DM}} \gg g_s$	$-$	0
$g_{\text{DM}} \ll g_s$	$+$	$++$

Determine $g_{DM,0}$ for each data point $(m_{DM}, \Delta m)$ such that DM is *not* overproduced.



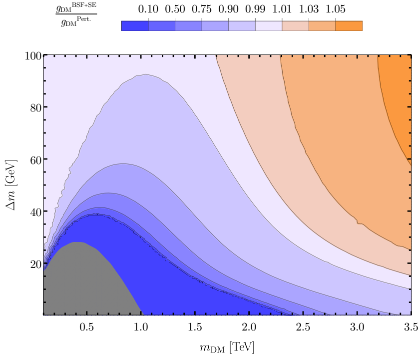
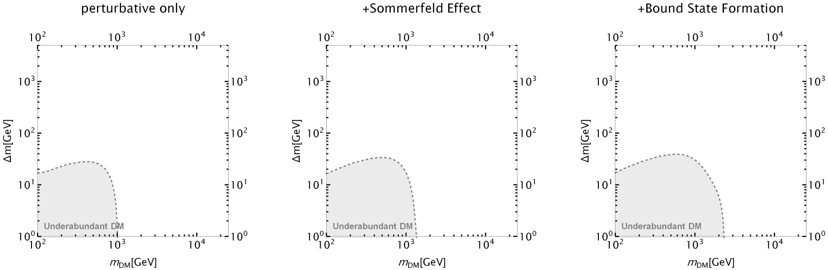


Figure from [MB,Copello,Harz,Mohan,Sengupta(2022)]



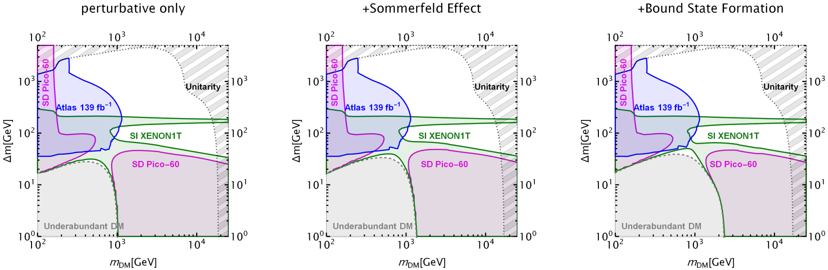
→ Bound State Formation increases the area where the strong interaction deplete relic density significantly!

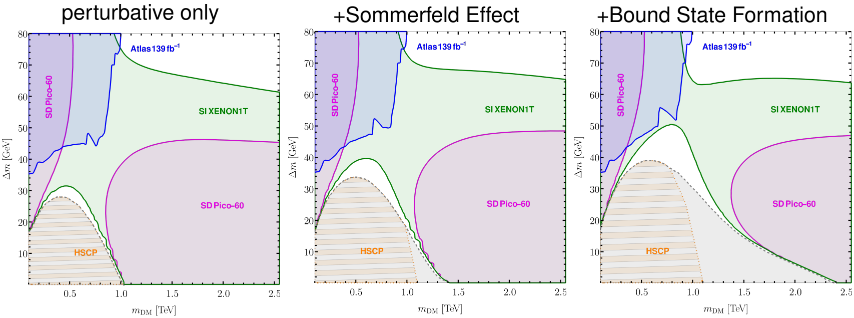
Experimental Constraints

RGE improved Direct Detection [Mohan et. al (2019)]

mono-jet + ETmiss search by ATLAS [arXiv:1711.03301]

multi-jets + ETmiss search by CMS [arXiv:1704.07781]





$(m_{\mathrm{DM}}, \Delta m) < (1\,TeV, 30\,GeV)$ to $(1.4\,TeV, 40\,GeV)$ (Sommerfeld Effect) and $(2.4\,TeV, 50\,GeV)$ (Bound State Formation)

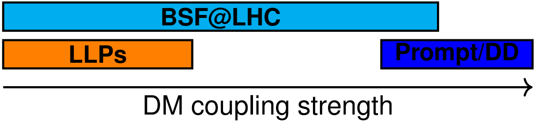
Bound State Formation at the LHC

Production Cross Section

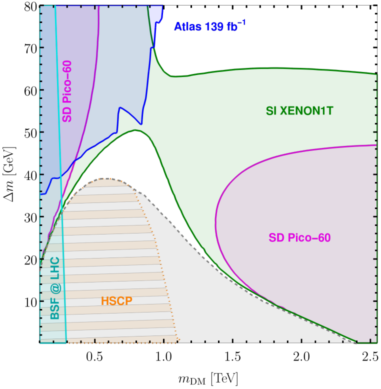
$$\sigma\left(pp \to \mathcal{B}(XX^\dagger)\right) = \frac{\pi^2}{8m_\mathcal{B}^3}\Gamma\left(\mathcal{B}(XX^\dagger) \to gg\right)\mathcal{P}_{gg}\left(\frac{m_\mathcal{B}}{13\ \text{TeV}}\right)$$

$\to$ try to observe the bound state resonance in $\gamma\gamma$ final state. ATLAS (2017)

Efficient for all g_DM small enough such that $\Gamma_X < E_B$, roughly speaking $g_\text{DM} \lesssim g_s$.

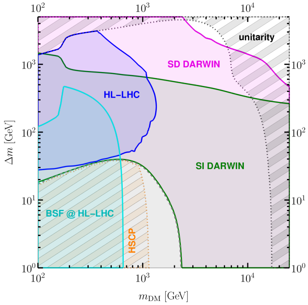


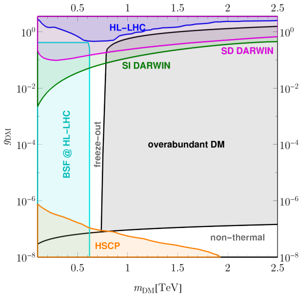
Sommerfeld Effect + Bound State Formation



Limits at 37 fb^{-1} relatively weak in mass ($\sim$ 300 GeV)
But huge potential: Closes the gap between prompt and LLP searches

Projected Experimental Limits (SE+BSF)





Note: We fix $\Delta m = 0.05 m_{\rm DM}$ here!

- Remember: HSCP not a strict exclusion here (BSF@LHC is!)

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Conclusion

- Non-perturbative Effects can increase or decrease the annihilation cross section of DM
  $\rightarrow$ Cannot be handled by a flat correction factor!
- Non-perturbative Effects are non-neglible in scenarios of colored coannihilation and open up small mass parameter space:

  Viable Parameter space shifts from $(m_{\mathrm{DM}}, \Delta m) < (1\,TeV, 30\,GeV)$ to $(1.4\,TeV, 40\,GeV)$ (Sommerfeld Effect) and $(2.4\,TeV, 50\,GeV)$ (Bound State Formation)
  $\rightarrow$ Sommerfeld Effect alone not a good approximation!
- Bound State searches at colliders close the gap in "coupling space" between prompt and long-lived-particle searches

Sommerfeld Effect

Sommerfeld Effect on the Annihilation Cross Section

$$\langle \sigma_{\text{eff}} v \rangle = \sum_{i,j \in \{\chi, X\}} \langle S(\alpha / v_{ij}) \cdot \sigma_{ij} v_{ij} \rangle \frac{n_i^{\text{eq}}}{n^{\text{eq}}} \frac{n_j^{\text{eq}}}{n^{\text{eq}}}$$

Sommerfeld Factor

$$S(\alpha / v_{ij}) = \begin{cases} \geq 1 & \text{, if } \alpha_{\text{eff}} > 0 \text{(attractive)}, \\ \leq 1 & \text{, if } \alpha_{\text{eff}} < 0 \text{(repulsive)} \end{cases}$$

- Has an effect independently of the hierarchy between g_{DM} and g_s
- Tends to lower $\langle \sigma_{\text{eff}} v \rangle$ for $g_{\text{DM}} > g_s$
- Tends to increase $\langle \sigma_{\text{eff}} v \rangle$ for $g_{\text{DM}} < g_s$

Bound State Formation (BSF)

Modified Coannihilation [Ellis,Luo,Olive(2015)]

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Bound states effectively provide an additional annihilation channel.

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Bound states effectively provide an additional annihilation channel.

$\rightarrow$ BSF always increases annihilation cross section

$\rightarrow$ Purely mediated by g_s, thus less important for $g_{\rm DM} \gg g_s$