Importance of Non-Perturbative Effects for the Exclusion or Discovery of Dark Matter Models

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in collaboration with

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Technische Universität München

Emmy Noether-Programm

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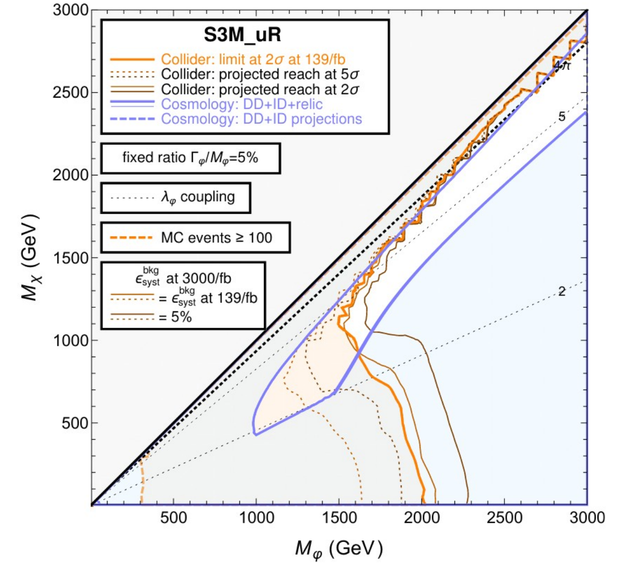
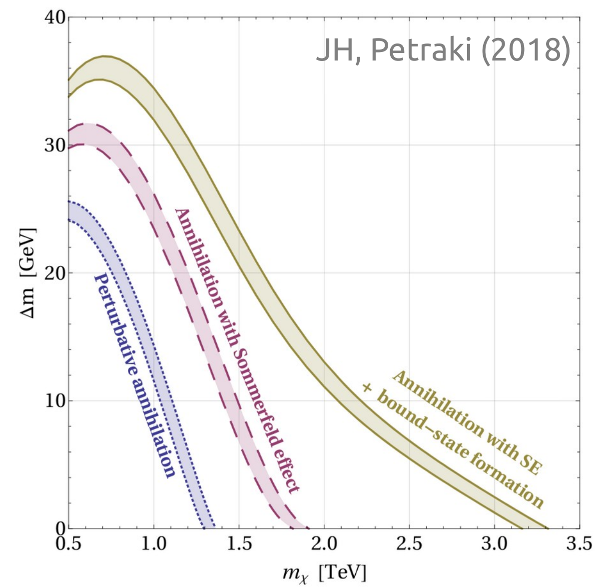
Motivation

- No discovery of a WIMP so far
- Possible reason: realisation of a more complex DM sector
- Recently common effort on t-channel DM models
  → see e.g. recent focus of LHC DM working group
- Known: these type of scenarios are subject to non-perturbative effects, such as the Sommerfeld effect and bound state formation

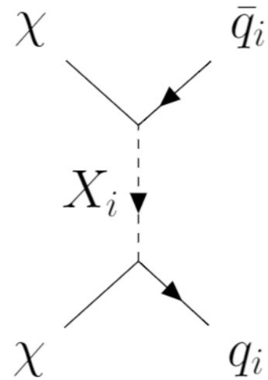
→ How do these effects impact our understanding of the favoured or excluded parameter space?

Arina, Fuks, Mantani, Mies, Panizzi, Salko (2020)





Simplified t-channel dark matter model



Universal framework for t-channel DM model Arina, Fuks, Mantani (2020)

$$\mathcal{L} \supset \sum_i (D_\mu X_i)^\dagger (D^\mu X_i) + g_{\mathrm{DM},ij} X_i^\dagger \bar{\chi} P_R q_j + g^*_{\mathrm{DM},ij} X_i \bar{q}_j P_L \chi$$

	$SU(3)_c \times SU(2)_L \times U(1)_Y$	
χ	$(1, 1, 0)$	
X	$(3, 1, +2/3)$	u_R
	$(3, 1, -1/3)$	d_R
	$(3, 1, -1/6)$	q_L

Assumptions:

- dark sector odd under Z_2 symmetry
- χ: Majorana singlet and lightest dark particle → dark matter candidate
- X_i: scalar particle with 3 generations with same mass m_X
- g_{DM}: diagonal, democratic coupling

Relevant parameters:

g_{DM}

$m_\chi = m_{\mathrm{DM}}$

$\Delta = m_X - m_{\mathrm{DM}}$

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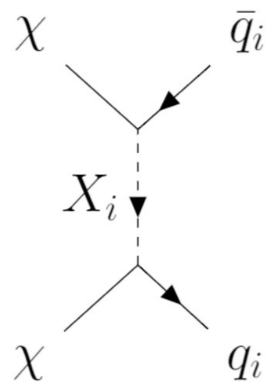

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Relevant parameters:

g_{DM}

$m_\chi = m_{\mathrm{DM}}$

$\Delta = m_X - m_{\mathrm{DM}}$

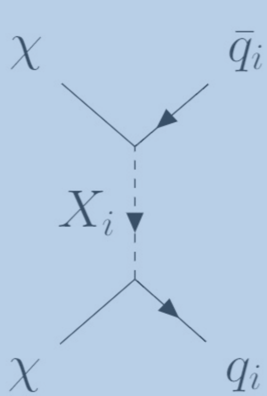
Contributing processes to the relic abundance

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

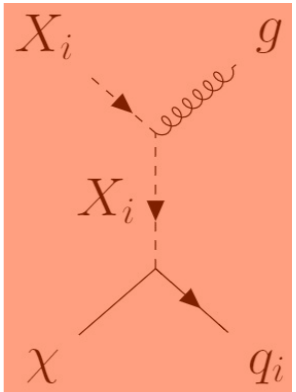
$$\langle \sigma_{\rm eff} v_{\rm rel} \rangle = \sum_{ij} \langle \sigma_{ij} v_{ij} \rangle \frac{n_{{\rm eq},i}}{n_{\rm eq}} \frac{n_{{\rm eq},j}}{n_{\rm eq}}$$

Assumptions:

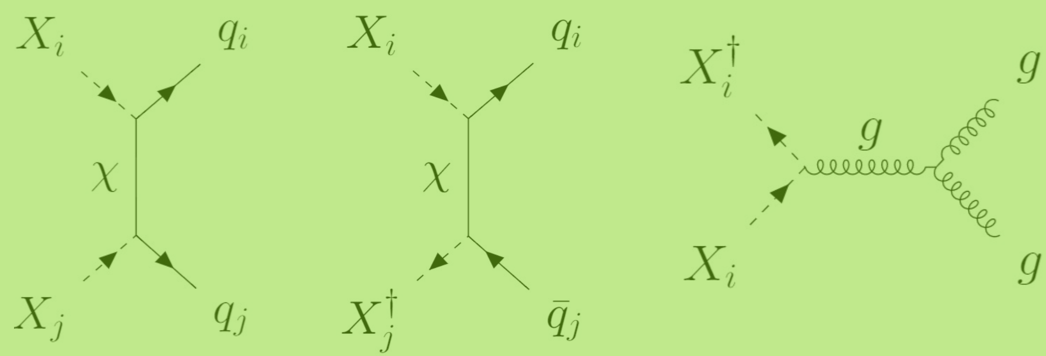
- Coannihilating particle will later decay into DM $n = \sum_{i=1}^{N} n_i$
- Coannihilating particle in thermal equilibrium with DM particle $\Gamma(X + SM \longleftrightarrow \chi + SM) >> H$



$g_{\rm DM}^4$



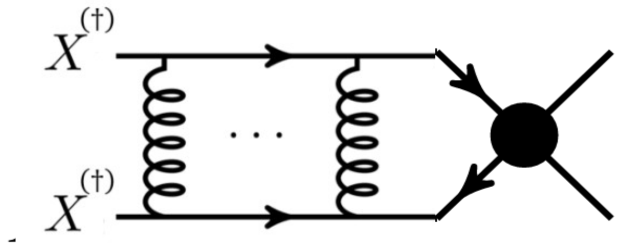
$g_{\rm DM}^2 g_{\rm s}^2 e^{-x\delta}$



$g_{\rm DM}^4 e^{-2x\delta}$ $(\alpha g_{\rm DM}^2 + \beta g_s^2)^2 e^{-2x\delta}$ $g_s^4 e^{-2x\delta}$

Δm $\delta = \frac{\Delta}{m_{\rm DM}}$

Sommerfeld effect



$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$$

$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \mathbf{6}$$

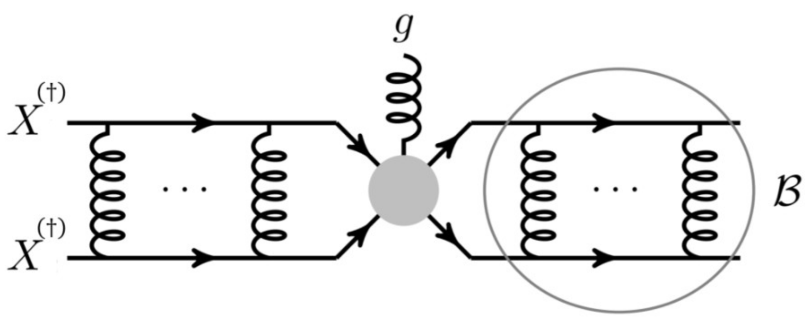
- Relevant for $\alpha \sim v_{\mathrm{rel}}$
- Exchange of n gluons lead to $\left(\frac{\alpha}{v_{\mathrm{rel}}}\right)^n \sim 1$, which requires resummation

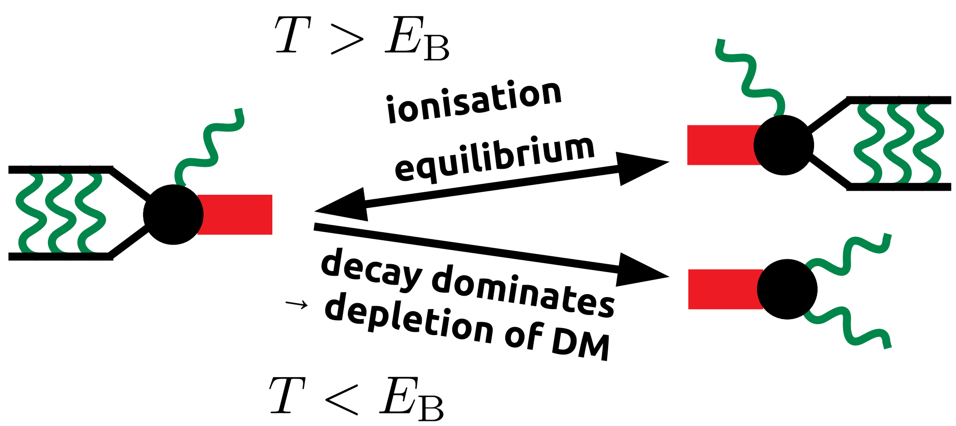
$$\left[-\frac{\nabla^2}{2\mu} + V^{\mathrm{S}}_{[\hat{\mathbf{R}}]}(\mathbf{r})\right] \phi_{\mathbf{k}}(\mathbf{r}) = \mathcal{E}_{\mathbf{k}}\, \phi_{\mathbf{k}}(\mathbf{r}) \qquad V(r)_{\mathbf{3}\otimes\bar{\mathbf{3}}} = \begin{cases} -\frac{4}{3}\frac{\alpha_s^S}{r} & [\mathbf{1}] \quad \textbf{attractive} \\ +\frac{1}{6}\frac{\alpha_s^S}{r} & [\mathbf{8}] \quad \textbf{repulsive} \end{cases}$$

$$\sigma_{\mathrm{SE}} = S_0\left(\frac{\alpha_s^S C_{[\hat{\mathbf{R}}]}}{v_{\mathrm{rel}}}\right)\sigma_0$$

→ increase or decrease of cross section

Bound state formation and decay





$(X + X^\dagger)_{[\mathbf{8}]} \to \mathcal{B}(XX^\dagger)_{[\mathbf{1}]} + g_{[\mathbf{8}]}$ **bound state formation**

$(\mathrm{XX}^\dagger)_{[\mathbf{1}]} + g_{[\mathbf{8}]} \to (X + X^\dagger)_{[\mathbf{8}]}$ **bound state ionisation**

$\mathcal{B}(XX^\dagger)_{[\mathbf{1}]} \to g_{[\mathbf{8}]}\ g_{[\mathbf{8}]}$ **bound state decay**

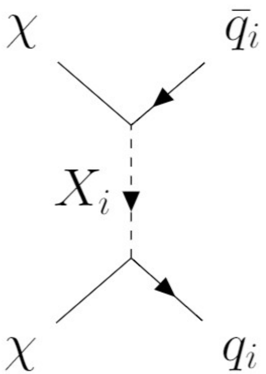
$$\langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle_{\mathrm{eff}} = \langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle \times \left(\frac{\Gamma_{\mathrm{dec}}}{\Gamma_{\mathrm{dec}} + \Gamma_{\mathrm{ion}}} \right)$$

→ **additional "annihilation" channel**

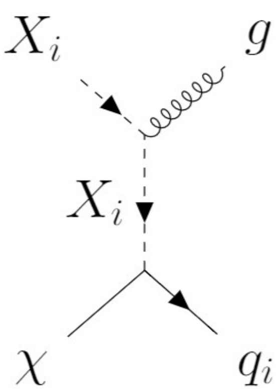
Complete Boltzmann equation

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

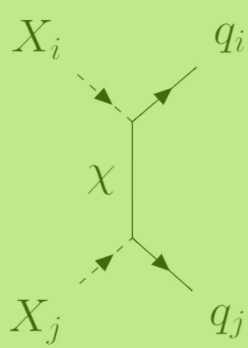
$$\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle = \sum_{ij} \langle S\left(\frac{\alpha}{v_{ij}}\right) \cdot \sigma_{ij} v_{ij} \rangle \frac{n_{\text{eq},i}}{n_{\text{eq}}} \frac{n_{\text{eq},j}}{n_{\text{eq}}} + \langle \sigma_{\text{BSF}} v_{\text{rel}} \rangle_{\text{eff}} \left(\frac{n_{\text{eq},X}}{n_{\text{eq}}}\right)^2$$



g_{DM}^4

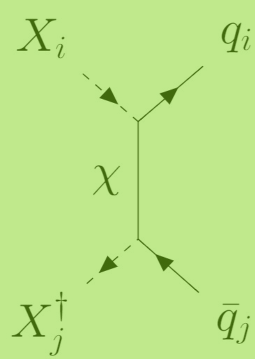


$g_{\text{DM}}^2 g_{\text{s}}^2 e^{-x\delta}$



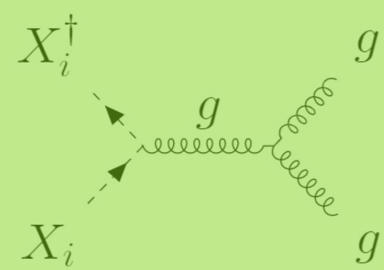
$g_{\text{DM}}^4 e^{-2x\delta}$

$\frac{1}{3}[\bar{\mathbf{3}}] + \frac{2}{3}[\mathbf{6}]$



$(\alpha g_{\text{DM}}^2 + \beta g_s^2)^2 e^{-2x\delta}$

$f_1\,(g_{\text{DM}}, g_s)\,[\mathbf{1}]$
$+ f_8\,(g_{\text{DM}}, g_s)\,[\mathbf{8}]$



$g_s^4 e^{-2x\delta}$

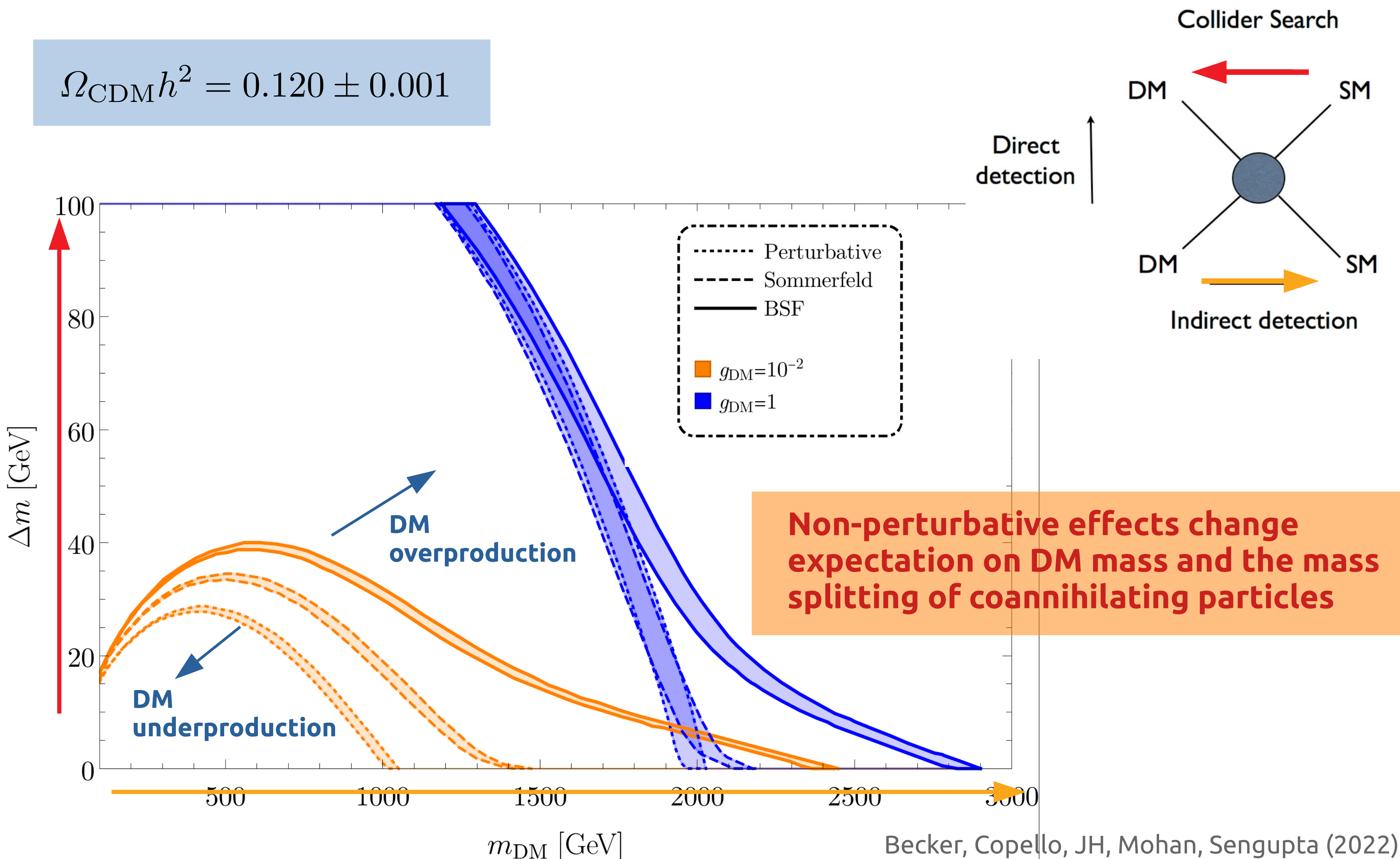
$\frac{2}{7}[\mathbf{1}] + \frac{5}{7}[\mathbf{8}]$

Δm

no BSF / SE **no BSF / SE** **BSF / SE**

Impact of non-perturbative effects on mass plane

$$\Omega_{\mathrm{CDM}} h^2 = 0.120 \pm 0.001$$

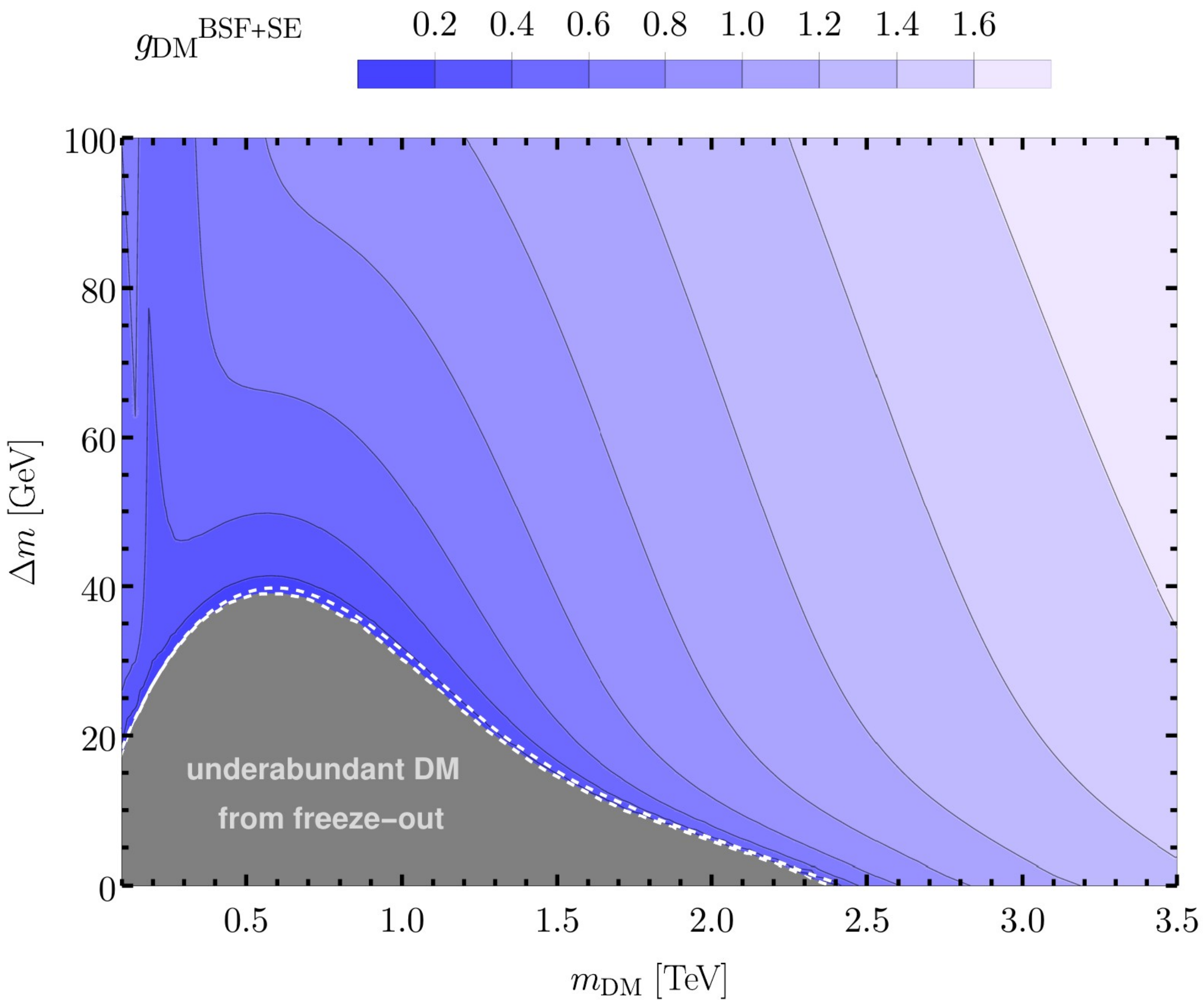


Non-perturbative effects change expectation on DM mass and the mass splitting of coannihilating particles

Becker, Copello, JH, Mohan, Sengupta (2022)

Impact on minimal dark matter coupling strength

Identify lower bound on g_{DM} in order not to overproduce DM



$X_i X_j^\dagger \to gg$	$g_s^4 e^{-2x\delta}$	$\lvert\mathcal{M}\rvert^2 \sim \frac{2}{7}[\mathbf{1}] + \frac{5}{7}[\mathbf{8}]$
$X_i X_j \to q_i q_j$	$g_{\rm DM}^4 e^{-2x\delta}$	$\lvert\mathcal{M}\rvert^2 \sim \frac{1}{3}[\bar{\mathbf{3}}] + \frac{2}{3}[\mathbf{6}]$
$X_i X_i \to q_i q_i$	$g_{\rm DM}^4 e^{-2x\delta}$	$\lvert\mathcal{M}\rvert^2 \sim [\mathbf{6}]$
$X_i X_j^\dagger \to q_i \bar{q}_j$	$(\alpha g_{\rm DM}^2 + \beta g_s^2)^2 e^{-2x\delta}$	$\lvert\mathcal{M}\rvert^2 \sim f_1(g_{\rm DM}, g_s)[\mathbf{1}]$ $+ f_8(g_{\rm DM}, g_s)[\mathbf{8}]$

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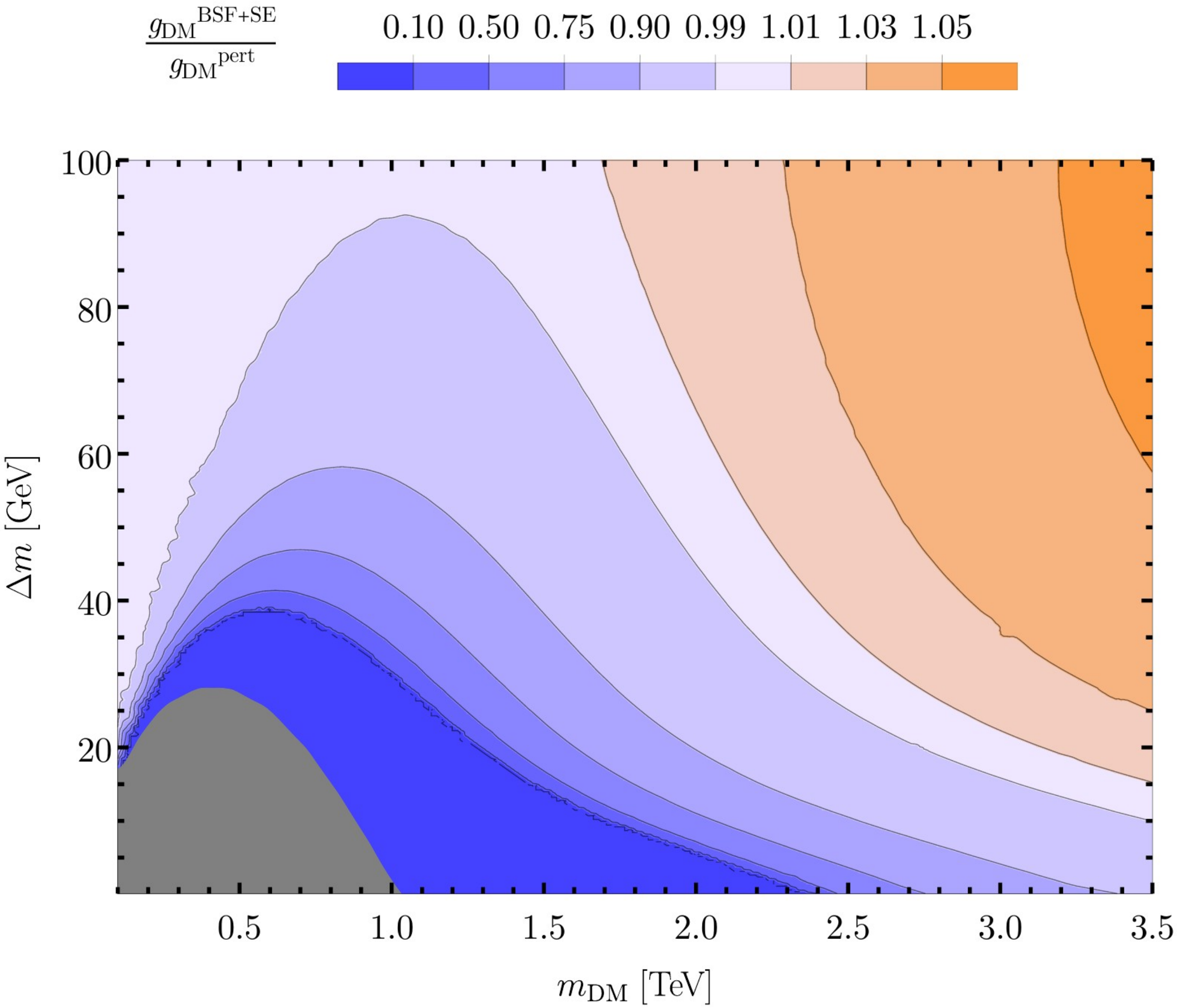

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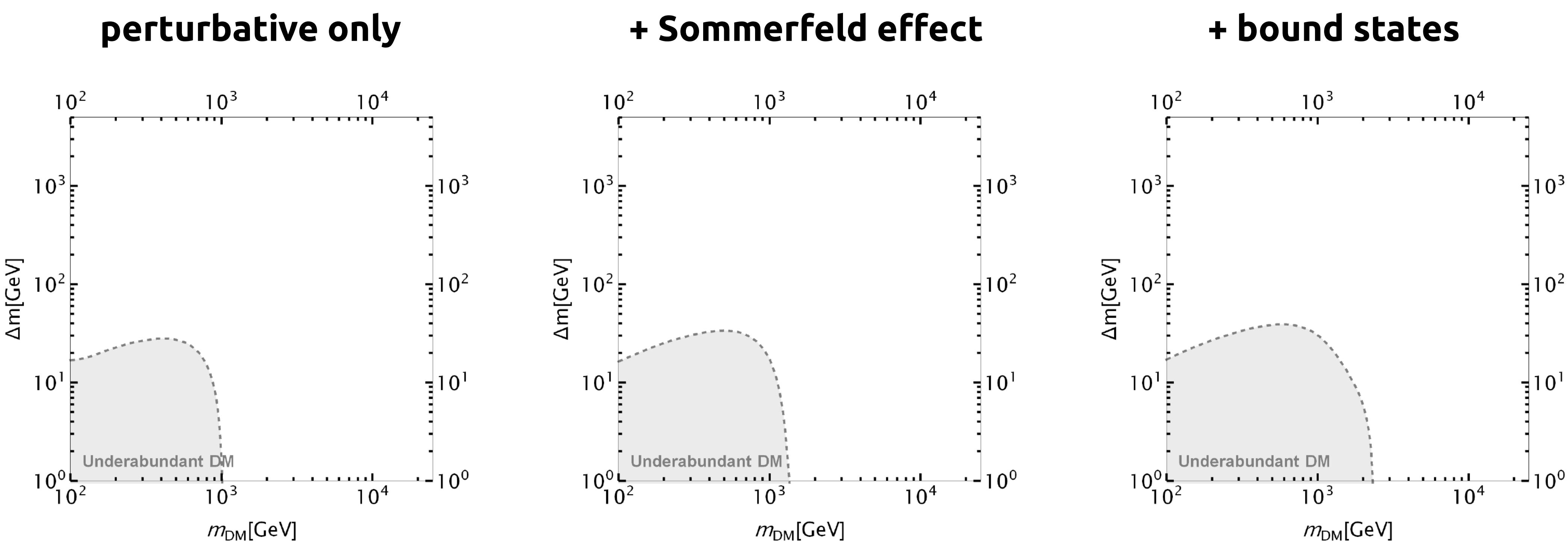
- **Non-perturbative effects result in corrections on minimal g_{DM}**
- **Depending on parameter space: positive or negative correction**

Becker, Copello, JH, Mohan, Sengupta (2022)

Impact on parameter space of t-channel model

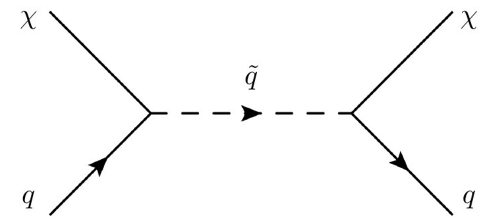


→ **Non-perturbative effects increase region of parameter space that lead to underabundant dark matter**

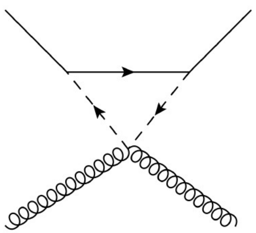
Becker, Copello, JH, Mohan, Sengupta (2022)

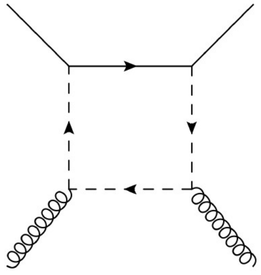
Constraints from LHC and direct detection

- **Spin dependent (SD) direct detection (DD)**
  - at tree-level due to Majorana nature
  - Most stringent constraints from PICO-60

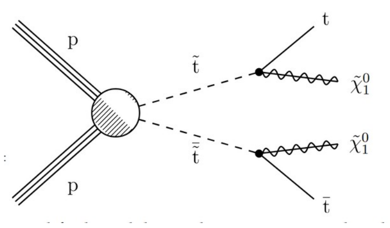


- **Spin independent (SI) direct detection (DD)**
  - only at one-level
  - Most stringent limits from Xenon1T

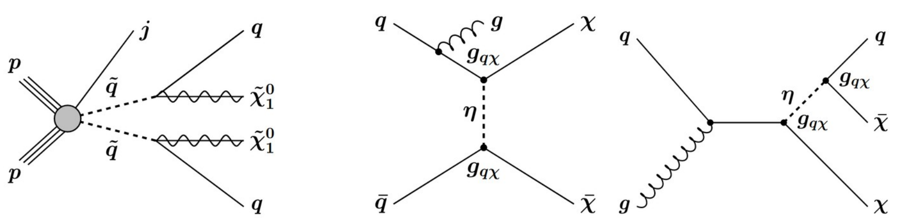




- **mono-jet + ETmiss search by ATLAS** [arXiv:1711.03301]



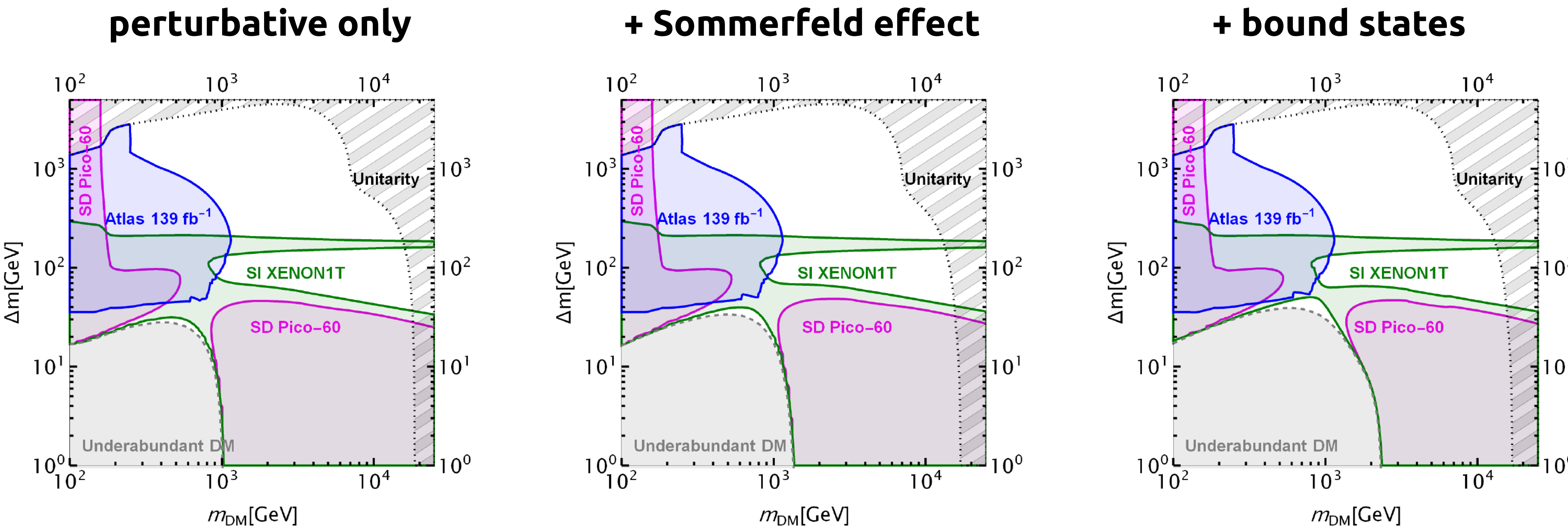
- **multi-jets + ETmiss search by CMS** [arXiv:1704.07781]



→ **constraints set upper limit on g_{DM}**

Becker, Copello, JH, Mohan, Sengupta (2022)

Constraints from LHC and direct detection

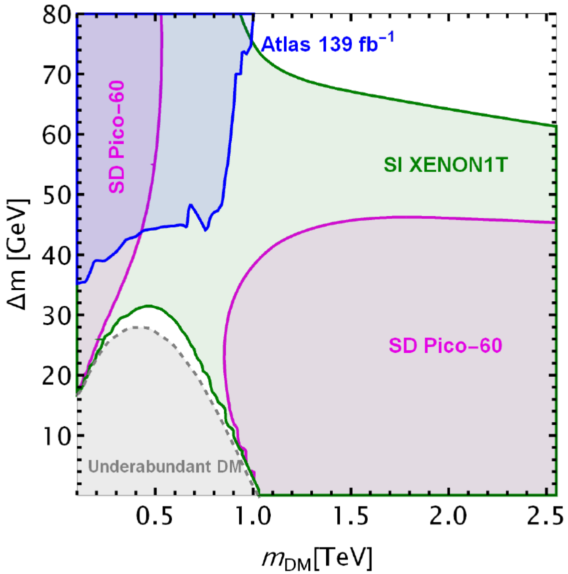


- DD and LHC searches set upper bound on g_{DM}
- Requirement of non-overproduction sets lower bound on g_{DM}

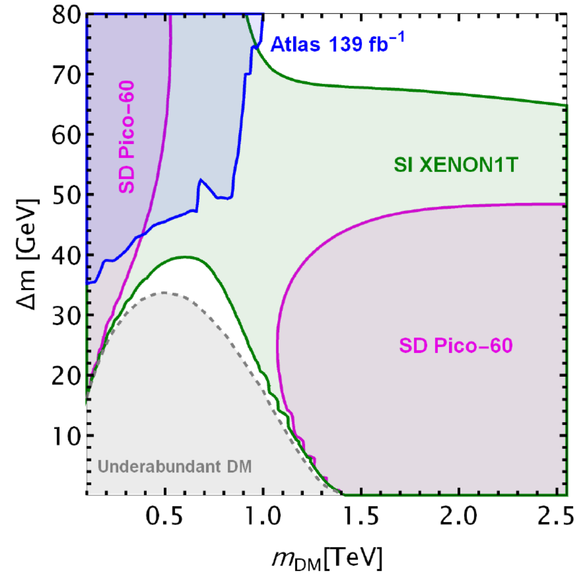
Becker, Copello, JH, Mohan, Sengupta (2022)

Impact of SE and BSF on exclusion limits

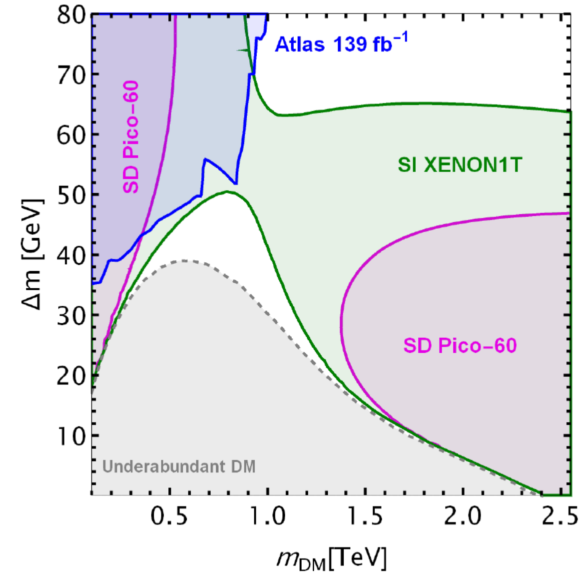
perturbative only



+ Sommerfeld effect



+ bound states



- DD and LHC searches set upper bound on g_{DM}
- Requirement of non-overproduction sets lower bound on g_{DM}

→ Correction on g_{DM} due to SE and BSF lead to altered exclusion limits

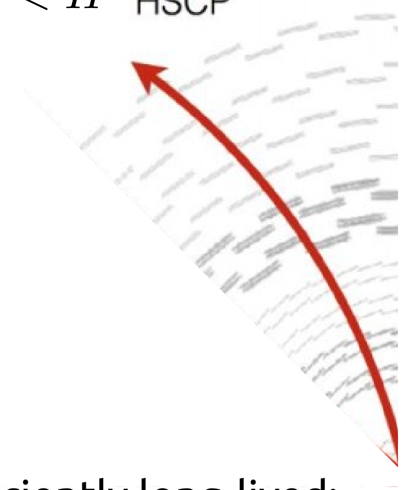
→ opens up parameter space that was previously thought to be excluded

Becker, Copello, JH, Mohan, Sengupta (2022)

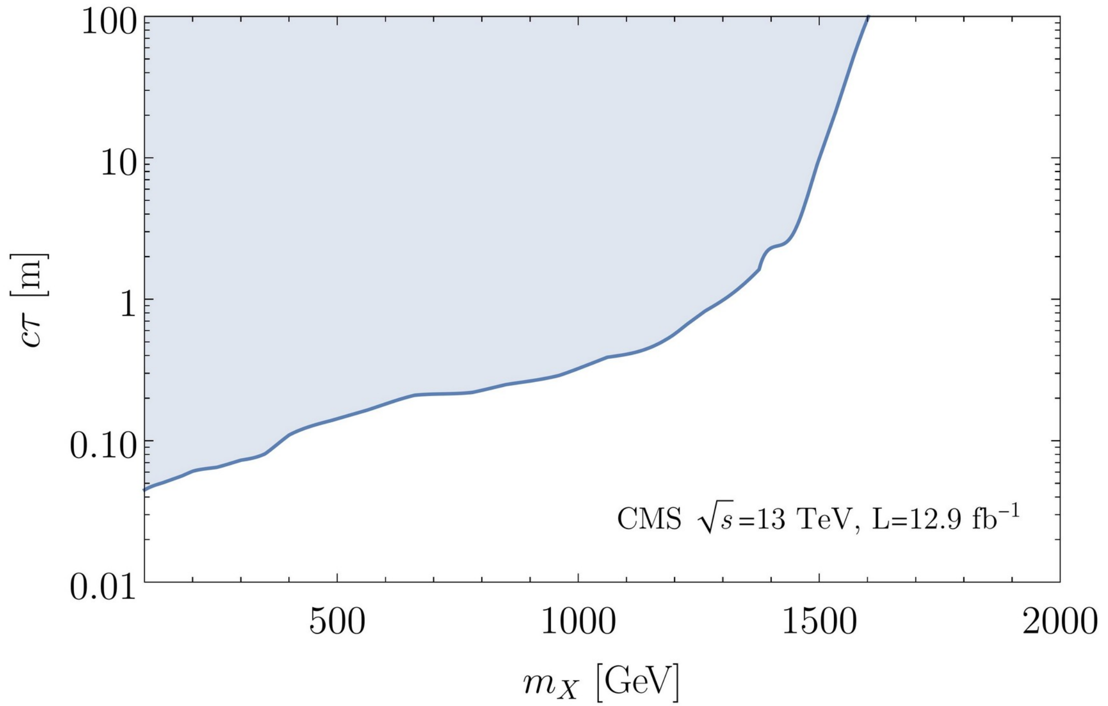
Interplay with long-lived particle searches

Could e.g. a freeze-in mechanism account for the missing dark matter?

→ Identify $g_{\rm DM} < \tilde{g}_{\rm DM}$ below which dark sector is out-of-equilibrium $\Gamma_X \frac{Y_X^{\rm eq}}{Y_\chi^{\rm eq}} < H$



First check: is this parameter space by long-lived parameter space already excluded?



- Colored mediator sufficiently long-lived: Heavy Stable Charged Particle (HSPC)
- 13 TeV CMS analysis 12.9 fb^{-1} [*CMS-PAS-EXO-16-036 (2016)*]

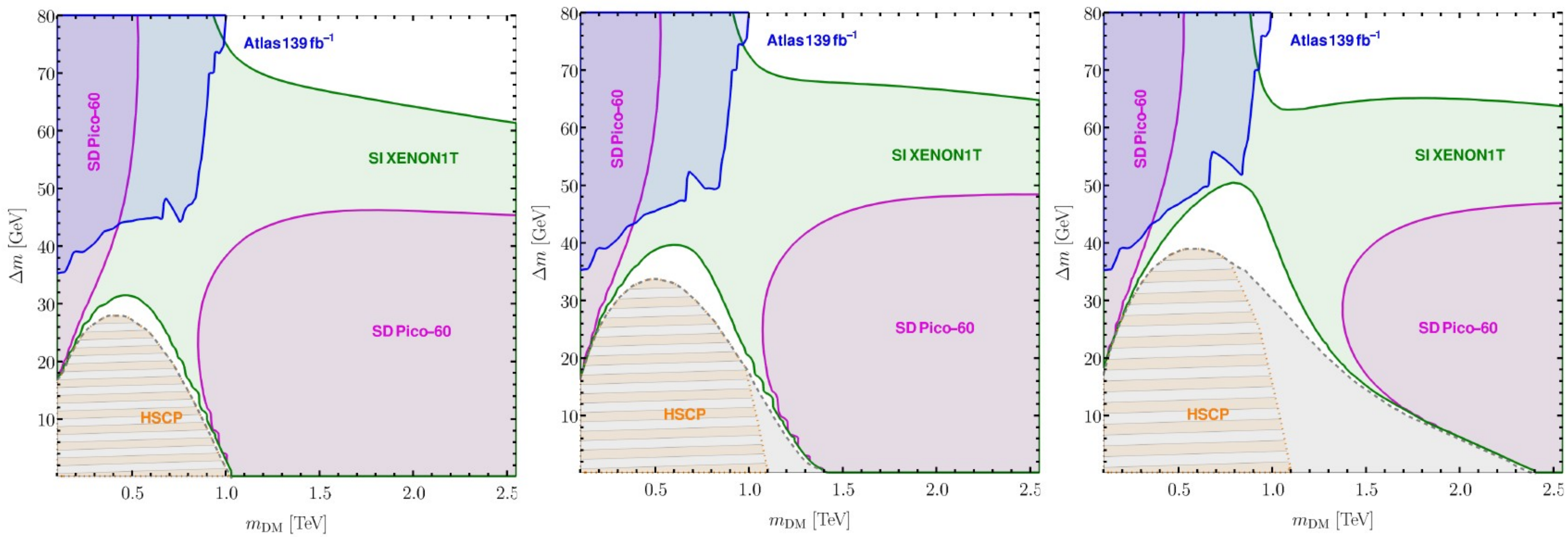
→ **LLP searches result in lower limit $g_{\rm DM}^{\rm LLP} < g_{\rm DM}$ and hence a constraint on the non-equilibrium parameter range**

Becker, Copello, JH, Mohan, Sengupta (2022)

Interplay with long-lived particle searches

Could e.g. a freeze-in mechanism account for the missing dark matter?

perturbative only | **+ Sommerfeld effect** | **+ bound states**



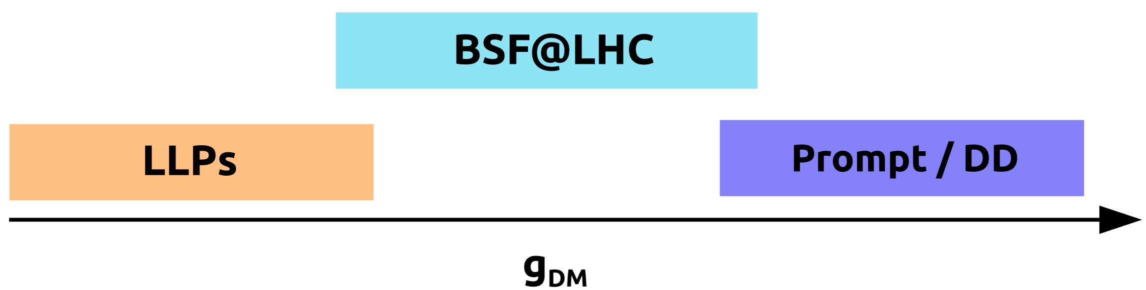
→ **LLP searches efficiently constrain parameter space for dark matter production mechanisms such as freeze-in**

Becker, Copello, JH, Mohan, Sengupta (2022)

Potential of bound state formation at colliders

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

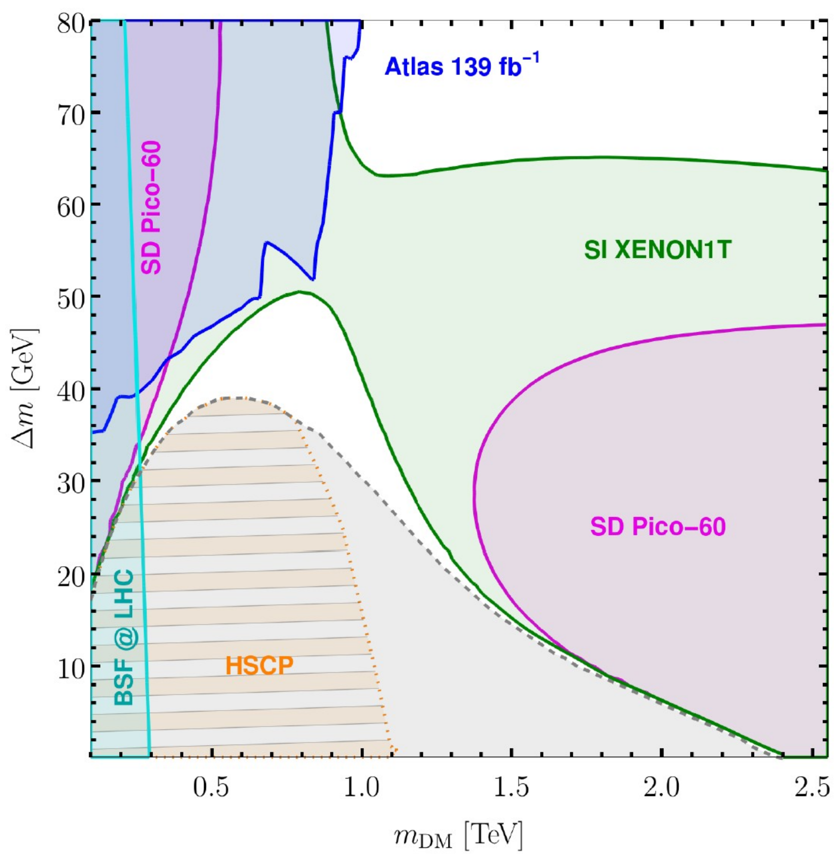
- Resonant production of bound state and subsequent decay (e.g. into photons)
- Dedicated searches, see e.g. *ATLAS coll. Phys. Lett. B 775 (2017) 105*
- Efficient for large range of g_{DM}, as long as $\Gamma_X < E_B$ ($g_{DM} < g_s$, when bound states are efficiently produced



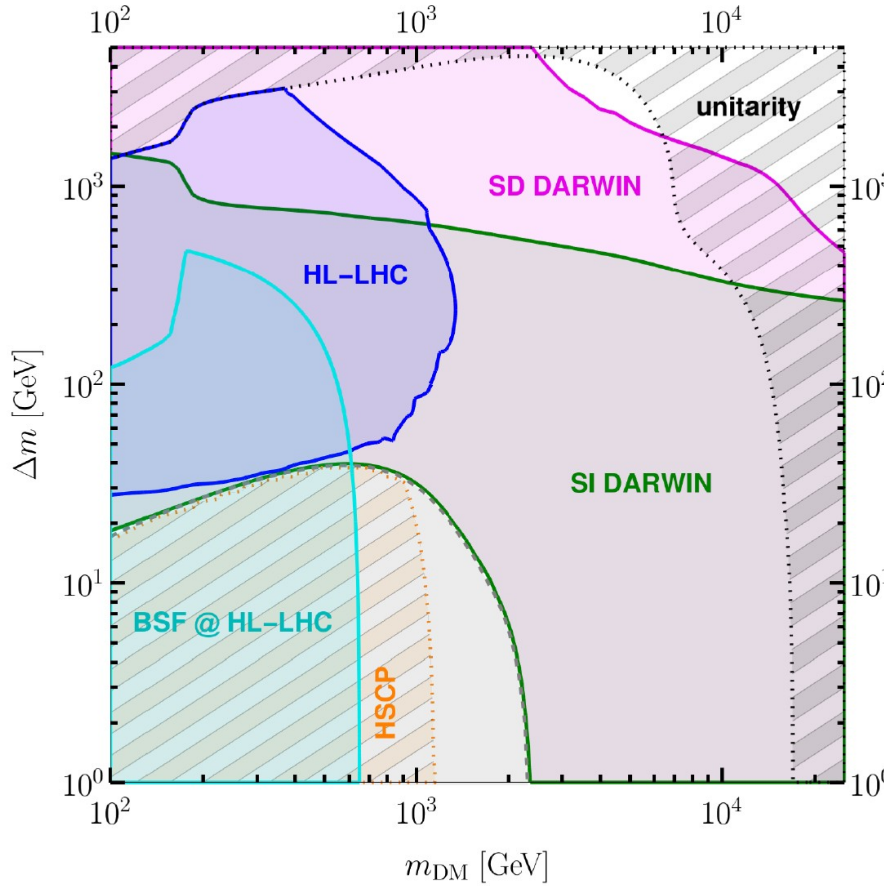
Becker, Copello, JH, Mohan, Sengupta (2022)

Potential of bound state formation at colliders

current limits



future limits



→ **limits relatively weak (300 GeV)**

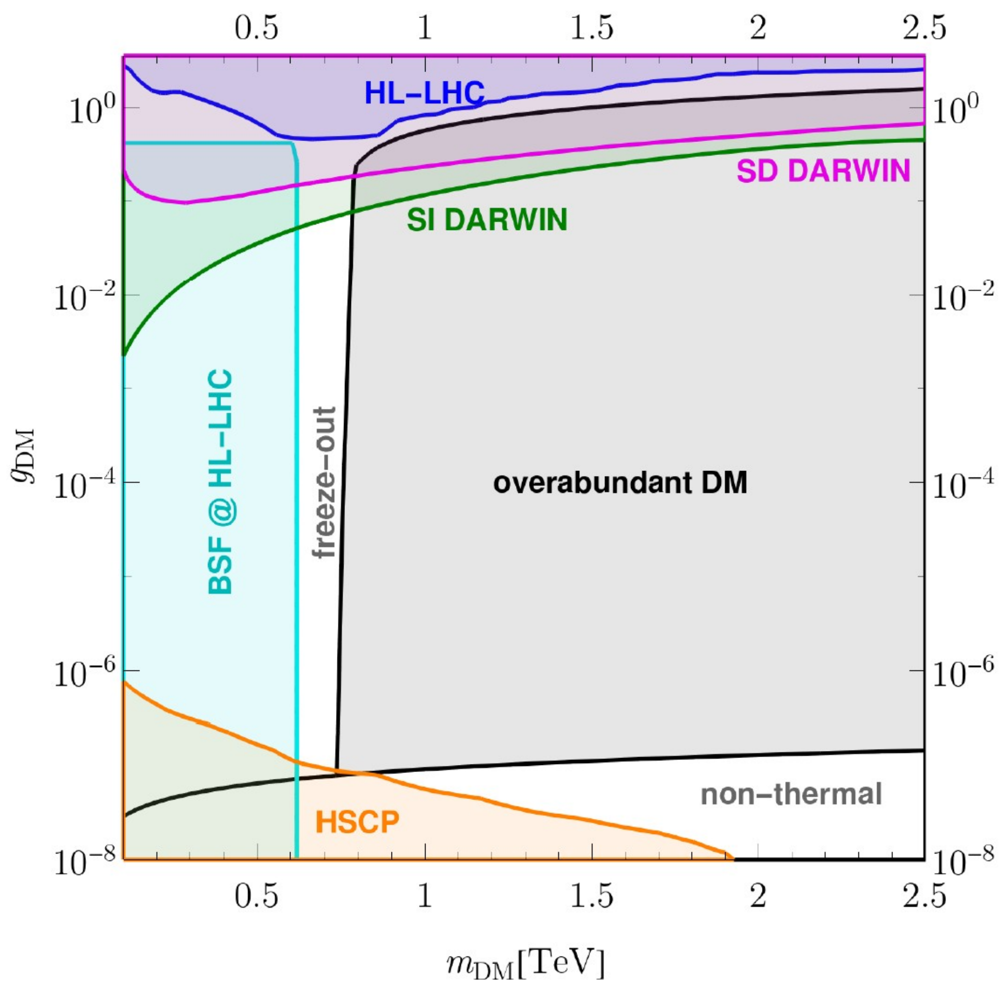
→ **closes gap between prompt and LLP searches**

→ **BSF@LHC narrows down enlarged parameter space**

→ **BSF@LHC (in contrast to HSPC limits) strict exclusion**

Becker, Copello, JH, Mohan, Sengupta (2022)

Potential of bound state formation at colliders



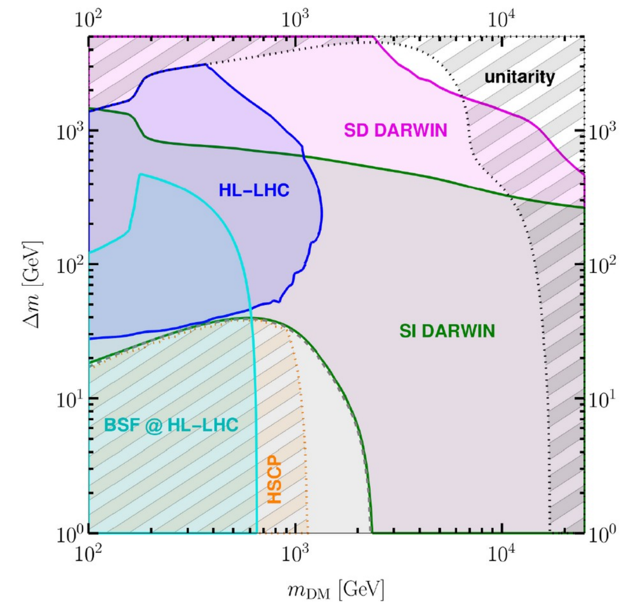
fixed $\Delta = 0.05 m_{\rm DM}$

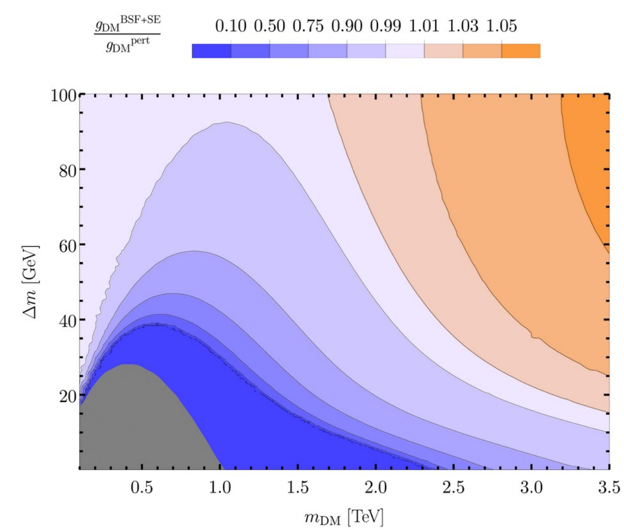
→ **BSF@LHC has potential to unambiguously close parameter space for small DM masses and mass splittings**

Becker, Copello, JH, Mohan, Sengupta (2022)

Conclusions

- **WIMPs are not yet dead**
- **(Colored) coannihilation scenarios could explain the no-show (higher expected DM masses)**
- **Sommerfeld effect and bound state formation**
  → **alter interpretation of experimental exclusion limits**
  → **change expected model parameters in case of a discovery**
- **Application of a simple correction factor is not sufficient due to the non-trivial behavior of SE and BSF over the parameter space**

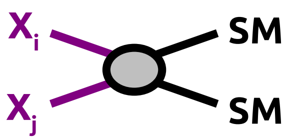




Generally, for conclusive exclusion of DM freeze-out scenarios, non-pertubative effects are crucial to be taken into account!

Thank you for your attention!

Dark Matter freeze-out with coannihilations



$$\frac{dn}{dt} + 3Hn = \sum_{i,j=1}^{N} -\langle \sigma_{ij} v \rangle (n_i n_j - n_{\mathrm{eq},i} n_{\mathrm{eq},j})$$

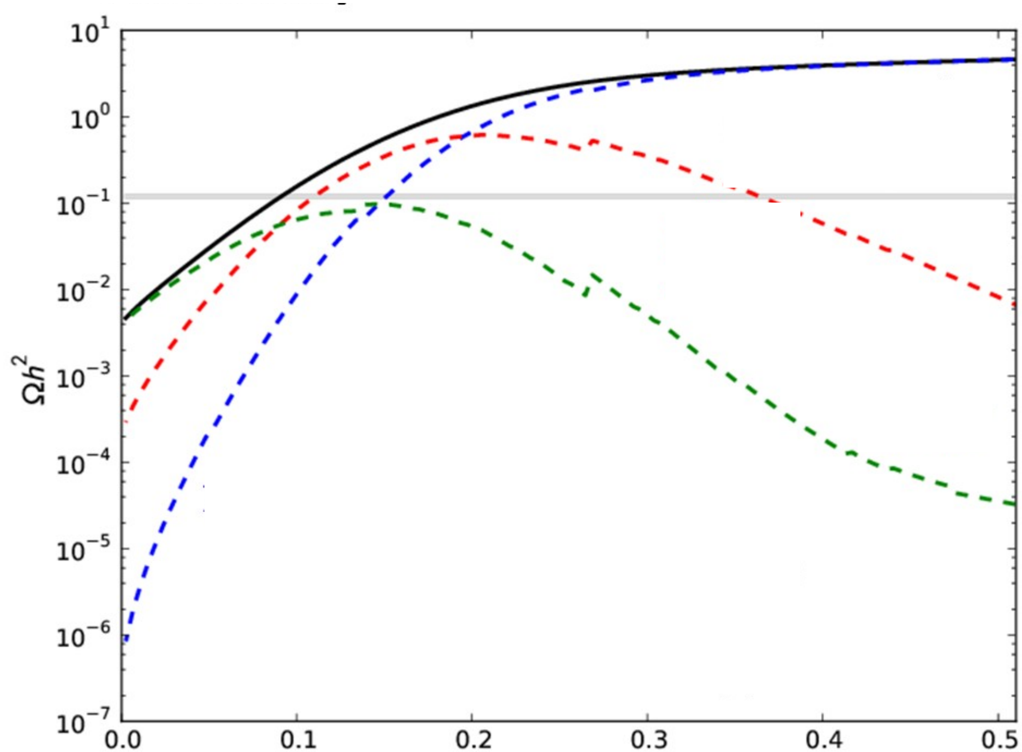
$$n = \sum_{i=1}^{N} n_i \qquad \frac{n_i}{n} \approx \frac{n_{\mathrm{eq},i}}{n_{\mathrm{eq}}}$$

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

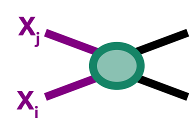
$$\langle \sigma_{\mathrm{eff}} v_{\mathrm{rel}} \rangle = \sum_{ij} \langle \sigma_{ij} v_{ij} \rangle \frac{n_{\mathrm{eq},i}}{n_{\mathrm{eq}}} \frac{n_{\mathrm{eq},j}}{n_{\mathrm{eq}}}$$

$$\frac{n_{\mathrm{eq},i}}{n_{\mathrm{eq}}} \propto \exp^{\frac{-(m_i - m_{\mathrm{DM}})}{T}}$$

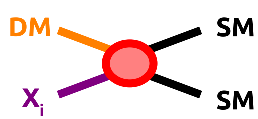
→ **for small mass splittings: co-annihilation**



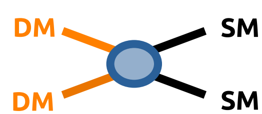
$$\delta \equiv \frac{m_i - m_\chi}{m_\chi}$$



$$\frac{n_{\mathrm{eq},i}}{n_{\mathrm{eq}}} \frac{n_{\mathrm{eq},j}}{n_{\mathrm{eq}}}$$



$$\frac{n_{\mathrm{eq},i}}{n_{\mathrm{eq}}} \cdot 1$$



$$1 \cdot 1$$

Effective Boltzmann description

$$\frac{\tilde{Y}}{x} = -\sqrt{\frac{\pi}{45}} m_{\mathrm{Pl}}\, m_\chi\, g_{*,\mathrm{eff}}^{1/2} \frac{\langle \sigma_{\mathrm{eff}} v_{\mathrm{rel}} \rangle}{x^2} \left(\tilde{Y}^2 - \tilde{Y}_{\mathrm{eq}}^2 \right)$$

With the effective dark matter yield

$$\tilde{Y} = Y_\chi + \sum_i Y_{X_i} + Y_{X_i}^\dagger$$

$$Y_\chi^{\mathrm{eq}} = \frac{90}{(2\pi)^{7/2}} \frac{g_\chi}{g_{*,S}} x^{3/2} e^{-x}$$

$$Y_X^{\mathrm{eq}} = Y_{X^\dagger}^{\mathrm{eq}} = \frac{90}{(2\pi)^{7/2}} \frac{g_\chi}{g_{*,S}} [(1+\Delta)x]^{3/2} e^{-(1+\Delta)x}$$

Assumptions:

- Coannihilating particle will later decay in DM
- Coannihilating particle in thermal equilibrium with DM particle

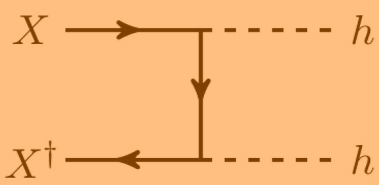
$$\Gamma(X + SM \longleftrightarrow \chi + SM) >> H$$

$$x_{\mathrm{dec}} = m_\chi / T_{\mathrm{dec}}$$

Towards new standards for the DM abundance

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

Tree level annihilation



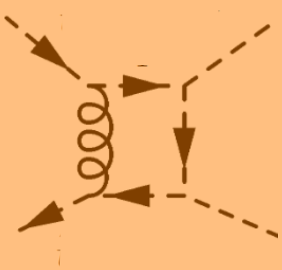
$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{tree}} v_{\text{rel}}$$

DM codes include *only* tree level

Towards new standards for the DM abundance

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

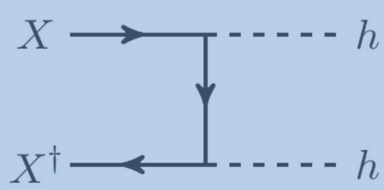
Higher order corrections



$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{NLO}} v_{\text{rel}}$$

sizeable corrections to the DM abundance

Tree level annihilation



$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{tree}} v_{\text{rel}}$$

DM codes include *only* tree level

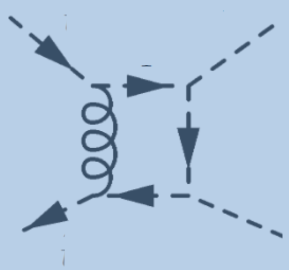
first study of theoretical error on relic abundance

JH et al. (2019), JH et al. (2016)
JH et al. (2015b), JH et al. (2015a)
JH et al. (2013)

Towards new standards for the DM abundance

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$

Higher order corrections



$$\sigma_{\rm eff} v_{\rm rel} = \sigma^{\rm NLO} v_{\rm rel}$$

sizeable corrections to the DM abundance

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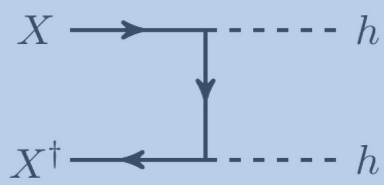
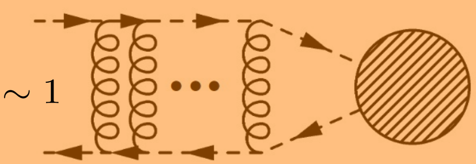


$$\sigma_{\rm eff} v_{\rm rel} = \sigma^{\rm tree} v_{\rm rel}$$

DM codes include *only* tree level

Sommerfeld enhancement

$$\left(\frac{\alpha}{v_{\rm rel}}\right)^n \sim 1$$



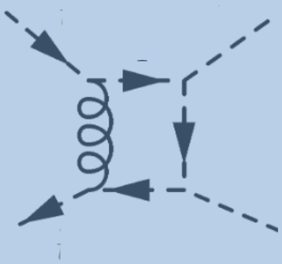
$$\sigma_{\rm eff} v_{\rm rel} = \sigma^{\rm tree} v_{\rm rel} \times S_0$$

JH et al., (2019), JH, Petraki (2018)
JH et al. (2015b)

Towards new standards for the DM abundance

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

Higher order corrections



$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{NLO}} v_{\text{rel}}$$

sizeable corrections to the DM abundance

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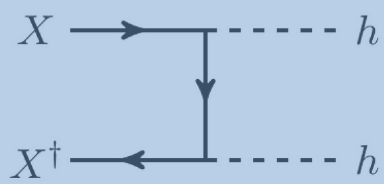

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DM codes include *only* tree level

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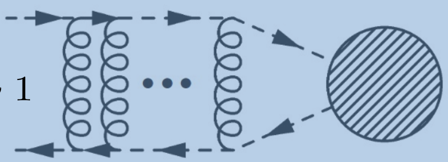
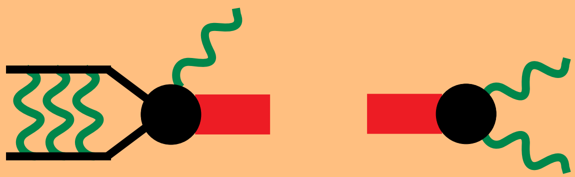


$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{tree}} v_{\text{rel}} \times S_0$$

Bound state formation



$$\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle = \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle + \langle \sigma_{\text{BSF}} v_{\text{rel}} \rangle_{\text{eff}}$$

bound state formation and **subsequent decay** open up a new **effective DM annihilation** channel

JH et al. (2019), JH et al. (2016)
JH et al. (2015b), JH et al. (2015a)
JH et al. (2013)

JH et al., (2019), JH, Petraki (2018)
JH et al. (2015b)

JH, Petraki (2019),
JH, Petraki (2018)