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

Julia Harz

May 10th 2023
10 years MITP Workshop

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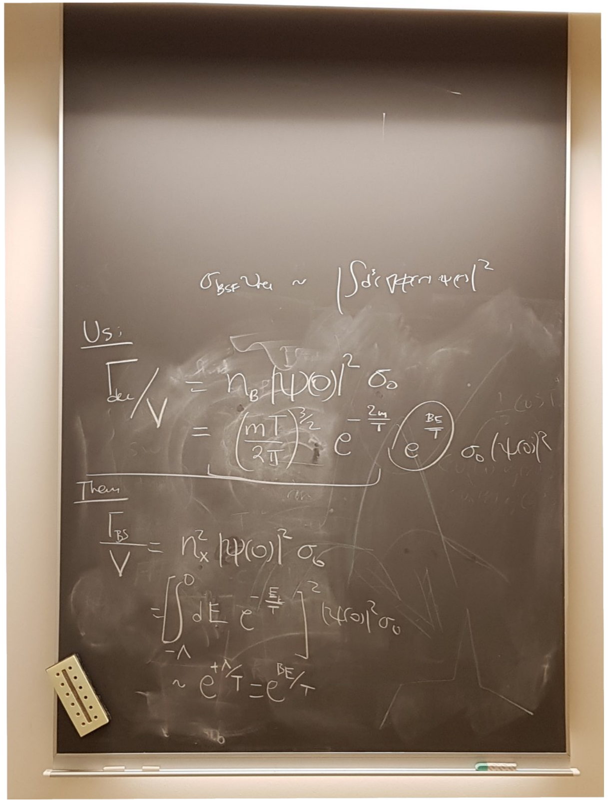

Pushing the limits of theoretical physics

Pushing the limits of the WIMP

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The 'WIMP Miracle' Hope For Dark Matter Is Dead

Ethan Siegel Senior Contributor
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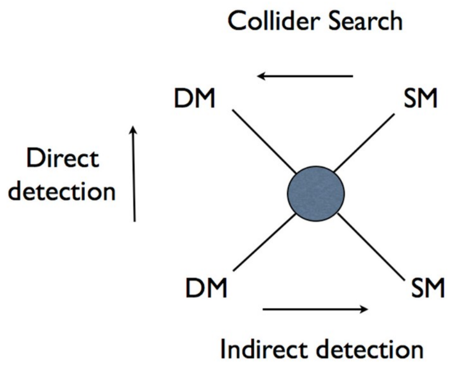
NEWS · 02 OCTOBER 2020

Last chance for WIMPs: physicists launch all-out hunt for dark-matter candidate

Researchers have spent decades searching for the elusive particles – a final generation of detectors should leave them no place to hide.

Pushing the limits of the WIMP



- **no observations** at the LHC, direct or indirect detection so far that supports the *minimal* WIMP model

- **Reasons** could be manifold:

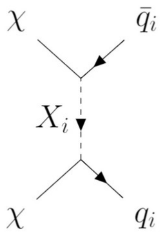
(1) completely **different type** of DM (PBHs, etc.)

(2) **another DM generation mechanism**, e.g. freeze-in instead of freeze-out

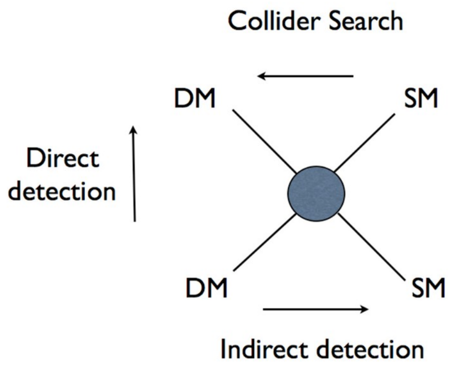
(3) more **complex WIMP** models can evade bounds

(4) "exceptions" in the **DM abundance calculation** that were previously not considered

(5) ...



Pushing the limits of the WIMP



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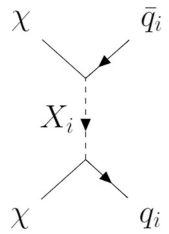
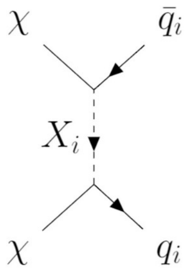


If we want to rule out WIMP models conclusively, we have to consider possible subtleties.

Community effort: LHC DM working group



Recently common focus on white paper about t-channel DM models

Closing in on *t*-channel simplified dark matter models

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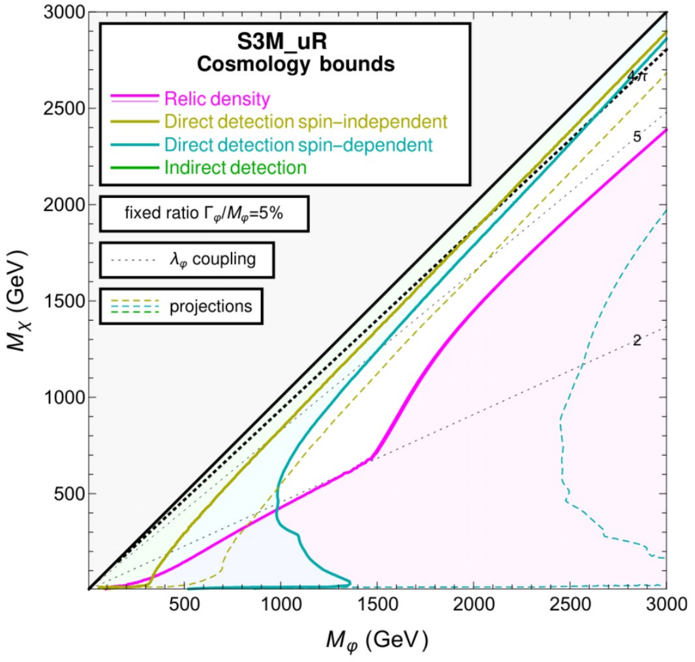
ARTICLE INFO

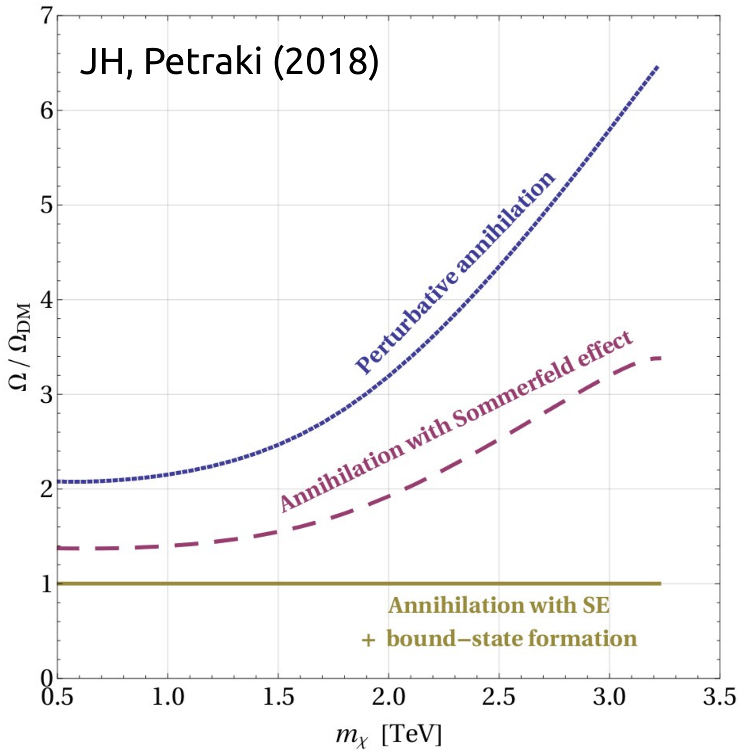
Keywords:
Dark matter simplified models, collider searches, cosmological bounds

ABSTRACT

A comprehensive analysis of cosmological and collider constraints is presented for three simplified models characterised by a dark matter candidate (real scalar, Majorana fermion and real vector) and a coloured mediator (fermion, scalar and fermion respectively) interacting with the right-handed up quark of the Standard Model. Constraints from dark matter direct and indirect detection and relic density are combined with bounds originating from the re-interpretation of a full LHC run 2 ATLAS search targeting final states with multiple jets and missing transverse energy. Projections for the high-luminosity phase of the LHC are also provided to assess future exclusion and discovery reaches, which show that analogous future search strategies will not allow for a significant improvement compared with the present status. From the cosmological point of view, we demonstrate that thermal dark matter is largely probed (and disfavoured) by constraints from current direct and indirect detection experiments. These bounds and their future projections have moreover the potential of probing the whole parameter space when combined with the expectation of the high-luminosity phase of the LHC.



Community effort: non-perturbative effects in DM



Non-perturbative effects such as Sommerfeld effect and bound state formation can significantly alter the theoretical prediction of the DM relic abuandance.

Community effort: non-perturbative effects in DM

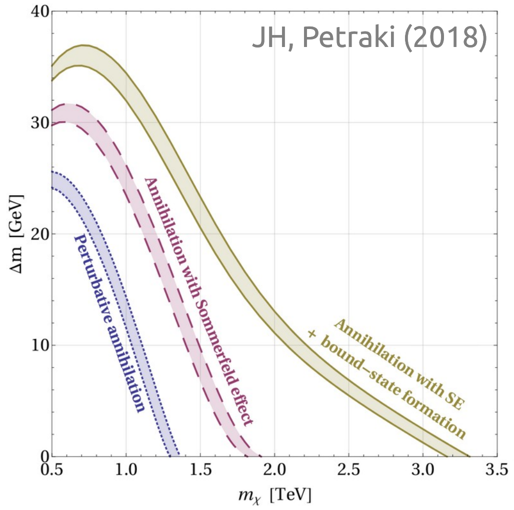
- Development of **formalism** to describe boundstate formation (and Sommerfeld effect) for dark matter abundance at zero-T incl. non-equilibrium dynamics Von Harling, Petraki (2014), Petraki, Postma, Wiechers (2015), Petraki, Postma, de Vries (2016)

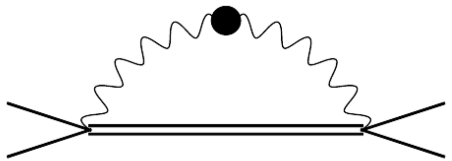
- Demonstrating **phenomenological impact** on EW and strongly coupled WIMP scenarios e.g. Asadi, Baumgart, Fitzpatrick, Krupczak, Slatyer (2016), Mitridate, Strumia, Smirnov, Redi (2017), JH, Petraki (2018), JH, Petraki (2018), JH, Petraki (2019)

- Development of **finite-T treatment** of bound state formation while still in **ionization equilibrium** Kim, Laine (2017), Biondini, Laine (2018), Biondini (2018), Covi, Binder, Mukaida (2018)

- **Phenomenology of finite-T** treatment of bound state formation while still in **ionization equilibrium** Biondini, Vogl (2018), Biondini, Vogl (2019)

- Presenting **finite-T treatment beyond ionization equilibrium** and comparison to other methods Binder, Blobel, JH, Mukaida (2020)





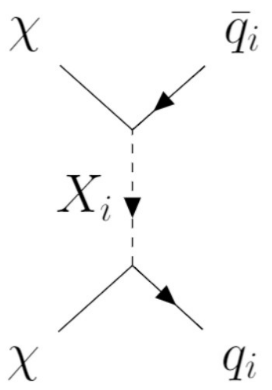
Common conclusion:
bound state formation and Sommerfeld effect can significantly affect relic abundance prediction

What is the goal?

→ How do bound state formation and Sommerfeld effect impact our understanding of the thought-to-be excluded parameter space?

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

Simplified t-channel dark matter model



Universal framework for t-channel DM models

Arina, Fuks, Mantani (2020)

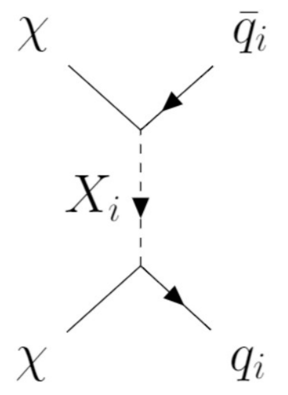
$$\mathcal{L} \supset \sum_i (D_\mu X_i)^\dagger (D^\mu X_i) + g_{\mathrm{DM},ij} X_i^\dagger \bar{\chi} P_R q_j + g^*_{\mathrm{DM},ij} X_i \bar{q}_j P_L \chi$$

	$SU(3)_c \times SU(2)_L \times U(1)_Y$	
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

Simplified t-channel dark matter model



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

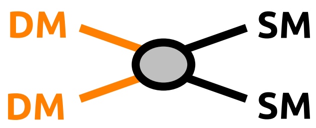
Relevant parameters:

g_{DM}

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

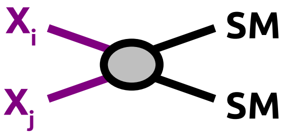
$\Delta = m_X - m_{\mathrm{DM}}$

Contributing processes to the relic abundance



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

Contributing processes to the relic abundance

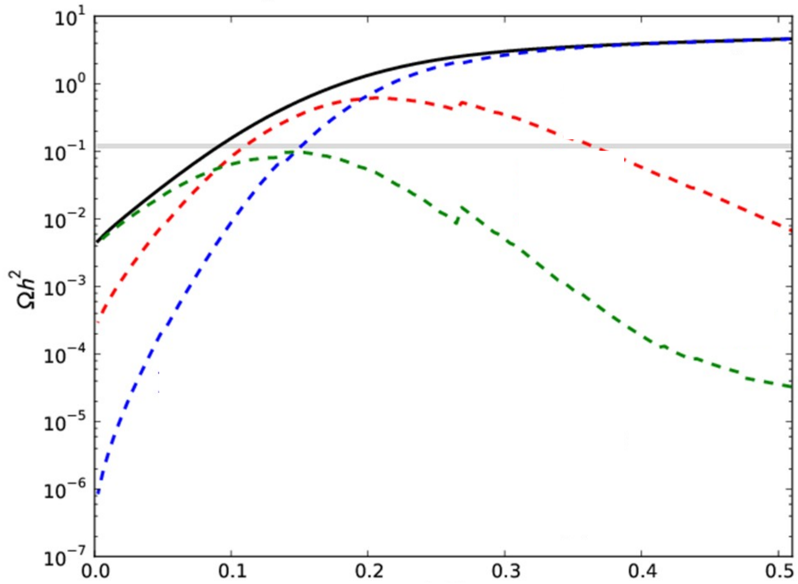


$$\frac{dn}{dt} + 3Hn = -\langle\sigma_{\rm eff} v\rangle(n^2 - n_{\rm eq}^2)$$

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

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

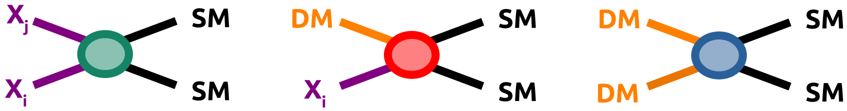
→ **for small mass splittings: coannihilation**



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

Assumptions:

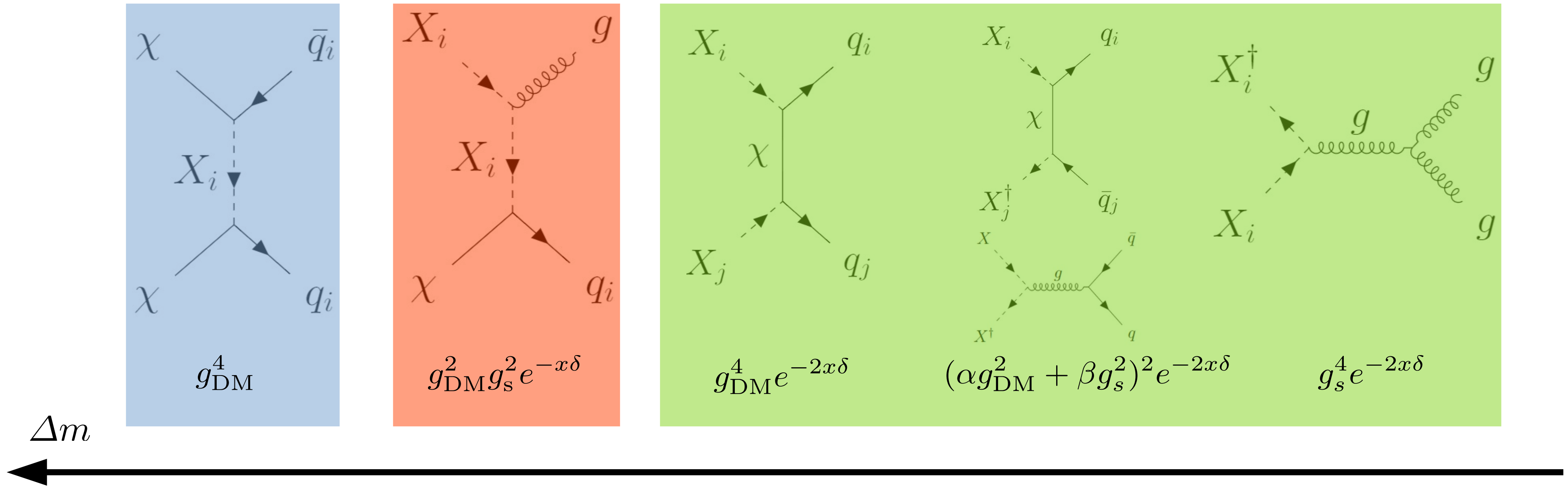
- Coannihilating particle will later decay into DM $n = \sum_{i=1}^{N} n_i$
- Dark sector particles in equilibrium $\Gamma(X + SM \longleftrightarrow \chi + SM) >> H$



$$\frac{n_{{\rm eq},i}}{n_{\rm eq}}\frac{n_{{\rm eq},j}}{n_{\rm eq}} \qquad \frac{n_{{\rm eq},i}}{n_{\rm eq}} \cdot 1 \qquad 1 \cdot 1$$

Contributing processes to the relic abundance

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

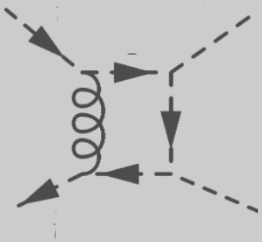


$$\delta = \frac{\Delta}{m_{\mathrm{DM}}}$$

Towards new standards in the relic abundance prediction

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

Higher order corrections



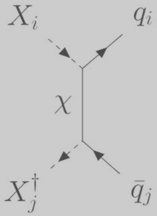
$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{NLO}} v_{\text{rel}}$$

sizeable corrections to the DM abundance

first study of theoretical error on relic abundance

JH, Herrmann, Klasen, Kovarik, et al. (2015+)

Tree level annihilation

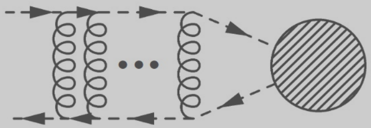


$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{tree}} v_{\text{rel}}$$

DM codes include *only* tree level

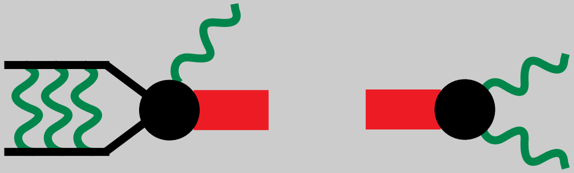
Sommerfeld enhancement

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



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

Bound state formation

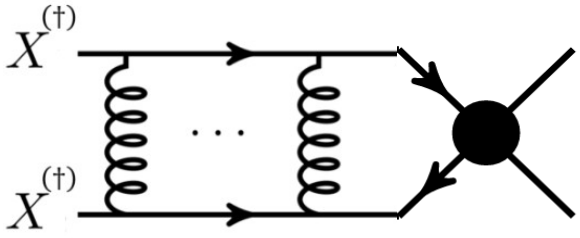


$$\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle = \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle + \langle \sigma_{\text{BSF}} v_{\text{rel}} \rangle_{\text{eff}}$$

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

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

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 if $\dfrac{\text{Bohr momentum}}{\text{momentum exchange of unbound particles}} = \dfrac{\mu\alpha_g}{\mu v_{\rm rel}} > 1$

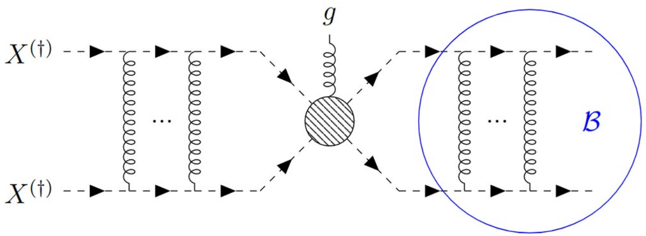
- When $\alpha \sim v_{\rm rel}$, exchange of *n* gluons lead to $\left(\dfrac{\alpha}{v_{\rm rel}}\right)^n \sim 1$

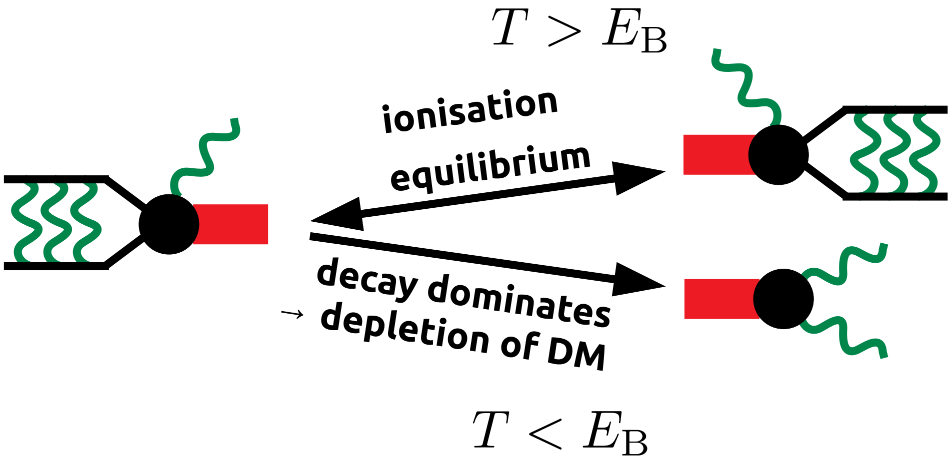
$$\left[-\frac{\nabla^2}{2\mu} + V^{\rm S}_{[\hat{\mathbf{R}}]}(\mathbf{r})\right]\phi_{\mathbf{k}}(\mathbf{r}) = \mathcal{E}_{\mathbf{k}}\,\phi_{\mathbf{k}}(\mathbf{r}) \qquad \text{with} \qquad V^{S}_{[\hat{\mathbf{R}}]}(r) = -\frac{\alpha_s^S C_{[\hat{\mathbf{R}}]}}{r}$$

$$V(r)_{\mathbf{3}\otimes\bar{\mathbf{3}}} = \begin{cases} -\dfrac{4}{3}\dfrac{\alpha_s^S}{r} & [\mathbf{1}] \quad \textbf{attractive} \\ +\dfrac{1}{6}\dfrac{\alpha_s^S}{r} & [\mathbf{8}] \quad \textbf{repulsive} \end{cases}$$

$$\sigma_{\rm SE} = S_0\left(\frac{\alpha_s^S C_{[\hat{\mathbf{R}}]}}{v_{\rm rel}}\right)\sigma_0 = \frac{2\pi\alpha_s^S C_{[\hat{\mathbf{R}}]}}{v_{\rm rel}\left(1 - e^{-2\pi\alpha_s^S C_{[\hat{\mathbf{R}}]}/v_{\rm rel}}\right)}\,\sigma_0$$

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**

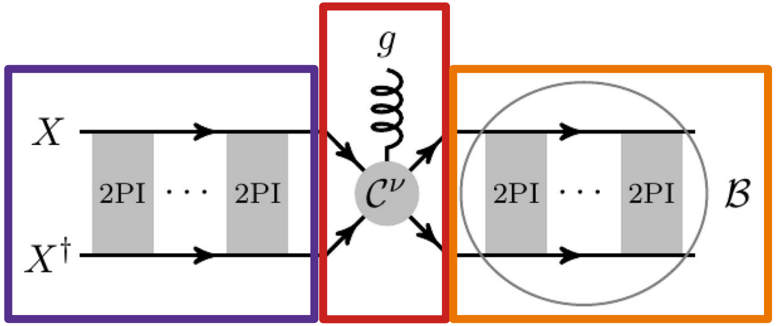
$$\mathcal{B}(XX^\dagger)_{[\mathbf{1}]} \to g_{[\mathbf{8}]}\ g_{[\mathbf{8}]}$$ **bound state decay**

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

Bound state formation

$$\left[-\frac{\nabla^2}{2\mu} + V_{\rm scatt}(\mathbf{r})\right] \phi_{\mathbf{k}}(\mathbf{r}) = \mathcal{E}_{\mathbf{k}}\, \phi_{\mathbf{k}}(\mathbf{r}) \qquad \mathcal{E}_{\mathbf{k}} \equiv \frac{\mathbf{k}^2}{2\mu} = \frac{\mu v_{\rm rel}^2}{2} > 0$$

$$\left[-\frac{\nabla^2}{2\mu} + V_{\rm bound}(\mathbf{r})\right] \psi_{n\ell m}(\mathbf{r}) = \mathcal{E}_{n\ell}\, \psi_{n\ell m}(\mathbf{r}) \qquad \mathcal{E}_{n\ell} \equiv -\frac{\mu^2\alpha^2}{n^2 2\mu} < 0$$



scattering state

radiative transition

bound state

Bound state formation

$$\left[-\frac{\nabla^2}{2\mu} + V_{\text{scatt}}(\mathbf{r})\right] \phi_{\mathbf{k}}(\mathbf{r}) = \mathcal{E}_{\mathbf{k}}\, \phi_{\mathbf{k}}(\mathbf{r}) \qquad \mathcal{E}_{\mathbf{k}} \equiv \frac{\mathbf{k}^2}{2\mu} = \frac{\mu v_{\text{rel}}^2}{2} > 0$$

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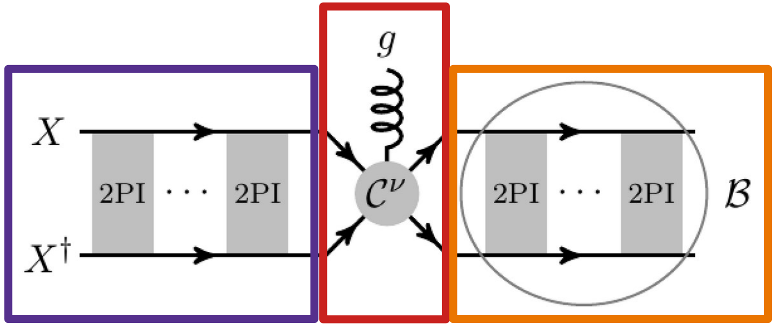
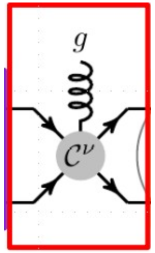


scattering state **radiative transition** **bound state**



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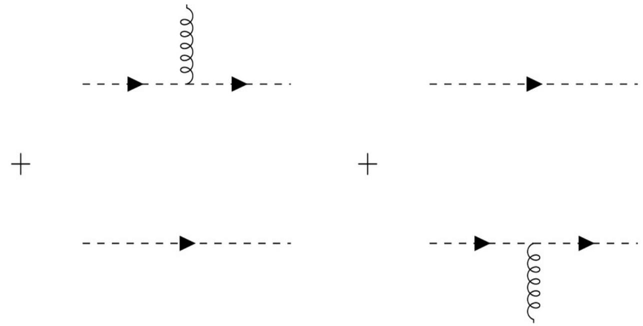


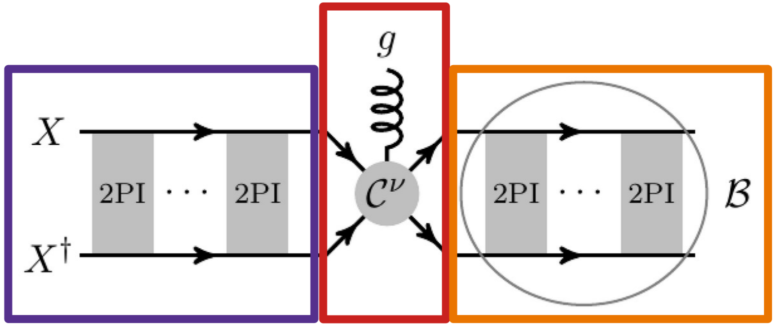
Reappraisal of dark matter co-annihilating with a top or bottom partner, Keung, Low, Zhang (2017)
Cosmological Implications of Dark Matter Bound States, Mitridate, Redi, Smirnov, Strumia (2017)
Capture and Decay of Electroweak WIMPonium, Asadi, Baumgart, Fitzpatrick, Krupczak, Slatyer (2016)

transition amplitude

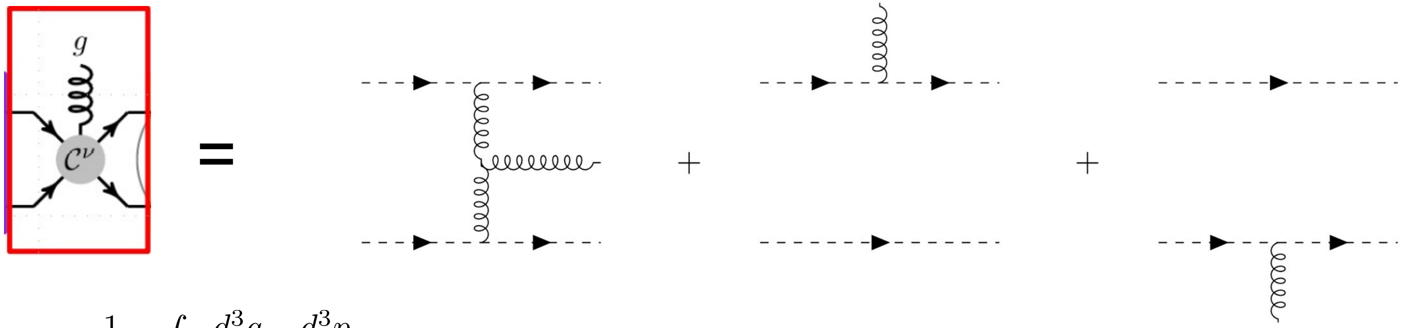
Bound state formation

$$\left[-\frac{\nabla^2}{2\mu}+V_{\rm scatt}(\mathbf{r})\right]\phi_{\mathbf{k}}(\mathbf{r})=\mathcal{E}_{\mathbf{k}}\,\phi_{\mathbf{k}}(\mathbf{r}) \qquad \mathcal{E}_{\mathbf{k}}\equiv\frac{\mathbf{k}^2}{2\mu}=\frac{\mu v_{\rm rel}^2}{2}>0$$

$$\left[-\frac{\nabla^2}{2\mu}+V_{\rm bound}(\mathbf{r})\right]\psi_{n\ell m}(\mathbf{r})=\mathcal{E}_{n\ell}\,\psi_{n\ell m}(\mathbf{r}) \qquad \mathcal{E}_{n\ell}\equiv-\frac{\mu^2\alpha^2}{n^2 2\mu}<0$$



scattering state **radiative transition** **bound state**



$$[\mathcal{M}^{\nu}_{\mathbf{k}\to\{n\ell m\}}]^{a}_{ii',jj'}=\frac{1}{\sqrt{2\mu}}\int\frac{d^3q}{(2\pi)^3}\frac{d^3p}{(2\pi)^3}\;\tilde{\psi}^{*}_{n\ell m}(\mathbf{p})\;\tilde{\phi}_{\mathbf{k}}(\mathbf{q})\;[\mathcal{M}^{\nu}_{\rm trans}(\mathbf{q},\mathbf{p})]^{a}_{ii',jj'}$$

$\langle\sigma_{\rm BSF}v_{\rm rel}\rangle_{\rm eff}$

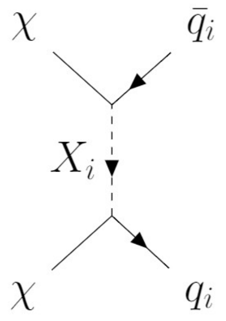
JH, Petraki (2018) derived from Feynman diagrammatic approach, see
DM bound states from Feynman diagrams, Petraki et al. JHEP 1506 (2015) 128

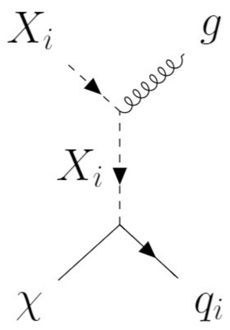
transition amplitude

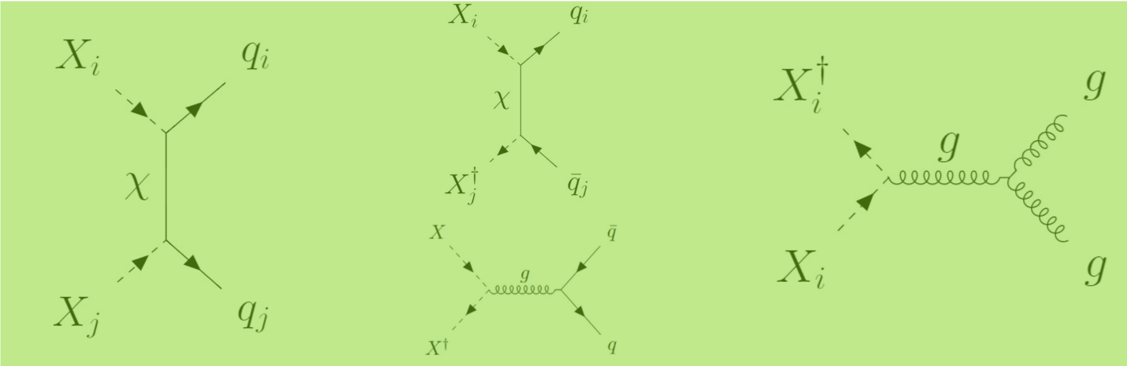
Complete Boltzmann equation

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

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





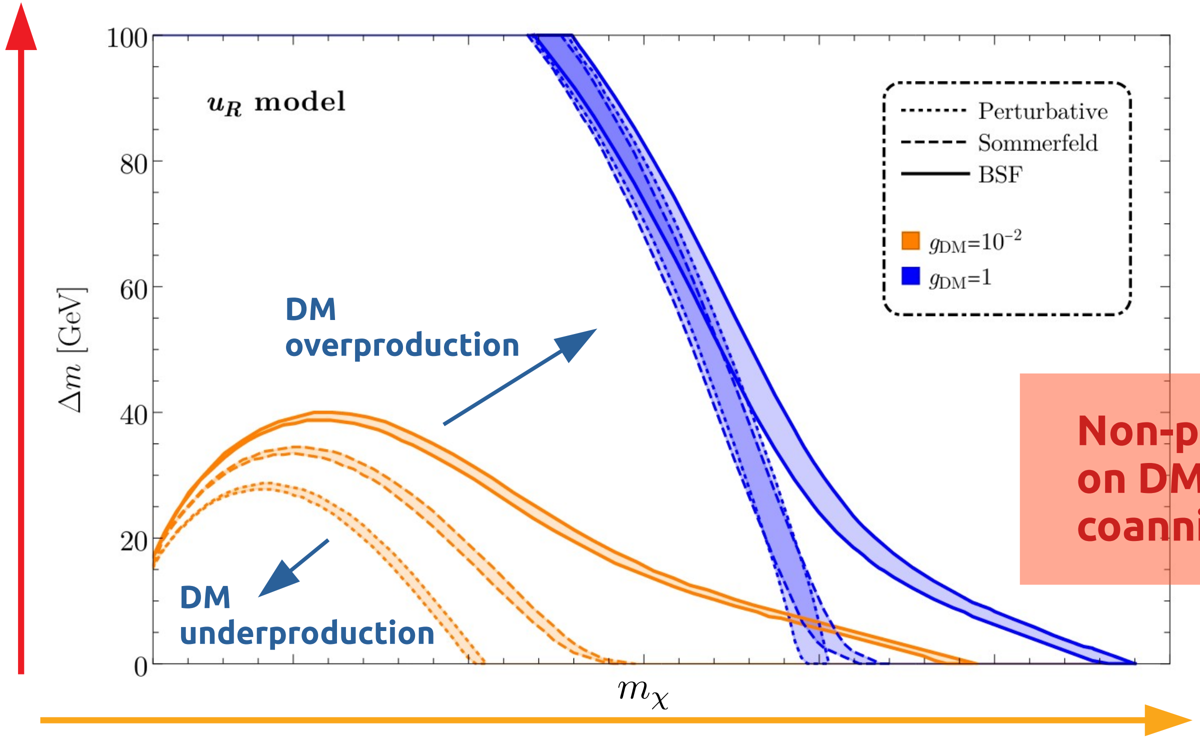


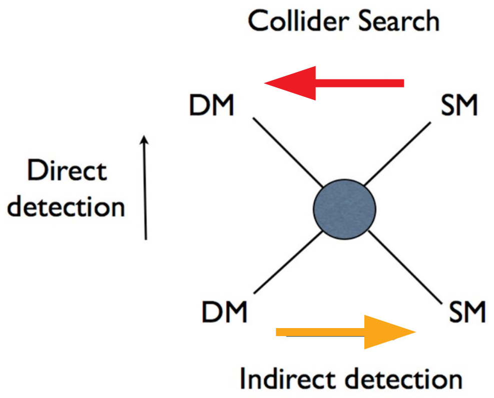
Δm

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

Impact of non-perturbative effects on mass plane

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



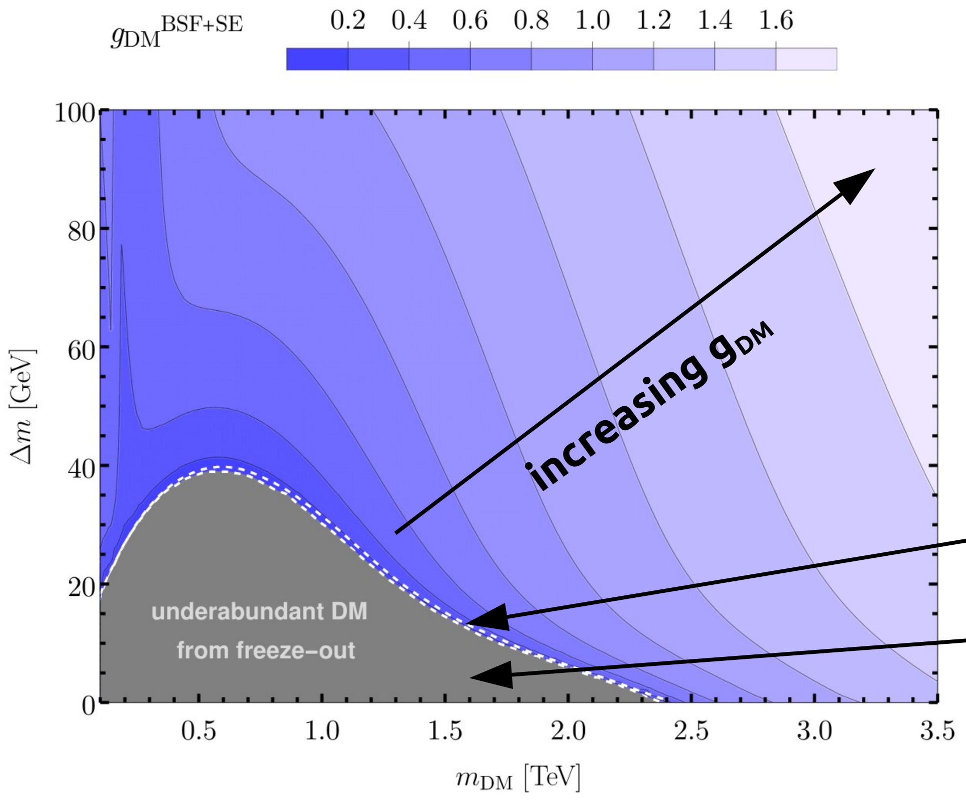


Non-perturbative effects change expectation on DM mass and the mass splitting of coannihilating particles

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



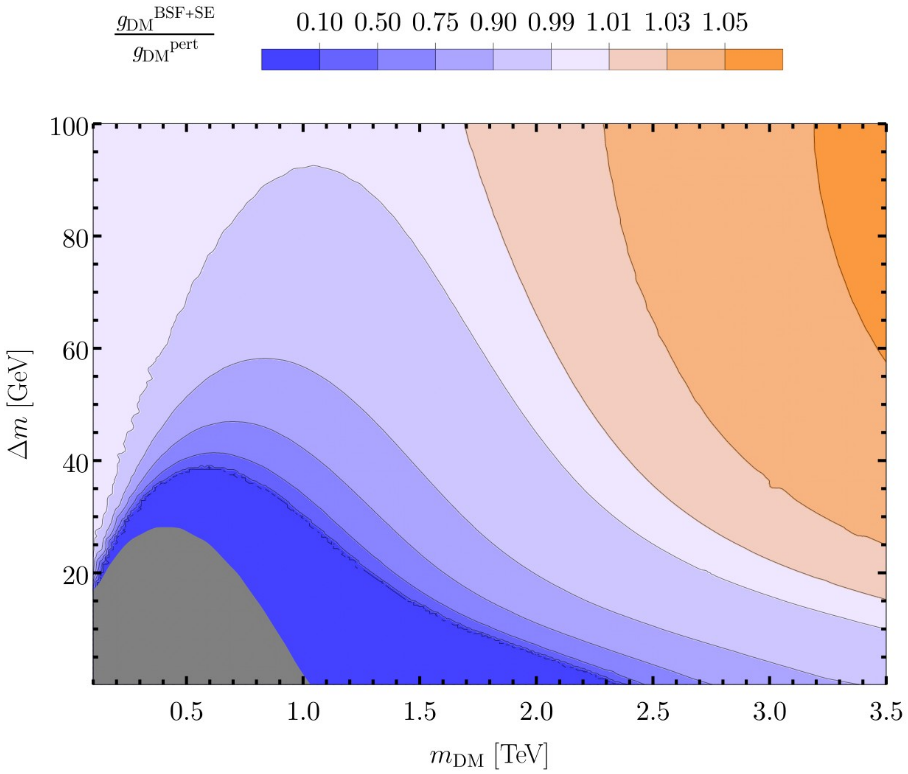
Lower bound on g_{DM} over a wide range $10^{-7} \leq g_{\rm DM} \leq 10^{-2}$

No equilibrium within the dark sector
→ conversion driven freeze-out, freeze-in production

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

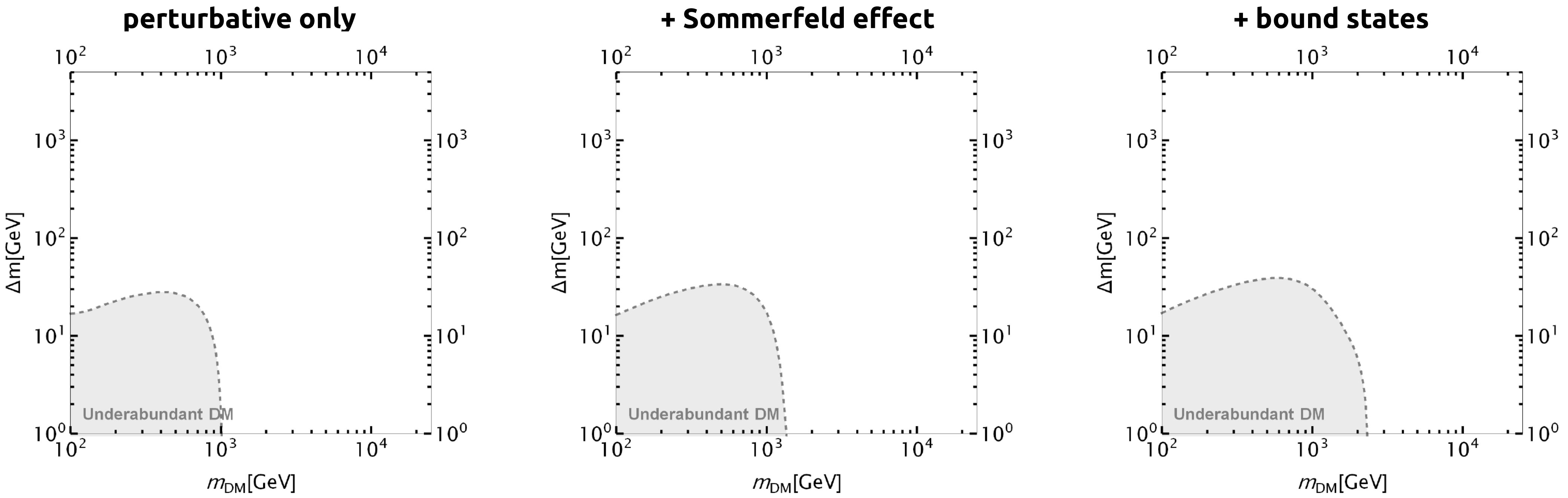


$X_i X_j^\dagger \to gg$	$g_s^4 e^{-2x\delta}$	$\lvert\mathcal{M}\rvert^2 \sim \frac{2}{7}[\mathbf{1}] + \frac{5}{7}[\mathbf{8}]$
$X_i X_j \to q_i q_j$	$g_{\rm DM}^4 e^{-2x\delta}$	$\lvert\mathcal{M}\rvert^2 \sim \frac{1}{3}[\bar{\mathbf{3}}] + \frac{2}{3}[\mathbf{6}]$
$X_i X_i \to q_i q_i$	$g_{\rm DM}^4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

- **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



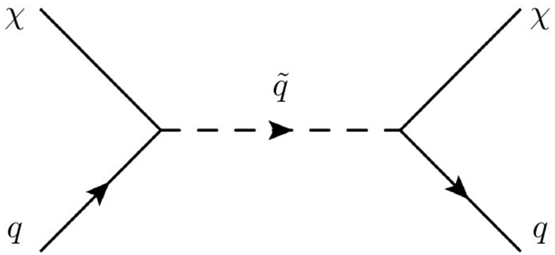
→ **Non-perturbative effects increase region of parameter space leading to underabundant DM**
→ **prediction of higher DM masses and larger mass splittings in freeze-out scenario**

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

Interplay with direct detection

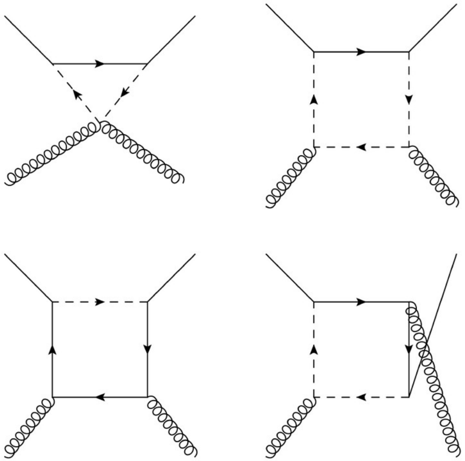
Spin dependent (SD) direct detection:

- Contribution at tree-level
- most stringent constraints from SD proton scattering
- PICO-60 limits



Spin independent (SI) direct detection:

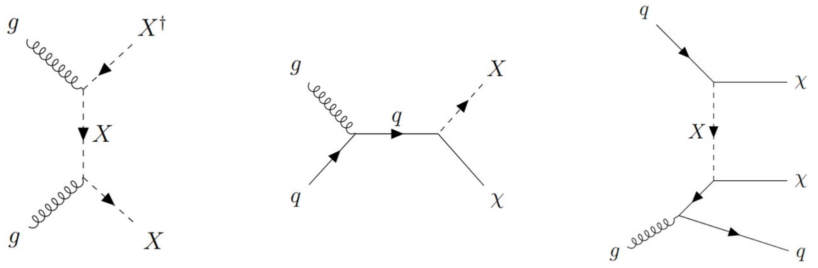
- only at one-level
- Including RGE running leads to enhancement
- most stringent limits from Xenon1T



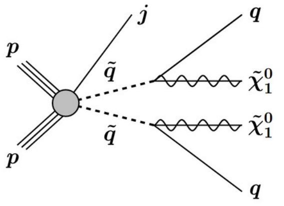
→ upper limit on g_{DM}

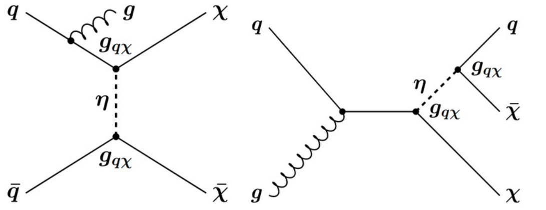
Mohan, Sengupta, Tait, Yan and Yuan (2019)

Constraints from LHC

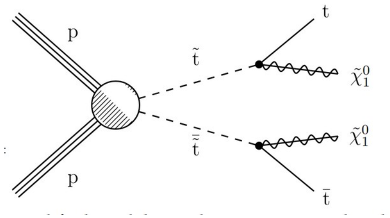


- **mono-jet + ETmiss search by ATLAS** [arXiv:1711.03301]





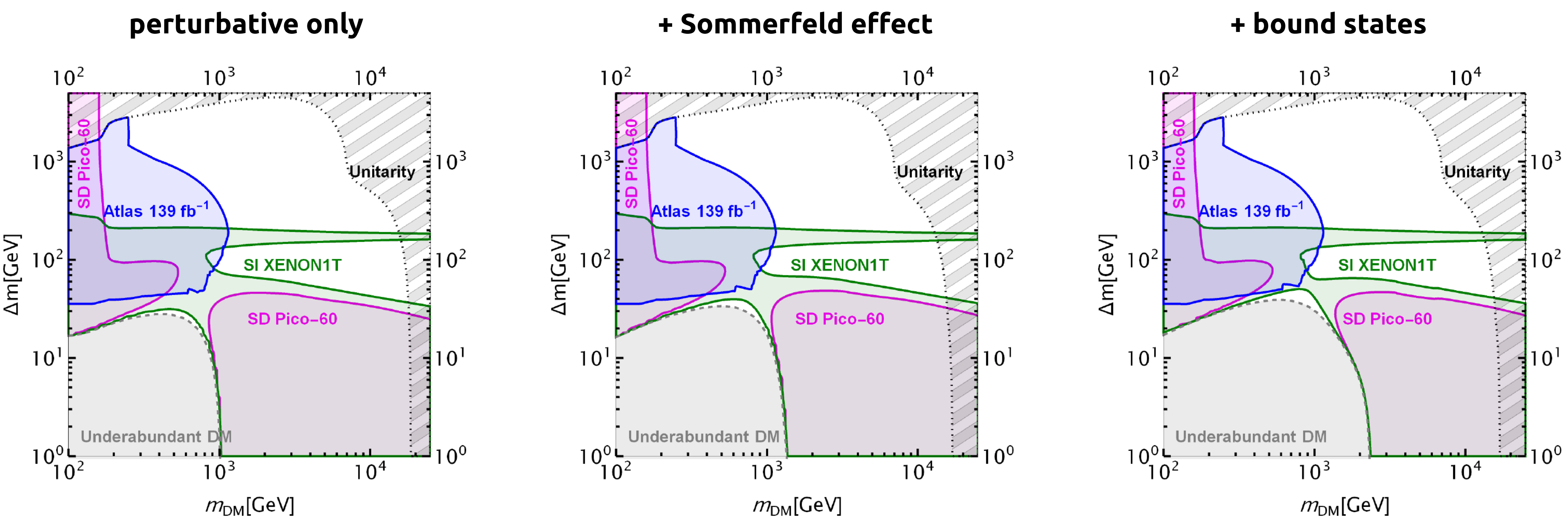
- **multi-jets + ETmiss search by CMS** [arXiv:1704.07781]



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

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

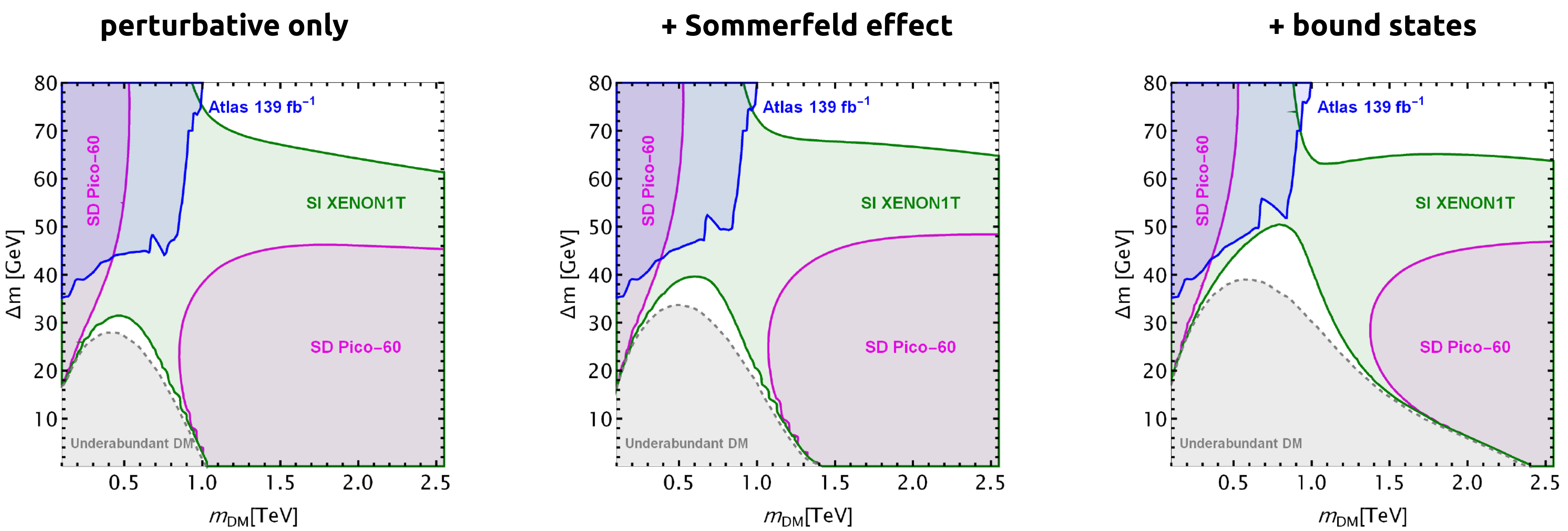
Impact of SE and BSF on exclusion limits



- DD and LHC searches set upper bound on g_{DM}
- Requirement of non-overproduction sets lower bound on g_{DM}
- LHC searches constrain mainly larger Δm, SI stronger than SD for $\Delta m < m_{DM}$

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

Impact of SE and BSF on exclusion limits

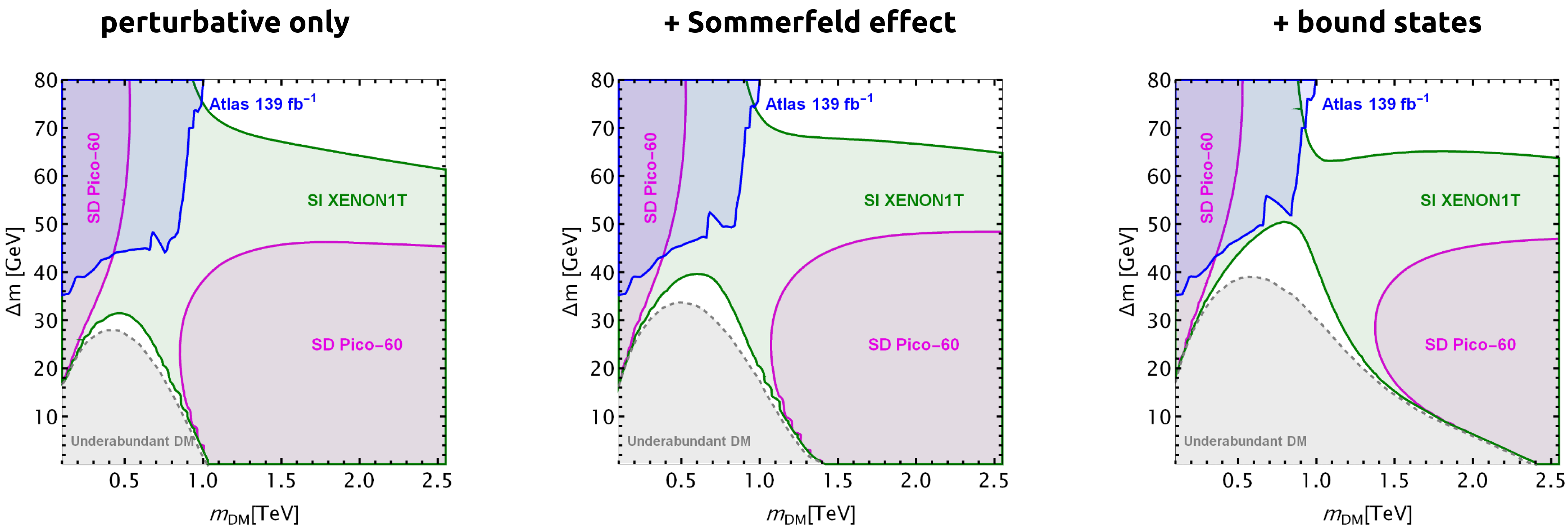


→ **Correction on g_{DM} due to SE and BSF lead to altered exclusion limits**

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

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

Impact of SE and BSF on exclusion limits



- based on tree-level calculations only, viable parameter space thought to be $(m_{DM}, \Delta m) < (1\text{ TeV}, 30\text{ GeV})$
- including SE extended to $(m_{DM}, \Delta m) < (1.4\text{ TeV}, 40\text{ GeV})$
- including BSF extended to $(m_{DM}, \Delta m) < (2.4\text{ TeV}, 50\text{ GeV})$

→ **Including SE alone not a good approximation!**

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

How to constrain the underabundant region?

Alternative mechanism needed, as dark sector out-of-equilibrium:

→ Identify $g_{\rm DM} < \tilde{g}_{\rm DM}$ below which dark sector is out-of-equilibrium

$$\Gamma_{X\to\chi q}\frac{Y_X^{\rm eq}}{Y_\chi^{\rm eq}} < H$$

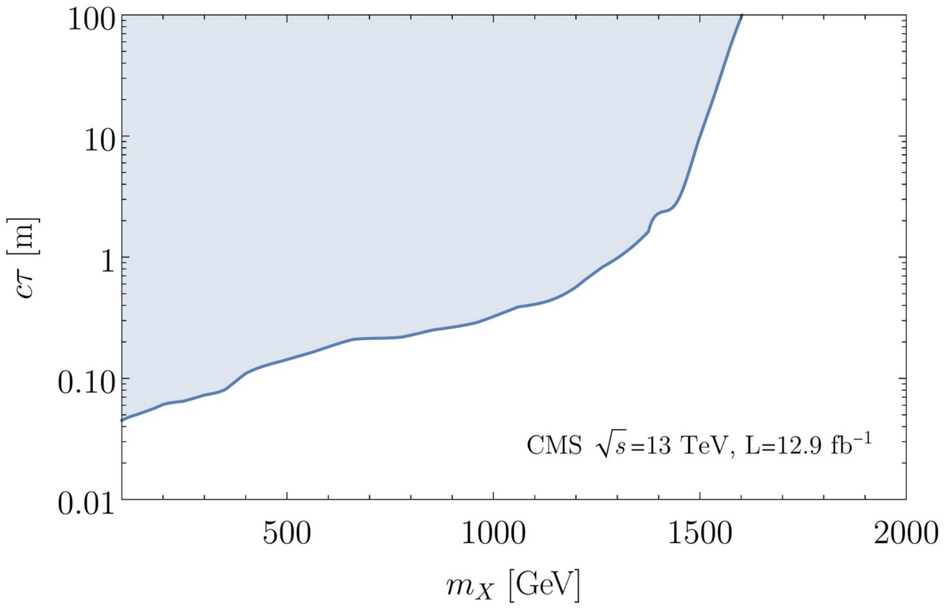
→ possibility to generate dark matter abundance via freeze-in mechanism

How constrained is this parameter space already by long-lived particle searches?

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

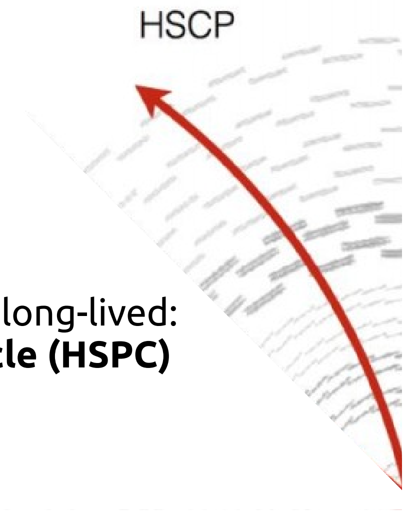
Interplay with long-lived particle searches

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



- Colored mediator sufficiently long-lived: **Heavy Stable Charged Particle (HSPC)**

- 13 TeV CMS analysis 12.9 fb^{-1} [*CMS-PAS-EXO-16-036 (2016)*]

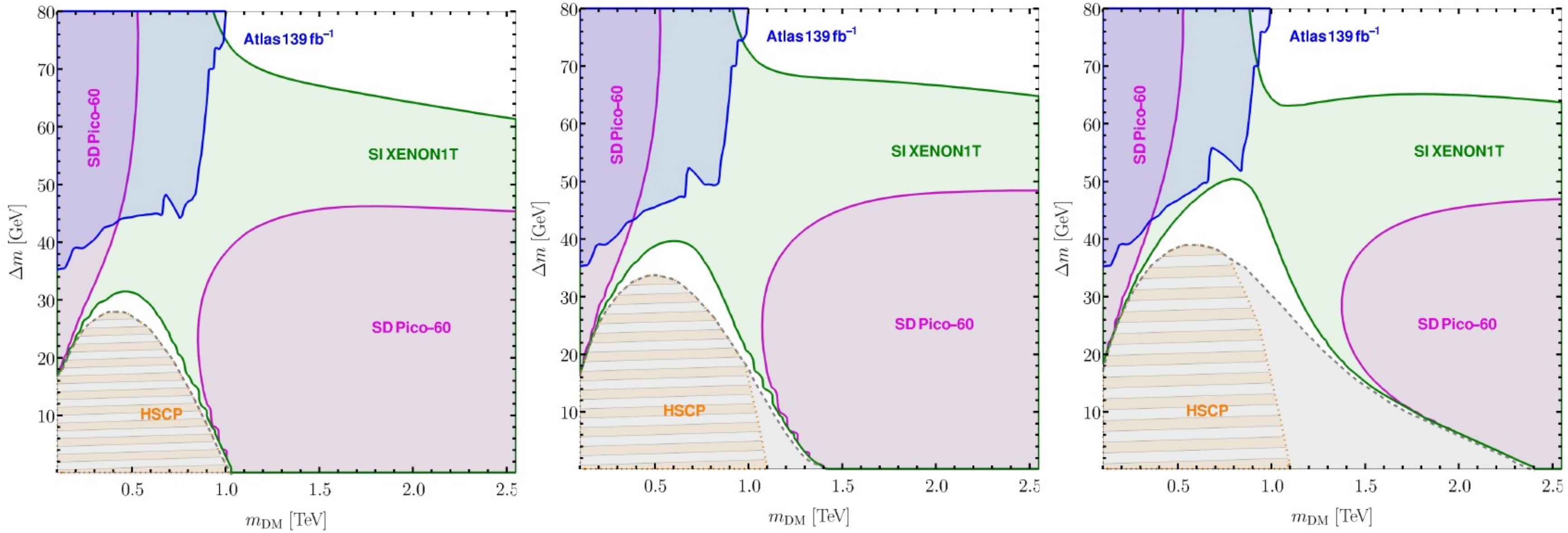


Becker, Copello, JH, Mohan, Sengupta (2022)

Interplay with long-lived particle searches

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

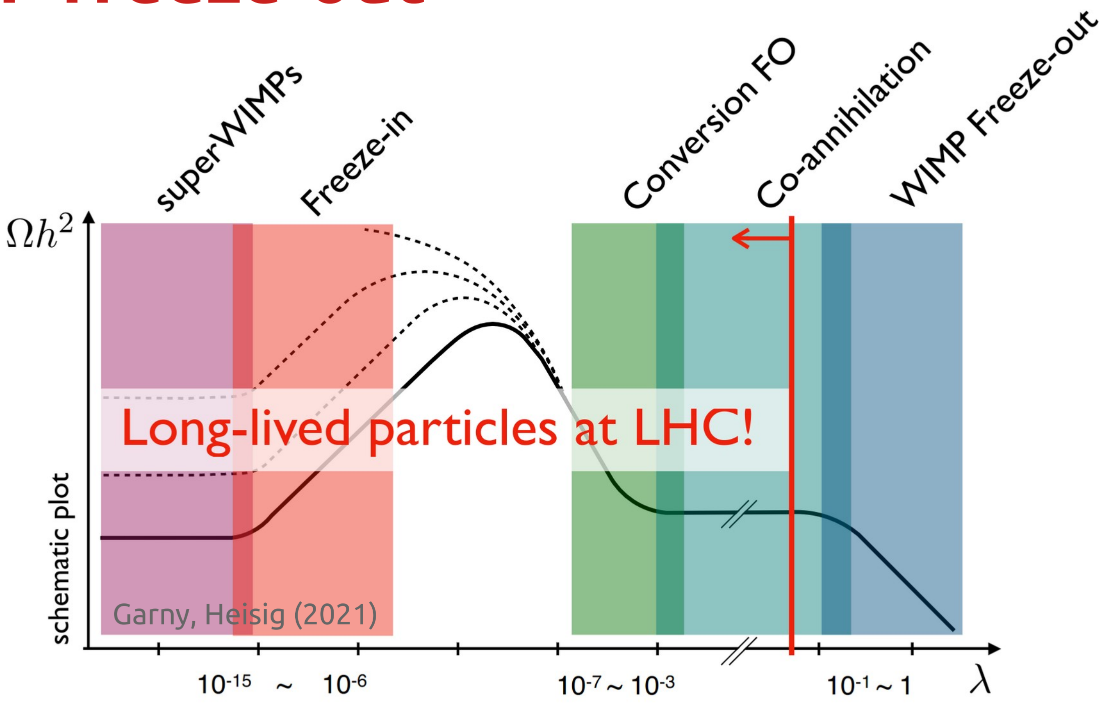
perturbative only | **+ Sommerfeld effect** | **+ bound states**



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

→ **LLP searches efficiently constrain parameter space for alternative DM production, e.g. via freeze-in**

Beyond WIMP freeze-out



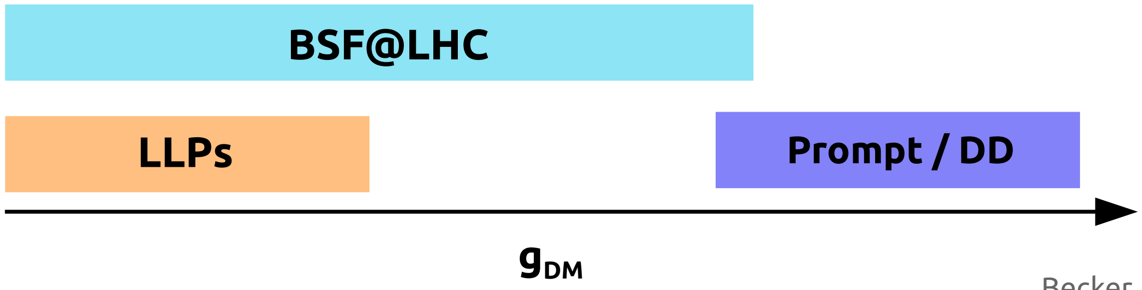
See e.g.: Garny, Heisig (2021), Bollig, Vogl (2021), Decant, Heisig, Hooper, Lopez-Honorez (2021, 2022)

→ **all include now also Sommerfeld effect and bound state formation!!!**

Potential of bound state formation at colliders

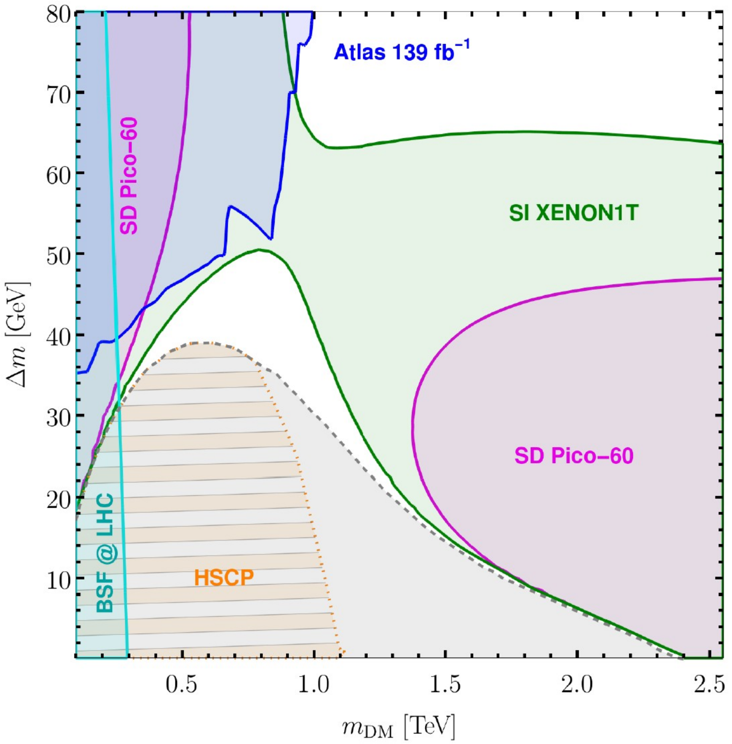
$$\sigma(pp \to \mathcal{B}(XX^\dagger)) = \frac{\pi^2}{8m_\mathcal{B}^3}\mathcal{P}_{gg}\left(\frac{m_\mathcal{B}}{13\ \mathrm{TeV}}\right)\Gamma(\mathcal{B}(XX^\dagger) \to gg)$$

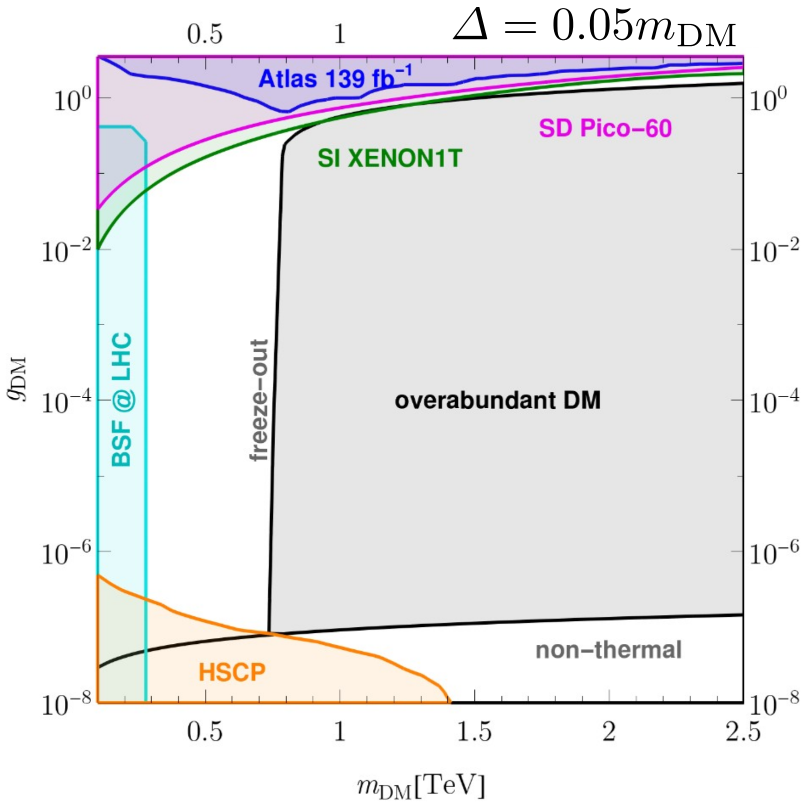
- Resonant production of bound state and subsequent decay (e.g. into photons)
- Dedicated searches, see e.g. *ATLAS coll. Phys. Lett. B 775 (2017) 105*
- Efficient for large range of g_{DM}, as long as $\Gamma_X < E_B$ ($g_{DM} < g_s$, when bound states are efficiently produced)



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

Potential of bound state formation at colliders





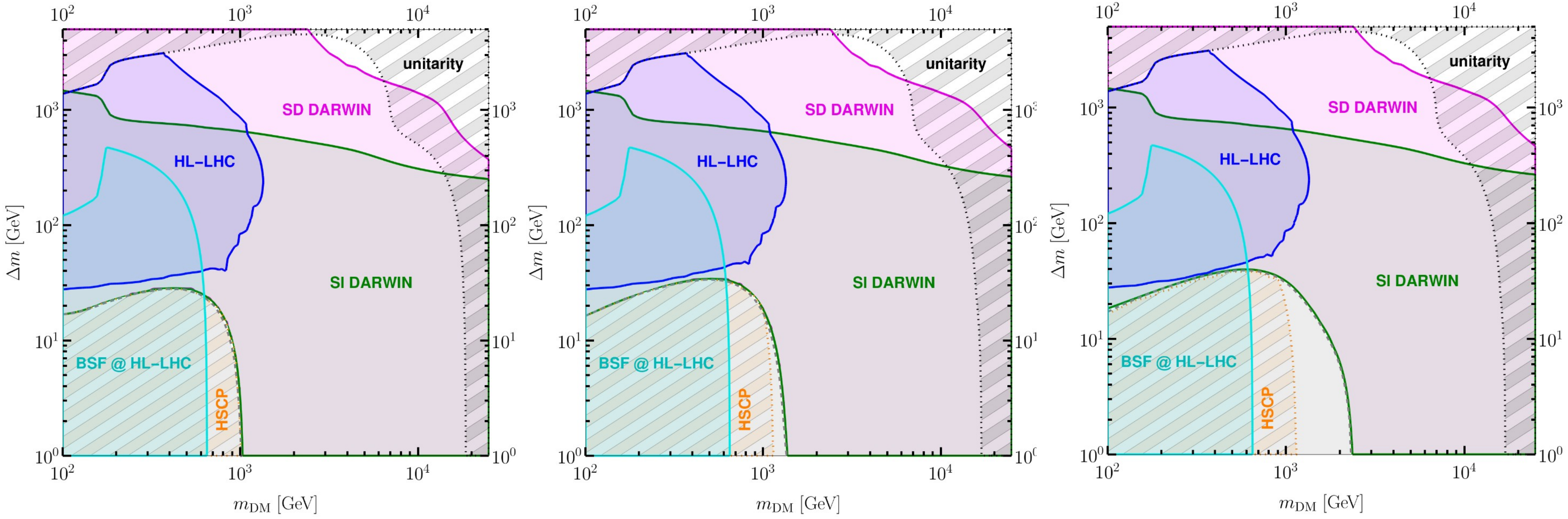
- **limits relatively weak (300 GeV)**

  BUT: closes gap between prompt and LLP searches

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

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

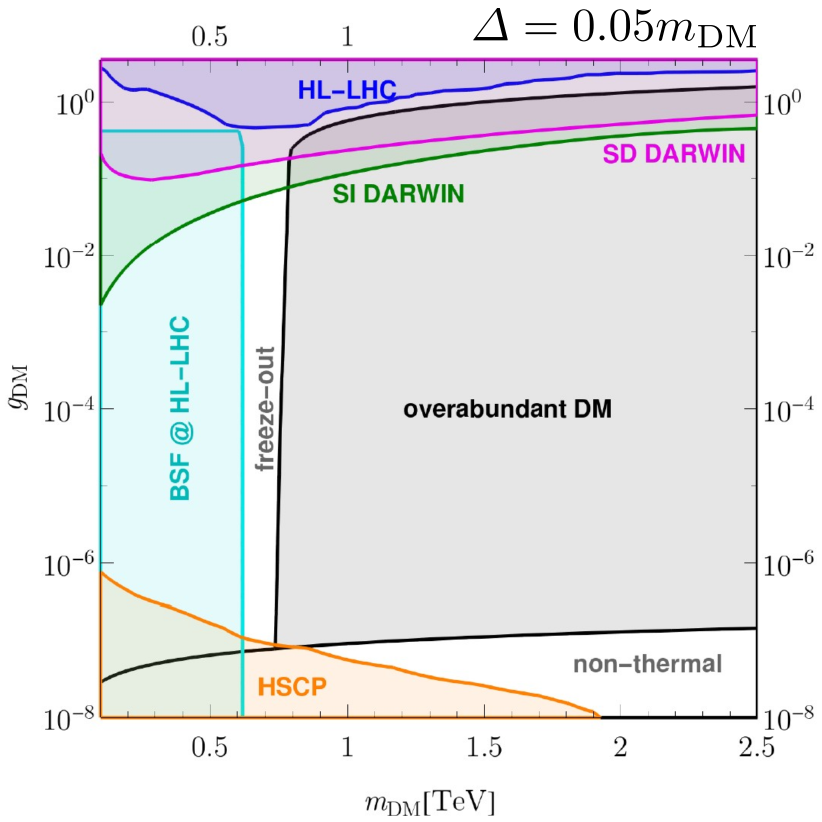
Future prospects



- **Remember: HSPC no strict exclusion limit (BSF@LHC is!)**
- **Highly testable: parameter space can be almost entirely probed (but three regions remain unconstrained!)**
- **BSF effects enlarge parameter range that still needs to be tested**

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

Future prospects for bound states at colliders



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

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

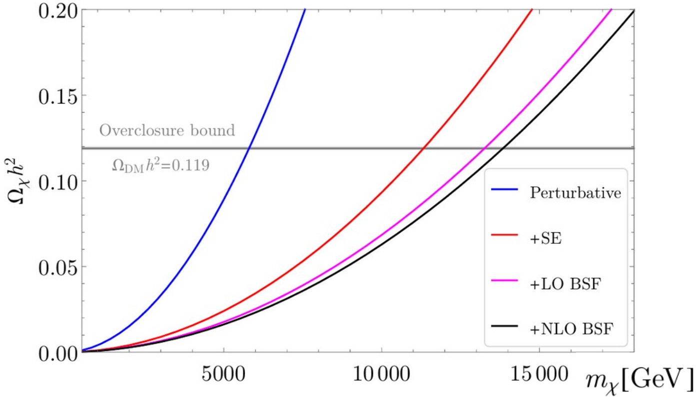
Going beyond finite temperature...

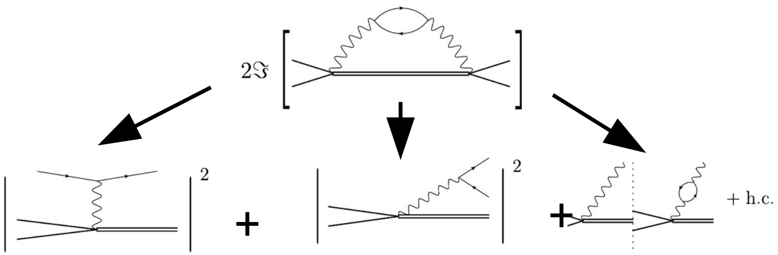
- Development of **finite-T treatment** of bound state formation while still in **ionization equilibrium** Kim, Laine (2017), Biondini, Laine (2018), Biondini (2018), Covi, Binder, Mukaida (2018)

- **Phenomenology of finite-T** treatment of bound state formation while still in **ionization equilibrium** Biondini, Vogl (2018), Biondini, Vogl (2019)

- Presenting **finite-T treatment beyond ionization equilibrium** and comparison to other methods Binder, Blobel, JH, Mukaida (2020)

- **Non-relativistic effective field theory at finite-T treatment** Biondini, Brambilla, Qerimi, Vairo (2023)





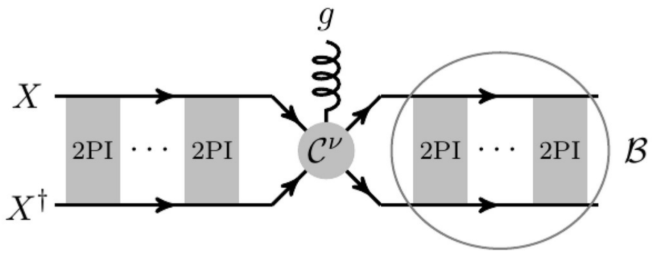
→ **very active research field both from phenomenological aspect as well as methodological one**

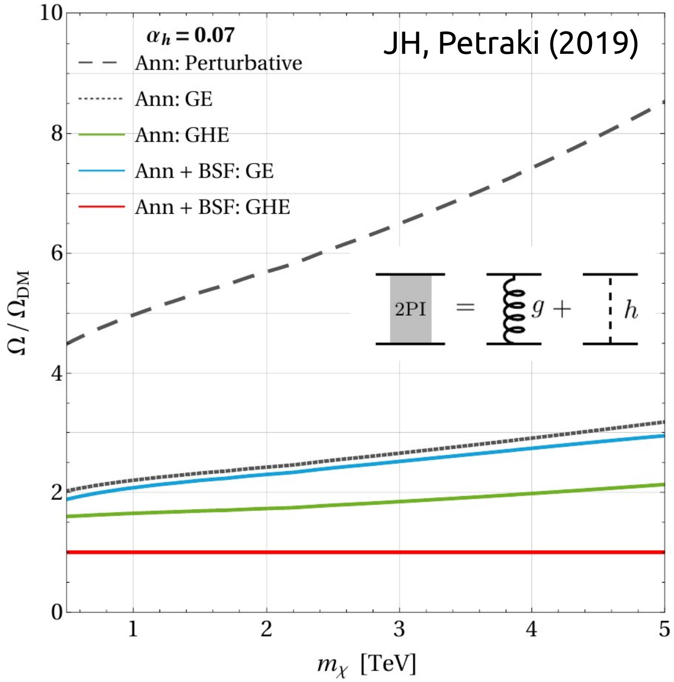
Going beyond coannihilation…

- **Non-perturbative effects are not limited to coannihilation scenarios** (t-channel model just an example to rise awareness)

- Corrections expected for **massless mediators** when v ~ α (Coulomb potential)

- Corrections expected for massive mediators when v ~ α and $\mathbf{m_{med} \ll m_{DM}}$ (Yukawa potential)





Conclusions

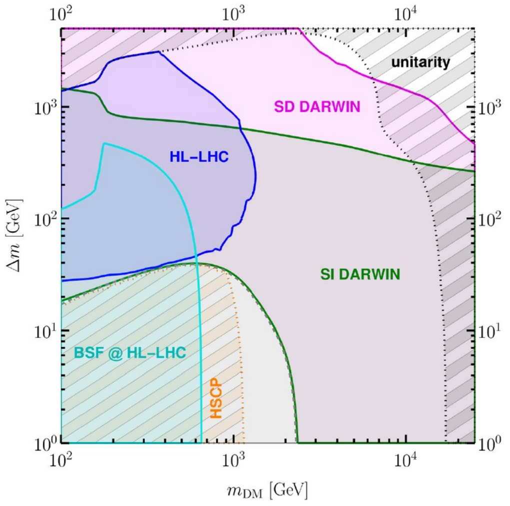
- Sommerfeld effect and bound state formation can

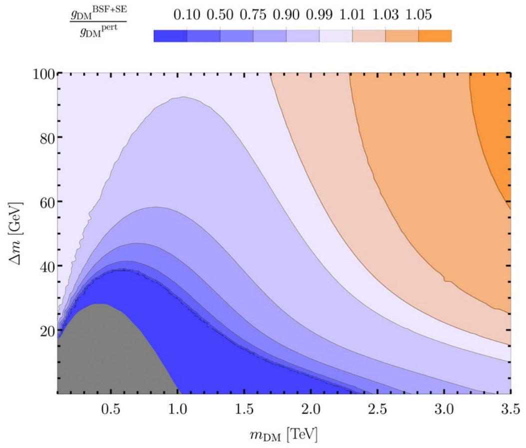
  → alter interpretation of experimental exclusion limits

  → change expected model parameters in case of a discovery

- Parameter space thought to be excluded remains still viable
- Application of a simple flat correction factor not sufficient
- Bound state searches at LHC can close gap for low DM masses
- Not limited to t-channel DM model example or coannihilation

→ For conclusive statements non-pertubative effects are crucial to be taken into account!





Save the date:

Mainz Institute for Theoretical Physics

The Dark Matter Landscape:
From Feeble to Strong Interactions

Organizers: Mathias Becker, JH, Laura Lopez Honorez, Tracy Slatyer, Juri Smirnov

August 26th – September 13th 2024

Thank you for your attention!