Phenomenological Impact of Non-Perturbative Effects for Colored Dark Sectors

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In collaboration with

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Emmy Noether-Programm

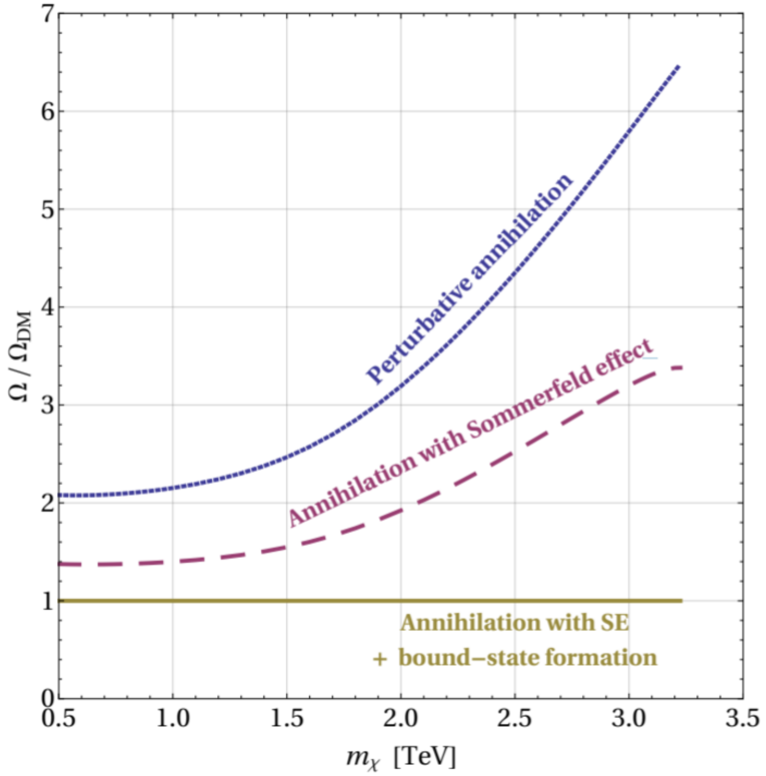
DFG Deutsche Forschungsgemeinschaft

DESY Theory Workshop 2021

Technische Universität München

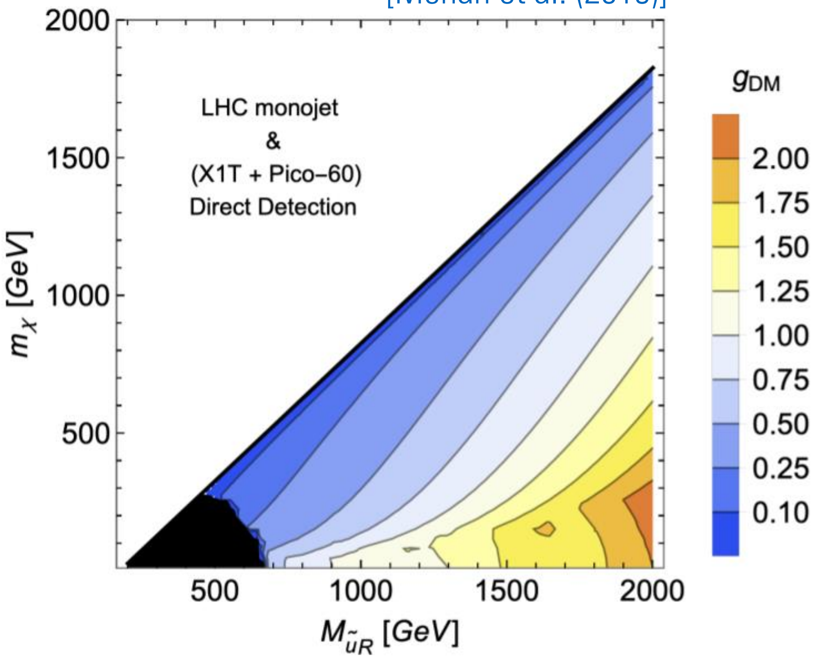
Motivations

[Harz and Petraki (2018)]

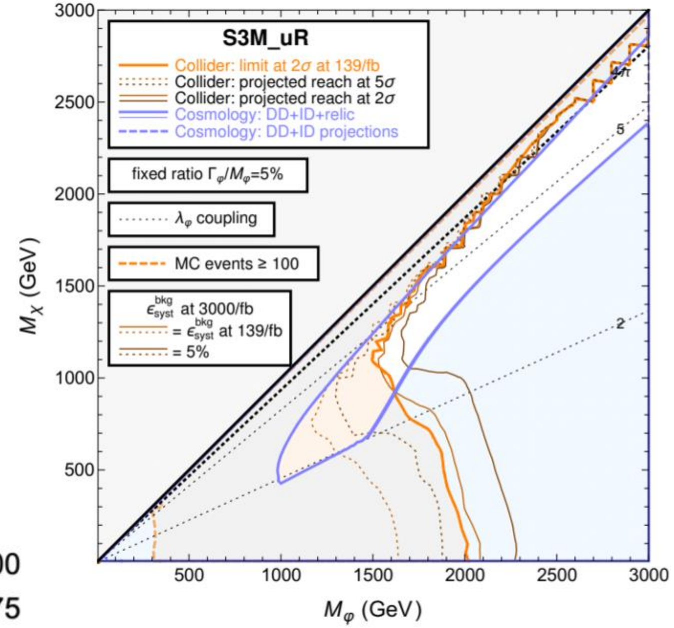


- Non-perturbative effects ✓
- Co-annihilations ✓
- Simplified DM model ✗
- Experimental limits ✗

[Mohan et al. (2019)]



[Arina et al. (2020)]



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- Co-annihilations (✓)
- Simplified DM model ✓
- Experimental limits ✓

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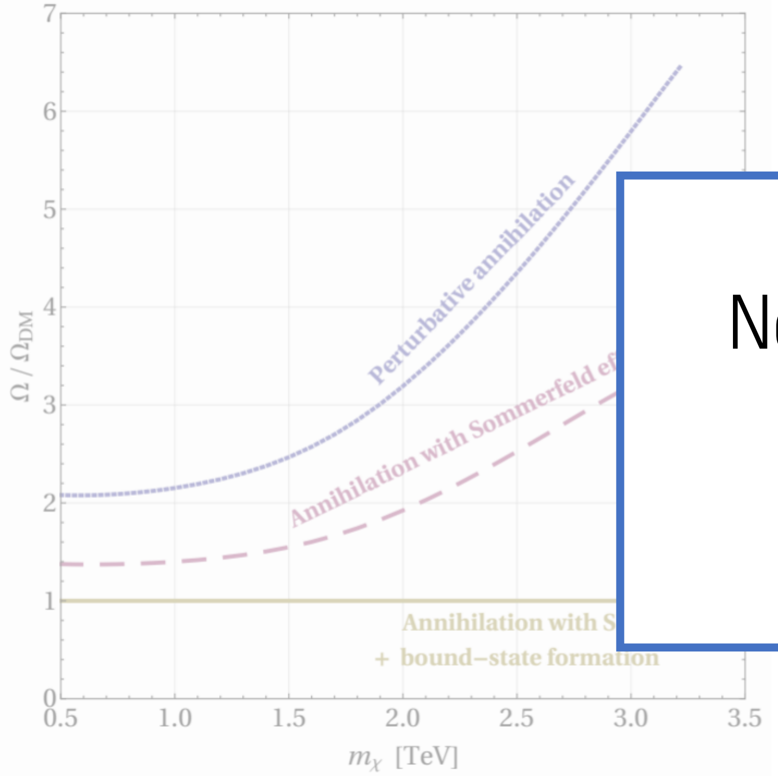

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THIS WORK

- Non-perturbative effects ✓
- Co-annihilation focus ✓
- Simplified DM model ✓
- Experimental limits ✓

[Arina et al. (2020)]

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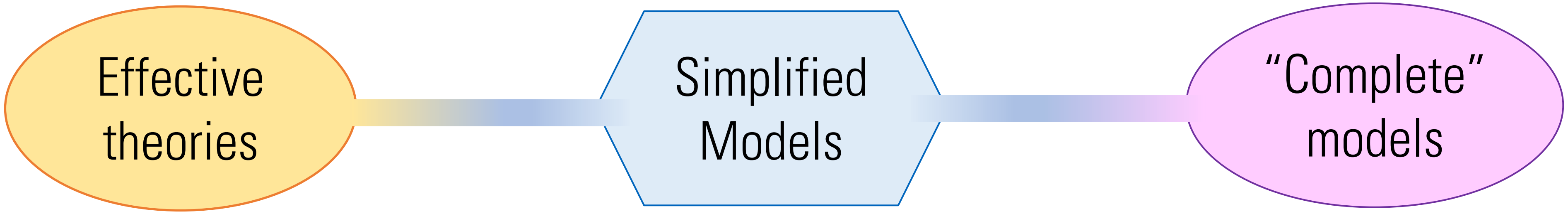
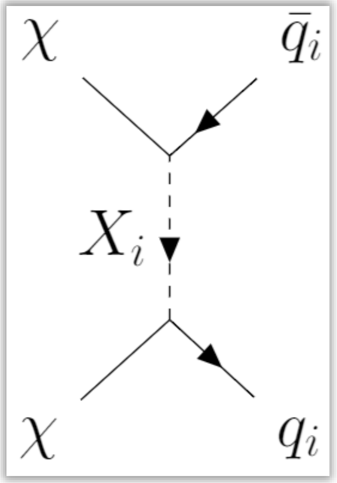
Simplified DM models

Spectrum of Dark Matter theories [Abdallah et al. (2015)]



Simplified t-channel DM models



$$\mathcal{L} \supset \sum_i (D^\mu \tilde{X}_i)^\dagger (D_\mu \tilde{X}_i) - m_X^2 \tilde{X}_i^\dagger \tilde{X}_i + g_{DM} \tilde{X}_i^\dagger \overline{\chi} P_R q_i + h.c.$$

[Mohan et al. (2019)]
[Arina et al. (2020)]
[Arina et al. (2021)]

	$SU(3)_c, SU(2)_L, U(1)_Y$	Model
χ	$(\mathbf{1}, \mathbf{1}, 0)$	
$\tilde{u}$	$(\mathbf{3}, \mathbf{1}, +2/3)$	$\boldsymbol{u_R}$
$\tilde{d}$	$(\mathbf{3}, \mathbf{1}, -1/3)$	$\boldsymbol{d_R}$
$\tilde{q}$	$(\mathbf{3}, \mathbf{2}, -1/6)$	$\boldsymbol{q_L}$

THIS TALK

ASSUMPTIONS

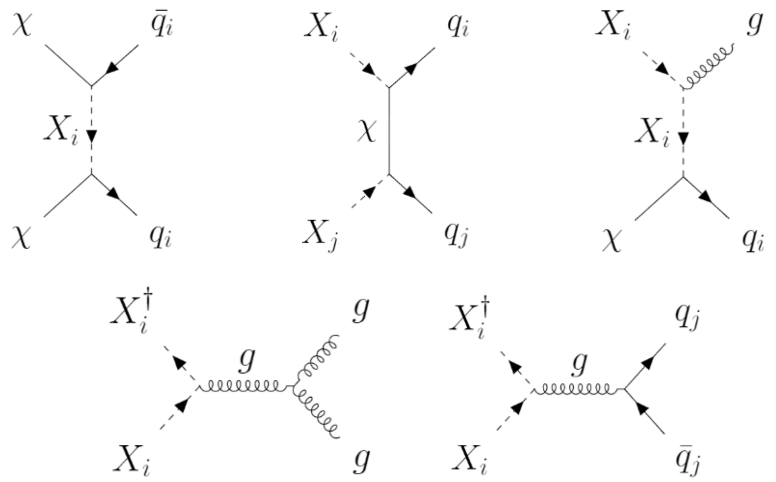
- Discrete $\mathbb{Z}_2$: odd for dark sector
- χ: Majorana and LSP → **DM**
- X_i: 3 flavors, same mass $\boldsymbol{m_X}$
- Democratic diagonal $\boldsymbol{g_{DM}}$

Freeze-out with co-annihilations

Co-annihilating region → $\Delta M = m_X - m_{\text{DM}} \ll m_{\text{DM}}$
Parameter space: $\{\boldsymbol{m_{\text{DM}}}, \boldsymbol{\Delta M}, \boldsymbol{g_{\text{DM}}}\}$

ASSUMPTIONS [Ellis et al. (2015)]
- Dark-visible sectors in kinetic equilibrium
- Chemical equilibrium within dark sector

$$\frac{d\tilde{Y}}{dx} = -\frac{c g_{*,\text{eff}}^{1/2}}{x^2} \langle \sigma_{\text{eff}} v_{\text{rel}} \rangle \left(\tilde{Y}^2 - \tilde{Y}_{\text{eq}}^2\right) \qquad \tilde{Y} = \sum_{i=\{\chi,X\}} Y_i \qquad \Omega_{\text{DM}} h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle}$$



...

$$\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle = \sum_{i,j=\{\chi,X\}} \langle \sigma_{ij} v_{ij} \rangle \frac{Y_i^{\text{eq}} Y_j^{\text{eq}}}{\left(\tilde{Y}^{\text{eq}}\right)^2}$$

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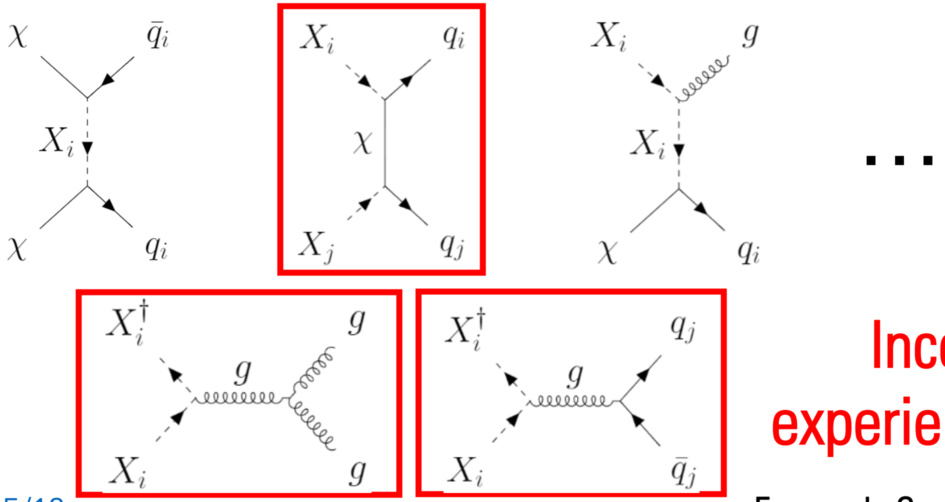

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Incoming colored states will experience gluonic long-range force!

Long-range non-perturbative effects

$$V_{\text{gluon}}^{[\hat{\mathbf{R}}]}(r) = -\frac{\alpha_g^{[\hat{\mathbf{R}}]}}{r} = -\frac{\alpha_s}{2r}\left[C_2(\mathbf{R_1}) + C_2(\mathbf{R_2}) - C_2(\hat{\mathbf{R}})\right]$$

$$\mathbf{R}_1 \otimes \mathbf{R}_2 = \sum \hat{\mathbf{R}}$$

$C_2(\mathbf{R})$: quadratic Casimir

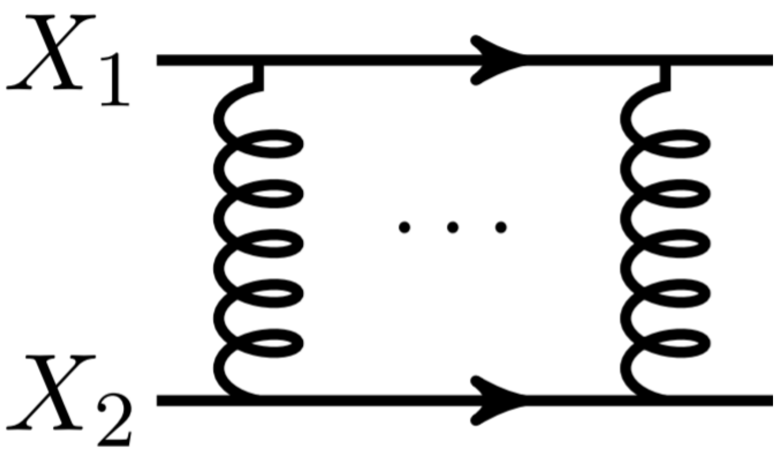
Colored states feel long-range forces → Wavefunctions of incoming particles are distorted

In non-relativistic regime, $\alpha_g \sim v_{\text{rel}}$, their interactions can be **enhanced** or **suppressed**.

SOMMERFELD EFFECT

Effect captured by **ladder diagram** (2PI-resummed):

n gluon exchanges contribute as $\left(\frac{\alpha_g}{v_{\text{rel}}}\right)^n \sim 1$



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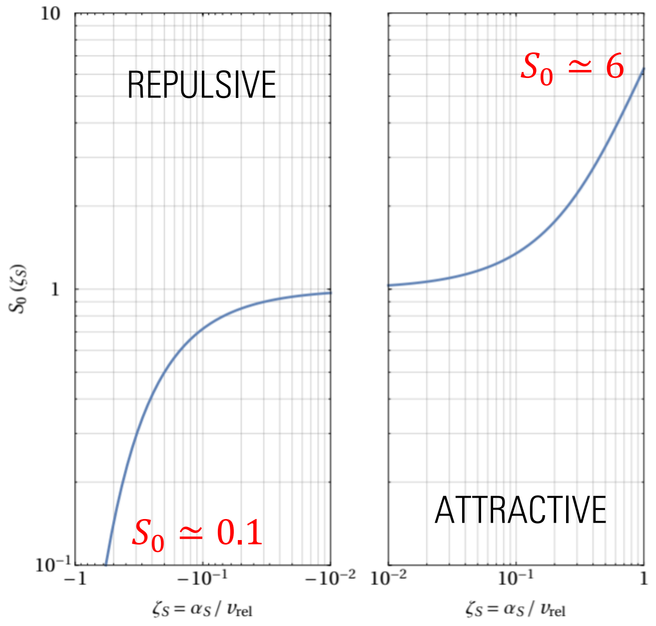
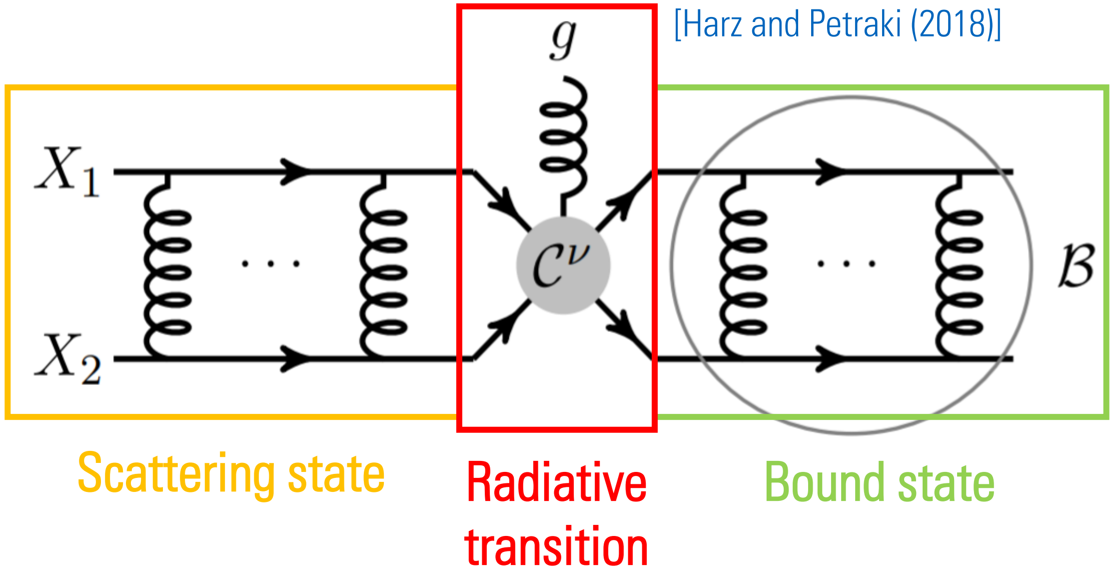
SOMMERFELD EFFECT

$$\langle \sigma^{\text{SE}} v_{\text{rel}} \rangle = \langle \sigma_0 S_0^{[\hat{\mathbf{R}}]} \rangle \to \langle \sigma_0 \frac{\alpha_g^{[\hat{\mathbf{R}}]}}{v_{\text{rel}}} \rangle, \; v_{\text{rel}} \ll 1$$



[Harz and Petraki (2018)]

Long-range non-perturbative effects

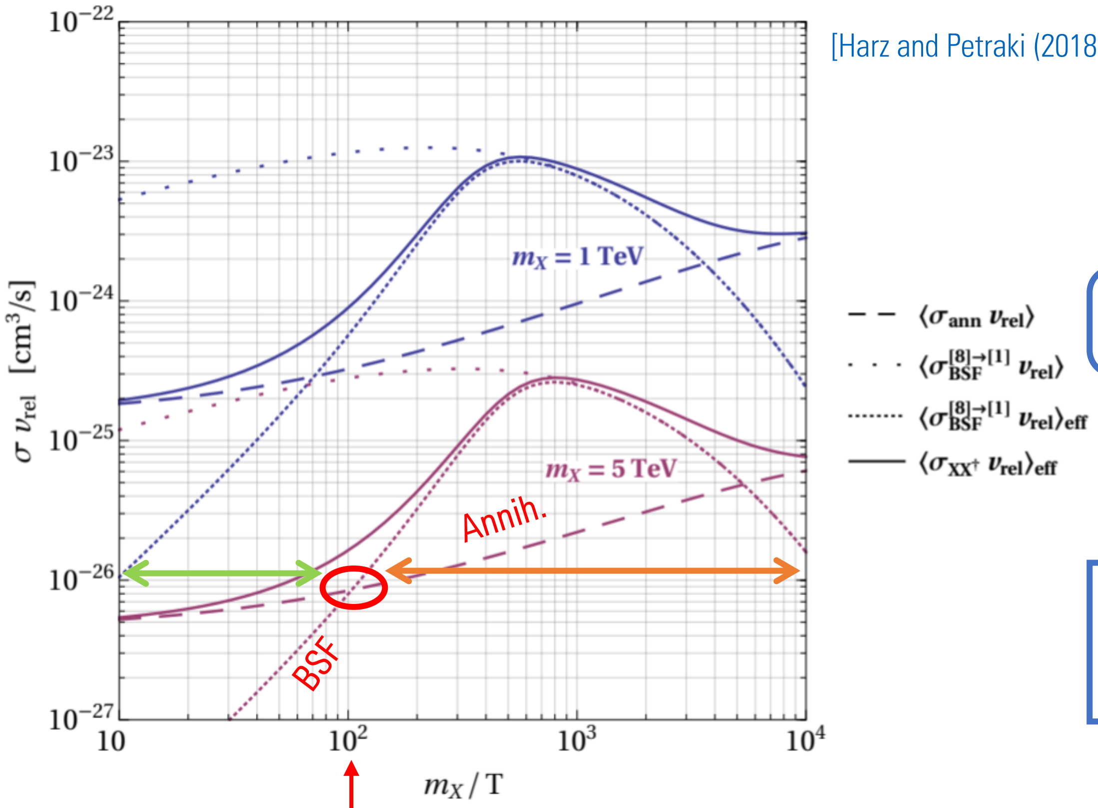


BOUND STATE FORMATION

$X_1 + X_2 \to \mathcal{B}(X_1X_2) + g$	$\mathcal{B}(X_1X_2) + g \to X_1 + X_2$	$\mathcal{B}(X_1X_2) \to g + g$
FORMATION	IONISATION	DECAY
$\sigma^{\mathrm{BSF}} v_{\mathrm{rel}} \simeq \sigma^{\mathrm{tree}} S_{\mathrm{BSF}}$	$\Gamma_{\mathrm{Ion.}} \propto \sigma^{\mathrm{BSF}}$	$\Gamma_{\mathrm{Dec.}} \sim \sigma_{\mathrm{ann.}} \lvert\psi_{\mathrm{BS}}(0)\rvert^2$

Co-annihilations with BSF

$$\langle\sigma_{\rm eff} v_{\rm rel}\rangle = \sum_{i,j=\{\chi,X\}} \langle\sigma_{ij} v_{ij}\rangle \frac{Y_i^{\rm eq} Y_j^{\rm eq}}{(\tilde{Y}^{\rm eq})^2} + \langle\sigma_{\rm BSF} v_{\rm rel}\rangle_{\rm eff} \frac{(Y_X^{\rm eq})^2}{(\tilde{Y}^{\rm eq})^2}$$



[Harz and Petraki (2018)]

BSF dominant from $x = m/T \sim 100$!!

$$\langle\sigma_{\rm BSF} v_{\rm rel}\rangle_{\rm eff} = \langle\sigma_{\rm BSF} v_{\rm rel}\rangle \frac{\Gamma_{\rm decay}}{\Gamma_{\rm decay} + \Gamma_{\rm ionization}}$$

$\mathcal{B}(X_1 X_2) \to g + g$

$X_1 + X_2 \to \mathcal{B}(X_1 X_2) + g$

$\mathcal{B}(X_1 X_2) + g \to X_1 + X_2$

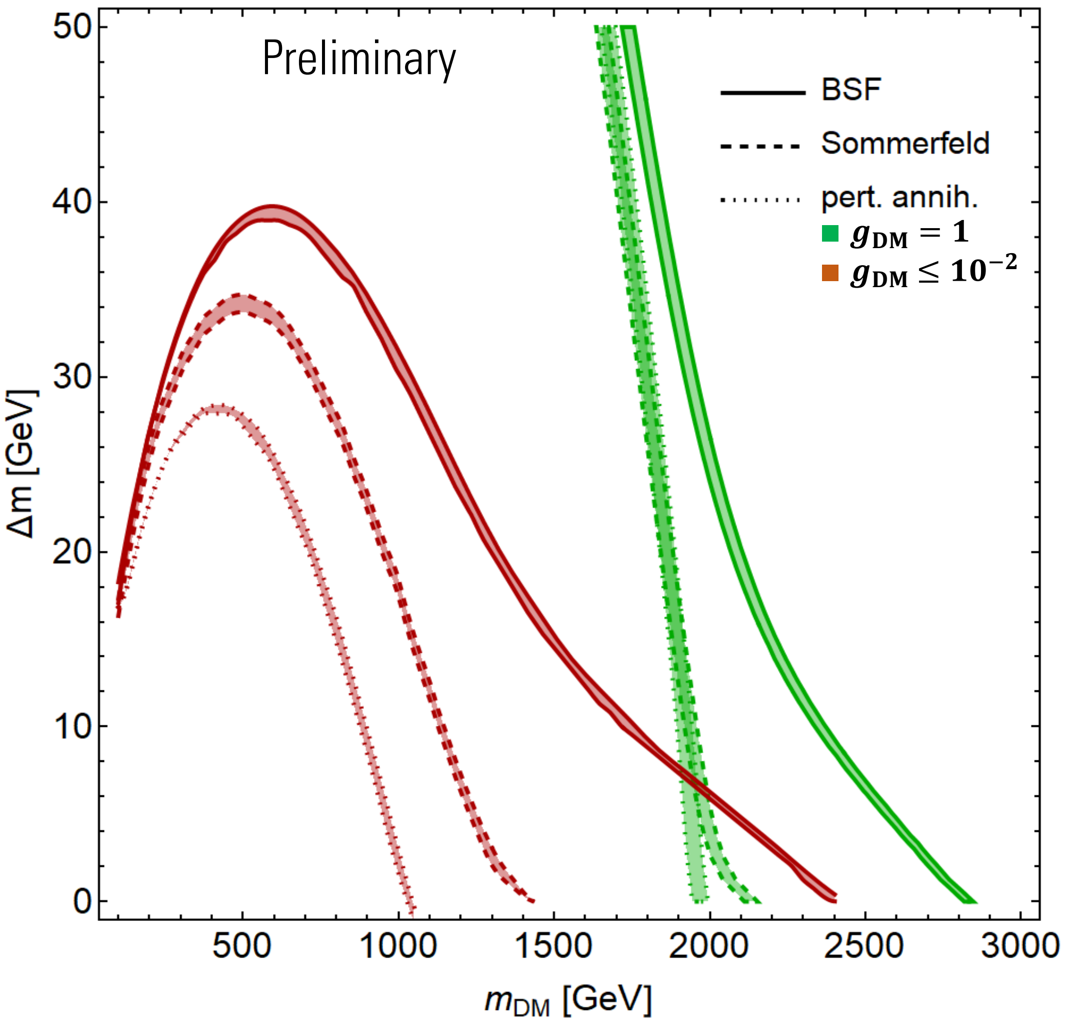
Large T	$\Gamma_{\rm Ion} \gg \Gamma_{\rm Dec}$	$\Rightarrow$	$\langle\sigma_{\rm BSF} v_{\rm rel}\rangle_{\rm eff} \to 0$
Small T	$\Gamma_{\rm Ion} \ll \Gamma_{\rm Dec}$	$\Rightarrow$	$\langle\sigma_{\rm BSF} v_{\rm rel}\rangle_{\rm eff} \to \langle\sigma_{\rm BSF} v_{\rm rel}\rangle$

Relic Density calculation: “mass spectrum”

micrOMEGAs 5.2.7 ***modified*** with **Sommerfeld** effect and **BSF** for **colored** particles
→ consistent with *Harz and Petraki (2018)*

- Dramatic change in DM density with SE or BSF for small g_{DM} when $\Delta m \ll m_{\mathrm{DM}}$.
- For $g_{\mathrm{DM}} \sim \mathcal{O}(1)$ still sizable effects
- Stronger effective annihilations
  → larger DM masses needed
  → larger mass splittings Δm

Becker, **EC**, Harz, Mohan, Sengupta



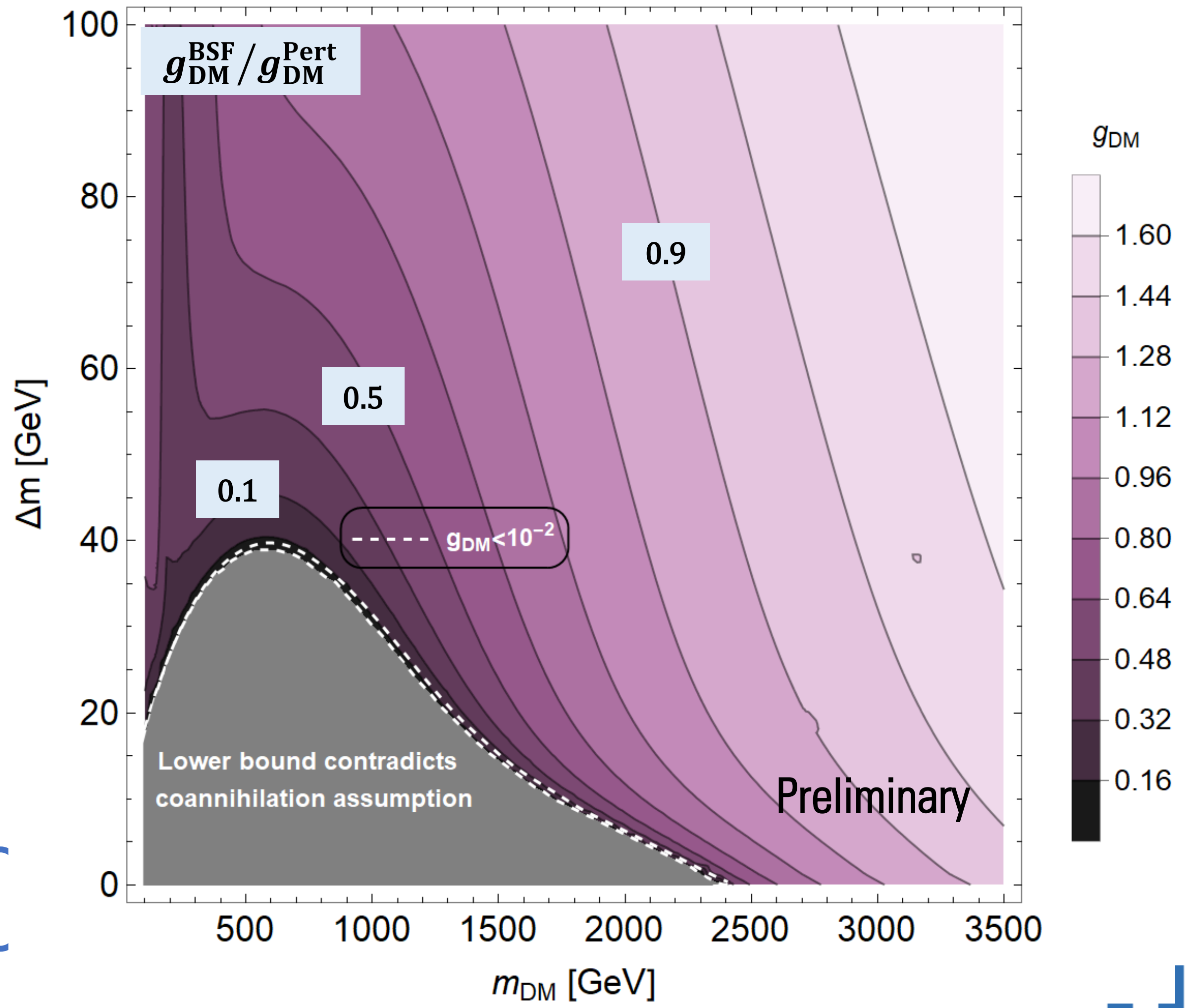
Relic Density calculation: lower bound on $g_{\rm DM}$

micrOMEGAs 5.2.7 ***modified*** with **Sommerfeld** effect and **BSF** for **colored** particles
→ consistent with *Harz and Petraki (2018)*

- $g_{\rm DM}^{\rm BSF}$ lower than $g_{\rm DM}^{\rm Pert.}$ up to ~ 10
- White dashed lines: $10^{-7} \leq g_{\rm DM} \leq 10^{-2}$
- Grey region: $g_{\rm DM}$ too small for freeze-out and coannihilation assumptions → freeze-in + LLP searches (in progress…)

Smaller $g_{\rm DM} \Rightarrow$ experimental limits evasion

Becker, **EC**, Harz, Mohan, Sengupta

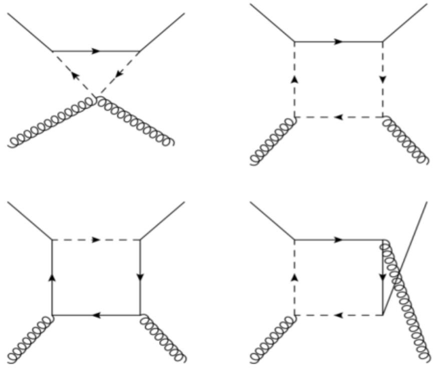


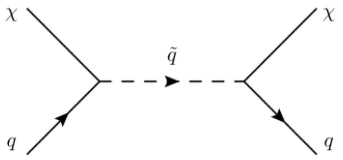
Direct detection constraints

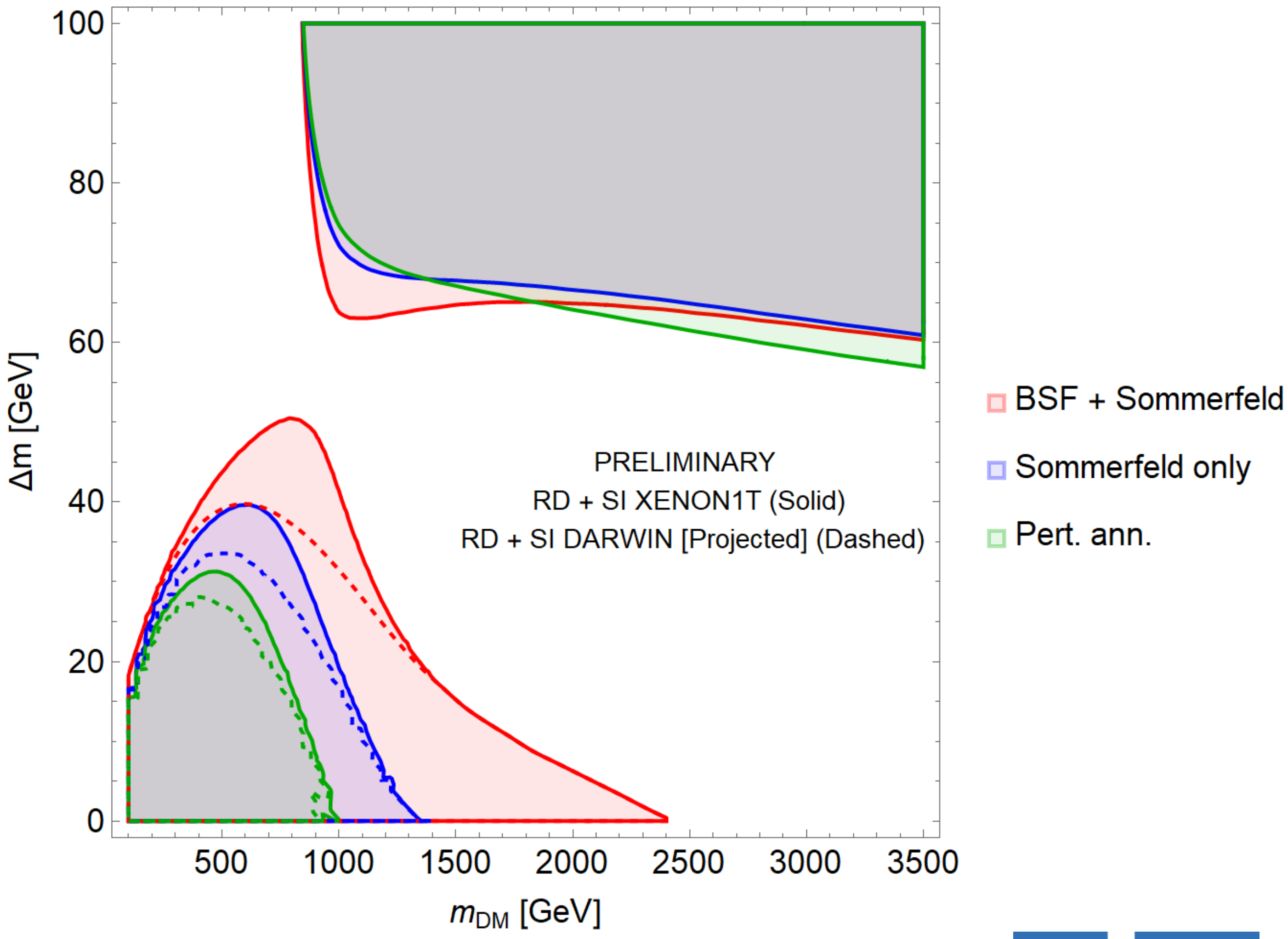
Becker, **EC**, Harz, Mohan, Sengupta

1-loop contribution to SI scattering (tree-level absent due to Majorana nature)
RGE evolution from $\mu \sim m_X$ to $\mu \sim$ GeV

[Mohan et al. (2019)]







SI limits with NLO contributions more constraining than SD limits

Adding LHC data…

Dominant processes of interest:

$gg \to \tilde{q}\tilde{q}$ (mediator pair production)

$qg \to \tilde{q}\chi$ (associated production)

Analyses utilized:

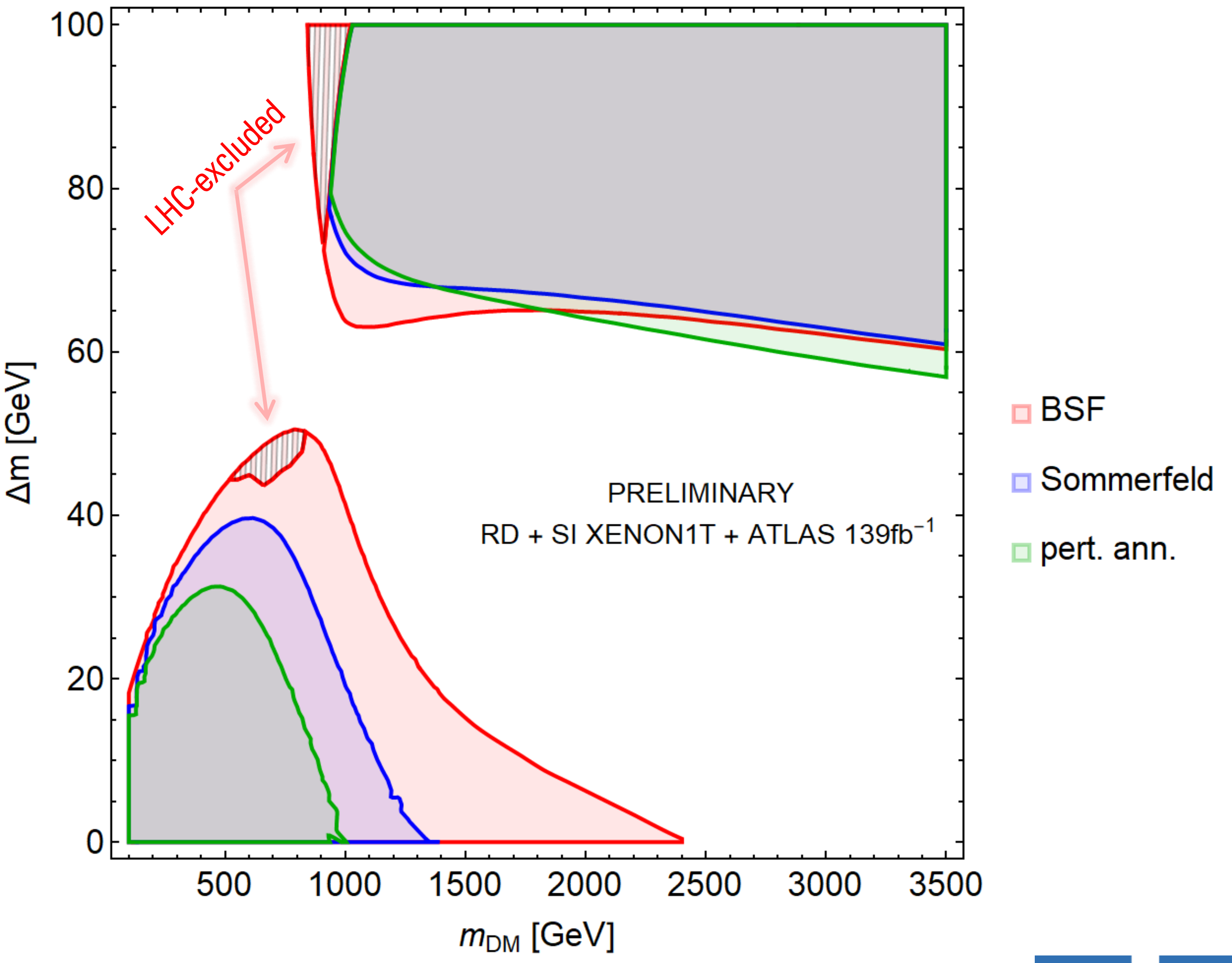
Mono-jet + MET [Atlas (2021)]

Multi-jet + MET [Atlas (2020)]

DD limits more important than LHC in this parameter region

- Largest m_{DM}: $1\ \mathrm{TeV} \to 2.4\ \mathrm{TeV}$
- Larger $\Delta m = m_X - m_{\mathrm{DM}}$

Becker, **EC**, Harz, Mohan, Sengupta



Conclusions

- Non-perturbative effects must be included when dark sector joins long-range interactions (e.g., QCD) → substantial alteration of DM relic abundance.

- Co-annihilating uR model: largest DM mass can be 2.5 times than without BSF and SE; mass splittings DM-mediators also larger (dR and qL in progress, effects similar)
→ multi-TeV region remains interesting

- SI DD provides stronger limits than LHC. But: small $m_{\rm DM}$ and small ΔM implies $g_{\rm DM} < 10^{-7}$
→ potentially interesting for LLPs searches (in progress).

- Future: - full micrOMEGAs implementation of SE and BSF for colored particles (other reps.)
  - Analysis with other potentially interesting simplified models.
  - Inclusion of SE and BSF from Yukawa potential (e.g., Higgs)
    → even stronger effects (see [Harz and Petraki (2019)])

Thank you for your attention!

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