# Impact of Sommerfeld enhancement and bound state formation in simplified t-channel models

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**in collaboration with**

**Mathias Becker, Emanuele Copello, Kirtimaan Mohan and Dipan Sengupta**

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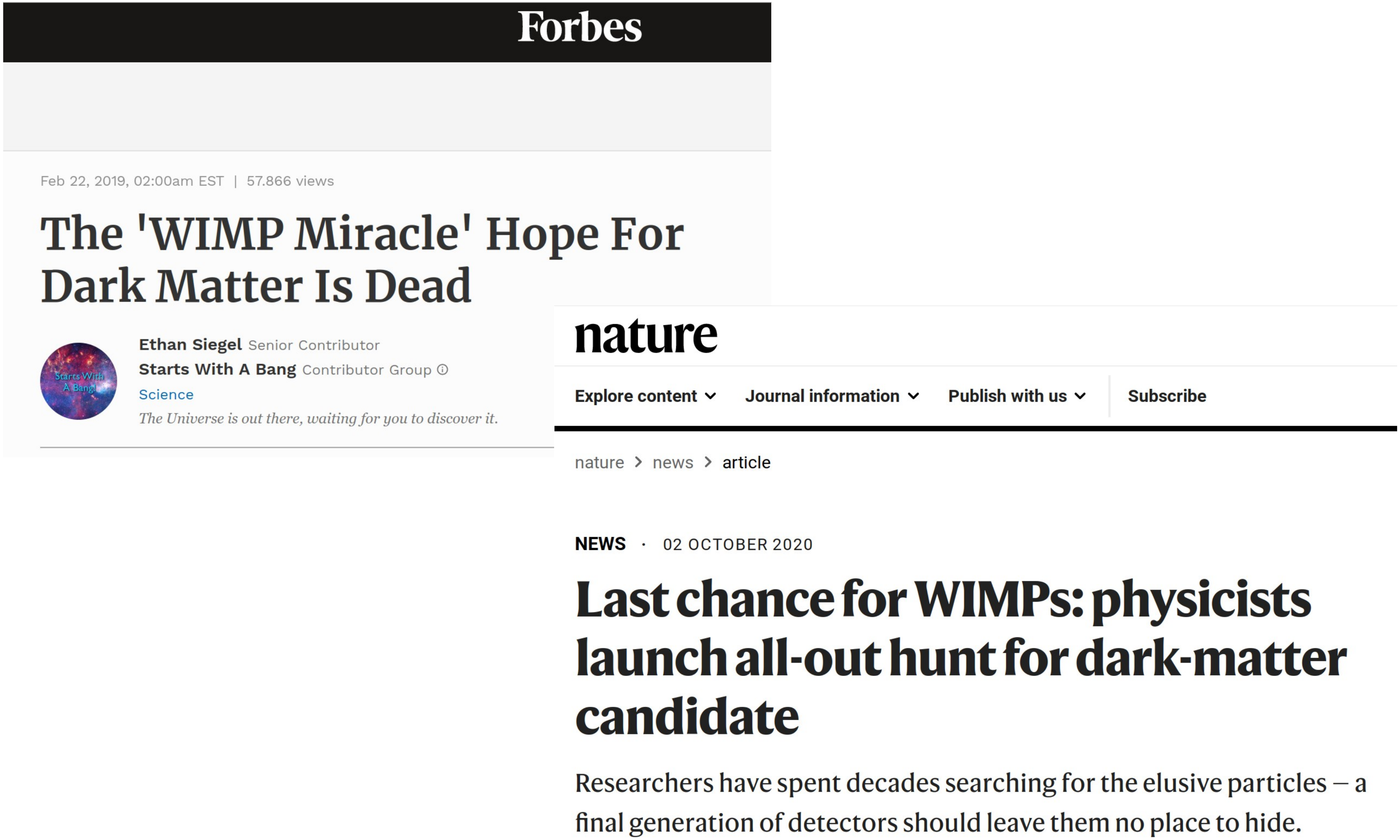
*LHC DM working group workshop*

Technische Universität München

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

# Motivation



Forbes

Feb 22, 2019, 02:00am EST | 57.866 views

## The 'WIMP Miracle' Hope For Dark Matter Is Dead

**Ethan Siegel** Senior Contributor
**Starts With A Bang** Contributor Group
Science
*The Universe is out there, waiting for you to discover it.*

---

nature

**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.

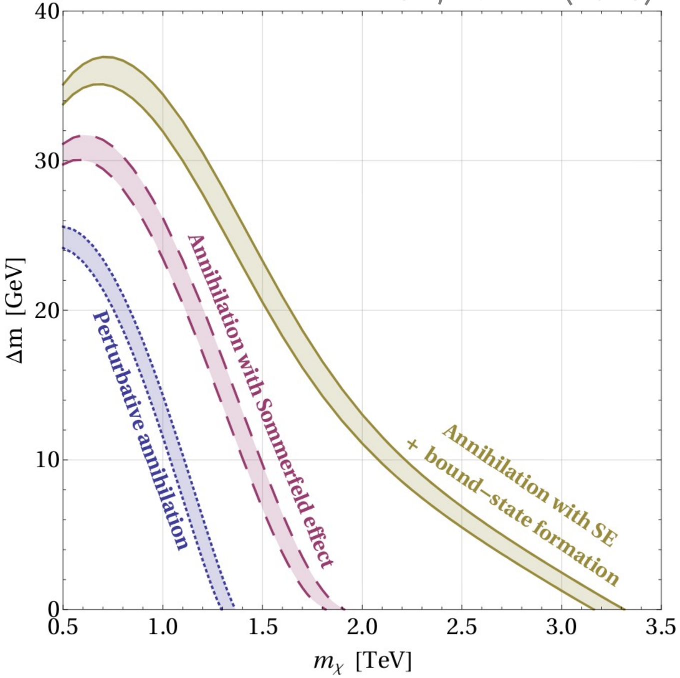
# Motivation

- **WIMPs are not dead!**
- **(Colored) coannihilation scenarios could explain the no-show (higher expected DM masses)**
- **t-channel simplified models are perfect examples for colored coannihilation scenarios**
- **effects of Sommerfeld enhancement and bound state formation can be huge**

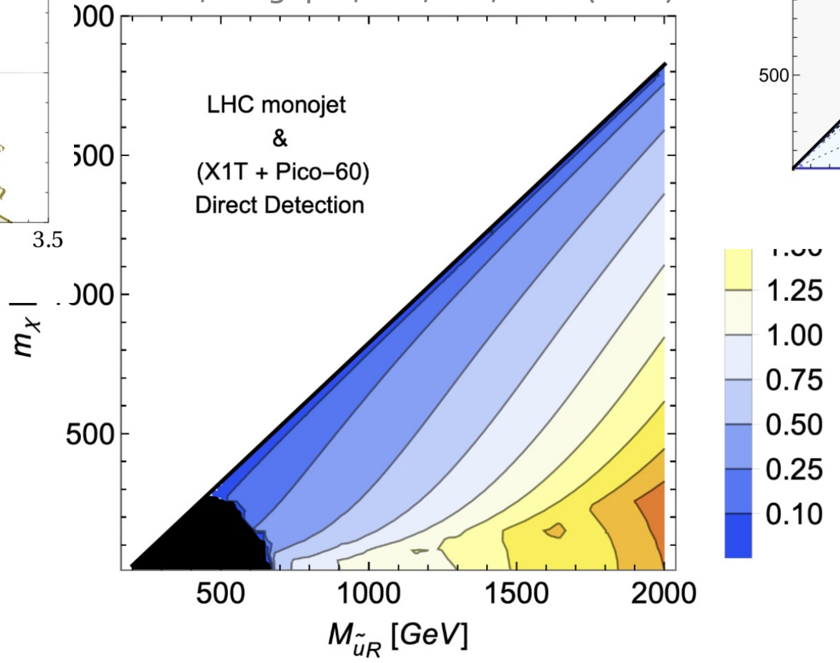
**→ How do non-perturbative effects impact our understanding of the favoured / excluded parameter space of t-channel models?**

# Motivation

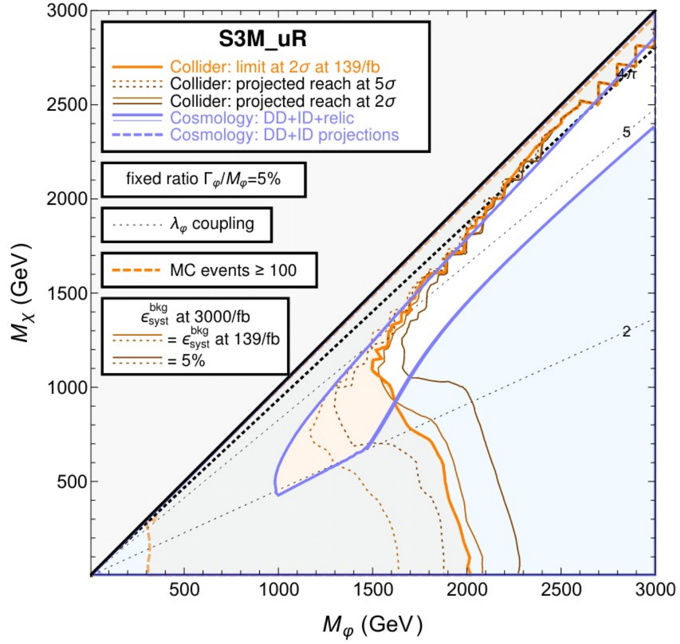
JH, Petraki (2018)



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



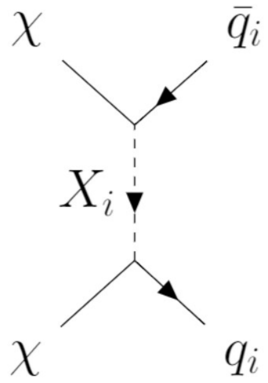
Arina, Fuks, Mantani, Mies, et al. (2020)



→ **How do non-perturbative effects impact our understanding of the favoured / excluded parameter space of t-channel models?**

# Simplified t-channel model

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



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

**Assumptions:**

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

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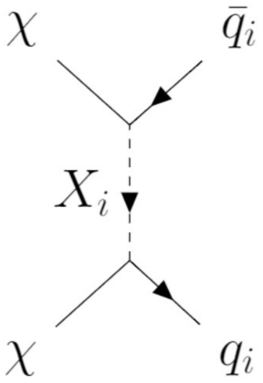

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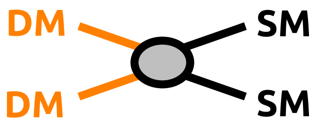
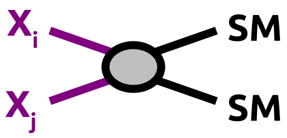
# Dark Matter freeze-out with coannihilations



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

# Dark Matter freeze-out with coannihilations



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

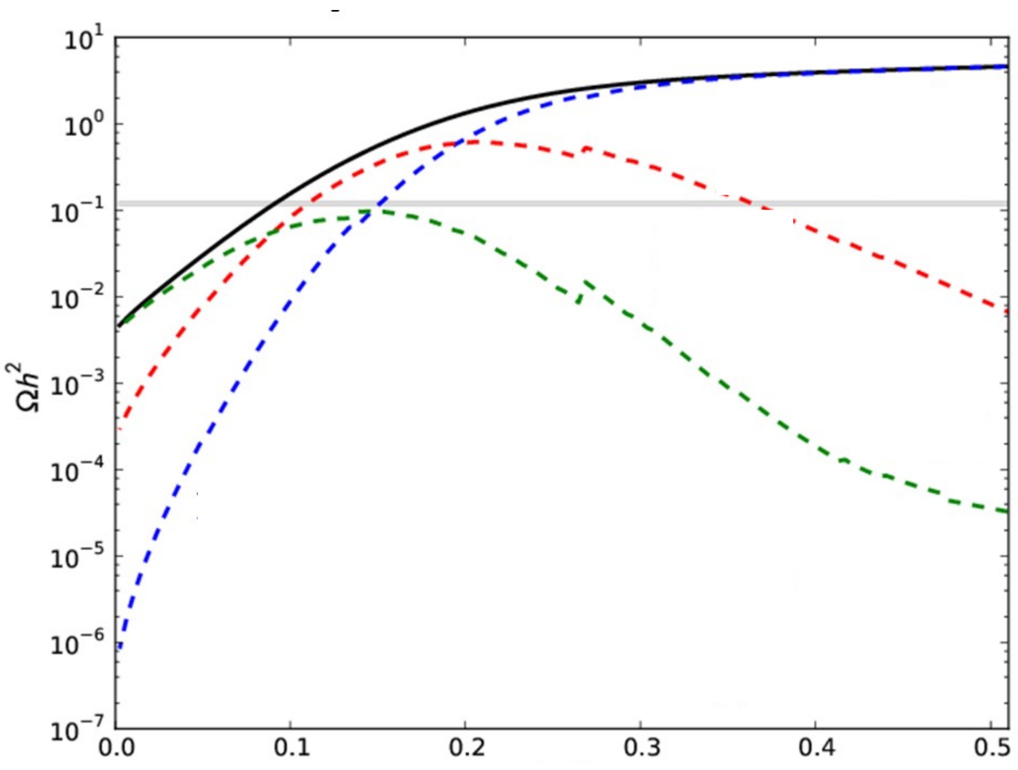
$$n = \sum_{i=1}^{N} n_i \qquad \frac{n_i}{n} \approx \frac{n_{\mathrm{eq},i}}{n_{\mathrm{eq}}}$$

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

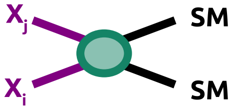
$$\langle\sigma_{\mathrm{eff}}v_{\mathrm{rel}}\rangle = \sum_{ij}\langle\sigma_{ij}v_{ij}\rangle\frac{n_{\mathrm{eq},i}}{n_{\mathrm{eq}}}\frac{n_{\mathrm{eq},j}}{n_{\mathrm{eq}}}$$

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

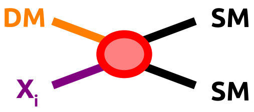
→ **for small mass splittings: co-annihilation**



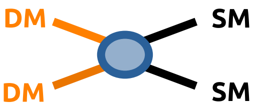
$$\delta \equiv \frac{m_i - m_\chi}{m_\chi}$$



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



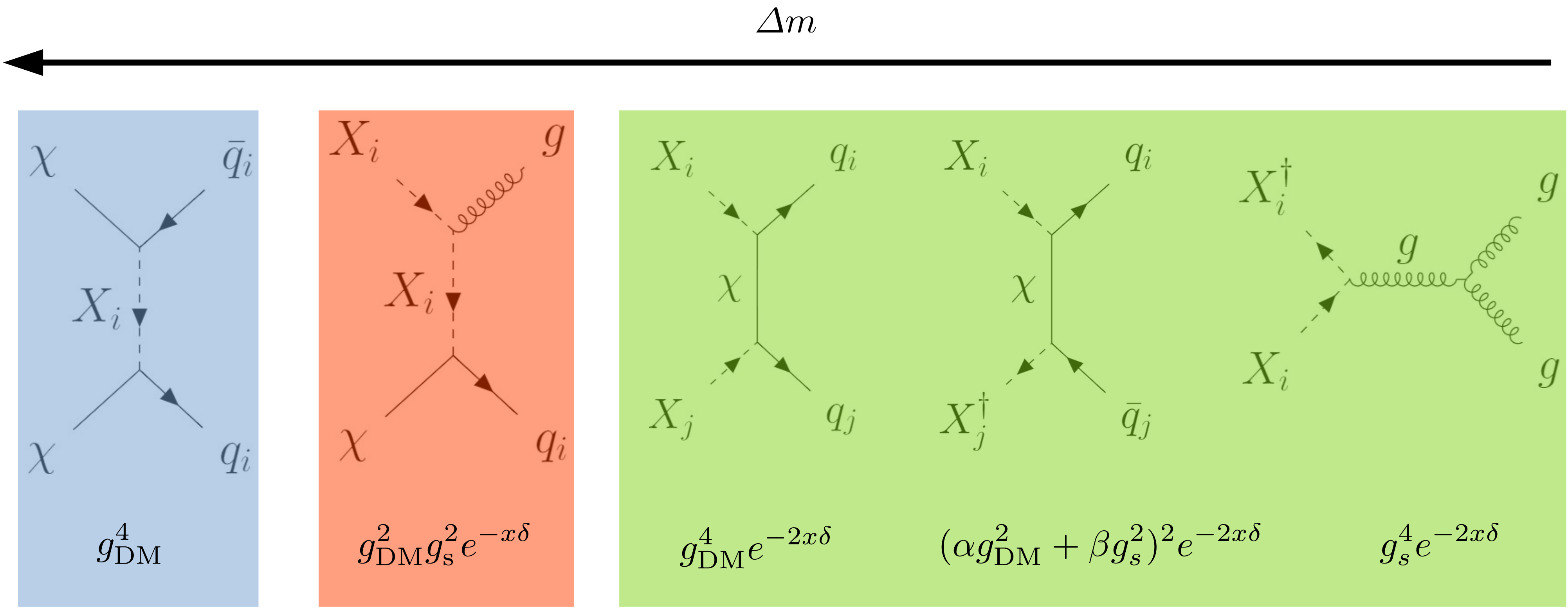
$$\frac{n_{\mathrm{eq},i}}{n_{\mathrm{eq}}} \cdot 1$$



$$1 \cdot 1$$

# Contributing processes to relic abundance

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



$g^4_{\mathrm{DM}}$

$g^2_{\mathrm{DM}} g^2_{\mathrm{s}} e^{-x\delta}$

$g^4_{\mathrm{DM}} e^{-2x\delta}$

$(\alpha g^2_{\mathrm{DM}} + \beta g^2_s)^2 e^{-2x\delta}$

$g^4_s e^{-2x\delta}$

# Effective Boltzmann description

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

preliminary

**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

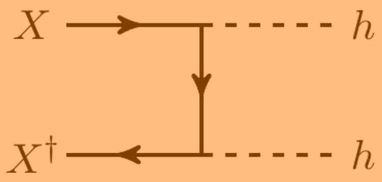
$$\Gamma(X + SM \longleftrightarrow \chi + SM) >> H$$

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

# Towards new standards for the DM abundance

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

**Tree level annihilation**



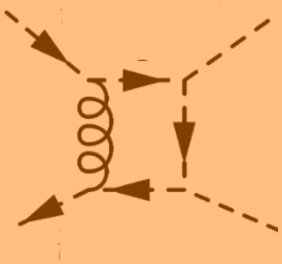
$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{tree}} v_{\text{rel}}$$

DM codes include *only* tree level

# Towards new standards for the DM abundance

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

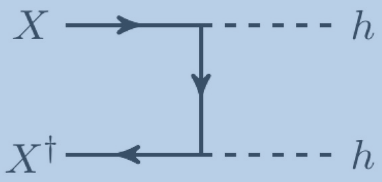
**Higher order corrections**



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

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)
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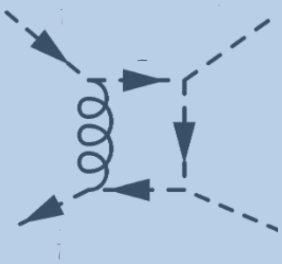
# Towards new standards for the DM abundance

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

### Higher order corrections



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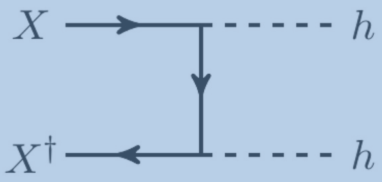

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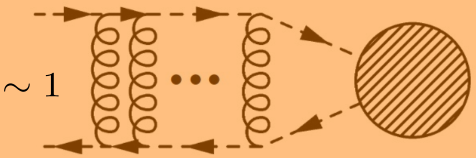
### Sommerfeld enhancement

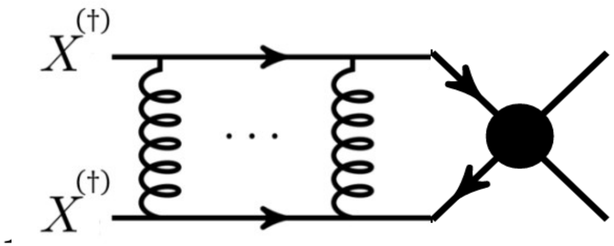
$$\left(\frac{\alpha}{v_{\mathrm{rel}}}\right)^n \sim 1$$



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

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

# Sommerfeld enhancement



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

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

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

with

$$V^{S}_{[\hat{\mathbf{R}}]}(r) = -\frac{\alpha_s^S C_{[\hat{\mathbf{R}}]}}{r}$$

$$C_{[\hat{\mathbf{R}}]} = \frac{1}{2}[C_2(\mathbf{R_1}) + C_2(\mathbf{R_1}) - C_2(\hat{\mathbf{R}})]$$

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

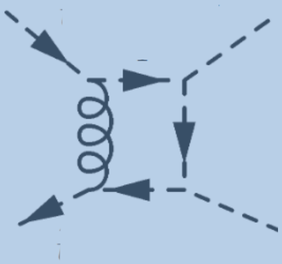
$$V(r)_{\mathbf{3}\otimes\mathbf{3}} = \begin{cases} -\frac{2}{3}\frac{\alpha_s^S}{r} & [\bar{\mathbf{3}}] \quad \textbf{attractive} \\ +\frac{1}{3}\frac{\alpha_s^S}{r} & [\mathbf{6}] \quad \textbf{repulsive} \end{cases}$$

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

# Towards new standards for the DM abundance

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

## Higher order corrections

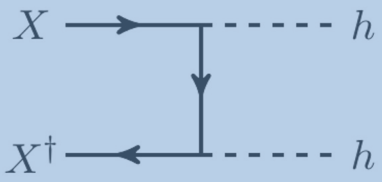


$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{NLO}} v_{\text{rel}}$$

sizeable corrections to the DM abundance

**first study of theoretical error on relic abundance**

## Tree level annihilation



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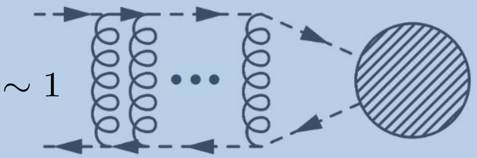
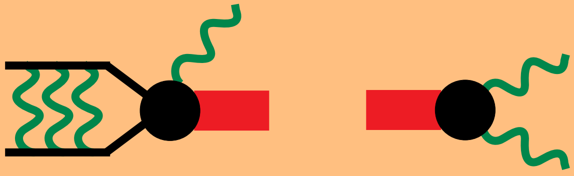
## Sommerfeld enhancement

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



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

## 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 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)
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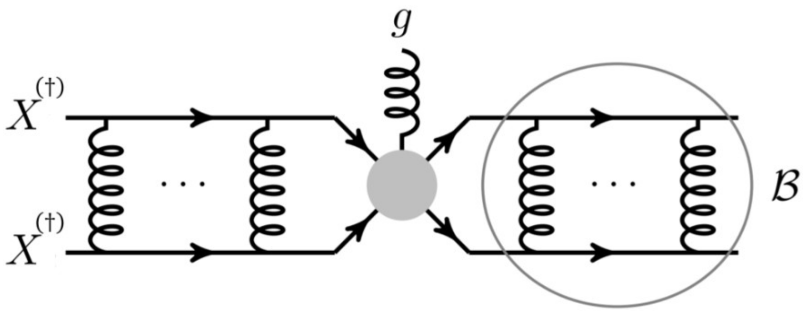
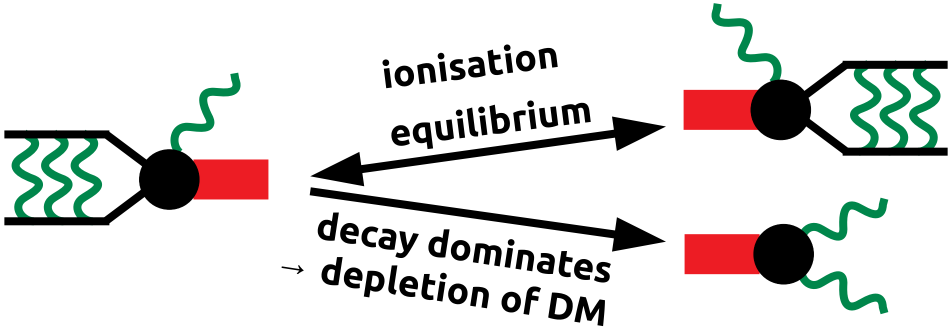
# Bound states formation and decay





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

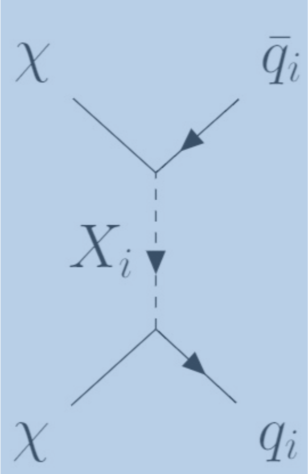
$$\langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle_{\mathrm{eff}} = \langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle \times \left( \frac{\Gamma_{\mathrm{dec}}}{\Gamma_{\mathrm{dec}} + \Gamma_{\mathrm{ion}}} \right)$$

→ **additional "annihilation" channel alters the relic density prediction**

# Contributing processes to relic abundance

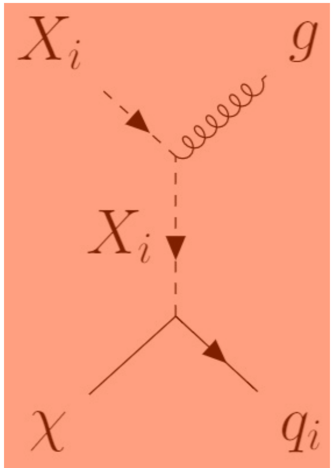
$$\mathcal{L} \supset \sum_i (D_\mu X_i)^\dagger (D^\mu X_i) + g_{\mathrm{DM},ij} X_i^\dagger \bar{\chi} P_R q_j + g^*_{\mathrm{DM},ij} X_i \bar{q}_j P_L \chi$$

$\Delta m$



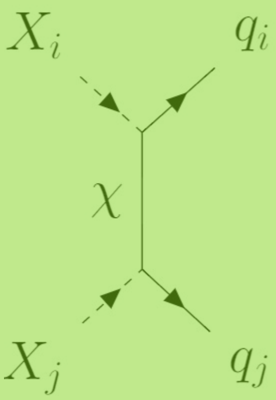
$g^4_{\mathrm{DM}}$

**no BSF / SE**



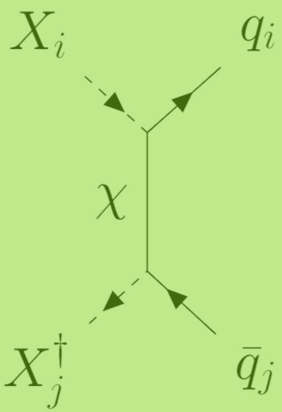
$g^2_{\mathrm{DM}} g^2_s e^{-x\delta}$

**no BSF / SE**



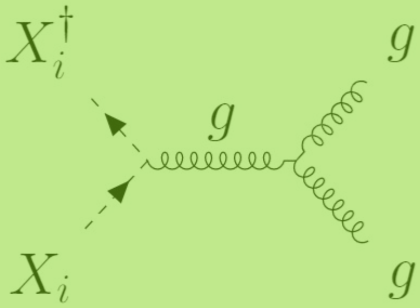
$g^4_{\mathrm{DM}} e^{-2x\delta}$

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



$(\alpha g^2_{\mathrm{DM}} + \beta g^2_s)^2 e^{-2x\delta}$

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



$g^4_s e^{-2x\delta}$

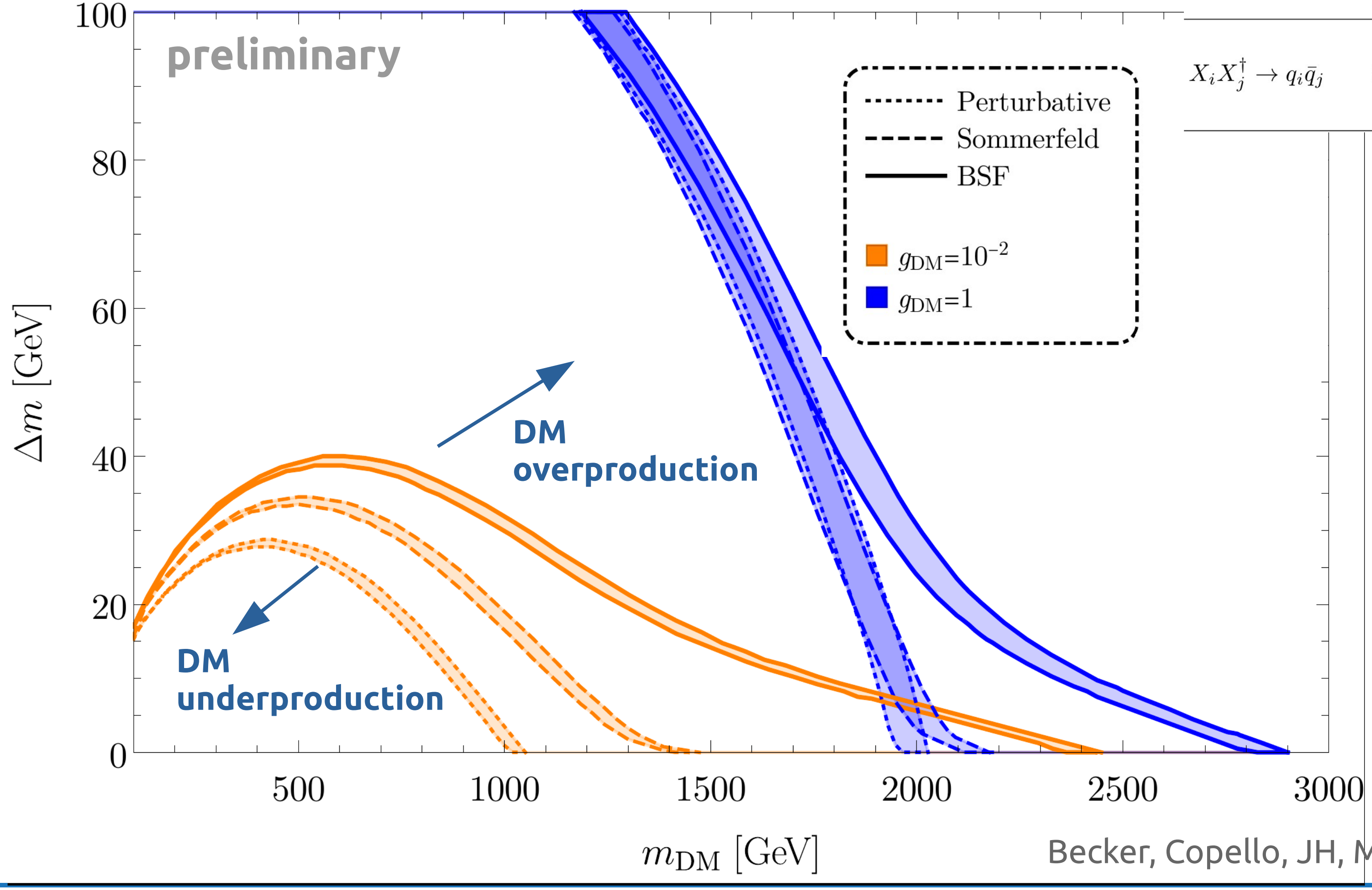
$\frac{2}{7}[\mathbf{1}] + \frac{5}{7}[\mathbf{8}]$

**BSF / SE**

# Impact of non-perturbative effects on mass plane

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

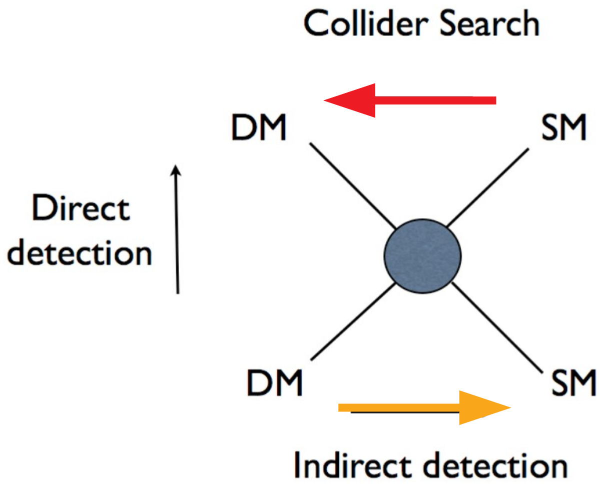
| | | |
|---|---|---|
| $X_i X_j^\dagger \to gg$ | $g_s^4 e^{-2x\delta}$ | $\lvert\mathcal{M}\rvert^2 \sim \frac{2}{7}[\mathbf{1}] + \frac{5}{7}[\mathbf{8}]$ |
| $X_i X_j \to q_i q_j$ | $g_{\text{DM}}^4 e^{-2x\delta}$ | $\lvert\mathcal{M}\rvert^2 \sim \frac{1}{3}[\bar{\mathbf{3}}] + \frac{2}{3}[\mathbf{6}]$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

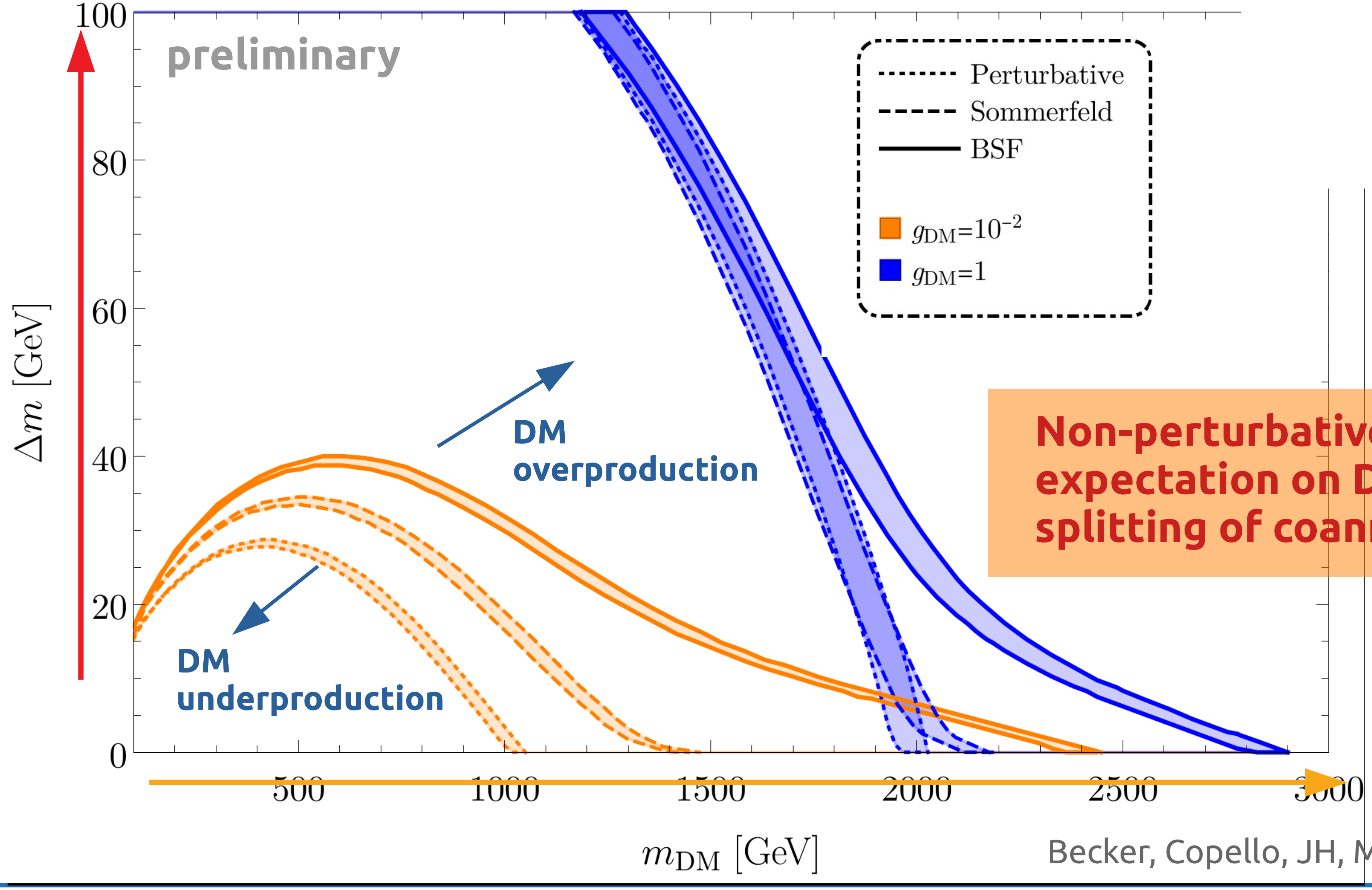


Becker, Copello, JH, Mohan, Sengupta, in preparation

# Impact of non-perturbative effects on mass plane

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



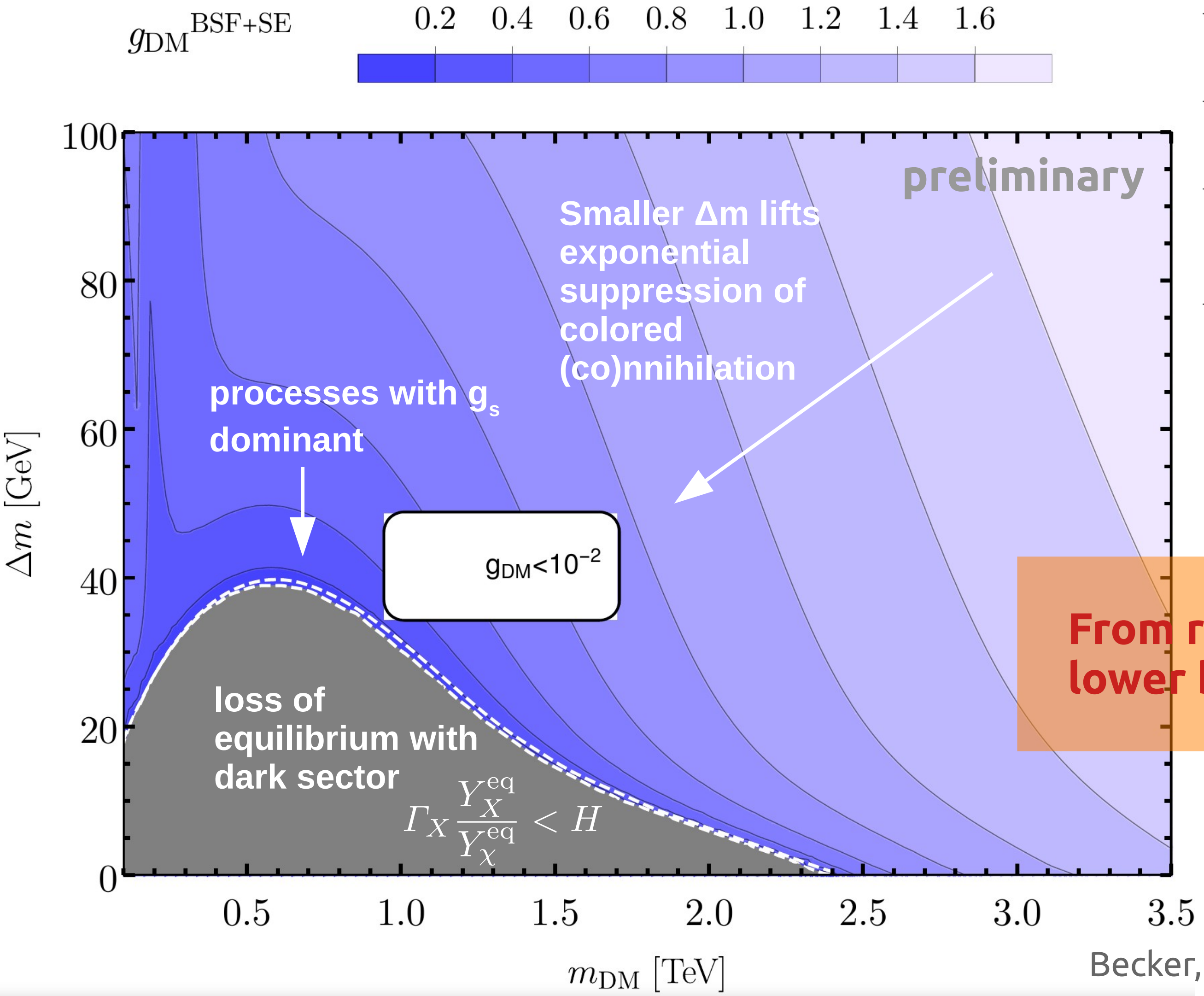


**Non-perturbative effects change expectation on DM mass and the mass splitting of coannihilating particles**

Becker, Copello, JH, Mohan, Sengupta, in preparation

# Impact on parameter space of t-channel model

**Goal**: **Lower bound on $g_{DM}$ in order not to overproduce DM**



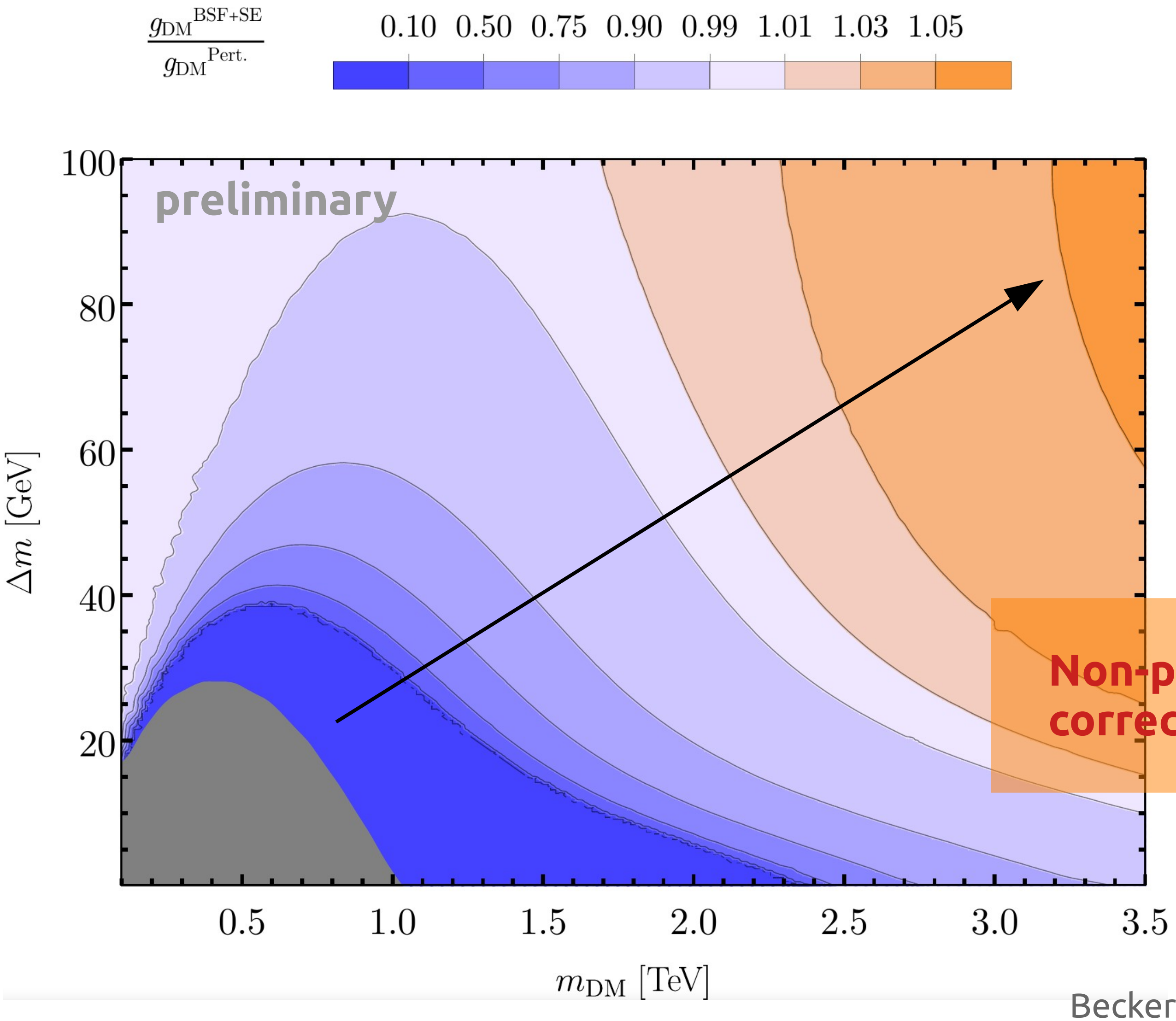
| | | |
|---|---|---|
| $X_i X_j^\dagger \to gg$ | $g_s^4 e^{-2x\delta}$ | $\lvert\mathcal{M}\rvert^2 \sim \frac{2}{7}[\mathbf{1}] + \frac{5}{7}[\mathbf{8}]$ |
| $X_i X_j \to q_i q_j$ | $g_{\rm DM}^4 e^{-2x\delta}$ | $\lvert\mathcal{M}\rvert^2 \sim \frac{1}{3}[\bar{\mathbf{3}}] + \frac{2}{3}[\mathbf{6}]$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

**From relic abundance we can obtain lower bound on $g_{DM}$**

Becker, Copello, JH, Mohan, Sengupta, in preparation

# Impact on parameter space of t-channel model

**Goal: Correction on $g_{DM}$ due to BSF and SE**



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

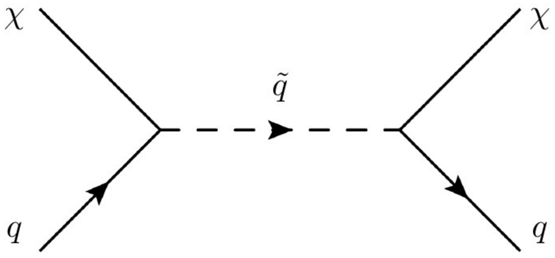
**Non-perturbative effects result in corrections on expected $g_{DM}$**

Becker, Copello, JH, Mohan, Sengupta, in preparation

# Interplay with direct detection

**Spin dependent (SD) direct detection:**

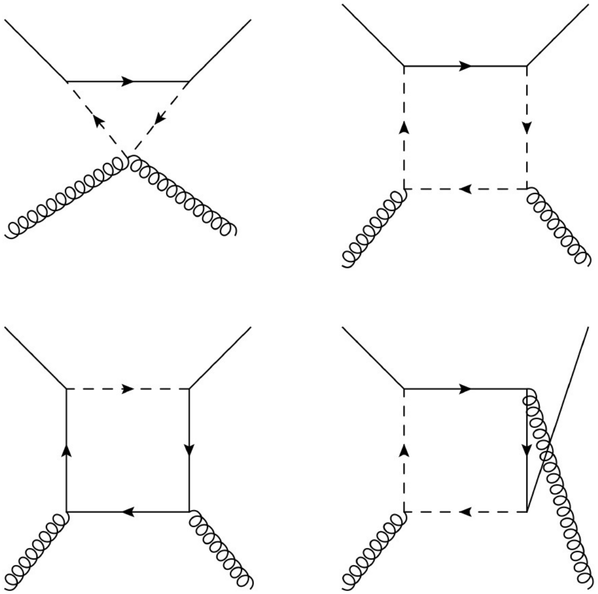
- at tree-level due to Majorana nature
- Most stringent constraints from SD proton scattering
- PICO-60 limits



→ **upper limit on $g_{DM}$**

**Spin independent (SI) direct detection:**

- only at one-level
- Most stringent limits from Xenon1T



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

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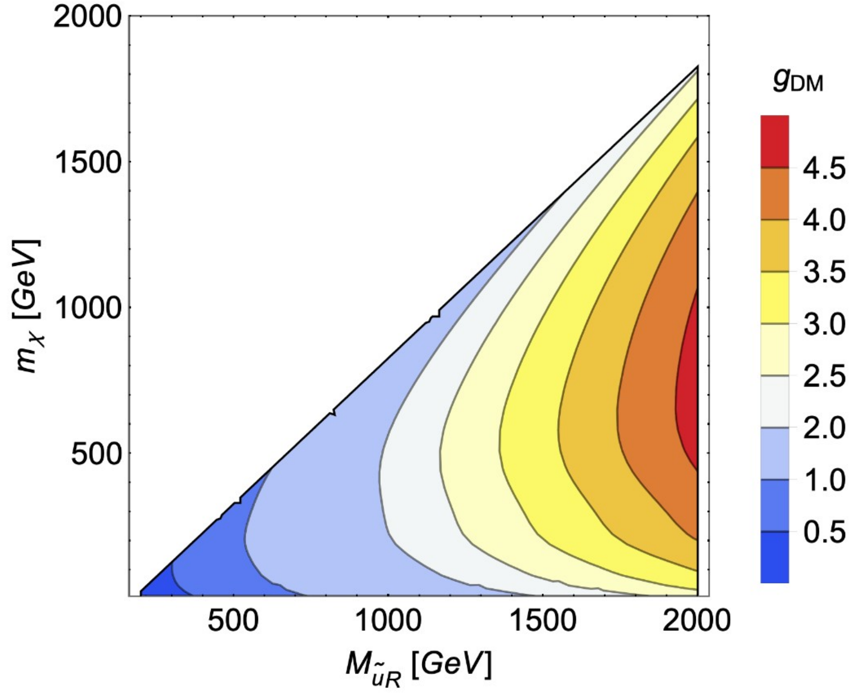

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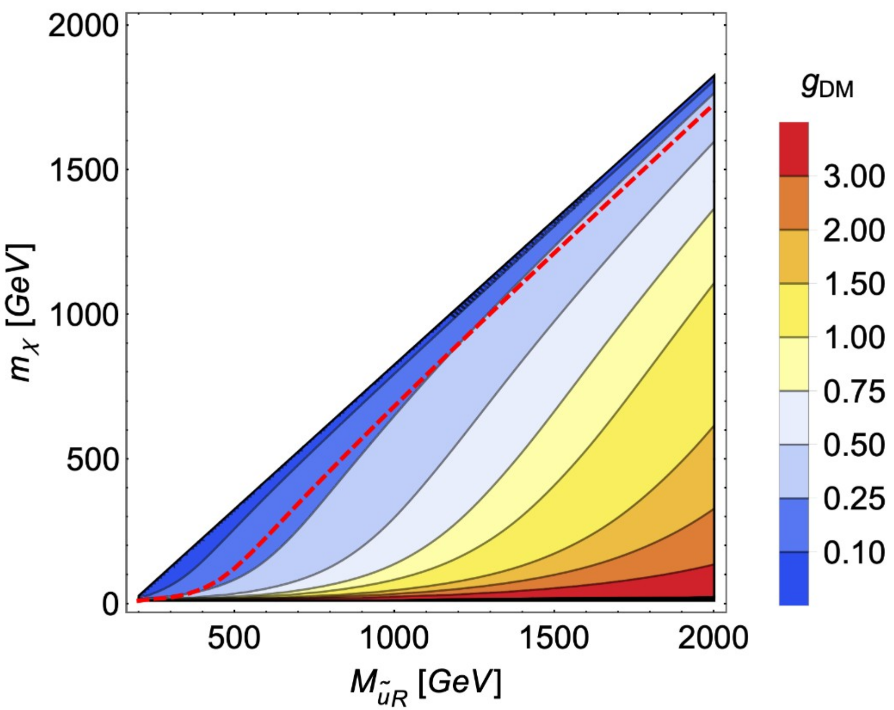

Mohan, Sengupta, Tait, Yan and Yuan (2019)

# Interplay with direct detection

**Spin dependent (SD) direct detection:**

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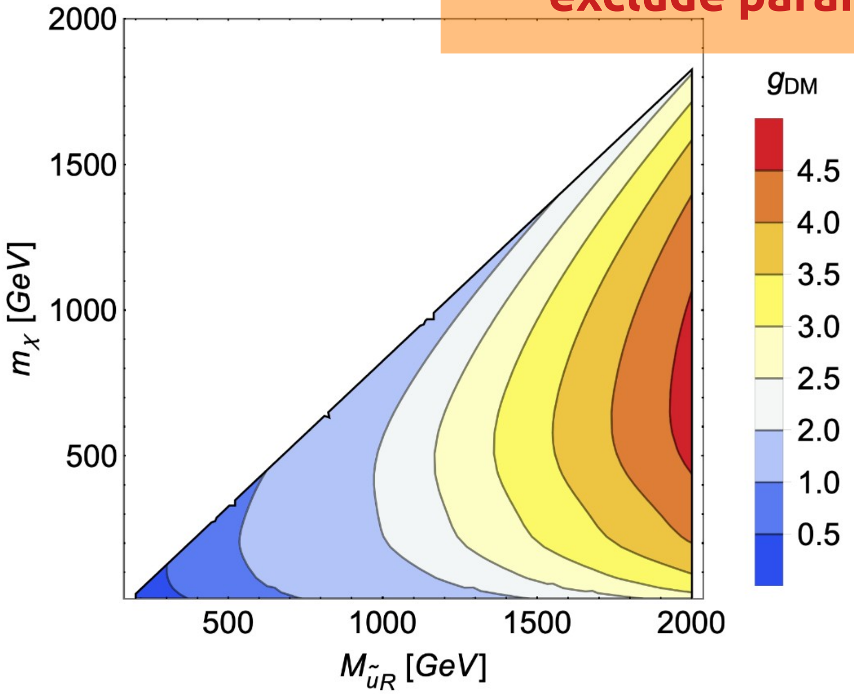
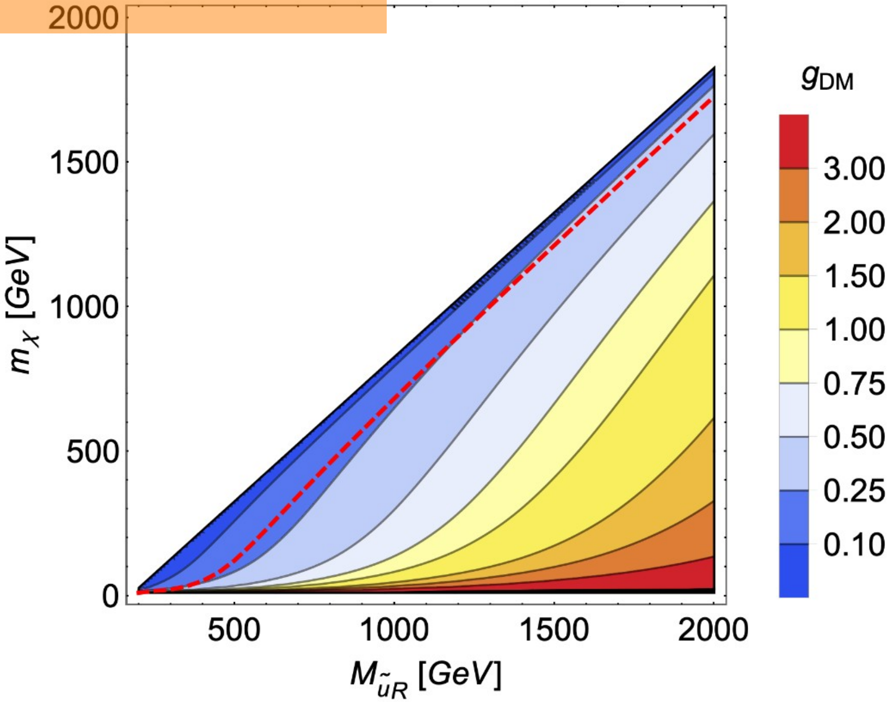
**Spin independent (SI) direct detection:**

- only at one-level
- Most stringent limits from Xenon1T

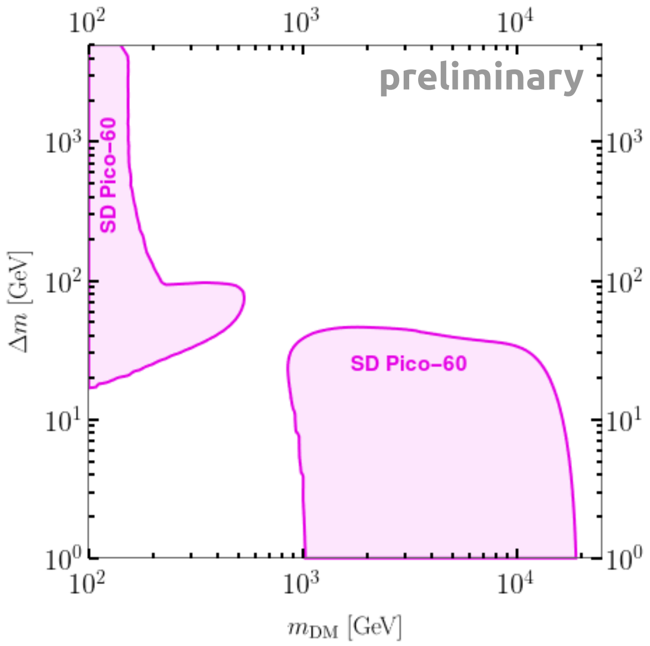
**Combination of limits allows us to exclude parameter space**



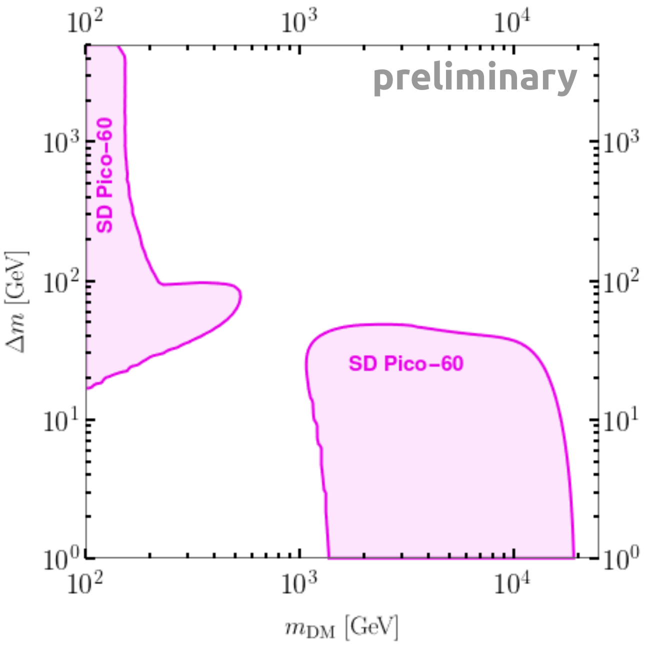


Mohan, Sengupta, Tait, Yan and Yuan (2019)

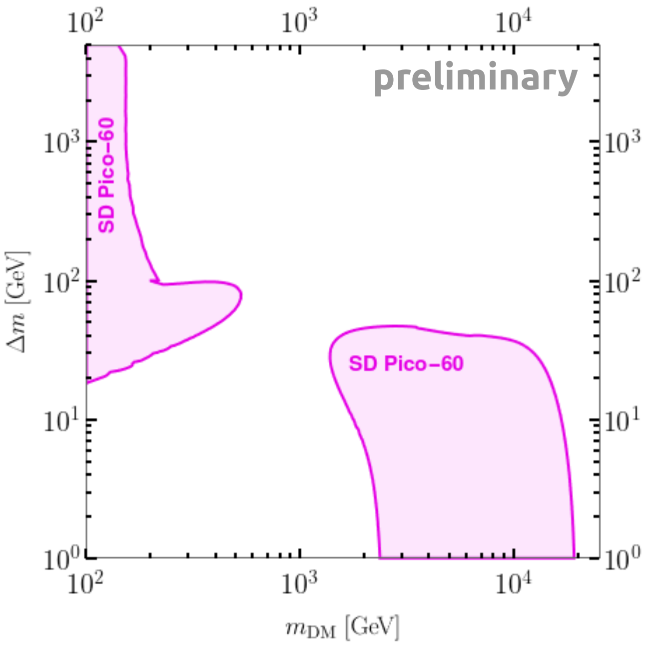
# Interplay with direct detection



**perturbative only**



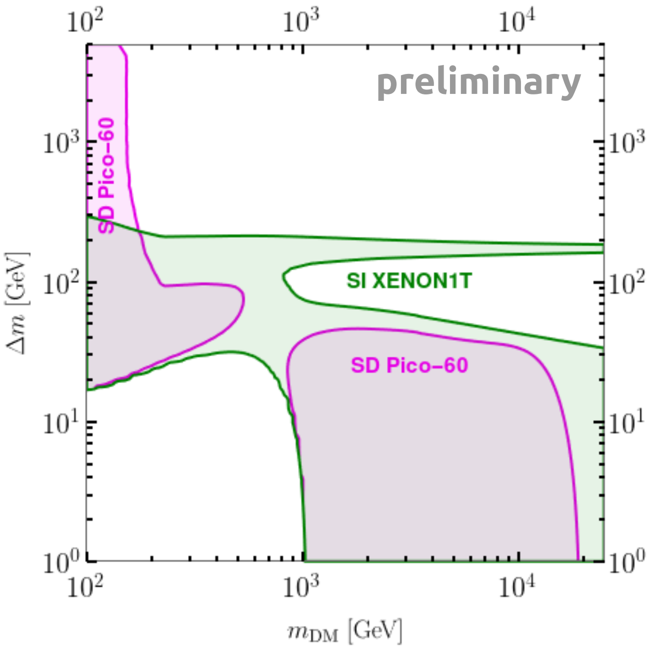
**+ Sommerfeld enhancement**



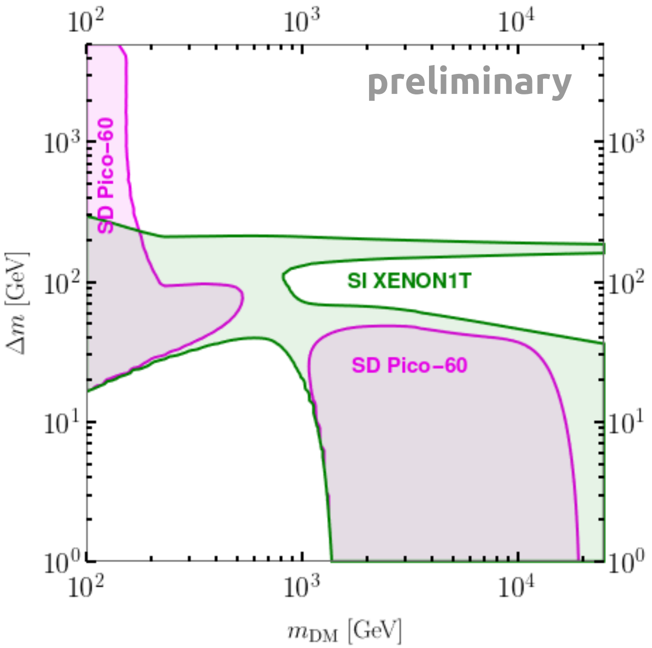
**+ bound state formation**

Becker, Copello, JH, Mohan, Sengupta, in preparation

# Interplay with direct detection



**perturbative only**



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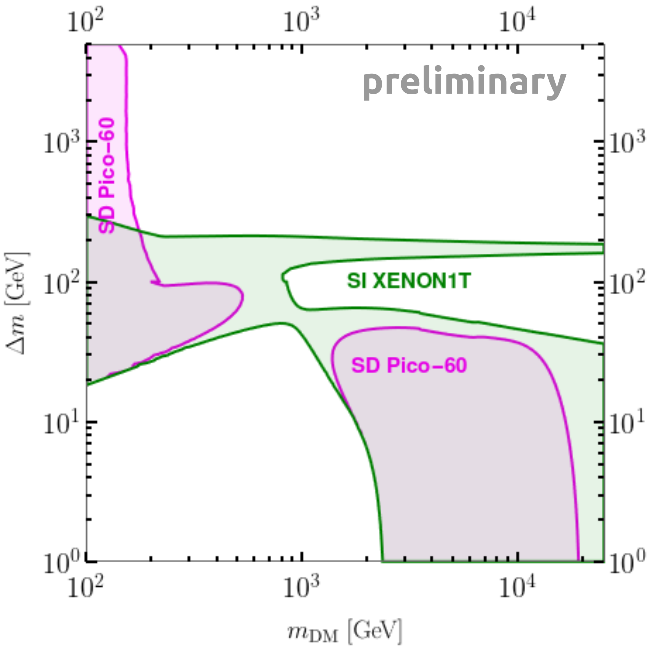
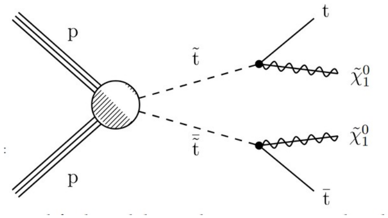


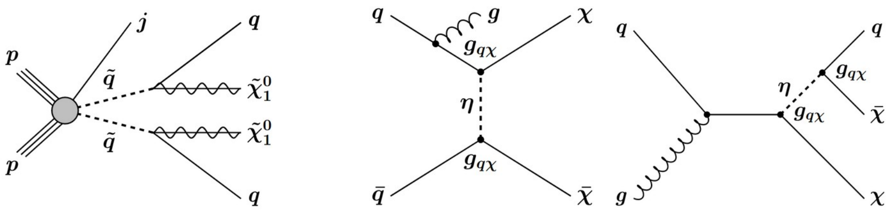
**+ bound state formation**

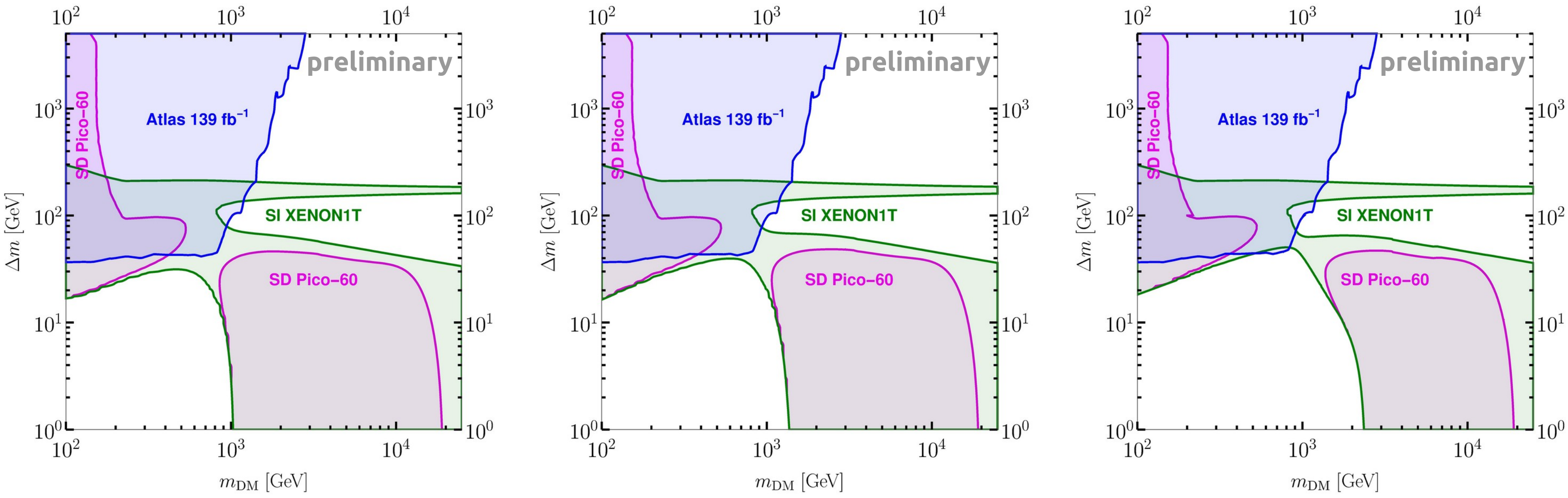
Becker, Copello, JH, Mohan, Sengupta, in preparation

# Interplay with LHC searches

- **mono-jet + ETmiss search by ATLAS** [arXiv:1711.03301]
- **multi-jets + ETmiss search by CMS** [arXiv:1704.07781]



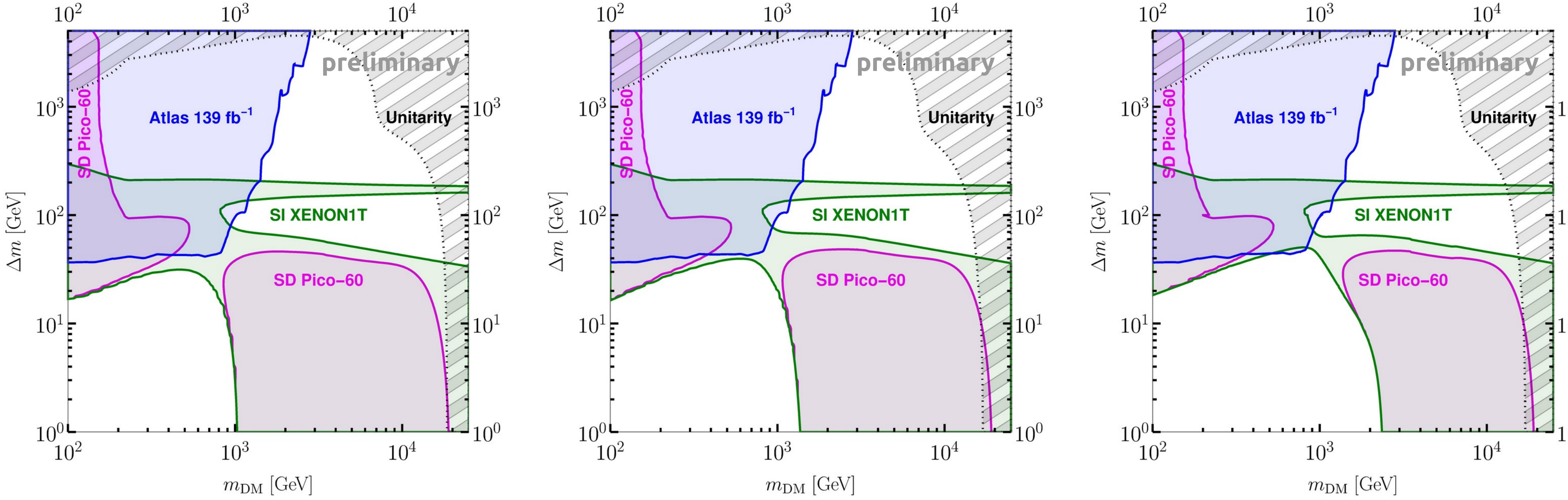




**perturbative only** **+ Sommerfeld enhancement** **+ bound state formation**

Becker, Copello, JH, Mohan, Sengupta, in preparation

# Interplay with LHC searches

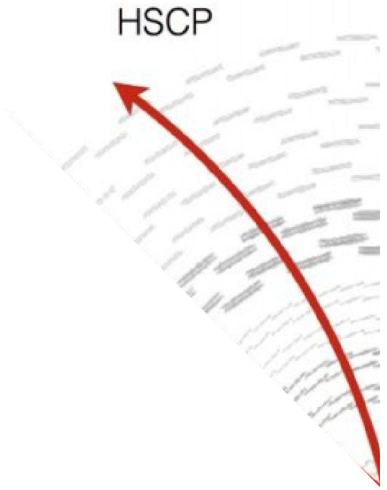


**perturbative only** **+ Sommerfeld enhancement** **+ bound state formation**

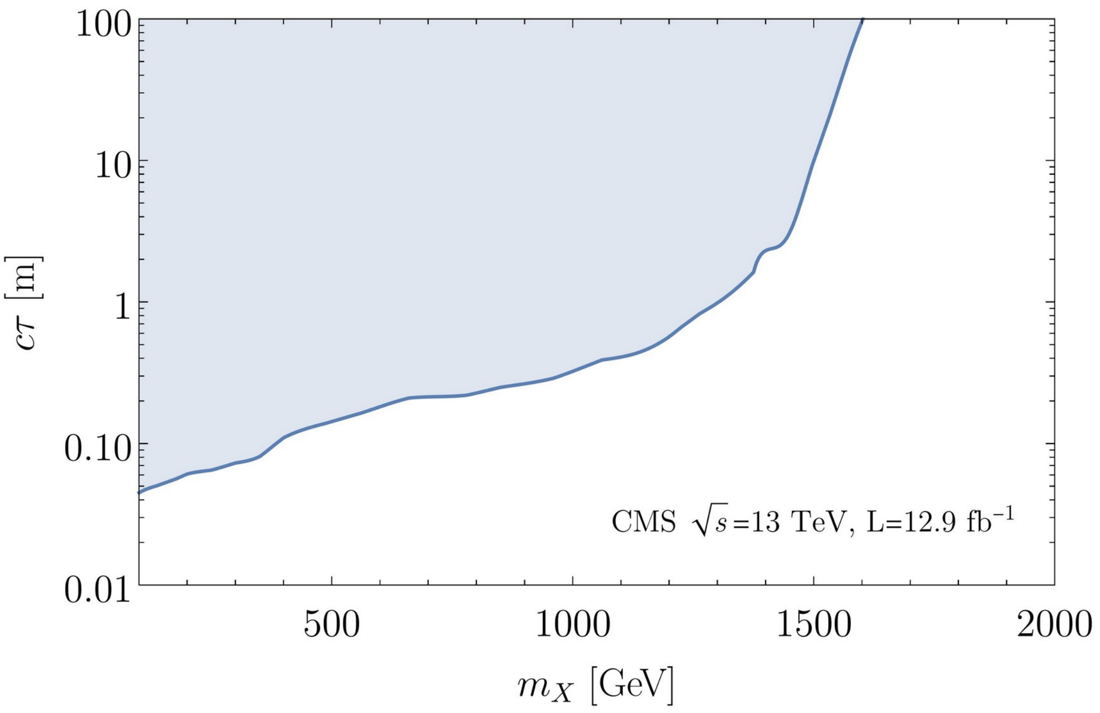
Becker, Copello, JH, Mohan, Sengupta, in preparation

# Interplay with long-lived particle searches

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



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



- Colored mediator sufficiently long-lived: Heavy Stable Charged Particle (HSPC)
- decay outside the tracker (tracker only) or muon chamber (tracker + TOF)
- 13 TeV CMS analysis 12.9 fb$^{-1}$ [*CMS-PAS-EXO-16-036 (2016)*]

**→ Upper bound on $g_{DM}$**

Becker, Copello, JH, Mohan, Sengupta, in preparation

# Interplay with long-lived particle searches

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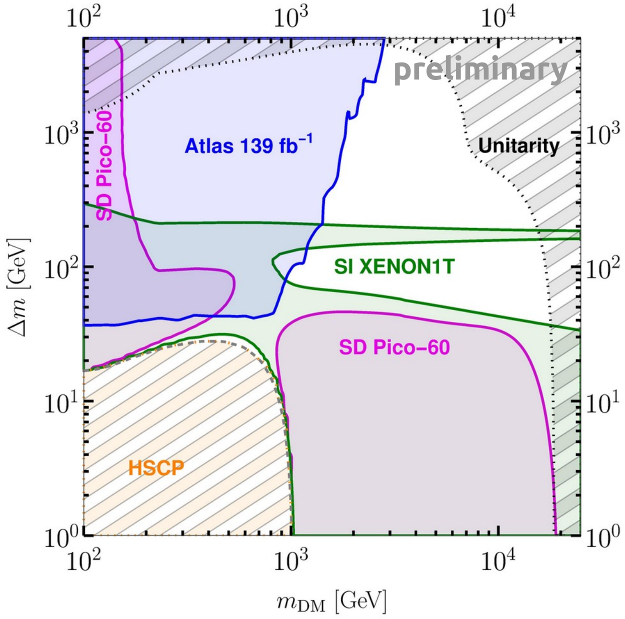
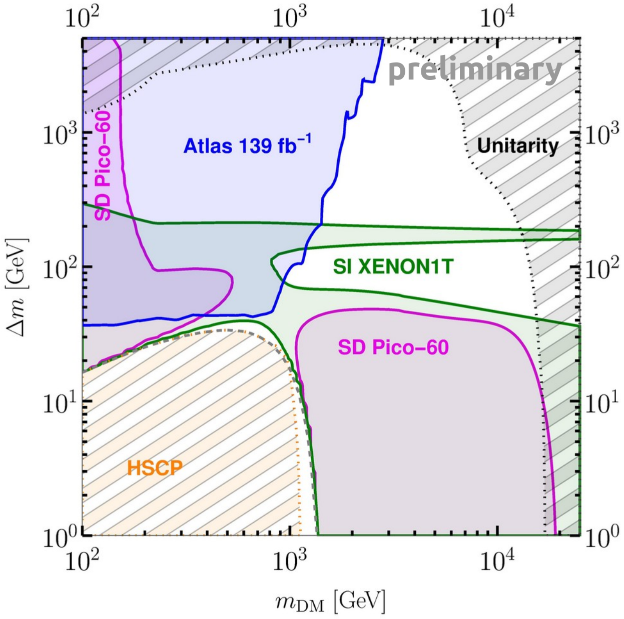


**perturbative only**



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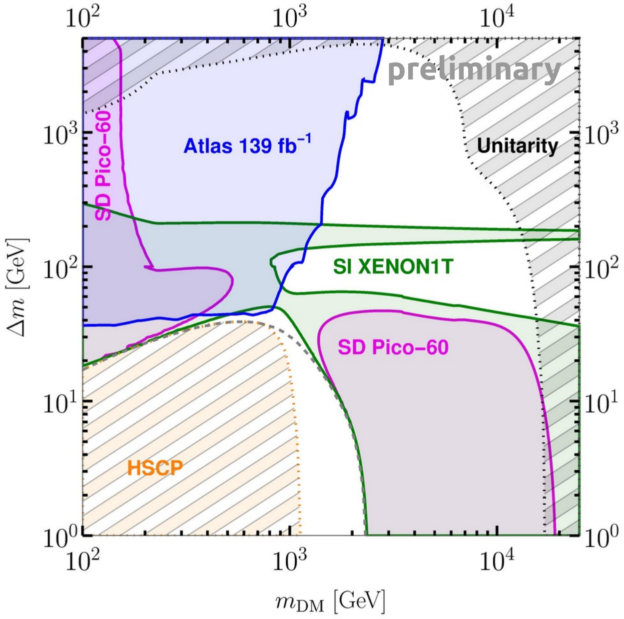
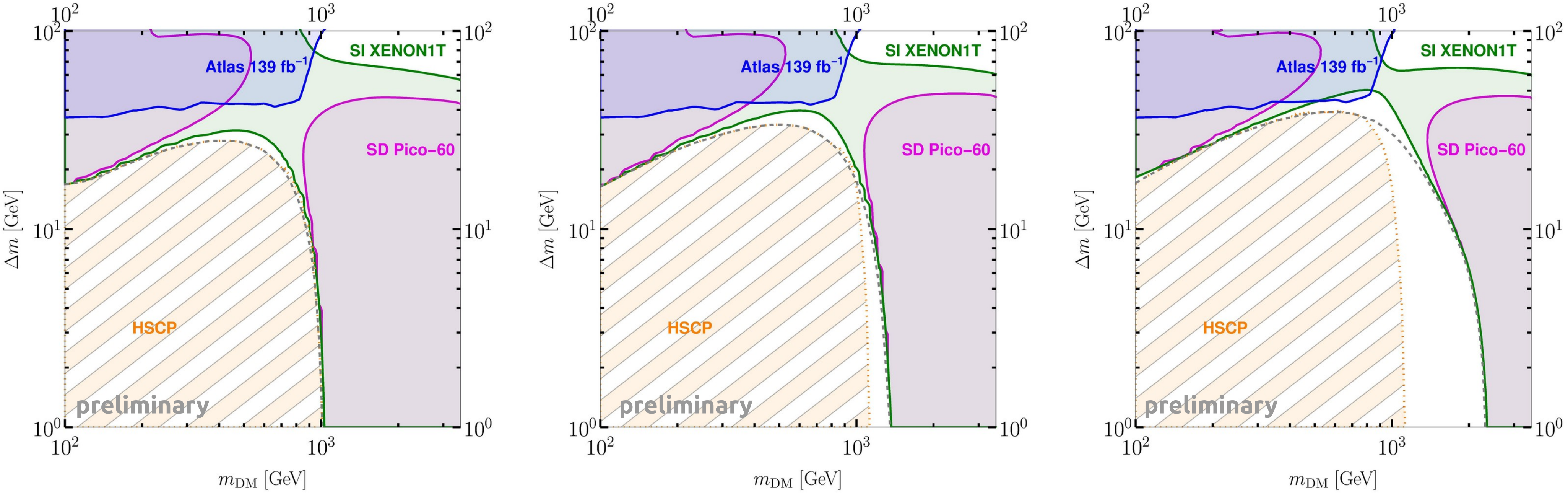


**+ bound state formation**

Becker, Copello, JH, Mohan, Sengupta, in preparation

# Interplay with long-lived particle searches



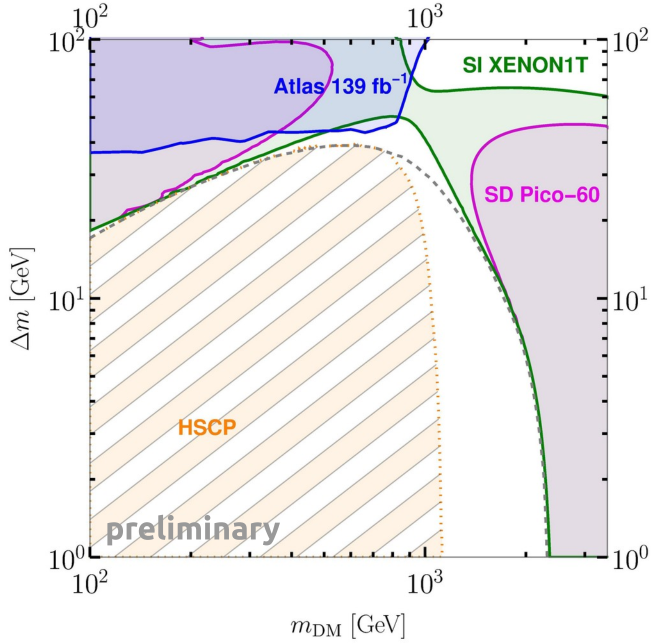
**perturbative only** **+ Sommerfeld enhancement** **+ bound state formation**

Becker, Copello, JH, Mohan, Sengupta, in preparation

# Conclusions

- **WIMPs are not dead!**
- **(Colored) coannihilation scenarios could explain the no-show (higher expected DM masses)**
- **effects of Sommerfeld enhancement and bound state formation are sizeable in t-channel models**

**For conclusive exclusion of DM freeze-out in such a scenario, non-pertubative effects have to be taken into account!**



# Thank you for your attention!