Sommerfeld Effect and Bound State Formation in Simplified Dark Matter Models

Emanuele Copello
Technical University of Munich

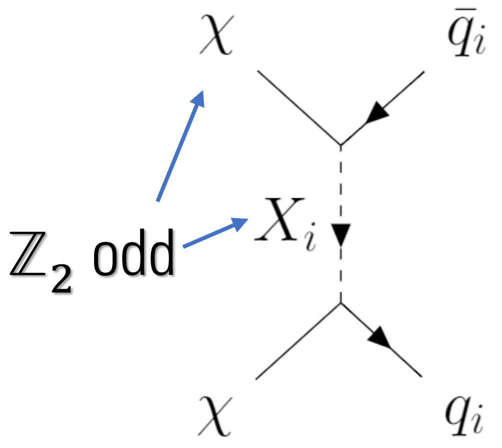
Based on arXiv:2203.04326 (soon on JHEP)
with Mathias Becker (TUM), Julia Harz (TUM), Kirtimaan Mohan (MSU) and Dipan Sengupta (UCSD)

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Planck 2022 – DM parallel session
Paris, June 1, 2022

Technische Universität München

Simplified *t*-channel models for DM



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

$\chi \sim (\mathbf{1}, \mathbf{0}, 0)$

Majorana and LSP
→ **DM**

THIS TALK

$\tilde{X}_i \sim (\mathbf{3}, \mathbf{1}, +2/3)$ $\boldsymbol{u_R}$ model

$\widetilde{X}_i \sim (\mathbf{3}, \mathbf{1}, -1/3)$ $\boldsymbol{d_R}$ model

$\widetilde{X}_i \sim (\mathbf{3}, \mathbf{2}, -1/6)$ $\boldsymbol{q_L}$ model

Model parameters: $\{m_\chi, \Delta = m_X - m_\chi, g_{\rm DM}\}$

- ✓ Few new particles and parameters
- ✓ Yet, rich phenomenology on vast parameter space

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

Emmy Noether-Programm DFG Deutsche Forschungsgemeinschaft

DM abundance and coannihilations

If dark sector particles are in chemical and kinetic equilibrium:

$$\Delta_i = m_{X_i} - m_\chi$$

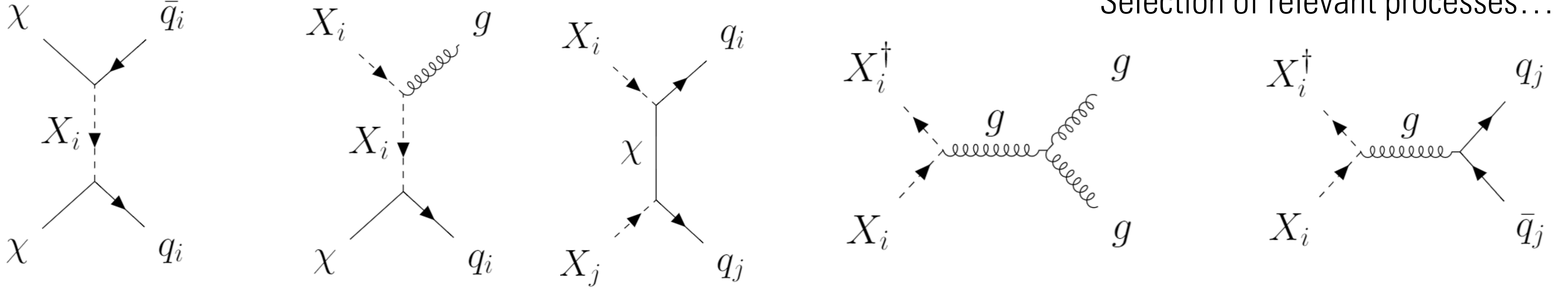
$$\frac{\mathrm{d}\tilde{Y}}{\mathrm{d}x} = -\frac{s}{H\,x}\langle\sigma_{\mathrm{eff}}v_{\mathrm{rel}}\rangle\left(\tilde{Y} - \tilde{Y}^{\mathrm{eq}}\right)$$

$$\langle\sigma_{\mathrm{eff}}v_{\mathrm{rel}}\rangle \sim \sum_{ij}\langle\sigma_{ij}v_{ij}\rangle\frac{e^{-\Delta_i/T}e^{-\Delta_j/T}}{(1+\sum_n e^{-\Delta_n/T})^2}$$

$$\Omega_{\mathrm{DM}}h^2 \propto \frac{1}{\langle\sigma_{\mathrm{eff}}v_{\mathrm{rel}}\rangle}$$

$$\tilde{Y} = \sum_i \frac{n_i}{s}$$

Selection of relevant processes…



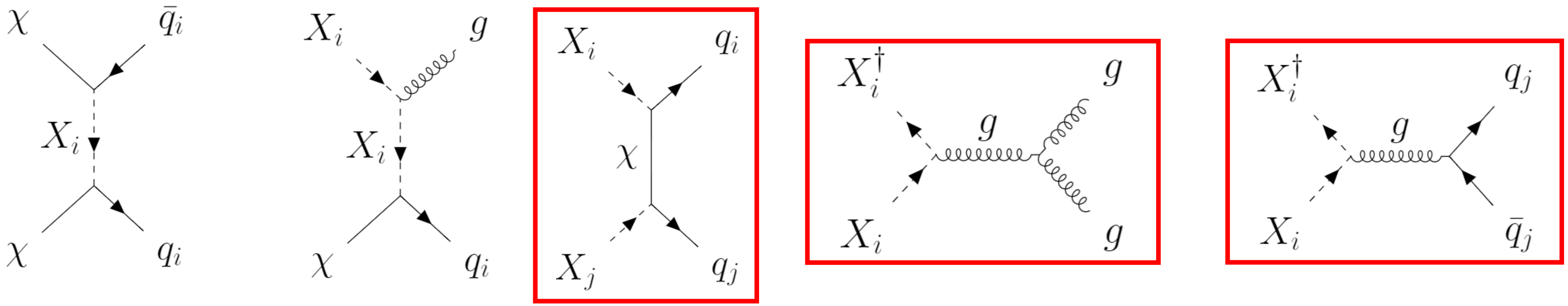
$$\langle\sigma_{\mathrm{eff}}v_{\mathrm{rel}}\rangle \sim \quad g_{\mathrm{DM}}^4 \qquad g_{\mathrm{DM}}^2 g_s^2 e^{-\Delta m/T} \qquad g_{\mathrm{DM}}^4 e^{-2\Delta m/T} \qquad \left(\alpha g_{\mathrm{DM}}^2 + \beta g_s^2\right)^2 e^{-2\Delta m/T} \qquad g_s^4 e^{-2\Delta m/T}$$

Relevant when mass splitting Δm small

DM abundance and coannihilations

! Incoming colored states experience gluonic long-range force!

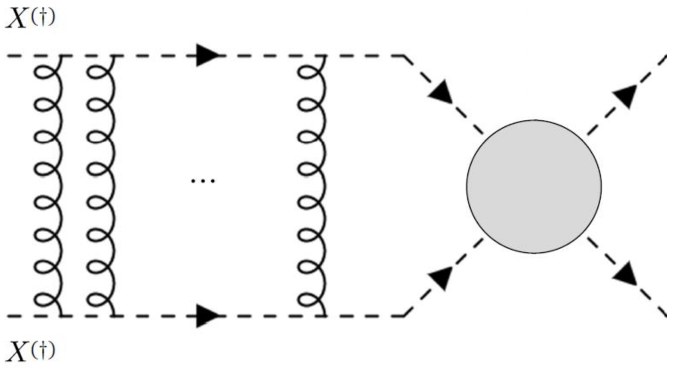
!! Non-perturbative effects relevant $\Longrightarrow$ Sommerfeld effect + Bound state formation



$\langle \sigma_{\mathrm{eff}} v_{\mathrm{rel}} \rangle \sim \quad g_{\mathrm{DM}}^4 \quad g_{\mathrm{DM}}^2 g_s^2 e^{-\Delta m/T} \quad g_{\mathrm{DM}}^4 e^{-2\Delta m/T} \quad (\alpha g_{\mathrm{DM}}^2 + \beta g_s^2)^2 \, e^{-2\Delta m/T} \quad g_s^4 e^{-2\Delta m/T}$

Relevant when mass splitting Δm small

Long-range colored interactions: Sommerfeld effect [Sommerfeld (1931)]



Each rung insertion $\sim \alpha/v_{\rm rel} \sim \mathcal{O}(1)$
for freeze-out ($\alpha_s \sim 0.1, v_{\rm rel} \sim 0.1$)

Resummation

$$\langle \sigma_0^S v_{\rm rel} \rangle = \left\langle S_0 \, \sigma_0^{\rm pert} \right\rangle$$

$$V(r)_{\mathbf{R}_1 \otimes \mathbf{R}_2 \to \hat{\mathbf{R}}} = -\frac{\alpha_s}{2\,r}\left(C_2(\mathbf{R}_1) + C_2(\mathbf{R}_2) - C_2(\hat{\mathbf{R}})\right)$$

At small $v_{\rm rel}$

$S_0 \sim \dfrac{\alpha}{v_{\rm rel}}$ $\quad \alpha > 0$ enhancement

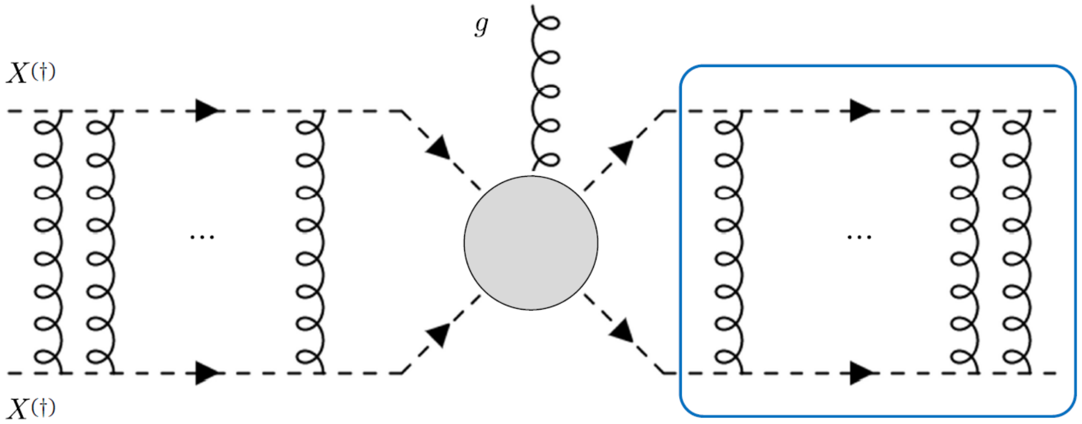
$S_0 \sim \dfrac{|\alpha|}{v_{\rm rel}} \exp(-2\pi|\alpha|/v_{\rm rel})$ $\quad \alpha < 0$ suppression

$$V(r)_{\mathbf{3}\otimes\bar{\mathbf{3}}} = \begin{cases} -\dfrac{4}{3}\dfrac{\alpha_s}{r} & [\mathbf{1}] \quad S_{0,[\mathbf{1}]} = S_0\left(\dfrac{4\alpha_s^S}{3v_{\rm rel}}\right) \\ +\dfrac{1}{6}\dfrac{\alpha_s}{r} & [\mathbf{8}] \quad S_{0,[\mathbf{8}]} = S_0\left(\dfrac{-\alpha_s^S}{6v_{\rm rel}}\right) \end{cases}$$

$$V(r)_{\mathbf{3}\otimes\mathbf{3}} = \begin{cases} -\dfrac{2}{3}\dfrac{\alpha_s}{r} & [\bar{\mathbf{3}}] \quad S_{0,[\bar{\mathbf{3}}]} = S_0\left(\dfrac{2\alpha_s^S}{3v_{\rm rel}}\right) \\ +\dfrac{1}{3}\dfrac{\alpha_s}{r} & [\mathbf{6}] \quad S_{0,[\mathbf{6}]} = S_0\left(\dfrac{-\alpha_s^S}{3v_{\rm rel}}\right) \end{cases}$$

$\bar{\mathbf{3}} \otimes \bar{\mathbf{3}}$ is the same

Long-range colored interactions: bound state formation



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

$$\sigma_{\rm BSF}^{[\mathbf{8}]\to[\mathbf{1}]} v_{\rm rel} \propto \left| \left\langle \psi_{100}^{[\mathbf{1}]} \middle| \mathbf{r} \middle| \varphi_{\mathbf{k}_{\rm rel}}^{[\mathbf{8}]} \right\rangle \right|^2 \sim \sigma_0^{\rm pert}\, S_{\rm BSF}(\zeta_S, \zeta_B)$$

$\sim (1 \div 10^2) \times \sigma_0^{\rm pert}$ if $v_{\rm rel} \sim \alpha$, suppressed if $v_{\rm rel} \gg \alpha$, $v_{\rm rel} \ll \alpha$

$\mathcal{B}(XX^\dagger) \to g + g$ DECAY: $\Gamma_{\rm Dec}$

$\mathcal{B}(XX^\dagger) + g \to X + X^\dagger$ IONISATION: $\Gamma_{\rm Ion}$

If $\Gamma_{\rm Dec}, \Gamma_{\rm Ion} \gg H \implies \frac{dY_{\rm BS}}{dM} \simeq 0$

$\to$ one-Boltzmann eq. effective description!

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

$$\langle \sigma_{\rm BSF} v_{\rm rel} \rangle_{\rm eff} \equiv \langle \sigma_{\rm BSF}^{[\mathbf{8}]\to[\mathbf{1}]} v_{\rm rel} \rangle \frac{\Gamma_{\rm dec[\mathbf{1}]}}{\Gamma_{\rm dec[\mathbf{1}]} + \Gamma_{\rm ion,[\mathbf{1}]}}$$

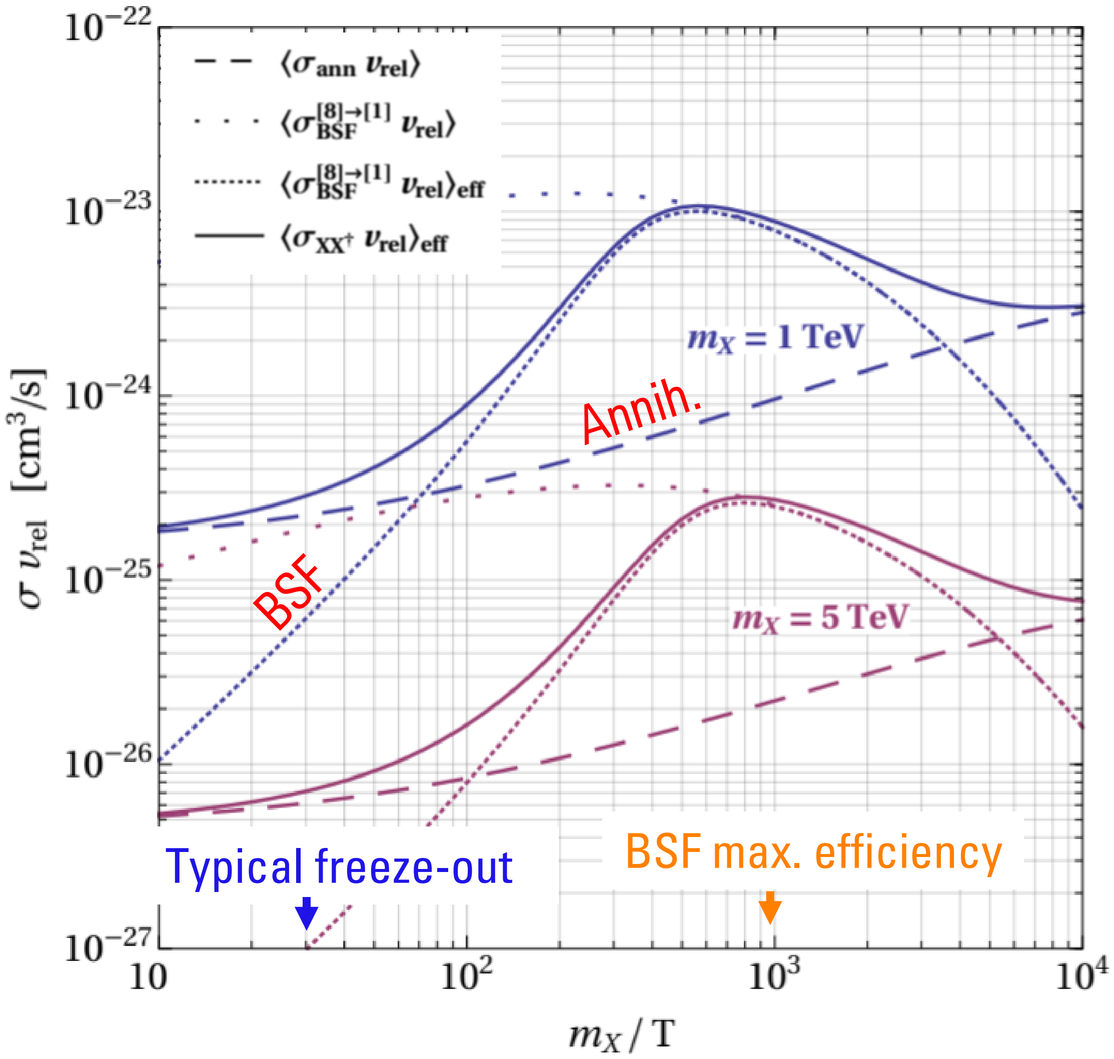
$$T \gg \mathcal{E}_{100} \qquad \Gamma_{\rm Ion} \gg \Gamma_{\rm Dec} \Rightarrow \langle \sigma_{\rm BSF} v_{\rm rel} \rangle_{\rm eff} \to 0$$

$$T \ll \mathcal{E}_{100} \qquad \Gamma_{\rm Ion} \ll \Gamma_{\rm Dec} \Rightarrow \langle \sigma_{\rm BSF} v_{\rm rel} \rangle_{\rm eff} \to \langle \sigma_{\rm BSF} v_{\rm rel} \rangle$$

[Ellis et al. (2015)], [Petraki et al. (2015)], [Mitridate et al. (2017)], [Harz and Petraki (2018)]

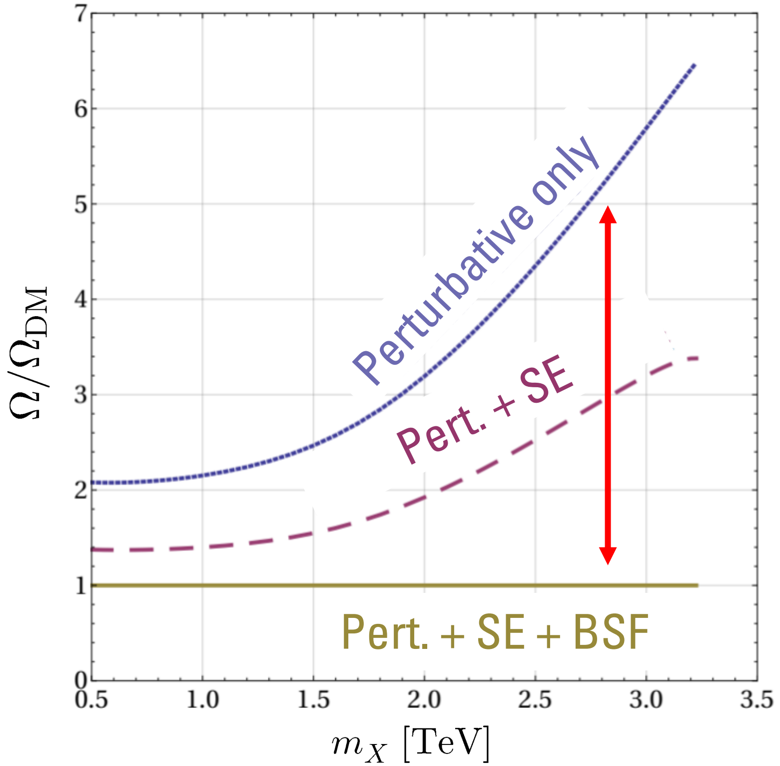
Impact on DM relic abundance: calculation

Adapted from [Harz and Petraki (2018)]

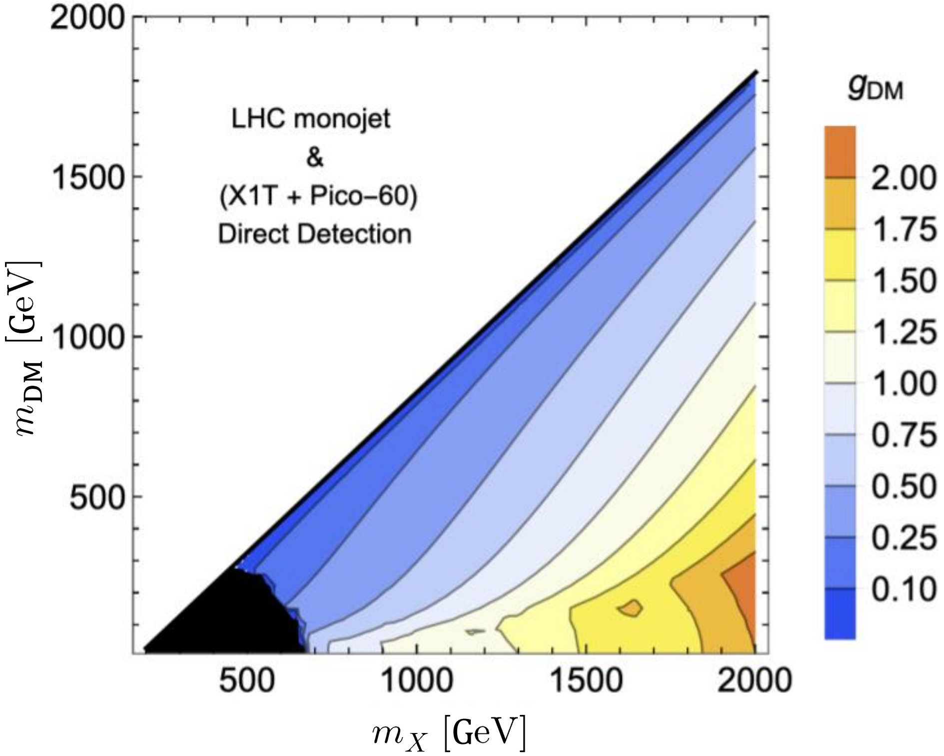


State-of-the-art…

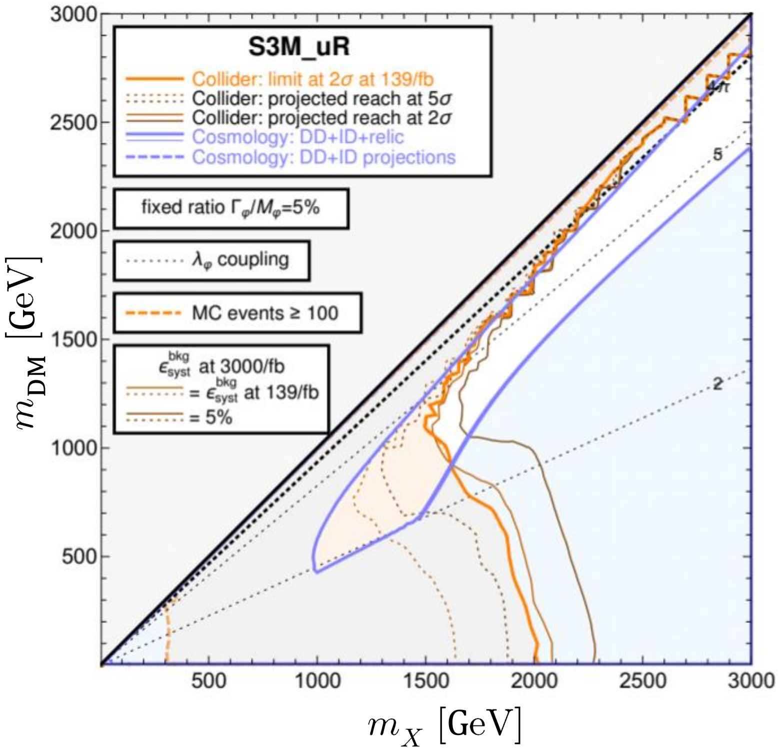
Adapted from [Harz & Petraki (2018)]



Adapted from [Mohan et al. (2019)]



Adapted from [Arina et al. (2020)]



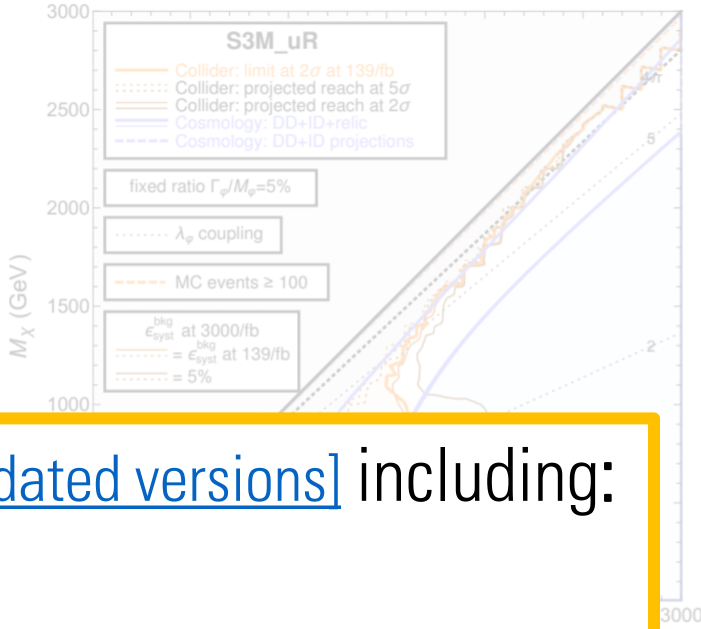
Non-perturbative effects ✓
Co-annihilations ✓
Simplified DM model ✗
Experimental limits ✗

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

… and our improvement

[Harz & Petraki (2

[Arina et al. (2020)]



THIS WORK

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

We modified **micrOMEGAs v.5.2.7** [Belanger et al. (2001) and updated versions] including:

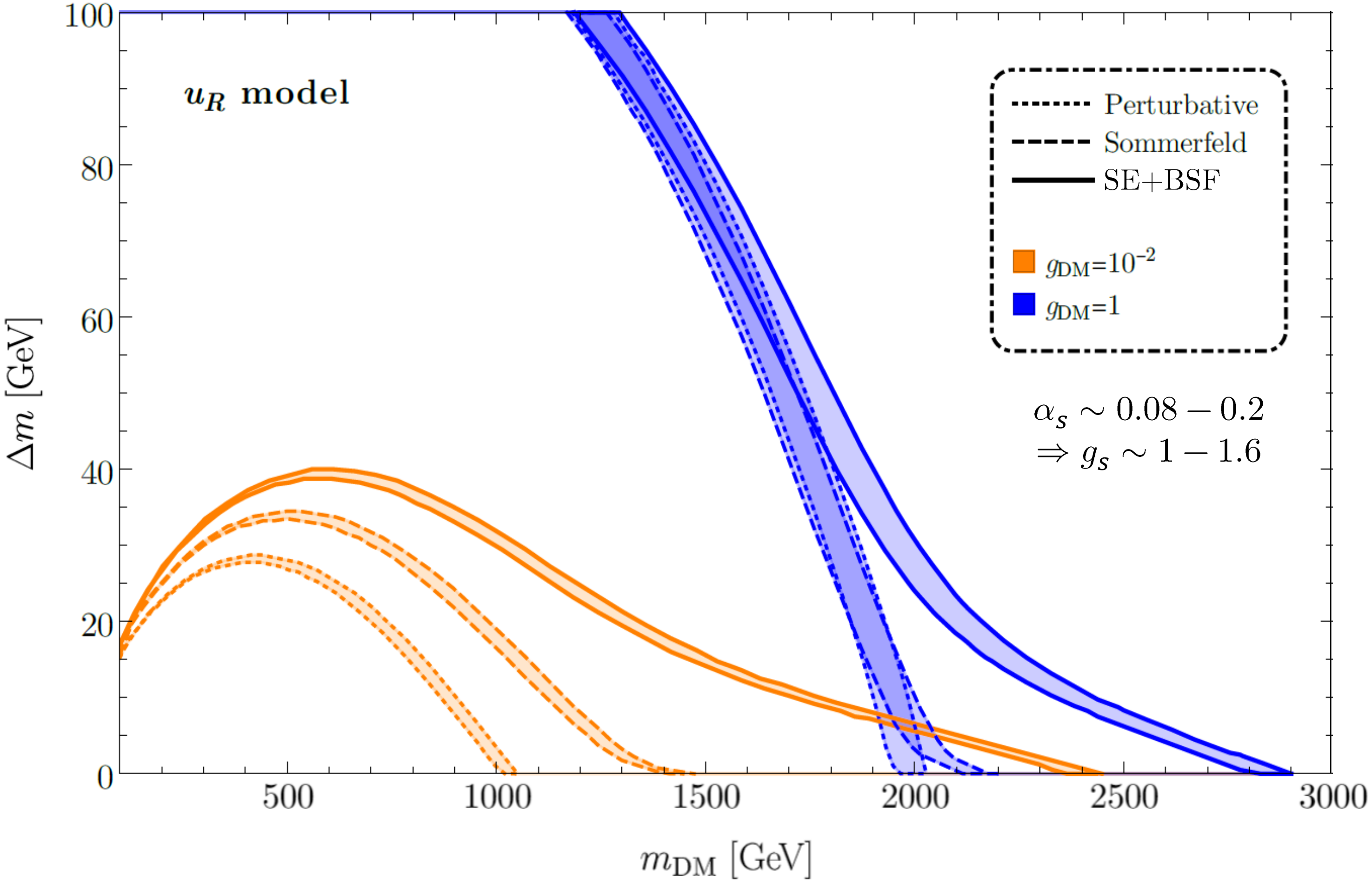
1. **Sommerfeld** effect ($\mathbf{3} \otimes \overline{\mathbf{3}}$ and $\mathbf{3} \otimes \mathbf{3}$)
2. **BSF** (singlet ground state) for **gluon emission**.
3. Exploitation of `CalcHEP` calculations + long-time integration ($z \lesssim 10^4$)

$\Longrightarrow$ Automatic + efficient RD computation $\Longrightarrow$ parameter space scan faster and easier

Simplified DM model ×
Experimental limits ×

Simplified DM model ✓
Experimental limits ✓

Impact on DM relic abundance: parameter space

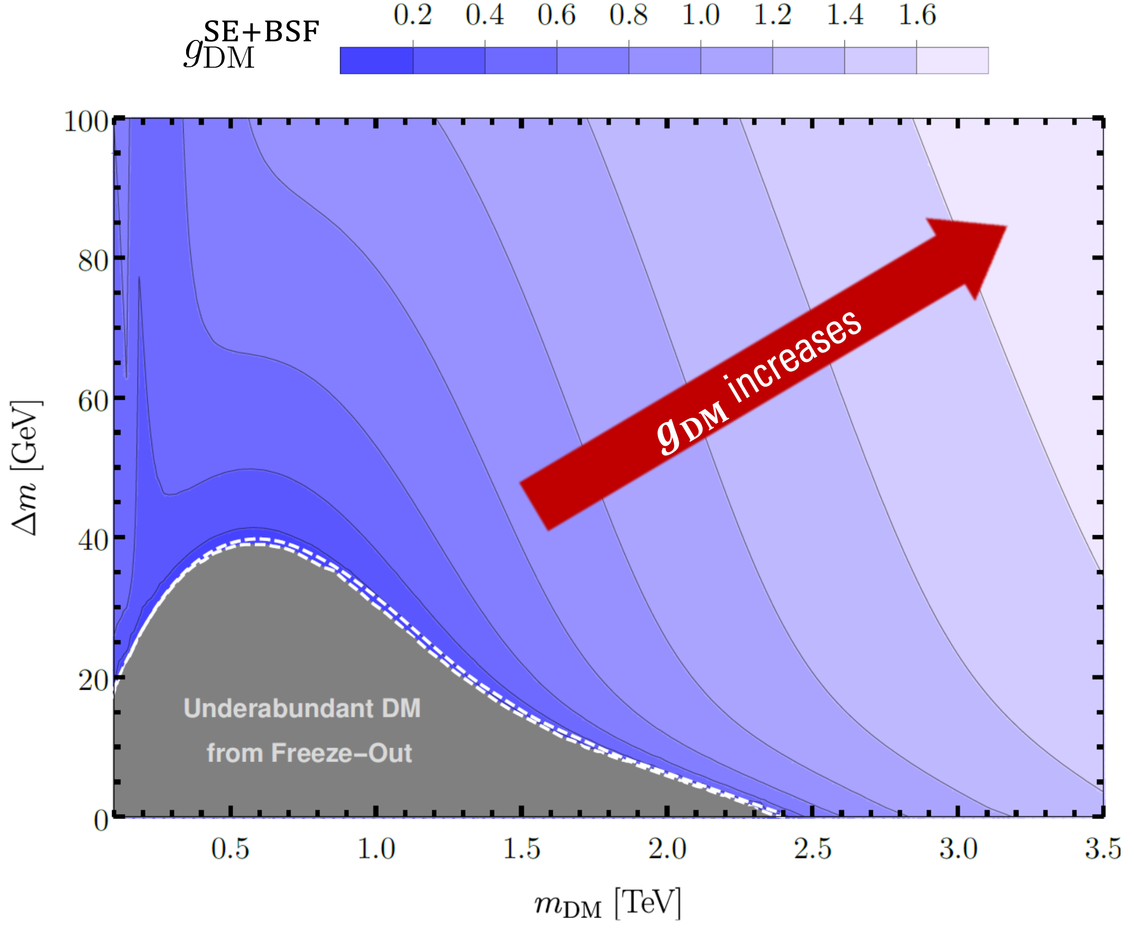


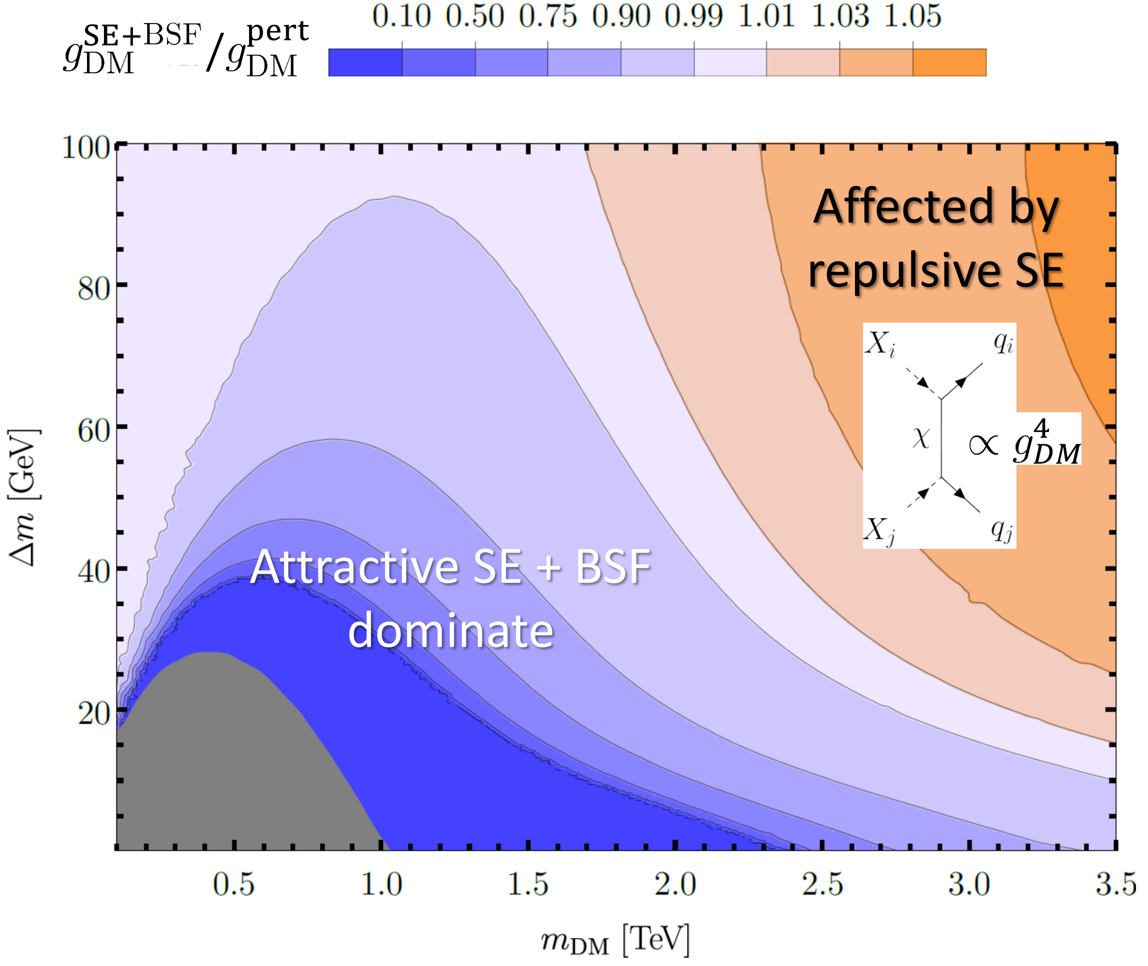
Becker, **EC**, Harz, Mohan, Sengupta (2022)

- Bands $\leftrightarrow \Omega_{DM}h^2 = 0.120 \pm 0.005$
- Dramatic change in DM density with SE and SE+BSF for small g_{DM} when $\Delta m \ll m_{DM}$.
- For $g_{DM} \sim \mathcal{O}(1)$ mild effects
- Stronger effective annihilations
  - $\Longrightarrow$ larger DM masses needed
  - $\Longrightarrow$ larger mass splittings Δm

Impact on DM relic abundance: parameter space

Fixed at maximum (+5σ) observable value: $\Omega_{DM} h^2 = 0.125$

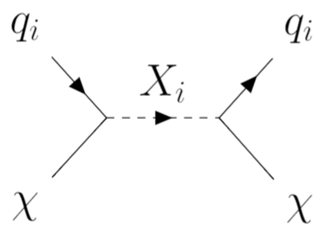




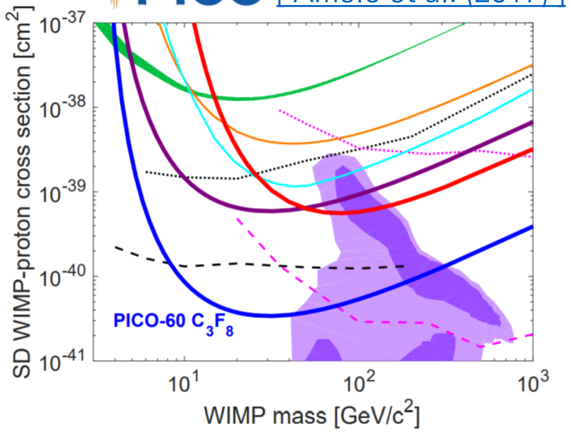
Becker, **EC**, Harz, Mohan, Sengupta (2022)

Direct detection constraints

Spin-dependent (SD): tree



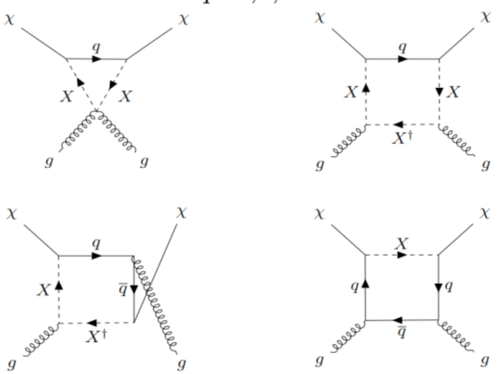
PICO [Amole et al. (2017)]



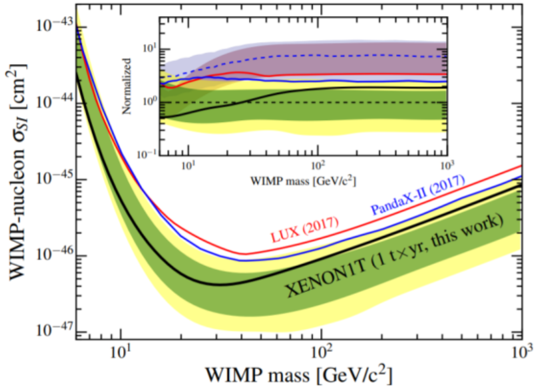
Spin-independent (SI) limits: 1 Loop+RGE (Majorana DM)

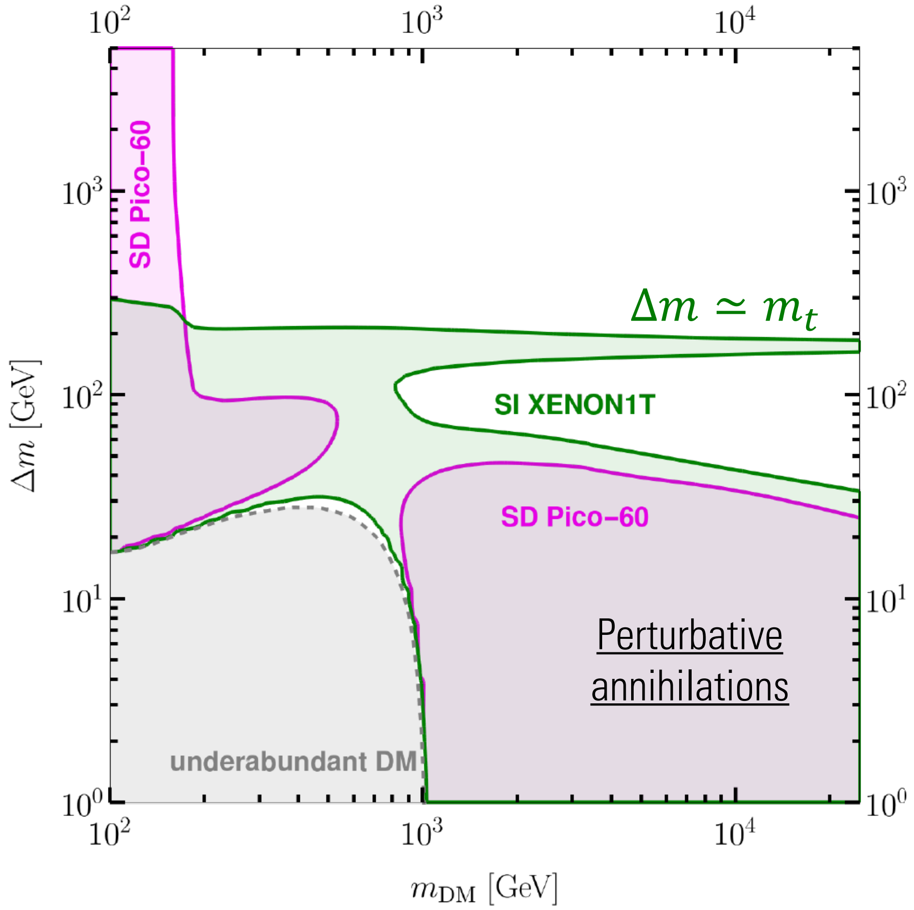
See also [Mohan et al. (2018)]

$$\mathcal{L}^{\rm eff}_{SI} = \sum_{q=u,d,s} \mathcal{L}^{\rm eff}_q + \mathcal{L}^{\rm eff}_g$$



[Aprile et al. (2018)]





Becker, **EC**, Harz, Mohan, Sengupta (2022)

Prompt searches: mono- and multi-jet + MET

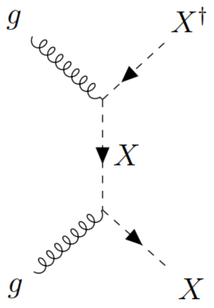
Prompt searches @ LHC

Recasting ATLAS mono-jet and multi-jet + MET analyses with 139 fb^{-1} @ $\sqrt{s}$ =13 TeV:

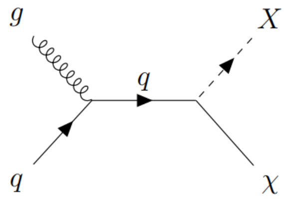
1. Pair-production of mediators followed by decay to quark + DM
2. Associated production of DM + mediator
3. Pair-production of DM + initial-state-radiated (ISR) jet

Mono- and multi-jet comparable at small Δm, multi-jet stronger at large Δm

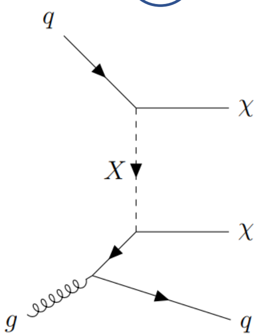
1

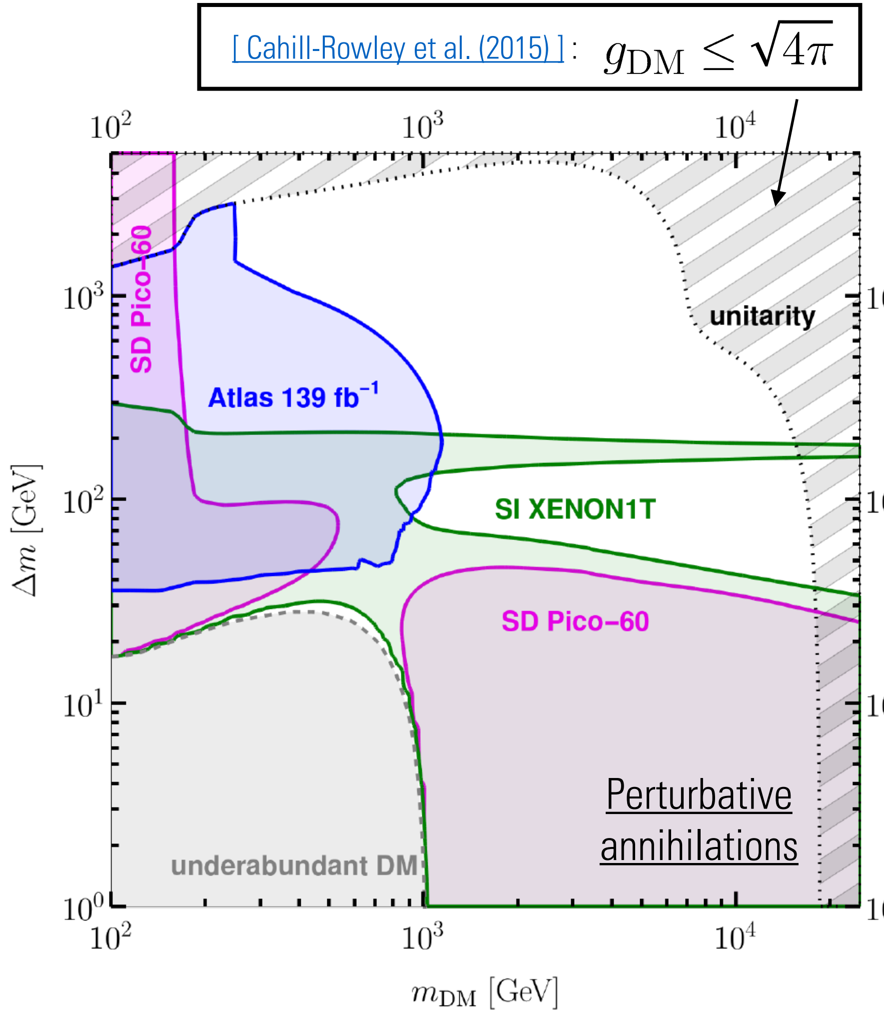


2



3





Becker, **EC**, Harz, Mohan, Sengupta (2022)

Prompt searches: bound state resonances

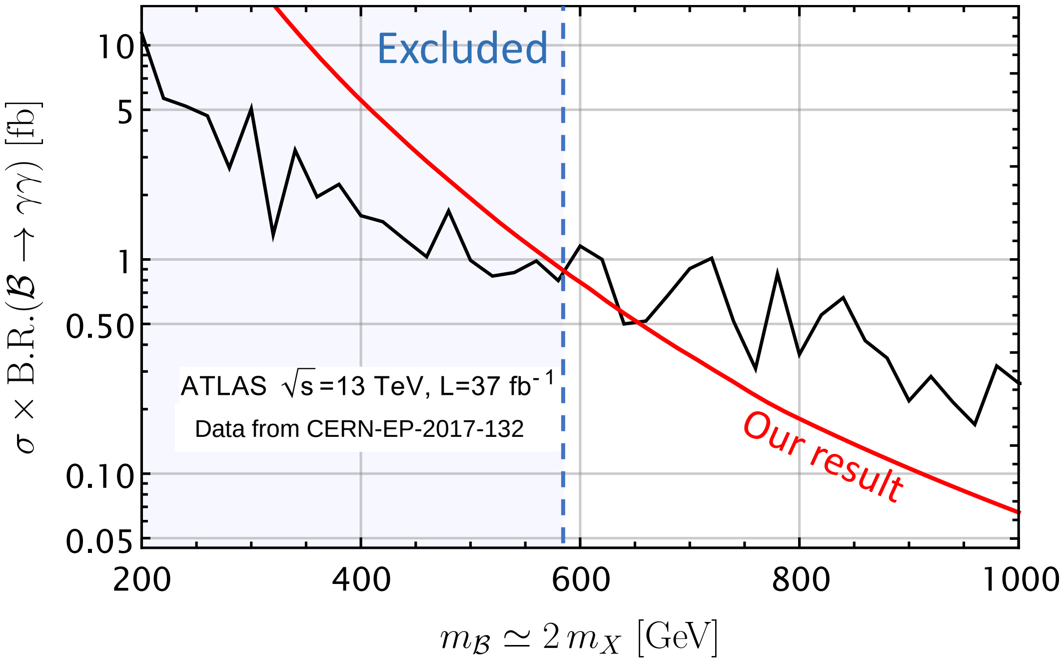
Prompt searches @ LHC

Squarkonium-like bound state resonances could form at the LHC

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

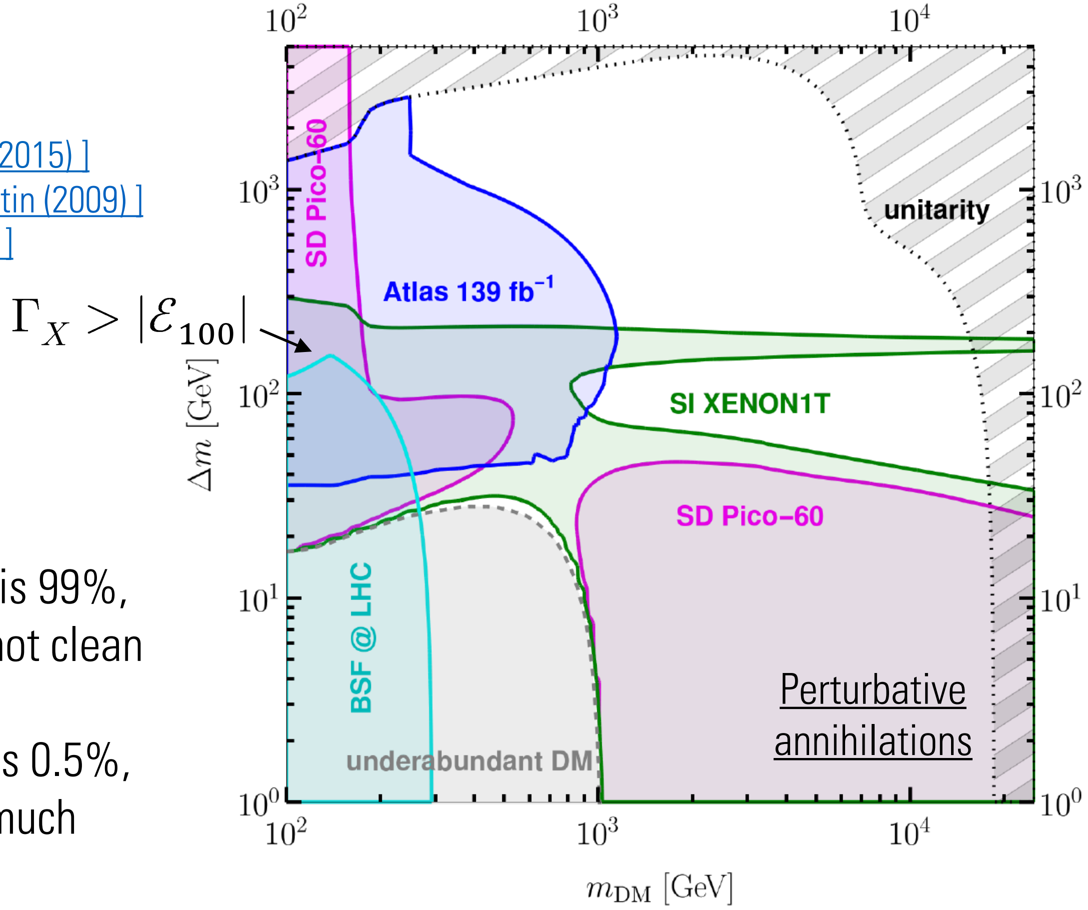
[Batell&Jung (2015)]
[Younkin&Martin (2009)]
[Martin (2008)]

Resonances can be detected via, e.g., diphoton signal:



Notice that:

- B.R. to gg is 99%, but signal not clean
- B.R. to $\gamma\gamma$ is 0.5%, but signal much cleaner



Becker, **EC**, Harz, Mohan, Sengupta (2022)

Potential of LLP searches

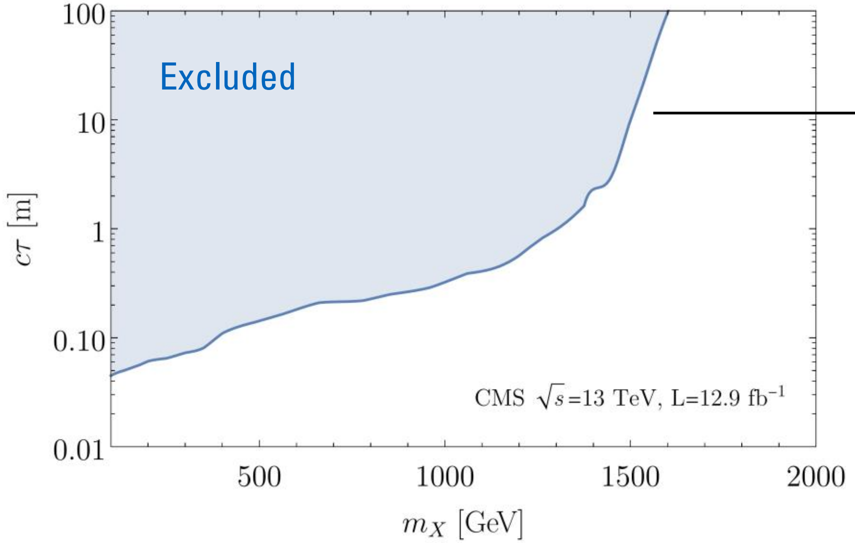
To address the parameter space where freeze-out DM is underabundant, we estimate $\tilde{g}_{\mathrm{DM}}$ below which DM proceeds non-thermally.
This roughly happens when (inverse) decays $X \leftrightarrow \chi\, q$ decouple:

$$\Gamma_X \frac{Y_X^{eq}}{Y_\chi^{eq}} \sim H \longrightarrow$$

Estimate of g_{DM} in CDFO
Upper bound on g_{DM} in FI

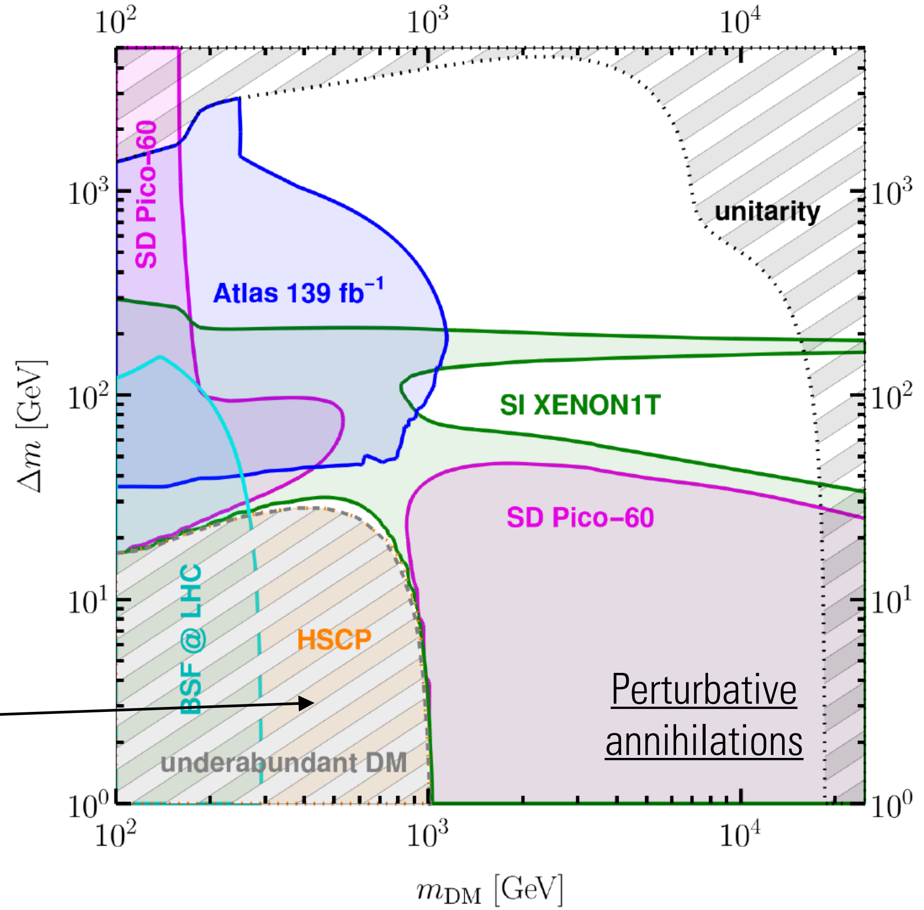
Long-lived particle searches @ LHC

Recast CMS Heavy Stable Charged Particles (HSCP) @ √s = 13 TEV, L=12.9 fb^{-1}



→ Lower bound on $g_{\mathrm{DM}} \equiv g_{\mathrm{DM}}^{\mathrm{LLP}}$

$\tilde{g}_{DM} < g_{DM}^{LLP}$:

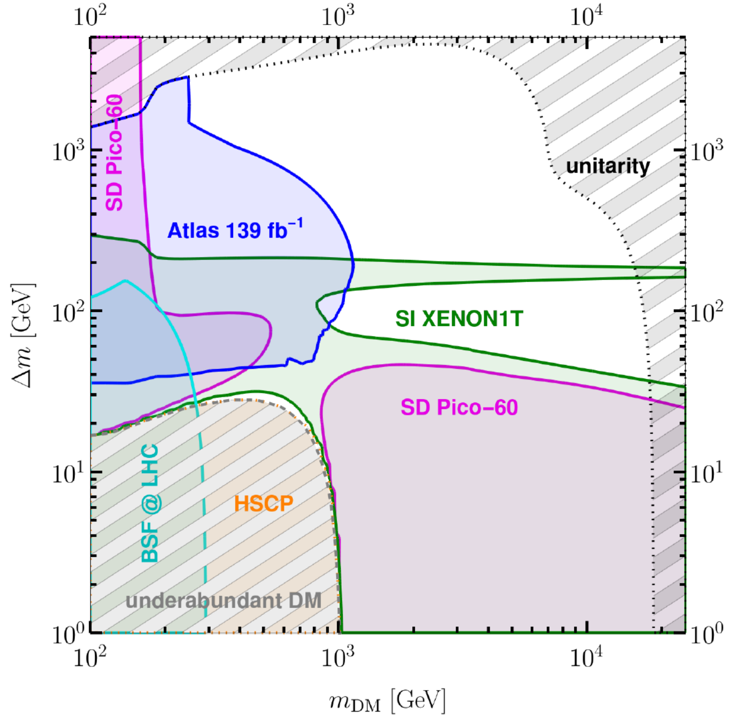


See, e.g.,
Garny et al. (2018), Quentin et al. (2021),
Bollig&Vogl (2021), Garny&Heisig (2021)

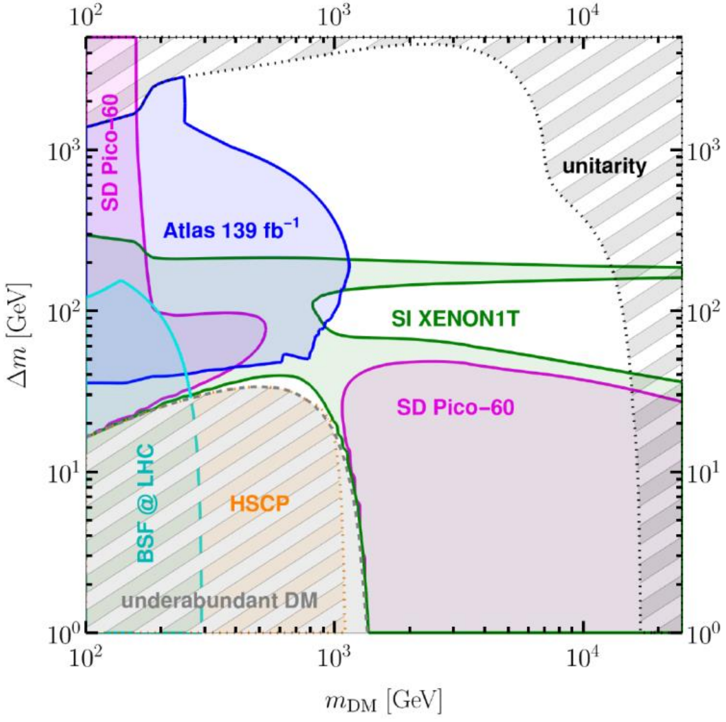
Becker, EC, Harz, Mohan, Sengupta (2022)

Combined constraints… with SE and SE+BSF

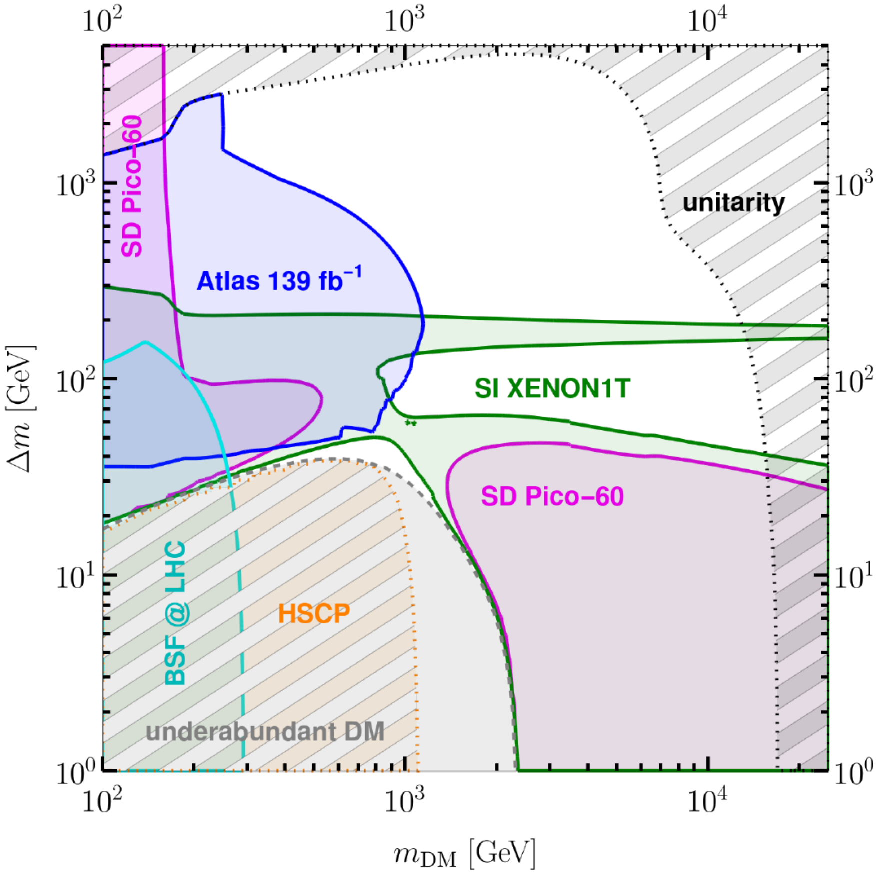
Becker, **EC**, Harz, Mohan, Sengupta (2022)



Perturbative annihilations



+ Sommerfeld

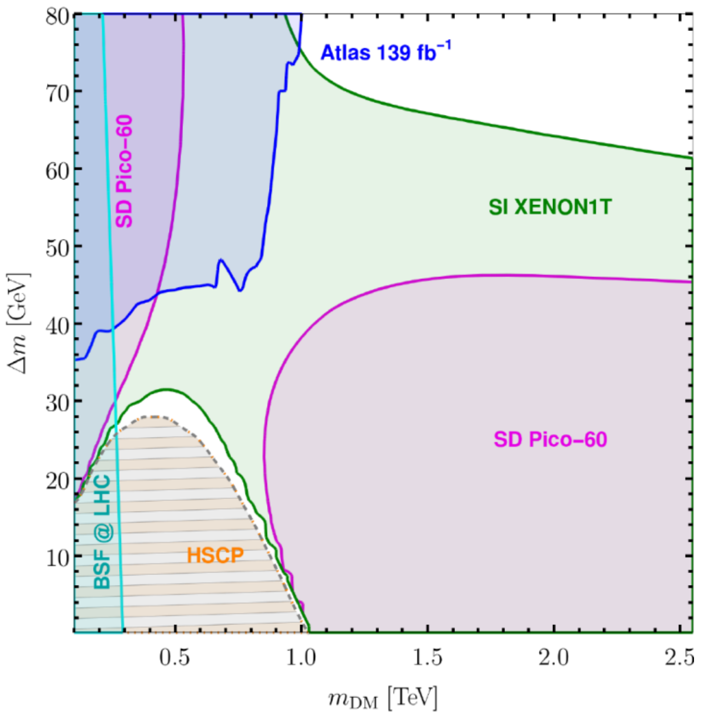


+ Sommerfeld + BSF

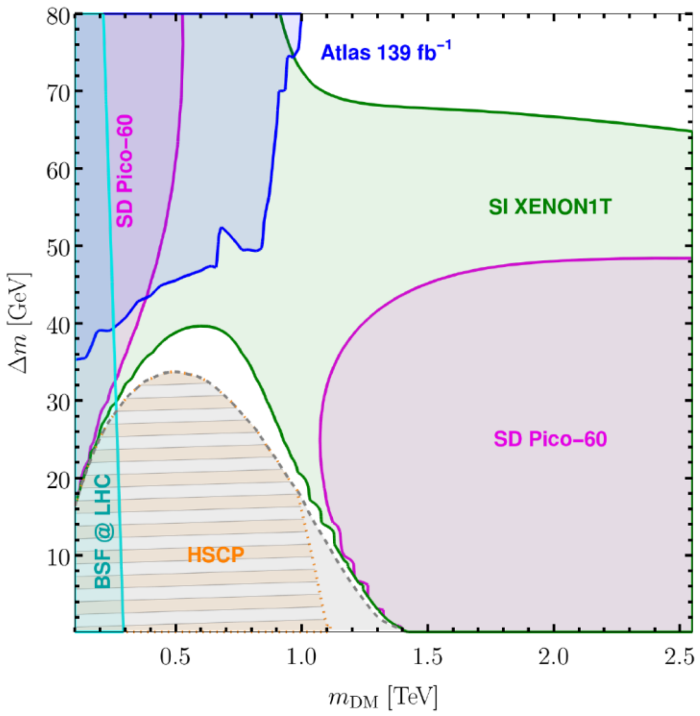
Combined constraints… with SE and SE+BSF

Becker, **EC**, Harz, Mohan, Sengupta (2022)

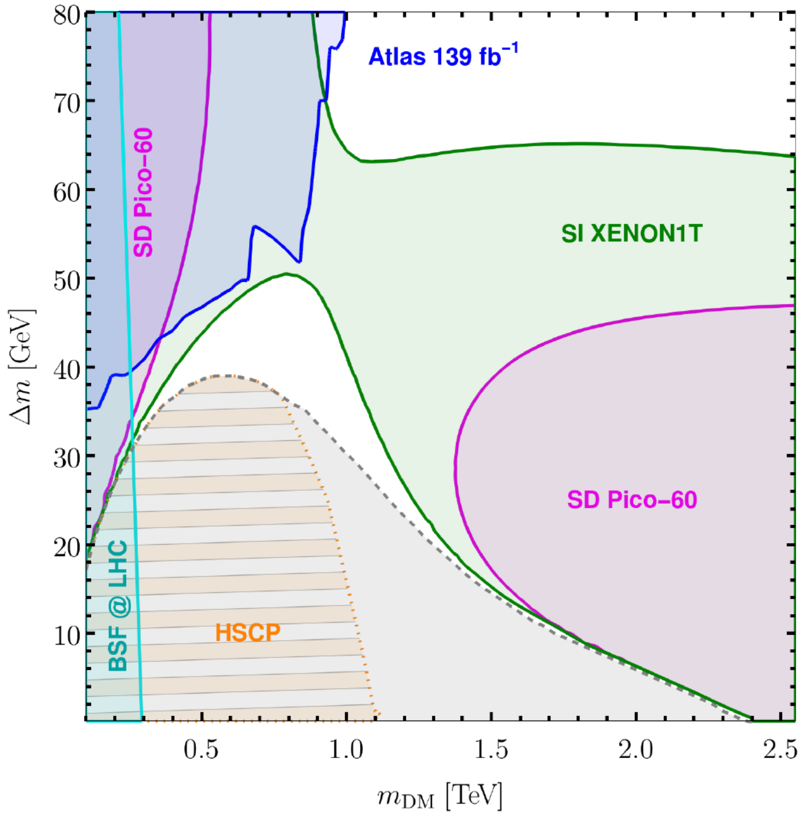
Zoomed in the strongly coannihilating region



Perturbative annihilations



+ Sommerfeld

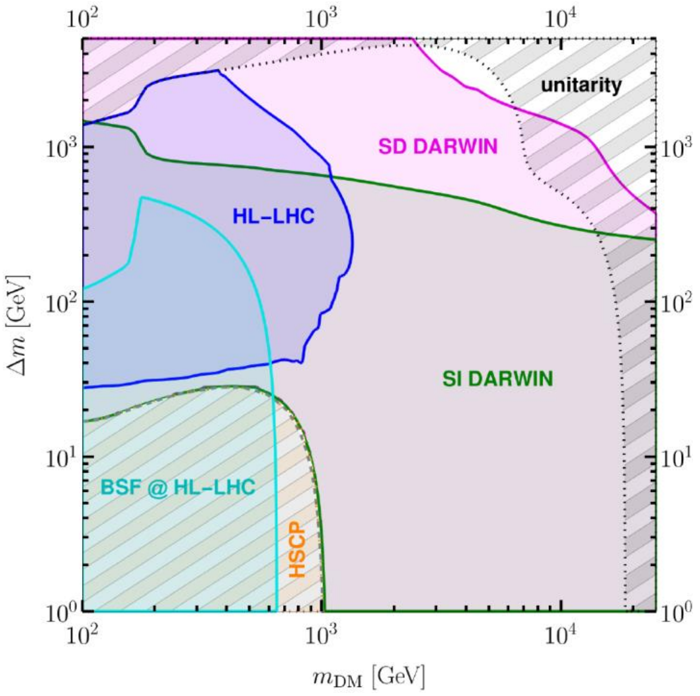


+ Sommerfeld + BSF

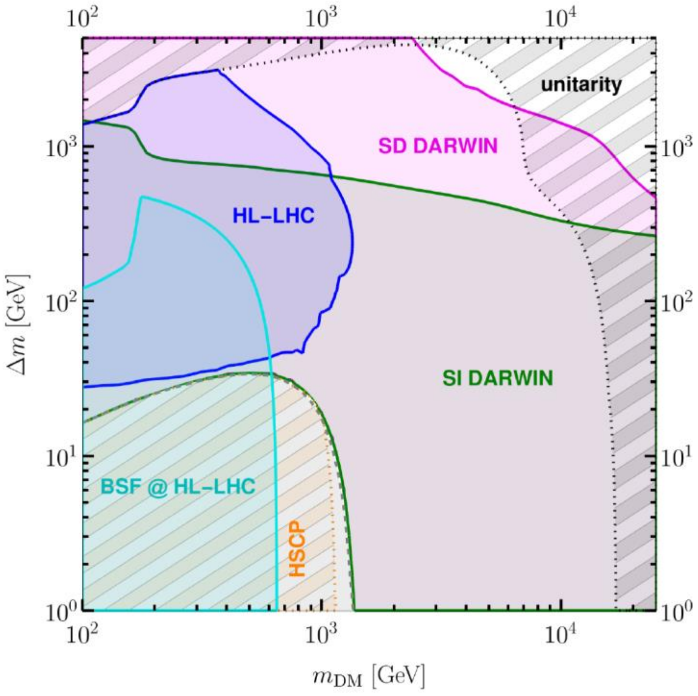
Future projections

Direct detection → Darwin project
Colliders → High-Lumi LHC

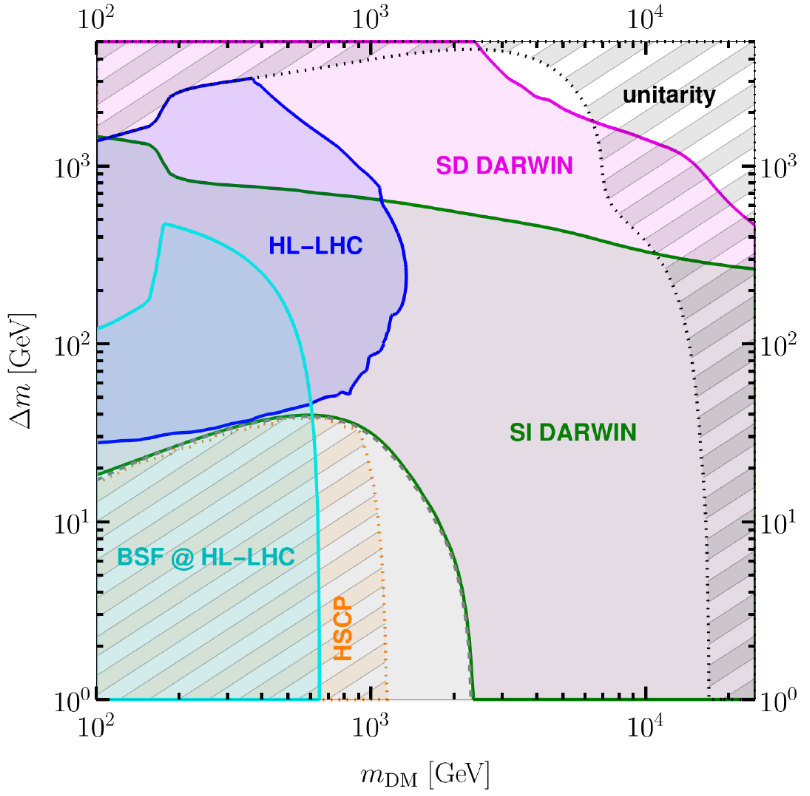
Becker, **EC**, Harz, Mohan, Sengupta (2022)



Perturbative annihilations



+ Sommerfeld



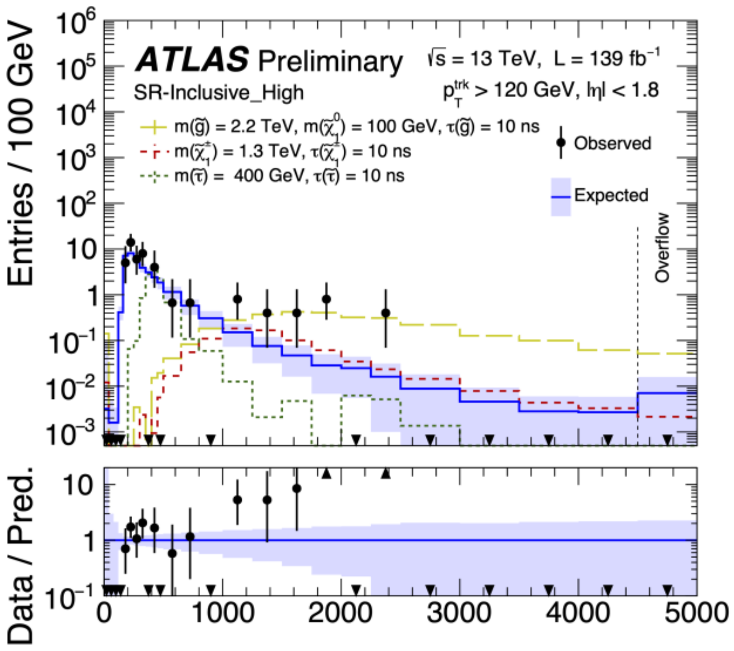
+ Sommerfeld + BSF

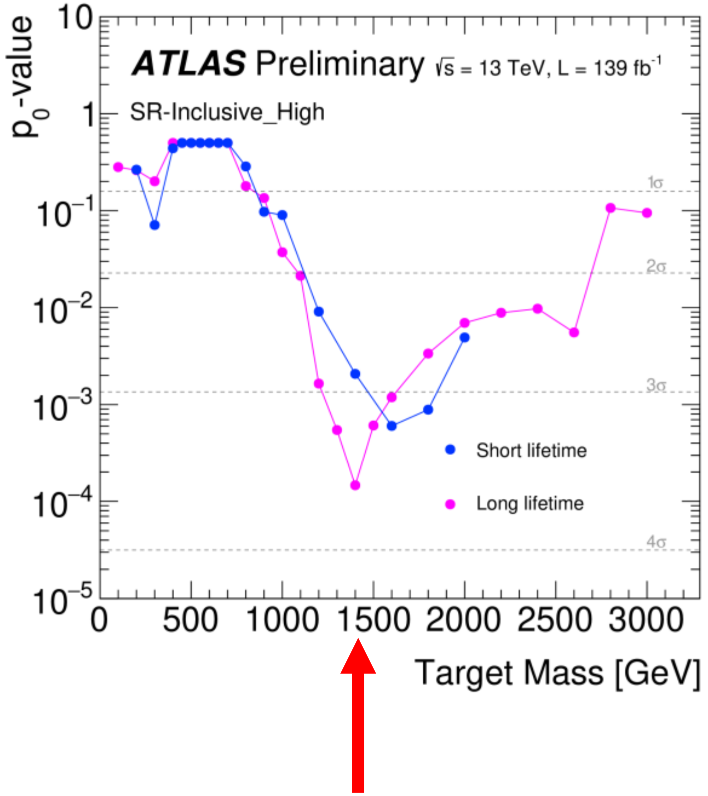
Final remarks: interesting LLP excess

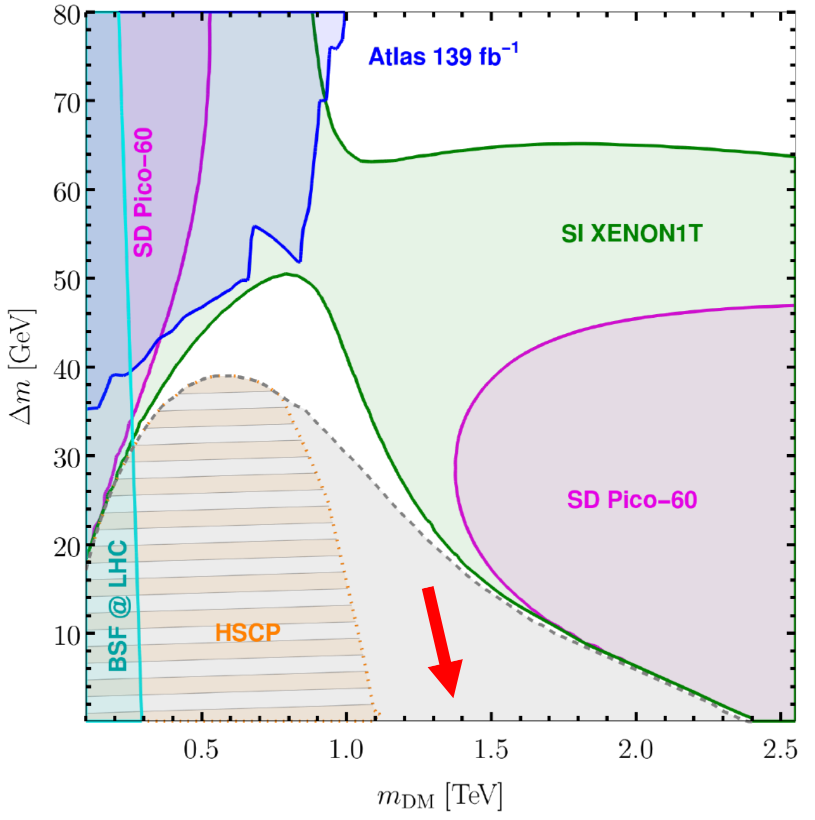
Interesting excess in LLP searches around $1.4\ \mathrm{TeV}$

(see talk by J. Gonski at Moriond 2022)

Becker, **EC**, Harz, Mohan, Sengupta (2022)







+ Sommerfeld + BSF

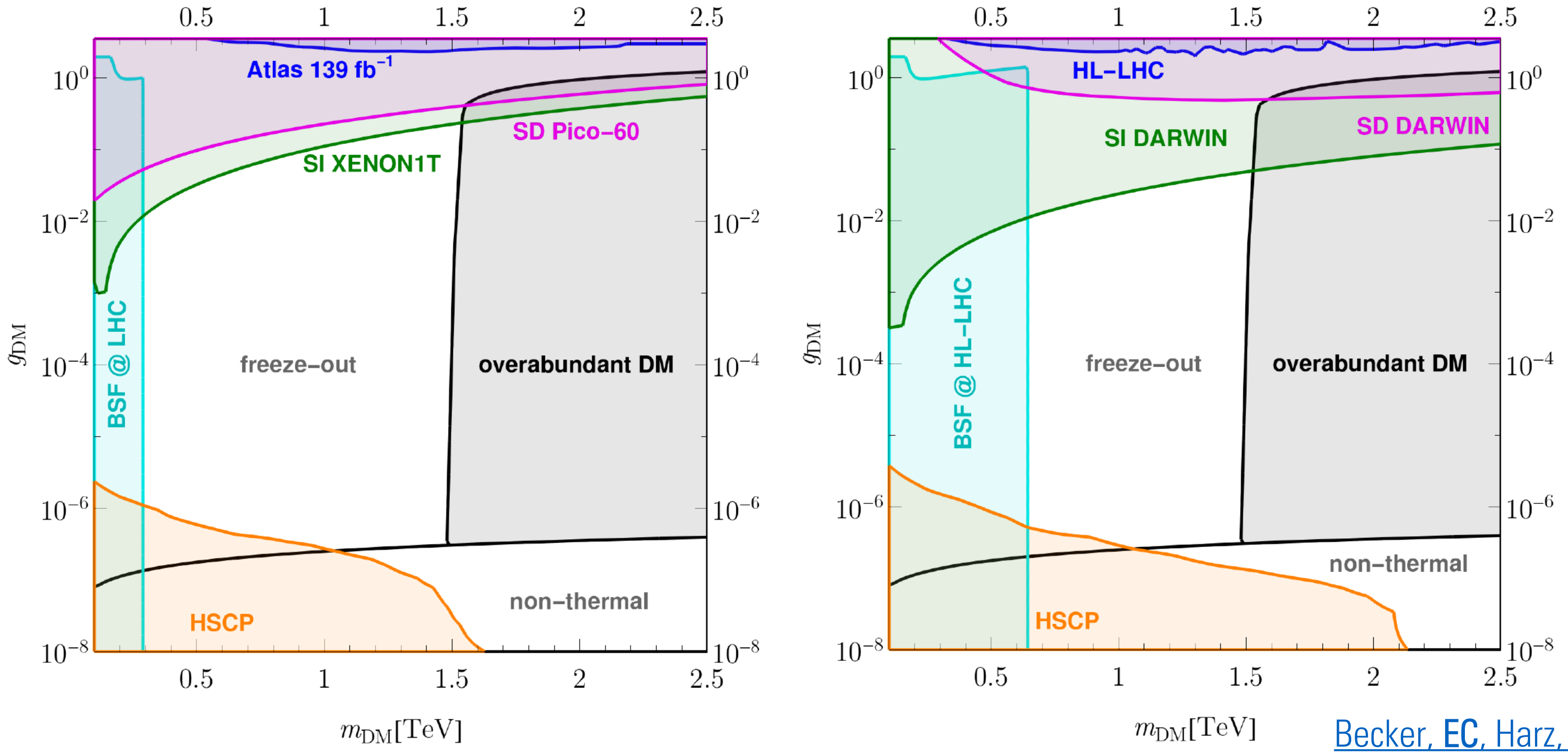
Final remarks: potential of bound state searches at LHC

BSF @ LHC | Prompt searches @ LHC

LLP @LHC | Direct detection

$\longrightarrow g_{DM}$

$\delta \equiv \frac{\Delta m}{m_X} = 1\%$



Becker, **EC**, Harz, Mohan, Sengupta (2022)

Conclusions

- Non-perturbative effects (SE and BSF) from long-range interactions have a sizable impact on the DM relic abundance in the coannihilating regime for colored dark sectors:
  smaller g_{DM}, larger m_{DM} and Δm wrt. the perturbative scenario.

- SE and BSF modify the effective annihilation cross-section in a non-trivial way, depending on the dominating processes (and the potential). A simple flat factor is not sufficient.

- SE and BSF extend unconstrained parameter space (small Δm), increasing region where portal coupling is small → non-thermal DM production (*see talk by J. Bollig tomorrow*).

- LLPs searches efficient for tiny couplings ($< 10^{-6}$). BS searches at colliders independent of portal coupling → bridge prompt and LLPs regimes ($10^{-6} \lesssim g_{DM} \lesssim 10^{-2}$).

- Model (almost) fully probed by future experiments → highly testable

Thank you for your attention!

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft