Simplified t-channel Dark Matter Model at the LHC

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KIRTIMAAN MOHAN

MICHIGAN STATE UNIVERSITY

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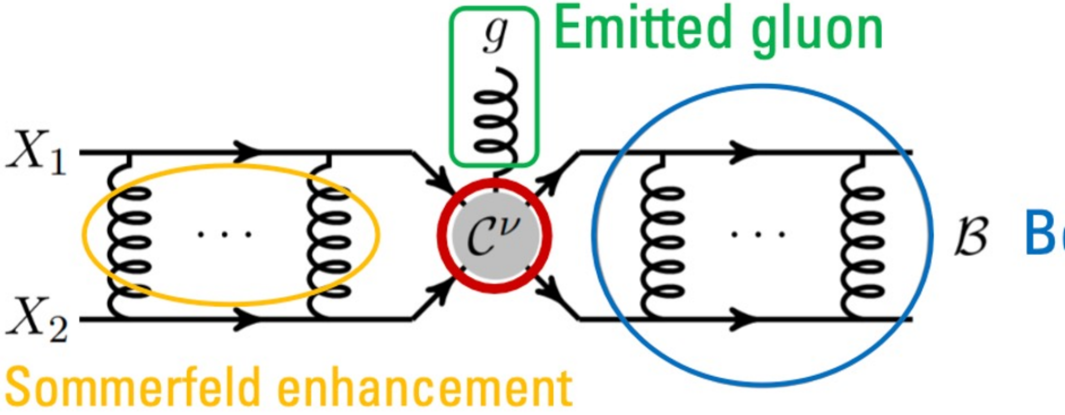

Simplified Models – What and Why?

- Many models feature a Dark Matter candidate.
- Many models; many parameters; difficult drawing general conclusions and repeating experimental analyses for each model.
- An EFT approach is very general and could cover all models; Validity of EFT at large momentum transfer? Not UV complete. Limitations when comparing between experiments that operate at different energy scales.
- **Simplified model** — A UV complete theory (not necessarily simplification of a more complete/complicated theory). Captures essential features of classes of models.
- **Construction of Simplified Model**—Inspired by more complete models, consider models that contain dark matter as well as the most important mediator(s).

s-channel vs t-channel

- S-channel couples separately to Dark Matter and SM

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}}\, Z'_\mu\, \bar{\chi}\gamma^\mu\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu\, \bar{q}\gamma^\mu q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu\, \bar{\ell}\gamma^\mu \ell\,,$$

- T-channel couples to Dark matter and SM in a single term.

$$g_{\text{DM}} \tilde{X}_i^\dagger \overline{\chi} P_R q_i$$

t-channel dark matter model classification

$$\mathcal{L}_{XY}^{\mathtt{F3S}} = \sum_{f=u,d} \lambda_f\, \bar{\psi}_f f_R\, \tilde{S} + \lambda_Q\, \bar{\psi}_Q Q_L\, \tilde{S} + \text{H.c.}\,, \qquad \mathcal{L}_{XY}^{\mathtt{F1S}} = \lambda_\ell\, \bar{\psi}_\ell \ell_R\, \tilde{S} + \lambda_L\, \bar{\psi}_L L_L\, \tilde{S} + \text{H.c.}\,,$$

$$\mathcal{L}_{XY}^{\mathtt{F3C}} = \sum_{f=u,d} \lambda_f\, \bar{\psi}_f f_R\, S + \lambda_Q\, \bar{\psi}_Q Q_L\, S + \text{H.c.}\,, \qquad \mathcal{L}_{XY}^{\mathtt{F1C}} = \lambda_\ell\, \bar{\psi}_\ell \ell_R\, S + \lambda_L\, \bar{\psi}_L L_L\, S + \text{H.c.}\,,$$

$$\mathcal{L}_{XY}^{\mathtt{S3M}} = \sum_{f=u,d} \lambda_f\, \bar{\tilde{\chi}} f_R\, \varphi_f^\dagger + \lambda_Q\, \bar{\tilde{\chi}} Q_L\, \varphi_Q^\dagger + \text{H.c.}\,, \qquad \mathcal{L}_{XY}^{\mathtt{S1M}} = \lambda_\ell\, \bar{\tilde{\chi}} \ell_R\, \varphi_\ell^\dagger + \lambda_L\, \bar{\tilde{\chi}} L_L\, \varphi_L^\dagger + \text{H.c.}\,,$$

$$\mathcal{L}_{XY}^{\mathtt{S3D}} = \sum_{f=u,d} \lambda_f\, \bar{\chi} f_R\, \varphi_f^\dagger + \lambda_Q\, \bar{\chi} Q_L\, \varphi_Q^\dagger + \text{H.c.}\,, \qquad \mathcal{L}_{XY}^{\mathtt{S1D}} = \lambda_\ell\, \bar{\chi} \ell_R\, \varphi_\ell^\dagger + \lambda_L\, \bar{\chi} L_L\, \varphi_L^\dagger + \text{H.c.}\,,$$

$$\mathcal{L}_{XY}^{\mathtt{F3V}} = \sum_{f=u,d} \lambda_f\, \bar{\psi}_f \gamma^\mu f_R\, \tilde{V}_\mu + \lambda_Q\, \bar{\psi}_Q \gamma^\mu Q_L\, \tilde{V}_\mu + \text{H.c.}\,, \qquad \mathcal{L}_{XY}^{\mathtt{F1V}} = \lambda_\ell\, \bar{\psi}_\ell \gamma^\mu \ell_R\, \tilde{V}_\mu + \lambda_L\, \bar{\psi}_L \gamma^\mu L_L\, \tilde{V}_\mu + \text{H.c.}\,,$$

$$\mathcal{L}_{XY}^{\mathtt{F3W}} = \sum_{f=u,d} \lambda_f\, \bar{\psi}_f \gamma^\mu f_R\, V_\mu + \lambda_Q\, \bar{\psi}_Q \gamma^\mu Q_L\, V_\mu + \text{H.c.}\,, \qquad \mathcal{L}_{XY}^{\mathtt{F1W}} = \lambda_\ell\, \bar{\psi}_\ell \gamma^\mu \ell_R\, V_\mu + \lambda_L\, \bar{\psi}_L \gamma^\mu L_L\, V_\mu + \text{H.c.}$$

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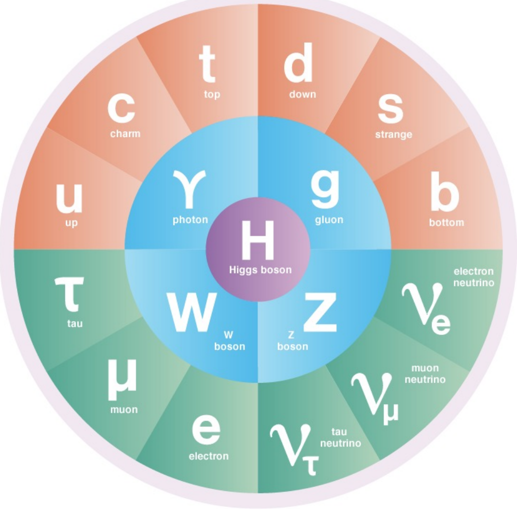
A Simplified t-channel Model

- SM + Dark Matter Particle (χ: $Majorana$) + mediator ($\tilde{X}_i$ $(\mathbf{3}, \mathbf{1}, +2/3)$)

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



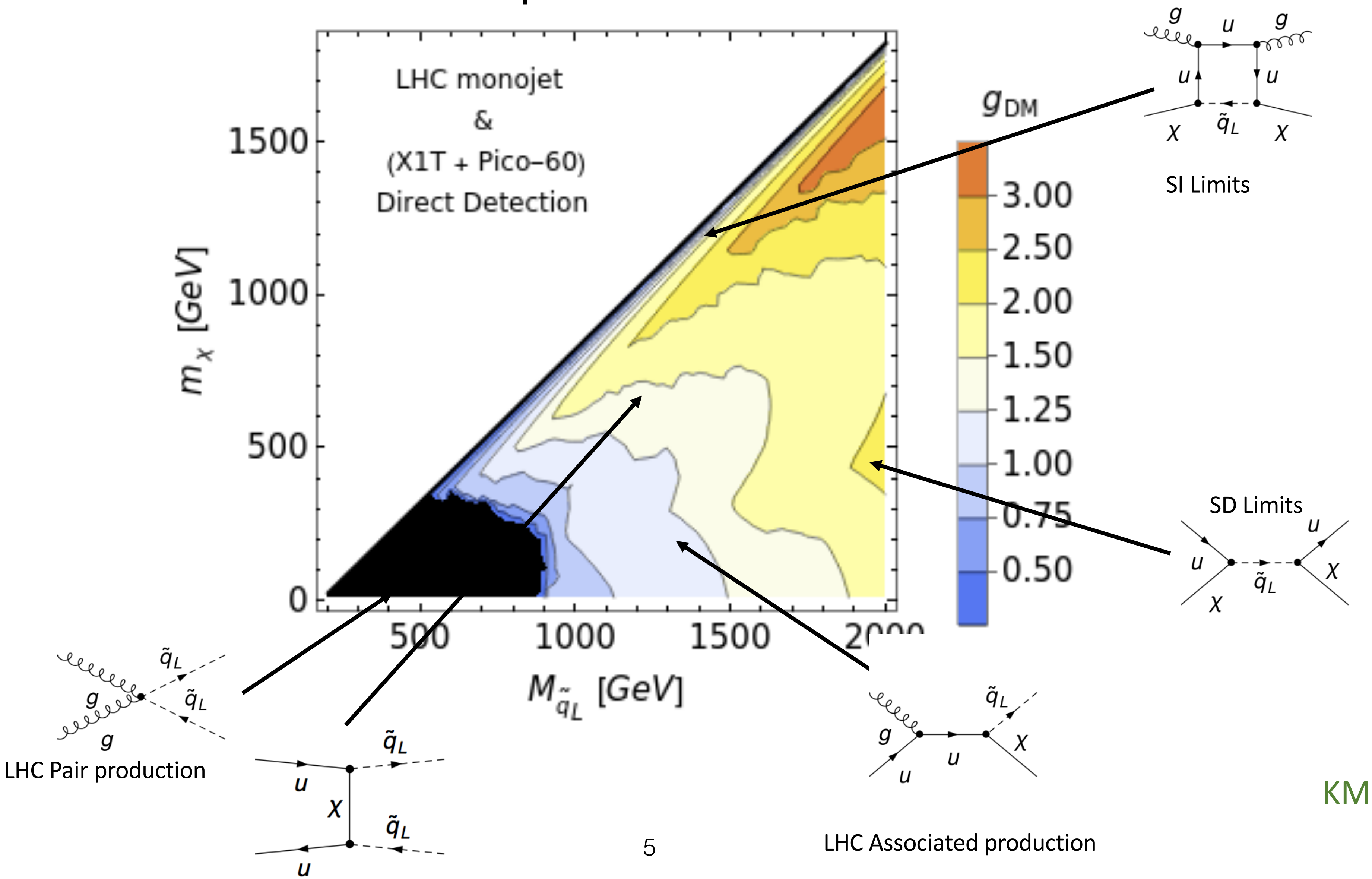
Mediator $\tilde{X}_i$ $\longleftrightarrow$ Dark Matter χ

<u>Simple model with three parameters;</u>

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

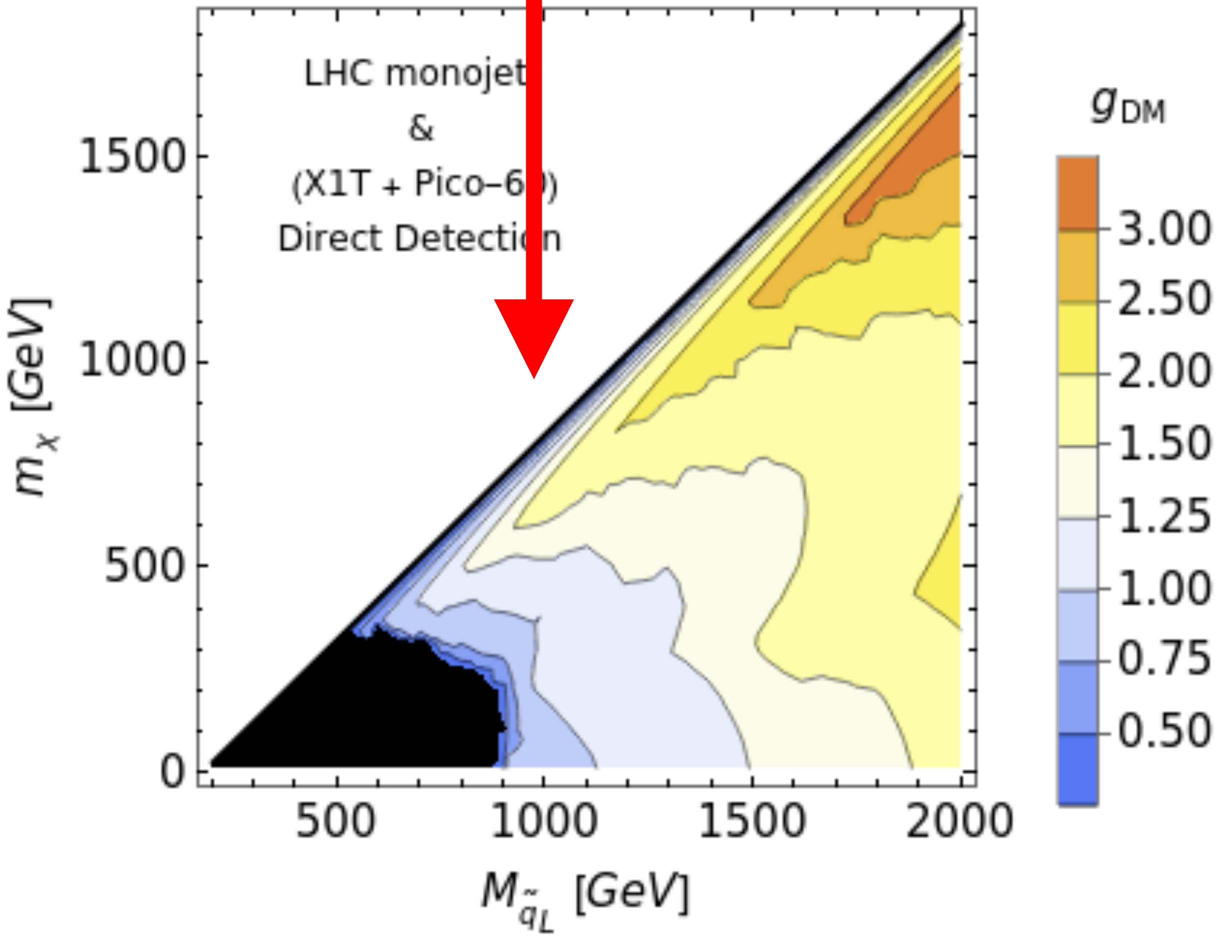
DiFranzo et. al. 2013, KM et. al 2019
Arina et. al. 2020 & 2021

Complementarity of DD & LHC experiments



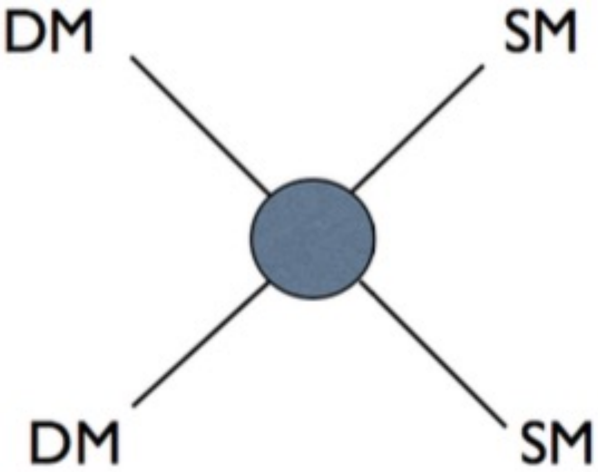
KM et. al 2019

This talk will focus on the phenomenology of the Compressed Region small $\Delta m = (m_X - m_\chi)$



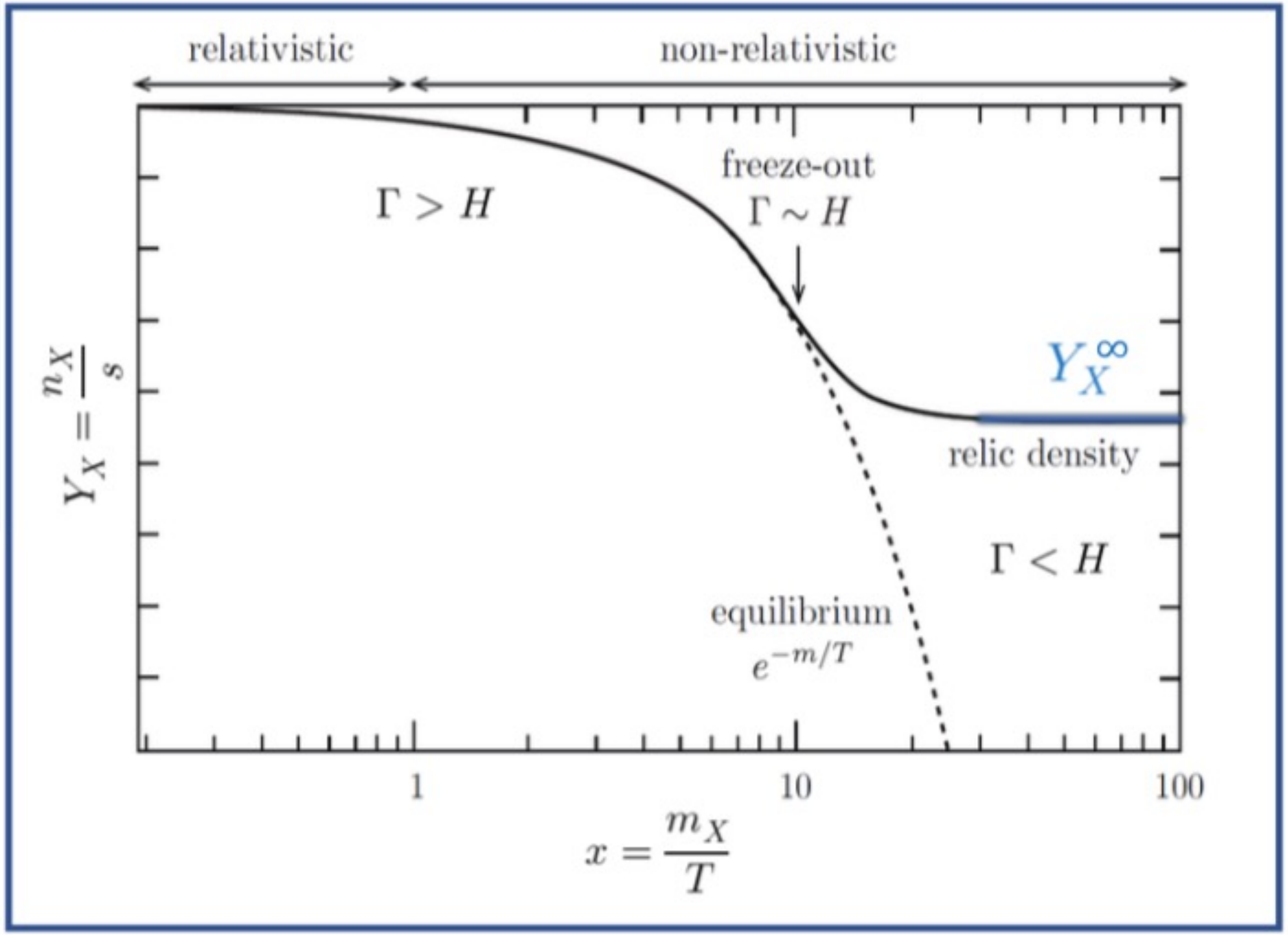
KM et. al 2019

- In the early universe, dark matter was in thermal equilibrium with SM



$$\dot{n}(t) + 3H(t)n(t) = -\langle \sigma_{\chi\chi}\, v \rangle \left(n(t)^2 - n_{\mathrm{eq}}(t)^2 \right)$$

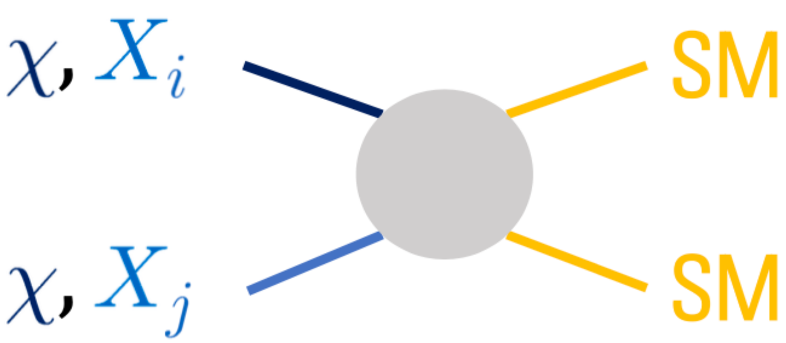
$$\boxed{\frac{dY_X}{dx} = -\frac{s\langle \sigma v \rangle}{Hx}[Y_X^2 - (Y_X^{eq})^2]}$$



Co-annihilation

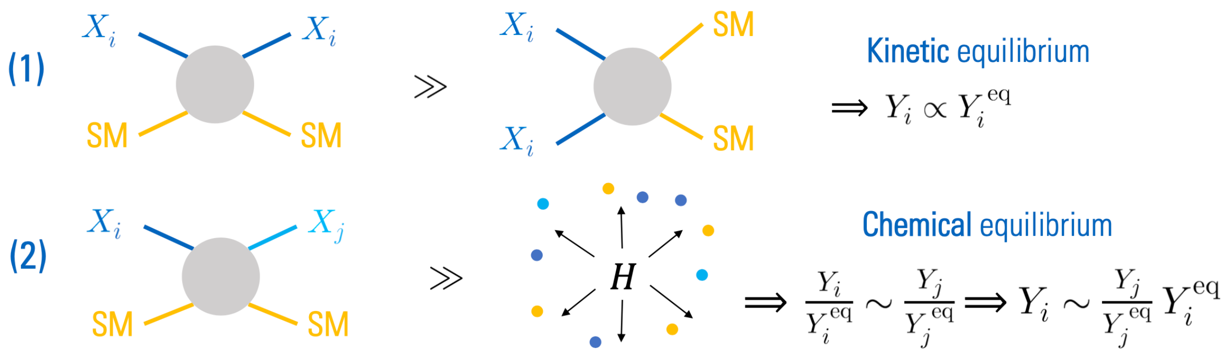
[Griest&Seckel (1991)], [Edsjö&Gondolo (1997)], …

Co-annihilations



dark sector = $\{ \chi, X_2, X_3, \dots, X_n \}$

- If $m_{X_i} \gg m_\chi$ then these are Boltzmann suppressed.
- If $m_{X_i} \sim m_\chi$ we would need a system of n Boltzmann equations



(3) Eventually, all the X_i will decay into the LSP DM

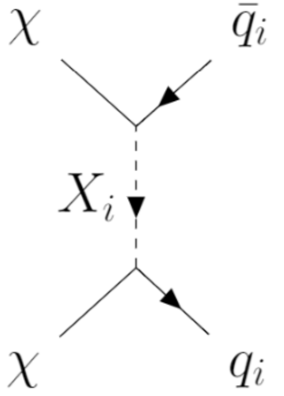
$$\tilde{Y} = Y_\chi + \sum Y_{X_i}$$

Effective Boltzmann equation

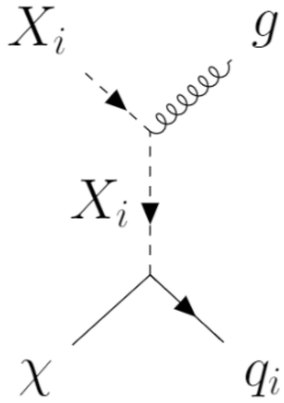
$$\frac{d\tilde{Y}}{dx} = -\frac{s}{H\,x} \langle \sigma_{\rm eff} v_{\rm rel} \rangle \left(\tilde{Y} - \tilde{Y}^{\rm eq} \right)$$

$$\langle \sigma_{\rm eff} v_{\rm rel} \rangle = \sum_{ij} \langle \sigma_{ij} v_{ij} \rangle \frac{Y_i^{\rm eq} Y_j^{\rm eq}}{\tilde{Y}^{\rm eq\,2}}$$

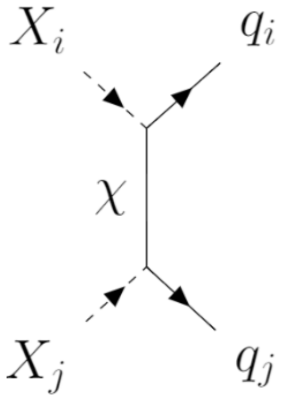
Co-annihilation



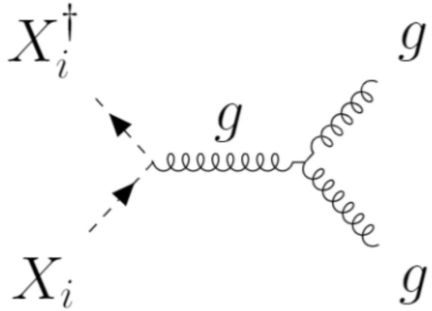
g_{DM}^4



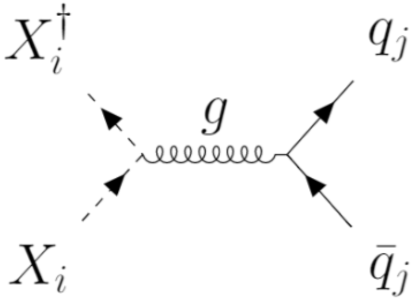
$g_{\mathrm{DM}}^2 g_s^2 e^{-\Delta/T}$



$g_{\mathrm{DM}}^4 e^{-2\Delta/T}$



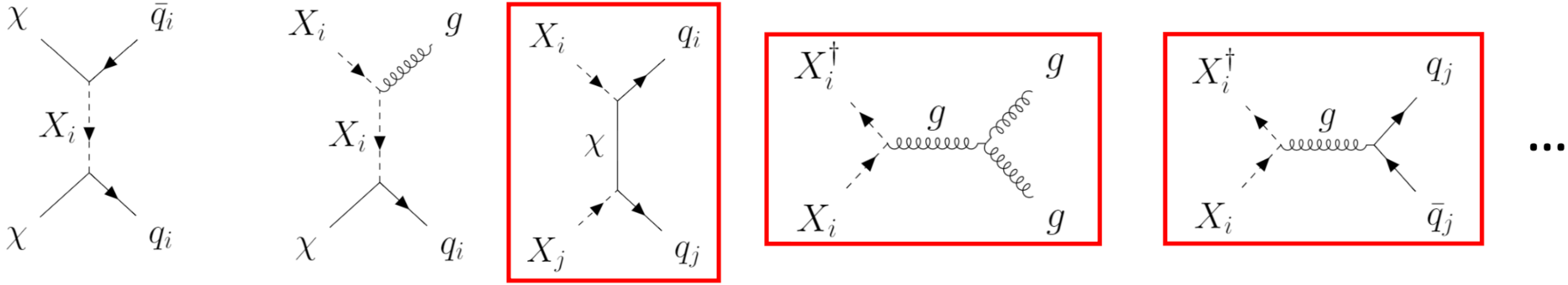
$(\alpha g_{\mathrm{DM}}^2 + \beta g_s^2)^2 \, e^{-2\Delta/T}$



$g_{\mathrm{t}}^4 e^{-2\Delta/T}$

…

Relevant when mass splitting Δm small



g_{DM}^4 $\quad$ $g_{\mathrm{DM}}^2 g_s^2 e^{-\Delta/T}$ $\quad$ $g_{\mathrm{DM}}^4 e^{-2\Delta/T}$ $\quad$ $\left(\alpha g_{\mathrm{DM}}^2 + \beta g_s^2\right)^2 e^{-2\Delta/T}$ $\quad$ $g_s^4 e^{-2\Delta/T}$ $\quad$ ...

Relevant when mass splitting Δm small

! Incoming colored states experience gluonic long-range force!

<u>Recall</u>: $X \sim \mathbf{3}$ and $X^\dagger \sim \overline{\mathbf{3}}$ of $\mathrm{SU}(3)$

Sommerfeld Effect

A. Sommerfeld Ann. Phys. 403 (1931) 257

Slowly-moving massive particles experience the presence of the **NR potential** between them:

- Wavefunctions are distorted already at large distances (long-range effect)
- Probability of finding particle at interaction vertex is modified (non-perturbative)

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dR_l}{dr}\right) = \left[2\mu\left[V(r)-E\right]+\frac{l(l+1)}{r^2}\right]R_l \qquad V_{\mathrm{Coulomb}}(r) = \pm\frac{\alpha}{r}$$

$$\mu = m_X/2$$

$$\boxed{\sigma_\ell^S v_{\mathrm{rel}} = S_\ell\,\sigma_\ell^{\mathrm{pert.}}} \qquad \boxed{\zeta = \alpha/v_{\mathrm{rel}}}$$

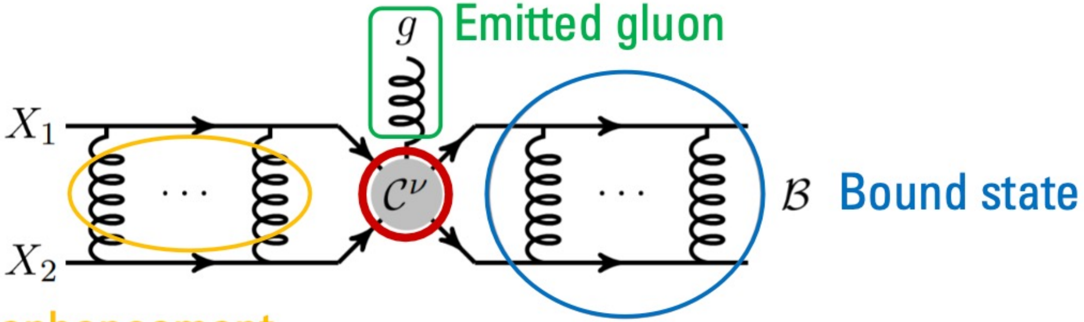
$$\boxed{S_\ell = \left|\frac{(2\ell+1)!!}{|p|^\ell \ell!}\frac{\partial^\ell R_\ell(r)}{\partial r^\ell}\bigg|_{r=0}\right|^2 \xrightarrow[\text{Coulomb}]{} S_\ell(\zeta) = \frac{2\pi\zeta}{1-e^{-2\pi\zeta}}\times\prod_{n=1}^{\ell}\left(1+\frac{\zeta^2}{n^2}\right)}$$

Bound State Formation

[Harz and Petraki (2018)]
[Petraki et al. (2015)]

$$\mathbf{R_1} \otimes \mathbf{R_2} = \sum \hat{\mathbf{R}}$$

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



$$V_{\text{gluon}}^{[\hat{\mathbf{R}}]}(r) = -\frac{\alpha_g^{[\hat{\mathbf{R}}]}}{r} = -\frac{\alpha_s}{2r}\left[C_2(\mathbf{R_1}) + C_2(\mathbf{R_2}) - C_2(\hat{\mathbf{R}})\right] \xrightarrow{\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}} V(r)_{\mathbf{3}\otimes\bar{\mathbf{3}}} = \begin{cases} \boxed{-\frac{4}{3}\frac{\alpha_s}{r} \quad [\mathbf{1}]} \\ +\frac{1}{6}\frac{\alpha_s}{r} \quad [\mathbf{8}] \end{cases}$$

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

$$\boxed{\sigma_{\{100\}}^{[\mathbf{8}]\to[\mathbf{1}]} v_{\text{rel}} = \frac{2^7\, 17^2}{3^5} \frac{\pi \alpha_{s,[\mathbf{1}]}^{\text{BSF}} \alpha_{s,[\mathbf{1}]}^{B}}{m_X^2} S_{\text{BSF}}(\zeta_S, \zeta_B)}$$

$$\boxed{S_{\text{BSF}}(\zeta_S, \zeta_B) = \left(\frac{2\pi\zeta_S}{1 - e^{-2\pi\zeta_S}}\right)(1 + \zeta_S^2)\frac{\zeta_B^4 e^{-4\zeta_S \operatorname{arccot}(\zeta_B)}}{(1 + \zeta_B^2)^3}}$$

Bound state decay and ionization

If X_1 and X_2 can (co-)annihilate into n lighter particles, then their bound states $\mathcal{B}(X_1, X_2)$ are unstable against decay into the same final-state particles.

Decay

$\mathcal{B}(XX^\dagger) \to gg$

$\to$ New effective annihilation channel!

$$\Gamma_{\text{dec},[\mathbf{R}]} = (\sigma^{s\text{-wave}}_{\text{ann},[\mathbf{R}]} v_{\text{rel}}) |\psi^{[\mathbf{R}]}_{nlm}(0)|^2$$

$$|\psi^{[\mathbf{1}]}_{100}(0)|^2 = 8 m_X^3 \mathfrak{S} \alpha^B_{s,[\mathbf{1}]} \mathfrak{T}^3 /27\pi$$

$$\Gamma_{\text{dec},[\mathbf{1}]} = \frac{32}{81} m_X (\alpha_s^{\text{ann}})^2 (\alpha^B_{s,[\mathbf{1}]})^3$$

At $T \gg \mathcal{E}_{100} = \omega$, energetic gluons in thermal plasma can also dissociate/ionize B.S. into their constituents

Ionization

$\mathcal{B}(XX^\dagger) + g \to X + X^\dagger + g$

$$\Gamma_{\text{ion}} = g_g \int_{\omega_{\min}}^{\infty} \frac{d\omega}{2\pi^2} \frac{\omega^2}{e^{\omega/T} - 1} \sigma_{\text{ion}}$$

$$\sigma_{\text{ion}} = \frac{g_X^2}{g_g g_{\mathcal{B}}} \left(\frac{\mu^2 v_{\text{rel}}^2}{\omega^2} \right) \sigma_{\text{BSF}}$$

BSF impact on Boltzmann equation

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

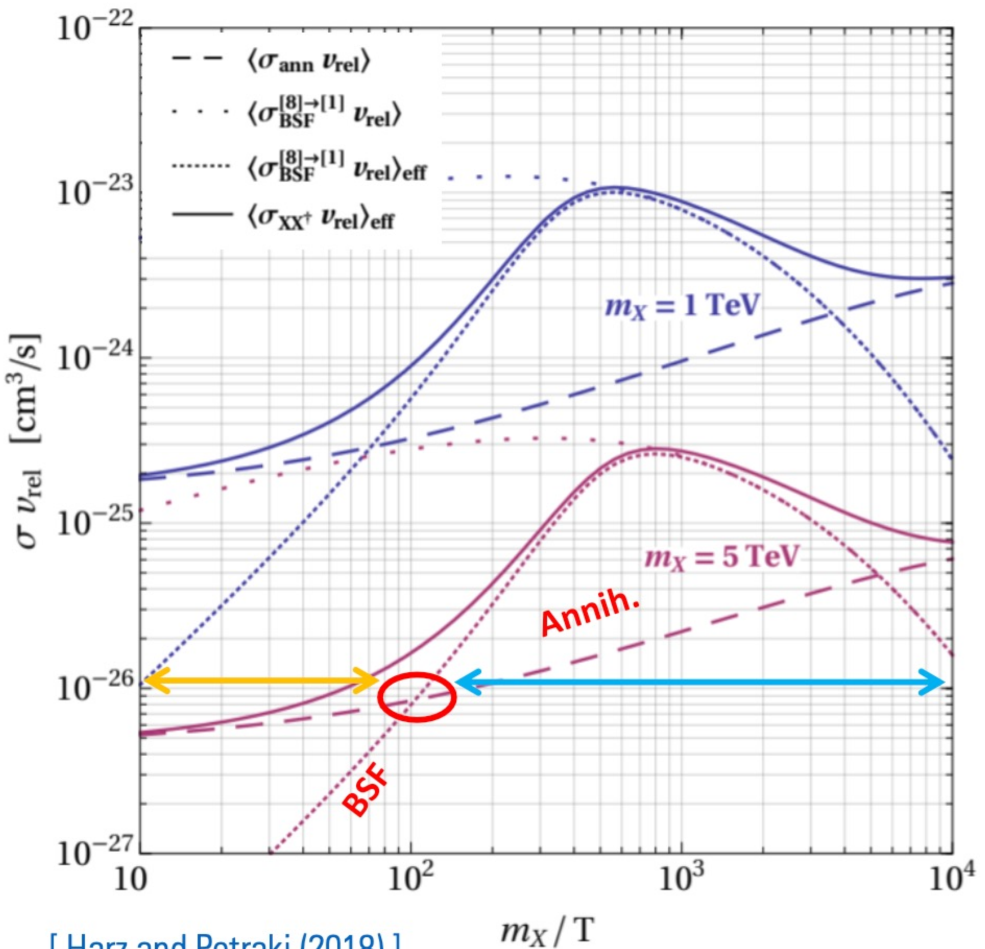
$$\mathcal{B}_{\mathrm{F}} X X^{\dagger}_{\mathrm{G}} \to g + g$$

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

$$\mathcal{B}_{\mathbb{W}} X X^{\dagger}_{\mathbb{X}} + g \to X + X^{\dagger}$$

Large T $\quad \Gamma_{\mathrm{Ion}} \gg \Gamma_{\mathrm{Dec}} \;\Rightarrow\; \langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle_{\mathrm{eff}} \to 0$

Small T $\quad \Gamma_{\mathrm{Ion}} \ll \Gamma_{\mathrm{Dec}} \;\Rightarrow\; \langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle_{\mathrm{eff}} \to \langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle$



[Harz and Petraki (2018)]

Relic density computation

- Several tools for calculating DM relic density + experimental signatures (non-exhaustive list)
  - MadDM [Backovic et al. (2013)]
  - SuperIso Relic [Arbey&Mahmoudi (2009)]
  - DarkSUSY [Gondolo et al. (2004)]
  - MicrOMEGAs [Belanger et al. (2010)]

- <u>BSF and Sommerfeld effects not included</u>
  <u>Exception</u>: DarkSUSY includes Sommerfeld effect only for electroweak interactions.

MadDM

SuperIso Relic

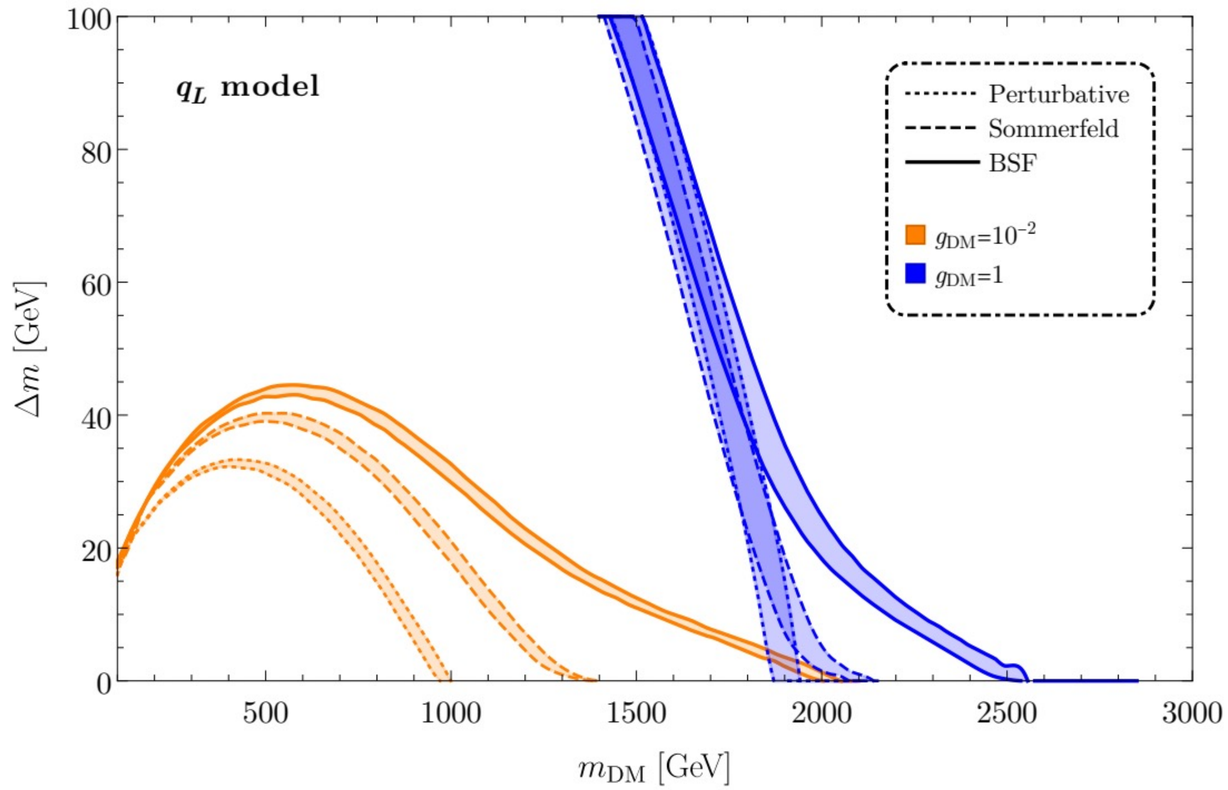
Dark SUSY

MicrOMEGAs

We modified **MicrOMEGAs v.5.2.7** including:

1. **Sommerfeld** effect ($\mathbf{3} \otimes \overline{\mathbf{3}}$ and $\mathbf{3} \otimes \mathbf{3}$)
2. **BSF** (singlet ground state) for **colored** particles.

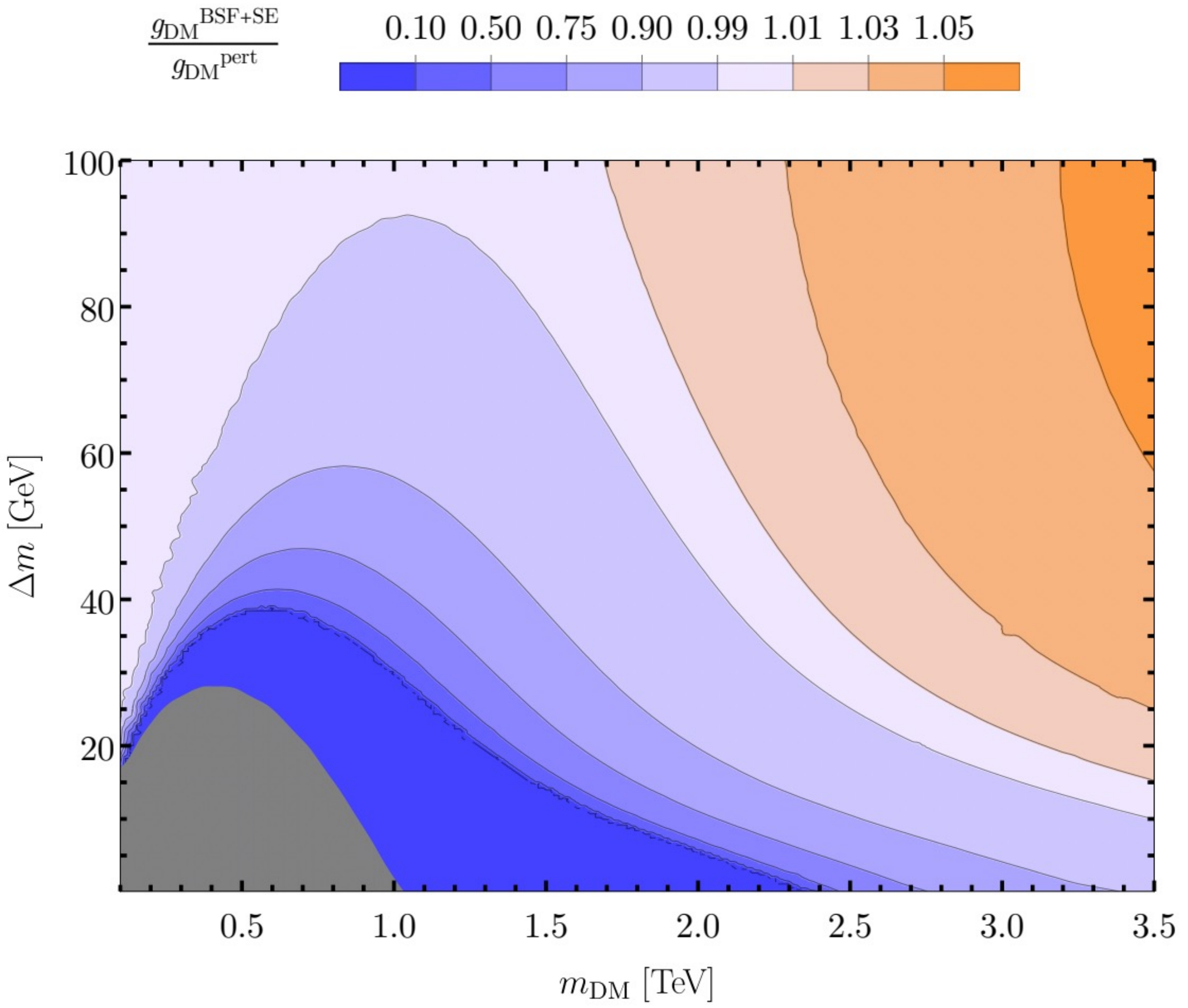
M. Becker, E. Copello, KM, J Harz, D. Sengupta (2022)



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

M. Becker, E. Copello, J. Harz, KM, D. Sengupta, 2022

Cannot use a constant k factor



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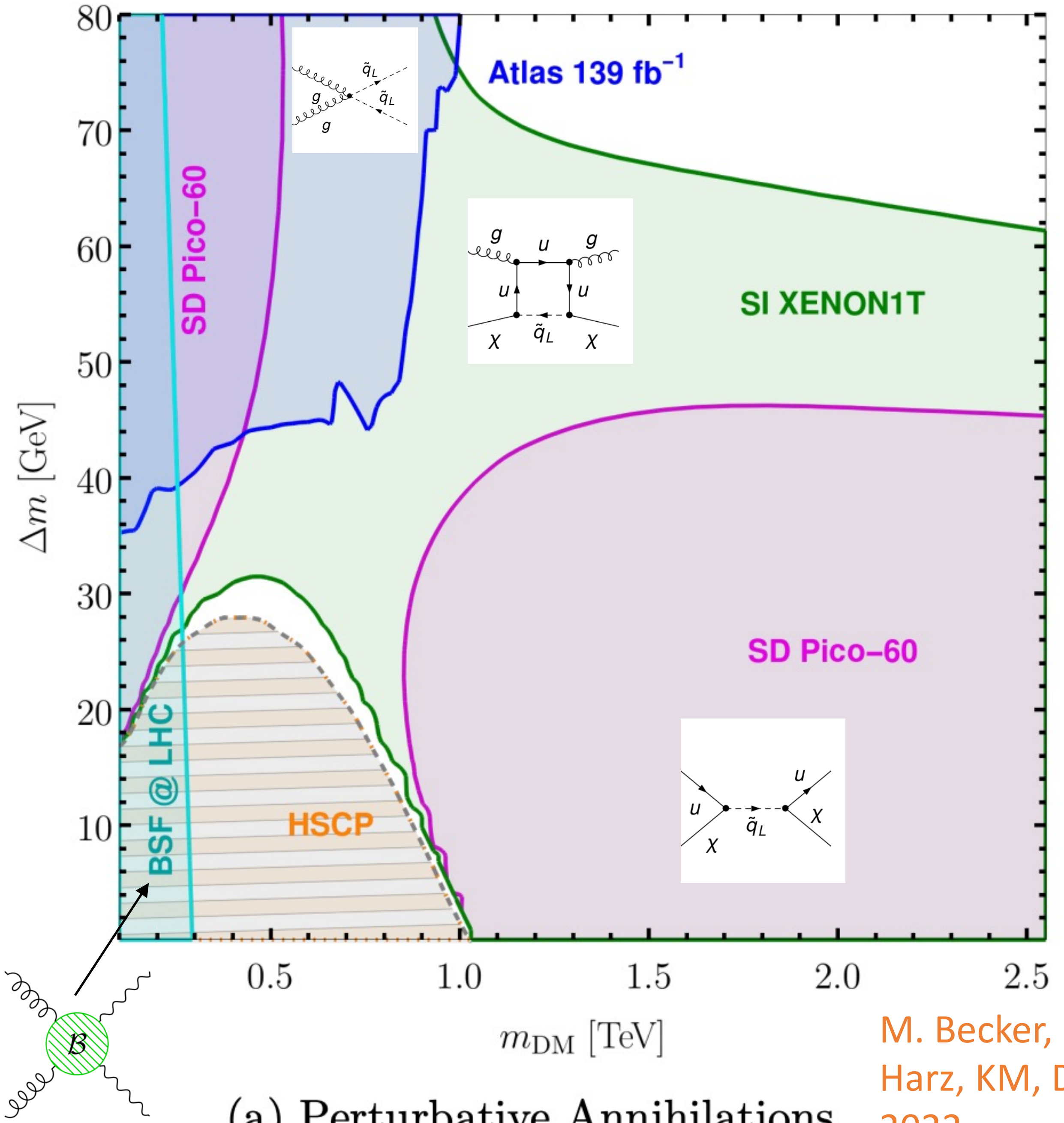

(a) Perturbative Annihilations

M. Becker, E. Copello, J. Harz, KM, D. Sengupta, 2022

- **HSCP**: Heavy stable charged particle searches (decays in or outside detector)
- **BSF**: Bound State Formation – Bound states form and decay to gauge bosons at LHC
- **SI** : Spin Independent Direct Detection
- **SD**: Spin Dependent Direct Detection

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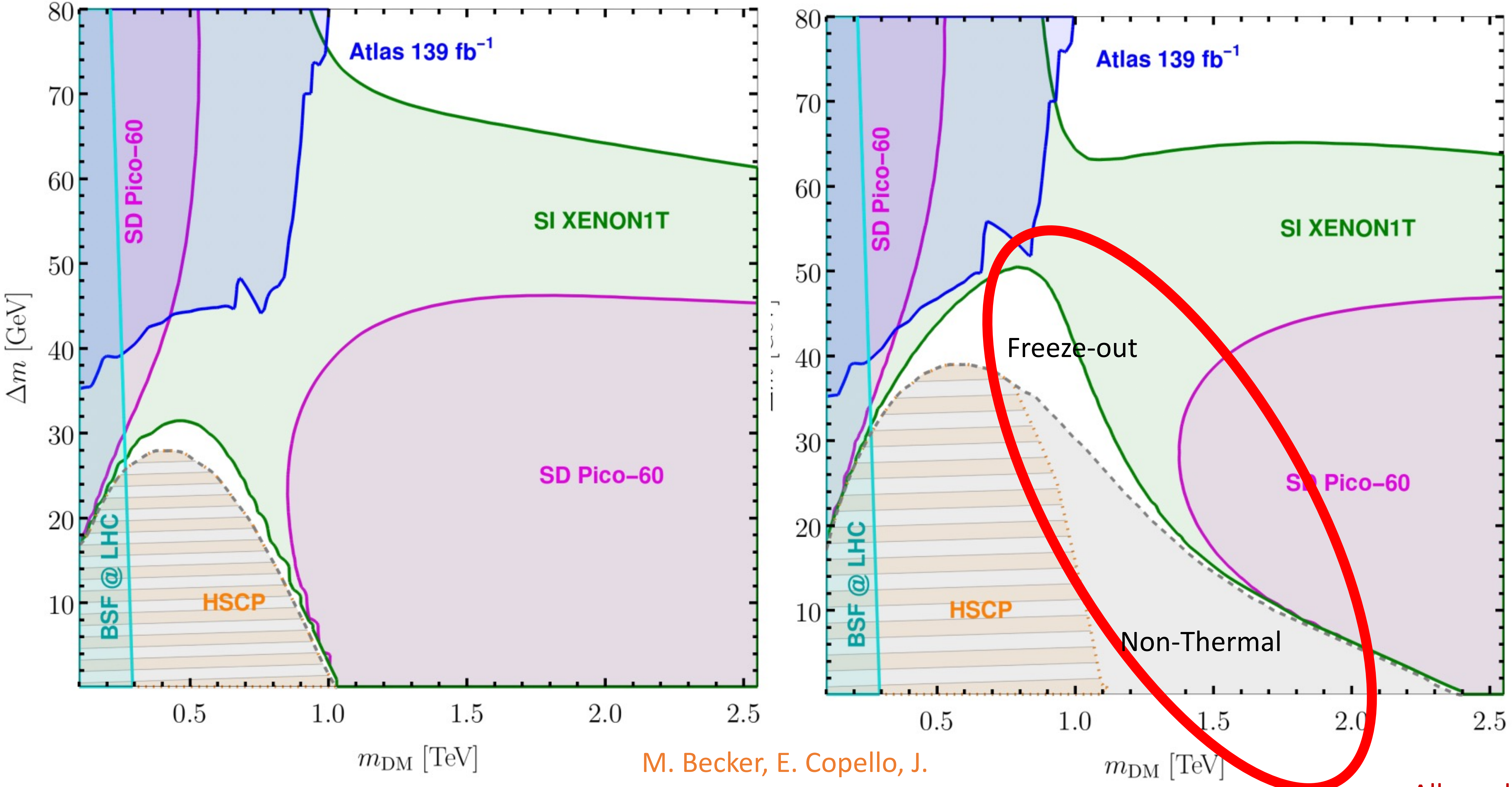


(a) Perturbative Annihilations

M. Becker, E. Copello, J. Harz, KM, D. Sengupta, 2022

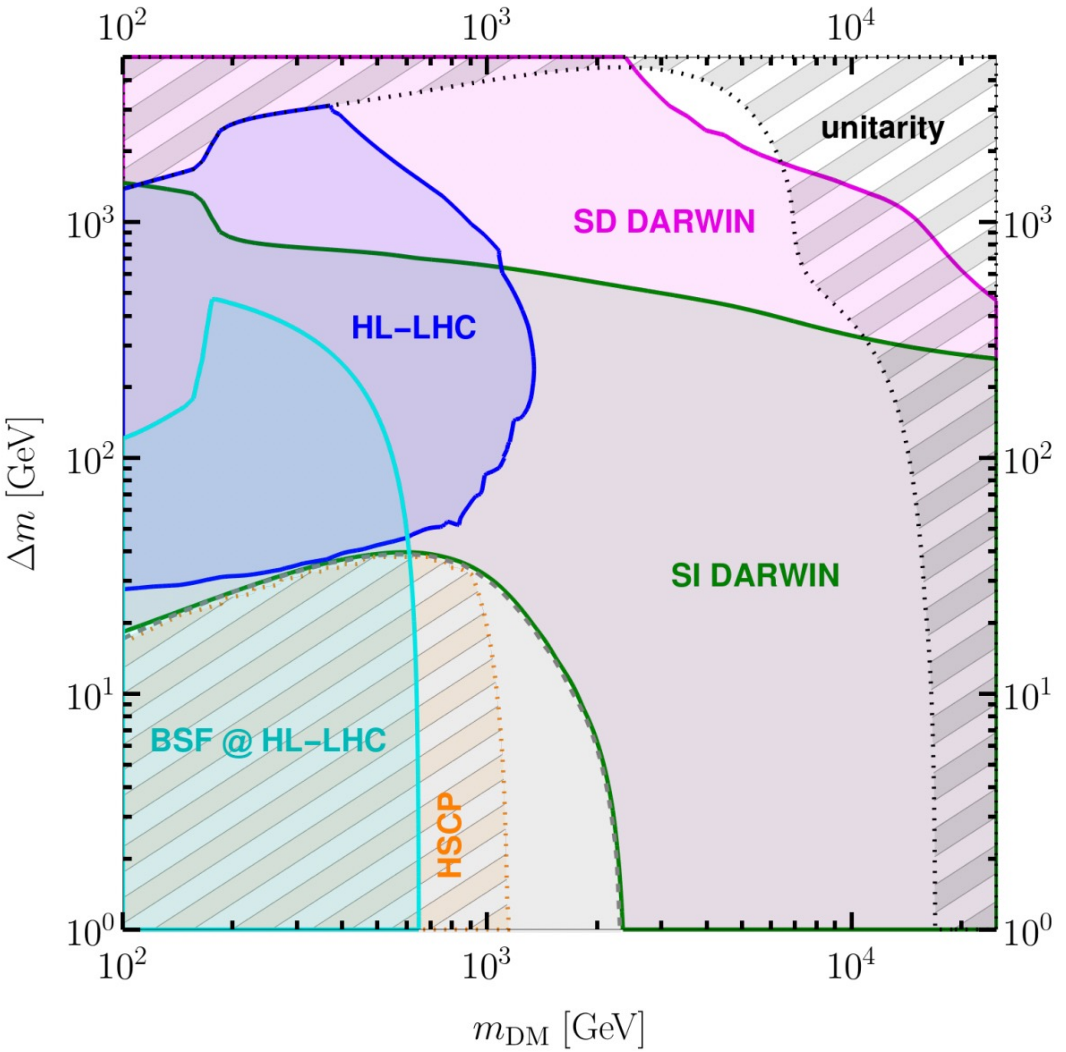
(c) Sommerfeld+BSF

Allowed Region

FCC 100TeV ?

Future Projection

- **HSCP**: Heavy stable charged particle searches (decays in or outside detector)
- **BSF**: Bound State Formation – Bound states form and decay to gauge bosons at LHC
- **SI** : Spin Independent Direct Detection
- **SD**: Spin Dependent Direct Detection



(c) Sommerfeld+BSF

M. Becker, E. Copello, KM, J Harz, D. Sengupta (2022)

Summary

- Simplified models useful to make more general statements about entire classes of models
- Classified t-channel dark matter models
- Looked at the impact of Sommerfeld enhancement and Bound State Formation on the relic density.
- Strong effect on the Simplified t-channel parameter space – and should be taken seriously.
- Leads to rich phenomenology at LHC including
  - Bound State formation
  - Heavy Stable Charged particle searches
  - Jets + missing energy
  - Complementarity with Direct Detection