Bound state formation effects for dark matter beyond WIMPs

work in progress with Mathias Garny

Jan Heisig

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Outline

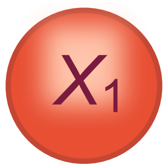
Beyond WIMPs:
Conversion-driven freeze out (CDFO)

Bound state formation effects for CDFO

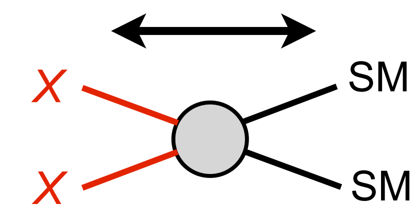
Beyond WIMPs:
Conversion-driven freeze out (CDFO)

Dark matter freeze-out (simplest case)

[Lee, Weinberg 1977; Binetruy, Girardi, Salati 1984; Bernstein, Brown, Feinberg 1985; Srednicki, Watkins, Olive 1988; Kolb, Turner 1990; Griest, Seckel 1991; Gondolo, Gelmini 1991; Edsjo, Gondolo 1997]



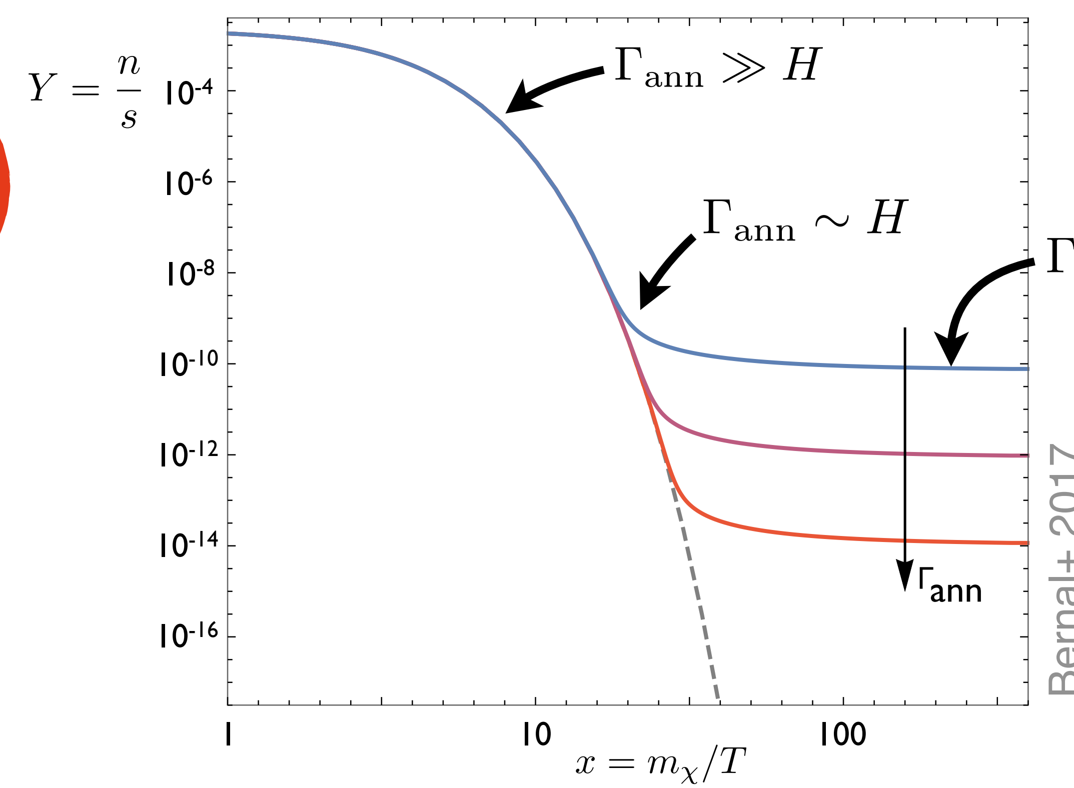
$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + \underline{3Hn_\chi} = \underline{-\langle\sigma v\rangle_{\mathrm{ann}}\left(n_\chi^2 - n_\chi^{\mathrm{eq}\,2}\right)}$$



$$\Gamma_{\mathrm{ann}} := n_\chi \langle\sigma v\rangle_{\mathrm{ann}}$$ **annihilation rate**

$\Gamma_{\mathrm{ann}} \gg H$: **efficient**

$\Gamma_{\mathrm{ann}} \ll H$: **inefficient**



Slightly more complex: coannihilations

[Griest, Seckel 1991; Edsjo, Gondolo 1997]

dark matter χ_1 $m_1 < m_2$ χ_2 co-annihilation partner

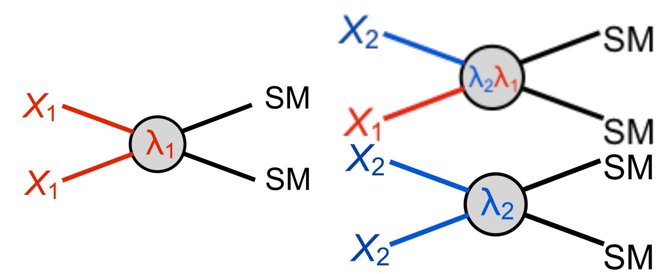
λ_1 λ_2

Slightly more complex: coannihilations

[Griest, Seckel 1991; Edsjo, Gondolo 1997]

Coupled set of Boltzmann equations:

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = -\sum_{j=1}^{N} \langle \sigma_{ij} v \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right)$$ annihilations



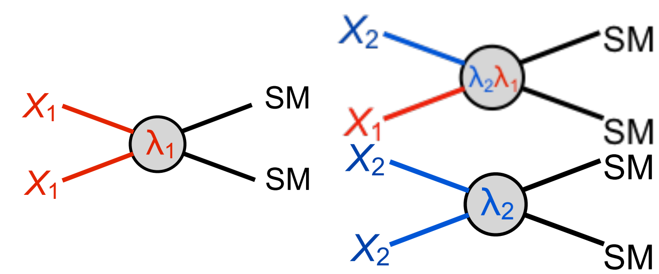
additional annihilation channels

Slightly more complex: coannihilations

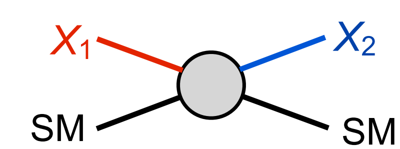
[Griest, Seckel 1991; Edsjo, Gondolo 1997]

Coupled set of Boltzmann equations:

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = -\sum_{j=1}^{N}\langle\sigma_{ij}v\rangle\left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}}\right) \quad \text{annihilations}$$



$$-\sum_{j\neq i}\left[\langle\sigma'_{Xij}v\rangle\left(n_i n_X - n_i^{\mathrm{eq}} n_X^{\mathrm{eq}}\right) - (i \leftrightarrow j)\right] \quad \text{conversions (scattering)}$$

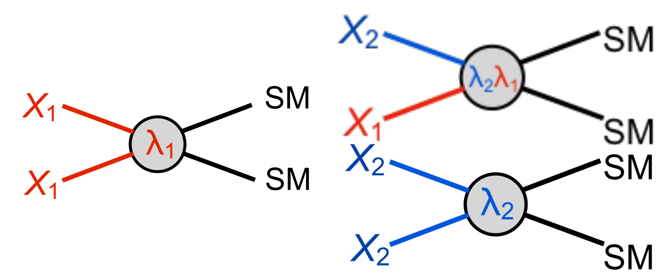


Slightly more complex: coannihilations

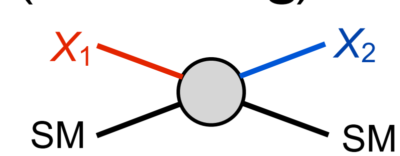
[Griest, Seckel 1991; Edsjo, Gondolo 1997]

Coupled set of Boltzmann equations:

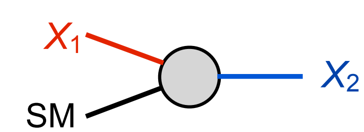
$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = -\sum_{j=1}^{N} \langle \sigma_{ij} v \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right)$$ annihilations



$$- \sum_{j \neq i} \left[\langle \sigma'_{Xij} v \rangle \left(n_i n_X - n_i^{\mathrm{eq}} n_X^{\mathrm{eq}} \right) - (i \leftrightarrow j) \right]$$ conversions (scattering)



$$- \sum_{j \neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\mathrm{eq}} \right) - (i \leftrightarrow j) \right]$$ conversions (decay)

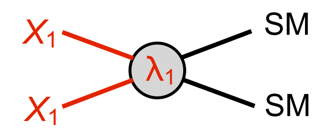


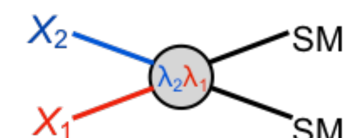
Slightly more complex: coannihilations

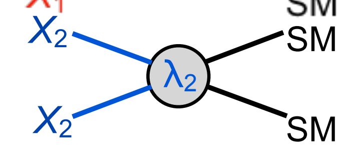
[Griest, Seckel 1991; Edsjo, Gondolo 1997]

Coupled set of Boltzmann equations:

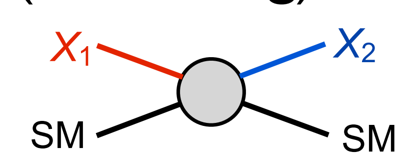
$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = -\sum_{j=1}^{N} \langle \sigma_{ij} v \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right)$$ annihilations



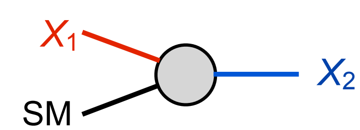




$$- \sum_{j \neq i} \left[\langle \sigma'_{Xij} v \rangle \left(n_i n_X - n_i^{\mathrm{eq}} n_X^{\mathrm{eq}} \right) - (i \leftrightarrow j) \right]$$ conversions (scattering)



$$- \sum_{j \neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\mathrm{eq}} \right) - (i \leftrightarrow j) \right]$$ conversions (decay)



For couplings $\lambda_1 \sim \lambda_2$ (e.g. SUSY): $\langle \sigma'_{Xij} v \rangle n_X \,,\ \Gamma_{ij} \gg \langle \sigma_{ij} v \rangle n_j$

⇒ conversions always efficient

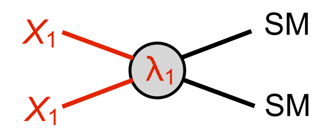
Boltzmann suppressed

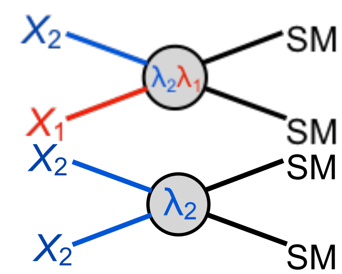
Slightly more complex: coannihilations

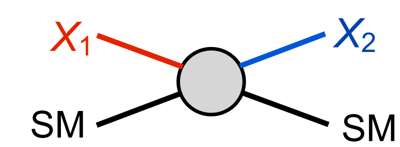
[Griest, Seckel 1991; Edsjo, Gondolo 1997]

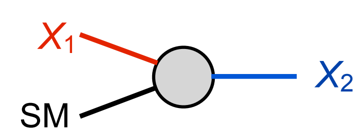
Coupled set of Boltzmann equations:

$$
\begin{aligned}
\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = & -\sum_{j=1}^{N} \langle \sigma_{ij} v \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right) \quad \text{annihilations} \\
& -\sum_{j \neq i} \left[\langle \sigma'_{Xij} v \rangle \left(n_i n_X - n_i^{\mathrm{eq}} n_X^{\mathrm{eq}} \right) - (i \leftrightarrow j) \right] \quad \text{conversions (scattering)} \\
& -\sum_{j \neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\mathrm{eq}} \right) - (i \leftrightarrow j) \right] \quad \text{conversions (decay)}
\end{aligned}
$$









For couplings $\lambda_1 \sim \lambda_2$ (e.g. SUSY): $\langle \sigma'_{Xij} v \rangle n_X \,,\; \Gamma_{ij} \gg \langle \sigma_{ij} v \rangle n_j$

⇒ conversions always efficient

⇒ chemical equilibrium: $\dfrac{n_i}{n_j} = \dfrac{n_i^{\mathrm{eq}}}{n_j^{\mathrm{eq}}}$

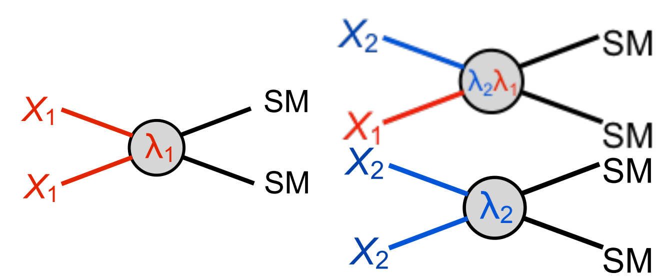
Conversion-driven freeze-out / co-scattering

[Garny, JH, Lülf, Vogl 1705.09292; D'Agnolo, Pappadopulo, Ruderman 1705.08450]

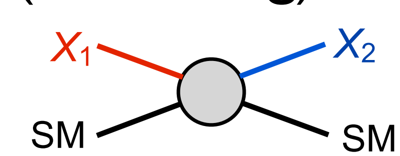
$$\boxed{\color{red}{\lambda_1} \color{black}{\ll} \color{blue}{\lambda_2}}$$

Coupled set of Boltzmann equations:

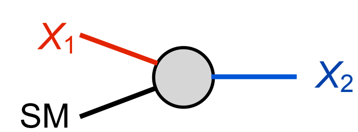
$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = -\sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right)$$ annihilations



$$- \sum_{j \neq i} \left[\langle \sigma'_{Xij} v_{ij} \rangle \left(n_i n_X - n_i^{\mathrm{eq}} n_X^{\mathrm{eq}} \right) - (i \leftrightarrow j) \right]$$ conversions (scattering)



$$- \sum_{j \neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\mathrm{eq}} \right) - (i \leftrightarrow j) \right]$$ conversions (decay)



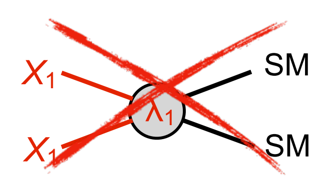
Conversion-driven freeze-out / co-scattering

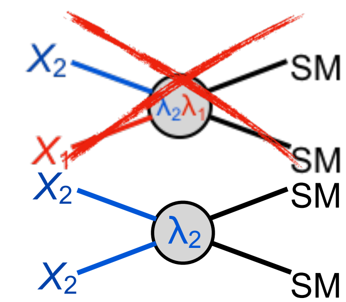
[Garny, JH, Lülf, Vogl 1705.09292; D'Agnolo, Pappadopulo, Ruderman 1705.08450]

$$\boxed{\lambda_1 \ll \lambda_2}$$

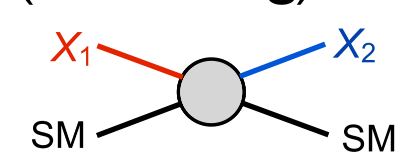
Coupled set of Boltzmann equations:

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = -\sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right) \quad \text{annihilations}$$

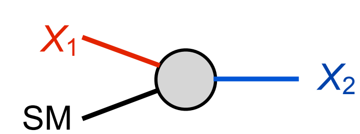




$$- \sum_{j \neq i} \left[\langle \sigma'_{Xij} v_{ij} \rangle \left(n_i n_X - n_i^{\mathrm{eq}} n_X^{\mathrm{eq}} \right) - (i \leftrightarrow j) \right] \quad \text{conversions (scattering)}$$



$$- \sum_{j \neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\mathrm{eq}} \right) - (i \leftrightarrow j) \right] \quad \text{conversions (decay)}$$



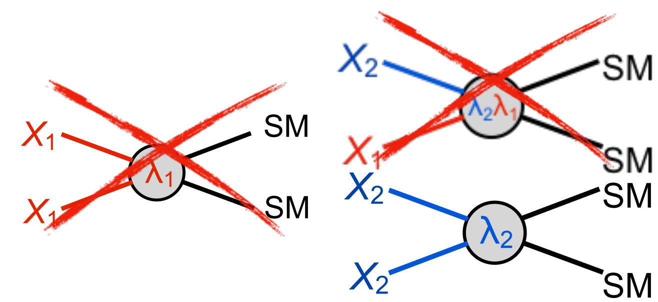
Conversion-driven freeze-out / co-scattering

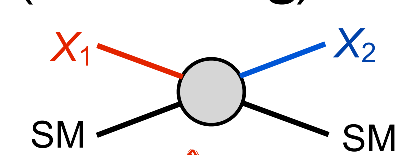
[Garny, JH, Lülf, Vogl 1705.09292; D'Agnolo, Pappadopulo, Ruderman 1705.08450]

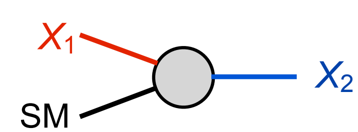
$$\boxed{\color{red}{\lambda_1} \ll \color{blue}{\lambda_2}}$$

Coupled set of Boltzmann equations:

$$
\begin{aligned}
\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = &-\sum_{j=1}^{N}\langle\sigma_{ij}v_{ij}\rangle\left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}}\right) \quad \text{annihilations}\\
&-\sum_{j\neq i}\left[\langle\sigma'_{Xij}v_{ij}\rangle\left(n_i n_X - n_i^{\mathrm{eq}} n_X^{\mathrm{eq}}\right) - (i \leftrightarrow j)\right] \quad \text{conversions (scattering)}\\
&-\sum_{j\neq i}\left[\Gamma_{ij}\left(n_i - n_i^{\mathrm{eq}}\right) - (i \leftrightarrow j)\right] \quad \text{conversions (decay)}
\end{aligned}
$$







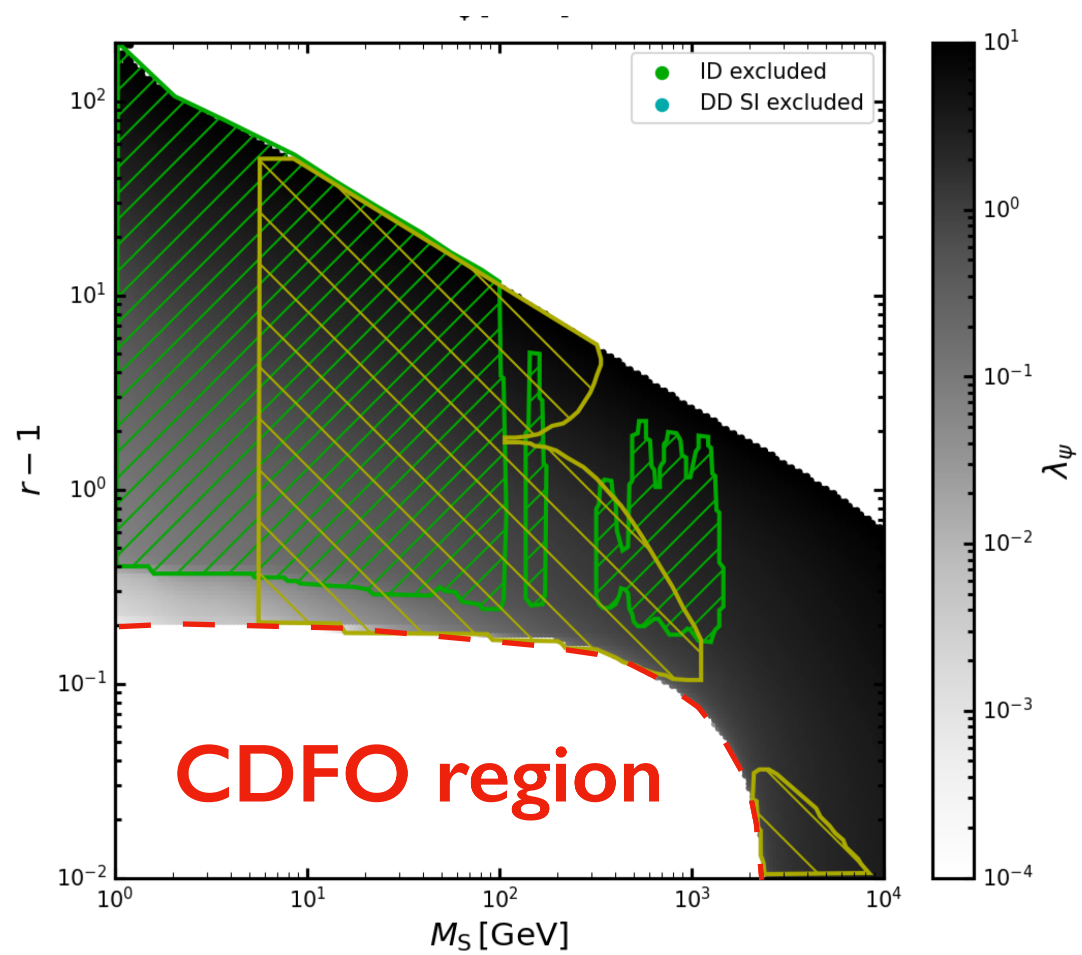
$\sim H$

Conversion initiates chemical decoupling and sets relic density!

Where is it relevant?

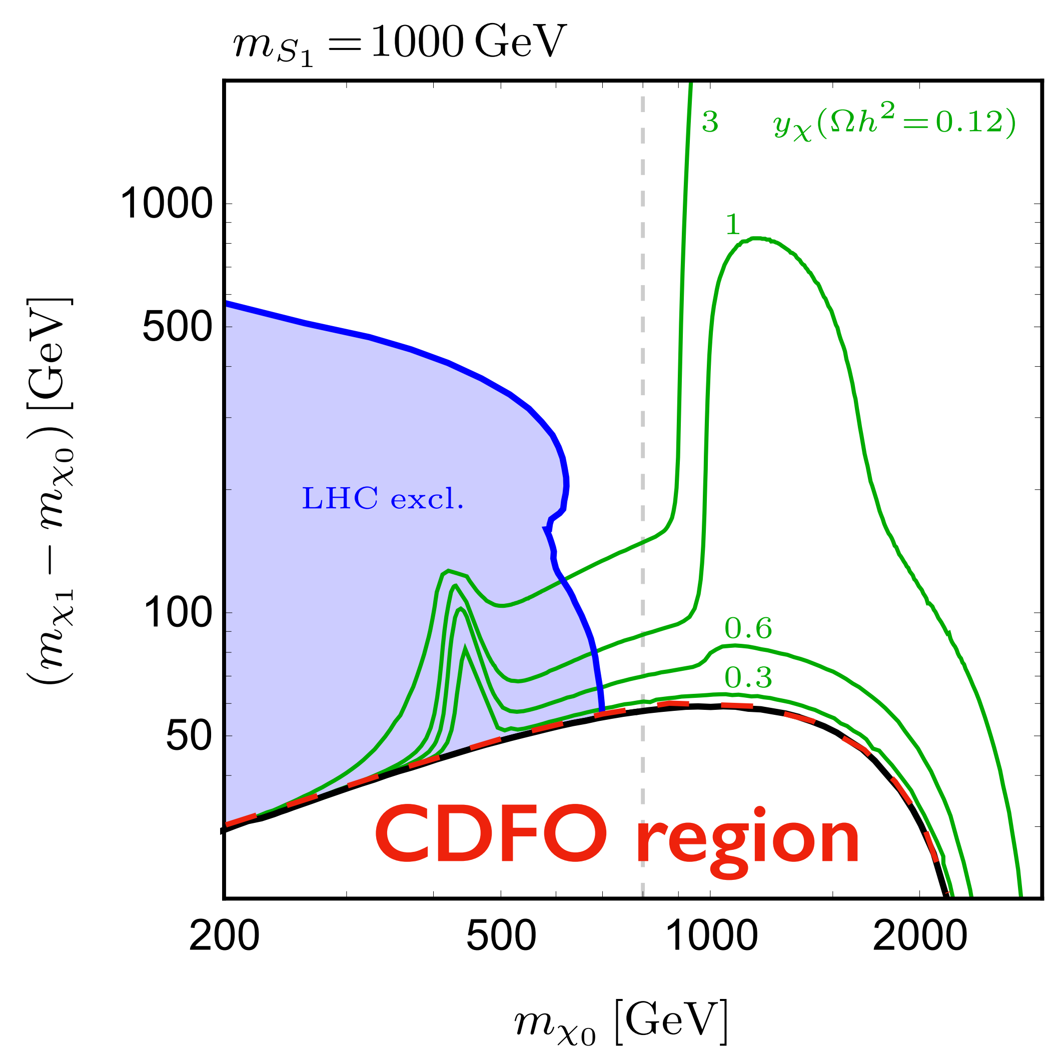
Simplified *t*-channel mediator models:

[e.g. C. Arina *et al.*; 2010.07559]



Leptoquark model:

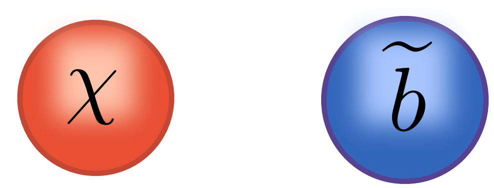
[Bélanger *et al.*; 2002.12220, 4]



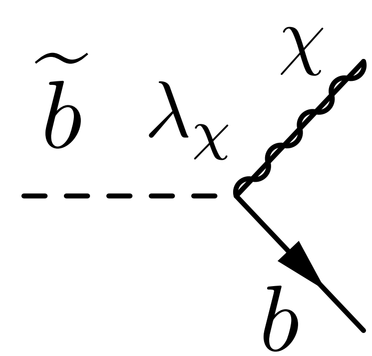
An explicit example

[Garny, JH, Lülf, Vogl 1705.09292]

- Specific model: $\mathcal{L}_{\text{int}} = |D_\mu \widetilde{q}|^2 - \lambda_\chi \widetilde{q} \bar{q} \frac{1-\gamma_5}{2} \chi + \text{h.c.}$
- SUSY-inspired simplified model:
  Choose Majorana DM and scalar bottom-partner



- Yukawa-type interaction:

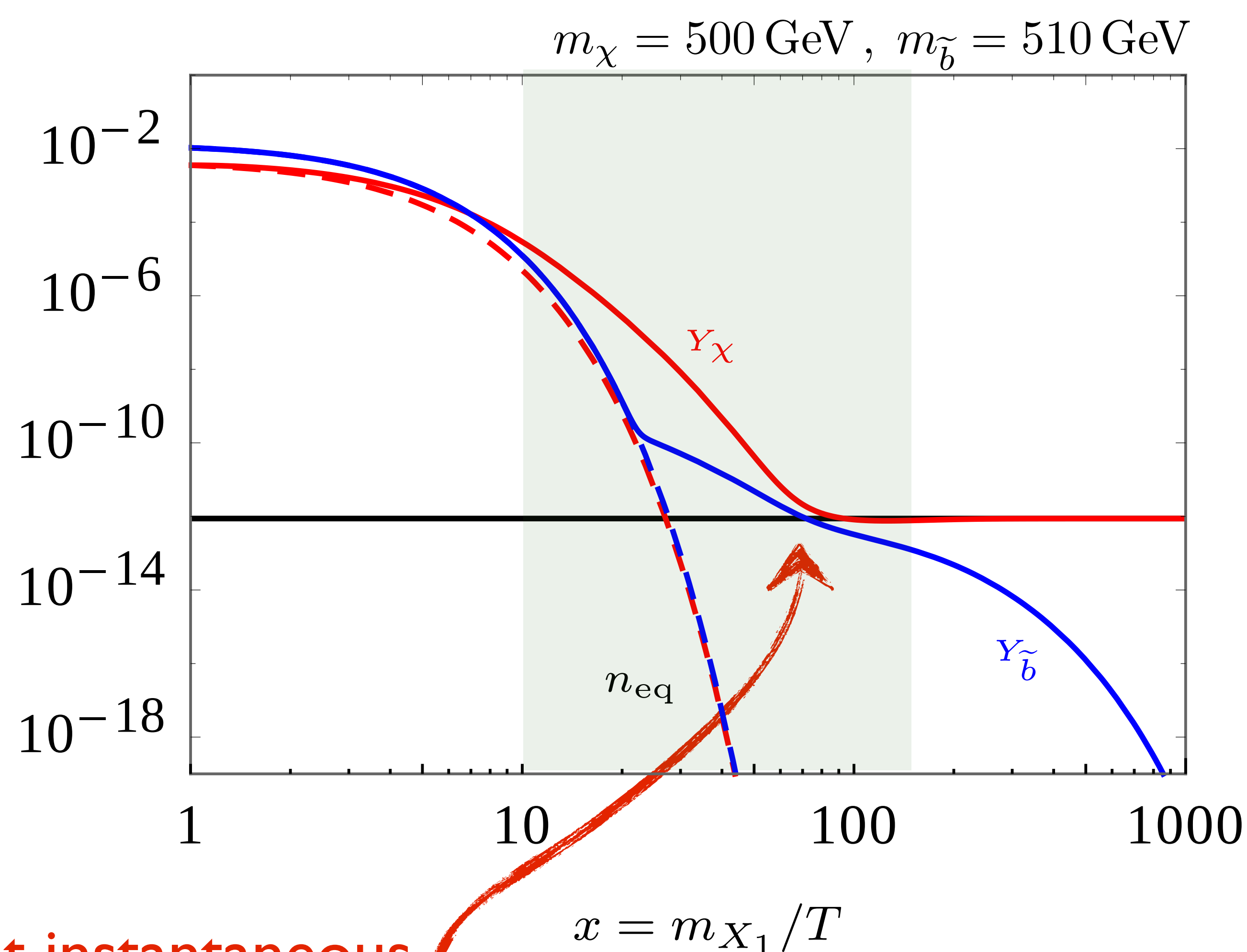


λ_χ is a free parameter here [see Ibarra et al. 2009 for SUSY realization]

Numerical solution of full coupled system

[Garny, JH, Lülf, Vogl 1705.09292]

- Very small coupling $\lambda_\chi \simeq 2.6 \times 10^{-7}$:



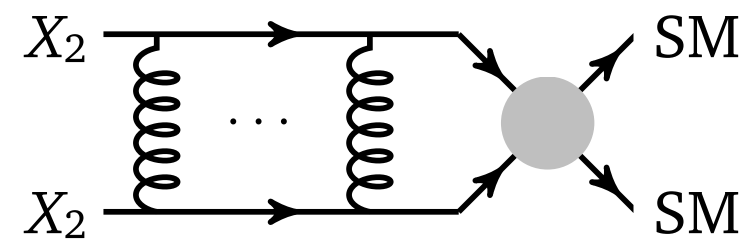
Freeze-out not instantaneous
Prolonged process!

Bound state formation effects for CDFO

Non-perturbative effects

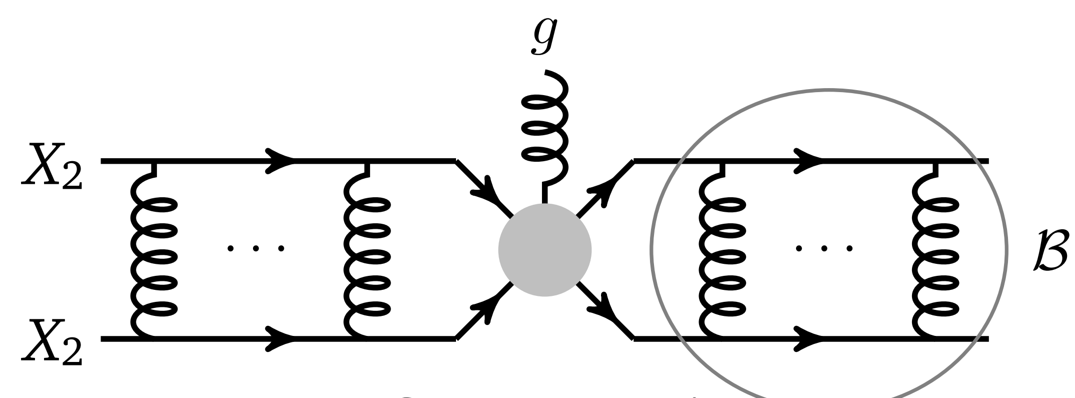
Pair of colored coannihilators: $\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$

Sommerfeld enhancement:



$$V(r) = -\alpha_g/r \qquad \alpha_g \equiv \alpha_s \times \begin{cases} 4/3, & \hat{\mathbf{R}} = \mathbf{1}, \\ -1/6, & \hat{\mathbf{R}} = \mathbf{8}. \end{cases}$$

Bound state formation:



$\mathbf{8} \longrightarrow \mathbf{1}$

[Harz, Petraki]

[see e.g. J. Harz and K. Petraki 1805.01200; A. Mitridate, M. Redi, J. Smirnov, and A. Strumia 1702.01141; J. Ellis, F. Luo, and K. A. Olive 1503.07142; T. Binder, B. Blobel, J. Harz, and K. Mukaida 2002.07145]

Including bound states

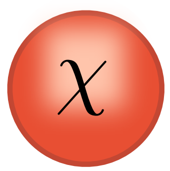
$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = -\frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\frac{\Gamma_{\tilde q}+\Gamma_{\tilde q\to\chi}}{s}\left(Y_{\tilde q}-Y_\chi\frac{Y_{\tilde q}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right),$$

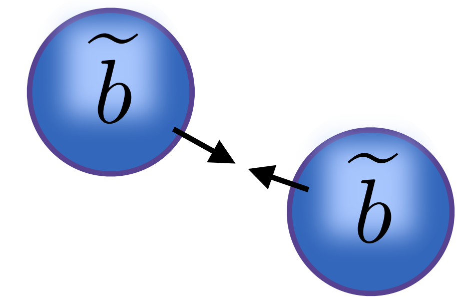
$$\begin{aligned}\frac{\mathrm{d}Y_{\tilde q}}{\mathrm{d}x} &= +\frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\frac{1}{2}\langle\sigma_{\tilde q\tilde q^\dagger}v\rangle\left(Y_{\tilde q}^2-Y_{\tilde q}^{\mathrm{eq}\,2}\right)+\frac{1}{2}\langle\sigma_{\mathrm{BSF}}v\rangle\left(Y_{\tilde q}^2-Y_{\tilde q}^{\mathrm{eq}\,2}\frac{Y_{\mathcal{B}}}{Y_{\mathcal{B}}^{\mathrm{eq}}}\right)\right.\\ &\qquad\left.+\frac{\Gamma_{\tilde q}+\Gamma_{\tilde q\to\chi}}{s}\left(Y_{\tilde q}-Y_\chi\frac{Y_{\tilde q}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right)\right],\end{aligned}$$

$$\frac{\mathrm{d}Y_{\mathcal{B}}}{\mathrm{d}x} = +\frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\Gamma_{\mathrm{break}}\left(Y_{\mathcal{B}}-Y_{\mathcal{B}}^{\mathrm{eq}}\frac{Y_{\tilde q}^2}{Y_{\tilde q}^{\mathrm{eq}\,2}}\right)+\Gamma_{\mathrm{dec}}\left(Y_{\mathcal{B}}-Y_{\mathcal{B}}^{\mathrm{eq}}\right)\right],$$

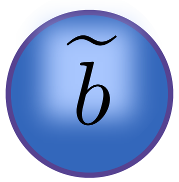
[see e.g. J. Harz and K. Petraki 1805.01200; A. Mitridate, M. Redi, J. Smirnov, and A. Strumia 1702.01141; J. Ellis, F. Luo, and K. A. Olive 1503.07142; T. Binder, B. Blobel, J. Harz, and K. Mukaida 2002.07145]

Including bound states

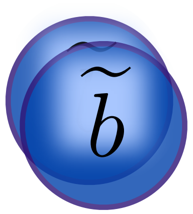




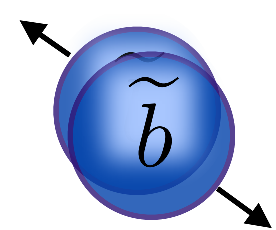
$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = -\frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\frac{\Gamma_{\tilde{q}} + \Gamma_{\tilde{q}\to\chi}}{s}\left(Y_{\tilde{q}} - Y_\chi \frac{Y_{\tilde{q}}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right),$$

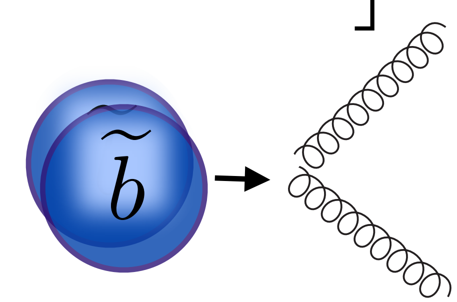


$$\frac{\mathrm{d}Y_{\tilde{q}}}{\mathrm{d}x} = +\frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\frac{1}{2}\langle\sigma_{\tilde{q}\tilde{q}^\dagger}v\rangle\left(Y_{\tilde{q}}^2 - Y_{\tilde{q}}^{\mathrm{eq}\,2}\right) + \frac{1}{2}\underline{\langle\sigma_{\mathrm{BSF}}v\rangle}\left(Y_{\tilde{q}}^2 - Y_{\tilde{q}}^{\mathrm{eq}\,2}\frac{Y_{\mathcal{B}}}{Y_{\mathcal{B}}^{\mathrm{eq}}}\right) + \frac{\Gamma_{\tilde{q}} + \Gamma_{\tilde{q}\to\chi}}{s}\left(Y_{\tilde{q}} - Y_\chi\frac{Y_{\tilde{q}}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right)\right],$$



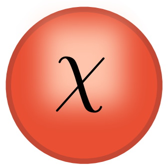
$$\frac{\mathrm{d}Y_{\mathcal{B}}}{\mathrm{d}x} = +\frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\underline{\Gamma_{\mathrm{break}}}\left(Y_{\mathcal{B}} - Y_{\mathcal{B}}^{\mathrm{eq}}\frac{Y_{\tilde{q}}^2}{Y_{\tilde{q}}^{\mathrm{eq}\,2}}\right) + \underline{\Gamma_{\mathrm{dec}}}\left(Y_{\mathcal{B}} - Y_{\mathcal{B}}^{\mathrm{eq}}\right)\right],$$



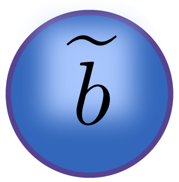


[see e.g. J. Harz and K. Petraki 1805.01200; A. Mitridate, M. Redi, J. Smirnov, and A. Strumia 1702.01141; J. Ellis, F. Luo, and K. A. Olive 1503.07142; T. Binder, B. Blobel, J. Harz, and K. Mukaida 2002.07145]

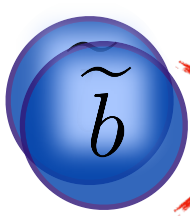
Including bound states



$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = -\frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\frac{\Gamma_{\tilde{q}} + \Gamma_{\tilde{q}\to\chi}}{s}\left(Y_{\tilde{q}} - Y_\chi \frac{Y_{\tilde{q}}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right),$$



$$\frac{\mathrm{d}Y_{\tilde{q}}}{\mathrm{d}x} = +\frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\frac{1}{2}\langle\sigma_{\tilde{q}\tilde{q}^\dagger}v\rangle\left(Y_{\tilde{q}}^2 - Y_{\tilde{q}}^{\mathrm{eq}\,2}\right) + \frac{1}{2}\langle\sigma_{\mathrm{BSF}}v\rangle\left(Y_{\tilde{q}}^2 - Y_{\tilde{q}}^{\mathrm{eq}\,2}\frac{Y_{\mathcal{B}}}{Y_{\mathcal{B}}^{\mathrm{eq}}}\right)\right.$$
$$\left. + \frac{\Gamma_{\tilde{q}} + \Gamma_{\tilde{q}\to\chi}}{s}\left(Y_{\tilde{q}} - Y_\chi\frac{Y_{\tilde{q}}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right)\right],$$



$$\cancel{\frac{\mathrm{d}Y_{\mathcal{B}}}{\mathrm{d}x}} = +\frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\underline{\Gamma_{\mathrm{break}}}\left(Y_{\mathcal{B}} - Y_{\mathcal{B}}^{\mathrm{eq}}\frac{Y_{\tilde{q}}^2}{Y_{\tilde{q}}^{\mathrm{eq}\,2}}\right) + \underline{\Gamma_{\mathrm{dec}}}\left(Y_{\mathcal{B}} - Y_{\mathcal{B}}^{\mathrm{eq}}\right)\right],$$

$$\Rightarrow \frac{Y_{\mathcal{B}}}{Y_{\mathcal{B}}^{\mathrm{eq}}} = \frac{\Gamma_{\mathrm{break}}\,Y_{\tilde{q}}^2/Y_{\tilde{q}}^{\mathrm{eq}\,2} + \Gamma_{\mathrm{dec}}}{\Gamma_{\mathrm{break}} + \Gamma_{\mathrm{dec}}}$$

[see e.g. J. Harz and K. Petraki 1805.01200; A. Mitridate, M. Redi, J. Smirnov, and A. Strumia 1702.01141; J. Ellis, F. Luo, and K.A. Olive 1503.07142; T. Binder, B. Blobel, J. Harz, and K. Mukaida 2002.07145]

Including bound states

χ
$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = -\frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\frac{\Gamma_{\tilde q}+\Gamma_{\tilde q\to\chi}}{s}\left(Y_{\tilde q} - Y_\chi \frac{Y_{\tilde q}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right),$$

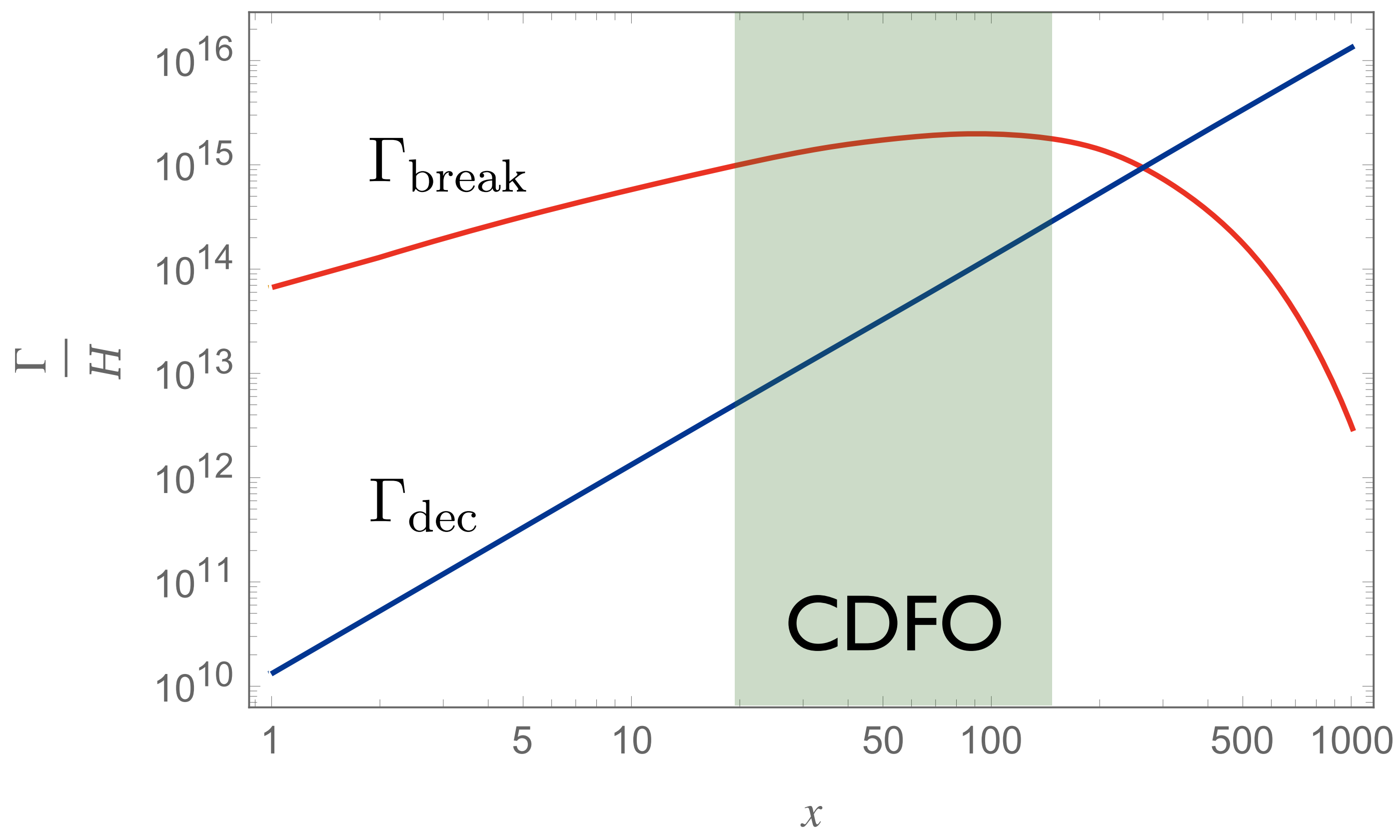
$\tilde b$
$$\frac{\mathrm{d}Y_{\tilde q}}{\mathrm{d}x} = +\frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\frac{1}{2}\langle\sigma_{\tilde q\tilde q^\dagger}v\rangle\left(Y_{\tilde q}^2 - Y_{\tilde q}^{\mathrm{eq}\,2}\right) + \frac{1}{2}\langle\sigma_{\mathrm{BSF}}v\rangle\left(Y_{\tilde q}^2 - Y_{\tilde q}^{\mathrm{eq}\,2}\frac{Y_{\mathcal{B}}}{Y_{\mathcal{B}}^{\mathrm{eq}}}\right)\right.$$
$$\left. + \frac{\Gamma_{\tilde q}+\Gamma_{\tilde q\to\chi}}{s}\left(Y_{\tilde q} - Y_\chi\frac{Y_{\tilde q}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right)\right]$$

$\tilde b$
$$\frac{\mathrm{d}Y_{\mathcal{B}}}{\mathrm{d}x} = +\frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\Gamma_{\mathrm{break}}\left(Y_{\mathcal{B}} - Y_{\mathcal{B}}^{\mathrm{eq}}\frac{Y_{\tilde q}^2}{Y_{\tilde q}^{\mathrm{eq}\,2}}\right) + \Gamma_{\mathrm{dec}}\left(Y_{\mathcal{B}} - Y_{\mathcal{B}}^{\mathrm{eq}}\right)\right],$$

$$\Rightarrow \frac{Y_{\mathcal{B}}}{Y_{\mathcal{B}}^{\mathrm{eq}}} = \frac{\Gamma_{\mathrm{break}}\,Y_{\tilde q}^2/Y_{\tilde q}^{\mathrm{eq}\,2} + \Gamma_{\mathrm{dec}}}{\Gamma_{\mathrm{break}}+\Gamma_{\mathrm{dec}}}\,,\qquad \langle\sigma_{\mathrm{BSF}}v\rangle \to \langle\sigma_{\mathrm{BSF}}v\rangle\frac{\Gamma_{\mathrm{dec}}}{\Gamma_{\mathrm{break}}+\Gamma_{\mathrm{dec}}}$$

[see e.g. J. Harz and K. Petraki 1805.01200; A. Mitridate, M. Redi, J. Smirnov, and A. Strumia 1702.01141; J. Ellis, F. Luo, and K. A. Olive 1503.07142; T. Binder, B. Blobel, J. Harz, and K. Mukaida 2002.07145]

Ionization equilibrium

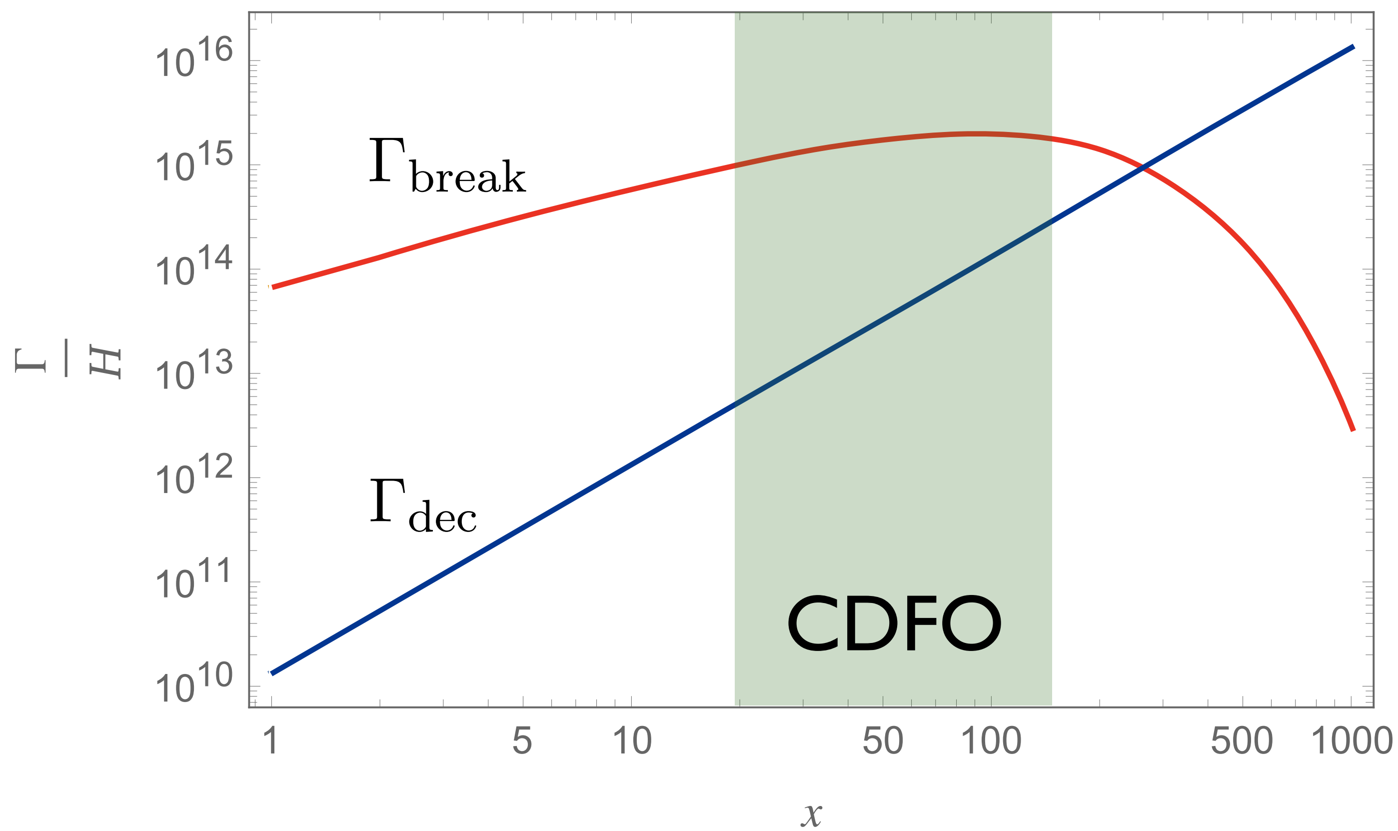


$$\langle \sigma_{\tilde{q}\tilde{q}^\dagger} v \rangle_{\rm eff} = \langle \sigma_{\tilde{q}\tilde{q}^\dagger} v \rangle + \underbrace{\langle \sigma_{\rm BSF} v \rangle \frac{\Gamma_{\rm dec}}{\Gamma_{\rm break} + \Gamma_{\rm dec}}} \qquad \Gamma_{\rm break} = \frac{s}{4} \frac{Y_{\tilde{q}}^{\rm eq\,2}}{Y_{\mathcal{B}}^{\rm eq}} \langle \sigma_{\rm BSF} v \rangle$$

$$\Gamma_{\rm break} \gg \Gamma_{\rm dec} \;\Rightarrow \propto \Gamma_{\rm dec}$$

$$\Gamma_{\rm break} \ll \Gamma_{\rm dec} \;\Rightarrow \propto \Gamma_{\rm break}$$

Ionization equilibrium



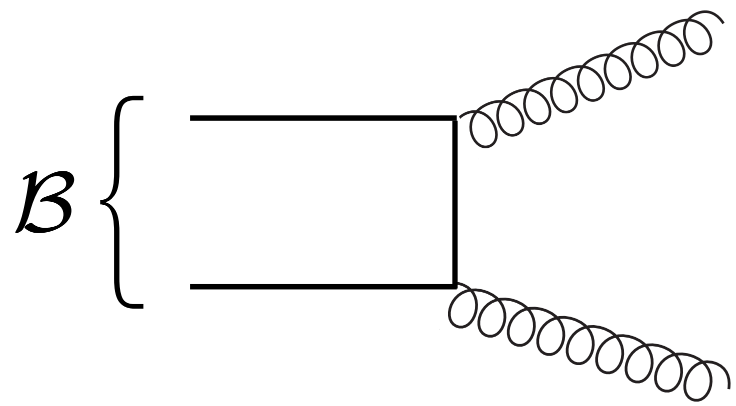
$$\langle \sigma_{\tilde{q}\tilde{q}^\dagger} v \rangle_{\rm eff} = \langle \sigma_{\tilde{q}\tilde{q}^\dagger} v \rangle + \langle \sigma_{\rm BSF} v \rangle \underbrace{\frac{\Gamma_{\rm dec}}{\Gamma_{\rm break} + \Gamma_{\rm dec}}} \qquad \Gamma_{\rm break} = \frac{s}{4} \frac{Y_{\tilde{q}}^{\rm eq\,2}}{Y_{\mathcal{B}}^{\rm eq}} \langle \sigma_{\rm BSF} v \rangle$$

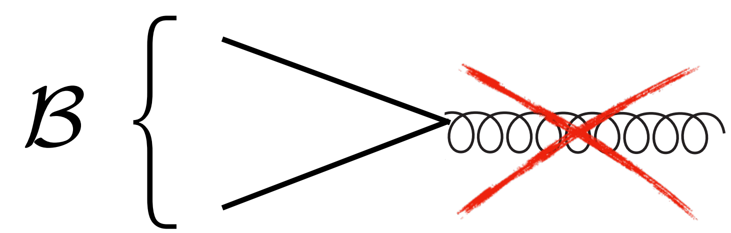
$$\Gamma_{\rm break} \gg \Gamma_{\rm dec} \;\Rightarrow \propto \Gamma_{\rm dec}$$

$$\Gamma_{\rm break} \ll \Gamma_{\rm dec} \;\Rightarrow \propto \Gamma_{\rm break}$$

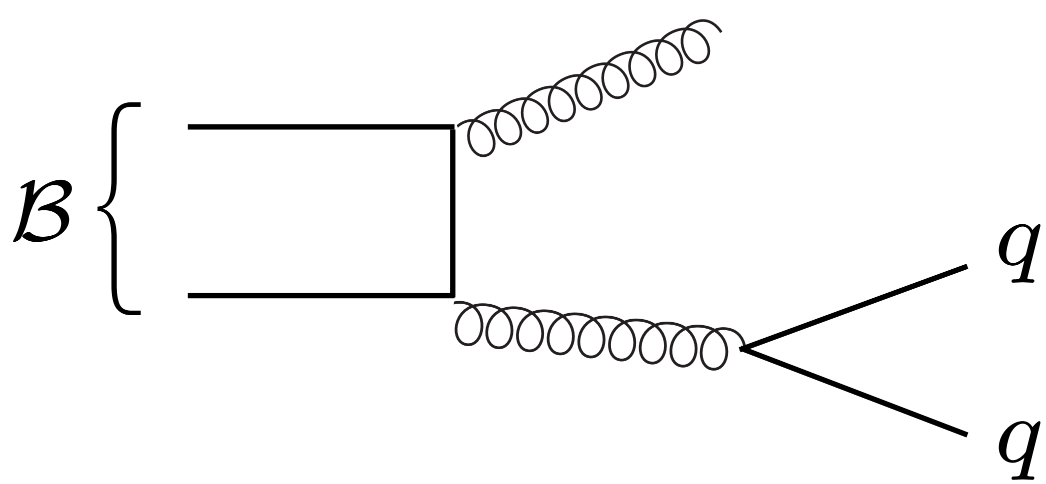
Corrections to the decay

Leading decay rate:

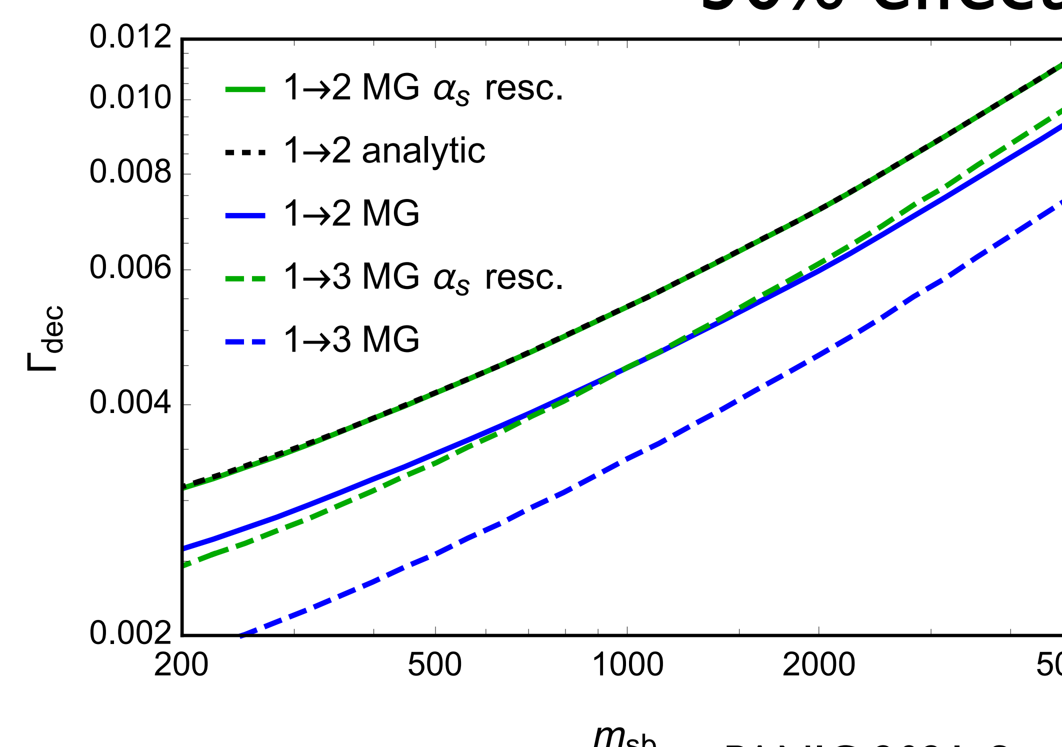




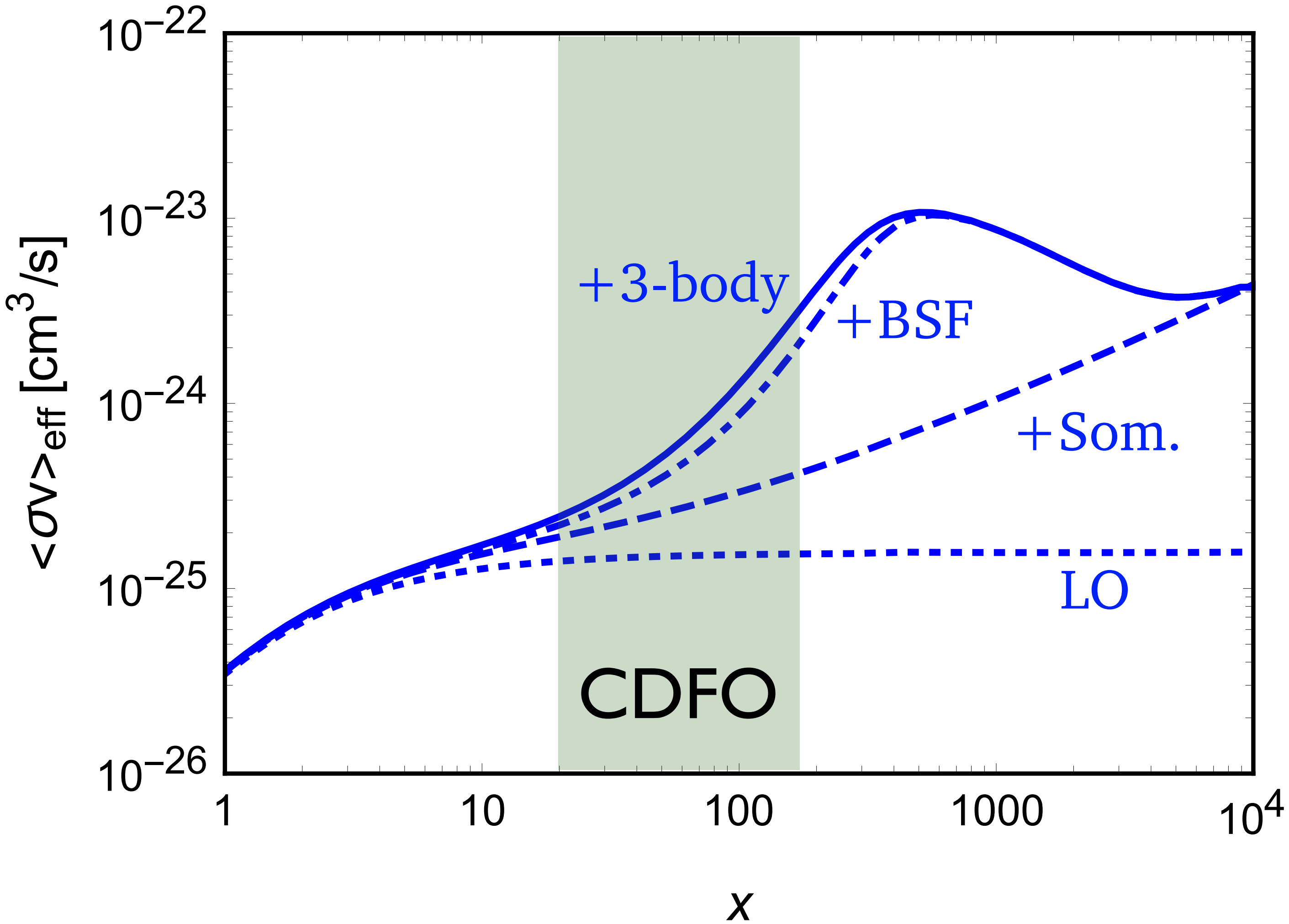
Three-body decay:



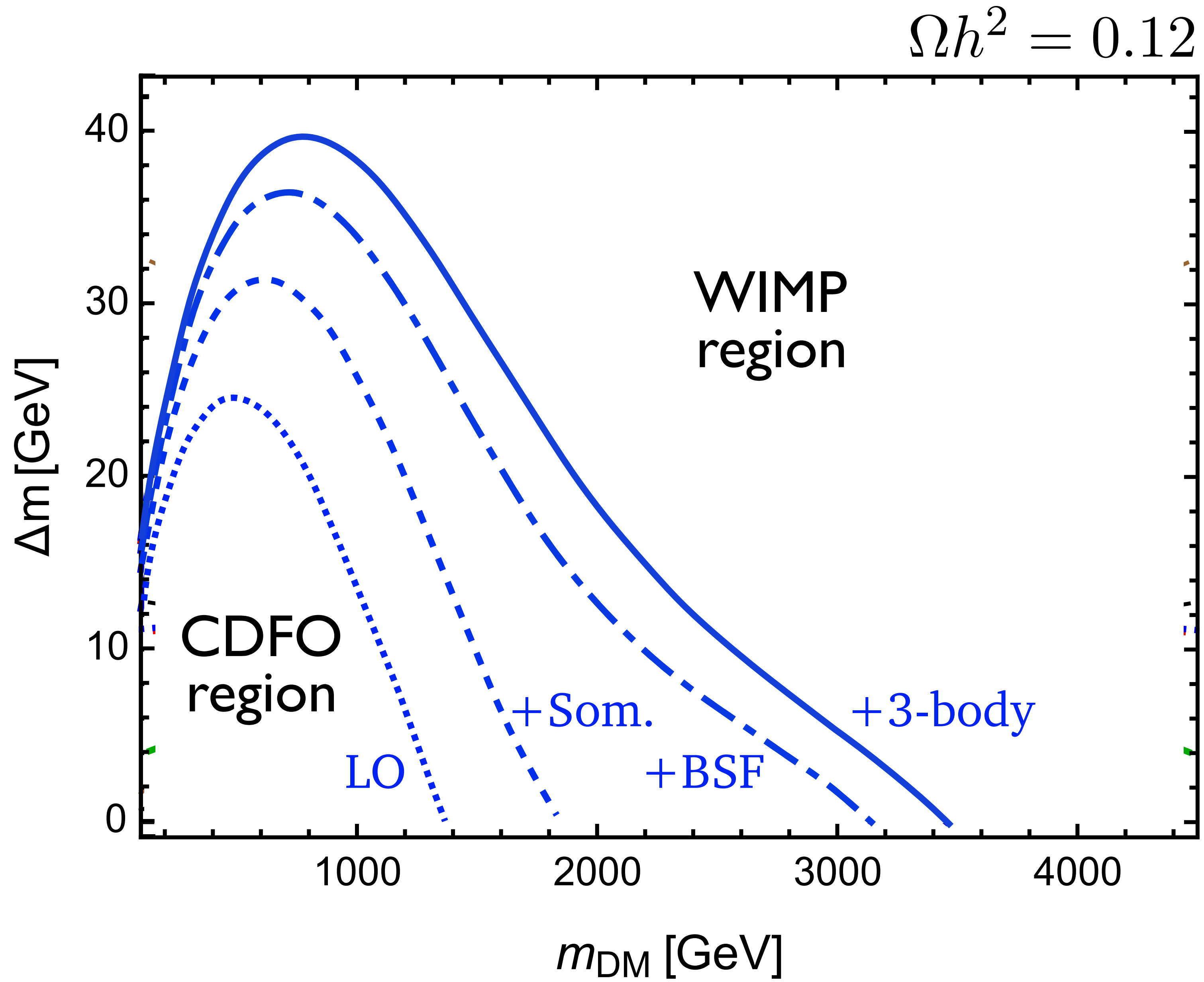
~80% correction
~30% effect



Impact on annihilation cross section



Impact on viable parameter space



Relevant for current searches?

Conversion rate on the edge of being efficient:

$$\Gamma_{\rm conv} \sim H$$

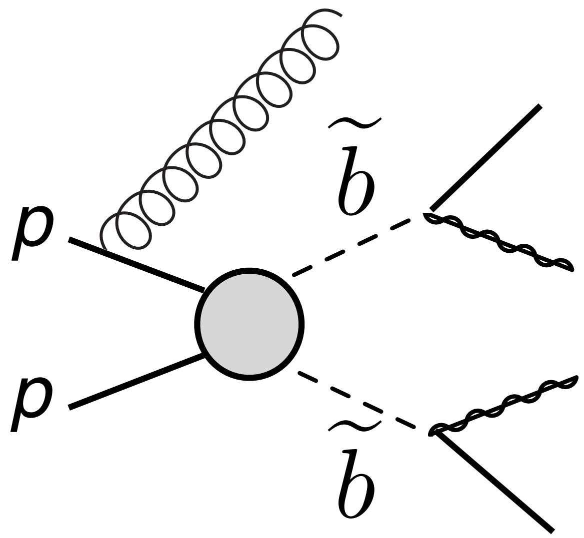
$$\Rightarrow \; \Gamma_{\rm dec} \lesssim H$$

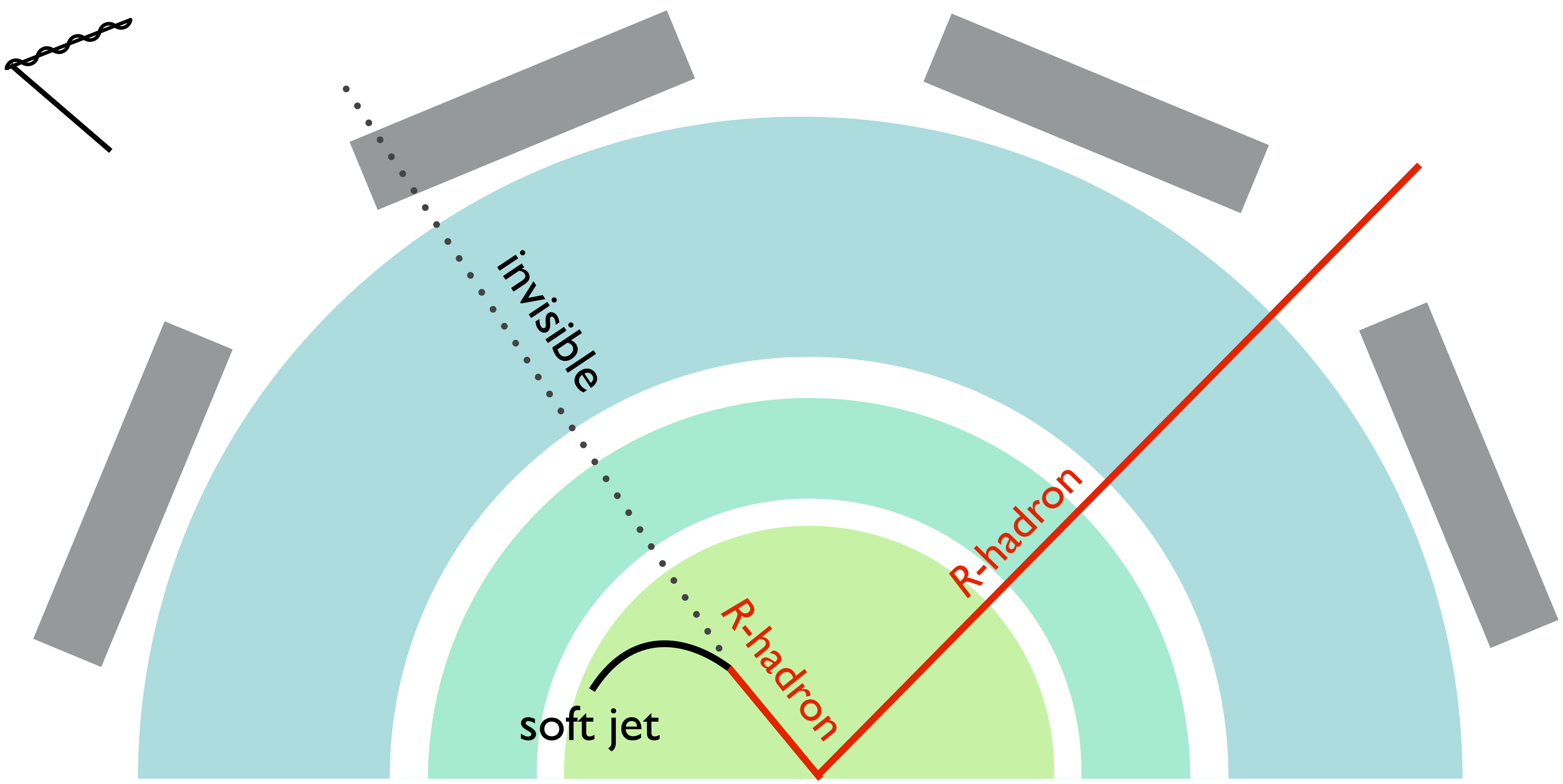
$$c\tau \gtrsim H^{-1} \simeq 1.5\,{\rm cm}\left(\frac{(100\,{\rm GeV})^2}{T^2}\right)$$

$$T \lesssim (10\text{–}100)\,{\rm GeV}$$

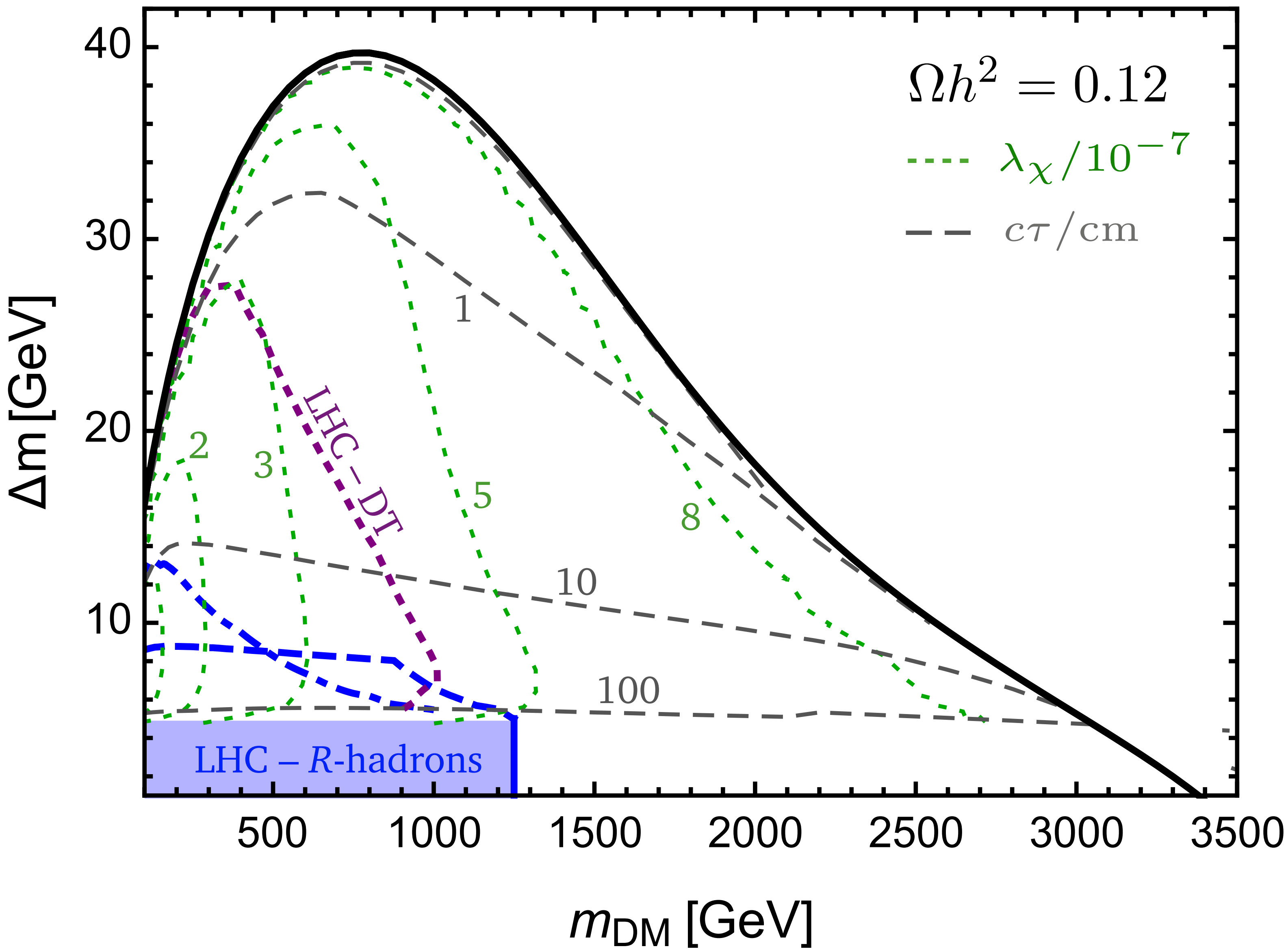
⇒ Long-lived particles at LHC!

Long-lived particles at LHC





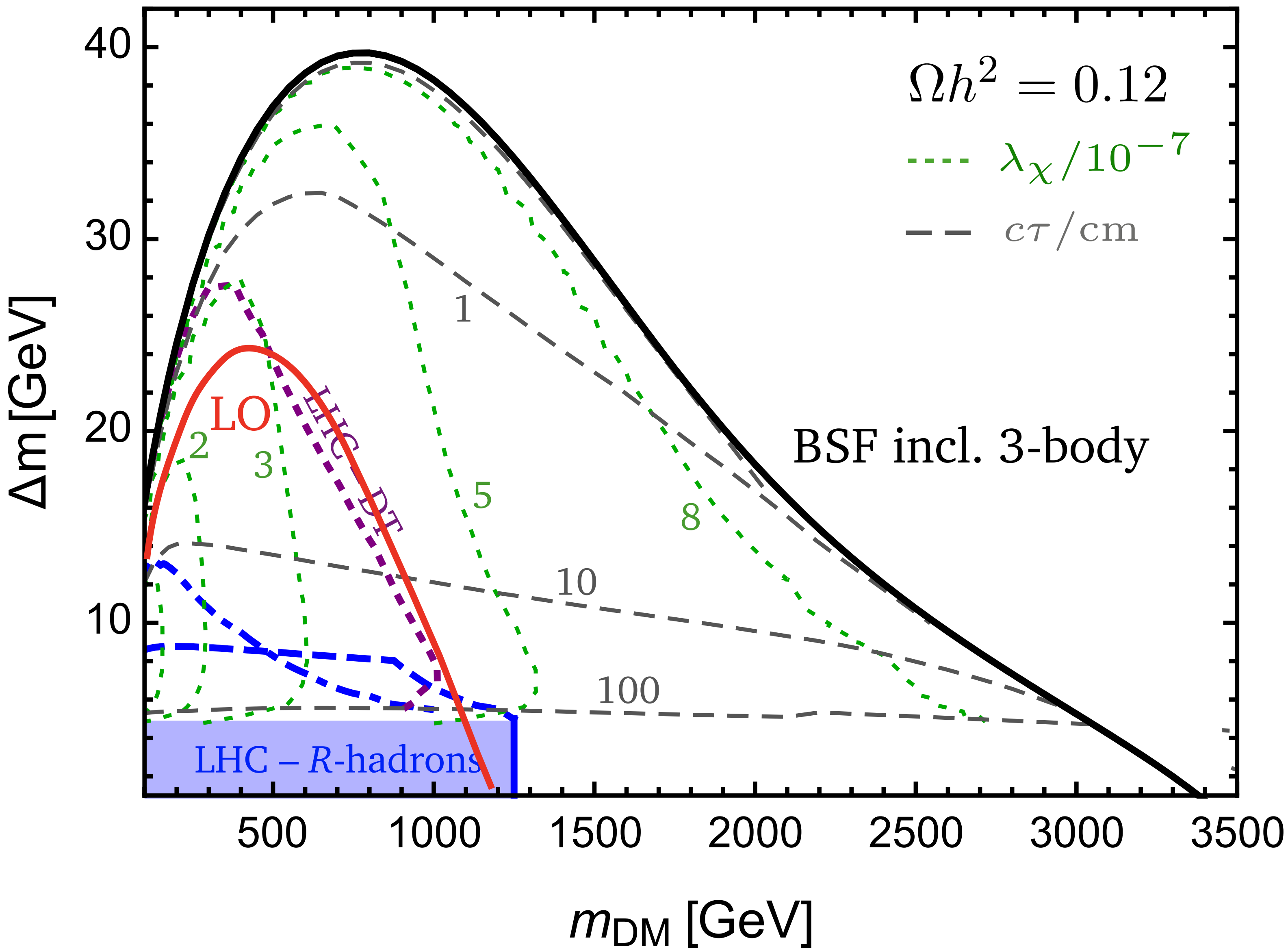
Viable parameter space



LHC – *R*-hadrons: ATLAS [1902.01636, 1808.04095 approximate reinterpretation];
CMS [CMS-PAS-EXO-16-036, recasting from 1705.09292]

LHC – DT: ATLAS Disappearing-track search [1712.02118, recasting from 2002.12220, 7]

Viable parameter space



LHC – *R*-hadrons: ATLAS [1902.01636, 1808.04095 approximate reinterpretation]; CMS [CMS-PAS-EXO-16-036, recasting from 1705.09292]

LHC – DT: ATLAS Disappearing-track search [1712.02118, recasting from 2002.12220, 7]

Summary

- Conversion-driven freeze-out less explored terrain
- Prolonged freeze-out process
- Bound states of coannihilator particularly important
- Leading correction in ionization equilibrium:
  bound state decay
- Colored coannihilator: viable parameter space significantly enlarged
- Important for long-lived particle searches at LHC
  $H \sim \Gamma$: Lifetimes naturally O(1-100cm)