Bound state effects on dark matter coannihilation - pushing the boundaries of *t*-channel mediator models

based on work with Mathias Garny
arXiv:2112.01499, *PRD* 105(2022)055004

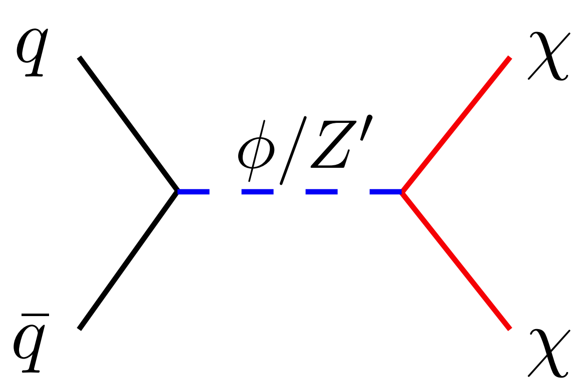
Jan Heisig

Chargé de recherches

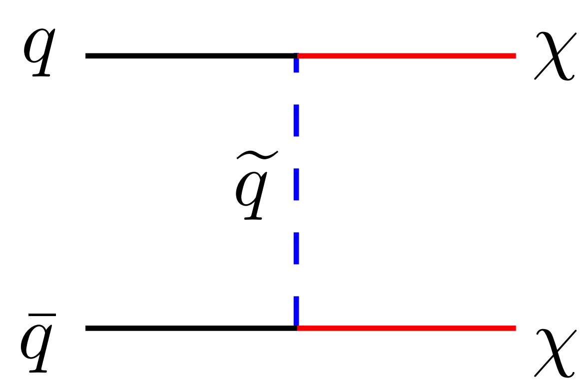
Phenomenology Symposium, Pittsburgh
May 10, 2022

Minimal dark matter models at LHC

s-channel mediator



t-channel mediator



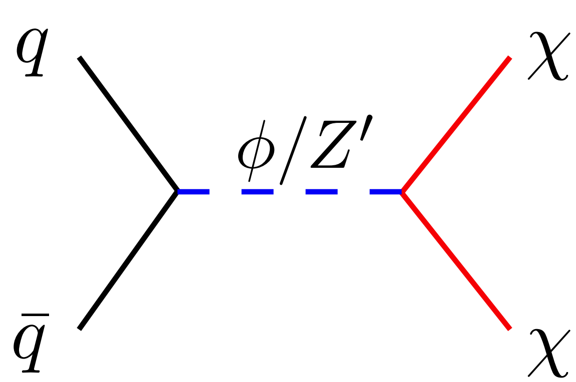
even

odd

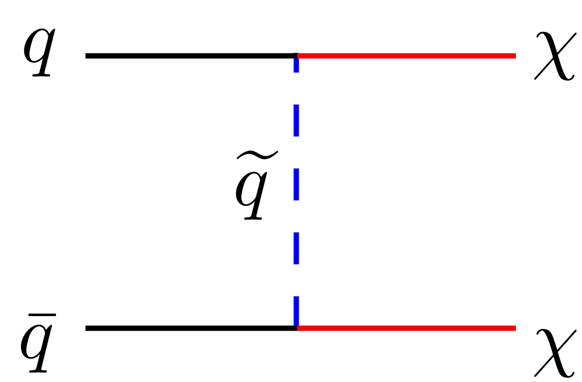
under Z_2-symmetry that stabilizes dark matter

Minimal dark matter models at LHC

s-channel mediator



t-channel mediator



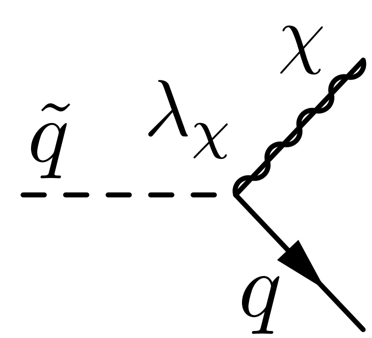
- Rich phenomenology beyond the WIMP paradigm
- Bound state effects of mediator particle $\tilde{q}$ important
  $\Rightarrow$ Large impact on signature at LHC

Example:
SUSY-like *t*-channel mediator model

Majorana DM χ λ_χ $m_\chi < m_{\tilde{q}}$ $\tilde{q}$ g_s scalar quark-partner

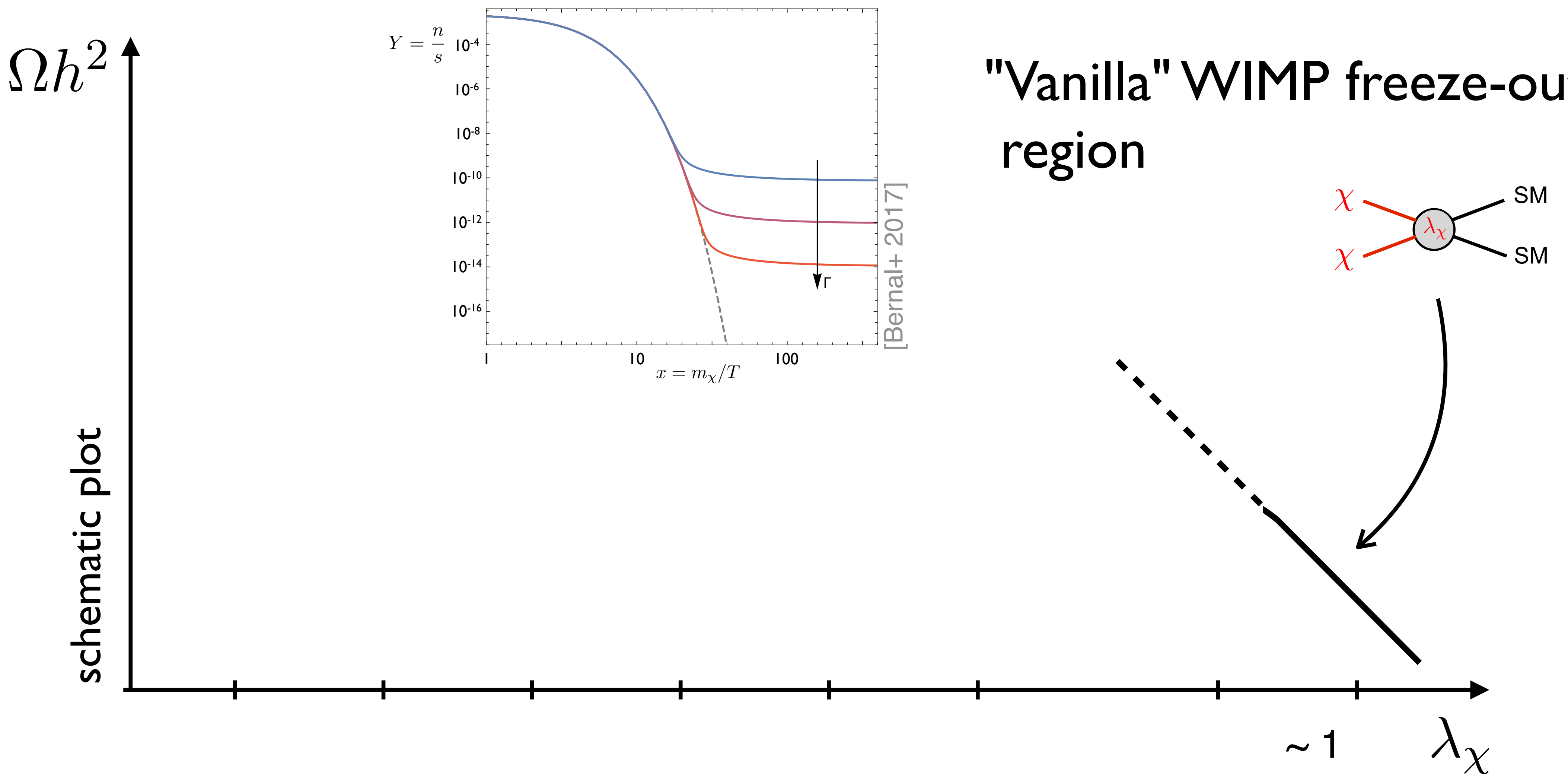
$$\mathcal{L}_{\rm int} = |D_\mu \tilde{q}|^2 - \lambda_\chi \tilde{q} \bar{q} \frac{1-\gamma_5}{2} \chi + \text{h.c.}$$

⇒ Yukawa-type interaction:



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

How does the relic density work out?



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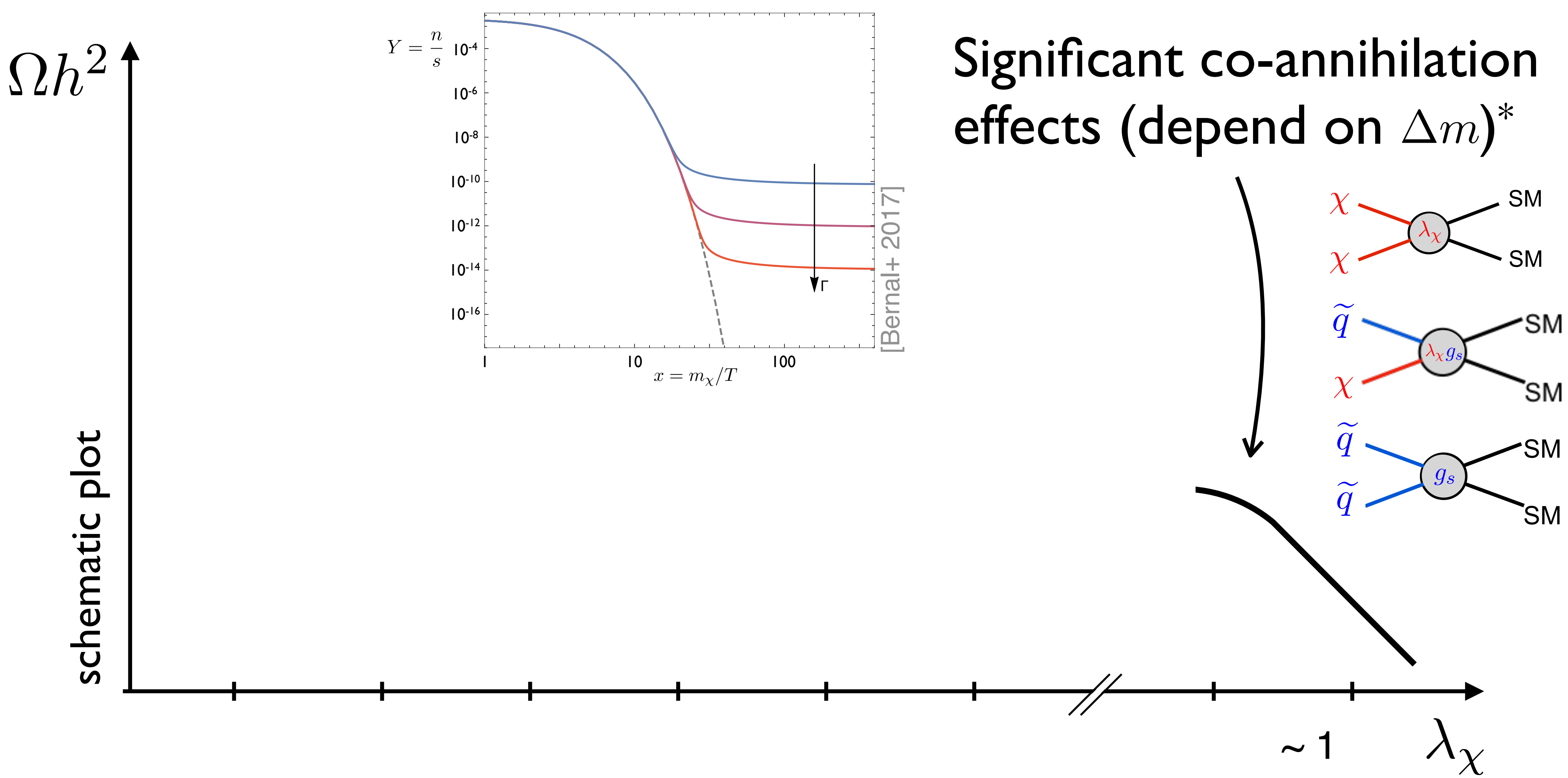

[* see e.g. D'Agnolo *et al.* 1803.02901]

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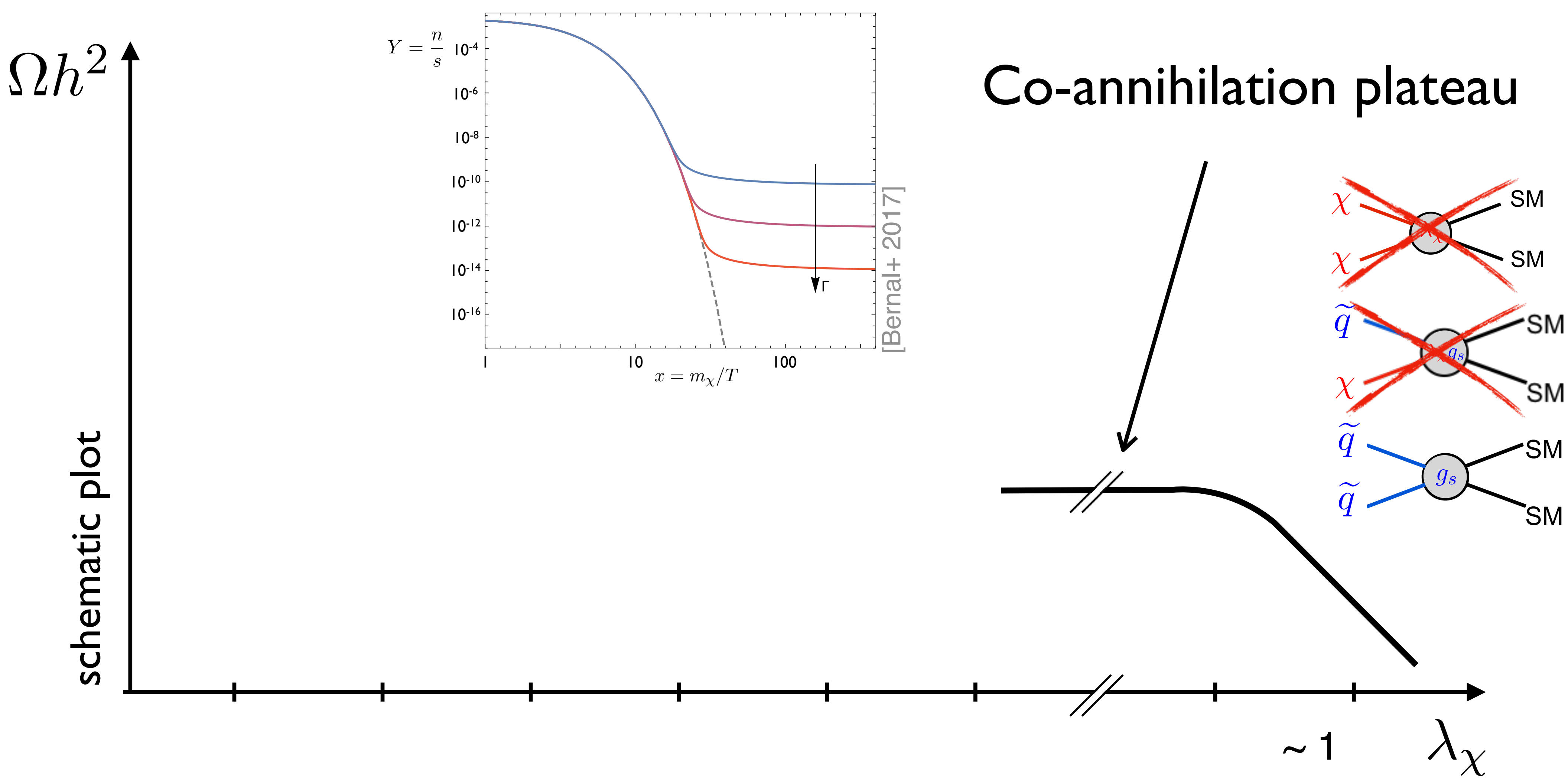

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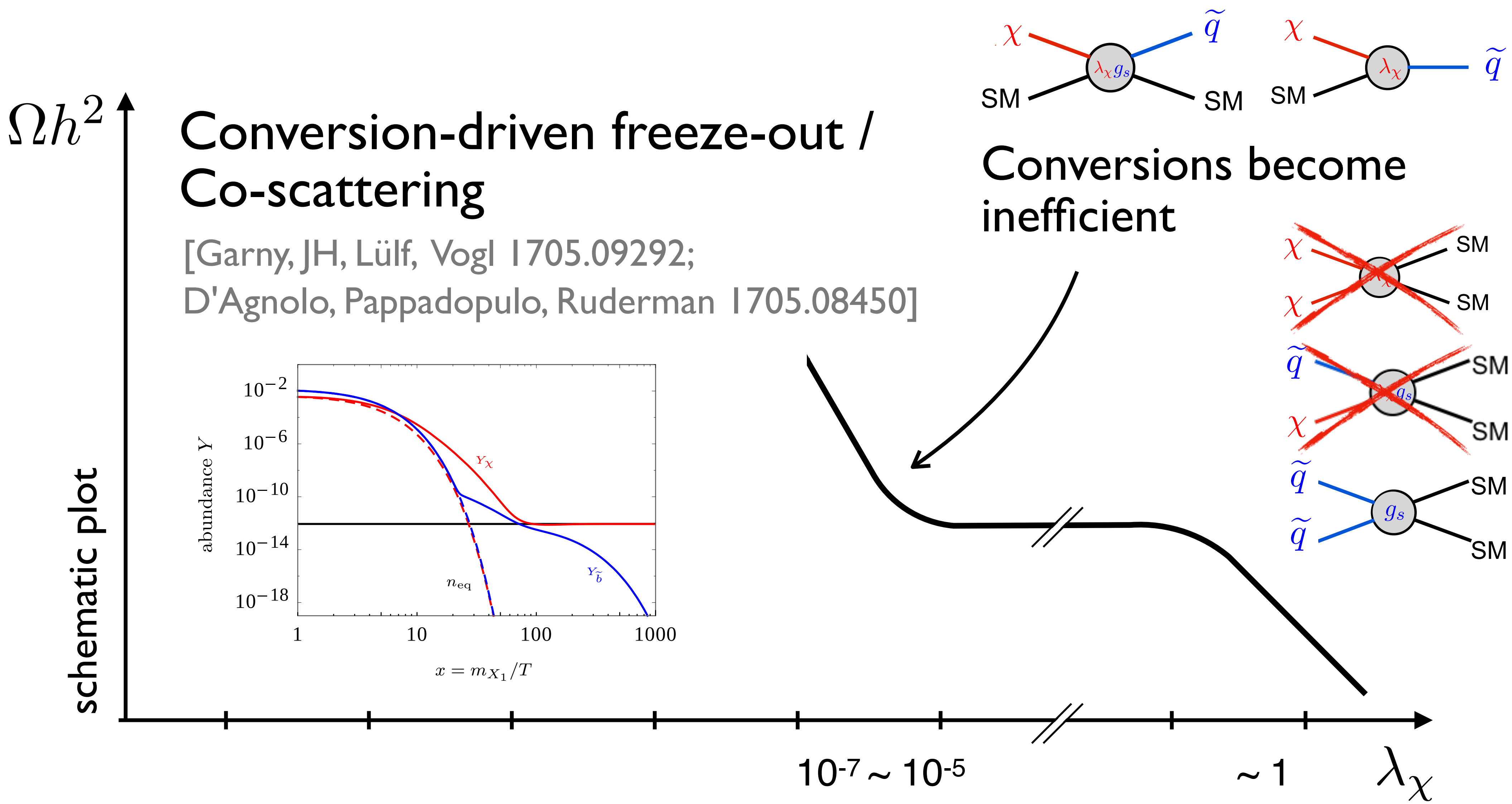

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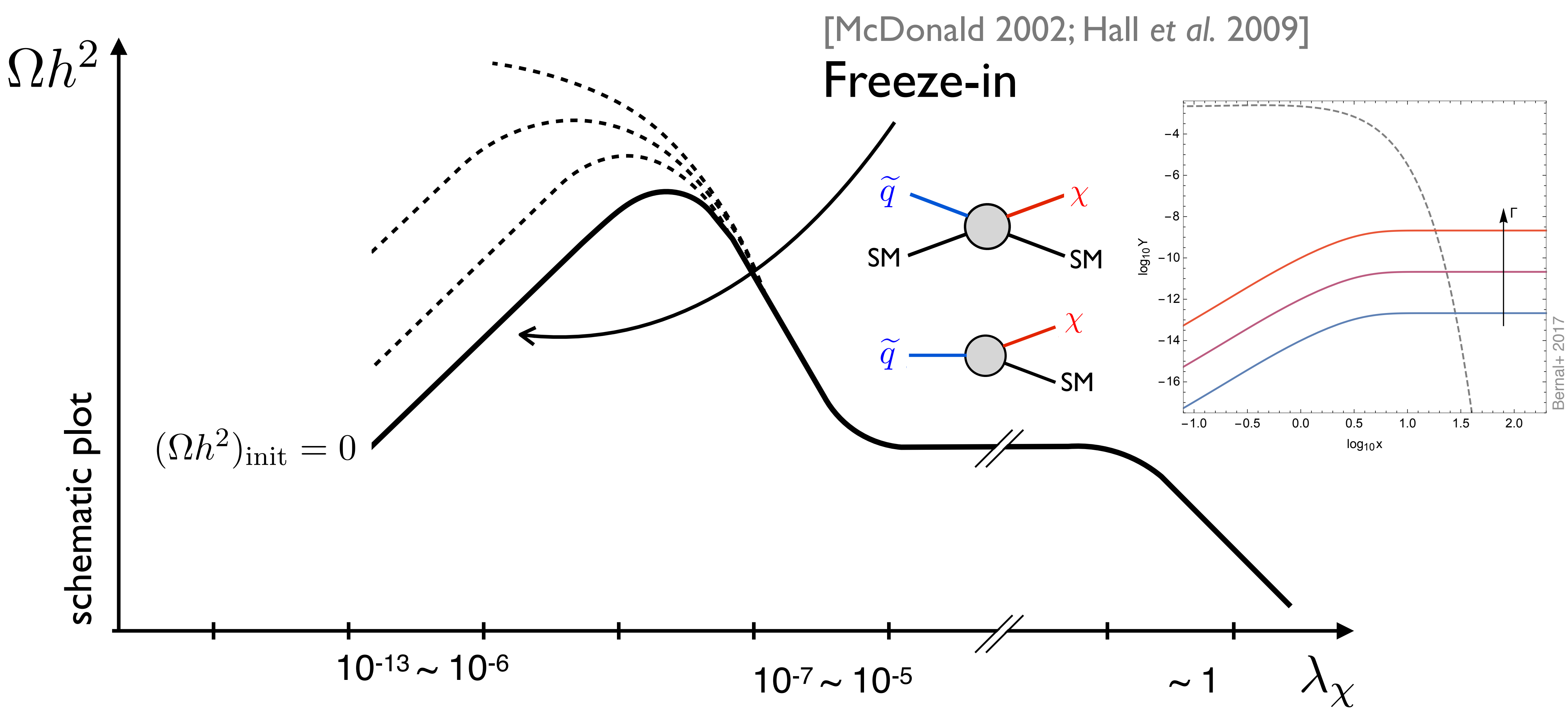
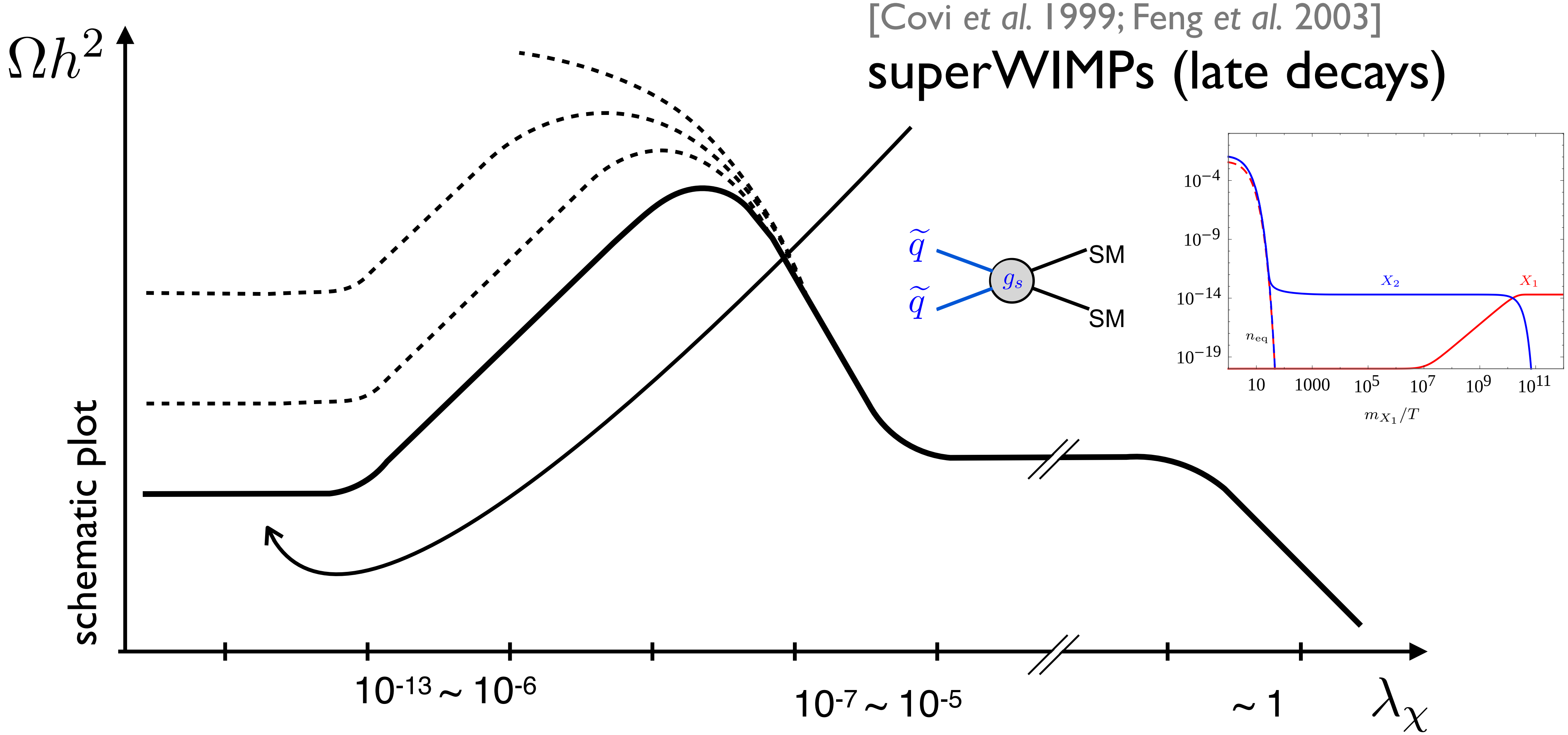


How does the relic density work out?

[Covi *et al.* 1999; Feng *et al.* 2003]

superWIMPs (late decays)



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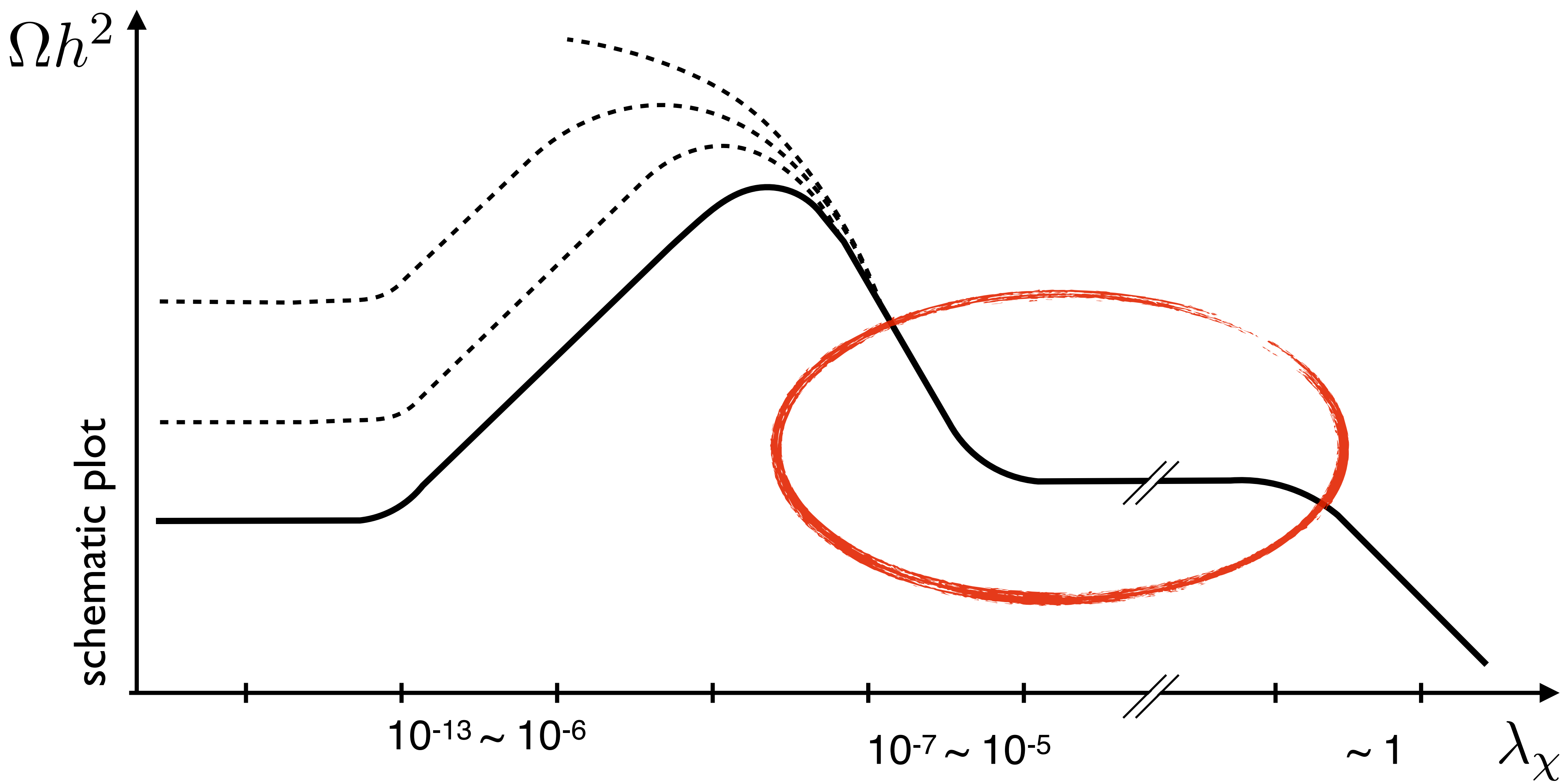

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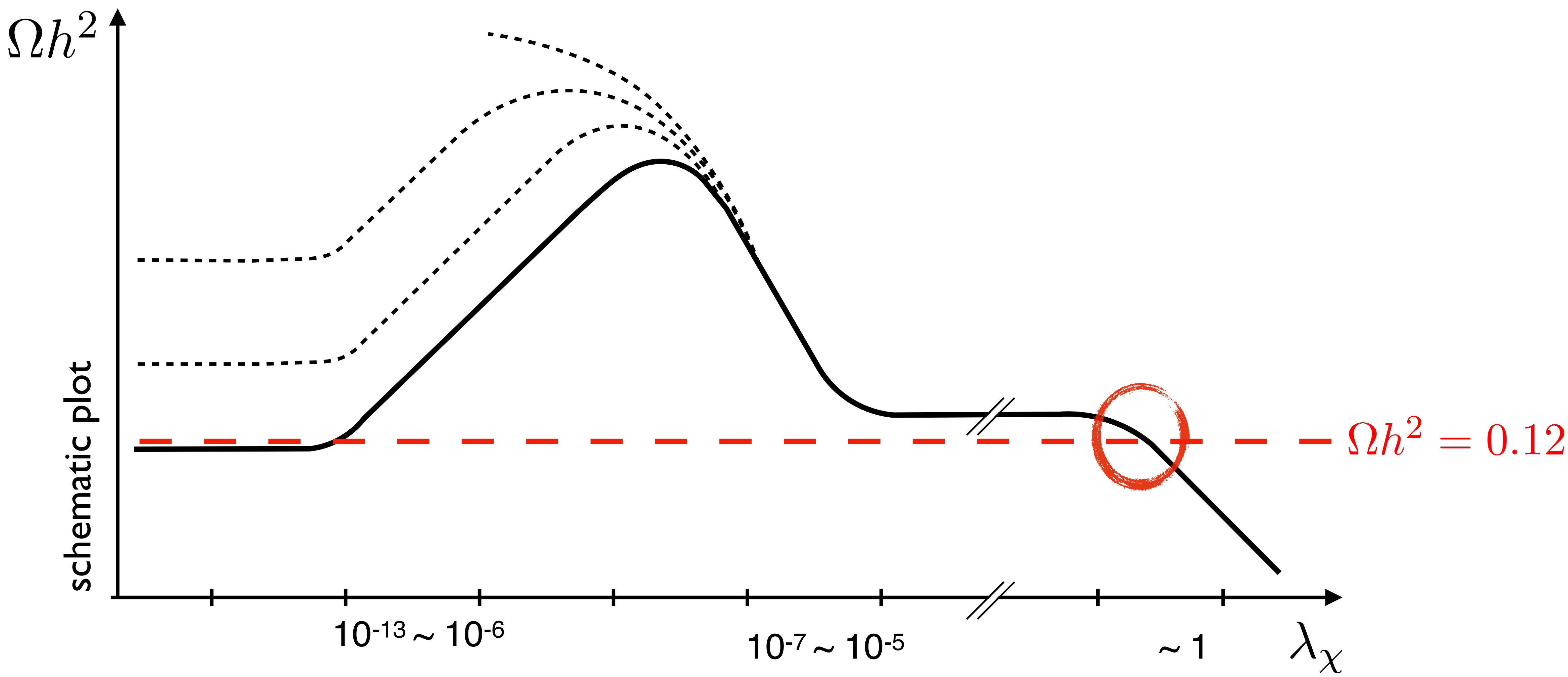

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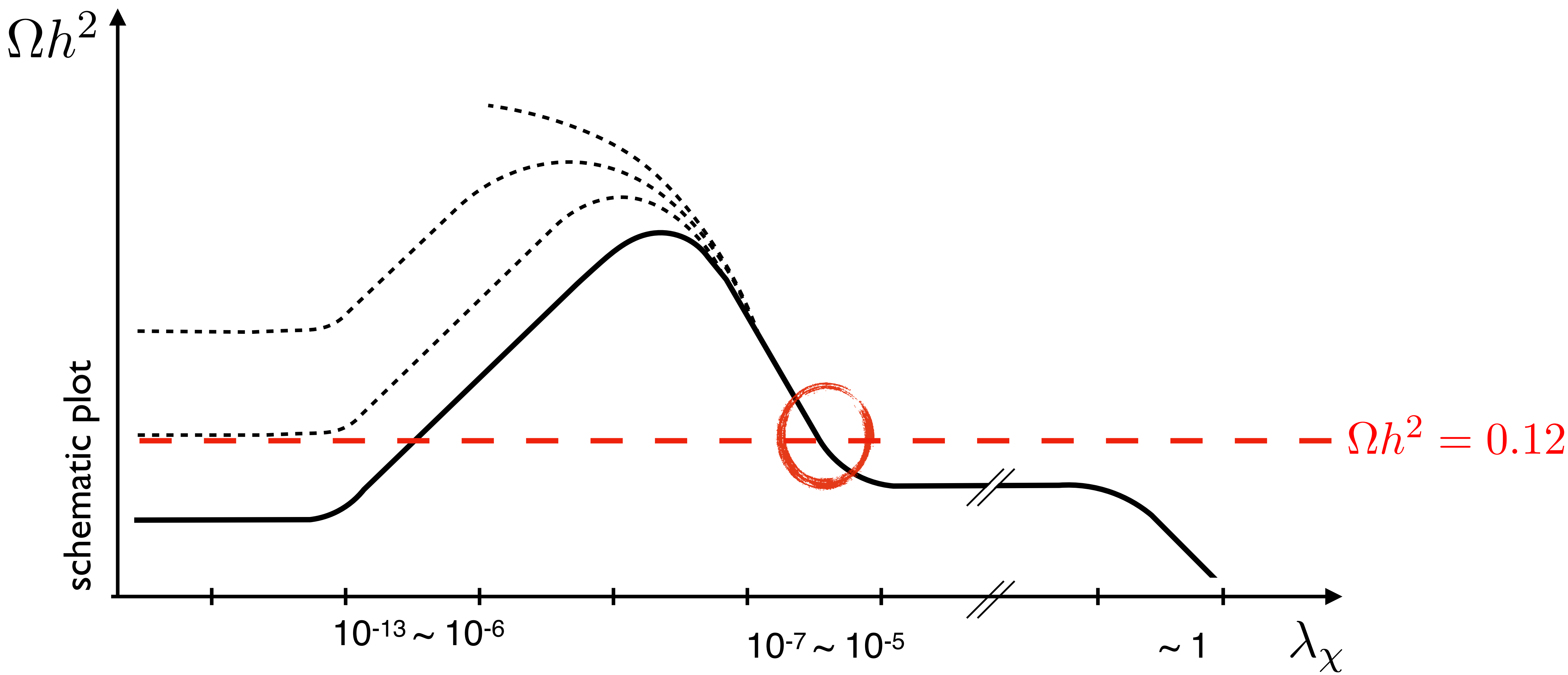

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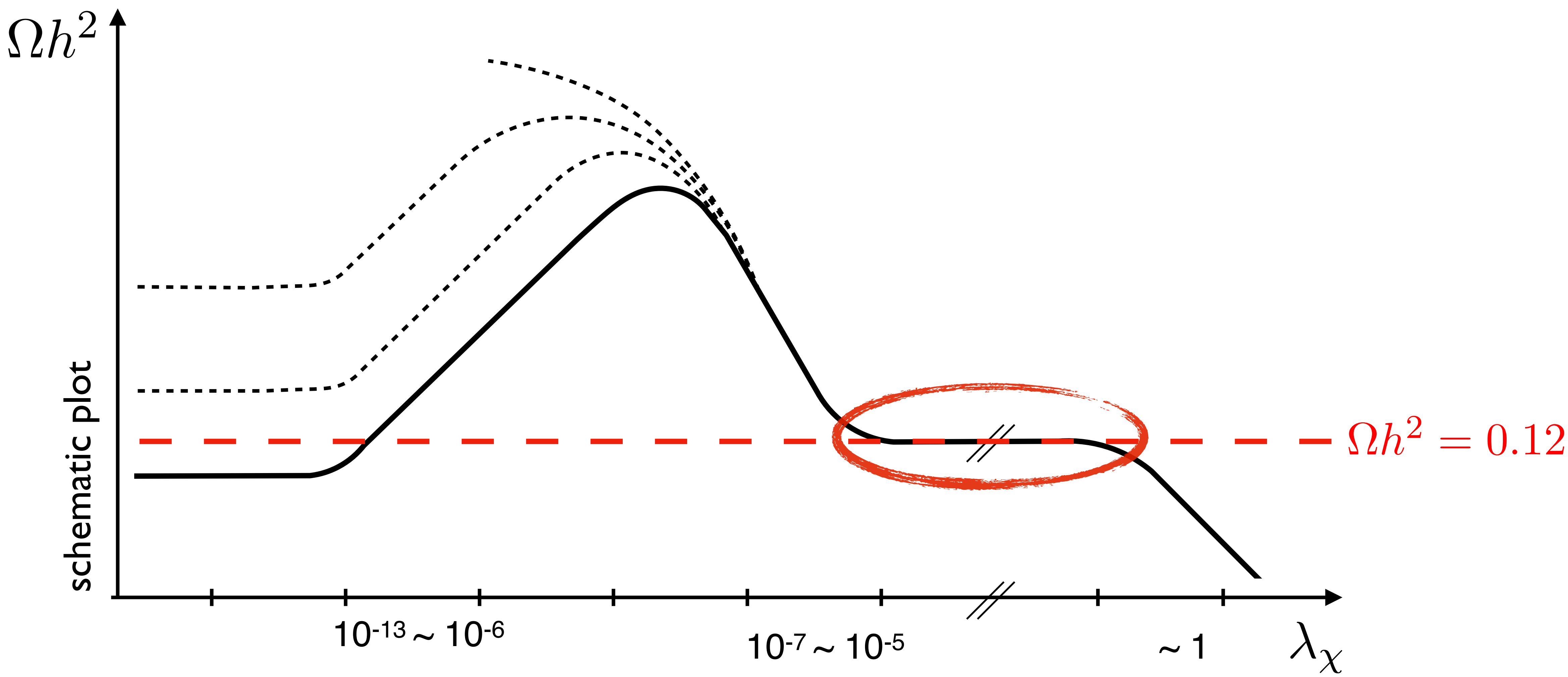
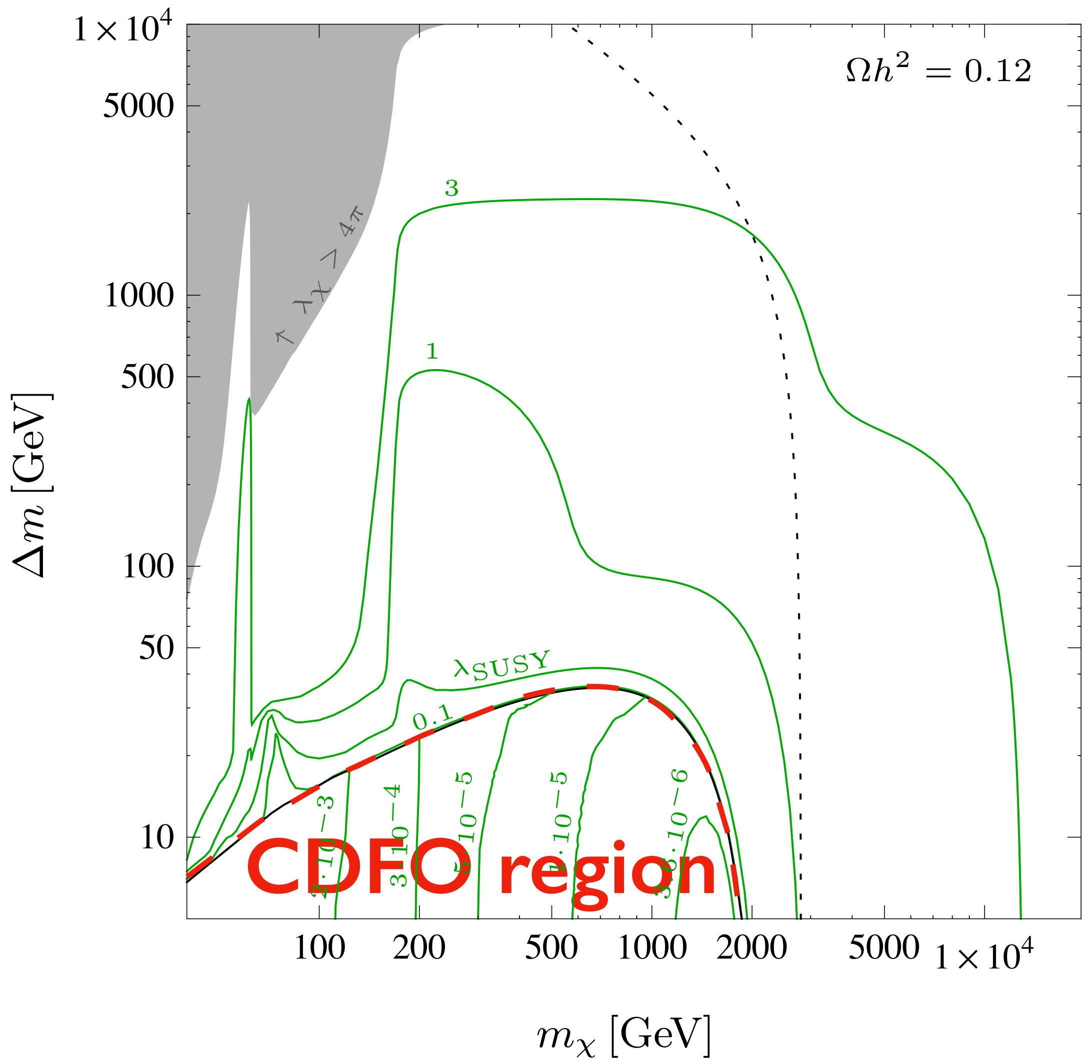


Conversion-driven freeze-out / co-scattering versus WIMP region

Simplified *t*-channel mediator models:

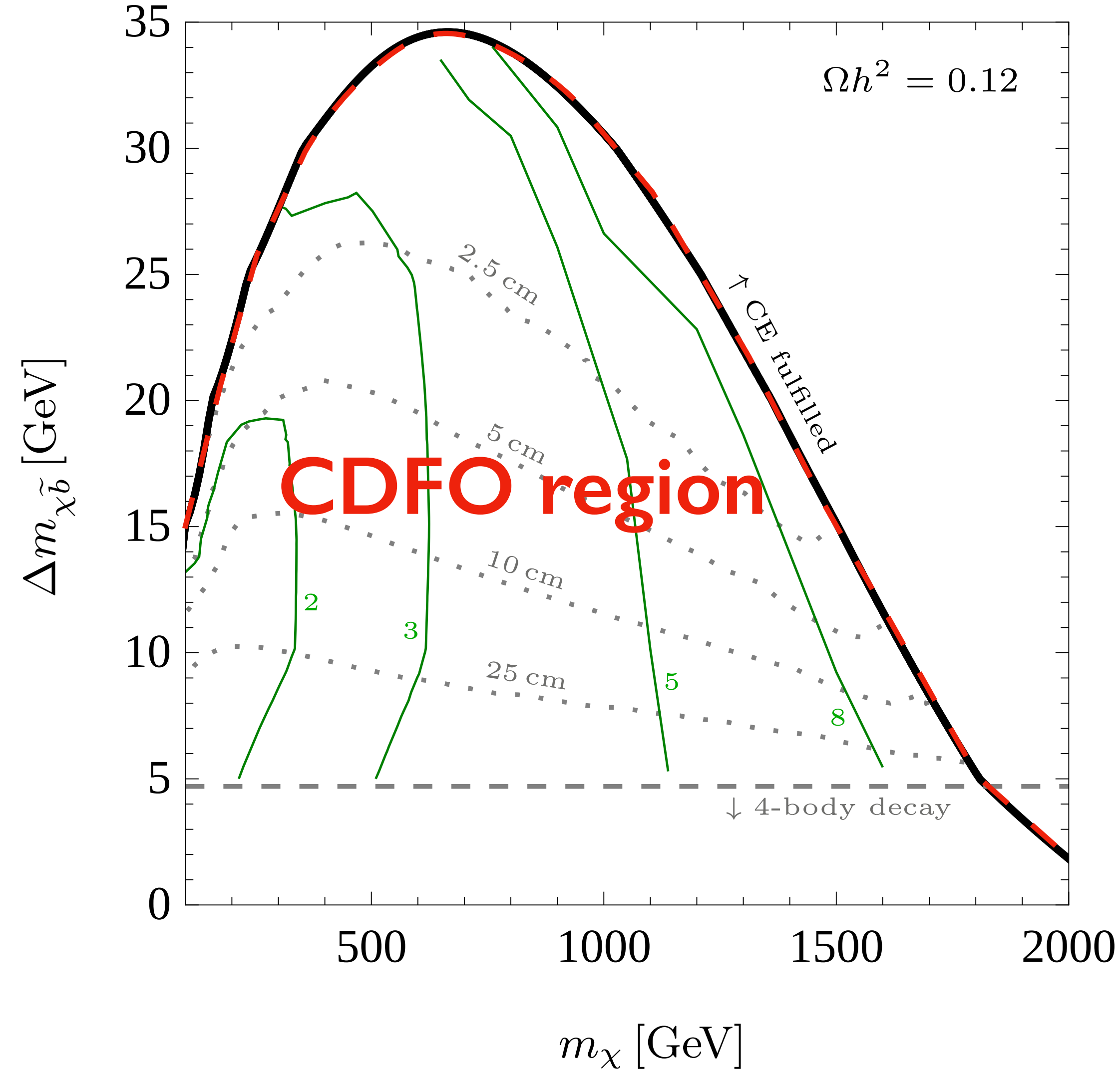
Top-philic

[Garny, JH, Hufnagel,Lülf 2018]



Bottom-philic

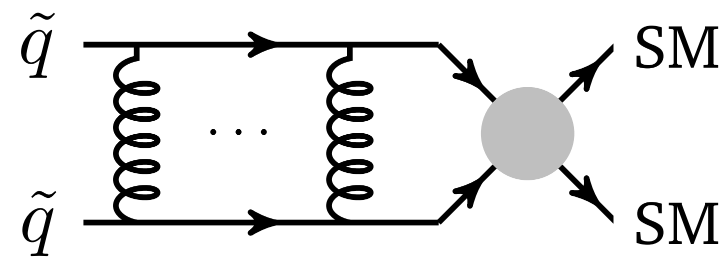
[Garny, JH, Lülf, Vogl 2017]



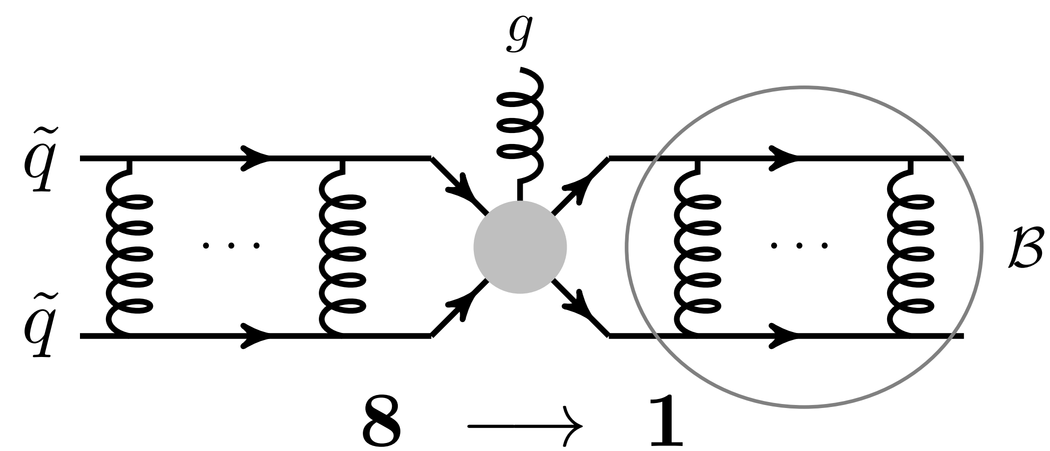
Non-perturbative effects

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

- Sommerfeld effect:



- Bound state formation:



[Harz, Petraki]

Coulomb limit: $V_{[\boldsymbol{R}]}(r) = -\frac{\alpha^{\text{eff}}_{[\boldsymbol{R}]}}{r}$, $\alpha^{\text{eff}}_{[\boldsymbol{R}]} = \alpha_s \times \begin{cases} 4/3, & \mathbf{R} = \mathbf{1}, \\ -1/6, & \mathbf{R} = \mathbf{8}. \end{cases}$

[see e.g. J. Ellis, F. Luo, K.A. Olive 1503.07142; S.P. Liew, F. Luo 1611.08133; J. Harz, K. Petraki 1805.01200; A. Mitridate, M. Redi, J. Smirnov, A. Strumia 1702.01141; T. Binder, B. Blobel, J. Harz, and K. Mukaida 2002.07145]

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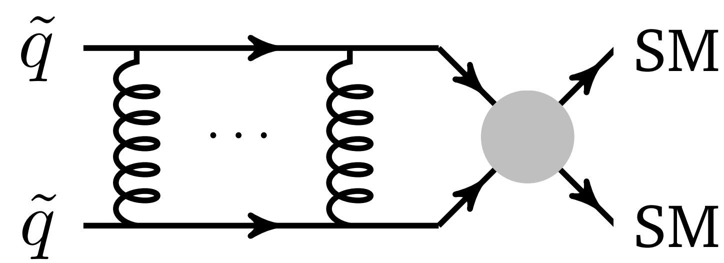
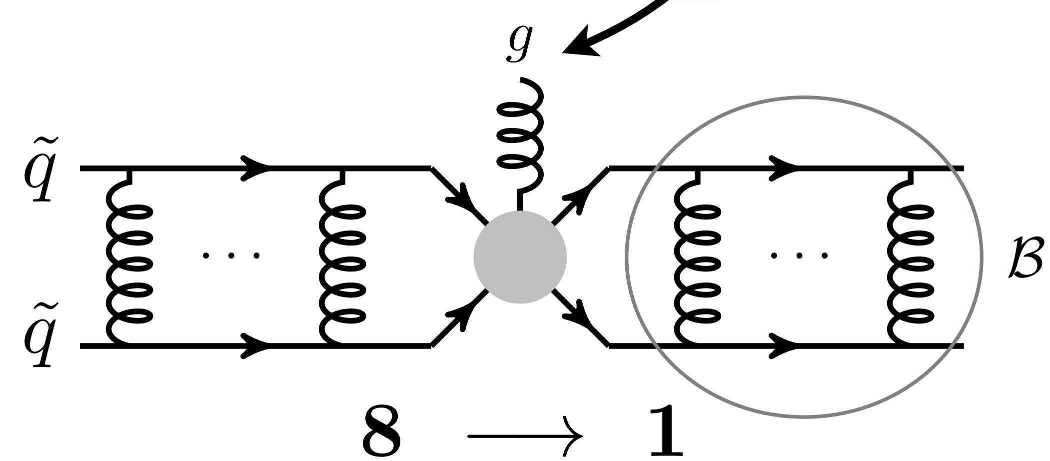


$$\omega = \frac{\mu(\alpha_b^{\rm eff})^2}{2n^2} + \frac{1}{2}\mu v_{\rm rel}^2$$

- Bound state formation:



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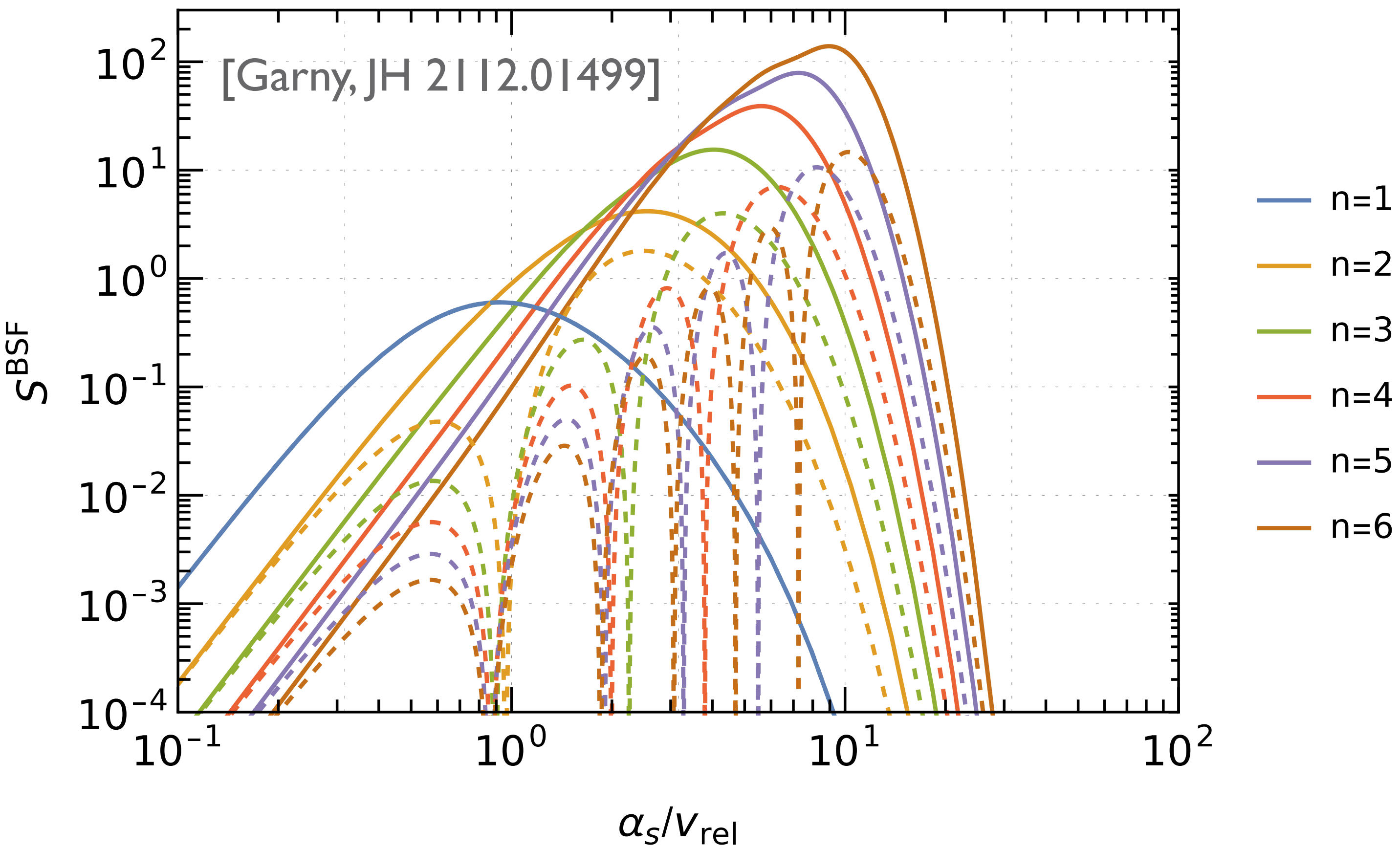
Bound state formation cross section

$$\sigma_{\mathrm{BSF},n\ell}^{\tilde{q}\tilde{q}^\dagger \to \mathcal{B}g} v_{\mathrm{rel}} \;\propto\; \alpha_{\mathrm{s}}\omega^3 \left|\langle \psi_{n\ell}^{[\mathbf{1}]} | \boldsymbol{r} | \psi_{\boldsymbol{p}_{\mathrm{rel}}}^{[\mathbf{8}]} \rangle\right|^2$$

[Color-electric dipol operator, computed in potential nonrel. QCD, see e.g. X. Yao, B. Müller 1811.09644]



small velocities ~ relevant for small temperatures

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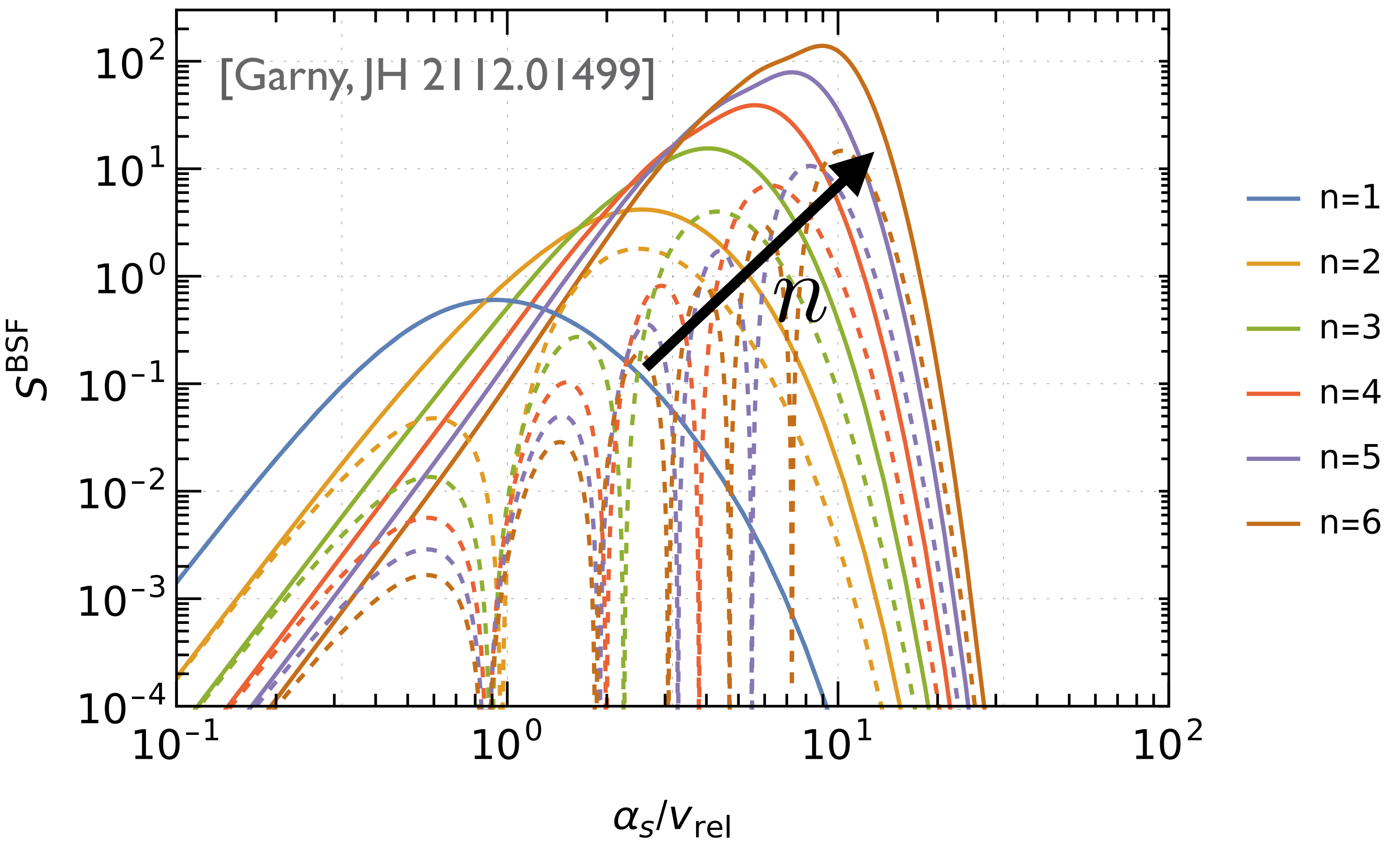
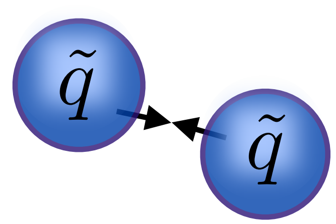


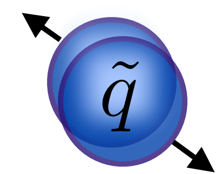
small velocities ~ relevant for small temperatures

Processes of (excited) bound states

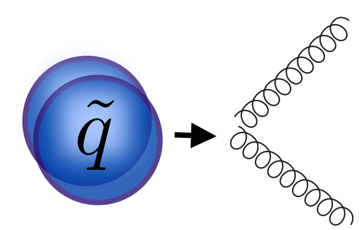
Bound state formation



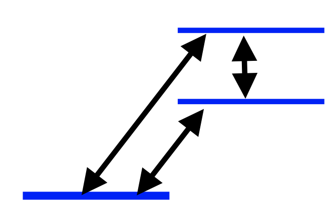
Ionization



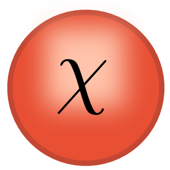
Decay



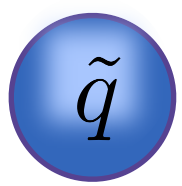
Transition



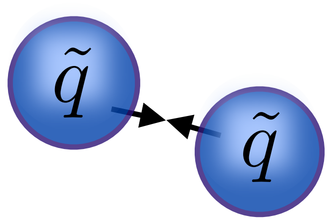
Boltzmann equations including excitations



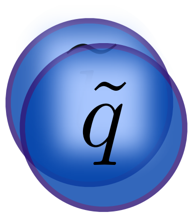
$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\langle\sigma_{\chi\chi}v\rangle\left(Y_\chi^2 - Y_\chi^{\mathrm{eq}\,2}\right) + \langle\sigma_{\chi\tilde{q}}v\rangle\left(Y_\chi Y_{\tilde{q}} - Y_\chi^{\mathrm{eq}}Y_{\tilde{q}}^{\mathrm{eq}}\right) - \frac{\Gamma_{\mathrm{conv}}}{s}\left(Y_{\tilde{q}}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



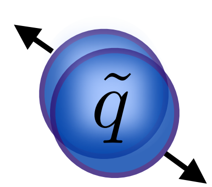
$$\frac{\mathrm{d}Y_{\tilde{q}}}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\frac{1}{2}\langle\sigma_{\tilde{q}\tilde{q}^\dagger}v\rangle\left(Y_{\tilde{q}}^2 - Y_{\tilde{q}}^{\mathrm{eq}\,2}\right) + \langle\sigma_{\chi\tilde{q}}v\rangle\left(Y_\chi Y_{\tilde{q}} - Y_\chi^{\mathrm{eq}}Y_{\tilde{q}}^{\mathrm{eq}}\right)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

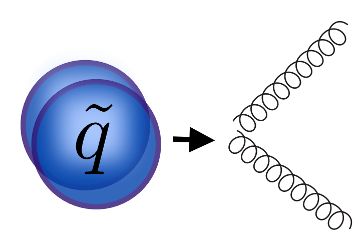


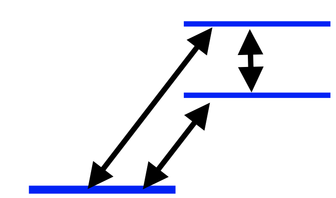
$$\left. + \sum_i \frac{1}{2}\langle\sigma_{\mathrm{BSF},i}v\rangle\left(Y_{\tilde{q}}^2 - Y_{\tilde{q}}^{\mathrm{eq}\,2}\frac{Y_{\mathcal{B}_i}}{Y_{\mathcal{B}_i}^{\mathrm{eq}}}\right)\right],$$



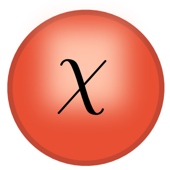
$$\frac{\mathrm{d}Y_{\mathcal{B}_i}}{\mathrm{d}x} = \frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\Gamma^i_{\mathrm{ion}}\left(Y_{\mathcal{B}_i} - Y_{\mathcal{B}_i}^{\mathrm{eq}}\frac{Y_{\tilde{q}}^2}{Y_{\tilde{q}}^{\mathrm{eq}\,2}}\right) + \Gamma^i_{\mathrm{dec}}\left(Y_{\mathcal{B}_i} - Y_{\mathcal{B}_i}^{\mathrm{eq}}\right) - \sum_{j\neq i}\Gamma^{j\to i}_{\mathrm{trans}}\left(Y_{\mathcal{B}_j} - Y_{\mathcal{B}_i}\frac{Y_{\mathcal{B}_j}^{\mathrm{eq}}}{Y_{\mathcal{B}_i}^{\mathrm{eq}}}\right)\right]$$



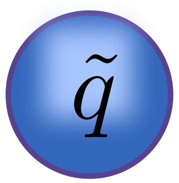




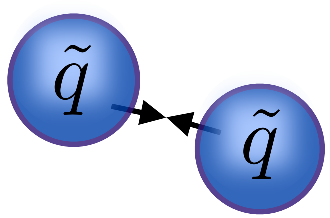
Boltzmann equations including excitations



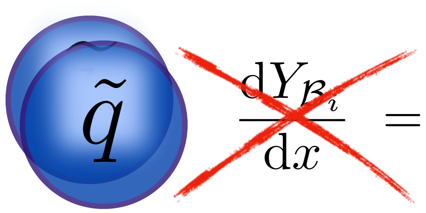
$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\langle\sigma_{\chi\chi}v\rangle\left(Y_\chi^2 - Y_\chi^{\mathrm{eq}\,2}\right) + \langle\sigma_{\chi\tilde{q}}v\rangle\left(Y_\chi Y_{\tilde{q}} - Y_\chi^{\mathrm{eq}}Y_{\tilde{q}}^{\mathrm{eq}}\right) - \frac{\Gamma_{\mathrm{conv}}}{s}\left(Y_{\tilde{q}}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



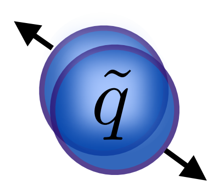
$$\frac{\mathrm{d}Y_{\tilde{q}}}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\frac{1}{2}\langle\sigma_{\tilde{q}\tilde{q}^\dagger}v\rangle\left(Y_{\tilde{q}}^2 - Y_{\tilde{q}}^{\mathrm{eq}\,2}\right) + \langle\sigma_{\chi\tilde{q}}v\rangle\left(Y_\chi Y_{\tilde{q}} - Y_\chi^{\mathrm{eq}}Y_{\tilde{q}}^{\mathrm{eq}}\right)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

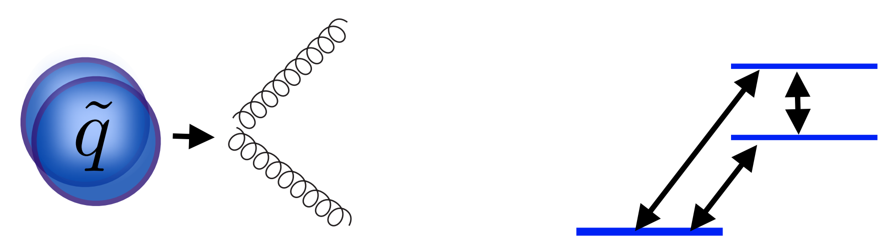


$$\left. + \sum_i \frac{1}{2}\langle\sigma_{\mathrm{BSF},i}v\rangle\left(Y_{\tilde{q}}^2 - Y_{\tilde{q}}^{\mathrm{eq}\,2}\frac{Y_{\mathcal{B}_i}}{Y_{\mathcal{B}_i}^{\mathrm{eq}}}\right)\right],$$



$$\frac{\mathrm{d}Y_{\mathcal{B}_i}}{\mathrm{d}x} = \frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\Gamma_{\mathrm{ion}}^i\left(Y_{\mathcal{B}_i} - Y_{\mathcal{B}_i}^{\mathrm{eq}}\frac{Y_{\tilde{q}}^2}{Y_{\tilde{q}}^{\mathrm{eq}\,2}}\right) + \Gamma_{\mathrm{dec}}^i\left(Y_{\mathcal{B}_i} - Y_{\mathcal{B}_i}^{\mathrm{eq}}\right) - \sum_{j\neq i}\Gamma_{\mathrm{trans}}^{j\to i}\left(Y_{\mathcal{B}_j} - Y_{\mathcal{B}_i}\frac{Y_{\mathcal{B}_j}^{\mathrm{eq}}}{Y_{\mathcal{B}_i}^{\mathrm{eq}}}\right)\right]$$





Steady-state approximation ⇒ reduce to linear set of algebraic equations

[see Garny, JH 2112.01499 *for details*; see *also* Binder *et al.* 2112.00042]

Boltzmann equations including excitations

χ

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

$\tilde{q}$

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

$$\langle\sigma_{\tilde{q}\tilde{q}^\dagger}v\rangle_{\mathrm{eff}} = \langle\sigma_{\tilde{q}\tilde{q}^\dagger}v\rangle + \sum_i\langle\sigma_{\mathrm{BSF},i}v\rangle R_i$$

Boltzmann equations including excitations

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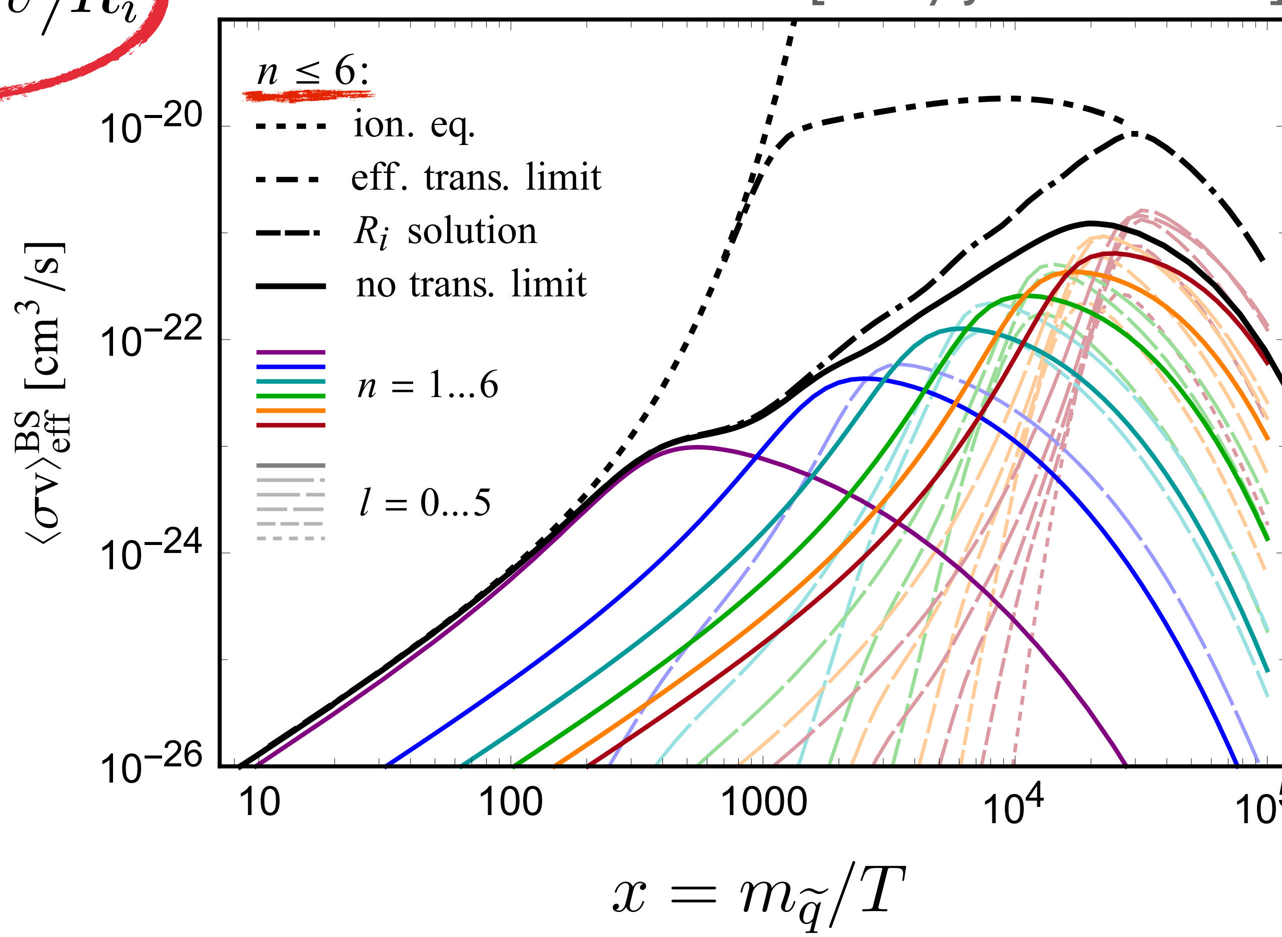
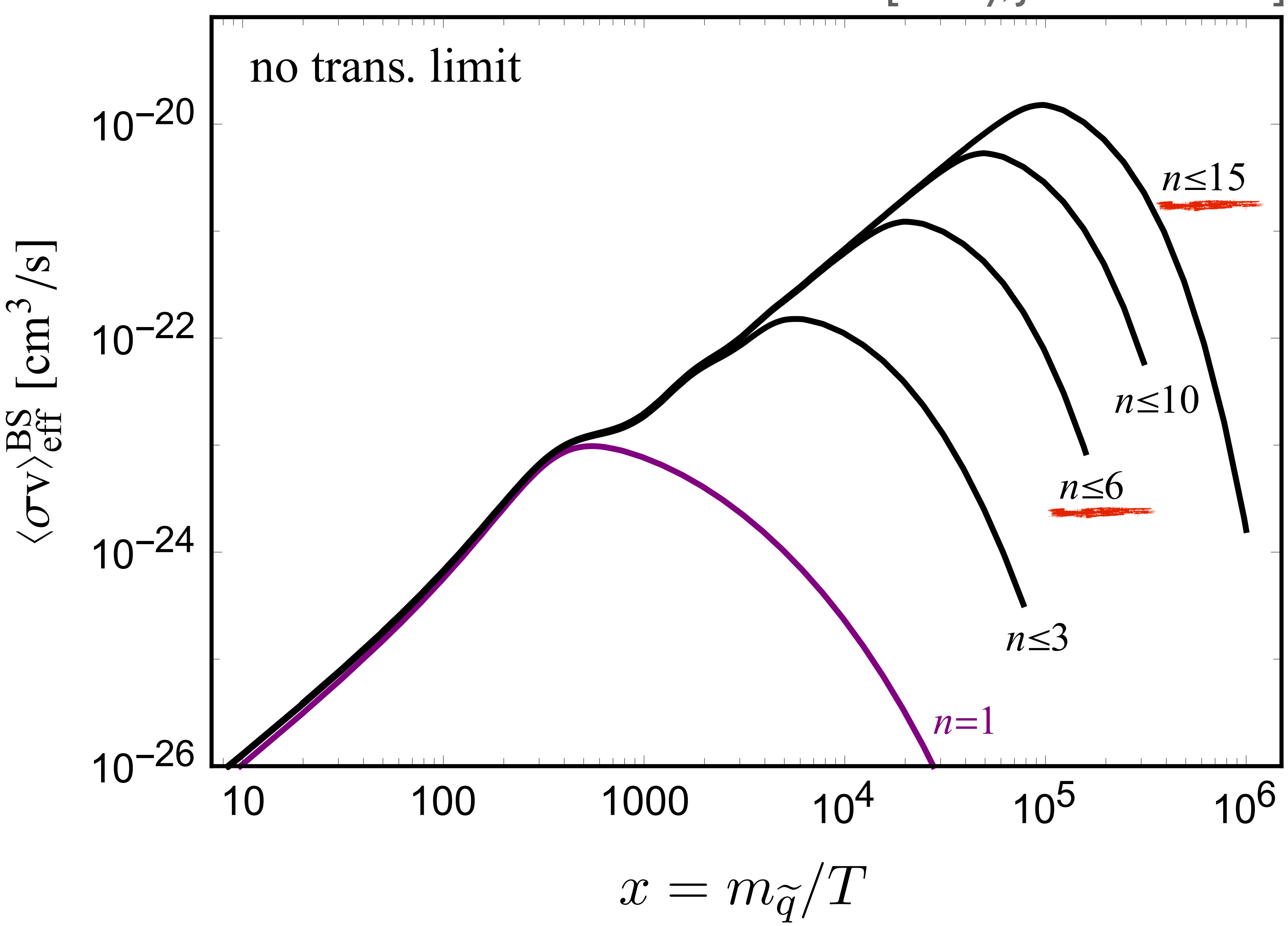
[Garny, JH 2112.01499]



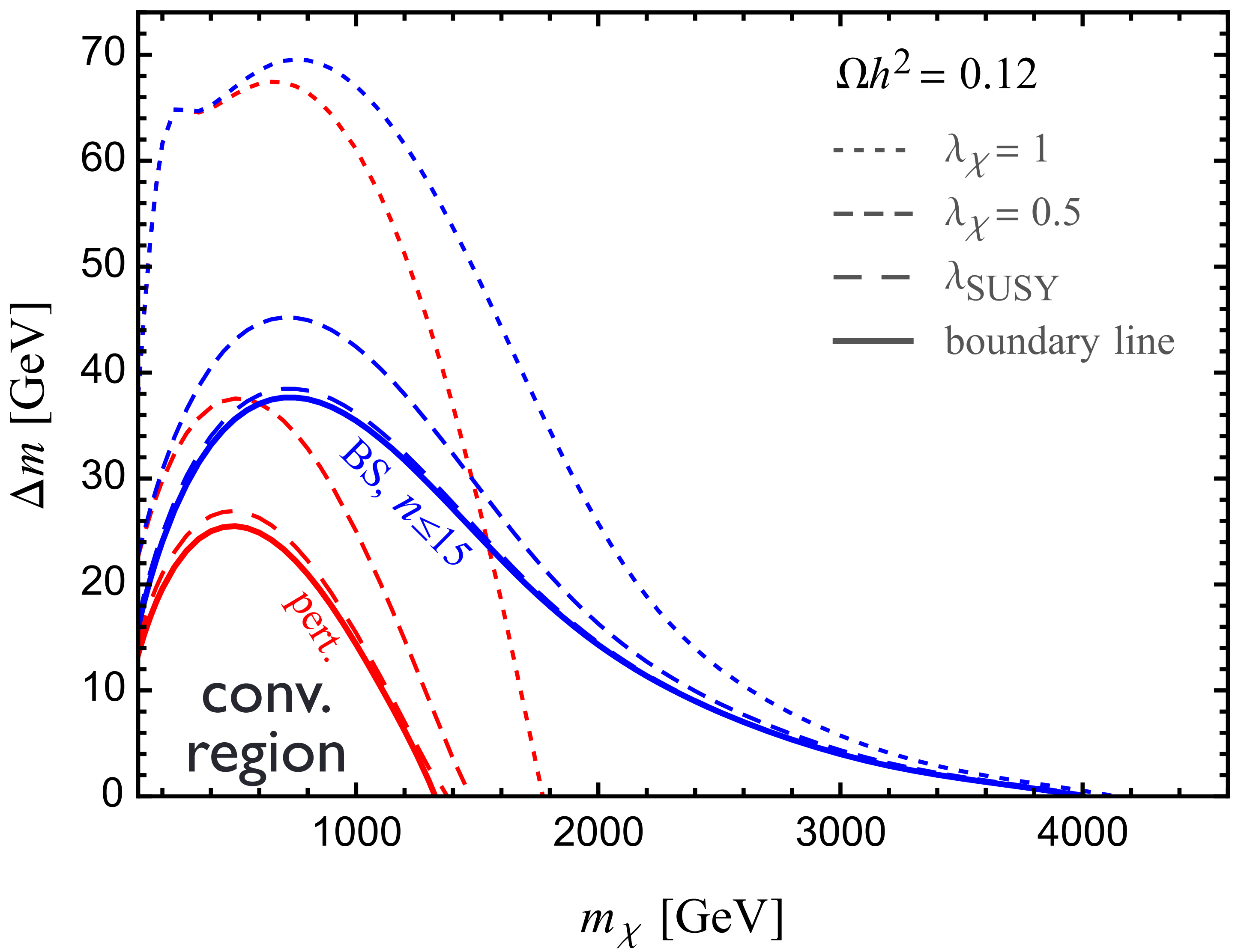
No transition limit

$$\langle \sigma_{\tilde{q}\tilde{q}^\dagger} v \rangle_{\rm eff} = \langle \sigma_{\tilde{q}\tilde{q}^\dagger} v \rangle + \sum_i \langle \sigma_{{\rm BSF},i} v \rangle \frac{\Gamma^i_{\rm dec}}{\Gamma^i_{\rm ion} + \Gamma^i_{\rm dec}}$$

[Garny, JH 2112.01499]



Bound state effects on the parameter space



Relevant for current searches?

Conversion rate on the edge of being efficient:

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

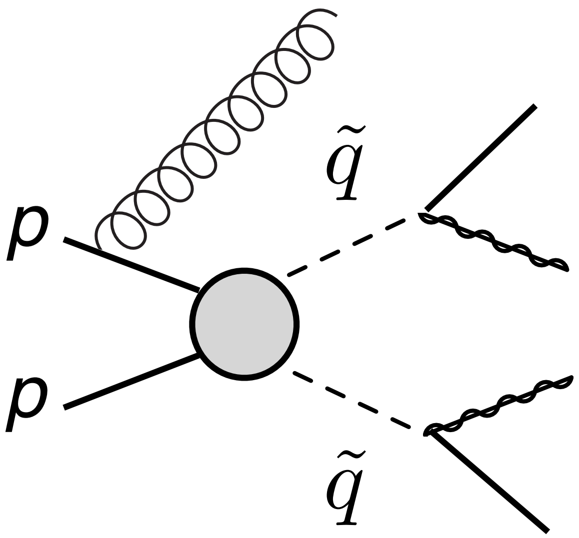
$$\Rightarrow \; \Gamma_{\rm dec} \lesssim H$$

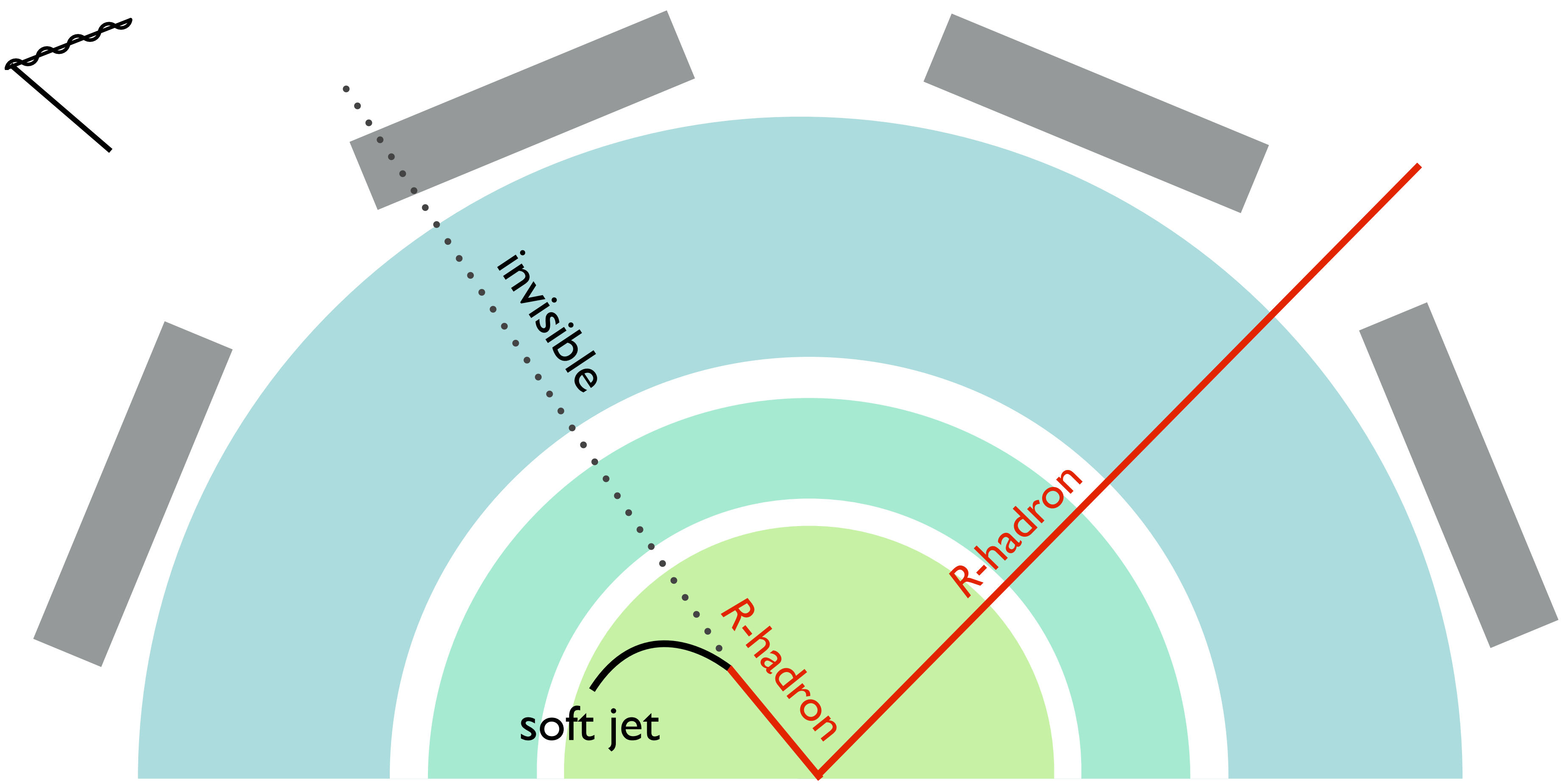
$$c\tau \gtrsim H^{-1} \simeq 1.5\,{\rm cm}\left(\frac{(100\,{\rm GeV})^2}{T^2}\right)$$

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

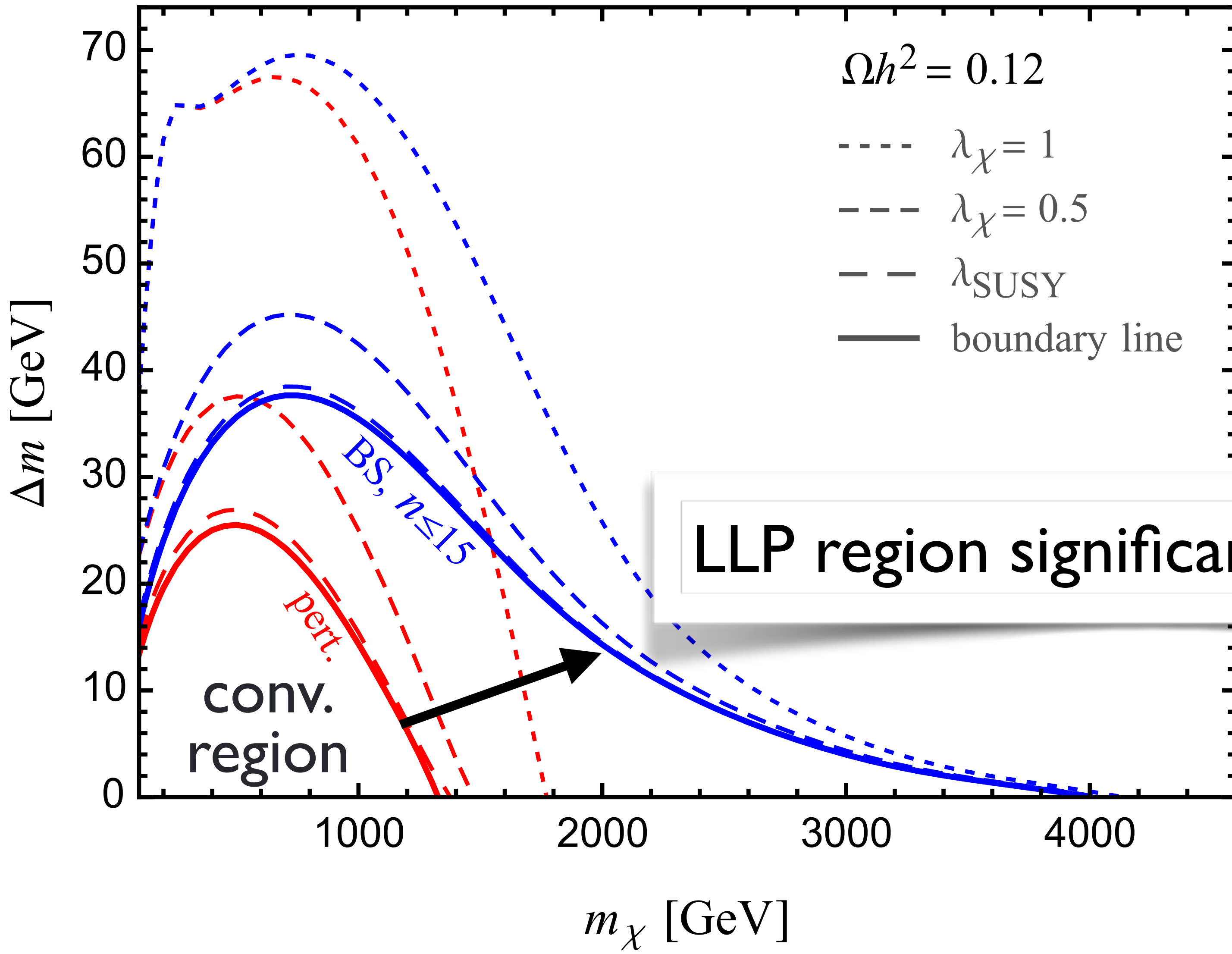
⇒ Long-lived particles (LLPs) at LHC!

Long-lived particles at LHC





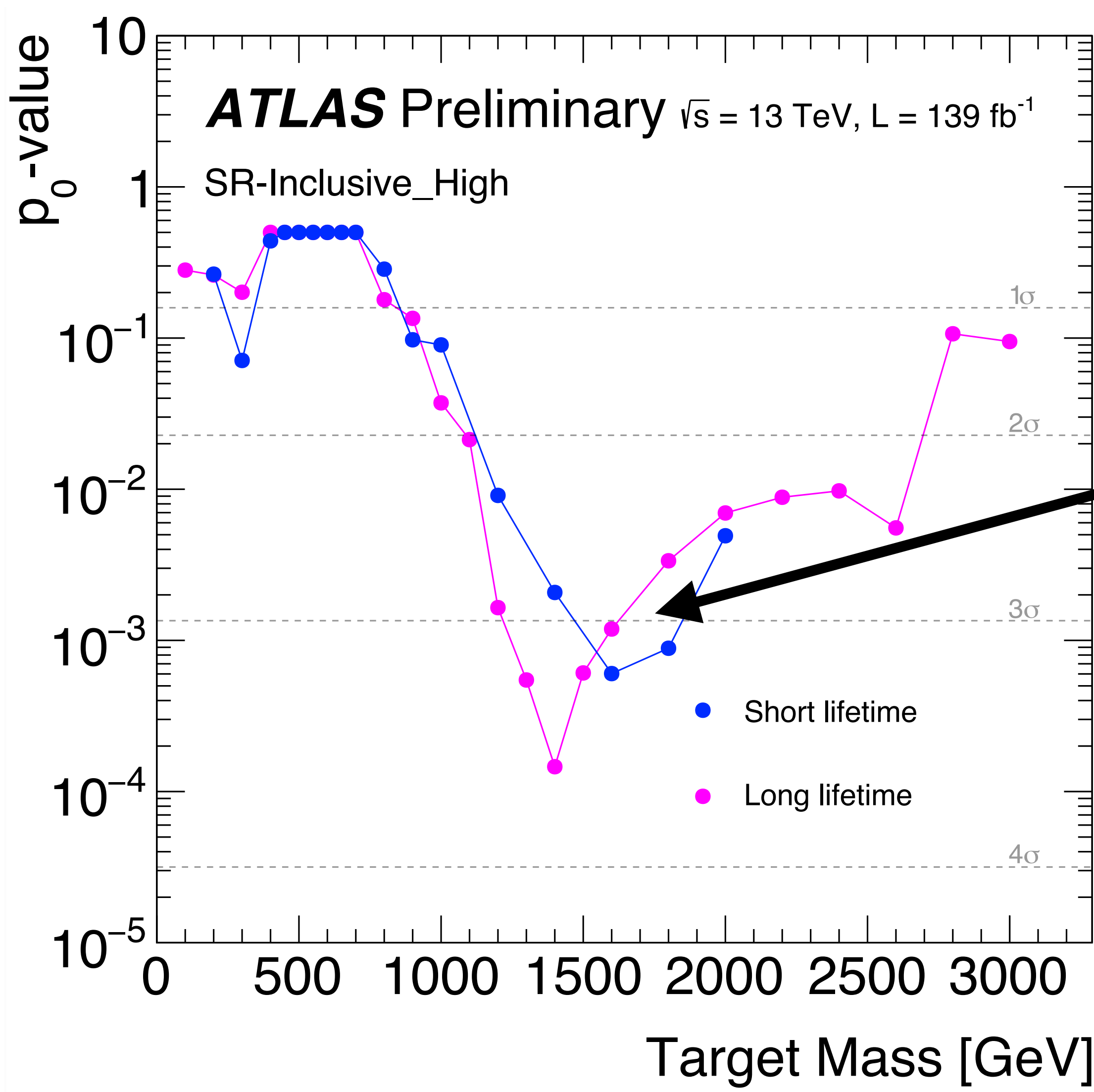
Implications for search strategies



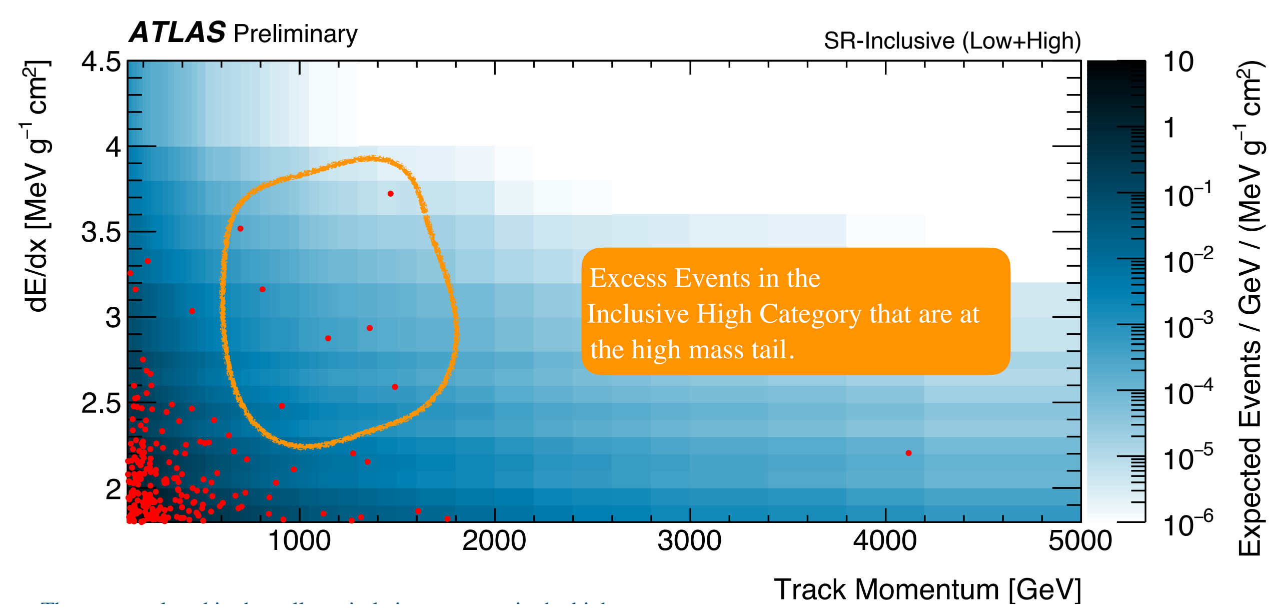
LLP region significantly enhanced!

Recent excess in LLP searches

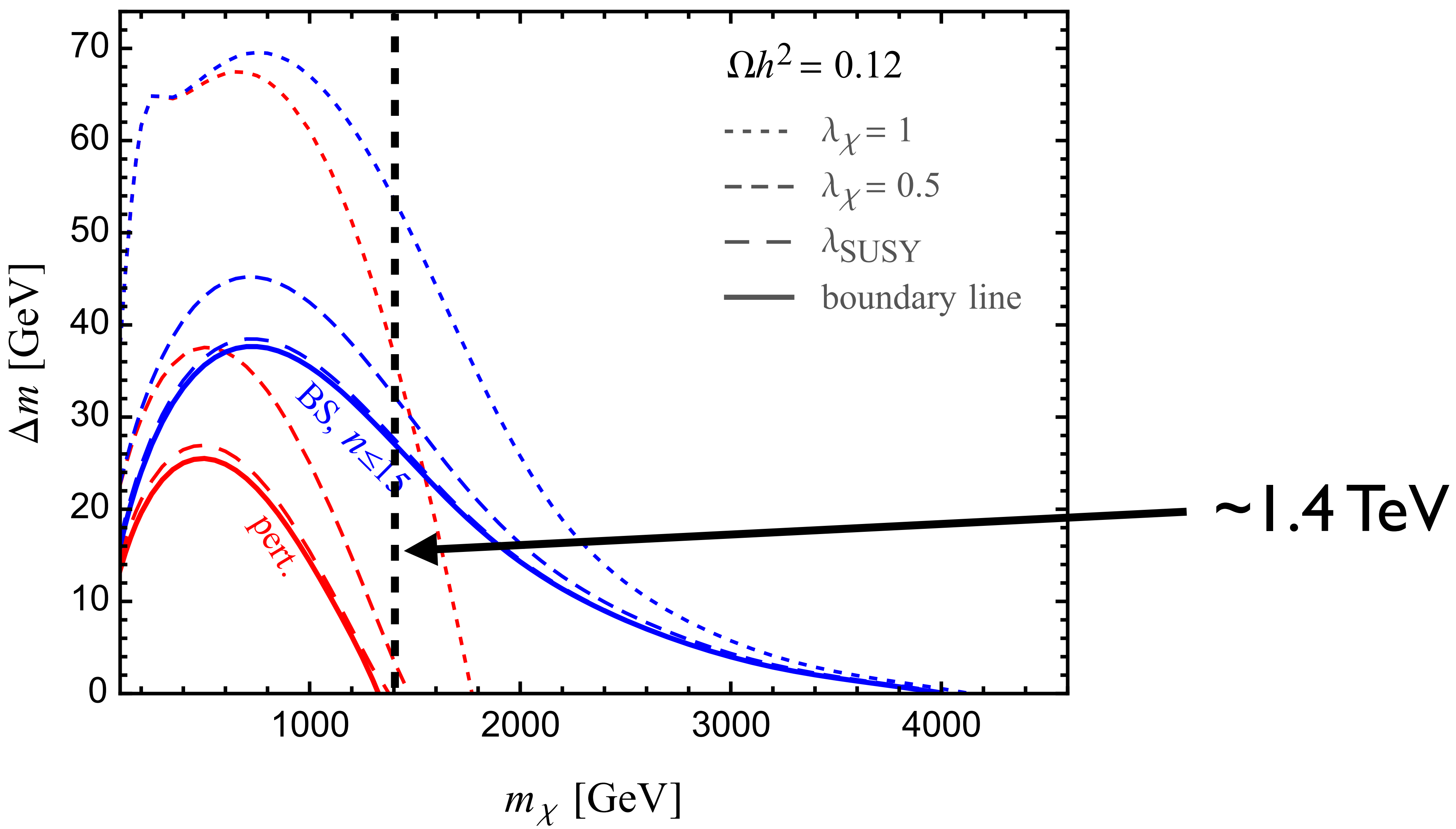
[ATLAS, Talk at Moriond 2022]



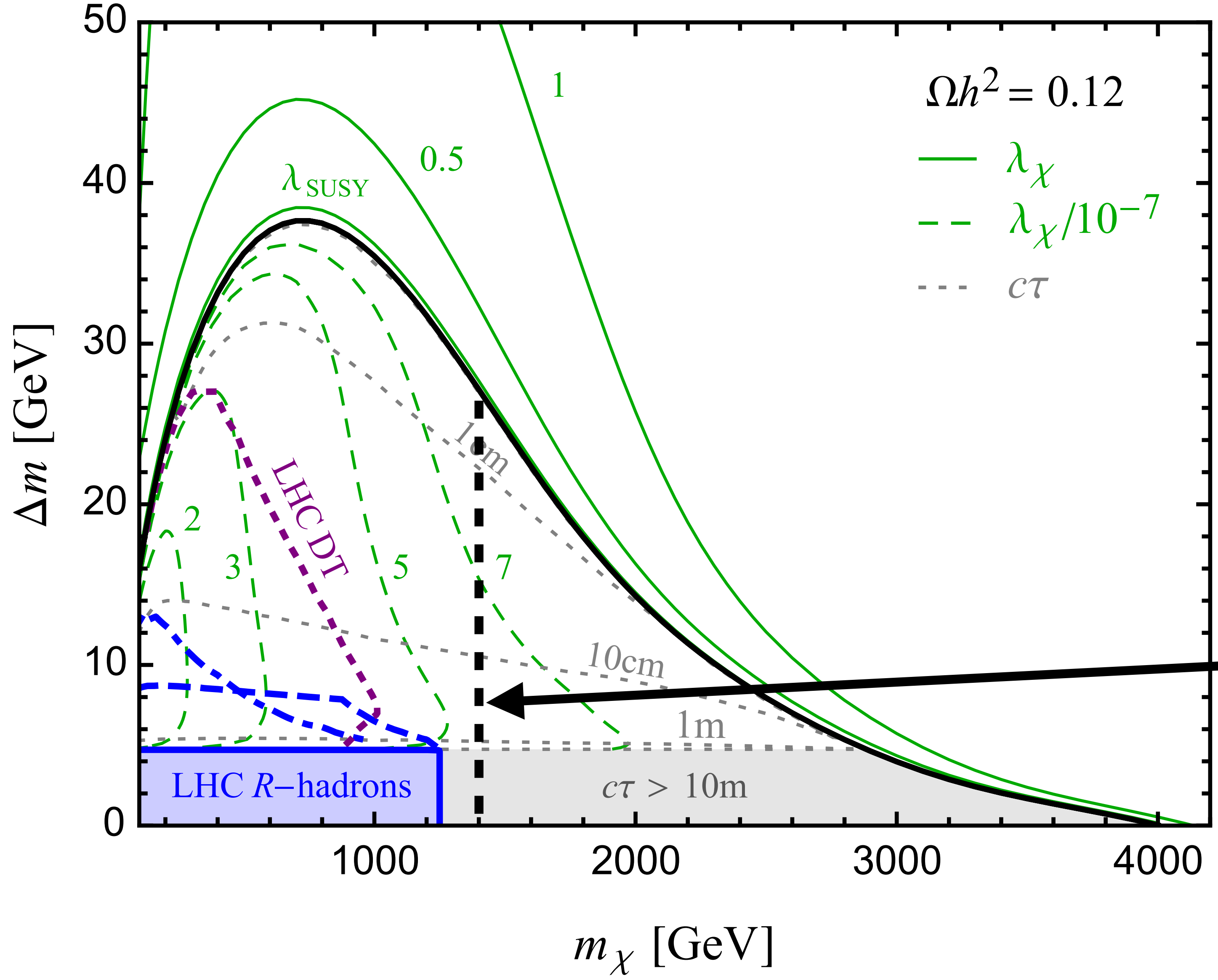
Heavy stable charge particle with mass ~1.4 TeV



Implications for search strategies



Collider constraints



~1.4 TeV

⇒ xs ~ 0.4 fb

~ 50 events

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

- t-channel mediator models provide rich pheno
- Conversion-driven freeze-out less explored terrain
- Prolonged freeze-out process: Bound states relevant, higher excitation important at low energies
- General formalism to include arbitrary excitations
- Viable parameter space significantly enlarged
- Important for long-lived particle searches at LHC
  $H \sim \Gamma$: Lifetimes naturally O(1-100cm)