Long-lived particles in *t*-channel mediator dark matter models

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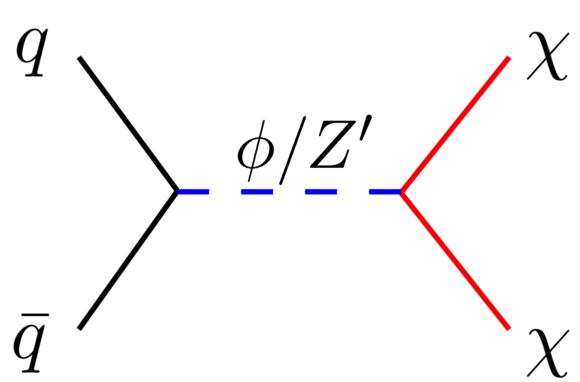
UCLouvain

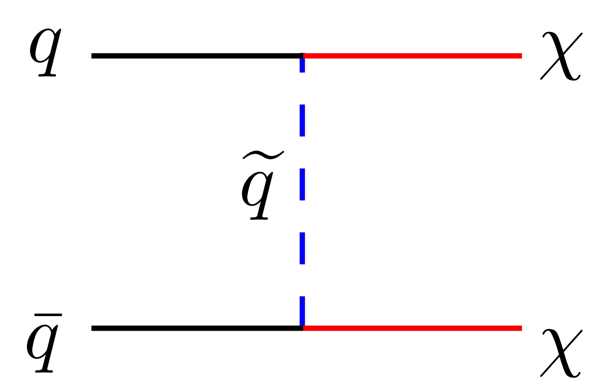
Searching for long-lived particles at the LHC and beyond:
Eleventh workshop of the LLP Community
June 2, 2022

Simplified dark matter models at LHC

s-channel mediator



t-channel mediator



even

odd

under Z_2-symmetry that stabilizes dark matter

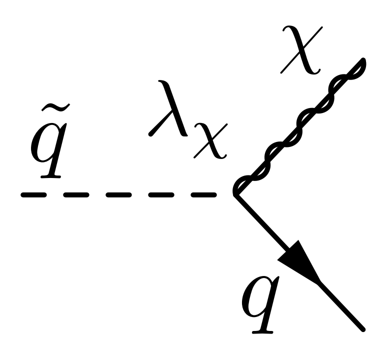
Example:
SUSY-like *t*-channel mediator model

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

λ_χ g_s

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

⇒ Yukawa-type interaction:

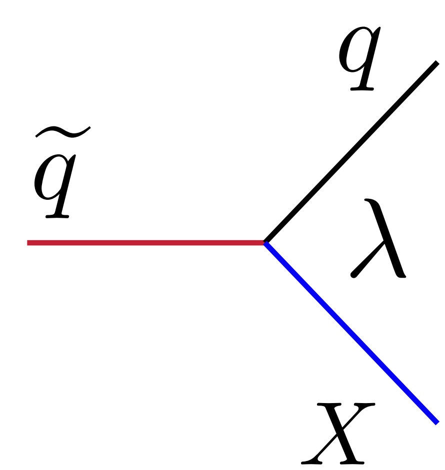


In general, λ_χ is a free parameter here [see Ibarra et al. 2009 for SUSY realization]

Simplified dark matter models with *t*-channel mediators

	Field	Spin	Repr.	Self-conj.
dark matter	$\tilde{S}$	0	$(\mathbf{1},\mathbf{1},0)$	yes
	S	0	$(\mathbf{1},\mathbf{1},0)$	no
	$\tilde{\chi}$	1/2	$(\mathbf{1},\mathbf{1},0)$	yes
	χ	1/2	$(\mathbf{1},\mathbf{1},0)$	no
	$\tilde{V}_\mu$	1	$(\mathbf{1},\mathbf{1},0)$	yes
	V_μ	1	$(\mathbf{1},\mathbf{1},0)$	no
t-channel mediator	$\varphi_Q = \begin{pmatrix} \varphi_Q^{(u)} \\ \varphi_Q^{(d)} \end{pmatrix}$	0	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	no
	φ_u	0	$(\mathbf{3},\mathbf{1},\frac{2}{3})$	no
	φ_d	0	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	no
	$\psi_Q = \begin{pmatrix} \psi_Q^{(u)} \\ \psi_Q^{(d)} \end{pmatrix}$	1/2	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	no
	ψ_u	1/2	$(\mathbf{3},\mathbf{1},\frac{2}{3})$	no
	ψ_d	1/2	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	no

[Arina, Fuks, Mantani 2001.05024]



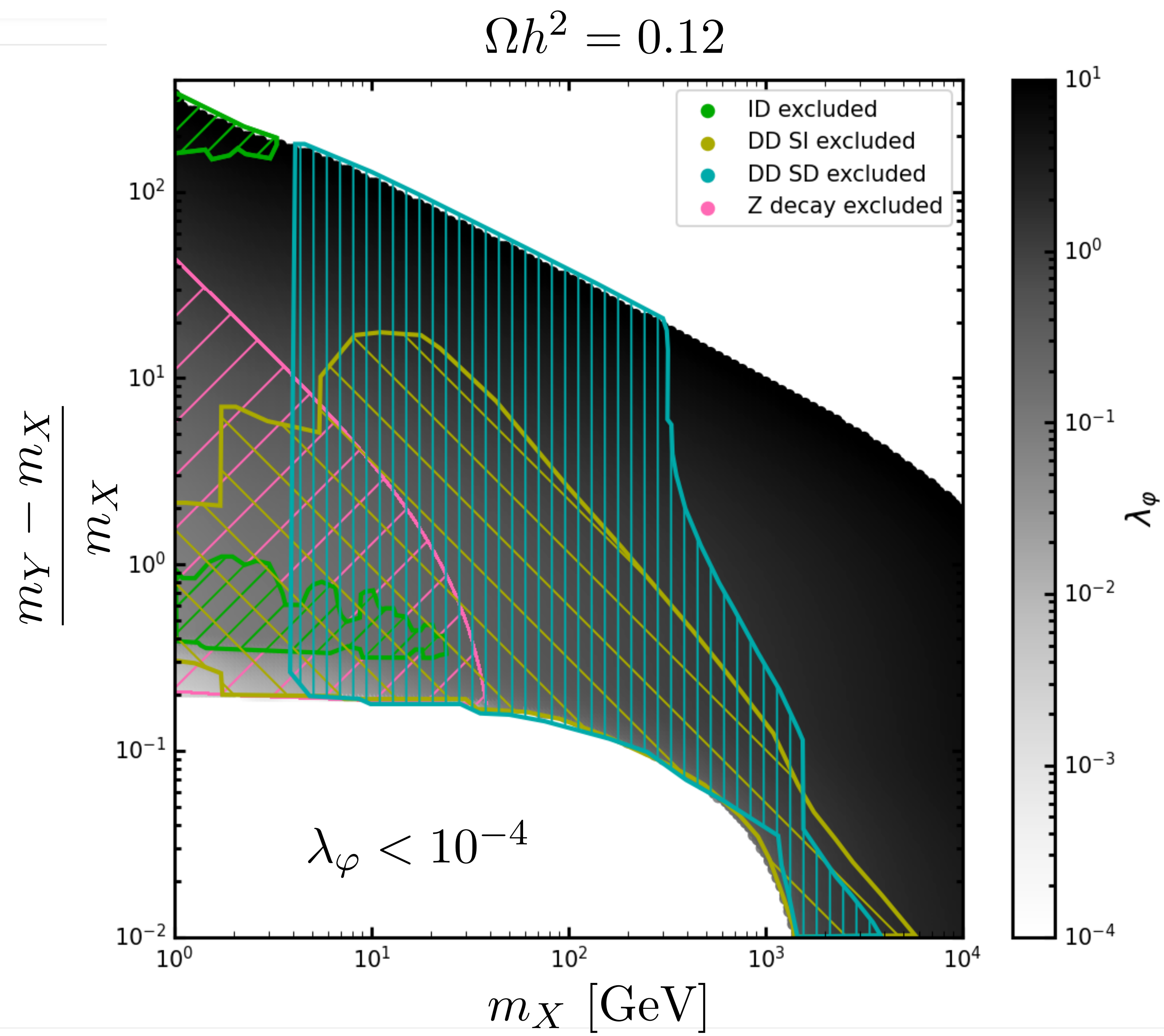
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \mathcal{L}_F(\chi) + \mathcal{L}_F(\tilde{\chi}) + \mathcal{L}_S(S) + \mathcal{L}_S(\tilde{S}) + \mathcal{L}_V(V) + \mathcal{L}_V(\tilde{V}),$$

$$\mathcal{L}_F(X) = \Big[\lambda_{\mathbf{Q}}\bar{X}Q\varphi_Q^\dagger + \lambda_{\mathbf{u}}\bar{X}u\varphi_u^\dagger + \lambda_{\mathbf{d}}\bar{X}d\varphi_d^\dagger + \text{h.c.}\Big]\ ,$$

$$\mathcal{L}_S(X) = \Big[\hat{\lambda}_{\mathbf{Q}}\bar{\psi}_Q QX + \hat{\lambda}_{\mathbf{u}}\bar{\psi}_u uX + \hat{\lambda}_{\mathbf{d}}\bar{\psi}_d dX + \text{h.c.}\Big]\ ,$$

$$\mathcal{L}_V(X) = \Big[\hat{\lambda}_{\mathbf{Q}}\bar{\psi}_Q \not{X} Q + \hat{\lambda}_{\mathbf{u}}\bar{\psi}_u \not{X} u + \hat{\lambda}_{\mathbf{d}}\bar{\psi}_d \not{X} d + \text{h.c.}\Big]\ .$$

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



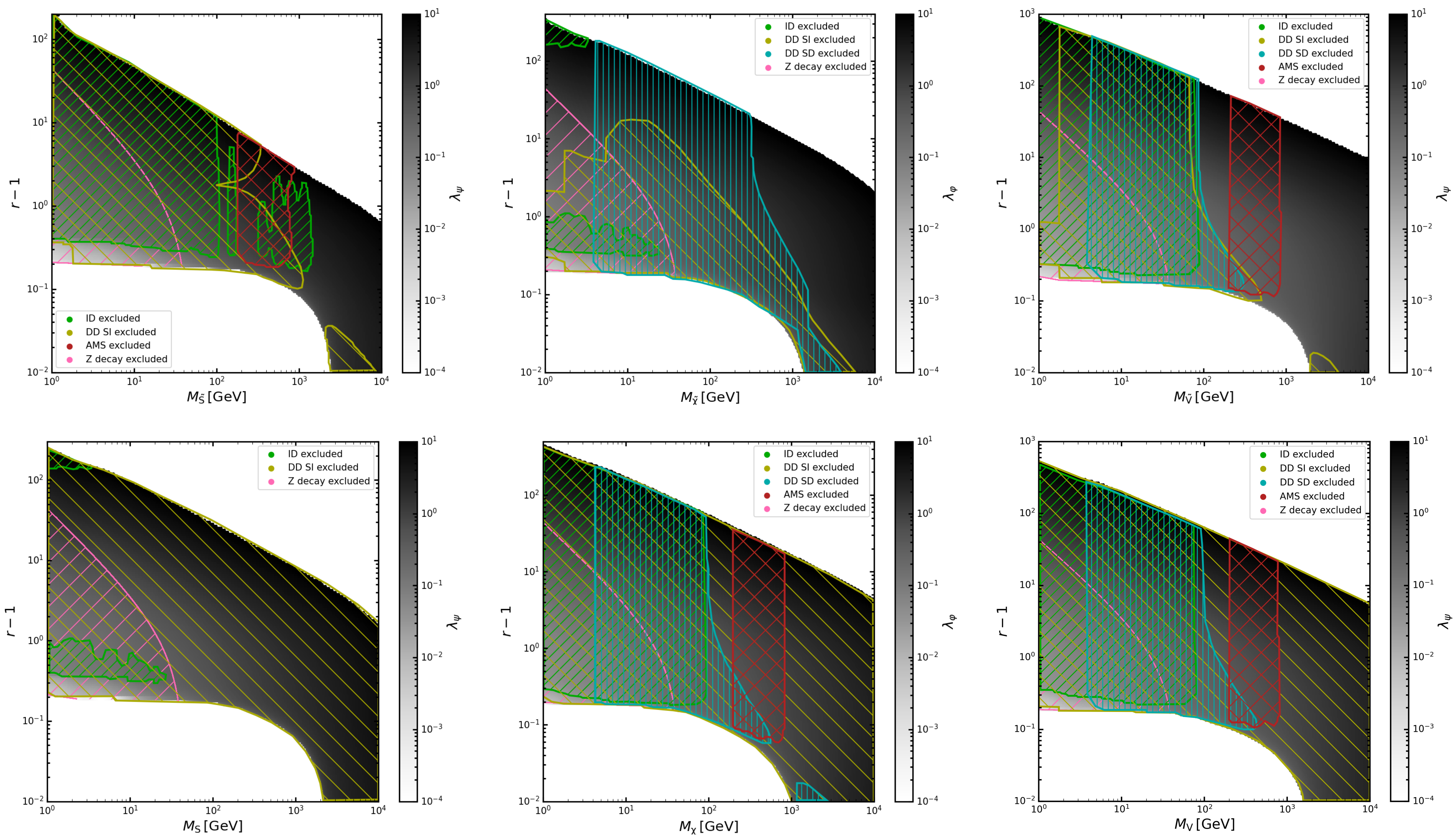
[Arina et al. 2010.07559;
Arina, Fuks, JH, et al., *in preparation*]

Other choices

scalar DM, fermion med. | fermion DM, scalar med. | vector DM, fermion med.

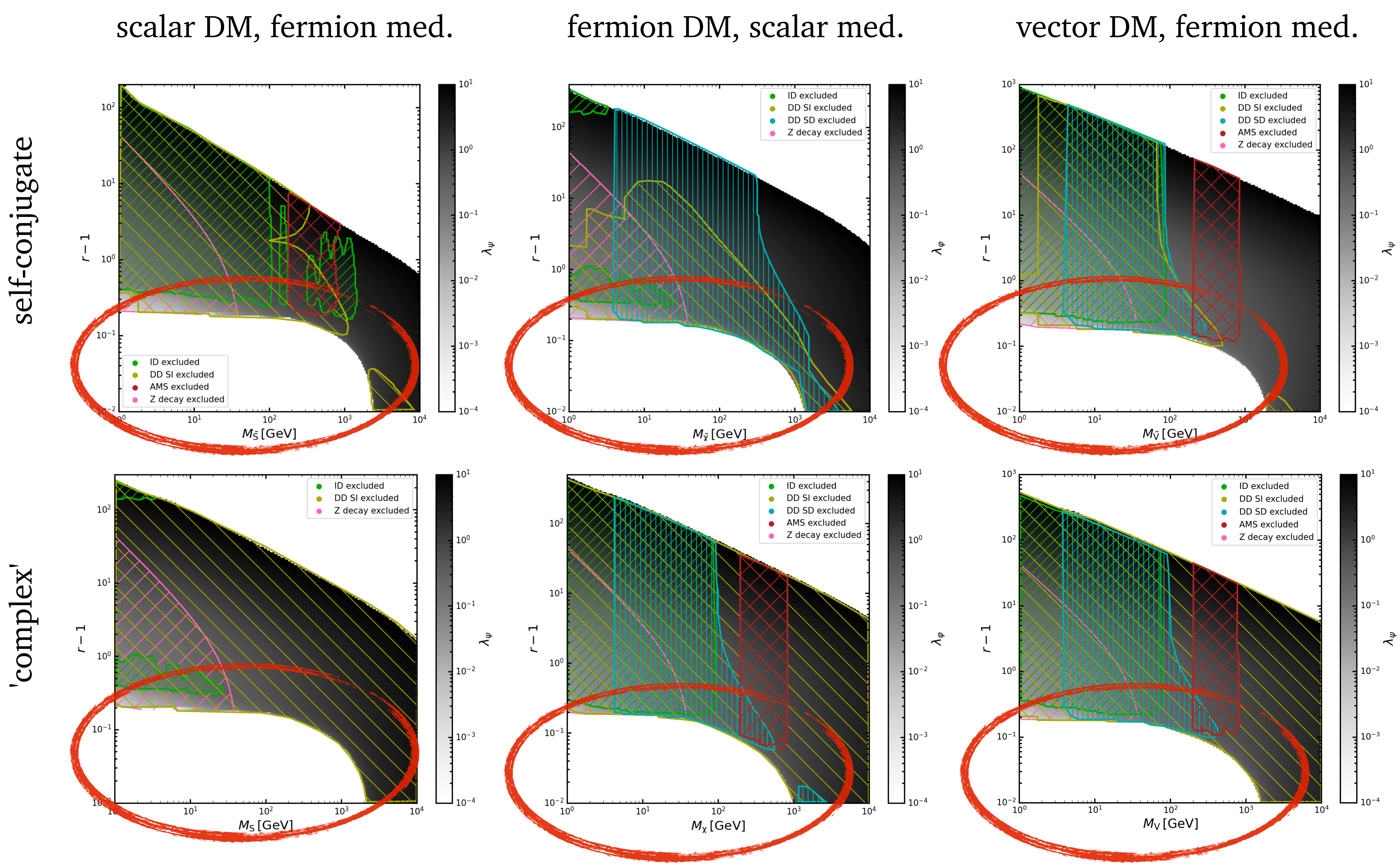
self-conjugate

'complex'



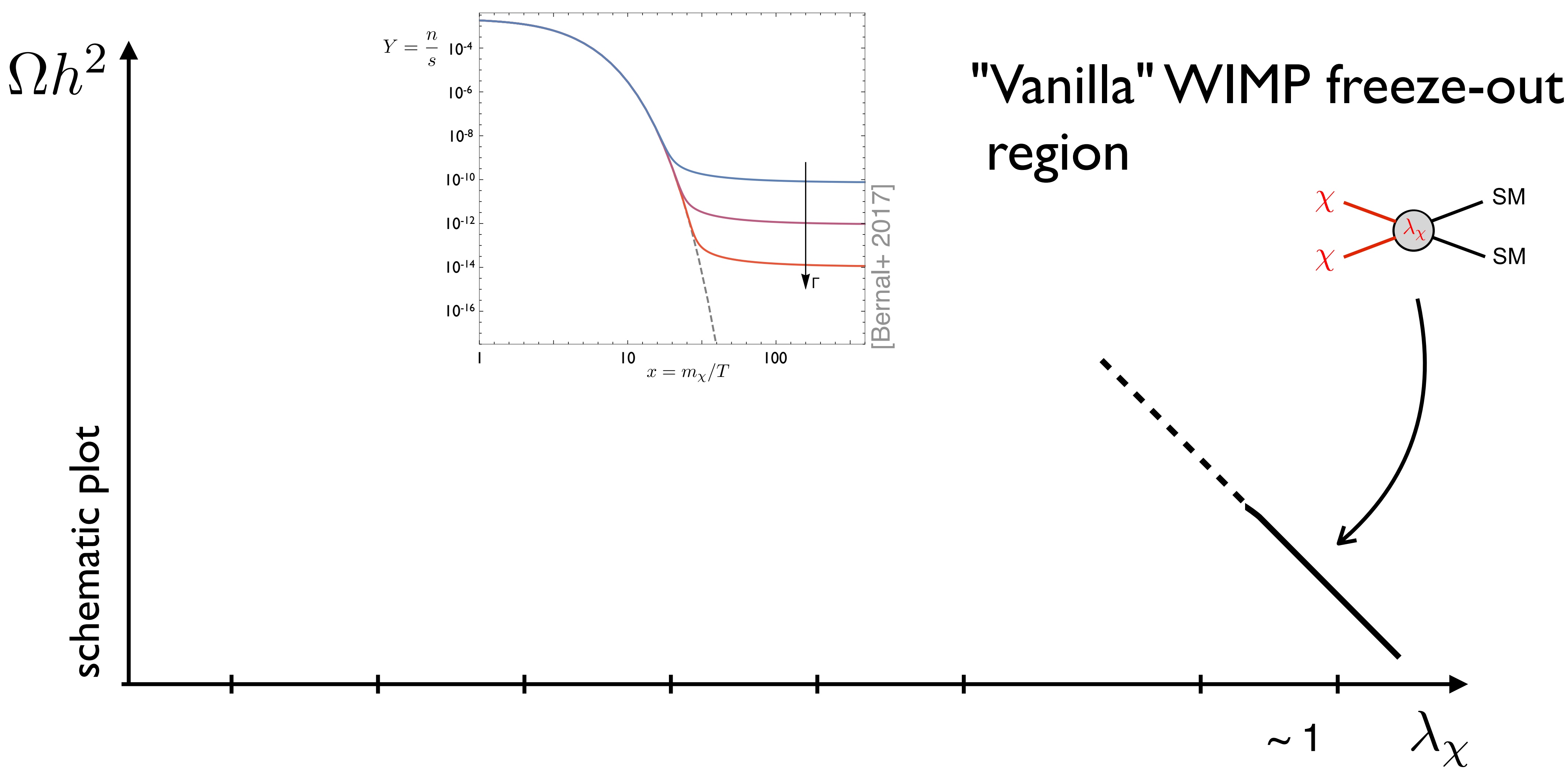
[Arina, Fuks, JH, Krämer, Mantani, Panizzi, Salko, *in preparation*]

Other choices



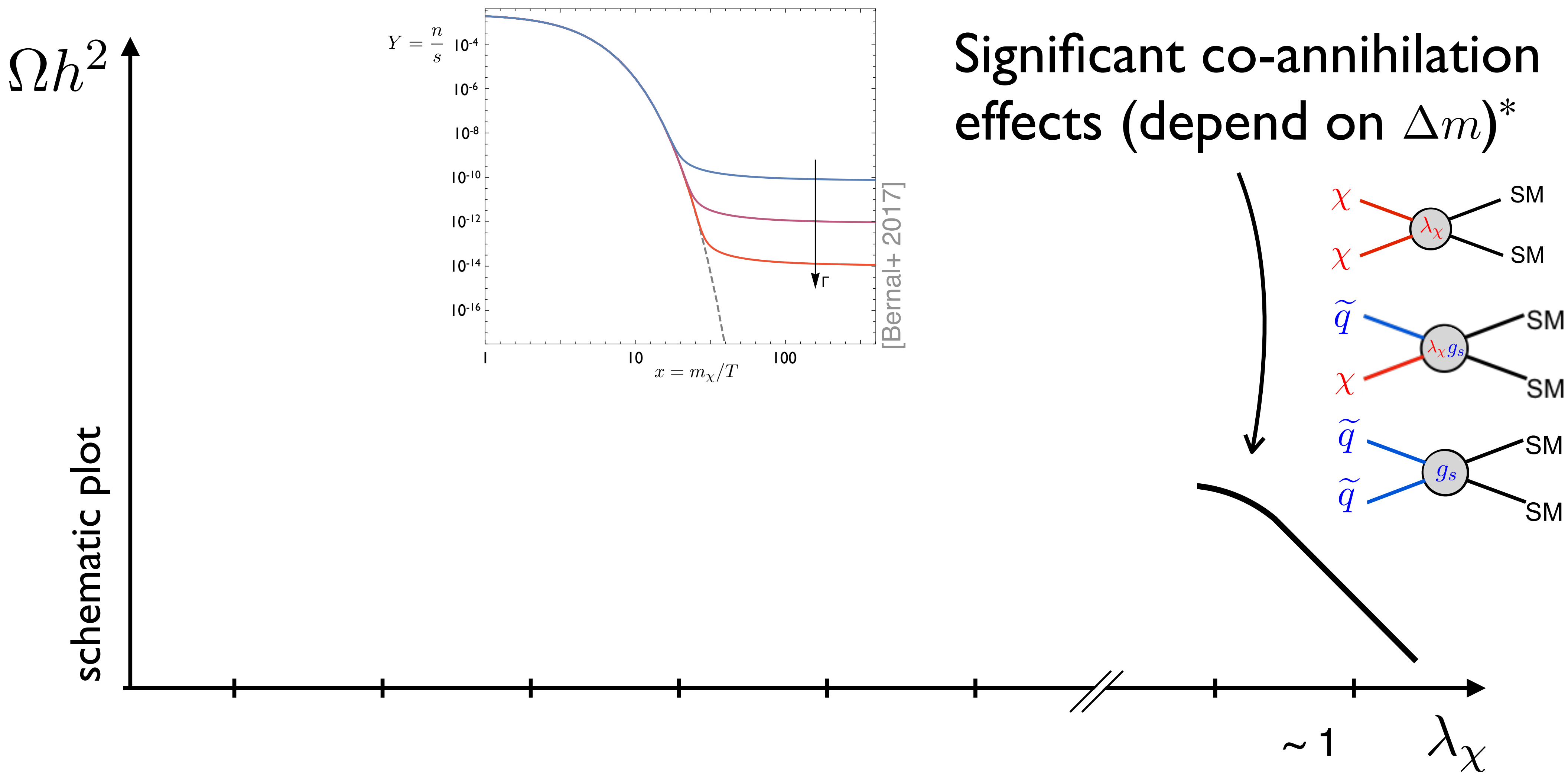
[Arina, Fuks, JH, Krämer, Mantani, Panizzi, Salko, *in preparation*]

How does the relic density work out?



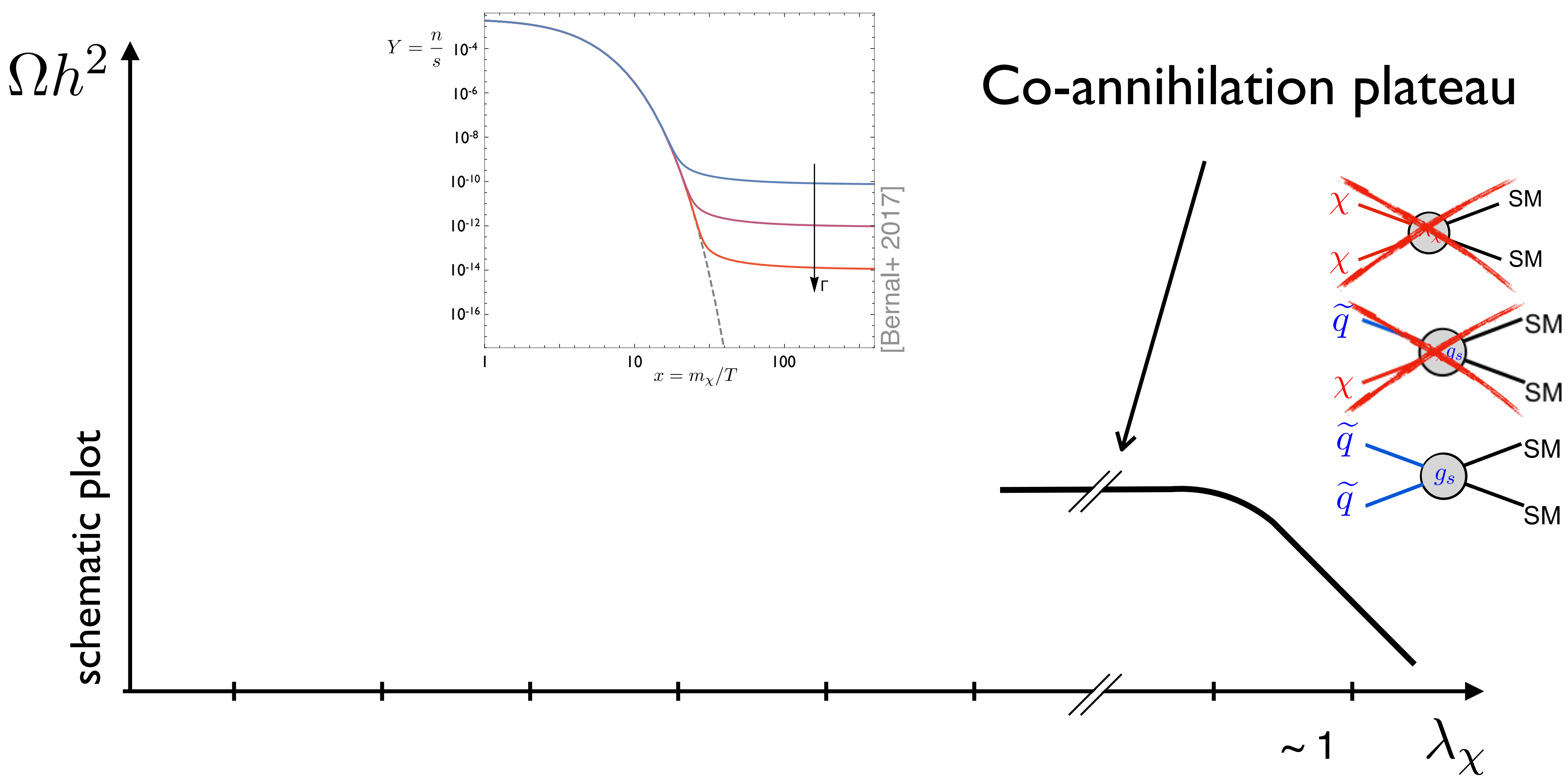
How does the relic density work out?

Significant co-annihilation effects (depend on Δm)*



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

How does the relic density work out?

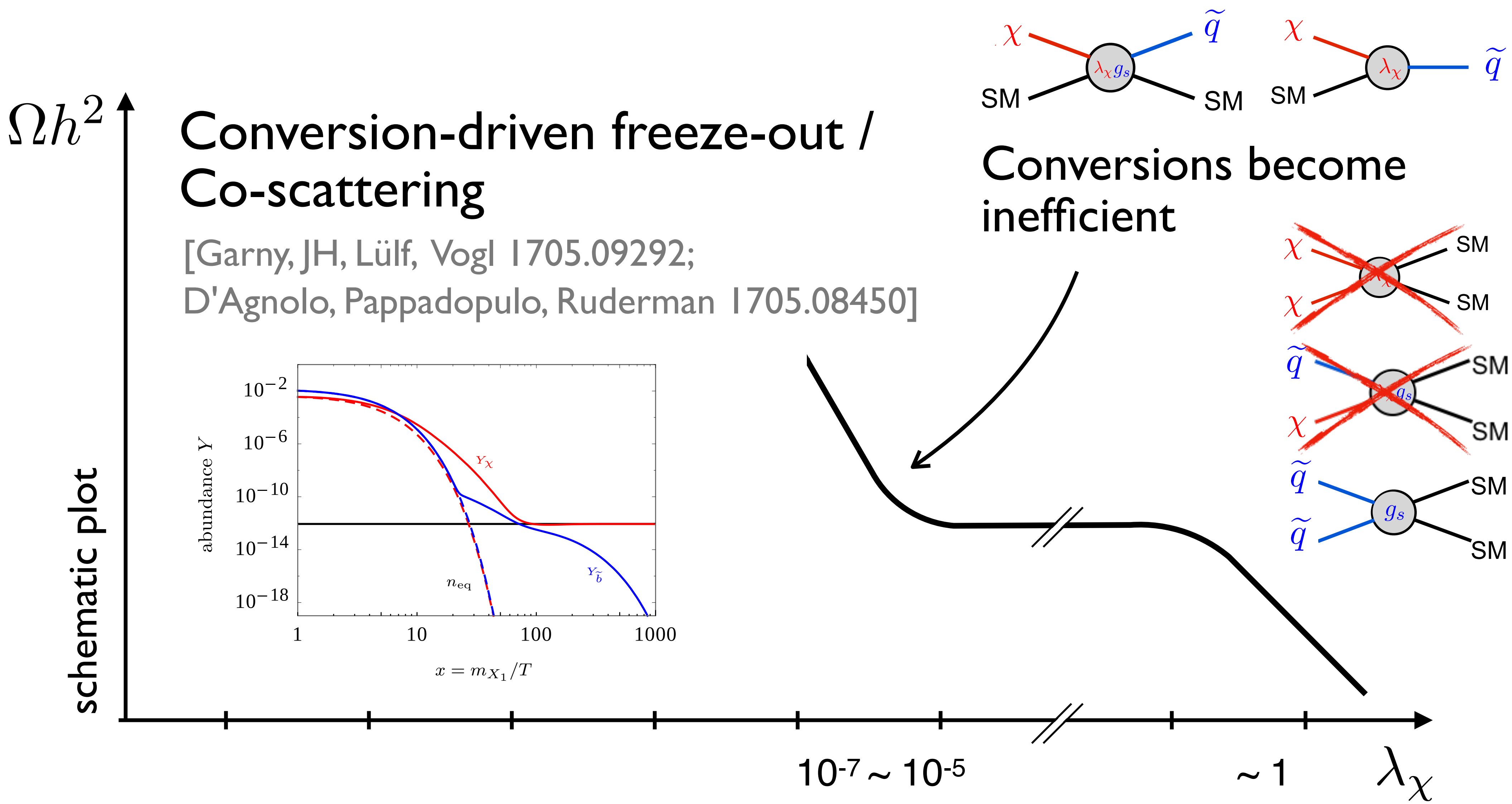


How does the relic density work out?

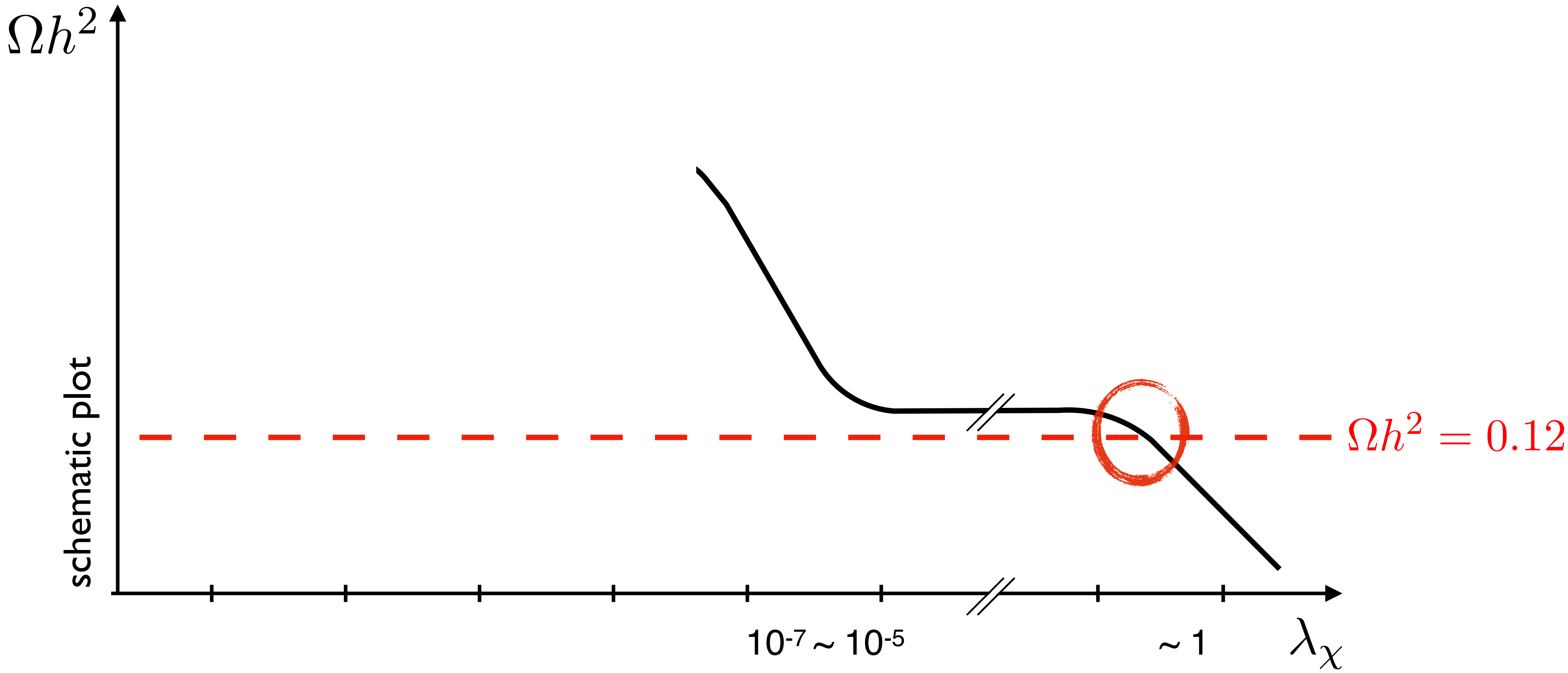
Conversion-driven freeze-out / Co-scattering

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

Conversions become inefficient



How does the relic density work out?



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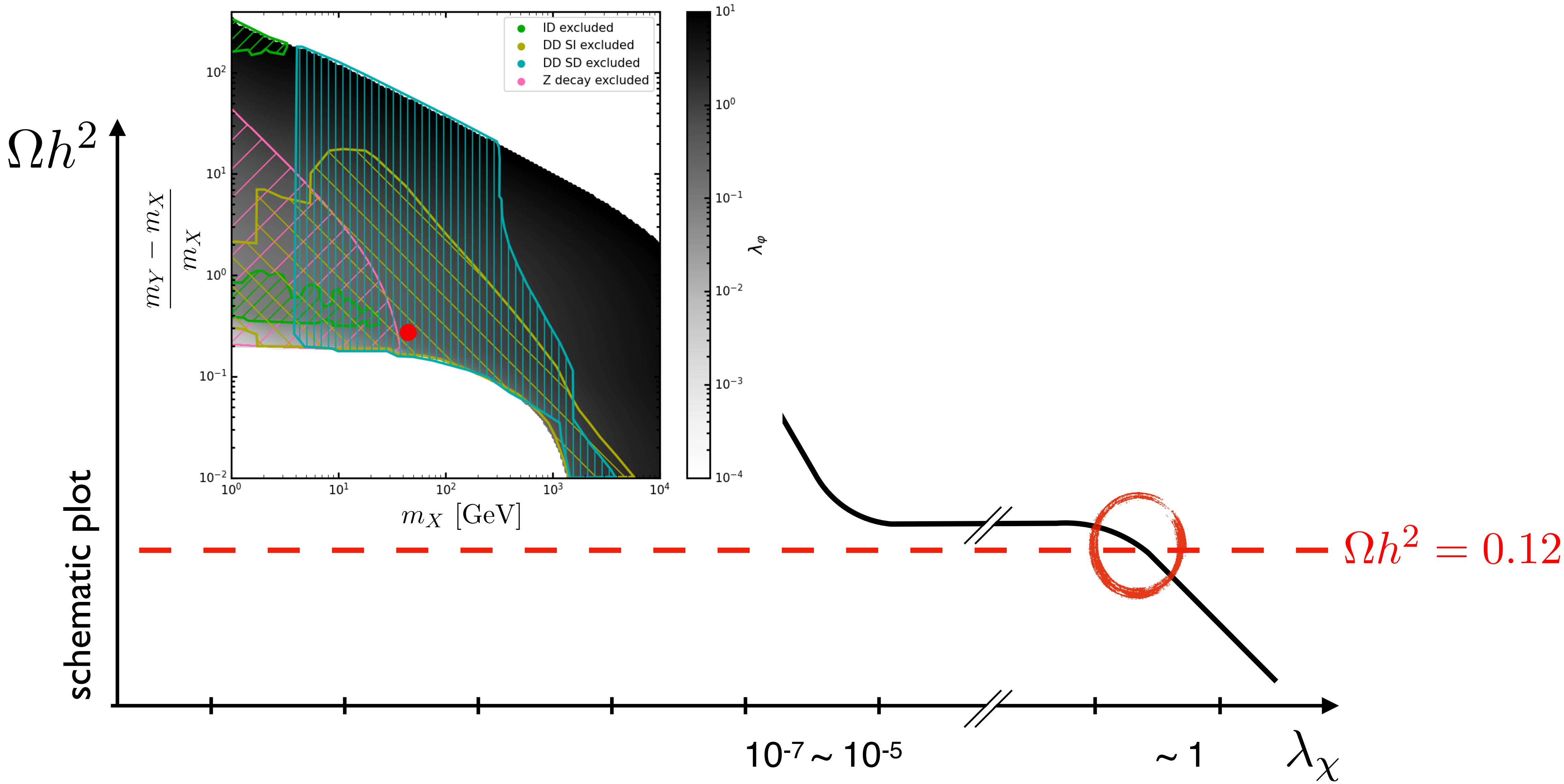

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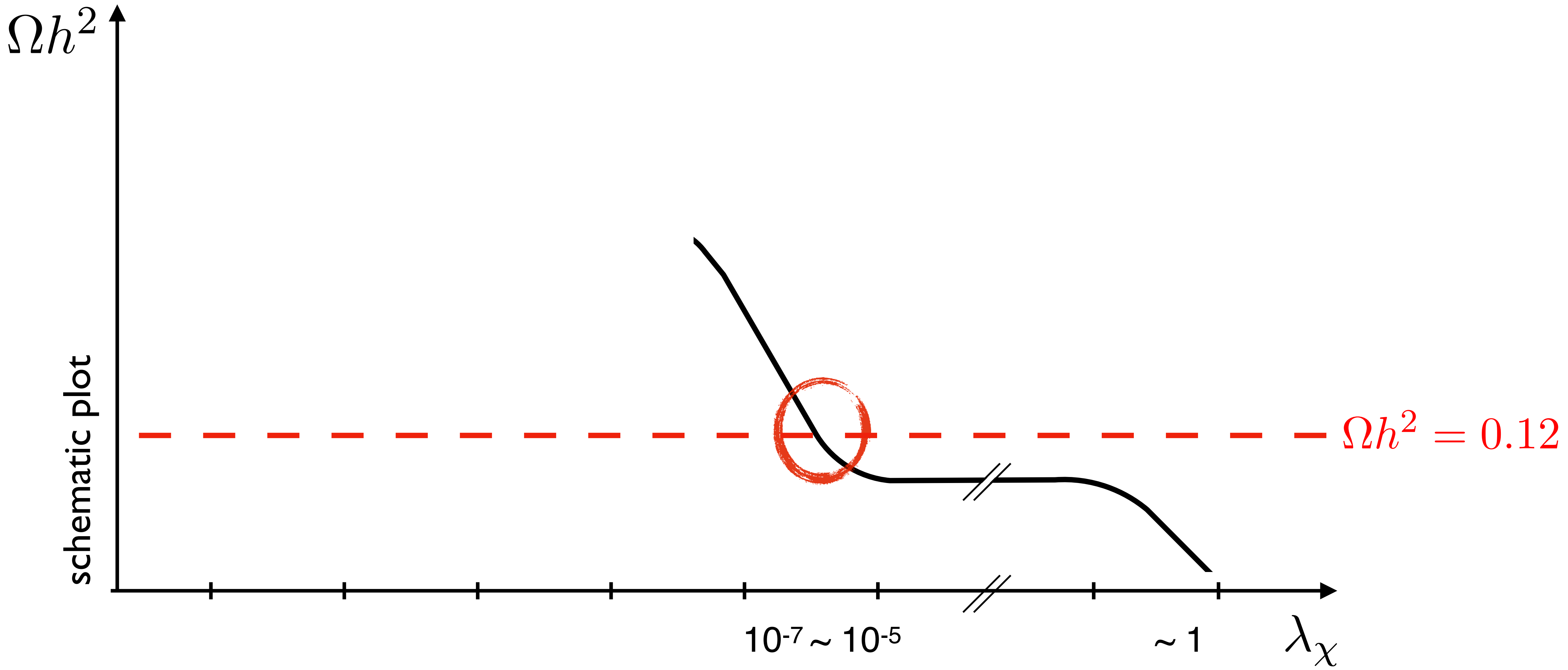

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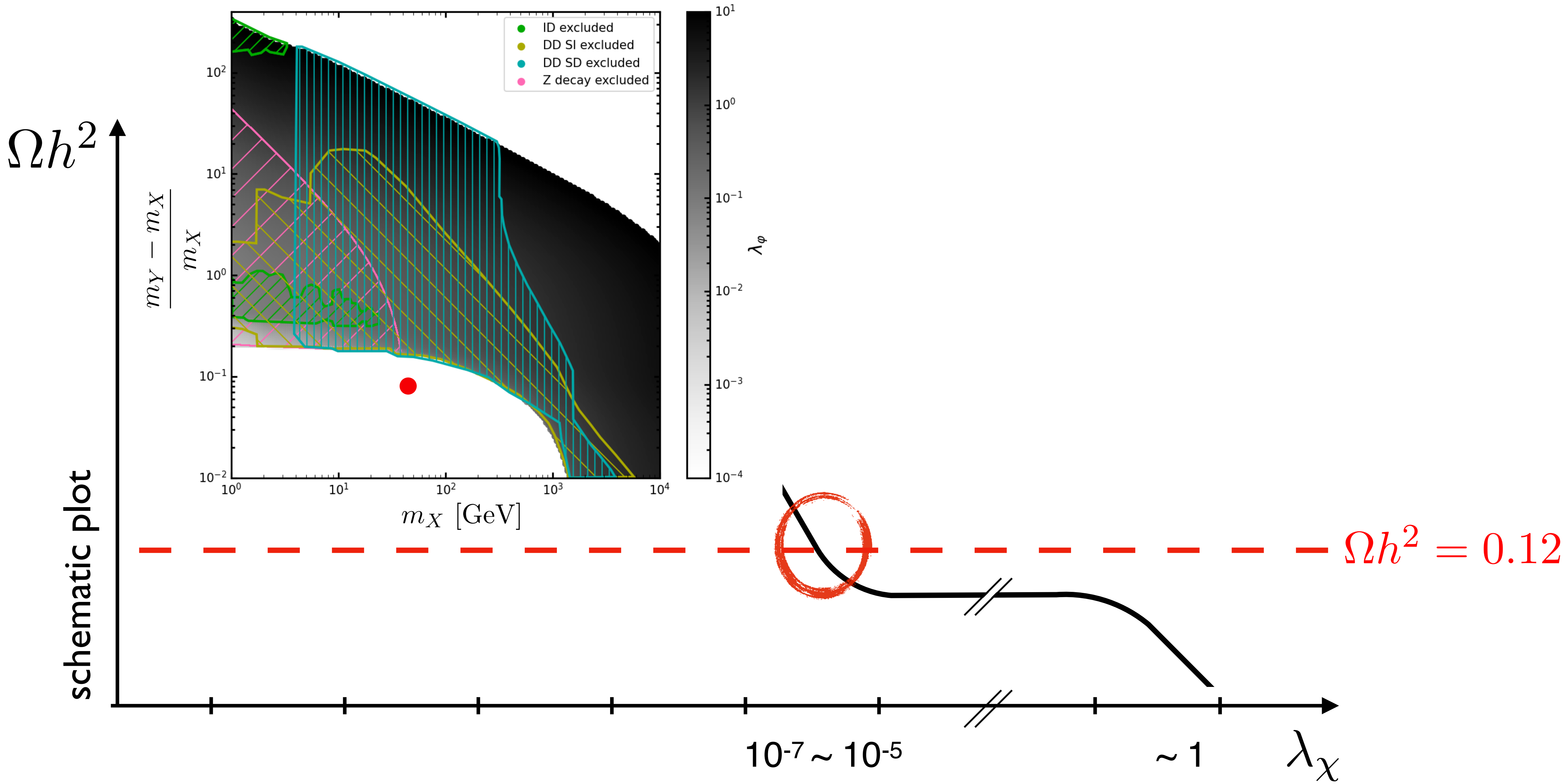

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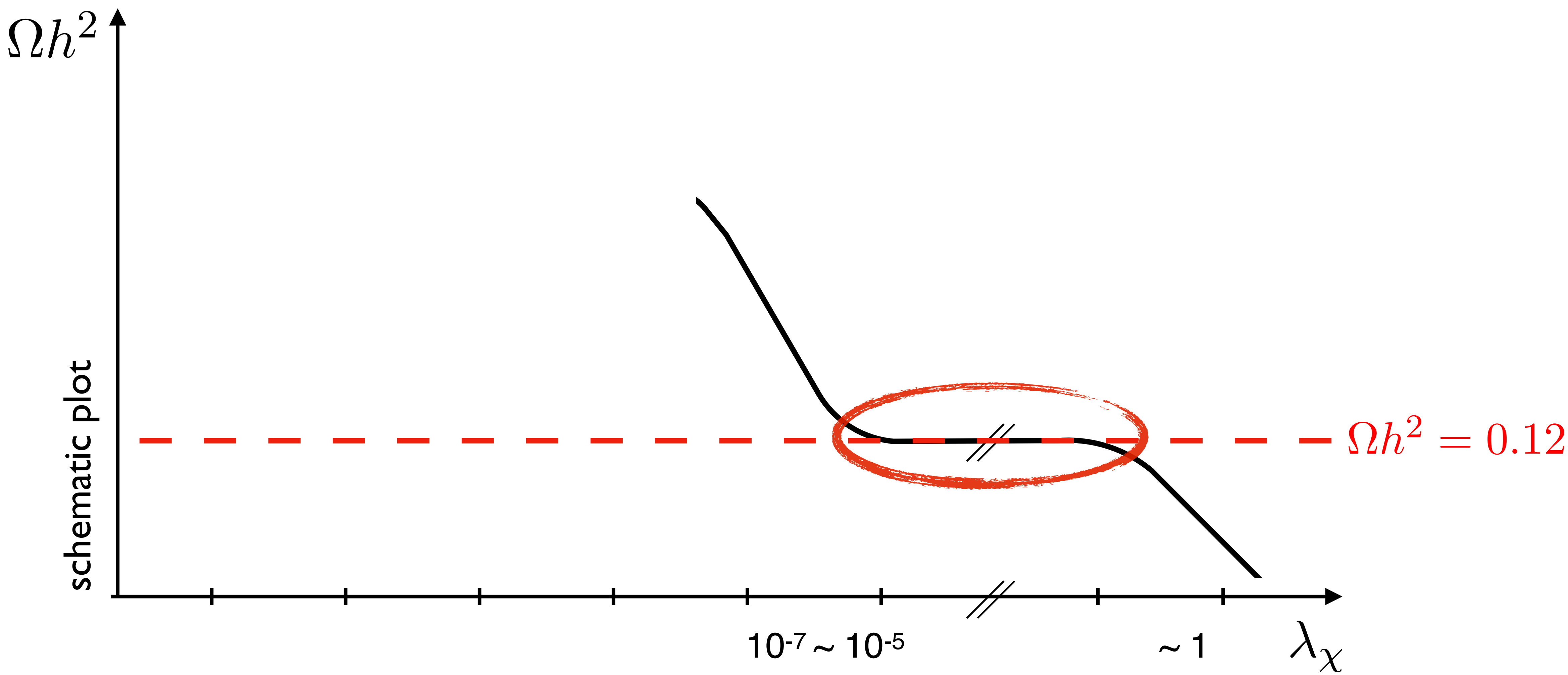

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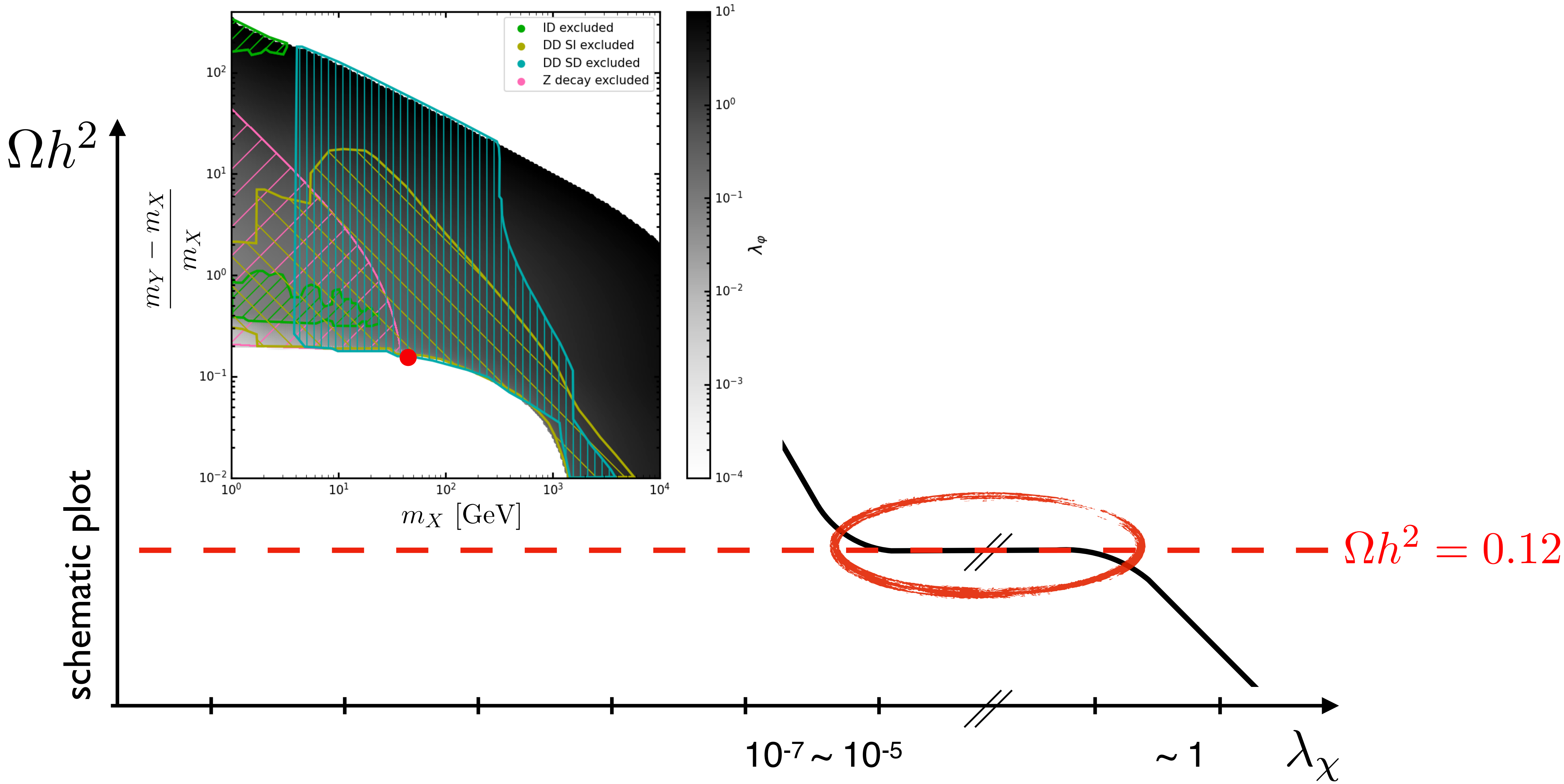


Generic signature?

Conversion rate on the edge of being efficient:

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

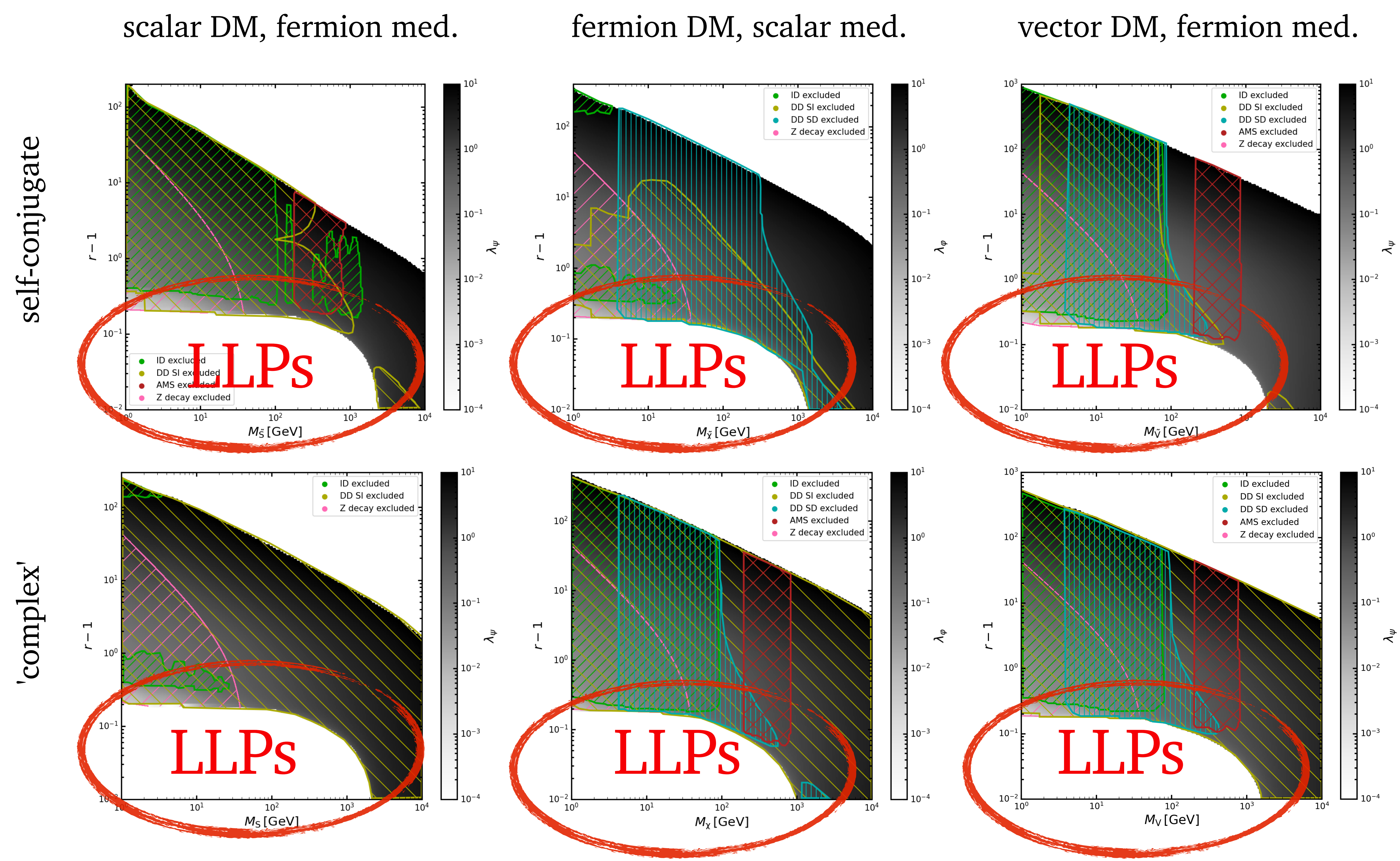
$$\Rightarrow \; \Gamma_{\rm dec} \lesssim H$$

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

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

$\Rightarrow$ Long-lived particles (LLPs) at LHC!

Other choices



Progress in relic density computation

arXiv:2112.01499

Bound-state effects on dark matter coannihilation: Pushing the boundaries of conversion-driven freeze-out

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Jan Heisig
Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, Sommerfeldstraße 16, D-52056 Aachen, Germany and Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université catholique de Louvain, Chemin du Cyclotron 2, B-1348 Louvain-la-Neuve, Belgium

Bound-state formation can have a large impact on the dynamics of dark matter freeze-out in the early Universe, in particular for colored coannihilators. We present a general formalism to include an arbitrary number of excited bound states in terms of an effective annihilation cross section, taking bound-state formation, decay and transitions into account, and derive analytic approximations in the limiting cases of no or efficient

arXiv:2203.04326

Impact of Sommerfeld Effect and Bound State Formation in Simplified t-Channel Dark Matter Models

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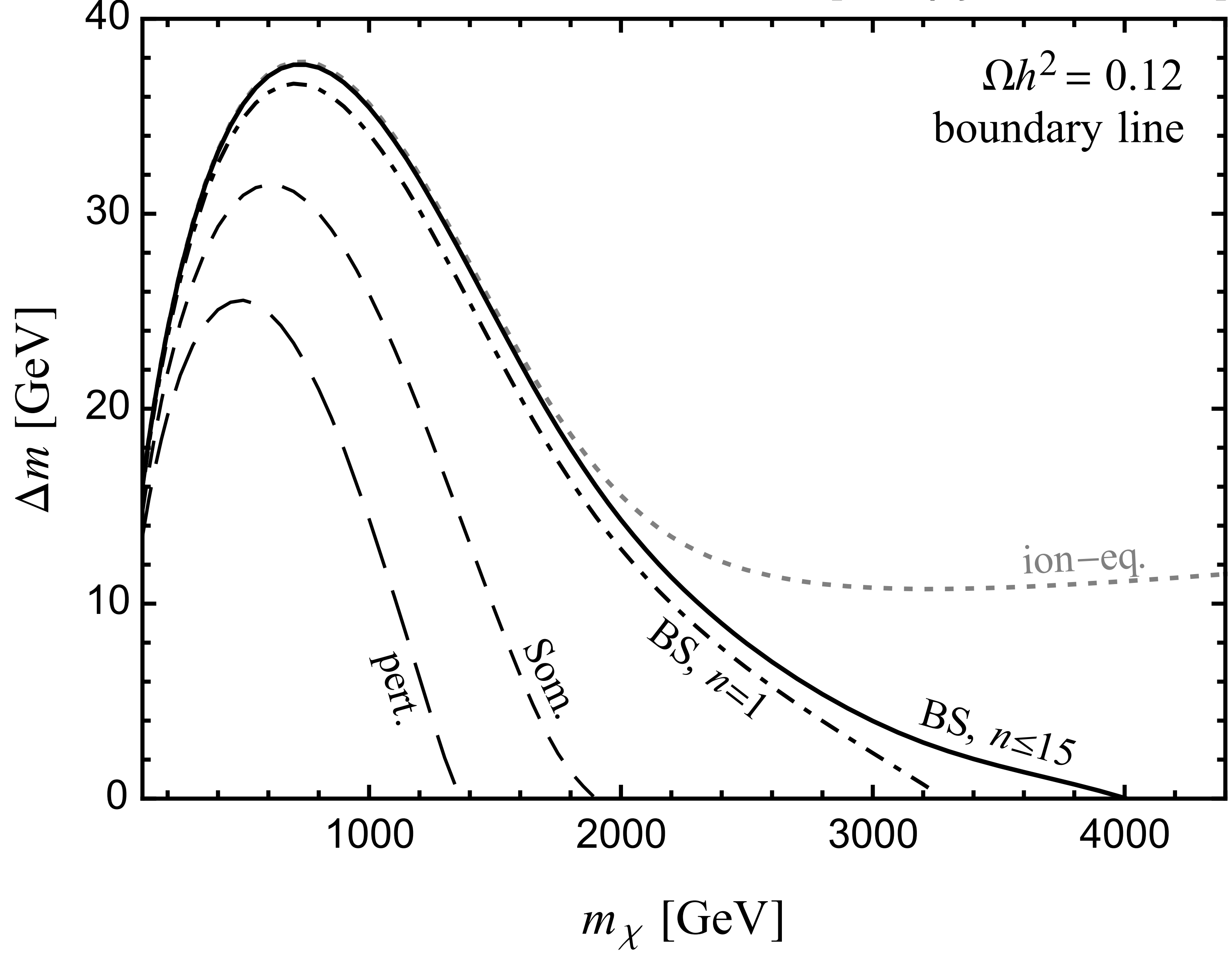
[2]Department of Physics and Astronomy, 567 Wilson Road, East Lansing, Michigan-48824, USA
[3]Department of Physics and Astronomy, 9500 Gilman Drive, University of California, San Diego, USA
[4]ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Adelaide, South Australia 5005, Australia

Boundary between WIMP region and conversion-driven region

[Garny, JH 2112.01499]



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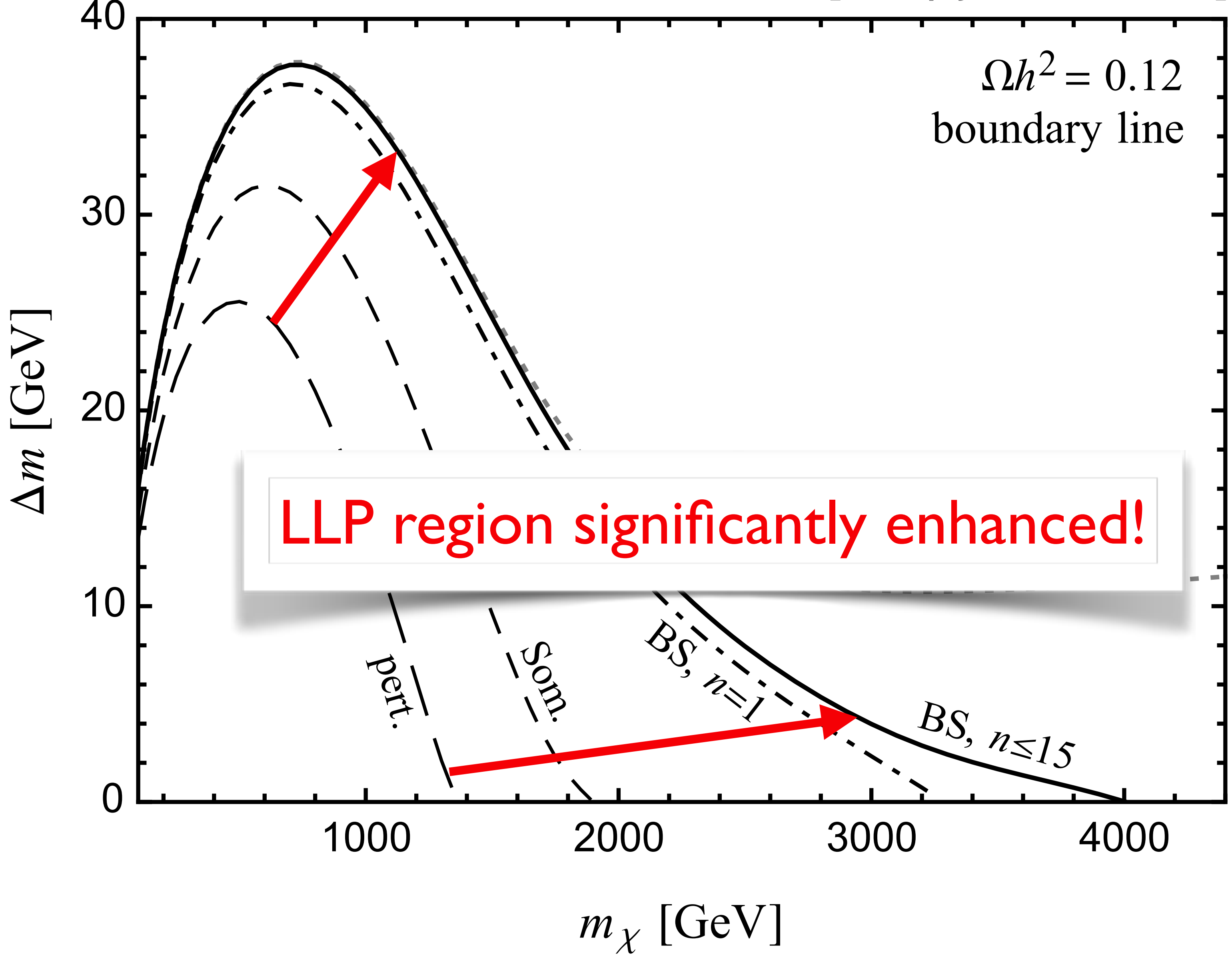
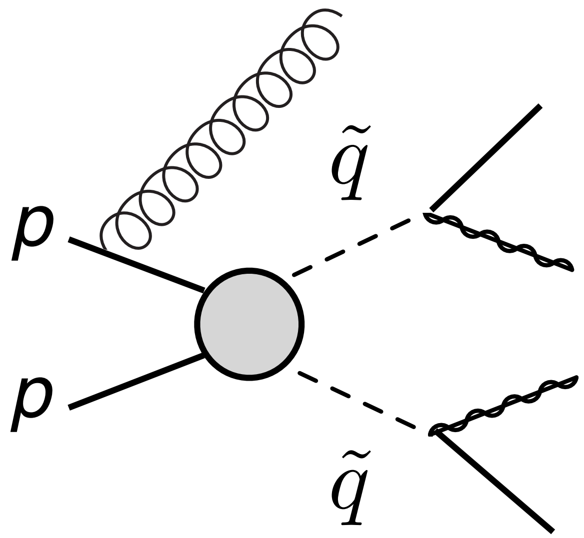
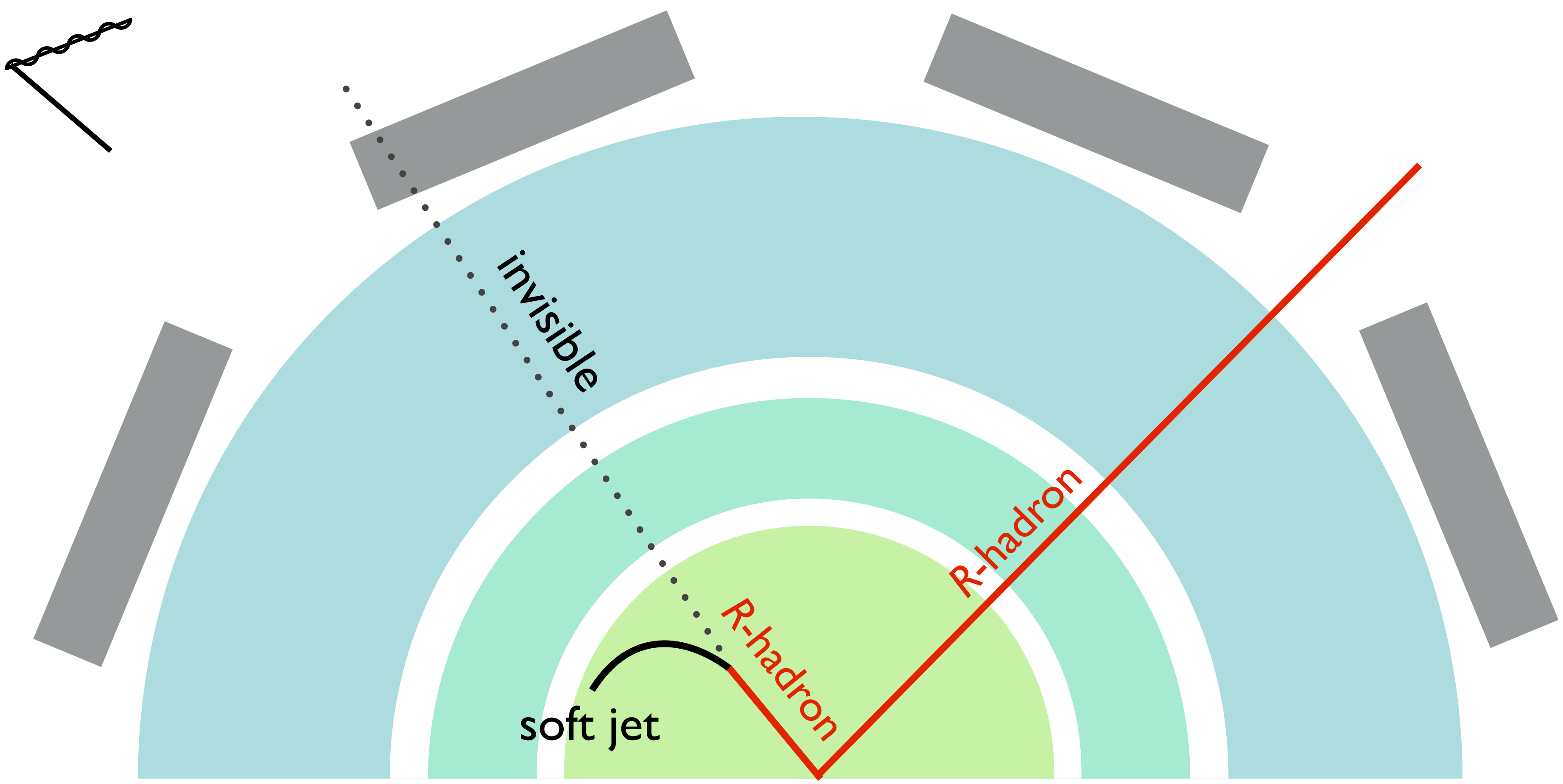
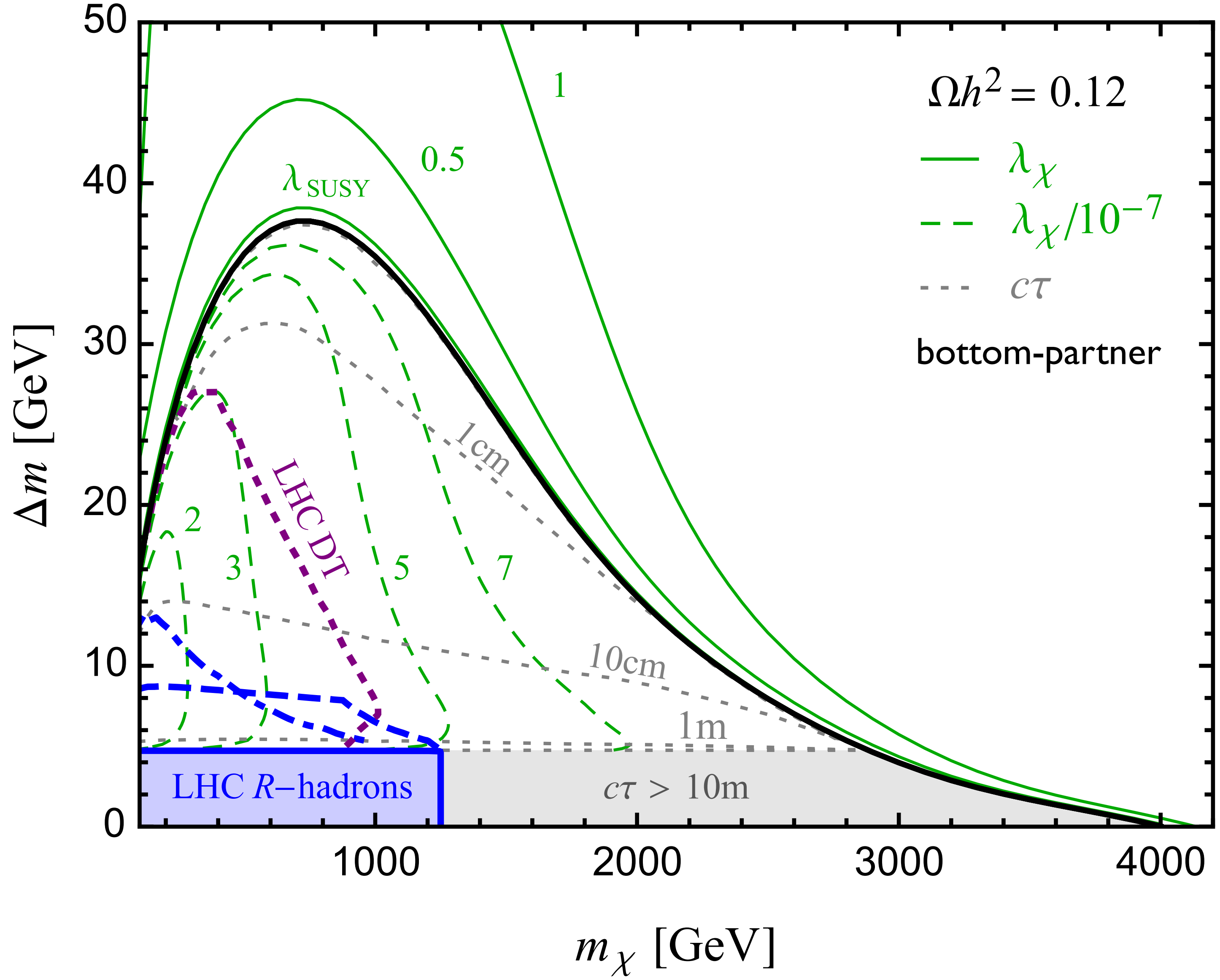


Long-lived particles at LHC





Current LLP constraints

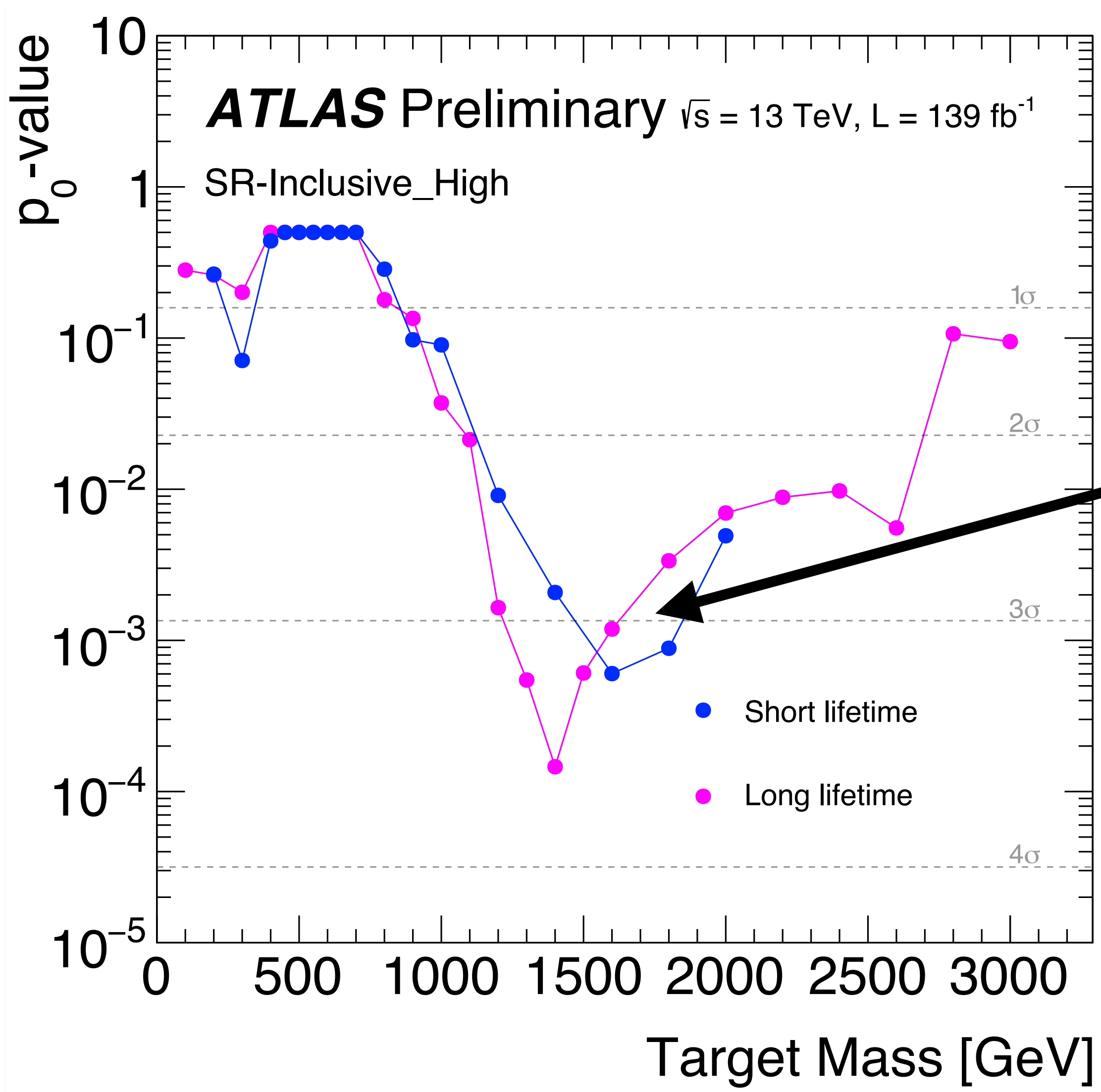


LHC – R-hadrons: ATLAS [1902.01636, 1808.04095 approximate reinterpretation];
CMS [CMS-PAS-EXO-16-036, recasting from 1705.09292]

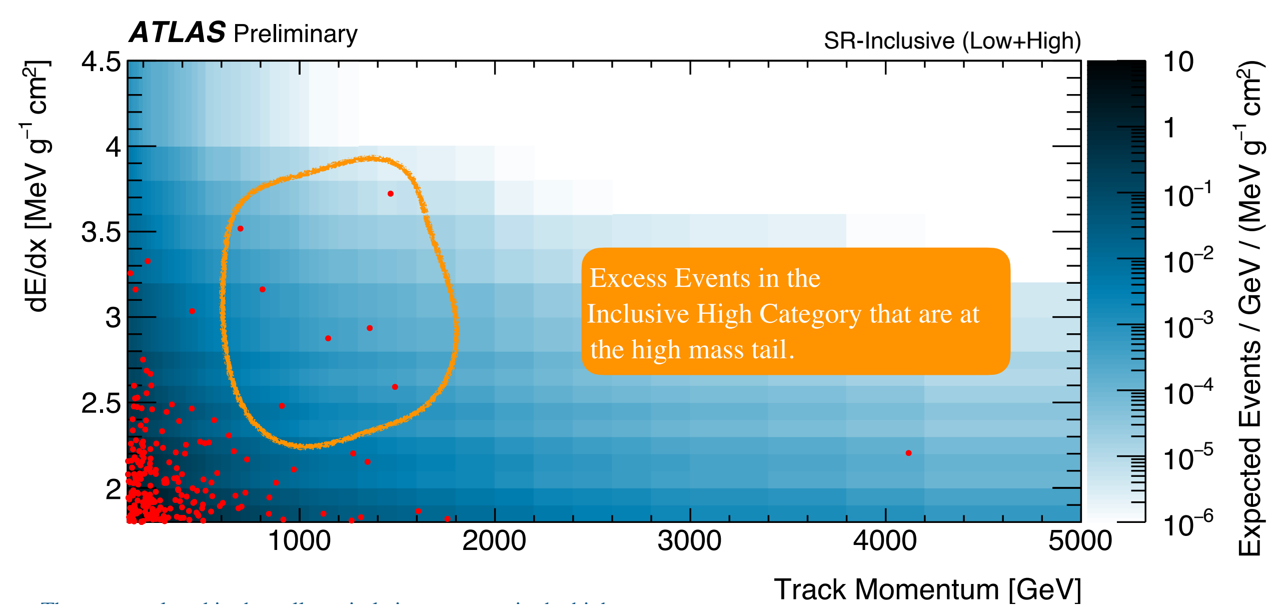
LHC – DT: ATLAS Disappearing-track search [1712.02118, recasting from 2002.12220, 7]

Recent excess in LLP searches

[ATLAS, Talk at Moriond 2022]

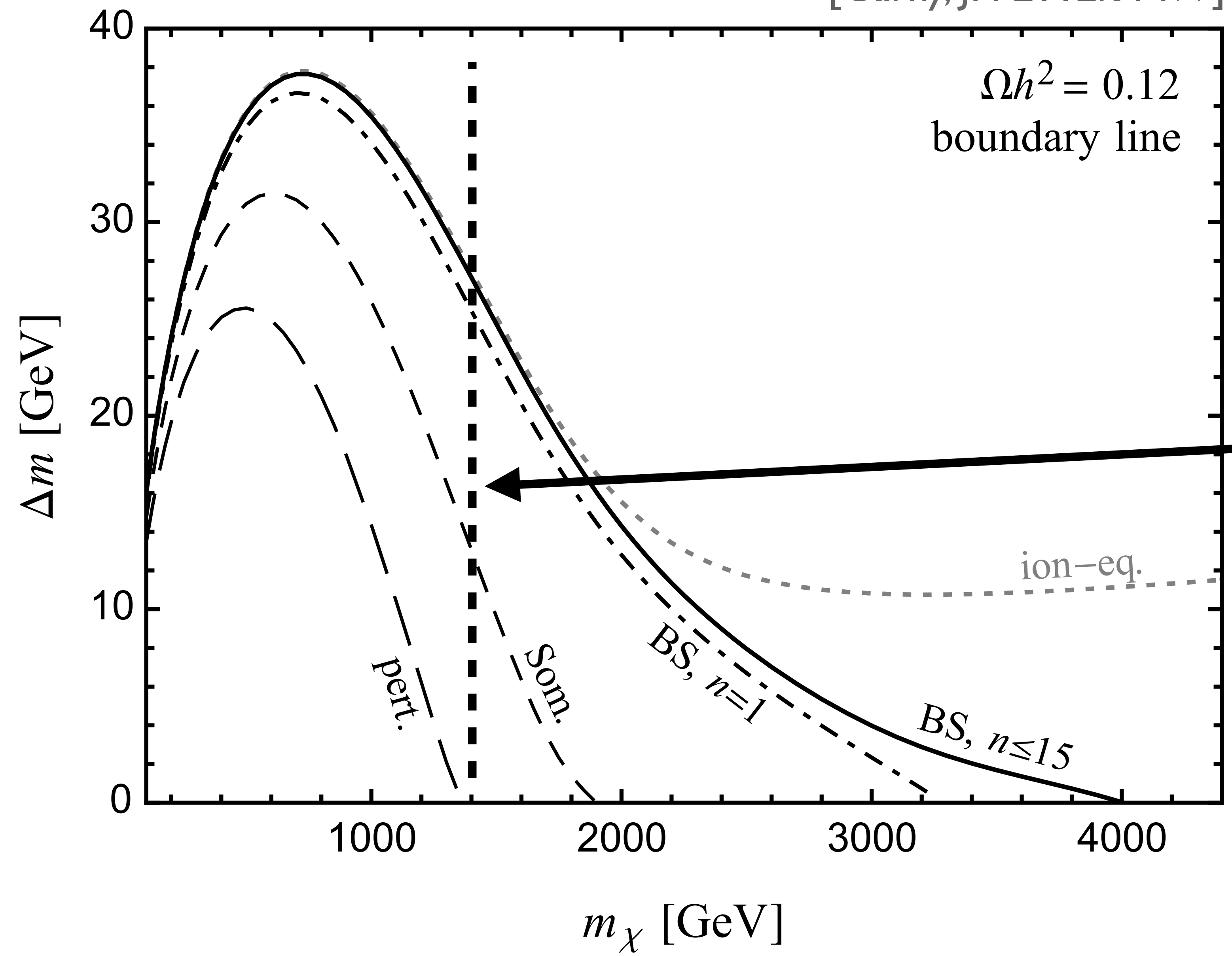


Heavy stable charge particle with mass ~1.4 TeV



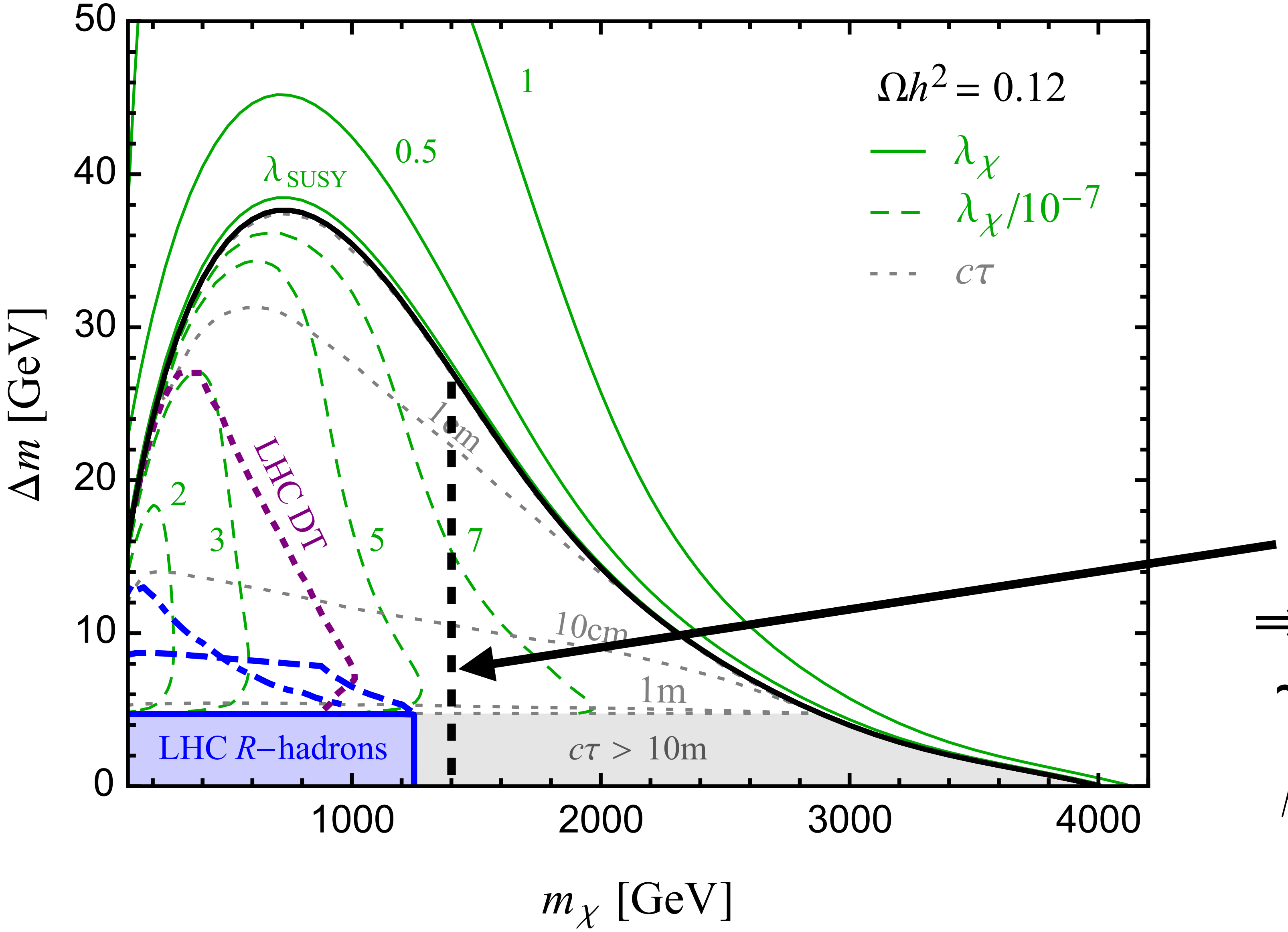
Boundary between WIMP region and conversion-driven region

[Garny, JH 2112.01499]



~1.4 TeV

Current LLP constraints



~1.4 TeV

⇒ xs ~ 0.4 fb

~ 50 events

$\beta > 0.9$??

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: WIMP parameter space almost excluded
- Remaining region: Conversion-driven freeze-out less explored terrain
- Long-lived particles main signature
  $H \sim \Gamma$: Lifetimes naturally O(1-100cm)
- Freeze-out revisited: Bound states very relevant, higher excitation important at low energies
- LLP parameter space significantly enlarged
- Kinematics differs from targets of current searches