Bound state effects in dark matter genesis: pushing the boundaries of higher excitations

based on 2112.01499 and 2308.01336
in collaboration with T. Binder, M. Garny, S. Lederer, K. Urban

Jan Heisig (RWTH/UVA)

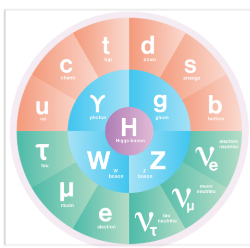
IFJ Seminar, Kraków, Poland
October 19, 2023

Outline

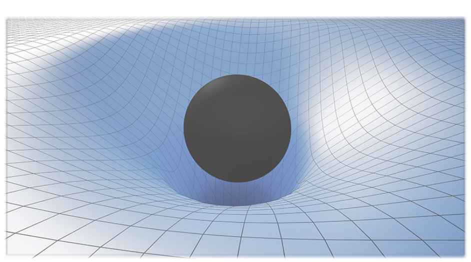
- Introduction to particle dark matter
- Effects of (excited) bound state
- Implications for *t*-channel mediator models
- Implications for LHC searches

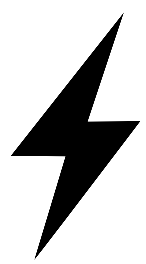
The phenomenon of Dark Matter

- More matter: gravitational effect on dynamics of visible matter
- Present on very different length scales

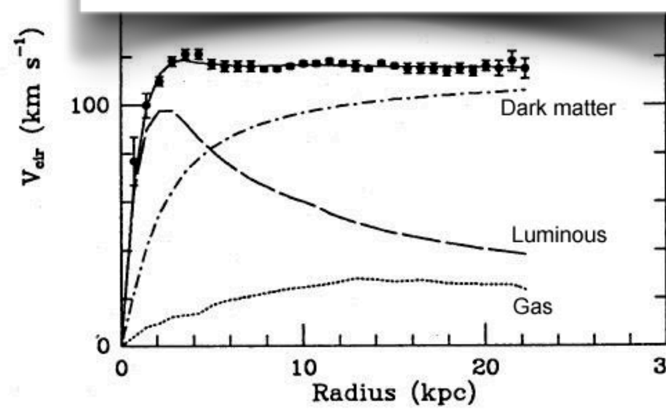


Standard model
+
general relativity

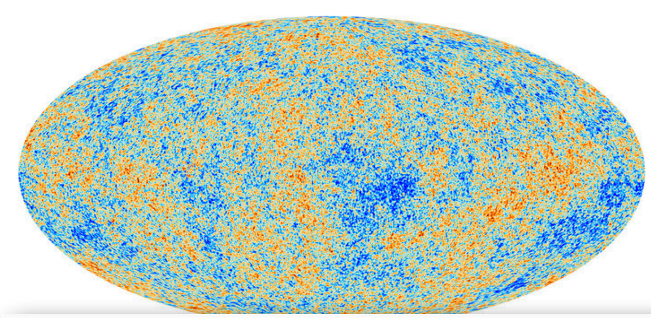




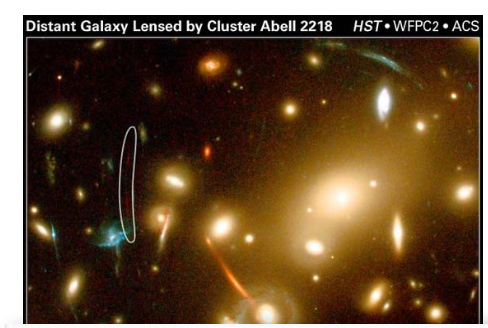
rotation curves



bullet cluster



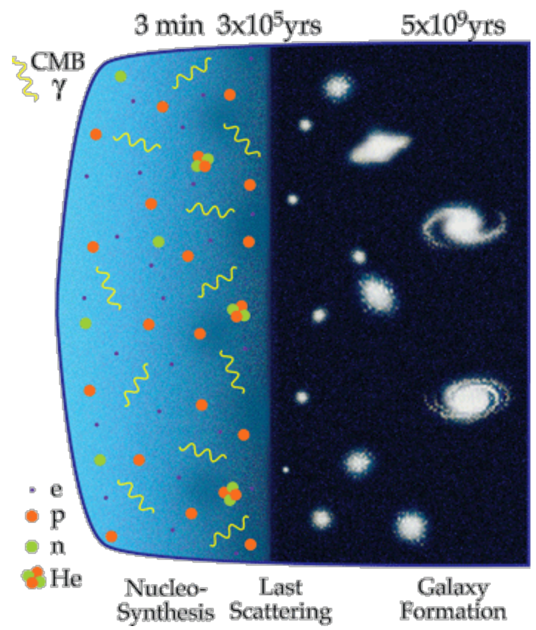
CMB anisotropies

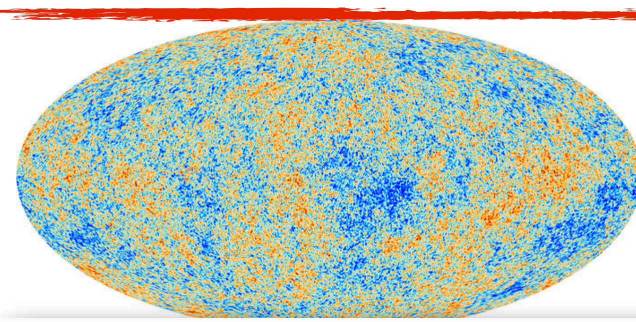


grav. lensing

The phenomenon of Dark Matter

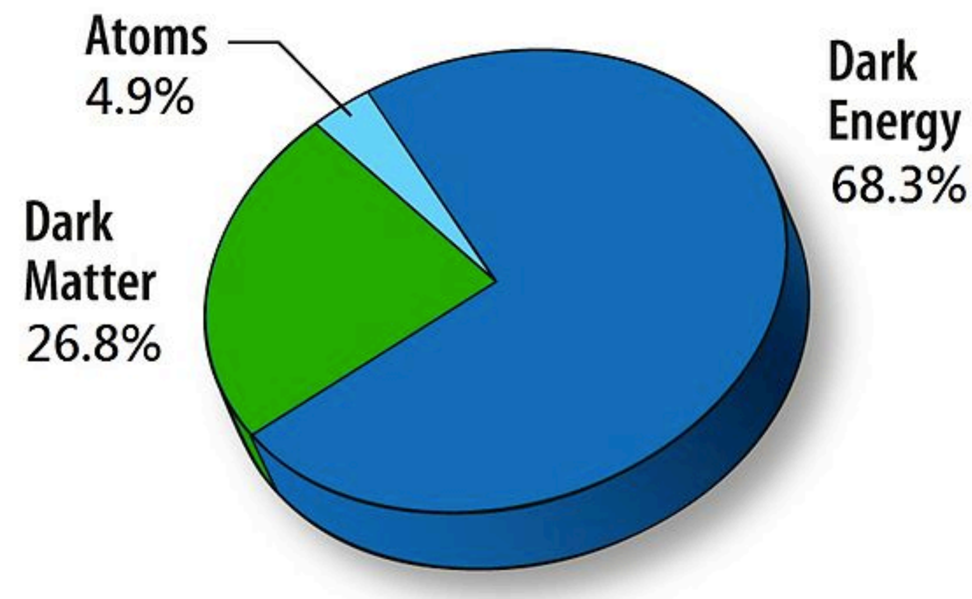
- More matter: gravitational effect on dynamics of visible matter





CMB anisotropies

Contributions Ω_i to the energy density of the Universe today:



TODAY

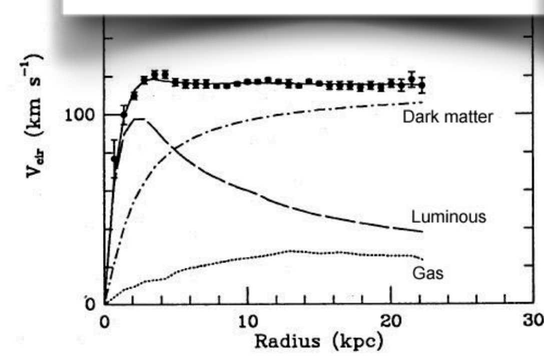
[Planck 2020]

$$\Omega_{\rm DM} h^2 = 0.12 \pm 0.001$$

Particle Dark Matter χ

Explain appearance on all scales:
Most plausible → new particle

rotation curves



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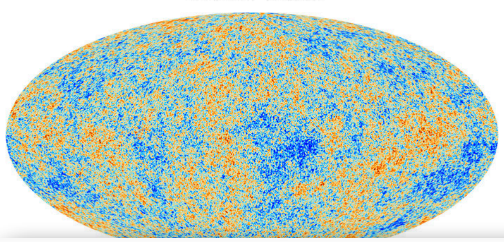

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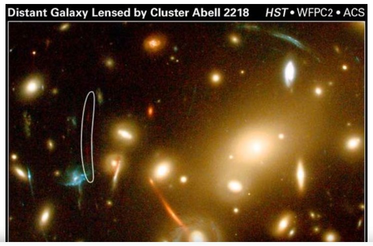
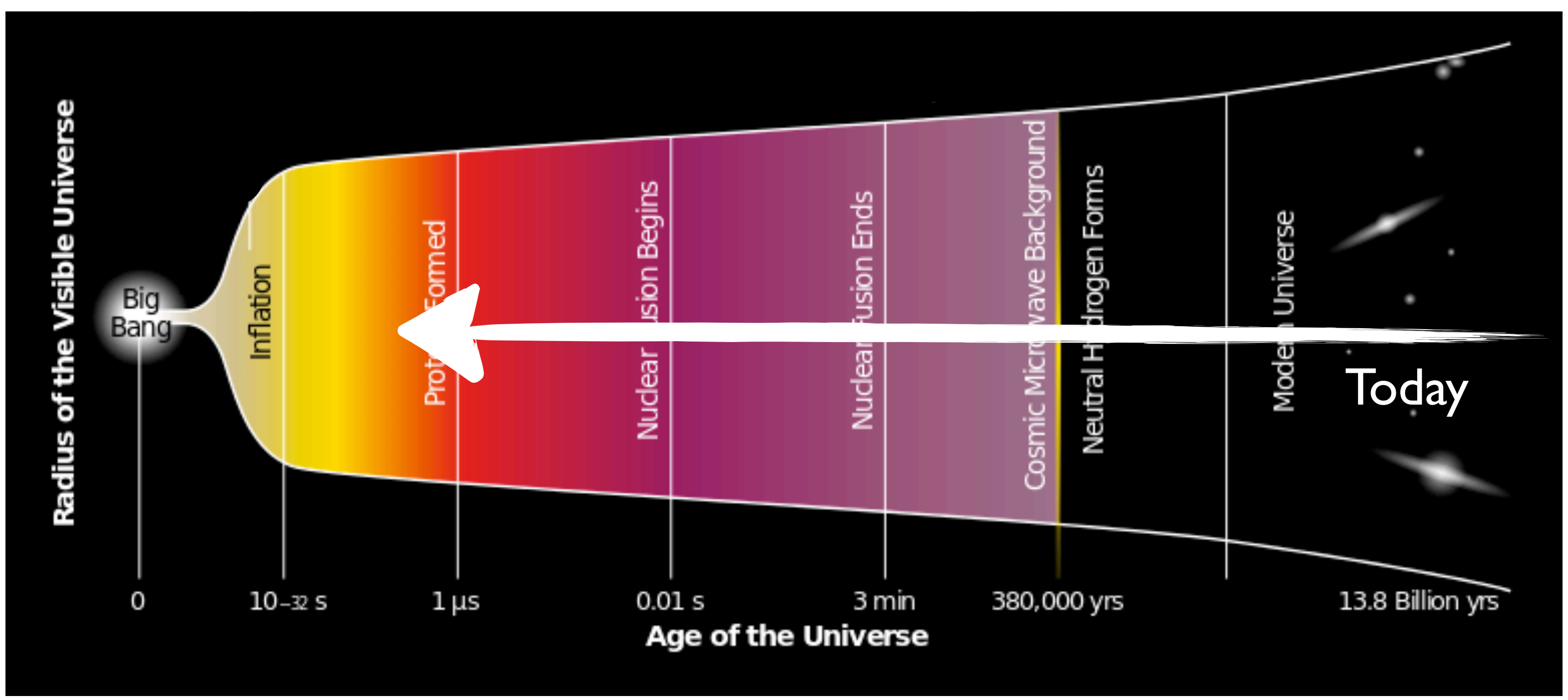


grav. lensing

Particle dark matter: a thermal relic

- Relic from thermal abundance
- Consider cosmological history of Universe:

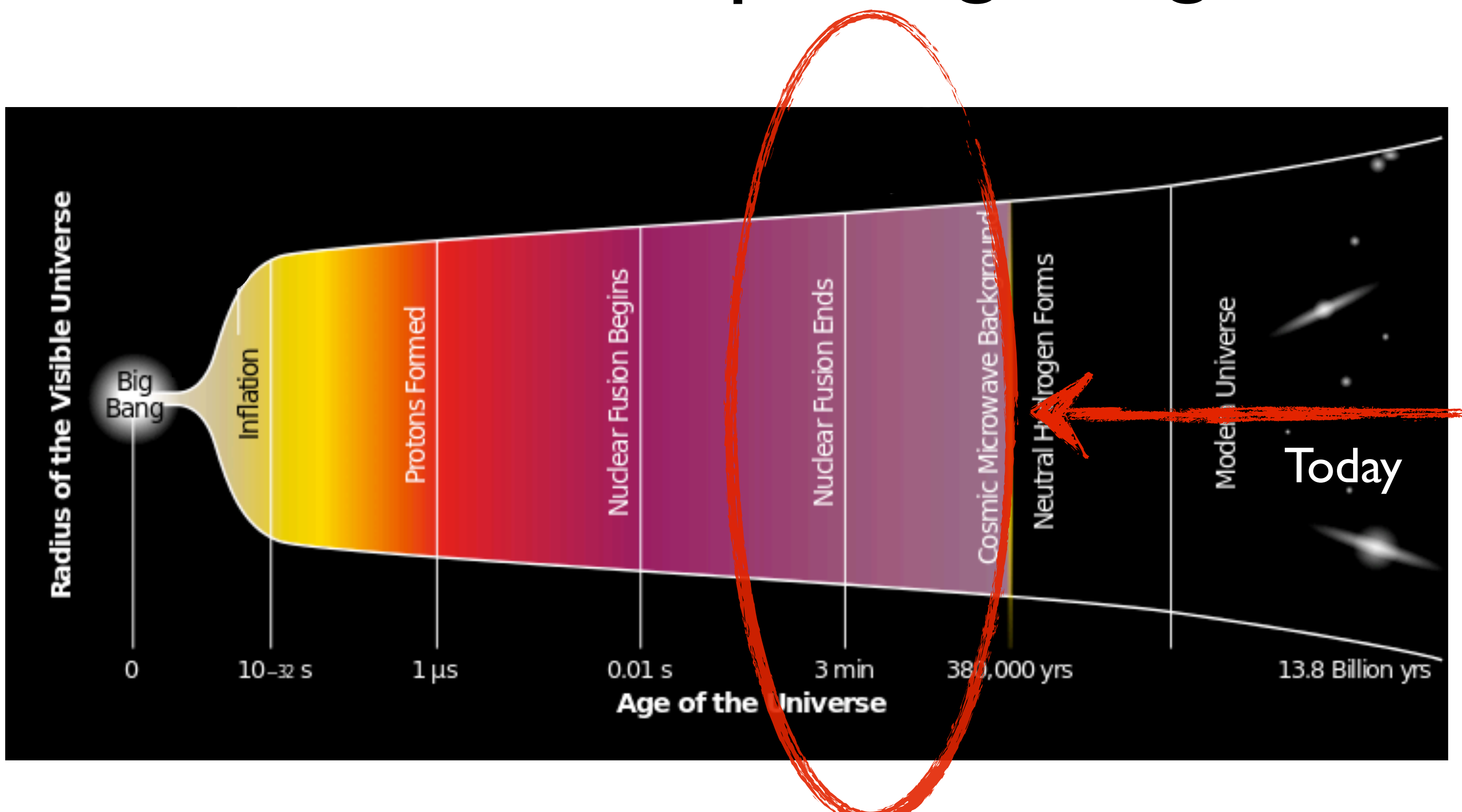


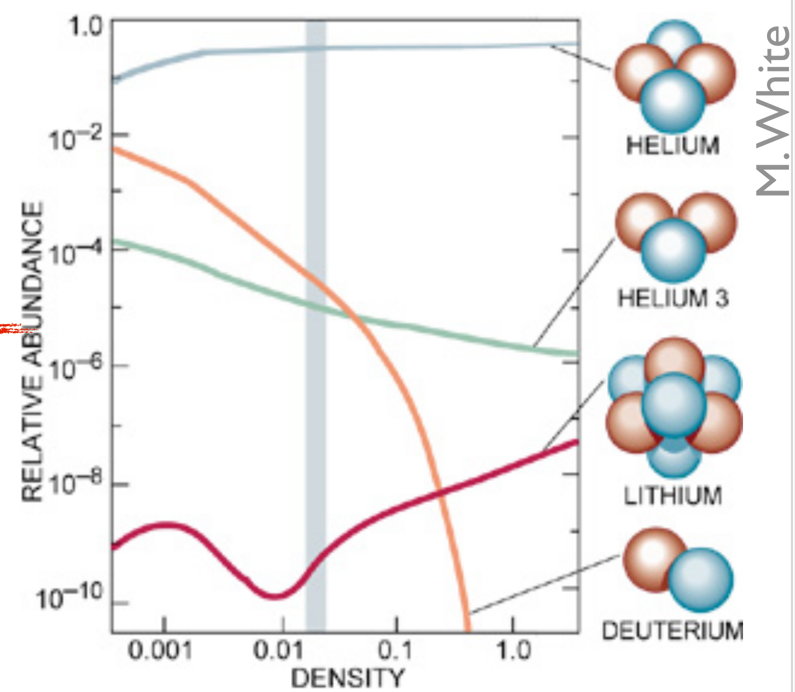
Particle physics +cosmology: Extrapolate to early hot Universe
⇒ Boltzmann Eqs.

Expansion with Hubble rate *H*

Particle dark matter: a thermal relic

- Successful example: Big Bang Nucleosynthesis





→ Explains primordial abundances of light elements

Particle dark matter: a thermal relic

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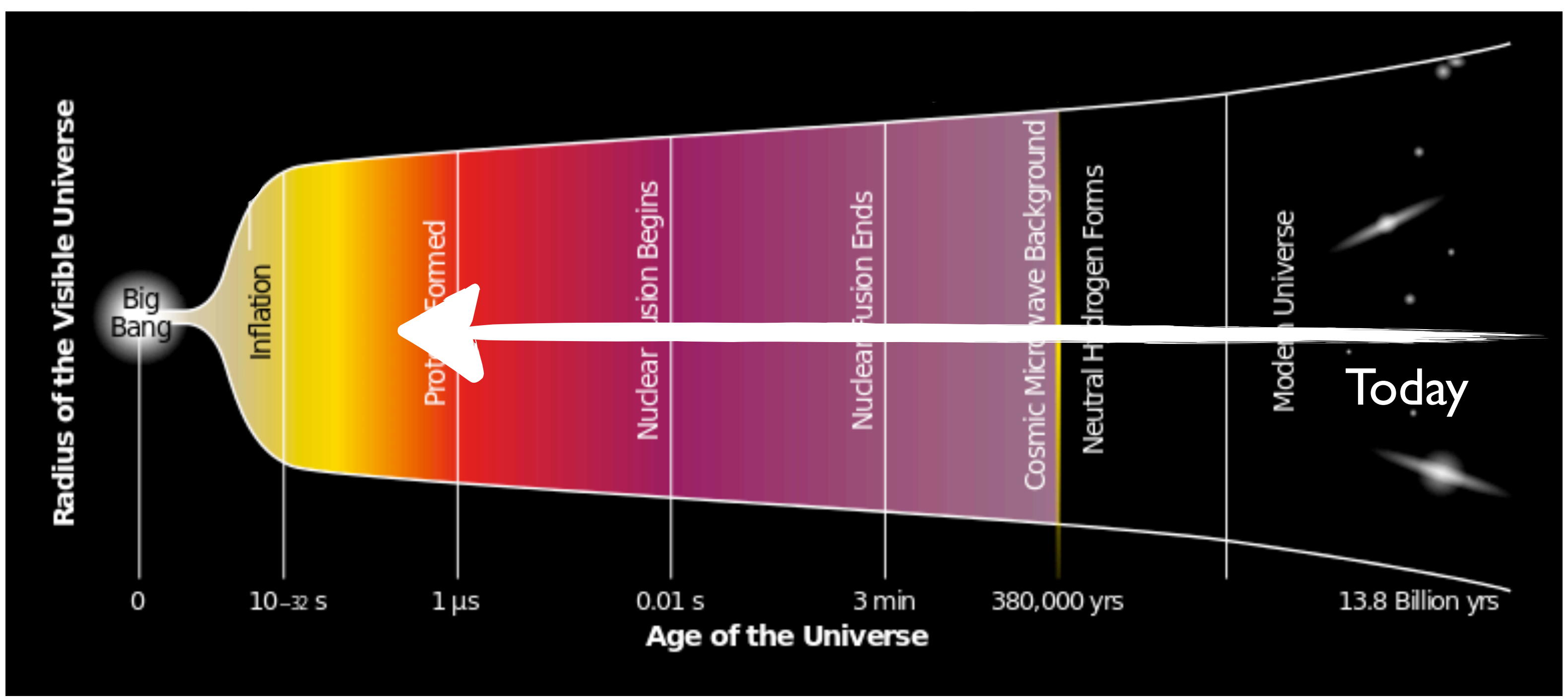

Particle physics
+cosmology:
Extrapolate to early
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Expansion with Hubble rate *H*

Boltzmann equations for particle densities

[Zel'dovich, Okun, Pikel'ner1966; 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]

$$\underbrace{E_\chi \left(\partial_t - H p\, \partial_p\right)}_{\text{Relativistic Liouville operator for homogeneous, isotropic Universe}} f_\chi(p,t) = \underbrace{C\left[f_\chi\right]}_{\text{Collision operator}}$$

Relativistic Liouville operator for homogeneous, isotropic Universe

Collision operator

Cosmology

Particle Physics

$$H \; \substack{<\\ \sim \\ >} \; \Gamma$$

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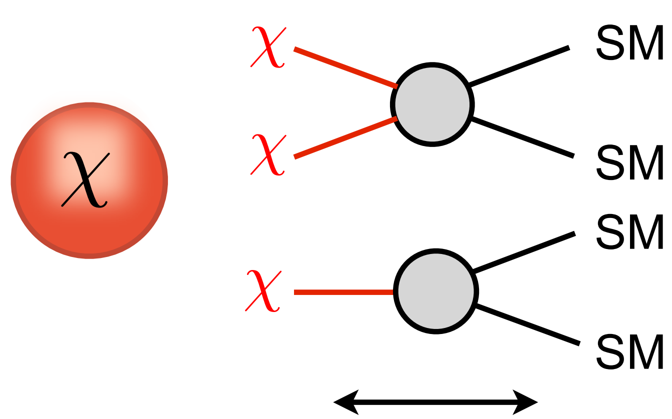

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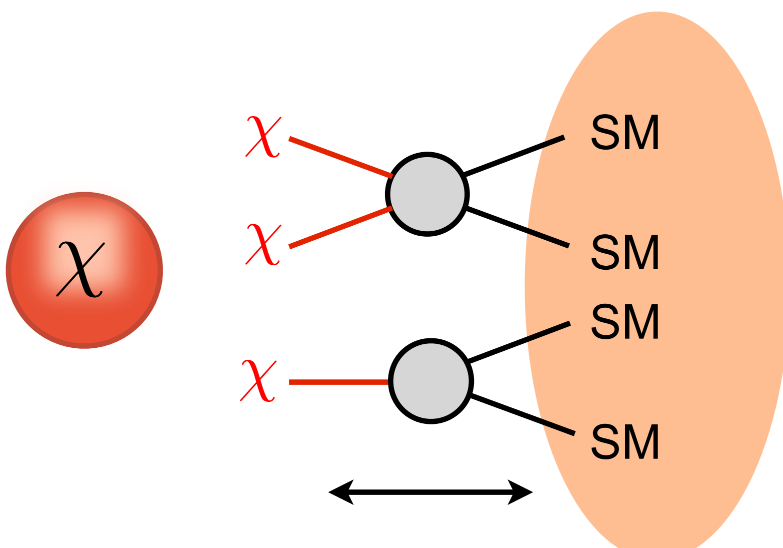

Standard Model
Thermal bath

Boltzmann equations for particle densities

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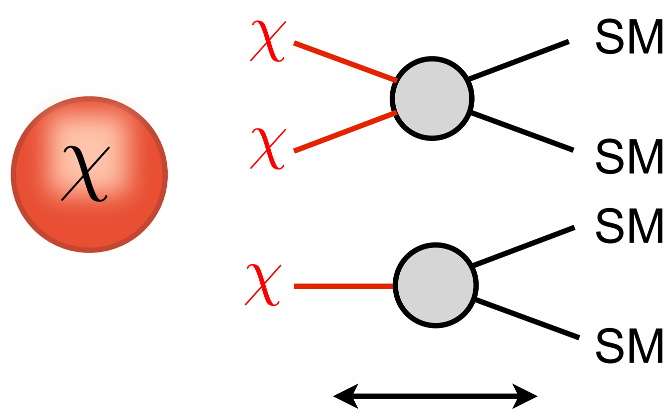

Thermal equilibrium:

$\Gamma_{\mathrm{ann}} = n_\chi \langle \sigma v \rangle_{\mathrm{ann}} \gg H$ and/or

$\Gamma_{\mathrm{dec}} \gg H$

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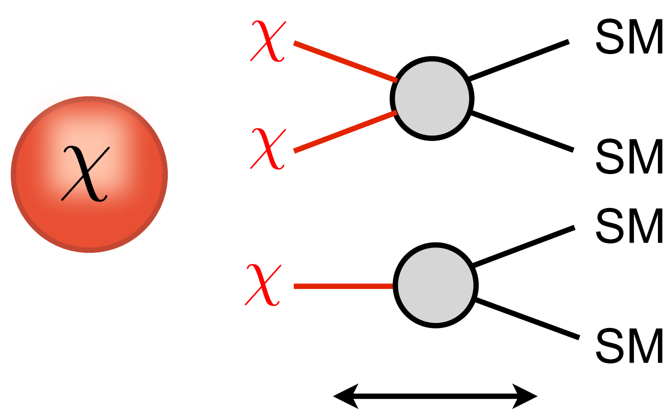
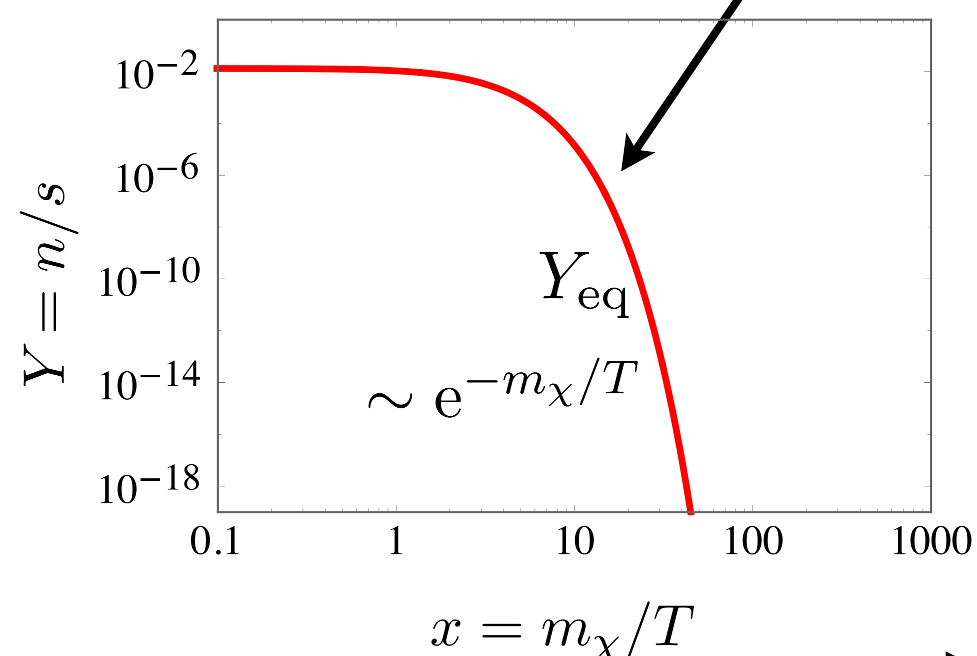
[Zel'dovich, Okun, Pikel'ner1966; Lee, Weinberg 1977; Binetruy, Girardi, Salati 1984; Bernstein, Brown, Feinberg 1985; Srednicki, Watkins, Olive 1988; Kolb, Turner 1990; Griest, Seckel 1991; Gondolo, Gelmini 1991; Edsjo, Gondolo 1997]



$$\Gamma_{\mathrm{ann}} \gg H$$

$$\Gamma_{\mathrm{dec}} \gg H$$

follow thermal equilibrium



time

Boltzmann equations for particle densities

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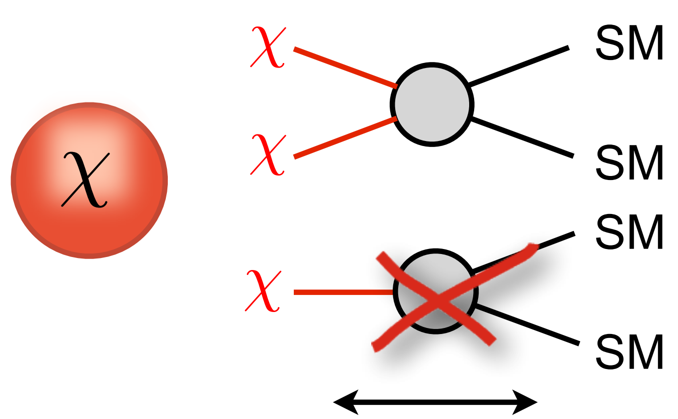
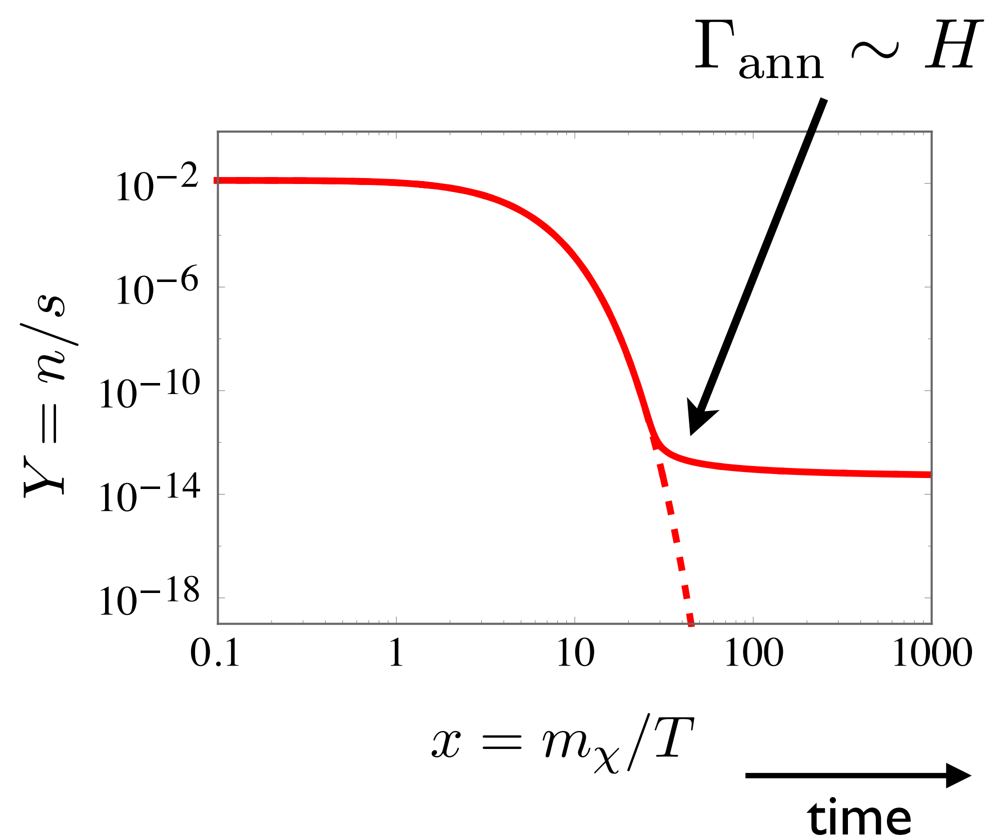


$\propto n_\chi \sim \mathrm{e}^{-m_\chi/T}$

$\Gamma_{\mathrm{dec}} = 0$

Forbid decay
e.g. via Z_2-symmetry



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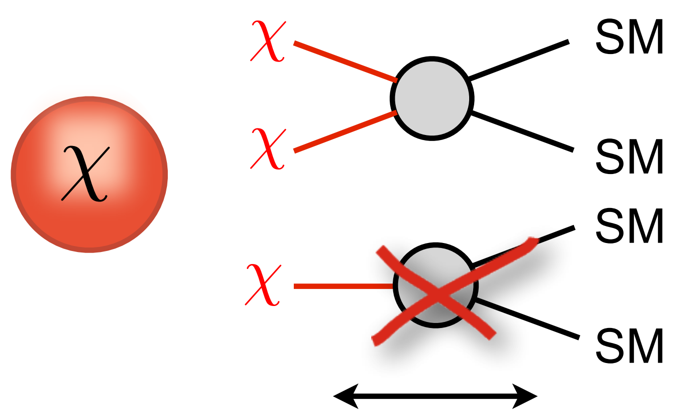

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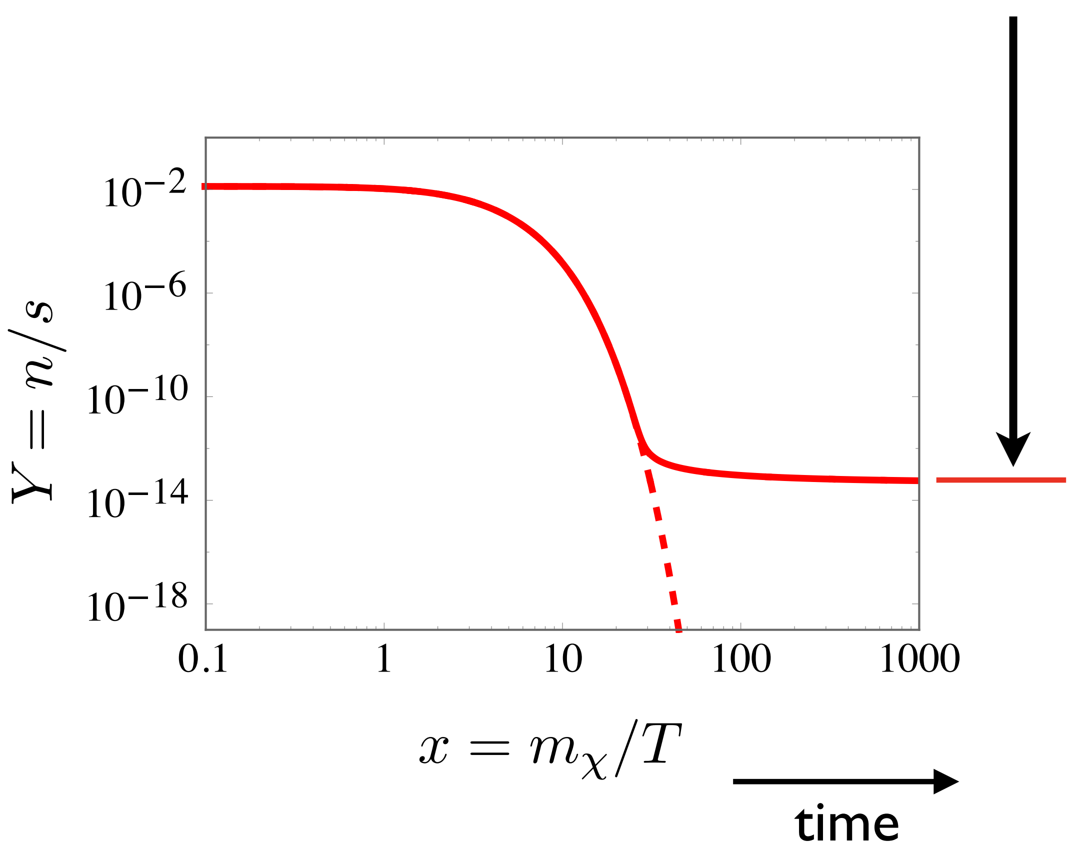
$(\Omega h^2)_{\mathrm{Planck}} \simeq 0.12$



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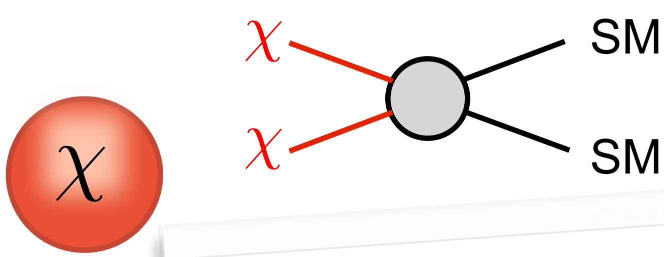

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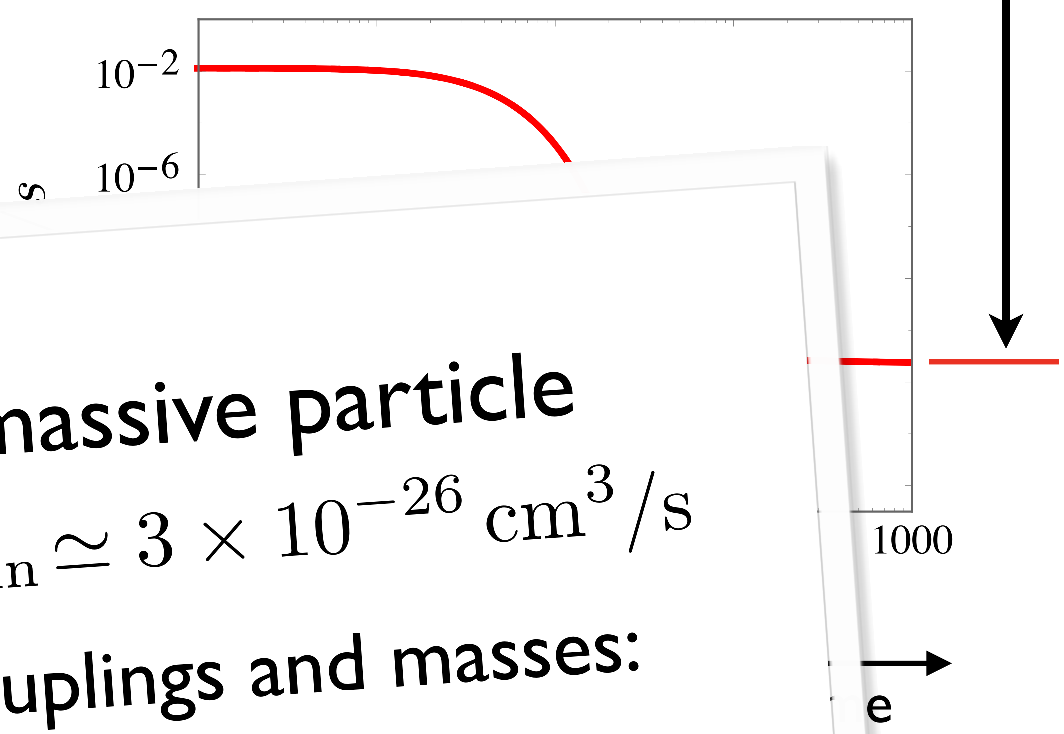


Weakly interacting massive particle

$\Omega_{\text{DM}} h^2 \simeq 0.12 \;\Rightarrow\; \langle \sigma v \rangle_{\text{ann}} \simeq 3 \times 10^{-26}\,\text{cm}^3/\text{s}$

$\Rightarrow$ roughly with weak couplings and masses:

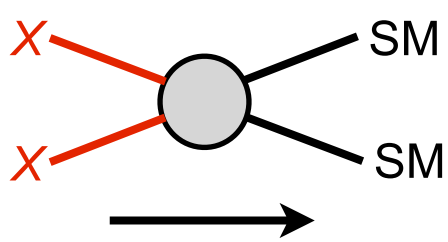
"WIMP miracle"

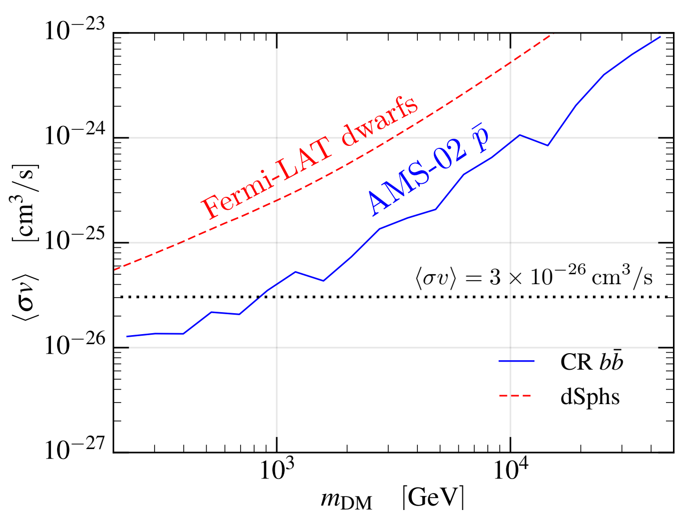
WIMP paradigm attractive

- Works with simple/natural models ("WIMP miracle")
- Independent of largely unconstrained/unknown physics of the very early universe (inflation/reheating)
- Naturally provides perfectly cold dark matter (CDM)
- Testable at indirect detection, direct detection and collider experiments

WIMP Dark Matter: searches

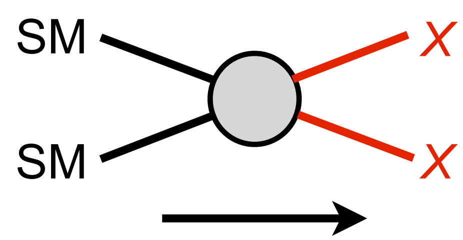
Indirect detection

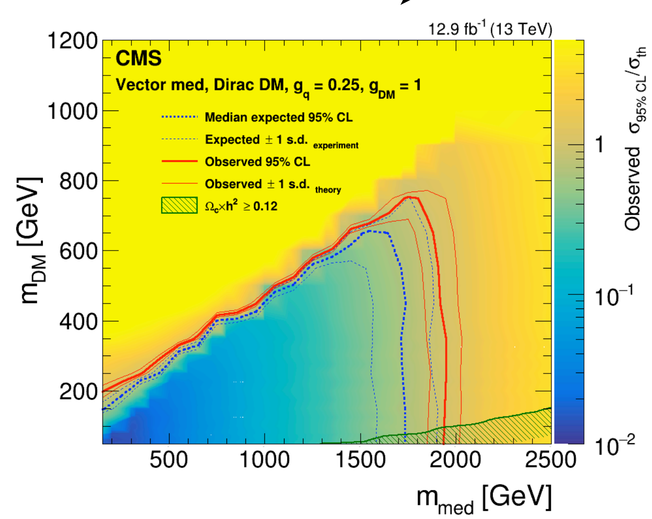




[Cuoco, JH, Korsmeier, Krämer 2017]

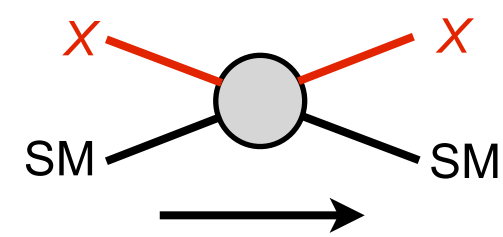
Direct production

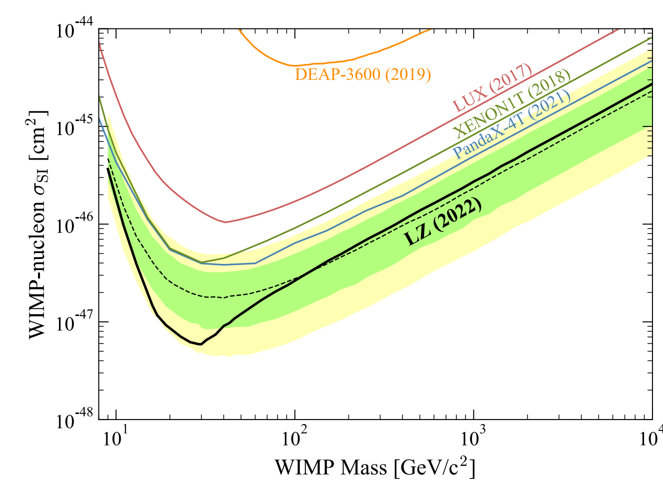




[CMS EXO-16-039]

Direct detection





[LZ 2207.03764]

Decouple constraints WIMP searches and relic density

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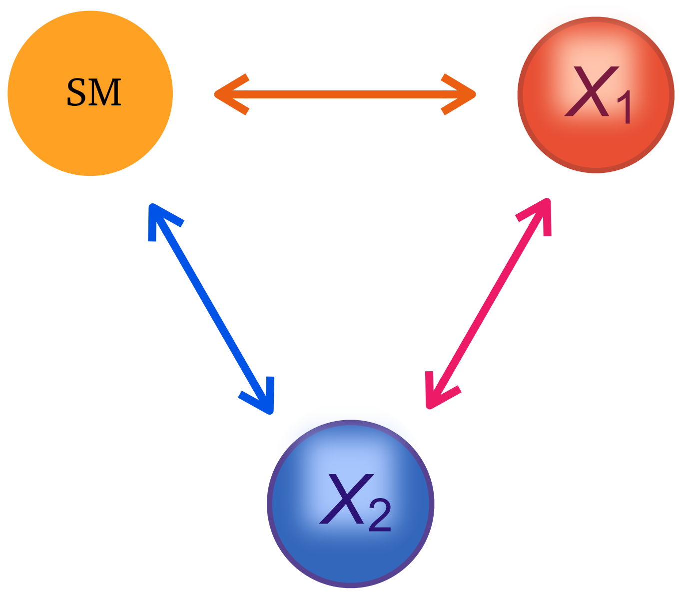
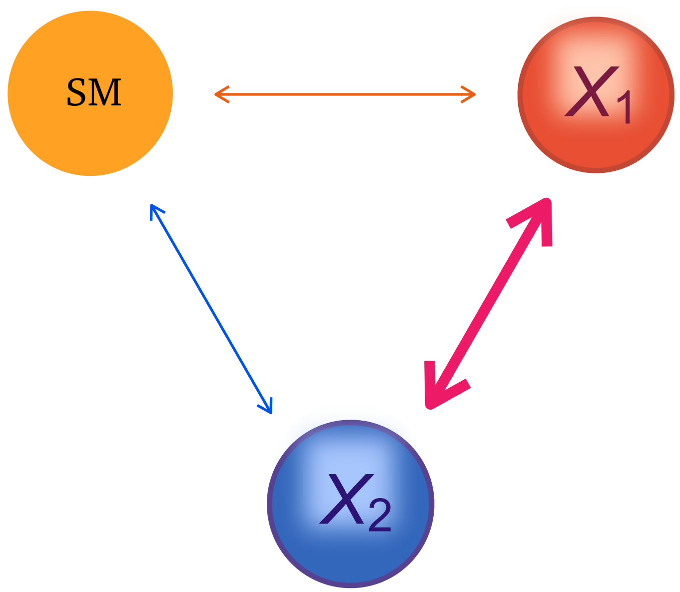
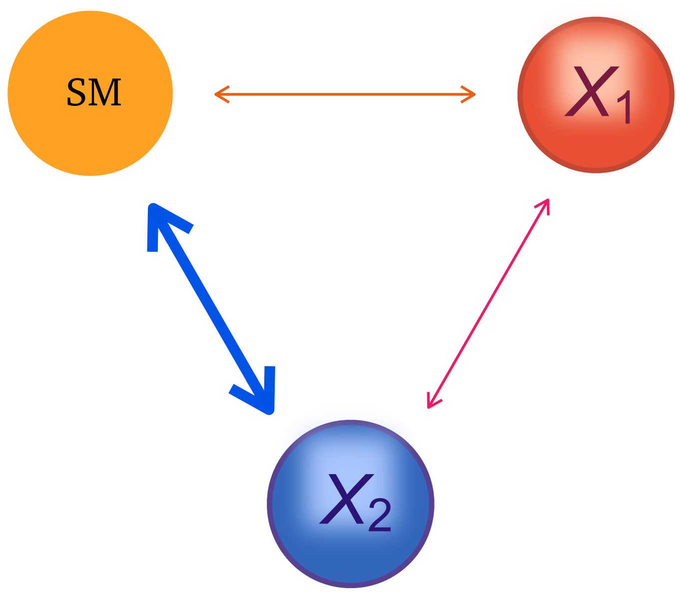


Decouple constraints WIMP searches and relic density



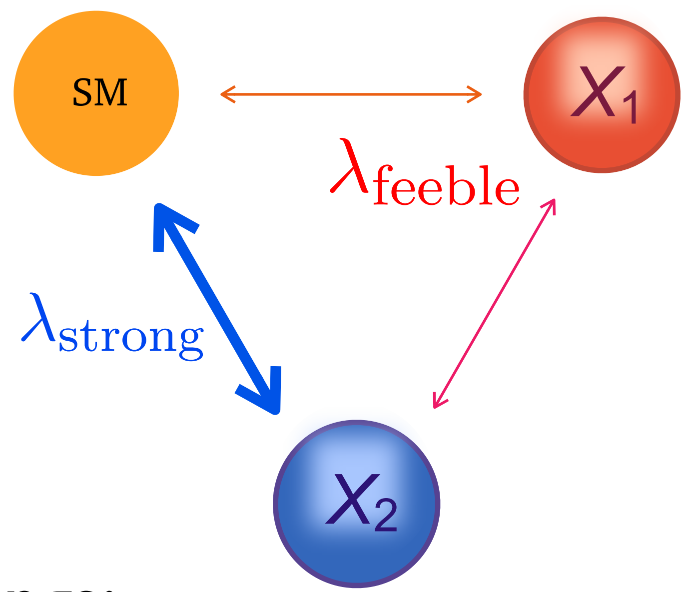
- Freeze-out in secluded sector

Decouple constraints WIMP searches and relic density



- Variety of scenarios in *t*-channel mediator models ('charged parent particle model')

Decouple constraints WIMP searches and relic density



- Large hierarchy of couplings:

$$\lambda_{\text{strong}} \gg \lambda_{\text{feeble}}$$

- Interesting for the subject for two reasons:

(i) 'strong' coupling: significant bound state effects

(ii) very weak ('feeble') coupling: suppresses scattering and decay rates

$\Rightarrow$ typically prolonged freeze-out process

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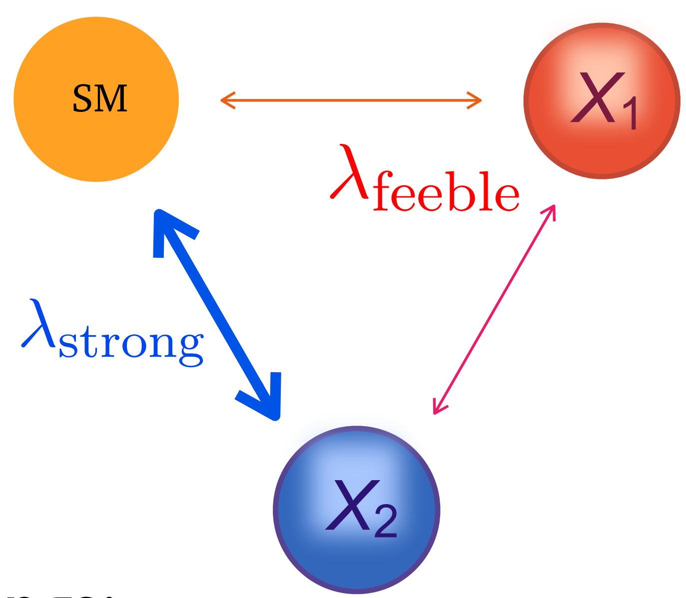

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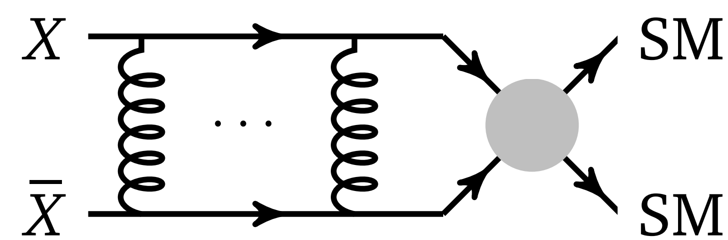
$\Rightarrow$ typically prolonged freeze-out process

$\Rightarrow$ bound state at late times (low T): excitations highly relevant

Effects of (excited) bound state

Non-relativistic effects

1. Sommerfeld effect:



[Harz, Petraki]

[see e.g. Hisano, Matsumoto, Nojiri hep-ph/0307216; Hisano, Matsumoto, Nojiri, Saito hep-ph/0412403; …]

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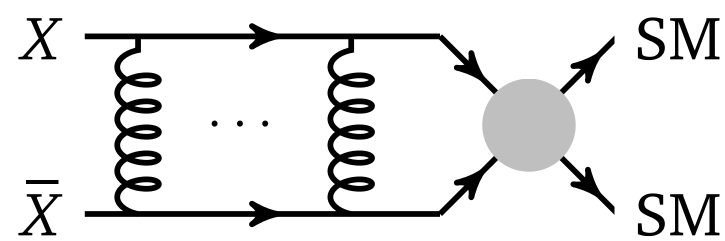
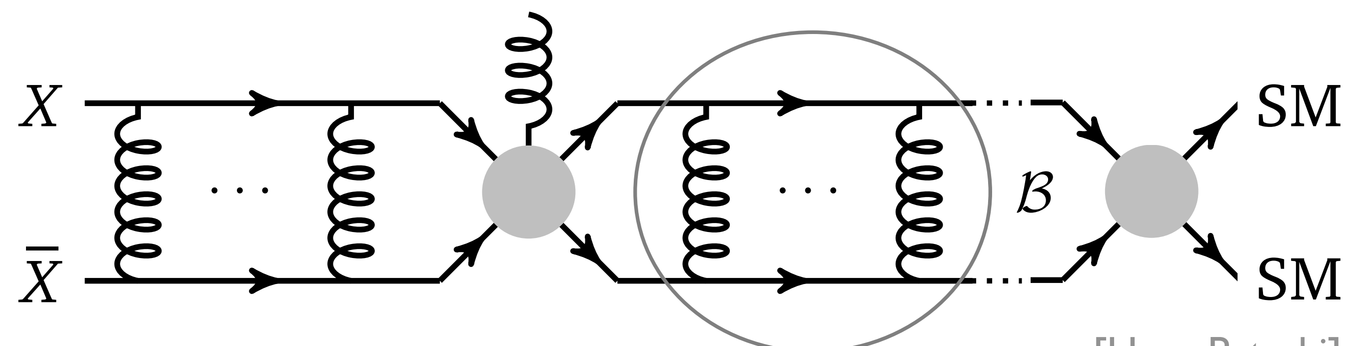


2. Bound state formation:



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[see e.g. K. Petraki, M. Postma, M. Wiechers 1505.00109; 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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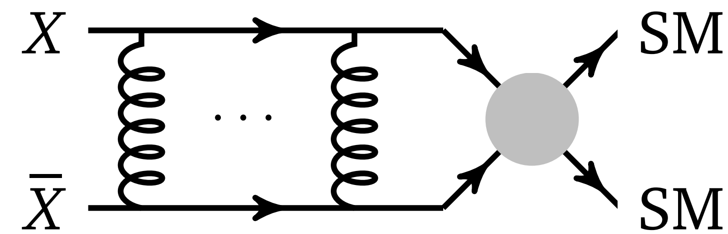

$$\Delta E = \frac{\mathbf{p}^2}{2\mu} + E_{\mathcal{B}}$$

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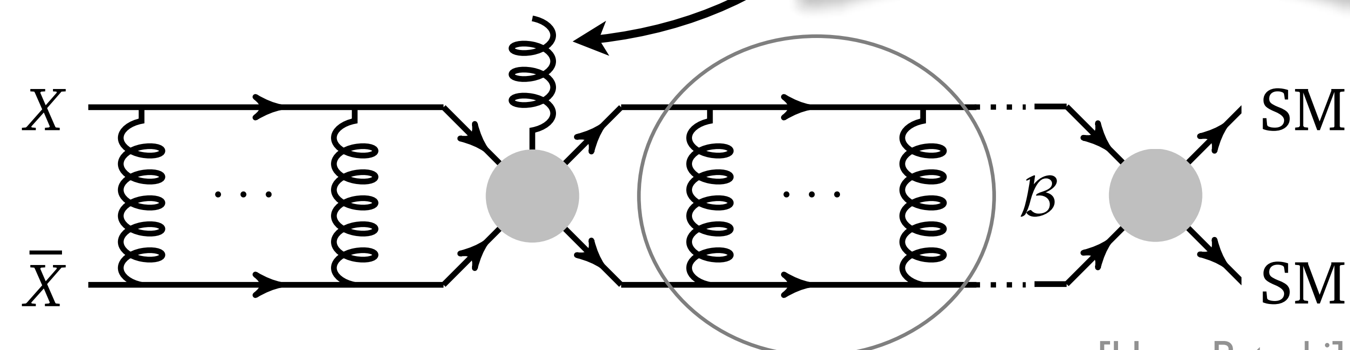

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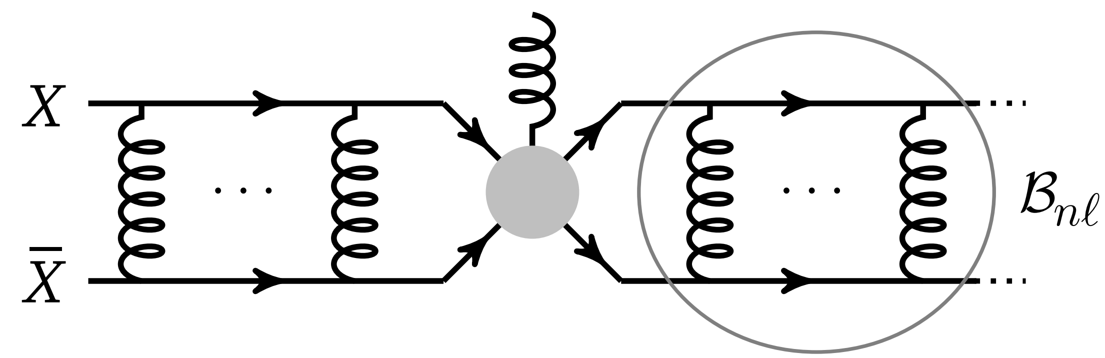

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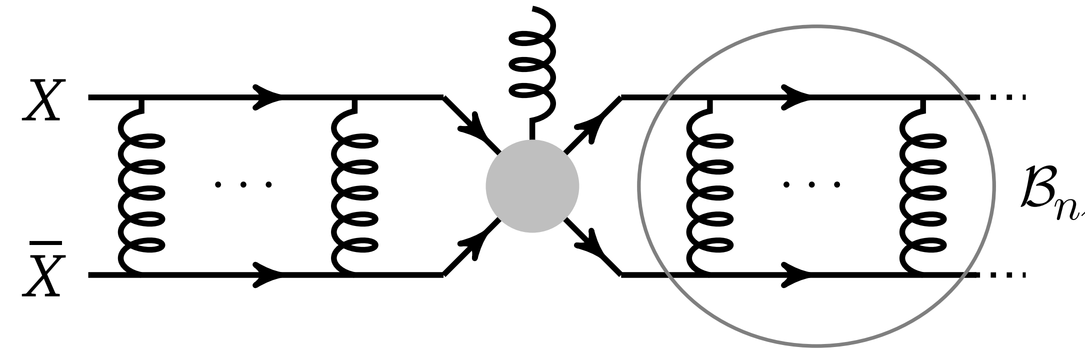

[Harz, Petraki]

- Force carrier = vector (gauge field):
  bound state formation XS ~ dipole transition:

$$(\sigma v)_{n\ell} \propto |\langle\psi_{n\ell}|\,\mathbf{r}\,|\psi_{\mathbf{p}}\rangle|^2$$

$$g\,\mathbf{r}\cdot\mathbf{E}$$

[(Color-)electric dipol operator (in pNRQCD), see e.g. Yao+ 2019]

bound state

scattering state

Wave functions: solutions to two-body Schrödinger eqs.

Computation of bound state formation

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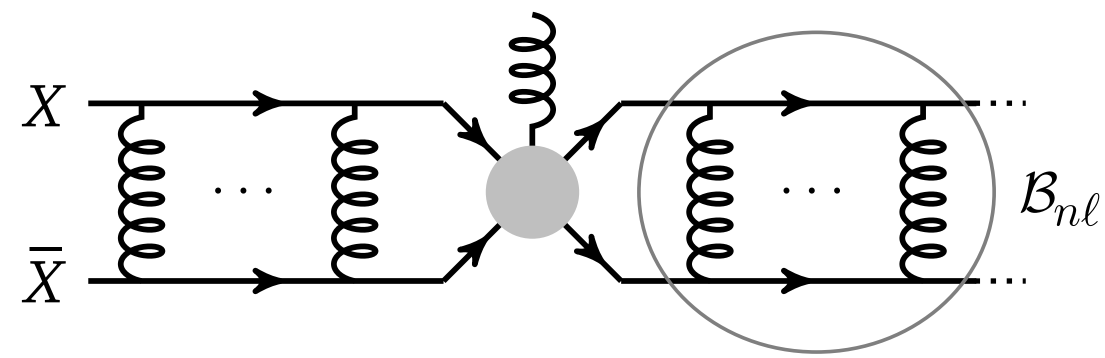

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- Force carrier massless (unbroken gauge theory):

Coulomb limit: $V_{[\boldsymbol{R}]}(r) = -\frac{\alpha^{\rm eff}_{[\boldsymbol{R}]}}{r}$ in unconfined phase

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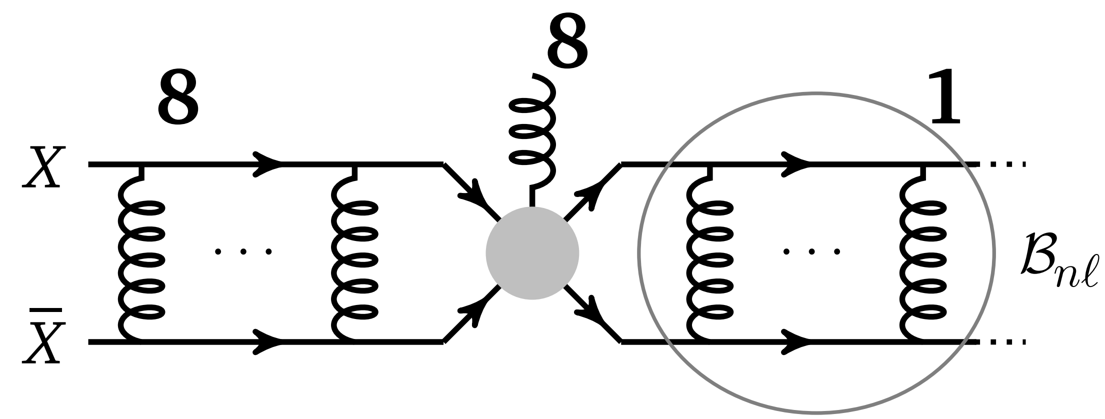

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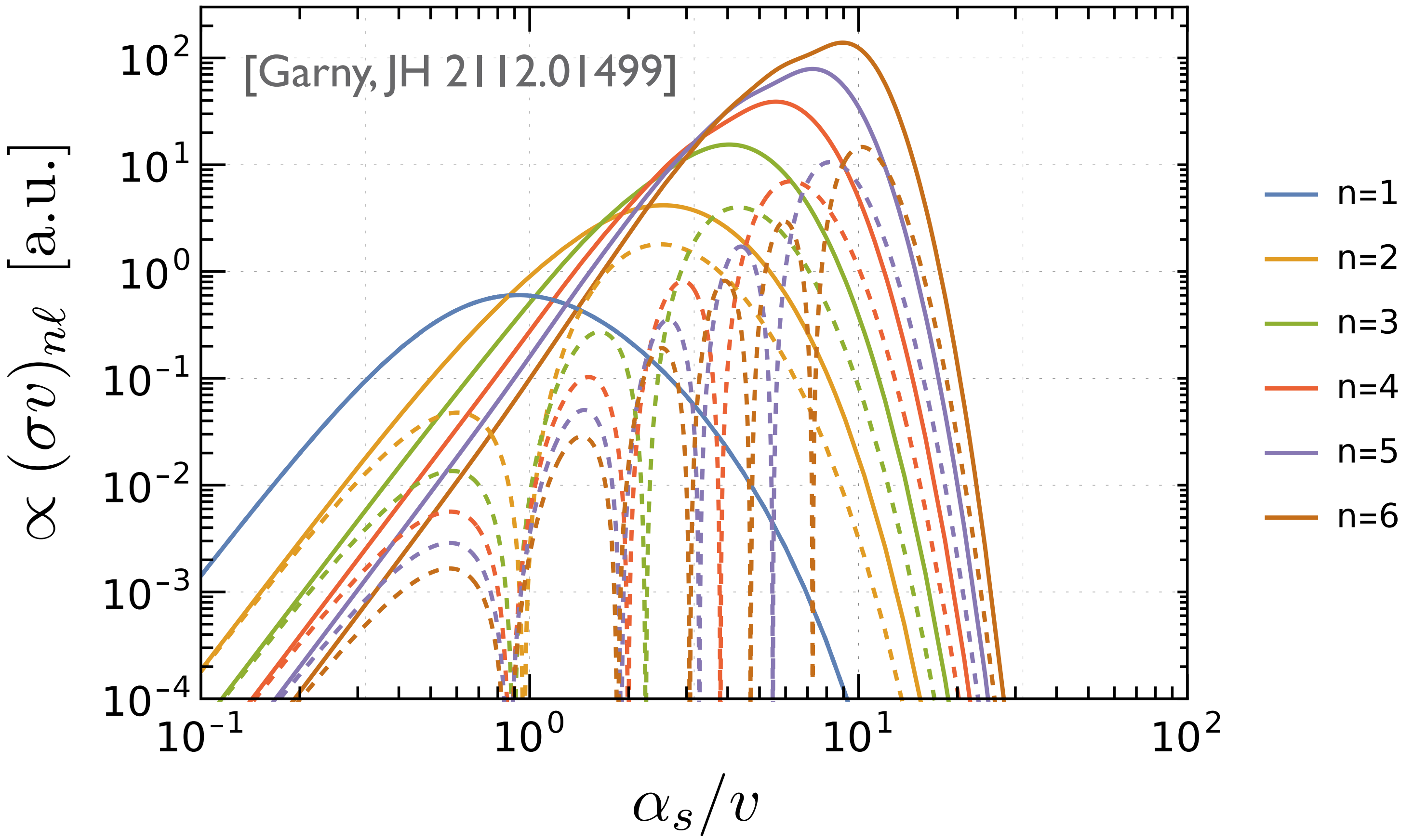
Coulomb limit: $V_{[\boldsymbol{R}]}(r) = -\frac{\alpha^{\mathrm{eff}}_{[\boldsymbol{R}]}}{r}\,, \quad \alpha^{\mathrm{eff}}_{[\boldsymbol{R}]} = \alpha_s \times \begin{cases} 4/3, & \mathbf{R} = \mathbf{1}, \\ -1/6, & \mathbf{R} = \mathbf{8}. \end{cases}$

- Non-abelian gauge theory:
  e.g. X in $\mathbf{3}$ of SU(3): $\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$

involves repulsive potential

Bound state formation cross section

$$(\sigma v)_{n\ell} \propto \left|\langle\psi_{n\ell}|\,\mathbf{r}\,|\psi_{\mathbf{p}}\rangle\right|^2$$



small velocities ~ relevant for small temperatures

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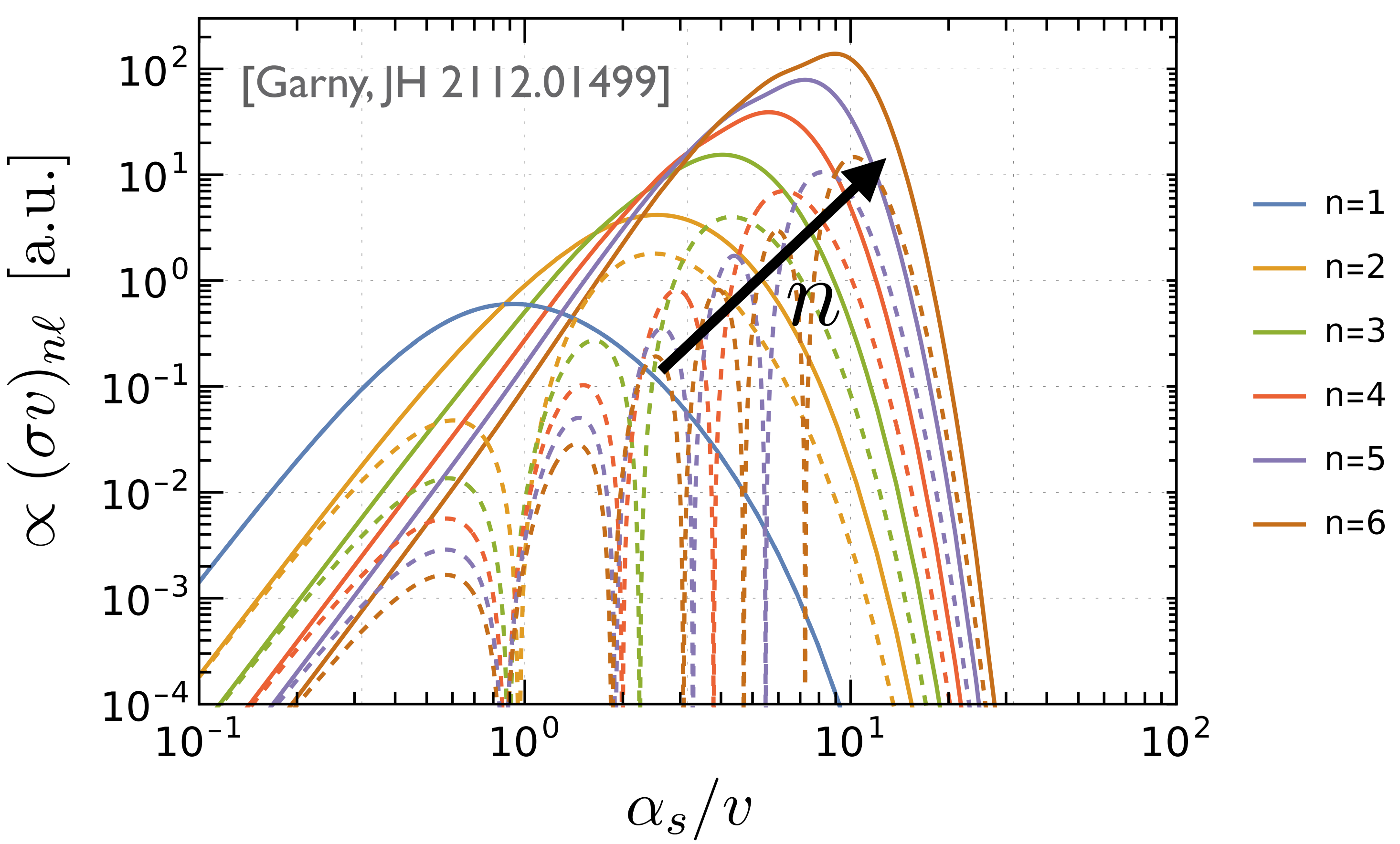


small velocities ~ relevant for small temperatures

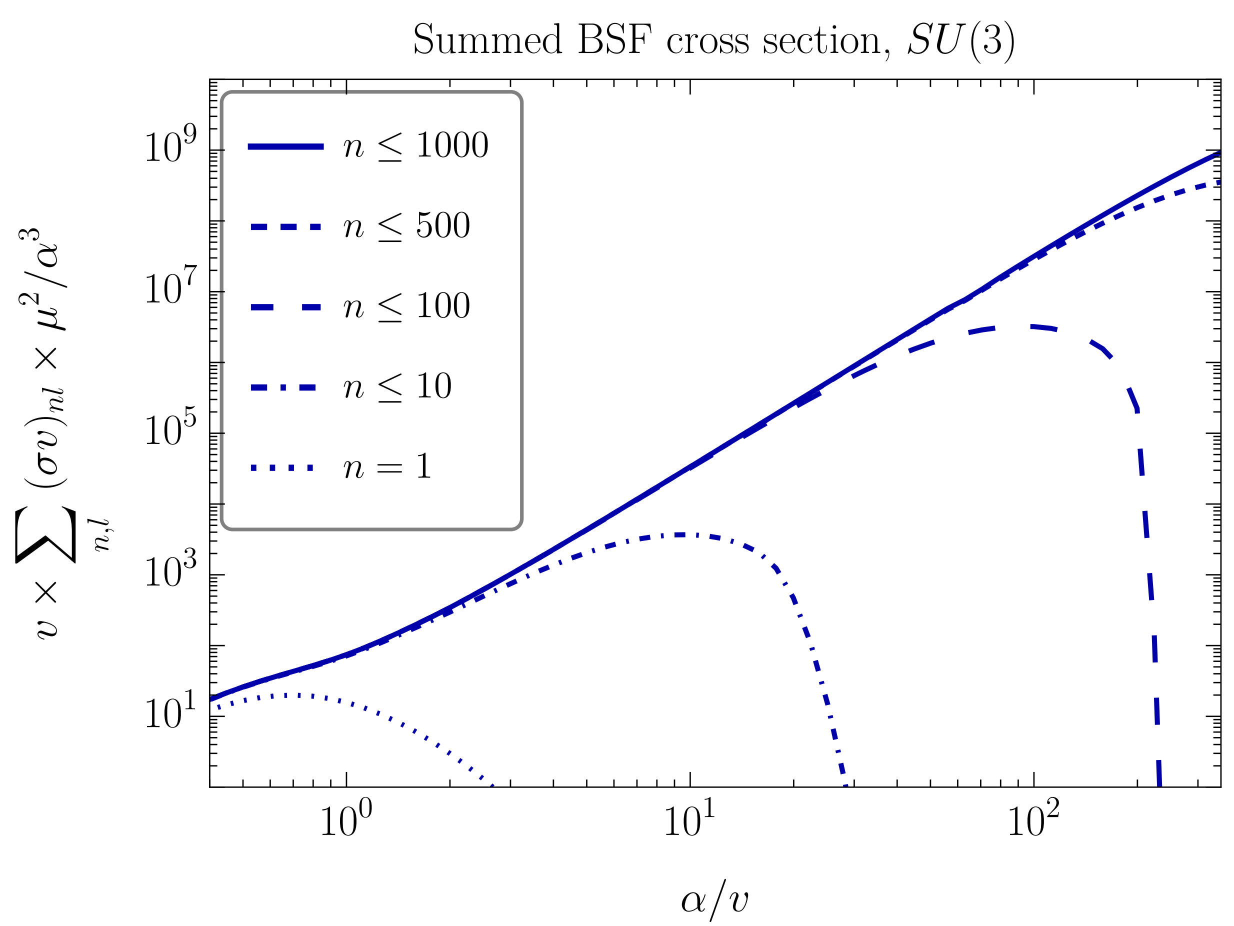
Partial-wave unitarity violating?

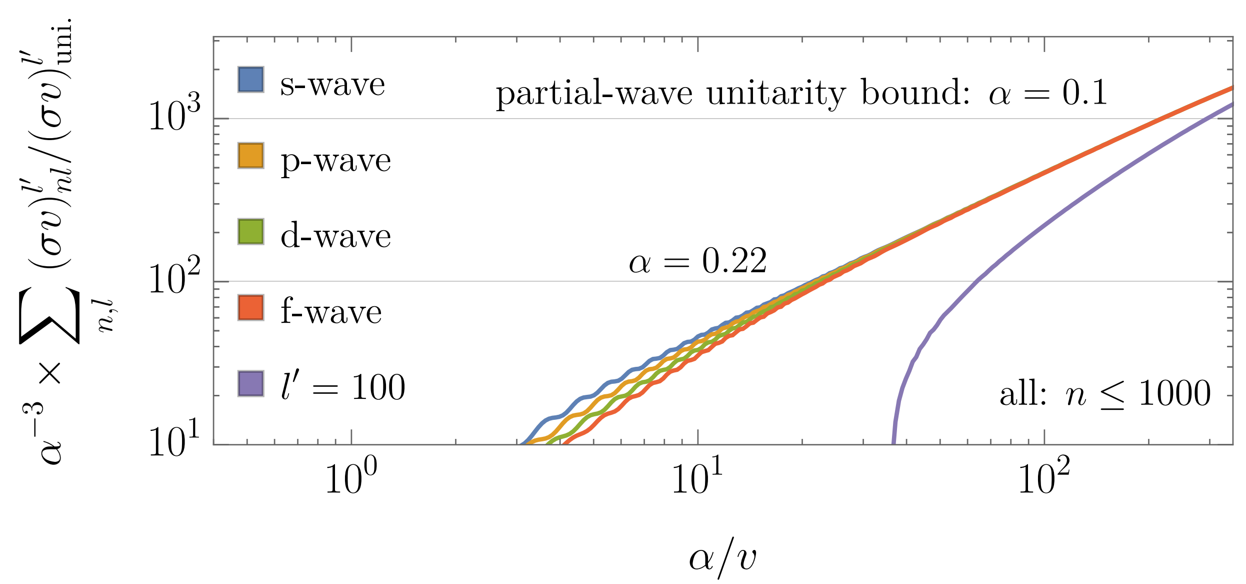
[Binder, Garny, JH, Lederer, Urban 2308.01336]

- Derived recursion formulas for highly efficient and stable computation of $(\sigma v)_{n\ell}$ up to $n = 1000,\ \ell \leq n-1$ (~million states)
- Impose partial-wave unitarity:
  [Griest, Kamionkowski 1990]

$$(\sigma v)^{\ell'} = \sum_{n,\ell} (\sigma v)^{\ell'}_{n\ell}$$
$$\leq \frac{\pi(2\ell'+1)}{\mu^2 v}$$

[*see also* Harling, Petraki 2014; Baldes, Petraki 2017; Smirnov, Beacom 2019; Bottaro, Redigolo 2023]





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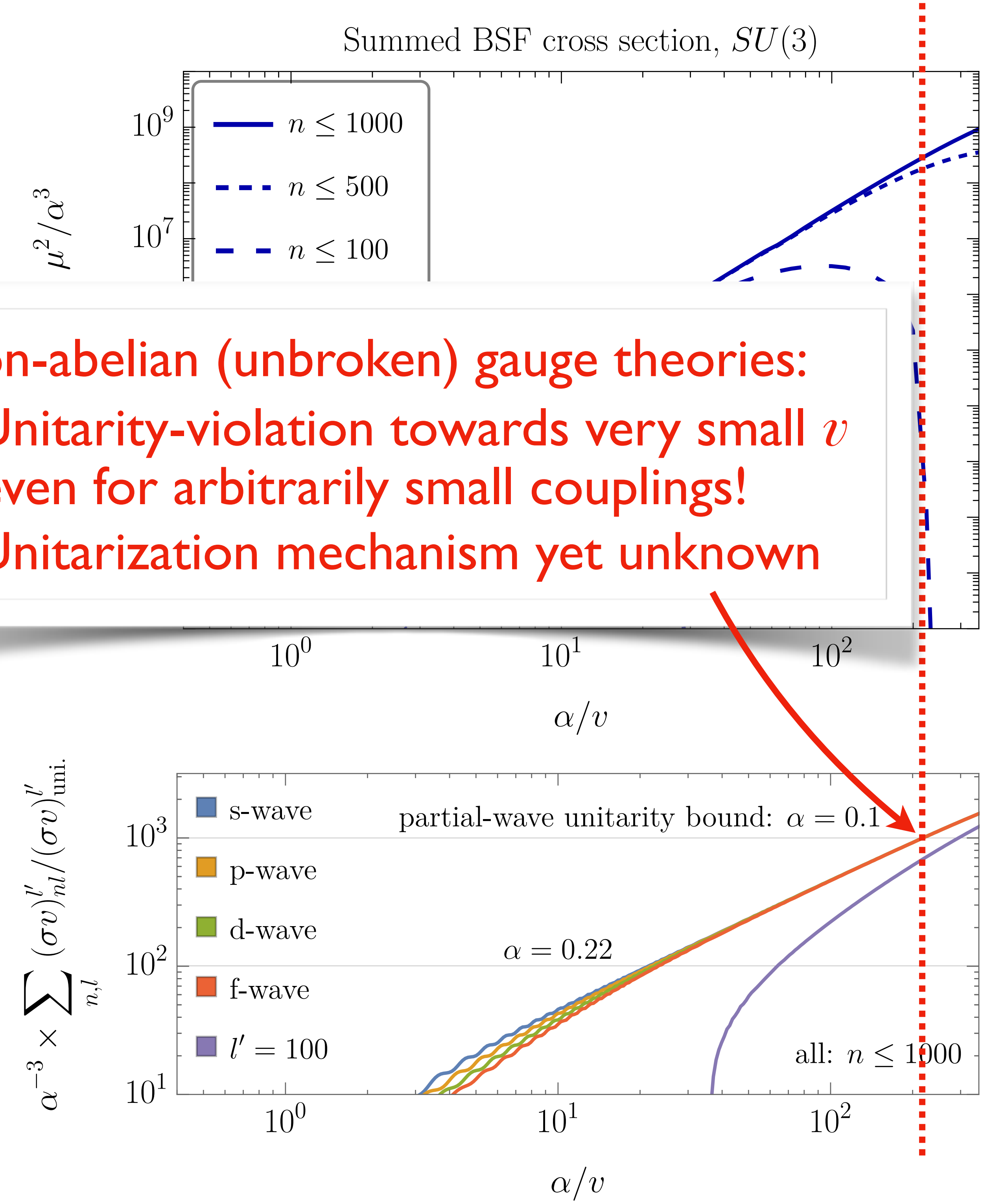
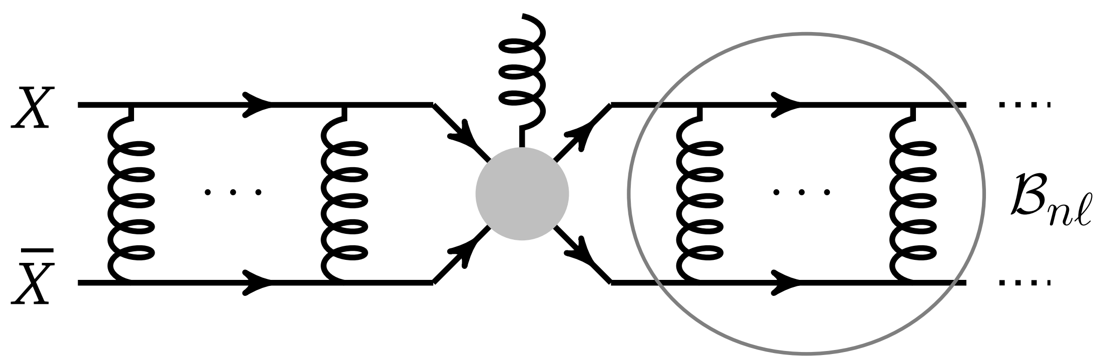


Non-abelian (unbroken) gauge theories:

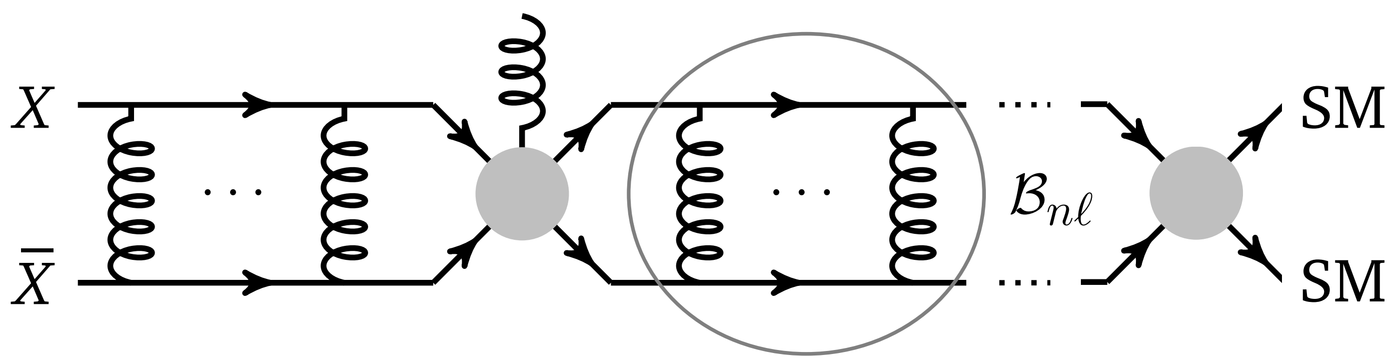
- Unitarity-violation towards very small v even for arbitrarily small couplings!
- Unitarization mechanism yet unknown

Excited bound states in the thermal bath



Bound state formation

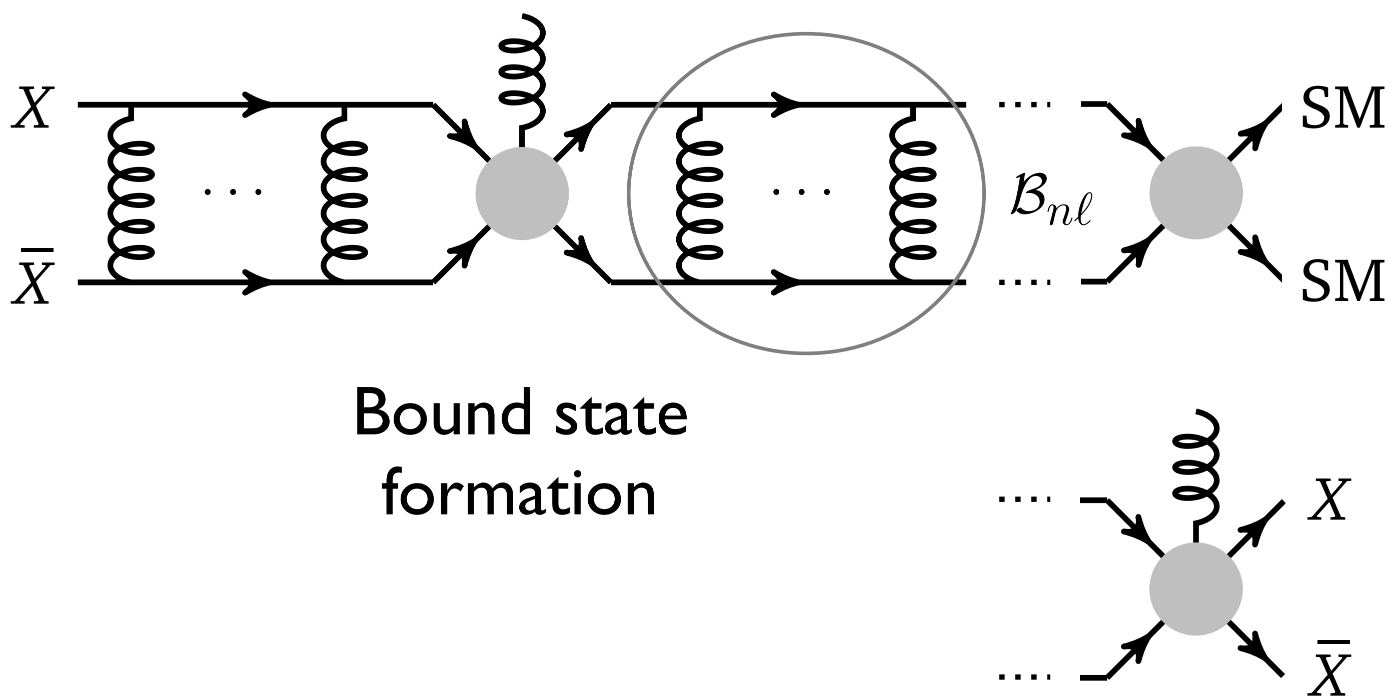
Excited bound states in the thermal bath



Bound state formation

Decay

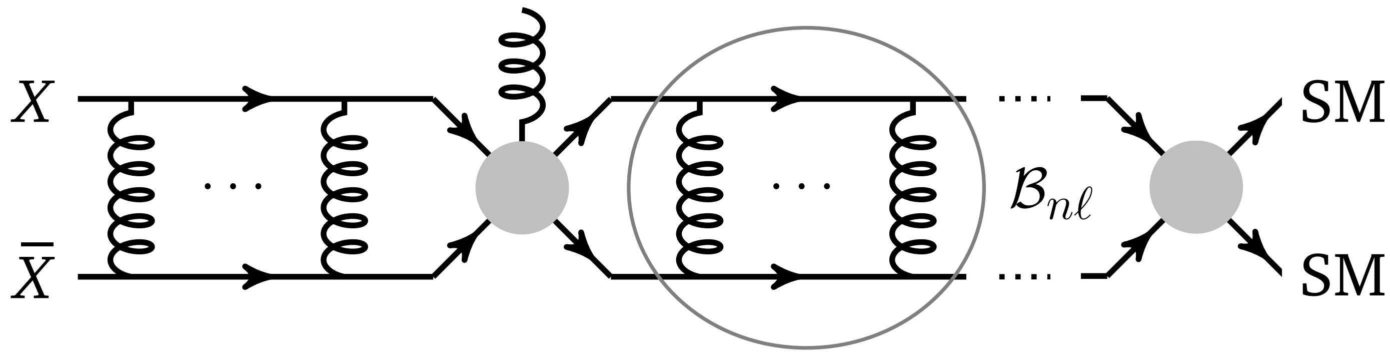
Excited bound states in the thermal bath



Decay

Ionization

Excited bound states in the thermal bath



Decay

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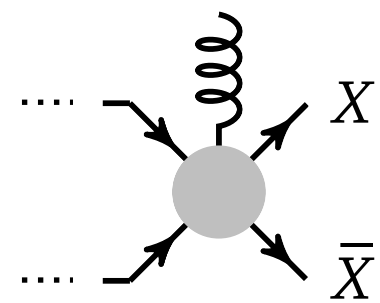
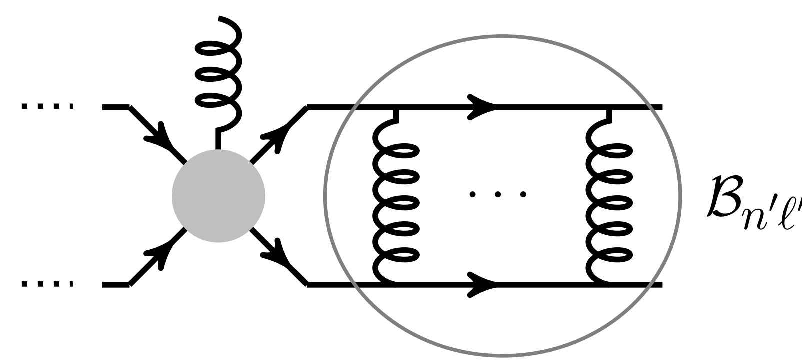
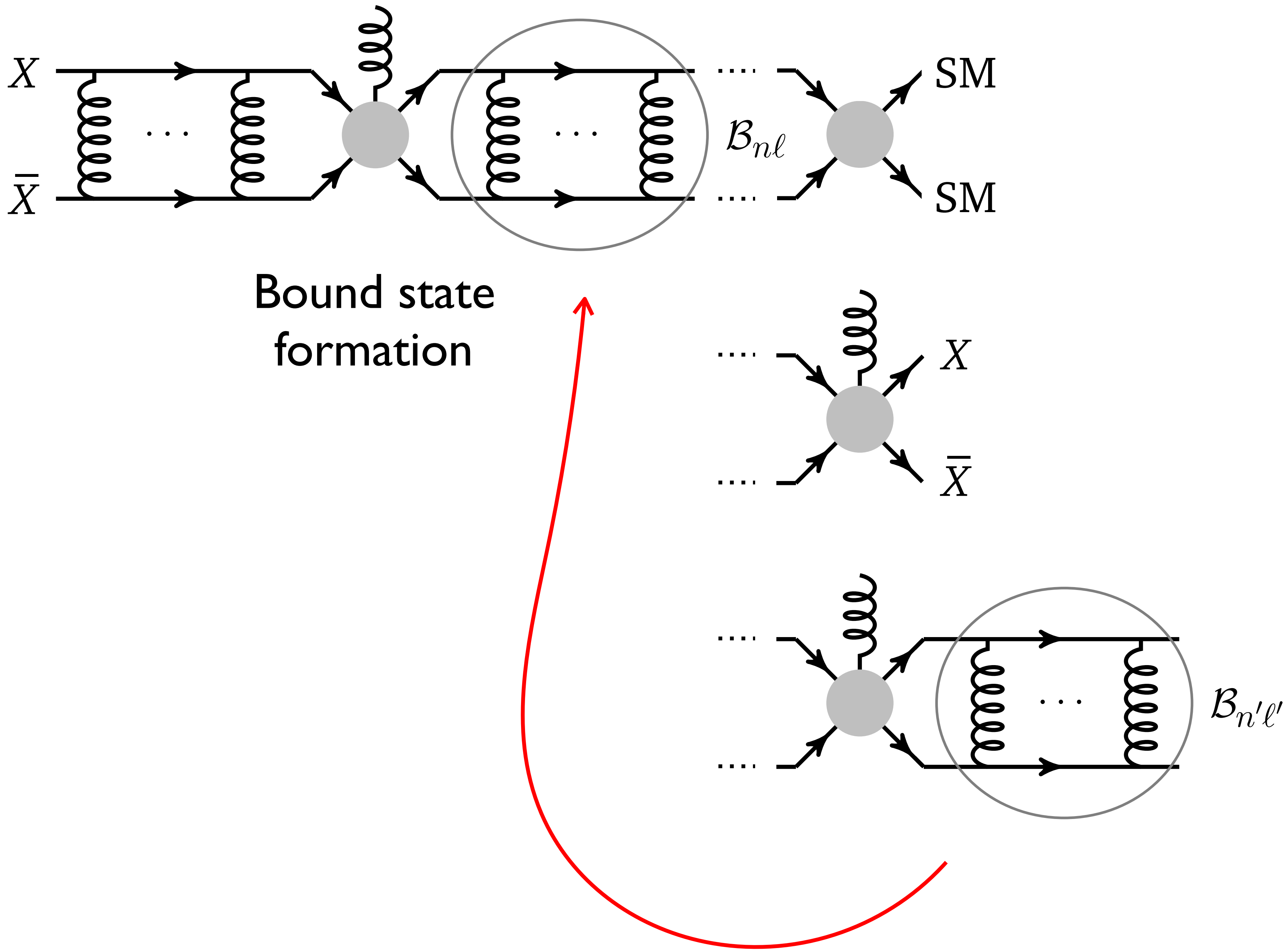


Ionization



Bound-to-bound transition

Excited bound states in the thermal bath

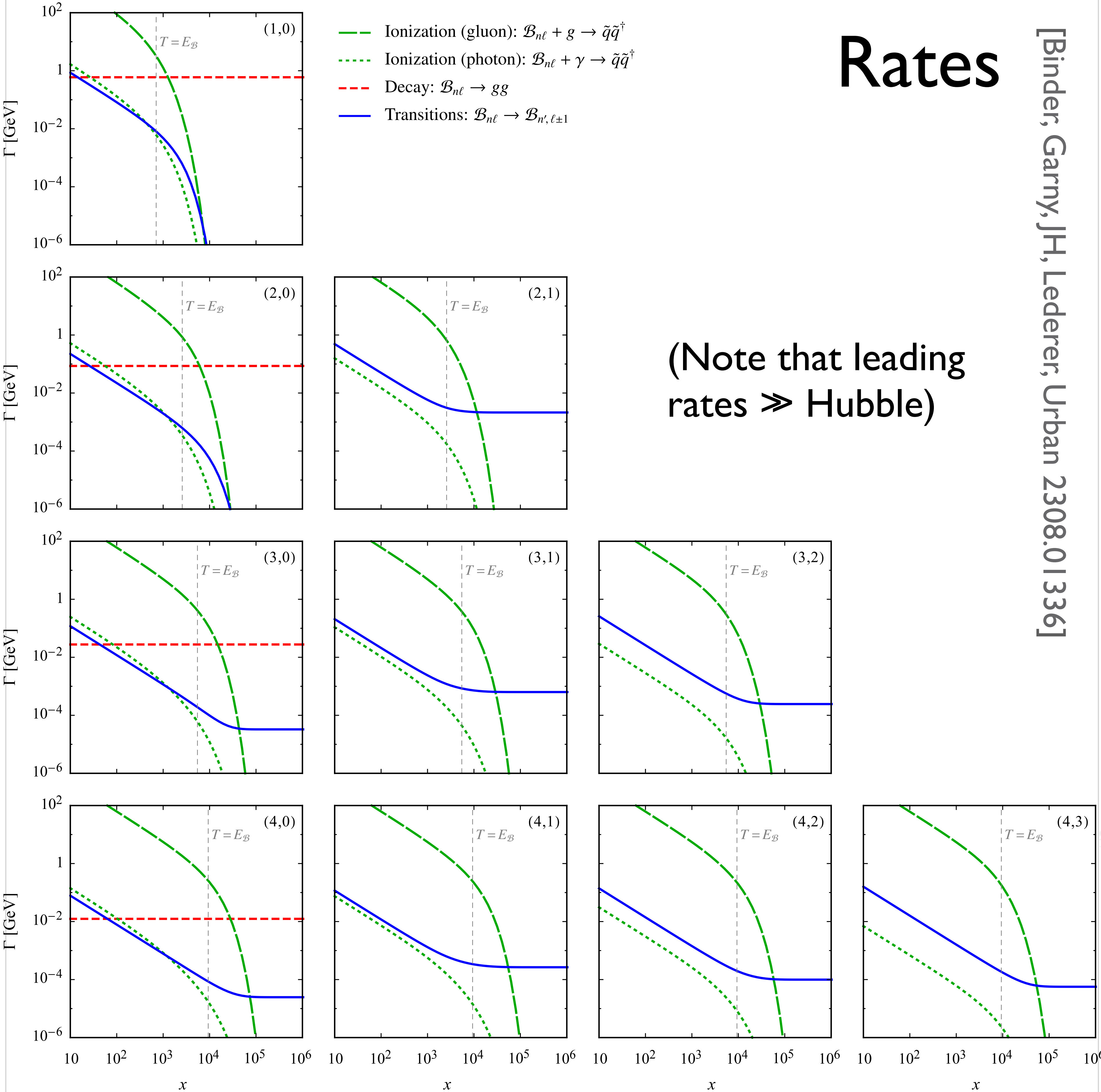


Decay

Ionization

Bound-to-bound transition

Rates



(Note that leading rates ≫ Hubble)

[Binder, Garny, JH, Lederer, Urban 2308.01336]

Decay

Ionization

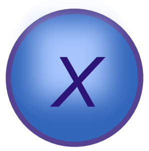
Bound-to-bound transition

Boltzmann equations including excitations

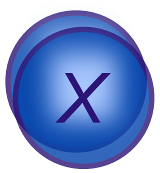
[Garny, JH 2112.01499]

X pair-annihilation
(hard process+Sommerfeld)

Bound state formation



: $$\frac{\mathrm{d}Y_X}{\mathrm{d}x} = \frac{1}{3H\,s}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\frac{1}{2}\langle\sigma_{XX^\dagger}v\rangle\left(Y_X^2 - Y_X^{\mathrm{eq}\,2}\right) + \sum_i \frac{1}{2}\langle\sigma_{\mathrm{BSF},i}v\rangle\left(Y_X^2 - Y_X^{\mathrm{eq}\,2}\frac{Y_{\mathcal{B}_i}}{Y_{\mathcal{B}_i}^{\mathrm{eq}}}\right)\right]$$



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

Ionization

Decay

Bound-to-bound transition

[see *also* Binder *et al.* 2112.00042]

Boltzmann equations including excitations

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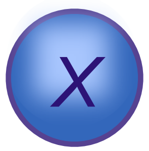
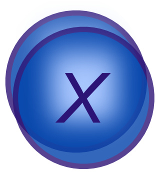
X pair-annihilation (hard process+Sommerfeld) | Bound state formation



$$: \frac{\mathrm{d}Y_X}{\mathrm{d}x} = \frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\frac{1}{2}\langle\sigma_{XX^\dagger}v\rangle\left(Y_X^2 - Y_X^{\mathrm{eq}\,2}\right) + \sum_i \frac{1}{2}\langle\sigma_{\mathrm{BSF},i}v\rangle\left(Y_X^2 - Y_X^{\mathrm{eq}\,2}\frac{Y_{\mathcal{B}_i}}{Y_{\mathcal{B}_i}^{\mathrm{eq}}}\right)\right]$$



$$: \underset{0}{\cancel{\frac{\mathrm{d}Y_{\mathcal{B}_i}}{\mathrm{d}x}}} = \frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\Gamma_{\mathrm{ion}}^i\left(Y_{\mathcal{B}_i} - Y_{\mathcal{B}_i}^{\mathrm{eq}}\frac{Y_X^2}{Y_X^{\mathrm{eq}\,2}}\right) + \Gamma_{\mathrm{dec}}^i\left(Y_{\mathcal{B}_i} - Y_{\mathcal{B}_i}^{\mathrm{eq}}\right) - \sum_{j\neq i}\Gamma_{\mathrm{trans}}^{j\to i}\left(Y_{\mathcal{B}_j} - Y_{\mathcal{B}_i}\frac{Y_{\mathcal{B}_j}^{\mathrm{eq}}}{Y_{\mathcal{B}_i}^{\mathrm{eq}}}\right)\right]$$

Ionization | Decay | Bound-to-bound transition

[see *also* Binder *et al.* 2112.00042]

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(hard process+Sommerfeld)

Bound state formation

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Ionization

Decay

Bound-to-bound transition

Solve for $Y_{\mathcal{B}_i}$ algebraically: set of linear equations!

[see *also* Binder *et al.* 2112.00042]

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Ionization

Decay

Bound-to-bound transition

Solve for $Y_{\mathcal{B}_i}$ algebraically: set of linear equations!
Reduce to single BME:

$$X + X: \quad \frac{\mathrm{d}Y_X}{\mathrm{d}x} = \frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\frac{1}{2}\langle\sigma_{XX^\dagger}v\rangle_{\mathrm{eff}}\left(Y_X^2 - Y_X^{\mathrm{eq}\,2}\right)$$

where $\langle\sigma_{XX^\dagger}v\rangle_{\mathrm{eff}} = \langle\sigma_{XX^\dagger}v\rangle + \sum_i \langle\sigma_{\mathrm{BSF},i}v\rangle \underline{R_i}\,, \quad 0 \leq R_i \leq 1$

[see *also* Binder *et al.* 2112.00042]

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to-bound
sition

Bound states effectively enhance the X pair-annihilation cross section

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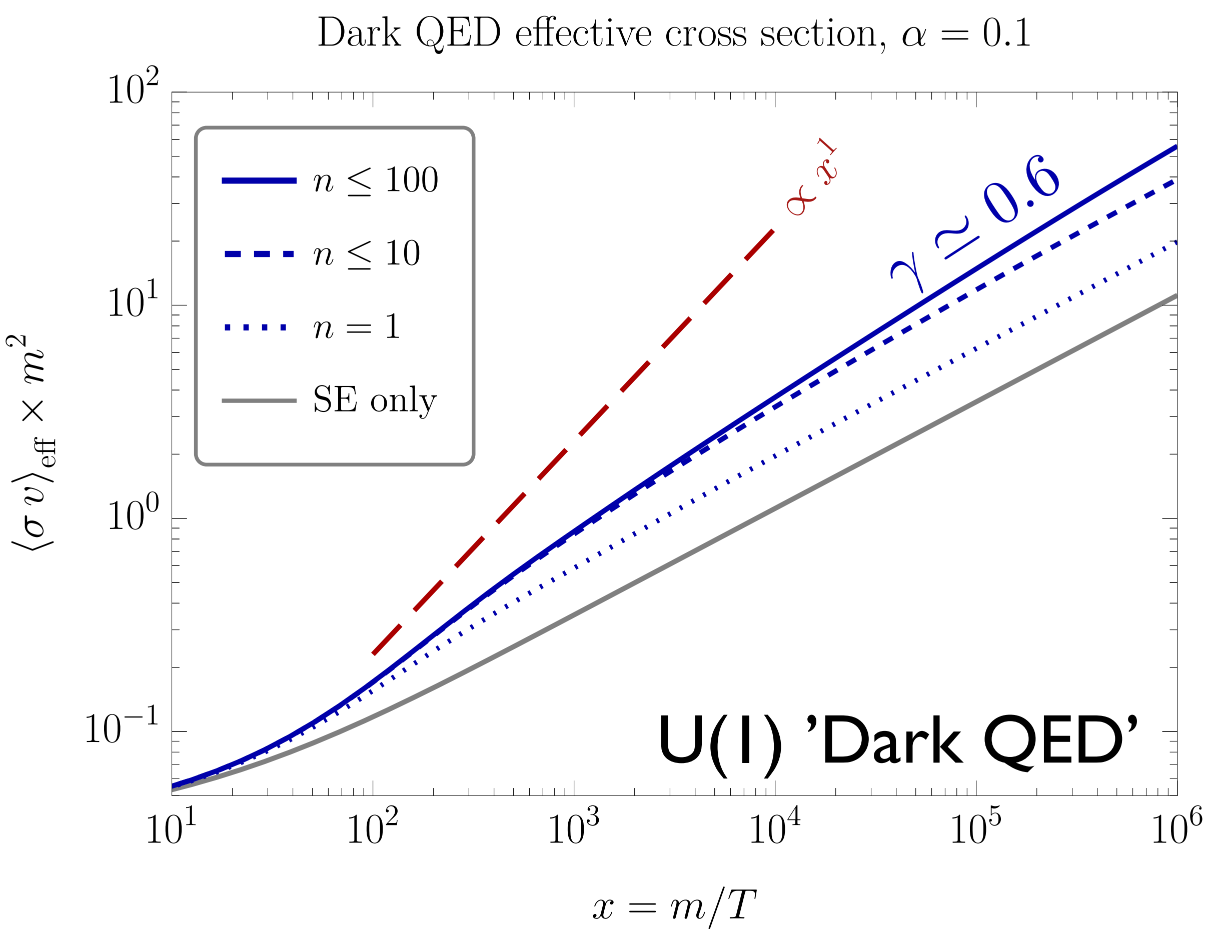
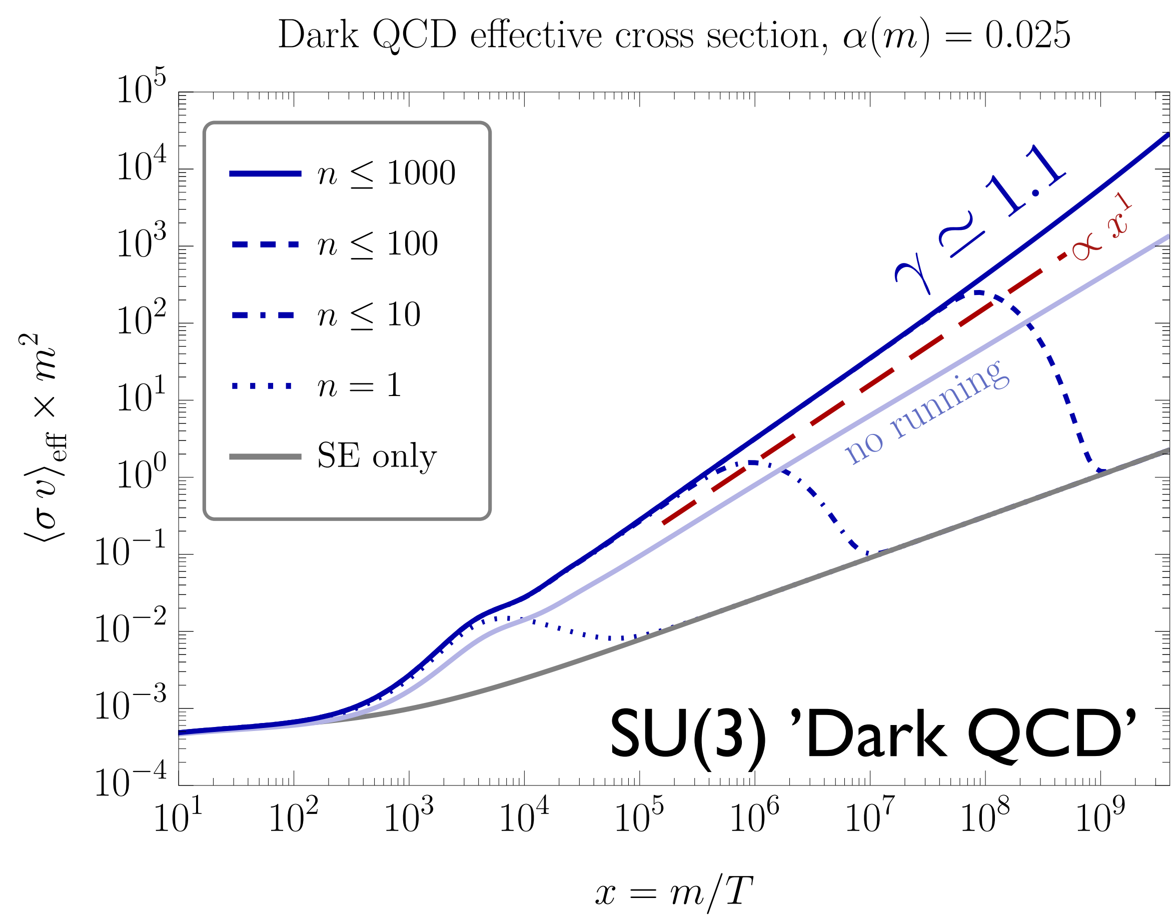
Effective annihilation cross section

[Binder, Garny, JH, Lederer, Urban 2308.01336]

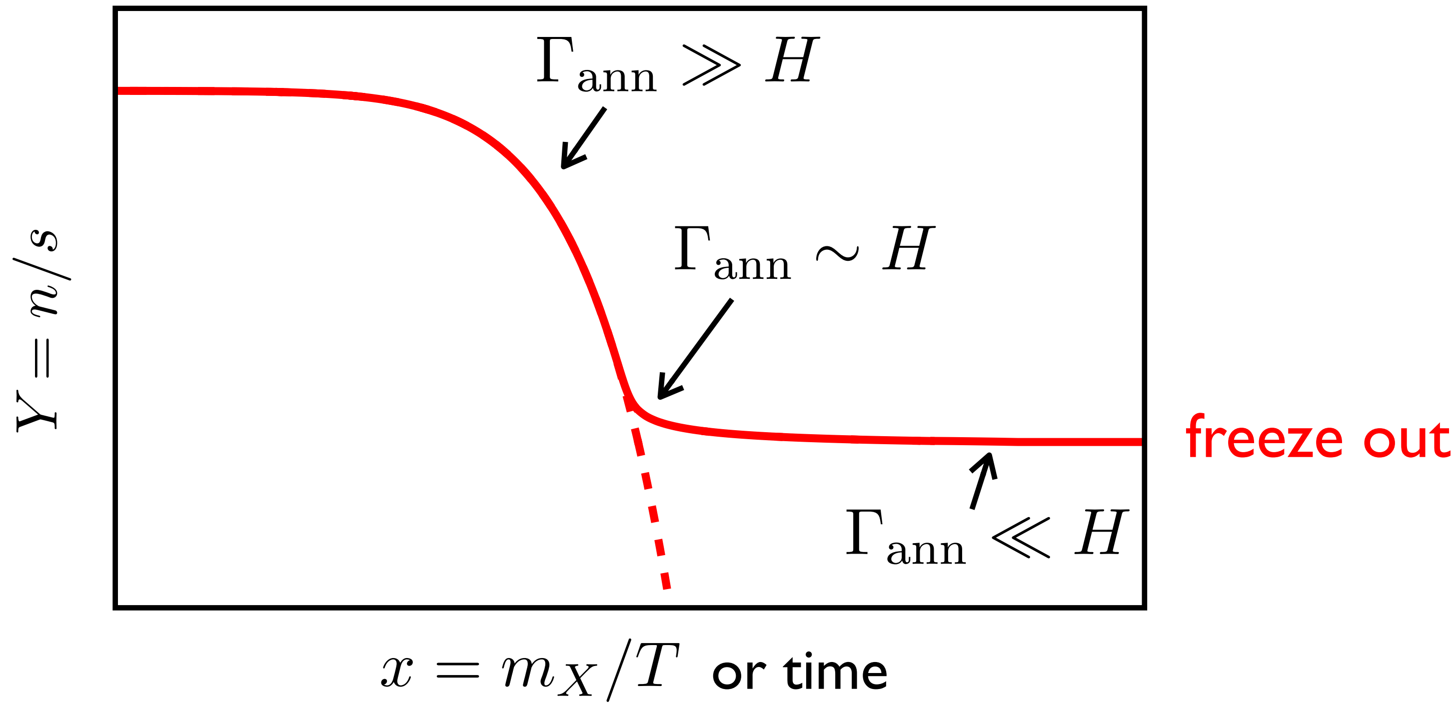




$$\langle \sigma v \rangle_{\rm eff} \propto x^\gamma$$

- Steepening of slope w.r.t. Sommerfeld only $\gamma = 0.5$
- Note: no unitarity violation within unconfined phase
- No bound-to-bound transition in 'dark QCD' because no $\mathbf{1} \rightarrow \mathbf{1}$ transitions mediated by a gluon (8)

Solutions to Boltzmann equations



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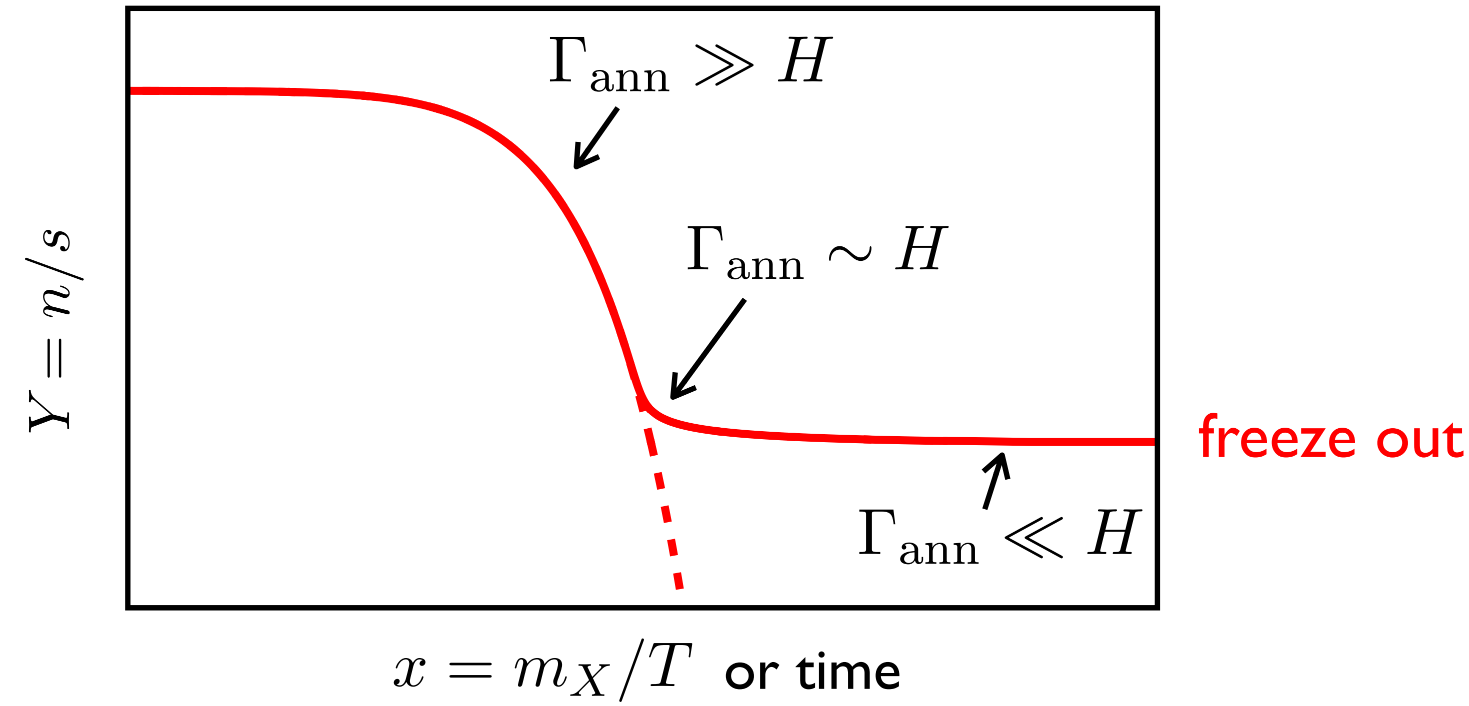
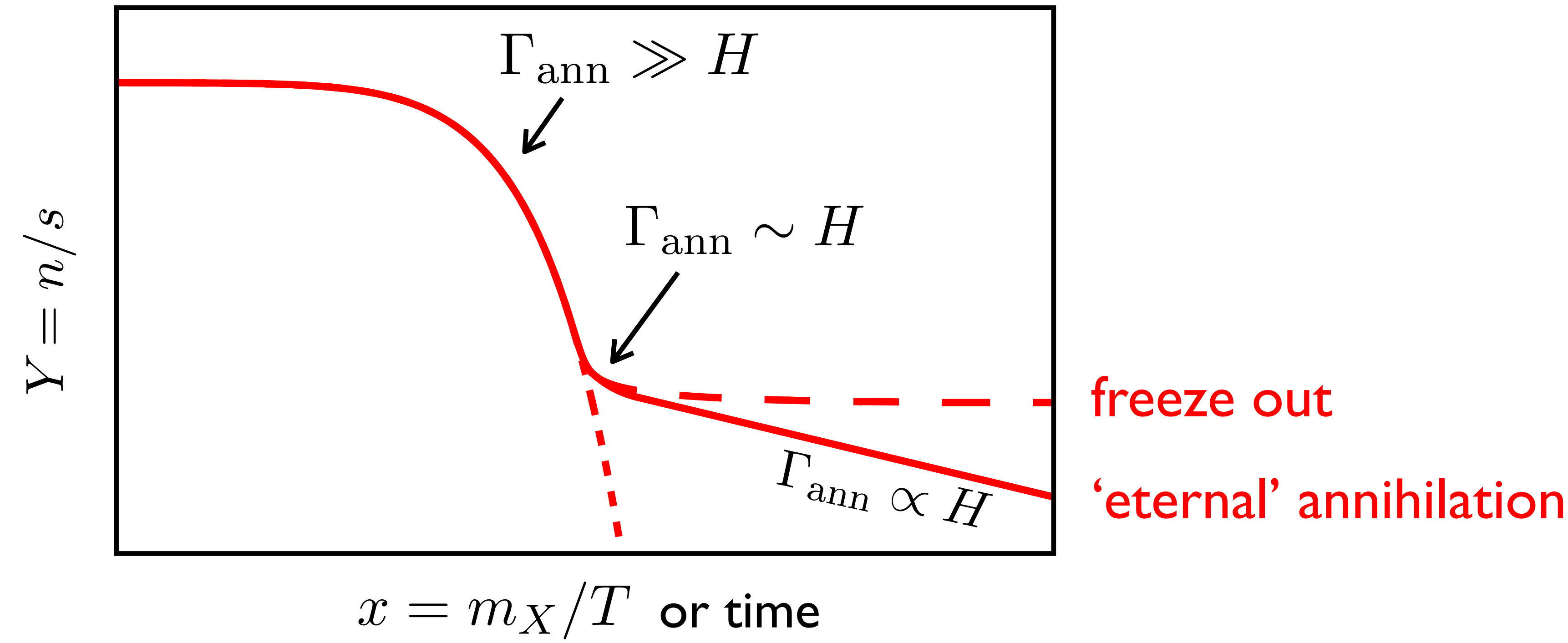


$$\Gamma_{\rm ann} = n_X \langle \sigma v \rangle_{\rm eff} \qquad \text{versus} \qquad H \propto T^2$$

$n \propto T^3$ $\qquad$ $\langle \sigma v \rangle_{\rm eff} \propto T^{-\gamma}$ if $\gamma < 1$

Solutions to Boltzmann equations



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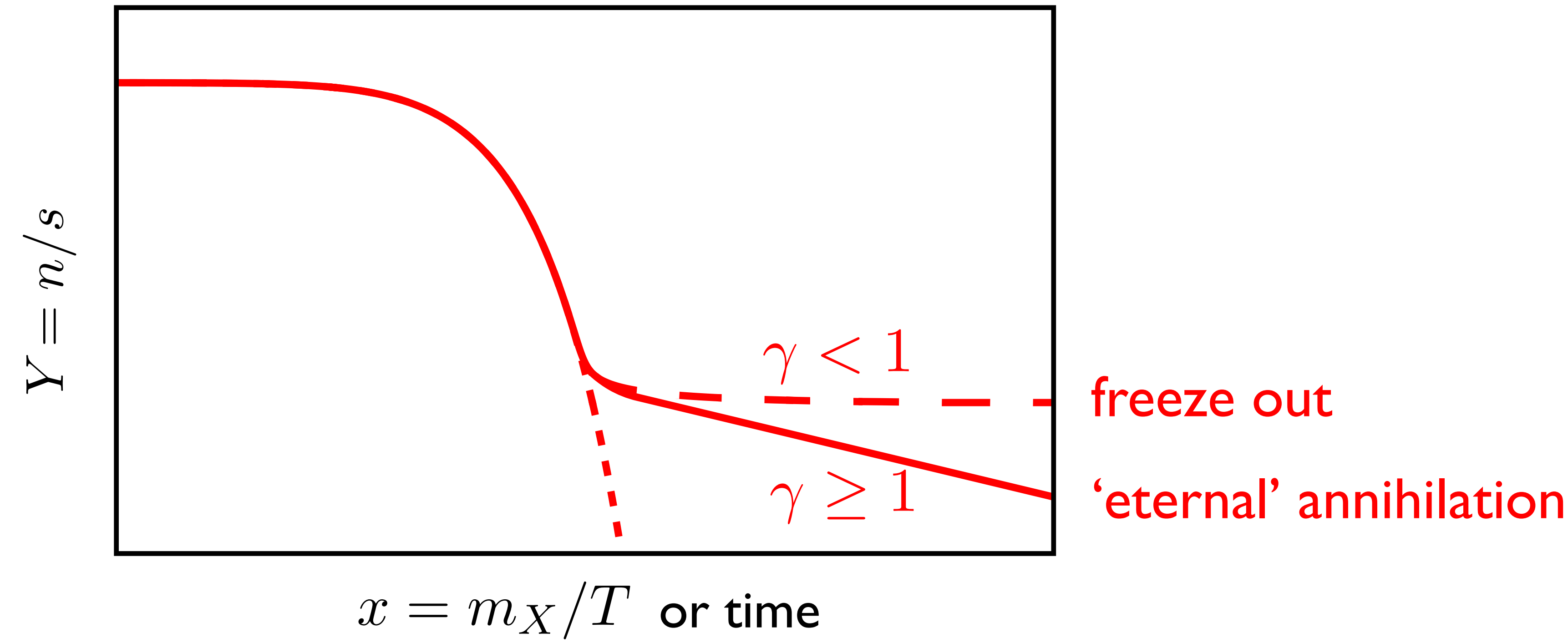
Solutions to Boltzmann equations



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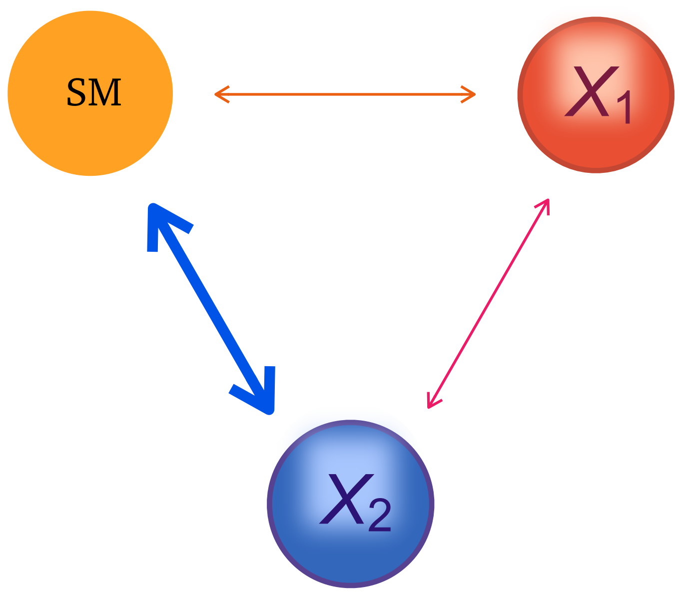
Implications for
t-channel mediator models

t-channel mediator dark matter model

(aka 'charged parent particle model')



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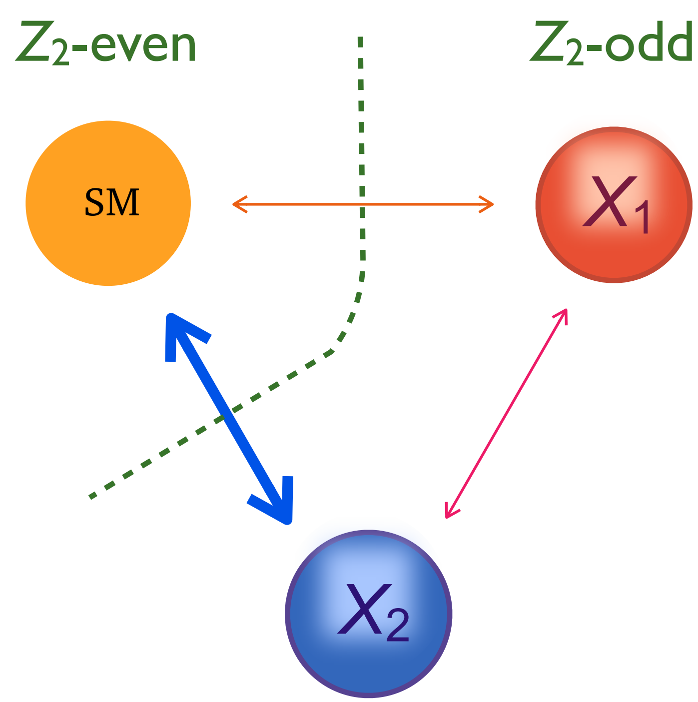

t-channel mediator dark matter model

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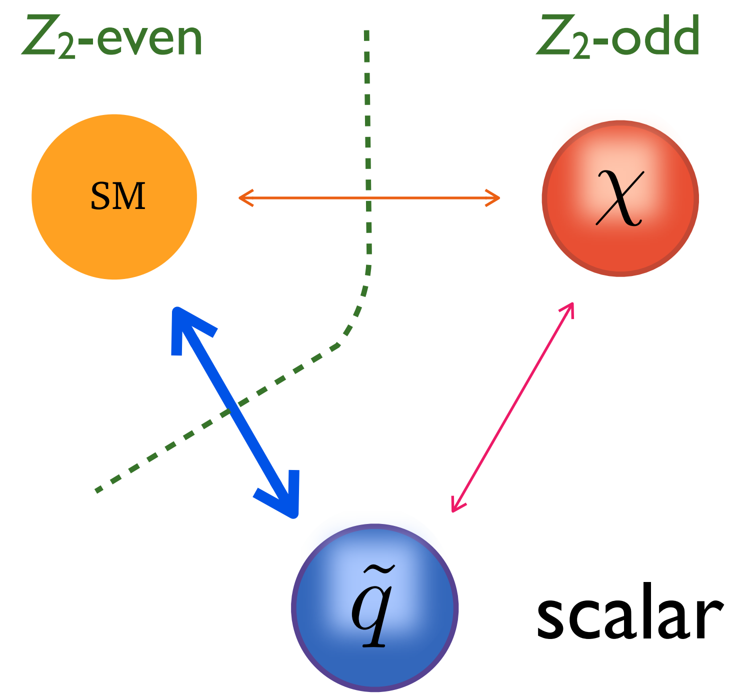
Supersymmetry-inspired simplified model



Majorana DM

$m_\chi < m_{\tilde{q}}$

scalar quark-partner

t-channel mediator dark matter model

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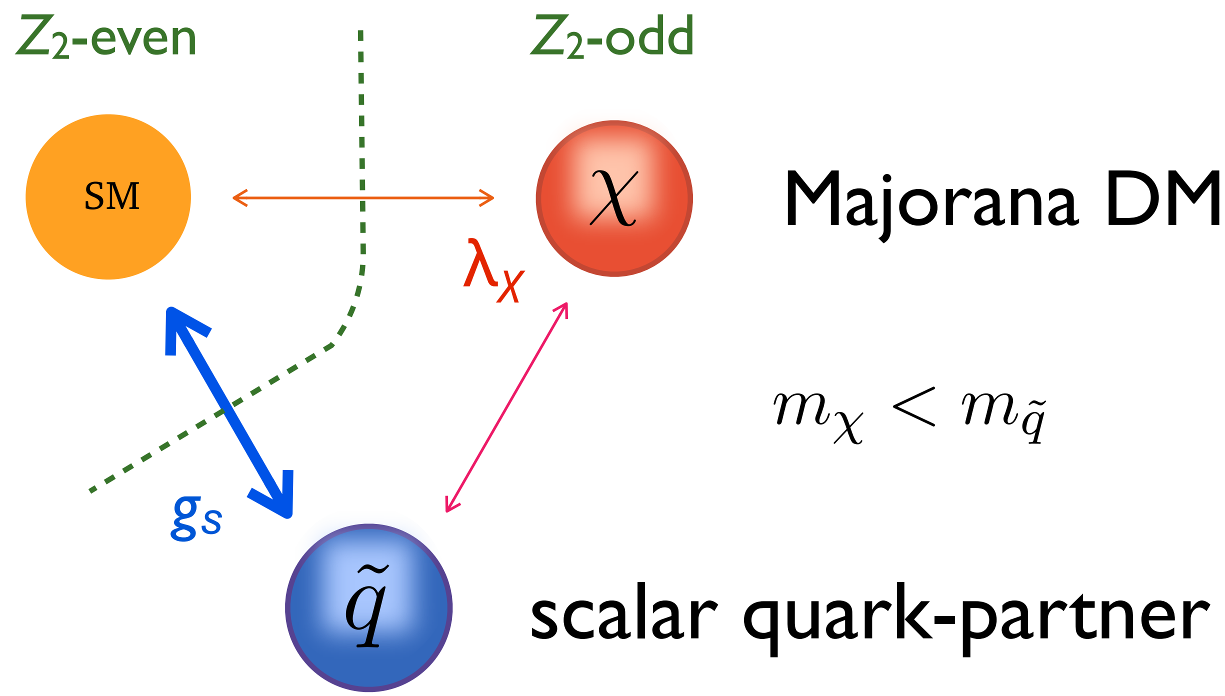
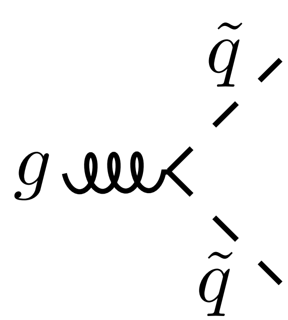
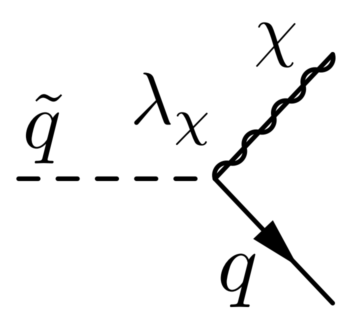
Supersymmetry-inspired simplified model



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





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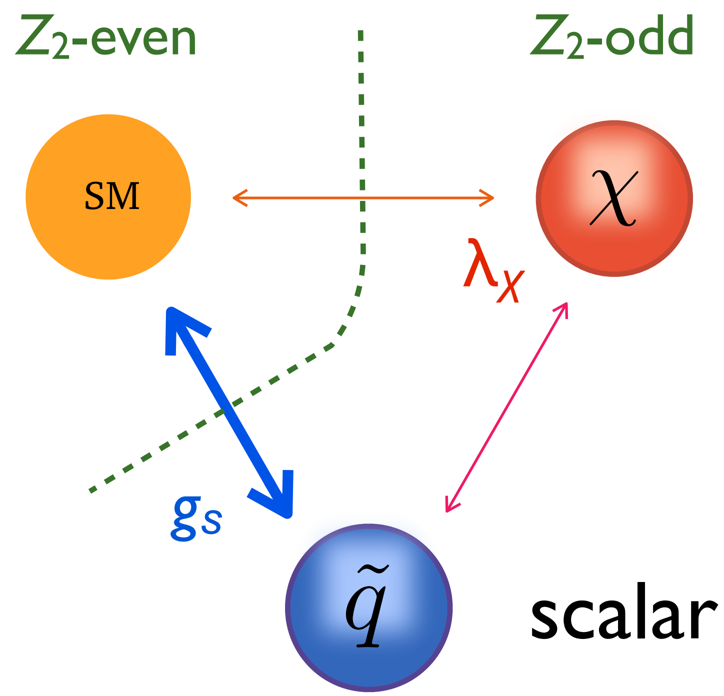

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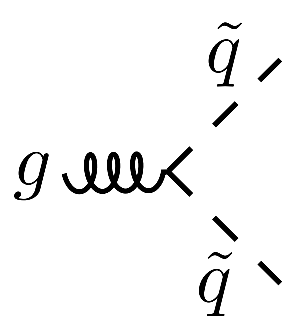
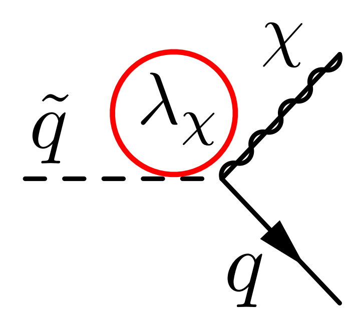
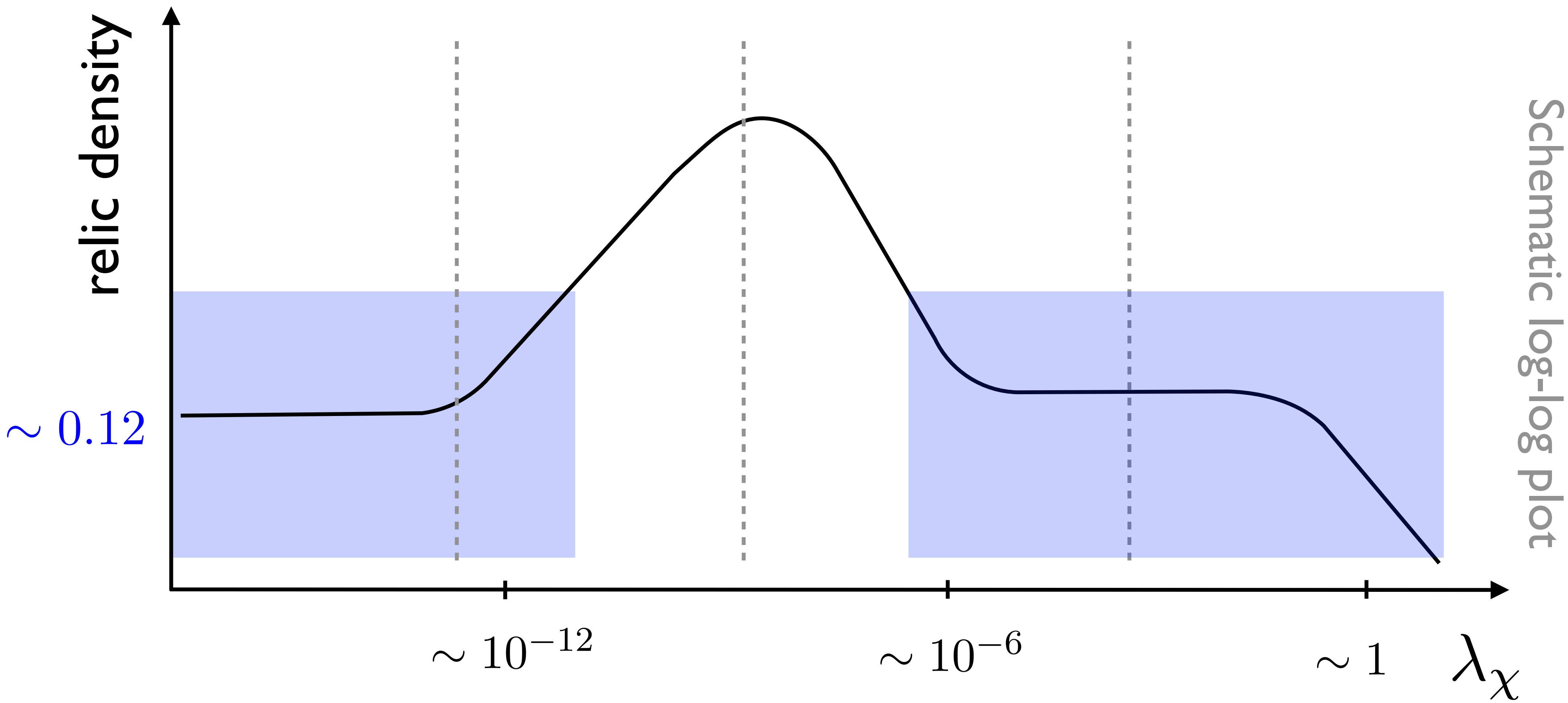




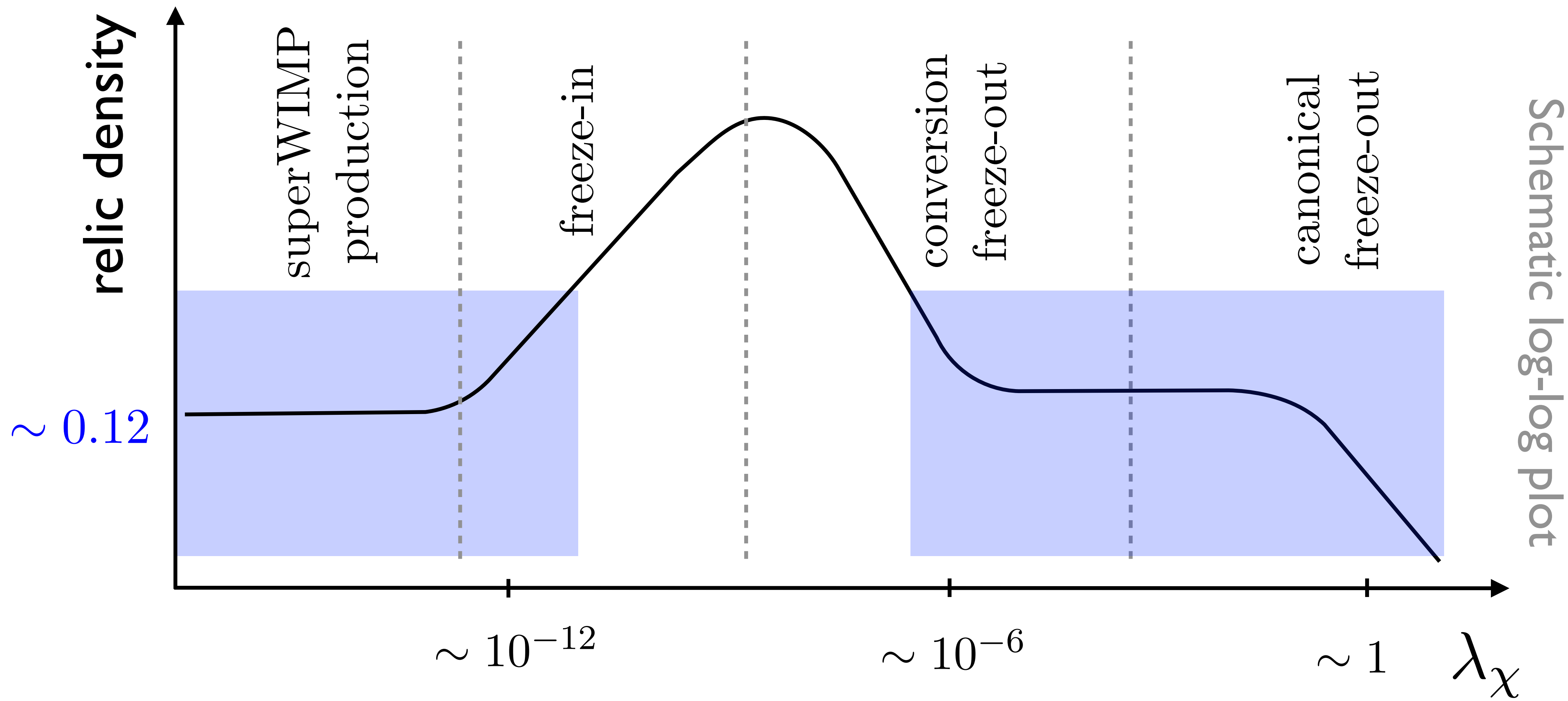
Unlike MSSM, λ_χ free parameter

t-channel models: Dark matter production scenarios



huge range of allowed couplings λ_χ!

t-channel models: Dark matter production scenarios



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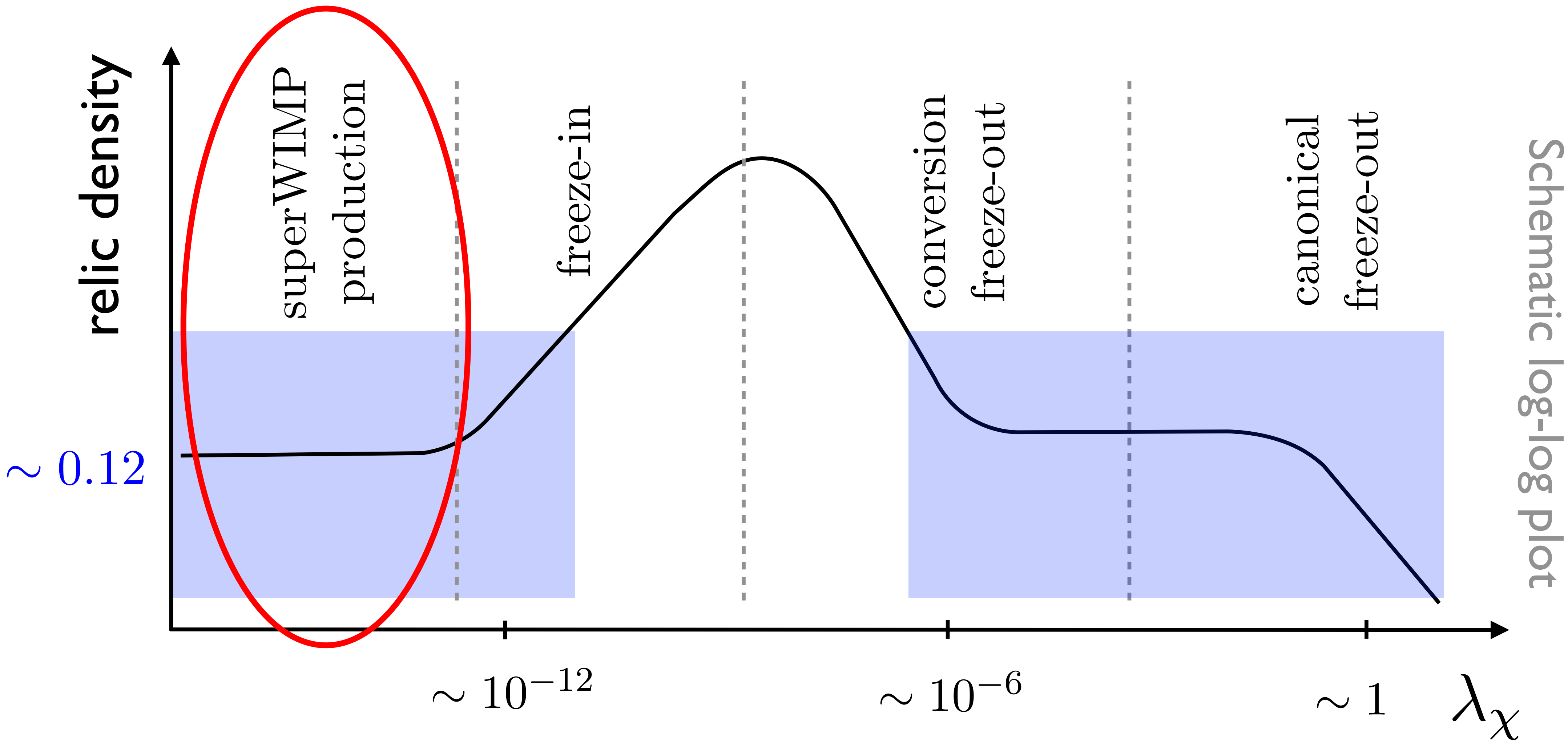
t-channel models: Dark matter production scenarios

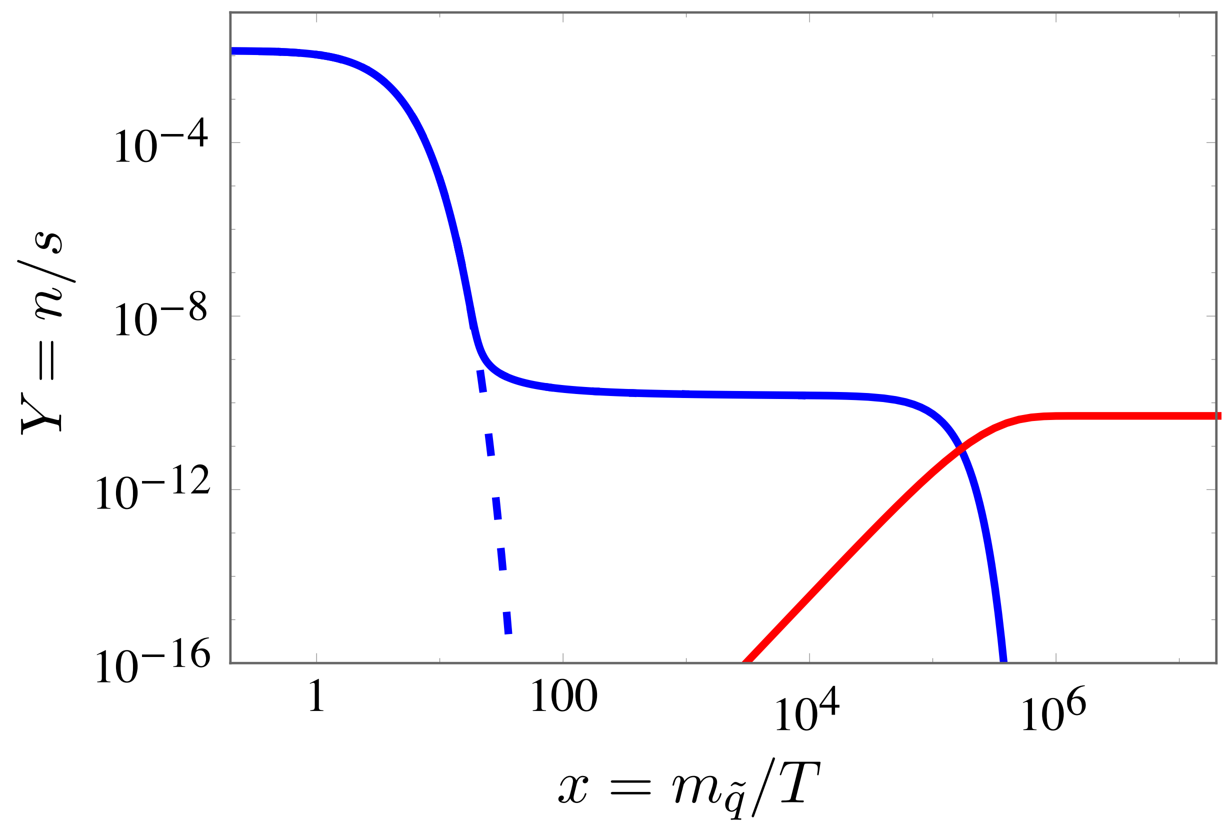


huge range of allowed couplings λ_χ!

superWIMP scenario

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

- Coupling $\lambda_\chi \sim 10^{-16}$–$10^{-10}$, dark matter thermally decoupled
- Produced in late decays of frozen out $\tilde{q}$
  $\Rightarrow$ Relic density independent of λ_χ



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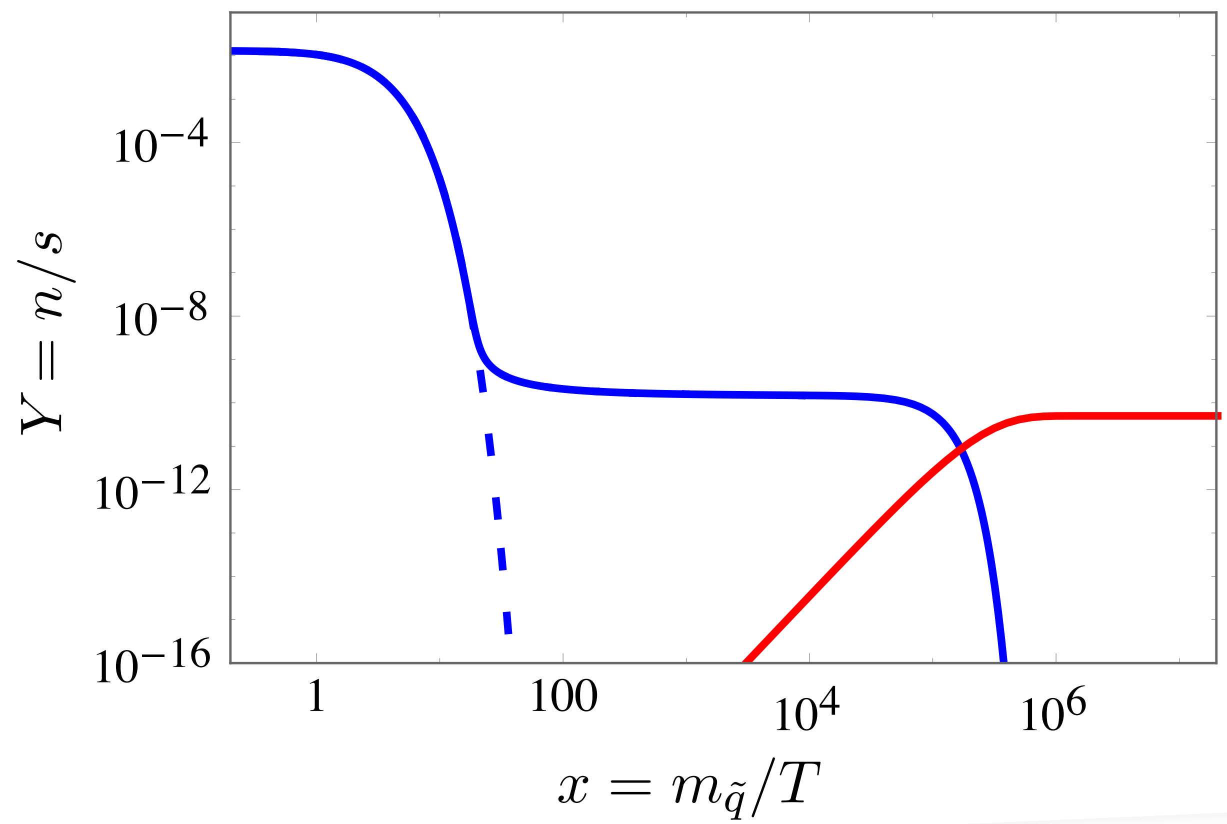
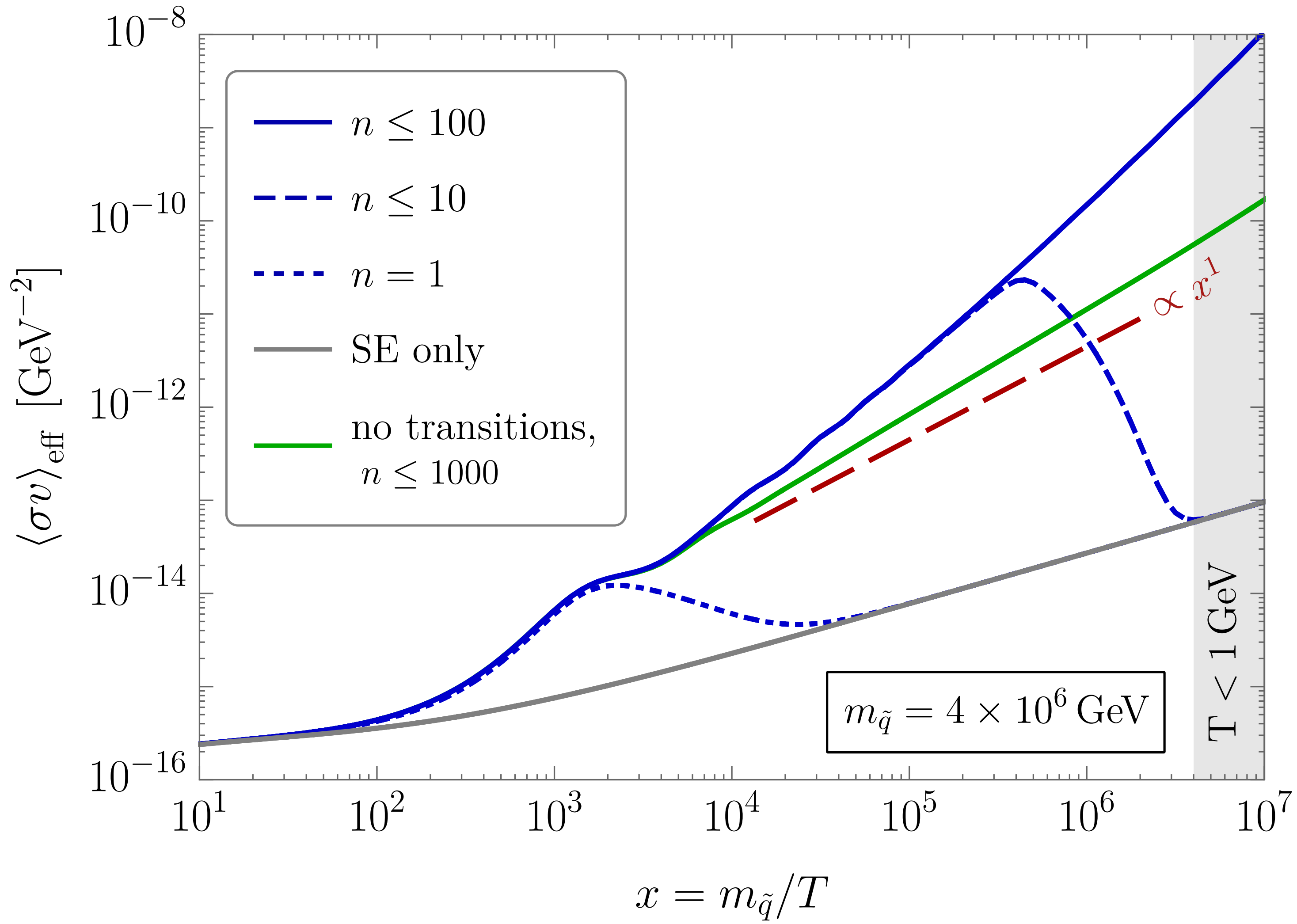


Does the picture change with bound states?

Effective annihilation cross section

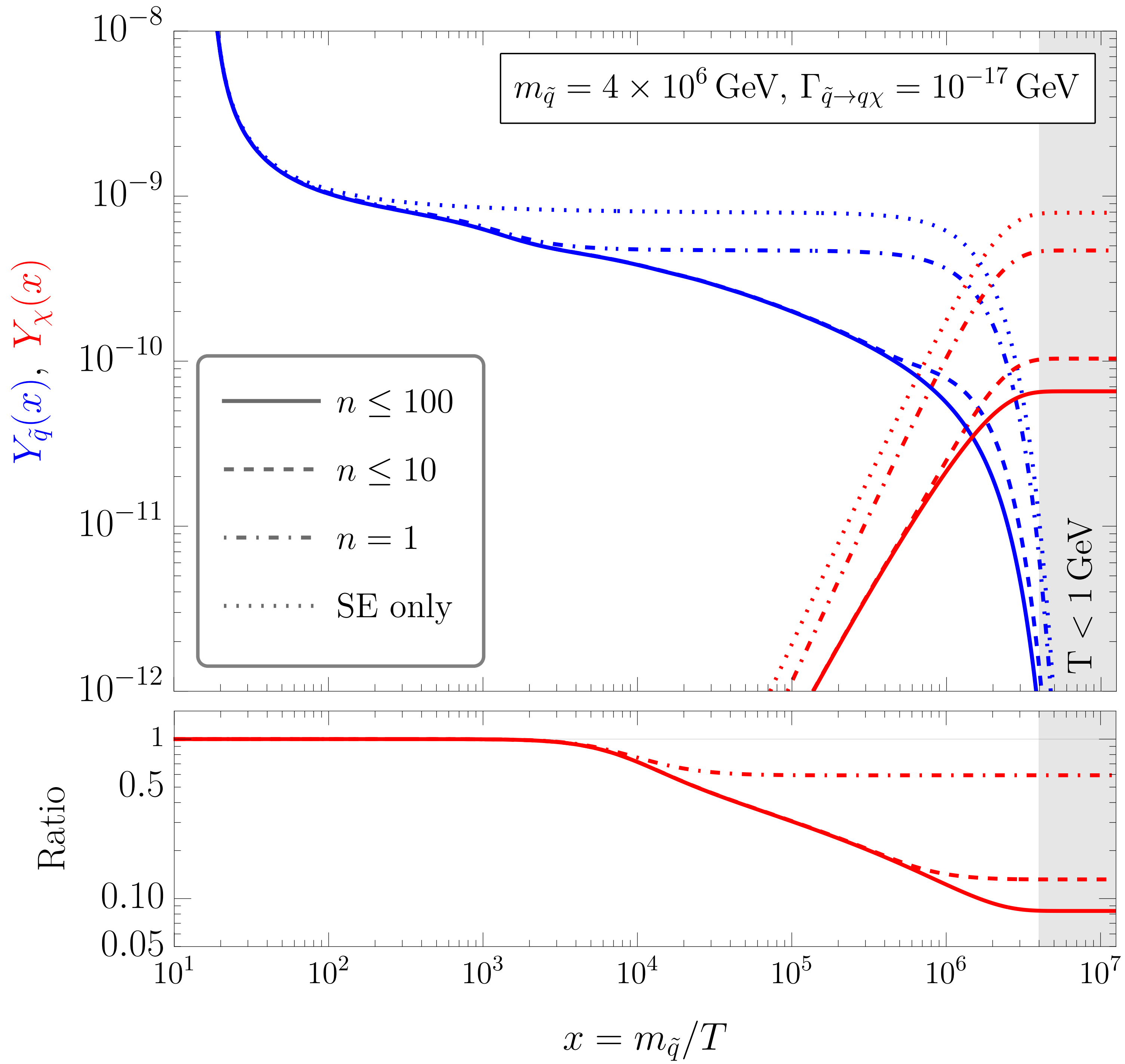
[Binder, Garny, JH, Lederer, Urban 2308.01336]



- $\tilde{q}$ also electrically charged: dipole transitions $\mathcal{B}_{nl} \leftrightarrow \mathcal{B}_{n'l'}$ via photons
  $\Rightarrow$ High impact on slope, super-critical (even w/o running)
- No unitarity-violating XS involved in unconfined phase, *i.e.* $T > \Lambda_{\mathrm{QCD}}$

Impact on the relic abundance

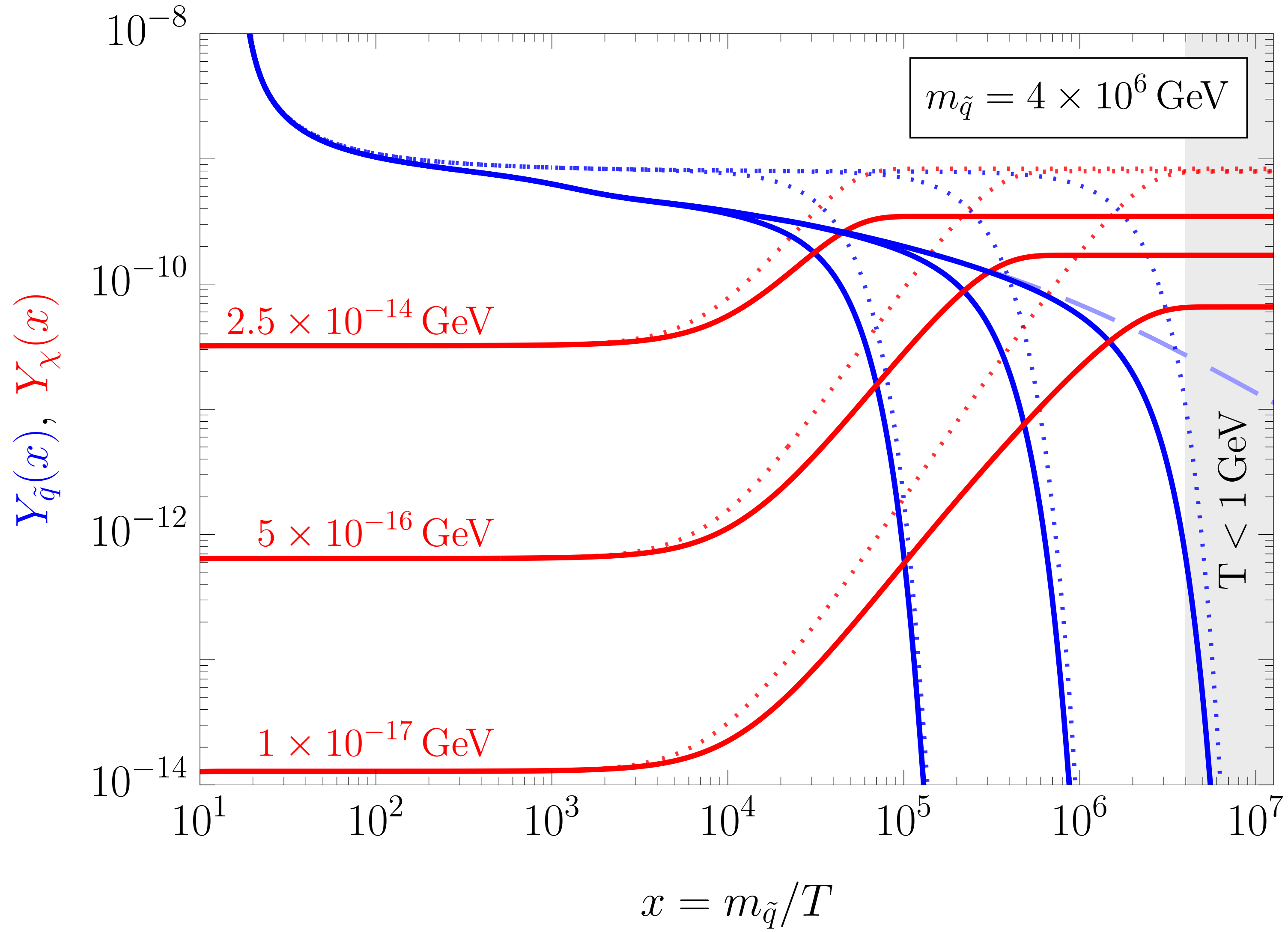
[Binder, Garny, JH, Lederer, Urban 2308.01336]



- Excited bound states highly relevant
- No freeze-out before decay ($T_{\mathrm{decay}} > 1\mathrm{GeV}$)
- Order-of-magnitude effect on relic density

Impact on the relic abundance

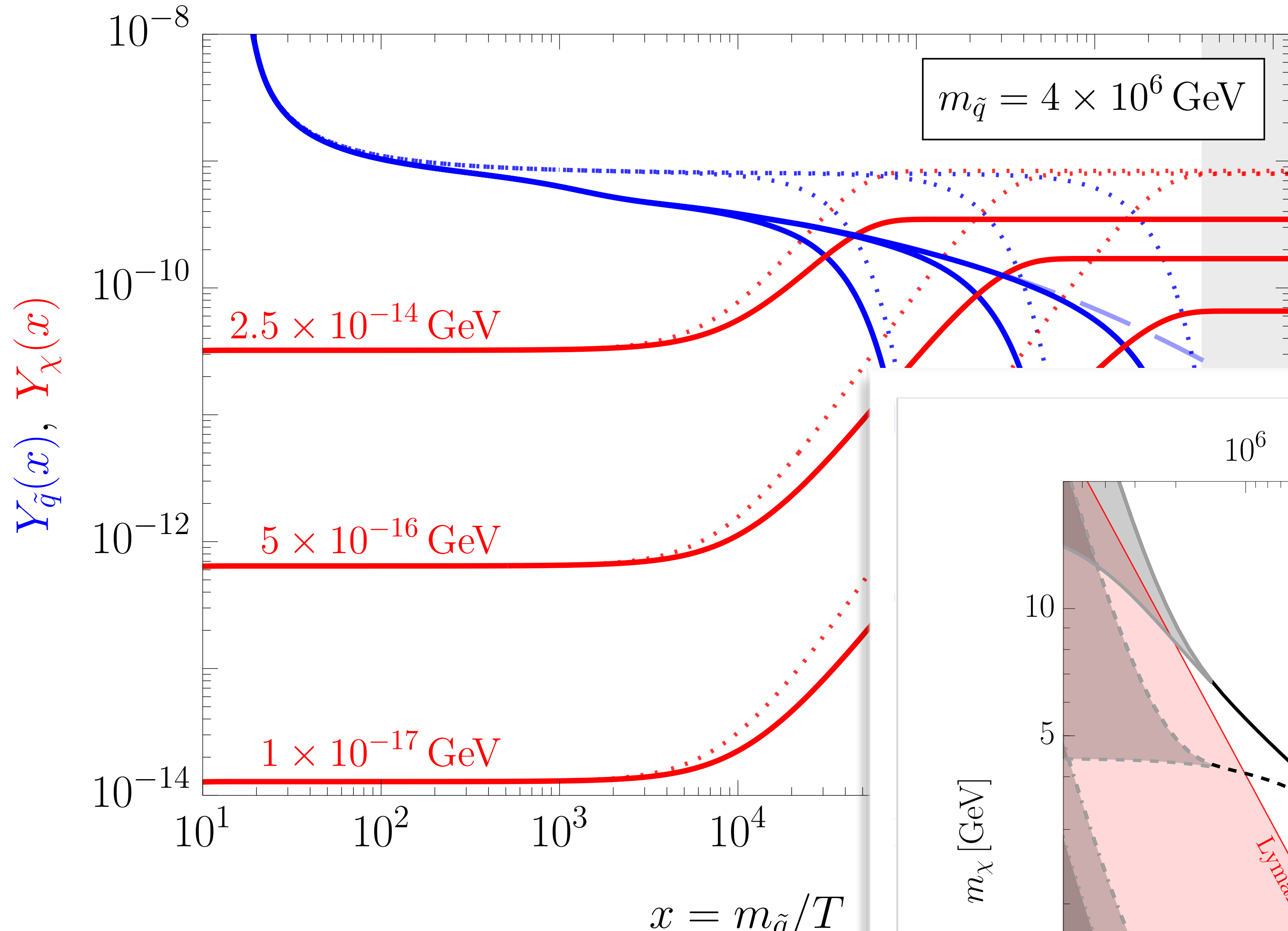
[Binder, Garny, JH, Lederer, Urban 2308.01336]



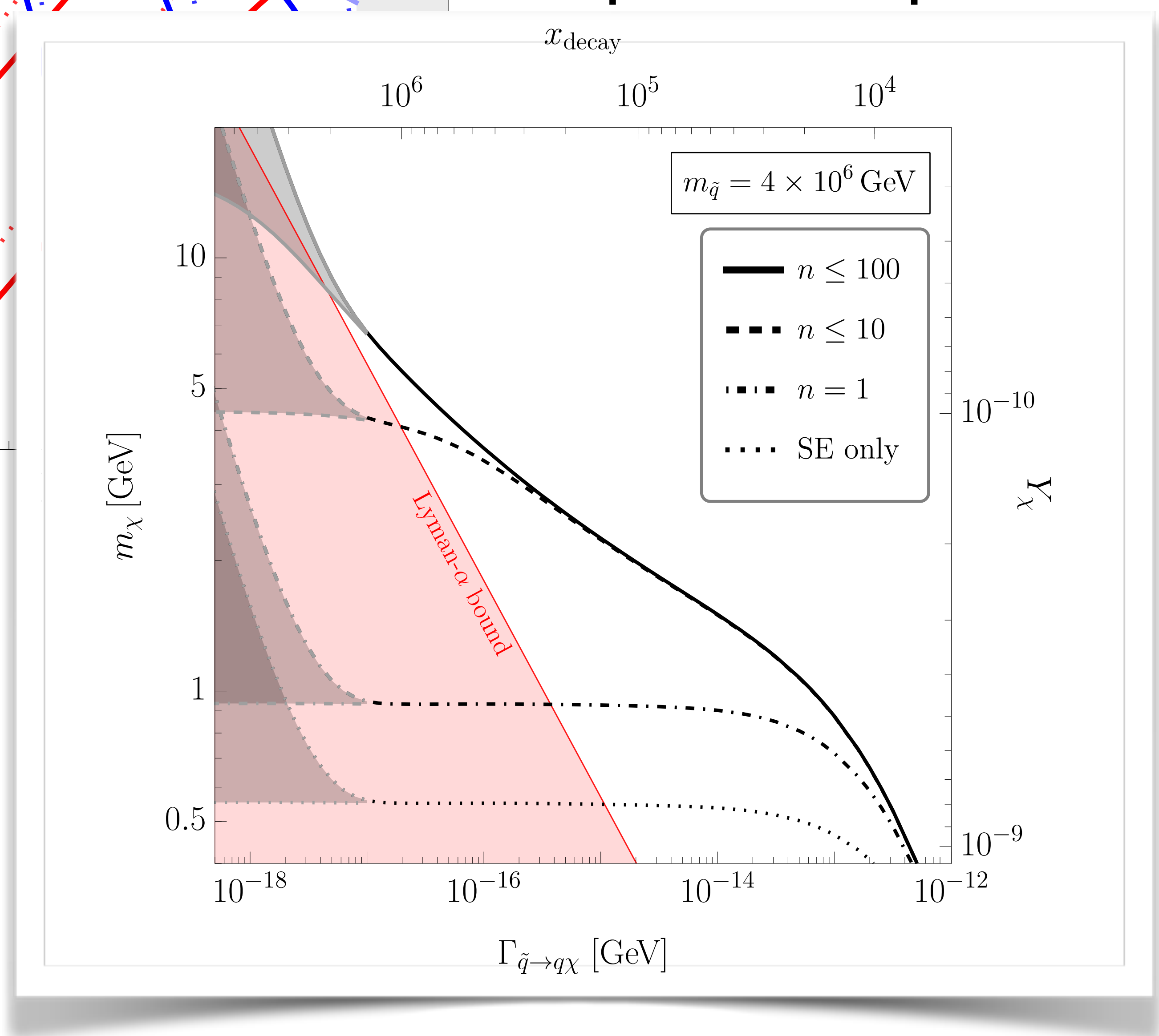
Bound states introduce dependence on λ_χ in superWIMP production!

Impact on the relic abundance

[Binder, Garny, JH, Lederer, Urban 2308.01336]

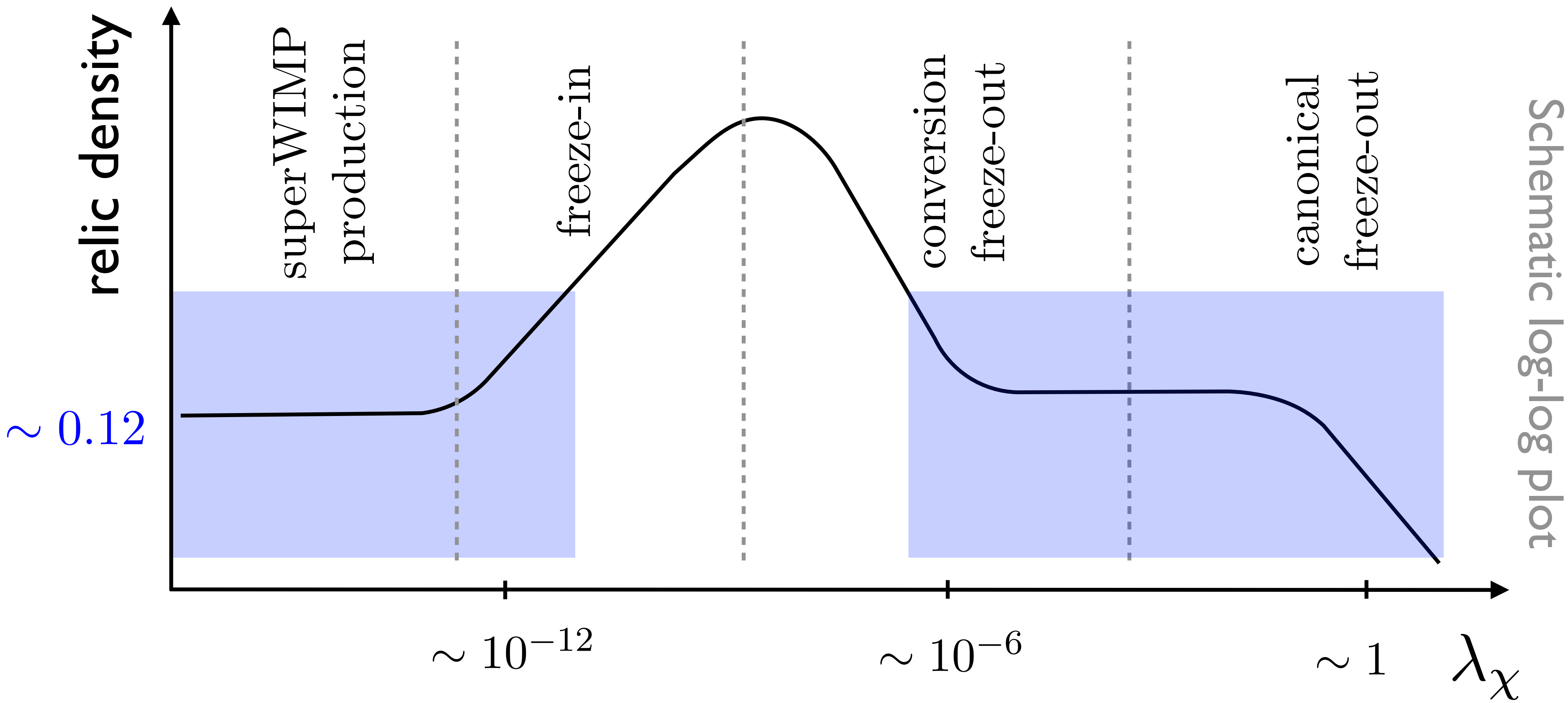


Bound states introduce dependence on λ_χ in superWIMP production!



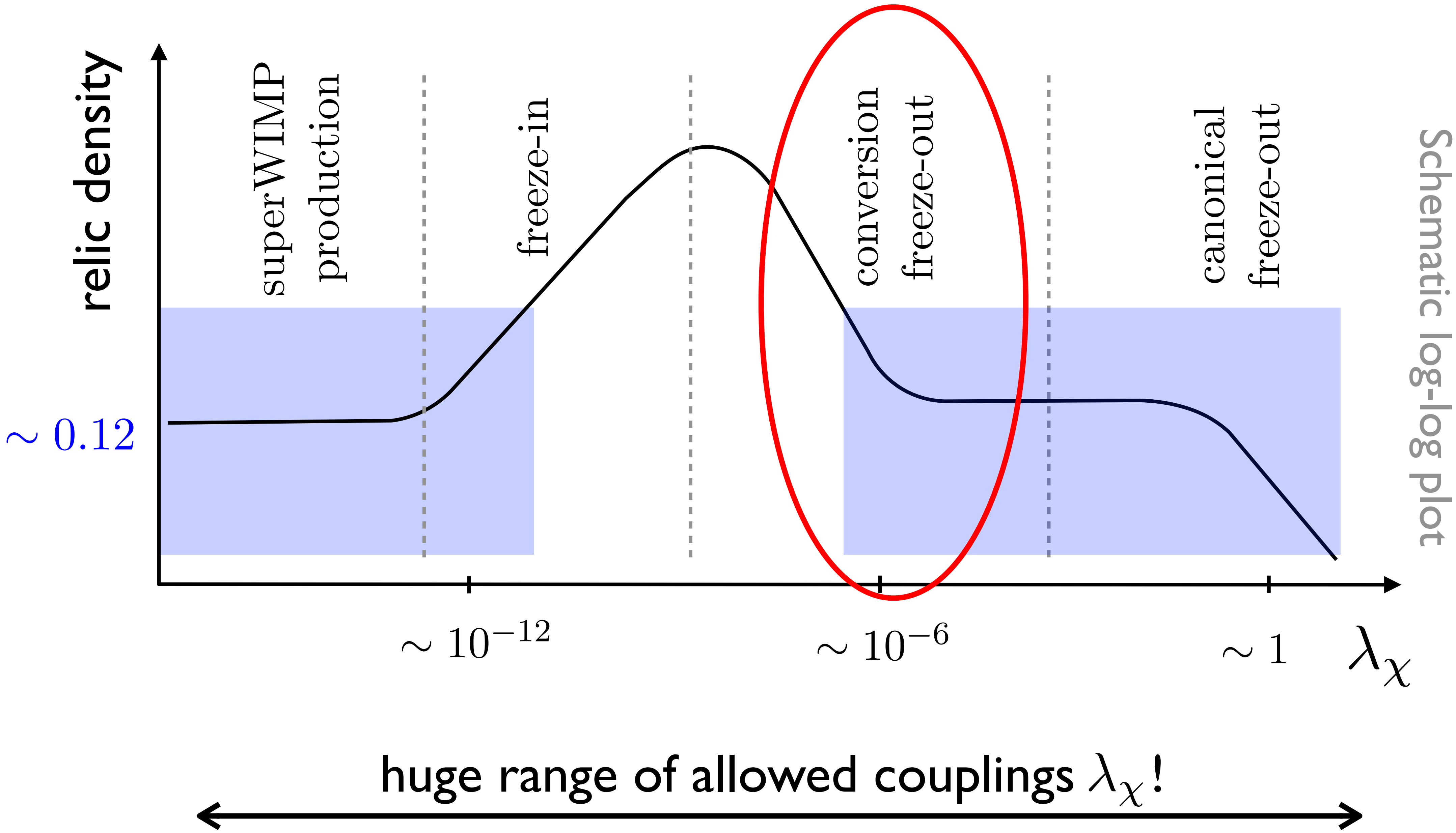
Relevant for constraints from cosmological structure formation (Lyman-alpha forest observations)

t-channel models: Dark matter production scenarios



huge range of allowed couplings λ_χ!

t-channel models: Dark matter production scenarios

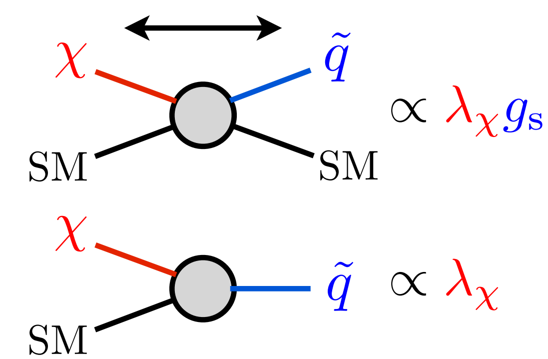


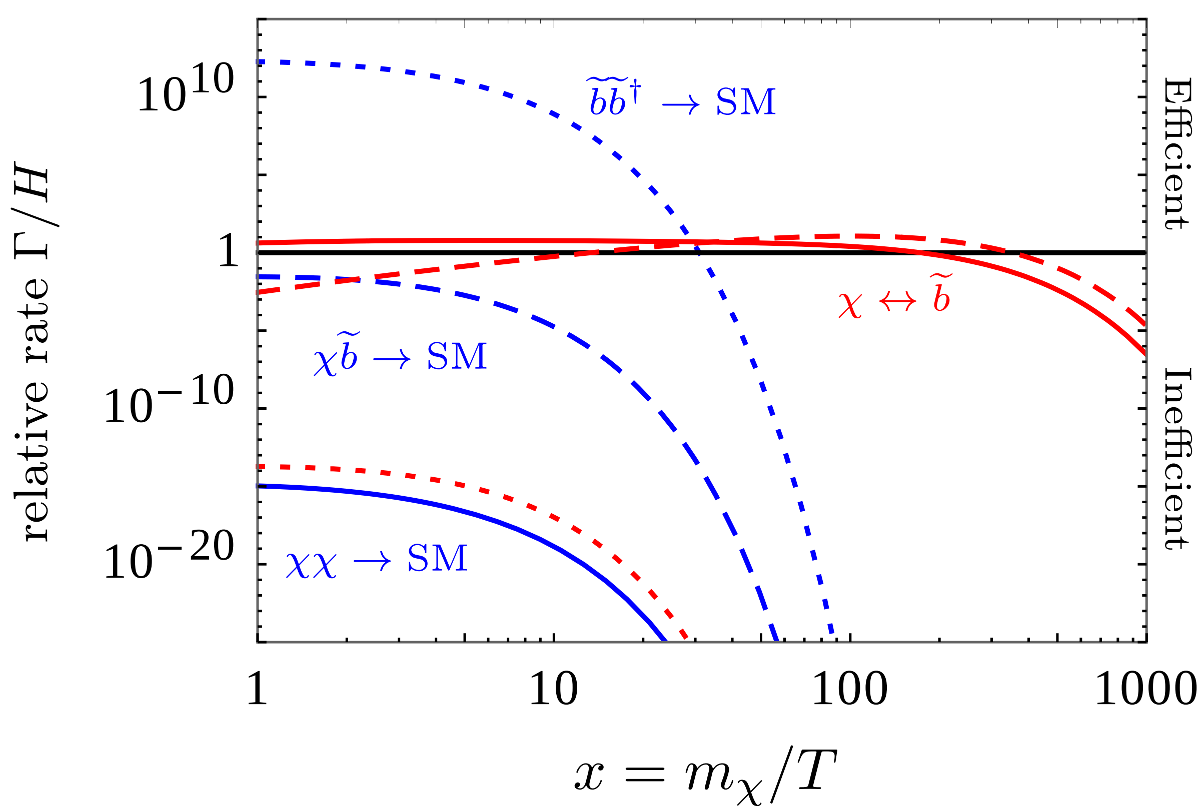
Conversion-driven freeze-out

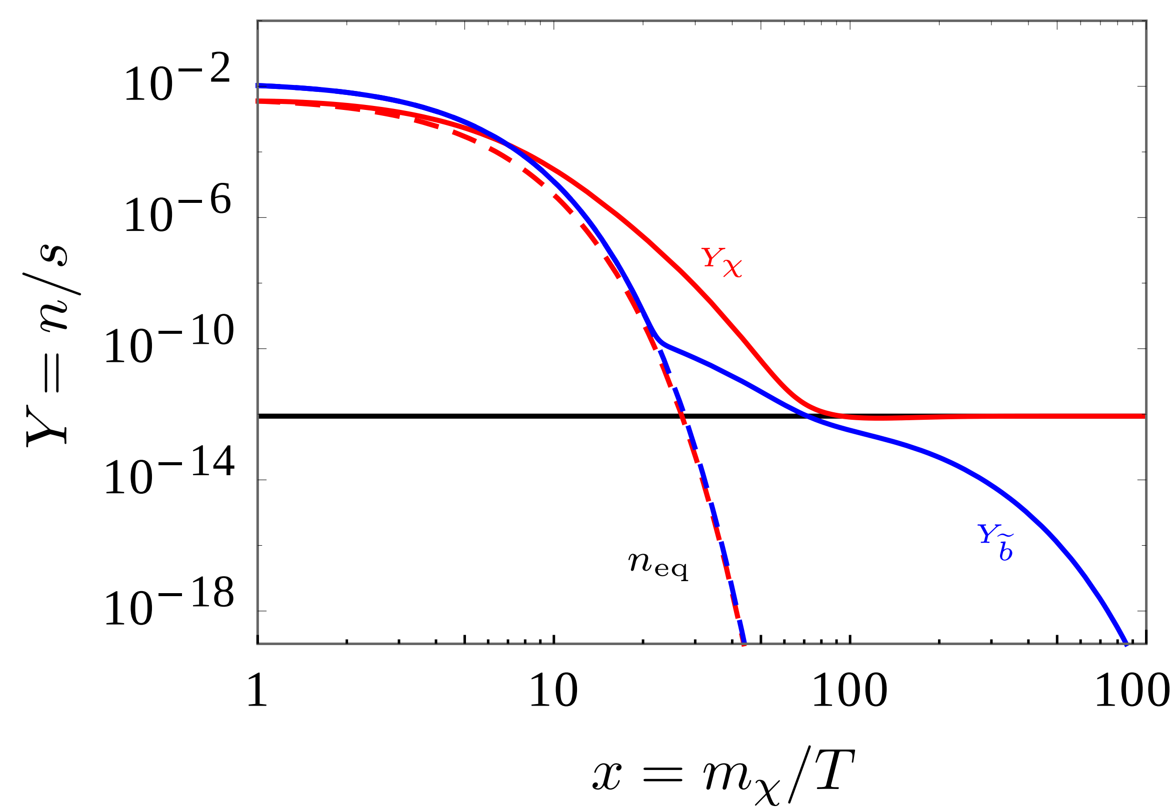
[Garny, JH, Lülf, Vogl 2017; D'Agnolo, Pappadopulo, Ruderman 2017]

- Coupling $\lambda_\chi \sim 10^{-6}$ just large enough to thermalize dark matter
- Conversions on the edge of being efficient $\Gamma \sim H$, initiate chemical decoupling
  $\Rightarrow$ prolonged freeze-out process

Conversion processes:







Conversion-driven freeze-out

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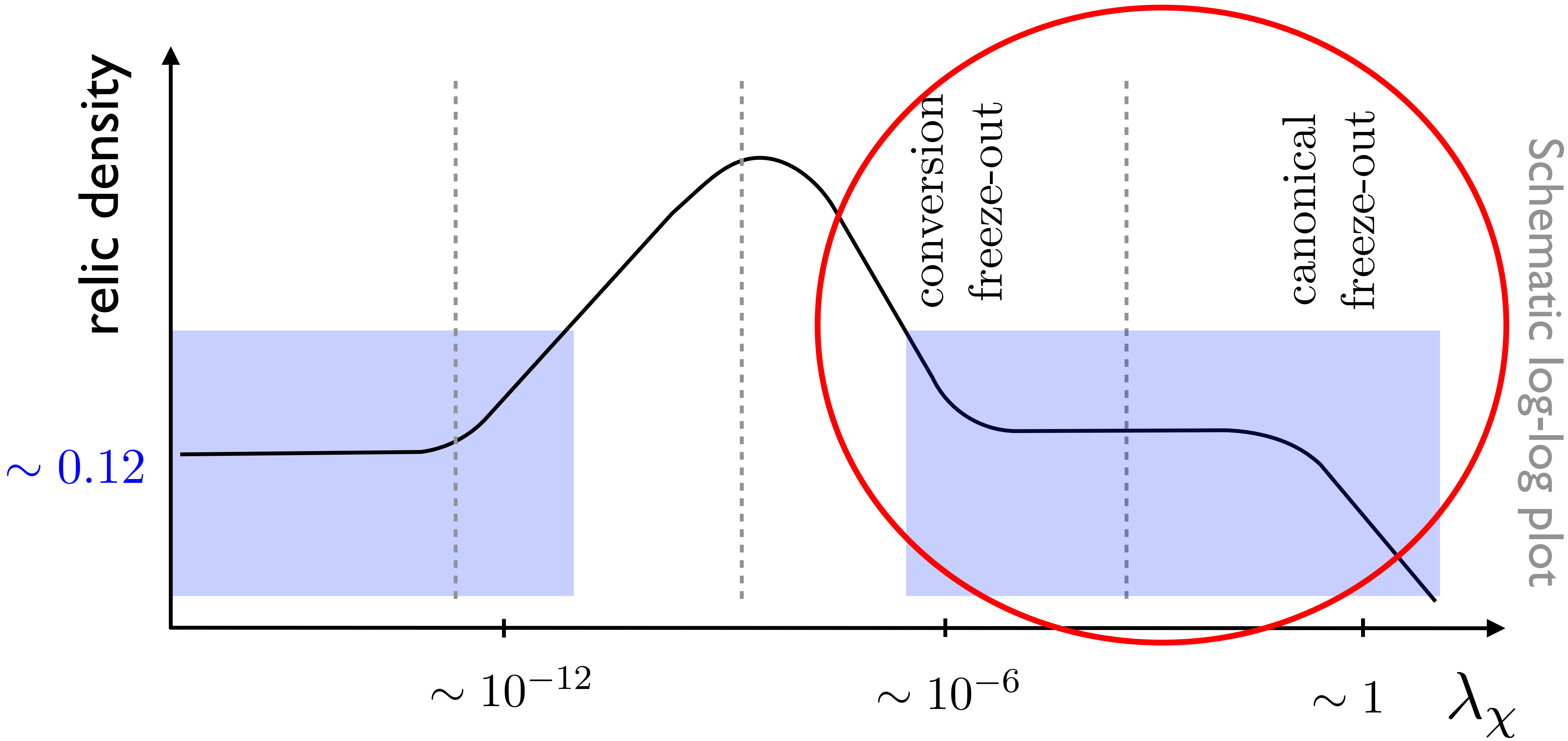

Conversion-driven freeze-out

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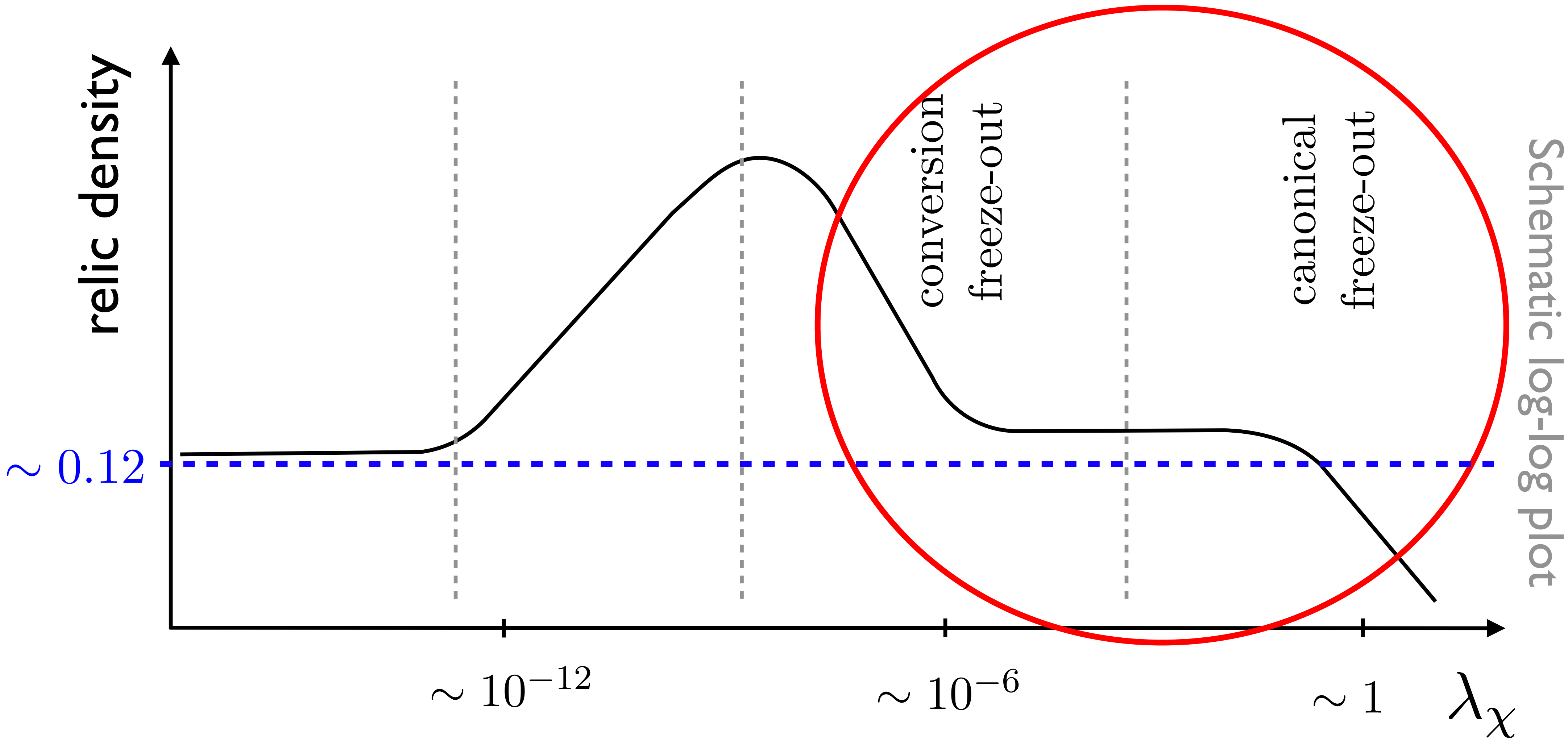
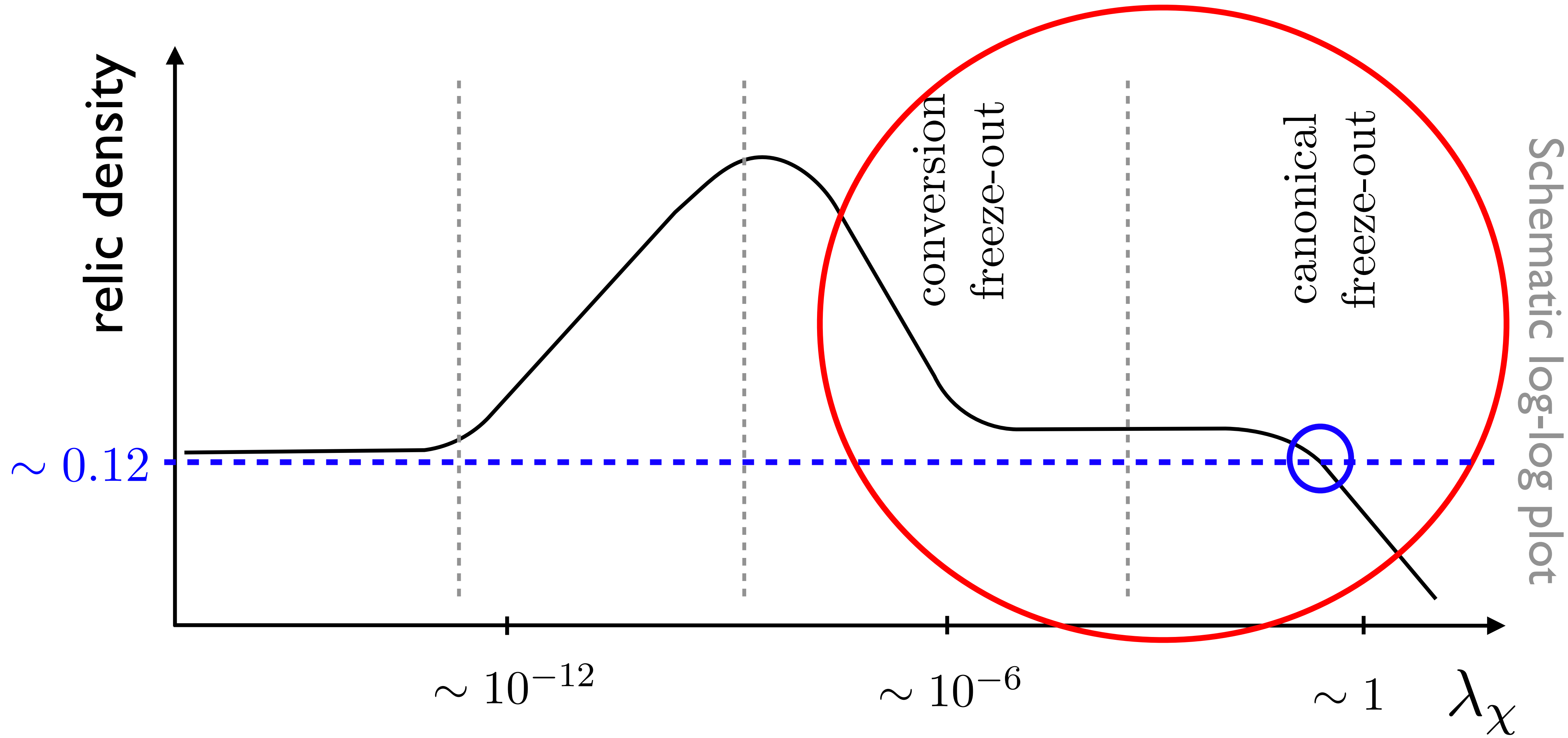


Conversion-driven freeze-out

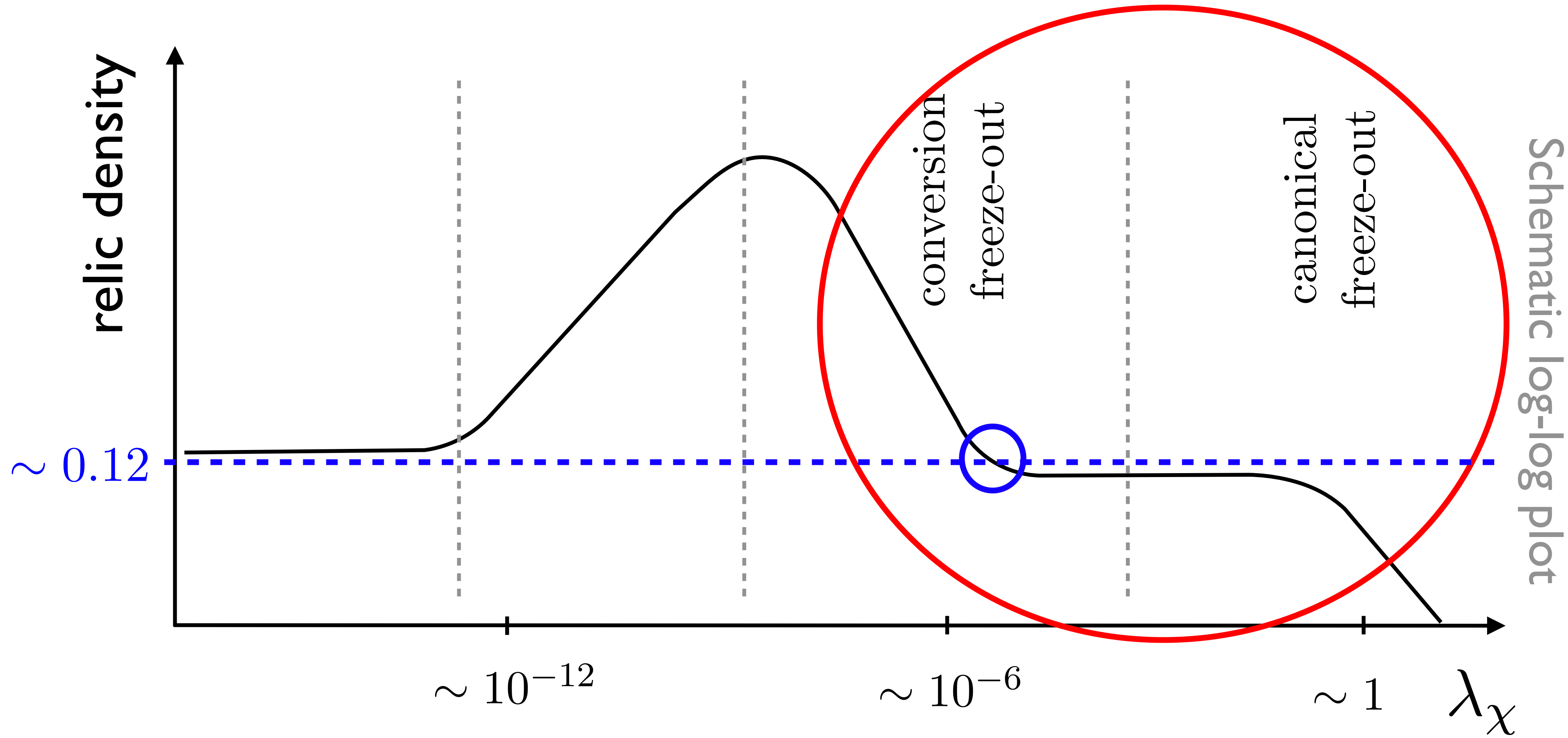
[Garny, JH, Lülf, Vogl 2017; D'Agnolo, Pappadopulo, Ruderman 2017]



Large mass splittings $\Delta m = m_{\tilde{q}} - m_\chi$ require large λ_χ

Conversion-driven freeze-out

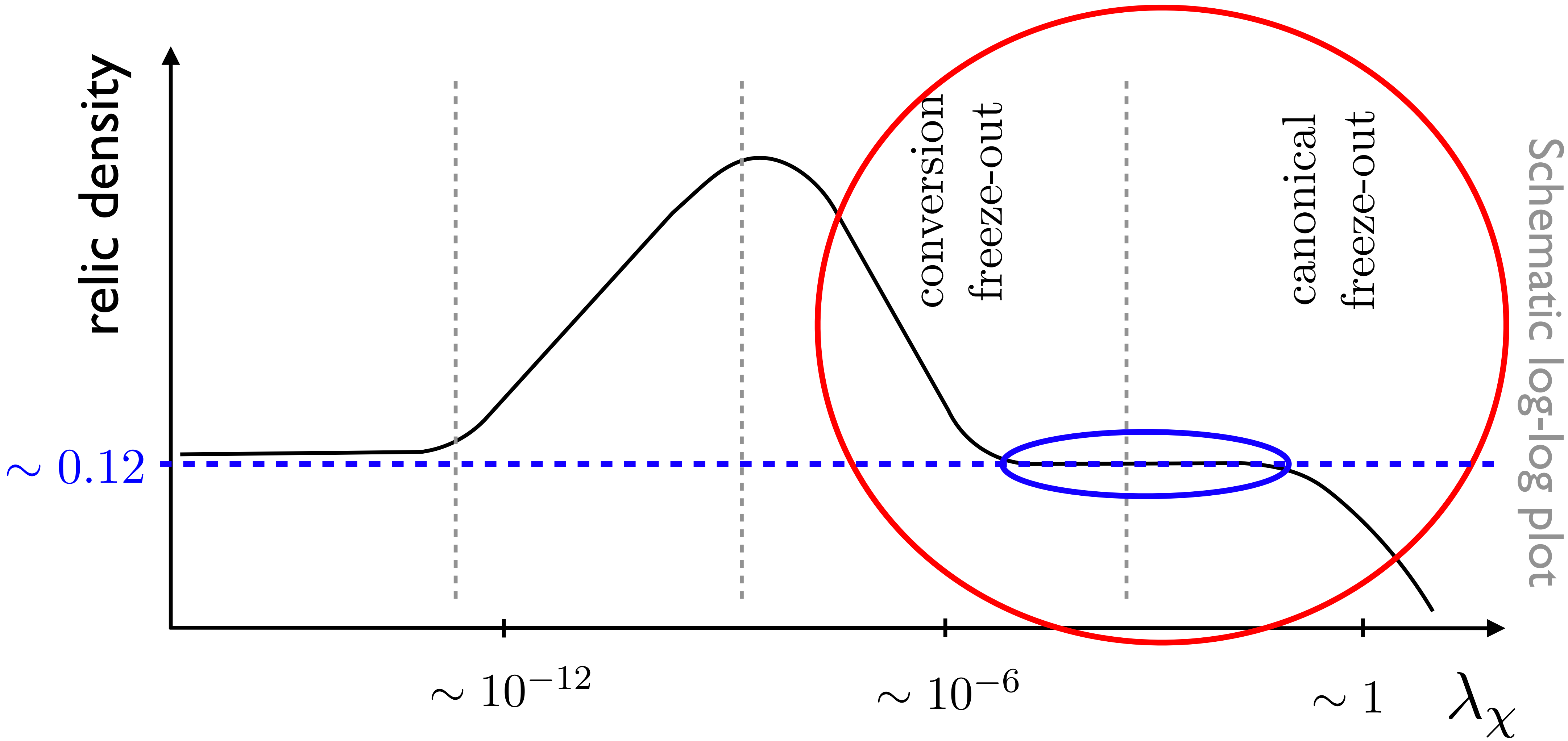
[Garny, JH, Lülf, Vogl 2017; D'Agnolo, Pappadopulo, Ruderman 2017]



Smaller mass splittings $\Delta m = m_{\tilde{q}} - m_\chi$ require much smaller λ_χ: sudden drop in the coupling!

Conversion-driven freeze-out

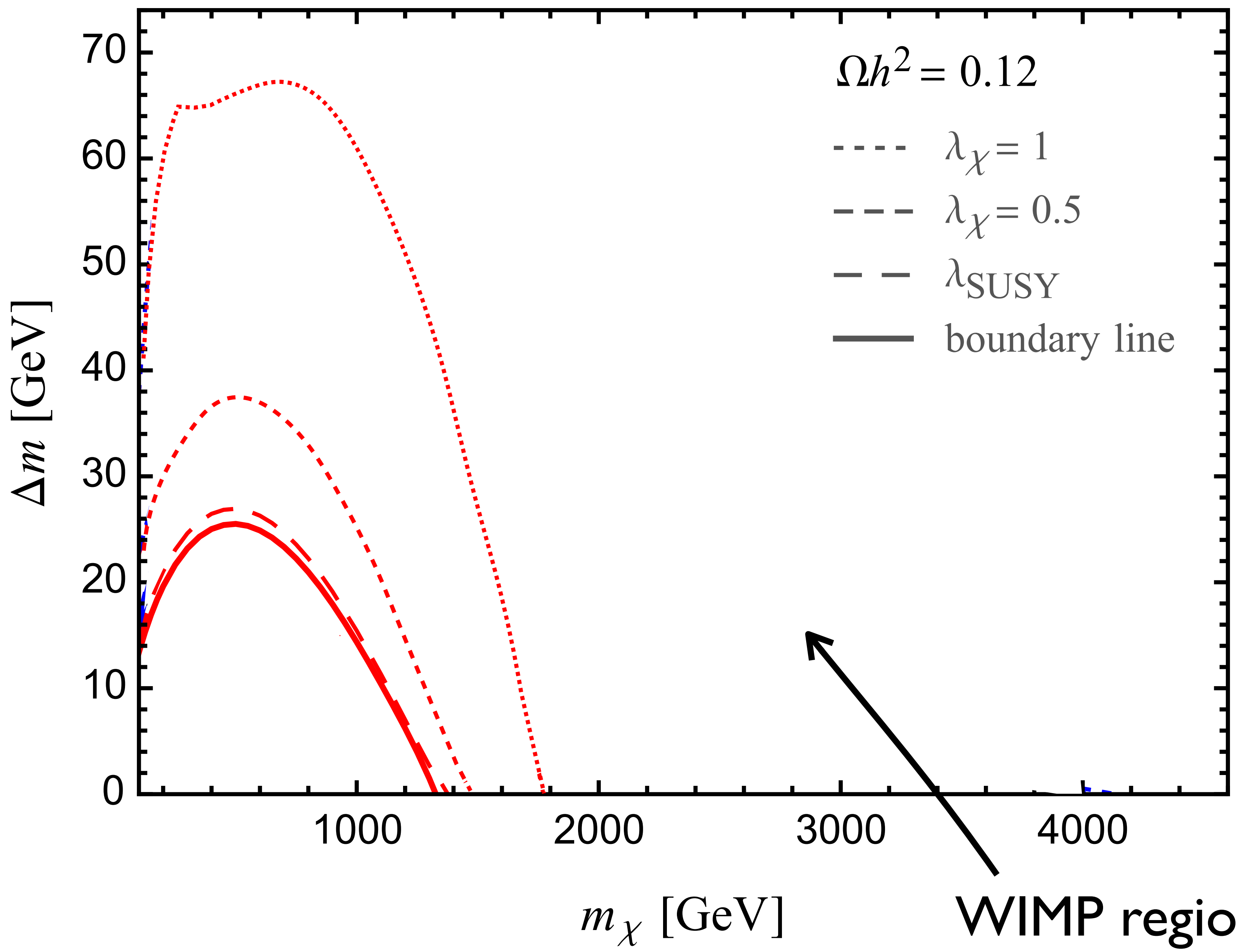
[Garny, JH, Lülf, Vogl 2017; D'Agnolo, Pappadopulo, Ruderman 2017]



Boundary between WIMP and conversion-driven region at characteristic $\Delta m = m_{\tilde{q}} - m_\chi$

Bound state effects on the parameter space

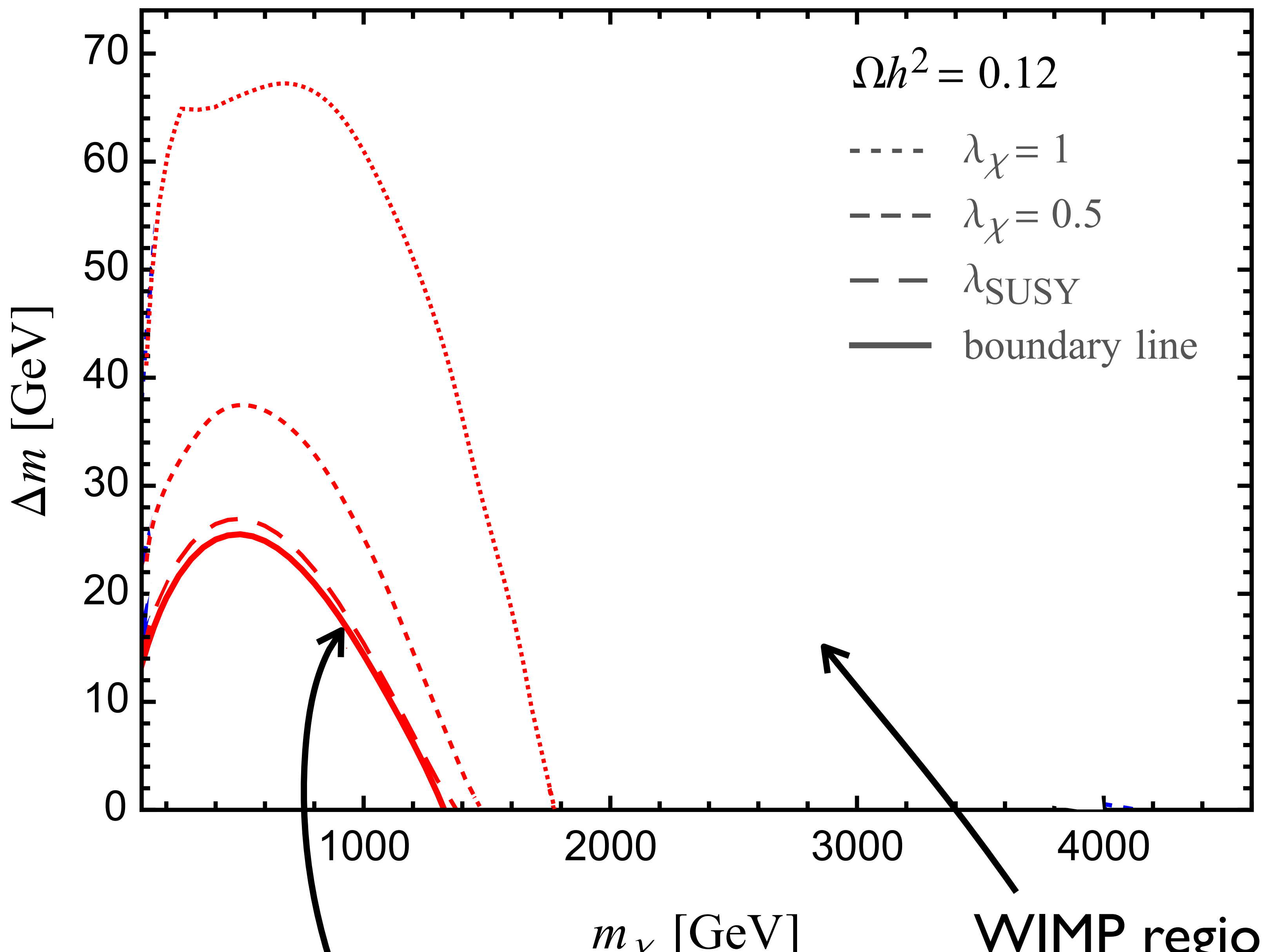
[Garny, JH 2112.01499]



WIMP region $\lambda_\chi \sim \mathcal{O}(1)$

Bound state effects on the parameter space

[Garny, JH 2112.01499]

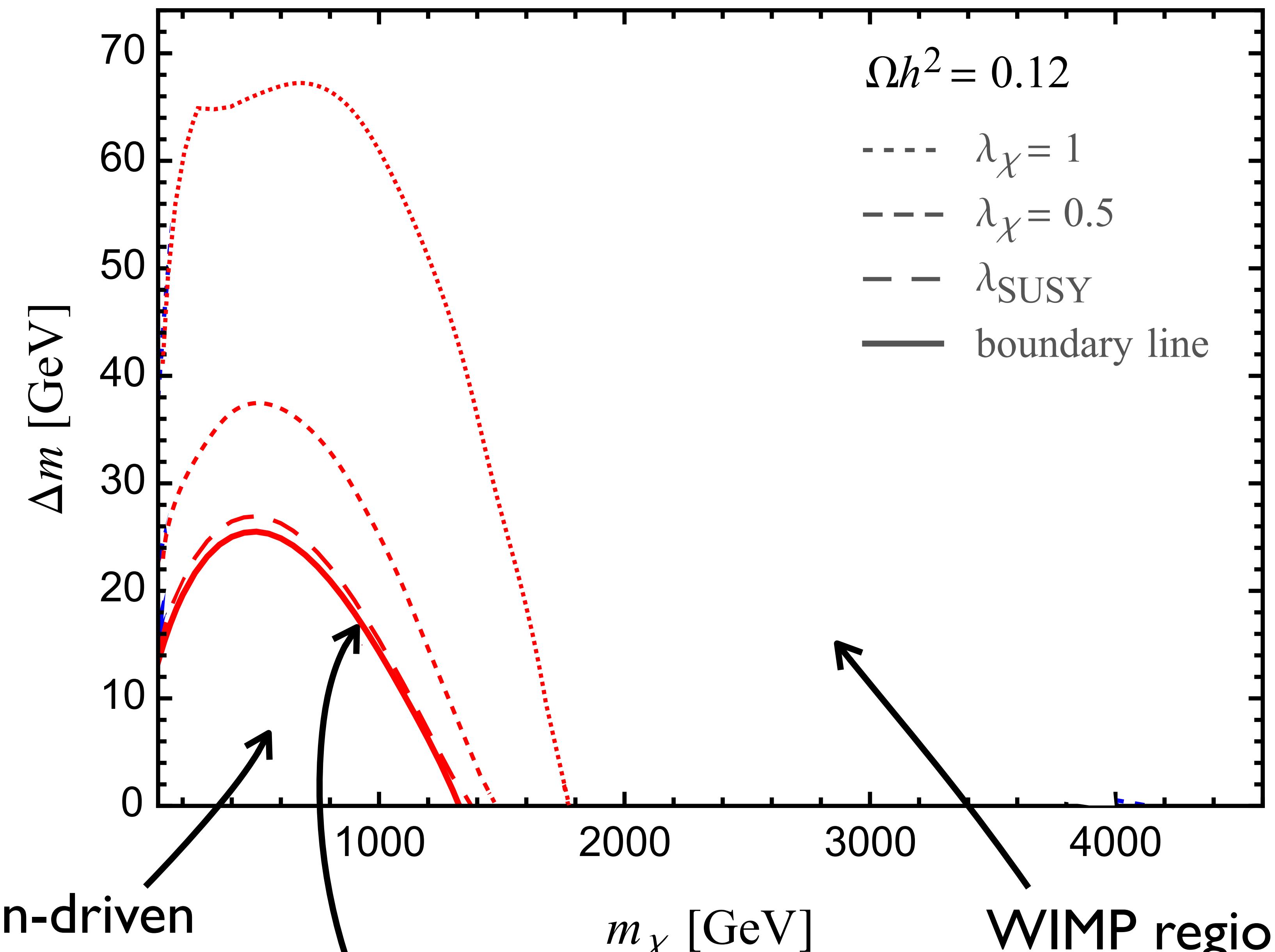


WIMP region $\lambda_\chi \sim \mathcal{O}(1)$

Boundary, λ_χ drops from $\mathcal{O}(1)$ to $\sim 10^{-6}$

Bound state effects on the parameter space

[Garny, JH 2112.01499]



Conversion-driven freeze-out region, $\lambda_\chi \sim 10^{-6}$

WIMP region $\lambda_\chi \sim \mathcal{O}(1)$

Boundary, λ_χ drops from $\mathcal{O}(1)$ to $\sim 10^{-6}$

Bound state effects on the parameter space

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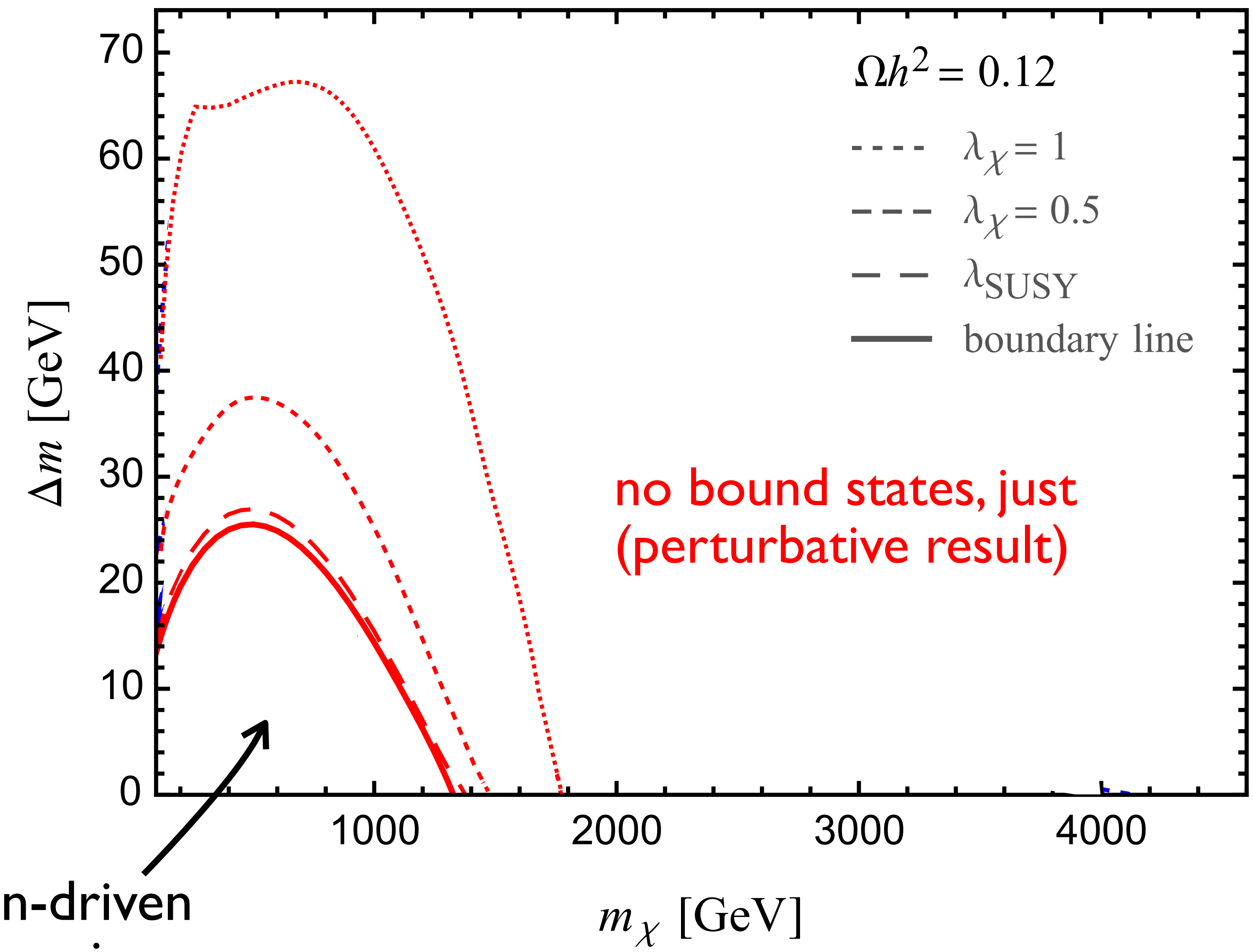
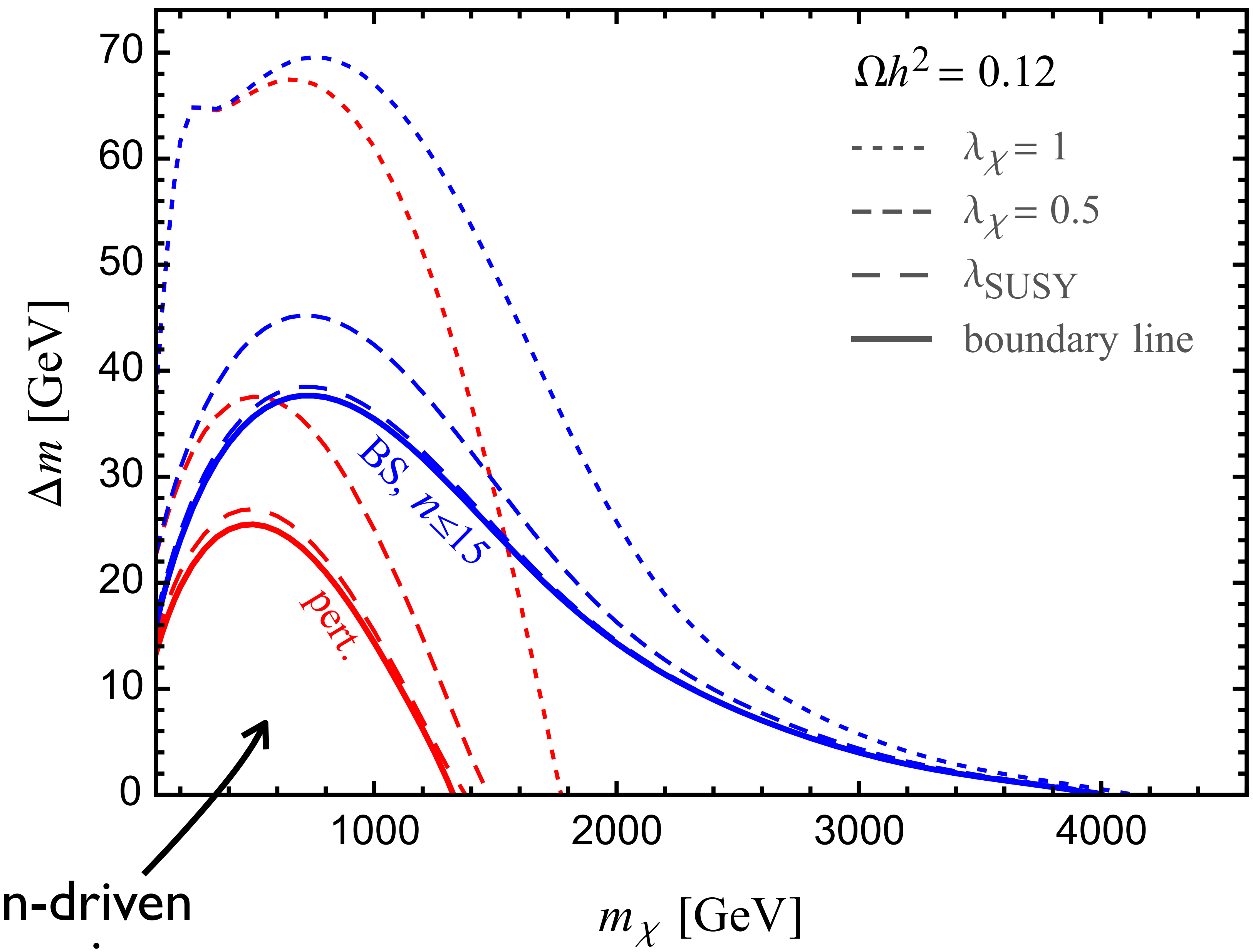


Conversion-driven freeze-out region, $\lambda_\chi \sim 10^{-6}$

Bound state effects on the parameter space

[Garny, JH 2112.01499]



Conversion-driven freeze-out region, $\lambda_\chi \sim 10^{-6}$

Bound state effects on the parameter space

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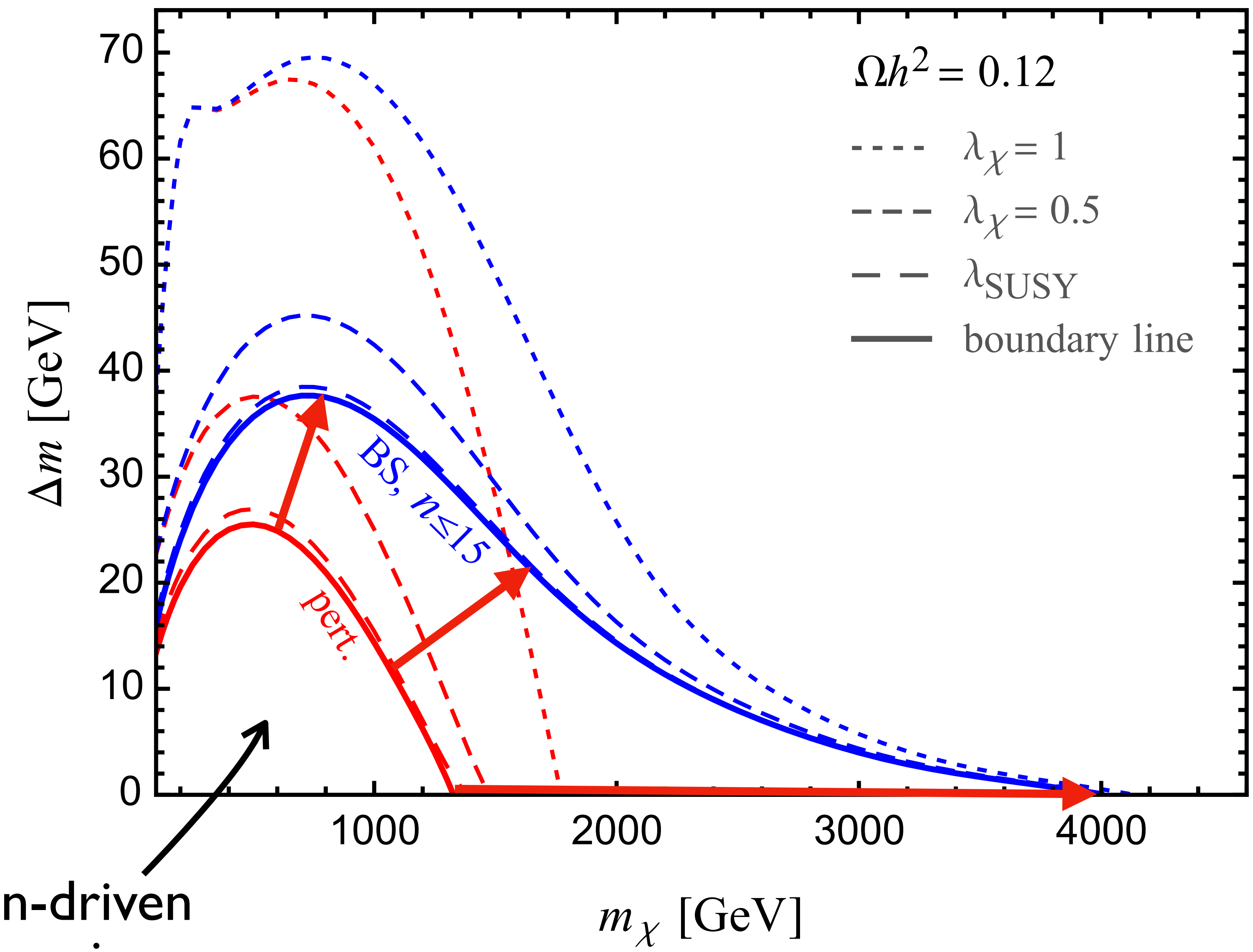
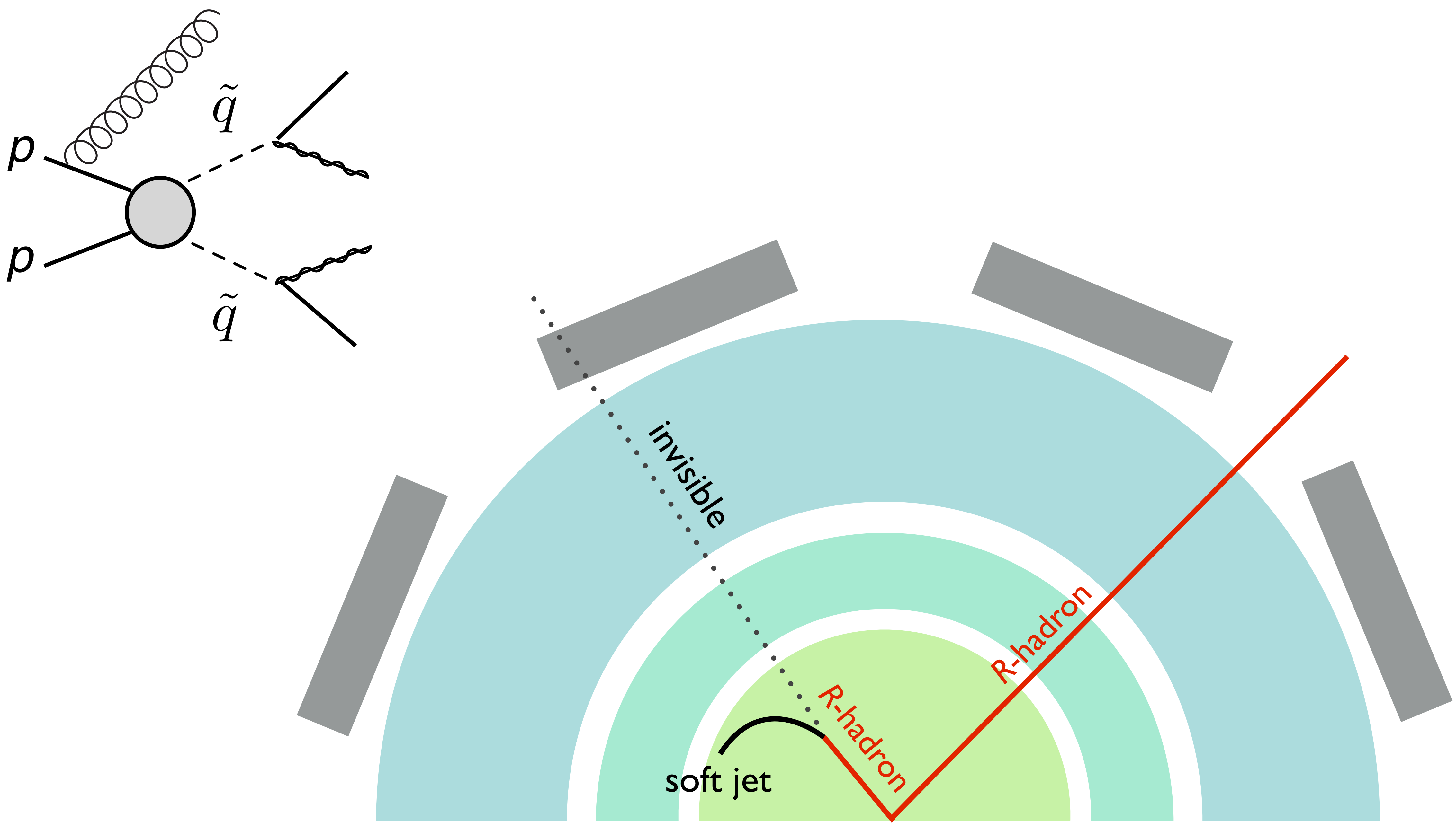


Conversion-driven freeze-out region, $\lambda_\chi \sim 10^{-6}$

Implications for LHC searches

Feeble couplings: Long-lived particles at LHC



Lifetime in conversion scenario

Conversion rate on the edge of being efficient:

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

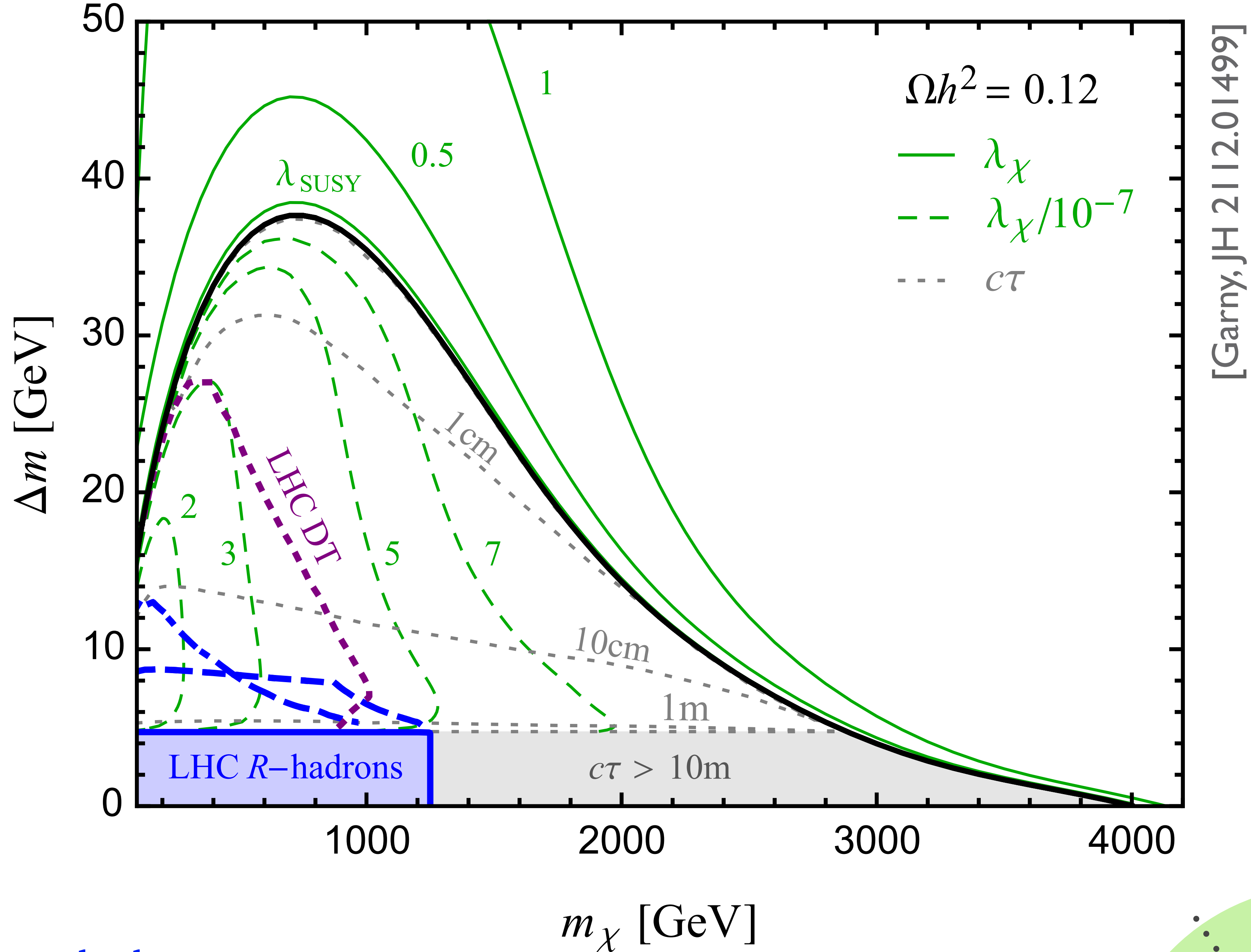
$$\Rightarrow \; \Gamma_{\rm dec} \lesssim H$$

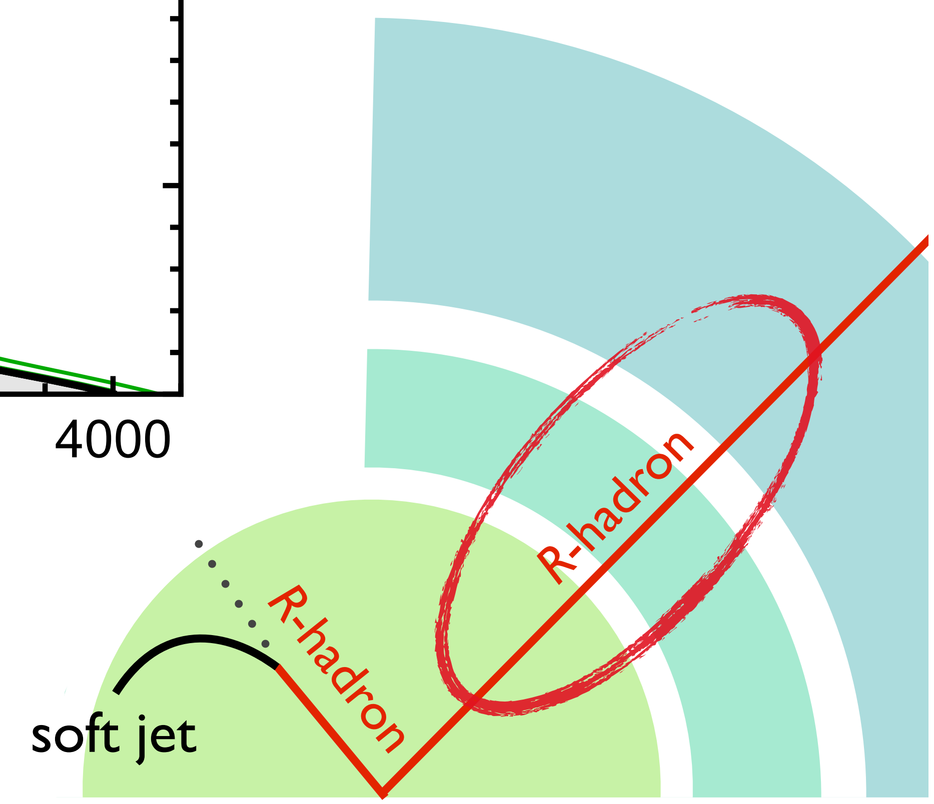
$$c\tau \gtrsim H^{-1} \simeq 1.5\,\mathrm{cm}\left(\frac{(100\,\mathrm{GeV})^2}{T^2}\right)$$

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

⇒ Long-lived particles (LLPs) at LHC!

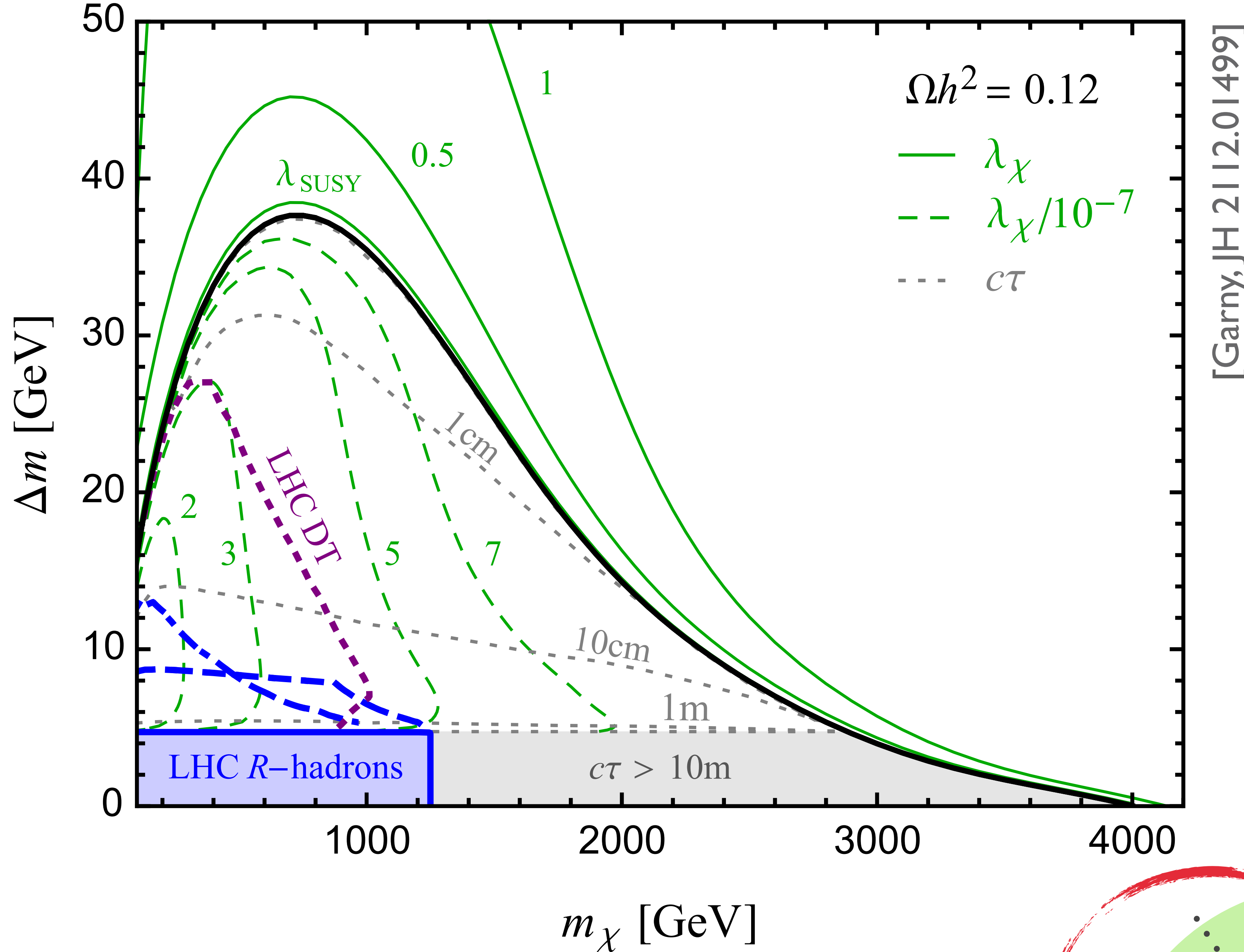
Collider constraints

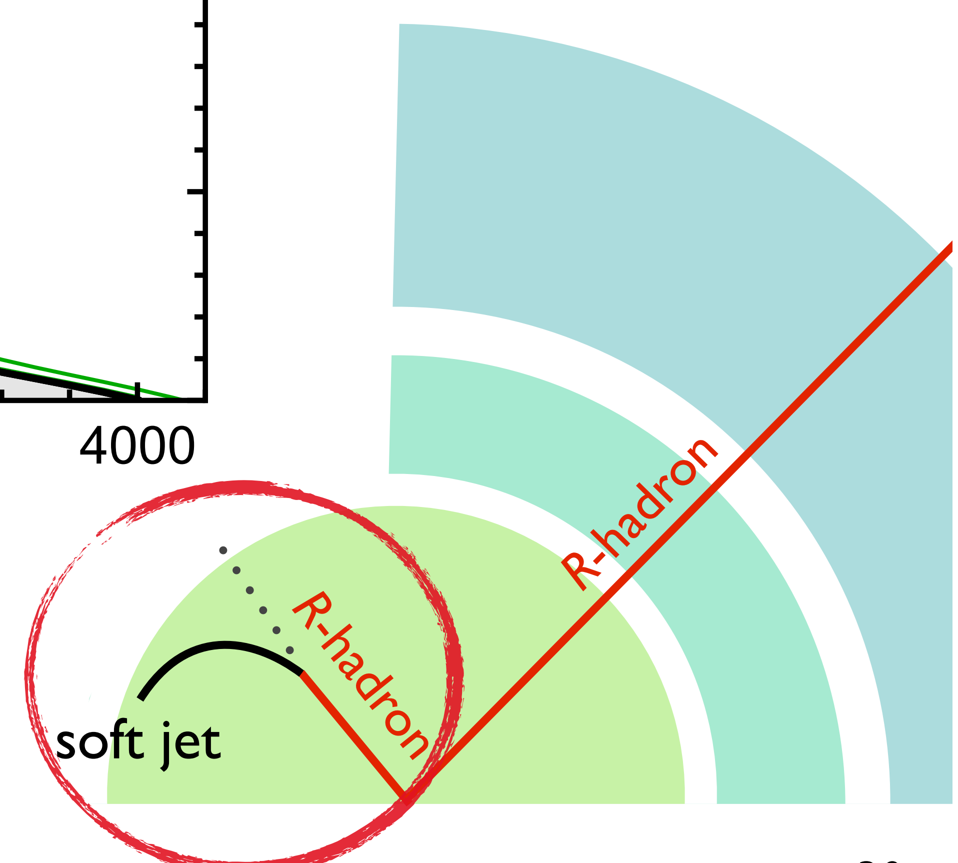




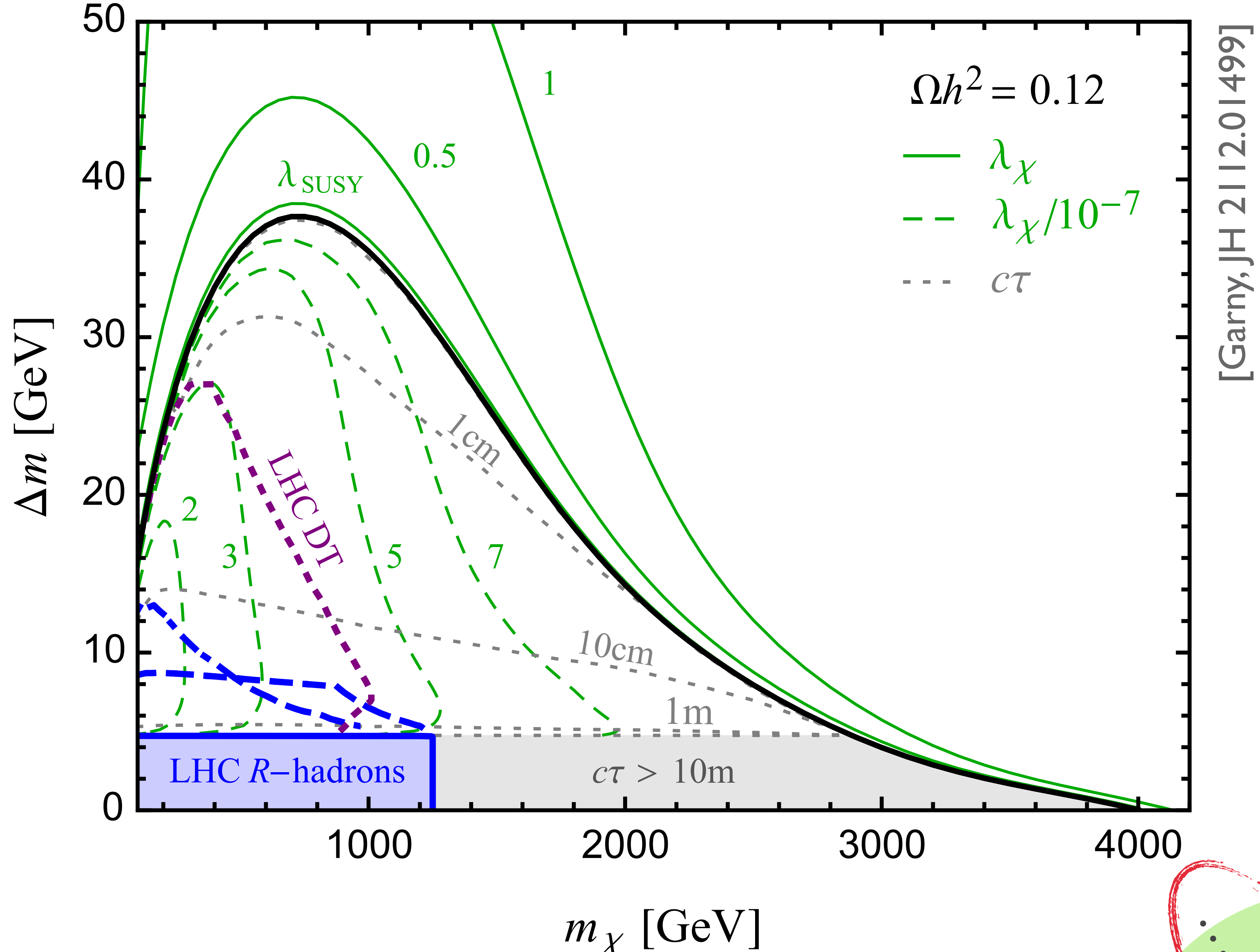
LHC – R-hadrons:
ATLAS [1902.01636, 1808.04095 approximate reinterpretation]
CMS [CMS-PAS-EXO-16-036, recasting from 1705.09292]

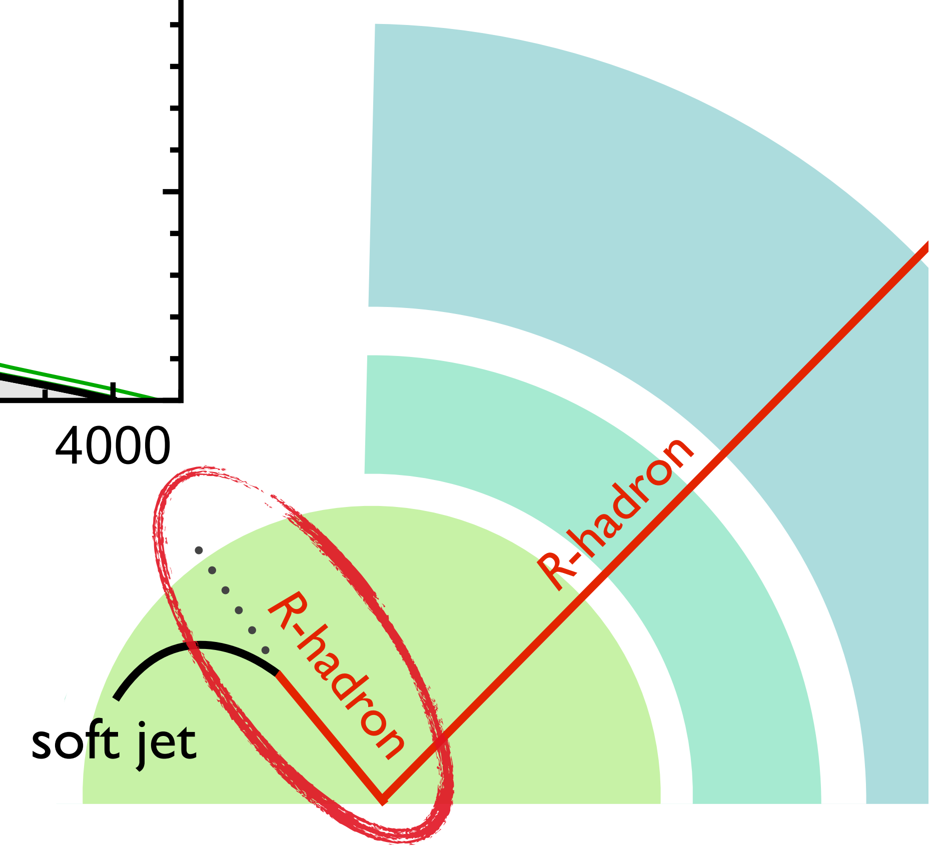
Collider constraints





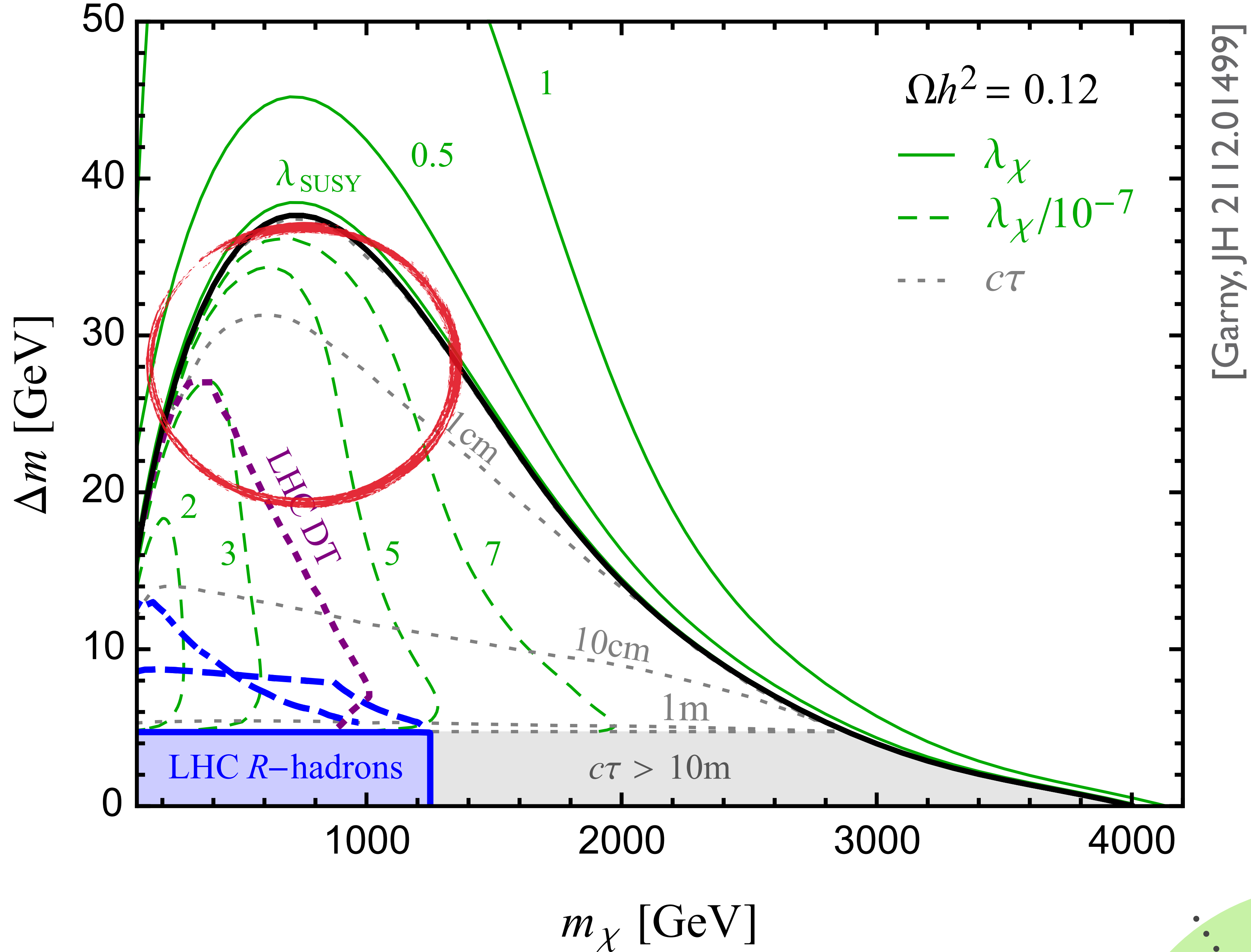
Collider constraints

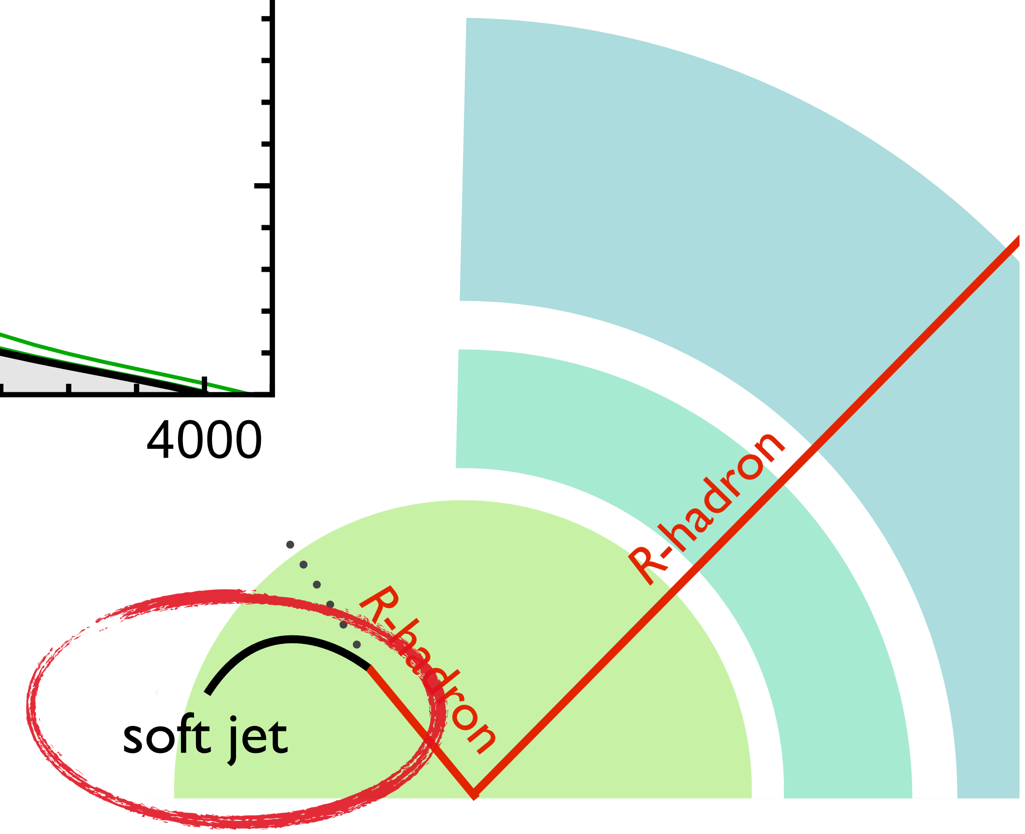




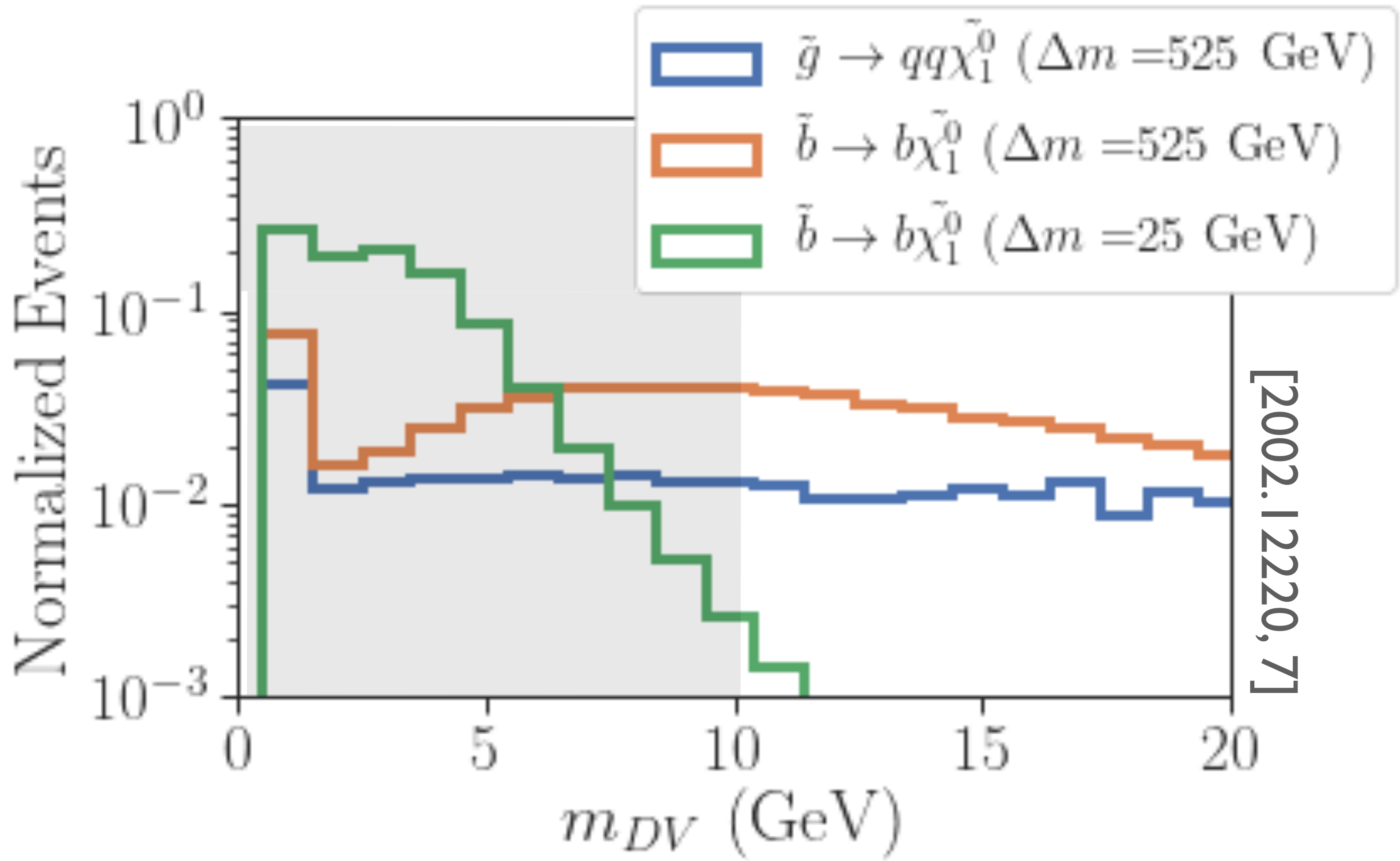
LHC – DT: ATLAS Disappearing-track search
[1712.02118, recasting from 2002.12220, 7]

Collider constraints

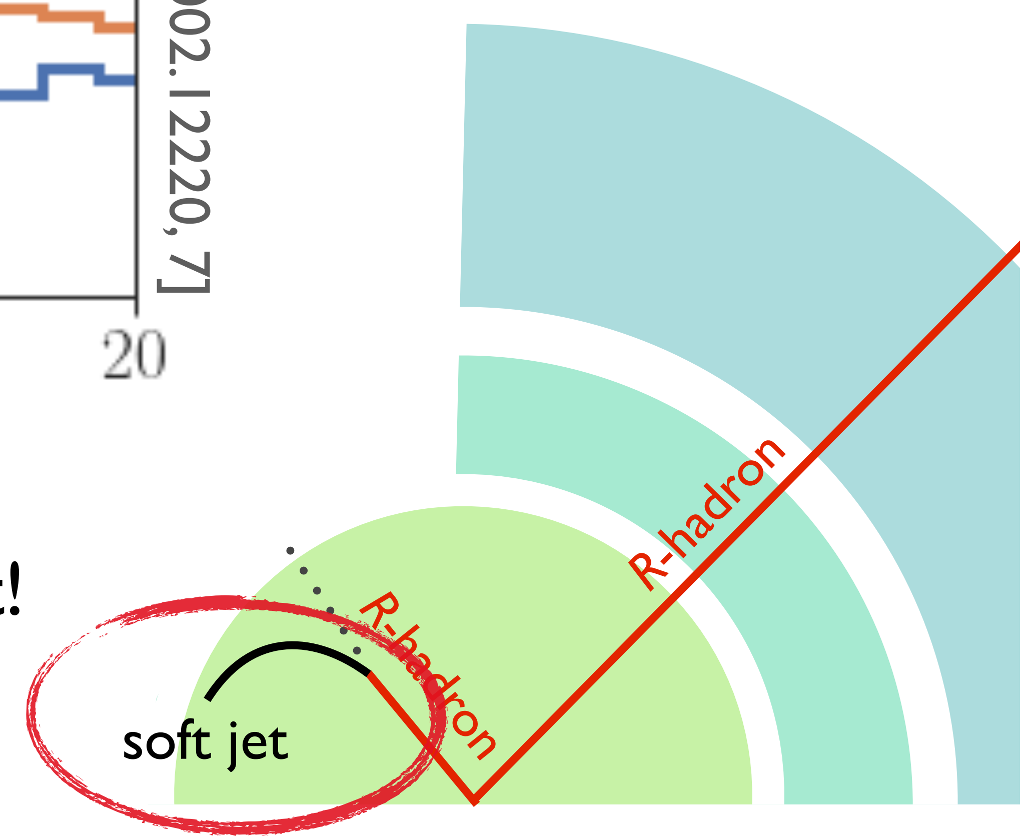




Collider constraints



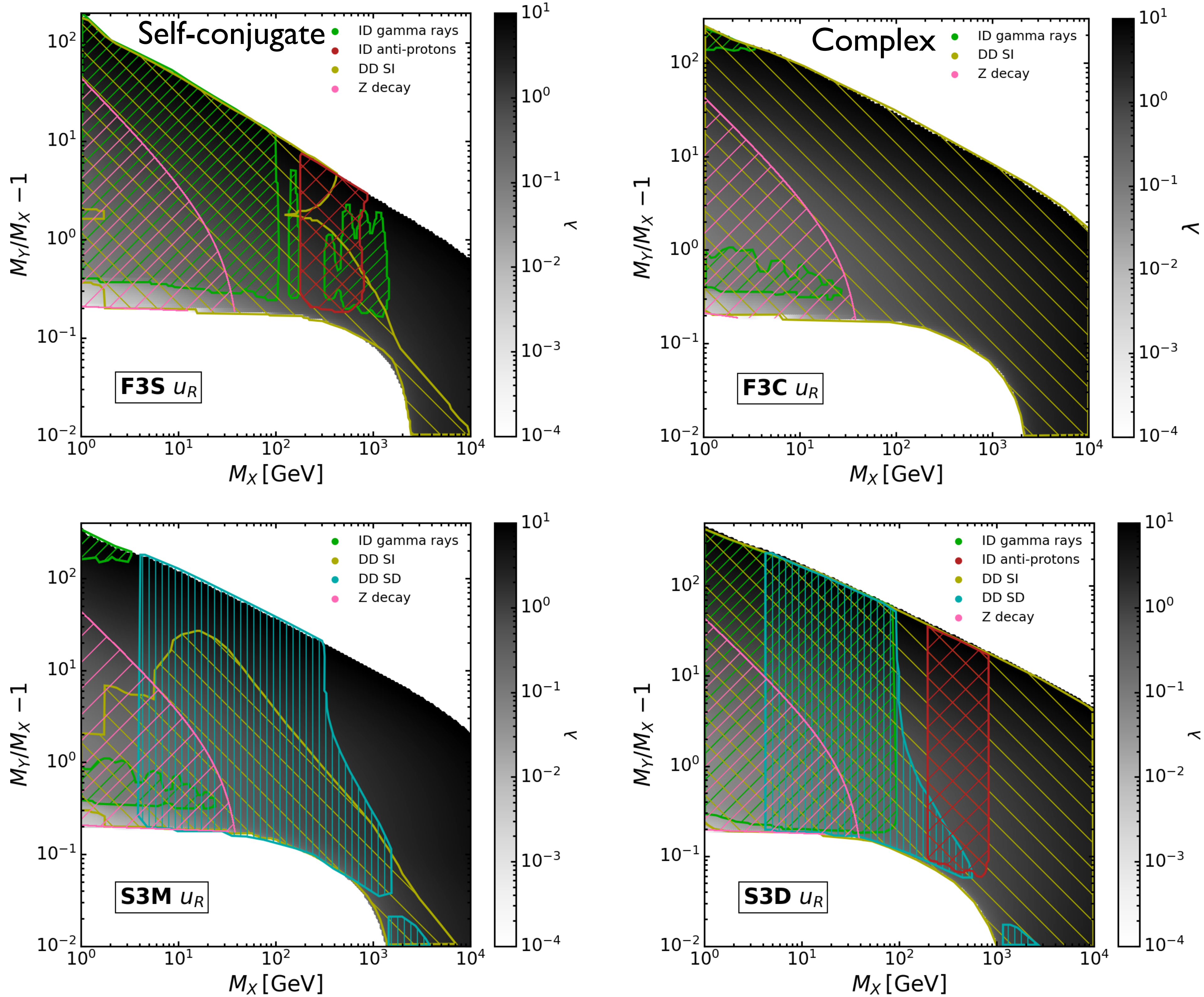
- Displaced jets+MET suffers from m_{inv}-cut!
  [ATLAS, 1710.04901]



Relevance for current searches

Scalar DM

Fermionic DM

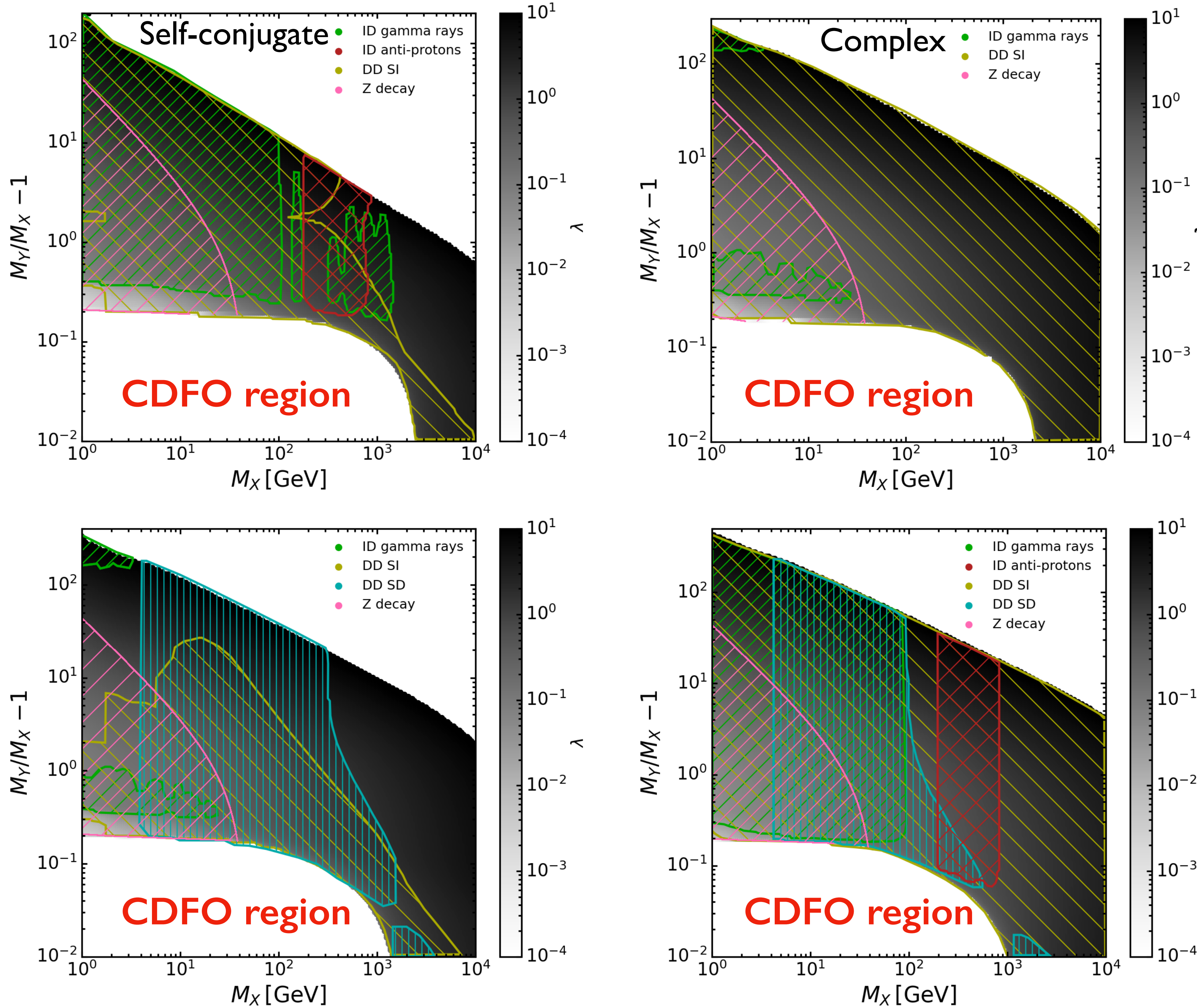


[Arina, Fuks, JH, Krämer, Mantani, Panizzi; 2307.10367]

Relevance for current searches

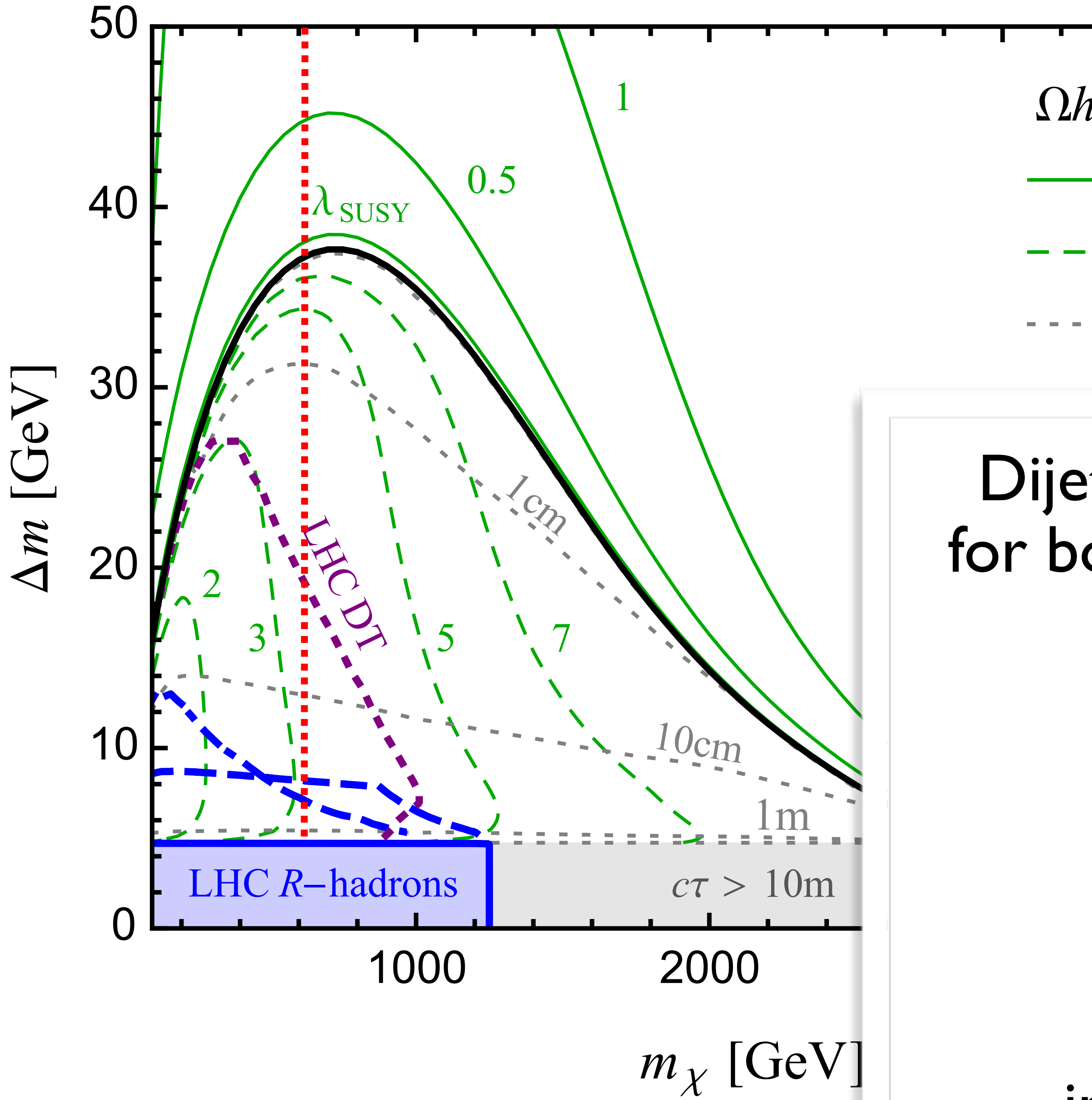
Scalar DM

Fermionic DM

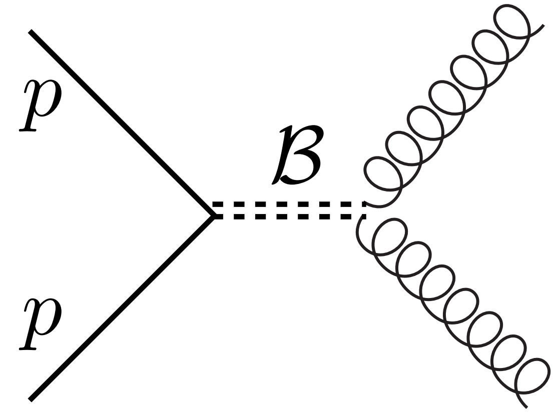


[Arina, Fuks, JH, Krämer, Mantani, Panizzi; 2307.10367]

Collider constraints



Dijet resonance searches for bound state production with $m_{\mathcal{B}} \simeq 2m_{\tilde{q}}$



independent of lifetime and Δm

Summary

- Dark matter elusive: systematically explore mechanisms of DM genesis
- Consider minimal extensions to SM with large hierarchy in couplings $\lambda_{\text{strong}} \gg \lambda_{\text{feeble}}$
- Prolonged freeze-out dynamics:
  $\Rightarrow$ effects of excited bound states highly relevant
- Non-abelian theory: 'eternal' annihilation
- superWIMP scenario: Relic density does depend on decay rate
- Conversion-driven freeze-out: parameter space largely enhanced
- Interesting prospects for long-lived particle searches
- Open problem: Unitarization of BSF cross section