Dark Matter Relic Density – The Many Ways to Make 0.12

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Dark Tools
Torino, Italy
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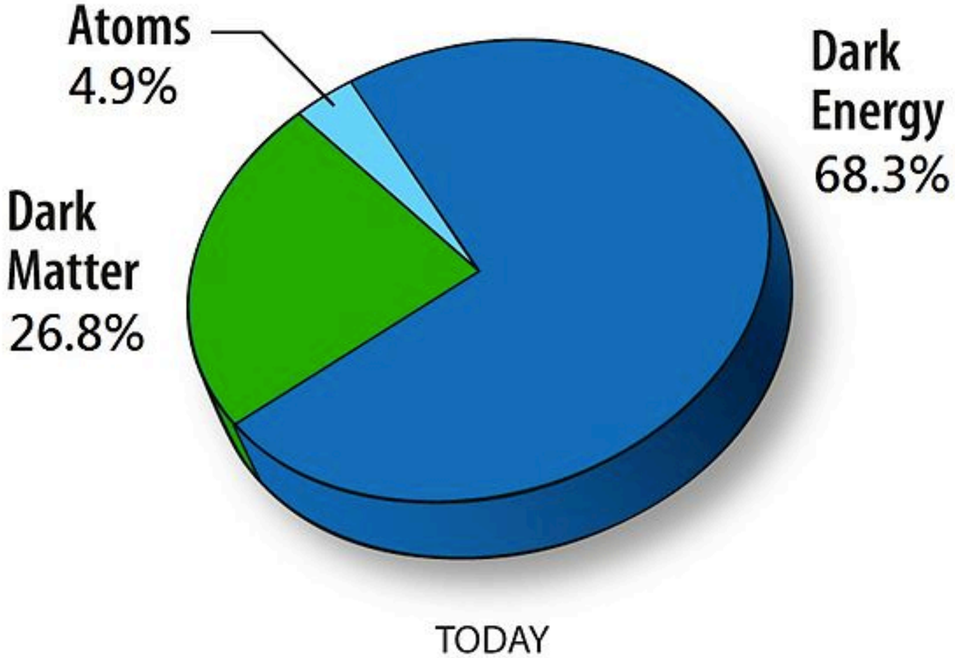
What we know about Dark Matter

Contributions Ω_i to the energy density of the Universe today:

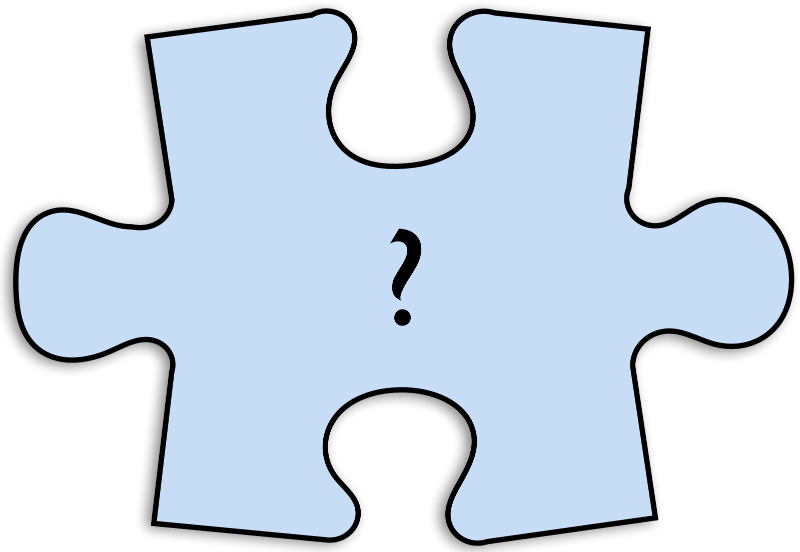


$$\Omega_{\rm DM} h^2 = 0.12 \pm 0.001$$

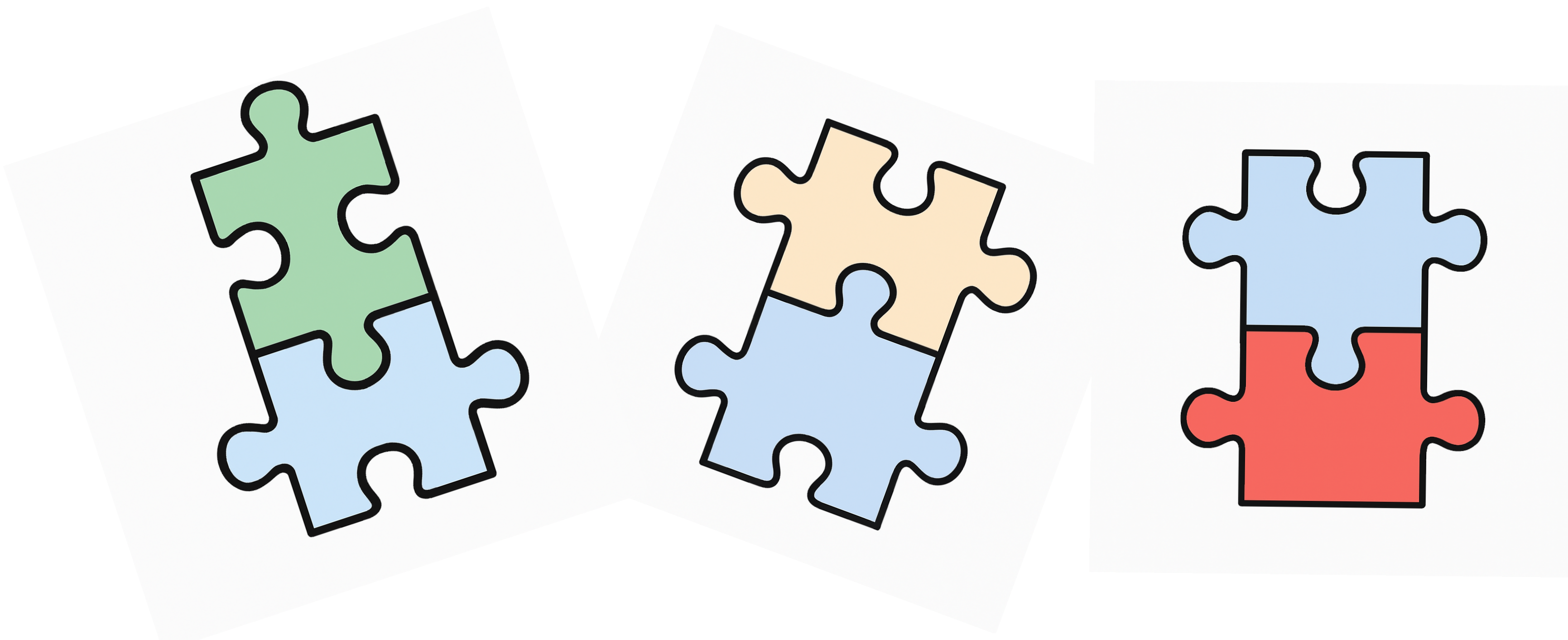
[Planck 2020]

- Dark
- Cold or slightly warm
- Long-lived
- Constrained self-interaction

What is the Origin?

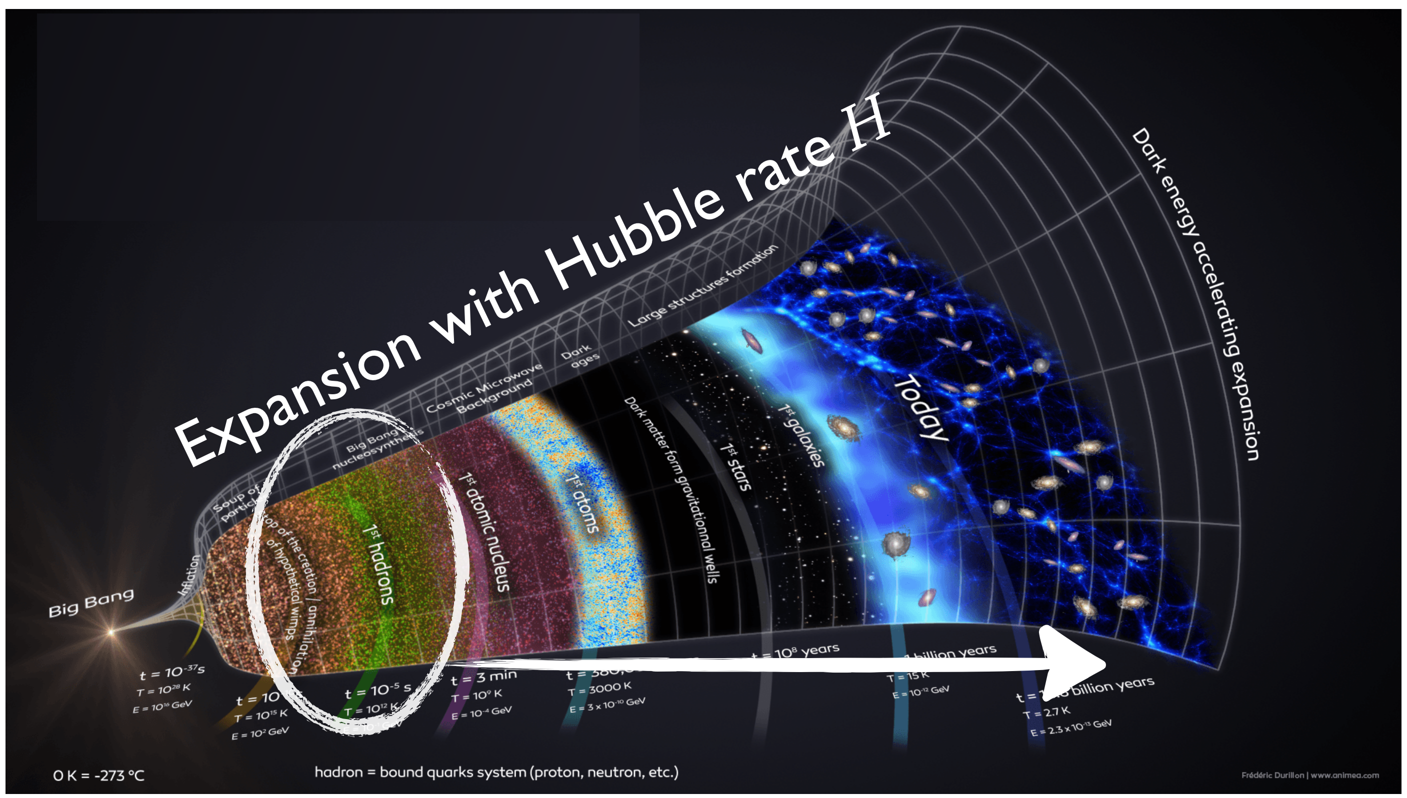


Many possibilities



Focus:
Dark Matter is (and behaves like) a particle
in early universe thermal bath
(no axions, no black holes)

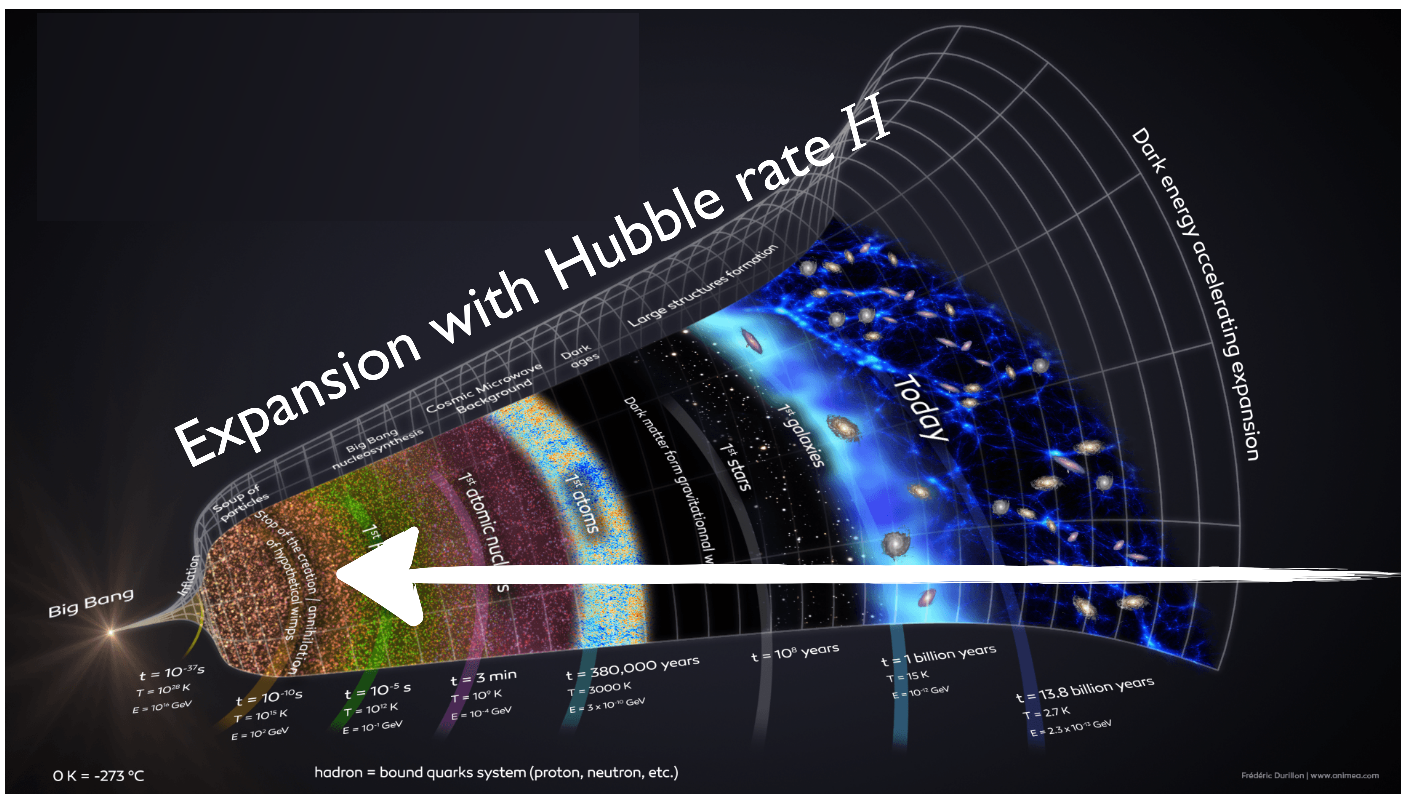
Particle dark matter: a thermal relic



CEA/Irfu 2018

Early Universe Today

Particle dark matter: a thermal relic



CEA/Irfu 2018

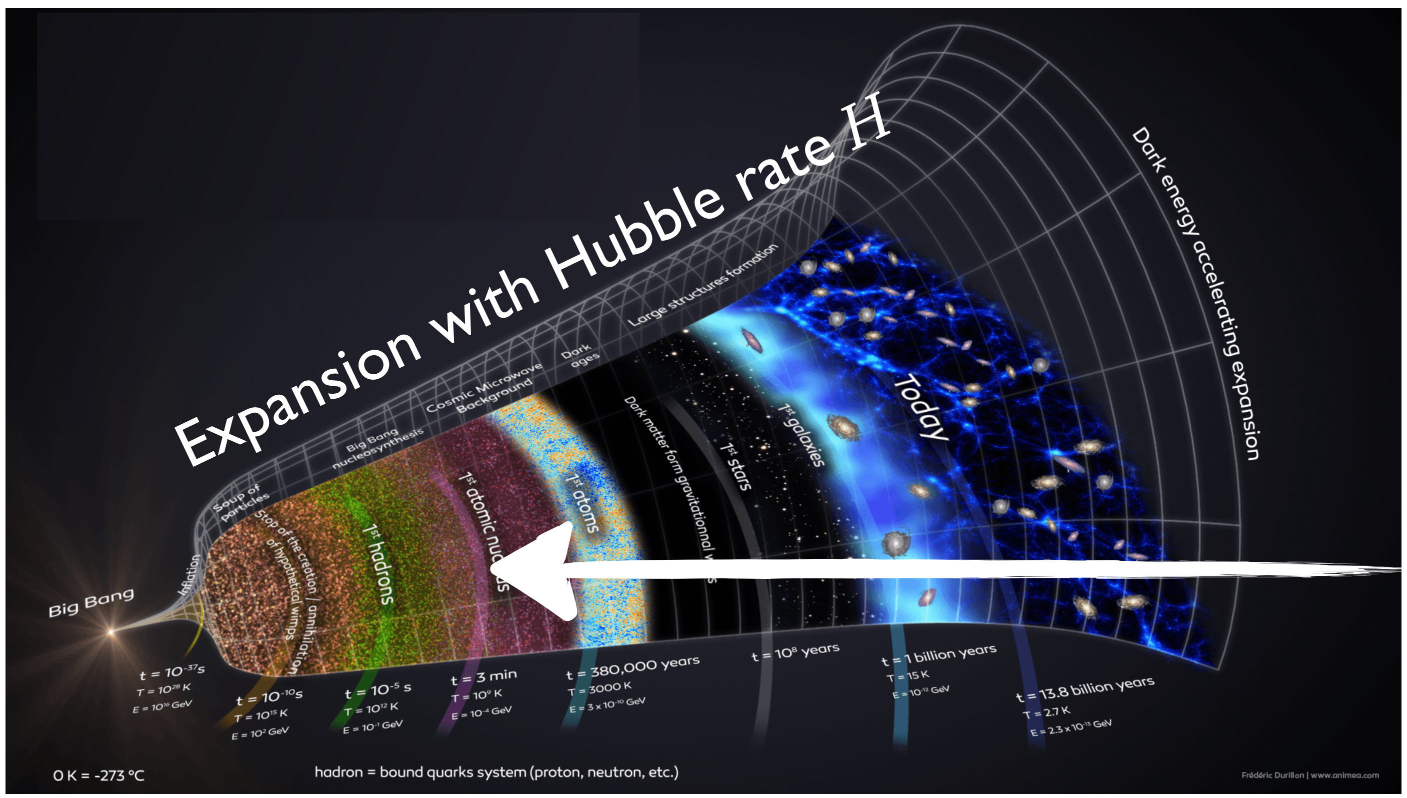
Early Universe

Today

Particle physics + cosmology:
Extrapolate to early, hot Universe

Particle dark matter: a thermal relic

- Successful example: Big Bang Nucleosynthesis



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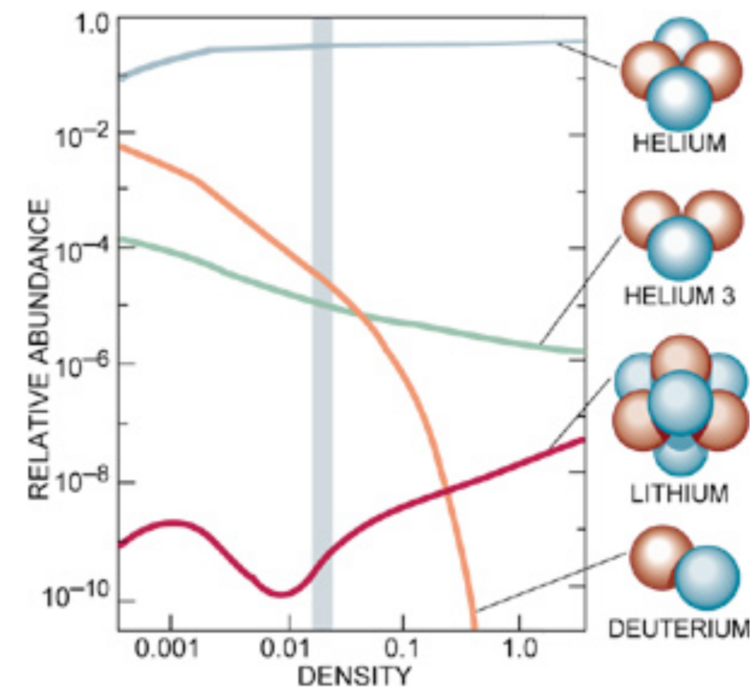
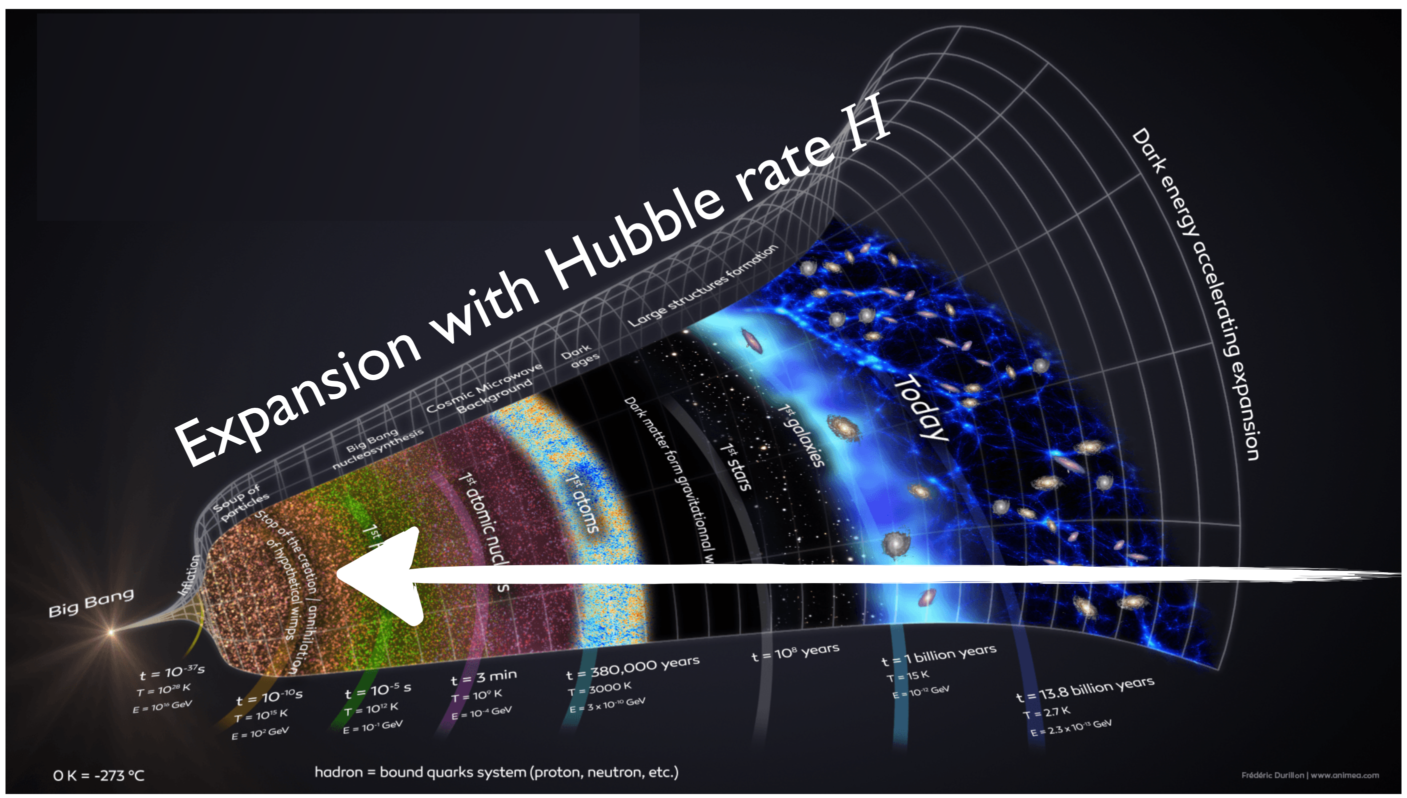
Early Universe   Today



➔ Explains primordial abundances of light elements

Particle dark matter: a thermal relic



CEA/Irfu 2018

Early Universe Today

Particle physics + cosmology: Extrapolate to early, hot Universe

⇒ Solving the Boltzmann Equations for Dark Matter

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]

$$E_\chi \left(\partial_t - H p \, \partial_p\right) f_\chi(p,t) = C\left[f_\chi\right]$$

Relativistic Liouville operator for homogeneous, isotropic Universe

Collision operator

Cosmology

Particle Physics

Boltzmann equations for particle densities

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DM distribution functions

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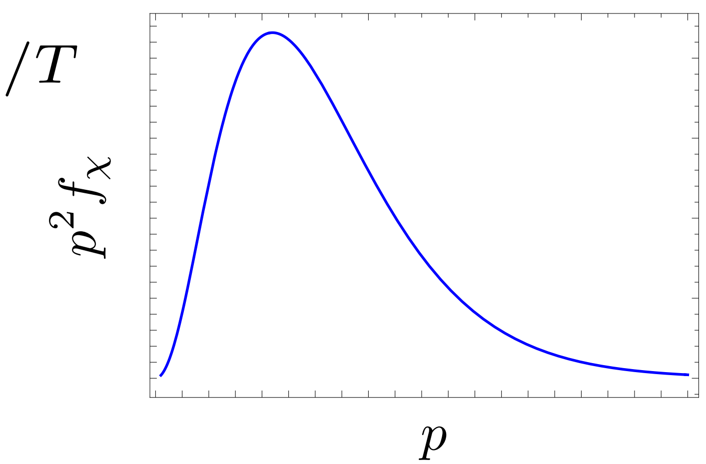
Assumption*: $f_\chi(p) \propto f_{\rm BM} = {\rm e}^{-E_p/T}$



* Dark Matter in kinetic equilibrium and non-relativistic at relevant times

Boltzmann equations for particle densities

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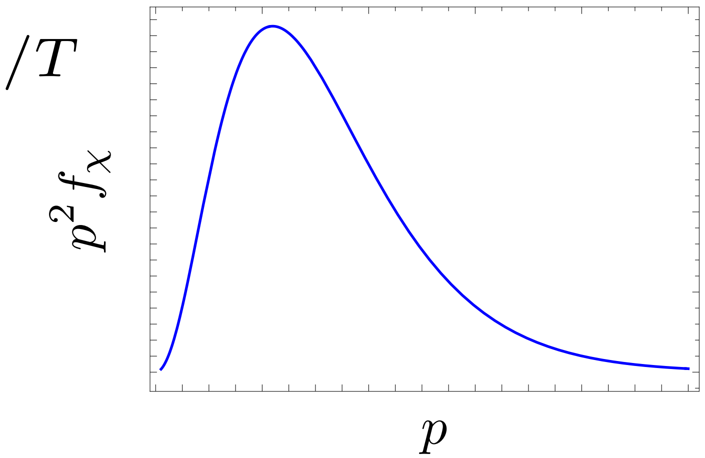

Integrated equation for $n_\chi(t) = \int {\rm d}\Pi_p\, f_\chi(p,t)$:

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

Cosmology

Particle Physics

Boltzmann equations for particle densities

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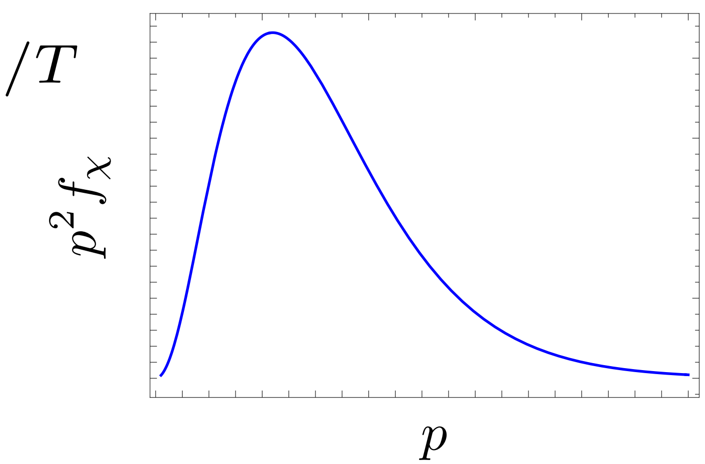

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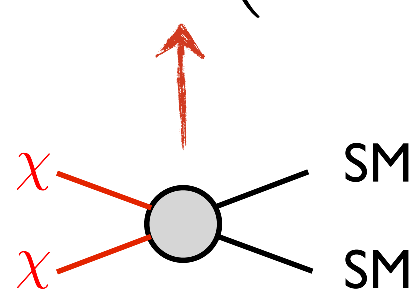

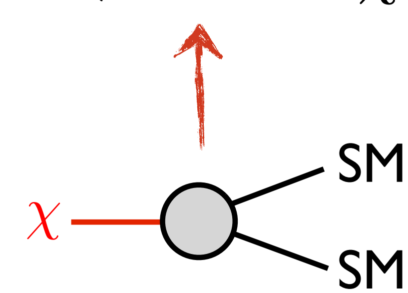

…just as an example

Boltzmann equations for particle densities

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Compare rates to Hubble expansion rate $H \propto T^2$

* in radiation dominated era

Larger than Hubble expansion ⇒ efficient

$$\Gamma_i \gtrless H$$

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Compare rates to Hubble expansion rate $H \propto T^2$

* in radiation dominated era

$$\Gamma_i \gtrless H$$

inefficient,
just Hubble expansion

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Compare rates to Hubble expansion rate $H \propto T^2$

* in radiation dominated era

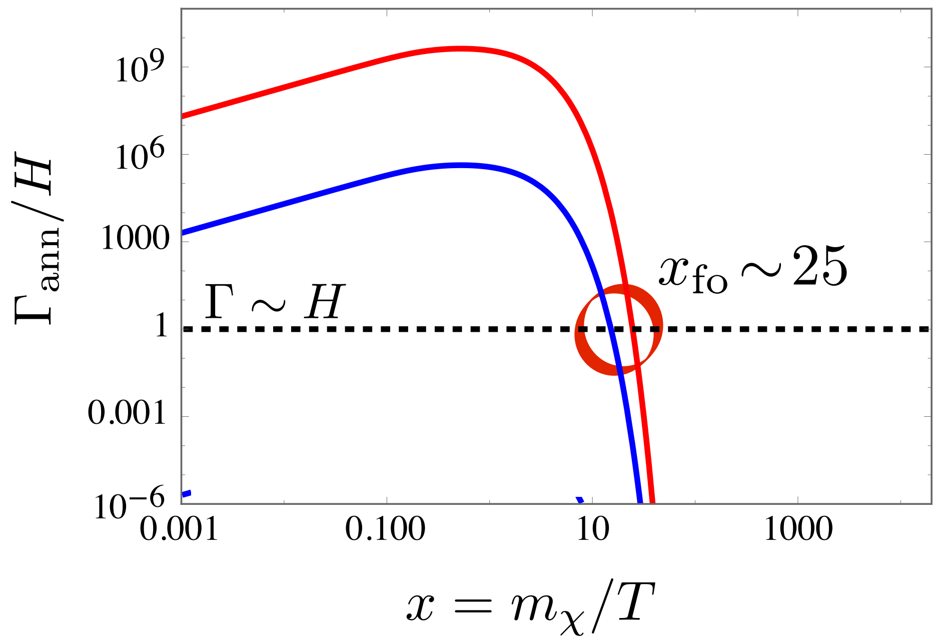
typically something interesting happens

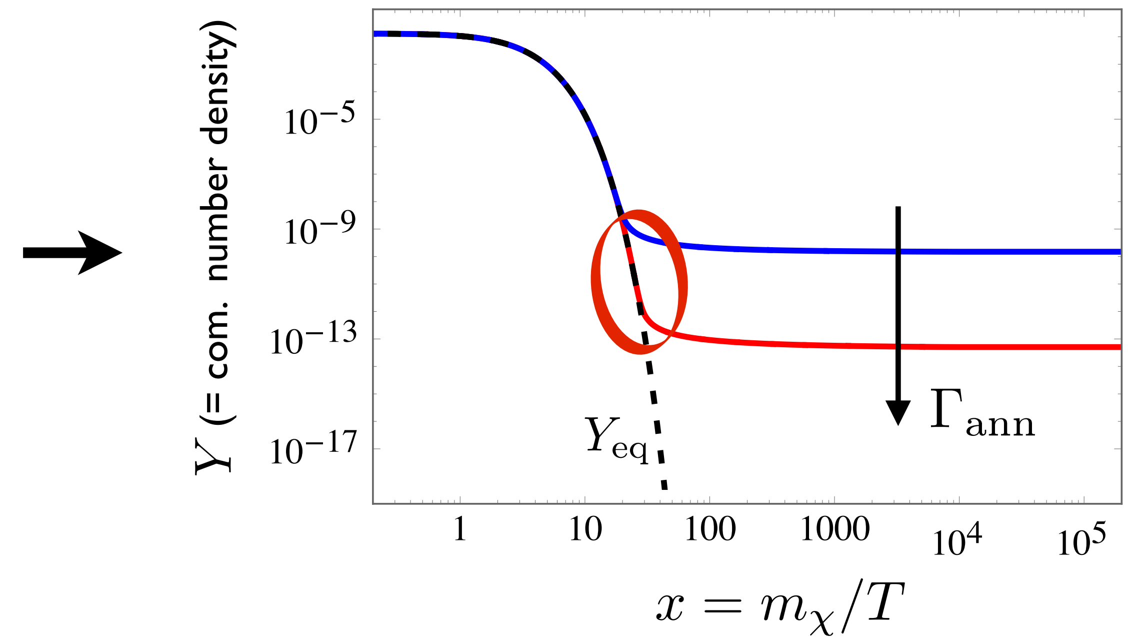
$$\Gamma_i \sim H$$

WIMP freeze-out

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = -\langle\sigma v\rangle_{\mathrm{ann}}\left(n_\chi^2 - n_\chi^{\mathrm{eq}\,2}\right) \qquad \textbf{(no decay!)}$$

$$\Gamma_{\mathrm{ann}} \coloneqq n_\chi \langle\sigma v\rangle_{\mathrm{ann}}$$



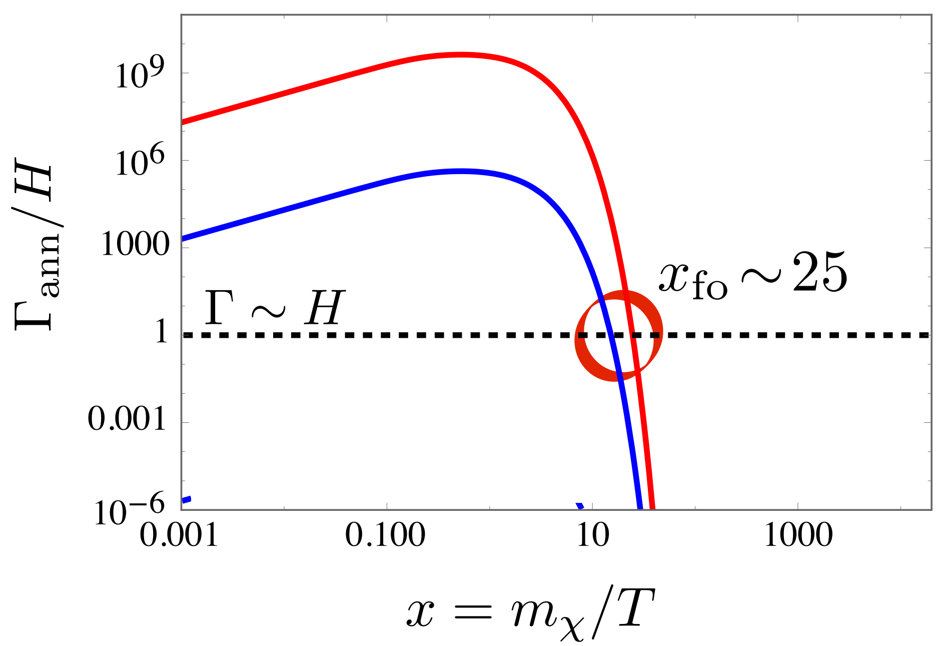


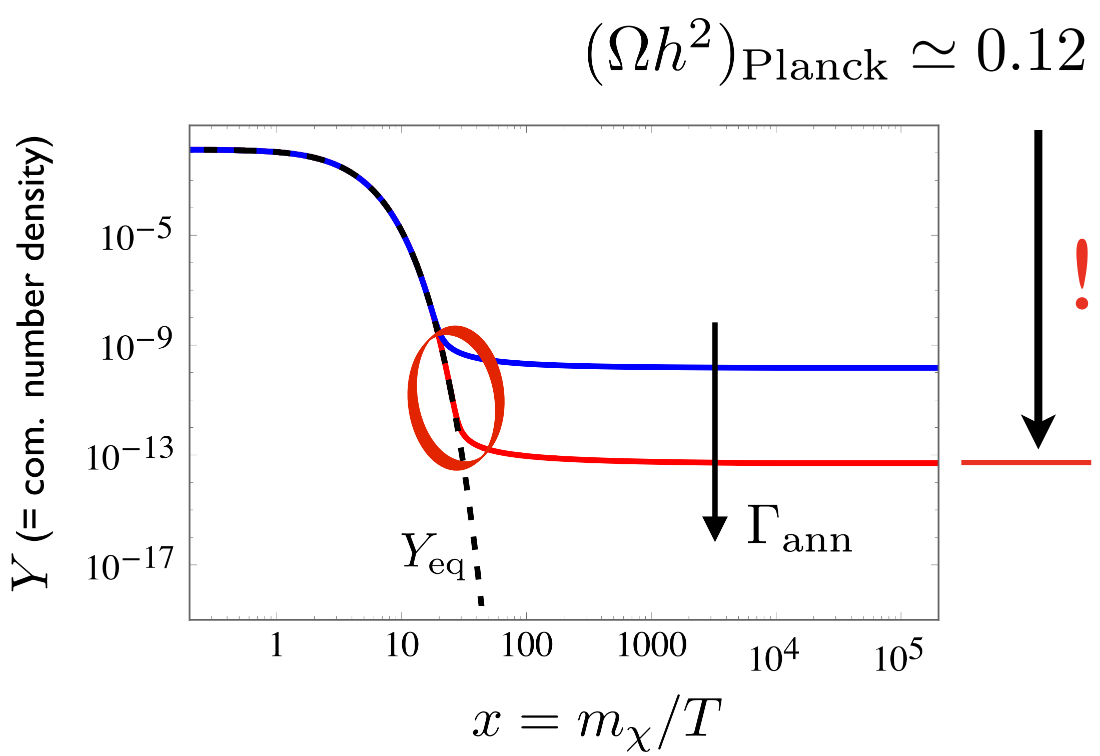
WIMP freeze-out

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{\rm ann}\left(n_\chi^2 - n_\chi^{\rm eq\,2}\right)$$

(no decay!)

$$\Gamma_{\rm ann} := n_\chi \langle\sigma v\rangle_{\rm ann}$$



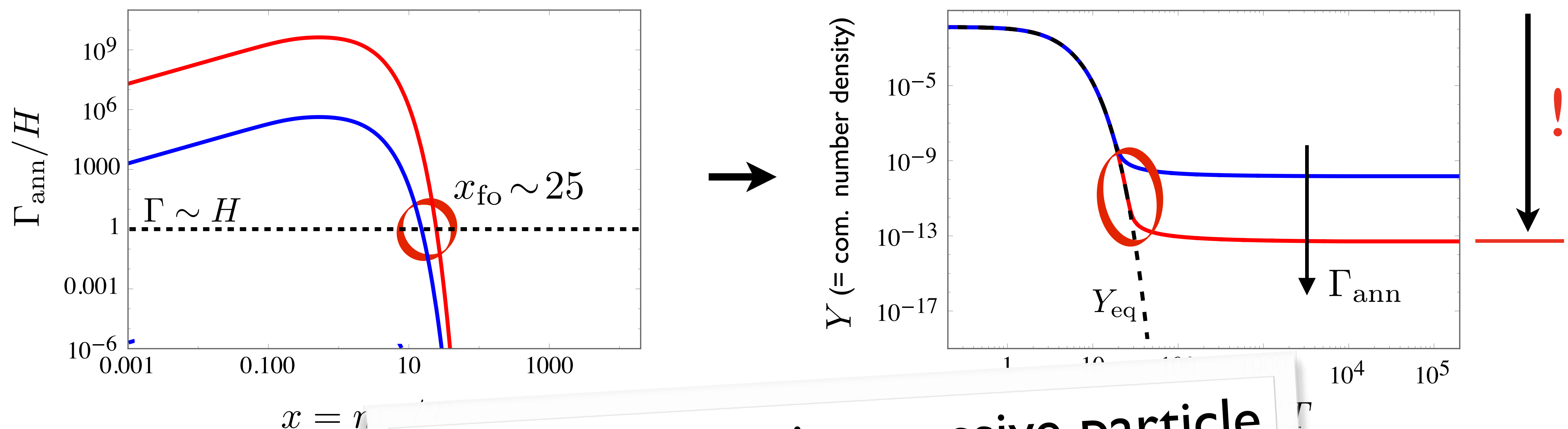


WIMP freeze-out

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = -\langle\sigma v\rangle_{\mathrm{ann}}\left(n_\chi^2 - n_\chi^{\mathrm{eq}\,2}\right)$$ **(no decay!)**

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

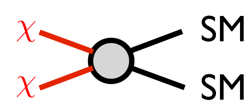
$(\Omega h^2)_{\mathrm{Planck}} \simeq 0.12$

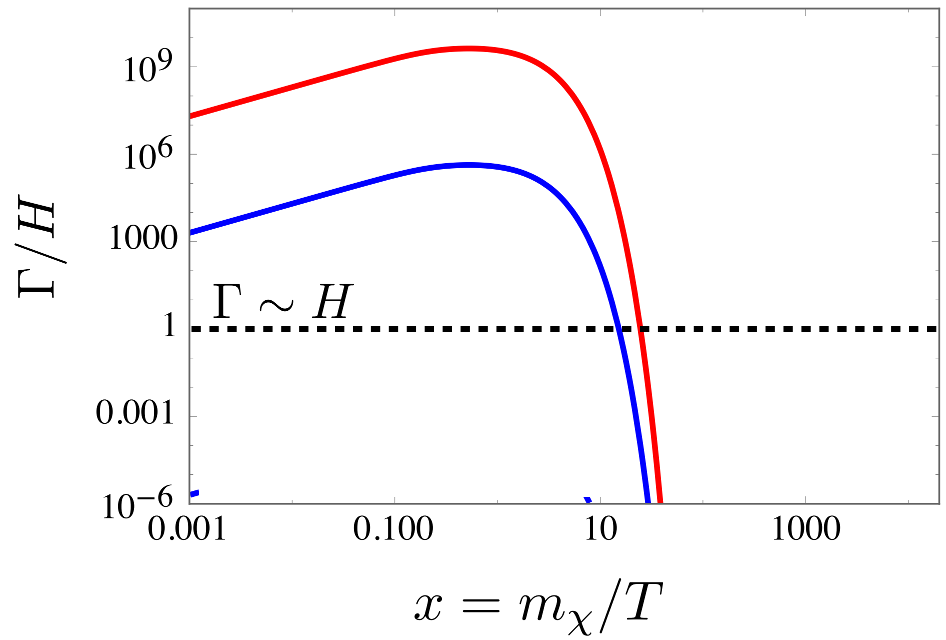


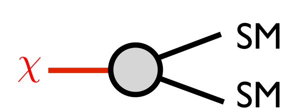
Weakly interacting massive particle
"WIMP miracle"

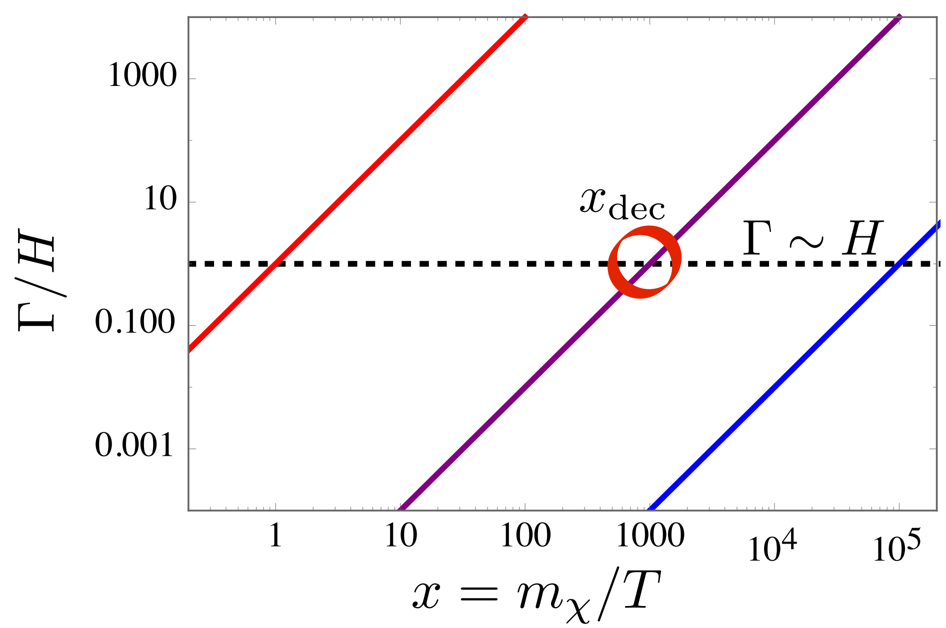
(

Side-remark: What if I add decay?

Annihilation: 



Add Decay: 



$$\Gamma_{\rm dec}/H \propto T^{-2}$$

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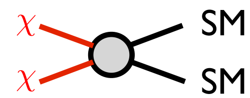
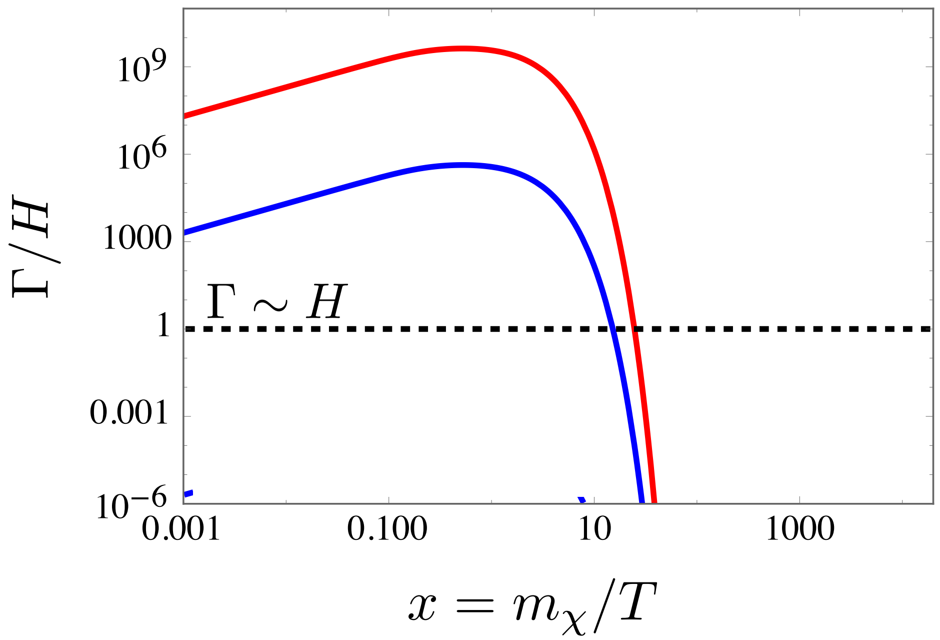
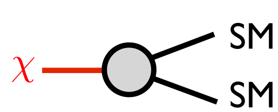
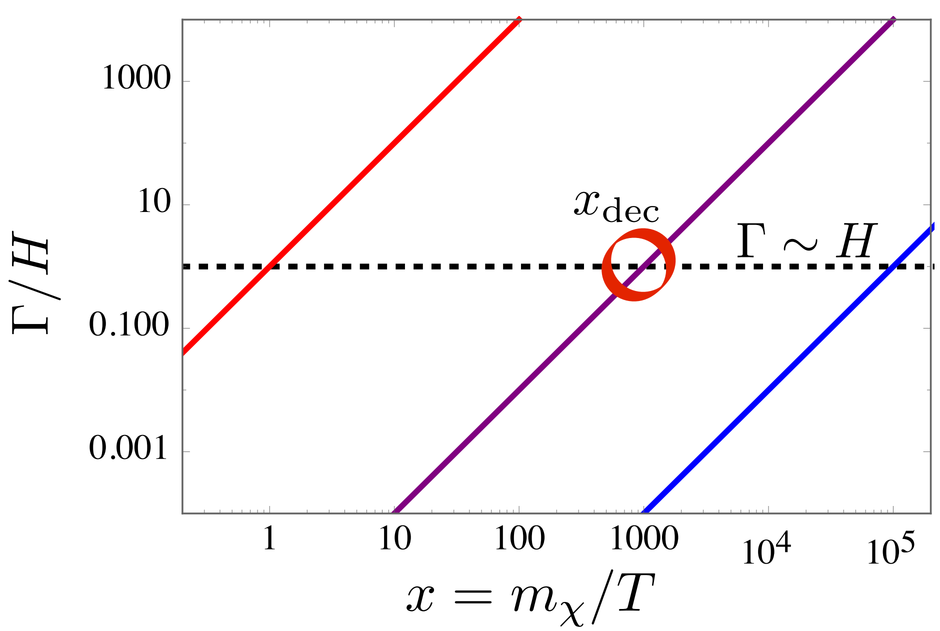
Annihilation: 



Add Decay: 



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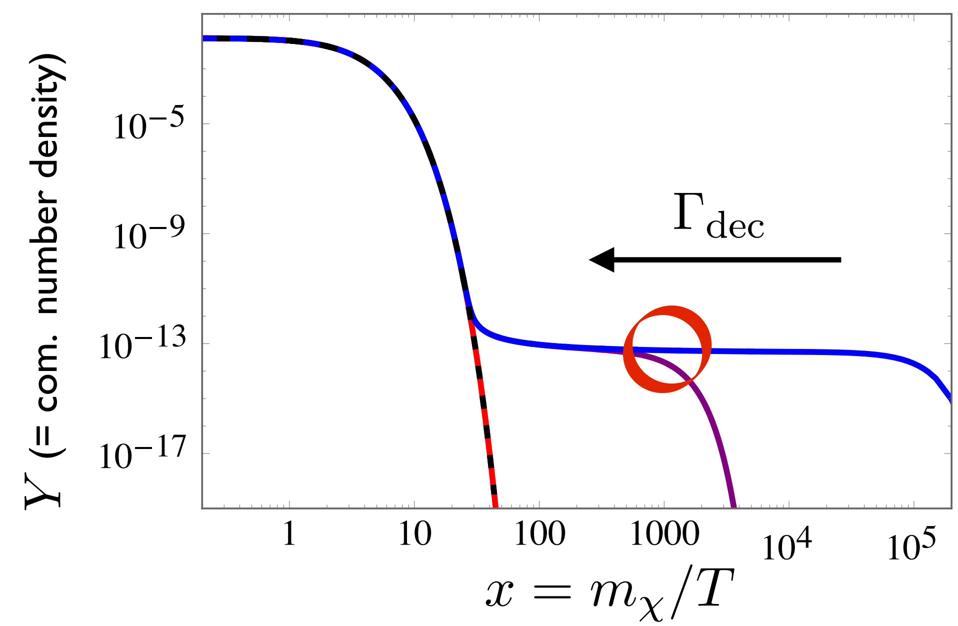

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Simplifying assumptions within the WIMP paradigm

- Radiation dominated era
- Dark sector non-relativistic
- Dark sector in kinetic eq. with SM
- Vanishing initial asymmetry
- DM initially thermalized
- No long-range force in dark sector
  (no bound states)
- Thermal eq. among dark sector particles
  (e.g. between coannihilating partners)

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for WIMPs

Simplifying assumptions within the WIMP paradigm

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- …

Beyond WIMPs:
some do not hold!

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Beyond WIMPs:
some do not hold!

Let's explore some departures from the WIMP paradigm…

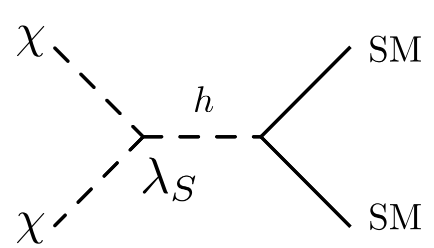
Outline

- WIMP-ish Variants
  Freeze-out from annihilation, hidden sectors
- Non-thermalized dark matter
  Freeze-in and superWIMPs
- Hybrid Regime
  freeze-out from conversions

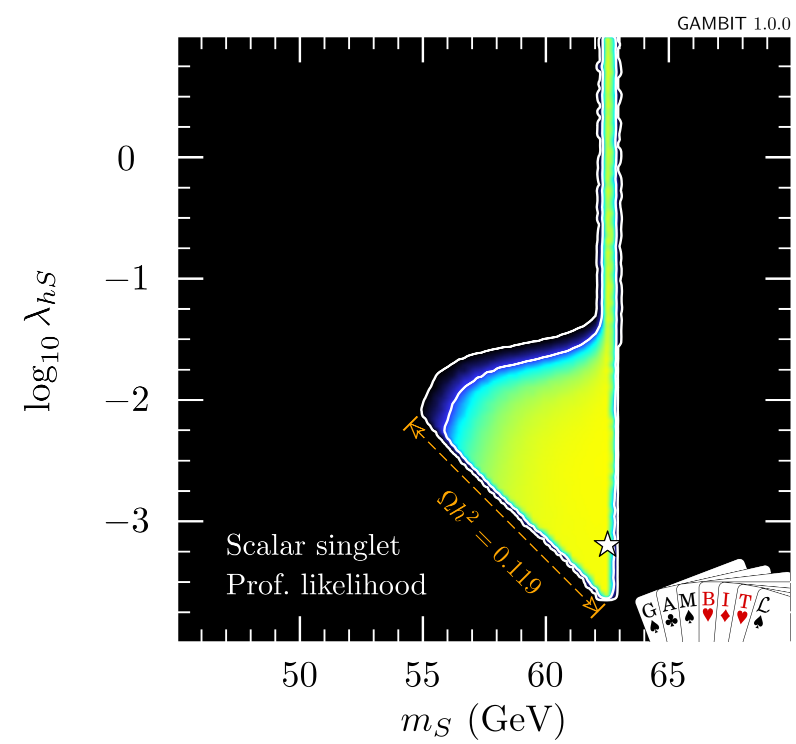
WIMP-ish Variants

Resonant annihilation: Higgs portal model

Annihilation enhanced:

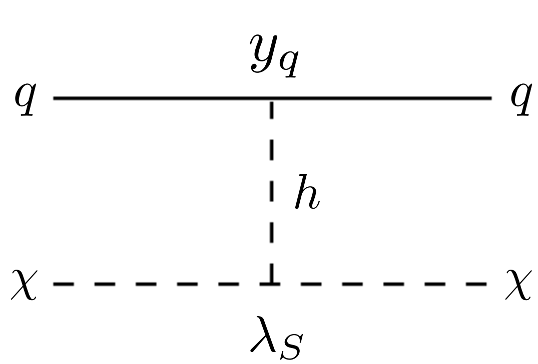


$m_\chi \sim m_h/2$



[GAMBIT Collaboration 2017]

but elastic scatterings are not:



[see also Di Mauro, Arina, Fornengo, JH, Massaro 2023]

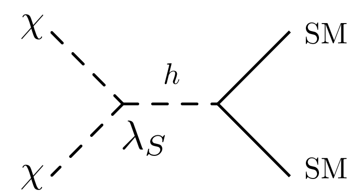
- No resonant enhancement
- Small couplings to light quarks, $T_{\rm fo} \sim 2\,{\rm GeV}$

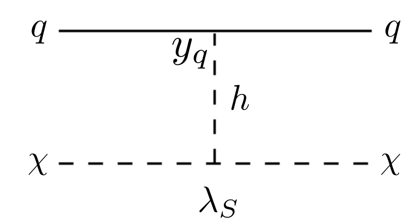
⇒ no kinetic equilibrium!

[Binder, Bringmann, Gustafsson, Hryczuk 2017;
Duch, Grzdkowski 2017]

Resonant annihilation: Higgs portal model

$$E_\chi(\partial_t - Hp\,\partial_p)\,f_\chi(p,t) = C_{\rm ann}\,[f_\chi] + C_{\rm el}\,[f_\chi]$$





- Semi-analytic calculation via leading moments

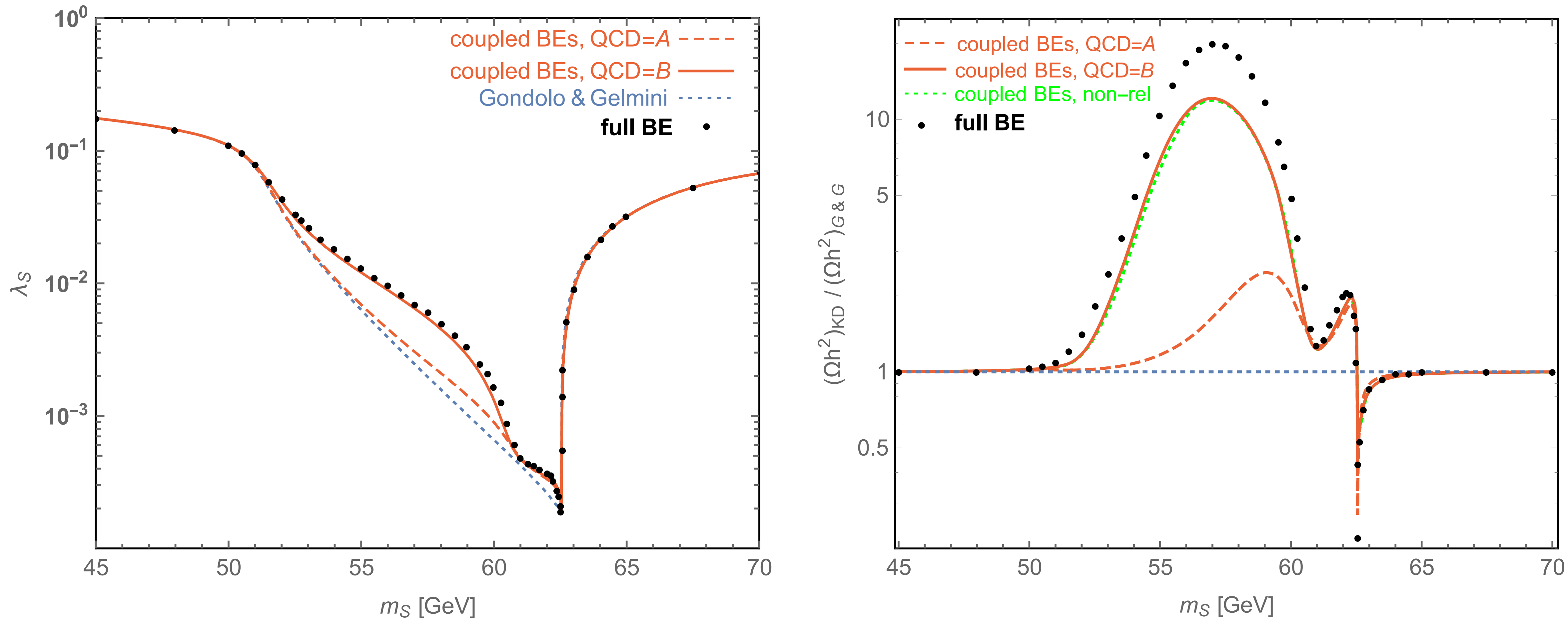
[van den Aarssen, Bringmann, Goedecke 2012]

$$n_\chi \propto \int \frac{\mathrm{d}^3p}{(2\pi)^3}\,f_\chi(p)\,, \qquad y_\chi \propto \int \frac{\mathrm{d}^3p}{(2\pi)^3}\,\frac{p^2}{E}\,f_\chi(p)$$

- Full numerical solution of unintegrated Boltzmann Eq.

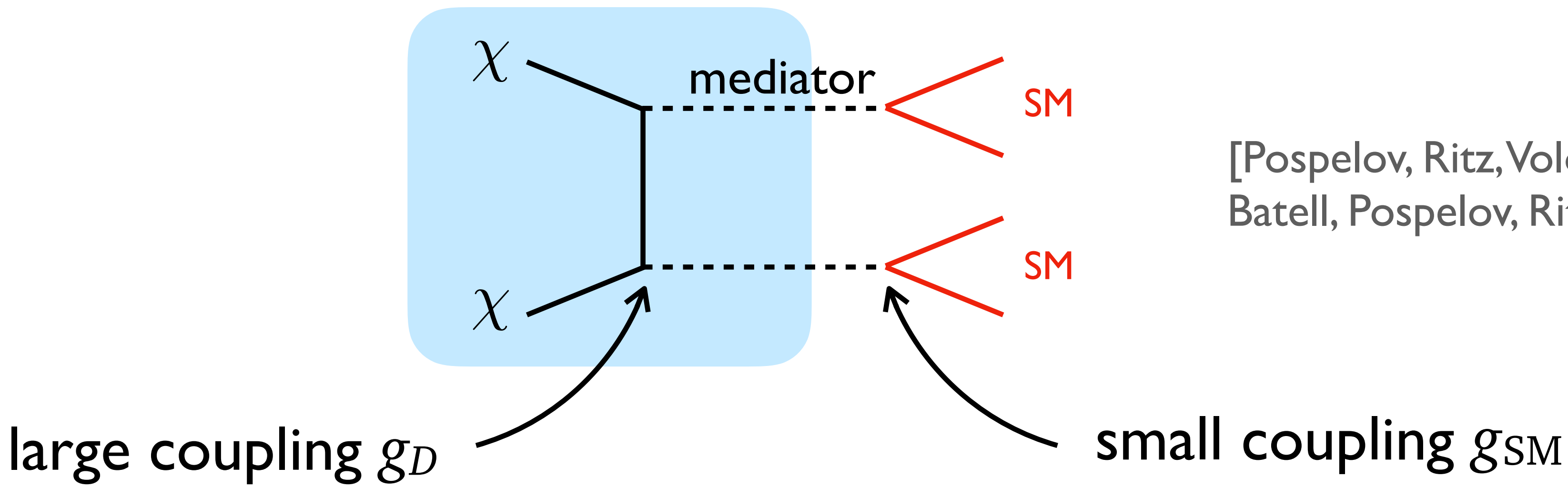
Solve on grid for *N* momentum modes
⇒ *N* coupled ordinary differential equations

Resonant annihilation: Higgs portal model



[Binder, Bringmann, Gustafsson, Hryczuk 2017]

Secluded Dark Matter / Hidden sectors



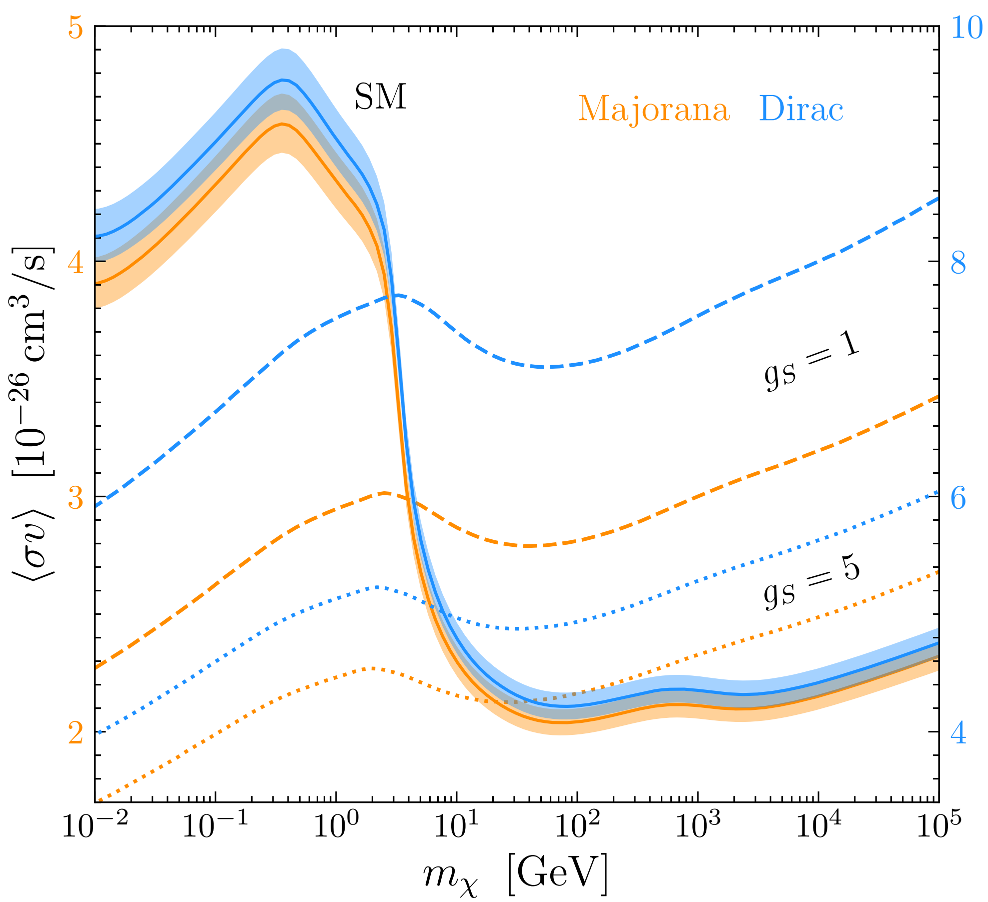
[Pospelov, Ritz, Voloshin 2008;
Batell, Pospelov, Ritz, Shang 2010]

- Annihilation governed by large coupling g_D
- Equilibration with SM governed by $g_D \times g_{SM}$

Questionable:

- Kinetic equilibrium with SM
- Initial equilibration with SM

Secluded Dark Matter / Hidden sectors



Assumptions:

- Initial thermalization with SM at large T
- Afterwards: thermal decoupling from SM
- Light mediator ⇒ dark thermal bath with:

$$\frac{T_\chi(T)}{T} = \frac{\left[g_*^{\mathrm{SM}}(T)/g_*^{\mathrm{SM}}(T_{\mathrm{dec}})\right]^{\frac{1}{3}}}{\left[g_*^{\mathrm{DS}}(T)/g_*^{\mathrm{DS}}(T_{\mathrm{dec}})\right]^{\frac{1}{3}}}$$

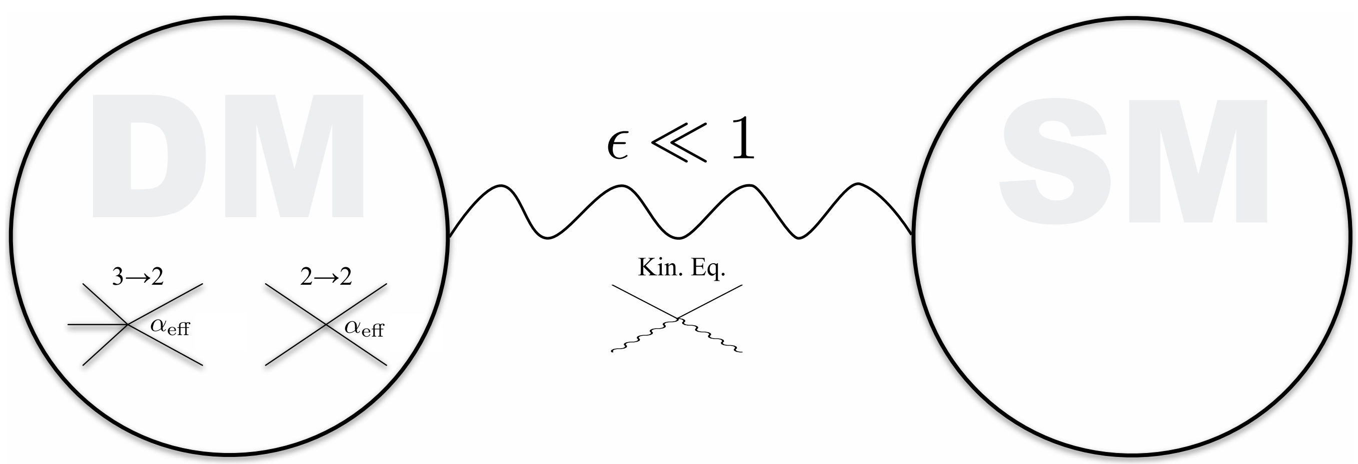
Consequences:

- Changes temperature in n_χ^{eq} and $\langle \sigma v \rangle_{\mathrm{ann}}$
- Increases Hubble rate

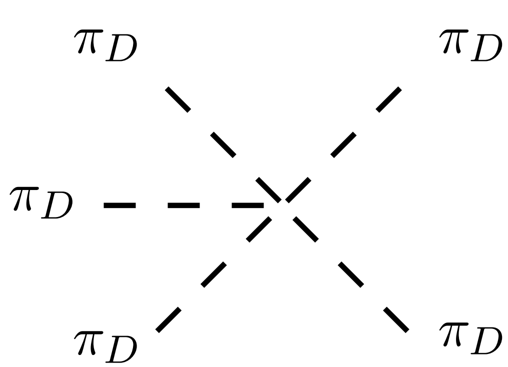
[Bringmann, Depta, Hufnagel, Schmidt-Hoberg 2021]

Hidden sectors with strong dynamics

- Dark interaction g_D subject to long-range force: bound states
- Example: Strongly interacting massive particles (SIMPs)



Wess-Zumino-Witten anomaly (3 ➔ 2 annihilation):



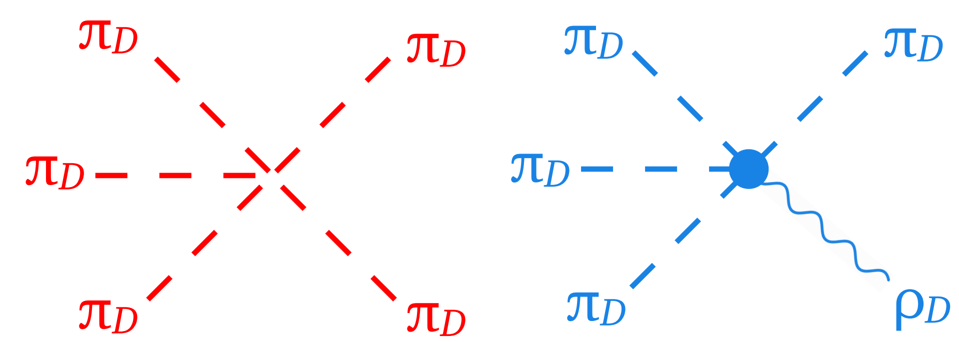
$$\partial_t n + 3Hn \;=\; -\left(n^3 - n^2 n_{\mathrm{eq}}\right)\langle \sigma v^2 \rangle_{3\to 2}$$

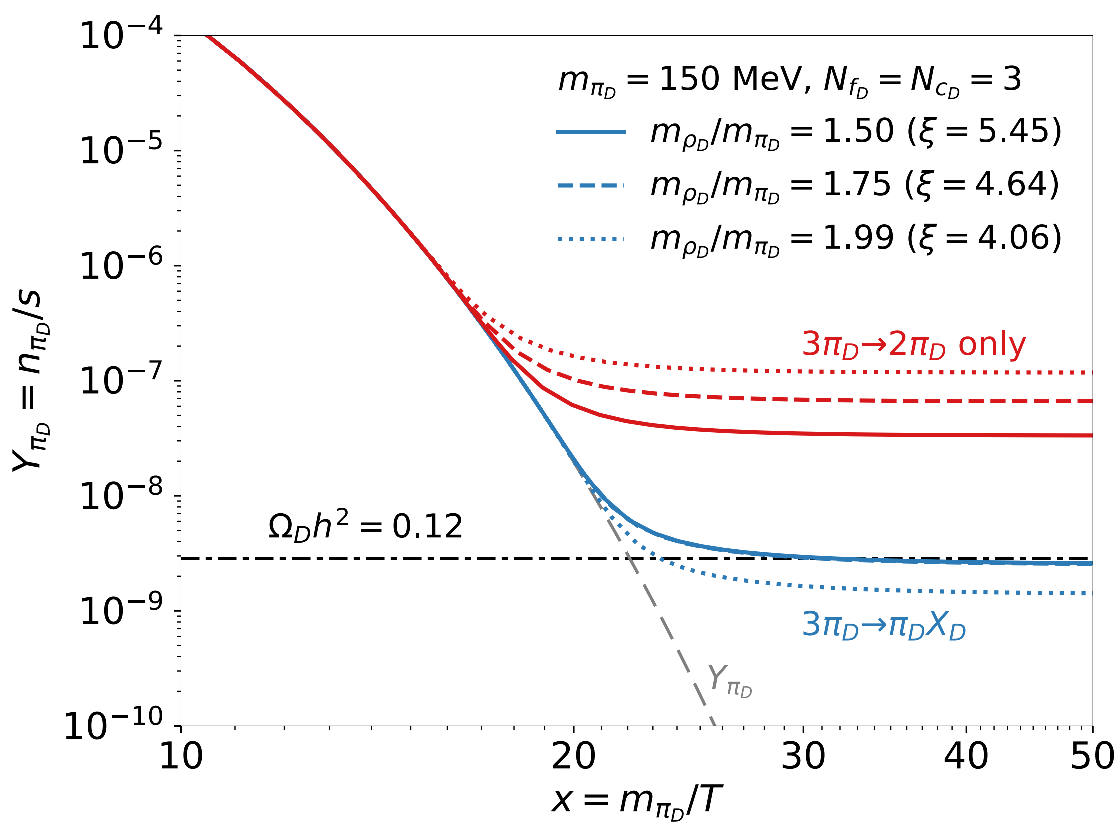
[Hochberg, Kuflik, Volansky, Wacker 2014]

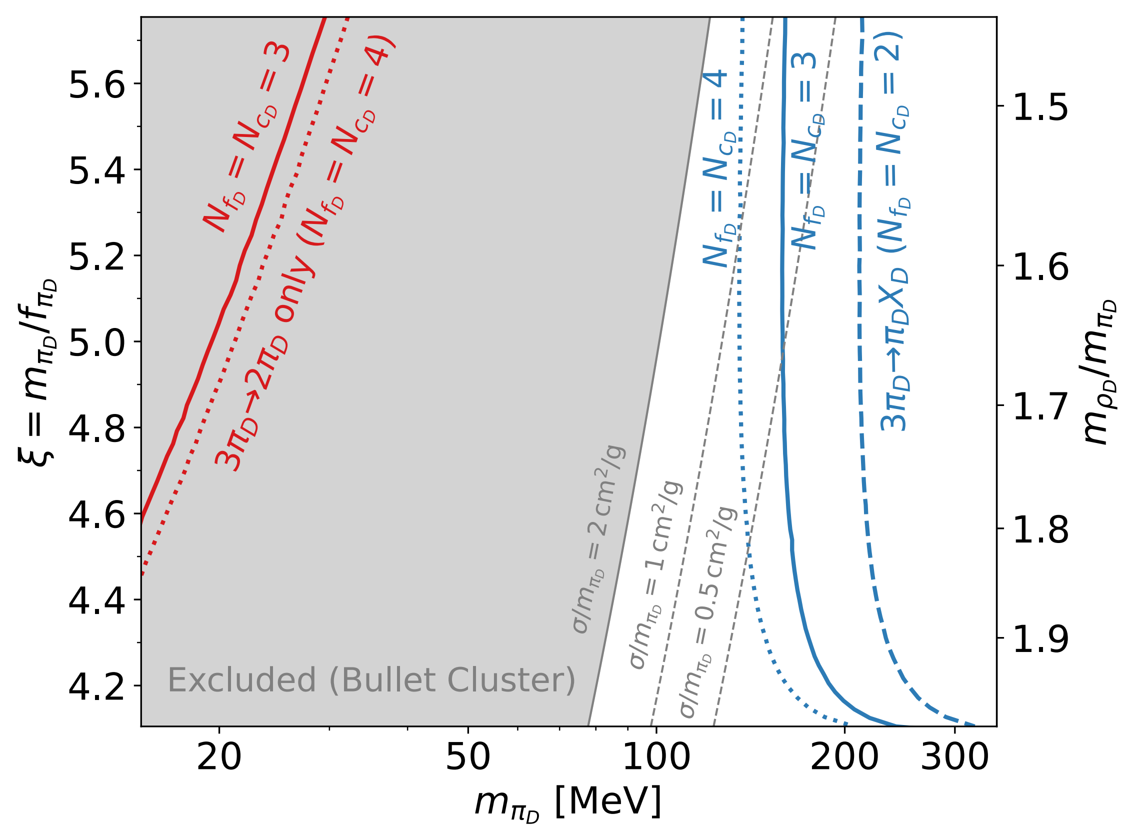
Hidden sectors with strong dynamics

[Bernreuther, Hemme, Kahlhoefer, Kulkarni 2024]

- SIMP paradigm challenged by self-interaction constraints
- Possible solution: light dark ρ-meson







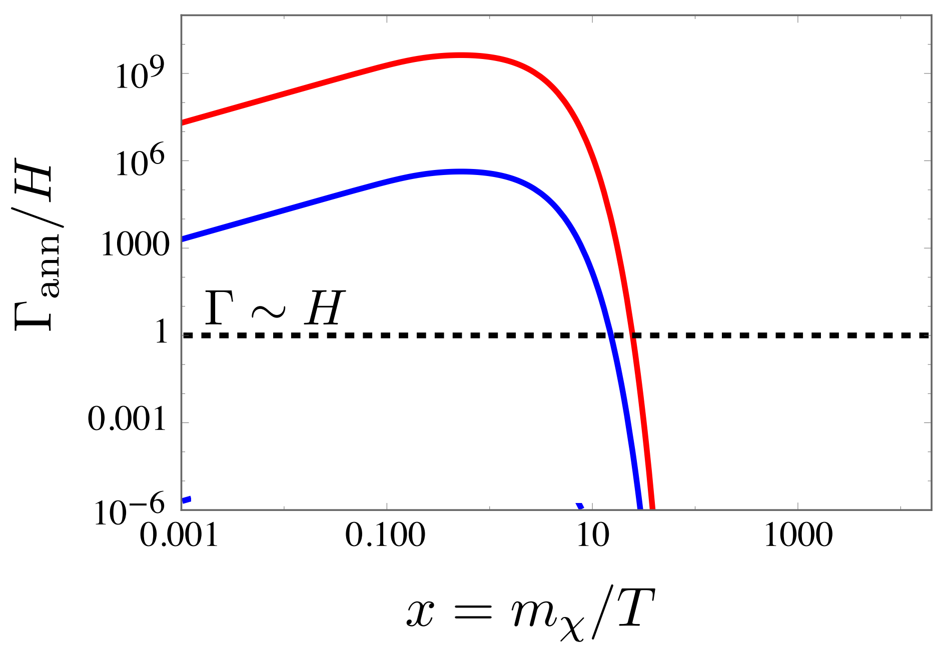
[see also Smirnov, Beacom 2020 for a different solution]

Non-thermalized dark matter

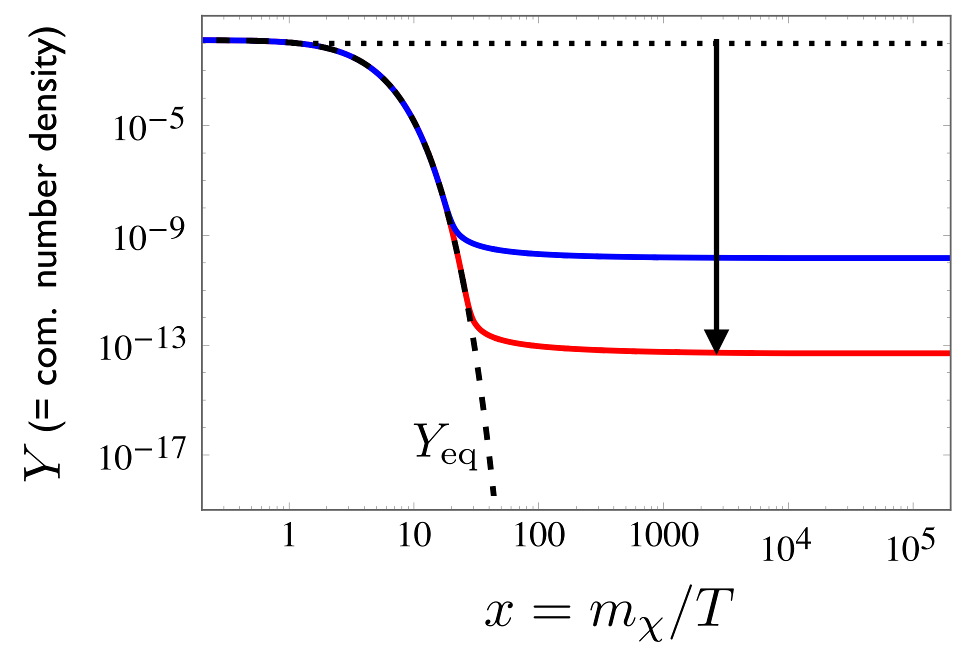
Non-thermalized dark matter
aka Feebly interacting massive particles (FIMPs)

So far:

- Sizeable dark matter interactions ➔ thermalization
- Challenge: Large enough annihilation rate



➔



Non-thermalized dark matter
aka Feebly interacting massive particles (FIMPs)

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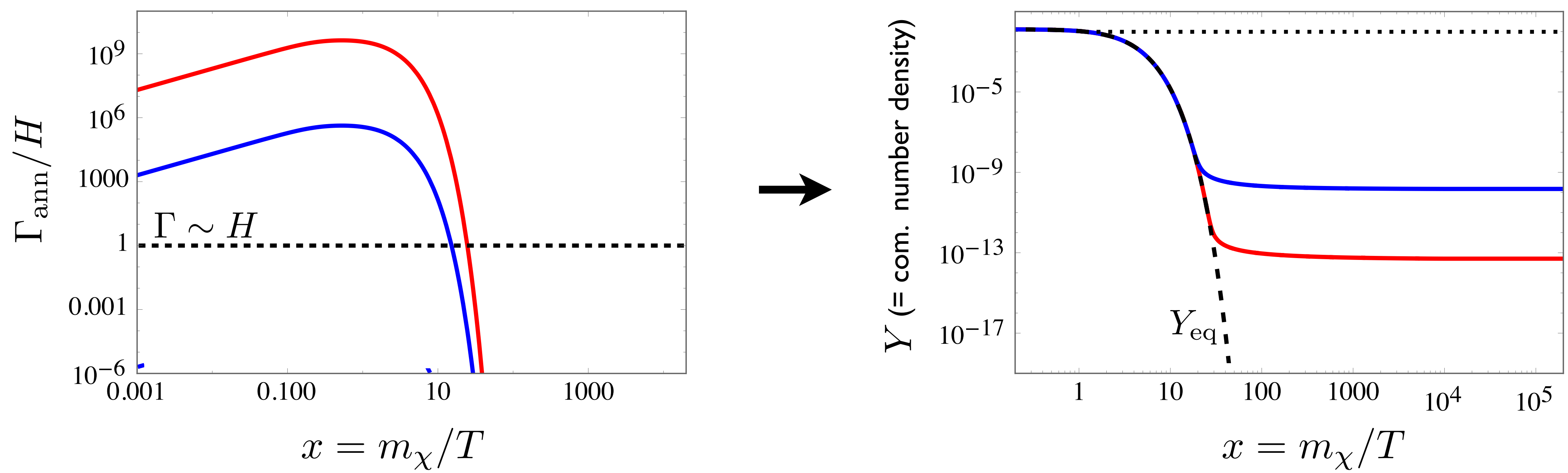

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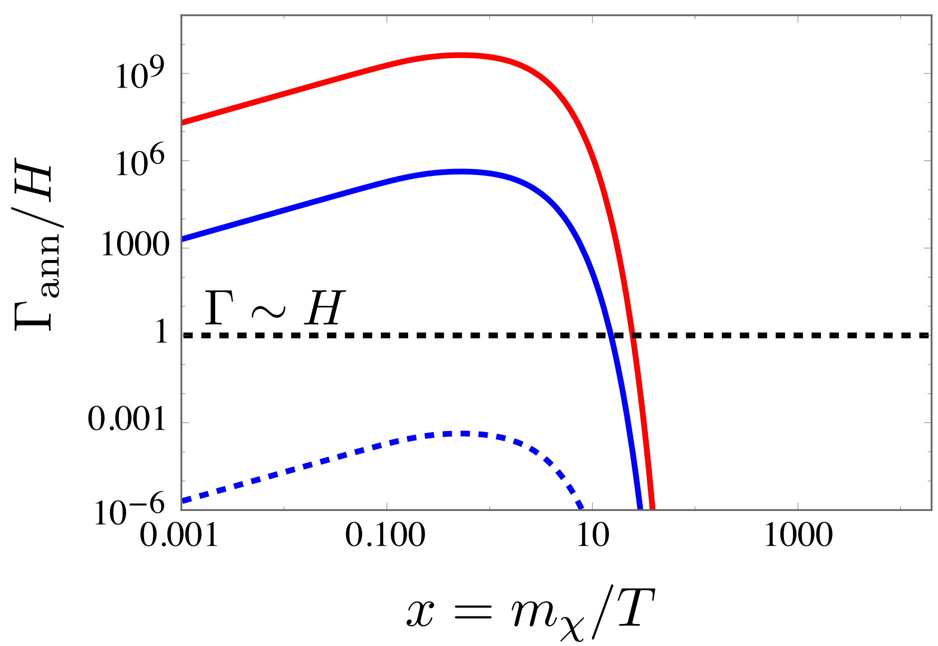

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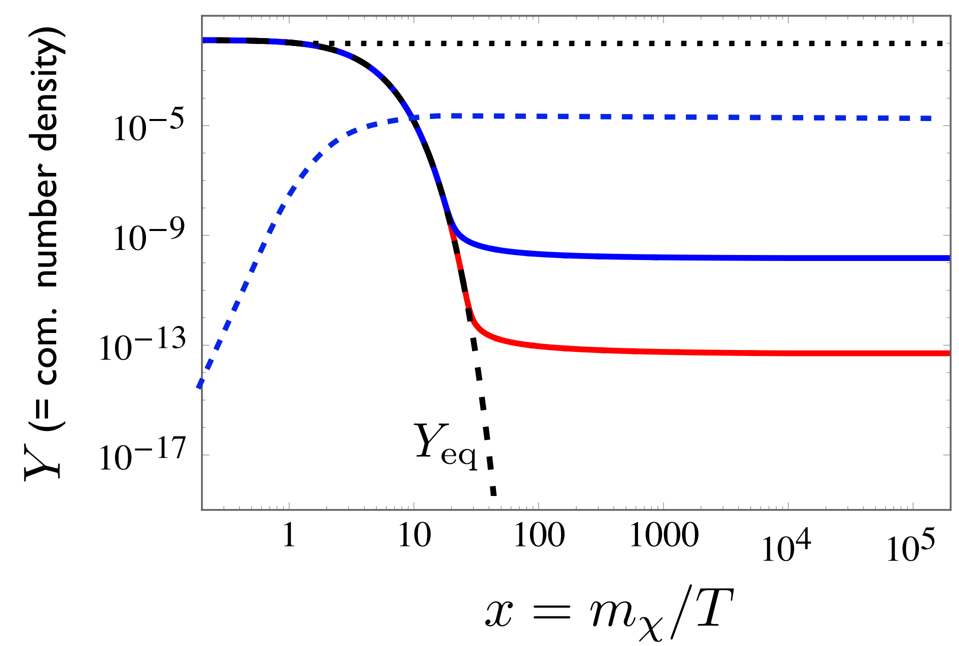

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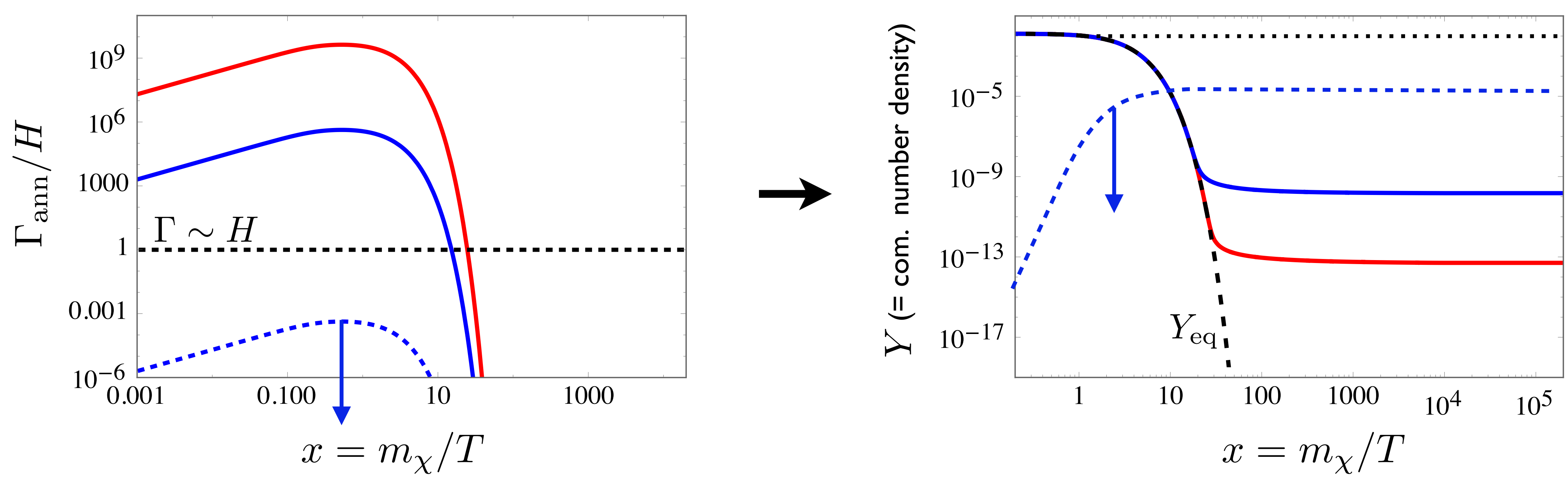

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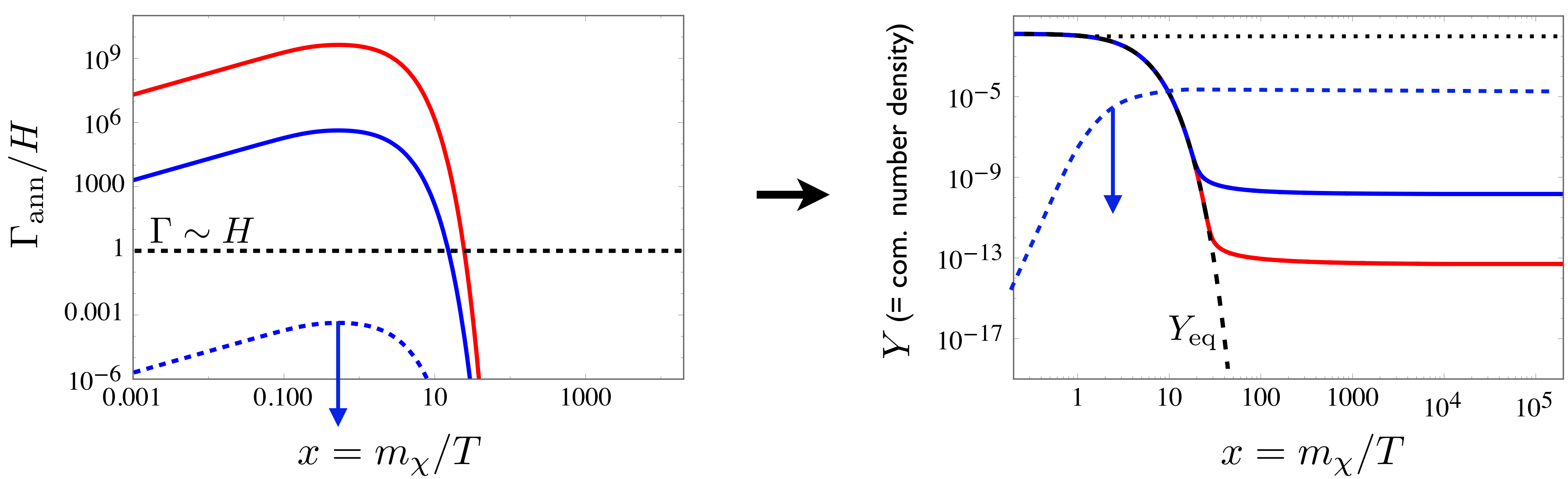
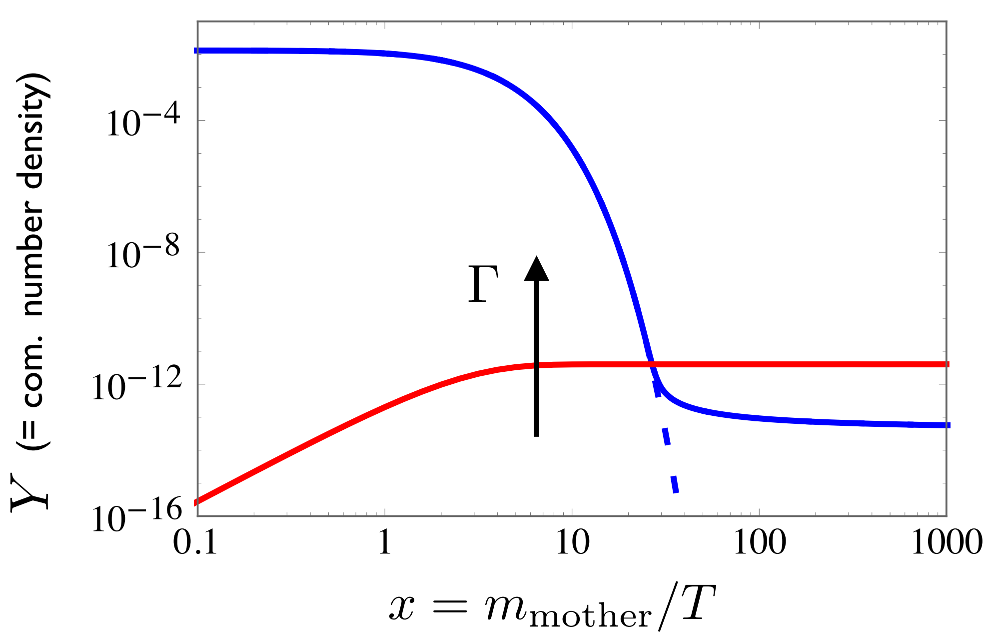


➔ extremely small couplings work again

Non-thermalized dark matter – FIMPs

- Only production ⇒ small initial abundance
- Freeze-in: occasional production from thermal bath
  - UV-sensitive scenarios (e.g. gravitino DM)
    ➔ dependence on reheating temperature
  - IR-sensitive scenarios (renormalizable operators)

[Bolz, Buchmüller, Plümacher 1998;
Bolz, Brandenburg, Buchmüller 2001;
McDonald 2002;
Covi, Roszkowski, Small 2002;
Choi, Roszkowski 2005;
Asaka, Ishiwata, Moroi 2006;
Petraki, Kusenko 2008;
Hall, Jedamzik, March-Russell, West, 2009]



$$\dot{n}_\chi + 3 n_\chi H = 2\left(C_{1\to 2} + C_{2\to 2}\right)$$

Mother (/bath-)particle

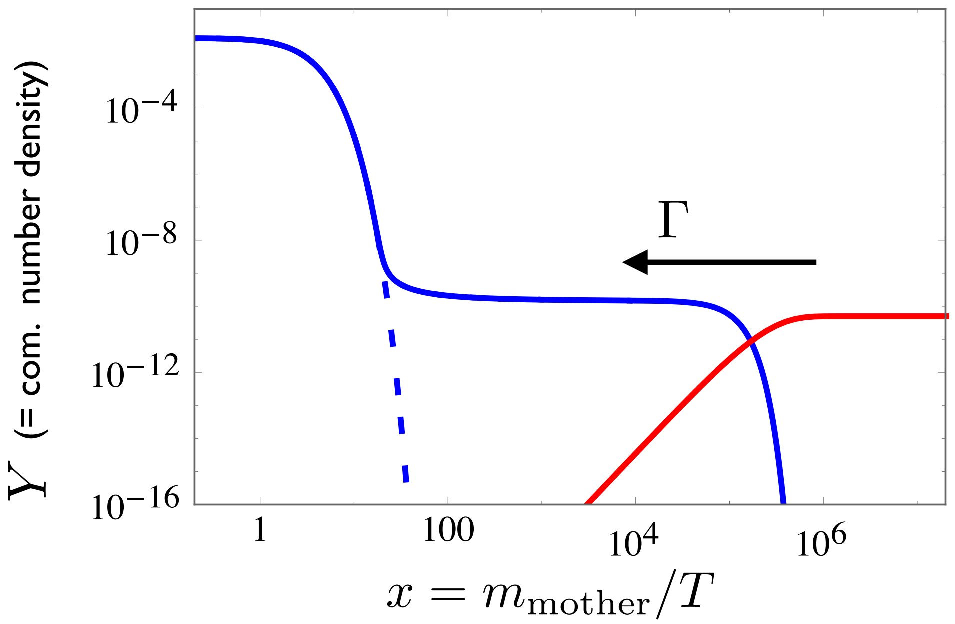
Z2-odd: $M \to \mathrm{SM}\,\chi\,, \quad M\,\mathrm{SM} \to \mathrm{SM}\,\chi\,, \ldots$

Z2-even: $M \to \chi\,\chi\,, \quad M\,M \to \chi\,\chi\,, \ldots$

Non-thermalized dark matter – FIMPs

- Only production ⇒ small initial abundance
- Freeze-in: occasional production from thermal bath
- SuperWIMP: late decay of frozen-out particle

[Covi, Kim, Roszkowski 1999; Feng, Rajaraman, Takayama 2003]



$$(\Omega h^2)_\chi = m_\chi / m_{\mathrm{mother}} \, (\Omega h^2)_{\mathrm{mother}}$$

Non-thermalized dark matter – FIMPs

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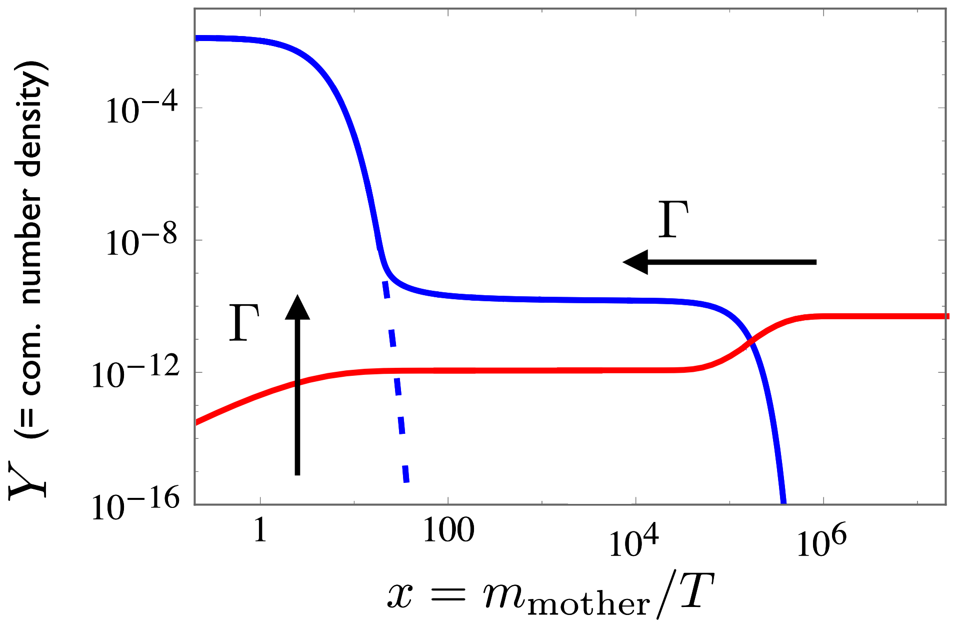
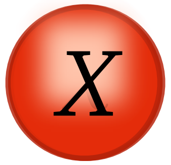
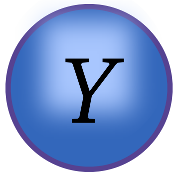
[Covi, Kim, Roszkowski 1999; Feng, Rajaraman, Takayama 2003]



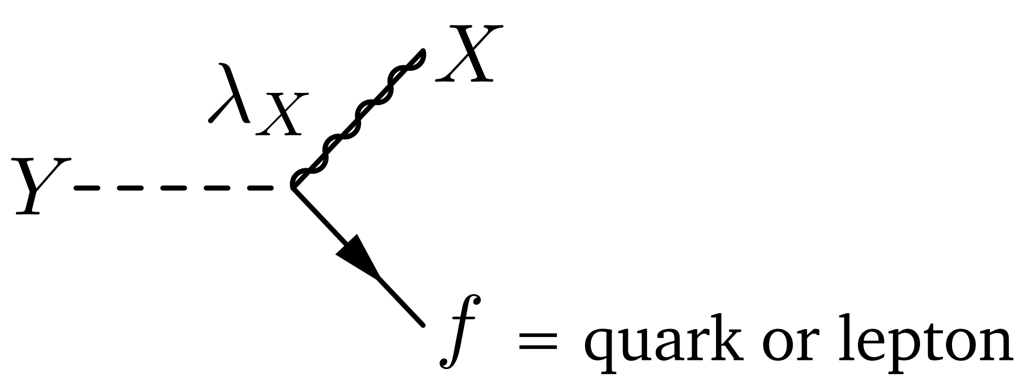
Z$_2$-odd mediator:
Generally both!

[see also Arcadi, Covi 2013]

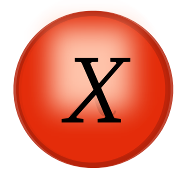
Example: *t*-channel mediator model

Dark matter  $m_X < m_Y$  *t*-channel mediator

λ_X $g_{\rm SM}$

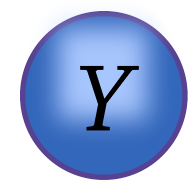


Example: *t*-channel mediator model

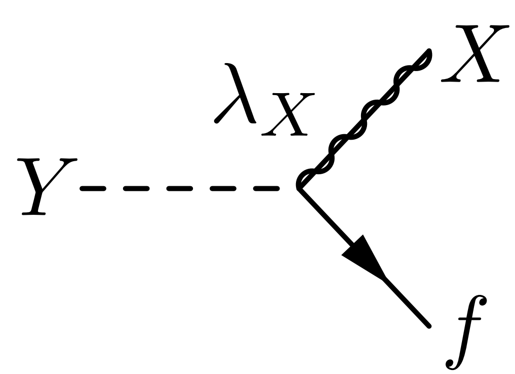
Dark matter 

λ_X

$m_X < m_Y$

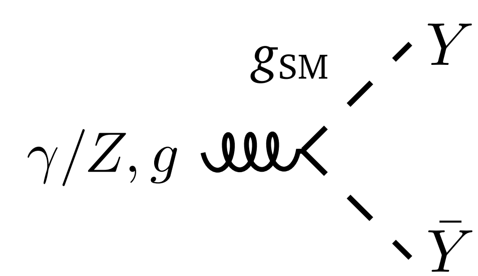


g_{SM} *t*-channel mediator

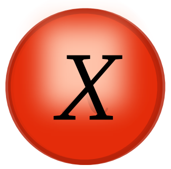
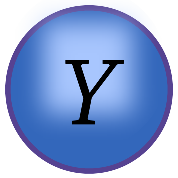


f = quark or lepton

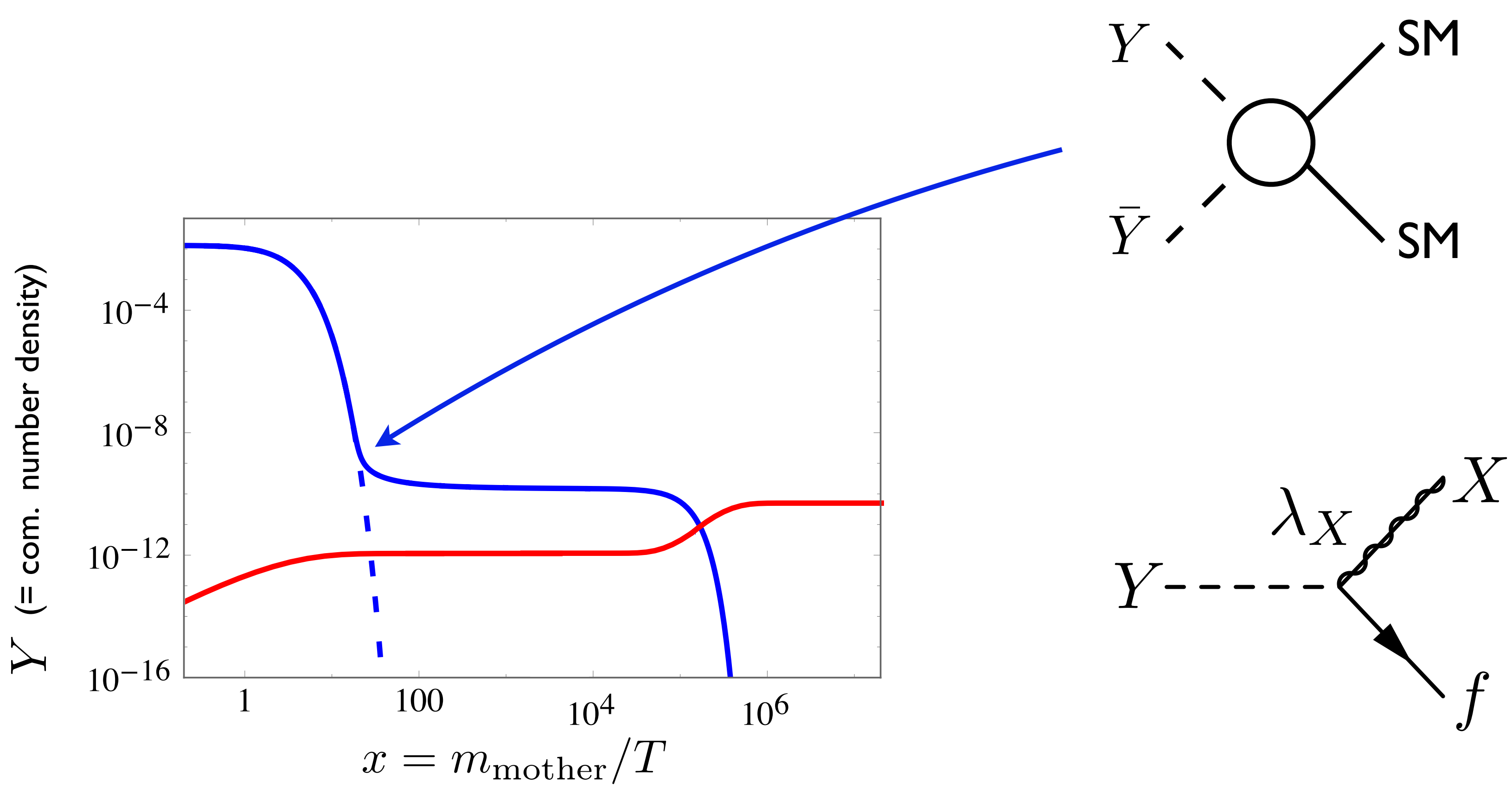
Mediator same gauge quantum no. as $f \Rightarrow$ (color-)charged:



Example: *t*-channel mediator model

Dark matter  $m_X < m_Y$  *t*-channel mediator

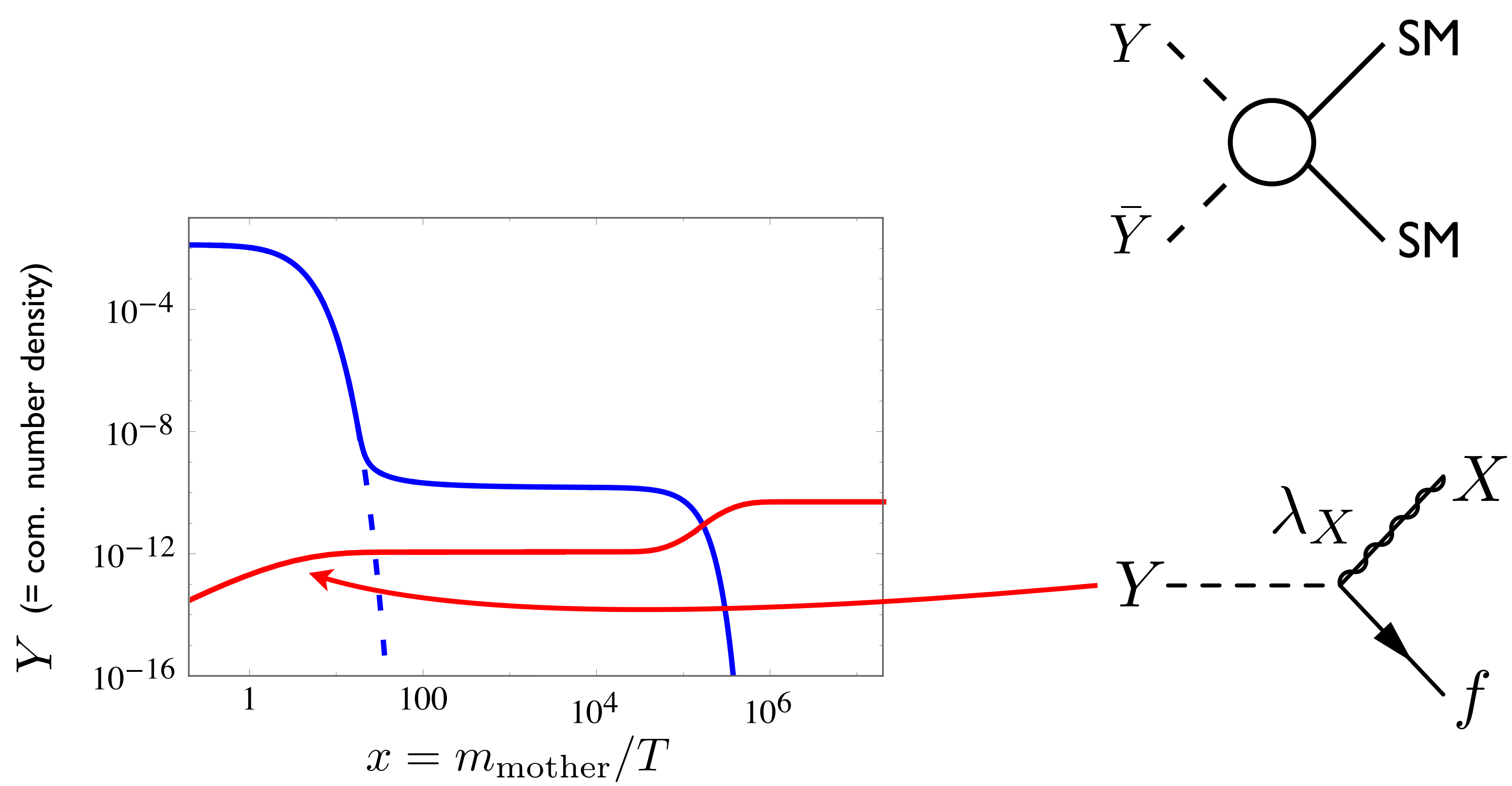
λ_X g_{SM}



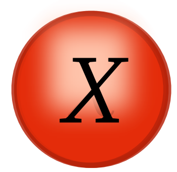
Example: *t*-channel mediator model

Dark matter X $m_X < m_Y$ Y *t*-channel mediator

λ_X $g_{\rm SM}$

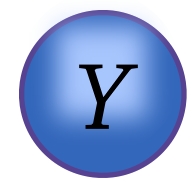


Example: *t*-channel mediator model

Dark matter 

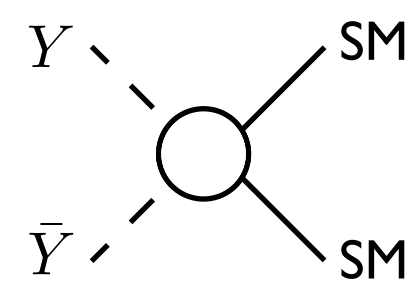
λ_X

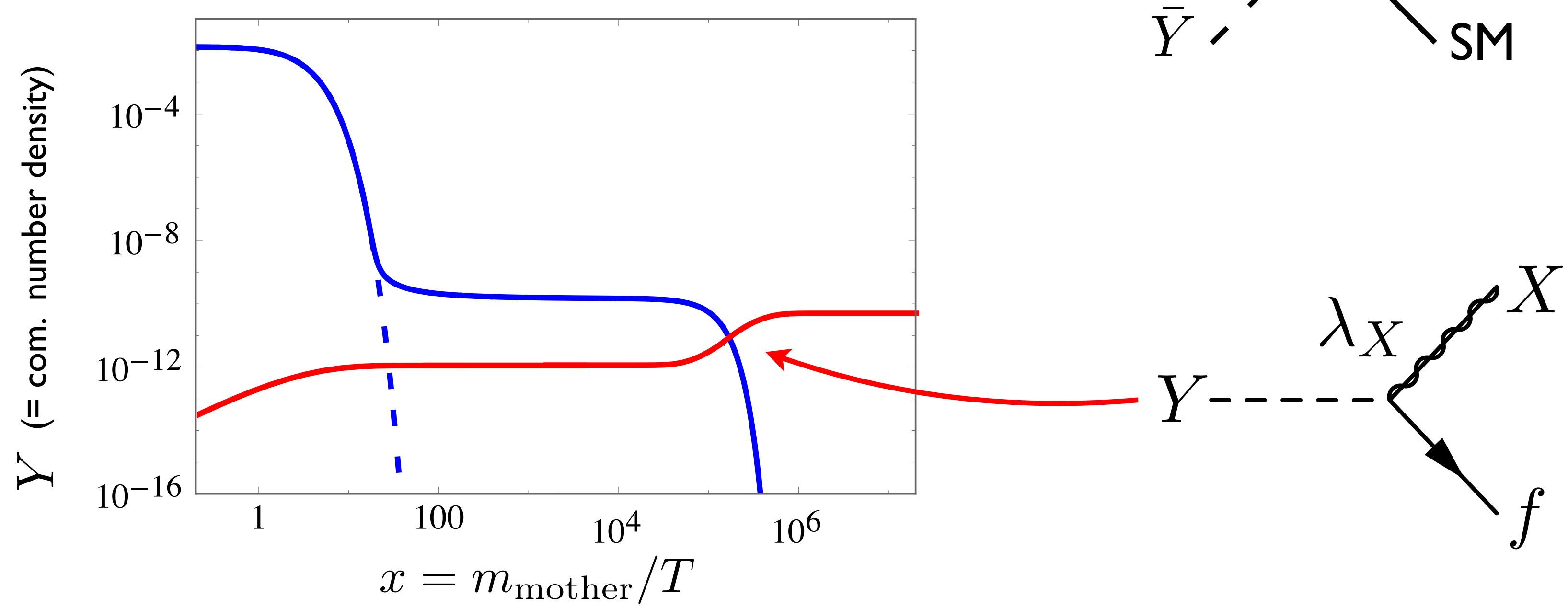
$m_X < m_Y$



g_{SM}

t-channel mediator





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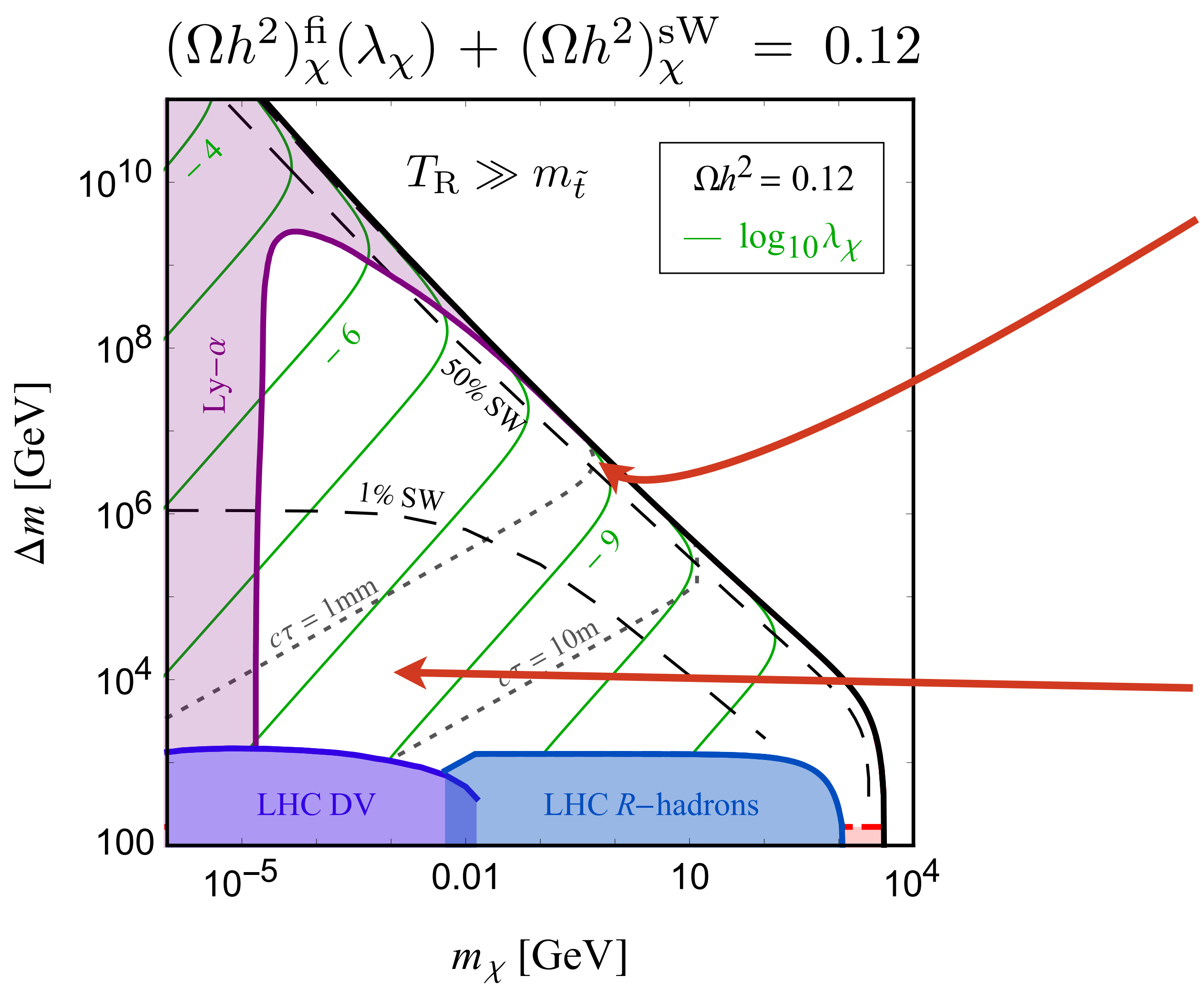
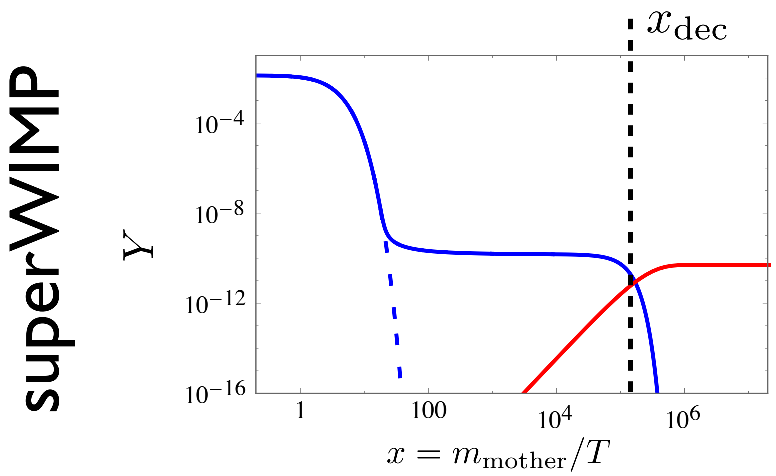
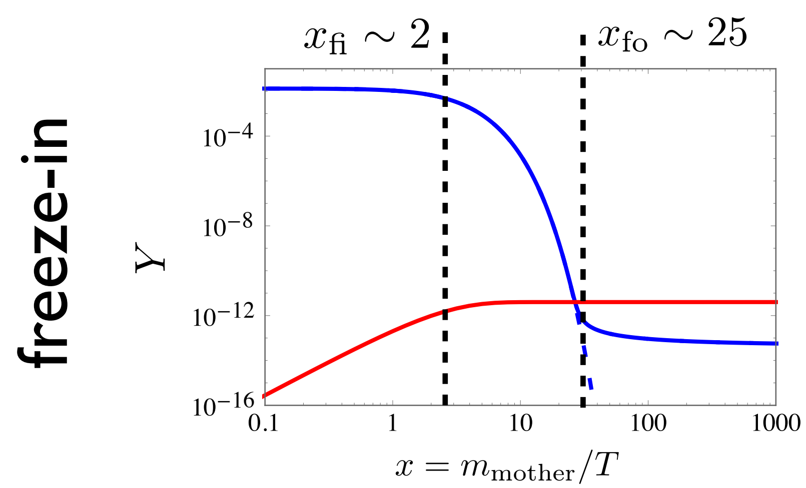




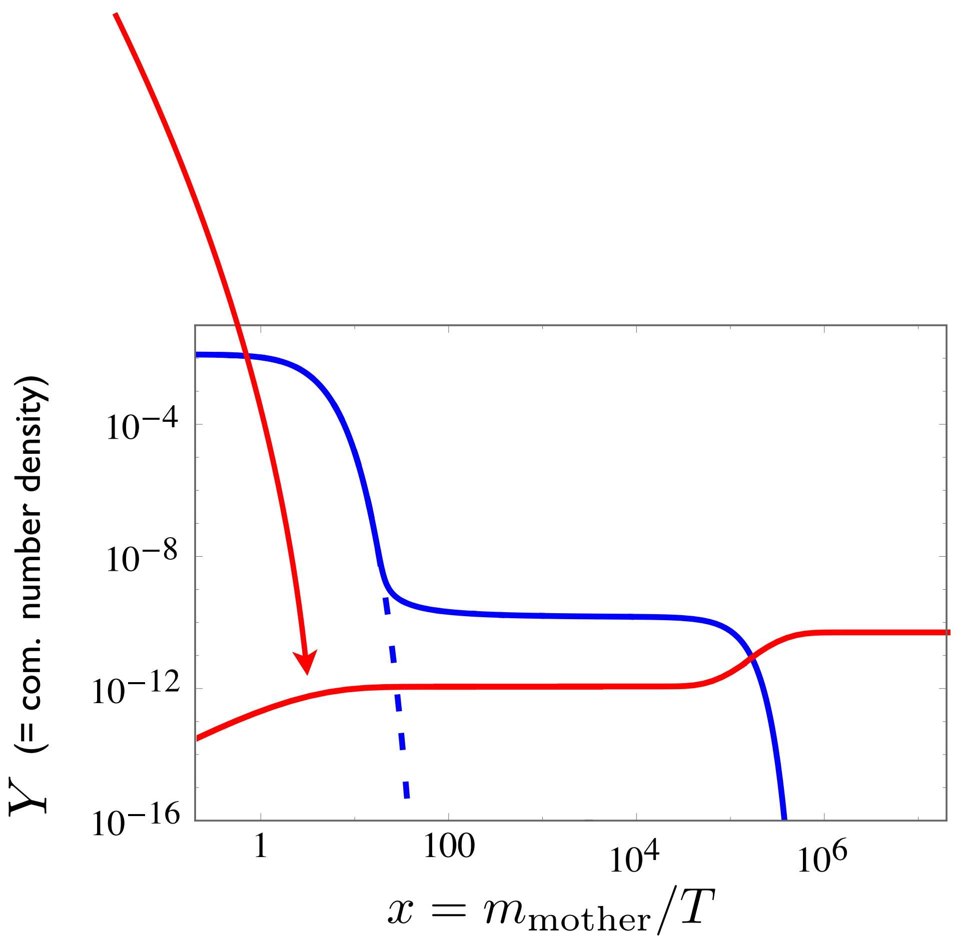


[Decant, JH, Hooper, Lopez-Honorez 2022, see also Garny, JH, 2018]

Scrutinising further assumptions

- Freeze-in production semi-relativistic: finite-temperature effect

[see e.g. Becker, Copello, Harz, Tamarit 2025]



Scrutinising further assumptions

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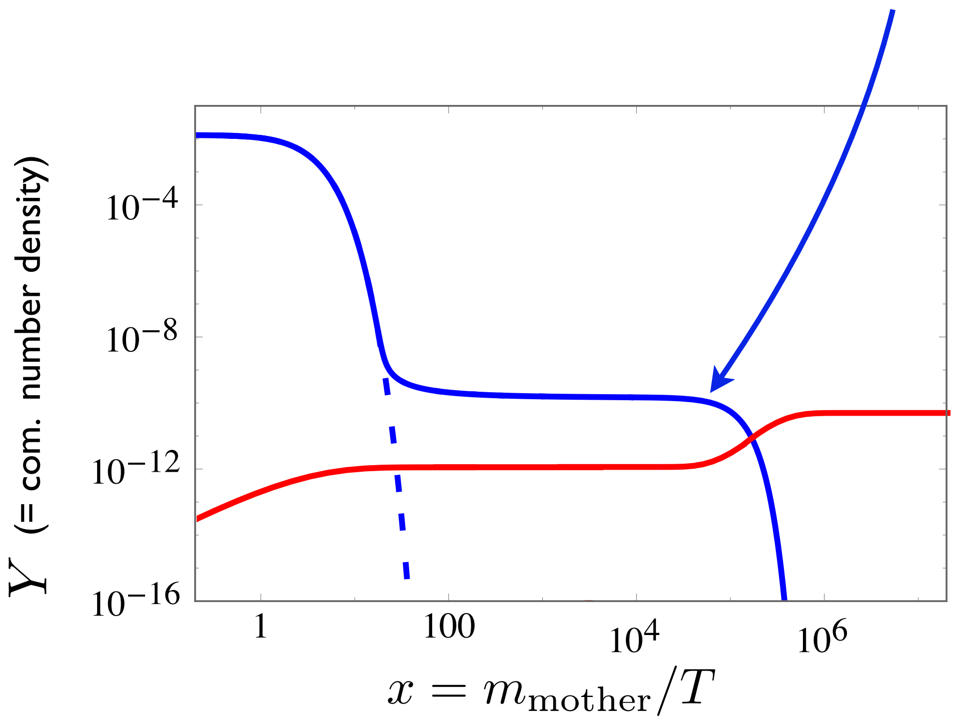
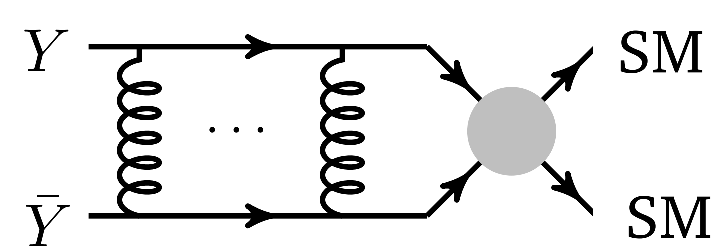
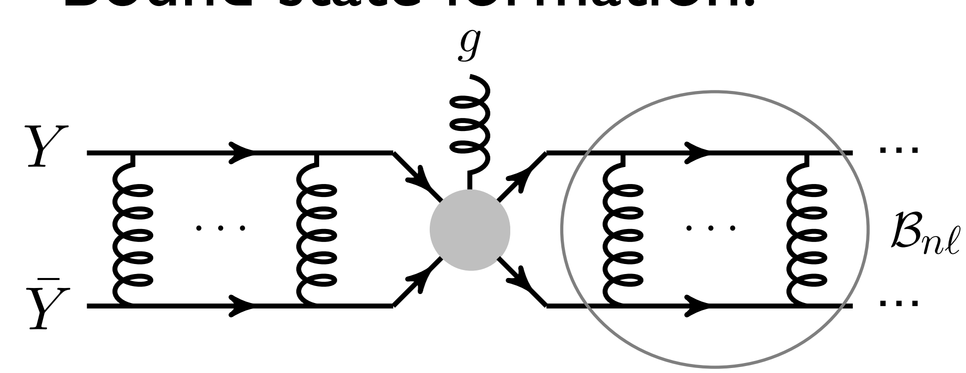
- SuperWIMP production: highly non-relativistic Y particle



Sommerfeld enhancement:



Bound state formation:

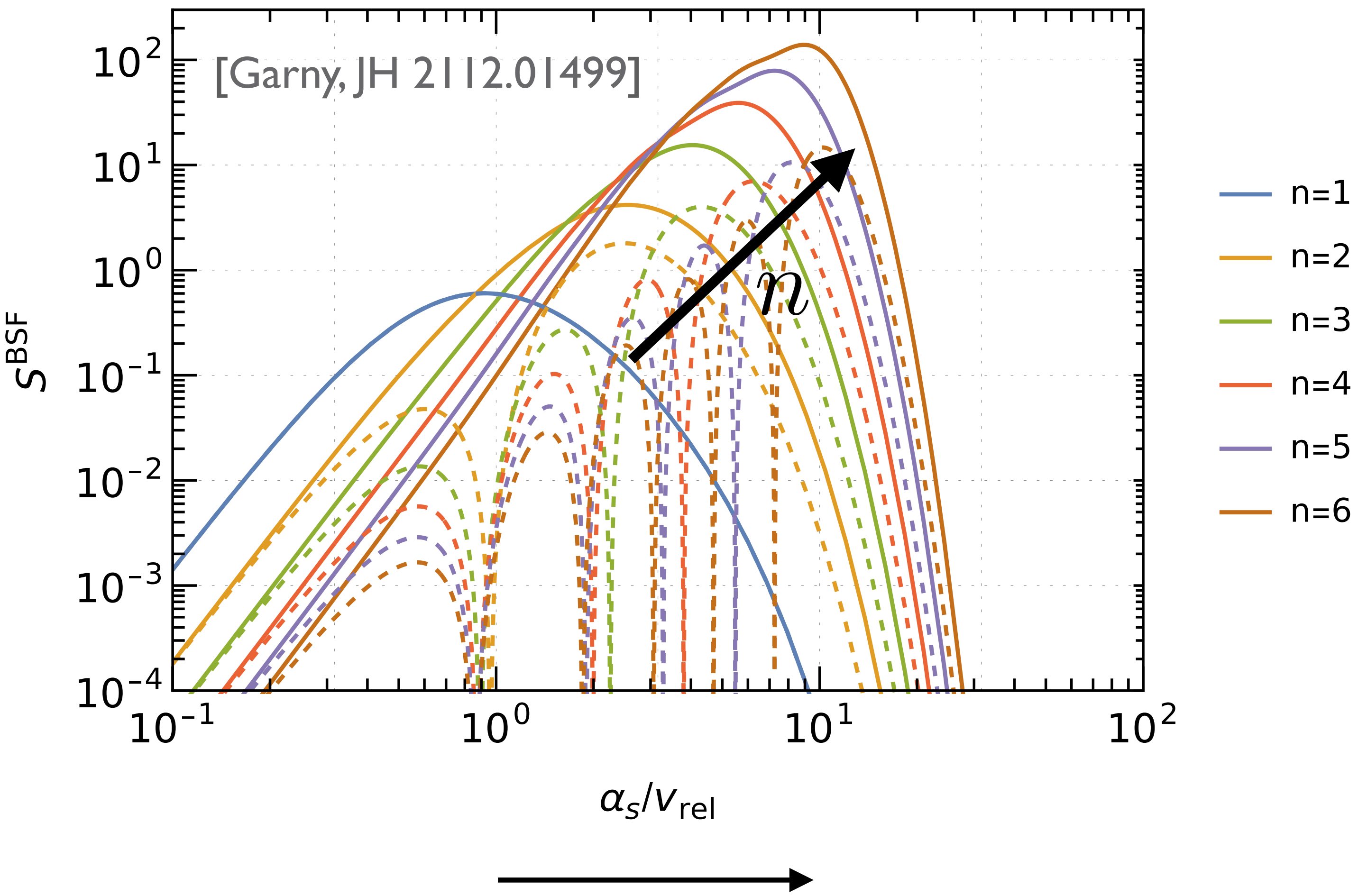


[see e.g. K. Petraki, M. Postma, M. Wiechers 1505.00109; S. P. Liew, F. Luo 1611.08133; J. Harz, K. Petraki 1805.01200; A. Mitridate, M. Redi, J. Smirnov, A. Strumia 1702.01141; T. Binder, B. Blobel, J. Harz, and K. Mukaida 2002.07145; ...]

Bound state formation cross section

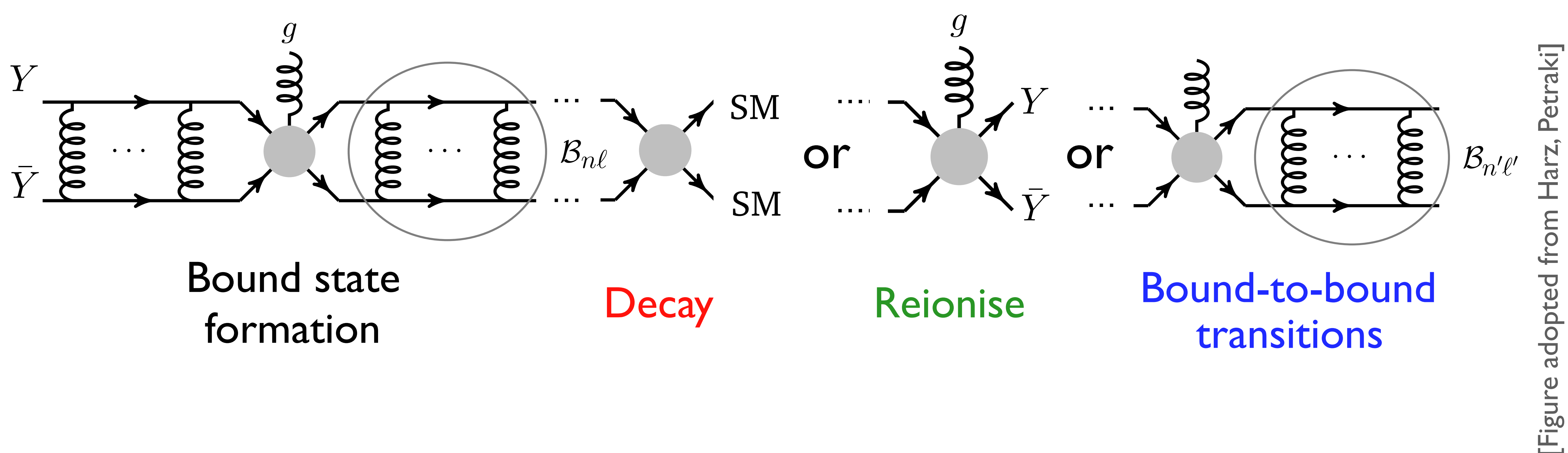
$$\sigma^{\tilde{q}\tilde{q}^\dagger \to \mathcal{B}g}_{\mathrm{BSF},n\ell} v_{\mathrm{rel}} \;\propto\; \alpha_{\mathrm{s}} \omega^3 \left| \langle \psi^{[\mathbf{1}]}_{n\ell} | \boldsymbol{r} | \psi^{[\mathbf{8}]}_{\boldsymbol{p}_{\mathrm{rel}}} \rangle \right|^2$$

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



small velocities ~ relevant for small temperatures

Inclusion of excited bound states



➔ Couple set of Boltzmann equations (one for each state)

Reformulation as effective cross section possible:

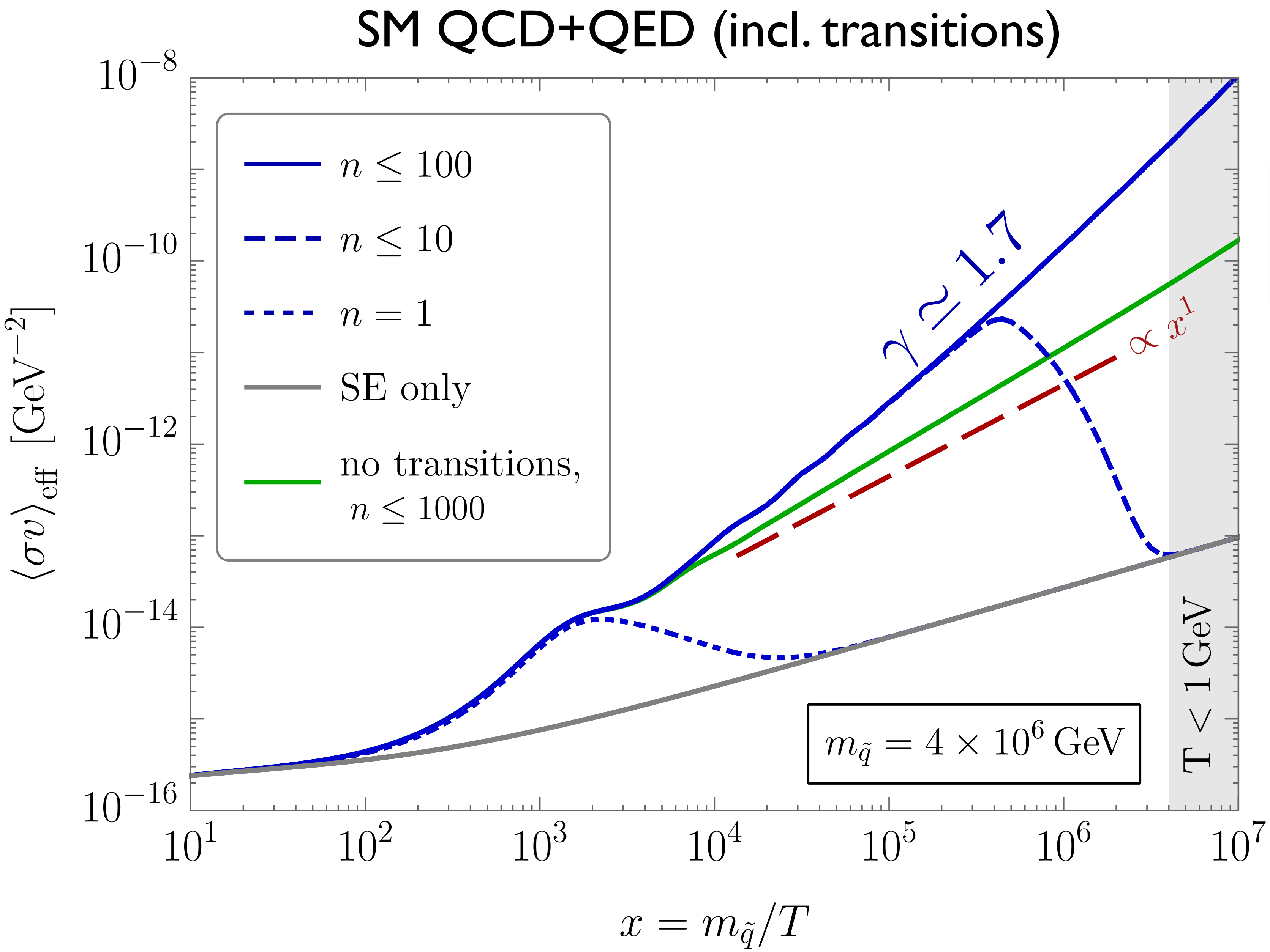
$$\langle \sigma_{XX^\dagger} v \rangle_{\text{eff}} = \langle \sigma_{XX^\dagger} v \rangle + \sum_i \langle \sigma_{\text{BSF},i} v \rangle R_i \,, \quad 0 \leq R_i \leq 1$$

[Binder Filimonova, Petraki, White 2112.00042; Garny, JH 2112.01499]

[*cf.* Ellis, Luo, Olive 1503.07142;
Mitridate, Redi, Smirnov, Strumia 1702.01141]

Effective annihilation cross section

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



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

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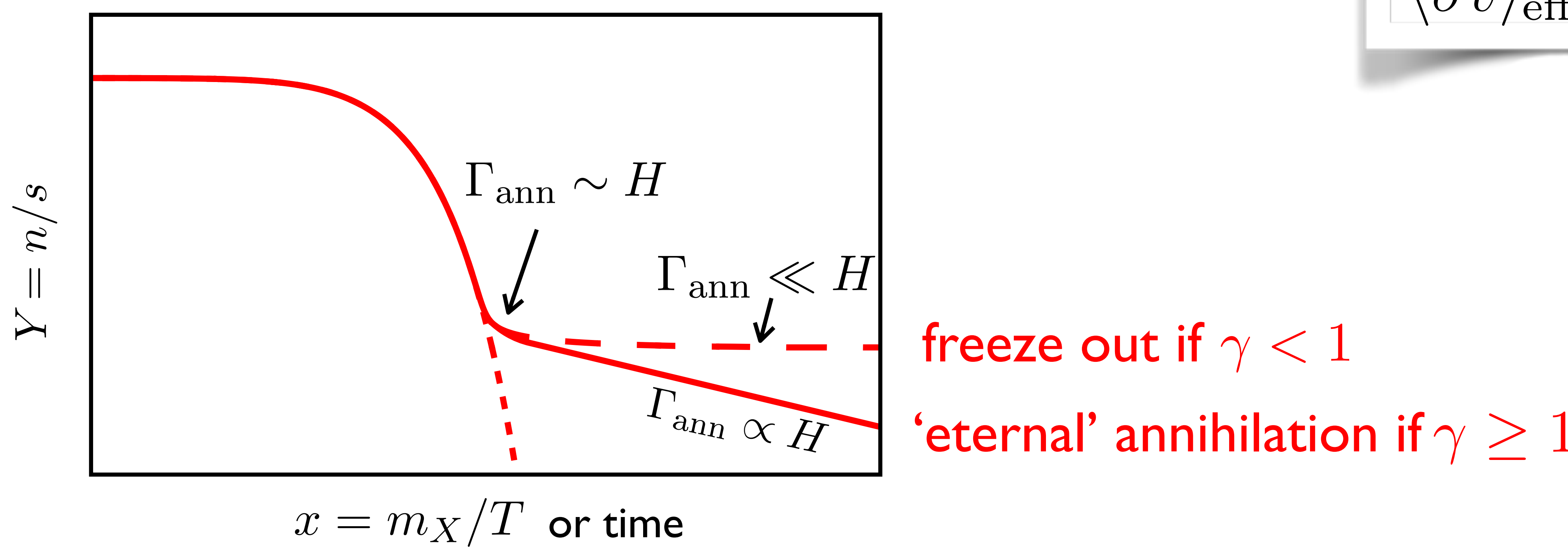

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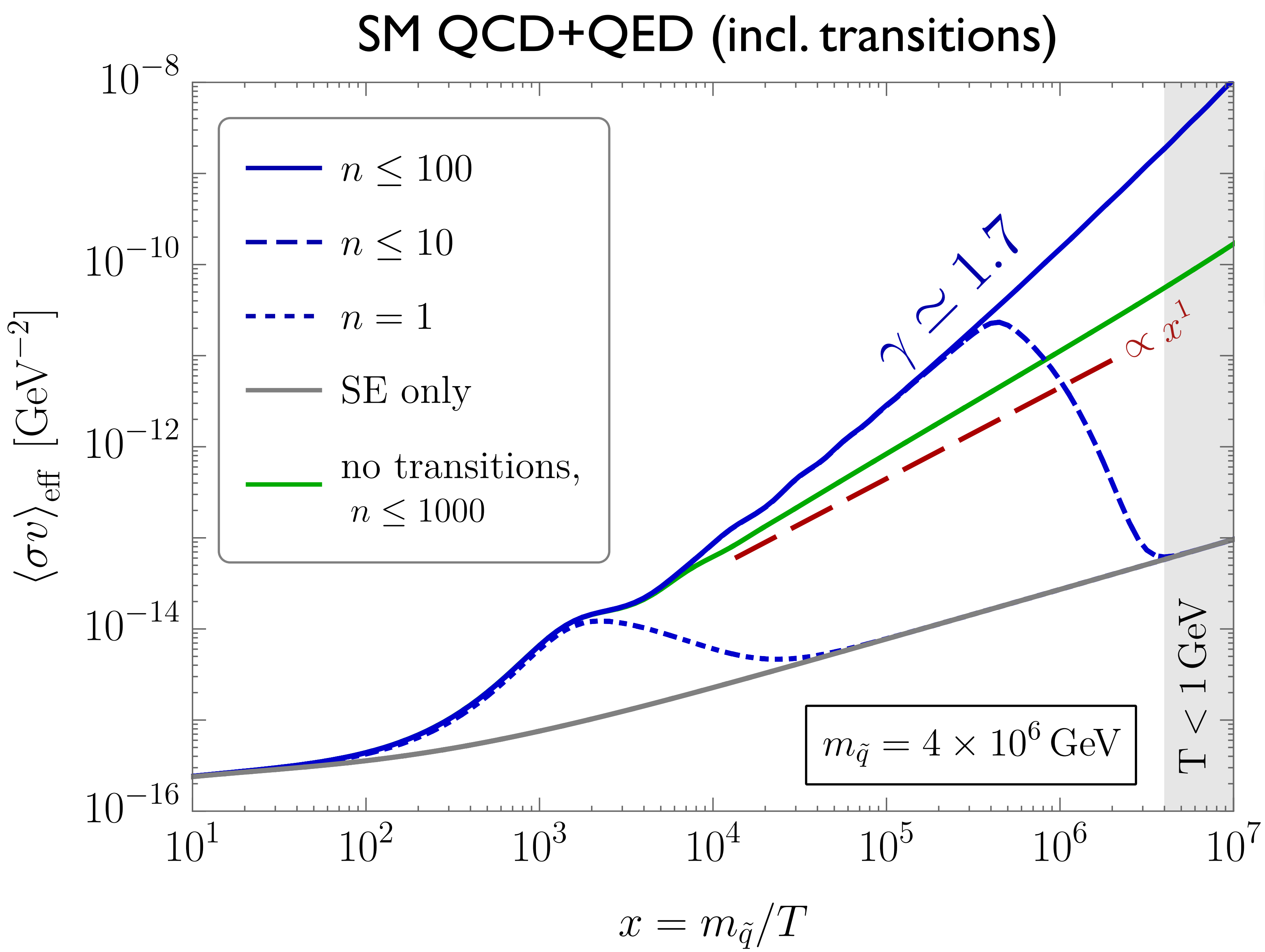
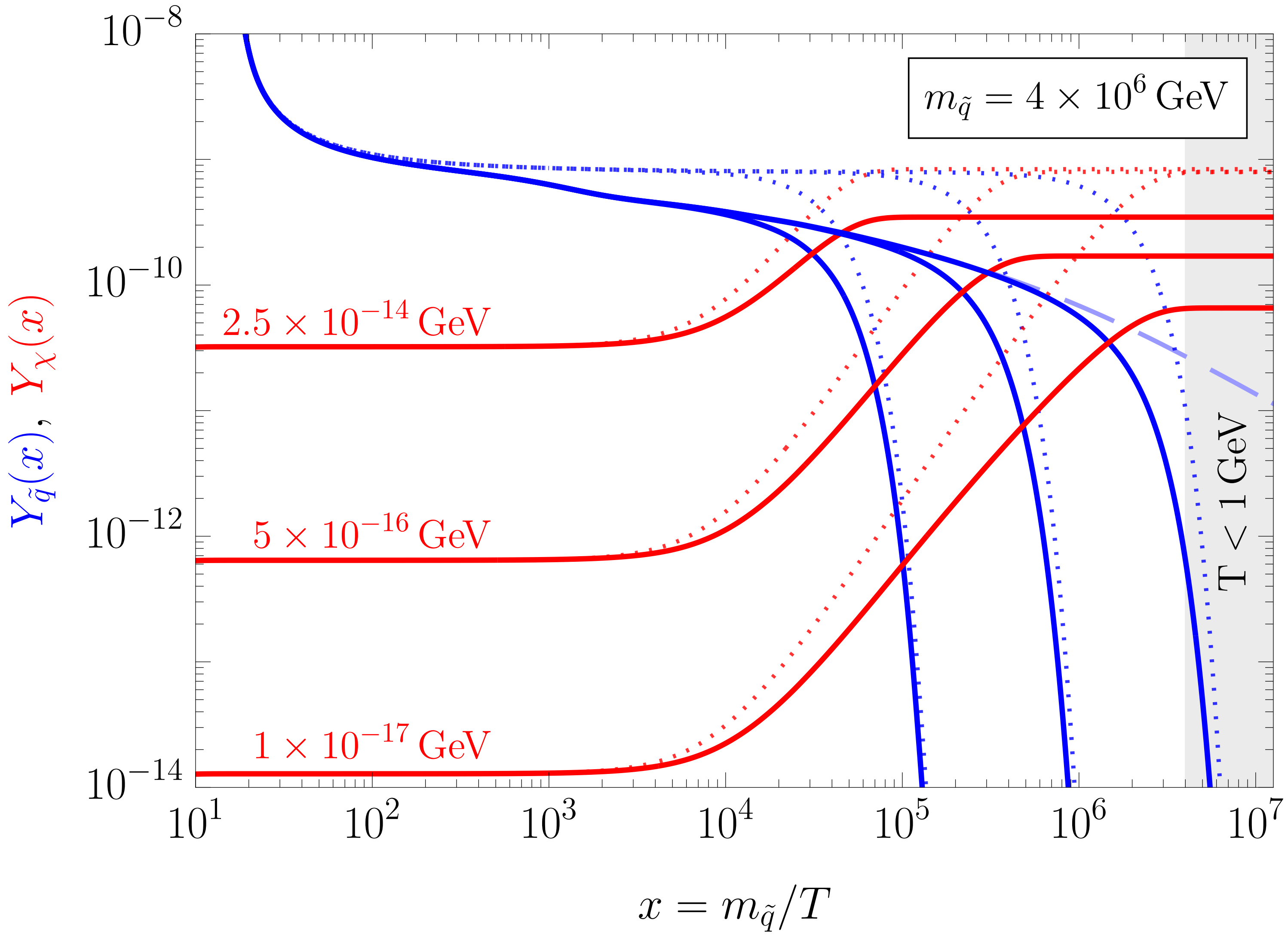


$\langle \sigma v \rangle_{\text{eff}} \propto x^{\gamma}$

Impact on the relic abundance

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



Bound states introduce dependence on λ_χ in superWIMP production!

[Result for $n=1$ *cf.* Decant, Hooper, Lopez-Honorez, JH 2111.09321, Bollig, Vogl 2112.01491]

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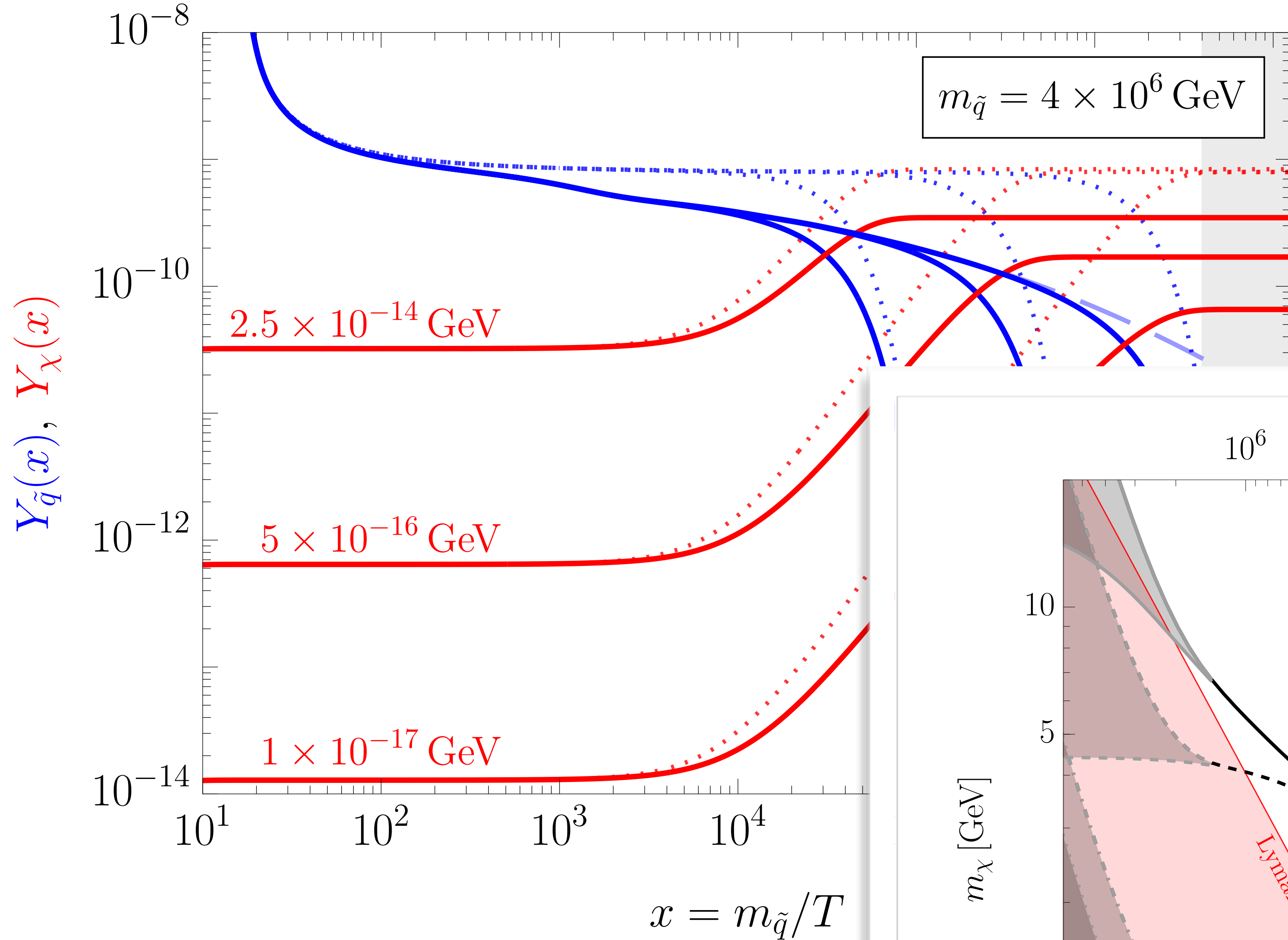

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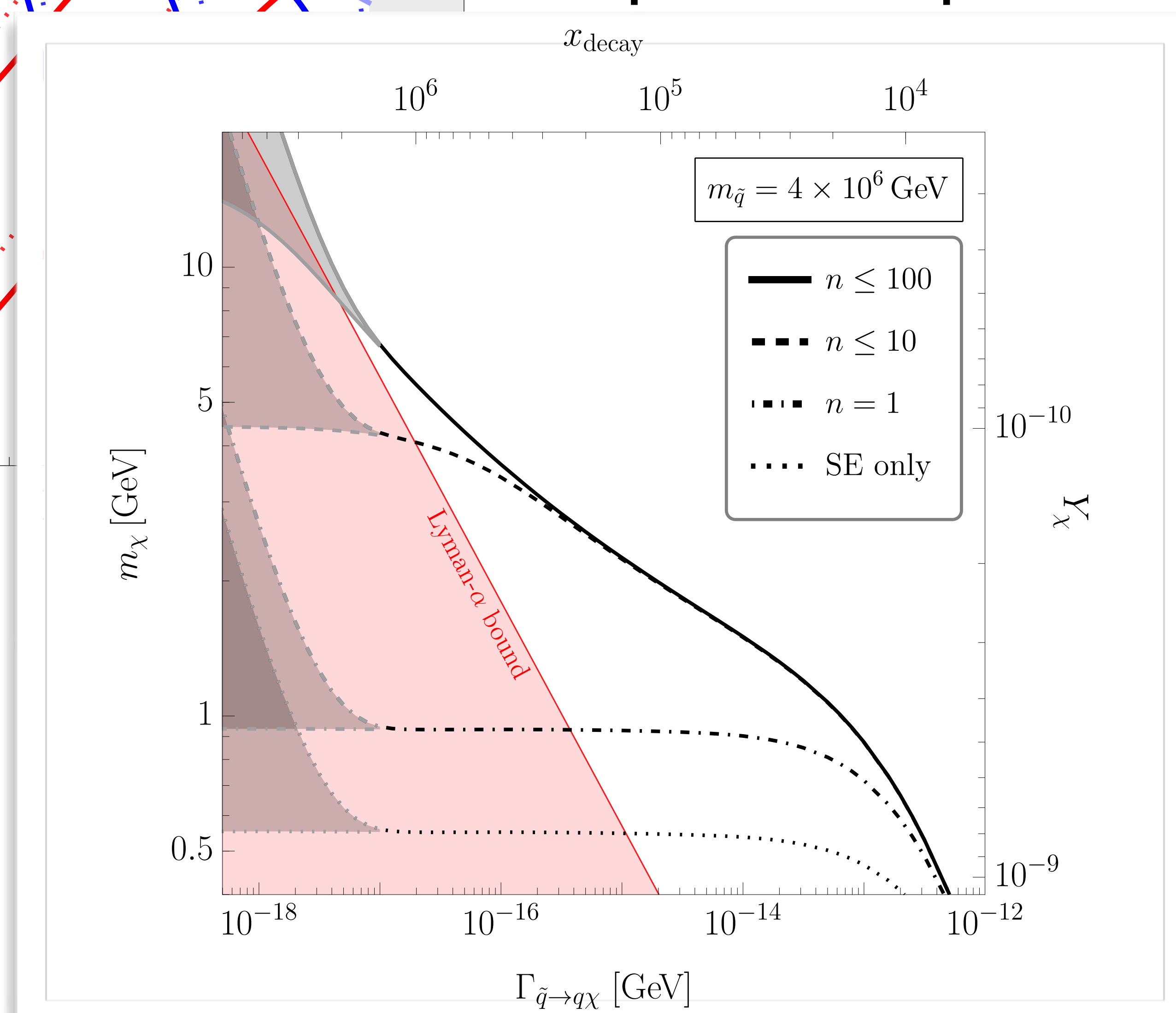


Relevant for constraints from cosmological structure formation (Lyman-alpha forest observations)

Hybrid Regime

Hybrid Regime

So far:

Large DM couplings $\longleftrightarrow$ thermalization

Feeble DM couplings $\longleftrightarrow$ no thermalization

Hybrid Regime

Possible?

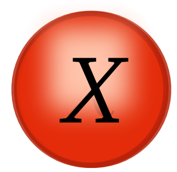
Large DM couplings → thermalization

Feeble DM couplings ← no thermalization

⇒ Revisit coannihilation scenario

... but drop an important assumption

Example: *t*-channel mediator model:

Dark matter 

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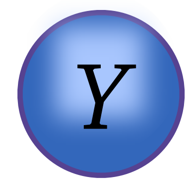
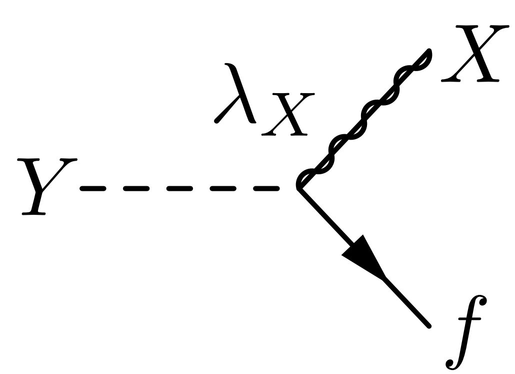


t-channel mediator

λ_X $g_{\rm SM}$



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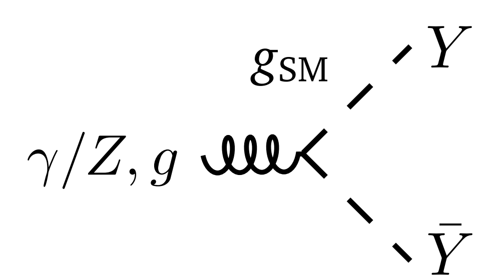
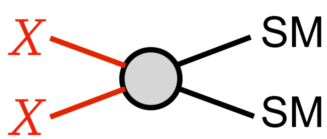


Revisiting the coannihilation scenario

[Griest, Seckel 1991; Edsjo, Gondolo 1997]

X ➔ SM



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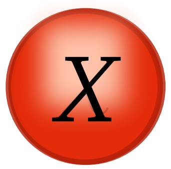
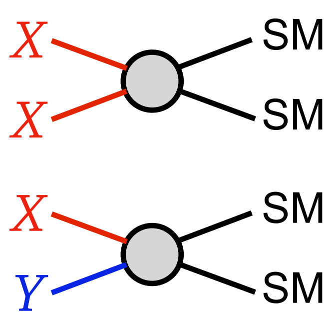


➔ SM



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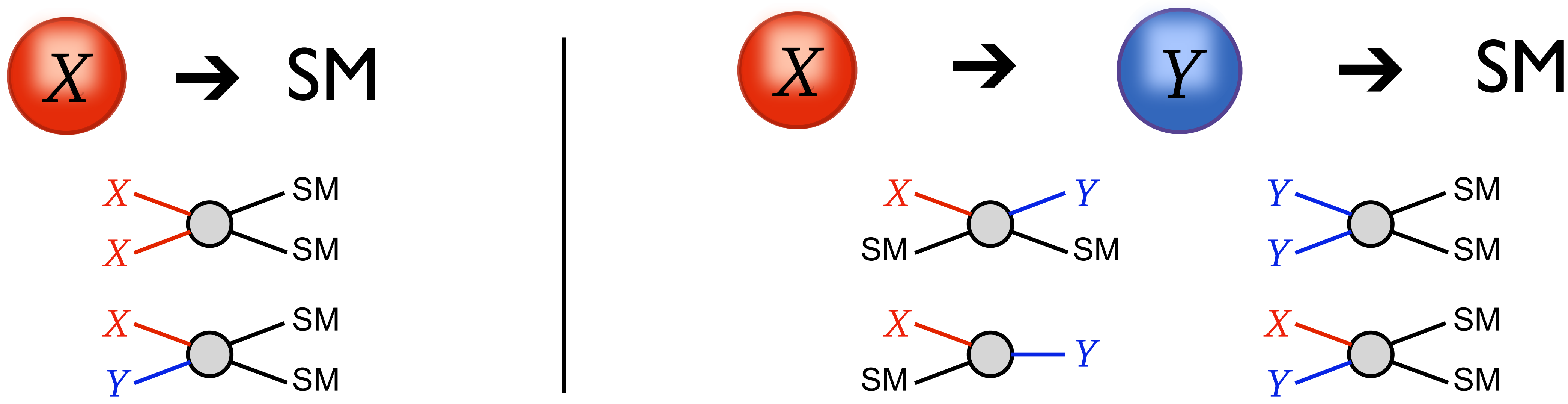

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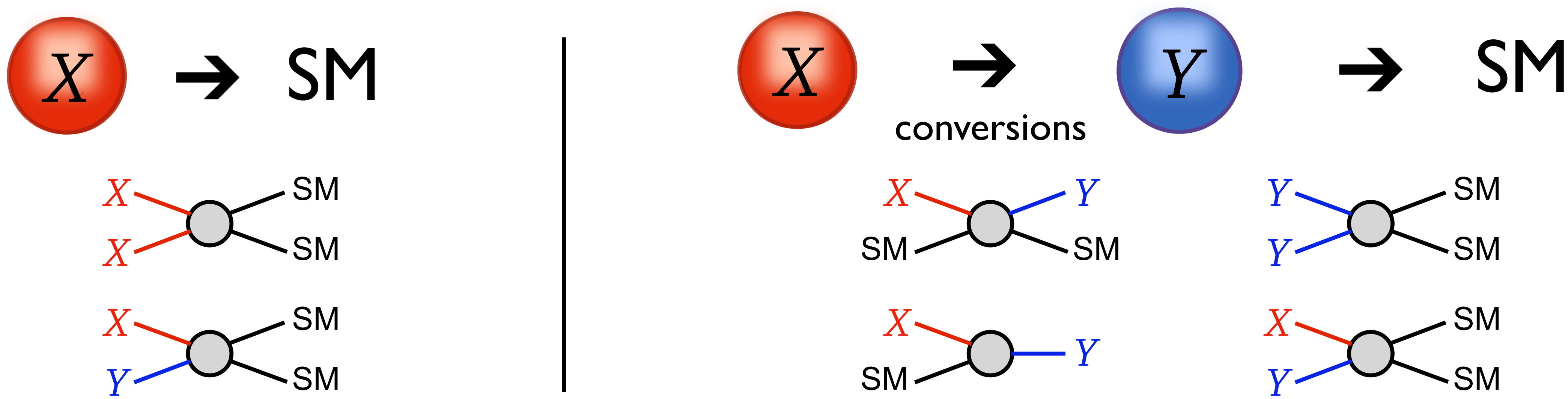

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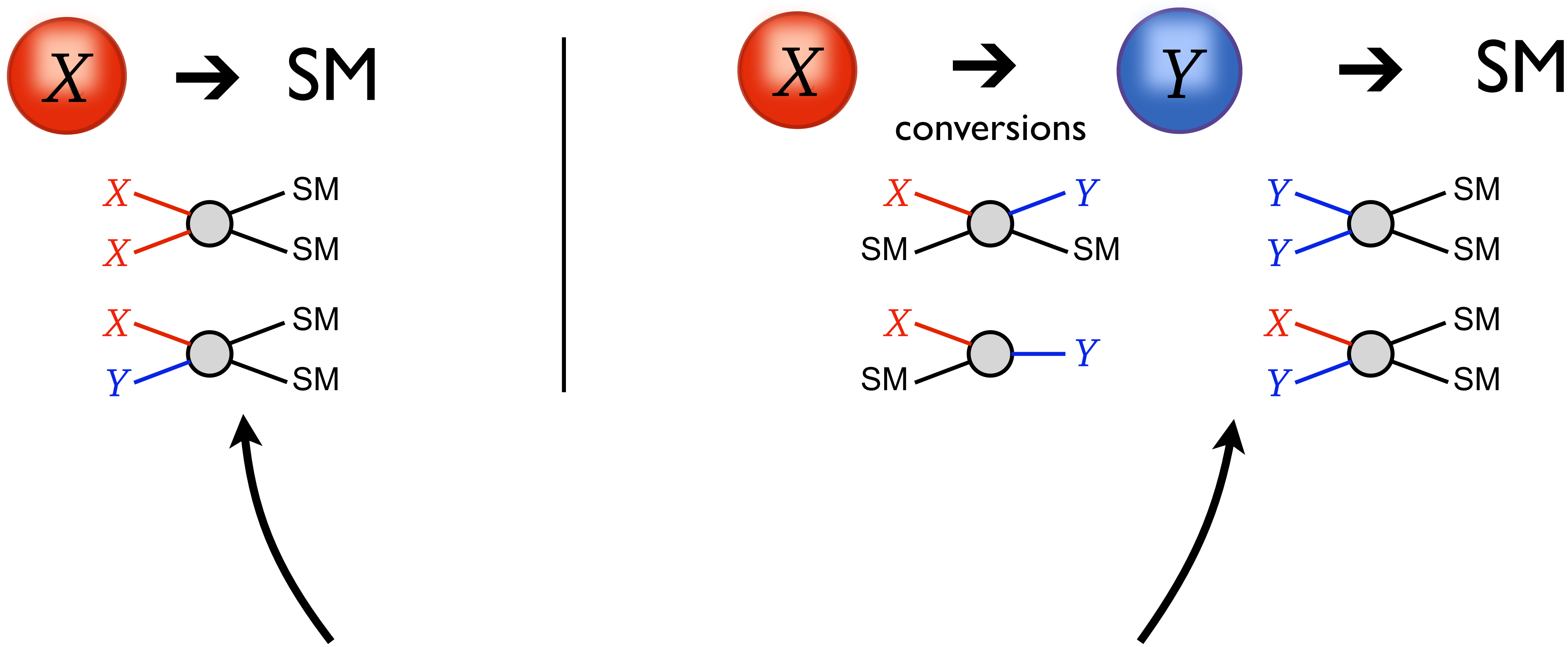
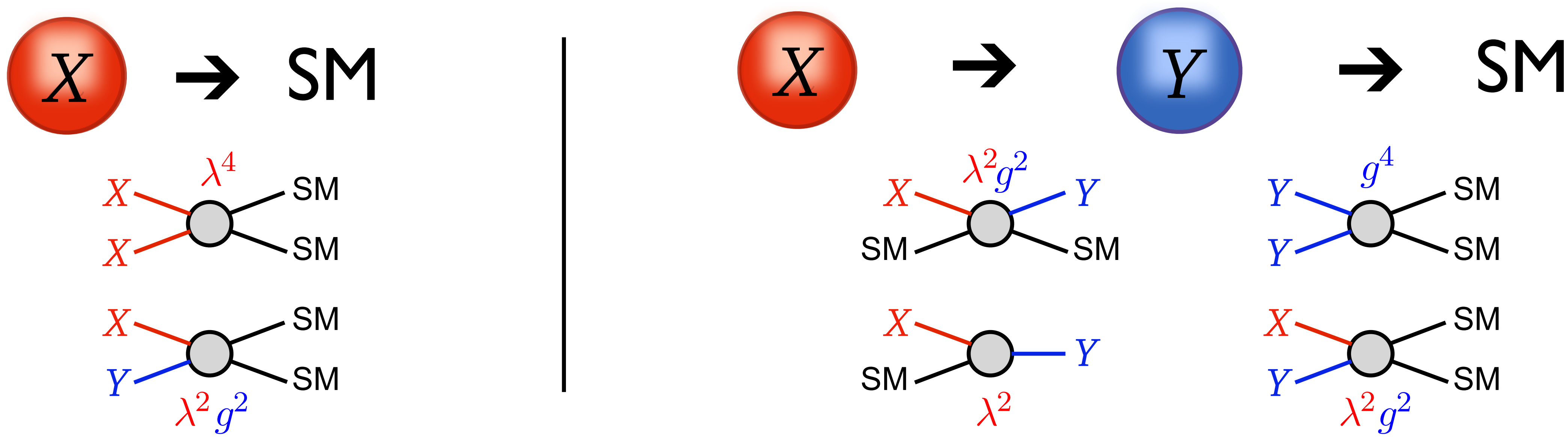


Two ways of dark matter depletion

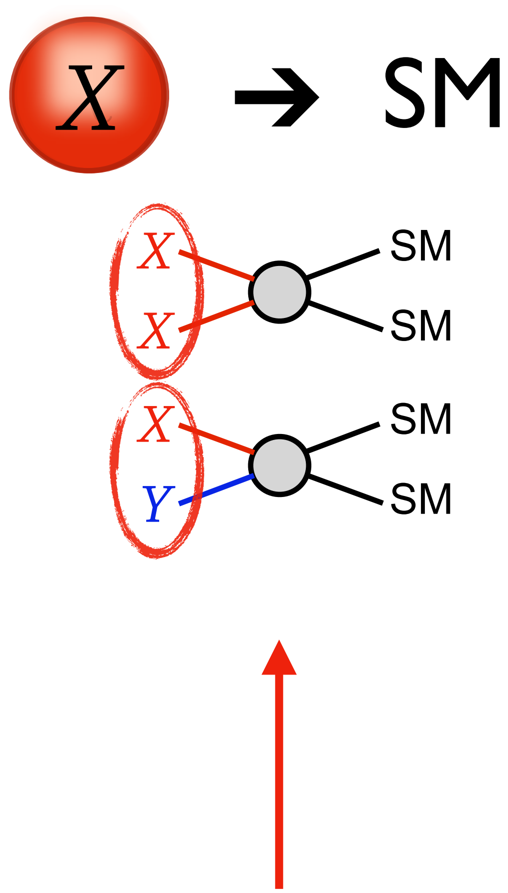
Revisiting the coannihilation scenario

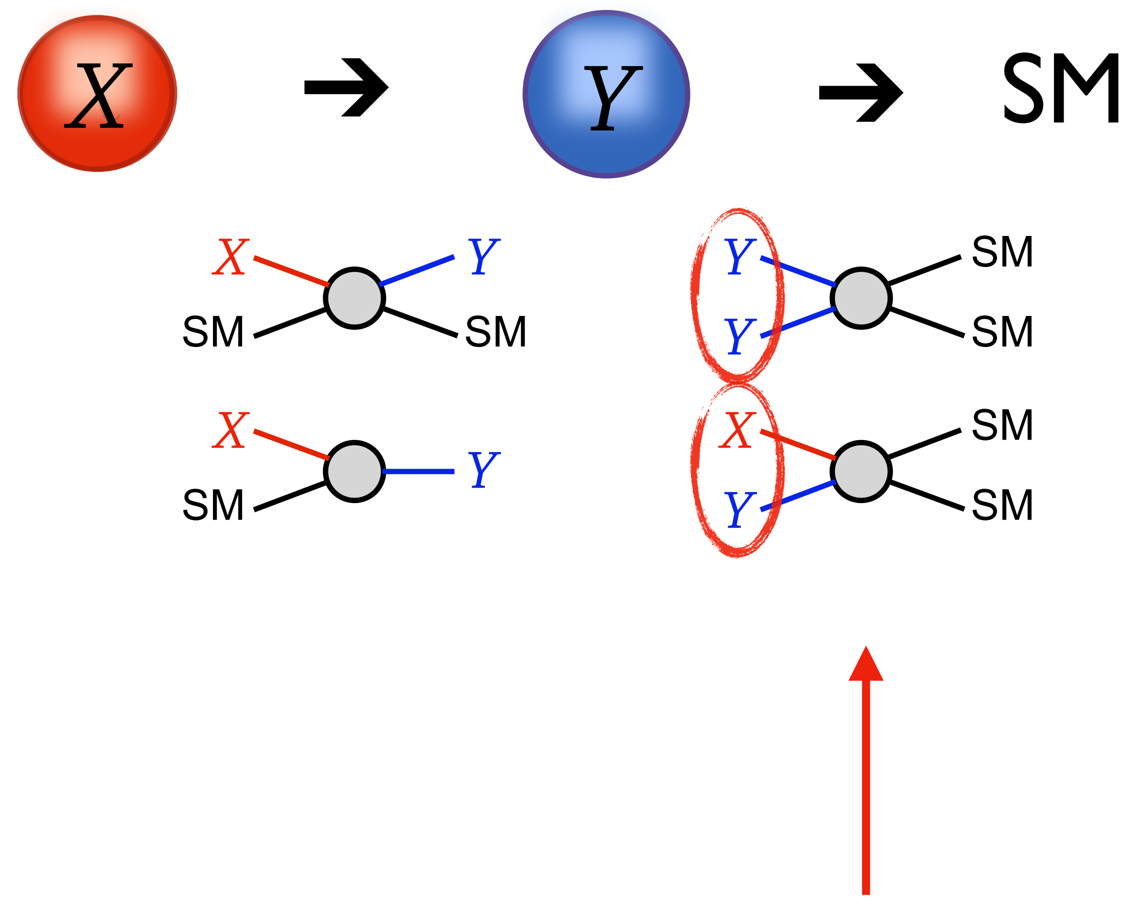
[Griest, Seckel 1991; Edsjo, Gondolo 1997]



Revisiting the coannihilation scenario

[Griest, Seckel 1991; Edsjo, Gondolo 1997]





$$\Gamma = \langle \sigma_{iX} v \rangle \, n_i$$

$\sim \mathrm{e}^{-m_\chi/T} \sim \mathrm{e}^{-25}$

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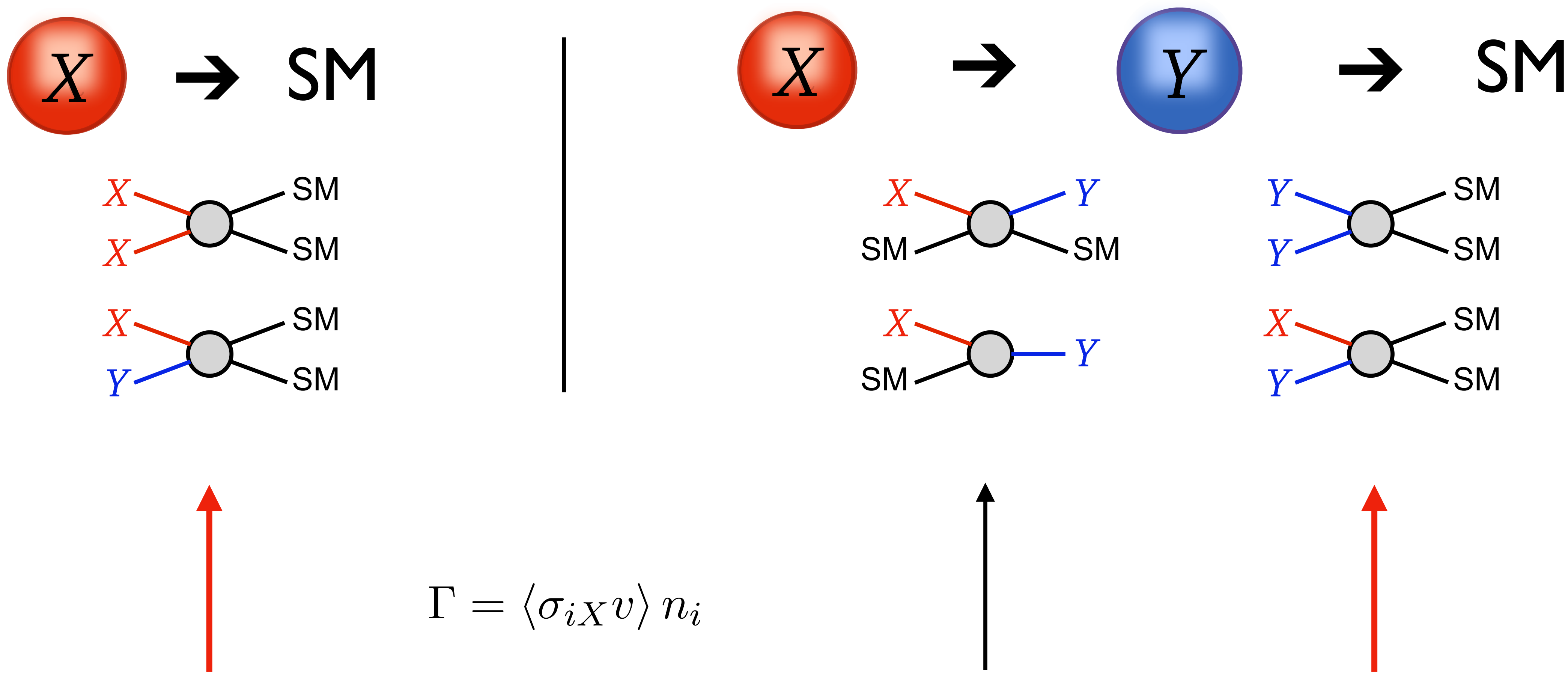
Revisiting the coannihilation scenario

[Griest, Seckel 1991; Edsjo, Gondolo 1997]



$$\Gamma = \langle \sigma_{iX} v \rangle \, n_i$$

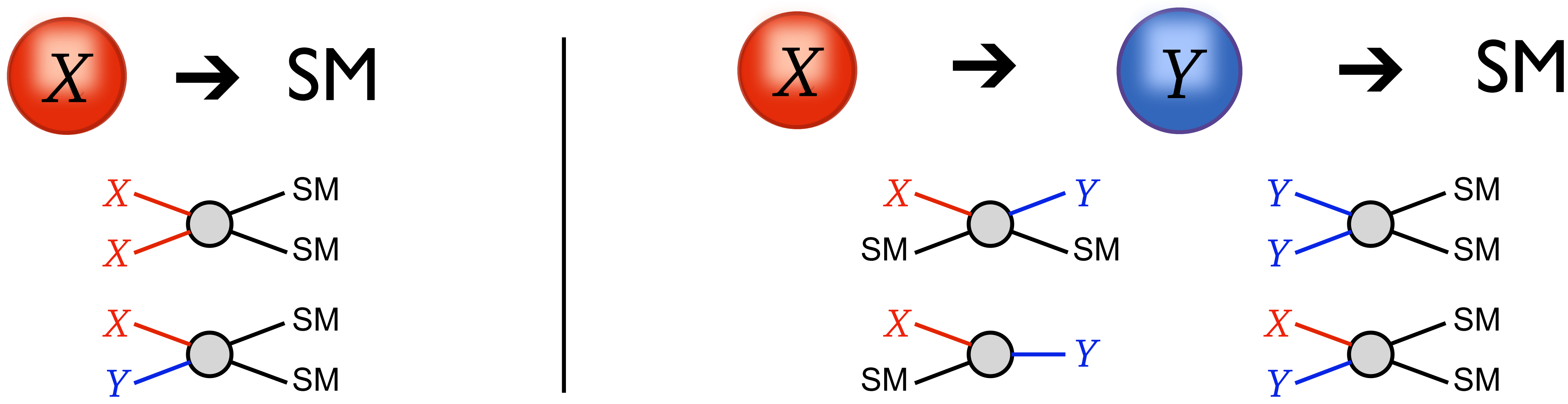
$$\sim \mathrm{e}^{-m_X/T} \sim \mathrm{e}^{-25}$$

$$\sim \mathrm{e}^{-m_{\mathrm{SM}}/T} \sim 1$$

$$\sim \mathrm{e}^{-m_X/T} \sim \mathrm{e}^{-25}$$

Revisiting the coannihilation scenario

[Griest, Seckel 1991; Edsjo, Gondolo 1997]



$$\lambda \sim g \;\Rightarrow\; \Gamma_{\rm conv} \gg \Gamma_{\rm ann}$$

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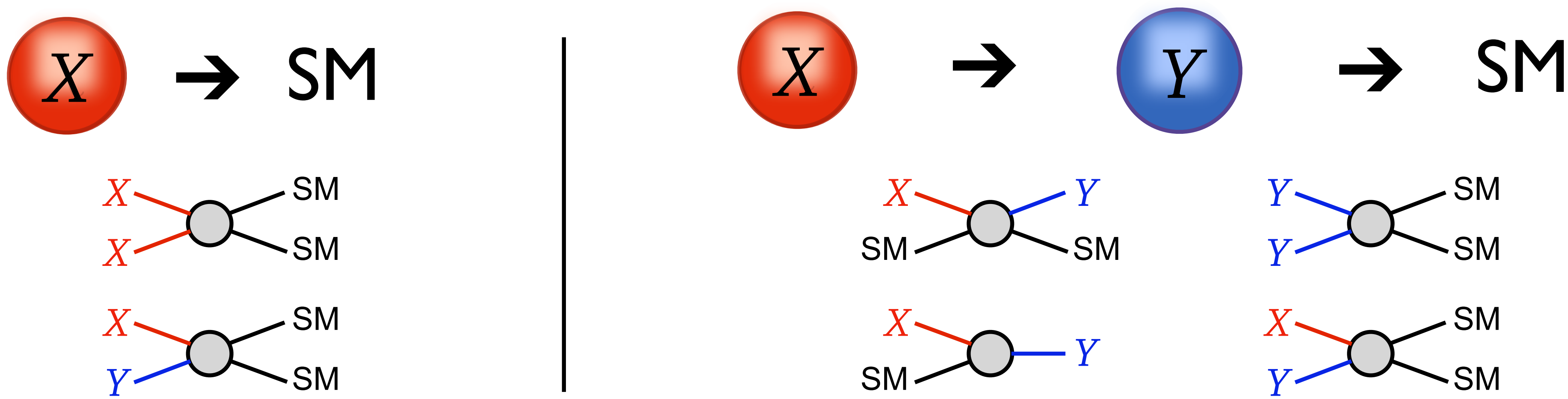

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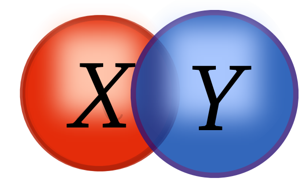
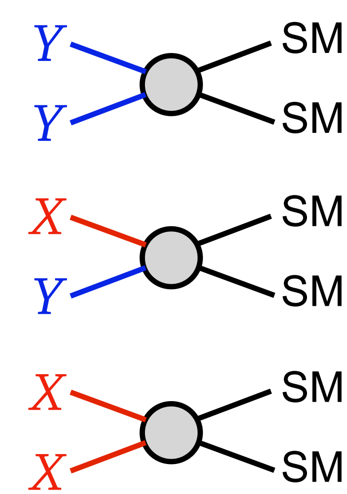


→ SM



Efficient conversions establish chemical equilibrium:

$$\frac{Y_X}{Y_Y} = \frac{Y_X^{\mathrm{eq}}}{Y_Y^{\mathrm{eq}}}$$

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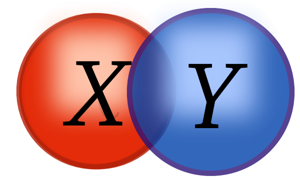
$$\Gamma_{\mathrm{conv}} \gg H \qquad\qquad \Gamma_{\mathrm{ann}} \sim H$$

What if I make λ smaller?



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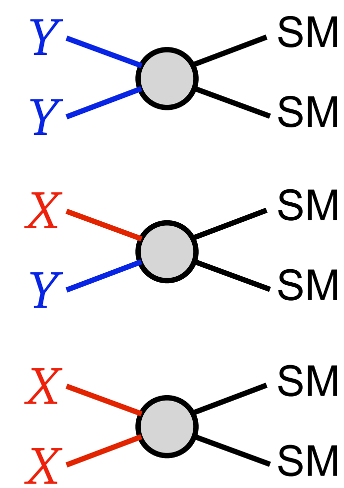

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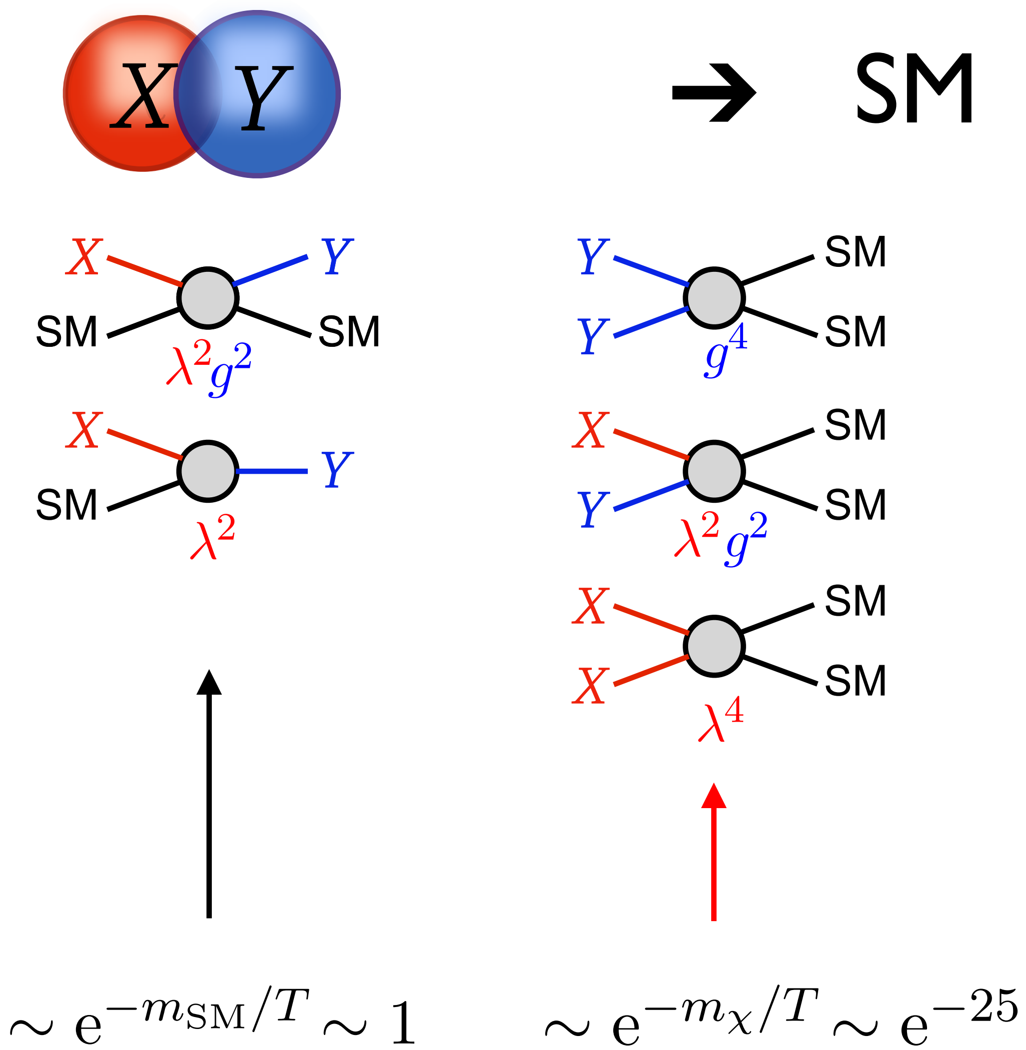

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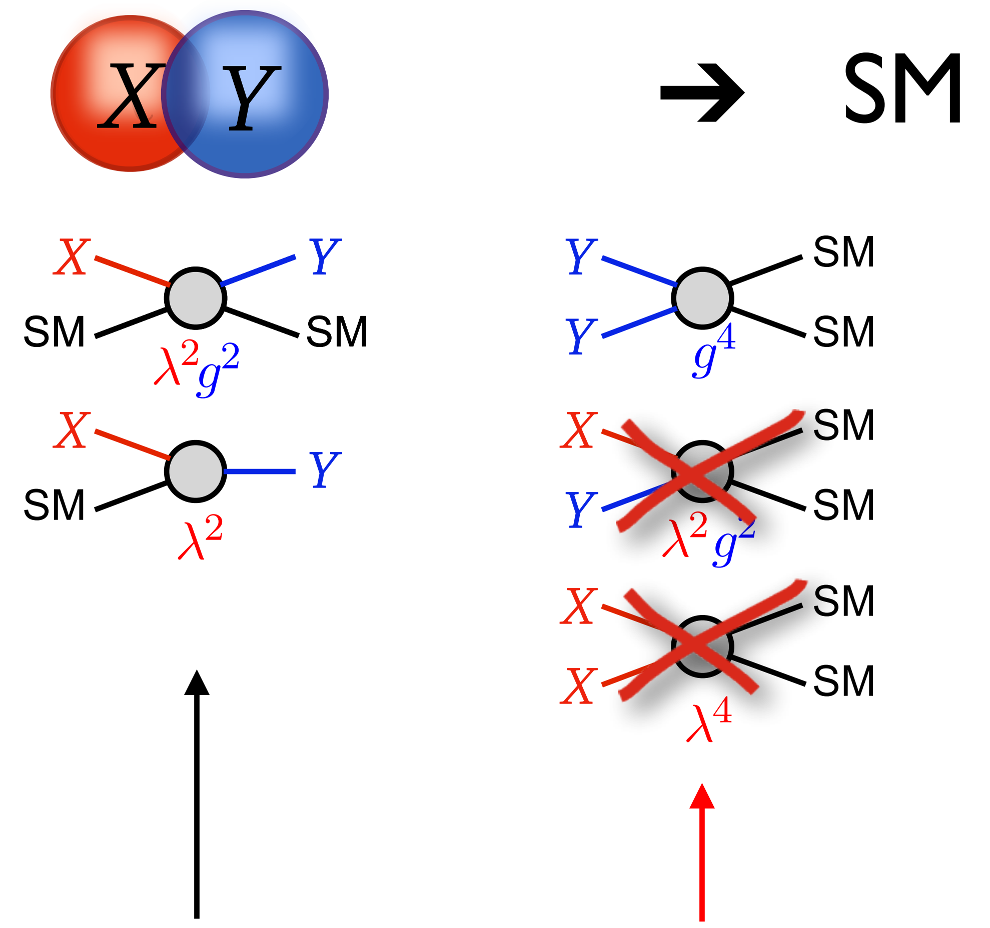

$\sim \mathrm{e}^{-m_{\mathrm{SM}}/T} \sim 1$ $\sim \mathrm{e}^{-m_\chi/T} \sim \mathrm{e}^{-25}$

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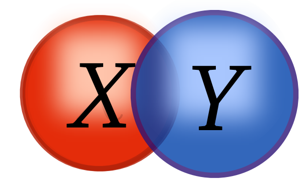

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Chemical equilibrium maintained
Only mediator drives dilution

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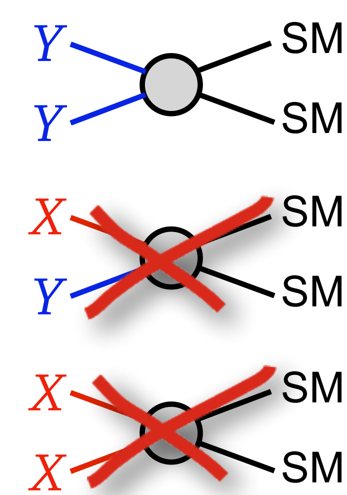

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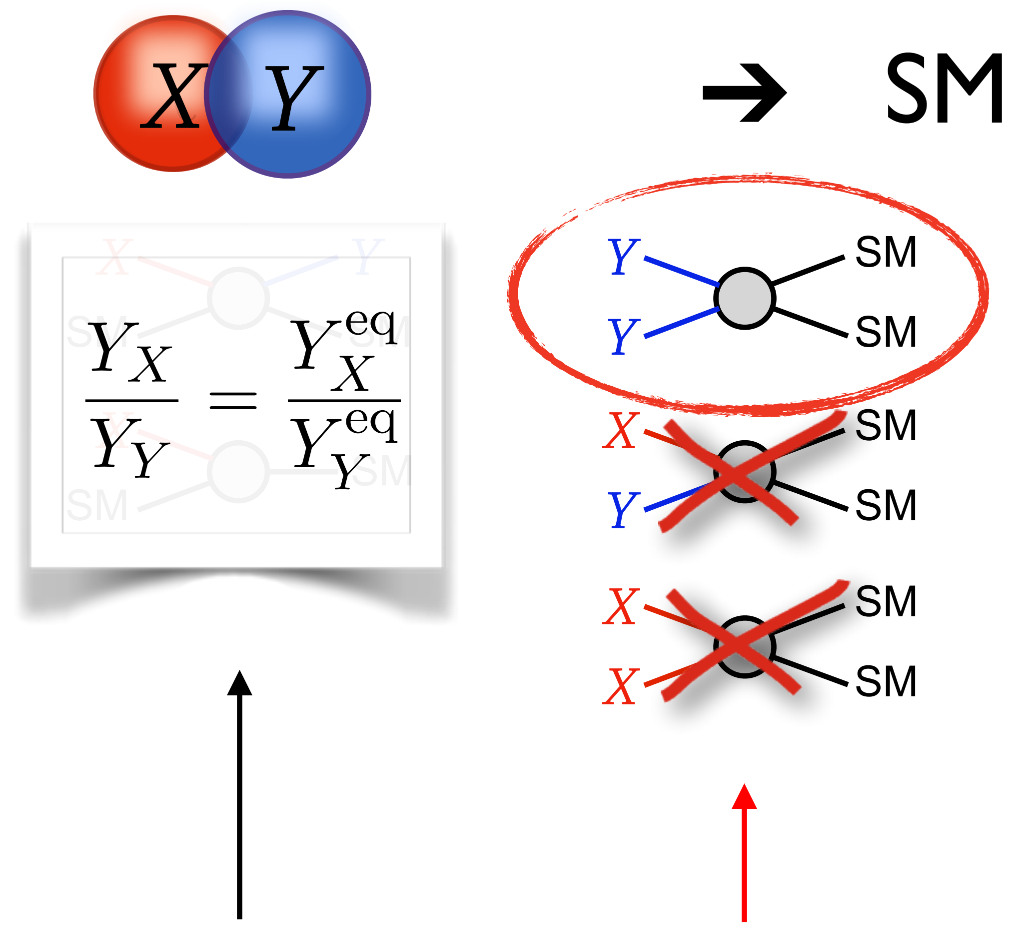

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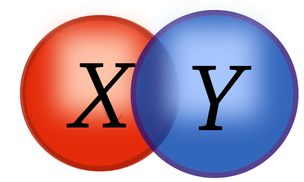
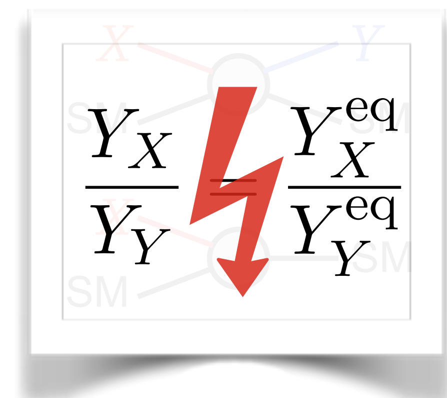
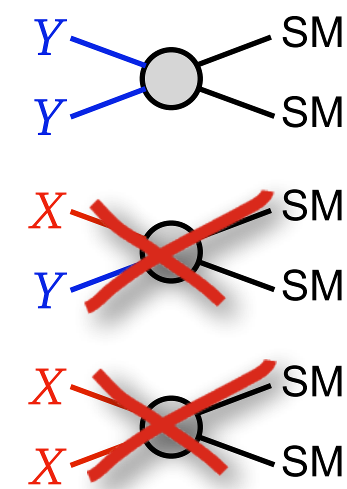


→ SM

At some point:

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





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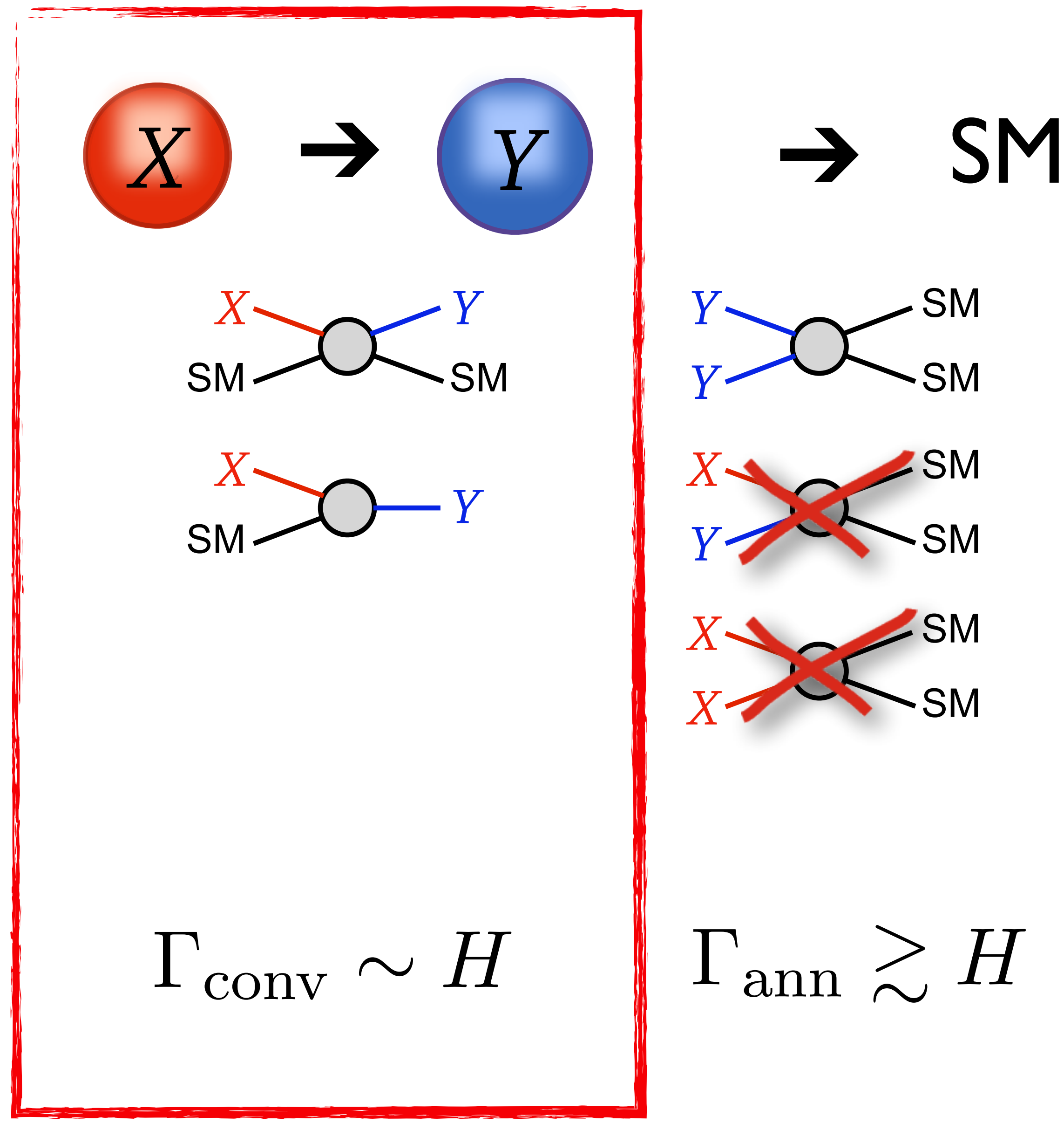


Conversion rate sets relic density!

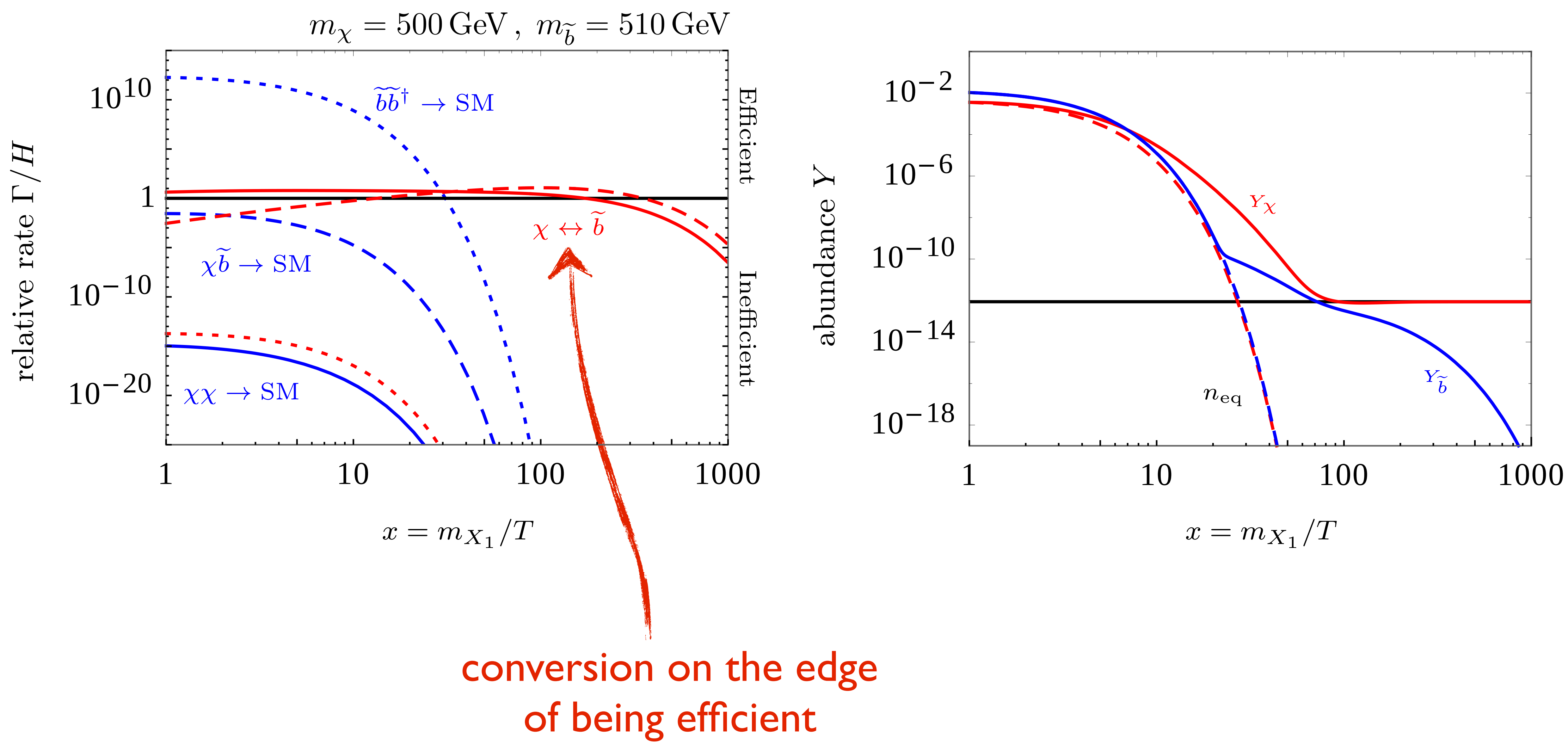
➔ Conversion-driven freeze-out
aka coscattering

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

Evolution of abundances

[Garny, JH, Lülf, Vogl 1705.09292]

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



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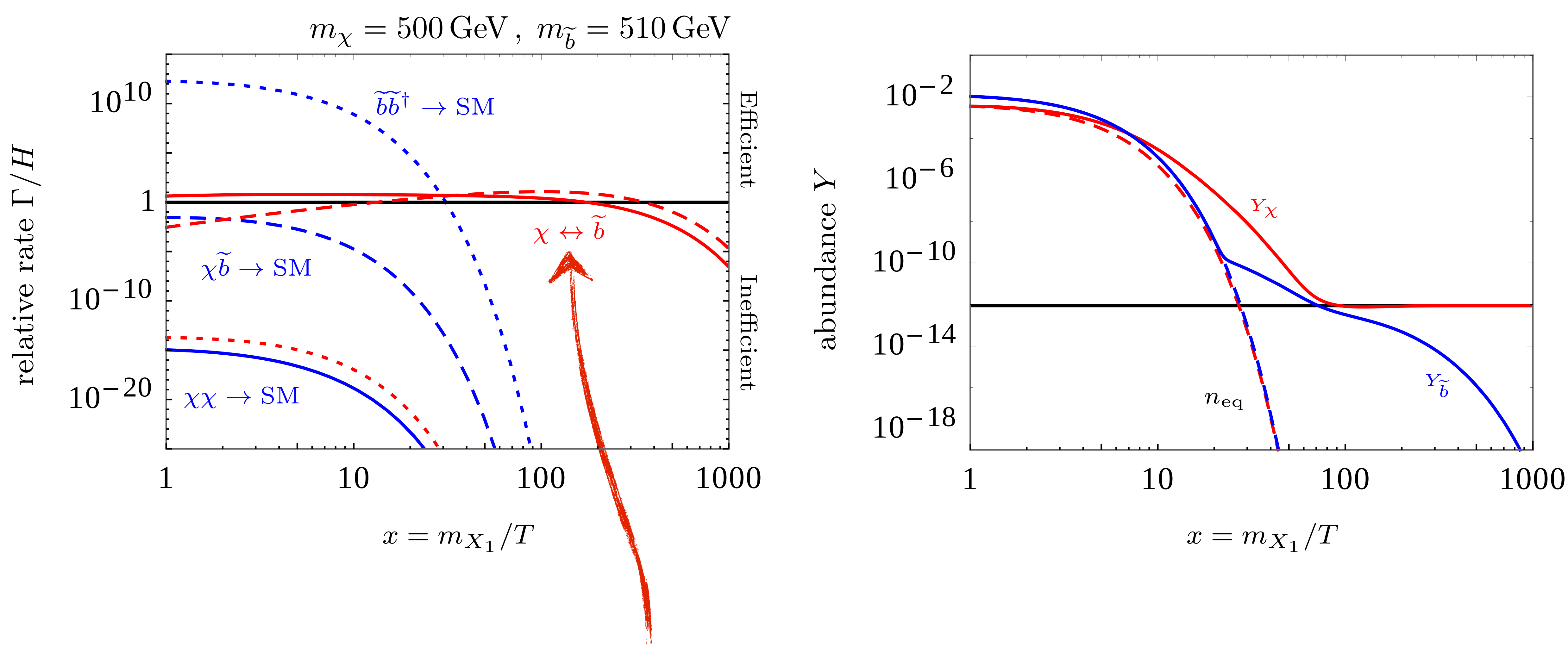

conversion on the edge of being efficient

Evolution of abundances

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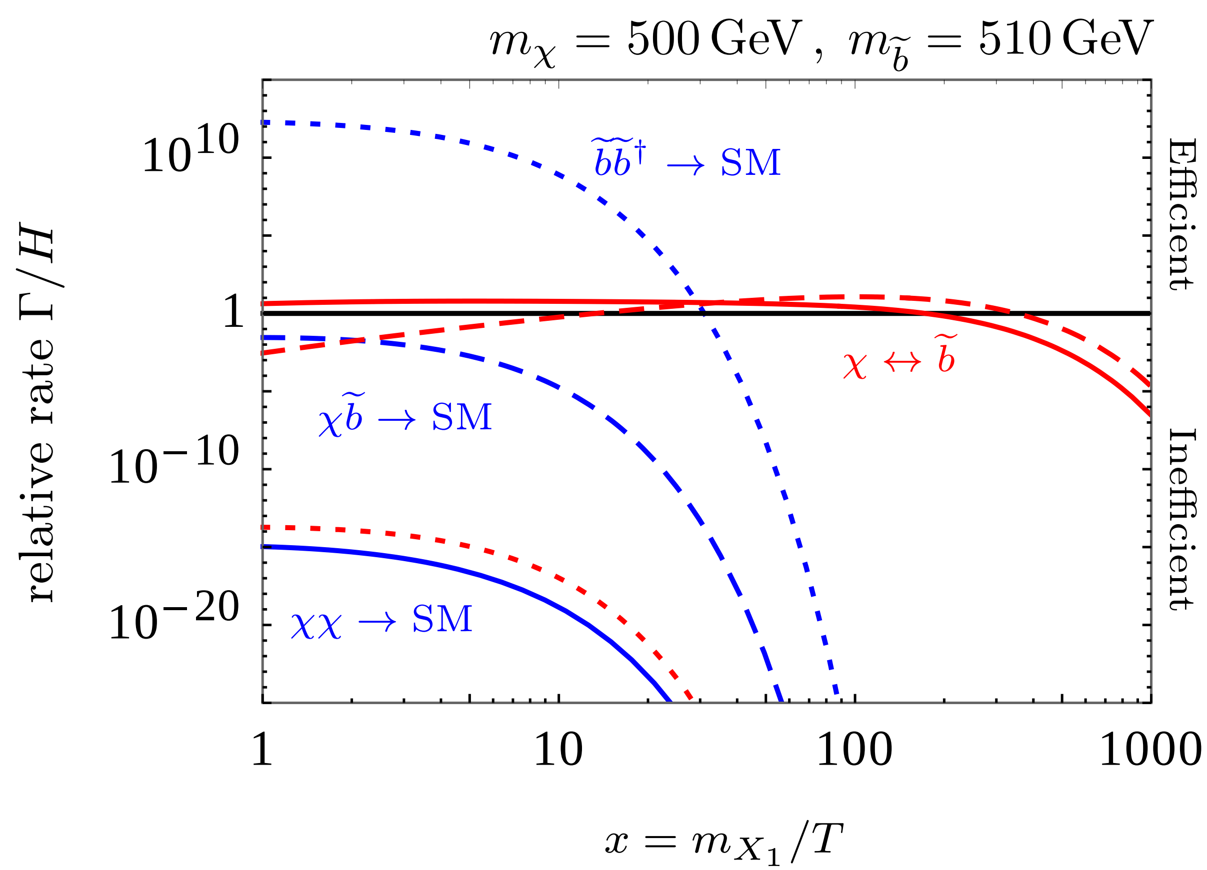
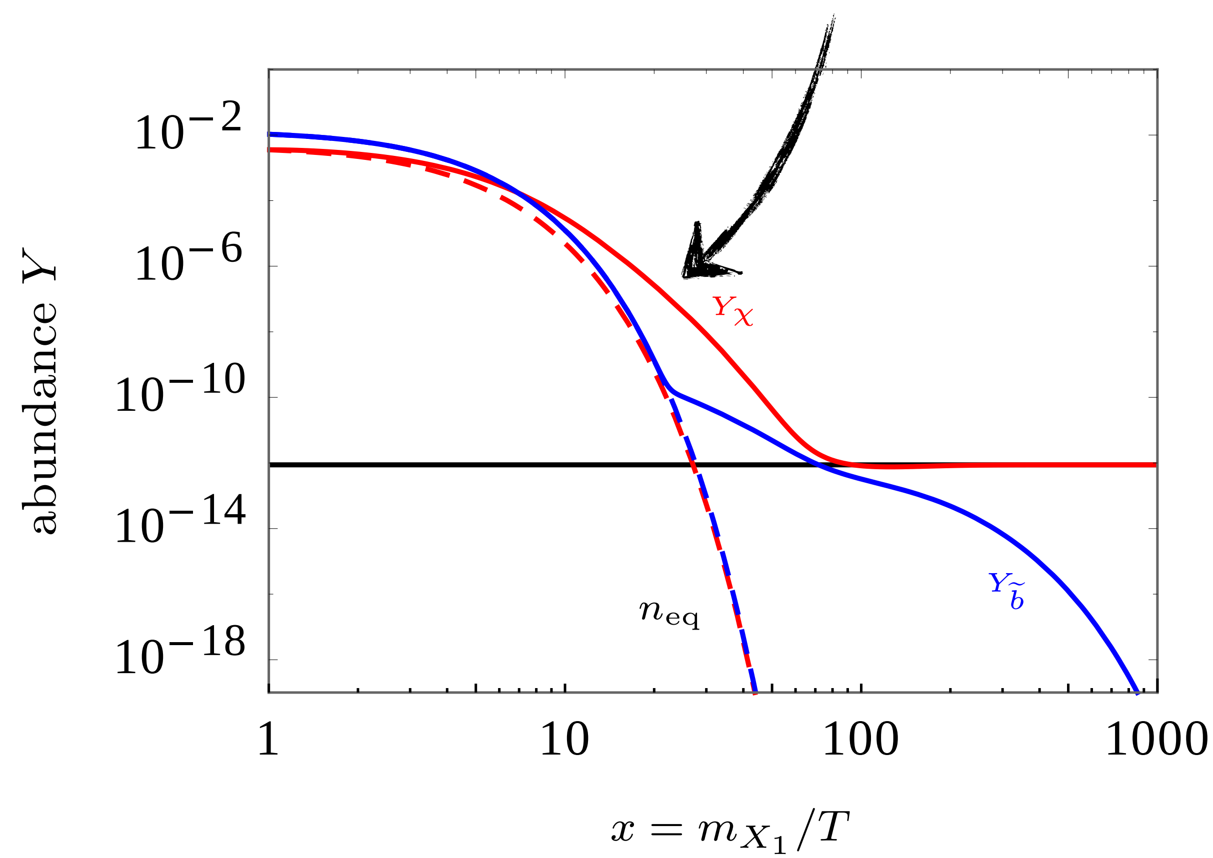
Prolonged freeze-out process





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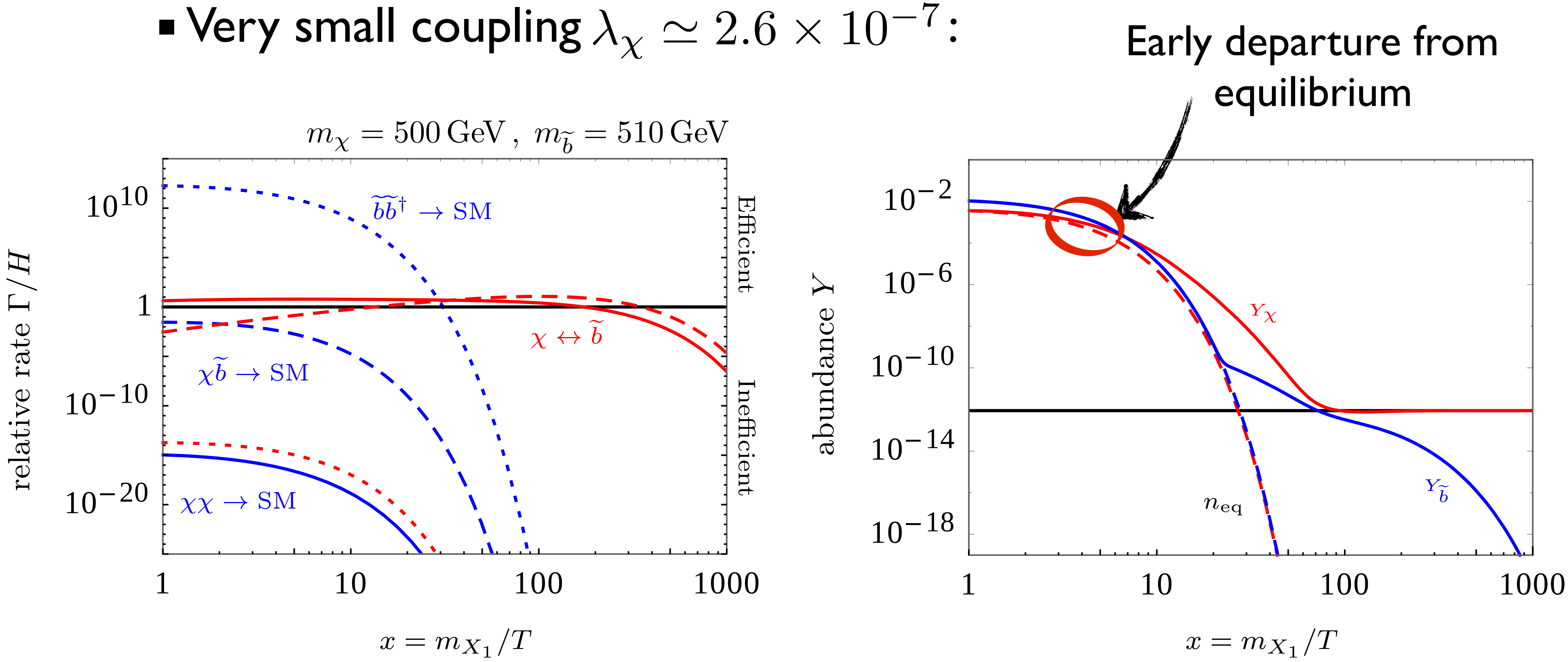
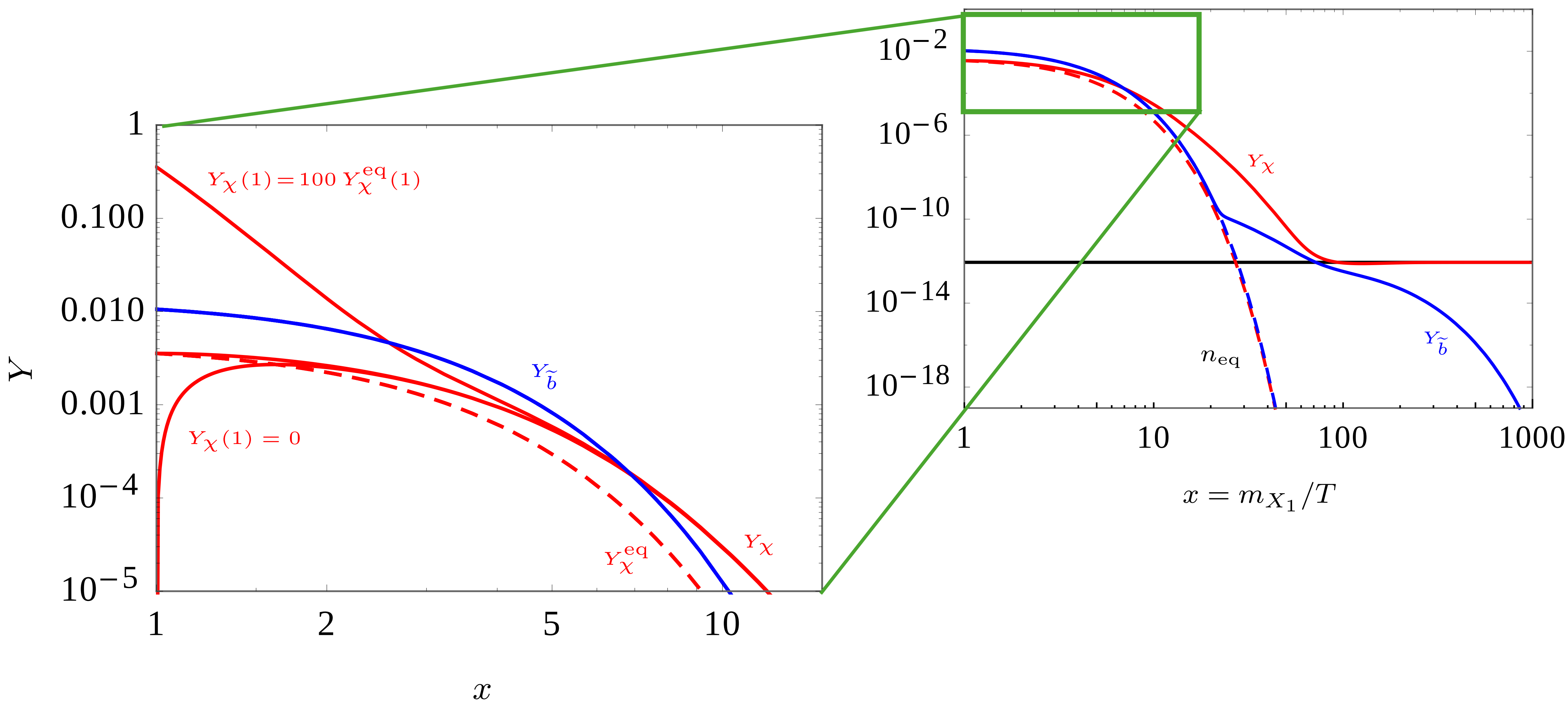


- Typical couplings of the order 10^{-6}

Evolution of abundances

[Garny, JH, Lülf, Vogl 1705.09292]

- Washes out initial conditions
- Converges directly to early out-of-equilibrium abundance



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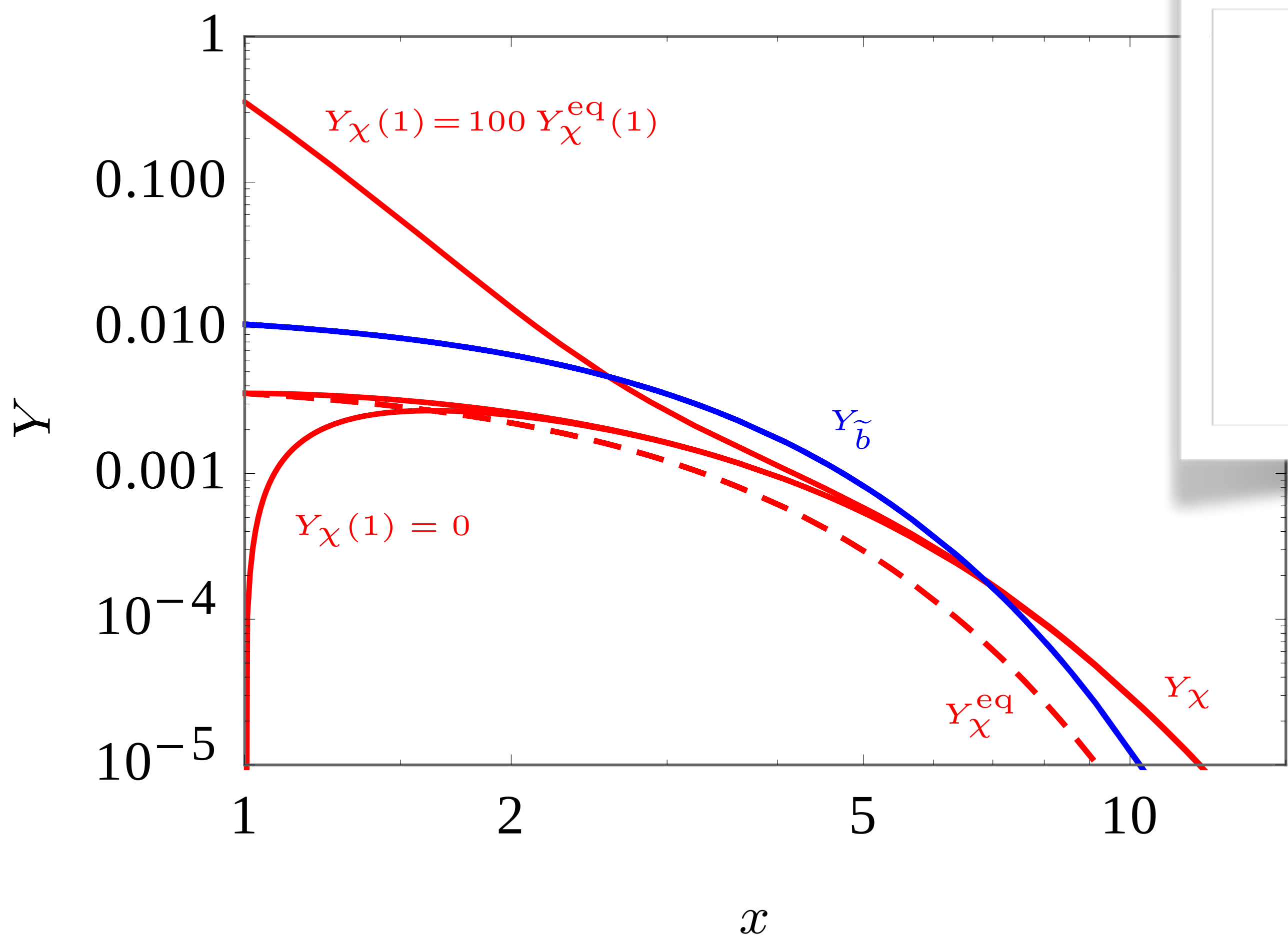

➔ Enables simultaneous baryogenesis from same processes [JH 2024]

Overview

	WIMP	Resonances	Secluded sector	Freeze-in	superWIMP	Conversion-driven
Kinetic eq.	✓					
Thermalization	✓					
Non-relativistic	✓					
No Bound states	✓					
Eq. in dark sector	✓					

Overview

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Kinetic eq.	✓	✗				
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Overview

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Kinetic eq.	✓	✗	✗			
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No Bound states	✓	✓	✗			
Eq. in dark sector	✓	✓	✗			

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No Bound states	✓	✓	✗	✓	✗	
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No Bound states	✓	✓	✗	✓	✗	✗
Eq. in dark sector	✓	✓	✗	✗	✗	✗

Numerical Tools

- Neutdriver (1995) [Jungman et al.]
- micrOMEGAs (2001–) [Bélanger et al.]
- IsaRed / IsaRes (2004) [Baer et al.]
- DarkSUSY / DRAKE (2004 –) [Bringmann et al.]
- SuperISORelic (2009, succeeded by DarkPack) [Arbey, Mahmoudi]
- MadDM (2013 –) [Arina et al.]
- DarkPack / MARTY (2022 –) [Palmiotto et al]
- RelExt (2025 –) [Capucha et al.]
- …

Conclusion

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  → allows for many simplifying assumptions
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Takeaway: The relic density is a target, not a recipe
→ many mechanisms can achieve it – explore broadly