Freeze-In at Strong Coupling in a Z'-Mediated Dark Matter Scenario

David Cabo-Almeida

Based on:

G. Arcadi, D. C-A, O. Lebedev, PLB **861** (9, 2024) 139268

Università degli Studi di Messina

INFN Catania
Istituto Nazionale di Fisica Nucleare

Universitat de Barcelona

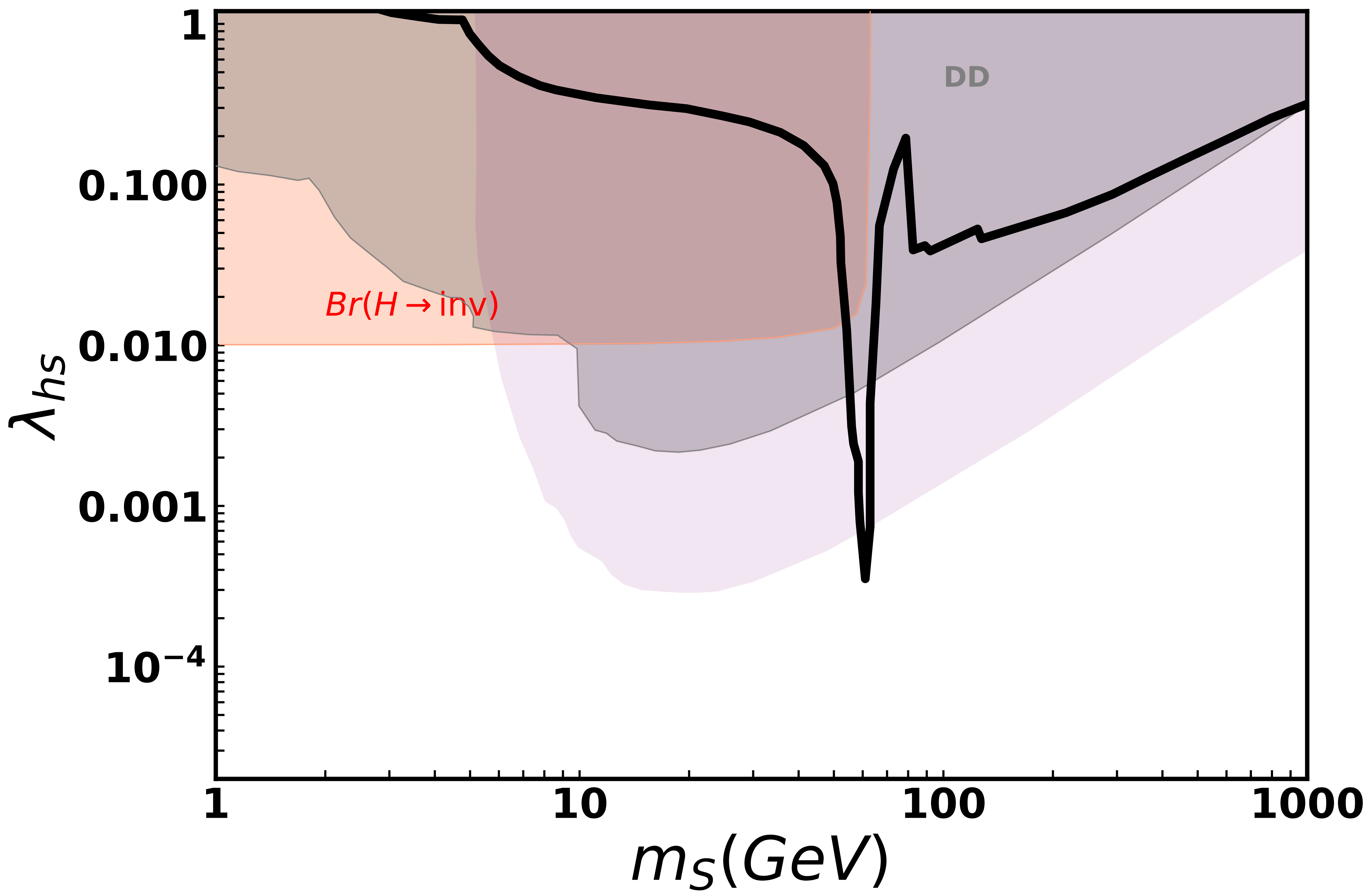
Outline

- Freeze-out vs Freeze-in
- Gravitational production of DM
- Low Reheating Freeze in
- Z’ model in Strongly coupling Freeze-In

Freeze-out

Simplest Model

$$\boxed{-\frac{1}{4}\lambda_{Hss}H^\dagger H s^2}$$



G. Arcadi, DCA, M. Dutra, P. Ghosh, M. Linder, Y. Mambrini, J. P. Neto, M. Pierre, S. Profumo, F. S. Queiroz, arXiv: 2403.15860

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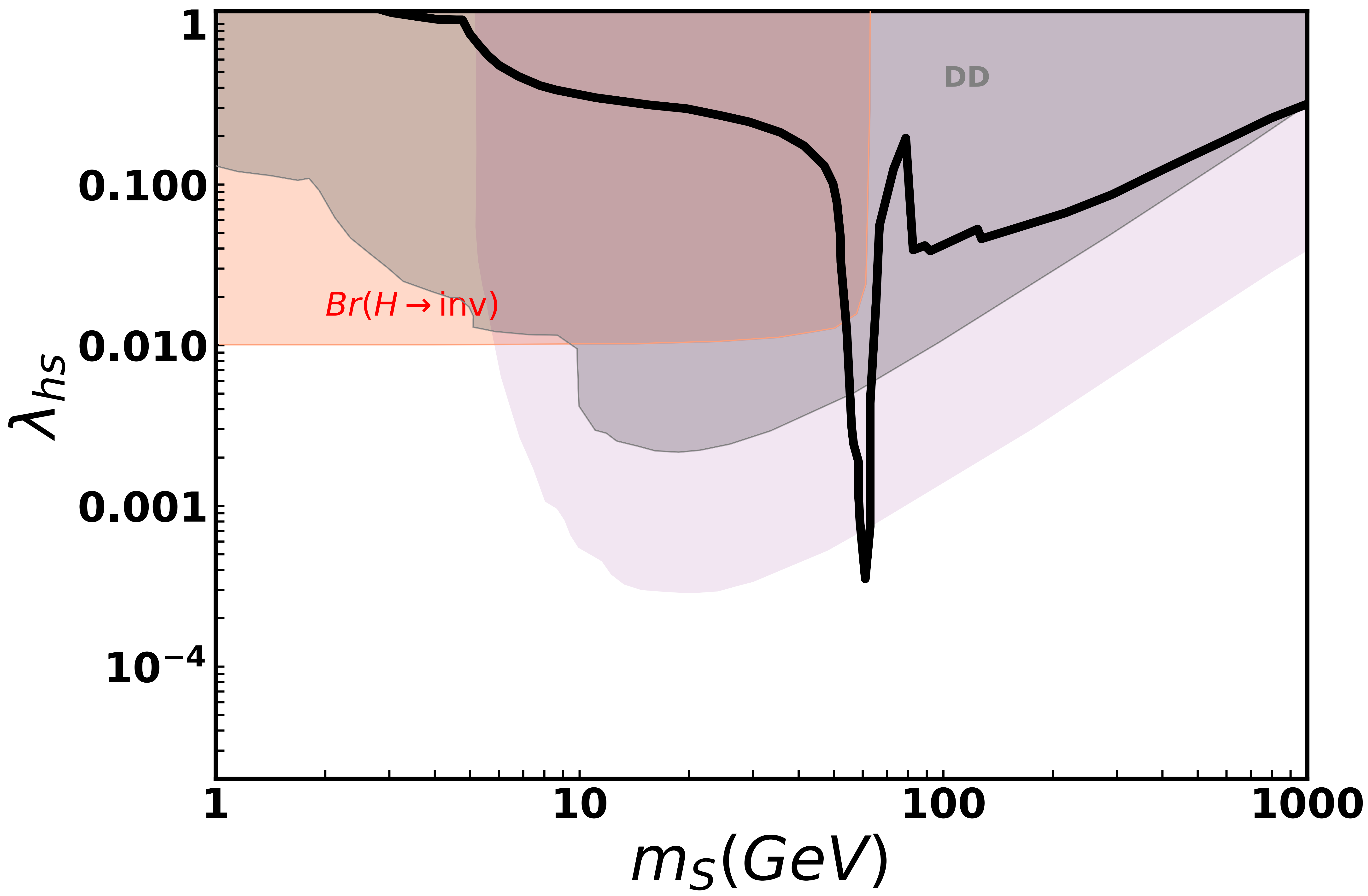
Strong constrains for vector mediated Z' models



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<u>Simplest Model</u>

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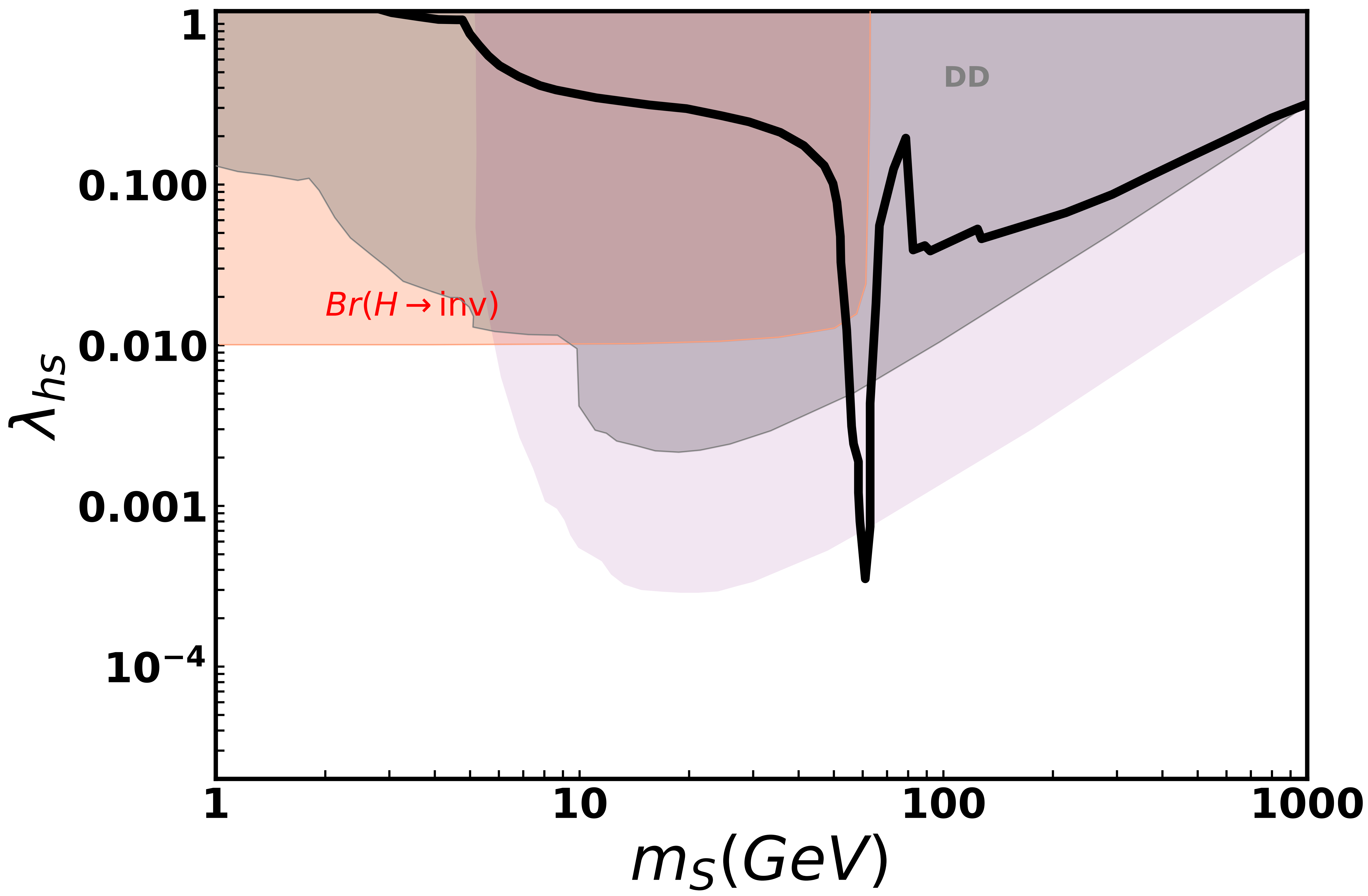
Strong constrains for vector mediated Z' models

"Standard" WIMPs models are very constrained.



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Freeze-in

- No equilibrium

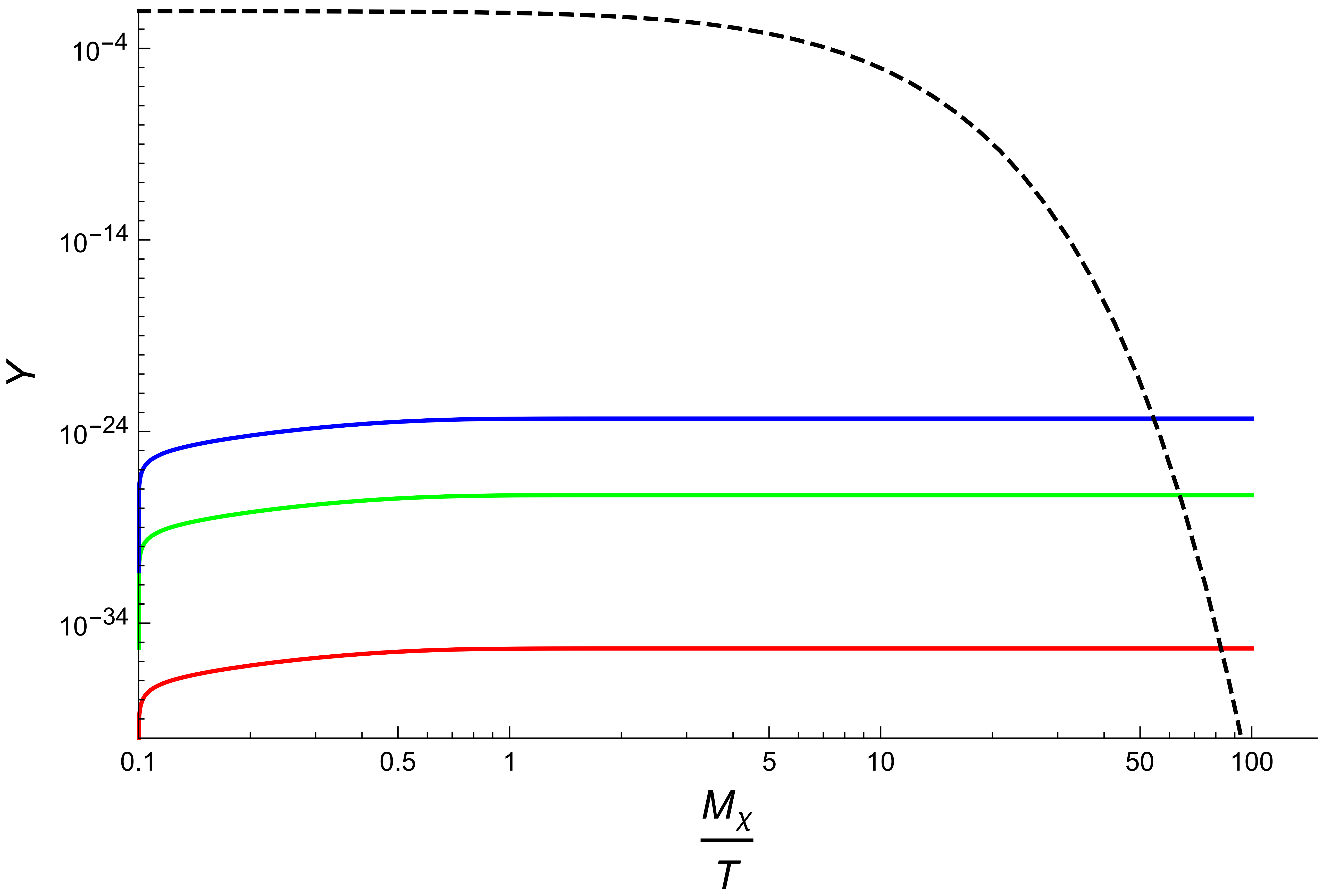
$$\text{SM SM} \rightarrow \chi\chi$$

- Dependences of early universe history

  ➡ Negligible initial abundances is assume

- Really feeble couplings → Hard to prove

$$\boxed{\Gamma(SM \rightarrow DM) \propto \lambda^2}$$



Gravitational production of Dark Matter

- Non thermal particles has memory $\longrightarrow$ They are sensible to early universe production

O. Lebedev, arXiv: 2210.02293

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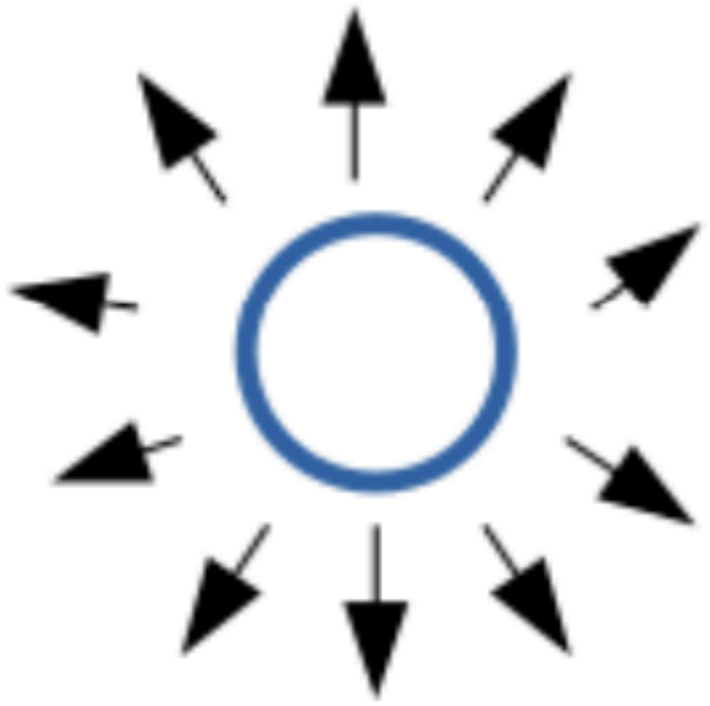
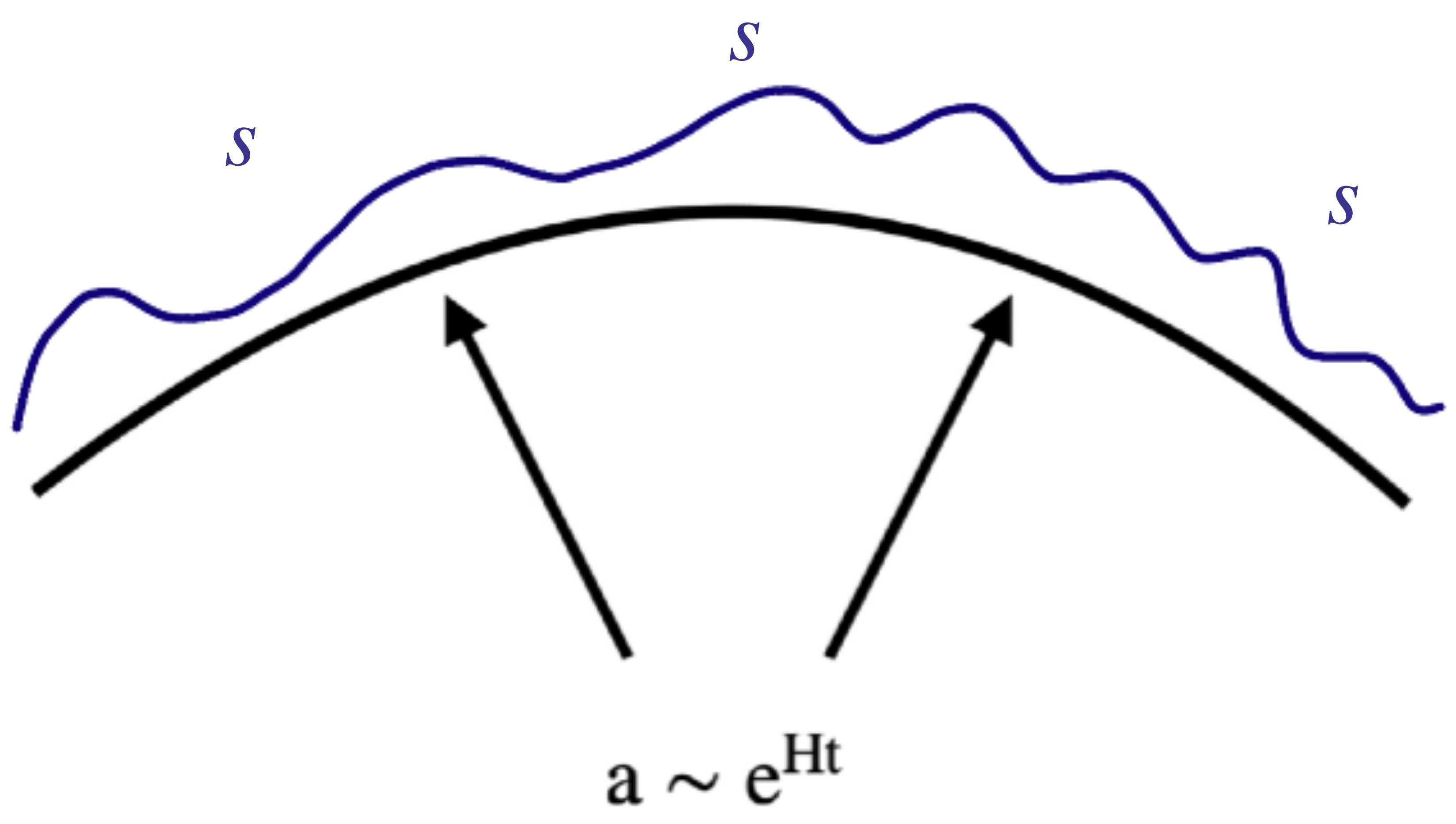
Field fluctuations



Inflation oscillation

O. Lebedev, arXiv: 2210.02293

During inflation



$$V(s) = \frac{1}{2}m_s^2 s^2 + \frac{1}{4}\lambda_s s^4$$

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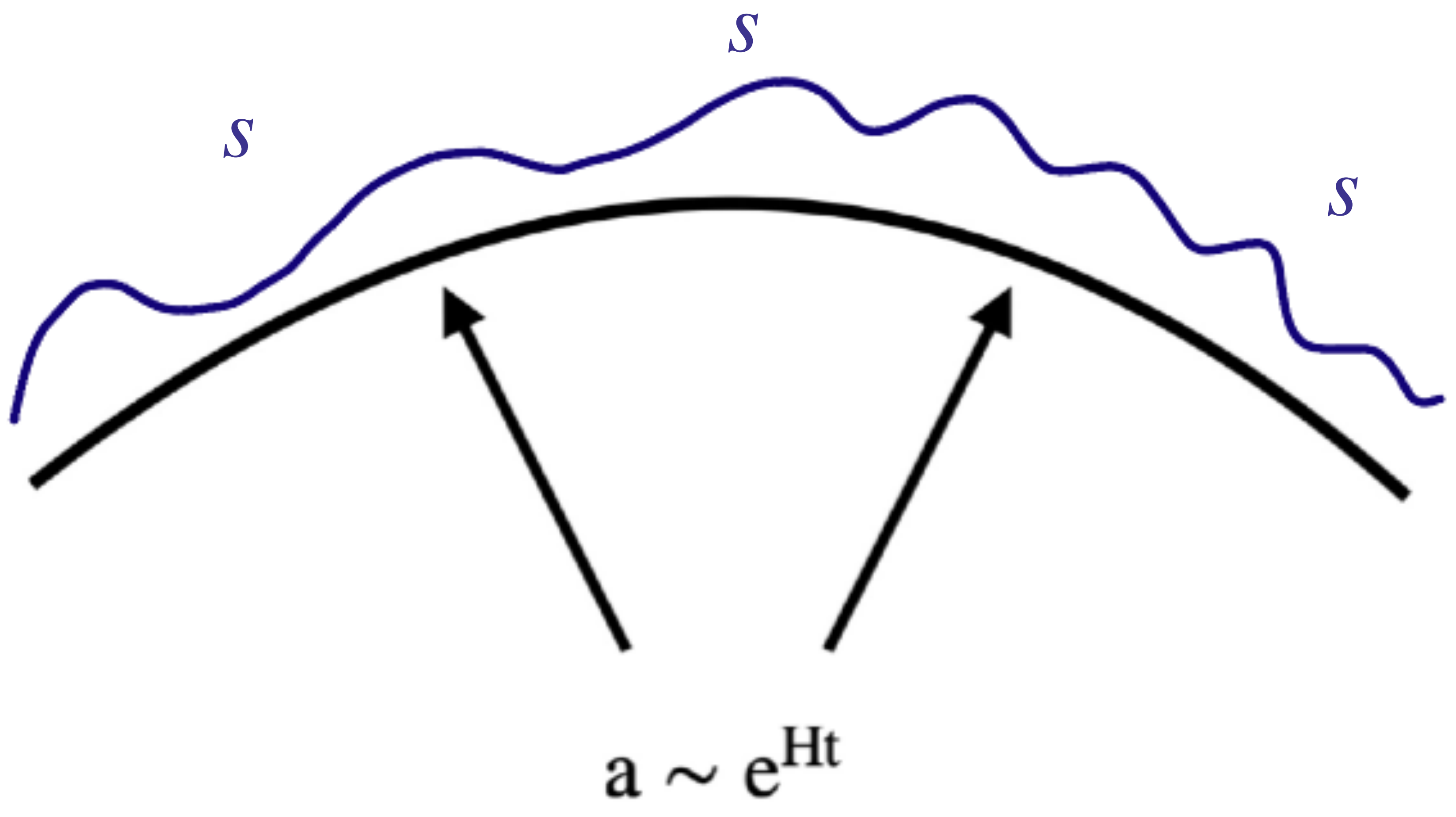
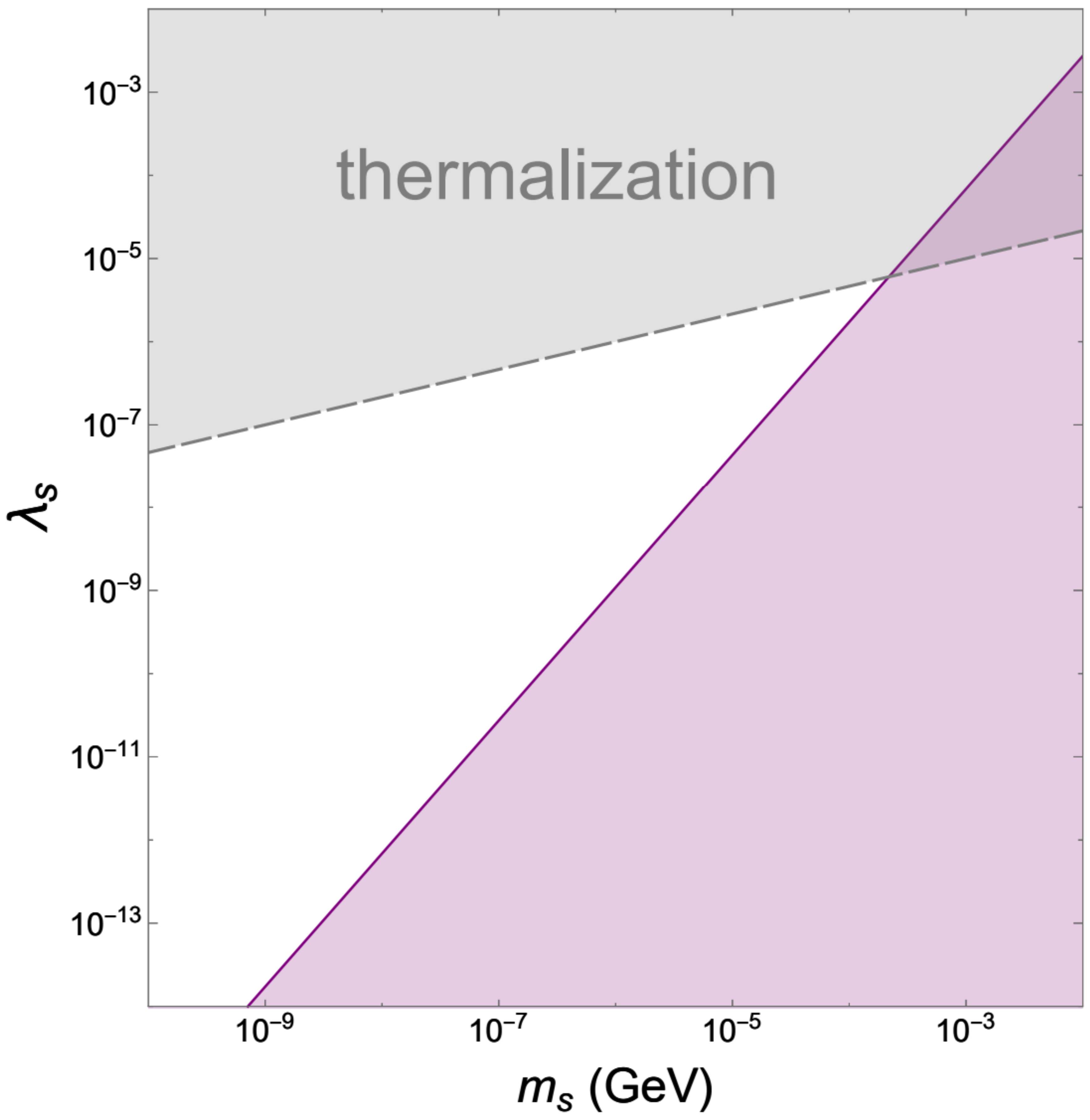


$$V(s) = \frac{1}{2}m_s^2 s^2 + \frac{1}{4}\lambda_s s^4$$

$$Y \leq 4.4 \times 10^{-10}\frac{\mathrm{GeV}}{m_s}$$

$$m_s \lambda_s^{-5/8} \lesssim 10^{-7}\left(\frac{M_{\mathrm{Pl}}}{H_{\mathrm{end}}}\right)^{3/2}\mathrm{GeV}$$



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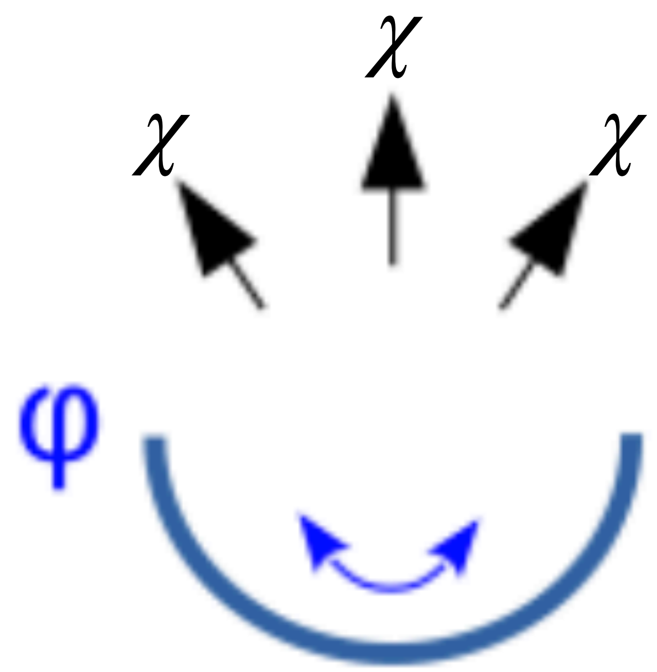
Planck suppressed operators are really efficient in particle production:

Fermions:



$$\boxed{\frac{\mathscr{C}}{M_{\mathrm{Pl}}}\phi^2\bar{\chi}\chi} \longrightarrow \boxed{\mathscr{C} \leq 10^{-5}\sqrt{\frac{\mathrm{GeV}}{M}}}$$

Even small Wilson Coefficients can generate all of the DM

F. Koutroulis, O. Lebedev, S. Pokorski, arXiv: 2310.15906

After inflation

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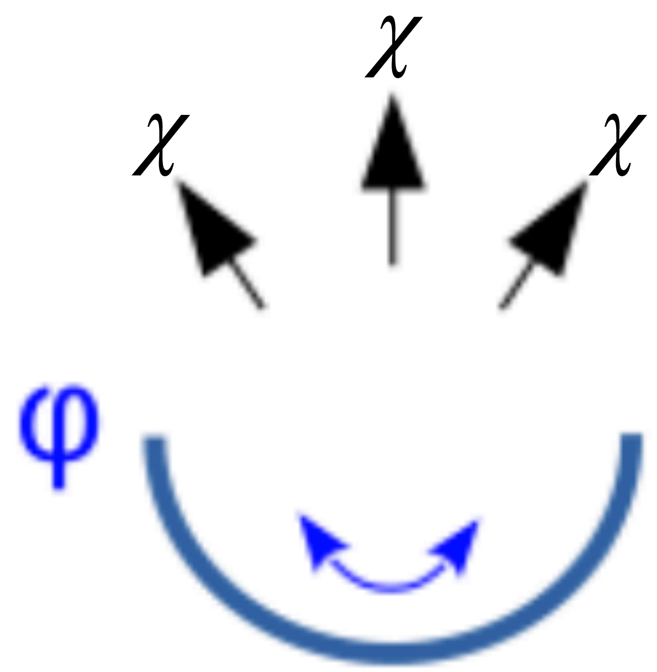

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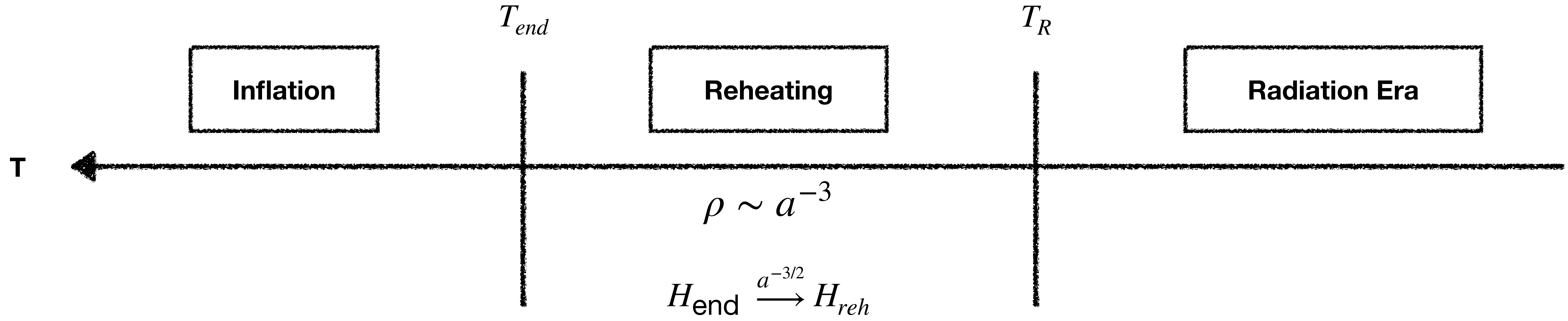
Zero DM abundance is impossible in the world with gravity

F. Koutroulis, O. Lebedev, S. Pokorski, arXiv: 2310.15906

Low reheating: Dilution



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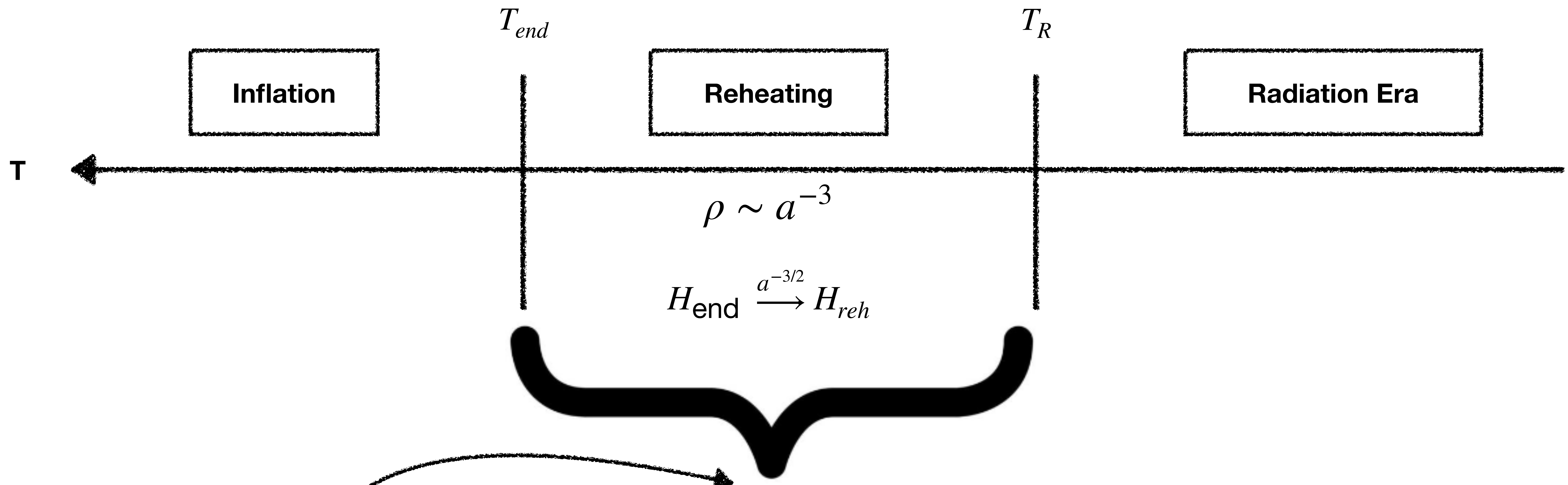

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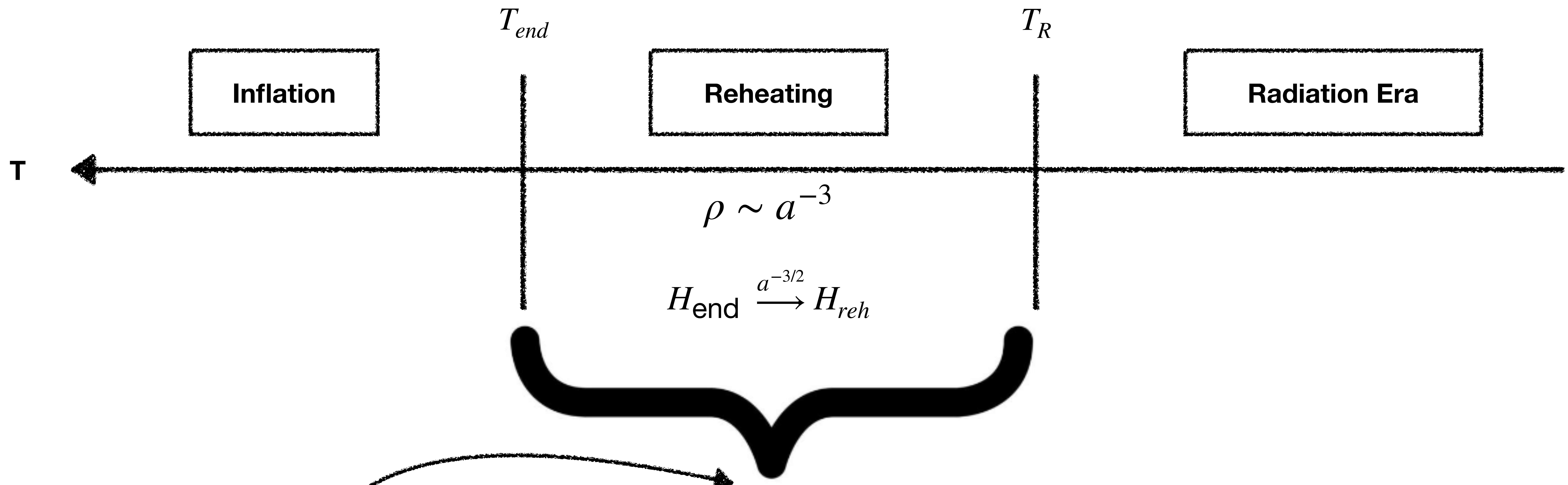

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Now we can consider $\mathbf{T_R}$ as a free parameter $\longrightarrow$ **All we know is $\mathbf{T_R} > \mathbf{4}\mathrm{MeV}$**

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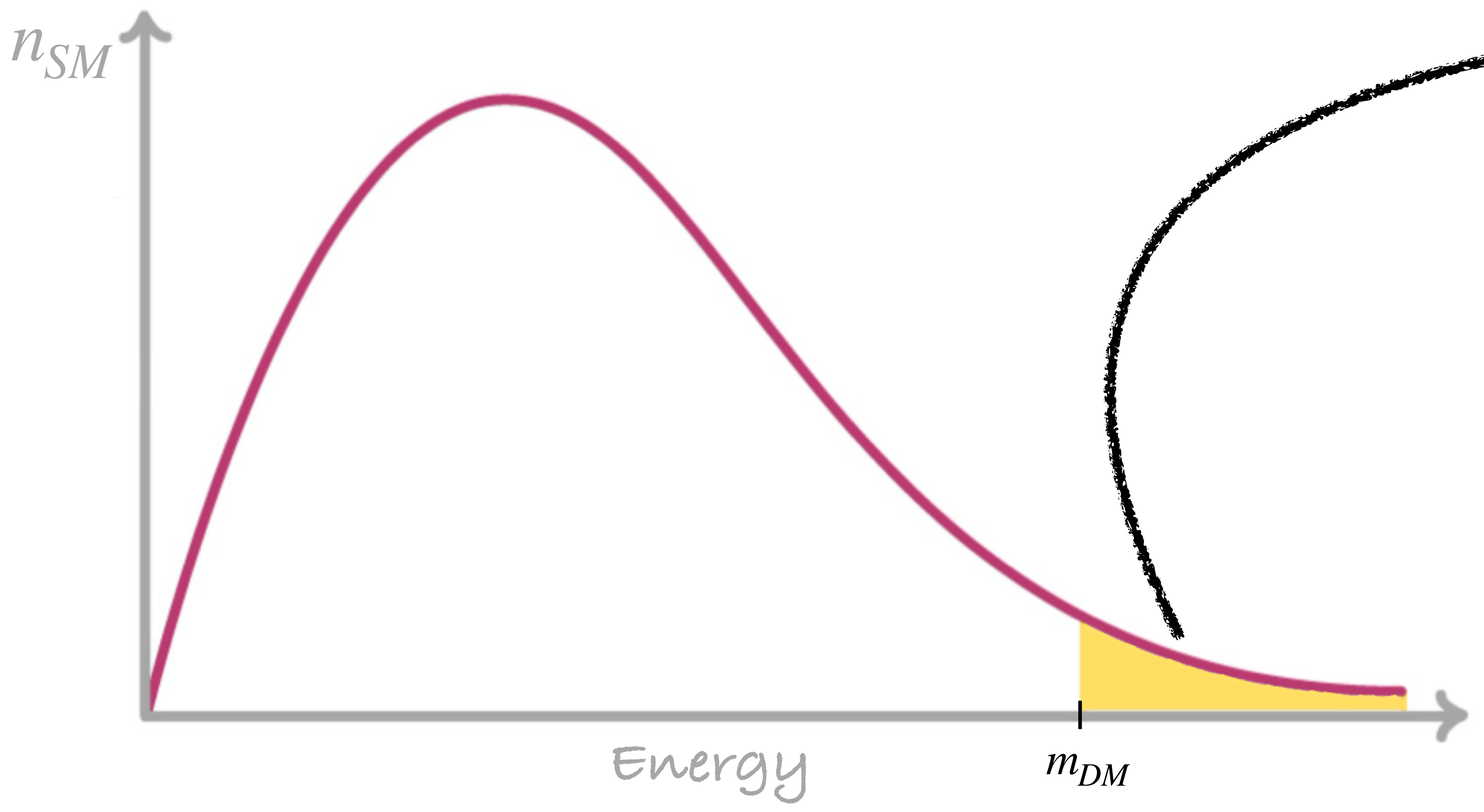

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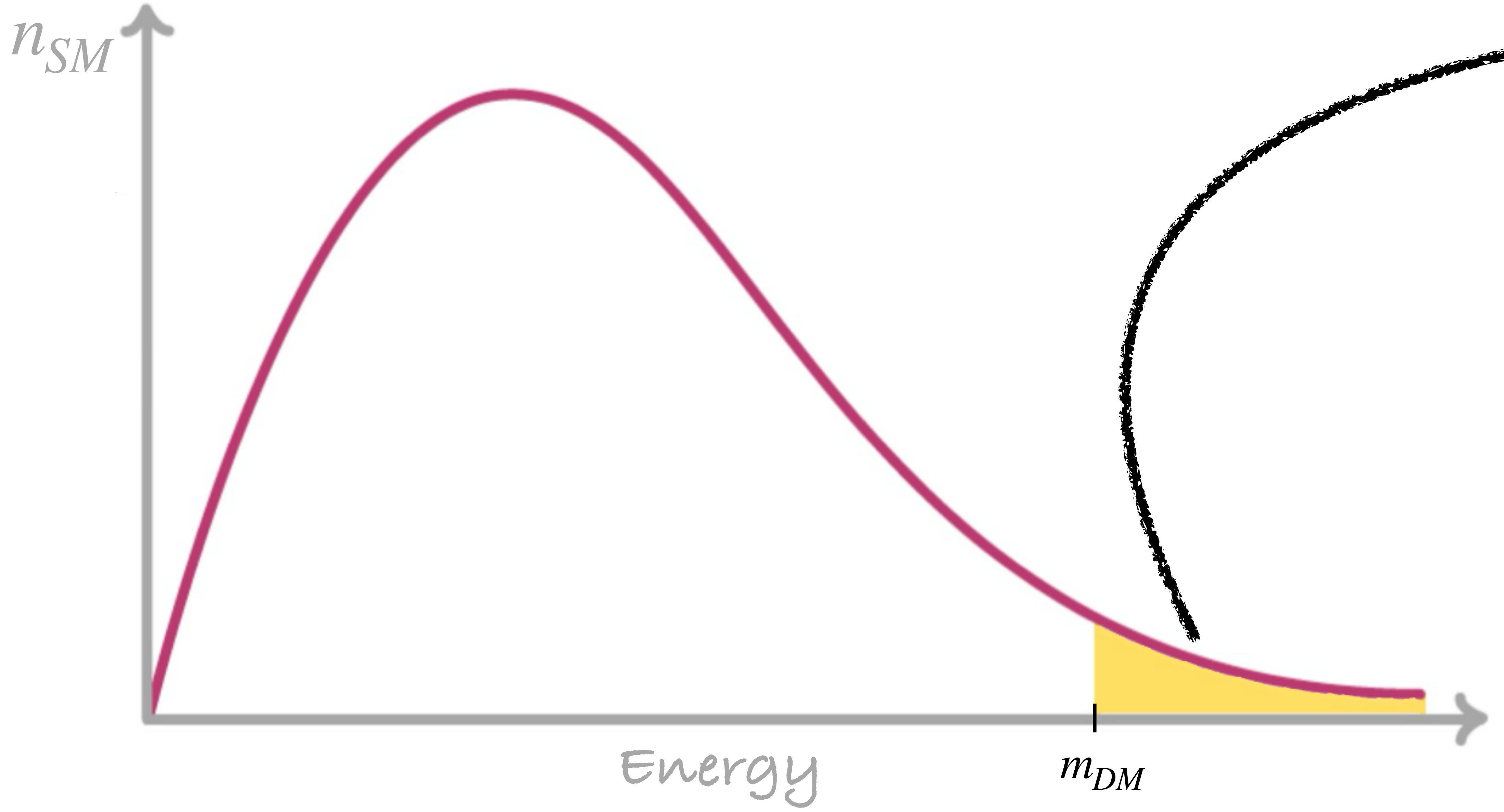

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$$\boxed{\Gamma(SM \to DM) \propto \lambda^2 e^{-2m/T_R}}$$

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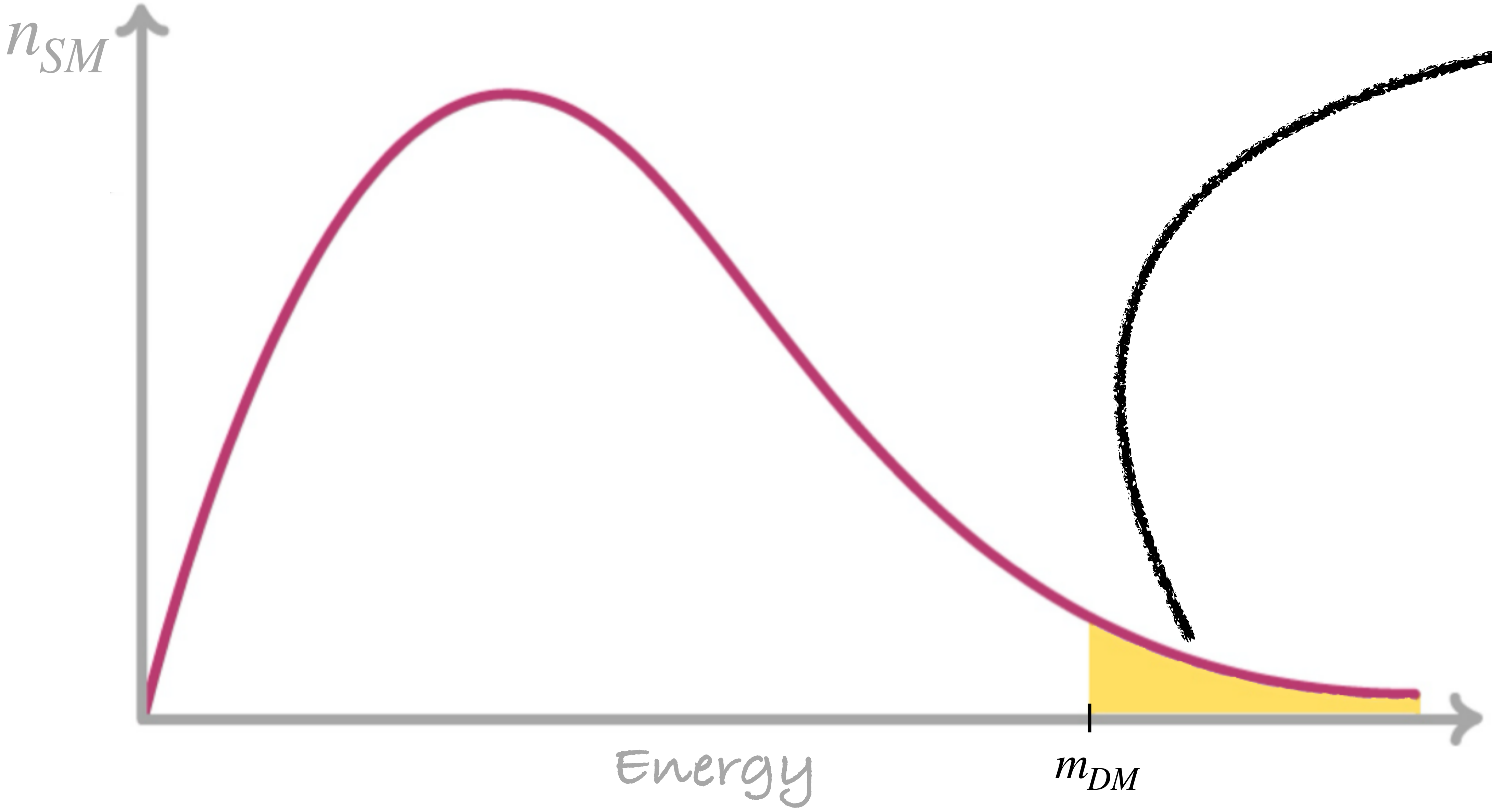

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↓

Freeze-In at strongly coupling

C. Cosme, F. Costa, O. Lebedev, arXiv: 2306.13061

The model: Z' model

Is natural to extend the SM symmetries $G_{\mathrm{SM}} = \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y$ to an extra $\mathrm{U}(1)'$ symmetry

$$\boxed{Z' \qquad \chi}$$

See e.g. P. Langacker, arXiv: 0801.1345

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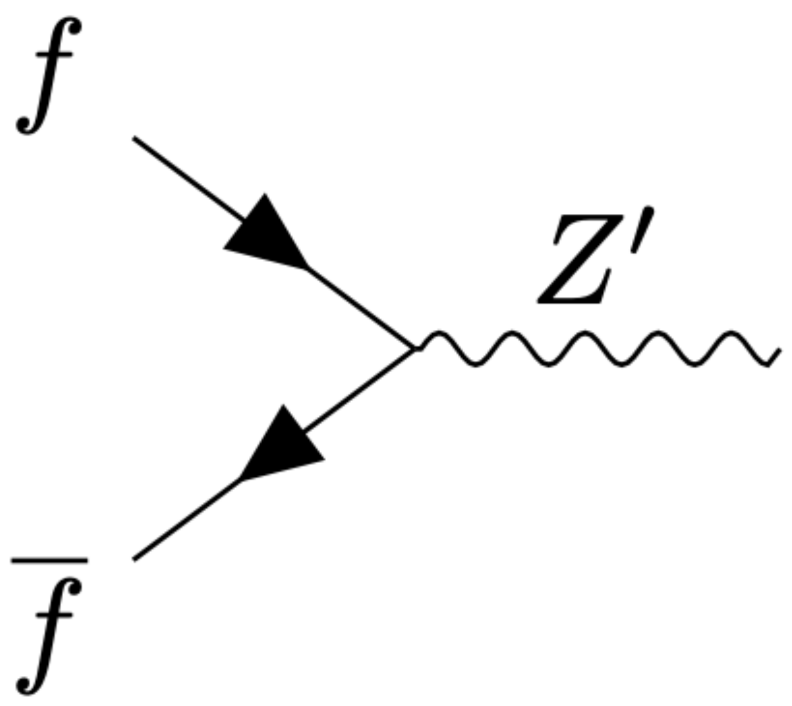
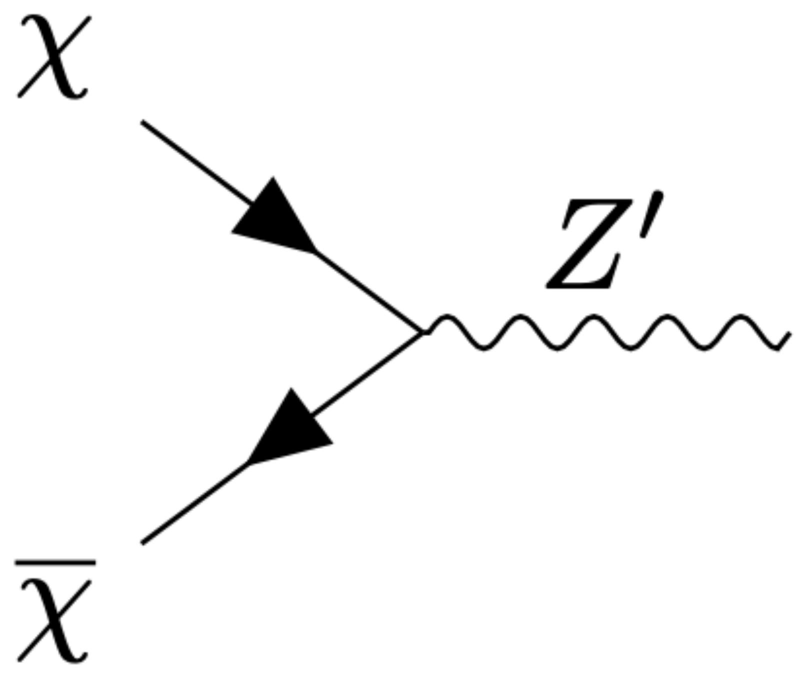
Keeping simple and neglecting the mixing with SM gauge Bosons, we end with the following couplings

$$\mathscr{L} \supset -m_\chi \bar{\chi}\chi - \frac{1}{2} M_{Z'}^2 Z'_\mu Z'^\mu + \bar{\chi}\gamma^\mu \left(V_\chi - A_\chi \gamma_5\right) \chi Z'_\mu + \sum_f \bar{f}\gamma^\mu \left(V_f - A_f \gamma_5\right) f Z'_\mu$$



$$= \gamma^\mu \left(V_f - A_f \gamma_5\right)$$



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The model: Freeze-In regime

$$\boxed{\dot{n} + 3Hn = 2\Gamma(\mathrm{SM} \to \bar{\chi}\chi) - 2\Gamma(\bar{\chi}\chi \to \mathrm{SM})} \longrightarrow \boxed{\dot{n} + 3Hn = 2\Gamma(\mathrm{SM} \to \bar{\chi}\chi)}$$

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- At heavy Z' regime
- Energy conservation + Boltzmann distribution $\longrightarrow$ $\Gamma(\text{SM} \to \bar{\chi}\chi) = \frac{2^3\pi^2 T}{(2\pi)^6} \int_{4m_\chi^2}^{\infty} d\text{s}\ \sigma\left(\ \text{s} - 4m_\chi^2\right)\sqrt{\text{s}}K_1(\sqrt{\ \text{s}}/T)$
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$$\boxed{\sigma(\bar{\chi}\chi \to \bar{f}f) \simeq \frac{V_f^2 V_\chi^2 m_\chi^2}{2\pi M_{Z'}^4}\sqrt{\frac{s}{s - 4m_\chi^2}}}$$

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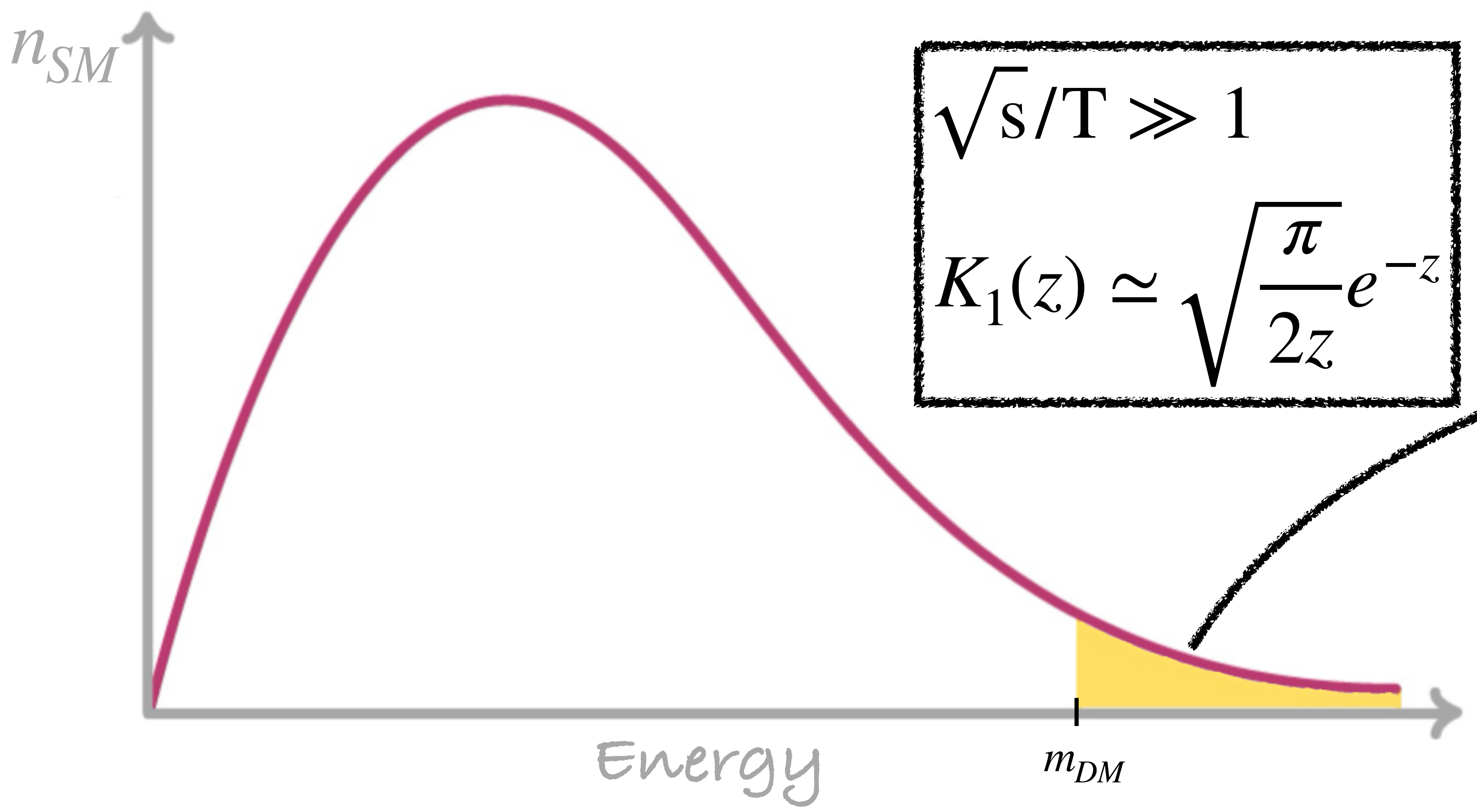


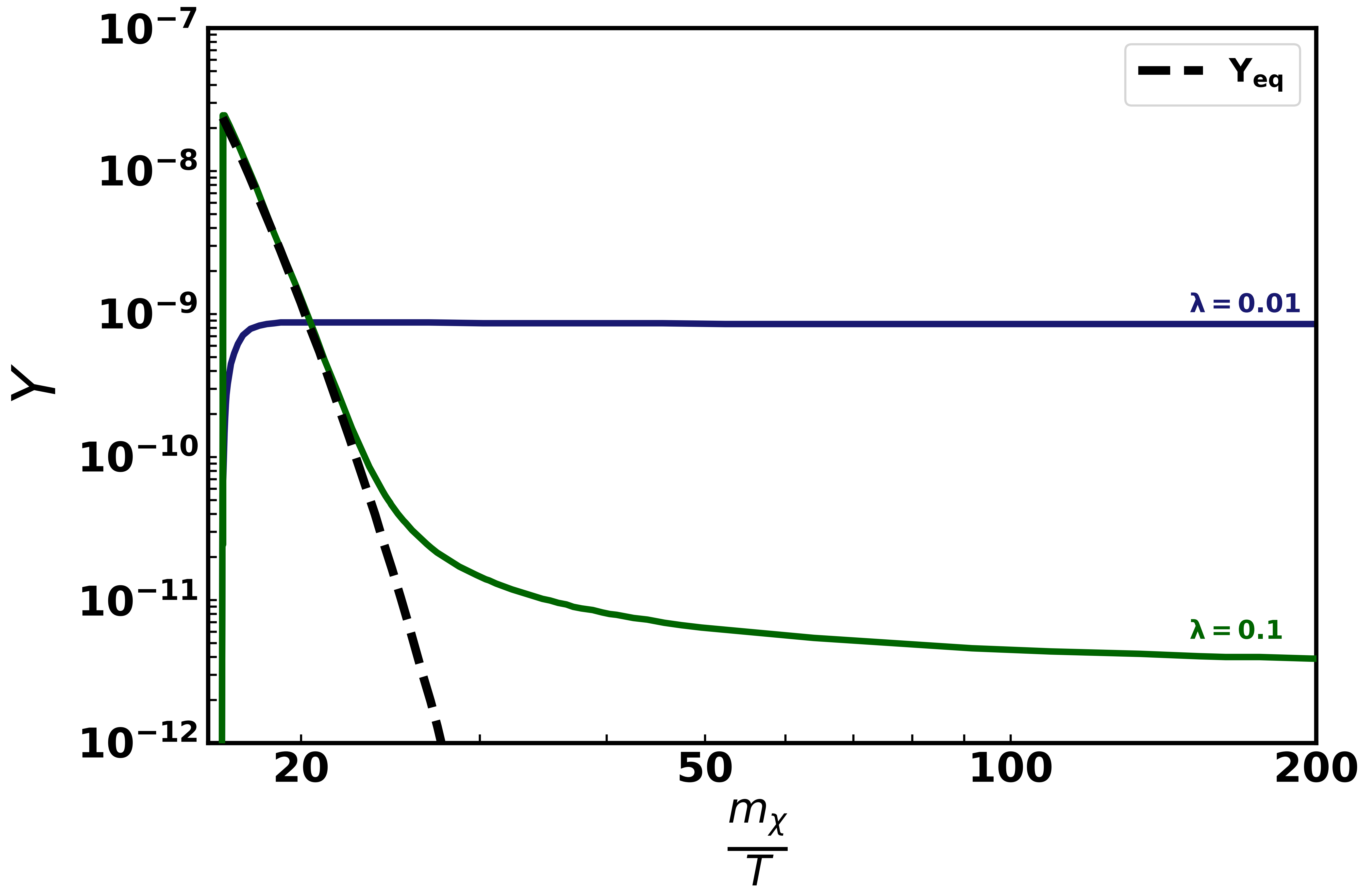
$$\boxed{\begin{aligned}&\sqrt{\mathrm{s}}/\mathrm{T} \gg 1\\ &K_1(z) \simeq \sqrt{\frac{\pi}{2z}}e^{-z}\end{aligned}}$$

$$\boxed{\sigma(\bar{\chi}\chi \to \bar{f}f) \simeq \frac{V_f^2 V_\chi^2 m_\chi^2}{2\pi M_{Z'}^4}\sqrt{\frac{s}{s - 4m_\chi^2}}}$$

$$\boxed{\Gamma(\bar{f}f \to \bar{\chi}\chi) = \frac{V_f^2 V_\chi^2 m_\chi^5 T^3}{2\pi^4 M_{Z'}^4}e^{-2m_\chi/T}}$$

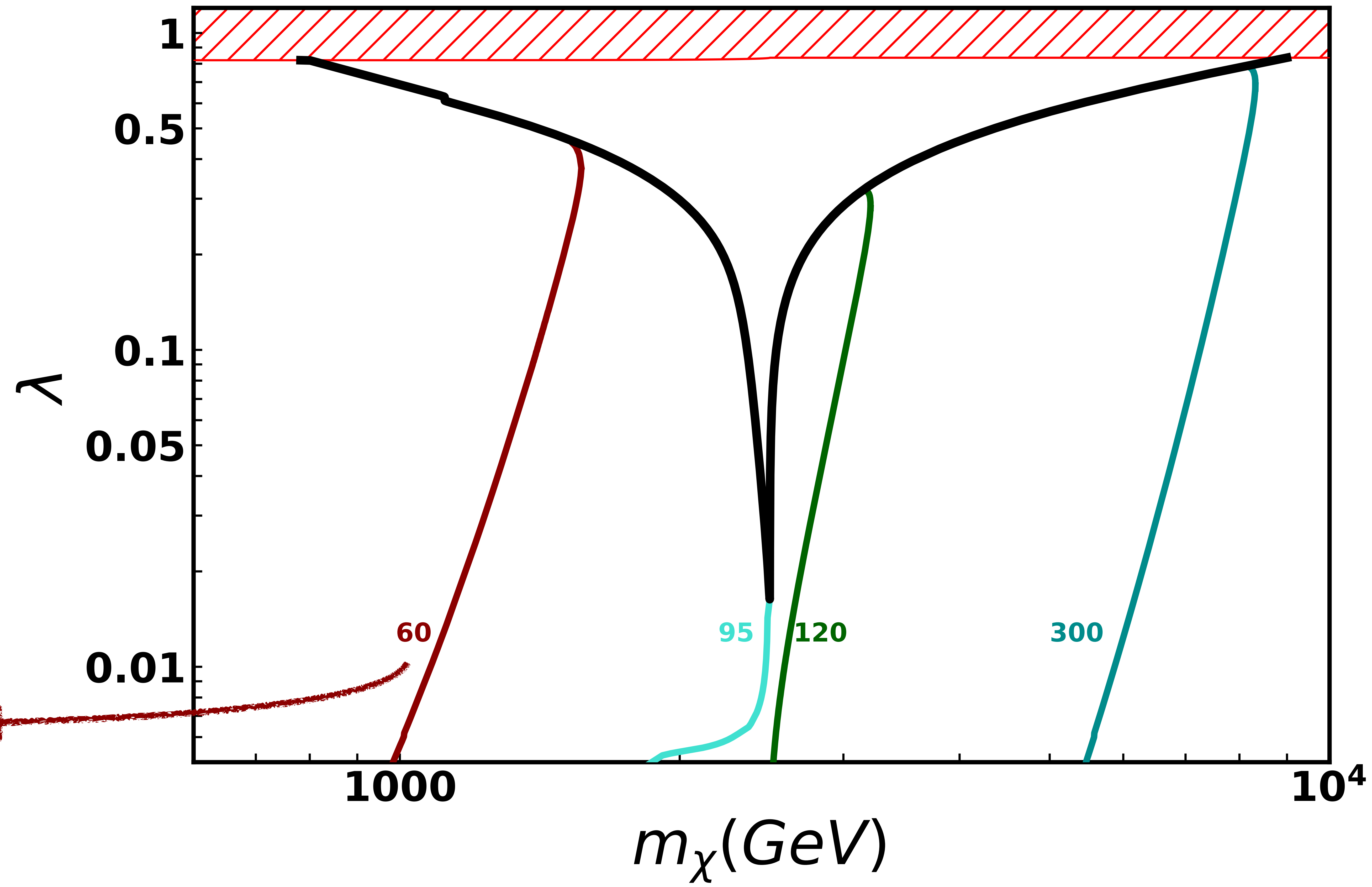
The model: Thermalisation

$$V_f = A_f = V_\chi = A_\chi = \lambda$$
$$T_R = 18\,\mathrm{GeV} \quad M_{Z'} = 900\,\mathrm{GeV} \quad M_\chi = 300\,\mathrm{GeV}$$



The model: Thermalisation

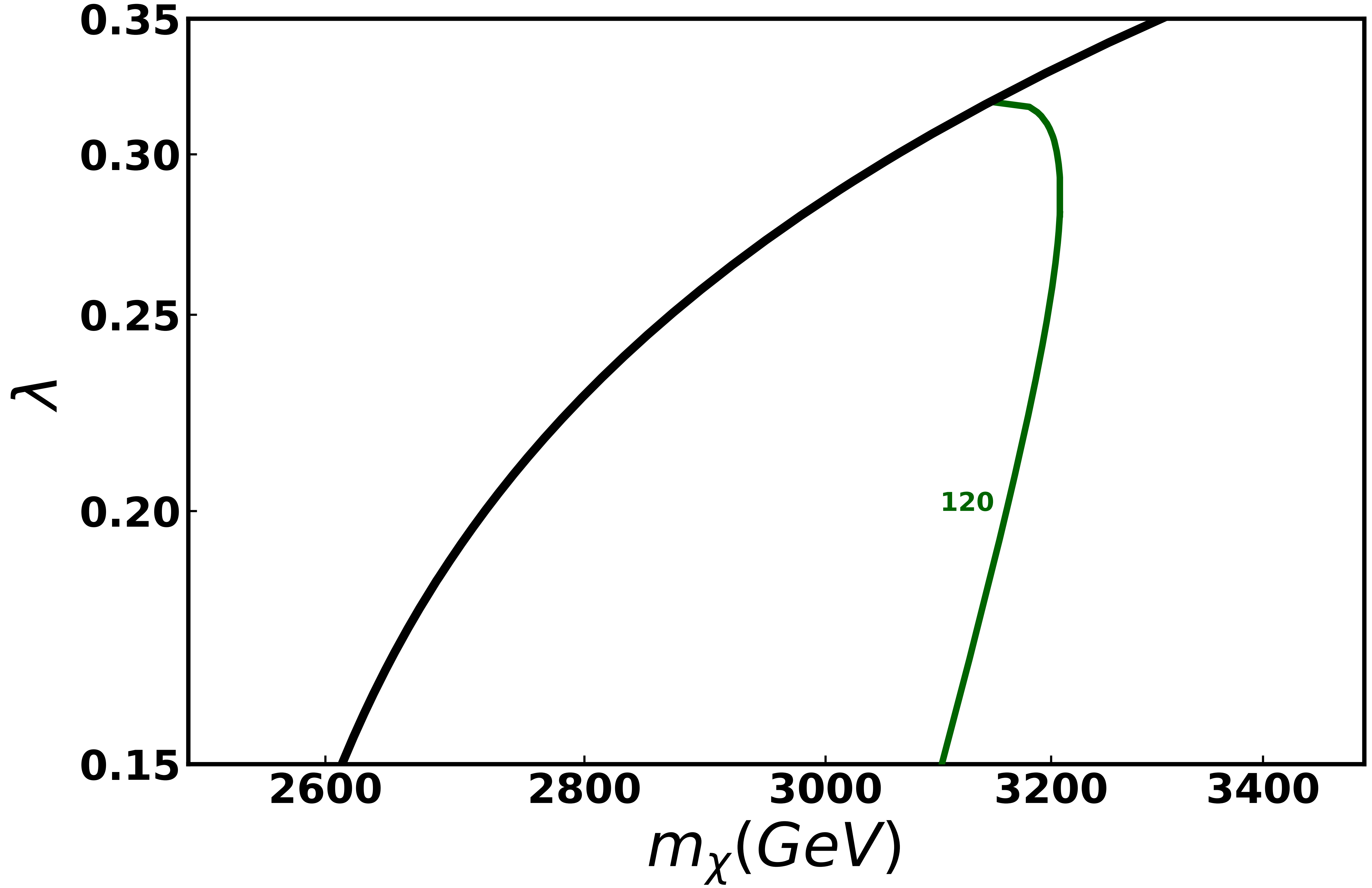
$$V_f = V_\chi = \lambda \quad A_f = A_\chi = 0$$
$$M_{Z'} = 5000\,\mathrm{GeV}$$



$$\lambda \simeq 10^{-6}\frac{M_{Z'}T_R^{1/4}}{m_\chi^{5/4}}e^{m_\chi/(2T_R)}$$

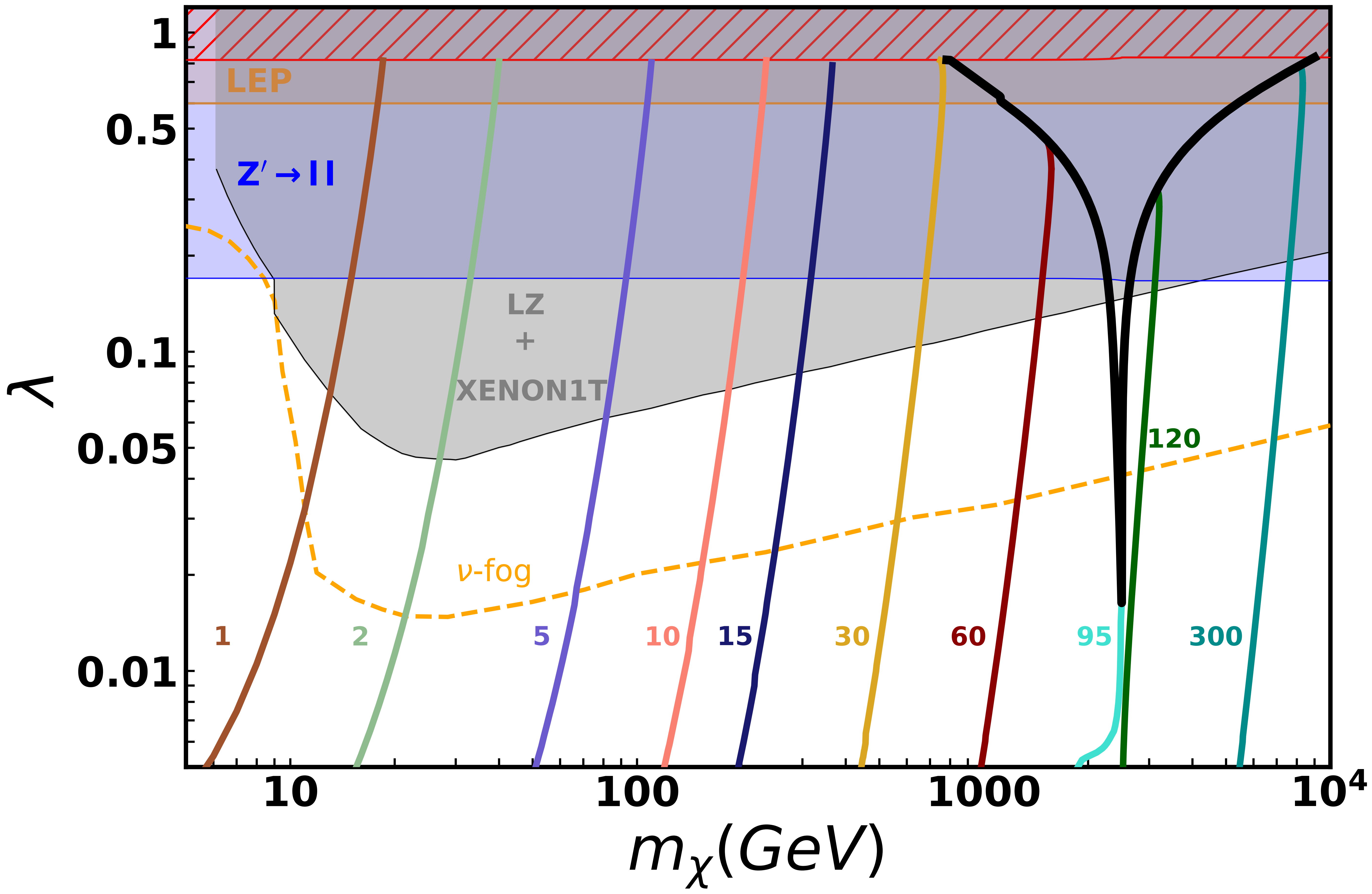
The model: Thermalisation

$$\boxed{\begin{array}{c} V_f = V_\chi = \lambda \quad A_f = A_\chi = 0 \\ M_{Z'} = 5000\,\mathrm{GeV} \end{array}}$$



Phenomenology: Results $M_{Z'} = 5\text{TeV}$

Vectorial



Conclusions

- Dark relics are (over)produced during/after inflation
- Non-thermal DM has memory
- Later reheating can dilute the production $\longrightarrow$ Boltzmann suppressed Freeze-In
- A new region in the parameter space is open!

Thank You!

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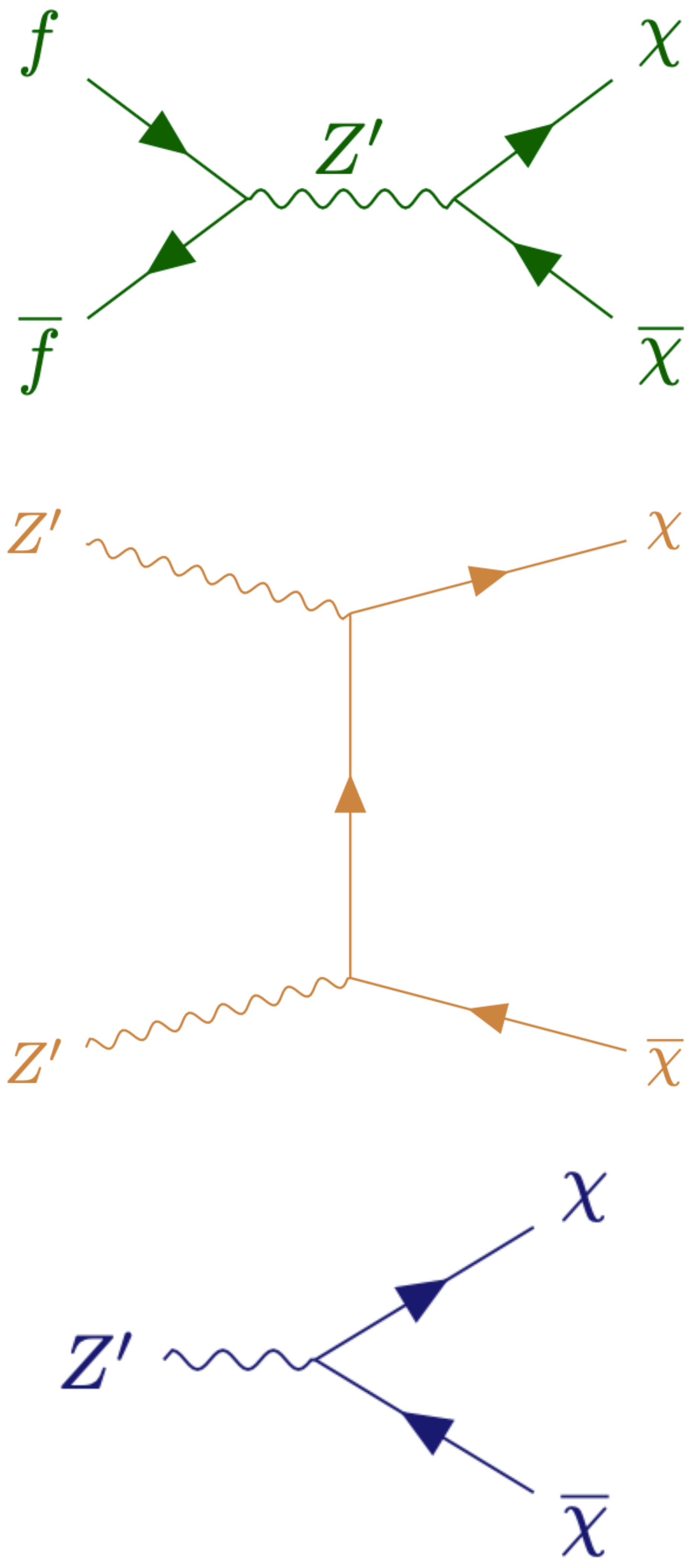
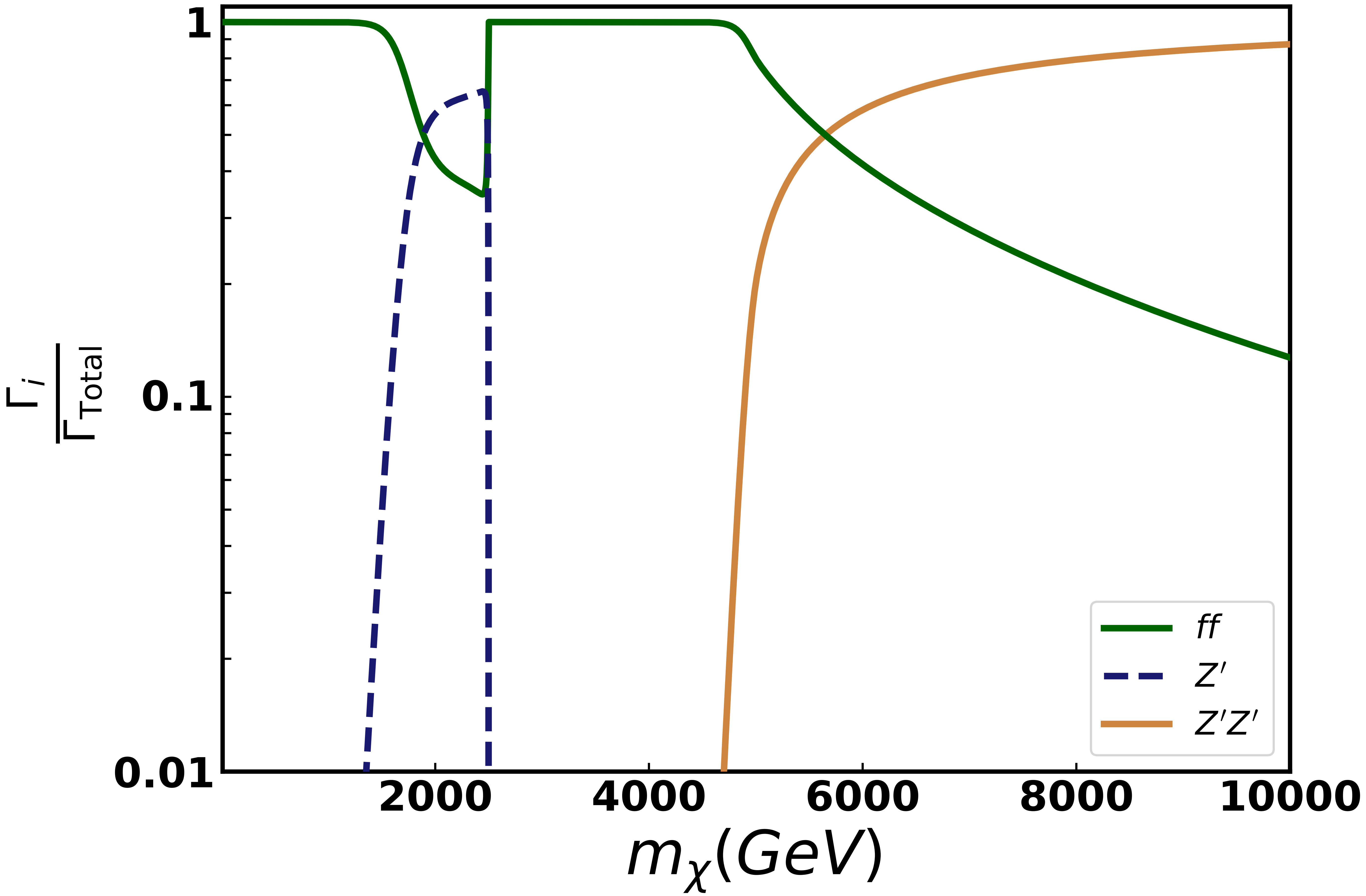
Back Up

Production process





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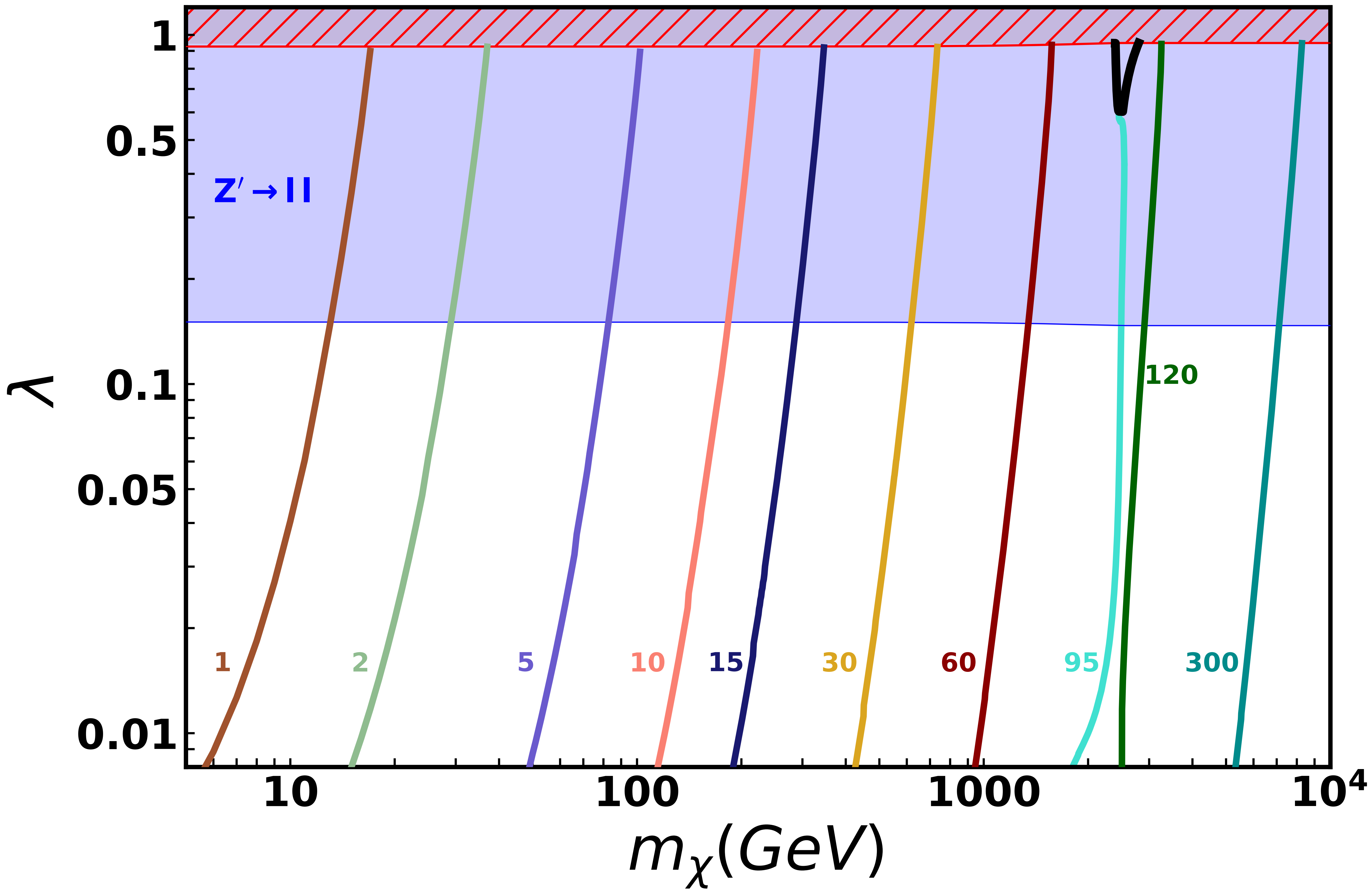
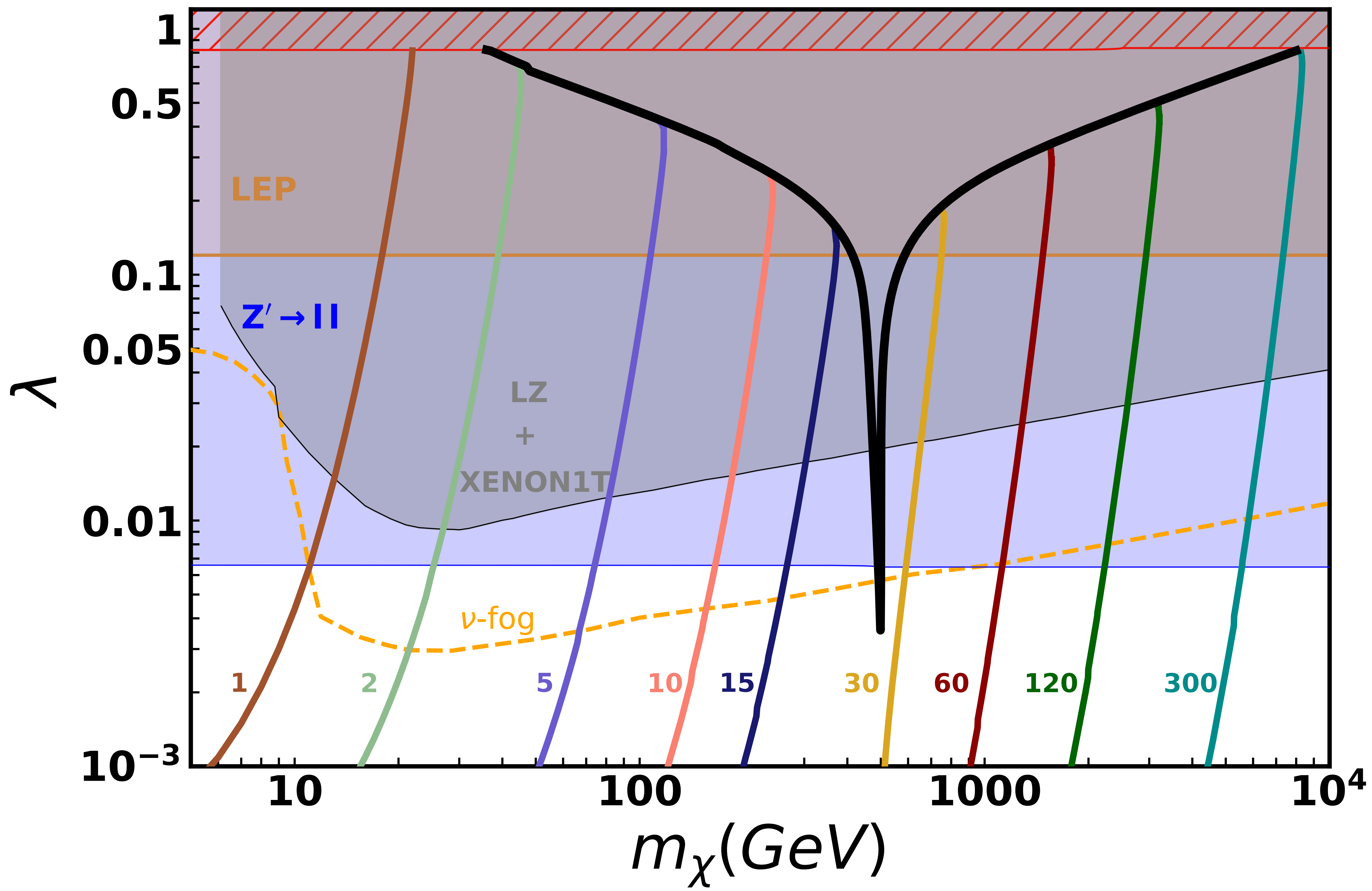


Results $M_{Z'} = 1\mathrm{TeV}$

Vectorial



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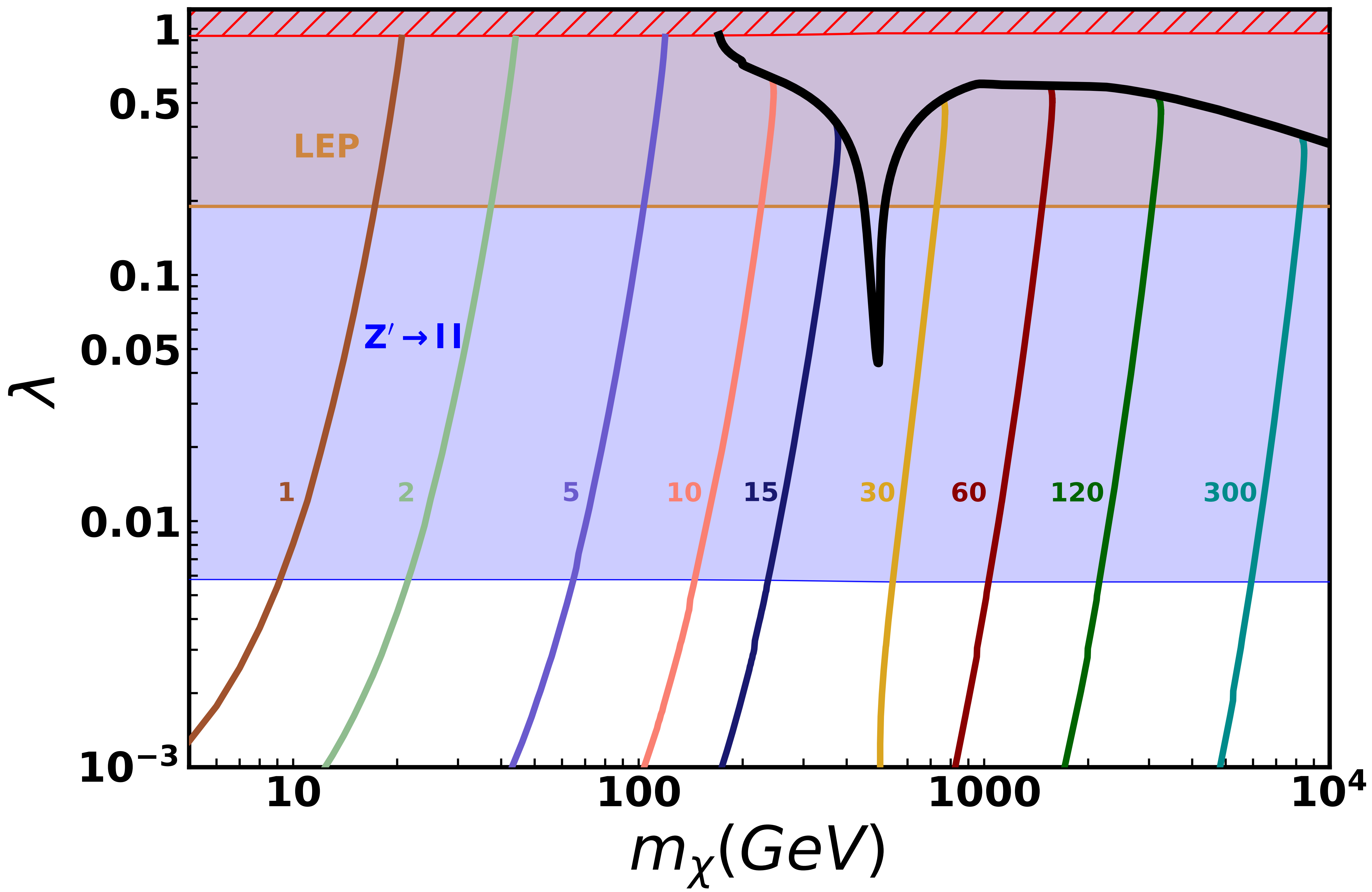
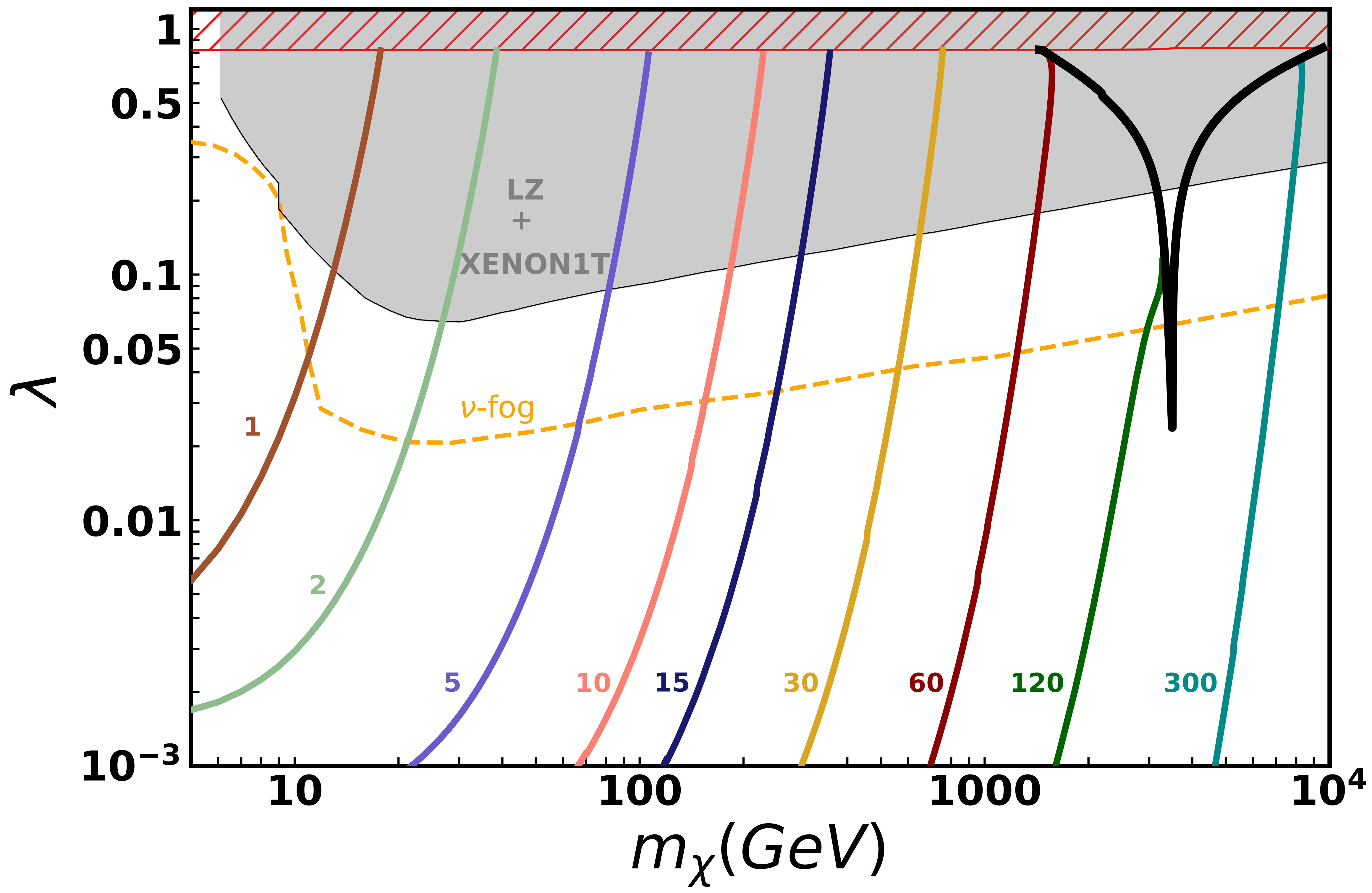


Results $M_{Z'} = 7\text{TeV}$

Vectorial



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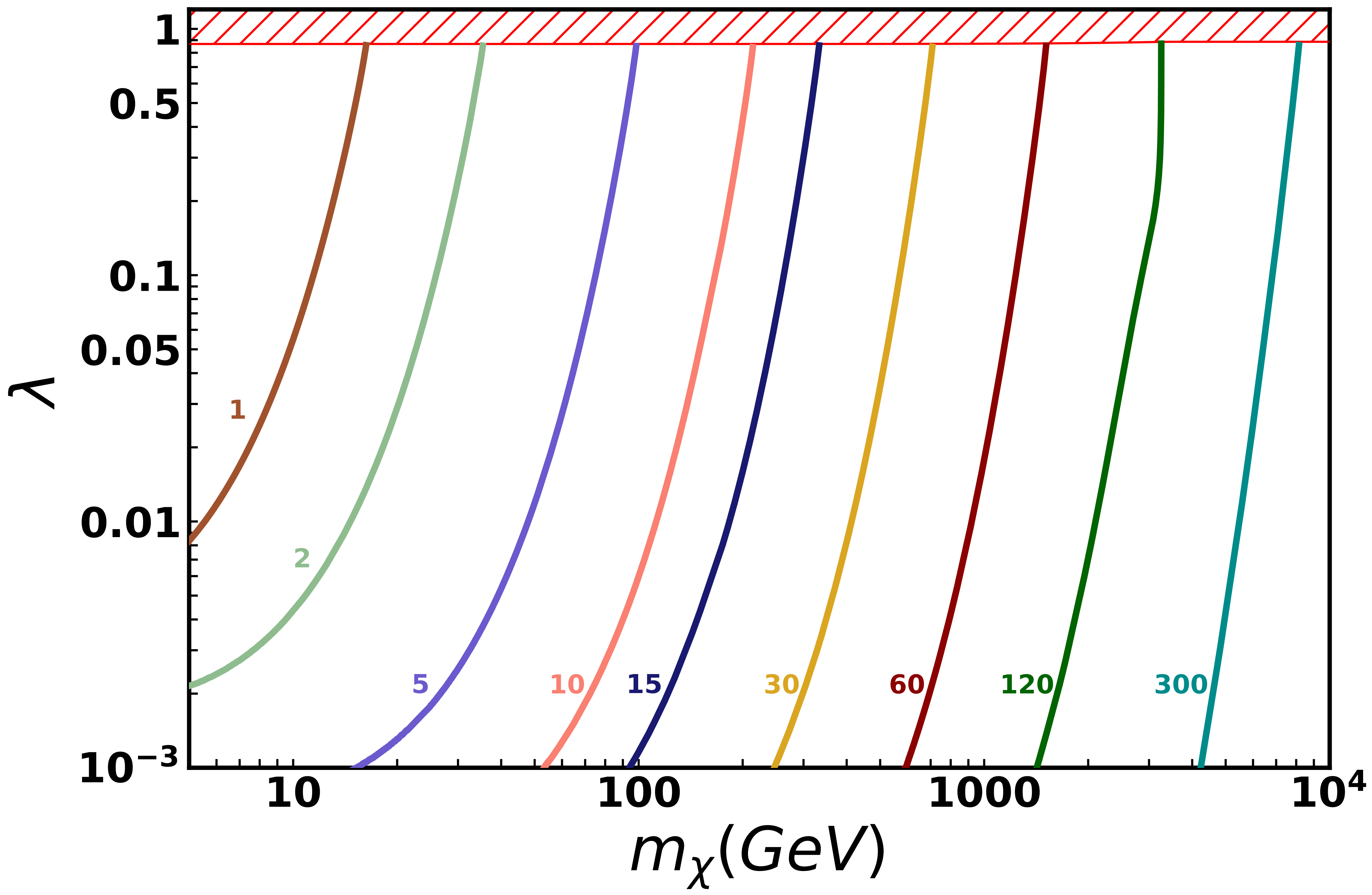


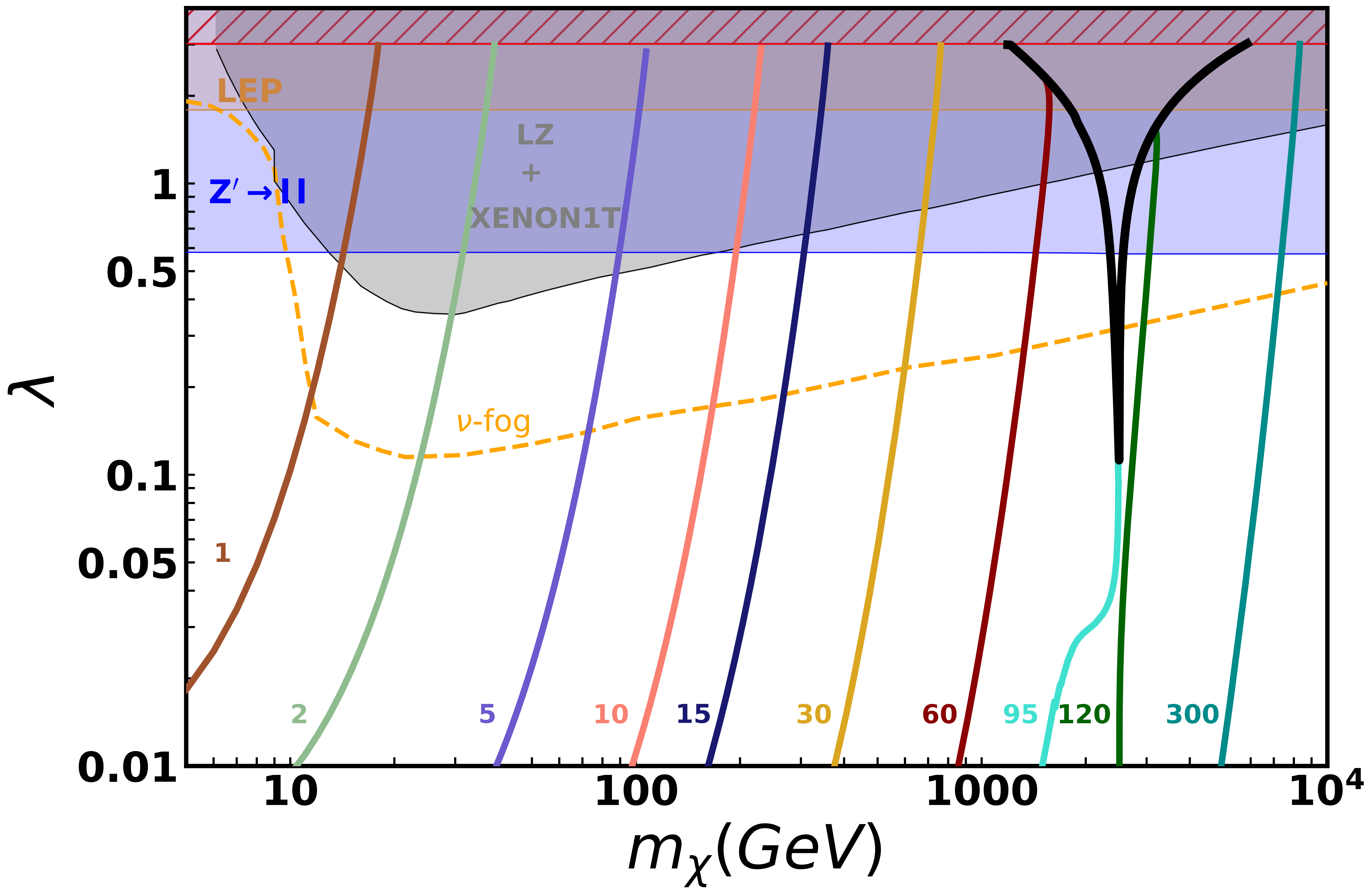
Z_χ Example

$$\boxed{V_f = g_{Z'}\left(X_{f_L} + X_{f_R}\right) \qquad A_f = g_{Z'}\left(X_{f_L} - X_{f_R}\right)}$$

$$\boxed{g_{Z'} = \lambda}$$

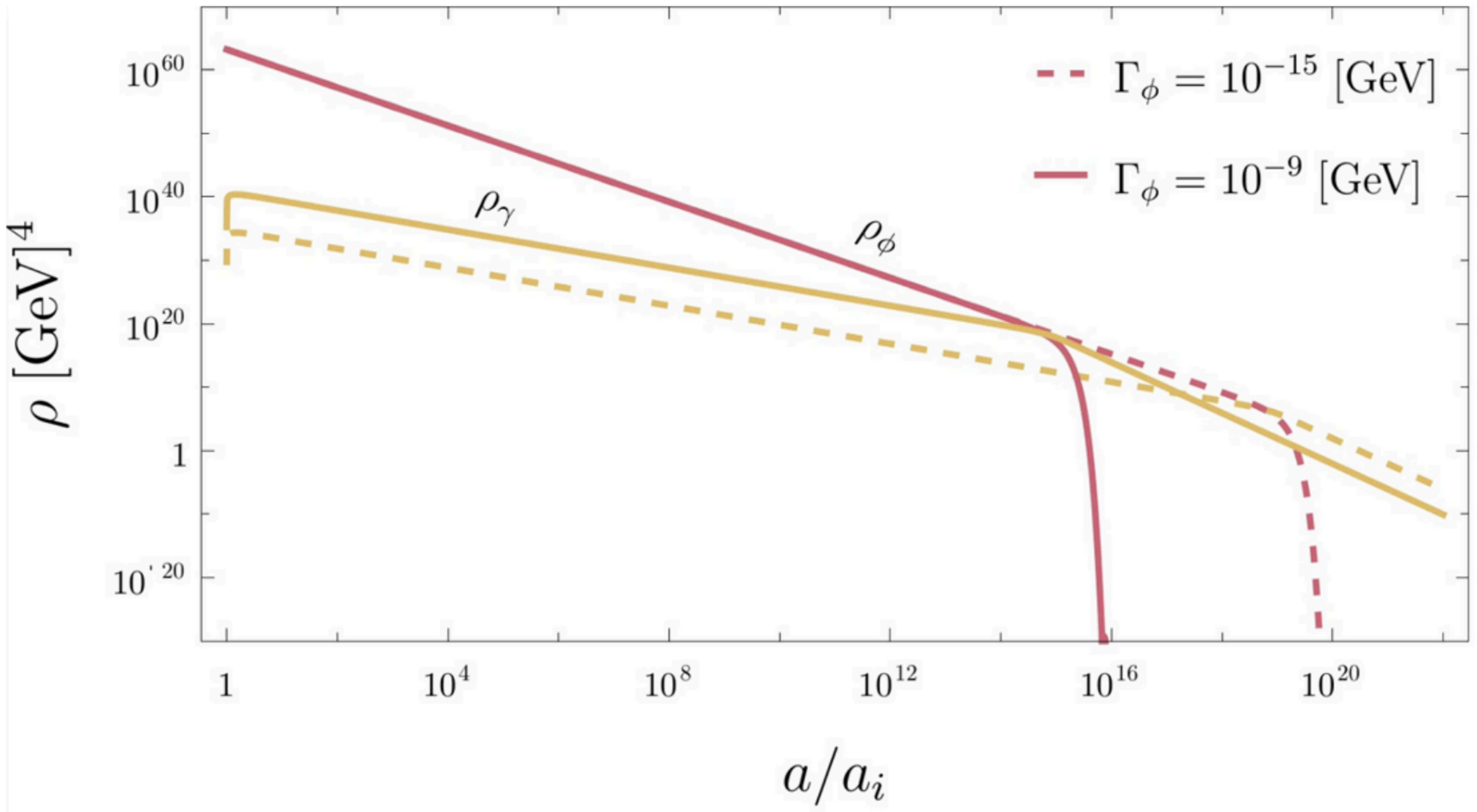
	Z'_χ	Z'_ψ	Z'_η	Z'_{LR}	Z'_{B-L}	Z'_{SSM}
D	$2\sqrt{10}$	$2\sqrt{6}$	$2\sqrt{15}$	$\sqrt{5/3}$	1	1
$\hat{\epsilon}^u_L$	-1	1	-2	-0.109	1/6	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$
$\hat{\epsilon}^d_L$	-1	1	-2	-0.109	1/6	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}^u_R$	1	-1	2	0.656	1/6	$-\frac{2}{3}\sin^2\theta_W$
$\hat{\epsilon}^d_R$	-3	-1	-1	-0.874	1/6	$\frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}^\nu_L$	3	1	1	0.327	$-1/2$	$\frac{1}{2}$
$\hat{\epsilon}^l_L$	3	1	1	0.327	$-1/2$	$-\frac{1}{2} + \sin^2\theta_W$
$\hat{\epsilon}^e_R$	1	-1	2	-0.438	$-1/2$	$\sin^2\theta_W$

$$\boxed{X_{f_{ct}} = \frac{\hat{\epsilon}^f_{ch}}{D}}$$

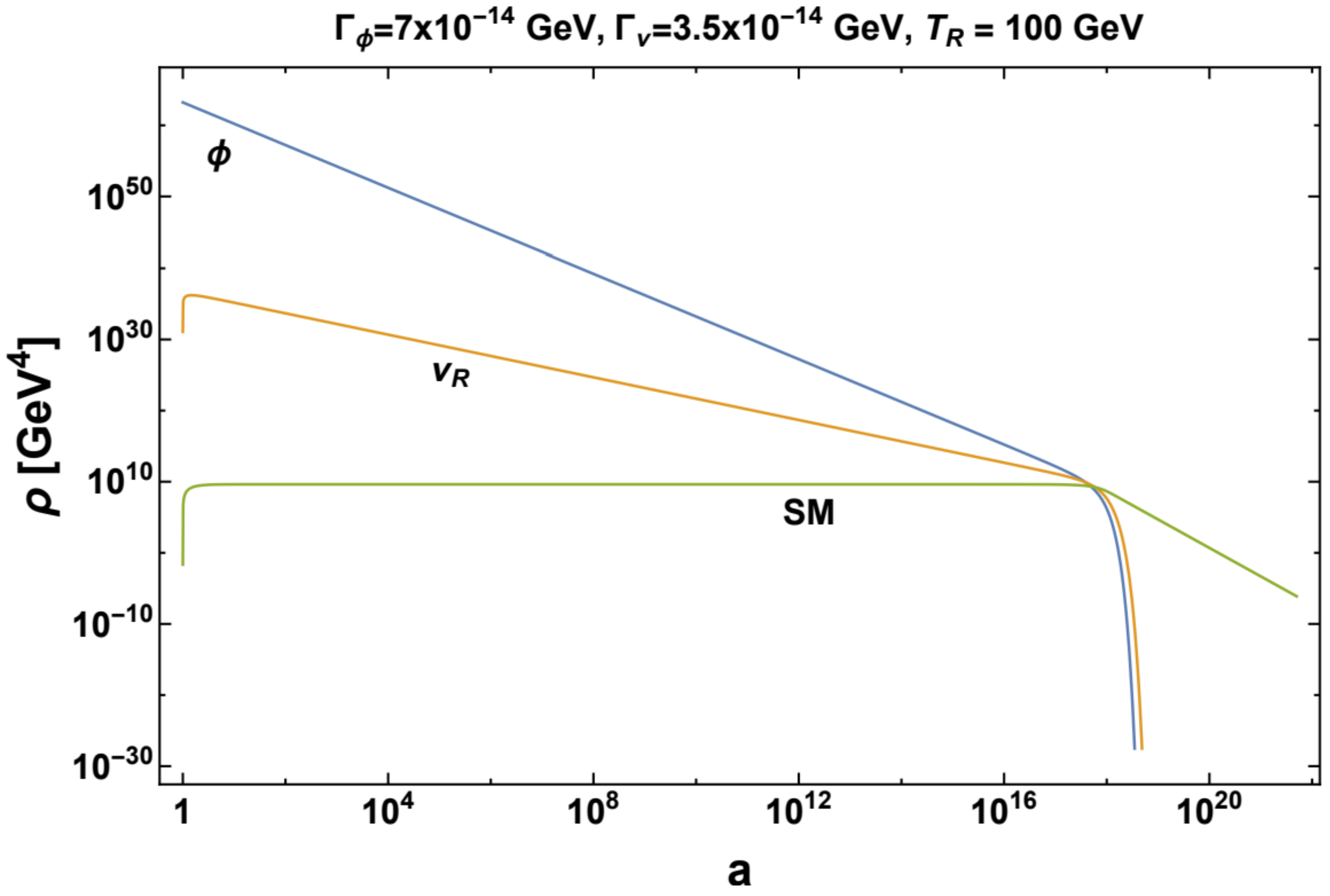


Instantaneous Reheating

$\phi \to \mathrm{SM}$



$\phi \to \nu_R \to \mathrm{SM}$



$$\boxed{T_R \to 0.95 \times T_R}$$

C. Cosme, F. Costa, O. Lebedev, arXiv: 2402.04743

Phenomenology: ID and colliders

- **Indirect Detection:** Stricter bounds come from Fermi-LAT observation of 30 dSphs

$$\boxed{\chi\bar{\chi} \to \tau^+\tau^- \qquad \chi\bar{\chi} \to b\bar{b}}$$

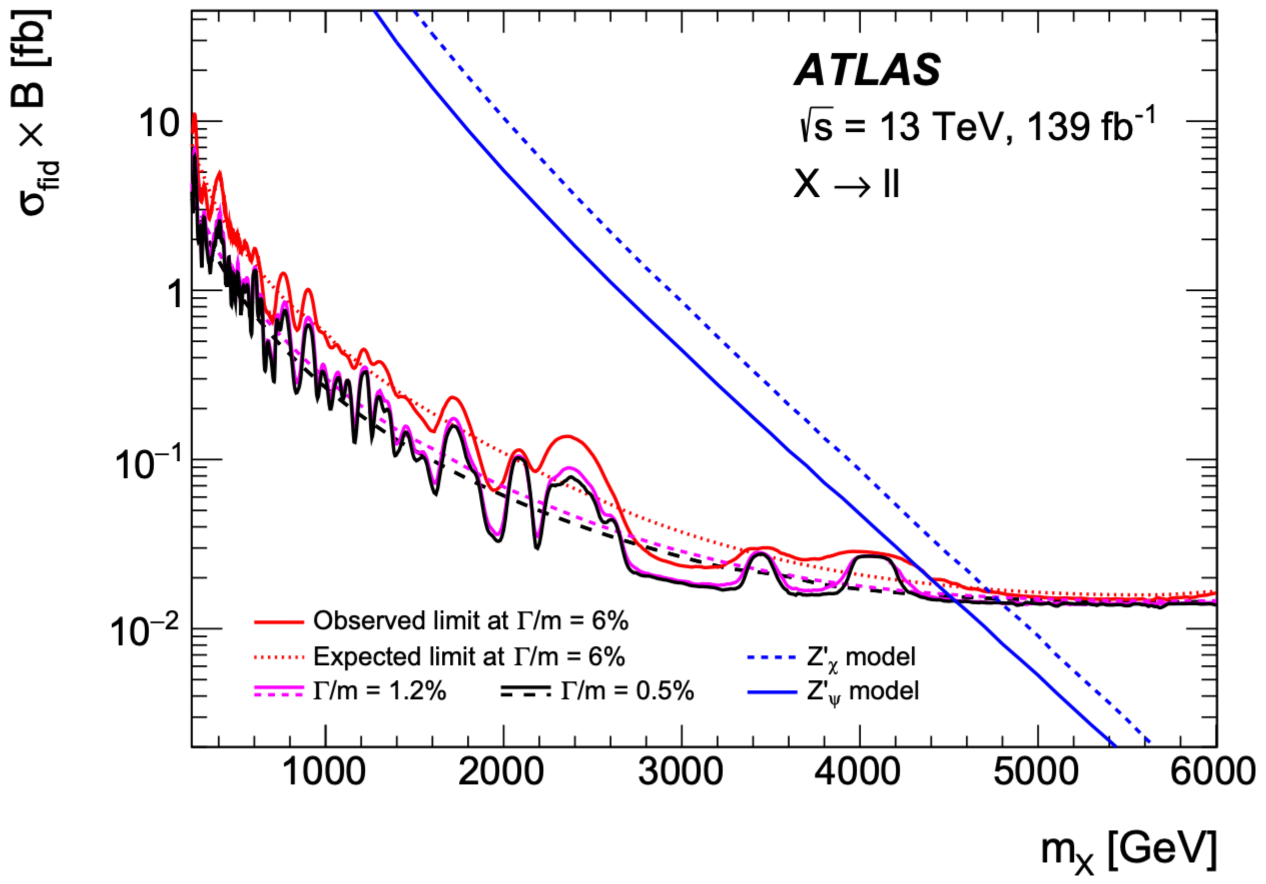
A. McDaniel, M. Ajello, C. M. Karwin, M. Di Mauro, A. Drlica-Wagner, M. A. Sanchez-Conde arXiv: 2311.04982

- **LEP:** stronger constraints from 4-lepton operators $\ell\ell\ell\ell$

$$\boxed{\frac{\lambda}{M_{Z'}} < \frac{0.12}{\mathrm{TeV}}} \quad 95\,\%\,\mathrm{CL}\,. \quad \boxed{\frac{\lambda}{M_{Z'}} < \frac{0.19}{\mathrm{TeV}}}$$

A. Falkowski, K. Mimouni, arXiv: 1511.07434

- **LHC:** direct search of new gauge boson Z' in the channel $pp \to \ell^+\ell^- X$



ATLAS Collaboration, arXiv: 1903.06248