Non-thermal production of Dark Matter in an EFT scenario

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS
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Based on: An EFT origin of secluded Dark Matter (arXiv:2312.17171)

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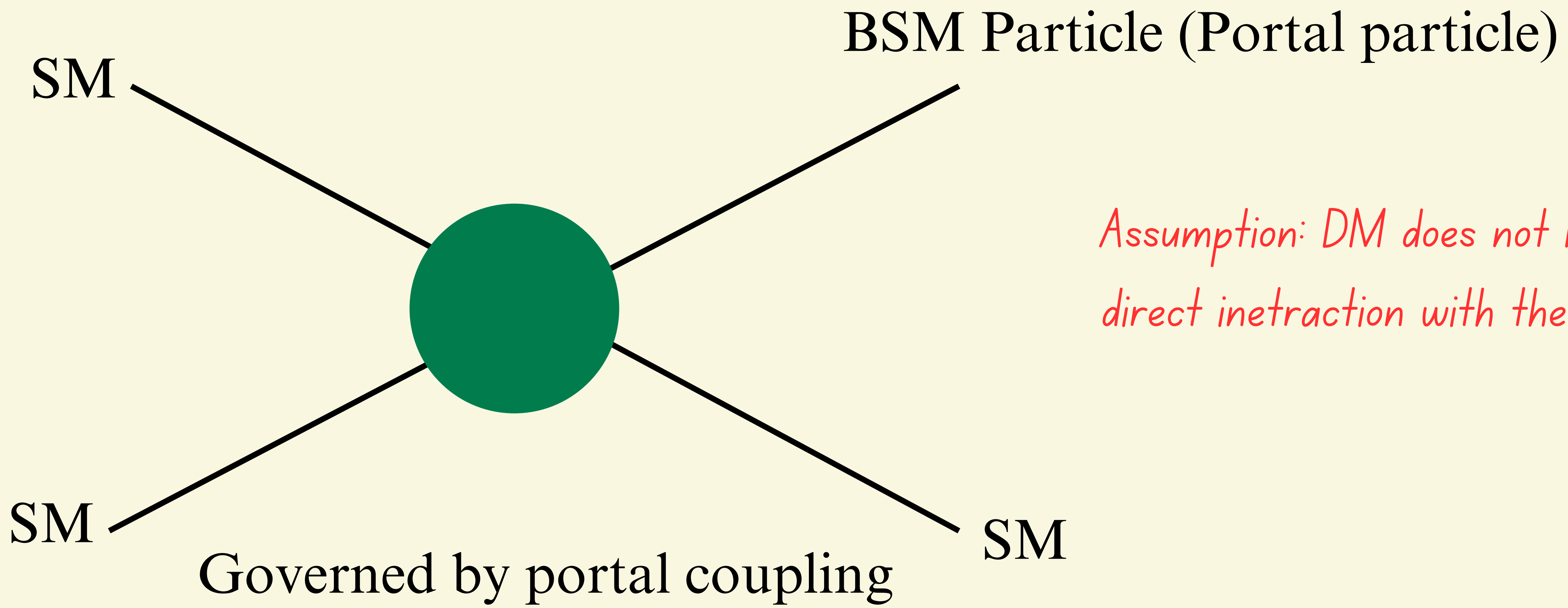
Overview

- Basic Mechanism of Dark Matter production.
- Model
- Dark Matter production
- Constraints on Model Parameter space
- Conclusion

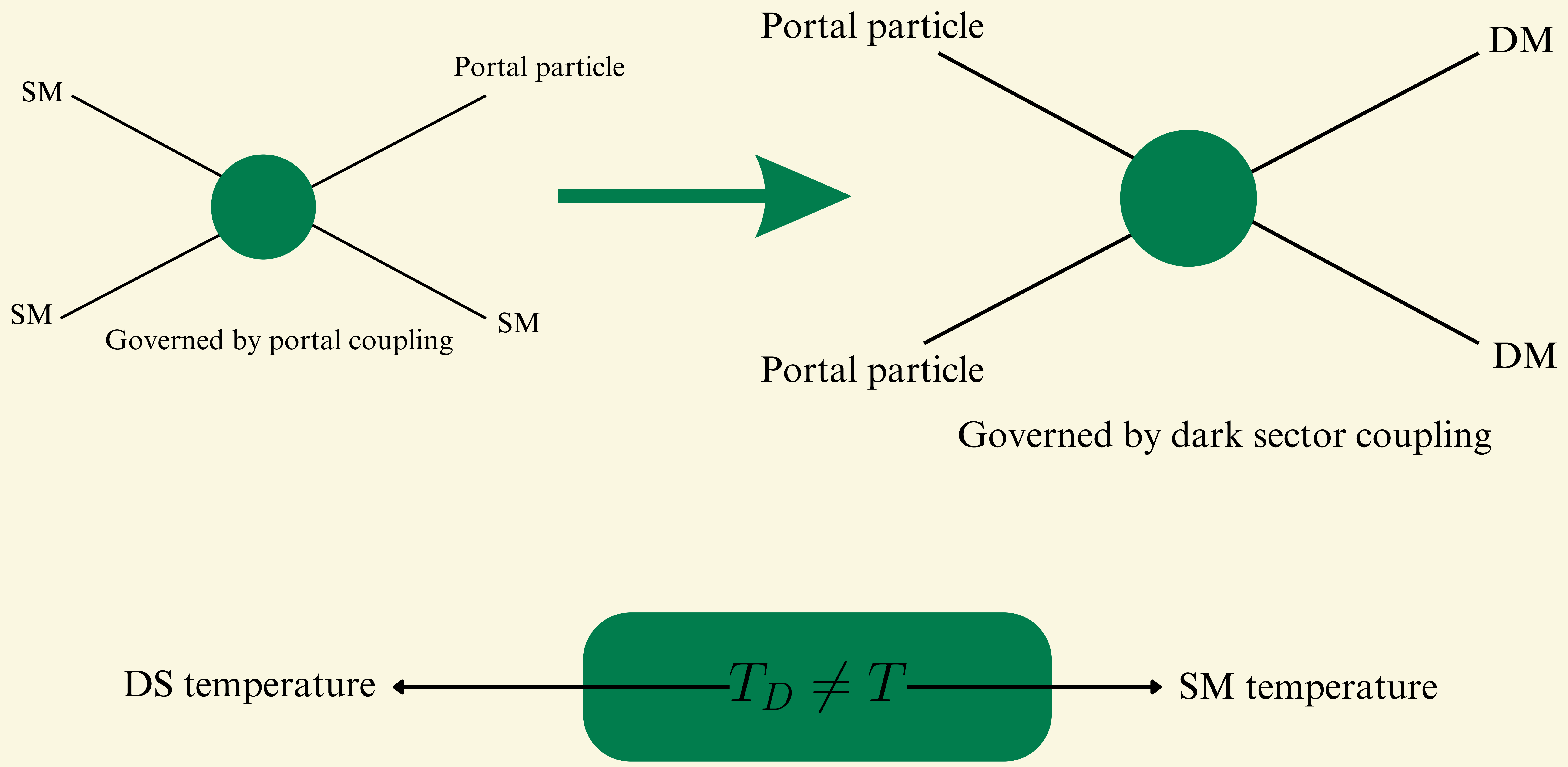
Basic Mechanism of Dark Matter production

- At early stage of the Universe,



Assumption: DM does not have any direct inetraction with the SM fields

Basic Mechanism of Dark Matter production



Model

- Type-X 2HDM extended with two SM gauge singlet fermions (ξ, χ) and one SM singlet scalar S.

- Presence of Global $U(1)_{L_e - L_\mu}$ symmetry under which new fields have some non-trivial charges.

Fields	$U(1)_{e-\mu}$
ξ	1
S	-2
χ	3

- Yukawa sector of the type-X 2HDM,

$$\mathcal{L} \supset y_{1i}\overline{L_i}\Phi_1 e_{R_i} + y_{2i}\overline{Q_i}\Phi_2 d_{R_i} + y_{3i}\overline{Q_i}\Phi_2^c u_{R_i}.$$

Fixed by lepton and quark masses

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portal interactions

DS interactions

Fixed by lepton and quark masses

- After electro-weak symmetry breaking, there are five massive scalar degrees of freedom.
- The selected mass hierarchies: $m_{S,H,H^{\pm}} \gg m_{\chi,\xi}$
- Effective scale of the theory: $100 \times m_{\chi}$
- Four Fermi operators emerge:

Integrating out $H^{\pm}$
$\frac{C_{1\tau}}{m^2_{H^{\pm}}} \sin^2\beta\, \overline{\nu_{L_i}} e_{R_i} \overline{e_L} \xi_R\,,\ \frac{C_{2\tau}}{m^2_{H^{\pm}}} \sin^2\beta\, \overline{\nu_{L_i}} e_{R_i} \overline{\mu_L} {\xi^c}_R\,,\ \frac{C_3}{m^2_{H^{\pm}}} \sin^2\beta\, \overline{e_L} \xi_R \overline{{\xi^c}_R} \mu_L$ $\frac{C_4}{m^2_{H^{\pm}}} \sin^2\beta\, \overline{e_L} \xi_R \overline{\xi_R} e_L\,,\ \frac{C_5}{m^2_{H^{\pm}}} \sin^2\beta\, \overline{\mu_L} {\xi^c}_R \overline{{\xi^c}_R} \mu_L$
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$$\{C_{\tau},\ \lambda_1,\ \lambda_2,\ m_{\chi},\ m_{\xi}\}$$

$$C_{\tau} : \frac{y_{1\tau} y_4 (y_5)}{\Lambda^2} \sin^2\beta \qquad \lambda_{1(2)} : \frac{y_7 y_6 (y_7)}{\Lambda^2}$$

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- Parameters of the theory:

$$\{C_{\tau},\ \lambda_1,\ \lambda_2,\ m_{\chi},\ m_{\xi}\}$$

- DM stability at tree level,

$$m_{\xi} < m_{\chi} < 3\, m_{\xi}$$

Boltzmann Equation

- The Number density Boltzmann equation:

$$\frac{dn_{\chi_{\text{tot}}}}{dt} + 3Hn_{\chi_{\text{tot}}} = \frac{1}{2}\langle\sigma v\rangle^{T_D}_{\xi\bar{\xi}^c \to \chi\bar{\xi}} \left[n^2_{\xi_{\text{tot}}} - n_{\chi_{\text{tot}}} n_{\xi_{\text{tot}}} \frac{n^{\text{eq}}_{\xi_{\text{tot}}}(T_D)}{n^{\text{eq}}_{\chi_{\text{tot}}}(T_D)} \right] + \frac{1}{2}\langle\sigma v\rangle^{T_D}_{\xi\bar{\xi} \to \chi\bar{\chi}} \left[n^2_{\xi_{\text{tot}}} - n^2_{\chi_{\text{tot}}} \frac{n^{\text{eq}}_{\xi_{\text{tot}}}(T_D)^2}{n^{\text{eq}}_{\chi_{\text{tot}}}(T_D)^2} \right]$$

$$\frac{dn^{\text{tot}}_{\xi}}{dt} + 3Hn^{\text{tot}}_{\xi} = -\frac{1}{2}\langle\sigma v\rangle^{T_D}_{\xi\bar{\xi}^c \to \chi\bar{\xi}} \left[n_{\xi_{\text{tot}}} - n_{\chi_{\text{tot}}} n_{\xi_{\text{tot}}} \frac{n^{\text{eq}}_{\xi_{\text{tot}}}(T_D)}{n^{\text{eq}}_{\chi_{\text{tot}}}(T_D)} \right]$$

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$$+2\gamma_{\text{SM,SM}\to\text{SM}\xi}(T)$$

Assumptions: 1) MB Distribution

2) DS is in thermal equilibrium

- The Energy density Boltzmann equation:

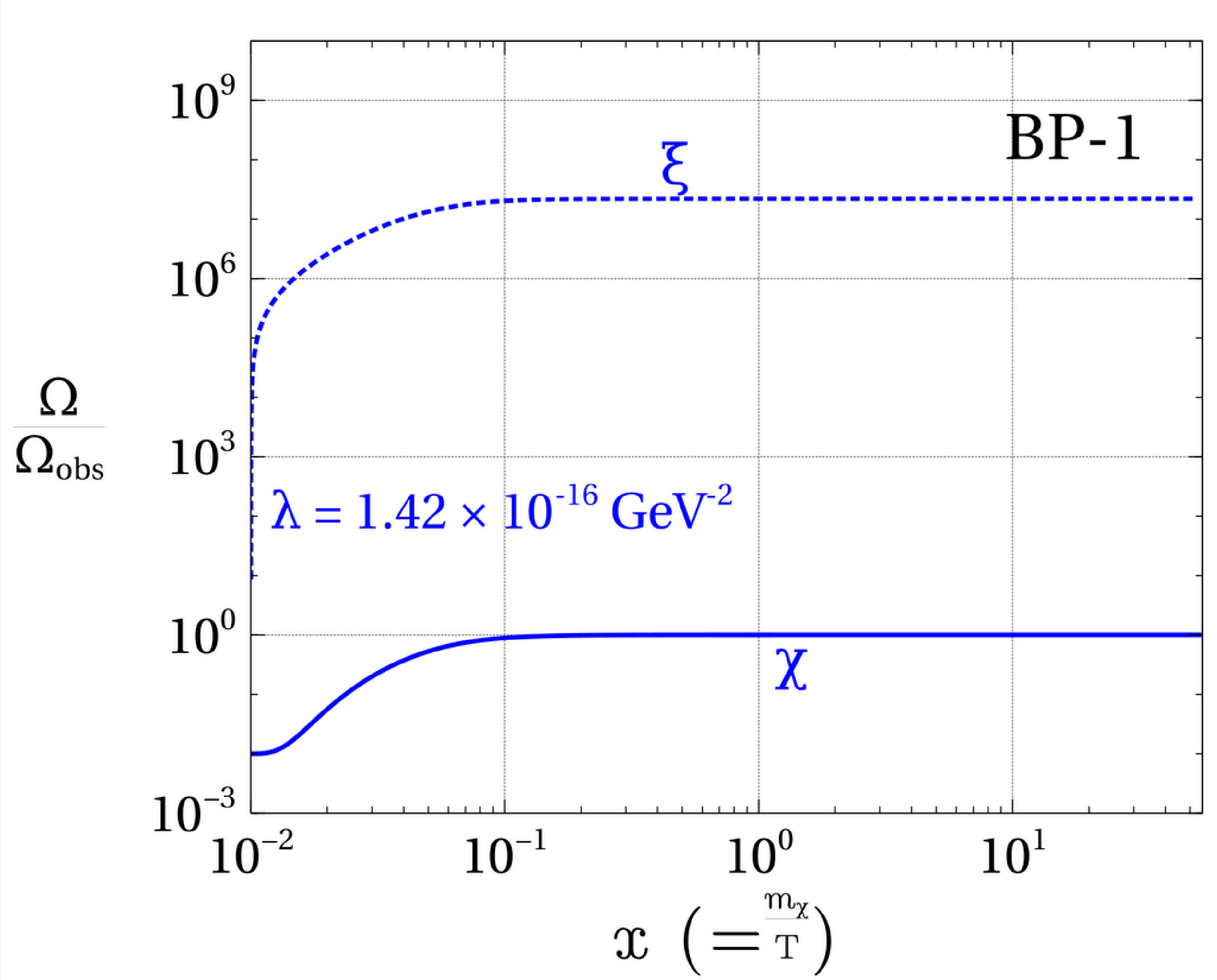
$$\frac{d\rho_{D_{\text{tot}}}}{dt} + 3H(\rho_{D_{\text{tot}}} + p_{D_{\text{tot}}}) = \frac{1}{2}\Gamma_{\xi\to\text{SM}}\, m_\xi (n^{\text{eq}}_{\xi_{\text{tot}}}(T) - n_{\xi_{\text{tot}}}) + 2\Upsilon_{\text{SM,SM}\to\text{SM}\xi}(T)$$

Solved by using Fortran code

CASE: I

$$\lambda_1 = \lambda_2 = \lambda$$

Recap: $\lambda_{1(2)} : \frac{y_7 y_6 (y_7)}{\Lambda^2}$



BP1 : $\{C_\tau, m_\xi, m_\chi\} = \{1.5\times10^{-16}\,\text{GeV}^{-2}, 100\,\text{GeV}, 110\,\text{GeV}\}$

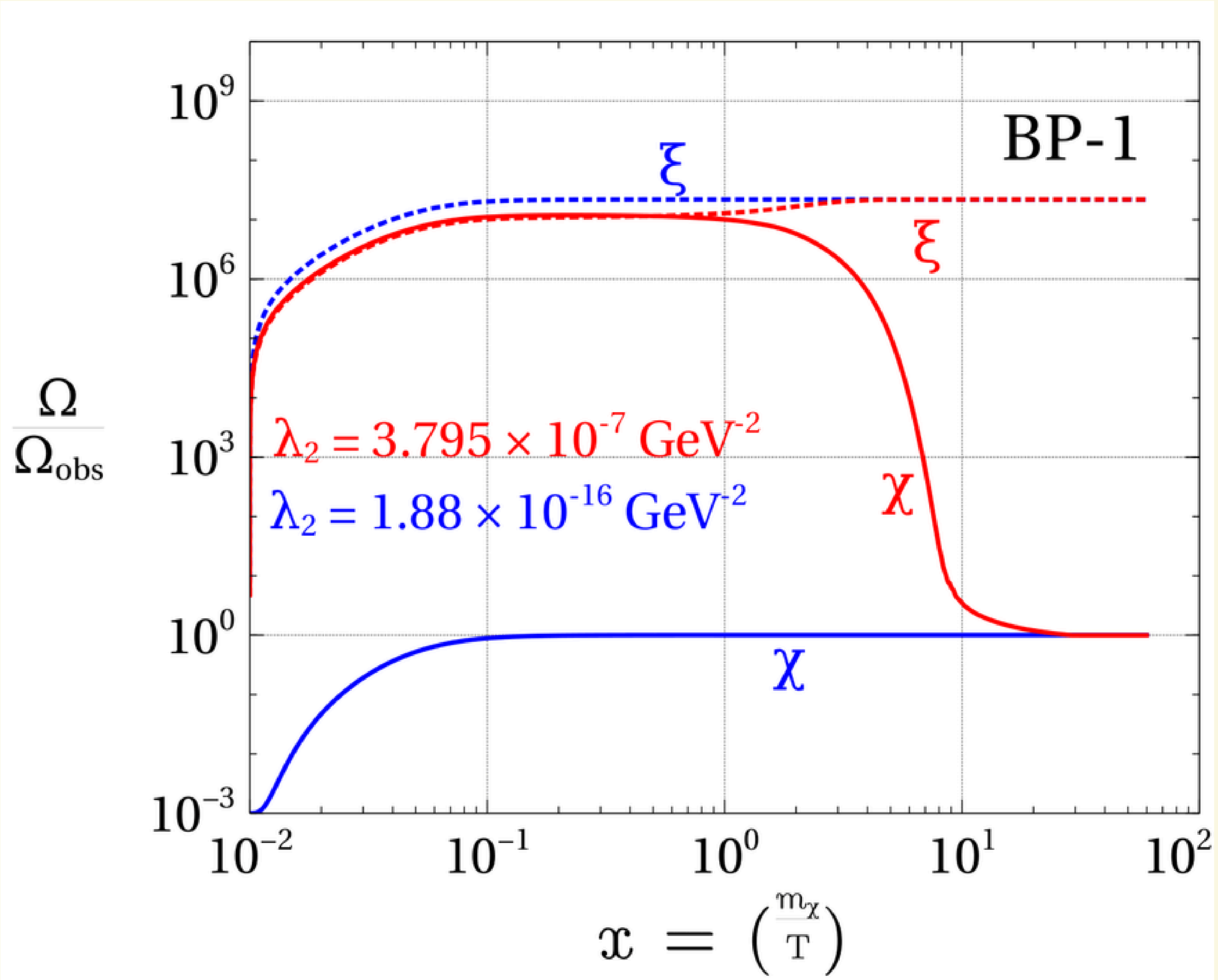
- Freeze-in is only possible production mechanism.
- Production processes :

$$\overline{\xi^c}\xi \to \chi\overline{\xi} \qquad \overline{\xi}\xi \to \overline{\chi}\chi$$

- Later ξ decay into leptons and χ is only DM candidate.

CASE: II

$$\lambda_1 \ll \lambda_2,\ \lambda_1 \simeq 0$$



- Production processes : $\bar{\xi}\xi \to \bar{\chi}\chi$

- Production mechanism :
  - Freeze-in λ_2 very small
  - Freeze-out λ_2 much larger

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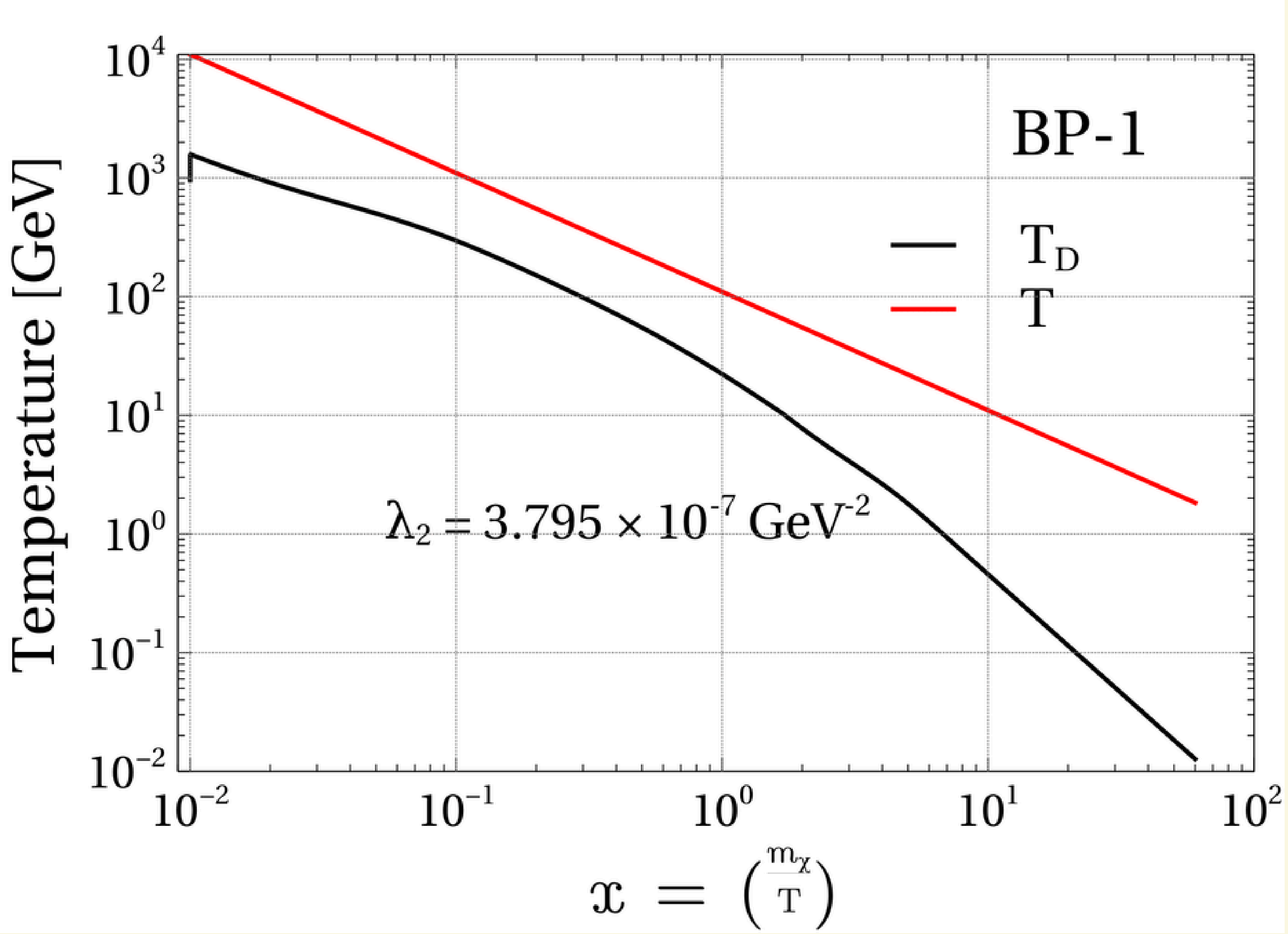

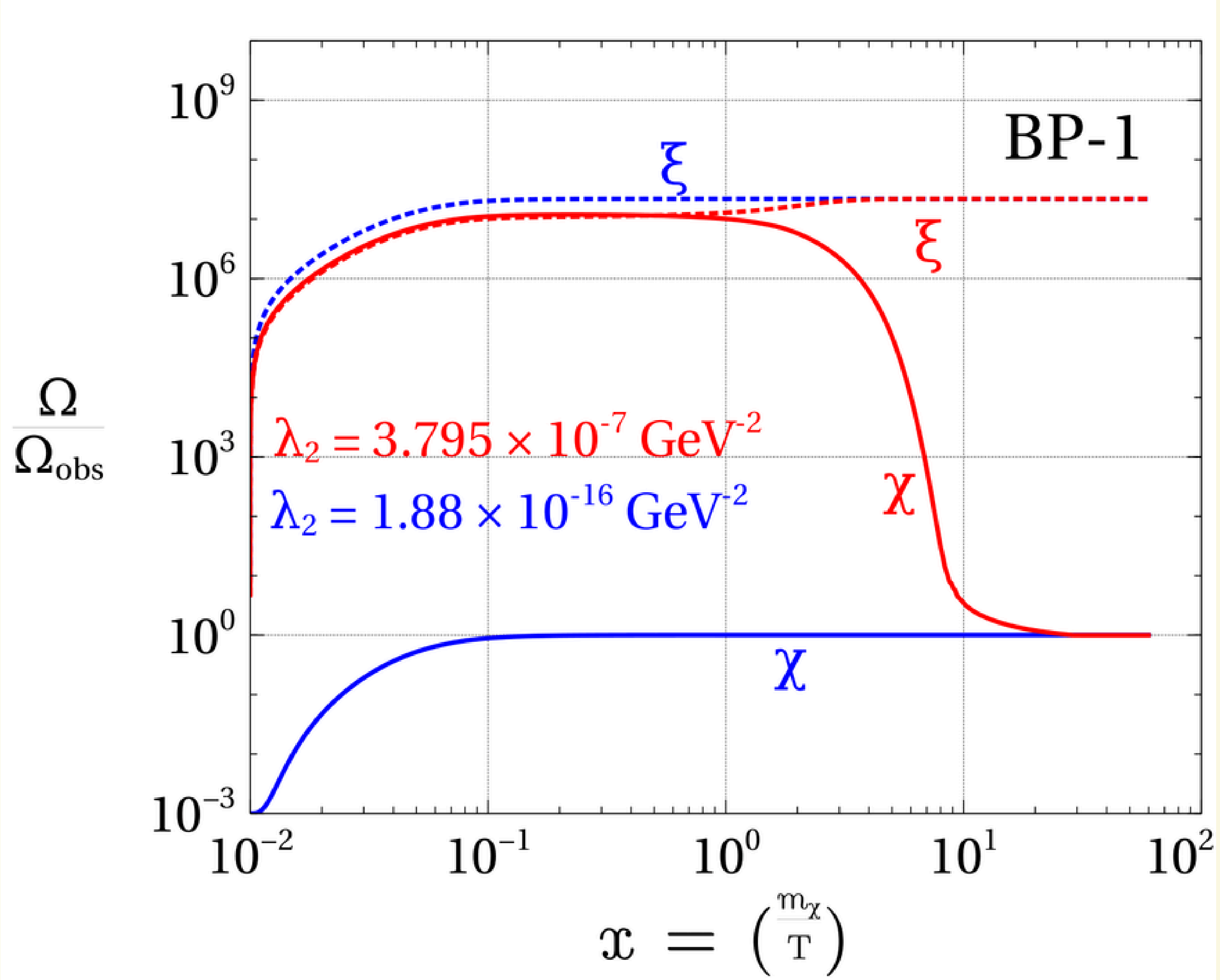

- Red solid line represent VS temperature. Black solid represent DS temperature

Production mechanism : Freeze-out

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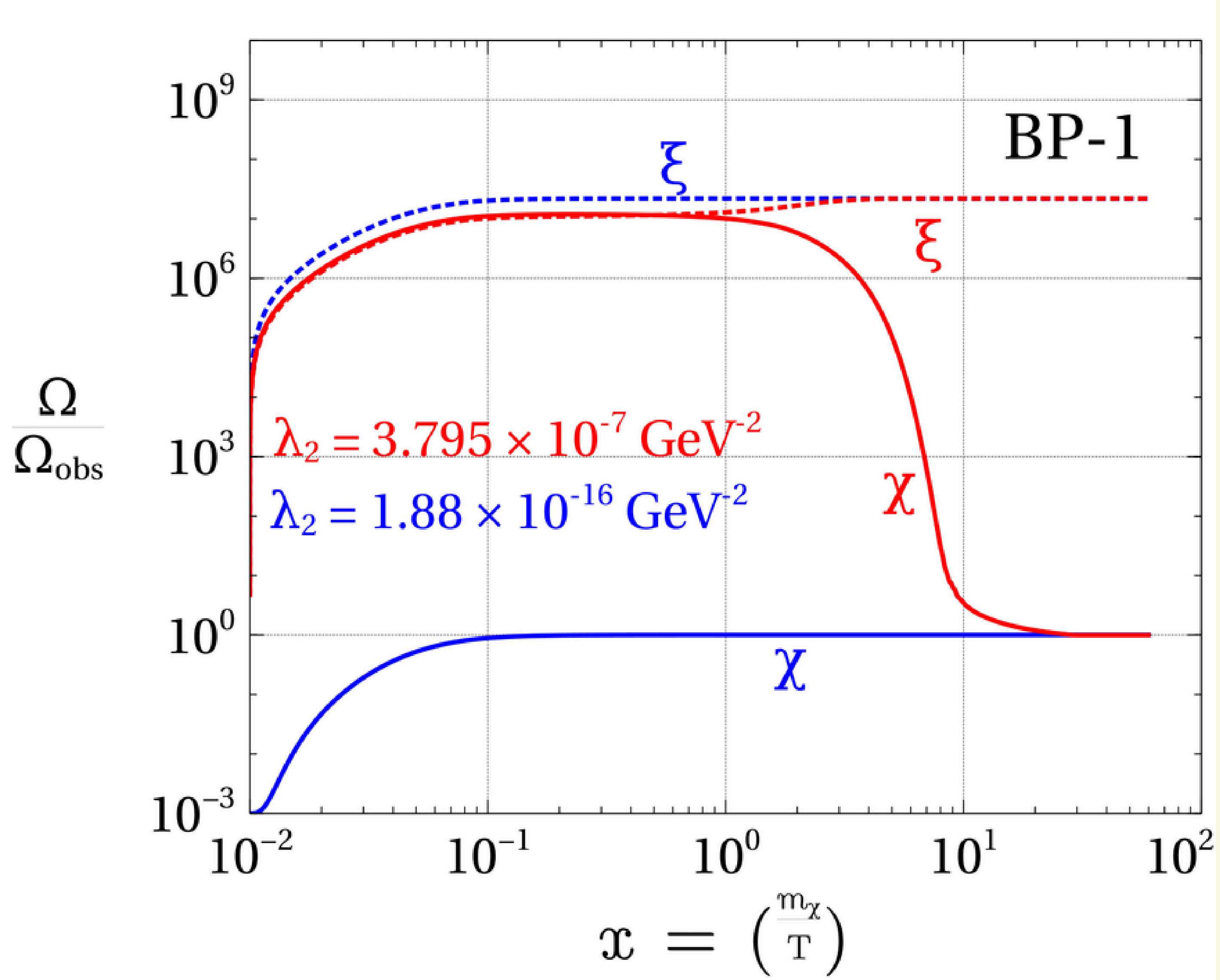

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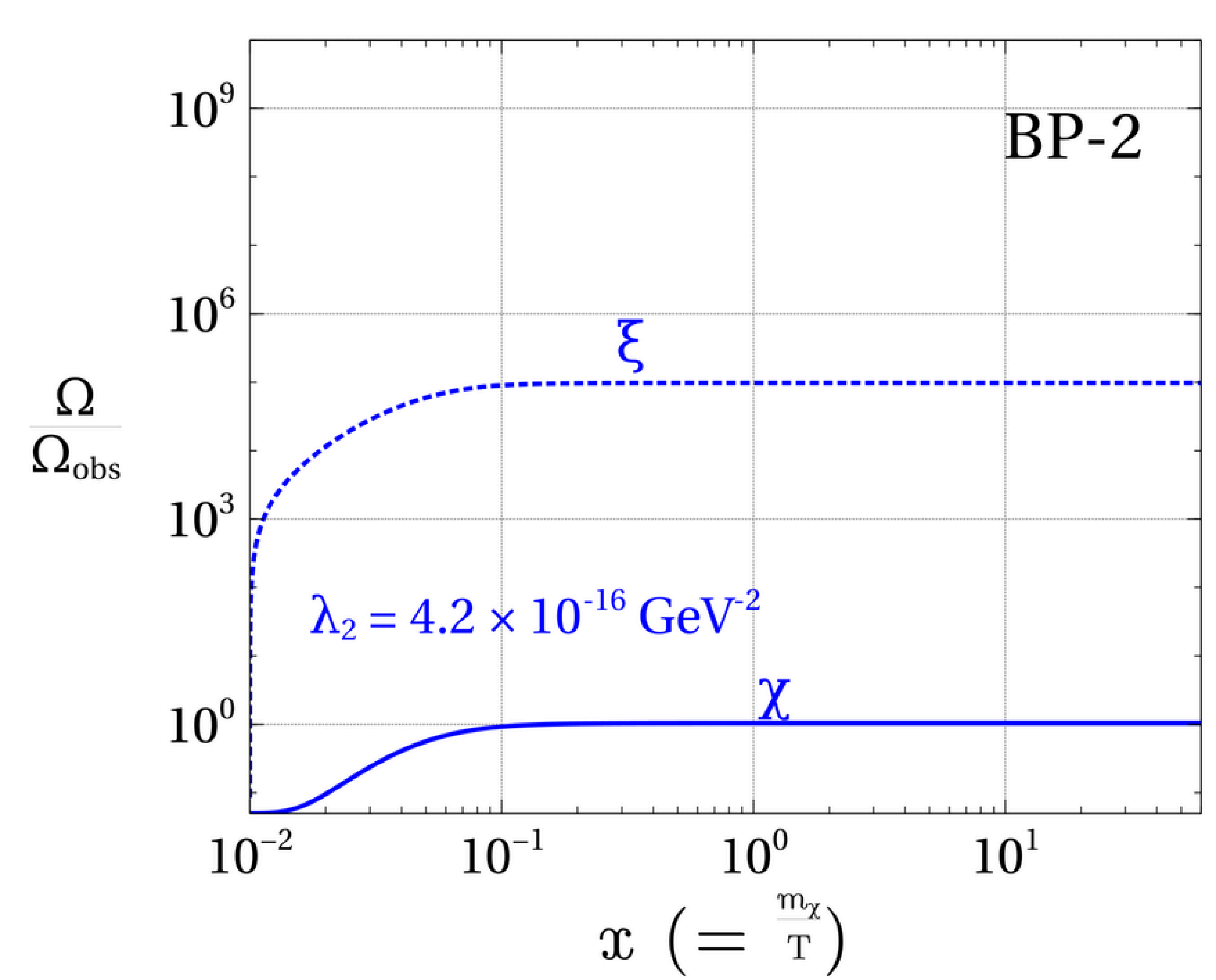
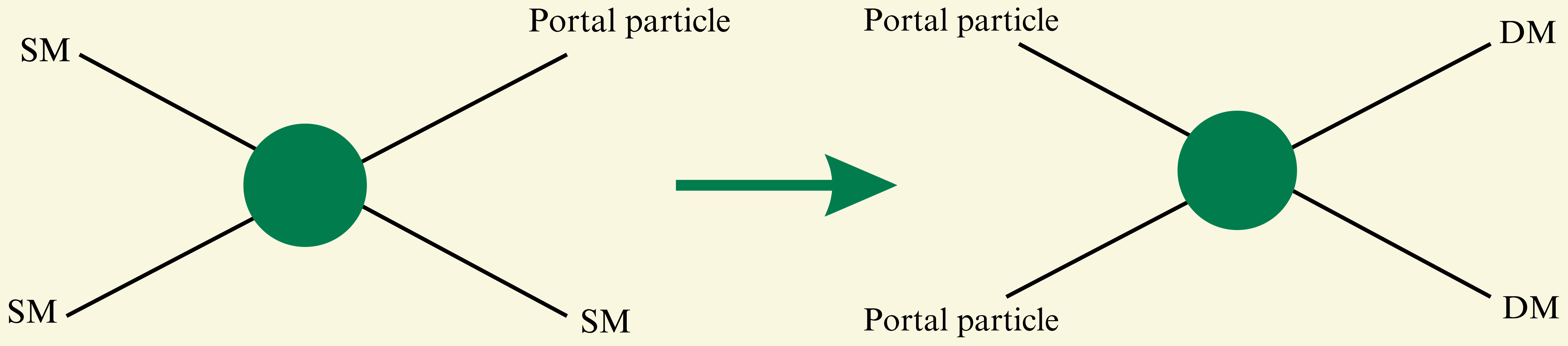
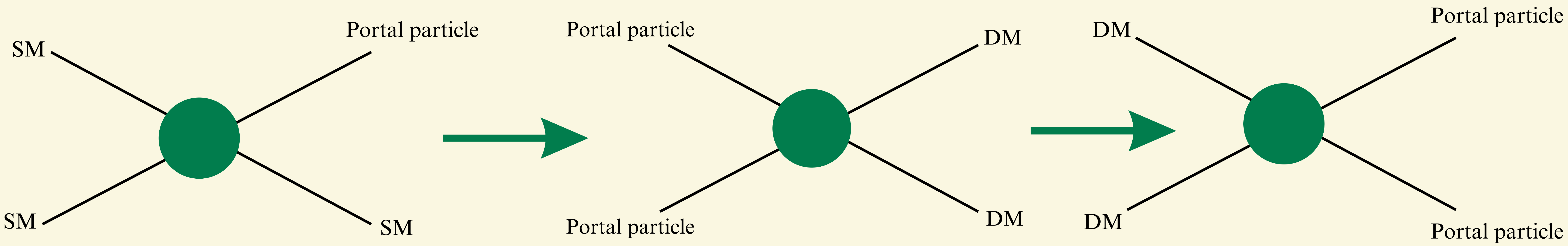


BP2: $\{C_\tau, m_\xi, m_\chi\} = \{10^{-21}\,\mathrm{GeV}^{-2},\ 10\,\mathrm{TeV},\ 11\,\mathrm{TeV}\}$

Summary of Production Processes

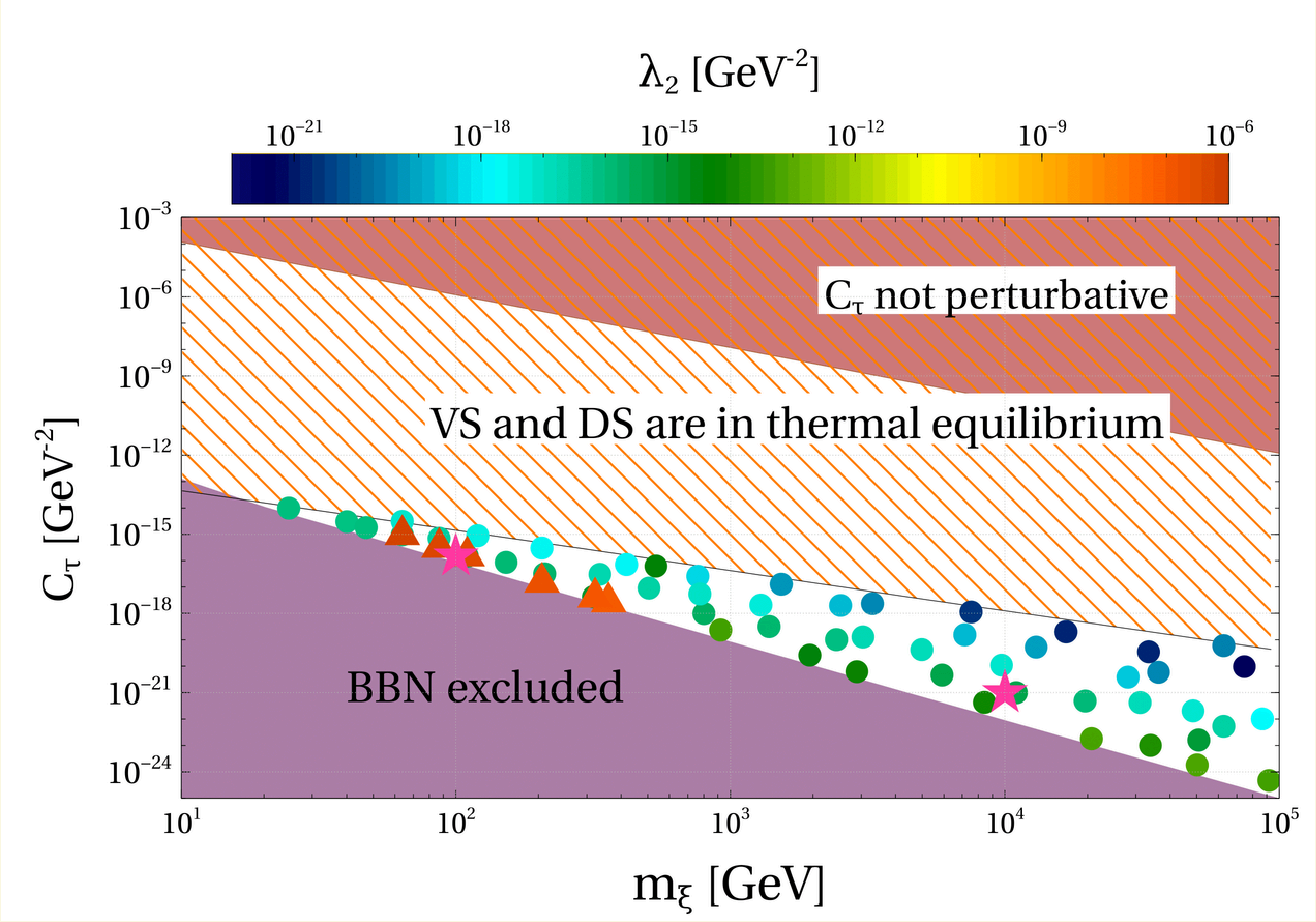


Freeze-in mechanism



Freeze-out mechanism

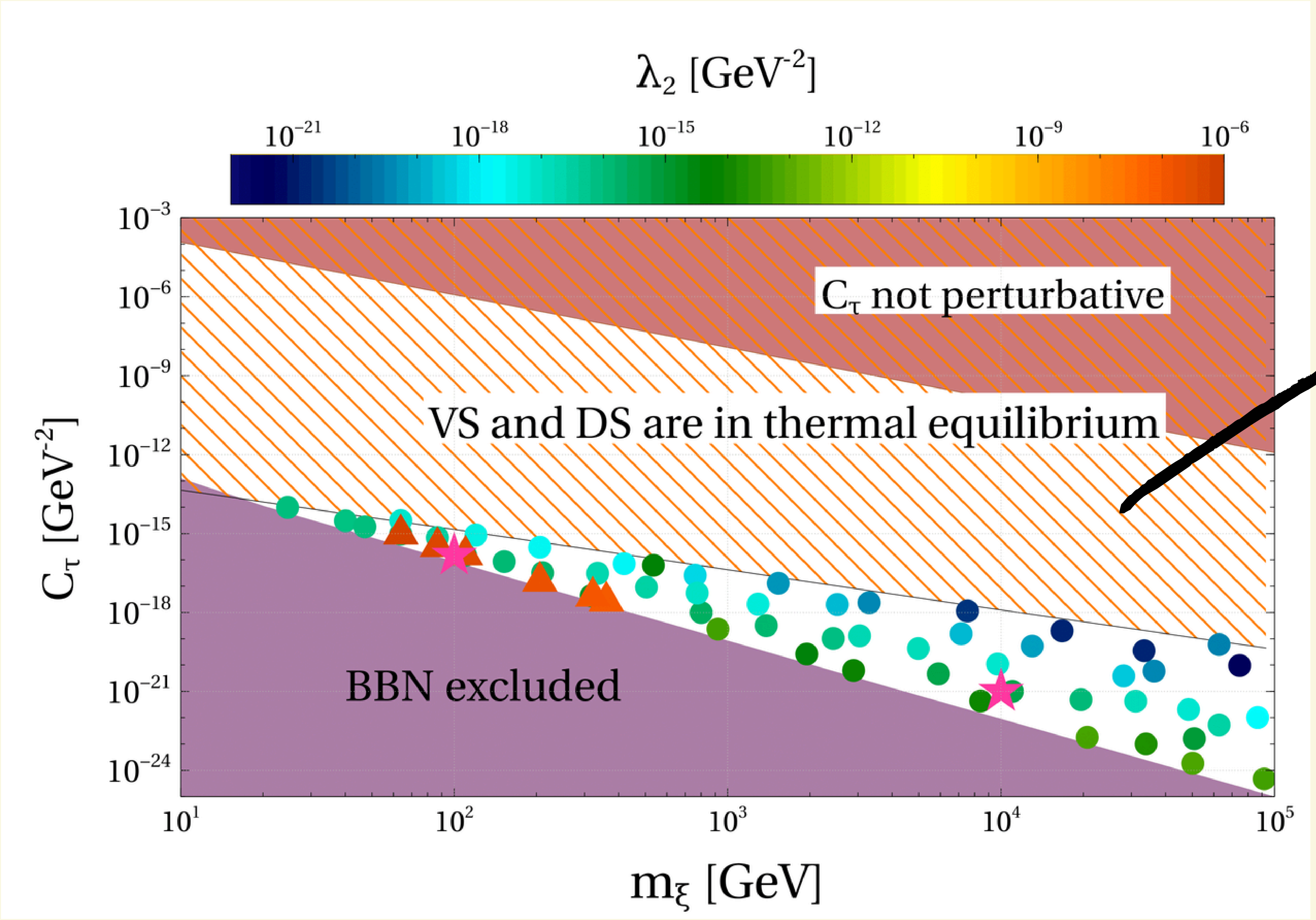
Model Parameter space



Production Mechanisms:

- ● Freeze-in
- ▲ Freeze-out
- ★ Benchmark Point

Model Parameter space



Shaded regions represent where DS and SM bath are in same temperature.

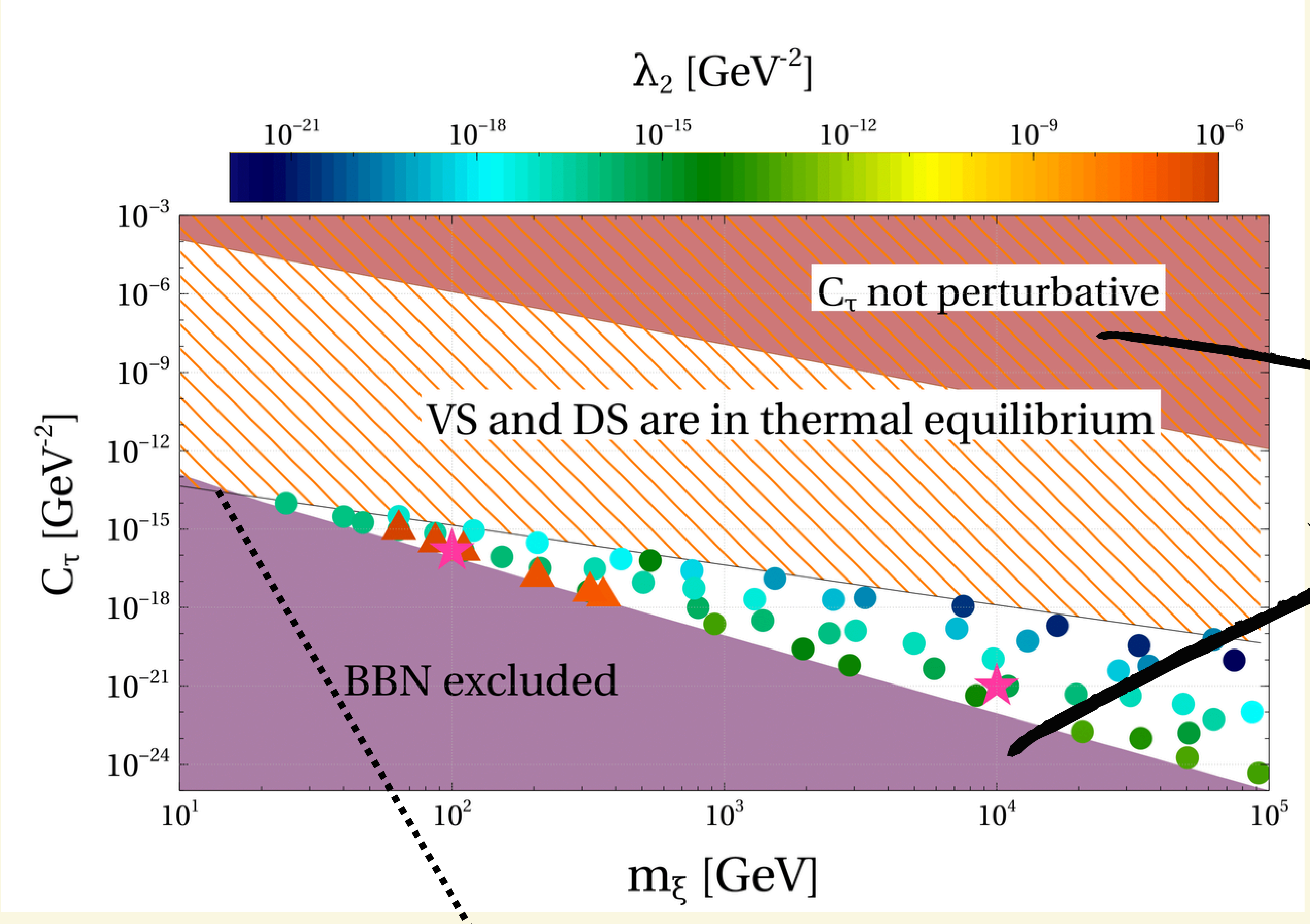
$$\frac{\Gamma_{\mathrm{SM}\to\xi}(T)}{H(T)} \gtrsim 1$$

Check: $T = \Lambda_{\text{cut-off}} = 100 \times m_\chi$

Sufficient condition,

$$m_H, m_{H^\pm} \geq \Lambda$$

Model Parameter space



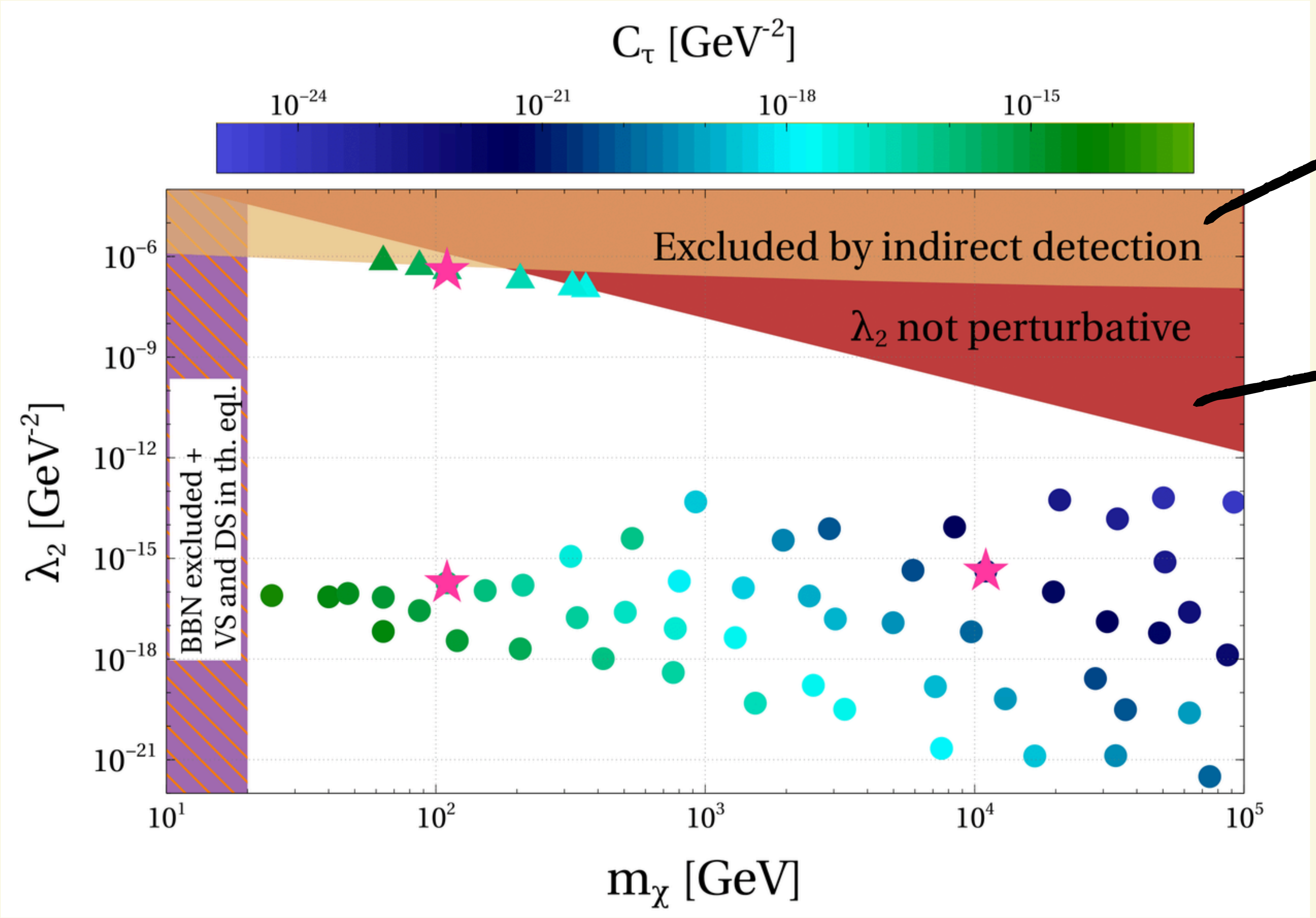
Recap: $C_\tau : \dfrac{y_{1\tau} y_4 (y_5)}{\Lambda^2}$

Perturbativity constraints

ξ must decay before BBN.

$\{20\,\text{GeV},\ 10^{-14}\,\text{GeV}^{-2}\}$

Model Parameter space



Constraints from Fermi-Lat experiment.

Perturbativity constraints

- Due to smallness of λ_2 at high mass of DM only possible production mechanism is Freeze-in.

Conclusion

- We have studied a secluded sector DM in the context of an effective theory.
- Different non-thermal production mechanisms of DM at early Universe originated from SM fileds .
- Freeze-in and freeze-out are possible production mechanisms in this context.
- For large DM mass due to large cut-off scale only possible production mechanism is Freeze-in.
- In the this model $C_\tau \lesssim 10^{-14}\,\mathrm{GeV}^{-2}$ and $m_\chi \lesssim 20\,\mathrm{GeV}$ region is disfavored .

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