Confronting Dark Matter with Dirac Neutrinos

JCAP2021, PRD2023
In collaboration with
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KIAS KOREA INSTITUTE FOR ADVANCED STUDY

- The existence of dark matter, neutrino mass, the nature of neutrinos, matter-antimatter asymmetry.... are the unsolved puzzles of nature.

Dirac or Majorana?

Talk by Yoshiki

- No positive signal so far in $0\nu\beta\beta$ experiments.

Dirac neutrinos?
Not sure!

Let’s say, Yes!

What are the minimal requirements?

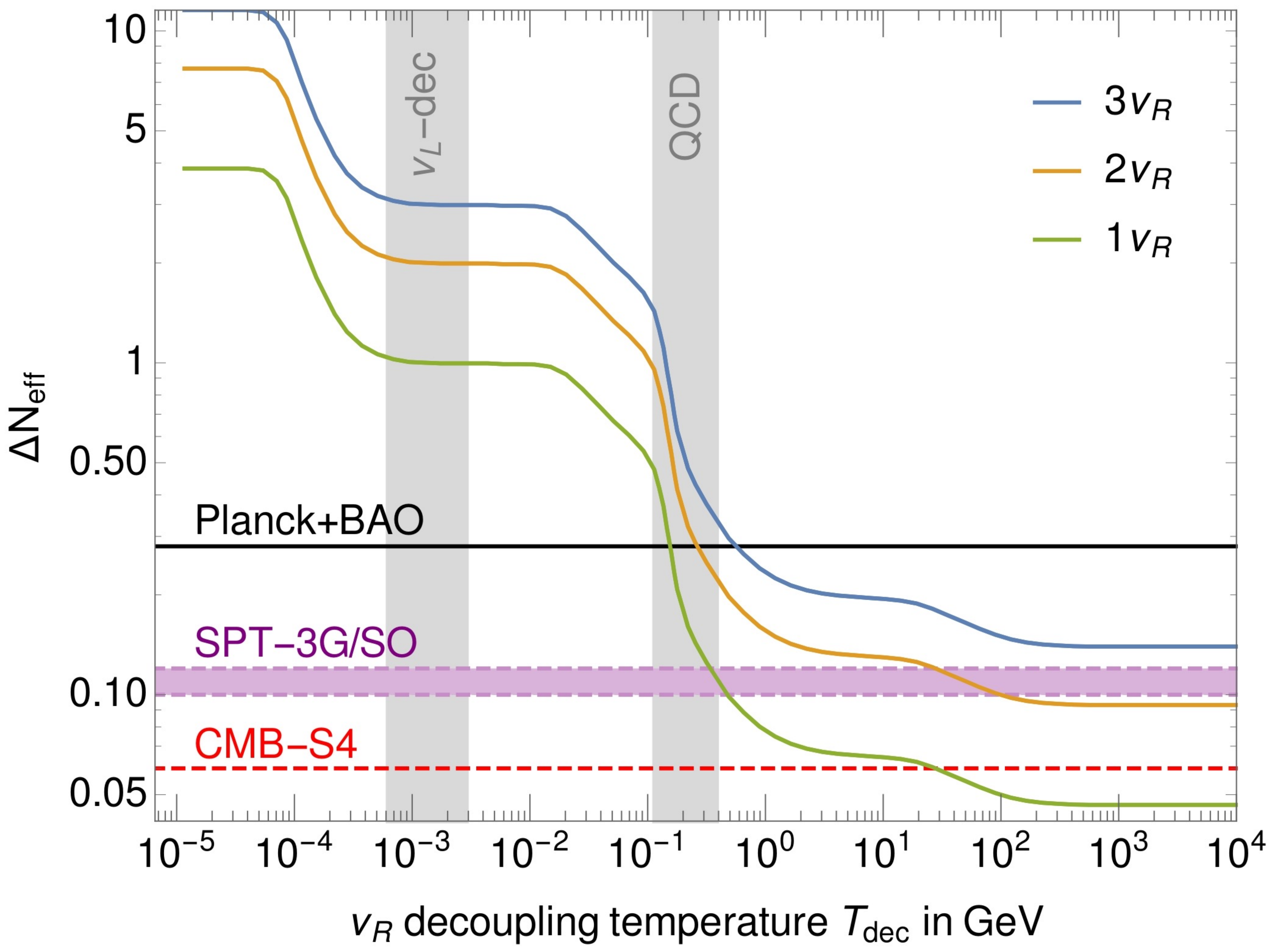
Motivation:

- Like other charged fermions, there will be ν_R as light as ν_L.
- If ν mass is generated via SM-like Higgs through $y_H \overline{L} \tilde{H} \nu_R$, then $y_H \approx 10^{-12}$.

Difficult to test.

- Tiny ν masses via Dirac seesaw (Logan et. al.2009, Ma et. al.2015, Valle et. al.2016, Baek2019 …) and loop induced processes (Babu et. al.1989, Ma et. al.2012 …)
- ν_R can act as dark radiation and be important from cosmological point of view.
- Effective number of relativistic DOF: $N_{\rm eff} = \dfrac{\rho_{rad} - \rho_\gamma}{\rho_{\nu_L}}$
- $N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ (PLANCK 2018);$N_{\rm eff}^{SM} = 3.046$; $\Delta N_{\rm eff} = 0.285$ at 2σ.

- ν_R can be thermalised or it can be produced from the non-thermally just like DM particles.
- In both cases, it will contribute to the total radiation energy density.
- If thermalised, $\Delta N_{\rm eff} = N_{\nu_R}\left(\frac{g_{*s}(T_{\nu_L})}{g_{*s}(T_{\nu_R})}\right)^{4/3}$
- If, it is produced non-thermally, the amount depends on the particular process.
- For example, from SM-like Higgs via $y_H \approx 10^{-12}$, $\Delta N_{\rm eff} = 7.5 \times 10^{-12}$ **Luo, Rodejohann and Xu, 2021**
- **What if the production of DM and ν_R are connected?**



Abazajian and Heeck 2019

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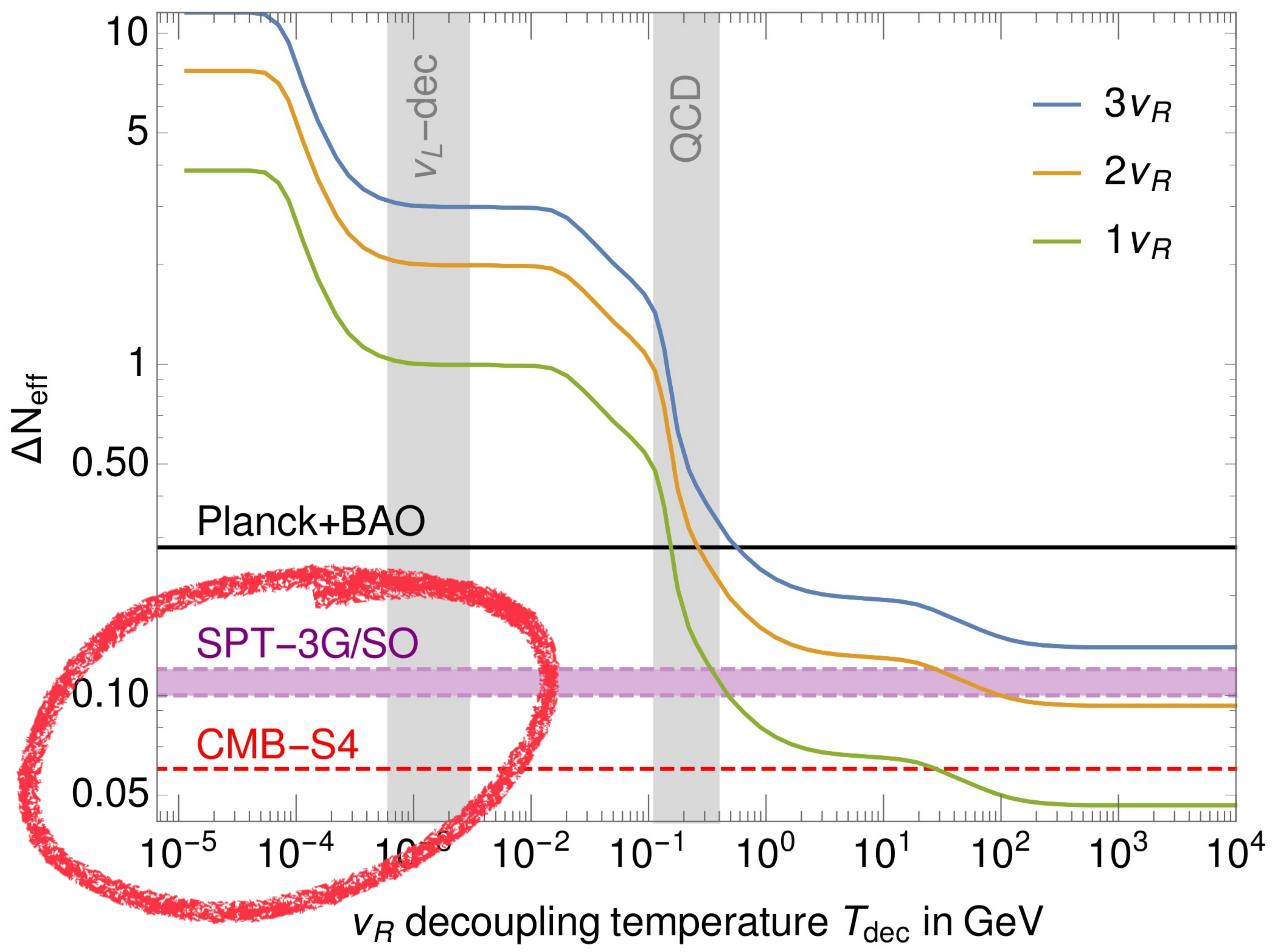


Abazajian and Heeck 2019

SM singlet scalar (ϕ)

SM singlet ν_R

The dark matter (ψ)

Particles	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$\mathbb{Z}_4$
ℓ_L^α	$(1, 2, -\frac{1}{2})$	i
e_R^α	$(1, 1, -1)$	i
ν_R^α	$(1, 1, 0)$	i
ψ	$(1, 1, 0)$	-1
ϕ	$(1, 1, 0)$	i

SM singlet scalar (ϕ)

SM singlet ν_R

The dark matter (ψ)

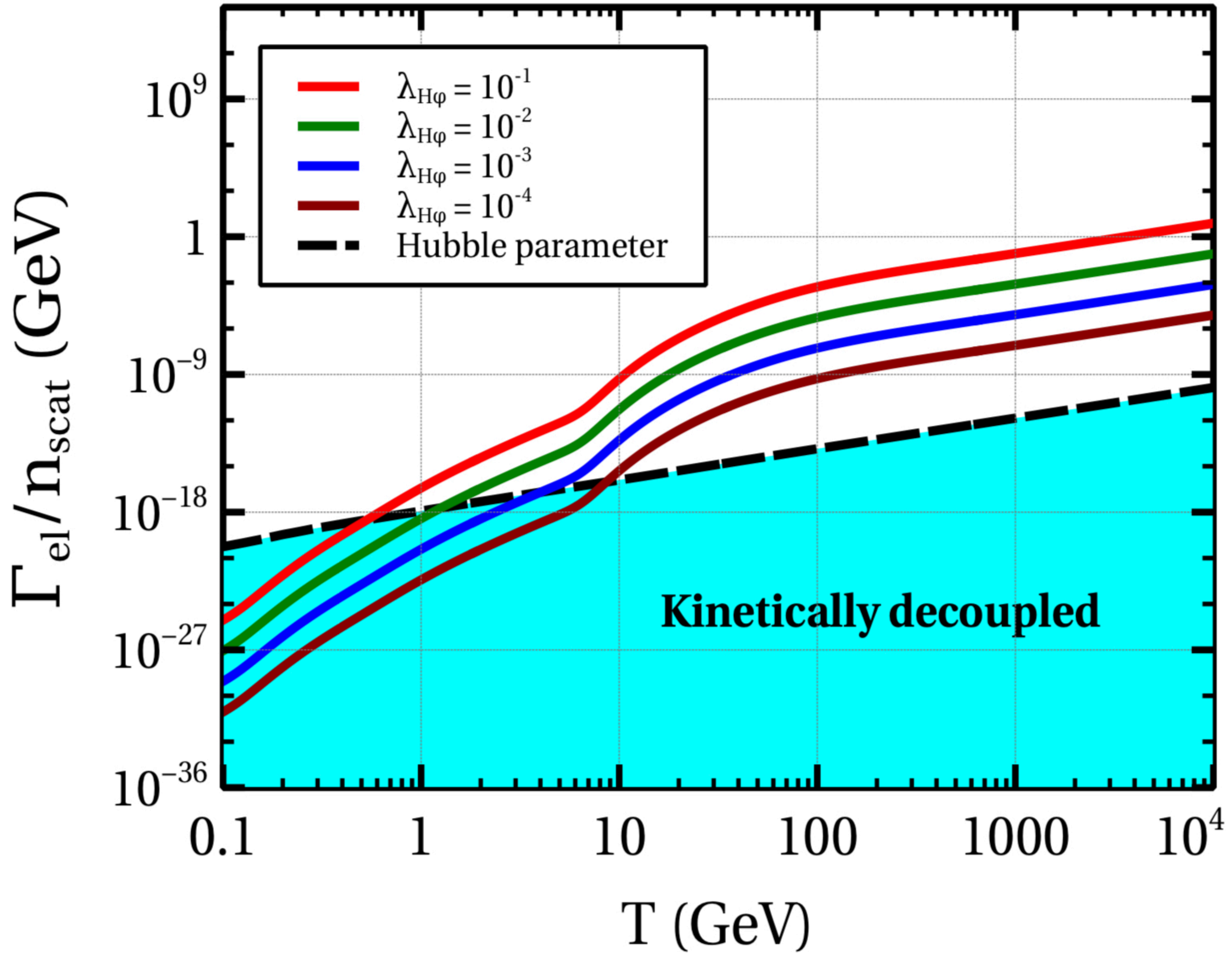
$$\mathcal{L}_{\text{fermion}} = i\,\overline{\nu}_R\,\gamma^\mu\,\partial_\mu\,\nu_R + i\,\overline{\psi}\,\gamma^\mu\,\partial_\mu\,\psi - m_\psi\overline{\psi}\psi - \left(y_H\,\overline{\ell}\,\tilde{H}\,\nu_R + y_\phi\,\overline{\psi}\,\nu_R\,\phi + \text{h.c.}\right) .$$

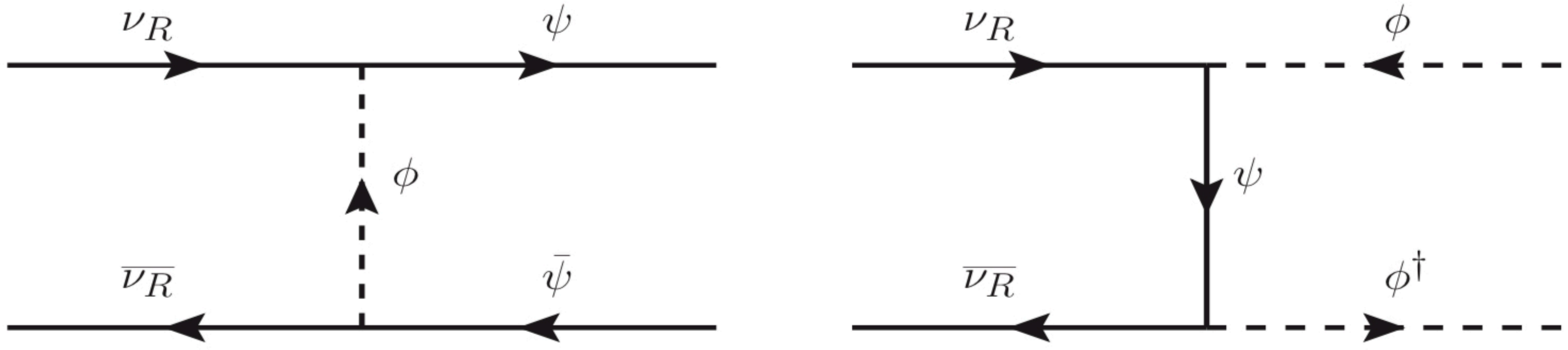
Similarly, the scalar Lagrangian of the model is

$$\begin{aligned}\mathcal{L}_{\text{scalar}} \;=\; & (D_{H\mu}H)^\dagger(D_H^\mu H) + (\partial_\mu\phi)^\dagger(\partial^\mu\phi) - \Big[-\mu_H^2\,(H^\dagger H) + \lambda_H\,(H^\dagger H)^2 + \mu_\phi^2\,(\phi^\dagger\phi) + \\ & \lambda_\phi\,(\phi^\dagger\phi)^2 + \lambda_{H\phi}\,(H^\dagger H)(\phi^\dagger\phi) + \lambda'_\phi\,\left(\phi^4 + (\phi^\dagger)^4\right)\Big] ,\end{aligned}$$

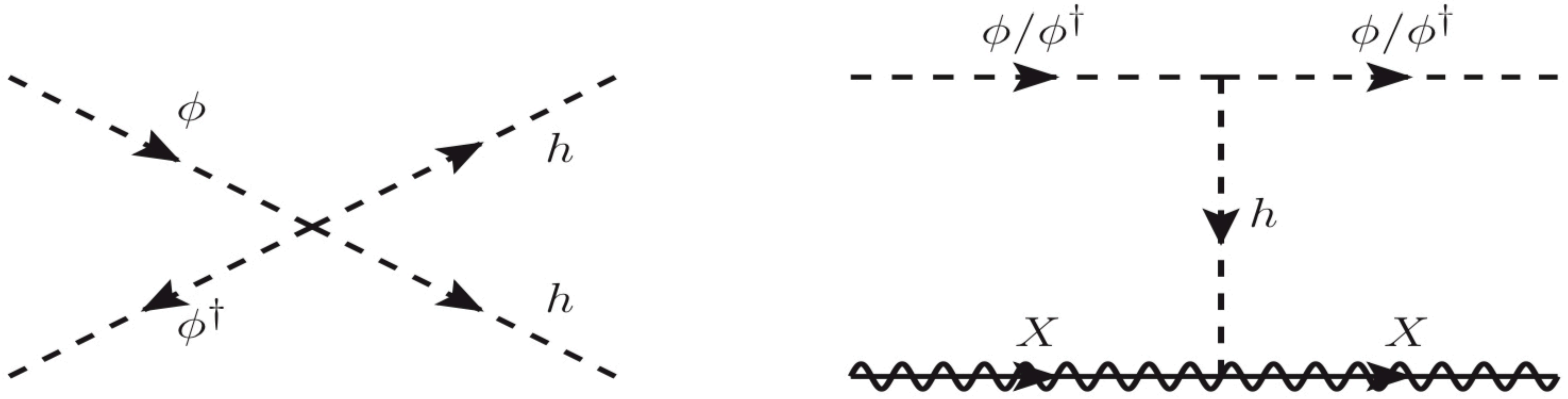
Decoupling from the thermal bath:

- DM and ν_R both are connected to the SM through a singlet scalar ϕ.





(a) Scatterings responsible for thermalisation of ν_R within the dark sector.



(b) Thermalisation processes of ϕ with the SM bath.

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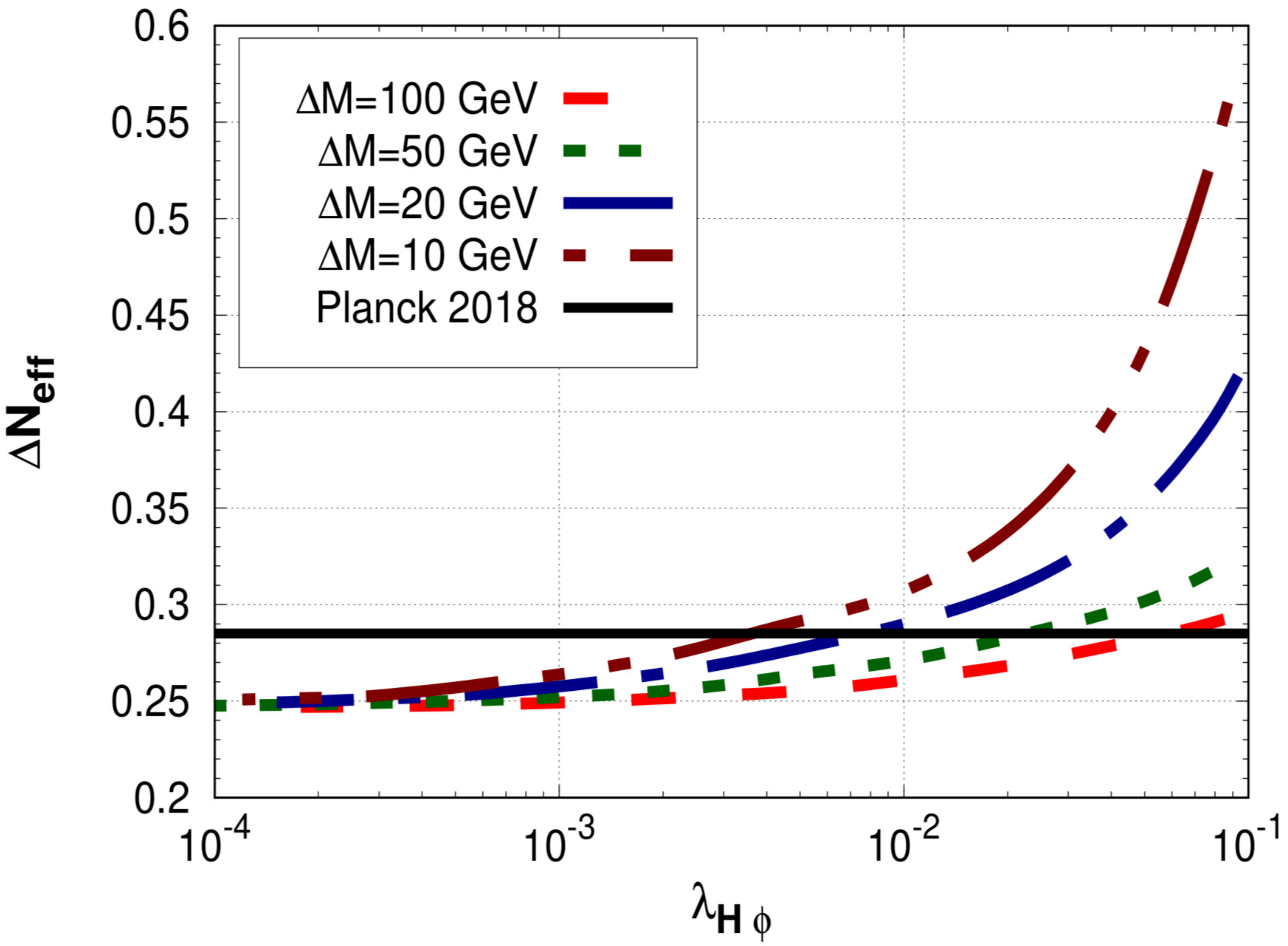

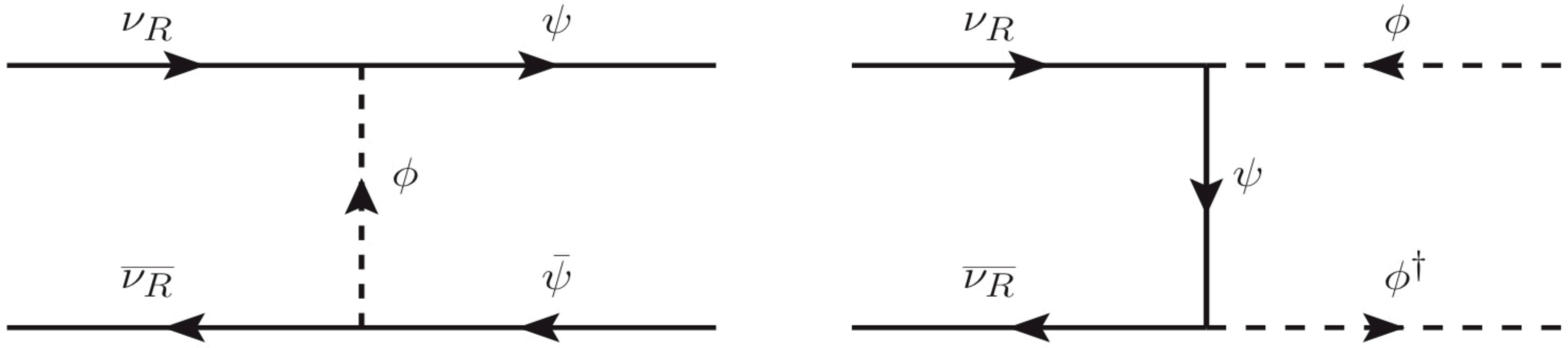

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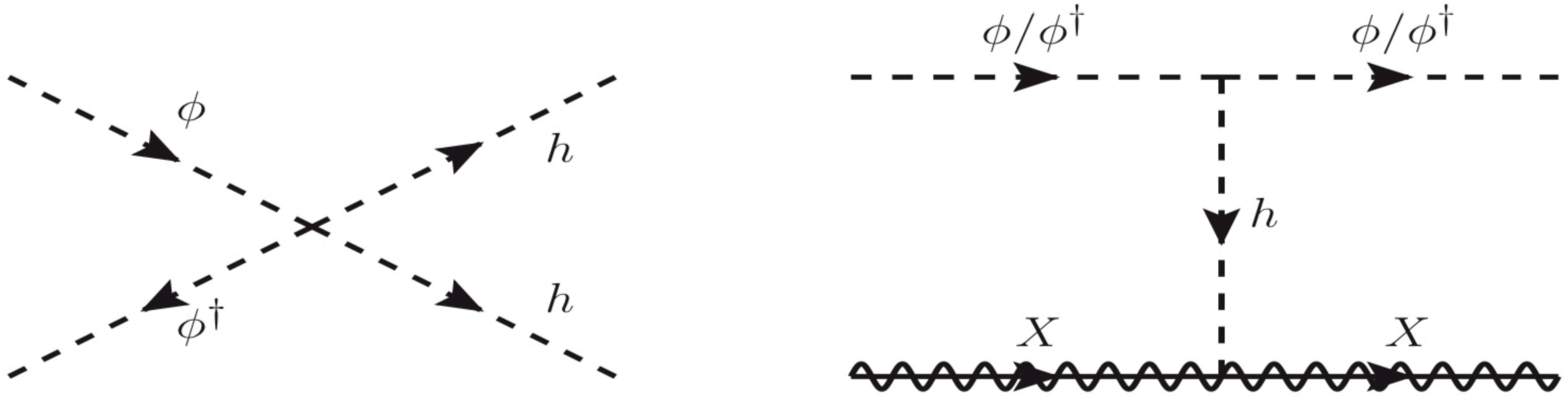

(b) Thermalisation processes of ϕ with the SM bath.

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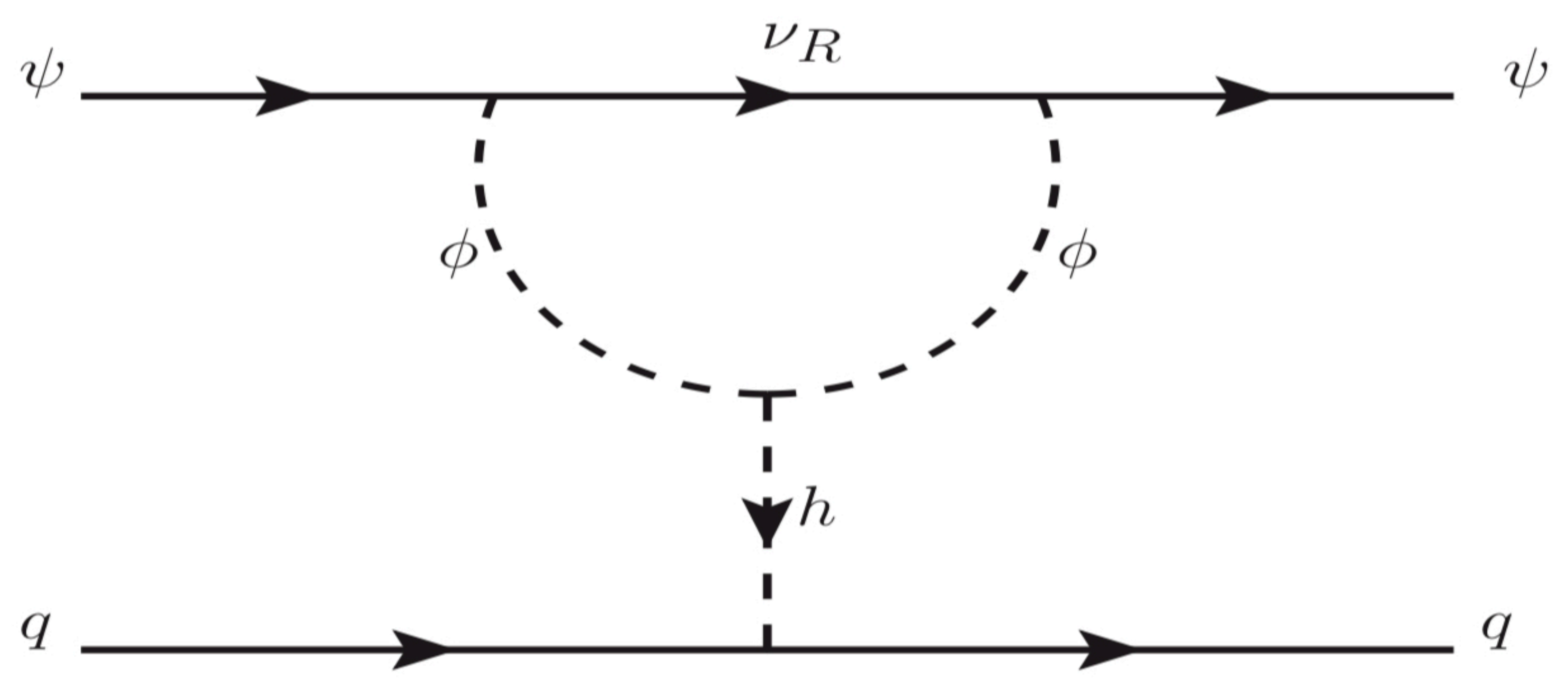
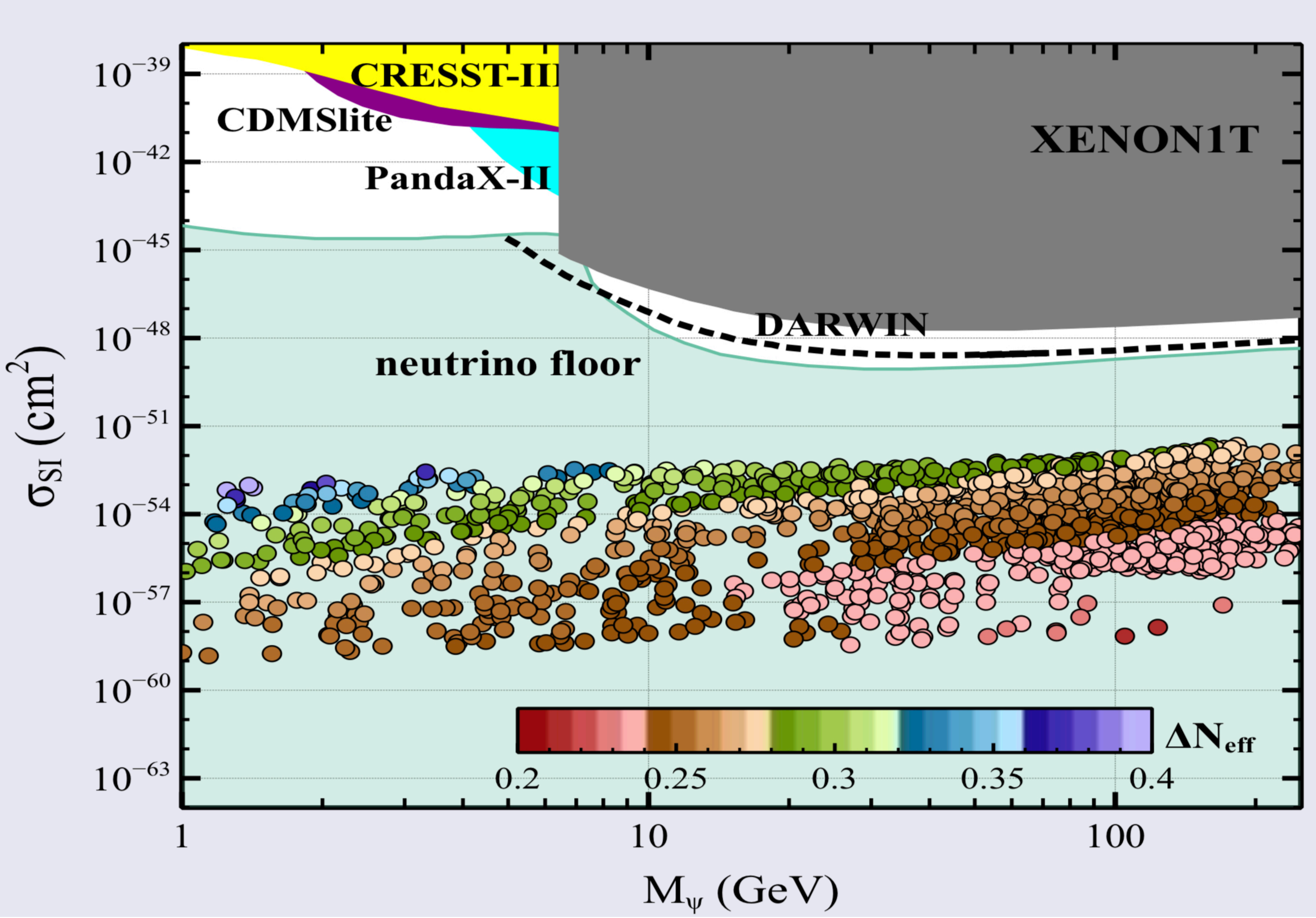
Indirect probe through ΔN_{eff}:

- $\psi\psi h$ vertex generates at one loop level. → σ_{SI} is suppressed.
- No possibility to detect in direct detection experiments.
- However, measurement of $\Delta N_{\rm eff}$ opens the possibility of probing such scenarios.
- Future CMB experiments will probe such model severely.





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What if y_ϕ is very small?

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- What is DM and ν_R are connected through tiny coupling: $y_\phi \overline{\psi} \phi \nu_R$

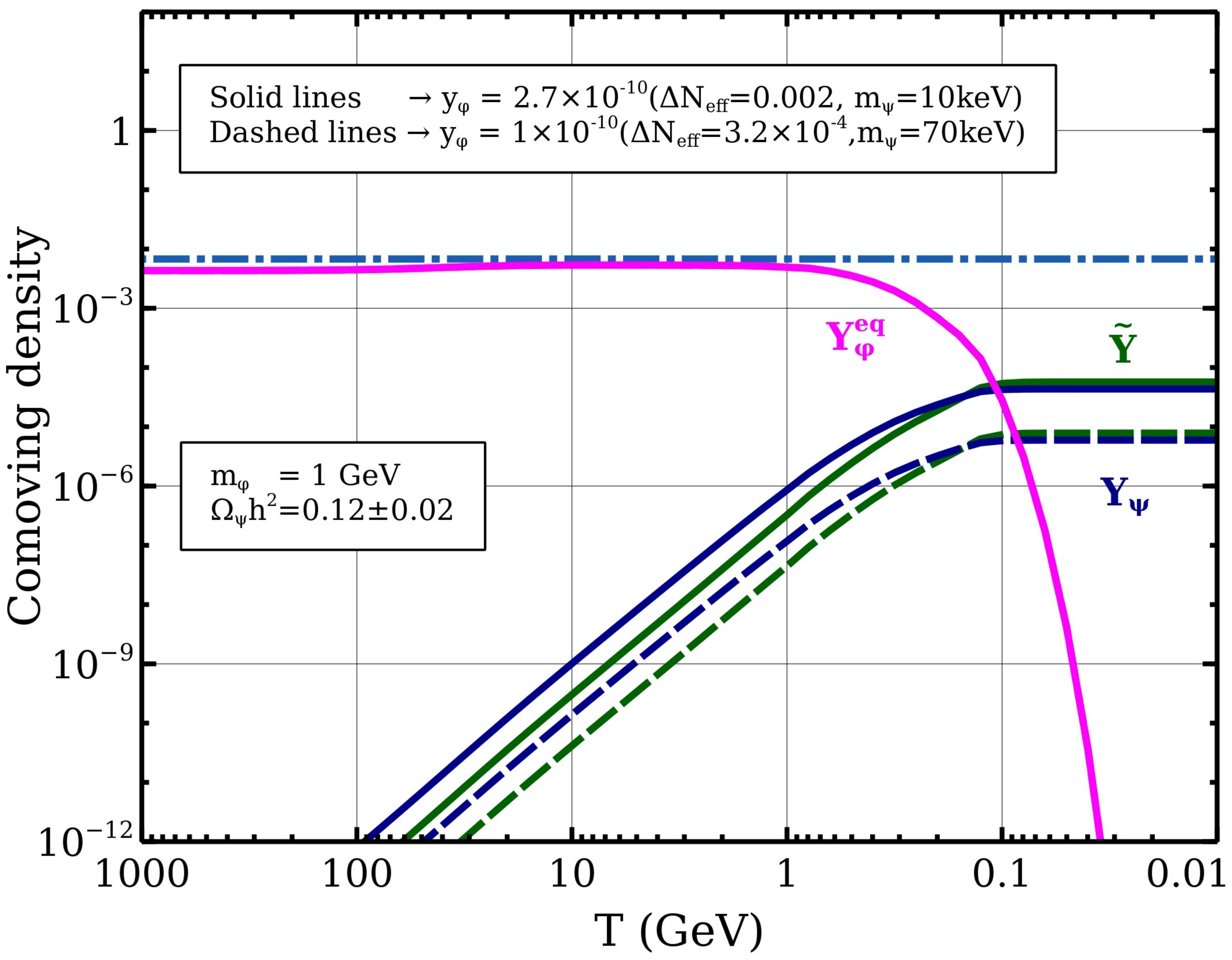
- Then there can be three different situations depending on $\lambda_{H\phi}(H^\dagger H)(\phi^\dagger \phi)$:

    - Case I: ϕ decays to DM and ν_R from the thermal bath.

    - Case II: ϕ freezes out from the thermal bath and then decays.

    - Case III: ϕ was never in the thermal bath but produced non-thermally from Higgs decay.

Case I: ϕ decays to DM and ν_R from the thermal bath.



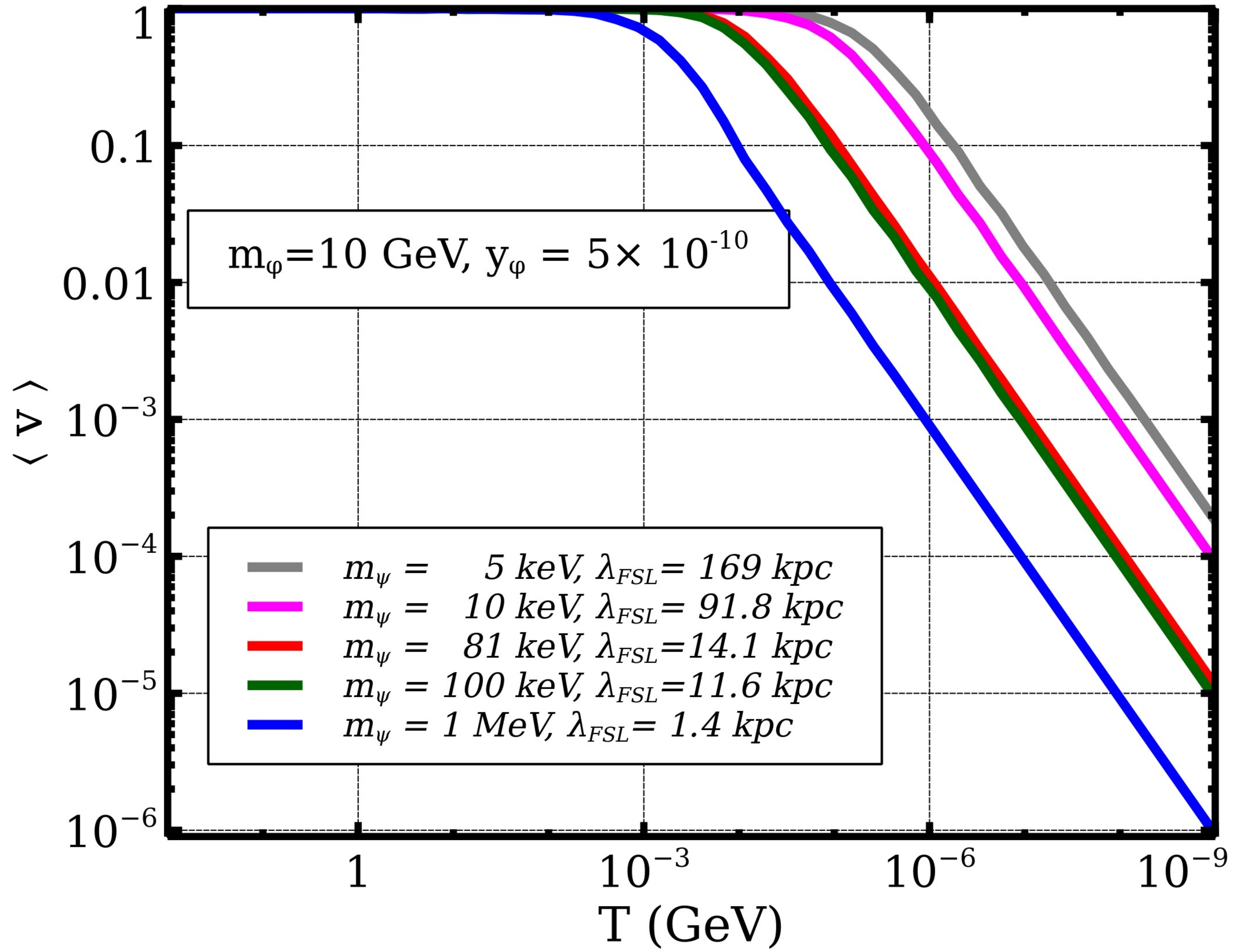


TABLE I: Table for case I

Parameters			$\Omega_{\rm DM}h^2$	$\Delta N_{\rm eff}$	FSL(Mpc)
m_ϕ(GeV)	y_ϕ	m_ψ(keV)			
10	5×10^{-10}	81	0.12	1.6×10^{-4}	0.0141
50	5×10^{-10}	440	0.12	2.9×10^{-5}	0.0030
50	10^{-9}	110	0.12	1.2×10^{-4}	0.0105

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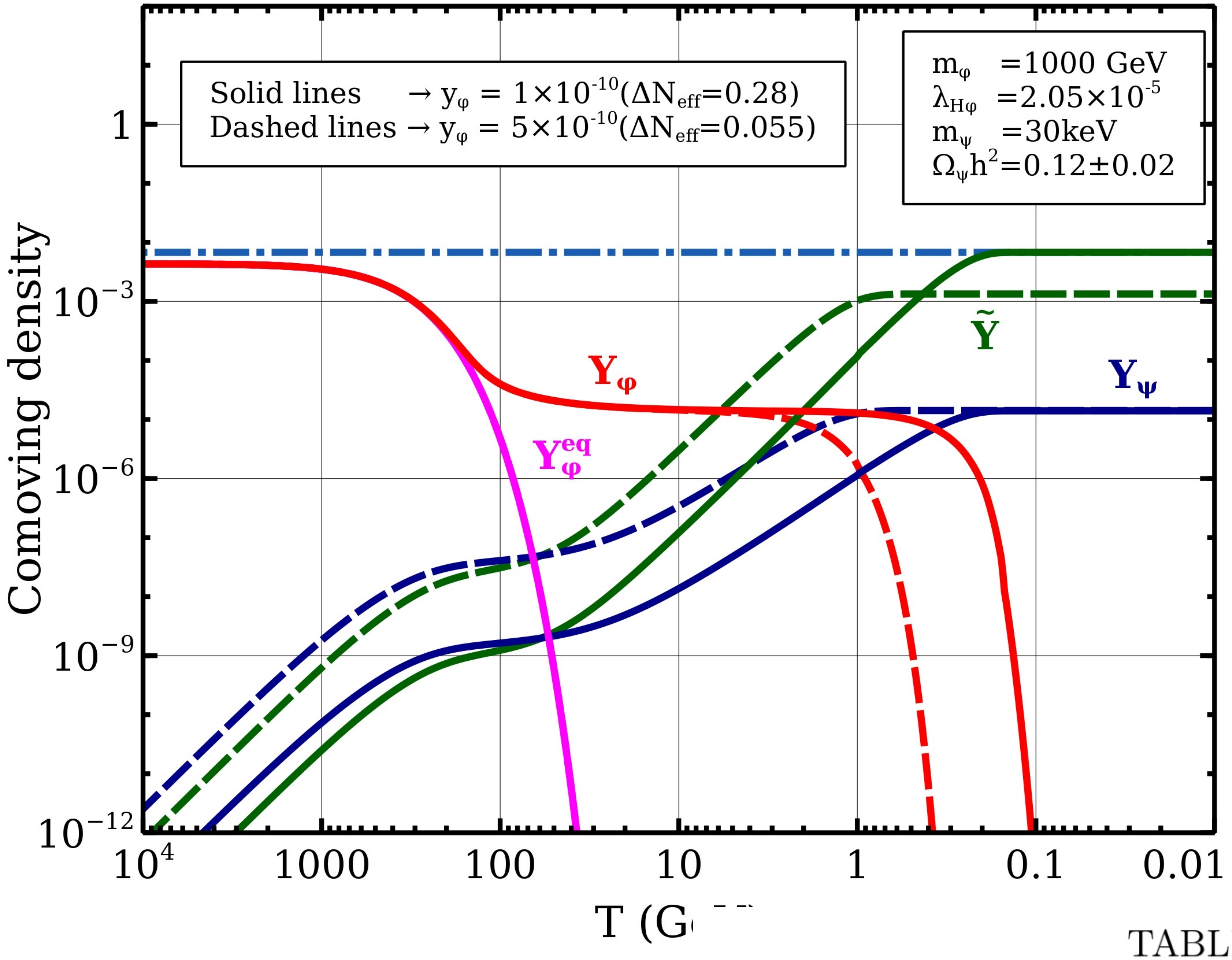
Case II: ϕ freezes out from the thermal bath and then decays.



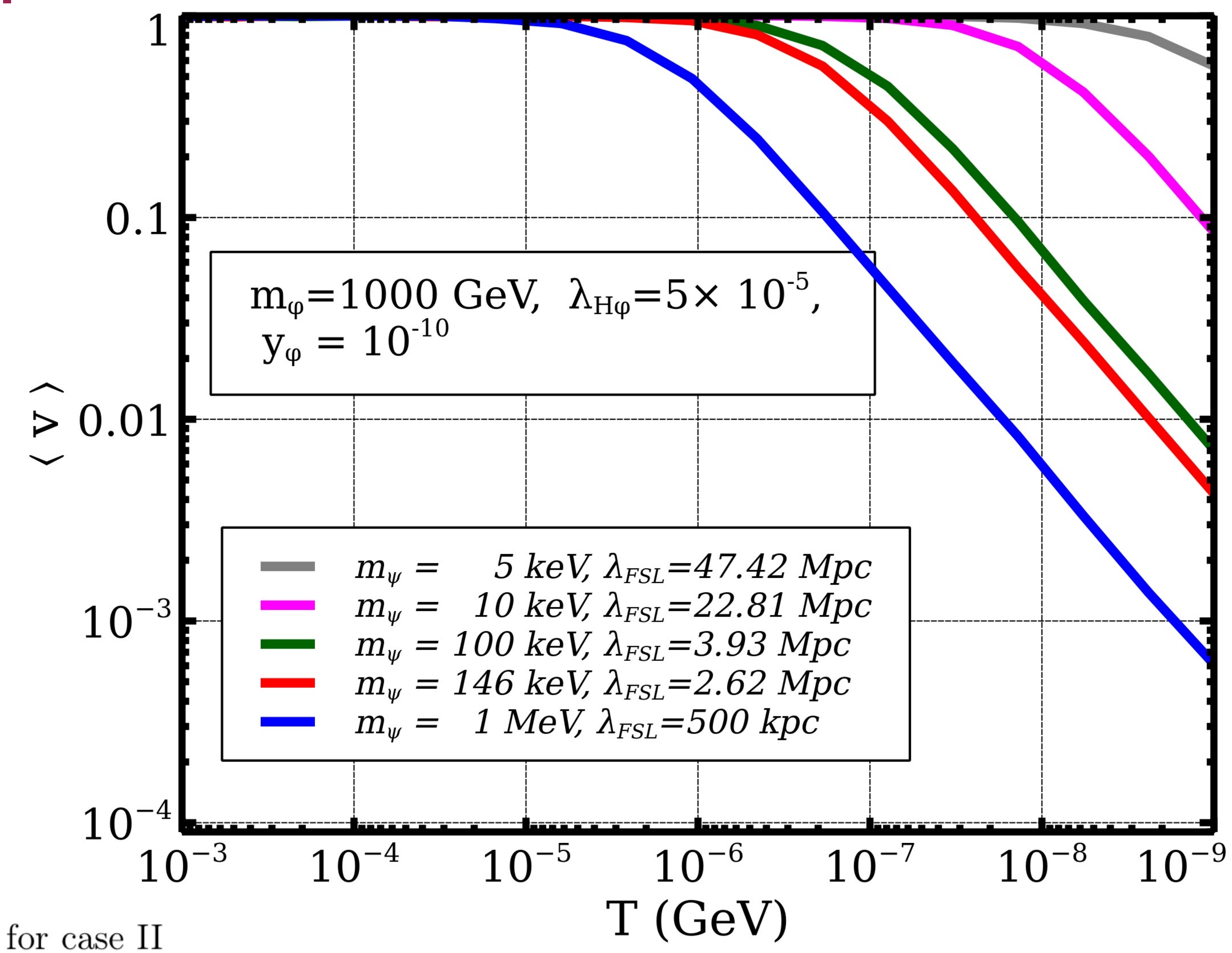
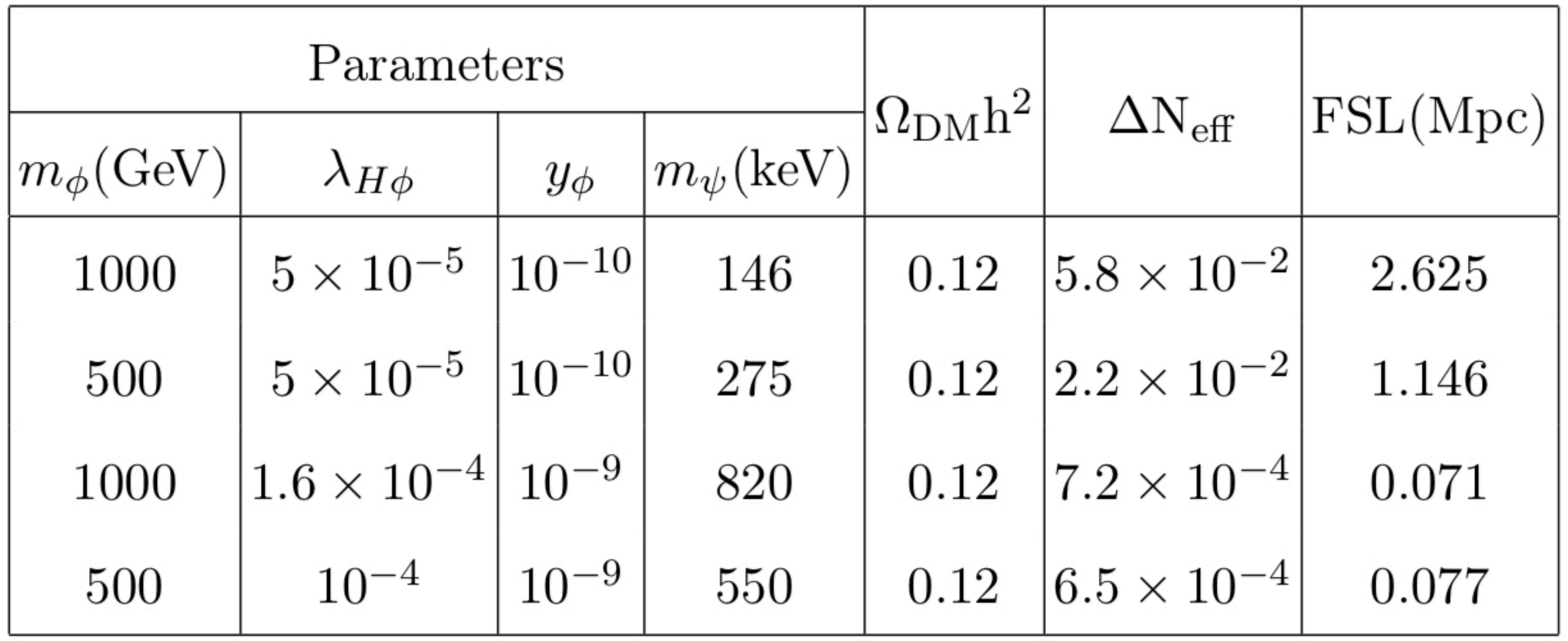


TABLE II: Table for case II



Parameters				$\Omega_{\rm DM}h^2$	$\Delta N_{\rm eff}$	FSL(Mpc)
m_ϕ(GeV)	$\lambda_{H\phi}$	y_ϕ	m_ψ(keV)			
1000	5×10^{-5}	10^{-10}	146	0.12	5.8×10^{-2}	2.625
500	5×10^{-5}	10^{-10}	275	0.12	2.2×10^{-2}	1.146
1000	1.6×10^{-4}	10^{-9}	820	0.12	7.2×10^{-4}	0.071
500	10^{-4}	10^{-9}	550	0.12	6.5×10^{-4}	0.077

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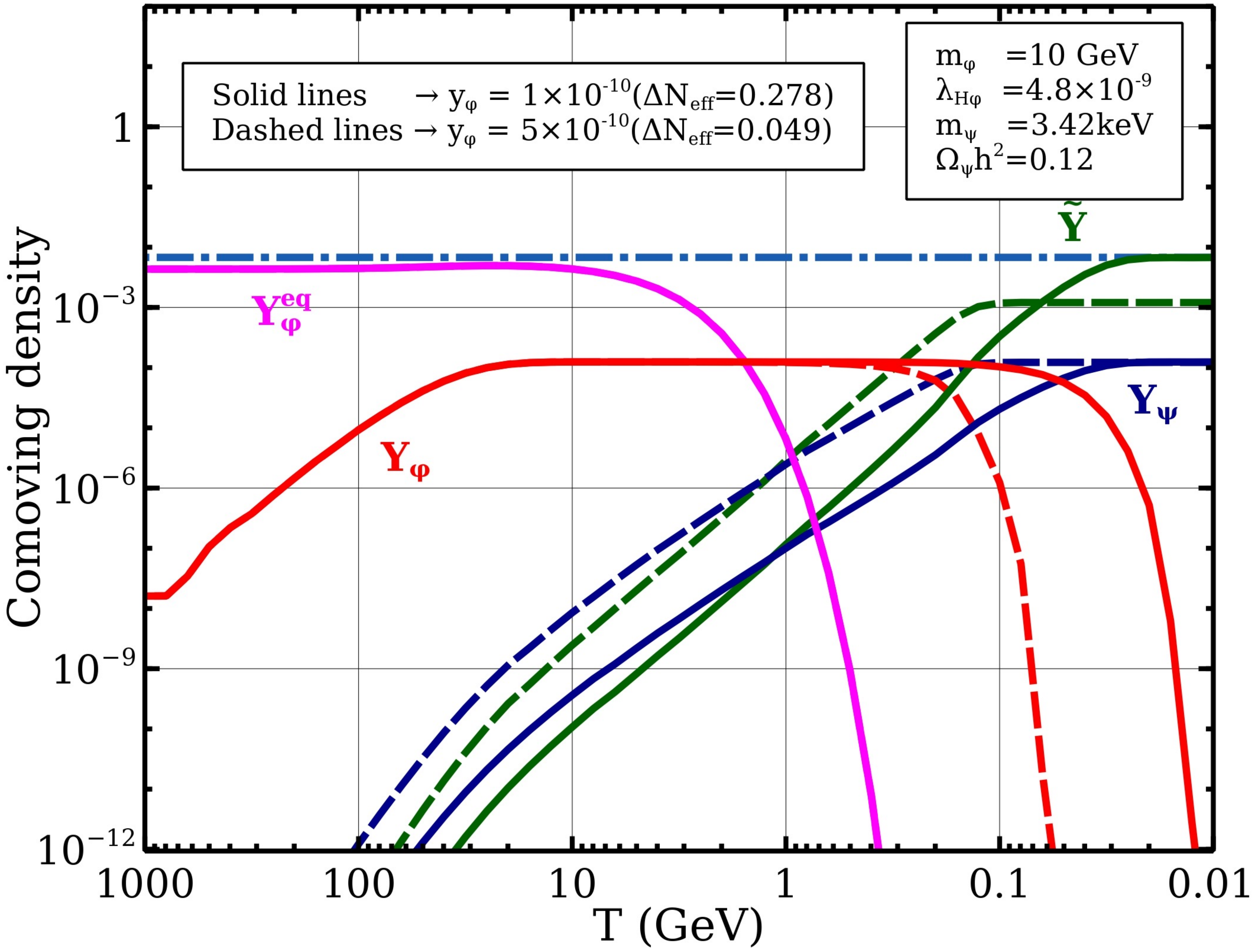
Case III: ϕ was never in the thermal bath but produced non-thermally from Higgs decay.



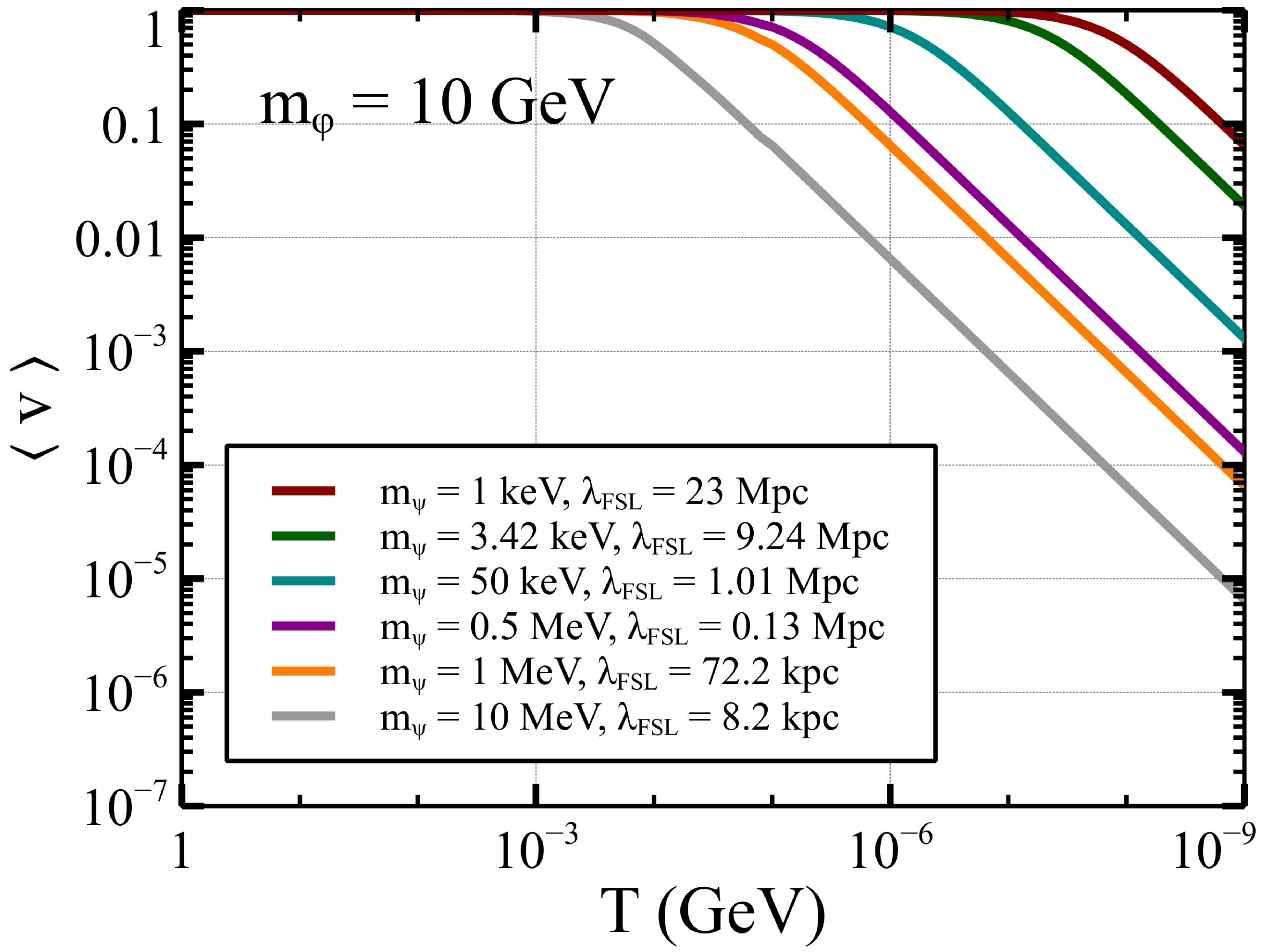


TABLE III: Table for case III

Parameters				$\Omega_{DM}h^2$	ΔN_{eff}	FSL(Mpc)
m_ϕ(GeV)	$\lambda_{H\phi}$	y_ϕ	m_ψ(keV)			
10	4.8×10^{-9}	10^{-10}	3.42	0.12	2.7×10^{-1}	9.42
50	4.8×10^{-9}	10^{-10}	5.63	0.12	3.6×10^{-1}	15.5

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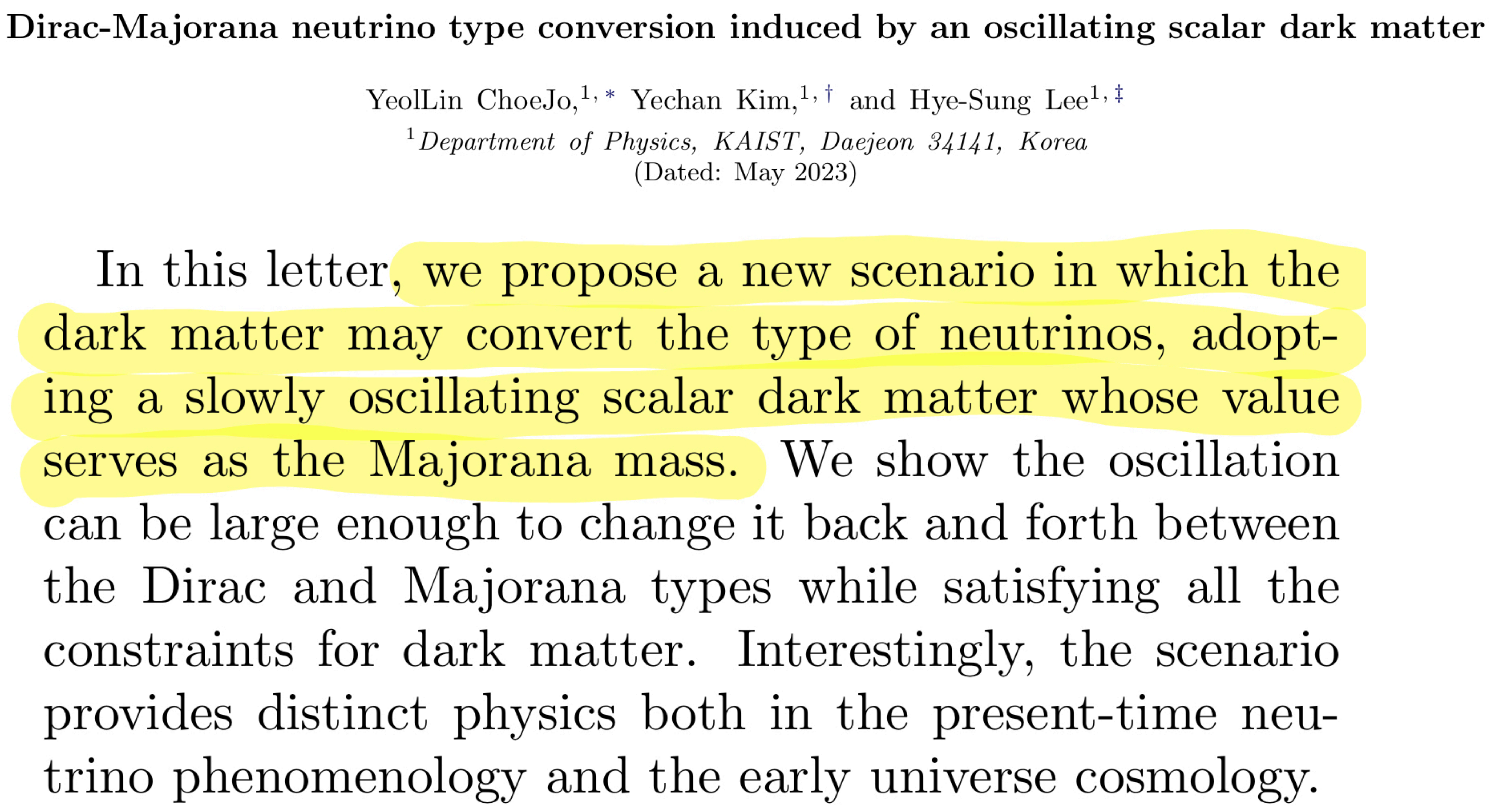
Conclusion

- We have studied the possibility where the nature of neutrinos and DM are connected and can be have observational prospects at CMB experiments.
- Discussed the possibility where DM and ν_R both are connected to the SM through a singlet scalar ϕ.
- We have discussed both thermal and non-thermal productions.
- Showed that $\Delta N_{\rm eff}$ and the FSL of DM can exclude some part of the parameter space of the model.
- Depending upon the choice of the parameters, FSL can rule out DM all the way up to a few hundred keV.

Note:



Dirac-Majorana neutrino type conversion induced by an oscillating scalar dark matter

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[1] *Department of Physics, KAIST, Daejeon 34141, Korea*
(Dated: May 2023)

In this letter, we propose a new scenario in which the dark matter may convert the type of neutrinos, adopting a slowly oscillating scalar dark matter whose value serves as the Majorana mass. We show the oscillation can be large enough to change it back and forth between the Dirac and Majorana types while satisfying all the constraints for dark matter. Interestingly, the scenario provides distinct physics both in the present-time neutrino phenomenology and the early universe cosmology.

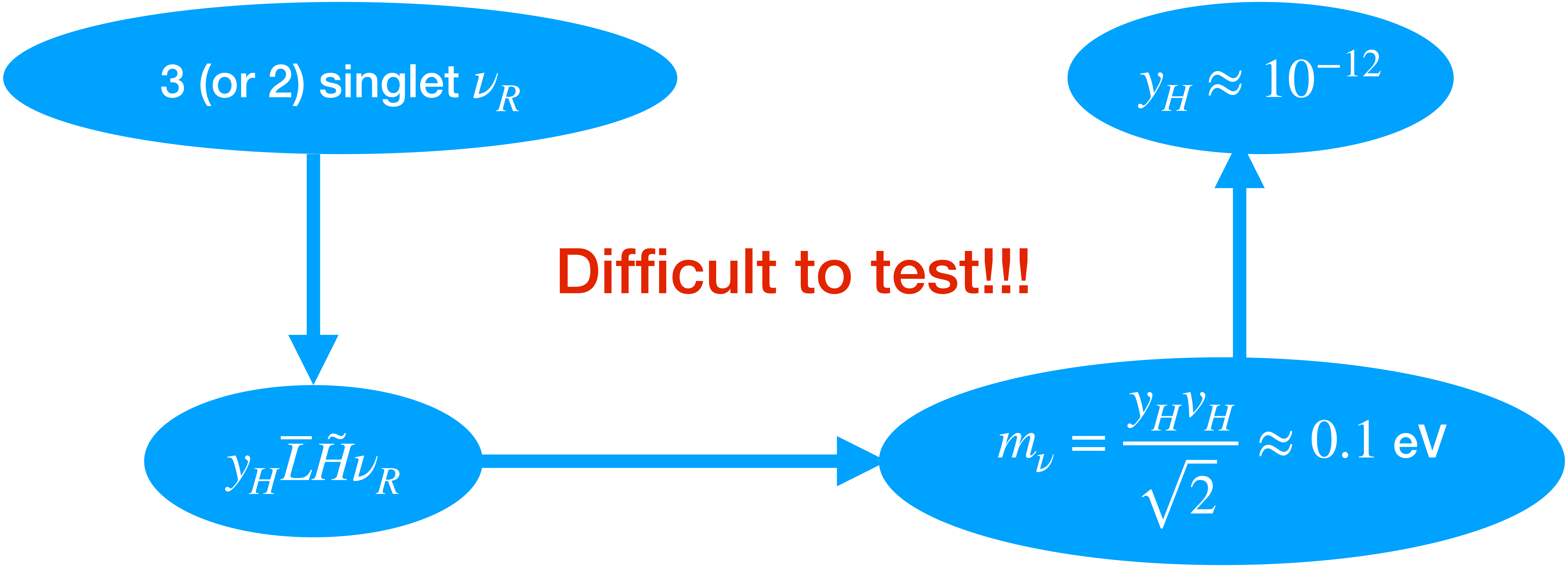
2305.16900

Thank you.

Comments and Questions?

Backup Slides

Minimal requirements:



3 (or 2) singlet ν_R

$y_H \overline{L} \tilde{H} \nu_R$

$m_\nu = \frac{y_H v_H}{\sqrt{2}} \approx 0.1$ eV

$y_H \approx 10^{-12}$

Difficult to test!!!

Relic density calculations

When $T > T_{\rm dec}$

$$\frac{dY}{dx} = -\frac{1}{2}\frac{\beta\,\mathrm{s}}{\mathcal{H}\,x}\langle\sigma\mathrm{v}\rangle_{eff}\left[Y^2-(Y^{eq})^2\right]$$

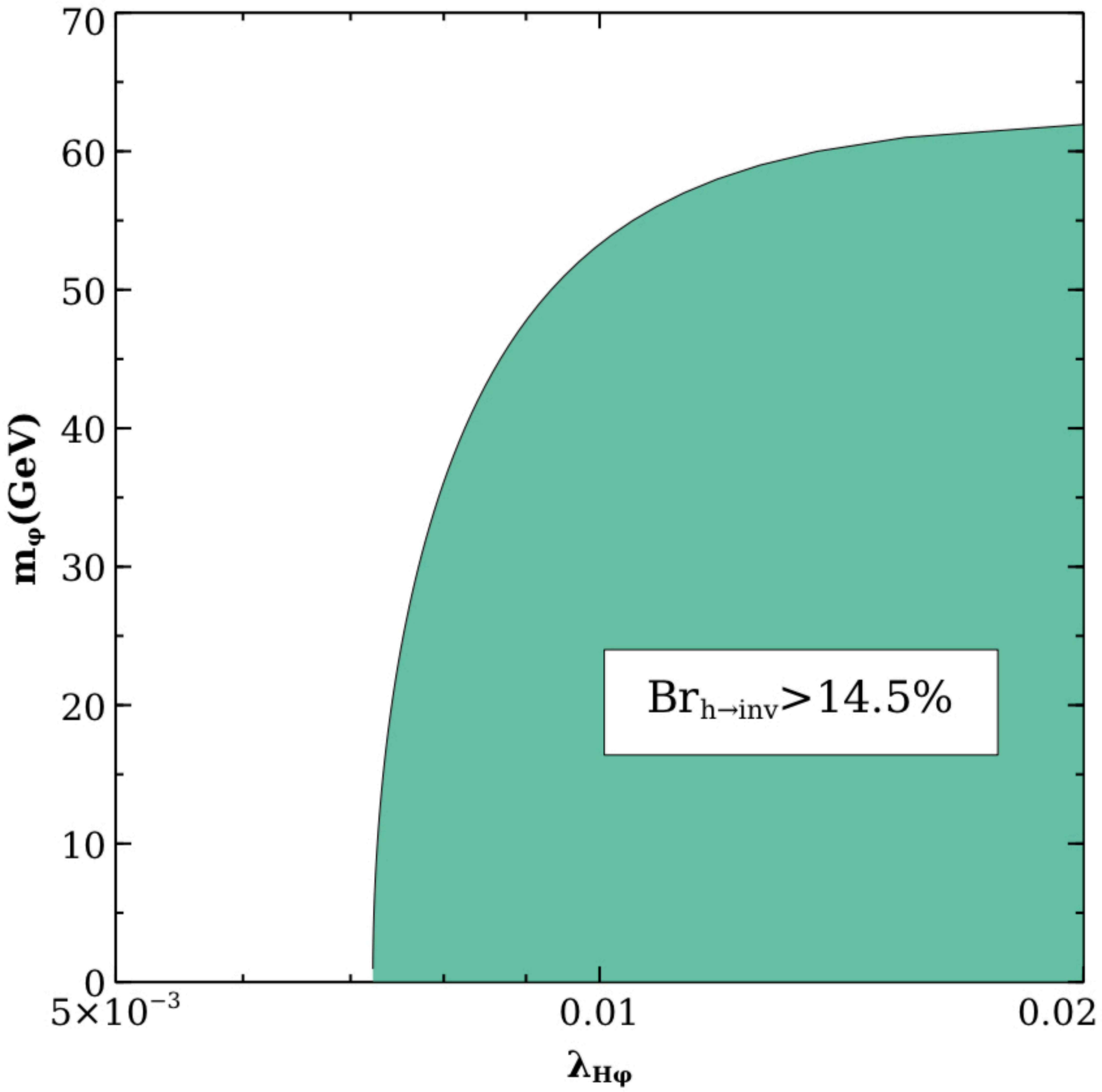
$$\left(\beta(T) = \frac{g_\star^{1/2}(T)\sqrt{g_\rho(T)}}{g_s(T)}\right)$$

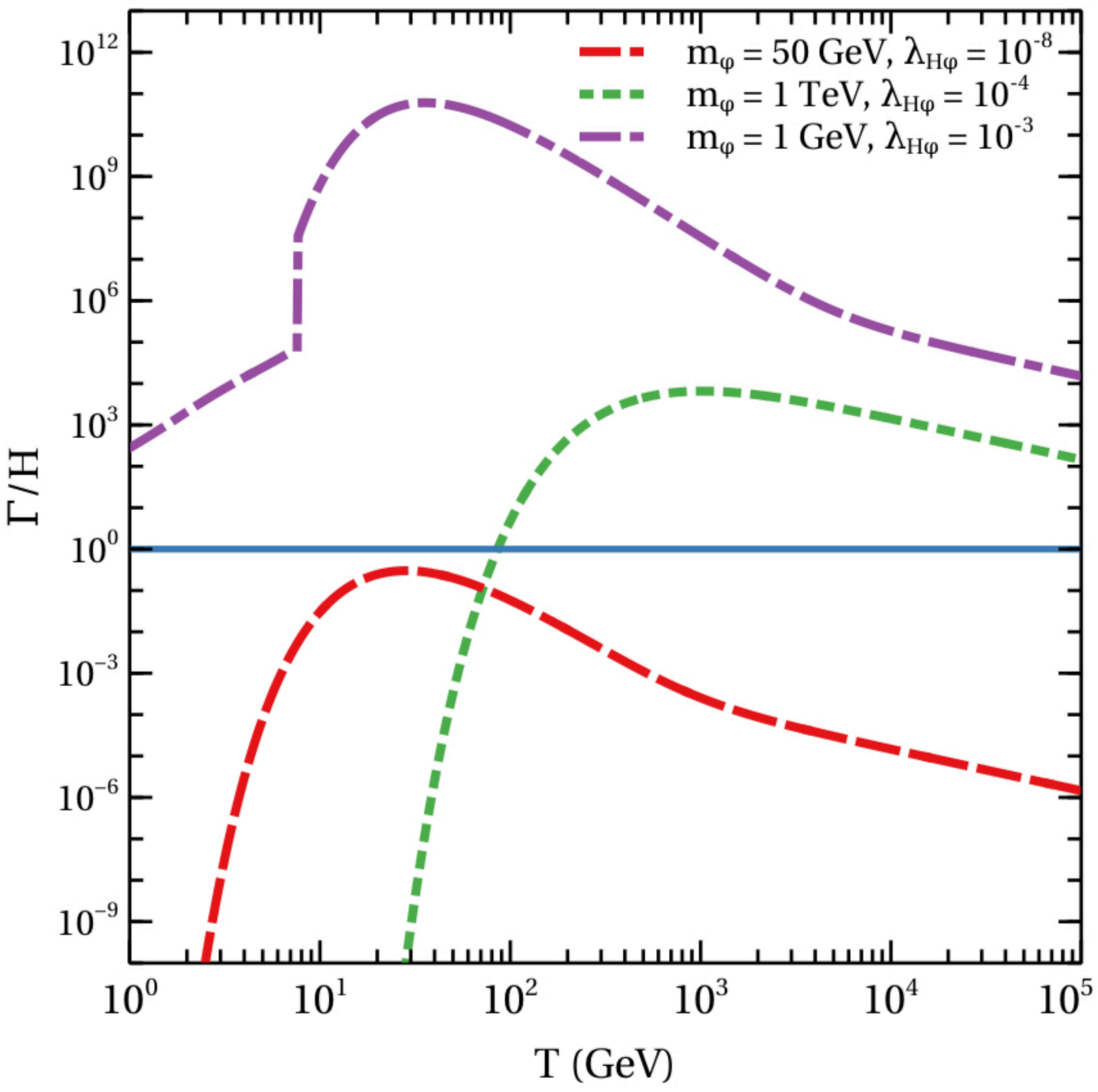
When $T < T_{\rm dec}$

$$\begin{aligned}\frac{dY}{dx} &= -\frac{1}{2}\frac{\beta\,\mathrm{s}}{\mathcal{H}\,x}\langle\sigma\mathrm{v}\rangle_{eff}\left[Y^2-(Y^{eq})^2\right] \,, \\ x\frac{d\xi}{dx}+(\beta-1)\xi &= \frac{1}{2}\frac{\beta\,x^4\,\mathrm{s}^2}{4\,\alpha\,\xi^3\,\mathcal{H}\,M_0^4}\langle E\sigma\mathrm{v}\rangle_{eff}\left[Y^2-(Y^{eq})^2\right]\end{aligned}$$

$$\left(\xi = \frac{T_{\nu_R}}{T}\right)$$

Invisible Higgs decay and $\lambda_{H\phi}$:





Boltzmann Equations: Case-I

$$\frac{dY_\psi}{dx} = \frac{\beta}{x\mathcal{H}}\Gamma_\phi \frac{K_1(x)}{K_2(x)} Y_\phi^{\rm eq},$$

$$\frac{d\widetilde{Y}}{dx} = \frac{\beta}{\mathcal{H} s^{1/3} x}\langle E\Gamma\rangle Y_\phi^{\rm eq},$$

$$\beta = \left[1 + \frac{T dg_s/dT}{3g_s}\right],$$

$$\langle E\Gamma\rangle = g_\psi g_{\nu_R} \frac{|\mathcal{M}|'^2_{\phi\to\bar{\nu}_R\psi}}{32\pi}\frac{(m_\phi^2 - m_\psi^2)^2}{m_\phi^4}.$$

Boltzmann Equations: Case-II

$$\frac{dY_\phi}{dx} = \frac{\beta s}{\mathcal{H}x}\left(-\langle\sigma v\rangle_{\phi\phi^\dagger\to\chi\bar{\chi}}\left((Y_\phi)^2 - (Y_\phi^{\rm eq})^2\right) - \frac{\Gamma_\phi}{s}\frac{K_1(m_\phi/T)}{K_2(m_\phi/T)} Y_\phi\right),$$

$$\frac{dY_\psi}{dx} = \frac{\beta}{x\mathcal{H}}\Gamma_\phi \frac{K_1(x)}{K_2(x)} Y_\phi,$$

$$\frac{d\widetilde{Y}}{dx} = \frac{\beta}{\mathcal{H} s^{1/3} x}\langle E\Gamma\rangle Y_\phi.$$

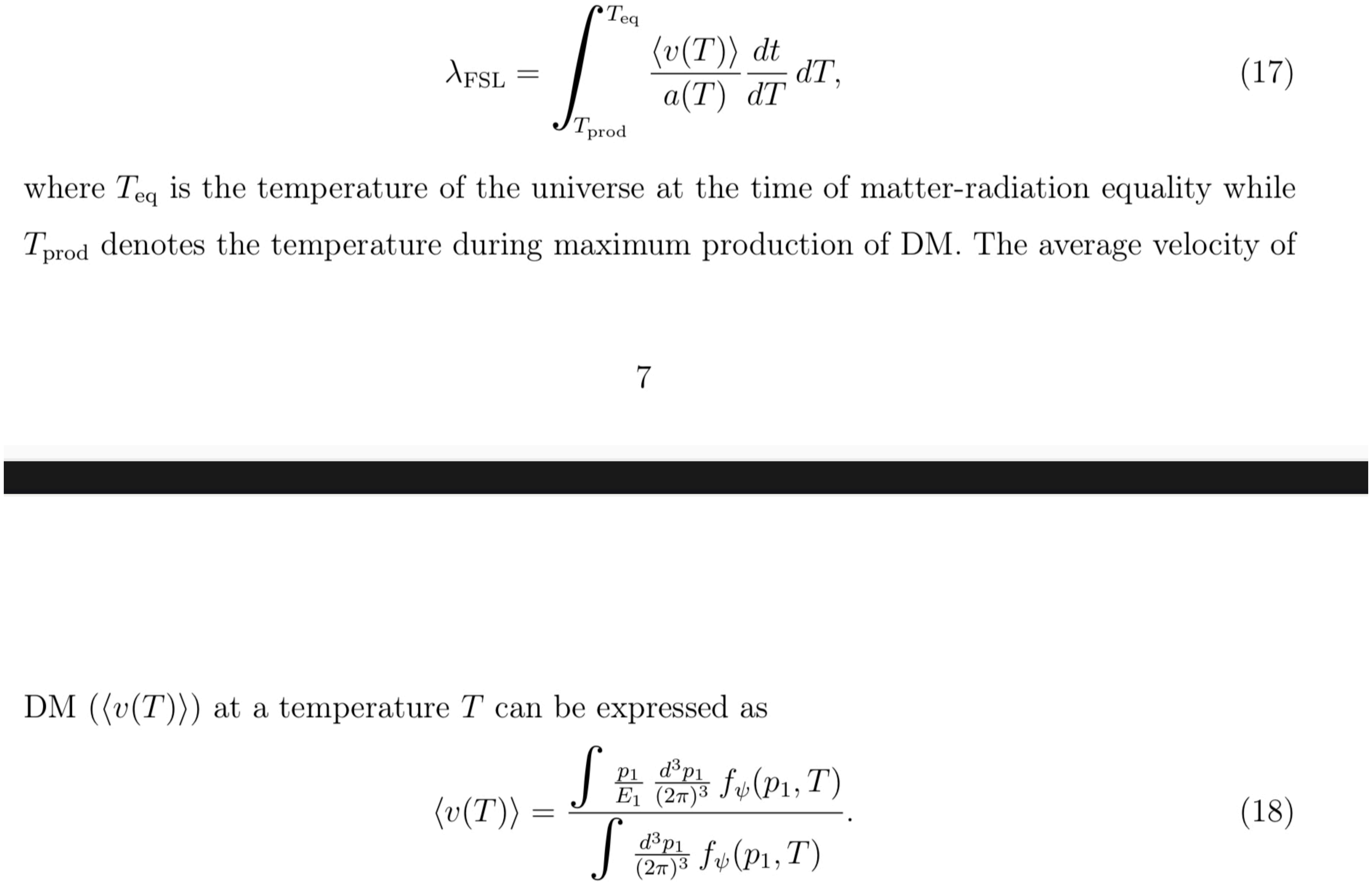
Boltzmann Equations: Case-III

$$\frac{\partial f_\phi}{\partial t} - \mathcal{H} p_1 \frac{\partial f_\phi}{\partial p_1} = C^{h\to\phi\phi^\dagger} + C^{hh\to\phi\phi^\dagger} + C^{\phi\to\bar{\nu}_R\psi},$$

$$\frac{dY_\psi}{dr} = \frac{g_\phi\beta}{r\mathcal{H}s}\frac{\Gamma_\phi m_\phi}{2\pi^2}\int \frac{\left(\mathcal{A}\frac{m_0}{r}\right)^3 \xi^2 f_\phi(\xi,r)}{\sqrt{\left(\xi\mathcal{A}\frac{m_0}{r}\right)^2+m_\phi^2}}\,d\xi\,,$$

$$\frac{d\widetilde{Y}}{dr} = \frac{g_\phi\beta}{r\mathcal{H}s^{4/3}}\langle E\Gamma\rangle\frac{1}{2\pi^2}\int_0^\infty \left(\mathcal{A}\frac{m_0}{r}\right)^3 \xi^2 f_\phi(\xi,r)\,d\xi\,,$$

Free streaming length:



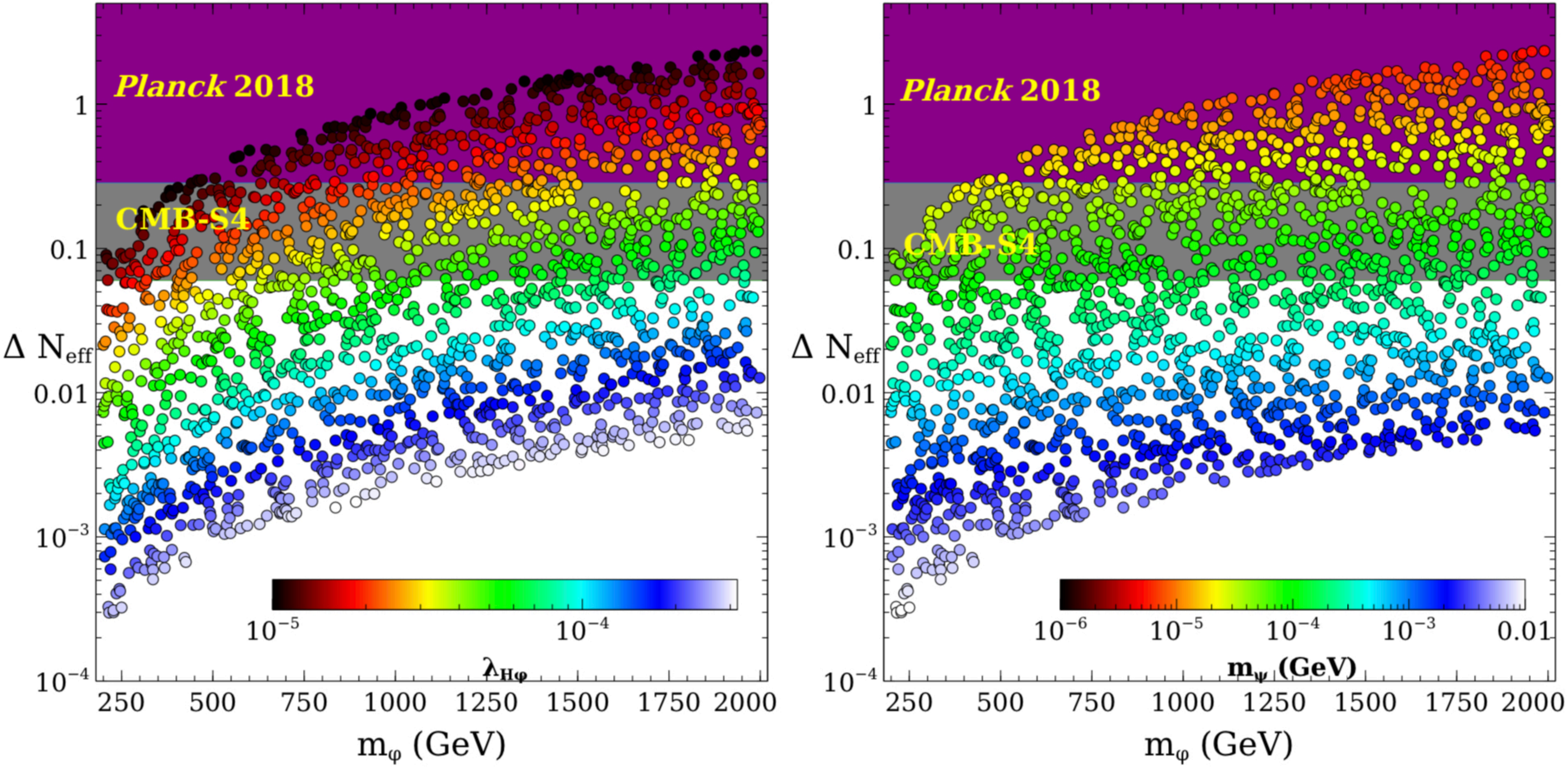
$$\lambda_{\rm FSL} = \int_{T_{\rm prod}}^{T_{\rm eq}} \frac{\langle v(T)\rangle}{a(T)} \frac{dt}{dT}\, dT, \tag{17}$$

where $T_{\rm eq}$ is the temperature of the universe at the time of matter-radiation equality while $T_{\rm prod}$ denotes the temperature during maximum production of DM. The average velocity of

DM ($\langle v(T)\rangle$) at a temperature T can be expressed as

$$\langle v(T)\rangle = \frac{\int \frac{p_1}{E_1} \frac{d^3p_1}{(2\pi)^3} f_\psi(p_1, T)}{\int \frac{d^3p_1}{(2\pi)^3} f_\psi(p_1, T)}. \tag{18}$$

Scan for case-II



Scan for case-III