Confronting Dark Matter with Dirac Neutrinos

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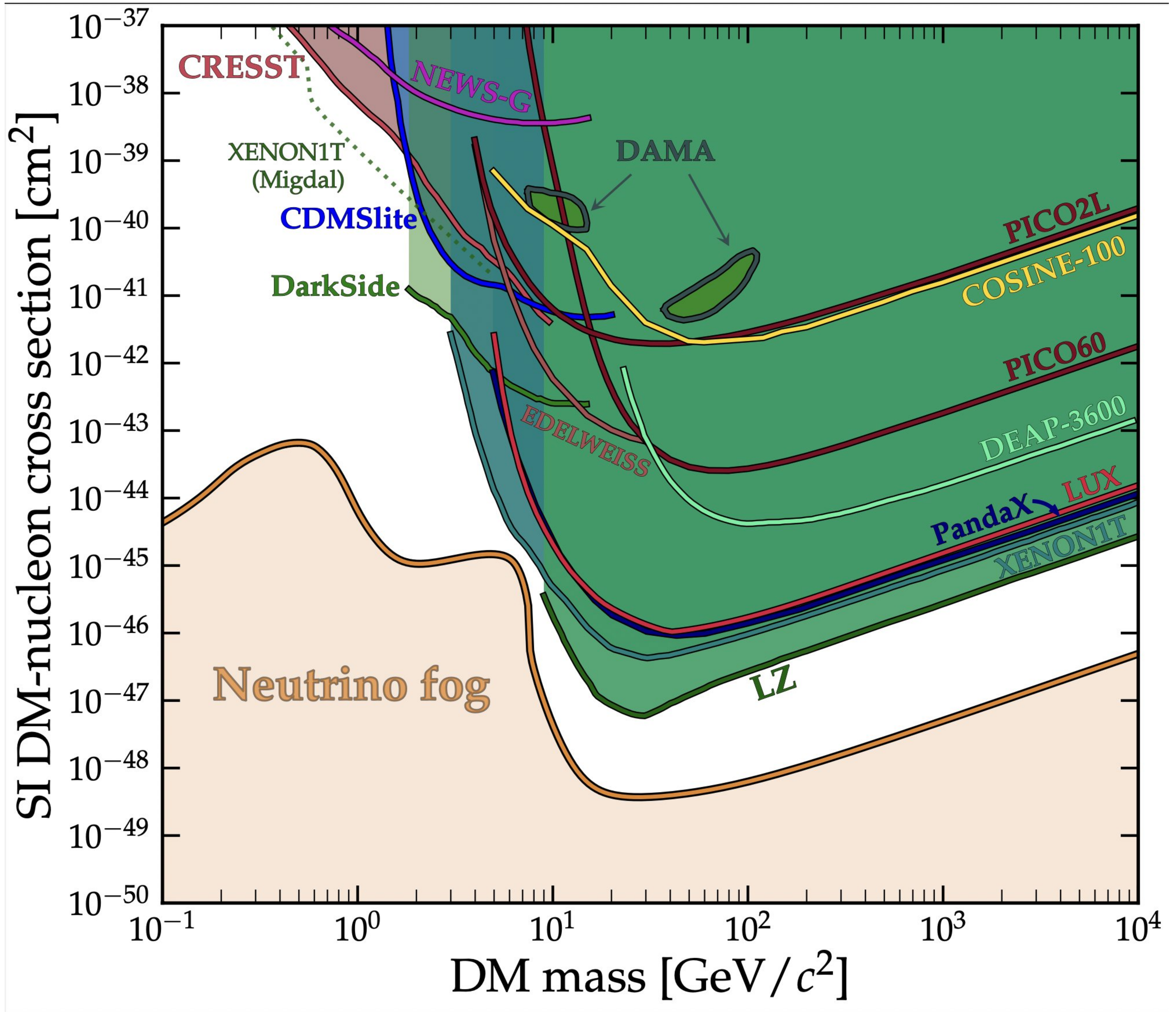
- The existence of dark matter, neutrino mass, the nature of neutrinos, matter-antimatter asymmetry…. are the unsolved puzzles of nature.

- Null results in direct detection experiments pushed the thermal WIMP scenarios in tension.

- Many different possibilities have been proposed to evade such strong DD bounds.

- We need to look for other possibilities to probe dark matter



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

Dirac or Majorana?

- 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/impossible 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);$N^{SM}_{\rm eff} = 3.046$; $\Delta N_{\rm eff} = 0.285$ at 2σ.

- ν_R can have additional interactions and 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.

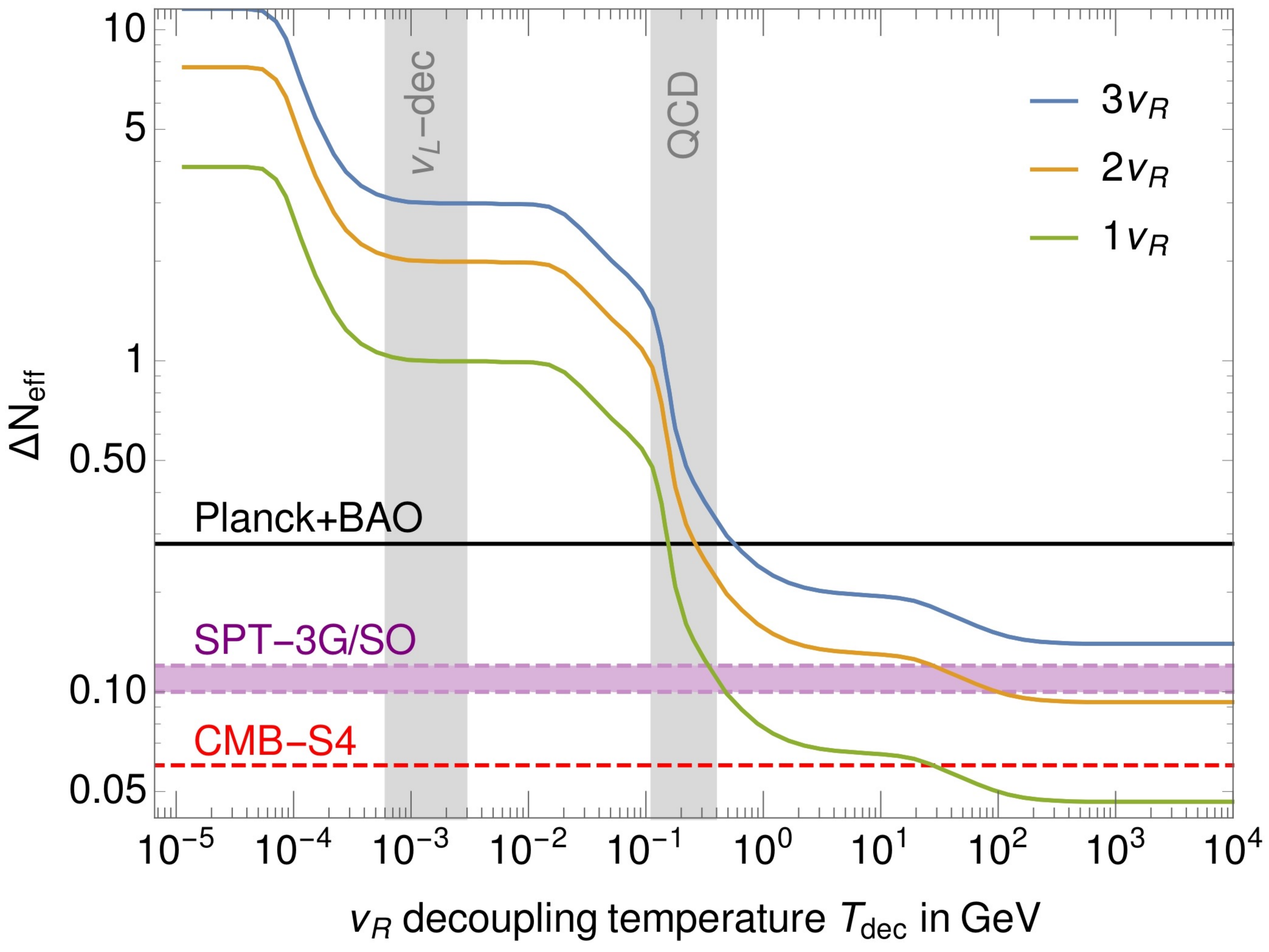
- If thermalised, $\Delta N_{\text{eff}} = N_{\nu_R} \left(\frac{g_{*s}(T_{\nu_L})}{g_{*s}(T_{\nu_R})} \right)^{4/3}$

- If, it is produced non-thermally, it depends on the particular process.

- For example, from SM-like Higgs via $y_H \approx 10^{-12}$, $\Delta N_{\text{eff}} = 7.5 \times 10^{-12}$

Luo, Rodejohann and Xu, 2021

- **What if the production of DM and ν_R are connected?**



Abazajian and Heeck 2019

- ν_R can be thermalised or it can be produced from the non-thermally just like DM particles.

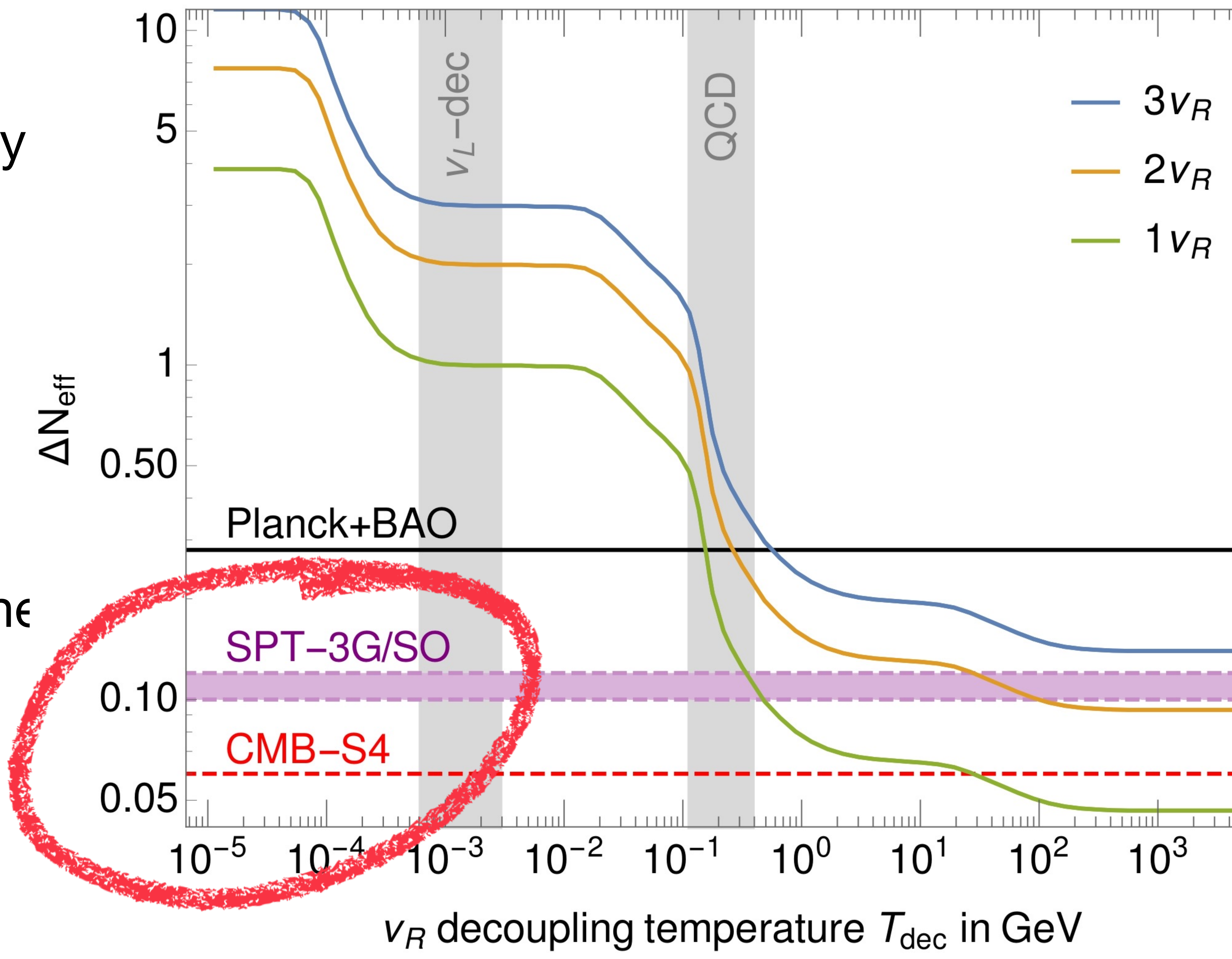
- In both cases, it will contribute to the total radiation energy density.

- If thermalised, $\Delta N_{\text{eff}} = N_{\nu_R} \left(\frac{g_{*s}(T_{\nu_L})}{g_{*s}(T_{\nu_R})} \right)^{4/3}$

- If, it is produced non-thermally, the amount depends on the particular process.

- For example, from SM-like Higgs via $y_H \approx 10^{-12}$, $\Delta N_{\text{eff}} = 7.5 \times 10^{-12}$

Luo, Rodejohann and Xu, 2021



Abazajian and Heeck 2019

- **What if the production of DM and ν_R are connected?**

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

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

SM singlet scalar (ϕ)

SM singlet ν_R

The dark matter (ψ)

$$y_H \bar{L} \tilde{H} \nu_R + \lambda_{H\phi}(H^\dagger H)(\phi^\dagger \phi) + y_\phi \bar{\psi} \phi \nu_R$$

- Case I: $\lambda_{H\phi}, y_\phi \approx \mathcal{O}(1)$
- Case II: $\lambda_{H\phi} \approx \mathcal{O}(1), y_\phi < < \mathcal{O}(1)$
- Case III: $\lambda_{H\phi} < < \mathcal{O}(1), y_\phi < < \mathcal{O}(1)$

- **No direct connection between dark matter and RHNs to SM particles.**

SM singlet scalar (ϕ)

SM singlet ν_R

The dark matter (ψ)

$$y_H \bar{L} \tilde{H} \nu_R + \lambda_{H\phi}(H^\dagger H)(\phi^\dagger \phi) + y_\phi \bar{\psi} \phi \nu_R$$

- **Case I:** $\lambda_{H\phi}, y_\phi \approx \mathcal{O}(1)$ → **DD is loop suppressed.**
- **Case II:** $\lambda_{H\phi} \approx \mathcal{O}(1), y_\phi < < 1$
- **Case III:** $\lambda_{H\phi} < < \mathcal{O}(1), y_\phi < < 1$

Cases II and III → **Loop suppressed + Small couplings. No DD.**

SM singlet scalar (ϕ)

SM singlet ν_R

The dark matter (ψ)

$$y_H \overline{L} \tilde{H} \nu_R + \lambda_{H\phi}(H^\dagger H)(\phi^\dagger \phi) + y_\phi \overline{\psi} \phi \nu_R$$

- Case I: $\lambda_{H\phi}, y_\phi \approx \mathcal{O}(1)$ → DD is loop suppressed.
- Case II: $\lambda_{H\phi} \approx \mathcal{O}(1), y_\phi << 1$
- Case III: $\lambda_{H\phi} << \mathcal{O}(1), y_\phi << 1$

Cases II and III → Loop suppressed + Small couplings. No DD.

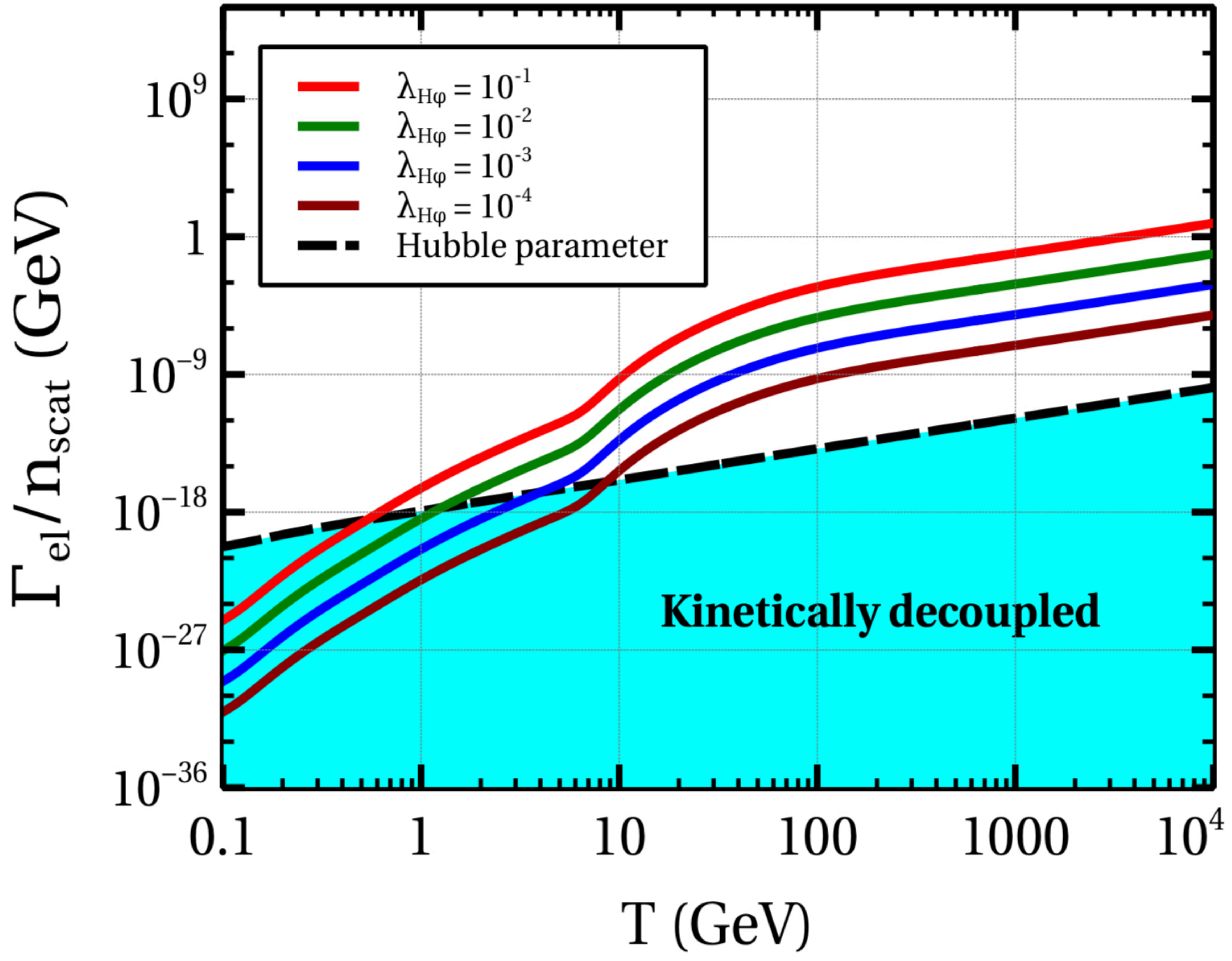
1) Relic Density of DM

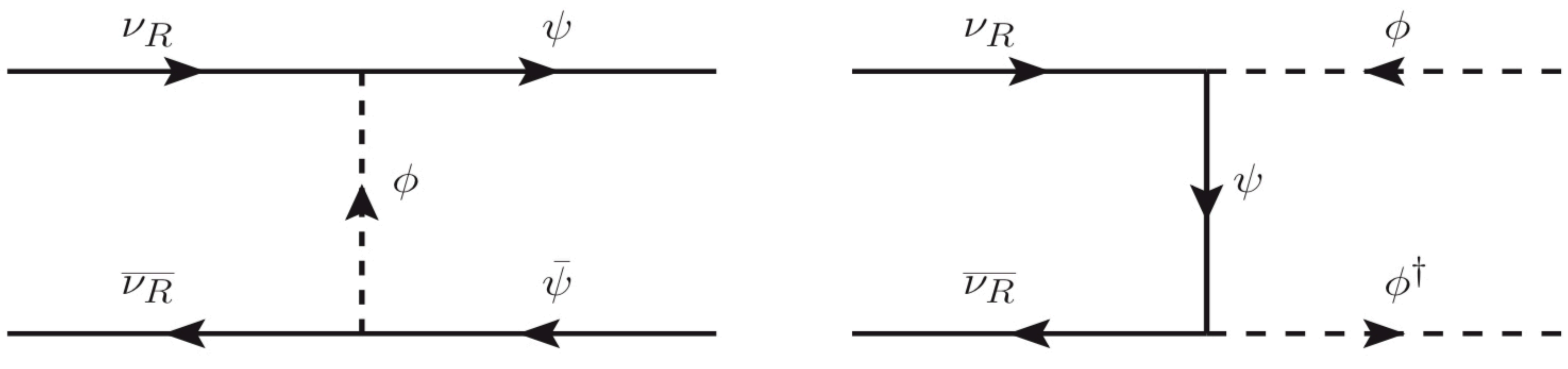
2) $\Delta N_{\rm eff}$

3) Free streaming length of DM

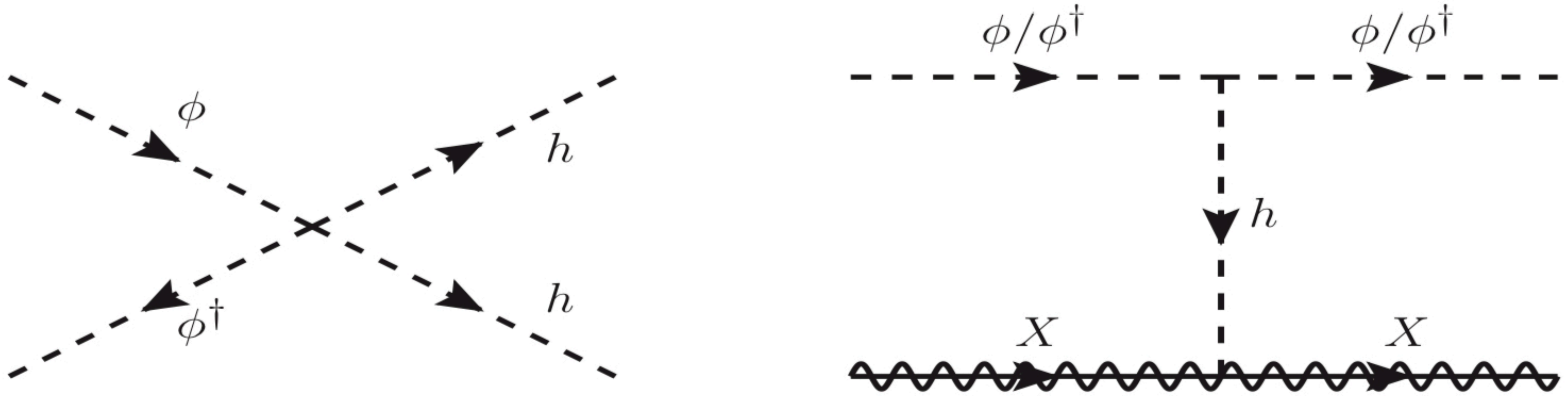
Decoupling from the thermal bath:

- 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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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 $T < T_{\rm dec}$

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

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

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

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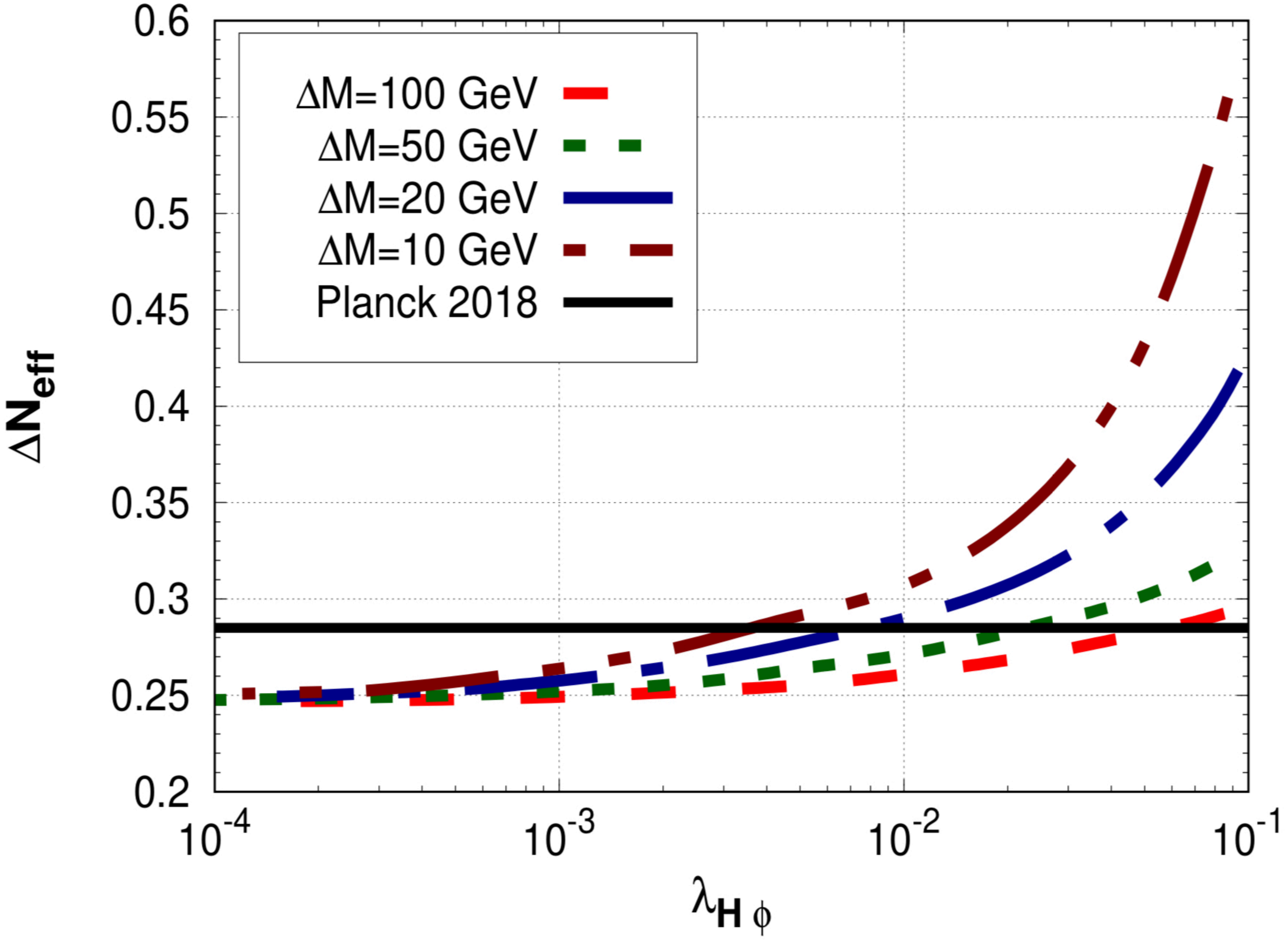
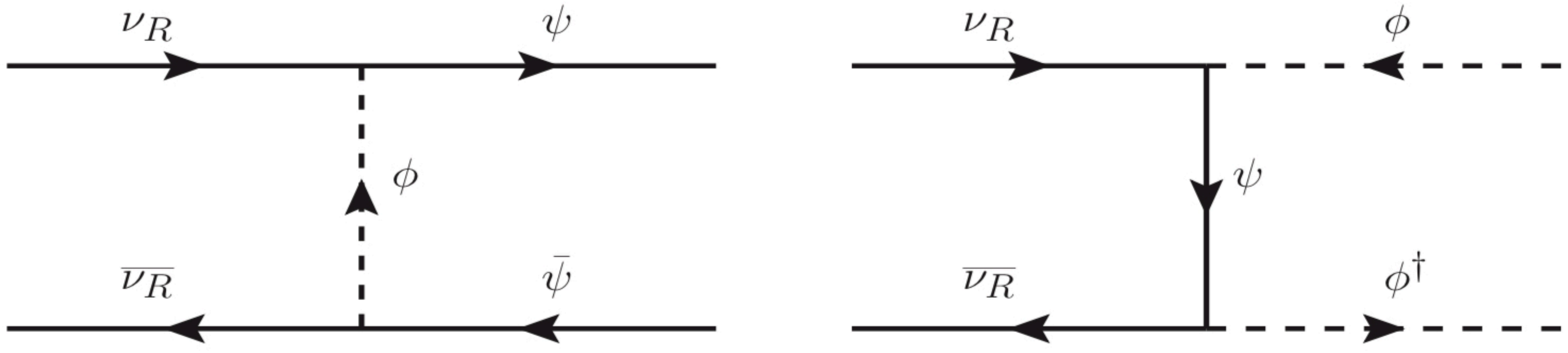
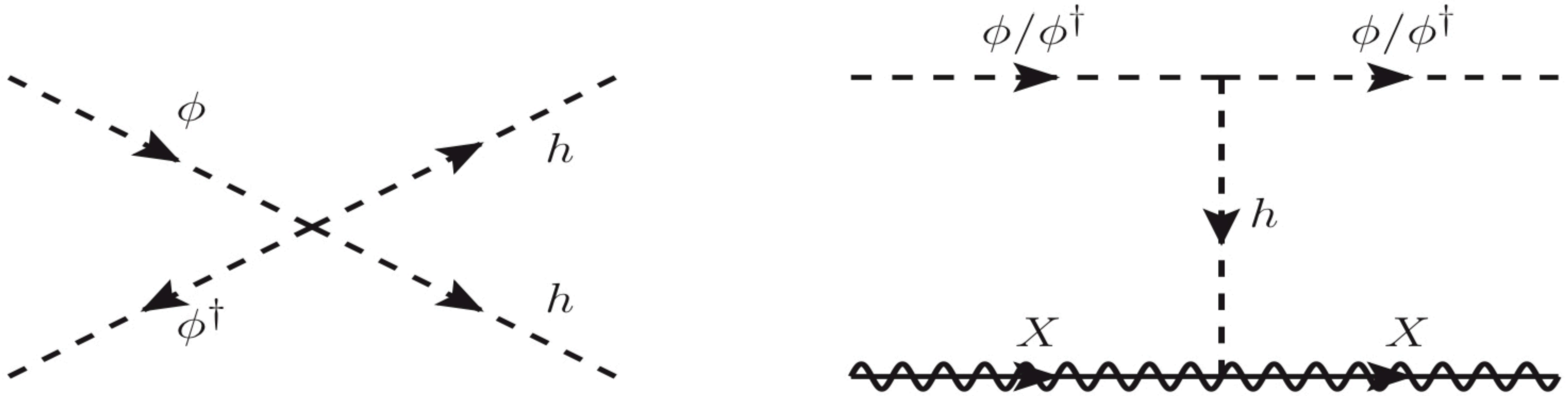
Decoupling from the thermal bath:





(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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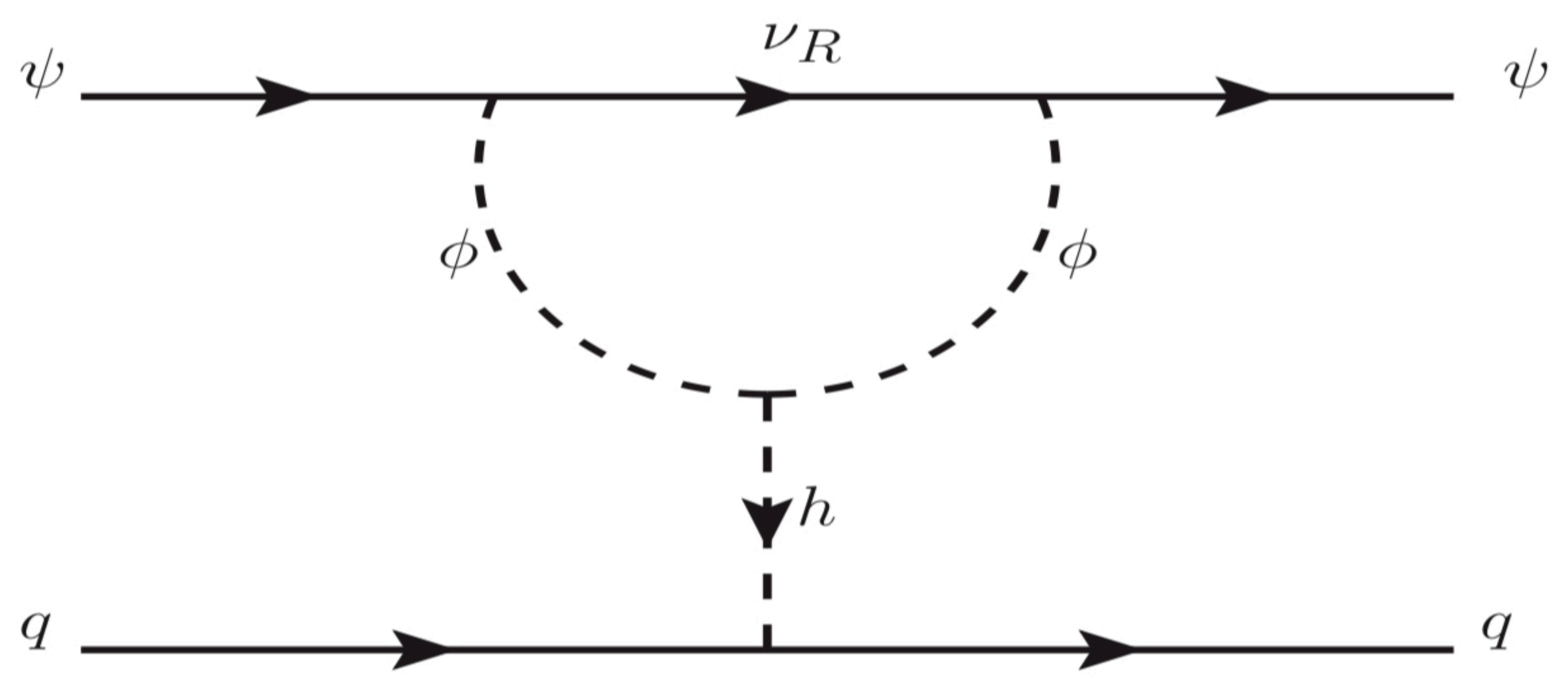
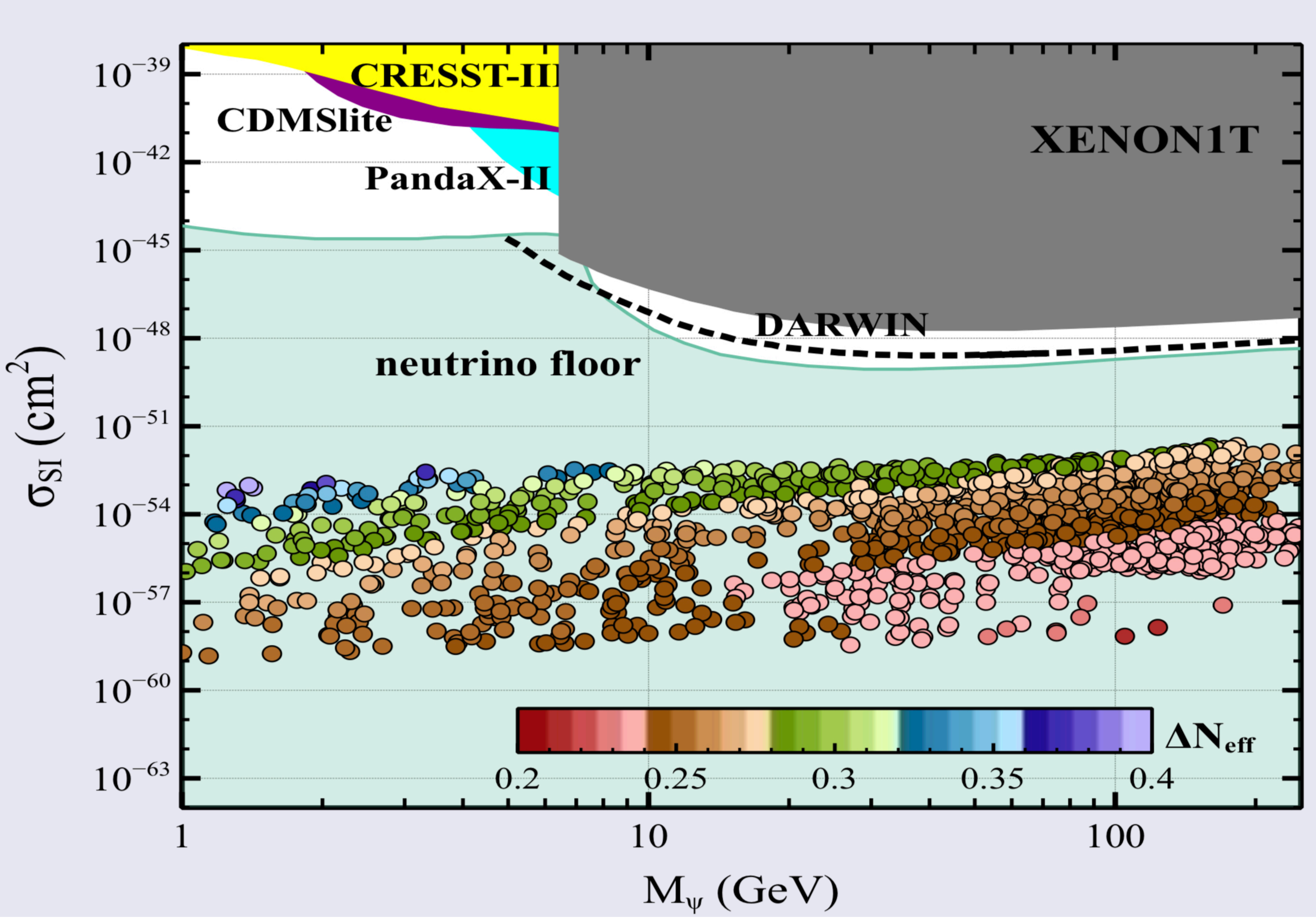
Indirect probe through ΔN_{eff}:

- $\psi\psi h$ 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: $y_\phi \overline{\psi} \phi \nu_R$

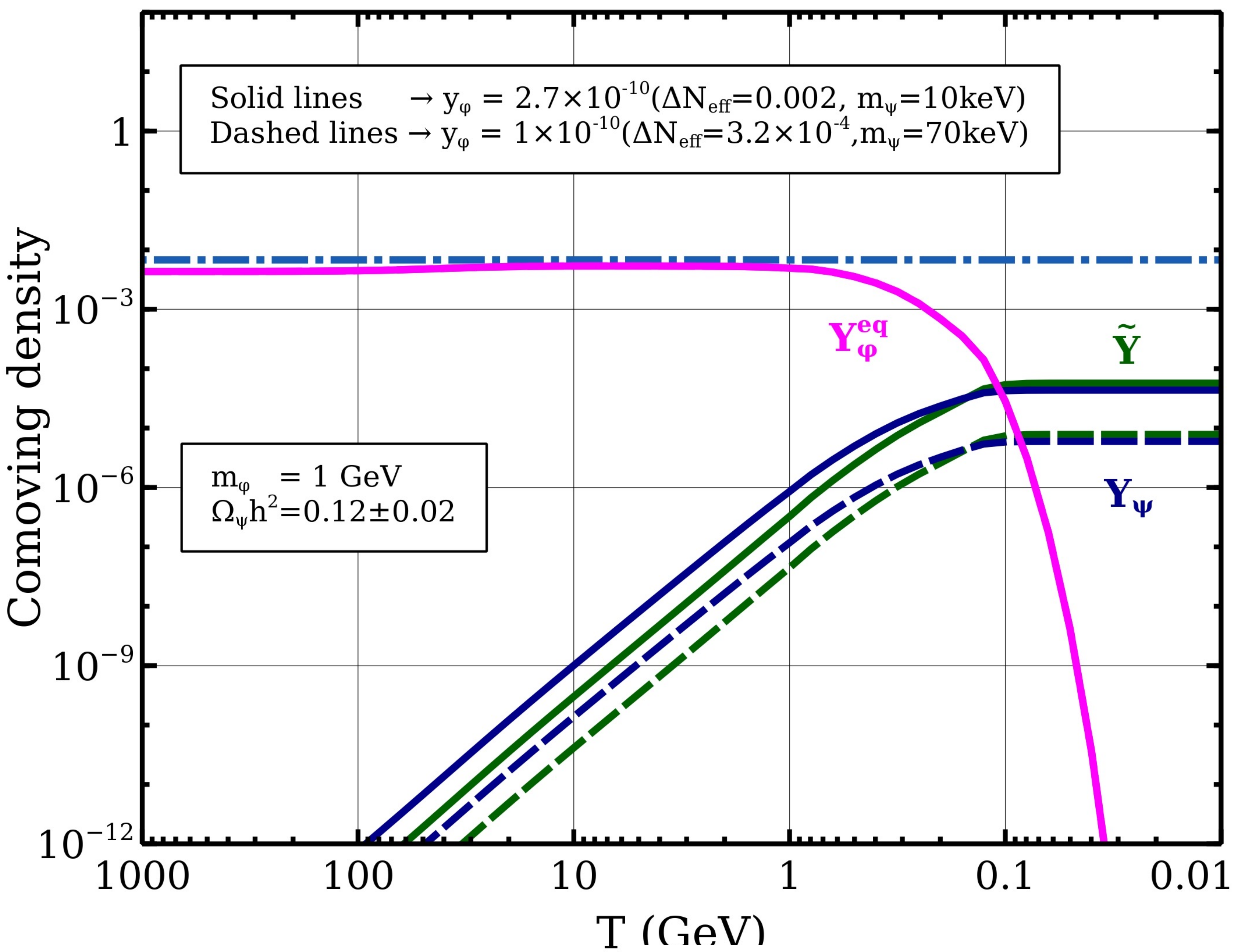
- Then there can be three different situations depending on $\lambda_{H\phi}(H^\dagger H)(\phi^\dagger \phi)$:

  - 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: $\lambda_{H\phi} \approx \mathcal{O}(1), y_\phi << 1$



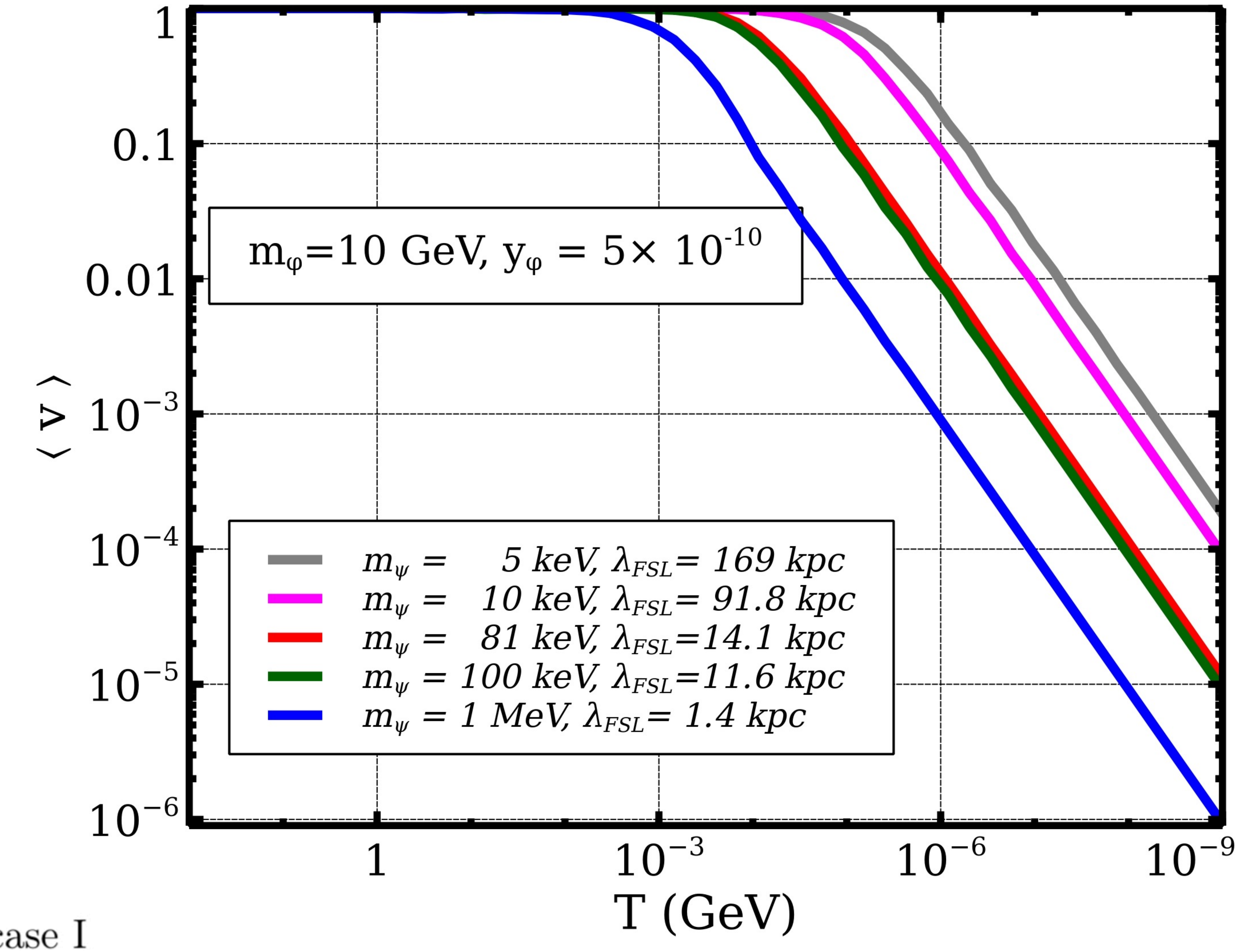


TABLE I: Table for case I

Parameters			$\Omega_{DM}h^2$	ΔN_{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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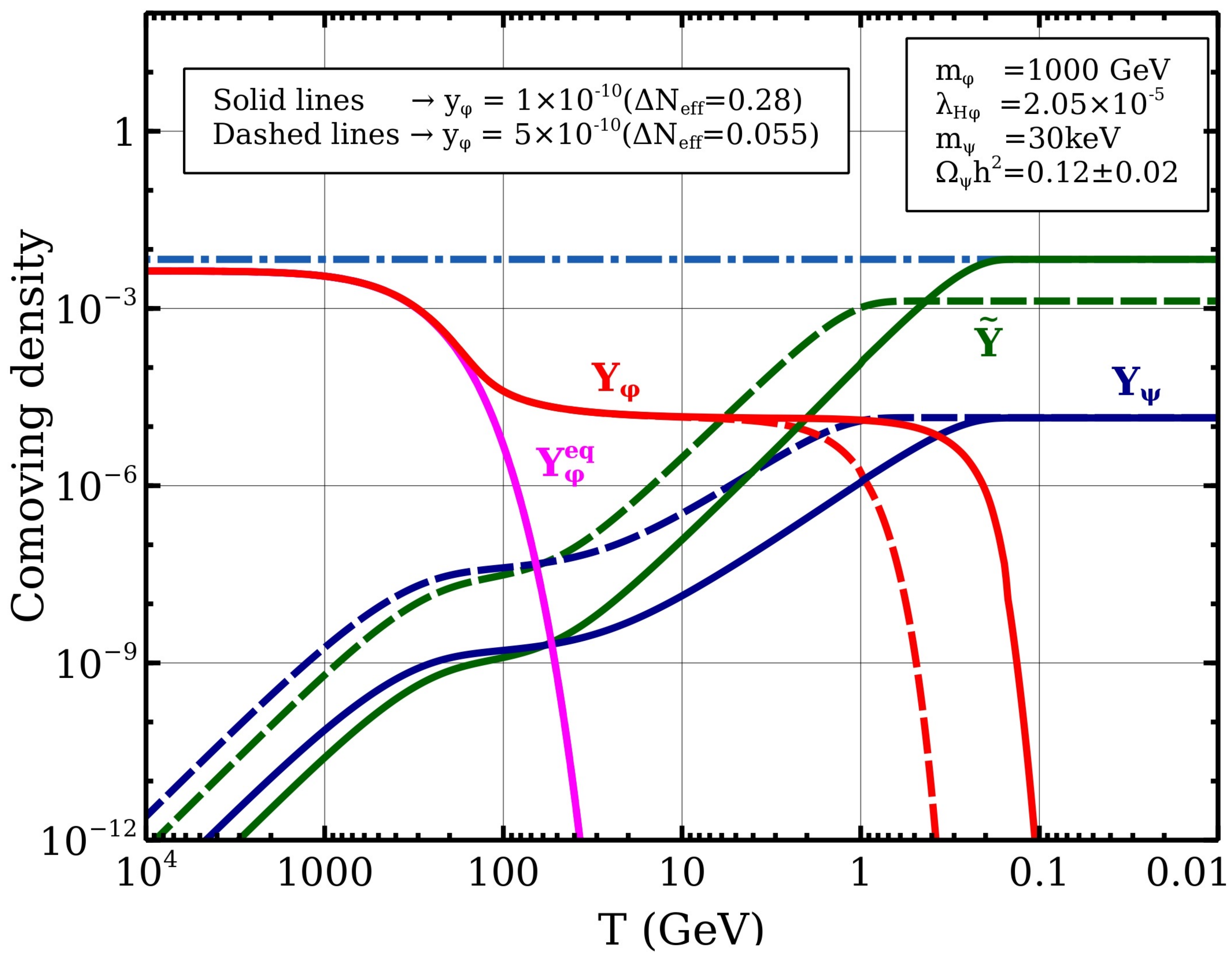
Case II: ϕ freezes out from the thermal bath and then decays: $\lambda_{H\phi} \approx 10^{-4}, y_\phi << 1$



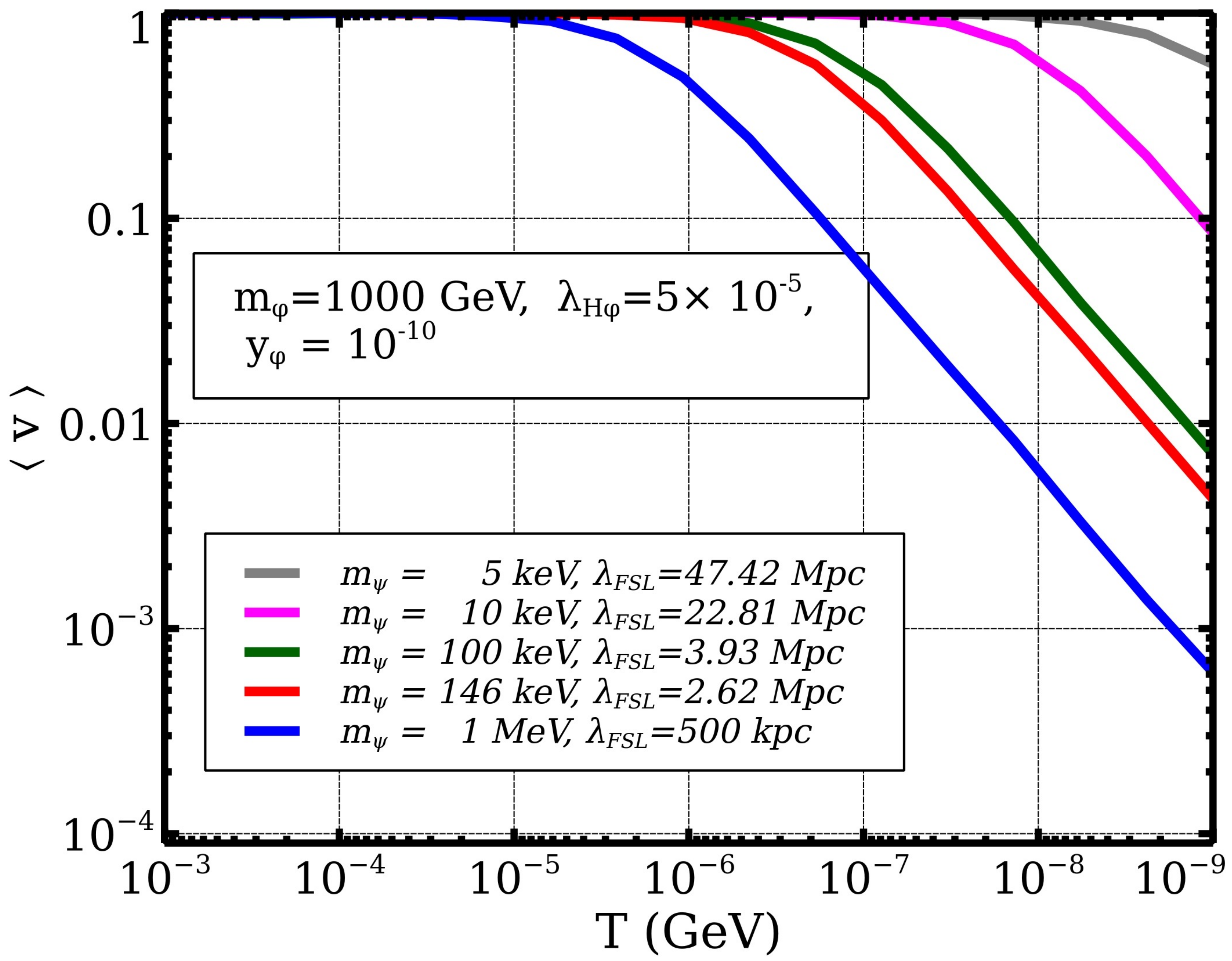


TABLE II: Table for case II

Parameters				$\Omega_{DM}h^2$	ΔN_{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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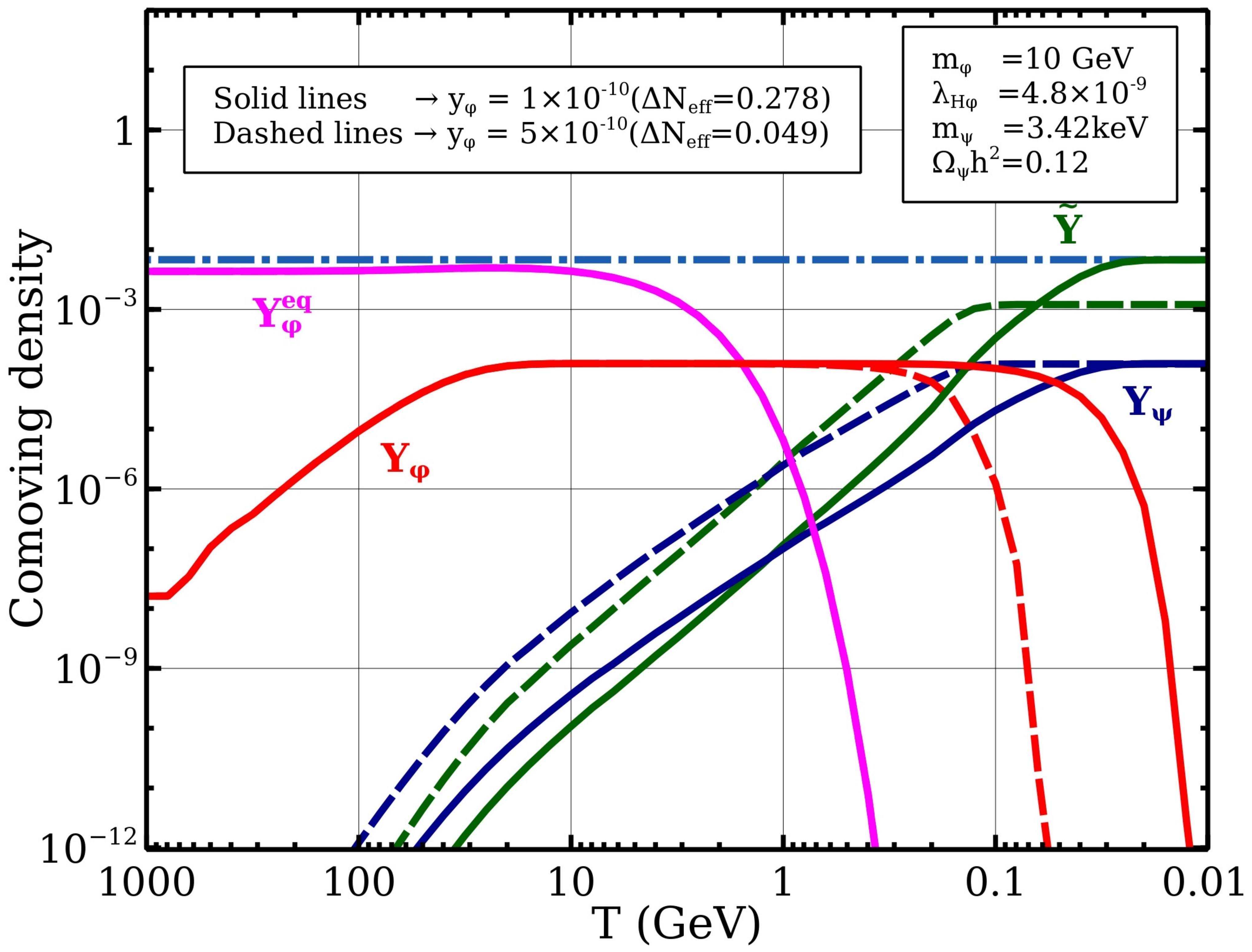
Case III: ϕ was never in the thermal bath but produced non-thermally from Higgs decay: $\lambda_{H\phi} << 1, y_\phi << 1$



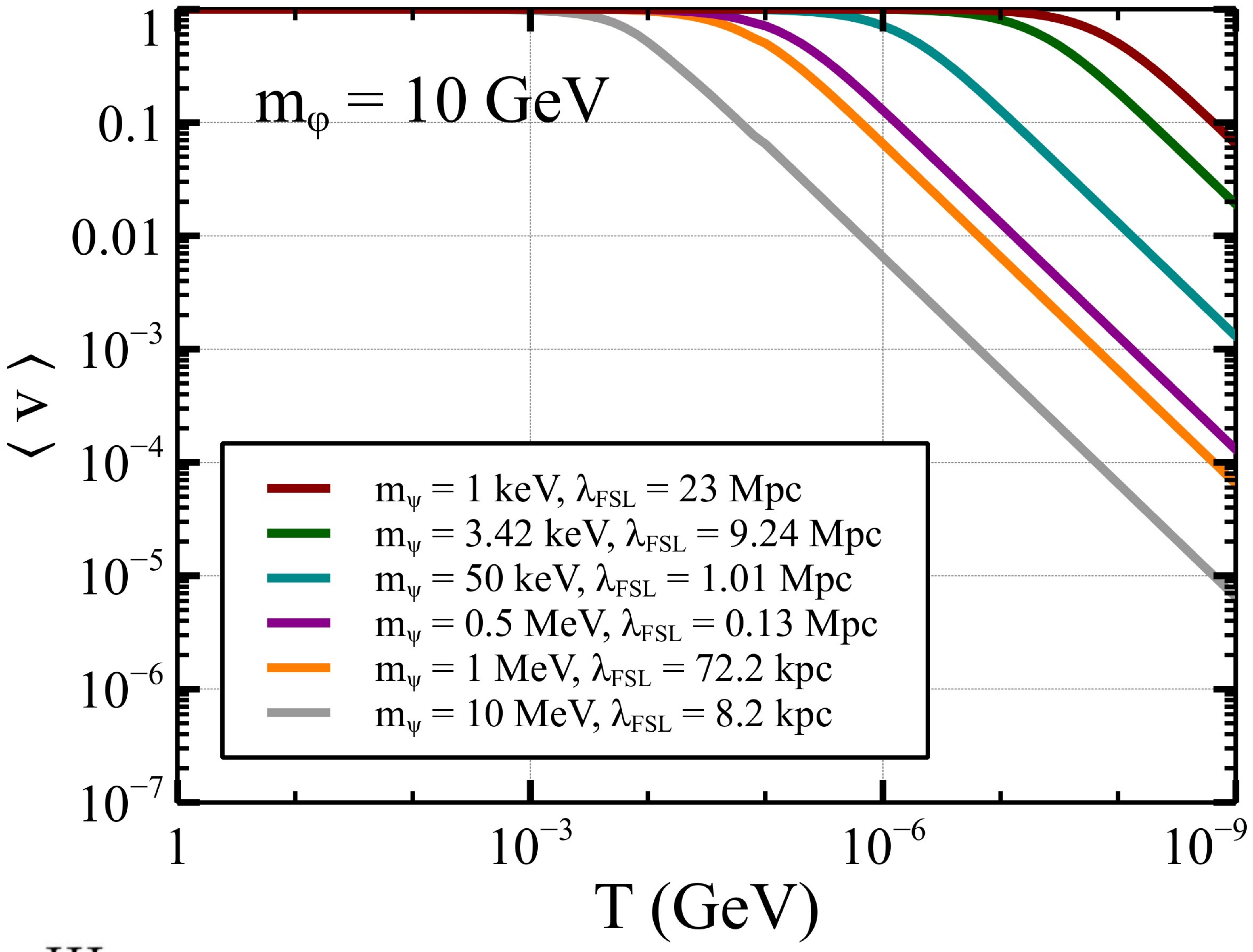


TABLE III: Table for case III

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.

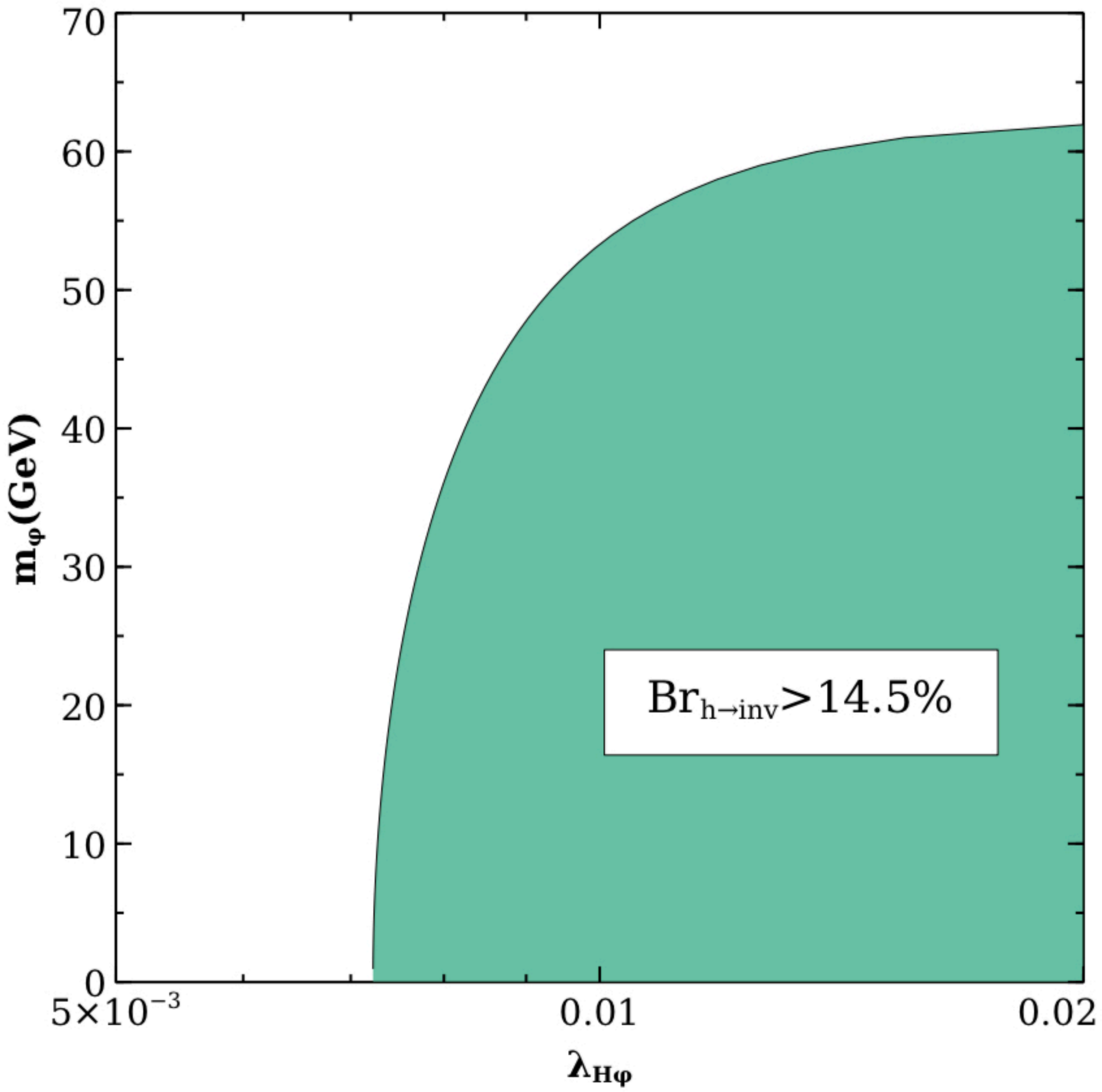
- Showed that $\Delta N_{\rm eff}$ and the FSL of DM can exclude some part of the parameter space of the model.

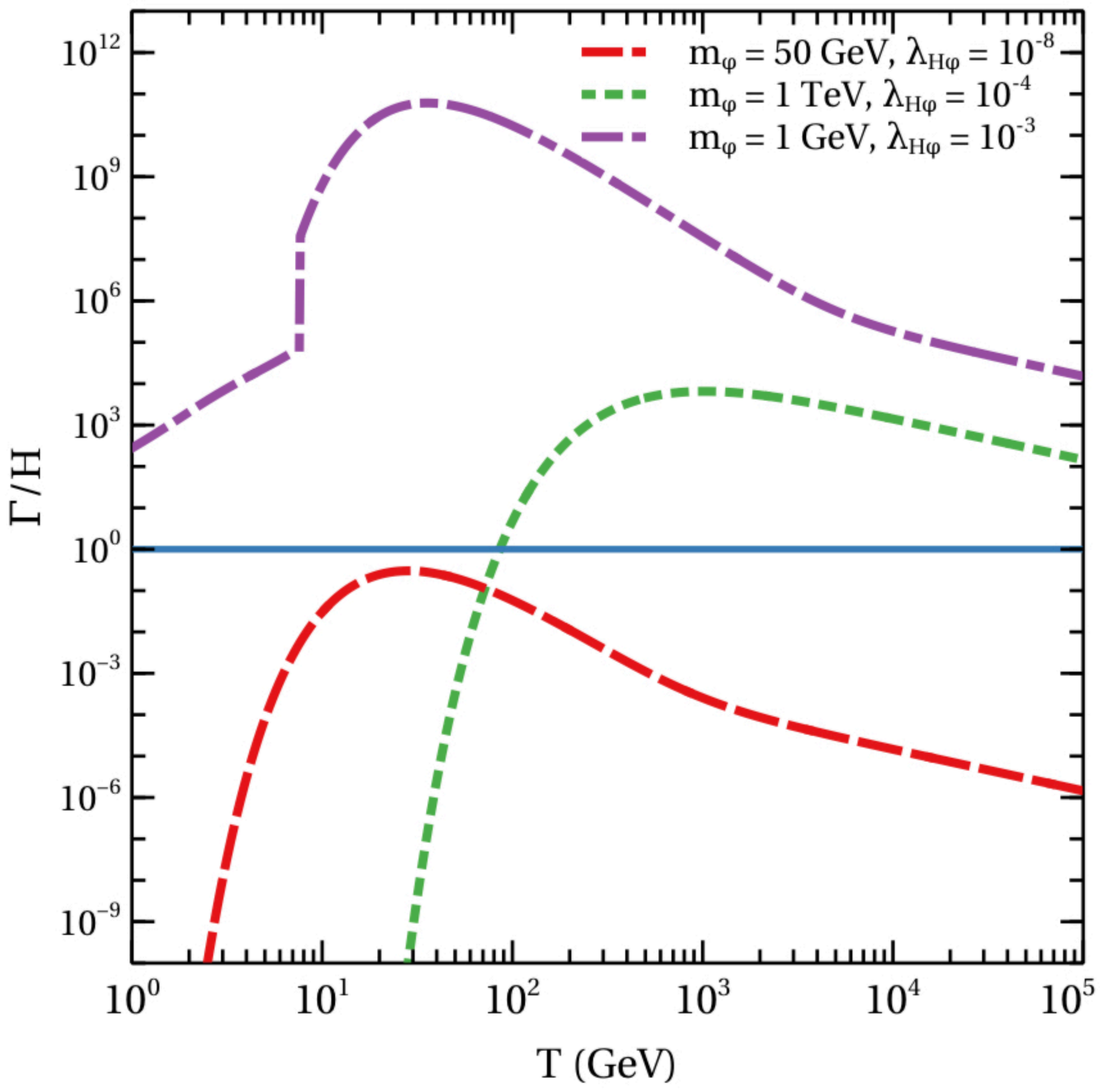
- Depending upon the choice of the parameters, FSL can rule out DM all the way up to a few hundred keV.

Thank you for your attention .

Backup Slides

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

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

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

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

Distribution functions of ϕ

(i) Case I: $f_\phi(k_1) = e^{-E_{k_1}/T}$.

(ii) Case II: we can find $f_\phi(k_1)$ after the freeze-out of ϕ by using

$$\frac{\partial f_\phi}{\partial t} - \mathcal{H} k_1 \frac{\partial f_\phi}{\partial k_1} = C^{\phi \to \psi \bar{\nu}_R}. \tag{26}$$

(iii) Case III: we can find $f_\phi(k_1)$ by using

$$\frac{\partial f_\phi}{\partial t} - \mathcal{H} k_1 \frac{\partial f_\phi}{\partial k_1} = C^{h \to \phi \phi^\dagger} + C^{hh \to \phi \phi^\dagger} + C^{\phi \to \bar{\nu}_R \psi}. \tag{27}$$

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:

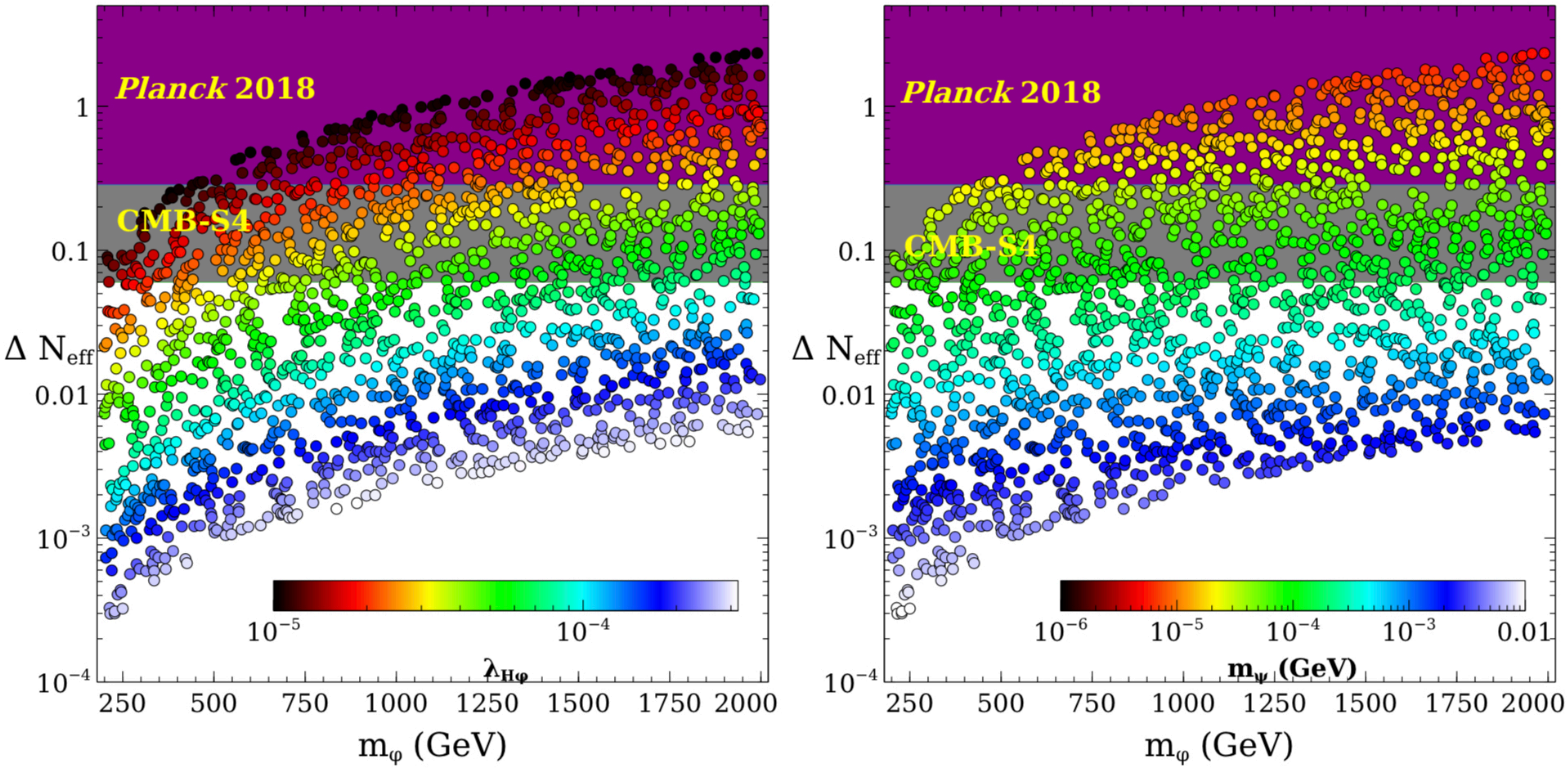
$$\lambda_{\rm FSL} = \int_{T_{\rm prod}}^{T_{\rm eq}} \frac{\langle v(T) \rangle}{a(T)} \frac{dt}{dT}\, dT, \tag{17}$$

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

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

Scan for case-II



Scan for case-III