Fingerprints of MeV scale secluded dark matter at CMB

Based on arXiv: 2201.00854
Published in Phys.Lett.B 834 (2022)

Authors: Sougata Ganguly, Sourov Roy, Abhijit Kumar Saha

Contact: **abhijitsaha118@gmail.com**

School of Physical Sciences

Indian Asscoiation for the Cutivation of Science

☛ PLANCK SATELLITE measures the number of effective relativistic degrees (Neff) of freedom at CMB.

$$N_{\rm eff}^{\rm CMB} = 2.99^{+0.34}_{-0.33} \quad \text{at } 95\% \text{ CL}$$

[arXiv: 1807.06209]

This constitutes a fundamental probe of thermal history of early Universe.

Q : How do you define N_{eff}?

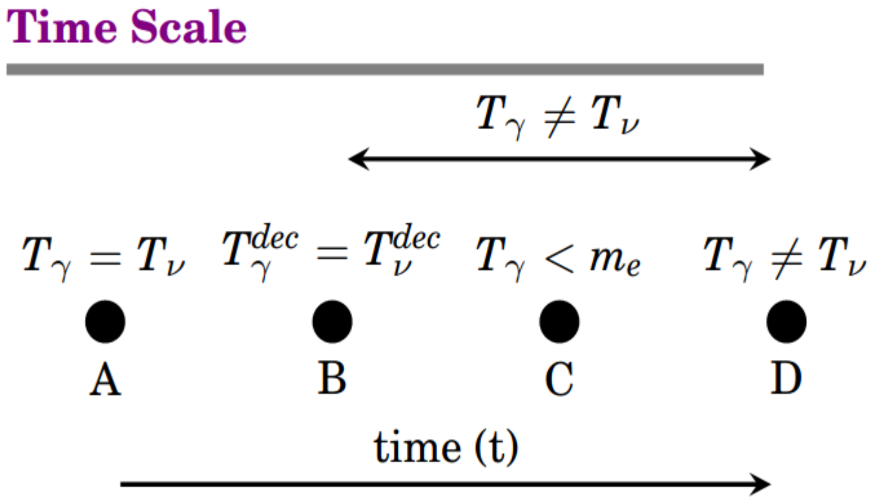
$$\Rightarrow N_{\rm eff} = 3 \times \left(\frac{11}{4}\right)^{4/3} \left(\frac{T_\nu^{\rm CMB}}{T_\gamma^{\rm CMB}}\right)^4$$

- Consider the change in effective number of degrees of freedom in entropy of the photon bath

$$g_{*s_\gamma} = \begin{cases} 2 + \frac{7}{8} \times 4 = \frac{11}{2}, & T \gtrsim m_e \\ 2 & T \lesssim m_e \end{cases}$$

The effective number of degrees of freedom in the neutrino bath entropy density remains same

$$g_{*s_\nu} = 3 \times 2 \times \frac{7}{8}$$



- Apply conservation of comoving entropy density

$$s_\gamma(T_d)a(T_d)^3 = s_\gamma(T_\gamma^{\mathrm{CMB}})a(T_\gamma^{\mathrm{CMB}})^3$$

$$s_\nu(T_d)a(T_d)^3 = s_\nu(T_\nu^{\mathrm{CMB}})a(T_\nu^{\mathrm{CMB}})^3$$

Using $s_\gamma = \frac{2\pi^2}{45} g_{*s_\gamma} T_\gamma^3$ and $s_\nu = \frac{2\pi^2}{45} g_{*s_\nu} T_\nu^3$

We obtain,

$$\frac{T_\nu^{\mathrm{CMB}}}{T_\gamma^{\mathrm{CMB}}} = \left(\frac{4}{11}\right)^{1/3}$$

Hence in SM of particle physics

$$N_{\mathrm{eff}} = 3$$

Instantaneous decoupling approximation !!

- If the neutrinos decoupling is instaneous, we find $N_{\rm eff} = 3$. But in practice this is not the case.

To obtain a clear prediction of $N_{\rm eff}$ in SM, on should corretly track the temperature evolutions for both neutrino bath and photon bath

$$\frac{dT_\nu}{dt} = \frac{\mathcal{C}_{inel.}(T_\gamma, T_\nu) + \mathcal{C}_{el}(T_\gamma, T_\nu) - 4H\rho_\nu}{\frac{\partial\rho_\nu}{\partial T_\nu}},$$

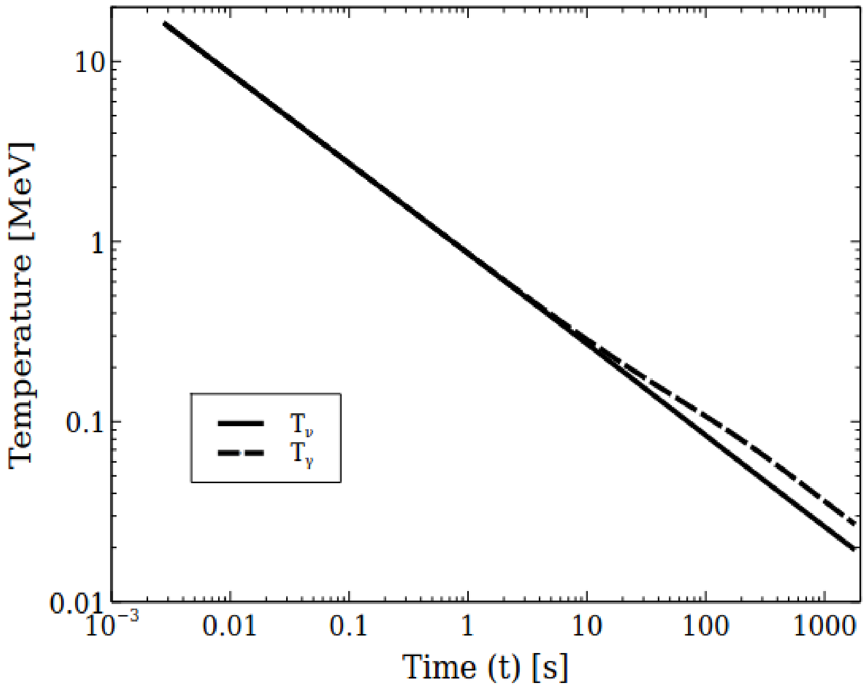
$$\frac{dT_\gamma}{dt} = \frac{-\mathcal{C}_{inel.}(T_\gamma, T_\nu) - \mathcal{C}_{el}(T_\gamma, T_\nu) - 3H(\rho_e + \rho_\gamma) - 3H(p_e + p_\gamma)}{\frac{\partial\rho_\gamma}{\partial T_\gamma} + \frac{\partial\rho_e}{\partial T_\gamma}}.$$

The relevant processes are

$$e^+e^- \leftrightarrow \overline{\nu_i}\nu_i, \; e^\pm\nu_i \leftrightarrow e^\pm\nu_i, \; e^\pm\overline{\nu_i} \leftrightarrow e^\pm\overline{\nu_i},$$

$$\nu_i\nu_j \leftrightarrow \nu_i\nu_j, \; \nu_i\overline{\nu_j} \leftrightarrow \nu_i\overline{\nu_j}, \; \text{and} \; \overline{\nu_i}\nu_i \leftrightarrow \overline{\nu_j}\nu_j$$

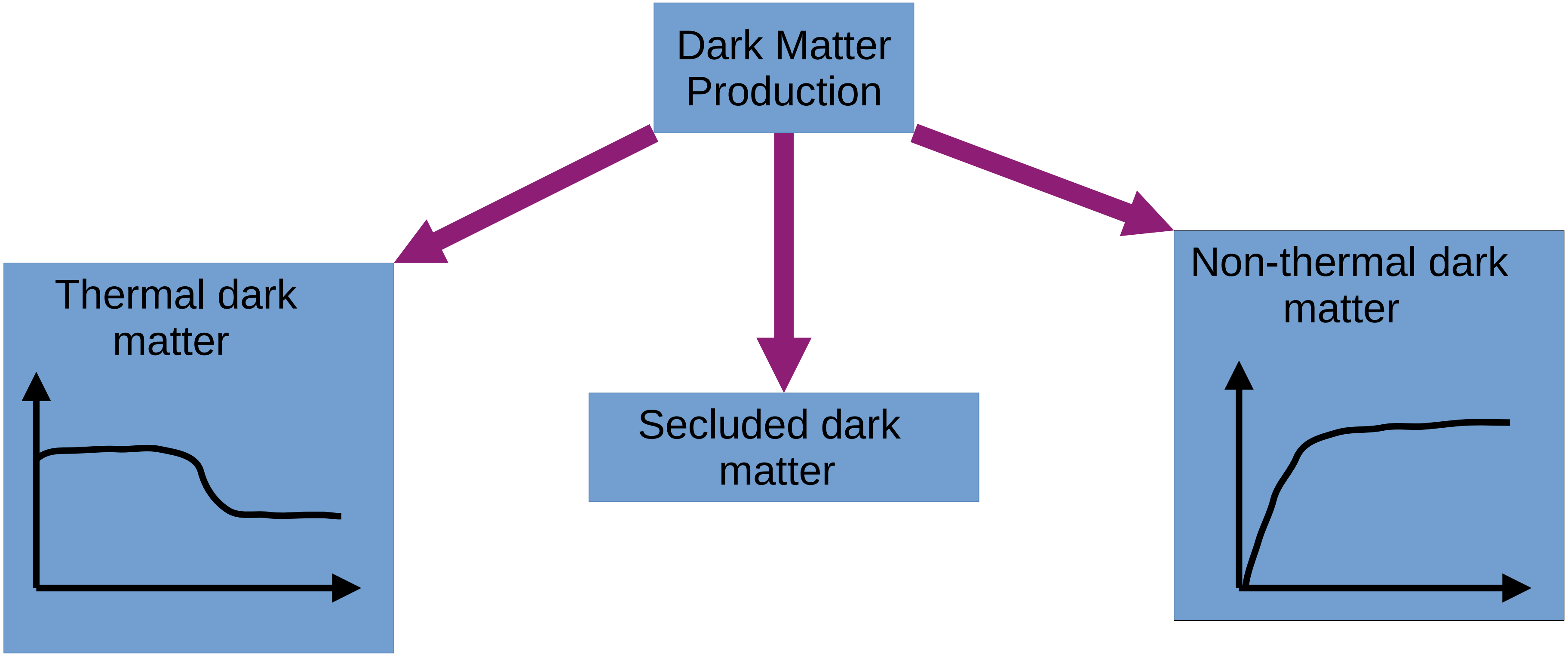
N_{eff} in SM of particle physics



Neutrino Decoupling in the SM	T_γ/T_ν	$N_{\rm eff}$
Instantaneous decoupling	1.4010	3
Instantaneous decoupling + QED	1.3998	3.011
MB collision term	1.3961	3.042
MB collision term + QED	1.3949	3.053

The most precise evaluation predicts $N_{\rm eff,SM}^{\rm CMB} = 3.045$.

N_{eff} in BSM: role of dark matter



Nucl.Phys.B 360 (1991) 145-179

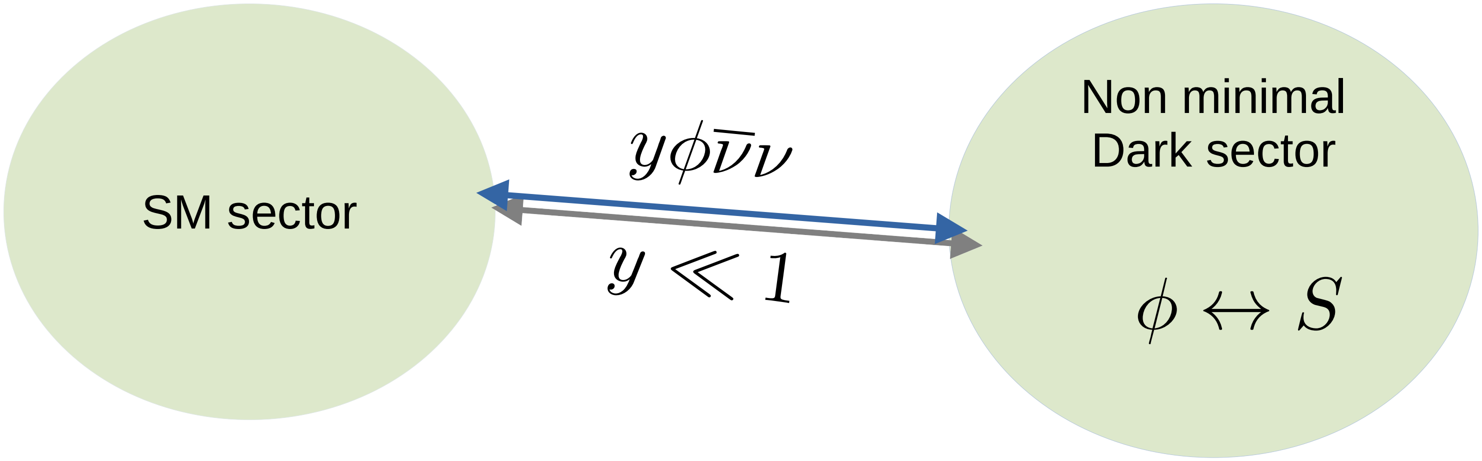
JHEP 03 (2010) 080

Dark Matter		Planck+BAO	
Particle	g-Spin	> 2.66	< 3.33
Majorana DM-ν	2-F	-	8.5
Dirac DM-ν	4-F	-	11.2
ϕ DM-ν	1-B	-	5.7
$\phi^\star$ DM-ν	2-B	-	8.5
Z' DM-ν	3-B	-	10.1
Majorana DM-e	2-F	6.4	-
Dirac DM-e	4-F	9.2	-
ϕ DM-e	1-B	3.5	-
$\phi^\star$ DM-e	2-B	6.5	-
Z' DM-e	3-B	8.1	-

[arXiv: 1812.05605]

Lower bounds on the masses of various thermal dark matter particles (in MeV) at 95% CL.

Neutrino decoupling and N_{eff} in BSM: role of non-thermal secluded dark matter

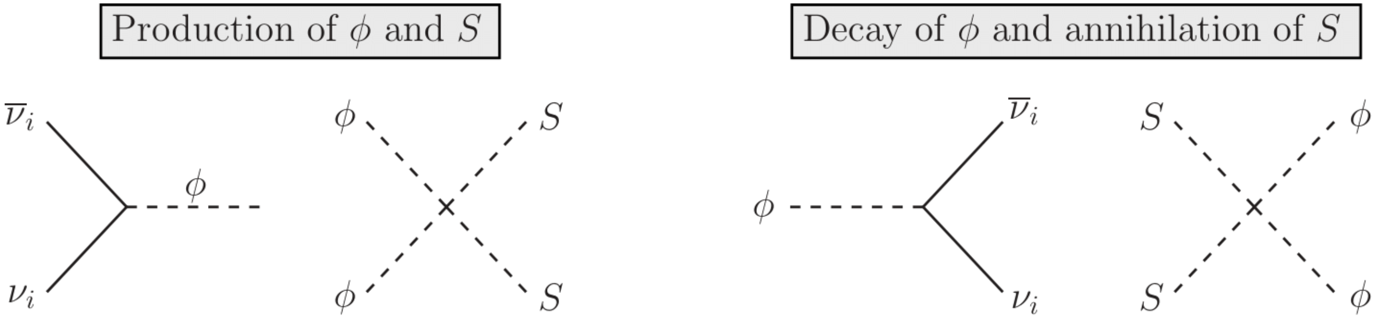


$$-\mathcal{L} \supset \frac{1}{2} m_S^2 S^2 + \frac{1}{2} m_\phi^2 \phi^2 + \frac{\lambda}{4} S^2 \phi^2 + \frac{\kappa}{2} \phi \overline{\nu_i} \nu_i$$

Motivation:

(i) Imprint of such an MeV scale hidden dark sector on N_{eff} at CMB

(ii) Contribution of dark matter *S* on N_{eff}



Model free parameters: $\{m_S, m_\phi, \lambda, y\}$ where $y^2 = \sum_{i=1}^{3} \kappa^2$

- The DS remains secluded, this imposes constraint on *y*.

  This can be quantified by

$$\sum_{i=1}^{3} n_{\nu_i}^{\rm eq} \langle \sigma v \rangle_{\overline{\nu_i}\nu_i \to \phi} < H$$

- We are interested in a situation where the dark sector is in internal thermal equilibrium and it has its own temperature

$$n_S^{\rm eq} \langle \sigma v \rangle_{SS \to \phi\phi} > H$$

Hubble parameter : $H = \sqrt{\frac{8\pi}{3M_{PL}^2}(\rho_\gamma + \rho_\nu + \rho_S + \rho_\phi)}$

$$\frac{dT_\nu}{dt} = \frac{\mathcal{C}_{inel.}(T_\gamma, T_\nu) + \mathcal{C}_{el}(T_\gamma, T_\nu) + \overbrace{\mathcal{C}_{\phi\to\bar{\nu}\nu} - \mathcal{C}_{\bar{\nu}\nu\to\phi}(T_\nu)}^{\text{New physics contribution to } T_\nu} - 4H\rho_\nu}{\frac{\partial\rho_\nu}{\partial T_\nu}},$$

$$\frac{dT_\gamma}{dt} = \frac{-\mathcal{C}_{inel.}(T_\gamma, T_\nu) - \mathcal{C}_{el}(T_\gamma, T_\nu) - 3H(\rho_e + \rho_\gamma) - 3H(p_e + p_\gamma)}{\frac{\partial\rho_\gamma}{\partial T_\gamma} + \frac{\partial\rho_e}{\partial T_\gamma}}.$$

$$\frac{dY_\phi}{dx} = \frac{h_{\rm eff}\, s_\gamma}{xH}\langle\sigma v_{\rm rel}\rangle^{T_D}_{SS\to\phi\phi}\left[Y_S^2 - \left(\frac{Y_S^{\rm eq}(T_D)}{Y_\phi^{\rm eq}(T_D)}\right)^2 Y_\phi^2\right] + \frac{h_{\rm eff}}{xH}\left(\langle\Gamma_\phi\rangle_{T_\nu} Y_\phi^{\rm eq}(T_\nu) - \langle\Gamma_\phi\rangle_{T_D} Y_\phi\right)$$

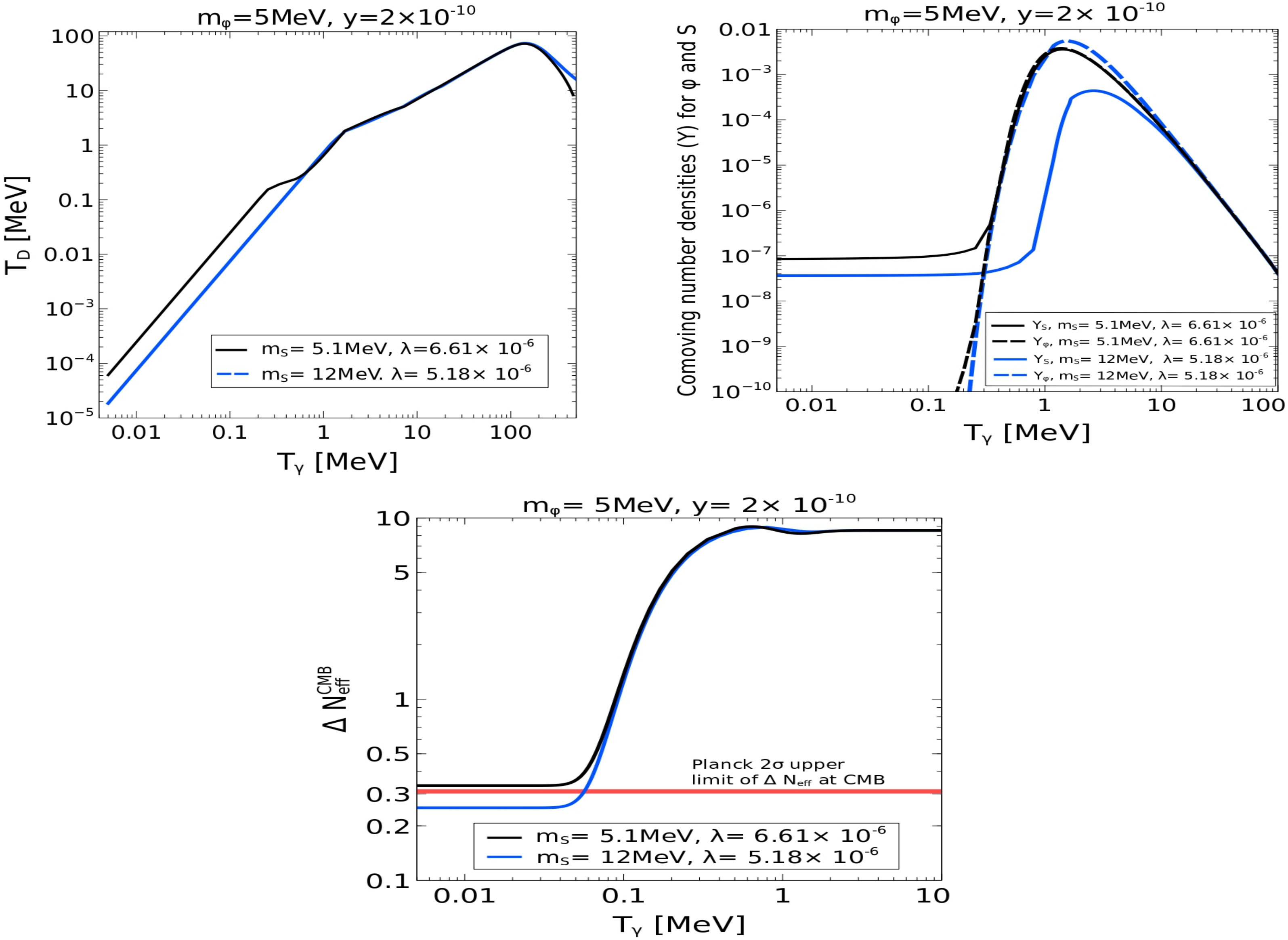
Where we define, $x = \frac{m_S}{T_\gamma}$,

$$\frac{dY_S}{dx} = -\frac{h_{\rm eff}\, s_\gamma}{xH}\langle\sigma v_{\rm rel}\rangle^{T_D}_{SS\to\phi\phi}\left[Y_S^2 - \left(\frac{Y_S^{\rm eq}(T_D)}{Y_\phi^{\rm eq}(T_D)}\right)^2 Y_\phi^2\right]$$

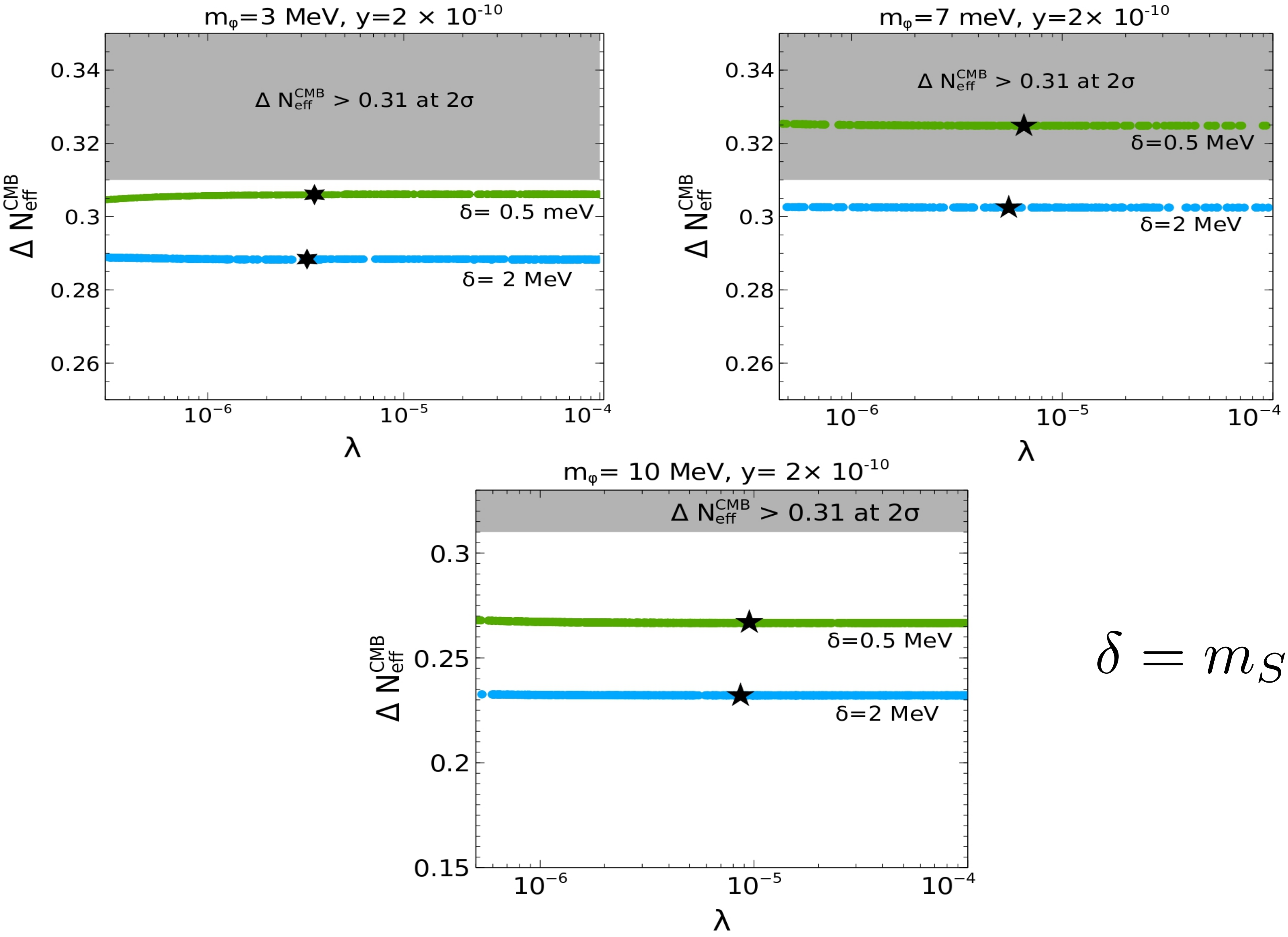
$$F_1 = s_\gamma\langle\sigma v\rangle^{T_D}_{SS\to\phi\phi}\left[Y_S^2 - \left(\frac{Y_S^{\rm eq}(T_D)}{Y_\phi^{\rm eq}(T_D)}\right)^2 Y_\phi^2\right]\left(\rho_S^{\rm eq} Y_\phi^{\rm eq} - \rho_\phi^{\rm eq} Y_S^{\rm eq}\right),$$

$$F_2 = -\rho_\phi^{\rm eq}(T_D) Y_\chi^{\rm eq}(T_D)\left[\langle\Gamma_{\phi\to\nu\nu}\rangle_{T_\nu} Y_\phi^{\rm eq}(T_\nu) - \langle\Gamma_{\phi\to\nu\nu}\rangle_{T_D} Y_\phi\right].$$

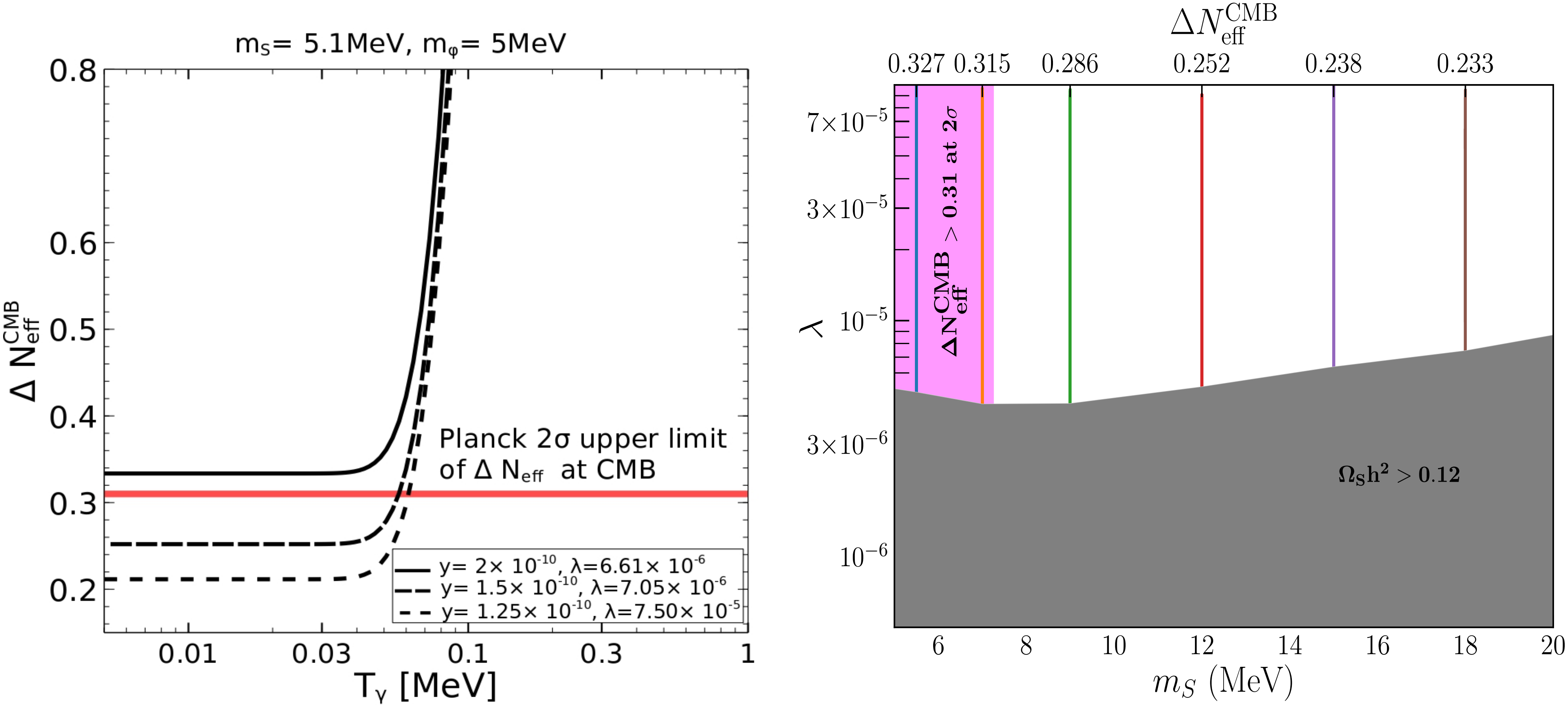
$$\frac{dT_D}{dx} = \frac{s_\gamma Y_\phi^{\rm eq}(T_D) Y_S^{\rm eq}(T_D)\left\{\frac{1}{s_\gamma}\mathcal{C}_{\nu\nu\leftrightarrow\phi} - 3H(Y_\phi + Y_S)T_D\right\} + F_1 + F_2}{xH\sum_{i\neq j} Y_i Y_j^{\rm eq}\left\{\frac{d\rho_i^{\rm eq}}{dT_D} - \frac{1}{n_i^{\rm eq}(T_D)}\frac{dn_i^{\rm eq}(T_D)}{dT_D}\rho_i^{\rm eq}(T_D)\right\}},$$



mφ=5MeV, y=2×10^-10
T_D [MeV]
T_γ [MeV]
m_S= 5.1MeV, λ=6.61× 10^-6
m_S= 12MeV. λ= 5.18× 10^-6
mφ=5MeV, y=2× 10^-10
Comoving number densities (Y) for φ and S
T_γ [MeV]
Y_S, m_S= 5.1MeV, λ= 6.61× 10^-6
Y_φ, m_S= 5.1MeV, λ= 6.61× 10^-6
Y_S, m_S= 12MeV, λ= 5.18× 10^-6
Y_φ, m_S= 12MeV, λ= 5.18× 10^-6
mφ= 5MeV, y= 2× 10^-10
Δ N_eff^CMB
T_γ [MeV]
Planck 2σ upper
limit of Δ N_eff at CMB
m_S= 5.1MeV, λ= 6.61× 10^-6
m_S= 12MeV, λ= 5.18× 10^-6



$$\delta = m_S - m_\phi$$



m_S= 5.1MeV, m_φ= 5MeV
0.8
0.6
0.5
0.4
0.3
0.2
ΔN_{eff}^{CMB}
Planck 2σ upper limit
of Δ N_{eff} at CMB
y= 2× 10^{-10}, λ=6.61× 10^{-6}
y= 1.5× 10^{-10}, λ=7.05× 10^{-6}
y= 1.25× 10^{-10}, λ=7.50× 10^{-5}
0.01
0.03
0.1
0.3
1
T_γ [MeV]
$\Delta N_{\rm eff}^{\rm CMB}$
0.327
0.315
0.286
0.252
0.238
0.233
7×10^{-5}
3×10^{-5}
10^{-5}
3×10^{-6}
10^{-6}
λ
$\Delta N_{\rm eff}^{\rm CMB} > 0.31$ at 2σ
$\Omega_S h^2 > 0.12$
6
8
10
12
14
16
18
20
m_S (MeV)

Conclusions

1. We obtain unique predictions for the ΔN_{eff} for a particular DM mass that satisfies the relic density bound with suitable value of λ, provided mass of the other scalar and its coupling strength with the SM neutrinos are fixed.

2. The dark matter mass has a nontrivial role on the prediction of ΔN_{eff}. The predictions for ΔN_{eff} turns out to be maximum in the nearly degenerate spectrum of dark sector particles and consideration of an increased hierarchy CMB between the dark sector particles reduces the impact of dark matter mass on ΔN_{eff}. We also find that prediction CMB for ΔN_{eff} is insensitive to the dark sector interaction rate, provided the dark thermal equilibrium is reached.

3. Increasing m_ϕ upto a certain value keeping other parameters (y, λ and δ) fixed, enhances ΔN_{eff} hence restricted by the present Planck limit. When m_ϕ is too large, the effect on ΔN_{eff} of ϕ diminishes.

4. For a particular m_ϕ with a constant y, we are able to impose a lower bound on the DM mass from the Planck 2σ CMB data on ΔN_{eff}. As an example we find $m_S \gtrsim 7$ MeV when $m_\phi = 5$MeV and $y = 2 \times 10^{-10}$. Additionally, a lower bound on λ can be derived such that the DM relic abundance remain below 0.12 as experimentally favored.

5. Finally, the upcoming CMB stage-IV experiment with improved sensitivity can probe the allowed region of model parameter space.