FIMP Dark Matter from Leptogenesis in Fast Expanding Universe

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Introduction

- Beyond standard model evidences —

  neutrino mass, baryon asymmetry, dark matter

- Common origin for BSM —

  νMSM, Scotogenic Model, sterile neutrino portal model ...

- Model Structure —
  - Sterile neutrinos N with the type-I seesaw mechanism
  - Baryon asymmetry is generated via the thermal leptogenesis
  - Dark sector: scalar singlet ϕ, fermion singlet χ under Z_2 symmetry
- The relevant Yukawa interactions and mass terms are

$$-\mathcal{L} = y\bar{L}\tilde{H}N + \lambda\bar{\chi}\phi N + \frac{1}{2}\overline{N^C}m_N N + m_\chi\bar{\chi}\chi + \text{h.c.}. \quad (1)$$

Introduction

- About the dark scalar ϕ —
  - For m_ϕ below electroweak scale, the dominant decay is $\phi \to \chi\nu$

$$\Gamma_{\phi\to\chi\nu} = \frac{\lambda^2}{16\pi}\frac{m_\nu}{m_N}m_\phi\left(1-\frac{m_\chi^2}{m_\phi^2}\right)^2 . \tag{2}$$

  - Decaying DM when its lifetime is larger than the age of Universe.
  - A scalar singlet S with the condition $m_\phi \sim m_S/2$

- In the standard cosmology the Universe is radiation dominant after inflation until Big Bang Nucleosynthesis.
- Scalar filed φ with energy density red-shifts as $\rho_\varphi \propto a^{-(4+n)}$
- Lead to a fast expanding Universe (FEU) when $n > 0$
- The period of FIMP DM generation from leptogenesis is right between inflation and BBN

A Fast Expanding Universe

In SC, radiation is the dominant component before BBN

$$\rho_r(T) = \frac{\pi^2}{30} g_*(T) T^4, \tag{3}$$

The Hubble parameter, is related to the radiation as

$$H_r(T) = \sqrt{\frac{8\pi G \rho_r(T)}{3}} = 1.66\sqrt{g_*(T)}\frac{T^2}{M_p}, \tag{4}$$

In a FEU, scalar component φ coexists with the radiation

$$\rho_\varphi \sim a^{-(4+n)}, n > 0. \tag{5}$$

Assuming entropy conservation $S = sa^3$ and using the relation $\rho_r(T) \propto g_*(T)T^4$ in Eqn. (3), we can have

$$\rho_\varphi(T) = \rho_r(T)\frac{g_*(T_r)}{g_*(T)}\left(\frac{g_{*s}(T)}{g_{*s}(T_r)}\right)^{\frac{4+n}{3}}\left(\frac{T}{T_r}\right)^n. \tag{6}$$

A Fast Expanding Universe

Therefore, the total energy density can be expressed as

$$\rho(T) = \rho_r(T) + \rho_\varphi(T) = \rho_r(T)\left[1 + \frac{g_*(T_r)}{g_*(T)}\left(\frac{g_{*s}(T)}{g_{*s}(T_r)}\right)^{\frac{4+n}{3}}\left(\frac{T}{T_r}\right)^n\right]. \quad (7)$$

The typical temperature for leptogenesis $T \sim M_N \gtrsim 10^9$ GeV, $g_*(T) = g_{*s}(T) = 106.75$ as a constant. Then

$$\rho(T) = \rho_r(T)\left[1 + \left(\frac{T}{T_r}\right)^n\right]. \quad (8)$$

The Hubble parameter in a fast expanding Universe is modified by

$$H(T) = 1.66\sqrt{g_*}\frac{T^2}{M_p}\left[1 + \left(\frac{T}{T_r}\right)^n\right]^{\frac{1}{2}} = H_r(T)\left[1 + \left(\frac{T}{T_r}\right)^n\right]^{\frac{1}{2}}. \quad (9)$$

FIMP DM from Leptogenesis in SC

The CP asymmetry is generated by out-of-equilibrium CP-violating decays of Majorana neutrino.

$$\varepsilon = -\frac{3}{16\pi(y^\dagger y)_{11}} \sum_{j=2,3} \mathrm{Im}\left[\left(y^\dagger y\right)^2_{1j}\right] \frac{M_1}{M_j}. \tag{10}$$

Casas-Ibarra parametrization of Yukawa coupling

$$y = \frac{\sqrt{2}}{v} U_{\mathrm{PMNS}} \hat{m}_\nu^{1/2} R (\hat{m}_N)^{1/2}, \tag{11}$$

Davidson-Ibarra bound on ε can be derived

$$|\varepsilon| \lesssim \frac{3}{16\pi} \frac{M_1 m_3}{v}. \tag{12}$$

FIMP DM from Leptogenesis in SC

The evolution of abundance Y_{N_1}, Y_χ and lepton asymmetry Y_L is described by the Boltzmann equations

$$\frac{dY_{N_1}}{dz} = -D_r(Y_{N_1} - Y_{N_1}^{eq}), \tag{13}$$

$$\frac{dY_L}{dz} = -\varepsilon D_r(Y_{N_1} - Y_{N_1}^{eq}) - W_r Y_L, \tag{14}$$

$$\frac{dY_\chi}{dz} = D_r\, Y_{N_1} \mathrm{BR}_\chi, \tag{15}$$

The decay and washout terms are

$$D_r(z) = Kz\frac{\mathcal{K}_1(z)}{\mathcal{K}_2(z)}, W_r(z) = \frac{1}{4}Kz^3\mathcal{K}_1(z), \tag{16}$$

The decay parameter K is defined as

$$K = \frac{\Gamma_1}{H_r(z=1)}, \tag{17}$$

FIMP DM from Leptogenesis in FEU

Boltzmann equations have the same form as the standard cosmology

$$\frac{dY_{N_1}}{dz} = -D(Y_{N_1} - Y_{N_1}^{eq}), \tag{18}$$

$$\frac{dY_L}{dz} = -\varepsilon D(Y_{N_1} - Y_{N_1}^{eq}) - WY_L, \tag{19}$$

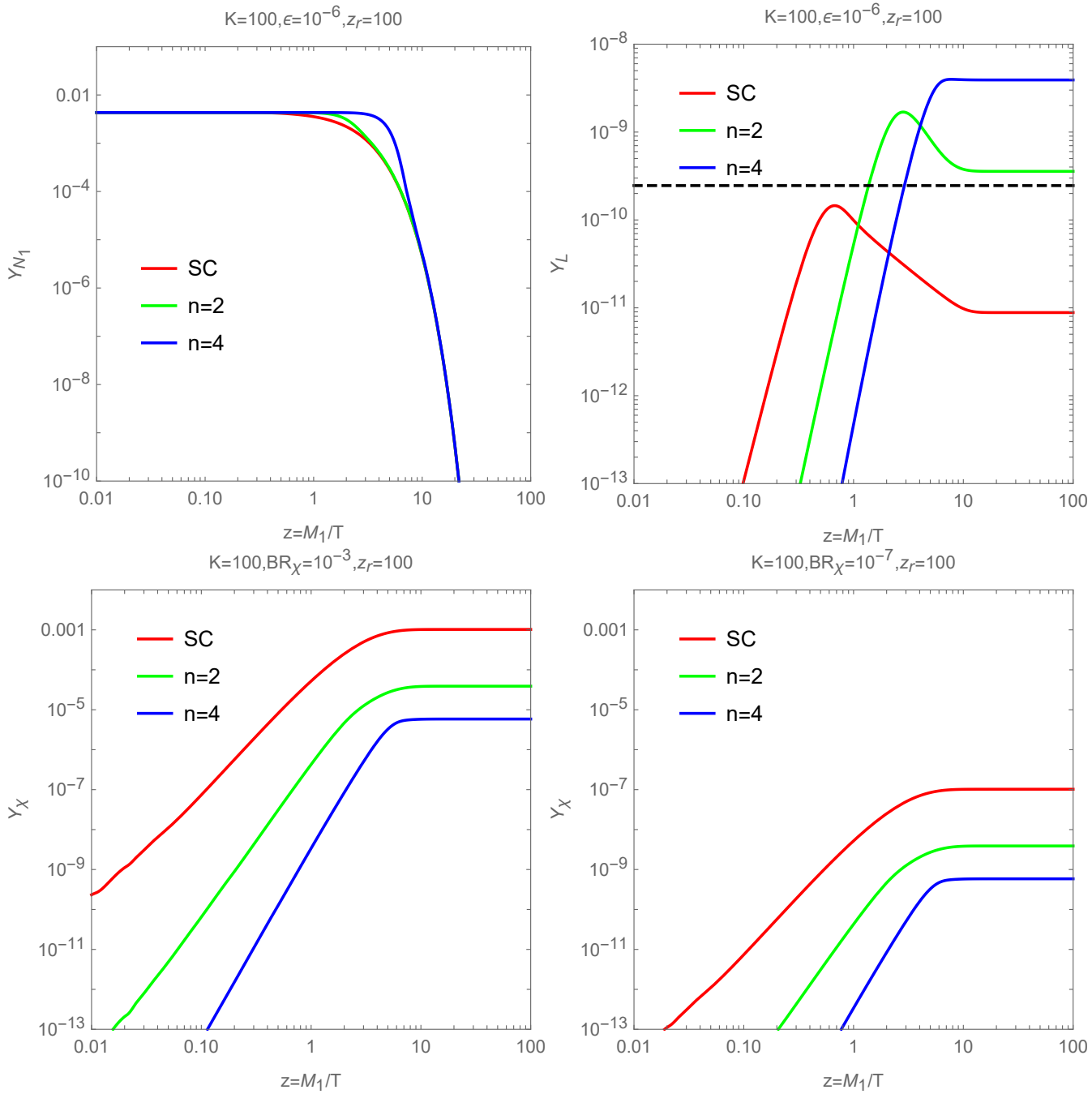
$$\frac{dY_\chi}{dz} = D\, Y_{N_1}\mathrm{BR}_\chi, \tag{20}$$

but the decay and washout terms are modified as

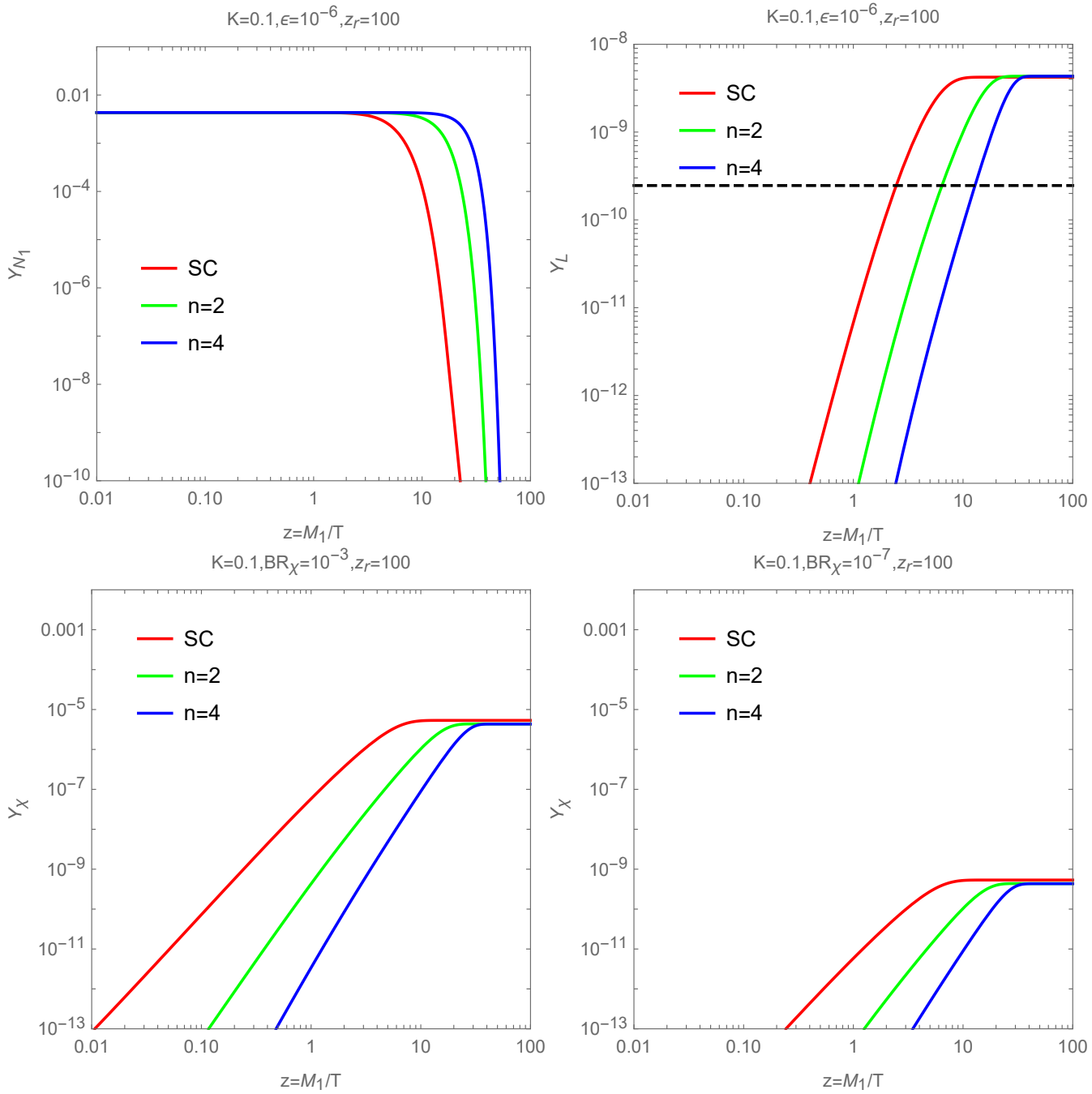
$$D(z) = Kz\frac{\mathcal{K}_1(z)}{\mathcal{K}_2(z)}\left[1+\left(\frac{z_r}{z}\right)^n\right]^{-1/2}, W(z) = \frac{1}{4}Kz^3\mathcal{K}_1(z)\left[1+\left(\frac{z_r}{z}\right)^n\right]^{-1/2},$$

The lepton asymmetry is converted into the baryon asymmetry via the sphaleron processes

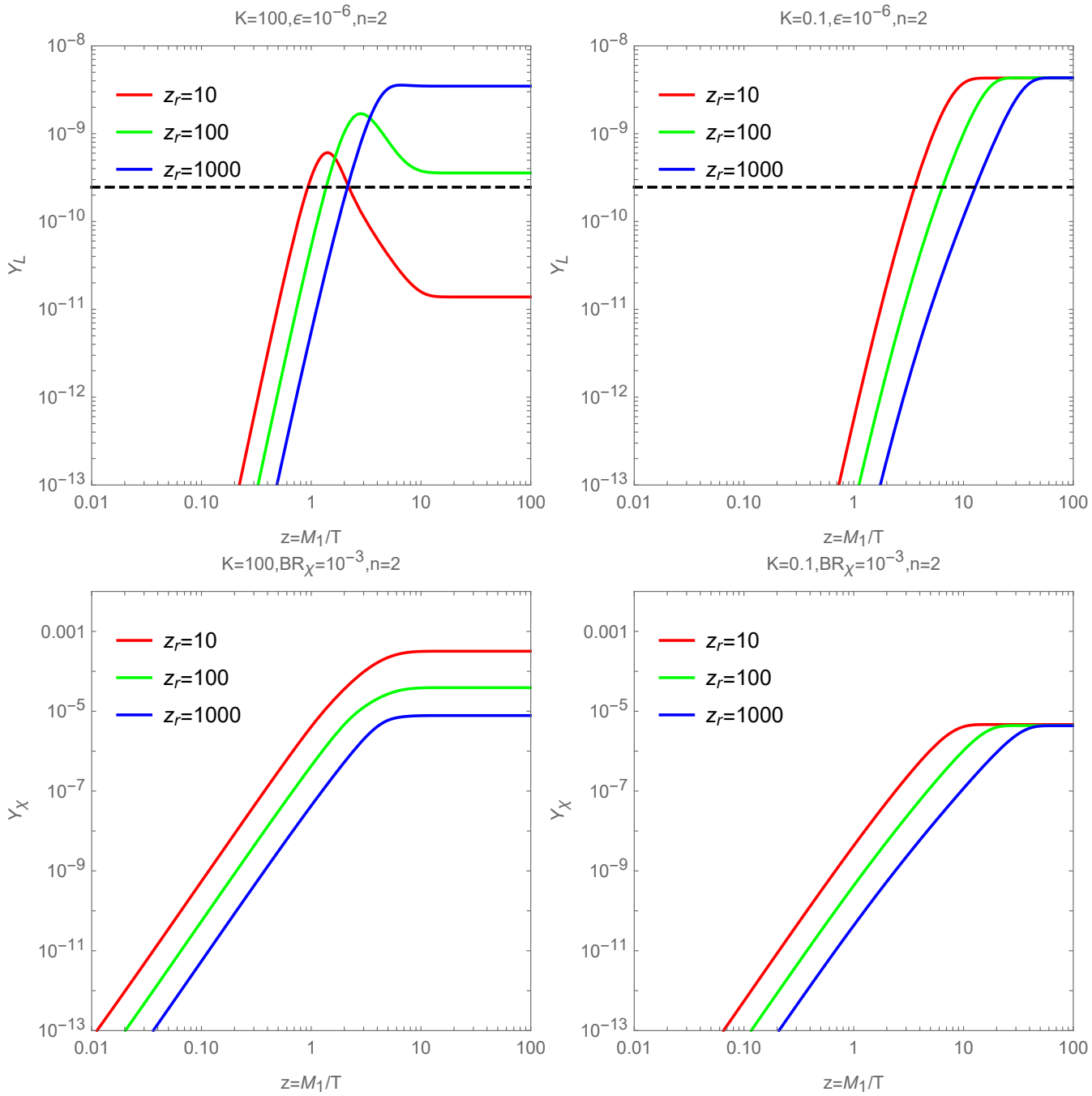
$$Y_B = \frac{28}{79}Y_L, \tag{21}$$



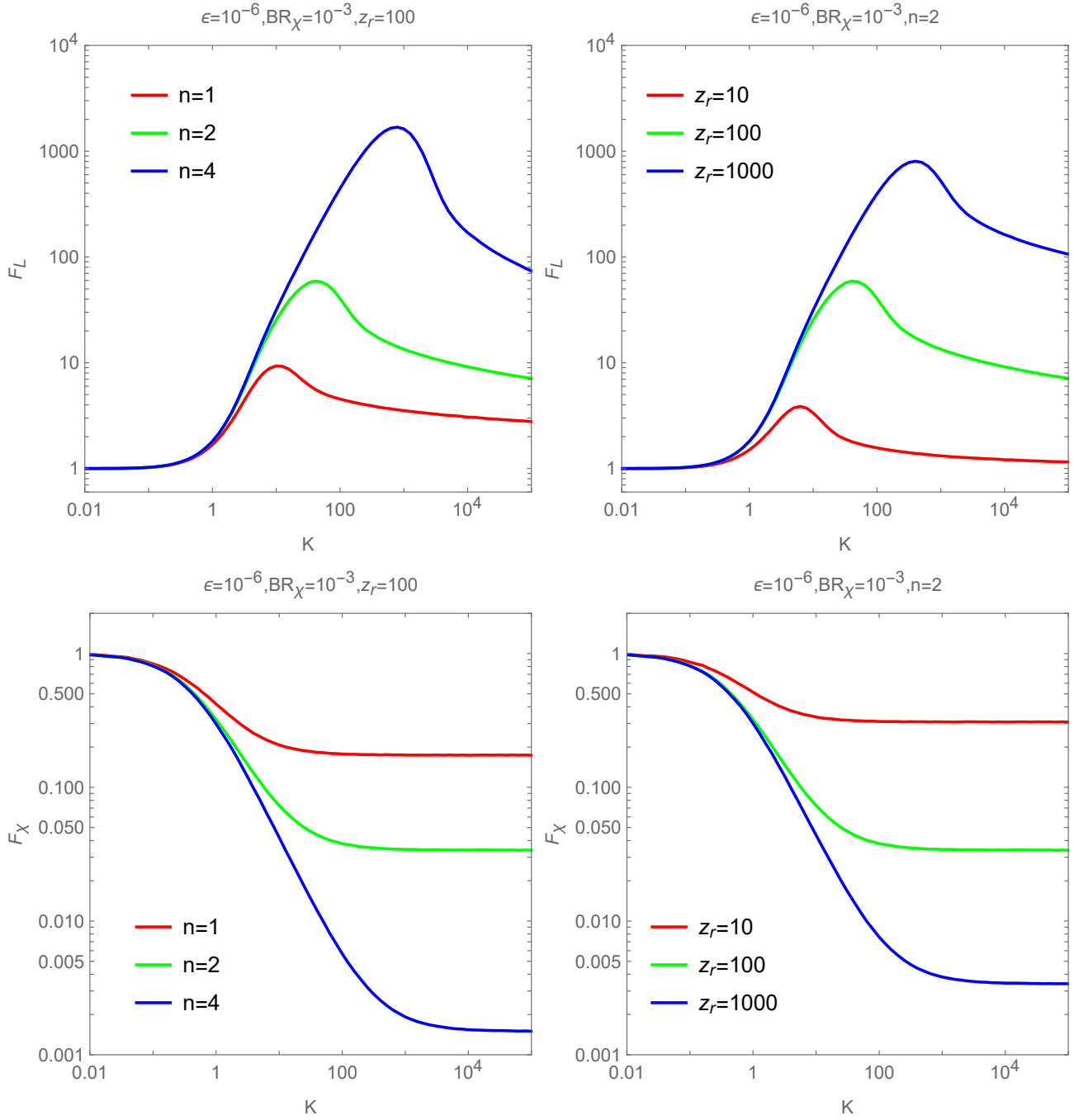
- Impact of parameter n for strong washout.
- Y_L increases as the parameter n increases
- Y_χ decreases as the parameter n increases



- Impact of parameter n for weak washout.
- Production of Y_L and Y_χ are postponed. But the final lepton asymmetry and DM abundance are of the same order for different n.



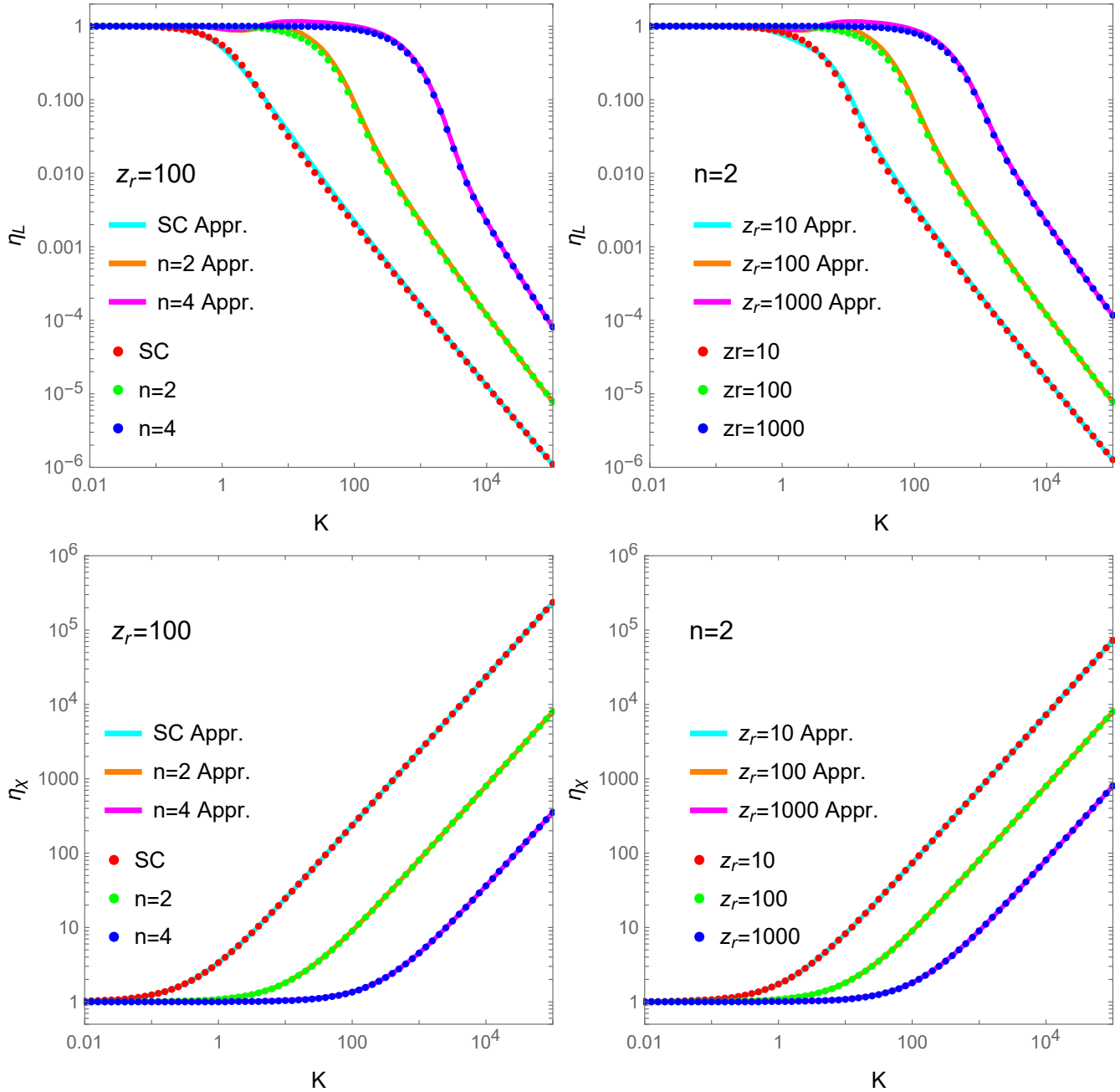
- Impact of parameter z_r.
- In the strong washout case, modifications of z_r will have a great impact on the evolution of Y_L and Y_χ.
- In the weak washout case, the impact is small.



- The scale factors F_L and F_χ as a function of K.

$$F_L = \frac{Y_L^{\text{FEU}}(\infty)}{Y_L^{\text{SC}}(\infty)},$$

$$F_\chi = \frac{Y_\chi^{\text{FEU}}(\infty)}{Y_\chi^{\text{SC}}(\infty)}.$$

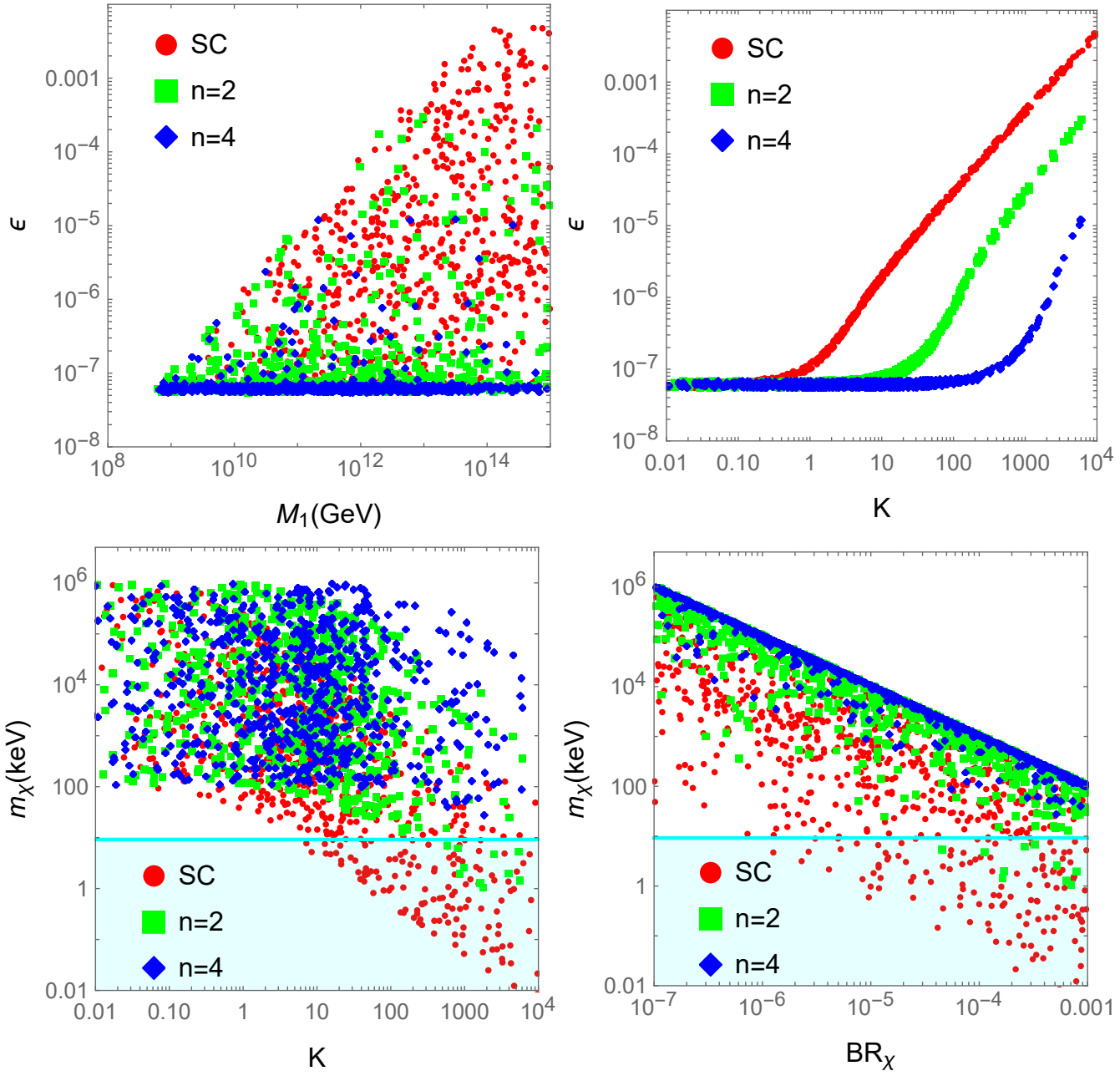


- The efficiency factors η_L and η_χ as a function of K

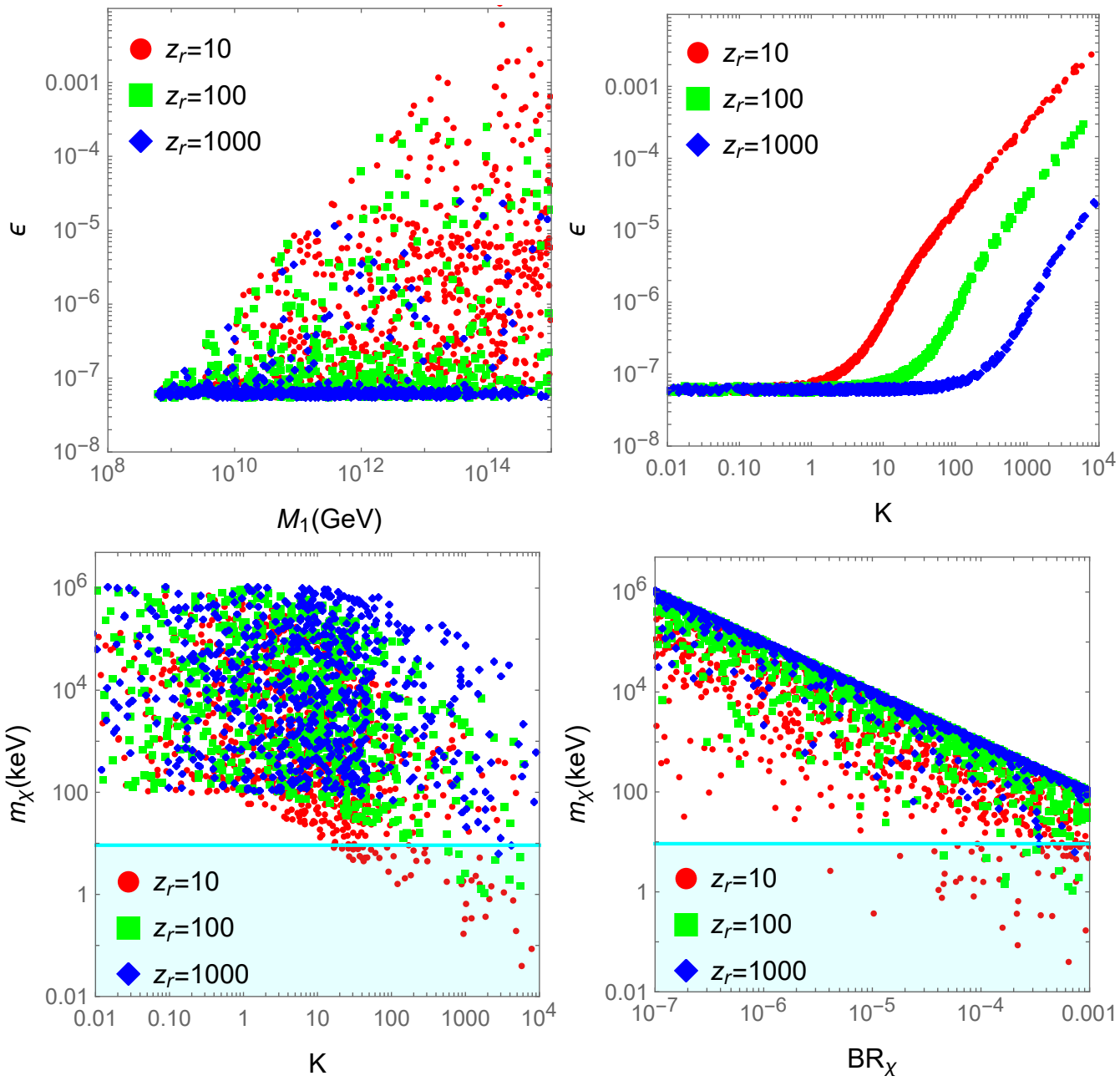
$$\eta_L^{\rm SC} \simeq \frac{1}{1+1.3K\ln(1+K)^{0.8}}$$

$$\eta_\chi^{\rm SC} \simeq 1+\frac{3\pi}{4}K.$$

$$\eta_L^{\rm FEU} = \eta_L^{\rm SC} F_L^{\rm FEU},$$
$$\eta_\chi^{\rm FEU} = \eta_\chi^{\rm SC} F_\chi^{\rm FEU}.$$



- Scanned results for SC and FEU with n=2, 4. For FEU, we take $z_r = 100$ to illustrate.
- For the FIMP DM χ, it is required $m_\chi > 9.2$ keV to satisfy all limits.



- Scanned results for FEU with $z_r = 10, 100, 1000$. Here, we take $n = 2$ to illustrate.

Conclusion

- Sterile neutrino portal model provides a common origin for neutrino mass, baryon asymmetry and DM.
- For weak washout scenario $K \lesssim 1$, modifications of final lepton asymmetry Y_L and DM abundance Y_χ are relatively small in FEU.
- But for strong washout case $K \gtrsim 1$, the final $Y_L(Y_\chi)$ could be increased (suppressed) by several orders of magnitudes.
- However, it seems hard to figure out explicit values of the two parameters n and z_r when only considering the results of FIMP DM from leptogenesis.