Freeze in of fermionic dark matter through Flavon Portal

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Published in JHEP 07 (2023) 143
(arXiv:2305.03167)

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Motivation: Why, Which, How

In spite of being very successful in explaining the electroweak scale phenomenon, Standard Model has its own limitations. Within this model framework, it fails to explain

- Neutrino mass
- Dark Matter Abundance
- Origin of fermion mass hierarchy and the list continues...

These facts provide strong motivation for going Beyond Standard Model(BSM). In our model, we try to take care of two problems at a time

- Origin of fermion mass hierarchy
- Dark matter abundance

Finally, How? $\rightarrow$ Rest of poster is our answer to that.

Model Description

The gauge group of our model is $SM \otimes U(1)_{FN}$. The Standard Model particle spectrum is augmented by two particles

- A complex scalar

$$S = \frac{1}{\sqrt{2}}\left(h_S + v_S + iA_S\right)$$

- A Majorana fermion, χ

Complex scalar creates the mass hierarchy in the quark sector and plays as the mother particle for dark matter where as χ plays the role of stable dark matter.

Frogatt-Nielson Mechanism in a nutshell

An introduction to Froggatt-Nielsen mechanism

$$\mathcal{L}_{\rm SM}^{\rm FN-Yuk} = -y_{ij}^{(u)}\left(\frac{S}{\Lambda}\right)^{n_{ij}^u} Q_i H u_j^c - y_{ij}^{(d)}\left(\frac{S}{\Lambda}\right)^{n_{ij}^d} Q_i \tilde{H} d_j^c - y_{ij}^{(e)}\left(\frac{S}{\Lambda}\right)^{n_{ij}^e} L_i \tilde{H} e_j^c + h.c.$$

Considering FN charge of S to be -1, from $U(1)_F N$ invariance, we get

$$n_{ij}^d = a_{Q_i} + q_H + a_{d_j},\; n_{ij}^u = a_{Q_i} - a_H + a_{u_j}$$

The $U(1)_{FN}$ symmetry is broken when S acquires vev v_S

$$\frac{S}{\Lambda} \rightarrow \epsilon = \frac{\langle S\rangle}{\Lambda} = \frac{v_S}{\sqrt{2}\Lambda} \approx 0.225$$

$$Y_{ij}^{(u)} = y_{ij}^{(u)}\epsilon^{n_{ij}^u}, \quad Y_{ij}^{(d)} = y_{ij}^{(d)}\epsilon^{n_{ij}^d}, \quad Y_{ij}^{(e)} = y_{ij}^{(e)}\epsilon^{n_{ij}^e}\,. \tag{1}$$

The flavour constraints of this flavon scenario with the following charge assignment has been discussed thoroughly in our paper:

$$\begin{pmatrix} a_{Q_1} & a_{Q_2} & a_{Q_3} \\ a_{u_1} & a_{u_2} & a_{u_3} \\ a_{d_1} & a_{d_2} & a_{d_3} \\ a_{L_1} & a_{L_2} & a_{L_3} \\ a_{e_1} & a_{e_2} & a_{e_3} \end{pmatrix} = \begin{pmatrix} 4 & 2 & 0 \\ 4 & 2 & 0 \\ 4 & 3 & 3 \\ 4 & 3 & 3 \\ 4 & 2 & 0 \end{pmatrix}$$

It successfully produces the fermion mass hierarchy and CKM matrix.

Dark Matter Phenomenology

To construct a model with minimal degrees of freedom, we chose a Majorana fermion as our dark matter candidate. The dark sector lagrangian looks like

$$\mathcal{L}_{\rm DM} = \frac{1}{2}\bar{\chi}\left(i\gamma^\mu\partial_\mu\right)\chi - y_\chi\left(\frac{S}{\Lambda}\right)^{2n-1} S\bar{\chi^c}\chi + h.c \tag{2}$$

where n is the $U(1)_{FN}$ charge of DM χ. Now n plays a crucial role here.

- For n being half integer, the dark matter is stable.
- For n being a little high, it can create freeze in coupling naturally.

The next step is to check the necessary conditions for non-thermal production of χ.

Necessary condition for non-thermal production of Dark Matter

As χ is produced from the decay of S, we check if S is in thermal equilibrium by comparing its interaction rate (Γ) to Hubble expansion rate(H). Similarly we check if χ is out of equilibrium from the thermal bath.

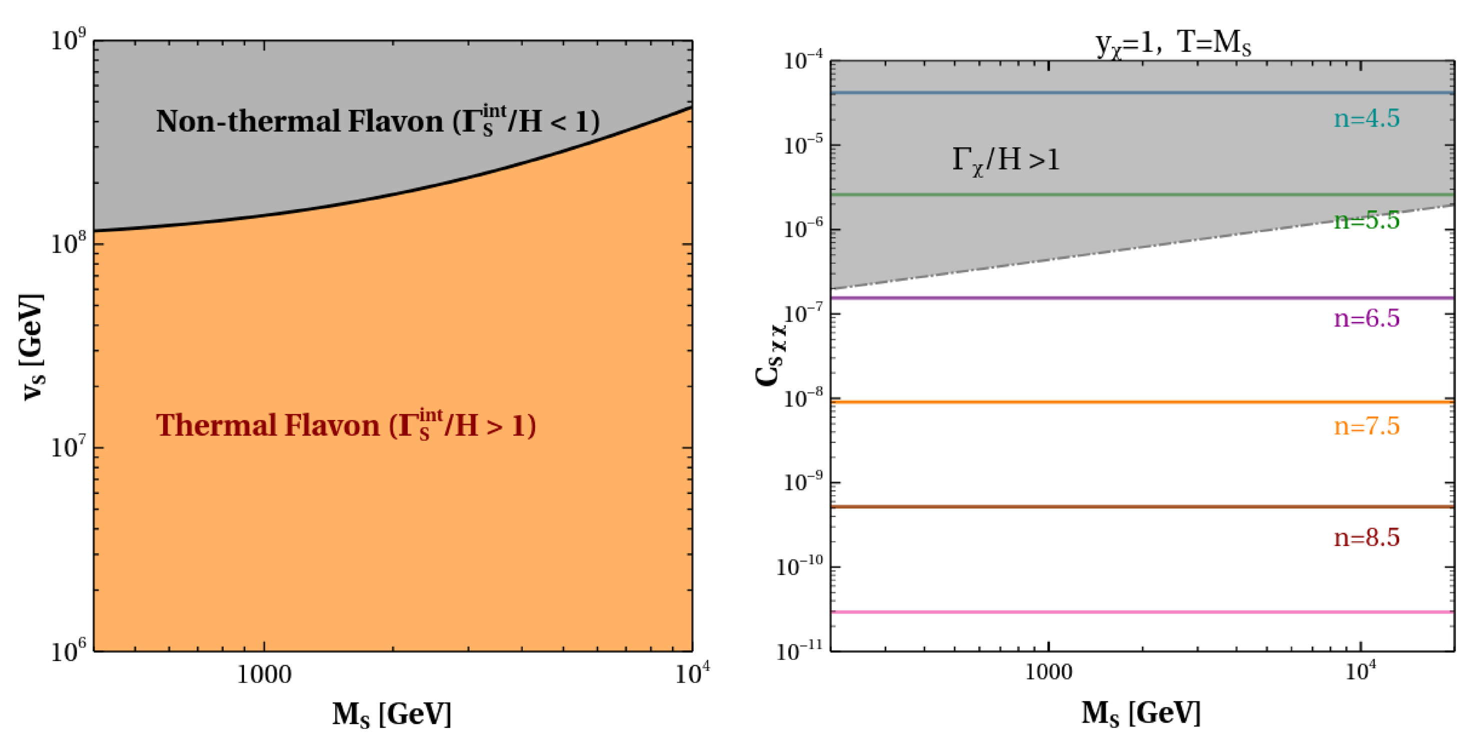

Fig. 1: *(Left) Thermalisation of flavon in v_S vs M_S plane. (Right) Region in $C_{S\chi\chi}$ vs M_S plane where χ is non-thermal.*

Boltzman equation

By solving these two coupled Boltzman equations of S and χ, we can calculate the relic abundance.

$$\frac{dY_\chi}{dz} = \frac{\langle\Gamma(S\to\chi\chi)\rangle}{\mathcal{H}\,z}Y_S(z) + \frac{4\pi^2}{45}\frac{M_{Pl}M_S}{1.66}\frac{\sqrt{g_\star(z)}}{z^2}\langle\sigma v_{SS\to\chi\chi}\rangle\, Y_S^2(z) \tag{3}$$

$$\frac{dY_S}{dz} = -\frac{\langle\Gamma(S\to\chi\chi)\rangle}{\mathcal{H}\,z}Y_S(z) - \frac{4\pi^2}{45}\frac{M_{Pl}M_S}{1.66}\frac{\sqrt{g_\star(z)}}{z^2}\langle\sigma v_{SS\to\chi\chi}\rangle\, Y_S^2(z) \tag{4}$$

+ Other interaction terms with Standard Model

Solution of Boltzman equation

Here we see that the parent particle S in thermal equilibrium.

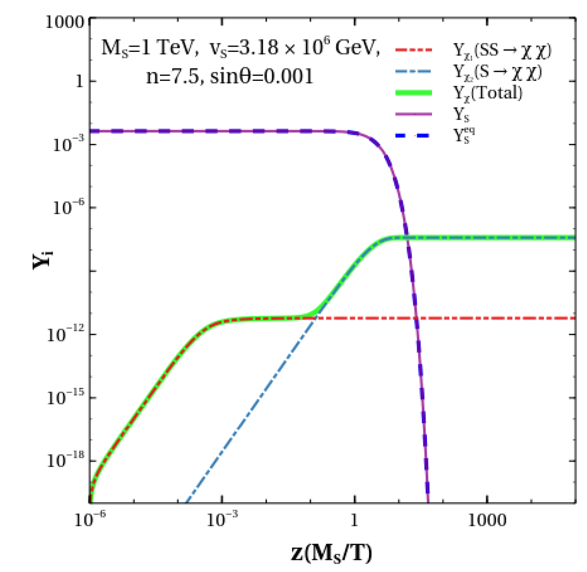

Fig. 2: *Evolution of the DM comoving number density and the flavon comoving number density as a function of z.*

Dark Matter Abundance

Finally we explore the correct relic abundance satisfied parameter space in our model.

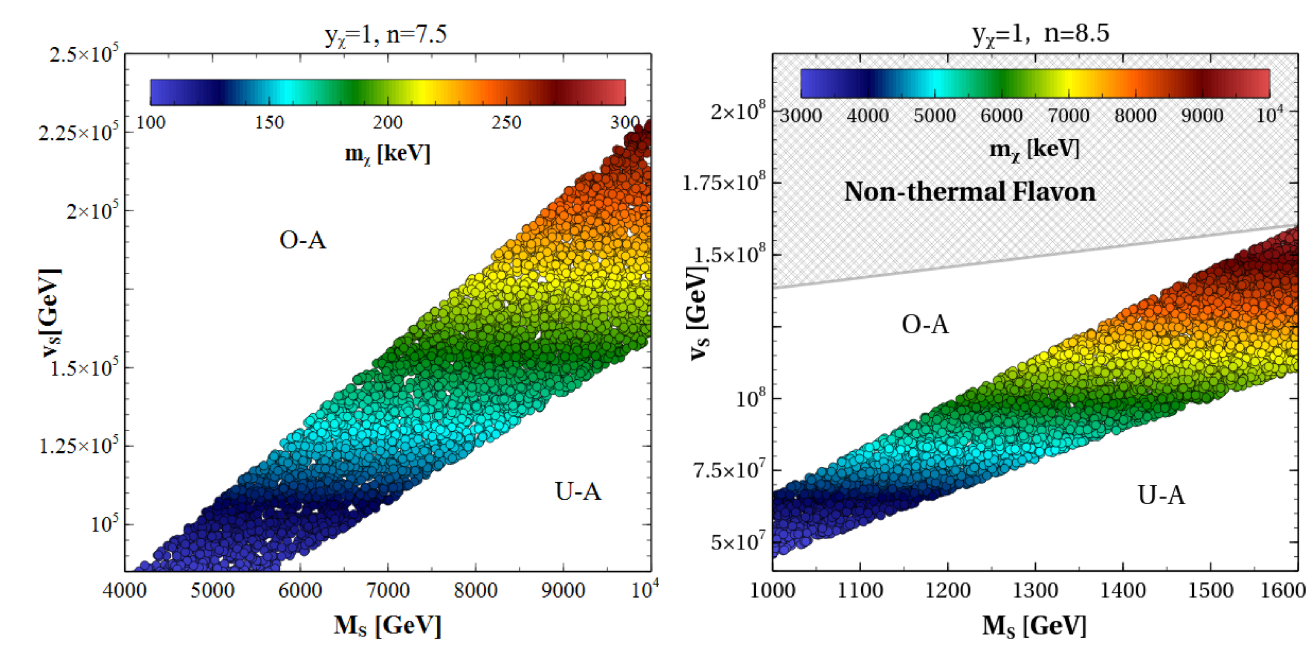

Fig. 3: *Observed dark matter abundance parameter space is shown in $v_S - M_S$ plane for two different choices of n values: (a) $n = 7.5$ (left panel) and (b) $n = 8.5$ (right panel).*

Conclusion

- In this work, we have proposed a unified solution to the fermion mass hierarchy and a FIMP dark matter within a class of $U(1)_{\rm FN}$ extensions of the Standard Model.
- We have shown a preferred range for the DM mass, which is $(100 - 300)$ keV and $(3 - 10)$ MeV, corresponding to $n = 7.5$ and 8.5 respectively.
- We have done this analysis for the global case. Analysing a gauged $U(1)_{FN}$ scenario with a thermal dark sector can provide us some interesting phenomenology.