Longevity Problem of Sterile Neutrino Dark Matter

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Introduction

・One of the biggest mysteries
in particle physics and cosmology : Dark matter

・Its existence has already been confirmed by many observation
but in fact we don't know what it is, so far.

・Properties of DM

*Electrically neutral

*Warm or cold

*Stable on a cosmological time scale

This doesn't mean necessarily dark matter is completely stable!

Introduction

- Neutrinos have the tiny masses

$$\Delta m^2_{\rm atm} = 2.6 \times 10^{-21}{\rm GeV}^2\,,\ \Delta m^2_{\rm sol} = 7.6 \times 10^{-23}{\rm GeV}^2$$

D. V. Forero et al. Phys. Rev. D **86** (2012)

- Right-handed neutrinos (RHνs) + seesaw mechanism

$$\mathcal{L} = i\bar{N}_I\gamma^\mu\partial_\mu N_I - \left(\lambda_{I\alpha}\bar{N}_I L_\alpha H + \frac{1}{2}M_I\bar{N}^c_I N_I + {\rm h.c.}\right)$$

Integrating out N_I

$$(m_\nu)_{\alpha\beta} = \lambda_{\alpha I}\lambda_{I\beta}\frac{v^2_{\rm EW}}{M_I}$$

*Supposing $|\lambda_{\alpha I}| \sim \mathcal{O}(1)$, $M_I \sim 10^{15}{\rm GeV}$ ⇨ $m_\nu \sim 0.1{\rm eV}$

However…

Mass spectrum of RHνs can be non-trivial.

Sterile neutrino dark matter

- Hierarchical structure among RHν masses can be realized in Froggatt-Nielsen (FN) framework.

$$\mathcal{L} = i\bar{N}_I \gamma^\mu \partial_\mu N_I - \left(\lambda_{I\alpha} \bar{N}_I L_\alpha H + \frac{1}{2} M_I \bar{N}_I^c N_I + \text{h.c.} \right)$$

If only N_1 is charged under some flavor symmetry,

$$M_1 = x^2 M$$
$$|\lambda_{1\alpha}| = x_\alpha$$

$$(m_\nu)_{\alpha\beta} \supset \lambda_{1\alpha}^2 \frac{v_{\rm EW}^2 v_{\rm EW}^2 v_{\rm EW}^2}{x^2 M M_1 M} \quad (x \sim x_\alpha)$$

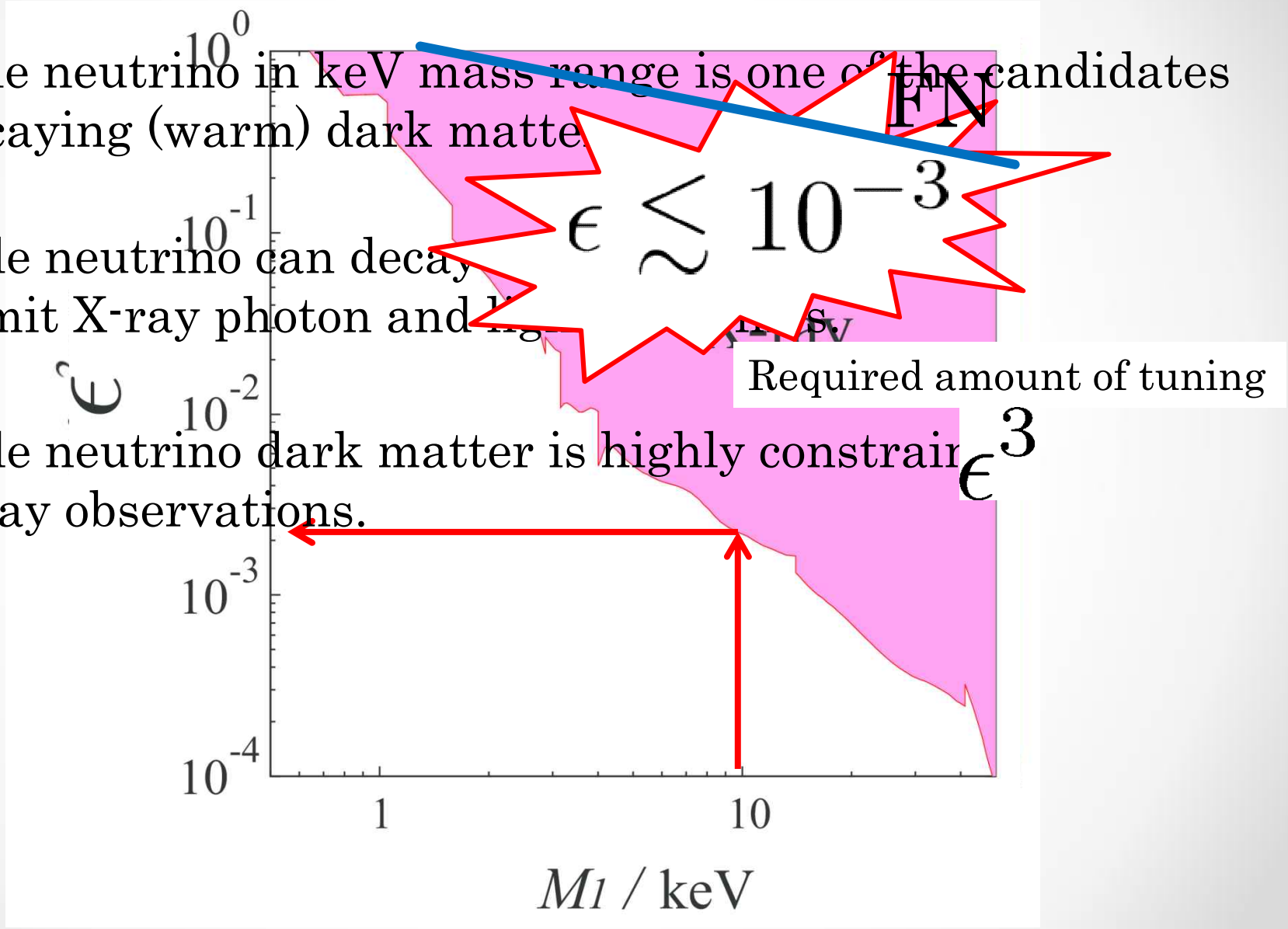
Seesaw formula is still preserved!

- Important parameter

$$\epsilon^2 \equiv \sum_\alpha \frac{x_\alpha^2}{x^2} \sim 1 \text{ (in this simple FN model)}$$

Longevity problem

- Sterile neutrino in keV mass range is one of the candidates for decaying (warm) dark matter.
- Sterile neutrino can decay and emit X-ray photon and light neutrino.
- Sterile neutrino dark matter is highly constrained by X-ray observations.



[K.S. Jeong, F. Takahashi and H.I (2013)]

Split flavor mechanism

[K.S. Jeong, F. Takahashi and H.I (2013)]

- Set up

Standard Model + 3 Right-handed Neutrinos $N_I = (N_1 , N_i)$ + 2 B-L Higgs Φ , Φ' + Flavor Symmetry

Though both Φ and Φ' are charged under B-L,
only Φ' and N_1 are charged non-trivially under flavor symmetry.

Split flavor mechanism

[K.S. Jeong, F. Takahashi and H.I (2013)]

- Charge assignments

	Φ	Φ'	N_1	N_i	L_α	H
$\mathrm{U}(1)_{\mathrm{B-L}}$	2	$-2n$	-1	-1	-1	0
Z_4	0	-1	$+1$	0	0	0

$(n > 0)$

- Lagrangian

$$-\Delta\mathcal{L} = \frac{1}{2}\kappa_i \Phi \bar{N}_i^c N_i + \lambda_i \bar{N}_i L H$$

$$+ \frac{1}{2}\kappa_1 \frac{\left(\Phi^{2n-1}\Phi'^2\right)^*}{M_p^{2n}} \bar{N}_1^c N_1 + \tilde{\lambda}\frac{\left(\Phi^n \Phi'\right)^*}{M_p^{n+1}} \bar{N}_1 L H + \mathrm{h.c.}$$

From now on $\langle\Phi\rangle \sim \langle\Phi'\rangle \sim M \sim 10^{15}\mathrm{GeV}$

Split flavor mechanism

[K.S. Jeong, F. Takahashi and H.I (2013)]

- Dark matter mass

$$M_1 \approx \left(\frac{M}{M_p}\right)^{2n} M \sim 10\mathrm{keV} \ (n=3)$$

- Yukawa couplings

$$\lambda_{1\alpha} \approx \left(\frac{M}{M_p}\right)^{n+1} \sim 10^{-14} \ (n=3)$$

$$\epsilon \approx \frac{M}{M_p} \sim 10^{-3} \ll 1$$

- Mixing angle

$$\theta_1^2 \simeq 2 \times 10^{-12} \left(\frac{m_{\mathrm{seesaw}}}{0.1\mathrm{eV}}\right) \left(\frac{M_1}{10\mathrm{keV}}\right) \left(\frac{M}{10^{15}\mathrm{GeV}}\right)$$

The emitted X-ray may be observed at future experiments!

Cosmological Aspects

- DM is produced via s-channel exchange of B-L gauge boson

*The abundance

$$\Omega_{\rm DM}h^2 \sim 0.3 \left(\frac{M_1}{10{\rm keV}}\right)\left(\frac{g_*}{100}\right)^{\frac{3}{2}}\left(\frac{M}{10^{15}{\rm GeV}}\right)^{-4}\left(\frac{T_R}{5\times 10^{13}{\rm GeV}}\right)^{3}$$

-Assumption : B-L symmetry is spontaneously broken during and after inflation

- In this set up, the baryon asymmetry of the universe is also created by thermal leptogenesis.

This scenario can explain dark matter, neutrino masses and the baryon asymmetry of the universe simultaneously!

Conclusions

- We have studied the possibility of sterile neutrino as a candidate of decaying dark matter.

*Simple FN mechanism is plagued with the longevity problem.

*To solve this, we have proposed split flavor mechanism.

-In this mechanism, we have introduced multiple B-L Higgs and single flavor symmetry in which one of B-L Higgs is charged under flavor symmetry.

Longevity problem can be solved naturally!

Predicted X-ray flux is just below the current bound!

Our model will be test at future experiments.

Thank you for you attention!

Back Up

U(1) flavor symmetry case

$\left(\Phi^a \Phi'^b\right)^* \bar{N} L H$ and $\Phi \left(\Phi^a \Phi'^b\right)^2 \bar{N}_1^c N_1$ are allowed.

where a and b are coprime positive integer.

If $\Phi \left(\Phi^a \Phi'^b\right)^2 \bar{N}_1^c N_1$ is dominant contribution

Recall

$M_1 = x^2 M$

$|\lambda_{1\alpha}| = x_\alpha$

$$x^2 = \left(\frac{M}{M_p}\right)^{2(a+b)} \quad , x_\alpha = \left(\frac{M}{M_p}\right)^{a+b}$$

$\epsilon \sim 1$: Longevity problem can not be solved

Split flavor mechanism (n=0)

- In the case of Φ' is neutral under B-L symmetry…

$$-\Delta\mathcal{L} = \frac{1}{2}\kappa_i \Phi \bar{N}_i^c N_i + \lambda_i \bar{N}_i L H + \frac{1}{2}\kappa_1 \frac{(\Phi\Phi'^2)}{M_p^2}\bar{N}_1^c N_1 + \tilde{\lambda}\frac{\Phi'}{M_p}\bar{N}_1 L H + \text{h.c.}$$

$$\Longrightarrow \quad x^2 \approx \left(\frac{M}{M_p}\right)^2 \quad \Longrightarrow \quad \epsilon \sim 1$$

$$x_\alpha \approx \frac{M}{M_p}$$

Longevity problem can not be solved