Singlet portal extensions of the standard seesaw models to dark sector with local dark symmetry: An alternative to the new minimal standard model

S. Baek, P. Ko, W.-I. Park

School of Physics, KIAS, Seoul 130-722, Korea

Assuming dark matter is absolutely stable due to unbroken dark gauge symmetry and singlet operators are portals to the dark sector, we present a simple extension of the standard seesaw model that can accommodate all the cosmological observations as well as terrestrial experiments available as of now, including leptogenesis, extra dark radiation of $\sim 8\%$ (resulting in $N_{\rm eff} = 3.130$ the effective number of neutrino species), Higgs inflation, small and large scale structure formation, and current relic density of scalar DM (X). The Higgs signal strength is equal to one as in the SM for unbroken $U(1)_X$ case with a scalar dark matter, but it could be less than one independent of decay channels if the dark matter is a dark sector fermion or if $U(1)_X$ is spontaneously broken, because of a mixing with a new neutral scalar boson in the models.

1 Introduction

The standard model (SM) based on $SU(3)_C \times SU(2)_L \times U(1)_Y$ is confirmed at quantum level with high accuracy, although there are a few places where the SM predictions do not reproduce the observations such as the muon $(g-2)$, top forward-backward asymmetry or ...

Still the SM has to be extended in order to accommodate the following observations: (i) neutrino masses and mixings, (ii) baryogenesis, (iii) nonbaryonic cold dark matter of the universe, and (iv) inflation and density perturbation.

For the 1st and the 2nd items, the most economic and aesthetically attractive idea is to introduce singlet right-handed neutrinos and the seesaw mechanism, and leptogenesis for baryon number asymmetry. For the 3rd item, there are many models for cold dark matter, from axion to lightest superparticles to hidden sector DMs, to name a few. For the 4th item the simplest inflation model without new inflaton fields would be R^2 inflation by Starobinsky [1] and Higgs inflation [2].

In nonsupersymmetric dark matter models, one often assumes ad hoc Z_2 symmetry in order to stabilize DM, without deeper understanding of its origin or asking if it is global or local discrete symmetry. If we assume that global symmetry is not protected by quantum gravity effects, this Z_2 symmetry would be broken by $1/M_{\rm Planck}$ suppressed nonrenormalizable operators [6]. Then the electroweak scale DM can not live long enough to be dark matter candidate of the universe. The simplest way to guarantee the stability of EW scale DM is to assume the DM carries its own gauge charge which is absolutely conserved. Then we are led

to local dark symmetry and dark gauge force. This would be a very natural route for the DM model building, since the unsurpassed successful SM is based on local gauge symmetry and its spontaneous breaking.

If weak scale DM carried nonzero SM gauge charges, it would be strongly constrained by direct detection cross section as well as electroweak precision observables and flavor physics. Therefore we assume the DM is neutral under the SM gauge interaction, and making a hidden sector. Hidden sector is quite common in many models beyond the SM, including SUSY models or superstring theories. For example, huge rank gauge group in the string theory would eventually break down to $G_{\text{SM}} \times G_{\text{hidden}}$, where G_{hidden} is nothing but the dark gauge symmetry acting on hidden sector dark matter. If G_{hidden} is unbroken, DM particles will be absolutely stable, like the electron is absolutely stable due to electric charge conservation. If dark gauge coupling is strong and dark gauge interaction is confining like ordinary QCD, the DM would be the lightest composite hadrons in the hidden sector. In this case it is possible to generate all the mass scales of the SM particles as well as the DM mass from dimensional transmutation in the hidden sector strong interaction [3]. If dark gauge coupling is weak, we can employ the standard perturbation method to analyze the problems, which we adopt in the model described in this talk.

Another guiding principle is renormalizability of the model. The present authors found that one would get erroneous results if the effective Lagrangian approach is used for singlet fermion or vector DM with Higgs portal [4, 5].

Finally we generalize the notion of Higgs portal to the singlet portal, assuming that the singlet operators in the standard seesaw model make portals to the dark sector. Note that there are only 3 singlet operators: $H^\dagger H$, N_R and the kinetic mixing between $U(1)_X$ and $U(1)_Y$ field strength tensors.

In this talk, I present a simple renormalizable model where the dark matter lives in a dark (hidden) sector with its own dark gauge charge along with dark gauge force. We mainly discuss the unbroken $U(1)_X$ dark gauge symmetry, and briefly mention what happens if $U(1)_X$ is spontanesouly broken. This talk is based on Ref. [6], to which we invite the readers for more detailed discussions on the subjects described in this talk.

2   Model

As explained in Introduction, we assume that dark matter lives in a hidden sector, and it is stable due to unbroken local $U(1)_X$ dark gauge symmetry. All the SM fields are taken to be $U(1)_X$ singlets. Assuming that the RH neutrinos are portals to the hidden sector, we need both a scalar (X) and a Dirac fermion (ψ) with the same nonzero dark charge (see Table 1). Then the composite operator $\psi X^\dagger$ becomes a gauge singlet and thus can couple to the RH neutrinos N_{Ri}'s [1].

With these assumptions, we can write the most general renormalizable Lagrangian as follows:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_X + \mathcal{L}_\psi + \mathcal{L}_{\text{portal}} + \mathcal{L}_{\text{inflation}} \tag{1}$$

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[1]If we did not assume that the RH neutrinos are portals to the dark sector, we did not have to introduce both ψ and X in the dark sector. This case is discussed in brief in Sec. 8.

where $\mathcal{L}_{\text{SM}}$ is the standard model Lagrangian and

$$\mathcal{L}_X = \left| \left(\partial_\mu + i g_X q_X \hat{B}'_\mu \right) X \right|^2 - \frac{1}{4} \hat{B}'_{\mu\nu} \hat{X}^{\mu\nu} - m_X^2 X^\dagger X - \frac{1}{4} \lambda_X \left(X^\dagger X \right)^2 \tag{2}$$

$$\mathcal{L}_\psi = i \bar{\psi} \gamma^\mu \left(\partial_\mu + i g_X q_X \hat{B}'_\mu \right) \psi - m_\psi \bar{\psi} \psi \tag{3}$$

$$\mathcal{L}_{\text{kin-mix}} = -\frac{1}{2} \sin \epsilon \, \hat{B}'_{\mu\nu} \hat{B}^{\mu\nu} - \frac{1}{2} \lambda_{HX} X^\dagger X H^\dagger H \tag{4}$$

$$- \frac{1}{2} M_i \overline{N_{Ri}^C} N_{Ri} + \left[Y_\nu^{ij} \overline{N_{Ri}} \ell_{Lj} H^\dagger + \lambda^i \overline{N_{Ri}} \psi X^\dagger + \text{H.c.} \right] \tag{5}$$

$$\mathcal{L}_{\text{inflation}} = \left[\xi_H H^\dagger H + \xi_X X^\dagger X \right] R \tag{6}$$

g_X, q_X, $\hat{B}'_\mu$ and $\hat{B}'_{\mu\nu}$ are the gauge coupling, $U(1)_X$ charge, the gauge field and the field strength tensor of the dark $U(1)_X$, and R is the scalar curvature, respectively. $\hat{B}_{\mu\nu}$ is the gauge field strength of the SM $U(1)_Y$. We assume $m_X^2 > 0$, $\lambda_X > 0$, $\lambda_{HX} > 0$, so that the local $U(1)_X$ remains unbroken and the scalar potential is bounded from below at tree level.

This model has only 3 more fields compared to the standard seesaw models, and is based on local gauge principle related with absolutely stable DM. And unbroken dark symmetry implies massless dark photon which contributes to dark radiation of the universe, and Higgs

3 Implications on particle physics and cosmology

Our model is simple enough, but has sufficiently rich structures, so that it can accommodate various observations from cosmology and astrophysics related with (self-interacting) dark matter and dark radiation, and inflation with correct relic density of the DM.

- Dark scalar X can improve the stability of the electroweak vacuum up to Planck scale, unlike the SM. For the mass of SM-like Higgs, $m_h \sim 125\,\text{GeV}$ hinted by the recent data from LHC experiments, with $m_t = 173.2\,\text{GeV}$ and $\alpha_s = 0.118$, the problem of vacuum instability is cured if $\lambda_X > 0$ and $\lambda_{HX} \gtrsim 0.2$.

- Perturbativity of quartic couplings for scalar fields H and X up to Planck scale puts theoretical constraints on λ_X and λ_{HX} such that $\lambda_X \lesssim 0.2$ and $\lambda_{HX} \lesssim 0.6$.

- Massless dark photon mediates long range between dark matter, and can solve the small scale problem of DM subhalo while satisfying constraints from inner structure and kinematics of dark matter halos. This will constrain the dark gauge coupling strength to be $g_X \lesssim 2.5 \times 10^{-2} \left(m_X/300\,\text{GeV} \right)^{3/4}$.

- If dark fermion ψ were lighter than X and became DM, then its thermal relic density would be too large since it can annihilate only into a pair of dark photon ($\sigma_{\text{ann}} v \propto g_X^4$). On the contrary the dark scalar X can be diluted efficiently even if g_X is very small, since there is a Higgs portal term which makes $XX^\dagger \leftrightarrow$ (SM particles).

- Direct detection experiments such as XENON100 and CDMS put strong bound on the combination of the gauge kinetic mixing $10^{-12} \lesssim \epsilon g_X \lesssim 10^{-5}$ for $6\,\text{GeV} \lesssim m_X \lesssim 1\,\text{TeV}$ when the upper bound on g_X is used.

- Massless dark photon would contribute to the number of effective neutrinos which can be measured accurately by Planck satellite and others. We find that dark photon contributes to dark radiation by ~ 0.08, which is in agreement with the recent measurement by Planck, $\Delta N_{\text{eff}} = 3.30 \pm 0.27$ at 68% CL.

- The decay of right-handed(RH) neutrinos generate both matter and dark matter thanks to see-saw mechanism. However the asymmetric component of dark matter disappears as the heavy dark fermion ψ decays eventually. Interestingly, the late decay of ψ also generates visible sector lepton number asymmetry which can be large enough to match the observation.

- Higgs inflation can work in our model since the gauge singlet scalar coupled to SM Higgs field cures the instability of potential in Higgs-singlet system. Inflation along the SM Higgs direction does not pose any new constraint on the model parameters.

- In case $U(1)_X$ is unbroken, the Higgs signal strength should be equal to "1", independent of production and decay channels. If we consider other variations of the model with broken $U(1)_X$ or only dark scalar or dark fermion, the number of Higgs-like scalar bosons can be more than one, with universally reduced Higgs signal strength. See Table 1 for summary

In conclusion, we presented a simple extension of the standard seesaw model where dark matter physics is constructed with local dark gauge symmetry. It has only 2 or 3 more fields compared with the standard seesaw models, is very simple due to local gauge principle, but has rich enough structure for thermalization and self interaction of dark matter, dark radiation, stable EW vacuum, Higgs inflation etc.

Dark sector fields	$U(1)_X$	Messenger	DM	Extra DR	μ_i
$\hat{B}'_\mu, X, \psi$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, N_R$	X	~ 0.08	$1\ (i=1)$
$\hat{B}'_\mu, X$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}$	X	~ 0.08	$1\ (i=1)$
$\hat{B}'_\mu, \psi$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, S$	ψ	~ 0.08	$< 1\ (i=1,2)$
$\hat{B}'_\mu, X, \psi, \phi$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, N_R$	X or ψ	~ 0	$< 1\ (i=1,2)$
$\hat{B}'_\mu, X, \phi$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}$	X	~ 0	$< 1\ (i=1,2)$
$\hat{B}'_\mu, \psi$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, S$	ψ	~ 0	$< 1\ (i=1,2,3)$

Table 1: Dark fields in the hidden sector, messengers, dark matter (DM), the amount of dark radiation (DR), and the signal strength(s) of the i scalar boson(s) (μ_i) for unbroken or spontaneously broken (by $\langle\phi\rangle \neq 0$) $U(1)_X$ models considered in this work. The number of Higgs-like neutral scalar bosons could be 1,2 or 3, depending on the scenarios.

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