Warm Dark Matter in Two Higgs Doublet Models
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Abstract
We show that a neutral scalar field $\sigma$ of two Higgs doublet extensions of the Standard Model incorporating the seesaw mechanism for neutrino masses can be identified as a consistent warm dark matter candidate with a mass of order keV. The relic density of $\sigma$ is correctly reproduced by virtue of the late decay of a right-handed neutrino N participating in the seesaw mechanism. Constraints from cosmology determine the mass and lifetime of N to be $M_N \sim 25$ GeV - 20 TeV and $\tau_N \sim 10^{-4} - 1$ sec. These models can also explain the 3.5 keV X-ray anomaly in the extra-galactic spectrum that has been recently reported in terms of the decay $\sigma \rightarrow \gamma\gamma$. Future tests of these models at colliders and in astrophysical settings are outlined.

Two Higgs Doublet Model for Warm DM
- The two Higgs doublet fields are denoted as $\Phi_1$ and $\Phi_2$ with a discrete $Z_2$ symmetry acting only on $\Phi_2$.
- While $\Phi_1$ acquires a vev of 174 GeV, $<\Phi_2> = 0$, $Z_2$ remains unbroken and the lightest member of the $\Phi_2$ doublet will be stable.
- We identify one of the neutral members of $\Phi_2$ as the WDM with a mass of order keV while neutral scalar and the charged scalar have masses $\sim$ few hundred GeV.
- Three $Z_2$ even singlet neutrinos, N, are introduced and neutrino masses are generated via the seesaw mechanism.

Electroweak Precision data and Constraints
- The precision EW parameters S, T receive additional contribution from the 2nd Higgs doublet.
- $T = 0.01 \pm 0.12$ and $S = -0.03 \pm 0.10$ are satisfied by charged higgs and pseudo scalars masses in range of 150-200 GeV.

Late decay of RH neutrino N
- One of the heavy RH neutrinos (N) participates in late decay with lifetime of $(10^{-4} - 1)$ sec.
- Such a decay is necessary to dilute the warm DM abundance, which would otherwise be too large.
- If kinematically allowed, N would have 2 body decays into $h\nu; W^\pm e^\mp, Z_\nu$. These decays arise through the $\nu-N$ mixing.
- When $m_N < 80$ GeV, 3 body decays involving virtual W and Z will be dominant.

Relic Abundance of Warm Dark Matter $\sigma$
- Since $\sigma$ has thermal abundance, it turns out that relic abundance today is too large compared to observations.
- This situation is remedied in the model by the late decay of $\nu_N$, the RH neutrino present in the seesaw sector.
- The freeze out temperature is computed to be $T_F \sim 150$ MeV, the relic abundance is given by:

$$\Omega_\sigma = 9.02 \left( \frac{17.25}{g_{eff}} \right) \left( \frac{m_\sigma}{1 \text{ keV}} \right)$$

- Here we have normalized $g_{eff} = 17.25$ appropriate for the freeze out temperature of $\sigma$. We see from this Equation that for a keV warm dark matter, $\Omega_\sigma$ is a factor of 34 larger than the observed value of 0.265.

Dilution of $\sigma$ abundance via late decay of N
- A dilution in the abundance of $\sigma$ is realized. For this the decay temperature $T_F$ should be above 1 MeV, so that BBN is not affected. The desired range for the lifetime of N is thus $N = (10^{-4} - 1)$ sec.

- Allowed parameter space of the model in the $M_N-\chi_N$ plane is shown. The shaded region corresponds to the decay temperature $T_F$ of N lying in the range 150 MeV-1 MeV. The three solid curves generate the correct dark matter density $\Omega_0$ for three different values of the WDM mass $m_\sigma = 3.5; 7; 15$ keV.
- The Final abundance of $\sigma$ is computed as:

$$\Omega_\sigma = (0.265) \left( \frac{m_\sigma}{1 \text{ keV}} \right) \left( \frac{7.87}{M_N} \right) \left( \frac{1}{\tau_N} \right) \left( \frac{g_{eff}}{106.75} \right) \left( \frac{17.25}{g_f} \right)$$

- From Eqn we see that the correct relic abundance of $\sigma$ can be obtained for $M_N \sim 10$ GeV and $\tau_N \sim 1$ sec.
- The mass of N should lie in the range $M_N = 25$ GeV - 20 TeV for the correct abundance of dark matter.

Other Implications of the Model
1. The extra-galactic X-ray anomaly:
- Recently two independent groups have reported the observation of a peak in the extra-galactic X-ray spectrum at 3.55 keV
- Softly breaking the $Z_2$ symmetry with inducing a vev u in the range $u = (0.03 - 0.09)$ eV can generate the reported signal.
- Decay rate is given by:

$$\Gamma (\sigma \rightarrow \gamma\gamma) = \left( \frac{\alpha}{4\pi} \right)^2 \frac{F_W^2}{W^2} \left( \frac{u^2}{v^2} \right) \frac{g_F m_\sigma^3}{8\sqrt{2}\pi}$$

2. Collider signals
- The charged scalar $H^\pm$ of the model can be pair produced at the LHC via the Drell-Yan process. $H^+$ will decay into $W^+ + \sigma$.
- Sensitivity for these charged scalars would require 300 fb$^{-1}$ luminosity of LHC running at 14 TeV.
- The pseudoscalar A can be produced in pair with a $\sigma$ via Z boson exchange. A will then decay into $\sigma + Z$. The Z boson can be tagged by its leptonic decay. Thus the final states will have two leptons and missing energy.

Conclusions
- We have shown that a neutral scalar boson of these 2HDM can have a mass in the keV range and can be a viable warm dark matter candidate.
- The abundance of such a thermal DM is generally much higher than observations; we have proposed a way to dilute this by the late decay of a heavy RH neutrino.
- A consistent picture emerges where the mass of N is in the range 25 GeV to 20 TeV.
- The model has several testable consequences at colliders as well as in astrophysical settings.
- It can also successfully explain the anomalous X-ray signal reported by different groups in the extra-galactic spectrum.

References

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