Warm Dark Matter in Two Higgs Doublet Models

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Abstract

We show that a neutral scalar field σ 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 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 $M_N \approx$ 25 GeV - 20 TeV and τ_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 $\sigma \to \gamma\gamma$.** 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 $\emptyset_1$ and $\emptyset_2$ with a discrete Z_2 symmetry acting only on $\emptyset_2$
- While $\emptyset_1$ acquires a vev of 174 GeV, $< \emptyset_2 > = 0$, Z_2 remains unbroken and the **lightest member of the $\emptyset_2$ doublet will be stable.**
- We identify one of the **neutral members of $\emptyset_2$ as the WDM with a mass of order keV** while neutral scalar and the charged scalar have masses ~ few hundred GeV.
- Three Z_2 even singlet neutrinos, N_i 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 $h\nu$; $W^{\mp} e^{\mp}$, Z_ν. These decays arise through the ν -N mixing.
- When $m_N < 80$ GeV, 3 body decays involving virtual W and Z will be dominant.

Relic Abundance of Warm Dark Matter σ

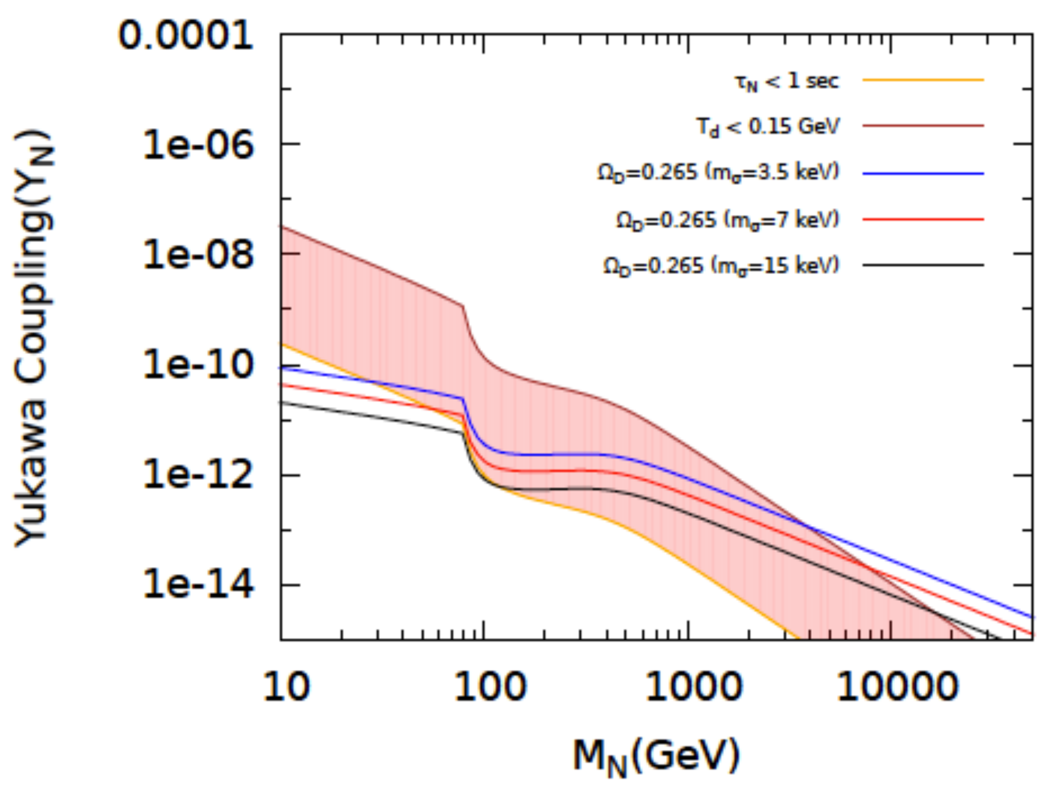
- Since σ has thermal abundance, it turns out that relic abundance today is too large compared to observations.
- This situation is remedied in the model by the late decay of N, the RH neutrino present in the seesaw sector.
- The freeze out temperature is computed to be $T_f \sim$150 MeV, the relic abundance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

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

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

Dilution of σ abundance via late decay of N

- A dilution in the abundance of σ is realized. For this the decay temperature T_d 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-Y_N plane is shown. The shaded region corresponds to the decay temperature T_d of N lying in the range 150 MeV-1 MeV. The three solid curves generate the correct dark matter density Ω_D for three different values of the WDM mass m_σ = 3.5; 7; 15 keV.
- The Final abundance of σ is computed as:

$$\Omega_\sigma = (0.265) \left(\frac{m_\sigma}{1\ keV}\right) \left(\frac{7.87\ GeV}{M_N}\right) \left(\frac{1\ s}{\tau_N}\right)^{\frac{1}{2}} \left(\frac{g\,(T_{f,N})}{106.75}\right) \left(\frac{17.25}{g_f^\sigma}\right)$$

- From Eqn we see that the correct relic abundance of σ 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 - 20TeV 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:

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

2. Collider signals

- The charged scalar $H^{\mp}$ 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 σ via Z boson exchange. A will then decay into a σ + 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 s**uccessfully explain the anomalous X-ray signal** reported by different groups in the extra-galactic spectrum.

References

1. M. Nemevsek, G. Senjanovic and Y. Zhang, JCAP 1207, 006 (2012) [arXiv:1205.0844 [hep-ph]].

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