Sterile neutrino, hidden dark matter and their cosmological signatures

Subinoy Das
Institut für Theoretische Teilchenphysik und Kosmologie
RWTH Aachen, D-52056 Aachen, Germany
E-mail: subinoy@physik.rwth-aachen.de

Abstract. Though thermal dark matter has been the central idea behind the dark matter candidates, it is highly possible that dark matter of the universe is non-thermal in origin or it might be in thermal contact with some hidden or dark sector but not with standard model. Here we explore the cosmological bounds as well as the signatures on two types of non-thermal dark matter candidates. First we discuss a hidden dark matter with almost no interaction (or very feeble) with standard model particles so that it is not in thermal contact with visible sector but we assume it is thermalized with in a hidden sector due to some interaction. While encompassing the standard cold WIMP scenario, we do not require the freeze-out process to be non-relativistic. Rather, freeze-out may also occur when dark matter particles are semi-relativistic or relativistic. Especially we focus on the warm dark matter scenario in this set up and find the constraints on the warm dark matter mass, cross-section and hidden to visible sector temperature ratio which accounts for the observed dark-matter density, satisfies the Tremaine-Gunn bound on dark-matter phase space density and has a free-streaming length consistent with cosmological constraints on the matter power spectrum. Our method can also be applied to keV sterile neutrino dark matter which is not thermalized with standard model but is thermalized with in a dark sector. The second part of this proceeding focuses on an exotic dark matter candidate which arises from the existence of eV mass sterile neutrino through a late phase transition. Due to existence of a strong scalar force the light sterile states get trapped into stable degenerate micro nuggets. We find that its signature in matter power spectra is close to a warm dark matter candidate.

1. Introduction
Here we briefly discuss a unified treatment [2] of the freeze-out of thermal relics in hidden sectors for arbitrary cross section $\sigma$, only requiring that constraints from cosmology are satisfied, and find viable dark matter that freezes out when it is relativistic, semi-relativistic, or non-relativistic. Our result applies to sterile neutrino warm dark matter which might or might not be in thermal equilibrium with visible sector. Especially, if the dark matter sterile neutrinos are not in thermal equilibrium with visible sector but somehow has enough interactions in the dark sector to thermalize it, this lower bound of 1.5 keV is pretty generic and applies in such situation.

In the last part of this proceeding we focus on recent hints by MiniBooNe and reactor experiment which along with LSND may point out to the existence of eV scale sterile neutrino. We discuss an exotic scenario where being triggered by a scalar field such eV sterile states which was highly relativistic deep in radiation dominated era went through a phase transition few e-foldings before
matter radiation equality and clumped into micro-nuggets. These nuggets composed of many sterile states can be very heavy—mass ranging from keV to TeV. But the signature of the this dark matter are always close to that of warm dark matter particle as far as matter power spectra is concerned. This is due the fact that light sterile neutrino behaves like hot dark matter before the phase transition and then transitions into cold dark matter nuggets. This means we always get suppression in power in smaller scales in the matter power spectra and it mimics CDM at larger scales.

2. Constraints on hidden warm dark matter

For a temperature-dependent dark matter cross section $\sigma(x)$, a general (warm, cold or hot) freeze-out is described by [2]

$$\frac{dy}{dx} = -\frac{1}{x^2} \left[ y^2 - y_0^2(x; \xi) \right] + y \frac{d\ln f(x)}{dx}. \quad (1)$$

where $y(x; \xi)$ is the scaled yield of dark matter and $f(x) = \left( \frac{3}{x^2} + \frac{\xi + x}{x} \right)$ with $x = m/T$. Numerically we solve this equation for different regimes of freeze-out and find the hidden dark matter relic density which depends on dark matter mass ($m_\chi$), cross-section ($\sigma(x)$) and hidden to visible sector temperature ratio ($\xi$).

Other than the correct dark matter relic density, we now discuss two more cosmological constraints which applies to hidden or visible sector dark matter candidate. Generally, hidden-sector dark matter does not need to freeze-out when non-relativistic (cold) in order to match observations. The dark-matter particles may have significant thermal momentum at freeze-out (it can be warm or hot from the hidden-sector perspective), and this can lead to a significant free-streaming length that can suppress the matter power spectrum on scales as large as those corresponding to galactic length scales. While the freeze-out process is thermal in the hidden sector, since the hidden sector is at a different temperature than the visible sector, it mimics a non-thermal freeze-out process.

$$\lambda^{FSH} = \frac{1}{\sqrt{\Omega_r H_0}} \left[ \int_{a_f}^{a_\lambda} da + \int_{a_\lambda}^{a_{nr}} \frac{a_{nr} da}{\sqrt{a^2 + a_e^2}} \right]. \quad (2)$$

where $a_e$ is the scale factor of the Universe at matter-radiation equality. Within our approximation, prior to $a_{nr}$ we take $<v> = 1$ while for $a > a_{nr}$ we take $<v> \propto a^{-1}$, and $a_\lambda = \max[a_f, a_{nr}]$. Here, $a_{nr}$ corresponds to a scale factor when dark matter particles becomes nonrelativistic ($T_{nr}^h \simeq m_\chi/3.15$) Here we use here the bound $\lambda^{FSH} \leq 230$ kpc to constrain hidden DM parameter space.

A robust and model independent lower bound on the mass of dark matter particles is obtained by bounding the phase-space density evolution of small galaxies like the dwarf spheroidal satellites (dSphs) of the Milky Way. For example, if the dark matter is fermion it gets a stringent bound, independent of cosmological evolution, as Pauli blocking enforces a densest packing of the dark matter phase space distribution. Since the microscopic phase space density (PSD) is exactly conserved for collision less and dissipation less particles by Liouville’s theorem the coarse-grained (averaged) PSD can not be an increasing function of time. This means that the maximum coarse-grained PSD in a galaxy today, with core radius $r_c$ and velocity dispersion
vacuum expectation value

its interaction with a scalar, the fermion mass is chameleon in nature and depends on the scalar and clumped into small dark matter nuggets in presence of a scalar-mediated fifth force. Due to fermions, at some point in the radiation dominated era (RDE) went through a phase transition early universe.

but might prefer such extra radiation degrees of freedom like light sterile neutrino states in the example, a scalar. Interestingly, recent analysis of WMAP 7 data can not only accommodate states (eV mass) and it is possible that these light states have non-trivial interactions with, for Data from MiniBooNE experiment [3] may indicate the existence of two light sterile neutrino 3. Warm dark matter through phase transition from light sterile states}

\[ \sigma_v, \text{ must not exceed} \left( \frac{\sigma}{\sigma_0, \xi} \right) \text{ plane for } m_\chi = 1900 \text{ eV (left panel), } 3 \text{ keV (middle panel), and } 12.5 \text{ keV (right panel). Here, } \sigma_0 = 10^{-9} \text{ GeV}^{-2}. \text{ The horizontal dashed lines are contours of free-streaming length while the bold one corresponds to } \lambda^{FSH} \simeq 230 \text{ kpc. The solid lines are contours of minimum Tremaine-Gunn mass, } m_{\min}^{TF} (\xi, \sigma). \text{ We see that the free-streaming bound is more stringent for such low dark matter mass. The colored region corresponds to the allowed values of dark matter density } (0.1 \leq \Omega_{DM} h^2 \leq 0.114) \text{ and that also obey the Free-streaming and Tremaine-Gunn bounds. The corresponding values of hidden-sector } x_f^h \equiv m/T_f^h \text{ are shown in the sidebar to illustrate the nature of decoupling (i.e., whether relativistic, nonrelativistic or semirelativistic). We see that for low mass } x_f^h \text{ is smaller and decoupling tends to be relativistic, while for higher mass } x_f^h \text{ is larger with values corresponding to either semirelativistic (warm) or nonrelativistic freeze out.}

\[ \sigma_v, \text{ must not exceed} \left( \frac{\sigma}{\sigma_0, \xi} \right) \text{ plane for } m_\chi = 1900 \text{ eV (left panel), } 3 \text{ keV (middle panel), and } 12.5 \text{ keV (right panel). Here, } \sigma_0 = 10^{-9} \text{ GeV}^{-2}. \text{ The horizontal dashed lines are contours of free-streaming length while the bold one corresponds to } \lambda^{FSH} \simeq 230 \text{ kpc. The solid lines are contours of minimum Tremaine-Gunn mass, } m_{\min}^{TF} (\xi, \sigma). \text{ We see that the free-streaming bound is more stringent for such low dark matter mass. The colored region corresponds to the allowed values of dark matter density } (0.1 \leq \Omega_{DM} h^2 \leq 0.114) \text{ and that also obey the Free-streaming and Tremaine-Gunn bounds. The corresponding values of hidden-sector } x_f^h \equiv m/T_f^h \text{ are shown in the sidebar to illustrate the nature of decoupling (i.e., whether relativistic, nonrelativistic or semirelativistic). We see that for low mass } x_f^h \text{ is smaller and decoupling tends to be relativistic, while for higher mass } x_f^h \text{ is larger with values corresponding to either semirelativistic (warm) or nonrelativistic freeze out.}

\[ m \geq m_{\min} = \left( \frac{9 h^3}{(2\pi)^{3/2} d_\chi G_N \sigma_v, r_f^2, f(q, T_f^h)_{\max}} \right)^{1/4} \]

In fig. 1 we show the free-streaming constraint, Phase-space bound as well as the bound from correct dark matter relic density on hidden sector dark matter candidates. As expected the the bound becomes stronger for the hidden warm dark matter.

3. Warm dark matter through phase transition from light sterile states

Data from MiniBooNE experiment [3] may indicate the existence of two light sterile neutrino states (eV mass) and it is possible that these light states have non-trivial interactions with, for example, a scalar. Interestingly, recent analysis of WMAP 7 data can not only accommodate but might prefer such extra radiation degrees of freedom like light sterile neutrino states in the early universe.

Motivated by this possibility, here in this paper we propose a new scenario where such light fermions, at some point in the radiation dominated era (RDE) went through a phase transition and clumped into small dark matter nuggets in presence of a scalar-mediated fifth force. Due to its interaction with a scalar, the fermion mass is chameleon in nature and depends on the scalar vacuum expectation value vev. So, the dynamics of φ is controlled by an effective potential instead of just V(φ) and the scalar field adiabatically tracks the minima of V_{eff}. As the background fermion density dilutes due to expansion of the universe, the minimum of V_{eff} is time dependent and so is the fermion mass. In our case, the attractive scalar force starts to dominate over the free-streaming when the fermion becomes heavy enough before MRE and results in dark matter micro nuggets[4]. As a result, the fermions within each scalar Compton
volume collapse into one nugget until the fermi pressure intervenes and balances the attractive force. The scalar field obtains a static profile as the nugget forms. We find that the scalar field radius is determined when number density drops to zero. The radius of the nugget is also smaller than outside, ensuring the stability of the nuggets. The radius of the nugget is also determined by the scalar profile which in our case can be as small as micrometer ($R_{\text{nug}} \leq \mu$m).

We take a lagrangian of the form

$$\mathcal{L} \supset m_D \psi_1 \psi_2 + f(\Phi) \psi_2 \psi_2 + V(\Phi) + \text{h.c.},$$

Here $\psi_1$ is the light fermion field, $\psi_2$ is heavier one and both of them are written as two component left chiral spinor field while $m_D$ is the Dirac mass term and $V(\phi)$ being the scalar potential. If $\psi_2$ is considerably heavier, we can integrate it out from the low energy effective theory obtaining $m_\psi = \frac{m_\psi^2}{f(\phi)}$.

So a rough estimate of the dark matter density at the time of phase transition is given by

$$\rho_{\text{DM}}^{\text{nug}} \equiv \frac{M_{\text{nug}}}{2\pi(m_\psi)^3} \left(1 + z_{\text{F}}\right)^{-3}$$

which basically assumes that all the sterile fermions in one scalar Compton volume get trapped into one nugget. Here $z_{\text{F}}$ denotes the redshift of nugget formation. Evolving this density to the present epoch we get $\rho_{\text{DM}}^{\text{F}} = \rho_{\text{DM}}^{\text{nug}} (1 + z_{\text{F}})^{-3}$ where $M_{\text{nug}}$ is the nugget mass which can be found by solving the scalar profile.

As shown in details [5], the nugget profile is obtained by solving two equations – Klein-Gordon equation for the scalar field and force balance equation between the scalar attraction and fermi pressure

$$\phi_\mu'' + \frac{2}{r}\phi_\mu' = \frac{dV(\phi)}{d\phi} - \frac{d\ln[m(\phi)]}{d\phi} T_\mu$$

where $m(\phi), p, \rho$ is the scalar field mass, pressure and energy density of the dark matter fermion. Using Thomas-Fermi approximation, one can numerically solve the profile for the dark matter nugget [5] which has been shown in Fig. 2.

4. References

[1] J. L. Feng and J. Kumar, Phys. Rev. Lett. 101, 231301 (2008) [arXiv:0803.4196 [hep-ph]].
[2] S. Das and K. Sigurdson, Phys. Rev. D 85, 063510 (2012) [arXiv:1012.4458 [astro-ph.CO]].
[3] J. Kopp, M. Maltoni and T. Schwetz, arXiv:1103.4570.
[4] N. Afshordi, M. Zaldarriaga and K. Kohri, Phys. Rev. D 72, 065024 (2005) [arXiv:astro-ph/0506663].
[5] S. Das and K. Sigurdson, “Degenerate Dark Matter Micronuggets from Ultralight Trapped Fermions”, Manuscript in preparation.