Tilted CDM versus WDM in the Subgalactic Scuffle

J. Bullock
1Department of Astronomy and Department of Physics, The Ohio State University, Columbus, OH 43210; james@astronomy.ohio-state.edu

Abstract. Although the currently favored cold dark matter plus cosmological constant model (LCDM) has proven to be remarkably successful on large scales, on subgalactic scales it faces some potentially fatal difficulties; these include over-producing dwarf satellite galaxies and predicting excessive central densities in dark halos. Among the most natural cosmological solutions to these problems is to replace cold dark matter with a warm species (LWDM). The warm component acts to reduce the small-scale power, resulting in fewer galactic subhalos and lower halo central densities. An alternative model with a mild “tilt” in the inflationary power spectrum (TLCDM; \( n = 0.9 \)) similarly reduces the central densities of dark halos, although the substructure abundance remains relatively high. Here I argue that because dwarf galaxy formation should be suppressed in the presence of a strong ionizing background, favored LWDM models will generally under-predict the observed abundance of dwarf galaxies. The satellite count for TLCDM fares much better, as long as the photoionization effect is taken into account. TLCDM provides a more successful alternative to LWDM on subgalactic scales with the added attraction that it relies on only a minor, natural adjustment to the standard framework of CDM.

1 The Matchup

Inflation-generated cold dark matter (CDM) models provide an elegant and well-motivated class of theories for the origin of structure in the universe. A diverse set of large-scale observational measurements, both at high and low redshifts, are well-accounted for within the CDM picture, and most point to a single model with \( \Omega_m \simeq 0.3, h \simeq 0.7 \), and with space made flat by a significant cosmological constant component (LCDM) 8, 24, 13.

On the scales of galaxies and smaller, the situation is much more uncomfortable. High-resolution, dissipationless N-body simulations have have led to robust predictions for the distribution of dark matter in and around (L)CDM galactic halos 11, 14. The predictions have allowed detailed comparisons with observations on subgalactic scales and have lead to two major discrepancies. First, the number of predicted subhalos with circular velocities \( \sim 10 - 30 \) km s\(^{-1}\) within the virialized extent of Milky Way-type halos is roughly an order of magnitude higher than the observed abundance similarly-sized satellites 14. Perhaps the biggest problem concerns the central densities of galaxies. Rotation curves of low-mass, dark-matter dominated galaxies seem to indicate lower central densities than would be expected 12 in the standard LCDM model. A similar problem may be present in bright galaxies 8, 15, including our own Milky Way 8, 15 (although see 26, 18).

These discrepancies have motivated the exploration of alternative scenarios. By stripping either the collisionless or cold properties of traditional CDM, or by considering additional exotic possibilities, many authors have sought to preserve the success of CDM on large scales while modifying the manifestations of CDM on small scales 8. Among these possibilities, a popular choice is to replace CDM with warm dark matter (WDM), thereby suppressing power below the free-streaming scale of the warm particles 7, 15, 17. A less radical, and perhaps more naturally motivated mechanism for suppressing the small scale power is to tilt the initial inflationary power spectrum to favor large scales (TLCDM, \( n = 0.9 \)) 1. In what follows, I pit LWDM against TLCDM in a bout to determine which model can best match the subgalactic data. The TLCDM model parameters are those favored by recent Ly\( \alpha \) forest measurements 21: \( n = 0.9, \Omega_m = 0.4, h = 0.65, \Omega_L = 0.6 \), and \( \sigma_8 = 0.66 \). The LWDM model has \( n = 1.0, \Omega_m = 0.3, h = 0.7, \Omega_L = 0.7 \), and \( \sigma_8 = 1.0 \), with a 1 KeV WDM particle.

\(^1\)\( R_f \simeq 0.1[m_w/\text{KeV}]^{-4/3}\)Mpc, for \( \Omega_w = 0.3, h = 0.7 \), where \( m_w \) is the mass of the WDM particle.
2 Round 1: Central Densities

Halo central densities are often characterized by a concentration parameter defined as the ratio of an outer halo radius to an inner radius where the log-slope of the density profile is $-2$: $c_v \equiv R_v / R_{-2}$. The outer radius $R_v$ is defined as the radius within which the mean density of the halo is a constant multiple of the critical density (in this case 100 at $z = 0$, see, e.g. [5] for details). A halo’s central density (or concentration) is set by the density of the universe at the time when the halo’s mass accretion rate was high [27], so halos that form early are more concentrated. LWDM has significantly reduced power on small scales, therefore low-mass WDM halos form later than their CDM counterparts, and end up with lower $c_v$ values [7].

A similar reduction in halo concentrations occurs in the TLCDM model because the tilt in the power spectrum reduces small scale power relative to large. Figure 1a shows concentrations of LCDM and TLCDM halos simulated using the Adaptive Refinement Tree Code [19]. The two simulations consisted of boxes of $15h^{-1}\text{Mpc}$ on a side with $128^3$ particles of mass $m_p \approx 4 \times 10^8 h^{-1} M_\odot$, and they each had an effective force resolution of $4h^{-1}\text{kpc}$. Solid points represent TLCDM halos, open points represent LCDM halos, and the lines show predictions from the model of Bullock et al. [5] (hereafter B) for each of the cosmologies. At a fixed mass, the TLCDM halos are roughly half as concentrated as their LCDM counterparts.

Figure 1b illustrates how predicted TLCDM central densities compare to those of several dark matter dominated Low Surface Brightness (LSB) and dwarf galaxies (see [1] for a description of the data). Central densities are characterized by the quantity $\Delta_{V/2} \equiv \rho(r_{V/2})/\rho_{\text{crit}}$. Here, $r_{V/2}$ is the radius where the rotation velocity falls to one half its maximum value $V_{\text{max}}$, $\rho(r_{V/2})$ is the average density within that radius, and $\rho_{\text{crit}}$ is the critical density. The line labeled TLCDM shows the B model prediction for TLCDM halos as a function of $V_{\text{max}}$. For comparison, the lines labeled LWDM show two different analytic model predictions for LWDM halos. The first line (ENS) [15] follows from a model developed to match N-body simulation results. Unfortunately, the ENS analytic model has not been tested against N-body simulations over the $V_{\text{max}}$ range that is most relevant for the data shown in Figure 1b. One may conservatively expect the properties of WDM halos to lie within the range given by the lines labeled ENS and B.
3 Round 2: Dwarf Satellites

One likely solution to the substructure crisis involves the expected suppression of low-mass galaxy formation in the presence of a strong ionizing background \[23\]. In \[4\] (BKW) we pointed out that the observed satellite abundance is well-accounted for if the dwarf galaxy host halos correspond only to those that had a significant fraction of their mass, \(f\), in place before the epoch of reionization, \(z_{\text{re}}\). Subsequently, this idea has been made more convincing by detailed semi-analytic and hydrodynamic modeling \[16, 25, 2\]. Not only does this effect provide a reasonable solution, it seems to be an inevitable consequence of having an ionized universe. The implication is that any model that makes predictions involving dwarf-sized systems must include photoionization suppression.

Figure 2 illustrates the expected number of subhalos as a function of circular velocity for a typical TLCDM Milky-Way halo. The calculations here were done following the techniques outlined in BKW. For reasonable values of \(z_{\text{re}}\) and \(f\), the expected number of observable dwarf galaxies (shaded region) is in good agreement with the observed dwarf population (points with error bars). There is similar agreement for a range of viable parameter choices. For example, the choice \(z_{\text{re}} = 6\) and \(f = 0.25\) works, as does \(z_{\text{re}} = 8\) and \(f = 0.15\). The LWDM model, on the other hand, is unable to produce any observable dwarfs, even if the reionization epoch occurs at an unrealistically low redshift \(z_{\text{re}} = 5.5\). Structure forms much later in the LWDM model, so fewer objects collapse early. This, coupled with the already reduced number of subhalos compared to LCDM, makes the abundance of dwarfs hard to match with a WDM model. One way out might be if dwarfs are produced via the fragmentation of larger objects, although this seems unlikely because mass-to-light ratios of dwarfs suggest a high dark matter content \[20\].

4 The Decision

WDM helps the central density issue by suppressing power below the free streaming scale of the warm particle. Halos less massive than a multiple of the free streaming mass will form later than their LCDM counterparts, and therefore have reduced central densities. For example, a 1KeV WDM particle will reduce concentrations in halos with circular velocities smaller than \(\sim 200\text{km s}^{-1}\). Figure 1b illustrates how an LWDM model of this kind provides a reasonable match to the average central densities of low-mass dark matter dominated systems. Note that the densities of bright, Milky-Way-type galaxies will not be affected unless the particle mass is made smaller than the \(\sim 1\text{KeV}\) bound set by the Lyman-alpha forest \[22\].
A TLCDM model normalized to COBE on large scales and with parameters motivated by recent Lyα forest data provides a similar remedy. Instead of a sharp cutoff at a free streaming scale, the power is reduced gradually via a long tilted “lever arm” \((n = 0.9\) rather than \(n = 1.0\) in the primordial spectrum). Because the reduction in power is continuous, all mass scales collapse later than they would in standard LCDM, and the central densities in galaxy-mass halos are reduced by roughly a factor of \(\sim 4\). As illustrated in Figure 1b, TLCDM does as well as LWDM in matching the central densities of a sample dark-matter dominated dwarf and LSB galaxies. In the arena of density comparisons, the matchup between TLCDM and LWDM must be declared a draw. Neither of the models solves the problem decidedly, but they both certainly help relative to LCDM. TLCDM may be more desirable because it is expected to reduce densities in bright galaxies as well less massive objects.

Compared to the central density issue, the Galactic satellite abundance is much less troublesome for LCDM. It has long been expected that photoionization (if not super nova explosions \([10]\)) should play a significant role in this mass regime \([23, 11]\). If reionization is taken into consideration, TLCDM can account for the observed number of dwarfs. LWDM, on the other hand, faces severe problems. Without an ionizing background the number of expected subhalos is roughly consistent with the observed dwarf abundance, but when the background is included, the number of satellites is vastly under-predicted in LWDM.

Based on two rounds of evidence, TLCDM is the clear winner over LWDM. Indeed, the seriousness of the small-scale density crisis makes TLCDM a viable contender for our cosmology of choice, a title held now by standard LCDM. The tilt required falls naturally within the range expected in standard inflation models, so TLCDM is just as attractive as LCDM in the “naturalness” category. Forthcoming observational constraints derived from CMB studies, Lyα forest measurements, large scale clustering analyses, and cluster counts will provide useful tests for TLCDM.

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