THE CASE AGAINST WARM OR SELF-INTERACTING DARK MATTER AS EXPLANATIONS FOR CORES IN LOW SURFACE BRIGHTNESS GALAXIES

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**ABSTRACT**
Warm dark matter (WDM) and self-interacting dark matter (SIDM) are often motivated by the inferred cores in the dark matter halos of low surface brightness (LSB) galaxies. We test thermal WDM, non-thermal WDM, and SIDM using high-resolution rotation curves of nine LSB galaxies. We fit these dark matter models to the data and determine the halo core radii and central densities. While the minimum core size in WDM models is predicted to decrease with halo mass, we find that the inferred core radii increase with halo mass and also cannot be explained with a single value of the primordial phase-space density. Moreover, if the core size is set by WDM particle properties, then even the smallest cores we infer would require primordial phase-space density values that are orders of magnitude smaller than lower limits obtained from the Lyα forest power spectra. We also find that the dark matter halo core densities vary by a factor of about 30 from system to system while showing no systematic trend with the maximum rotation velocity of the galaxy. This strongly argues against the core size being directly set by large self-interactions (scattering or annihilation) of dark matter. We therefore conclude that the inferred cores do not provide motivation to prefer WDM or SIDM over other dark matter models.

**Key words:** cosmology: observations – cosmology: theory – dark matter – galaxies: kinematics and dynamics

**Online-only material:** color figure

1. INTRODUCTION

In the prevailing theory of galaxy formation, galaxies assemble inside cuspy cold dark matter (CDM) halos. Dissipationless CDM simulations show that these halos have steeply rising central densities that roll over from \(\rho \sim r^{-1}\) at \(\sim 1\) kpc scales to \(\rho \sim r^{-0.8}\) at \(\sim 100\) pc scales (e.g., Navarro et al. 2004; Graham et al. 2006; Navarro et al. 2010). There has been continued debate in the literature over this prediction as numerous observational results indicate that rotation curve data are often more consistent with dark matter halos having a roughly constant density core (e.g., Flores & Primack 1994; Moore 1994; McGaugh et al. 2001; Marchesini et al. 2002; Gentile et al. 2005; Simon et al. 2005; Kuzio de Naray et al. 2006, 2008; de Blok et al. 2008, 2010).

The mismatch between the dissipationless CDM simulations and galaxy rotation curve data has motivated a serious exploration of warm dark matter (WDM) models (Hogan & Dalcanton 2000; Avila-Reese et al. 2001; Abazajian et al. 2001; Kaplinghat 2005; Cembranos et al. 2005; Strigari et al. 2007) and self-interacting dark matter (SIDM; Spergel & Steinhardt 2000; Kaplinghat et al. 2000) as alternatives to CDM. The goal is to maintain the success of CDM on large scales while producing cores in the dark matter distribution of small halos.

Two generic classes of WDM particles are thermal particles that are light and which kinetically decouple when relativistic (Blumenthal et al. 1982; Dodelson & Widrow 1994; Asaka et al. 2006), and particles that are as massive as typical CDM particles but populated by decays in the early universe (Kaplinghat 2005; Cembranos et al. 2005). In both classes, there are regions of parameter space that are endowed with large particle velocities and correspondingly low primordial phase-space densities \(Q_p = \bar{\rho}/\sigma^3\). The initial phase-space density imposes a limit on the central phase-space density of collapsed WDM halos for both thermal WDM particles (Tremaine & Gunn 1979) and non-thermal particles arising from early decays (Kaplinghat 2005). Warmer dark matter models have lower \(Q_p\) and correspondingly larger limiting core sizes at fixed halo mass. If the cores in dark matter halos are set by primordial phase-space constraints, then for a given \(Q_p\) there are predicted relationships between halo structural parameters (e.g., core radius and central density). This provides a means to evaluate WDM as a solution to the cusp-core problem.

In SIDM models, the interactions lead to either thermalization or particle loss and the subsequent formation of a core. Models that have been studied are those with large cross sections for scattering (Spergel & Steinhardt 2000; Firmani et al. 2000) or annihilations (Kaplinghat et al. 2000). In the simplest case where the s-wave contributions dominate the cross section, we expect all core densities to cluster around a common value. For more complicated models, the core density should correlate with the velocity dispersion in the core.

In this Letter, we fit high-resolution rotation curves of low surface brightness (LSB) disk galaxies using cored dark matter density profiles of the type expected in WDM and SIDM models. These galaxies are dark matter-dominated down to small radii (e.g., de Blok & McGaugh 1996, but see Fuchs 2003), therefore providing a good laboratory for testing dark matter halo predictions. In Section 2, we describe the density profiles we use for models of thermal WDM and non-thermal WDM from early decays. In Section 3, we fit the galaxy data with these halo models and determine the sizes of the halo cores. In Section 4, we discuss predictions for particle dark matter models based on the measured core sizes. A summary is presented in Section 5.

2. CORED DARK MATTER HALO MODELS

Provided below are brief descriptions of the cored halo profiles used in our analysis. We consider four different profiles...

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to bracket both a range of behavior in the outer region of the density profile and the rapidity of the transition from the core to the outer region. In all cases, the profiles are set by two independent parameters: a scale density and a scale radius. Recent WDM (Colín et al. 2008) and SIDM (Davé et al. 2001) simulations support this assumption. The specific forms of the profiles we use are motivated by arguments in the limit of no phase-space mixing. However, given the wide range of behaviors encapsulated by these profiles, we also use them for our analysis of SIDM models.

2.1. Thermal Warm Dark Matter

The density profile for the thermal WDM halo, in the limit of no phase-space mixing, is subject to the constraint that as $r \to 0$, $\rho \to \rho_0 [1 - (r/r_{\text{core}})^2]$. This ensures that the phase-space density is finite for all values of total energy. This is necessary because the phase-space density of thermal particles in the early universe is finite for all momenta. We assume the following form for the thermal WDM halo density profile:

$$\rho_{\text{Th}}(r) = \frac{\rho_0}{\left[1 + \frac{r}{r_{\text{core}}}^2\right]^{\alpha}}$$

where $\rho_0$ is the central core density and $r_{\text{core}}$ is the core radius.

We test the thermal WDM model with $\alpha = 1$ and $\alpha = 2$. The $\alpha = 1$ case can be recognized as the cored pseudoisothermal halo traditionally used in rotation curve fitting. We use this case to how sensitive our results are to the assumed density profile.

The $\alpha = 1$ (Th1) and $\alpha = 2$ (Th2) rotation curves are

$$V^2_{\text{Th1}}(r) = 4\pi G \rho_0 r^2_{\text{core}}\left[1 - \frac{1}{\alpha} \arctan(x)\right],$$

$$V^2_{\text{Th2}}(r) = 4\pi G \rho_0 r^2_{\text{core}}\left[\frac{\arctan(x)}{x} - \frac{1}{x^2 + 1}\right],$$

with $x = r/(\sqrt{\alpha} r_{\text{core}})$.

2.2. Non-thermal Warm Dark Matter from Early Decays

For particles populated by decays of massive particles in the early universe, the density profile is subject to the constraint that as $r \to 0$, $\rho \to \rho_0 [1 - (r/r_{\text{core}})^2]$. This is a milder core than that created by thermal WDM as $\alpha \to \infty$. Early-universe, the density profile is subject to the constraint that as $r \to 0$, $\rho \to \rho_0 [1 - (r/r_{\text{core}})^2]$. This is a milder core than that created by thermal WDM as $\alpha \to \infty$.

The early-decay model with $\alpha = 3$ and $\alpha = 4$. The choice of these exponents is motivated by the range of slopes seen in CDM simulations in the outer regions of the halos (Navarro et al. 2004; Graham et al. 2006; Navarro et al. 2010). Because the outer regions are built up from accreted dark matter particles, there should be no difference between cold and WDM predictions (Colín et al. 2008).

The rotation curves corresponding to the $\alpha = 3$ (ED3) and $\alpha = 4$ (ED4) cases are

$$V^2_{\text{ED3}}(r) = 36\pi G \rho_0 r^2_{\text{core}}\left[\ln(1 + x) - \frac{2 + 3x}{2(1 + x)^2}\right],$$

$$V^2_{\text{ED4}}(r) = 64\pi G \rho_0 r^2_{\text{core}}\frac{x^2}{3(1 + x)^3},$$

with $x = r/(\alpha r_{\text{core}})$.

3. CORED DARK MATTER HALO FITS

We fit the cored dark matter models to the observed rotation curves of a sample of nine LSB galaxies. The rotation curves are derived from high-resolution $H_\alpha$ integral field unit spectroscopy (Kuzio de Naray et al. 2006, 2008) and are combined with rotation curves derived from long-slit $H_\alpha$ spectra (de Blok et al. 2001; de Blok & Bosma 2002) and $H_\alpha$ velocity fields (de Blok et al. 1996; Stil 1999; Swaters 1999). The inner part of the rotation curves set the central core density, $\rho_0$, for each halo model, and the data at large radii fix $\rho_0 r^2_{\text{core}}$. Because the dark matter is the dominant mass component in these galaxies at all radii, we neglect the (minimal) contribution to the observed rotation from the baryons. To demonstrate that the effect of the baryons on the fit parameters is indeed small, we include in the figures a representative example (F583-1) where a stellar mass-to-light ratio based on galaxy color is assumed (Kuzio de Naray et al. 2008).

In Figure 1, we plot the four cored halo fits over the data. The central density and core radius derived for each dark matter model are listed in Table 1.

We find that for most galaxies, the best-fitting halo rotation curves match the observed galaxy rotation curves well. In general, the early-decay and thermal WDM models produce very similar fits to the data, and there is little dependence on the value of the exponent $\alpha$. With the exception of the thermal WDM model with $\alpha = 2$ for some of the galaxies, the best-fitting halo rotation curves typically overlap at most radii. For the four halo models, the sizes of the derived cores are on the order of a kpc and span a range of about a factor of 10.

The observed rotation curves of UGC 4325 and DDO 64 are not well described by the halo models ($x^2 \geq 3$). Rather than turning over, the models continue to rise past the last observed rotation curve point. The implied cores would be larger than the observed radial range of the data, and the masses of the systems would be about $10^{12} M_\odot$ or larger. Given the poor fits, we exclude UGC 4325 and DDO 64 from the remaining analysis. We note that the $x^2$ values for the NGC 4395 halo fits are also large (2.6–5.1). These high values are the result of the features seen in the rotation curve around 2.5 kpc that cannot be fit by smooth dark matter density profiles. However, the velocity profiles do follow the overall shape and turnover of the observed rotation curve.

4. DISCUSSION

Given a candidate dark matter particle with primordial phase-space density $Q_p$, any halo with total gravitationally bound mass $M_{\text{tot}}$ must have a minimum constant density core radius that scales inversely with the total halo mass as $r_{\text{core}} \propto Q_p^{-2/3} M_{\text{tot}}^{1/3}$ (Kaplinghat 2005; Martinez & Kaplinghat 2009). This relation follows from dimensional analysis given our assumption that the shape of the density profile only depends on a scale density and scale radius. It can also be explicitly calculated in the context of the “excess mass function” of Dehnen (2005), as shown by Kaplinghat (2005). Given the total mass and primordial phase-space density, a lower bound on the core size can be placed.
because entropy increases or, equivalently, because “phase-space density” decreases. More correctly, the values of the minimum core size reflect a situation where the particles have not phase-space mixed. The lower limit to the primordial average phase-space density for thermal WDM models may be written as

\[
Q_p \gtrsim \frac{84}{71} \, \left( \frac{\text{pc}}{\text{M}_\odot \text{pc}^{-3}} \right)^{1/3} \rho_0^{-1/2} r_{\text{core}}^{-3}, \quad (5)
\]

where the upper and lower numbers are for Th1 and Th2 models, respectively, and \( \rho_0 \) is in \( \text{M}_\odot \text{pc}^{-3} \) and \( r_{\text{core}} \) is in pc. Note that the dependence on the actual shape of the halo profile is mild.

For models of non-thermal WDM from early decays, the lower limit to the primordial average phase-space density may be written in terms of the total mass of the dark matter halo as follows:

\[
Q_p \gtrsim 82 \, \left( \frac{\text{M}_\odot}{\text{M}_\odot} \right)^{-1/3} \sqrt{\frac{\rho_0}{\rho_{\text{core}}}} \left( \frac{\text{pc}}{\text{M}_\odot \text{pc}^{-3}} \right)^{1/3} \left( \frac{\text{M}_\odot}{\text{M}_\odot} \right)^{1/3}. \quad (6)
\]
We note that this argument does not rule out the possibility that the underlying dark matter is warm, but only that core sizes are not set by the primordial phase-space density of dark matter particles. In particular, some of the cores could be due to phase-space mixing as a result of mergers, but this makes the attribution of cores to fundamental dark matter physics ambiguous. In addition, we will show that the values of the primordial phase-space density required are much too small to be consistent with constraints arising from the matter power spectrum.

In Figure 2, we present a more detailed comparison of theory and data by plotting the inferred total mass of each galaxy–halo system, \( M_{\text{tot}} \), against the measured halo core radii. For clarity, we plot only the results for the early-decay \( \alpha = 4 \) and thermal WDM \( \alpha = 2 \) cases. Qualitatively similar results are obtained for the ED3 and Th1 cases if we use \( M_{\text{vir}} \) rather than \( M_{\text{tot}} \) and do not modify the conclusions. For each galaxy, we plot the combined range of core radii and masses for the two dark matter models. For comparison, we have also plotted the \( M_{\text{tot}} \) versus (minimum) \( r_{\text{core}} \) relationship that is expected for early-decay dark matter for two choices of \( Q_p \). It is immediately obvious from Figure 2 that (1) the data span a range of only about 1 order of magnitude in mass, (2) the data are not consistent with a single value of \( Q_p \), and (3) mass and core radius are not anti-correlated as would be expected from Equation (6).

The simplest interpretation of this result in the context of dark matter models is that the cores in these galaxies cannot be set directly by the primordial phase-space density of dark matter and therefore must be the result of baryonic processes. If, however, we insist that a WDM model explain these data, then to have a single value of \( Q_p \) for this sample, galaxies with small cores must preferentially lose more than 2 orders of magnitude in mass, while galaxies with large cores lose very little. This is highly unlikely in these undisturbed disk galaxies, as feedback from powerful radio sources is observed to occur almost always only in elliptical galaxies or obvious recent mergers (Wilson & Colbert 1995; Urry & Padovani 1995; Antonucci 1993).

Additionally, feedback from supernova winds is also unlikely to affect these galaxies, as the star formation rates in LSBs are known to be lower than the rates in high surface brightness galaxies of similar morphological type (Bothun et al. 1997; O’Neil et al. 2007). We note here that recent high-resolution hydrodynamical simulations have produced galaxies with cored CDM halos by including baryonic processes that effectively remove mass (Governato et al. 2010; Mashchenko et al. 2008), though Ceverino & Klypin (2009) reach a different conclusion. Finally, even if there were a plausible model to explain Figure 2, we show below that the required value of \( Q_p \) is in strong disagreement with Ly\( \alpha \) forest data.

In Figure 3, we plot the range of \( Q_p \) for the galaxies and again find that, for a given dark matter model, the data are not consistent with a single \( Q_p \) value. For our sample of galaxies, \( Q_p \) ranges between \( \sim 10^{-9} \) and \( 10^{-7} \) in units of \( M_\odot \, \text{pc}^{-3} \left( \text{km} \, \text{s}^{-1} \right)^{-3} \). This result does not change when the baryons are accounted for by assuming a non-zero stellar mass-to-light ratio, as shown for F583-1 in Figure 3. These limits on \( Q_p \) are about 4 orders of magnitude smaller than the lower limit on thermal WDM implied by the Ly\( \alpha \) forest power spectrum of \( \sim 10^{-3} \, M_\odot \, \text{pc}^{-3} \left( \text{km} \, \text{s}^{-1} \right)^{-3} \) (Seljak et al. 2006; Viel et al. 2008). Thus, even if there were a WDM model whose primordial phase-space density value was in tandem with some other process that sets the core sizes in these galaxies, we would have a model that is inconsistent with the Ly\( \alpha \) forest data by orders of magnitude.
WDM models from early decays with high-resolution rotation curves for LSB galaxies. We infer the observed halo core radii to span about an order of magnitude around a kpc, while WDM models would predict a spread of only about a factor of 2. Additionally, the values of $Q_\alpha$ inferred from these LSB galaxies are orders of magnitude smaller than the lower limits implied by the Ly$\alpha$ forest power spectra. Taken together, we interpret these results to mean that the cores in these LSB disk galaxies cannot be a direct result of WDM particle properties. We also find the data to be inconsistent with a single value of core density $\rho_0$ and find no evidence for a trend in $\rho_0$ with the maximum circular velocity. This strongly argues against the possibility that large self-interactions of dark matter are directly responsible for setting the cores.

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5. SUMMARY

WDM models and strongly SIDM models have been proposed to alleviate some of the difficulties that CDM faces on small scales. We have tested models of thermal WDM and non-thermal
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