The cosmic web of dwarf galaxies
in a warm versus cold dark matter universe:
Mock galaxies in CDM and WDM simulations

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Using cosmological simulations, we show that the cosmic web of dwarf galaxies in a warm
dark matter (WDM) universe, wherein low mass halo formation is heavily suppressed, is
nearly indistinguishable to that of a cold dark matter (CDM) universe whose low mass
halos are not seen because galaxy formation is suppressed below some threshold mass.
Low mass warm dark matter halos are suppressed nearly equally in all environments.
For example, WDM voids in the galaxy distribution are neither larger nor emptier than
CDM voids, once normalized to the same total galaxy number density and assuming
galaxy luminosity scales with halo mass. It is thus a challenge to find hints about the
dark matter particle in the cosmic web of galaxies. However, if the scatter between dwarf
galaxy luminosity and halo properties is large, low mass CDM halos would sometimes
host bright galaxies thereby populating voids that would be empty in WDM. Future
surveys that will capture the small scale clustering in the local volume could thus help
determine whether the CDM problem of the over-abundance of small halos with respect
to the number density of observed dwarf galaxies has a cosmological solution or an
astrophysical solution.

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1. Halos and Galaxies in Warm and Cold Dark Matter
Cosmologies

In WDM cosmological models, small scale power is suppressed, reducing the number
of low mass dwarf galaxy halos. This brings dwarf galaxy numbers into agreement
with the reduced number of satellite galaxies in the Milky Way and M31 relative
to the large number of CDM satellite halos in simulations1,2, solving the missing
satellite problem. Inefficient star and galaxy formation within low mass halos has
also been proposed as a solution within CDM cosmology (e.g. Ref. 3). Hence either
a cosmological solution (warm dark matter) or an astrophysical solution (baryon
physics) has the potential to explain this CDM problem.

By design, the two classes of solutions are degenerate with each other in many
ways since they both reduce visible small scale structures. We thus consider whether
other clustering statistics might show some discriminating power. Voids, in particular,
have often been noted to be larger and emptier in WDM than CDM4,5. However,
since voids are delineated by galaxies (lying in halos), the sizes and emptiness
of voids is highly sensitive to the number abundance of galaxies in a survey, as well
as to the relation and scatter between halo mass and galaxy properties. We consider
how these issues affect void statistics as a constraint for CDM versus WDM.

We use gravity-only numerical simulations to model two twin 25 Mpc volumes,
one with a ΛCDM cosmology and one with a ΛWDM cosmology, presented in Ref. 6.
Each volume is a periodic cube of $10^{24}h^{-3}$ equal mass particles, for a particle mass
of $3.9 \times 10^5h^{-1}M_\odot$. The ΛWDM assumes a 2 keV thermal relic warm particle.
Simulations are evolved using the particle gravity tree-code PKDGRAV$^7$.

1.1. Mock galaxy catalog

We construct a mock galaxy catalog using halos identified by the Amiga Halo Finder
(AHF$^8,9$), which finds self-bound halos and satellite halos (subhalos). Mock galaxies
are matched by circular velocity ($V_c$) at the peak of the rotation curve. The catalogs
for each cosmology are matched to each other by galaxy abundance, necessary
for a fair comparison of their clustering properties. We sample into the range of
small-scale WDM suppression. At the minimum WDM $V_c$ of 13.7 km s$^{-1}$, galaxy
numbers are reduced by approximately a factor of ten. The CDM catalog extends
only to $V_c > 22.9$ km s$^{-1}$ to match the WDM galaxy abundance. Each catalog has
approximately $10^4$ mock galaxies. Contamination from artificial WDM structure is
small for the halo masses we include, and we apply an additional criteria based on
the shape of the initial Lagrangian region of each halo to remove spurious WDM
halos (See details in Ref. 6). We consider also the effects of large scatter between
luminosity, $L$, and $V_c$.

2. The Distribution of Dwarf Galaxies

2.1. With a one-to-one relation of luminosity versus halo $V_c$

Fig. 1 slows a slice of the galaxy distribution from each mock catalog. In the case of
no scatter between luminosity and $V_c$, the properties of the distribution of galaxies
is visually indistinguishable in CDM and WDM. With no scatter in $L/V_c$, the self
abundance-matched CDM and WDM catalogs are nearly identical for all statistics
that we examined: the auto-correlation function; the numbers and radial profiles of
satellites; the numbers of isolated galaxies; and the PDF of small voids. Thus, the
cosmic web of CDM and WDM galaxies is essentially identical if one assumes that
low mass CDM halos cannot host galaxies. WDM voids are not larger or “emptier”
of halos than CDM, as is sometimes loosely stated, but are nearly identical if one
links galaxy properties to halo properties by simple abundance matching.

2.2. With scatter in luminosity versus halo $V_c$

The situation changes, however, in the case of high $L/V_c$ scatter for dwarf galaxies.
Differences become apparent in the cosmic web. We demonstrate this by allowing
luminosity to scatter by up to 2.5 magnitudes (one dex in mass to light ratio) for
Fig. 1. 25 Mpc wide slice of our simulation volume. Each point is a mock dwarf galaxy. Catalogs are constructed with different minimum $V_c$ selection thresholds so that the WDM and CDM catalogs contain the same number of galaxies. CDM and WDM are visually indistinguishable unless large scatter (one dex here) is assumed between dwarf galaxy luminosity and halo $V_c$. With large $L/V_c$ scatter, CDM voids become somewhat populated by galaxies hosted by low mass halos that have been scattered up to relatively high luminosity (panel c).

Low mass halos by applying the following relation for the rms scatter in galaxy magnitude: 

$$\sigma_{Mag}(V_c) = 0.4 + (V_c/80 \text{ km s}^{-1})^{-2},$$

and 

$$\sigma_{Mag}(V_c) = 2.5 \text{ for } V_c < 55 \text{ km s}^{-1};$$

we set $\sigma_{Mag}(V_c) = 0.4$ for $V_c > 80 \text{ km s}^{-1}$. This large scatter causes some low mass CDM halos in low density regions that were below the $V_c$ threshold for inclusion into the catalog to scatter up in luminosity such that voids become sparsely populated with relatively isolated dwarfs; this is apparent in panel c of...
Fig. 1. The $L/V_c$ scatter has no noticeable effect in the WDM sample because there are very few low mass WDM halos available to scatter up in luminosity.

The effect of this scatter on void statistics is readily seen in the void volume fraction, $f_{\text{void}}$, defined as the fraction of randomly-placed spheres that contain no mock galaxies – i.e. the fraction of the total volume occupied by empty (spherical) voids. Fig. 2 shows that the void volume fraction ($f_{\text{void}}$) becomes significantly lower with increasing void size for CDM voids with high $L/V_c$ scatter.

3. Discussion of Luminosity Scatter in Dwarf Galaxies

One should ask whether a large $L/V_c$ is expected or even plausible. For bright galaxies (lying in massive halos), one can use the clustering strength with e.g. the auto-correlation function to constrain halo masses, utilizing the fact that halos become increasingly more strongly clustered with increasing mass. However, for dwarfs, clustering strength has little constraining power on halo mass because the clustering strength of low mass halos has only weak dependence on halo mass and is very similar to that of the dark matter distribution – i.e. halos are not highly biased. Scatter for dwarfs is thus not well-constrained.

Some hints can be found from kinematic mass measurements from individual dwarfs. A large scatter between galaxy luminosity and halo mass is suggested
by the Tully-Fisher relation for dwarfs, which exhibits increased scatter between luminosity and circular velocity for decreasing \( V_c \) for dwarf galaxies\(^{10}\). Considering luminosities of even fainter galaxies, the common 300 parsec dynamical mass scale of \( 10^7 h^{-1} M_\odot \) over \( \sim 5 \) orders of magnitude in luminosity for Milky Way satellites\(^{11}\) may reflect a very large scatter in dwarf galaxy luminosity to halo mass, though it may instead simply reflect a rapid drop in luminosity over a narrow halo mass range.

Ref. 12 cites the existence of more than expected relatively bright but isolated galaxies in the local volume as a potential CDM problem; massive halos in CDM simulations prefer to lie instead in the walls, filaments, and knots that bound void volumes. Our results may alleviate any such problem. We show that within a CDM universe that also has large halo mass to luminosity scatter, there is the potential for a population of relatively isolated and bright galaxies.

3.1. Prospects for the future

Sufficiently large and deep future surveys (e.g., the Large Synoptic Survey Telescope) should provide sufficient statistics to detect whether we live in a CDM universe with large scatter in \( L/V_c \) using local volume void statistics. Large enough numbers of dwarf galaxies in small voids would rule out WDM. If it happens instead that we live in a WDM universe, such void statistics combined with an independent determination of a large \( L/V_c \) scatter could allow CDM to be ruled out by the emptiness of small voids. Finally, we note that if the dwarf galaxy \( L/V_c \) scatter is small, there would seem to be little potential of using the cosmic web to constrain whether we have CDM versus a WDM cosmology.

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References