Galaxy Formation: Warm Dark Matter, Missing Satellites, and the Angular Momentum Problem

Martin Götz (gotz@tac.dk) and Jesper Sommer-Larsen
Theoretical Astrophysics Center, Copenhagen, Denmark

Abstract. We present warm dark matter (WDM) as a possible solution to the missing satellites and angular momentum problem in galaxy formation and introduce improved initial conditions for numerical simulations of WDM models, which avoid the formation of unphysical haloes found in earlier simulations. There is a hint, that the mass function of satellite haloes has been overestimated so far, pointing to higher values for the WDM particle mass.

Keywords: cosmology: theory — dark matter — galaxies: formation — methods: N-body simulations

The cold dark matter (CDM) scenario for structure formation is well established, and is particularly successful in explaining the formation of large-scale structure and galaxies. But there exist problems on small (i.e. galactic) scales, among them: (1) The missing satellites problem: CDM produces too many small galaxies, e.g. about five times as many satellites as are observed in the local group (Klypin et al., 1999; Moore et al., 1999; Kamionkowski and Liddle, 2000). (2) The angular momentum problem: Galaxies in CDM simulations consistently have smaller specific angular momenta, and therefore have smaller disks than what is observed (Sommer-Larsen and Dolgov, 2001 and references therein).

One possible solution to these problems is to go from CDM to warm dark matter (WDM). The free-streaming motion of the WDM particle reduces power on small scales, but keeps it unchanged at long wavelengths, not disturbing the predictions of CDM for the formation of large-scale structure. This leads to the formation of fewer low-mass systems, explaining the missing satellites problem, and to fewer merging events, during which subclumps, which are assembled into galactic disks, would loose orbital angular momentum and energy by dynamical friction. Typically, WDM particle masses of the order $1h^{5/4}\text{keV}$ (corresponding to a free-streaming mass of $M_f \approx 3 \times 10^{11} h^{-1} M_\odot$ for $\Omega_0 = 0.3$) are necessary to explain the missing satellites (Kamionkowski and Liddle, 2000; Colin et al., 2000; White and Croft, 2000; Bode et al., 2001; Governato et al., 2002) and to reduce the discrepancy of the specific angular momenta from a factor of 10 or more to about a factor of 2 (Sommer-Larsen and Dolgov, 2001).

Thus to check WDM against observations, it is necessary to study, how many small haloes there are, and how the large disk galaxies
Figure 1. Dark matter particles at redshifts $z = 0$ and $z = 2$ within a slice of size $10 \times 10 \times 0.325 \, (h^{-1}\text{Mpc})^3$ for two AWDM simulations starting with identical phases from grid and glass initial conditions, respectively. The regularly spaced, unphysical haloes along filaments in grid simulations are clearly visible at $z = 0$ (in particular along the filament running from the halo in the center to the one close to the lower right corner), and how they form as artifacts due to trains of particles falling onto the forming filaments at high redshifts. They are not present in the run starting from a glass.

are formed. This requires numerical simulations, even for the relatively simple task of calculating the halo mass function in a WDM scenario. There, structure formation does not follow the hierarchical picture well-known from CDM, since haloes smaller than the free-streaming scale form later than the larger ones by non-linear transfer of power from large to small scales. That means that analytical schemes (e.g. Press-Schechter theory and its variations) can not be applied to WDM. Figure 1 in Götz and Sommer-Larsen (2002) clearly shows the discrepancy between Press-Schechter theory and the numerical mass function.

But numerical simulations with WDM have problems of their own. To check the effect of reduced power on small scales, they have to be
Figure 2. The cumulative number density of subhaloes as a function of their maximum circular velocity $V_{c,\text{max}}$. The subhaloes have to be located within $400 h^{-1}$kpc of the density peak of the host halo, which are selected to be Milky Way-like with $V_{c,\text{max}}$ between 220 and 280 km/s. The solid and dotted lines show the numerical results for the $\Lambda$CDM and $\Lambda$WDM (with a free streaming mass of $M_f = 1.5 \times 10^{11} h^{-1} M_{\odot}$) simulations with glass initial conditions presented in this paper, together with their 1σ Poisson errors. The gray area indicates, where these simulations are incomplete. The observed number density for the Milky Way and M31 from Klypin et al. (1999) is shown by filled circles, and their numerical result for a $\Lambda$CDM-model by the dashed line, which agrees with our result.

set up such, that the mean particle separation is (much) smaller than the wavelength, below which the power spectrum is cut off. Thus initial displacements and velocities of neighboring particles are highly correlated. Since at high redshifts, matter moves perpendicularly onto the forming filaments, there will be “trains” of particles falling onto them in the usual set-up, where one starts from a regular cubic mesh. They create unphysical haloes along the filaments, with a separation given by the grid spacing projected onto the filament (Götz and Sommer-Larsen, 2002). These “beads on a string”, and how they form, can clearly be seen in the left hand panels of Figure 1. To avoid this problem, the grid structure needs to be broken by starting from glass-like initial conditions (White, 1996), where the particles are irregularly distributed, but still (almost) evenly spaced. The right hand panels in Figure 1 show the now much smoother distribution of matter along the filaments.

To calculate a more reliable satellite mass function, not affected by the presence of unphysical haloes, we ran a WDM simulation starting with glass initial conditions. We chose a $\Lambda$-cosmology ($\Omega_0 = 0.3,$
\( \Omega = 0.7, h = 0.65 \) with a cluster-abundance normalized power spectrum \( (\sigma_8 = 1.0) \) and a free streaming mass of \( M_f = 1.5 \times 10^{11} h^{-1} M_\odot \), corresponding to a WDM particle mass of \( 1.2 h^{5/4} \text{keV} \) close to the value found by other authors. We used the publicly available Hydra code (Couchman et al., 1995) with \( 128^3 \) dark matter particles in a \( 10h^{-1}\text{Mpc} \) box. A corresponding CDM simulation was also run. Candidate host haloes were identified with friends-of-friends, and Milky Way-like hosts with a maximum circular velocity \( V_{c,\text{max}} \) between 220 and 280 km/s were selected — 8 in the AWDM and 9 in the ΛCDM run. Within these haloes, subhaloes were found with a variation of the HOP algorithm (Eisenstein and Hut, 1998), and Figure 2 shows the cumulative number densities of those satellites, which lie within \( 400h^{-1}\text{kpc} \) of the density peak of the host halo, as a function of their \( V_{c,\text{max}} \). As expected, CDM seems to overpredict the number of satellites compared to the observed distribution for the Milky Way and M31 (Klypin et al., 1999), but our improved WDM simulations without the unphysical haloes now give numbers which are too low. This hints a lower \( M_f \) and higher WDM particle mass than has been suggested so far. But that result has to be taken with caution, since the identification of subhaloes is non-trivial, and we have not yet checked the effects of different algorithms on it.

In conclusion, WDM can solve the missing satellites and angular momentum problems, but improved initial conditions starting with a glass-like distribution of the particles are necessary for numerical studies to avoid the appearance of unphysical haloes which are purely grid artifacts. Thus there is the possibility that the satellite mass function has been overestimated in previous studies, and that the WDM particle mass actually has to be higher. But it should be mentioned that there are other open questions for WDM. E.g., high velocity clouds could be the missing satellites (Braun and Burton, 1999), CDM with feedback from star formation may solve the angular momentum problem (Sommer-Larsen et al., 2002; Thacker and Couchman, 2001), and the late structure formation in WDM can be a problem, if the trend of finding quasars at ever higher redshifts continues.

References

Bode, P., Ostriker, J. P. and Turok, N.: 2001, ApJ 556, 93–107.
Braun, R. and Burton, W. B.: 1999, A&A 341, 437–450.
Colín, P., Avila-Reese, V. and Valenzuela, O.: 2000, ApJ 542, 622–630.
Couchman, H. M. P., Thomas, P. A. and Pearce, F. R.: 1995, ApJ 452, 797–813.
Eisenstein, D. J. and Hut, P.: 1998, ApJ 498, 137–142.
Götz, M. and Sommer-Larsen, J.: 2002, Astroph. & Space Science 281, 415–416.
Governato, F. et al.: 2002, astro-ph/0207044.
Kamionkowski, M. and Liddle, A. R.: 2000, *Phys. Rev. Lett.* 84, 4525–4528.
Klypin, A. et al.: 1999, *ApJ* 522, 82–92.
Moore, B. et al.: 1999, *ApJL* 524, L19–L22.
Sommer-Larsen, J. and Dolgov, A.: 2001, *ApJ* 551, 608–623.
Sommer-Larsen, J., Götz, M. and Portinari, L.: 2002, astro-ph/0204366.
Thacker, R. J. and Couchman, H. M. P.: 2001, *ApJL* 555, L17–L20.
White, M. and Croft, R. A. C.: 2000, *ApJ* 539, 497–504.
White, S. D. M.: 1996, in: R. Schaeffer et al. (eds.), *Cosmology and Large-Scale Structure: Les Houches, Session LX*, Elsevier, Amsterdam, p. 349–430.
