NIHAO V: Too big doesn’t fail – reconciling the conflict between ΛCDM predictions and the circular velocities of nearby field galaxies

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ABSTRACT
We compare the half-light circular velocities, $V_{1/2}$, of dwarf galaxies in the Local Group to the predicted circular velocity curves of galaxies in the NIHAO suite of ΛCDM simulations. We use a subset of 34 simulations in which the central galaxy has a stellar luminosity in the range $0.5 \times 10^5 < L_V/L_\odot < 2 \times 10^8$. The NIHAO galaxy simulations reproduce the relation between stellar mass and halo mass from abundance matching, as well as the observed half-light size vs luminosity relation. The corresponding dissipationless simulations over-predict the $V_{1/2}$, recovering the problem known as too big to fail (TBTF). By contrast, the NIHAO simulations have expanded dark matter haloes, and provide an excellent match to the distribution of $V_{1/2}$ for galaxies with $L_V \sim 2 \times 10^6 L_\odot$. For lower luminosities our simulations predict very little halo response, and tend to over predict the observed circular velocities. In the context of ΛCDM, this could signal the increased stochasticity of star formation in haloes below $M_{\text{halo}} \sim 10^{10} M_\odot$, or the role of environmental effects. Thus, haloes that are “too big to fail”, do not fail ΛCDM, but haloes that are “too small to pass” (the galaxy formation threshold) provide a future test of ΛCDM.

Key words: dark matter – cosmology: theory – galaxies: dwarf – galaxies: kinematics and dynamics – galaxies: haloes – Local Group

1 INTRODUCTION
The Dark Energy plus Cold Dark Matter (ΛCDM) model provides an extremely successful cosmological framework for understanding the large (> Mpc) scale structure of the universe and its evolution with time. On small (kpc) scales the ΛCDM model has faced challenges related to the number density and structure of dark matter haloes. At face value ΛCDM predicts too many low mass haloes (Moore et al. 1999; Klypin et al. 1999) and too much mass on scales near galaxy half-light radii (de Blok et al. 2001). While these “missing satellite” and “cusp-core” problems may signal the need for alternatives to cold dark matter (e.g., Vogelsberger et al. 2014; Macciò et al. 2015), there are plausible solutions related to the baryonic physics of galaxy formation.

Recently, Boylan-Kolchin et al. (2011, 2012), introduced a related problem. Using dissipationless ΛCDM simulations they found that the 10 most massive sub-haloes in simulated Milky Way mass haloes have circular velocities a factor of ~ 1.5 higher than that observed at the half-light radii of the MW satellites. This is often referred to as the too big to fail (TBTF) problem because the haloes are too big ($V_{\text{max}} > 30 \text{ km s}^{-1}$) for the effects of the cosmic UV background to suppress gas cooling and thus prevent star formation (Bullock et al. 2000). Thus each halo must host a visible galaxy. While possibly related to the missing satellites problem, in that the largest subhaloes may not have been found, TBTF is a distinct problem related to the internal structure of subhaloes, and hence to the cusp-core problem, rather than strictly to their abundances.

A somewhat trivial solution to the TBTF problem is to reduce the mass of the Milky Way, with proportionally fewer massive subhaloes (Vera-Ciro et al. 2013). However, a lower
Milky Way halo mass significantly reduces the likelihood of finding two subhaloes as massive as the LMC and SMC (Kennedy et al. 2014). A comprehensive statistical analysis of the sub-halo population indeed concludes that there are too many massive CDM sub-haloes (Jiang & van den Bosch 2015).

On the galaxy formation side there are processes that can solve the TBTF problem. Gas outflows or bulk motions driven by feedback from stars can cause halo expansion (e.g., Navarro et al. 1996; Mashchenko et al. 2006; Pontzen & Governato 2012; Ogiya & Mori 2014). A number of studies using fully cosmological galaxy formation simulations have indeed found halo expansion in isolated dwarf galaxies (e.g., Mashchenko et al. 2008; Governato et al. 2010; Di Cintio et al. 2014; Madau et al. 2014; Oñorbe et al. 2015; Tollet et al. 2015; Trujillo-Gomez et al. 2015). In addition Zolotov et al. (2012) and Brooks & Zolotov (2014) studied the satellite population in two Milky Way mass simulations. The combination of feedback before infall and tidal stripping after infall resulted in reduced circular velocities, at the scale of 1kpc, of the magnitude required to resolve the TBTF problem.

Recently it has been shown that field galaxies follow the same trends between velocity dispersion and half-light radius as satellite galaxies (Kirby et al. 2014), and thus the over-prediction of galaxy circular velocities persists in the field (Garrison-Kimmel et al. 2014). see also Papastergis et al. (2015). This Field TBTF problem is a cleaner test of ΛCDM, as the mass of the Milky Way and environmental processes are not plausible solutions. Within the ΛCDM framework halo expansion driven by feedback from stars and supernova is the only solution. If this solution fails, then an alternative to Cold Dark Matter is required.

A key question for the feedback solution is whether there is enough energy available in low mass galaxies to drive sufficient outflows. Idealized simulations and energy arguments have been used to conclude that the answer is no (Boylan-Kolchin et al. 2012; Peñarrubia et al. 2012; Garrison-Kimmel et al. 2013). However, subsequent studies have challenged these conclusions, arguing that there is in fact sufficient energy available to cause halo expansion on mass scales relevant to the TBTF problem (Madau et al. 2014; Maxwell et al. 2015; Chan et al. 2015).

Thus, on an individual basis the field TBTF problem can be solved, but what about for the full population of ΛCDM haloes, with realistic galaxy masses and sizes? In this letter we answer this question with a subset of the NIHAO (Numerical Investigations of Hundred Astrophysical Objects) galaxy formation simulations (Wang et al. 2015). Reproducing the stellar masses is critical, as if star formation is too efficient one will likely overpredict the amount of expansion, and draw erroneous conclusions. Previous simulations tend to over-predict the stellar masses by up for a factor of ~10 (see Fig. 1).

\footnote{Nihao is the Chinese word for hello}
Figure 2. Size vs luminosity (left) and velocity vs luminosity (right) relations for NIHAO galaxy simulations (red symbols) compared to observed galaxies in the local group compiled by Kirby et al. (2014) split into isolated (black) and satellites of the Milky Way (blue squares) and M31 (blue triangles). The simulations correspond well with observations, especially for the isolated galaxies (black open symbols) which are a fairer comparison sample to our isolated simulated galaxies. Below $L_V \sim 2 \times 10^6 L_\odot$ there is a large observational scatter in both relations, with no clear trend, while above $L_V \sim 2 \times 10^6 L_\odot$ the scatter is smaller and there are clear trends for more luminous galaxies to be larger with higher circular velocities. We note that at least part of the increased scatter at low luminosities is observational, and especially including M31 galaxies.

The fact that our simulations reproduce the stellar mass-halo mass, size-luminosity, and velocity-luminosity relations would suggest that they also resolve the too-big-to-fail problem.

3 SCALING RELATIONS

Fig. 2 shows the size-luminosity and velocity-luminosity relations for NIHAO simulations with luminosities $0.5 \times 10^5 < L_V / L_\odot < 2 \times 10^8$ (red filled symbols) vs observations (open symbols) from Kirby et al. (2014). In the simulations we calculate 3D half-light radii, $r_{1/2}$, using the cumulative V-band luminosity profile (computed with PYNBODY, Pontzen et al. 2013) inside 20% of the virial radius. Note that since the sizes are typically 2 per cent of the virial radius, they are insensitive to the exact choice of outer aperture. We measure the circular velocity at the half-light radius, $V_{1/2} = \sqrt{GM(r_{1/2})/r_{1/2}}$. We convert the observed 2D half-light radii into 3D half-light radii by multiplying by 4/3. The observed circular velocities at the half-light radius are computed by converting the $M_{1/2}$ from Kirby et al. (2014) into $V_{1/2}$. In the absence of rotation, this corresponds to $V_{1/2} = \sqrt{3} \sigma$.

4 TOO BIG TO FAIL

Fig. 3 shows the circular velocity profiles of our simulations (with luminosities $0.5 \times 10^5 < L_V / L_\odot < 2 \times 10^8$) vs observations of satellite and isolated galaxies in the local group compiled by Kirby et al. (2014). Simulations are plotted with solid lines down to the radius where the circular velocity profile has converged to 10% according to the criteria of Schaller et al. (2015). The dotted lines continue the profiles down to the softening length of the dark matter particles. It has been noted that isolated galaxies (black circles) fall in the same part of the velocity vs radius plane as the satellites of the Milky Way (blue squares) and M31 (blue triangles). This suggests that environmental processes do not significantly affect the average dark halo mass profile, limiting the range of physical processes available to solve the TBTF problem in the context of ΛCDM.

We split the sample into two luminosity groups at
Figure 3. Circular velocity vs radius for cosmological simulations (lines) compared to observations (symbols with error bars) of local group galaxies from Kirby et al. (2014), split into isolated (black) and satellites of the Milky Way (blue squares) and M31 (blue triangles). Upper and lower panels show galaxies greater and less than a luminosity of $L_V = 2 \times 10^6 L_\odot$, respectively. The arrows for the three brightest isolated galaxies show alternative measurements of circular velocity at 2 kpc. The left panels show dark matter only simulations (in cyan), while the right panels show the NIHAO galaxy simulations (in red). The solid lines show the simulated profiles down to where the velocity profile has converged to 10%, while the dotted lines continue the profile to the dark matter softening length.

$L_V = 2 \times 10^6 L_\odot$ as galaxies above and below this luminosity appear to have qualitatively different behavior. Observationally, the low luminosity galaxies have large variation in sizes and velocities at fixed luminosity, while the high luminosity galaxies follow well defined scaling relations (given the small sample sizes). Theoretically, at low luminosities the stellar mass vs halo mass relation breaks down, and the halo response to galaxy formation is minimal.

The cyan lines in the left-hand panels of Fig. 3 show the circular velocity profiles of the dark matter only simulations. At both high and low luminosities these simulations predict systematically higher velocities than observed. For low-luminosity galaxies the median half-light size and circular velocity of observed galaxies is $r_{1/2} = 0.37$ kpc and $V_{1/2} = 12.3$ km s$^{-1}$. At 0.37 kpc the median circular velocity in the dark matter only simulations is 16.1 km s$^{-1}$. For high-luminosity galaxies the median half-light size and circular velocity of observed galaxies is $r_{1/2} = 0.79$ kpc and $V_{1/2} = 18.6$ km s$^{-1}$. The corresponding median circular velocity in the dark matter only simulations is 28.9 km s$^{-1}$, i.e. 55% too high. This discrepancy in circular velocity corresponds to a factor of $\sim 2$ in enclosed mass, and is consistent with previous studies of the TBTF problem.

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of satellite and field galaxies (Boylan-Kolchin et al. 2012; Garrison-Kimmel et al. 2014).

5 A BARYONIC SOLUTION TO TBTF

In the right-hand panels of Fig. 3 the red lines show the circular velocity profiles of the NIHAO galaxy simulations. Focusing first on the upper panel, there is no systematic offset and the scatter is comparable, showing that the effects of galaxy formation, and particular the prescription for star formation and stellar feedback implemented in NIHAO cause the right amount of halo expansion (a factor of 1.5 lower circular velocity at 0.79 kpc). An interesting feature of the halo response is that the more massive haloes have larger reductions in central rotation velocities, and shallower density slopes (Tollet et al. 2015). This causes the rank order of circular velocity at sub-kpc scales to no-longer correspond to the rank order of their halo masses.

For the three most luminous isolated galaxies (NGC6822, IC1613, WLM) the arrows show a measurement of the circular velocity at 2 kpc from resolved neutral hydrogen rotation curves as compiled by Oman et al. (2015). With these observations NGC6822 is now consistent with the hydro simulations, and our galaxy formation simulations are consistent with all of the luminous field galaxies.

6 A PROBLEM FOR LOW MASS GALAXIES?

Lower luminosities and halo masses are potentially interesting, as our (and other) simulations predict that baryonic processes have negligible impact on the structure of dark matter haloes. For luminosities below $L_V \sim 2 \times 10^6 L_\odot$ the halo response is minimal: the median circular velocities at 0.37 kpc in the NIHAO simulations are just 2% lower than the dark matter only simulations.

There are only three observed isolated galaxies in this luminosity range, two are consistent with our simulations, while one (Tucana – black circle at $r_{1/2} \sim 0.3$ kpc, $V_{1/2} \sim 30$ km s$^{-1}$) is significantly above. If the measurements of the circular velocity and half-light size are robust, then it must have formed in a massive dark matter halo with $V_{\text{max}} \gtrsim 70$ km s$^{-1}$. Some of the satellites are consistent with the simulations, but half are significantly below, including two MW satellites (although it should be noted that most of the discrepant galaxies are M31 satellites and carry larger measurement errors).

The larger scatter in observed circular velocities than predicted by our simulations may indicate a lingering problem for LCDM. This problem is distinct from the TBTF problem, as the typical host haloes are no longer too-big-to-fail for ΛCDM. This problem is distinct from the TBTF predicted by our simulations may indicate a lingering problem. The discrepant galaxies are M31 satellites and carry larger two MW satellites (although it should be noted that most it must have formed in a massive dark matter halo with the circular velocity and half-light size are robust, then $30$ km s$^{-1}$).

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