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Review Article

Triumphs and tribulations of ΛCDM, the double dark theory

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ΛCDM has become the standard cosmological model because its predictions agree so well with observations of the cosmic microwave background and the large-scale structure of the universe. However ΛCDM has faced challenges on smaller scales. Some of these challenges, including the "angular momentum catastrophe" and the absence of density cusps in the centers of small galaxies, may be overcome with improvements in simulation resolution and feedback. Recent simulations appear to form realistic galaxies in agreement with observed scaling relations. Although dark matter halos start small and grow by accretion, the existence of a star-forming band of halo masses naturally explains why the most massive galaxies have the oldest stars, a phenomenon known as known as galactic "downsizing." The discovery of many faint galaxies in the Local Group is consistent with ΛCDM predictions, as is the increasing evidence for substructure in galaxy dark matter halos from gravitational lensing flux anomalies and gaps in cold stellar streams. However, the "too big to fail" (TBTF) problem challenges ΛCDM. It arose from analysis of the Acquarius and Via Lactea very high-resolution ΛCDM simulations of dark matter halos like that of the Milky Way. Each simulated halo has ~ 10 subhalos that were so massive and dense that they would appear to be too big to fail to form lots of stars. The TBTF problem is that none of the observed satellite galaxies of the Milky Way or Andromeda have stars moving as fast as would be expected in these densest subhalos. This may indicate the need for a more complex theory of dark matter – or perhaps just better understanding of dark matter simulations and/or baryonic physics.

1 Introduction

The first thing everyone interested in dark matter and cosmology should know is that we now have a standard model. This represents a breakthrough: cosmology has finally become a serious science during the past decade, with predictions now routinely confirmed by observations. The standard model is known as ΛCDM – Λ for the cosmological constant, and CDM for Cold Dark Matter, particles that moved sluggishly in the early universe and thereby preserved fluctuations down to small scales. However, if you are talking with a non-astronomer about modern cosmology, there should be a more friendly name for the standard model. Since according to ΛCDM the cosmic density is mostly dark energy (either a cosmological constant with $\Omega_\Lambda = 0.728 \pm 0.016$ or some dynamical field that plays a similar cosmic role) and dark matter, we recommend the simple name "Double Dark Theory" for the modern cosmological standard model [1, 2].

Of course, a standard model also has standard limitations. Like the standard model of particle physics, ΛCDM requires the determination of a number of relevant constants, and the theory does not attempt to explain why they have the measured values – or to explain the fundamental nature of the dark matter and dark energy. These remain challenges for the future. But the good news is that the key cosmological parameters are now all determined to an accuracy of a few percent, including the power spectrum normalization parameter $\sigma_8 = 0.809 \pm 0.024$ [3]. It is remarkable and reassuring that the cos-

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mic microwave background (CMB) [3], the expansion history of the universe from Type 1a supernovae (e.g., [4]), galaxy cluster data [5–8], and the large-scale distribution of galaxies [9,10] all agree so well. The same cosmological parameters that are such a good match to the CMB observations also predict the observed distribution of density fluctuations from small scales probed by the Lyman alpha forest[1] to the entire horizon, as shown in Fig. 1 [11]. The near-power-law galaxy-galaxy correlation function at low redshifts is now known to be a cosmic coincidence [12]. I was personally particularly impressed that the evolution of the galaxy-galaxy correlations with redshift predicted by ΛCDM [13] turned out to be in excellent agreement with the subsequent observations [14].

Potential challenges to ΛCDM on large scales come from the tails of the predicted distribution functions, such as CMB cold spots and massive clusters nearby or at high redshifts. However, the existing observations appear to be consistent thus far with predictions of standard ΛCDM [3, 15–17] with standard primordial power spectra; non-Gaussian initial conditions are not required. Larger surveys now underway may provide more stringent tests.

Large, high-resolution simulations permit detailed predictions of the distribution and properties of galaxies and clusters. For the past half-decade, the benchmark simulations were Millennium-I [18] and Millennium-II [19], which have been the basis for more than 400 papers. However, these simulations used first-year Wilkinson Microwave Anisotropy Probe (WMAP) cosmological parameters, including $\sigma_8 = 0.90$, that are now in serious disagreement with the latest observations. Improved cosmological parameters, simulation codes, and computer power have permitted the more accurate simulations Bolshoi [20] and BigBolshoi [21]. The predicted cluster concentrations appear to be in good agreement with observations [21].

Dark matter halos can be characterized in a number of ways. A common one is by mass, but the mass attributed to a halo depends on a number of factors including how the outer edge of the halo is defined; popular choices include the spherical radius within which the average density is either 200 times critical density or the virial density (which depends on redshift). Properties of all the halos in many stored time steps of both the Bolshoi and BigBolshoi simulations are available on the web in the MultiDark database [22]. For many purposes it is more useful to characterize halos by their maximum circular velocity $V_{\rm max}$, which is defined as the maximum value of $[GM(<r)/r]^{1/2}$, where G is Newton's constant and $M(<r)$ is the mass enclosed within radius r. The reason this is useful is that $V_{\rm max}$ is reached at a relatively low radius $r_{\rm max}$, closer to the central region of a halo where stars or gas can be used to trace the velocity of the halo, while most of the halo mass is at larger radii. Moreover, the measured internal velocity of a galaxy (line of sight velocity dispersion for early-type galaxies and rotation velocity for late-type galaxies) is closely related to its luminosity according to the Faber-Jackson and Tully-Fisher relations. In addition, after a subhalo has been accreted by a larger halo, tidal stripping of its outer parts can drastically reduce the halo mass but typically decreases $V_{\rm max}$ much less. (Since the stellar content of a subhalo is thought to be determined before it was accreted, some authors define $V_{\rm max}$ to be the peak value at any redshift for the main progenitor of a halo.) Because of the connection between halo internal velocity and galaxy luminosity, a common simple method of assigning galaxies to dark matter halos and subhalos is to rank order the galaxies by luminosity and the halos by $V_{\rm max}$, and then match them such that the number densities are comparable [13, 14, 23–25]. This is called "halo abundance matching" or (more modestly) "sub-halo abundance matching" (SHAM).

Halo abundance matching using the Bolshoi simulation predicts galaxy-galaxy correlations in good agreement with the Sloan Digital Sky Survey (SDSS) observations [26]. However, a semi-analytic model based on the Millennium simulations predicted correlations of Milky Way and smaller galaxies a factor of 2 or more higher than observed on Mpc and smaller scales [27], which the authors attribute to the too-large assumed value of σ_8. Correlations of such galaxies on sub-Mpc scales come mainly from two such galaxies in the same large halo, and the higher value of σ_8 used in the Millennium simulations produces more large halos. Abundance matching with the Bolshoi simulation also predicts galaxy velocity-mass scaling relations consistent with observations [26], and a galaxy velocity function in good agreement with observations for maximum circular velocities $V_{\rm max} \gtrsim 100$ km/s, but higher than the HI Parkes All Sky Survey (HIPASS) and the Arecibo Legacy Fast ALFA (ALFALFA) Survey radio observations [28, 29] by about a factor of 2 at 80 km/s and a factor of 10 at 50 km/s. This either means that these radio surveys are increasingly incomplete at lower velocities, or else ΛCDM is in trouble because it predicts far more small-$V_{\rm max}$ halos than there are observed low-V galaxies. A deeper optical survey out

[1] The Lyα forest is the many absorption lines in quasar spectra due to clouds of neutral hydrogen along the line of sight to the quasar.

to 10 Mpc by Klypin, Karachentsev, and Nasonova[2] found no disagreement between $V_{\max}$ predictions and observations for $V_{\max} > 50$ km/s, and only a factor of 2 excess of halos compared to galaxies at 40 km/s. This is encouraging, since for $V \lesssim 40$ km/s reionization and feedback can plausibly explain why there are fewer observed galaxies than dark matter halos [30–35], and also explain the observed scaling laws including metallicity [36–38].

The Milky Way has two rather bright satellite galaxies, the Large and Small Magellanic Clouds. Using the Bolshoi simulation, it is possible using sub-halo abundance matching to determine the number of Milky-Way-mass dark matter halos that have subhalos with high enough circular velocity to host such satellites. It turns out that about 55% have no such subhalos, about 28% have one, about 11% have two, and so on [39]. Remarkably, these predictions are in excellent agreement with an analysis of photometric observations by the Sloan Digital Sky Survey (SDSS) [40]. The distribution of the relative velocities of central and bright satellite galaxies from SDSS spectroscopic observations is also in very good agreement with the predictions of the Millennium-II simulation [41], and the Milky Way's lower-luminosity satellite population is not observationally unusual [42]. Considered in a cosmological context, the Magellanic clouds are likely to have been accreted within about the last Gyr, and the Milky Way halo mass is $1.2^{+0.7}_{-0.4}(\text{stat.})\pm 0.3(\text{sys.})\times 10^{12} M_{\odot}$ according to [43].

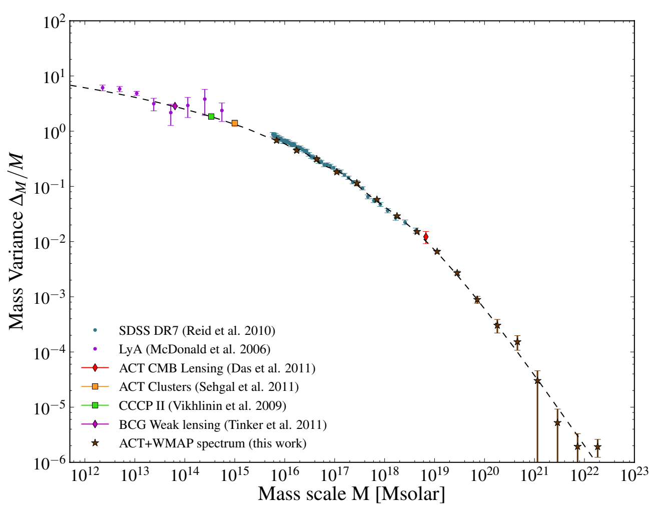


Figure 1 (online color at: www.ann-phys.org) The ΛCDM predicted r.m.s. mass variance $\Delta M/M$ compared with observations, from WMAP and the Atacama Cosmology Telescope (ACT) on large scales, brightest cluster galaxy weak lensing, clusters, the SDSS galaxy distribution, and the Lyman alpha forest on small scales. This figure highlights the consistency of power spectrum measurements by an array of cosmological probes over a large range of scales. (Fig. 5 in [11], which gives the sources of the data.)

2 Galaxy formation

An old criticism of ΛCDM has been that the order of cosmogony is wrong: halos grow from small to large by accretion in a hierarchical formation theory like ΛCDM, but the oldest stellar populations are found in the most massive galaxies – suggesting that these massive galaxies form earliest, a phenomenon known as "downsizing" [45]. The key to explaining the downsizing phenomenon is the realization that star formation is most efficient in dark matter halos with masses in the band between about 10^{10} and $10^{12} M_{\odot}$. This goes back at least as far as the original Cold Dark Matter paper [44], from which Fig. 2 is reproduced. A dark matter halo that has the total mass of a cluster of galaxies today will have formed from

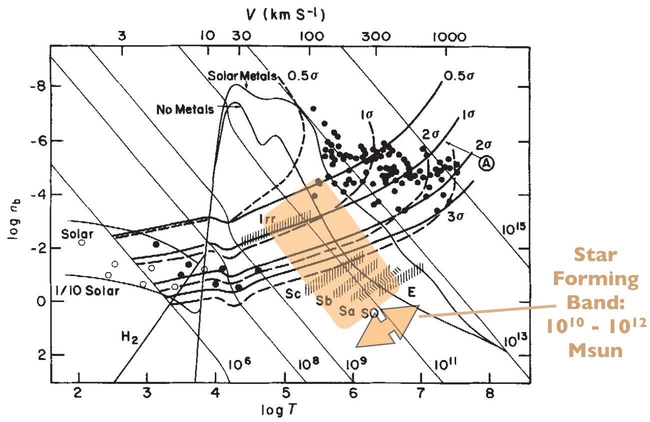


Figure 2 (online color at: www.ann-phys.org) Baryon density n_b versus the virial temperature T for structures of various sizes in the universe, where $T = \mu V^2/3k$, μ is mean molecular weight (≈ 0.6 for ionized primordial H + He), V is the three-dimensional r.m.s. velocity dispersion, and k is Boltzmann's constant. Below the No Metals and Solar Metals cooling curves, the cooling timescale is more rapid than the gravitational timescale. Dots are groups and clusters. Diagonal lines show the halo masses in units of $M_{\odot}$. Irr-Sc-Sb-Sa-E are observed galaxy populations. (Fig. 3 in [44], with the Star Forming Band added.)

[2] Presented by Anatoly Klypin at the "First Light and Faintest Dwarfs" conference at the Kavli Institute for Theoretical Physics (KITP) in February 2012.

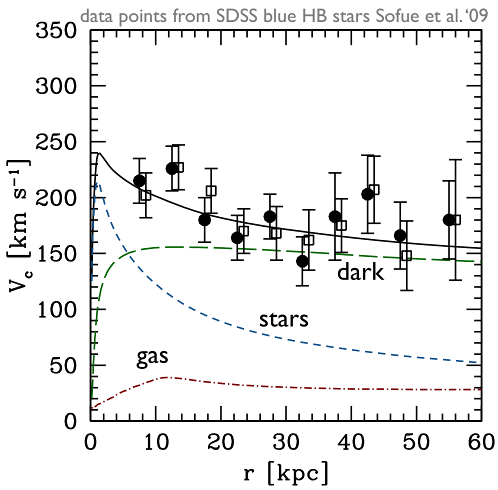


Figure 3 (online color at: www.ann-phys.org) Rotation curve of the ERIS galaxy at $z = 0$ compared to data on the Milky Way. This simulation assumed that star formation only occurs at high density peaks, and supernova feedback becomes more efficient in removing gas from high-density regions. These outflows preferentially remove low angular momentum material, suppressing the formation of a large bulge. Simulations based on the same cosmological initial conditions but with lower resolution or lower feedback produce rotation curves that are more centrally peaked and a worse match to the data. (Figure from Javiera Guedes, private communication.)

halos that crossed this star-forming mass band at an early epoch, and it will therefore contain galaxies whose stars formed early. These galaxies will be red and dead today.[3] A less massive dark matter halo that is just entering the star-forming band today will just be forming stars, and it will be blue today with much of the light coming from the short-lived massive stars. The details of the origin of the star-forming band are still being worked out. Back in 1984, we argued [44] that cooling would be inefficient for masses greater than about $10^{12} M_\odot$ because the density would be too low, and inefficient for masses less than about $10^8 M_\odot$ because the gas would not be heated enough by falling into these small potential wells. Now we know that reionization, supernovae [46], and other energy input additionally impedes star formation for halo masses below about $10^{10} M_\odot$, that gas efficiently streams down filaments into halos up to $\sim 10^{12} M_\odot$ [47–51], and that feedback from active galactic nuclei (AGN) additionally impedes star formation for halo masses above about $10^{12} M_\odot$ [52].

Early simulations of disk galaxy formation found that the simulated stellar disks had much less angular momentum than disks in observed galaxies [53]. This problem seemed so serious that it became known as the "angular momentum catastrophe." A major cause of this was excessive cooling of the gas in small halos before they merged to form larger galaxies [54]. Simulations with higher resolution and more physical treatment of feedback from star formation appear to resolve this problem. In particular, the Eris cosmological simulation [55] produced a very realistic spiral galaxy, as shown by the rotation curve in Fig. 3.

It still remains to be seen whether the entire population of galaxies can be explained in the context of ΛCDM. A concern regarding disk galaxies is whether the formation of bulges by both galaxy mergers and secular evolution will prevent the formation of as many pure disk galaxies as we see in the nearby universe [56]. A concern regarding massive galaxies is whether theory can naturally account for the relatively large number of ultraluminous infrared galaxies. These bright sub-millimeter galaxies were the greatest discrepancy between semianalytic model predictions compared with observations out to high redshift [57]. This could possibly be explained by a top-heavy stellar initial mass function, or maybe just by more realistic simulations including self-consistent treatment of dust [58]. Clearly, there is much still to be done, both observationally and theoretically.

It is possible that all the potential discrepancies between ΛCDM and observations of relatively massive galaxies will be resolved by better understanding of the complex astrophysics of their formation and evolution. But small galaxies might provide simpler tests of ΛCDM.

3 Smaller scale issues: Cusps

Cusps were perhaps the first potential discrepancy pointed out between the dark matter halos predicted by CDM and the observations of small galaxies that appeared to be dominated by dark matter nearly to their centers [61, 62]. Pure dark matter simulations predicted that the central density of dark matter halos behaves roughly as $\rho \sim r^{-1}$. Navarro, Frenk, and White showed that dark matter halos have a density distribution that can be roughly approximated as $\rho_{\rm NFW} = 4\rho_s x^{-1}(1+x)^{-2}$, where $x \equiv r/r_s$ [63]. But this predicted central cusp in the dark matter distribution seemed inconsistent with published observations of the rotation velocity of neutral hydrogen as a

[3] That is, their stellar populations will be old with little or no ongoing star formation and with most of the light coming from red giant stars.

function of radius in small dim galaxies, where the dark matter dominates the ordinary (baryonic) matter.

Some of these early observations turned out to be unreliable, but a very high-resolution set of two-dimensional observations of gas in small galaxies by Joshua Simon and collaborators appears to show that most of these galaxies did not appear to have dark matter with $\rho \sim r^{-1}$ [64]. Since there were strong non-circular motions observed in the discrepant galaxies, a possible explanation for the observations was that the dark matter is known to be anisotropic in dark matter halos, especially near their centers [65]. If the gas behaved like test particles in such an anisotropic potential, it would look like the observations from certain directions [66]. This explanation was rendered statistically unlikely when high-quality neutral hydrogen observations of a large number of galaxies in The HI Nearby Galaxy Survey (THINGS) favored central density closer to $\rho \sim$ constant rather than $\rho \sim r^{-1}$ [67].

New work now calls into question the interpretation of these observations of gas motion in small galaxies. Joshua Adams and collaborators found that in NGC 2976, one of the galaxies most discrepant with a dark matter cusp in the previous observations by Simon et al. [64], the stellar motions near the center are consistent with $\rho \sim r^{-1}$ [68]. These authors, now including Joshua Simon, argue[4] that the stellar motions are a more robust tracer of the gravitational potential, due to the collisionless nature of stars. They are making observations of stellar motion in a number of other small nearby galaxies.

In some small galaxies, the evidence against central dark matter cusps may be stronger. For example, in Sculptor and Fornax, the brightest dwarf spheroidal satellite galaxies of the Milky Way, stellar motions may imply a flatter dark matter radial profile than $\rho \sim r^{-1}$ [69–71]. But in small galaxies like these with significant stellar populations, central starbursts can naturally produce a similar density profile in simulations [59, 72, 73]. Gas cools into the galaxy center and becomes gravitationally dominant, adiabatically pulling in some of the dark matter [74]. But then the gas is driven out very rapidly by supernovae and the entire central region expands with the density correspondingly dropping. Several such episodes can occur, producing a more or less constant central density consistent with observations, as shown in Fig. 4.

Will this explanation work for low surface brightness (LSB) galaxies? These are among the most common galaxies. They have a range of masses but many have fairly

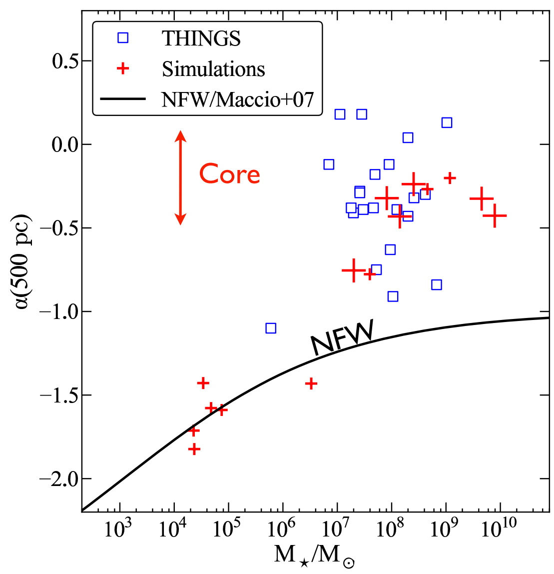


Figure 4 (online color at: www.ann-phys.org) The slope α of the dark matter central density profile r^α vs. stellar mass measured at 500 pc for the resolved halos in [59]. The solid NFW curve assumes the halo concentrations given by [60] and the relation of stellar mass to halo mass given by the simulations of [59]. Large crosses: halos with $> 5 \times 10^5$ dark matter particles; small crosses: $> 5 \times 10^4$ particles. Squares represent galaxies observed by THINGS. (Fig. 1 in [59].)

large rotation velocities indicating fairly deep potential wells, and many of them do not appear to have enough stars for the scenario just described to be plausible [75]. Can we understand the observed distribution of the $\Delta_{1/2}$ measure of central density [76]? This is a serious challenge for galaxy simulators.

Some authors have proposed that warm dark matter (WDM), with initial velocities large enough to prevent formation of small dark matter halos, could solve some of these problems. However, that does not appear to work: the systematics of galactic radial density profiles predicted by WDM do not at all match the observed ones [77]. Yet another constraint on WDM is the evidence for a great deal of dark matter substructure in galaxy halos [78], as we discuss next.

4 Smaller scale issues: Dark matter halo substructure

The first strong indication of galaxy dark matter halo substructure was the flux ratio anomalies seen in quadruply

4 See Joshua Adams's poster at the "First Light and Faintest Dwarfs" conference at KITP in February 2012.

imaged radio quasars ("radio quads") [79–81]. Smooth mass models of lensing galaxies can easily explain the observed positions of the images, but the predictions by such models of the corresponding fluxes are frequently observed to be strongly violated. Optical and X-ray quasars have such small angular sizes that the observed optical and X-ray flux ratio anomalies can be caused by stars ("microlensing"), which has recently allowed a measurement of the stellar mass along the lines of sight in lensing galaxies [82]. But because the quasar radio-emitting region is larger, the observed radio flux anomalies can only be caused by relatively massive objects, with masses of order $10^6 M_\odot$ to $10^8 M_\odot$ along the line of sight. After some controversy regarding whether ΛCDM simulations predict enough dark matter substructure to account for the observations, the latest papers concur that the observations are consistent with standard theory, taking into account uncertainty in lens system ellipticity [83] and intervening objects along the line of sight [84]. But this analysis is based on a relatively small number of observed systems (Table 2 of [85] lists the 10 quads that have been observed in the radio or mid-IR), and further observational and theoretical work would be very helpful.

Another gravitational lensing indication of dark matter halo substructure consistent with ΛCDM simulations comes from detailed analysis of galaxy-galaxy lensing [86, 87], although much more such data will need to be analyzed to get strong constraints. Other gravitational lensing observations including time delays can probe the structure of dark matter halos in new ways [88]. Doing these sorts of observations at various wavelengths accessible from space has motivated the Observatory for Multi-Epoch Gravitational Lens Astrophysics (OMEGA) satellite proposal [89].

The great thing about gravitational lensing is that it directly measures mass along the line of sight. This can provide important information that is difficult to obtain in other ways. For example, the absence of anomalous skewness in the distribution of high redshift Type 1a supernovae brightnesses compared with low redshift ones implies that massive compact halo objects (MACHOs) in the enormous mass range $10^{-2} M_\odot$ to $10^{10} M_\odot$ cannot be the main constituent of dark matter in the universe [90]. The low observed rate of gravitational microlensing of stars in the Large and Small Magellanic clouds by foreground compact objects implies that MACHOs in the mass range between $0.6 \times 10^{-7} M_\odot$ and $15 M_\odot$ cannot be a significant fraction of the dark matter in the halo of the Milky Way [91]. Gravitational microlensing could even detect free-floating planets down to $10^{-8} M_\odot$, just one percent of the mass of the earth [92].

A completely independent way of determining the amount of dark matter halo substructure is to look carefully at the structure of dynamically cold stellar streams. Such streams come from the tidal disruption of small satellite galaxies. In numerical simulations, the streams suffer many tens of impacts from encounters with dark matter substructures of mass 10^5 to $10^7 M_\odot$ during their lifetimes, which create fluctuations in the stream surface density on scales of a few degrees or less. The observed streams contain just such fluctuations [93, 94], so they provide strong evidence that the predicted population of subhalos is present in the halos of galaxies like the Milky Way and M31. Comparing additional observations of dynamically cold stellar streams with fully self-consistent simulations will give more detailed information about the substructure population. Larger satellites such as Sagittarious have so much internal motion that the tidal streams are dynamically too warm to be useful for this purpose. (Sagittarious possibly had as much as 10% of the mass of the entire Milky Way before it began to interact with the Milky Way and was tidally stripped, and its first passage through the Milky Way disk may well be mainly responsible for the bar at the center [95].)

5 Smaller scale issues: Satellite galaxies

ΛCDM predicts that there are many more fairly massive subhalos within dark matter halos of the Milky Way and M31 than there are observed satellite galaxies [97,98], but this is not obviously a problem for the theory since reionization, stellar feedback, and other phenomena are likely to suppress gas content and star formation in low-mass satellites [30-35]. As more faint satellite galaxies have been discovered, especially using multicolor information from SDSS observations, the discrepancy between the predicted and observed satellite population has been alleviated. Many additional satellite galaxies are predicted to be discovered by deeper surveys [99], including those planned for the Southern Hemisphere such as the Dark Energy Survey and eventually the Large Synoptic Survey Telescope (LSST) survey.

However, a potentially serious discrepancy between theory and observations has recently come to light: the "too big to fail" (TBTF) problem [96, 100]. The Via Lactea-II high-resolution dark-matter-only simulation of a Milky Way size halo [101, 102] and the six similar Aquarius simulations [103] all have several subhalos that are too dense in their centers to host any observed Milky Way satellite galaxy. The best-fitting hosts of the observed dwarf spheroidal (dSph) satellites all have 12 km/s $\lesssim V_{\max}$

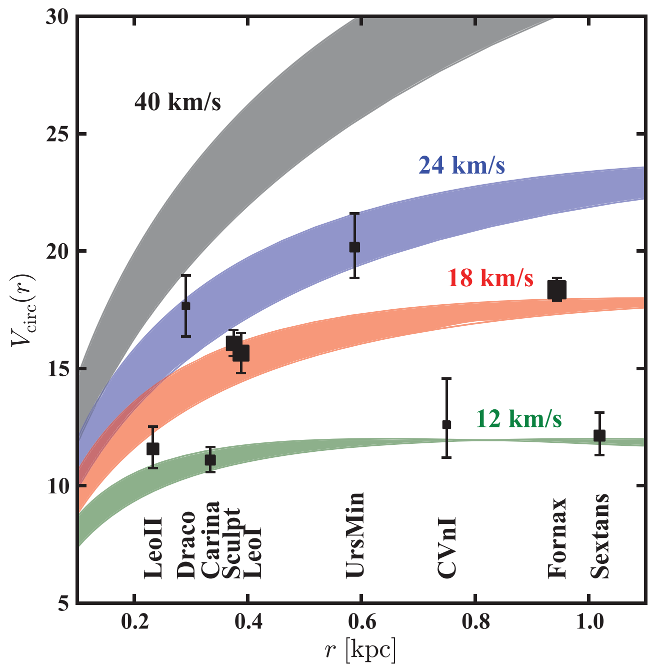


Figure 5 (online color at: www.ann-phys.org) Observed circular velocities of the nine bright dSph satellites of the Milky Way (squares, with sizes proportional to $\log L_V$), along with rotation curves corresponding to NFW subhalos with V_{max} = (12, 18, 24, 40) km/s. The shading indicates the 1σ scatter in the radius r_{max} at which V_{max} occurs in the Aquarius simulations. All of the bright dSphs are consistent with subhalos having $V_{max} \lesssim 24$ km/s, and most require $V_{max} \lesssim 18$ km/s. Only Draco, the least luminous dSph pictured, is consistent within 2σ with a massive subhalo of $V_{max} \approx 40$ km/s at $z = 0$. (Fig. 1 in [96].)

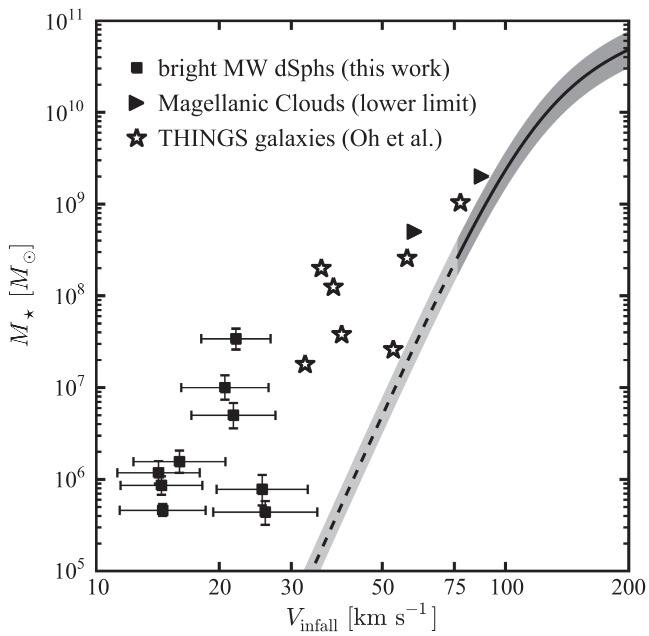


Figure 6 Inferred stellar mass M_* vs. V_{max} at infall V_{infall} for bright Milky Way dSphs. The Magellanic Clouds are placed on the plot at their current values of V_{flat} which is a lower limit to V_{infall}. Low-mass field galaxies from the THINGS survey as well as the dSphs all lie higher than the $z = 0$ abundance-matching relation (solid curve) as well as its extrapolation to lower V_{infall} (dashed curve), and the deviations are systematically larger at lower values of V_{infall}. The shaded region corresponds to a scatter of 0.2 dex in M_* at fixed V_{infall}. (Fig. 9 in [96].)

$\lesssim 24$ km/s, as illustrated in Fig. 5. But the Aquarius simulations predict ~ 10 subhalos with $V_{max} > 24$ km/s. These halos are also among the most massive at early times, and thus are not expected to have had their star formation greatly suppressed by reionization. They thus appear to be too big to fail to become observable satellites [96]. The Aquarius simulations were run with the Millennium cosmological parameters, including the too-large fluctuation spectrum normalization $\sigma_8 = 0.90$. However, the Via Lactea-II simulation, run with $\sigma_8 = 0.73$, which is now known to be too small, had six subhalos with $V_{max} > 30$ km/s, so the value of σ_8 is evidently not the cause of this problem.

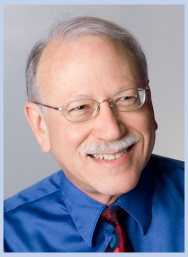
A curious fact illustrated in Fig. 5 is that Draco, the least luminous dSph satellite pictured, corresponds to the highest circular velocity subhalo, while Fornax and Sculptor, the brightest dSphs, correspond to lower V_{circ} subhalos. The same dSphs are plotted as squares in Fig. 6, which shows that they all have much larger stellar masses M_* than would be predicted by an extrapolation of the abundance-matching relation that works for the Magellanic Clouds and halos with larger V_{infall}. The intermediate-mass THINGS galaxies plotted on Fig. 6 also lie above this extrapolation, but not as much as the dSphs. However, since there are many more low-V halos predicted by ΛCDM than observed faint galaxies, as was discussed in section 1, the observed luminous dwarf galaxies at lower V_{infall} must be increasingly exceptional if ΛCDM is correct. Perhaps there are additional factors controlling star formation in low-V_{max} subhalos that can make their luminosities essentially stochastic. Perhaps there are even aspects of dark matter simulations that are not yet understood. An issue that needs to be examined is the statistical variation in dark matter substructure in Milky-Way-mass halos, especially the effect of the mass of the Milky Way on its predicted subhalos. Recent papers [104–107] claim that the TBTF problem is alleviated if the Milky Way halo mass is lower than about $1 \times 10^{12} M_\odot$, which is allowed by current observations.

Alternatively, perhaps there is additional physics beyond ΛCDM that comes into play on small scales. One possibility that has been investigated is warm dark matter (WDM). A simulation like Aquarius but with WDM has fewer high-V_{max} halos [108]. But it is not clear that such WDM simulations with the lowest WDM particle mass allowed by observations of the Lyman alpha forest [109] will have enough substructure to account for the observed faint satellite galaxies [110], and as already mentioned WDM does not appear to be consistent with observed systematics of small galaxies [77]. Another possibility is that the dark matter particles interact with themselves much more strongly than they interact with ordinary matter [111]. An Aquarius-type simulation but with velocity-dependent dark matter self-interaction produced subhalos with inner density structure that may be compatible with the bright dSph satellites of the Milky Way [112]. Whether higher-resolution simulations of this type will turn out to be consistent with other observations such as those discussed above remains to be seen.

6 Conclusions

ΛCDM appears to be extremely successful in predicting the cosmic microwave background and large-scale structure, including the observed distribution of galaxies both nearby and at high redshift, and the abundance of bright satellite galaxies like the Magellanic Clouds. ΛCDM has therefore become the standard cosmological framework within which to understand the formation and evolution of galaxies.

However, ΛCDM faces challenges on smaller scales. Although starbursts can rapidly drive gas out of the central regions of galaxies and thereby reduce the central dark matter density, it remains to be seen whether this and/or other baryonic physics can explain the observed rotation curves of the entire population of dwarf and low surface brightness (LSB) galaxies. As discussed in the previous section, the high circular velocities of the largest subhalos in high-resolution dark matter simulations of Milky Way mass halos are not a good match for the observed bright satellite galaxies. Their large masses and dense centers suggest that such subhalos are "too big to fail" to host bright satellite galaxies – but the observed dSphs do not fit into such high-V_{max} subhalos. Again, it is unclear whether this can be explained by baryonic physics that has not yet been considered, whether it indicates that there is dark matter physics beyond that in ΛCDM, or whether it merely implies that the total mass of the Milky Way is at the low end of the range allowed by observations. Standard ΛCDM appears to be successful in predicting the dark matter halo substructure that is now observed via gravitational lensing and stellar streams, and any alternative theory must do at least as well.



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Key words. Cosmology, dark matter, cusp, galaxy, subhalo, satellite galaxy.

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ERRATUM

Between the online publication on June 29, 2012 and the print publication of this article in Vol. 524, issue 9–10 (2012), an incorrect version of figure 3 had accidently been published online.
The correct figure is included in this version.