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Galaxy Rotation Curves in the Context of Λ CDM Cosmology

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1. Introduction

The motion of stars and gas in spiral galaxies provide a means of measuring the density profile of such galaxies. In the late 1960s, Vera Rubin started to take observations of the rotation velocities of disk galaxies (otherwise known as rotation curves). One of the most famous rotation curves she obtained was that of M31 (Rubin & Ford 1970). A key result of this study is that the rotation velocity of M31 remains high at very large radii ($r > 20$ kpc; see Fig. 1). The conclusion from these rotation curve data is that galaxies must contain much more mass than the visible light would otherwise indicate.

These so-called flat rotation curves were confirmed in a series of papers in the late-1970s (Rubin et al., 1977, 1978a, b, 1979; Peterson et al., 1978) and early 1980s (Rubin et al., 1980, 1982, 1985). These rotation curves have now been extended to much larger radii with sensitive HI measurements (e.g., Carignan et al., 2006) demonstrating that the rotation velocities remain high far beyond the optical disk in galaxies. This suggests that the visible light (and thus stellar mass) accounts for only a small fraction ($\sim 15\%$) of the mass in spiral galaxies. This still remains one of the best pieces of evidence in favor of dark matter cosmology.

The outline of this chapter is as follows: Section 2 describes the growth of structure in the Universe and how halos of cold dark matter assemble over cosmological times. Section 3 describes one of the fundamental problems with cold dark matter cosmology, that simulations predict cuspy central densities in dark matter halos, yet observations (particularly of dwarf galaxies) prefer constant density cores. Section 4 describes the Tully-Fisher zeropoint problem, the fact that cosmological models cannot reproduce the luminosity-rotation velocity relation for galaxies (Tully & Fisher, 1977) without overproducing the number density of galaxies at fixed luminosity. Finally, in Section 5 we make some conclusions about the present state of cosmological simulations on galaxy-sized scales.

2. Dark matter halo assembly and the growth of structure

The basic assumptions of modern cosmology are that the Universe is homogeneous and isotropic (LeMaitre, 1931). While these assumptions work on large scales it is clear that they are violated on cosmologically small scales (i.e., galaxy-sized scales). The structure of the Universe becomes much more complicated at these scales, with the growth of structure dominated by gravity. The standard model for the cosmology of the Universe has proven to

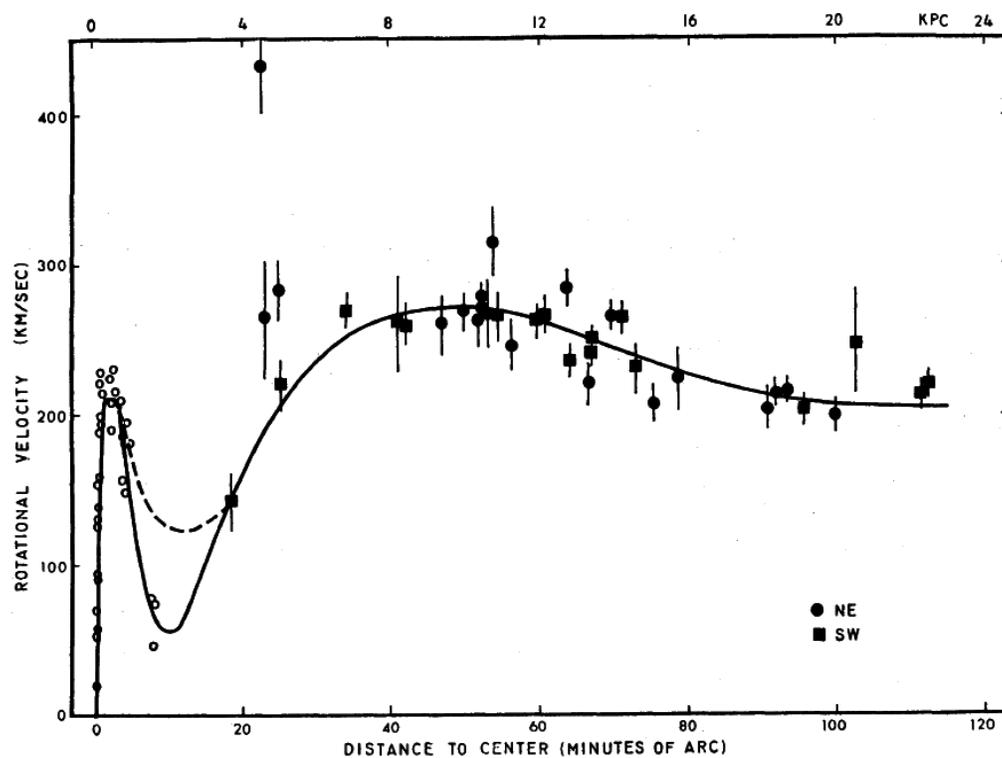


Fig. 1. Rotation curve of M31 from Rubin & Ford, (1970). Rotational velocities for OB associations in M31, as a function of distance from the center. The solid curve is the adopted rotation curve. For $r < 12'$, the curve is a fifth-order polynomial; for $r > 12'$ the curve is a fourth-order polynomial which is required to make the rotation curve approximately flat near $r = 120'$.

be an invaluable tool as this cosmology reproduces the large scale structures observed in the Universe.

The initially small quantum perturbations in the early Universe grow rapidly due to inflation in the standard Λ CDM cosmology. These overdense regions provide the seeds for gravitational collapse. These collapsing overdensities, which are primarily composed of dark matter, provide the initial potential wells for baryons to condense and begin the process of galaxy formation. Observations of the cosmic microwave background (CMB; Spergel et al., 2007) show that the initial perturbations appear to have a Gaussian random distribution. The idea is that these initial perturbations grow to become the galaxies and clusters of galaxies that we see in the local Universe.

The fluctuations in the Universe are characterized by a power spectrum which may be expressed as the Fourier transform of the two-point correlation function — the average number of pairs in a spherical shell at radius r of thickness dr above what is expected from a purely random distribution (Peebles, 1980). Thus, the correlation function measures the clustering of galaxies. Another means to express these perturbations is as the mass variance of the fluctuations. Galaxy surveys are able to calculate the mass density fluctuations within a spherical region to measure the rms variance of the Universe. Early surveys suggested that a sphere of radius 8 Mpc was needed to bring the variance to unity. This standard measurement was demonstrated to be incorrect, but it is still traditional to use σ_8 as a measure of the clumpiness of matter in the Universe. Current cosmologies from WMAP results combined with other data sets place $\sigma_8 = 0.816 \pm 0.024$ (Komatsu et al., 2011).

The overdensities are the seeds for structures to grow through gravitational interactions. Observations provide abundant evidence that the structure in the Universe formed hierarchically (Blumenthal et al., 1984; Lacey & Cole, 1993). In the regions which are overdense compared to the mean density of the Universe, the first dark matter halos begin to form after inflation. Dark matter dominates the total matter density of the Universe, and, as it does not interact with radiation, is the first matter to undergo spherical collapse due to gravity.

The initial power spectrum of the perturbations produces few large potential wells. Early halos of dark matter will grow through two processes. The first of these is smooth accretion of additional material. The second growth mechanism is mergers with other dark matter halos. In the standard cosmological paradigm the merger rate of distinct dark matter halos is robustly predicted. Several studies have predicted that the rate of major mergers for galaxy-sized cold dark matter halos scales with redshift as $(1+z)^m$, where the exponent lies in the range $2.5 \leq m \leq 3.5$ (e.g. Governato et al., 1999; Gottlober et al., 2001).

We expect that galaxies are formed inside larger dark matter halos (White & Rees, 1978; White & Frenk, 1991). The early galaxies begin to form as the potential wells created by the dark matter halos draw baryonic matter into the halo, allowing galaxies to form earlier than would otherwise be possible. These galaxies grow through mass accretion as additional material is drawn into the deepening potential well of the dark matter halo. Galaxy mergers allow the growth of more massive galaxies as the Universe continues to age. These merger events are key in altering galaxy morphologies by growing bulges in disk galaxies, transforming disks into ellipticals and inducing star formation.

Comparisons between predictions from models of a Λ CDM Universe and observations show remarkable agreement on large scales (Blumenthal et al., 1984; Springel et al., 2005). The two point correlation function of galaxies is similar to the measured two point function for dark matter halos. Simulations of large volumes of the Universe in this cosmology reproduce the clustering and distribution of galaxies on large scales.

3. Spiral galaxy rotation curves and the cusp-core problem

Despite the successes of the Λ CDM cosmology at describing the large scale structure of the Universe, the model remains far from perfect. Observations show significant differences on small-scales from the theoretically predicted structure of Λ CDM. A detail of significant difference comes in the density profiles of dark matter halos. N-body simulations of structure growth have shown that galaxy-sized halos have density profiles with central cusps (e.g., Navarro et al., 1997), yet observations of late-type galaxies tend to favor a constant density core (e.g., Kuzio de Naray, 2008). In the mid 1990s, some authors realised that cuspy profiles would prove difficult for a CDM cosmology (e.g., Flores & Primack, 1994; Moore, 1994)

It has been 40 years since the discovery that galaxies are surrounded by extended massive halos of dark matter (e.g., Rubin & Ford, 1970). A variety of observational probes—disk rotation curves, stellar kinematics, gas rings, motions of globular clusters, planetary nebulae and satellite galaxies, hot gaseous atmospheres, and gravitational lensing effects—are now making it possible to map halo mass distributions in some detail. These distributions are intimately linked to the nature of the dark matter, the way halos formed, and the cosmological context of halo formation.

Insight into these links came first from analytic studies. Building on the early work of Gunn & Gott, (1972), similarity solutions were obtained by Fillmore & Goldreich, (1984) and Bertschinger, (1985) for the self-similar collapse of spherical perturbations in an Einstein–de Sitter Universe. Such solutions necessarily resemble power laws in the virialized regions. Hoffman & Shaham, (1985) and Hoffman, (1988) extended this analysis by considering open

universes and by modeling as scale-free spherical perturbations the objects that form by hierarchical clustering from power-law initial density perturbation spectra [$P(k) \propto k^n$]. They argued that isothermal structure ($\rho \propto r^{-2}$) should be expected in an Einstein–de Sitter Universe if $n \leq -2$ and that steeper profiles should be expected for larger n and in open universes.

Despite the schematic nature of these arguments, their general predictions were verified as numerical data became available from N -body simulations of hierarchical cosmologies. Power-law fits to halo density profiles in a variety of simulations all show a clear steepening as the density of the Universe decreases (Frenk et al., 1985, 1988; Quinn, Salmon & Zurek, 1986; Efstathiou et al., 1988; Zurek, Quinn & Salmon, 1988; Warren et al., 1992; Crone, Evrard & Richstone, 1994). An apparent exception was the work of West, Dekel & Oemler, (1987), who found that *galaxy cluster* density profiles show no clear dependence on n .

Significant departures from power-law behavior were first reported by Frenk et al., (1988), who noted that halo profiles in cold dark matter (CDM) simulations steepen progressively with increasing radius. Efstathiou et al., (1988) found similar departures—at odds with the analytic predictions—in their simulations of scale-free hierarchical clustering. They also noted that these departures were most obvious in their best resolved halos. Similar effects were noted by Dubinski & Carlberg, (1991) in a high-resolution simulation of a galaxy-sized CDM halo. These authors found their halo to be well described by a density profile with a gently changing logarithmic slope, specifically the one proposed by Hernquist, (1990).

In a series of papers by Navarro et al., (1995, 1996, 1997), these authors used high-resolution simulations to study the formation of CDM halos with masses spanning about 4 orders of magnitude, ranging from dwarf galaxy halos to those of rich galaxy clusters. They showed that the equilibrium density profiles of CDM halos of all masses can be accurately fitted over two decades in radius by the simple formula:

$$\frac{\rho(r)}{\rho_{\text{crit}}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}, \quad (1)$$

where r_s is a scale radius, δ_c is a characteristic (dimensionless) density, and $\rho_{\text{crit}} = 3H^2/8\pi G$ is the critical density for closure. This profile, dubbed the NFW profile, differs from the Hernquist (1990) model only in its asymptotic behavior at $r \gg r_s$ (it tends to r^{-3} instead of R^{-4}). Power-law fits over a restricted radial range have slopes that depend on the range fitted, steepening from -1 near the center to -3 at large r/r_s .

While the predictions of these simulations are self consistent they differ from the observed rotation curves of late-type disk and dwarf galaxies. These quite often show mass distributions with lower than predicted densities or with constant density cores, where $\gamma \simeq 0$. These observations would suggest a preference for a pseudo-isothermal density profile (Gentile et al., 2004, 2005; Kuzio de Naray et al., 2006, 2008; Shankar et al., 2006; Simon et al., 2005; Spano et al., 2008; Swaters et al., 2003; see Fig. 2). This problem is referred to as the cusp-core problem due to the significant differences between the observed measured dark matter halo density profile and the halo profiles derived from theory and simulations.

Studies that reveal constant density cores in galaxies have concentrated on dwarf galaxies and low-surface brightness galaxies. Swaters et al., (2003) obtained high-resolution H α rotation curves for 15 dwarf and low surface brightness galaxies. They found that the central mass distributions of these galaxies follow a power law at small radii, $\rho(r) \propto r^{-\alpha}$, with inner slopes in the range $0 < \alpha < 1$ for most of their galaxies, and claim that the inner slopes are therefore poorly constrained. In general, they claim that galaxies with constant density cores (i.e., $\alpha = 0$)

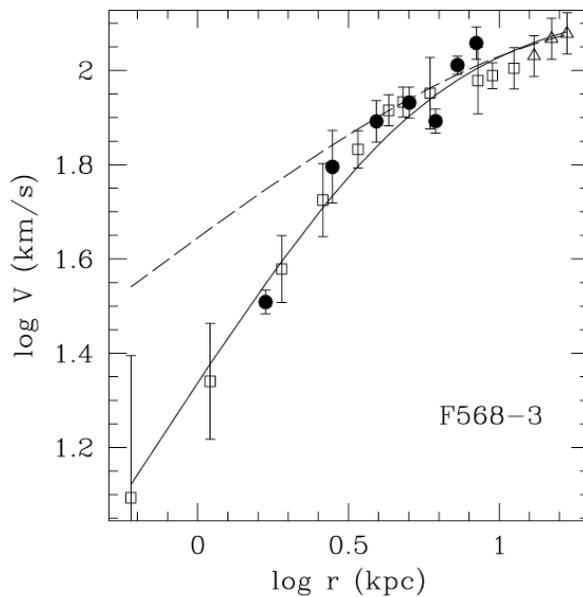


Fig. 2. Rotation curve from Kuzio de Naray et al., (2006) for the galaxy F568-3. A pseudo-isothermal fit (solid line) and a forced NFW fit (dashed line) to rotation curve IFU data (black points) is shown. This is combined with long-slit data (open squares) from de Blok et al., (2001) and HI data (open triangles) from de Blok et al., (1996). The fit is in the limit of no baryons, and clearly shows that the data is better described by a cored halo (or pseudo-isothermal fit) than a cuspy halo (or NFW fit), particularly at small radii.

provide somewhat better fits, but the majority of their sample (around 75%) are also consistent with $\alpha = 1$. An NFW-type model (with $\alpha = 1.5$) was however ruled out in every case.

A potential solution for this conflict could be that the observational results are affected by a significant amount of non-circular motion in the central regions of a galaxy. Triaxial halos (or asphericity) or a strong bar in the central regions of a halo have been suggested as a means to include significant non-circular motion in the central regions of galaxies (Hayashi et al., 2007; Bailin et al., 2007). These non-circular motions may result in observations of lower than expected velocities in the central regions of galaxies. However, several studies have shown that, even in the presence of a triaxial halo, and taking into account the non-circular motions induced by such a halo, it is difficult to reproduce the dark halo densities expected by Λ CDM (e.g., Gentile et al., 2005).

Low surface brightness galaxies and dwarf galaxies are dominated by dark matter content at all radii. As a result, they provide an ideal test case in which baryonic physics cannot affect the shape of the dark matter halo as strongly. Most studies, to date, have concentrated on these late-type galaxies, and below we describe the most significant contributions to the field. Gentile et al., (2004, 2005) studied a total of 6 galaxies (including DDO 47 in their 2005 paper) using a combination of HI and H α rotation data. They decompose their rotation curve data into stellar, gaseous and dark matter contributions, and their inferred density distribution was compared with various model mass distributions. Their observations point to a power law density distribution that follows either $\rho(r) \propto r^{-2/3}$ or a constant density core, i.e., $\rho(r) \propto r^0$, where the core size $r_{\text{core}} \simeq r_{\text{opt}}$. They conclude that Λ CDM models are in clear conflict with their data, even in the case of DDO 47, which has a clear triaxial halo.

Simon et al., (2005) used a combination of high-resolution $H\alpha$ velocity fields and CO velocity fields of five nearby, low-mass galaxies. They find power law density distributions with a power-law index in the range $0.0 < \alpha < 1.2$. They also find that the scatter in α is 0.44, which is three times as large as in Λ CDM simulations. The mean density profile shape that they find is $\alpha = 0.73$, shallower than that predicted by Λ CDM by a factor of ~ 2 . Only one galaxy in their sample, NGC 5963, has a cuspy density profile that closely resembles those seen in Λ CDM simulations (see Fig. 3).

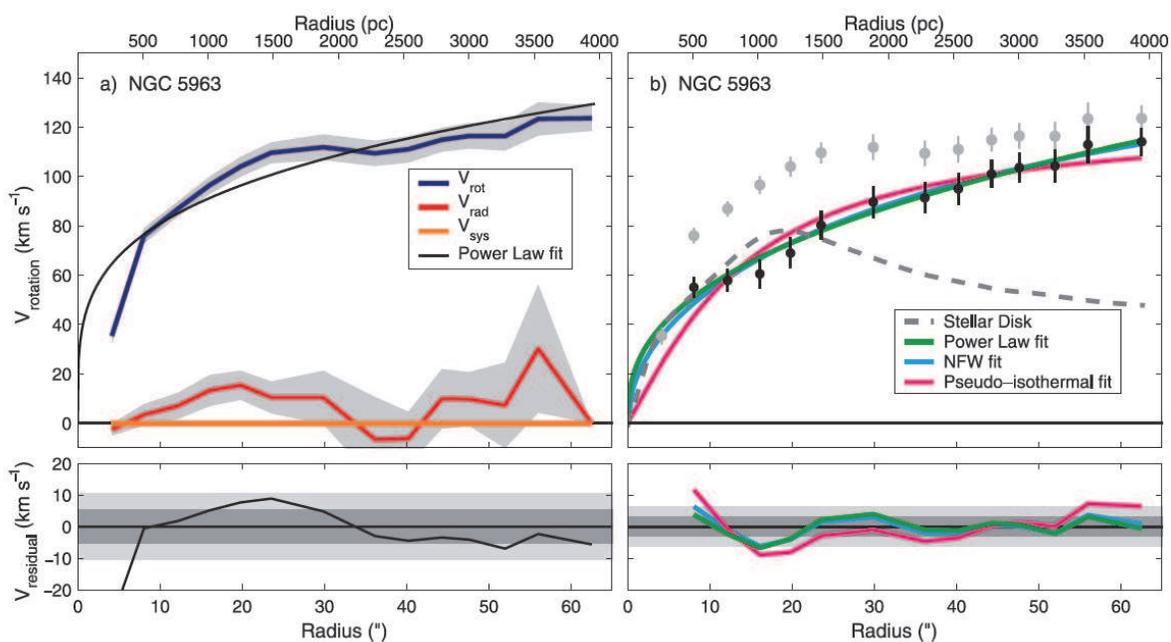


Fig. 3. Rotation curve from Simon et al., (2005) for the galaxy NGC 5963. (a) Tilted-ring model for NGC 5963. The thick blue curve represents the rotation curve. The thick red and orange curves show the radial velocity curve and the systemic velocities, respectively. The shaded grey regions surrounding the rotation and radial velocity curves represent the combined systematic and statistical $1\text{-}\sigma$ uncertainties. The thin black curve is a power-law fit to the rotation curve. The residuals to this fit are plotted in the bottom panel and the 1- and $2\text{-}\sigma$ scatter of the data points around the fit is shown by the shaded grey areas. (b) Disk-subtracted rotation curve of NGC 5963 (for $M_*/L_R = 1.24 M_\odot/L_{\odot,R}$). The grey points are the original rotation velocities from panel (a), and the black points are the dark matter halo rotation curve after subtracting the stellar disk ($M_*/L_R = 1.01 M_\odot/L_{\odot,R}$), which is shown as a grey-dashed line. The thick green, cyan, and magenta curves show power-law, NFW, and pseudo-isothermal fits to the halo rotation curve, respectively. The residuals from these fits are displayed in the bottom panel. The 1- and $2\text{-}\sigma$ scatter of the data points around the power-law fit is shown by the shaded grey areas.

Kuzio de Naray et al., (2006, 2008) observed $H\alpha$ velocity fields of a sample of 17 low-surface brightness galaxies with the DensePak Integral Field Unit (IFU) on the 3.5-m WIYN telescope at the Kitt Peak National Observatory. In the limit of no baryons, they fit the NFW and pseudoisothermal halo models to the data and found that the rotation curve shapes and halo central densities were better described by the isothermal halo.

One of the most comprehensive studies so far is that of Spano et al., (2006), who presented high-resolution $H\alpha$ two-dimensional velocity fields of 36 spiral galaxies. They combined

their kinematical data with photometric data and derived mass models using two different functional forms: an isothermal sphere and an NFW profile. Their results point to the existence of a constant density core in the centers of dark matter halos (i.e., a power law slope of $\alpha = 0$) rather than a cuspy core for all Hubble types from Sab to Im.

In an effort to investigate whether it is possible to confuse a cuspy-type central density profile for a constant density core due to the observational setup, Kuzio de Naray & Kaufmann, (2011) performed a study of simulated LSB galaxies in simulations with mock observations using the parameters of the DensePak IFU. Their simulations included cuspy, cored, and triaxial dark matter halos. Using mock observations of the simulated galaxies under a variety of conditions, Kuzio de Naray & Kaufmann, (2011) were able to identify signatures in the velocity fields which allowed the recovery of the correct halo information. From this study, and that presented by Gentile et al., (2005), it is natural to conclude that these late-type, low surface brightness and dwarf galaxies really do have central density profiles that are inconsistent with the expectations of Λ CDM cosmology. The question now is, how can we explain these inconsistencies?

In contrast to the results presented so far, one of the best-studied and closest galaxies, M33, shows clear evidence of a central density cusp. This is consistent with the expectations of the NFW profile and Λ CDM cosmology (Corbelli & Salucci 2000; Seigar 2011; see Fig. 4). Given the late Hubble type (Scd; de Vaucouleurs et al., 1991) and the small size of M33, one might expect it to have a density profile consistent with those of the late-type galaxies described above. Nevertheless, the two studies of the halo density profile of M33 from the last decade have shown that it does seem to conform to the expectations of Λ CDM cosmology. While Corbelli & Salucci (2000) find a dark halo mass of $M_{\text{vir}} = 7.4 \times 10^{10} M_{\odot}$ and a halo concentration of $c_{\text{vir}} = 5.6$, and Seigar (2011) finds a dark halo mass of $M_{\text{vir}} = 2.2 \times 10^{10} M_{\odot}$ and a halo concentration of $c_{\text{vir}} = 4.0$, both studies conclude that an NFW profile clearly provides a better fit to the data than a pseudo-isothermal profile. However, given the discrepancy in the dark halo virial mass between these two studies, it is worth noting the differences in the analyses. The difference really comes down to how the stellar mass distribution is derived. To derive the stellar mass, Corbelli & Salucci, (2000), use a rather old K band image from Regan & Vogel, (1994). Seigar (2011) uses a Spitzer 3.6- μm image, which has a far superior signal-to-noise ratio. Furthermore, Corbelli & Salucci (2000) assume a distance to M33 of 0.7 Mpc, whereas Seigar (2011) adopts the more accurate measurement of 0.84 Mpc (Magrini et al., 2007). As a result of this underestimate of the distance to M33, Corbelli & Salucci (2000) have underestimated the size of the visible galaxy by $\sim 17\%$, and this will propagate into a much larger error in their total mass estimate for the dark halo. It should also be noted that the dark halo mass estimate provided by Corbelli & Salucci (2000) is only around 25% less than the best estimates for M31 of $M_{\text{vir}} \simeq 10^{12} M_{\odot}$ (e.g., Seigar et al., 2008). In terms of visible size, M33 is about 20% the size of M31, and, if we assumed that the halo mass scaled (more or less) linearly with visible size, one would naturally expect a halo mass similar to that found by Seigar (2011).

Despite the work on M33 pointing towards a dark halo density profile that is consistent with Λ CDM cosmology, the many other studies (already mentioned above) clearly indicate that there is a problem. Several possible solutions to resolving this conflict have been suggested. One possibility is that these observations are pointing to a real problem with Cold Dark Matter cosmology, perhaps indicating that the dark matter is not cold, but rather warm (Zentner & Bullock, 2002), or possibly even a form of self interacting dark matter (e.g. Spergel & Steinhardt, 2000; Kaplinghat et al., 2000), in which case it is easier to produce constant density cores at the centers of dark matter halos. More recent results from Kuzio de Naray et al.,

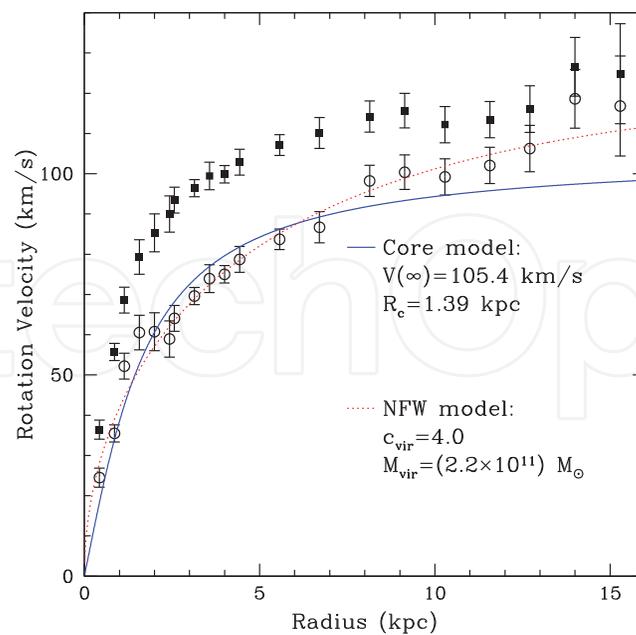


Fig. 4. Rotation curve from Seigar, (2011) for the galaxy M33. This figure shows the HI rotation curve from Corbelli & Salucci, (2000) modeled using a pseudo-isothermal model (core model; blue-solid line) and a NFW model (red-dotted line). The squares represent the total rotation velocities, and the circles represent the contribution of the dark matter to the rotation velocities (after subtraction of the stellar and gas mass distributions).

(2010) suggest these scenarios are unlikely due to discrepancies in the size of the cores created in these models and phase space densities that are orders of magnitude too small. In this paper, the authors present $H\alpha$ velocity fields of 9 low-surface brightness galaxies, and they fit the data with models representing warm dark matter and self-interacting dark matter. They find that the inferred core radii increase with halo mass (whereas warm dark matter predicts that the core radius should decrease with halo mass). They also find that the dark matter halo core densities vary by a factor of ~ 30 from galaxy to galaxy, while showing no systematic trend with the maximum rotation velocity of the galaxy. Their result strongly argues against the core size being directly set up by large self-interactions (whether scattering or annihilation) of dark matter. One would therefore naturally conclude that the inferred cores do not provide motivation to prefer warm or self-interacting dark matter over cold dark matter.

Another possible explanation for the prevalence of constant density cores in these late-type galaxies is because they form late in the history of the Universe (Wechsler et al., 2002), unlike earlier-type bulge-dominated galaxies, which form at earlier times and therefore conform to the standard expectations of Λ CDM cosmology. This is because the central mass densities of galaxies tend to reflect the density of the Universe at their formation time (Wechsler et al., 2002). Nevertheless, while this explanation may be appropriate for the lower central densities typically found in later-type galaxies, it does not explain the shape of the inner density profiles, as the N-body simulations presented by Wechsler et al., (2002) still result in central cuspy densities for all mass scales.

The last possible explanation of this discrepancy between theory and observations is that the simulations are based on pure dark matter, and do not contain any baryonic physics. If one were to include baryonic physics in the simulations, the baryons may interact with the dark matter in some way to resolve the cusp/core problem. However, the effect of

baryons on the dark matter halo may work to make the problem even worse. As early as the mid-1980s it was shown that as baryons cool and fall into the center of a dark matter halo to form a visible galaxy, the halo contracts adiabatically. This makes the central density profile of the halo even steeper and sets up other problems, such as the Tully-Fisher zeropoint problem which we discuss further in section 4. Nevertheless, feedback from star formation has been suggested as a method to transform the halo profile from a cuspy, NFW profile, to a more shallow power law or constant density core. If feedback from star formation can affect the early stages of halo formation, steep cuspy density profiles may be transformed into the observed flat cores (Governato et al., 2010). Governato et al., (2010) use hydrodynamical simulations (in the framework of Λ CDM cosmology) in which the inhomogeneous interstellar medium is resolved. In their simulations, strong outflows from supernovae remove low-angular-momentum gas, which inhibits the formation of bulges and decreases the dark-matter density to less than half of what it would otherwise be within the central kiloparsec. Galaxies that are bulgeless and have shallow central dark-matter profiles arise from their simulations. These are the analogues of the low surface brightness and dwarf galaxies that are observed to have constant density core profiles in their central regions. Fig. 5 shows a result of the Governato et al., (2010) simulations. A comparison is made between a simulated dwarf galaxy rotation curve and an observed rotation curve of a real dwarf galaxy. The simulations by Governato et al., (2010) seem to provide a working solution to the cusp/core problem. From their work, it appears that supernova feedback provides a mechanism for transforming NFW density profiles into shallower power-law central density profiles. However, even in the case of the simulations by Governato et al., (2010), all of the observational studies that have dealt with the cusp/core problem have focused on the properties of late-type dwarf and low-surface brightness galaxies (Gentile et al., 2004, 2005; Kuzio de Naray et al., 2006, 2008; Shankar et al., 2006; Simon et al., 2005; Spano et al., 2008; Swaters et al., 2003). Galaxies with dominant bulges have yet to be explored in detail. In the few cases where such galaxies have been explored, a cuspy profile seems to result from the observational data (Seigar et al., 2008; Tamm et al., 2007; Tempel et al., 2007). Also, in the case of elliptical galaxies (which could be thought of as pure-bulge galaxies) and clusters of galaxies the NFW model provides a remarkable fit to the density profile down to $\sim 1\%$ of the dark matter halo's virial radius (Humphrey et al., 2006; Zappacosta et al., 2006). This highlights the need to extend these studies to include galaxies with significant bulges. In the past, such studies have been difficult because the central regions of these galaxies are dominated by baryonic matter (unlike late-type systems which are dark matter dominated over large radial ranges). Determining the central baryonic mass depends on several factors such as signal-to-noise ratio and the accuracy of stellar mass-to-light ratios derived from stellar population synthesis codes (e.g., Maraston 2005). With new imaging surveys of nearby galaxies providing exquisite data quality and extremely good signal-to-noise ratio in the central regions of galaxies, it is likely that in the next decade these studies will be extended to bulge-dominated galaxies. One such survey is the Carnegie-Irvine Galaxy Survey (CGS; Ho et al., 2011) which consists of deep $BVRIK_s$ imaging of the 605 brightest southern hemisphere galaxies and will also include integral field spectroscopy of every galaxy in the southern hemisphere with a B band magnitude $B_T \leq 12.9$.

To complement these observational studies, simulations of the effects of supernova feedback (similar to those of Governato) on the halos of bulge-dominated galaxies are necessary. Since there is more stellar mass in the central regions of these systems, one might naively expect there to be a higher star formation rate and therefore a higher supernova rate in the histories of such galaxies. Presumably, this would have the effect of making central cores larger, yet

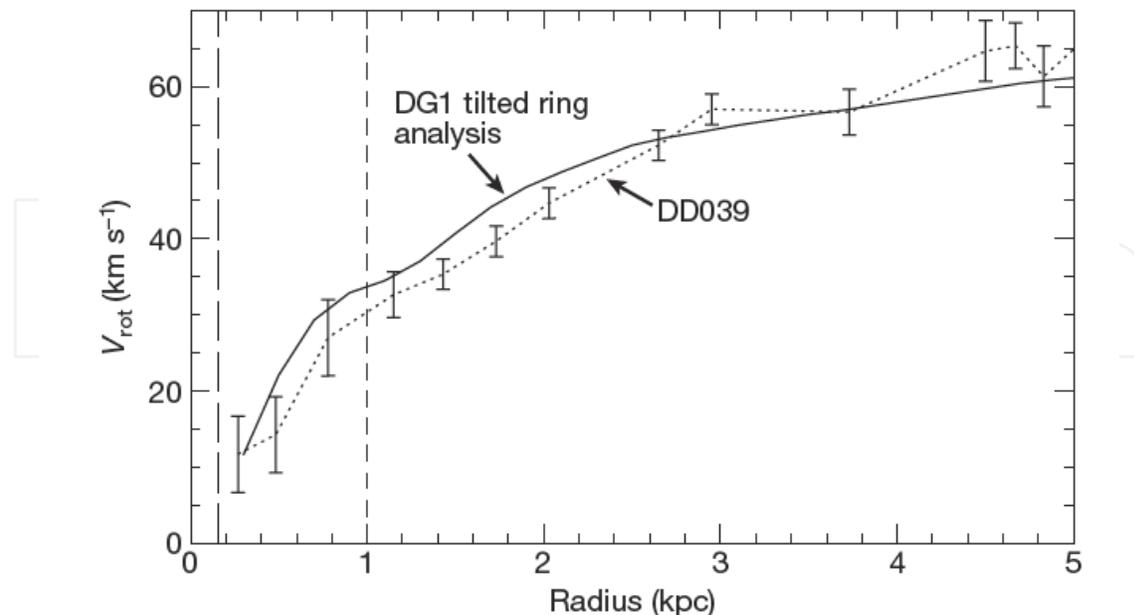


Fig. 5. Simulated rotation curve of a dwarf galaxy from Governato et al., (2010) compared to that measured for a real galaxy. The continuous black line shows the rotation velocity of the galaxy using the actual projected velocity field and the tilted ring analysis (Valenzuela et al., 2007). The dotted line shows the rotation curve of the galaxy DDO 39 as measured using a similar technique (Swaters et al., 2003), with standard deviation error bars. The velocity profile of both the observed and simulated galaxies imply a dark-matter distribution with a core scale length of about one kiloparsec, as directly measured in the simulation. The long-dashed vertical line shows the force resolution of the simulation, whereas the short-dashed vertical line marks the approximate scale length of the dark-matter “core”. The underlying dark matter density is proportional to $r^{-\alpha}$, with $\alpha = 0.6$ in the central kiloparsec, consistent with observational estimates and shallower than a dark-matter-only simulation that would predict a steeper profile with $\alpha = 1.3$.

the observational data that does exist (admittedly for just a handful of bulge-dominated objects) suggests that these systems have central density cusps (e.g., Klypin et al., 2002; Seigar et al., 2008). It is therefore important to actually undertake a program of simulations to see how supernova feedback effects the central density profiles of dark matter halos of bulge-dominated galaxies.

4. The Tully-Fisher zero-point problem

As visible matter or baryons cool and fall into the center of a dark matter halo, an adiabatic invariant is set up and this leads to the adiabatic contraction of the halo. This so-called “adiabatic contraction” was used as early as Eggen et al., (1962) to explain the formation of the Milky Way galaxy, albeit without a dark matter halo. In the modern context of Λ CDM cosmology, the idea is that as baryons cool, they sink dissipatively to the center of a halo, decreasing their radial extent by about a factor of 10. Using this idea of baryonic infall, Blumenthal et al., (1986) showed that the underlying dark matter distribution is strongly perturbed. The dark matter distribution gets pulled inward, creating denser central profiles than would have evolved without dissipation. Blumenthal et al., (1986) found that under such

dissipational collapse, baryonic infall yields rotation curves that are flat over large distances, consistent with observations of spiral galaxies (e.g., Rubin et al., 1980, 1985). Blumenthal et al. (1986) assume that the initial spherically symmetric mass distribution, $M_i(r)$, represents a dynamical equilibrium state with a constant fraction, F , of dissipational baryons as a function of r . The dissipational particles then cool and fall into a final mass distribution, $M_b(r)$, which, in the case of a spiral galaxy, is constrained by the initial angular momentum distribution. The adiabatic invariant of the dissipationless particle orbits implies

$$r[M_b(r) + M_x(r)] = r_i M_i(r_i) = \frac{r_i M_x(r)}{(1 - F)}, \quad (2)$$

which can be solved iteratively for the final dark-matter mass distribution $M_x(r)$ given the initial total mass distribution $M_i(r_i)$ and the final mass distribution $M_b(r)$. The parameter r_i is the initial orbital radius, and $M_x(r) = (1 - F)M_i(r_i)$, because dissipationless particle orbits cannot cross. Blumenthal et al., (1986) assume that the final baryonic mass distribution is of the form $M_b(r) \propto 1 - (1 + r/b) \exp(-r/b)$, which describes the radial mass distribution of a thin disk whose density in the plane of the disk decreases exponentially with scale length b . The resulting model rotation curves from Blumenthal et al., (1986) are shown in Fig. 6, which shows curves for various values of F and b , assuming there is no baryonic infall and therefore no change in the dissipationless matter beyond $r = 1$. They showed that for $F = 0.1$ and $b = 0.07$, the rotation curve is flat beyond ~ 2 disk scale lengths, even though the initial rotation curve is not flat. One can also see that for $F > 0.1$, the rotation curve declines after ~ 2 disk scale lengths, while for $F < 0.1$, dissipation produces too little change in the rotation curve. Blumenthal et al., (1986) therefore conclude that their choice of b requires that $0.05 < F < 0.2$ to produce observed rotation curves.

In Λ CDM simulations of structure formation, as galaxies form, and adiabatic invariant (similar to that shown in equation 2) is setup as a natural consequence of baryon infall, and this leads to the contraction of the host dark matter halo (e.g., Bullock et al., 2001; Gnedin et al., 2004). However, this leads to a problem with Λ CDM cosmology. Such models cannot reproduce the relation between galaxy luminosity and circular velocity (Tully & Fisher, 1977; Fig. 7) without over-producing the number density of galaxies at fixed luminosity (Benson et al., 2003; Cole et al., 2000; Gonzalez et al., 2000; Yang et al., 2003). This is known as the Tully-Fisher zero-point problem.

The Tully-Fisher relation can be used as a method to determine distances to galaxies. If we can determine the rotational velocity of a galaxy, we know the absolute magnitude of the galaxy from the Tully-Fisher relation, so given its apparent magnitude, the distance to the galaxy can be determined. Before the discovery of this relation, astronomers typically used the virial theorem to determine galaxy distances. This method was first adopted by Opik (1922), who used the virial theorem to determine the distance to M31. The argument is simple. A self-gravitating system will obey the law

$$M = kW^2R/G \quad (3)$$

where M is the mass, W is a characterization of the motions in the body with units of speed and dominated by rotation in the case of a disk galaxy, R is a measure of the linear size, G is the universal gravitational constant, and k is a dimensionless constant of order unity that depends on the geometry of the system. Opik (1922) took a dependence of the mass $M \propto (M/L)ld^2$, where M/L is the mass-to-light ratio, l is the observed brightness and d is the observed distance. The virial theorem continued to be used to determine galaxy distances into

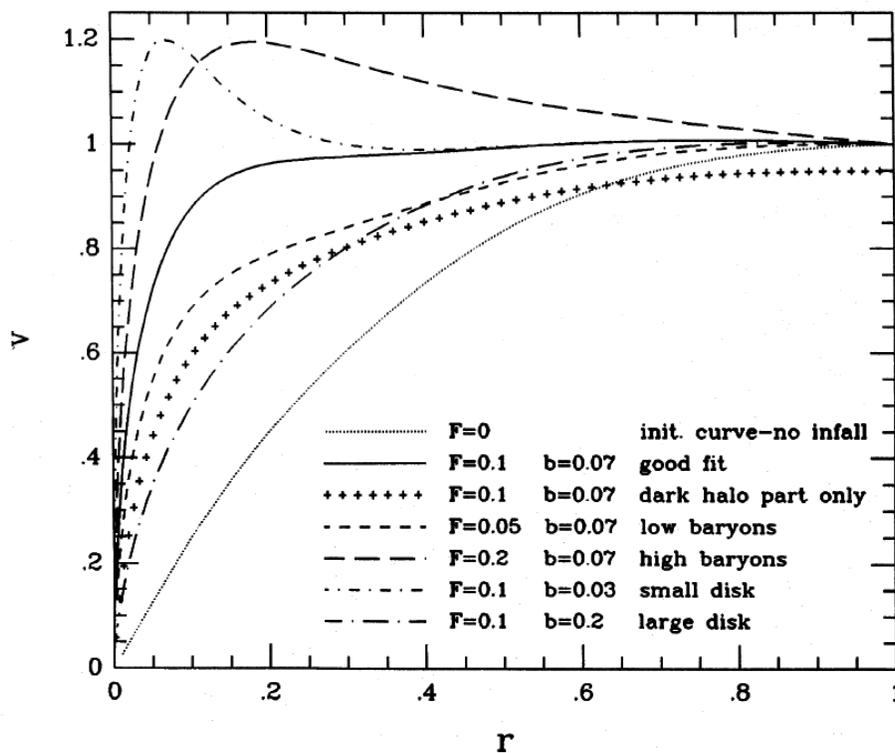


Fig. 6. A plot of the rotational velocity, $v = (M/R)^{1/2}$, versus radius, r , for the adiabatic invariant given in equation 2. The baryon fraction F is assumed to dissipate and fall into an exponential disk with scale length b . No dissipation is assumed to occur beyond $r = 1$. All curves except the pluses correspond to a total rotational velocity; the curve denoted by plus signs is the rotational velocity due to the dissipationless particles (i.e., the dark matter) alone for the case where $F = 0.1$ and $b = 0.07$.

the 1970s, with what was usually referred to as the “indicative mass” method. It was stripped down to the form $L \propto W^2 R$. With the discovery of the Tully-Fisher relation, Tully & Fisher (1977) suggested the use of two alternatives:

$$L \propto W^\alpha \quad (4)$$

$$L \propto R^\beta. \quad (5)$$

These alternatives reduce the number of variables and allow departures from the virial theorem. Equation 4 has the attraction that only one parameter depends on distance. It is this equation that became known as the Tully-Fisher Relation.

The motivation for the development of the relationship was based on well founded physics: more massive galaxies would be both more luminous and rotate faster. It was appreciated that there was a lot of leverage for the measurement of distances because of the d^2 dependence of observed luminosity. However the small scatter and apparent universality of the relationship could not have been fully anticipated. These properties have made the relationship interesting not only for the determination of distances but also as a constraint on models of the formation and evolution of galaxies. In particular, note that Opik’s derivation of the virial relation above assumes a universal value for the mass-to-light ratio, M/L . Given the dominance of dark matter in spiral galaxies, it is not at all obvious that there would be a universal relationship between mass and light. The fact that the Tully-Fisher relation has as little scatter as it does is

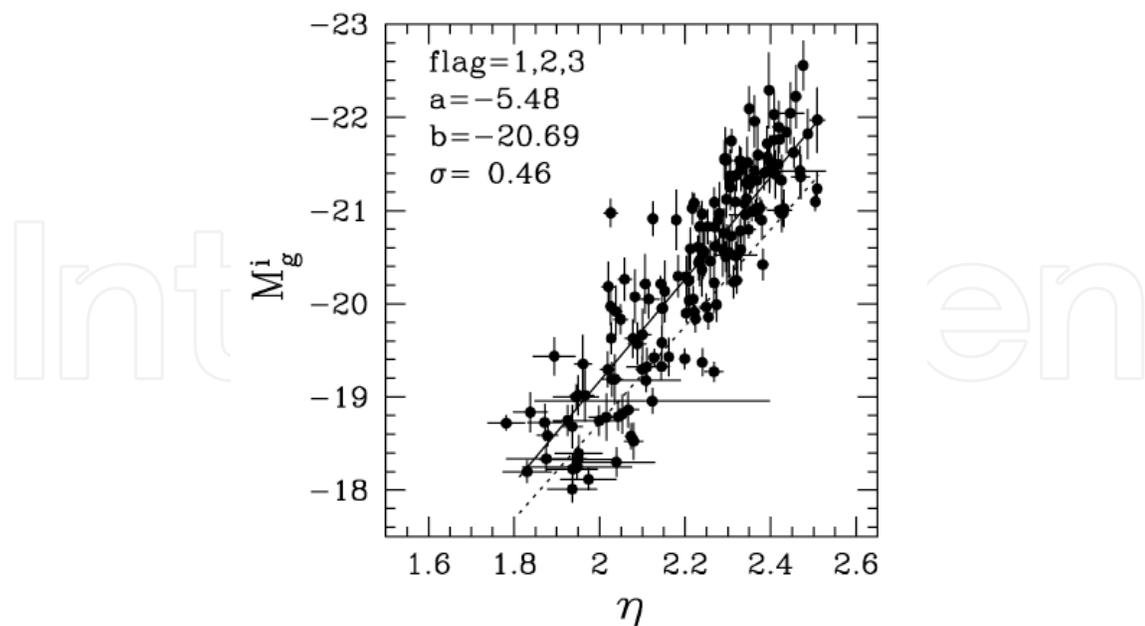


Fig. 7. Tully-Fisher relation from Pizagno et al., (2007). The plot shows the internal-extinction corrected g -band magnitude (M_g^i) as a function of the inclination-corrected maximum rotation velocity ($\eta = \log(v) / \sin i$, where i is the inclination angle to the line of sight). The solid line is the best fit Tully-Fisher relation. The dotted line shows the best-fit Tully Fisher relation without correction for internal extinction.

seen as an important clue regarding the connection between the luminous and non-luminous components of spirals.

The fact that standard cosmological models cannot reproduce the Tully Fisher relation without over-producing the number density of galaxies at fixed luminosity is a fundamental problem for our cosmological models. Recently, Dutton et al., (2007) and Gnedin et al., (2007) revisited this problem using two large, well-defined, samples of disk-dominated (late-type) galaxies. They both took, as a starting point, the “standard” model of disk galaxy formation, which assumes that NFW dark halos respond to the formation of a disk via adiabatic contraction or AC (Blumenthal et al., 1986; Choi et al., 2006; Gnedin et al., 2004; Sellwood & McGaugh, 2005). Dutton et al., (2007) used the observed Tully-Fisher relation and the observed size-luminosity relation to single out a specific scenario for disk galaxy formation in Λ CDM cosmology. Their models involved four independent lognormal random variables: dark halo concentration c_{vir} , disk spin λ_{gal} , disk mass fraction m_{gal} , and stellar mass-to-light ratio Γ_I . In order to get a simultaneous match of the Tully-Fisher and size-luminosity zero points with adiabatic contraction, Dutton’s models require low-concentration halos, but this model has $V_{2.2} \sim 1.8V_{\text{vir}}$ (where $V_{2.2}$ and V_{vir} are the circular velocity at 2.2 disk scale lengths and the virial radius, respectively), which is unable to match the luminosity function of galaxies (the observed ratio, $V_{2.2}/V_{\text{vir}}$ as a function of halo concentration, as demonstrated in Dutton et al., (2007) is shown in Fig. 8). Similarly Dutton’s models without adiabatic contraction but standard c_{vir} also predict high values of $V_{2.2}/V_{\text{vir}}$ (see Fig. 9). Dutton et al., (2007) concluded that models in which disk formation induces an expansion rather than the commonly assumed contraction of the dark matter halos have $V_{2.2} \sim 1.2V_{\text{vir}}$, which allows a simultaneous fit of the luminosity function (see Fig. 10). This may result from non-spherical, clumpy gas accretion, where dynamical friction transfers energy from the gas to the dark matter. This model requires

low λ_{gal} and m_{gal} values, contrary to naive expectations. However, the low λ_{gal} is consistent with the notion that disk galaxies predominantly survive in halos with a quiet merger history, while a low m_{gal} is also indicated by galaxy-galaxy lensing. The smaller than expected scatter in the radius-luminosity relation and the lack of correlation between the residuals of the Tully-Fisher and radius-luminosity relations (found in Dutton's expansion models), respectively, imply that the scatter in λ_{gal} and in c_{vir} needs to be smaller than predicted for ΛCDM halos. Again this is consistent with the idea that disk galaxies preferentially reside in halos with a quiet merger history.

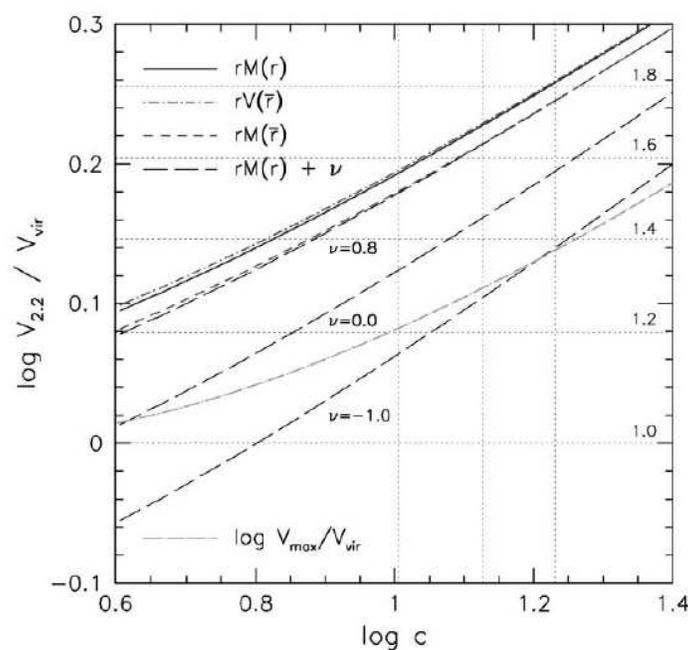


Fig. 8. Ratio of observed to virial circular velocities, $V_{2.2}/V_{\text{vir}}$, as a function of the concentration parameter, for various forms of adiabatic contraction. All models have $\lambda_{\text{gal}} = 0.048$ and $m_{\text{gal}} = 0.05$. The vertical dotted lines show the mean concentration parameter according to the model of Bullock et al., (2001) for halos with virial mass, $M_{\text{vir}} = 10^{13}, 10^{12},$ and $10^{11} h^{-1} M_{\odot}$. The horizontal dotted lines show $V_{2.2}/V_{\text{vir}}$ ratios of 1–1.8 at intervals of 0.2. The relation using the standard Blumenthal et al., (1986) adiabatic invariant, $rM(r)$, is given by the solid line. The modified adiabatic invariant, $rM(\bar{r})$, as proposed by Gnedin et al., (2004), results in only a $\simeq 0.02$ dex ($\simeq 5\%$) reduction in $V_{2.2}$ (short-dashed line). Most of this reduction is taken back if specific angular momentum is used as the adiabatic invariant and the disk geometry is taken into account when computing V_{circ} (dot-short-dashed line). For all of these adiabatic contraction models, standard concentration parameters yield $V_{2.2}/V_{\text{vir}} \simeq 1.6$. The long-dashed lines show models where the contraction factor has been artificially modified by Dutton et al., (2007). Starting from the standard model ($\nu = 1$), the $rM(\bar{r})$ relation is approximately reproduced with $\nu = 0.8$, $\nu = 0$ results in no adiabatic contraction of the halo, while $\nu = 1$ gives halo expansion. The dot-long-dashed line shows $V_{\text{max}}/V_{\text{vir}}$, where V_{max} is the maximum halo circular velocity (without adiabatic contraction).

In contrast, Gnedin et al., (2007) investigate the structural properties of dark matter halos of disk galaxies, using a well-defined sample of 81 disk-dominated galaxies from the Sloan Digital Sky Survey (SDSS). They model the mass Tully-Fisher and fundamental plane relations

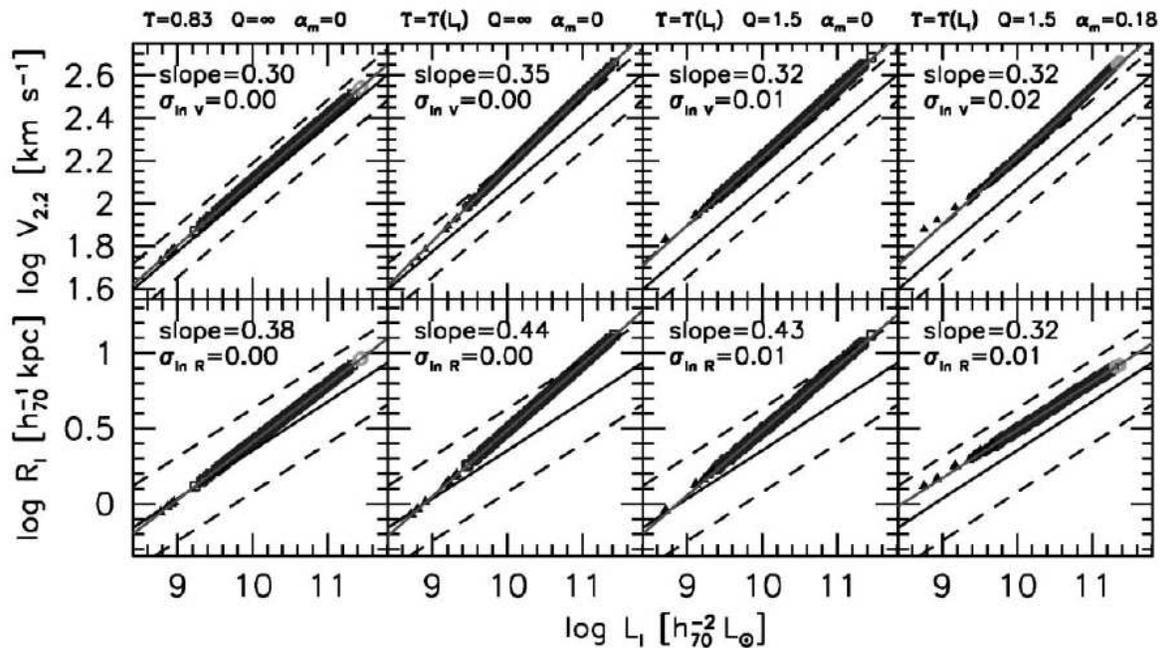


Fig. 9. Tully-Fisher and size-luminosity relations using fiducial mean c_{vir} , λ_{gal} , and m_{gal} parameters and different values of mass-to-light ratio, Γ_l , Toomre stability parameter, Q , and galaxy mass fraction slope, α_m , from Dutton et al., (2007). The black solid and dashed lines show the mean and $2\text{-}\sigma$ scatter of the observations. The grey line is a fit to the model galaxies, whose slope is given in the top left corner of each box. The model on the far left is the Mo et al., (1998) model with $\Gamma_l = 0.83$, $Q = \infty$ (a pure stellar disk), and $\alpha_m = 0$. The model in the left middle only differs from the left model in the value of Γ_l . This steepens the slopes of both relationships, making them incompatible with the data. The right middle model includes the star formation threshold, which results in a gas fraction that increases with decreasing luminosity and hence a shallower slope for the Tully-Fisher relationship, in agreement with the data. The effect on the slope of the size-luminosity relationship is not as strong because as the luminosities decrease, the stellar disk scale-lengths also decrease. In order to match the size-luminosity relationship slope, Dutton et al., (2007) set $\alpha_m = 0.18$ (far right panel). While this model matches the slope of the Tully-Fisher and size-luminosity relationships, it fails to reproduce the zero-points.

of these galaxies, using the observed stellar mass, M_* , the disk scale-length, R_d , and the optical $H\alpha$ rotation velocity at $2.2R_d$ ($V_{2.2}$). Gnedin et al., (2007) include the effects of adiabatic contraction in their models, arguing that it is a fundamental prediction in galaxy formation. They find that models with a constant stellar disk-to-total mass fraction, m_d , under-predict the intrinsic scatter in the Tully-Fisher and fundamental plane relations. Introducing a scatter in m_d and allowing the mean value, $\overline{m_d}$, to significantly scale with the stellar surface density, improves the observational match. The distribution of angular momentum parameters required to match the observed scale-lengths is an output of the Gnedin models and is narrower than that predicted for halo spin. However, the best-fit models from Gnedin et al., (2007), with a Kroupa (2001) initial mass function (IMF), overproduce the galaxy stellar mass function and predict virial mass-to-light ratios lower than those inferred from galaxy-galaxy weak lensing (Hoekstra et al., 2005; Mandelbaum et al., 2006) and satellite dynamics (Prada et al., 2006). Gnedin et al., (2007) therefore argue that the IMF needs to be modified by adopting a “light” stellar IMF with M_*/L lower by 0.15 dex. Adopting such an IMF reproduces the

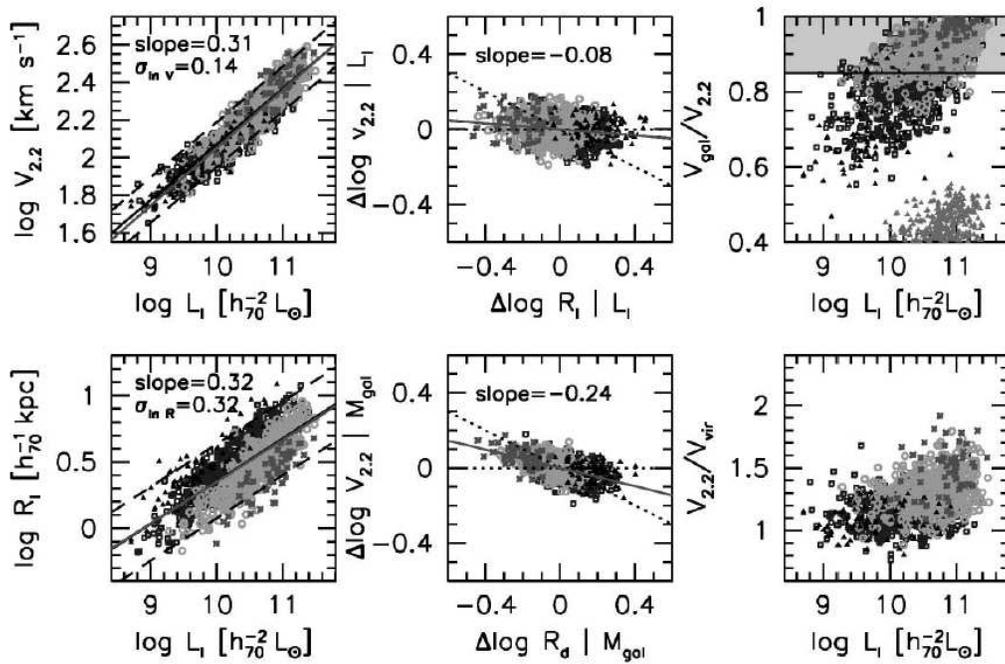


Fig. 10. Scaling relations and residual correlations of Dutton’s halo expansion model from Dutton et al., (2007). This model reproduces the slopes, scatter, and zero points of the Tully-Fisher and size-luminosity relations. This model has a median $V_{2.2}/V_{vir} = 1.22$, which is often required in order to simultaneously fit the Tully-Fisher and size-luminosity relations.

slope and zero point of the Tully Fisher relation and other fundamental plane relations (see Fig. 11).

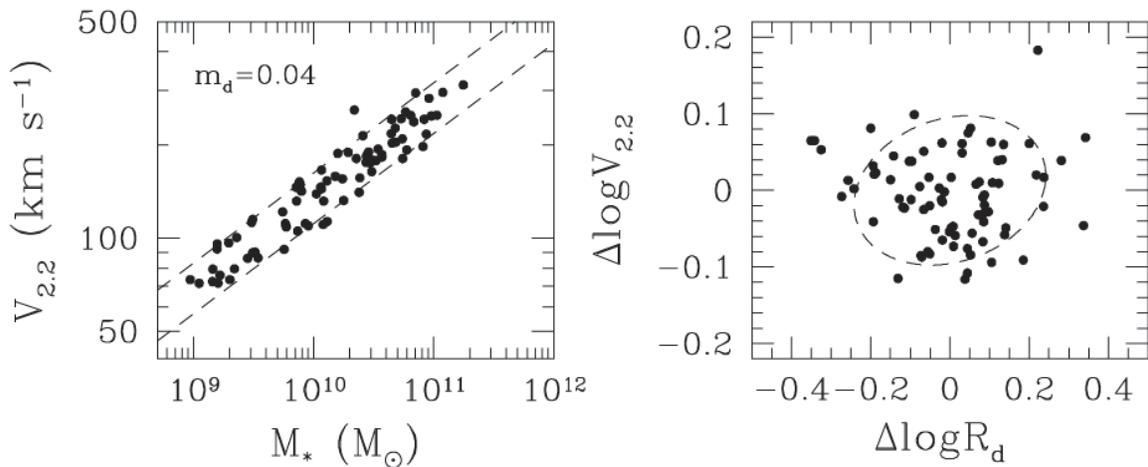


Fig. 11. Best fit models from Gnedin et al., (2007) to the Tully-Fisher relation for the case of a “light” IMF, including adiabatic contraction. The dashed lines representing the observations in the left panel and shifted by -0.15 dex in M_* to account for the modified IMF.

More recently, Dutton et al., (2010) have investigated the origin of the relations between stellar mass and optical circular velocity for early-type and late-type galaxies — the Faber-Jackson and Tully-Fisher relations. They combine measurements of dark halo masses (from satellite kinematics and weak lensing) and the distribution of baryons in galaxies (from a new compilation of galaxy scaling relations) with constraints on dark halo structure from

cosmological simulations. The principle unknowns are the halo response to galaxy formation and the stellar IMF. The slopes of the Tully-Fisher and Faber-Jackson relations are naturally reproduced for a wide range of halo response and IMFs within Dutton's models. However, models with a universal IMF and universal halo response cannot simultaneously reproduce the zero points of both relations. For a model with a universal Chabrier (2003) IMF, late-type galaxies require halo expansion, while early-type galaxies require halo contraction (see Fig. 12). A Salpeter (1955) IMF is permitted for high mass ($\sigma > 180$ km/s) early-type galaxies, but is inconsistent for intermediate masses, unless $V_{\text{circ}}(R_e)/\sigma_e > 1.6$. If the IMF is universal and close to the Chabrier IMF, Dutton et al., (2010) speculate that the presence of a major merger may be responsible for the contraction in early-type galaxies while clumpy accreting streams and/or feedback leads to expansion in late-type galaxies. Alternatively, a recently proposed variation in the IMF disfavors halo contraction in both types of galaxies. The models from Dutton et al., (2010) naturally reproduce flat and featureless circular velocity profiles within the optical regions of galaxies without fine-tuning.

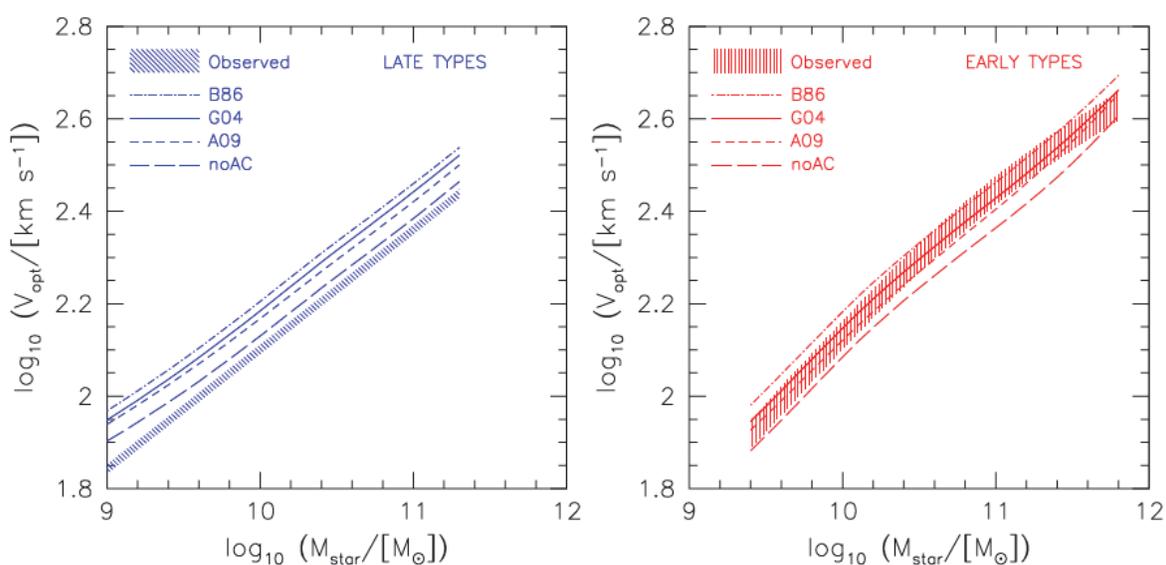


Fig. 12. Effect of adiabatic contraction on the circular velocity (V_{opt}) versus stellar mass (M_{star}) relation for early type (right panel) and late-type (left panel) galaxies using the models of Dutton et al., (2010). Adiabatic contraction results in higher optical circular velocities. Compared to a model with no halo contraction (long dashed lines), the increase in optical circular velocities is $\simeq 0.1$ dex for the Blumenthal et al., (1986) model, $\simeq 0.08$ dex for the Gnedin et al. (2004) model, and $\simeq 0.05$ dex for the Abadi et al., (2010) halo contraction model. For these models (with a Chabrier IMF and standard halo concentrations from Maccio et al., 2008) early-type galaxies favor models with strong halo contraction, whereas late-type galaxies favor models with halo expansion.

The idea that early-type bulge-dominated disk galaxies (Dutton et al., 2010) require halo contraction is consistent with observational evidence that suggests that the halo of our nearest large neighbor (M31, a bulge-dominated galaxy) has a rotation curve that is consistent with a dark matter halo that has undergone adiabatic contraction (Klypin et al., 2002; Seigar et al., 2008). Seigar et al., (2008) model the dark matter contribution to the rotation curve of M31 using several different models for adiabatic contraction and a model that includes no halo contraction. They find that the halo model that best reproduces the rotation curve of M31,

with a halo concentration in the expected range (Maccio et al., 2008) requires a halo model with the strongest version of adiabatic contraction (see Fig. 13).

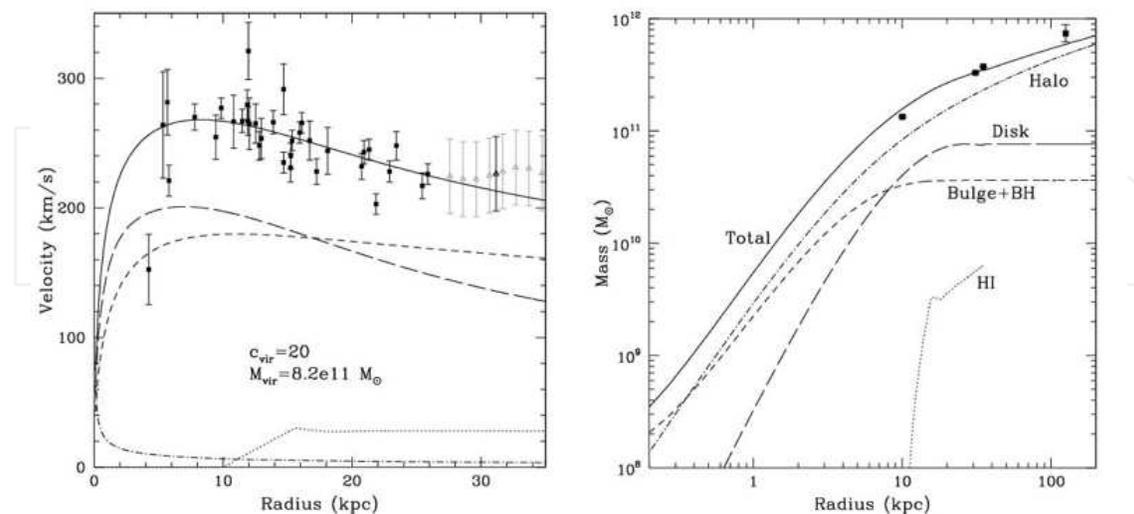


Fig. 13. Left panel: Rotation curve data (solid square points) from Rubin & Ford, (1970) with the best-fitting model, with adiabatic contraction overlaid (solid line). For comparison the HI rotation velocities (grey open triangles) from Carignan et al., (2006) are shown (the black point corresponds to the average velocity and radius of the Carignan data). The best-fitting rotation curve is decomposed into four components, the contribution from dark matter (short-dashed line), the contribution from baryonic matter (long-dashed line), the HI contribution (dotted line) from Carignan et al., (2006) and the contribution from the central $10^8 M_{\odot}$ black hole (dot-dashed line) from Bender et al., (2005). Right panel: Enclosed mass as a function of radius for the best-fitting rotation curve model with adiabatic contraction. The solid line indicates the total mass. Also indicated are the HI mass out to a 35 kpc radius (dotted line), the bulge+BH mass (short-dashed line), the disk mass (long-dashed line), and the halo mass (dot-dashed line). The data points indicate masses derived using other observational methods at fixed radii of 10 kpc, 31 kpc, 35 kpc, and 125 kpc from Rubin & Ford, (1970), Evans & Wilkinson, (2000), Carignan et al., (2006), and Fardal et al., (2006) respectively. Both figures are taken from Seigar et al., (2008).

On the contrary, disk-dominated galaxies, with little or no bulge, should undergo a halo expansion according to the models of Dutton et al., (2007, 2010). However, observations of disk-dominated galaxies, including M33, suggest that a pure NFW model is sufficient to describe the dark matter halo contribution to their rotation curves (Kassin et al., 2006; Seigar 2011). For a sample of 34 bright spiral galaxies, Kassin et al., (2006) compared their rotation curve data to the NFW parametrization for dark matter profiles with and without including adiabatic contraction. All but two of their galaxies are better fit if adiabatic contraction does not occur. However, their fits are generally poor, and the possibility that the fits may improve if a halo expansion model is applied cannot be ruled out.

Finally, Klypin et al. (2010) claim to have run simulations that reproduce the Tully-Fisher relation slope and zero-point without the need for halo contraction or expansion. Their method consists of matching the abundance of galaxies in the local Universe to that of halos in their simulation. Their simulation (termed the Bolshoi simulation) was done in a volume $250 h^{-1} \text{ Mpc}$ on a side using 8 billion particles with mass and force resolution adequate to follow subhalos down to a completeness limit of $V_{\text{circ}} = 50 \text{ km s}^{-1}$ maximum circular velocity. The

halos in this simulation are matched to the abundance of galaxies in the local Universe by using the triple-Schechter fit to the galaxy luminosity function obtained from the Sloan Digital Sky Survey Data Release 6 galaxy sample by Montero-Dorta & Prada, (2009) and assigning r -band absolute magnitudes to their dark matter halos starting with the largest until they reach the maximum circular velocity completeness limit of the simulation. This assumption is reasonable for halos of Milky Way-sized galaxies or smaller, but it is not adequate for larger galaxies. For larger, brighter galaxies, the circular velocities are overestimated. Fig. 14 shows the Tully-Fisher relation plot for all halos in the Bolshoi simulation, compared with several observational data sets. The plotted V_{circ} is measured at 10 kpc and includes the effect of baryons estimated to have reached the central regions of galaxies, but does not include the effects of halo contraction. The agreement with the galaxy data is remarkably good from $V_{\text{circ}} \sim 50 \text{ km s}^{-1}$ to $V_{\text{circ}} \sim 200 \text{ km s}^{-1}$. At higher V_{circ} Klypin et al., (2010) claim that an increasing fraction of halos host early-type galaxies, groups, or clusters (although it should be noted that M31 has a $V_{\text{circ}} \simeq 270 \text{ km s}^{-1}$ and observational data suggest halo contraction is required for M31). Given the lack of disk galaxies with $V_{\text{circ}} > 300 \text{ km s}^{-1}$, a bright elliptical galaxy, M87, is included in Fig. 14. The circular velocity was obtained by the mass modeling of Strom et al., (1981) and the r -band magnitude was found by integrating the surface brightness profile of Strom et al., (1981). The result of the method presented by Klypin et al., (2010) is that the Tully-Fisher relation is reproduced without the need for contraction or expansion. Nevertheless, Fig. 14 seems to show that the datapoints all seem to lie systematically above the models produced by Klypin et al., (2010). It also needs to be demonstrated that this model can reproduce the rotation curves of individual galaxies.

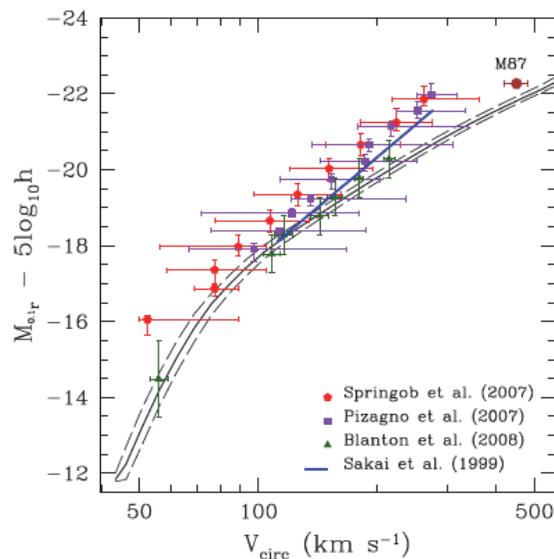


Fig. 14. Comparison of the Tully-Fisher relation of different observational datasets with the theoretical predictions of “abundance-matching” produced in Klypin et al., (2010). Median and 90% contours of r -band magnitudes versus circular velocity of the mock galaxies in the Bolshoi simulation are shown.

Given the fundamental issues at hand, the question of whether adiabatic contraction or a halo expansion occurs in nature is of significant interest. Most simulations favor the idea that halos contract, especially when the infall of baryons is smooth and adiabatic (Blumenthal et al., 1986; Ryden & Gunn, 1987; Sellwood & McGaugh, 2005). Simulations also suggest that halos will contract even when galaxies (or clusters) form quickly from an irregular collapse (Barnes,

1987; Choi et al., 2006; Flores et al., 1993; Gnedin et al., 2004; Jesseit et al., 2002; Sellwood & McGaugh, 2005; Weinberg et al., 2008). However, there is the possibility that halos (especially of disk-dominated galaxies) expand (Dutton et al., 2010). Furthermore, a new approach where the galaxy abundances are matched based on simulated halos and subhalos seems to alleviate the need for any change (either expansion or contraction) of the halo density profile (Klypin et al., 2010). Few of these relatively new ideas have been tested. To date, observational studies that have dealt with the Tully-Fisher zero-point problem have all focused on the properties of late-type spiral galaxies (Hubble types Sc and later, i.e., galaxies with little or no bulge) or dwarf galaxies (Kassin et al., 2006; Pizagno et al., 2005, 2007). When galaxies with dominant bulges have been explored, a contracted NFW halo does seem to fit the data, as is the case for M31 (see Fig. 13; Klypin et al., 2002; Seigar et al., 2008; Tamm et al., 2007; Tempel et al., 2007). This highlights the need to extend these studies to include galaxies with significant bulges. Once again, for such a study, surveys such as the CGS (Ho et al., 2011) will prove invaluable.

5. Conclusions

In conclusion, Λ CDM cosmology reproduces the large scale structure of the Universe extremely accurately (Blumenthal et al., 1984; Springel et al., 2005). However, on galaxy-sized scales there are several known issues with the theory. Here, we have highlighted two particular problems. The first, namely the cusp/core problem, highlights the fact that Λ CDM simulations of structure formation predict central cusps in the density profiles of dark matter halos. However, observations, particularly of LSB galaxies, suggest that the central densities are flat over the inner ~ 1 kpc. This is a serious issue with Λ CDM cosmology. A solution involving supernova feedback may be the answer (e.g., Governato et al., 2010), but this model needs to be applied to large spiral and elliptical galaxies to see how widely applicable it is. The second problem, the Tully-Fisher zeropoint problem, highlights the fact that Λ CDM simulations cannot reproduce the Tully-Fisher relation without over-producing the number density of galaxies at fixed luminosity. Recently, Klypin et al., (2010) claim to have solved this issue, but it seems to systematically overestimate galaxy rotation velocities, and so further study of their model is required.

6. Acknowledgements

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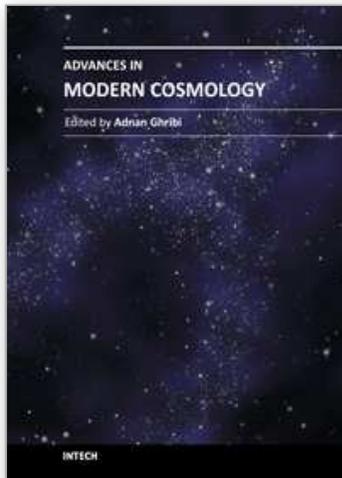
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The twentieth century elevated our understanding of the Universe from its early stages to what it is today and what is to become of it. Cosmology is the weapon that utilizes all the scientific tools that we have created to feel less lost in the immensity of our Universe. The standard model is the theory that explains the best what we observe. Even with all the successes that this theory had, two main questions are still to be answered: What is the nature of dark matter and dark energy? This book attempts to understand these questions while giving some of the most promising advances in modern cosmology.

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