Galaxy Masses as Constraints of Formation Models
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The Dwarfs Beyond: Relating Stellar and Halo Mass in Dwarf Galaxies to $z \sim 1$

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Abstract. Do the kinematics and mass profiles of dwarf galaxies present a fundamental challenge to standard cold dark matter (CDM) models? New, deep spectroscopy using DEIMOS on Keck for hundreds of low stellar mass (10^7-10^9 M$_\odot$) star-forming galaxies at intermediate redshift ($0.2 < z < 1$) addresses this inquiry in a way that is less subject to cosmic variance and environmental bias than previous, more local work. Half of this sample reveals resolved, doppler-shifted nebular emission, used to constrain rotation curves. From these we can construct the stellar mass Tully-Fisher relation to masses as low as $\sim 10^7$ M$_\odot$, and a persistent discrepancy is found between predictions from simulations and models compared to our observations. We suggest on-going and future tests that will be more effective in distinguishing between the effects of baryonic feedback and alternative models of dark matter in this remarkable regime.

Keywords. galaxies: dwarfs - galaxies: evolution - galaxies: formation

1. Introduction

The foremost challenge to the favored dark matter paradigm (WIMP-like CDM) is the discrepancy between the predicted inner densities of galaxies compared to those observed (Boylan-Kolchin *et al.* 2011; Ferrero *et al.* 2012; Weinberg *et al.* 2013; Papastergis *et al.* 2014). Revealed across the shapes and amplitudes of rotation curves, this discrepancy is particularly clear in low-mass galaxies where dark matter is predicted to dominate even their inner-most potential wells – much more so than in massive galaxies. Before Miller *et al.* (2014, M14) directly resolved dwarf rotation curves to intermediate redshifts ($0.2 < z < 1$), this issue had only been explored in the low-redshift, local universe. The limits of earlier samples subjected results to cosmic variance issues, and the local range of environments left open the possibility that dwarf galaxy densities were discrepant with theoretical predictions because of their complicated interaction histories in our particular cosmic neighborhood (or that this was simply a case of "small-number statistics").

To surmount cosmic variance, limited statistics, and environmental caveats, we have been leading a novel study of directly-resolved internal kinematics of some of the lowest mass galaxies at the highest redshifts ever targeted. We are amassing a large, rich dataset selecting from Hubble Space Telescope imaging and acquiring deep Keck DEIMOS spectroscopy that will serve as a valuable archive for years to come, not only for kinematics, but also for exploring the exotic interstellar medium environments of these dwarfs, including both emission and absorption feature diagnostics. Typically we find that half of the observed sample, selected simply by photometric redshift ($0.2 < z < 1$), stellar mass ($\log M_*/M_\odot < 9.3$), and magnitude ($i_{AB} > 25$), presents significant signal-to-noise for both spatially and spectrally resolving emission with DEIMOS after 6-10 hours of observing on Keck in good conditions. With hundreds of new dwarfs now observed, we have found persistent inconsistencies between abundance/simulation methods and the observational kinematic method (using the extrapolated weak lensing relation of Reyes *et al.* 2012, to convert to halo mass) that cannot be explained by the classic understanding

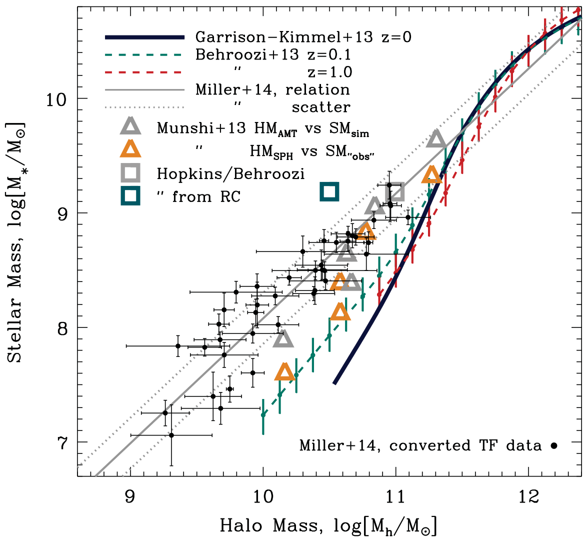

Figure 1. The stellar-to-halo mass relation according to the latest abundance matching curves (navy, aqua and red curves at z=0.0, 0.1 and z=1.0, of Garrison-Kimmel *et al.* (2013) & Behroozi *et al.* (2013), respectively) derived from CDM simulations matched to observed stellar mass functions, compared to that inferred for our sample of intermediate redshift dwarf galaxies by converting the measured rotation velocities in the Tully-Fisher relation to halo masses using the procedure discussed in M14 (summarized in the text). Black points represent the data, the solid grey line is the best-fit relation and the scatter is indicated with dotted grey lines. The triangles and squares denote various numerical simulations (Munshi *et al.* 2013, P. Behroozi & P. Hopkins - private communication).

of the missing satellites or the cusp-core problems (see Fig. 1 for the pilot sub-sample in M14). With this sample representing star-forming galaxies in group, field, and void environments from over half the age of the universe, these early results help us more precisely define questions to identify what is missing from our current theoretical and observational picture of both galaxy evolution and dark matter.

2. Extending the Measurement of the M_* Tully-Fisher Relation

A tripling of the M14 pilot sample will be published later this year (Miller *et al.*, in prep), offering a more robust assessment of the scatter of the stellar mass Tully-Fisher relation to lower mass, which stands as one of the more limiting uncertainties in connecting observable galaxies to their dark halos. A wide range of techniques has been used in the past decade or two to make this connection, from halo occupation distribution modeling (Berlind & Weinberg 2002; Wechsler *et al.* 2006) to more simplified abundance matching techniques (Behroozi *et al.* 2013). While a consistent picture can be constructed over the mass ranges typically explored in extra-galactic surveys to intermediate redshifts (where $\log M_*/M_\odot > 9$), this picture begins to diverge at lower masses. A favored explanation is the increased scatter of stellar and gas fractions in dwarf-regime halos, however this has yet to be well constrained observationally.

The problem with comparing observations to models using axes such as those in Fig. 1 is that halo mass is a particularly indirect measurement and the assumptions made to place curves and symbols on such a plot may not ultimately be consistent with each other (or with nature, for that matter). For instance in the case of the converted TF data points, optically measured velocities have been converted to halo velocities using an extrapolated

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weak lensing relation, which are then converted to a halo mass. An important next step will be to conduct consistency tests between models and observations on more directly observable measurements, like enclosed mass at radii which are directly observable, such as various optical radii, or simply the stellar mass Tully-Fisher relation itself.

Why does the Tully-Fisher relation exist in its observed shape and scatter? Neither vanilla ΛCDM, nor calculations with naive gravitational physics give satisfactory answers (Courteau *et al.* 2007; Dutton *et al.* 2011; McGaugh 2012), and narrow implementations of modified Newtonian dynamics appear unrealistic by independent lines of evidence. After 35 years of seeking this answer, are we on the brink of understanding what drives the evolution of not just the slope and intercept of this unique scaling relation, but very importantly, of the scatter? Is this relation a key piece of the dark matter puzzle, or are we simply seeing how baryons scale with baryonic effects where they matter most, in the inner regions of galaxies, even down to masses far lower than implementations of the CDM paradigm have typically predicted?

3. Future Opportunities

Looking long-term, the ultimate galaxy laboratory for distinguishing between baryonic feedback effects and fundamentally-altered dark matter physics from the vanilla CDM implementation will be the unique performance regime of the next generation of giant segmented mirror telescopes and the James Webb Space Telescope. These telescopes will push well into the sensitivity and resolution regime needed to trace the dynamics of many galaxies, both isolated and interacting, of lower stellar mass and slower rotation rates at higher redshifts than what has previously been possible on Earth or in space. By tracking the evolving shapes of supposedly dark matter dominated galaxy rotation curves through the age of the universe, we will be tracking the transfer of star-formation energy to the mass redistribution. Both the low-mass and high-redshift regimes of galaxy formation, with their limited scope of star-formation, reveal particularly strong discriminators between feedback effects and intrinsic dark matter properties.

Complete dynamical characterization of this regime (dwarf galaxies to high-redshift) must be conducted while accounting for environment, making up the three prongs of an ideal future survey:

(*a*) **Low-Mass Regime** (log $M_*/M_\odot<8$, especially log $M_*/M_\odot<6$) to be squarely in the dark matter -dominated regime where baryons and star-formation have a limited share of the energy budget, selected as simply as possible and ideally where completeness is well understood.

(*b*) **Evolution Sensitivity** (to $z \sim 1$ and beyond) to track the smoothness of density profile change across both time and environment, as well as star-formation.

(*c*) **Environmental Variation** (from the densest environments to voids) to compare those galaxies which would have had limited interaction to those that are entirely governed by their interaction history, to better assess the driving forces in the internal dynamics of dwarf galaxies.

Will we see the statistical spread of erratic baryonic feedback redistributing cold dark matter particles in episodic jumps according to environment? Or might we see the telltale profile evolution of warm dark matter, or even perhaps the progressive coring-out of profiles from self-interacting dark matter? In the latter possibility, the rate of profile evolution may even constrain the interaction cross-section of dark matter. Without a wide-range sampling in mass, time, and environment for spatially and spectrally resolved kinematics, answers will remain elusive.

Just as important as the type of observational campaign proposed is the continued development of well-understood, well-controlled models of both standard and alternative physics of both the baryonic and dark matter components of galaxies. If we have learned anything in the past decade of galaxy evolutions studies, it is that the relationship between baryonic and dark matter in galaxies is non-trivial. Hydrodynamic, analytic, and semi-analytic models all contribute to the framework we use to interpret our observations. For the types of comparison studies needed in this work, which are some of the most direct and detailed comparisons we can make in the dark-baryon connection, the focus for model building must be the physical processes that affect the *observable* part of the rotation curve. A huge challenge in the next generation of model-building is to resolve the observables predicted from physically relevant processes. While difficult, some studies have begun to show this is possible. The continued, creative development of resolved, and *observably relevant* models, in preparation for the exciting observational regimes on the horizon, will be a worthwhile investment.

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