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# Dark Matter Halo Masses from Abundance Matching and Kinematics: Tensions for the Milky Way and M31

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## ABSTRACT

The dark matter halo masses of galaxies can be estimated from their stellar masses via abundance matching (AM). For both the Milky Way and M31, the AM mass is higher than the mass inferred from kinematics. The higher AM masses exacerbate the missing satellite problem. The difference is especially pronounced for M31, for which $M_{200}^{\mathbf{AM}} \gtrsim 10^{13}$ $M_{\odot}$ but $M_{200}^{\mathbf{kin}} < 2 \times 10^{12}$ $M_{\odot}$. This is more than expected from scatter in the AM relation, and may suggest the need for separate AM relations for early and late type galaxies.

*Keywords:* Galaxy dark matter halos, Milky Way dark matter halo

## COMPARING HALO MASS ESTIMATORS

Mass is a fundamental property of galaxies. Stellar masses follow from observed luminosities, while dark matter halo masses must be inferred indirectly. The two masses can be connected through abundance matching (AM), which relates the observed number density of galaxies to the corresponding number density of dark matter halos. This leads to a stellar mass–halo mass relation (e.g., Moster et al. 2013; Behroozi et al. 2013) that has become an essential element of the ΛCDM paradigm.

As shown in Fig. 1, the halo mass of the Milky Way (MW) predicted by AM is at or above the high end of the range estimated from kinematics (Bland-Hawthorn & Gerhard 2016). This has implications for the missing satellite problem, as the predicted number of satellites scales with mass (Bullock & Boylan-Kolchin 2017). The modest number of observed MW satellites is more readily reconciled with a halo mass at the low end of the range indicated by kinematics. However, a self-consistent ΛCDM prediction employing AM for the mass of the Milky Way implies an uncomfortably large number of satellites.

For M31 the problem is more pronounced. The stellar mass of M31 predicts an AM halo mass $\gtrsim 10^{13}$ $M_{\odot}$, considerably larger than the mass of the Milky Way. However, kinematic estimates indicate a halo mass for M31 that is similar to (Chemin et al. 2009) or even *lower* (Kafle et al. 2018) than that of the Milky Way. These kinematic mass estimates are inconsistent with AM by an order of magnitude.

Approaching the issue from the other direction, the timing mass of the Local Group ranges from 3 to $5 \times 10^{12}$ $M_{\odot}$ (van der Marel et al. 2012). The low end of this range is equal to the sum of the halo masses inferred from rotation curve fits. The high end is consistent with the mass inferred from larger scale motions (Shaya et al. 2017). According to AM, halos in this mass range should contain a central galaxy with a stellar mass about that of the Milky Way (Fig. 1). That is, the entire Local Group should contain only the Milky Way as its most massive galaxy, not the Milky Way plus Andromeda.

There is considerable scatter in the halo mass–stellar mass relation (Bullock & Boylan-Kolchin 2017), so one might wonder if the Local Group and its two most massive galaxies are simply atypical. This might suffice to explain the Milky Way, in which case we should expect to see larger halo masses and richer satellite systems around galaxies of similar stellar mass. There is certainly diversity in this respect (Müller et al. 2017; Smercina et al. 2018; Müller et al. 2019; Bennet et al. 2019), with more scatter in the data than expected (Carlsten et al. 2020; Font et al. 2020; Wang et al. 2021). It seems a stretch to attribute the large offset between the kinematic and AM halo mass of M31 to bad luck. The Local Group has a kinematic mass-to-light ratio that is similar to that of other groups (Karachentsev & Kudrya 2014), so is not unusual in this respect.

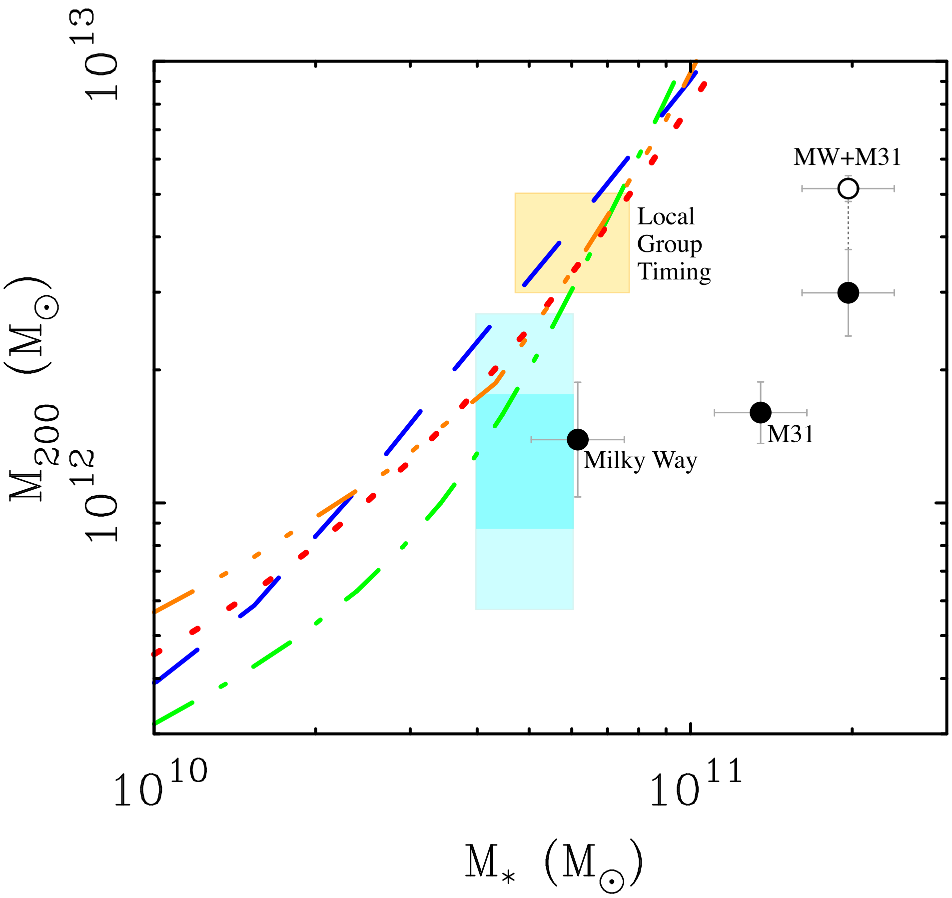


**Figure 1.** Galaxy stellar and halo masses. Filled points are from rotation curve fits to the Milky Way (McGaugh 2018) and M31 (Chemin et al. 2009) and their sum. The open circle adopts for the summed total mass that estimated by Shaya et al. (2017). The blue box shows the full range of mass estimates for the Milky Way from Bland-Hawthorn & Gerhard (2016) with the lighter shading illustrating the outer quintiles of halo mass estimates. Lines are the stellar mass–halo mass relation from abundance matching, as estimated by Moster et al. (2013, green dot-dashed line), Behroozi et al. (2013, orange dash-triple dotted line), Kravtsov et al. (2018, red dotted line), and Mowla et al. (2019, blue dashed line). The yellow box shows where the timing mass of the Local Group (van der Marel et al. 2012) overlaps with the AM lines. A typical halo of the mass of the Local Group should contain a central galaxy with the stellar mass of the Milky Way, not the Milky Way plus Andromeda.

In addition to scatter in the halo mass–stellar mass relation, there is also scatter in the relation between halo mass and concentration, and uncertainties in stellar population mass-to-light ratios. These variations are relatively modest, and seem unlikely to explain the discrepancy between kinematic and AM halo masses. Moreover, the scatter between stellar mass and halo mass is constrained by the small observed scatter in the Tully-Fisher relation (Lelli et al. 2016). Neither the Milky Way nor Andromeda is atypical in this respect (McGaugh 2016).

The problem we encounter is most severe at high masses where the AM relation bends in response to the knee in the Schechter function[1] so that a factor of two in stellar mass goes much further in halo mass. High mass spiral galaxies are rare compared to early-type galaxies; they might reside in very different halos (Peebles 2020). It may thus be desirable to construct separate AM relations by morphological type: one for spirals and another for ellipticals. Whether this suffices to address the problem highlighted here, or if it is a symptom of a deeper issue, is beyond the scope of this note.

This note stems from a conversation between the authors at IAU Symposium 353, illustrating the value of in-person interaction.

[1] A related issue arises with the gas content of high mass galaxies (see Li et al. 2019).

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