The dark matter crisis

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Abstract I explore several possible solutions to the "missing satellites" problem that challenges the collisionless cold dark matter model.

INTRODUCTION

Most dark matter candidates cannot be distinguished by observations on large scales. Although the observed universe appears consistent with hierarchical structure formation, this still leaves a wide range of potential dark matter candidates. For example, the clustering properties of galaxies, abundances of rich clusters or even halo masses and sizes are all very similar in universes with matter density dominated by cold dark matter, warm dark matter or collisional dark matter. We therefore seek tests of the nature of the dark matter that are sensitive to its interaction properties and small scale power which manifests itself on non-linear scales.

Cold dark matter (CDM) halos form via a complicated sequence of hierarchical mergers that lead to a global structure set primarily by violent relaxation. Numerical simulations have played an important role in determining the shape and scaling of CDM halo profiles that have subsequently lead to new observational tests of the model. A single functional form can fit CDM halos from a mass scale of $10^7 M_\odot$ – $10^{15} M_\odot$, where the density at a fixed fraction of the virial radius is higher in lower mass halos and the central profiles have steep singular cusps (c.f. Dubinski & Carlberg 1991, Warren etal 1992, Navarro etal 1996, Fukushige & Makino 1997, Moore etal 1998, Jing 2000 etc).

Galaxy clusters form via a similar process as individual galaxies, however most of the galactic fragments that formed clusters have survived the hierarchical growth, whereas on galaxy scales we find little trace of the merging hierarchy. Only a dozen satellites orbit the Milky Way, whereas a thousand satellites orbit within the Coma cluster. Numerical simulations of CDM halo formation have revealed that the abundance of dark matter subhalos within a galaxy is the same as found within a scaled galaxy cluster (Moore etal 1999, Klypin etal 1999). There are two solutions to this problem: (i) CDM is incorrect and the nature of the dark matter suppresses the formation of substructure halos, (ii) CDM is correct and the dark matter satellites of the Milky Way are present but only a few percent of them formed stars. Here I focus on the latter possibility.

I DARK MATTER SUBSTRUCTURE

Figure 1. The distribution of dark matter with a CDM "Local Group" candidate. This is a binary pair of dark matter halos at a redshift z=0, separated by 1 Mpc and infalling at 100km/s. The large halos have virial masses of $\approx 2 \times 10^{12} M_\odot$, and with a particle mass of $10^6 M_\odot$ they are resolved with over 10^6 particles and 0.5 kpc force resolution. The grey scale represents the local density of dark matter – there are over 2000 dark matter satellites with circular velocity larger than 10 km/s.

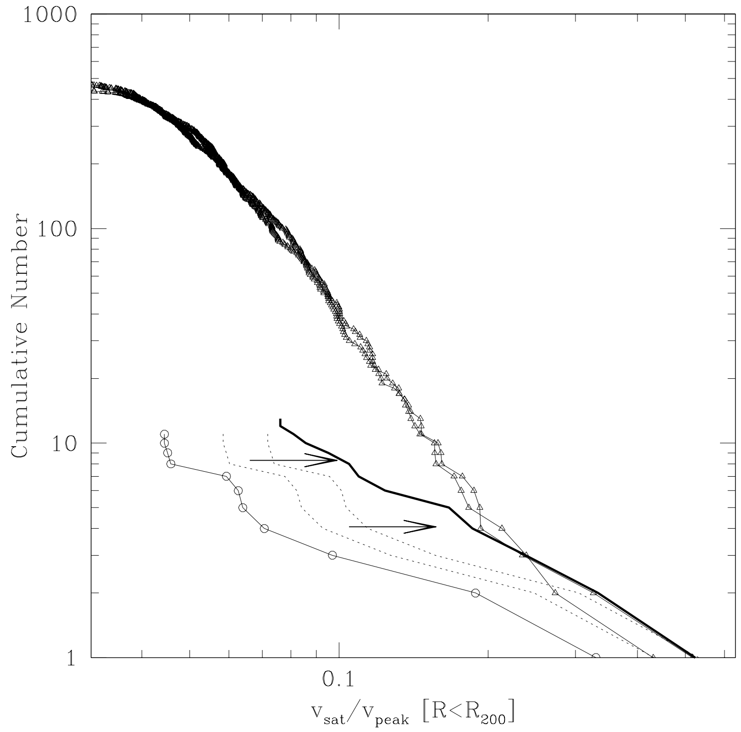

Figure 2. The cumulative number of satellites within the virial radius of the Milky Way (open circles) and within the two CDM halos from Figure 1 (open triangles). Here I have taken v_{peak} = 210 km/s for the Milky Way, however the CDM contribution to the Milky Way can be constrained to lie in the range 130 – 160 km/s once the baryonic component has been considered (Moore etal 2001). The dotted curves show the effects of this correction. The arrows show a correction for converting central velocity dispersion to v_{sat}. The thick solid curve shows the distribution of CDM satellites that could form stars before the universe is re-ionised.

Interpreting the observations

Figure 2 shows the cumulative distribution of subhalos within the high resolution Local Group halos of Figure 1. The open circles show the observed distribution for the Milky Way satellites, where I have normalised the distribution using $v_{peak} = 210$ km/s. However, baryons dominate the central region of the Galaxy and subtracting the contribution from the disk and bulge gives the maximum allowed CDM halo that has v_{peak} = 160 km/s (Moore etal 2001). A minimum value of v_{peak} = 130 km/s is required for the Galactic CDM halo to be massive enough to cool the observed mass of baryons. Figure 2 shows the effect of this correction.

Simon White has pointed out that the velocity dispersion of the dSph's are measured well within the cores of their dark matter halos (White 2000). We originally assumed isotropic orbits and isothermal potentials to derive v_{sat} from observations of the 1d central velocity dispersion (Moore etal 1999). CDM halos have central density profiles flatter than r^{-2} therefore one expects the velocity dispersion to drop in the inner region. M87 provides a good example of this. This galaxy lies at the center of the Virgo cluster and has a central velocity dispersion of ≈ 350 km/s whereas the cluster has a global value that is a factor of two larger. If we assume that the dSph's are similar to M87, then the correction should scale roughly as the concentration parameter. Since $c_{M87}/c_{dSph} \approx 0.4 - 0.5$, then we expect the maximum correction to v_{peak} to be an increase of 50% over our quoted values. This correction is indicated by the arrows in Figure 2 which brings the observed data into good agreement with a crude model for re-ionisation discussed later.

II FEEDBACK

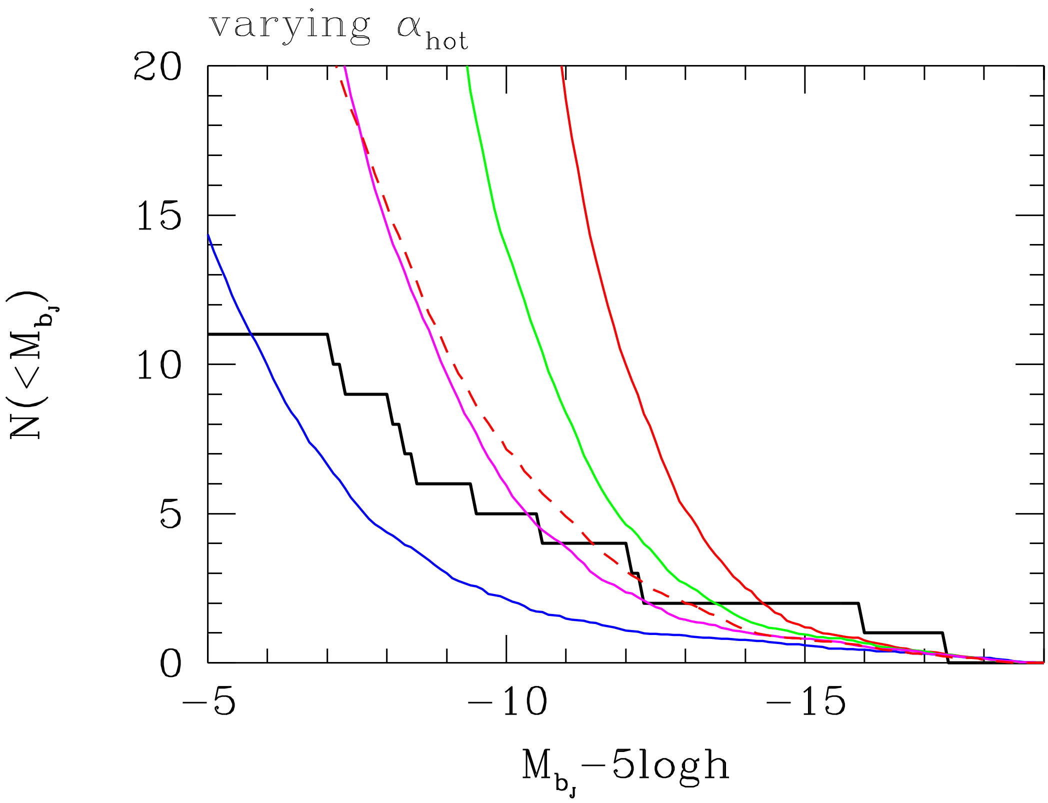

Figure 3. The histogram shows the cumulative distribution of absolute magnitudes of the 11 Galactic satellites. The curves show predictions from the Durham semi-analytic models of galaxy formation (Cole etal 2000) varying the parameter α that controls the efficiency of feedback. This can be tuned to give the correct distribution of satellite luminosities which in this case would lie somewhere in between the blue and pink curves.

Feedback is an essential component of galaxy formation within CDM models. It is invoked primarily to flatten the luminosity function given the steep mass function of CDM halos. For example, the faint end of the luminosity function in the Local Group is flat over a range that is about 10 magnitudes fainter than M_*. By varying the efficiency of feedback with halo mass, it is possible to get a reasonably flat luminosity function as Figure 3 demonstrates. The parameter α controls how much gas is ejected from dark matter halos of a given circular velocity and allows one to form systematically less stars in smaller mass halos.

The problem with a uniform feedback scheme is that the mass to light ratios of galaxies will increase rapidly for fainter galaxies. Thus we find that a satellite halo with absolute magnitude $M_B = -10$ is predicted to have a circular velocity of 40 km/s, roughly three times that observed for the dSph's. Figure 4 shows the "Tully-Fisher" relation for the 11 Galactic satellites compared with the curves predicted from the semi-analytic models employed in Figure 3. The circular velocities are overestimated by a factor of 3–4.

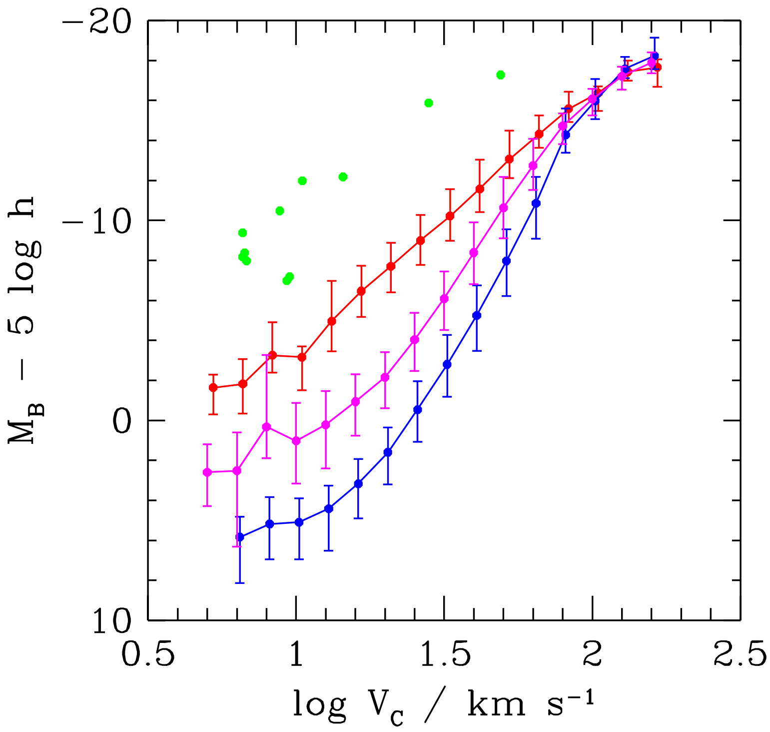

Figure 4. The Tully-Fisher relation for the Galactic satellites (green points) where the velocity dispersions of the spheroidals have been converted to circular velocity assuming isotropic orbits and isothermal potentials. The curves show the Tully-Fisher relation predicted by the semi-analytic models from Figure 3 where we varied the efficiency of feedback to match the numbers of dwarf galaxies.

III RE-IONISATION

We have just demonstrated that feedback does not solve the overabundance of CDM satellites – clearly some form of stochastic biasing is required. A solution was proposed by Bullock etal (2000) in which only those dark matter halos that have virialised prior to re-ionisation can cool gas and form stars. Once the IGM has been reheated then the smallest CDM halos cannot capture or cool gas and they remain completely dark.

In Figure 5 we mark all the progenitor halos that satisfy the condition for cooling gas prior to z=10, which we will take as the redshift of re-ionisation. We mark particles red if they lie within a region of overdensity larger than 1000. The locations of these particles are subsequently tracked to z=0 and marked in the right panel of Figure 5. Roughly 100 satellites satisfy the density criteria at a redshift z=10 and ≈ 80 of these physically merger together to form the very central region of the final galaxy halos. The remaining 20 survive intact and can be found orbiting within the virial radius of the two halos (see Figure 6). The mean radius of the surviving satellites is ≈ 80 kpc, which is a factor of 2.5 smaller than the half mass radius of the final halos.

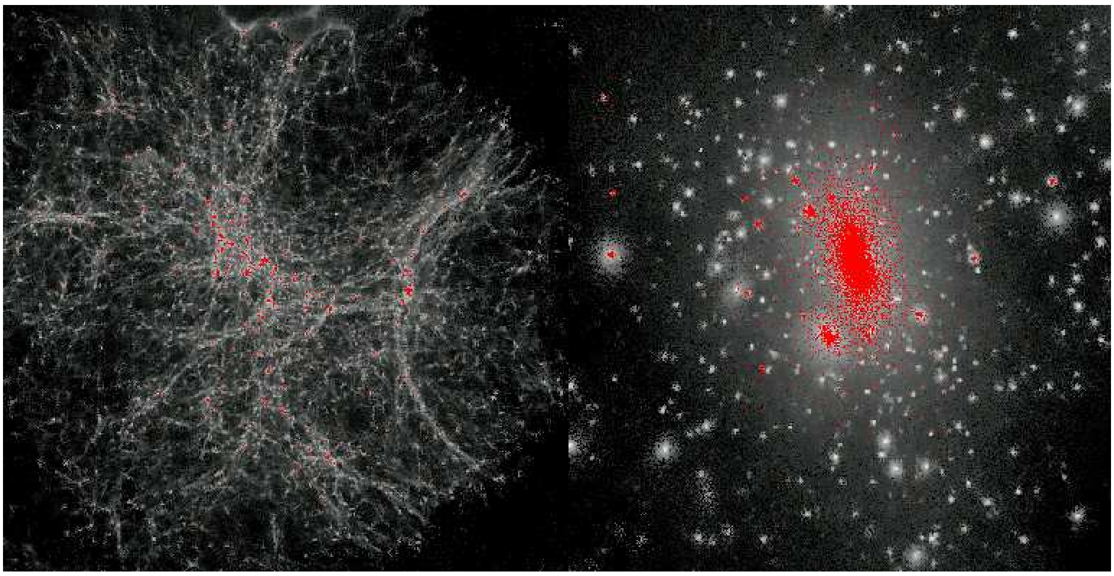

Figure 5. The left panel shows the Local Group simulation at z=10. Marked in red are all those particles that lie in regions with an overdensity larger than 1000. The right panel shows one of the high resolution halos at z=0 and the locations of the red particles marked at z=10.

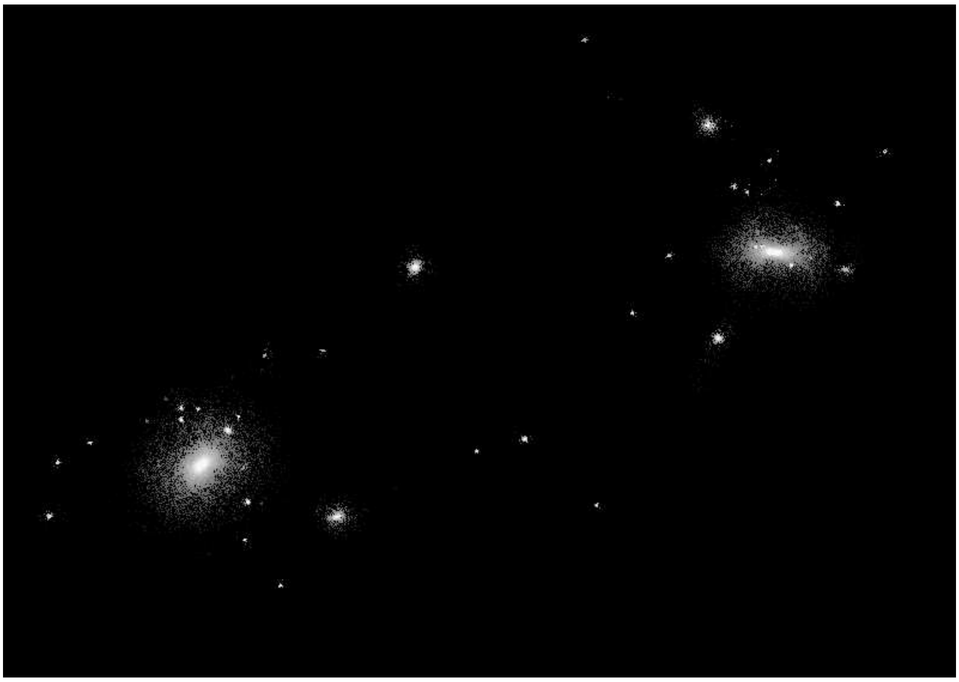

Figure 6. The smoothed distribution of "starlight" in the Local Group at the present day. I plot only those stars that could form in dark matter halos prior to re-ionisation at z=10. The distribution of these stars is highly biased. Roughly a dozen dark matter dominated satellites orbit within each of the parent halos and they have a spatial distribution that matches the real Local Group. Most of the population II/III stars lie at the very centers of the halos surrounding M31 and the Galaxy. Their half light radius is just a few kiloparsecs (c.f. White & Springel 1999) and their luminosity density falls as r^{-3} (c.f. Figure 7).

The final cumulative distribution of satellites within one of the simulated halos is shown in Figure 2 and provides a good match to the corrected observational data points. Several puzzles remain. Why don't we find any satellites in the Galactic halo with velocity dispersion less than ~ 7 km/s? Is cooling that inefficient below ≈ 10 km/s such that we do not find any dark matter dominated systems containing just a handful of stars?

The star formation histories of the Local Group satellites presents a further puzzle. Most of the satellites show evidence for several bursts of star formation, some continuing to the present day. Both re-ionisation and the "essential" feedback have been extremely inefficient at removing gas from these tiny halos that have masses $\approx 10^8 M_\odot$.

IV RESOLUTION ISSUES

Central halo profiles

Have we really converged on the unique central structure of CDM halos? This is a hard numerical calculation to perform since we are always relaxation dominated on small scales. In a hierarchical universe the first halos to collapse will contain just a few particles and have relaxation times much shorter than a Hubble time.

Figure 7 shows the final density profile of one of the high resolution Local Group CDM halos. We also plot the final density profile of those particles that were located within highly non-linear regions at redshifts z=10 and z=20. The central 5 kpc of the halo is dominated by those particles that were in virialised halos at z=10. Most of these halos contained just a few particles and their internal structure is completely dominated by resolution effects. Until we can adequately resolve objects collapsing at z=10, we cannot claim to have converged upon the slope of the density profile at 1–2% of the virial radius.

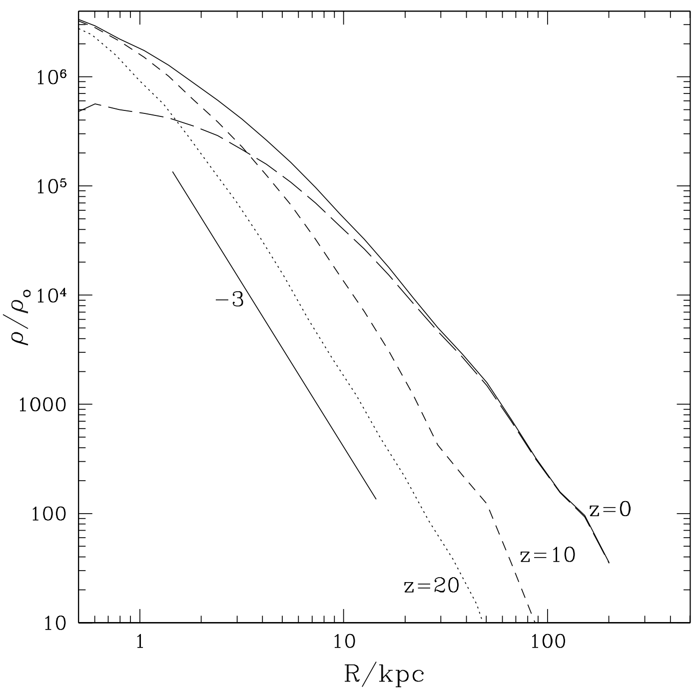

Figure 7. The solid curve shows the density profile of the high resolution halo shown in Figure 5. The dotted and dashed curves show the density profiles of those particles that lie in regions of overdensity larger than 50 at z=20 and z=10 respectively. The long-dashed curve shows the difference between the solid and short-dashed curves. The radial density profile of the marked particles at z=0 has a gradient of -3 which is similar to that of the Galactic spheroid.

Beam Smearing

Rotation curves of dwarf galaxies first highlighted potential problems with the structure of CDM halos (Moore etal 1994, Flores etal 1994, Burkert 1995). The quality of these data were recently questioned by several authors including van den Bosch & Swaters (2000) used rotation curves from 19 dwarf galaxies to claim that CDM halos are *consistent* with the data. However, to make this statement these authors had to throw away half of the galaxies and adopt unphysical (zero) mass to light ratios. Furthermore, seven of the remaining nine galaxies require concentration parameters in the range c=3–5 which cannot be obtained in any reasonable ΛCDM model. One could rephrase the conclusions of these authors by stating that only 2 galaxies from a sample of 19 are consistent with CDM!

Finally, I show the H_α and HI rotation curves of the nearby dwarf NGC3109 (Blais-Oullette etal 2001). These data clearly show that beam smearing is not an issue for the nearby dwarf galaxies. Furthermore, only a constant density core can fit these data. CDM profiles with central cusps < -1 are ruled out for any value of the concentration parameter. If CDM is correct then we are forced to conclude that galaxies such as NGC3109, NGC5585, IC2574, etc, are somehow strange and that their disk kinematics are somehow not measuring the mass distribution.

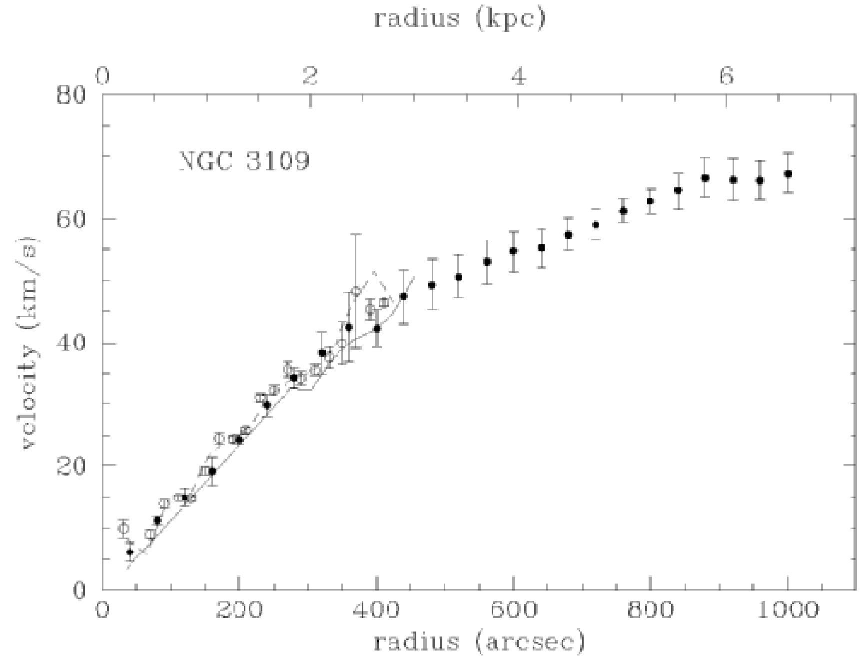

Figure 8. The rotation curve of NGC3109 (Blais-Oullette etal 2000) measured in HI (filled circles) and H_α (open circles). Beam smearing is clearly not an issue with nearby dwarf galaxies.

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