Dwarf Galaxies in 2010: Revealing Galaxy Formation's Threshold and Testing the Nature of Dark Matter

James S. Bullock† and Manoj Kaplinghat
Physics & Astronomy Department, University of California, Irvine; †bullock@uci.edu

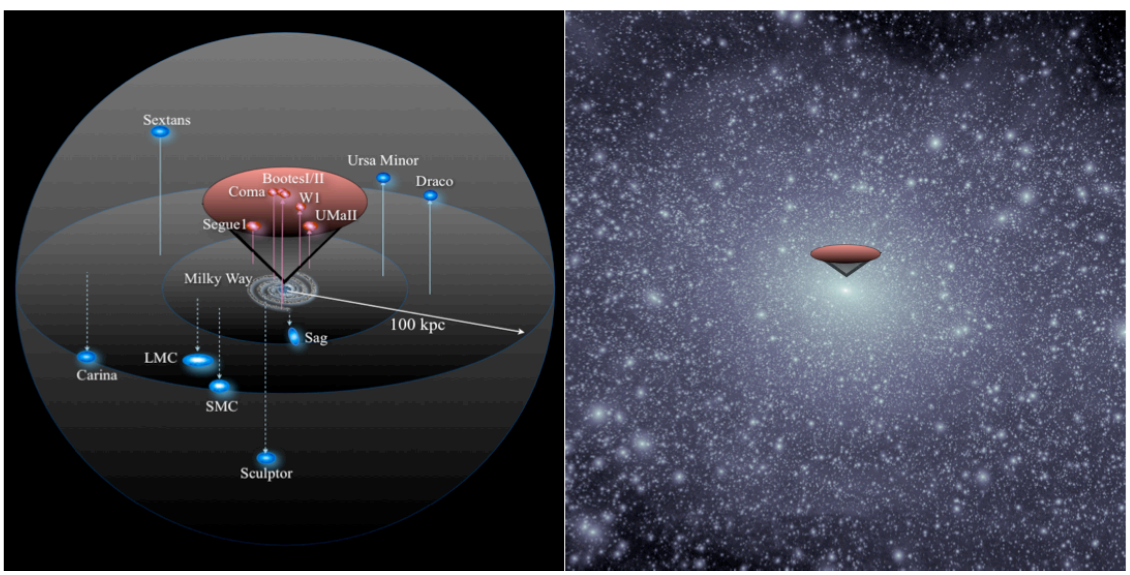
Andrew Fruchter
Space Telescope Science Institute

Marla Geha
Astronomy Department, Yale University

Joshua D. Simon
Observatories of the Carnegie Institution of Washington

Louis E. Strigari
Physics Department, Stanford University

Beth Willman
Astronomy Department, Haverford College



(*Left*) Known satellite galaxies of the Milky Way within 100 kpc. (*Right*) LCDM simulation of a Milky Way size halo (Diemand et al. 2008; spanning 800 kpc). The red-shaded cones represent the volume that is currently complete for discovery and characterization of ultra-faint dwarf galaxies.

<u>Panels</u>: GAN and CFP

Abstract

Searches in Sloan Digital Sky Survey data have more than doubled the number of known dwarf satellite galaxies of the Milky Way, and have revealed a population of ultra-faint galaxies with luminosities smaller than typical globular clusters, $L \sim 1000$ $L_{\odot}$. These systems are the faintest, most dark matter dominated, and most metal poor galaxies in the universe. Completeness corrections suggest that we are poised on the edge of a vast discovery space, with hundreds more to be discovered as future instruments explore the low-luminosity threshold of galaxy formation. Dark matter dominated dwarfs of this kind probe the small-scale power-spectrum and offer unique tests of the particle nature of dark matter. Full use of dwarfs as dark matter laboratories will require synergy between deep, large-area photometric searches; spectroscopic and astrometric follow-up with next-generation optical telescopes; and subsequent observations with gamma-ray telescopes for dark matter indirect detection.

1. Introduction and Outline

Since 2004, twenty-five new dwarf galaxy companions of the Milky Way and M31 have been discovered, with most of them less luminous than any galaxy previously known (e.g., Willman et al. 2005; Belokurov et al. 2007; McConnachie et al. 2008). The most extreme ultra-faint dwarfs have luminosities smaller than the average globular cluster ($L_V \simeq 10^3 - 10^4$ $L_{\odot}$) and can only be detected as slight overdensities of resolved stars in deep imaging surveys. Follow-up spectroscopy reveals that these, the faintest galaxies known, are also the most dark matter dominated (Martin et al. 2007; Simon & Geha 2007; Strigari et al. 2008a) and most metal poor (Kirby et al. 2008; Geha et al. 2008) stellar systems yet observed.

Perhaps the most exciting aspect of these recent discoveries is that they hint at a much larger population. As discussed in §2 and illustrated in Figure 1, detection is complete only to ~ 50 kpc for the faintest dwarfs (Koposov et al. 2008; Walsh et al. 2009). Straightforward luminosity bias corrections suggest as many as ~ 500 ultra-faint dwarf galaxies within the virial radius of the Milky Way (Tollerud et al. 2008). The implication is that we are poised at the edge of a vast new discovery space in galaxy phenomenology. Deep searches for these galaxies will explore galaxy formation's threshold, and follow-up studies will allow us to test ideas about galaxy formation suppression and chemical enrichment in the smallest dark matter halos at the earliest times (Bullock et al. 2000; Kravtsov et al. 2004; Strigari et al. 2007b; Li et al. 2008; Macciò et al. 2009; Koposov et al. 2009; Busha et al. 2009).

The discovery of these nearby dark matter dominated galaxies provides a great opportunity to understand the microscopic nature of dark matter and test the Cold Dark Matter (CDM) paradigm. As discussed in §3, Local Group dwarf spheroidal galaxies (dSphs) are

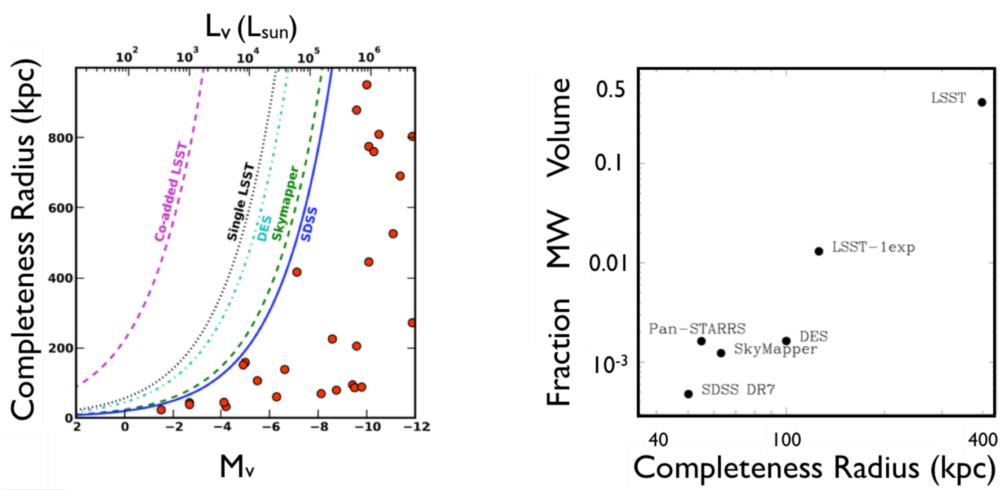


Fig. 1.— (*Left*) The radius out to which detection is complete for faint dwarf galaxies in various surveys (Tollerud et al. 2008). Known dwarfs are indicated as red circles, which trace the completeness threshold for SDSS. (*Right*) The fraction of the Milky Way halo volume (out to 400 kpc) within which a given survey can detect $L \sim 10^3 L_\odot$ dwarfs as a function of completeness radius.

ideally suited for this purpose: 1) they are close enough to be studied using kinematics of *individual stars*; 2) their high dark matter fractions ($M/L > 100$) render them relatively free of the usual baryonic uncertainties that make dark matter profile determinations difficult; and 3) they inhabit the smallest dark matter halos known to host stars and therefore provide the best direct laboratories for testing dark matter clustering properties on small scales – scales where CDM theory faces its most serious challenges.

Dwarf galaxies are also excellent laboratories for indirect detection of dark matter. As discussed in §4, if the dark matter is of the WIMP variety, then dark matter annihilations can produce potentially-detectable gamma-ray photons (see e.g., Strigari et al. 2008b, and references therein). Indirect dark matter detection of this kind is one of the major goals of current and proposed gamma ray telescopes. Unlike the Galactic Center, dSphs are devoid of gas and ongoing star formation, and therefore contamination from astrophysical gamma-ray sources like pulsars will be minimal. If dark matter self-annihilates with weak-scale cross sections (as many theories predict) then dwarf satellites will complement the Galactic Center to provide the most robust means for dark matter detection. In order to turn such a detection (or upper limits on the flux) into constraints on particle physics models, we need accurate dynamical mass models for the dwarfs. This fact points to an important synergy between deep, wide field photometric searches for new dwarf galaxies, optical kinematic follow-up for dark matter mass models, and subsequent observations with gamma-ray telescopes for dark matter indirect detection studies.

2. Hunting for the Low-Luminosity Threshold of Galaxy Formation

The recent discoveries of dark matter dominated galaxies with luminosities as low as $\sim 10^3 L_\odot$ raise a number of fundamental questions. Is there a low-luminosity threshold for galaxy formation? If so, what physics sets this scale? Is there a dark matter halo mass scale below which galaxy formation is completely suppressed? What are the chemical enrichment histories for galaxies that are themselves less luminous than a star cluster? While it is difficult to answer these questions with current facilities, the future is promising.

By carefully filtering star catalogs, based on color and magnitude, it is possible to find ultra-faint galaxies as overdensities of resolved stars. This technique requires homogeneous photometric coverage over a large portion of the sky. The Sloan Digital Sky Survey (SDSS) is the first survey with sufficient depth and sky coverage to perform this test and all of the Milky Way ultra-faint galaxies have so far been discovered in this dataset. The left panel of Figure 1 illustrates the radius out to which dwarf galaxies of a given luminosity can be discovered with several proposed surveys. Known dwarfs are red circles. The right panel shows the fraction of the Milky Way halo's volume in which ultra-faint dwarf galaxies may be detected, as a function of the associated radius of completeness. We see that **LSST, covering nearly half the sky, will be able to detect ultra-faint dwarf galaxies out beyond the edge of the Milky Way's virial radius.**

Reasonable predictions for the total number of luminous Milky Way satellites range between 60 – 600, depending on the physics of low-mass galaxy formation (and associated radial distribution of dwarfs). The new galaxies that should be discovered by future surveys will greatly influence our interpretation of the so-called 'Missing Satellites Problem' in CDM (Klypin et al. 1999). The census of dwarf galaxies in the Milky Way volume will also provide a robust upper limit on the free-streaming scale of the dark matter particle – warm dark matter models are ruled out if they predict fewer subhalos than observed satellite galaxies

3. Taking Dark Matter's Temperature

Photometric surveys are necessary to discover new faint dwarf galaxies. Once found, *we can learn about the nature of these objects and the dark matter within them only through spectroscopic followup.* With medium-resolution spectroscopy of stars in dwarf galaxies, it is possible to measure velocities of individual stars (good to a few km s^{-1}) and hence the masses of dwarf galaxies. Over the past 20 years, these measurements have revealed that dwarf galaxies — including the newly discovered ultra-faint dwarfs — are highly dark matter-dominated systems, with central mass-to-light ratios approaching 1000 in solar units (e.g., Aaronson 1983; Mateo et al. 1993; Simon & Geha 2007; Geha et al. 2008).

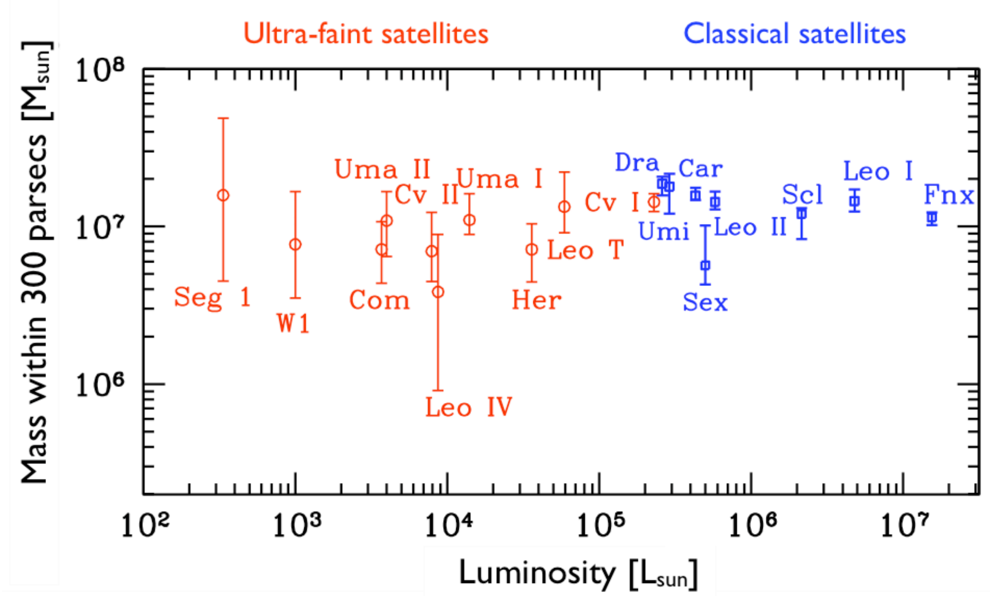


Fig. 2.— The integrated mass within the inner 300pc of Milky Way satellite galaxies as a function of their luminosities (Strigari et al. 2008). Satellites discovered since 2004 are shown in red.

One of the most striking recent findings about Milky Way satellite galaxies was the discovery that *all nineteen* dSphs, covering more than four orders of magnitude in luminosity, inhabit dark matter halos with the same mass ($\sim 10^7$ $M_\odot$) within their central 300 pc (Strigari et al. 2008a). This result is shown in Figure 2. It suggests either a lower mass limit for galaxy formation, or conceivably a cutoff in the mass function of dark matter halos, which would map to the properties of dark matter particles. Improved mass measurements (utilizing much larger samples of stellar velocities) and detailed studies of the lowest luminosity objects are urgently needed to determine more accurately the mass-luminosity relationship and verify the non-existence of galaxies with masses below the apparent threshold. Unfortunately, confirming whether stellar overdensities fainter than $M_V \sim -4$ are truly dark matter dominated dwarfs is already a significant challenge because of the difficulty of identifying a small number of kinematically associated stars in the face of a large Milky Way foreground population covering a range of velocities. **Future instruments such as a wide-field spectrograph on an extremely large ground-based telescope (providing a factor of ~ 10 improvement in collecting area compared to Keck) or WFMOS on an 8 m telescope would tremendously enhance our ability to study dark matter and galaxy formation with ultra-faint dwarfs.**

An important area where dwarf galaxy kinematic studies will be useful is in placing limits on (or measuring the existence of) a phase-space limited core in their dark matter

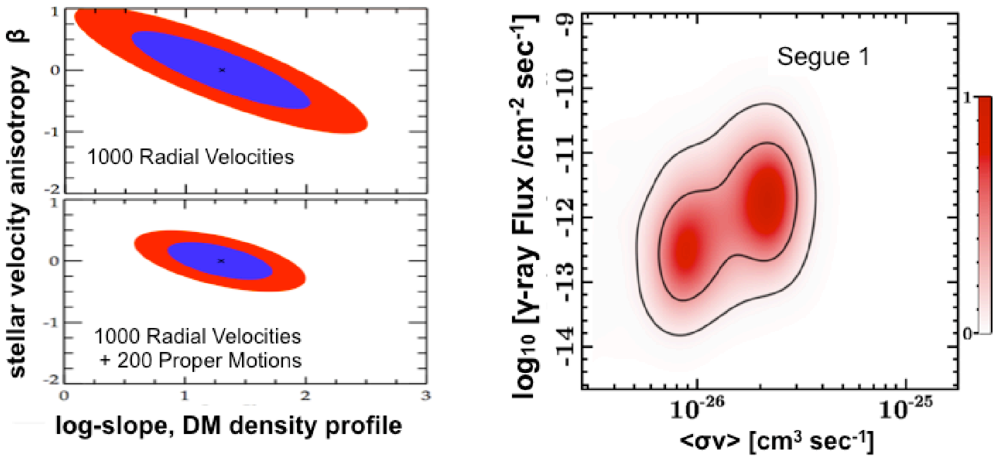


Fig. 3.— (*Left*) Errors in the measured stellar velocity anisotropy vs. dark halo density profile slope for a simulated dSph. Upper panel shows the implied errors for 1000 radial velocities at 5 km s^{-1} accuracy and lower panel includes 200 proper motions at 15 μas yr^{-1}. We see an experiment like SIM Lite would be able to discriminate between a cusp and a core. (*Right*) Likelihood of predicted flux of $E > 1$GeV gamma rays from the dwarf galaxy Segue 1, based on a joint marginalization over Constrained Minimal Supersymmetric Standard Model parameter space and the current kinematic data for this dwarf (Martinez et al. 2009).

halos. This will provide an important constraint on the nature of dark matter. The ability for dark matter to pack in phase space is limited by its intrinsic properties such as mass and formation mechanism. CDM particles have negligible velocity dispersion and very large central phase-space density, resulting in cuspy density profiles over observable scales (Navarro et al. 1997). Warm Dark Matter (WDM) halos, in contrast, have smaller central phase-space densities, so that density profiles saturate to form constant central cores. Owing to their small masses, dSphs have the highest average phase space densities of any galaxy type, and this implies that for a given DM model, phase-space limited cores will occupy a larger fraction of the virial radii. This means that dSphs are the most promising galaxy candidates for manifesting phase-space cores. Unfortunately, kinematic measurements of the *stars* in galaxies provide only a lower limits on the coarse-grained phase space density of the *dark matter particles* in those galaxies. The only way to detect a phase-space core within a dark matter halo is to detect the presence of a constant-density core in its density profile.

Current observations are unable to measure the density profile slopes within dSph galaxies because of a strong degeneracy between the inner slope of the DM density profile and the velocity anisotropy, β, of the stellar orbits. Radial velocities alone cannot break this degeneracy (Fig. 3), even if the present samples of radial velocities are increased to several thousand stars (Strigari et al. 2007a). Combining *proper motions* with the present samples of radial velocities will provide orthogonal constraints and is the only robust means of breaking the anisotropy-inner slope degeneracy. The most promising dSphs for this experiment will be nearby and high surface brightness systems such as Fornax and Sculptor, for which the upper giant branches require proper motions of stars with $V \simeq 19$. The needed measurements will include proper motions for ~ 100 stars per galaxy with accuracies better than 10 km s^{-1} ($< 40\mu$as yr^{-1} at 60 kpc). Figure 3 shows that with about 1000 radial velocities and 200 transverse velocities of this accuracy, it will be possible to reduce the error on the log-slope of the dark matter density profile to about 0.2 (Strigari et al. 2007a). This will enable us to rule out a large class of warm dark matter models or invalidate the cold dark matter paradigm. **The required observations are well-matched to the projected performance of SIM Lite** but well-beyond the capabilities of Gaia. This kind of measurement may also be possible with giant ground-based or space telescopes (like TMT, GMT, and eventually ATLAS-T) with repeated observations over a few years. Astrometry at the 100 μas level has already been demonstrated with a laser guide star adaptive optics system on the Palomar 5 m telescope, and extrapolating those results to a 25 m or 30 m aperture indicates an expected limit of 10 μas (Cameron et al. 2009). The increased number of radial velocities made possible with 30 m telescopes will also reduce the associated errors on the log-slope compared to those presented in Fig. 3.

4. Indirect Detection of Dark Matter

Detecting dark matter through the products of its decay or self-annihilation in an astrophysical system is an exciting prospect. Moreover it is possibly the *only way* we can infer or confirm the nature of *all* of the dark matter in the universe. Dark matter models from theories with new physics at the weak scale (the scale the LHC is designed to probe) generically predict high-energy annihilation products such as gamma-rays. The flux of gamma-rays depends both on the dark matter particle properties as well the spatial distribution of dark matter in the astrophysical source of photons. The closest and densest dwarf galaxies are expected to be the brightest sources (Strigari et al. 2008b; Kuhlen et al. 2008) after the Galactic Center, so identifying the most promising targets and predicting the flux ratios between different objects strongly motivates extensive stellar velocity measurements of the lowest luminosity systems.

Kinematics in dark matter dominated dwarf satellites provide robust constraints on the spatial distribution of dark matter in them. A complicating factor here is dark matter substructure in dwarf galaxies. Substructure does not contribute significantly to the dynamical mass but because of its elevated density "boosts" the annihilation signal. Recent work has shown that using a combination of numerical simulations (Springel et al. 2008) and analytic modeling (Martinez et al. 2009), it is possible to account for the substructure contribution in flux calculations. Figure 3 shows such a calculation for the predicted gamma-ray flux above 1 GeV (appropriate for the Fermi satellite observatory) versus annihilation cross-section for Segue 1, a new Milky Way satellite at 23 kpc. The particle model assumed here is the Constrained Minimal Supersymmetric Standard Model (CMSSM, Ruiz de Austri et al. 2006) including WMAP and current accelerator constraints. Most of the likely flux values for the CMSSM are, however, below the sensitivity limit of the Fermi observatory.

Imaging Air-Cerenkov Telescopes (IACTs) such as HESS, MAGIC and VERITAS have angular resolutions of $\sim 0.1^\circ$ at high energies, and allow pointed observations of dwarf satellites. Present limits from ACT observations of dwarf satellites are unable to probe down to the WMAP-favored CMSSM parameter space (Aharonian et al. 2008; Aliu 2008; Wood et al. 2008). However, a 1 km^2 IACT instrument (Buckley et al. 2008) with better background rejection techniques should get down to these sensitivities. A facility of this type holds real promise for detecting dark matter through non-gravitational means.

REFERENCES

Aaronson, M. 1983, ApJ, 266, L11
Aharonian, F., et al. 2008, Astropart. Phys., 29, 55
Aliu, E. et al. 2008, ArXiv e-prints 0810.3561
Belokurov, V., et al. 2007, ApJ, 654, 897
Buckley, J., et al. 2008,, ArXiv e-prints 0812.0795
Bullock, J. S., Kravtsov, A. V., & Weinberg, D. H. 2000, ApJ, 539, 517
Busha, M. T., et al. 2009, ArXiv e-prints 0901.3553
Cameron, P. B., Britton, M. C., & Kulkarni, S. R. 2009, AJ, 137, 83
Diemand, J., Kuhlen, M., Madau, P., et al. 2008, Nature, 454, 735
Geha, M., et al. 2008, ArXiv e-prints 0809.2781
Kirby, E. N., Simon, J. D., Geha, M. et al. 2008, ApJ, 685, L43
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Koposov, S., Belokurov, V. et al. 2008, ApJ, 686, 279
Koposov, S. E. et al. 2009, ArXiv e-prints 0901.2116
Kravtsov, A. V., Gnedin, O. Y., & Klypin, A. A. 2004, ApJ, 609, 482
Kuhlen, M., Diemand, J., & Madau, P. 2008, ApJ, 686, 262
Li, Y.-S., Helmi, A., De Lucia, G., & Stoehr, F. 2008, ArXiv e-prints 0810.1297
Macciò, A. V., Kang, X., & Moore, B. 2009, ApJ, 692, L109
Martin, N. F., et al. 2007, MNRAS, 380, 281
Mateo, M., et al. 1993, AJ, 105, 510
Martinez, G., Bullock, J.S., Kaplinghat, M., Strigari, L., Trotta, R., 2009, Submitted
McConnachie, A. W. et al. 2008, ApJ, 688, 1009
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Ruiz de Austri, R., Trotta, R., & Roszkowski, L. 2006, Journal of High Energy Physics, 5, 2
Simon, J. D., & Geha, M. 2007, ApJ, 670, 313
Springel, V. et al. 2008, Nature, 456, 73
Strigari, L. E., Bullock, J. S., & Kaplinghat, M. 2007a, ApJ, 657, L1
Strigari, L. E., Bullock, J. S., Kaplinghat, M. et al. 2007b ApJ, 669, 676
Strigari, L. E., Bullock, J. S., Kaplinghat, M. et al. 2008a, Nature, 454, 1096
Strigari, L. E., Koushiappas, S. M., Bullock, J. S., Kaplinghat, M. et al. 2008b, ApJ, 678, 614
Tollerud, E. J., Bullock, J. S., Strigari, L. E., & Willman, B. 2008, ApJ, 688, 277
Walsh, S. M., Willman, B., & Jerjen, H. 2009, AJ, 137, 450
Willman, B., Dalcanton, J. J. et al. 2005, ApJ, 626, L85
Wood, M., et al. 2008, ApJ, 678, 594