A Fundamental Curve for Hot Stellar Systems in Dark Matter Halos

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We consider how dark matter-dominated ultra-faint Milky Way dwarf spheroidal galaxies fit on galactic scaling relations. In the process, we introduce an alternative to fundamental plane space that relies on the half-light mass in place of velocity dispersion. This space clearly reveals a plane of observables that separates globular clusters from ultrafaint dwarf galaxies. It also reveals a fundamental curve (or "tube") upon which all spheroidal galaxies lie, including the Galactic satellites, dwarf ellipticals, giant ellipticals, and intra-cluster light distributions. This fundamental curve allows us to place dwarf spheroidals in a unified empirical framework that directly connects to all other pressure-supported stellar systems embedded in dark matter halos. We further show that this framework provides a new method for connecting galaxies of all types to their host dark matter halo properties. This approach is consistent with abundance matching, but also complimentary, as it allows probing of dark matter halos over a much wider dynamic range in both mass and luminosity.

Data Sets

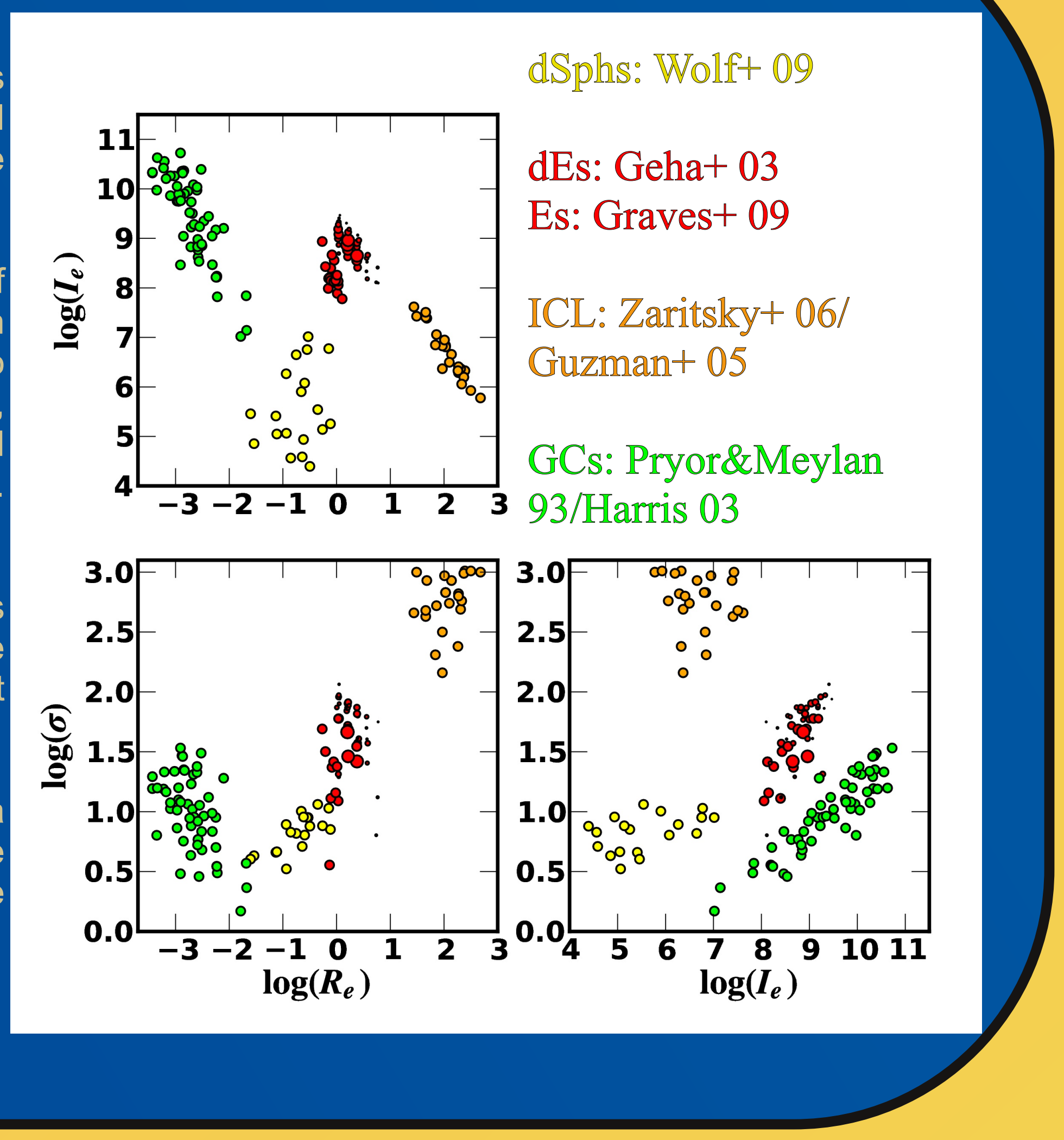
Due to the large dynamic range investigated, a variety of different data sets are necessary. All photometric data is in, or corrected to, V-band, and plotted in Fundamental plane parameter space of surface brightness, effective radius, and velocity dispersion.

Milky Way dwarf spheroidal data is from the compilation of Wolf et al. 2009, based primarily on Mateo 1998 and Simon & Geha 2007. These include ultra-faint satellites down to $<10^3$ $L_{sun,}$ a regime poorly understood with scaling relations, but valuable due to the karge numbers likely to be detected in upcoming surveys (Tollerud et al. 2008, Bullock et al. 2009).

Elliptical data are from Geha et al. 2003 (dEs), and Graves et al. 2009. The Graves data is binned data of a large number of SDSS galaxies, and point size on the plot indicates the number of galaxies in each bin.

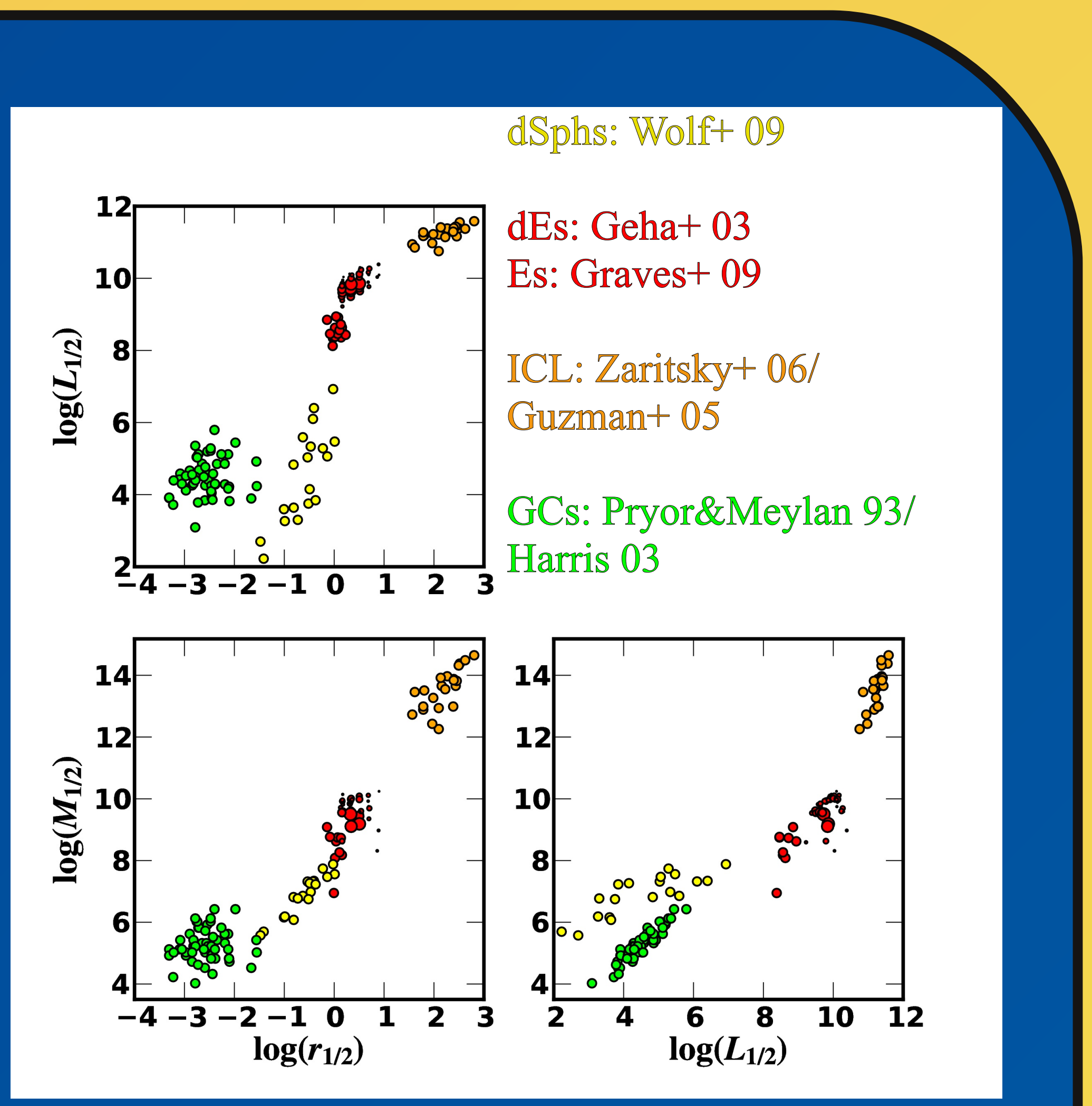
Clusters are included using the Intra-Cluster Light (ICL) data set of Zaritsky et al. 2006. The ICL is used rather than the cluster galaxy light, as it is a more direct comparison to the integrated galaxy light for the non-cluster samples.

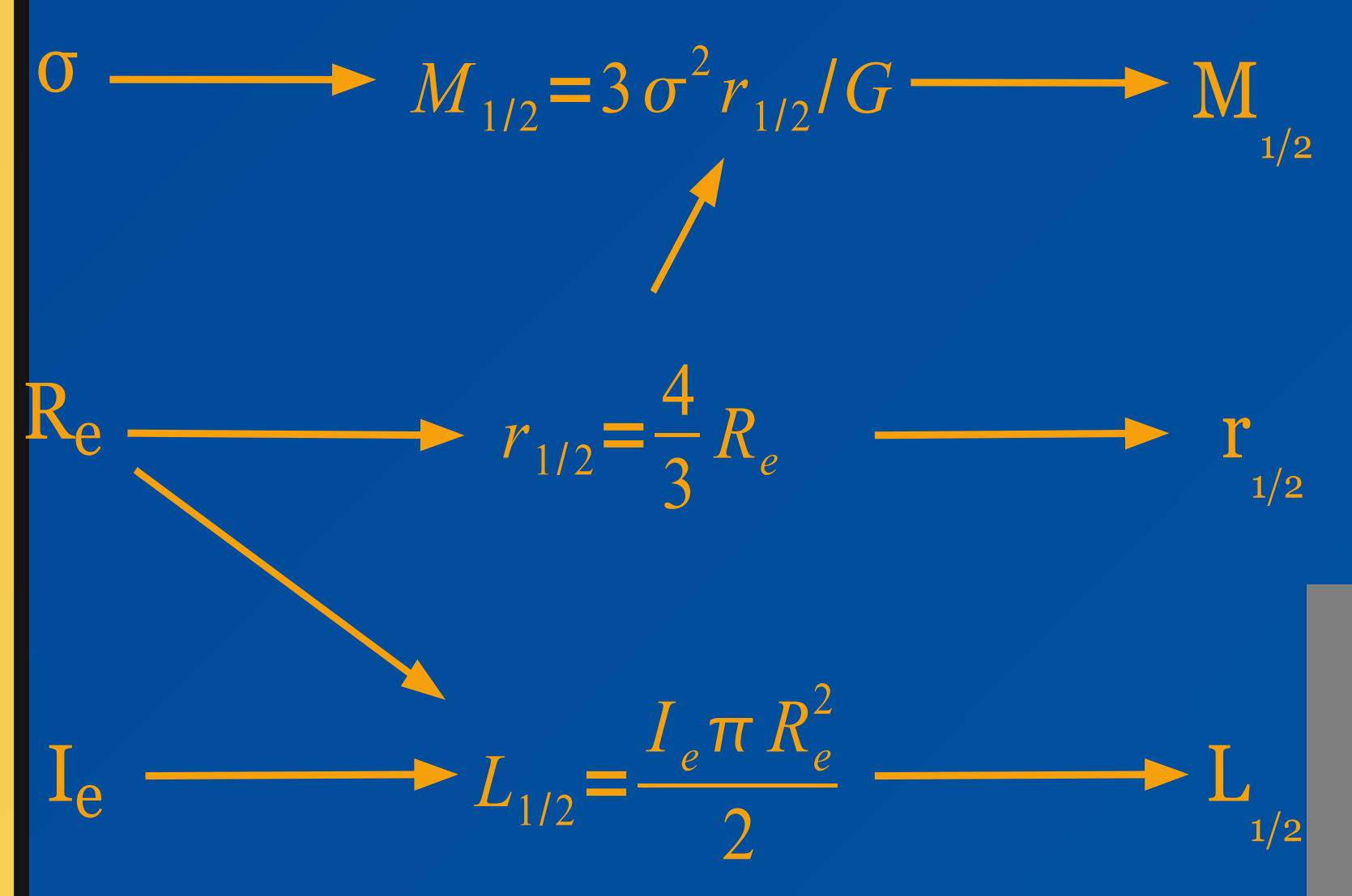
For comparison, a Globular Cluster (GC) sample is also included using kinematics from Pryor & Meylan 1993 and photometric properties from Harris 2003.



MLR Space

As show above, in fundamental plane space, these data sets are difficult to interpret - the dSph, dE, and ICL data sets lift away from the fundamental plane (e.g. Hyde & Bernardi 2009), but in a complex fashion. Hence, we introduce the "MLR space" to act as an intermediate perameter space between observables and theory/simulations, using the transforms below. The primary change is the use of $M_{1/2}$, which, as described in Wolf et al. 2009, is independent of anisotropy and hence unambiguously represents the dynamical radius within the 3D half-light radius $r_{1/2}$.



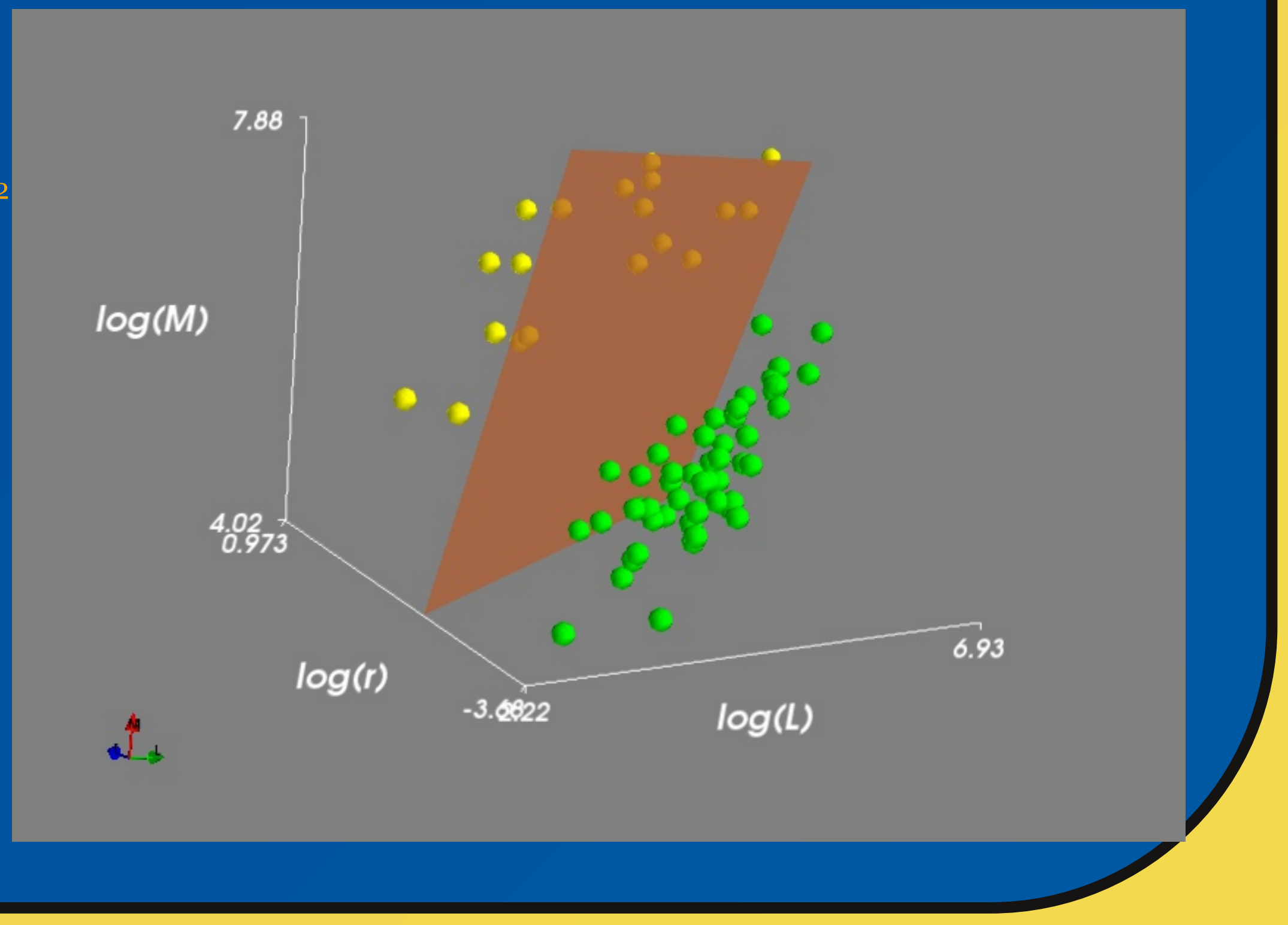


$$\sigma \longrightarrow M_{1/2}=3\sigma^2 r_{1/2}/G \longrightarrow \mathrm{M}_{1/2}$$

$$\mathrm{R_e} \longrightarrow r_{1/2}=\frac{4}{3}R_e \longrightarrow \mathrm{r}_{1/2}$$

$$\mathrm{I_e} \longrightarrow L_{1/2}=\frac{I_e \pi R_e^2}{2} \longrightarrow \mathrm{L}_{1/2}$$

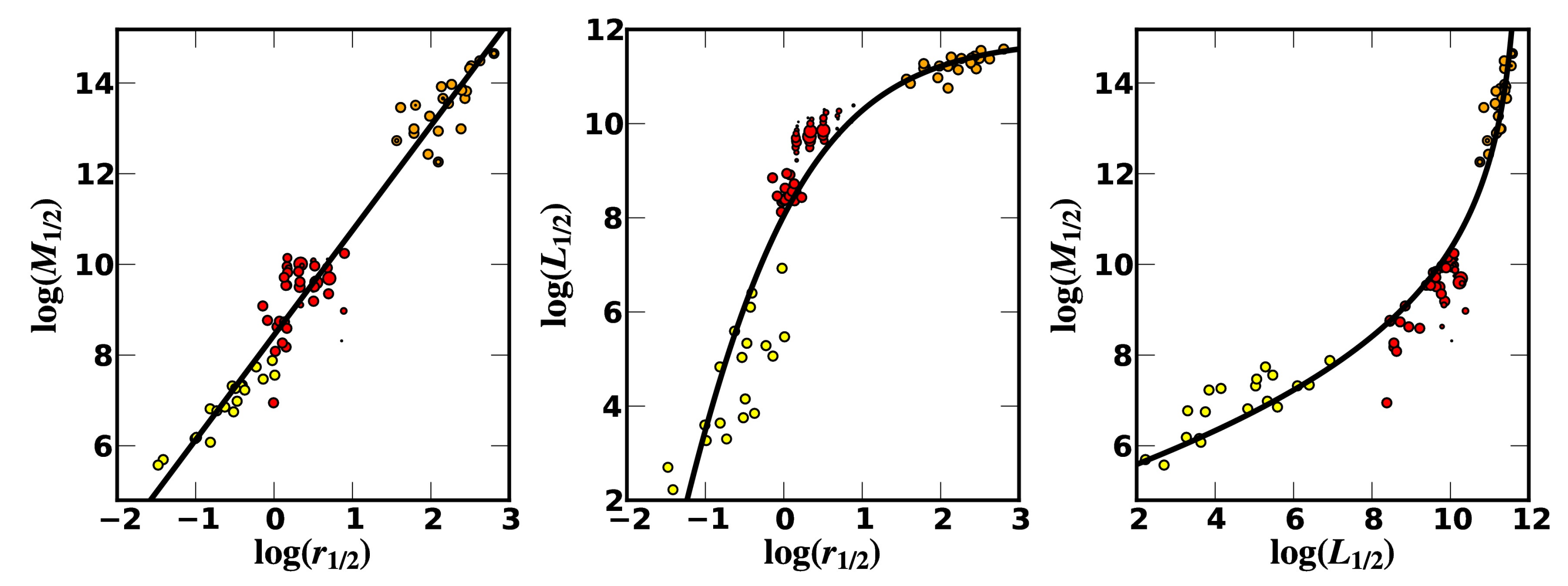
In this space, the data sets clearly seperate into a sequence of galaxies (the "Fundamental Curve"), and a seperate locus for Globular Clusters. This allows us to define a seperation plane (figure on right) in this space that cleanly seperates GCs from dSphs, but this plane requires the full 3D parameter space - typical 2D projections such as Luminosity/ Effective Radius space will incorrectly classify some objects, particularly in the presence of large photometric errors.



References

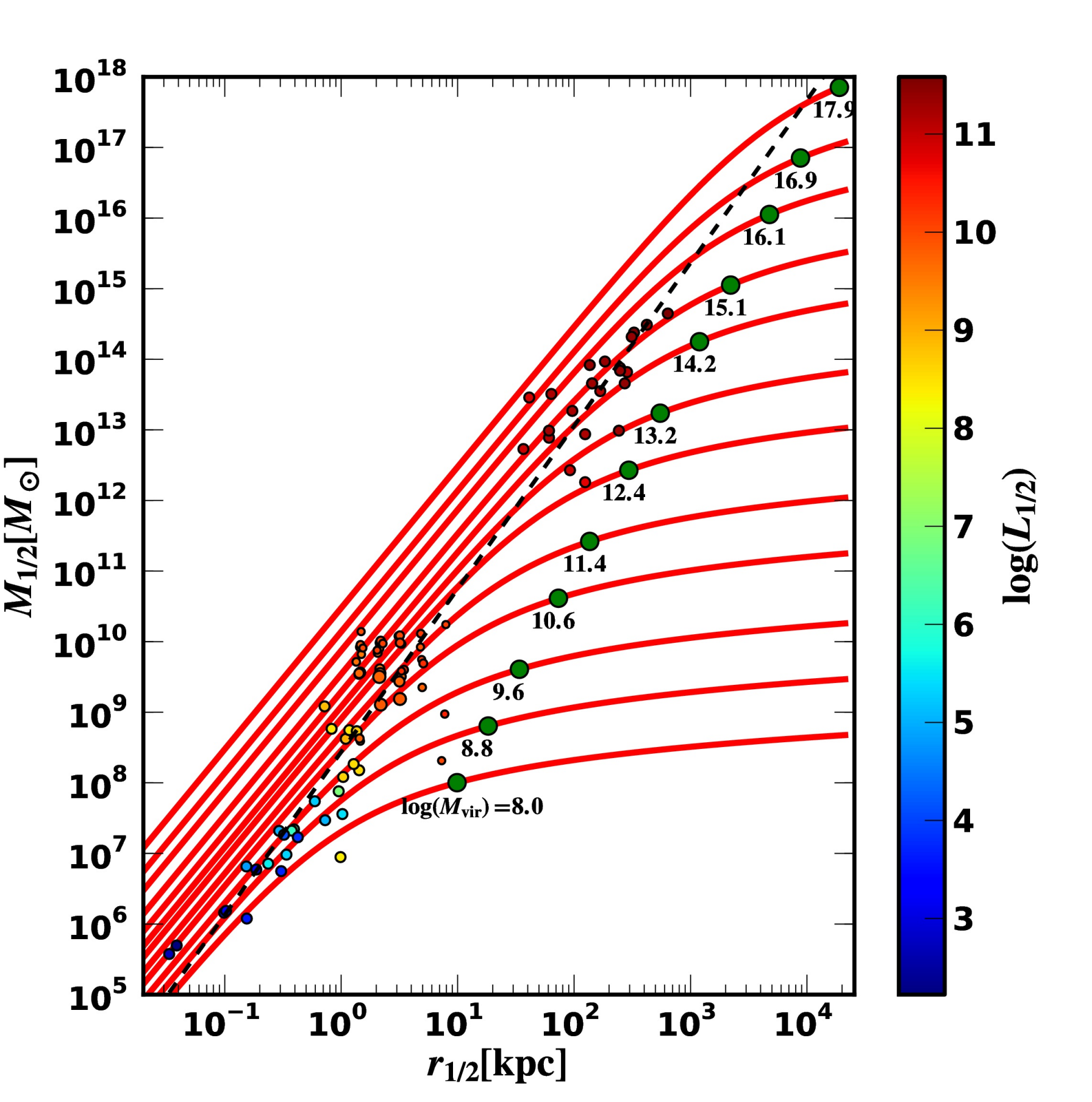
- Bullock et al. 2001, MNRAS, 321,559
- Bullock et al. 2009, arXiv 0912.1873
- Conroy & Wechsler 2009, ApJ, 696, 620
- Geha et al. 2003, ApJ, 126, 1794
- Graves et al. 2009, ApJ, 698, 1590
- Guhathakurta 2009, AAS 213, 317.03
- Harris 2003, ASPC, 50, 35
- Hyde & Bernardi 2009, MNRAS, 394, 1978
- Maccio 2008 et al., MNRAS, 391,1940
- Moster et al. 2009, arXiv 0903.4682
- Navarro, Frenk, & White 1997, ApJ, 490, 493
- Pryor, C. and Meylan, G. 1993, ASPC, 50, 357
- Wolf et al. 2009, arXiv:0908.2995
- Zaritsky et al. 2006, ApJ, 638, 725

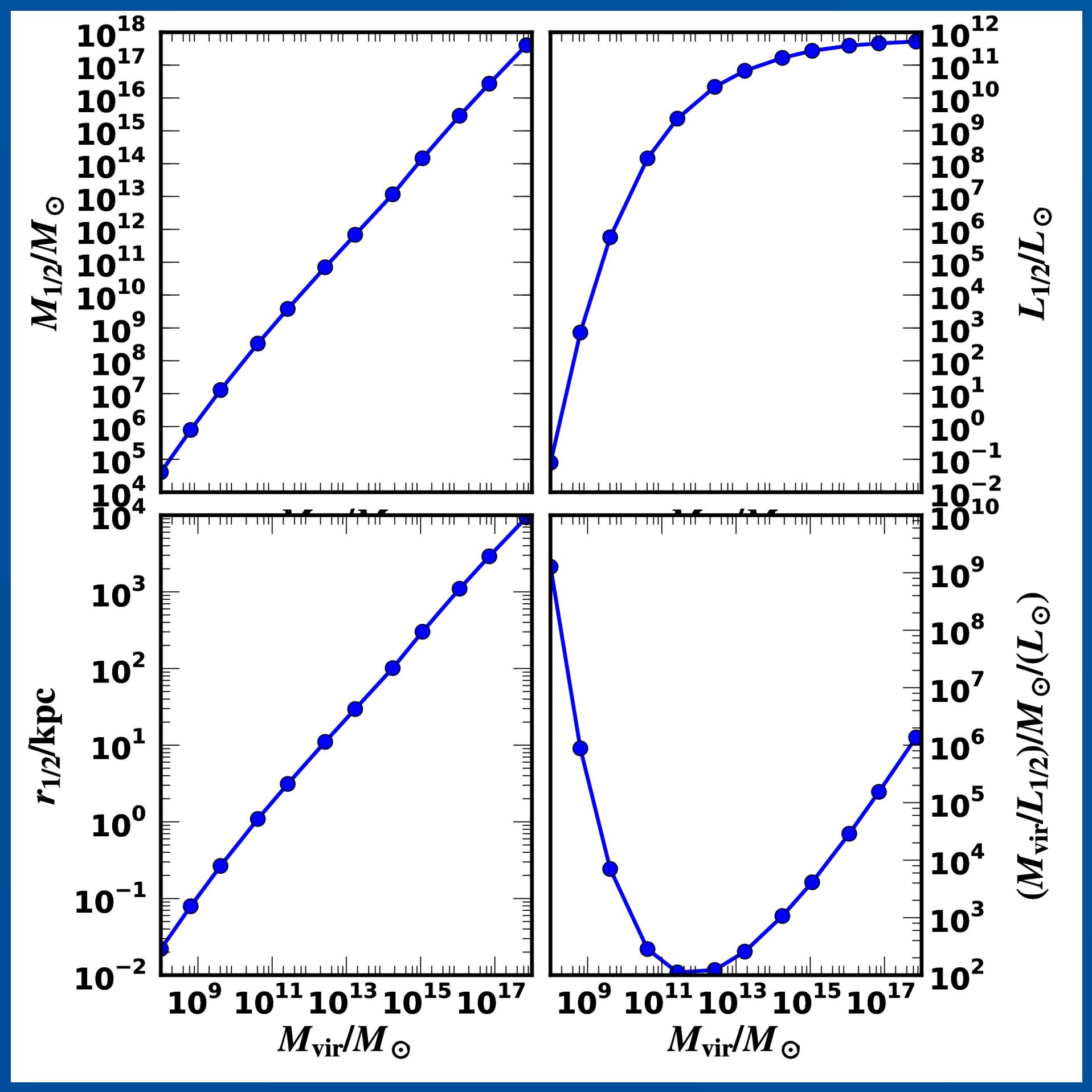
Fundamental Curve



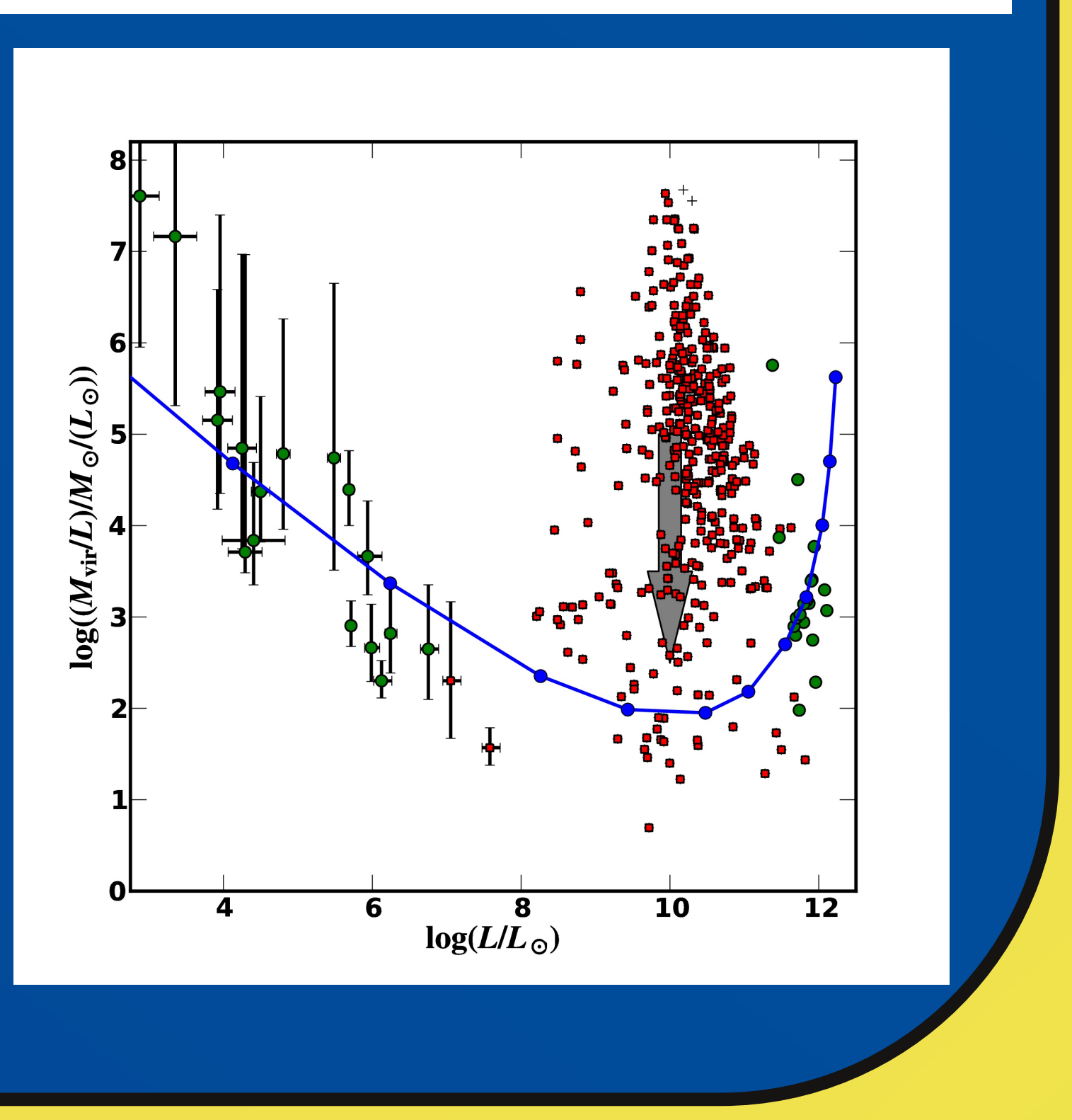
In MLR space, the galaxies and ICL all fall along a one-dimensional sequence - the "Fundamental Curve." This sequence is well parameterized by a power law in $M_{1/2}$ vs. $r_{1/2}$ and a two-power relation in $L_{1/2}$ vs. $r_{1/2}$. This curve is valid over ~10 orders of magnitude in luminosity, from the faintest dSph galaxies to rich clusters. As described below, it can further be used to connect the luminous properties of galaxies to their dark matter halos.

Profile Matching





Assuming that the dark matter halos hosting galaxies follow an NFW (1997) form with a Bullock 2001/Maccio 2008 c-M_{vir} relation, the MLR space can map points on the Fundamental Curve onto the host dark matter halos. Because M_{vir} of the halo uniquely defines the mass profile, and $M_{1/2}$ traces the mass within $r_{1/2}$, a point in the $r_{1/2}/M_{1/2}$ portion of the fundamental curve can be mapped to a specific M_{vir} of the galaxy halo (upper-left figure). Thus, we can plot the luminous properties of each point on the fundamental curve against the appropriate M_{vir} , providing an averaged relation between the scaling relations of pressure-supported galaxies and their dark matter halos (upper-right figure). This reproduces the U-shaped plot in M/L vs. M_{vir} expected from abundance matching, with the peak in star formation at ~ M_* .



As the figure to the right shows, however, this technique is most effective for the ICL and dSphs, which are dark matter-dominated, meaning $M_{1/2}$ traces dark matter mass. For the other galaxies, baryonic contamination means the inferred M_{vir} is too high. For the Graves 2009 data set, we subtract the stellar mass inferred from SDSS photometry and spectra in the fundamental curve fits and the above plots, but the additional step likely admits further scatter and systematic errors. Further, while the faintest dSphs may be consistent with the onset of a scale in galay formation seperate from L_*, the errors are currently too large to make a definite conclusion.

Conclusions

Tying the scaling relations of ultra-faint dwarf spheroidals to larger galaxies using the MLR space provides a number of interesting results:

- Galaxies seperate from GCs in the MLR Space, and follow a definite one-dimensional sequence instead of a two-dimensional plane.
- This sequence can be used to connect the globally-averaged properties of galaxies to the globally-averaged properties of their dark matter halos over 10 orders of magnitude in Luminosity.
- These results are consistent with and complementary to abundance matching (e.g. Conroy & Wechsler 2009, Moster et al. 2009), providing better results in the regime where abundance matching is ineffective.
- The faintest galaxies show hints of a change in scaling relations, but not enough ultra-faints are yet available with small enough error bars to determine this (or test the assumption of monotonicity in the M_{vir} - L relation).

The possibility of finding new dSphs in upcoming surveys like PanSTARRS and LSST (Tollerud et al. 2009), or characterization of the faintest companions of M31 (e.g. Guhathakurta et al. 2009) will likely increase the size of this data set, providing an excellent opportunity for future application of this technique to better understand the faint end of galaxy formation.