Hundreds of Milky Way Satellites and a Fundamental Curve connecting Dark Matter Halos to Galaxies

CENTER FOR COSMOLOGY
UNIVERSITY OF CALIFORNIA, IRVINE

Erik J. Tollerud[1], James S. Bullock[1], Elizabeth J. Barton[1], Joe Wolf[1], Genevieve J. Graves[2], Louis E. Strigari[1,3], Beth Willman[4], and Kyle R. Stewart[1]

[1]University of California, Irvine [2]University of California, Berkeley [3]Stanford/KIPAC [4]Haverford College

We consider bias corrections to the numerous newly discovered dwarf spheroidal galaxies (dSph) bound to the Milky Way and conclude that there may be hundreds yet to be discovered. Future searches for these galaxies promise to provide important constraints on the low-luminosity threshold of galaxy formation. We go on to consider how these dwarfs fit on galactic scaling relations and introduce an alternative to fundamental plane space that relies on the half-light mass in place of velocity dispersion. This space clearly reveals a fundamental curve (or "tube") upon which all dispersion-supported galaxies lie, including the Galactic satellites, dEs, giant ellipticals, and intra-cluster light distributions, and provides a clean seperation in observables between globular clusters and dSphs. This fundamental tube 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.

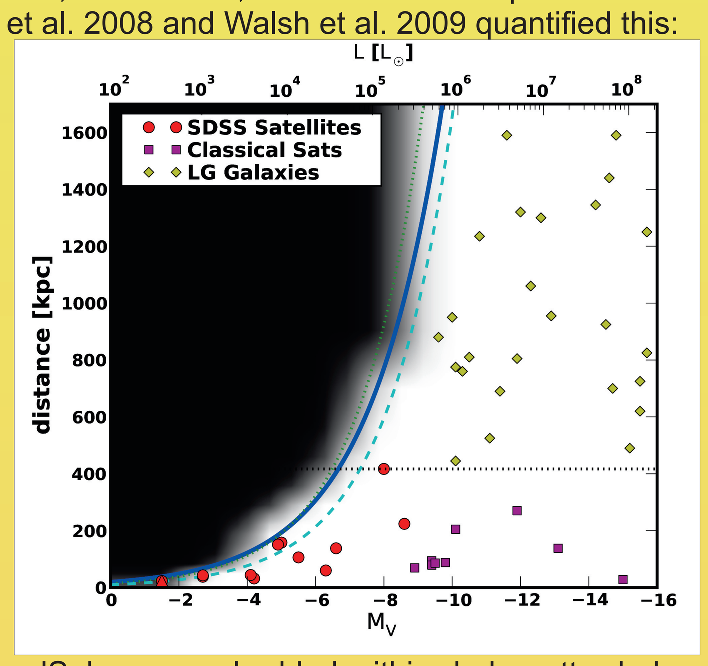
Hundreds of Satellites

The Missing Satellites Problem has concerned LCDM for some time (Klypin 99, Moore 99) - there exist too few satellite galaxies bound to large halos to account for all of the subhalos predicted by simulations. The recent doubling of the number of known Milky Way satellite galaxies due to SDSS suggests an explanation: detection bias.

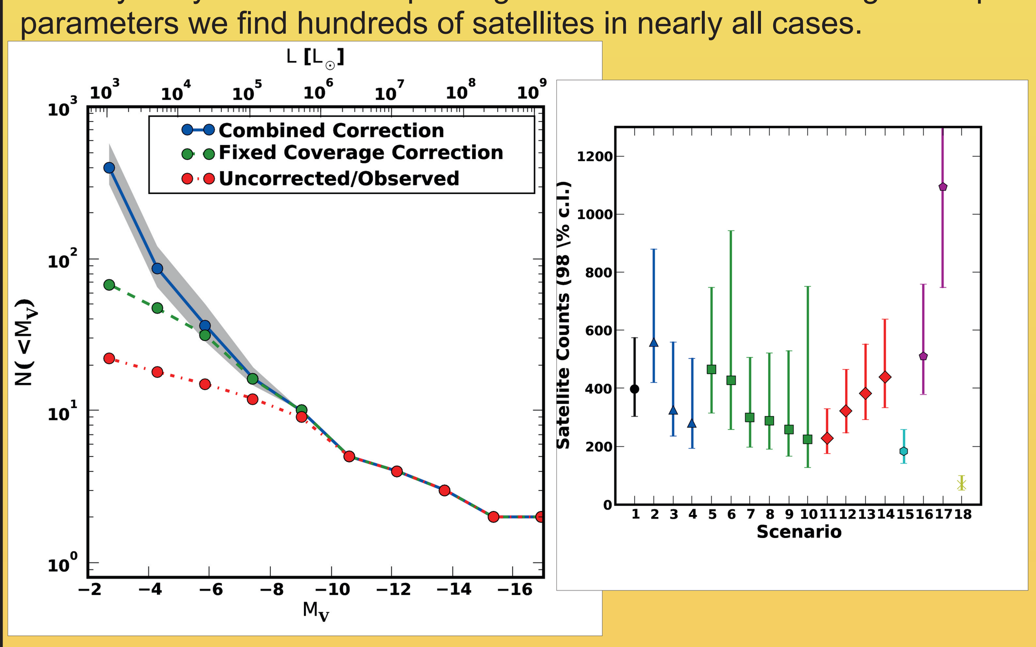
Luminosity Bias

(Tollerud et al. 08, ApJ, 688, 277)

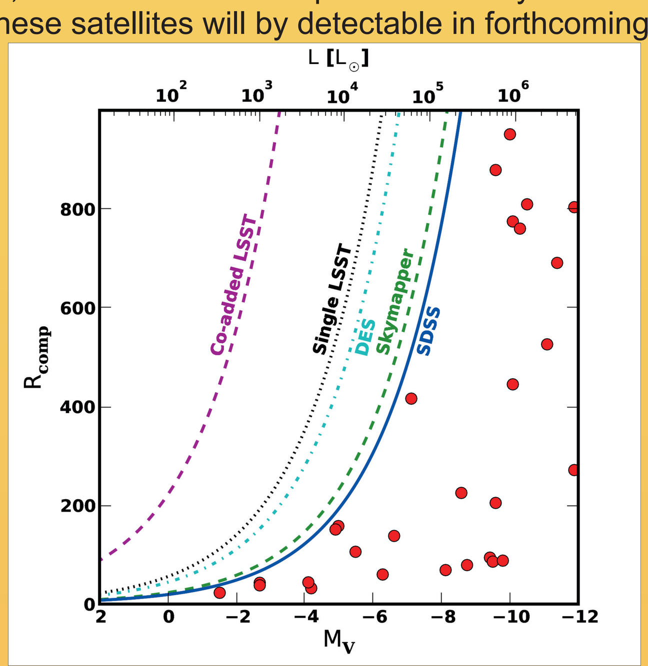
Ultra-faint dSphs ($-2 > M_V > -9$) are detected by resolved stars in the SDSS. Thus, the fainter, more distant dSphs are harder to detect. Koposov et al. 2008 and Walsh et al. 2009 quantified this:



Assuming dSphs are embedded within dark matter halos, we can use the spatial distributions of subhalos in an n-body simulation to correct the observed dSph distribution, producing a correct luminosity function of Milky Way satellites. Repeating the correction for a range of input parameters we find hundreds of satellites in nearly all cases.



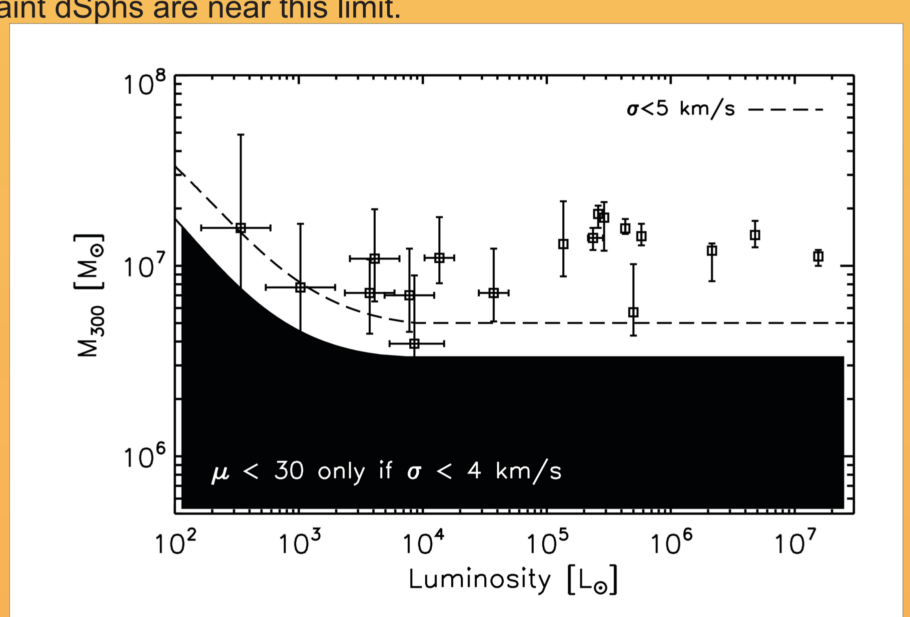
If this is correct, we can use this complete luminosity function to determine how many of these satellites will by detectable in forthcoming surveys:



"Stealth" Galaxies

(Bullock et al. 2009 in prep)

Walsh 09 and Koposov 08 both find sharp falloffs in detection efficiency for surface brightness muv > 30. If we assume NFW dark matter halos, we can compute the halo mass that would go undetected due to low surface brightness and find that t most ultra-faint dSphs are near this limit.



Conclusions

- Correcting for sky coverage and luminosity bias, we find there are likely hundreds of ultra-faint Milky Way satellites to be discovered in near-term surveys.
- There are likely even more slightly lower-mass satellites that go undetected due to low surface brightness.
- These corrections imply the presence of many more subhalos with properties consistent with simulations, ameliorating the Missing Satellite Problem.

Fundamental Curve

(Tollerud et al. 09, in prep)

The existence of a statistically large population of satellites implied by these corrections prompts an examination of what we can learn about the averaged properties of these galaxies and their dark matter halos. These satellites are the faintest known galaxies and provide a unique window into processes that can be studied nowhere else.

Data

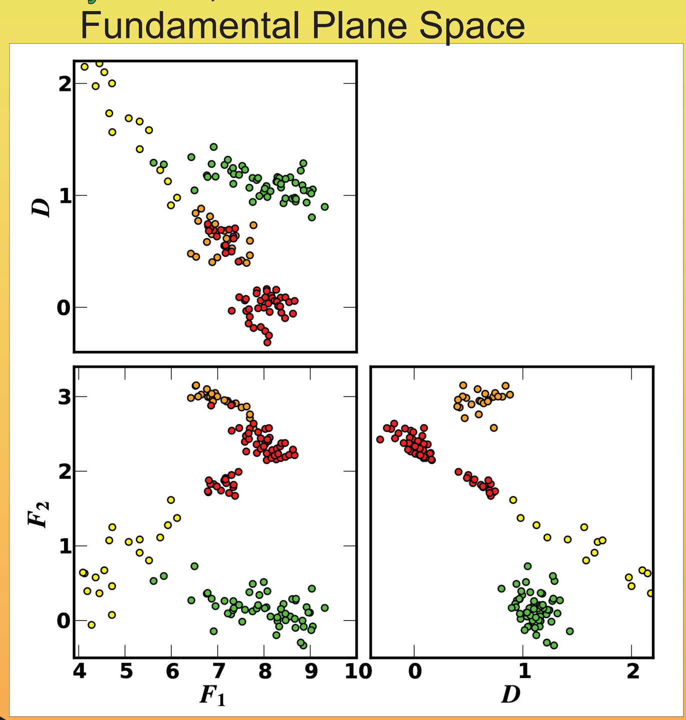
Globular Clusters: Pryor & Meylan 93, Harris 03

dSph: Multiple sources, compiled in Wolf 09

Ellipticals: Graves 09, Geha 03 (dE)

Clusters (Intra-cluster Light): Zaritsky 06

Fundamental Plane Space



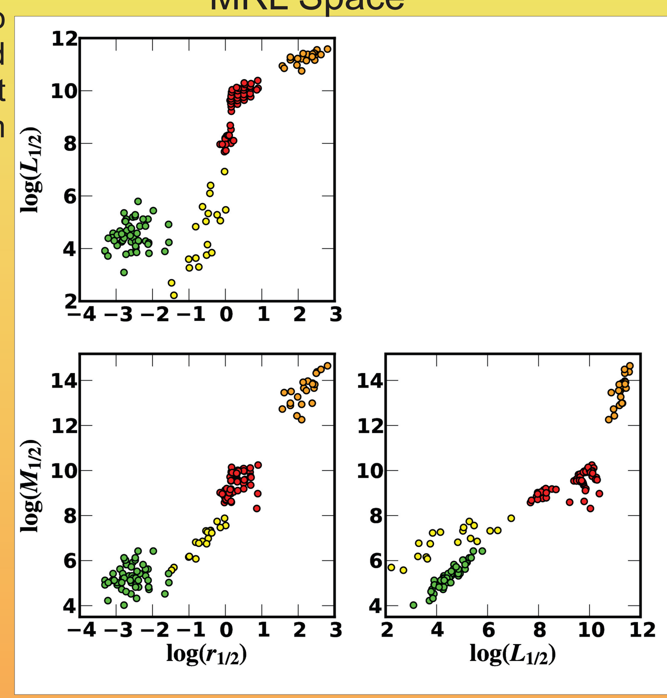
Wolf 09 find that the mass estimator $M_{1/2}$ is insensitive to anisotropy for light profiles like that of all systems considered here. Hence we use it along with the corresponding 3D half-light radius to define a new space of observables derived from fundamental plane parameters: MRL Space.

$$\sigma \rightarrow M_{1/2} = 3\sigma^2 r_{1/2}/G \rightarrow M_{1/2}$$

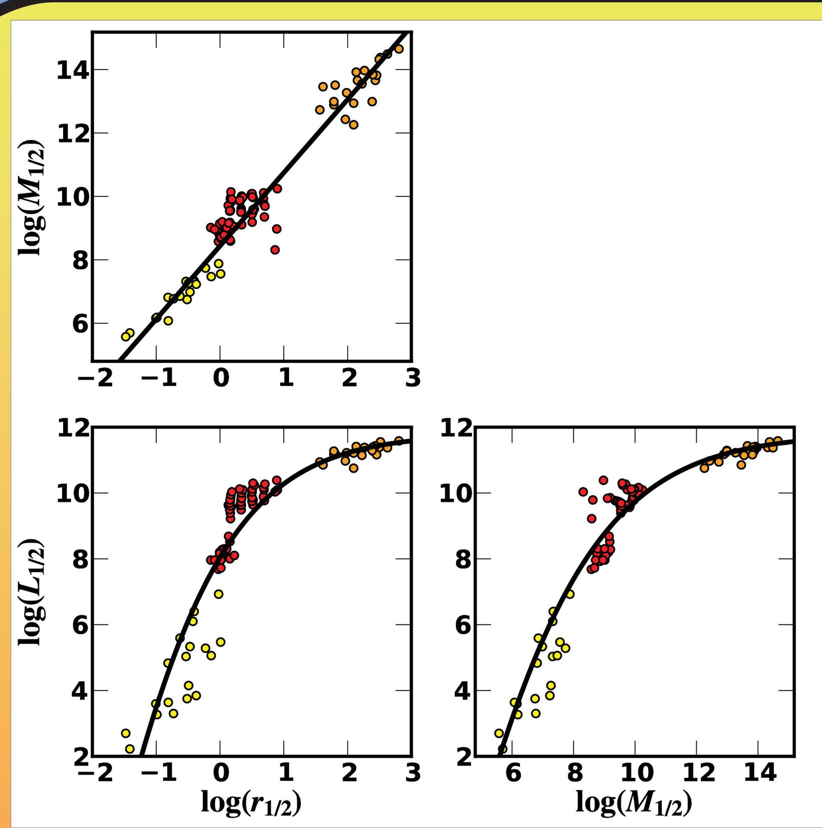
$$R_e \rightarrow r_{1/2} = \frac{4}{3} R_e \rightarrow r_{1/2}$$

$$I_e \rightarrow L_{1/2} = \frac{I_e \pi R_e^2}{2} \rightarrow L_{1/2}$$

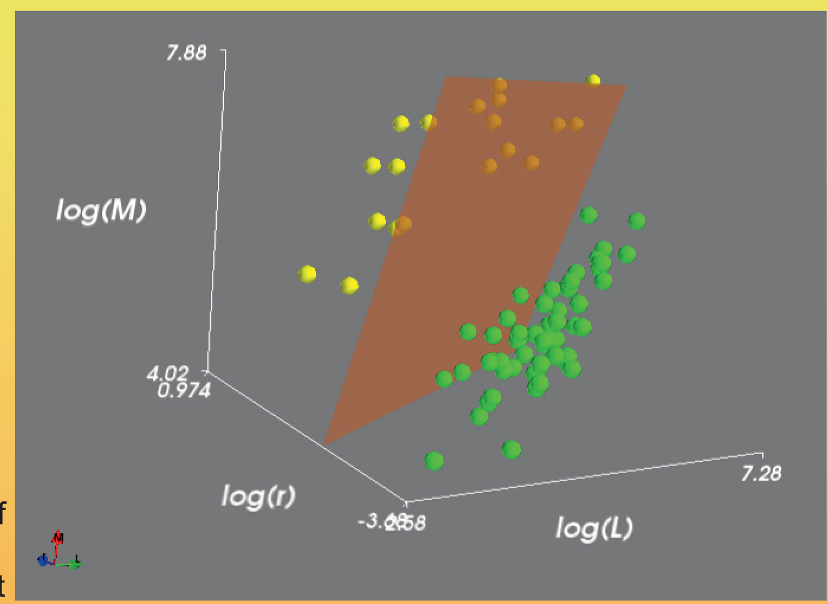
MRL Space



Fundamental Curve



In MRL Space the galaxy data set spans a sequence rather than a plane this "Fundamental Curve" spans 10 dex in Luminosity, 5 in physical size, and 10 in half-light mass.

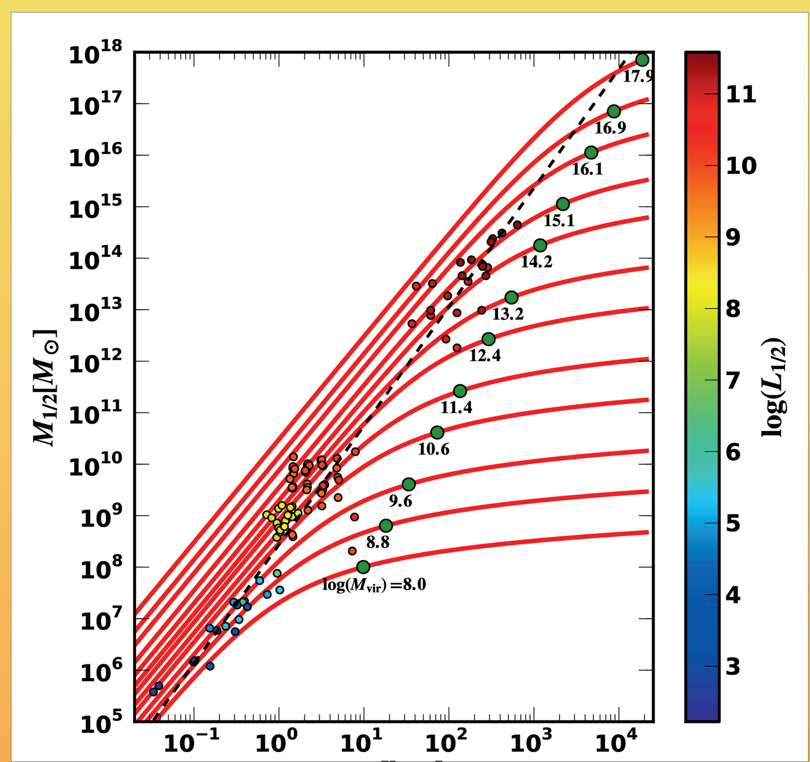


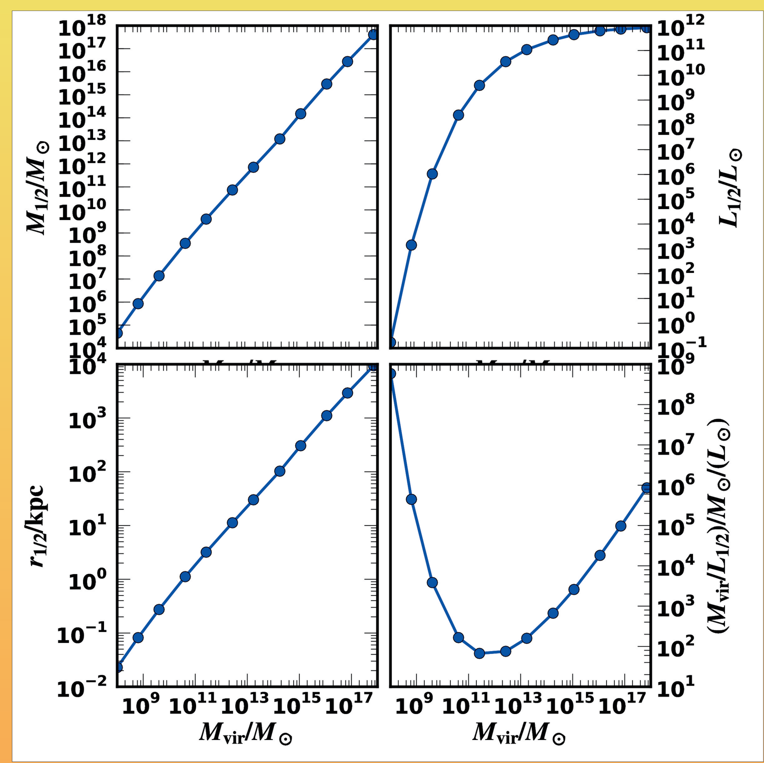
To examine dark matter properties, we must remove the baryonic contribution for those galaxies with nearly-stellar mass-to-light ratios. For SDSS ellipticals, we adopt the median binned values of stellar mass measurements in Gallazzi 05 as estimates of baryonic mass within the half-light radius. We subtract this from the measured half-light mass to provide a dark matter mass estimate. dSphs and intra-cluster light are already dark matter-dominated so this process is unecessary for these populations.

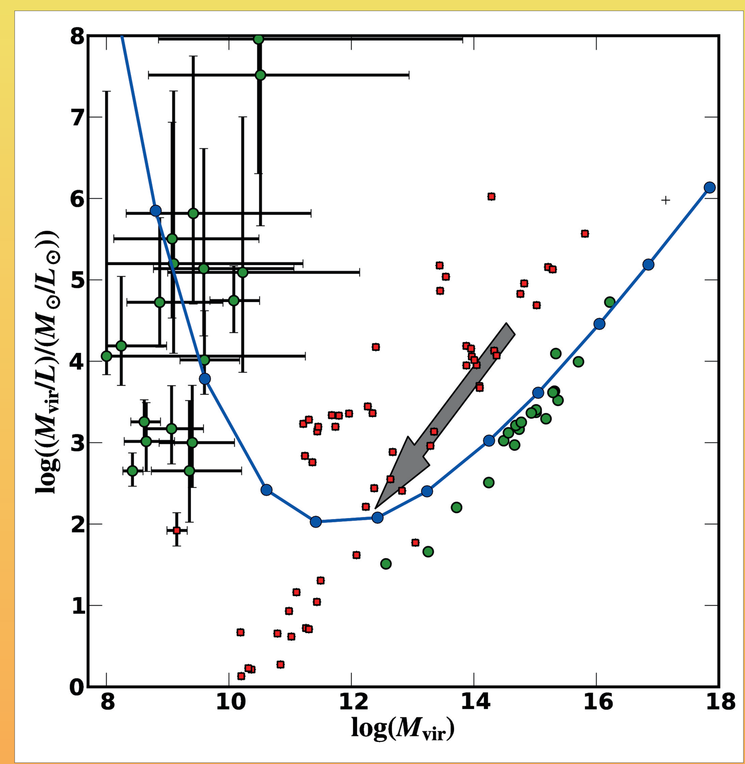
Globular Clusters are clearly seperate from this sequence, but not in most projections - all three dimensions are necessary to cleanly seperate dSphs and GCs

Connecting Galaxies to Halos

With an averaged curve relating mass within a particular radius to luminosity, we can determine where this relation meets the mass profile of an NFW Halo of a particular virial mass assuming a Bullock 01/Maccio 08 concentration-mass relation for z=0. This allows us to perform "profile matching" and determine the implied virial mass for the typical halo hosting a galaxy at a point along the fundamental curve. Thus we can connect the averaged baryonic properties of a galaxy to the properties of its host halo.







Conclusions

- The MLR Plane is a valuable tool for understanding galaxy scaling relations over the full range of galaxy properties.
- This method is consistent with and complements abundance matching, as it is most sensitive at the highest and lowest-mass ends, where abundance matching is unreliable due to low number counts.
- If hundreds of satellites are subsequently found as we predict, this method can be applied with tremendous statistical power to the low end and allows stringent constraints on the properties of the lowest-luminosity galaxies and their lowest-mass dark matter halos.

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