The Formation of Planes of Satellite Galaxies

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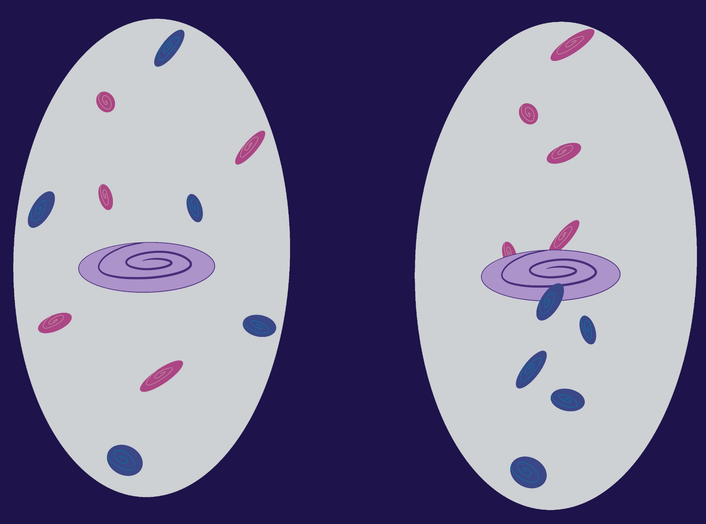
1. Observations Find 10 Planes of Satellites in Nearby Galaxies

Numerous observations in recent years have shown that the satellite galaxies orbiting our local galaxies tend to align their orbits in thin planes around the host galaxy [1,2,3,4,5,6]. The apparent ubiquity of well-defined planar structures are rare occurrences in cold dark matter simulations, existing in < 2% [7,8,9] of Milky Way type systems.

Host Galaxy	Number of Satellite Galaxies on Plane	Measure of Plane Thickness, Δ_{rms}
Milky Way	11	19.6 kpc
	40-50	~ 20 – 30 kpc
M 31*	15 -19	12.6 kpc
Cen A	28	N/A
M 81	19	61 kpc
M 83	6	20 kpc
M 101	11	46 kpc
NGC 253	7	31 kpc
NGC 2750	7	N/A

Adapted from Pawlowski 2021 [1]

2. Are Observations Compatible With Our ΛCDM Model of Cosmology?



What we expect to see! A uniform isotropic distribution of satellites around their host galaxy.

What we observe! A spatially elongated and kinematically coherent plane of satellites.

Central Host Galaxy

Satellite with Receding Velocity*

Satellite with Approaching Velocity*

Dark Matter Halo

*Relative to the line of sight

We observe:

(1) Spatially thin alignments of satellite galaxies in planes

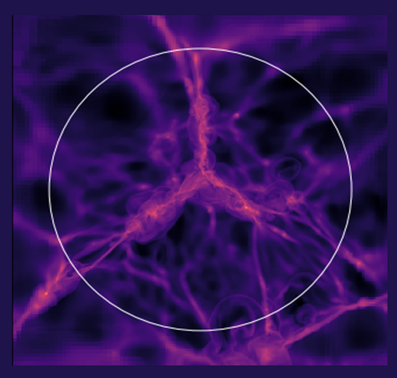
- Measured by the c/a ratio of their spatial distribution, the ratio of the minor to major axis

(2) Kinematically coherent (synchronized) orbital motions

- The fraction of satellites moving in the same orbital direction, $R_{cr,}$ is close to 1

Simulations find < 2% of such systems in a ΛCDM context raising the question of whether such alignments are compatible with our model of cosmology [10,11].

3. Need for High Resolution, Large Volume Simulation



New Horizon
Volume: 20 h^{-1} Mpc
Spatial Resolution: 34 pc
Stellar Mass Resolution: 10^4 M_*

If planes of satellites occur due to motions down cosmic filaments, then past attempts had neither the resolution nor the volume to recover them.

We use the cosmological zoom-in simulation, New Horizon [12]. New Horizon ensures that the large-scale environment - satellite interaction is properly described

- High Resolution ⟶ Satellites
- Large Volume ⟶ Large Scale Environment

4. We Find Planes in New Horizon!

We identify 13 Milky Way type systems in New horizon and measure the plane of best fit for each one.

Example of a plane identified in New Horizon for a host galaxy of mass 4.5×10^{10} $M_\odot$:

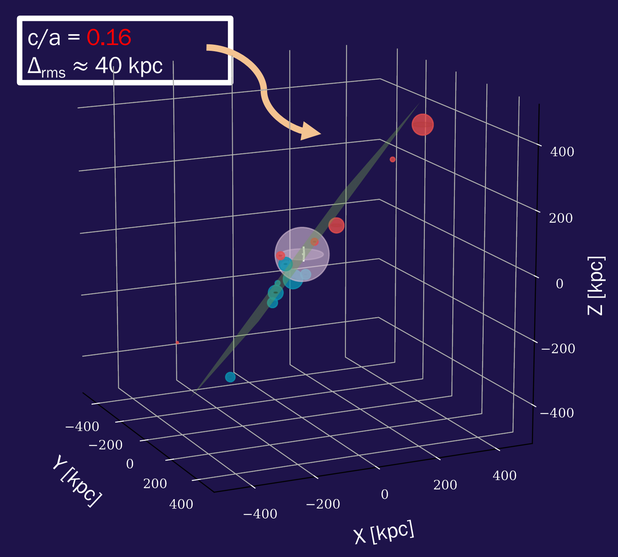
Host Galaxy

Satellite with Receding Velocity*

Satellite with Approaching Velocity*

Plane of Best Fit

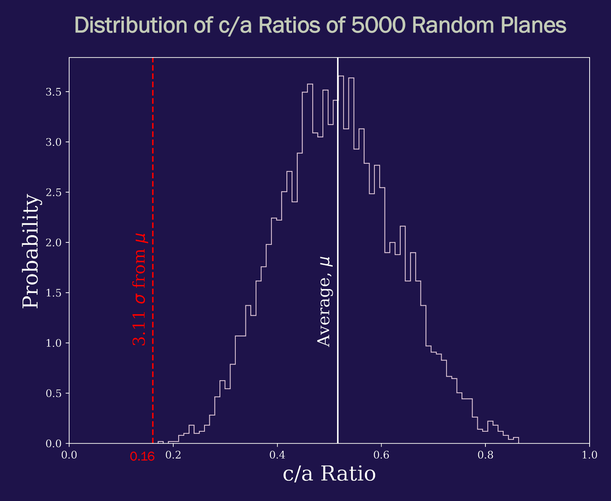
*Relative to the line of sight



5. Are These Planes Random Occurrences?

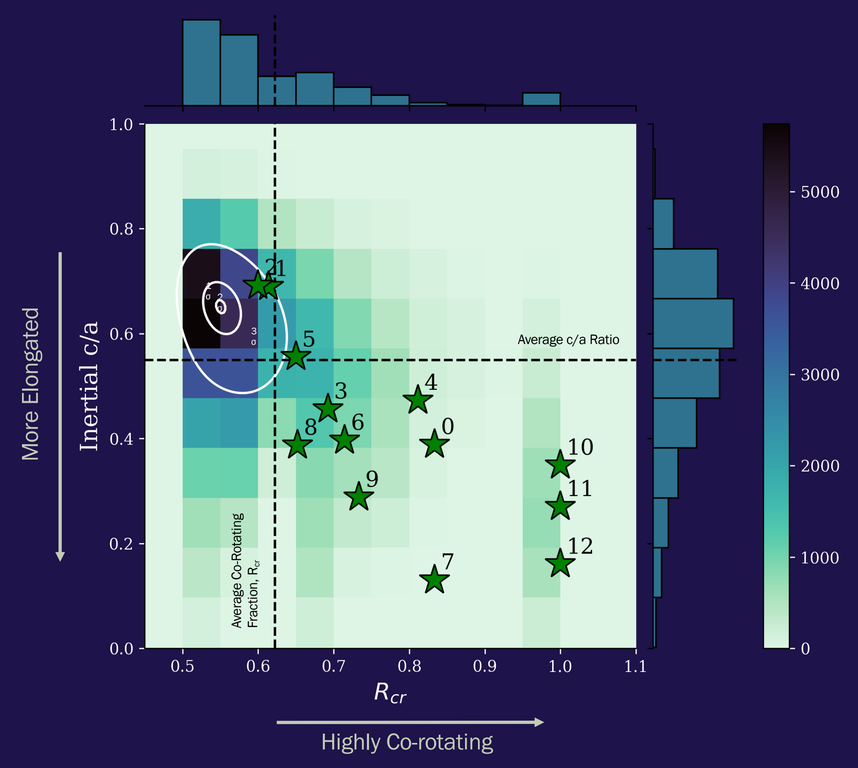
No!

The above plane's c/a ratio (0.16) is > 3σ away from the average of a randomly generated background of 5000 planes centered on the host galaxy.



6. More than 30% of Planes in New Horizon Are Comparable to Observations

Out of 13 candidate systems, we find planes in 5 of them, or ~ 38% of them.



Significant planes are those which are both

(1) spatially elongated and have a low c/a ratio and

(1) kinematically coherent and have a high corotating fraction, R_{cr}.

The 13 systems in our sample are shown at left as green stars over the composite background of 5000 synthetic planes generated for each system.

We find:

1. that the distribution of satellites is elongated in general when considering the shape of the underlying dark matter halo, skewing the distribution of c/a ratios to lower values, but we still find significant planes despite this.

2. that co-rotating planes of satellites do exist in simulations, strongly so in many systems, and do not pose a significant threat to *ΛCDM* as previously thought.

Will appear in Madhani et al. in prep!

References: [1] Lynden-Bell, D. 1976, MNRAS, 174, 695, [2] Kroupa, P., Theis, C., & Boily, C. M. 2005, A&A, 431,517, [3] Metz, M., Kroupa, P., & Jerjen, H. 2007, MNRAS, 374, 1125, [4] Conn, A. R., et al. 2013, ApJ, 766, 120, [5] Ibata, R. A., et al. 2013, Nature, 493, 62, [6] Müller, O., Pawlowski, M. S., Jerjen, H., & Lelli, F. 2018, Science, 359, 534, [7] Pawlowski et al. 2020, MNRAS 491,3042, [8] Müller et al. 2020, A&A, 645, 7 [9] Shao et al. 2018, MNRAS, 476, 1796, [10] Pawlowski, M. S. 2018, Modern Physics Letters A, 33, 1830004, [11] Pawlowski, M., 2021, Galaxies, 9(3), 66, [12] Dubois Y., et al., 2021, A&A, 651, A109

Contact me!