The Planes of Satellite Galaxies Problem:
A challenge invigorated by detailed modeling of observational uncertainties and biases

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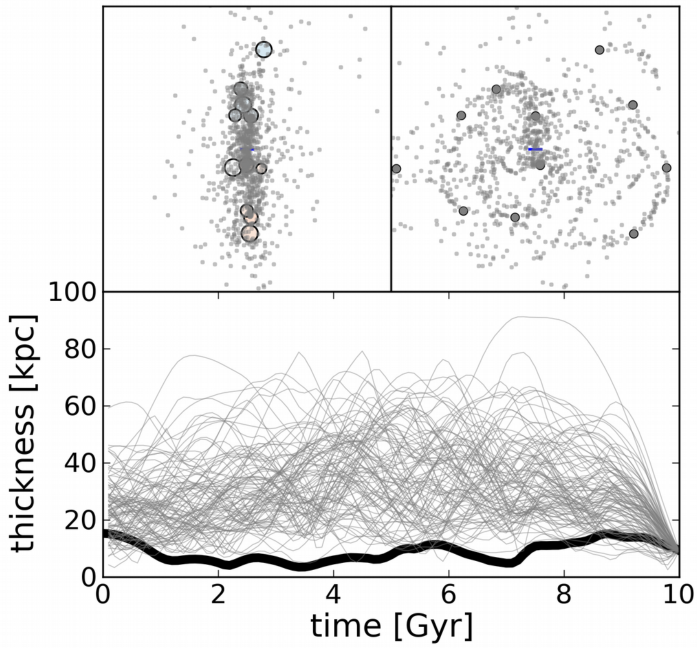
The phase-space distribution of satellite galaxies around their hosts provides unique opportunities to test our understanding of galaxy evolution. Some anisotropy in the distribution of satellite galaxy systems is expected because the satellites are accreted from the cosmic web and can fall in together in groups. However, the observed degree of phase-space correlation in the Local Group is surprising. The Milky Way (MW) is surrounded by a “Vast Polar Structure” (VPOS) of co-orbiting satellites (Pawlowski et al. 2012, 2013), and also the Andromeda Galaxy (M31) hosts a narrow plane of satellites with strongly correlated line-of-sight velocities indicative of co-rotation (Ibata et al. 2013). The existence of these satellite planes is now firmly established, and indications of similar structures beyond the Local Group emerge, such as a plane of satellite galaxies around Centaurus A that also displays correlated velocities (Müller et al. 2016, 2017).

However, the rarity of satellite planes in cosmological simulations – and thus the degree of tension they pose with ΛCDM – is still controversially debated. One reason why no consensus has been reached yet is that some studies lack in their modeling of survey footprints and other biases, or use only incomplete subsets of the available observational information (see e.g. Pawlowski et al. 2015, 2017 for more details).

The effects of observational uncertainties have also not yet been considered when comparing the observed satellite planes with cosmological simulations. Incorporating uncertainties in mock-observed simulations is essential for a statistically meaningful comparison, because observational errors act to decrease the measured correlation, especially if the underlying distribution is highly correlated. Modeling uncertainties thus substantially reduces the chance to find structures in simulations that are comparable to the observed ones. For example, a satellite plane as flattened as that around M31 is ~3.3 times less frequent in ΛCDM simulations if observational uncertainties are considered. Current estimates of the tension of satellite planes with ΛCDM are thus severely underestimated. Similarly, due to observational uncertainties the dynamical stability of the VPOS can not be accurately tested with current proper motions: a stable plane of satellite galaxies model, mock-observed with realistic proper motion errors, does not appear stable when integrated backwards (see Figure). This reveals that current proper motion uncertainties are unsuitable to conclude that the VPOS is dynamically unstable.

The existence of planes of satellite galaxies therefore continues to pose a serious challenge to our understanding of galaxy formation, evolution, and the assembly of satellite systems within the framework of ΛCDM. In contrast to other “small-scale problems”, baryonic physics does not offer an obvious solution: (1) The internal dynamics of satellite galaxies, most affected by baryonic feedback effects, does not directly influence their overall distribution around a host, and (2) so far there is no evidence that hydrodynamical cosmological simulations contain more correlated satellite systems. The planes of satellite galaxies problem is thus one of the most-pressing small-scale challenges for ΛCDM.



Caption: Thickness of a thin, stable plane of satellites integrated forward for 10 Gyr (thick black line), mock-observed with realistic proper motion errors to generate 100 realizations, which are then integrated backwards (thin grey lines). This shows that observational uncertainties can lead to falsely concluding a disk of satellites is dispersing, because a strong correlation is washed out by observational uncertainties.

References: Ibata, et al., 2013, Nature, 493, 62 – Müller, Jerjen, Pawlowski & Binggeli, 2016, A&A, 595, 119 – Müller, Pawlowski, Lelli & Jerjen (submitted) – Pawlowski, Pflamm-Altenburg, & Kroupa, 2012, MNRAS, 423, 1109 – Pawlowski, Famaey, Merritt & Kroupa, 2015, ApJ, 815, 19 – Pawlowski, et al., 2017, arXiv:1702.06143