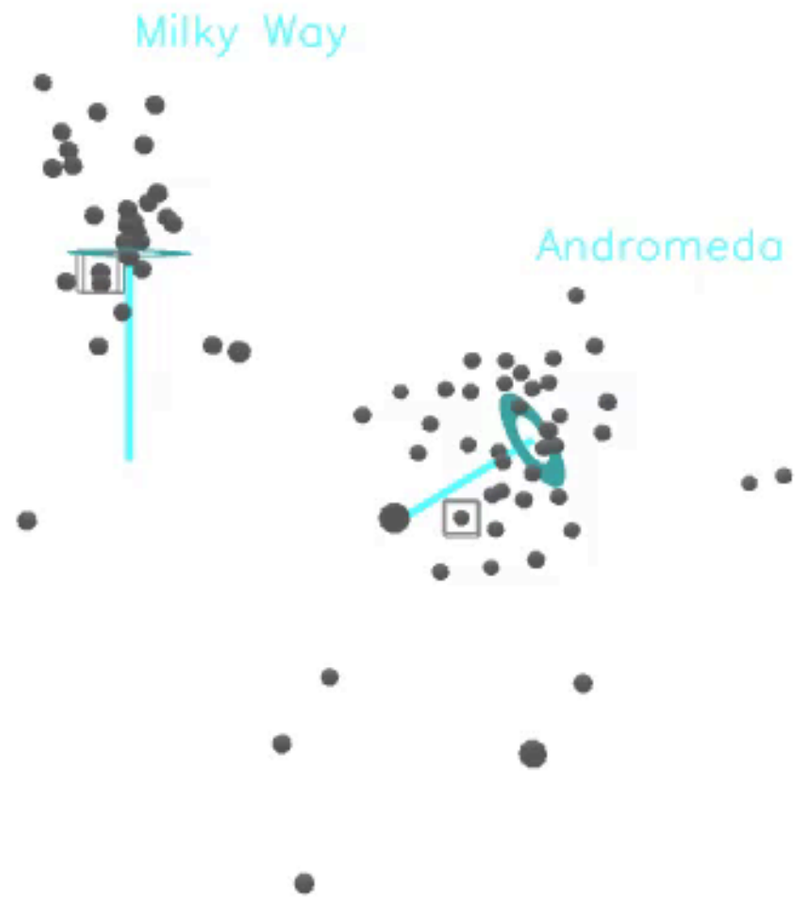
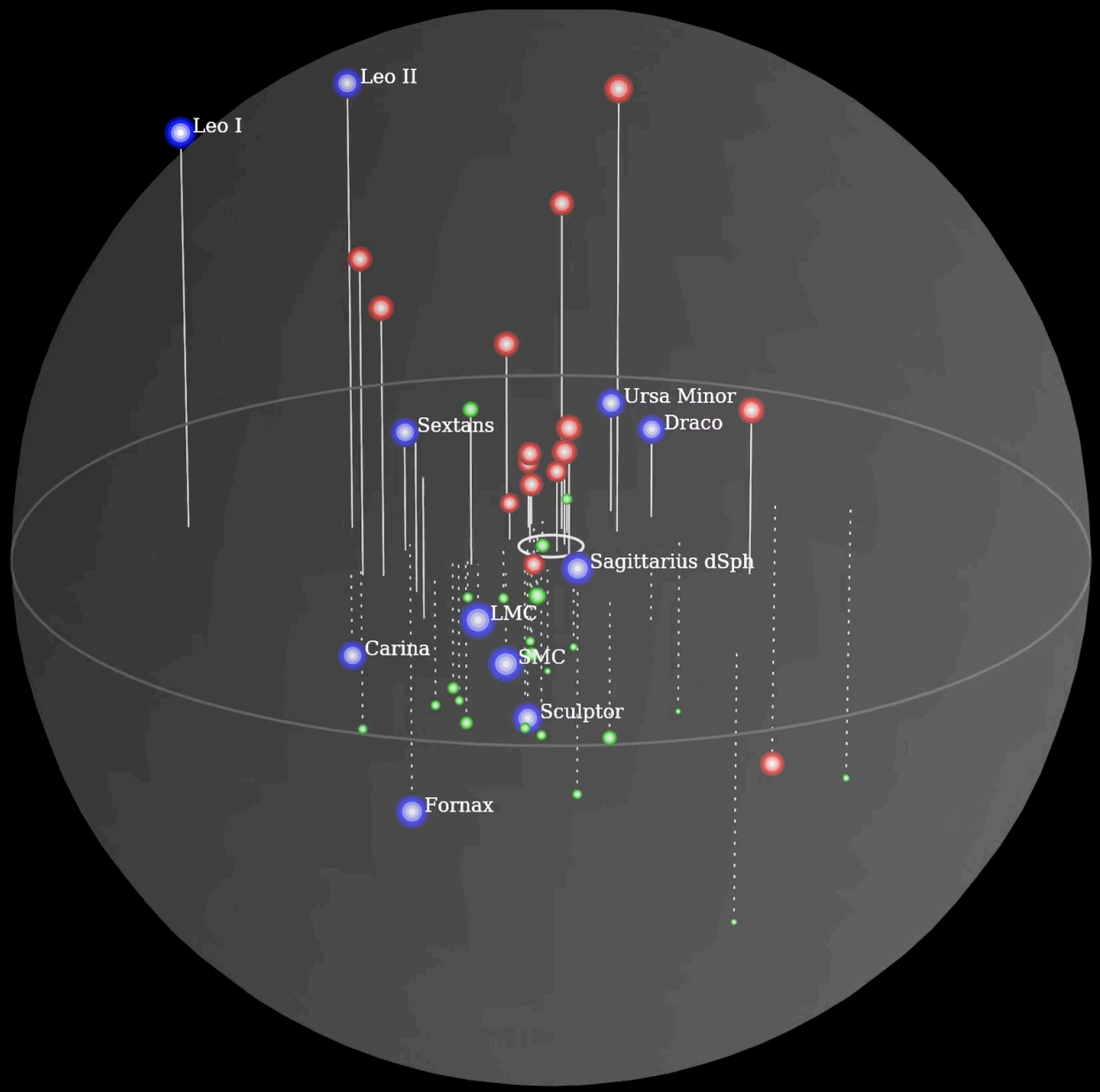
Phase-space structures in satellite galaxy systems
… and a serious problem for ΛCDM



Marcel S. Pawlowski

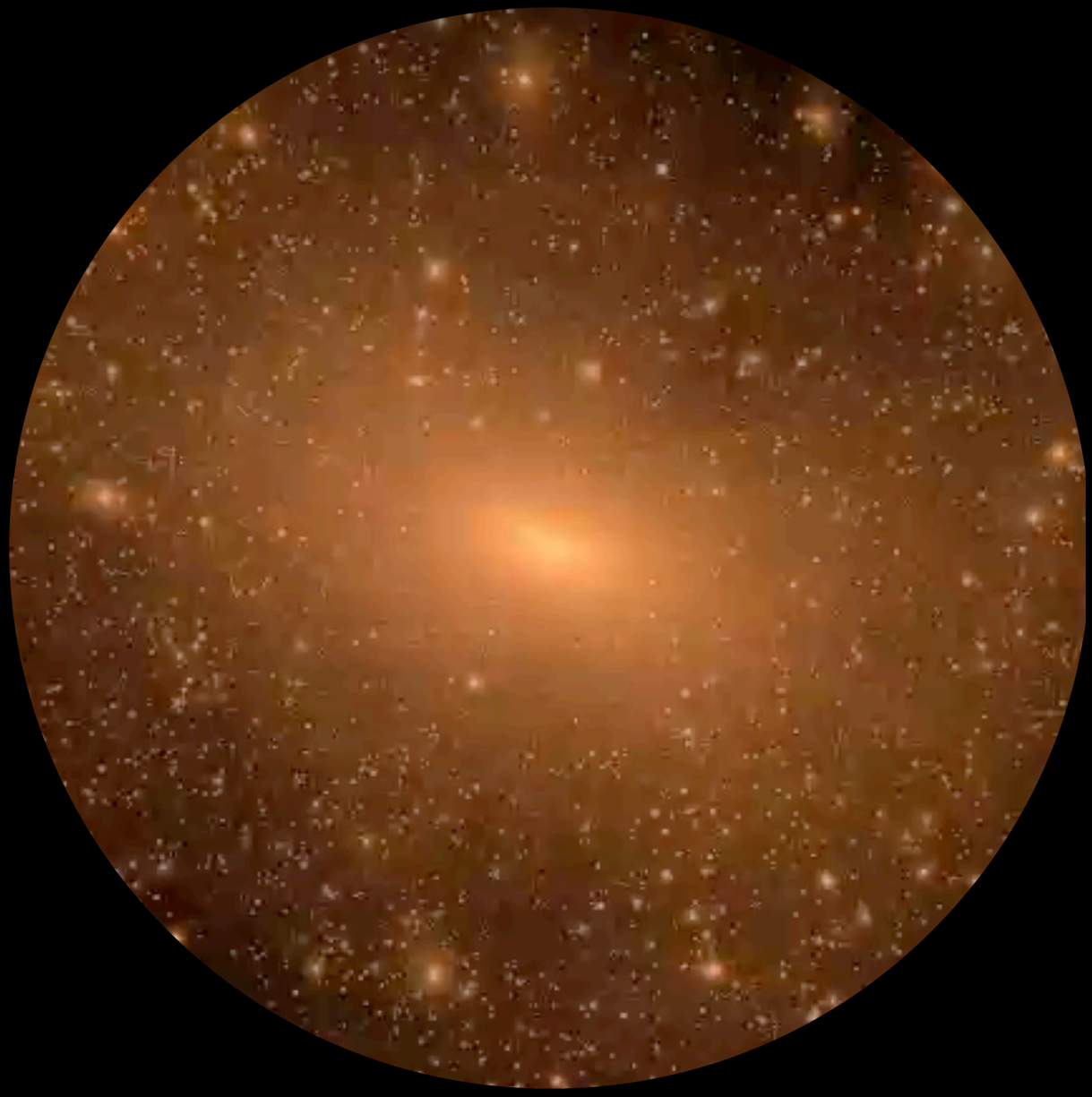
Hubble Fellow at
University of California Irvine
Email: marcel.pawlowski@uci.edu
Twitter: @8minutesold
Web: marcelpawlowski.com

Observed MW satellites



Year 2016

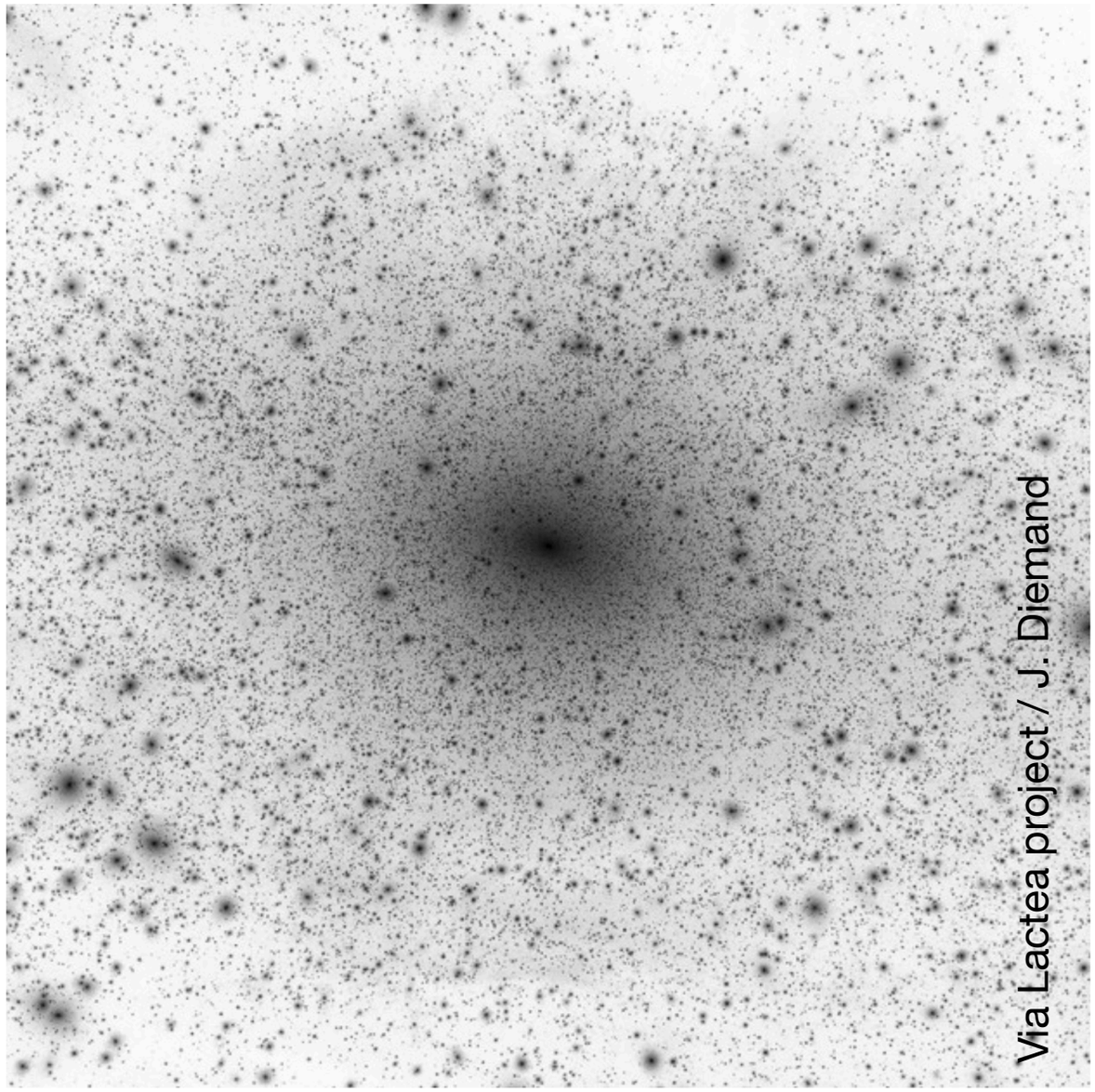
Simulated DM subhalos



Diemand et al. (2006)

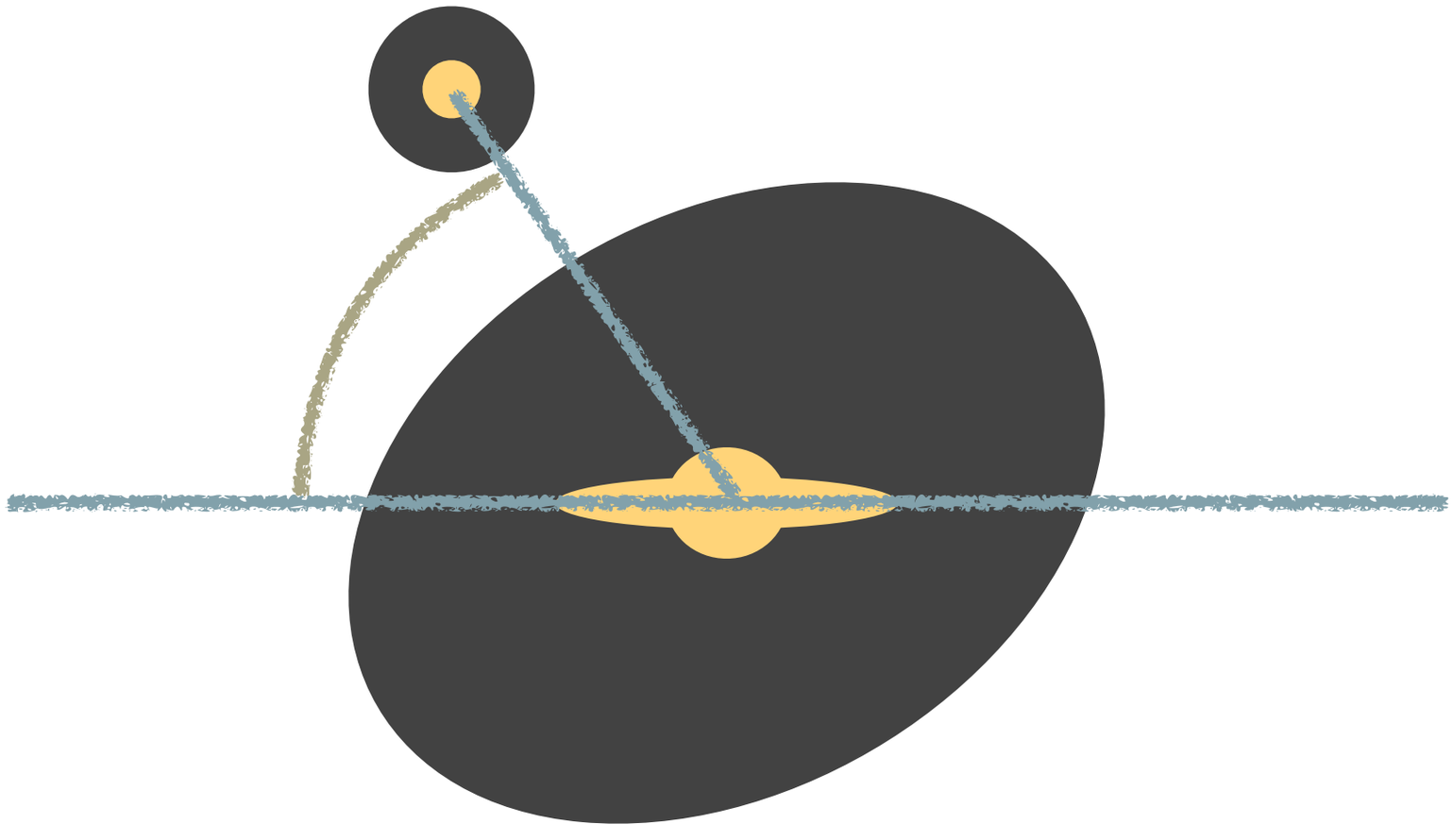
Is the phase-space distribution of satellite galaxies consistent with ΛCDM expectations?

- Know 40-50 satellite galaxies for Milky Way and Andromeda.
- Can we use the Local Group (and other nearby host galaxies) as a testbed for cosmological models?
- Overall positions and velocities of satellite sub-halos on scales of 100s of kpc should be robust against internal dynamics and feedback processes.
    - Radial distribution is affected.
      Ahmed+2017, Garrison-Kimmel+2017



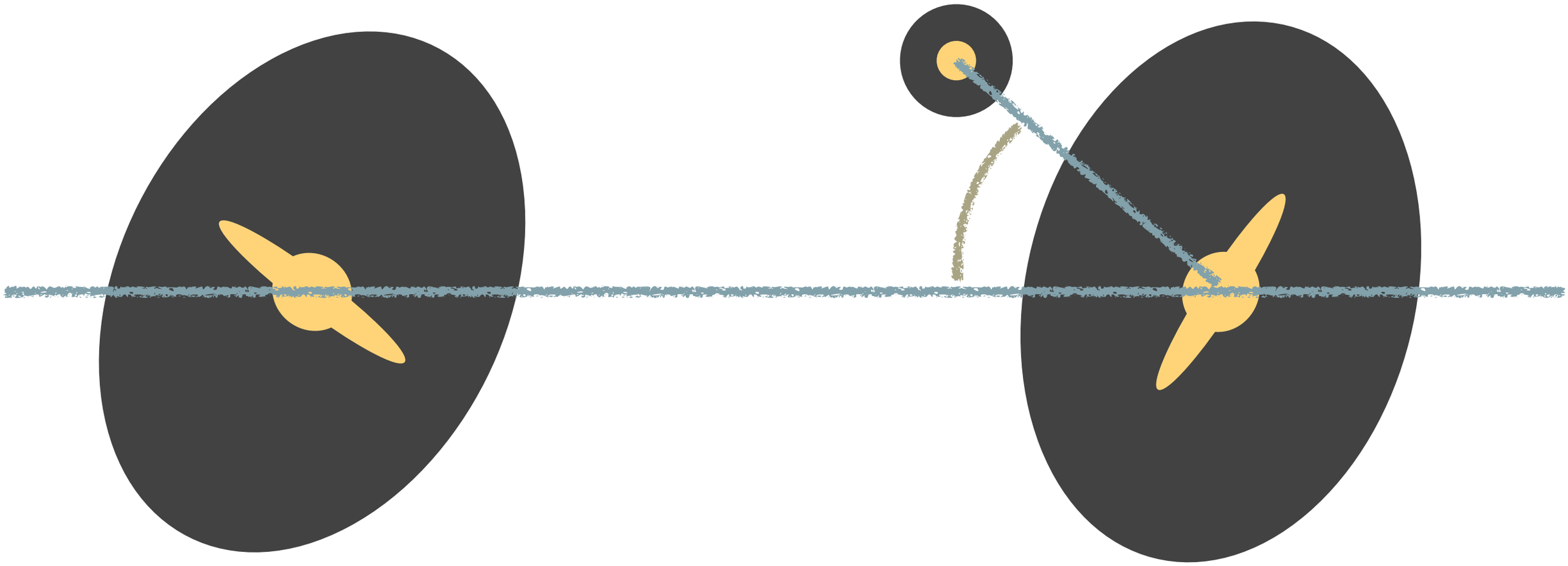
Simple (?) Example: the Holmberg Effect

- Are satellite galaxies preferentially aligned with the *minor* axis of their host galaxy? Holmberg1969
- Only very few satellites per distant host are known (0-2), need to stack many satellite systems.
- More data showed that alignment, if there, seems to be along *major* axis.
- Problem: compares to the orientation of the central galaxy, defined by baryons.



Lopsidedness of Satellite Galaxy Systems

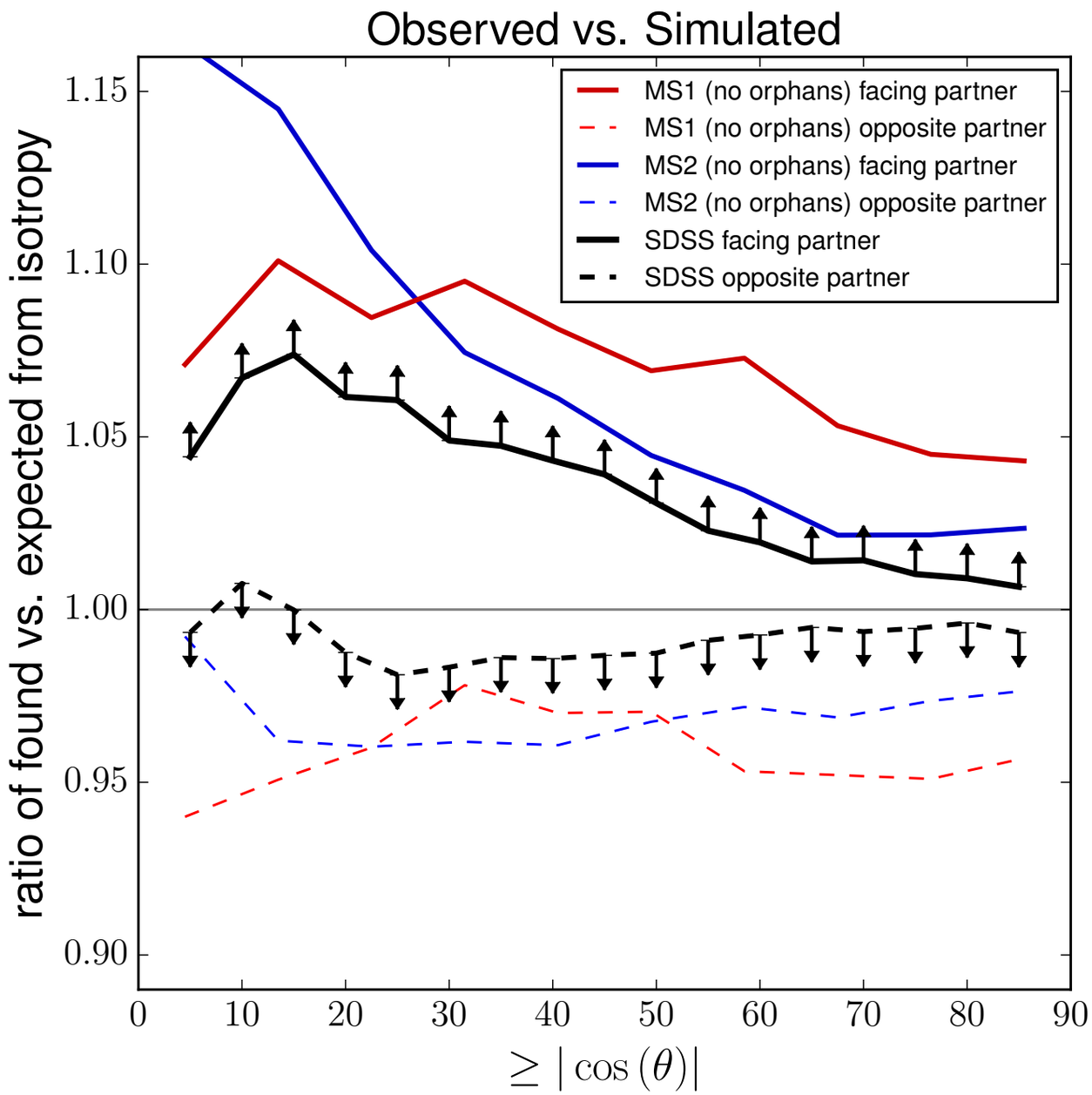
- Better compare to host galaxy position than orientation: not dependent on details of baryonic physics.
- Look at satellite distributions in *paired* host galaxies. Still needs stacking.
- In SDSS data, an excess of satellites towards the partner host galaxy was found.
  Libeskind+2016
- Is this consistent with ΛCDM?



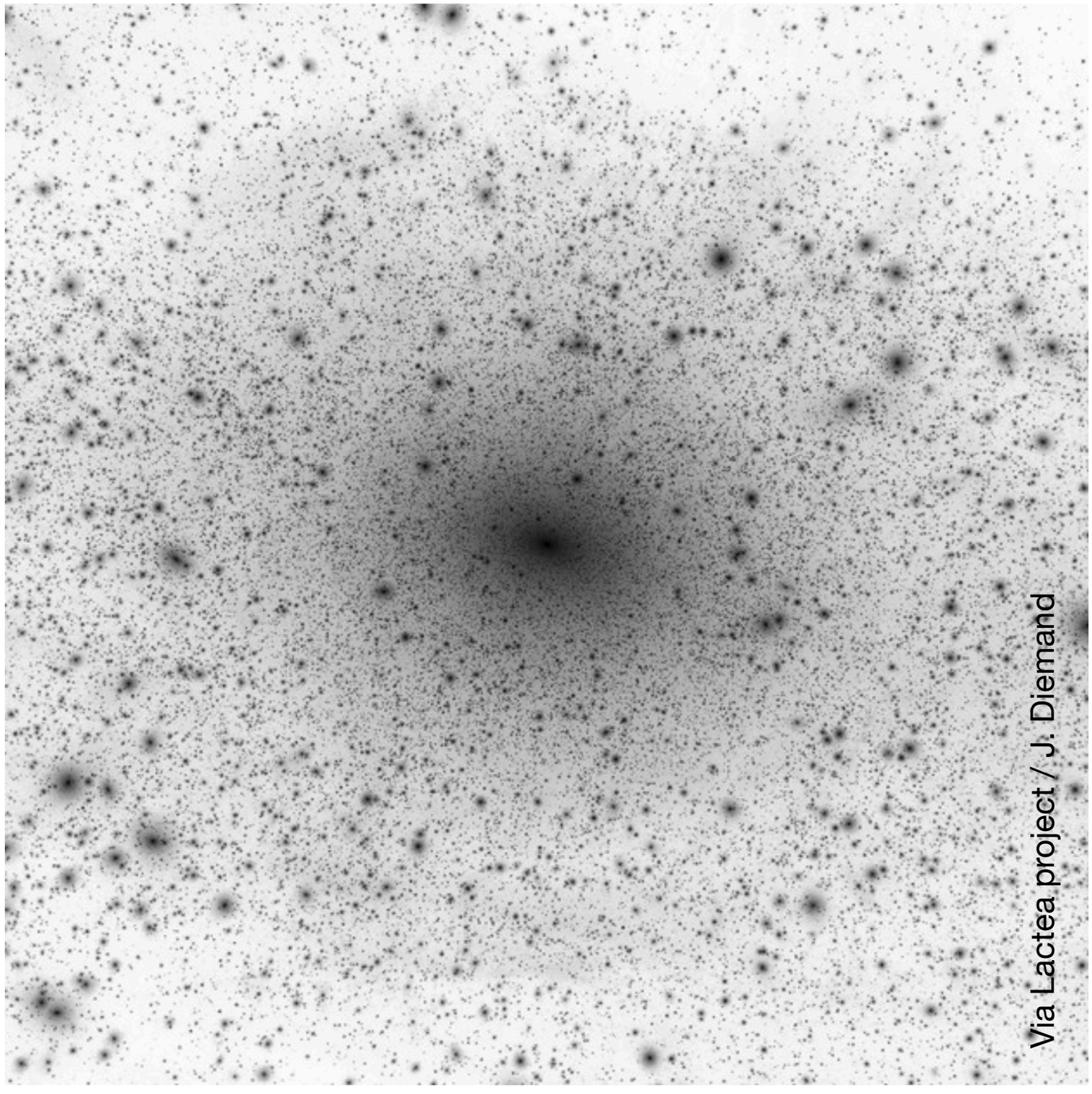
Lopsidedness of Satellite Systems in Simulations

Pawlowski, Ibata & Bullock (2017)

- Cumulative number of satellites in wedges of opening angle θ.
- Observed overabundance of satellites in direction to partner galaxy (**black**). Libeskind+2016
- Millennium **1**+**2** simulations show such an excess! Pawlowski+2017
- ΛCDM passes this test.



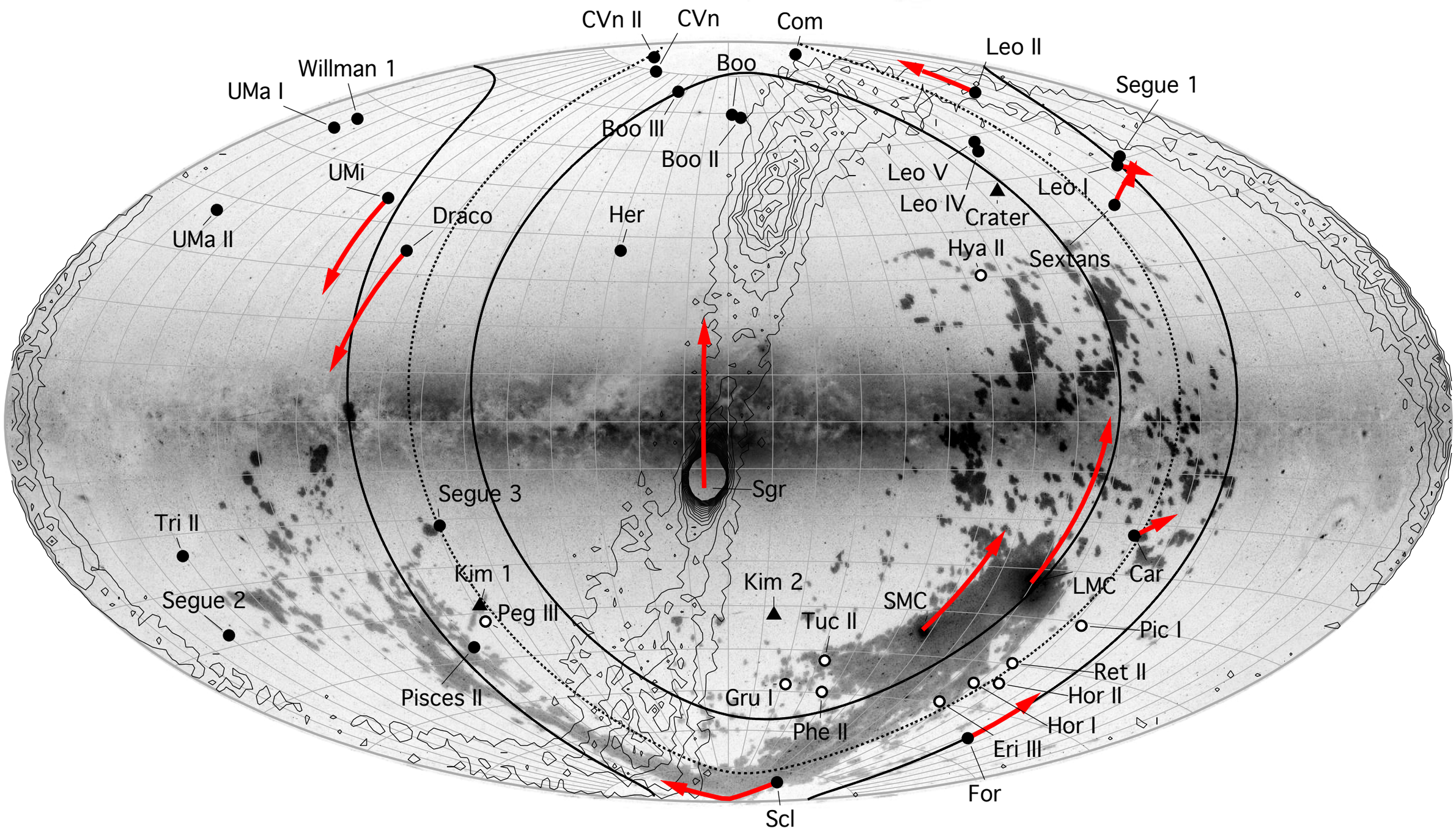
How about mutual distribution and motion of satellites? The Planes of Satellite Galaxies Problem



The Vast Polar Structure of the Milky Way (VPOS)

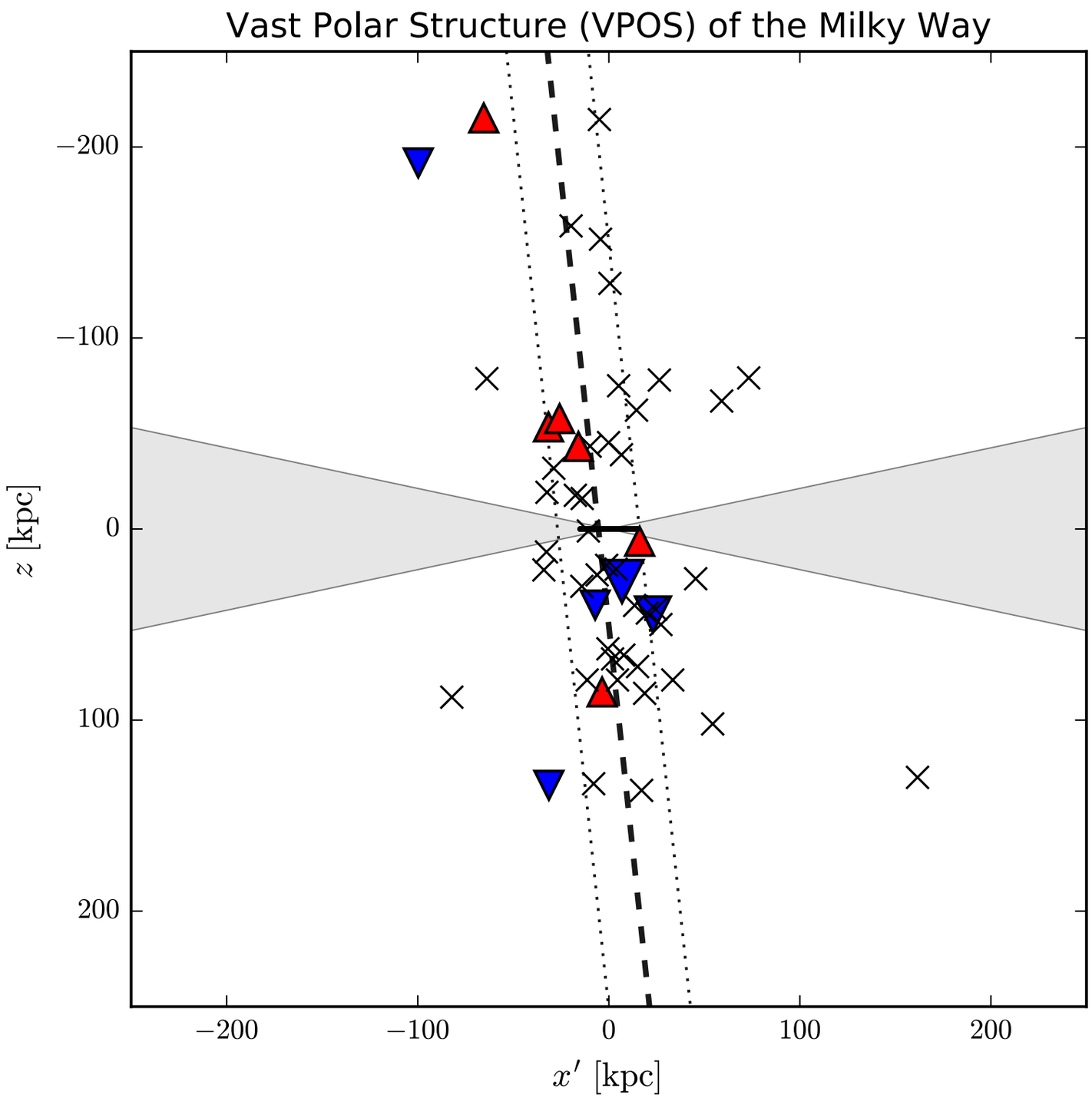
Pawlowski, Pflamm-Altenburg & Kroupa (2012, MNRAS, 423, 1109), Pawlowski & Kroupa (2013, MNRAS, 435, 2116), Pawlowski, McGaugh & Jerjen (2015, MNRAS, 453, 1047)

Majority of MW satellites with measured proper motions co-orbit along VPOS



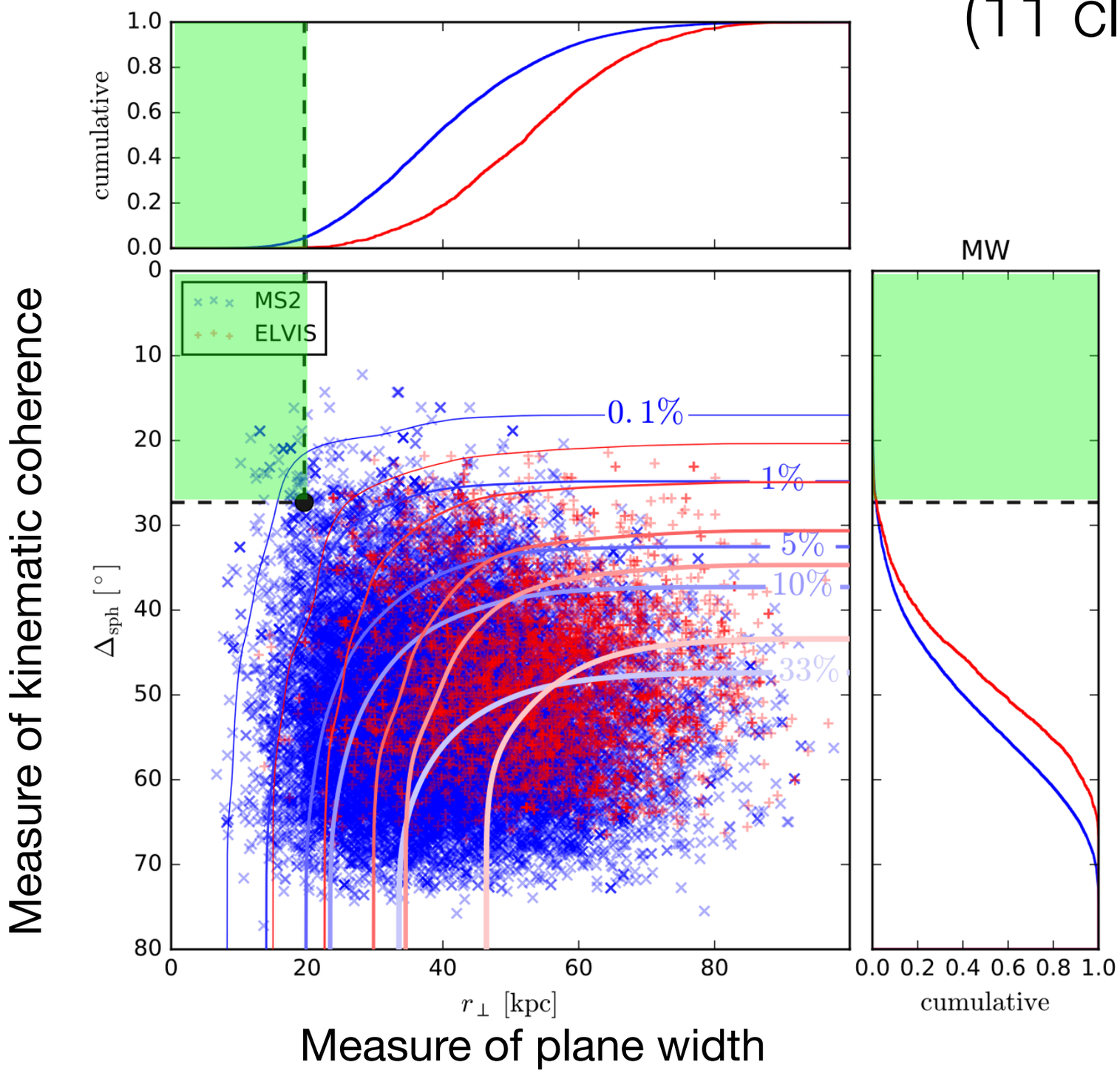
The Vast Polar Structure of the Milky Way (VPOS)

Pawlowski 2018 (invited brief review in MPLA, arXiv:1802.02579)



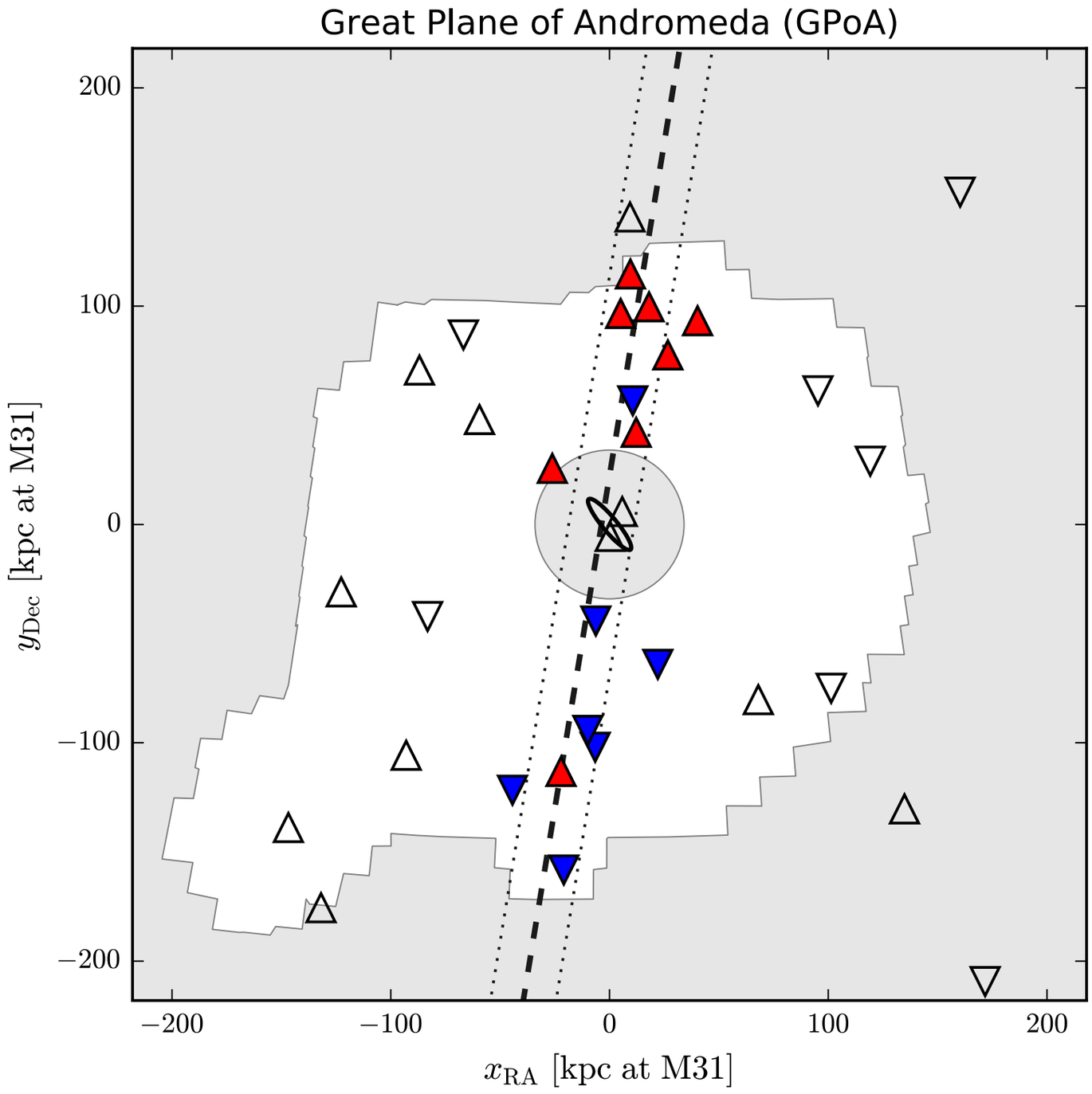
How does the VPOS compare to ΛCDM expectations?

(11 classical satellites only!)



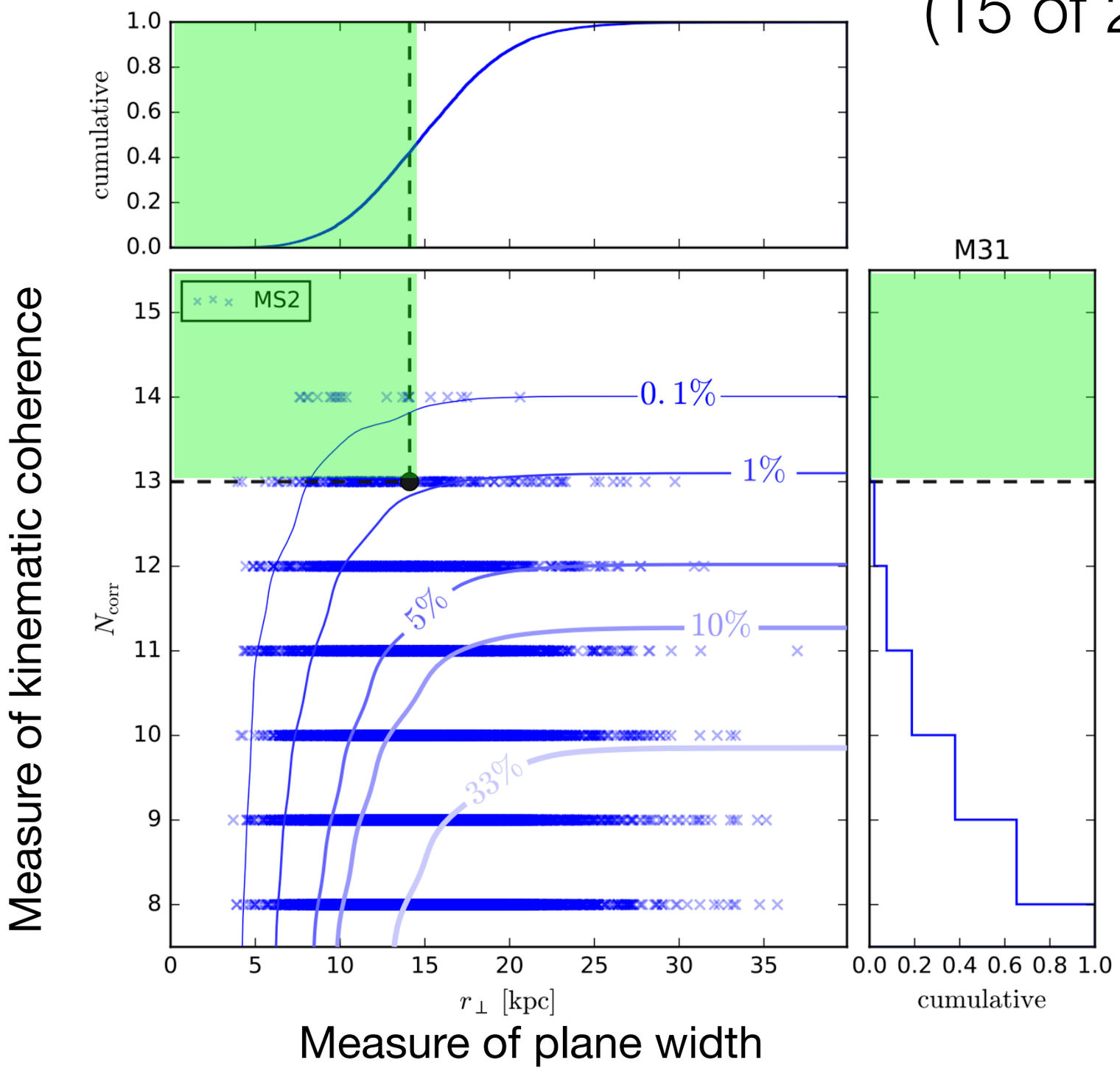
Frequency of similarly extreme satellite arrangements in cosmological simulations is ≤ 0.1%

Is the Milky Way special? The Great Plane of Andromeda (GPoA) Ibata+2013



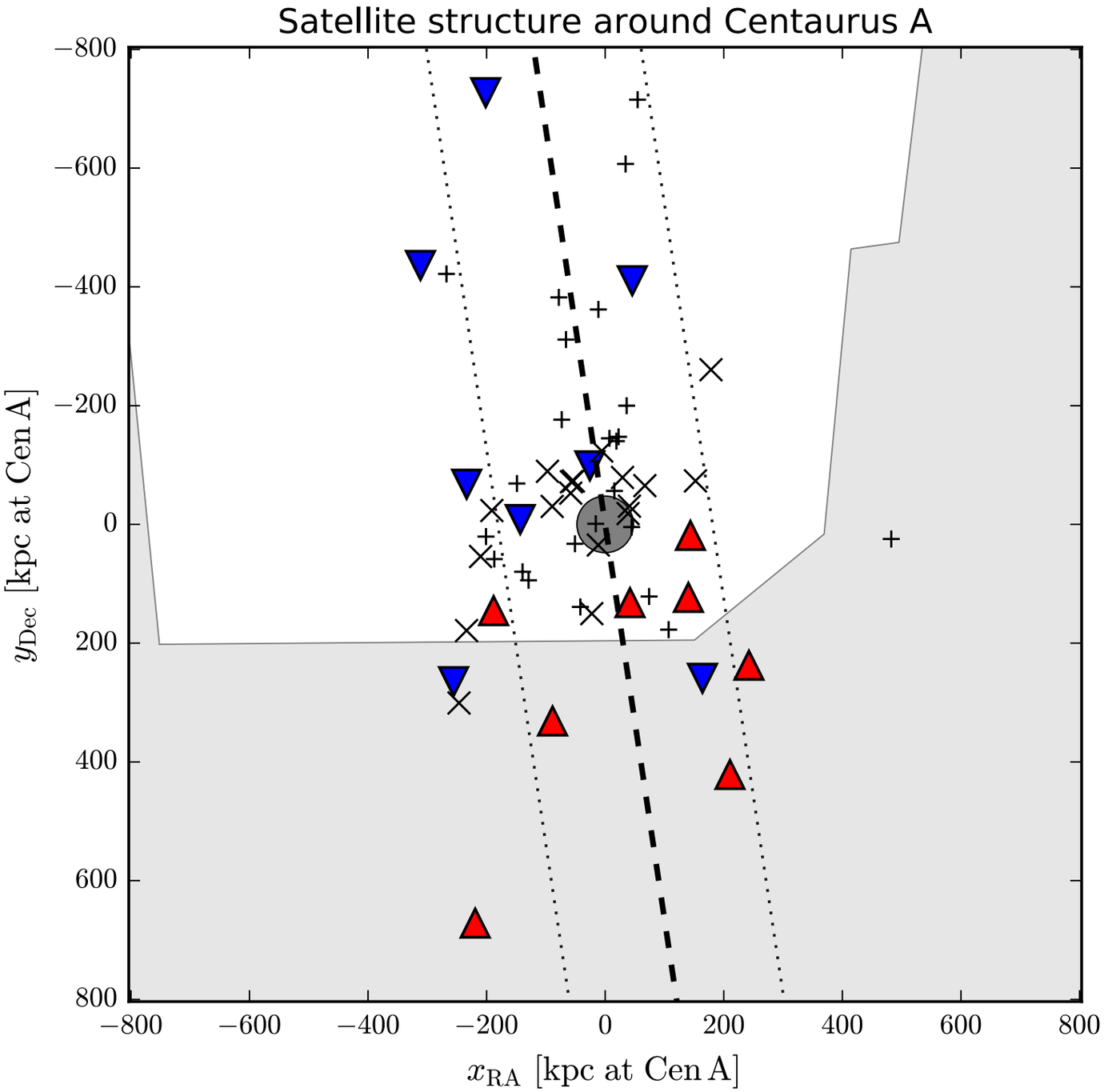
The GPoA is also in tension with ΛCDM expectations!

(15 of 27 satellites form plane)



Frequency of similarly extreme satellite arrangements in cosmological simulations is ≤ 1%, ≤0.1% if considering radial distribution.

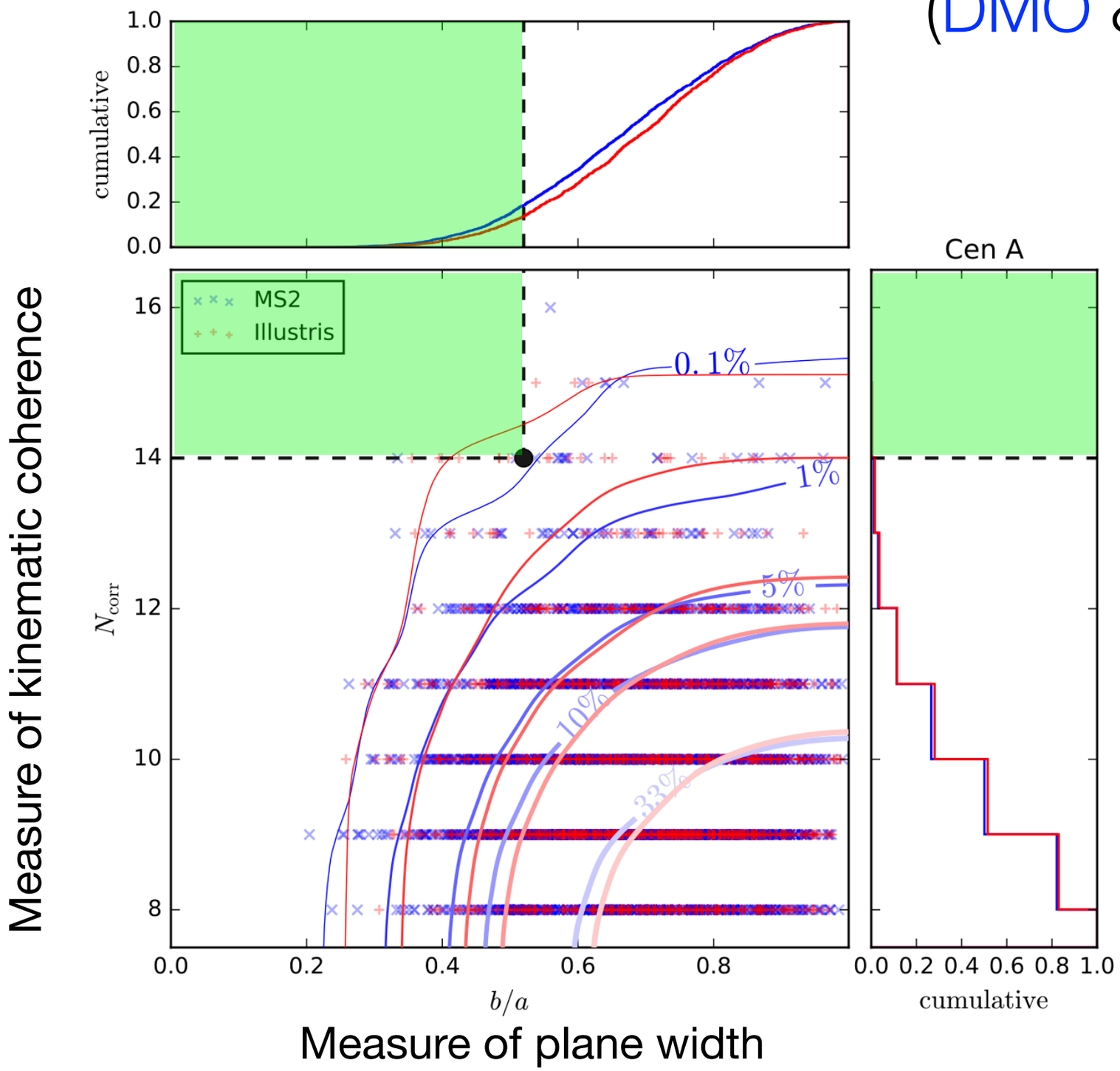
Is the Local Group special?
The Centaurus A Satellite Plane (CASP)



Müller, Pawlowski, Jerjen & Lelli (2018)
Science, Volume 359, Issue 6375, 534

The CASP spells more trouble for ΛCDM

(DMO & hydro simulations)



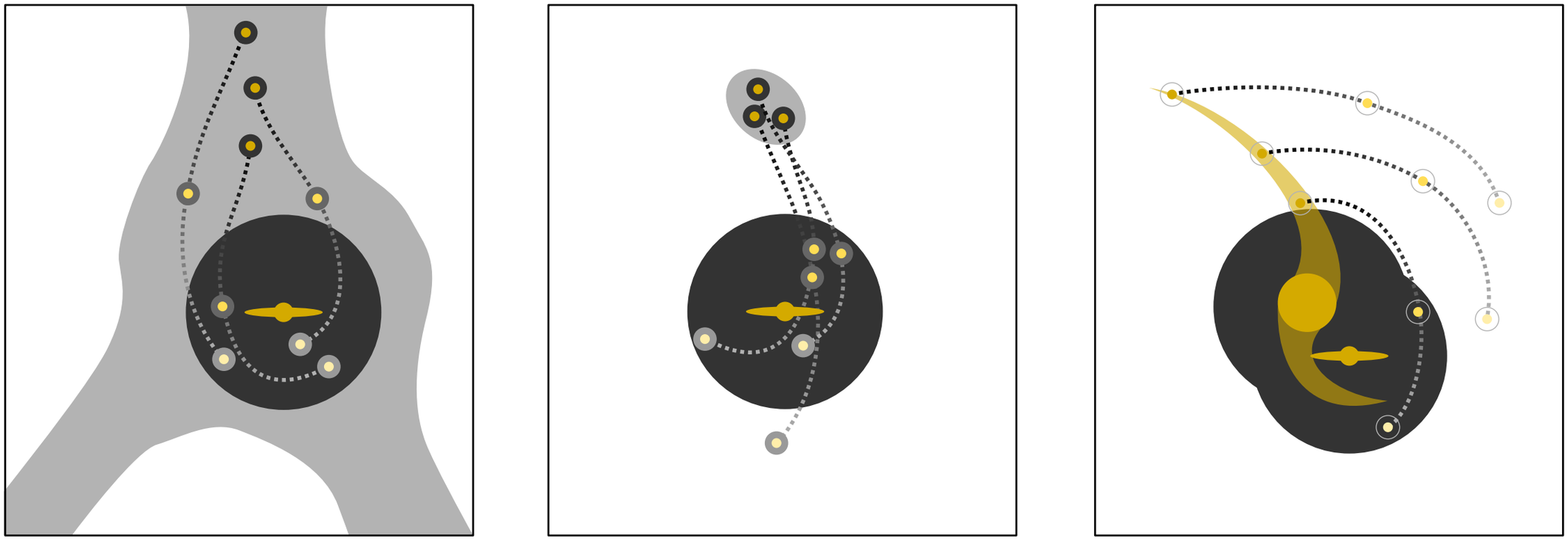
Frequency of similarly extreme satellite arrangements in cosmological simulations is ≤ 0.5%

3/3 satellite systems studied in detail contain kinematically coherent satellite planes. What could be their origin?

Filamentary Accretion

Group Infall

Tidal Dwarf Galaxies



Pawlowski (2018)

Self-consistently included in cosmological simulations (Any way to boost these?)

TDGs should be dark matter free. (Might require radical changes, e.g. MOND?)

Conclusions

- The phase-space distribution of satellite galaxies is a powerful test of cosmological models: it does not strongly depend on baryonic physics.

- Co-rotating Planes of Satellite Galaxies have been found for at least three systems: Milky Way, Andromeda & Centaurus A.

- Satellite galaxy planes are in severe tension with ΛCDM simulations, where similarly extreme structures should occur with a frequency of only 1 in ~1000 hosts.

- This and other small-scale puzzles (e.g. RAR) might require radical changes to our understanding of the dark matter effect.

Further Reading

Centaurus A: Müller, Pawlowski, Jerjen & Lelli (2018); Science, Volume 359, Issue 6375, 534

RESEARCH ARTICLE

NEAR-FIELD COSMOLOGY

A whirling plane of satellite galaxies around Centaurus A challenges cold dark matter cosmology

Oliver Müller,[1]* Marcel S. Pawlowski,[2] Helmut Jerjen,[3] Federico Lelli[4]

The Milky Way and Andromeda galaxies are each surrounded by a thin plane of satellite dwarf galaxies that may be corotating. Cosmological simulations predict that most satellite galaxy systems are close to isotropic with random motions, so those two well-studied systems are often interpreted as rare statistical outliers. We test this assumption using the kinematics of satellite galaxies around the Centaurus A galaxy. Our statistical analysis reveals evidence for corotation in a narrow plane: Of the 16 Centaurus A satellites with kinematic data, 14 follow a coherent velocity pattern aligned with the long axis of their spatial distribution. In standard cosmological simulations, <0.5% of Centaurus A–like systems show such behavior. Corotating satellite systems may be common in the universe, challenging small-scale structure formation in the prevailing cosmological paradigm.

See also Mike BK's *Perspectives* article in the same issue!

Invited review on the Planes of Satellites Galaxies Problem in MPLA arXiv:1802.02579

Modern Physics Letters A

THE PLANES OF SATELLITE GALAXIES PROBLEM, SUGGESTED SOLUTIONS, AND OPEN QUESTIONS

MARCEL S. PAWLOWSKI*

Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
marcel.pawlowski@uci.edu

Received (Day Month Year)
Revised (Day Month Year)

Satellite galaxies of the Milky Way and of the Andromeda galaxy have been found to preferentially align in significantly flattened planes of satellite galaxies, and available velocity measurements are indicative of a preference of satellites in those structures to co-orbit. There is increasing evidence that such kinematically correlated satellite planes are also present around more distant hosts. Detailed comparisons show that similarly anisotropic phase-space distributions of sub-halos are exceedingly rare in cosmological simulations based on the ΛCDM paradigm. Analogs to the observed systems have frequencies of ≤ 0.5 per cent in such simulations. In contrast to other small-scale problems, the satellite planes issue is not strongly affected by baryonic processes because the distribution of sub-halos on scales of hundreds of kpc is dominated by gravitational effects. This makes the satellite planes one of the most serious small-scale problem for ΛCDM. This review summarizes the observational evidence for planes of satellite galaxies in the Local Group and beyond, and provides an overview of how they compare to cosmological simulations. It also discusses scenarios which aim at explaining the coherence of satellite positions and orbits, and why they all are currently unable to satisfactorily resolve the issue.