

Λ CDM's most severe small-scale problem:
The ubiquity of co-orbiting
satellite galaxy planes

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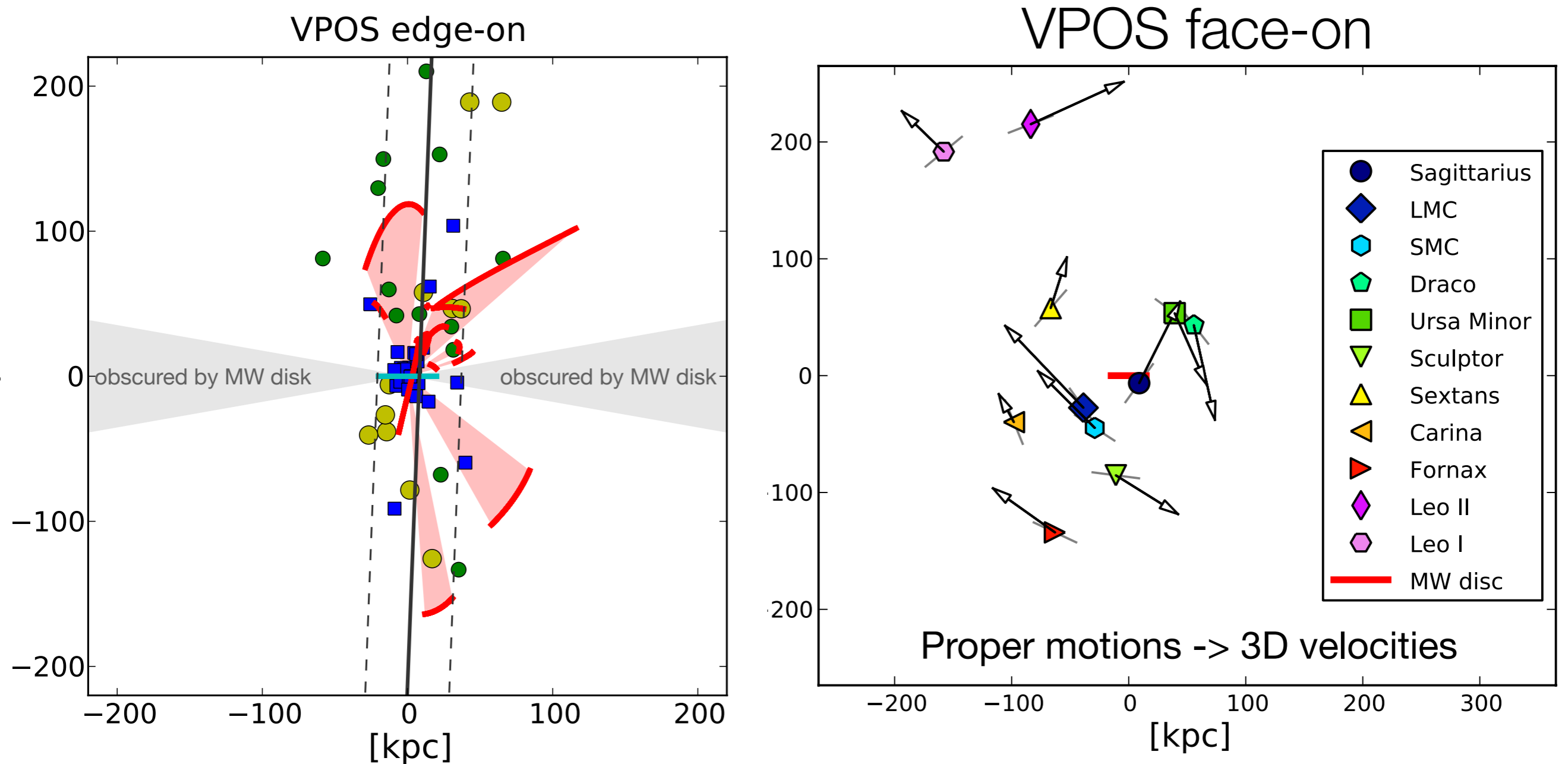


Expected distribution of Λ CDM sub-halo satellites

The Vast Polar Structure of the Milky Way (VPOS)

Pawlowski, Pflamm-Altenburg & Kroupa (2012, MNRAS, 423, 1109)

Pawlowski & Kroupa (2013, MNRAS, 435, 2116)

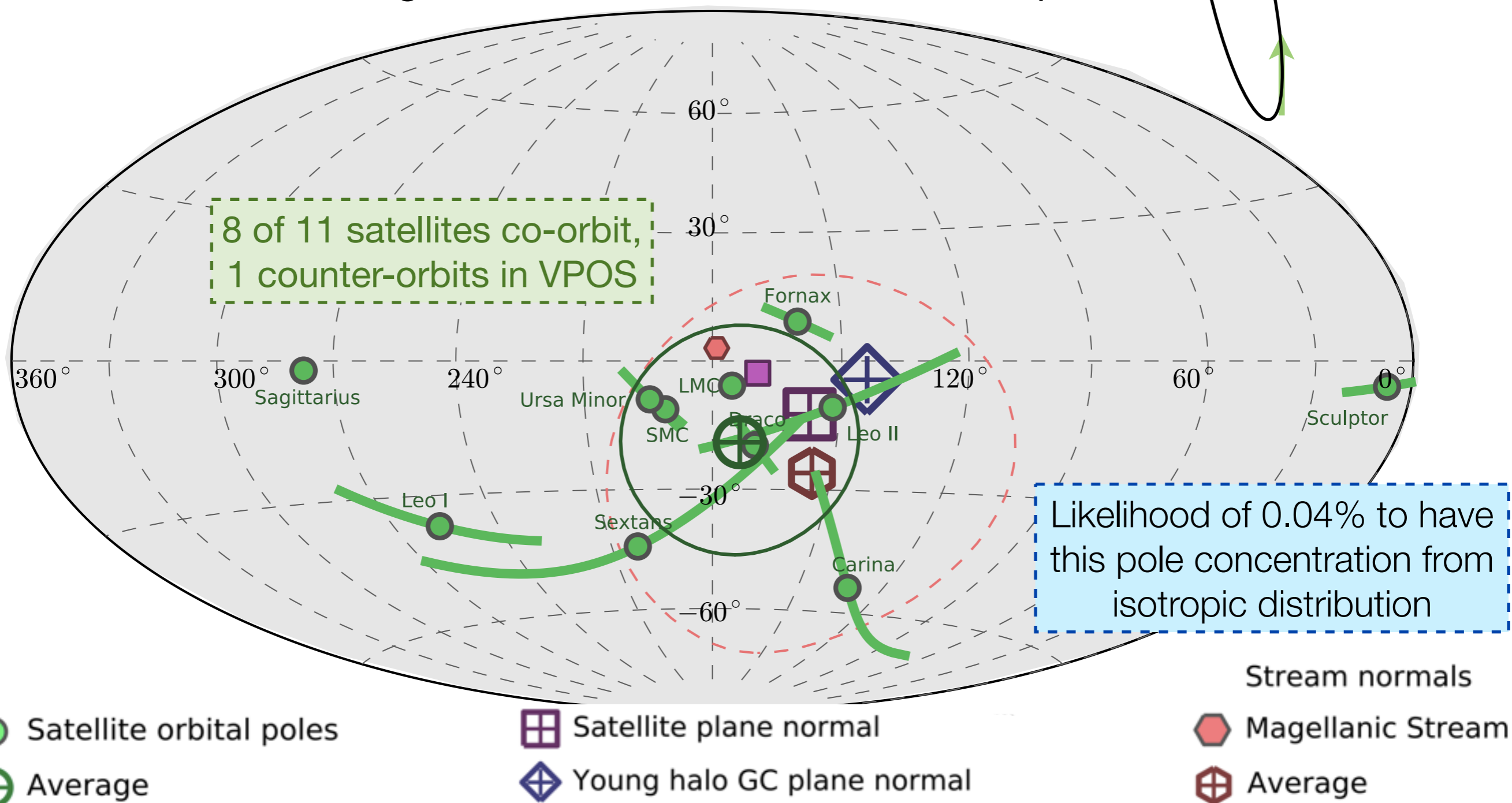
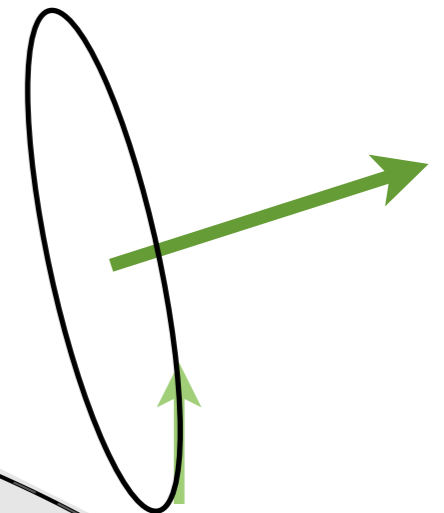


'Classical' and faint MW satellites, young halo globular clusters and 50% of streams align in highly flattened (20-30 kpc), co-orbiting structure

Coherent velocities: the VPOS is rotationally stabilized

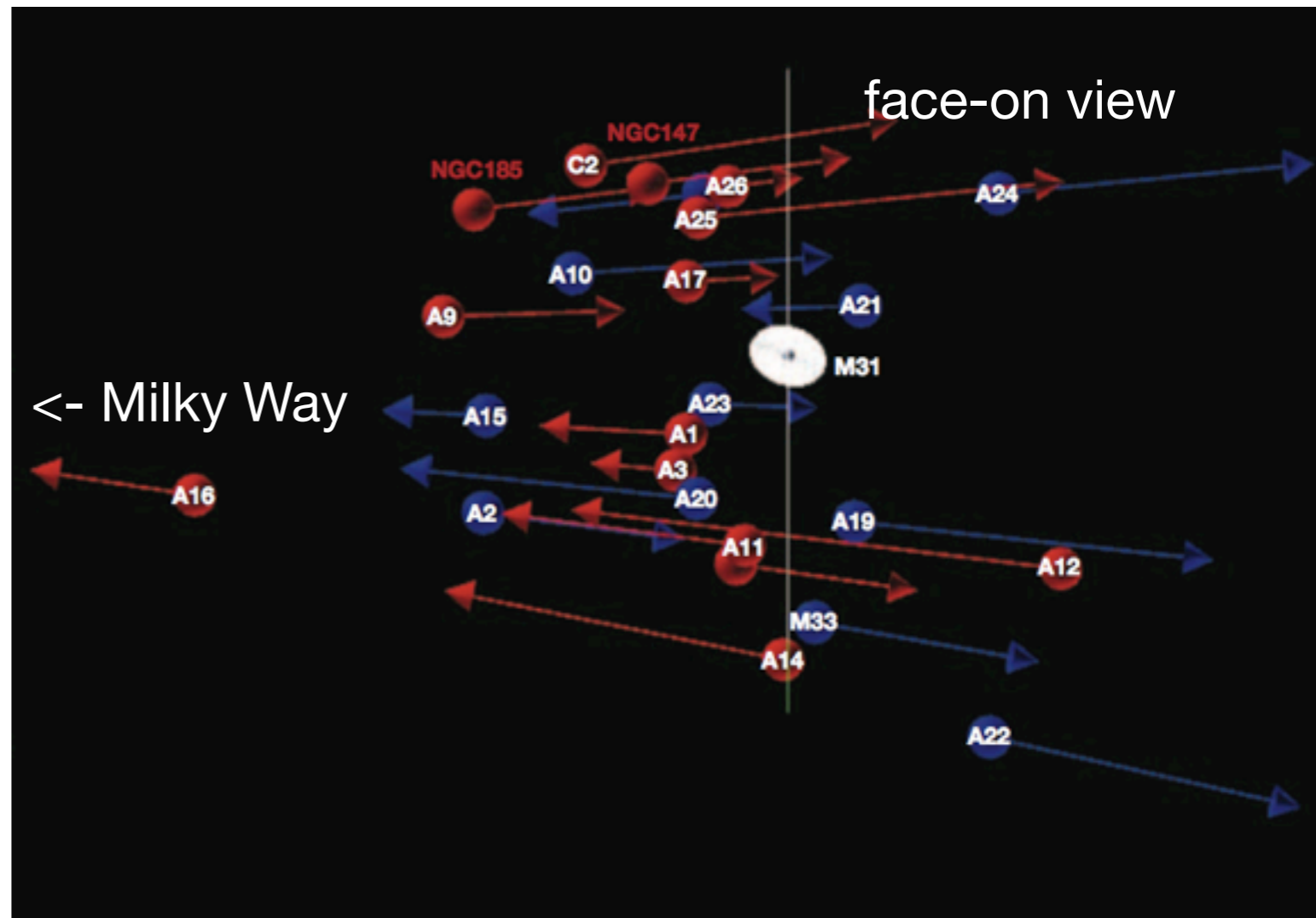
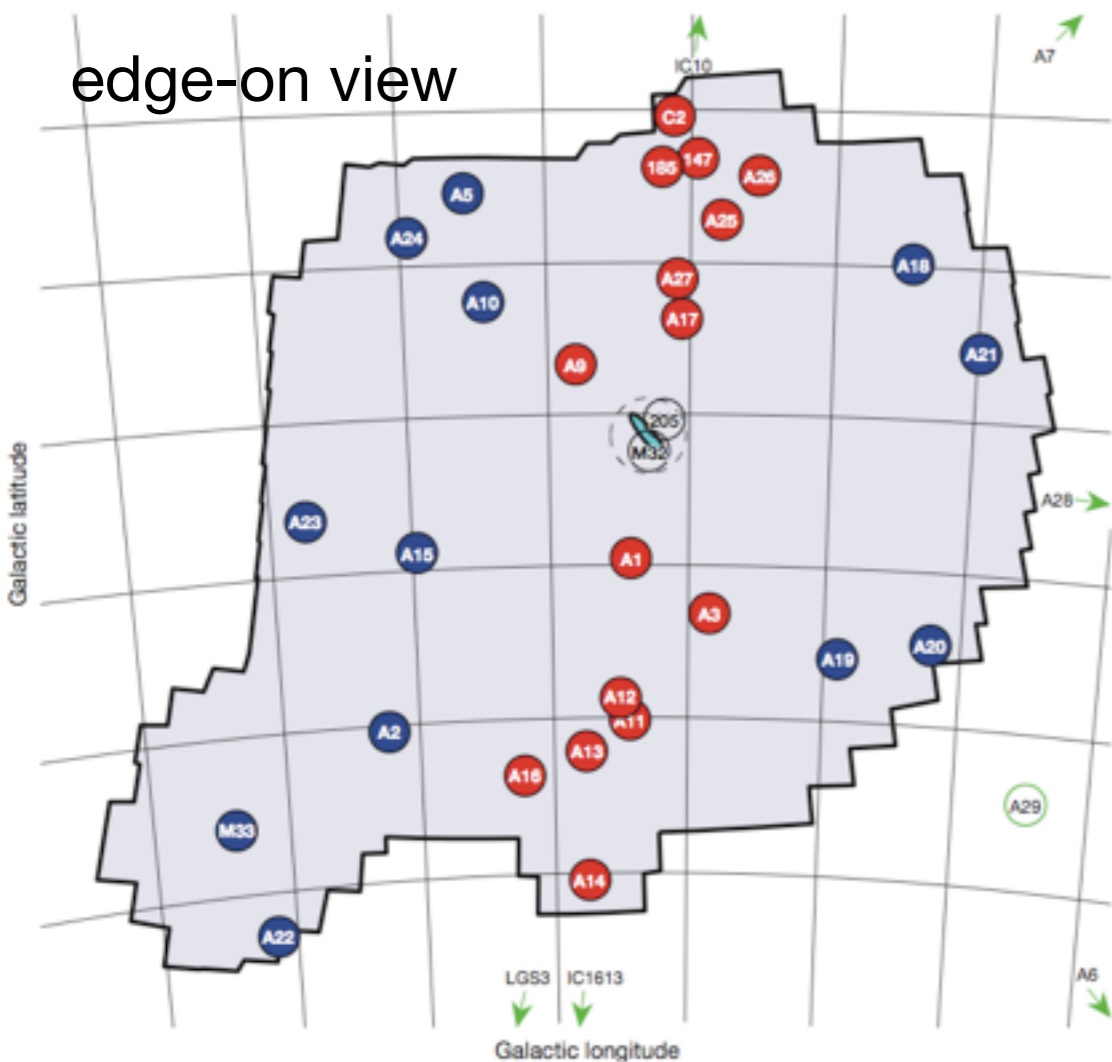
Pawlowski & Kroupa (2013, MNRAS, 435, 2116)

- **Orbital poles of the MW satellites**
 - ➔ directions of angular momenta = normals to orbital planes



The Great Plane of Andromeda (GPoA)

Ibata et al. (2013, Nature, 493, 62)



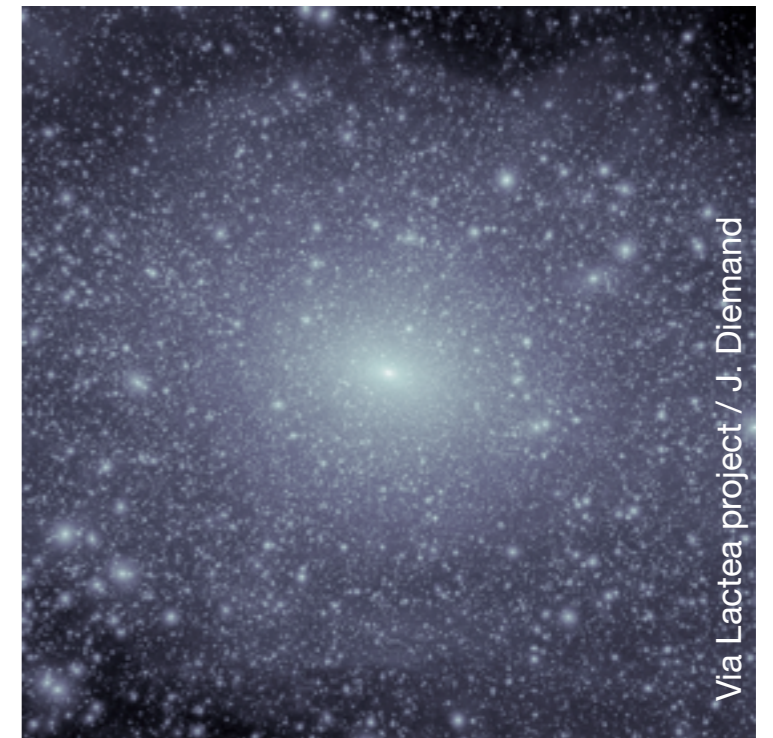
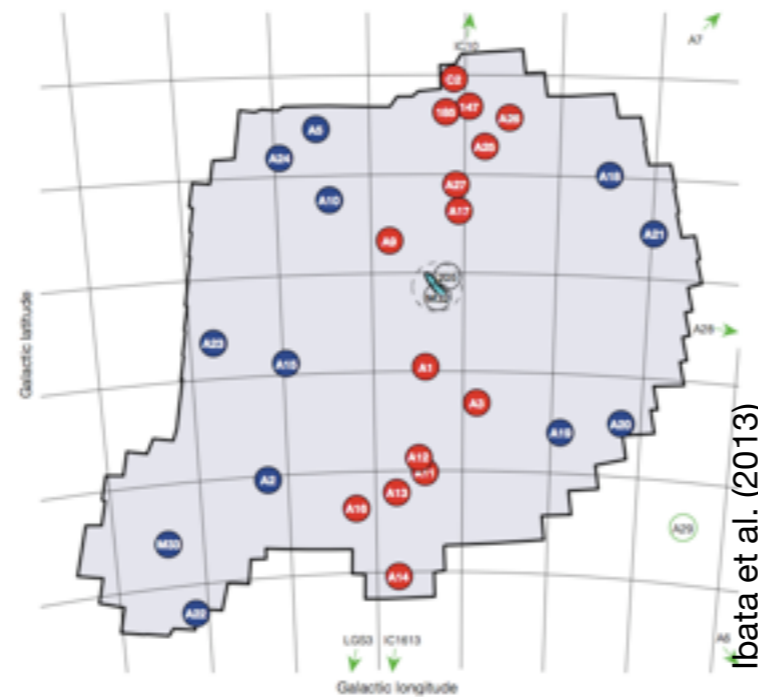
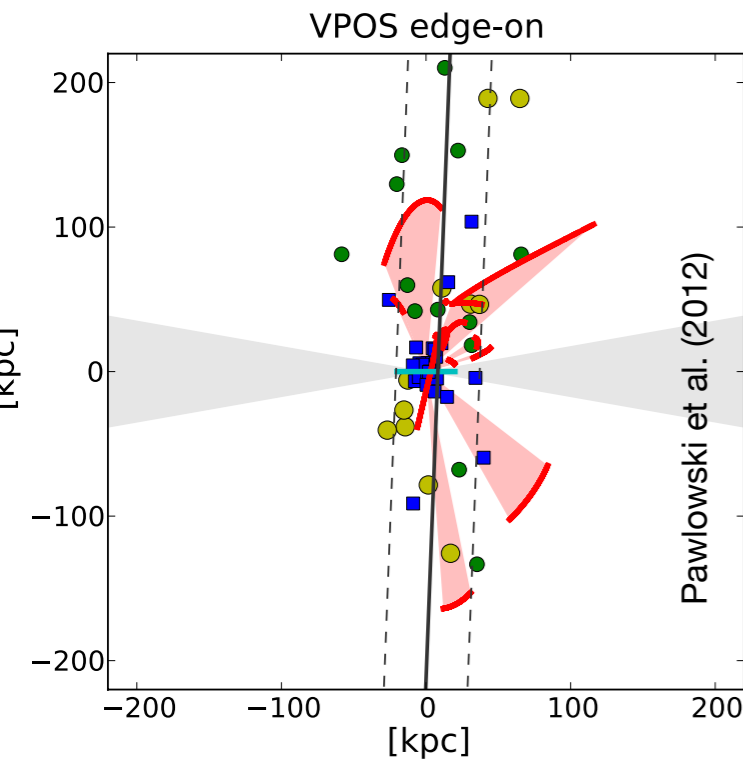
50% of M31 satellites align in highly flattened (14 kpc) co-orbiting (13 of 15 members) structure.

Likelihood of 0.002% if drawn from isotropic distribution

Local Group Satellite Planes as Tests of Λ CDM

Can this ...

... be found in this?



- **Important:** Planes of co-orbiting sats not predicted by cosmological sims.
 - ➔ Fundamental problem of Λ CDM?
- **Robust:** largely independent of exact baryon physics (>100 kpc scales).
- **Promising:** Origin of satellite planes might provide important information to find (unified) solution for other small-scale problems.

Co-orbiting satellite planes extremely rare in Λ CDM

Pawlowski & Kroupa (2013, MNRAS, 435, 2116), Pawlowski+(2014, MNRAS, 442, 2362),
Pawlowski & McGaugh (2014, ApJL, 789, 24)

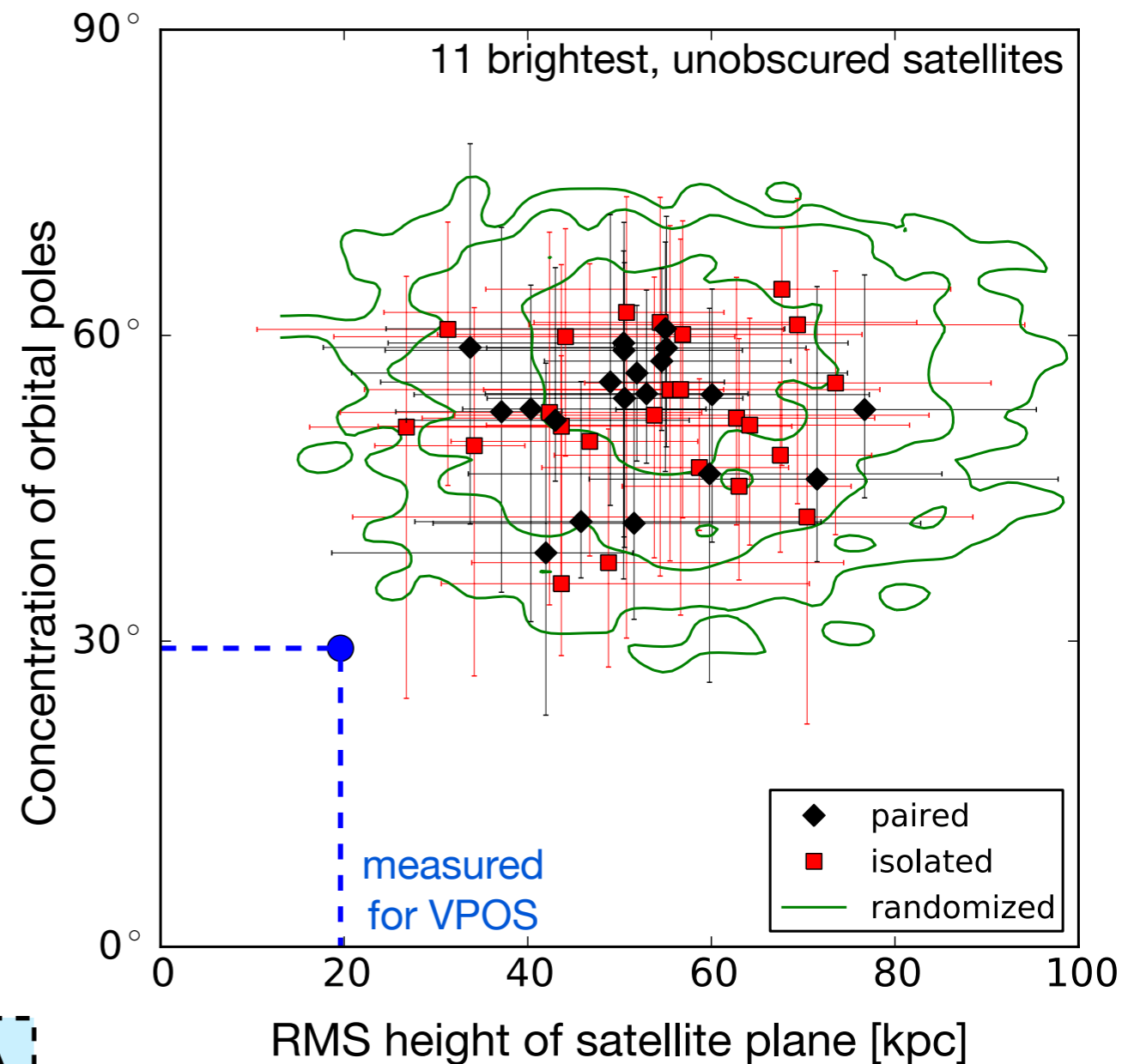
Comparing observed satellite population
with cosmological simulations (ELVIS,
Millennium-II, Via Lactea 1 & 2, Aquarius)

Shown example: ELVIS simulations
(Local-Group-like host pairs)

(Garrison-Kimmel et al 2014, MNRAS, 438, 2578)

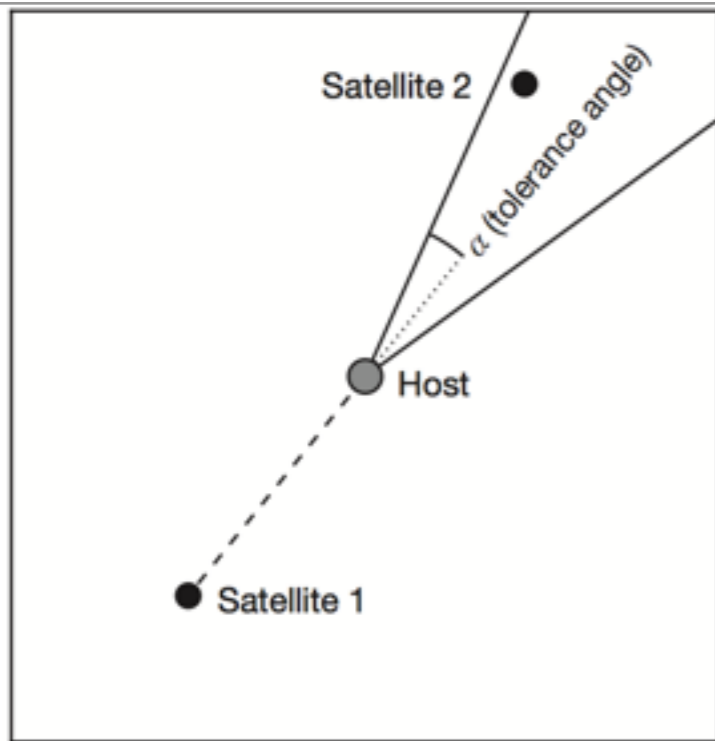
➔ 1 of 4800 realizations fulfills thickness
and co-orbiting criterion *simultaneously*
(checking 11 brightest MW sats only!)

Chance to find VPOS *and* GPOA
in Λ CDM sims $< 0.001\%$



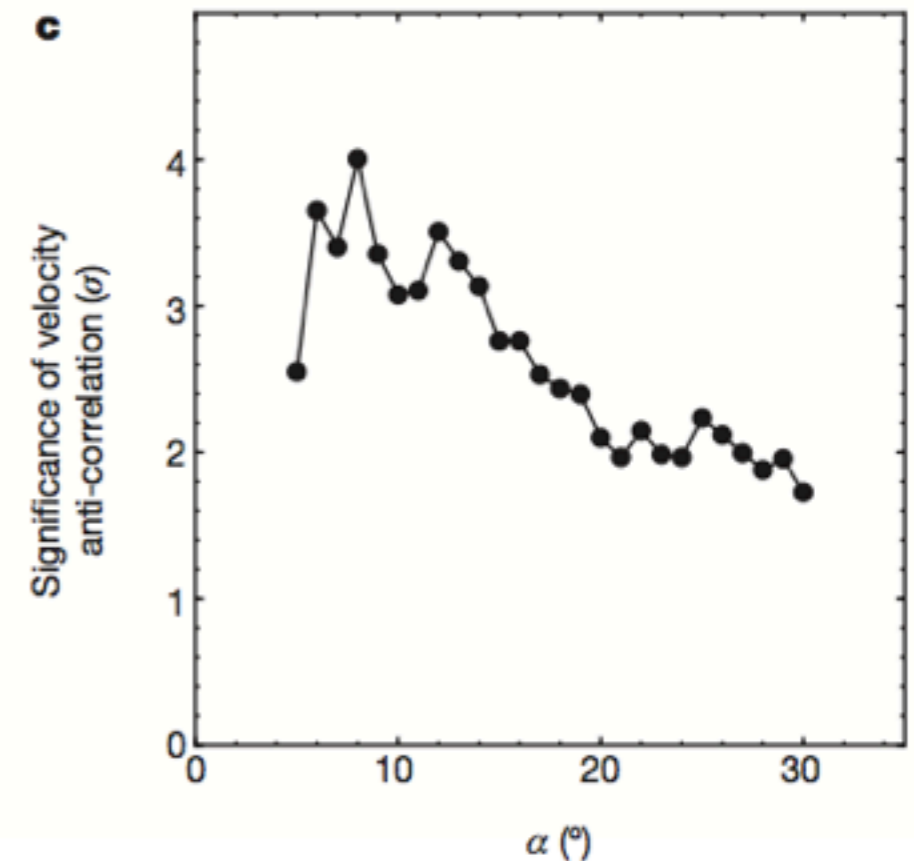
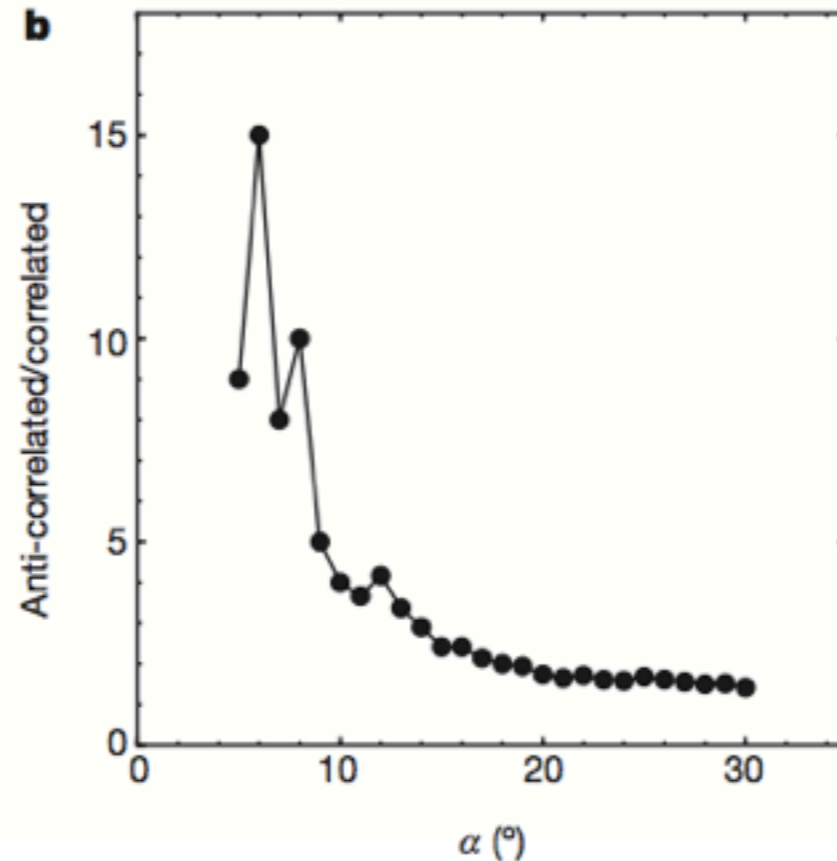
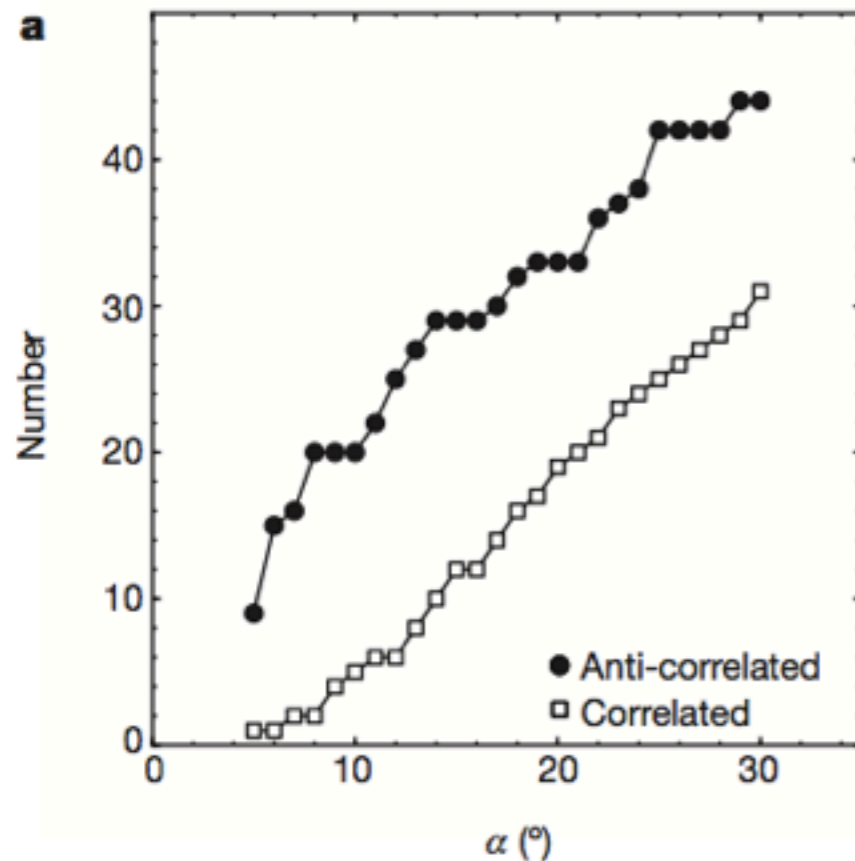
Beyond the Local Group: Velocity anti-correlation of opposed satellites in SDSS

Ibata et al. (2014, Nature, 511, 563)



Most pairs have anti-correlated velocities, suggests 60% of sats co-orbit in planes

Likelihood of 0.006% if drawn from Λ CDM simulation



Claims of consistency of sat. planes with Λ CDM

Pawlowski et al. (2012, MNRAS, 424, 80), Pawlowski et al. (2014, MNRAS, 442, 2362)

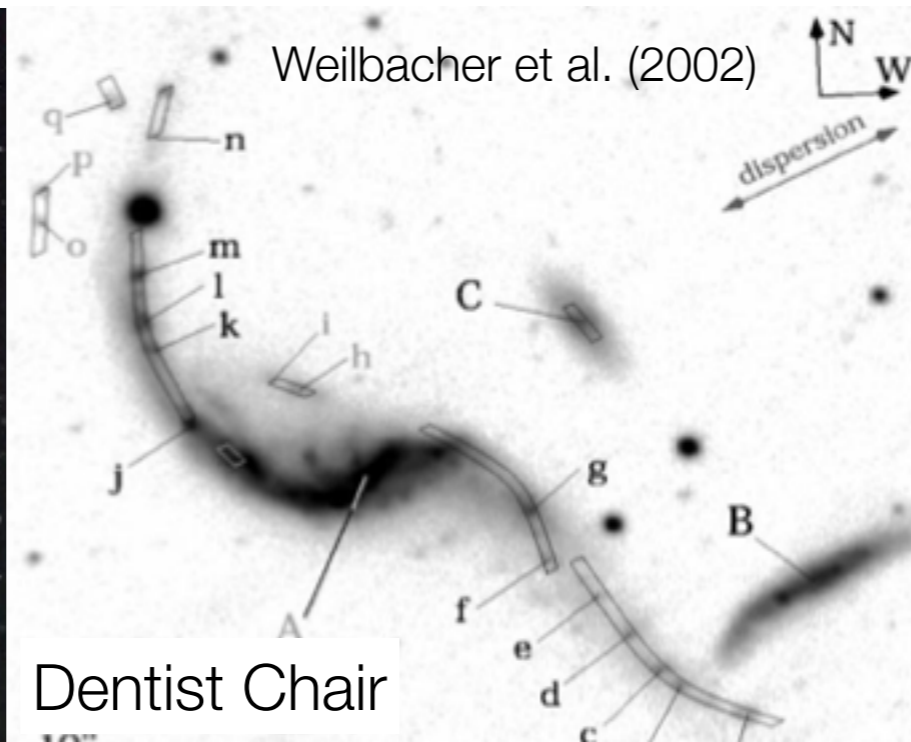
- Published claims of consistency between Λ CDM and observed satellite structures are based on flawed analyses. Problems include:
 - **Consistency claimed** in abstract **but not tested** in paper.
 - **Problem changed** to one more easily solved in Λ CDM.
 - Correlated satellite **kinematics** have been **ignored**.
 - Simulated satellites selected from **different survey volume** than observed.
 - Initial model **assumptions** already **inconsistent** with observed situation.

Tidal dwarf galaxies (TDGs)

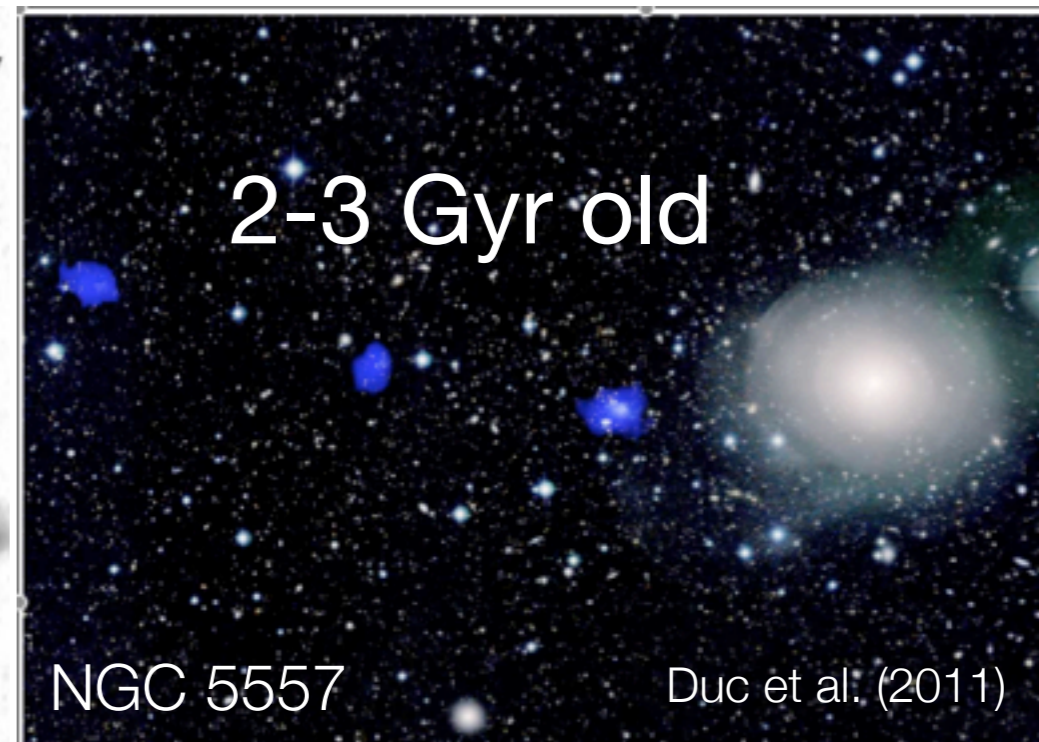
- Second-generation galaxies in debris of galaxy collisions.
 - Phase-space correlated
 - ➔ Consistent with VPOS & GPoA. (Pawlowski+2011, 2012a,b, Hammer+2013)
 - Can survive formation phase
 - ➔ Observed (Duc+2011)
 - ➔ Simulated (Recchi+2007; Plöckinger+2014)
- Open issues:
- Should be dark-matter-free
 - ➔ Non-equilibrium dynamics? (Kroupa 1997; Casas+2012)
 - ➔ Gas stripping? (Yang+2014)
 - ➔ MOND? (Benoit's talk on Thursday)
 - Mass-Metallicity relation
 - ➔ Ancient TDGs less pre-enriched?



Tadpole



Dentist Chair



2-3 Gyr old

NGC 5557

Duc et al. (2011)

Conclusions

- Co-orbiting satellite planes observed around MW, M31, and in SDSS, are extremely rare in Λ CDM simulations: e.g. Pawlowski+ 2014, Pawlowski & McGaugh 2014b
 - ➔ Fundamental problem, baryons don't help.
- TDGs consistent with sat. planes, but open issues: vel. disp., mass-metallicity. e.g. Pawlowski+ 2011, Pawlowski+ 2012a, Hammer+ 2013, Yang+ 2014
- Whole Local Group is highly structured: Pawlowski+ 2013, Pawlowski & McGaugh 2014a

