Can we solve the Planes of Satellites Problem by invoking special host halo properties or baryonic effects?

Bonus: Preview of the classical satellite plane of the MW in light of Gaia DR2

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@8minutesold

Do you live-tweet?
Tired of missing half the talk while typing? This is the solution:
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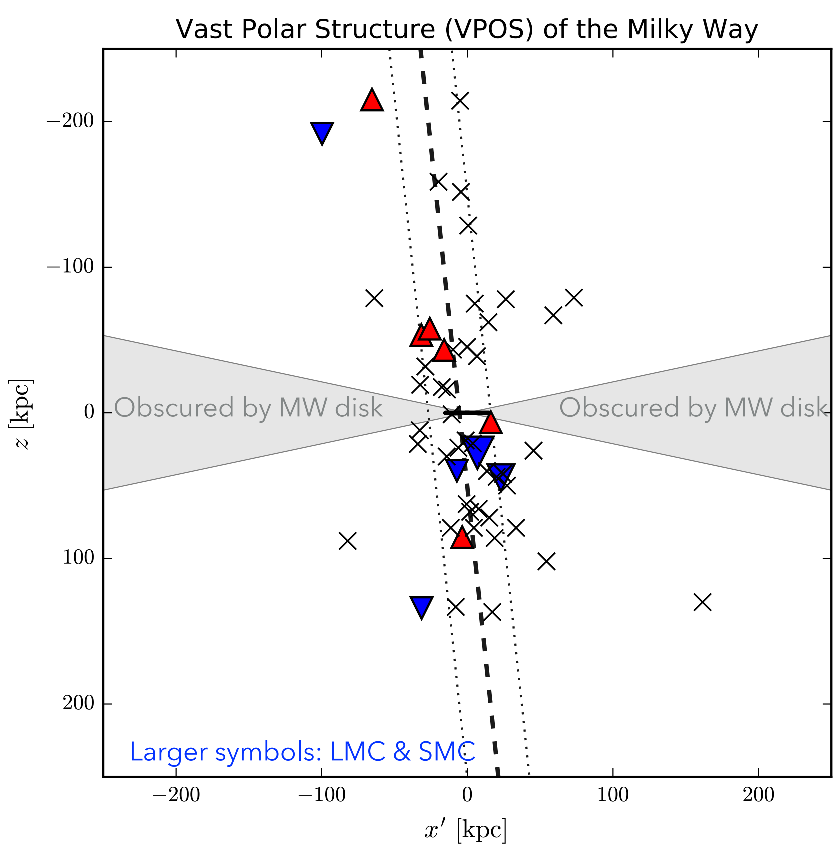
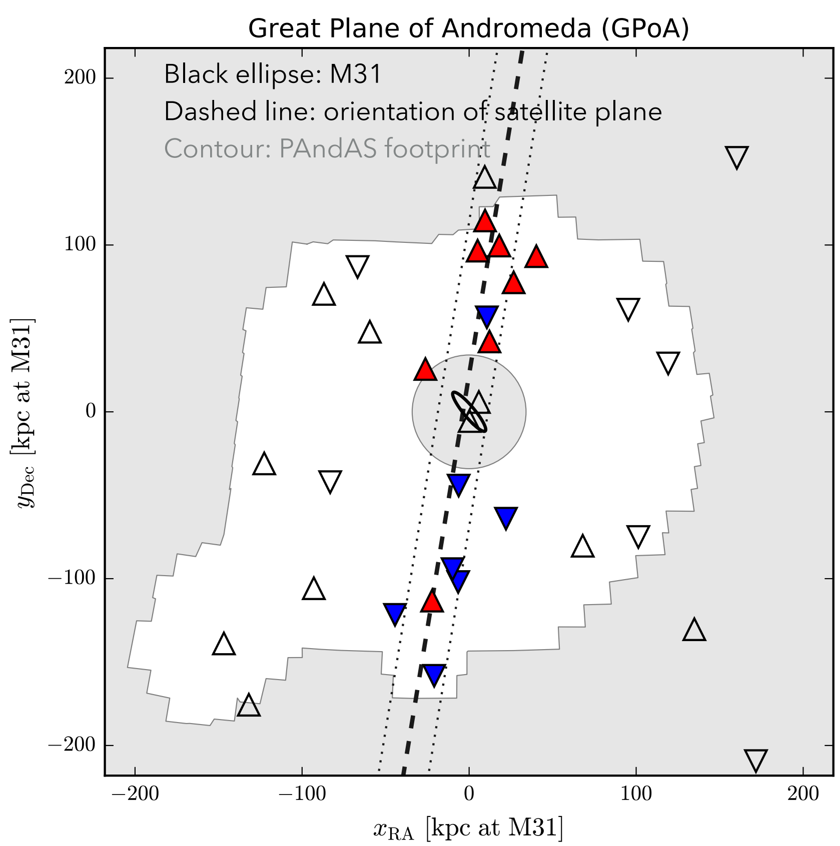
See review (Pawlowski, 2018)

Planes of Satellite Galaxies

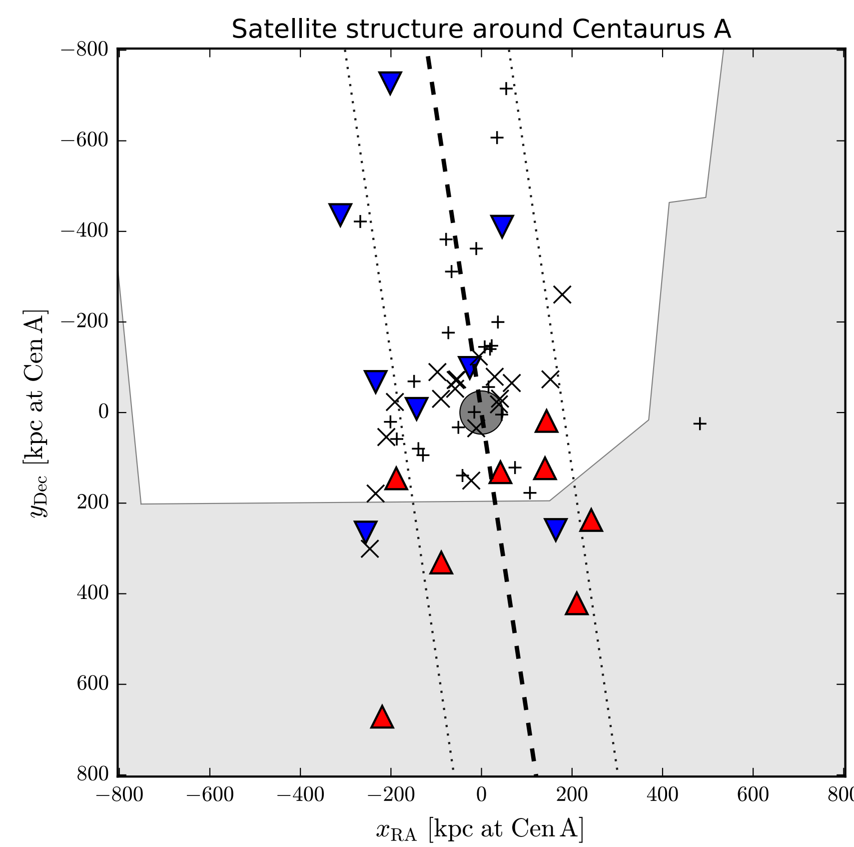
- Observed satellite galaxy systems (Milky Way, Andromeda, Centaurus A) are flattened and show signs of kinematic correlation indicative of co-rotation
- Frequency of as strongly flattened and kinematically coherent satellite systems in ΛCDM simulations is very low (on order 0.1%).



Pawlowski, Kroupa & Jerjen
(2012, MNRAS, 423, 1109)



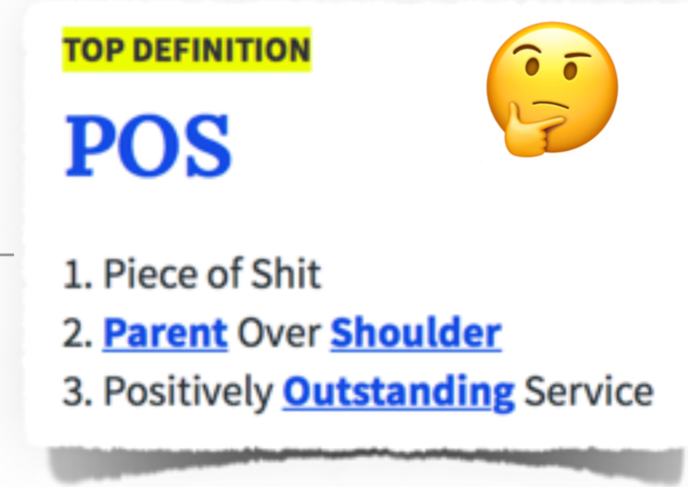
Ibata et al.
(2013, Nature, 493, 62)



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

("POS" problem?)

Can we solve the Planes of Satellites problem by saying MW/M31 are special?

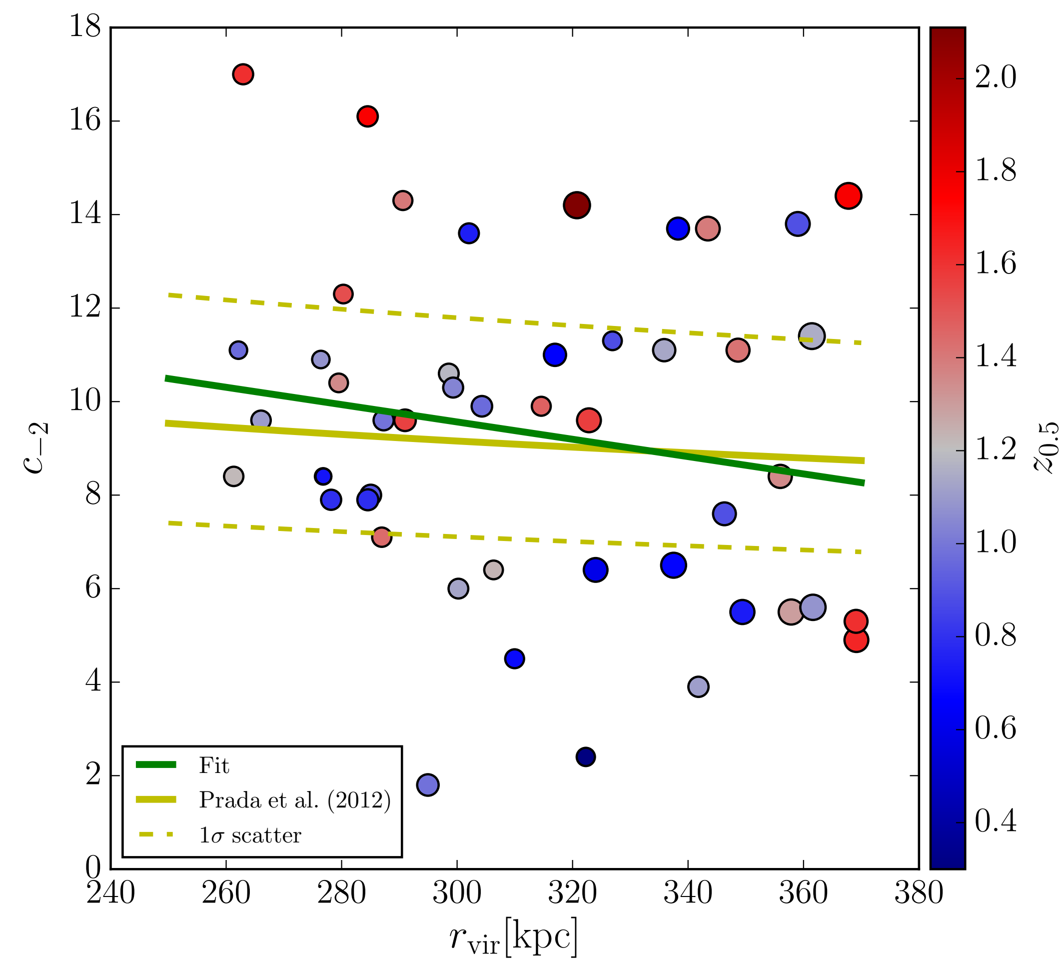


Buck et. al (2015), based on 21 hosts:

- High host halo concentration (proxy for early formation) gives more narrow satellite planes.
- Solves problem if MW & M31 formed early and/or have high concentration halos.

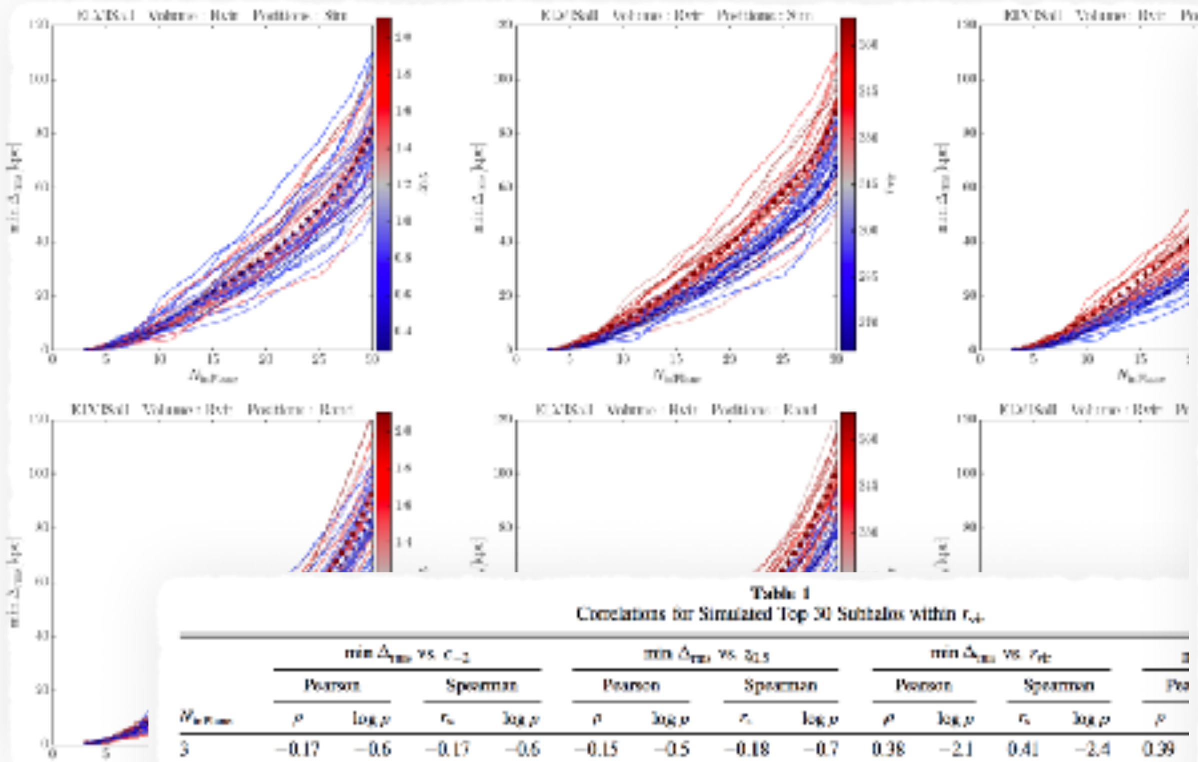
We test these findings with a number of improvements:

- 60 (Phat)ELVIS hosts, similar parameter space.
- Compare to randomized satellite systems, too.
- Consider PAndAS survey footprint.
- Employ *quantitative* tests of correlations.



Pawlowski, Bullock, Kelley & Famaey; 2019, ApJ, 875, 105

We employ many different tests to look for correlations … I'll spare you the details, check out the paper if interested.



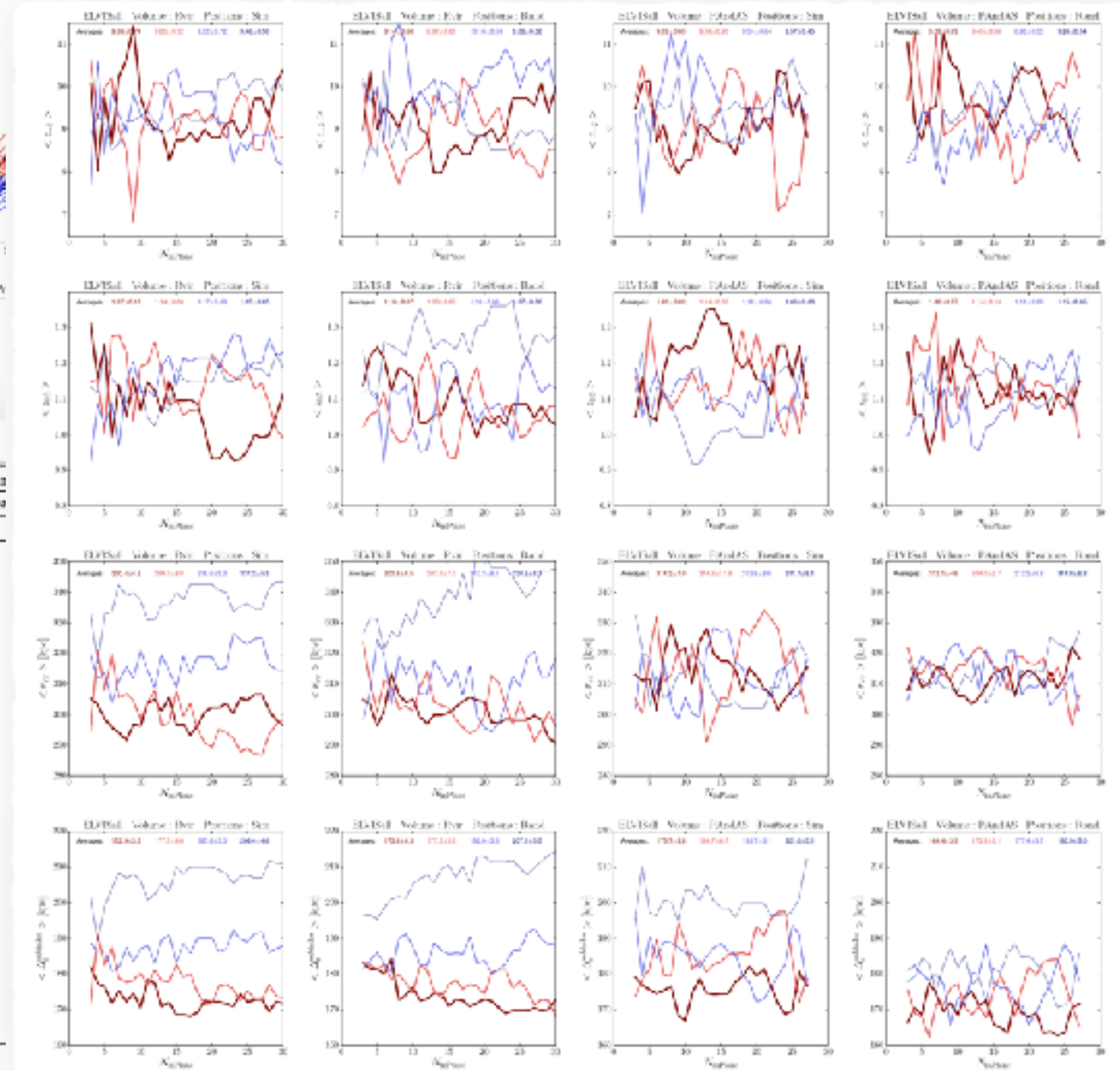


Table 1
Correlations for Simulated Top 30 Subhalos within r_{vir}

	min Δ_{rms} vs. c_{-2}				min Δ_{rms} vs. $z_{0.5}$				min Δ_{rms} vs. r_{vir}				
	Pearson		Spearman		Pearson		Spearman		Pearson		Spearman		Pea
$N_{inPlane}$	ρ	log p	r_s	log p	ρ	log p	r_s	log p	ρ	log p	r_s	log p	ρ
3	−0.17	−0.6	−0.17	−0.6	−0.15	−0.5	−0.18	−0.7	0.38	−2.1	0.41	−2.4	0.39
4	0.24	−1.0	0.20	−0.7	0.05	−0.1	−0.03	−0.1	0.22	−0.9	0.18	−0.6	0.27
5	−0.03	−0.1	−0.06	−0.2	0.03	−0.1	0.02	−0.1	0.40	−2.4	0.38	−2.1	0.45
6	−0.10	−0.3	−0.06	−0.2	−0.04	−0.1	0.00	−0.0	0.39	−2.2	0.32	−1.6	0.54
7	−0.14	−0.5	−0.15	−0.5	−0.08	−0.2	−0.09	−0.3	0.52	−3.8	0.50	−3.5	0.58
8	−0.15	−0.5	−0.13	−0.4	−0.04	−0.1	0.01	−0.0	0.58	−4.8	0.57	−4.5	0.65
9	−0.10	−0.3	−0.14	−0.5	−0.06	−0.2	0.02	−0.0	0.53	−3.9	0.50	−3.5	0.63
10	−0.11	−0.3	−0.03	−0.1	−0.11	−0.3	0.01	−0.0	0.47	−3.1	0.47	−3.1	0.61
11	−0.11	−0.3	−0.04	−0.1	−0.13	−0.4	−0.10	−0.3	0.42	−2.5	0.37	−2.0	0.54
12	−0.12	−0.4	−0.07	−0.2	−0.13	−0.4	−0.13	−0.4	0.41	−2.4	0.37	−2.0	0.56
13	−0.08	−0.2	−0.04	−0.1	−0.03	−0.1	−0.02	−0.1	0.42	−2.5	0.41	−2.4	0.65
14	−0.06	−0.2	0.01	−0.0	−0.04	−0.1	−0.05	−0.1	0.42	−2.5	0.43	−2.6	0.66
15	−0.05	−0.1	0.03	−0.1	0.00	−0.0	0.01	−0.0	0.44	−2.7	0.43	−2.6	0.70
16	−0.03	−0.1	0.03	−0.1	0.01	−0.0	0.04	−0.1	0.47	−3.1	0.49	−3.4	0.72
17	−0.03	−0.1	−0.00	−0.0	0.04	−0.1	0.05	−0.1	0.51	−3.7	0.52	−3.9	0.73
18	0.00	−0.0	0.01	−0.0	0.10	−0.3	0.09	−0.3	0.53	−3.9	0.53	−4.0	0.74
19	−0.01	−0.0	0.00	−0.0	0.11	−0.3	0.14	−0.5	0.52	−3.8	0.51	−3.6	0.74
20	−0.00	−0.0	0.01	−0.0	0.13	−0.4	0.16	−0.6	0.53	−3.9	0.51	−3.7	0.74
21	−0.00	−0.0	0.04	−0.1	0.12	−0.4	0.15	−0.5	0.51	−3.7	0.49	−3.4	0.72
22	−0.00	−0.0	0.01	−0.0	0.13	−0.4	0.16	−0.5	0.51	−3.7	0.48	−3.2	0.71
23	−0.00	−0.0	−0.01	−0.0	0.16	−0.5	0.16	−0.6	0.50	−3.6	0.46	−3.0	0.71
24	0.00	−0.0	−0.00	−0.0	0.17	−0.6	0.16	−0.6	0.49	−3.4	0.44	−2.8	0.71
25	−0.01	−0.0	−0.03	−0.1	0.17	−0.6	0.13	−0.4	0.48	−3.3	0.45	−2.8	0.72
26	−0.01	−0.0	−0.05	−0.1	0.17	−0.6	0.13	−0.4	0.46	−3.0	0.46	−2.9	0.70
27	−0.01	−0.0	−0.03	−0.1	0.16	−0.6	0.14	−0.5	0.45	−2.9	0.48	−3.2	0.70
28	−0.00	−0.0	−0.02	−0.1	0.15	−0.5	0.14	−0.4	0.45	−2.9	0.48	−3.3	0.70
29	−0.01	−0.0	−0.02	−0.0	0.17	−0.6	0.14	−0.5	0.44	−2.7	0.47	−3.2	0.69
30	−0.04	−0.1	−0.05	−0.2	0.14	−0.4	0.11	−0.3	0.45	−2.9	0.47	−3.1	0.68
Average	−0.04	−0.2	−0.03	−0.2	0.04	−0.3	0.05	−0.3	0.46	−3.1	0.45	−3.0	0.64

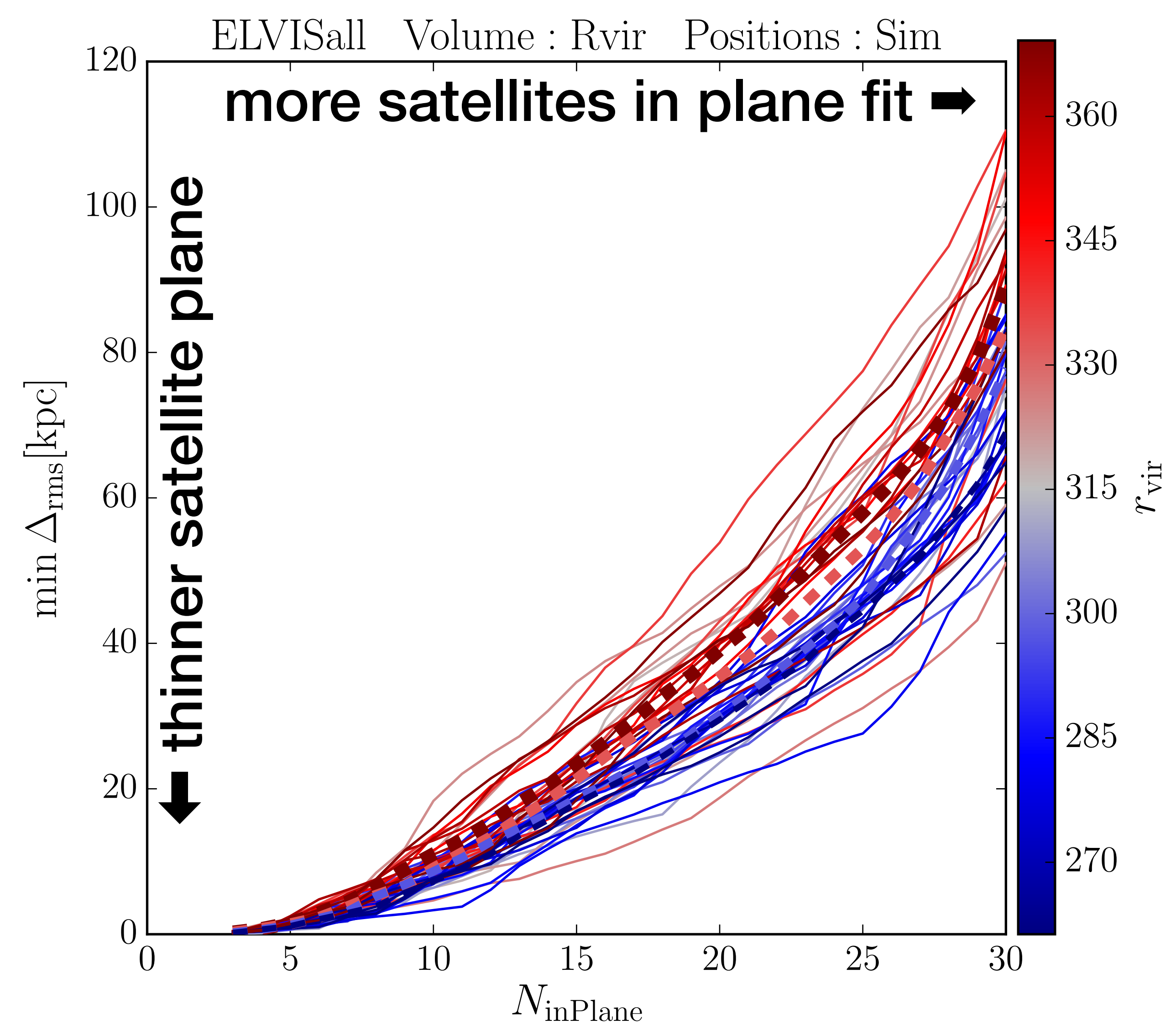
Note. Correlation coefficients and logarithms of the corresponding p-values for Pearson (ρ) and Spearman (r_s) tests of correlations between the minimum plane heights min Δ_{rms} for different numbers of satellites in a plane $N_{inPlane}$ vs. various halo parameters: halo concentration c_{-2}, formation redshift $z_{0.5}$, virial radius r_{vir}, and rms radius of the subhalo distribution $\Delta^{subhalo}$.

Pawlowski, Bullock, Kelley & Famaey; 2019, ApJ, 875, 105

Correlation with halo mass / viral radius?

Correlation seen if 30 satellites selected from virial volume.

➡ Absolute plane width sensitive to overall extent of satellite distribution.



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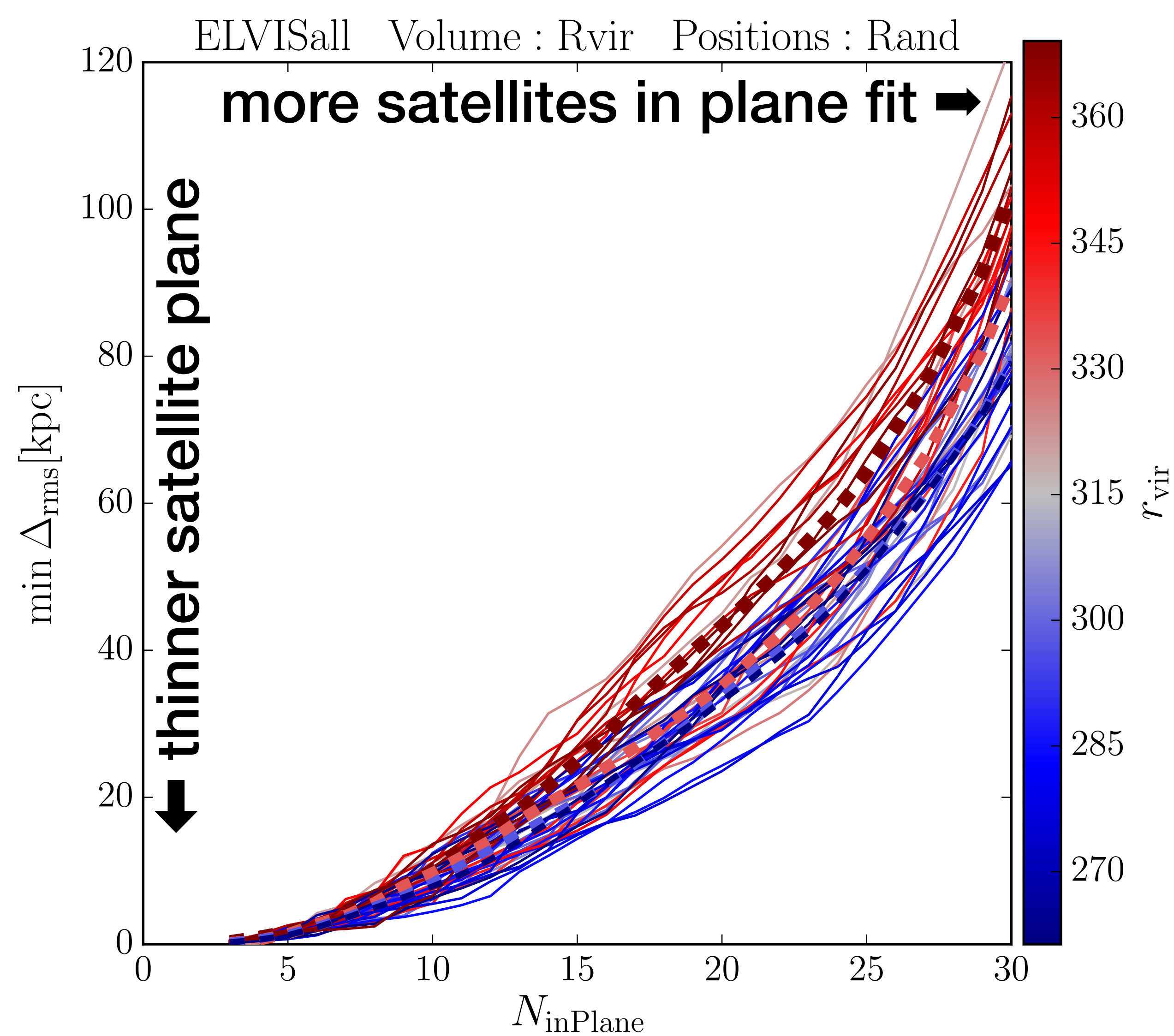
➡ Absolute plane width sensitive to overall extent of satellite distribution.

➡ Same present in distributions drawn from isotropy.

➡ Not a feature of ΛCDM.



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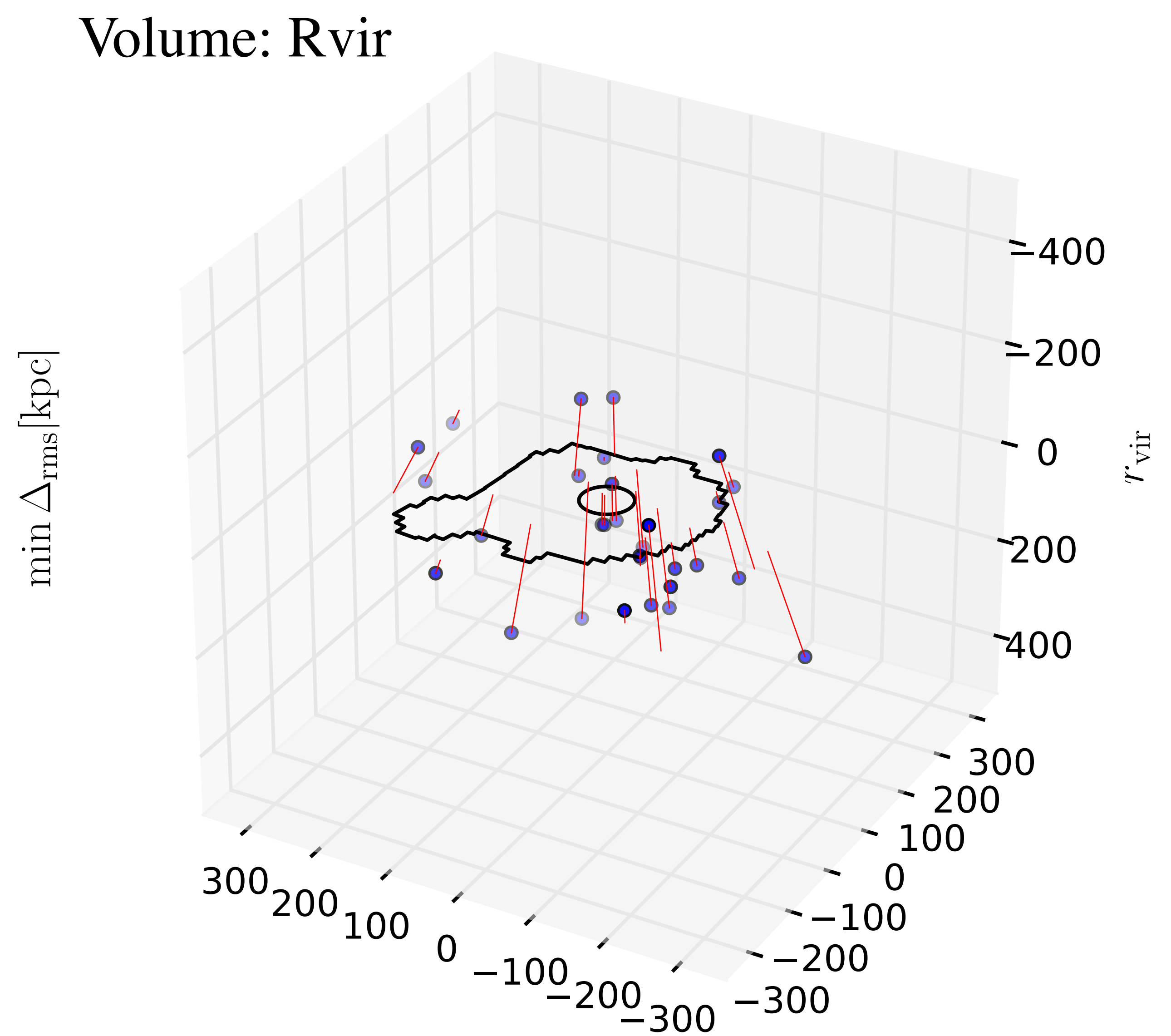
Need to select satellites from mock-PAndAS volume.



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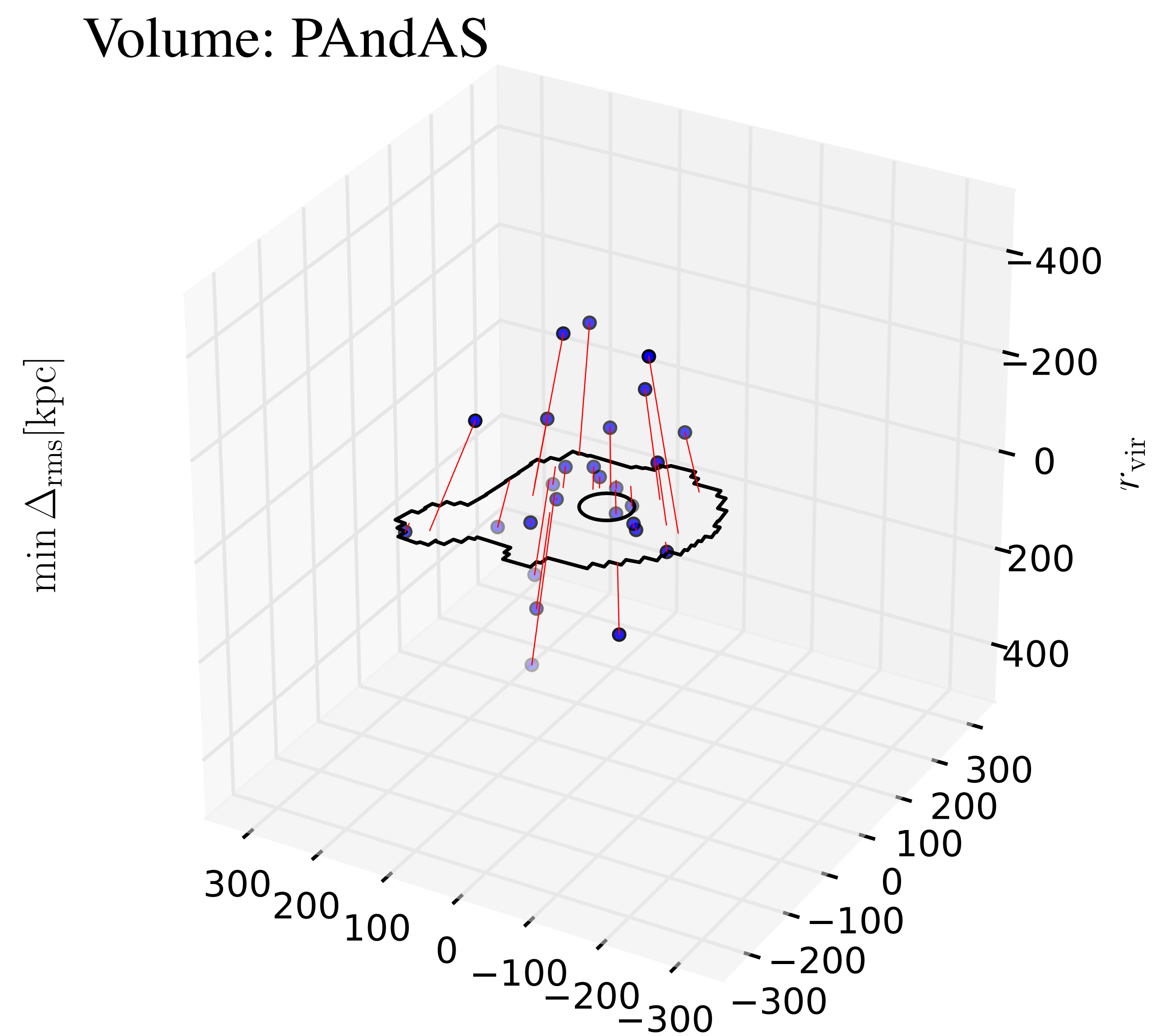


Pawlowski, Bullock, Kelley & Famaey; 2019, ApJ, 875, 105

Correlation with halo mass / viral radius?

No

Correlation seen if 30 satellites selected from virial volume.

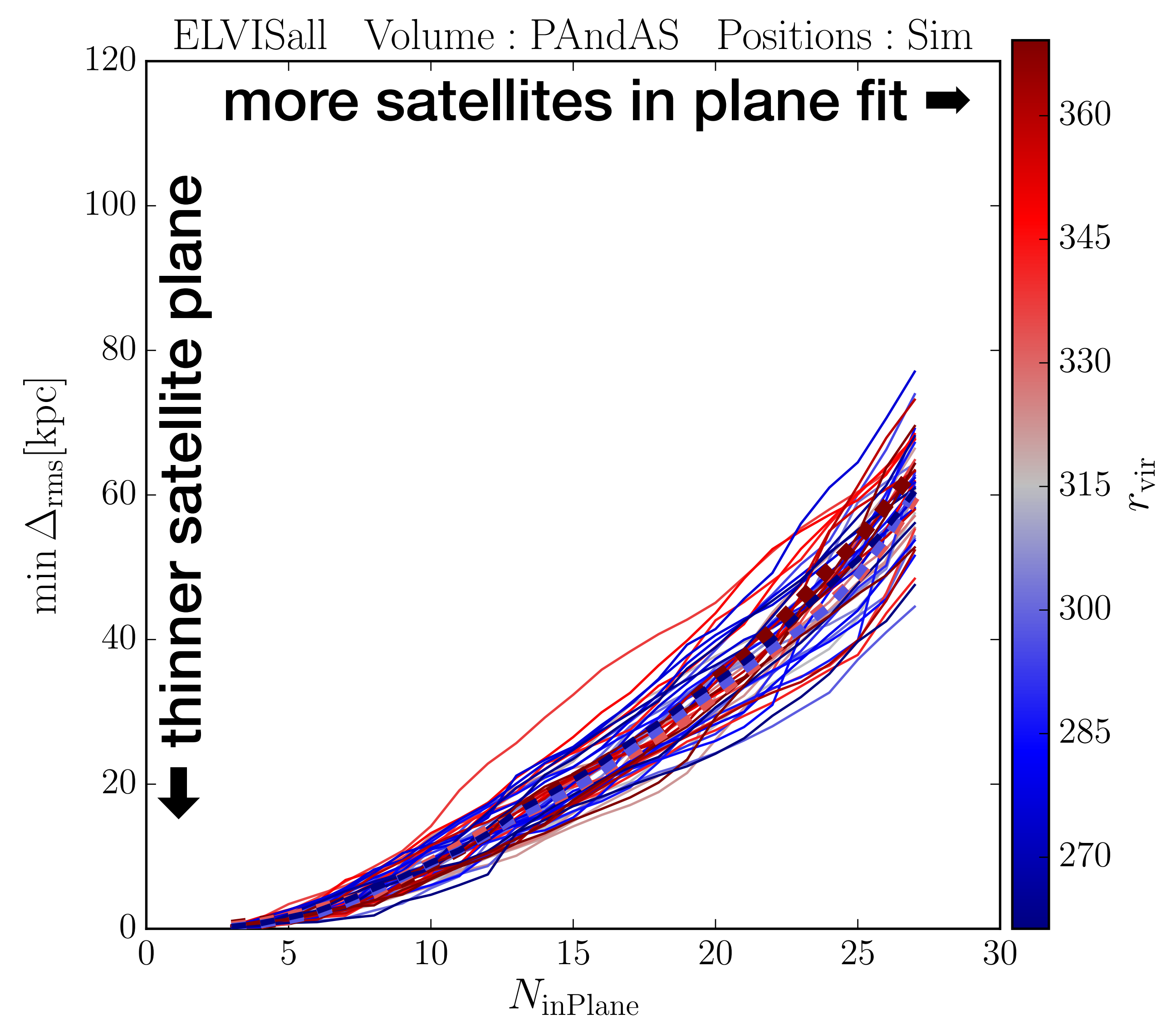
➡ Absolute plane width sensitive to overall extent of satellite distribution.

➡ Same present in distributions drawn from isotropy.

➡ Not a feature of ΛCDM.

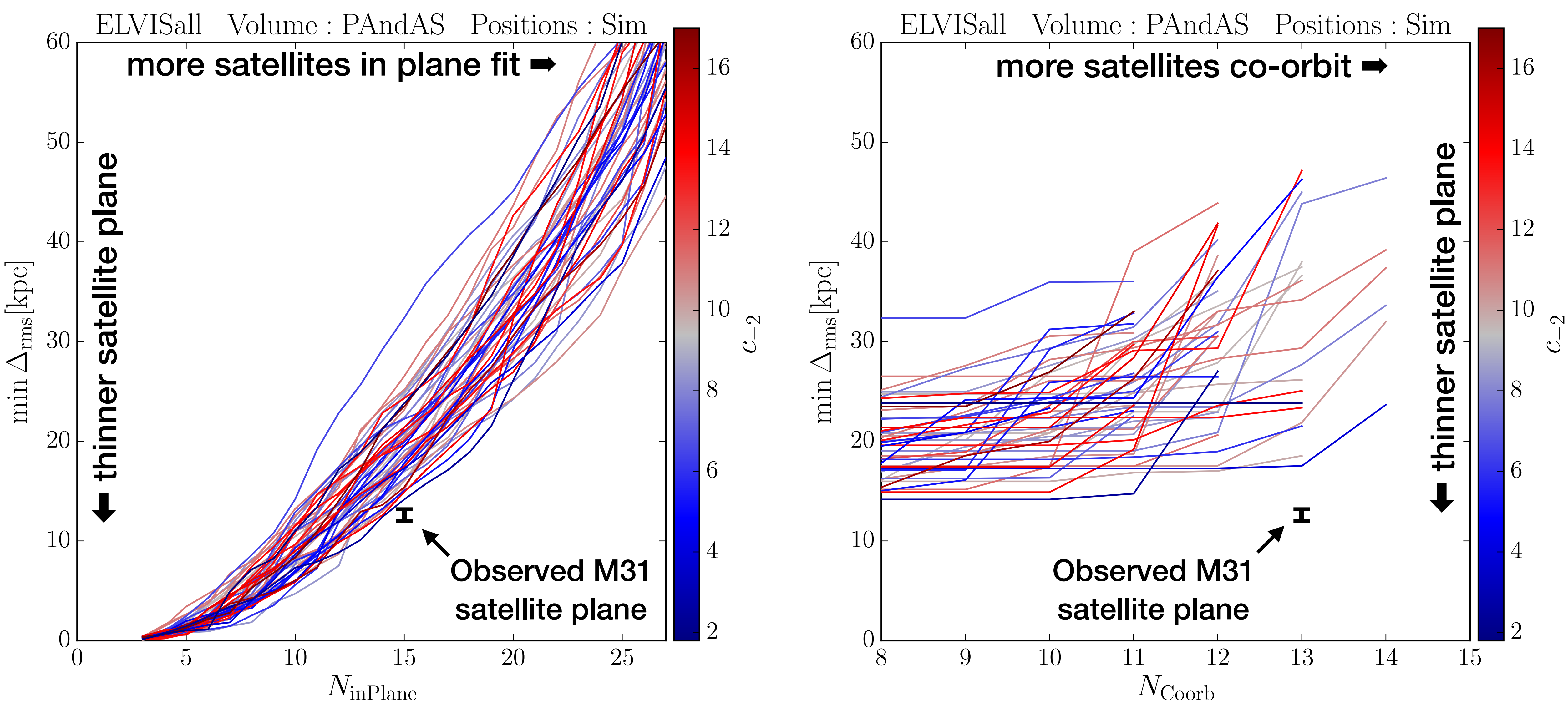
Need to select satellites from mock-PAndAS volume.

Then no correlation with viral mass/radius.



Correlation with halo concentration / formation time?

No correlation of satellite plane width or kinematic coherence with c_{-2} or $z_{0.5}$.



Pawlowski, Bullock, Kelley & Famaey; 2019, ApJ, 875, 105

Correlation with halo concentration / formation time?

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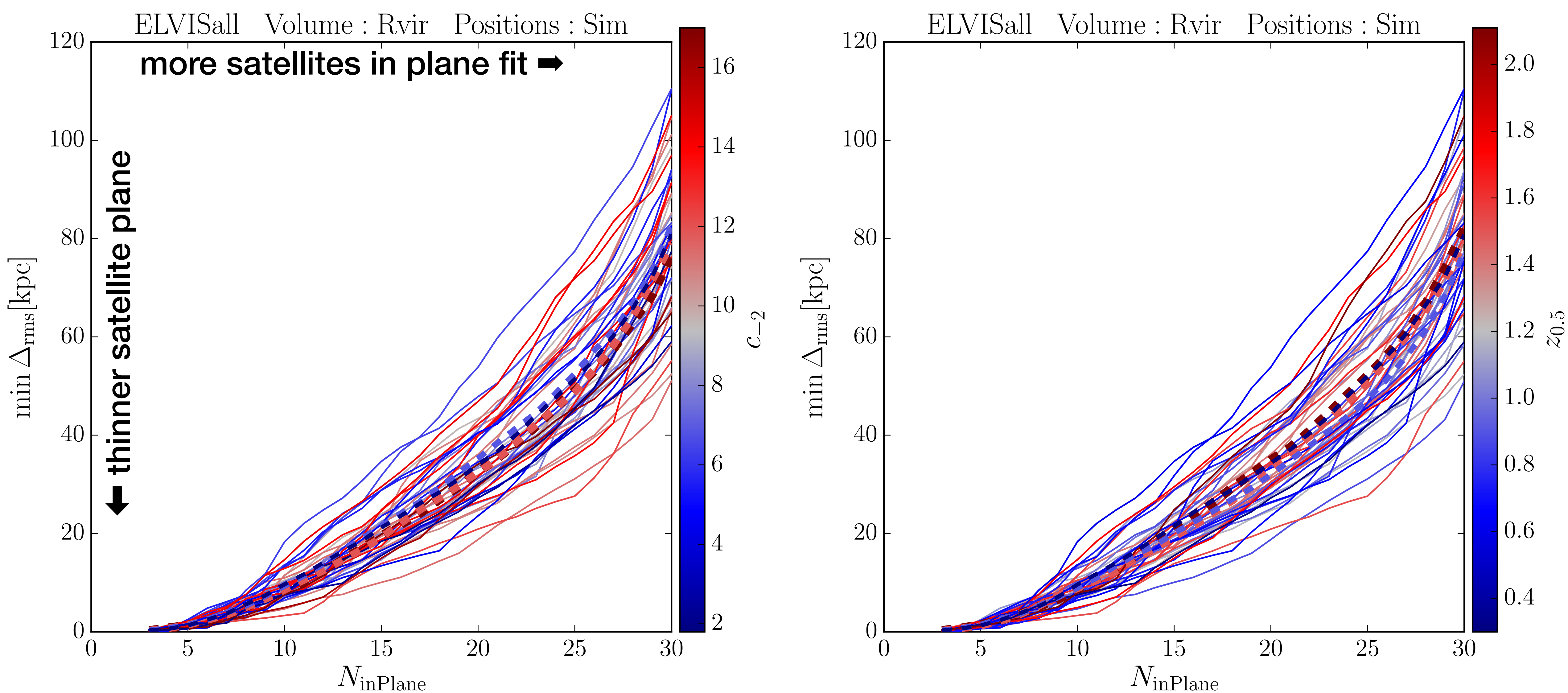
Not even if satellites selected from virial volume.



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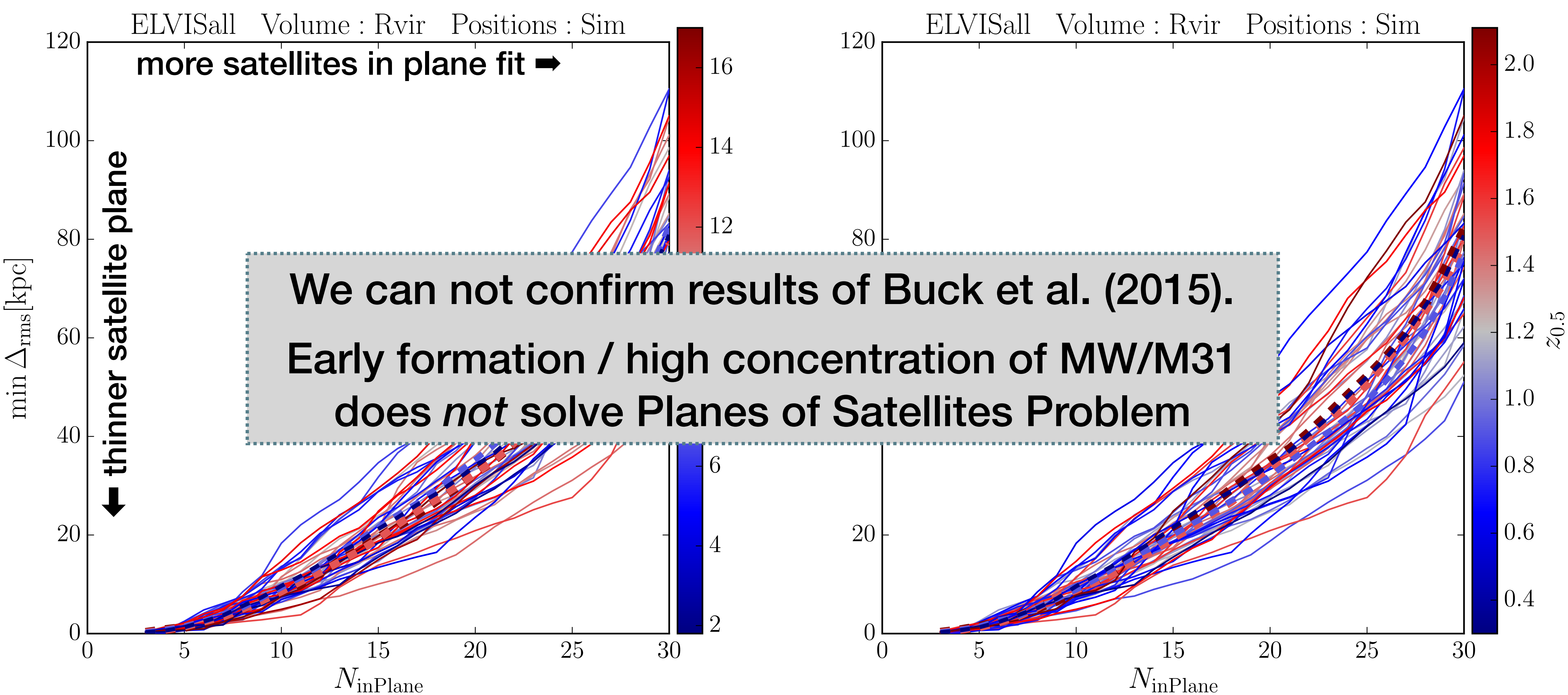


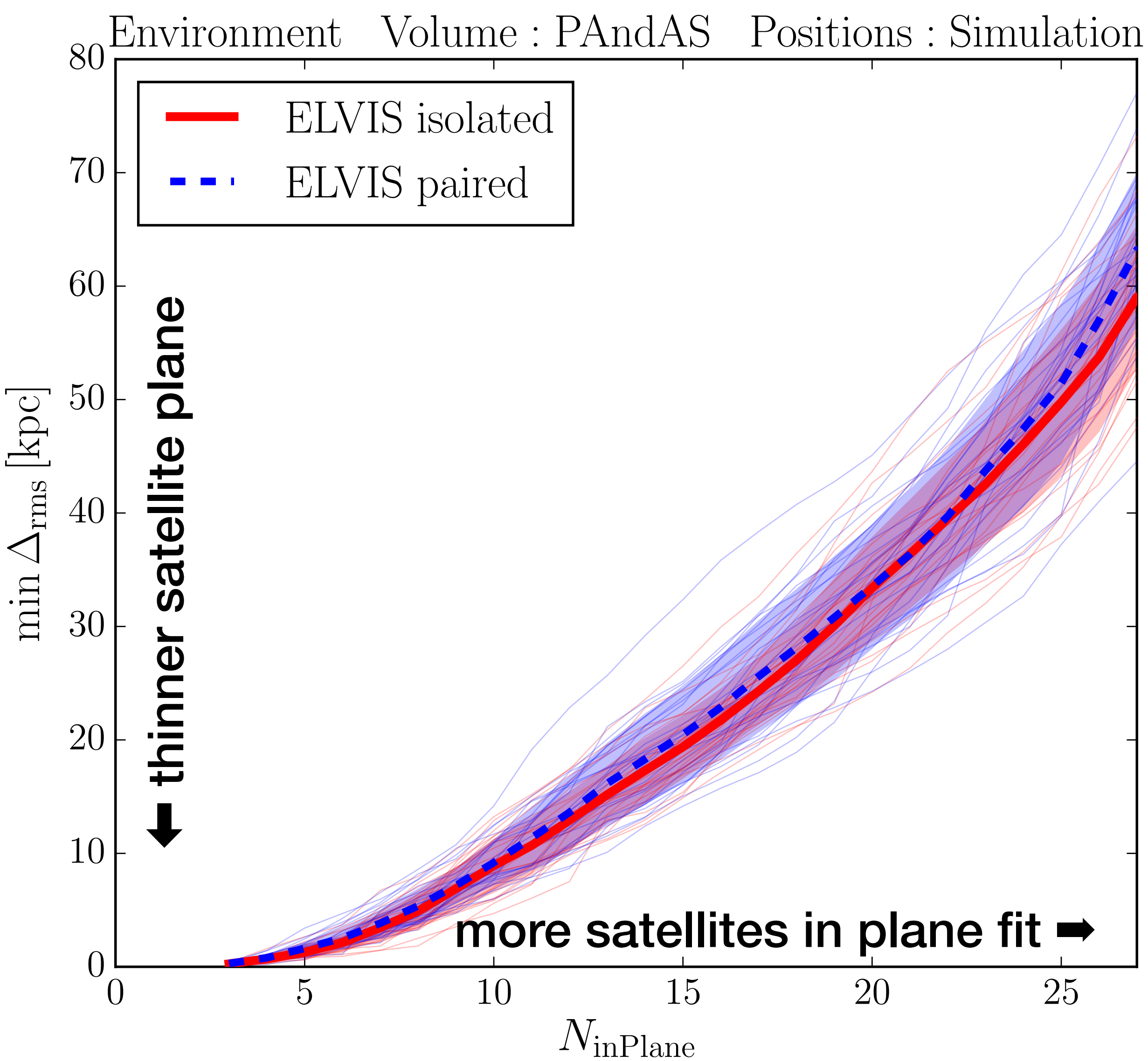
We can not confirm results of Buck et al. (2015).

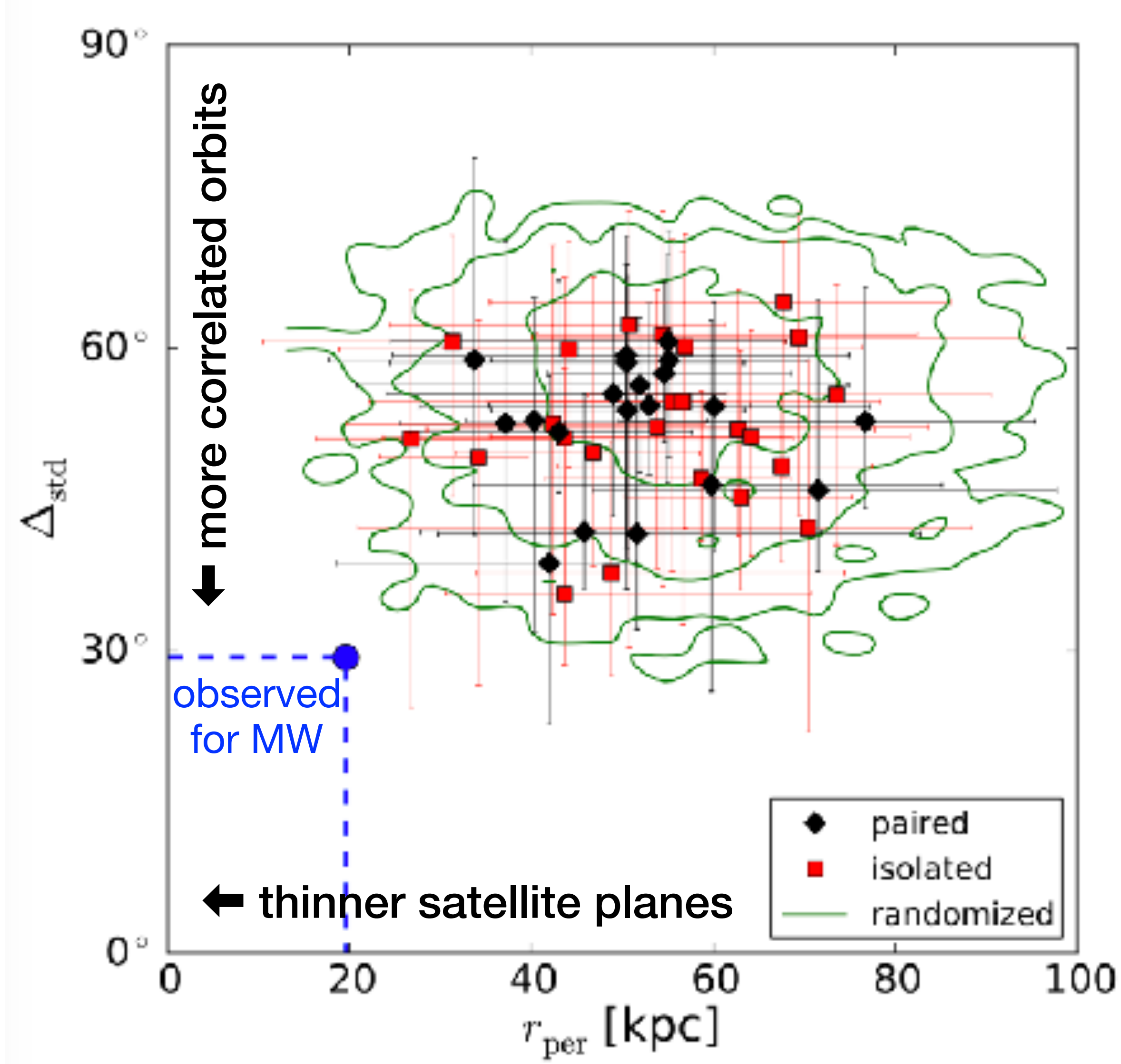
Early formation / high concentration of MW/M31 does *not* solve Planes of Satellites Problem

Correlation with being in a paired configuration of hosts? No

No difference whether in a pair of hosts or isolated.

Confirms similar result for VPOS-like selection (Pawlowski & McGaugh 2014).





Pawlowski, Bullock, Kelley & Famaey; 2019, ApJ, 875, 105

Correlation with existence of a central disk galaxy potential?

PhatELVIS: 12 MW analogs once with and without analytically grown central disk.

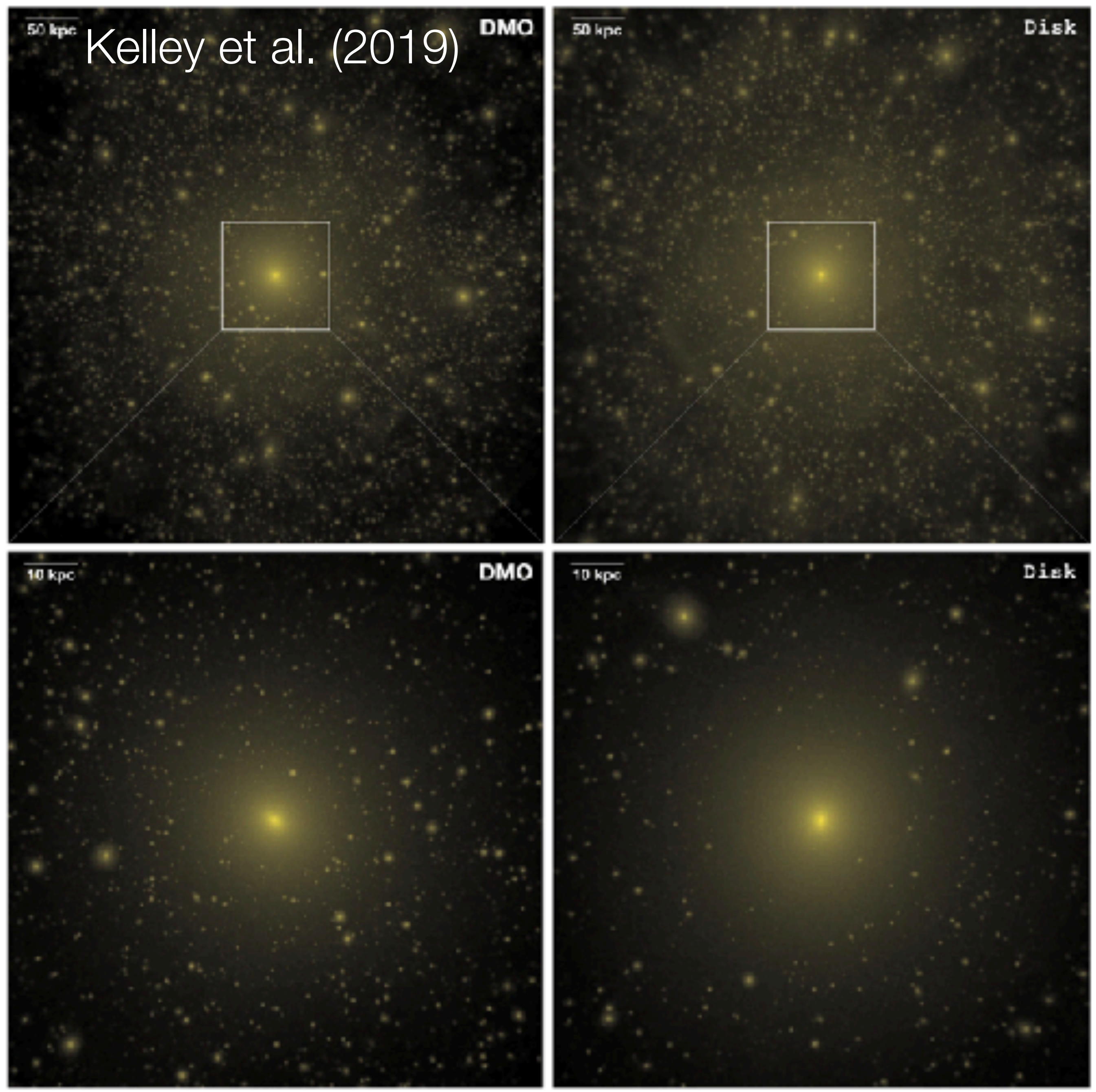


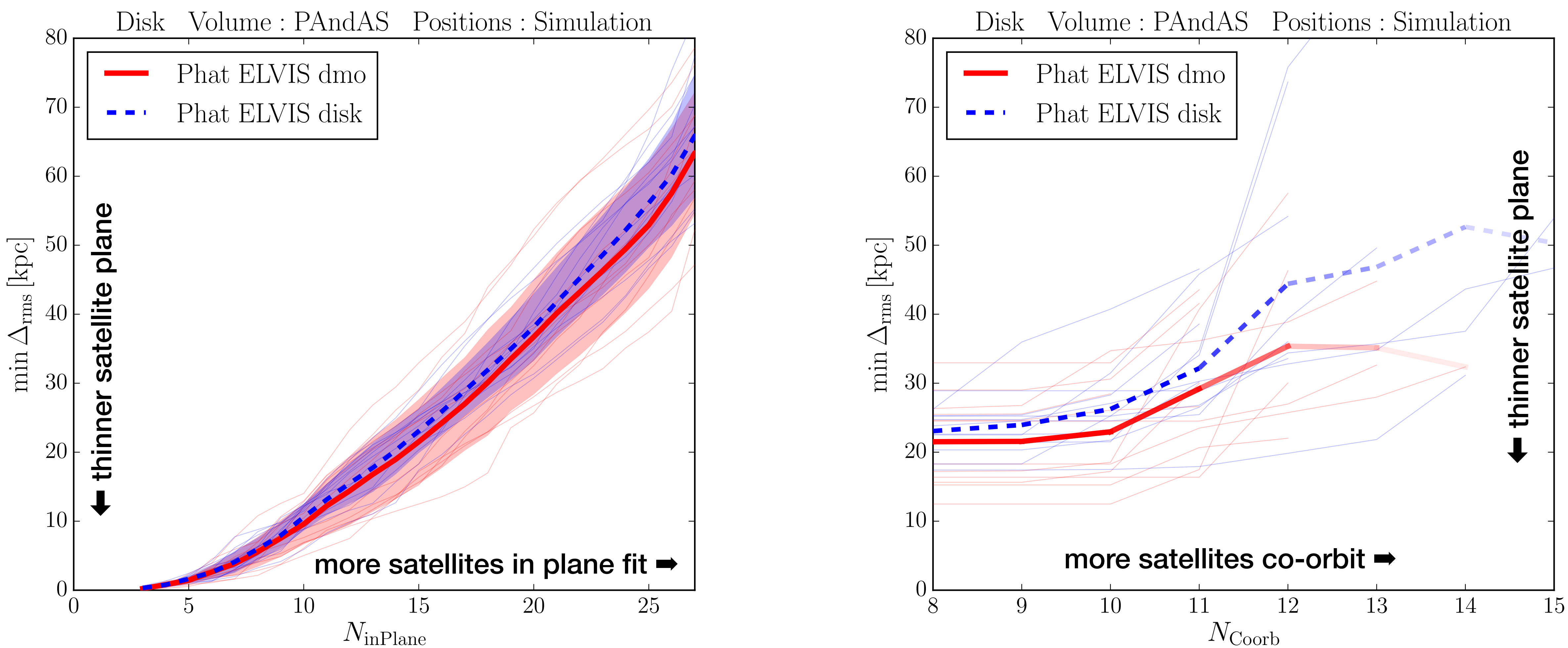
Figure 1. Visualization of the dark matter for Kentucky (left) and Kentucky Disk (right). The top panels span 500 kpc, approximately the virial volume of this halo. The bottom panels span 100 kpc. The absence of substructure at small radii in the Disk runs is striking. An enhancement in central dark matter density is also seen in the Disk runs, which is a result of baryonic contraction. The disk potentials are oriented face-on in these images.

Pawlowski, Bullock, Kelley & Famaey; 2019, ApJ, 875, 105

Correlation with existence of a central disk galaxy potential?

PhatELVIS: 12 MW analogs once with and without analytically grown central disk.

No differences in flattening of satellite system whether central disk present or not.

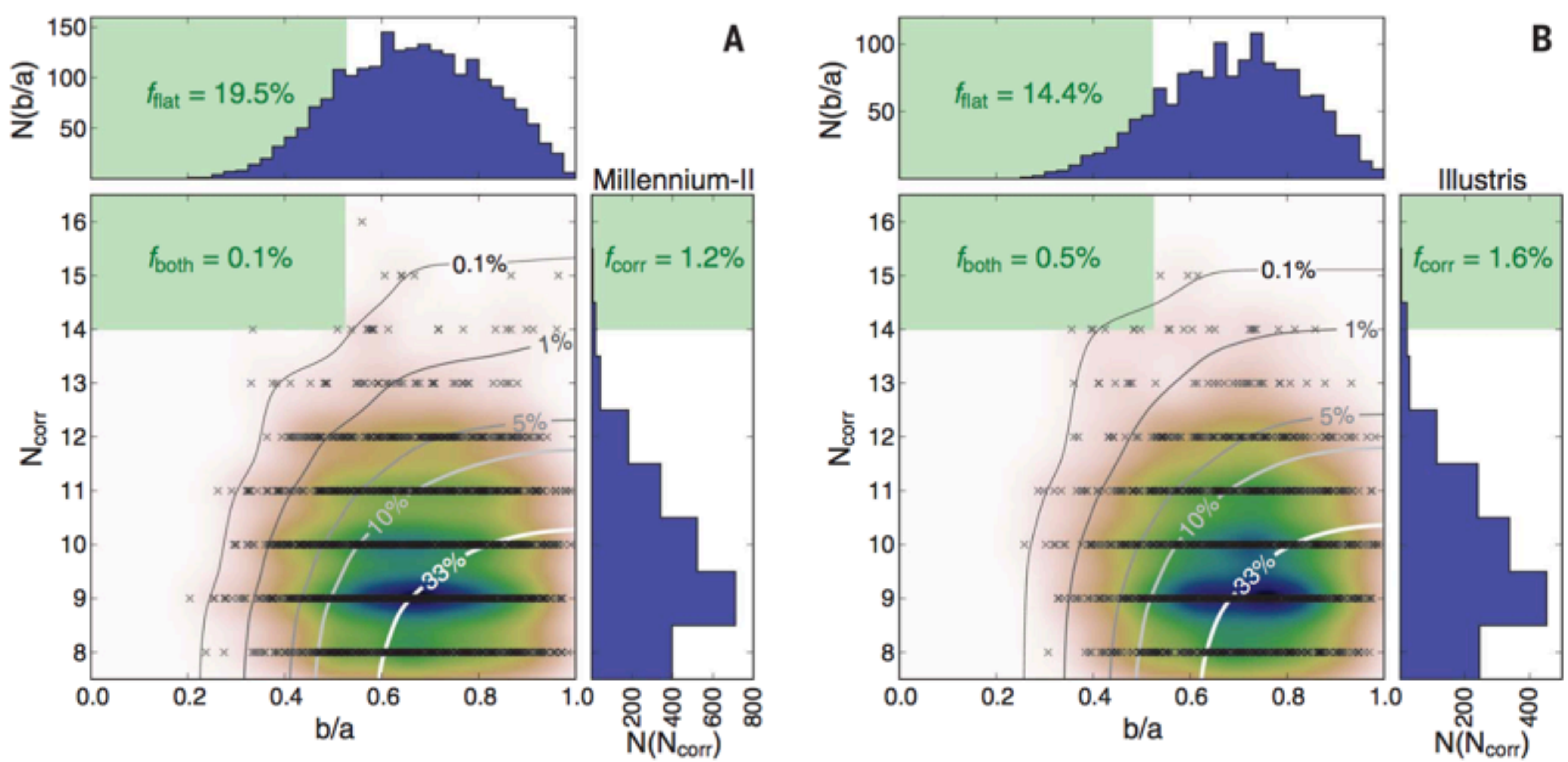


Correlation with existence of a central disk galaxy potential? No

PhatELVIS: 12 MW analogs once with and without analytically grown central disk.

No differences in flattening of satellite system whether central disk present or not.

Also no difference for Centaurus A plane in hydrodynamical Illustris simulation or dark-matter-only analog (Müller, Pawlowski, Lelli & Jerjen, 2018).

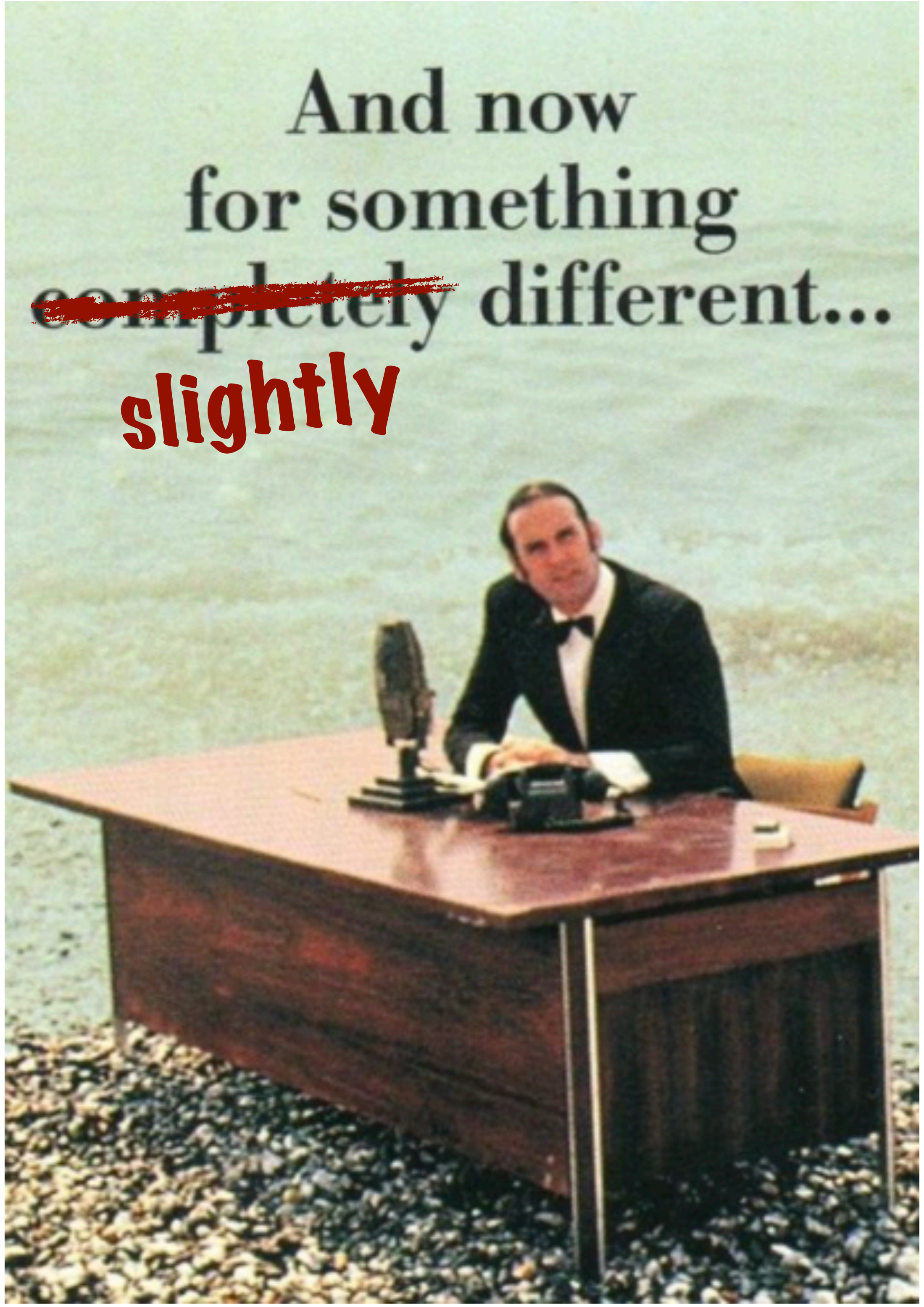


Summary

We find no indication that width or degree of kinematic coherence of satellite planes correlates with any of the studied host halo properties.

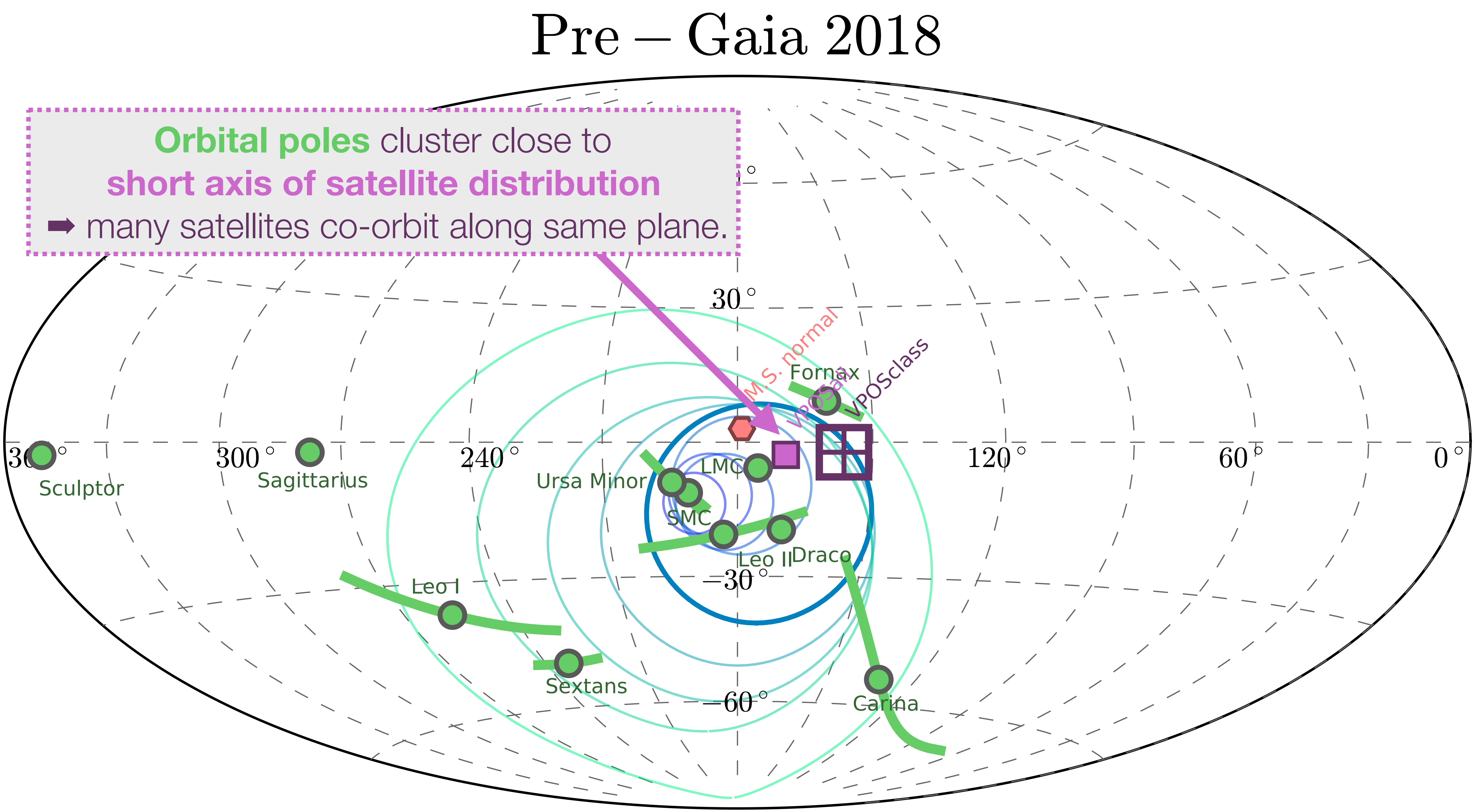
The Planes of Satellite Galaxies problem is **not solved by** claiming an **early formation** time or **high concentration** of MW/M31 halo, their **paired configuration**, or **baryonic effects** acting on the satellite distribution/orbits.

The orbital alignment of the 11 classical MW satellites with the VPOS in light of Gaia DR2



Pawlowski et al. in prep.

Orbital Poles (= directions of angular momentum)



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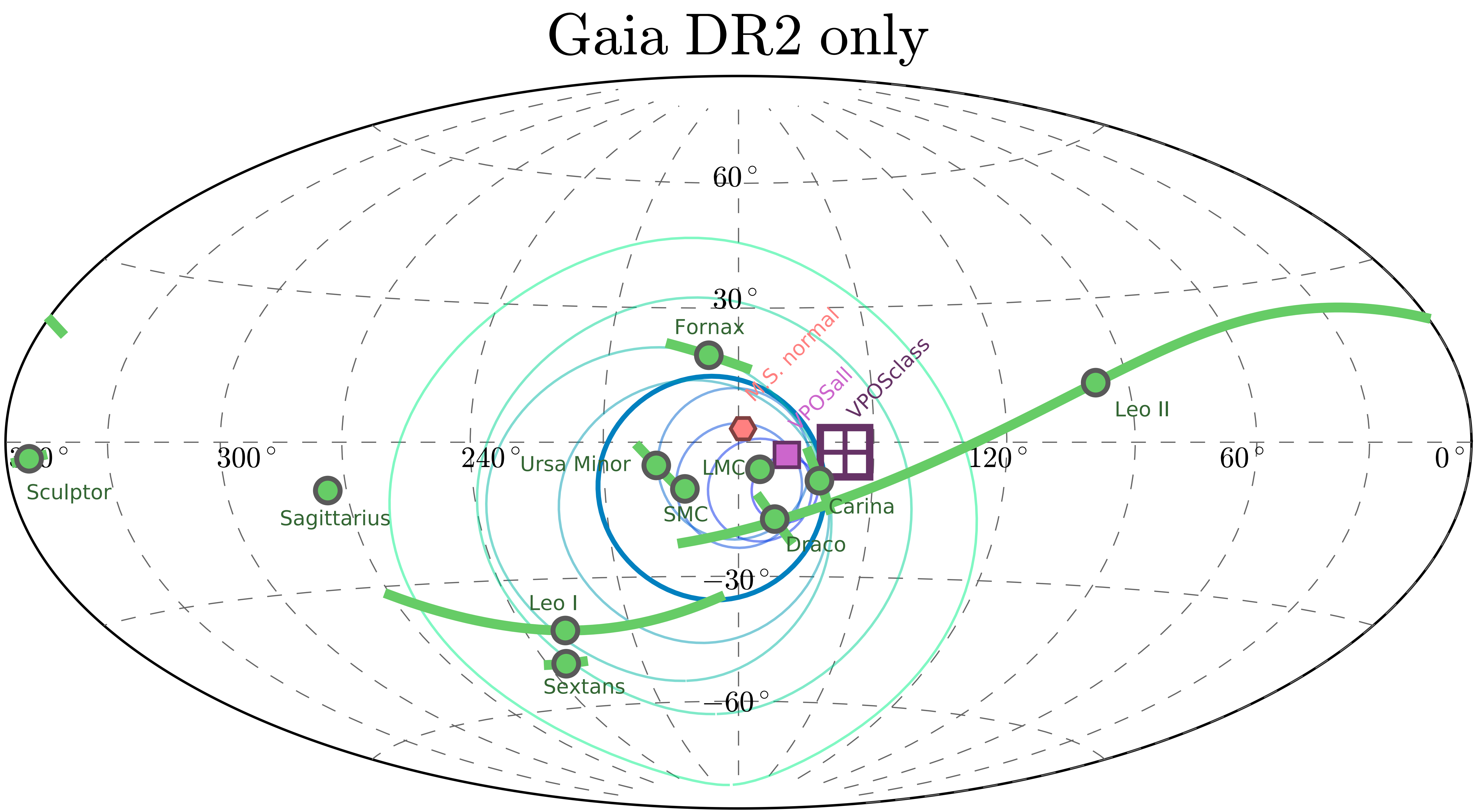

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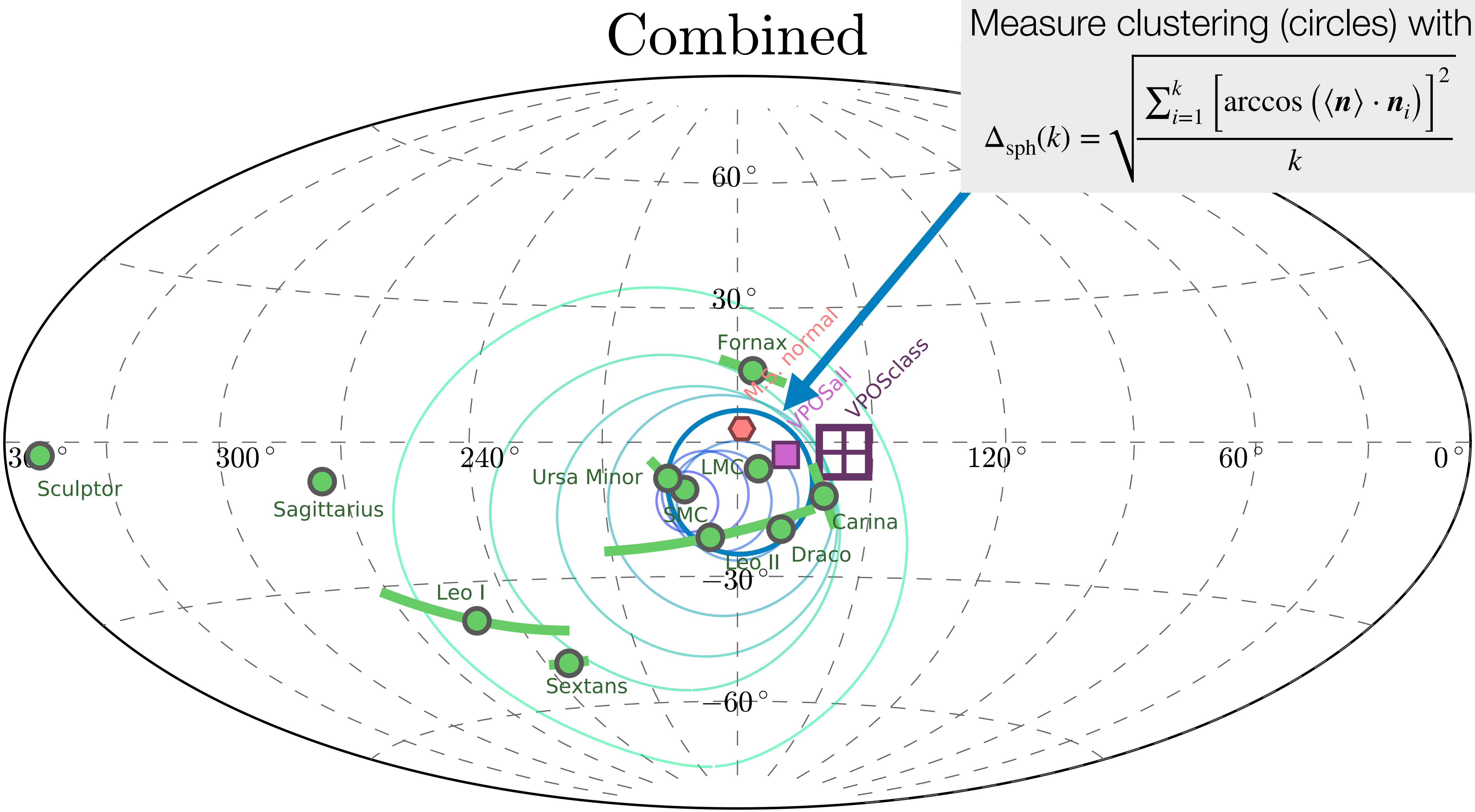
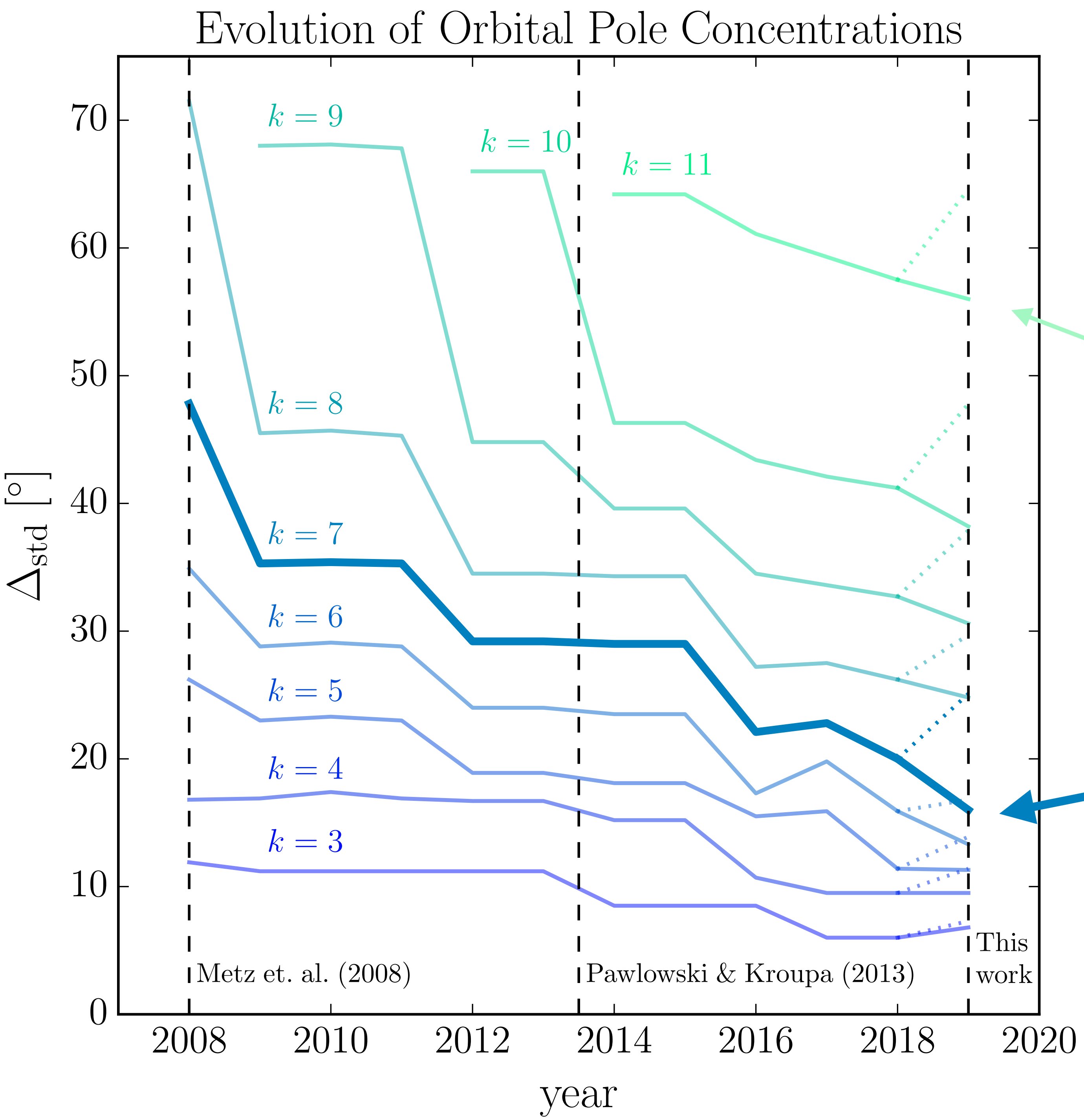


Measure clustering (circles) with

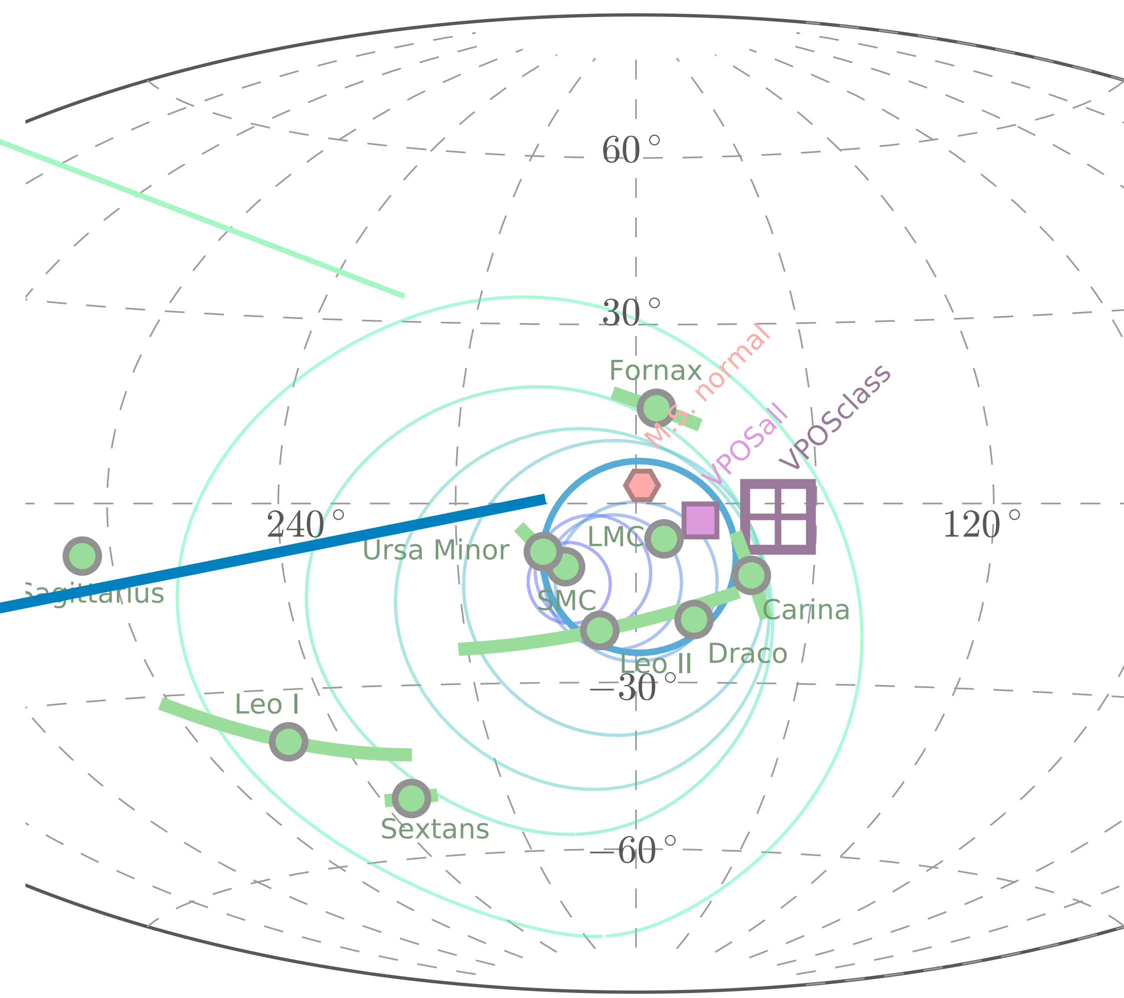
$$\Delta_{\mathrm{sph}}(k) = \sqrt{\frac{\sum_{i=1}^{k}\left[\arccos\left(\langle \boldsymbol{n} \rangle \cdot \boldsymbol{n}_i\right)\right]^2}{k}}$$

Pawlowski et al. in prep.

Evolution of Orbital Pole Clustering

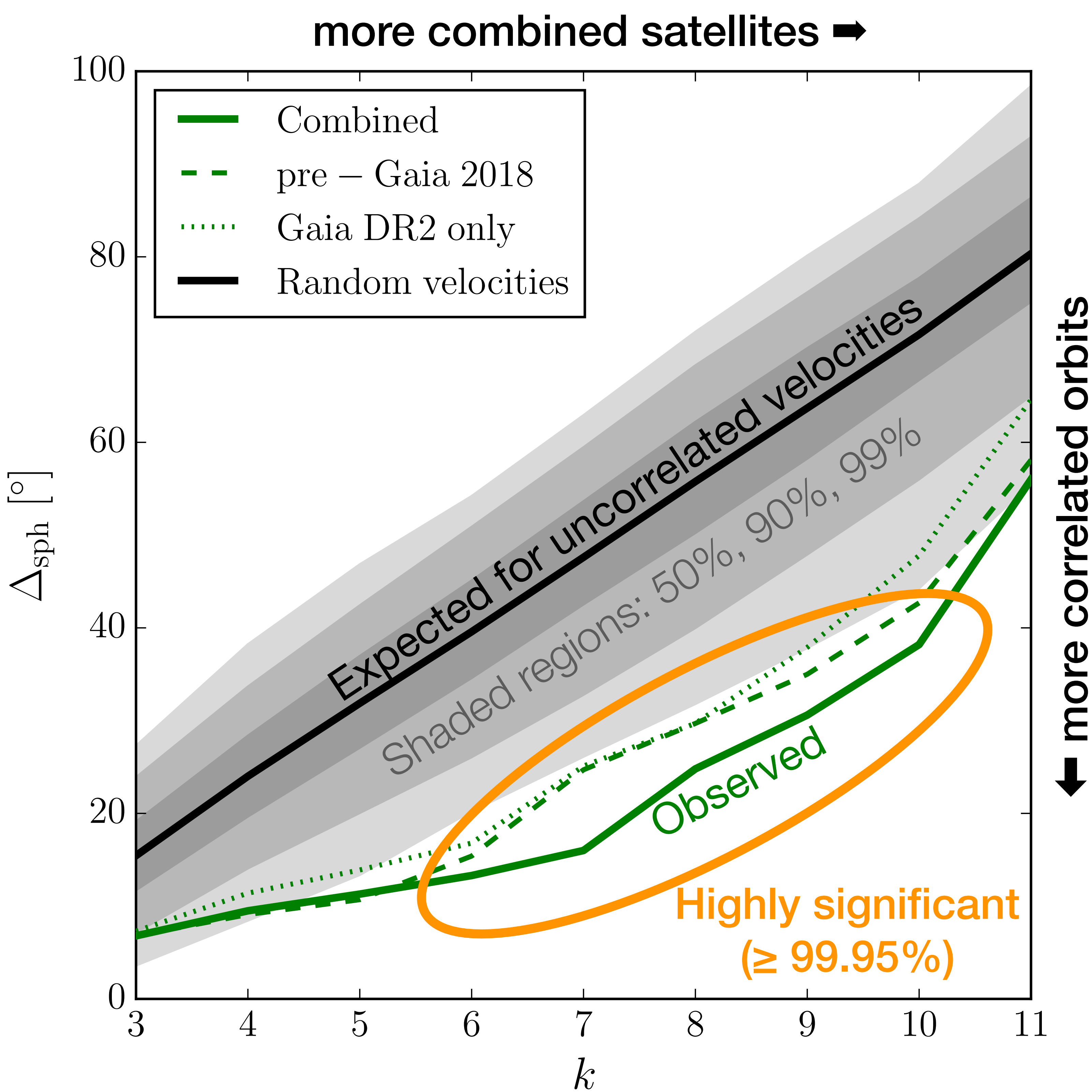


As proper motions improved, correlation became more pronounced!



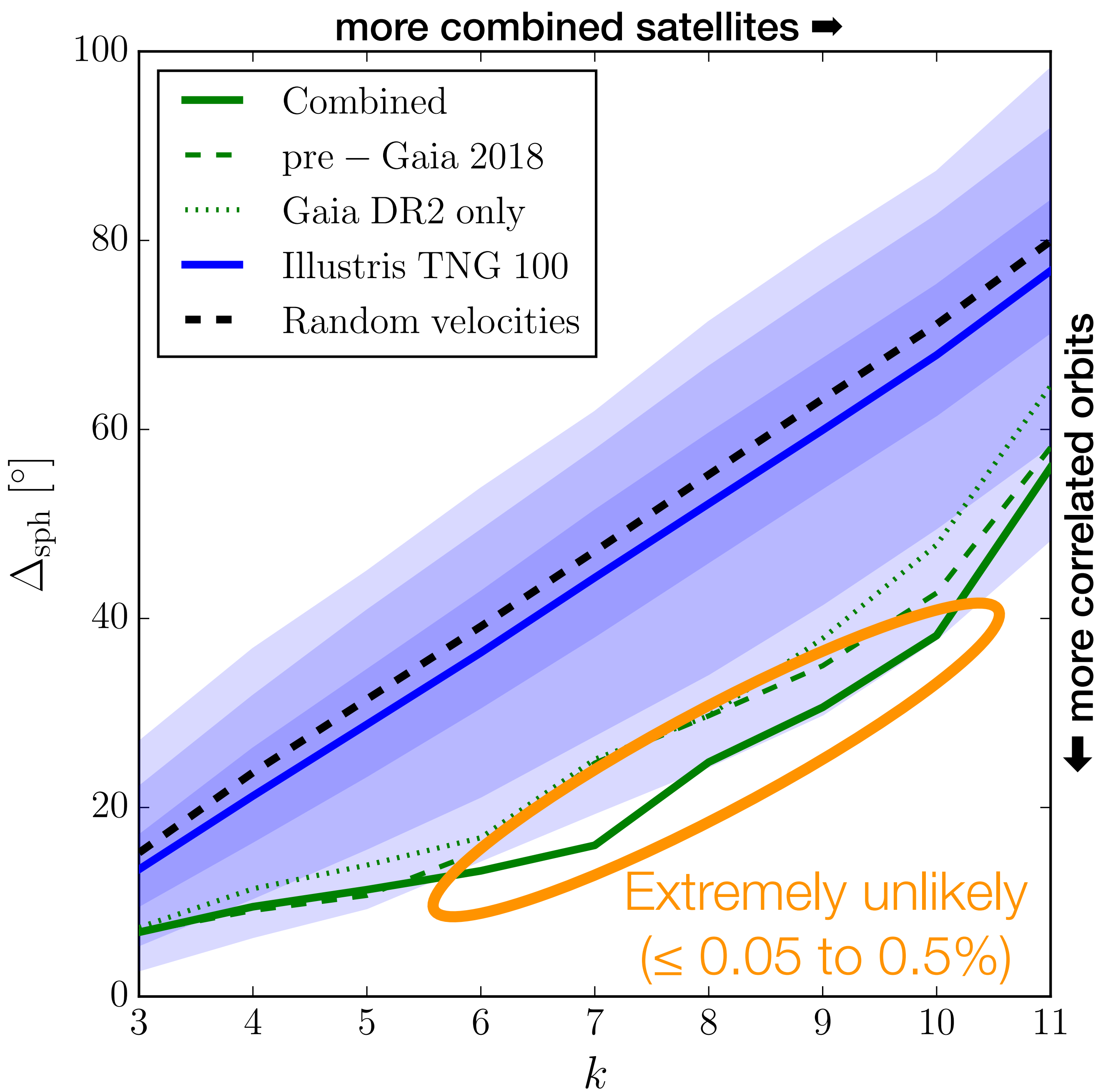
Pawlowski et al. in prep.

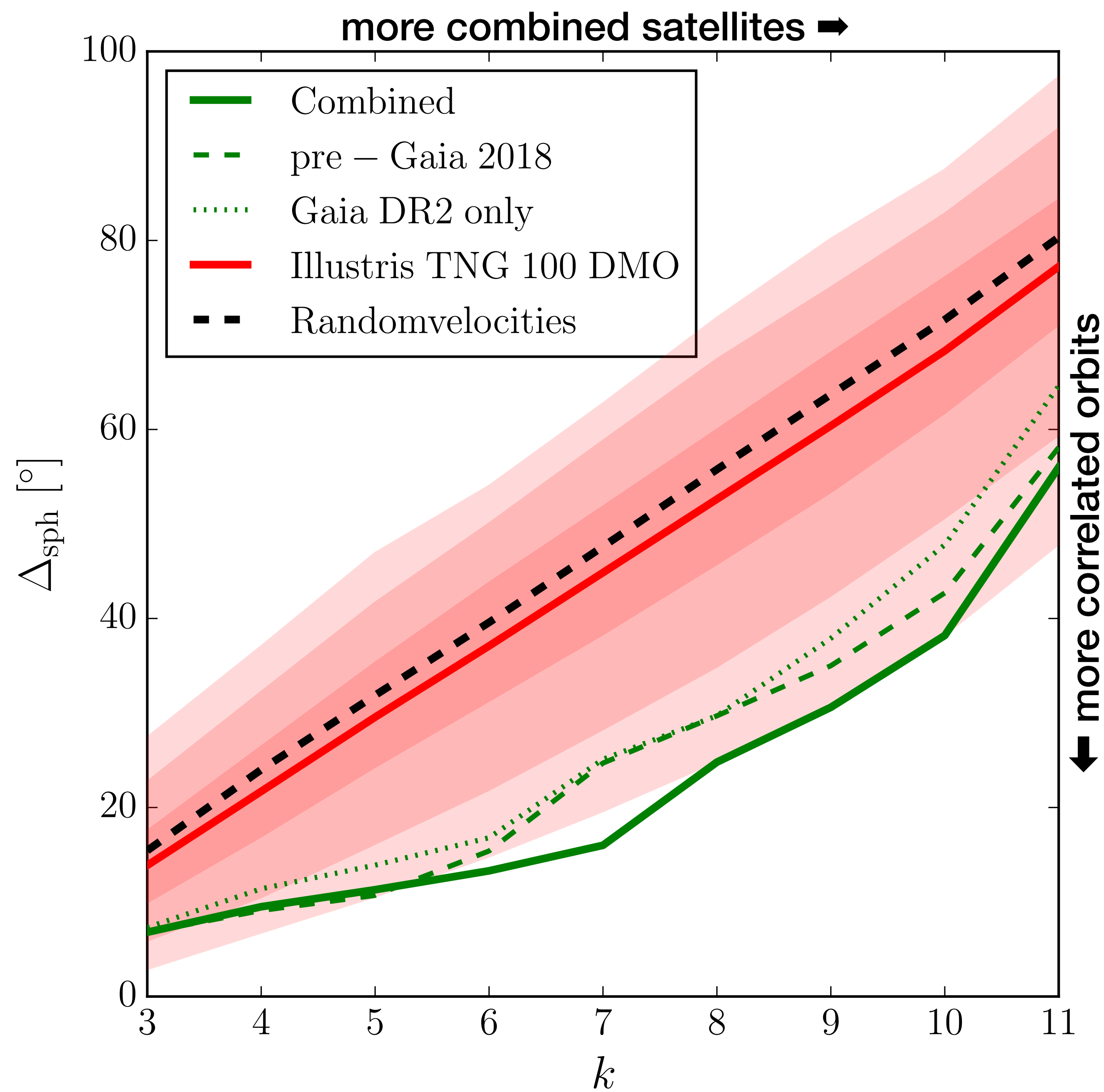
Orbital Pole Concentration vs. Random Velocities



Pawlowski et al. in prep.

Orbital Pole Concentration vs. Illustris TNG 100 simulation (hydro & DMO)



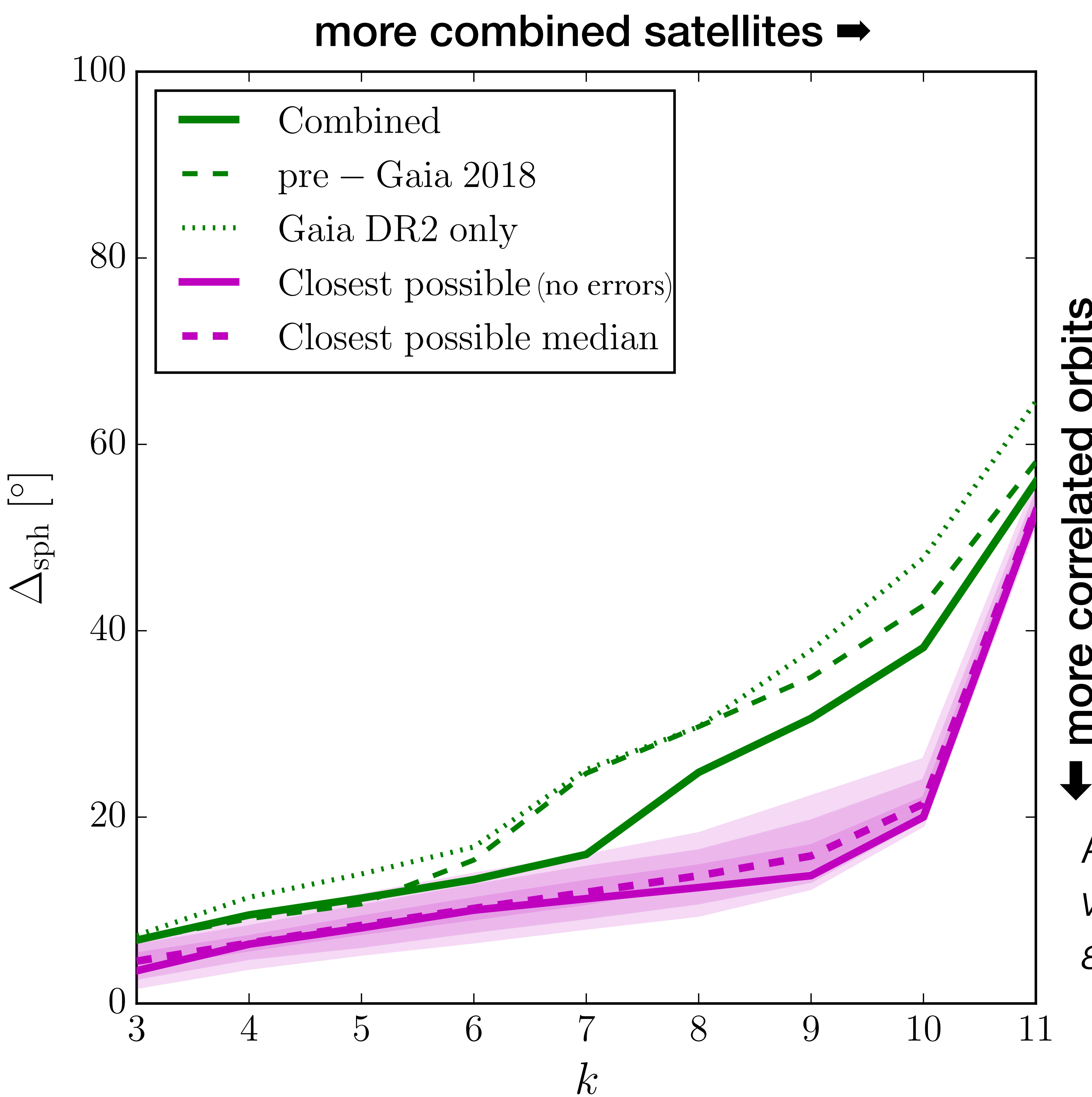


BUT: Must consider orbital pole distribution *and* spatial flattening

➡ **frequencies** drop to **≤ 0.1%** for all k.

Pawlowski et al. in prep.

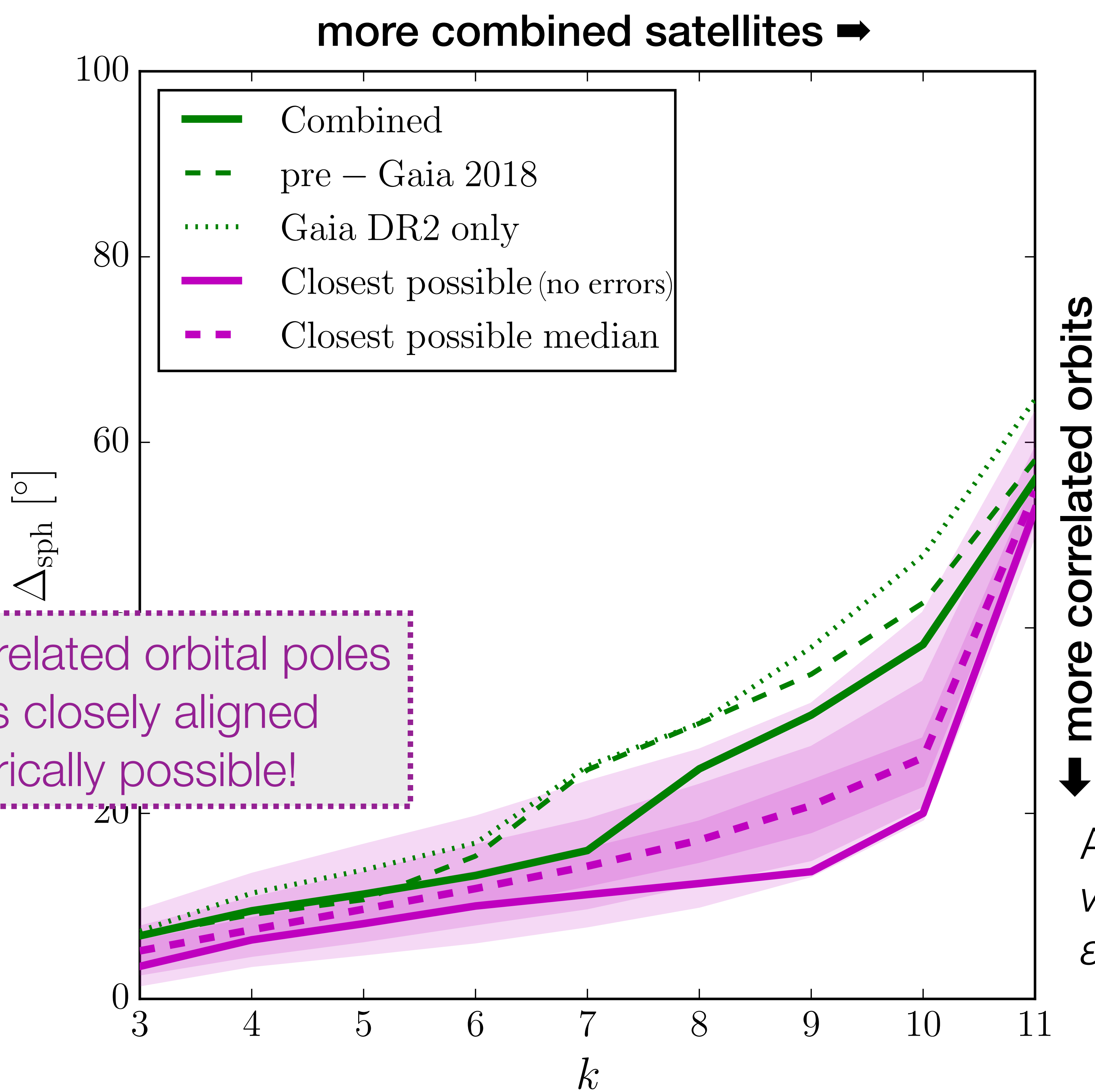
Orbital Pole Concentration vs. Best-Possible Alignment (given satellite positions)



Assumes:
v_{tan} = 175 km/s
$\varepsilon_{\mathrm{PM}}$ = 0.05 mas/yr

Pawlowski et al. in prep.

Orbital Pole Concentration vs. Best-Possible Alignment (given satellite positions)



The 7 most correlated orbital poles are about as closely aligned as geometrically possible!

Assumes:
$v_{\rm tan}$ = 175 km/s
$\varepsilon_{\rm PM}$ = 0.10 mas/yr

Conclusions

Review of Satellite Plane Problem ➡ Pawlowski (2018, MPLA, 33, 1830004).

The Planes of Satellite Galaxies problem is **not solved by** claiming an **early formation** time or **high concentration** of MW/M31 halo, their **paired configuration**, or **baryonic effects** acting on the satellite distribution/orbits.
➡ Pawlowski, Bullock, Kelley & Famaey (2019, ApJ, 875, 105)

Gaia DR2 confirms **previous work** with independent data: 8/11 classical satellites orbit close to common plane. **Improved PMs** result in **tighter clustering of orbital poles** (expected if strong underlying correlation). Combining best PMs **increases tension with ΛCDM**: ≤0.1% of simulated systems as extreme.