The Planes of Satellite Galaxies Problem:

1) What does Gaia DR2 say about the plane of classical MW satellites?
2) Do baryonic effects or special host halo properties help?

Marcel S. Pawlowski

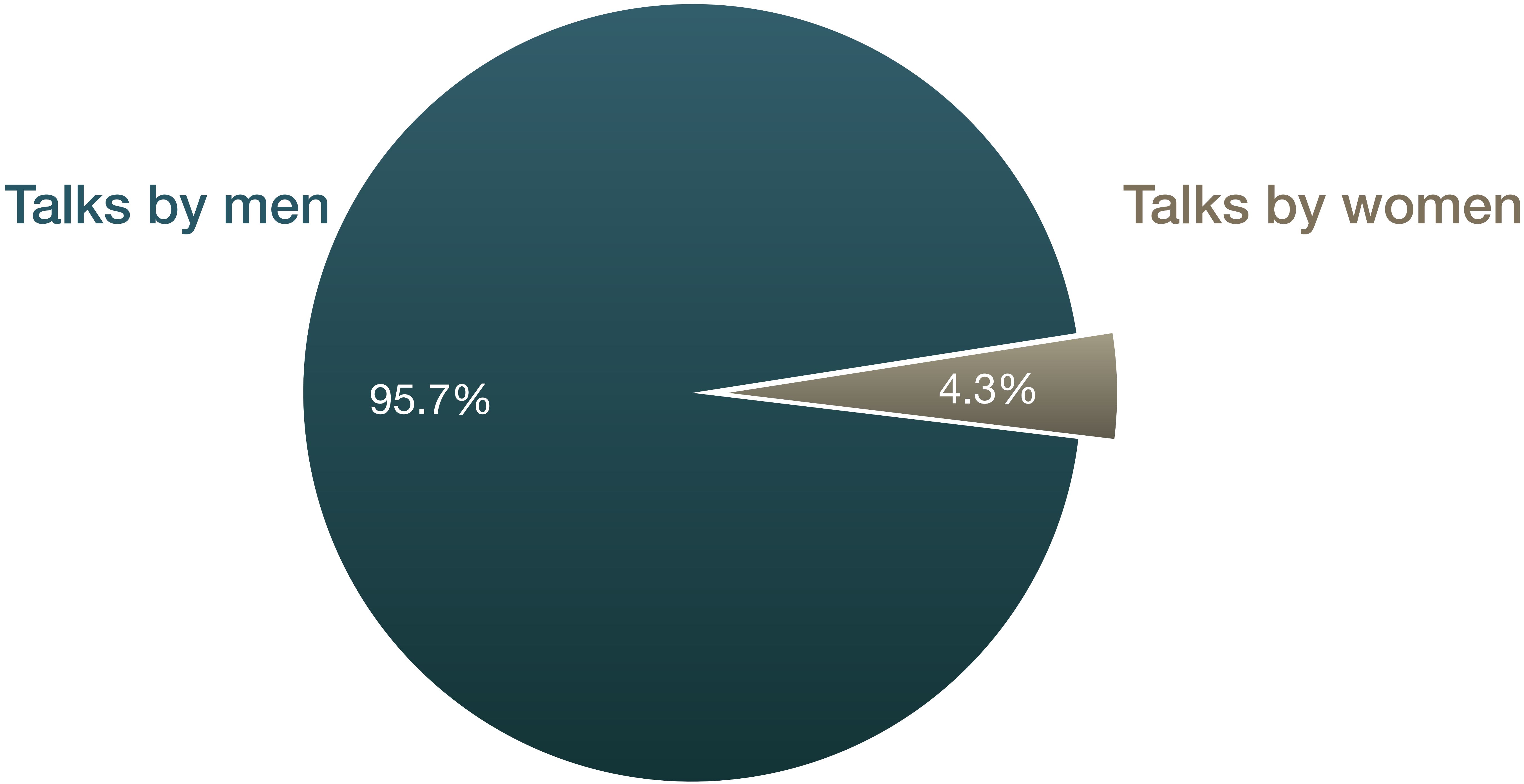
Schwarzschild Fellow at Leibniz-Institute for Astrophysics, Potsdam

marcel.pawlowski@uci.edu

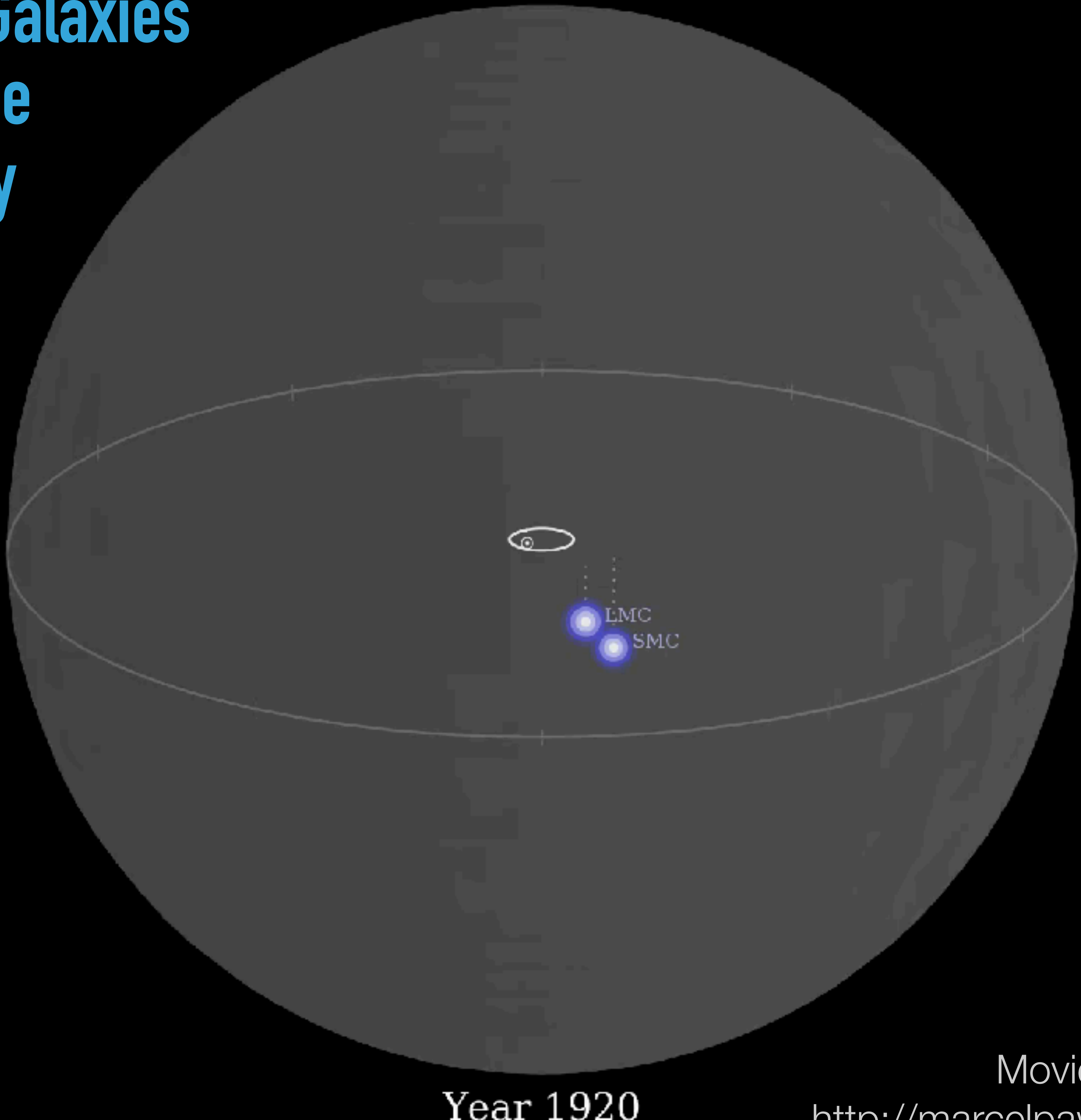
@8minutesold

Collaborators: James Bullock, **Benoit Famaey**, Tobias Fritz, Helmut Jerjen, Tyler Kelley, **Pavel Kroupa**, **Federico Lelli**, Noam Libeskind, **Oliver Müller**, Isabel Santos-Santos, Tony Sohn, Peng Wang, …

A major problem nobody talked about yet



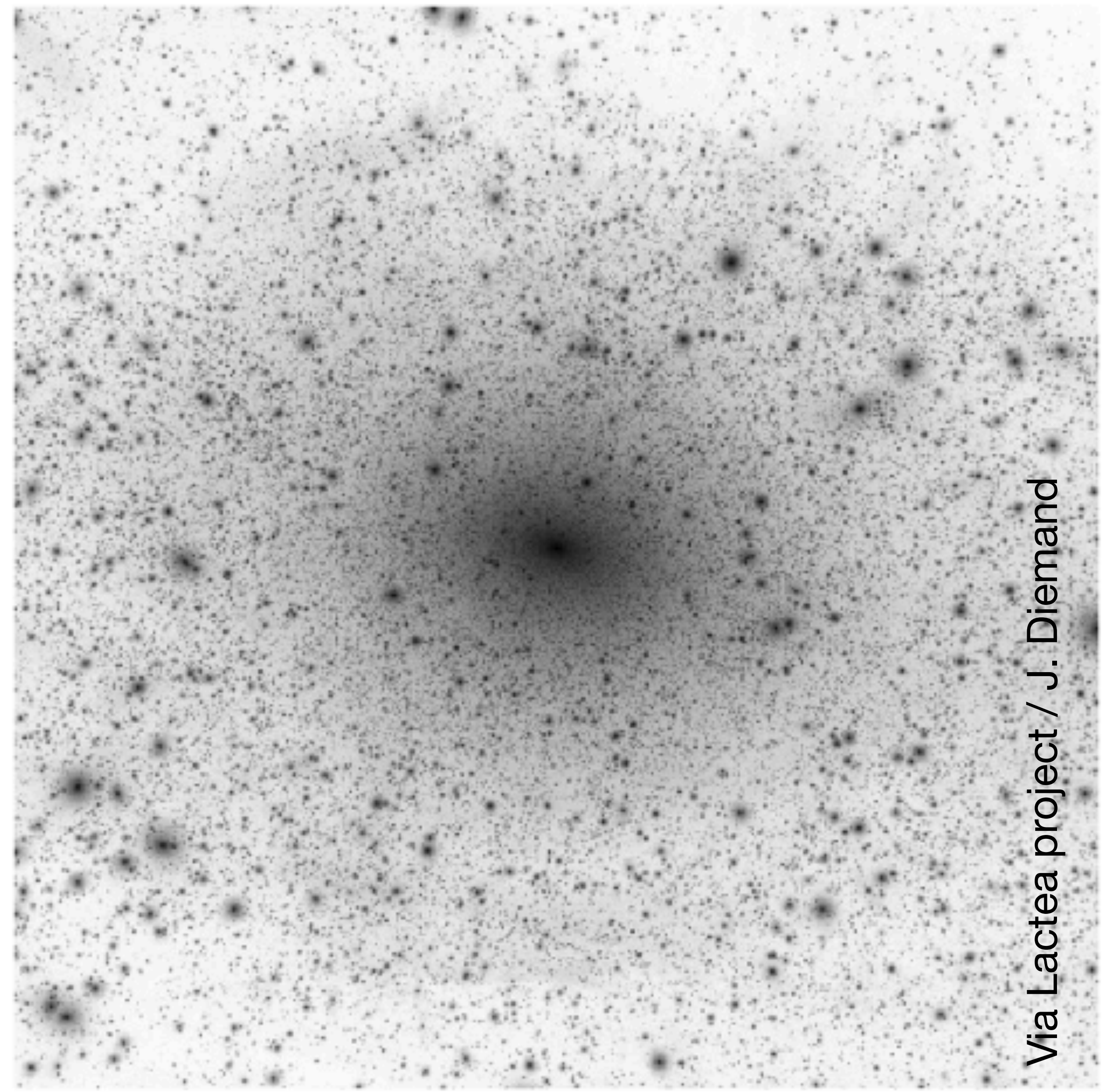
Satellite Galaxies around the Milky Way



Movie available at
http://marcelpawlowski.com

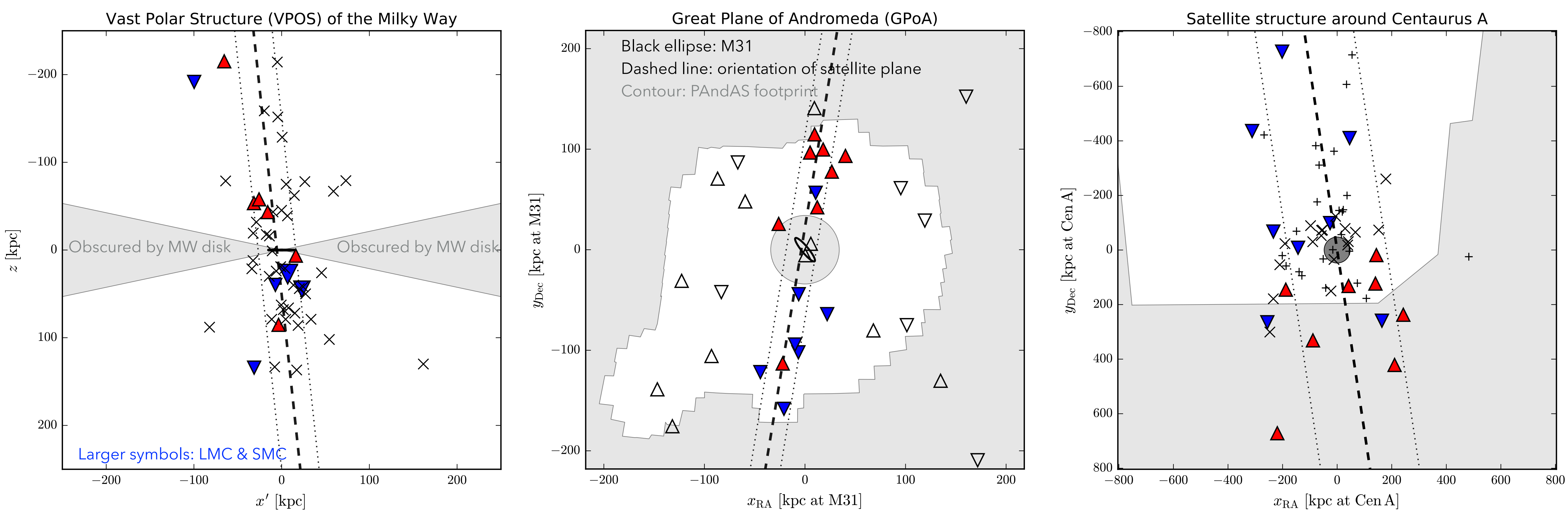
My Question: Is the phase-space distribution of satellite galaxies consistent with ΛCDM expectations?

- Comparing satellite dwarf galaxies with ΛCDM simulations resulted in numerous small-scale problems (Missing Satellites, Core-Cusp, Too-Big-To-Fail) but affected by baryonic physics.
  - ➡ Possibly failure of the simulations, not the cosmological model.
- Positions and velocities of satellite sub-halos on ≥100 kpc scales robust against internal baryonic physics and feedback processes.
  - ➡ Better test of the underlying model.



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%).



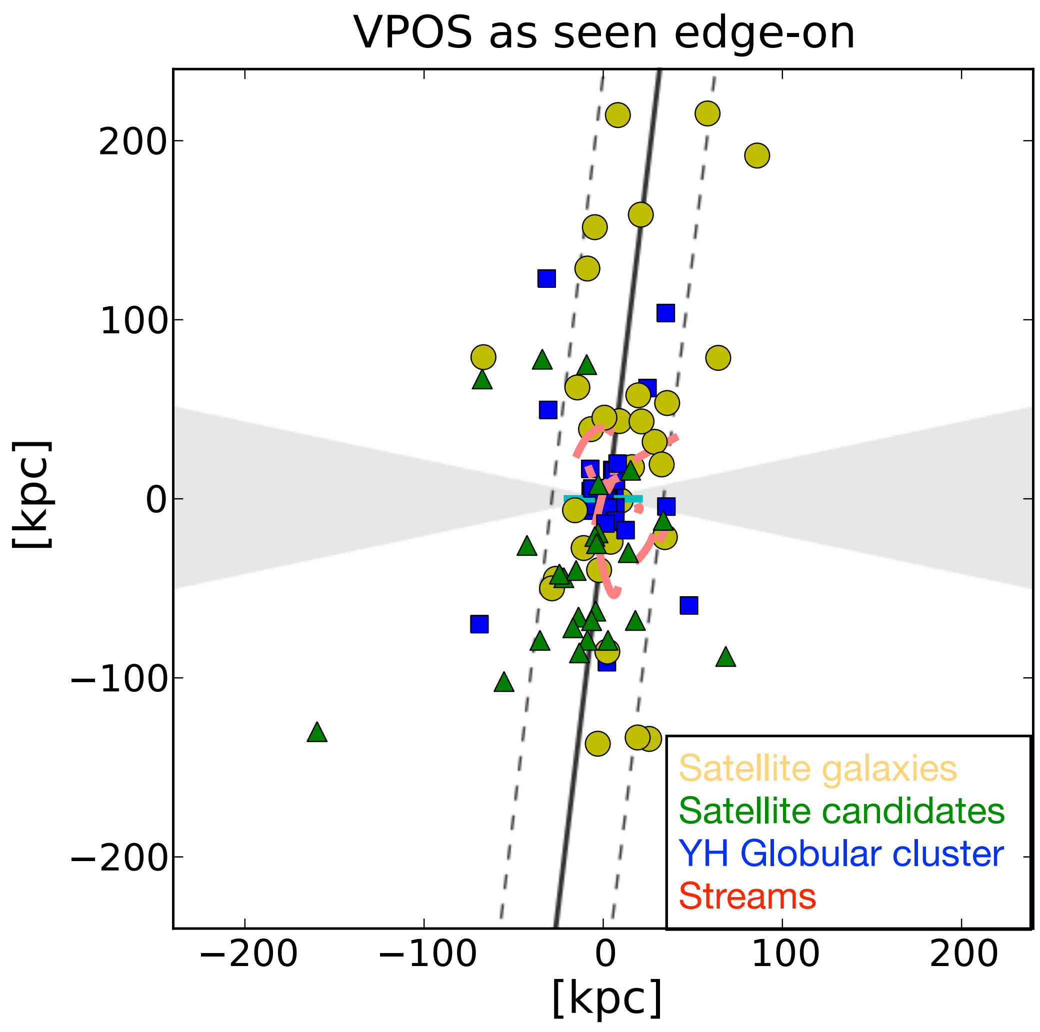
Pawlowski, Kroupa & Jerjen (2012, MNRAS, 423, 1109)

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

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

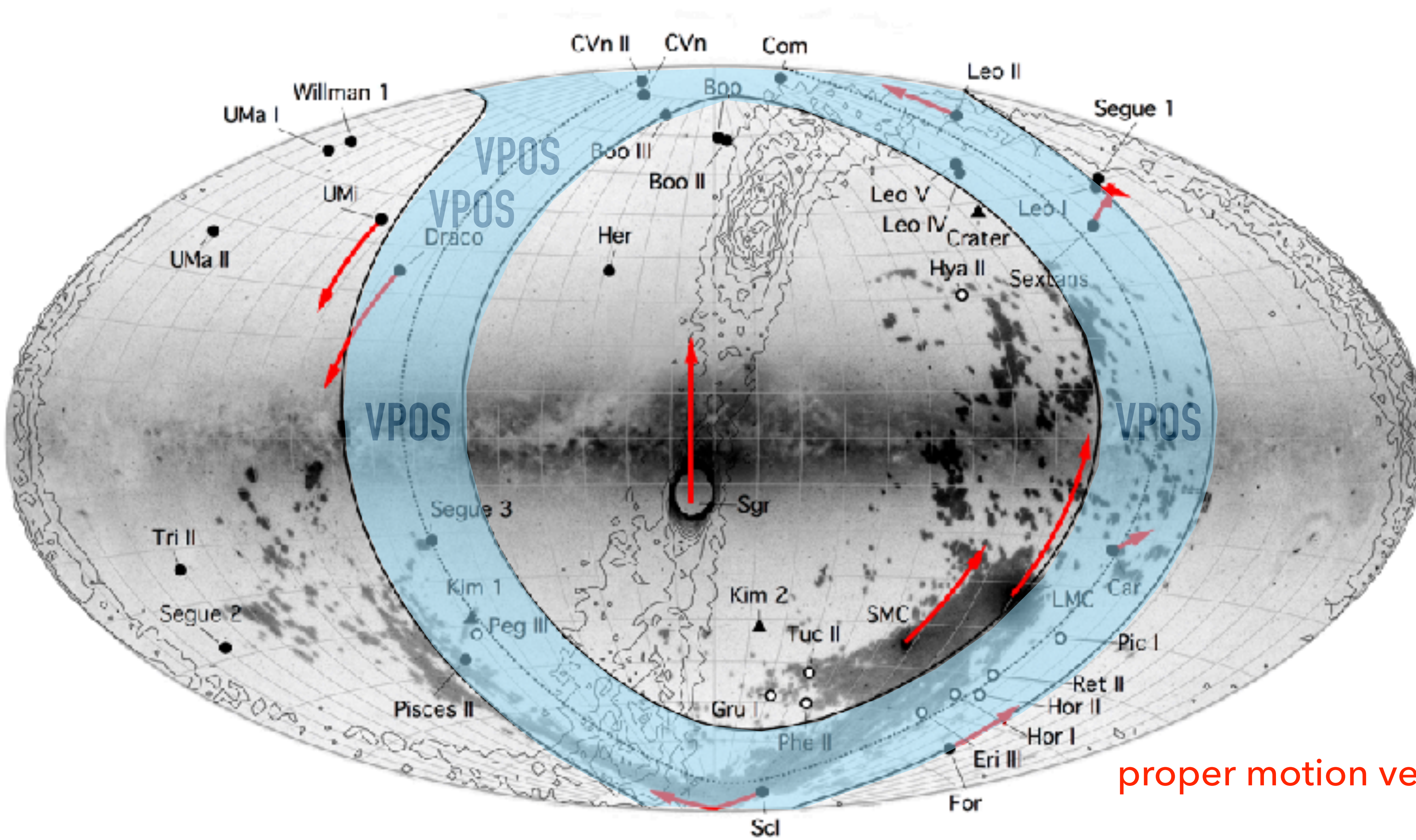
Satellite Positions: a Thin Plane of Satellite Galaxies

- Milky Way satellite galaxies arrange in a narrow **Vast Polar Structure (VPOS)**
- Fainter satellites, young halo GCs, and several streams align, too.
- Unlikely, but could be a chance alignment (i.e. transient).
- Do the satellites co-orbit? Need velocities!



Milky Way Satellite Galaxies Orbit Along the VPOS

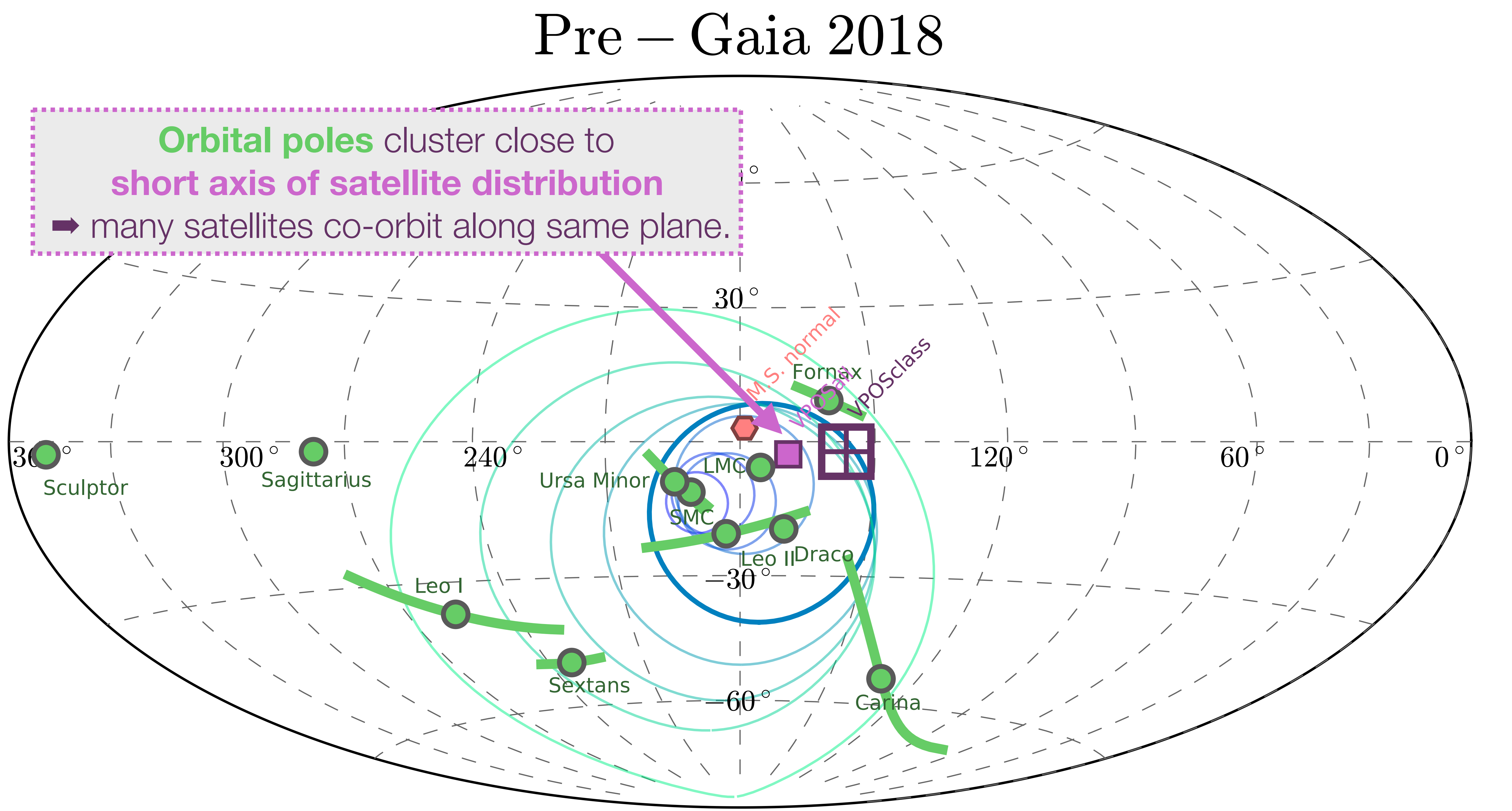
Pawlowski, McGaugh & Jerjen (2015)



proper motion vectors

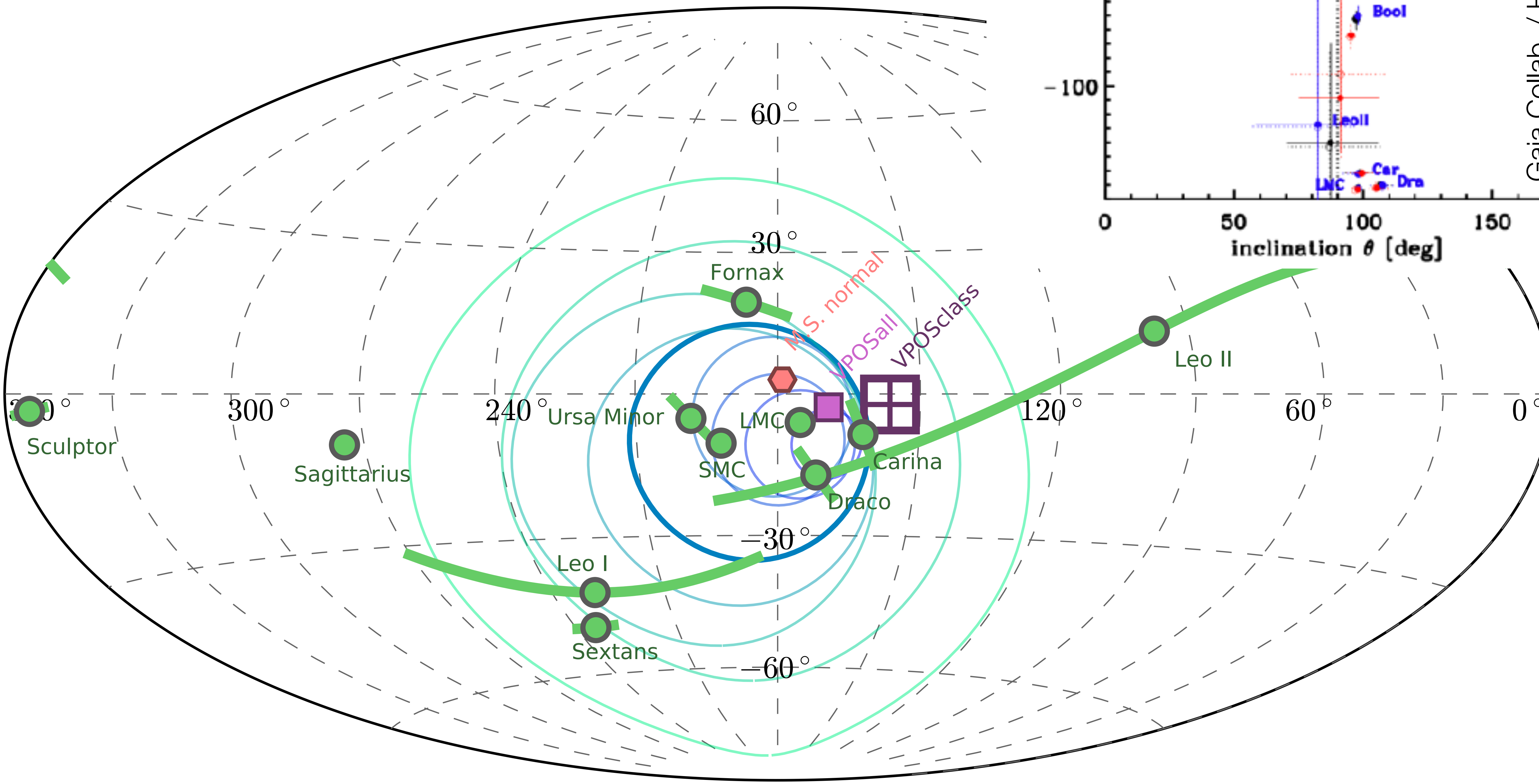
Considering 11 brightest ('classical') satellite galaxies

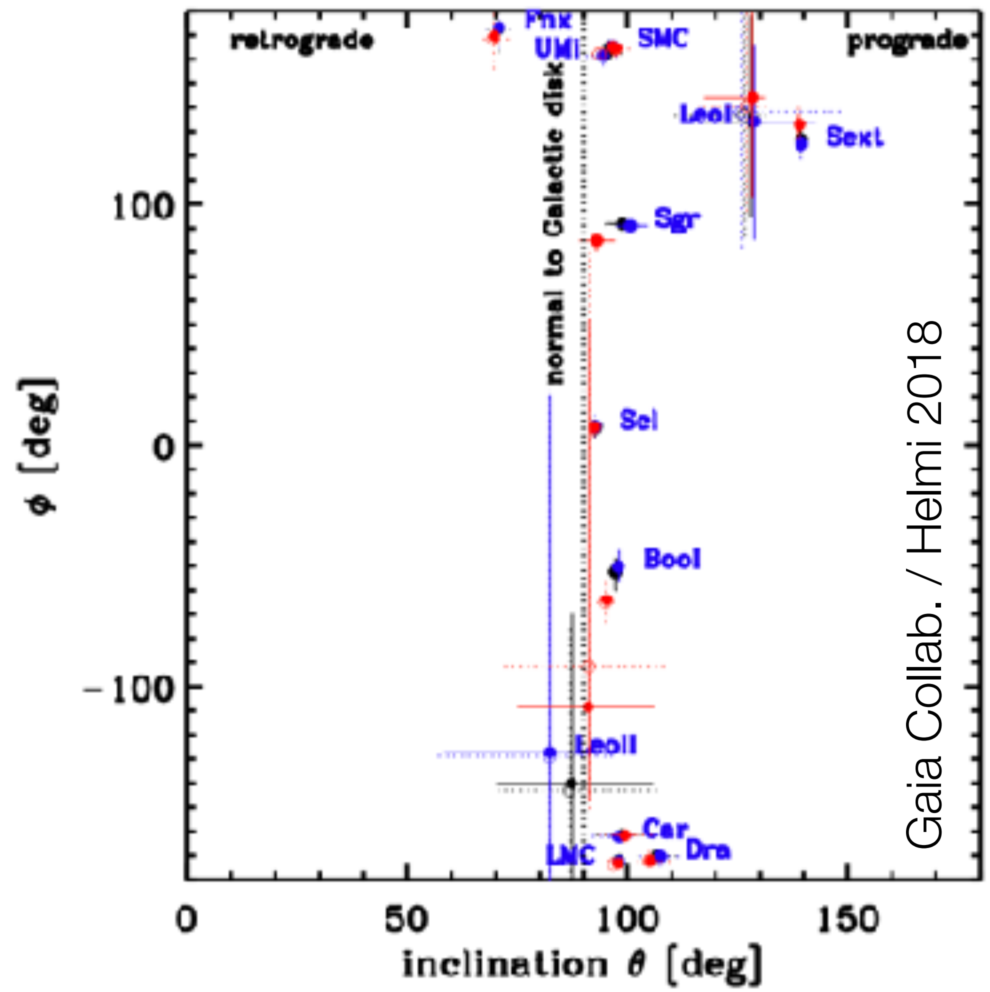
Orbital Poles (= directions of angular momentum)



Orbital Poles (= directions of ang

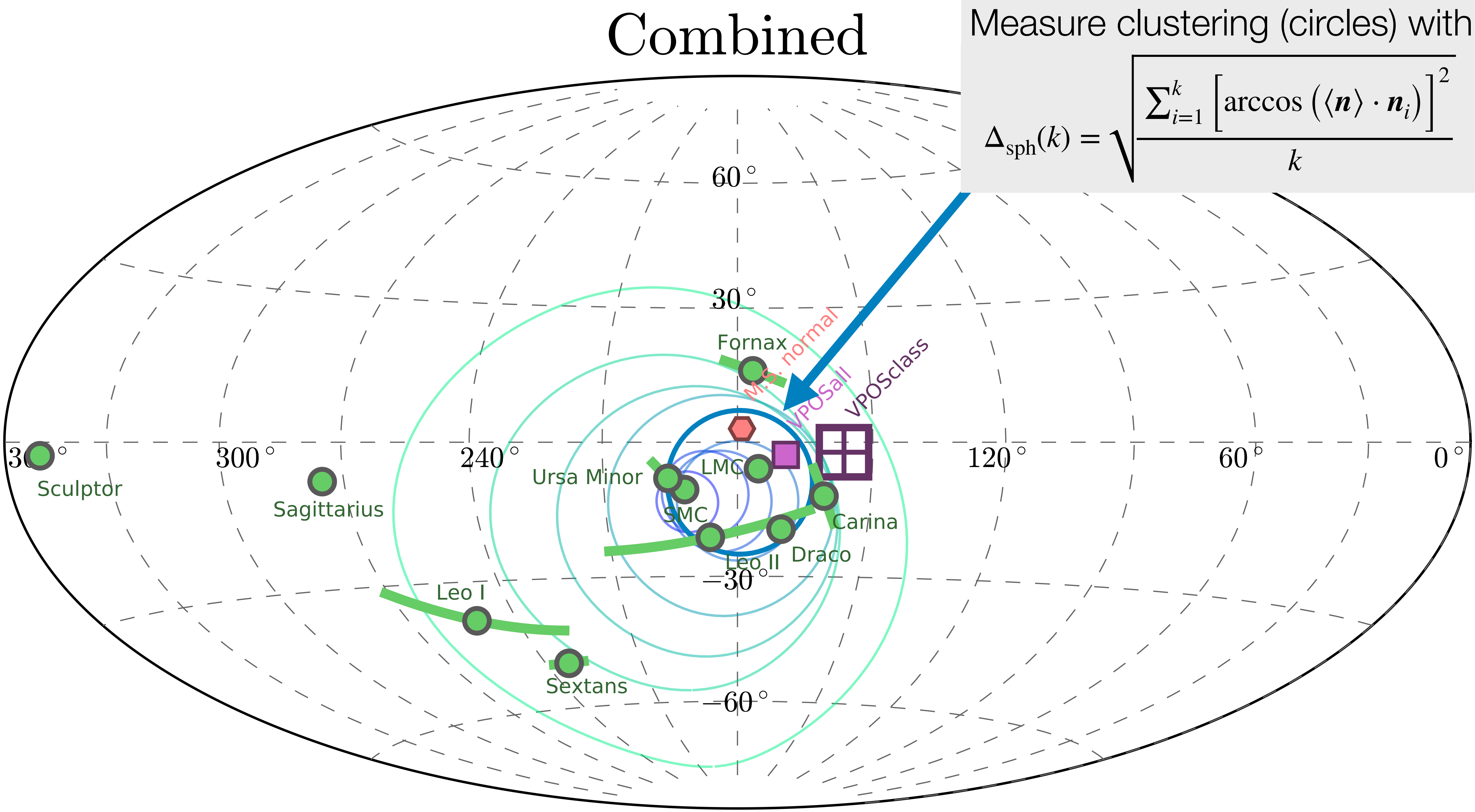
Gaia DR2 only





Gaia Collab. / Helmi 2018

Orbital Poles (= directions of angular momentum)

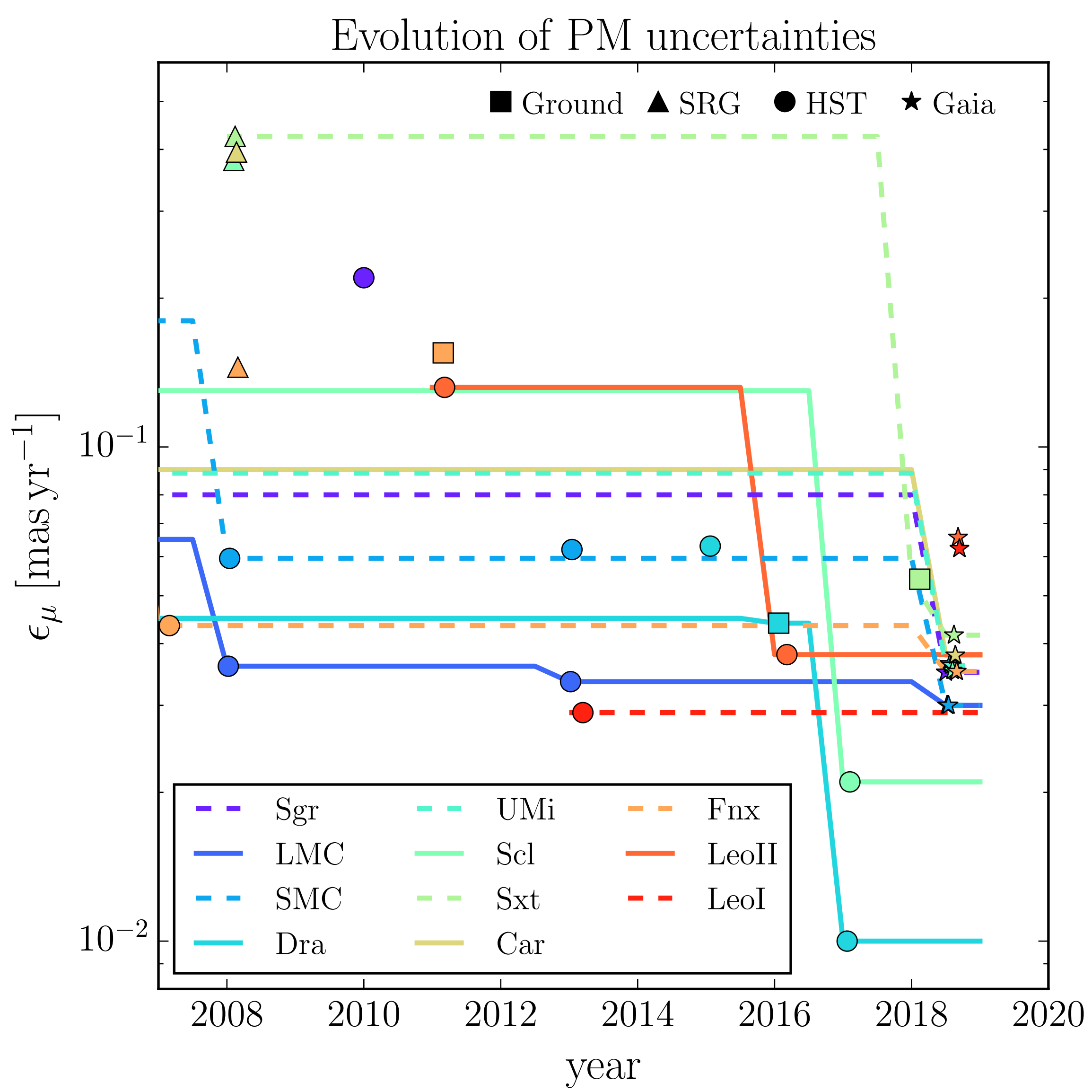


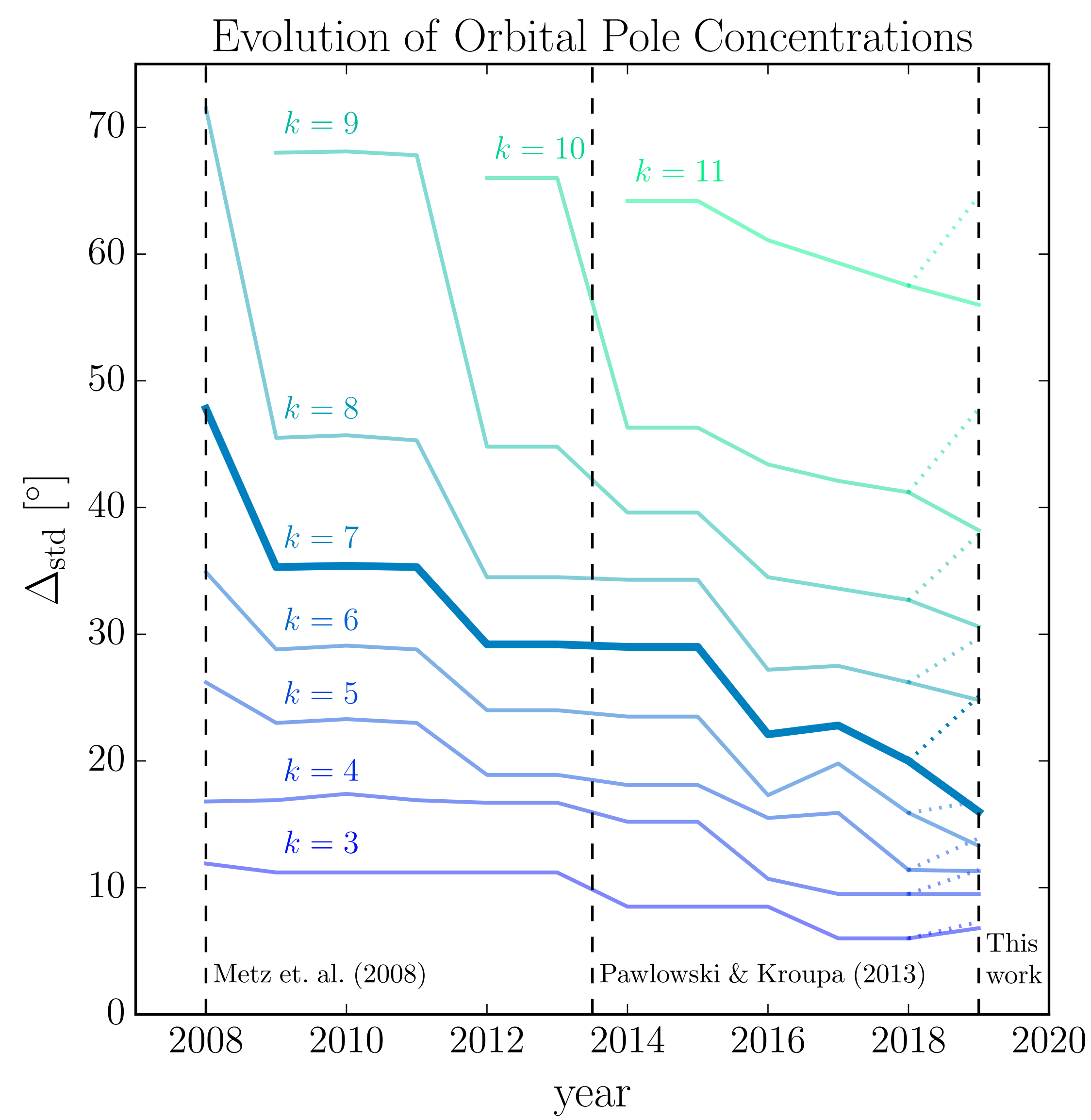
Measure clustering (circles) with

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

Pawlowski & Kroupa subm.

Evolution of Proper Motion Uncertainties and Concentration of Orbital Poles

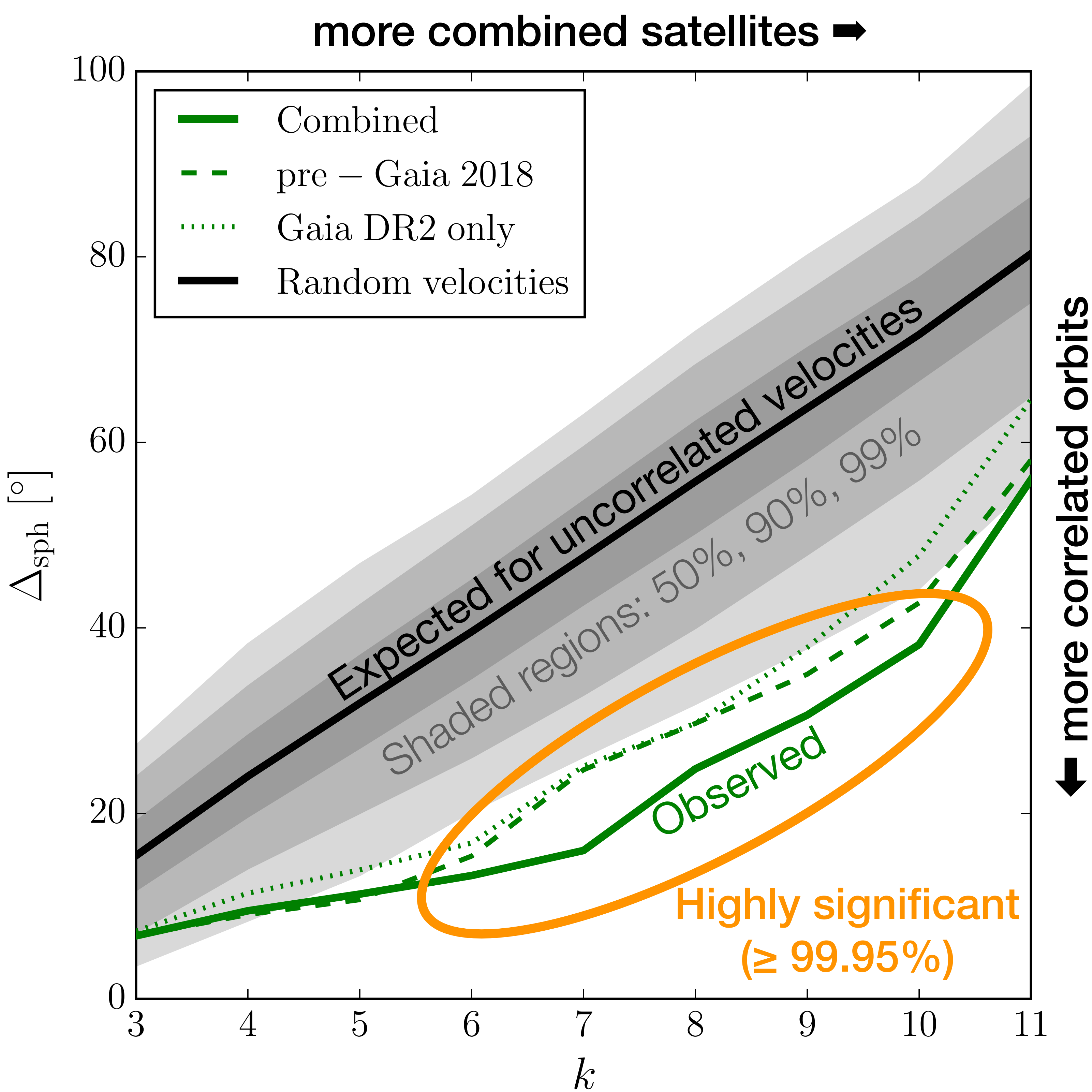




Better data -> more pronounced correlation

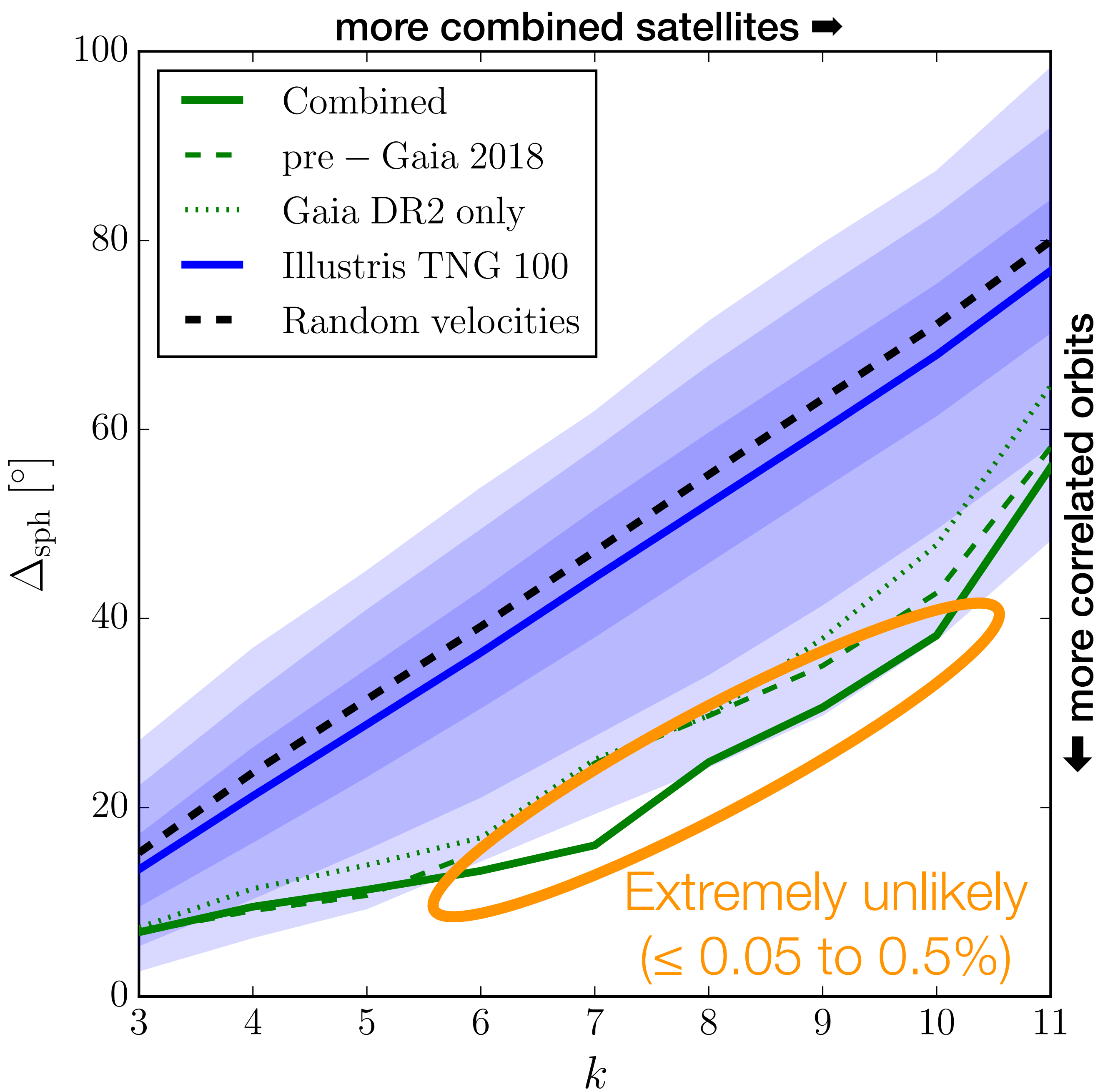
$$\Delta_{\mathrm{sph}}(k) = \sqrt{\frac{\sum_{i=1}^{k} \left[\arccos\left(\langle \boldsymbol{n} \rangle \cdot \boldsymbol{n}_i\right)\right]^2}{k}}$$

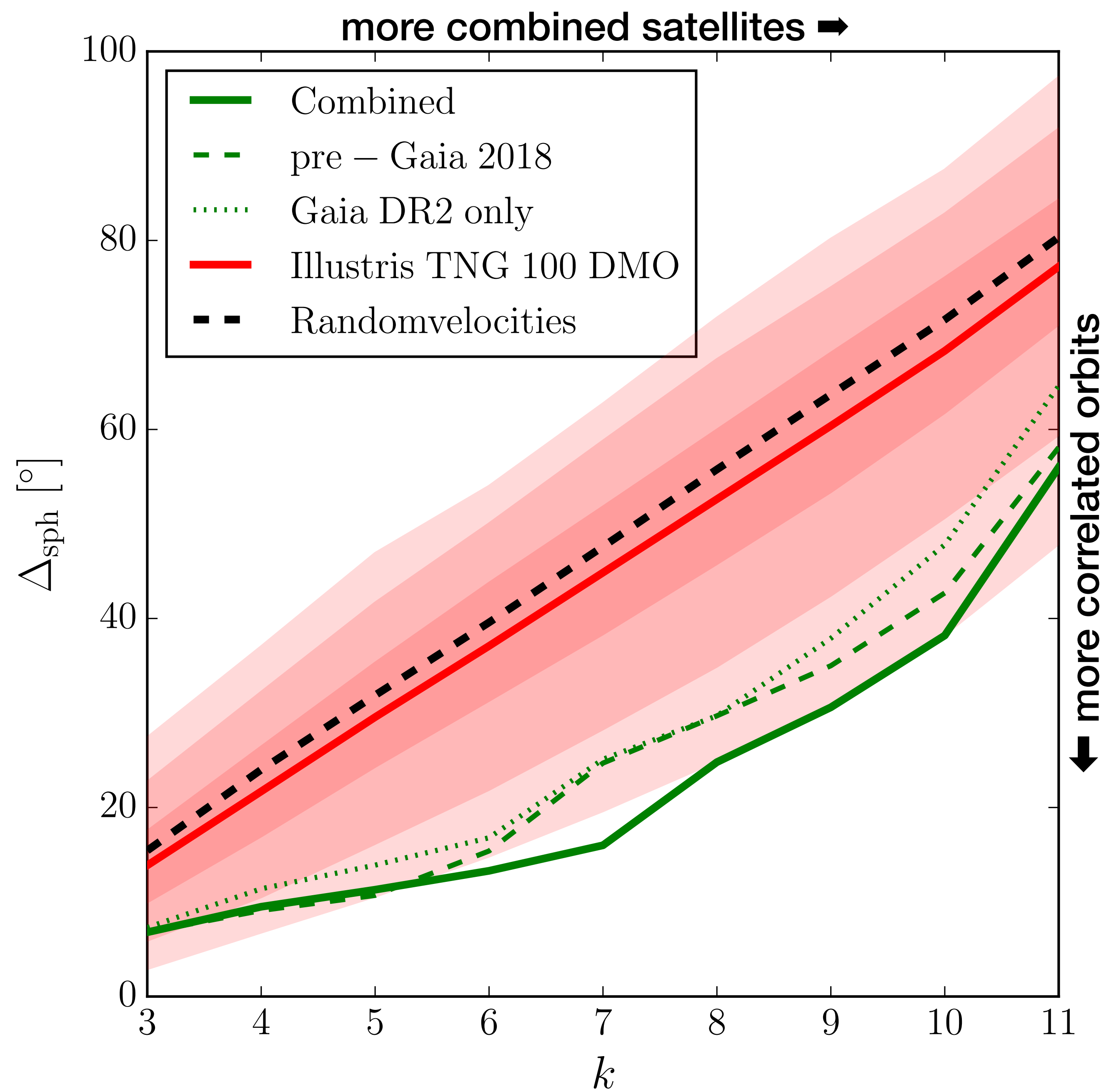
Orbital Pole Concentration vs. Random Velocities



Pawlowski & Kroupa subm.

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



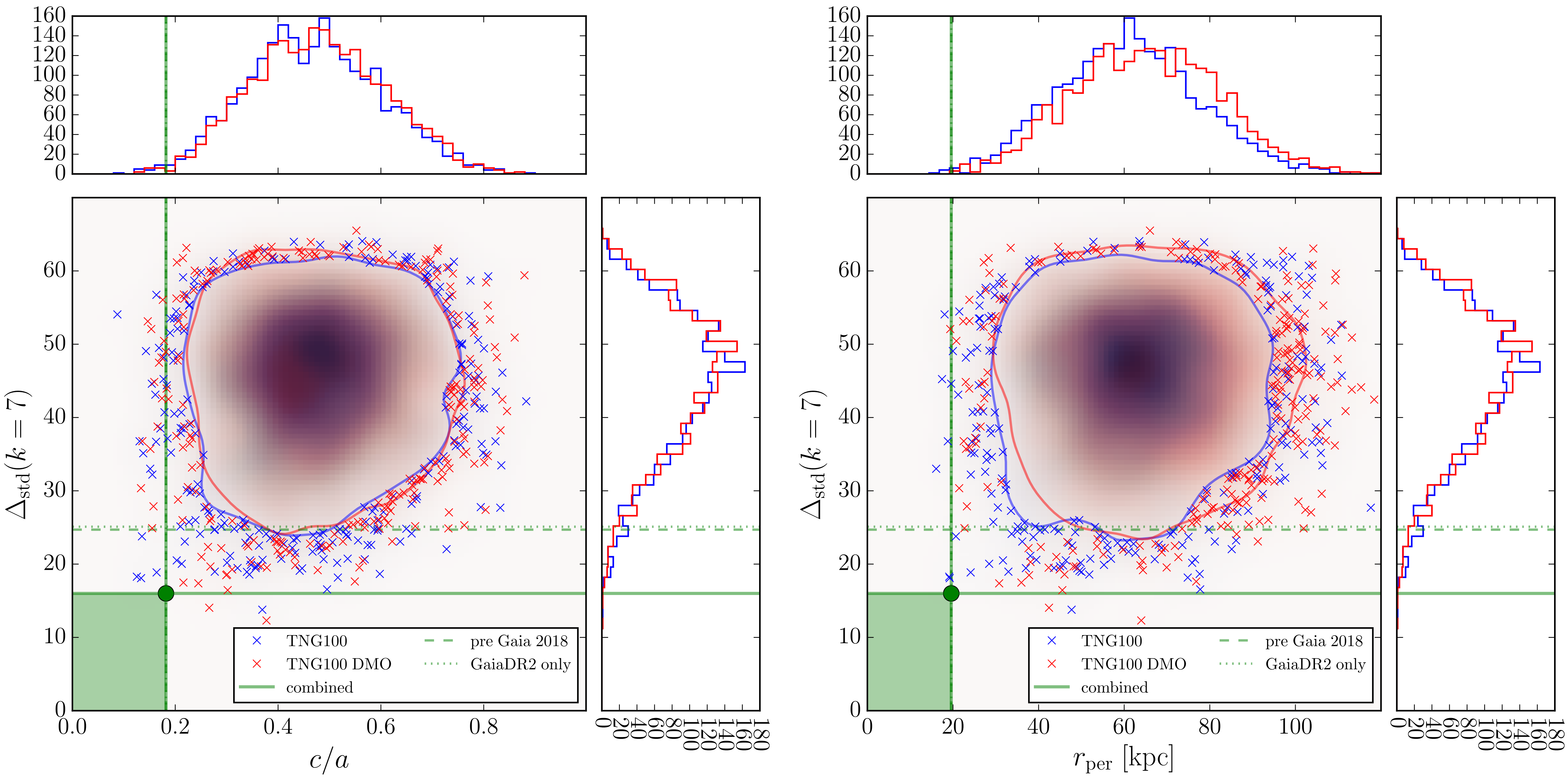


BUT: Must consider orbital pole distribution *and* spatial flattening

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

Pawlowski & Kroupa subm.

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



None of the 2341 (hydro) or 2352 (DMO) simulated satellite systems are simultaneously as flattened and as kinematically coherent as the observed 11 classical satellites.

Shao, Caution & Frenk (2019)

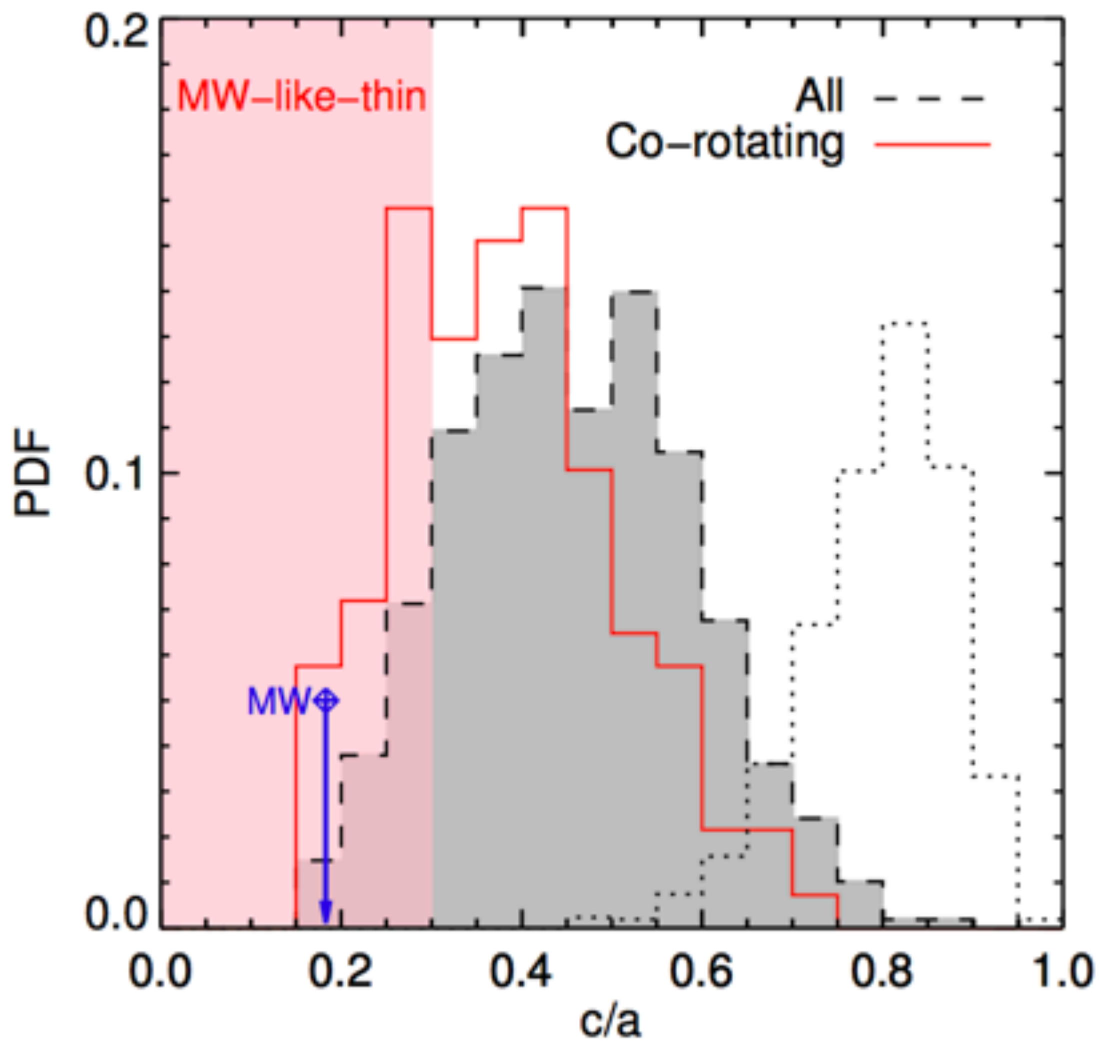


Figure 1. The axis ratio, c/a, distribution for the 11 most massive satellites of EAGLE MW-mass host haloes at $z = 0$. The dashed line corresponds to all haloes, while the solid line shows the hosts with an abundance of co-rotating satellites (see Sec. 3.2), that is hosts for which at least 8 of the 11 satellites have orbital planes within a $35°$ opening angle. The vertical arrow shows the Galactic value, $c/a = 0.183$. The red shaded region indicates systems with $c/a < 0.3$, which represent our EAGLE sample of *MW-like-thin* systems. The grey dotted line shows the c/a distribution of the mass for MW-mass dark matter haloes (to better fit the plot, the halo c/a PDF is normalized to 0.5 and not to unity).

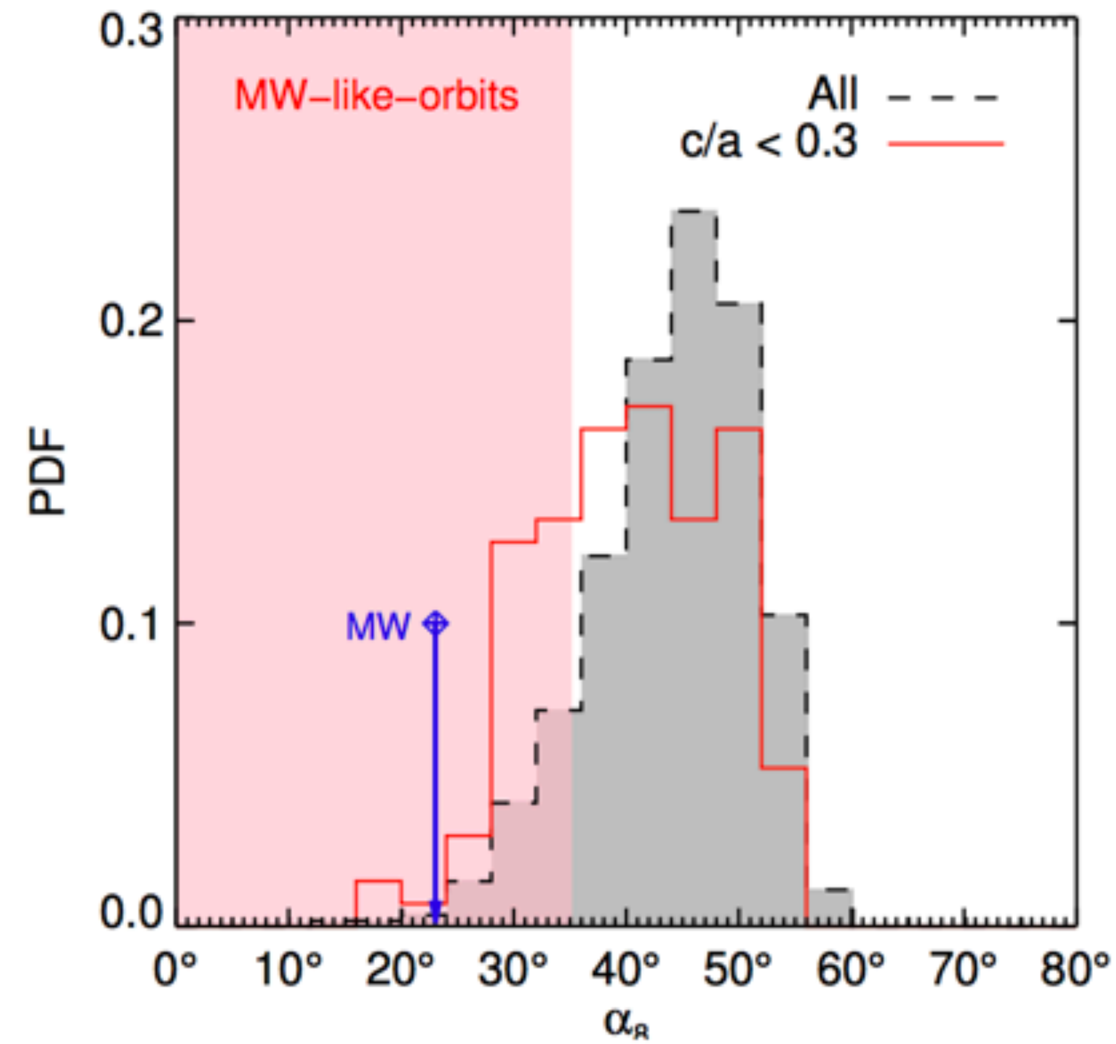


Figure 4. The distribution of opening angles, α_8, corresponding to 8 out of the top 11 satellites with the most co-planar orbits. The dashed and solid lines correspond to all and $c/a<0.3$ MW-mass systems in EAGLE. The vertical line indicates the Galactic value, $\alpha_8 = 22°$. The red shaded region corresponds to the selection of *MW-like-orbit* systems, that is those with $\alpha_8<35°$.

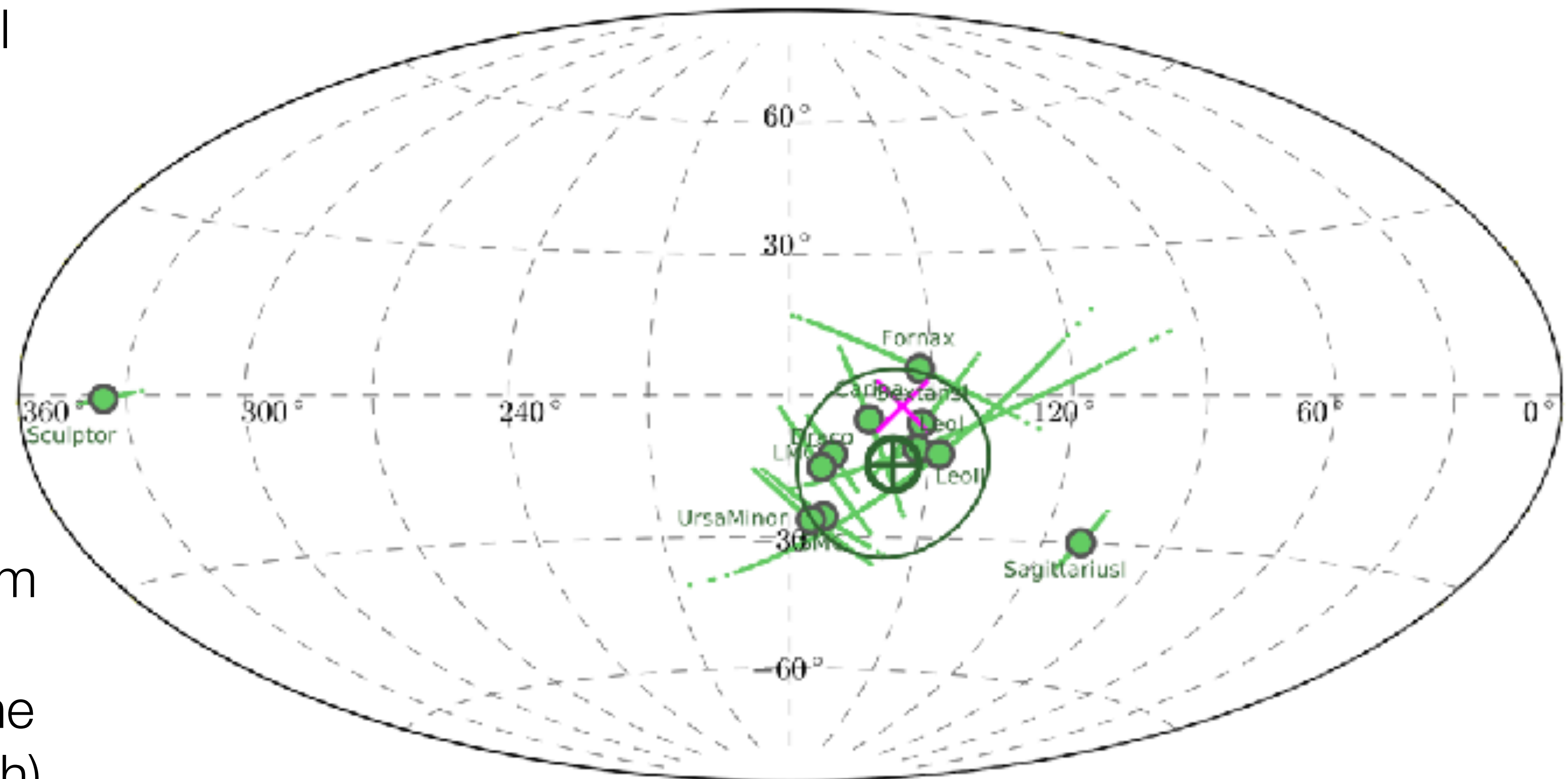
Best-Possible Alignment of Orbital Poles

For a given plane, each satellite has a closest-possible orbital pole given by its position.

If the plane contains the satellite, the pole can be perfectly aligned.

If the satellite is 20º away from the plane, its orbit can't be closer than 20º from the plane (it can be further away though).

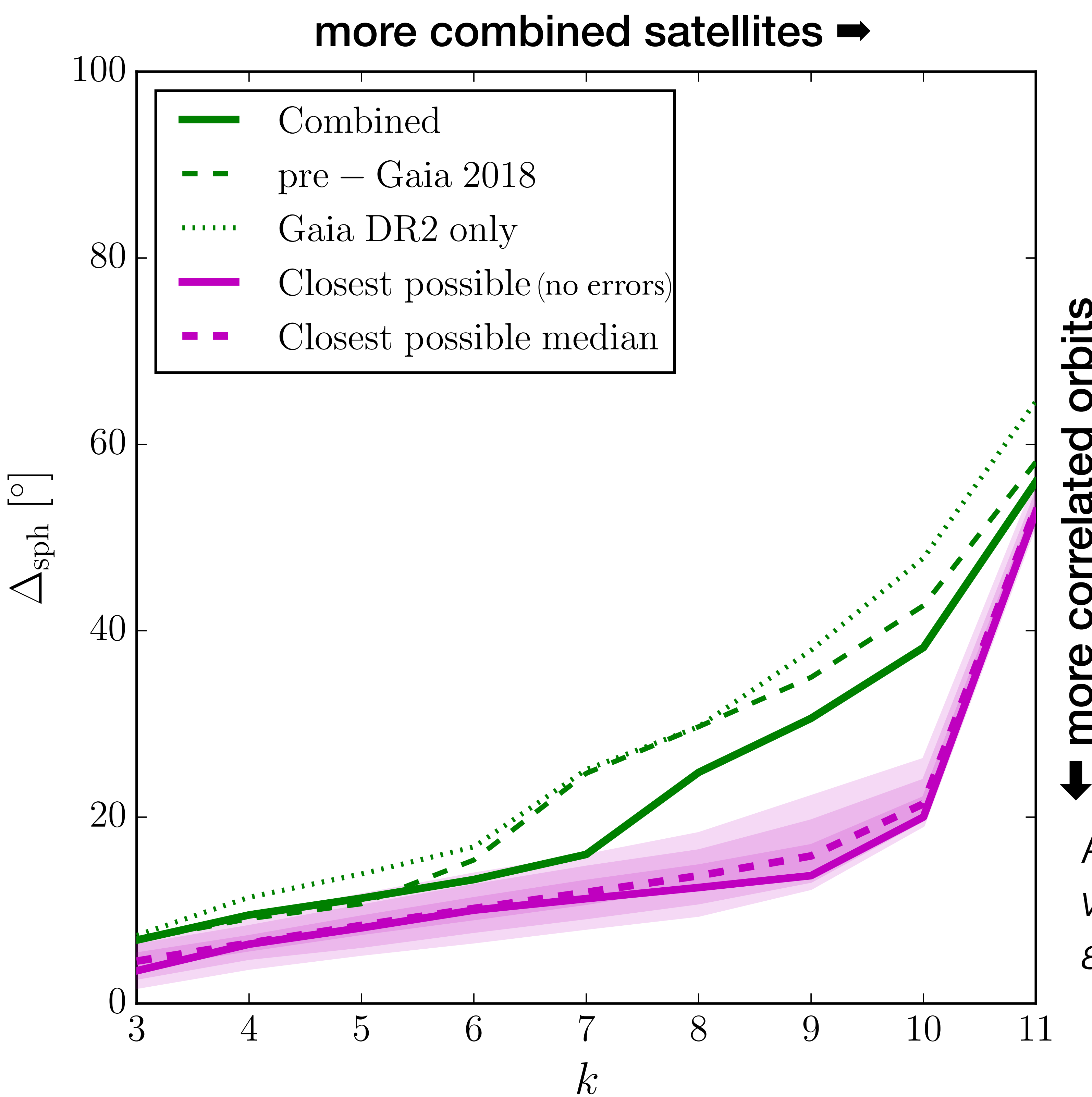
Force Sculptor to be counter-orbiting.



When mock-observing best-aligned velocities with realistic PM errors.

Pawlowski & Kroupa subm.

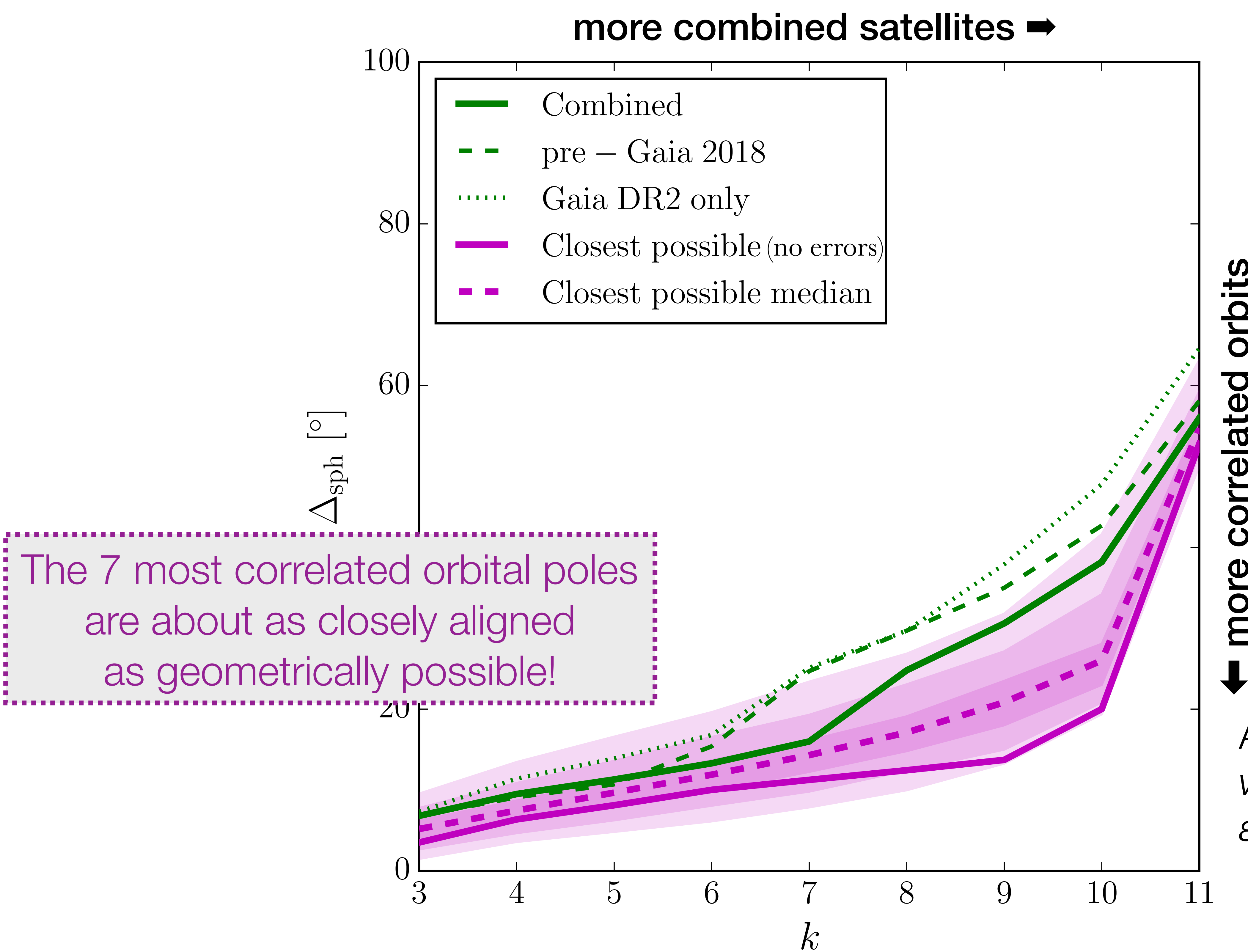
Orbital Pole Concentration vs. Best-Possible Alignment (given satellite positions)



Assumes:
v_{tan} = 175 km/s
ε_{PM} = 0.05 mas/yr

Pawlowski & Kroupa subm.

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



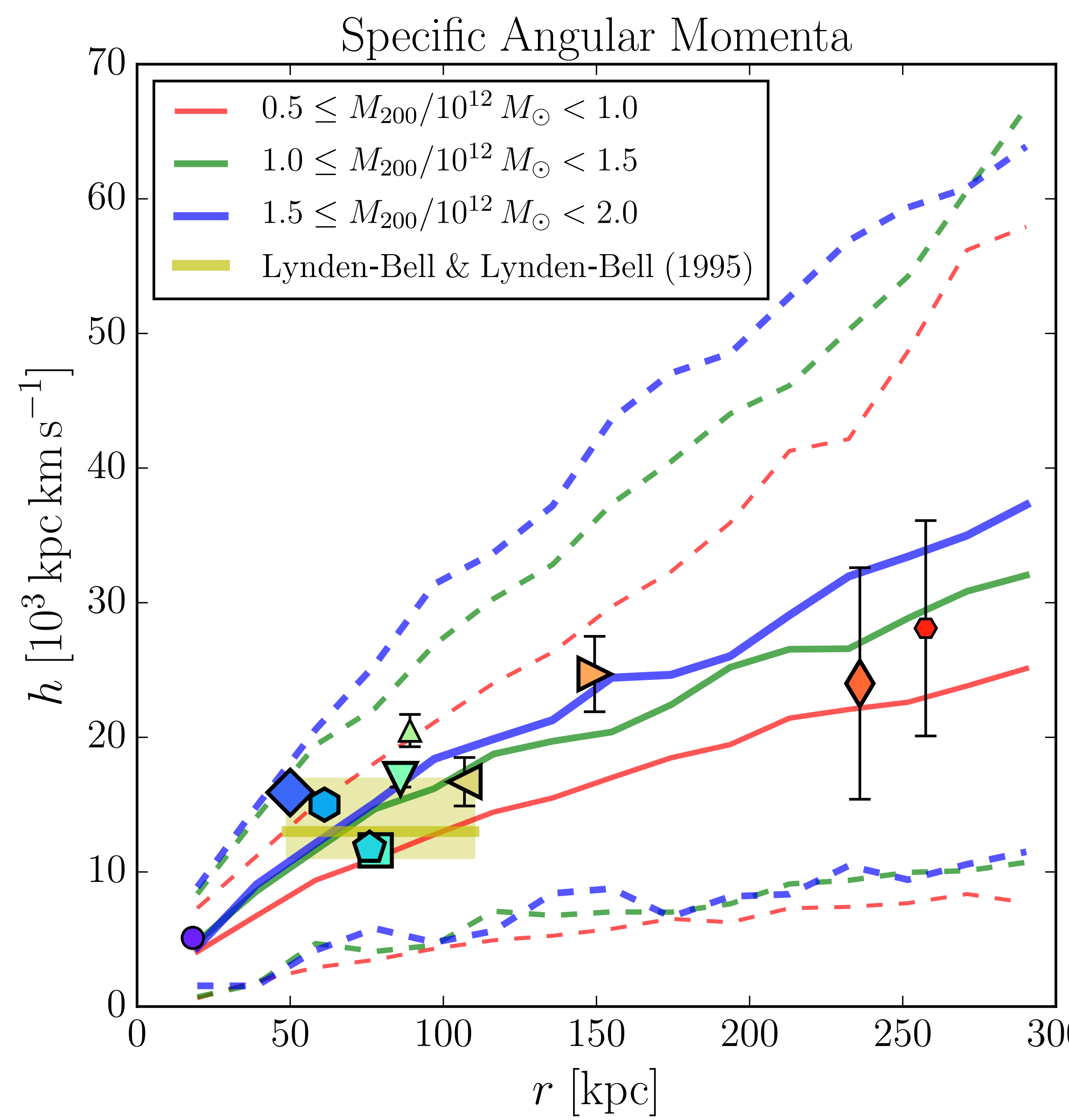
Assumes:
$v_{\rm tan}$ = 175 km/s
$\varepsilon_{\rm PM}$ = 0.10 mas/yr

Specific Angular Momenta

Lynden-Bell & Lynden-Bell (1995) suggested six members of a "Magellanic Stream of Satellites": LMC, SMC, Draco, Carina, Sculptor, Ursa Minor

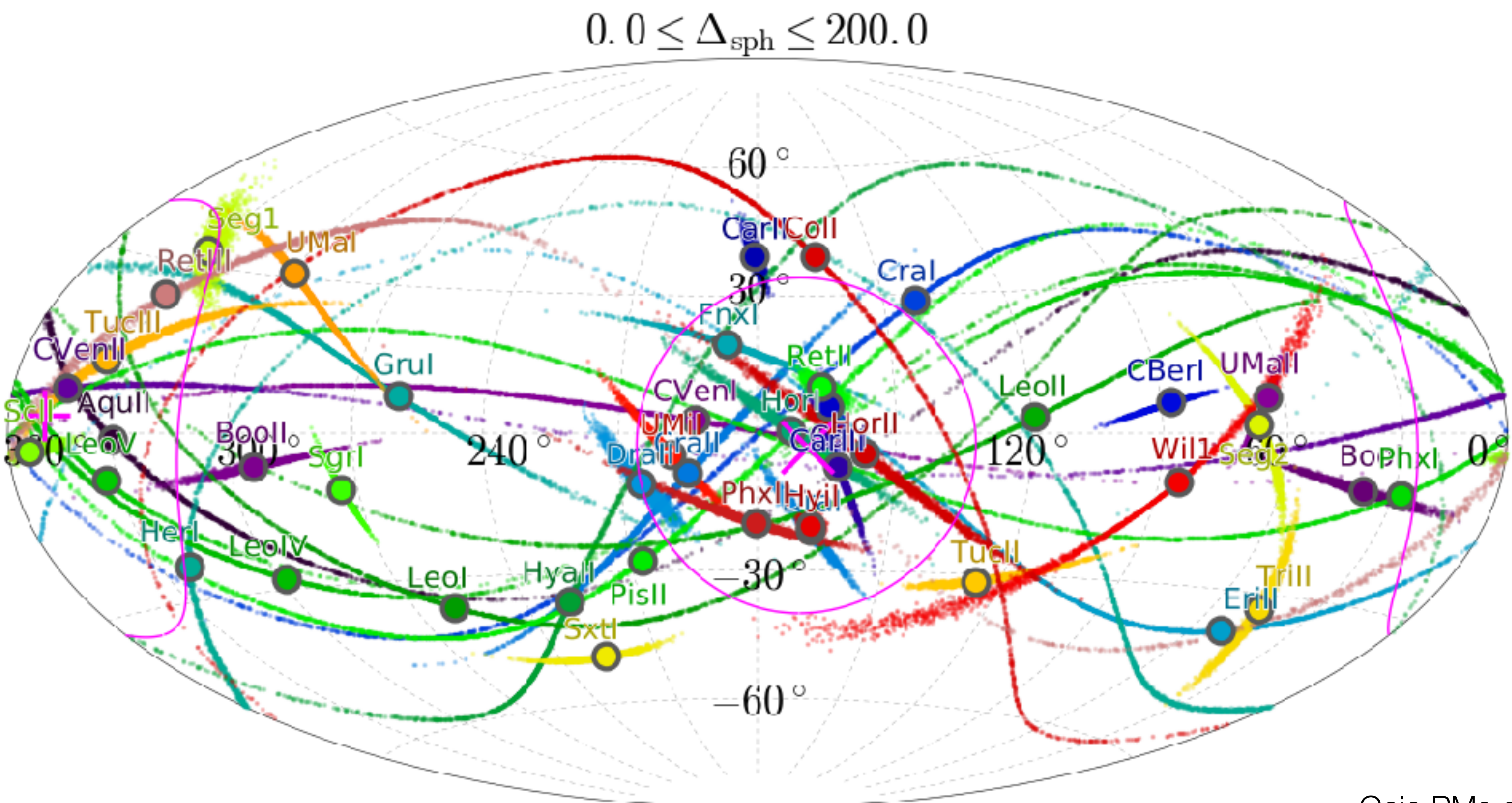
All of them from orbit to within 20° of a common plane aligned with Mag. Stream.

All have specific angular momenta h within 30% of the predicted value!



VPOS Kinematics Including Fainter Satellites:

Well constrained orbital poles preferentially align with VPOS



Gaia PMs only!
LMC/SMC not included

Pawlowski et al. in prep.

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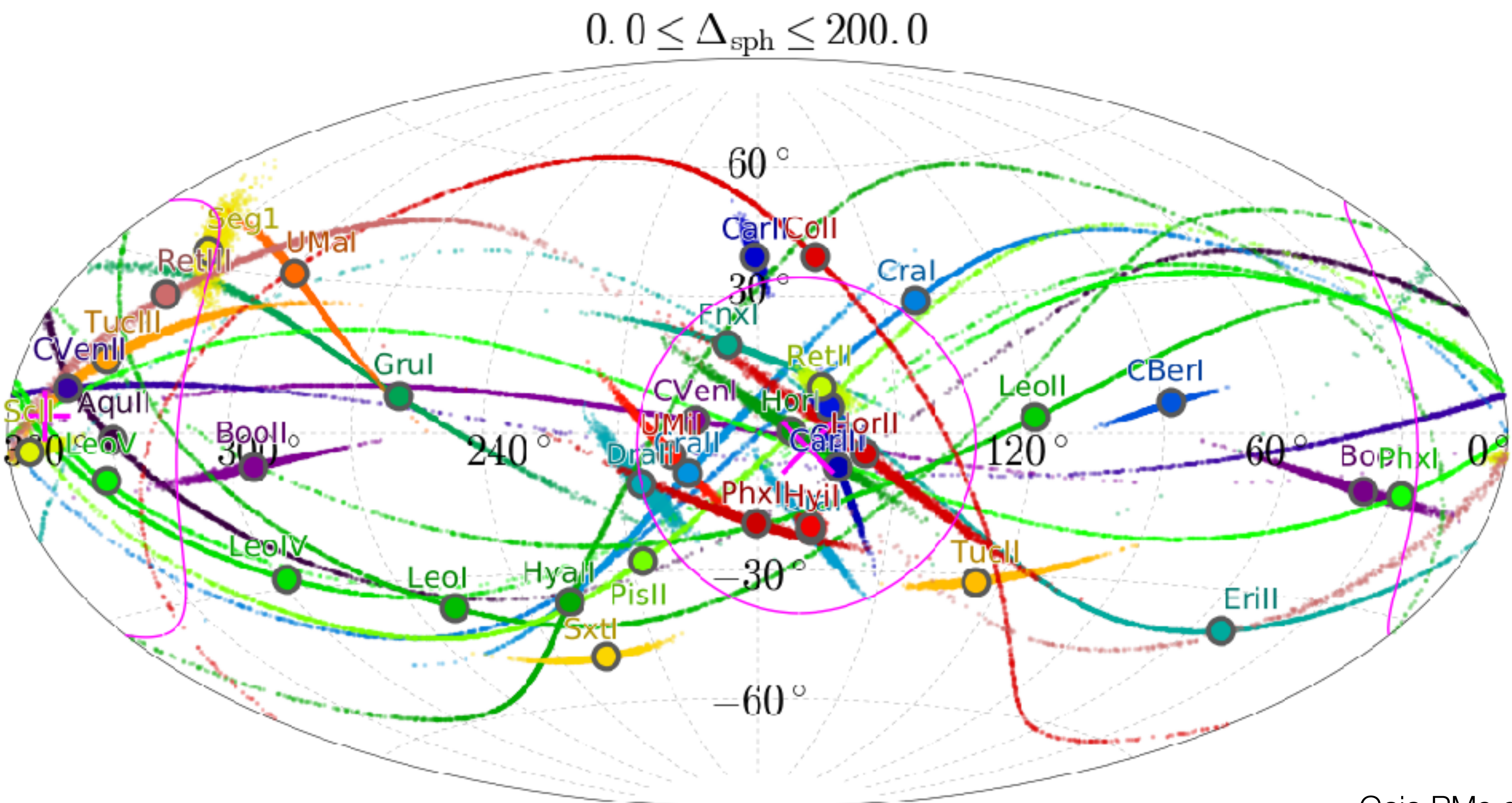

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Poles of 6 satellites that can not align excluded (no predictions)

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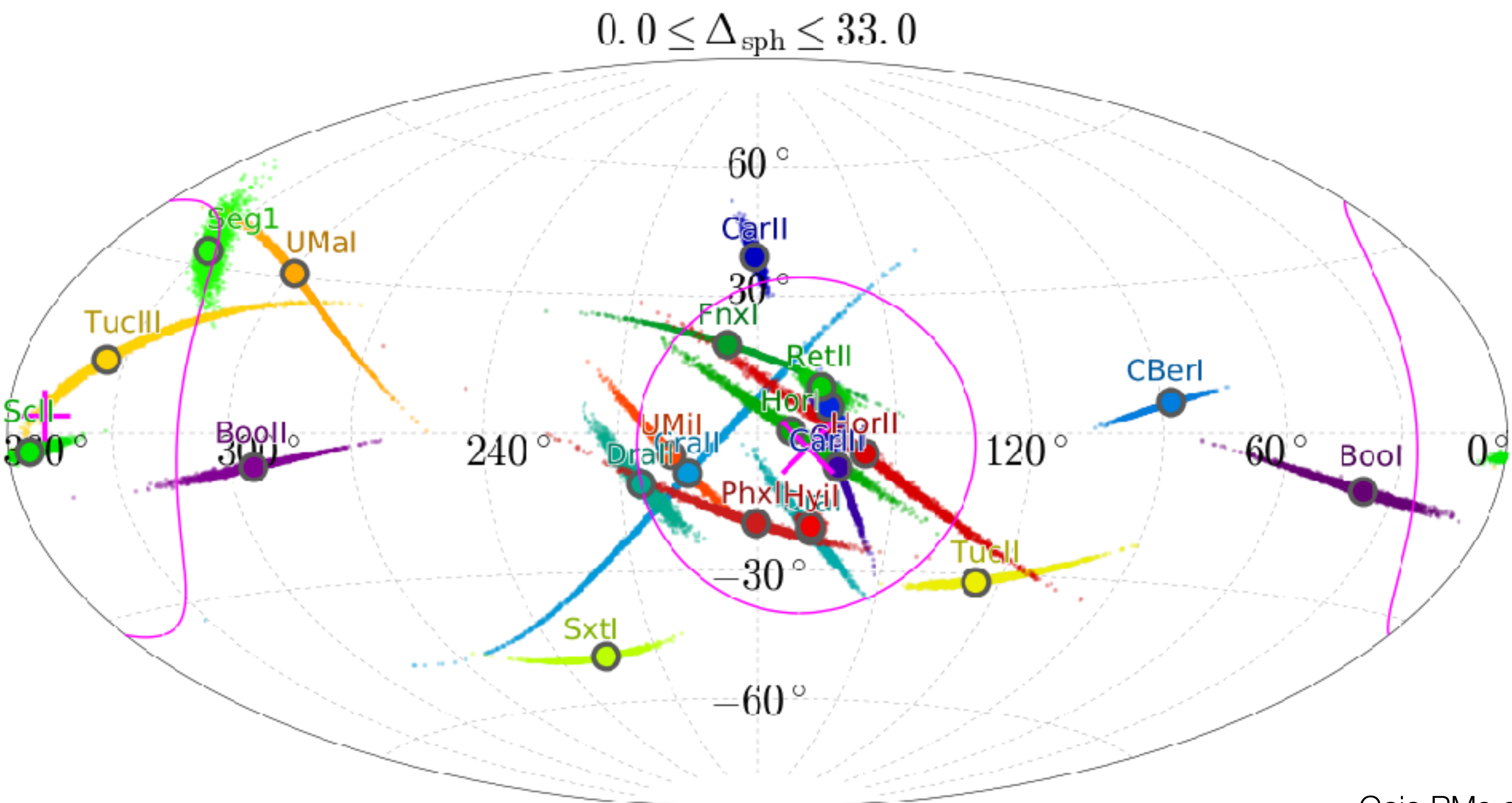

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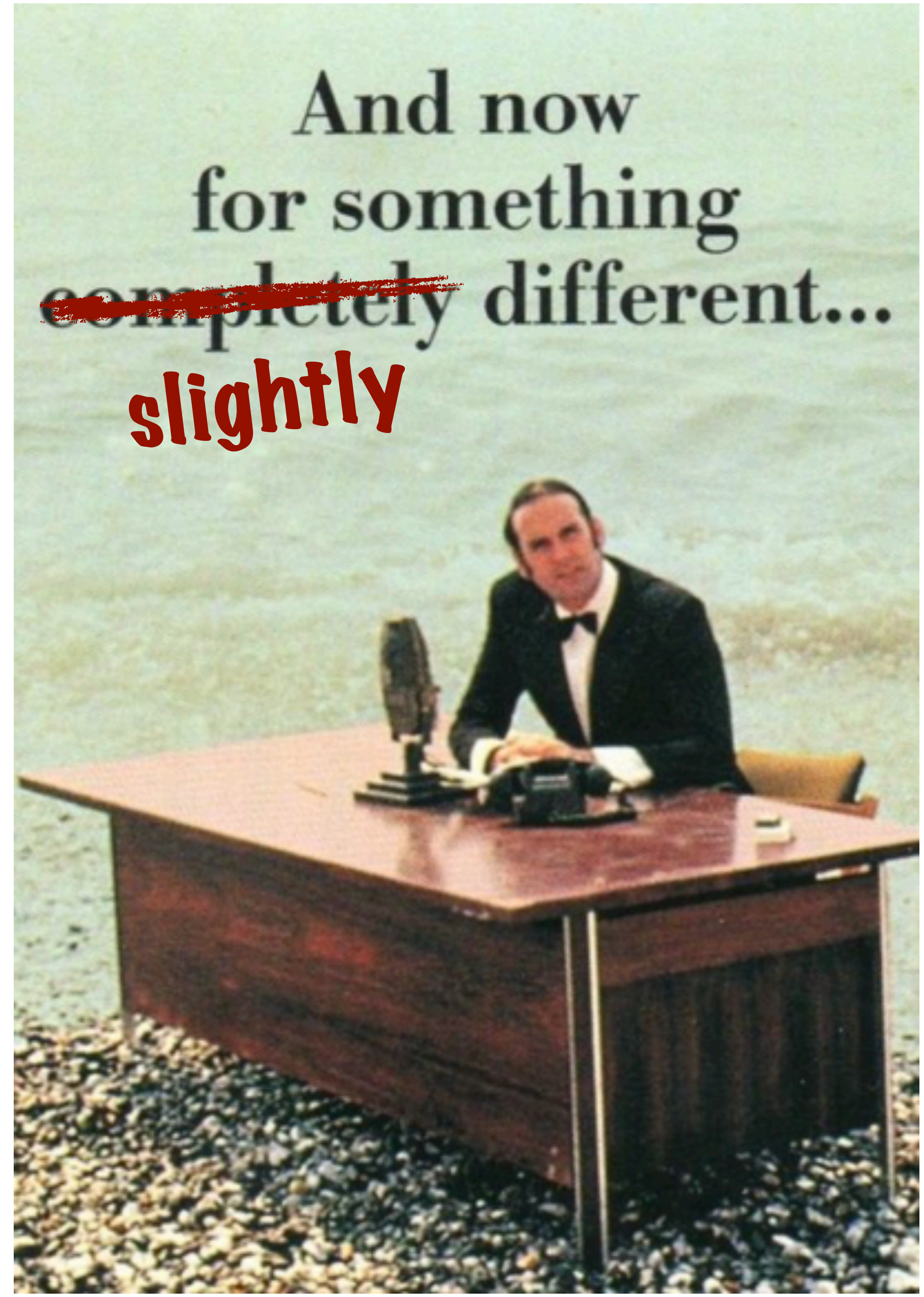
Pawlowski et al. in prep.

Do halos that form early,
have high concentration,
are part of a pair, or
contain a central galaxy potential
host more pronounced Planes of
Satellite Galaxies?

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



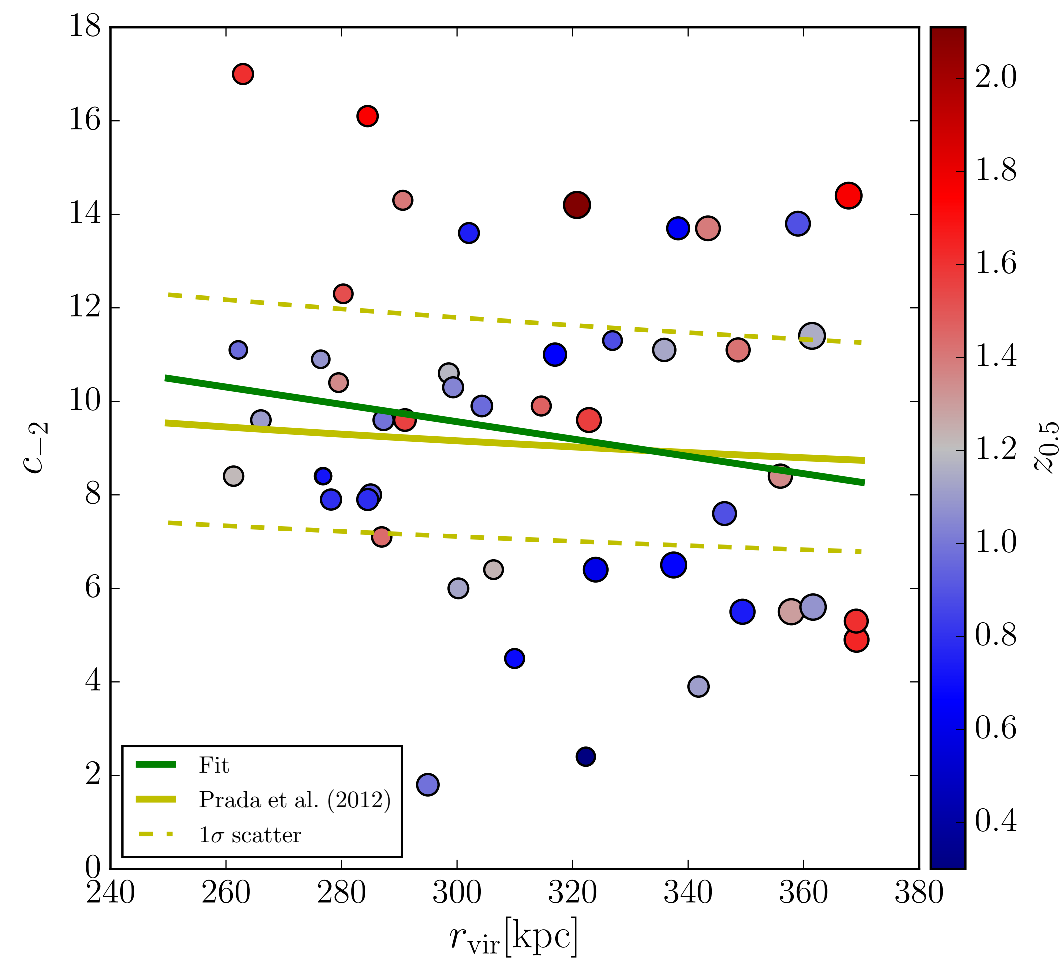
Can we solve the Planes of Satellites problem by saying MW/M31 are special?

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

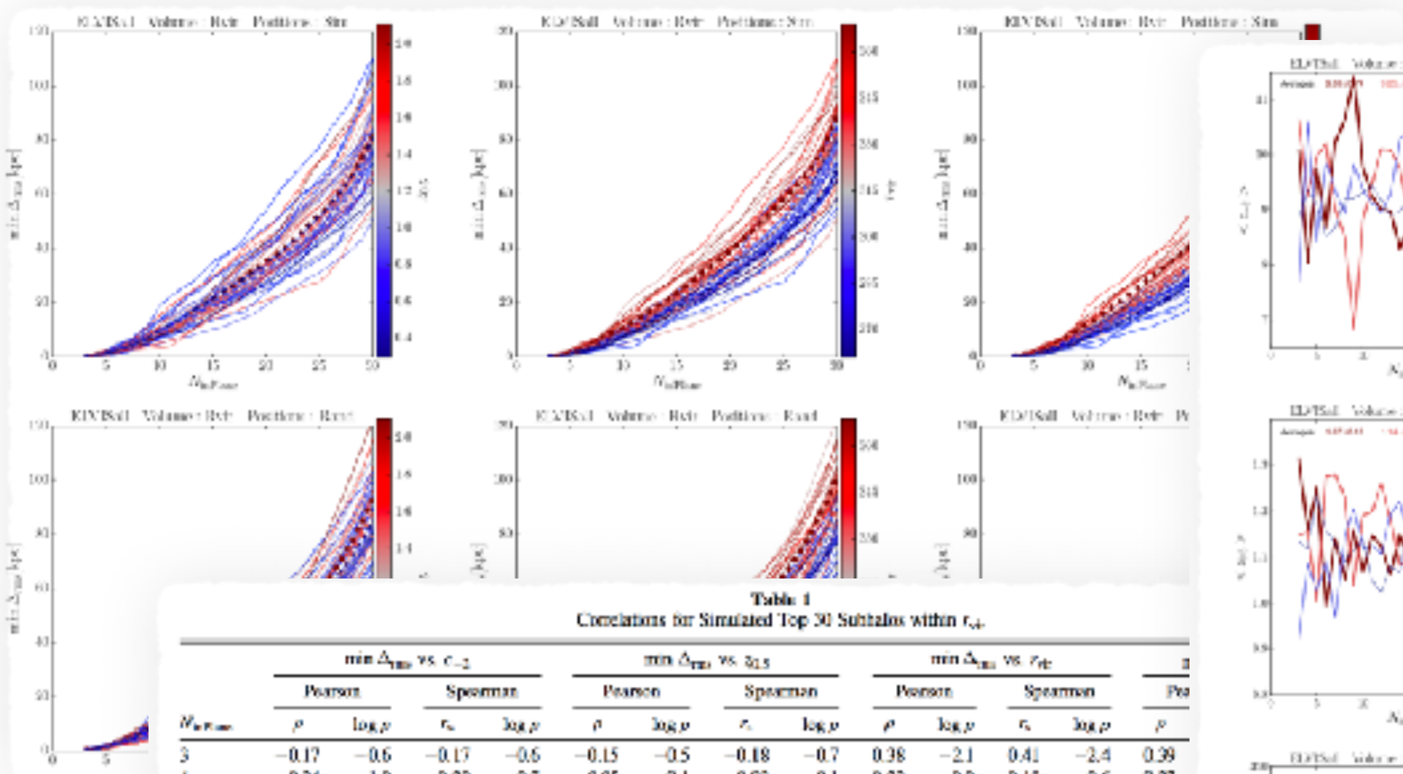
- High host halo concentration (proxy for early formation) gives more narrow satellite planes.
- Solves (?!) problem if MW & M31 formed early and/or have high concentration halos.

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.



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



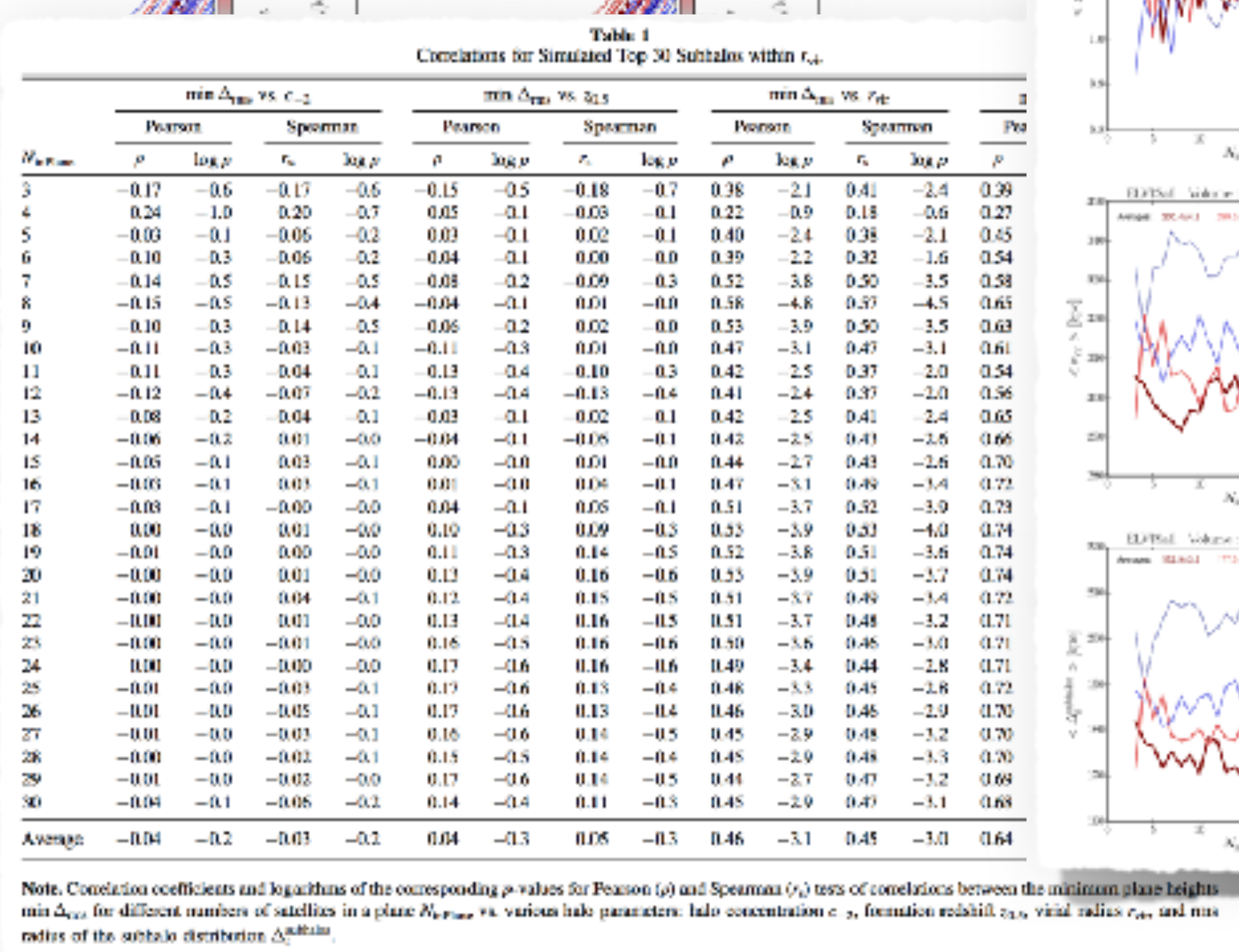
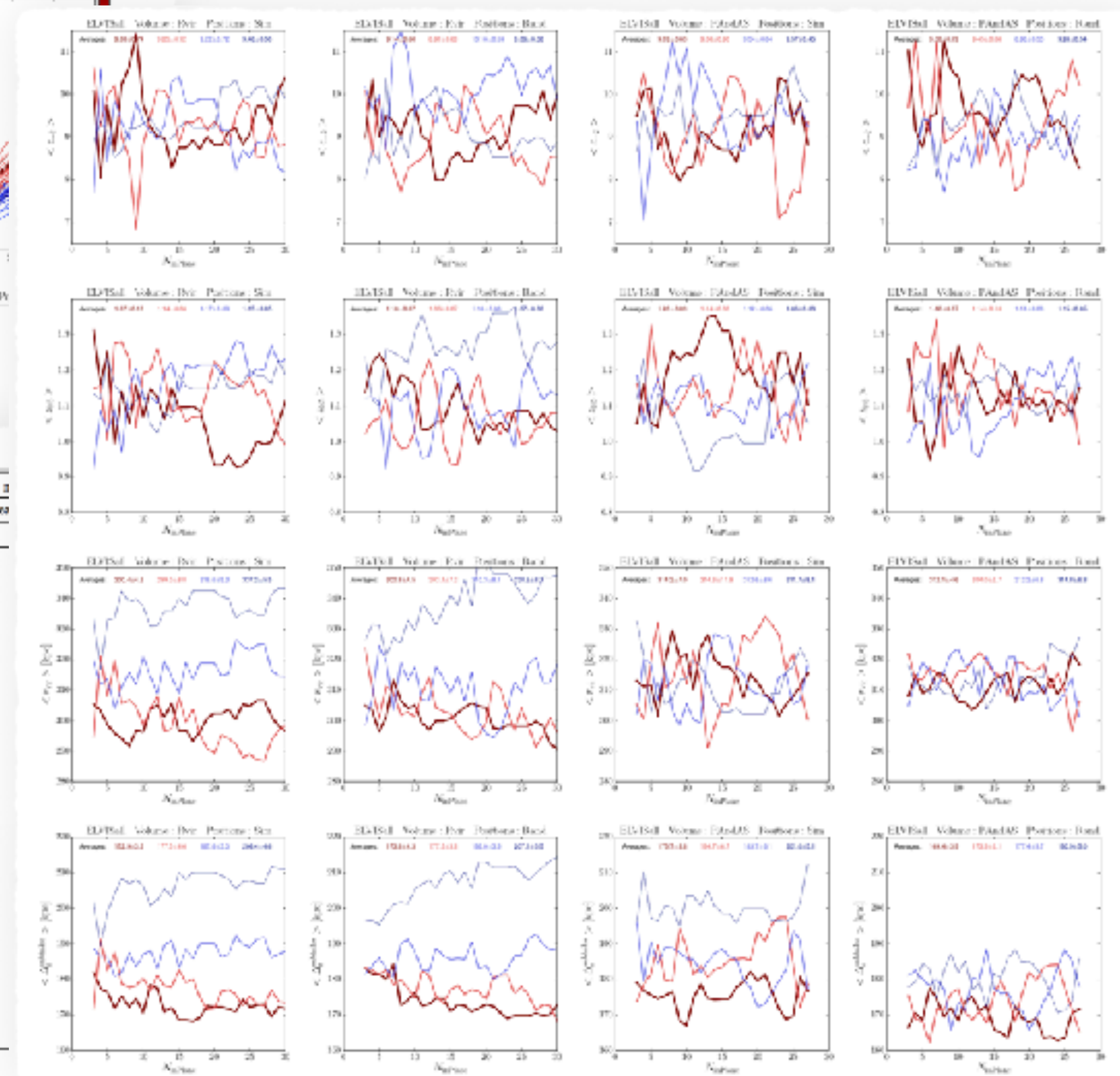


Table 1
Correlations for Simulated Top 30 Subhalos within r_{vir}

	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	−0.03	−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	−0.06	−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 $\Delta_r^{subhalo}$.



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

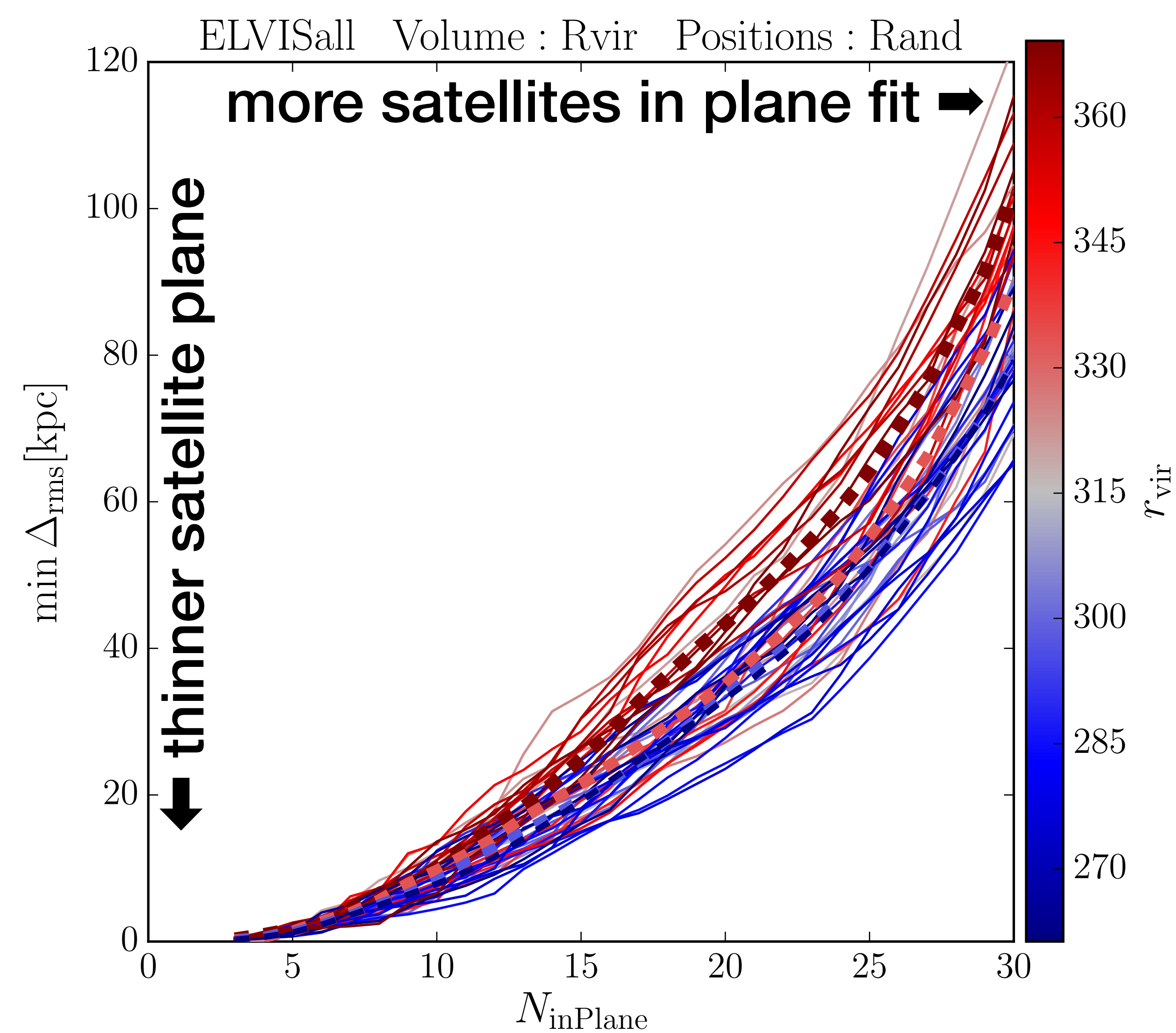
Correlation with halo mass / viral radius?

Correlation seen if 30 satellites selected from virial volume.

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

➡ Same present in distributions drawn from isotropy.

➡ Not a feature of ΛCDM.



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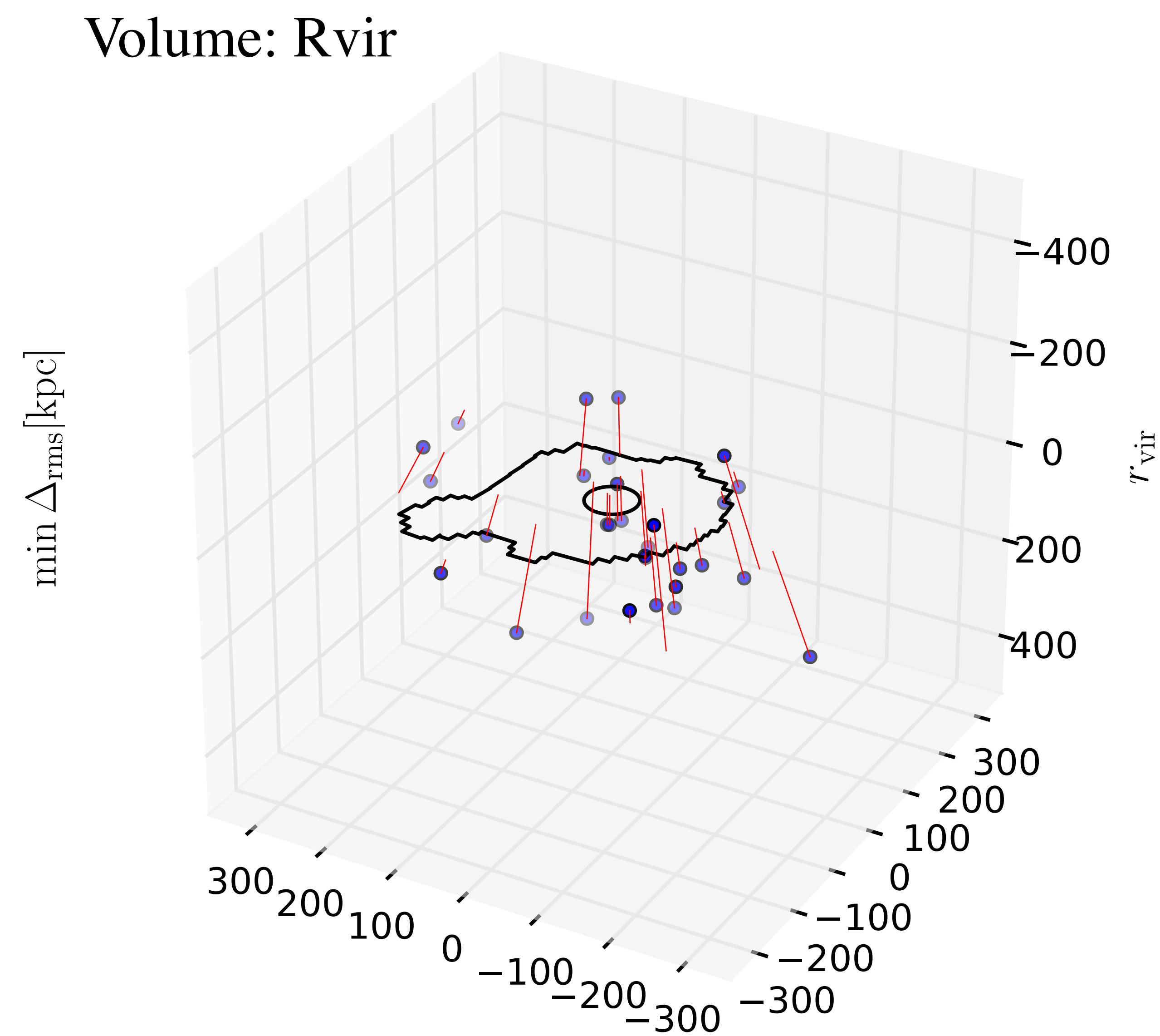
Need to select satellites from mock-PAndAS volume.



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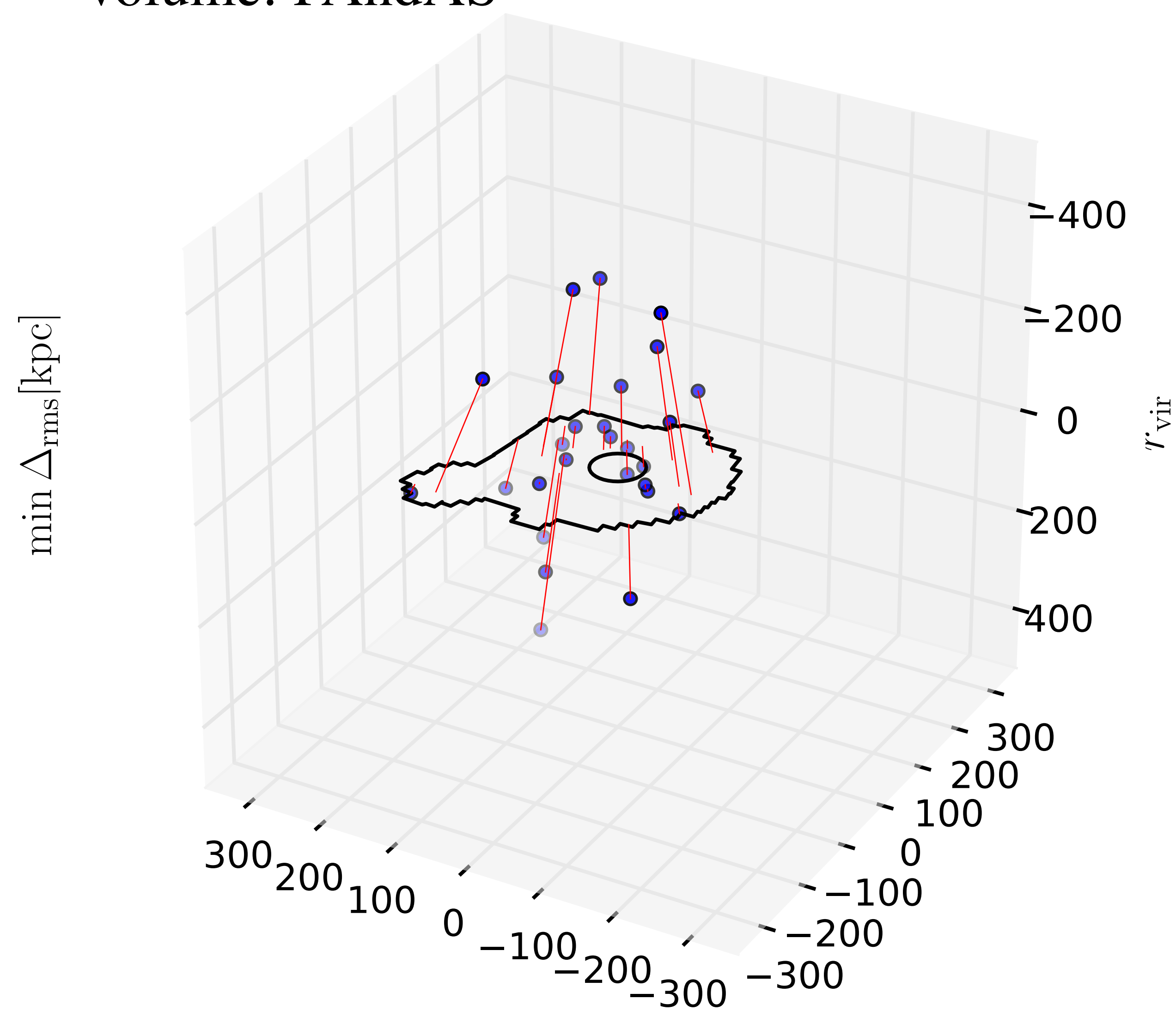
Volume: PAndAS



Correlation with halo mass / viral radius?

No

Correlation seen if 30 satellites selected from virial volume.

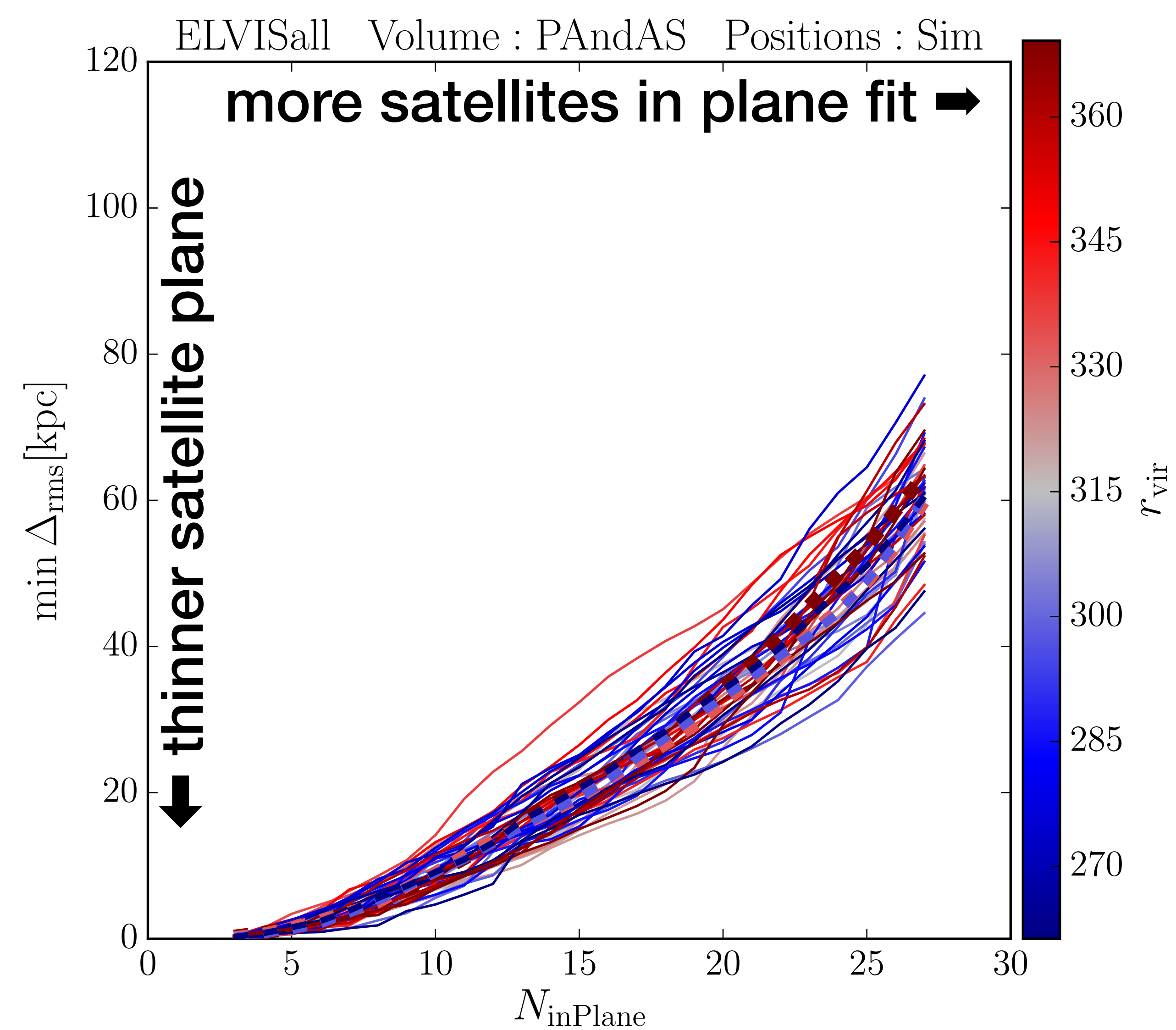
➡ Absolute plane width sensitive to overall extent of satellite distribution.

➡ Same present in distributions drawn from isotropy.

➡ Not a feature of ΛCDM.

Need to select satellites from mock-PAndAS volume.

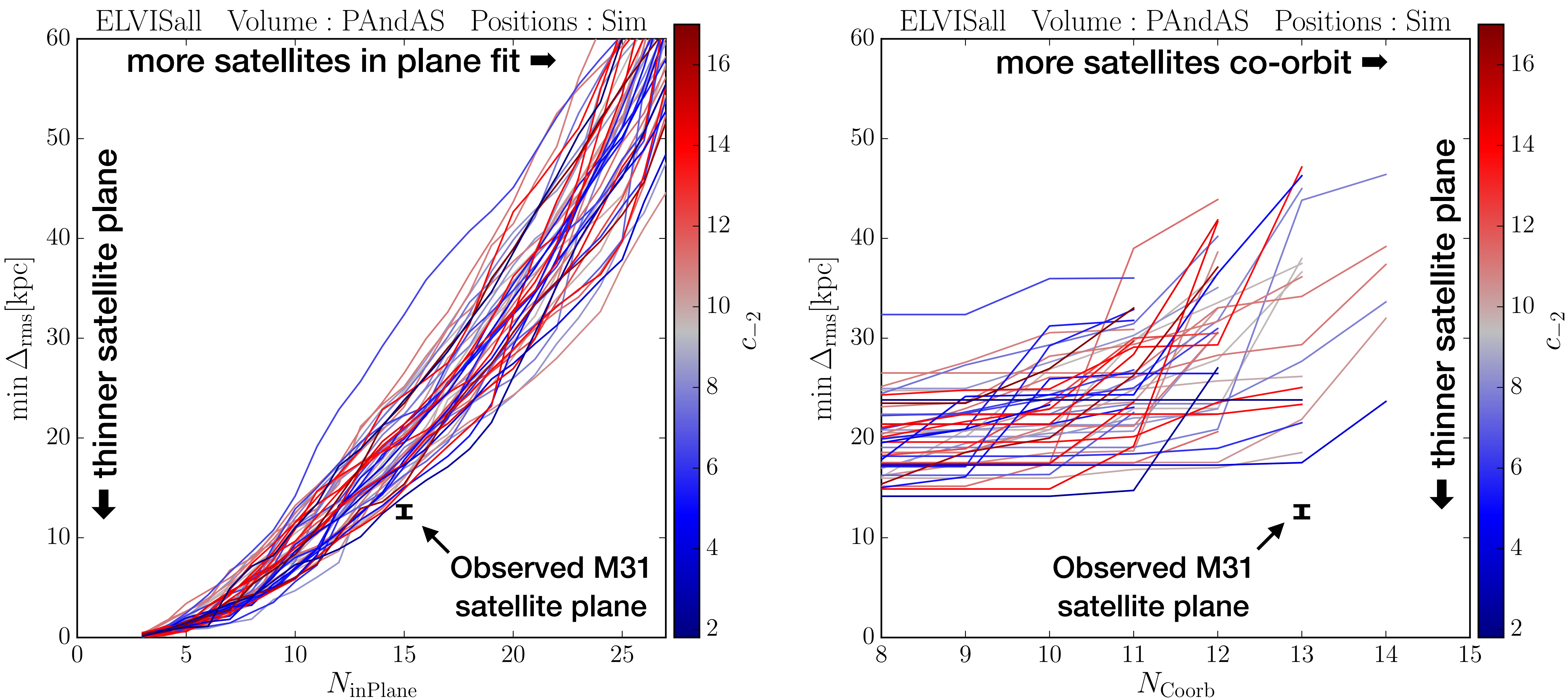
Then no correlation with viral mass/radius.



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

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

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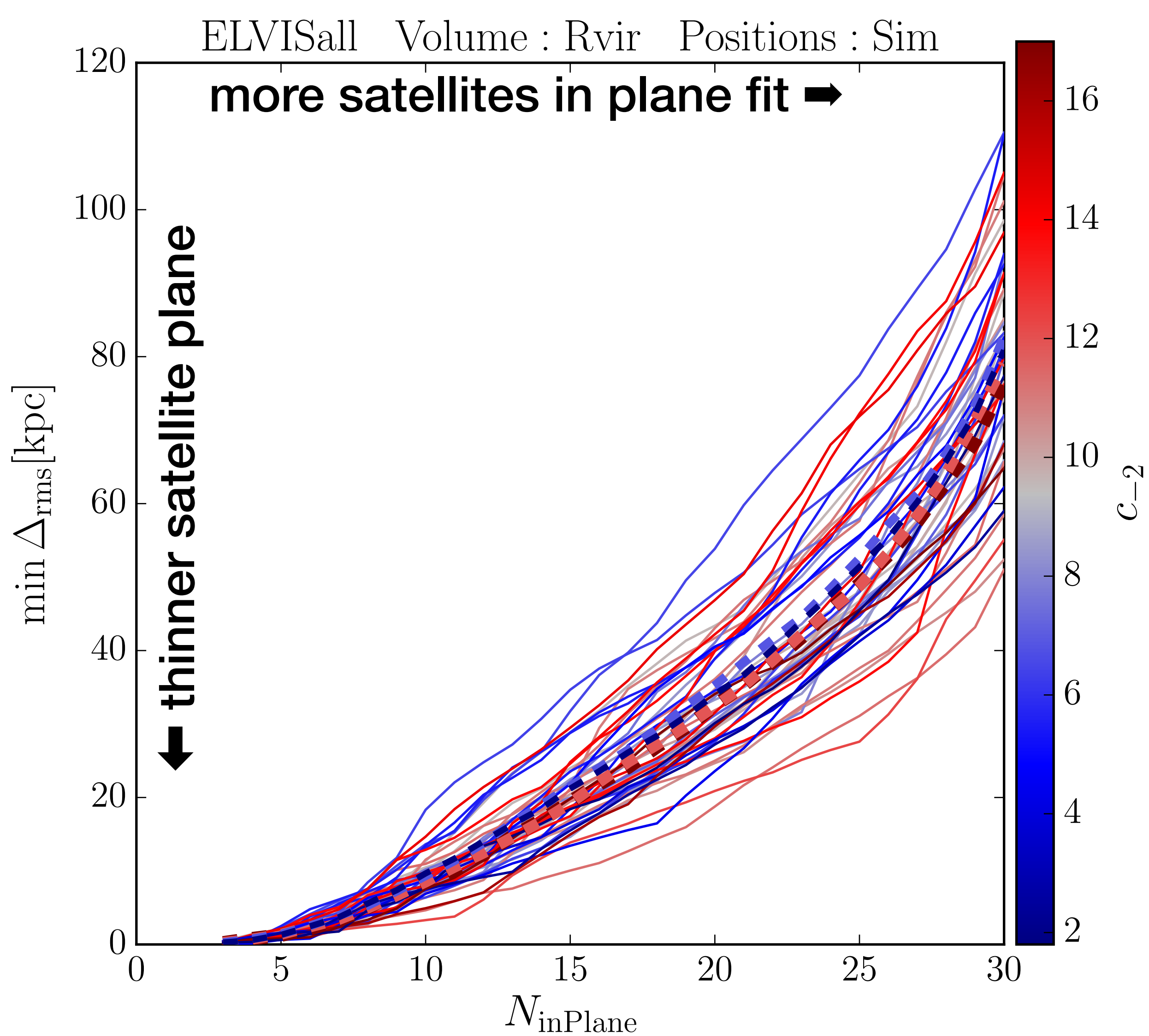

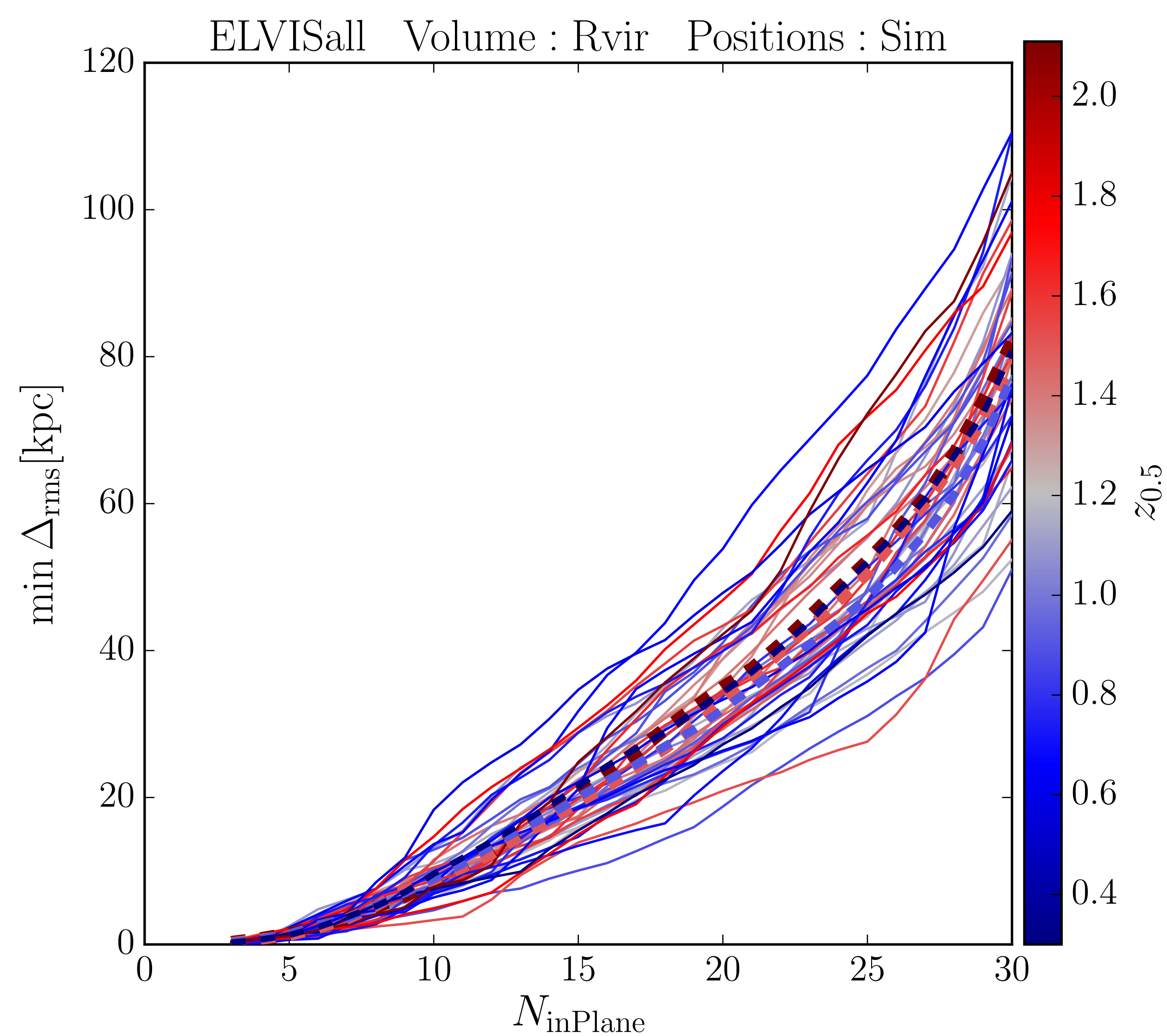

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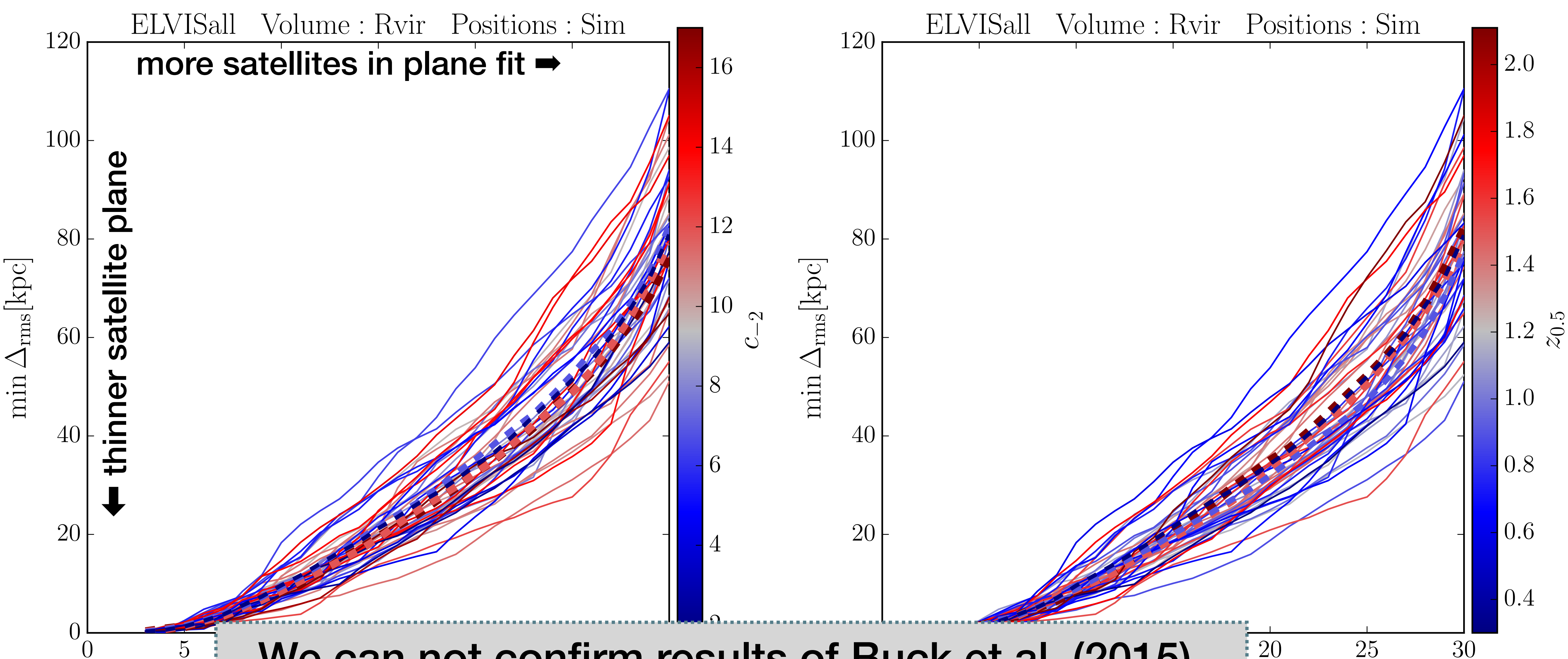


We can not confirm results of Buck et al. (2015).

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

Correlation with being in a paired configuration of hosts?

The **Vast Polar Structure** / **Great Plane of Andromeda** have:

- Similar heights:

  VPOS: 20-30 kpc

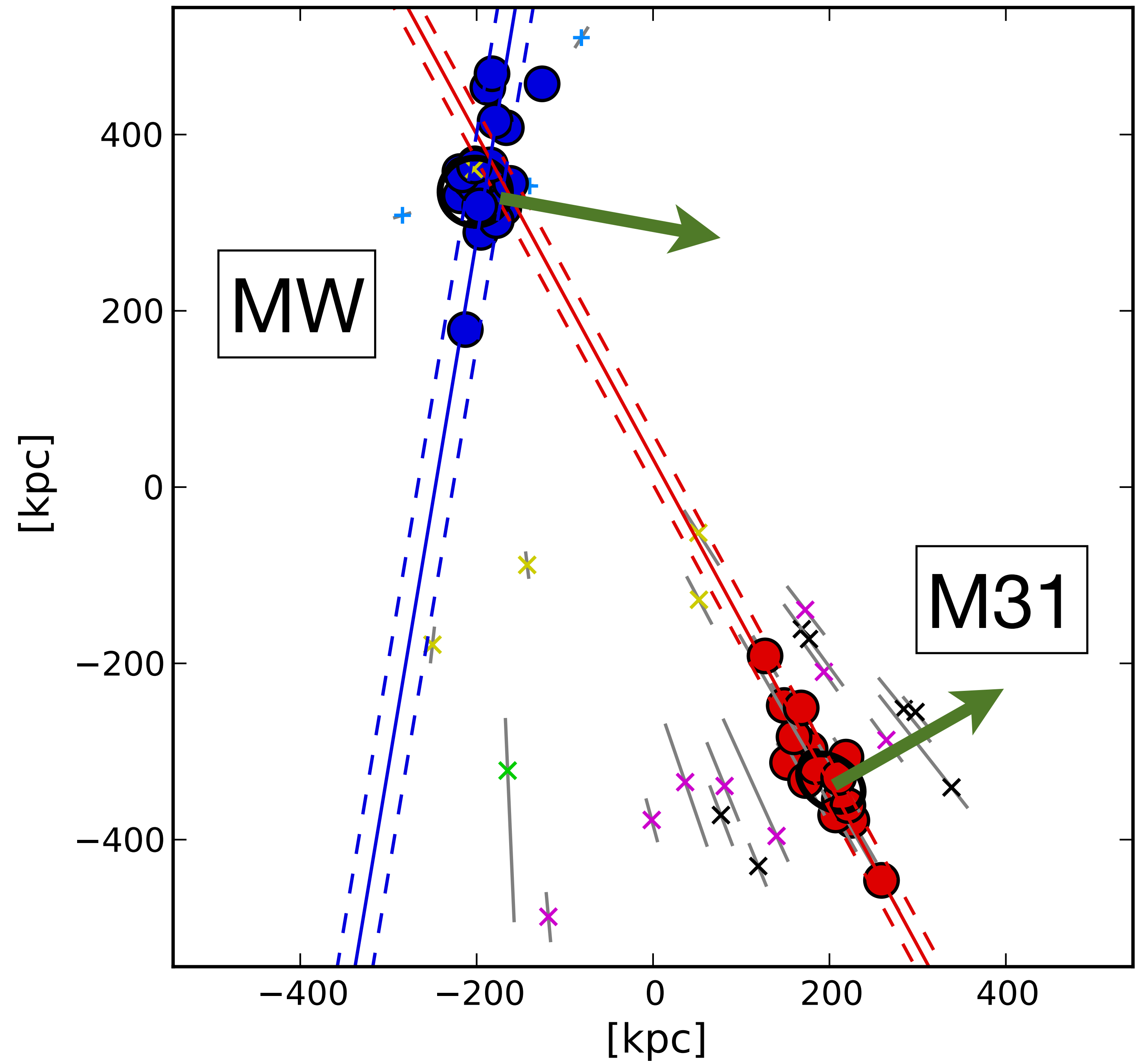
  GPoA: 14 kpc

- Similar diameters: 400 kpc
- Similar **spin directions**

- Additional alignments:

  VPOS: YH GCs, 50% streams

  GPoA: Giant Stream, NW-S1

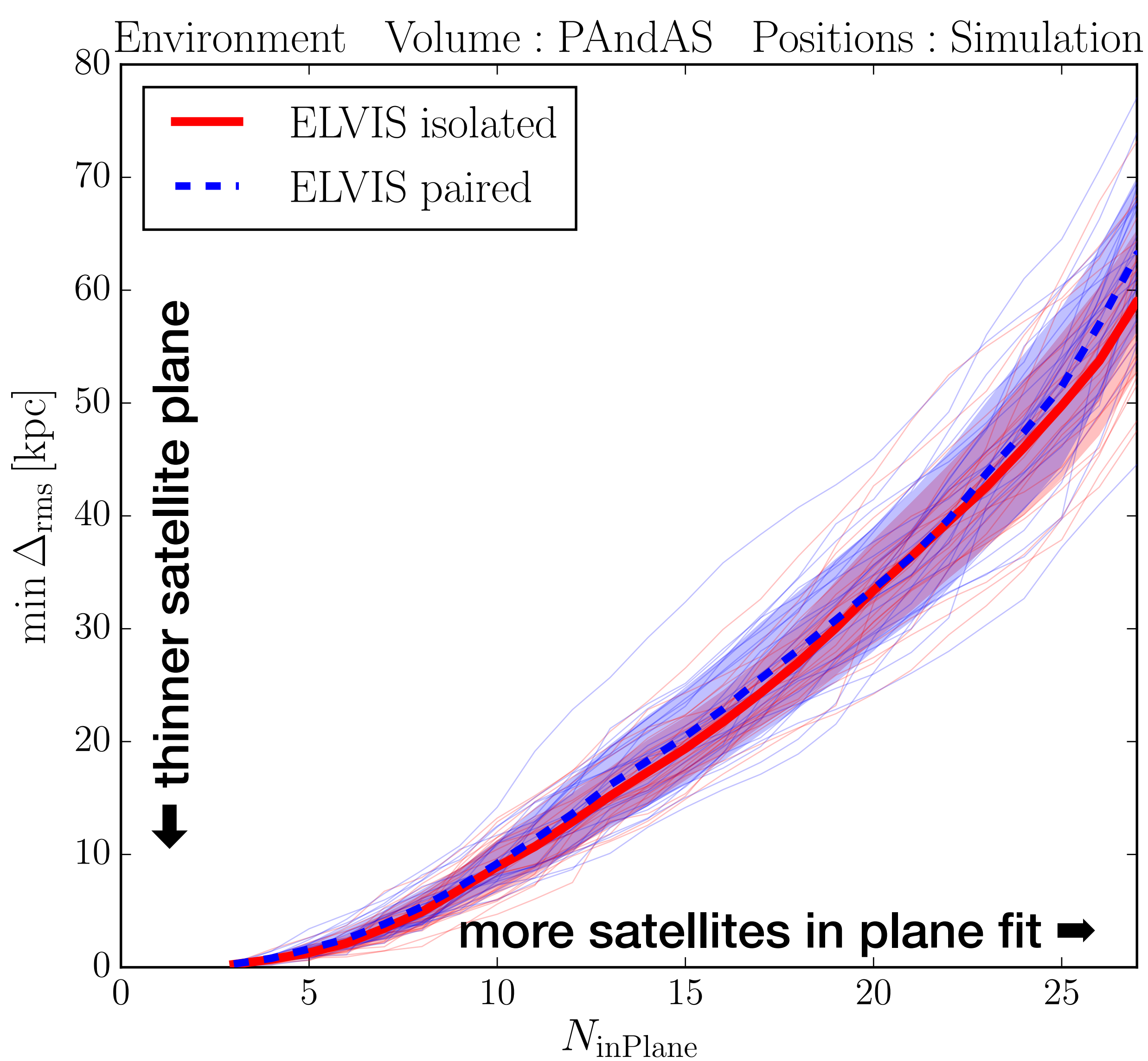


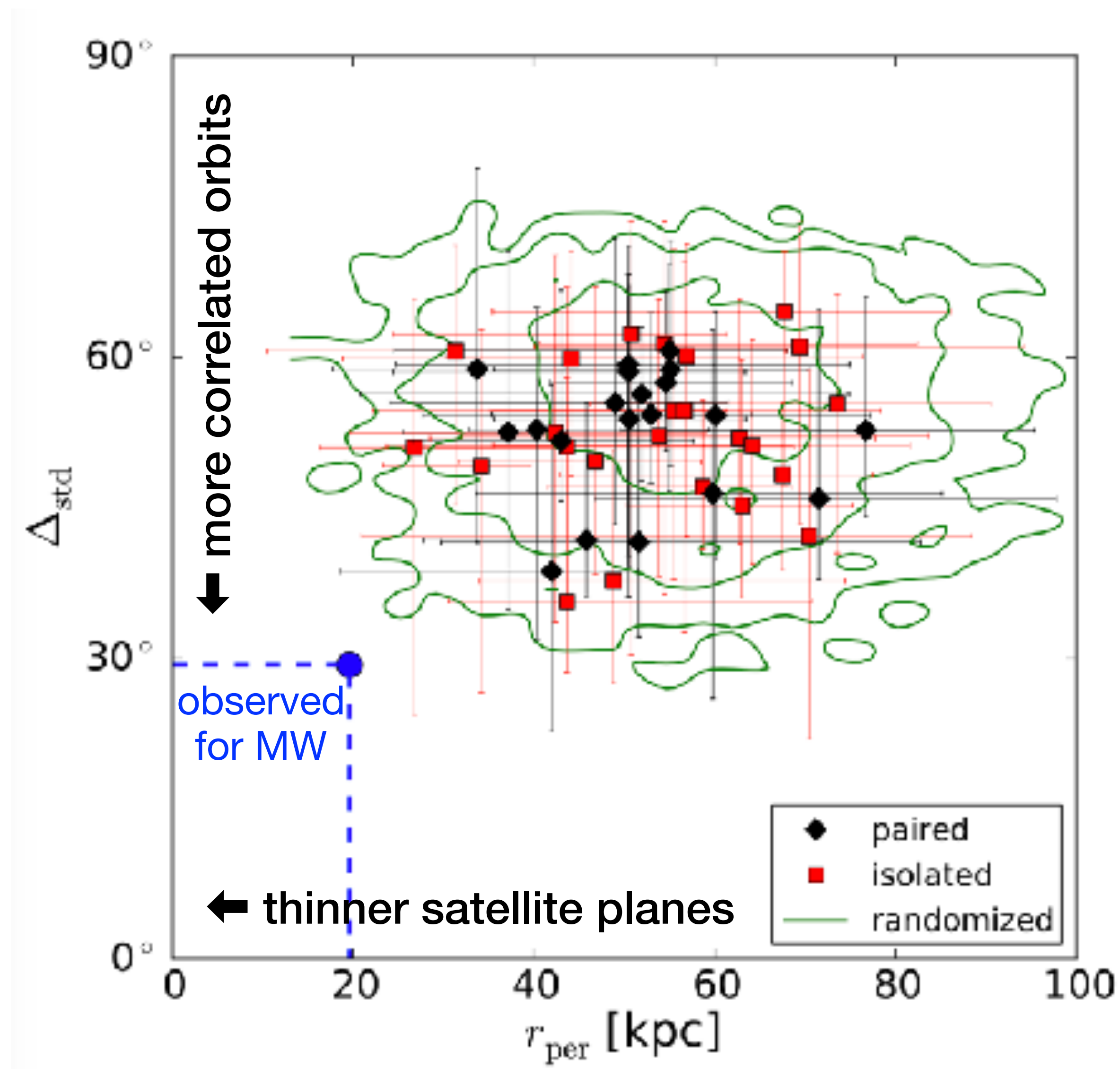
Correlation with being in a paired configuration of hosts?

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.

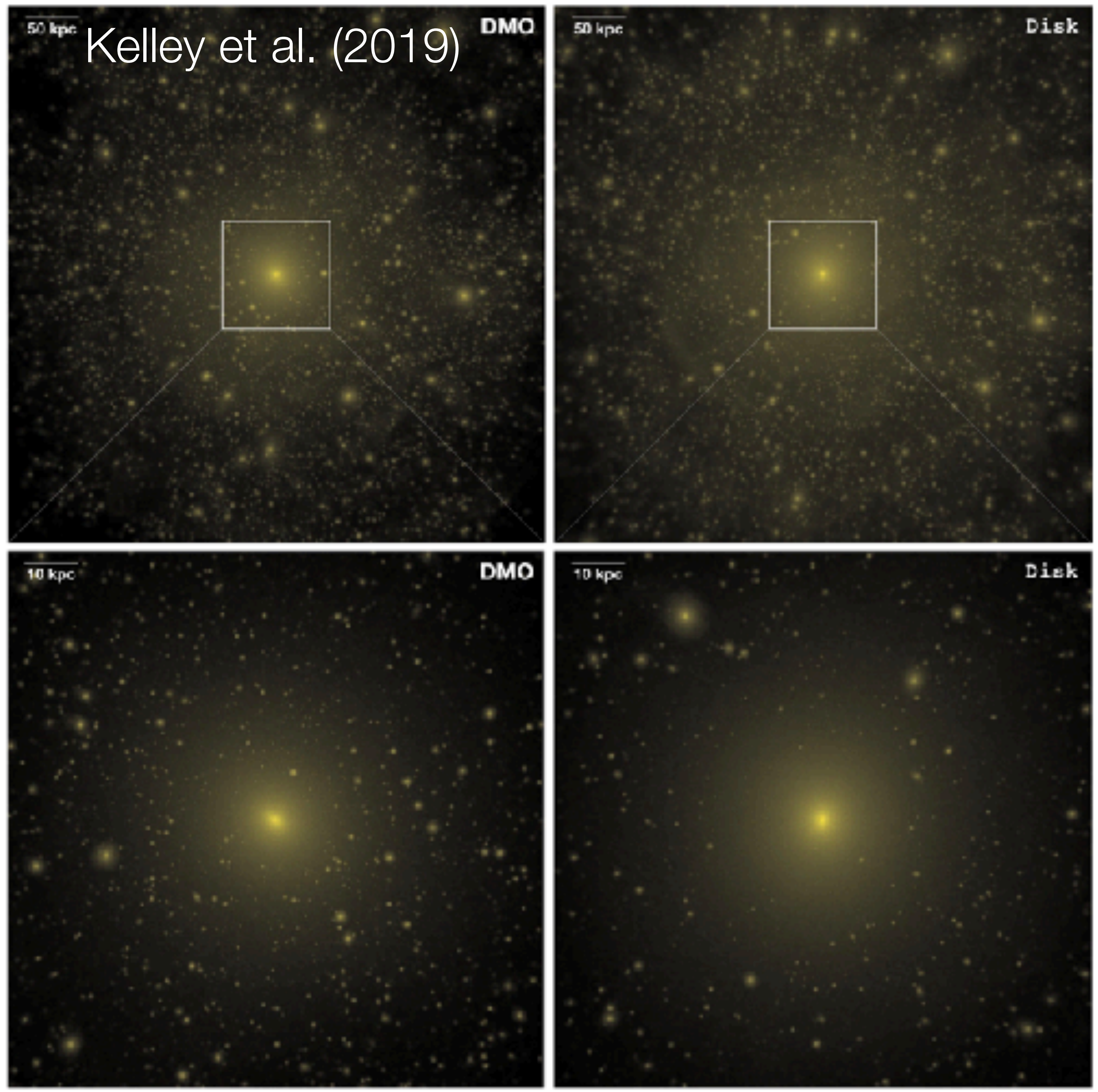


Figure 1. Visualization of the dark matter for Kentucky (left) and Kentucky Disk (right). The top panels span 500 kpc, approximately the virial volume of this halo. The bottom panels span 100 kpc. The absence of substructure at small radii in the Disk runs is striking. An enhancement in central dark 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?

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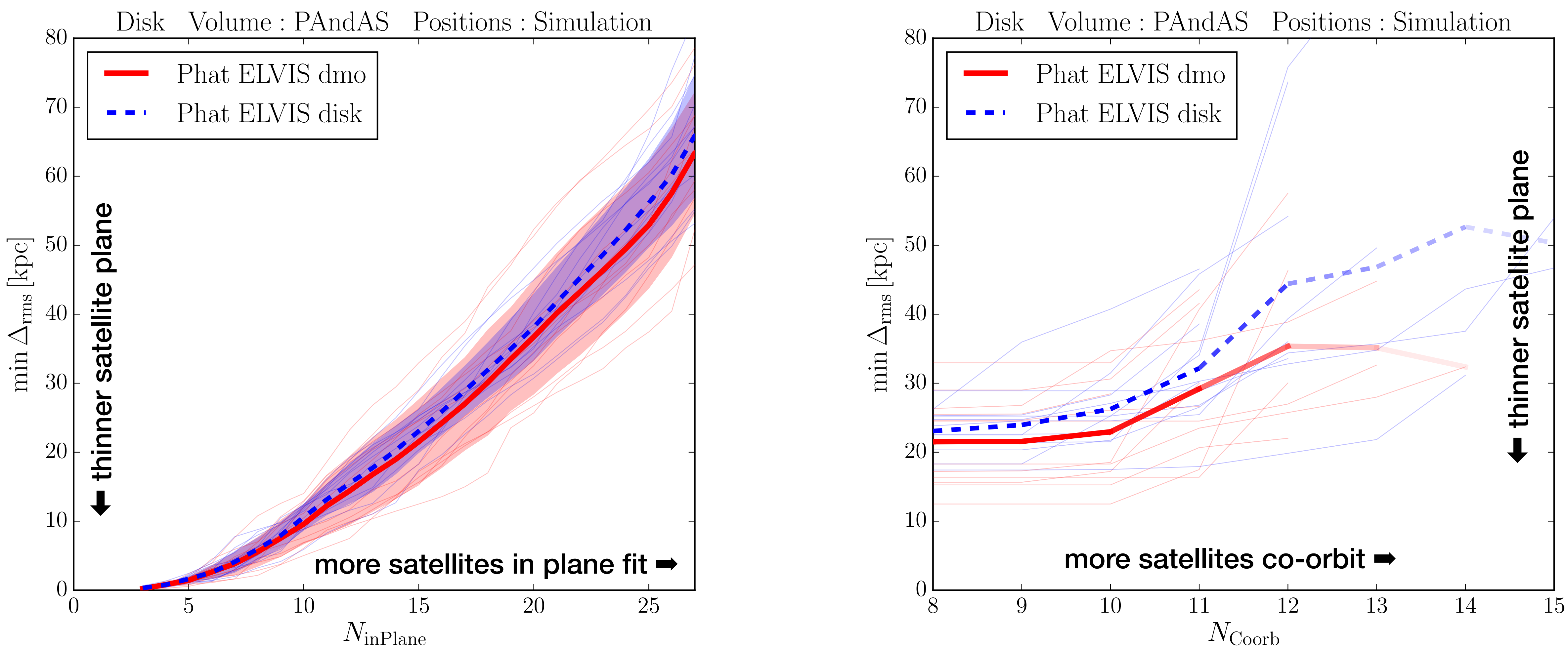
No differences in flattening of satellite system whether central disk present or not.



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

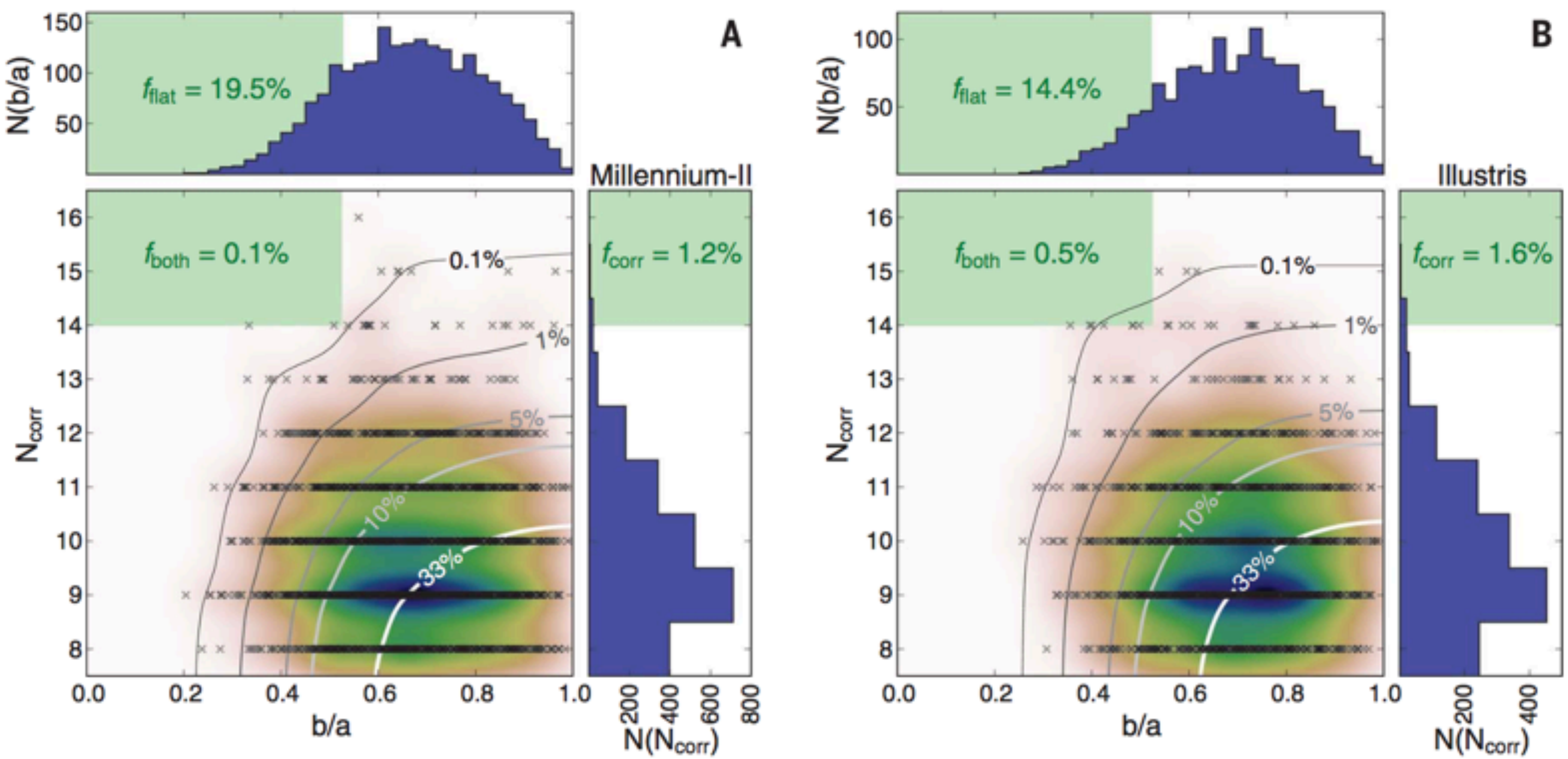
Correlation with existence of a central disk galaxy potential?

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.

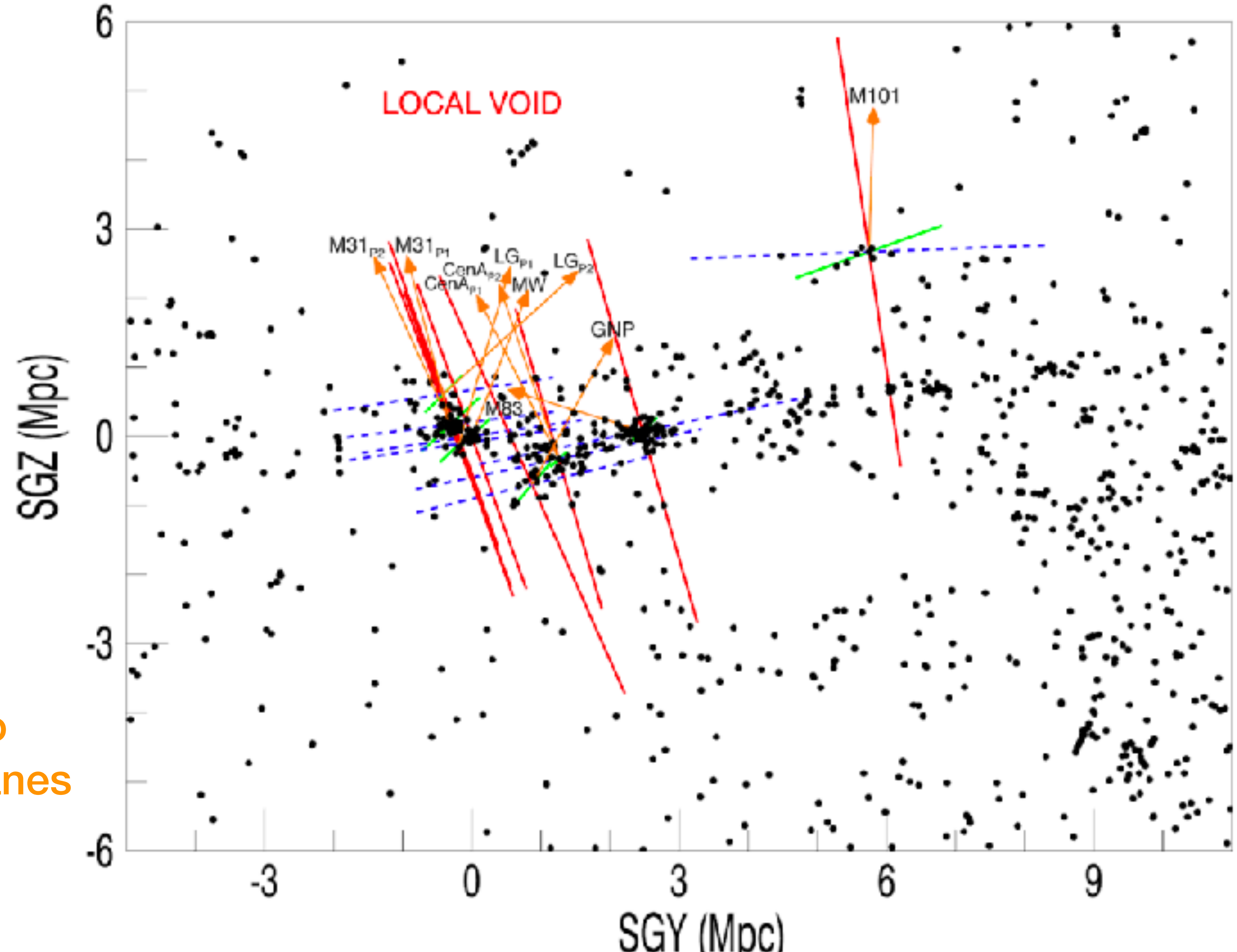
Also no difference for Centaurus A plane in hydrodynamical Illustris simulation or dark-matter-only analog (Müller, Pawlowski, Lelli & Jerjen, 2018).



The orientation of planes of dwarf galaxies in the quasi-linear Universe

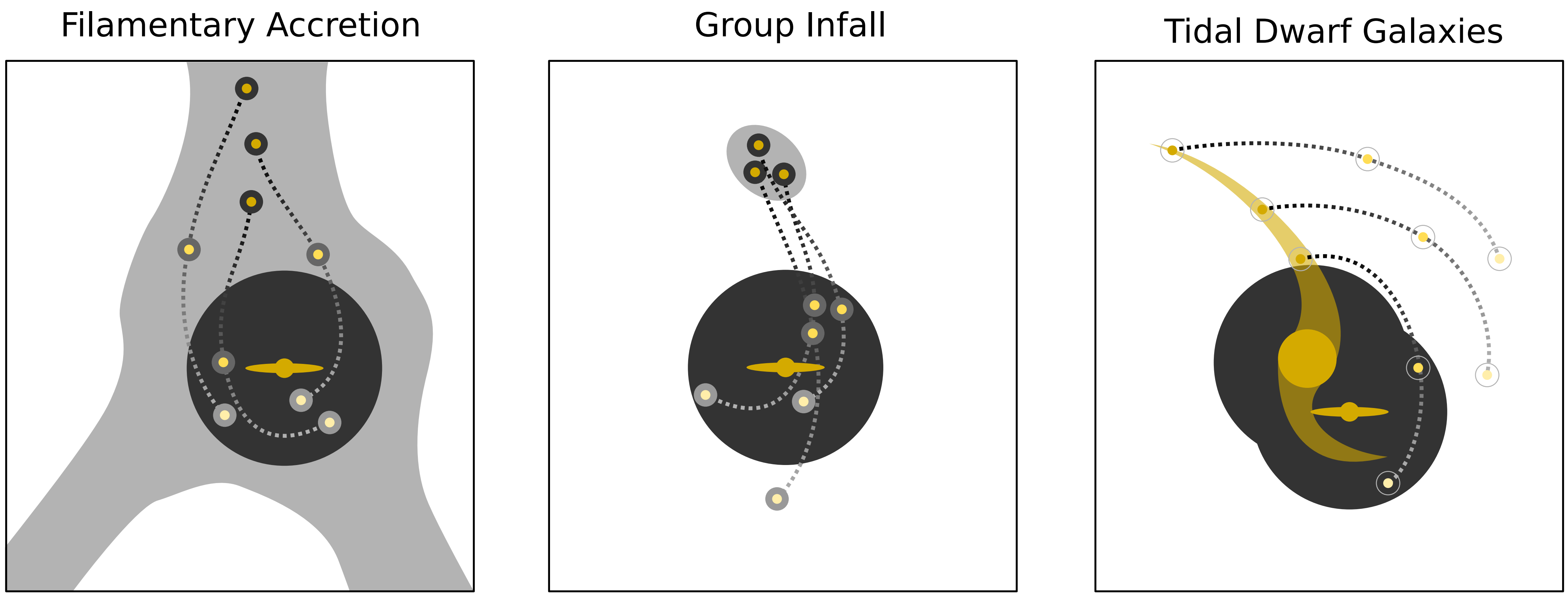
Noam I Libeskind[1,2], Edoardo Carlesi[1], Oliver Müller[3], Marcel S Pawlowski[1,4], Yehuda Hoffman[5], Daniel Pomarède[6], Helene M Courtois[2], R. Brent Tully[7], Stefan Gottlöber[1], Matthias Steinmetz[1], Jenny Sorce[8,1], Alexander Knebe[9,10,11]

On the arXiv last week!



→: Normal vectors to satellite/dwarf galaxy planes

Suggested origins of planes of satellite galaxies



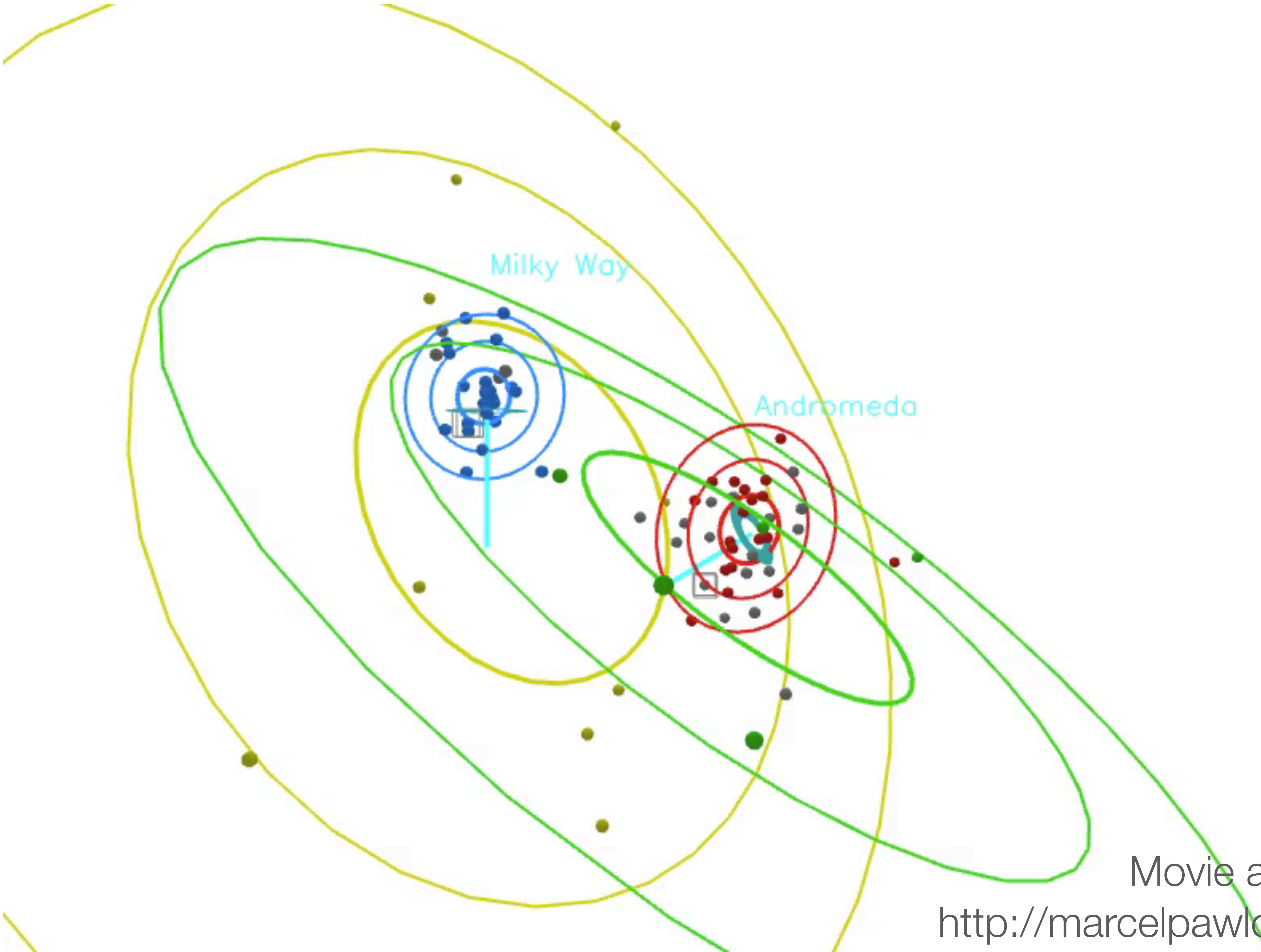
Pawlowski (2018)

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

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

Pawlowski, Kroupa & Jerjen (2013)

The Bigger Picture:
Clues from the Local Group Dwarf Galaxy Distribution



Movie available at
http://marcelpawlowski.com

Conclusions

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

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.

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)