Possible origins of phase-space structures among satellite galaxies in the Local Group

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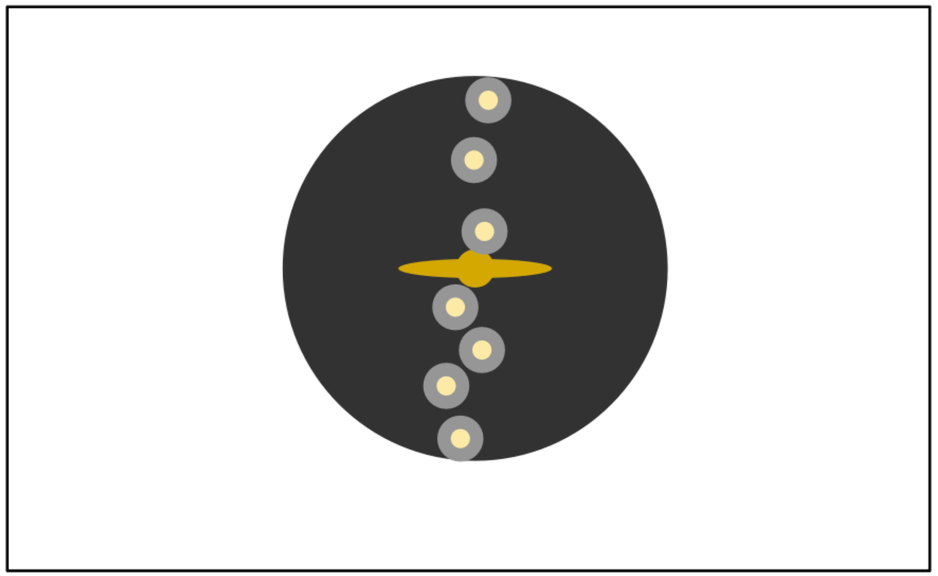
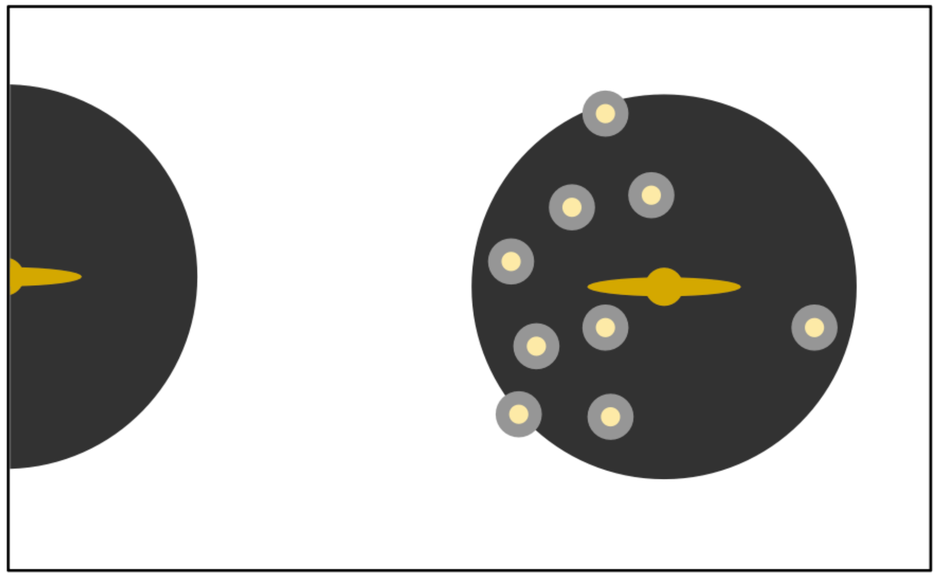
AIP

Two types of satellite galaxy phase-space correlations that challenge expectations

Plane of Satellites

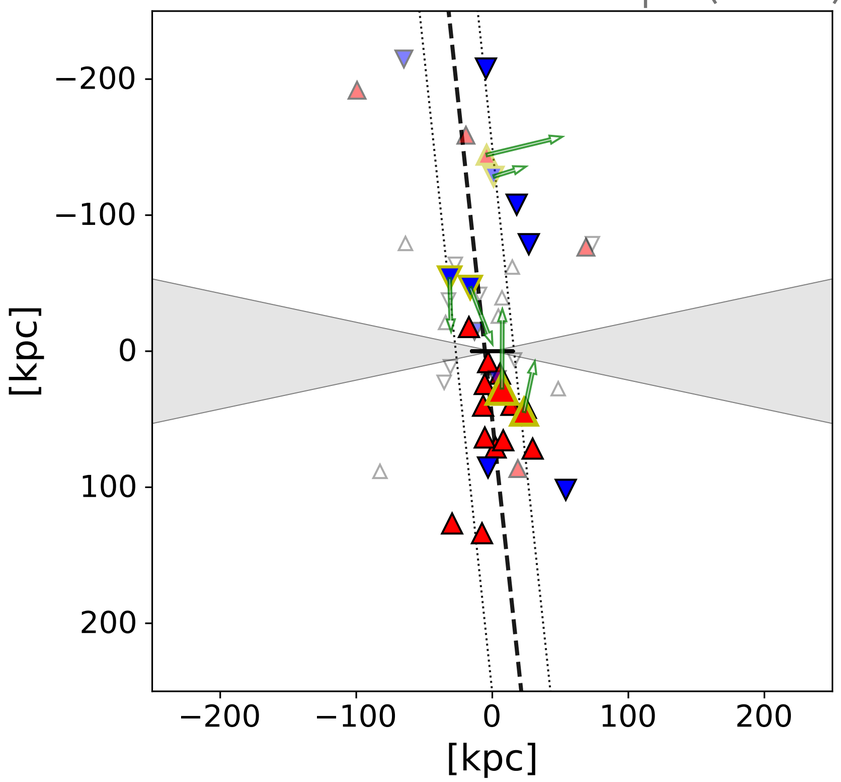


Lopsidedness



Both the Milky Way and M31 host a "Plane of Satellite Galaxies"

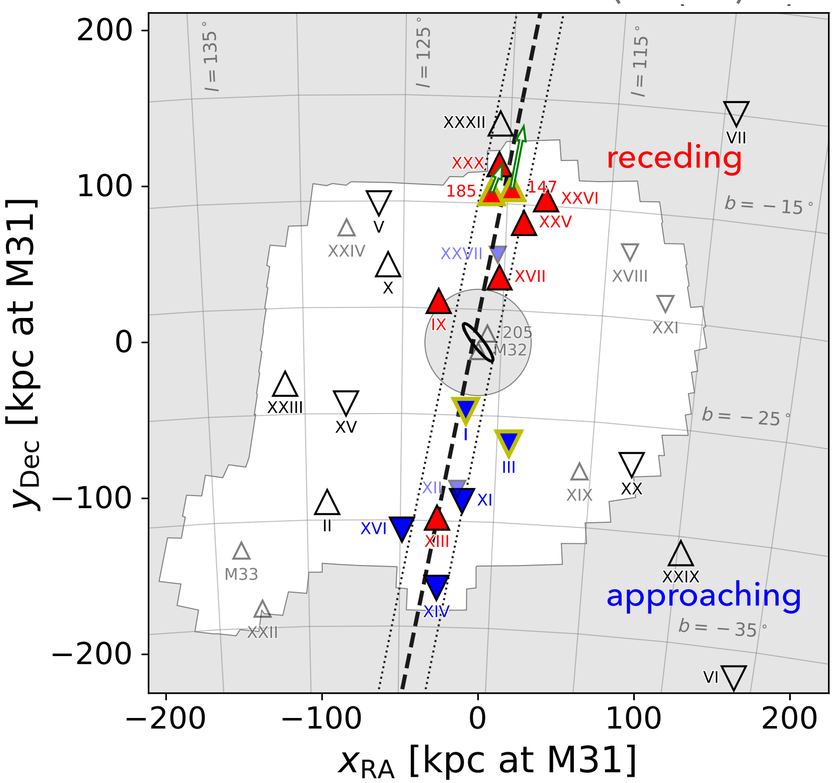
MW: Pawlowski & Kroupa (2020)



Co-rotation along plane confirmed with proper motions, especially for most classical dwarfs

(see Salvatore's talk yesterday)

M31: Ibata et al. (2013)



Two dwarfs with **proper motions** confirm co-rotation along plane

(Sohn et al. 2020, Pawlowski & Sohn 2021)

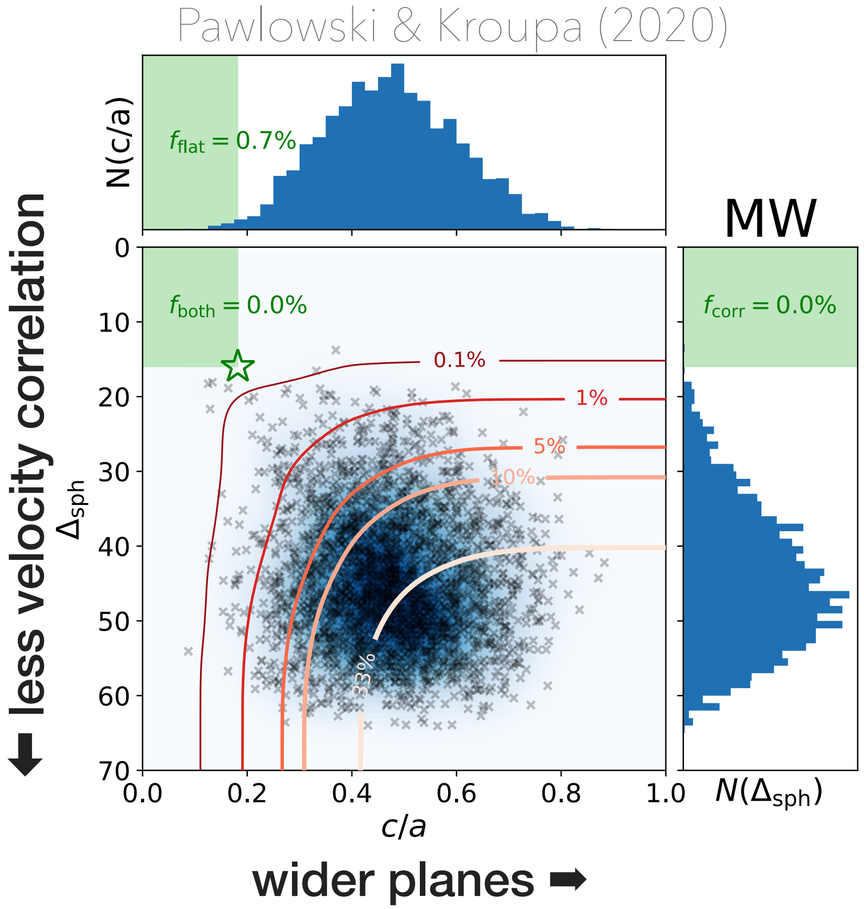
Other cases outside the Local Group, e.g.:

- **Centaurus A** (Müller, Pawlowski, et al. 2018, 2021)
- **NGC 4490** (Pawlowski et al. 2024, on arXiv two weeks ago).
- **25% of host in MATLAS** (Heesters et al. 2021).

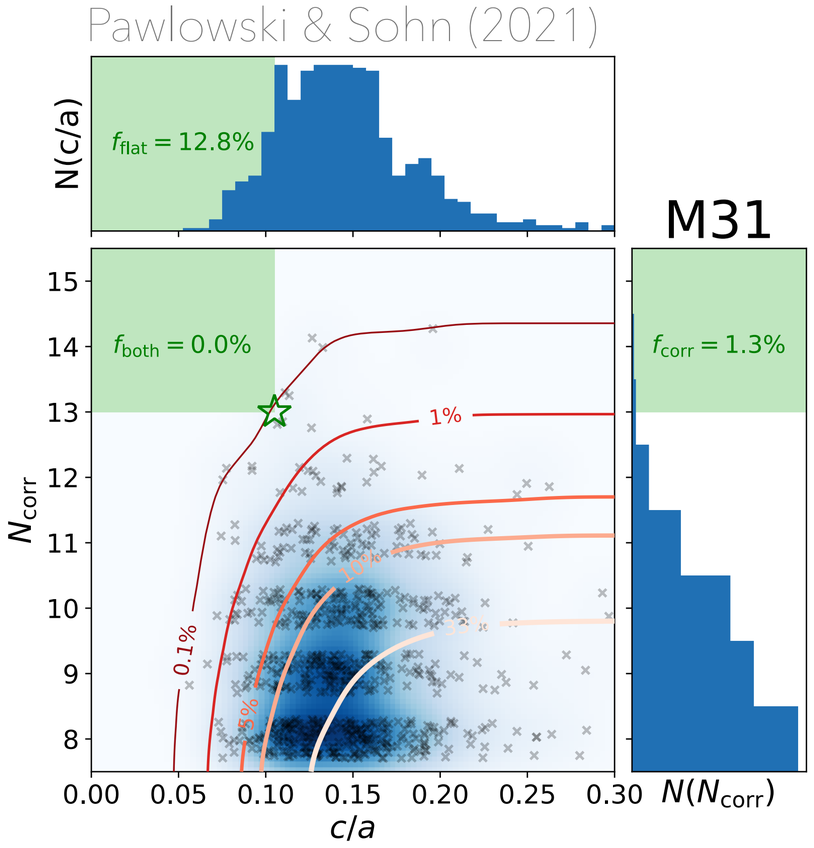
Plots from my review: Pawlowski (2021, Galaxies, 9, 66)

Similarly extreme structures are very rare in cosmological simulations

Pawlowski & Kroupa (2020)



Pawlowski & Sohn (2021)



1:1000 outliers in simulated analogs.

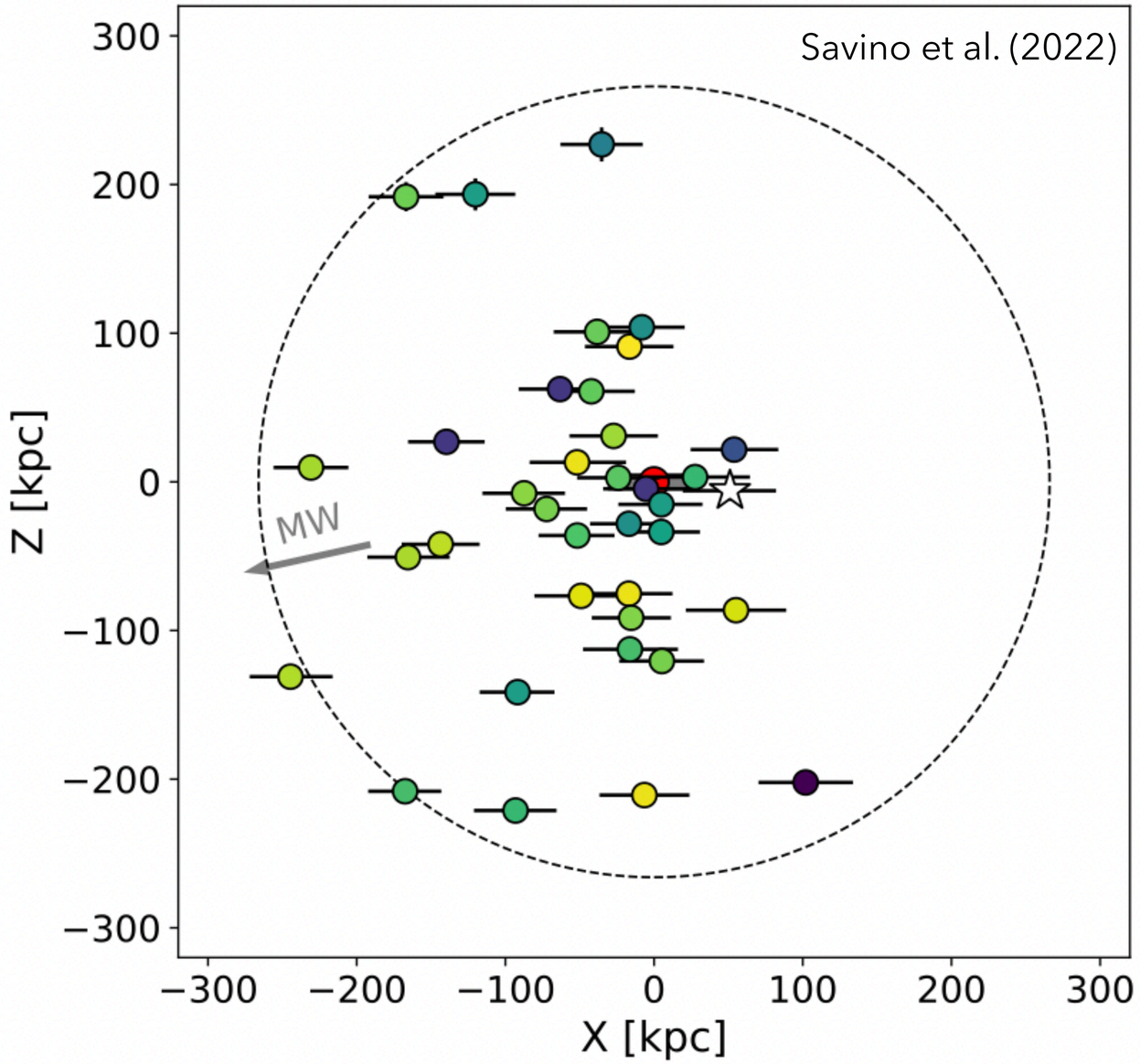
- Planes of Satellite Galaxies Problem of ΛCDM (robust to baryonic effects)
- **We need specific formation scenario for observed systems.**

Similar low frequencies for:

- **Centaurus A** (Müller, Pawlowski, et al. 2018, 2021)
- **NGC 4490** (Pawlowski et al. 2024, on arXiv two weeks ago).

Plots from my review: Pawlowski (2021, Galaxies, 9, 66)

Lopsidedness of M31 satellite system



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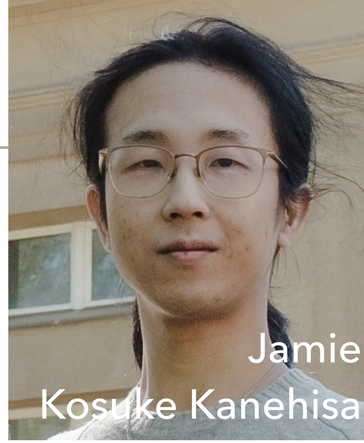
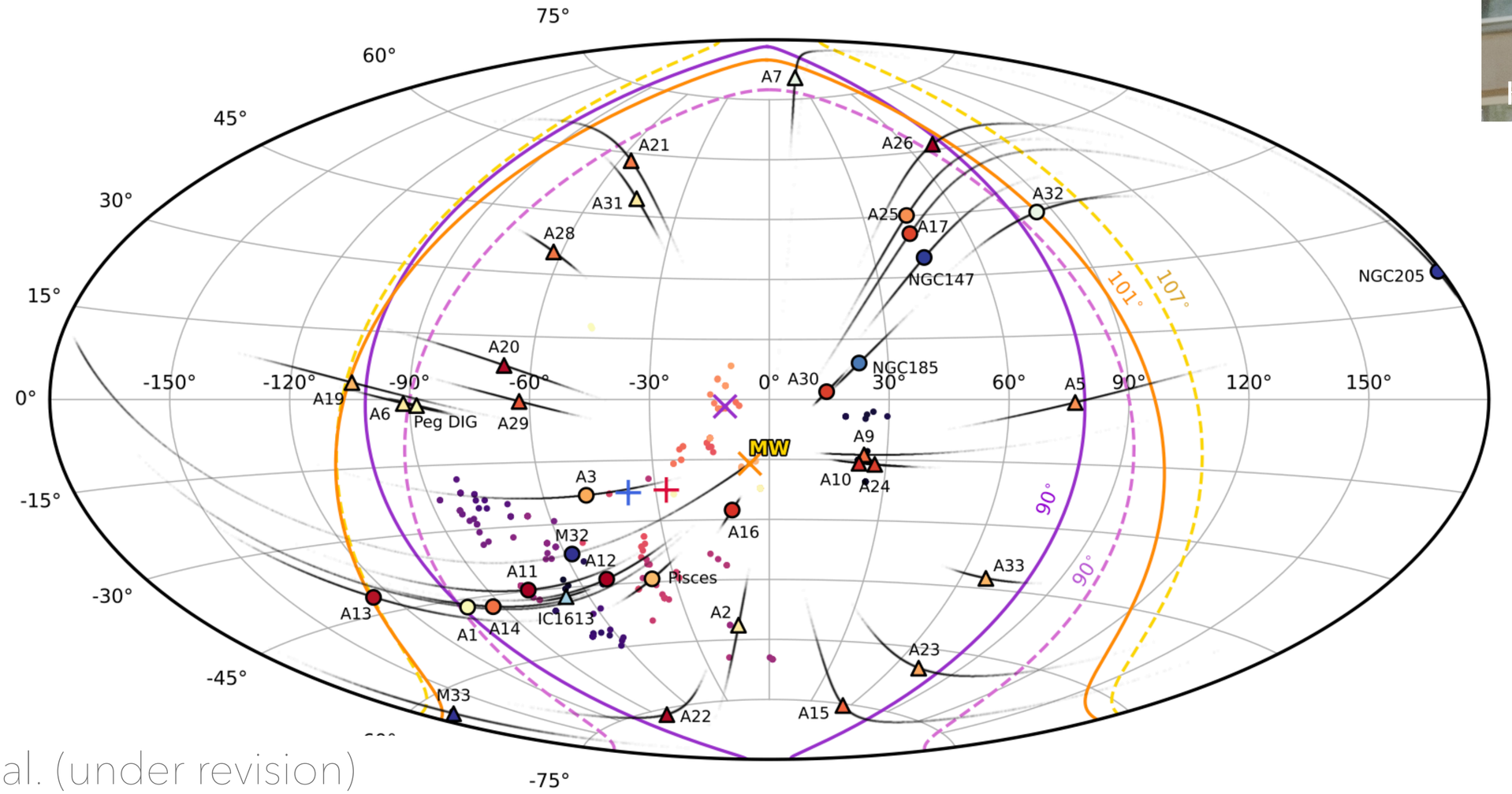
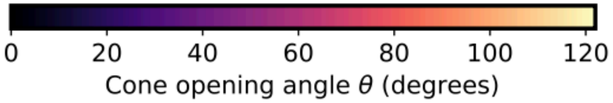
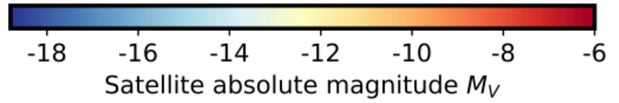




Kanehisa et al. (under revision)





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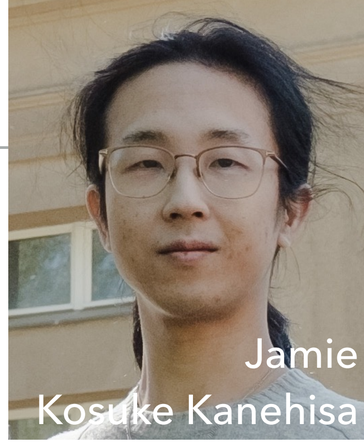
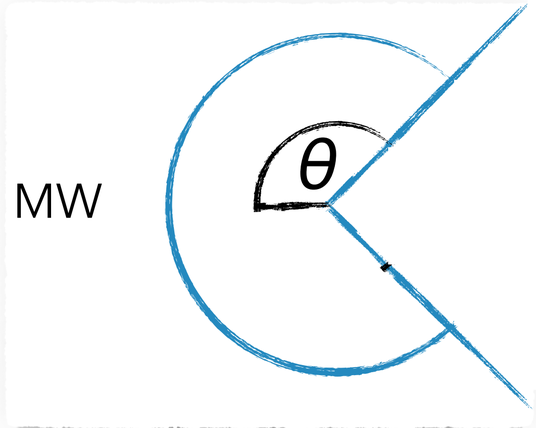
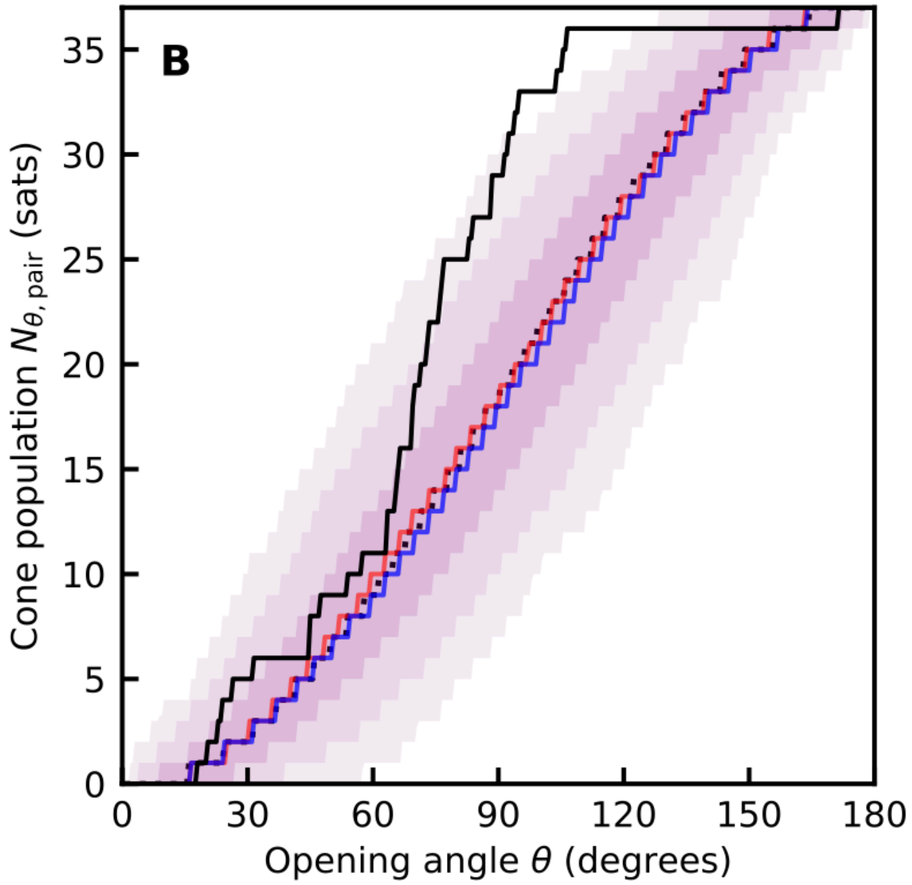


- Andromeda's satellites have long been known to preferentially lie on the hemisphere facing the MW.
- We show: **all but one of 37 satellites within cone of θ = 107° from Milky Way.**
- Comparison to ΛCDM simulations (TNG, EAGLE): **<0.4% of simulated analogs are as extreme!**
- **In conjunction with** its **satellite plane**, this paints the **Andromeda system** as **an extreme outlier** in the prevailing **cosmological paradigm**.





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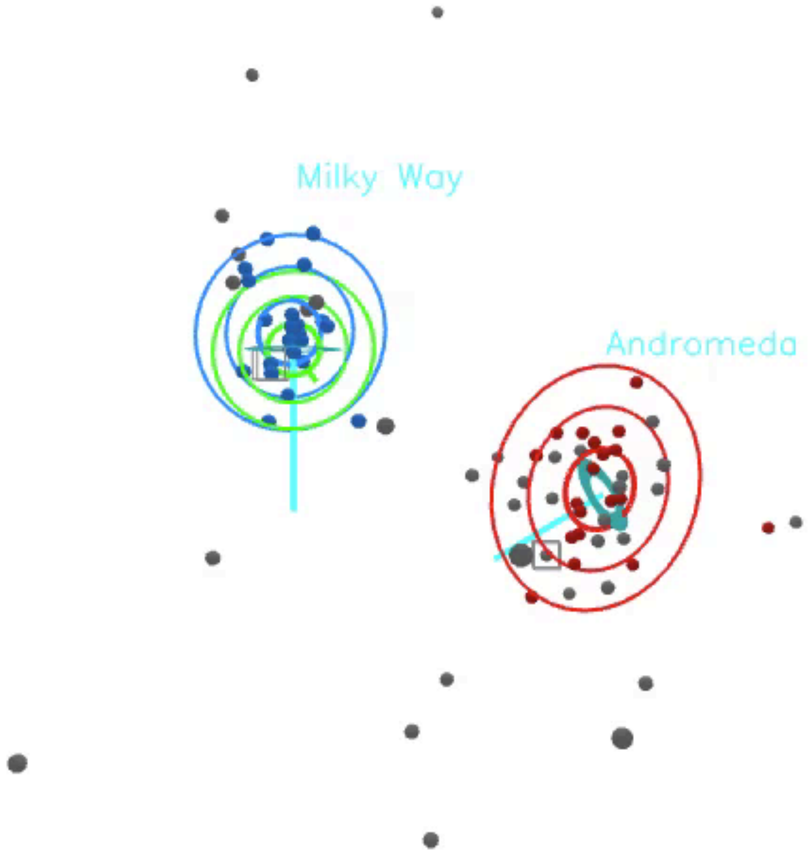
Local Group: Satellite vs. more distant dwarf galaxy planes

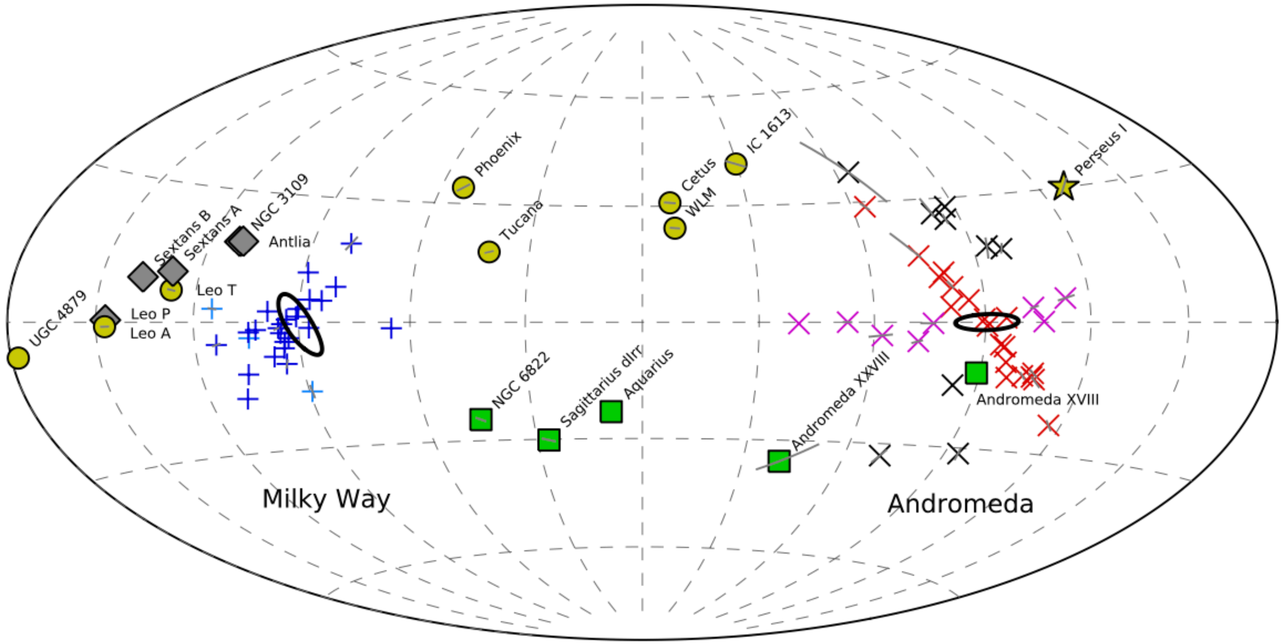


MOVIE AVAILABLE AT
HTTP://MARCELPAWLOWSKI.COM

PAWLOWSKI, KROUPA & JERJEN (2013)

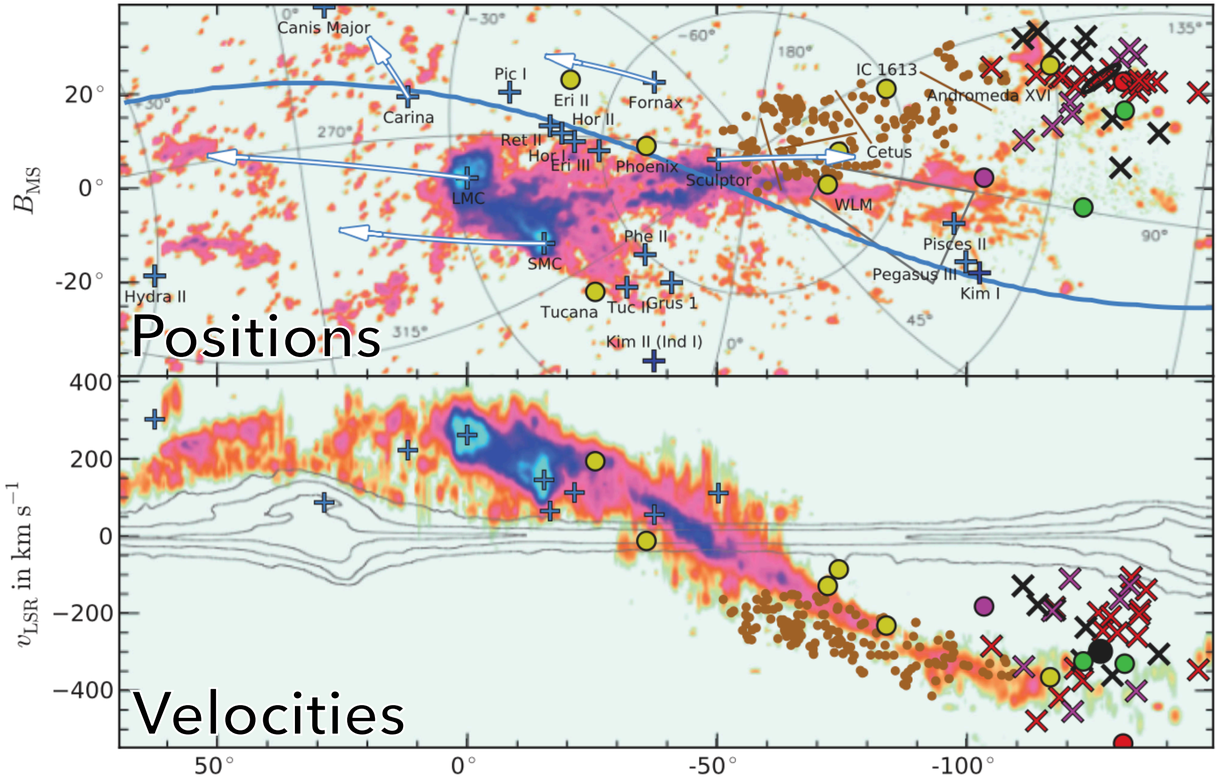
Local Group: Non-satellite dwarf galaxy plane connecting MW and M31?

Distribution as seen from MW-M31 midpoint



PAWLOWSKI & MCGAUGH (2014)

Overlap with Magellanic Stream

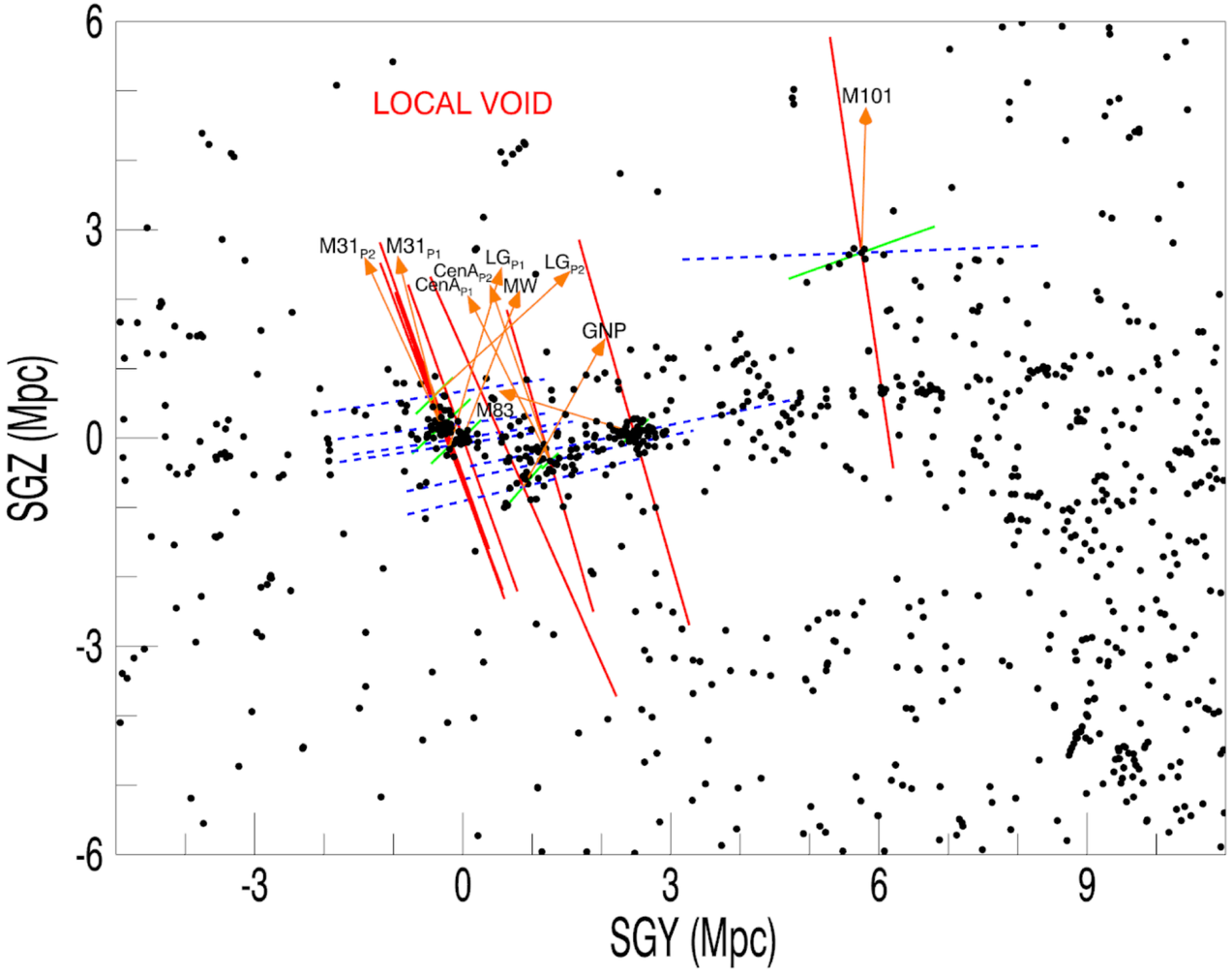


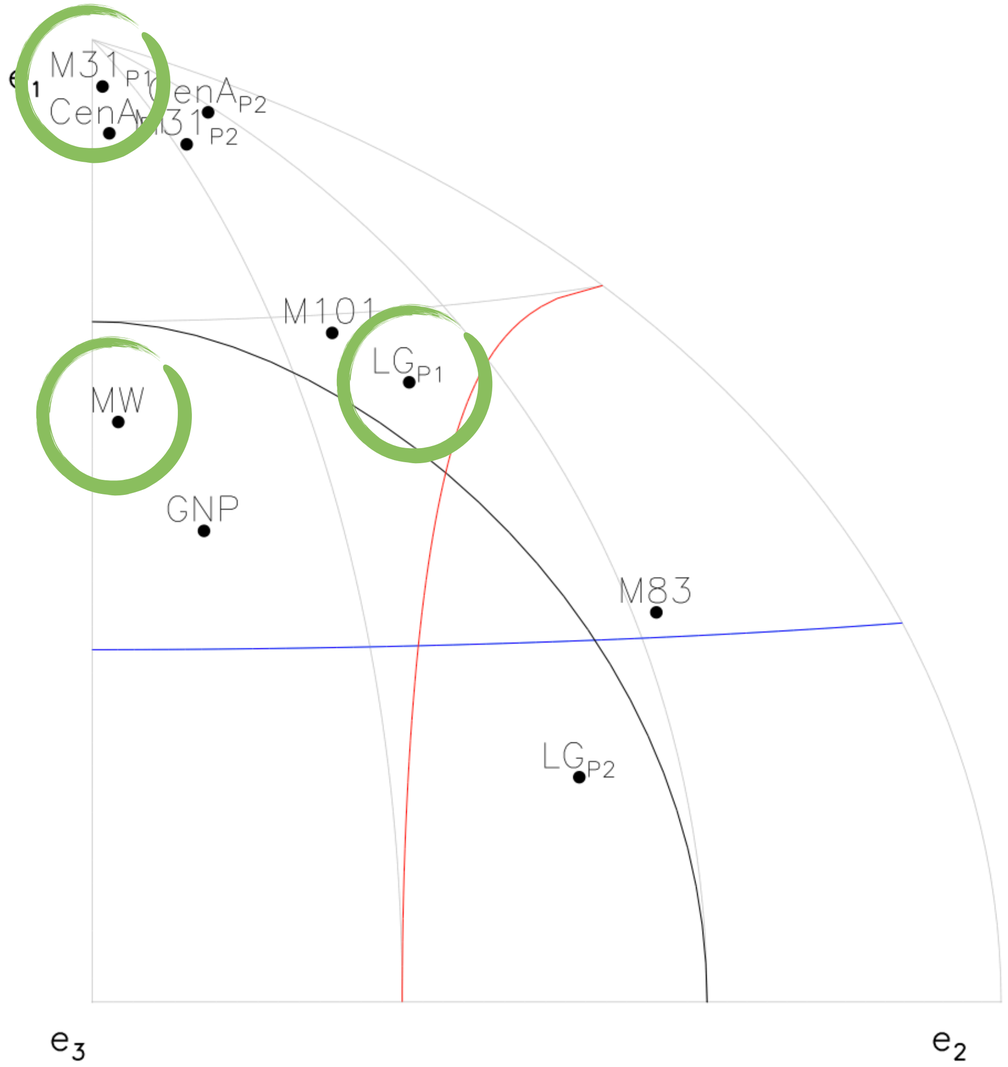
PAWLOWSKI ET AL. (2015)

Libeskind et al. (2019)

Satellite planes preferentially align with flattening of large-scale structure

Plane normal vectors

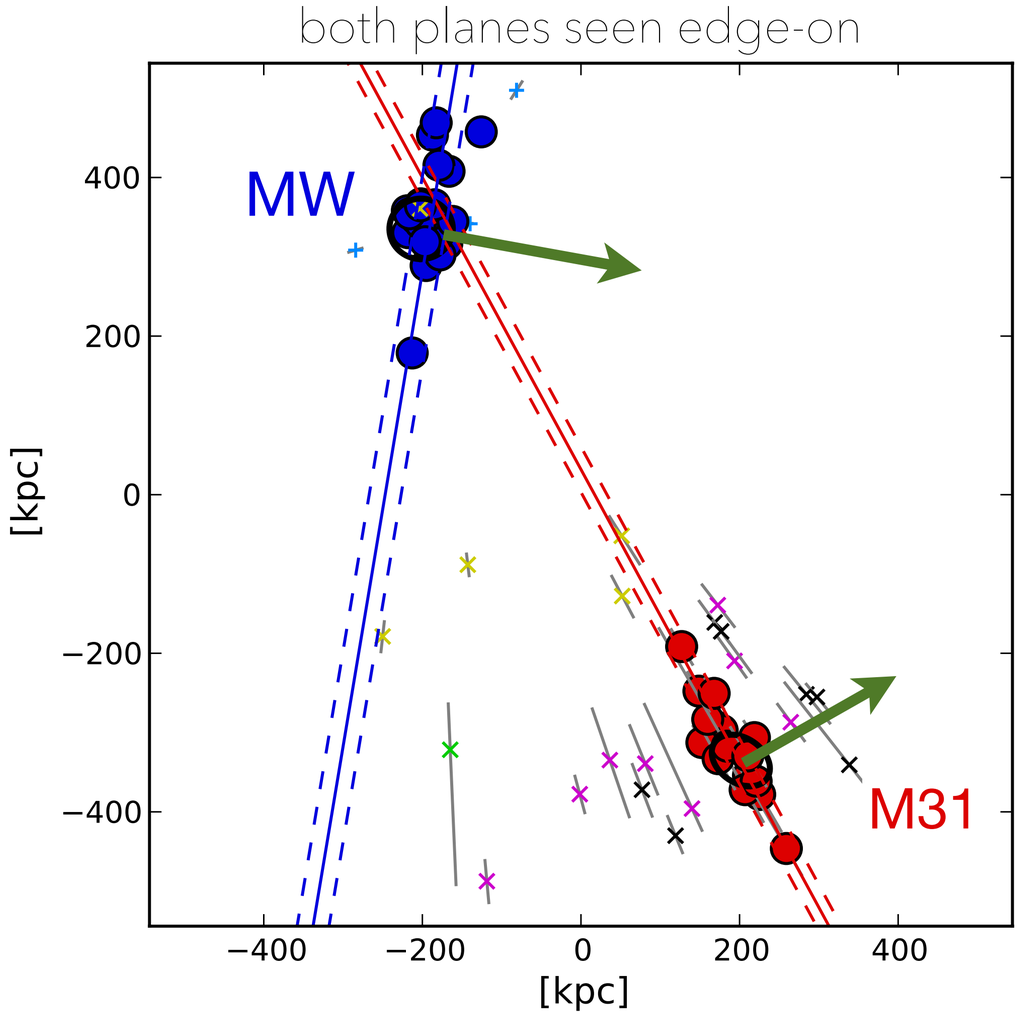




What observed features might assembly scenarios want to explain?

MW and M31 satellite planes have:

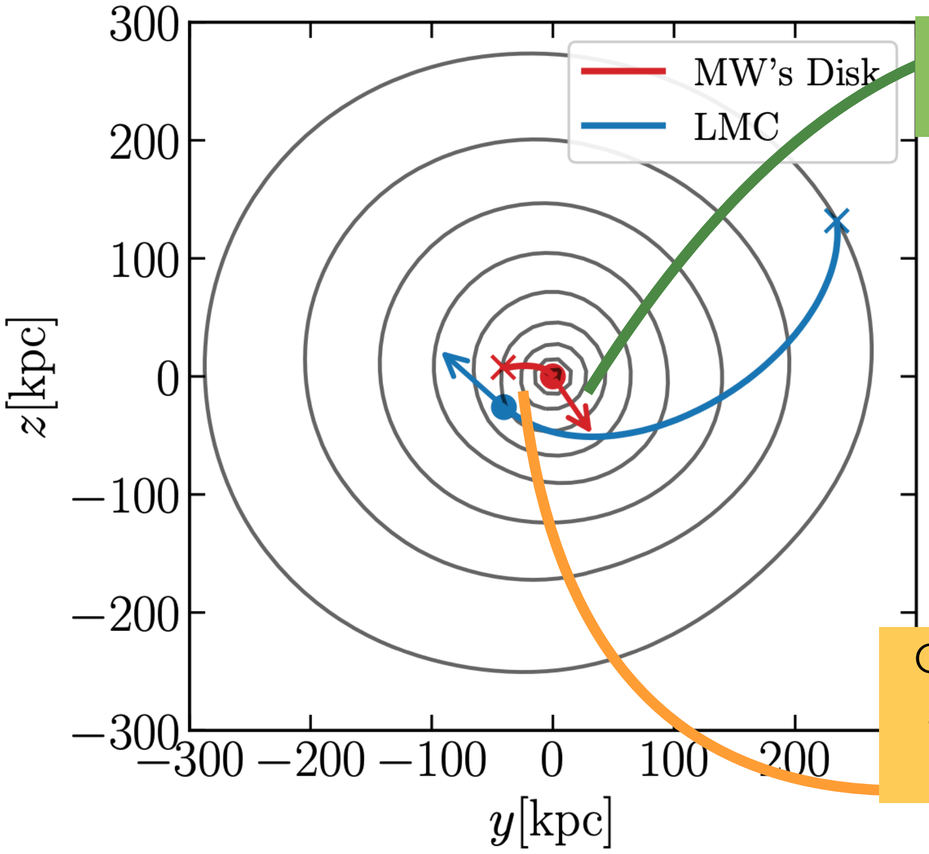
- Similar heights & diameters: 15-30 kpc / 400 kpc
- Similar spin directions; MW-M31 orbit consistent
- M31 satellite plane & lopsidedness point to MW
- Some prominent streams & YH GCs also aligned
- Co-orbiting MW sats. approach → recent infall → young feature? *(see Salvatore's & Francois' talks)*
- Non-satellite dwarf galaxy planes in LG, some overlap with Magellanic Stream?
- Satellite planes tend to align with cosmic web



PAWLOWSKI, KROUPA & JERJEN (2013, MNRAS, 435, 1928)

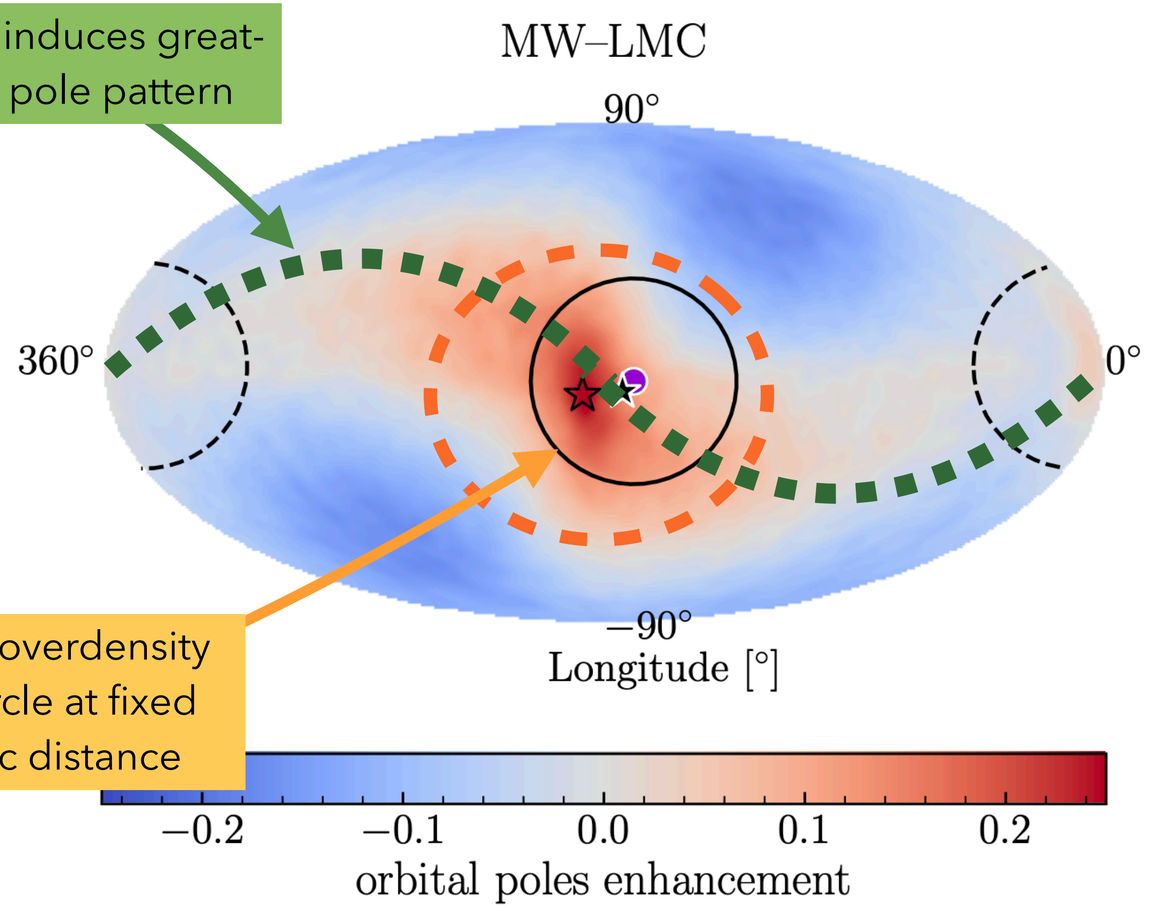
Possible Origins

Could the interaction of the MW with a massive LMC cause the observed orbital pole clustering?



Reflex motion induces great-circle orbital pole pattern

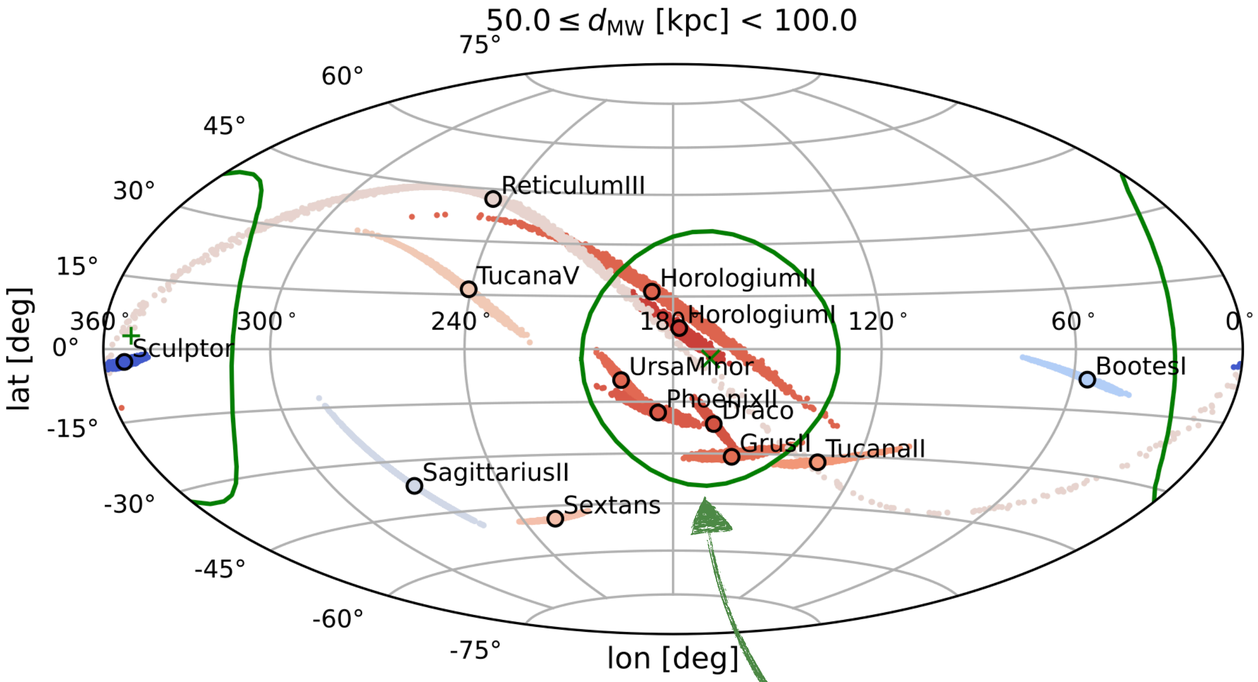
Offset induces overdensity along great circle at fixed Galactocentric distance

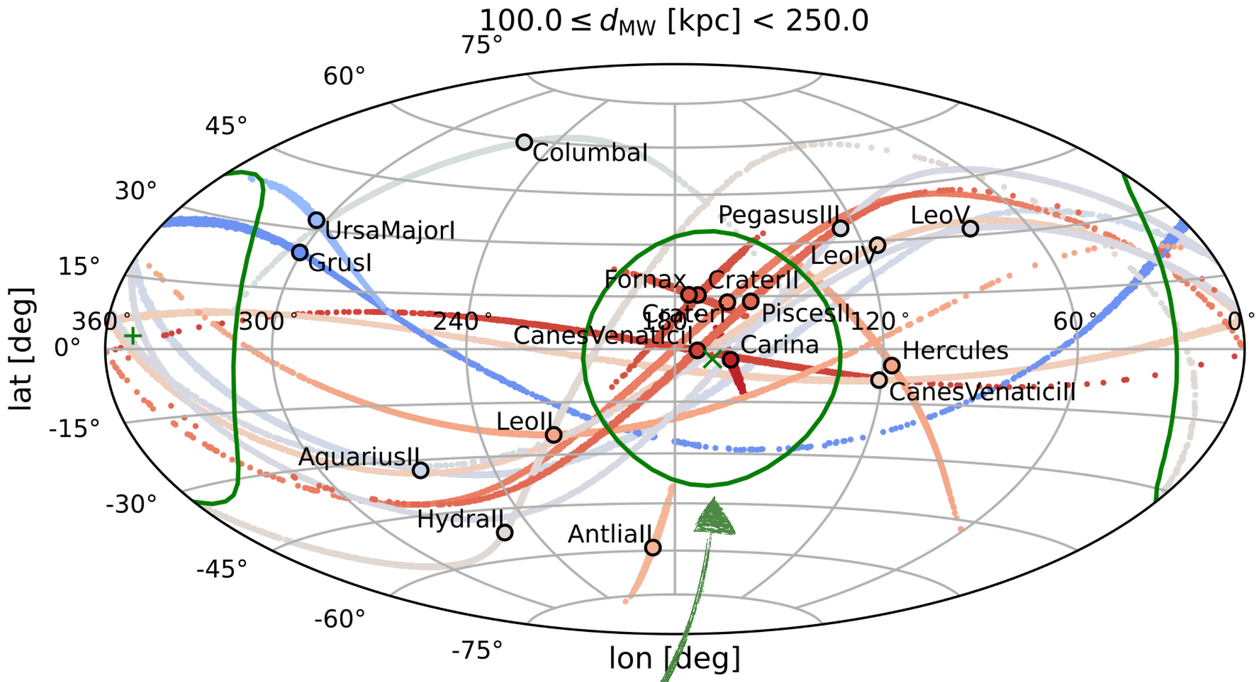


Garavito-Camargo et al. (2021)

In dark matter halo particles!

Orbital poles remain clustered after correcting for LMC influence

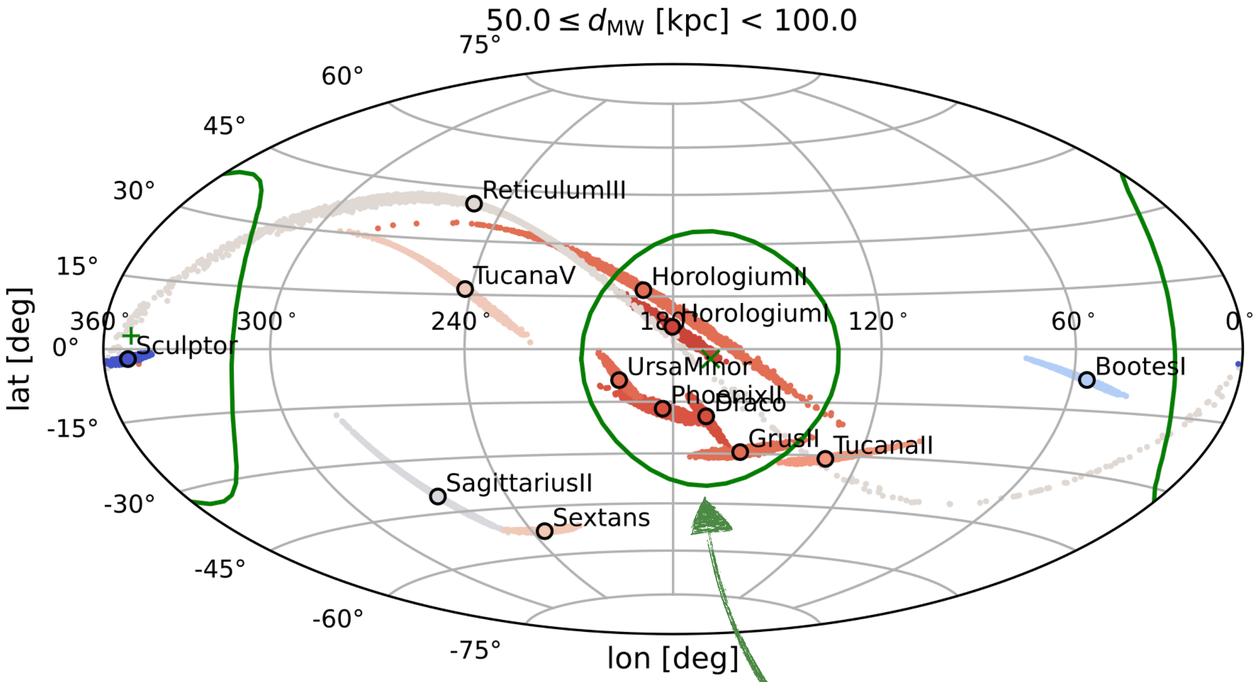


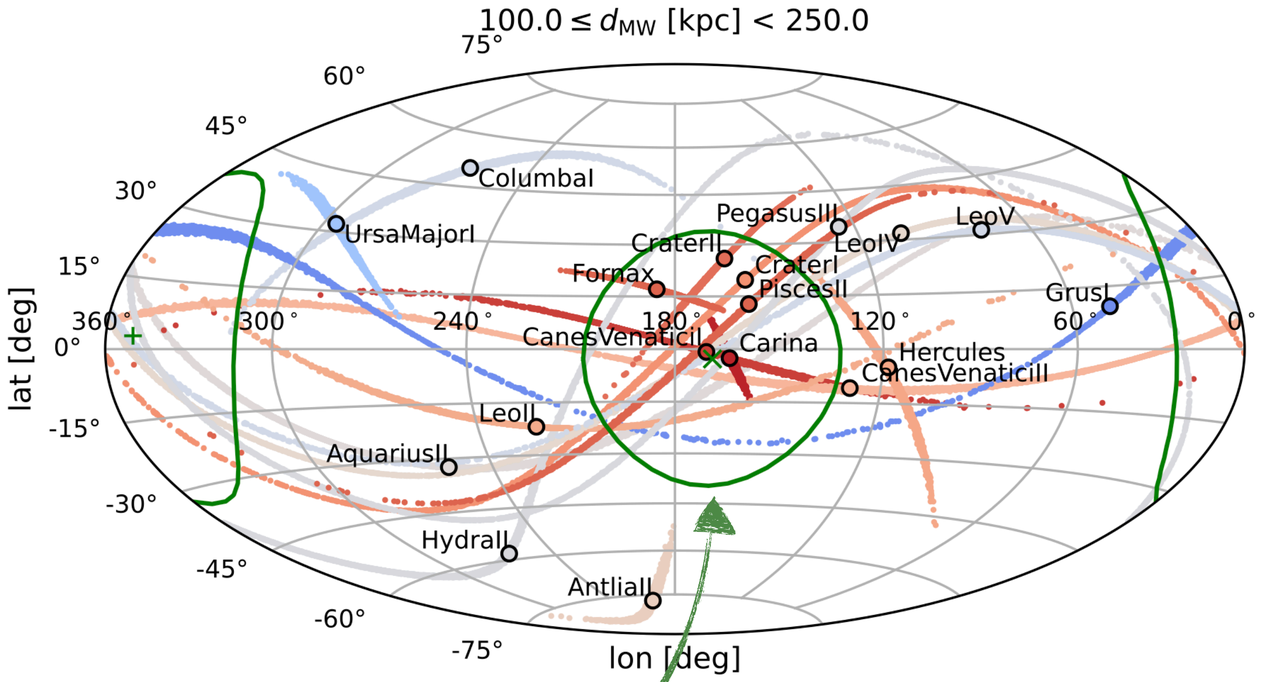


Orbital poles cluster close to normal vector to satellite plane

Pawlowski et al. (2022)

Orbital poles remain clustered after correcting for LMC influence

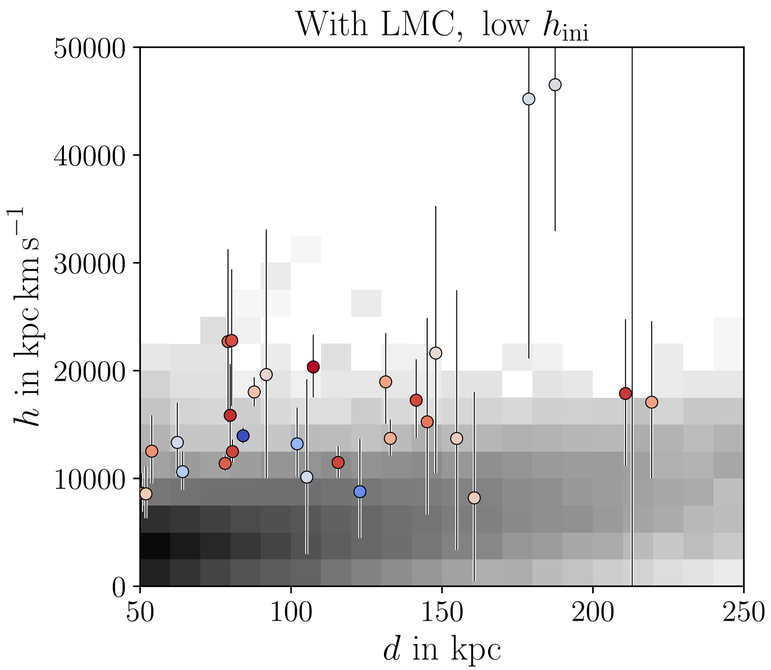




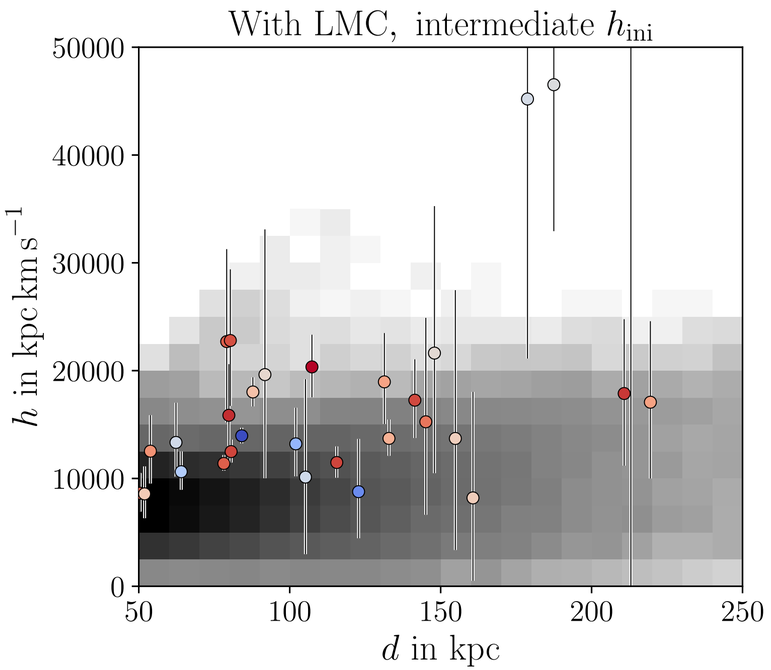
Orbital poles cluster close to normal vector to satellite plane

Pawlowski et al. (2022)

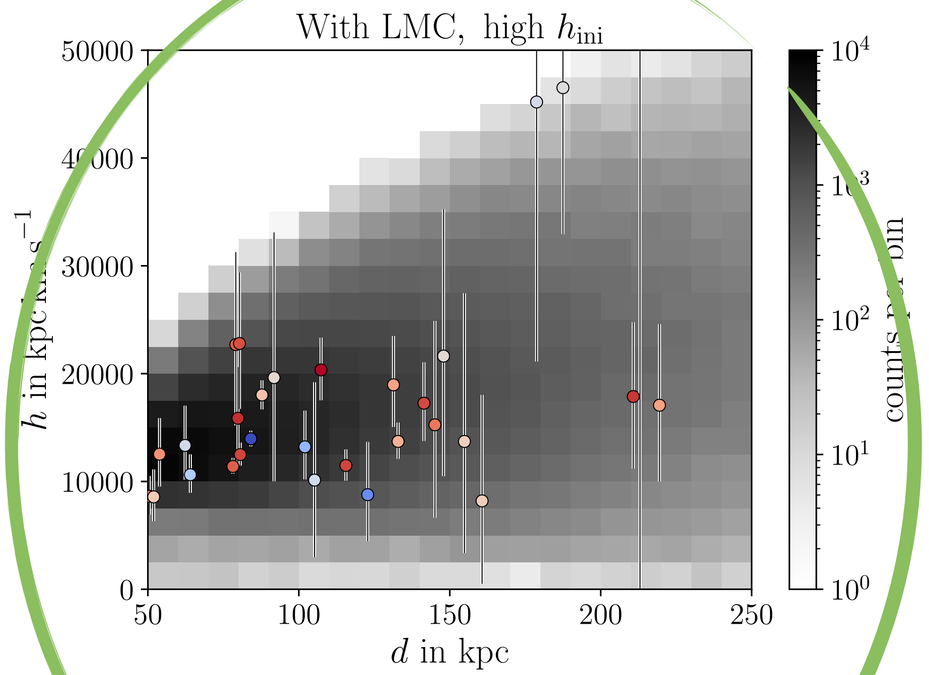
Milky Way satellite galaxies have higher angular momentum than many dark matter halo particles



Low angular momentum particles



Intermediate angular momentum particles

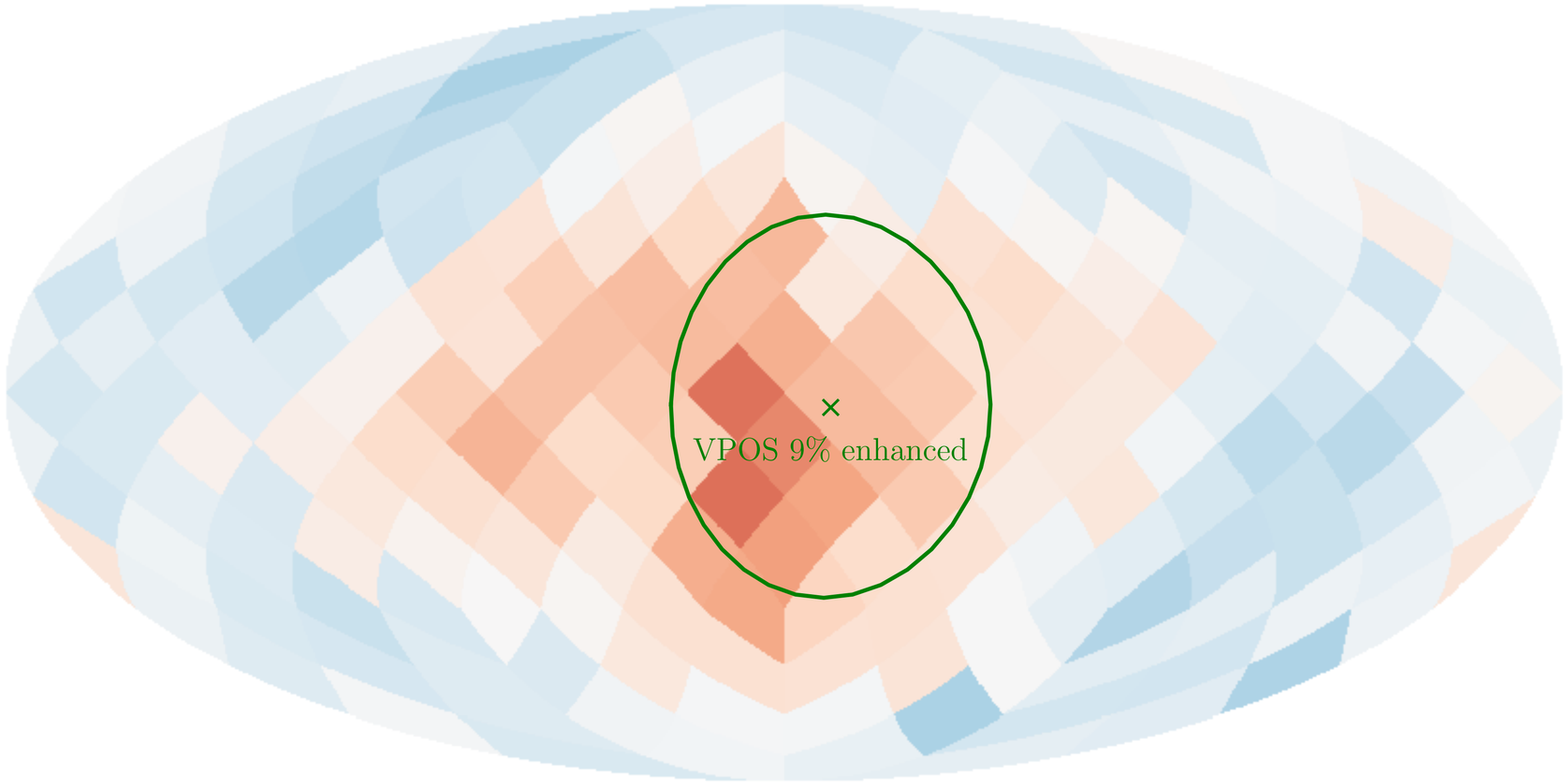


High angular momentum particles

Pawlowski et al. (2022)

Only low-angular momentum particles (= radial orbits) are affected by LMC, but no orbital pole over density for satellite-like orbits

$$50 \leq d \leq 250\,\mathrm{kpc}, \quad 0 \leq h_{\mathrm{ini}} \leq \infty\,\mathrm{kpc\,km\,s^{-1}}, \quad N = 392322$$



Pawlowski et al. (2022)

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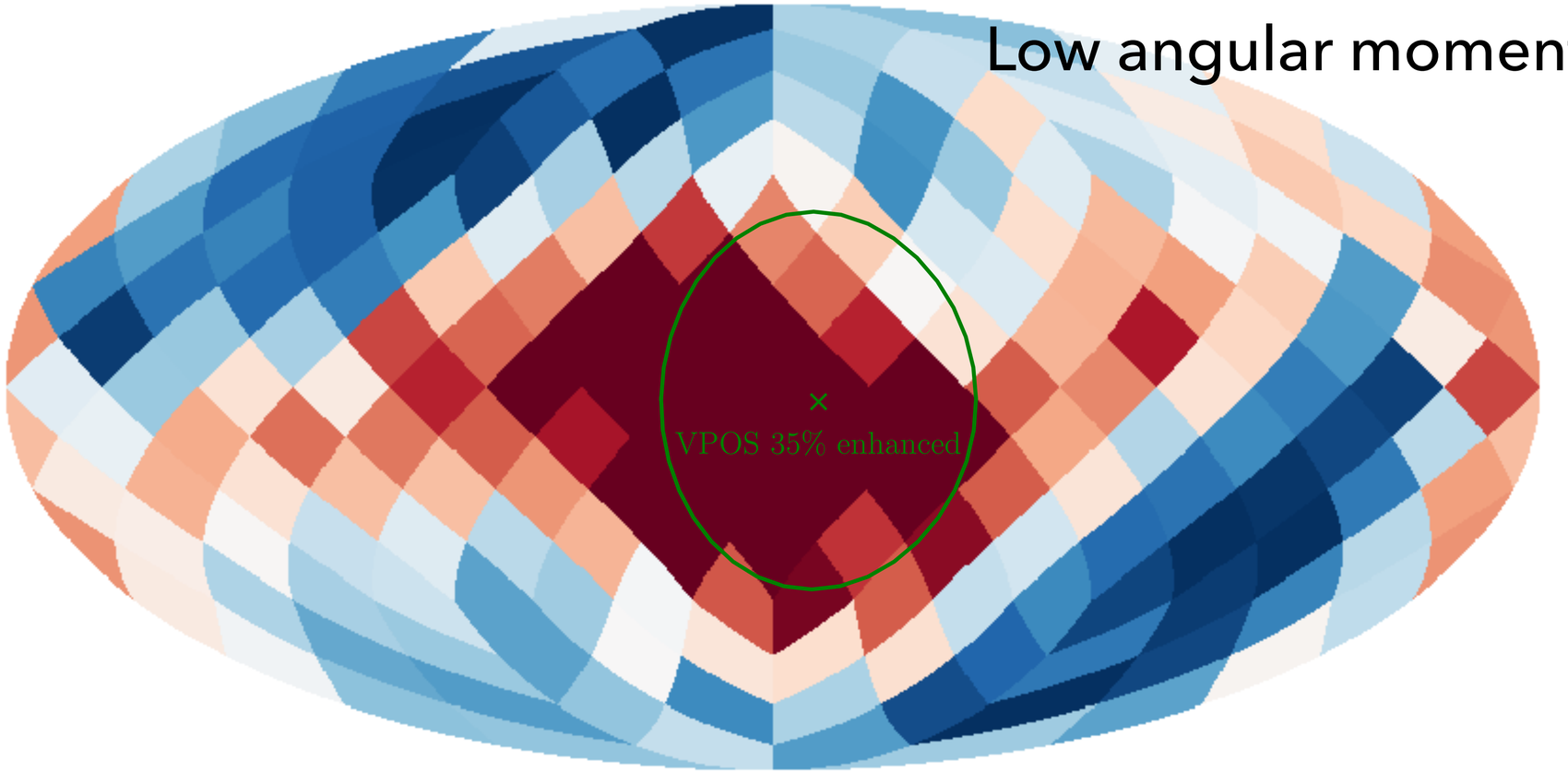
$$50 \leq d \leq 250\,\mathrm{kpc}, \quad 0 \leq h_{\mathrm{ini}} \leq 5000\,\mathrm{kpc\,km\,s^{-1}}, \quad N = 49884$$



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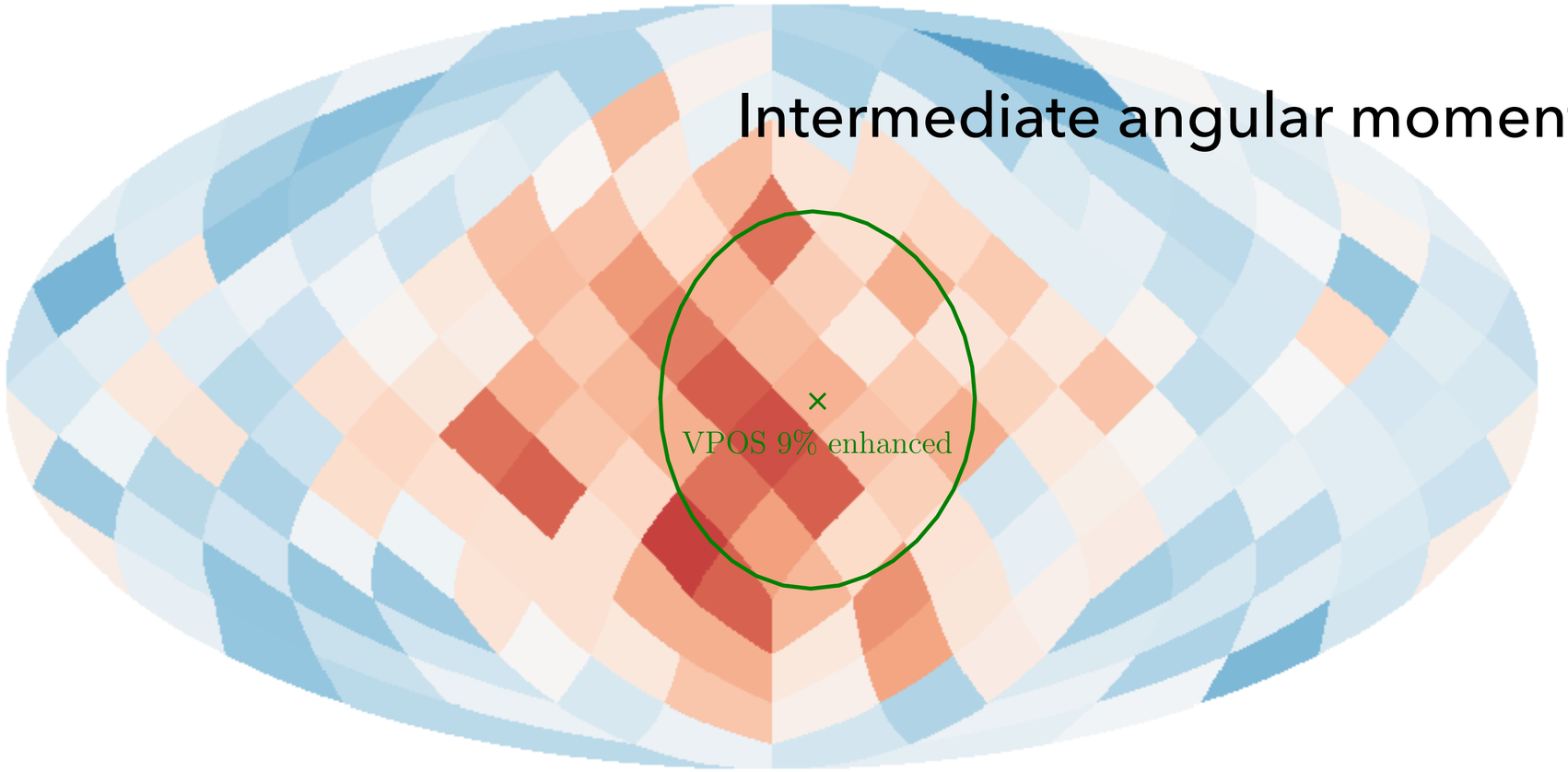
$$50 \leq d \leq 250\,\mathrm{kpc}, \quad 5000 \leq h_{\mathrm{ini}} \leq 10000\,\mathrm{kpc\,km\,s^{-1}}, \quad N = 109905$$



Pawlowski et al. (2022)

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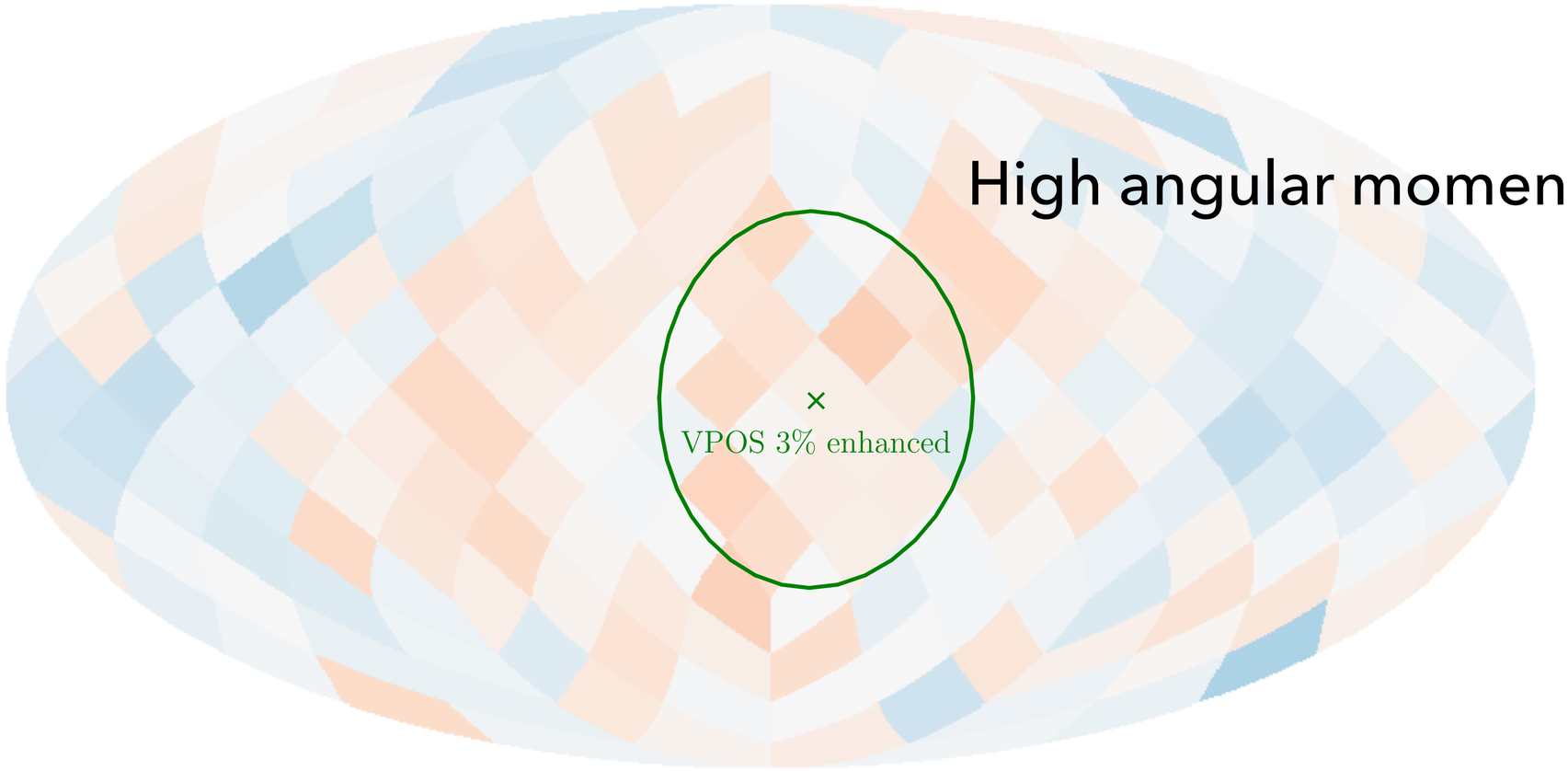
$$50 \leq d \leq 250\,\mathrm{kpc}, \quad 10000 \leq h_{\mathrm{ini}} \leq \infty\,\mathrm{kpc\,km\,s^{-1}}, \quad N = 232533$$



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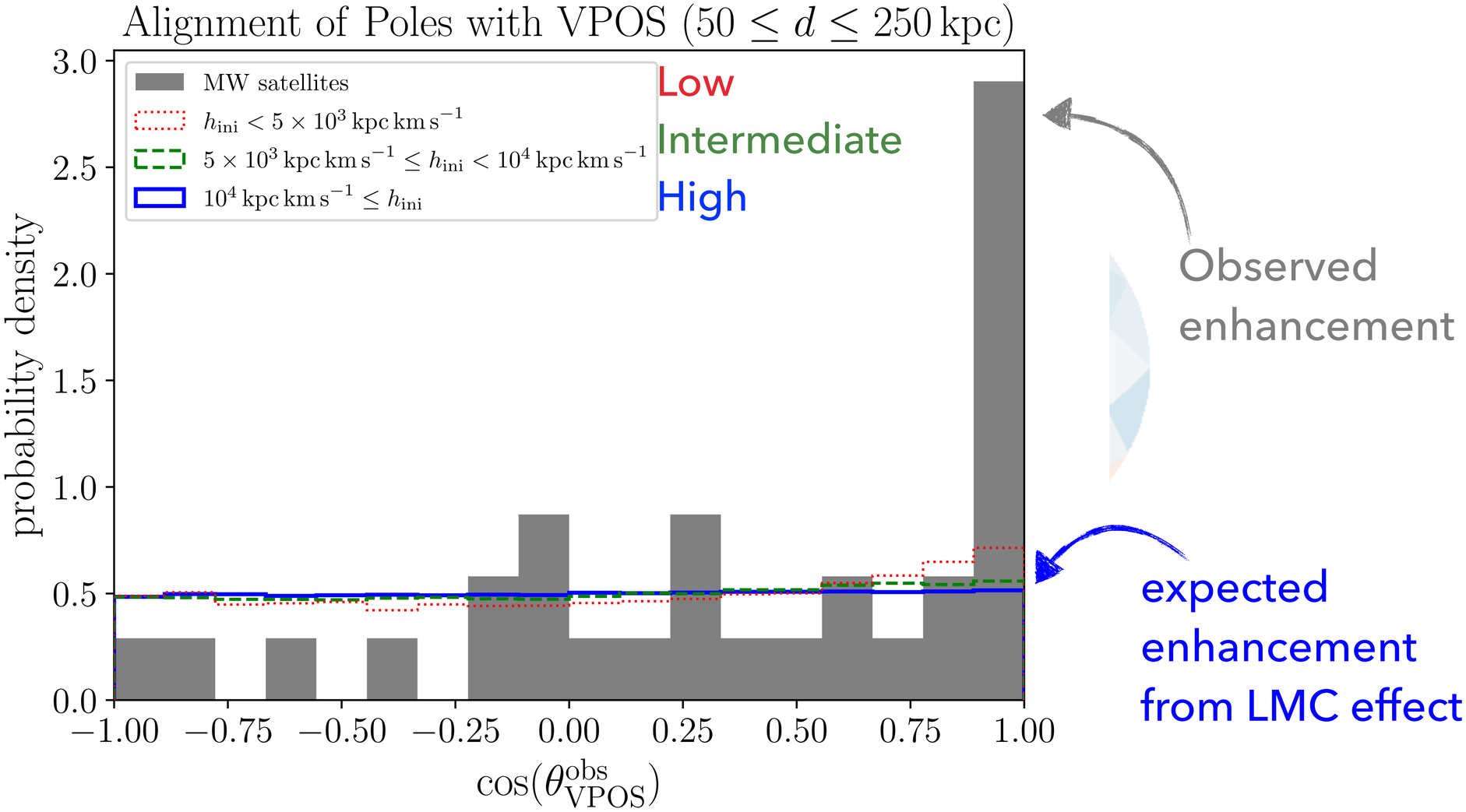
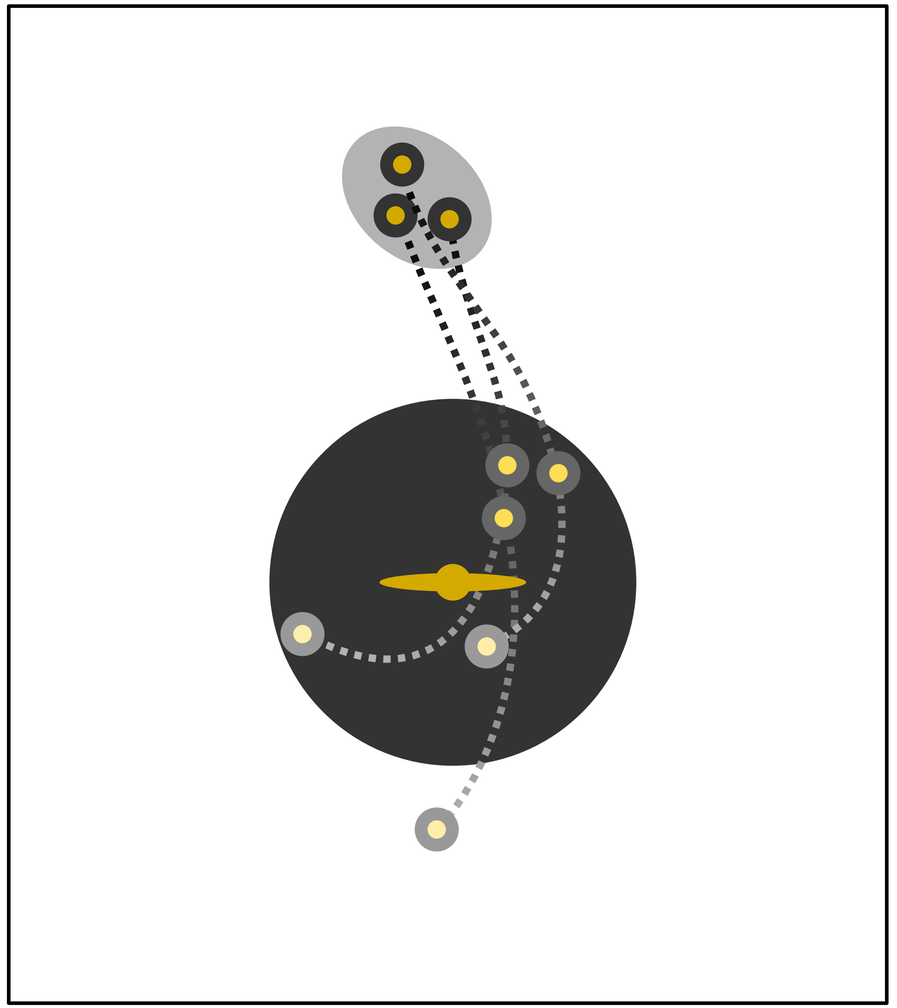


Pawlowski et al. (2022)

Group Infall

- Accretion of satellite galaxies in groups can result in orbital correlation (e.g. Li & Helmi, 2008): Group shares similar orbits, disperses along common plane.

Group Infall



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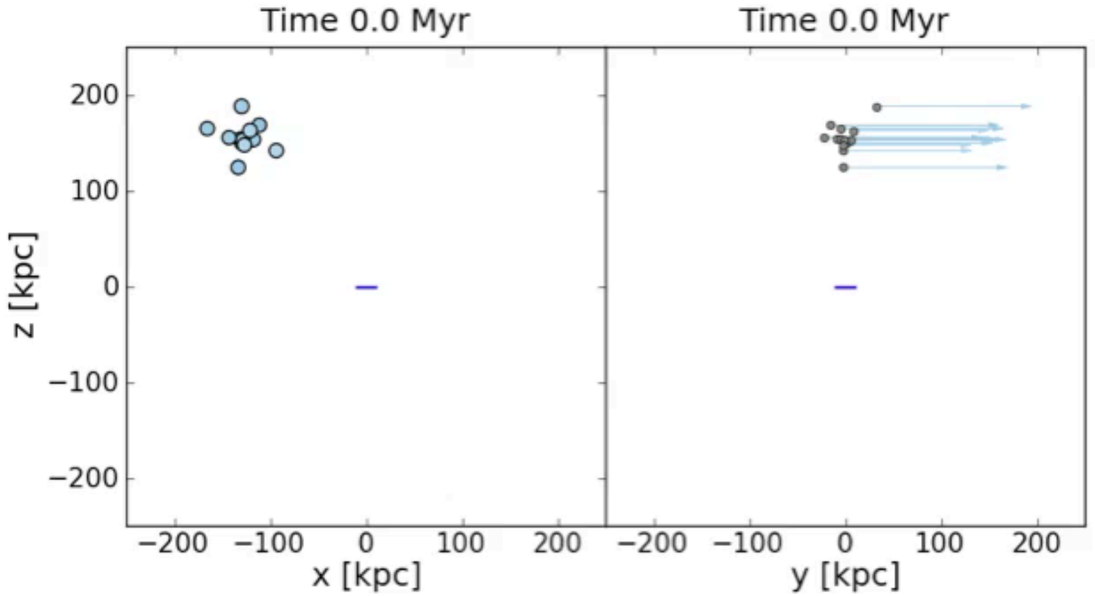

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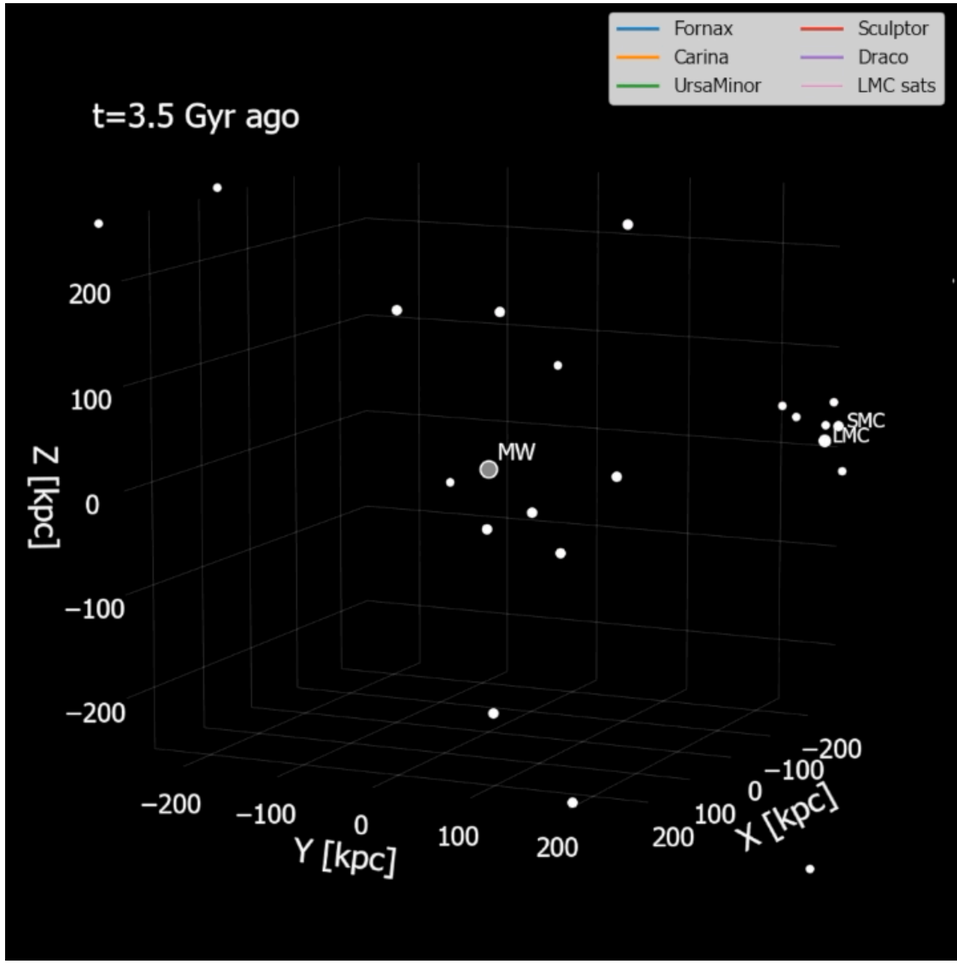
- LMC brought its own satellites (e.g. Patel et al. 2020) but very hierarchical system. Second infall an intriguing possibility; some on-plane satellites stripped during 1st wide passage? (*see Eugene's talk*)



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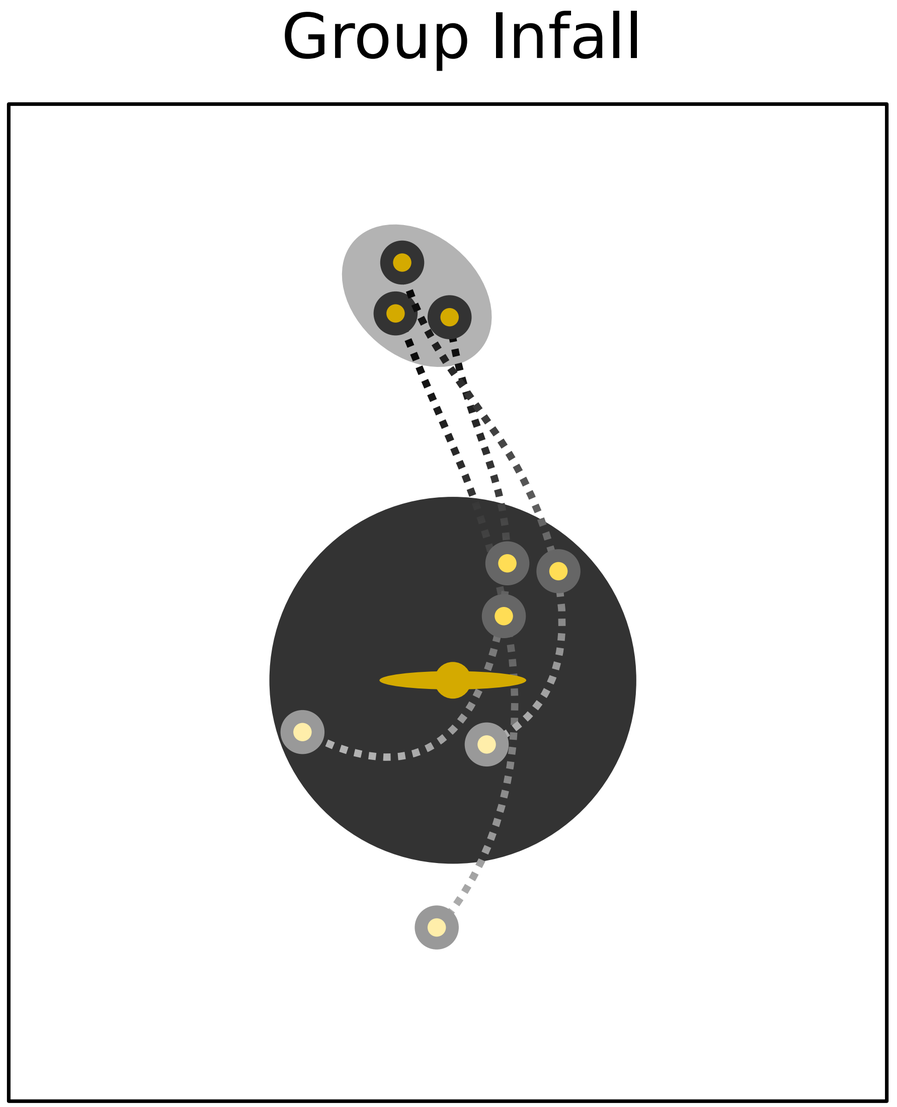
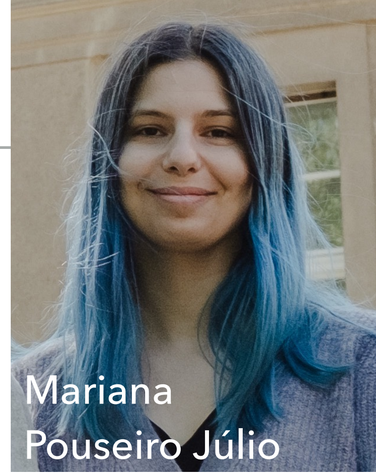
- Some 30-60% of subhalos in ΛCDM simulations are accreted in groups of 3-5.

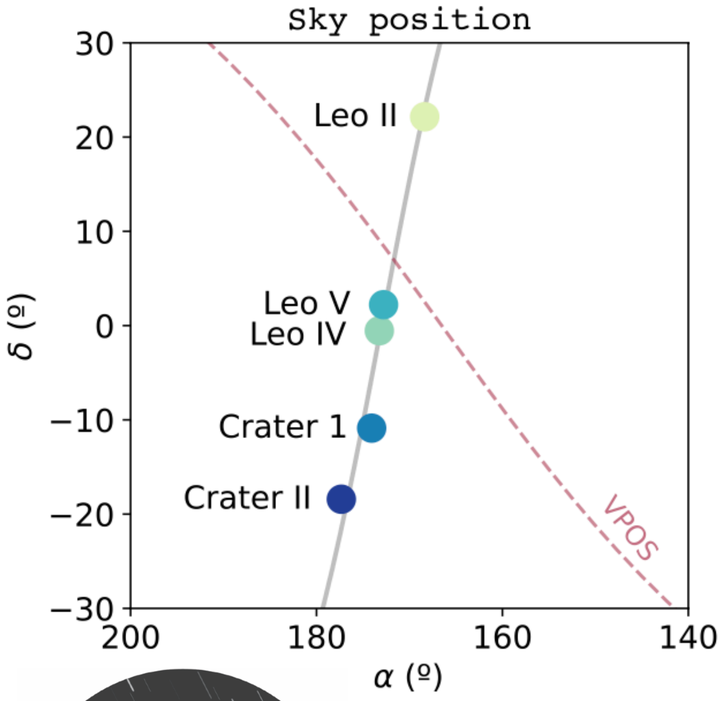


Group Infall: the case of the Crater–Leo Objects

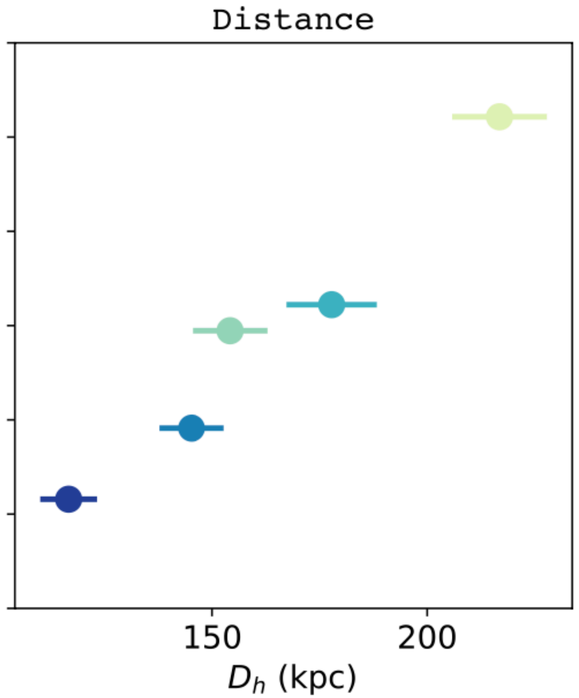
Pouseiro Júlio et al. (2024)



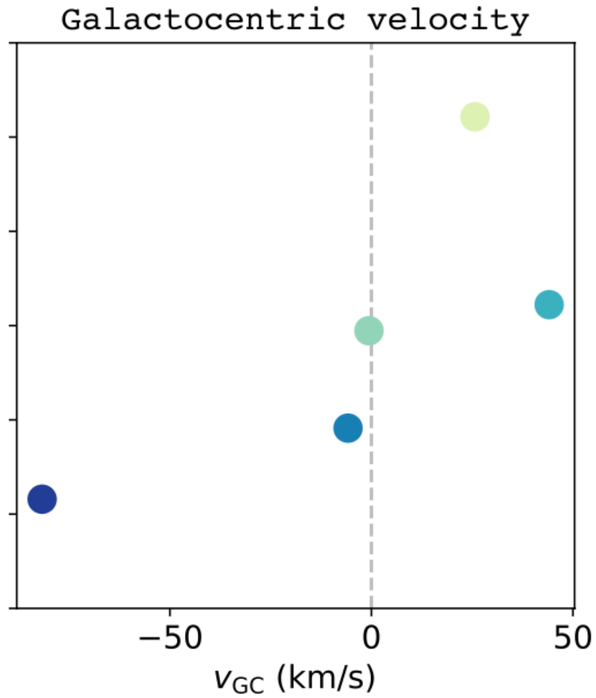
Align along great circle:



Clear **distance gradient**:



Similar radial **velocities**:

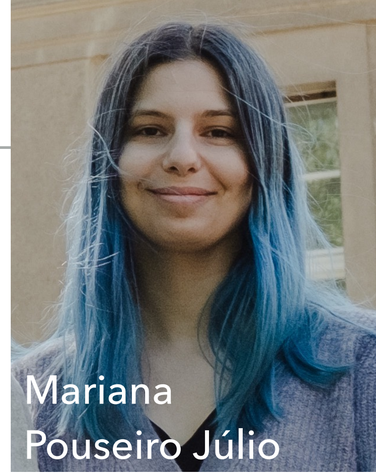


SFHs: Leo II & IV stopped 5-6 Gyr ago, Leo V possibly similar.

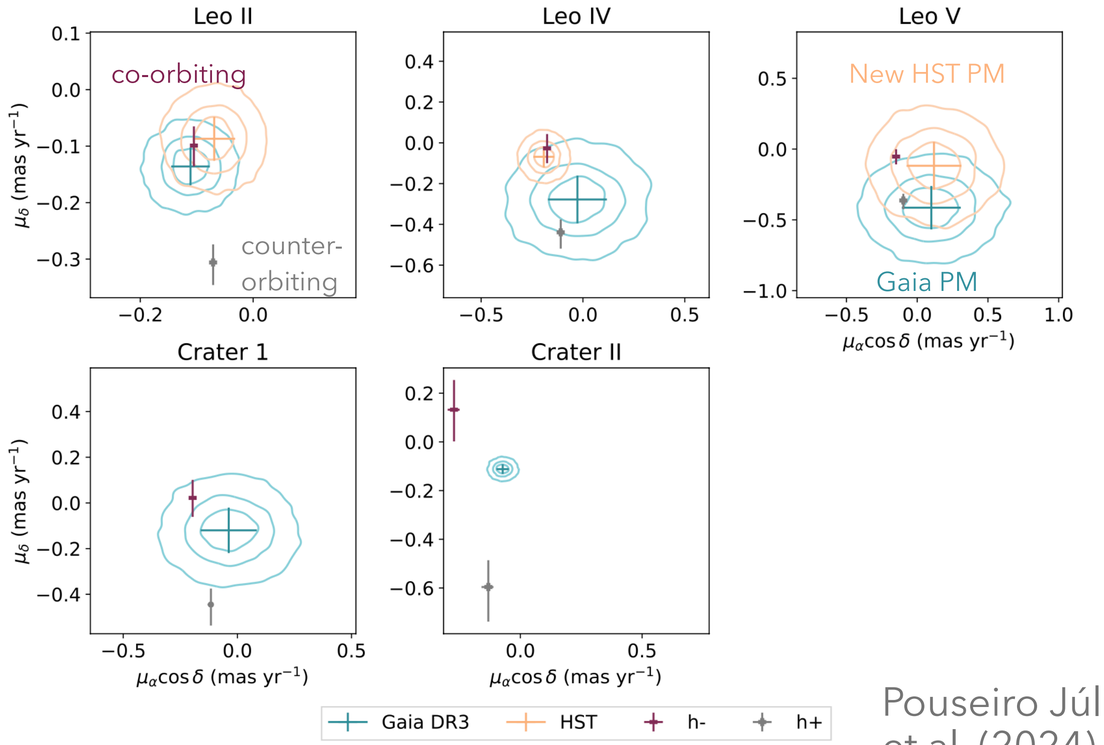
Crater 1 has same Fe/H as Leo II and consistent age.

- In collaboration with T. Sohn & R. van der Marel:
  We measured new HST proper motions for Leo IV + V.

Group Infall: the case of the Crater–Leo Objects



- Assume common group (similar energy and angular momentum)
  → predict expected PMs
  → test with measurements.

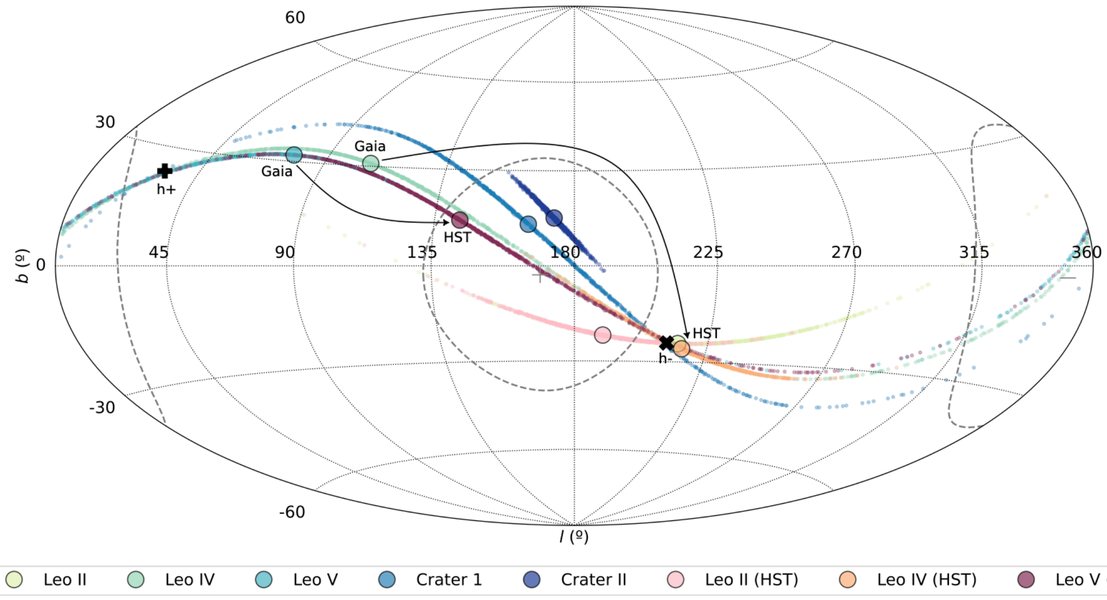


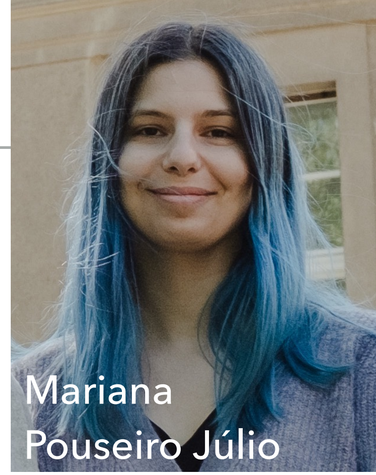
Pouseiro Júlio et al. (2024)

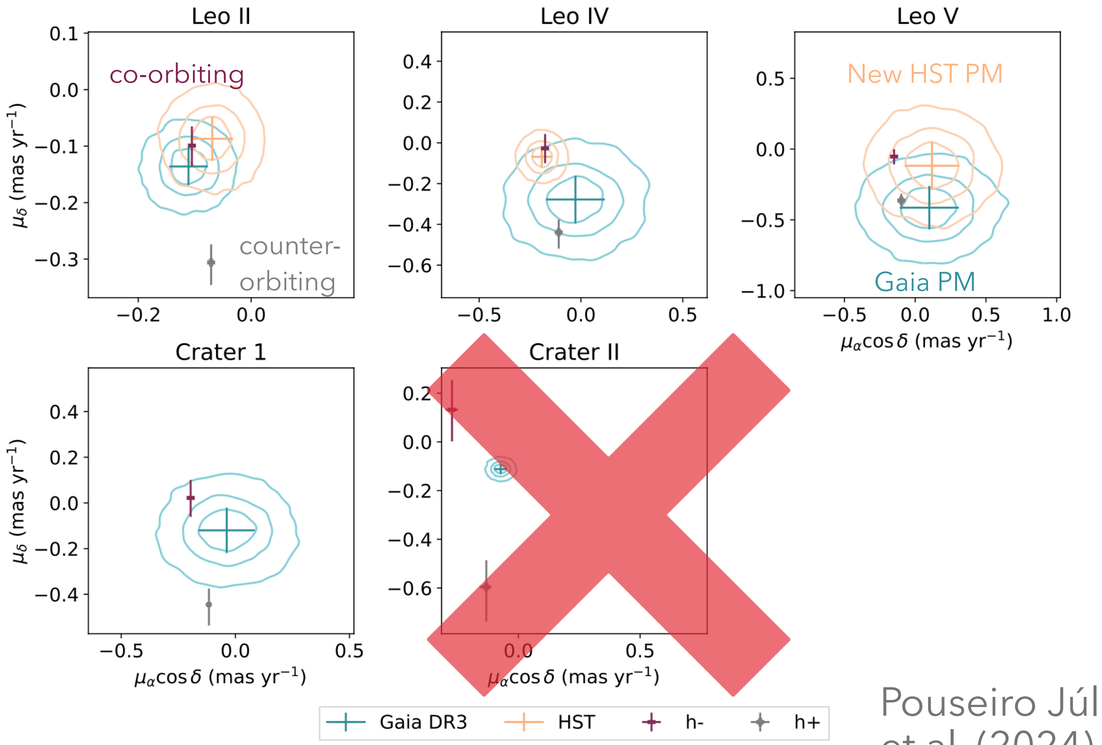
Group Infall: the case o

- Assume common group (similar e
  and angular momentum)
  → predict expected PMs
  → test with measurements.

- Can exclude Crater II as group member.
  Others are consistent within 1-2σ of
  (some) PM measurement.

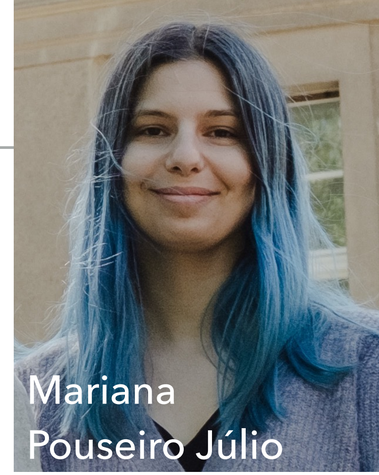




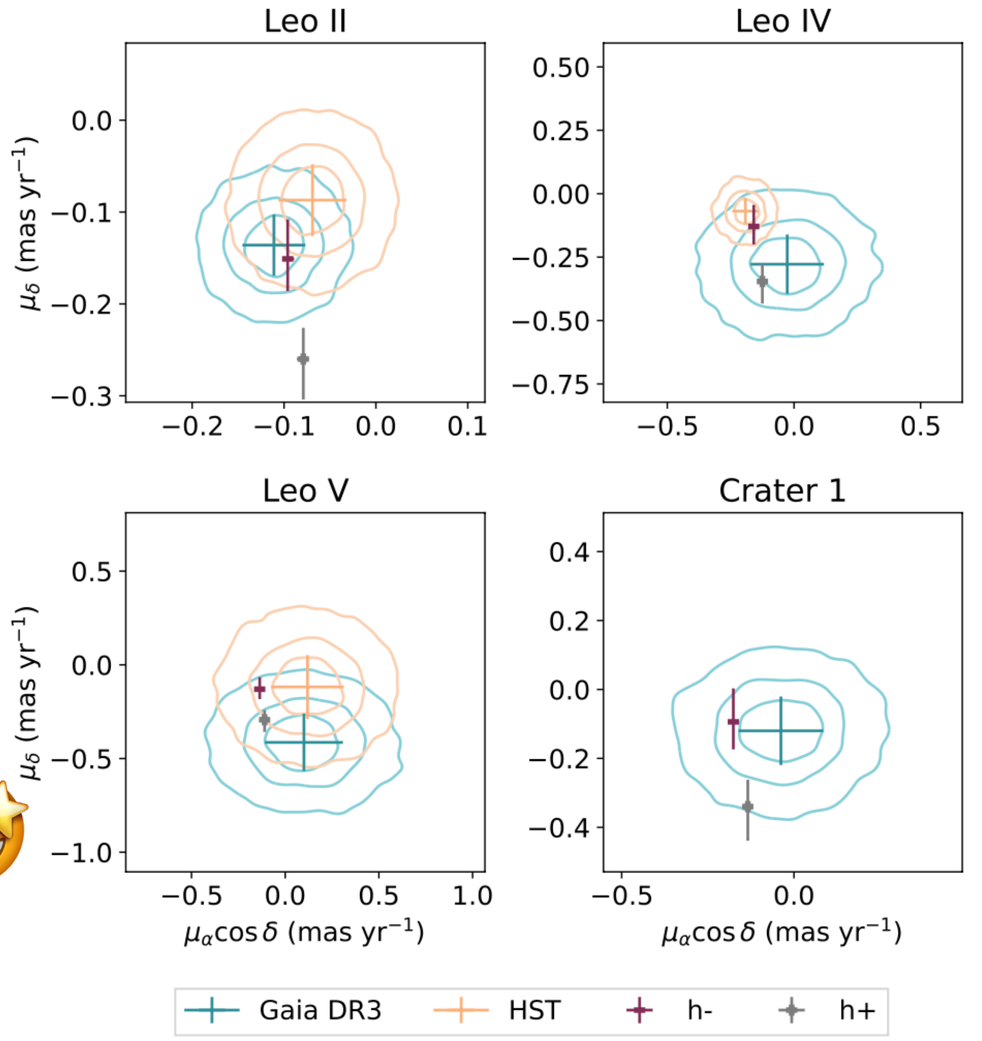


Pouseiro Júlio et al. (2024)

Group Infall: the case of the Crater–Leo Objects



- Assume common group (similar energy and angular momentum)
  → predict expected PMs
  → test with measurements.
- Can exclude Crater II as group member. Others are consistent within 1-2σ of (some) PM measurement.
- Repeating prediction without Crater II improves the match! HST PMs agree better than Gaia.
- *Possibly the first evidence of a more typical group infall event (in contrast to hierarchical LMC satellite system)!*

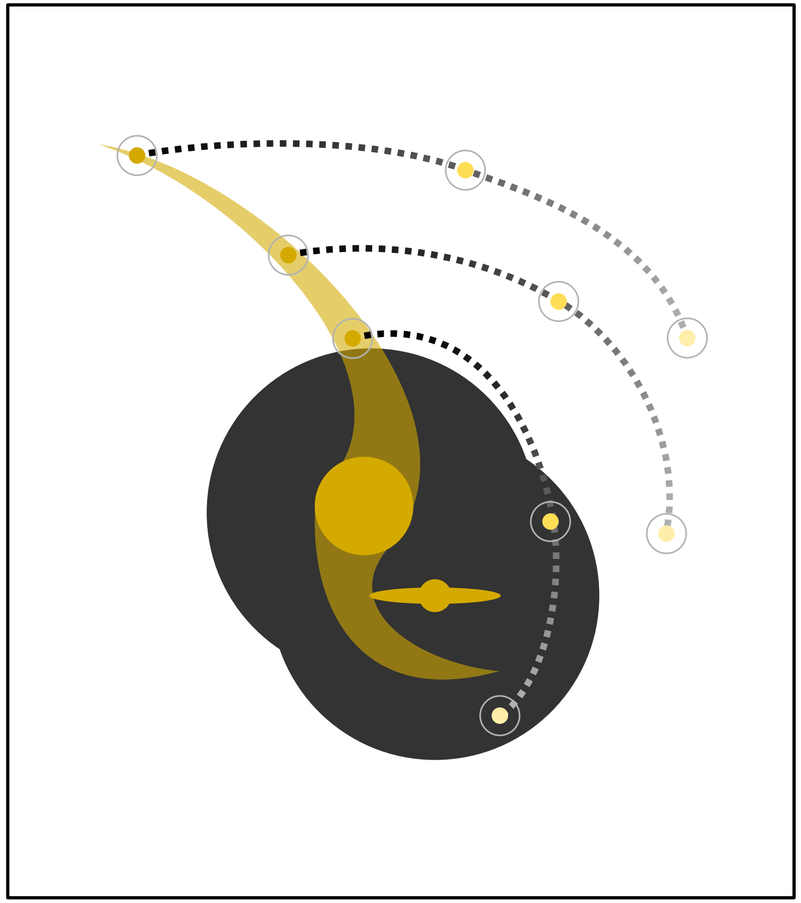


Pouseiro Júlio et al. (2024)

Tidal Dwarf Galaxies:

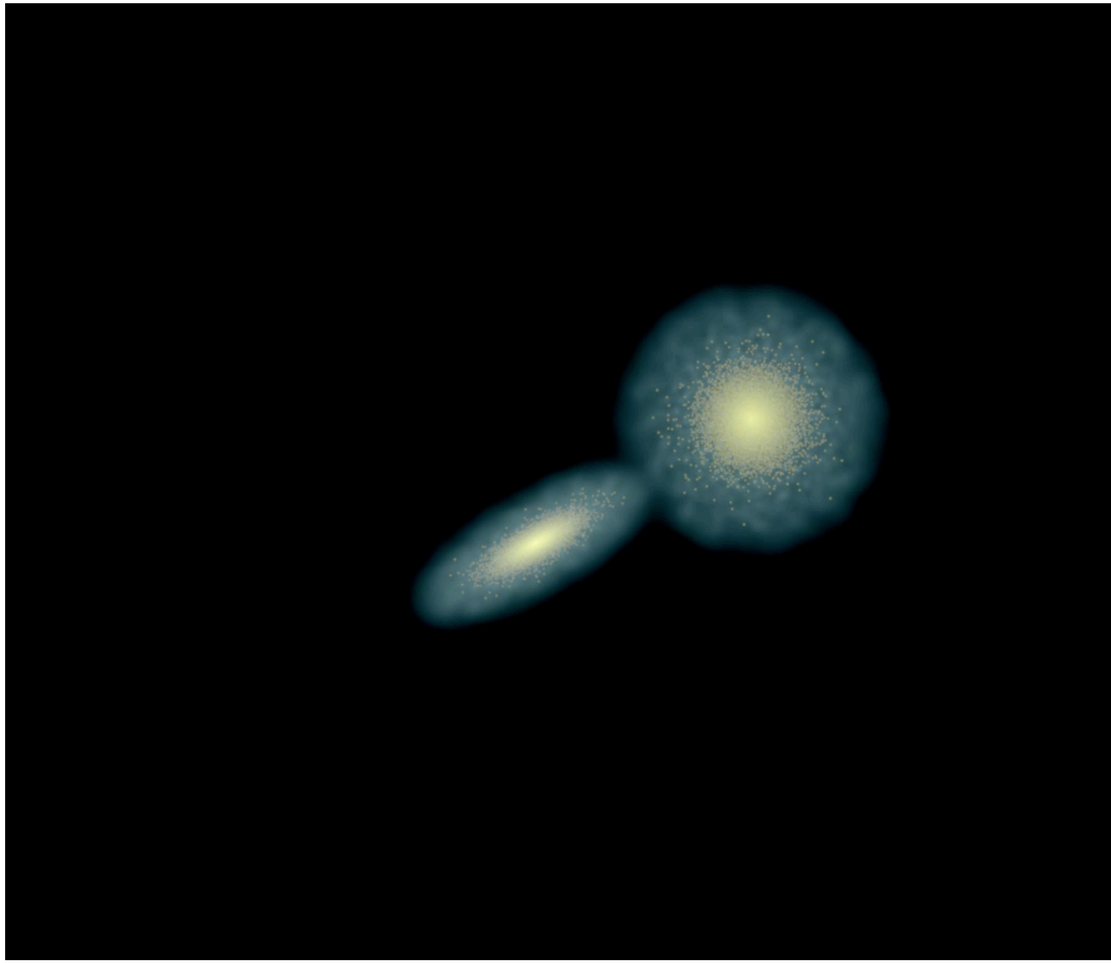
- 2nd generation galaxies formed from the debris of interacting galaxies.

Tidal Dwarf Galaxies



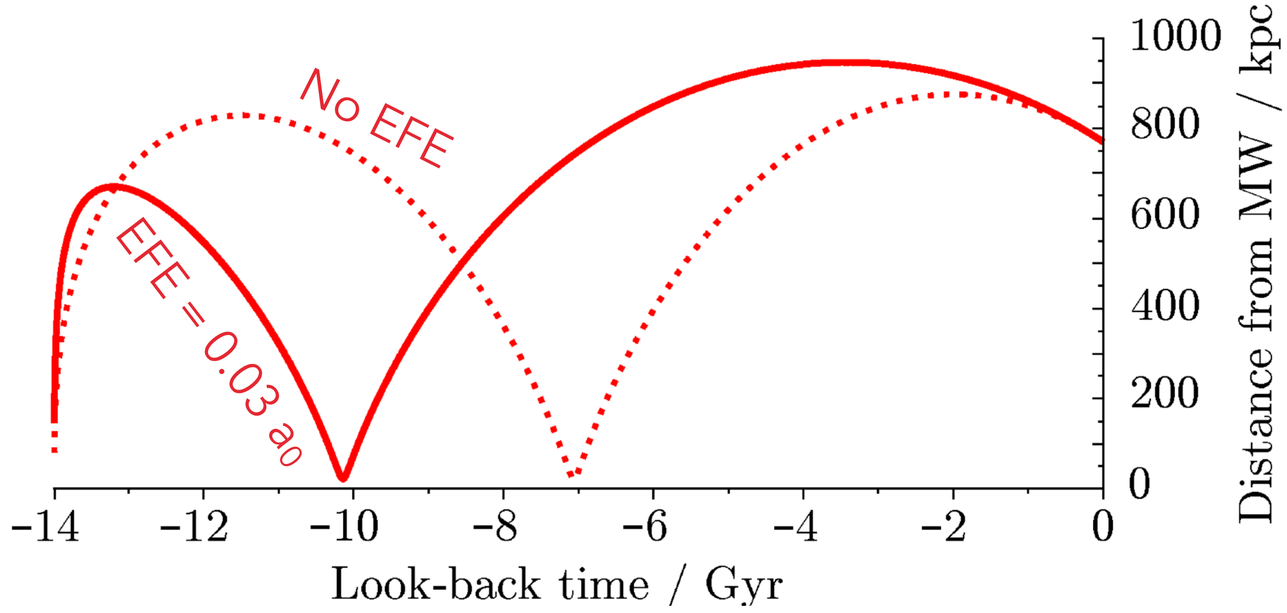
Tidal Dwarf Galaxies:

- 2nd generation galaxies formed from the debris of interacting galaxies.
- Require past galaxy encounter/merger in LG → possible merger in M31 (*see Akib's poster*)
- **Pro:** Explains flattened distribution & coherent motion of satellite systems. Can explain LG-wide consistencies and MW-M31 connection.
- **Con:** TDGs should be dark matter free (or non-equilibrium?). Should also show higher metallicity than primordial dwarfs. Yet on-plane satellites follow same scaling relations (*see Salvatore's talk*).



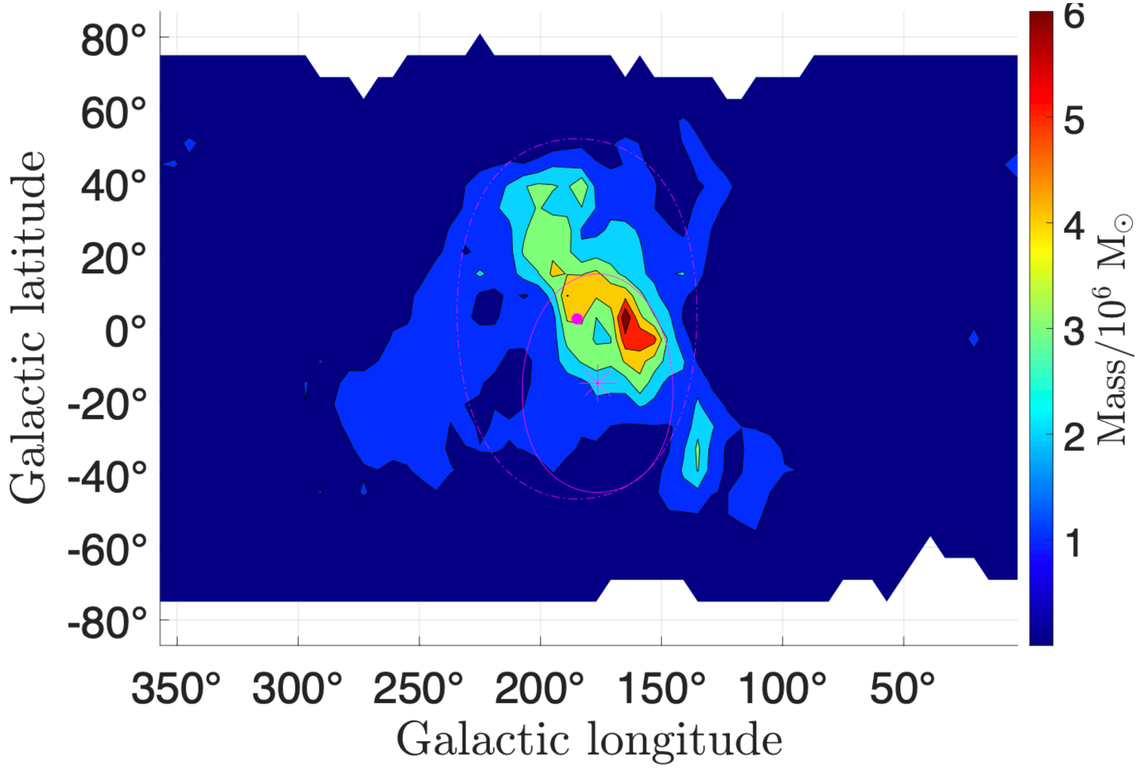
Past MW–M31 encounter in MOND produces tidal debris consistent with VPOS and GPoA

MW-M31 orbit in MOND



Zhao et al. (2013)

Orbital poles of tidal debris



Banik et al. (2022)

Conclusions

- **Milky Way, M31 host satellite planes**: flattened distributions of satellite galaxies that appear to co-orbit in similar orientation.
- The **M31 satellite system is strongly lopsided** towards the MW.
- As extreme structures **exceedingly rare in ΛCDM simulations** → *Planes of satellite galaxies & lopsidedness problems*.
- The observed features require an explanation. Possible origins:
  - **LMC: effect on MW alone does not explain** satellite plane, but has brought in at least some satellites.
  - **Accretion of satellites in groups:** might help, good evidence for **group origin of Crater-Leo objects** with our new HST PMs.
  - **MW-M31 interaction / M31 merger**: intriguing Local Group-wide consistencies!

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