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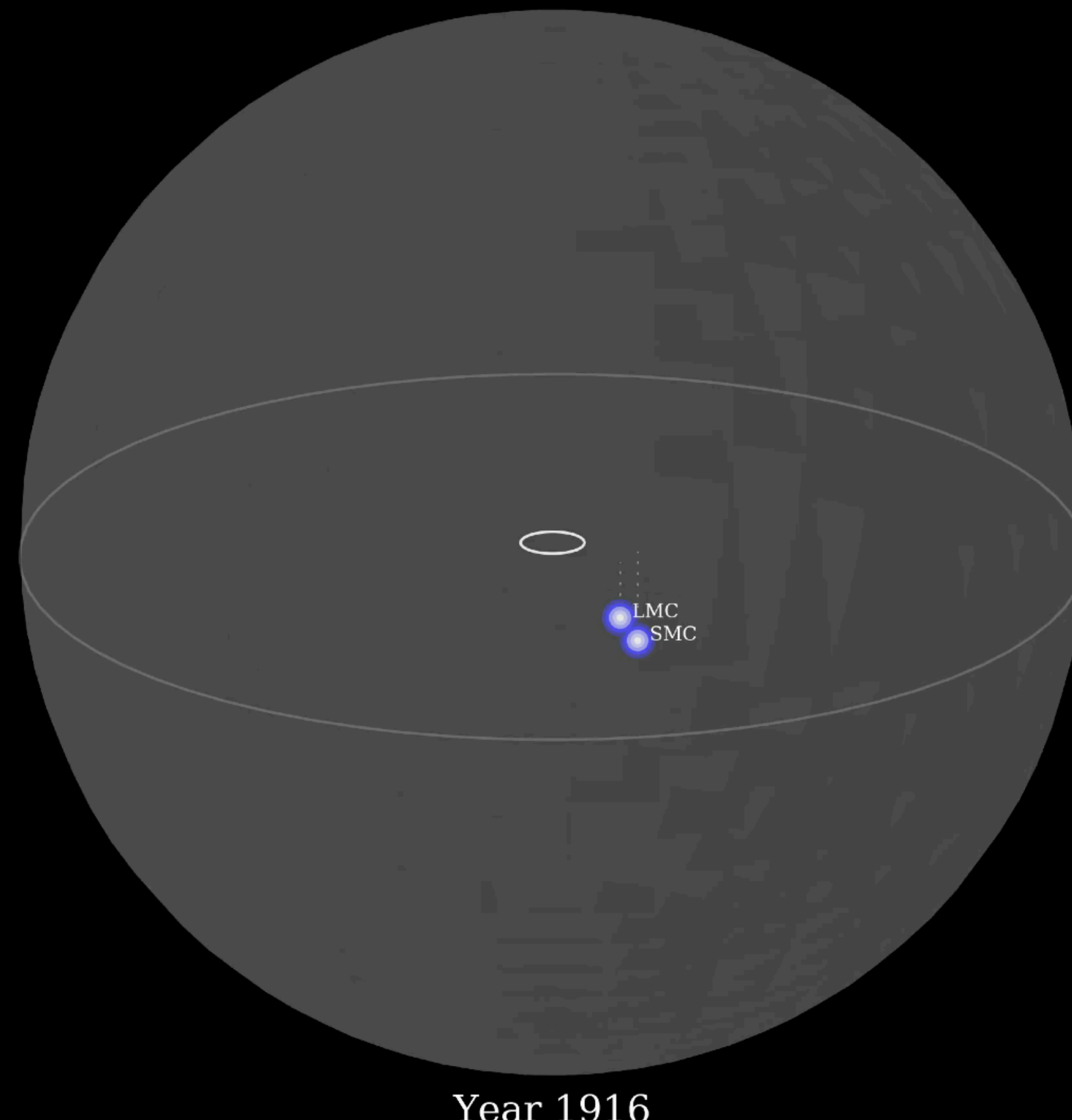

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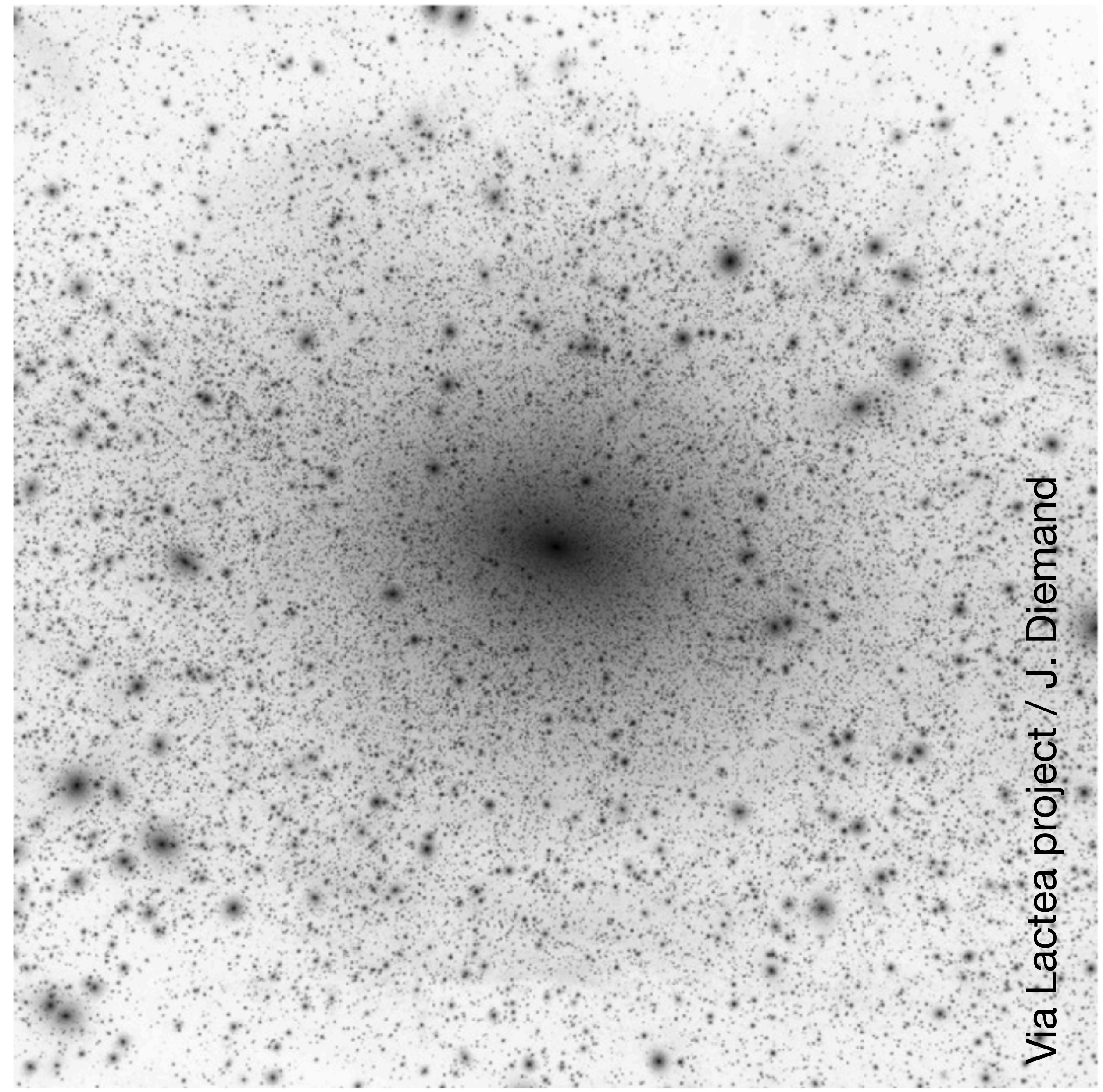
Satellite galaxies of the Milky Way and of the Andromeda galaxy have been found to preferentially align in significantly flattened planes of satellite galaxies, and available velocity measurements are indicative of a preference of satellites in those structures to co-orbit. There is an increasing evidence 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 $\leq 0.5\%$ 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 problems 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.

Keywords: Dark matter; cosmology; dwarf galaxies; near-field cosmology.

PACS Nos.: 95.35.+d, 98.80.Es

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

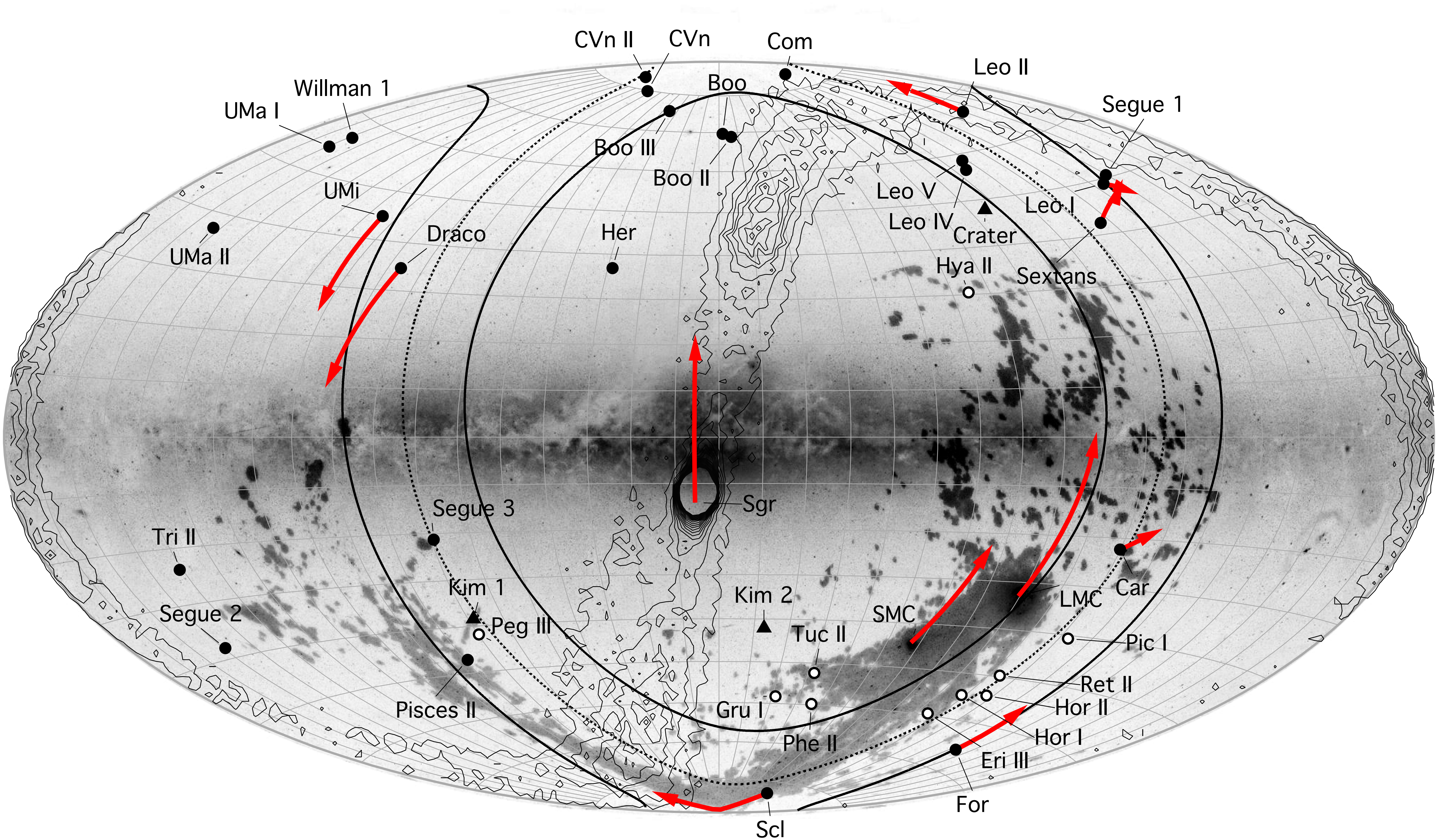
- Know 40-50 satellite galaxies for Milky Way and Andromeda.
- Can we use the Local Group (and other nearby host galaxies) as a testbed for cosmological models?
- Overall positions and velocities of satellite sub-halos on scales of 100s of kpc should be robust against internal dynamics and feedback processes.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



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



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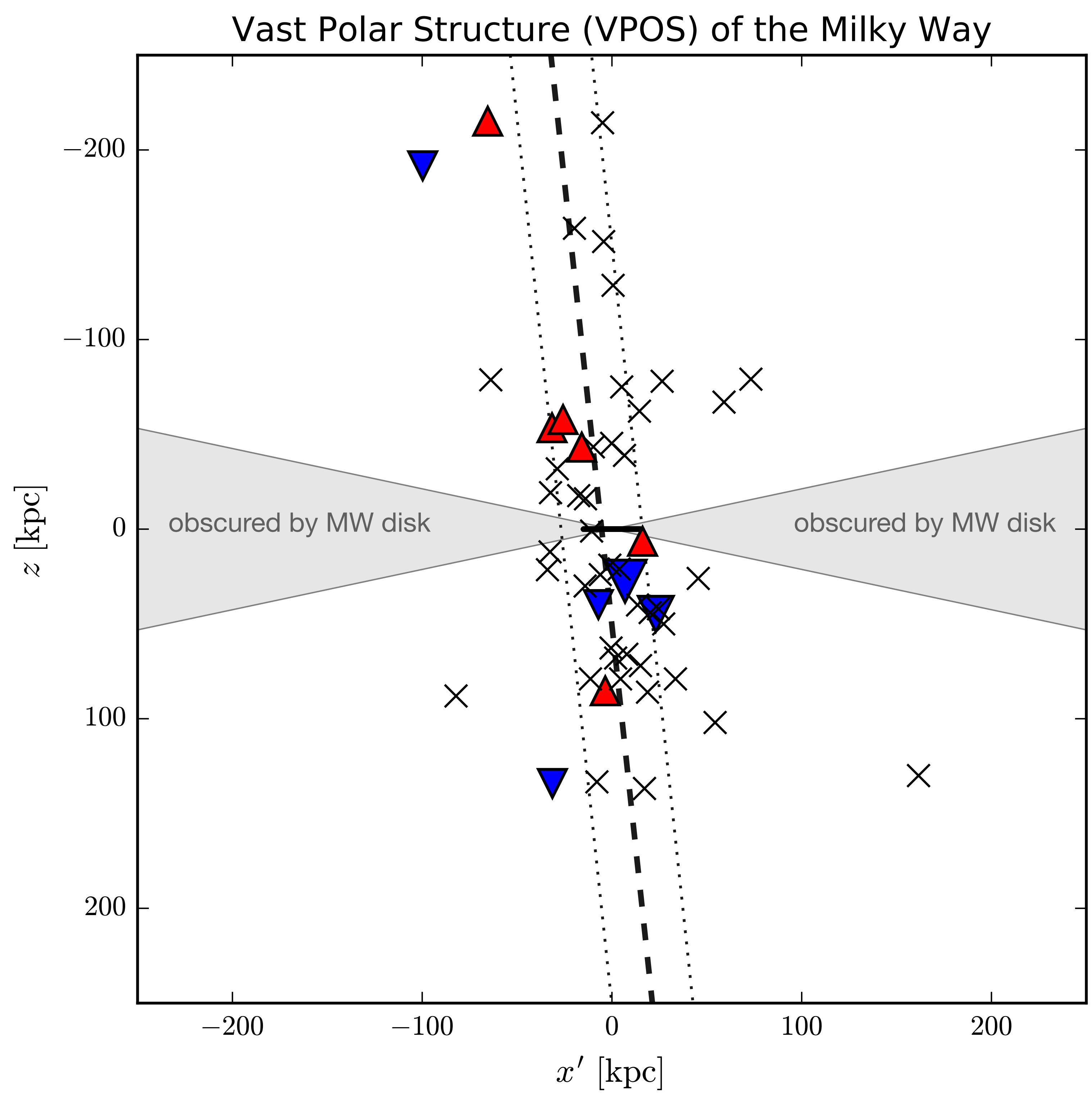
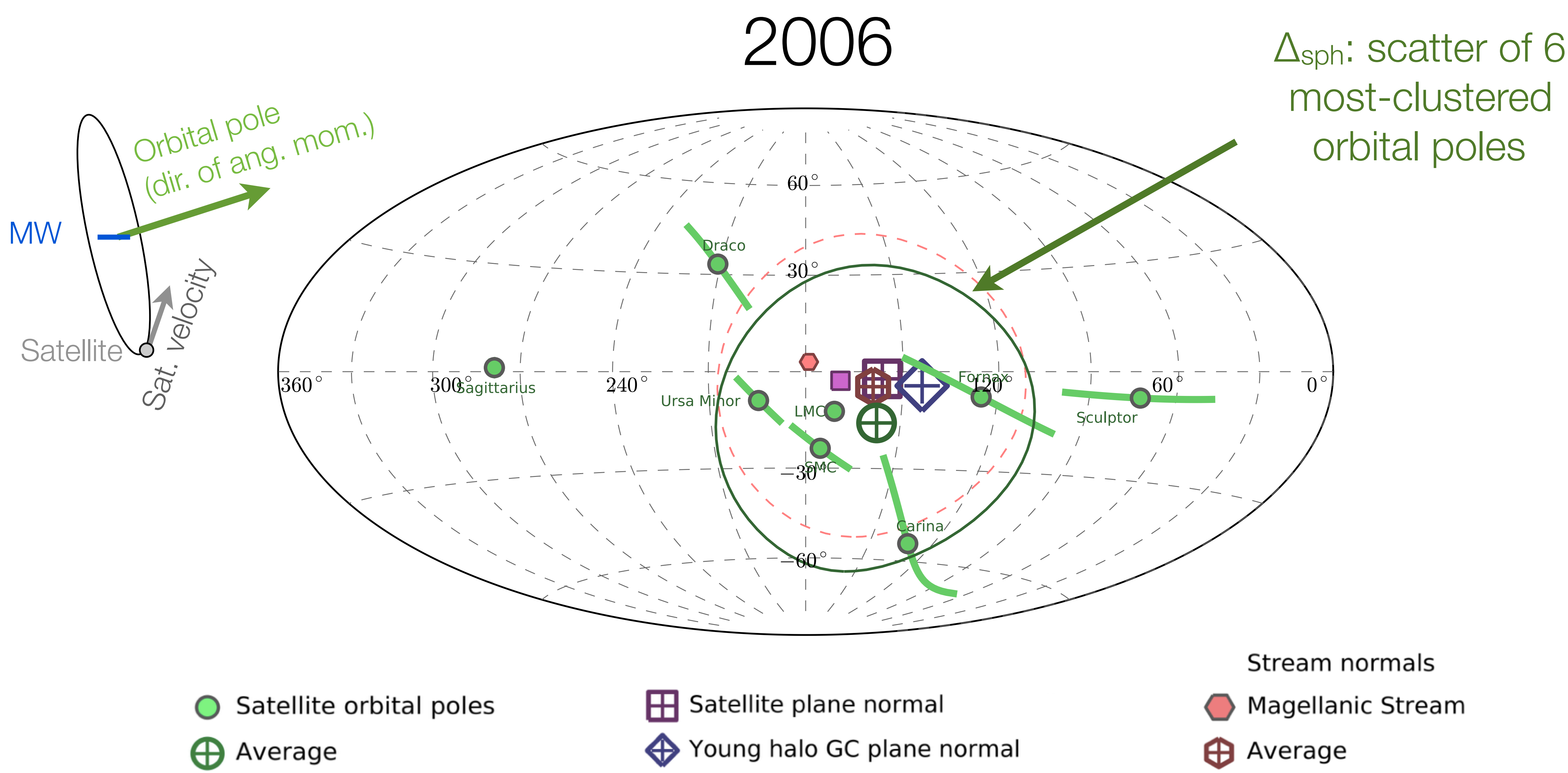
Pawlowski 2018 (invited brief review in MPLA, arXiv:1802.02579)

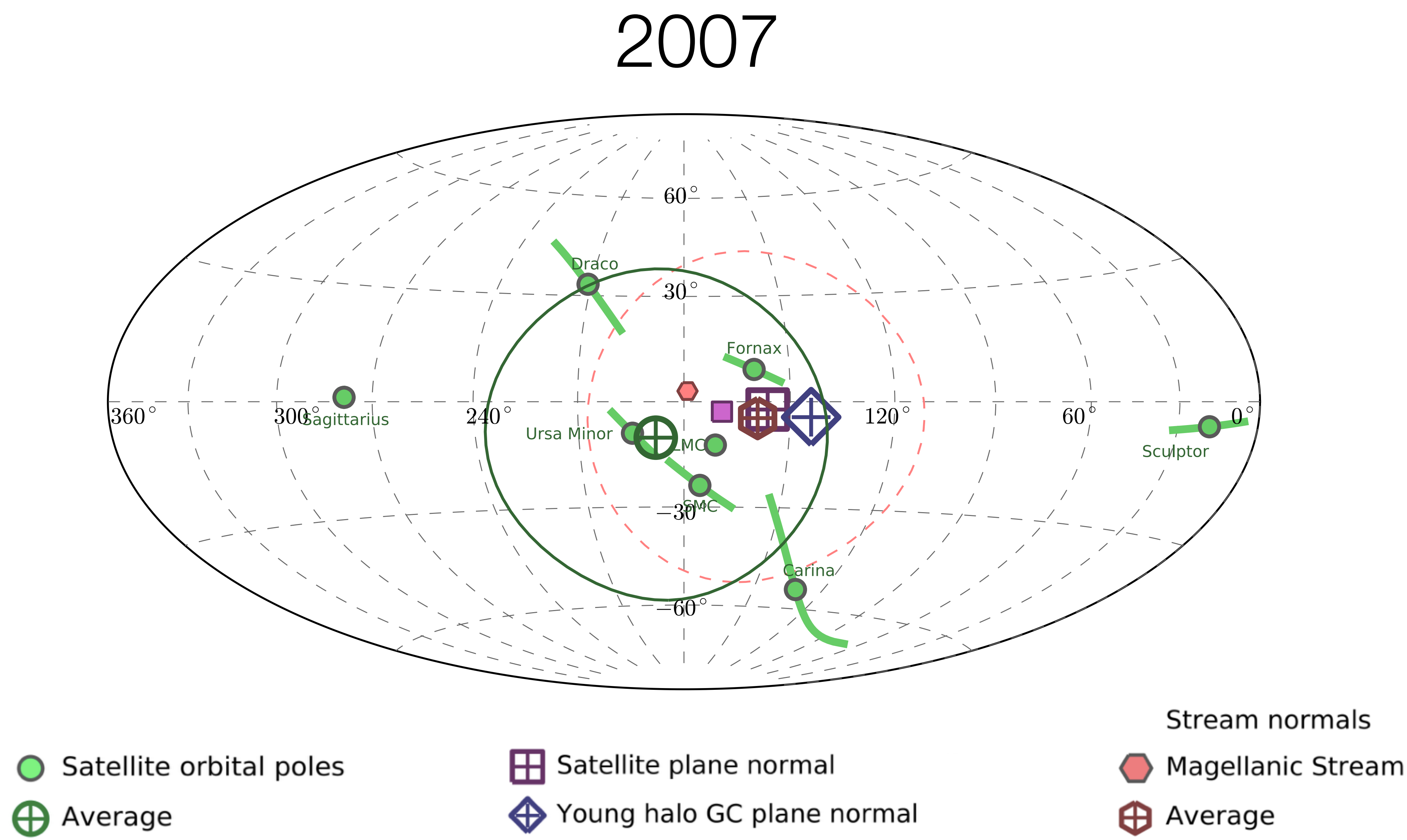


A Rotationally Supported VPOS: Better PM Measurement Result in Tighter Orbital Pole Distribution



Coherent velocities: the VPOS is rotating

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



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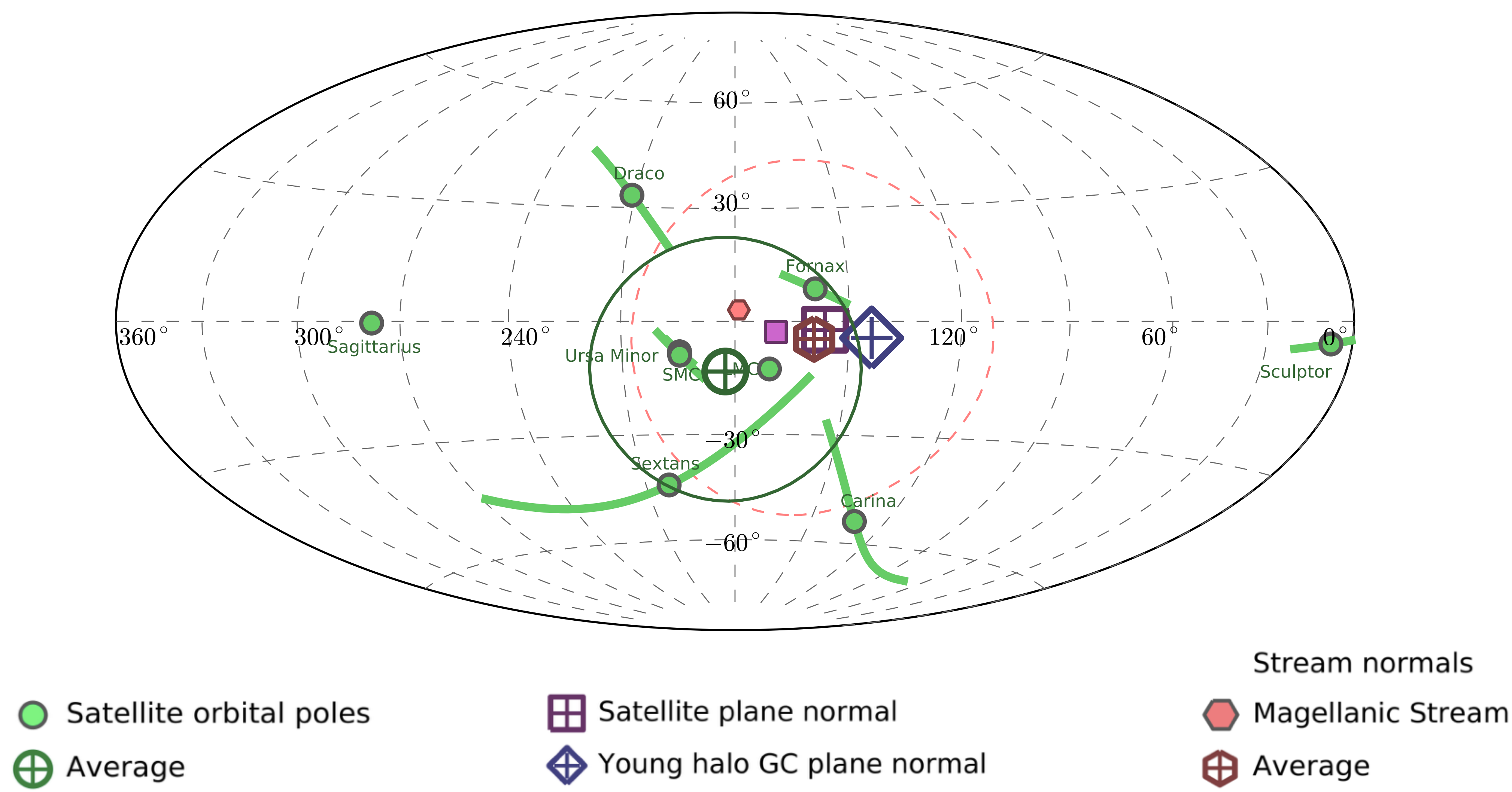
2008



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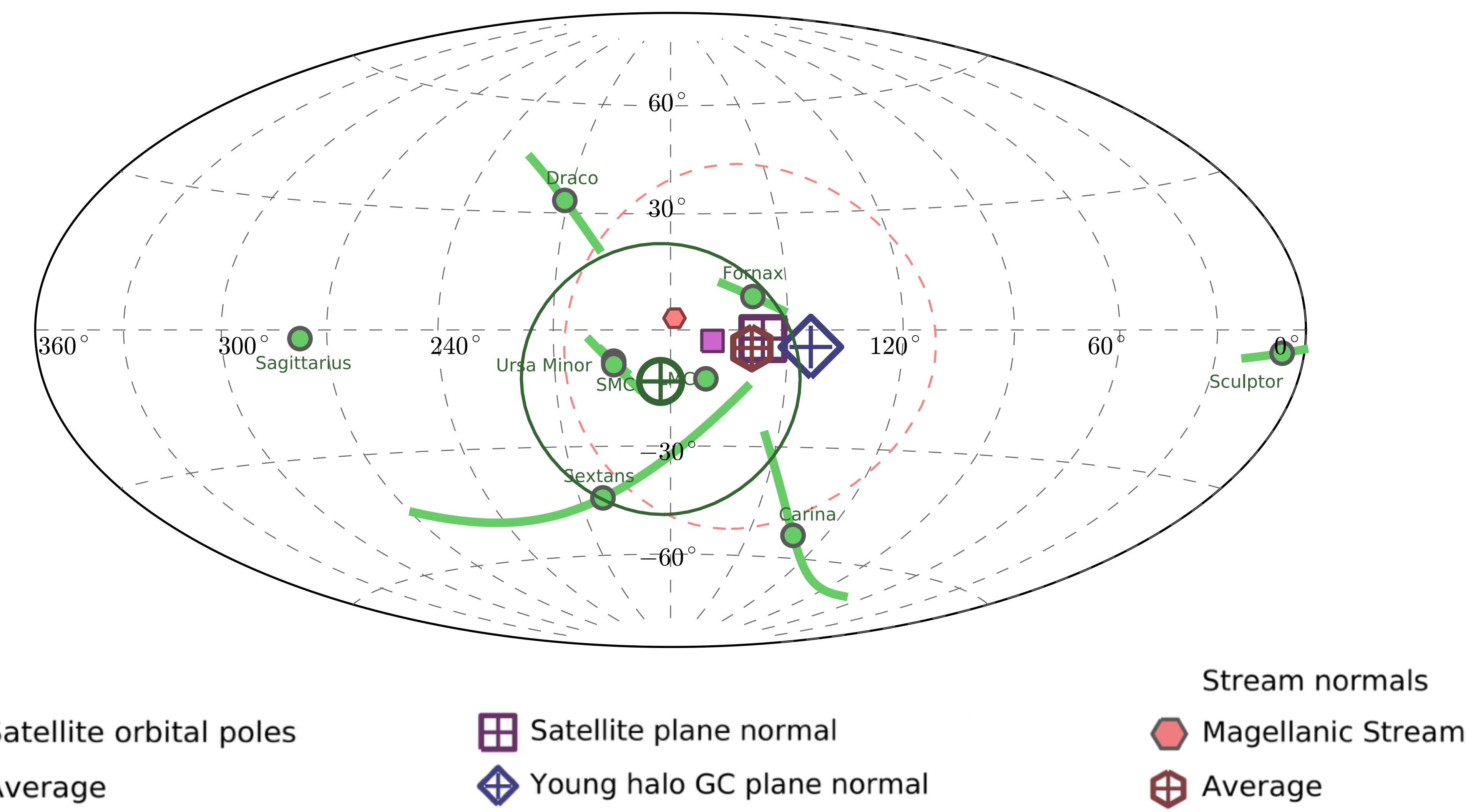

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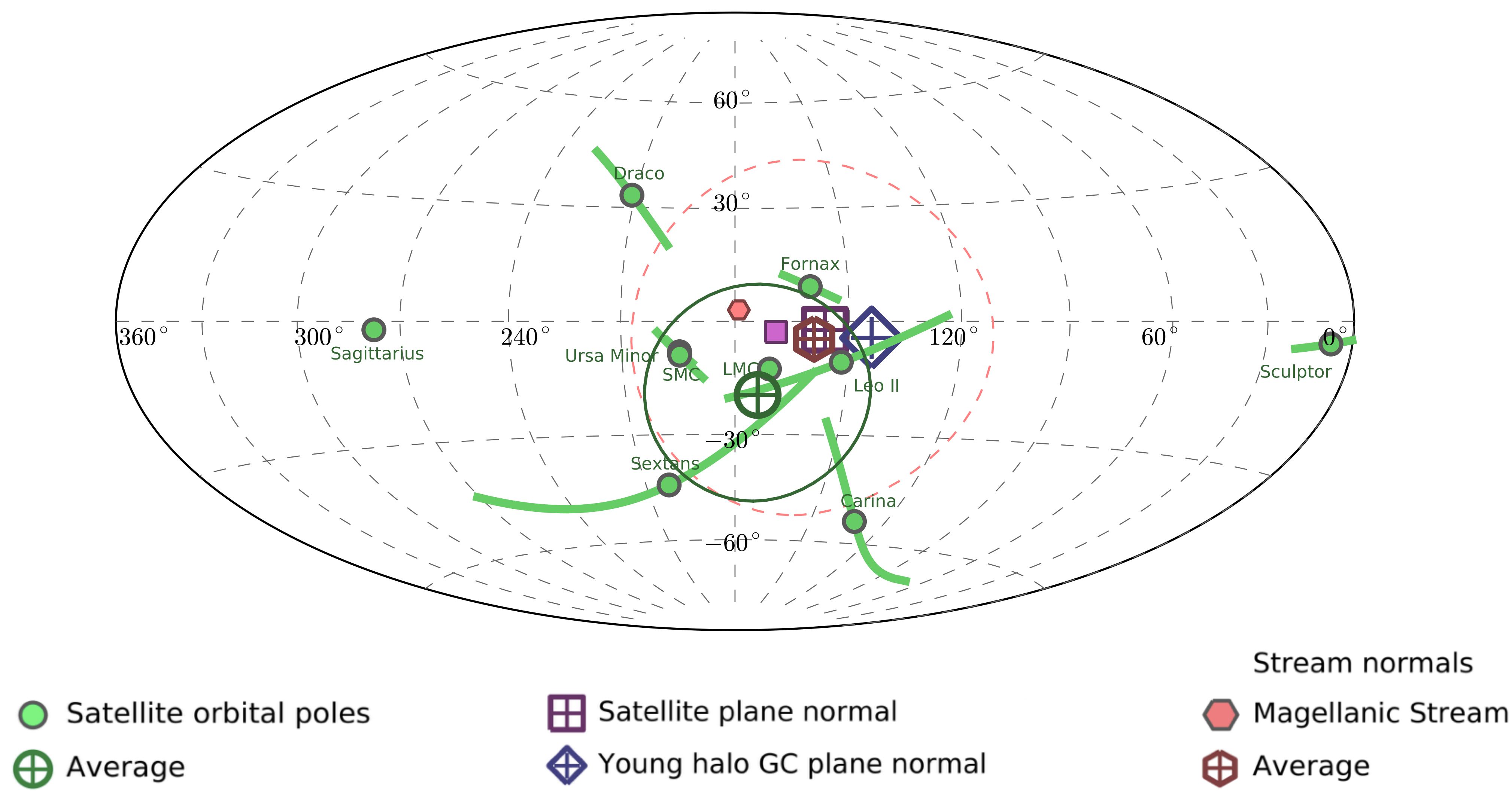

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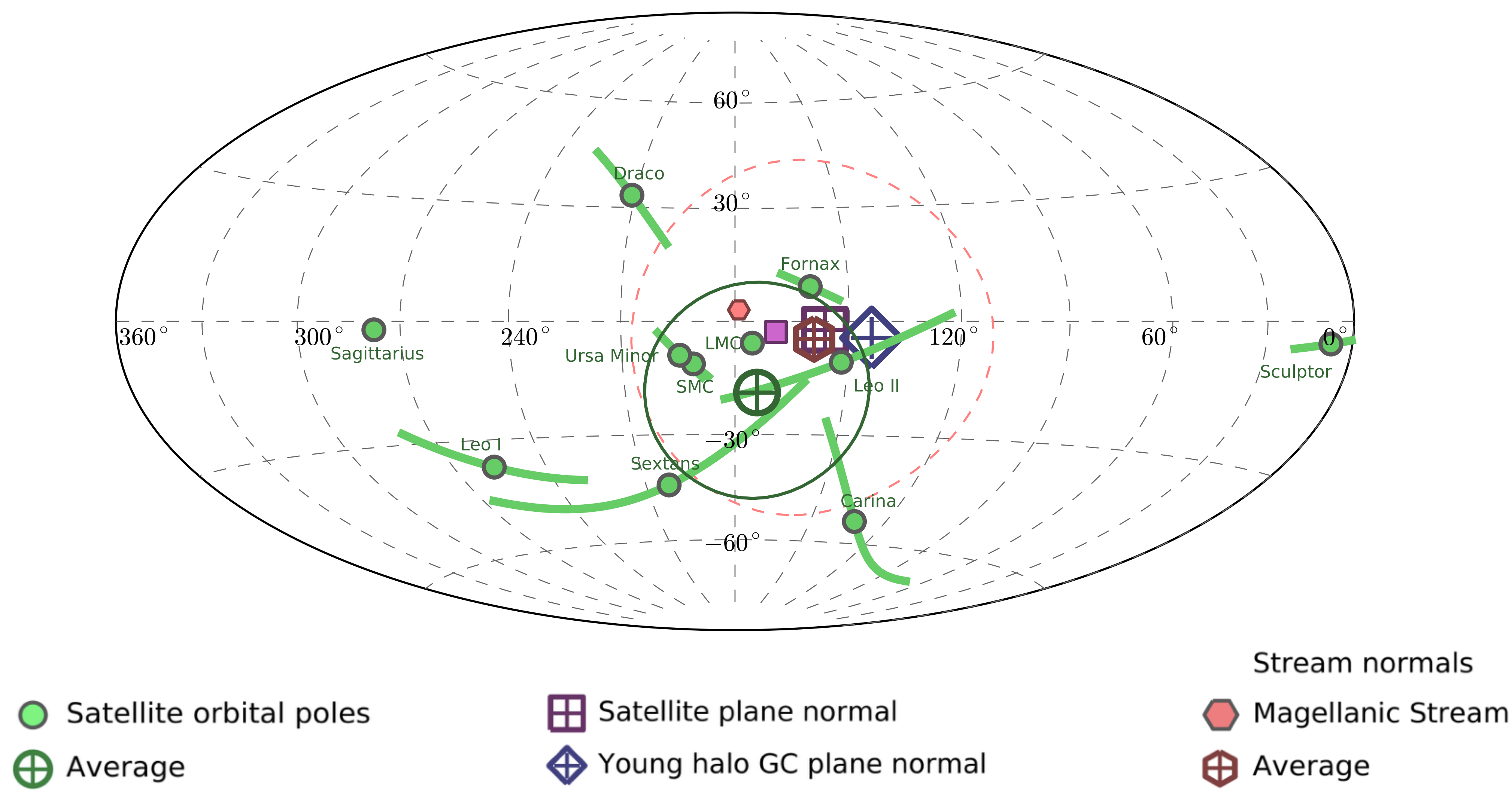

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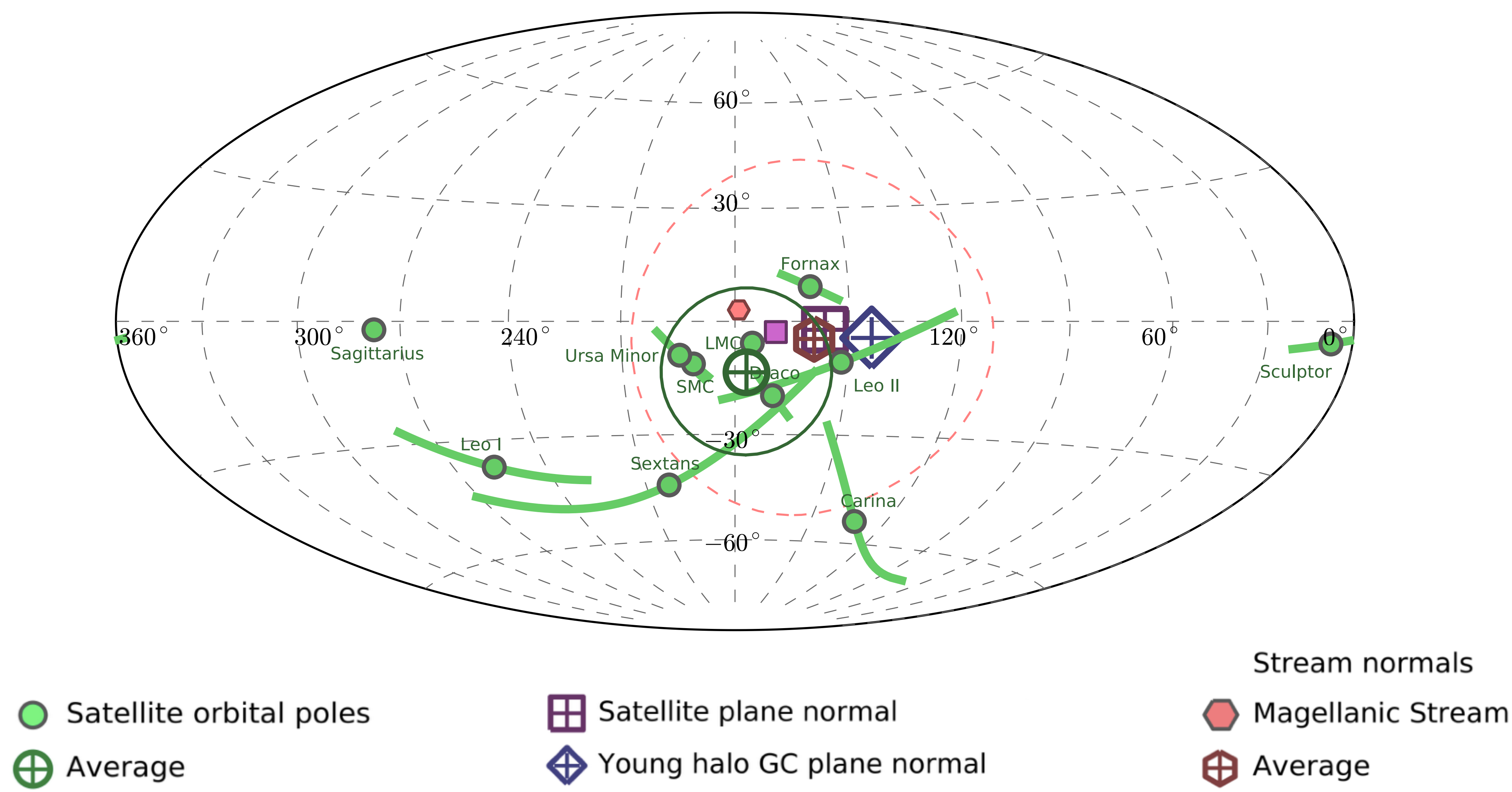

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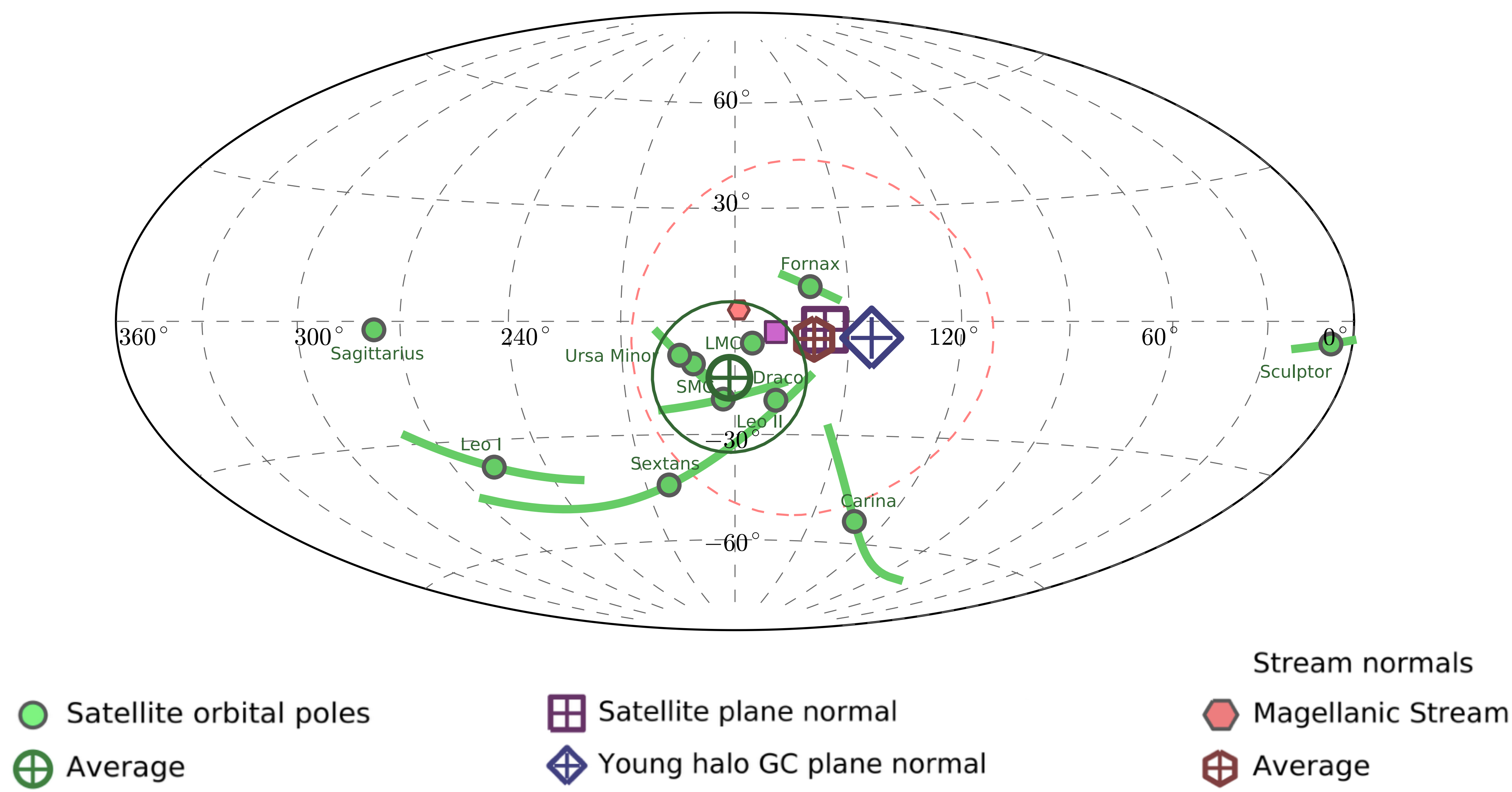

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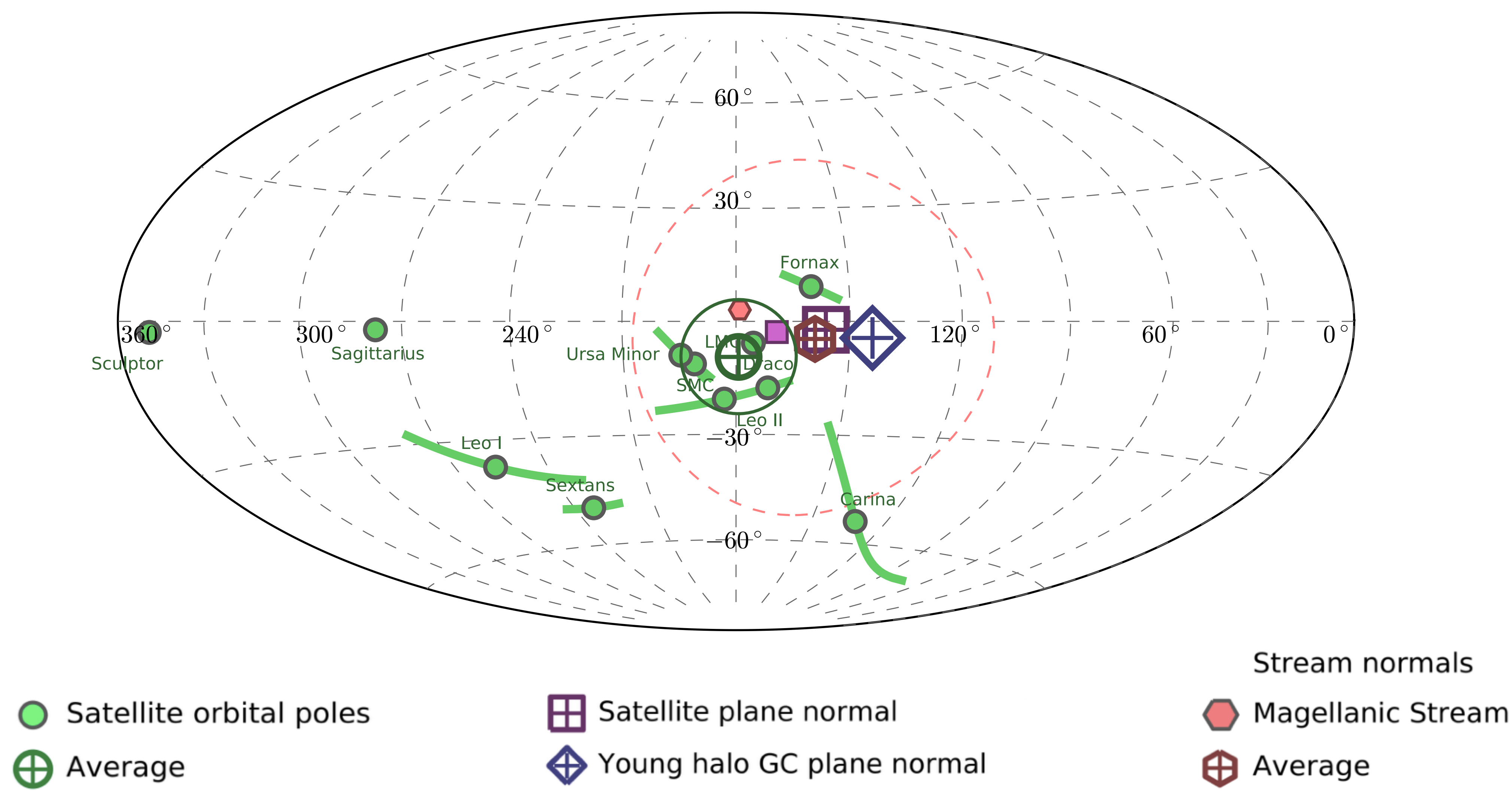

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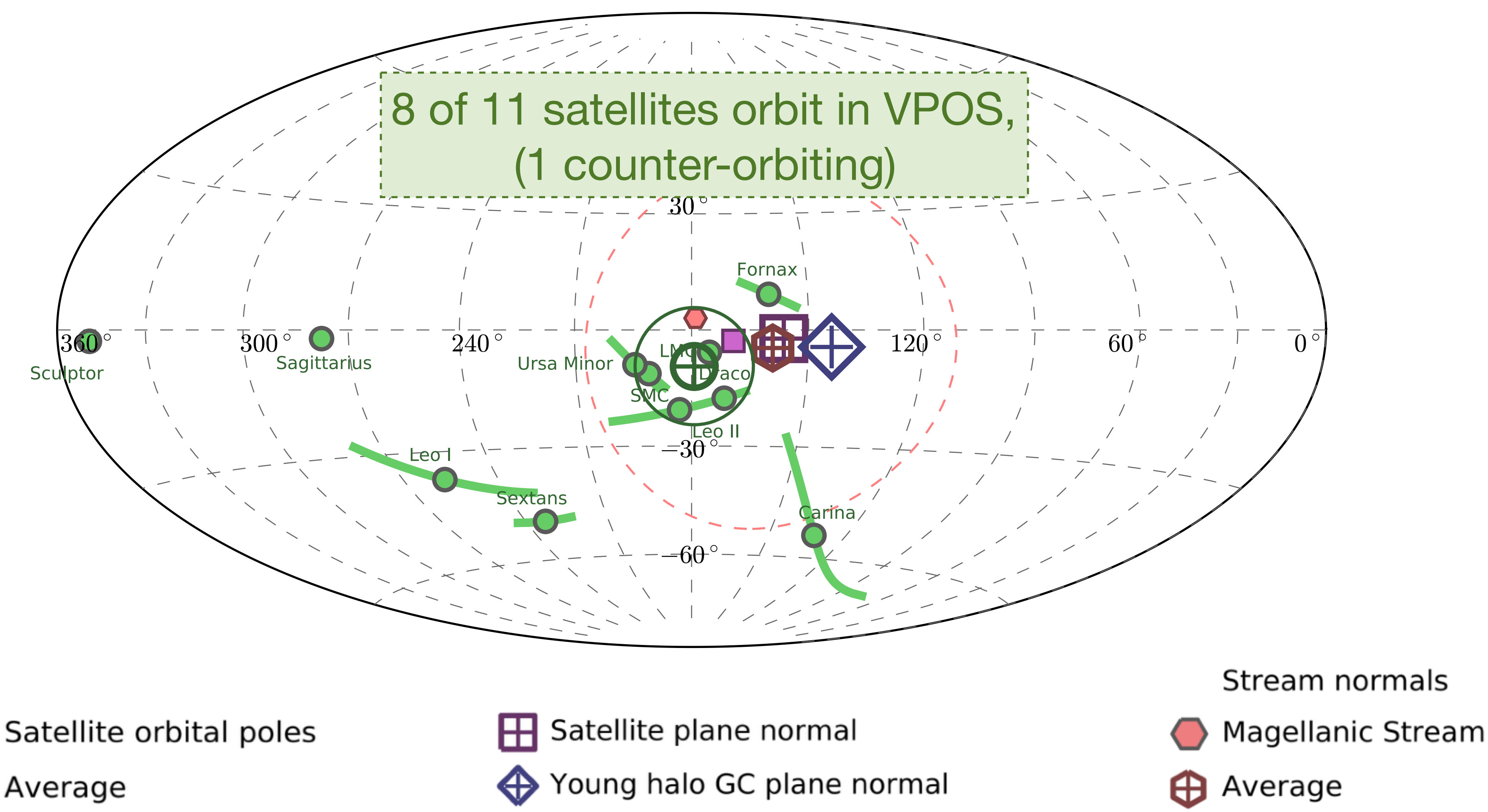
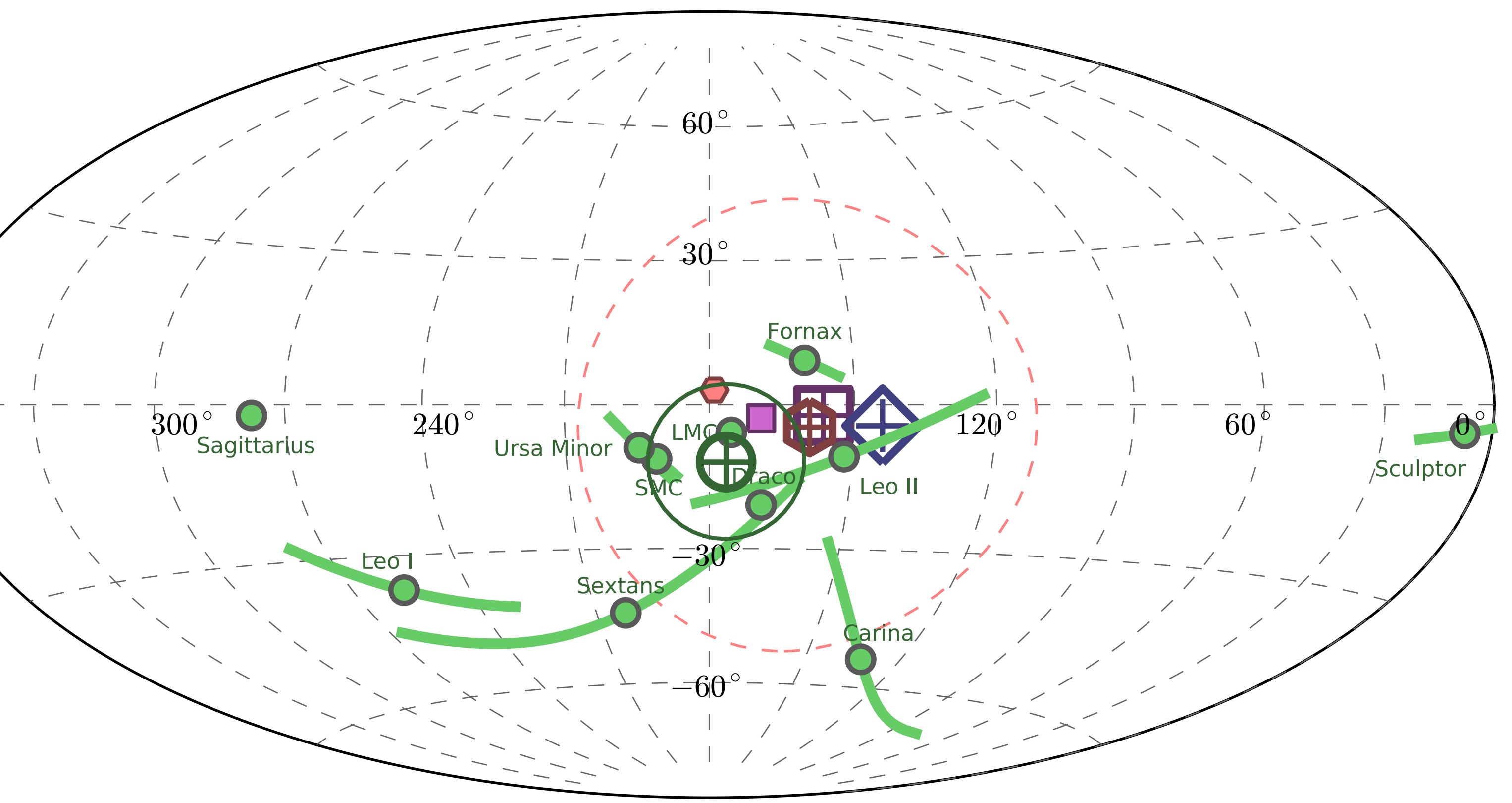
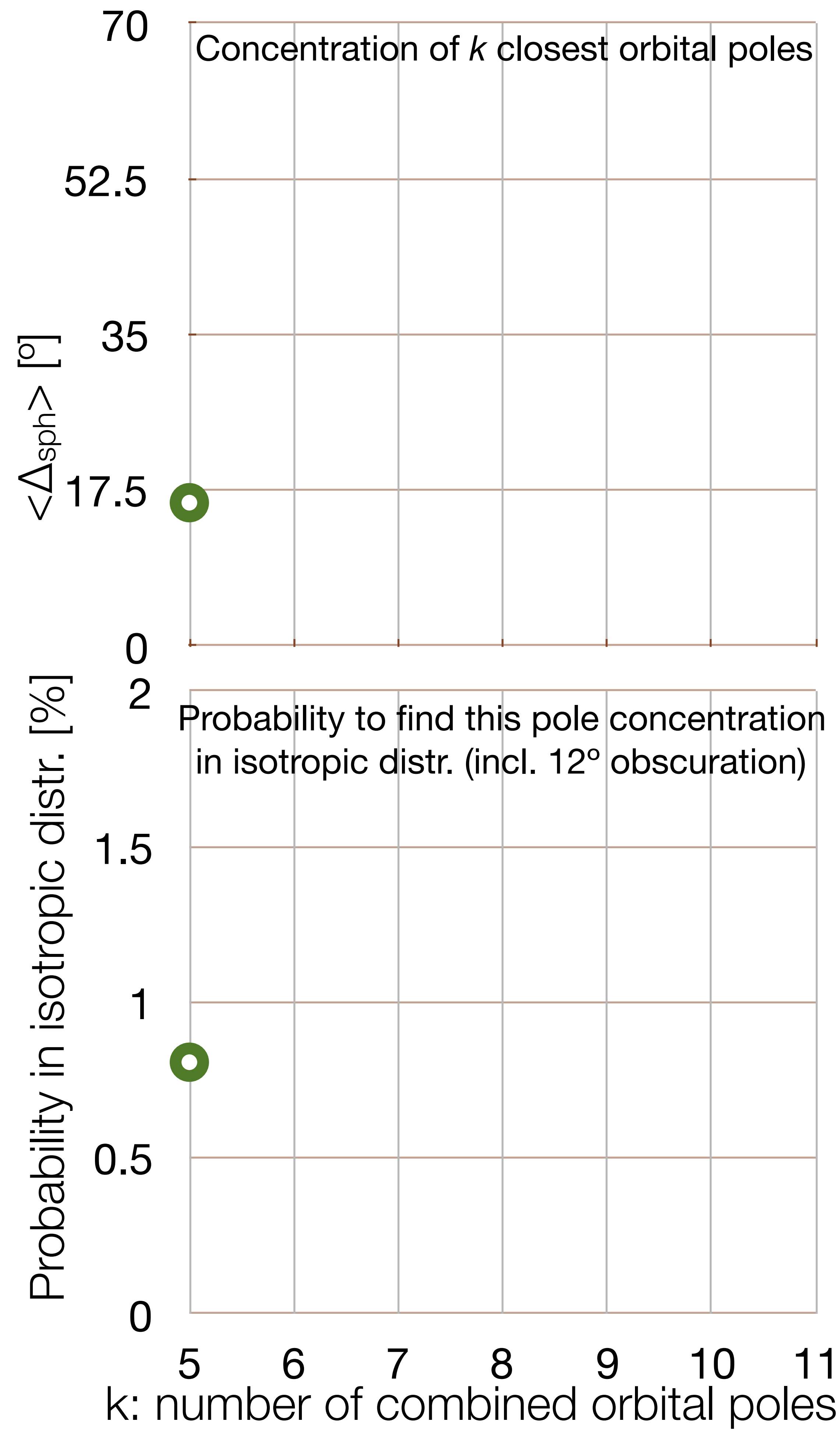


Δ_{sph}: the scatter of the *k* most-concentrated orbital poles





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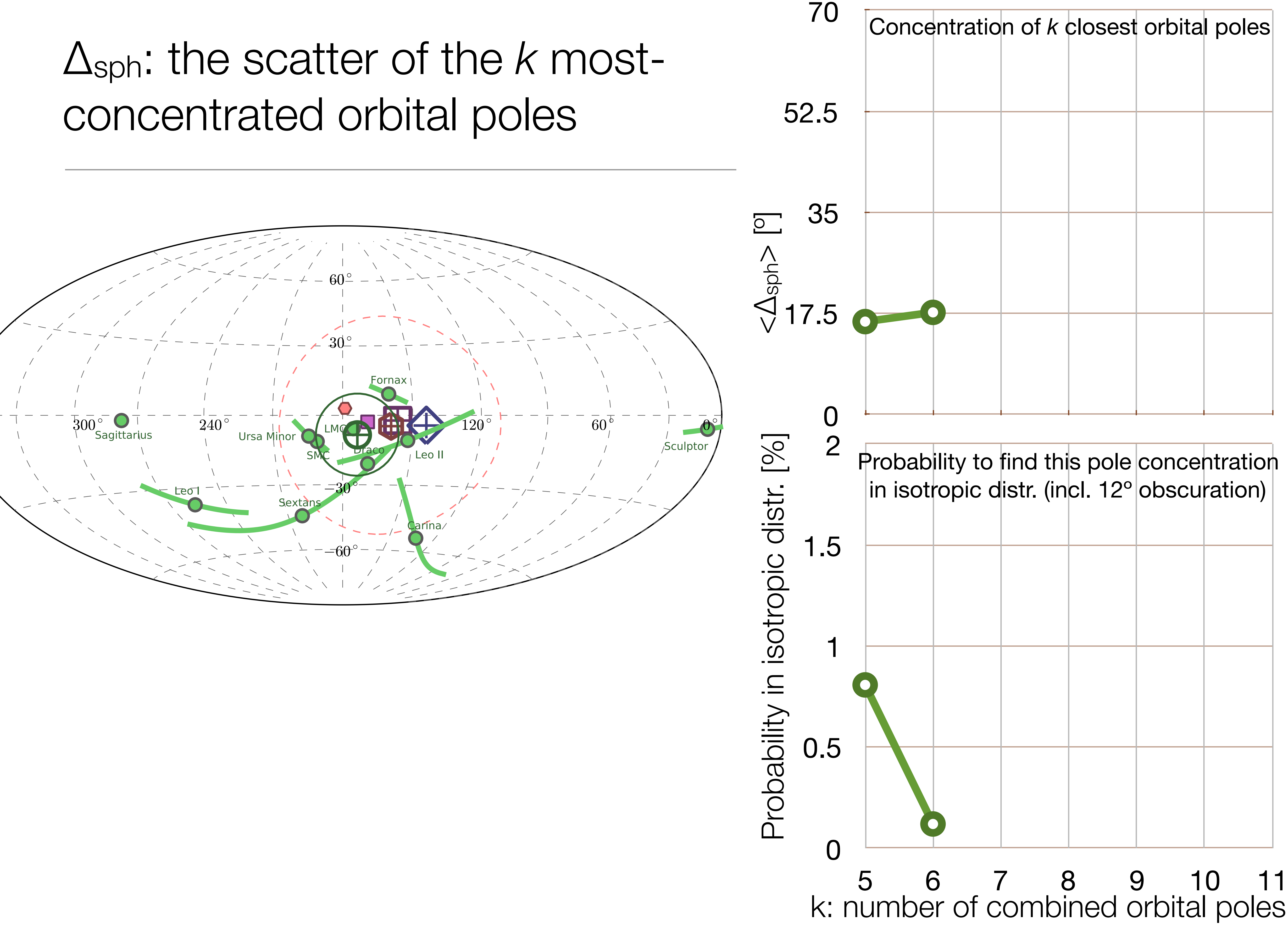

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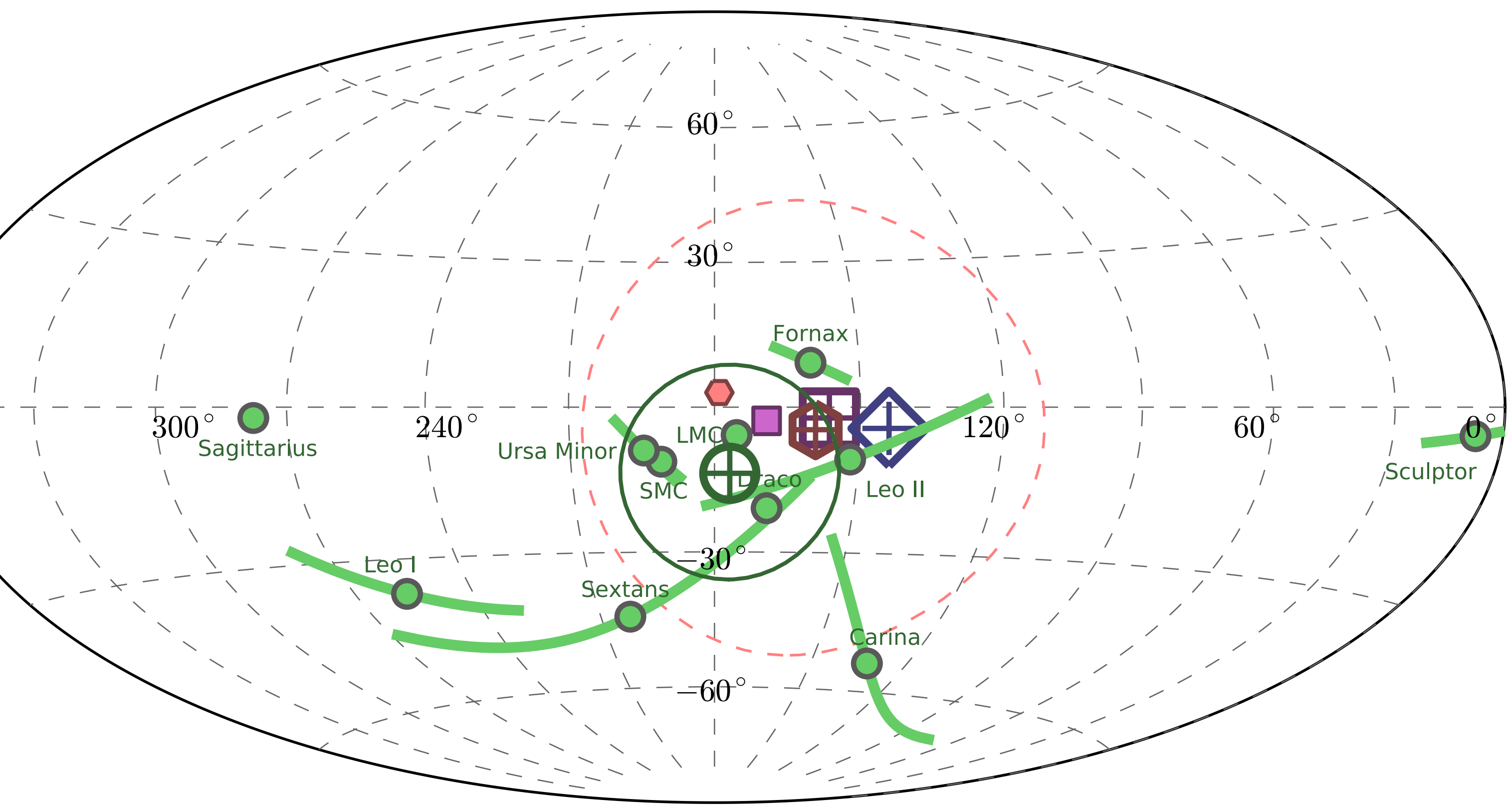

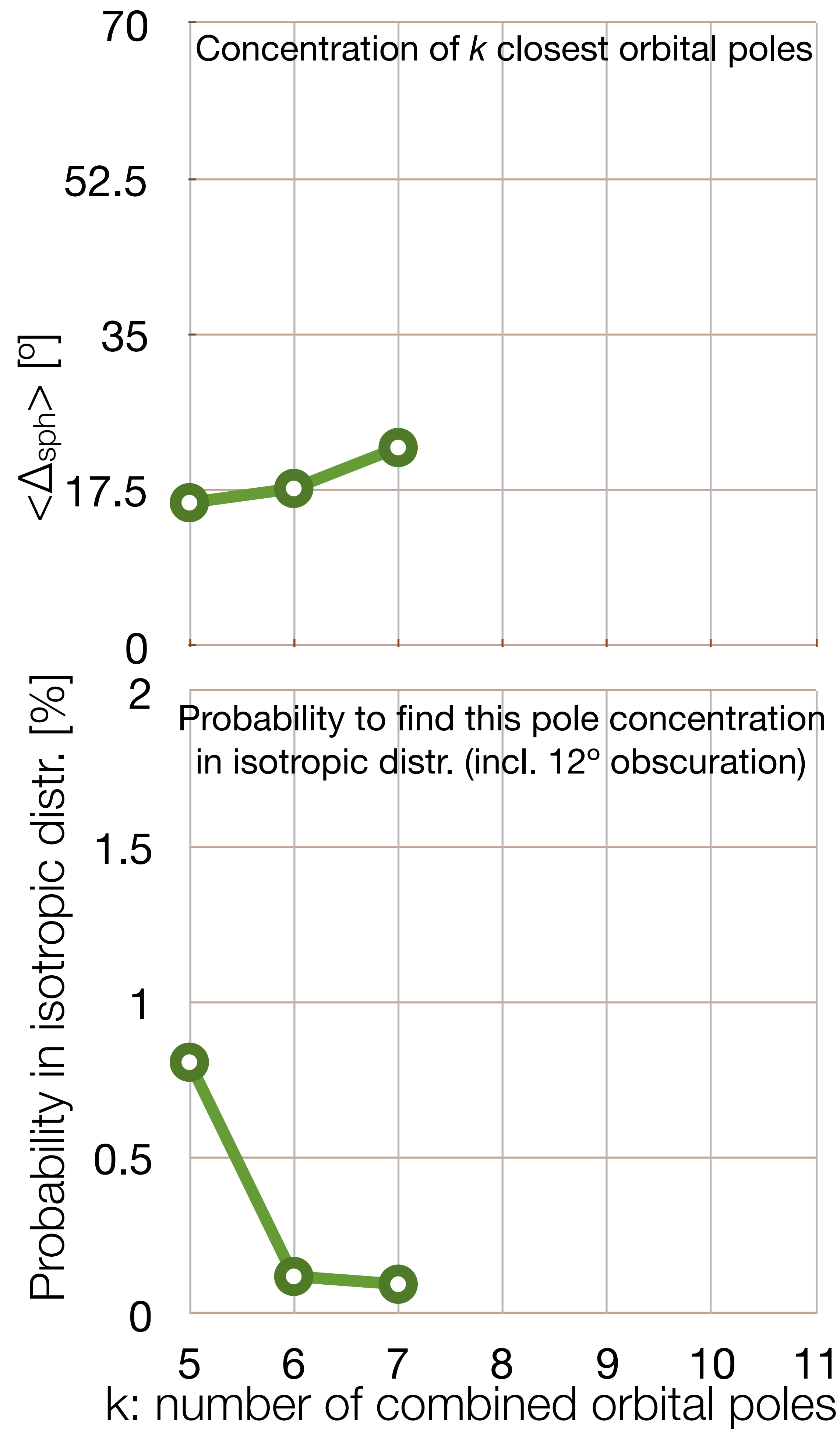

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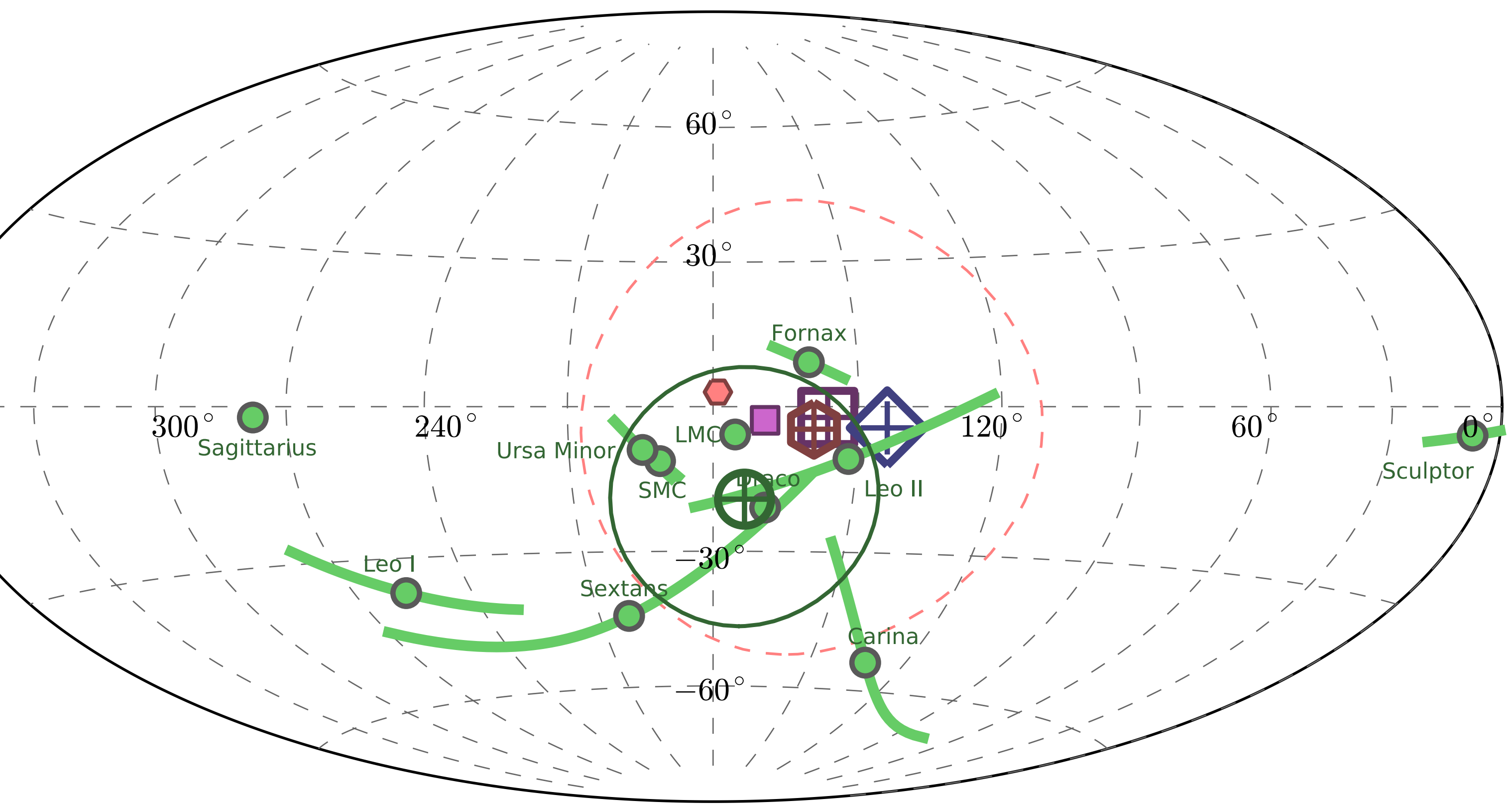

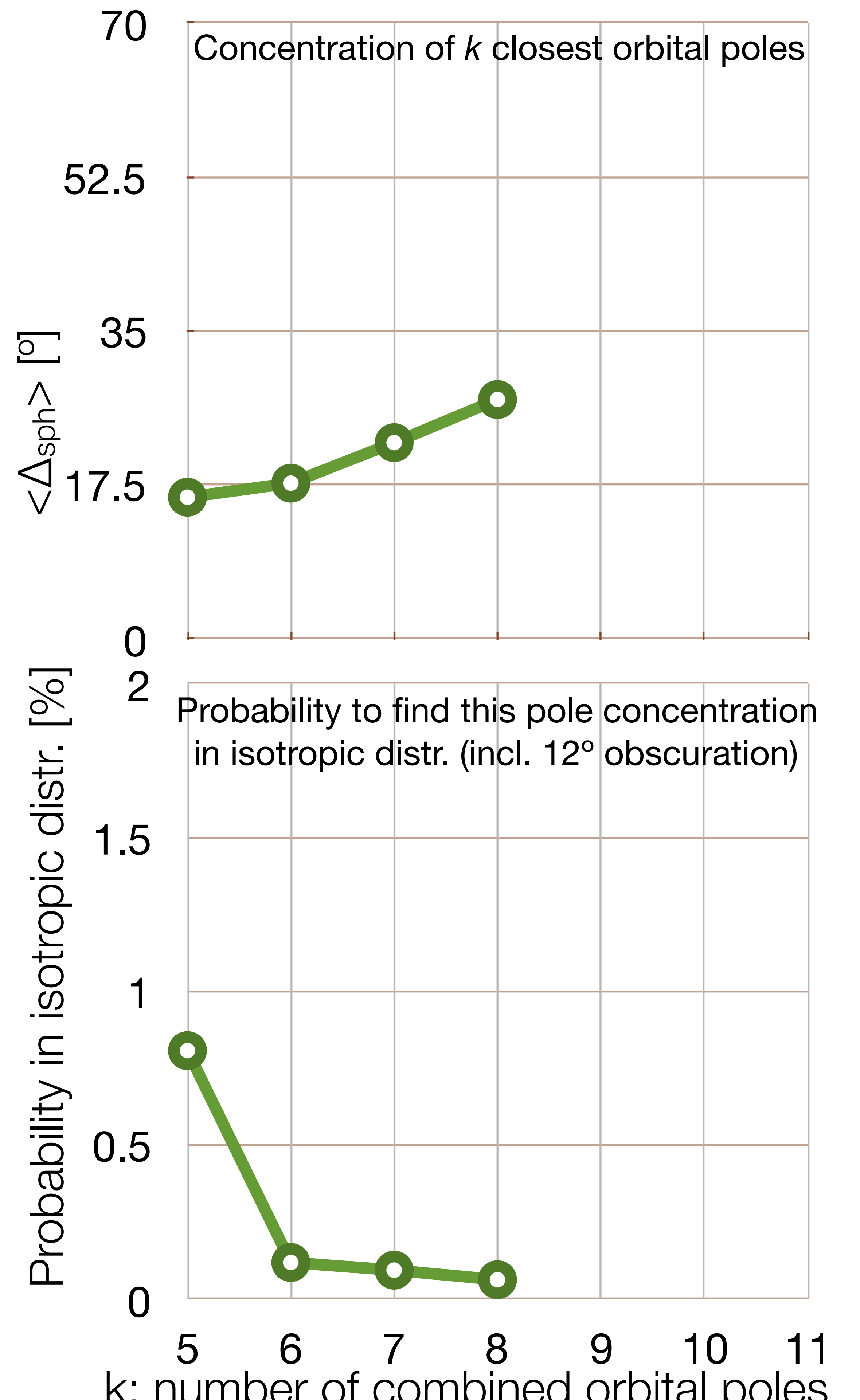

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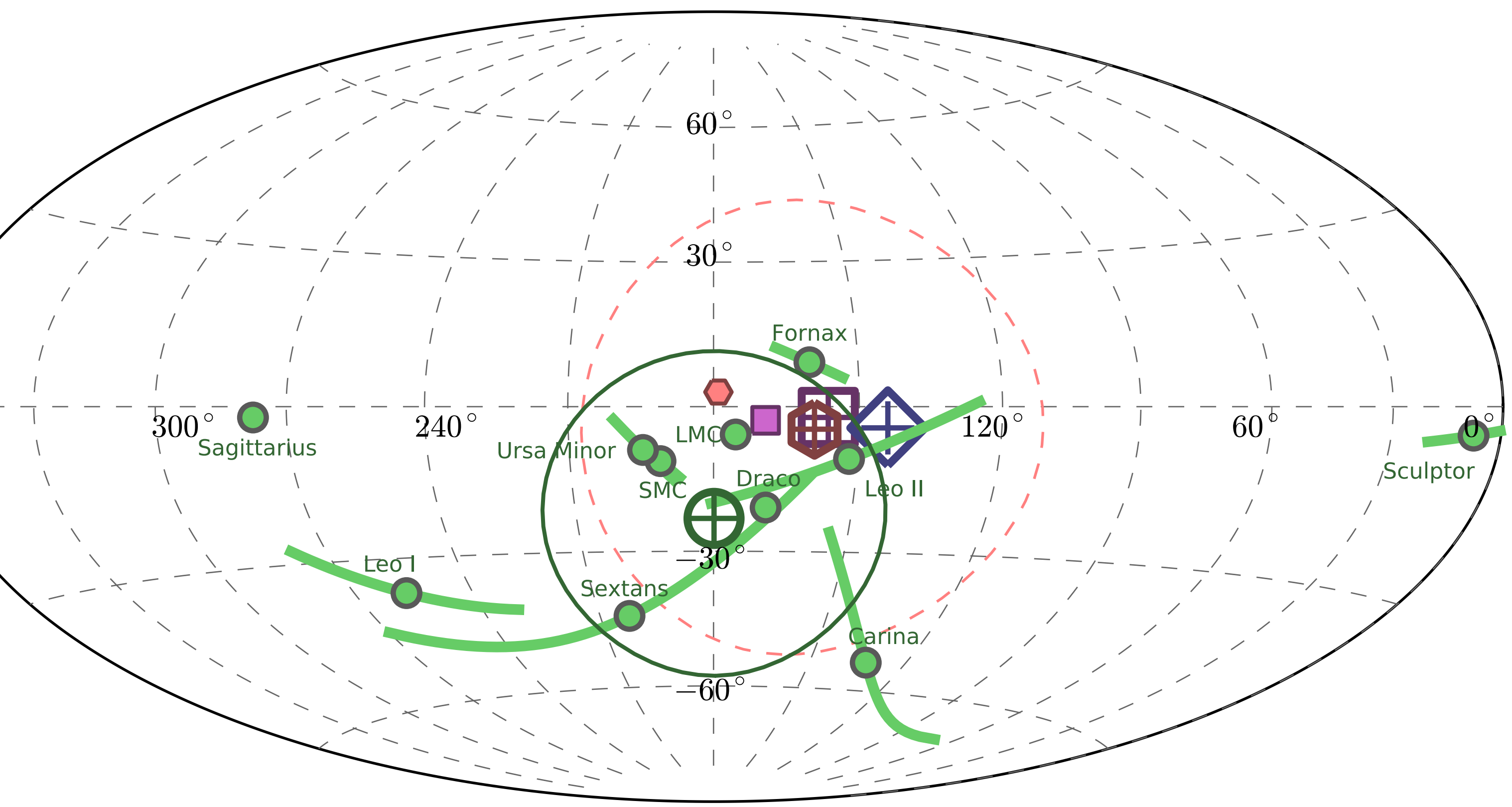

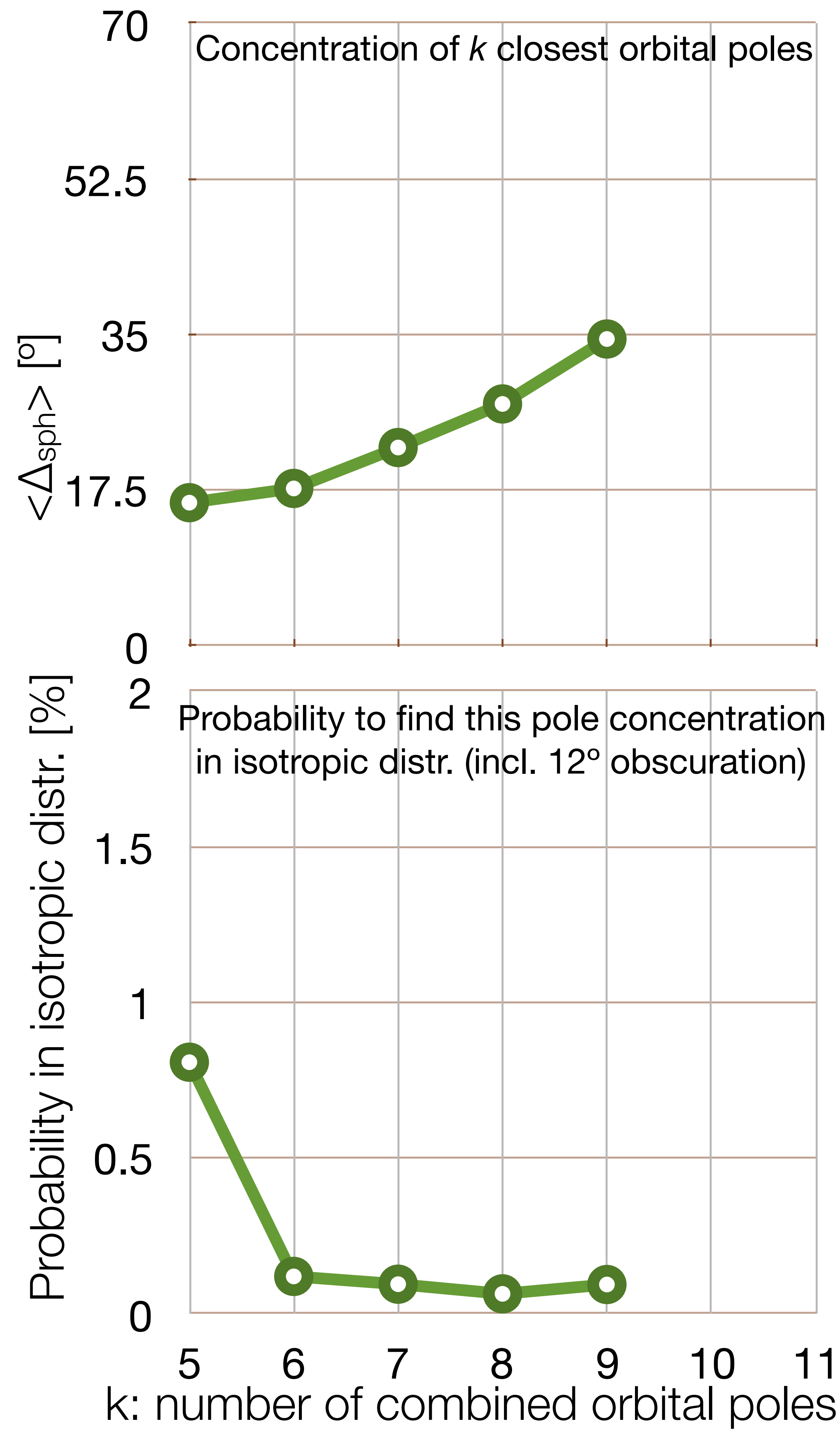

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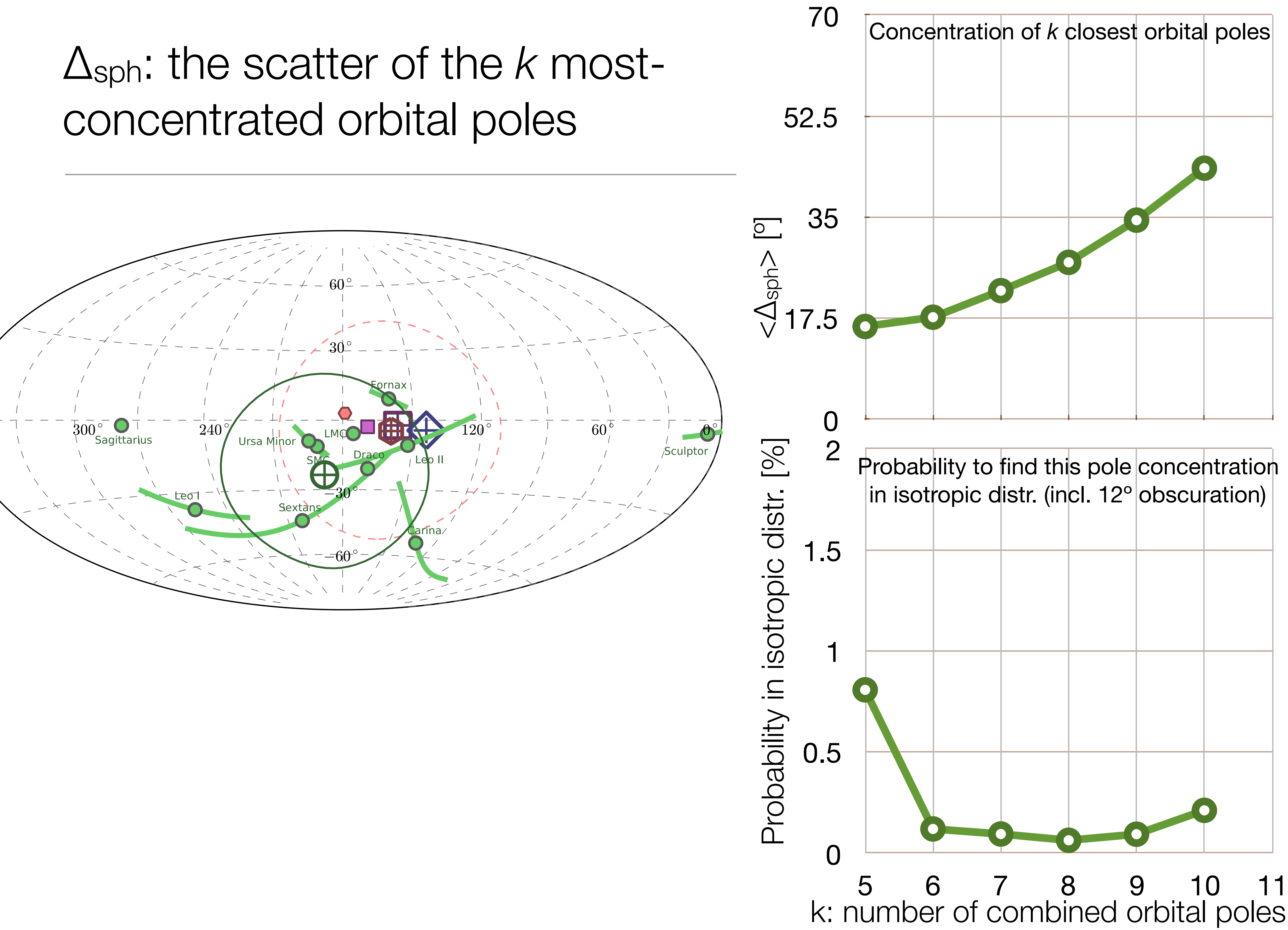
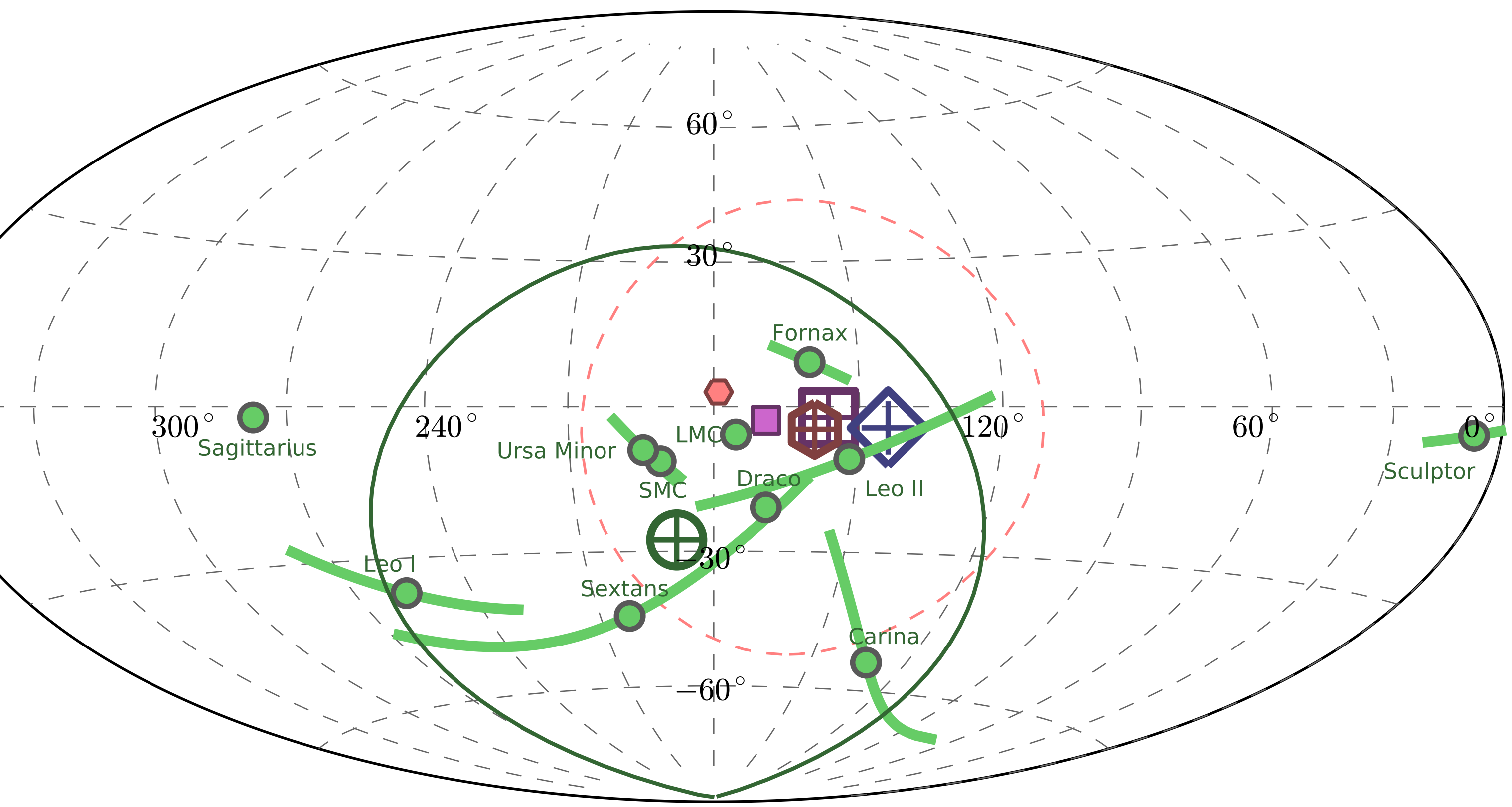
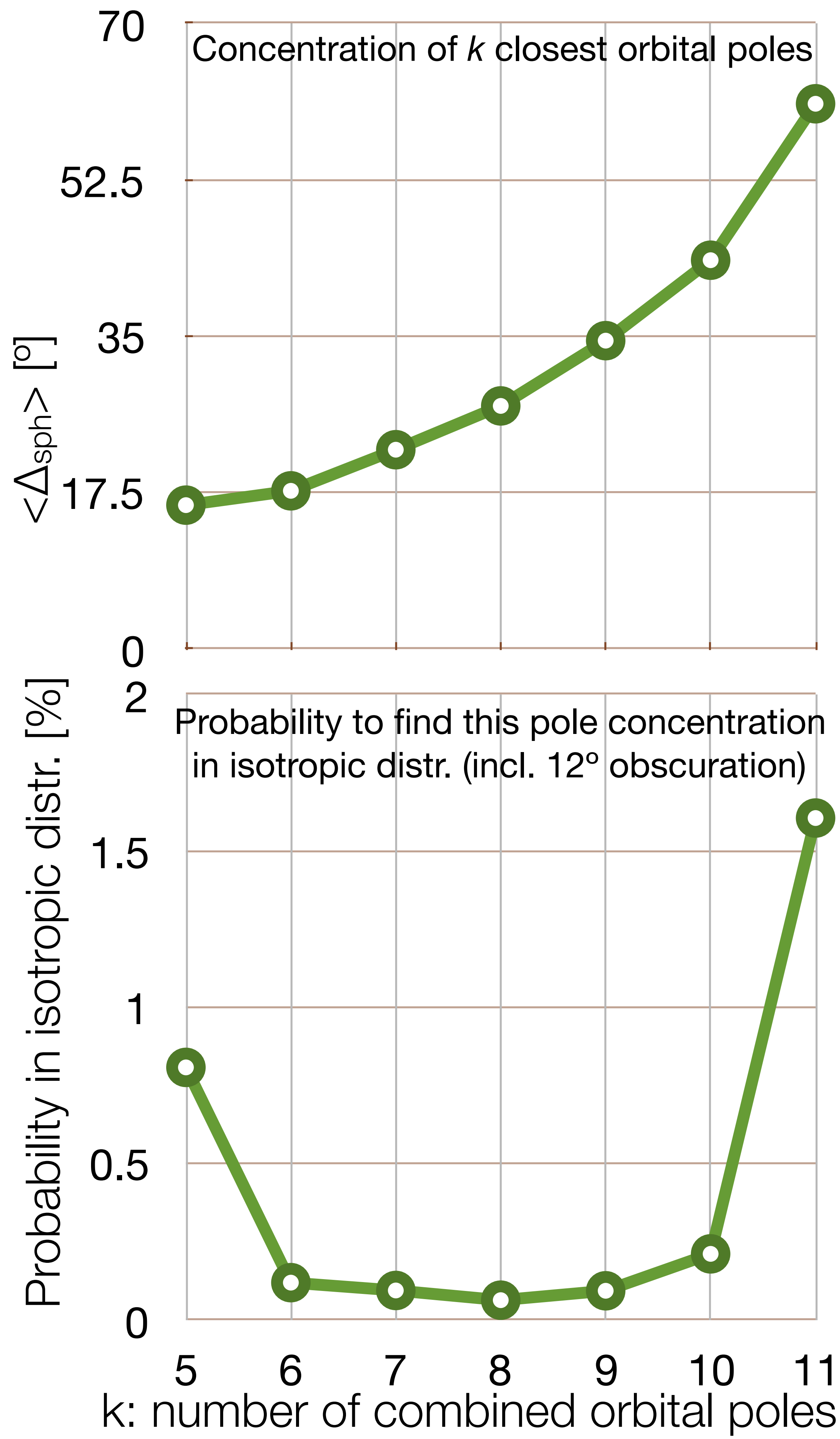


Δ_{sph}: the scatter of the *k* most-concentrated orbital poles





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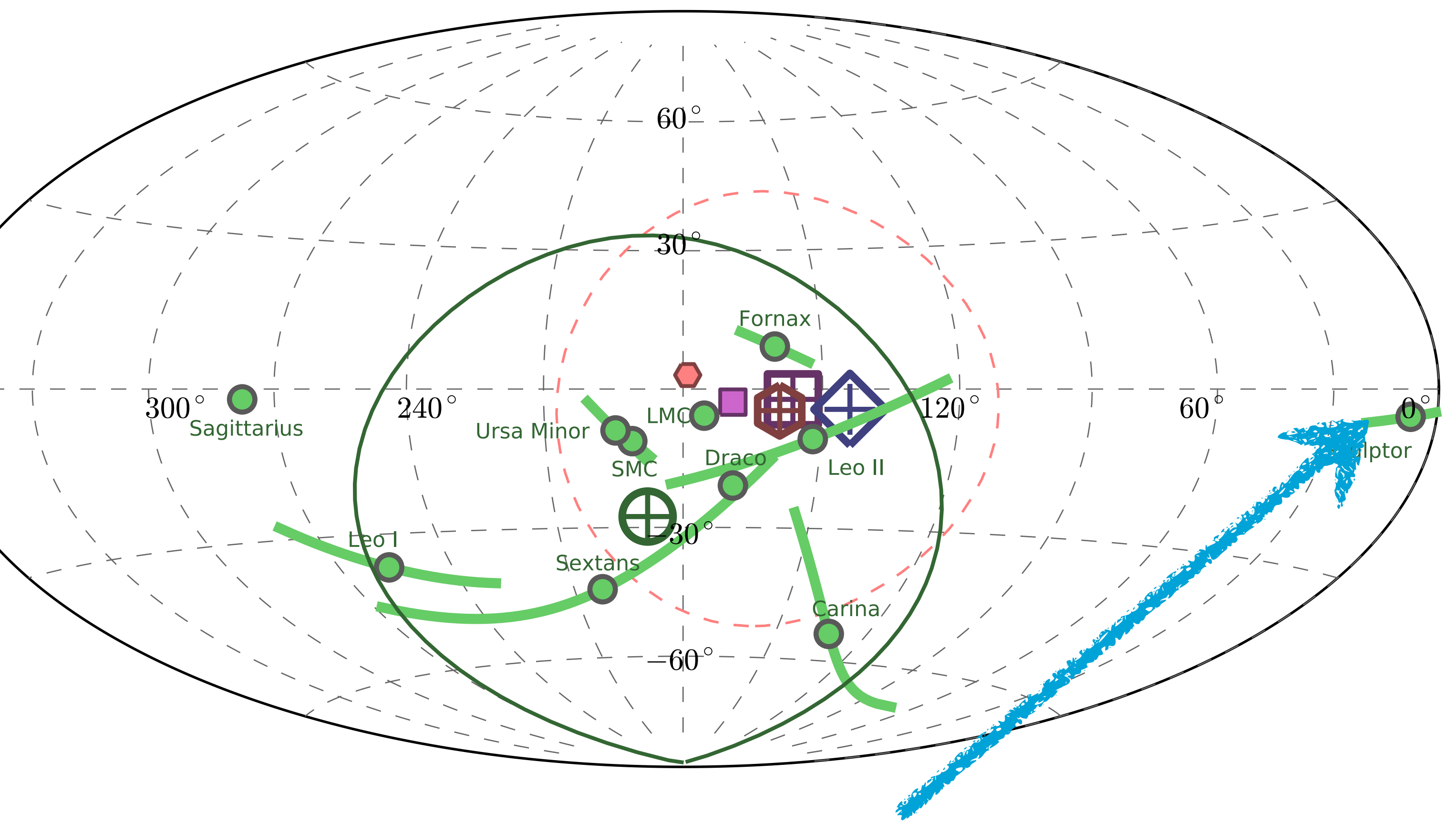
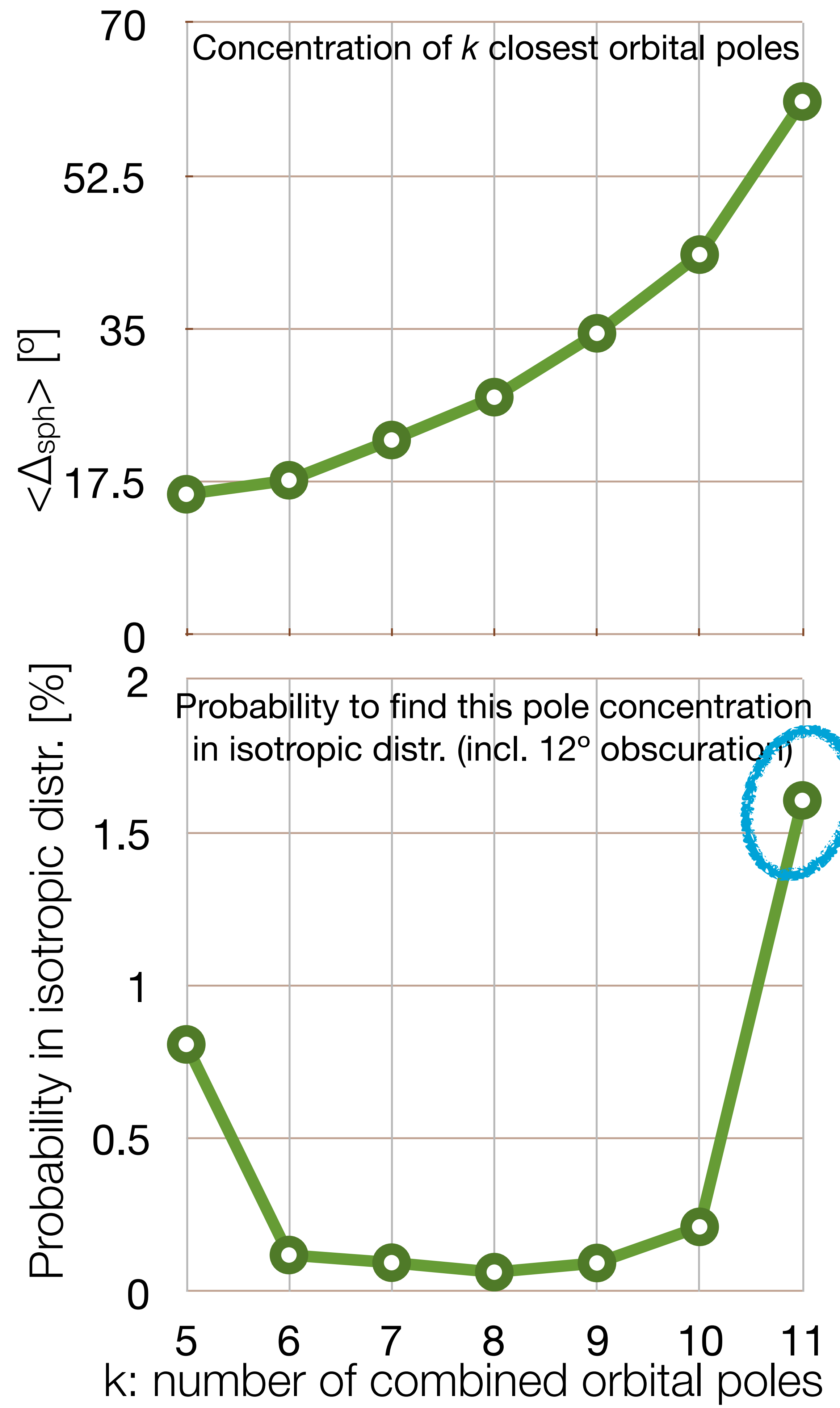
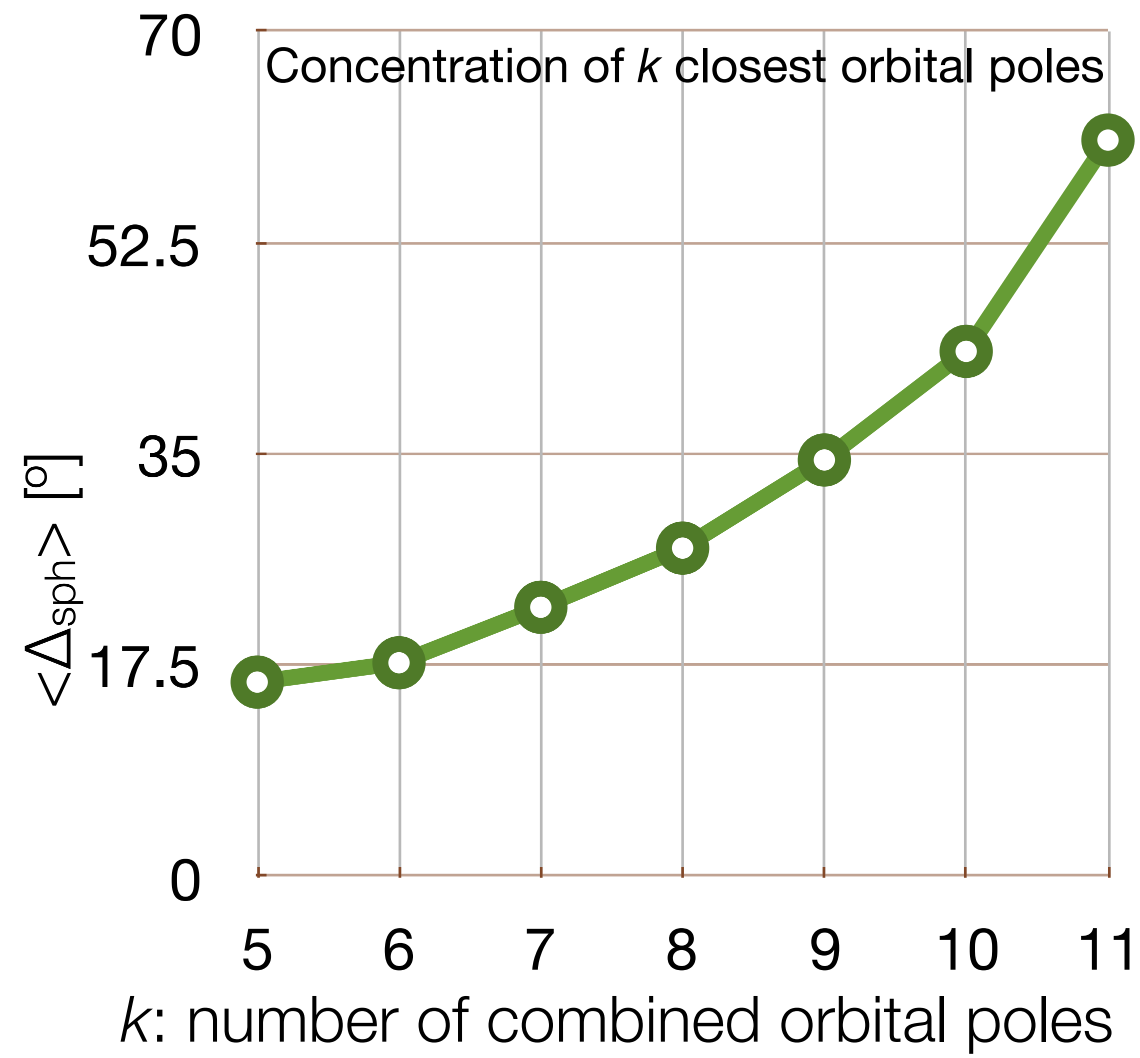


Sculptor orbits in the opposite direction but is well aligned with the VPOS.
Δ_{sph} ignores this!



Minimum pole concentration and proper motion uncertainties

Assign each satellite tangential velocity which makes it orbit **as close as possible** to sat. plane.



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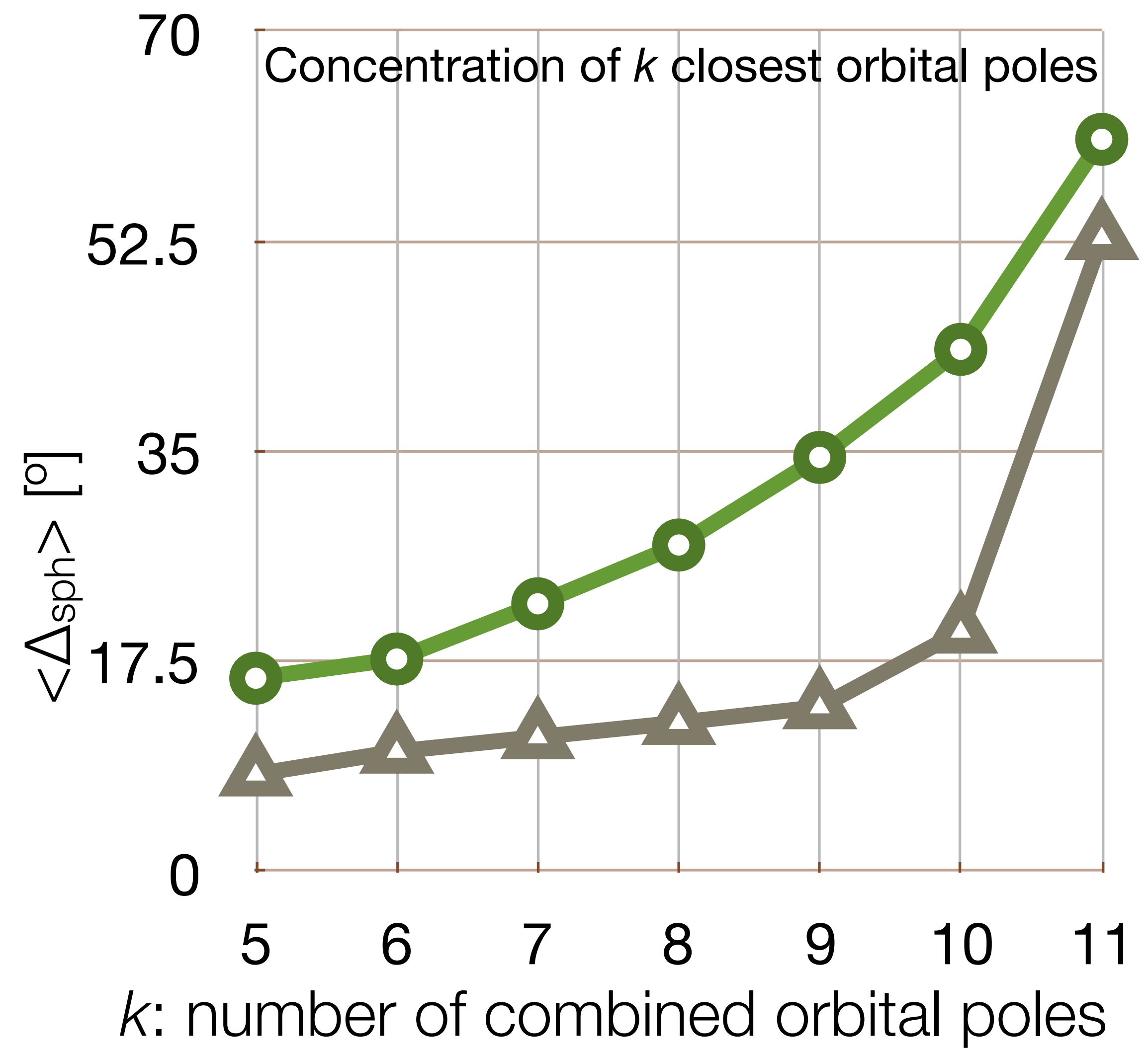

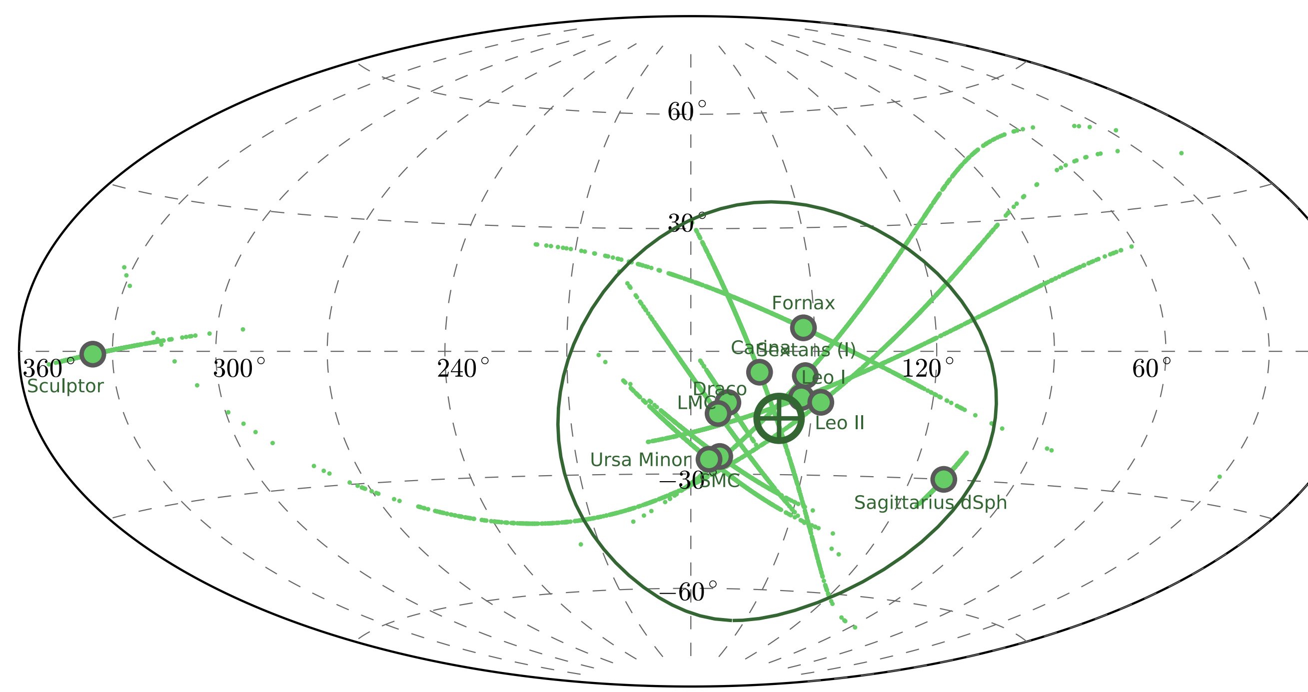

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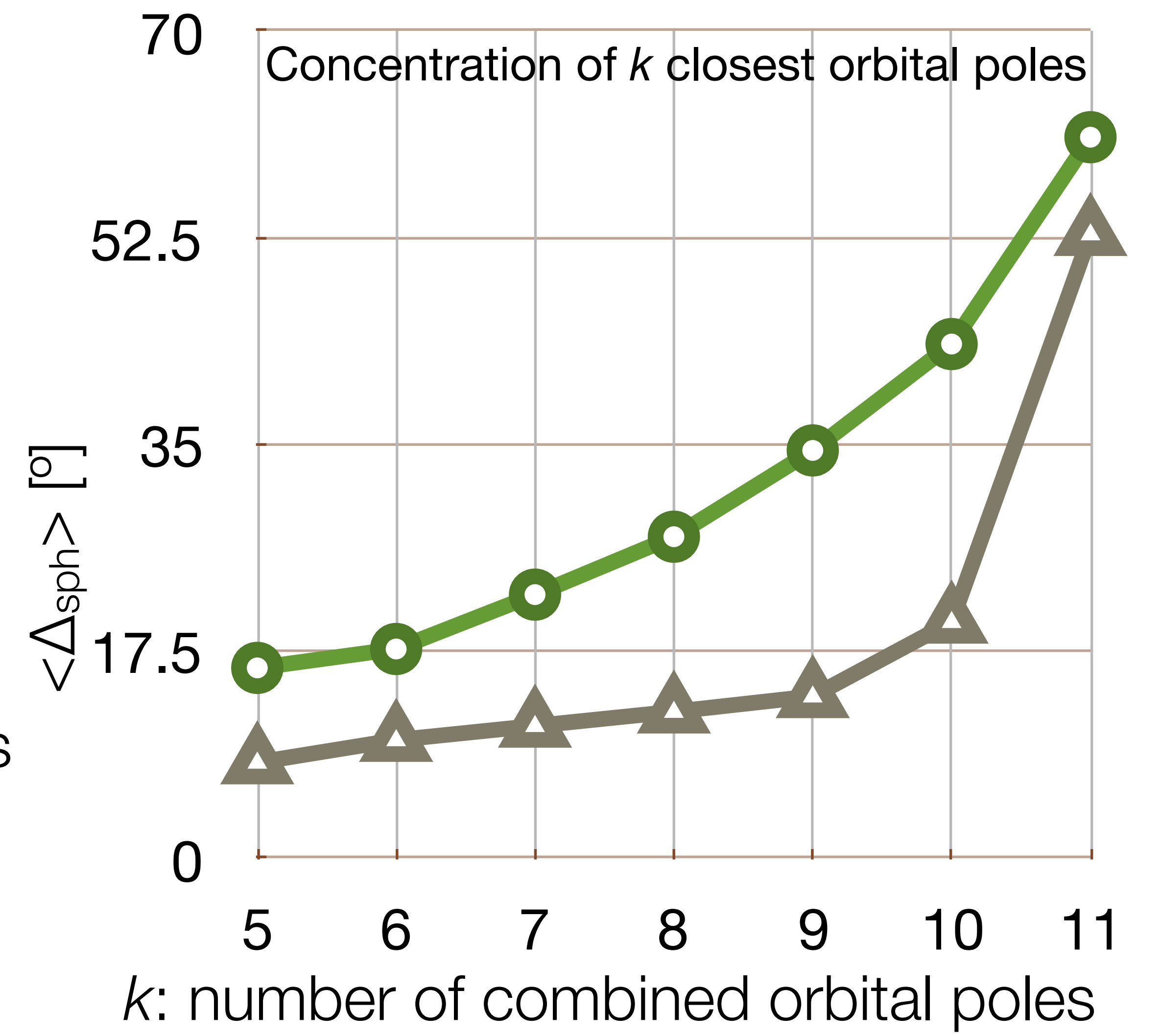
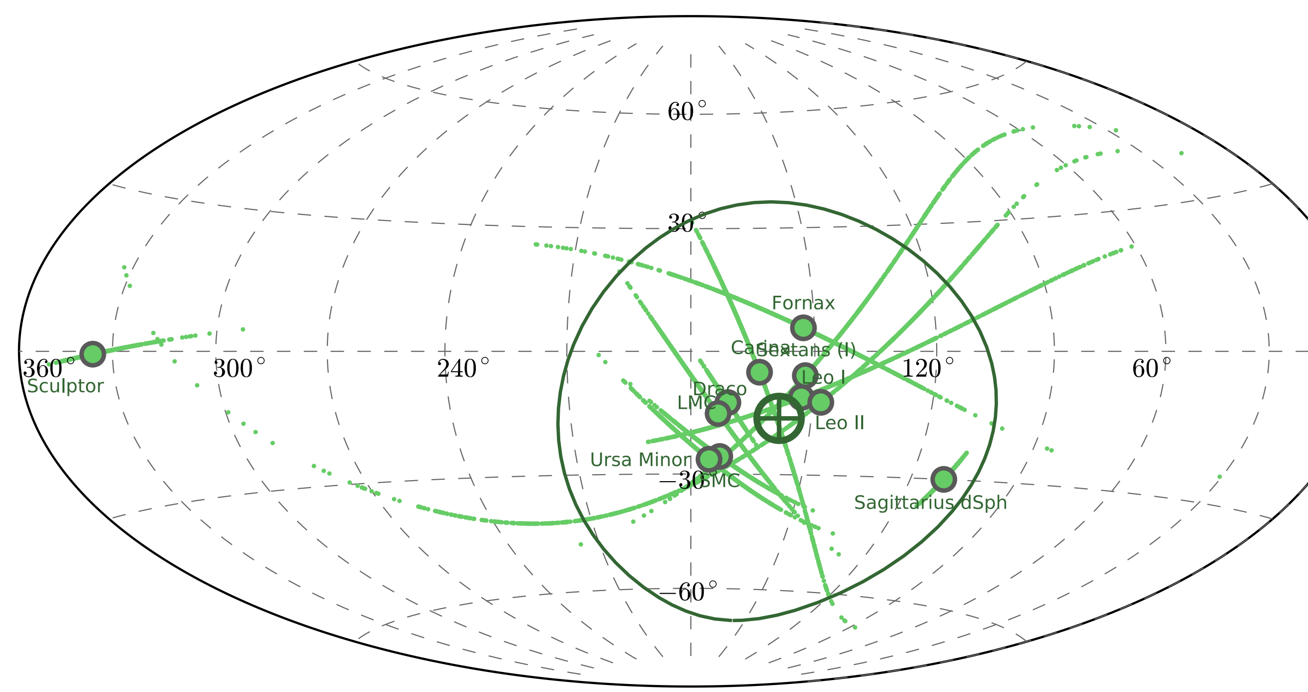
➡ Using Δ_{sph} of all 11 satellites is not a good measure of orbital coherence!





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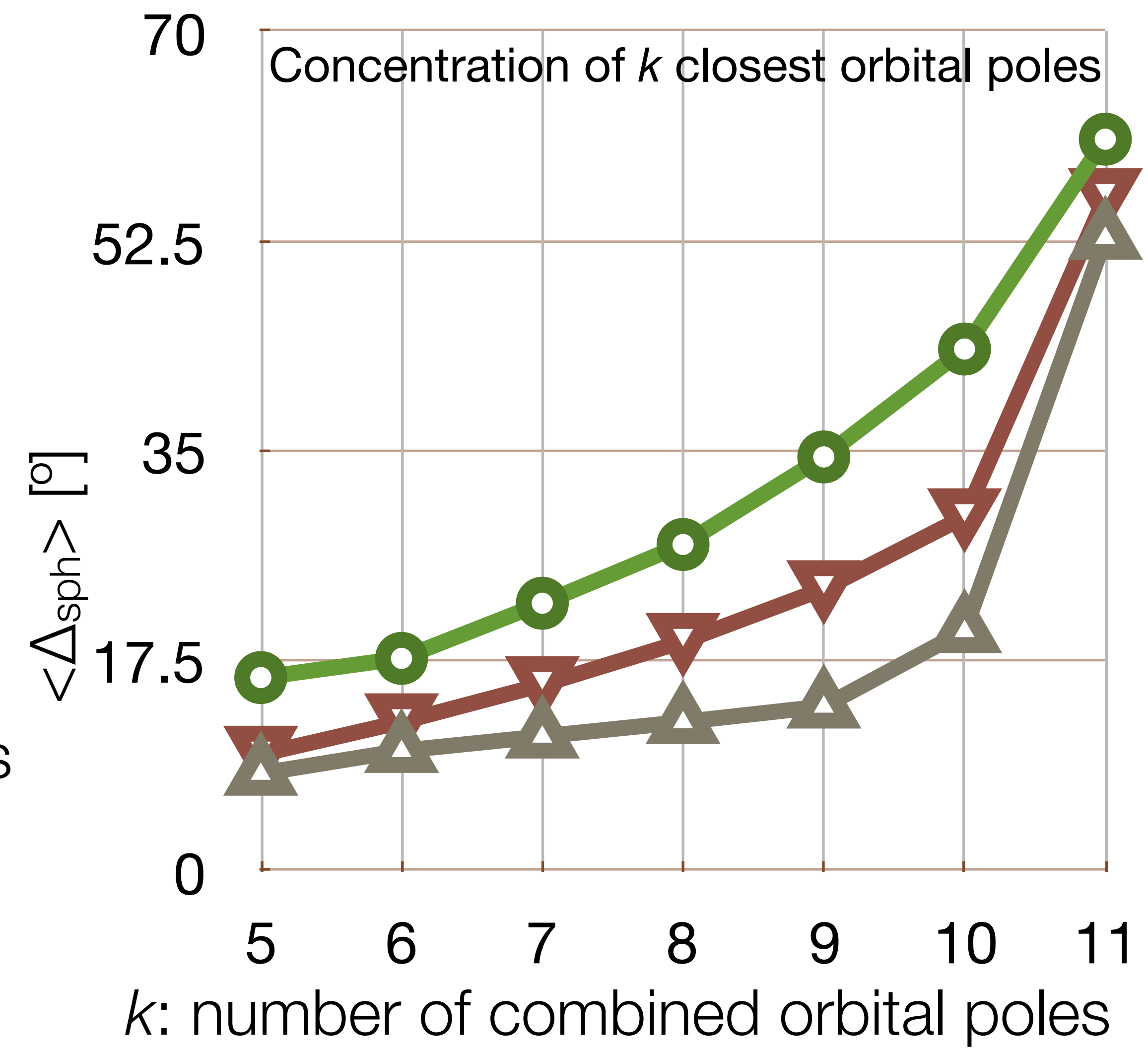
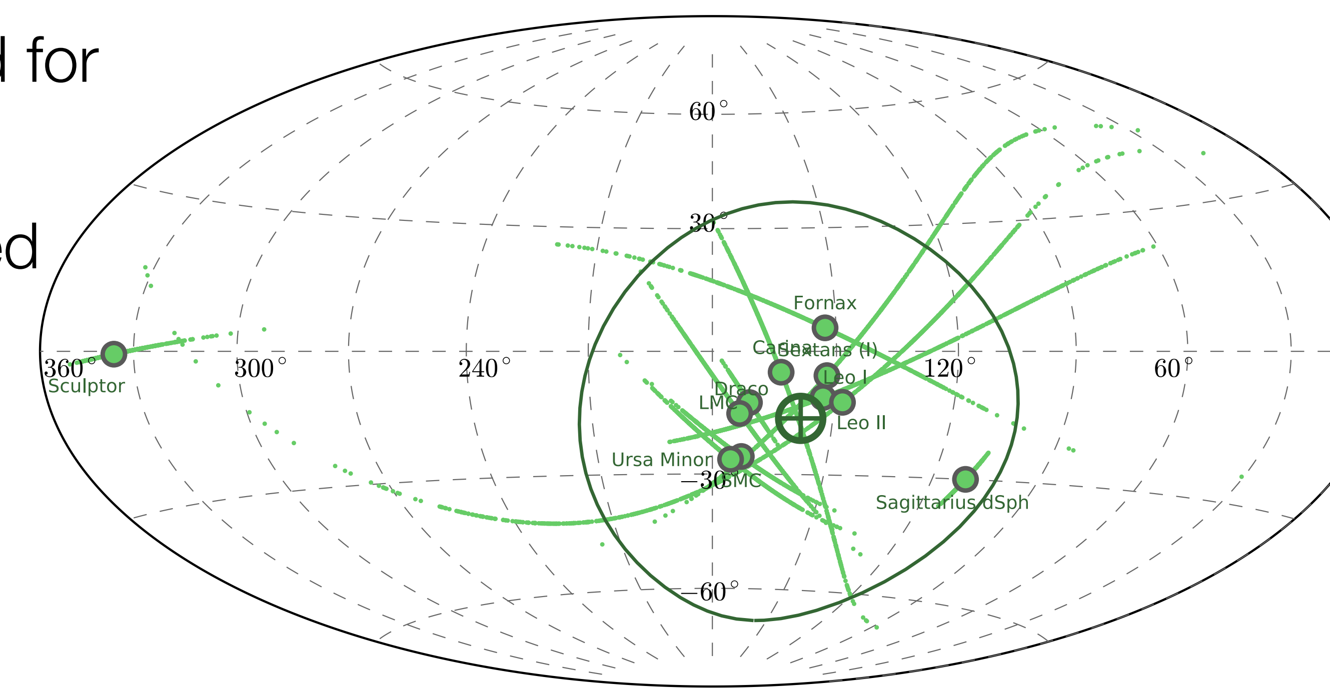
- Now add **random uncertainties** as reported for **observed proper motions (≤0.1 mas/yr)**:
  - ➡ Poles on average much less concentrated





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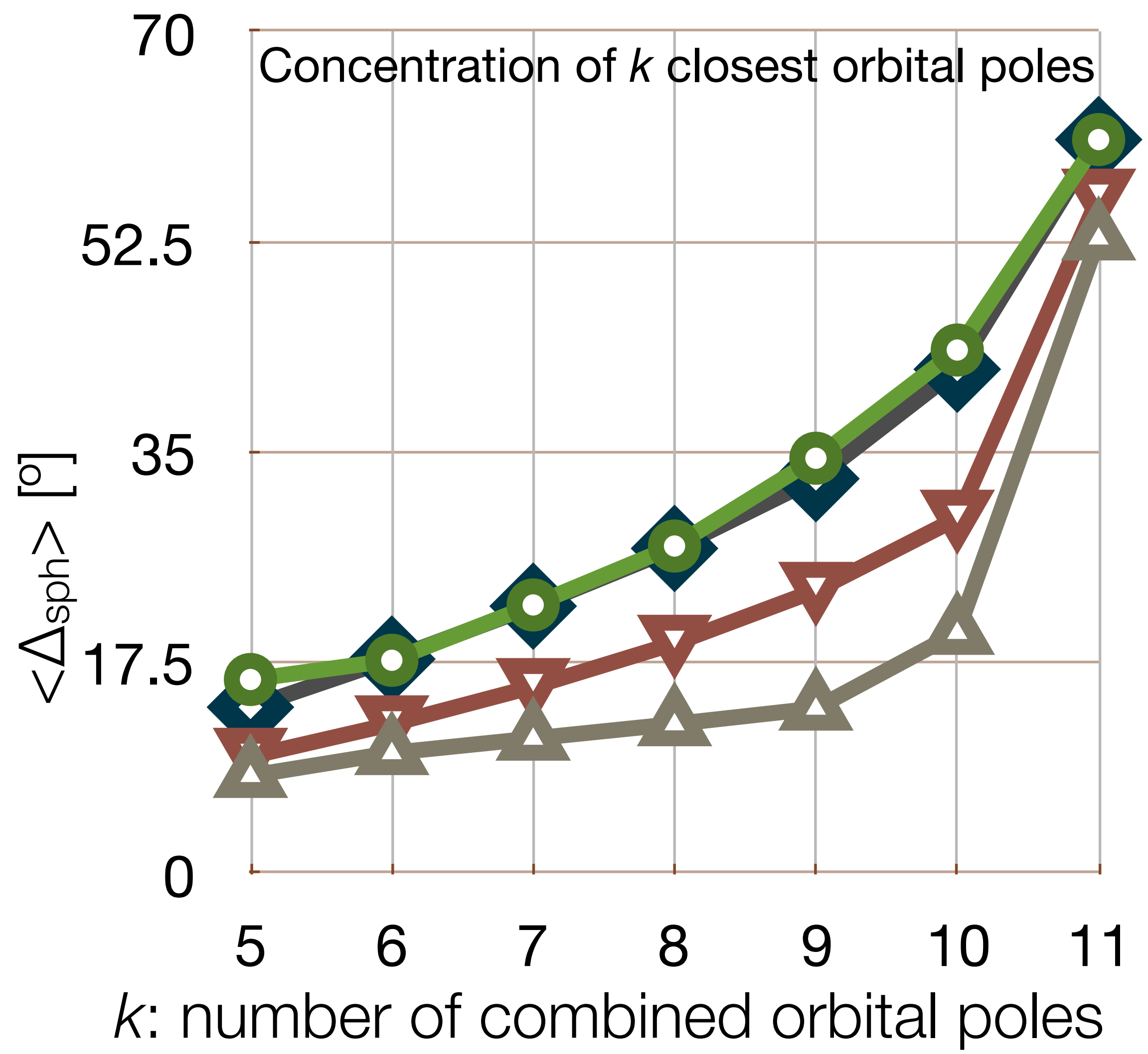
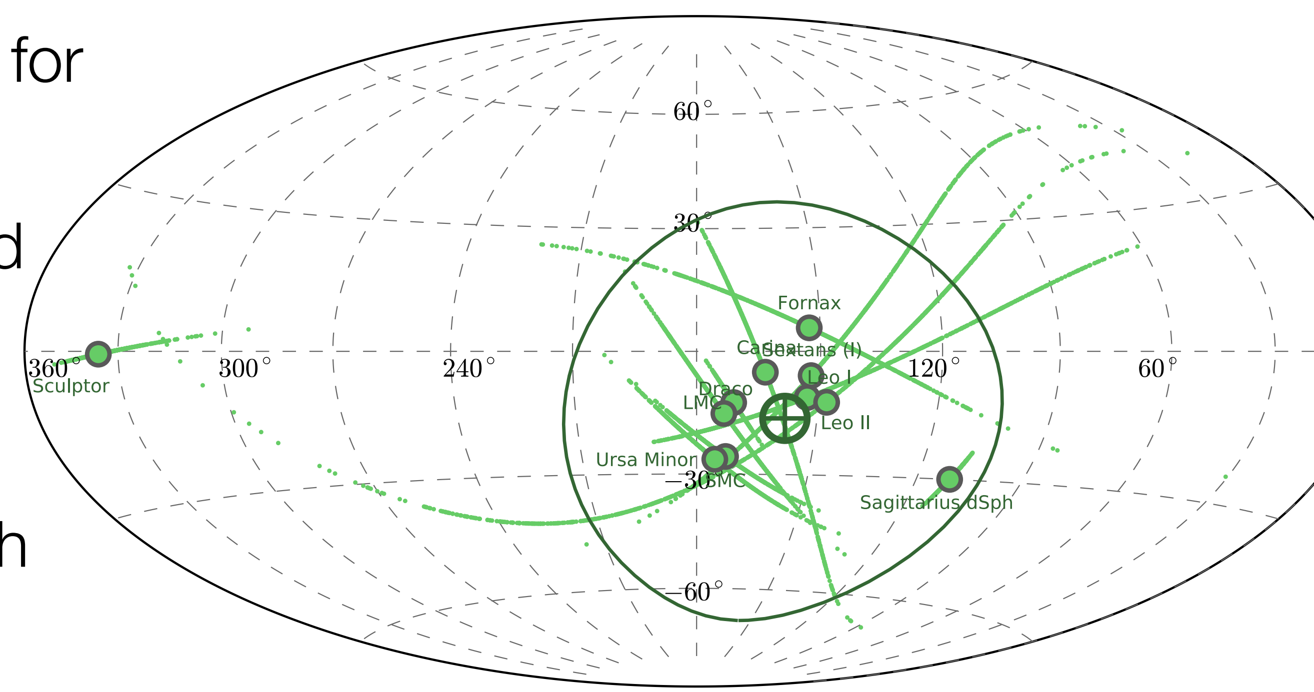
- Now add **random uncertainties** as reported for **observed proper motions (≤0.1 mas/yr)**:
  - ➡ Poles on average much less concentrated
- What if total **PM uncertainties are under-estimated by only 50%**?
  - ➡ Average observed Δ_{sph} are consistent with perfect alignment + uncertainties!



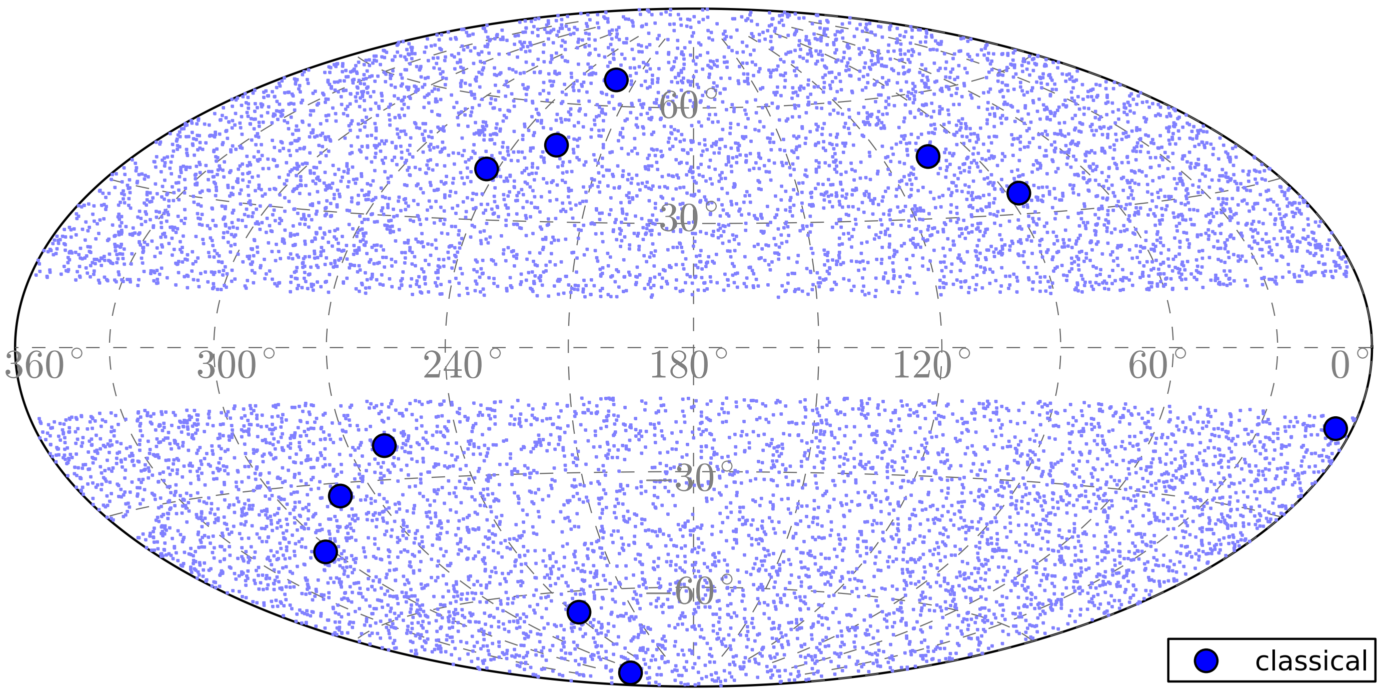


Significance: Could the VPOS be a pure chance alignment? Pawlowski (2016, MNRAS, 456, 448)

Probability to find at least as extreme structure in isotropic distribution

11 classical satellites in narrow plane (Δ_{rms} = 19.6 kpc height)
(consider 12° obscuration by Milky Way)

P = 1.3 x 10^{-2}
(~ 2.5 σ)



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+ of these **8 co-orbit** (Δ_{sph} = 27.2° orbital pole concentration)

$P = 0.7 \times 10^{-4}$
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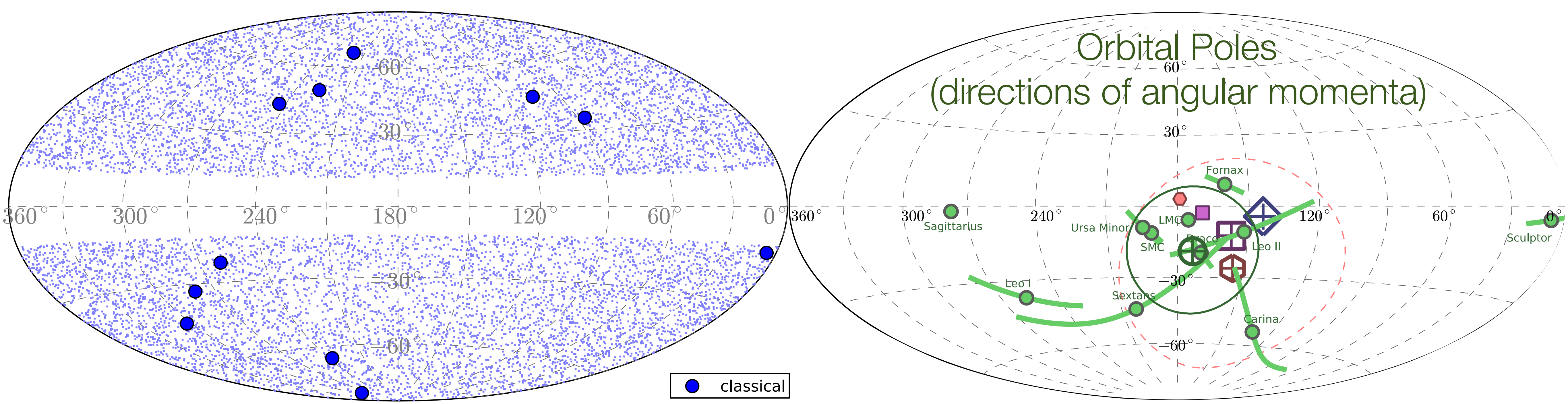

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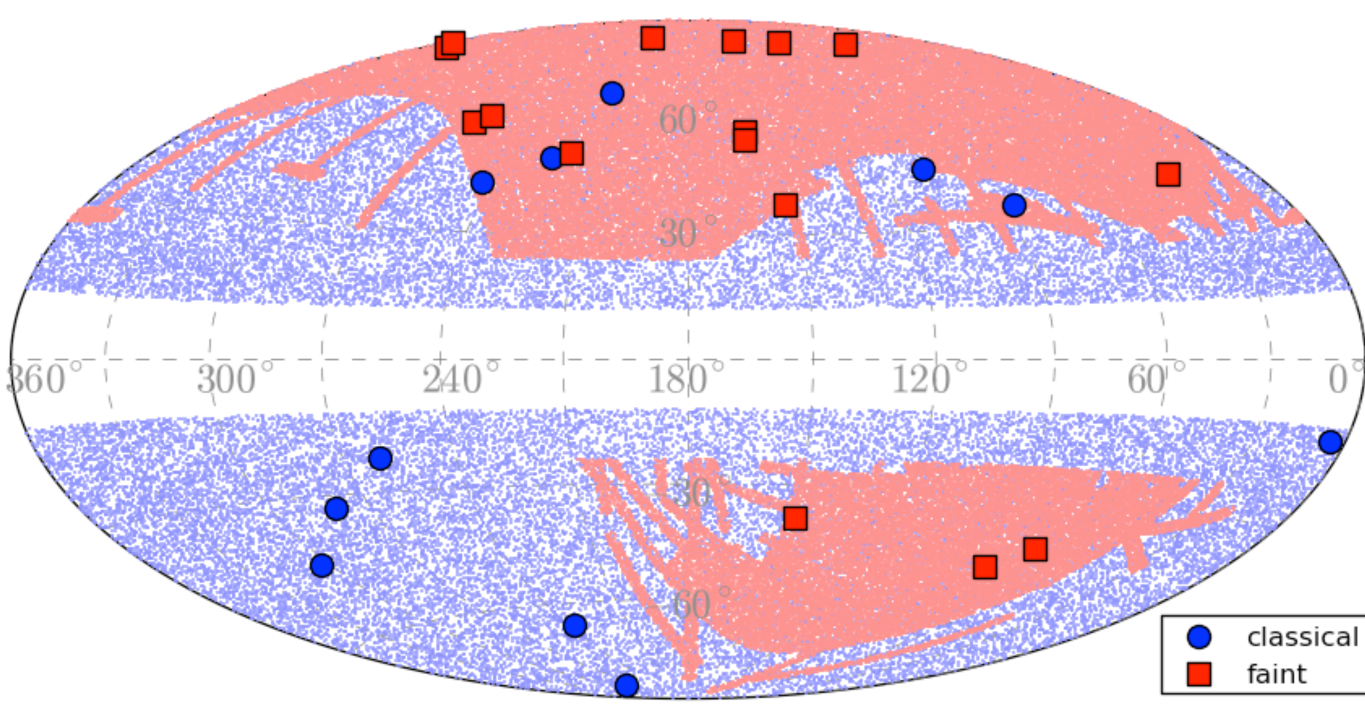
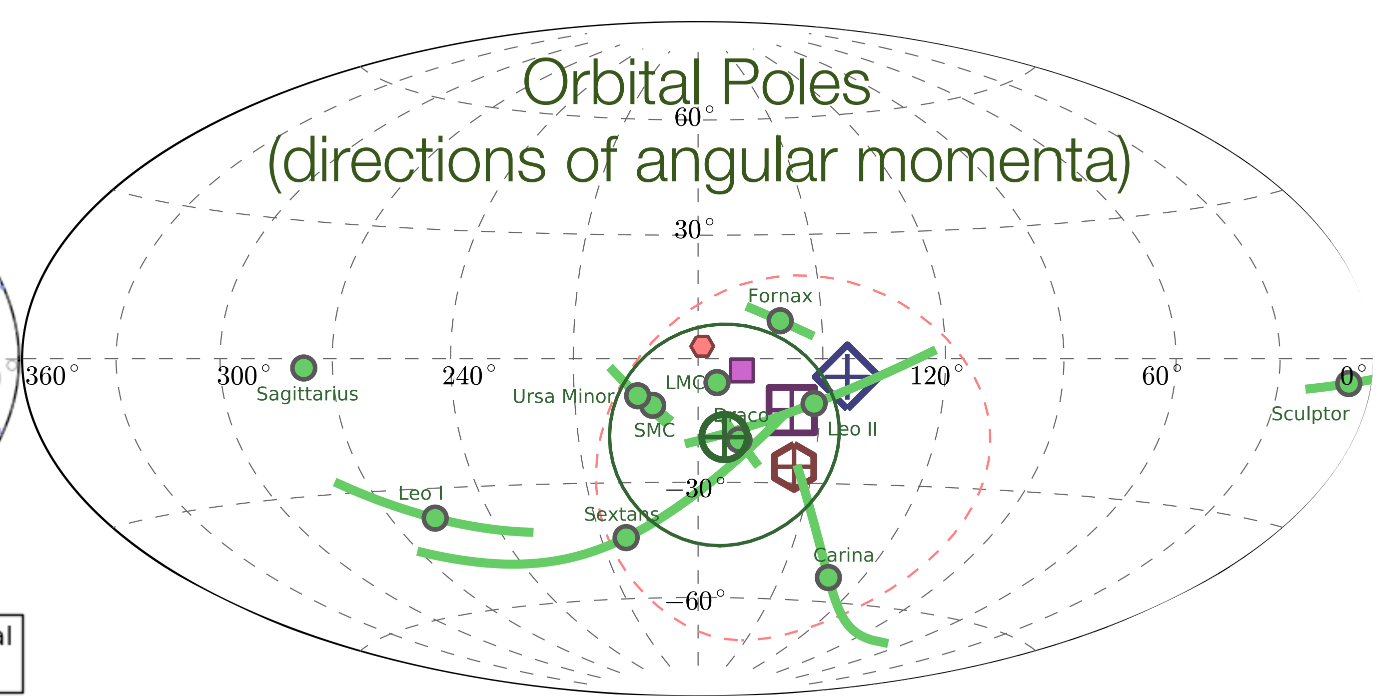
+ of these **8 co-orbit** (Δ_{sph} = 27.2° orbital pole concentration)

$P = 0.7 \times 10^{-4}$ (~ 4.0 σ)

+ **16 SDSS satellites** define narrow plane (Δ_{rms} = 25.9 kpc)
aligned with classical satellites (22°)
(consider exact SDSS DR10 footprint and 2x MW obscuration)

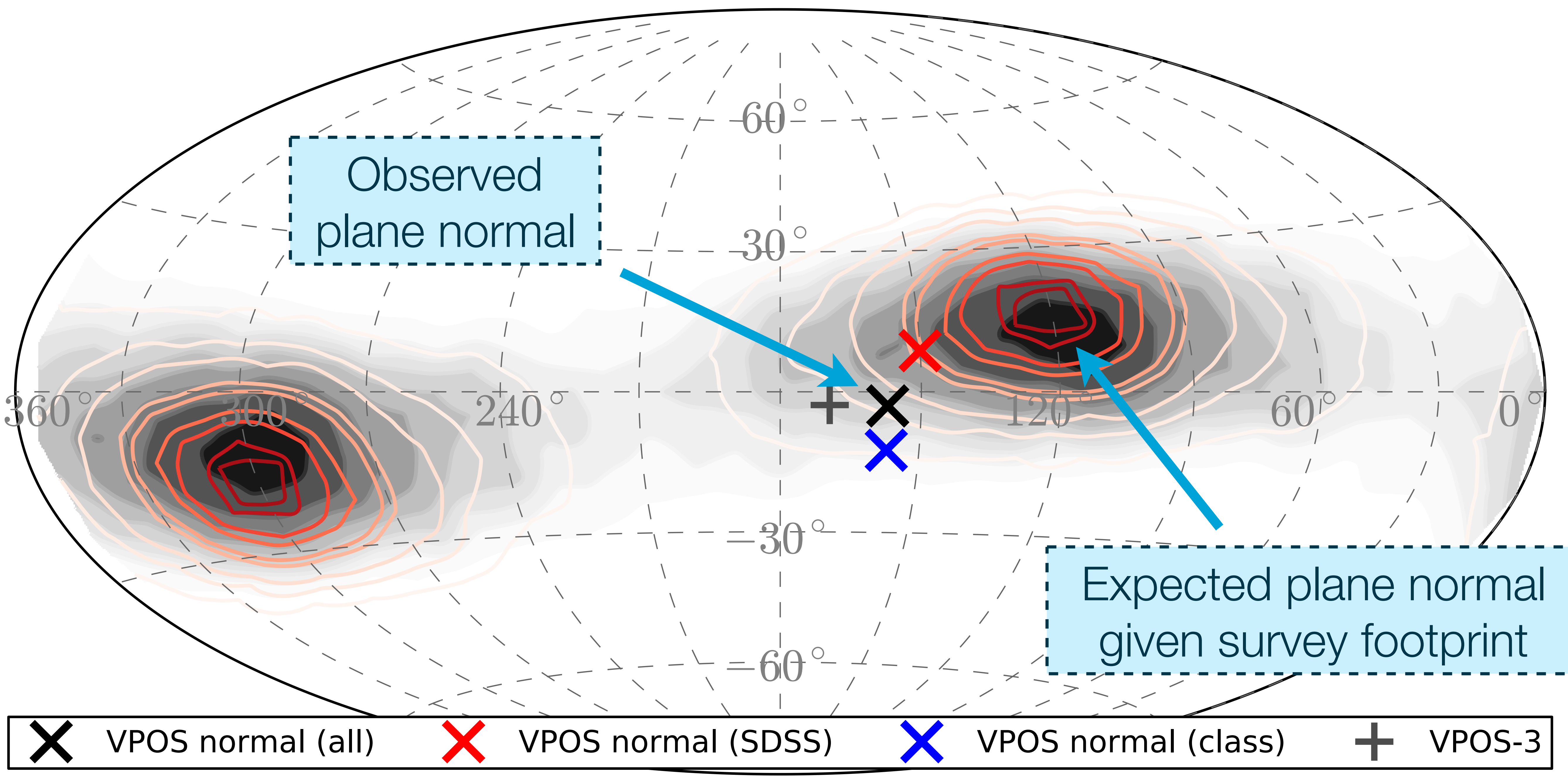
$P = 3.7 \times 10^{-7}$ (~ 5.1 σ)





SDSS footprint biases away from alignment with plane fitted to 11 classical sats. Pawlowski (MNRAS, 456, 448)

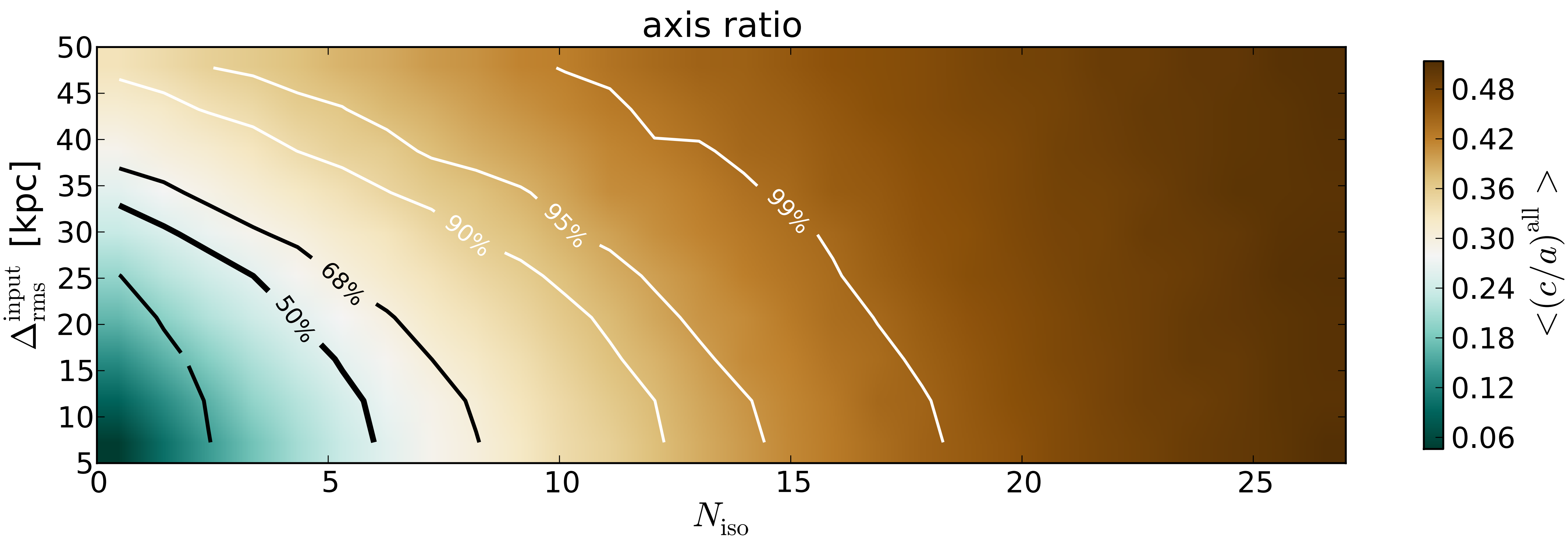
Distribution of normal vectors for $N_{\rm iso} = 27$ (isotropic only)



How many MW satellites can be part of an isotropic distribution? Pawlowski (2016, MNRAS, 456, 448)

Set up artificial MW satellite distributions following SDSS survey footprint:

- Preserve Galactocentric distances.
- $N_{\rm iso}$: 0 to 27 satellites in isotropic distribution.
- The others in planar, polar distribution with input rms height of 5 to 50 kpc.



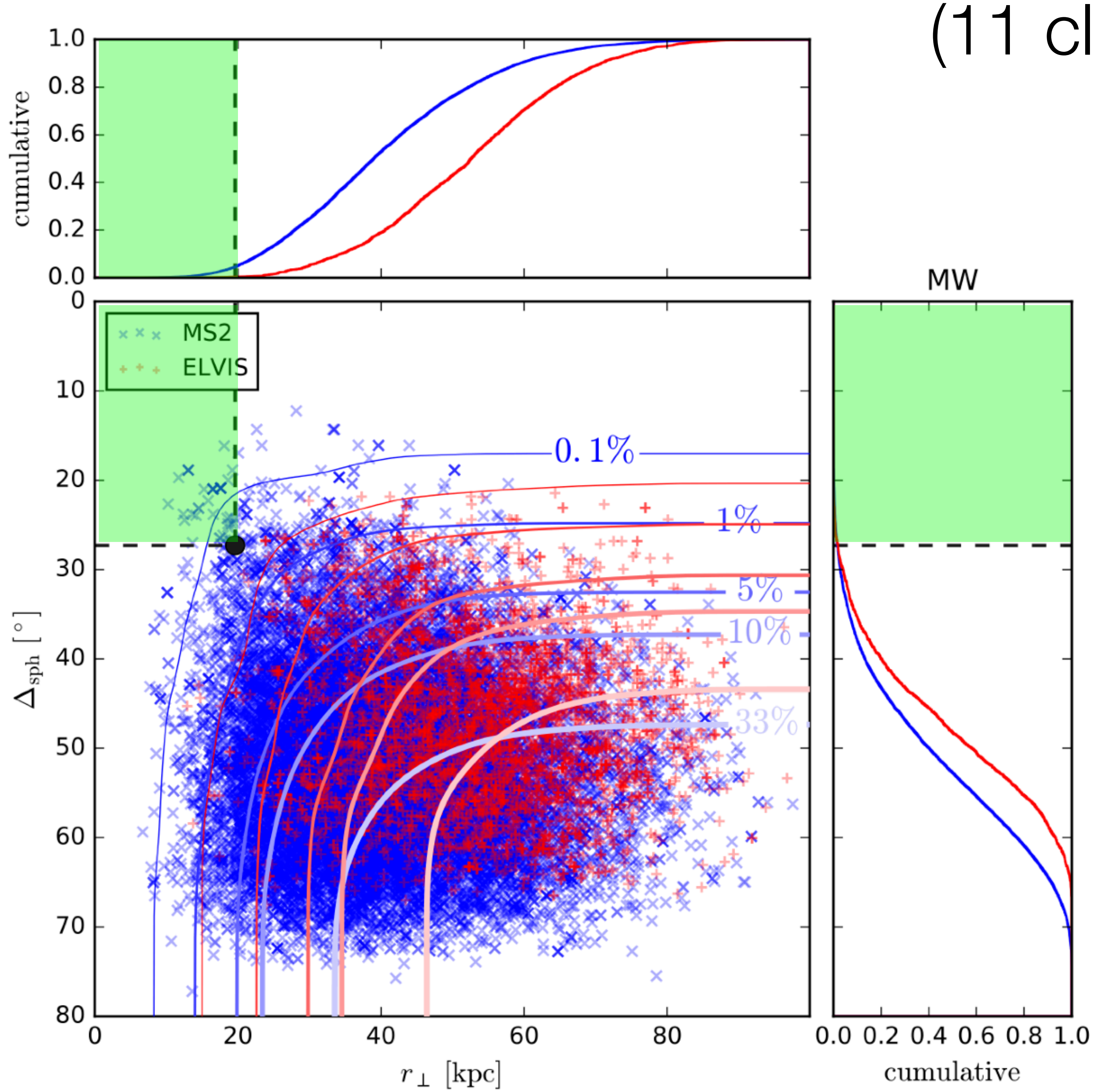
➡ Expect 1 to 6 of the considered satellites to not be part of satellite plane.

➡ > 50% in isotropic distribution excluded at ≥ 95%.

How does the VPOS compare to ΛCDM expectations?

(11 classical satellites only!)

Measure of kinematic coherence



Measure of plane width

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

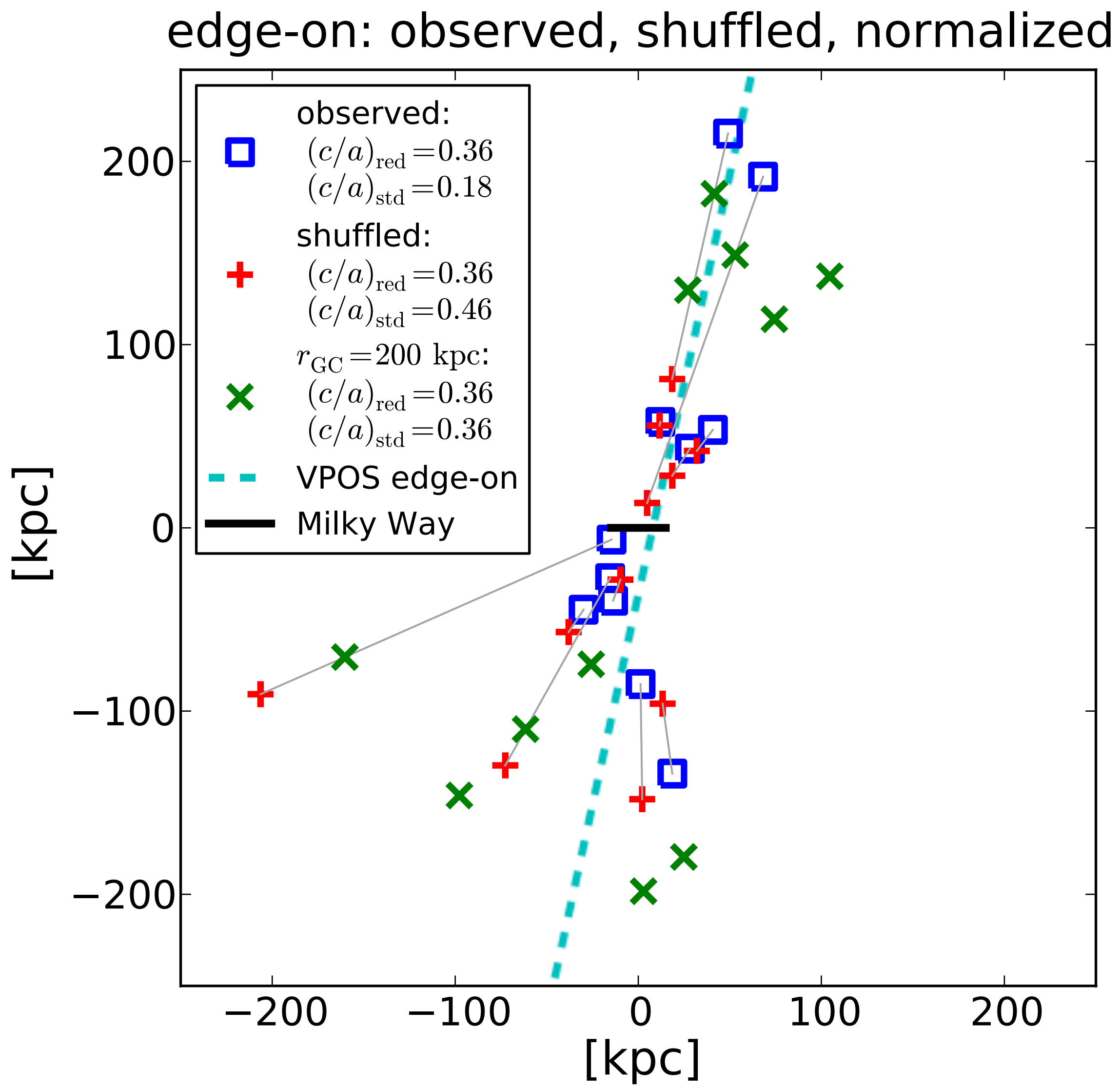
Pawlowski (2018, MPLA, 33, 1830004)

Do Baryons help?

Pawlowski et al. (2015, ApJ, 815, 19), Pawlowski et al. (2017, AN, 338, 854)

Sawala et al. (2015): APOSTLE hydro simulations solve small-scale problems incl. satellite planes.

- Only measure flattening of satellite system projected onto unit sphere:
  - ➡ Does not test for planar alignment.



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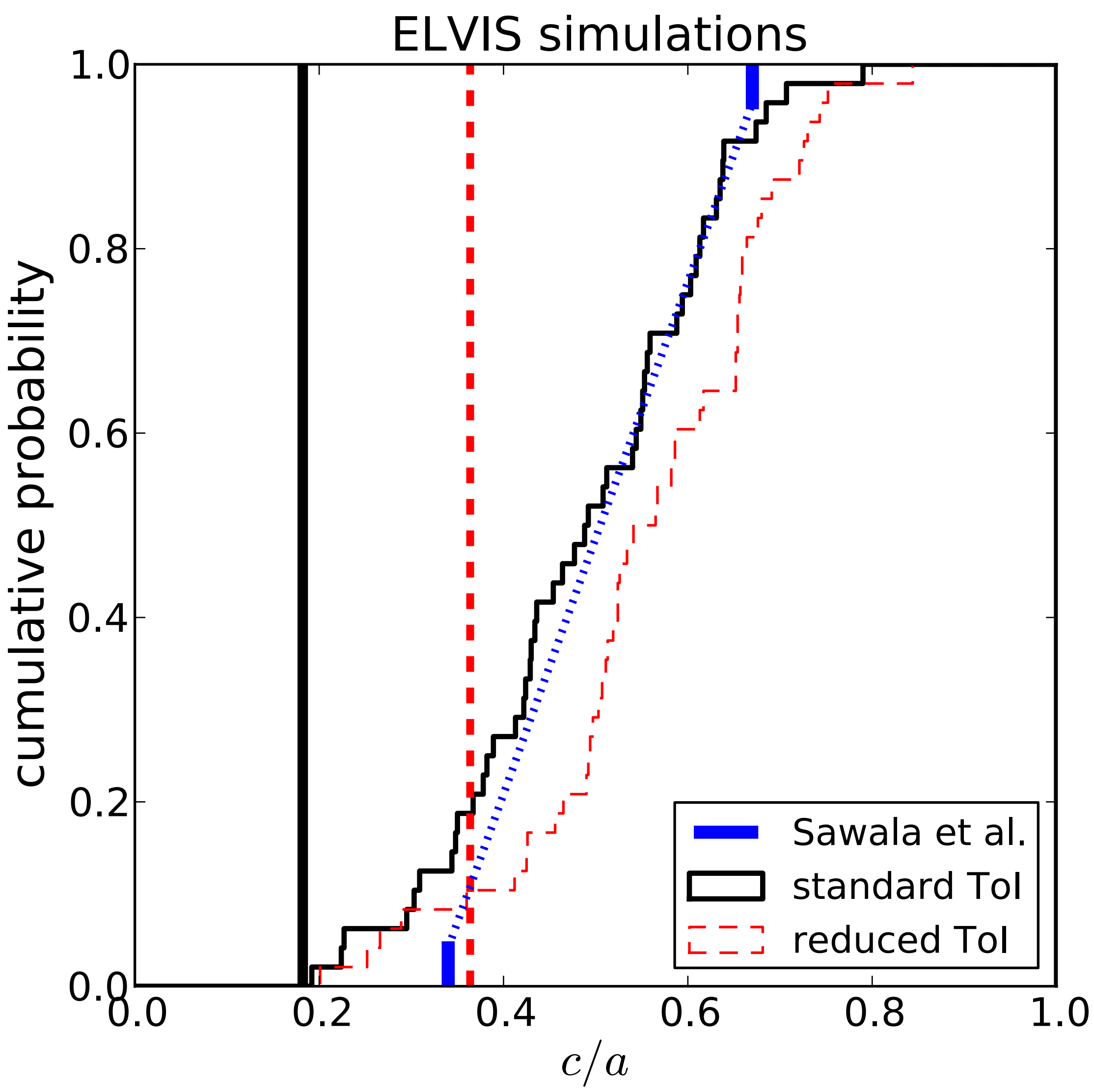

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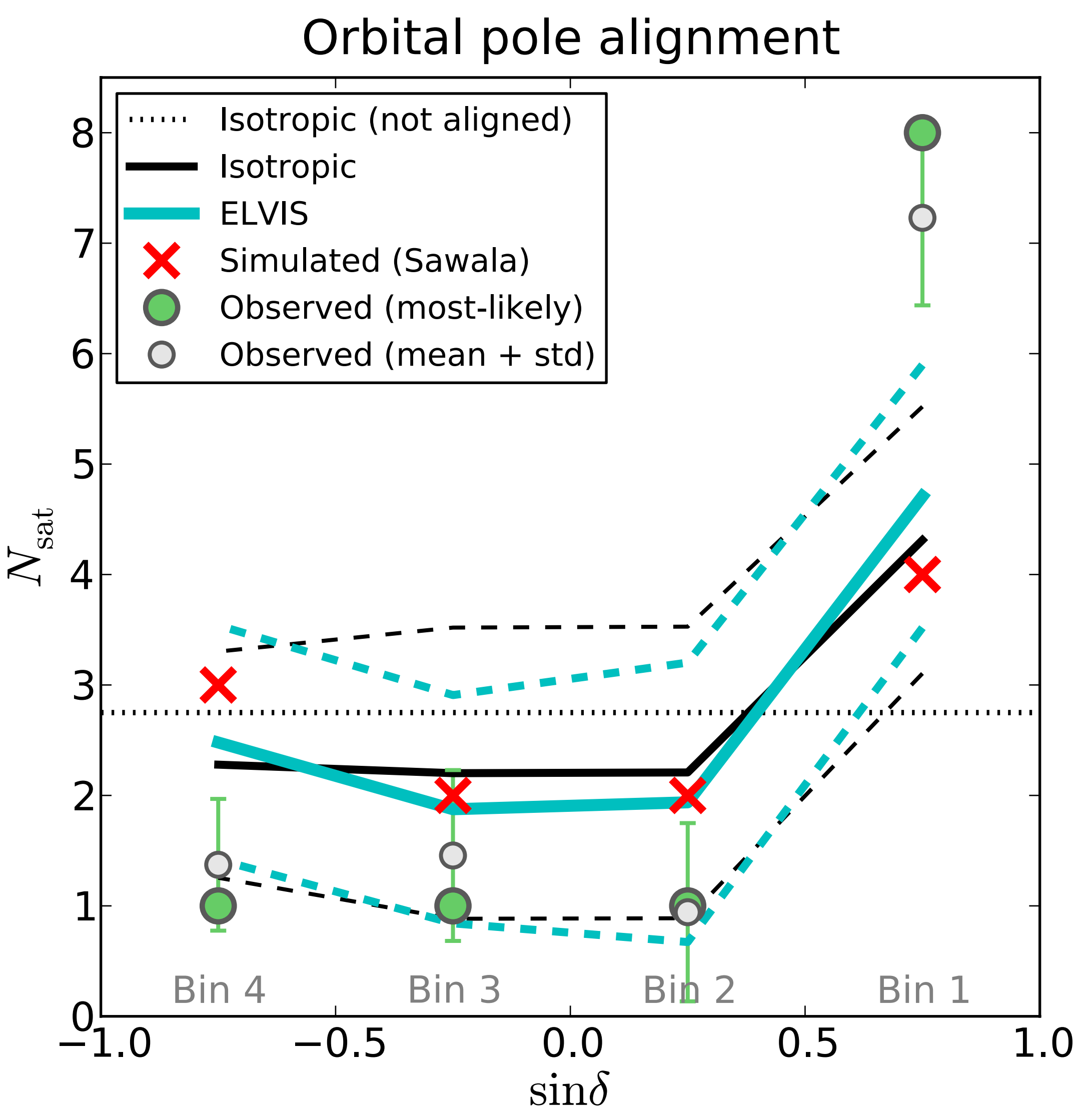
- Do not test coherence of orbits and alignment with best-fit plane.
    - ➡ Their orbital pole distribution is consistent with isotropic one.



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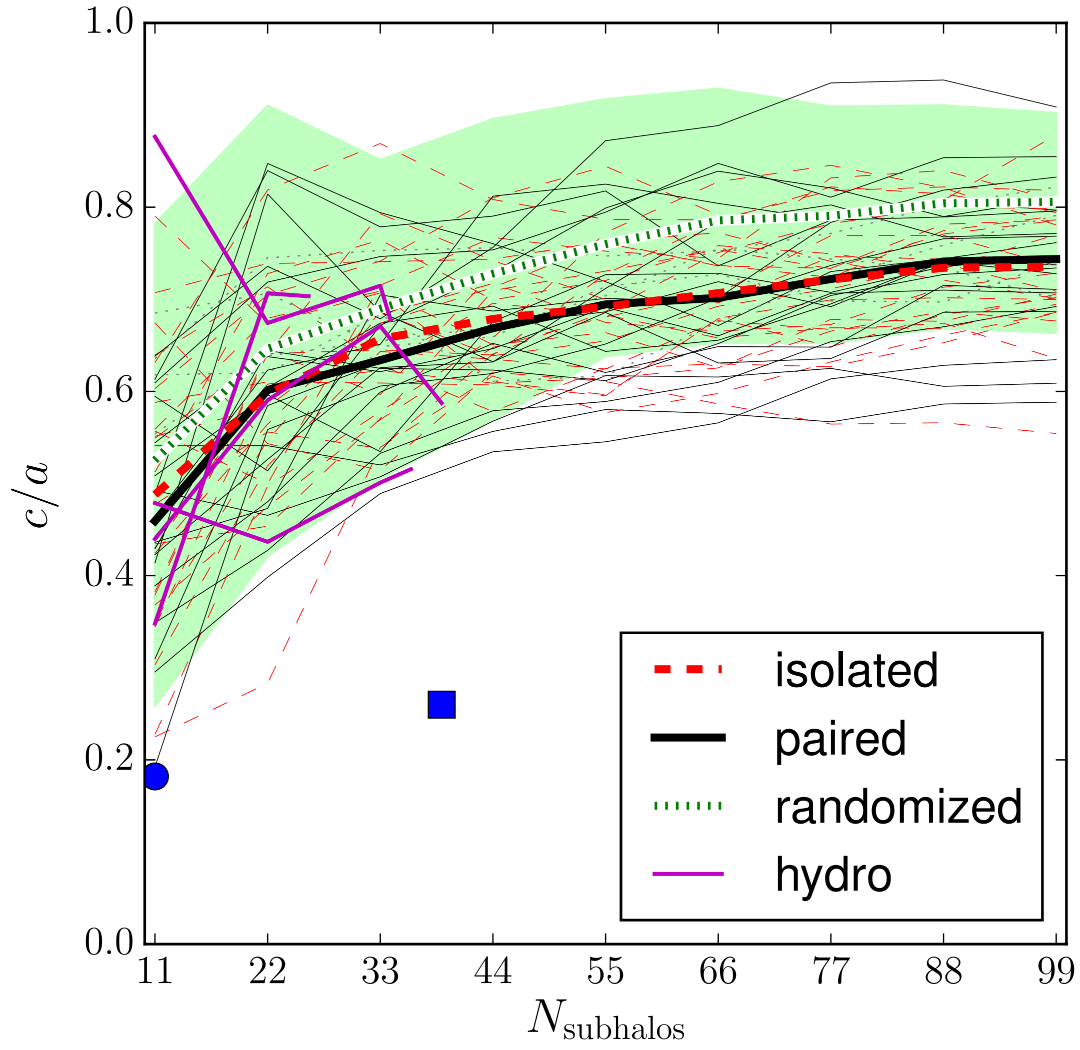
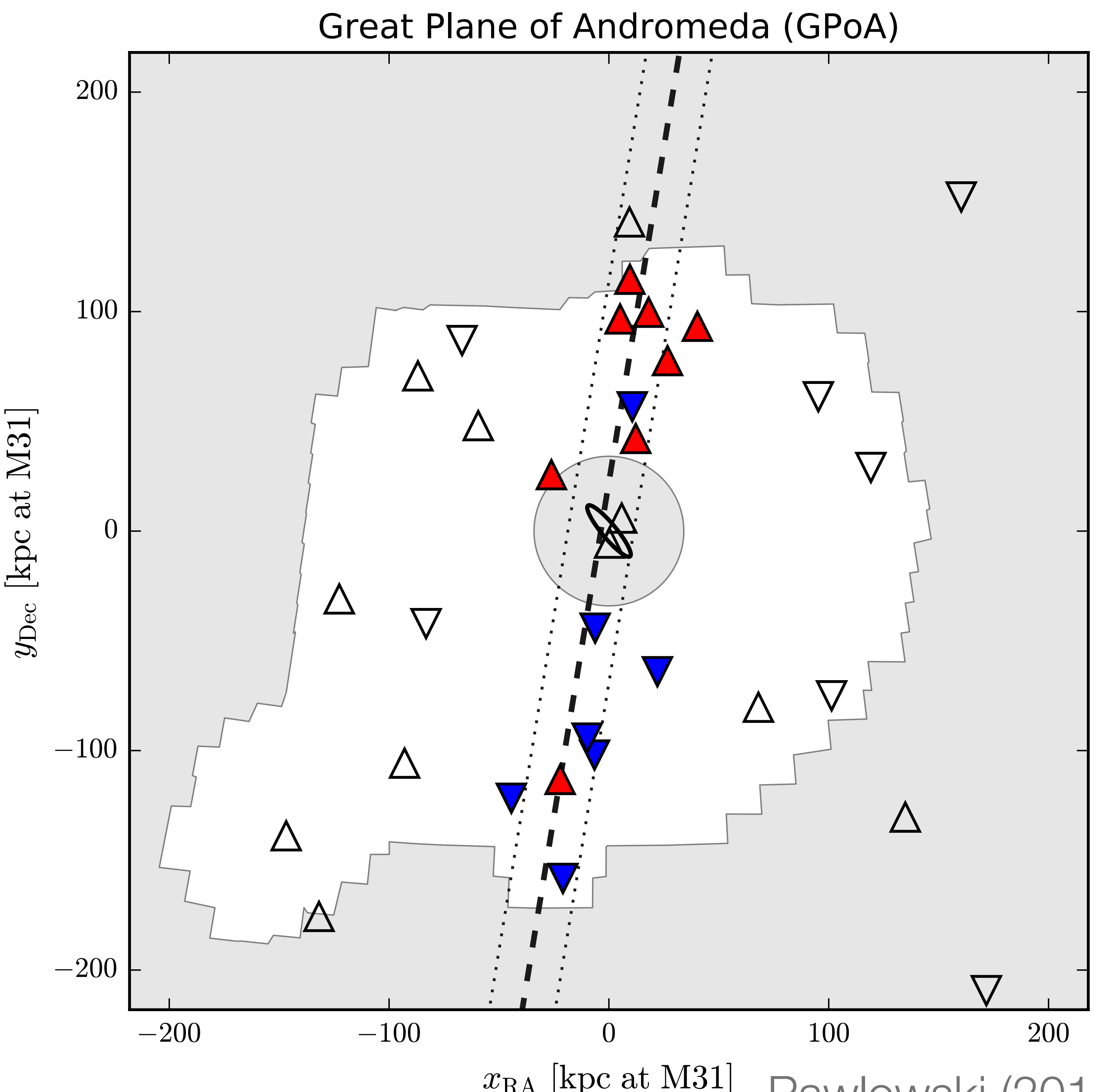
    - ➡ Does not test for planar alignment.
    - ➡ Resulting flattening same as that for ELVIS DM-only simulations.
- Do not test coherence of orbits and alignment with best-fit plane.
    - ➡ Their orbital pole distribution is consistent with isotropic one.
- Satellite systems in hydro-simulations (Ahmed et al. 17) not more flattened than in DMO-simulations.



No indication that baryons help address satellite planes problem.

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



Pawlowski (2018, MPLA, 33, 1830004)

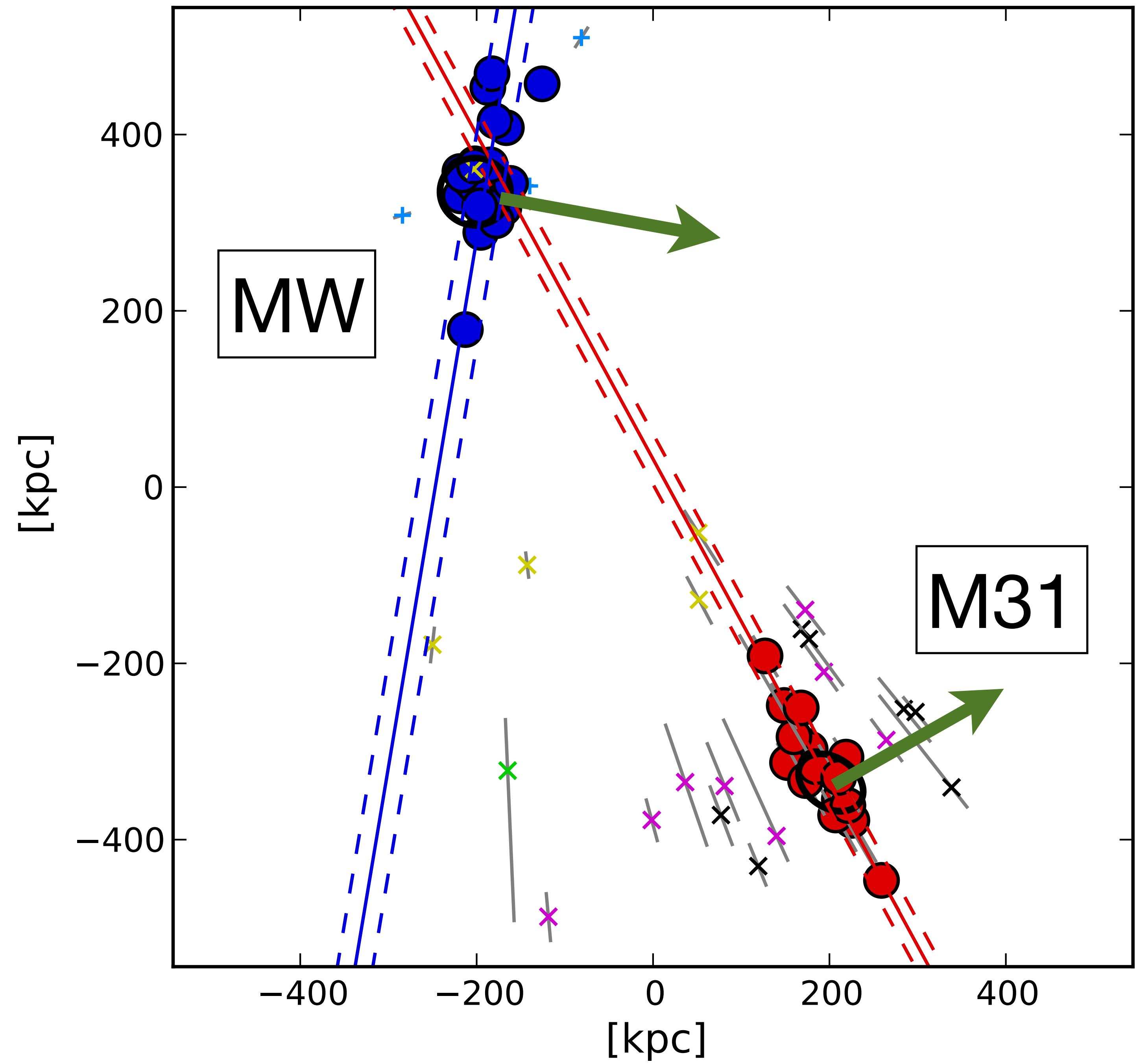
Edge-on view of LG satellite planes from MW north

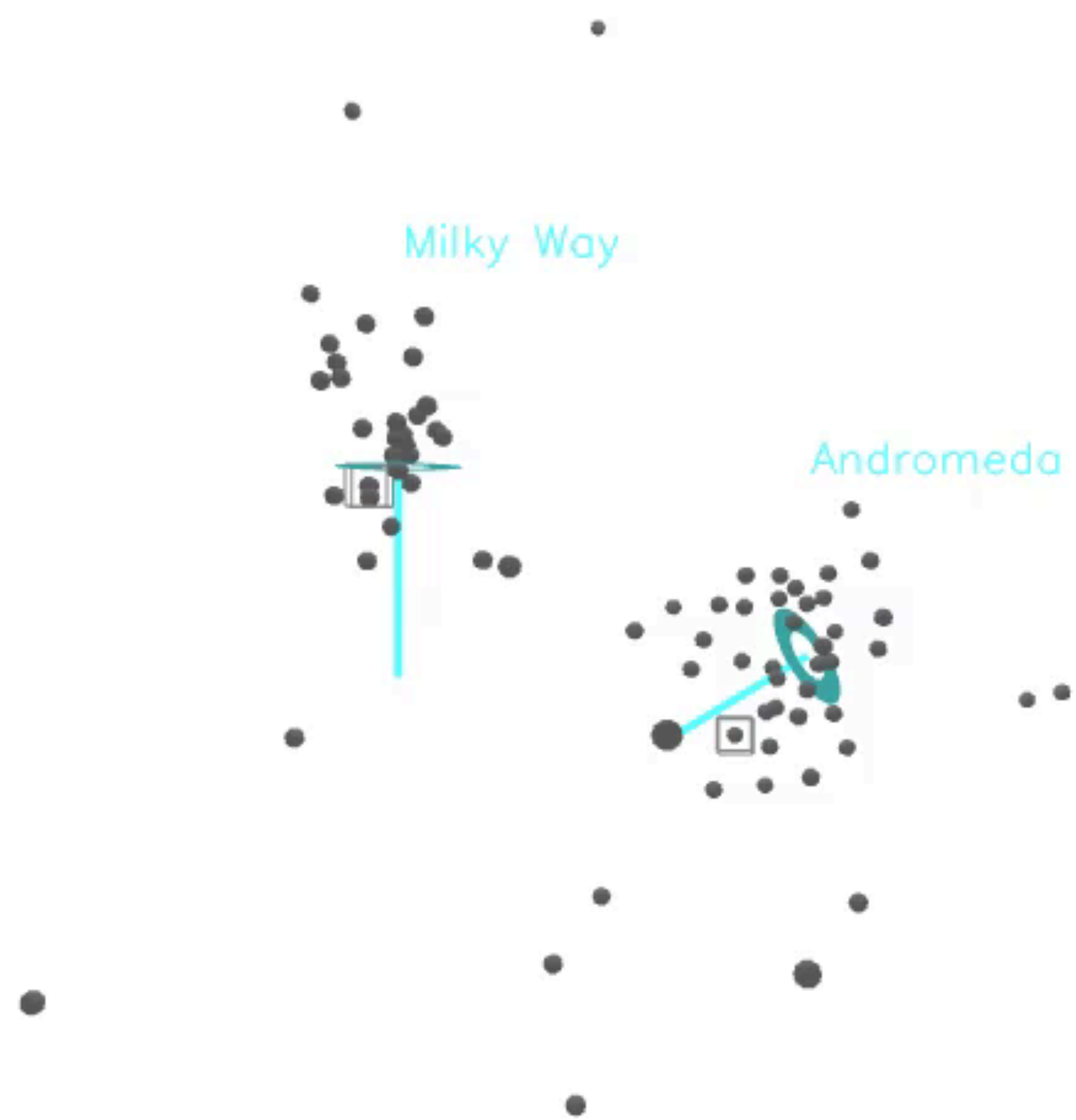
Pawlowski, Kroupa & Jerjen (2013, MNRAS, 435, 1928)

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

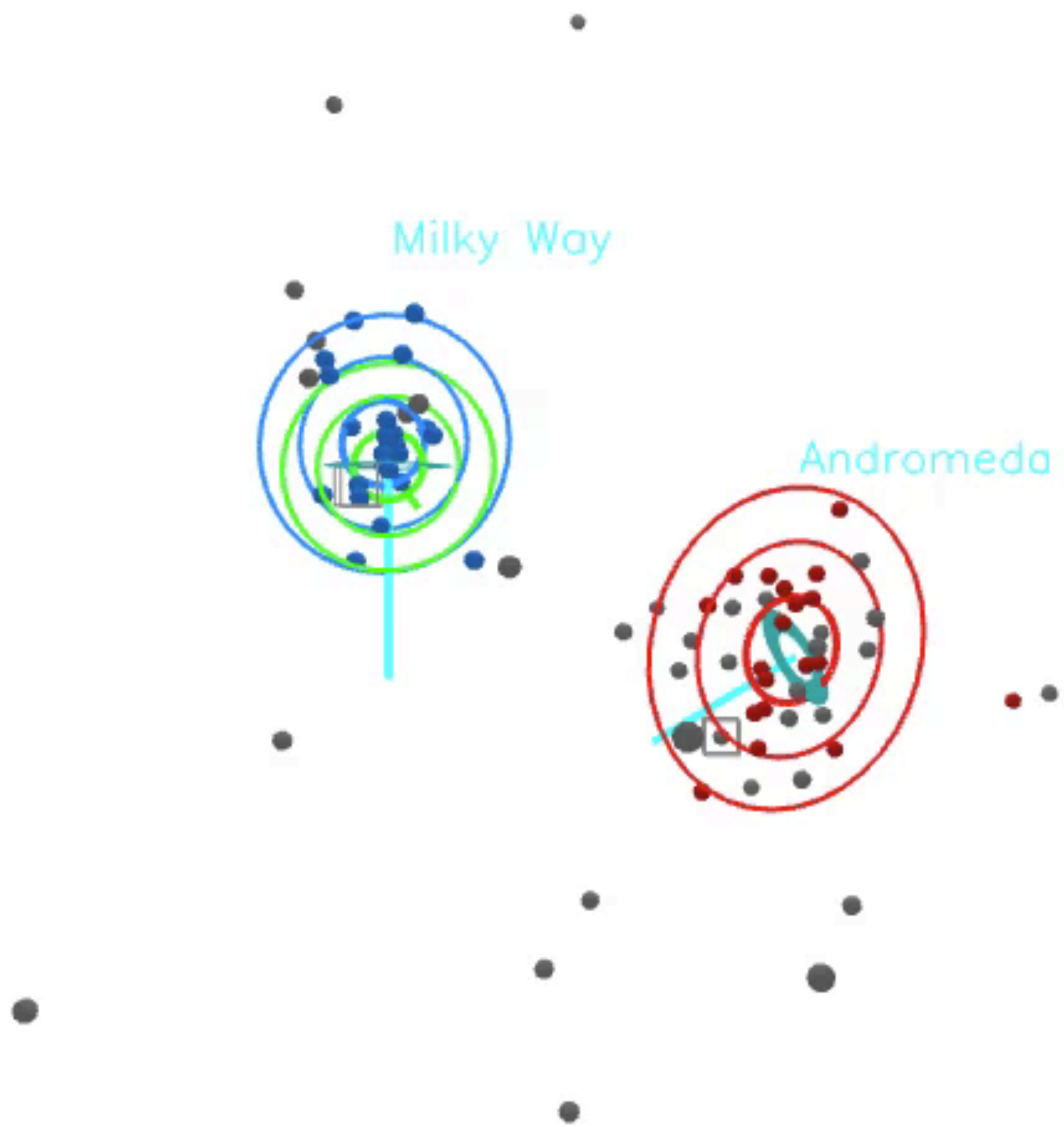
- Similar heights:
  VPOS: 20-30 kpc
  GPoA: 14 kpc
- Similar diameters: 400 kpc
- Similar **spin directions**

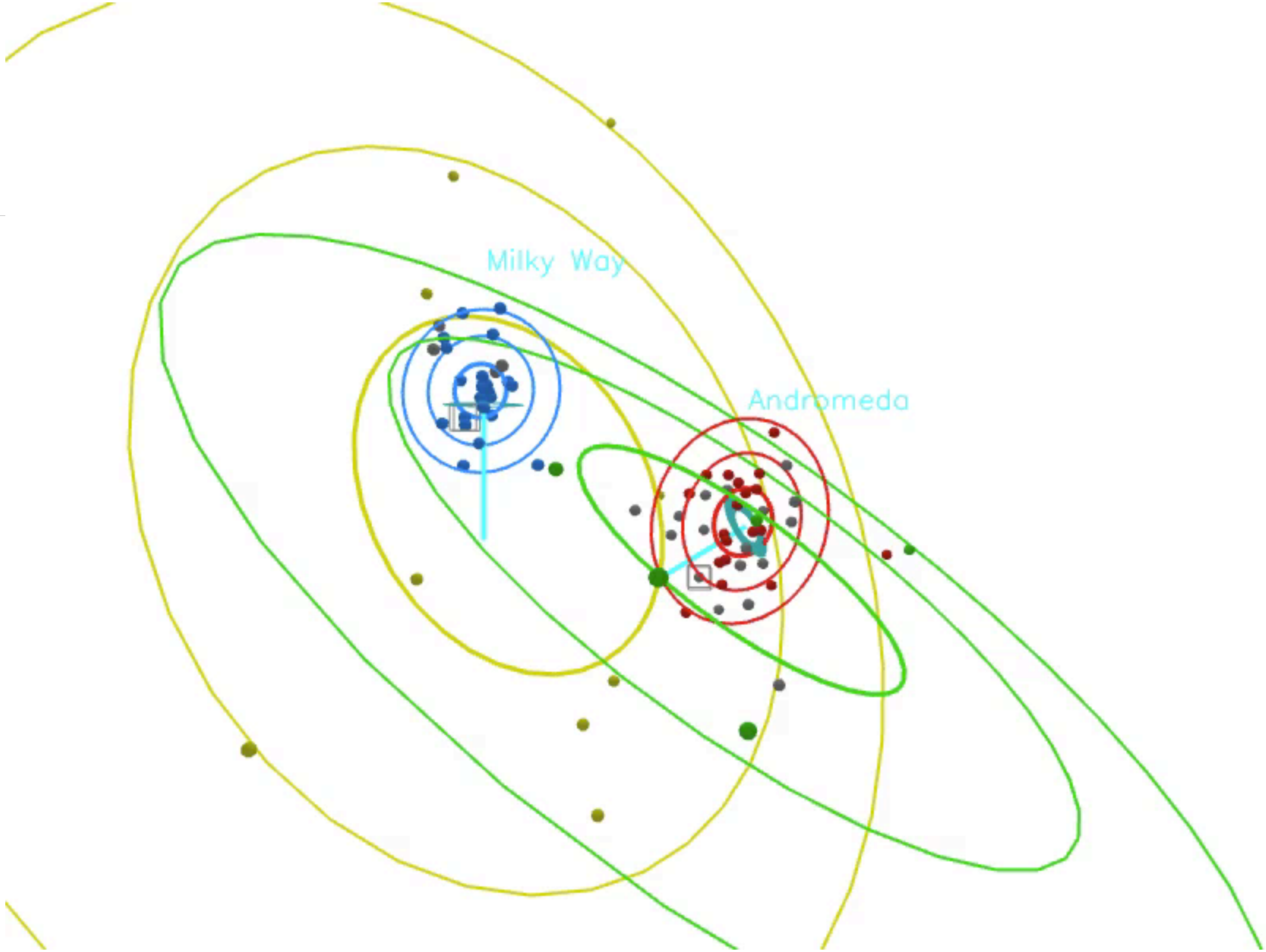
- Additional alignments:
  VPOS: YH GCs, 50% streams
  GPoA: Giant Stream, NW-S1





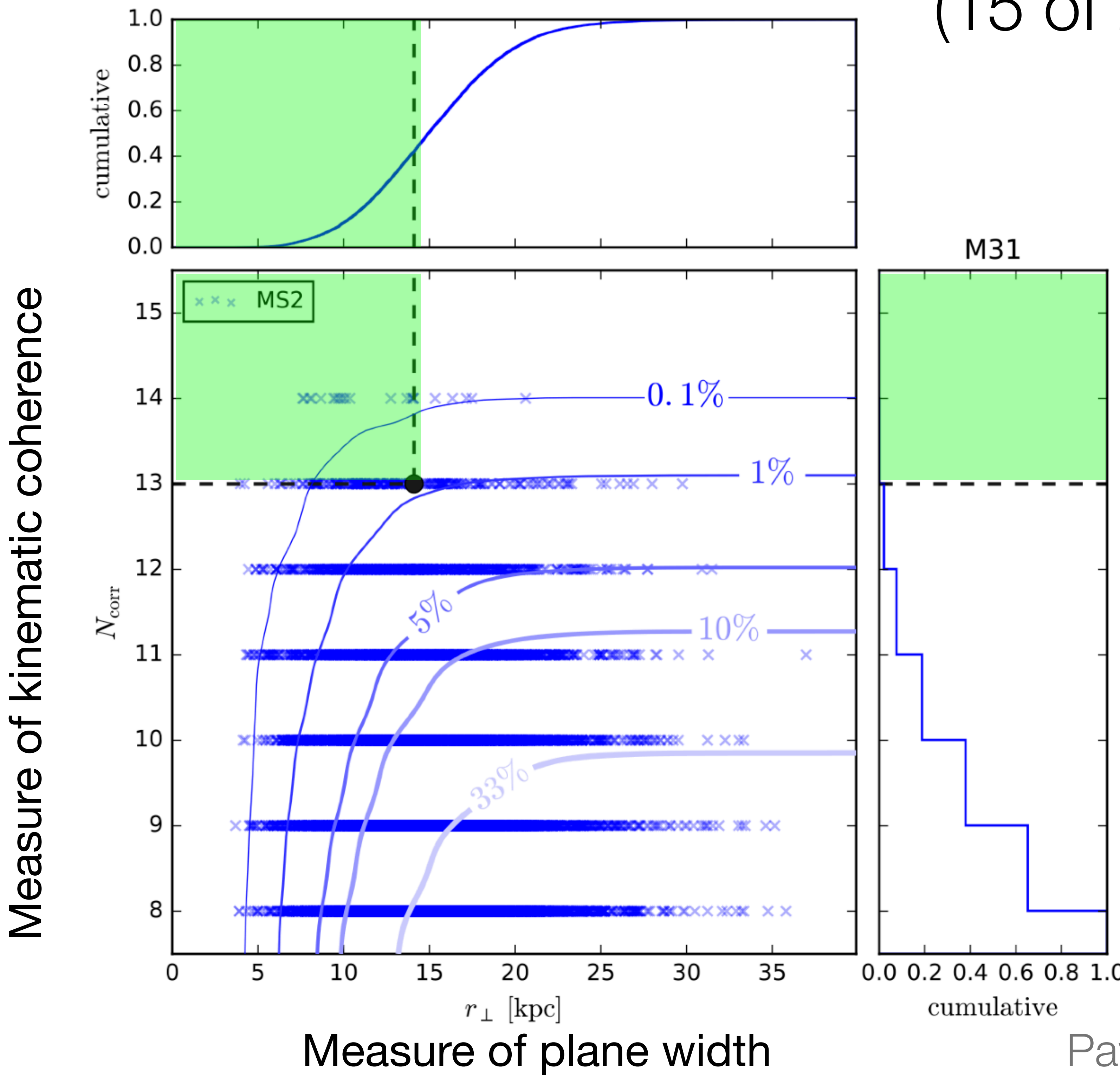
Milky Way
Andromeda


Milky Way
Andromeda


Milky Way
Andromeda

The GPoA is also in tension with ΛCDM expectations!

(15 of 27 satellites form plane)



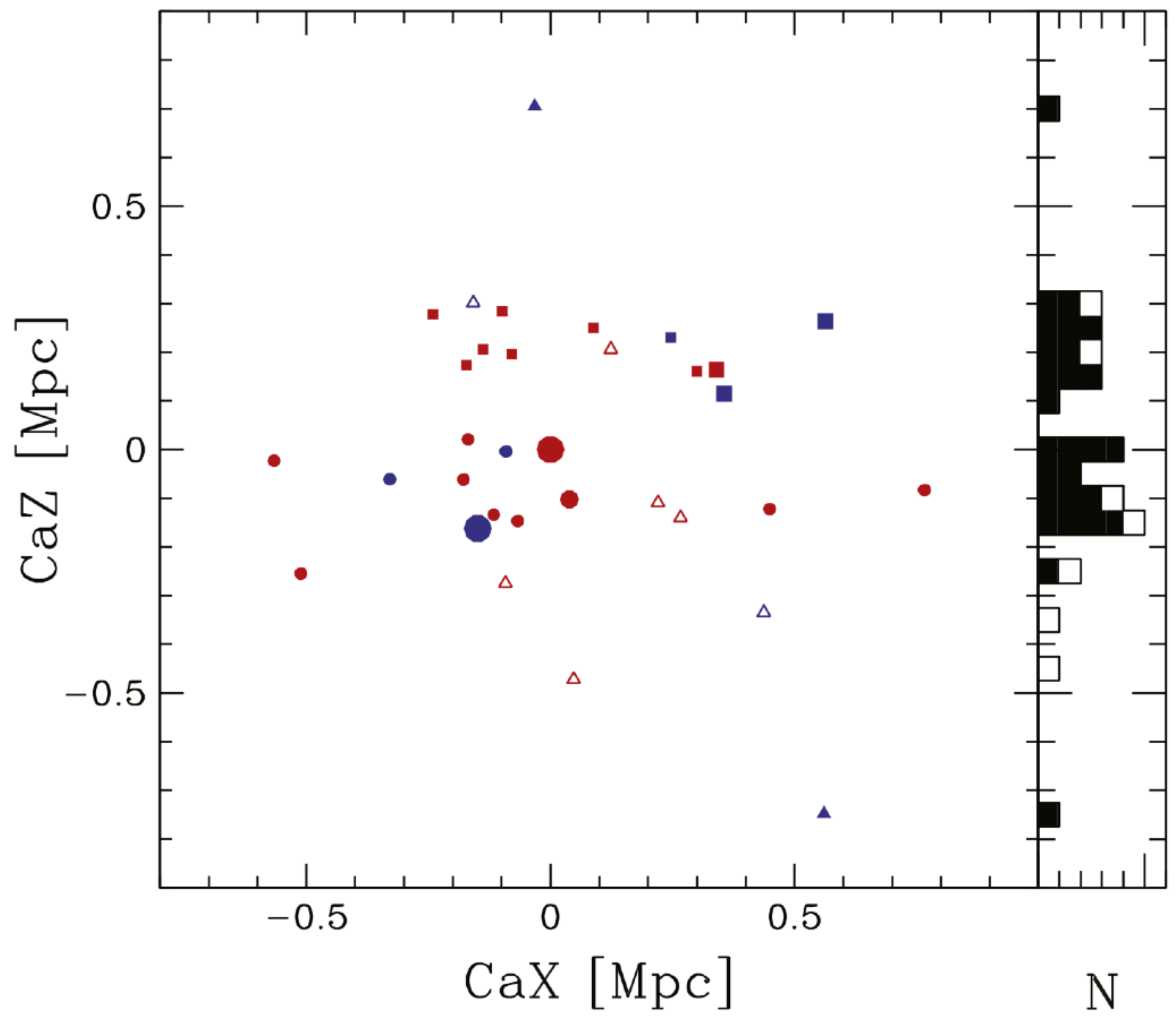
Frequency of similarly extreme satellite arrangements in cosmological simulations is ≤ 1%, ≤0.1% if considering radial distribution.

Pawlowski (2018, MPLA, 33, 1830004)


Christian Wolf and the SkyMapper team / Australian National University)

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

- Tully et al. (2015) had suggested double-planar structure of satellite galaxies.



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

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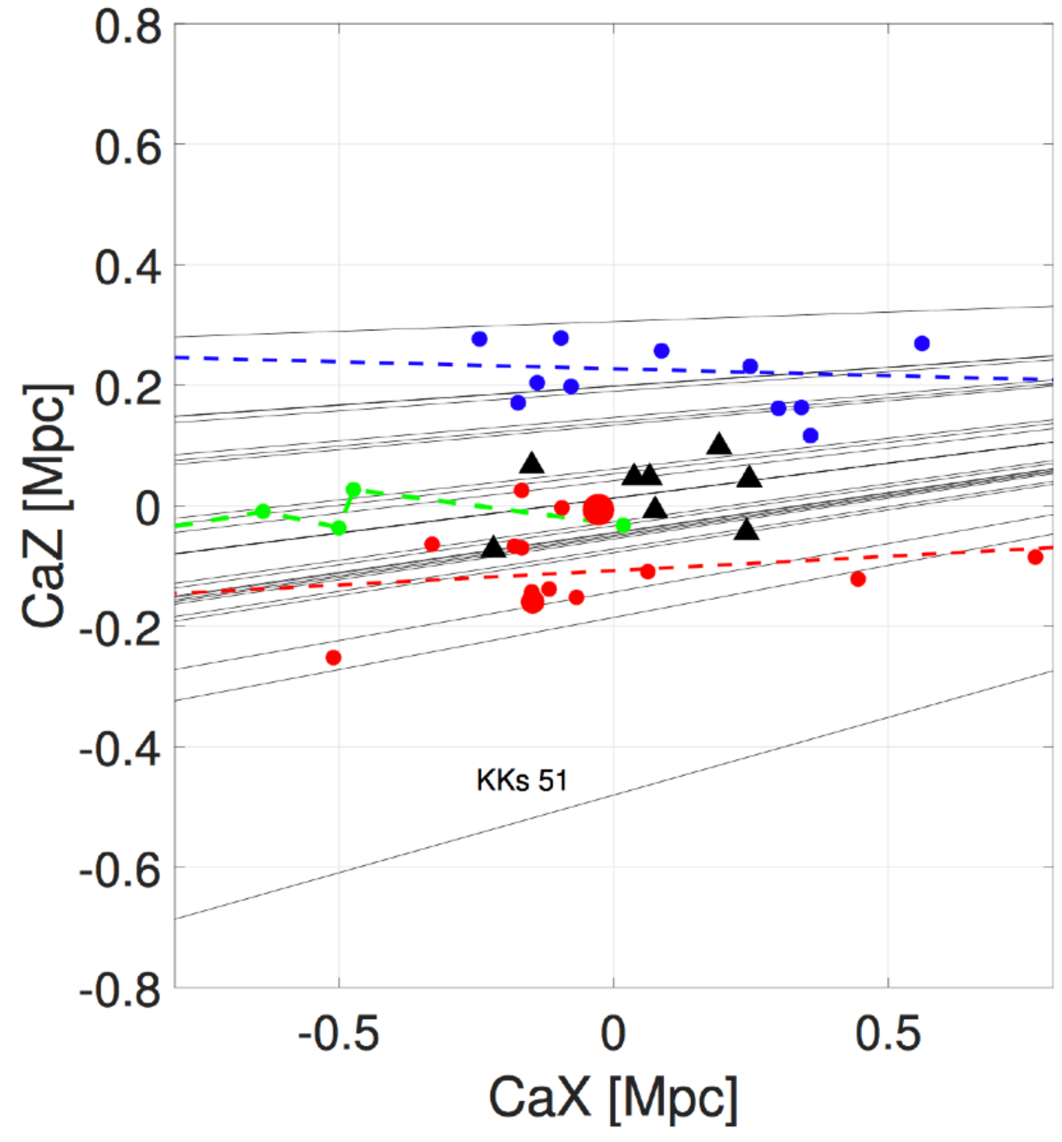
- With additional candidates, we see less evidence for two planes, but increased significance of single-plane interpretation.



Müller, Jerjen, Pawlowski, Binggeli (2016) A&A, 595, 119

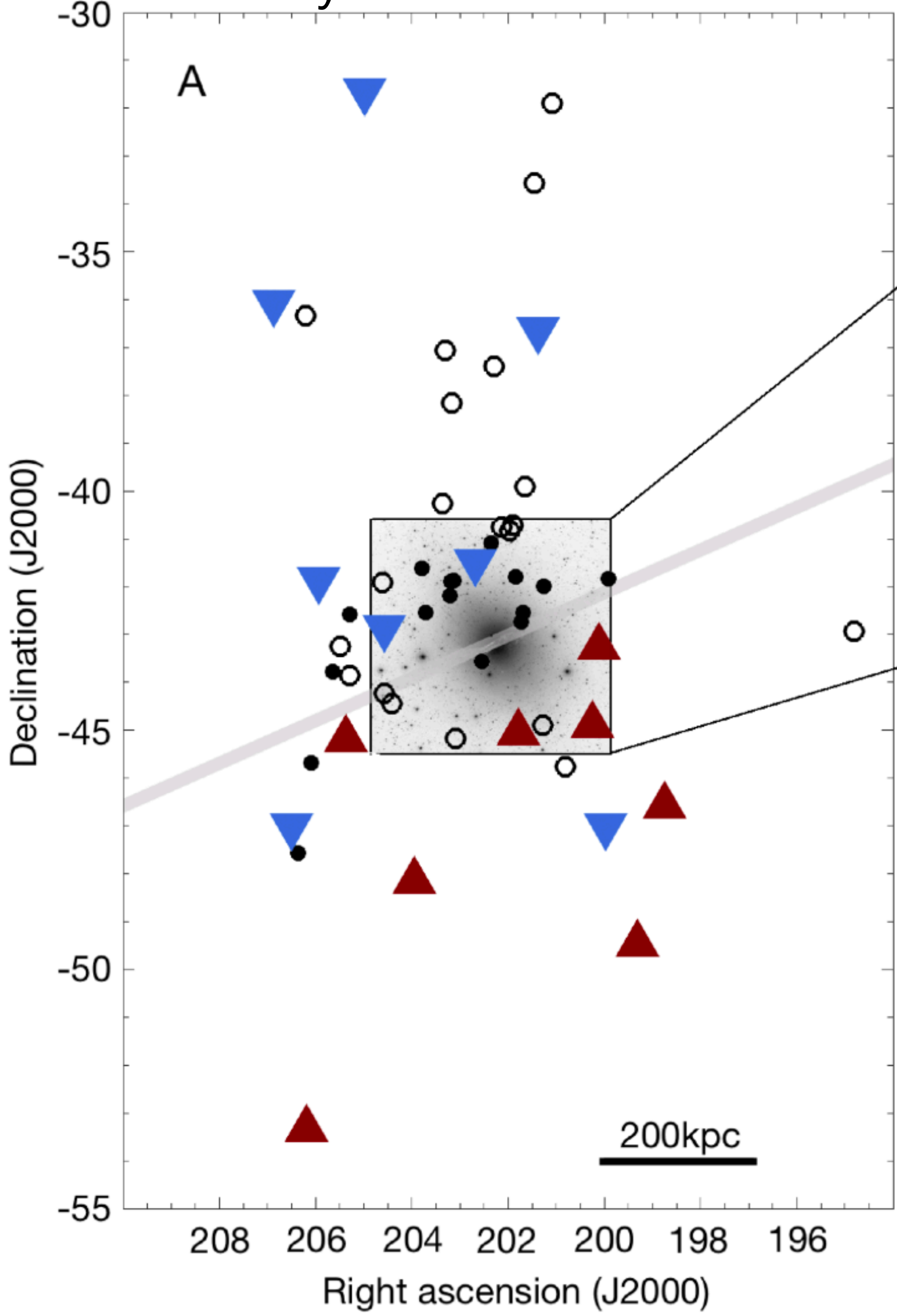
Is the Local Group special?
The Centaurus A Satellite Plane (CASP)

- Tully et al. (2015) had suggested double-planar structure of satellite galaxies.
- With additional candidates, we see less evidence for two planes, but increased significance of single-plane interpretation.
- **Does the satellite plane rotate? YES!**

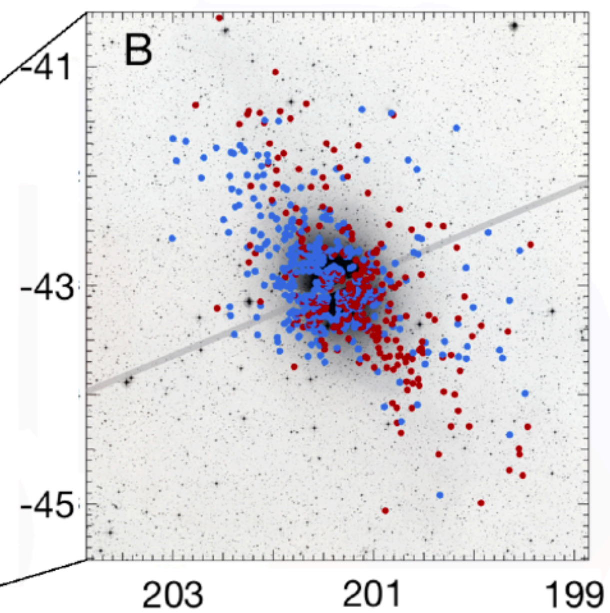
Müller, Pawlowski, Jerjen & Lelli (2018)
Science, Volume 359, Issue 6375, 534

The Centaurus A Satellite Plane (CASP):
A coherent line-of-sight velocity trend indicative of rotation

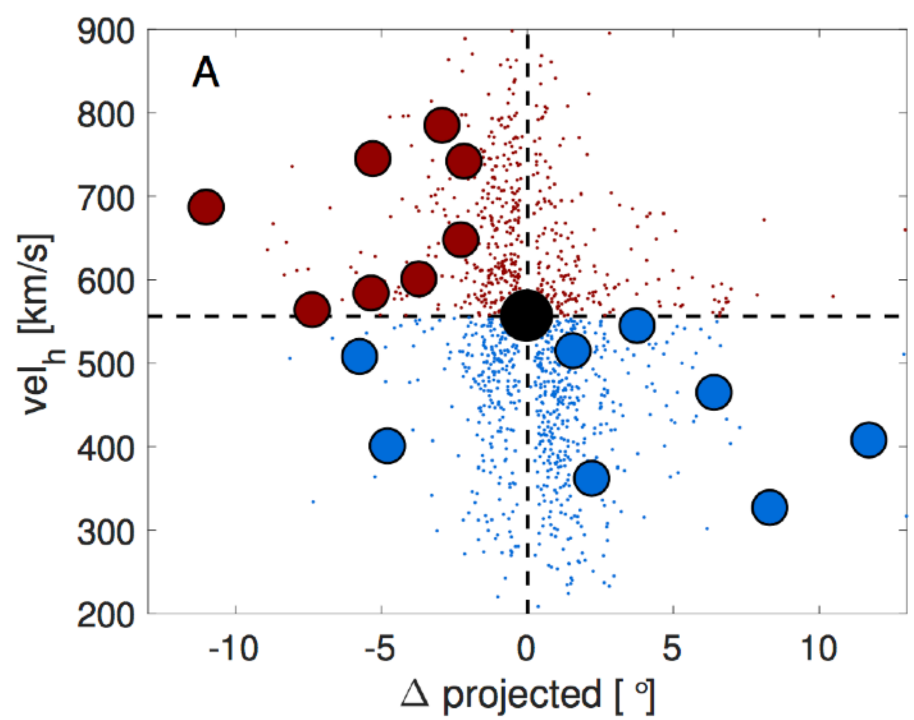
On-sky satellite distribution



Planetary Nebulae



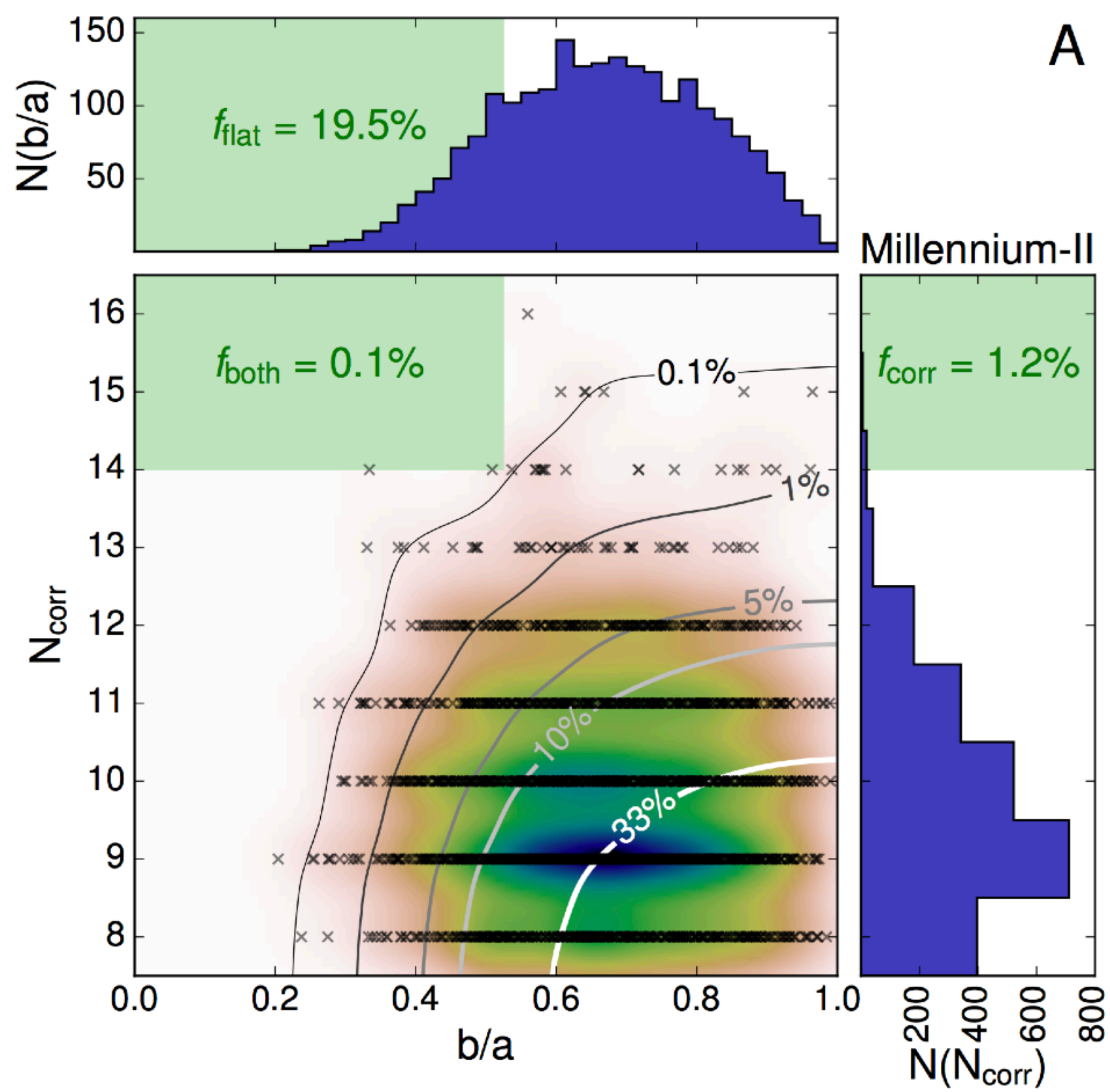
Velocities vs. angular distance



14/16 satellites follow kinematic trend; ~0.4% chance to find this at random

Analogs of the CASP are very rare in cosmological simulations

Dark Matter Only



- Pick hosts similar to Centaurus A:
  1. Viral mass M_{vir} = 4.0 to 12.0 × 10^{12} $M_\odot$
  2. Isolated: no halo of $M_{vir} \geq 1.0 \times 10^{12}$ $M_\odot$ within $d \leq 1.4$ Mpc
- Mock-observe at Cen A distance from 10 random direction.
- Draw 16 out of top 30 satellites, or chose top 16 (results no different).
- Apply simplified criteria to define satellite structure (avoids look-elsewhere effect):

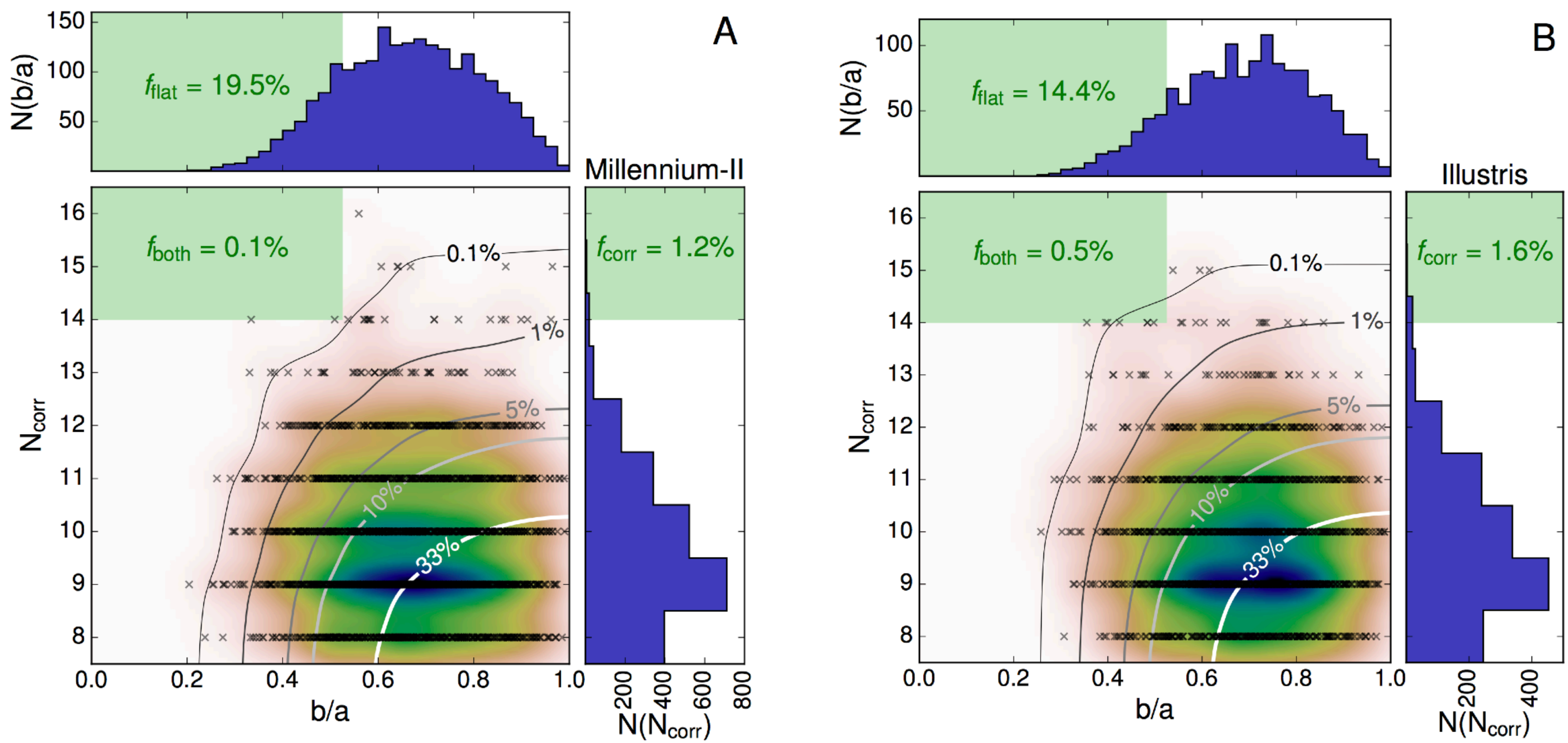
  b/a: Projected on-sky flattening b/a (x-axis).

  N_{corr}: Number of correlated velocities (y-axis).

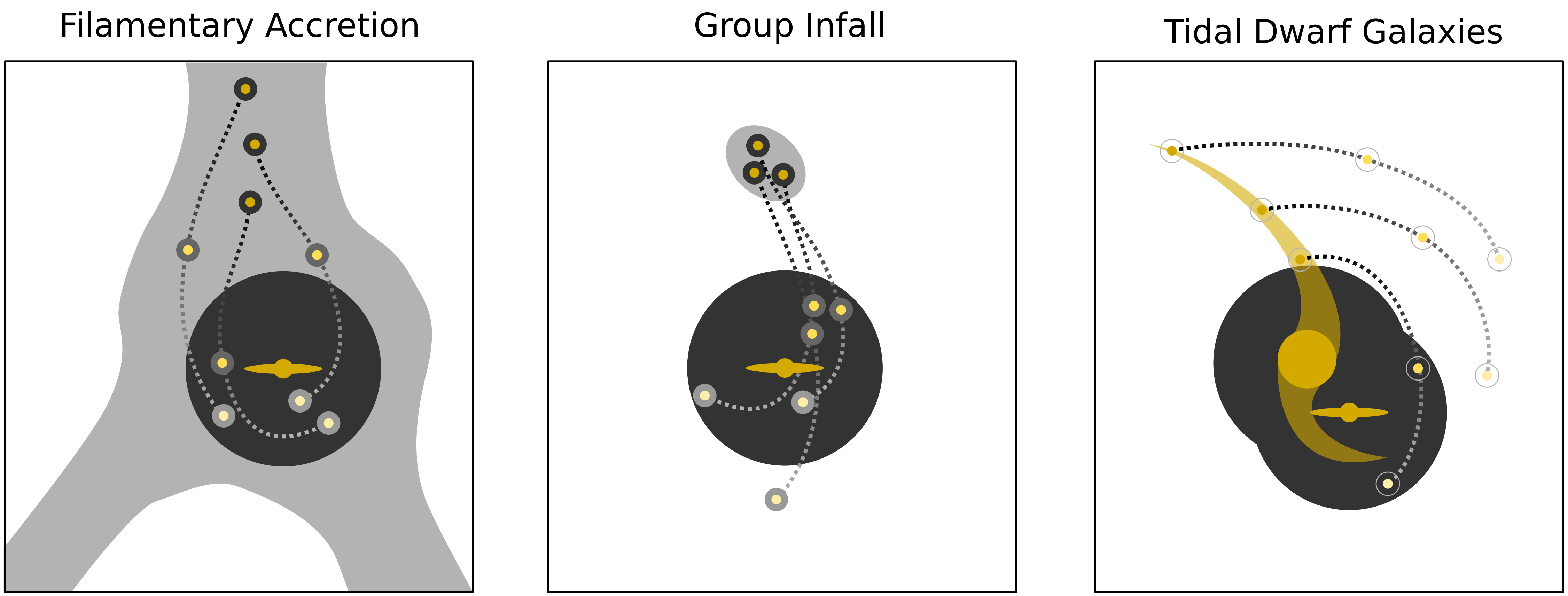
Analogs of the CASP are very rare in cosmological simulations *and baryons don't help!*

Dark Matter Only

Hydrodynamics + Feedback



Suggested origins of planes of satellite galaxies



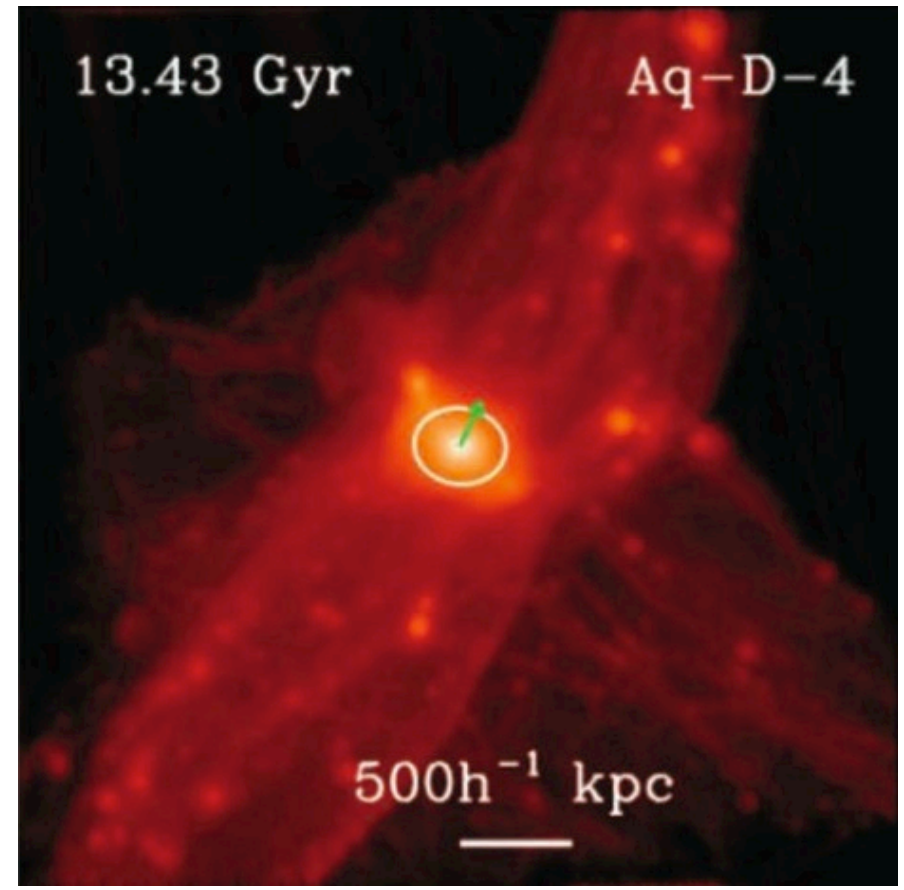
Pawlowski (2018, MPLA, 33, 1830004)

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

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

Why filamentary accretion does solve the satellite plane problem

- Intuitively convincing: Sub-halos are accreted mostly along filaments, i.e. from preferred directions. Thus, they end up anisotropically distributed around host.
- The GPoA & CASP align with the large-scale shear field. (Libeskind+2015)



Why filamentary accretion does NOT solve the satellite plane problem

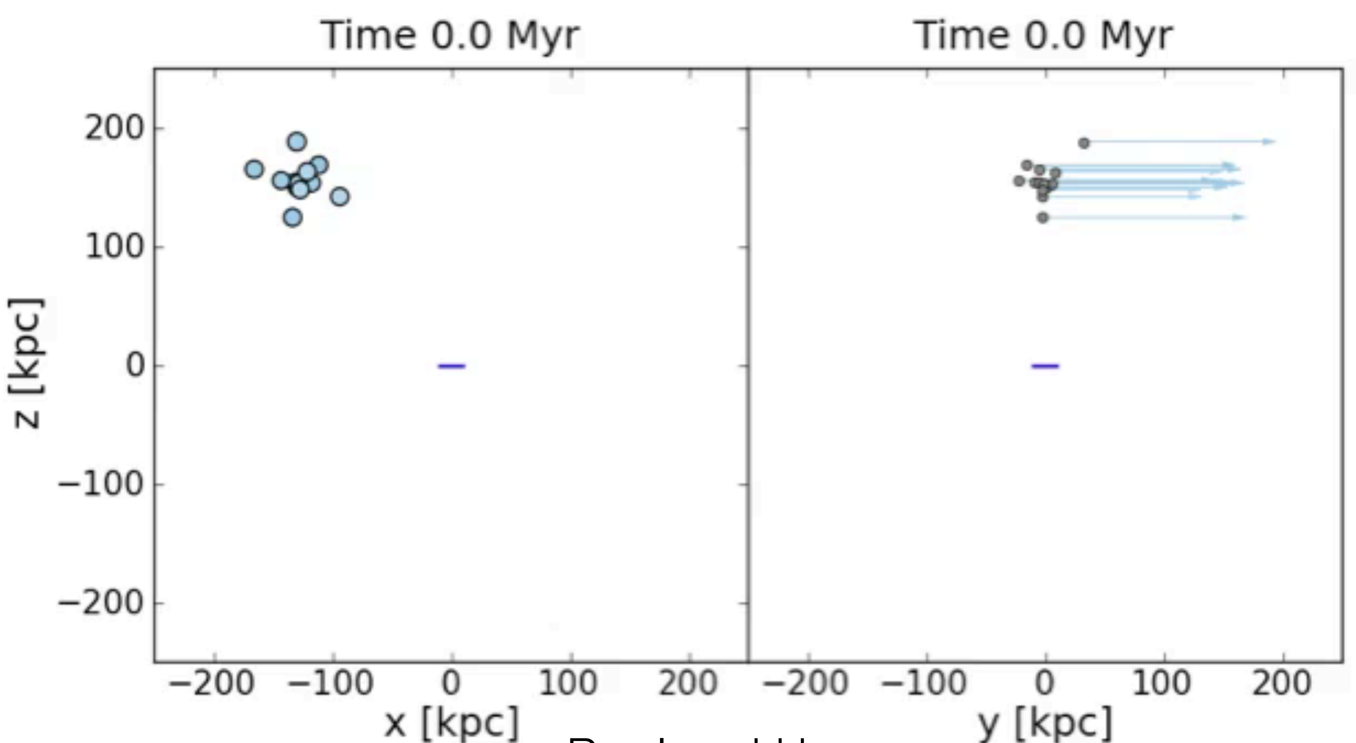
- Intuitively convincing: Sub-halos are accreted mostly along filaments, i.e. from preferred directions. Thus, they end up anisotropically distributed around host.
- The GPoA & CASP align with the large-scale shear field. (Libeskind+2015)

BUT:

- Effect of filaments included self-consistently in cosmological simulations!
- Significant anisotropy ≠ sufficiently strong planar alignment
- Cosmic filaments too wide to account for narrow satellite planes.
- Coherent angular momentum of satellites in plane not expected from radial accretion along filament.
- The VPOS does not align with the large-scale shear field.

Why group infall does solve the satellite plane problem

- Some sub-halos in simulations are accreted in groups.
- Satellites in one group share similar orbit, disperse along common plane.
- Thus, satellites accreted in the same group should for long time co-orbit along a common plane.



Pawlowski in prep.

Why group infall does NOT solve the satellite plane problem

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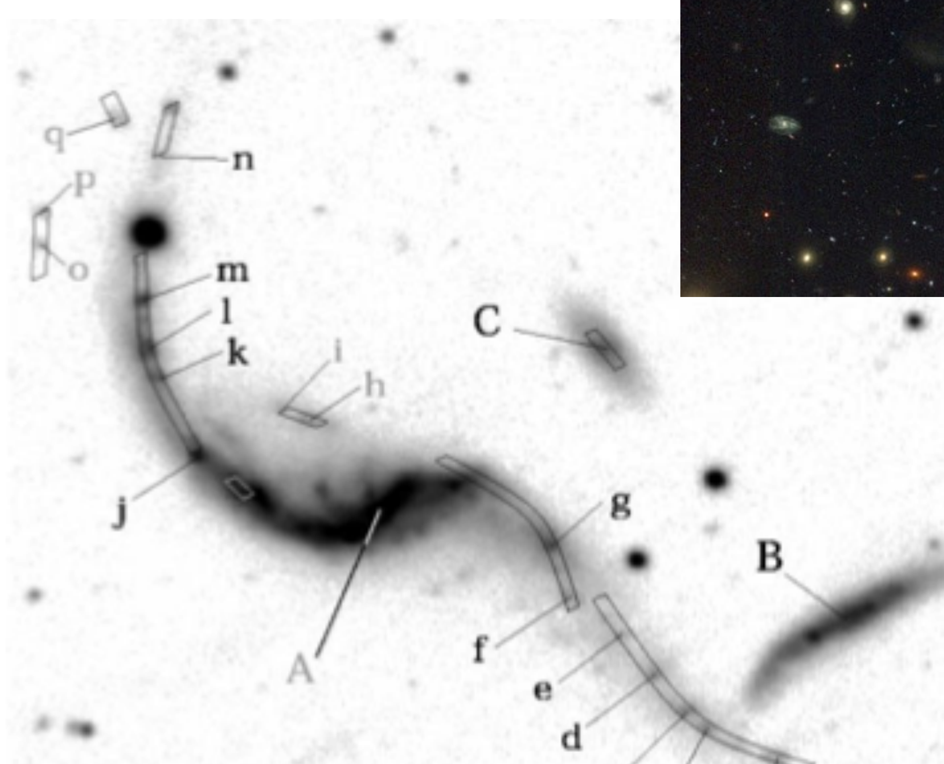
- Satellites in one group share similar orbit, disperse along common plane.
- Thus, satellites accreted in the same group should for long time co-orbit along a common plane.

BUT:

- Effect of group infall included self-consistently in cosmological simulations!
- Too many groups fall in over the lifetime of a halo, and groups consist of small number of galaxies only.
- In conflict with observational constraints: Infalling groups need to be compact, but all observed dwarf associations are wider. (Metz+2009)

Why Tidal Dwarf Galaxies (TDGs) do solve the satellite plane problem

- Second-generation galaxies formed in the debris of galaxy collisions.
- Survive their formation phase.
  (Duc+2011; Recchi+2007; Plöckinger+2014)
- Naturally result in planar, phase-space correlated dwarf galaxy populations!
  Even explains counter-orbiting satellite.
  (Pawlowski+2011, 2012a,b)



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  (Pawlowski+2011, 2012a,b)

BUT:

- TDGs should be DM free!
  (or non-eq. dyn., modifying DM/gravity?)
- TDGs should deviate from mass-metallicity relation.
  (But if very old, material less pre-enriched)
- On- and off-plane M31 satellites not systematically different (Collins+2015)
  (But what if all are TDGs?)
- Major open questions: Do enough TDGs form? With the right mass-function? And SFHs consistent with observed ones?

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.
- None of the suggested solutions to the Planes of Satellites Problem can satisfactorily address the issue.
- More details? See recent review: Pawlowski (2018, MPLA, 33, 1830004)

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

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The planes of satellite galaxies problem, suggested solutions, and open questions

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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 an 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 $\leq 0.5\%$ 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 problems 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.

Keywords: Dark matter; cosmology; dwarf galaxies; near-field cosmology.

PACS Nos.: 95.35.+d, 98.80.Es