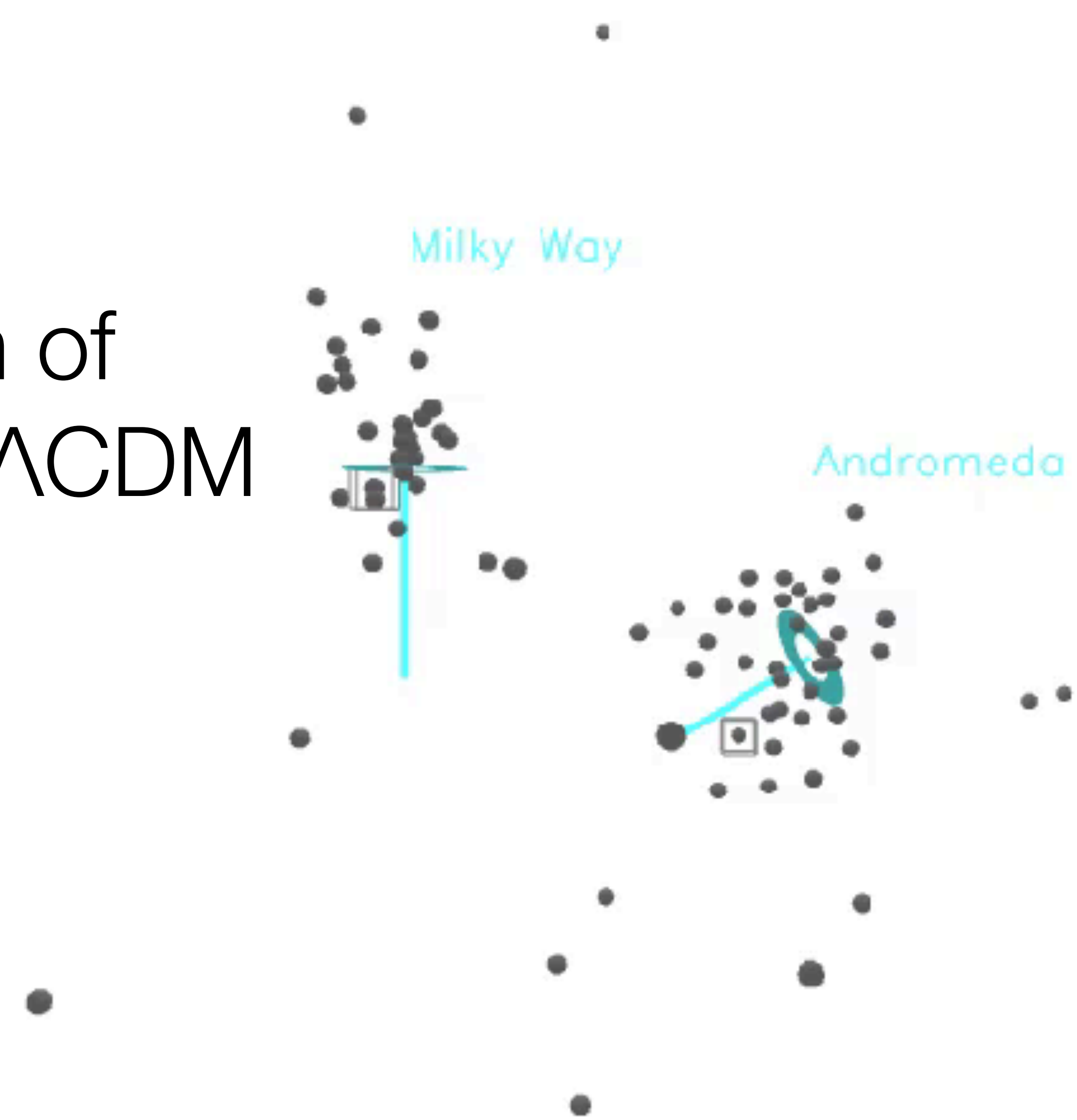
The phase-space distribution of satellite galaxies as a test of ΛCDM



Marcel S. Pawlowski

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Collaborators: **James Bullock**, **Jörg Dabringhausen**, **Benoit Famaey**, Hector Flores, **Francois Hammer**, Gerhard Hensler, Rodrigo Ibata, **Pavel Kroupa**, **Federico Lelli**, **Stacy McGaugh**, **David Merritt**, **Oliver Müller**, Helmut Jerjen, Yanbin Yang

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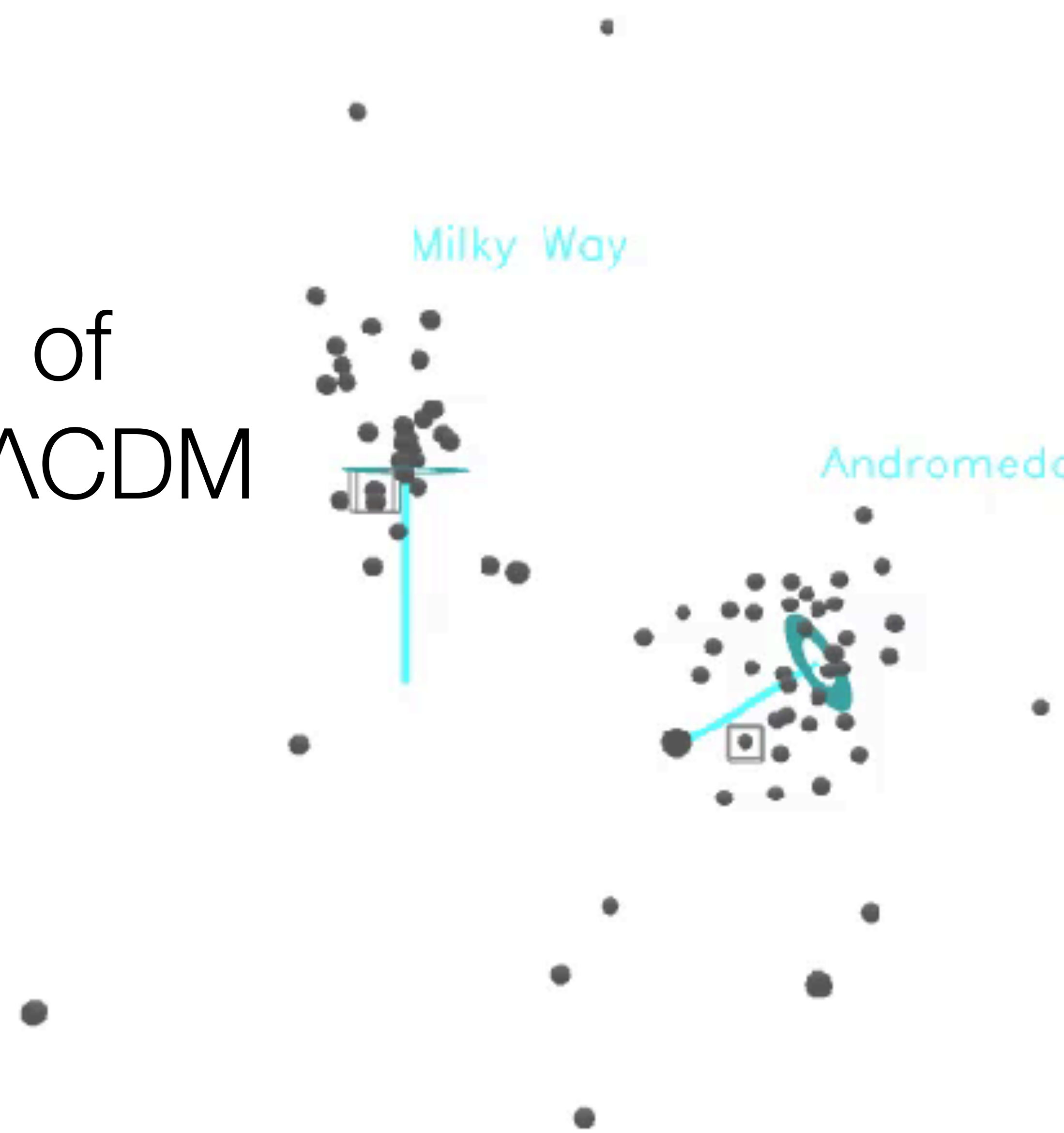

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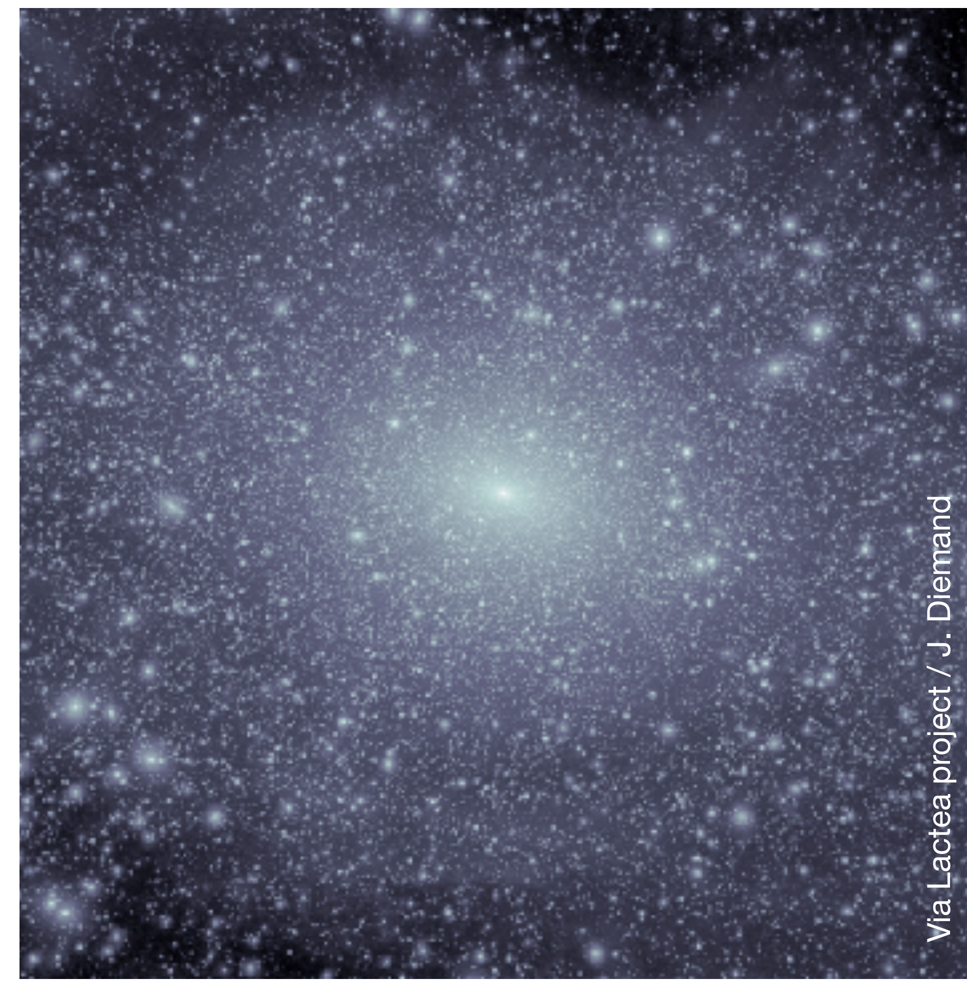
Comparing Observed Satellite Galaxies with ΛCDM Expectations

- Use the LG as a testbed for cosmological models.
- Comparisons have revealed “small-scale” problems, e.g.:
    - Missing Satellites
    - Core-Cusp
    - Too-big-to-fail
- Comparisons have often relied on DMO simulations.
    - Baryonic effects (gas, stars, star formation, feedback processes) *might* be able to solve many problems.
- What about the overall phase-space distribution of satellite systems?
    - Position &velocities more robust (not directly affected by internal dynamics and feedback processes).
    - Radial distr. affected Ahmed+2017, Garrison-Kimmel+2017

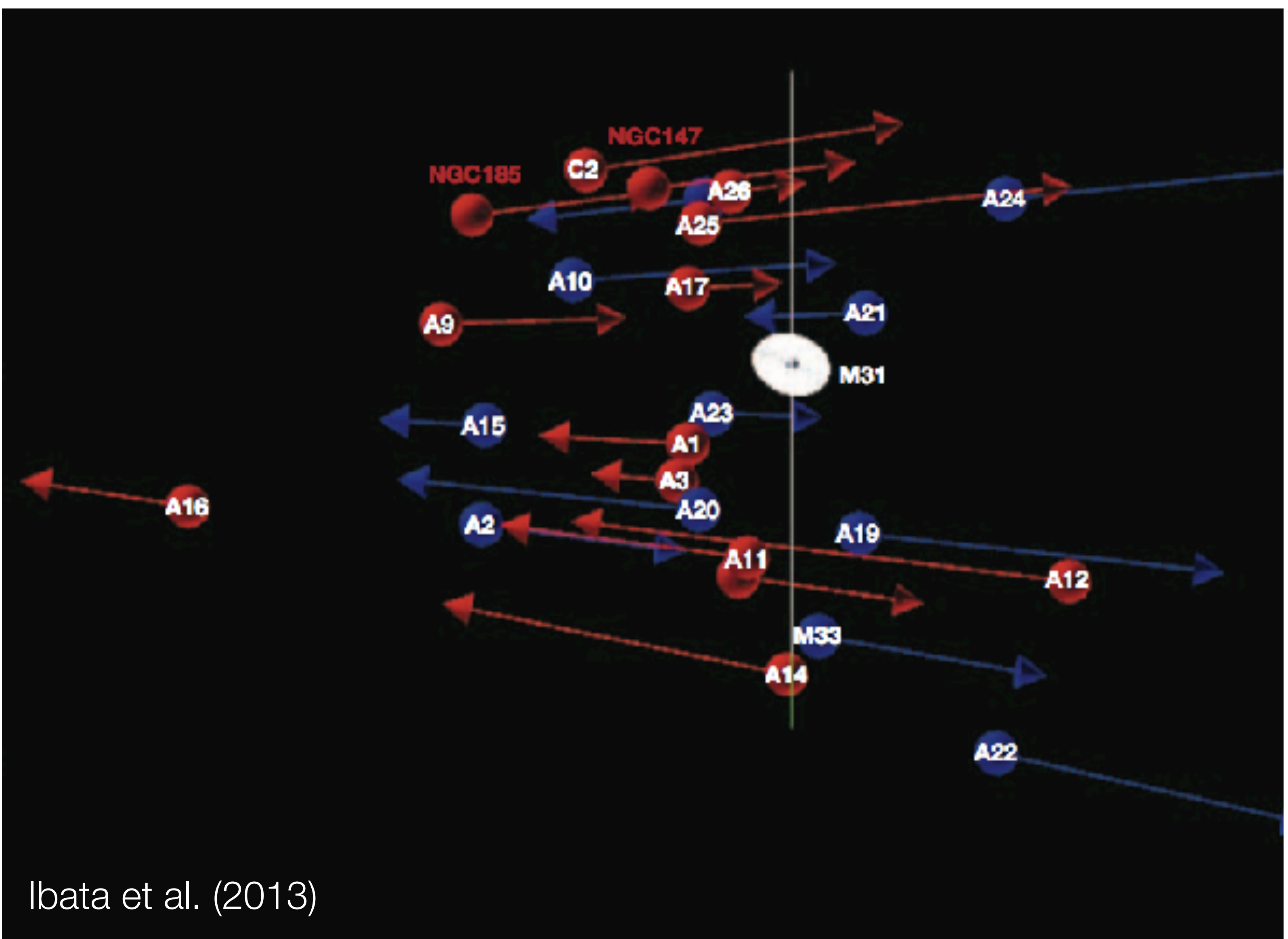


Lopsided Satellite Distributions

Do we trust DMO simulations?

Lopsidedness of Satellite Systems: Motivation

- M31 satellite plane Ibata+2013
- also M83 Müller+2015



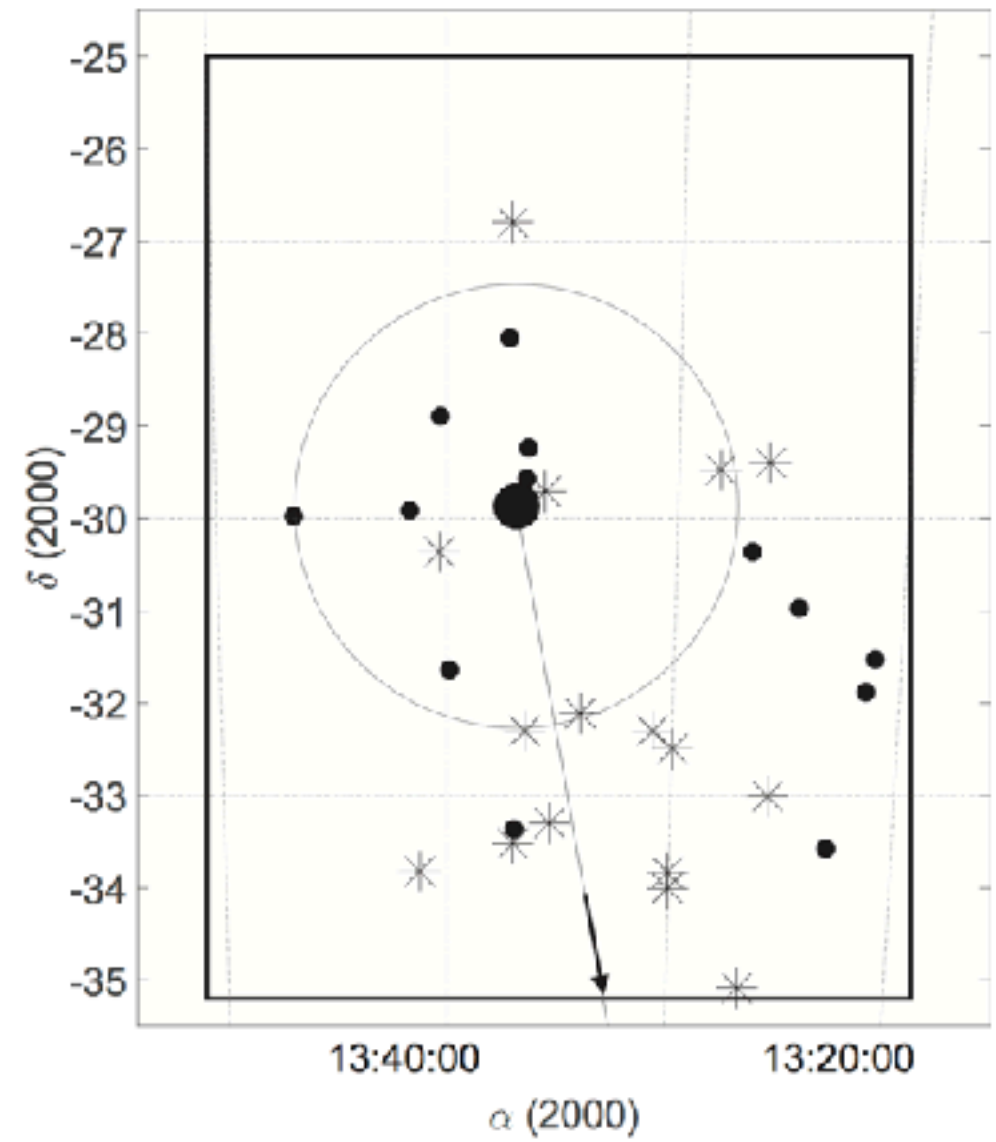
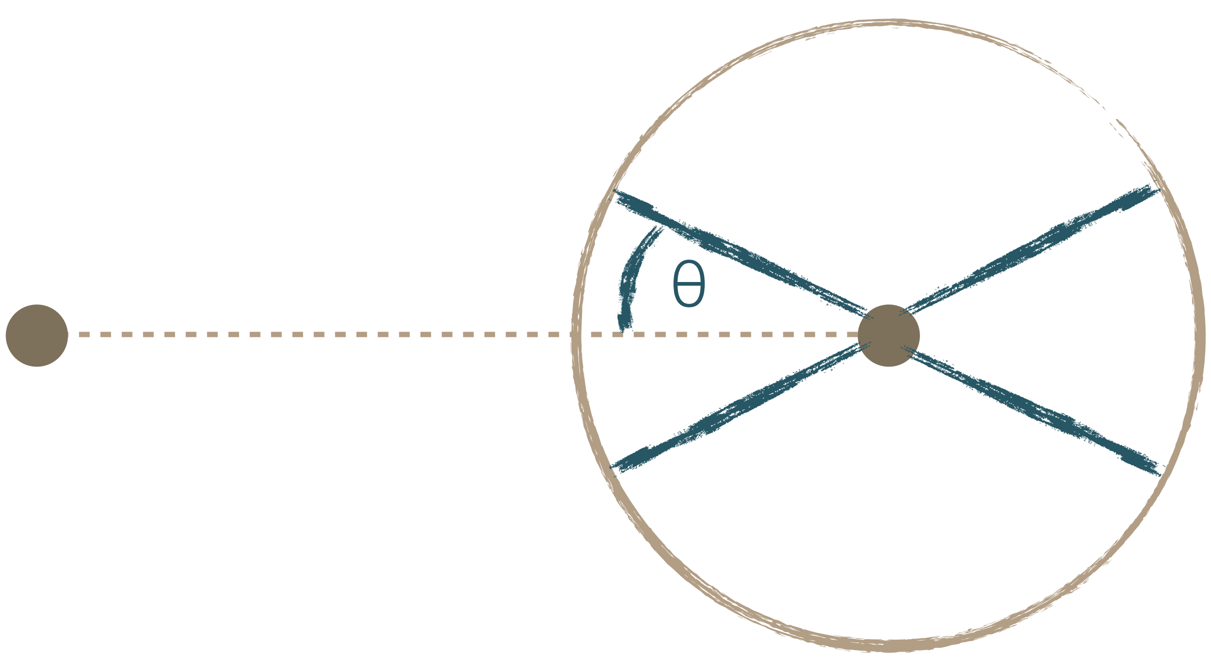
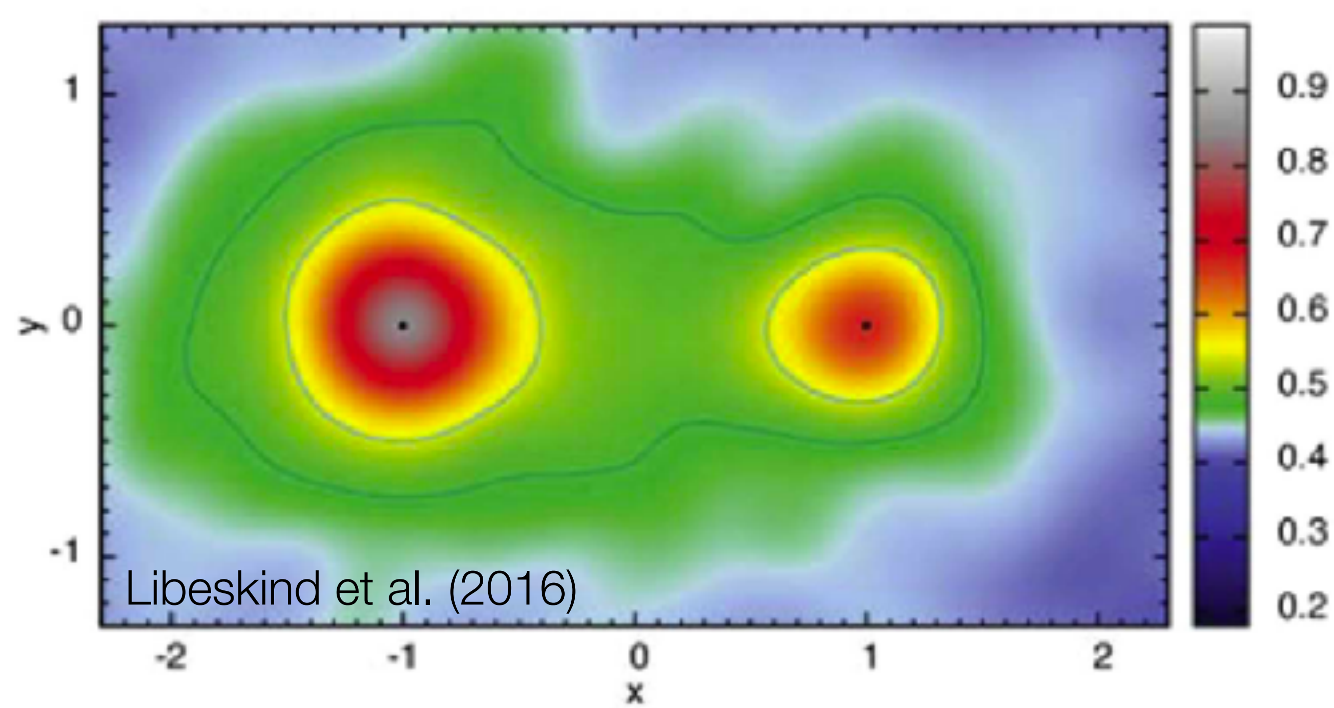


Fig. 1. Survey area of 60 sq. deg (rectangle) around the galaxy M 83 (large filled circle). The newly detected dwarf galaxy candidates are indicated with stars. Small filled circles are known M 83 group members. The large circle indicates the virial radius of the M 83 subgroup (see text). The vector points toward the Cen A galaxy. We note an overdensity of new dwarfs in that direction.

Lopsidedness of Satellite Systems in SDSS

- Libeskind et al. (2016) looked at satellite distribution around host galaxy pairs in SDSS.
- Find significant excess in direction towards partner galaxy.
- What about ΛCDM?





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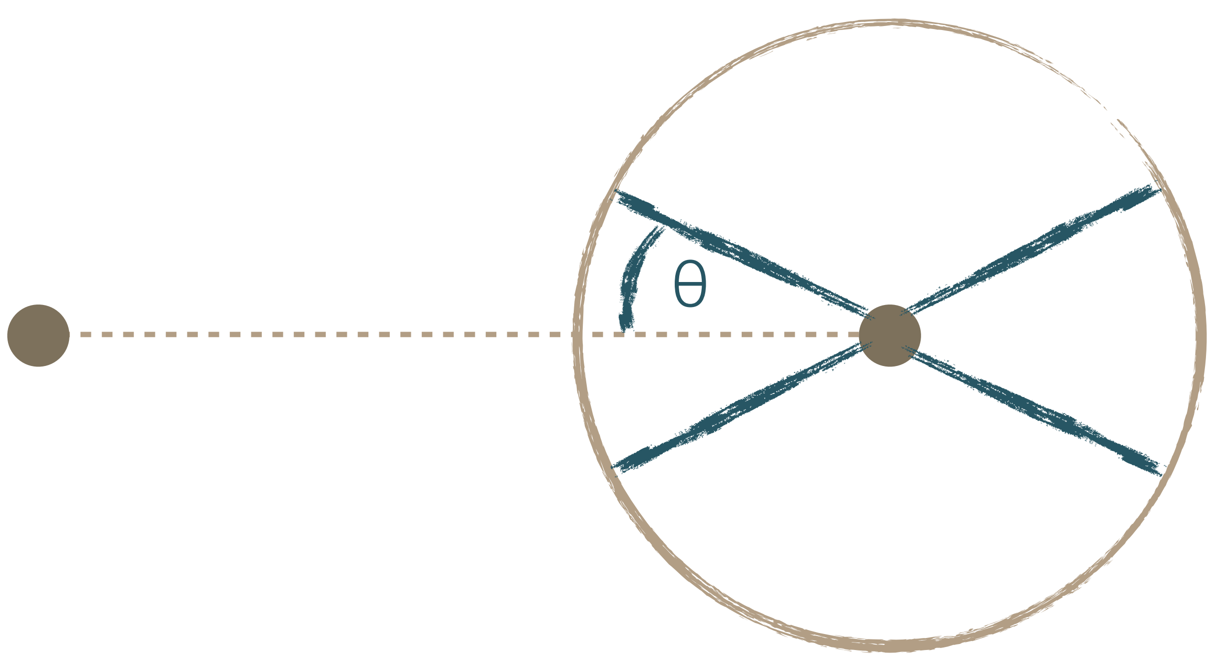
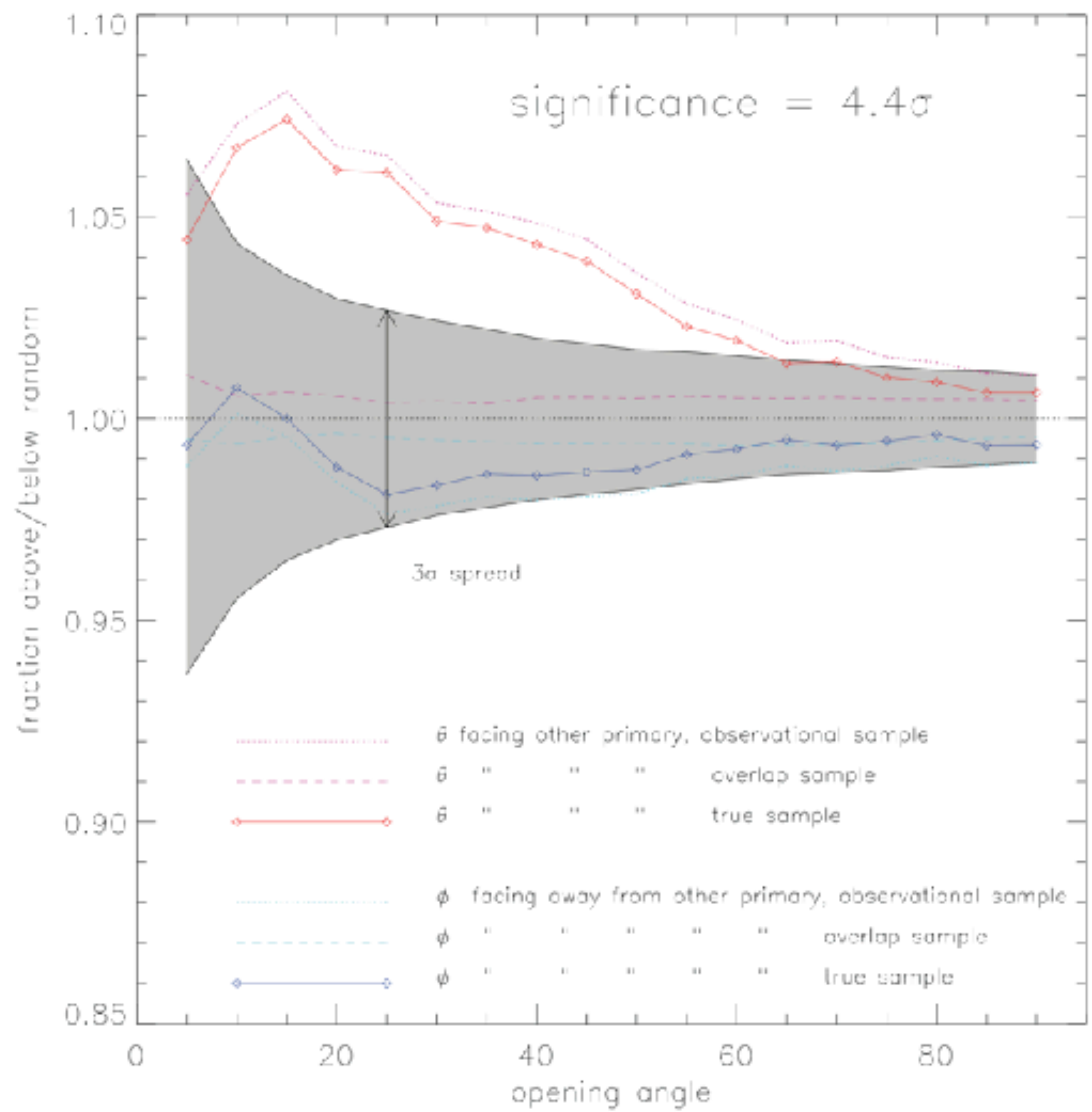
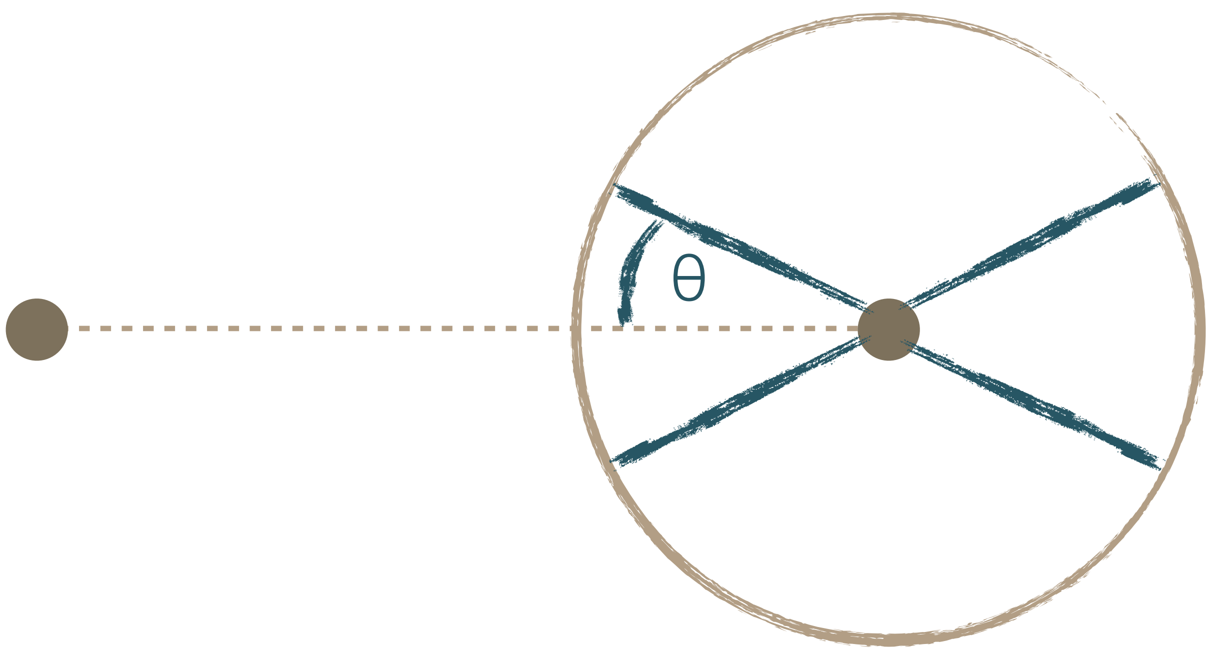


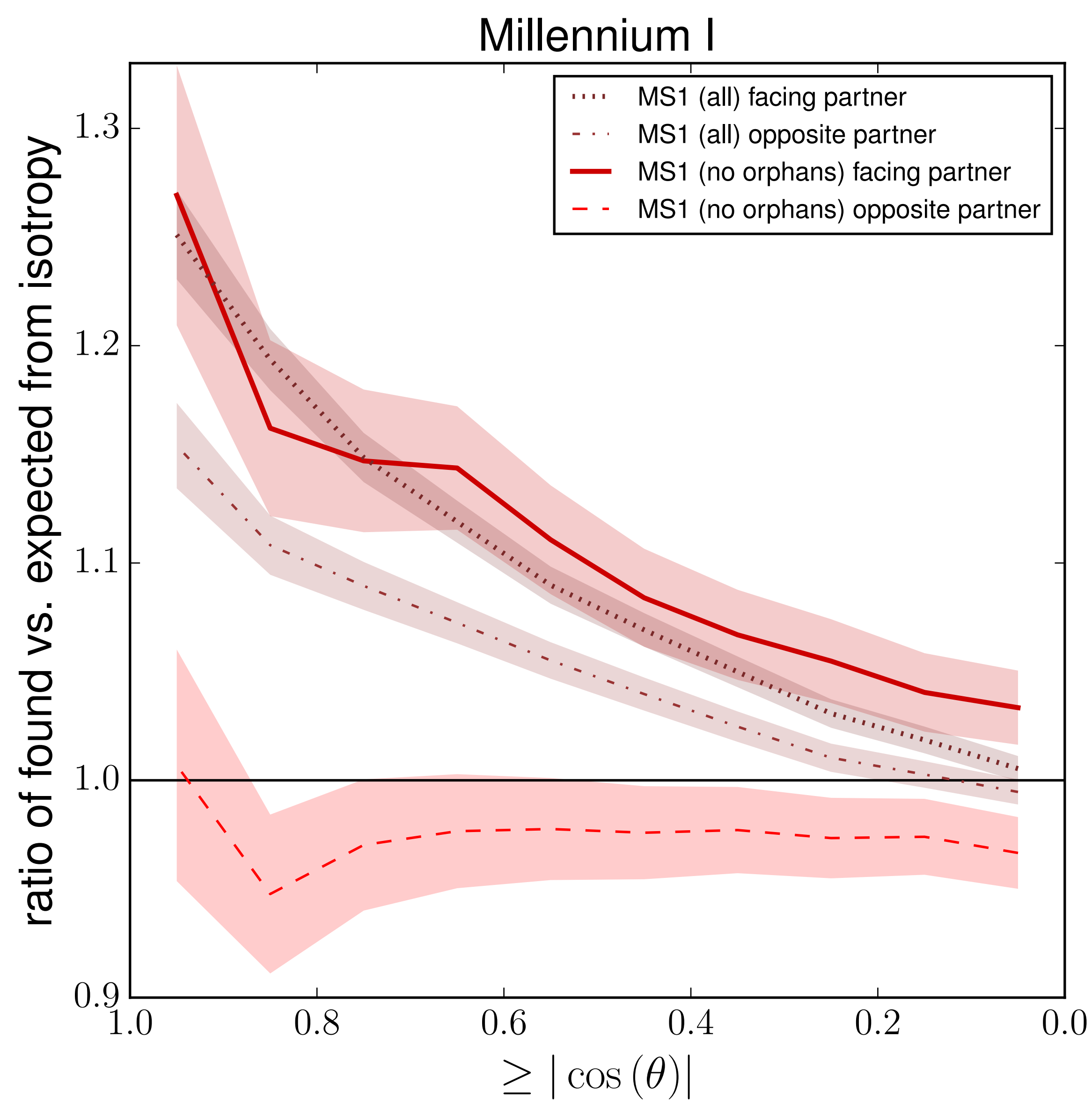


Similar Signal found in Simulations

Pawlowski et al. in prep

- Cumulative number of satellites in cones of opening angle θ.
- Overabundance of satellites in direction to partner galaxy in all simulations!
- Orphan galaxies in MS (dotted lines):
    - Galaxies traced beyond the disruption of their host halo.
    - Show secondary peak on opposite side.





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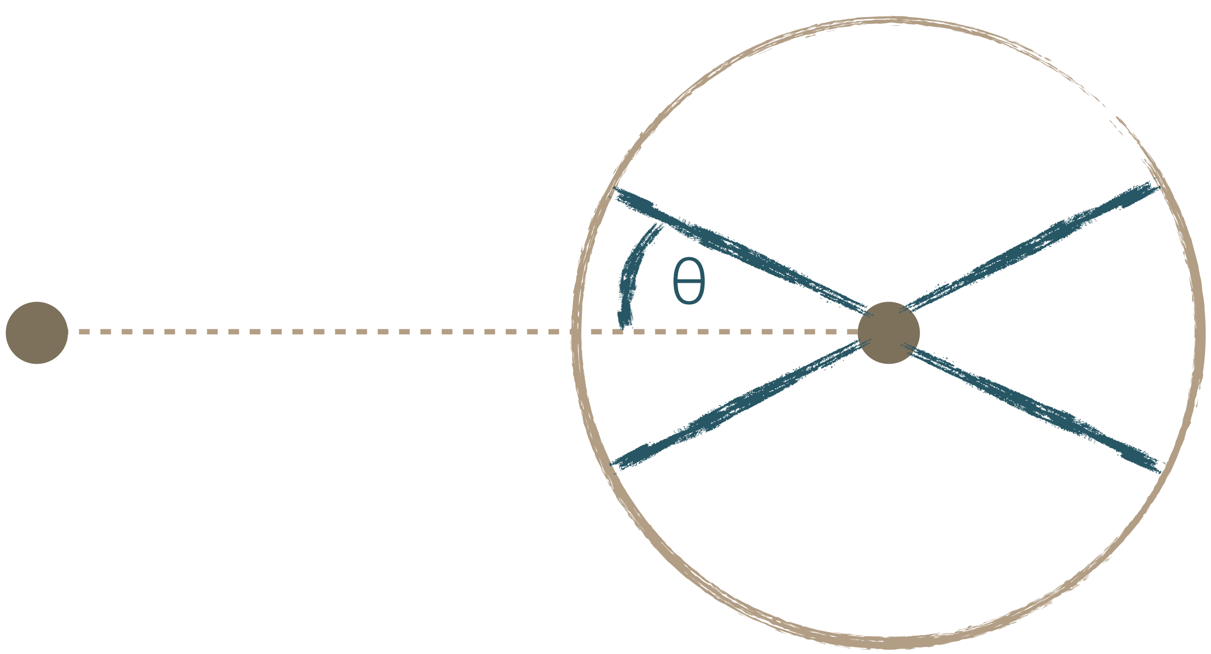

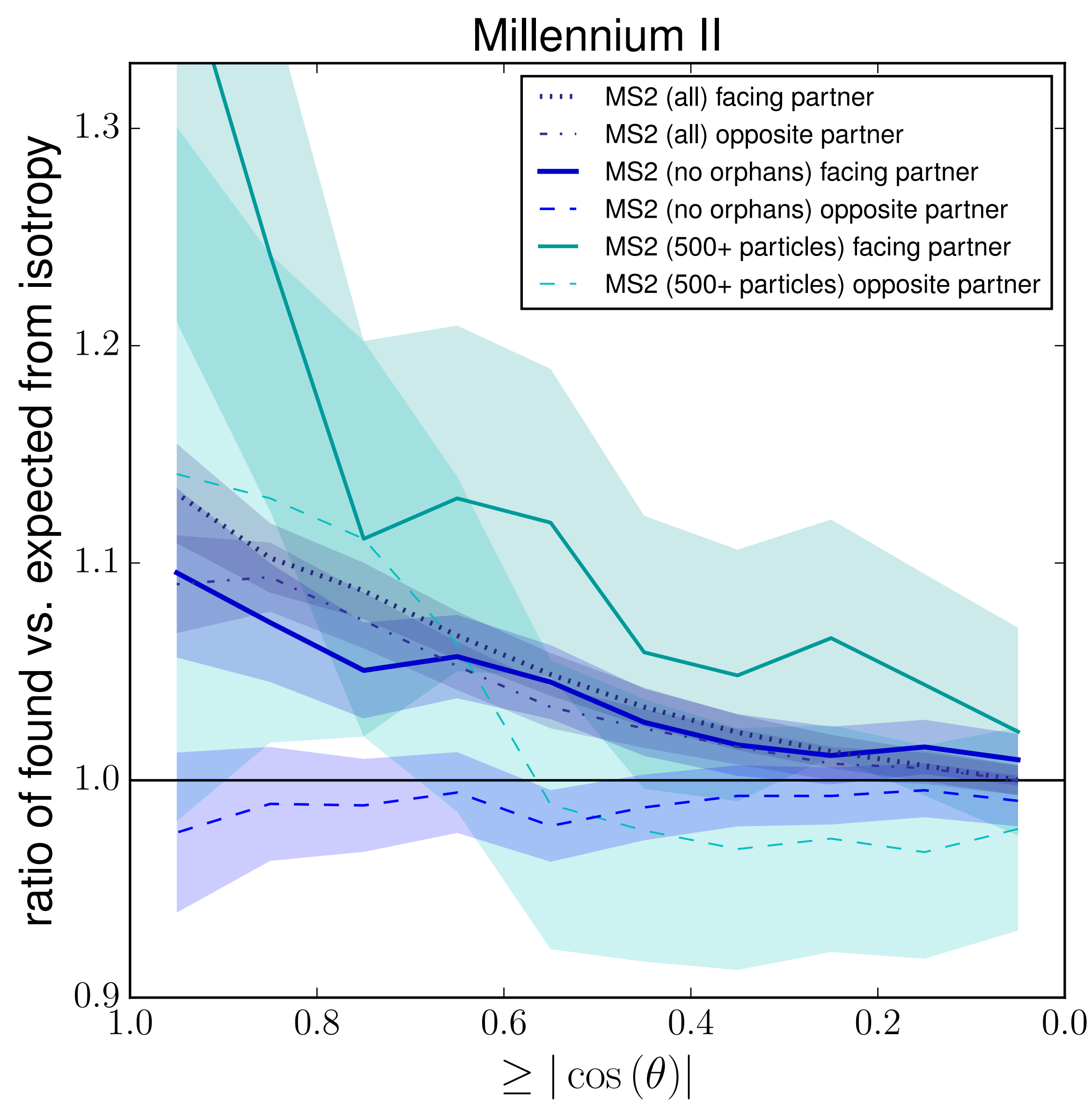

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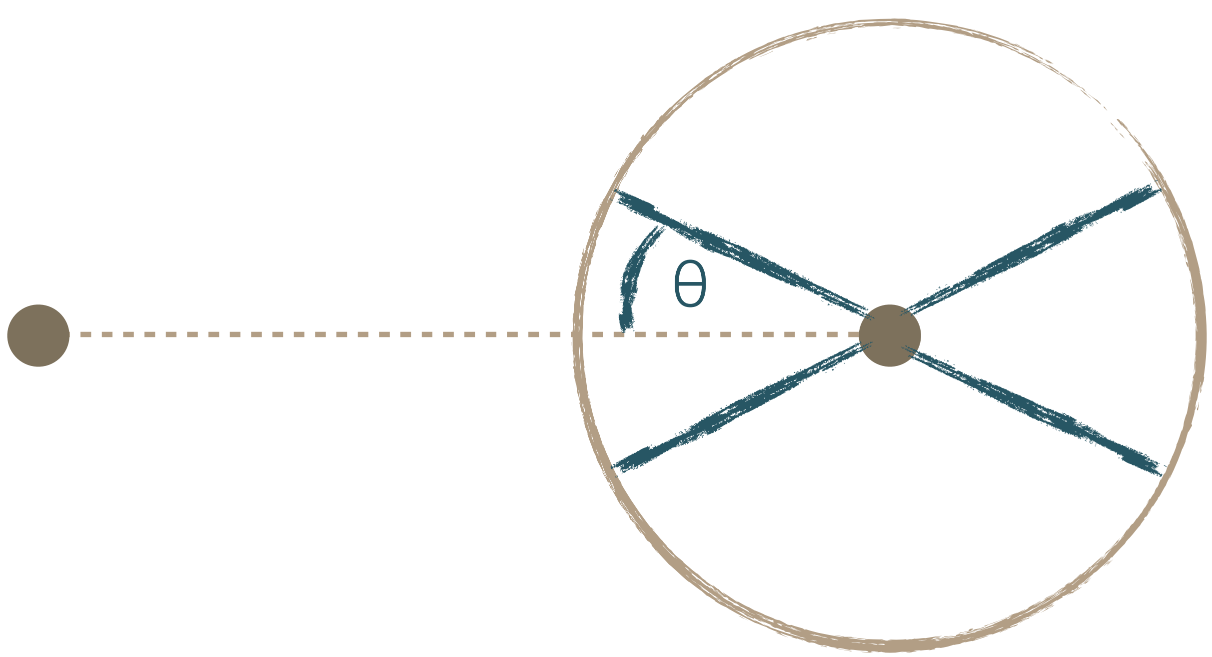
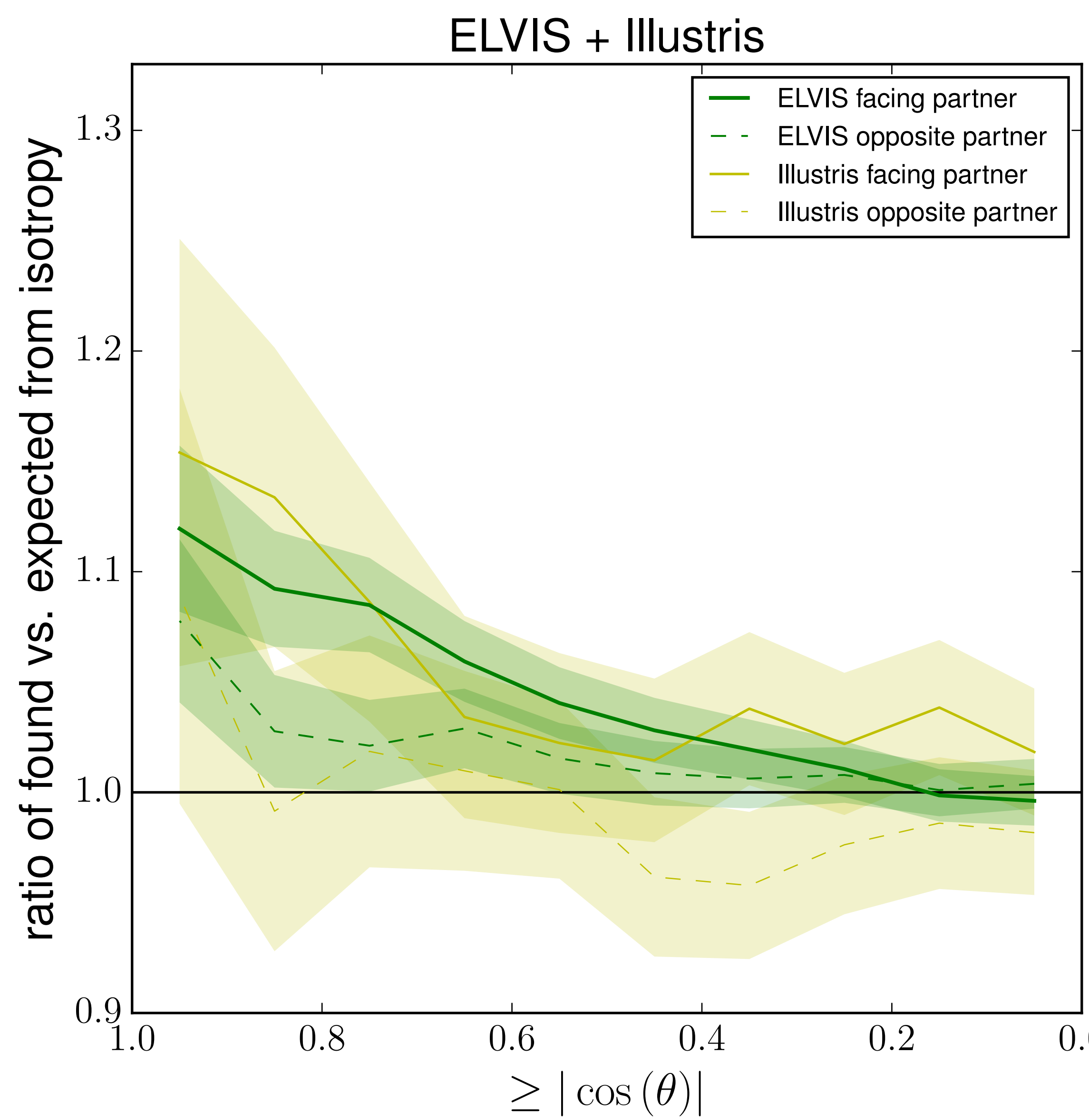
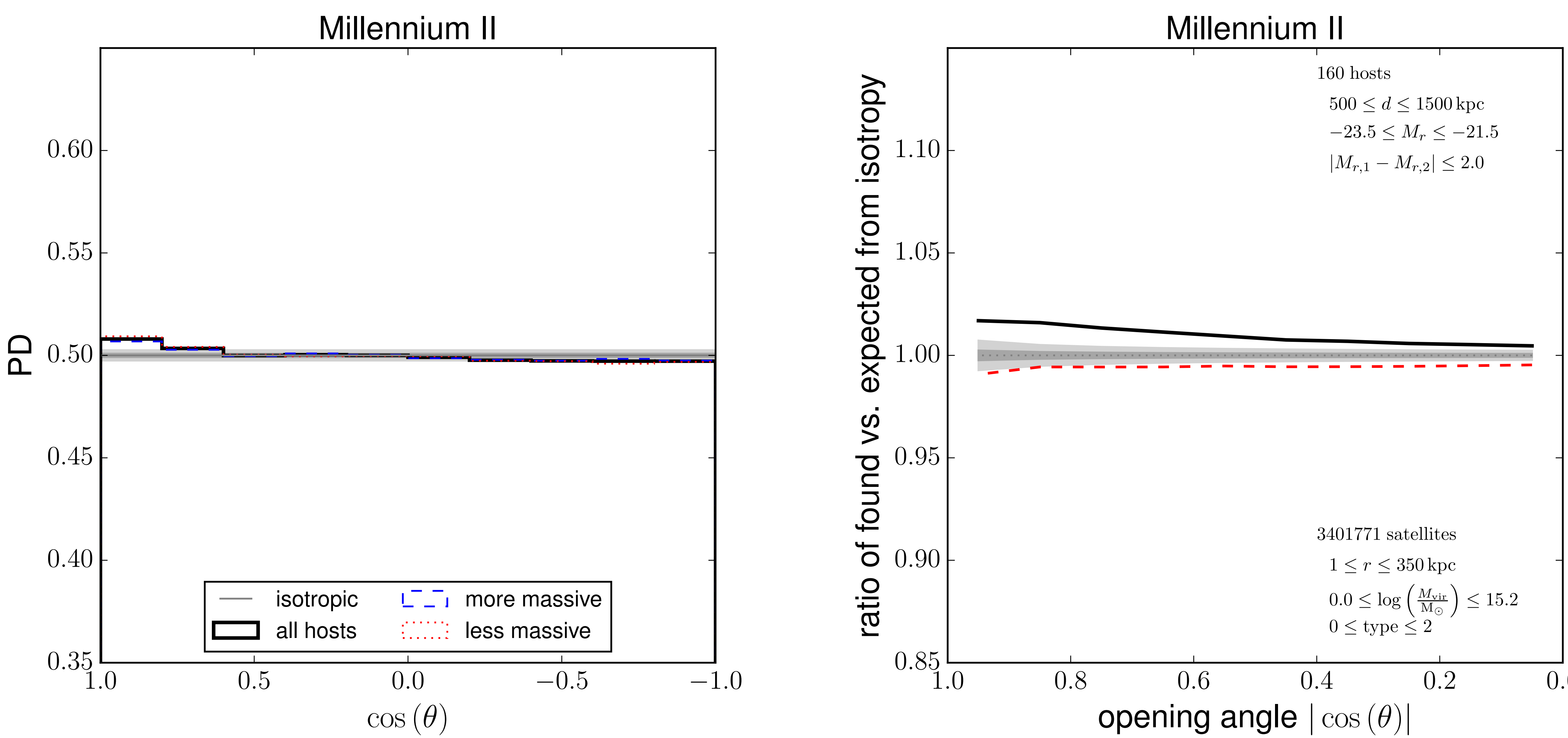




“Overlap” of satellite systems is not sufficient to explain excess.

Pawlowski et al. in prep

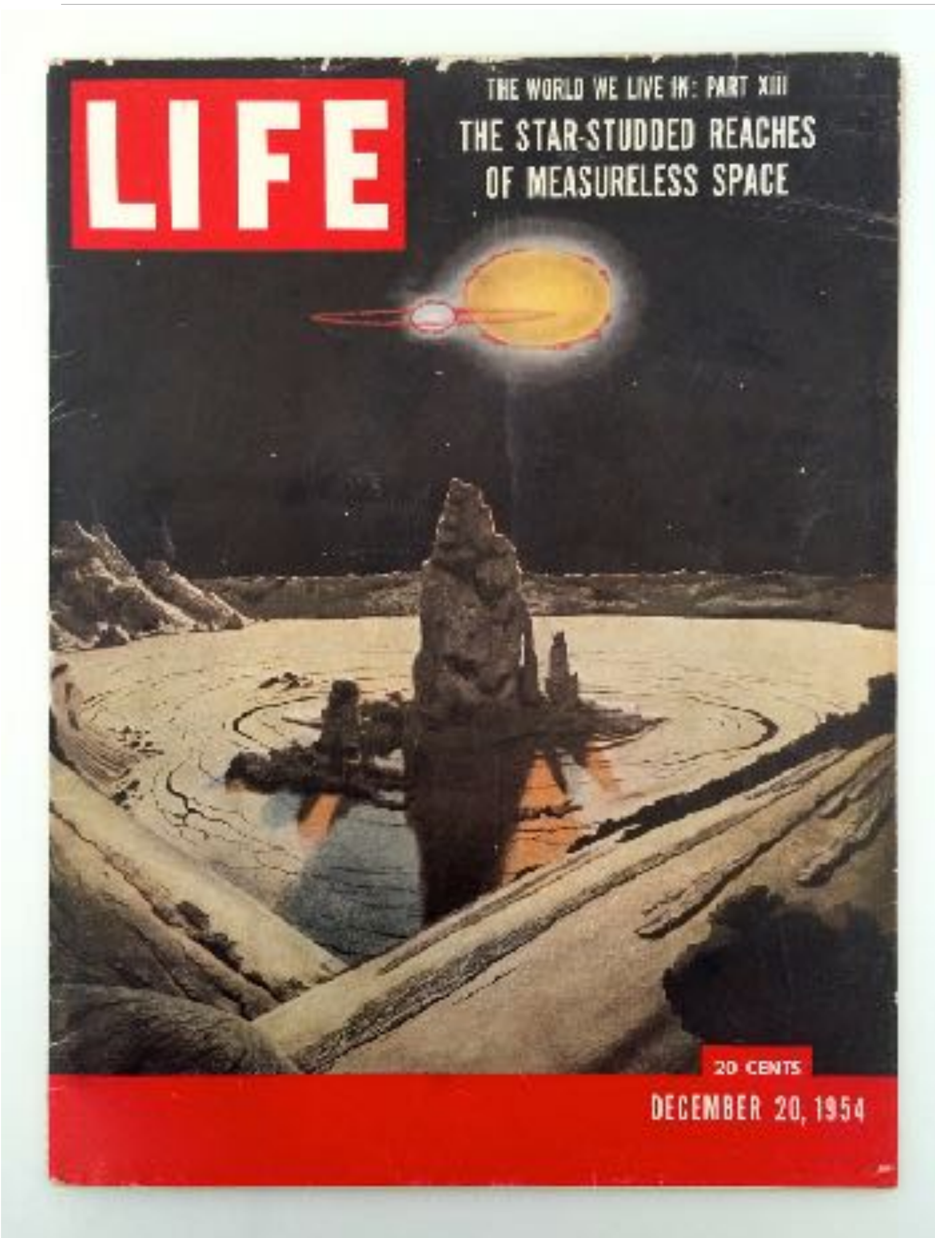
- Equivalent isolated hosts placed (with surrounding) at same distances to form artificial pairs.

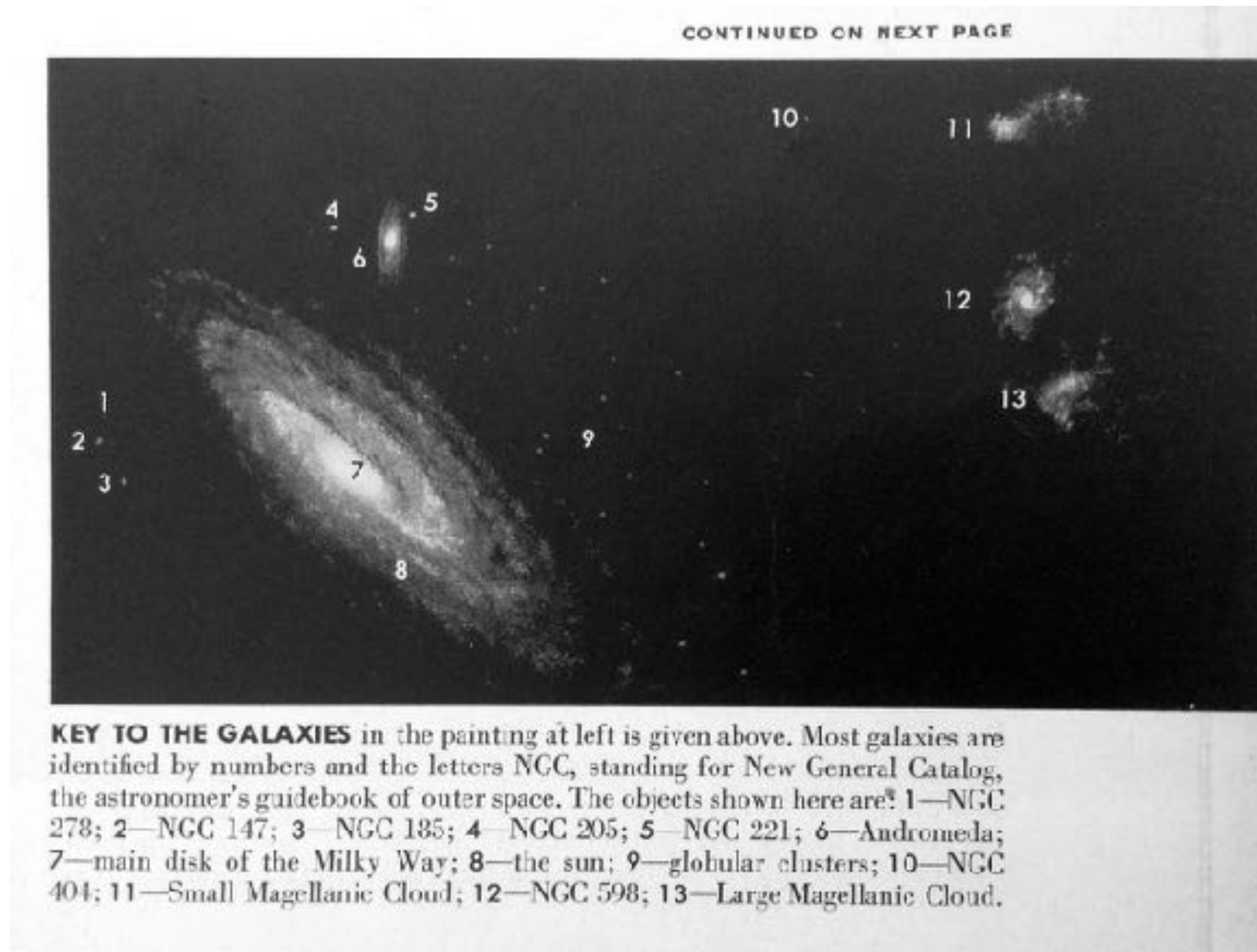


Questions

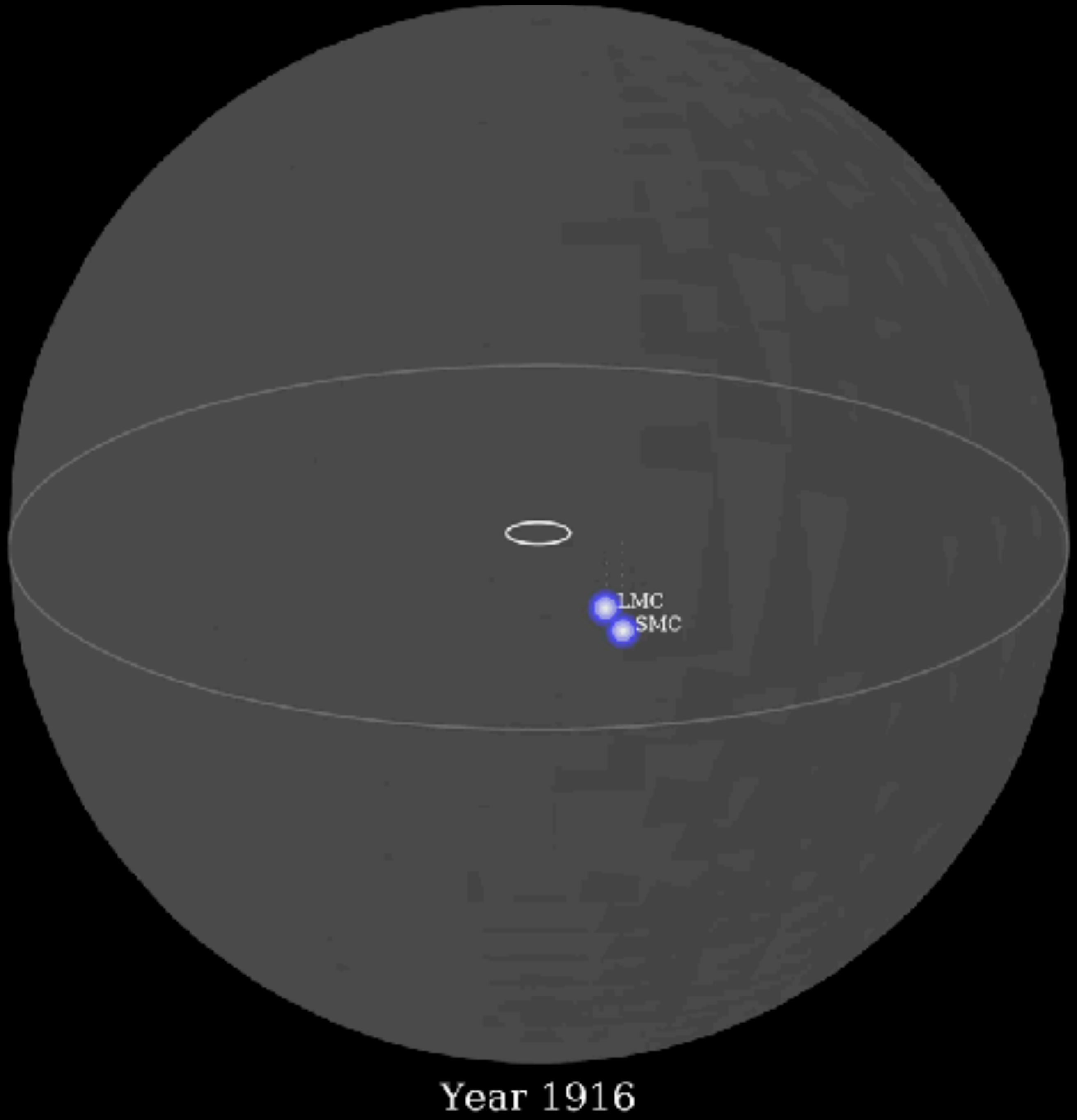
- What causes the signal?
- Is it unique to ΛCDM or universal in any dynamics?
- Is this a success for ΛCDM? Was this a prediction because the sims were run before?
- Why do orphan galaxies show a second peak on opposite side?
- Should we trust these dark matter only simulations results? If yes, then why not when we find a disagreement? If no, then why did we even bother to run them?

Let's move back to the Local Group





Observed MW satellites



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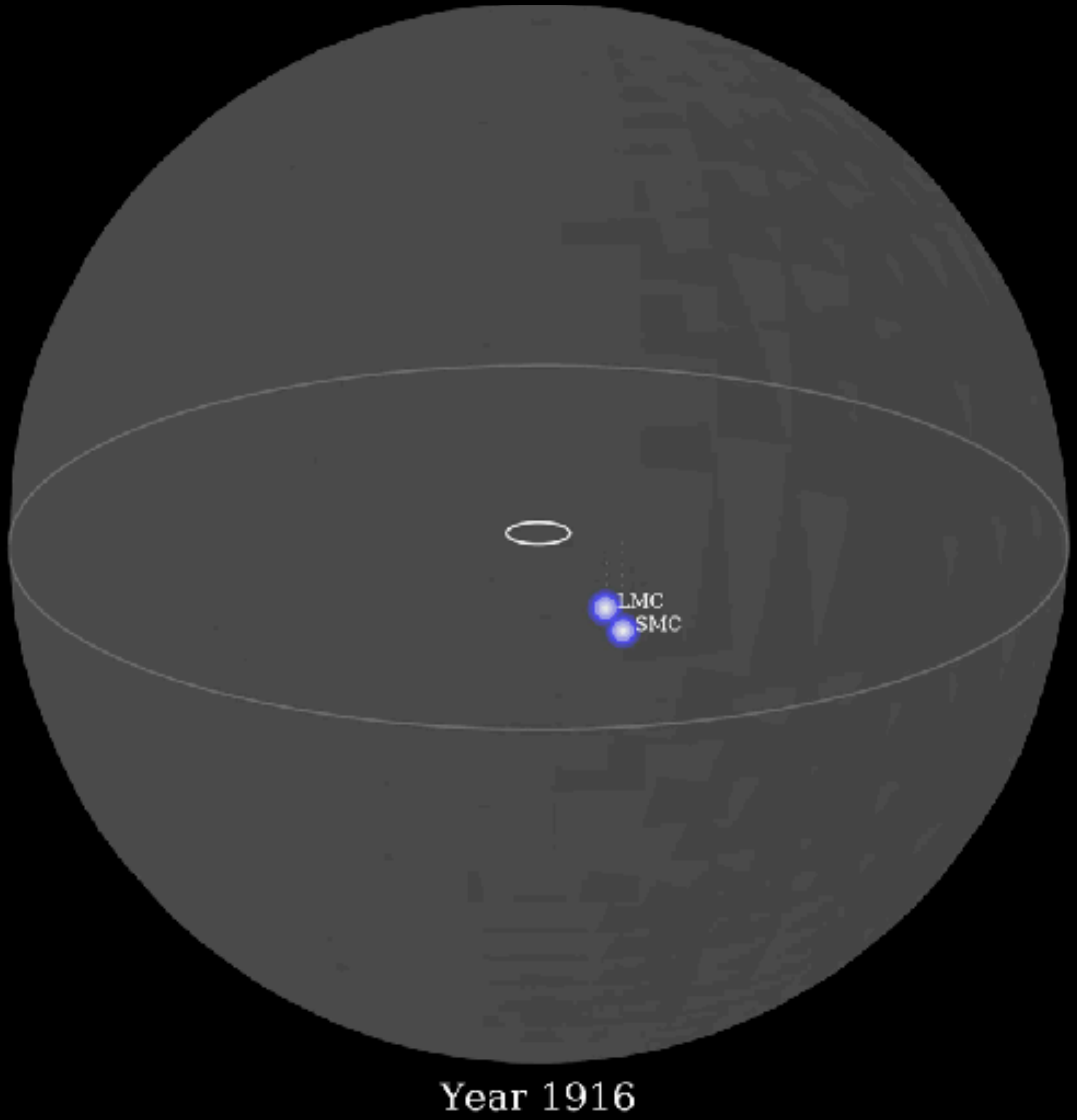
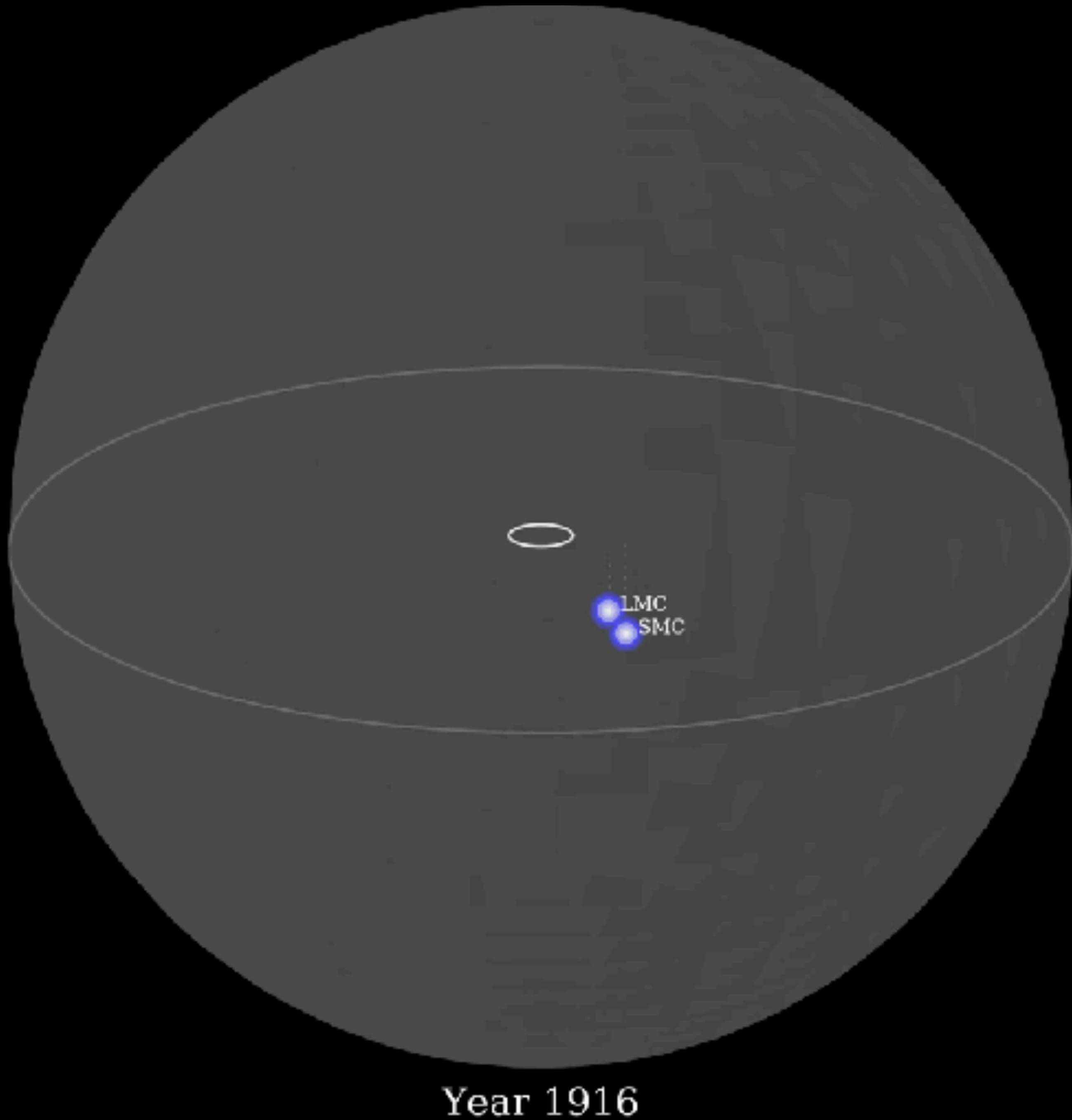
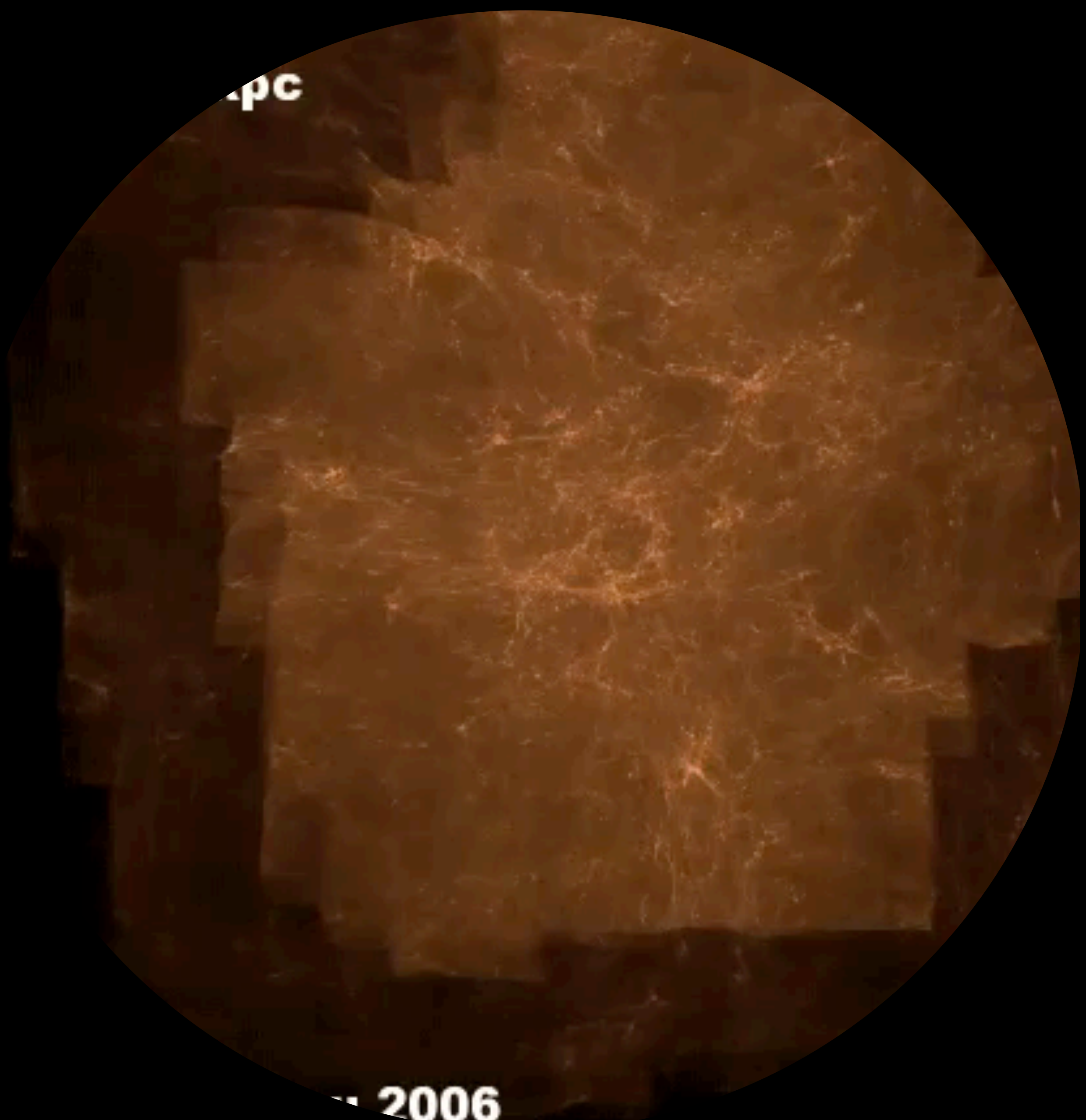


Observed MW satellites

Simulated DM subhalos





Diemand et al. (2006)

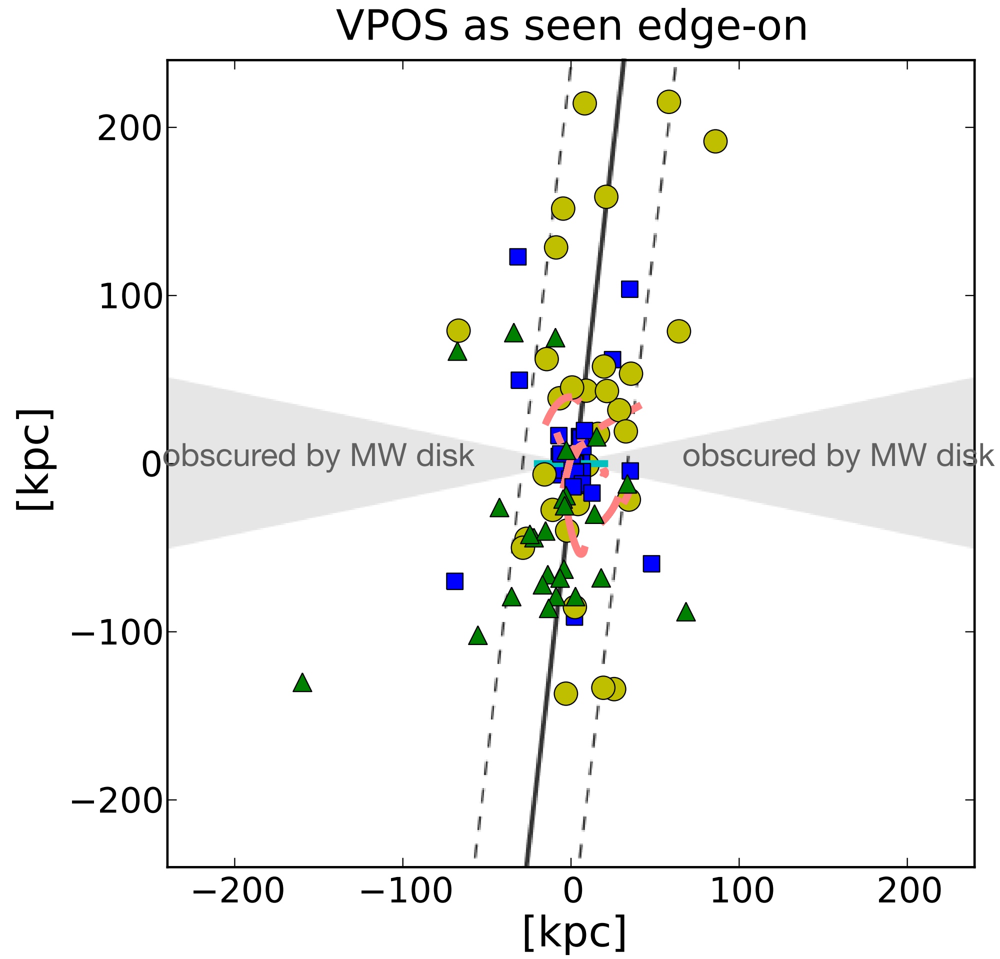
Co-rotating planes of satellite galaxies in the Local Group

So do we *really* trust those simulations?

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)

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



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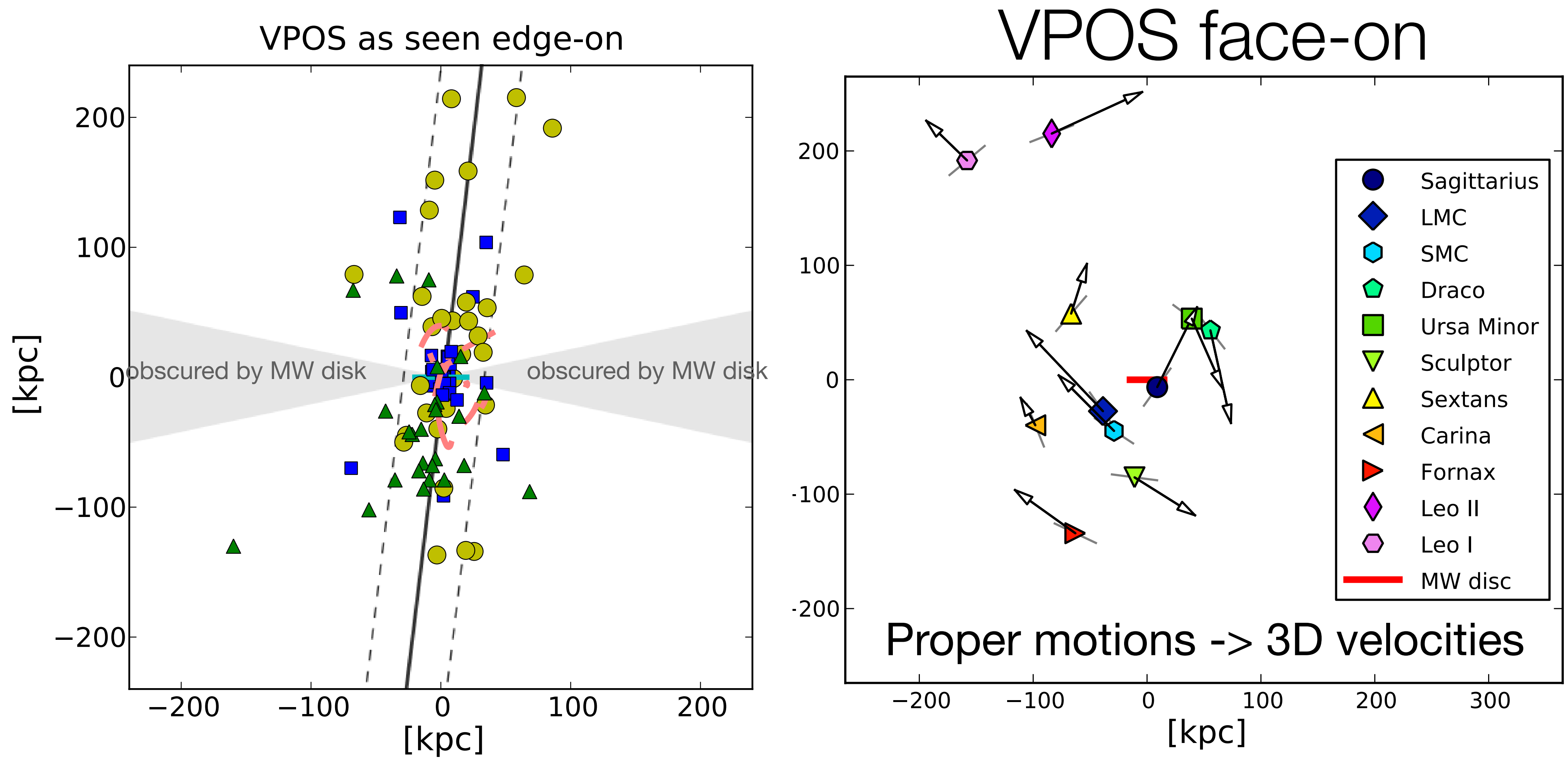

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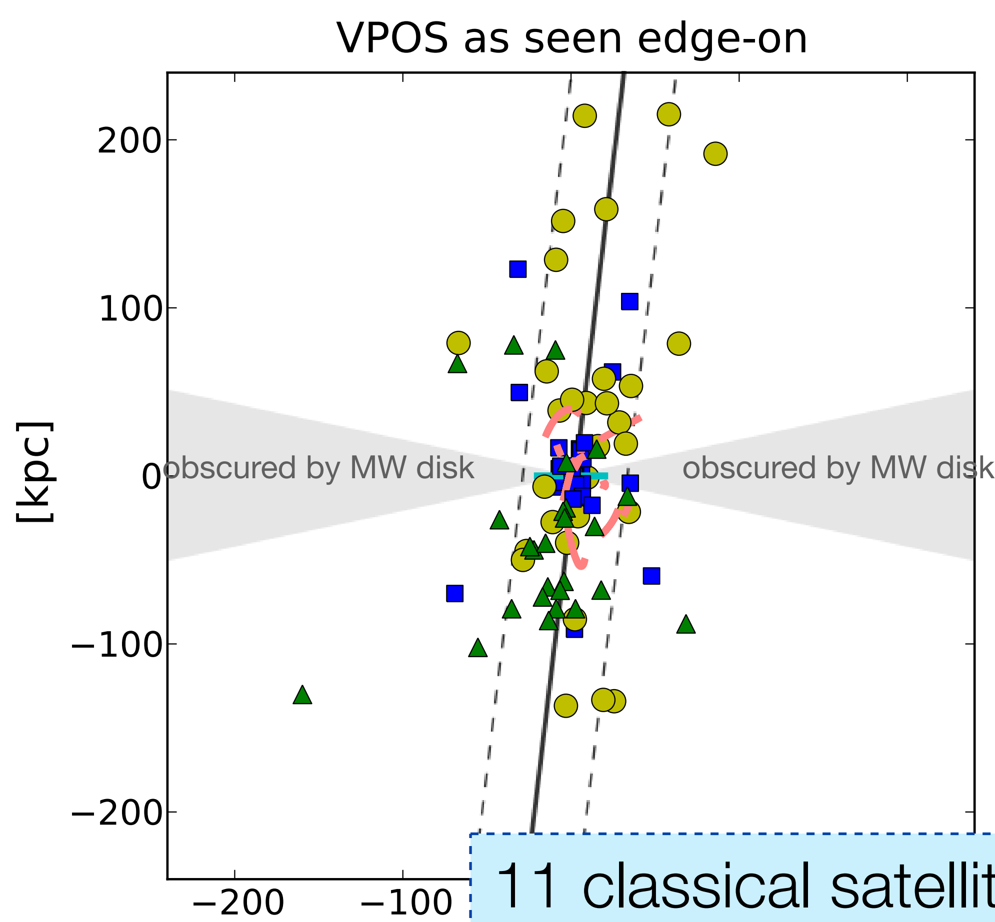
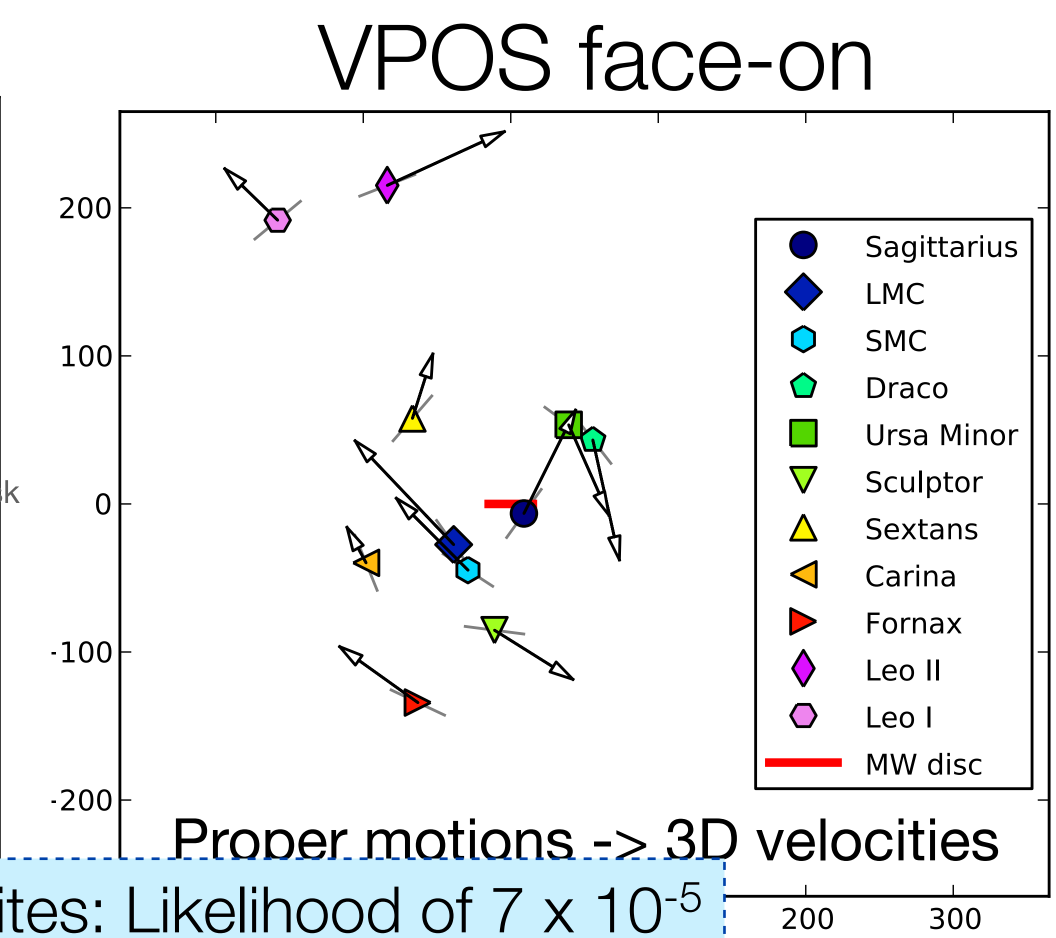




11 classical satellites: Likelihood of 7 x 10^{-5} if drawn from isotropic distribution (~4σ)

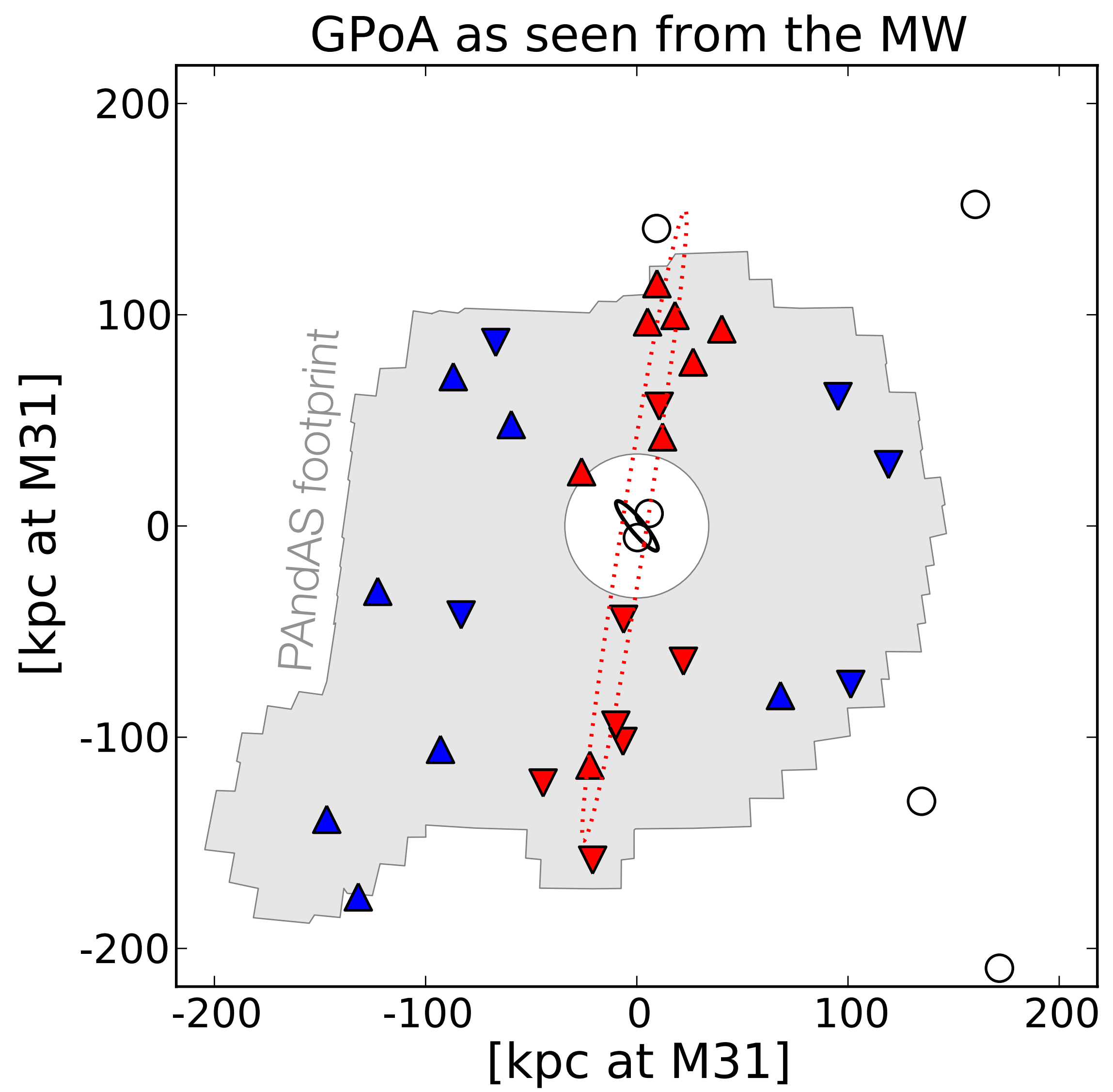
+ SDSS satellites: 4 x 10^{-7} (~5σ)

Pawlowski (2016, MNRAS, 456, 448)

The Great Plane of Andromeda (GPoA)

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

- **50%** of M31 satellites align in highly flattened structure (~14 kpc height).
- Seen almost edge-on from the MW.
- Line-of-sight velocities (▲/▼) indicate 13 of 15 members might co-orbit.



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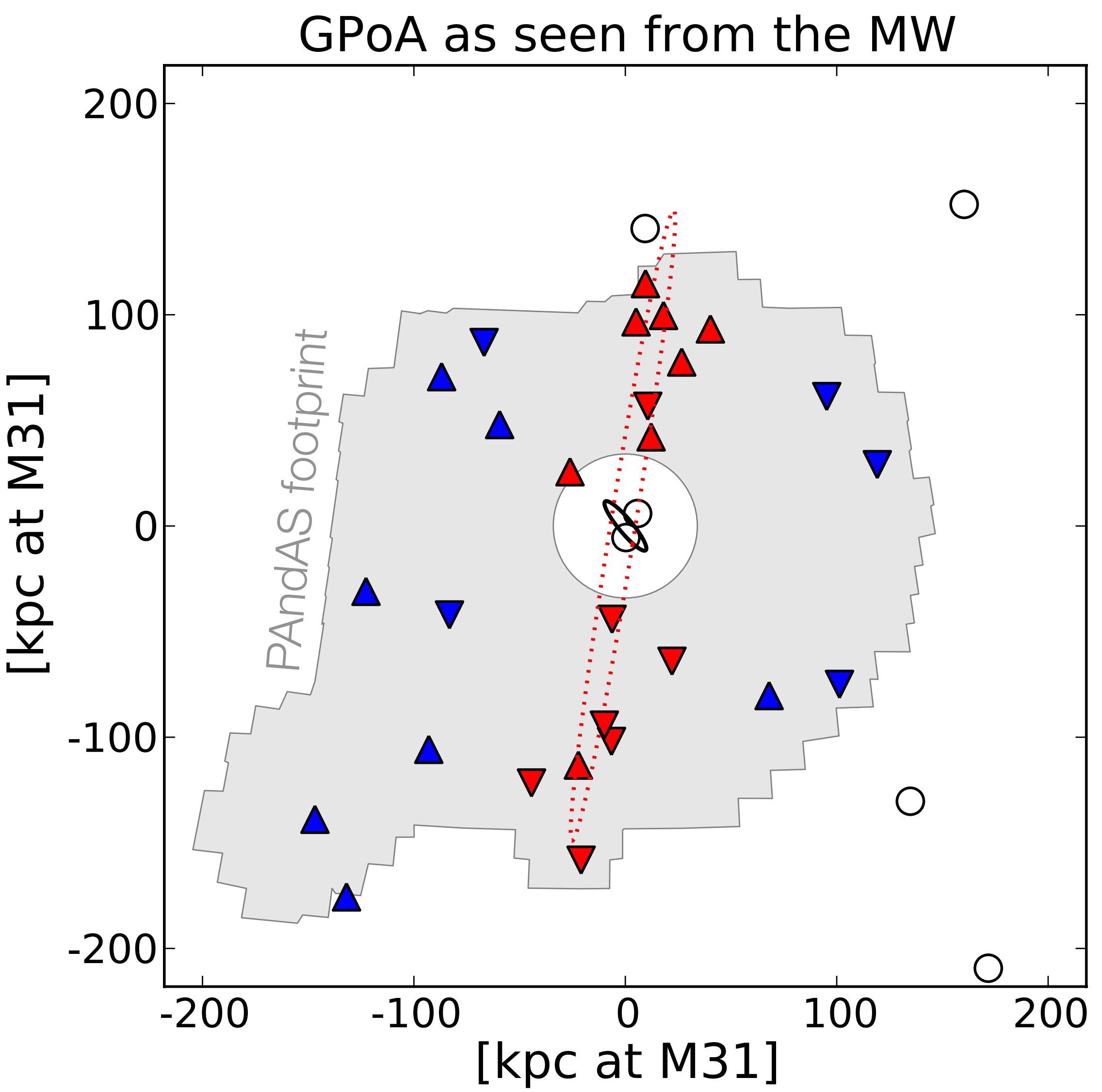
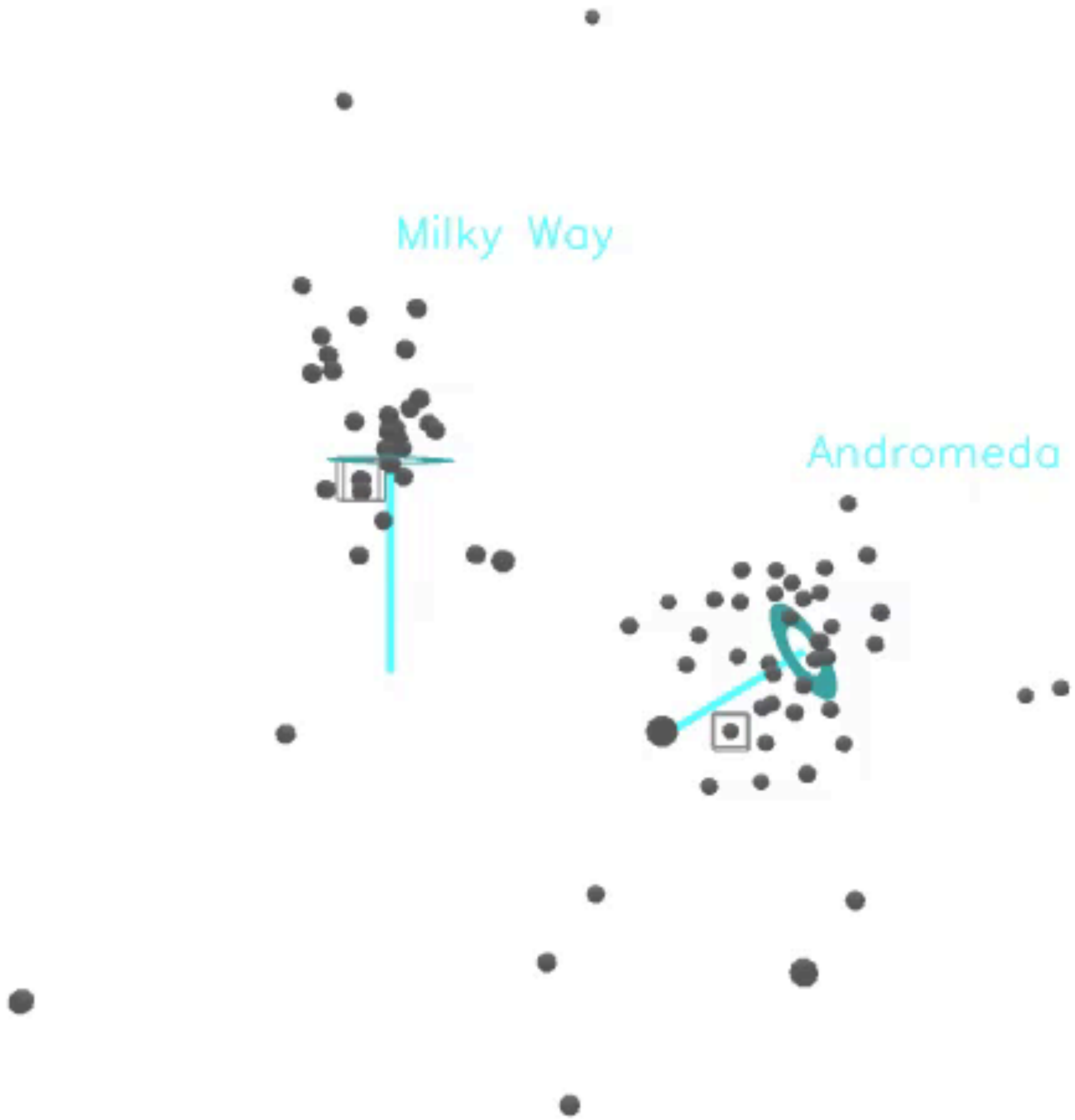
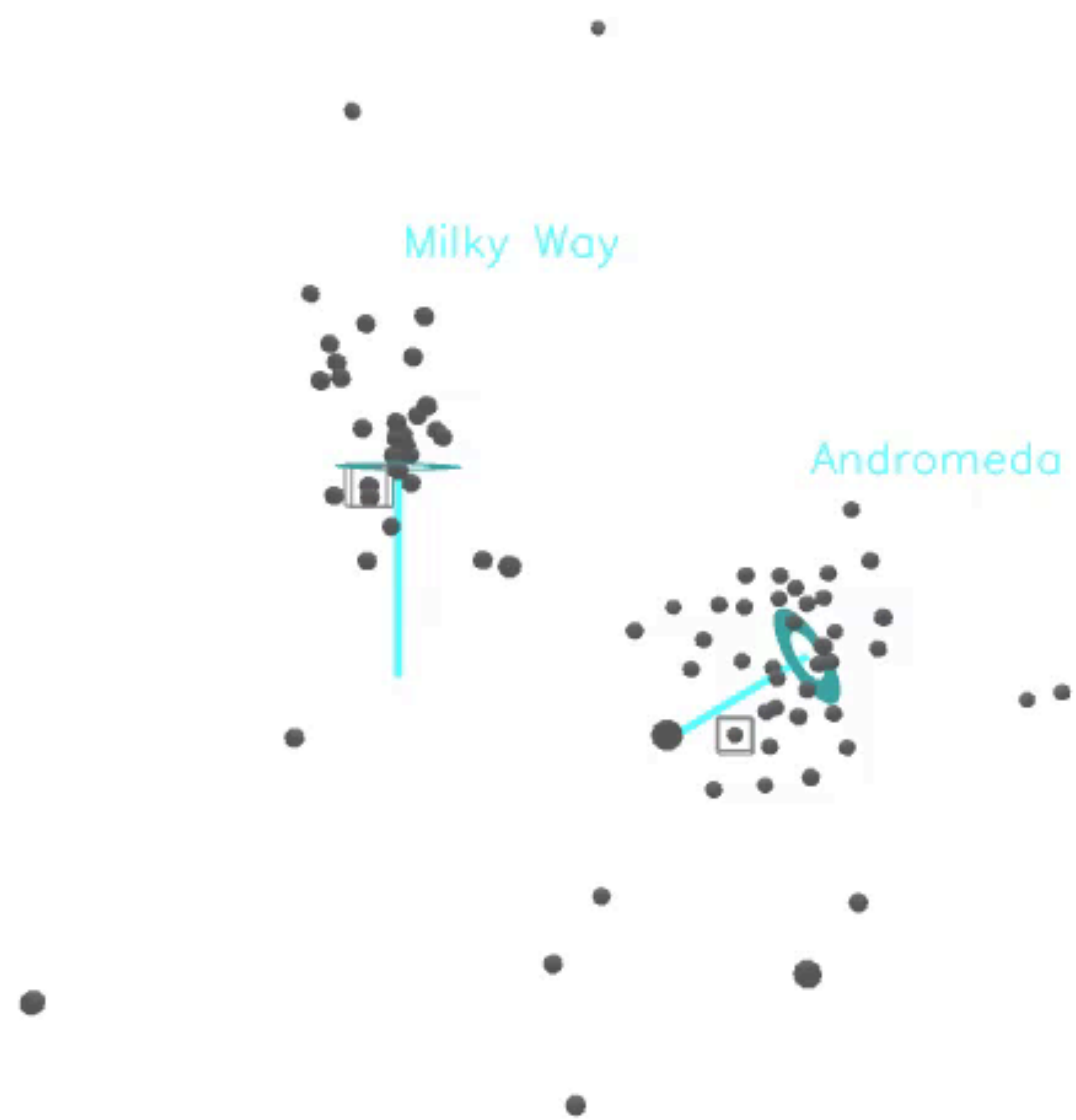
Likelihood of 2×10^{-5} if drawn from isotropic distribution (~3.7σ)




Milky Way
Andromeda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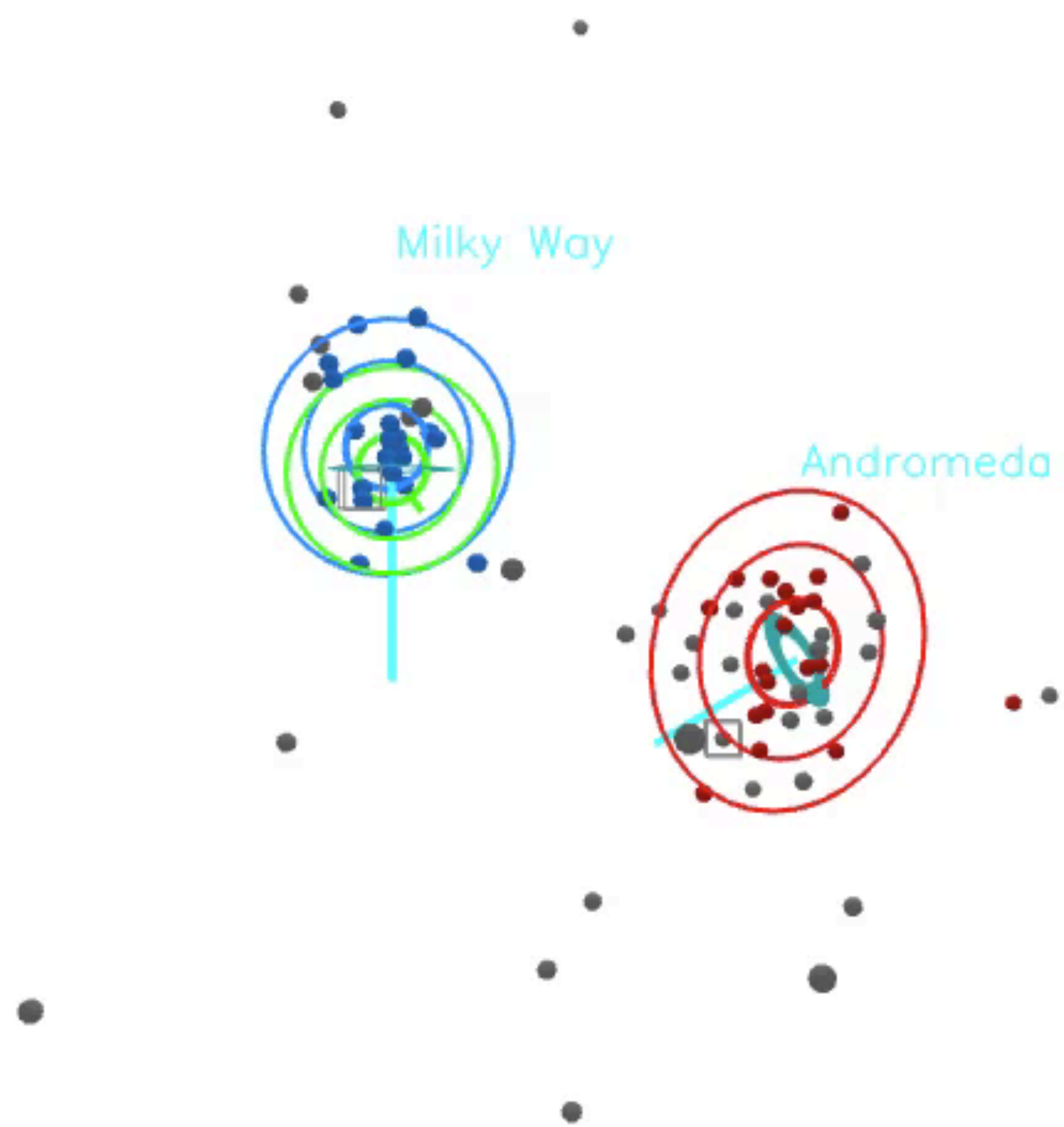
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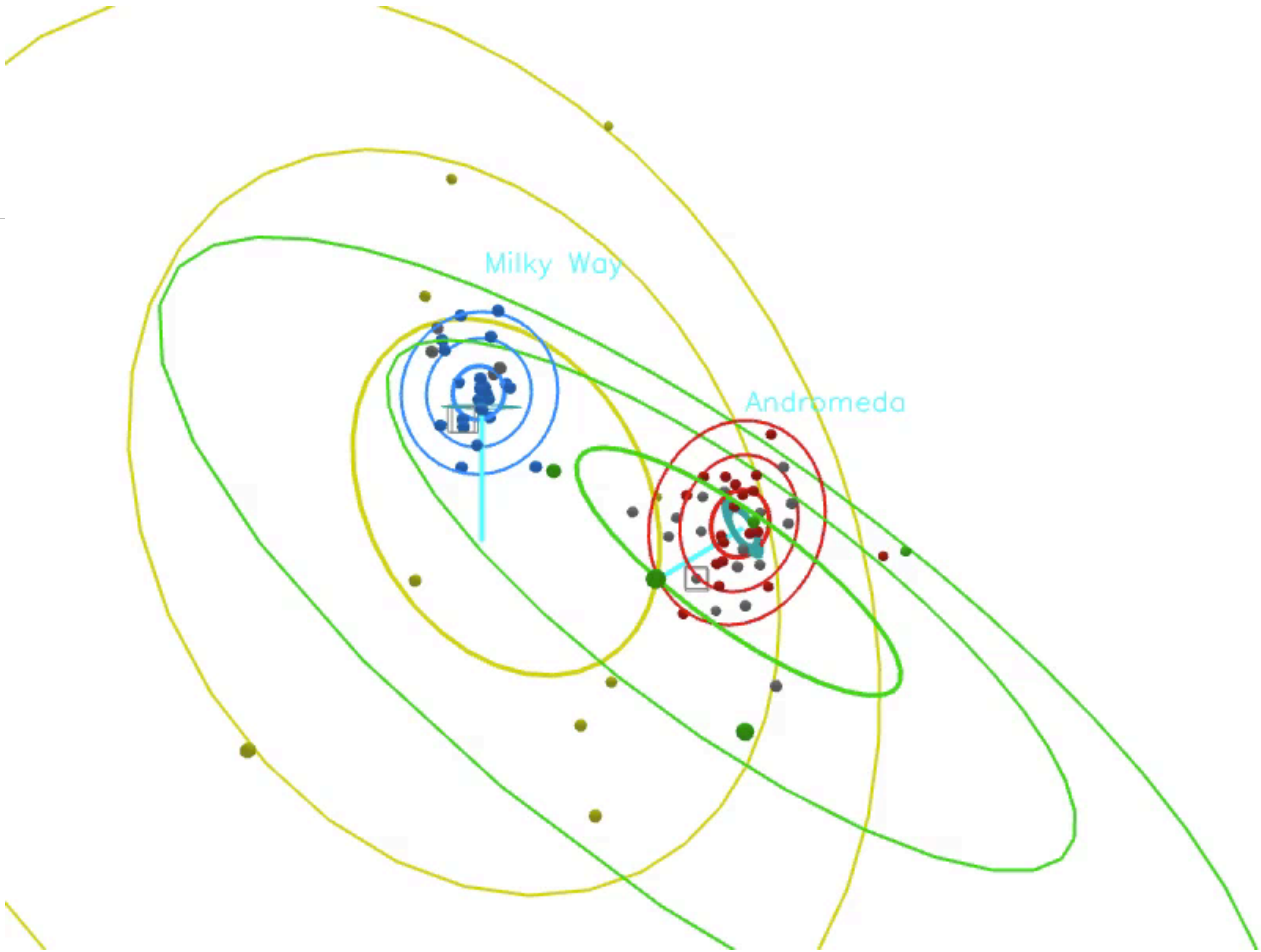
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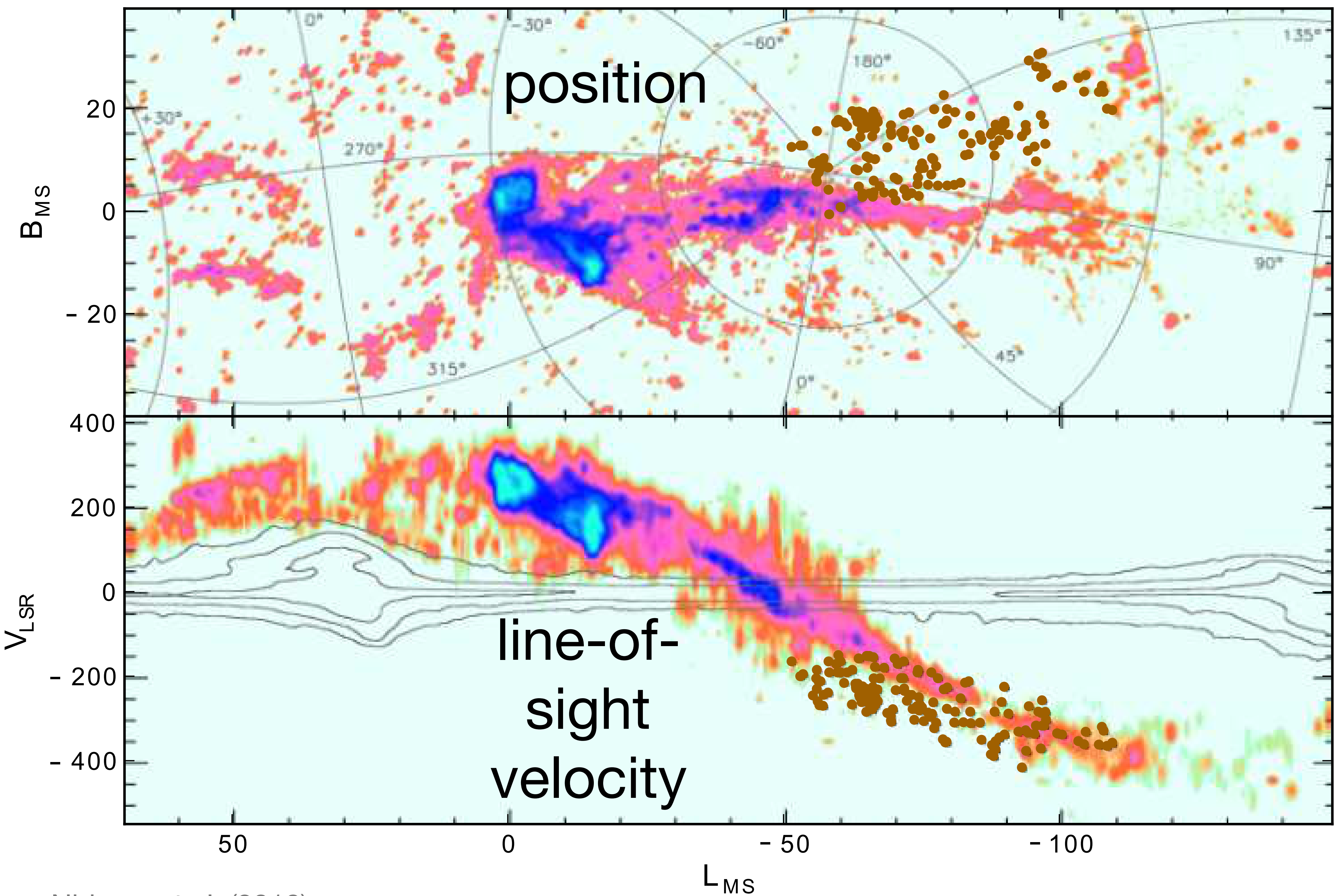
MW south: Magellanic Stream connecting VPOS, GPoA, LGP1?

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



MS map from Nidever et al. (2010)
HVCs from Westmeier & Koribalski (2008)

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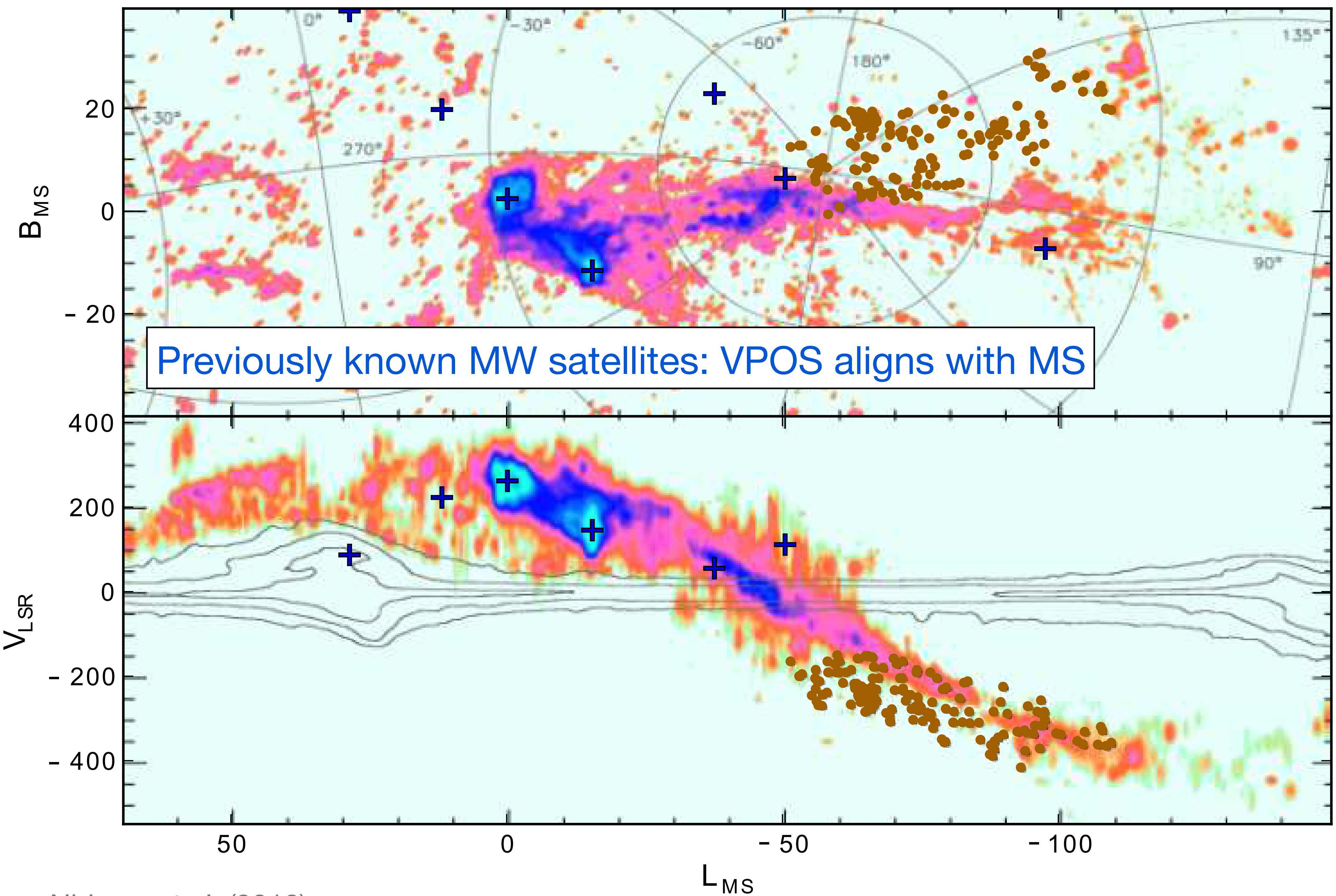

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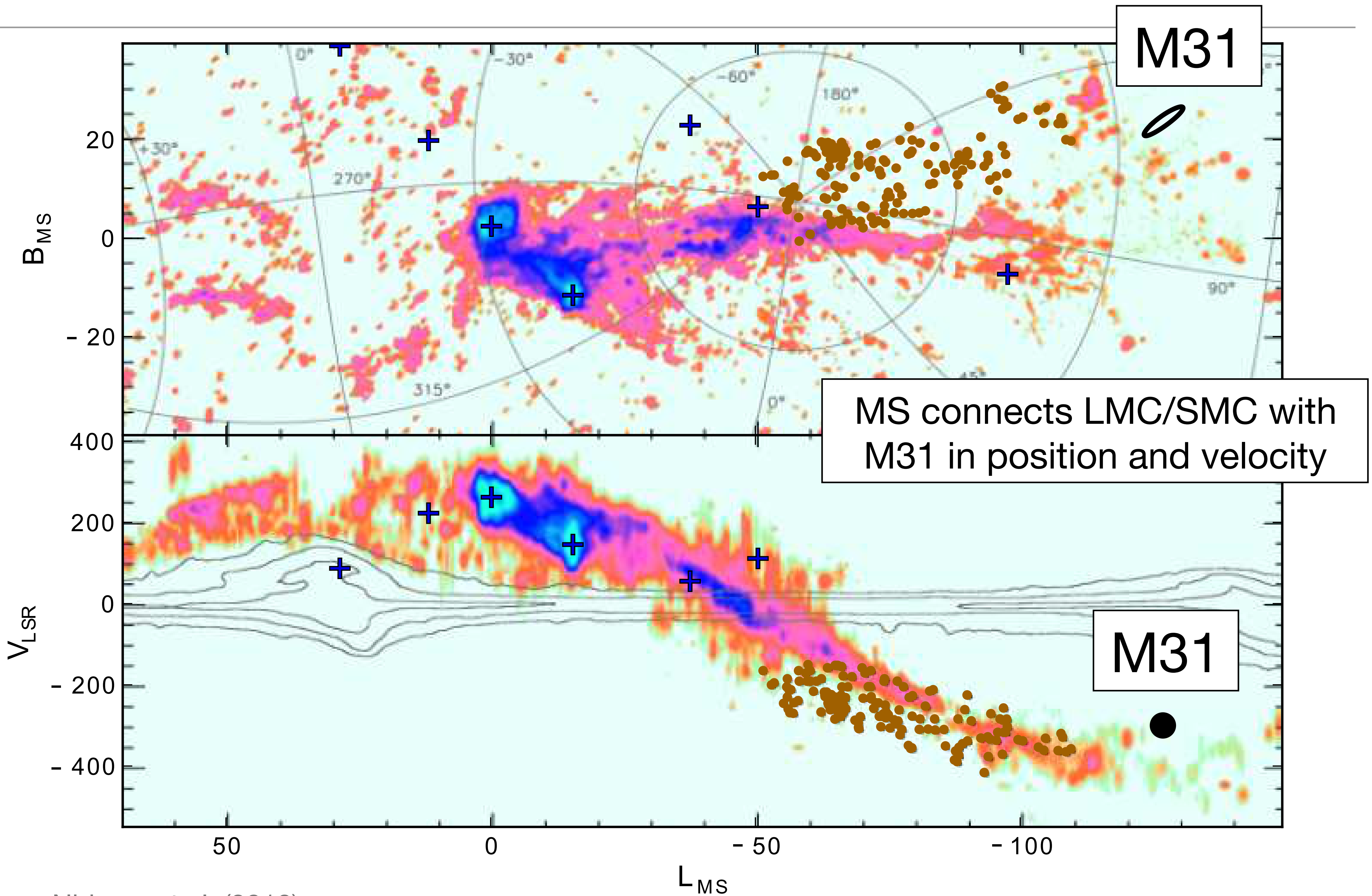

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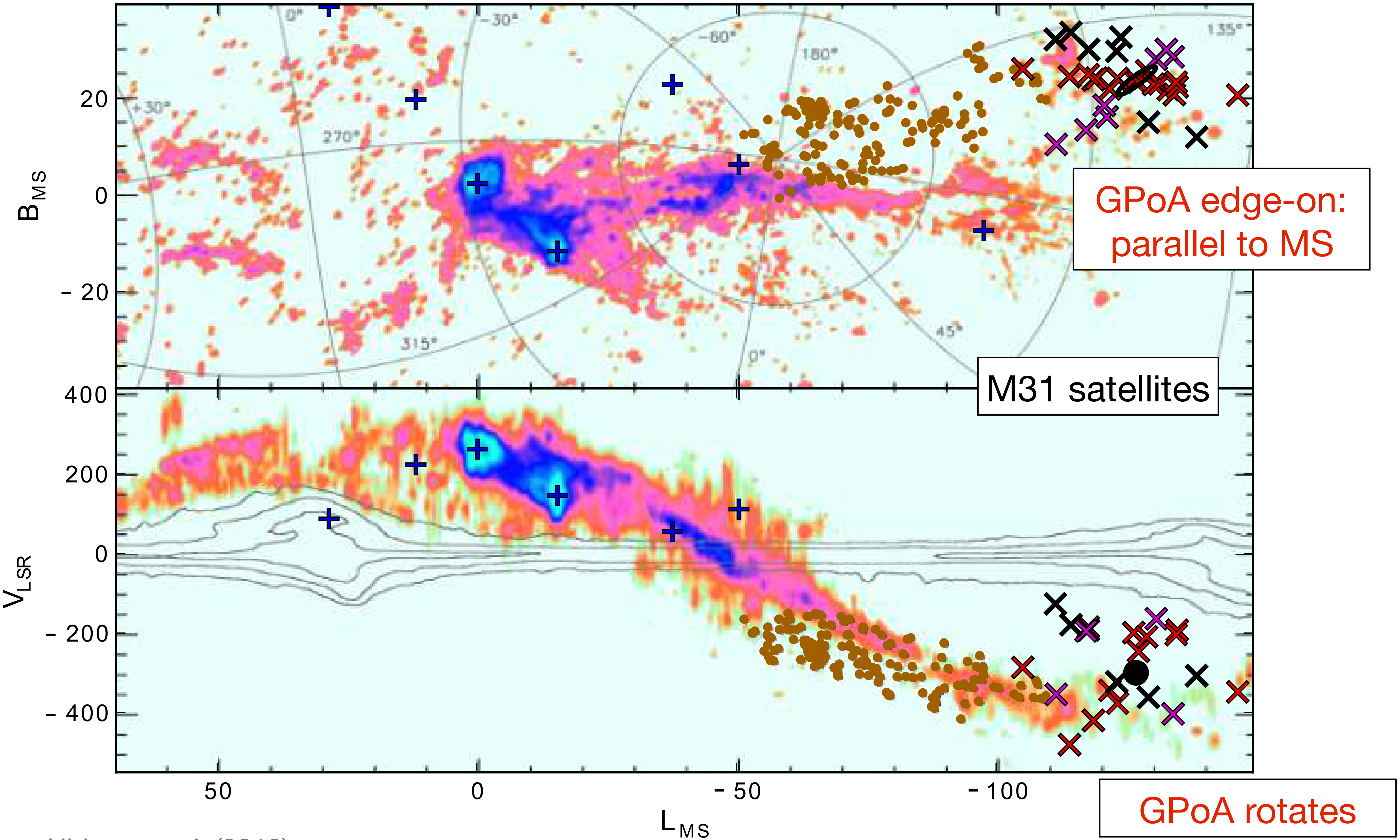

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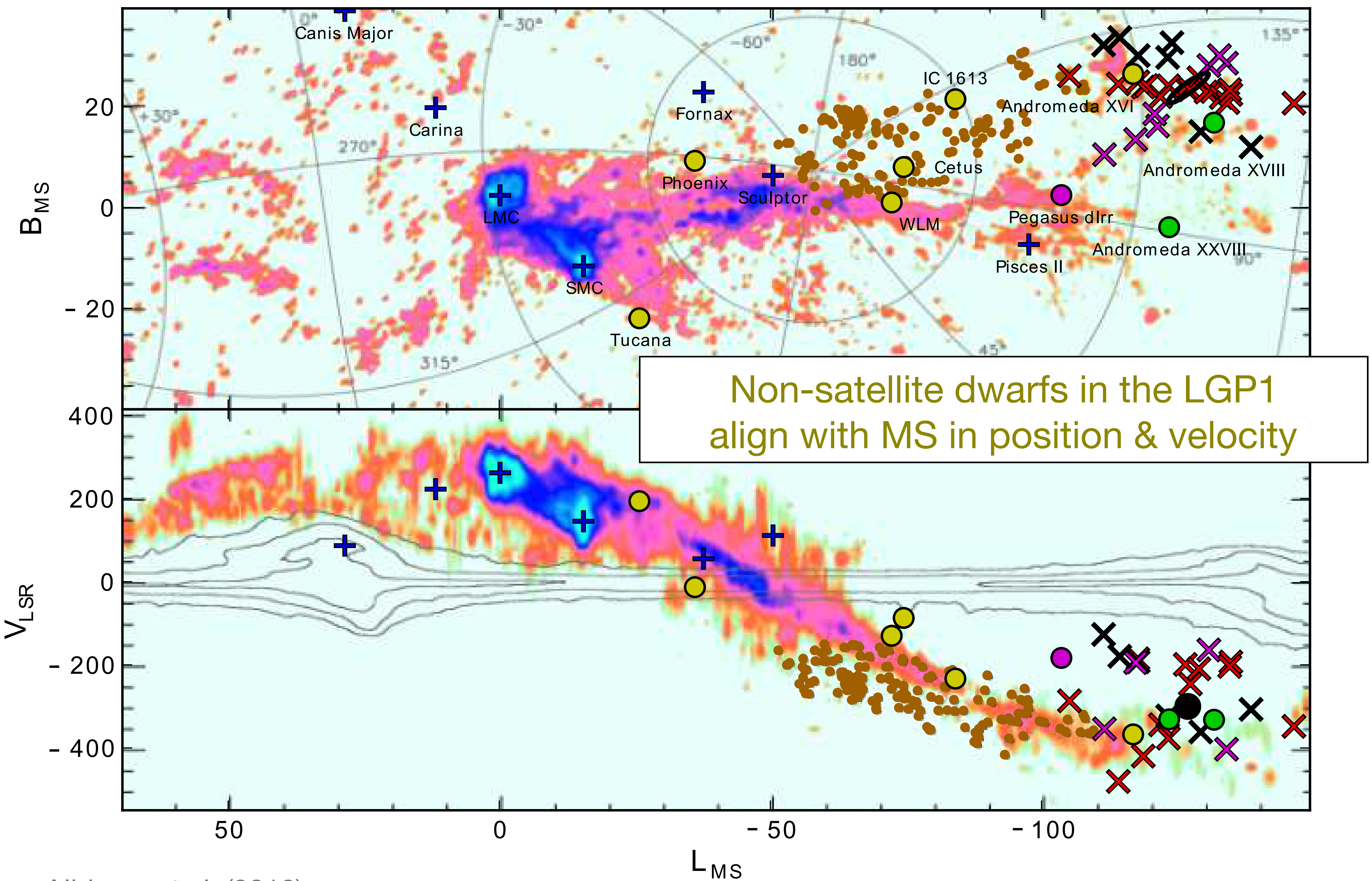

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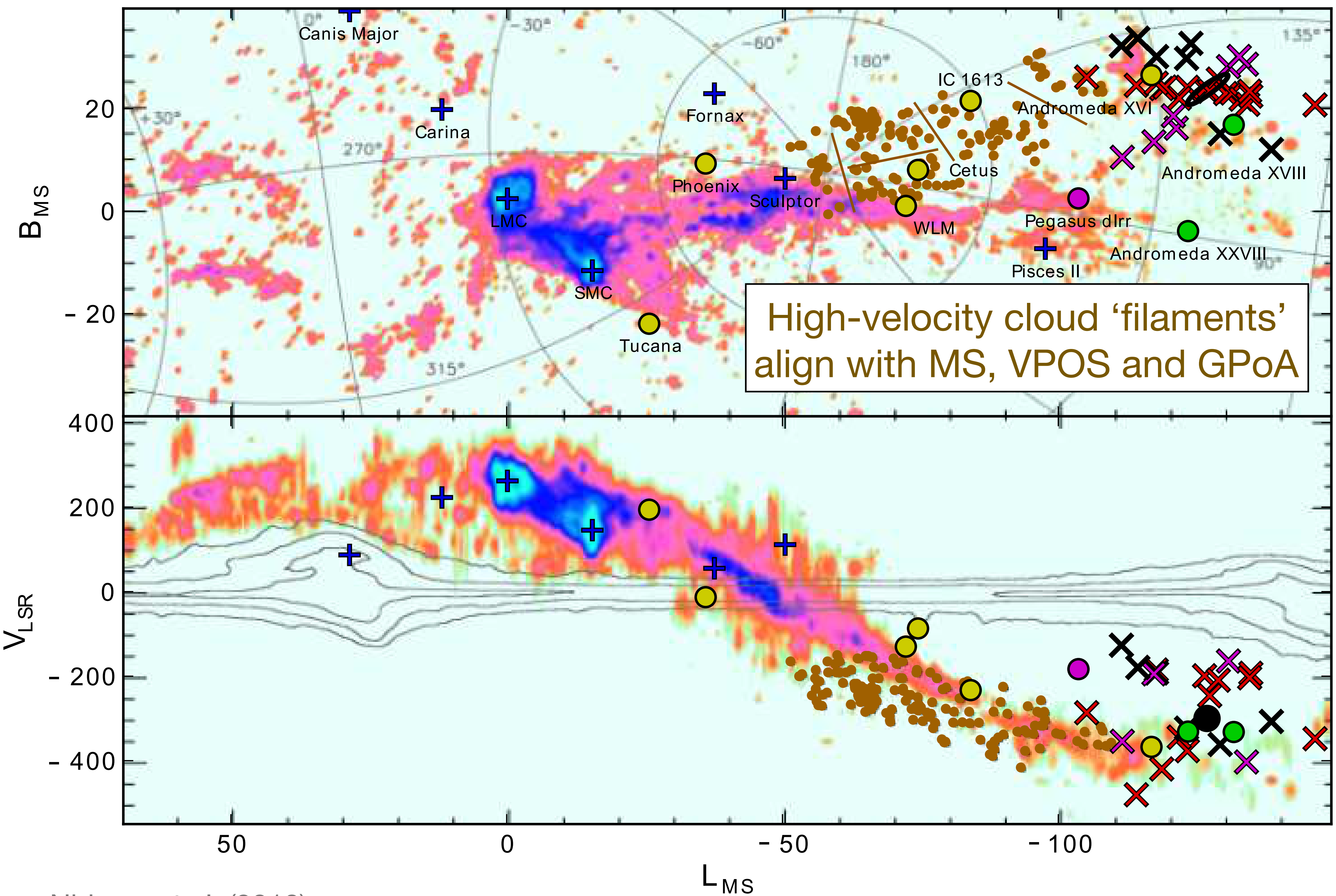

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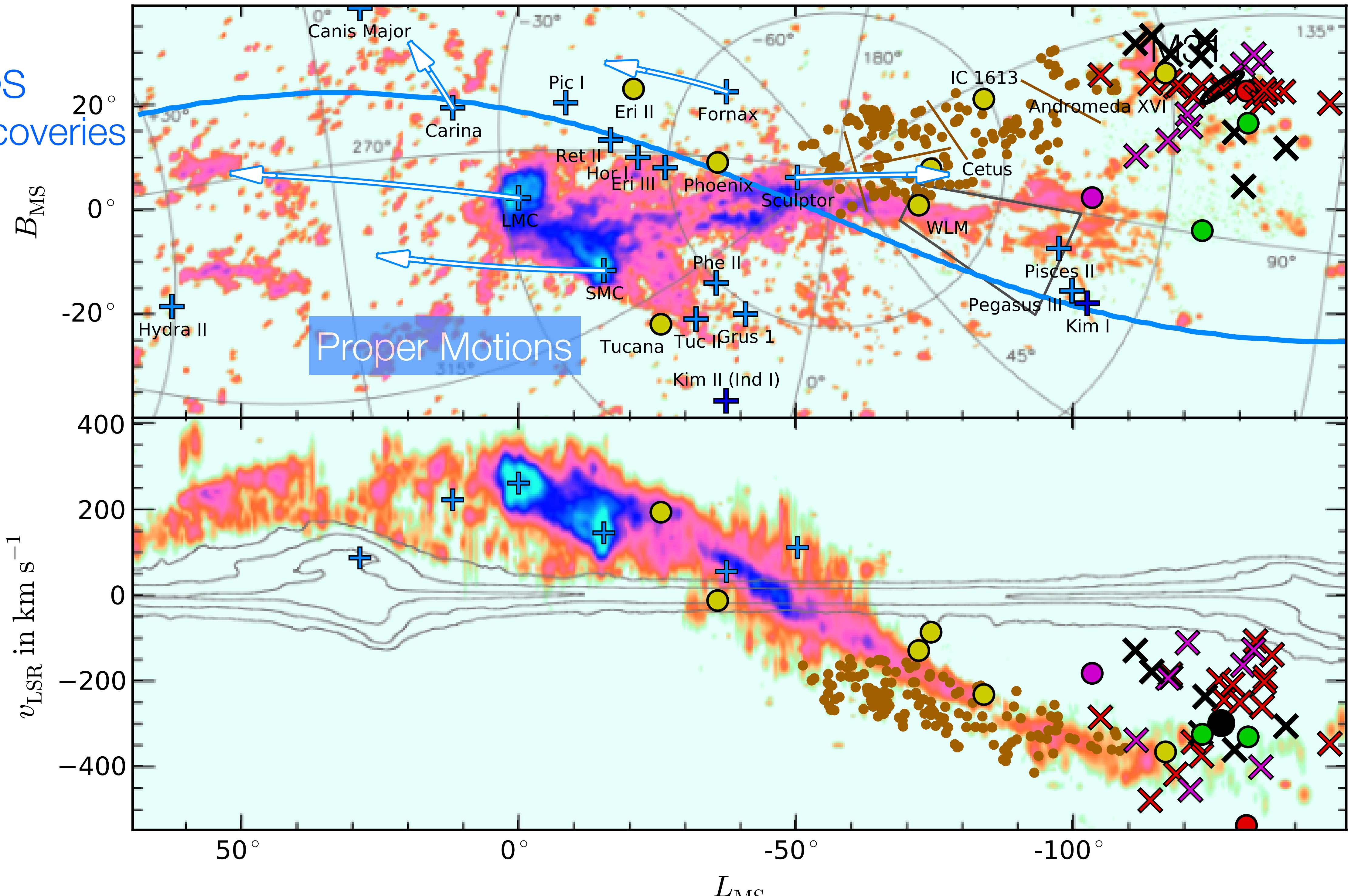
VPOS
new discoveries



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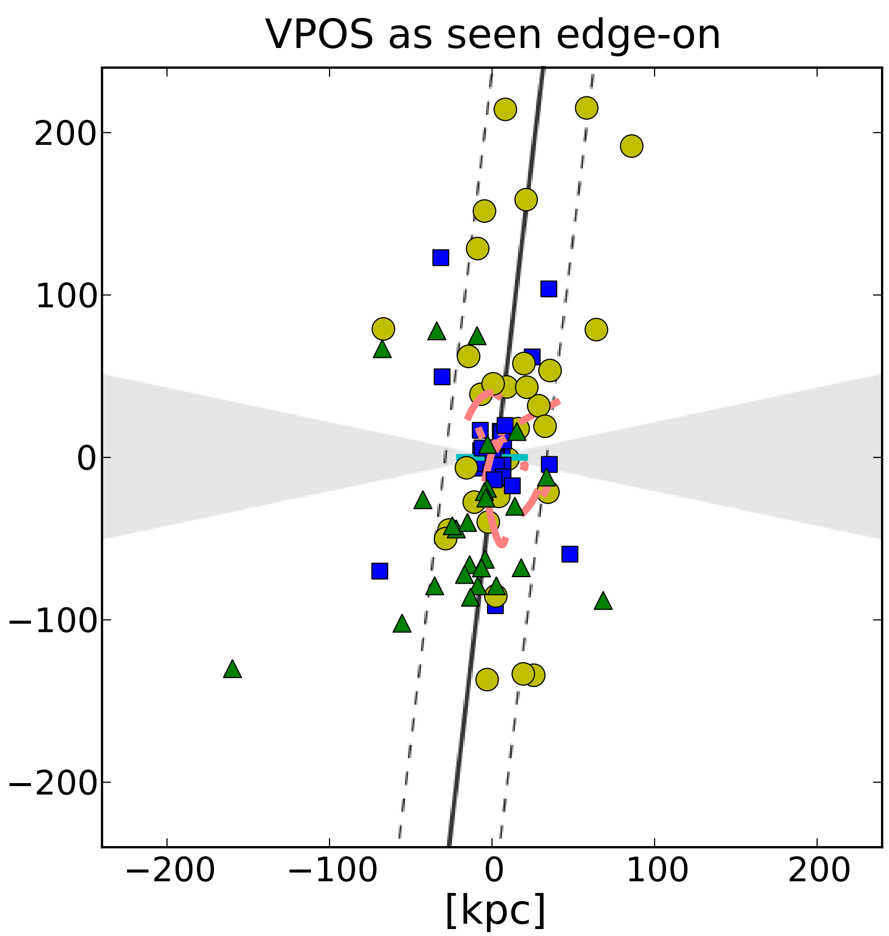
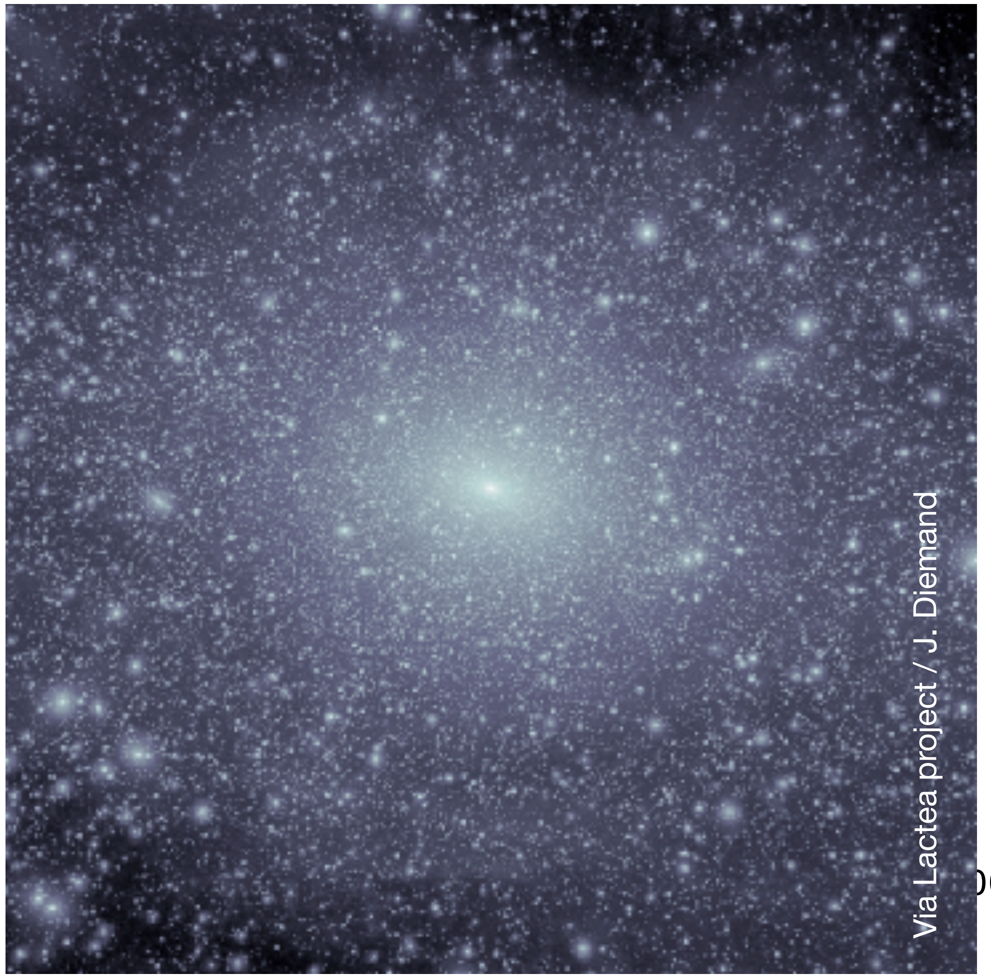
Testing ΛCDM with planes of satellite galaxies

Pawlowski+(2014, MNRAS, 442, 2362); Pawlowski & McGaugh (2014, ApJL, 789, 24); Ibata et al. (2014)





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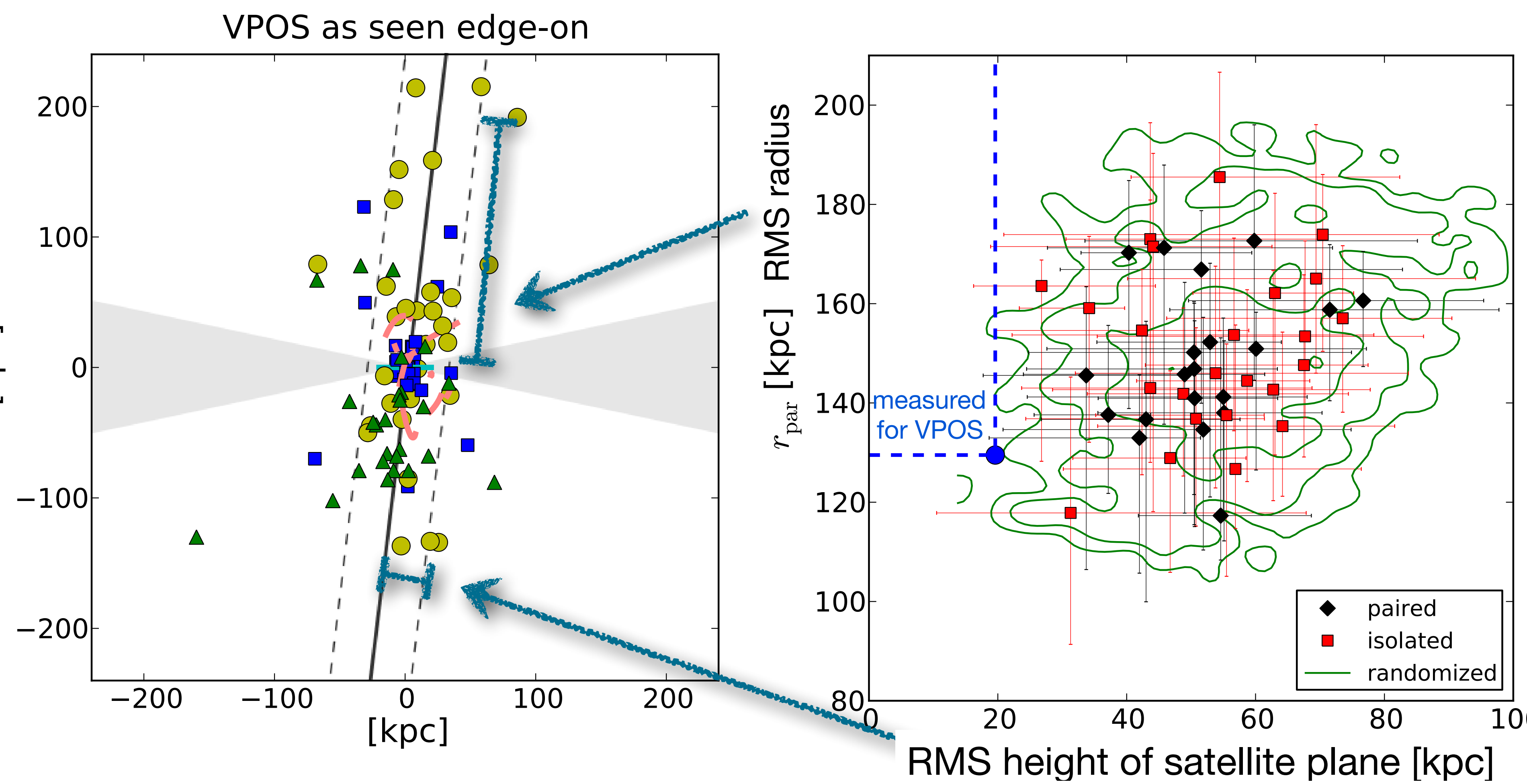

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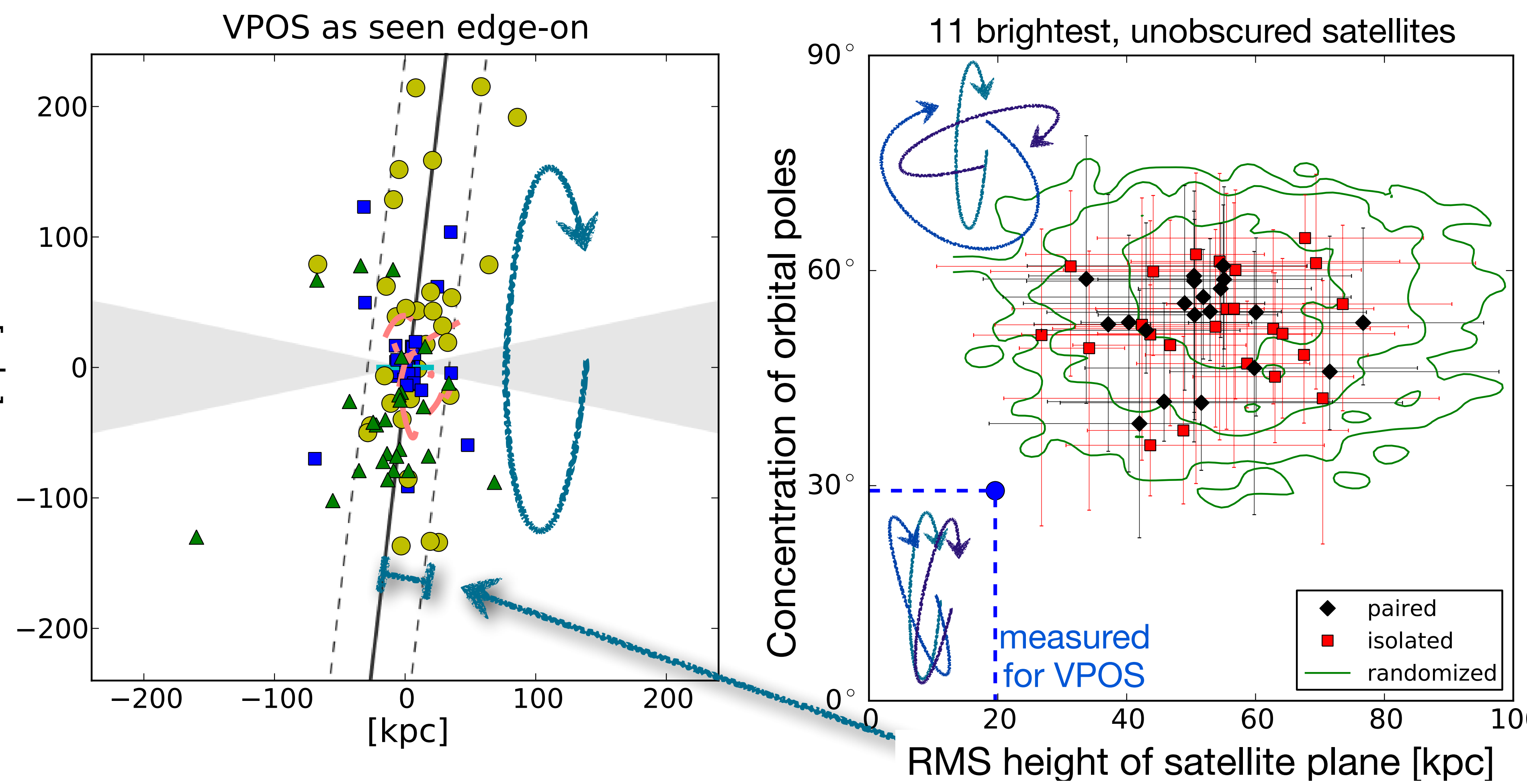

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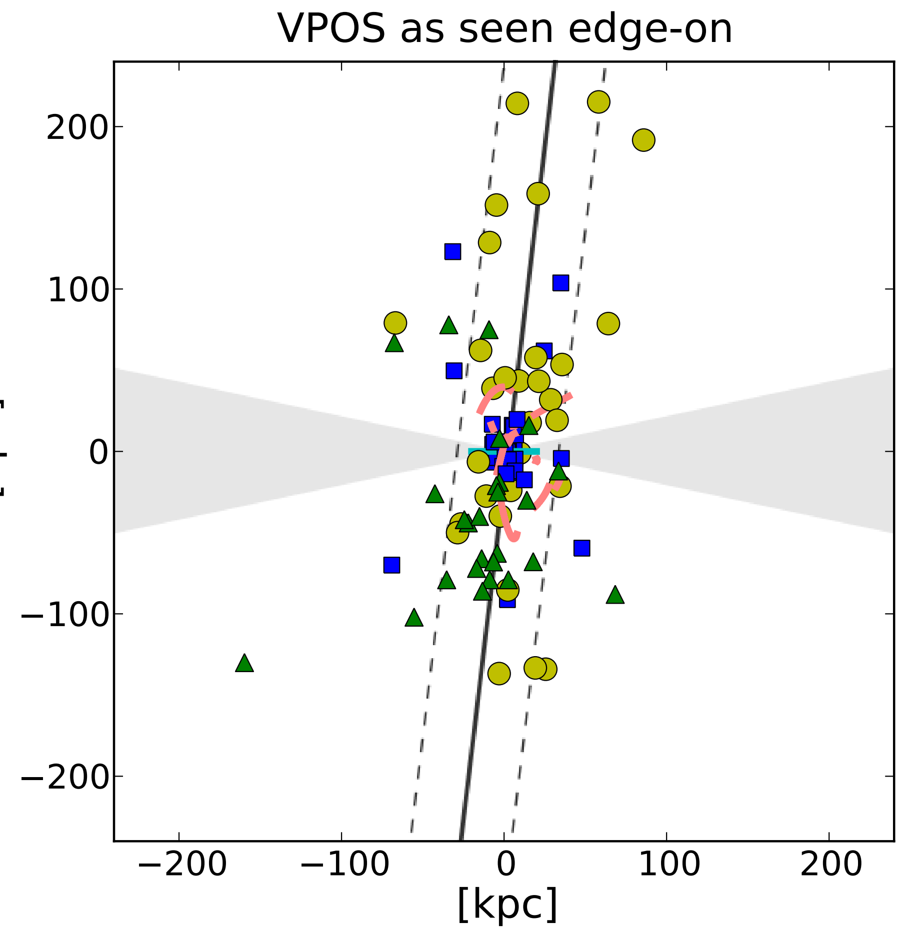

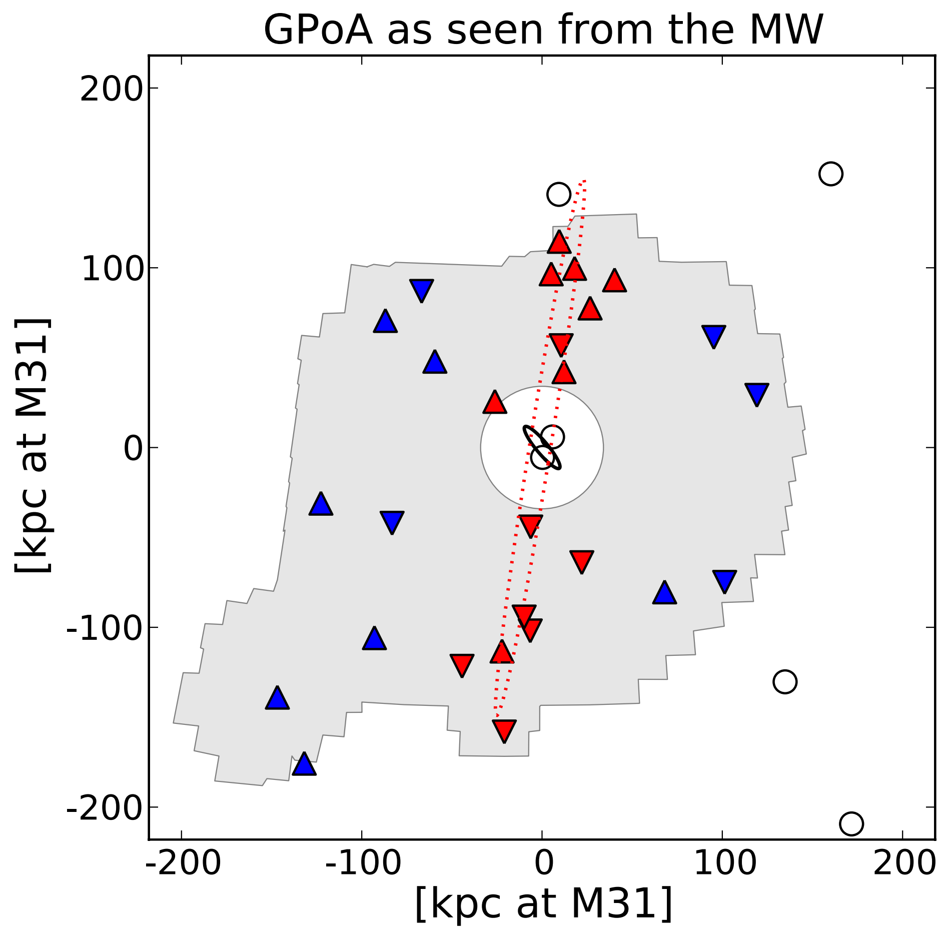

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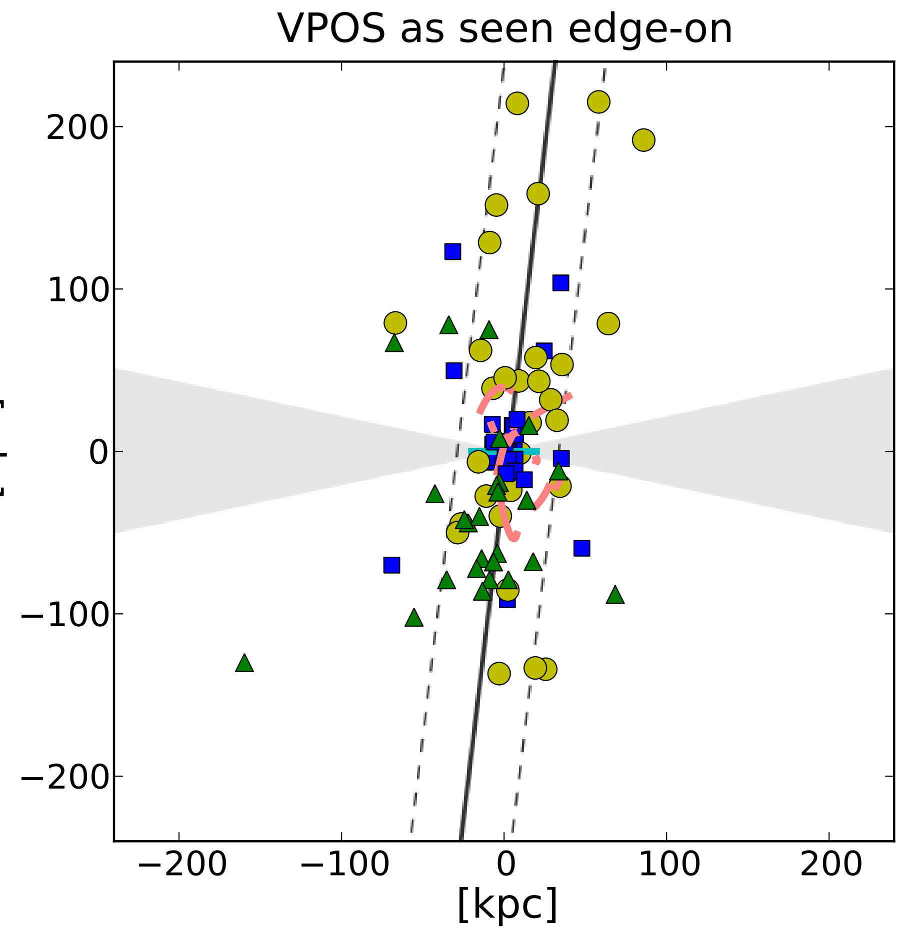

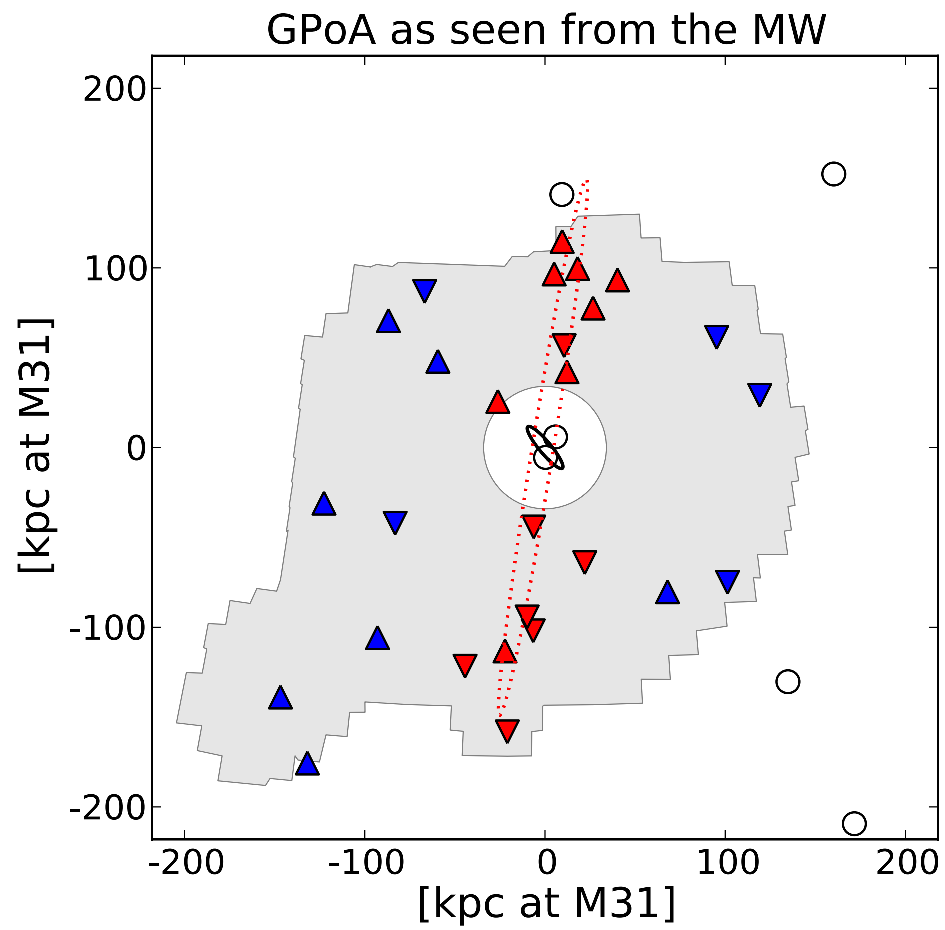

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- 2 out of 2 systems in LG:

  < 0.001 %

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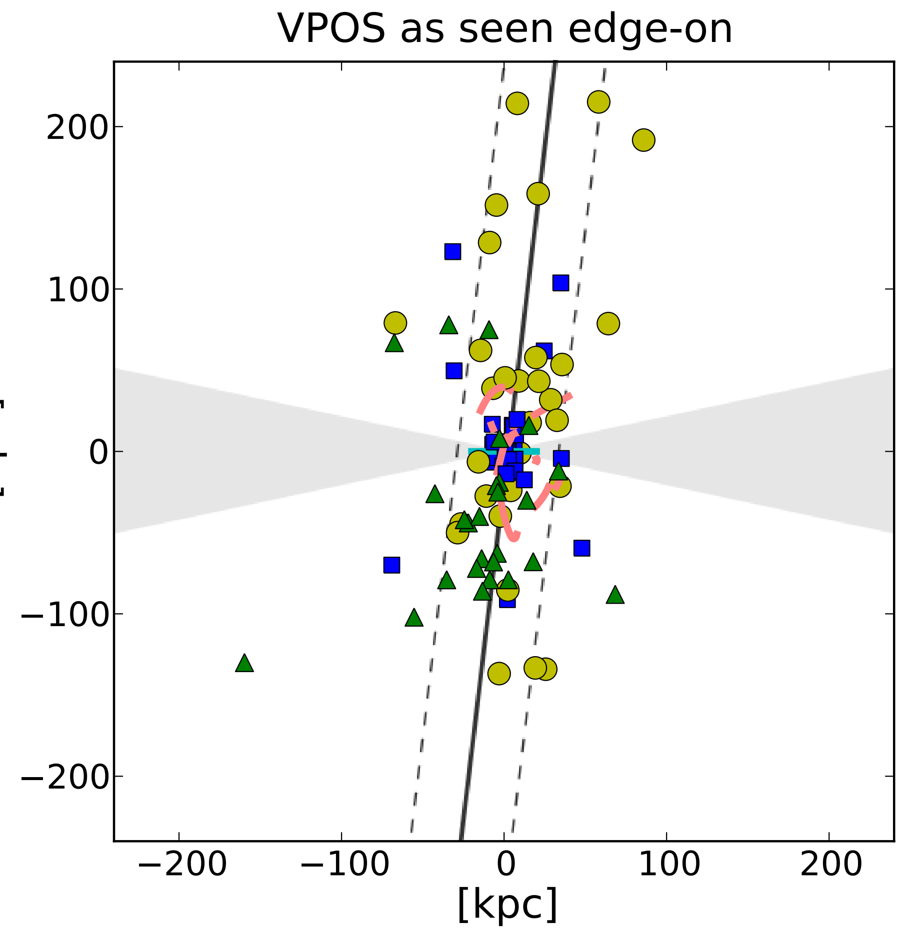
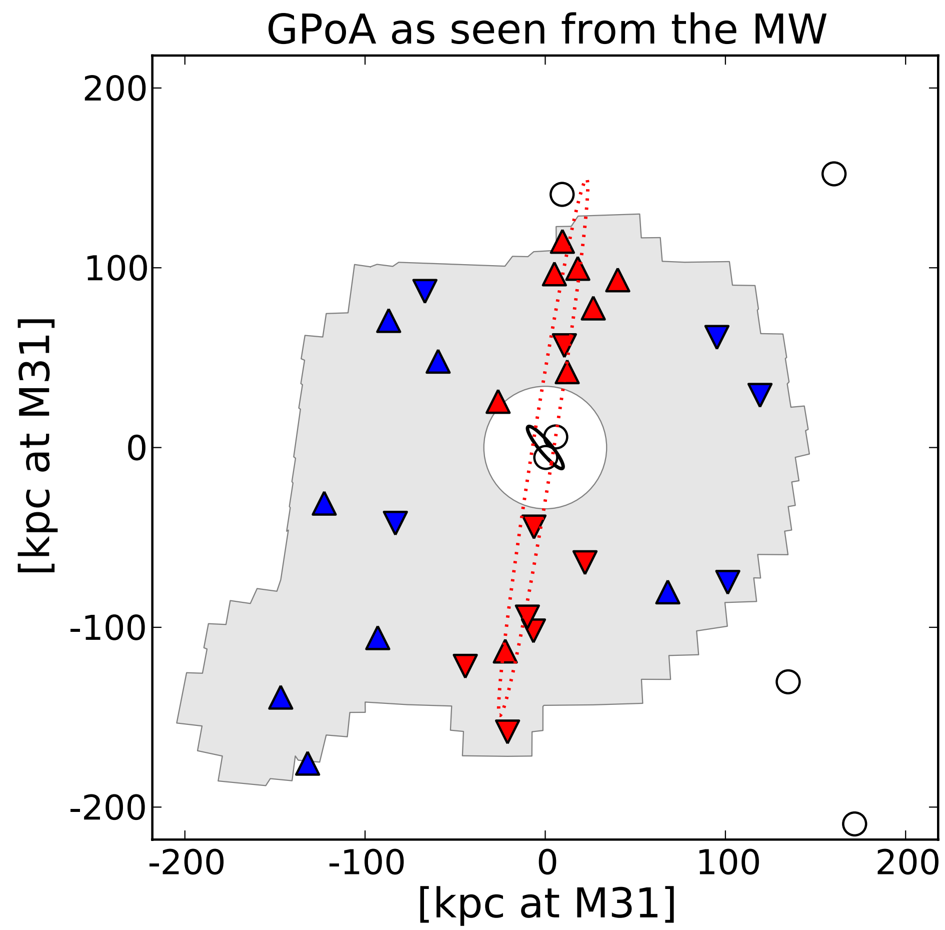
Pawlowski+(2014, MNRAS, 442, 2362); Pawlowski & McGaugh (2014, ApJL, 789, 24); Ibata et al. (2014)





How frequent around MW/M31-like hosts in ΛCDM?

- Same flattening as 11 classical satellites in VPOS:

  ***height*: 0.3 - 1.2%**

  ***axis ratio*: 0.8 - 1.6%**

  (but: additional objects align)

- Satellites co-orbit in VPOS:

  0.02 - *0.15 %*

- Similar for M31 sat. plane:

  0.04 - 0.17 %

- 2 out of 2 systems in LG:

  < 0.001 %

Elsewhere?
Stay tuned for Oliver's talk

Are satellite galaxy planes a problem for ΛCDM?
An (incomplete!) list

Reference	ΛCDM problem?	Main argument
Kroupa et al. (2005)	yes	observed spatial distribution vs. isotropy
Zentner et al. (2005), Libeskind et al. (2005)	no	sub-halo distribution not isotropic
Metz et al. (2008)	yes	some orbital poles align with satellite plane normal
D'Onghia & Lake (2008), Li & Helmi (2008)	no	group infall could explain anisotropy
Metz et al. (2009)	yes	no sufficiently compact groups observed for infall idea
Lovell et al. (2011)	no	filamentary accretion -> orbital pole distr. anisotropic
Pawlowski et al. (2012)	yes	insufficient to explain strong orb. pole alignment, sub-halos expected to align with MW not perpendicular
Pawlowski et al. (2013)	yes	VPOS: not only sat. galaxies, but also GCs & streams
Wang et al. (2013)	no	Can find similarly flattened satellite distribution in sims
Ibata et al. (2013, 2014)	yes	M31 sat. plane in addition to MW VPOS (2/2 in LG)
Bahl & Baumgardt (2014)	no	M31 satellite plane parameters can be found in MS-II
Ibata et al. (2014), Pawlowski et al. (2014)	yes	Must reproduce plane params simultaneously & model obs. biases correctly; then planes v. unlikely in MS-II
Sawala et al. (2015)	no	Baryons can solve all problems.
Pawlowski et al. (2015)	yes	No evidence that baryons help satellite planes issue.

Different measures of satellite planes in different studies (aka “Why not use what discovery is based on?”)

Selection of simulated satellites should closely follow observed situation.

- Measure plane flattening in absolute or relative way?
- Full 3D positions or projected onto unit sphere?
- Kinematics considered or ignored?
- Sats selected from observable volume, viral volume, or …?
- Different sample size than observed?
    - e.g.~9x more ways to combine 15 of 30 than 15 of 27.

vs.

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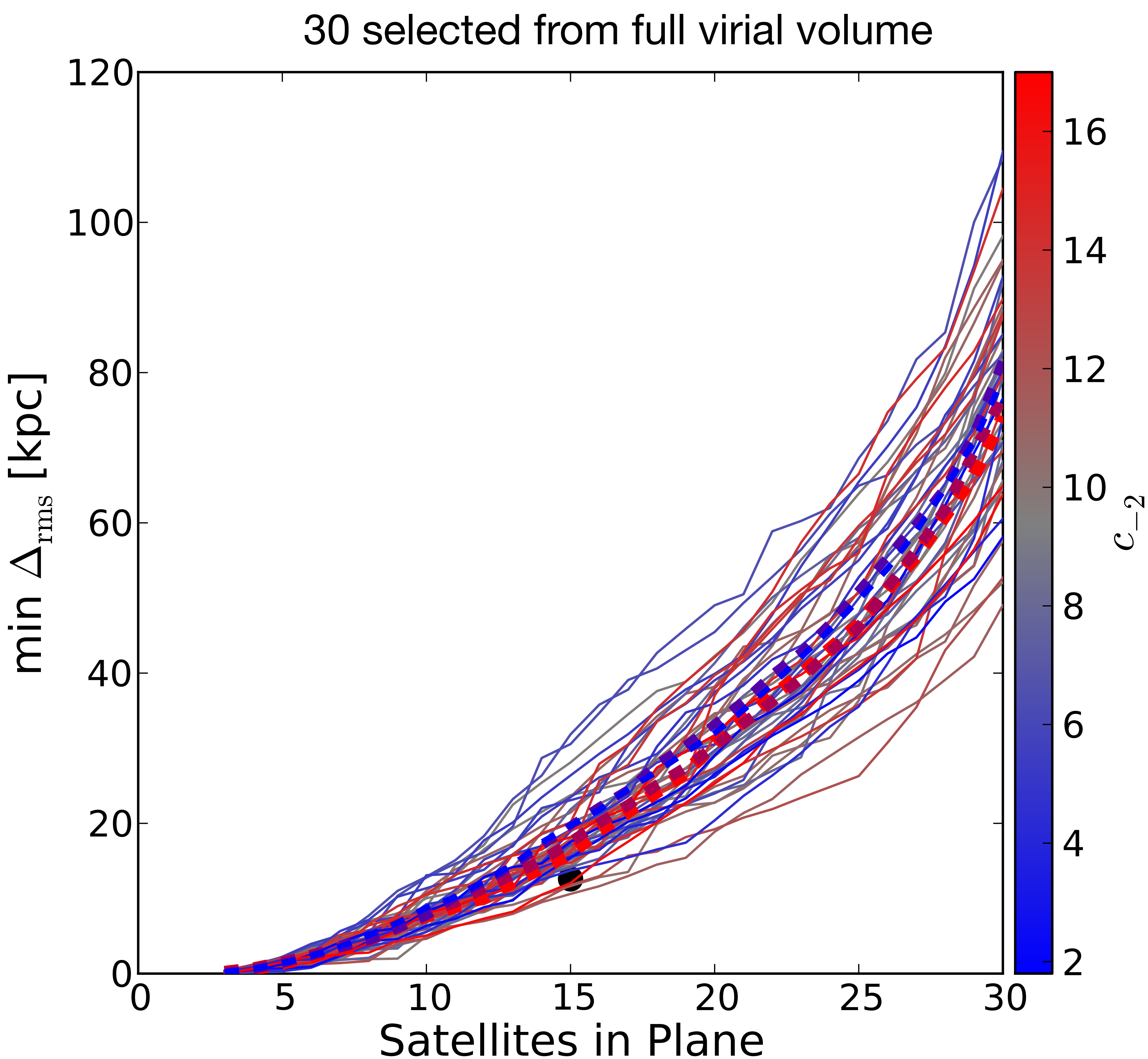
What host halo property correlates with more narrow satellite planes (ELVIS simulations)



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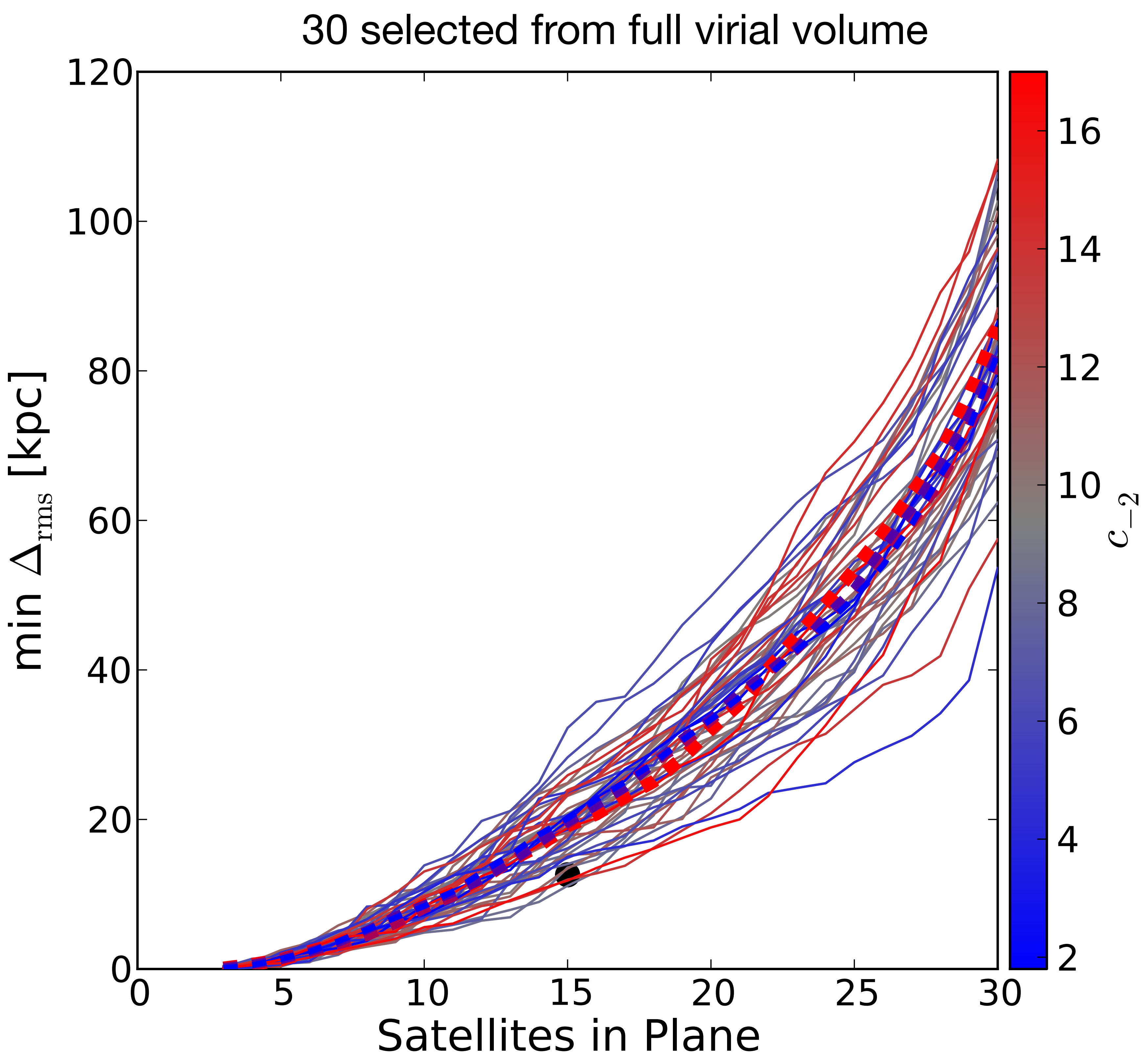

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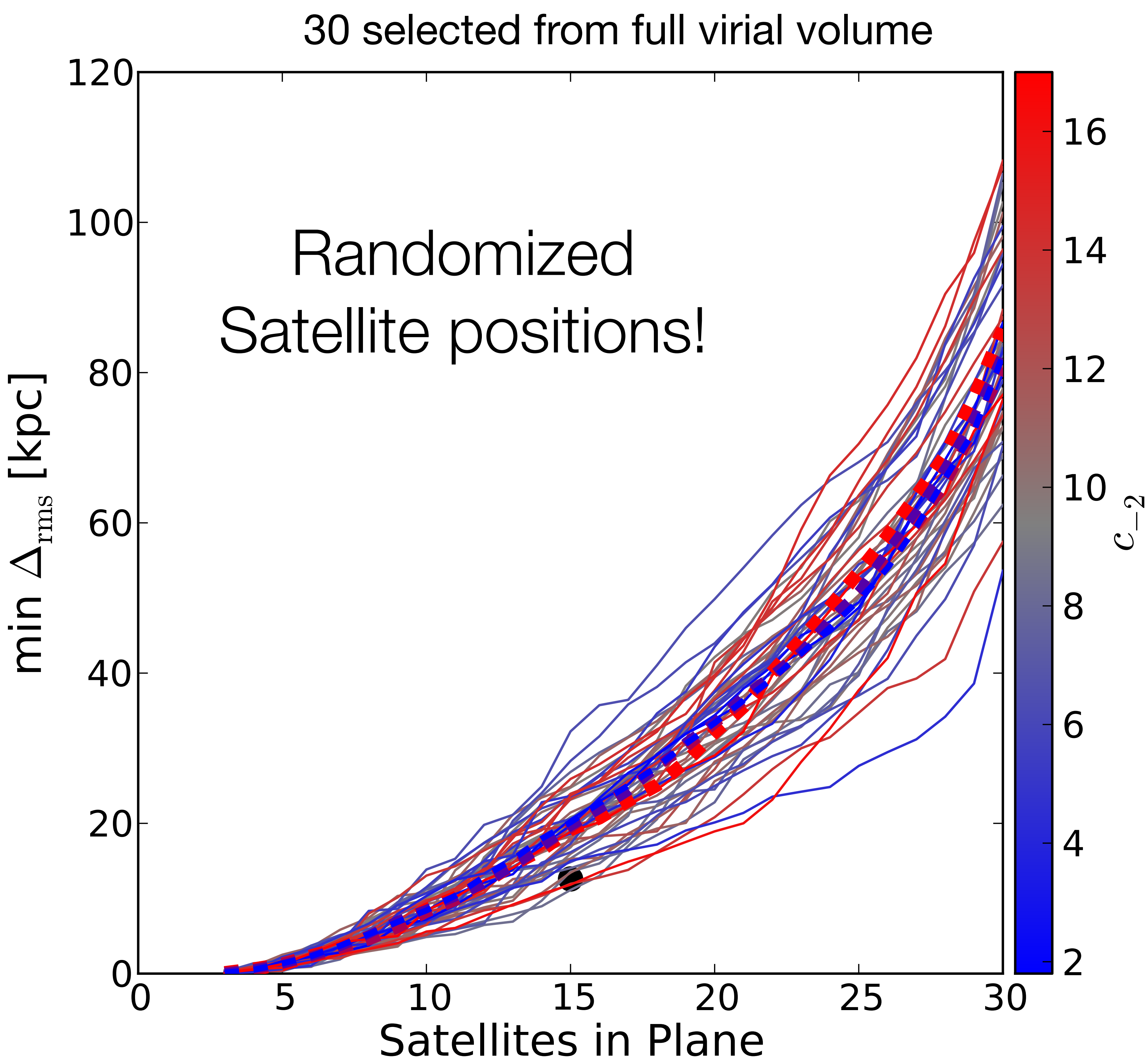

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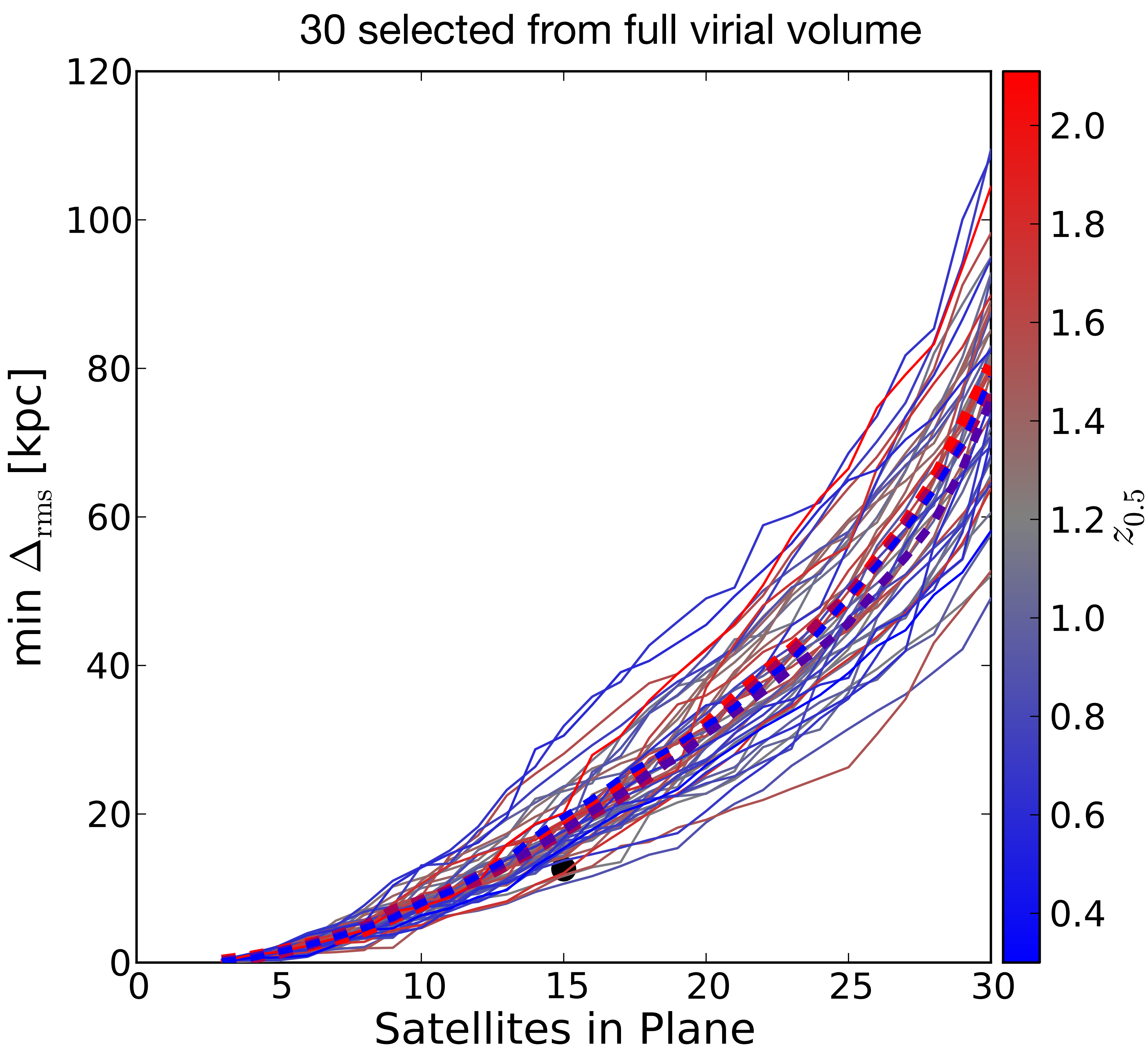

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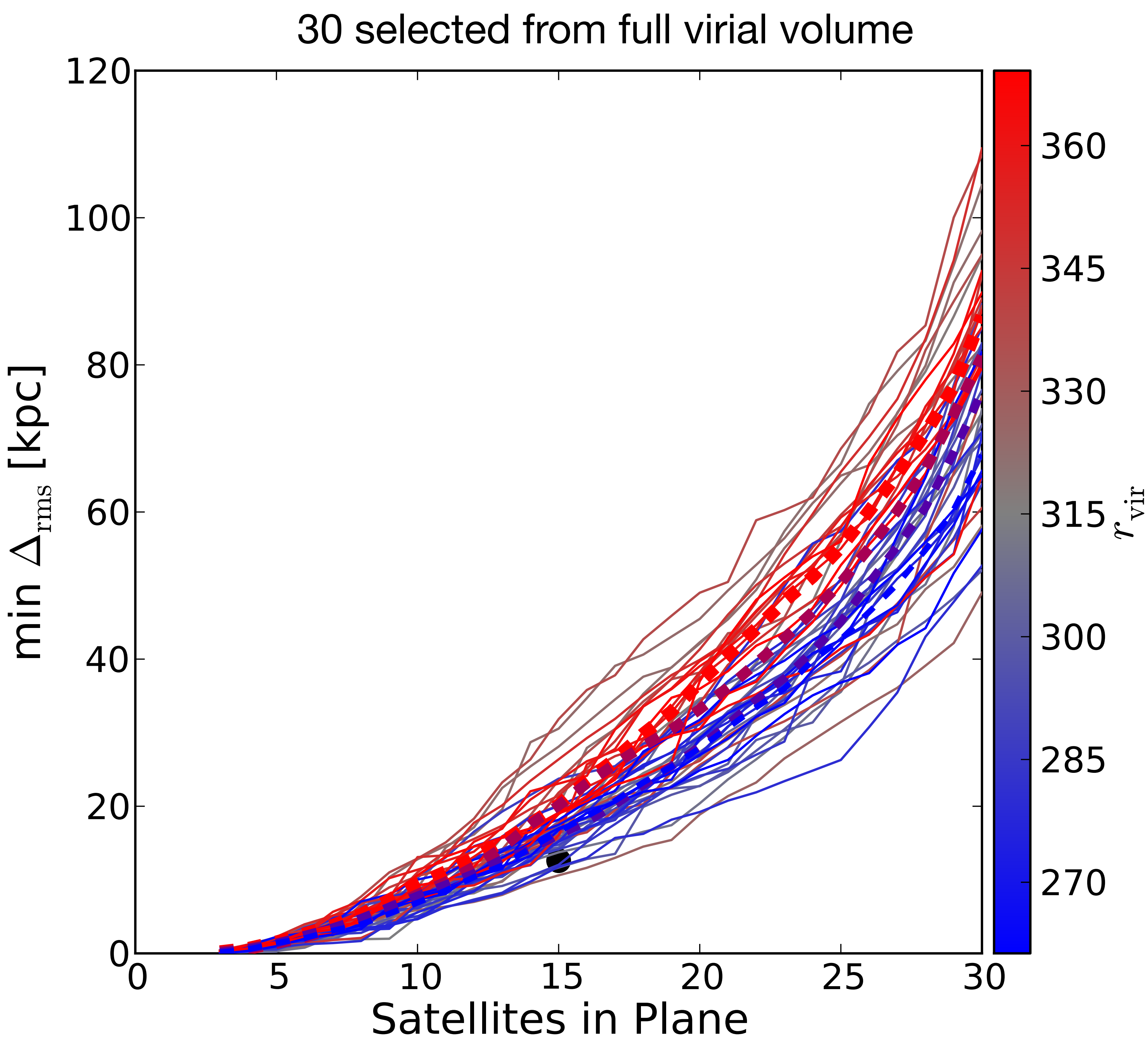

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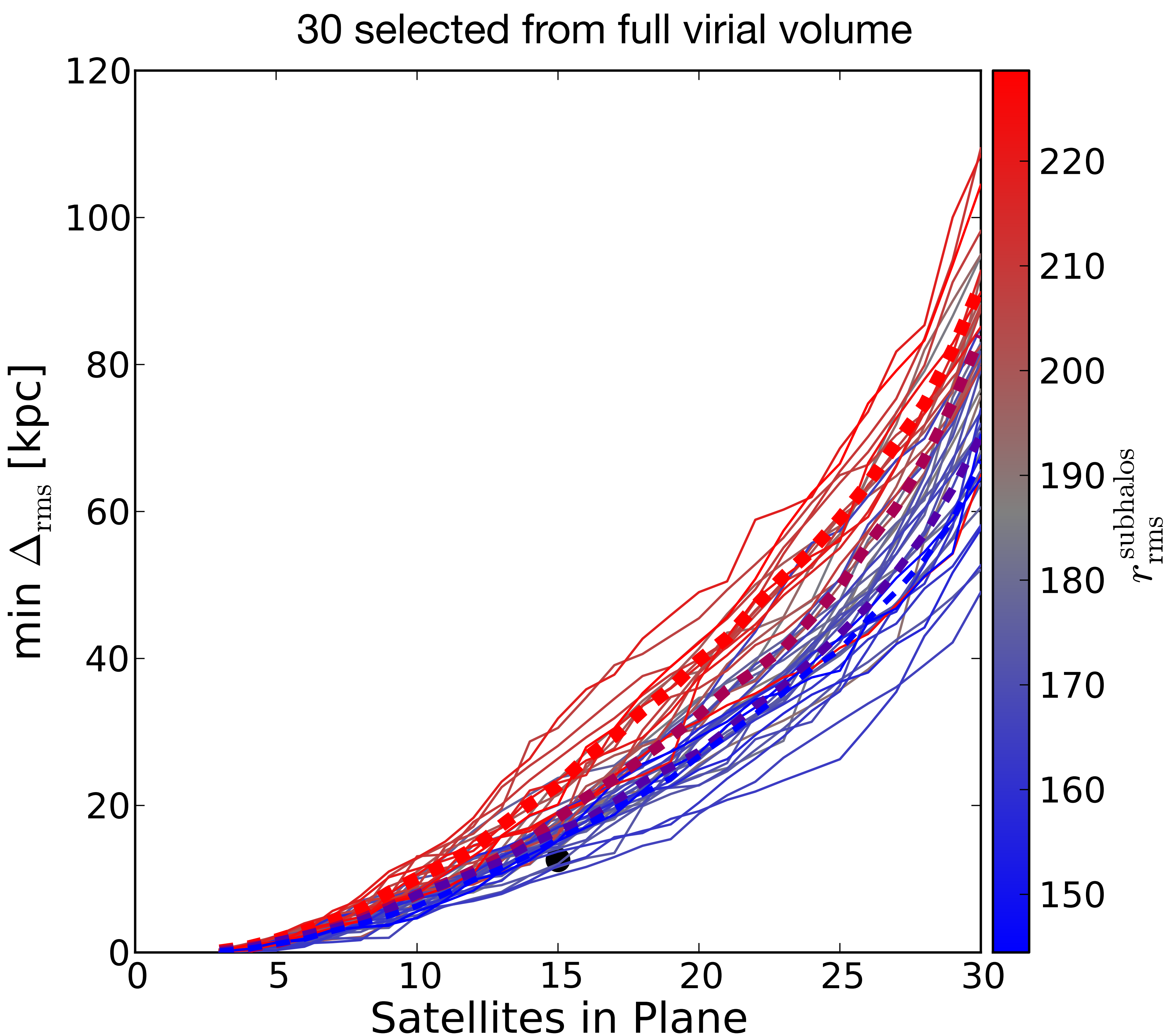

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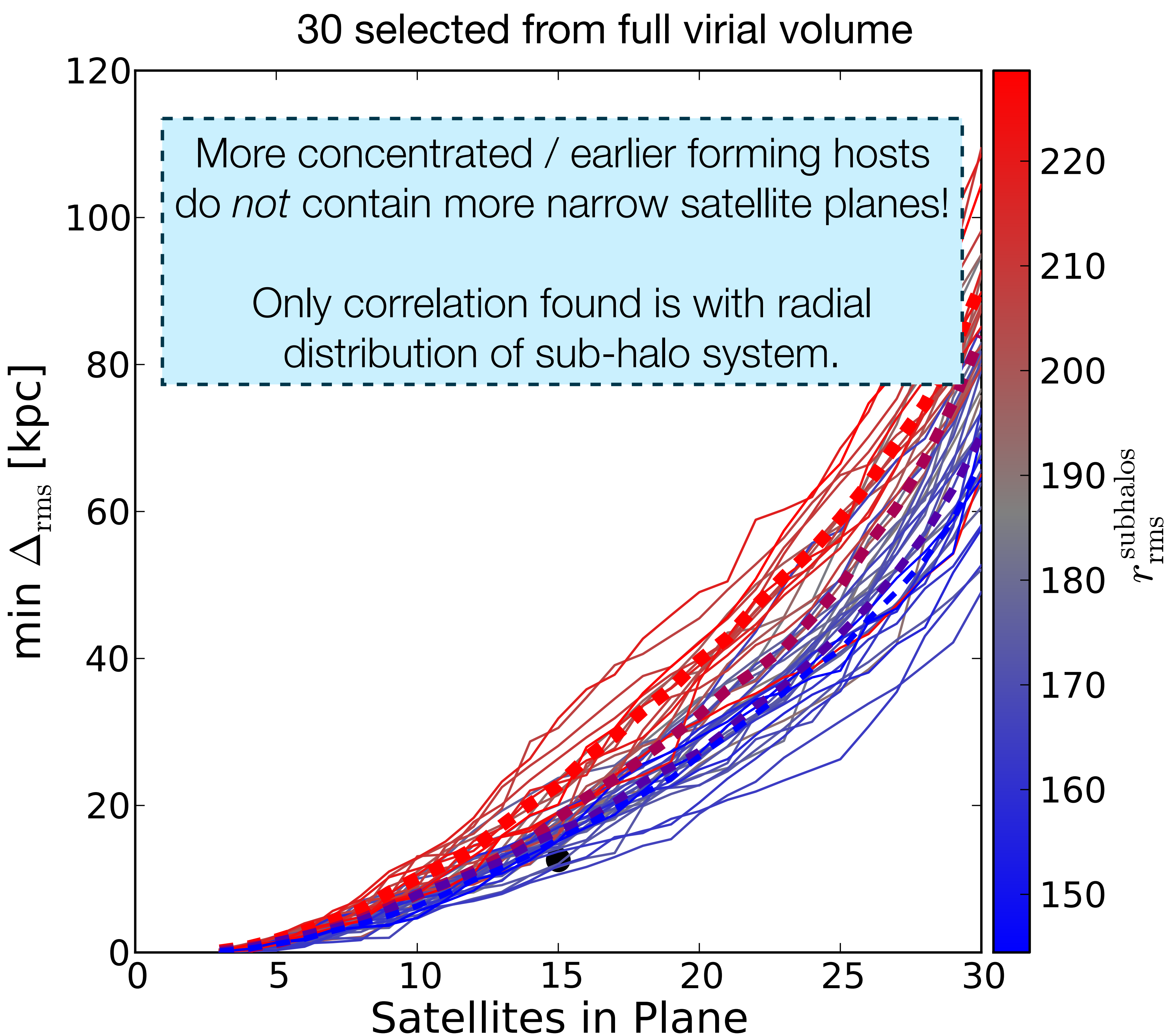
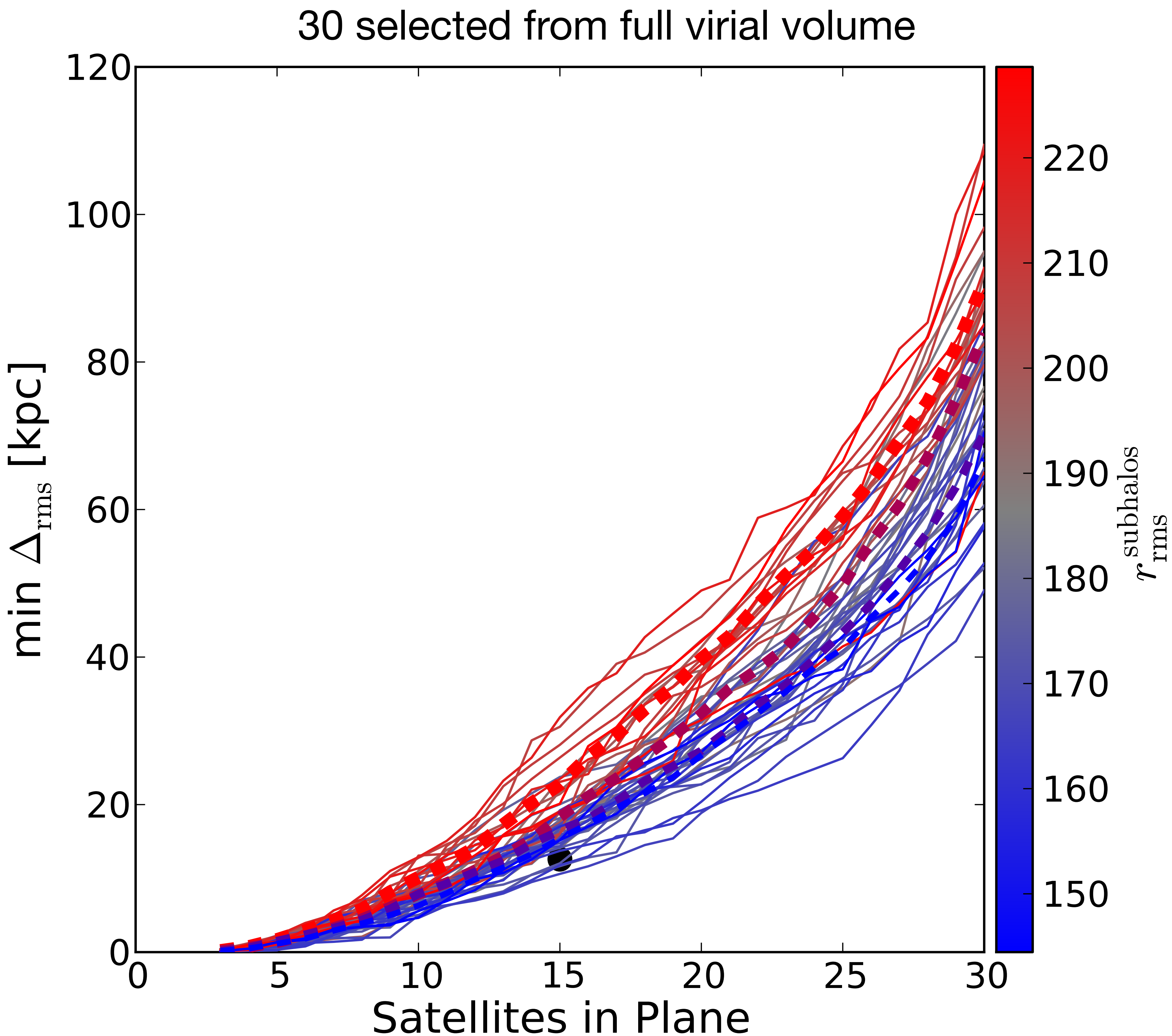


Satellite selection volume and number of satellites makes a difference



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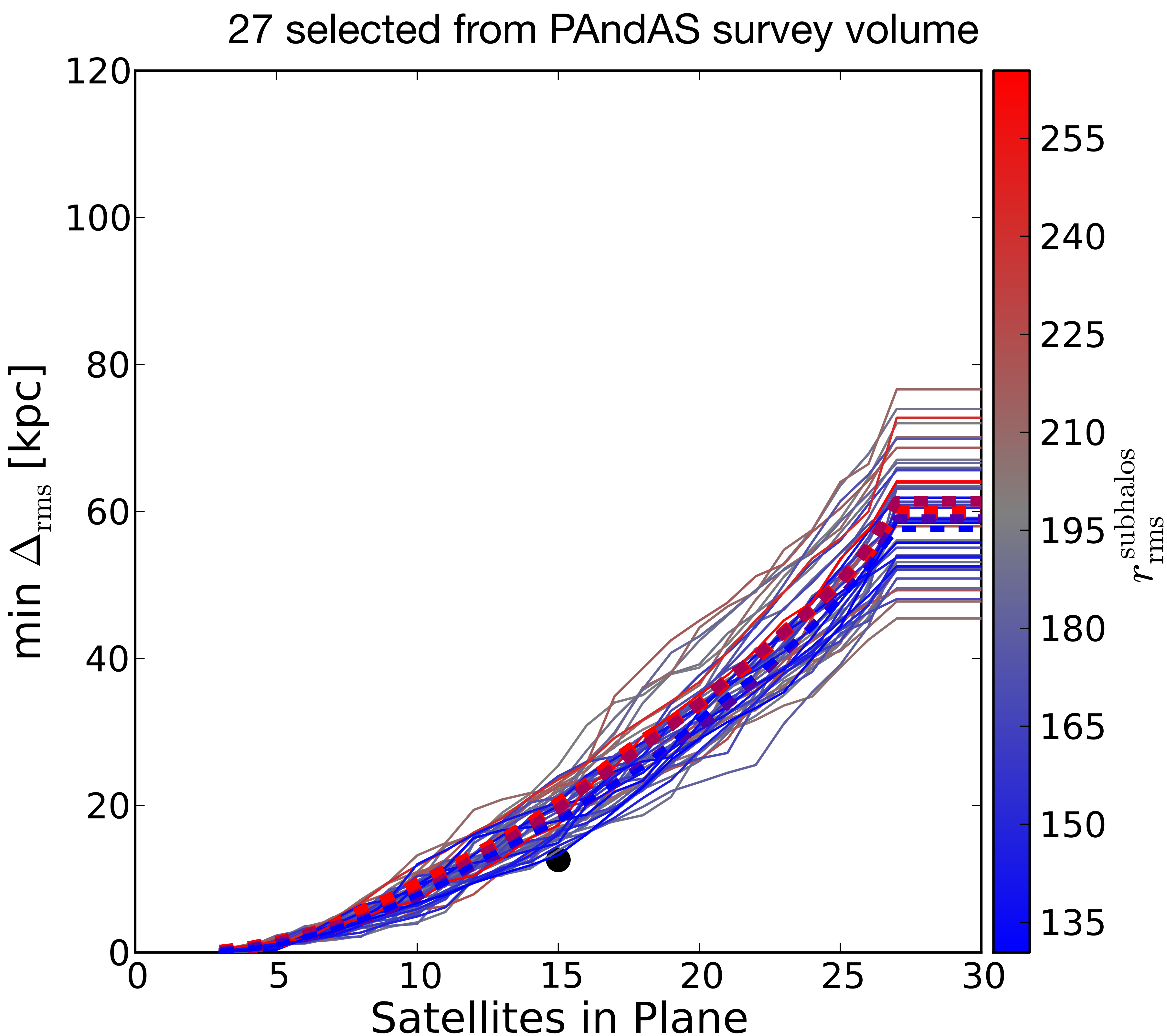
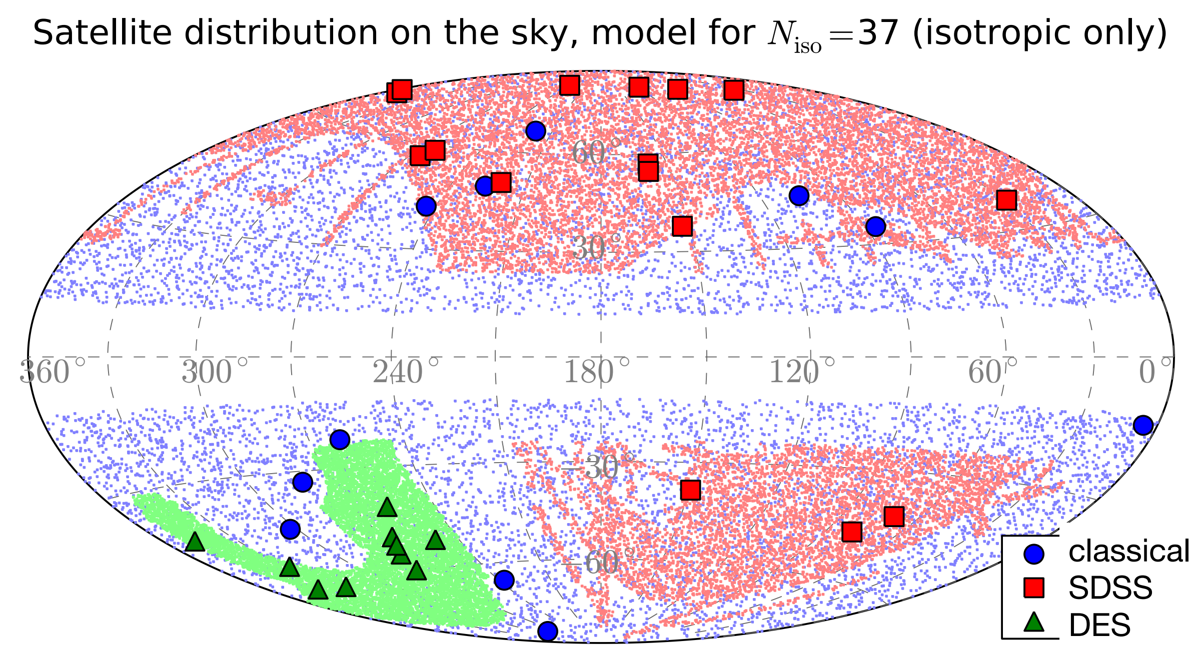


Different measures of satellite planes in different studies (Why not use what discovery is based on?)

Selection of simulated satellites should closely follow observed situation.

- Survey footprints can introduce strong spatial biases.
- Observational uncertainties. Two examples:
  - Proper motions of MW satellite galaxies.
  - Distances to M31 satellite galaxies.



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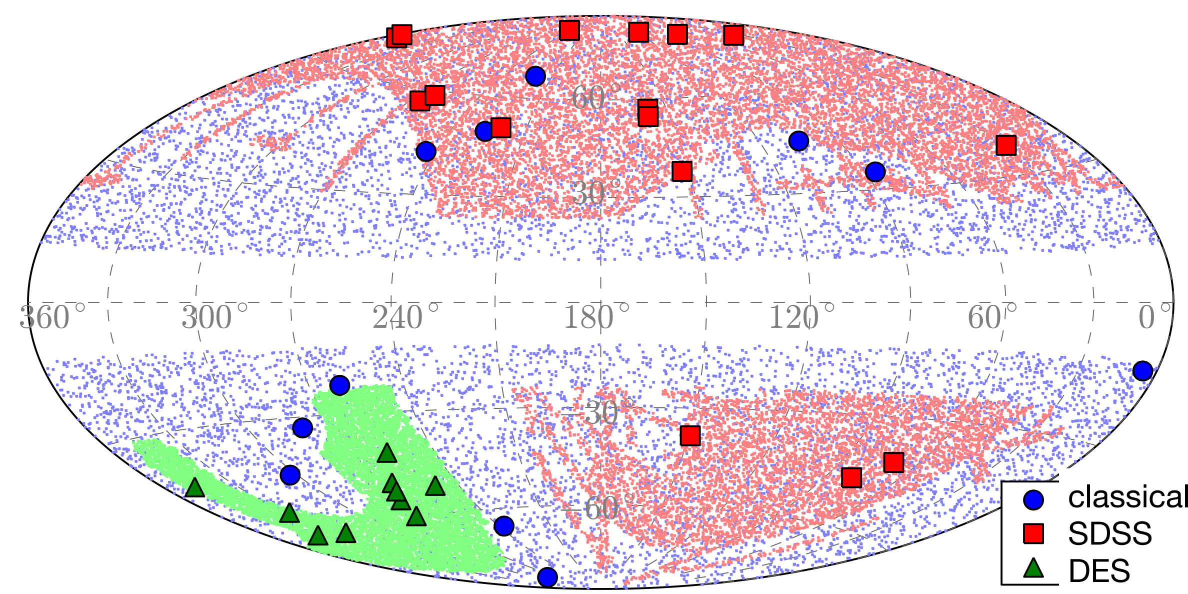
Satellite distribution on the sky, model for $N_{\mathrm{iso}} = 37$ (isotropic only)



Observational uncertainties: The VPOS, a coherently rotating structure?

- If underlying structure is well correlated, uncertainties will always act to reduce the degree of apparent correlation.
- Attempts to determine dynamical stability of VPOS by integrating satellite orbits based on most-likely PMs are doomed to fail.

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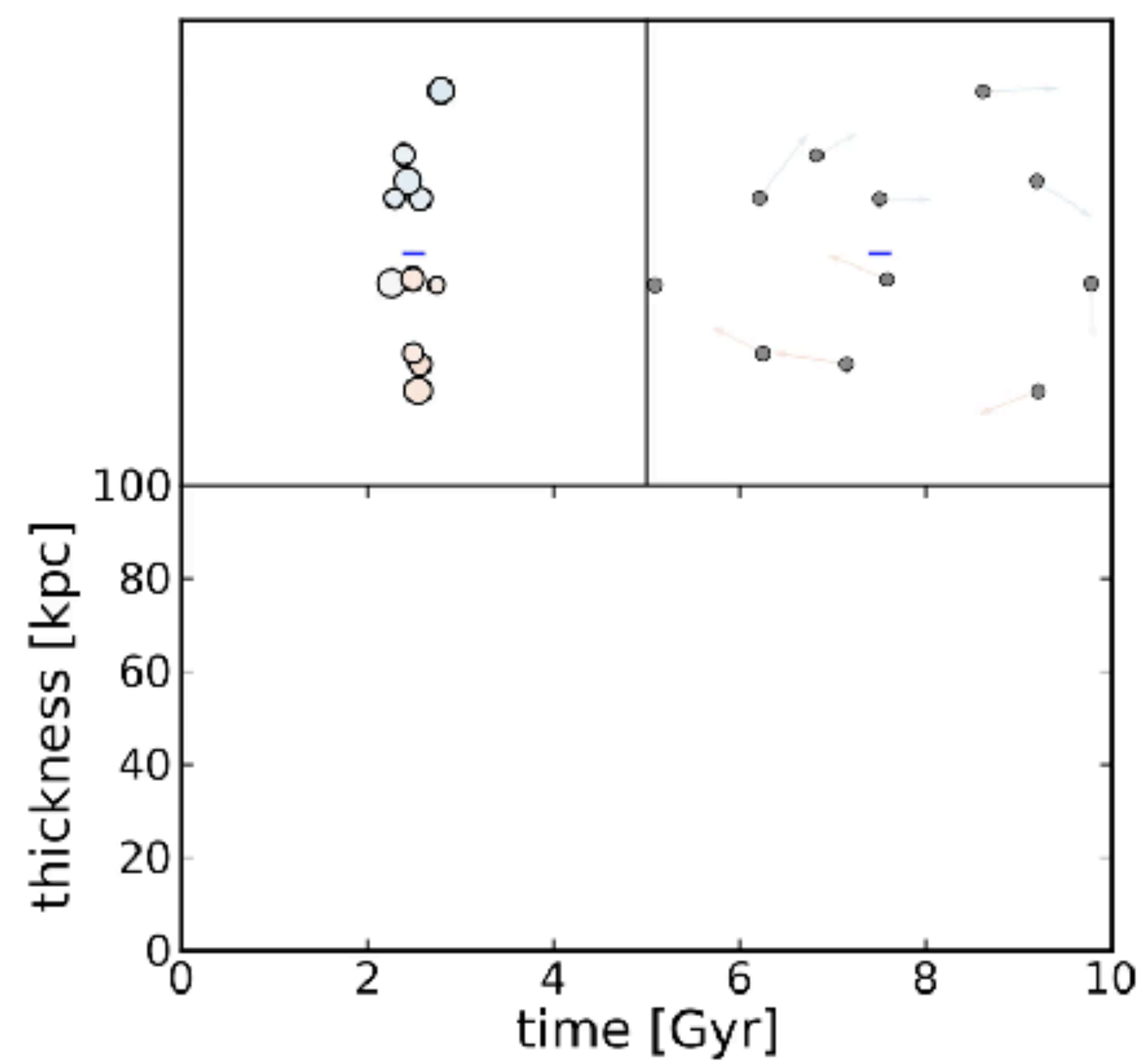

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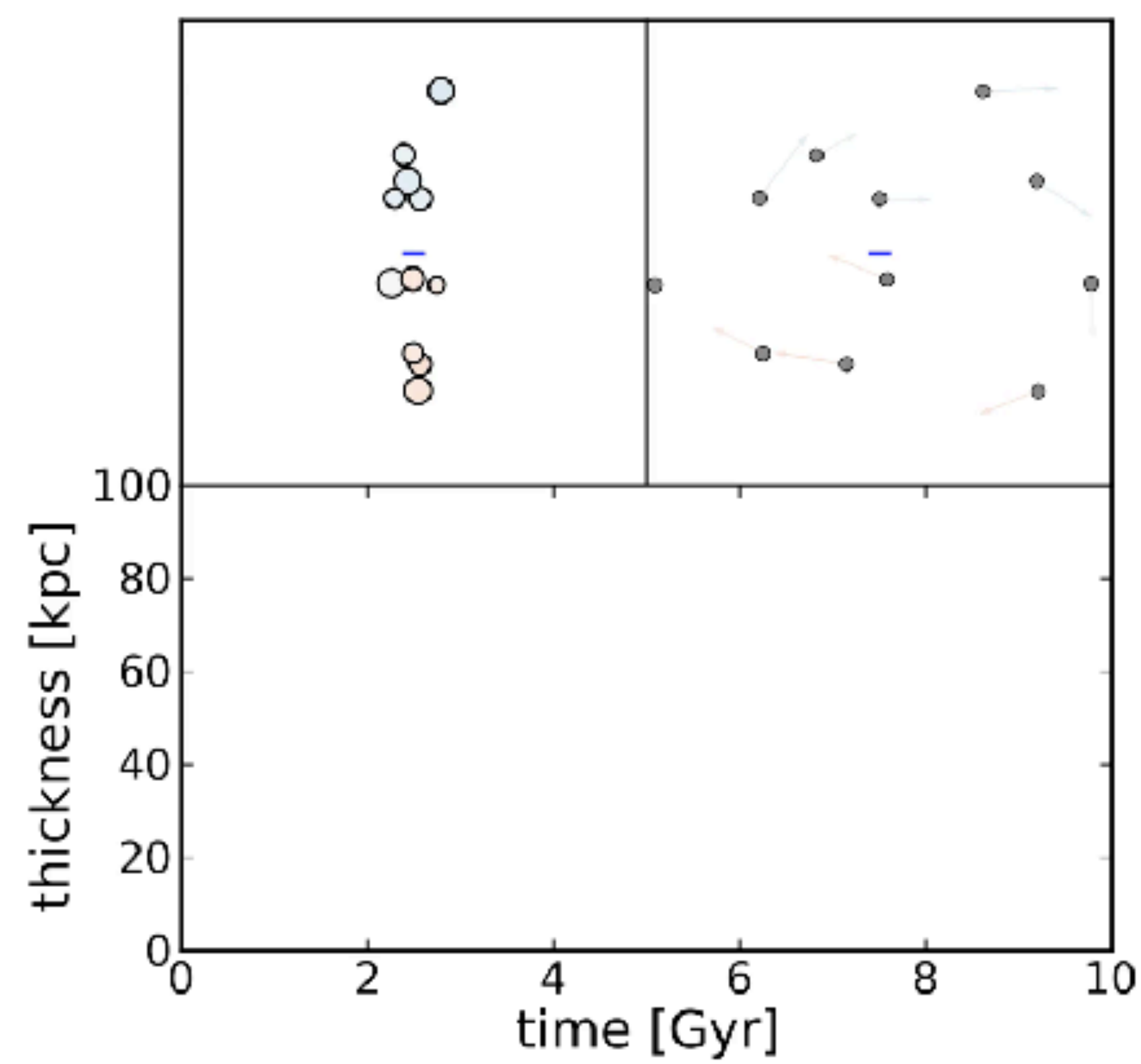

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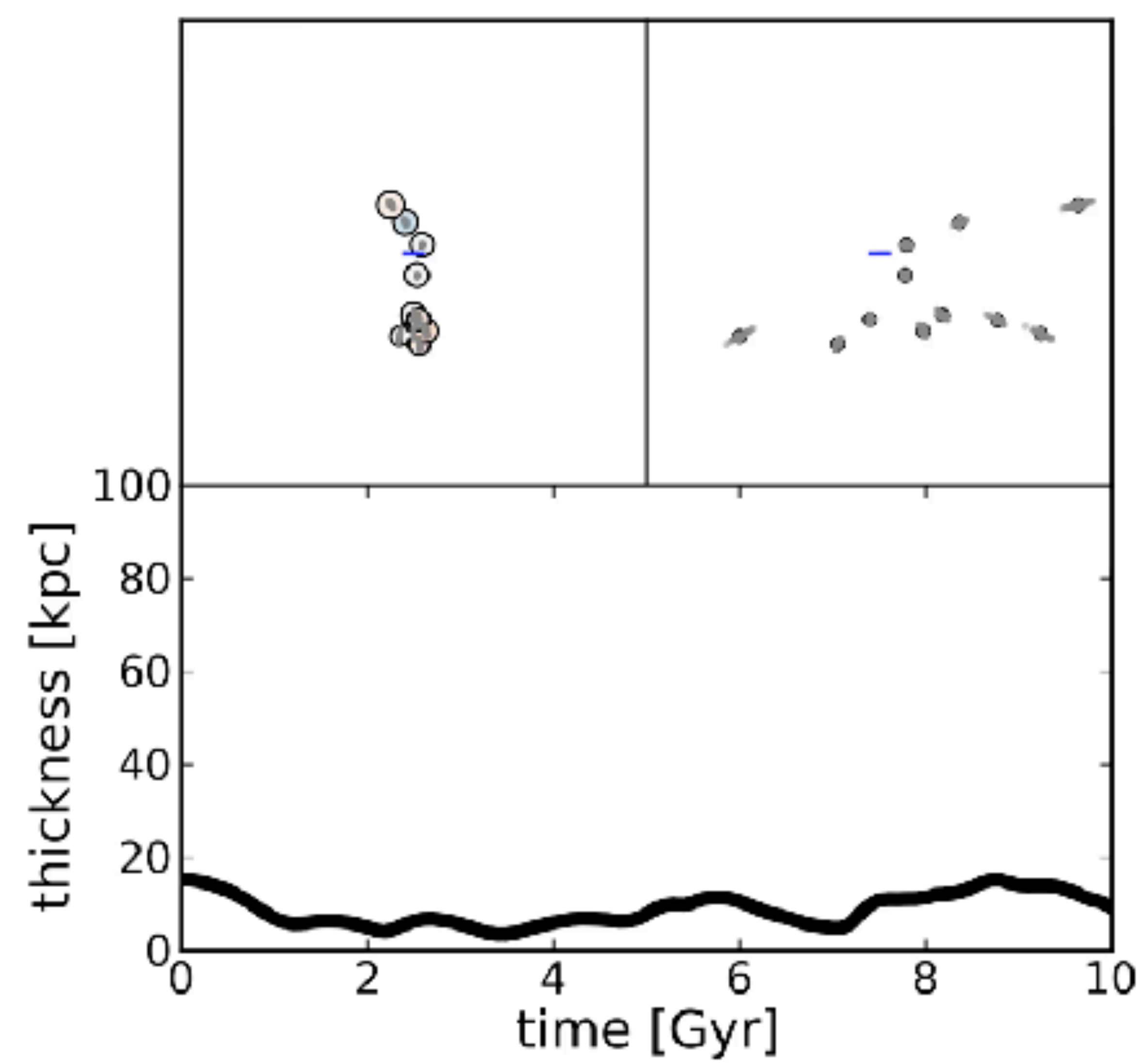

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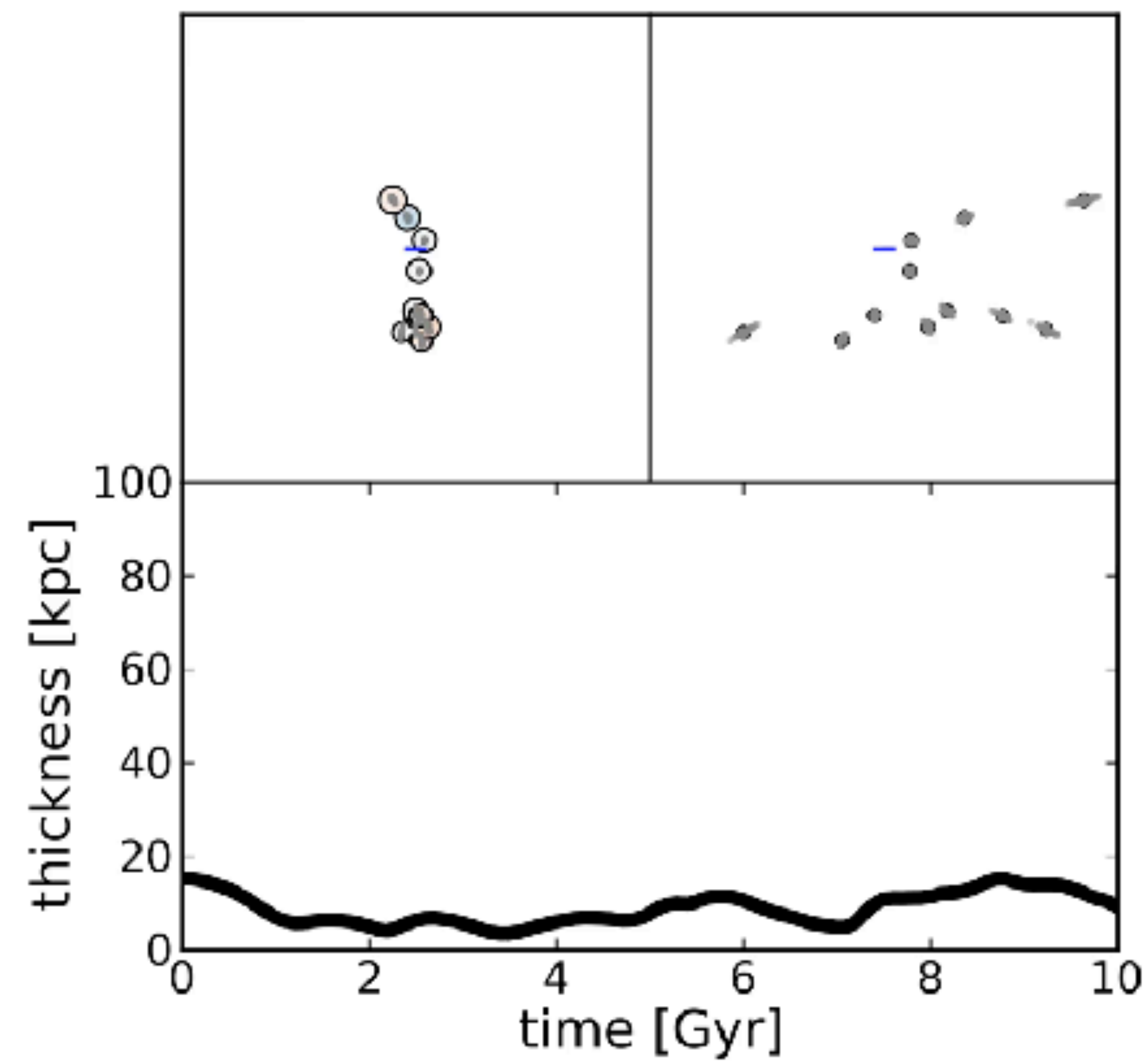
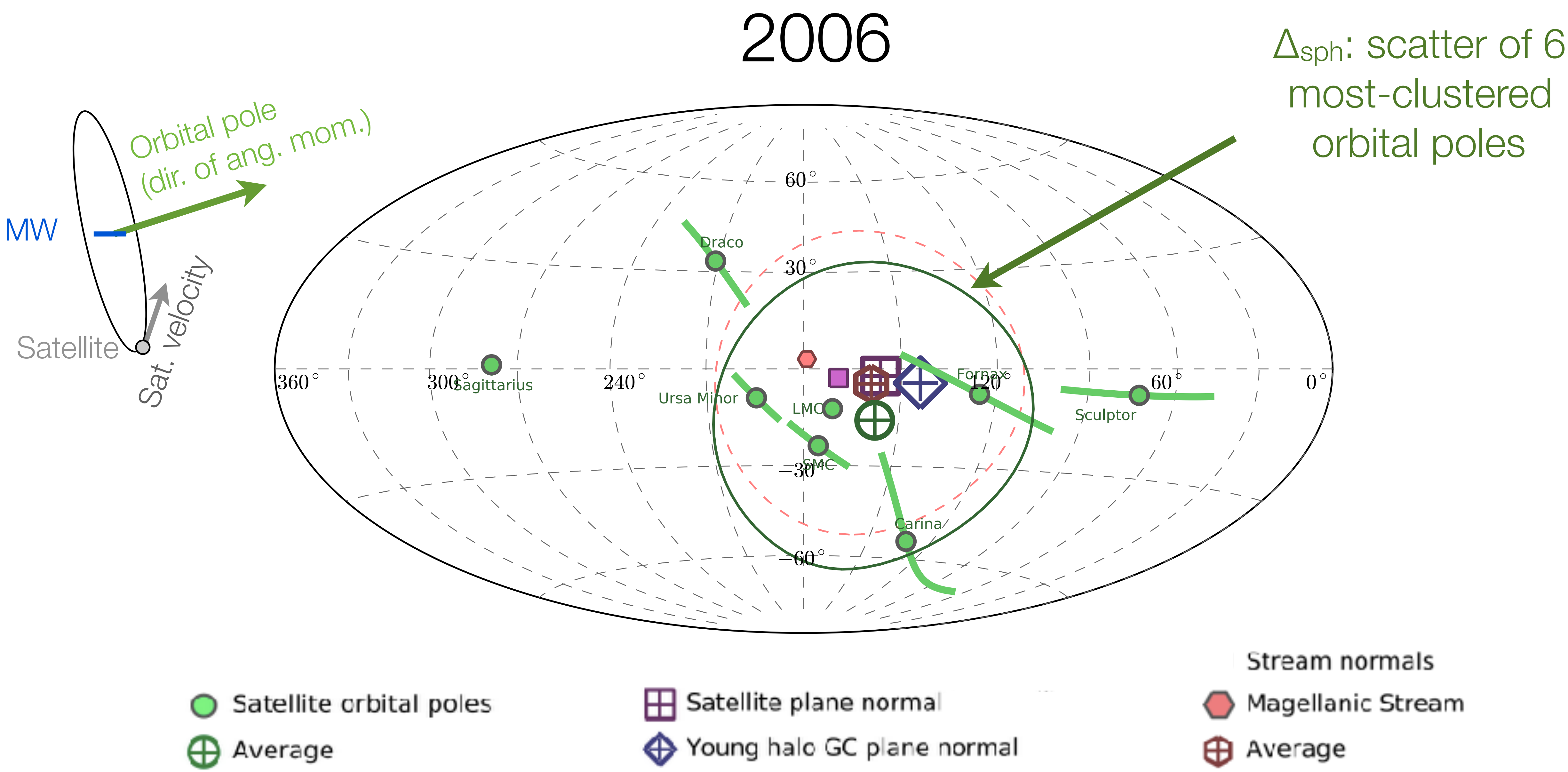


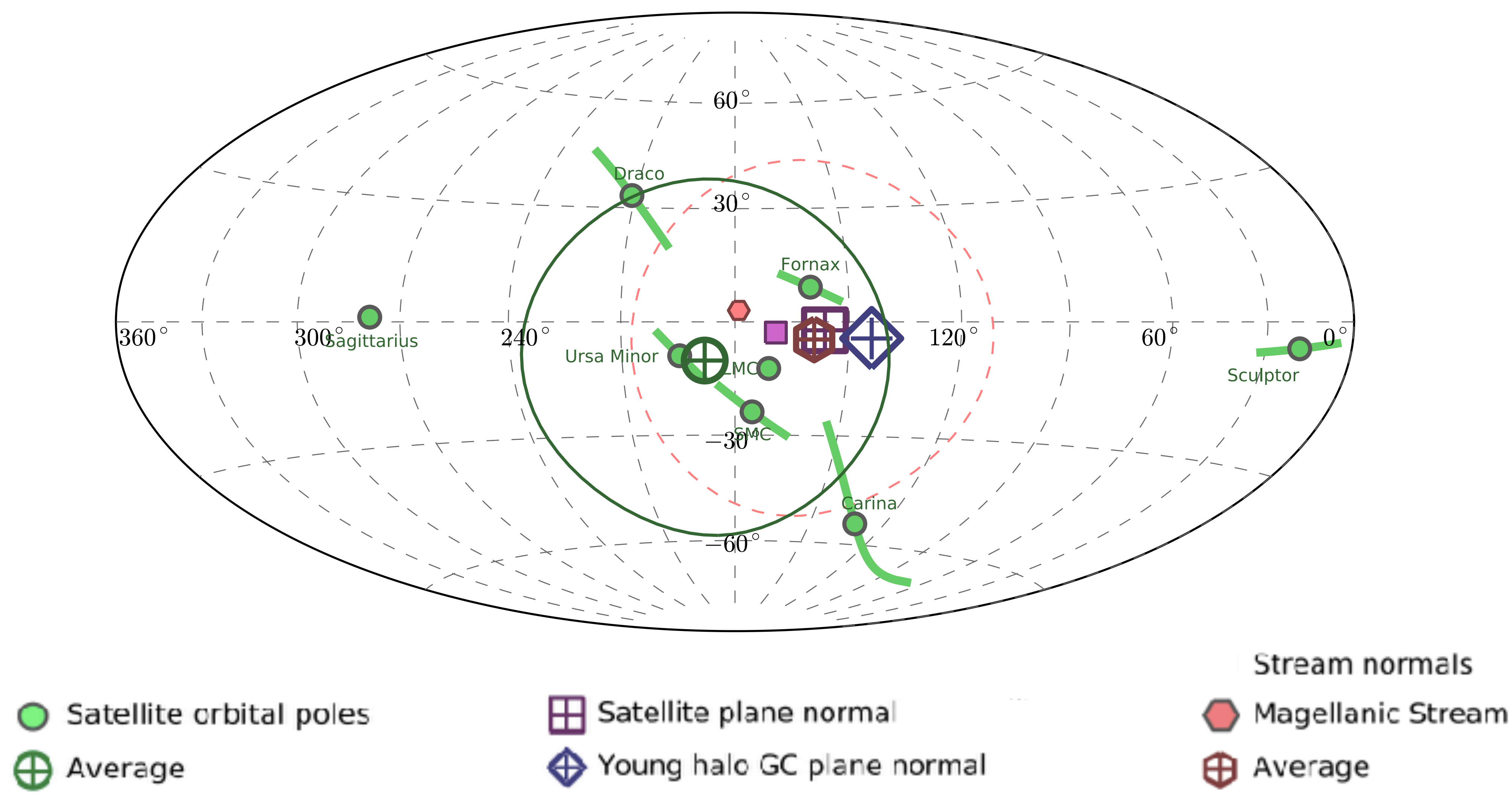
A Rotationally Supported VPOS: Better PM Measurement Result in Tighter Orbital Pole Distribution



Coherent velocities: the VPOS is rotating

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

2007



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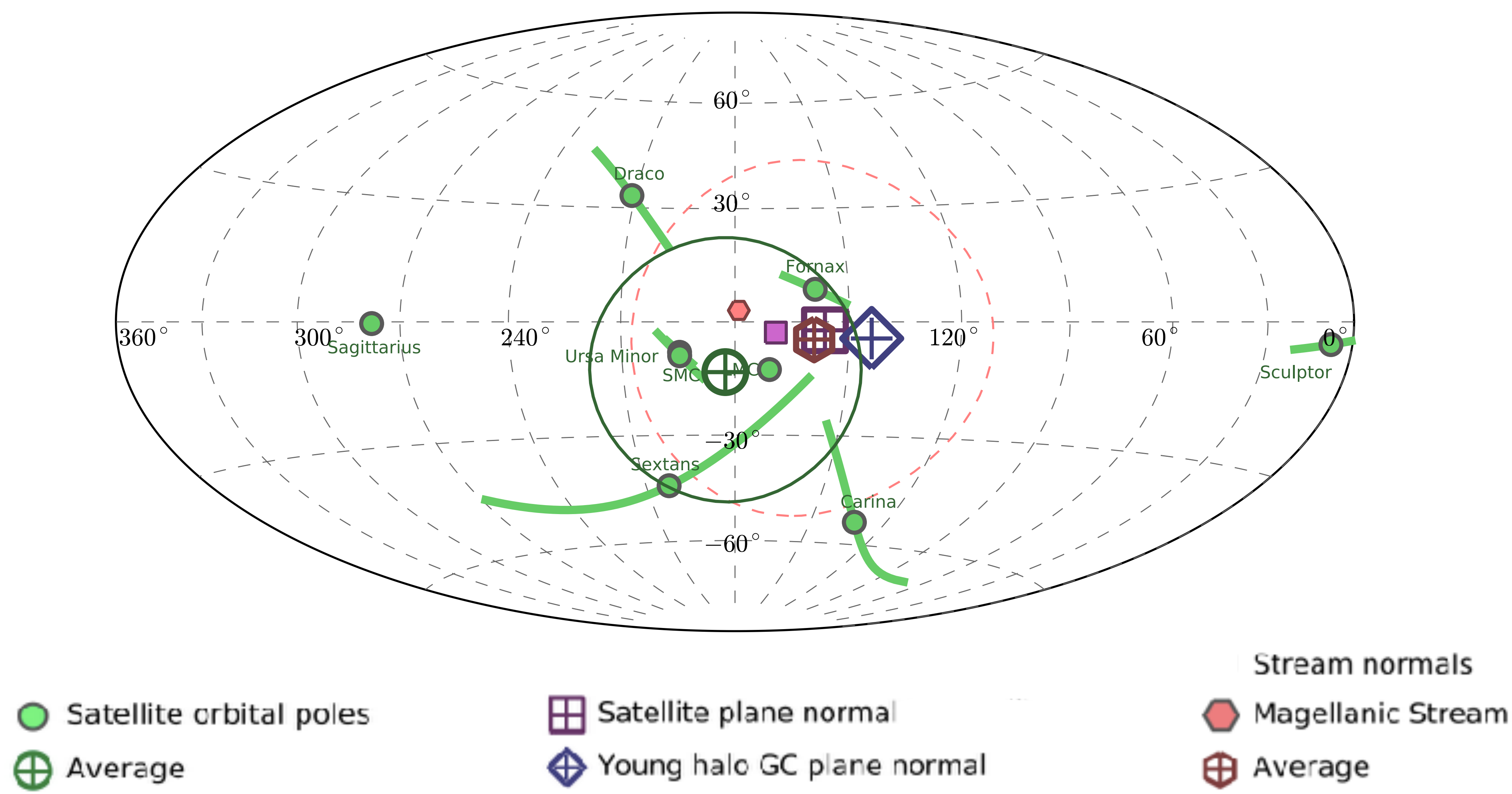

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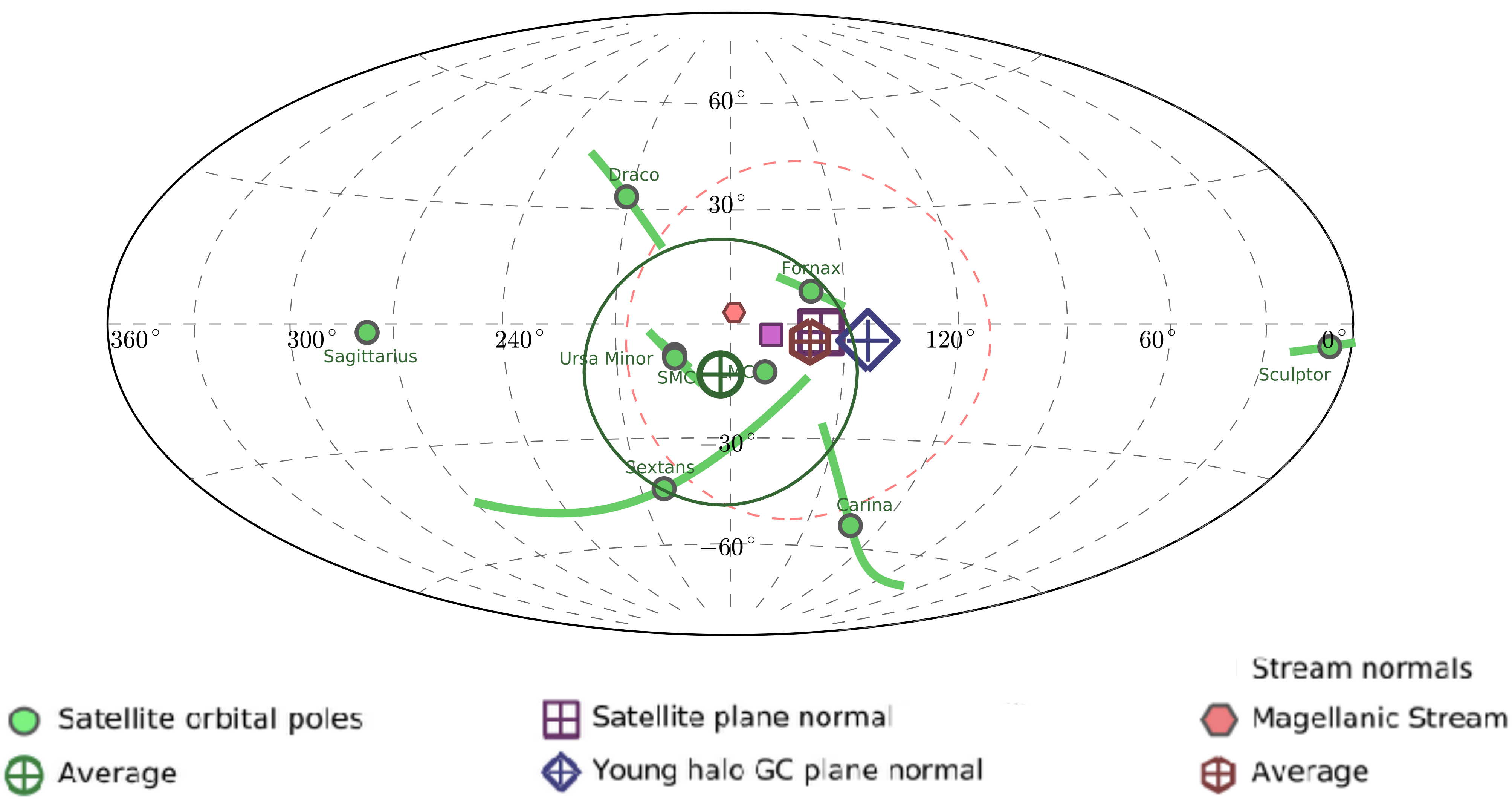

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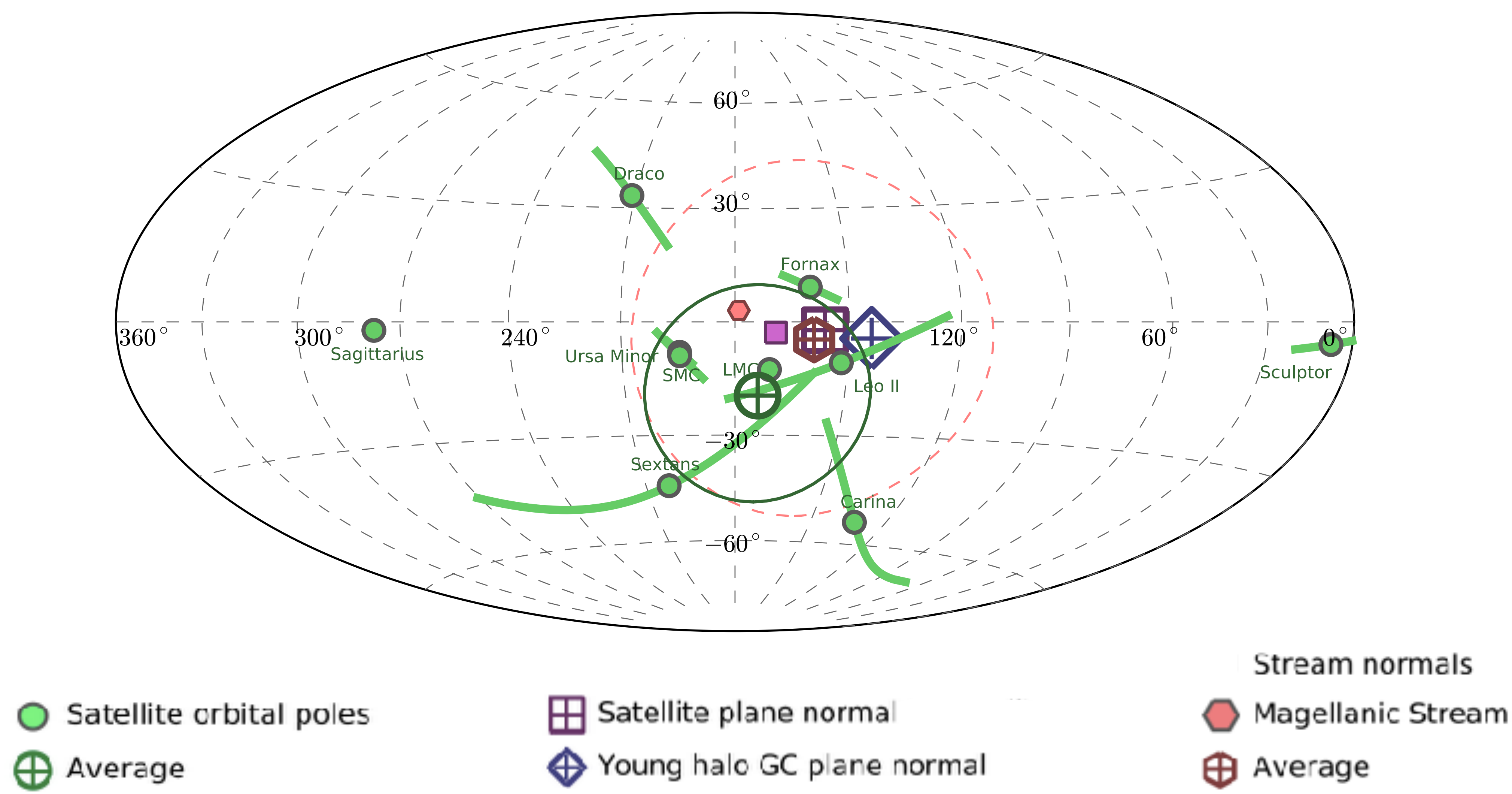

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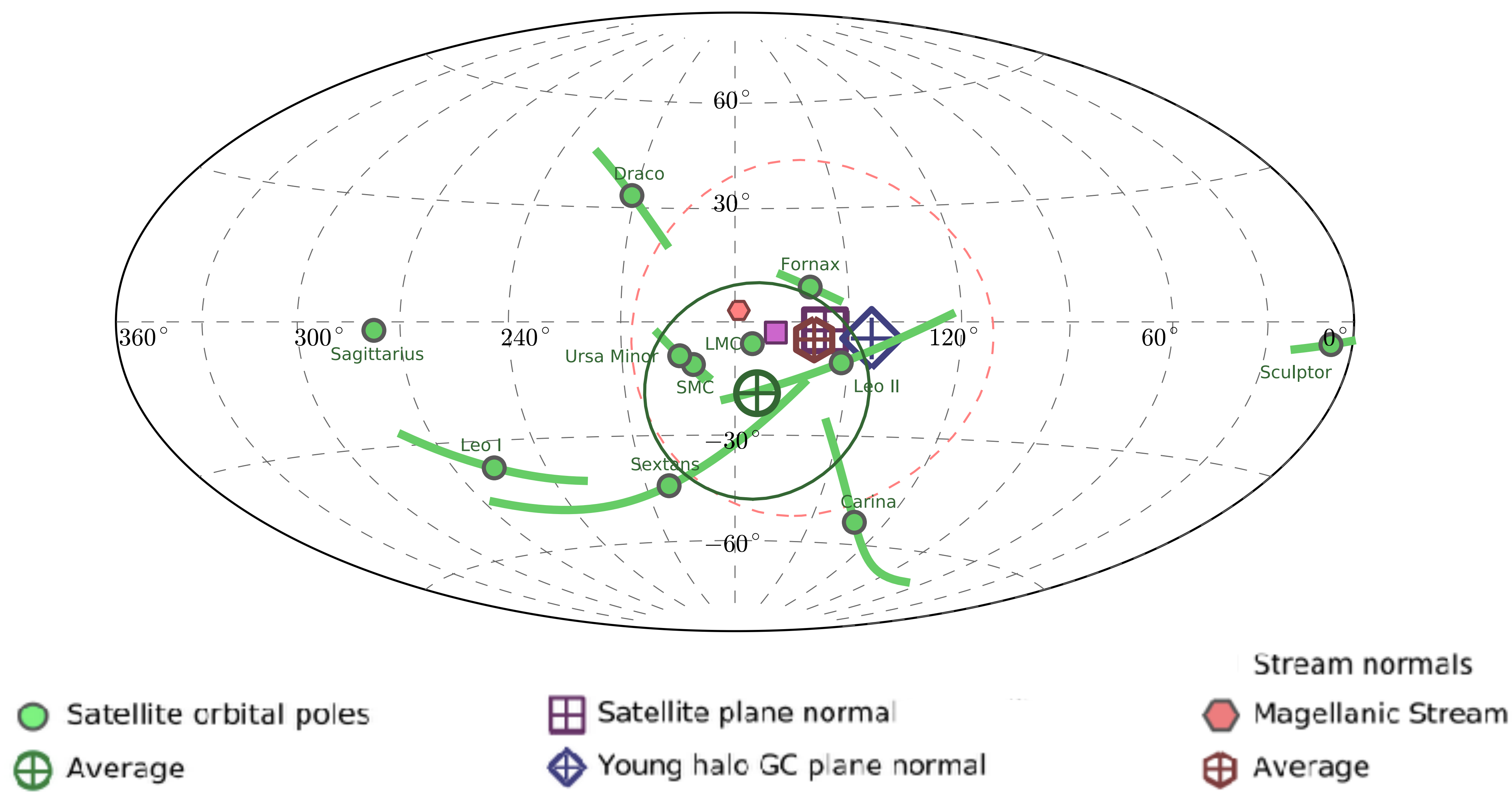

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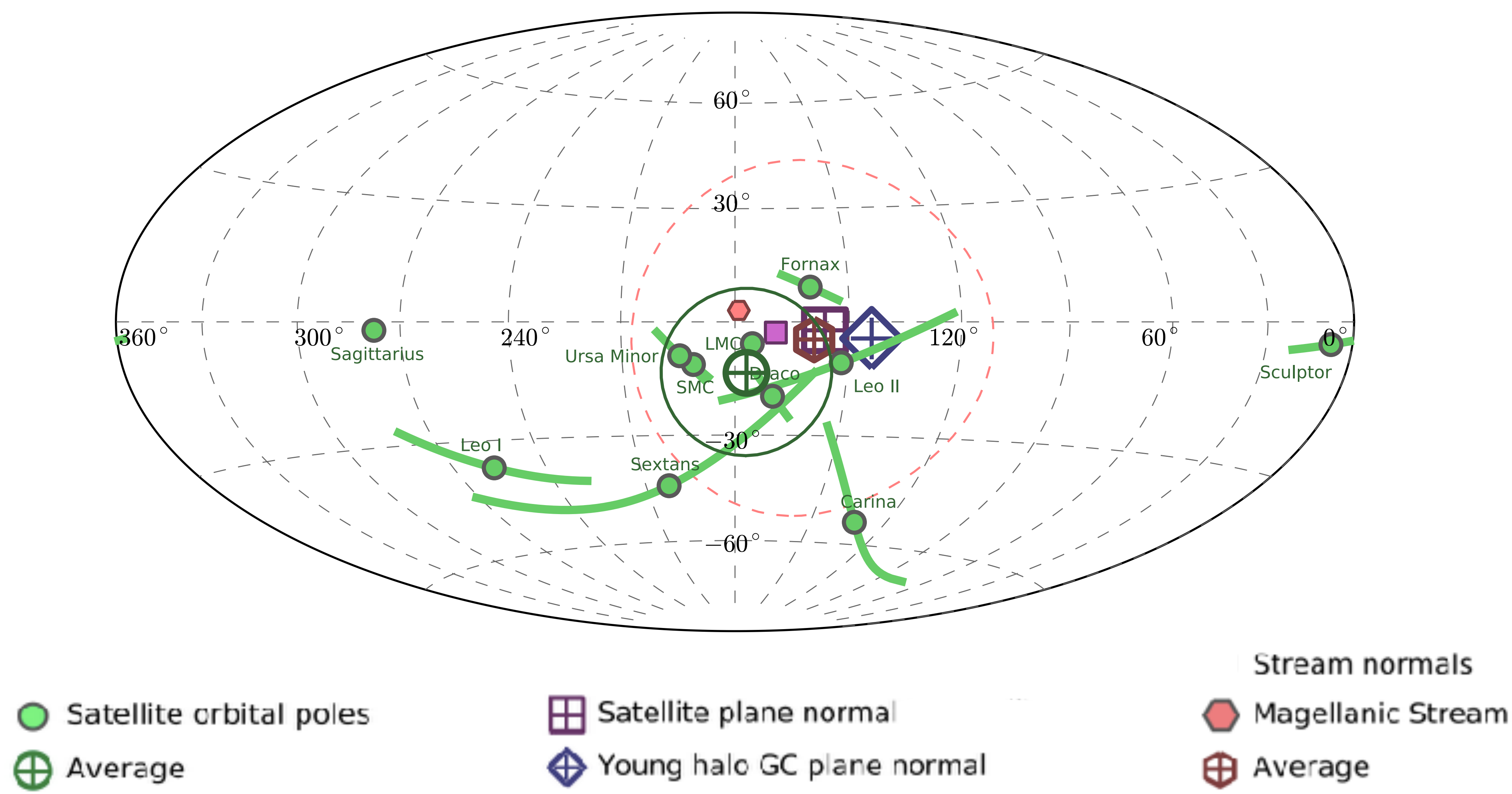

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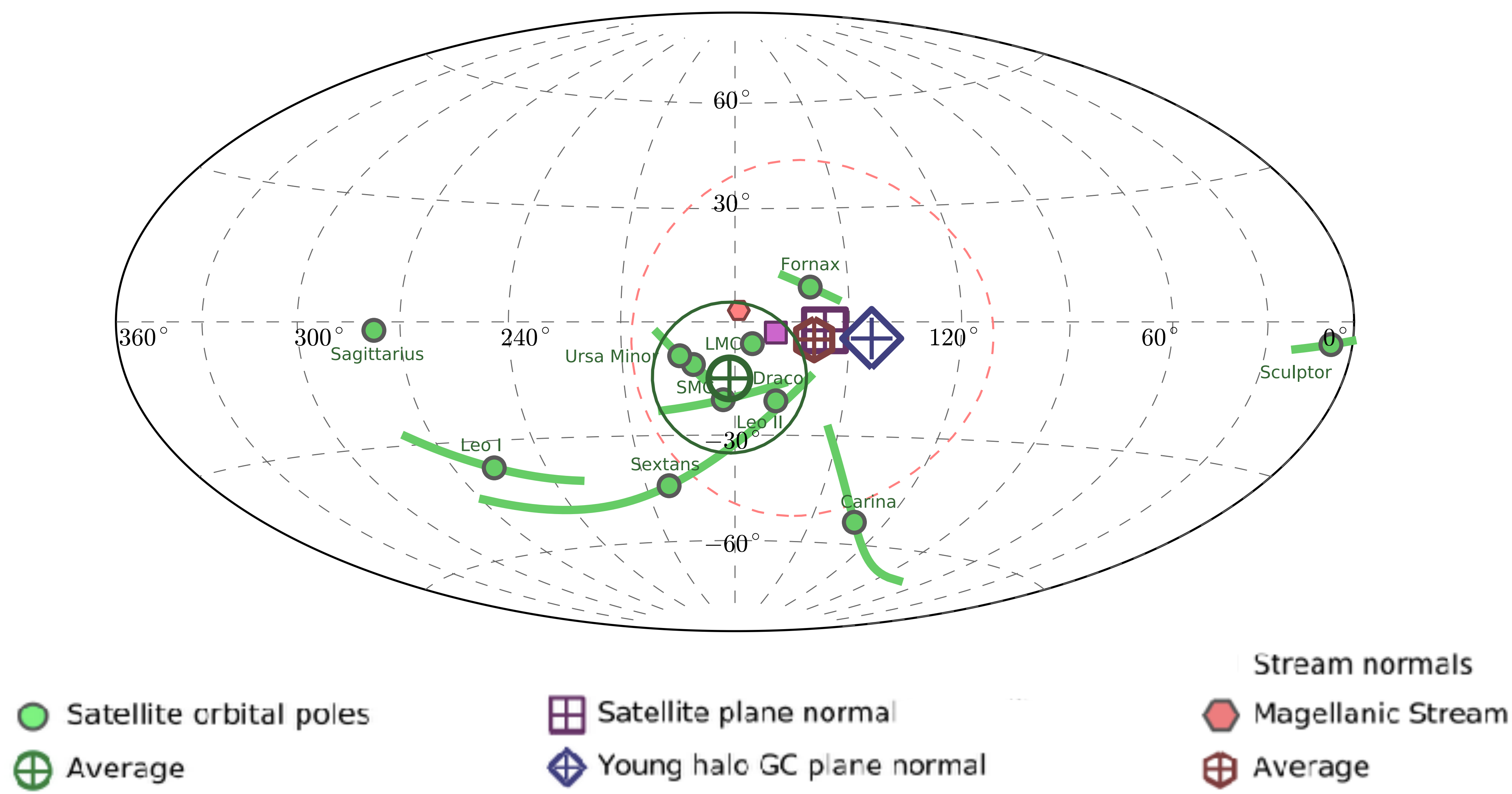

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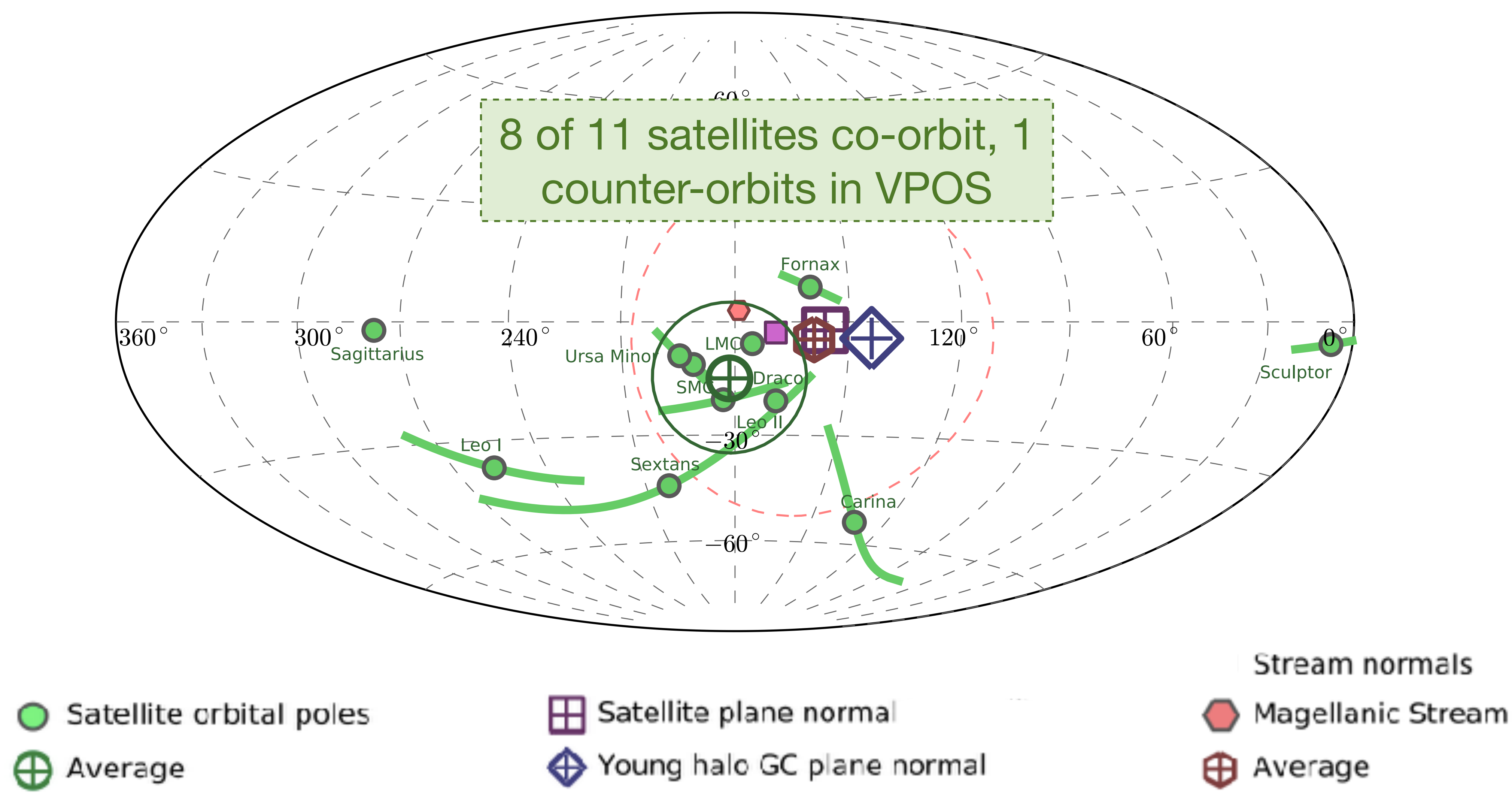

Distance uncertainties for Andromeda satellite galaxies

Pawlowski et al. (in prep.)

- Least certain information for M31 satellites is distance (typically ±10%, ~80 kpc)
- Observed, edge-on plane has ~14 kpc height.
- Comparisons with simulations look for planes with **same # of satellites** and **≤ height**.
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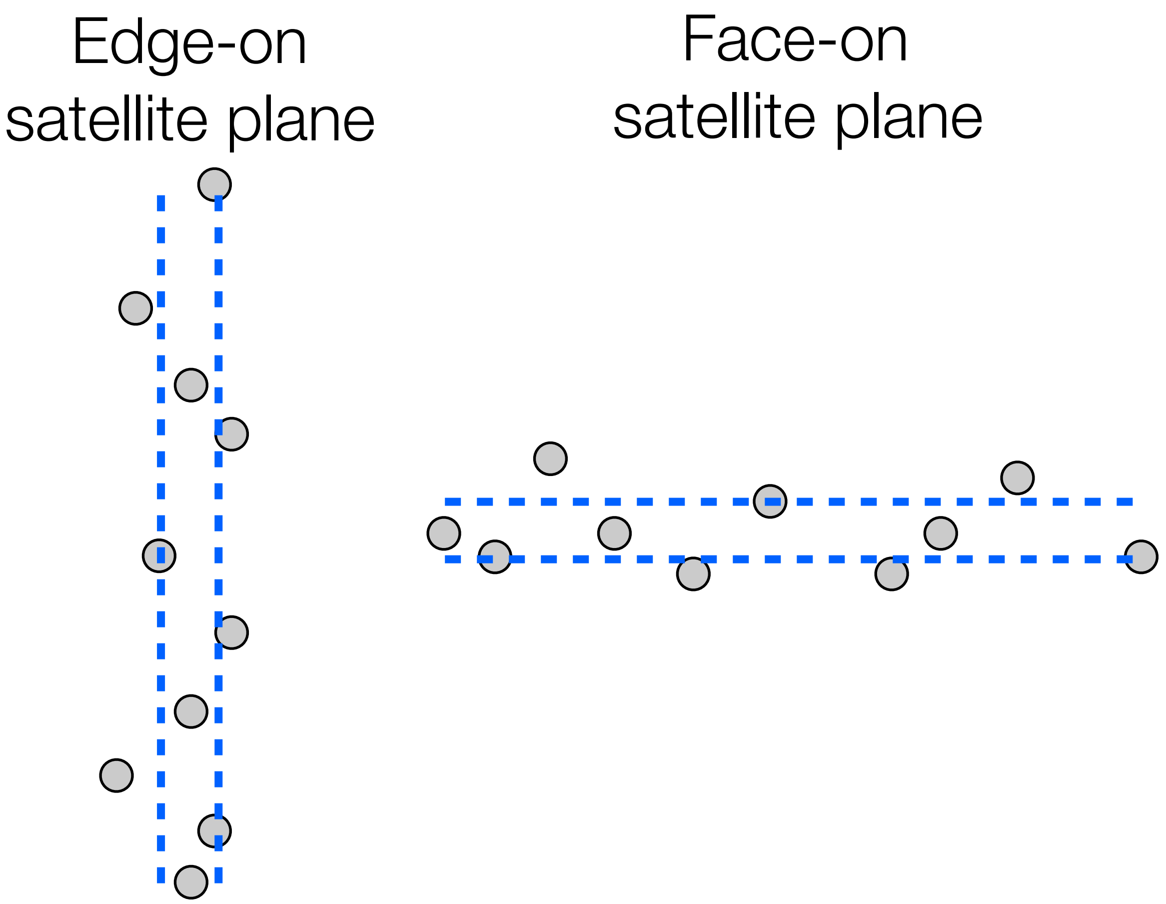

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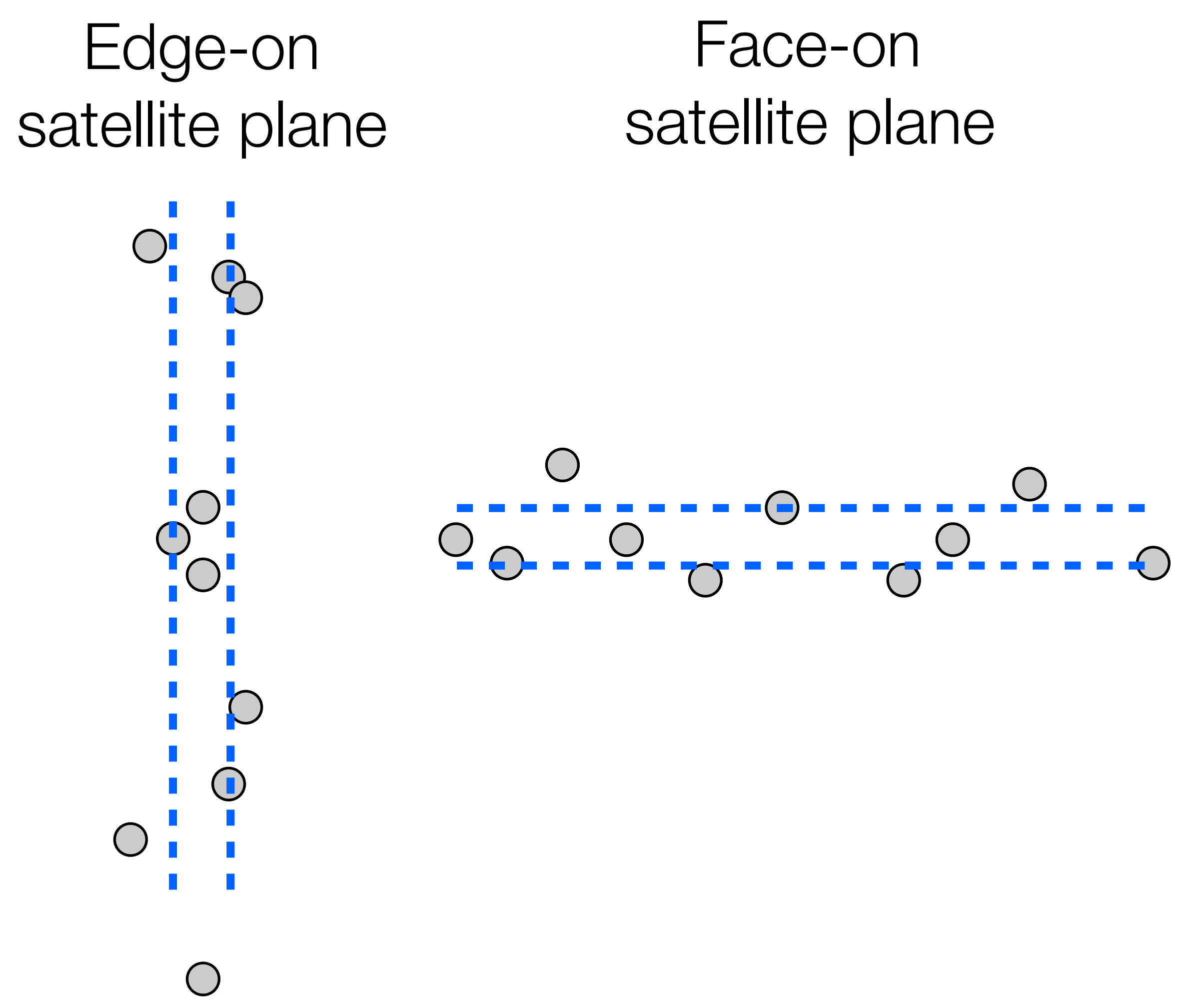

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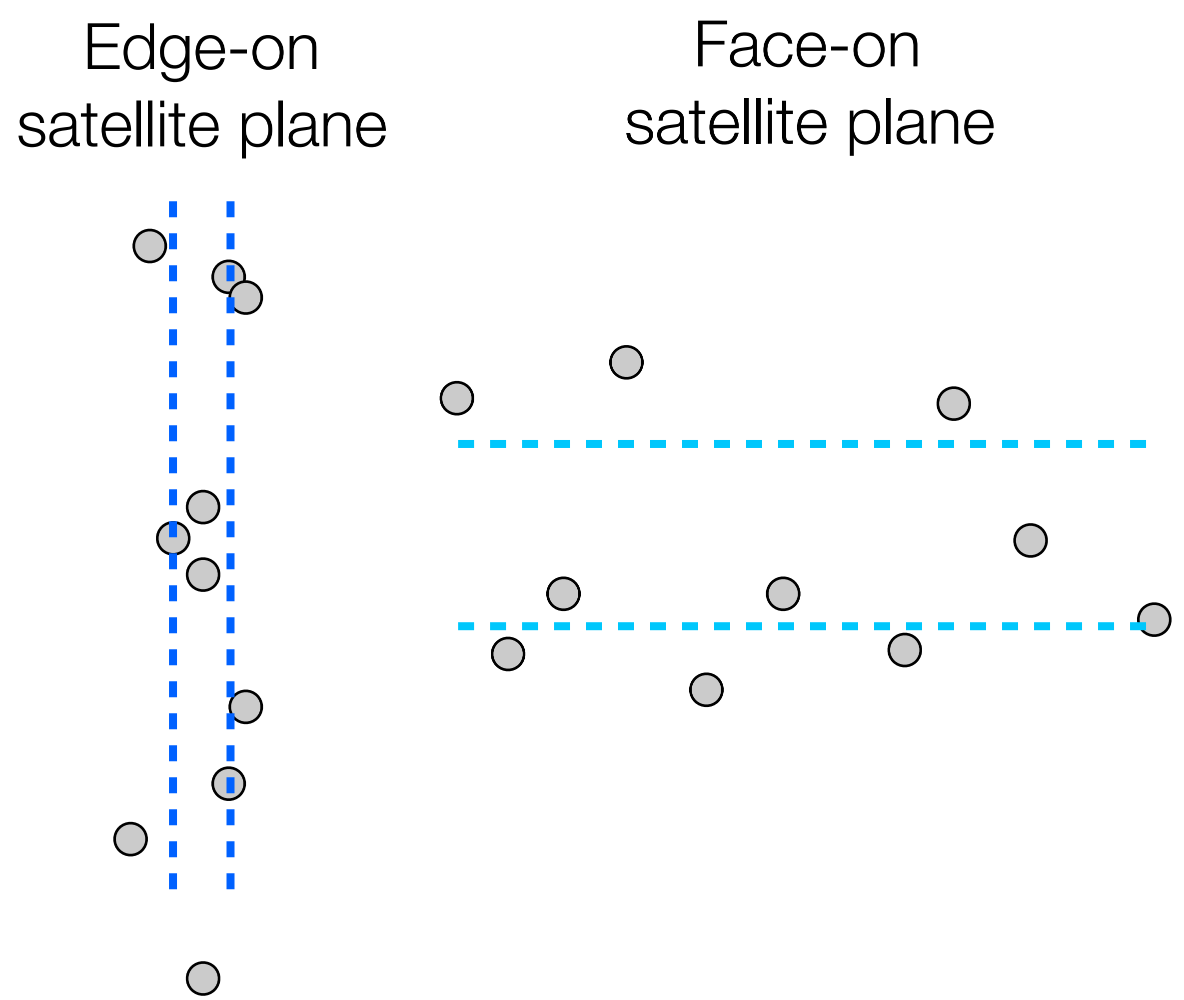

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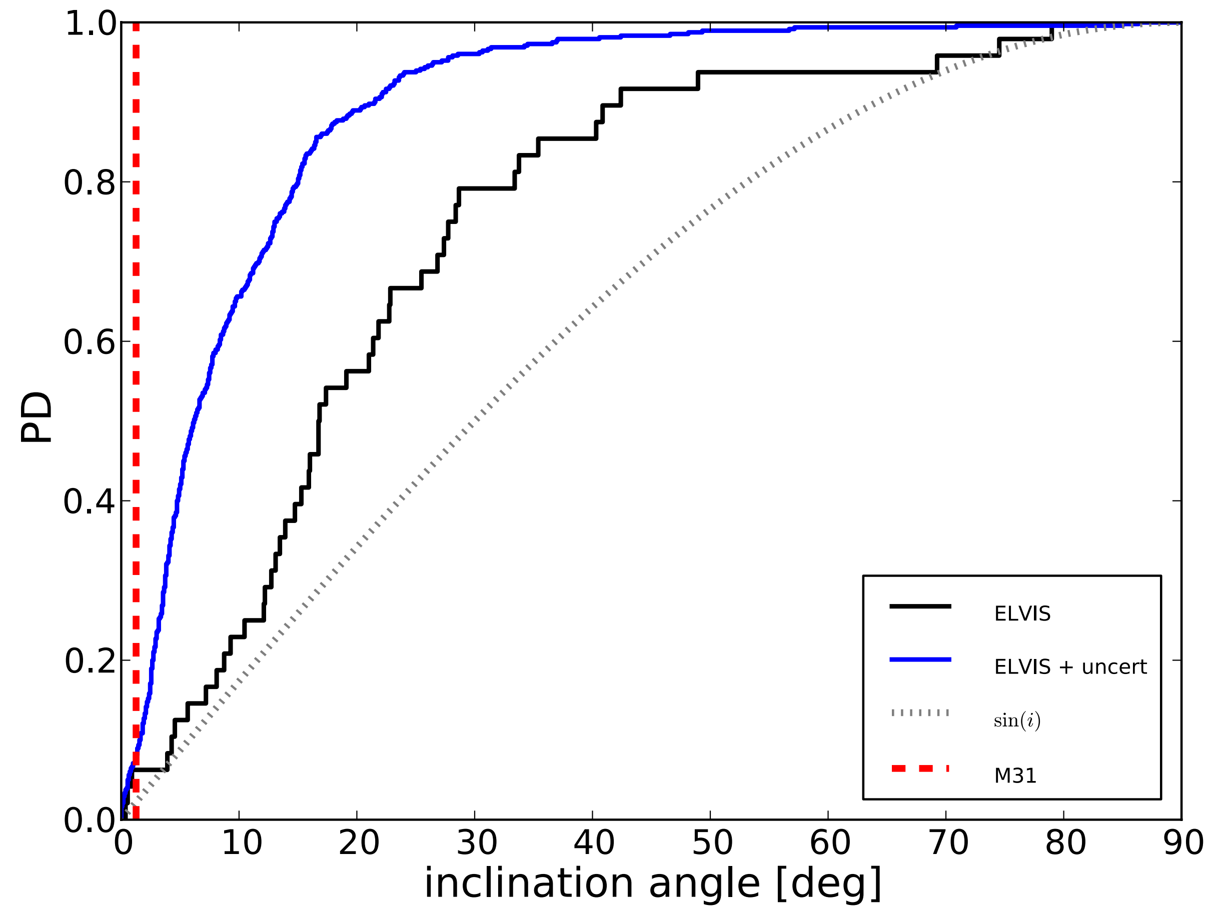

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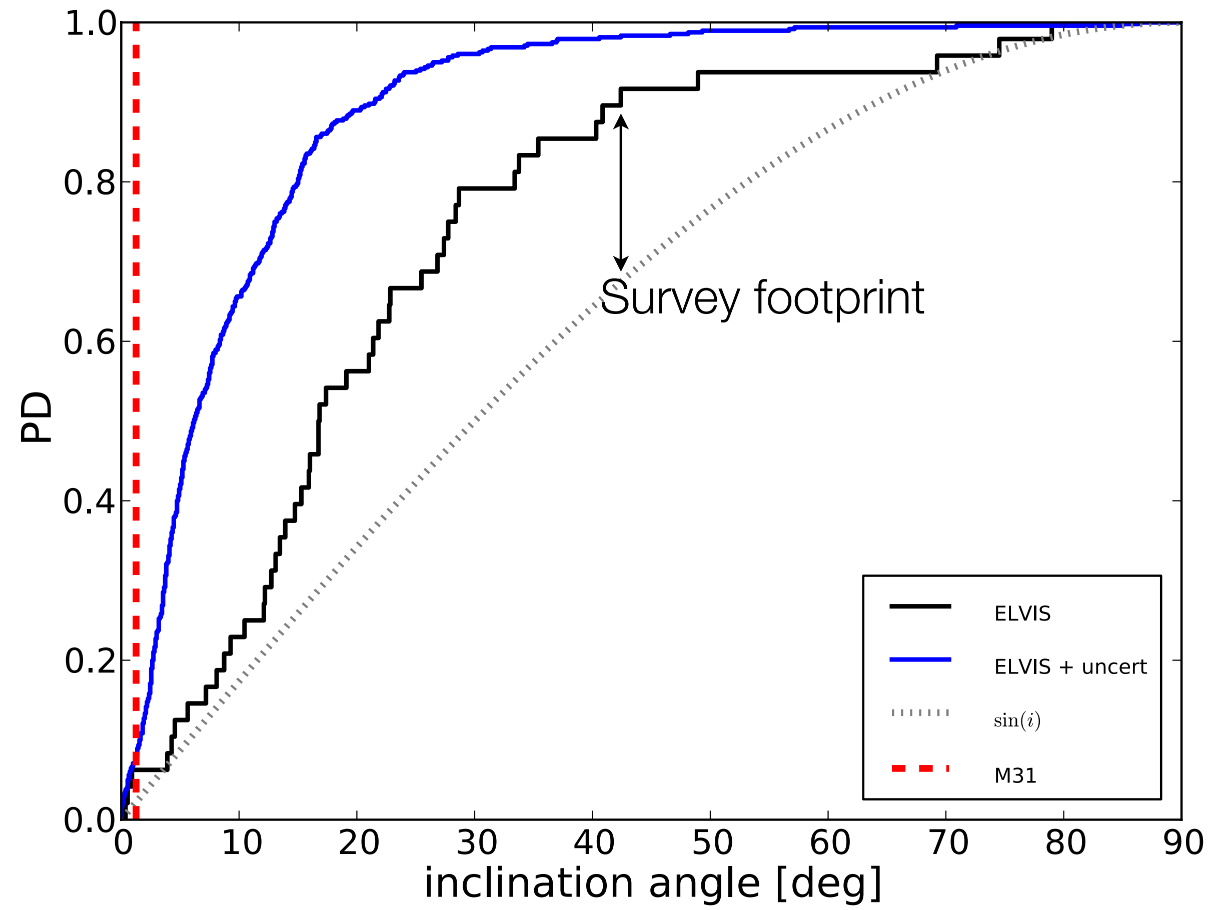

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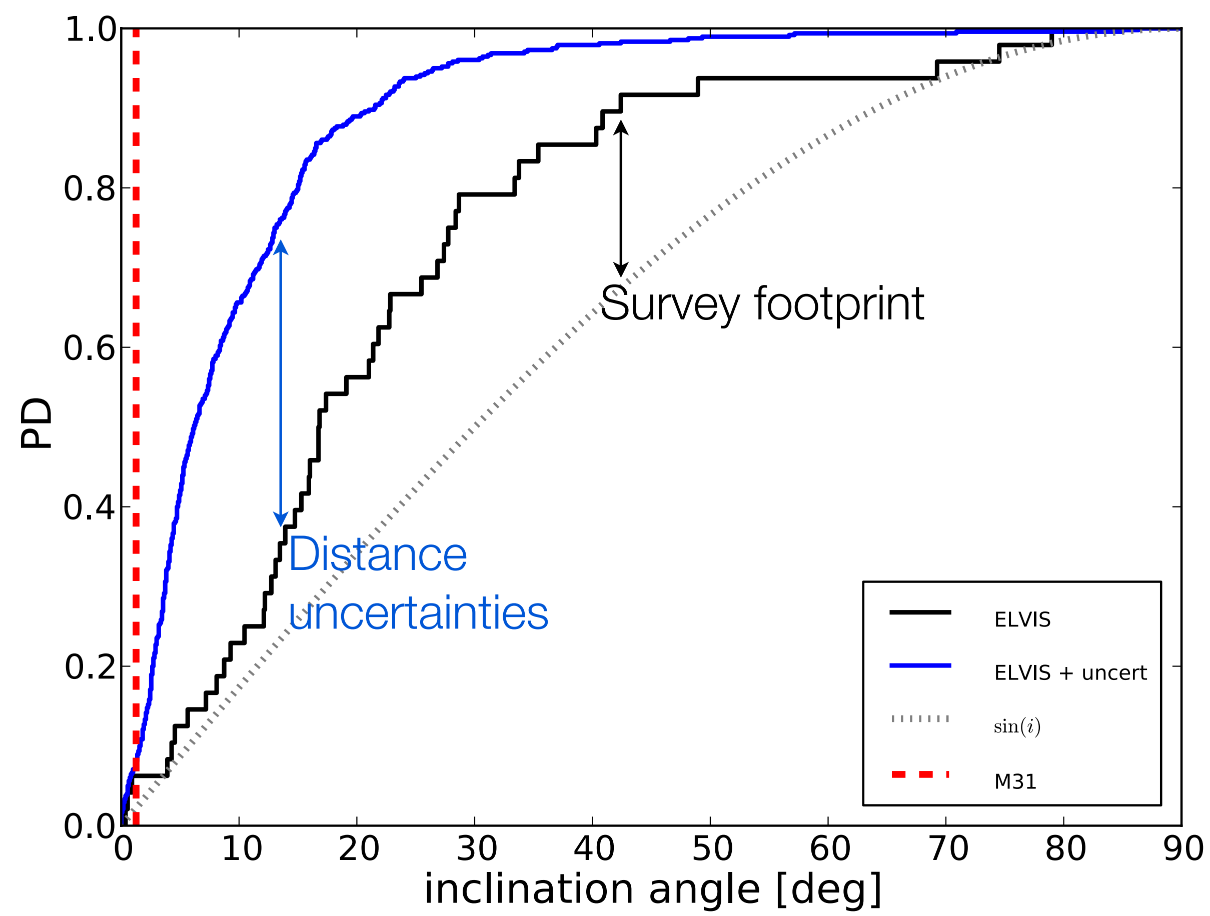

Questions

- Do we really want to believe that all these dwarf galaxy structures are coincidences?
- What is the origin of these dwarf galaxy structures?
- If LMC/SMC fell in recently, why are they so well aligned with the VPOS? And with the Local Group Plane 1?
- What does baryonic physics do that could affect the frequency of such structures in simulations? (e.g. Ahmed et al. 2017)

Conclusions

- **Both major galaxies in the Local Group host planes of satellite galaxies**:
  - ➡ Vast Polar Structure (VPOS) of the Milky Way: 20-30 kpc height, consistent with co-orbiting.
  - ➡ Great Plane of Andromeda (GPoA): ~50% of sats., ~14 kpc height, LOS vel. indicate rotation.

- **Sub-halo systems in ΛCDM not sufficiently anisotropic & kinematically correlated**:
  - ➡ Fundamental problem, baryons offer no easy way out.
  - ➡ One of the most-pressing small-scale problems of ΛCDM today!

- **For reliable comparisons obs. uncertainties need to be applied to simulated systems:**
  - ➡ If not then coherence (and thus frequency of configs. as extreme as obs.) is over-estimated.
  - ➡ Tension with ΛCDM might well be worse than currently thought.