Can we tell the plane's truth?

On the suggested origins of co-orbiting planes of satellites

Download the LG movies at:
http://marcelpawlowski.com/movies-astronomy/

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think beyond the possible℠

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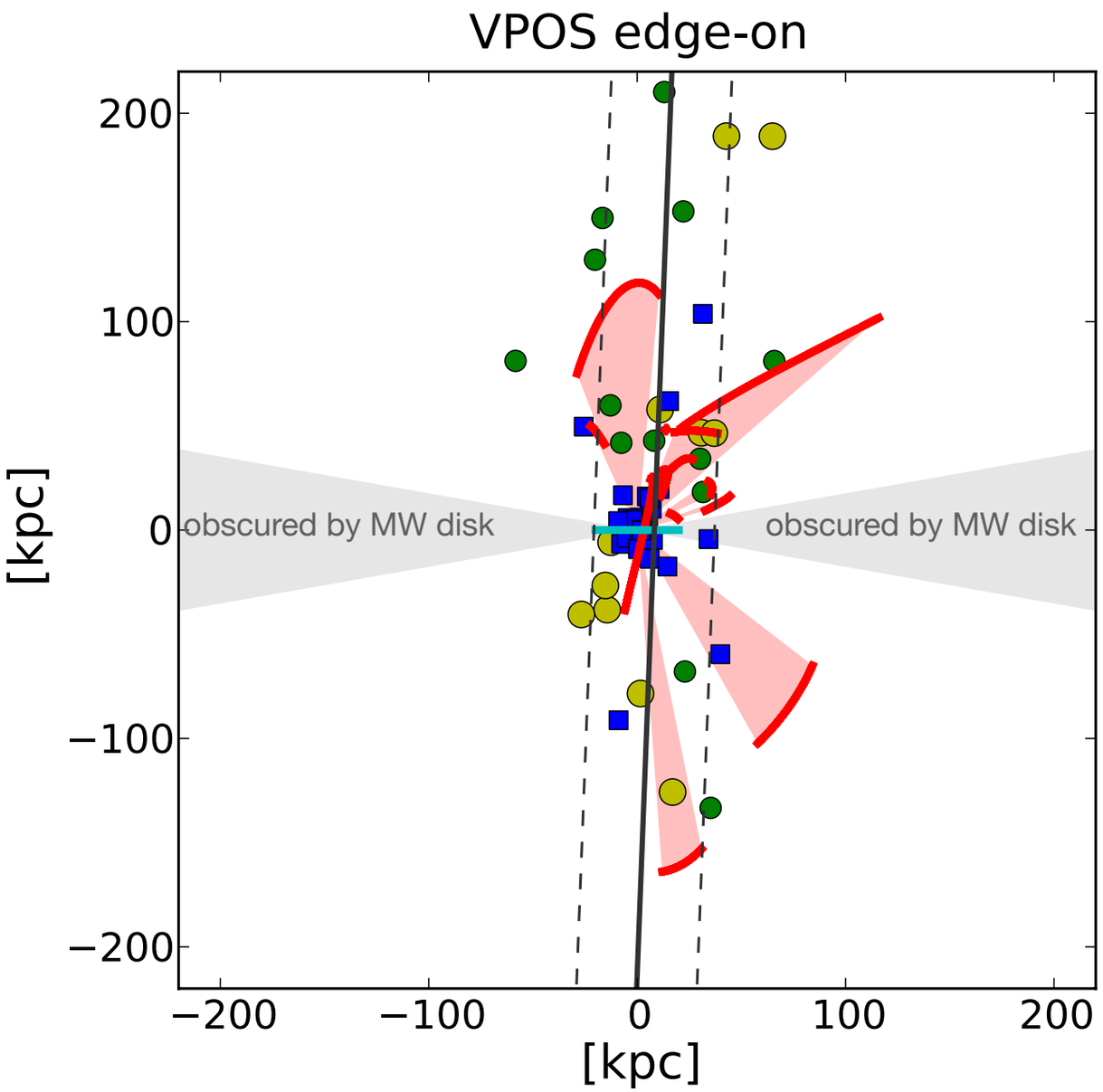
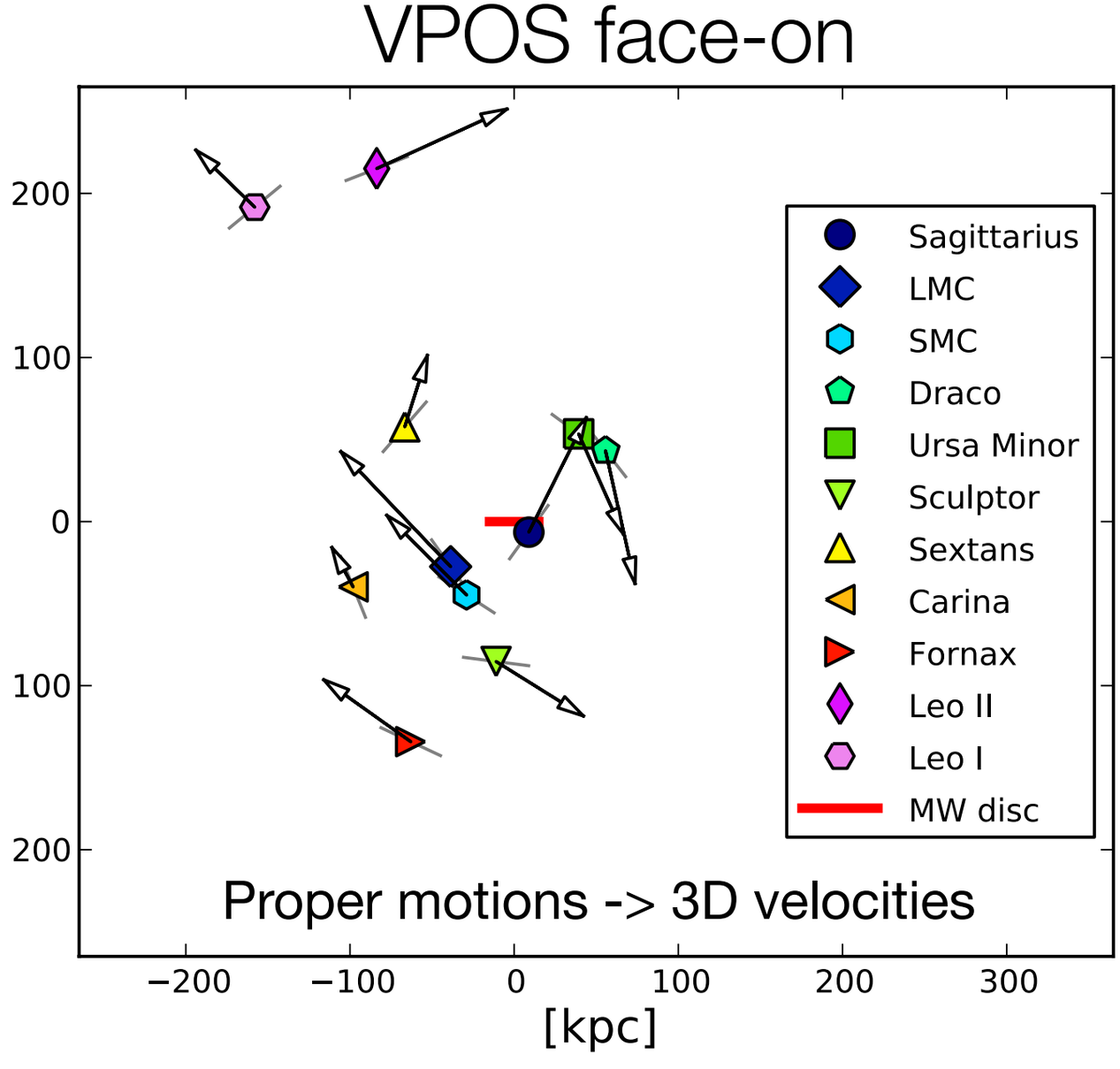
The Vast Polar Structure of the Milky Way (VPOS)

Pawlowski, Pflamm-Altenburg & Kroupa (2012, MNRAS, 423, 1109)
Pawlowski & Kroupa (2013, MNRAS, 435, 2116)





‘Classical’ and faint MW satellites, young halo globular clusters and 50% of streams align in highly flattened (20-30 kpc), co-orbiting structure

Significance of the VPOS

Pawlowski in prep.

Probability to find at least as extreme structure in isotropic distribution?

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11 classical satellites in narrow plane (Δ_{rms} = 19.6 kpc height)
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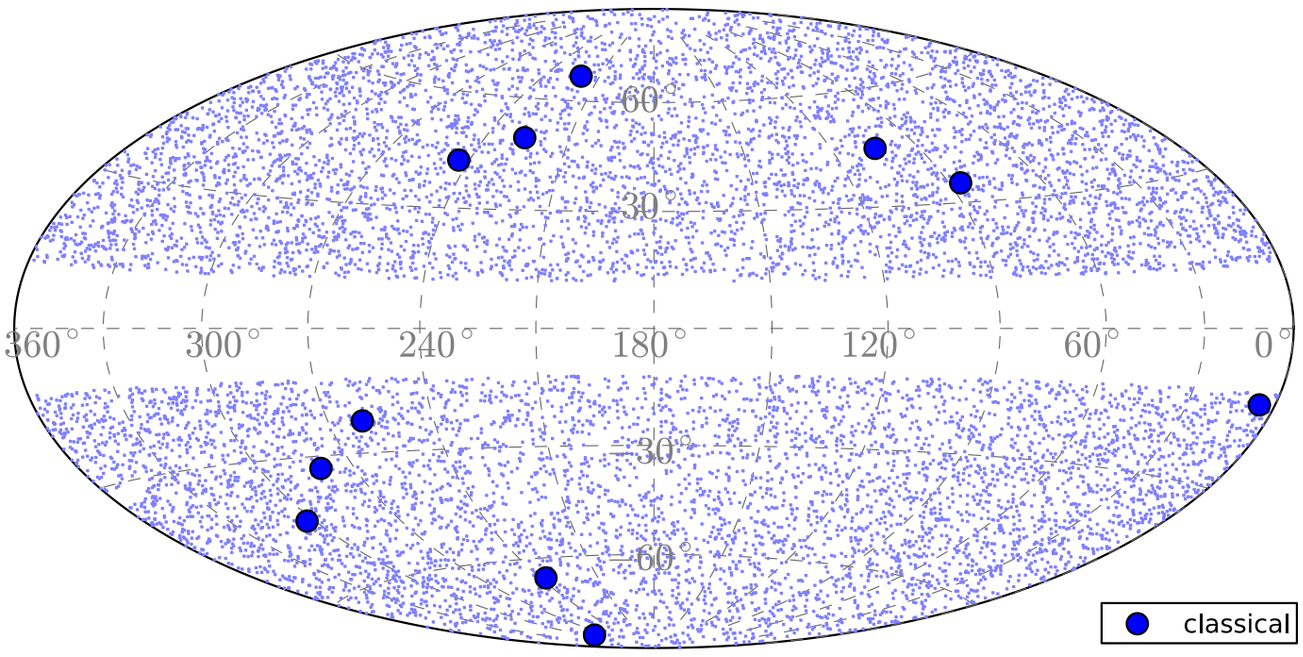
$P = 1.5 \times 10^{-2}$
(~ 2.4 σ)



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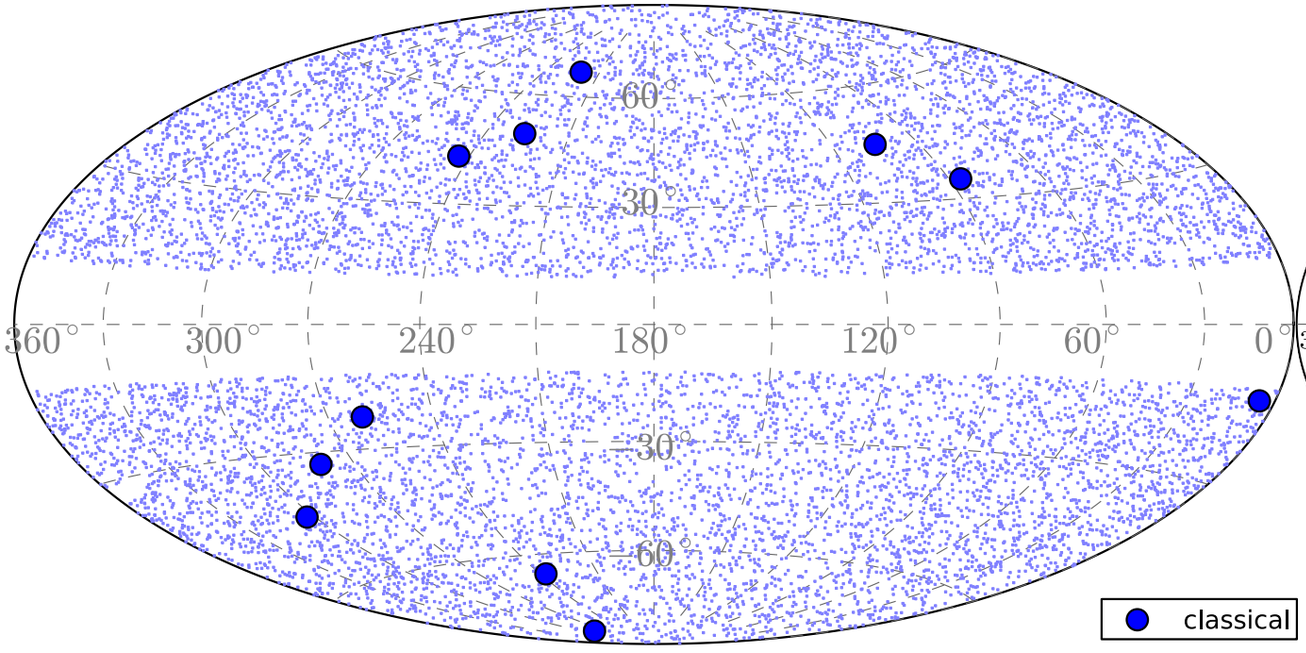
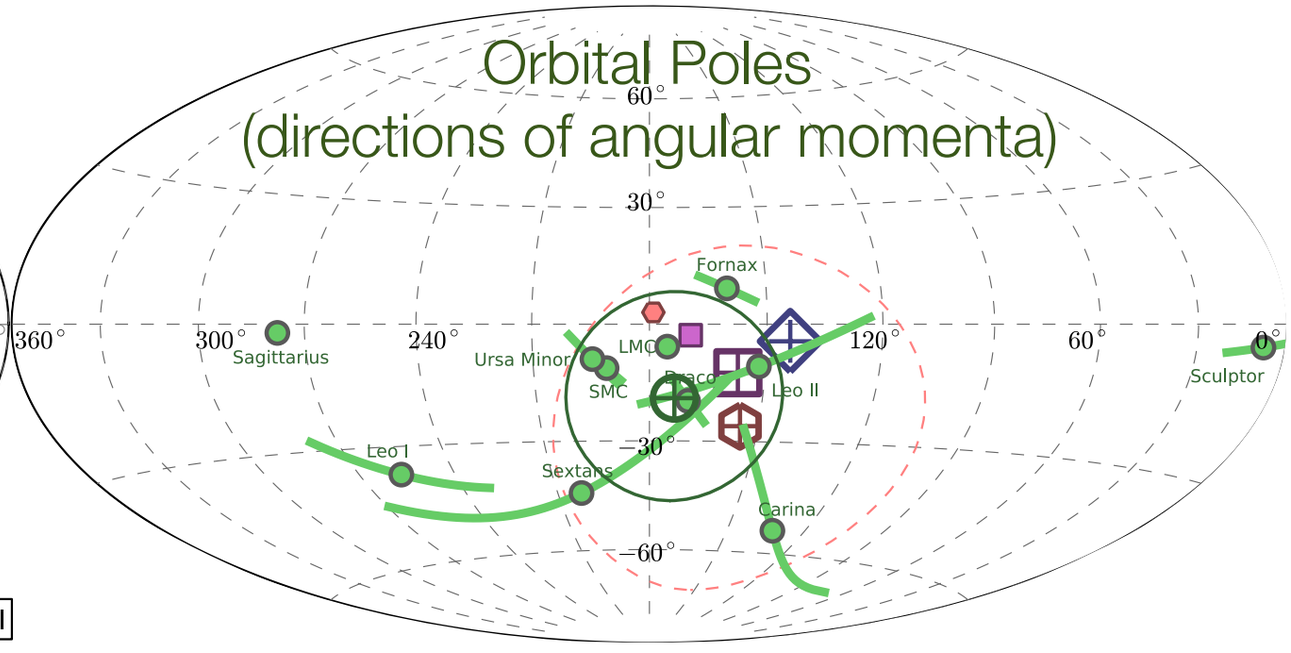
+ of these **8 co-orbit** (Δ_{sph} = 27.2° orbital pole concentration)

$P = 1.2 \times 10^{-4}$ (~ 3.8 σ)

Satellite distribution on the sky, model for $N_{\rm iso}=26$ (isotropic only)





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$P = 1.2 \times 10^{-4}$ (~ 3.8 σ)

+ **15 SDSS satellites** define narrow plane (Δ_{rms} = 26.6 kpc) aligned with classical satellites (~20º) (consider exact SDSS DR7 footprint and 2x MW obscuration)

$P = 4.3 \times 10^{-6}$ (~ 4.6 σ)

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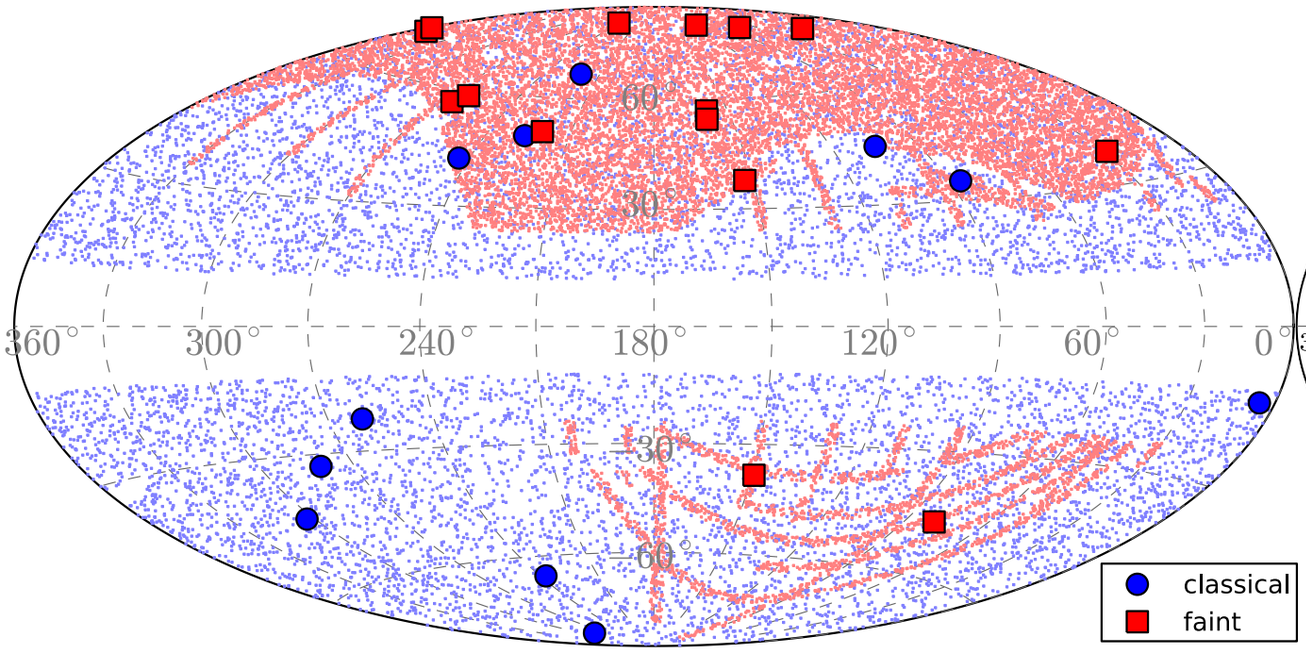
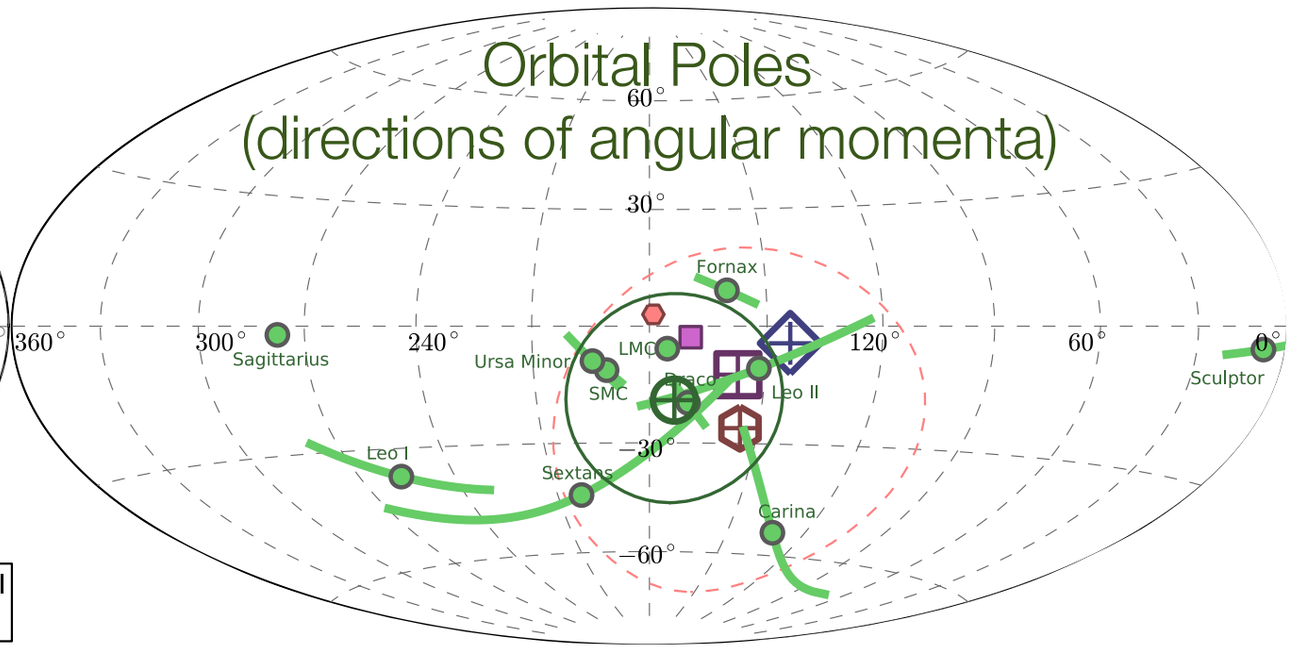
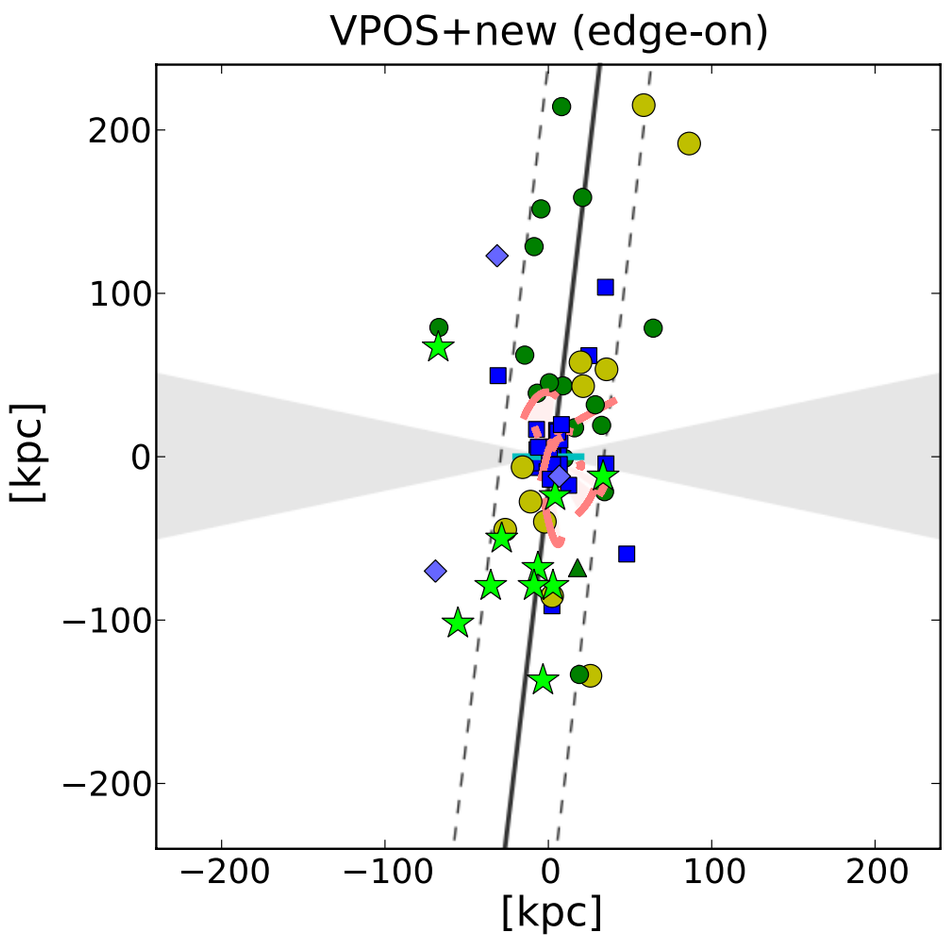


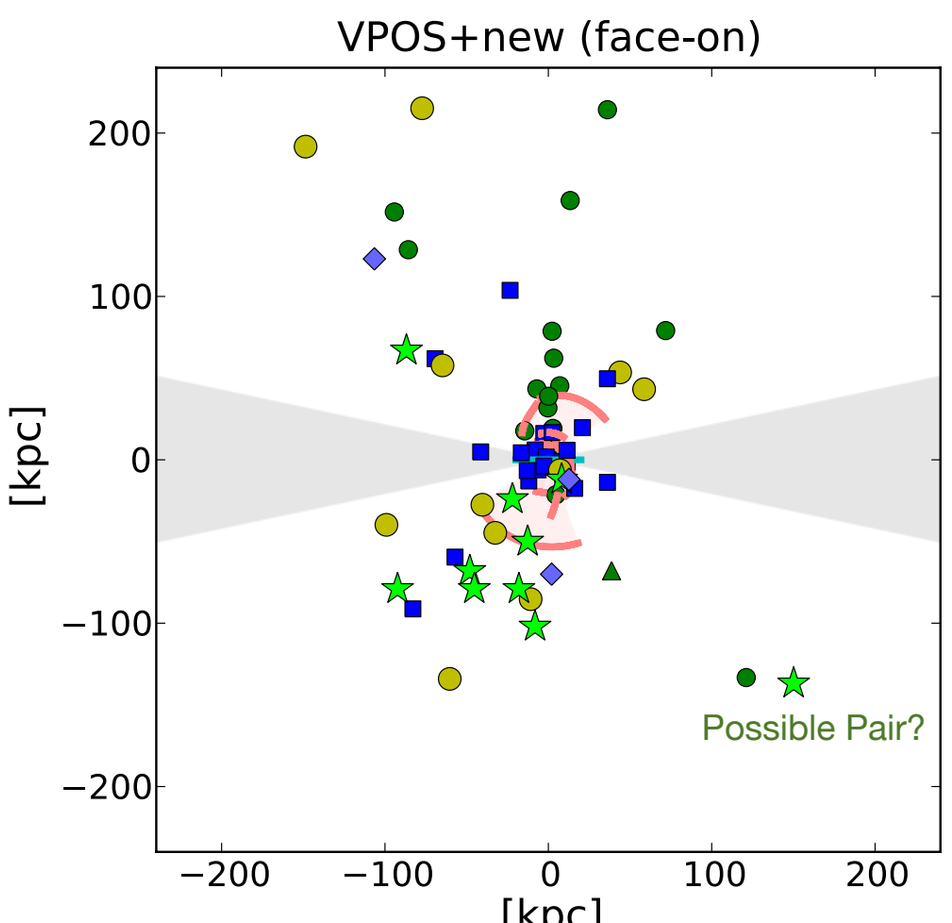


VPOS and the new Satellites

Pawlowski et al. in prep.

- 12 new MW satellite objects discovered in recent weeks, mostly in southern galactic hemisphere.
  (DES collaboration, Belokurov+, Kim+, Martin+, Laevens+)
- Align well with previous VPOS plane.
- VPOS fit almost unchanged, but:
  - Offset from MW center reduced to 2.6 kpc. (balanced out?)
- VPOS+new aligns even better with LMC orbit. (difficult to reconcile with LMC on first infall?)





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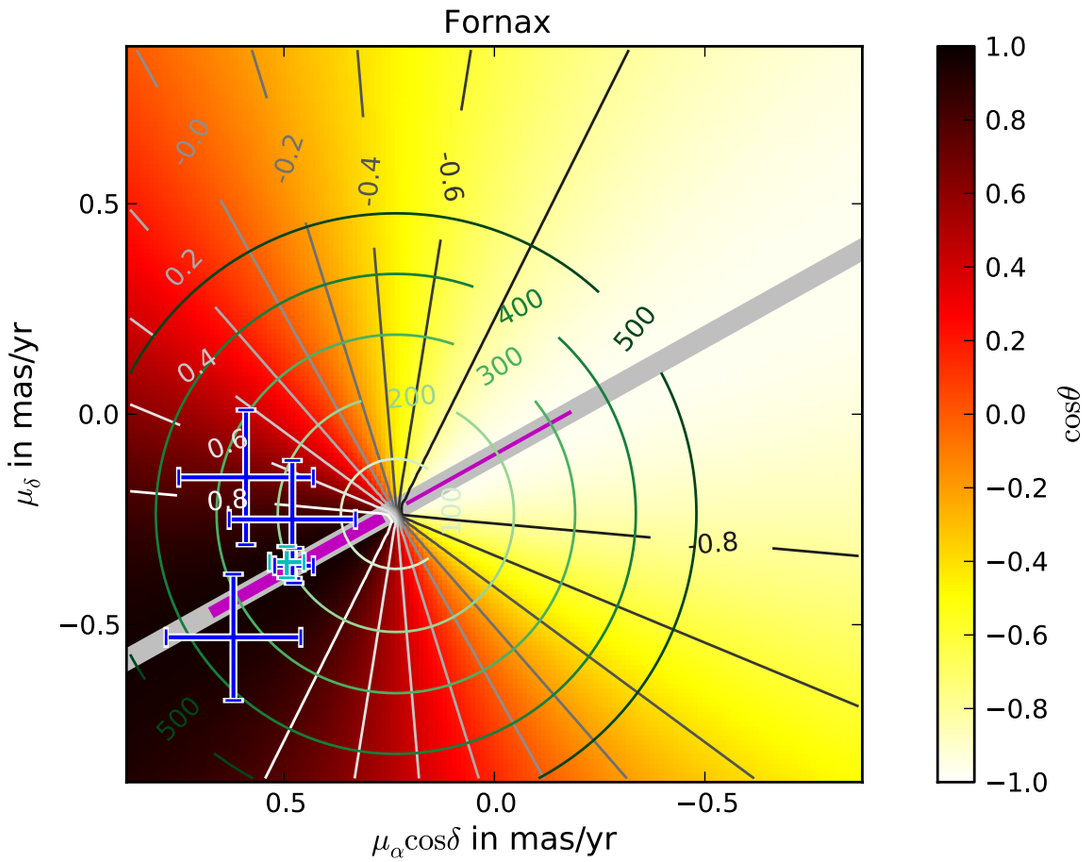

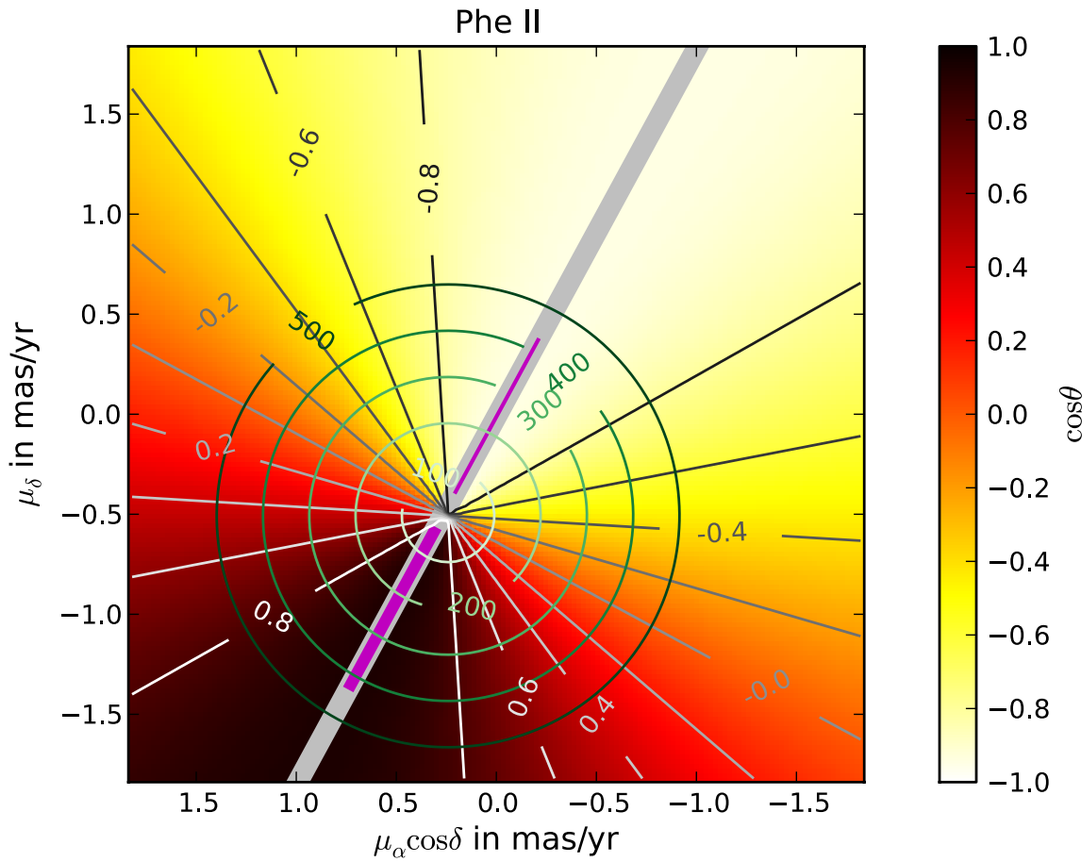

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- Predict proper motions of satellites. (Pawlowski&Kroupa2013,2014;Pawlowski+in prep.)
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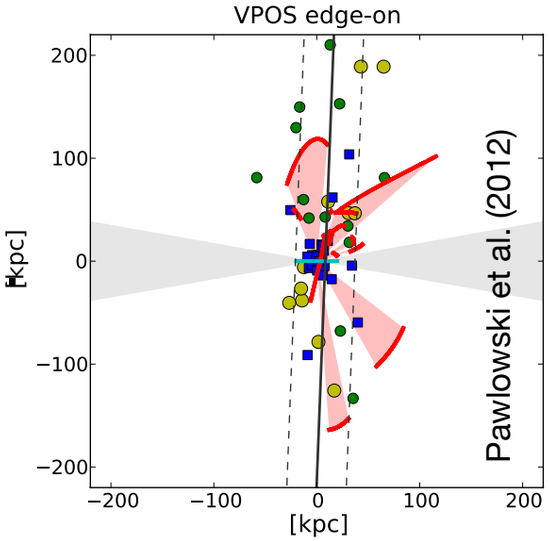
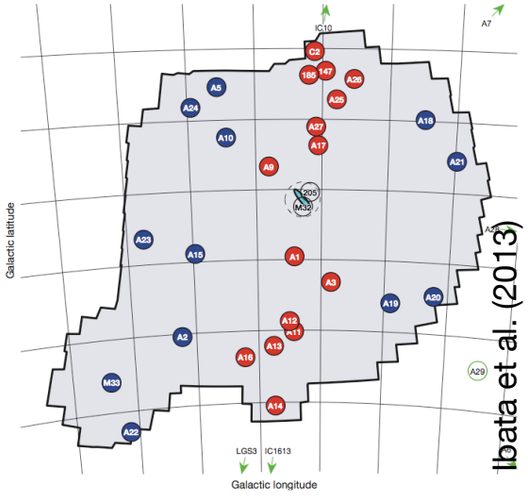
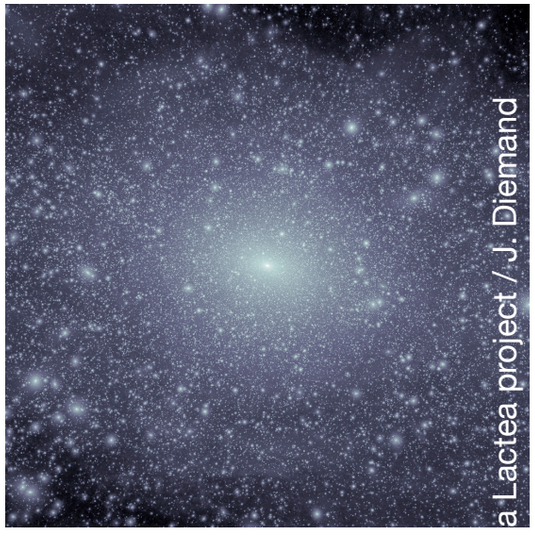
- **Test cosmology**
  - **Important**: co-orbiting satellite planes not predicted by ΛCDM simulations.
    - ➡ Fundamental problem of cosmological standard model?
  - **Robust**: independent of internal baryon physics (>100 kpc scales).
  - **Promising**: origin of satellite planes might provide important information to find (unified) solution for other small-scale problems.

Can this ...





... be found in this?



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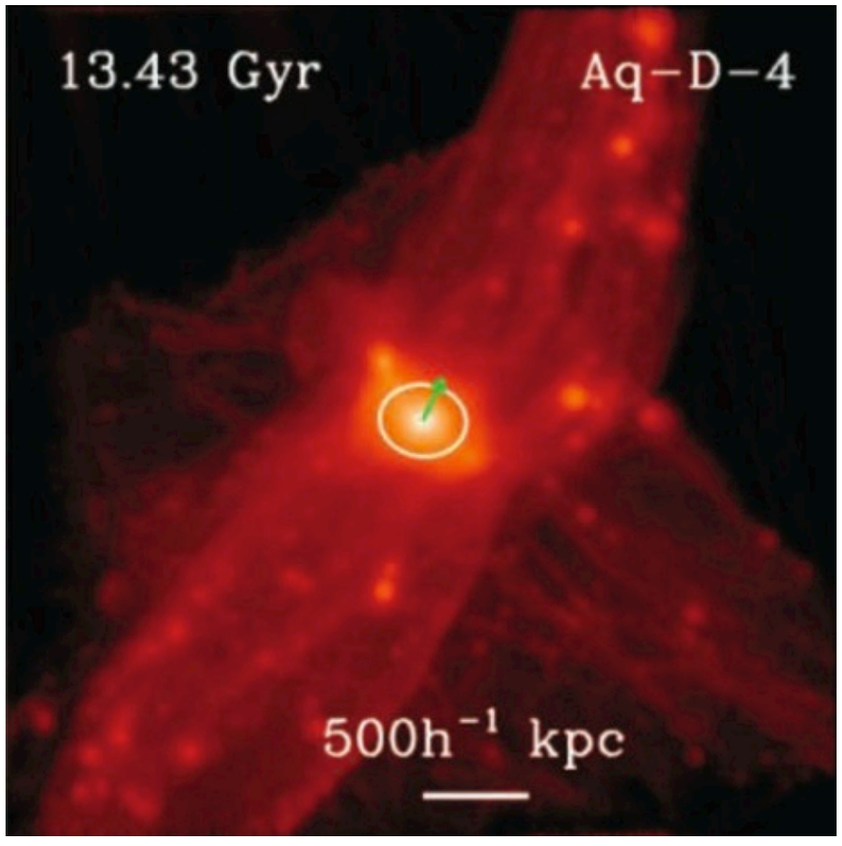

Vera-Ciro et al. (2011)

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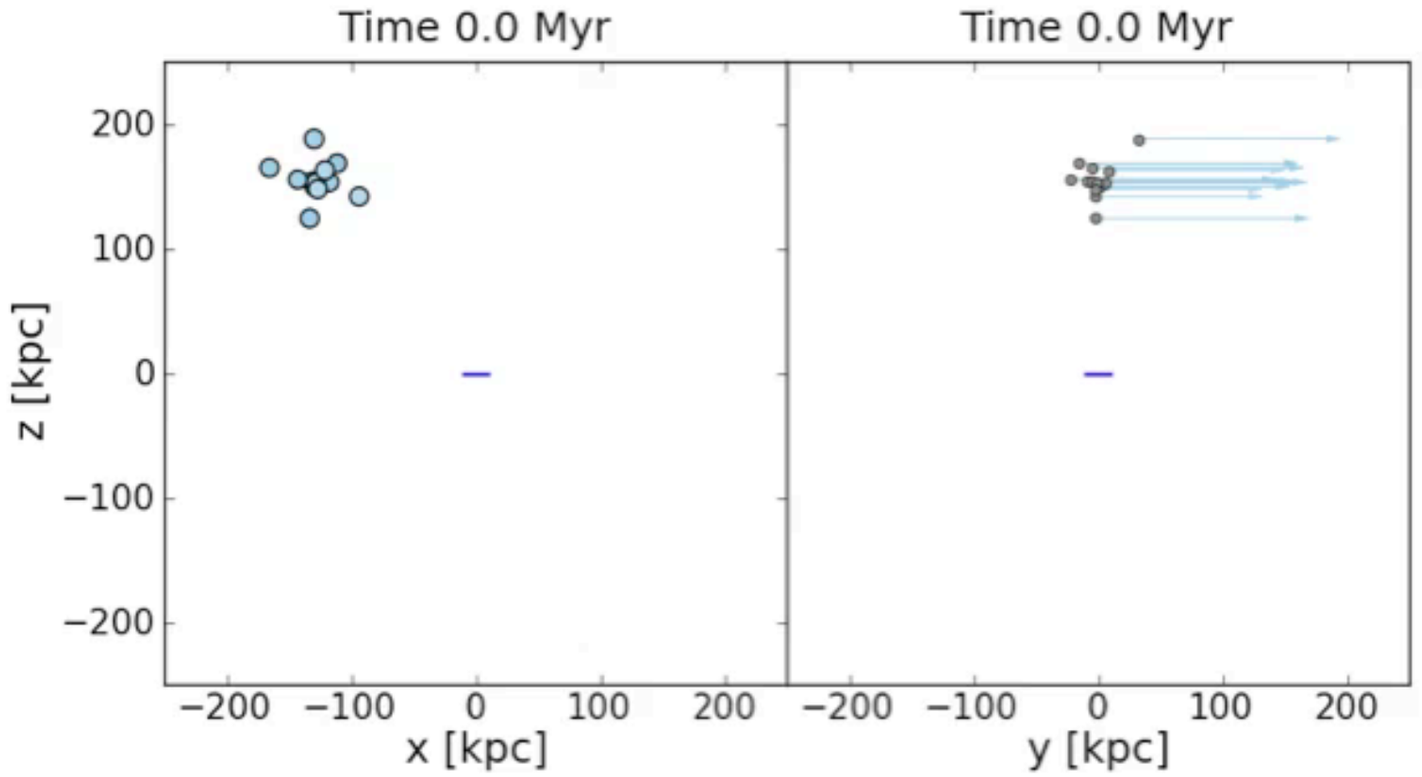

Pawlowski

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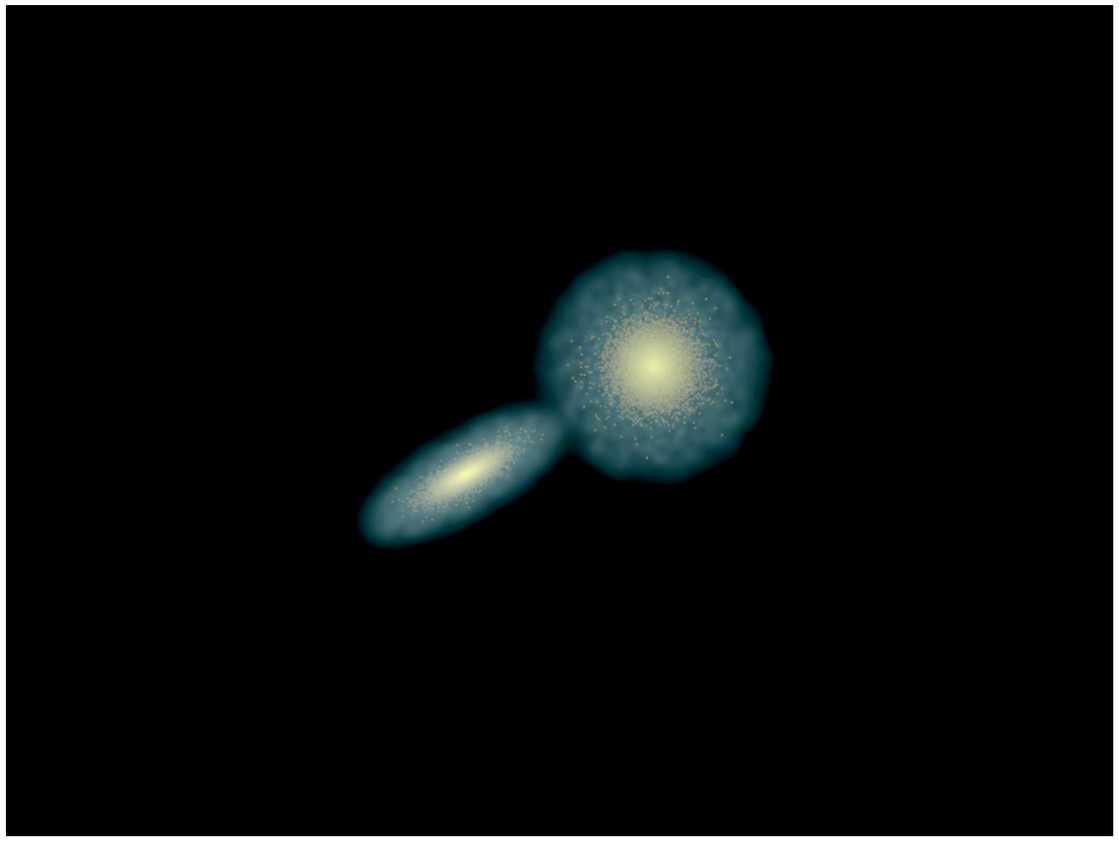

Wetzstein et al. (2007)

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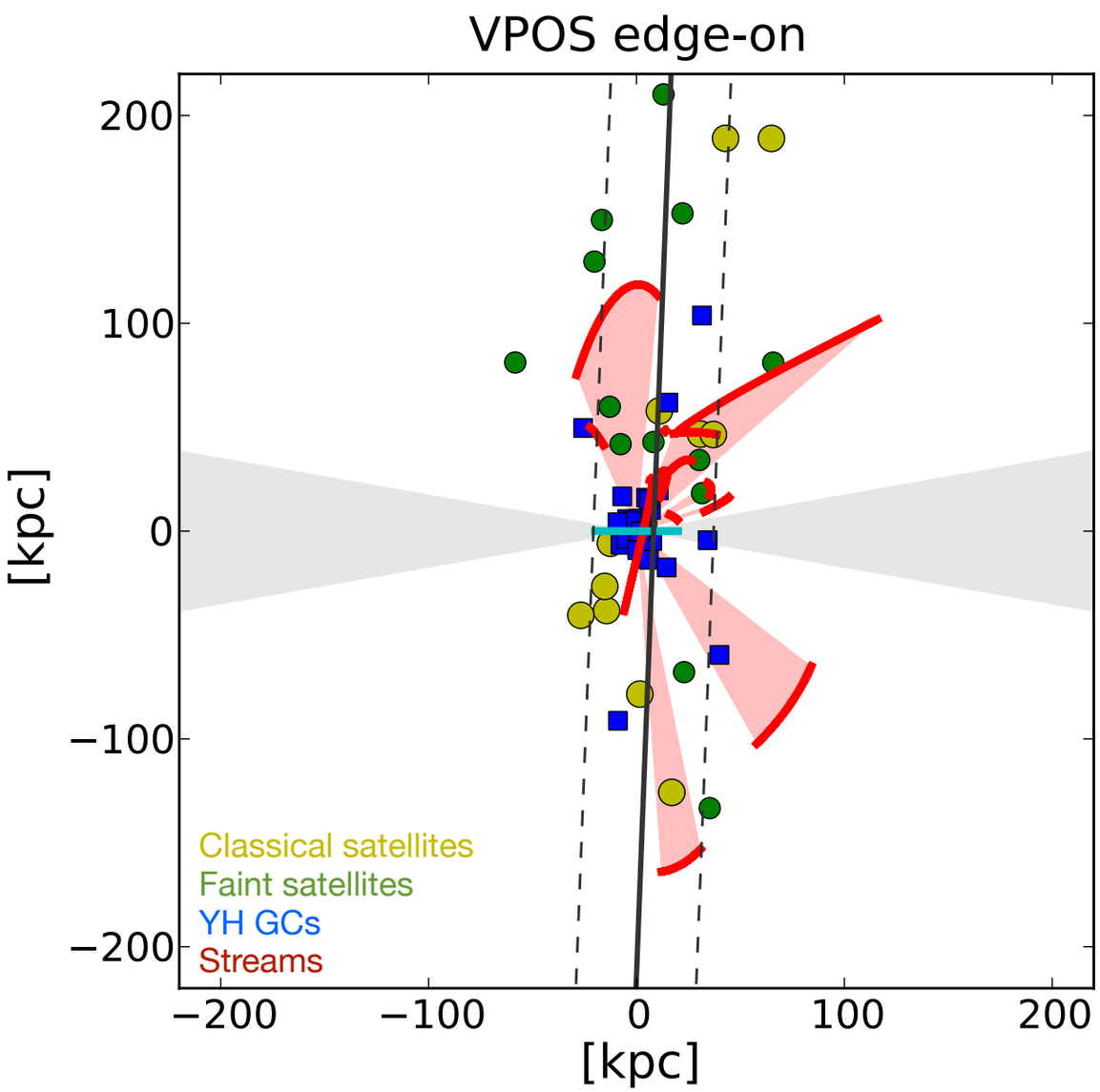
} Must already be part of cosmological simulations

Significant anisotropy ≠ sufficiently strong planar alignment

How frequent are such *spatial* distributions in ΛCDM?

Pawlowski+(2014, MNRAS, 442, 2362); Pawlowski & McGaugh (2014, ApJL, 789, 24)



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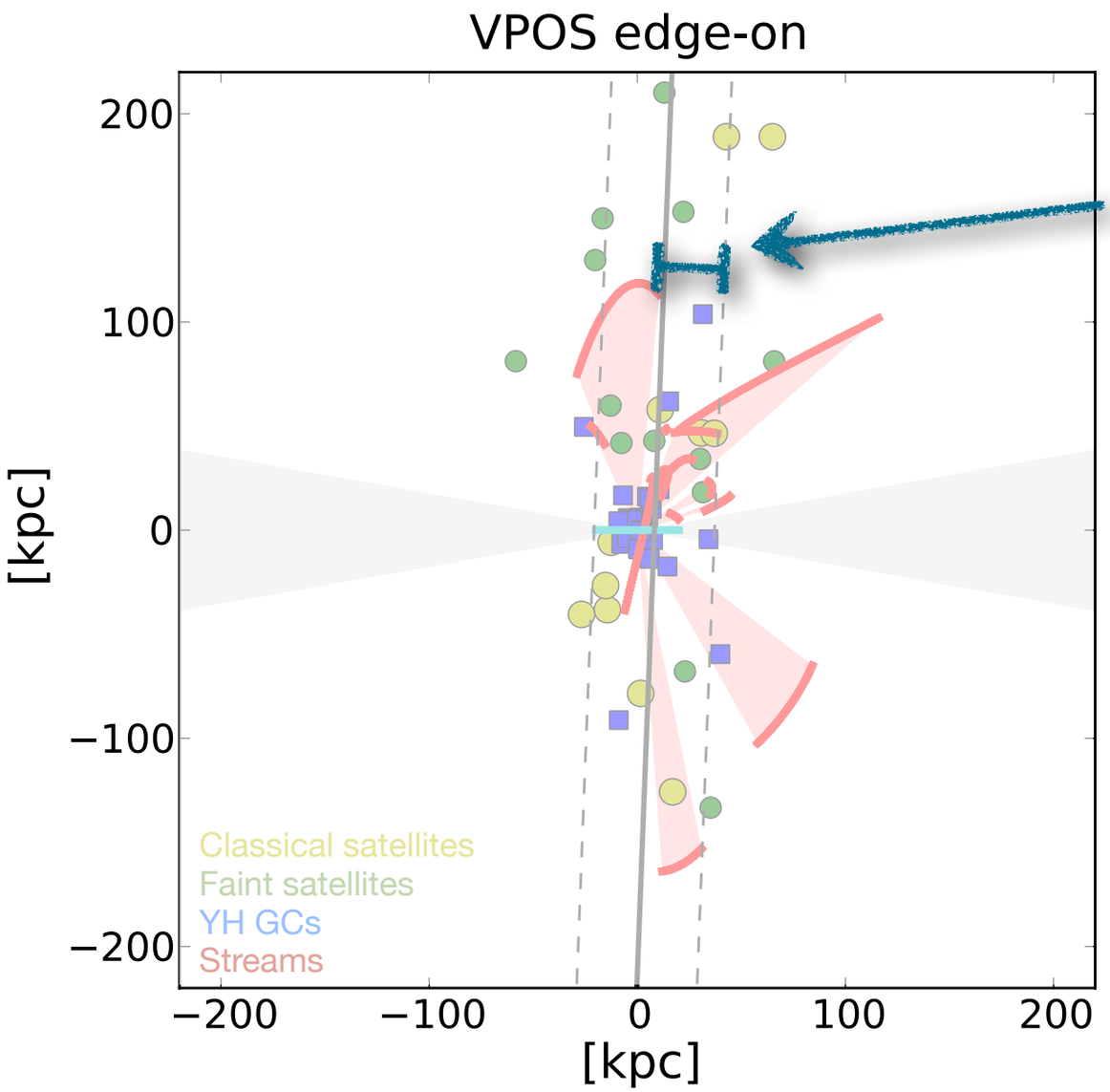

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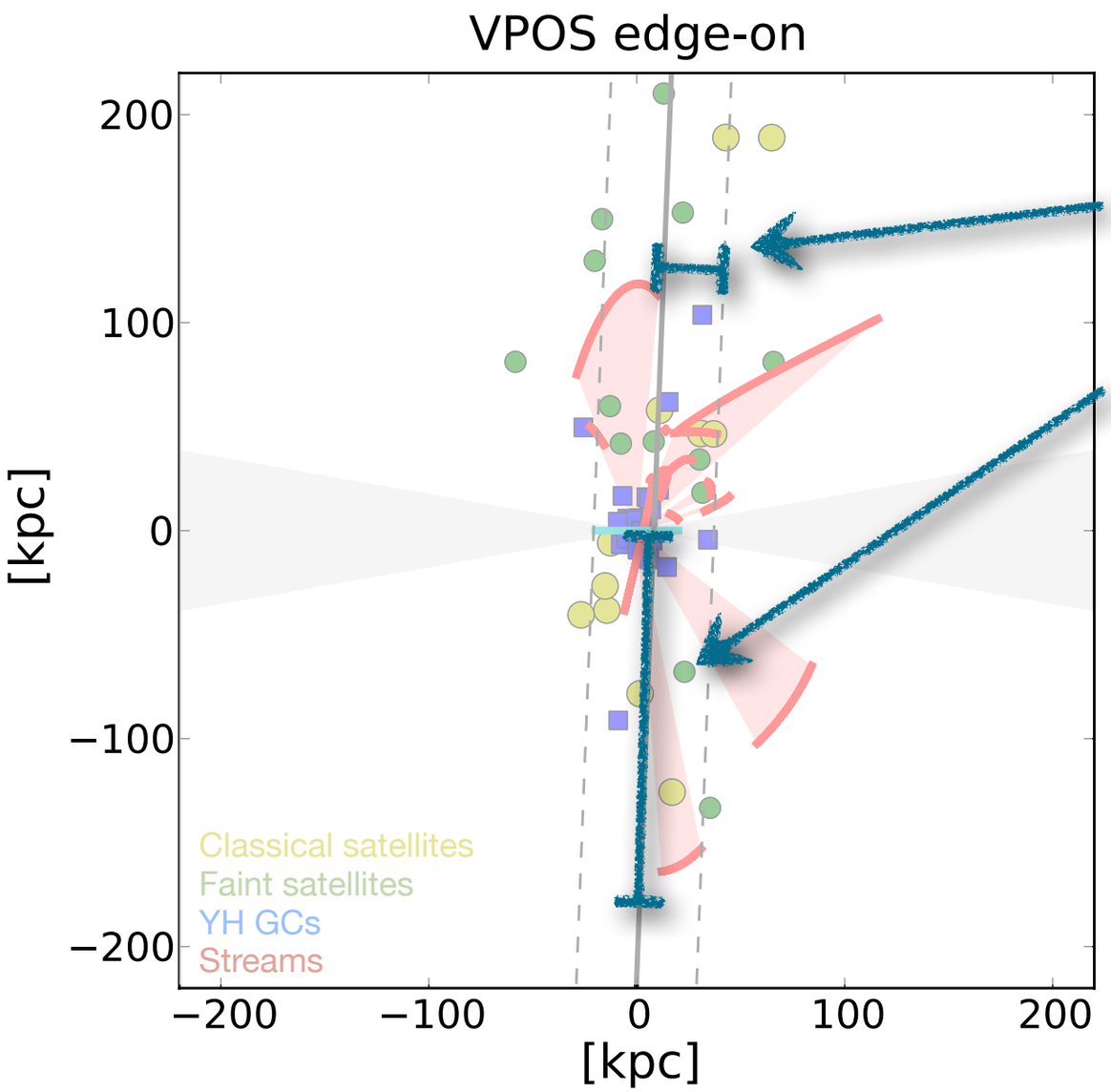

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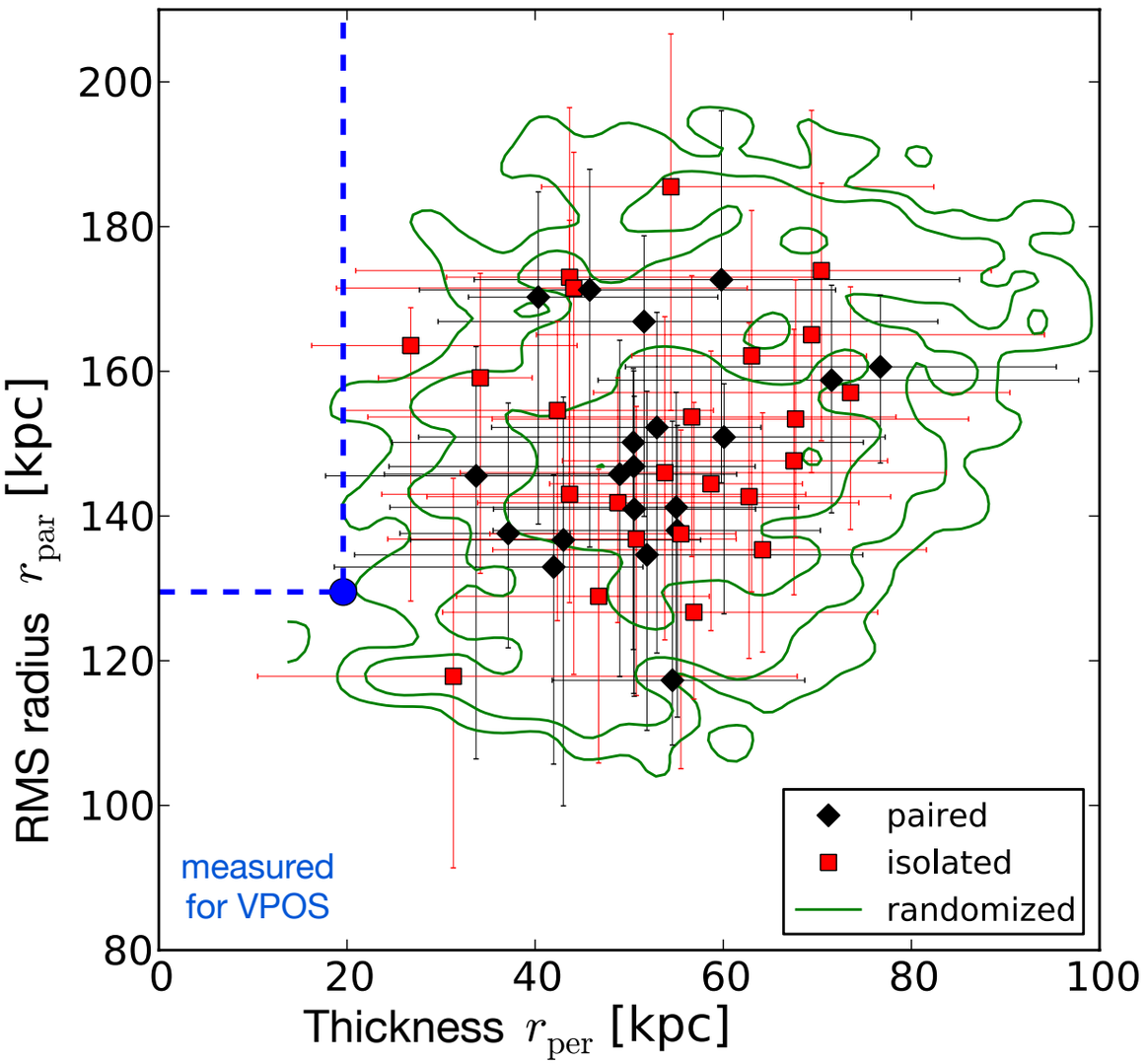

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How frequent are VPOS-like planes?

- ELVIS, Millennium-II (unresolved sat.!):

  $r_{\rm per}$, $r_{\rm par}$: ~ 0.3 to 1.2%

  ***c/a*, *b/a*: ~ 0.8 to 1.6%**

- BUT: additional objects align with VPOS!
- BUT: what about kinematics (co-orbiting)?

How frequent are *co-orbiting* satellites in ΛCDM?

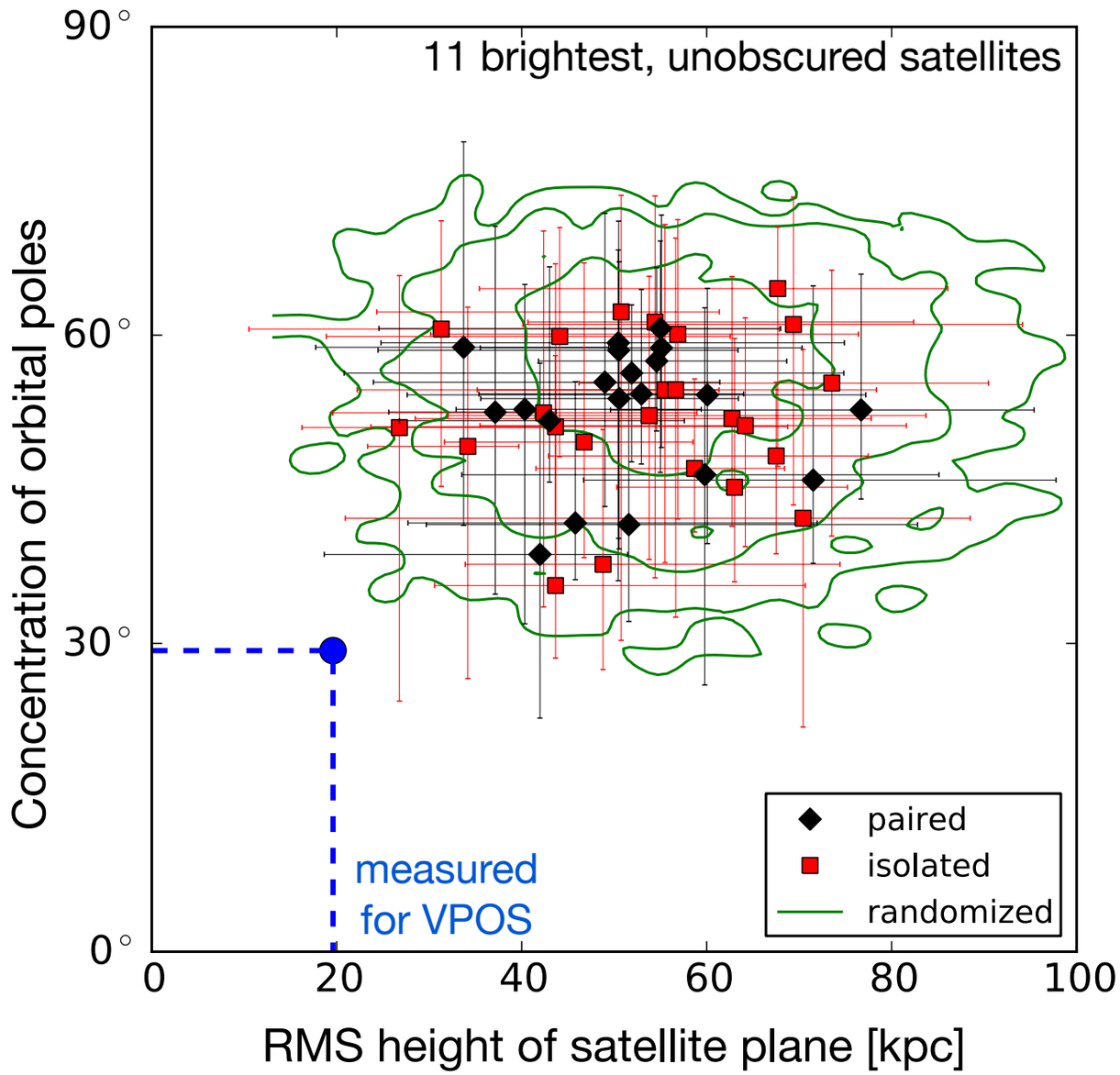
Pawlowski & McGaugh (2014, ApJL, 789, 24)

e.g. ELVIS simulations (LG-like pairs)
(Garrison-Kimmel+2014)

➡ 1.3 % of realizations have as concentrated orbital poles (~Millennium-II, VL1 & VL2, Aq)

➡ But only 1 of 4800 realizations fulfills thickness and orbital pole criterion simultaneously.

➡ LG environment: VPOS-like planes similarly unlikely around **paired** and **isolated** hosts.



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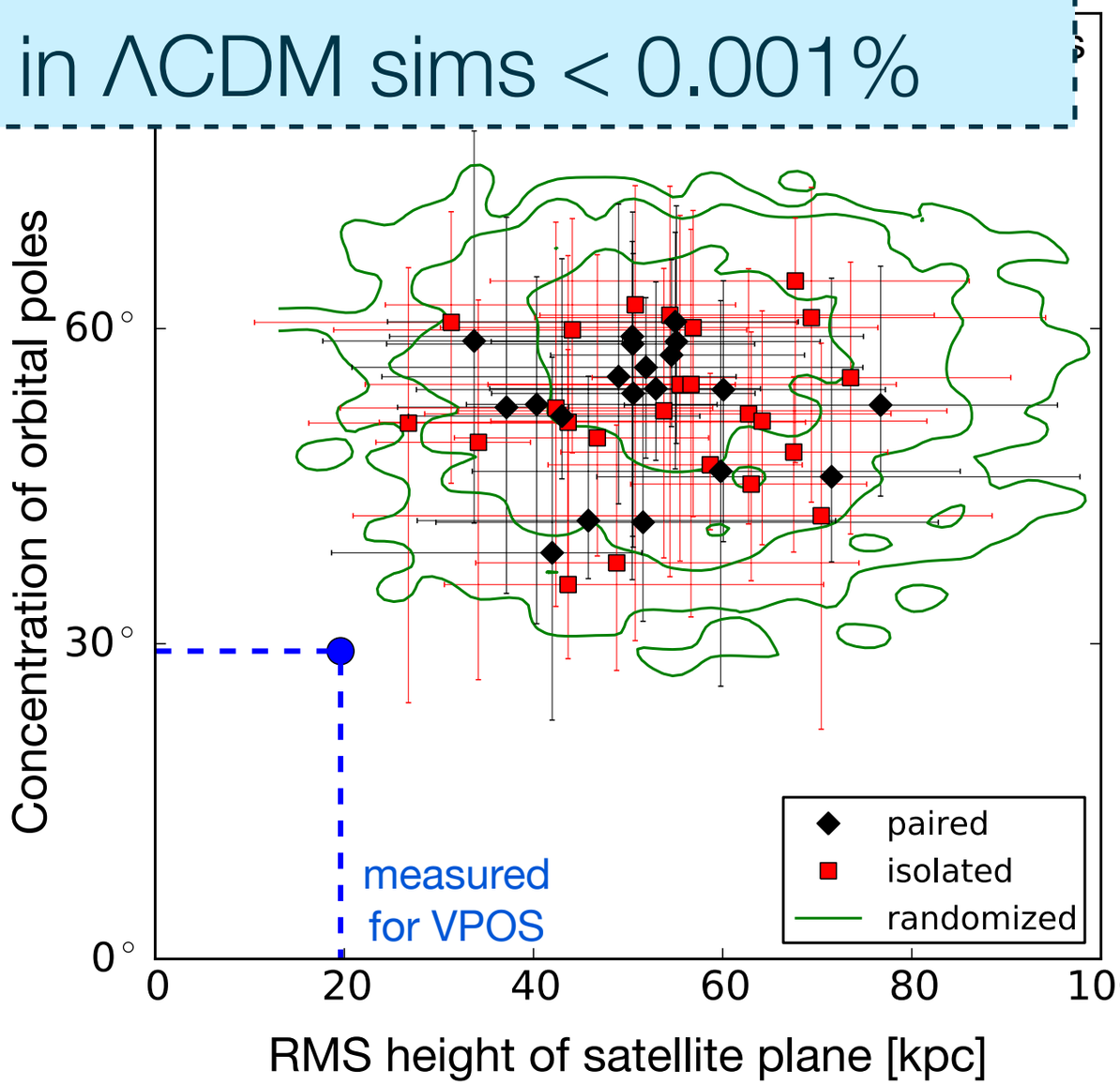
Chance to find VPOS *and* GPoA in ΛCDM sims < 0.001%



What to avoid when testing for satellite planes

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  (e.g. Bahl&Baumgardt2014)

Ibata et al. (2014):

> [8] To make the issue perfectly clear, consider measuring the incidence of animals that have stripes and paws and are nocturnal. Clearly, selecting only two of these three properties will yield a larger (and incorrect) sample of such animals, giving a falsely optimistic measurement of how common they are.

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  (e.g. Goerdt+~~2013~~ ~~2014~~ 2015?)
- Radial **distances** of satellites **not considered**.
  (e.g. Sawala+~~2014~~ 2015?)

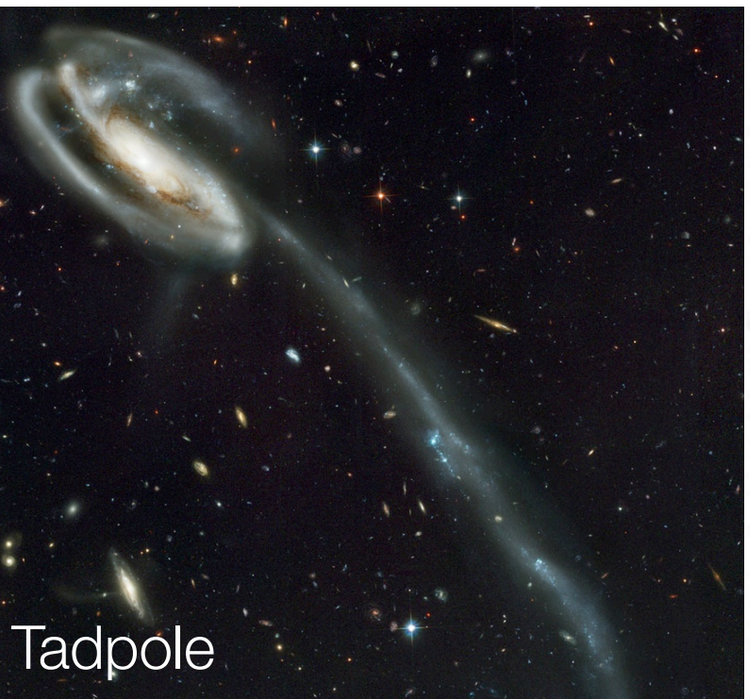
Tidal dwarf galaxies (TDGs)

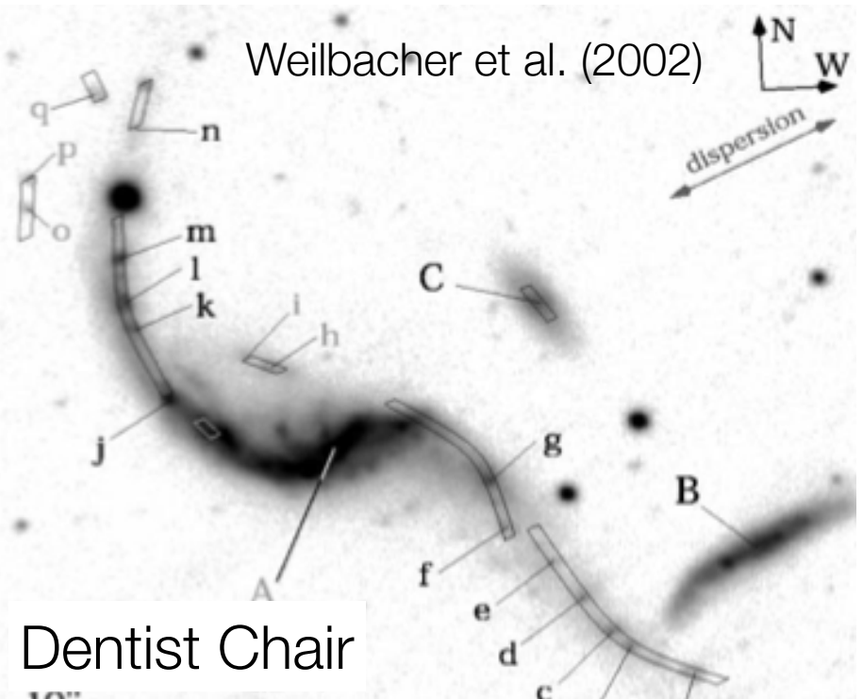
see Pavel's, Pierre-Alain's & Sylvia's talks, Jörg's poster and others

- Second-generation galaxies in debris of galaxy collisions.
- Can survive formation phase
  - ➡ Observed (Duc+2011)
  - ➡ Simulated (Recchi+2007; Plöckinger+2014)
- Phase-space correlated
  - ➡ Consistent with VPOS & GPoA.
    (Pawlowski+2011, 2012a,b, Hammer+2013)

Concerns:

- Should be dark-matter-free
  - ➡ Non-equilibrium dynamics?
    (Kroupa 1997; Casas+2012)
  - ➡ Gas stripping? (Yang+2014)
  - ➡ Dissipative DM? (Randall+2014), MOND?
- Mass-Metallicity relation
  - ➡ Ancient TDGs less pre-enriched
    (arXiv yesterday: Recchi+2015)


Tadpole



Dentist Chair

NGC 5557 Duc et al. (2011)

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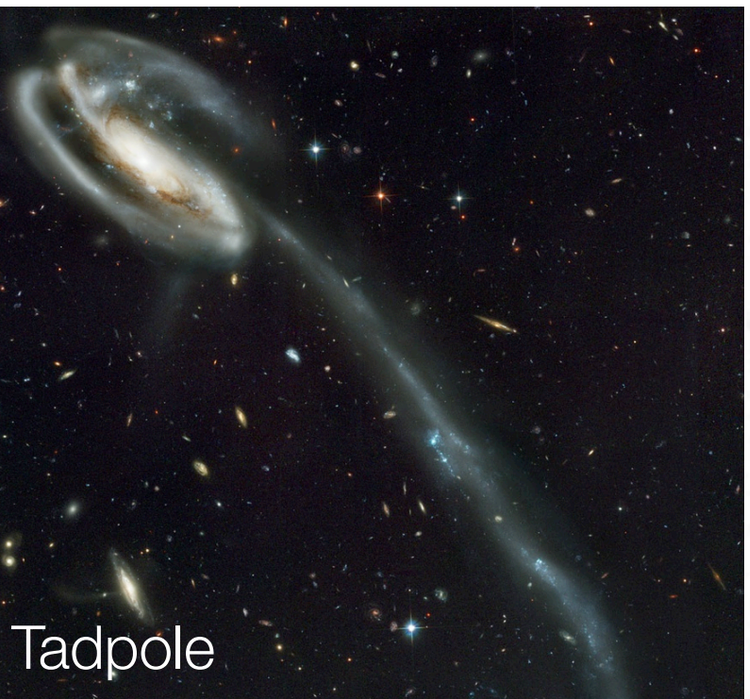

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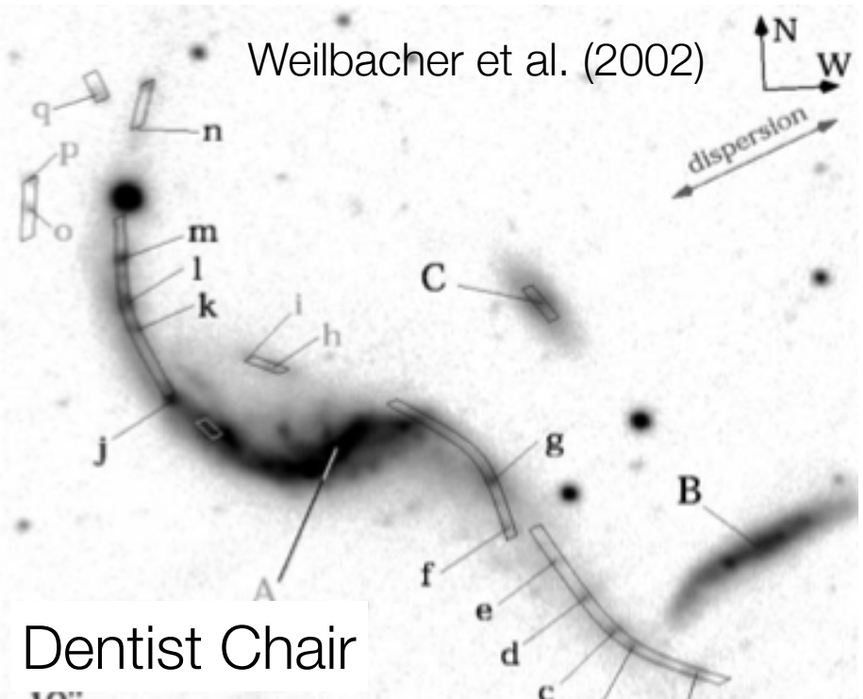

Dentist Chair

NGC 5557

Duc et al. (2011)

MNRAS **429,** 1502–1513 (2013) doi:10.1093/mnras/sts442

The spatial distribution of galactic satellites in the Λ cold dark matter cosmology

Jie Wang,[1]★ Carlos S. Frenk[1] and Andrew P. Cooper[2]

[1]*Institute for computational cosmology, Department of Physics, University of Durham, South Road, Durham,*
[2]*Max–Planck Institut für Astrophysik, Karl Schwarzschild Str. 1, D-85748 Garching, Germany*

"A larger sample of satellites around other galaxies will test the tidal formation hypothesis of Pawlowski et al. (2012) in which highly flattened configurations are easily achieved and should therefore be the norm. If, on the other hand, the CDM model is a realistic description of nature, then the average satellite configurations should be only moderately flattened."

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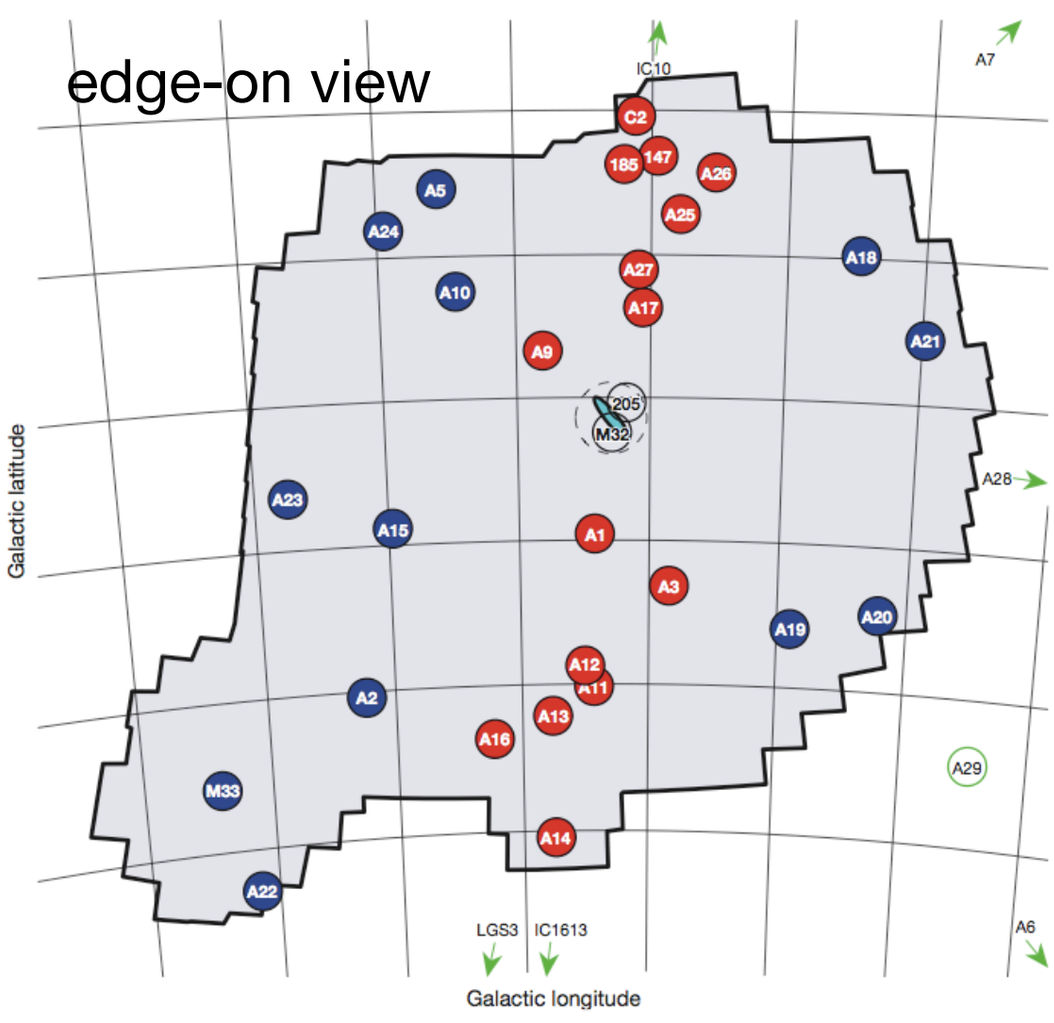
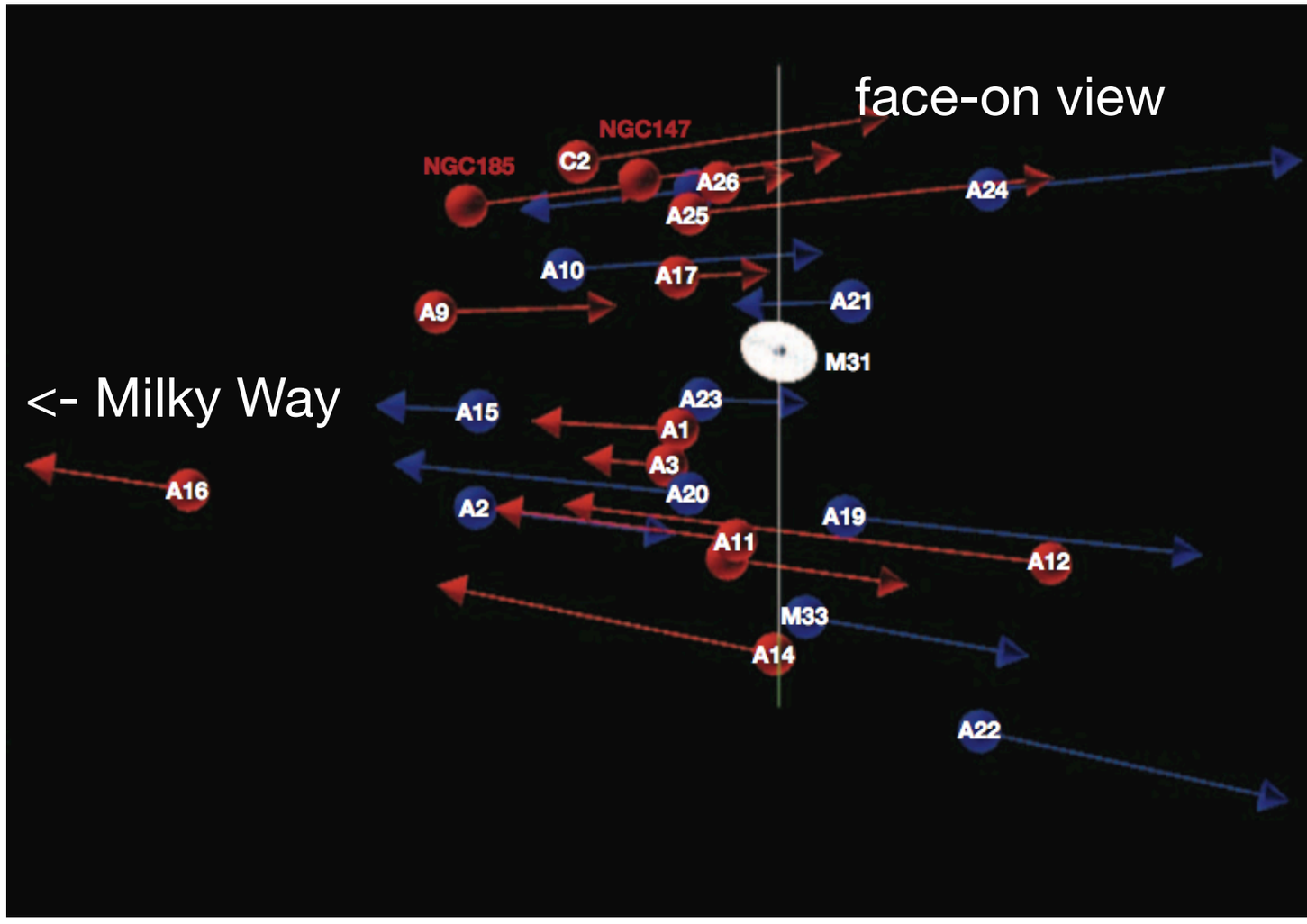
Many flattened satellite arrangements have been discovered since:

- 50% of M31 satellites in narrow, possibly co-orbiting plane. (Ibata et al. 2013)





MNRAS **429,** 1502–1513 (2013) doi:10.1093/mnras/sts442

The spatial distribution of galactic satellites in the Λ cold dark matter cosmology

Jie Wang,[1]★ Carlos S. Frenk[1] and Andrew P. Cooper[2]

[1]*Institute for computational cosmology, Department of Physics, University of Durham, South Road, Durham,*
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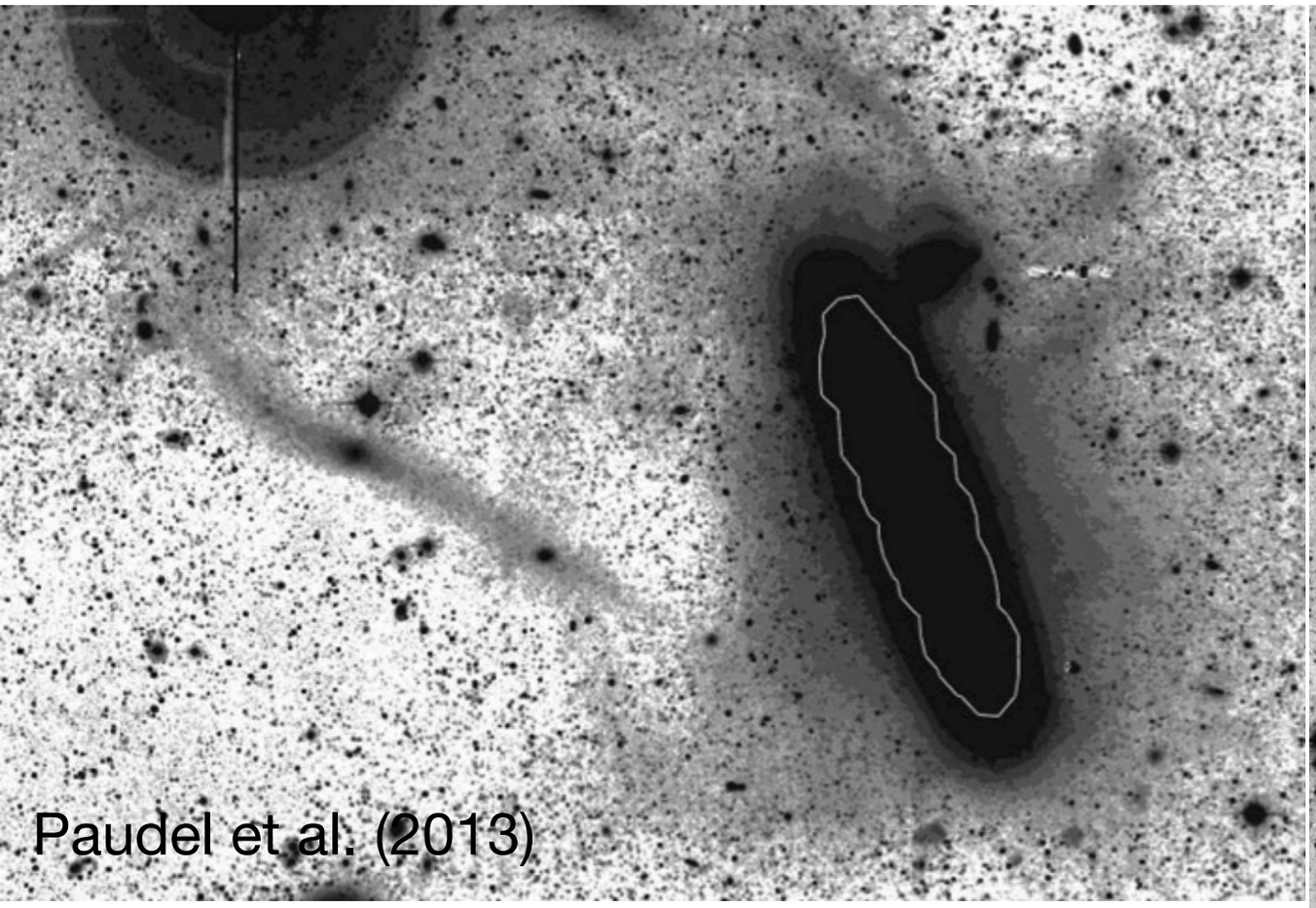

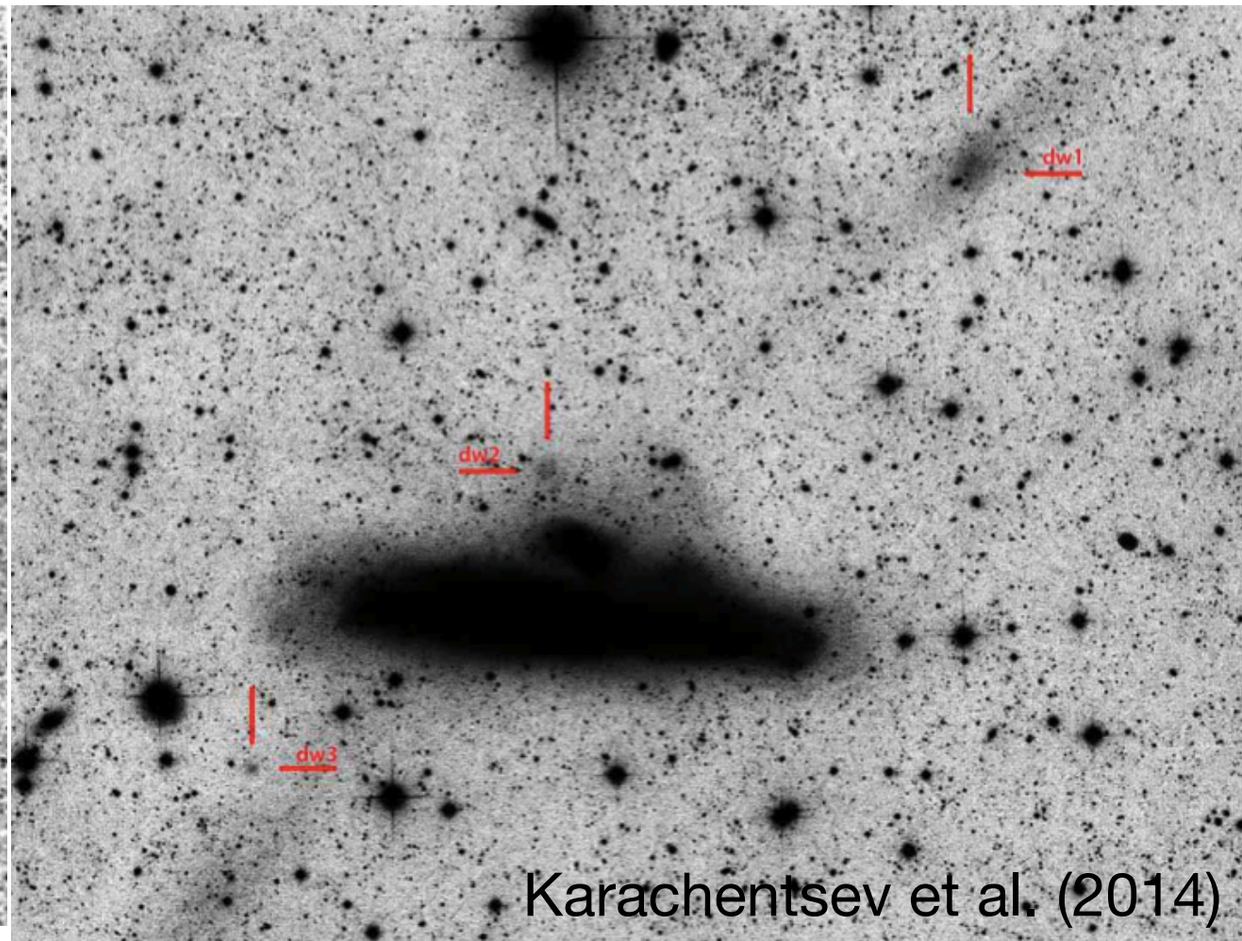

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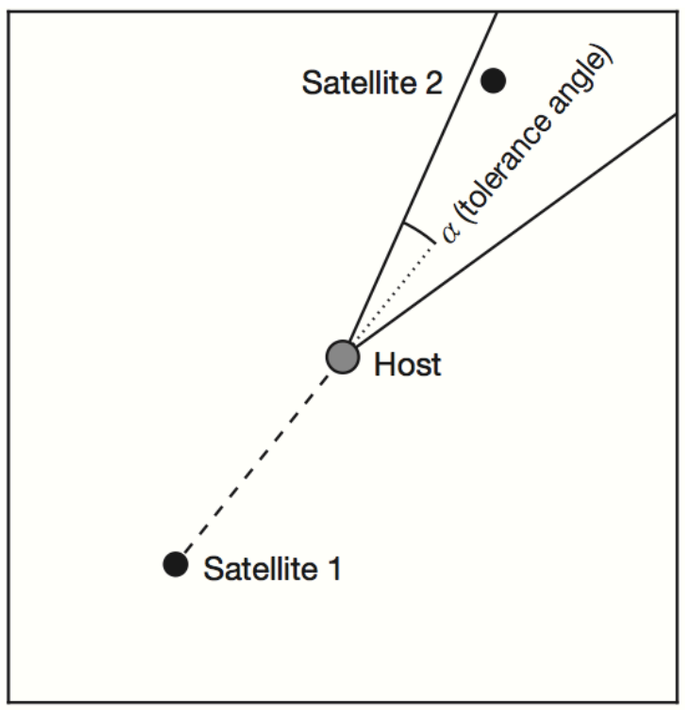

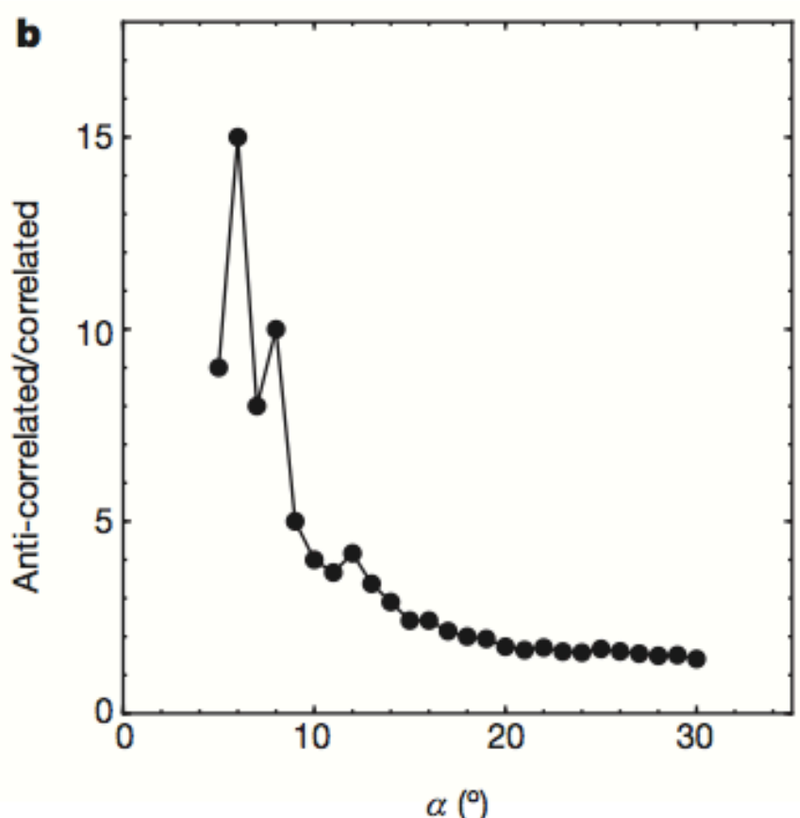

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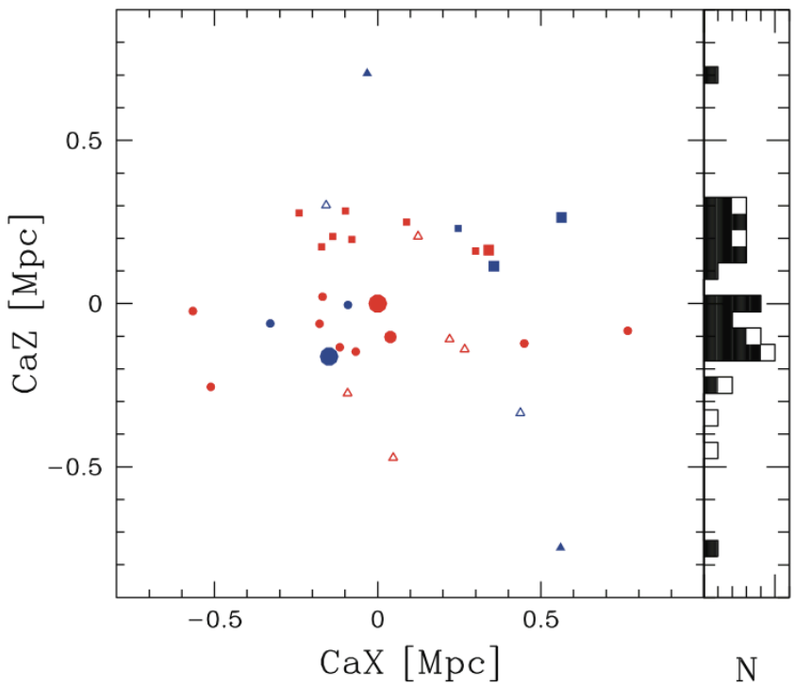

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- M81 group is flattened, too (Chiboucas+2013)

Two scenarios that could cause TDG planes around both the MW and M31

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Encounter between (proto) MW and M31

(e.g. Pawlowski+2012a, Sawa & Fujimoto 2005)

- Debris around and between both galaxies.
- Requires radial, prograde M31 orbit: consistent with M31 PM. (Sohn+2013)
- MW-M31 encounter expected in MOND. (Zhao+2013)

Merger of two galaxies formed M31

(e.g. Hammer+2010, Hammer+2013)

- Reproduces M31 features (e.g. fractions of bulge/thin/thick disc, Giant Stream).
- Forms disc of co-orbiting TDGs (oriented like observed satellite plane around M31).
- Expels TDGs towards MW where they can form the VPOS. (Fouquet+2012, Yang+2014)

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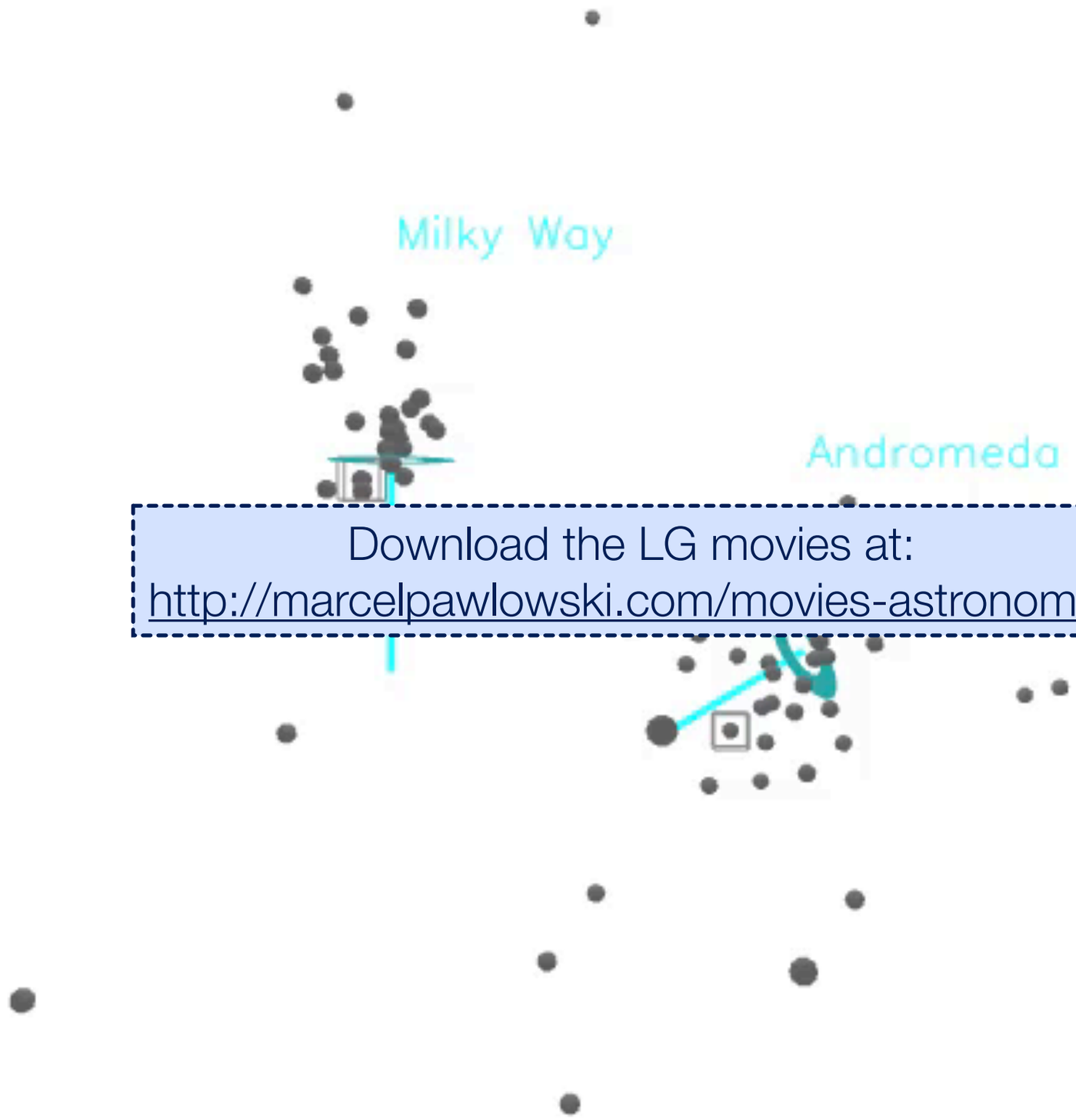
Both imply signatures on LG scale connecting M31 & MW

Irrespective of what we think of TDG idea, this highlights that:

- Satellite planes might not be isolated structures.
- Larger scale can provide hints to solution.

See also Noam's talk for alignment with even larger structure



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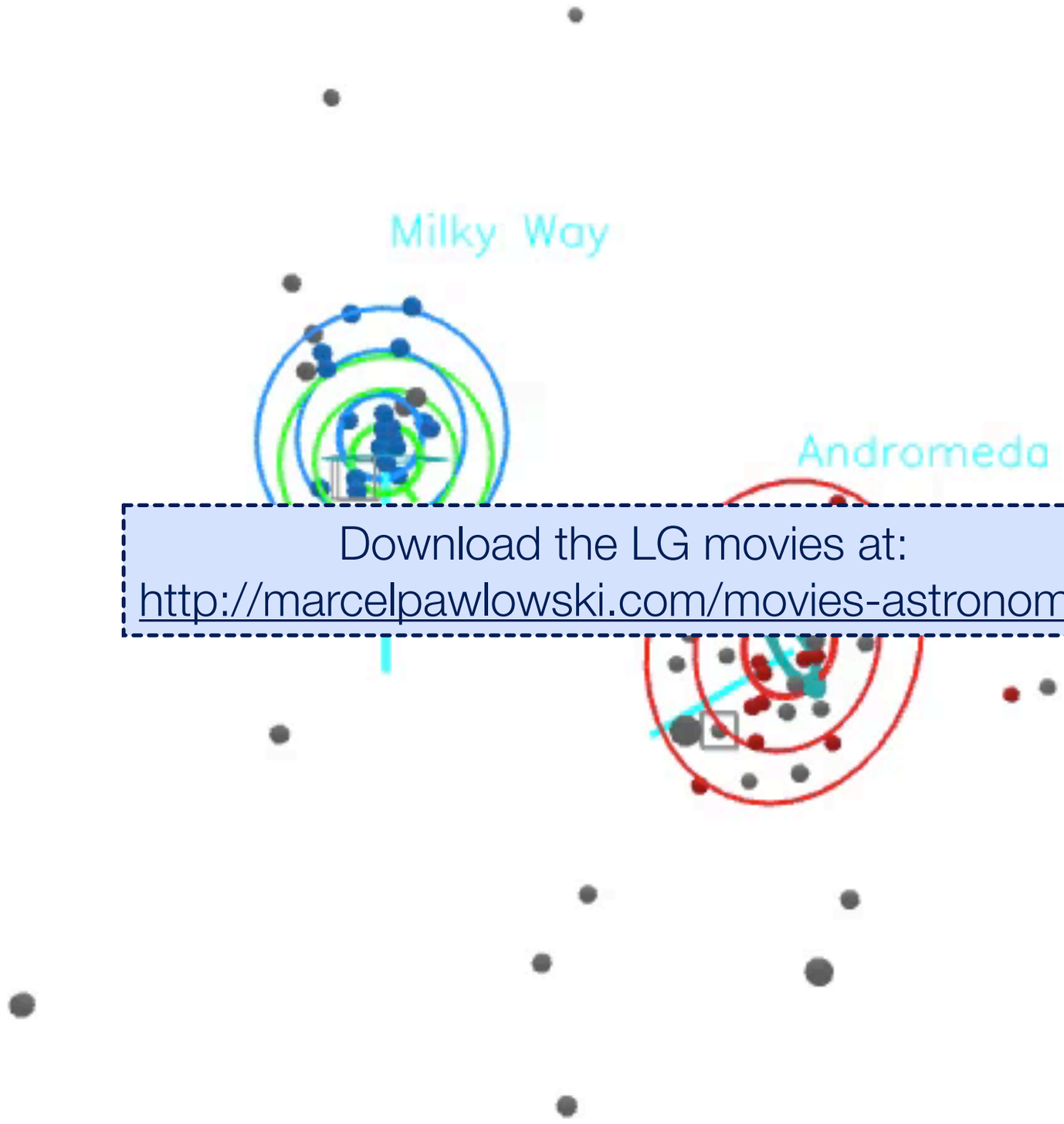

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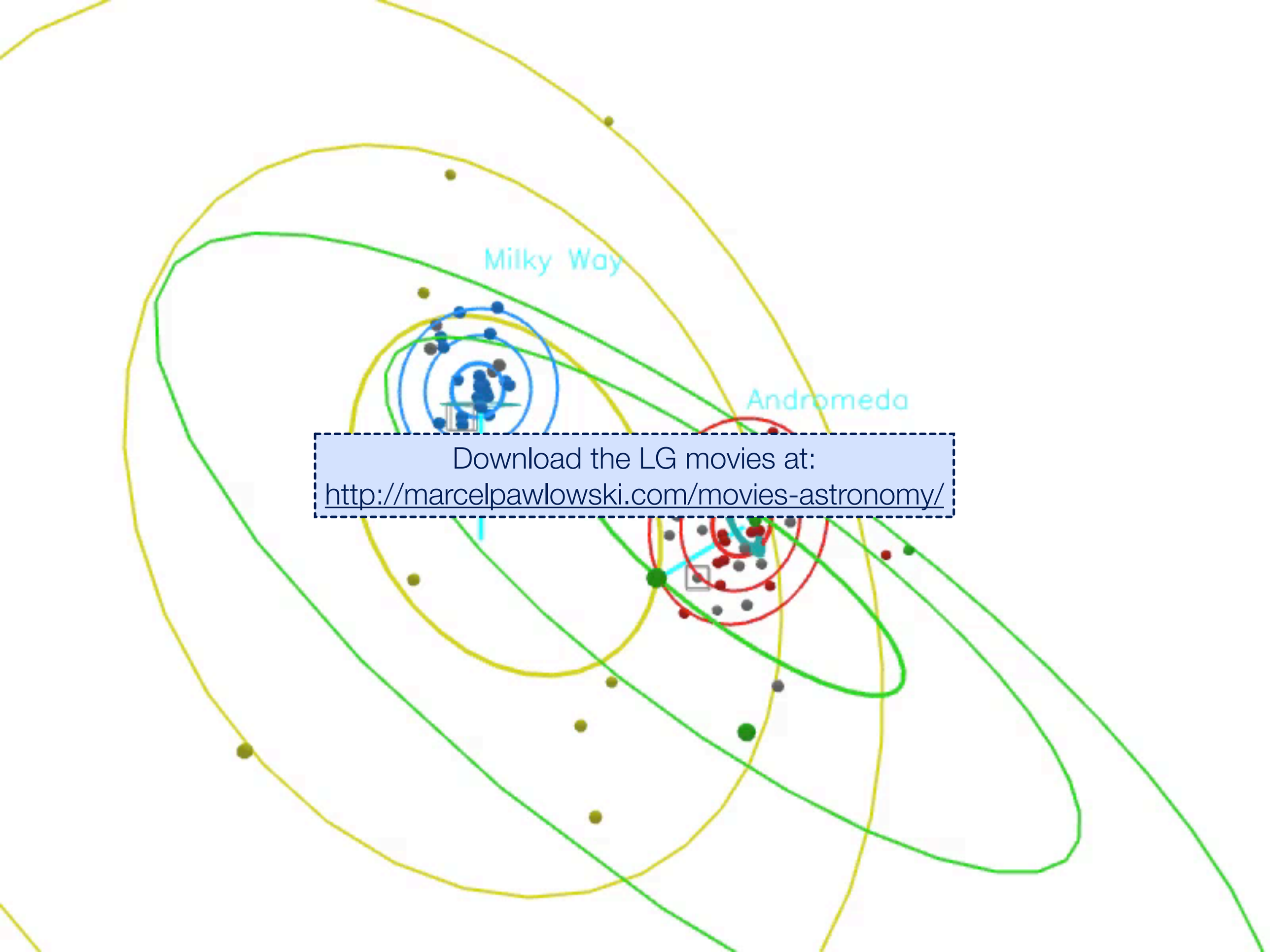
Milky Way
Andromeda
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LGP1 and LGP2 are highly symmetric

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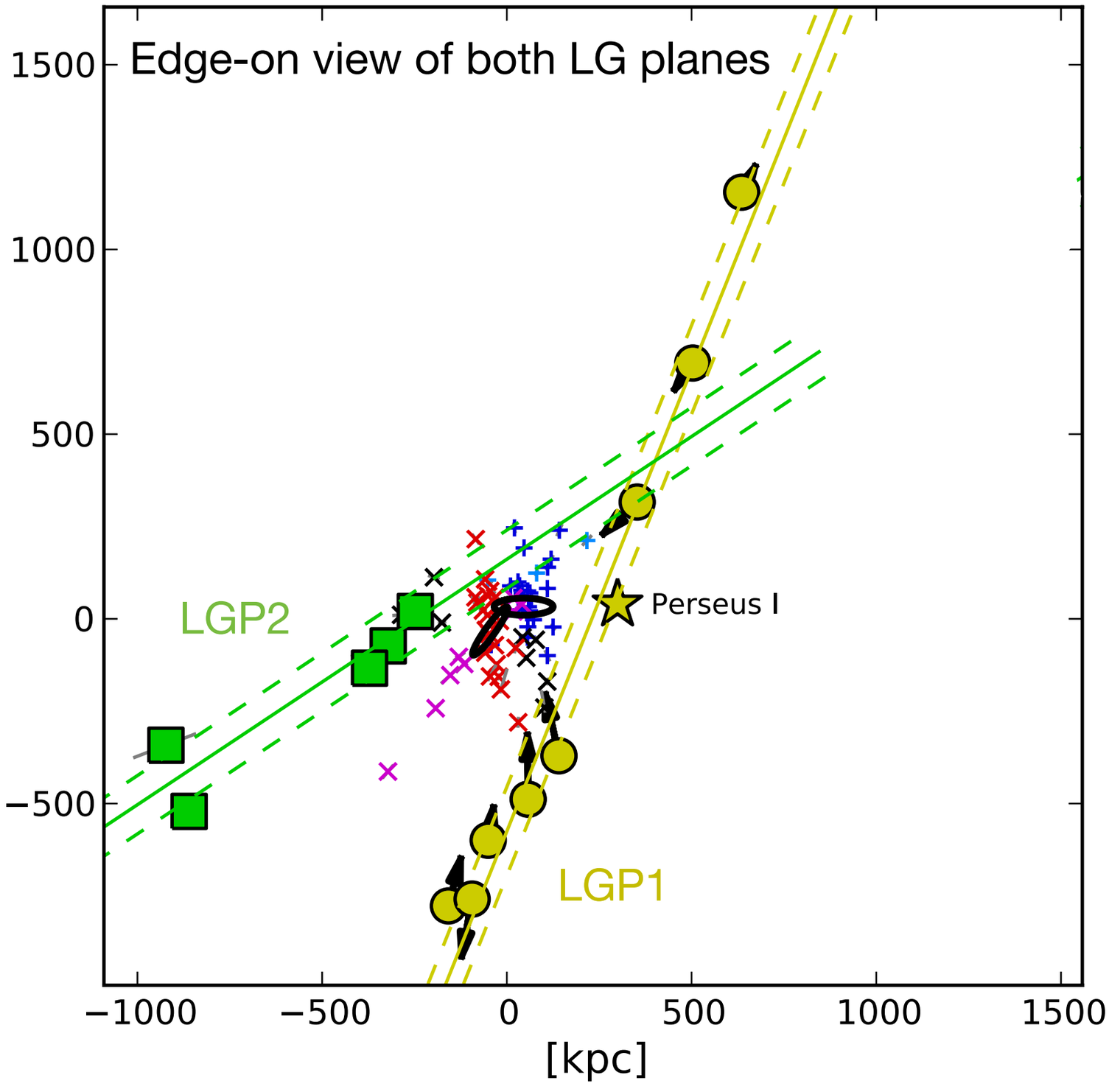

Non-satellites are in one of two thin planes which have:

- similar heights
  (~ 60 kpc, diameter 1-2 Mpc!)
- similar offsets from MW & M31
  (130 to 170 kpc).
  ➡ parallel to MW-M31 line.
- same inclination to M31 (20º)

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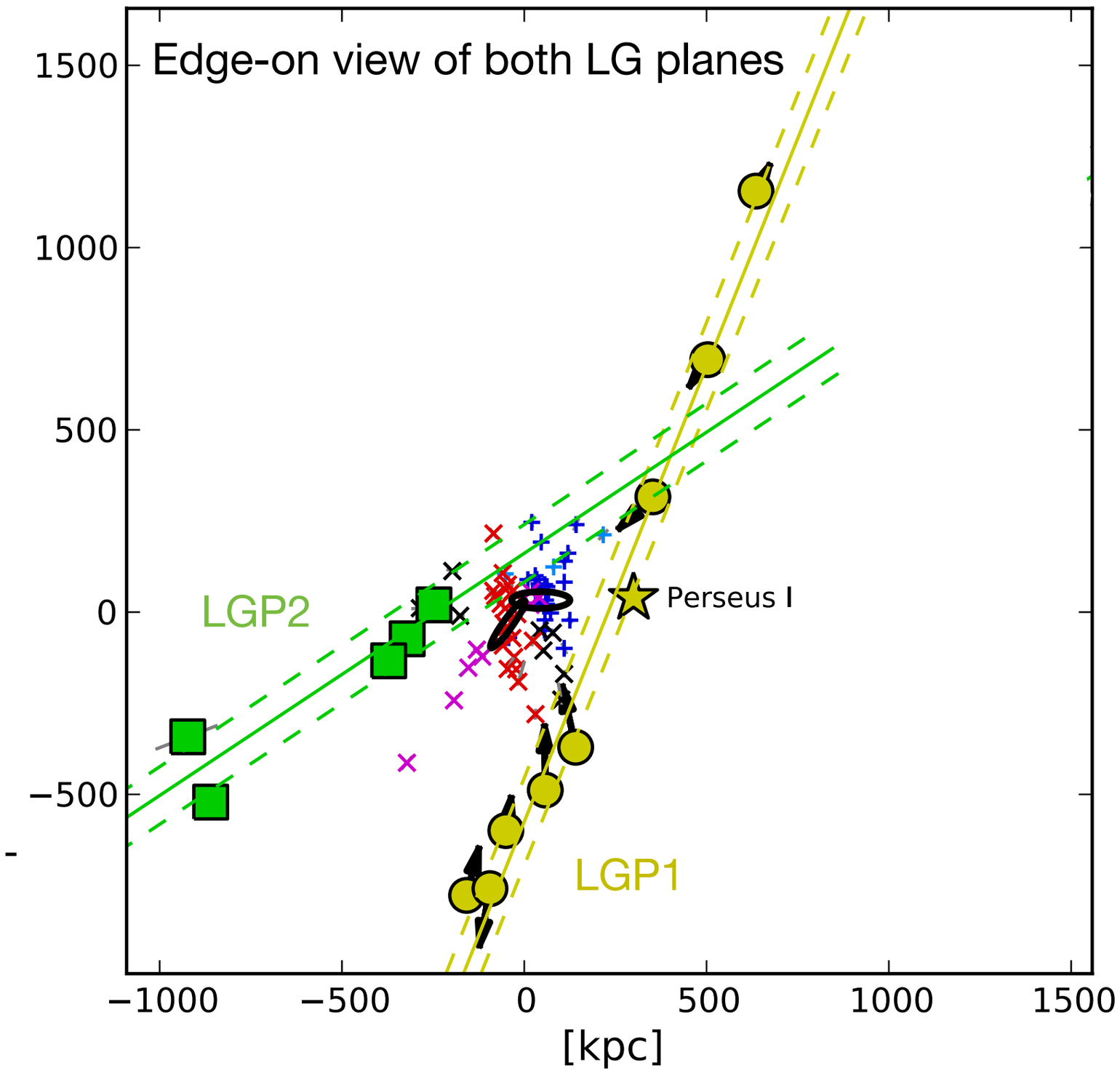

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MW south: Magellanic Stream connecting VPOS, GPoA, LGP1

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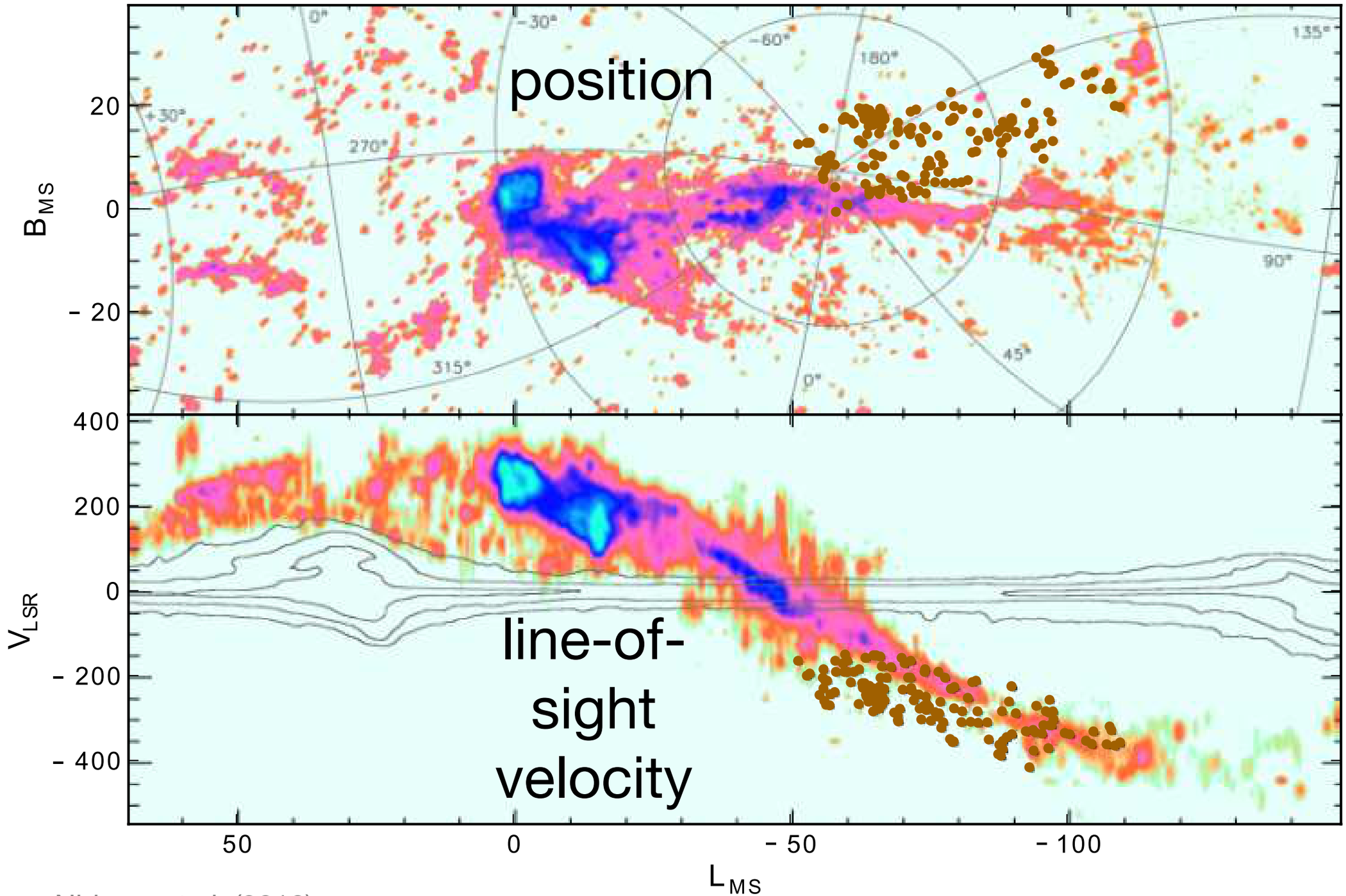

MS map from Nidever et al. (2010)
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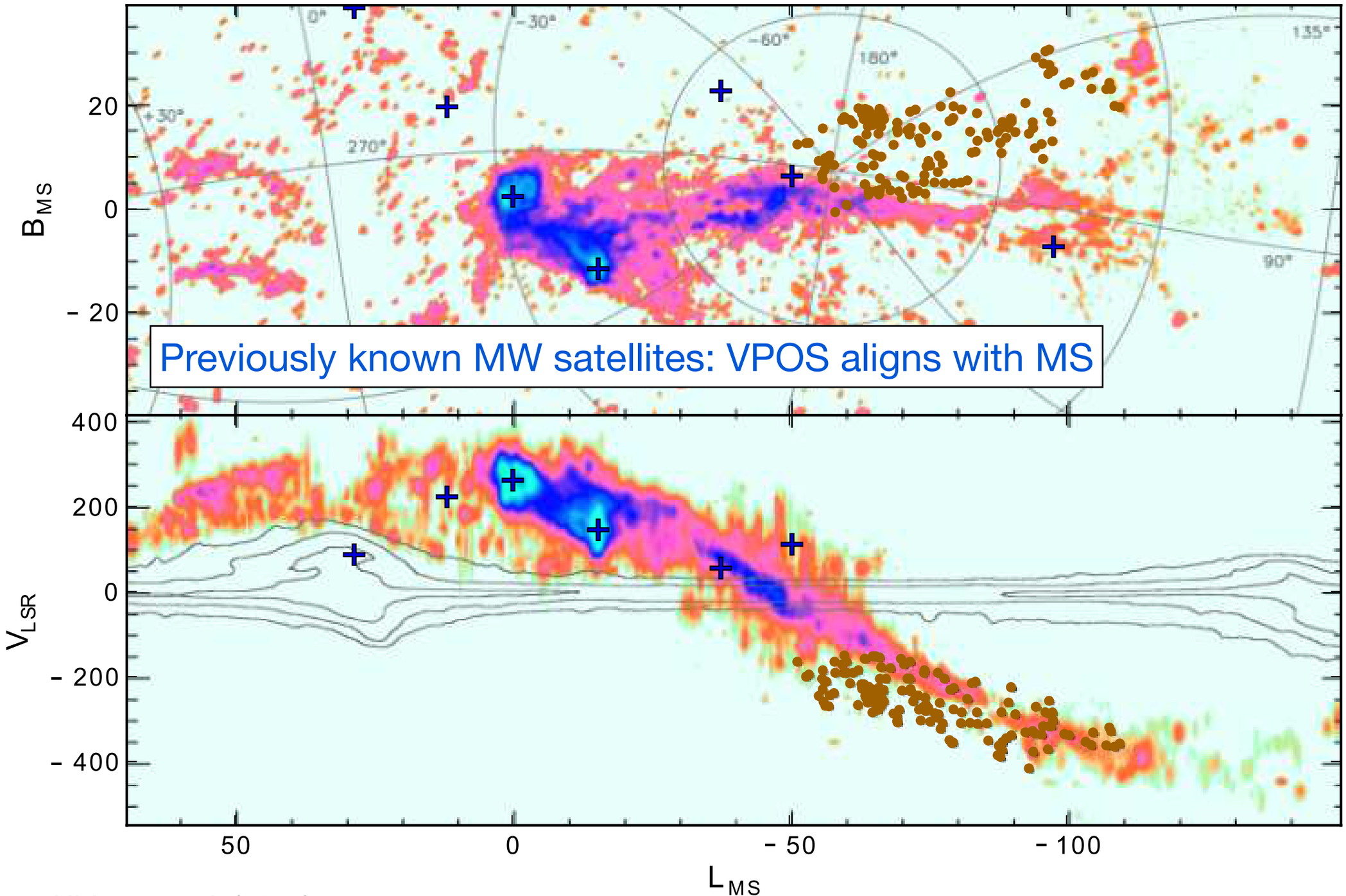

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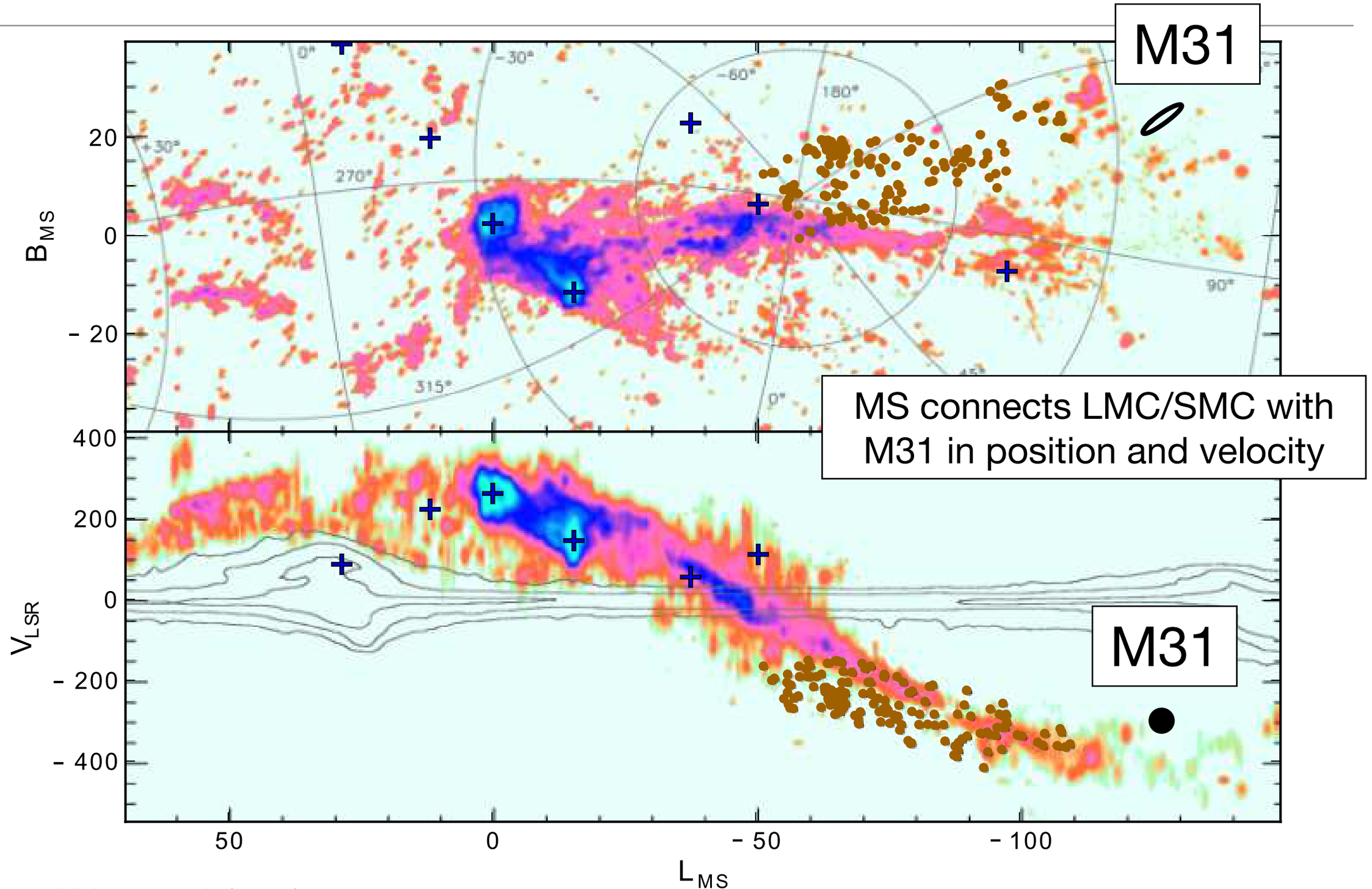

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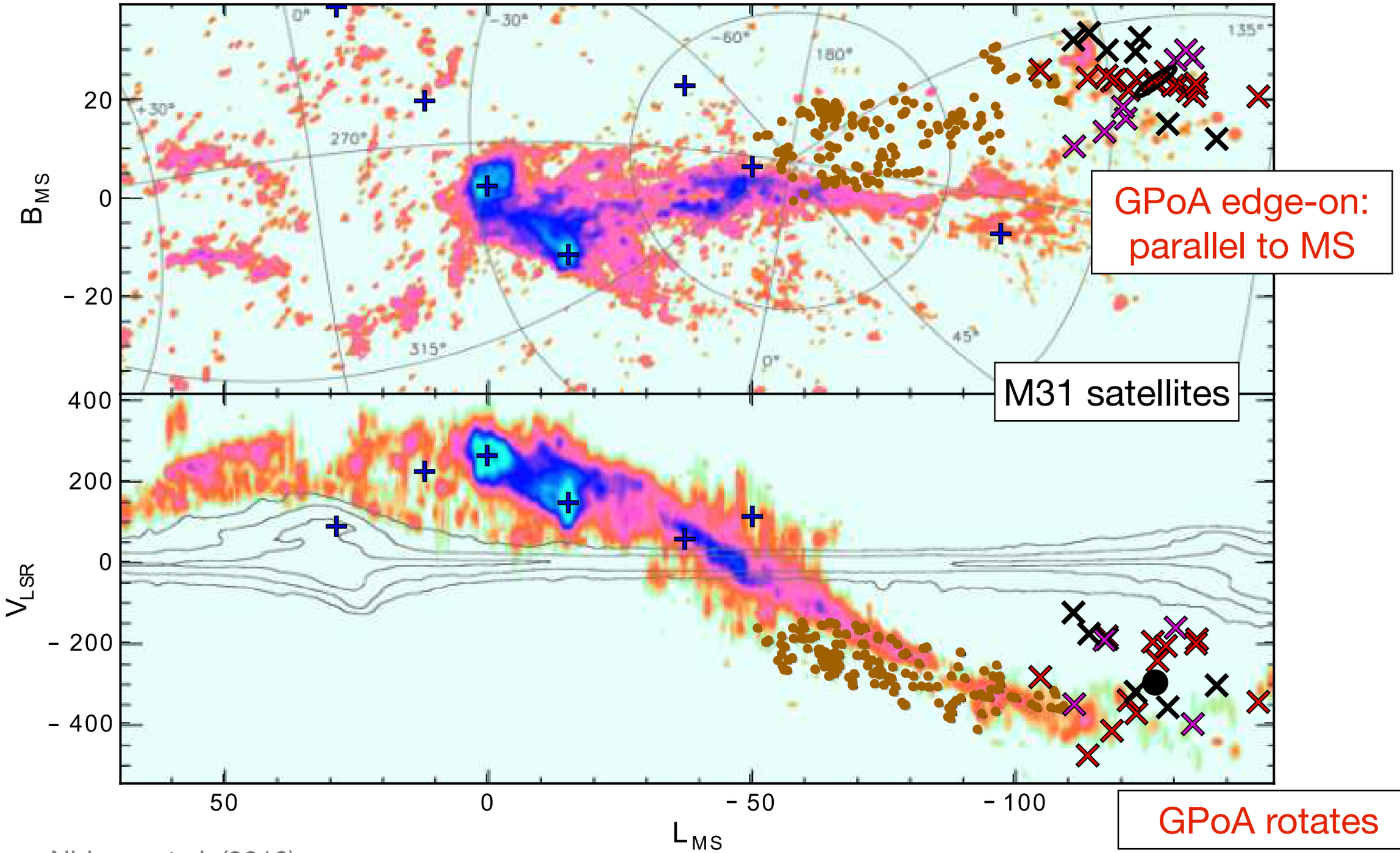

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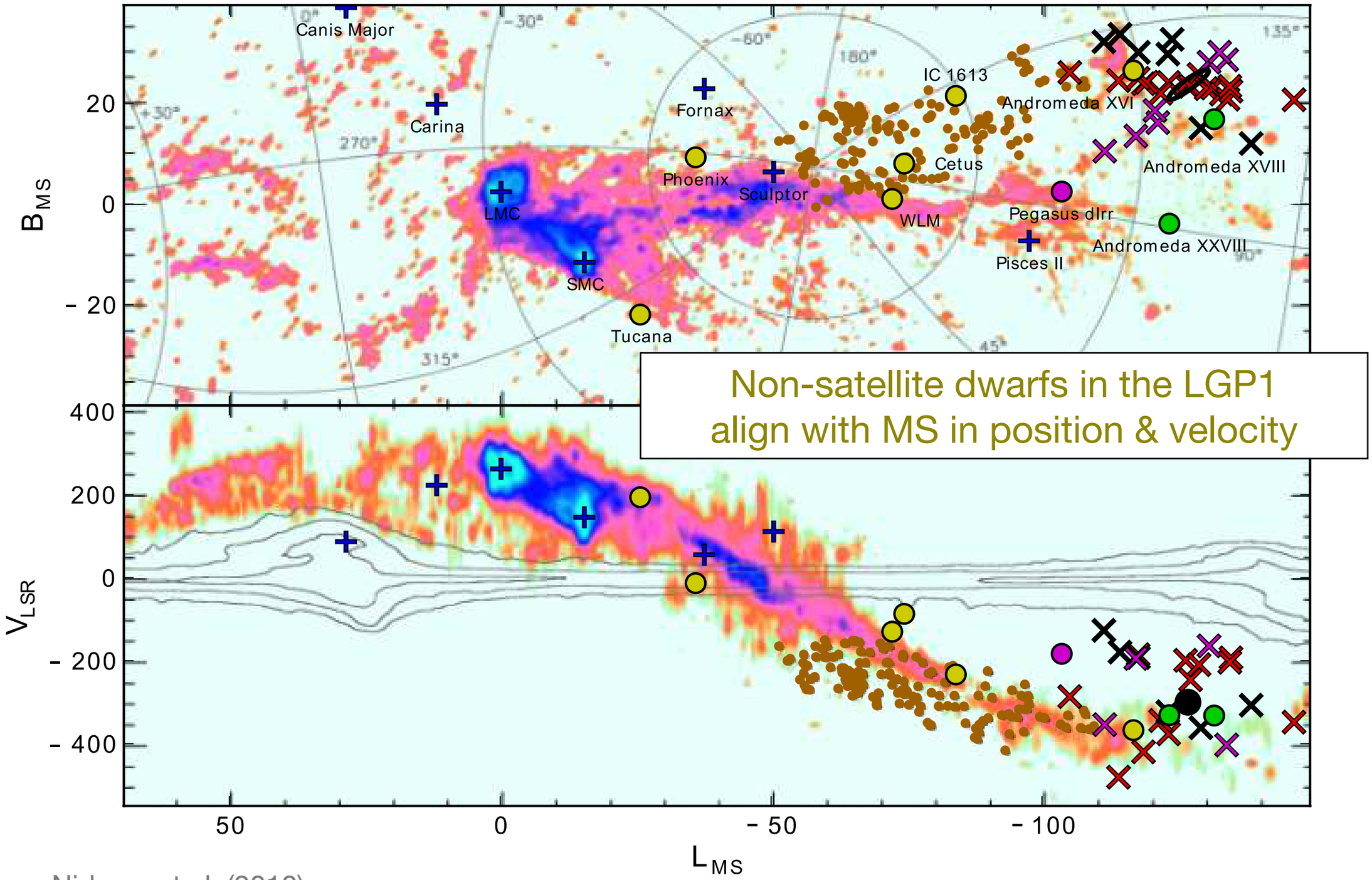

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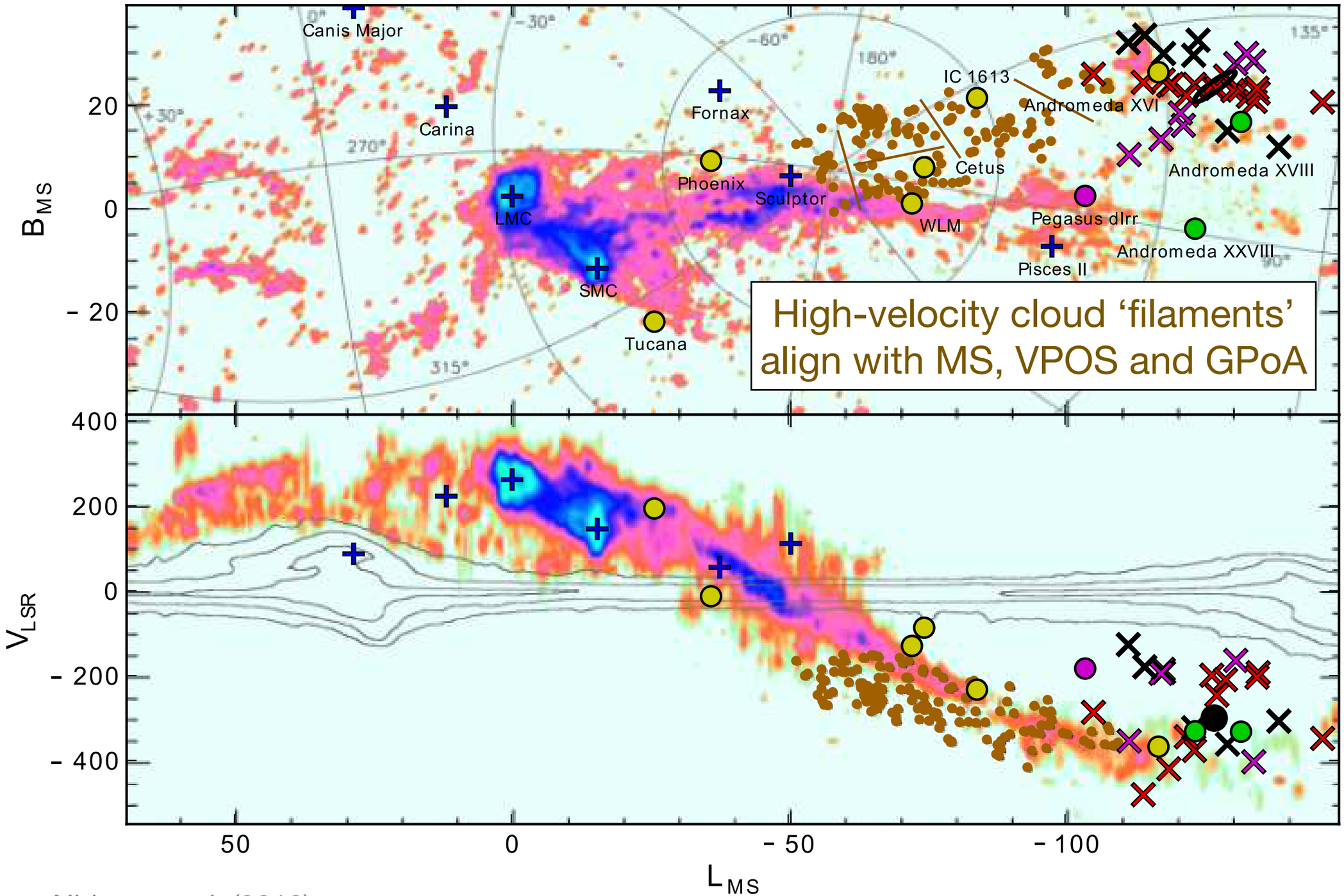

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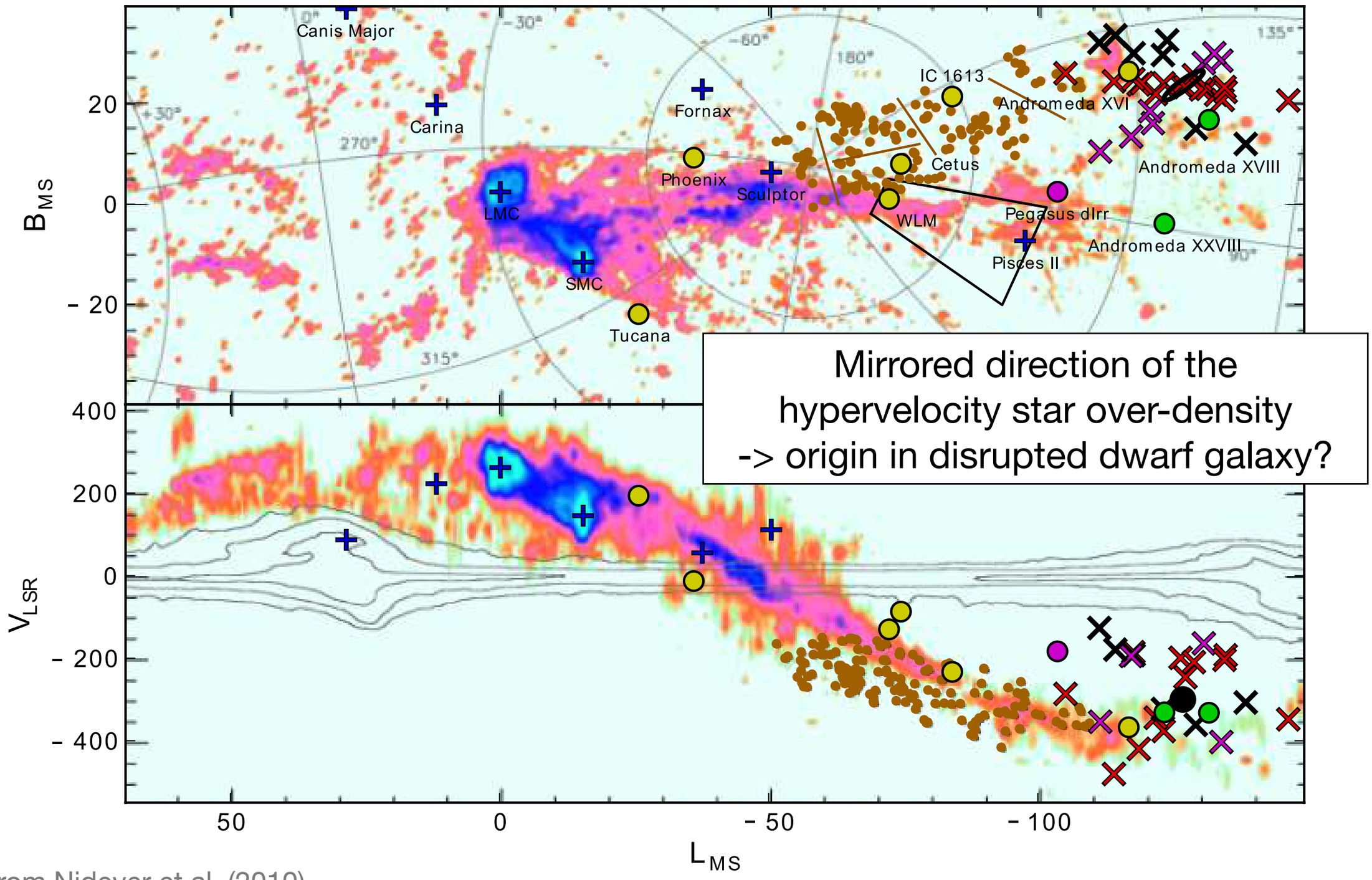

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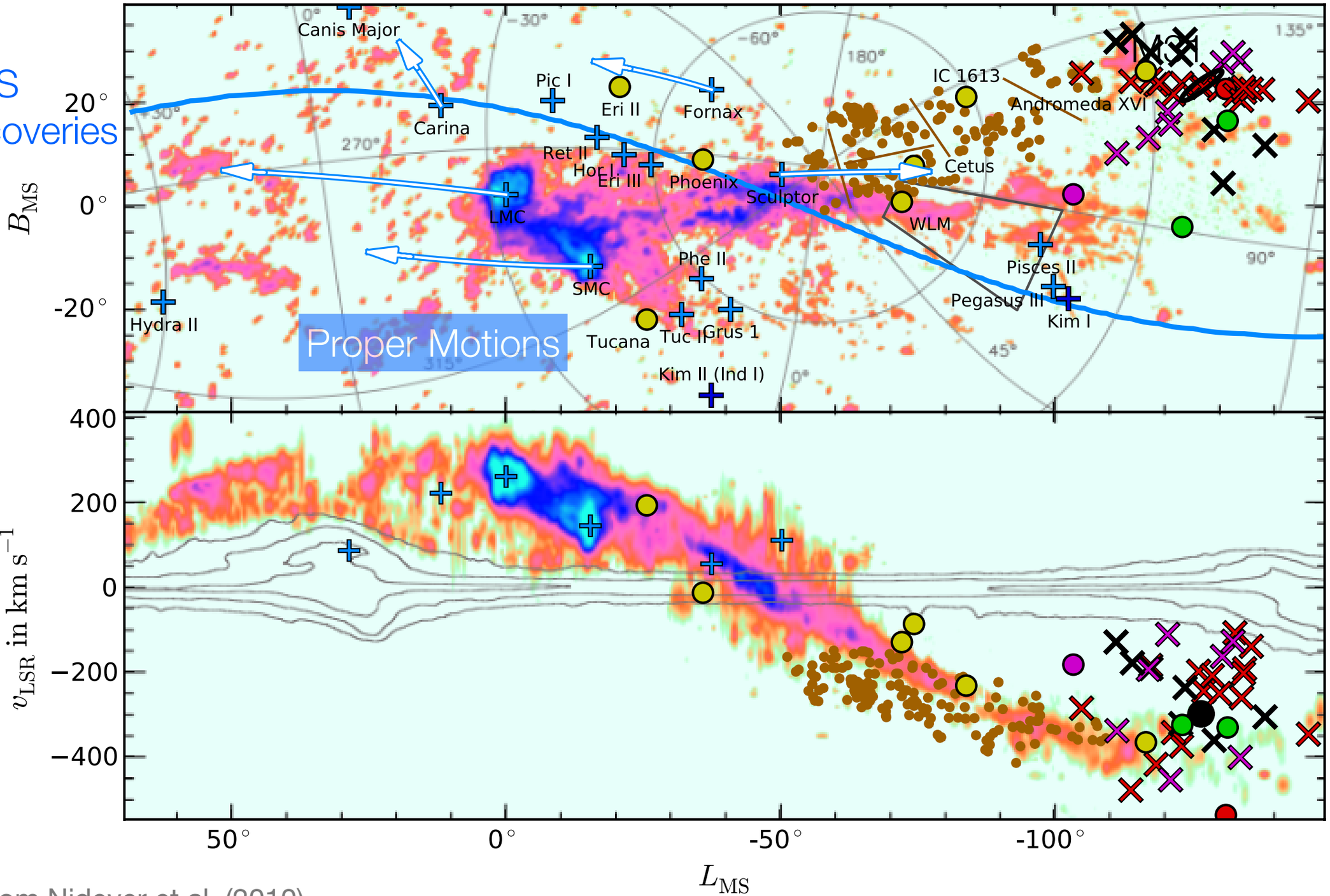
Pawlowski in prep.

VPOS
new discoveries



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Conclusion

The rotationally stabilized VPOS is highly significant & new satellites align.

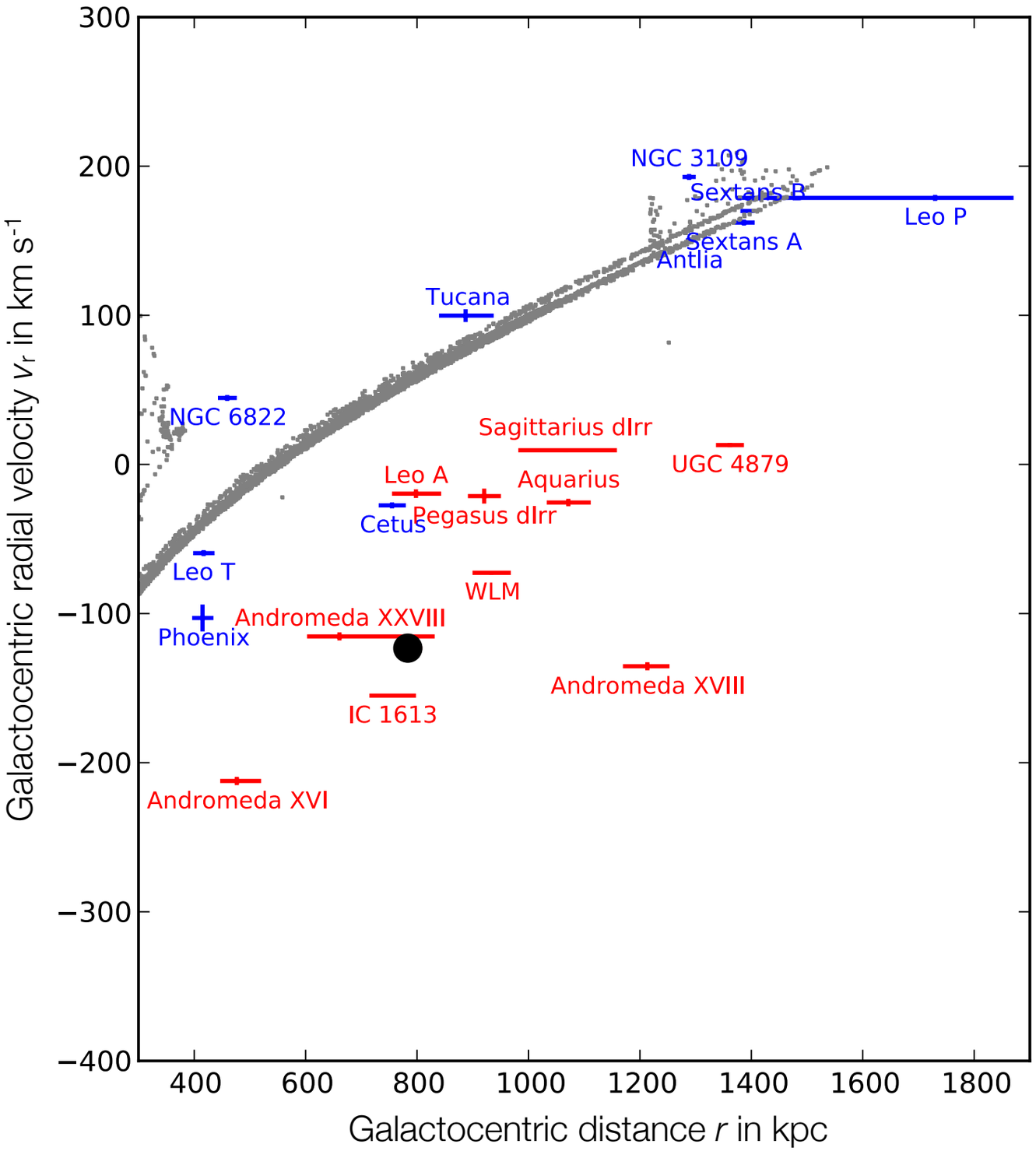
None of the suggested origins is without problems (in ΛCDM):

- Simulations include group infall and filamentary accretion, but don’t reproduce small height and rotation of LG satellite planes.
- TDGs explain phase-space coherence, but should be DM-free.
- Tweaking the analysis or re-defining the problem to find consistency does not help to understand or solve the satellite plane problem!

Highly symmetric dwarf galaxy structure in LG, might provide more insights.

Too many of the ‘northern’ dwarfs are backsplash galaxies (ask me later).

Too many backsplash galaxies in MW north (opposite M31) Pawlowski & McGaugh (2014, MNRAS, 440, 908)



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- All 8 non-satellite dwarfs **in the MW north** are in a thin plane (c/a < 0.1).
- At least 6 of 8 are **likely backsplash galaxies** (Teyssier et al. 2012)
- ΛCDM simulation predicts only 1 of 8
  - ➡ **Over-abundant backsplash problem?**
- **Tidal debris** (not adjusted to fit) have similar properties in r-v_r plot.
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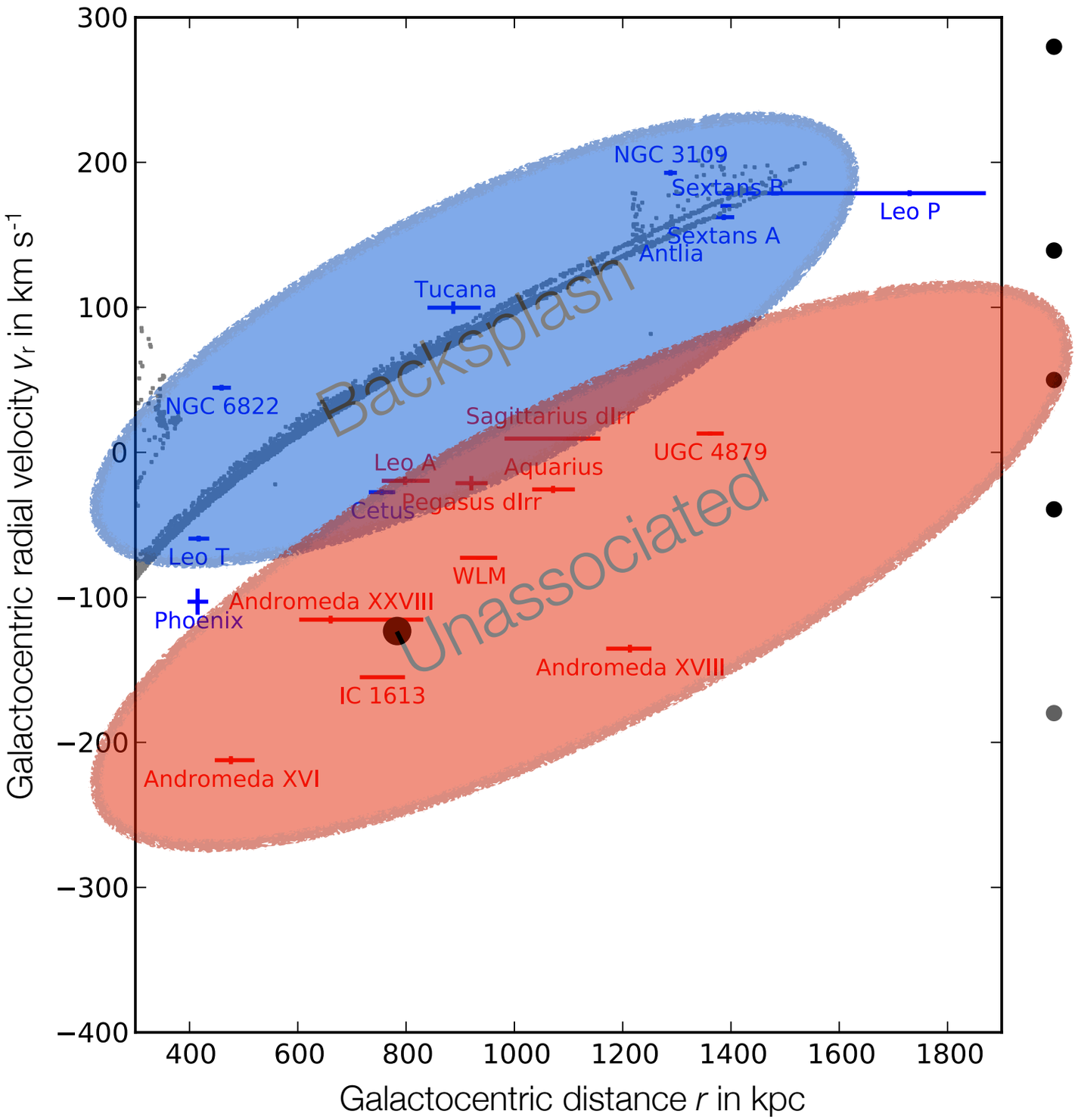

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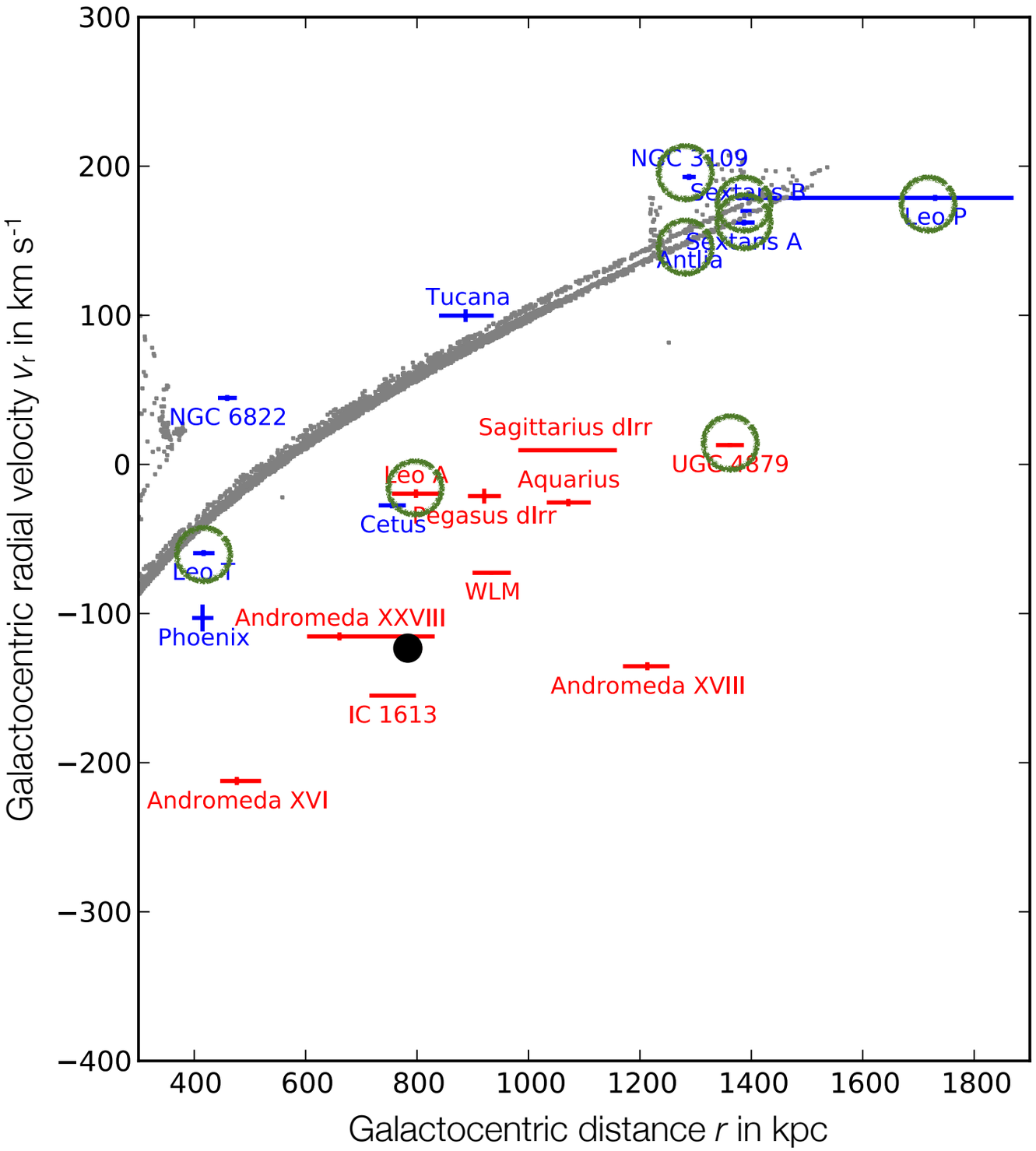

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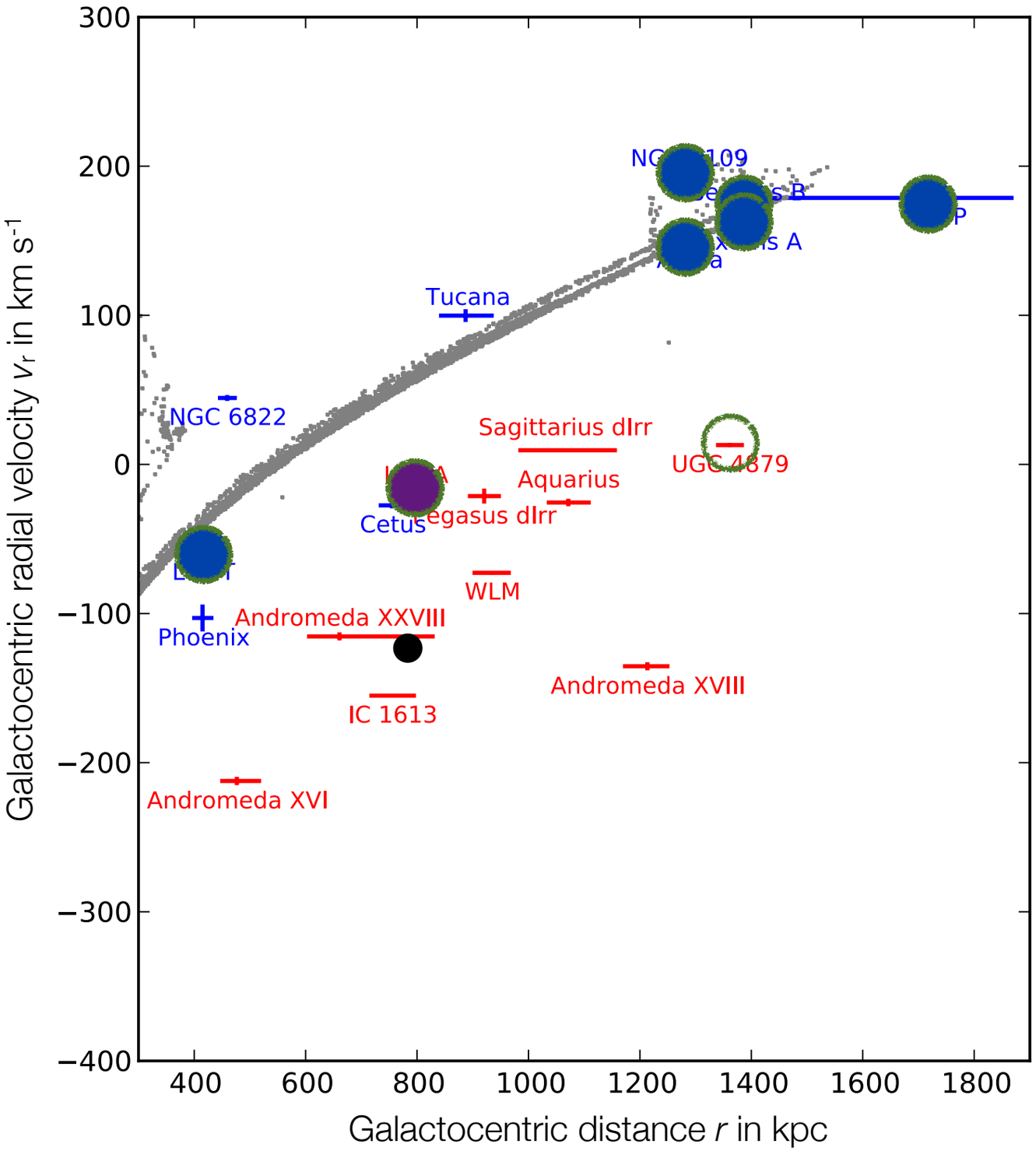

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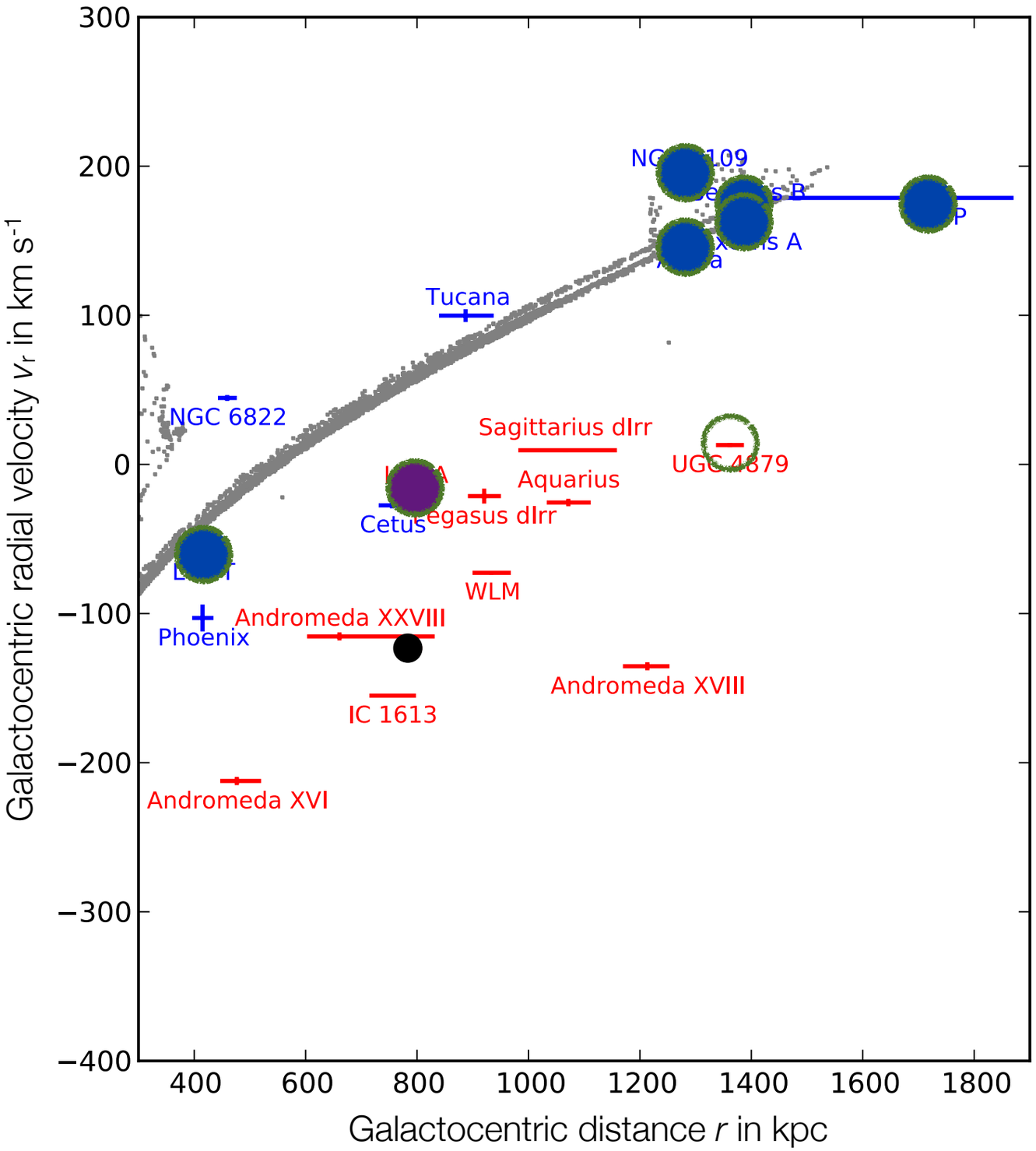

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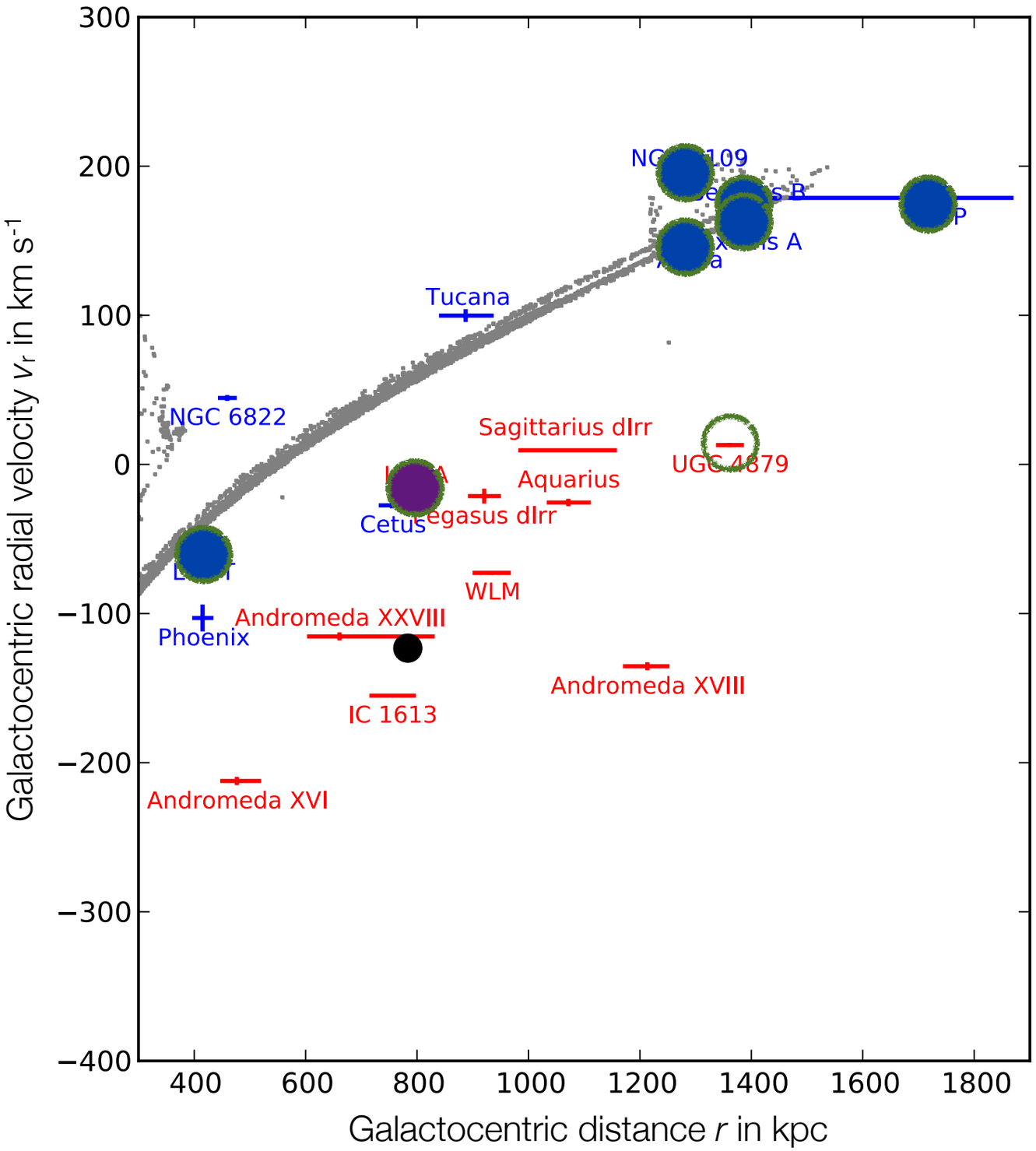

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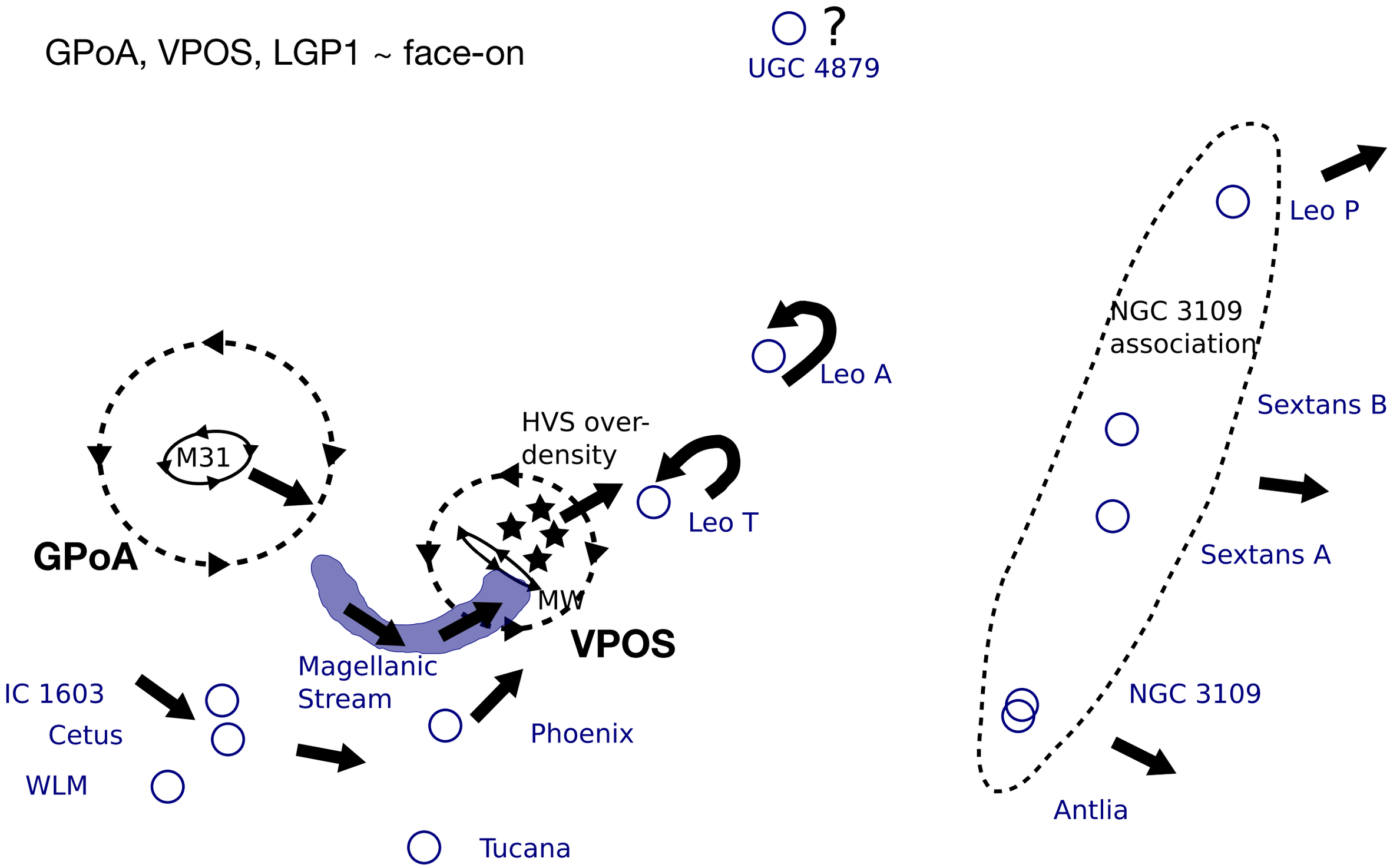
Pawlowski & McGaugh (2014, MNRAS, 440, 908)

GPoA, VPOS, LGP1 ~ face-on



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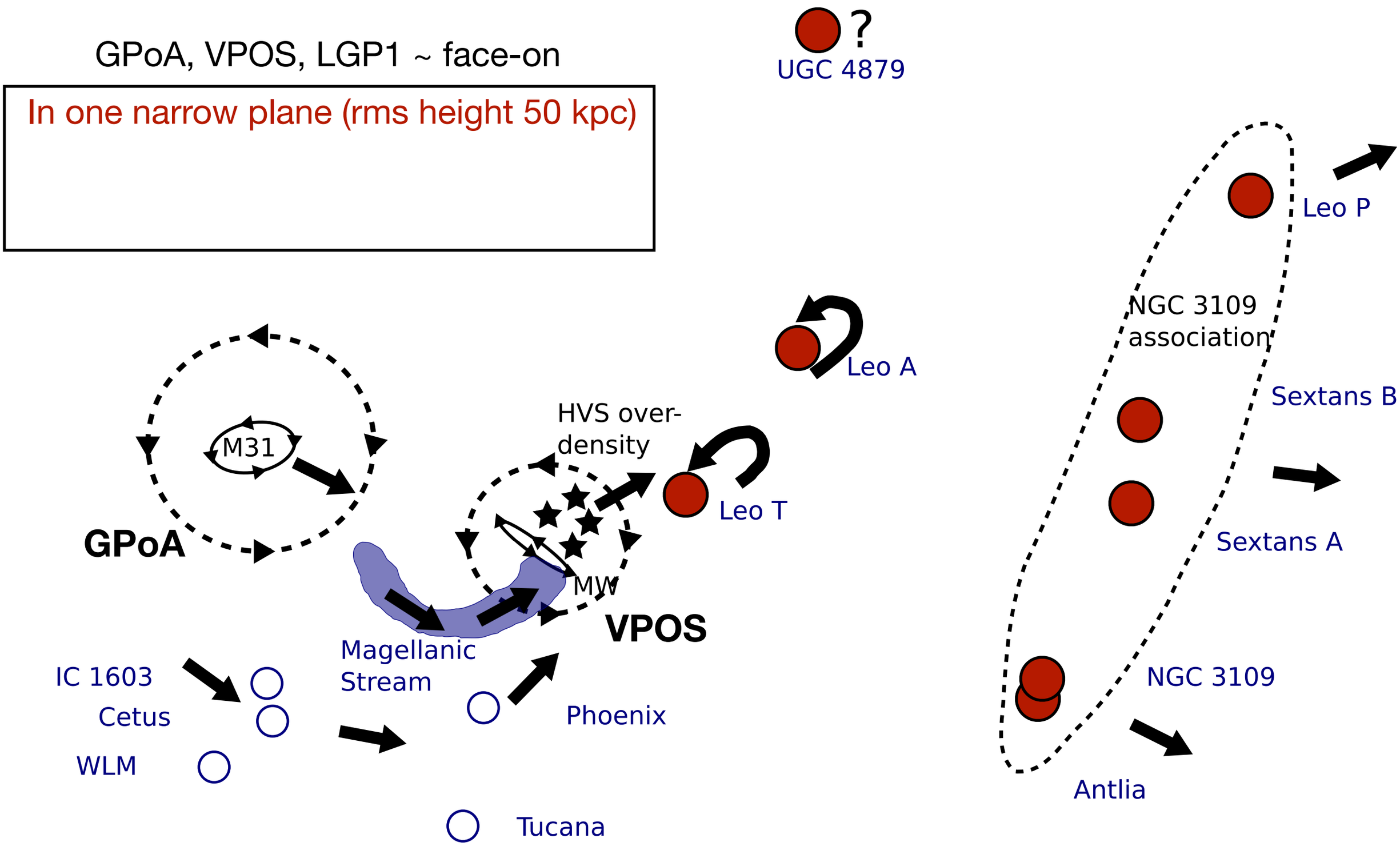

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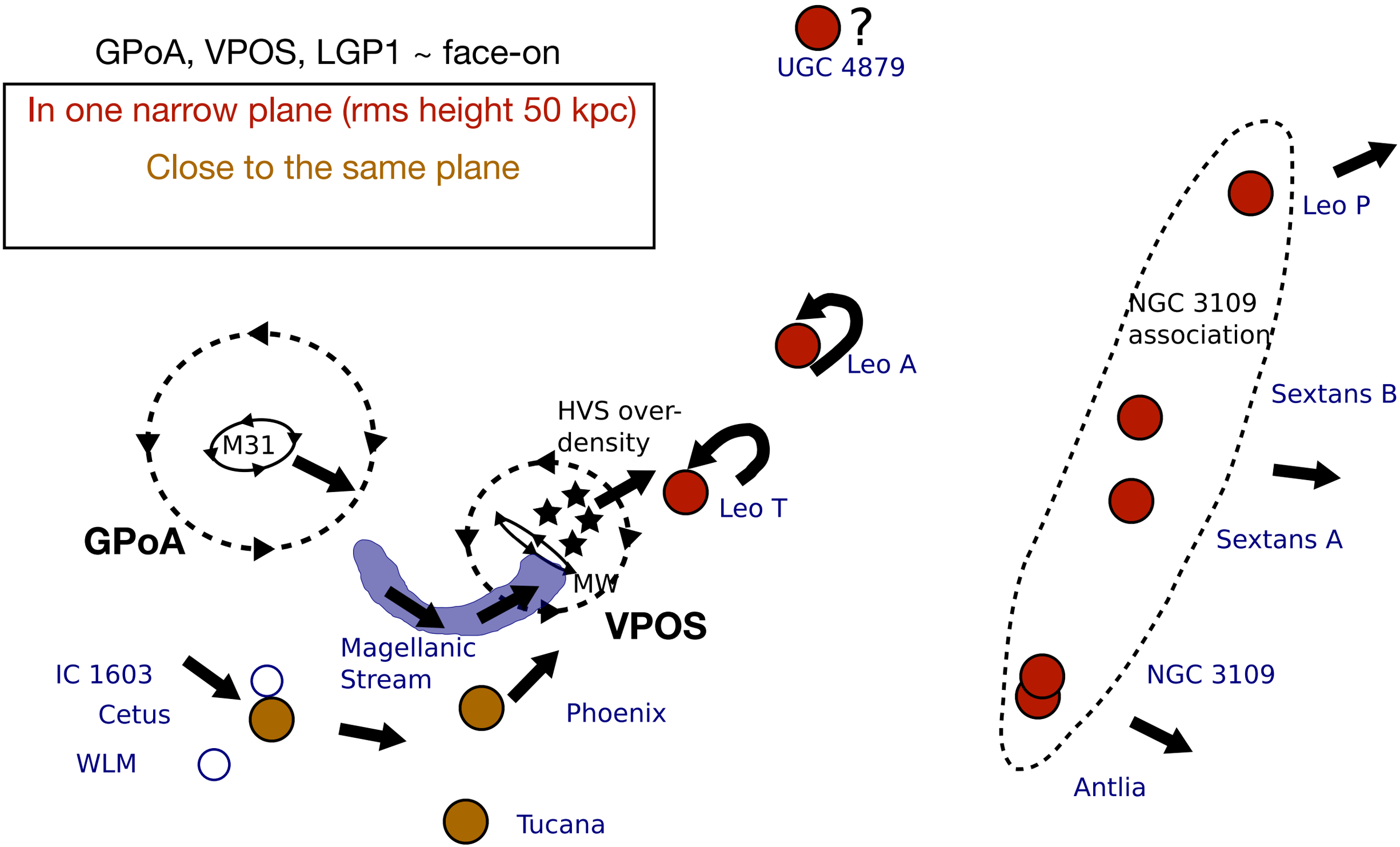

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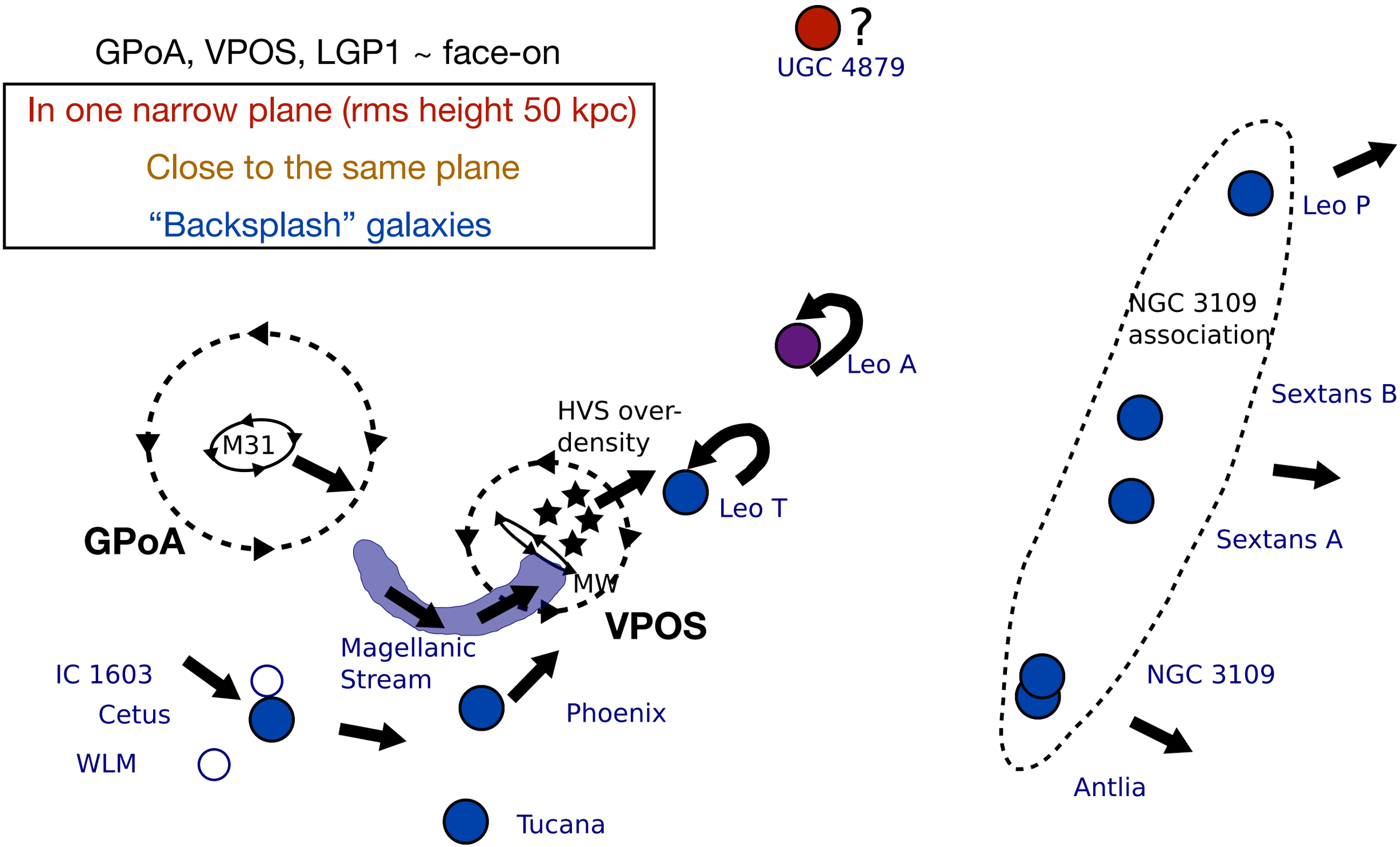
“Backsplash” galaxies



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