Dwarf galaxy structures in the Local Group

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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

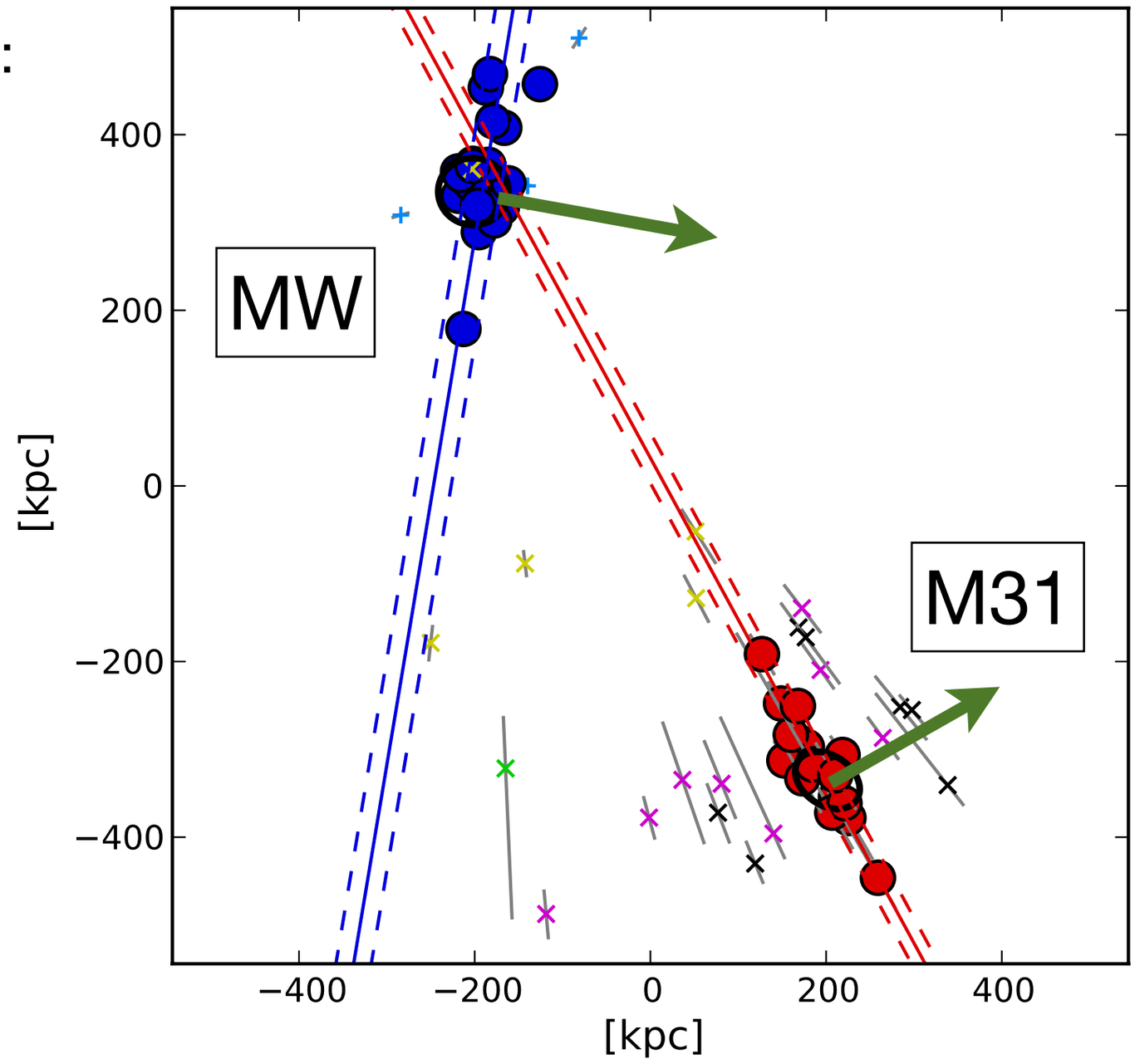
  GPoA: 14 kpc

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

- Additional alignments:

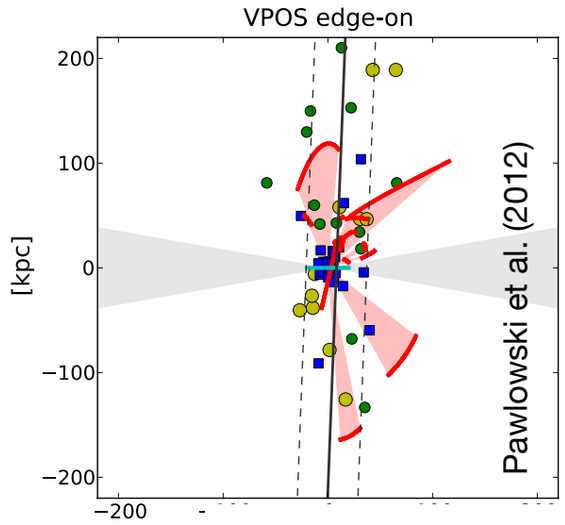
  VPOS: YH GCs, 50% streams

  GPoA: Giant Stream, NW-S1

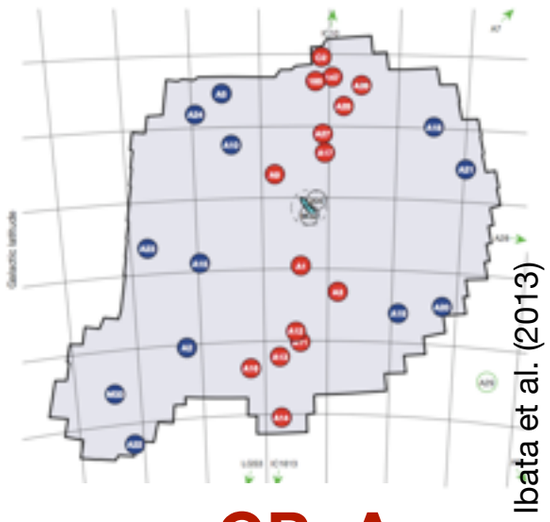


LG Satellite Planes as tests of ΛCDM

Can this ...

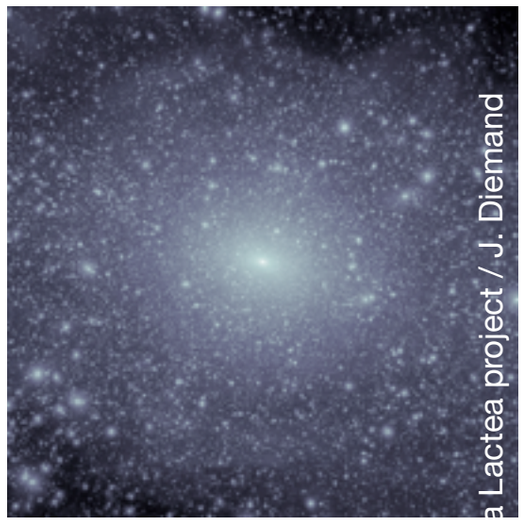


VPOS



GPoA

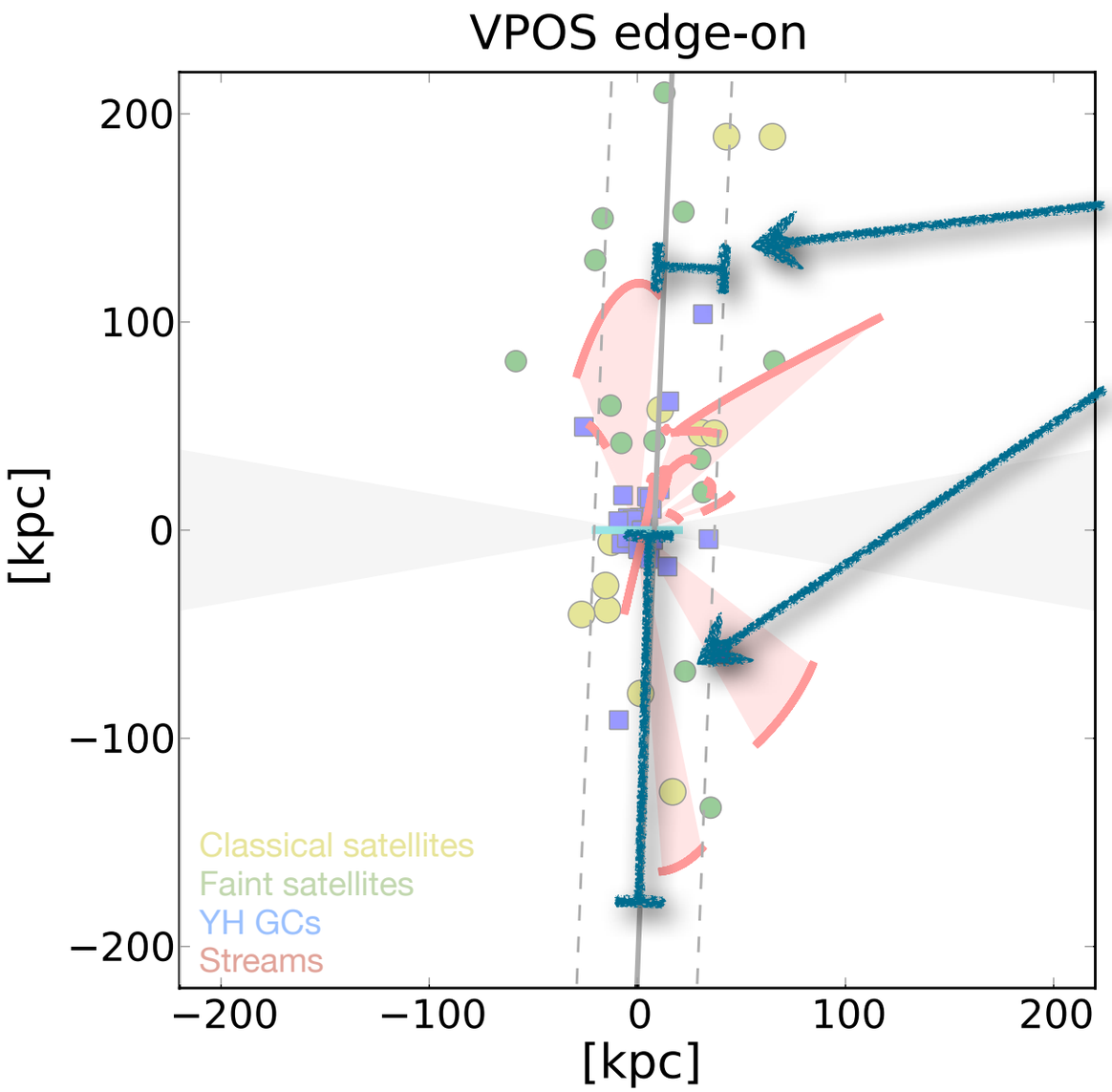
... be found in this?



- Planes of co-orbiting satellites not predicted by cosmological simulations.
  - ➡ Fundamental problem of LCDM?
- Robust test: largely independent of exact baryon physics (100 kpc scales).
- Origin of satellite planes might provide important information to find (unified) solution for other small-scale problems.

How frequent are such *spatial* distributions in ΛCDM?

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



- Select same # of brightest satellites. (e.g. 11 classical MW satellites in VPOS)
- Model- and observational selection must agree. (MW obscuration or survey area)
- **Thickness**: (absolute) RMS height $r_{\rm per}$ or (relative) axis ratio *c/a*.
- **Radial distribution**: RMS radius $r_{\rm par}$ (*b/a*) More concentrated distributions can have small thickness without being planar.

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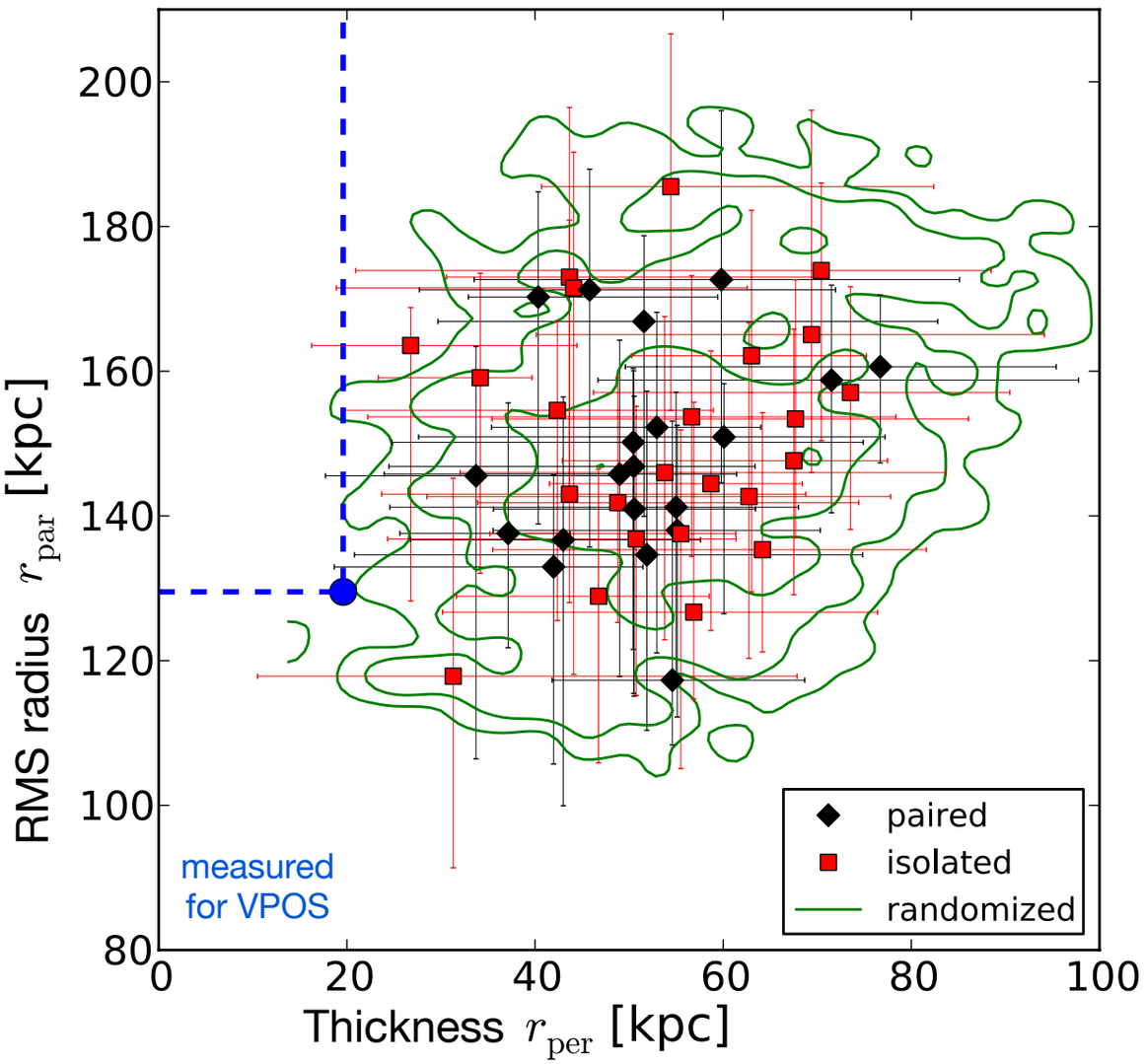

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How frequent are VPOS-like planes?

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

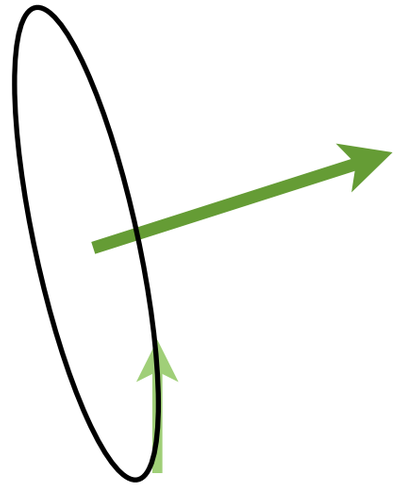
  $r_{\rm per}$, $r_{\rm par}$: ~ 0.3 to 1.2%

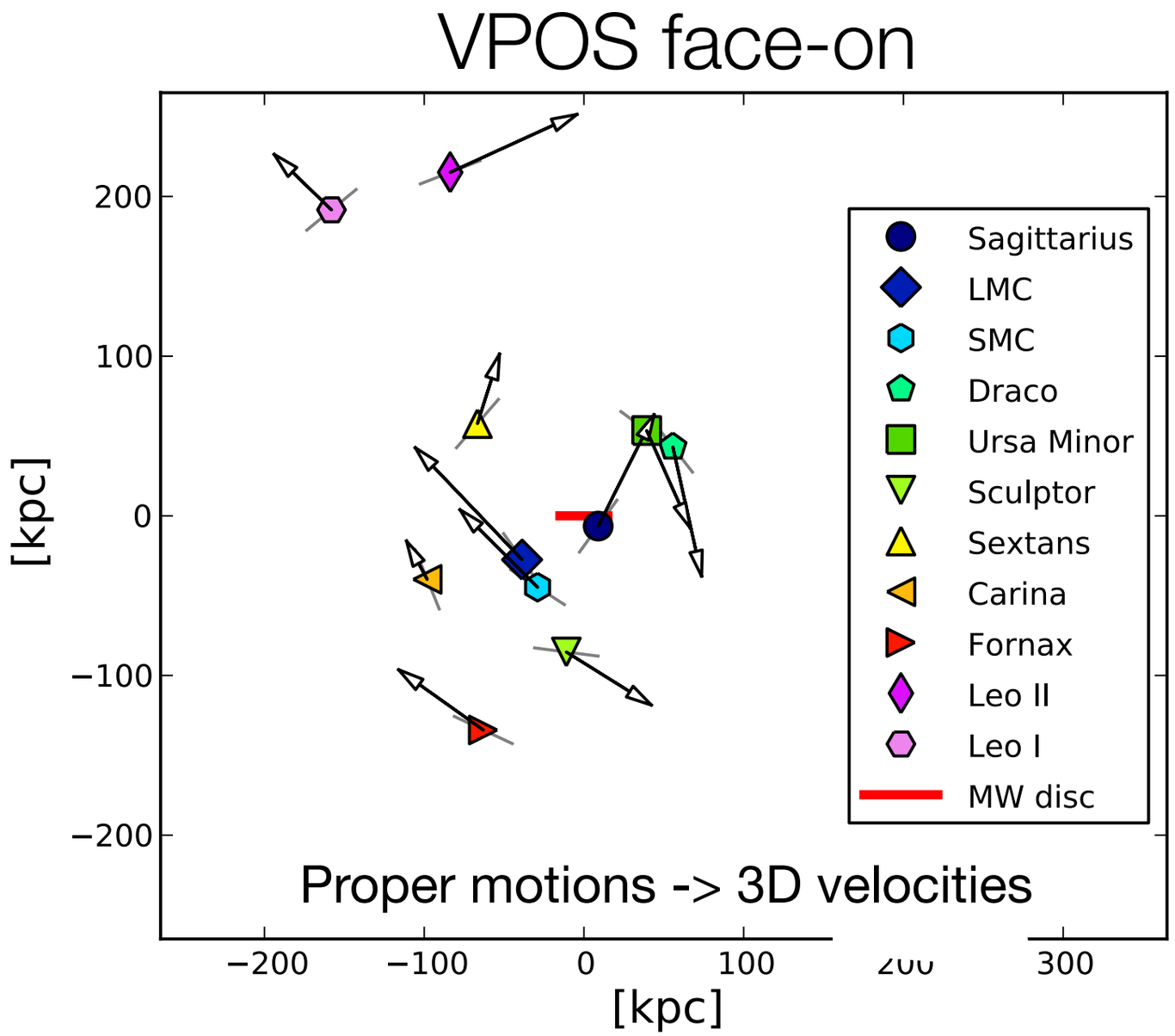
  ***c/a*, *b/a*: ~ 0.8 to 1.6%**

- BUT: additional objects align with VPOS
- BUT: two similarly rare structures in LG

Coherent velocities: the VPOS is rotationally stabilized Pawlowski & Kroupa (2013, MNRAS, 435, 2116)

- Orbital poles of the MW satellites
  - ➡ directions of angular momenta = normals to orbital planes





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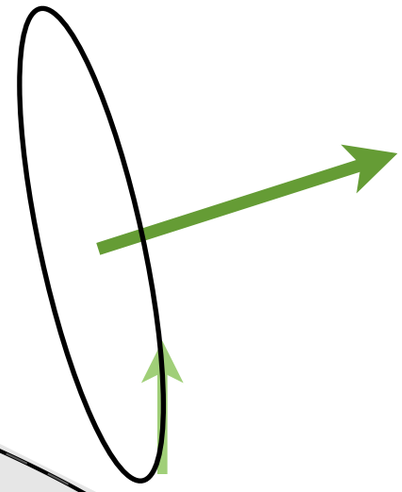
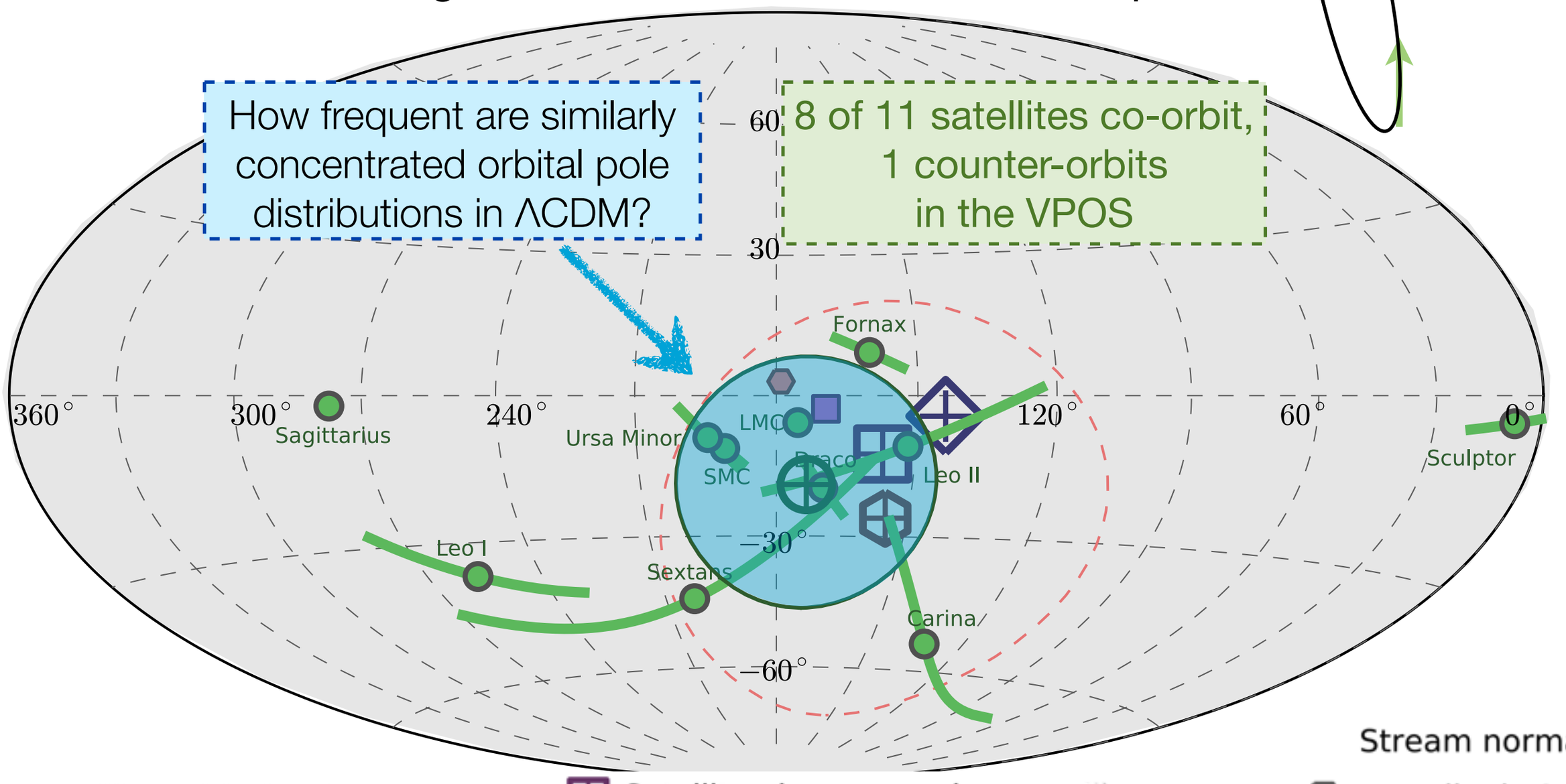


How frequent are similarly concentrated orbital pole distributions in ΛCDM?

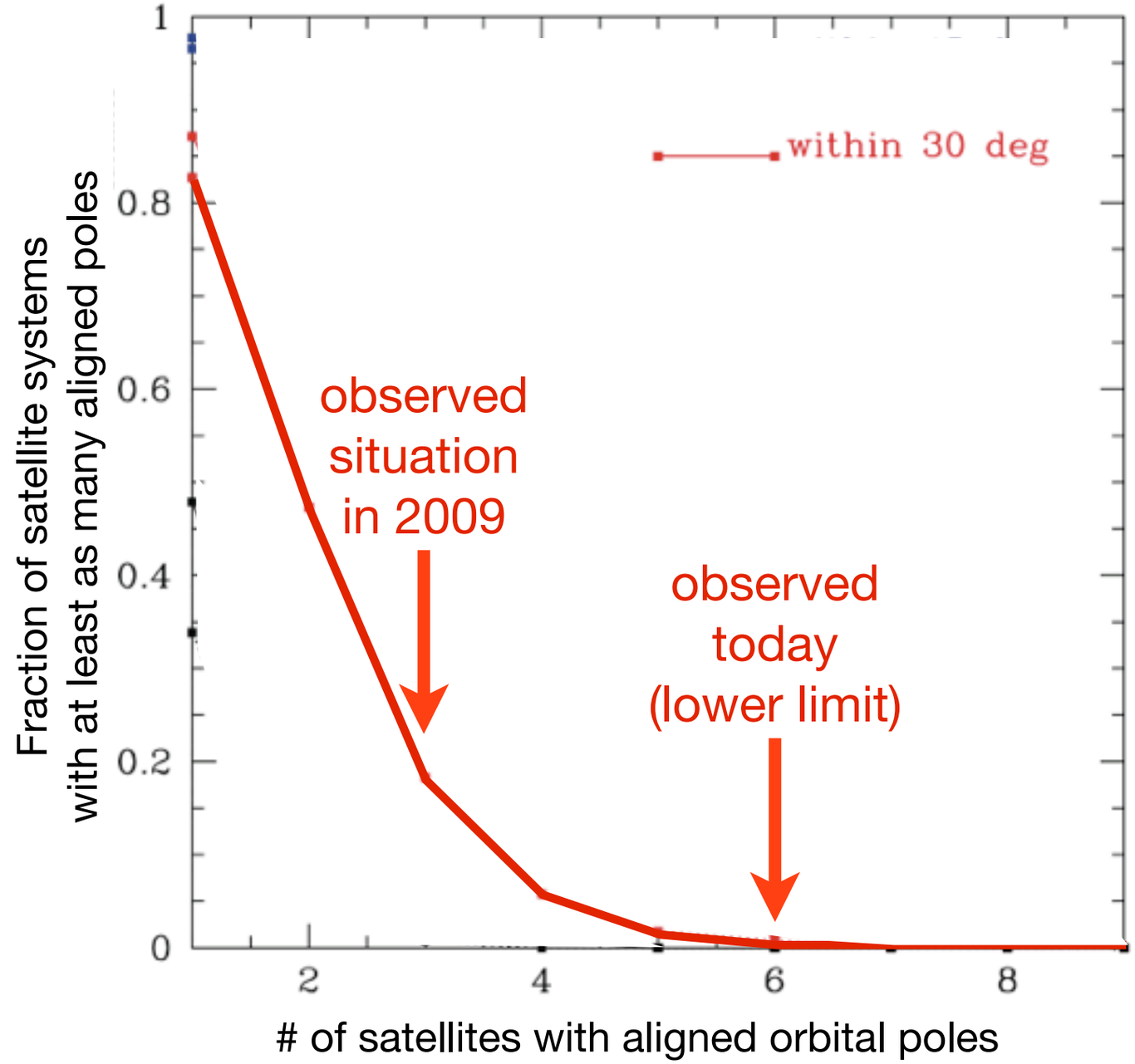
8 of 11 satellites co-orbit, 1 counter-orbits in the VPOS



How frequent are co-orbiting satellites in ΛCDM?

Pawlowski & Kroupa (2013, MNRAS, 435, 2116), Pawlowski+(2014, MNRAS, 442, 2362), Pawlowski & McGaugh (2014, ApJL, 789, 24)

Libeskind et al. (2009): ~0% of simulated systems contain 6 of 11 satellites co-orbiting to 30º.



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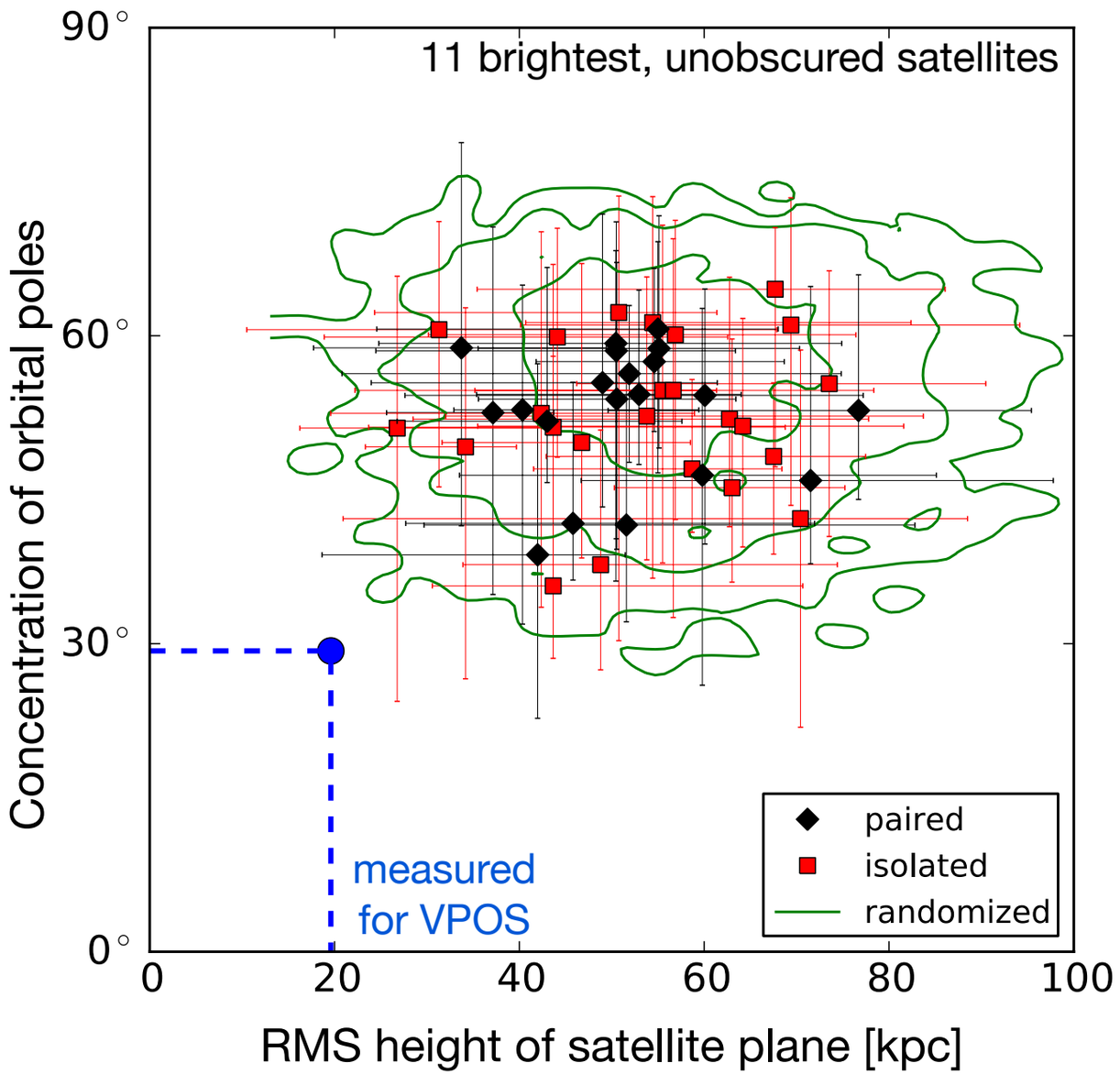
ELVIS simulations: LG-like pairs
(Garrison-Kimmel et al 2014, MNRAS, 438, 2578)

- ➡ 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.



Chance to find VPOS *and* GPoA in such simulations < 10^{-5}

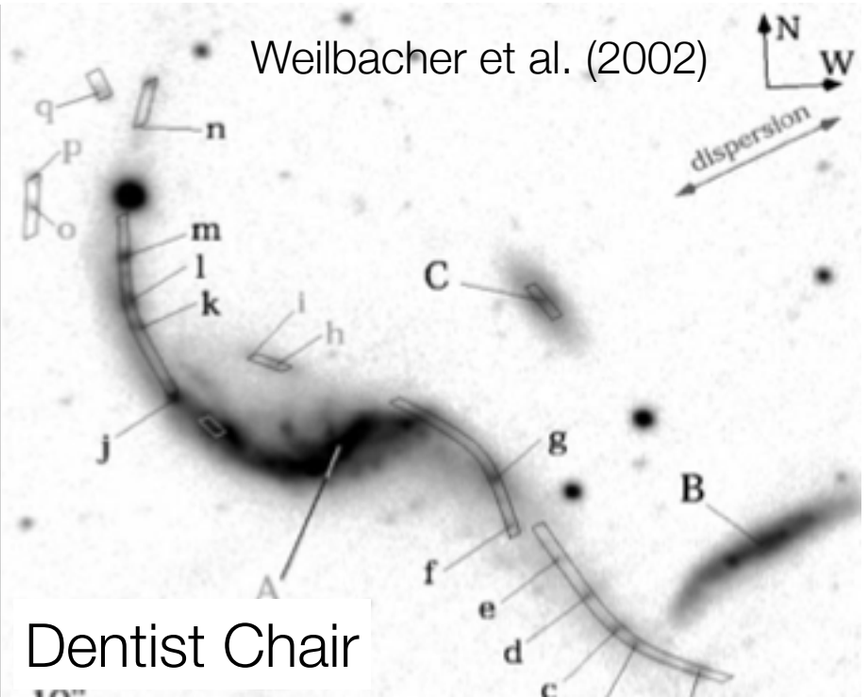
Tidal dwarf galaxies (TDGs) naturally co-orbit in common planes

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

Open issues:

- Should be dark-matter-free
  - ➡ Non-equilibrium dynamics? (Kroupa 1997; Casas+2012)
  - ➡ Gas stripping? (Yang+2014)
  - ➡ MOND? (see Benoit's talk on Friday)
- Mass-Metallicity relation
  - ➡ Ancient TDGs less pre-enriched?

Tadpole



Dentist Chair

NGC 5557 Duc et al. (2011)

Two scenarios that could cause TDG planes around both the MW and M31 (9-11 Gyr ago)

1) Encounter between (proto) MW&M31
e.g. Sawa&Fujimoto 2005, Pawlowski+2012a

- Debris/TDGs would orbit both galaxies and spread in between.
- Requires almost radial, prograde orbit. (Sohn+2012a,b; v.d.Marel+2012)
- MW-M31 encounter expected in MOND. (Zhao+2013, see Benoit's talk on Friday)

2) 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).
- Co-orbiting TDGs around M31 like GPoA.
- Expels TDGs towards MW, accreted to form as VPOS. (Fouquet+2012; Yang+2014)

Both imply signatures on LG scale connecting M31 & MW

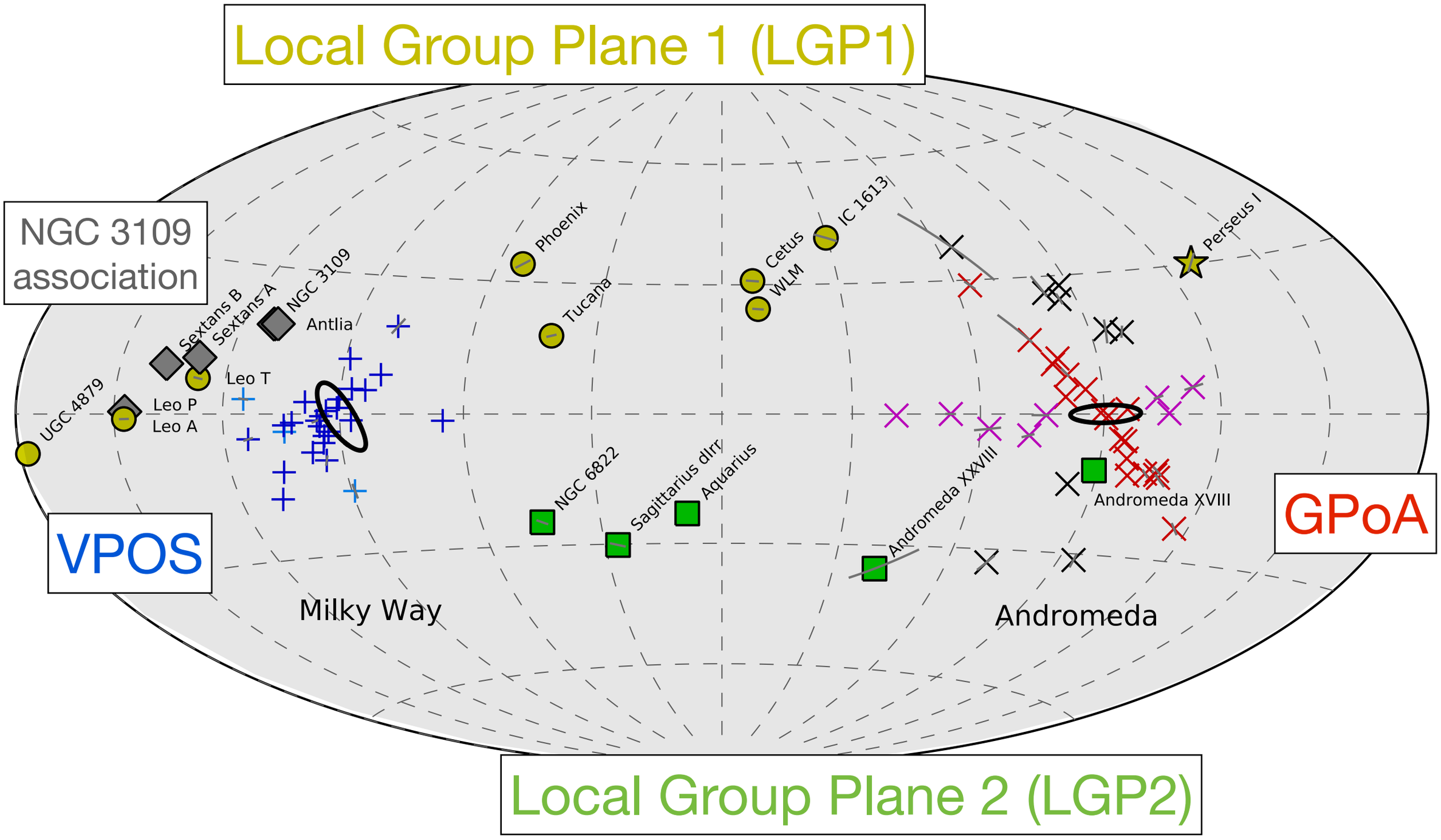
Irrespective of what we think of TDG idea, this highlights that:

- Satellite planes might not be isolated structures.
- Large-scale distribution of dwarfs in LG can provide hints to solving satellite-plane puzzle.

Dwarf galaxy planes connecting the MW and M31

Pawlowski, Kroupa & Jerjen (2013, MNRAS, 435, 1928)
+ Pawlowski & McGaugh (2014, MNRAS, 440, 908)

LG galaxy positions (<1.5 Mpc) in all-sky plot ‘seen’ from the MW-M31 midpoint



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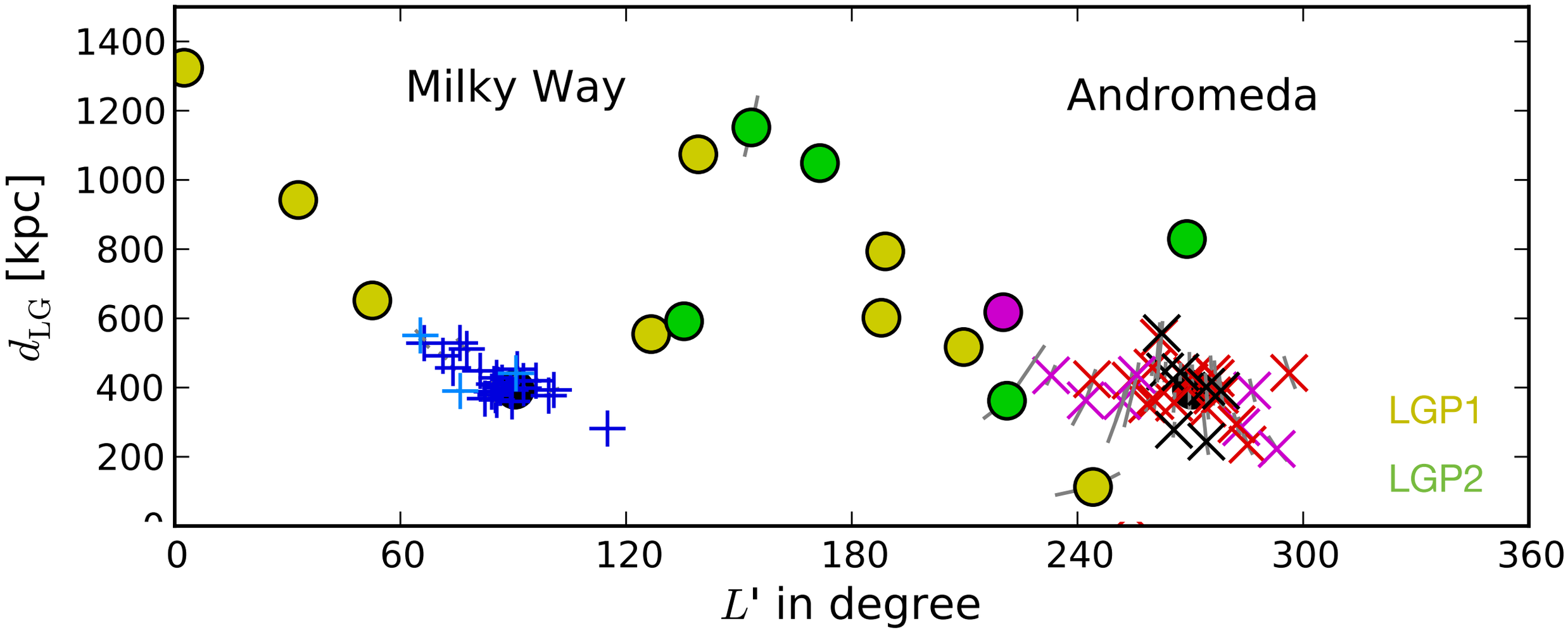
Distances of LG galaxies from MW-M31 midpoint (along LGP 'equator', *L'*):



LGP1 and LGP2 are highly symmetric

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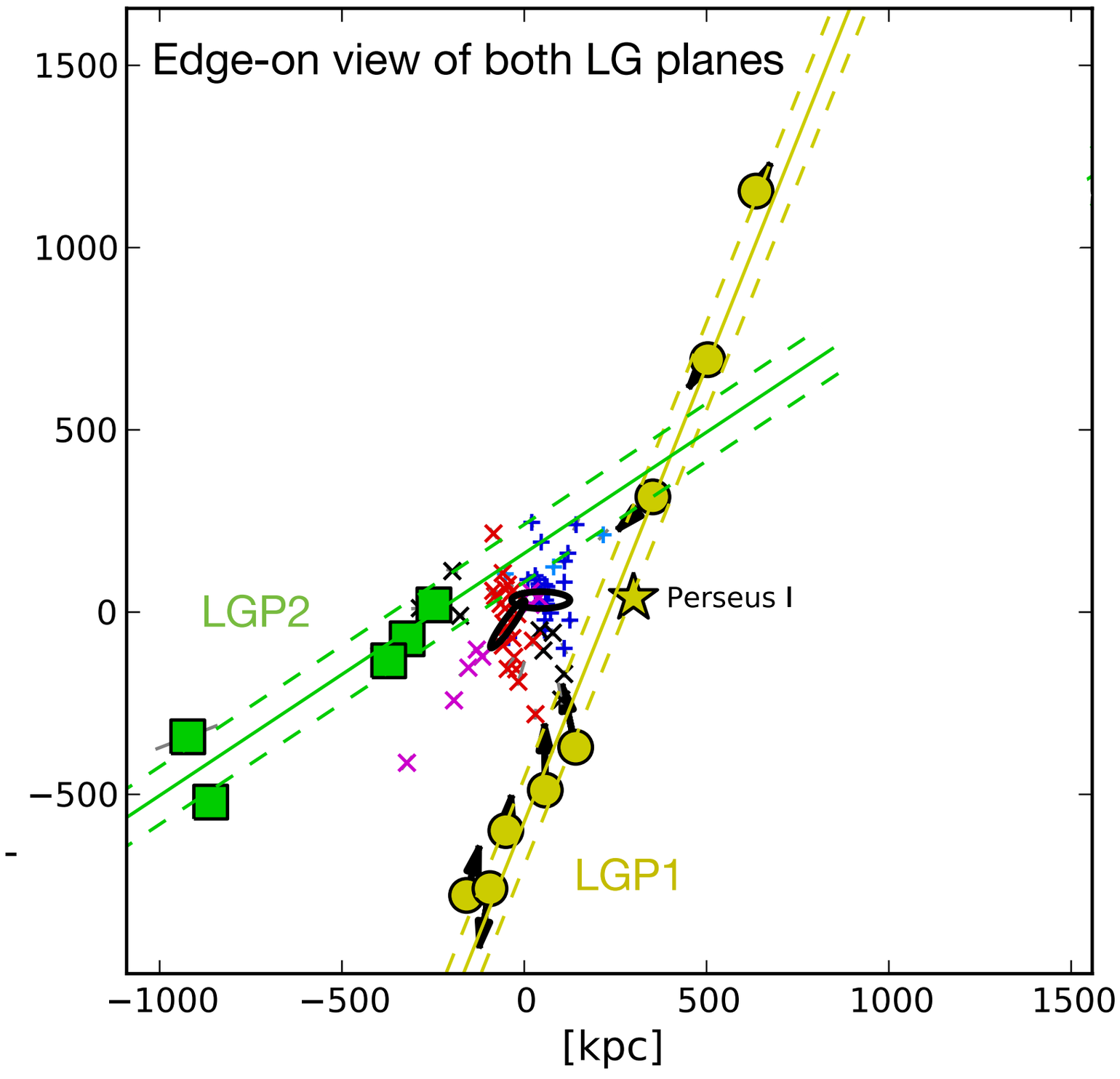
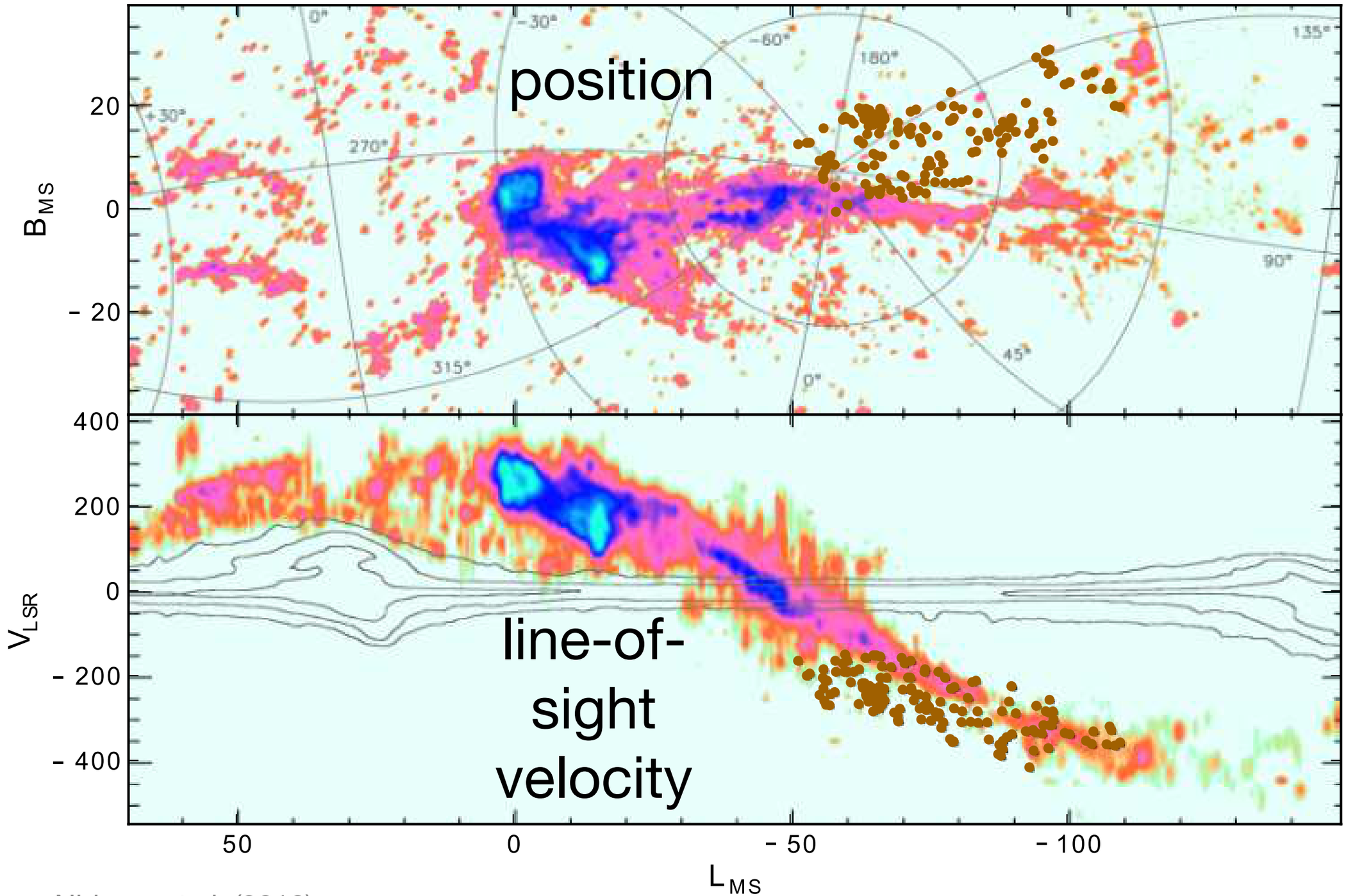


Non-satellites are in one of two thin planes which have:

- 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)

MW south (to M31): 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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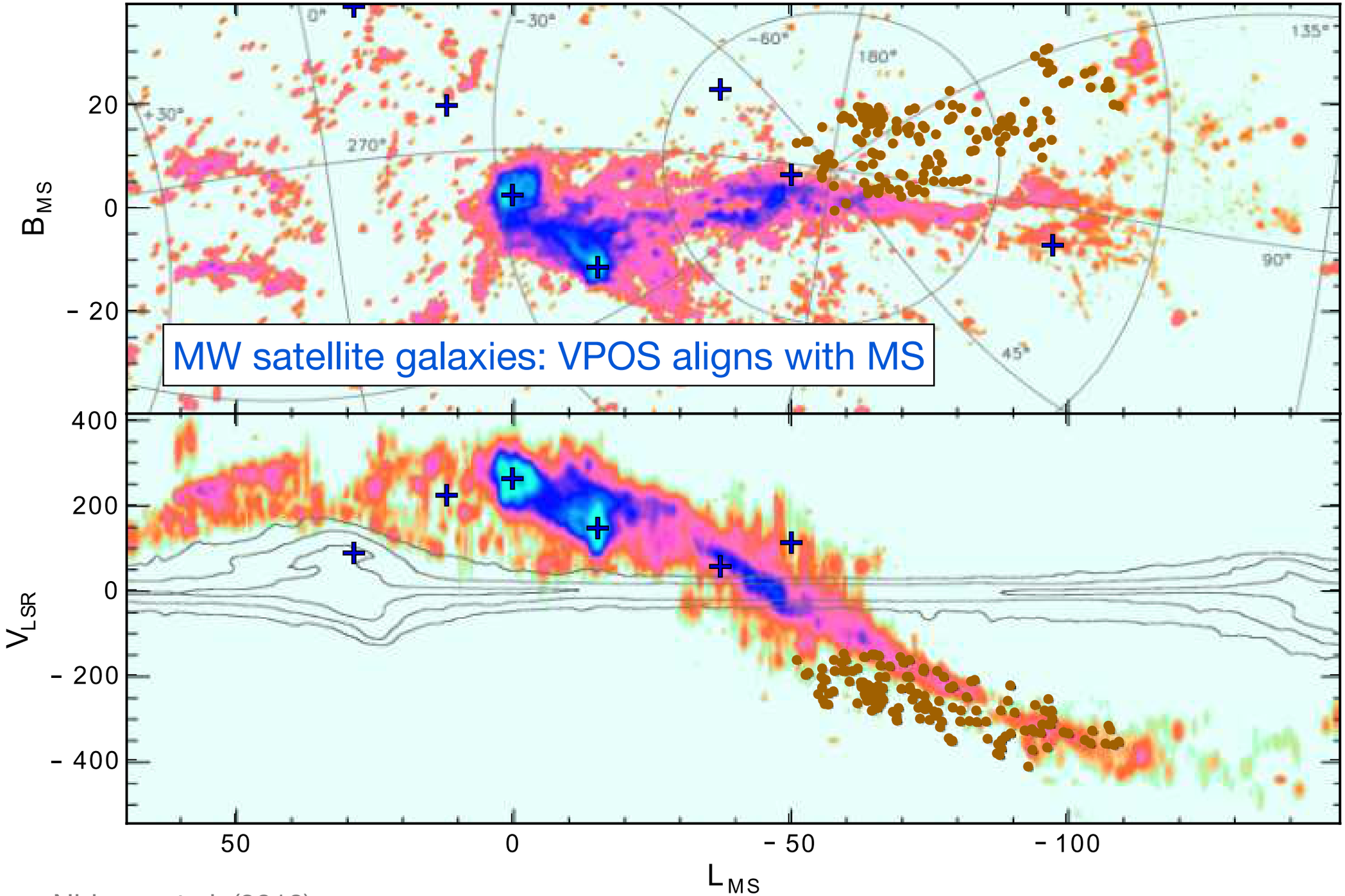

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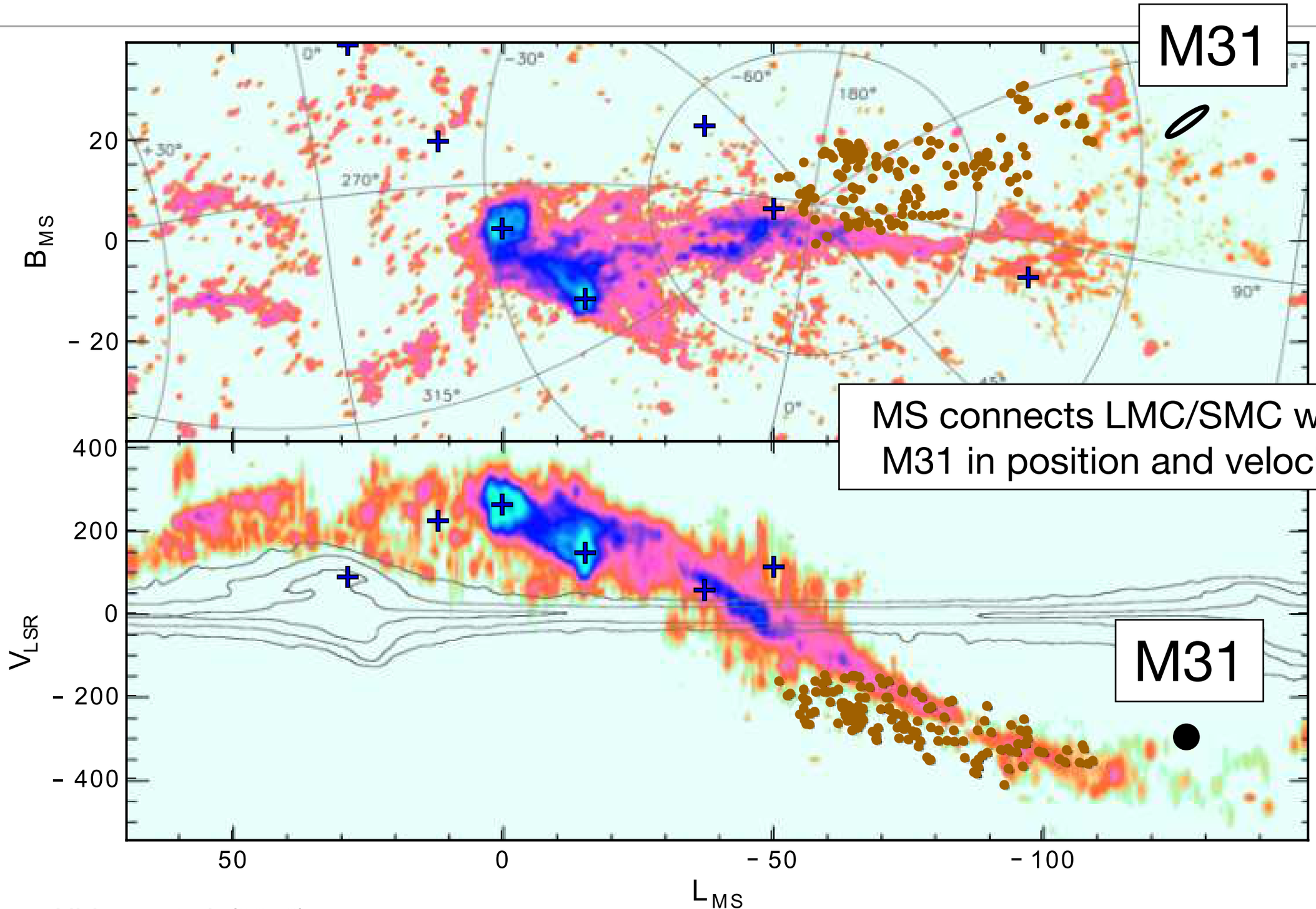

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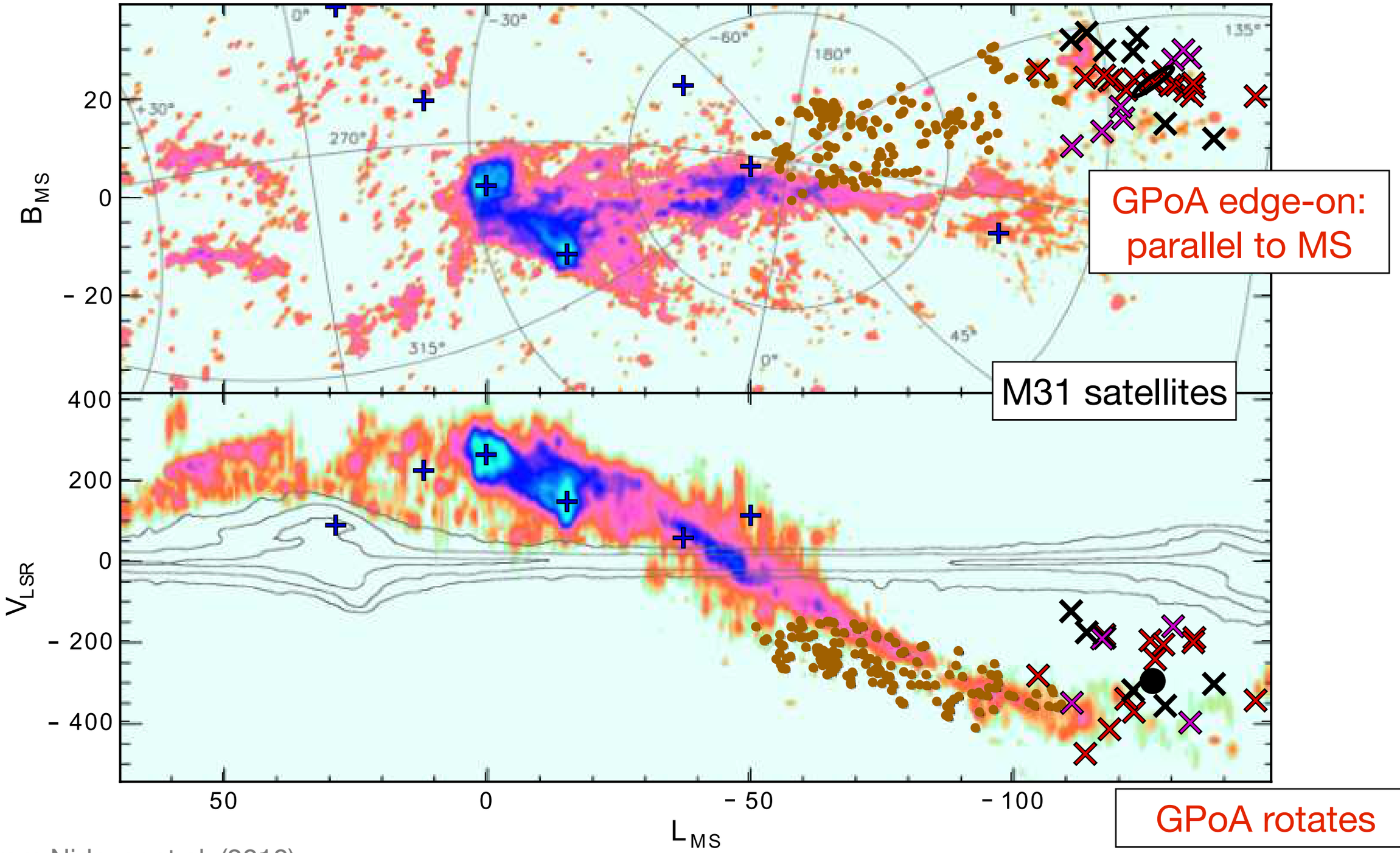

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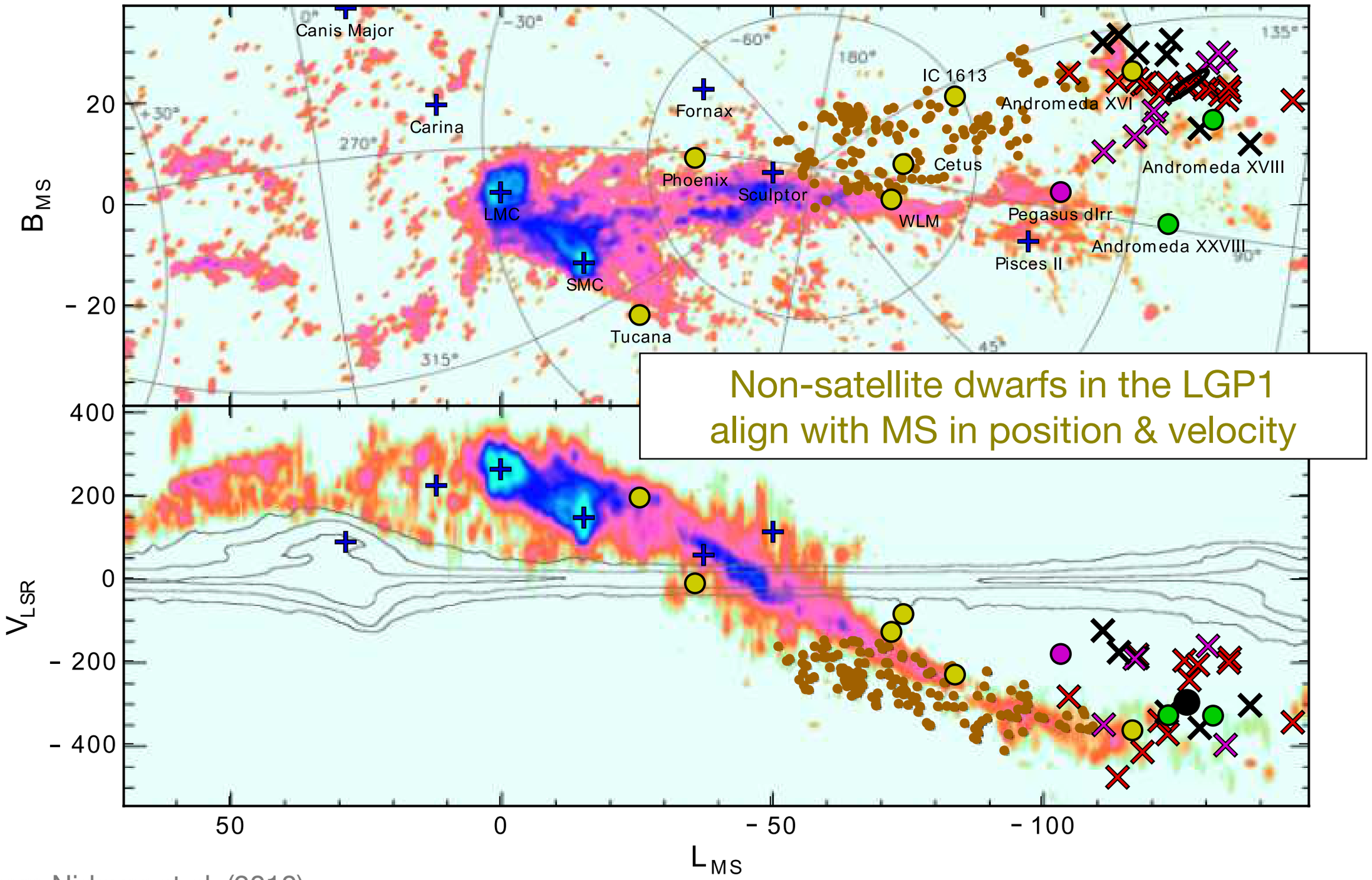

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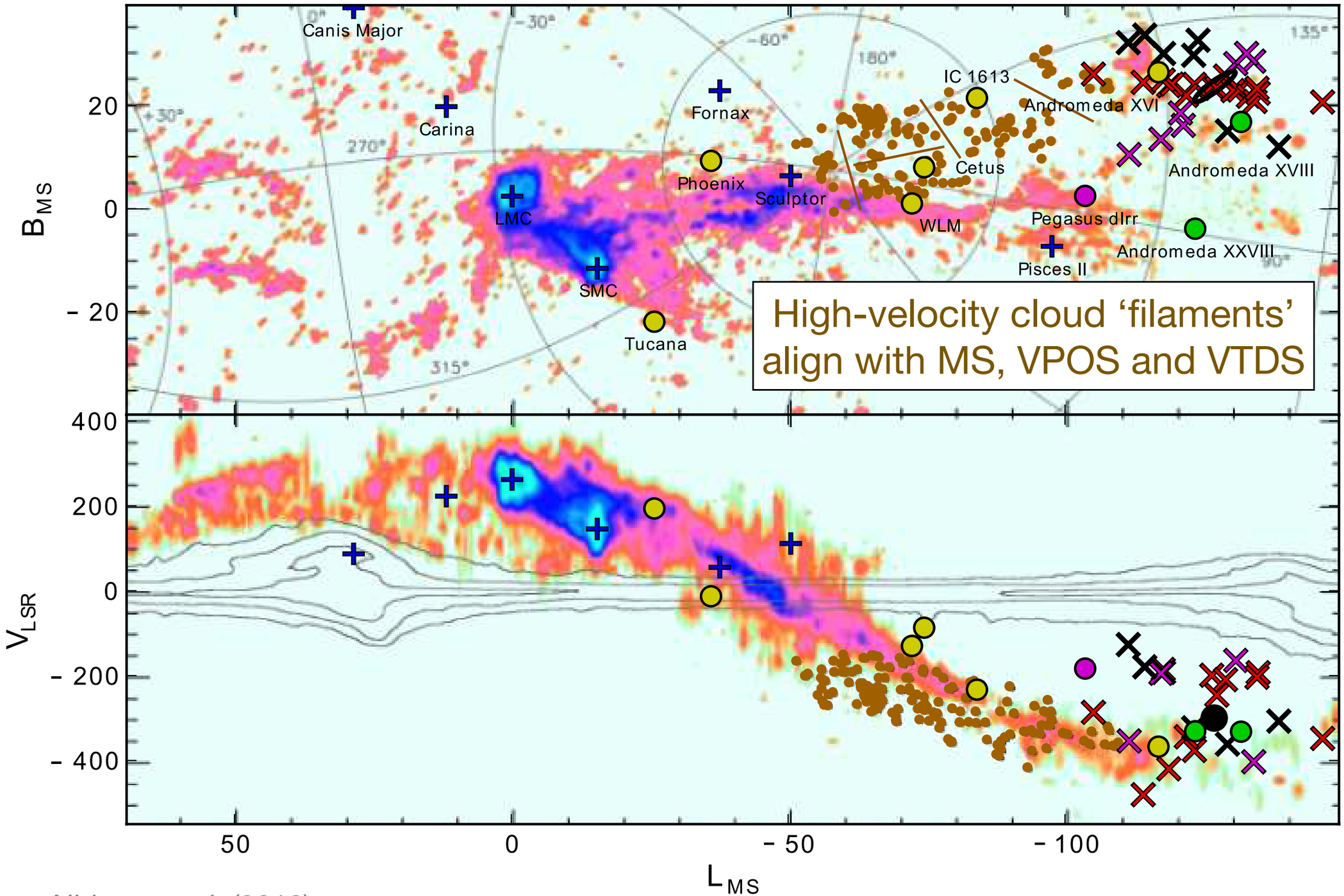

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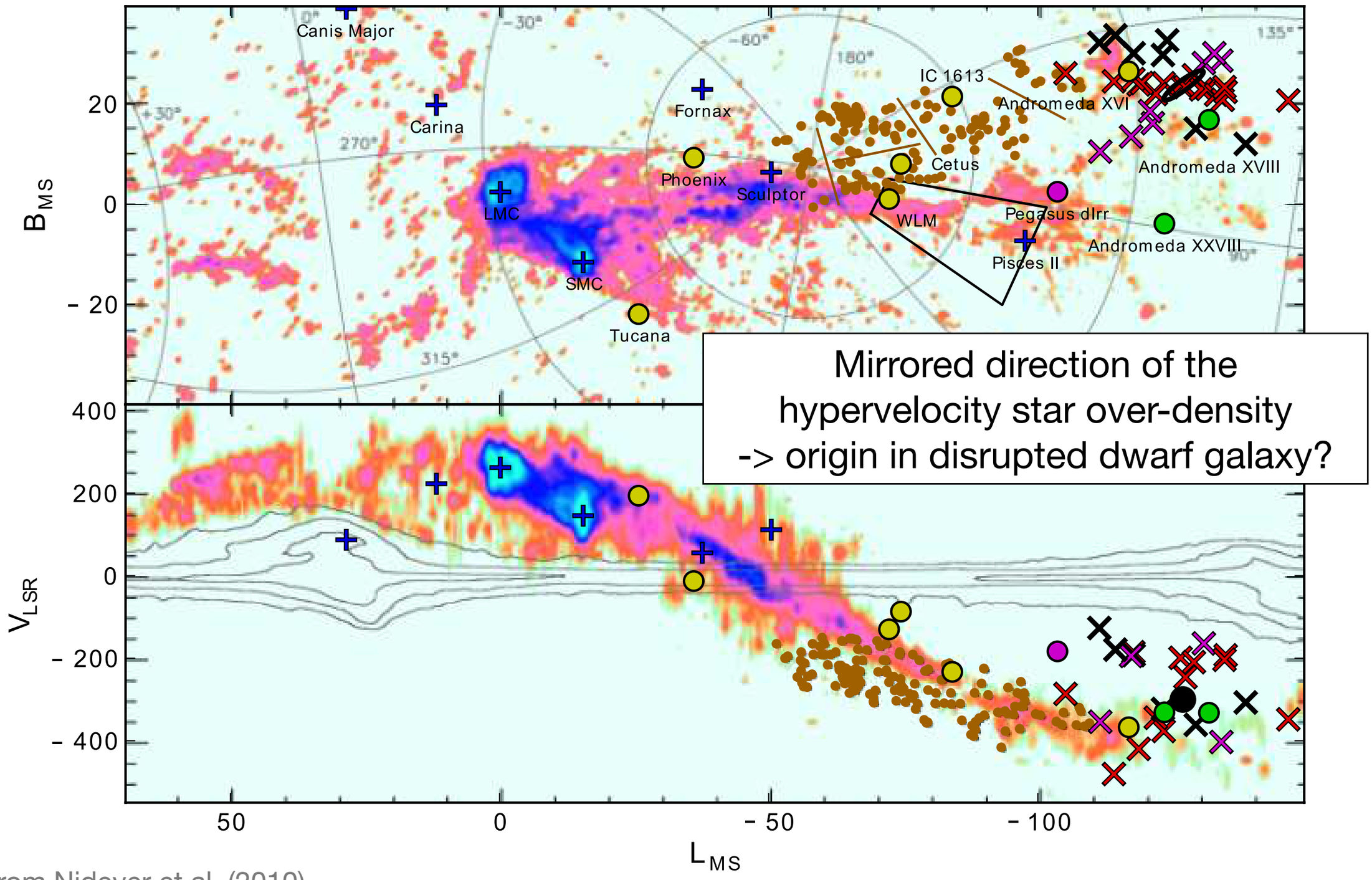
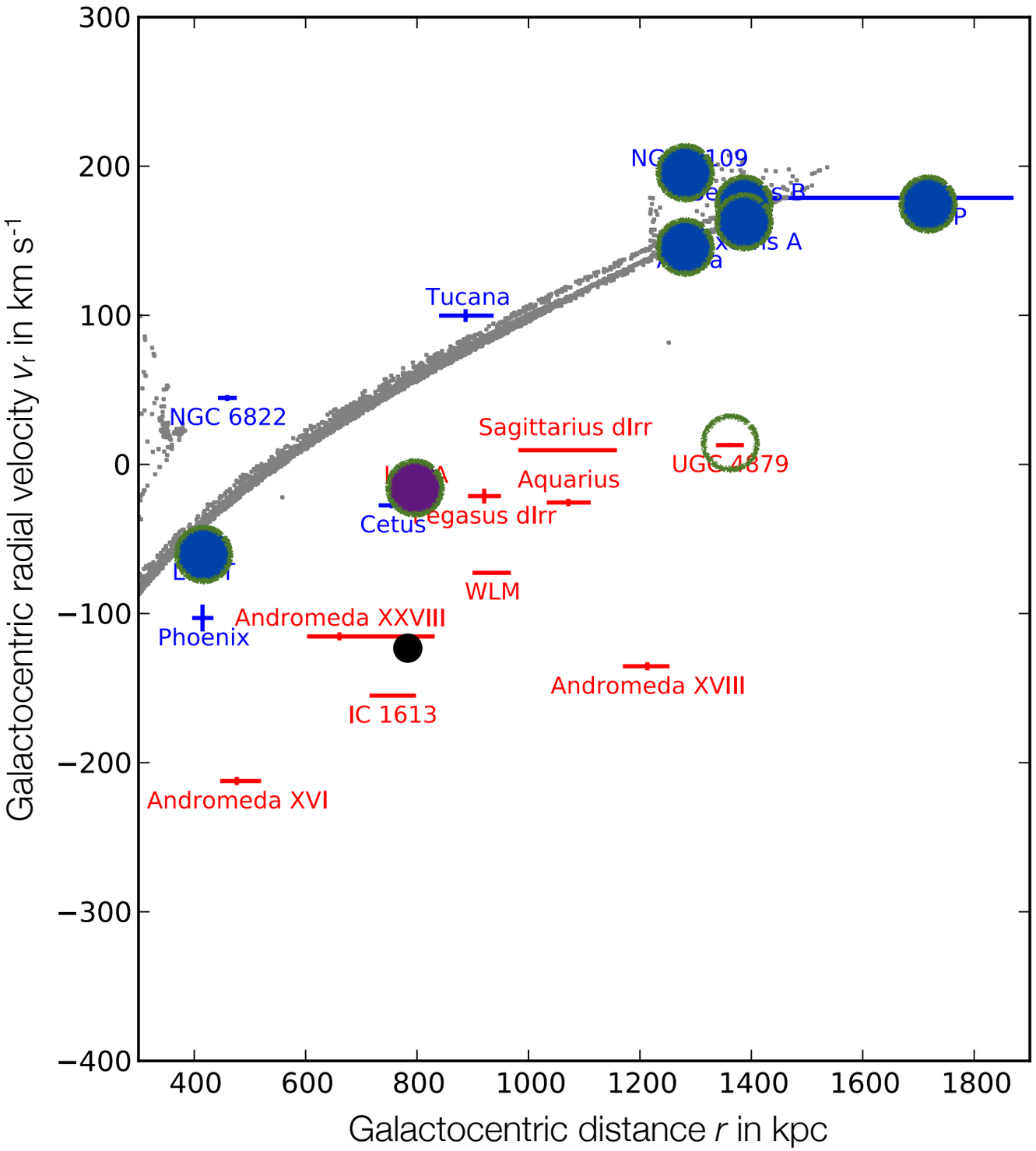


MS map from Nidever et al. (2010)
HVCs from Westmeier & Koribalski (2008)

MW north (opposite M31): why are the dwarfs running away?

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

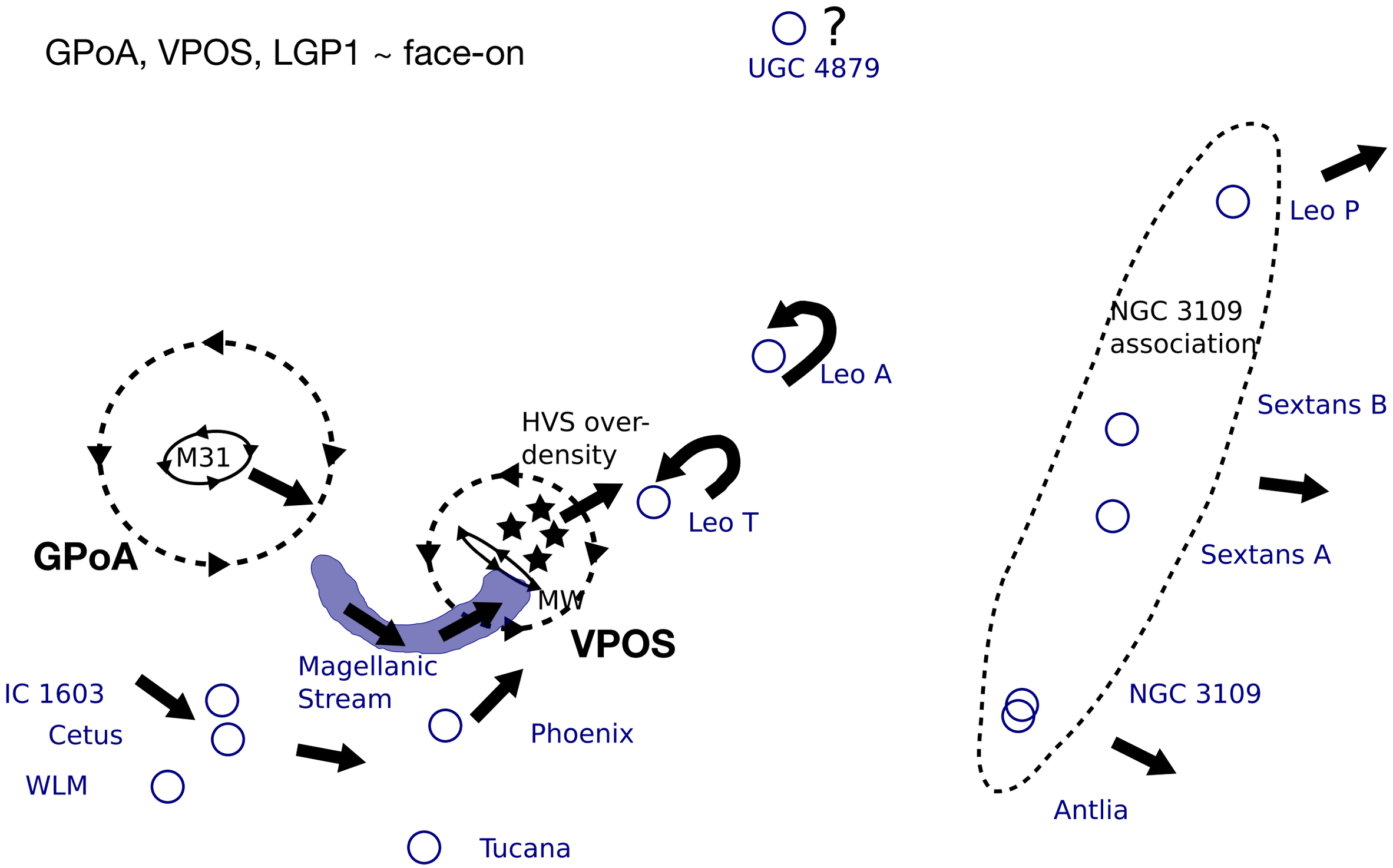


- Backsplash (sub-) halos have passed through but left the virial radius of a main halo. (Teyssier et al. 2012)
- All 8 non-satellite dwarfs **in the MW north** are in a thin plane ($c/a < 0.1$).
- At least 6 of 8 are **likely backsplash galaxies** (Teyssier et al. 2012)
- ΛCDM simulation predicts only 1 of 8
  - ➡ **Over-abundant backsplash problem?**
- **Tidal debris** (not adjusted to fit) have similar properties in r-v_r plot.
  - ➡ TDGs might be misinterpreted as backsplash objects

Preferred direction of motion of LG dwarf galaxies?

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

GPoA, VPOS, LGP1 ~ face-on



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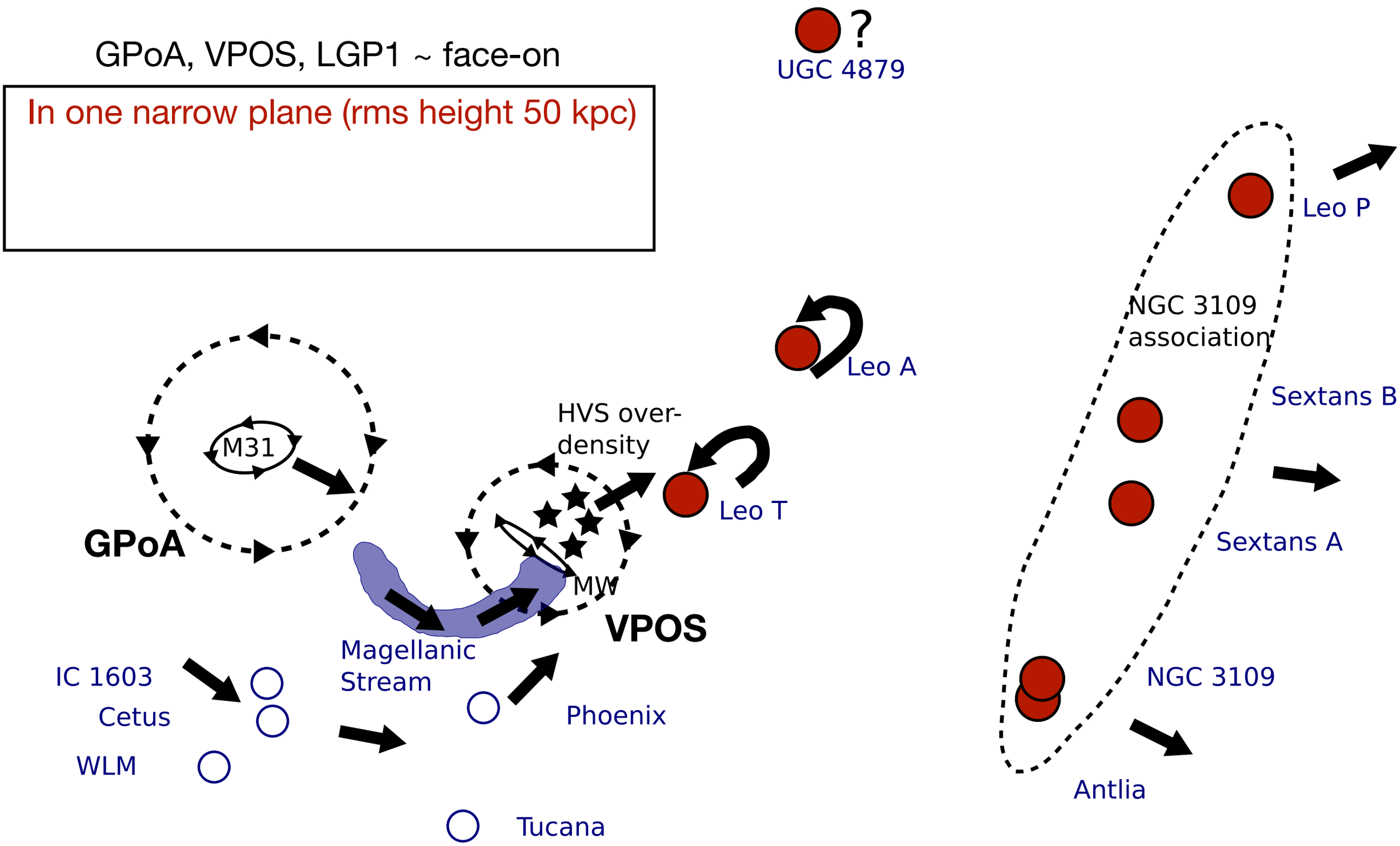
In one narrow plane (rms height 50 kpc)



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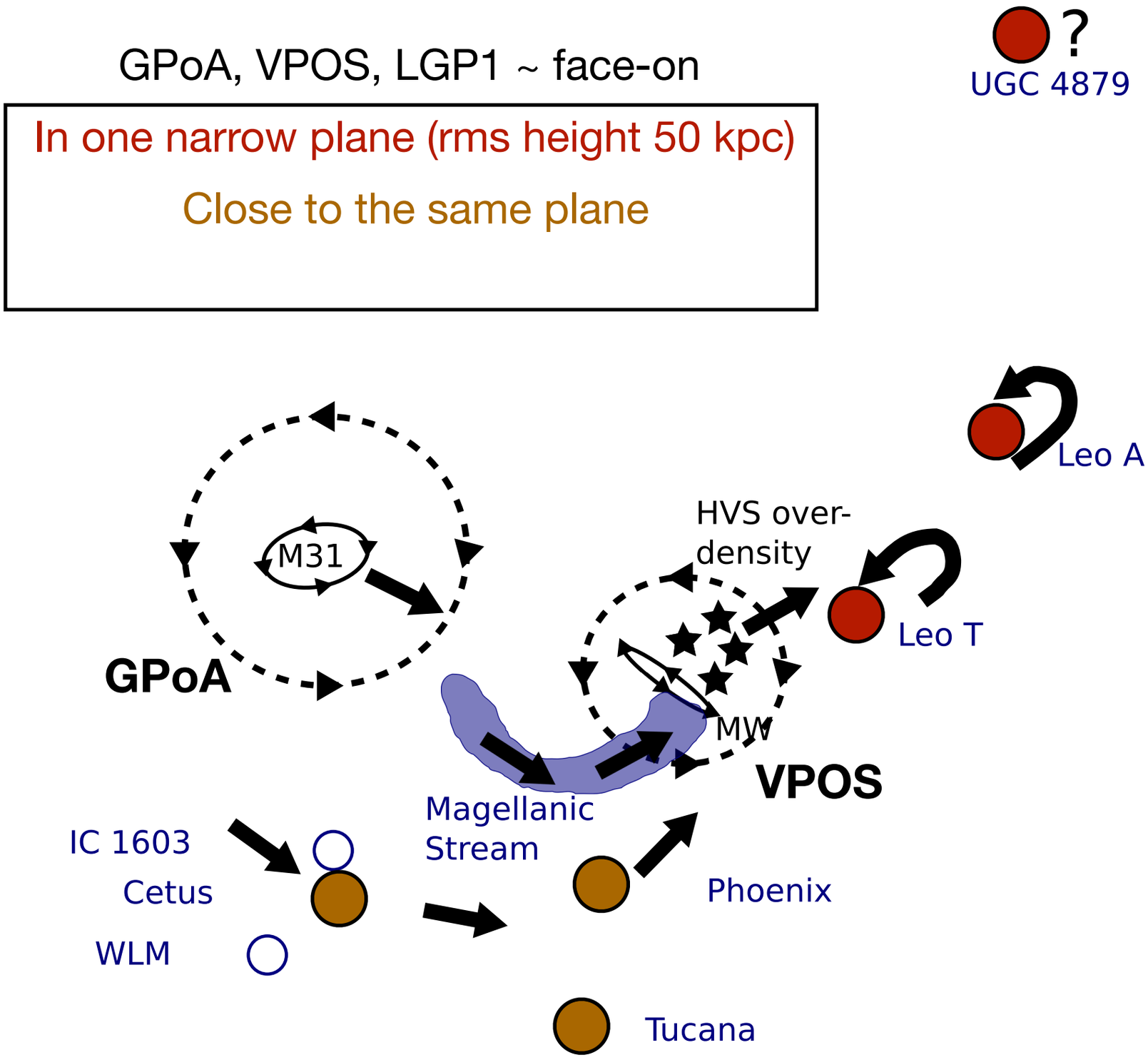
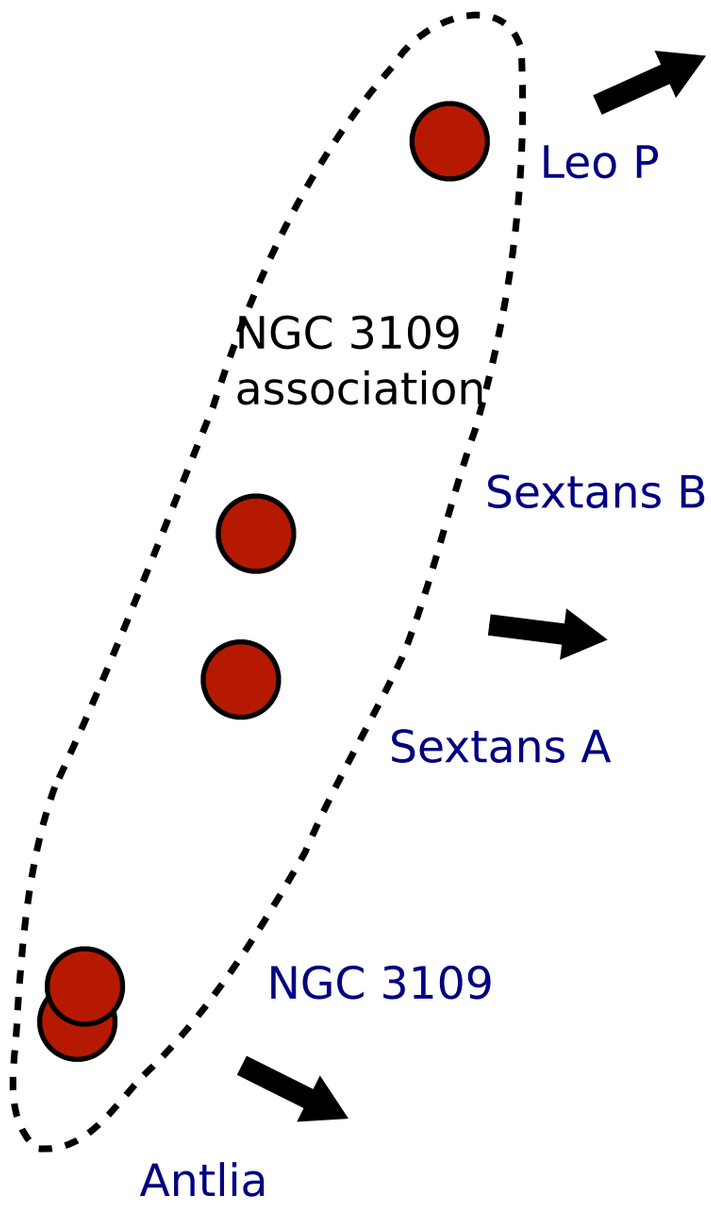
Close to the same plane





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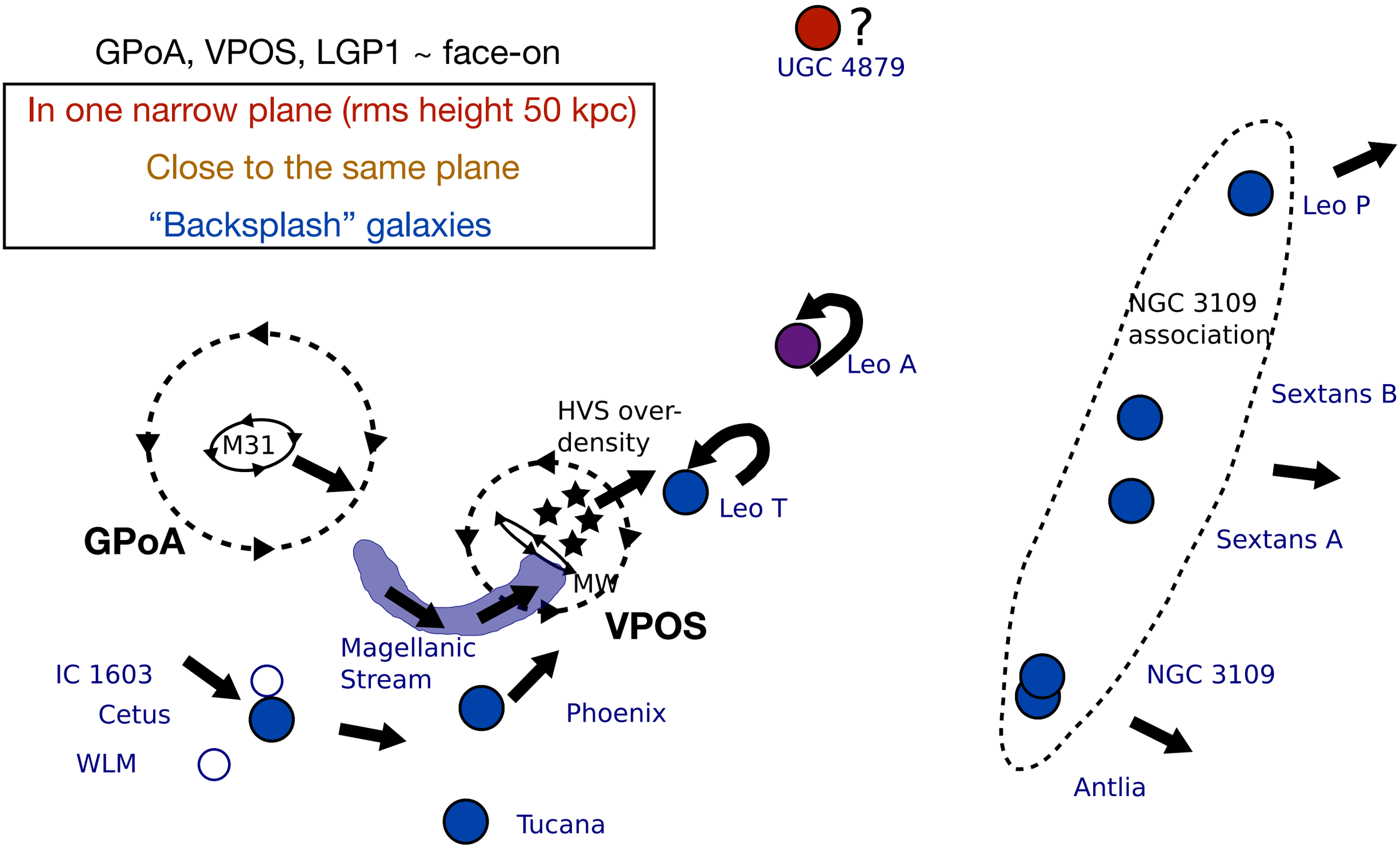
“Backsplash” galaxies



Conclusions

- Correlated satellite structures (position *and* velocity space) as observed in LG are extremely rare in ΛCDM simulations:

  ➡ Fundamental anisotropy problem.

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

- Non-satellite dwarfs in LG are confined to two narrow, symmetric planes.
  - MW south (towards M31): dominant LG plane aligns with MS (pos. & vel.), dwarfs approach.
  - MW north (opposite M31): all dwarfs in narrow plane, most recede too fast:

    ➡ Over-abundant backsplash problem?

    Pawlowski, Kroupa & Jerjen (2013, MNRAS, 435, 1928) + Pawlowski & McGaugh (2014, MNRAS, 440, 908)

- TDGs: consistent with structures, but open issues: vel. disp., mass-metallicity.

e.g. Pawlowski et al. (2011, MNRAS, 532, 118) + Pawlowski & Pflamm-Altenburg, Kroupa (2012, MNRAS, 423, 1109)