ΛCDM's most severe small-scale problem: The ubiquity of co-orbiting satellite galaxy planes

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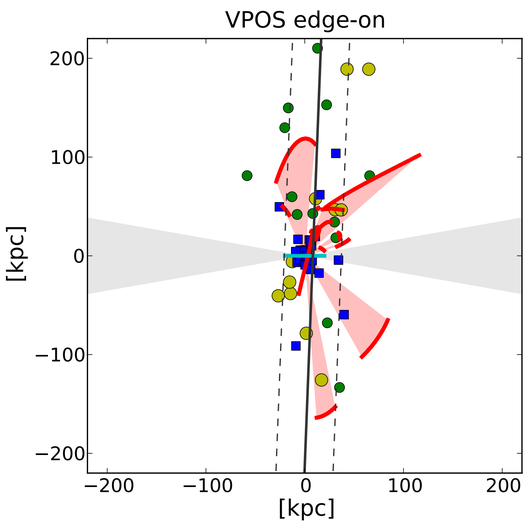
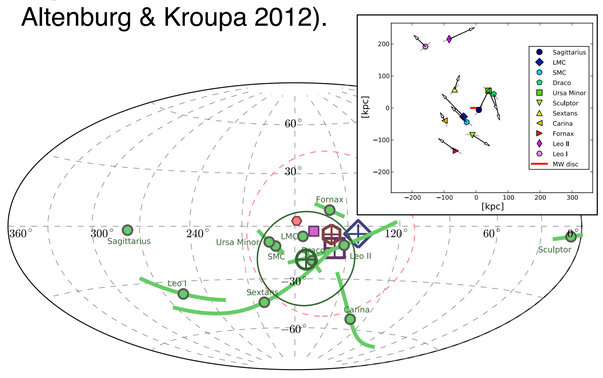
think beyond the possible

Satellite galaxy structures

Vast Polar Structure (VPOS):



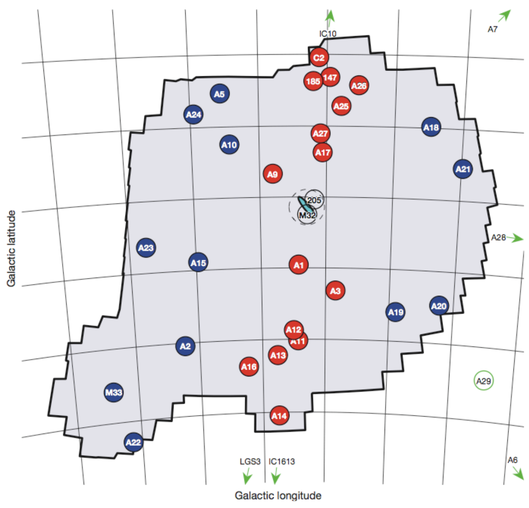
- The 11 **classical satellite galaxies** of the **Milky Way** (MW) are distributed in a highly flattened (18 kpc rms height), polar structure.
- The later discovered **fainter MW satellites** define the same satellite plane.
- In addition, **young halo globular clusters** (YH GCs) and ~50% of the known **stellar and gaseous streams** (tracing their orbital planes) align with the VPOS (Pawlowski, Pflamm-Altenburg & Kroupa 2012).



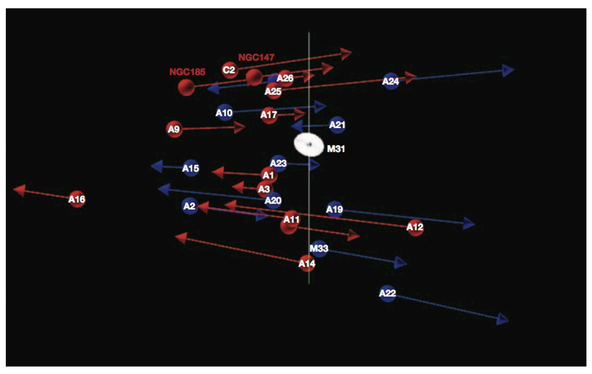
- The **orbital poles** (directions of angular momenta determined from measured proper motions) of the 11 classical satellite galaxies cluster close to the **VPOS plane normal**, the **YH GC plane normal** and the **average stream normal**. The VPOS is thus rotationally stabilized (Pawlowski & Kroupa 2013).

This observed, highly correlated phase-space distribution is at odds with cosmological expectations. Tidal dwarf galaxies formed in an ancient galaxy-collision are a very natural alternative formation scenario of the VPOS.

Great Plane of Andromeda (GPoA):

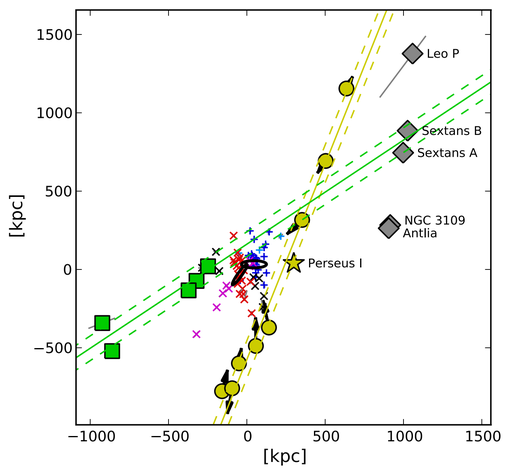


- **15** of 27 satellite galaxies of M31 lie in a highly significant, narrow plane (14 kpc rms height, Ibata et al. 2013).



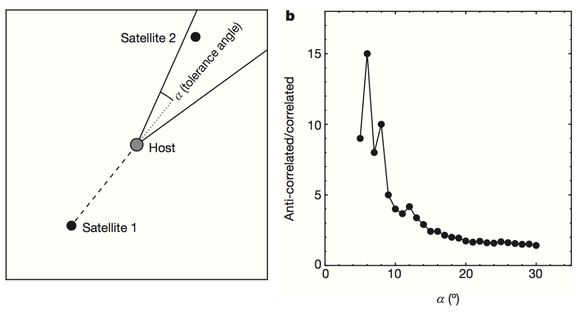
- The GPoA is seen edge-on from the MW. The line-of-sight velocities of its satellites reveal a signature indicative of a common orbital direction (similar to the VPOS).

Non-satellite galaxies in the Local Group:



- The dwarf galaxies in the Local Group (> 300 kpc from MW & M31 are confined to two narrow planes, too (Pawlowski, Kroupa & Jerjen, 2013).
- These are highly symmetric: parallel to MW-M31 line, have similar rms heights (60 kpc), diameters (1-2 Mpc) and are both inclined by 20° relative to M31.

Velocity anti-correlation of diametrically opposed satellites:



- Are satellites of more distant hosts found in co-orbiting planes, too?
- Detailed 3D positions only available for LG, but selecting diametrically opposed satellites (small opening-angle α) preferentially selects edge-on planes.
- If the satellites are indeed co-orbiting in such planes, they should have anti-correlated velocities.
- Selecting satellites with spectroscopic velocities from SDSS reveals a large and significant (4σ) over-abundance of anti-correlated velocities.
- This indicates that > 60% of all satellites are part of co-orbiting planes (Ibata et al. 2014).

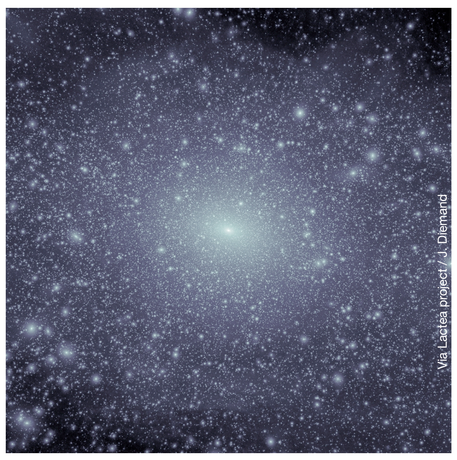
Further reading: *Pawlowski, Pflamm-Altenburg & Kroupa (2012); Pawlowski, Kroupa & Jerjen (2013); Ibata et al. (2013); Ibata et al. (2014)*

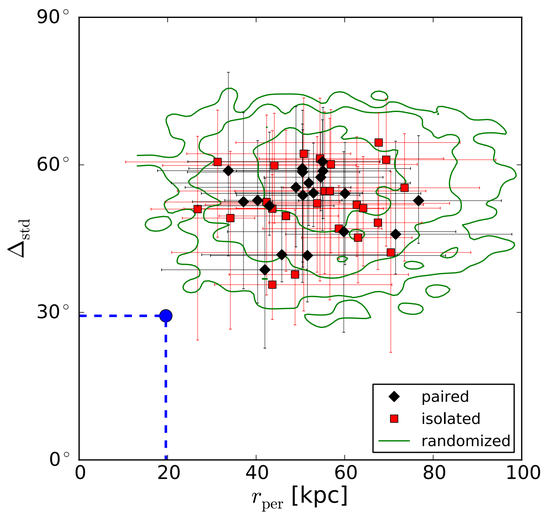
Table 2: Known correlated dwarf galaxy structures.

Host	Name	N_{dwarf}[a]	Kinematic coherence[b]	Aligned streams[c]	Reference
Milky Way	VPOS	≥ 24	yes[d]	yes (stellar & gaseous, incl. MS)	1, 2
Andromeda	GPoA	≥ 15	yes[e]	yes (stellar NW-S1 & GS)	3, 4, 5
NGC 1097	Dog Leg	2	unknown	yes, stellar	6
NGC 5557	Tidal Tail-E	3	yes[f]	yes, stellar	7, 8
NGC 4216	F1	3	unknown	yes, stellar	9, 10
NGC 4631	bridge	3	unknown	possible stellar, Hα & HI bridge	11
M 81 group		19	unknown	unknown[g]	12
Local Group	NGC 3109 association	5	yes[h]	no stream known	13, 14

References. — (1) Pawlowski et al. (2012b); (2) Pawlowski & Kroupa (2013); (3) Ibata et al. (2013); (4) Conn et al. (2013); (5) Hammer et al. (2013); (6) Galianni et al. (2010); (7) Duc et al. (2011); (8) Duc et al. (2014); (9) Paudel et al. (2013); (10) Martínez-Delgado et al. (2010); (11) Karachentsev et al. (2014); (12) Chiboucas et al. (2013); (13) Bellazzini et al. (2013); (14) Pawlowski & McGaugh (2014).

ΛCDM expectation





ΛCDM predicts that sub-halos (and thus satellite galaxies) are distributed approximately spheroidally around their hosts and have many different orbital directions. Merging of hosts and anisotropic infall of sub-halos along filaments causes some degree of non-isotropy. These effects are accounted for by cosmological simulations. Are they strong enough to explain the observed satellite structures?

Do as strongly correlated satellite structures exist in ΛCDM simulations?

- Compare spatial flattening (e.g. RMS plane height r_{per}) of observed and simulated satellite populations.
- Important: simultaneously test velocity correlation (e.g. concentration of orbital poles Δ_{std}).
- Make sure observational biases are realistically applied to simulations (e.g. MW obscuration, survey area).
- Tested with many simulations: ELVIS (shown in plot), Millennium II, Via Lactes I & II, Aquarius.

Results

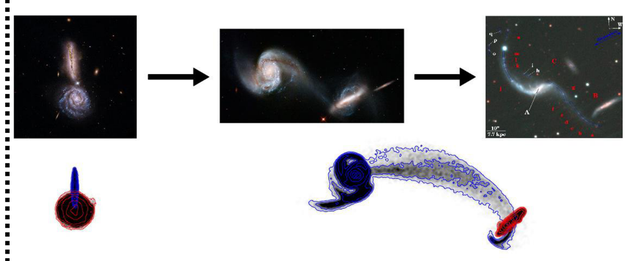
- Frequency to find equivalent structure:
  - VPOS: 0.02 – 0.06%
  - GPoA: 0.04 – 0.17%
  - Velocity anti-correlation: 0.006%
- The observed satellite structures are extremely unexpected in a ΛCDM universe.

Some studies claim consistency of satellite planes with LCDM but ...

- ... do not perform quantitative test (e.g. Lovell et al. 2011).
- ... ignore velocity coherence (e.g. Wang et al. 2013, Goerdt & Burkert 2013).
- ... use a wrong sample selection from simulations (e.g. Bahl & Baumgardt 2014).
- ... make assumptions that are inconsistent with observed situation (e.g. Goerdt & Burkert 2013).

Further reading: *Pawlowski et al. (2011, 2012b, 2014), Pawlowski & Kroupa (2013), Pawlowski & McGaugh (2014b)*

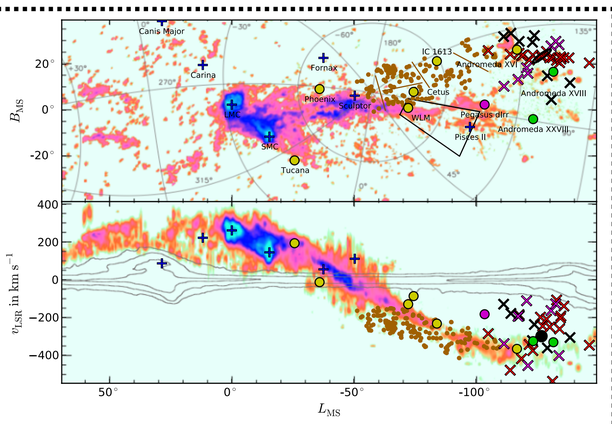
Tidal Dwarf Galaxies (TDGs): a possible explanation



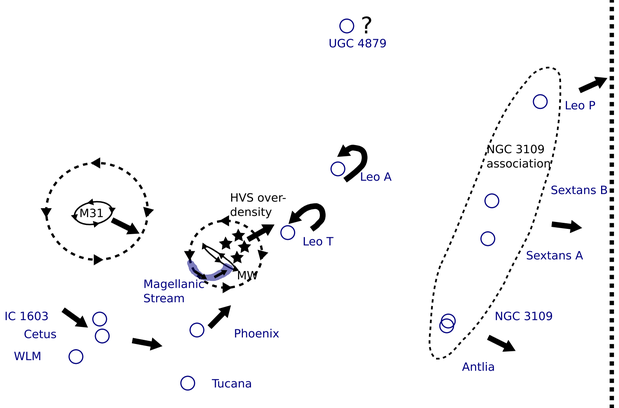
- The observed phase-space correlation of satellite galaxies co-orbiting in one plane indicates that they share a common origin.
- One possible formation scenario for correlated satellite populations are second-generation galaxies formed in the tidal tails expelled from interacting galaxies. These tidal debris naturally orbit within a plane defined by the colliding galaxies (Pawlowski et al. 2011).
- We suggest that 10-11 Gyr ago a major galaxy collision occurred in the Local Group, forming new objects (dwarf galaxies and GCs) from the tidally stripped material. Possible scenarios are a MW-M31 encounter (Zhao et al. 2013), or a merger forming M31 (Hammer et al. 2013).
- Such an origin would require major modifications to the ΛCDM model (e.g. in ΛCDM TDGs can not contain dark matter, missing satellites problem becomes much more serious, ...), but might resolve other small-scale problems.

Other features in the Local Group (LG) consistent with a TDG origin:

- Over-abundance and planar arrangement of backsplash galaxies (Pawlowski & McGaugh 2014a).



- Magellanic Stream (MS) aligns with **VPOS**, but also with **dominant non-satellite dwarf galaxy plane** in LG (in projected position *and* velocity), and is parallel to **GPoA**. MS might trace a bridge between the MW and M31.



- General trend of dwarf galaxies to approach from the direction of M31 and recede (within in a narrow plane) in the opposite direction (more pronounced than in ΛCDM simulations).

Further reading: *Pawlowski, Kroupa & Jerjen (2013), Pawlowski & McGaugh (2014a).*

References

My publications related to this poster (**recommended intro**):

- 'Making counter-orbiting tidal debris. The origin of the Milky Way disc of satellites?', Pawlowski, Kroupa, de Boer, 2011, A&A, 532, 118.
- **'The VPOS: a vast polar structure of satellite galaxies, globular clusters and streams around the MW'**, Pawlowski, Pflamm-Altenburg, Kroupa, 2012, MNRAS, 423, 1109.
- 'Filamentary accretion cannot explain the orbital poles of the Milky Way satellites', M. S. Pawlowski, P. Kroupa, G. Angus et al., 2012, MNRAS, 424, 80.
- **'Dwarf galaxy planes: the discovery of symmetric structures in the Local Group'**, Pawlowski, Kroupa & Jerjen, 2013, MNRAS, 435, 1928.
- 'The rotationally stabilized VPOS and predicted proper motions of the Milky Way satellite galaxies', Pawlowski & Kroupa, 2013, MNRAS, 435, 2116.
- **'Co-orbiting satellite galaxy structures are still in conflict with the distribution of primordial dwarf galaxies'**, Pawlowski, Famaey, Jerjen, et al., 2014, MNRAS, 442, 2362.
- 'Perseus I and the NGC 3109 association in the context of the Local Group dwarf galaxy structures', Pawlowski & McGaugh, 2014, MNRAS, 440, 908.
- 'Co-orbiting Planes of Sub-halos are Similarly Unlikely around Paired and Isolated Hosts', Pawlowski & McGaugh, 2014, ApJL, 789, 24.
- 'The Vast Polar Structure of the Milky Way Attains New Members', Pawlowski & Kroupa, 2014, ApJ, 790, 74.

Other cited publications:

- Bahl & Baumgardt, 2014, MNRAS, 438, 2916.
- Goerdt & Burkert, 2013, arXiv:1307.2102.
- Hammer, Yang, Fouquet, et al., 2013, MNRAS, 431, 3543.
- Ibata, Lewis, Conn, et al., 2013, Nature, 493, 62.
- Ibata, Ibata, Lewis, et al., 2014, ApJL, 784, 6.
- Ibata, Ibata, Famaey, & Lewis, 2014, Nature, 511, 563.
- Lovell, Eke, Frenk, Jenkins, 2011, MNRAS, 413, 3013.
- Wang, Frenk, & Cooper, 2013, MNRAS, 429, 1502.
- Zhao, Famaey, Lü}ghausen, & Kroupa, 2013, A&A, 557, 3.

Online Material

Watch a movie rotating around the VPOS of the MW (1st plot), find links to the references and download the poster as a pdf file:
http://marcelpawlowski.com/beyondlcdm/

Acknowledgement

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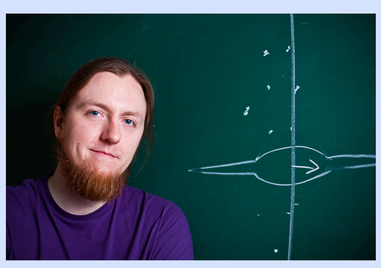
John Templeton Foundation

About Me

Postdoc at CWRU



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