Planes of Satellites

ΛCDM or not?

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[1412.1839], [1904.03192], more in prep...

BAM

From Darklight to Dark Matter: Understanding the galaxy/matter connection to measure the Universe

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The Dark Universe: A Synergic Multimessenger Approach

UNIVERSITÀ DEGLI STUDI DI TORINO

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Dwarf Galaxy Systems

- The haloes of typical galaxies like Milky Way or Andromeda (typical mass $\sim 10^{12} M_\odot$) tend to have a many dark matter subhalos in their own dark matter halo.
- Some of these subhalos (if they are massive enough) retain their gas and form their own stars. As a result, the large-ish galaxies have visible Satellite galaxies.
- These are the so called dwarf galaxies, their DM content can range from $10^{11} M_\odot$ down to anything. However, below $10^{5-6} M_\odot$, the visible contents drops below detecteable rate (depends on their distance).
- Often we use the term Dwarf Spheroidal Galaxies, but not all the satellites are spheroidals (also, spheroidals don't have to be spherical, they can easily achieve 3:1 axial ratio).
- Some of the satellite galaxies can be tidally disrupted (destroyed) and become Streams.
- On other occasions, when large galaxies merge the ejecta can self-asemble into small Dwarf Tidal Galaxies (which have differen chemical properties and light-to-mass ratios)

Small Scale (Non)problems

There used to be small scale problems that might have been guiding us to specific properties of he DM candidates:

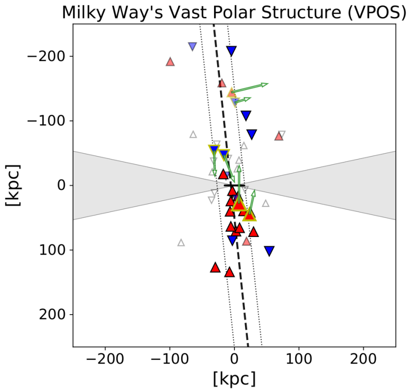
- Missing Satellites (turned out to be an observational problem – smaller haloes don't have enough stars)
- Too-big-to-fail (Better abundance matching has helped, in particular below $10^10 M_\odot$ the matching used to be wrong)
- The Mass Discrepancy-Acceleration Relation (MDAR) (resolved by non-linear clustering of DM: the DM and baryons gravitationally backreact)
- The cusp/core problem (probably baryon driven down to much smaller sizes $10^5 M_\odot$)
- Diversity of Rotational Curves...
- Maybe the Planes of Satellite Galaxies.

Planes

- The three closest large systems we observe are the Milky Way (duh), Andromeda, and Centaurus A.
- Each of them has a plane.
- We are super lucky because we can see these planes edge-on.
- They are not independent! They are all part of the local group...

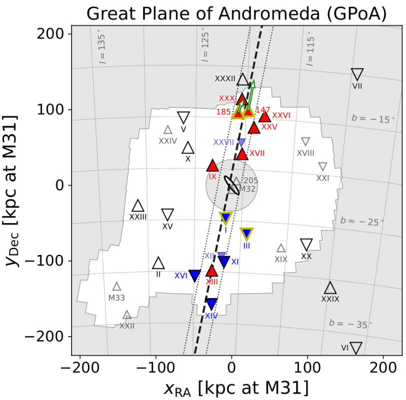
The Milky Way: The Vast Polar Structure (VPoS)

- **Distance:** we live here (8kpc)
- As the name suggests this plane potentialy contains the galactic pole: i.e. it is perpendicular to the disc of the galaxy.
- Out of the 50 Milky Way satellite galaxies, about 20+ are members. (though membership is a tricky thing)
- According to NBODY simulations this structure happens somewhere between 0.01 – 0.1 [1506.04151] of the time on its own (depends on whether you include angular momentum alignement).



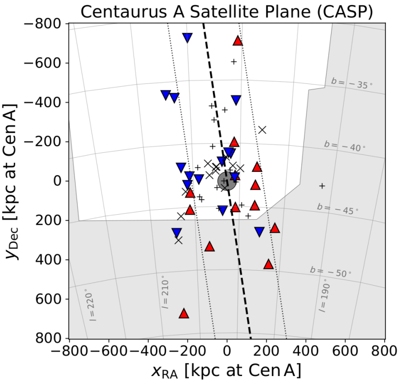
Andromeda: The Great Plane of Andromeda (GPoA)

- **Distance**: 760 kpc
- First discussed in [1301.0446] (by none other than Ibata Jr.)
- Out of the 27 then known galaxies about 15 were members.
- With radius of about 200kpc, the thickness of this plane is less than 20kpc – this is super thin.
- We see the plane edge-on (we are super lucky: 5% – 10% distance error is 38kpc-76kpc)
- Inclined by about 50degrees to the Andromeda galactic plane.
- Accoding to NBODY people this also happens somewhere at sub 10% chance [1506.04151].



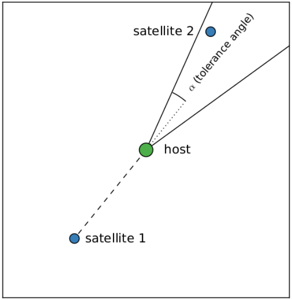
Centaurus A: Centaurus A Satellite Plane (CASP)

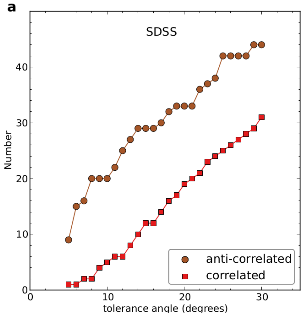
- **Distance**: 3.8 MPc (5% error budget about the same as the size of the system).
- First discussed by [1503.05599]
- Almost all of the 29 known satellites were in two planes: each roughly 60kpc thick and 300kpc radius.
- As more satellites were seen, the two planes merged into a thick less significant plane.
- Yours truly has some serious doubts about this one – when I run 1000 realizations of this system the pole of the structure ranges over a cone with opening of about 120 degrees.



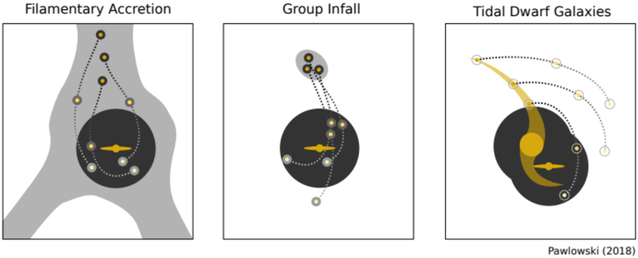
Statistical Samples

- In 2014 there was a set of papers [1407.8178], [1411.3718] one of which is actually titled "Eppur si muove,..." that claim there is a strong anti-correlation between position and line-of-sight velocity of pairs of satellite gaalxies in the SDSS sample.
- This was done relatively close ($z < 0.05$ – you need to see the satellites)
- The claimed excess was 7σ.
- Eventually, the claim was walked back, especially after [1410.7778] by Cautun, Wang, Frenk and Sawala showed the result was dependent on the quality cuts.





Solutions?

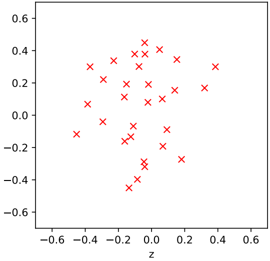


- Filaments don't work because their width is of order of the virial radius of the galaxy (200kpc), while the planes are about 20-60kpc thick.
- Group infall: typical size of infall groups in Nbody simulations is 2-5. Sometimes when dominated by one large member (say LMC, NGC205) it is possible to bring in more than5, but unlikely to be so tightly correlated [1712.05409]
- Tidal Dwarfs: while fun, those are meant to be chemically different and have a problem with DM contents. However, there are exotic solutions [1412.1839].

How to find them?

- The key is the trade-off between thin planes with few satellites or thicker planes with more satellites. (Collider jet people might appreciate this). This can be adressed two ways:
- Model dependent methods (can define likelihood): The Most Significant Plane (expensive)
- Model independent (no likelihoods, no memberships)
  - Moment of Inertia method (sensitive to outliers)
  - Normal accumulations (3point and 4point)

How to find them? II



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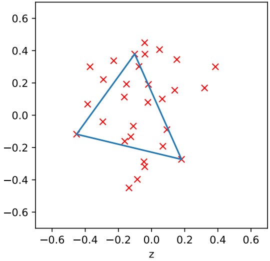

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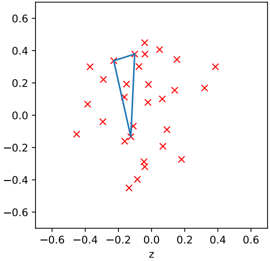

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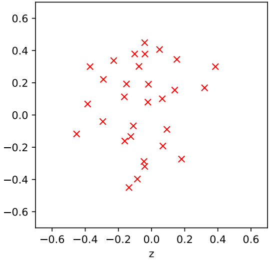

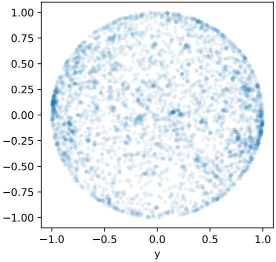

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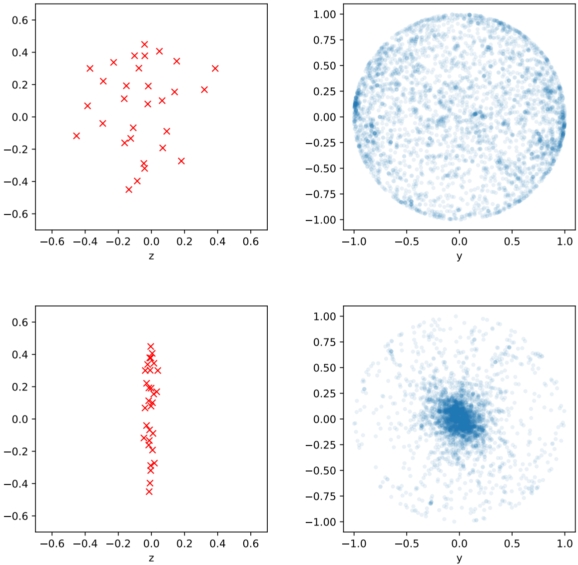
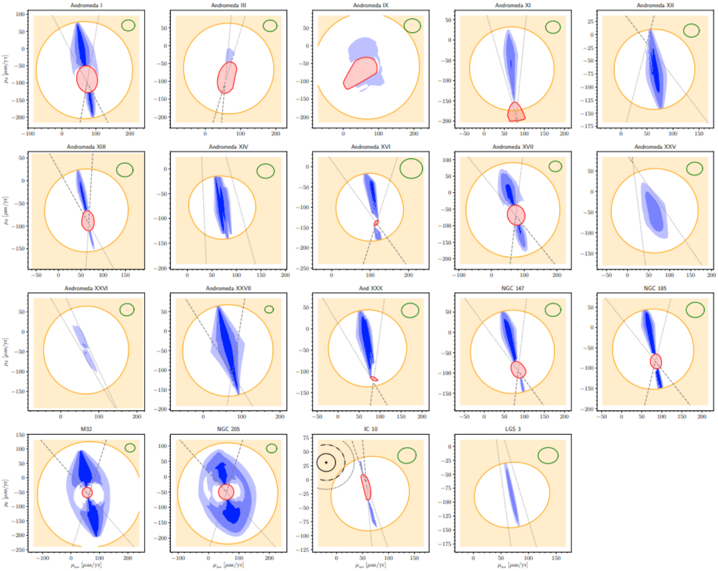


Are they persistent? [1904.03192]



Conclusion

- Planes of Satellites are one of the few "surviving" anomalies in the "small" scale structure.
- It is unclear how anomalous they are.
- As a community we are working on the correct way to describe these objects in a fair language.
- There will be future observations (HST, GAIA, JWST) that will allow us to determine if these structure are accidents of time, or persistent structures that tell us something about the Universe.