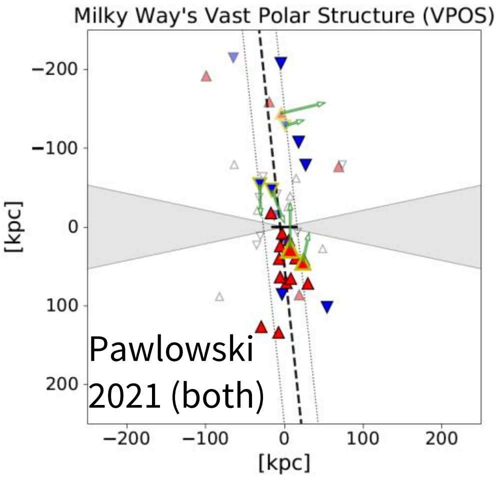
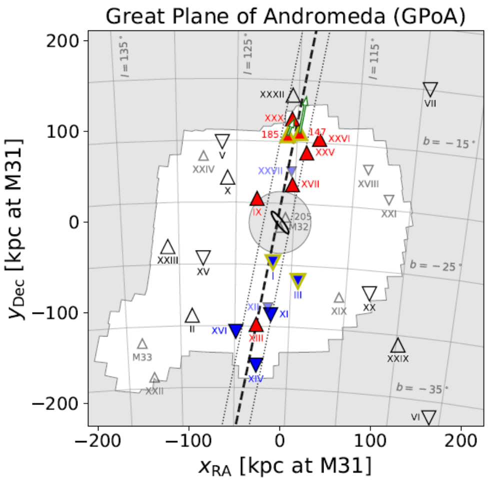
Speaker: Dr. Indranil Banik, University of Saint Andrews





3D hydrodynamic simulations for the origin of the Local Group satellite planes (Banik+ 2022, MNRAS, 513, 129)

ABSTRACT

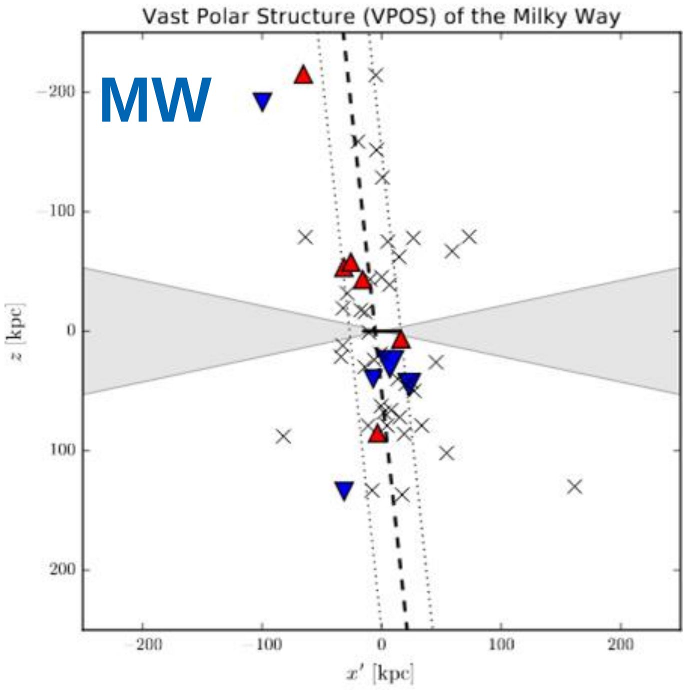
The existence of mutually correlated thin and rotating planes of satellite galaxies around both the Milky Way (MW) and Andromeda (M31) calls for an explanation. Previous work in Milgromian dynamics (MOND) indicated that a past MW–M31 encounter might have led to the formation of these satellite planes. We perform the first-ever hydrodynamical MOND simulation of the Local Group using PHANTOM OF RAMSES. We show that an MW–M31 encounter at $z \approx 1$, with a perigalactic distance of about 80 kpc, can yield two disc galaxies at $z = 0$ oriented similarly to the observed galactic discs and separated similarly to the observed M31 distance. Importantly, the tidal debris are distributed in phase space similarly to the observed MW and M31 satellite planes, with the correct preferred orbital pole for both. The MW–M31 orbital geometry is consistent with the presently observed M31 proper motion despite this not being considered as a constraint when exploring the parameter space. The mass of the tidal debris around the MW and M31 at $z = 0$ compare well with the mass observed in their satellite systems. The remnant discs of the two galaxies have realistic radial scale lengths and velocity dispersions, and the simulation naturally produces a much hotter stellar disc in M31 than in the MW. However, reconciling this scenario with the ages of stellar populations in satellite galaxies would require that a higher fraction of stars previously formed in the outskirts of the progenitors ended up within the tidal debris, or that the MW–M31 interaction occurred at $z > 1$.

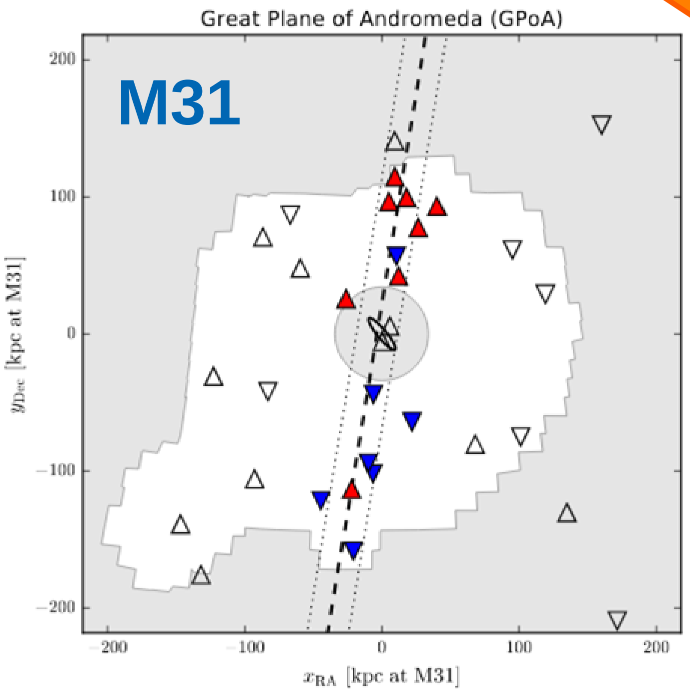
Related to high radial velocity of galaxies in NGC 3109 association (MNRAS, 503, 6170)

Local Group satellite planes

MW satellite galaxies lie within a thin plane (Pawlowski & Kroupa 2013, 2020). Analogous situation for M31 (Ibata+ 2013)

Galaxies observed forming within tidal tails (Mirabel+ 1992)





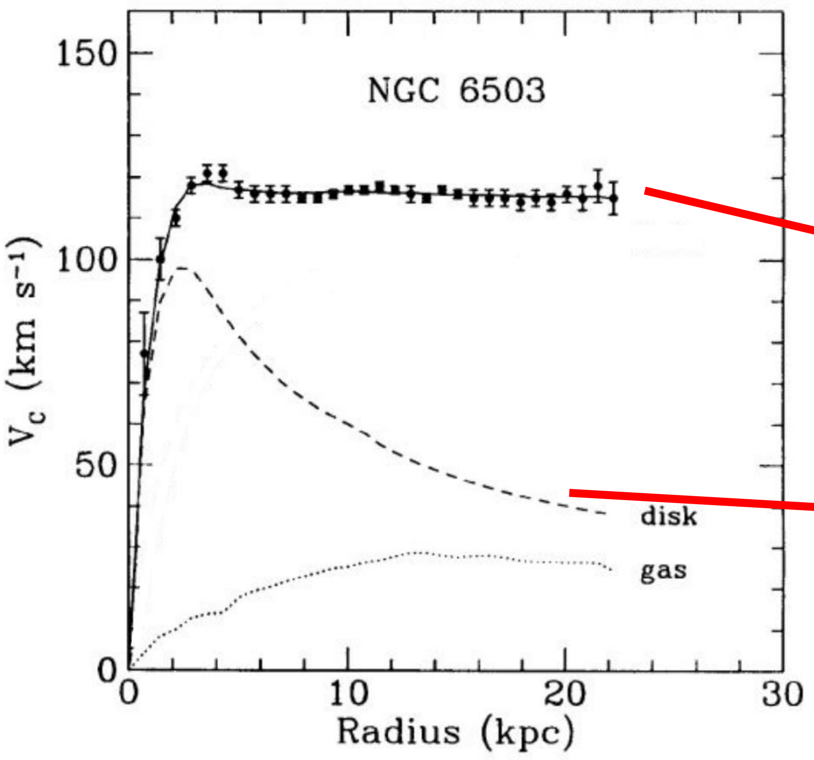
Satellites were formed from tidal debris. Alternatives not very likely (Pawlowski+ 2014, and references therein)

Should only contain baryons as DM can't cool and form dense tidal tails (Wetzstein+ 2007)

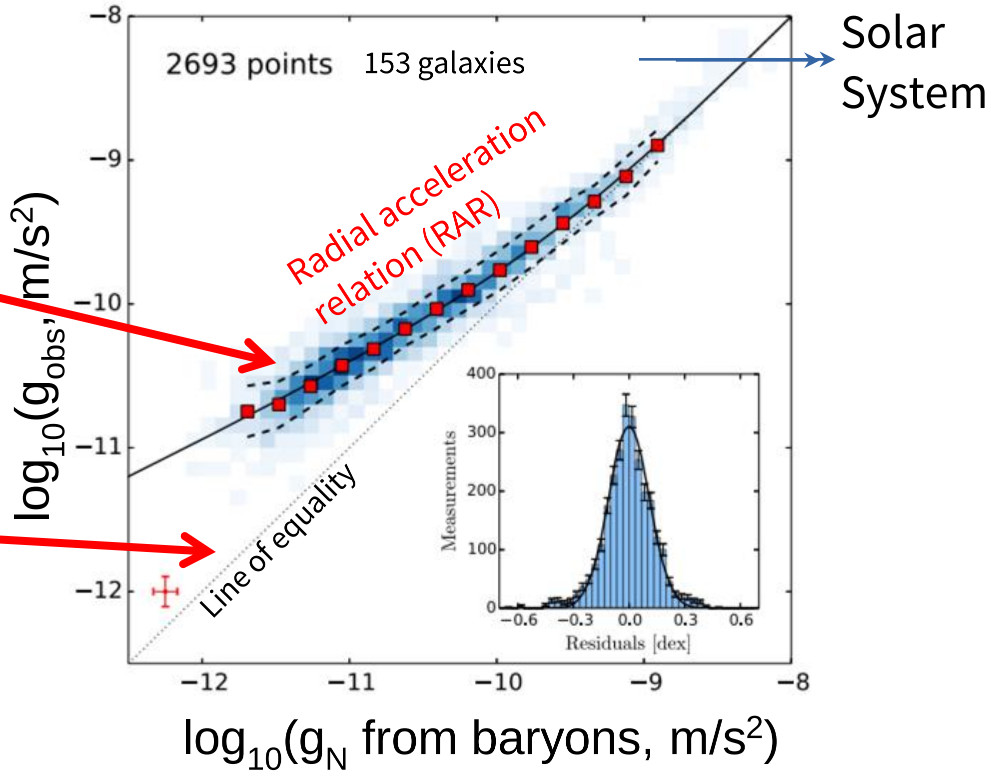
MW and M31 satellite galaxies have high internal velocity dispersions, requiring strong self-gravity (McGaugh & Wolf 2010; McGaugh & Milgrom 2013a, b)

Internal dynamics can't be explained by Newtonian gravity (Kroupa 2015)

Constraints from disc galaxies

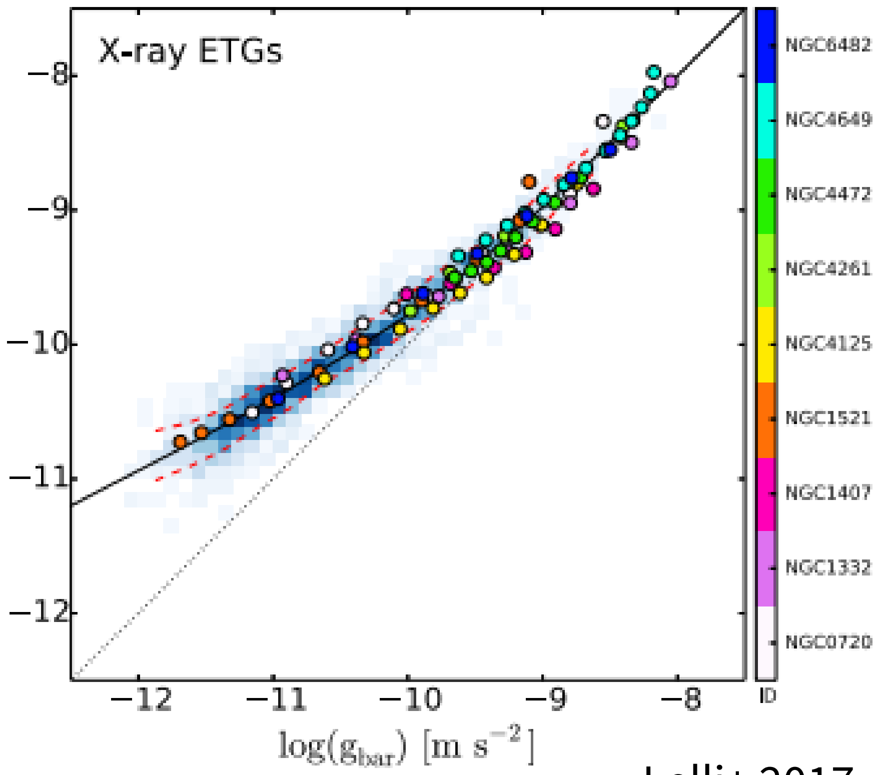


Freese 2008

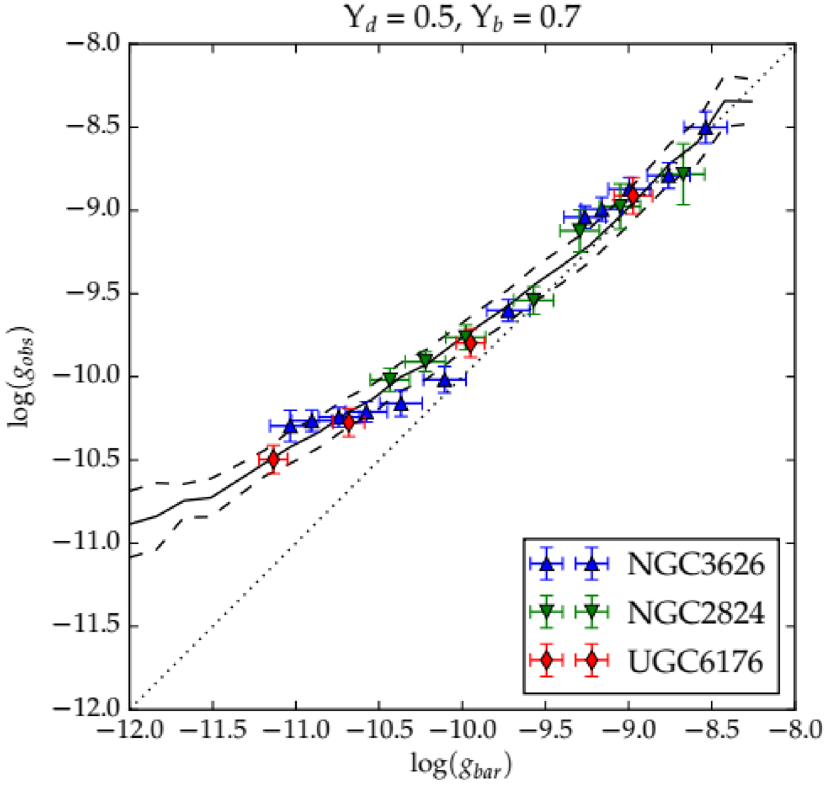


McGaugh, Lelli, Schombert 2016

Constraints from elliptical galaxies



Lelli+ 2017



Shelest & Lelli 2020

Milgromian dynamics (MOND)

- Newtonian gravity/GR developed using Solar System constraints
- MOND developed by M. Milgrom (1983) to address galaxy rotation curves without cold dark matter by going beyond Newton

$$g_N \ll a_0:\ g = \sqrt{a_0 g_N}, \quad g_N \gg a_0:\ g = g_N$$

$$a_0 = 1.2 \times 10^{-10}\, m/s^2$$

$$\nabla \cdot \boldsymbol{g} = \nabla \cdot \left[\nu \left(\frac{g_N}{a_0} \right) \boldsymbol{g}_N \right], f \Leftrightarrow \nu$$

- Relativistic MOND theory where gravitational waves travel at c (Skordis & Zlosnik 2019, 2021, PRL) and GR-like light deflection

From galactic bars to the Hubble tension: weighing up the astrophysical evidence for Milgromian gravity

Indranil Banik, Hongsheng Zhao

Download PDF

Astronomical observations reveal a major deficiency in our understanding of physics — the detectable mass is insufficient to explain the observed motions in a huge variety of systems given our current understanding of gravity, Einstein's General theory of Relativity (GR). This missing gravity problem may indicate a breakdown of GR at low accelerations, as postulated by Milgromian dynamics (MOND). We review the MOND theory and its consequences, including in a cosmological context where we advocate a hybrid approach involving light sterile neutrinos to address MOND's cluster-scale issues. We then test the novel predictions of MOND using evidence from galaxies, galaxy groups, galaxy clusters, and the large-scale structure of the Universe. We also consider whether the standard cosmological paradigm (ΛCDM) can explain the observations and review several previously published highly significant falsifications of it. Our overall assessment considers both the extent to which the data agree with each theory and how much flexibility each has when accommodating the data, with the gold standard being a clear *a priori* prediction not informed by the data in question. Our conclusion is that MOND is favoured by a wealth of data across a huge range of astrophysical scales, ranging from the kpc scales of galactic bars to the Gpc scale of the local supervoid and the Hubble tension, which is alleviated in MOND through enhanced cosmic variance. We also consider several future tests, mostly on scales much smaller than galaxies.

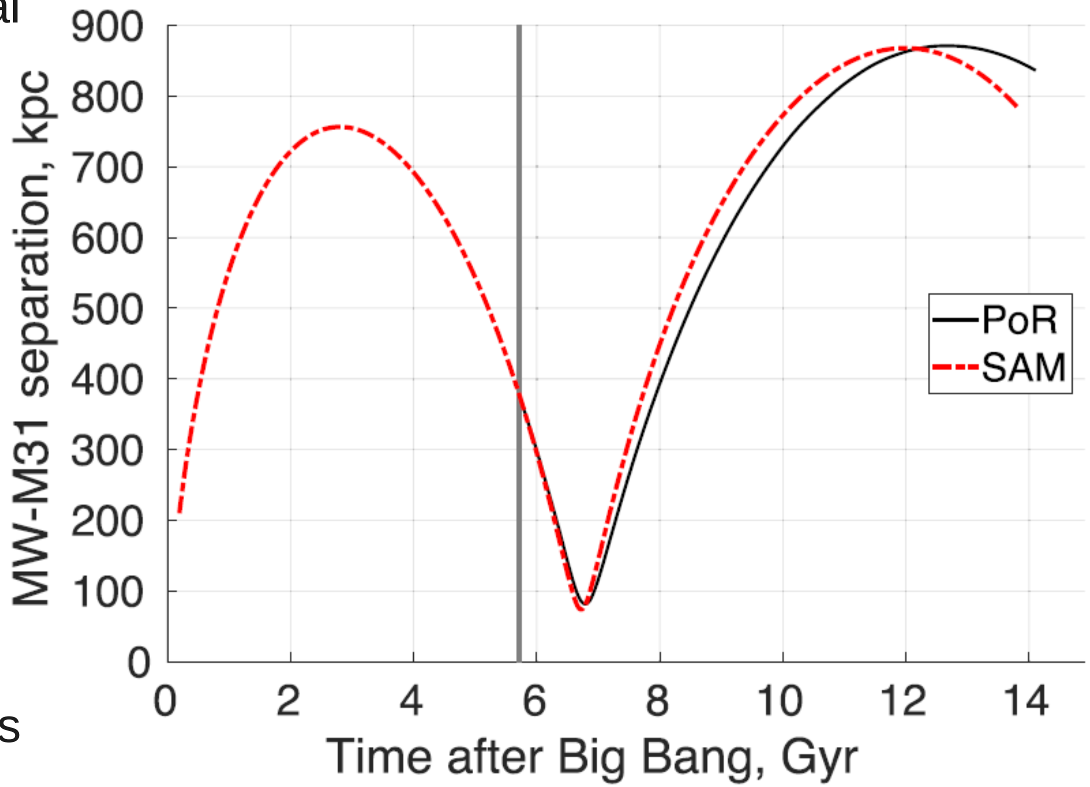
Comments: 87 pages, 37 figures, 6 tables, 864 references. Invited review published in special issue of Symmetry, style matched to that of journal as closely as possible
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; Astrophysics of Galaxies (astro-ph.GA)
Cite as: arXiv:2110.06936 **[astro-ph.CO]**
(or arXiv:2110.06936v9 **[astro-ph.CO]** for this version)
https://doi.org/10.48550/arXiv.2110.06936
Journal reference: Symmetry, 14, 1331 (2022)
Related DOI: https://doi.org/10.3390/sym14071331

Banik & Zhao (2022)

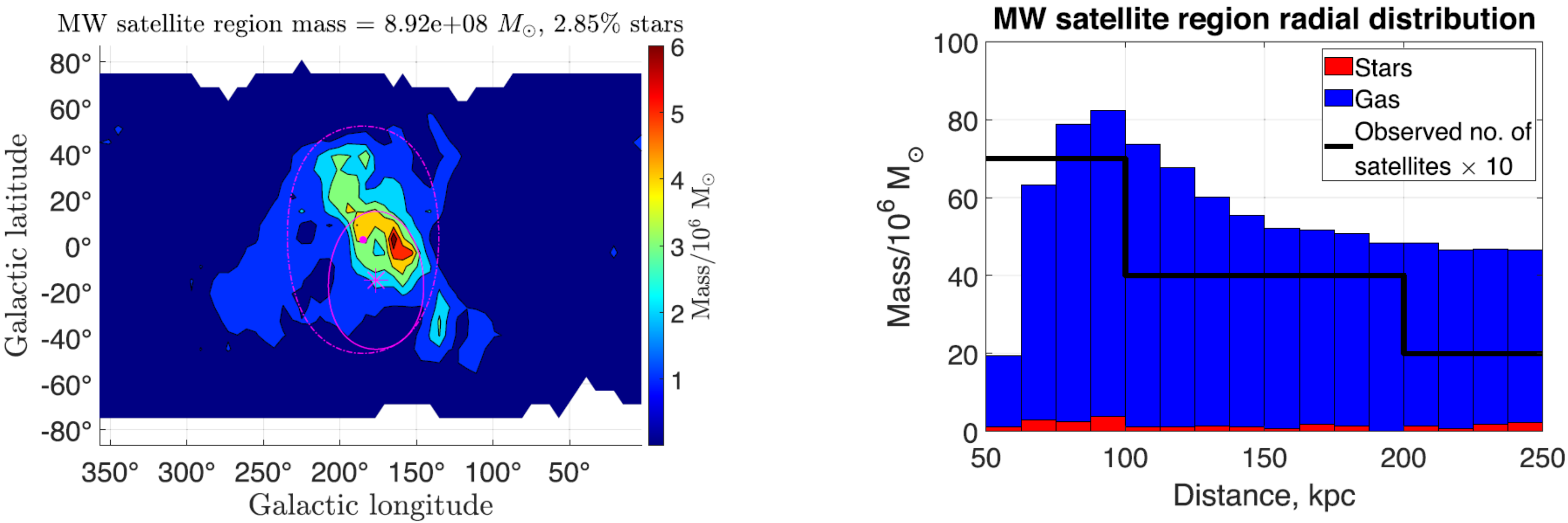
The Local Group in MOND

MOND implies a past MW-M31 flyby (Zhao+ 2013)

- 1/r gravity law persists beyond conventional edges of dark matter halos
- Resulting much stronger gravity acting on nearly radial orbit implies a past flyby
- Tidal debris expelled from the interacting discs could have formed anisotropically distributed tidal debris
- These could subsequently coalesce into bound tidal dwarf galaxies, forming the Local Group satellite planes
- Our aim was to check if the tidal debris prefer the same orbital pole as the satellites

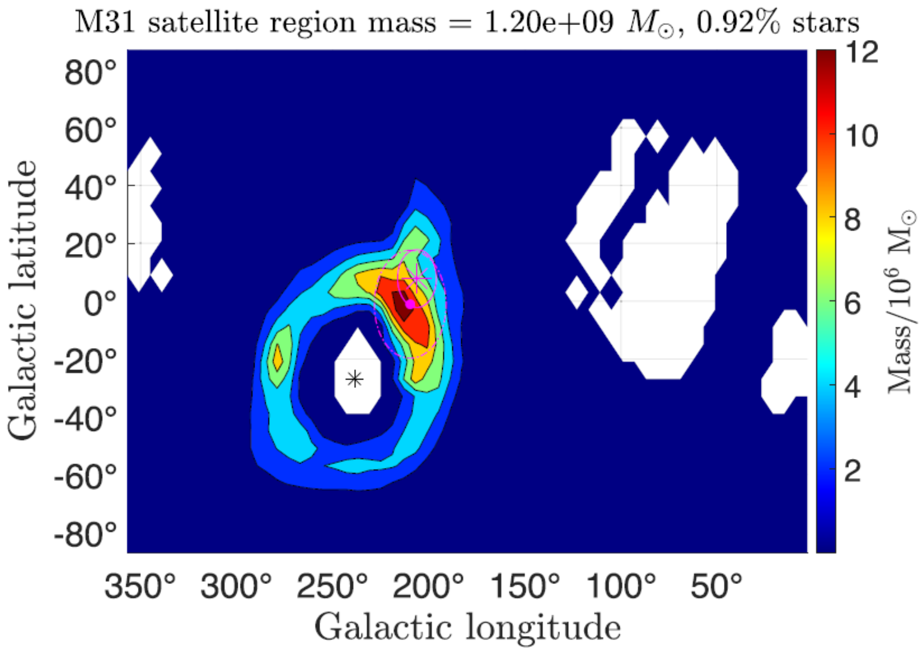


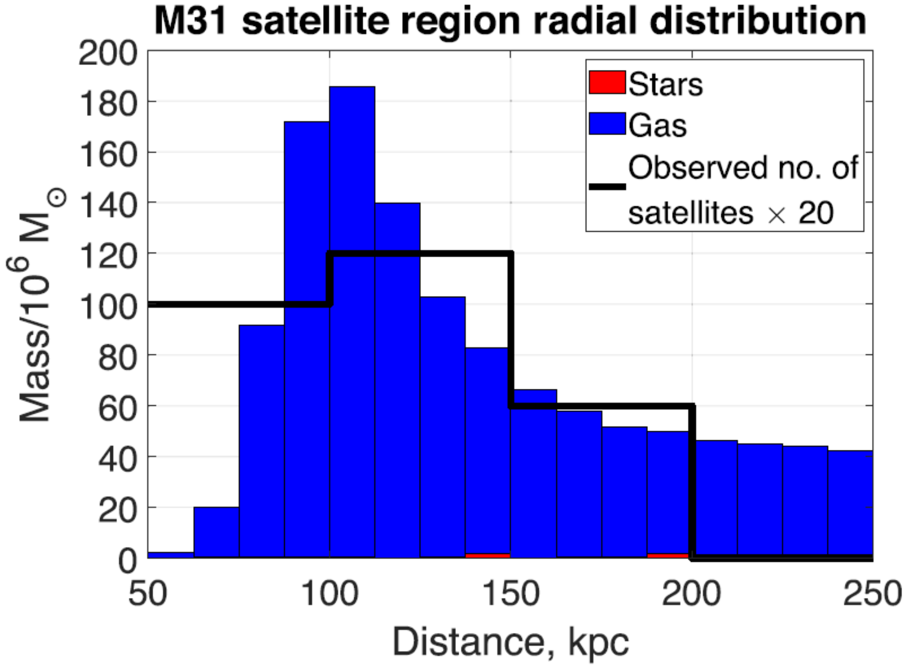
The (proto) MW satellite plane



- Pink star = observed, so the simulated tidal debris orbit within the right plane
- Radial distribution of material also about right, but expected to be mostly gas (50% initially)

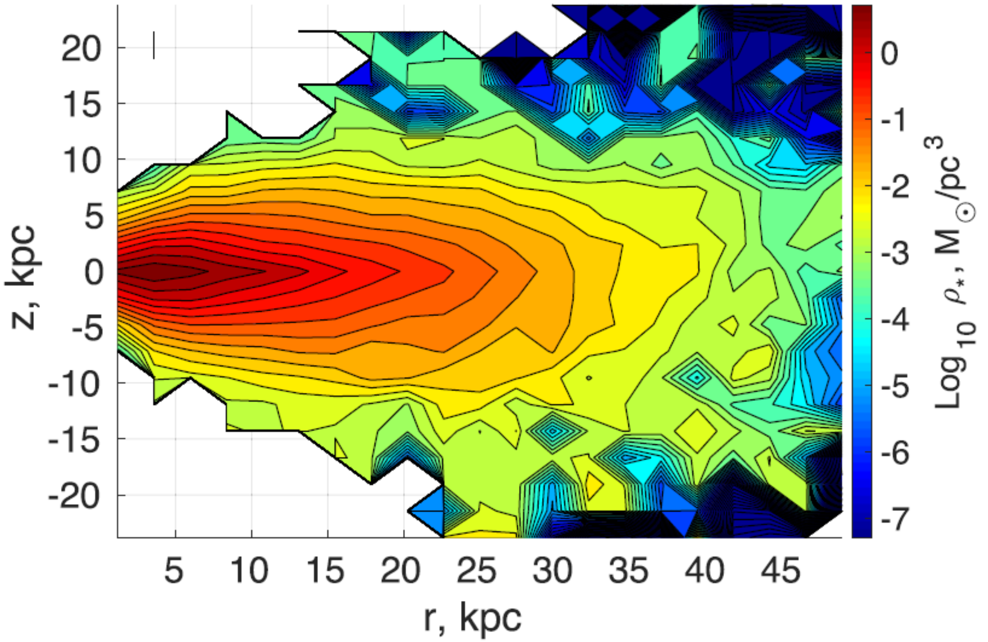
The (proto) M31 satellite plane

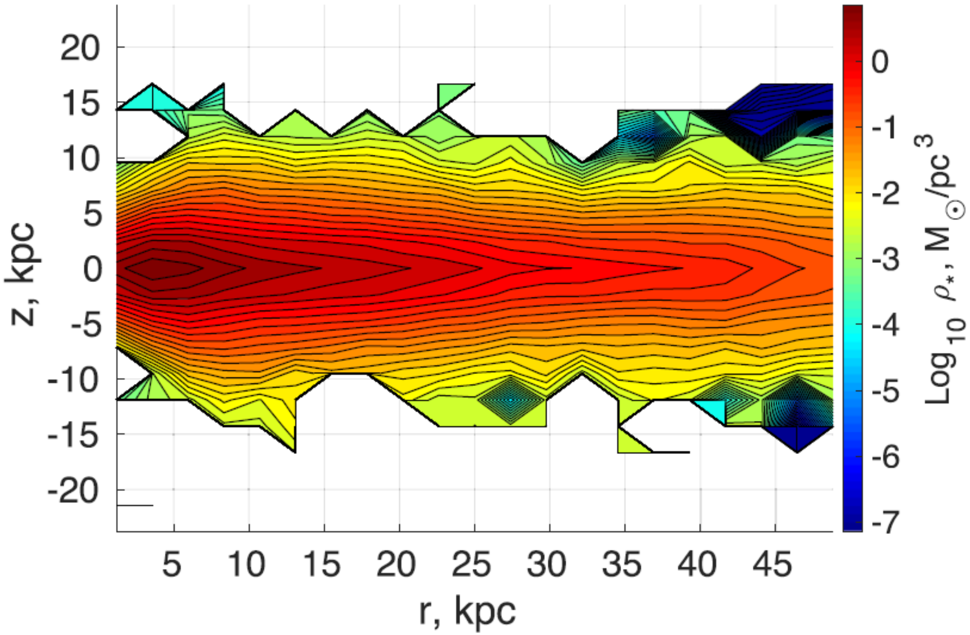




- Black star = disc spin, pink star = observed: simulated tidal debris orbit within the right plane
- Radial distribution of the material is also about right, but expected to be mostly gas initially

Thin discs preserved

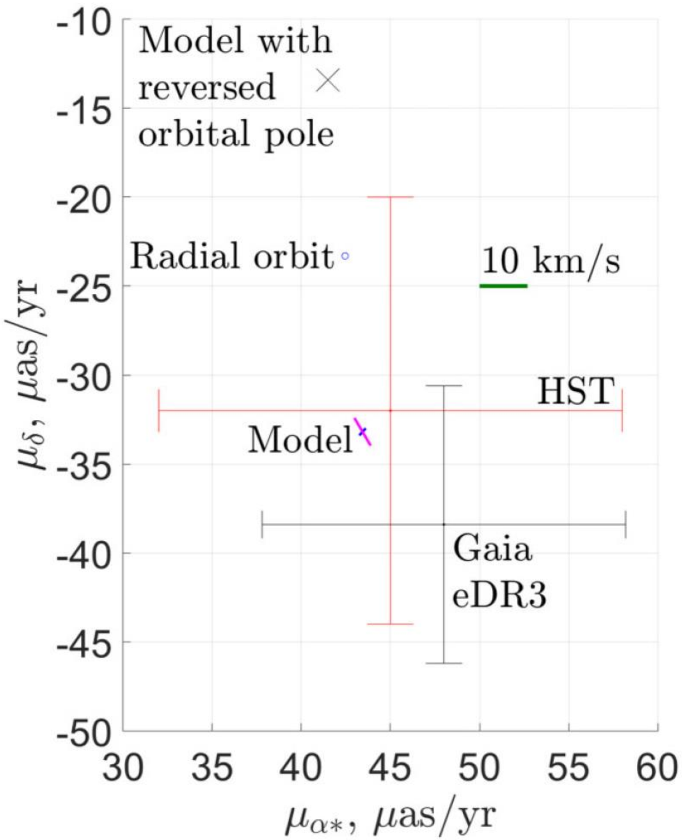


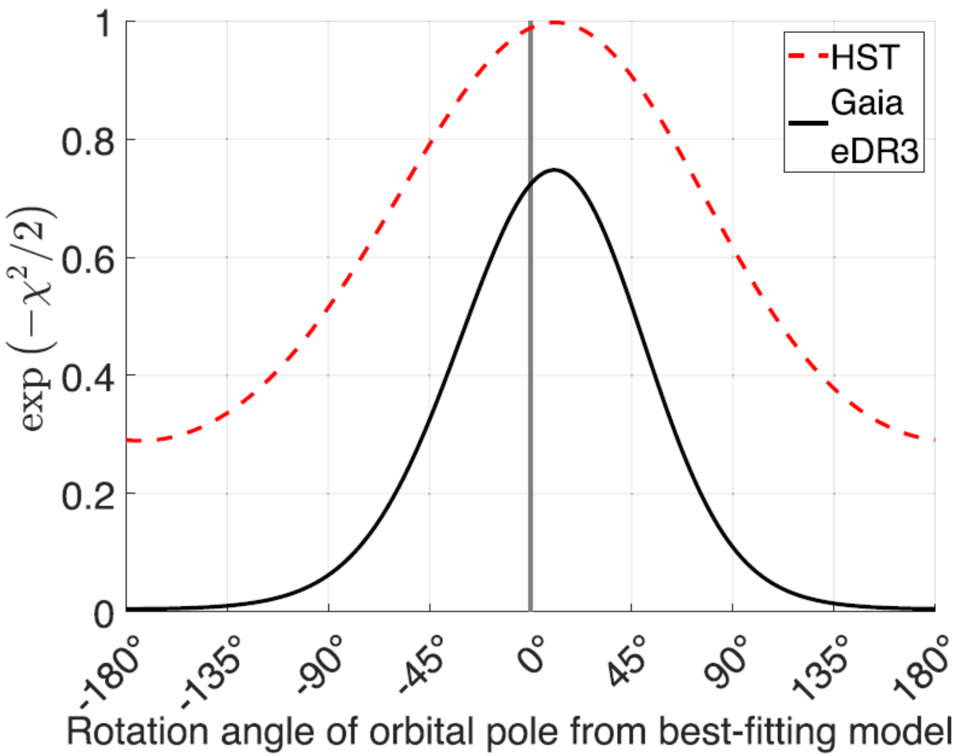


- MW (left) and M31 (right) retain their thin discs, with reasonable stellar disc scale lengths and for the MW a reasonable gas disc scale length (more complicated merger history for M31)

The M31 proper motion in the best model

- Only the SP orientations were considered when finding best model
- M31 proper motion agrees well with Gaia observations
- This success is non-trivial as rotating the orbital plane worsens the agreement





Conclusions

- The Local Group satellite planes are extremely difficult to understand because their anisotropy implies a tidal origin, but Newtonian tidal dwarf galaxies have low internal velocity dispersions
- Purely baryonic dwarf galaxies can have elevated σ in MOND, where there is no CDM. In this case, it is not relevant how the dwarf galaxy formed (no dual dwarf galaxy theorem)
- Hydrodynamic MOND simulation of a past close MW-M31 flyby (inevitable in MOND due to stronger gravity & observed nearly radial orbit) reproduces many features of the observations
  - ➢ Tidal debris preferentially orbit in the same plane as the observed satellites
  - ➢ The proper motion of M31 comes out right, but is not used in fitting procedure and data are quite precise
  - ➢ Thin discs preserved by the flyby and have reasonable final sizes
  - ➢ In the MW remnant, the 40 km/s vertical velocity dispersion at the Solar circle is reasonable (Yu & Liu 2018)
  - ➢ Flyby could have slingshot NGC 3109 association outwards at high speed (Pawlowski & McGaugh 2014)
- Past flyby scenario offers a more promising explanation for the LG satellite planes than ΛCDM.