Decoding Galaxy Assembly with Andromeda

III. The Satellite and Globular Cluster Systems as Dynamical Tracers

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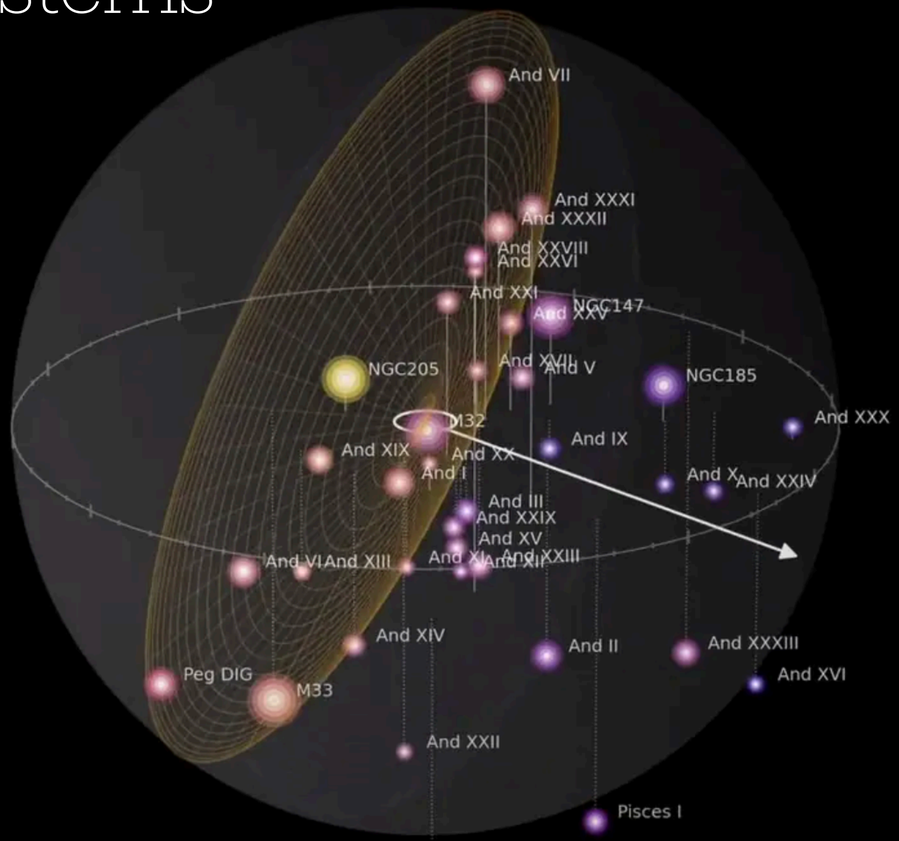


Image credit: Kosuke Jamie Kanehisa, AIP

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Outline

- Overview of M31 satellite system
  - Lopsidedness
  - Plane of satellites
- Group infall scenarios in the context of M31
  - NGC 147 / 185
  - The M31-M33 interaction
- The star formation history of M31 satellites
- Overview of M31 globular cluster system
- The mass distribution of M31
- Future advances: Gaia DR4, HST, JWST, and Roman in M31

Satellite galaxies and globular clusters trace the potential and accretion history of their host

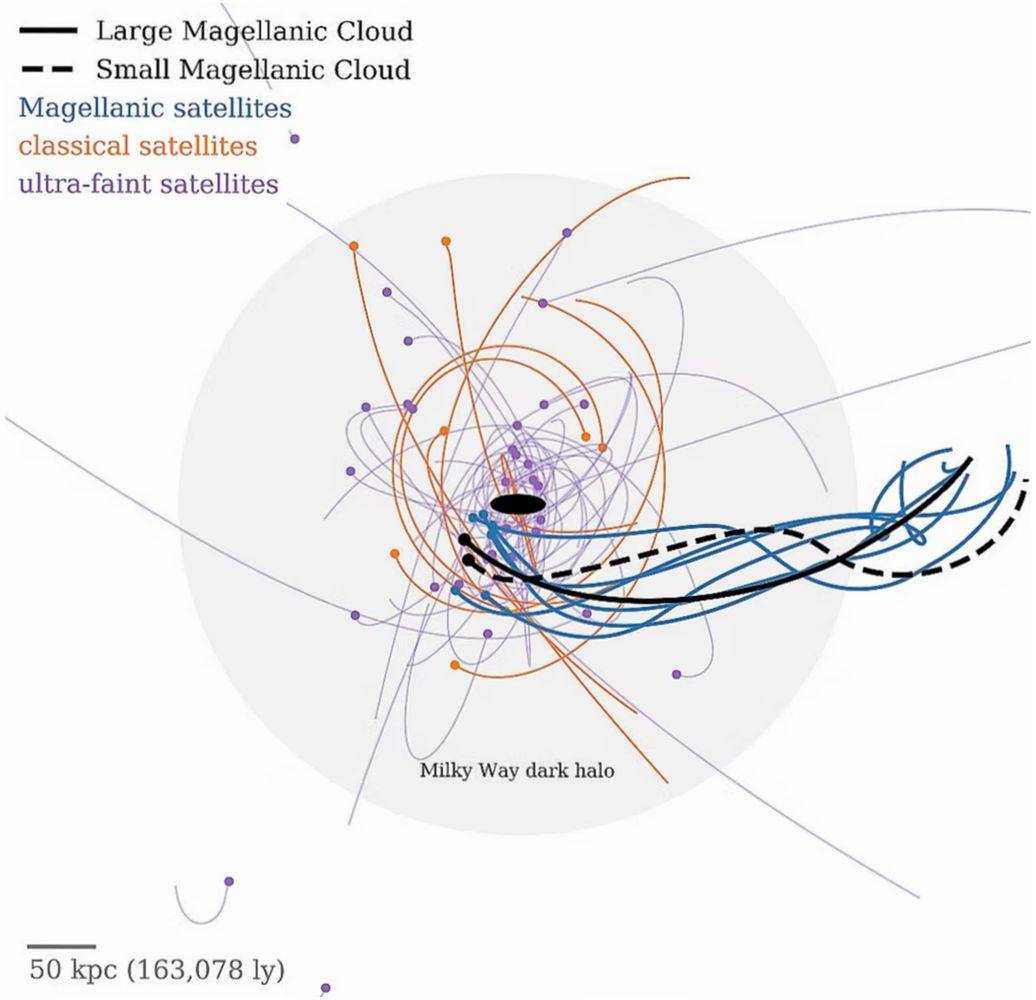
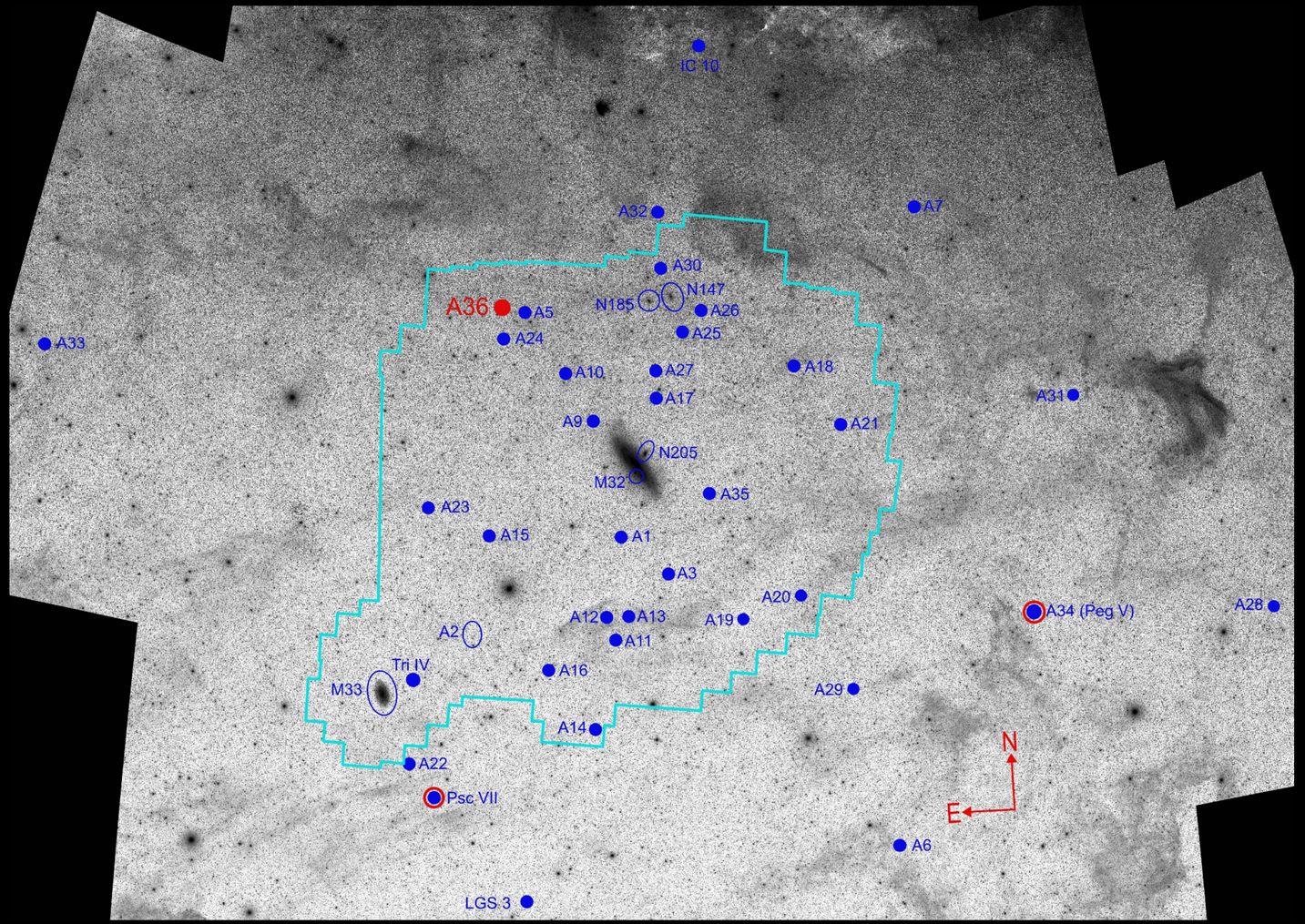


Image credit: Ekta Patel

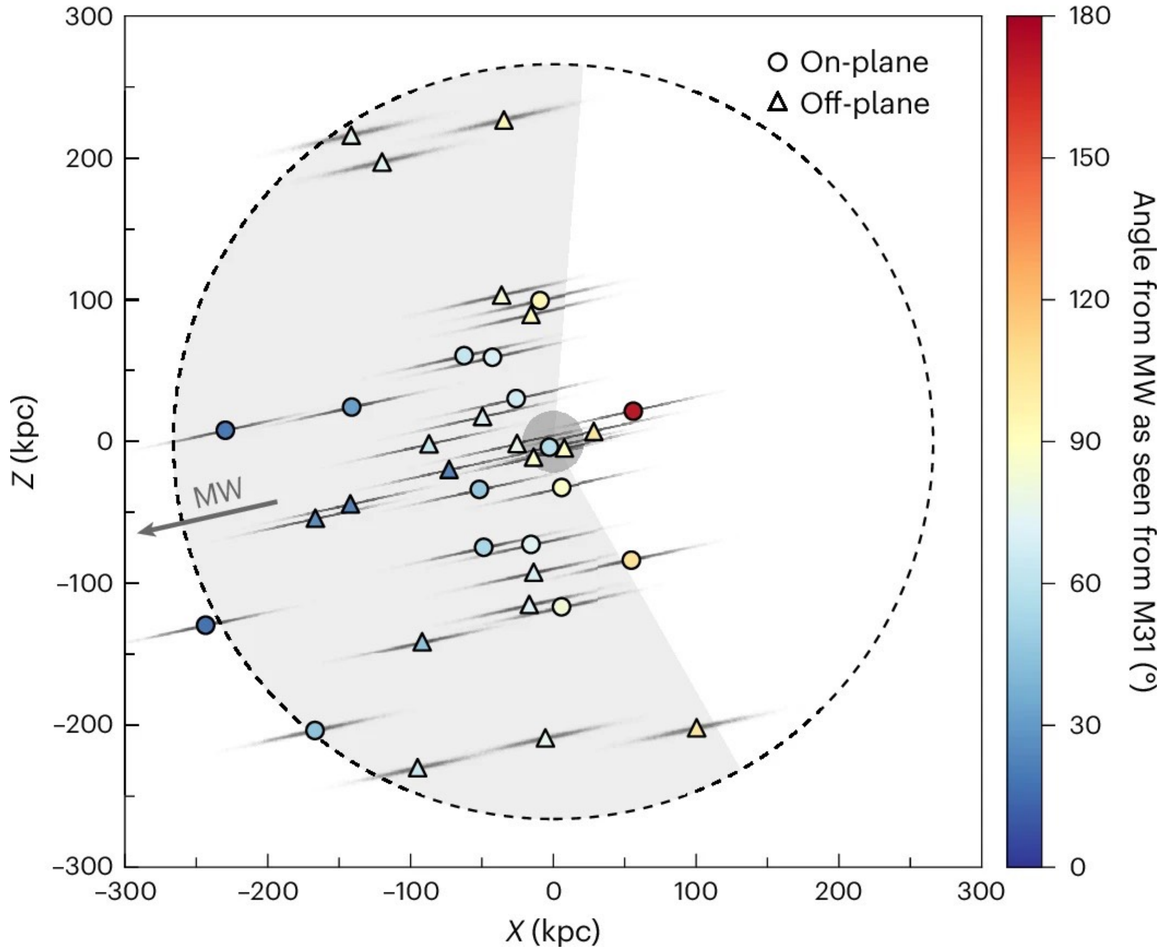
M31 has a rich satellite (and globular cluster) system distinct from the Milky Way



- 37 known satellites with RRL-based distances (Savino+22), plus 5-6 new ultra-faints (Mv < -5)
- M31 should host ~90 with Mv < -5.5 from 30-300 kpc (Doliva-Dolinsky+23)
- M31 hosts a class of elliptical satellites (M32, NGC 205, NGC 147, NGC 185) the MW lacks
- M31 has three times as many luminous satellites as the MW (Mv < -14.5)

Sakowska+26
Collins+22,24; Martinez-Delgado+22;McQuinn+23; Arias+25; Smith+25

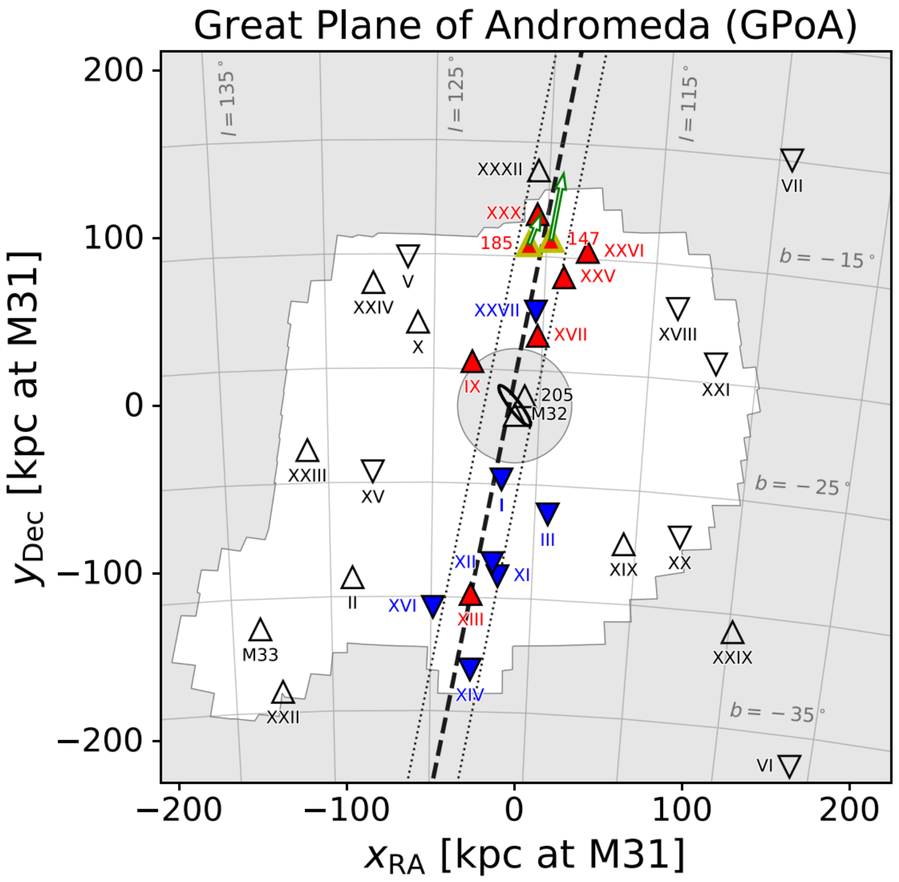
Its spatial distribution is intrinsically lopsided, which appears to be cosmologically rare



- All but one of M31's 37 satellites lie within 107° of the direction toward the MW (Kanehisa+25)
- Fewer than 0.3% of M31 analogs show comparable asymmetry, or 0.5% accounting for observational incompleteness (Doliva-Dolinsky+23, Kanehisa+25)

Kanehisa+25
McConnachie & Irwin +06; Conn+12,13; Ibata+13; Wan+20; Savino+22: Doliva-Dolinsky+23

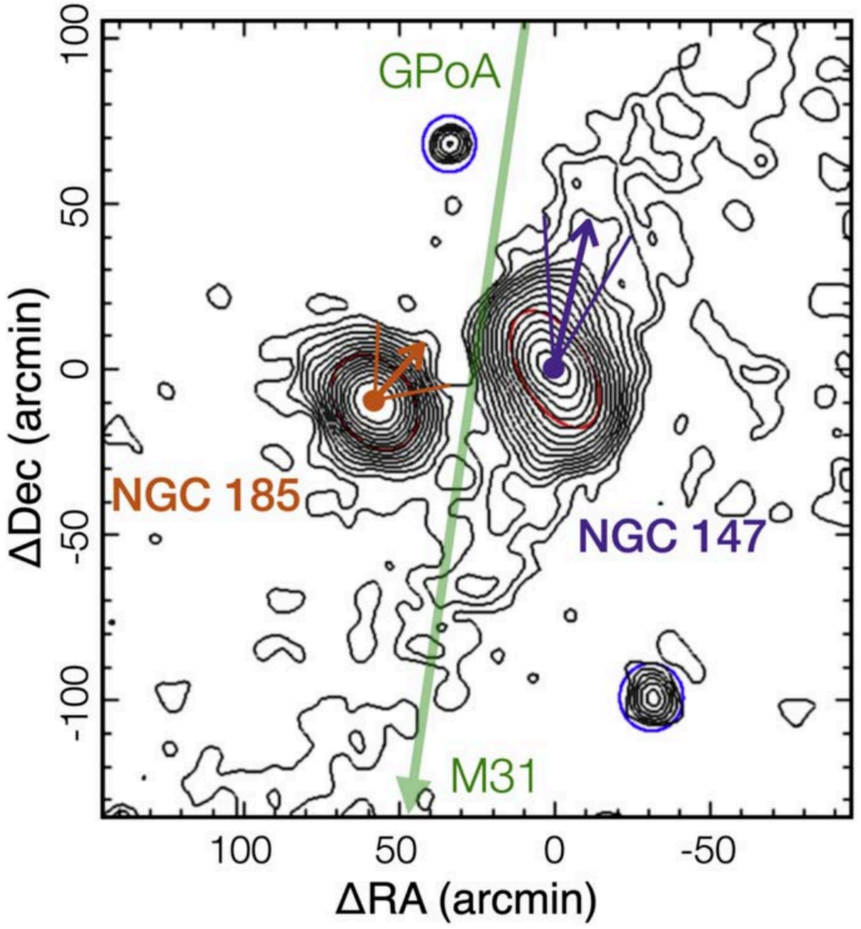
Half of these M31 satellites lie in a narrow plane, and appear to have correlated velocities



- 7-23 kpc width for satellites within 300 kpc (Savino+22), roughly aligned with MW-M31 direction
- The edge-on orientation of the plane means line-of-sight velocities alone cannot establish rotation
- Spatial flattening and LOS velocity correlation reproduced in only 3-4% of simulated analogs (based on NGC 147/185)

Pawlowski & Sohn 2021
e.g., Koch & Grebel 2006; McConnachie & Irwin 2006; Metz, Kroupa, & Jergen 2007, Ibata+13; Conn+13; Savino+22

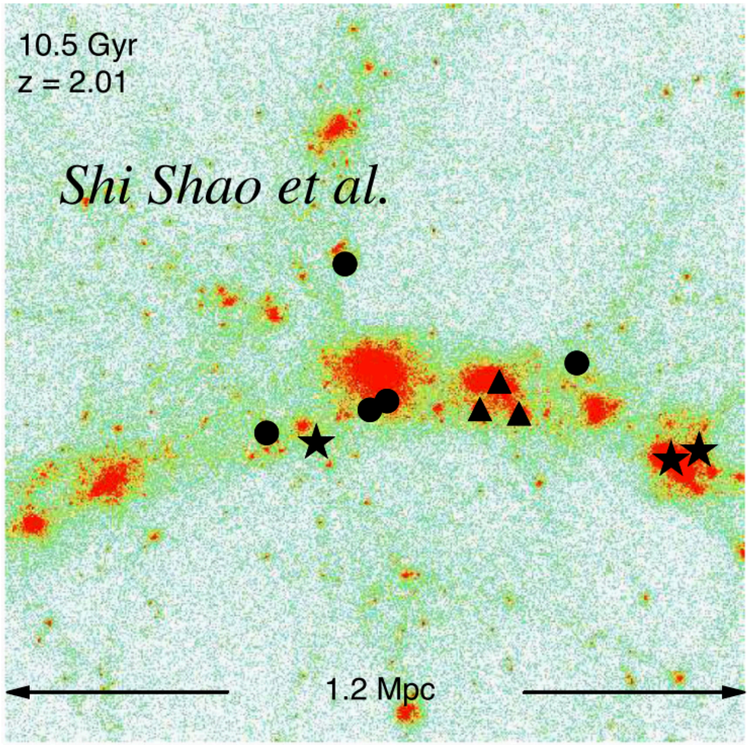
The first proper motions of satellites in the plane, NGC 147 and 185, reveal they co-orbit without being bound

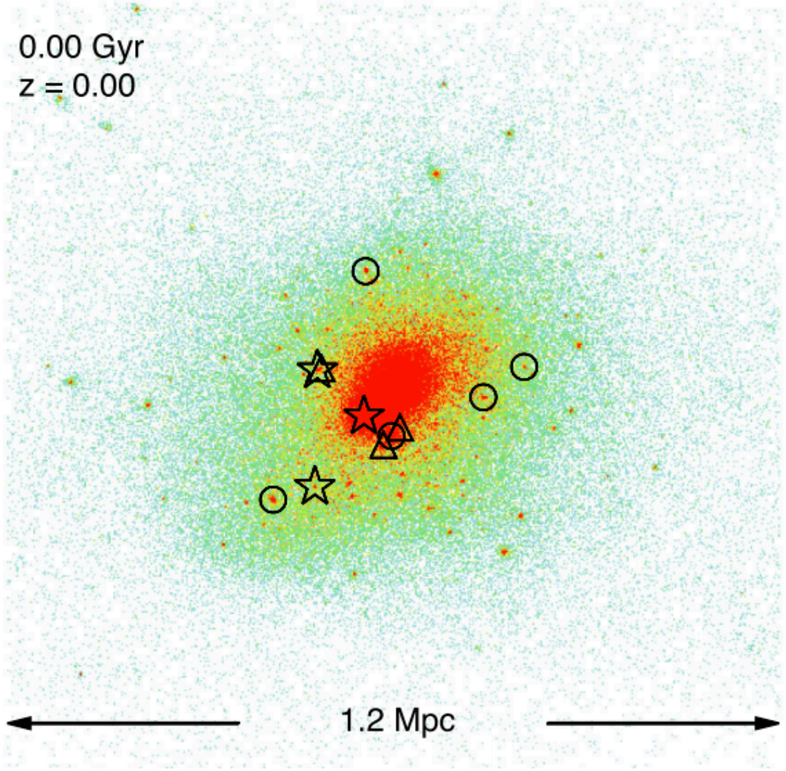


- At the distance of M31, Gaia provides *bulk* PMs for young stellar populations in M31 and M33 — not in other structures
- *Proper motions (PMs) must come from HST and JWST imaging*
- Long assumed to be a bound pair (12 kpc projected separation), but not associated

Sohn+20
See also Casetti-Dinescu+24,25; Patel+26

Group infall, including satellites-of-satellites, is the most common explanation for satellite lopsidedness and planes

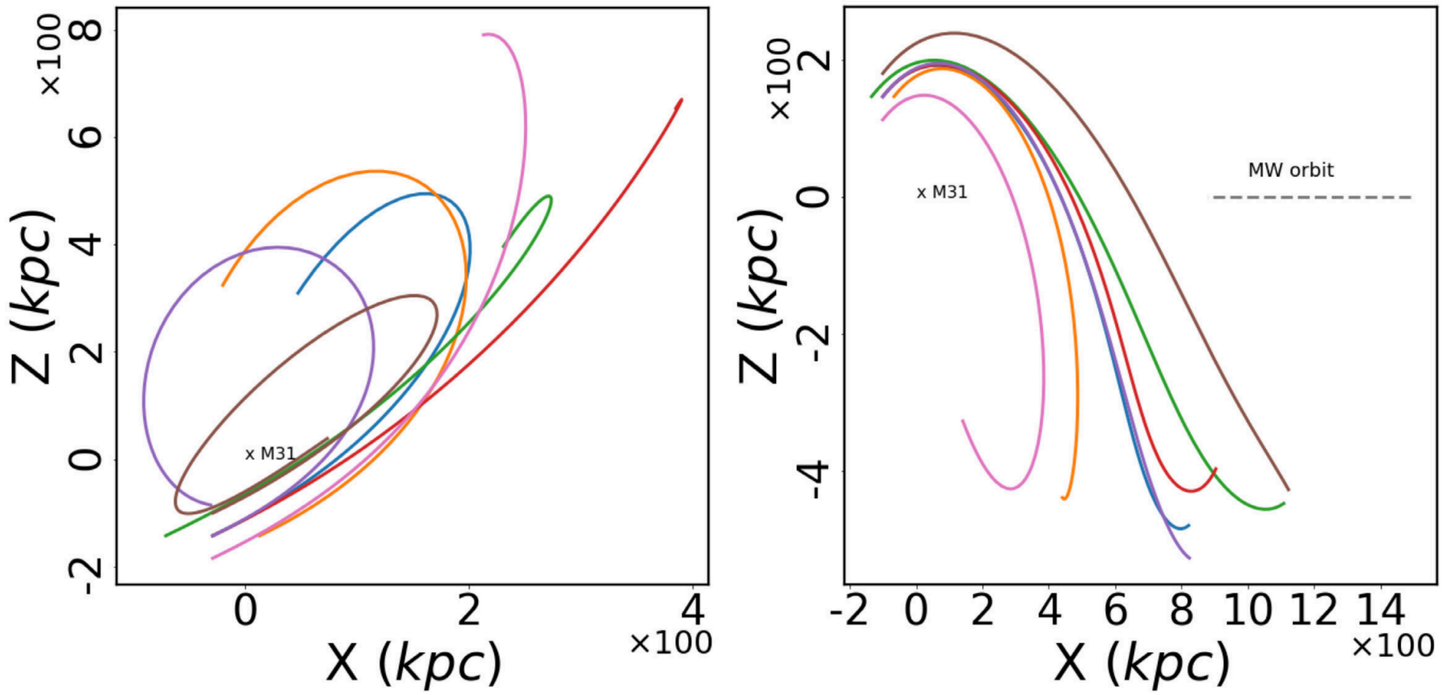




- The majority of satellites fall in alone, but a significant fraction (~30-40%) in pairs or large groups, becoming increasingly common for fainter satellites
- Size of group is dependent on stellar mass of largest member (satellites-of-satellites, e.g. Kallivayalil+18, Patel+20 for LMC)

Shao et al. 2018
e.g., D'Onghia & Lake 2008, Li & Helmi 2008; Wetzel, Deason & Garrison-Kimmel 2015, D'Souza & Bell 2021, Watkins, Evans, & van de Venn 2013 (in M31)

Could the spatial structure of M31's satellite system result from the accretion of satellites in a group infall scenario?

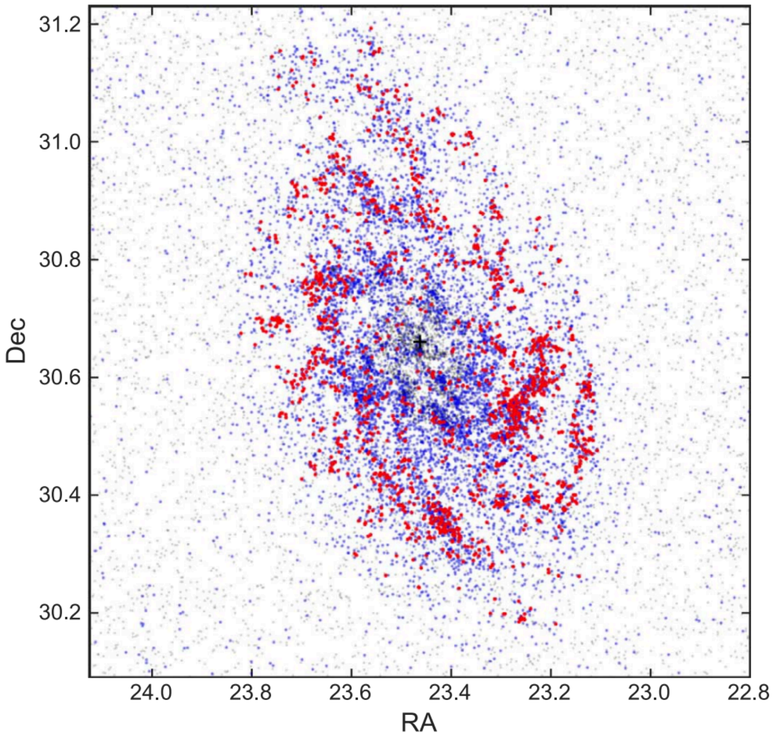


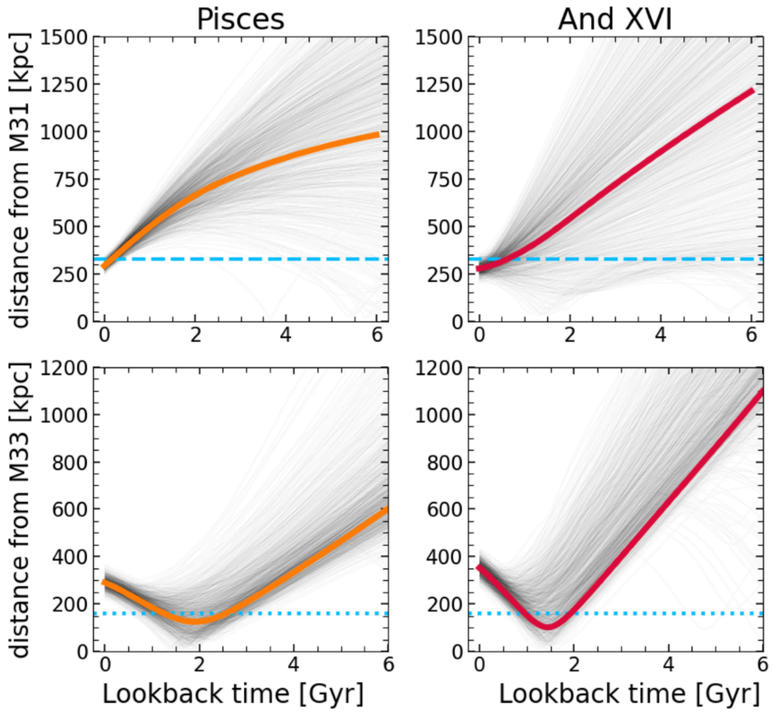
- Either dynamically young (<500 Myr), or does not originate from a single event
- MW influence? Displacement of 10-50 kpc in this direction (Doliva-Dolinsky+26)

Wan+20

e.g., Pawlowski+17, Forero-Romero & Arias 2018, Wang+ 21, Patel, Garavito-Camargo, & Escala 25

The LMC analog, M33, may have brought companions into the halo of M31



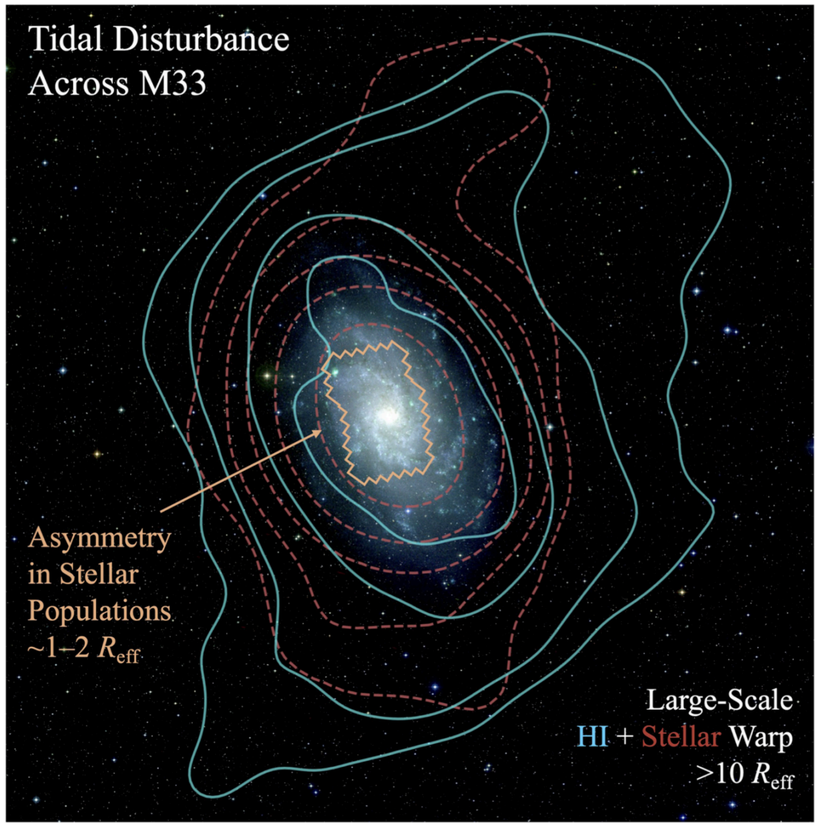


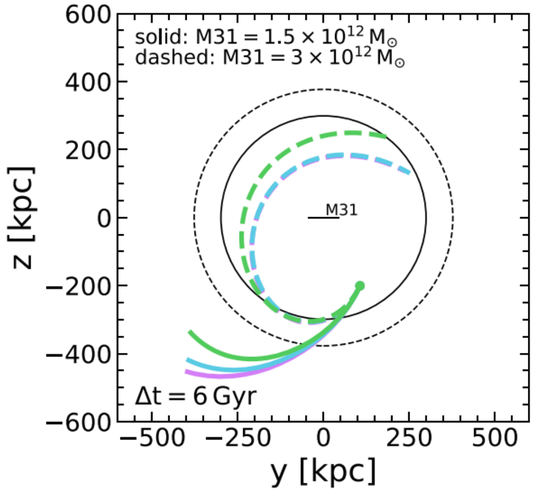
- ≈3 × 10^9 M ⊙ , but with a ~10^{11} M ⊙ infall mass (Patel+18), D = 859 kpc (Savino+22)
- M33-mass analogs should host satellite companions, predicting ~10 satellites within 160 kpc of M33 (Patel+18)
- Only two satellite candidates, And 22 and Pisces 7 (Martin+09, Martinez-Delgado+22)
- Has M33 interacted with M31, exchanging satellites between the galaxies? (Patel+26)

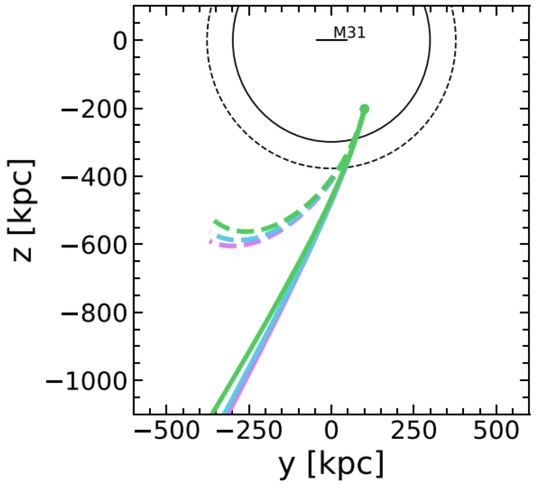
van der Marel+19, Patel+26
e.g.,Martin+09; Tollerud+12; Chapman+13; Patel+18, Martinez-Delgado+22; Collins+24, Ogami+24; Jones+26

The warped outer disk of M33 suggests an encounter, but proper motions support first infall onto M31

- First infall orbit >90% of cases
- HST (vs. Gaia) PMs for M33, combined with a high-mass M31, allows a 65% probability of previous encounter (>100 kpc)

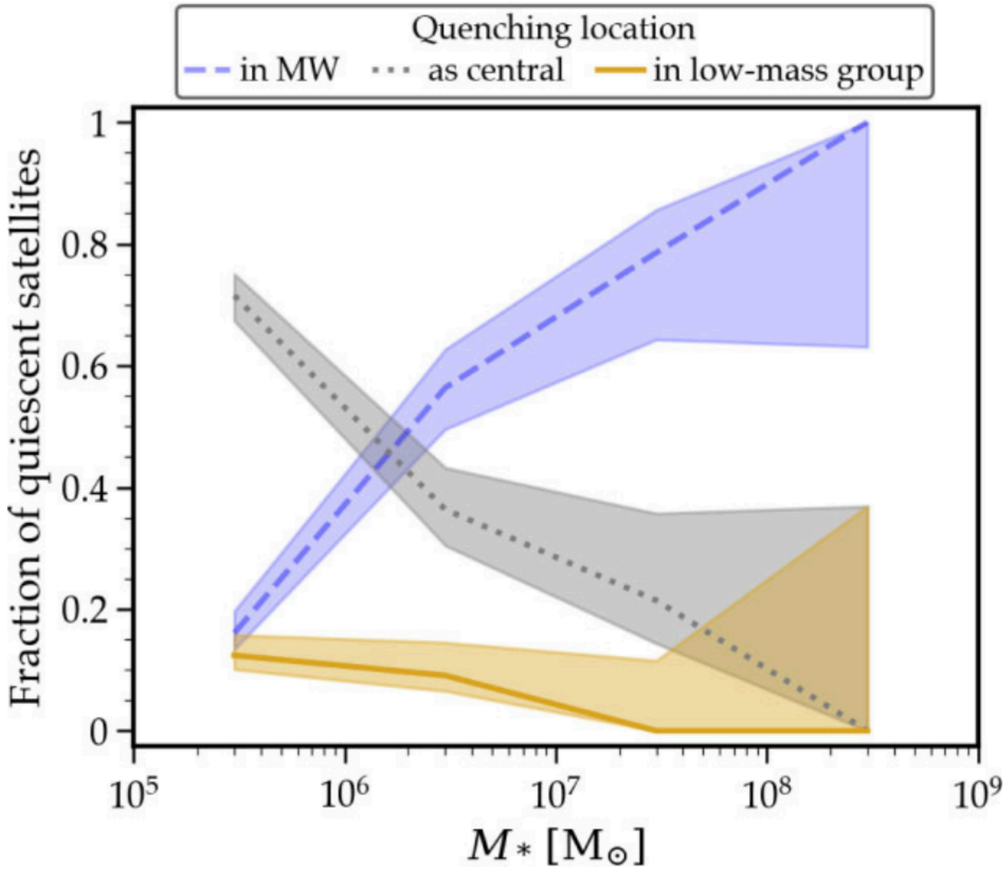






Smercina+23, Patel+25
e.g., Putnam+09; McConnachie+09; Martin+13; Corbelli+24
Brunthaler+05; Patel+17; van der Marel+19; Salomon+21; Rusterucci+24; Wu+25

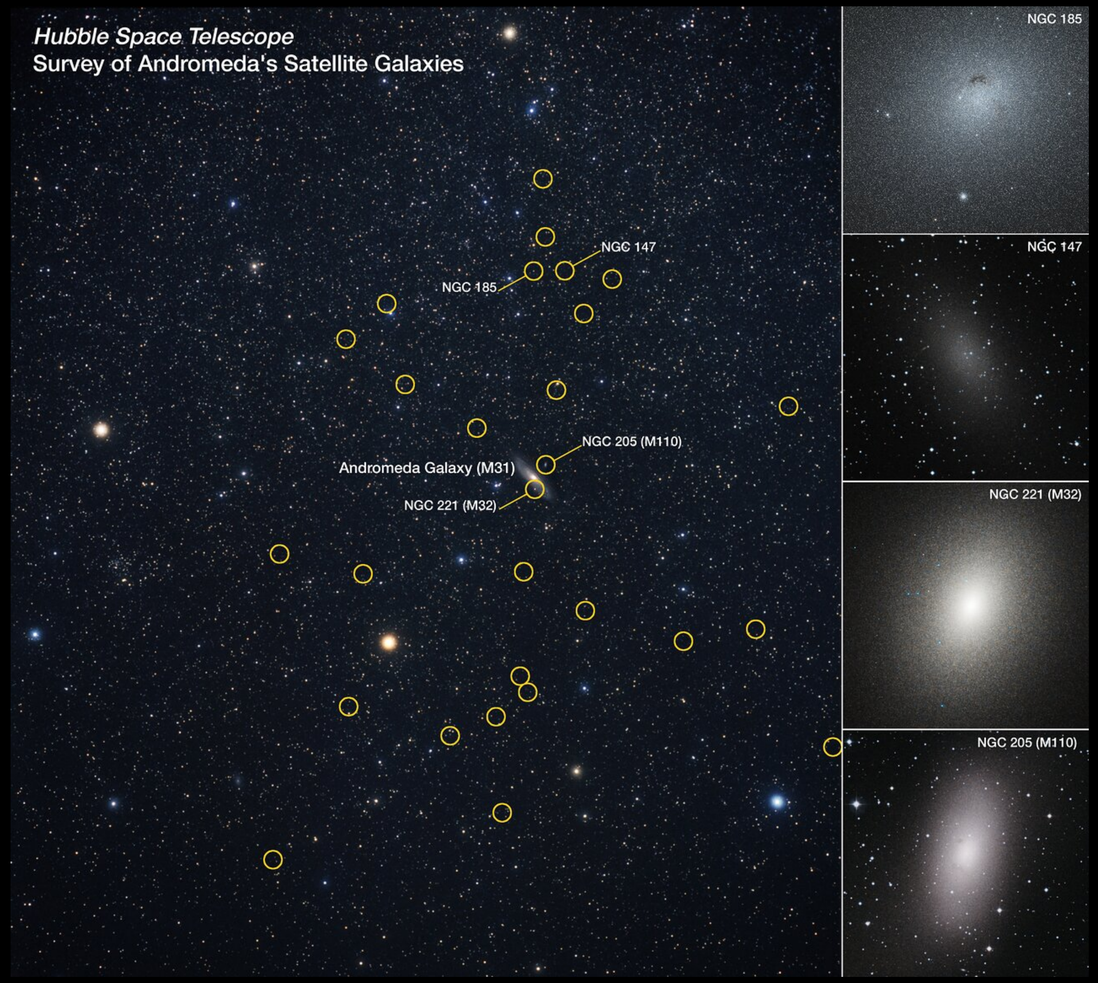
Satellite pre-processing during infall is common, affecting star formation in dwarf galaxies



- Most satellites quench within a massive halo, but some experience pre-processing in low-mass groups prior to infall
- Satellites-of-satellites in the LMC (e.g., Sacchi+21, Durbin+25) and M33
- Preprocessing combined with pericentric passages should set when galaxies quench

Samuel+22
e.g., Wetzel+15; Filingham+19; Akins+21; Bakels+21; Jahn+22; Santistevan+23; Merrow+25

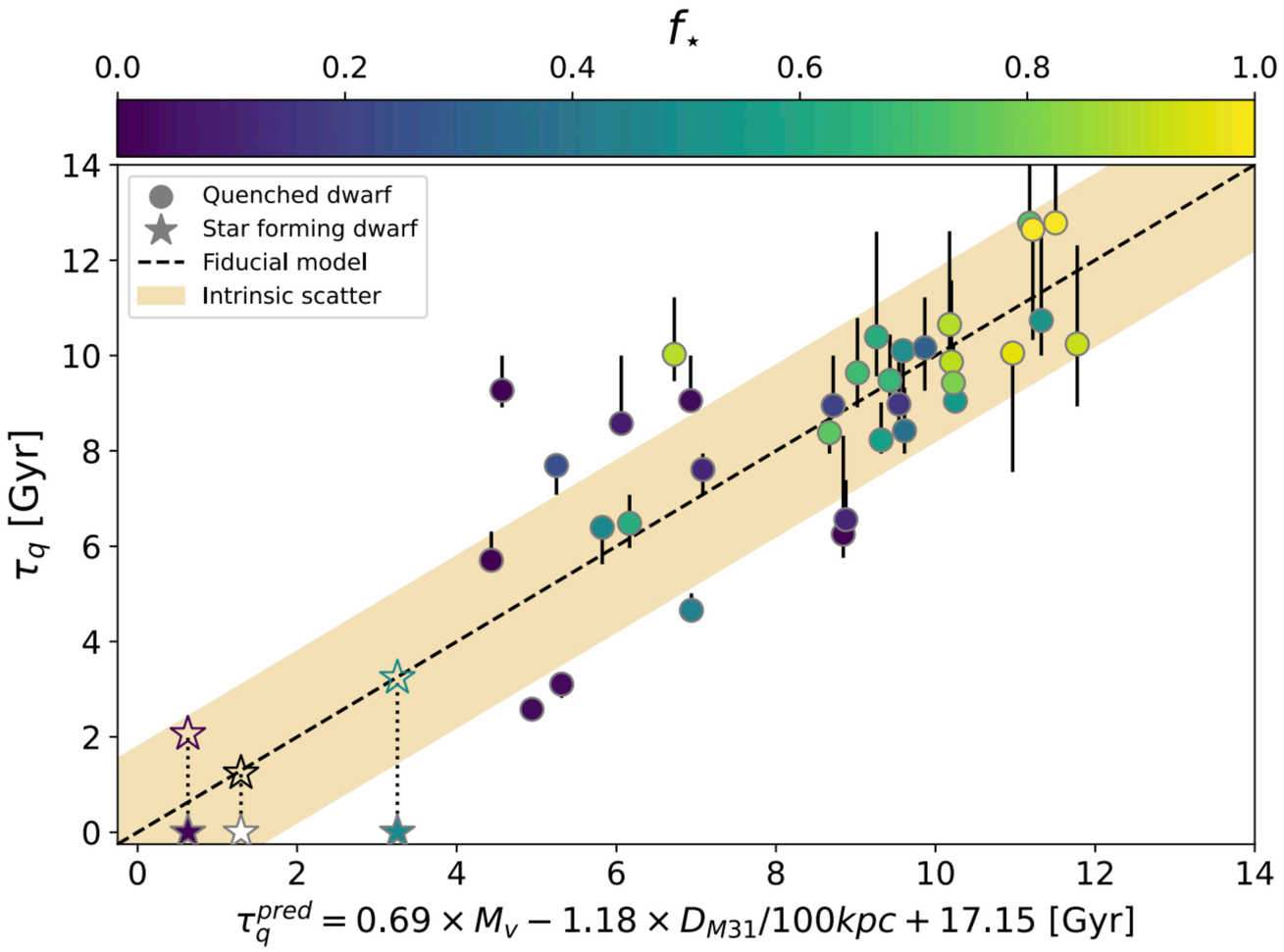
What do the star formation histories of M31 satellites suggest about their orbital histories, and the accretion history of M31?



- HST treasury survey of 36 M31 satellites, >1000 orbits
- Homogenous RRL-based distances and CMD-based SFHs reaching down to the oldest main-sequence turnoff
- Complete down to Mv = -6

Image credit: NASA, ESA, A. Savino (UC Berkeley), J. DePasquale (STScI), A. Fujii DSS2
e.g., Weisz +14; Monelli+16; Skillman+17; Martin+17; Weisz+19; Savino+23, 25

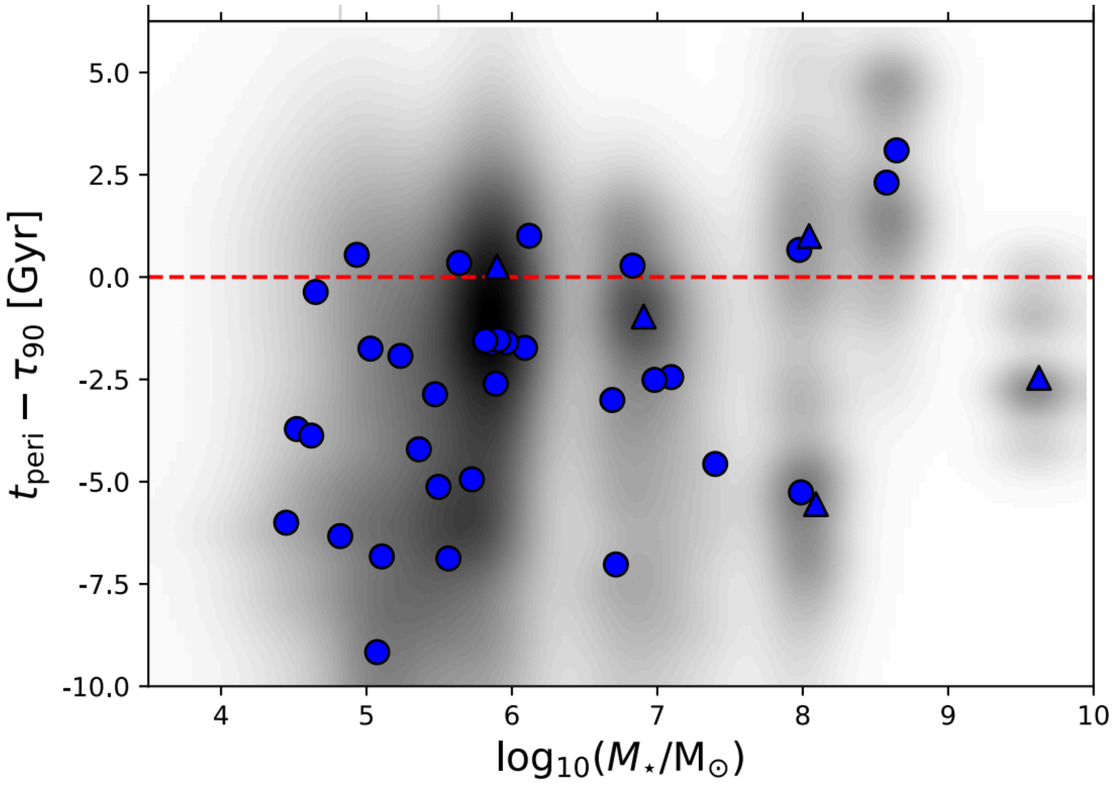
Satellite galaxies in M31 show post-reionization quenching correlated with distance from their host, or infall times



- Satellite luminosity and present-day distance from M31 predict quenching epoch within 1.8 Gyr
- Half show prominent ancient star formation, following by delayed quenching — uncommon in the MW
- No differences in SFHs between on- and off-plane satellites (see also Collins+15)

Savino+25

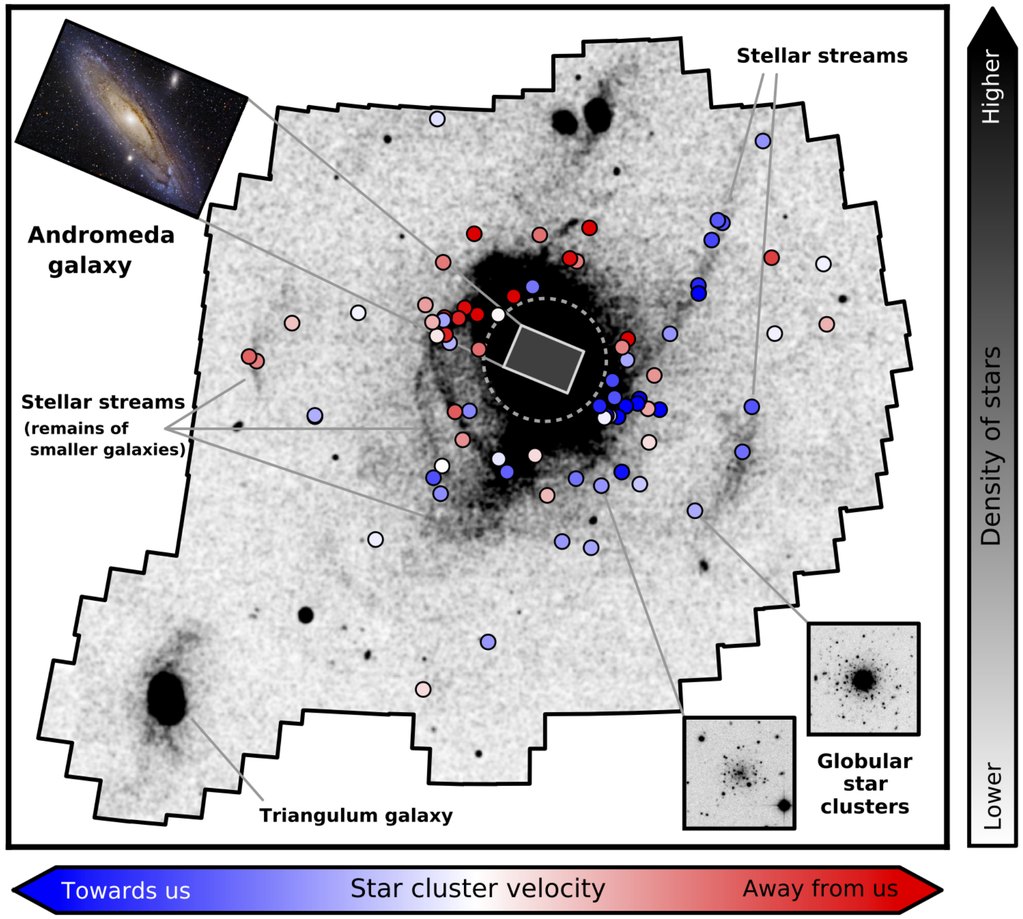
Simulations suggest M31 satellites show the same mass-dependent quenching as in the MW, despite its more recent accretion history



- The most massive satellites quench after first pericenter
- Most faint satellites quenched before entering M31´s halo at all
- Distance-dependent quenching may therefore record pre-infall birth environment (e.g., Christensen+24), not stripping by M31

Merrow+25
e.g., Simpson+18; Digby+19; Joshi+21; Engler+23; Savino+25

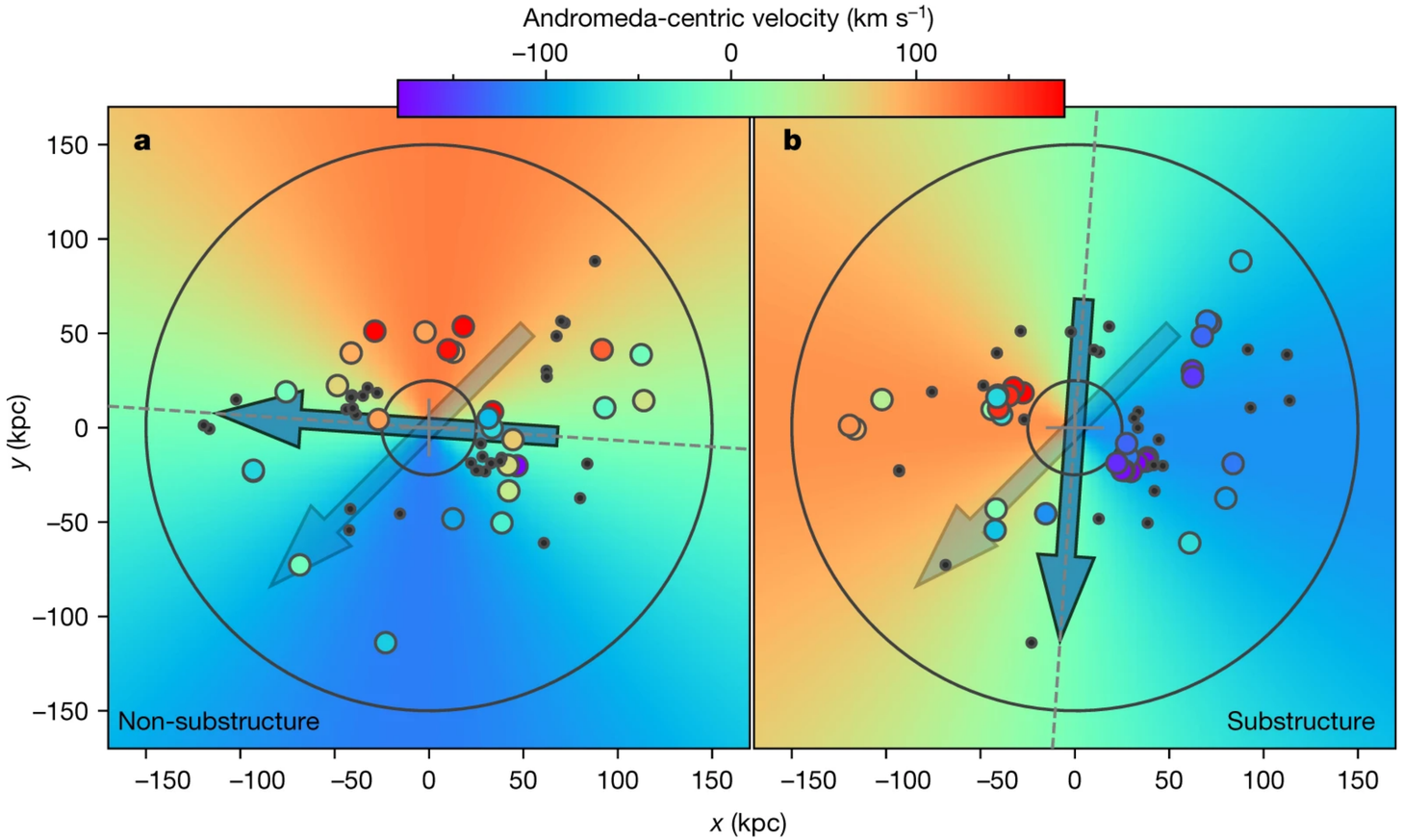
The kinematics of M31's globular cluster (GC) system suggest two distinct accretion epochs



- M31 has ~450 GCs, compared to ~160 in the MW, and far more in the outer halo (~7:1)
- Inner GCs rotate with the disk, as do outer halo GCs (~86 km/s)
- Outer halo GCs projected onto substructure, and onto the smooth halo, have distinct kinematics (Mackey+19b)

Image credit: D. Mackey and the PAndAS team
e.g., Perret+02; Mackey+10; Veljanoski+13,14; Caldwell & Romanowsky+16; Huxor+14; McConnachie+18; Mackey+19a

The smooth-halo GCs are aligned with the satellite plane, whereas substructure GCs may originate from a recent event

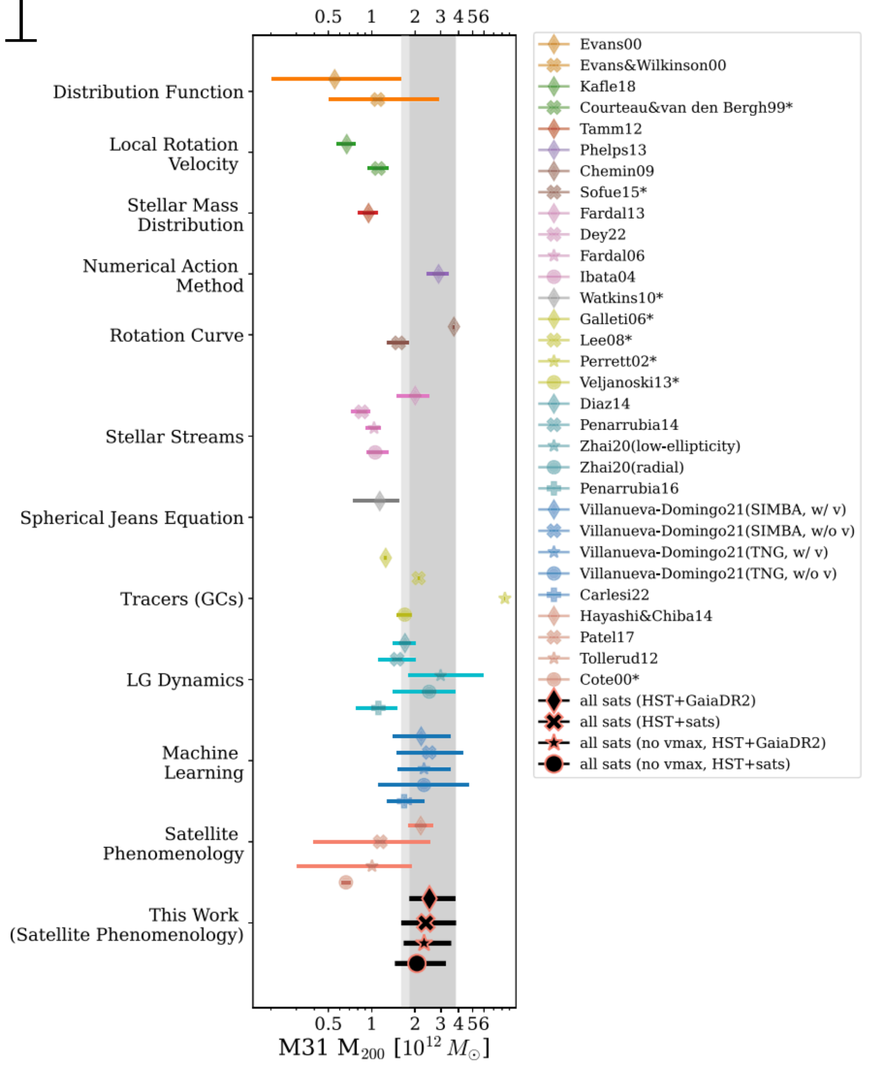


- Alignment between short-lived plane and smooth-halo GCs may point to filament
- Not strictly supported by satellite SFHs (Savino+25), though two distinct GC populations are
- Unclear if smooth-halo GCs originate from one early major event or many early accretions
- Substructure GCs brought in by GSS progenitor, or associated with reshaped disk? (Fardal+13; D'Souza & Bell 18; Hammer+18, Tsakonas+26)

Mackey+19b
e.g. Usher, Caldwell, & Cabrera-Ziri 2024; McGill+25

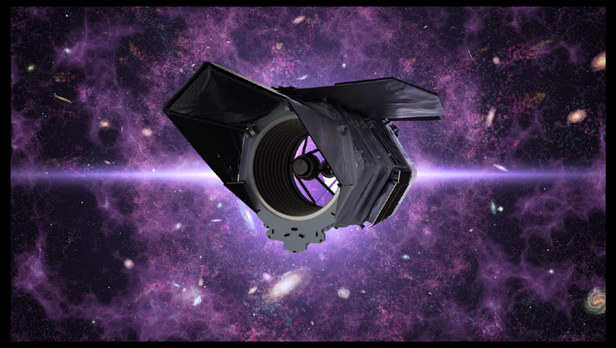
The kinematics of GCs, and satellites, trace the underlying mass distribution of M31

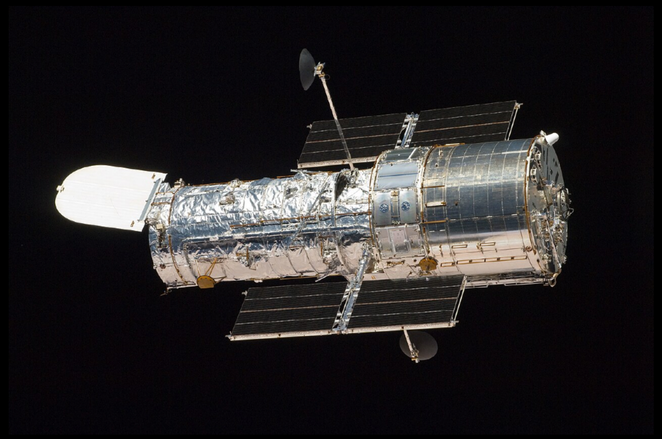
- Mass estimates within 200-300 kpc from LOS GC and satellite kinematics are biased lower (1.5 x 10^{12} Msun)
- Incorporating satellite PMs favors a high mass M31 (>2.5 x 10^{12} Msun)
- M31 more massive than the MW

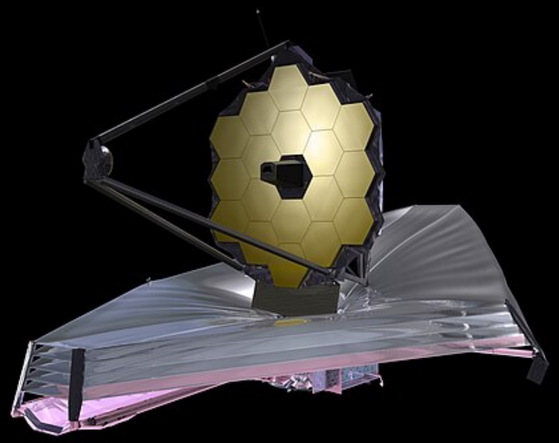


Patel & Mandel 23
e.g. Watkins+10; Tollerud+12; Hayashi & Chiba 14; Veljanoski+13,14; Patel+17; Makarov+25
See also Fardal+13

Looking forward: M31 satellite dynamics with Gaia DR4, JWST, HST, and Roman







- Gaia DR4: December 2, 2026
  - PM uncertainties should improve by a factor of ~3
  - Bring Gaia to HST's level of uncertainty in M31
  - *More precise bulk tangential velocity for M31*
- HST and JWST imaging paves the way forward (JW GO 1305, 4514, HST GO 18029 and 15658)
- Roman Treasury of M31 and M33 (PI Gilbert) will provide *bulk* PMs for dense substructures in M31's halo

Image credit: NASA GSFC SVS

Summary: M31 satellites and globular clusters as dynamical tracers of their host galaxy

- **A richer, more accreted system than the MW.** M31 has ~40 known satellites, with more bright-end galaxies and dwarf ellipticals. It has ~3x the GCs, with ~7x beyond 25 kpc.

- **The spatial anomalies of satellites are real, but their origin is unexplained.** About 80% of sallites lie on the MW-facing side of M31, and about half are in a thin, apparently co-rotating plane. Each is rare in LCDM, and group infall alone may be insufficient.

- **Satellite quenching is late, unlike the MW, and mass-dependent.** M31 satellites show prominent ancient star formation followed by delayed quenching 8-10 Gyr ago, a pattern that remains unexplained. Massive satellites may have been quenched after first pericenter, where faint satellites were likely quenched before first infall by their birth environment.

- **Globular clusters suggest at least two distinct populations, and accretion epochs.** Substructure GCs follow stream kinematics, unlike smooth-halo GCs, and the two groups rotate about perpendicular axes. Smooth-halo GCs trace the plane, whereas substructure GCs may originate from a recent major accretion event.

- **Proper motions are the bottleneck.** Gaia works for the systemic motions of M31 and M33, not the satellites, which need HST and JWST imaging. Full 6D data will settle the satellite plane and infall histories, and M31's mass distribution

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