

M31's satellite system: too asymmetric for CDM cosmology?

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The asymmetric M31 satellite system

The Andromeda galaxy (M31) is surrounded by a striking asymmetrical distribution of dwarf satellite galaxies aligned towards the Milky Way (Fig 1). However, Λ CDM cosmology predicts that most satellite systems are near-isotropic in nature, and other dwarf associations observed in the local Universe are only weakly lopsided. We characterised the M31 system's asymmetry using novel metrics and, for the first time, tested its agreement with expectations from concordance cosmology.

Comparison to cosmological simulations

We use a homogeneous set of RR Lyrae-based distances for 37 M31 satellites published in *Savino et al.* [1]. M31 analogs were identified in two hydrodynamic cosmological simulations, TNG100 and EAGLE, by selecting halo mass analogs ($0.5-3 \times 10^{12} M_{\text{sun}}$) with a comparably massive companion. We thus obtain a total of 325 M31 analogs truncated to exactly 37 satellites each to match the observed system.

We quantified the asymmetry of the M31 system and its simulated analogs by counting the satellite population contained within conical regions with varying opening angle facing the companion galaxy (Fig 2,3). We further correct for the *look-elsewhere effect* by comparing M31 and its analogs to the degree of asymmetry expected in isotropy, thus comparing the most significant configuration of each.

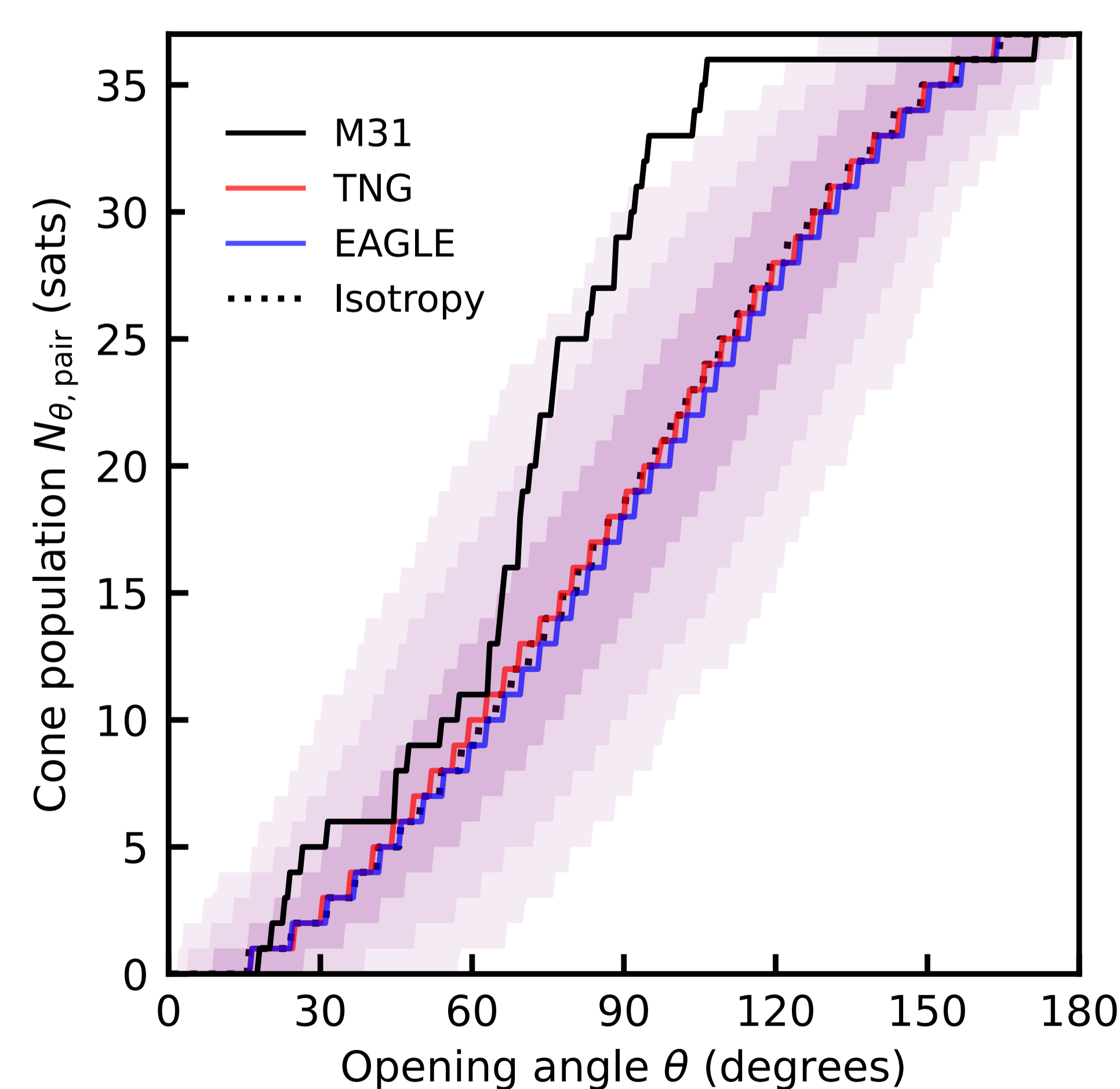


Figure 2. The number of M31 satellites within a cone with opening angle θ facing the Milky Way (black), along with medians for analogs in TNG100 (red) and EAGLE (blue) and their $1-3\sigma$ spread (purple).

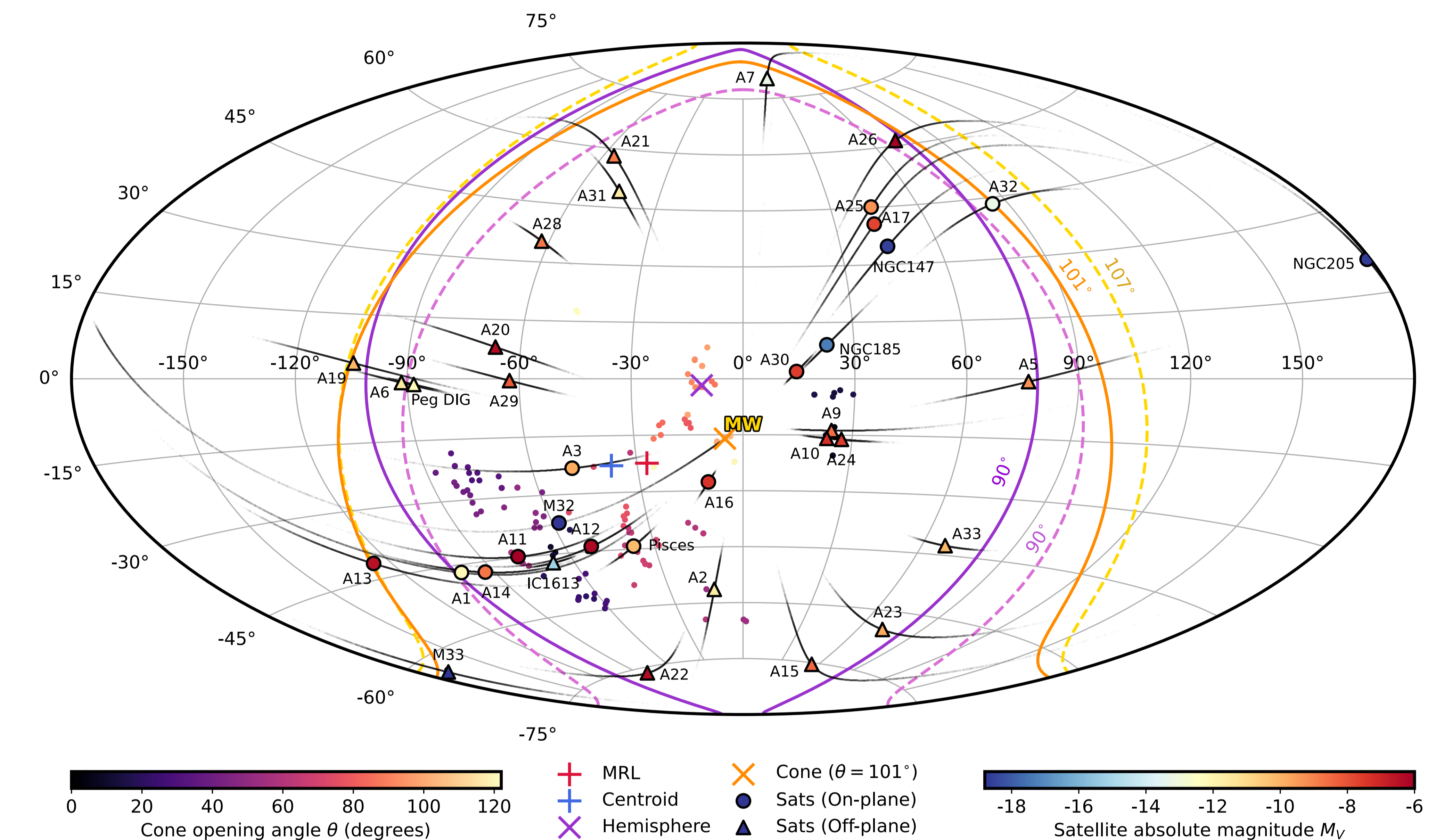


Figure 1. An equal-area Aitoff sky projection in our adopted M31-centric coordinate system showing the expected positions of 37 M31 satellites, with Monte Carlo uncertainties in black. Satellites likely and unlikely to participate in M31's satellite plane are marked as circles and triangles respectively. Over 80% of M31's satellites are contained within a hemisphere roughly aligned with the Milky Way (purple cross and line), while all but one satellite lies within 107° of our Galaxy's direction (dotted orange line).

A striking outlier from Λ CDM expectations

All but one of M31's 37 satellites lie within 107° of the Milky Way's direction. Only 0.3% of M31 simulated analogs can match the significance of the observed asymmetry at any cone opening angle, and the M31 system's lopsidedness occurs on a more population-wide scale than any equally significant analog (Fig 4). Around one-half of M31's satellites also

form a flattened and co-rotating plane, a structure rare in simulations at the 0.04% level [2]. In conjunction with its satellite plane, our results present Andromeda's satellite galaxy system as a striking outlier in Λ CDM cosmology.

References

- [1] Savino, A., Weisz, D.R., Skillman, E.D., et al. 2022, *ApJ*, 938, 2
[2] Ibata, R., Ibata, N.G., Lewis, G.F., et al. 2014, *ApJL*, 784, 1

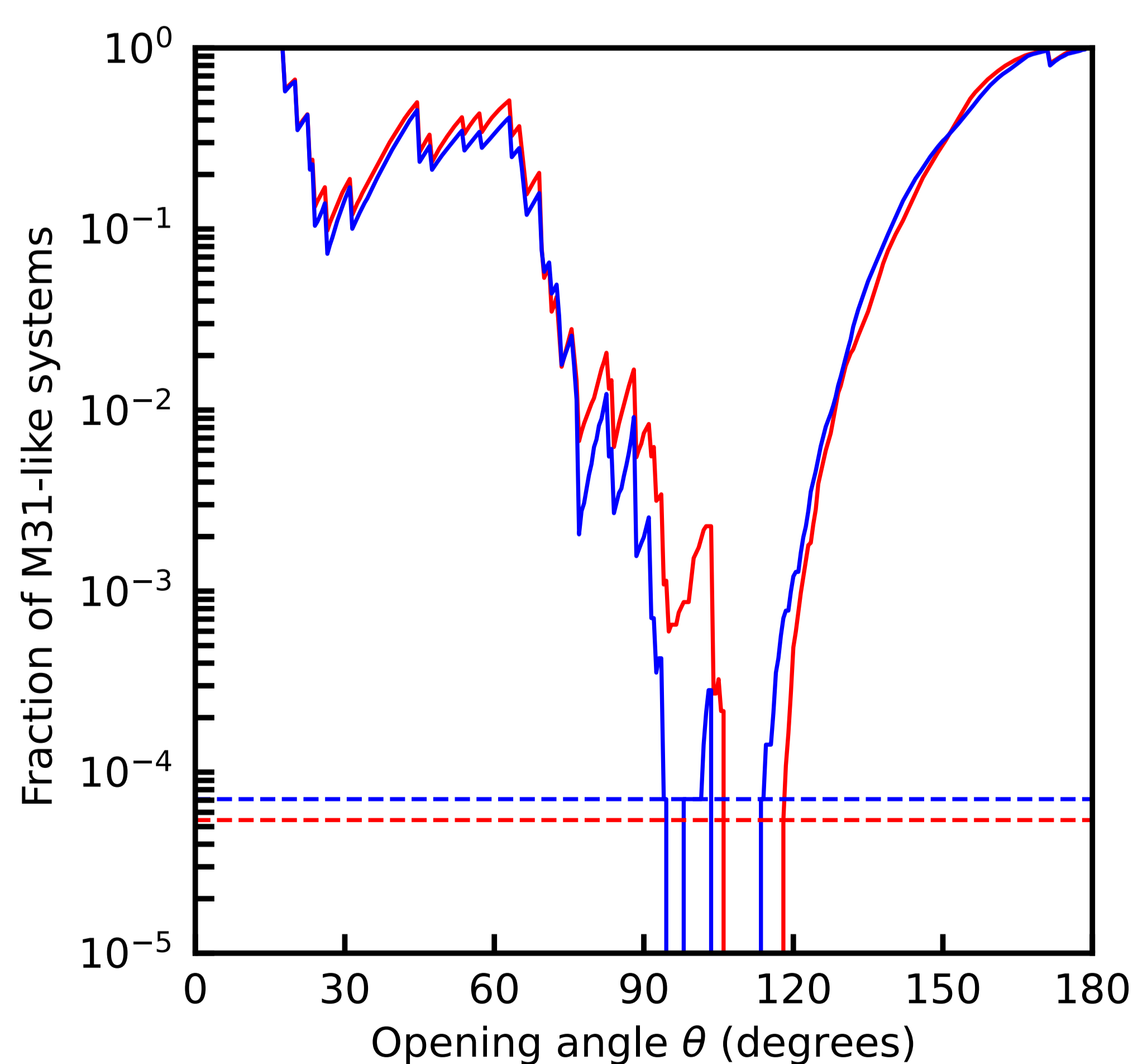


Figure 3. The simulated incidence of M31 analogs as asymmetric as the observed system. Dashed lines indicate incidences equivalent to exactly 1 simulated MC realisation, and no TNG100/EAGLE analog can replicate the M31 system's degree of lopsidedness.

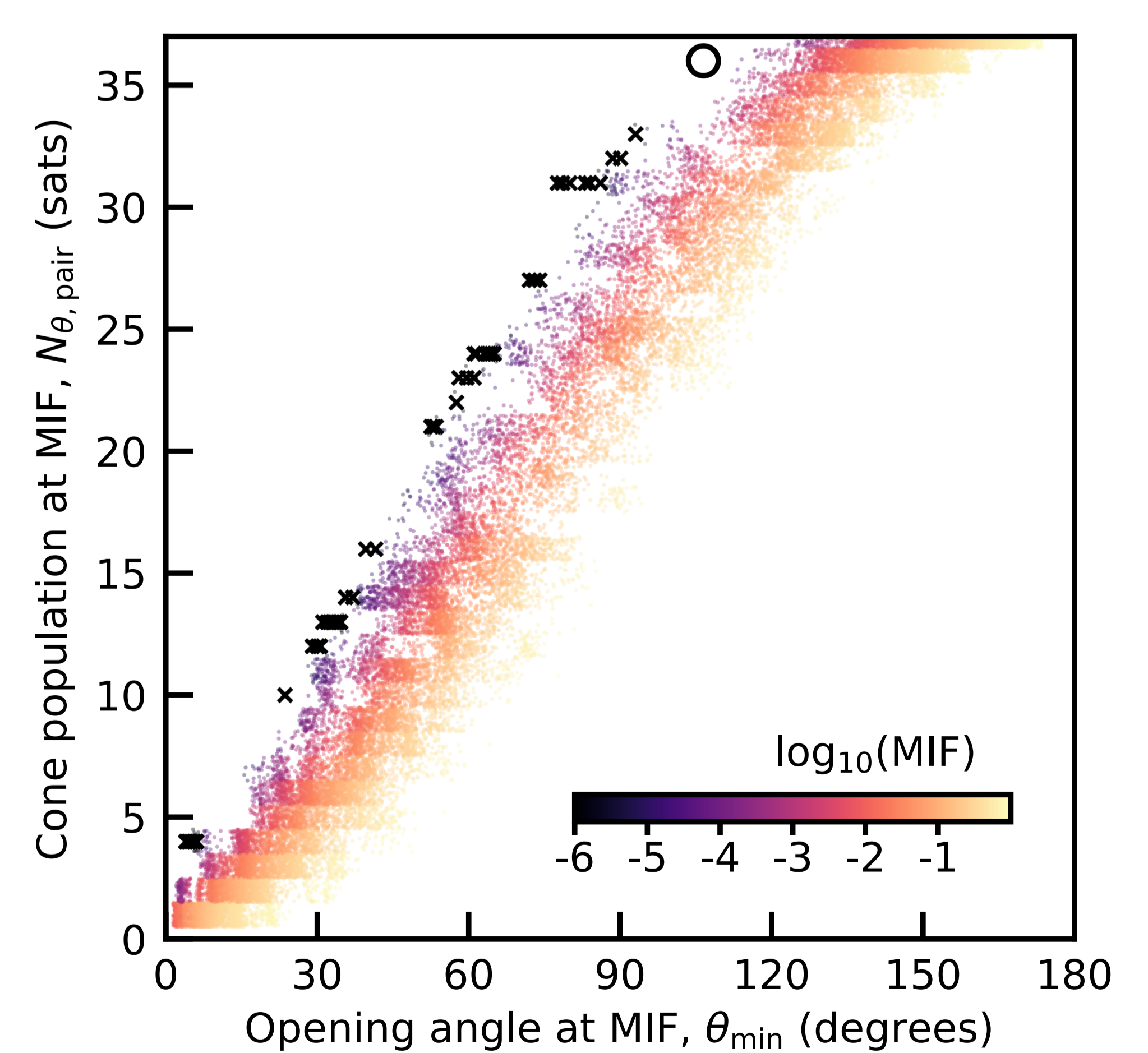


Figure 4. The most significantly asymmetrical configuration of the M31 system (white circle) and simulated analogs (coloured points). The 0.3% of analogs as significant as M31 is shown as black crosses, but none are as collectively lopsided as the observed M31 system.