Satellite galaxies challenging cold dark matter expectations
Moving from specific hosts to demographic samples

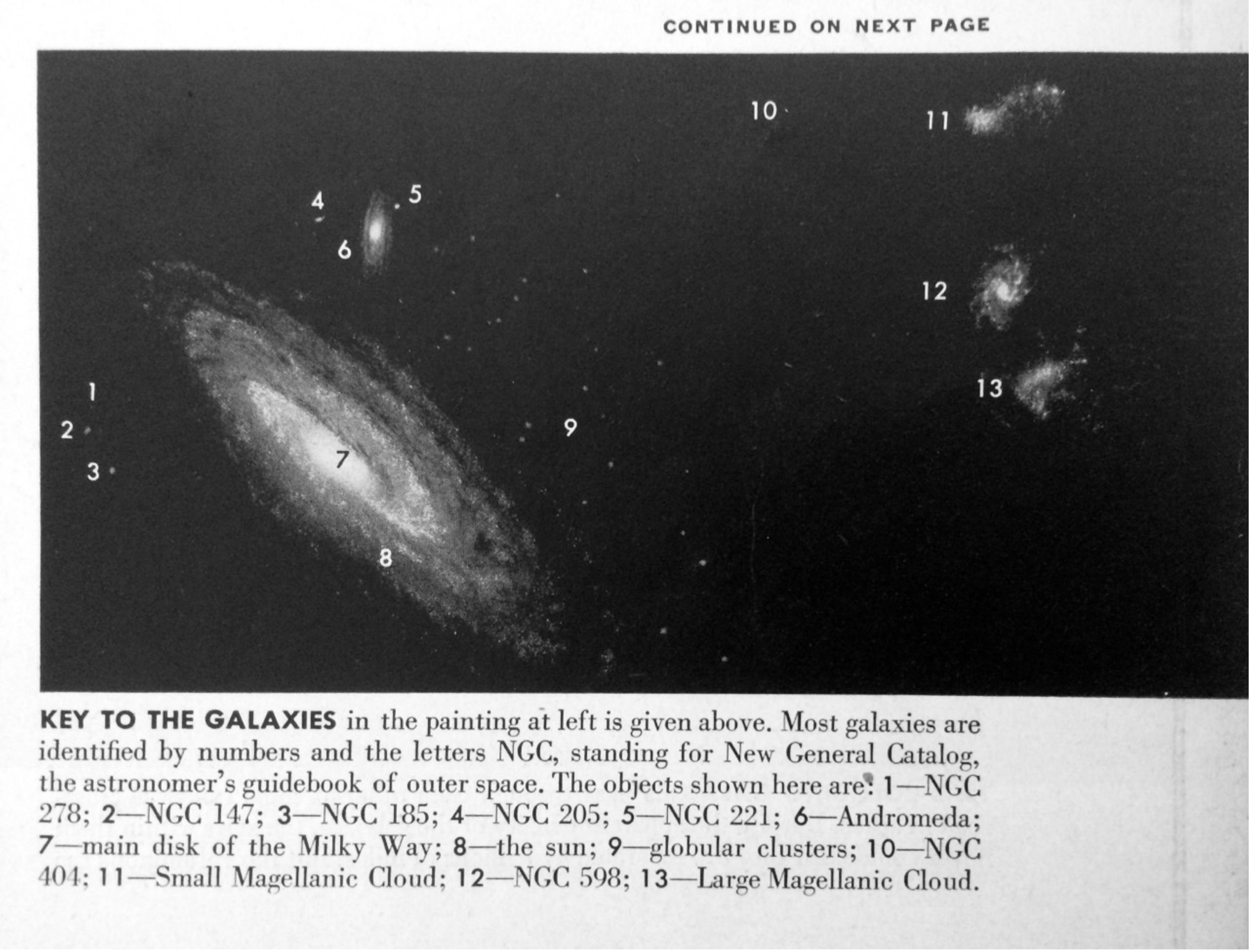
Marcel S. Pawlowski

AIP
Leibniz-Institut für
Astrophysik Potsdam
1700 - 2025
325 Jahre

→

SDU
University of
Southern Denmark

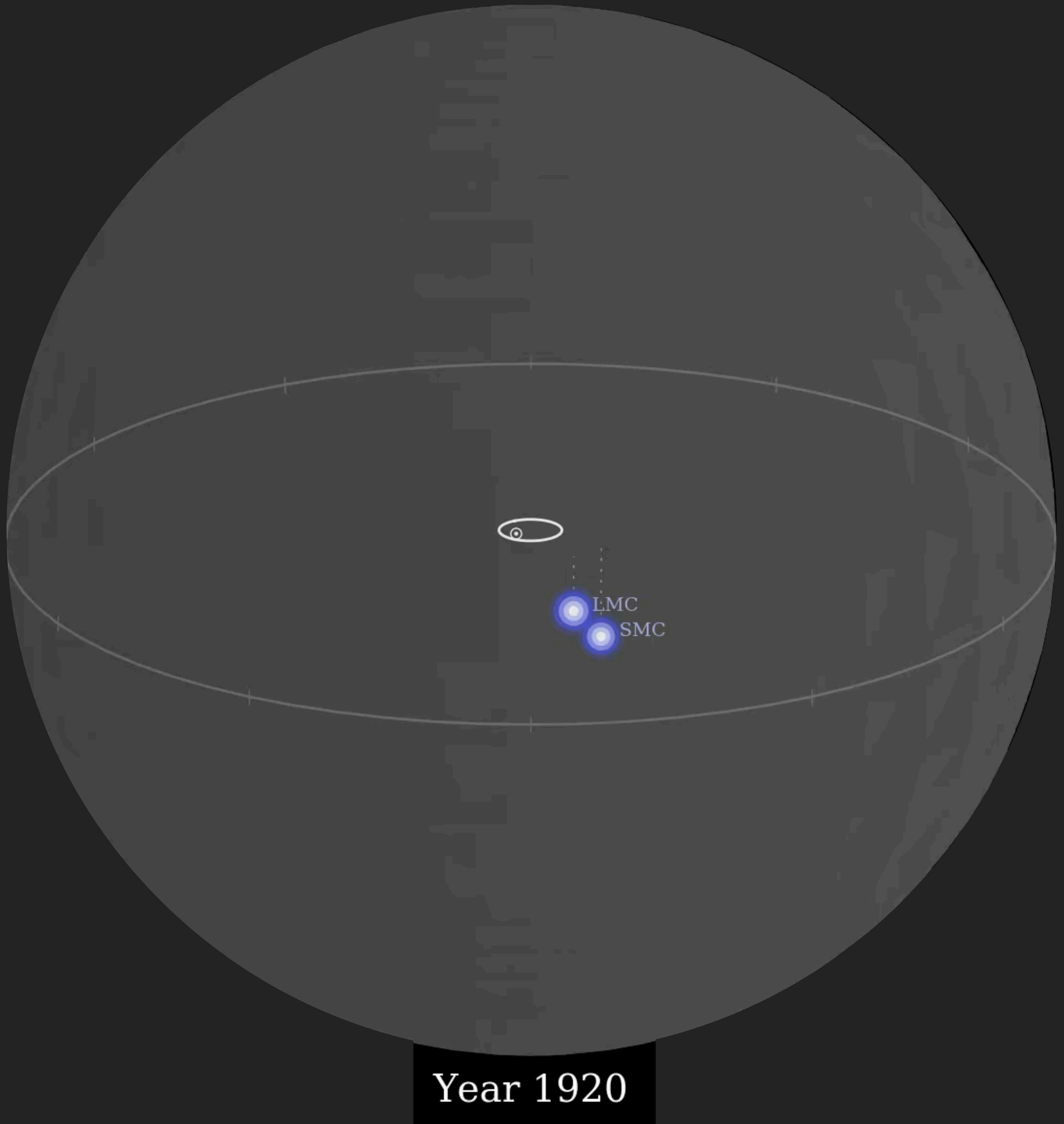
The Local Group of Galaxies: Milky Way, Andromeda, and many Dwarfs



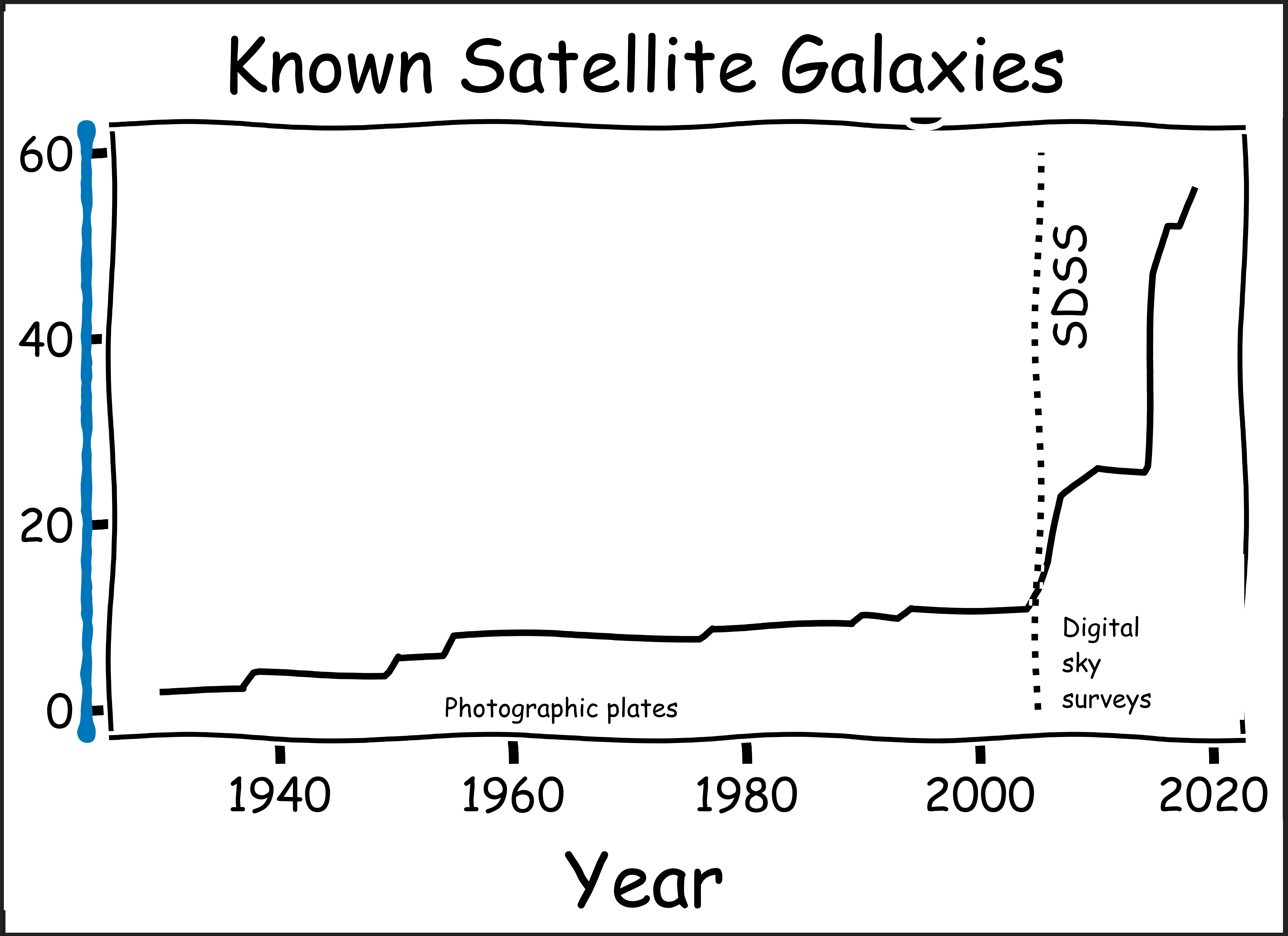
CONTINUED ON NEXT PAGE

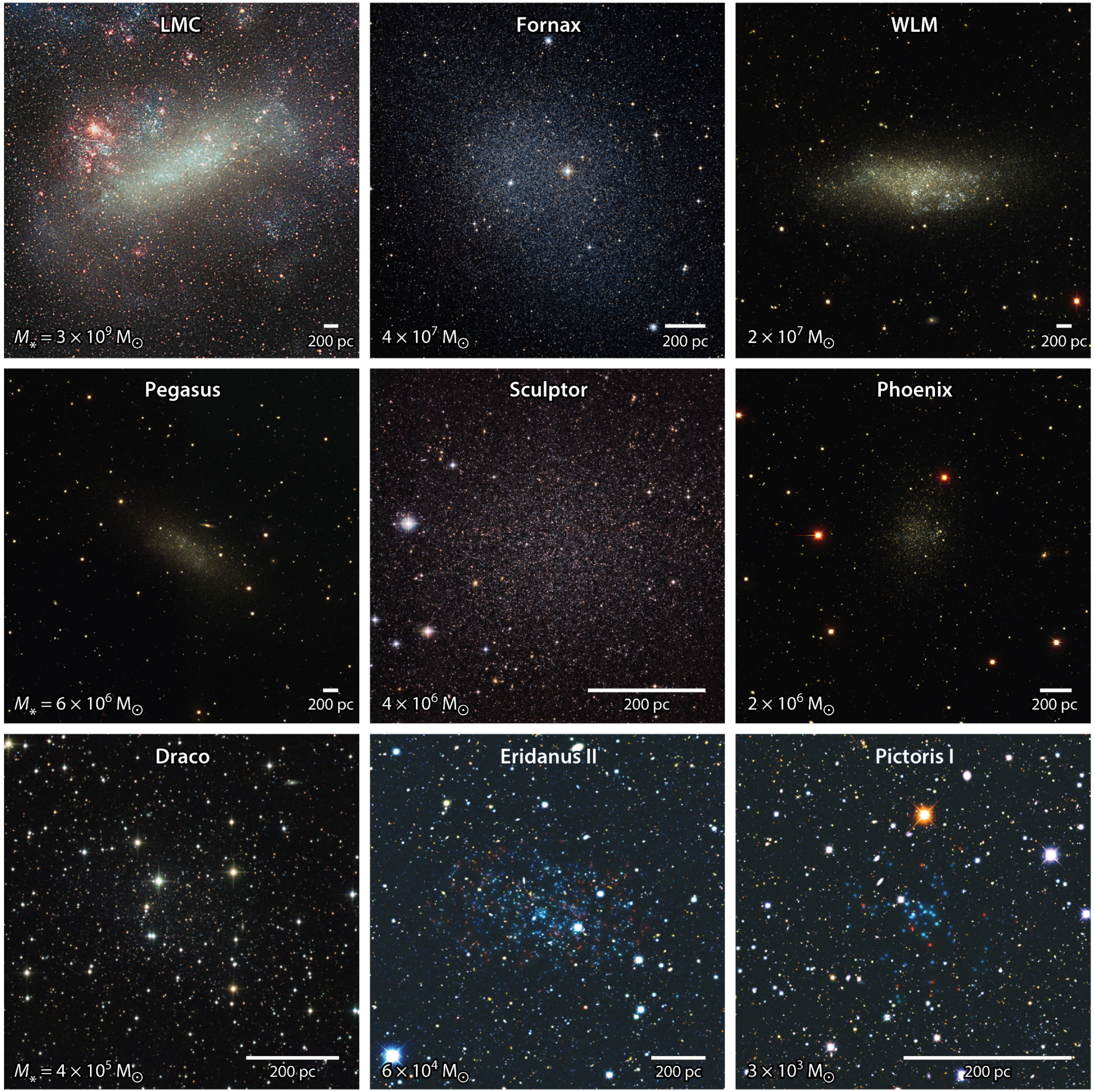
KEY TO THE GALAXIES in the painting at left is given above. Most galaxies are identified by numbers and the letters NGC, standing for New General Catalog, the astronomer's guidebook of outer space. The objects shown here are: **1**—NGC 278; **2**—NGC 147; **3**—NGC 185; **4**—NGC 205; **5**—NGC 221; **6**—Andromeda; **7**—main disk of the Milky Way; **8**—the sun; **9**—globular clusters; **10**—NGC 404; **11**—Small Magellanic Cloud; **12**—NGC 598; **13**—Large Magellanic Cloud.

Discovery History of Milky Way Satellite Galaxies

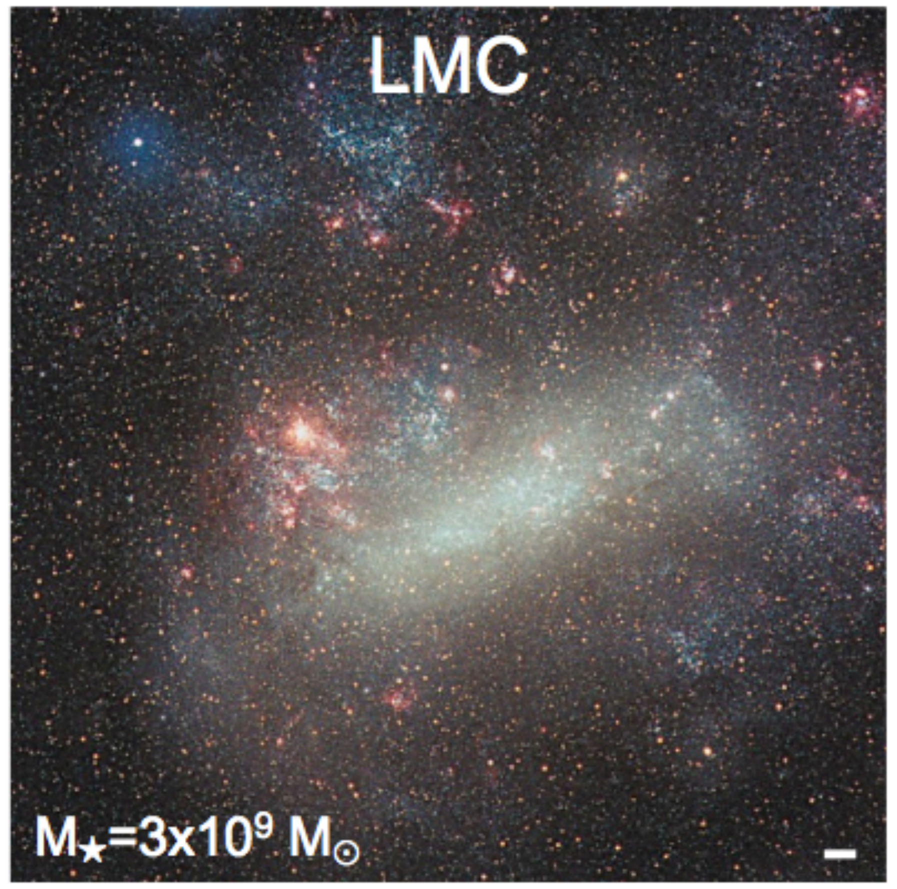


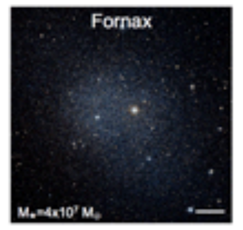
Quelle Video: http://marcelpawlowski.com/research/movies-astronomy/

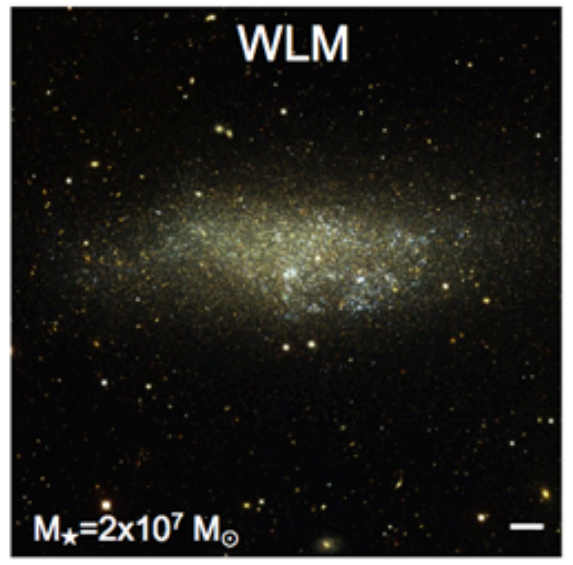


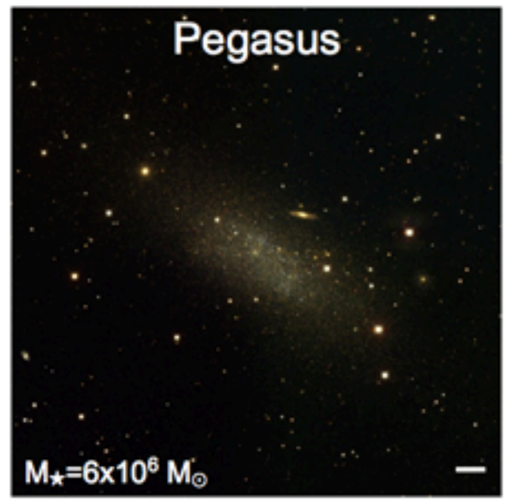


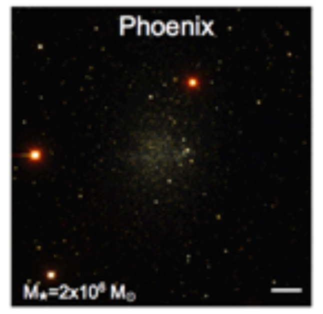
Bullock JS, Boylan-Kolchin M. 2017.
Annu. Rev. Astron. Astrophys. 55:343–87

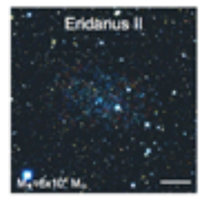












On same scale!

Bullock JS, Boylan-Kolchin M. 2017.
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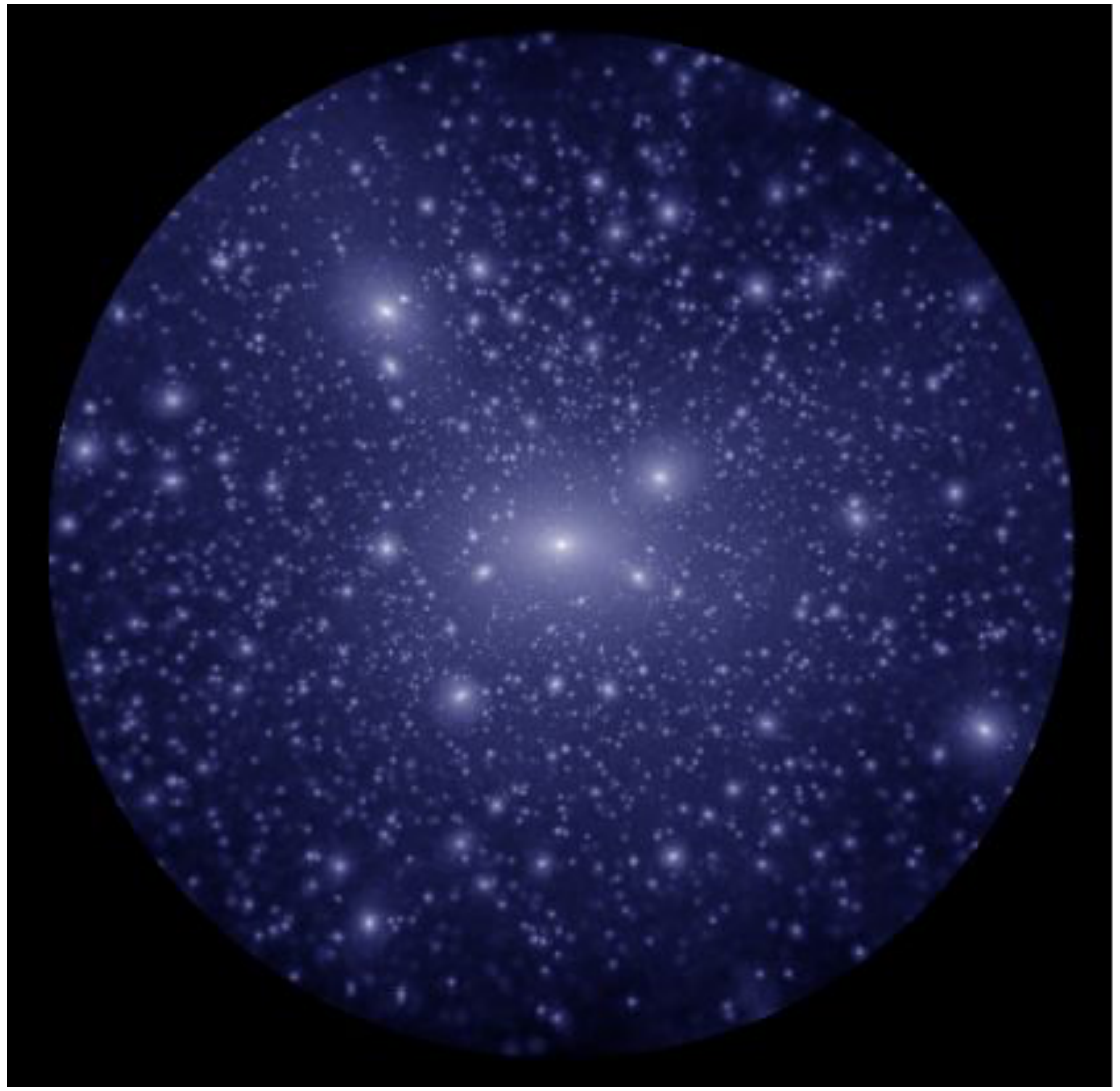
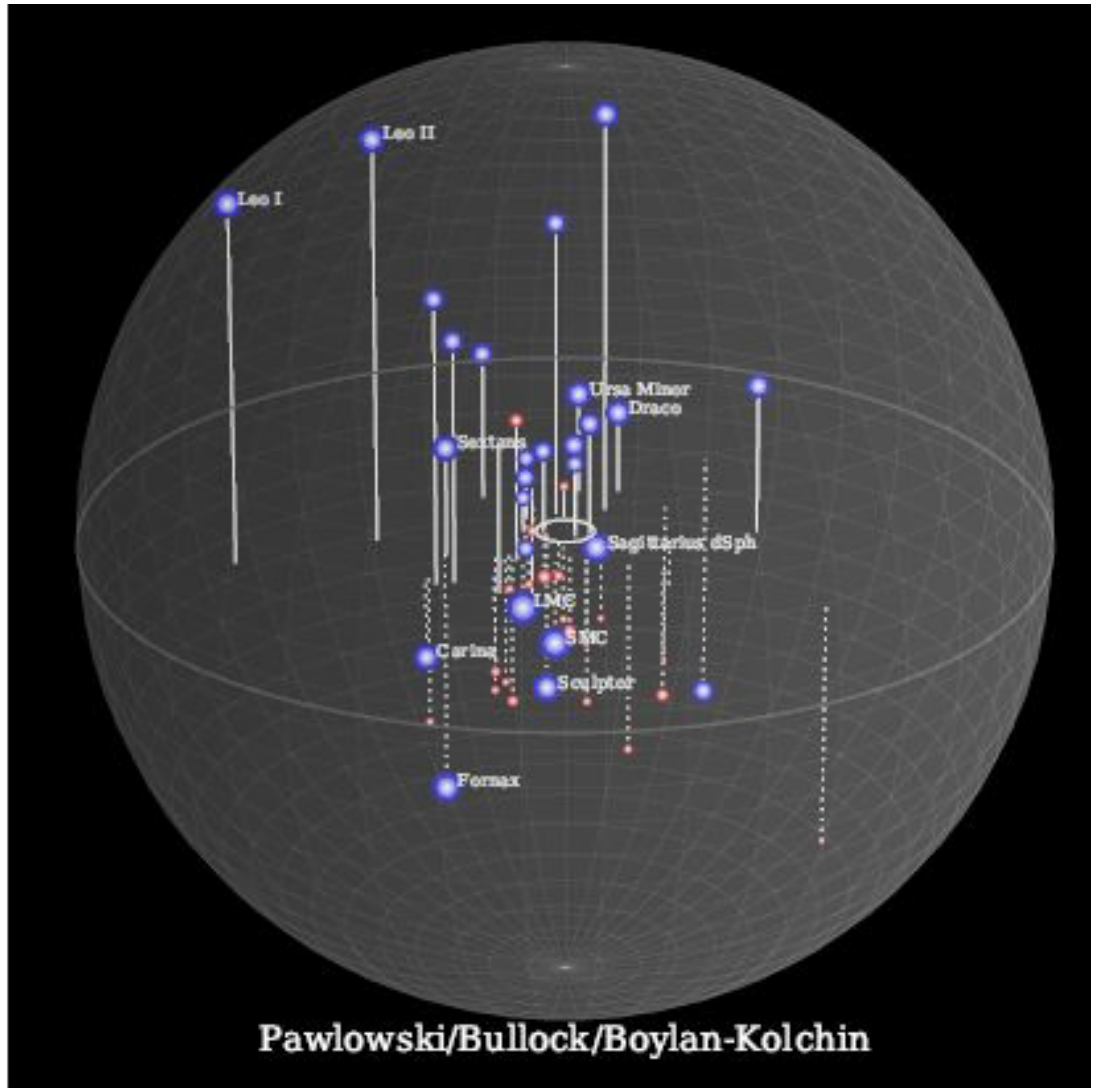
Let's just count them

Missing Satellite Galaxies of the Milky Way

One of the first “small-scale problems” for ΛCDM (Klypin et al. 1999), Moore et al. 1999):

Hundreds to thousands of subhalos expected, but only a few tens of satellites discovered.





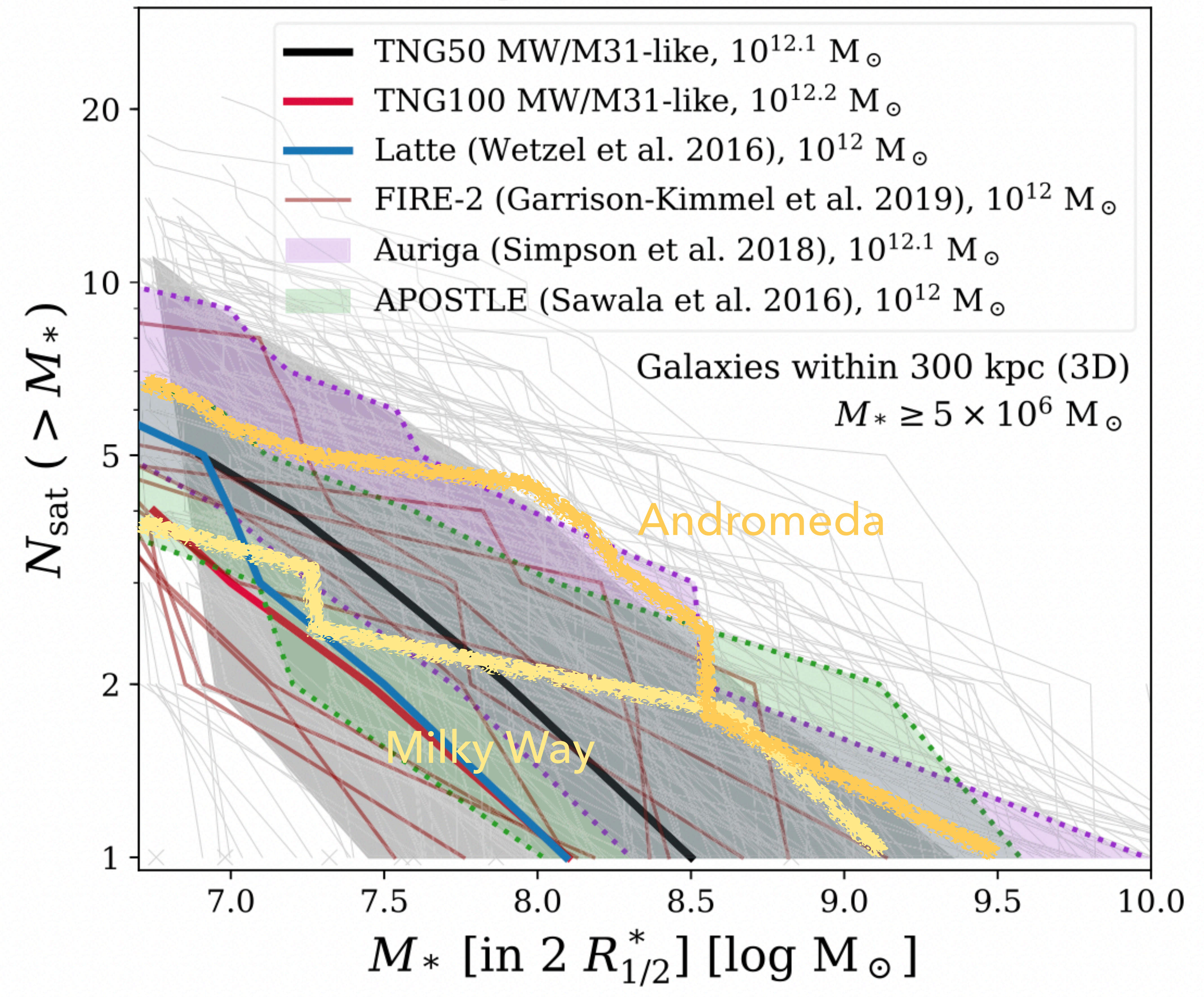
Pawlowski/Bullock/Boylan-Kolchin

Likely Solution: Baryonic Physics

- Better than counting: compare **satellite galaxy luminosity function** with simulation expectations.
- Modern simulations account for **baryonic effects which can prevent subhalos from forming stars**, i.e. dark matter subhalos do not all host a luminous galaxy.
- Simulations generally agree with each other and with number of satellites in Local Group.

➡ **Missing Satellites Problem solved! (?)**

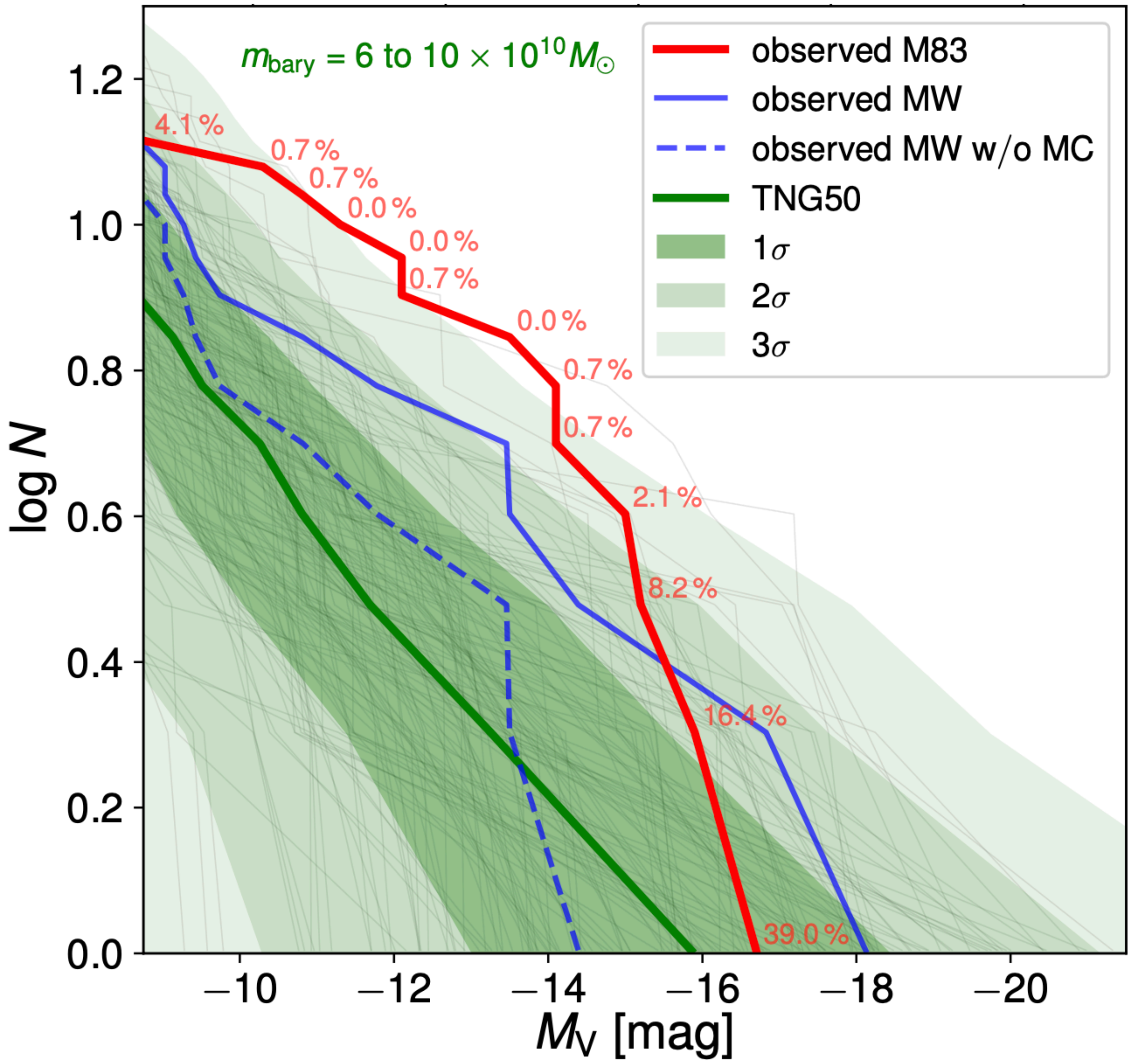
Stellar mass functions from various simulation (Engler et al. 2021)



A too-many-dwarfs problem?

M83: one specific galaxy of MW mass where we find too many satellites: 3-5 σ discrepancy

M83 (Müller, Pawlowski et al. 2024)



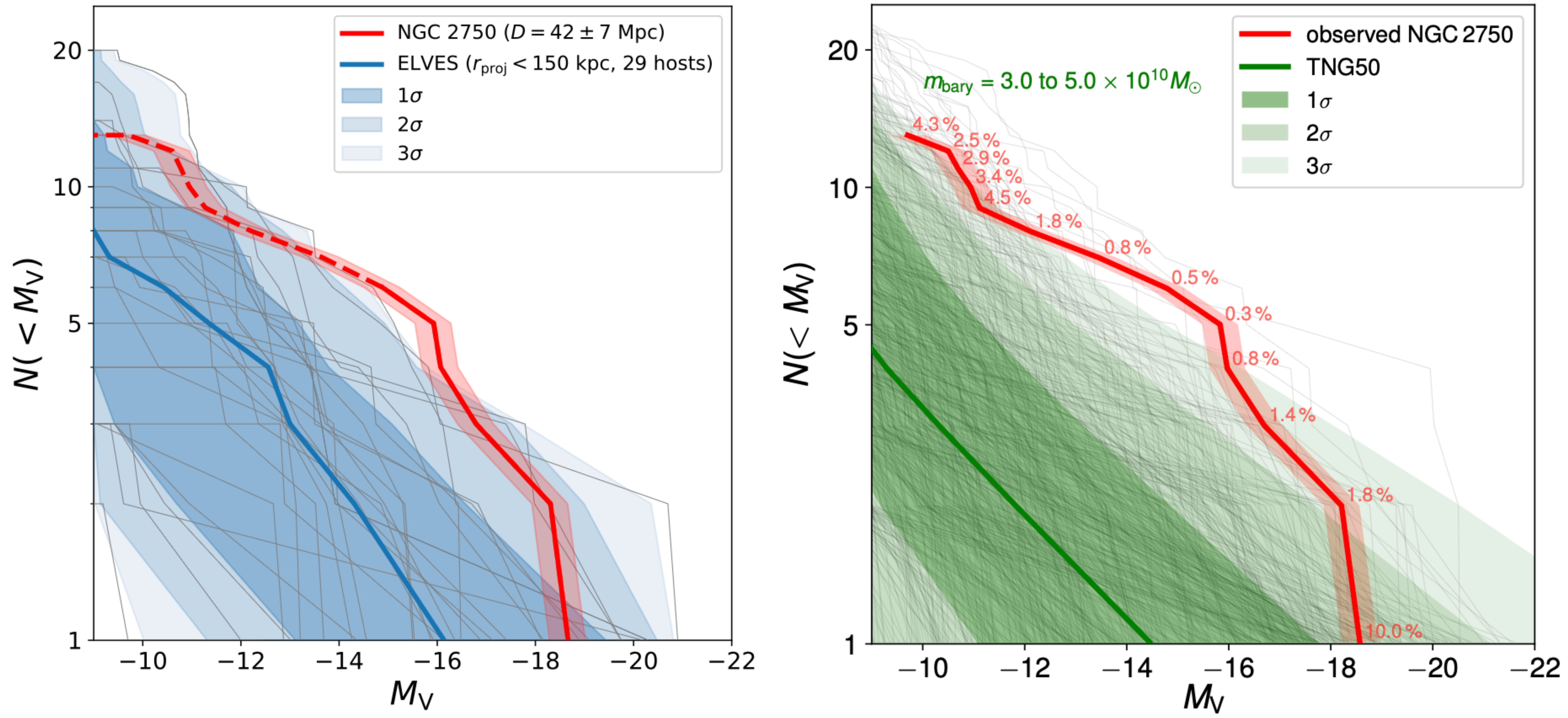
A too-many-dwarfs problem?


Salvatore Taibi

M83: one specific galaxy of MW mass where we find too many satellites: 3-5 σ discrepancy

NGC 2750: also shows an excess of bright satellites.

NGC 2750 (Taibi, Pawlowski et al. 2025)



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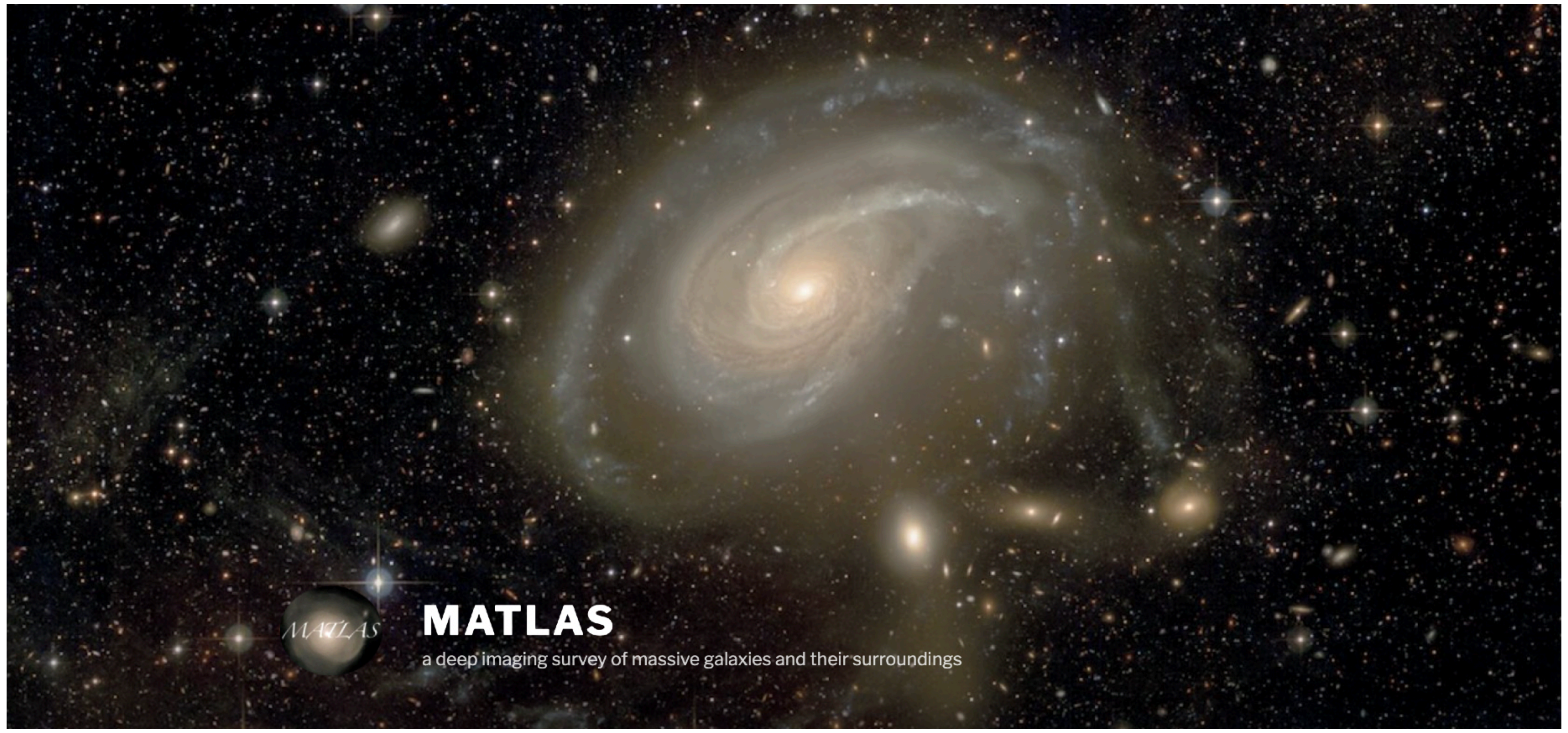
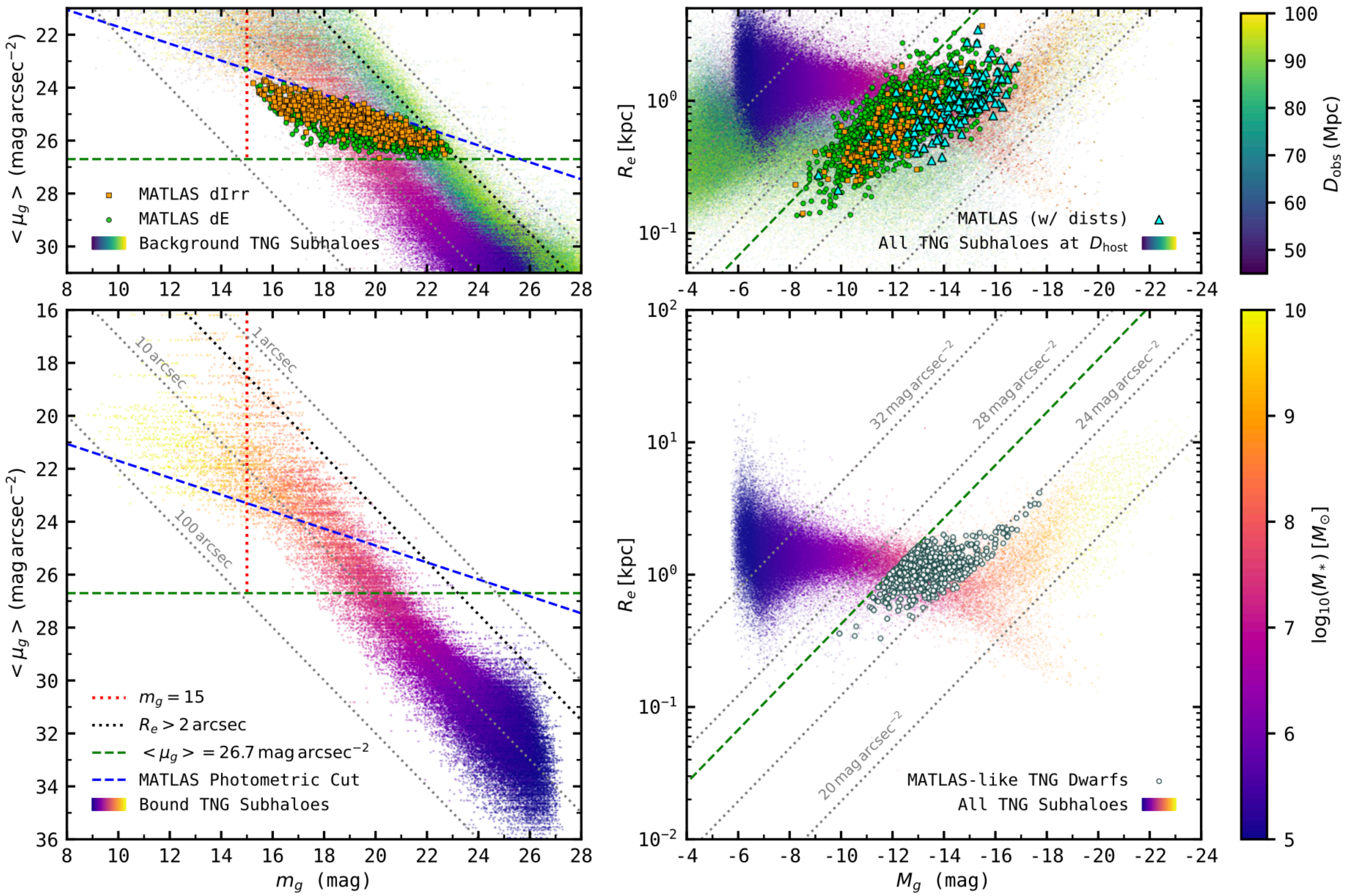
NGC 2750: also shows an excess of bright satellites.

MATLAS fields: 48 fields around isolated galaxies.
We "mock-observe" TNG50 to find analogs for comparison.
→ ***6σ discrepancy*** in dwarf galaxy counts!



Kanehisa, K. J., et al.: A&A, 686, A280 (2024)



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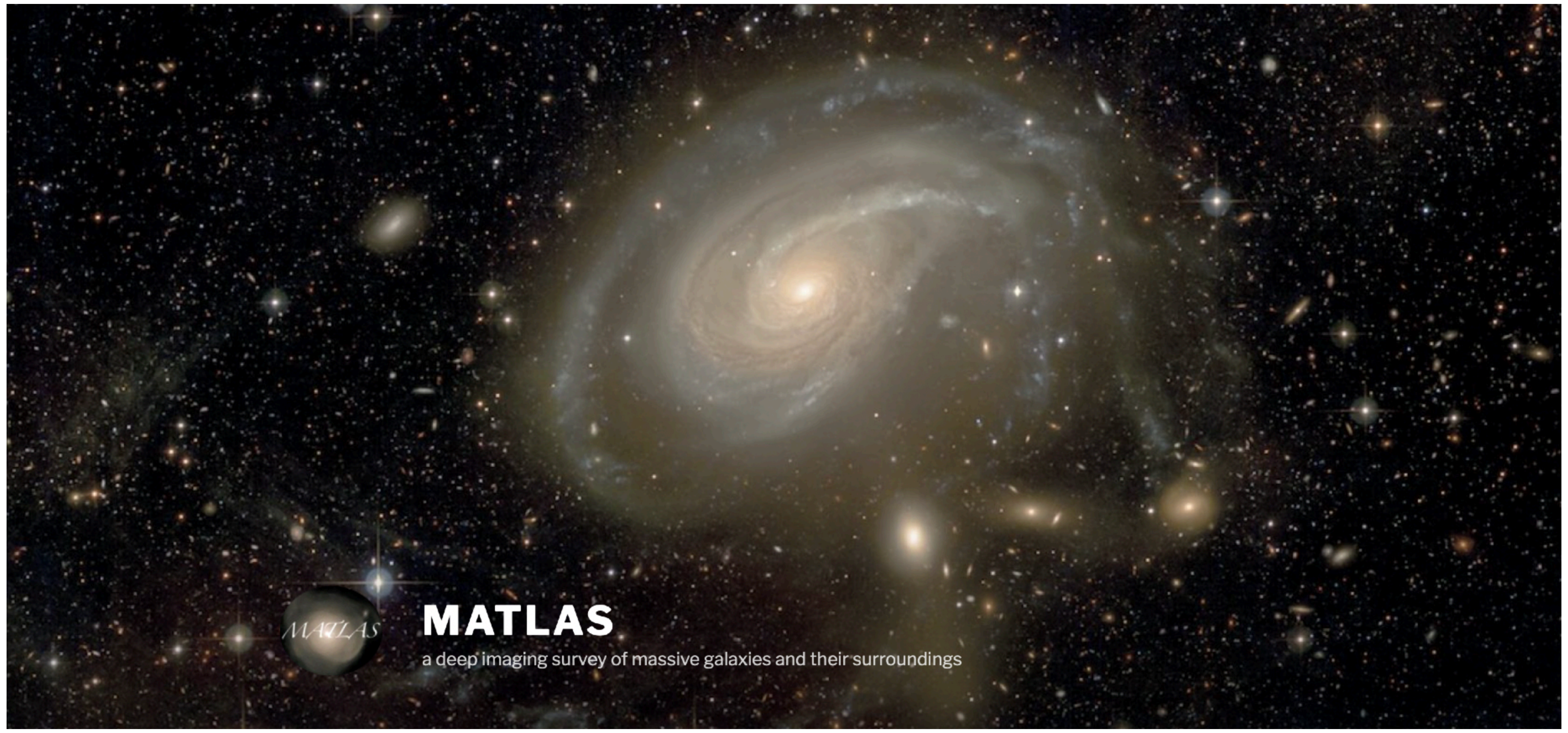
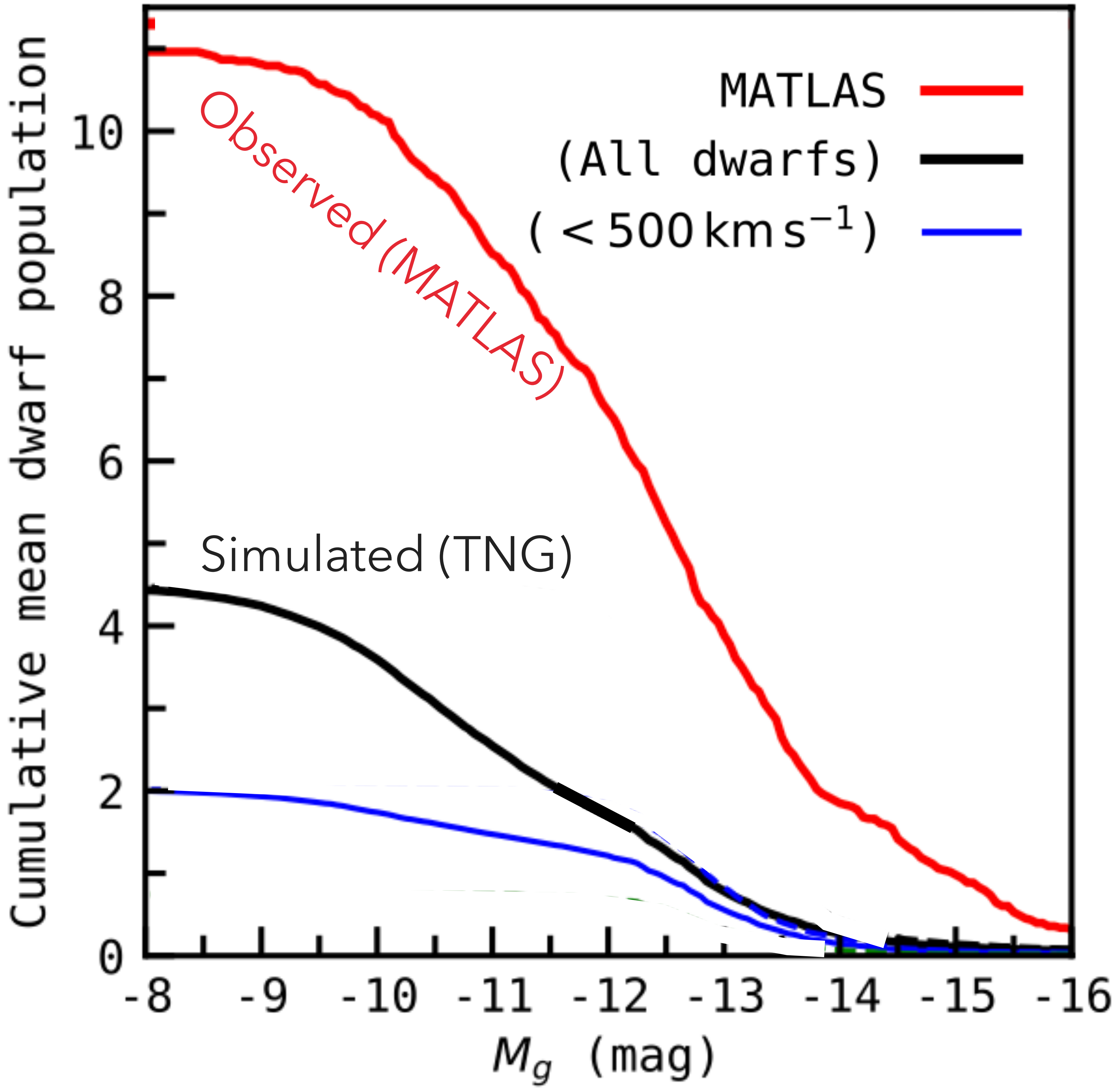


MATLAS (Kanehisa, Pawlowski et al. 2024)



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Has the Missing Satellites Problem been over-solved?
Did we focus too much on the Local Group?

Need to be cautious when assessing apparent solutions: might be tailored to the Local Group.

We need more robust tests!

Testing Cosmological Expectations with Satellite Galaxy Systems

- Predictions on galaxy scales via numerical simulations involve

Underlying Model + **Implementation of Baryonic Physics**

- Found a mismatch between observation and expectation?

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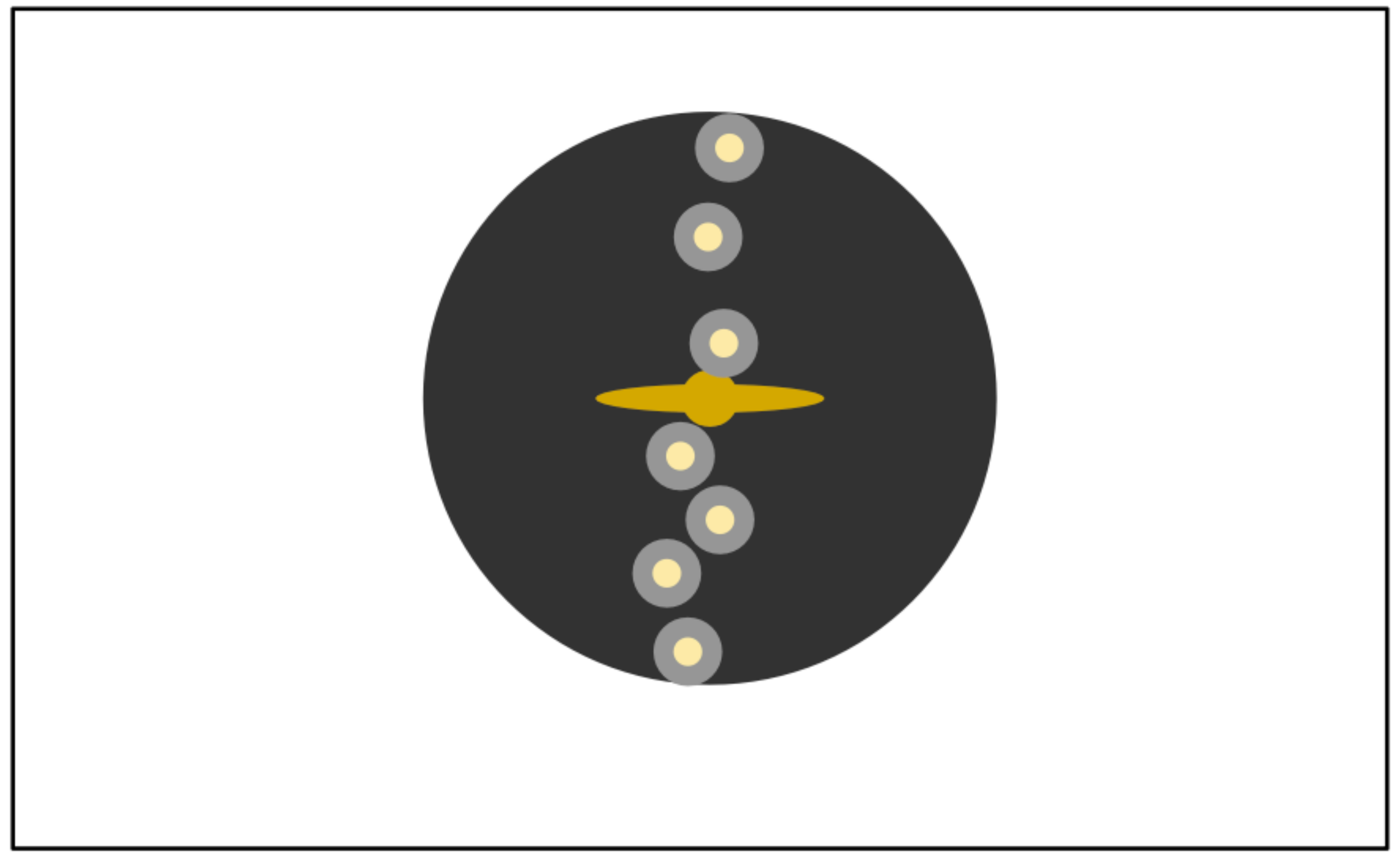
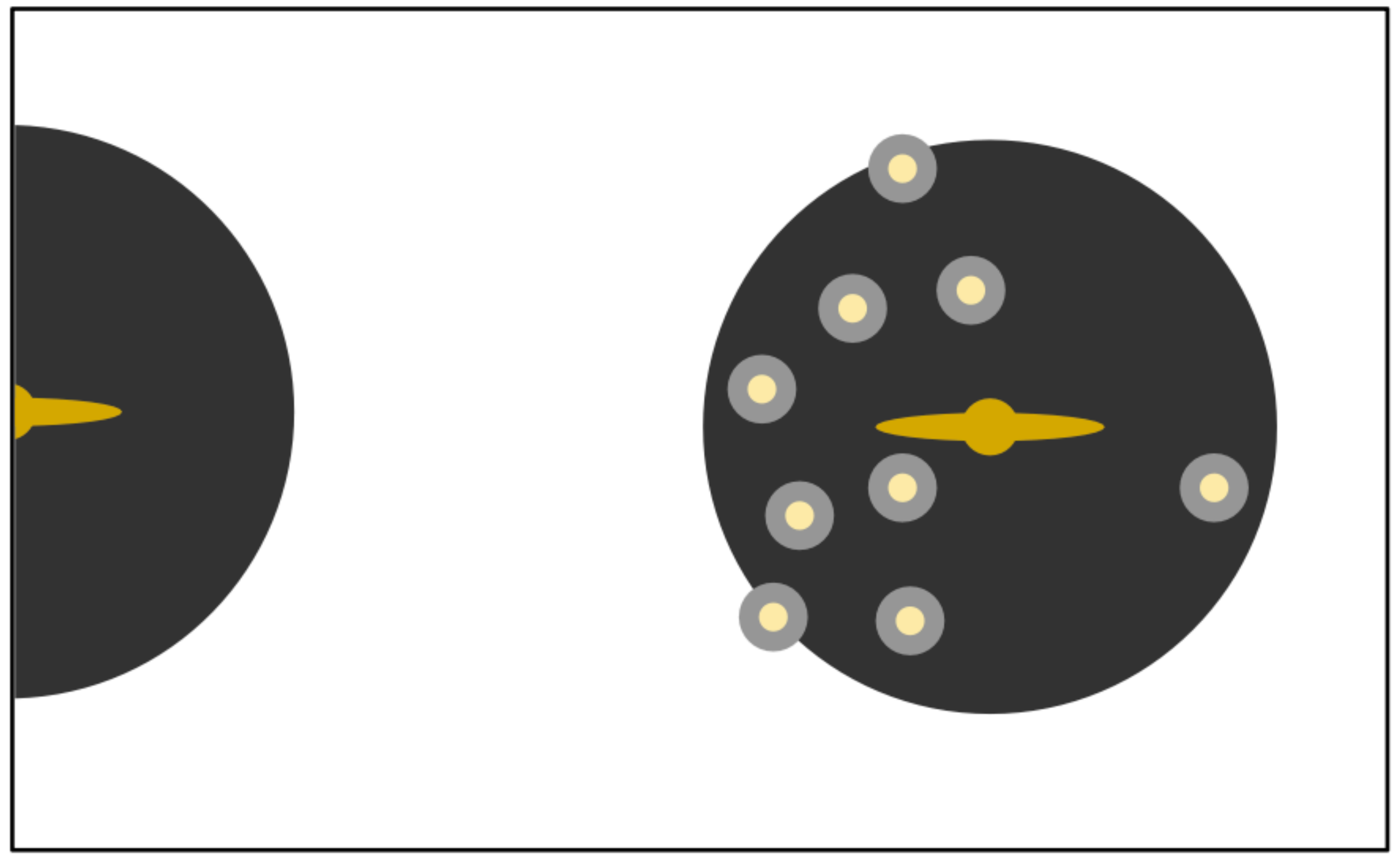
Need tests that are robust against details of baryonic physics.

← what we do

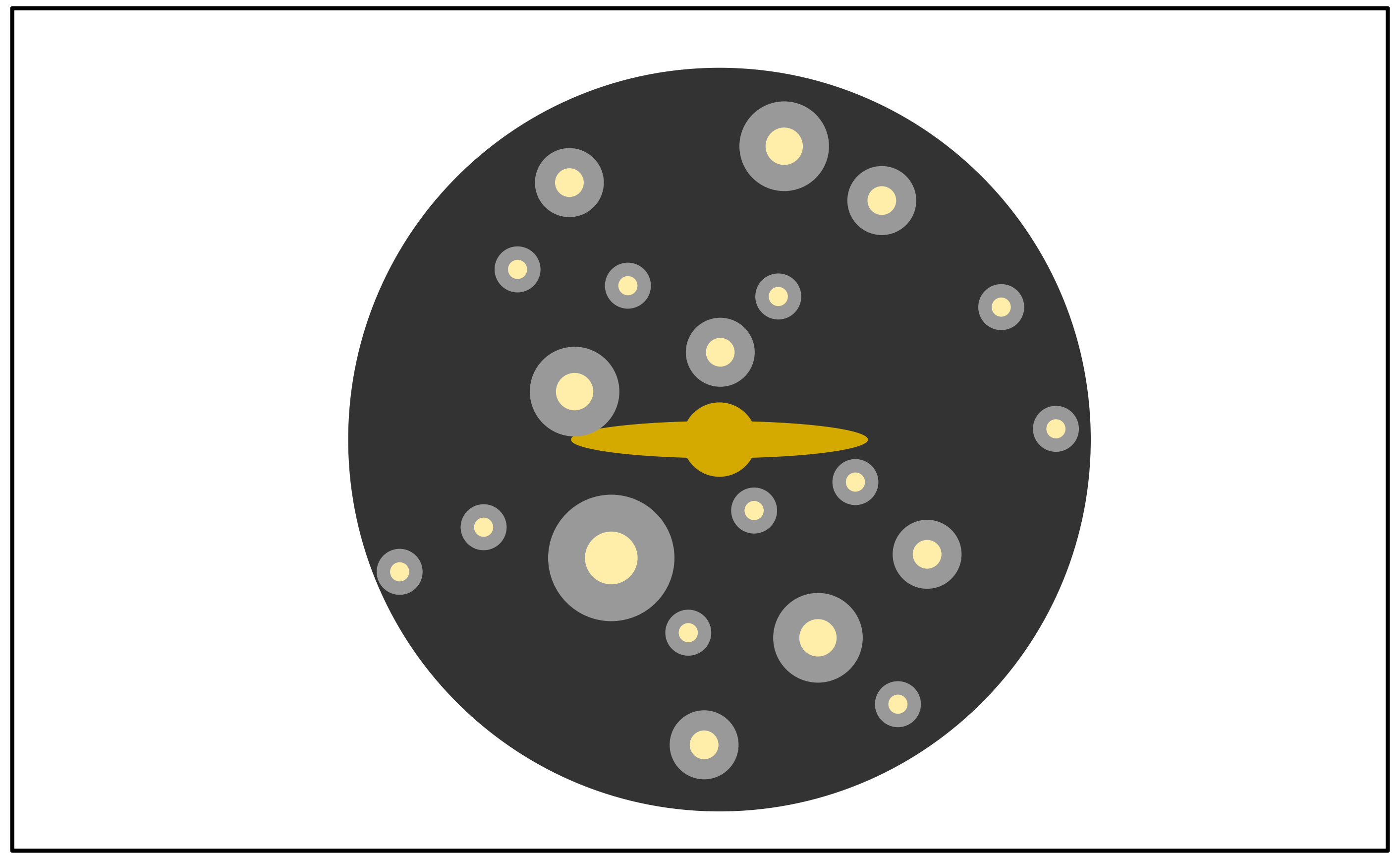
Features and Peculiarities of Satellite Galaxy Systems



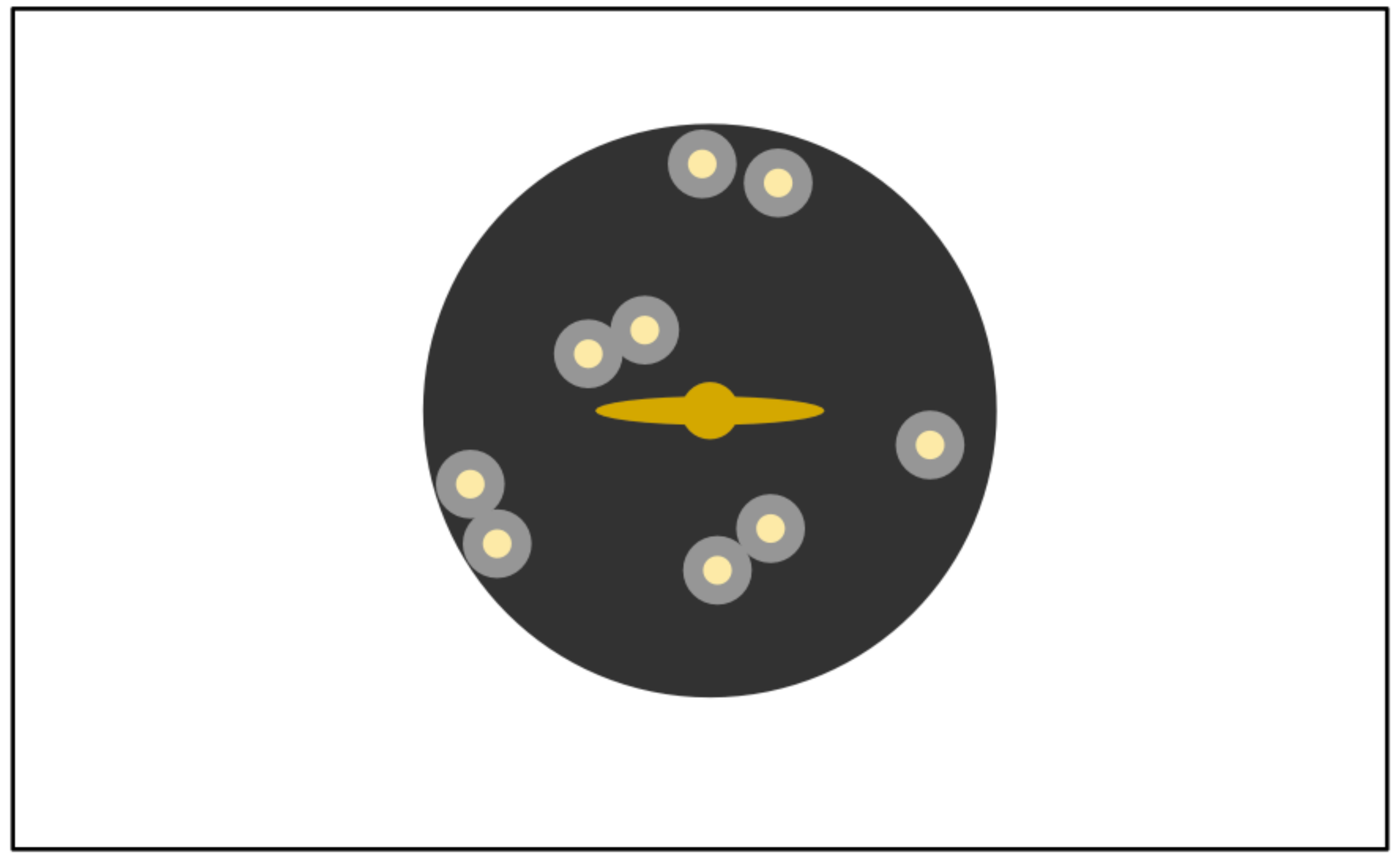
Plane of Satellites



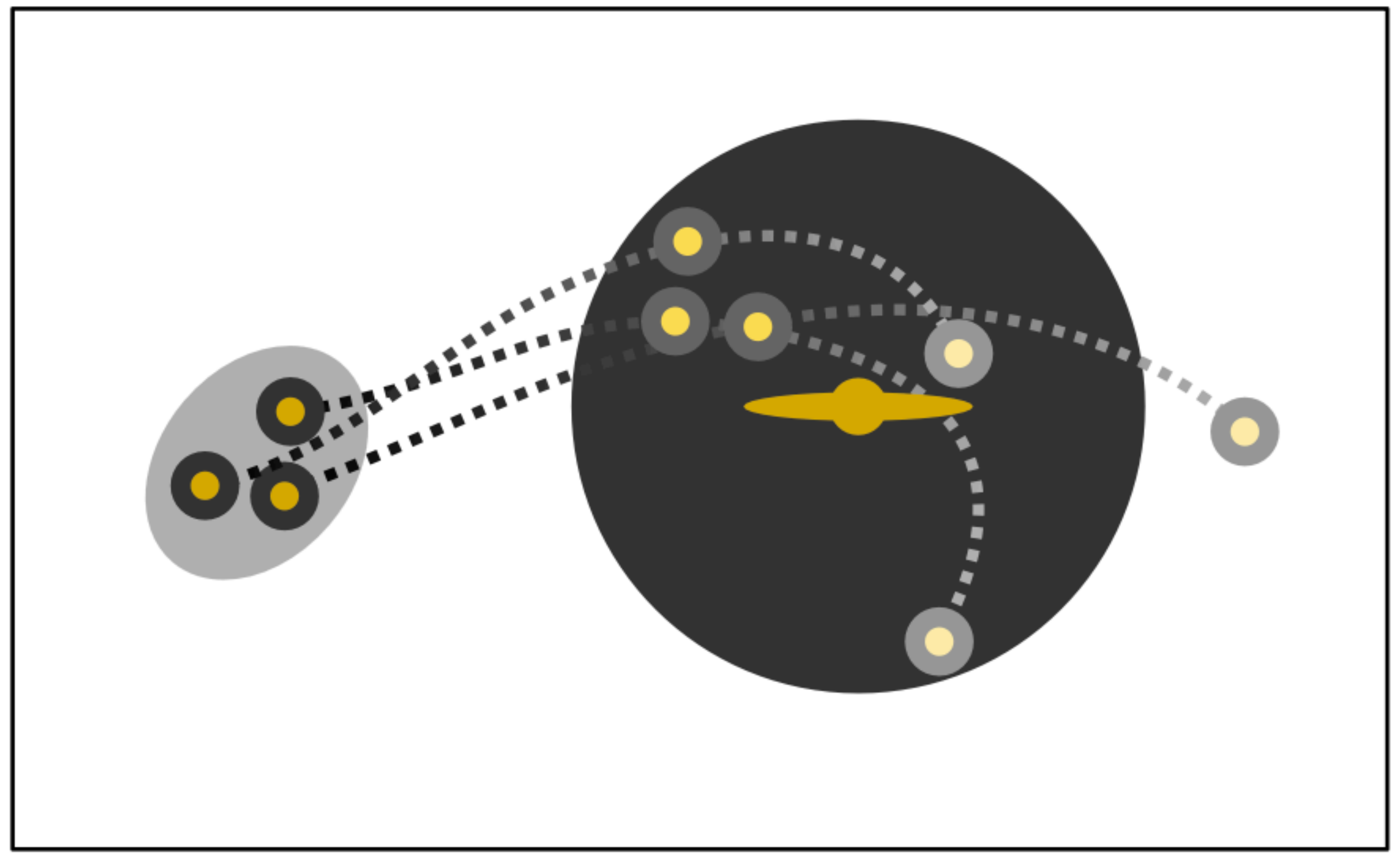
Lopsidedness



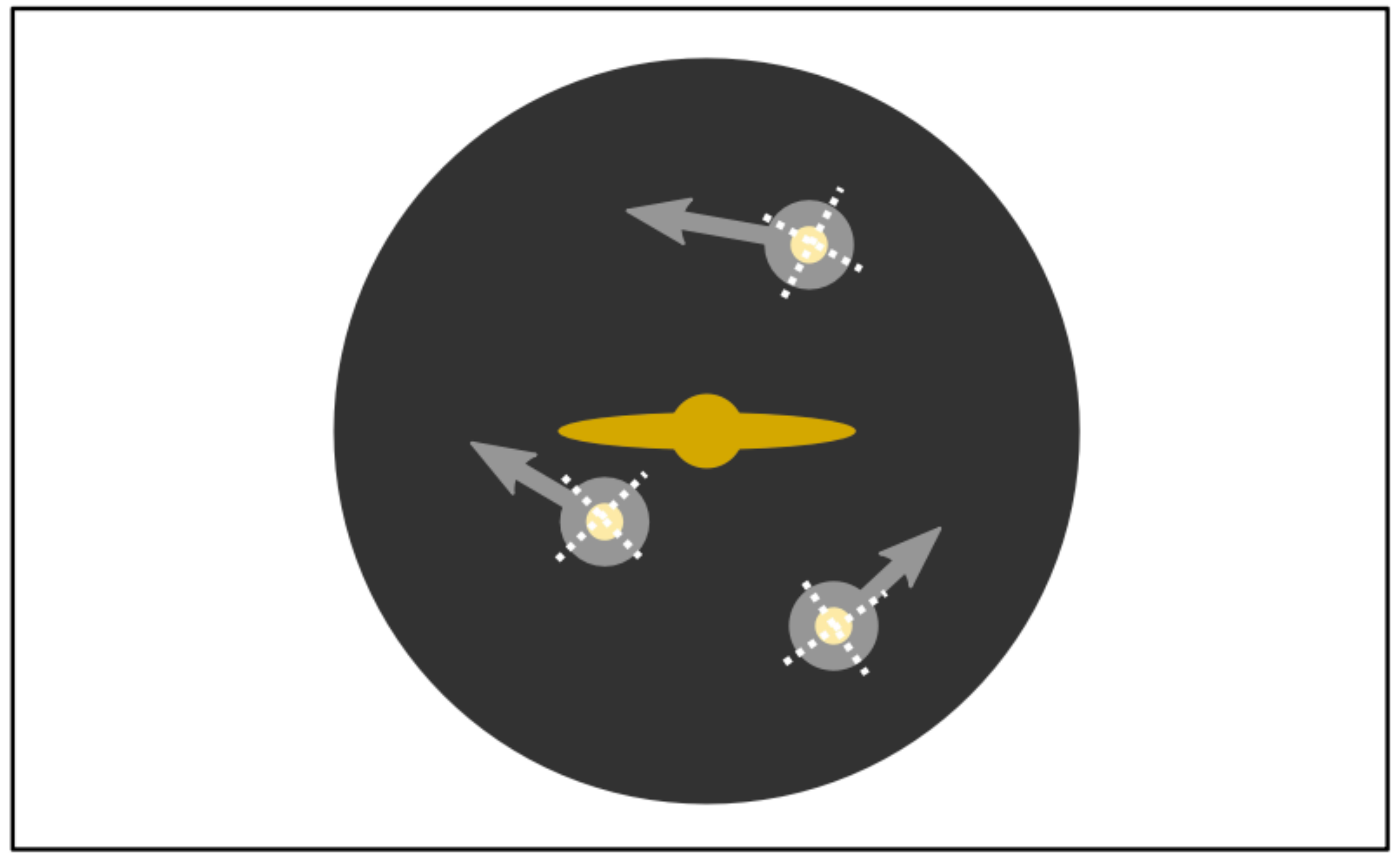
Luminosity Function



Satellite Pairs



Group Infall



Tangential Velocity Excess

Features and Peculiarities of Satellite Galaxy Systems

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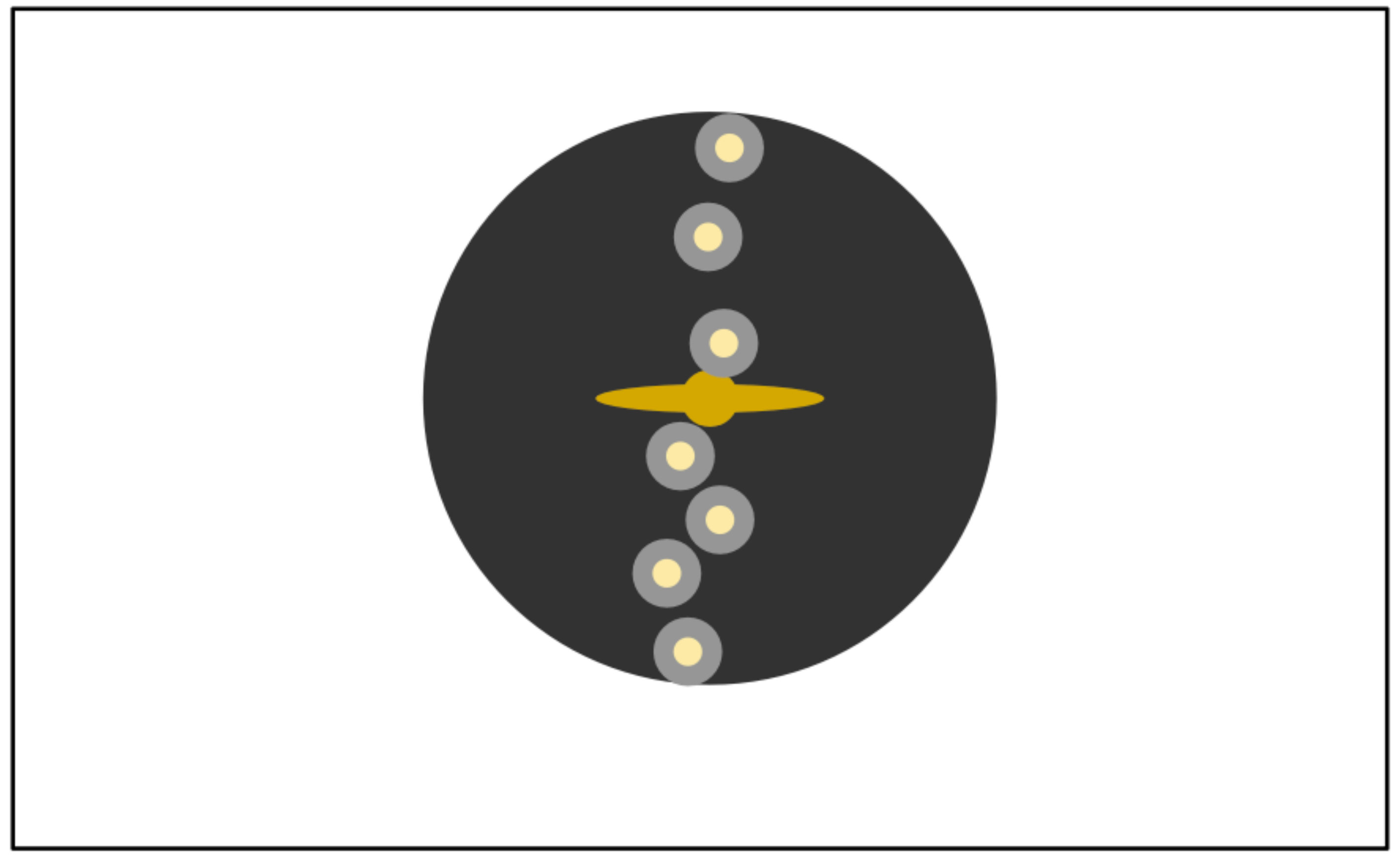

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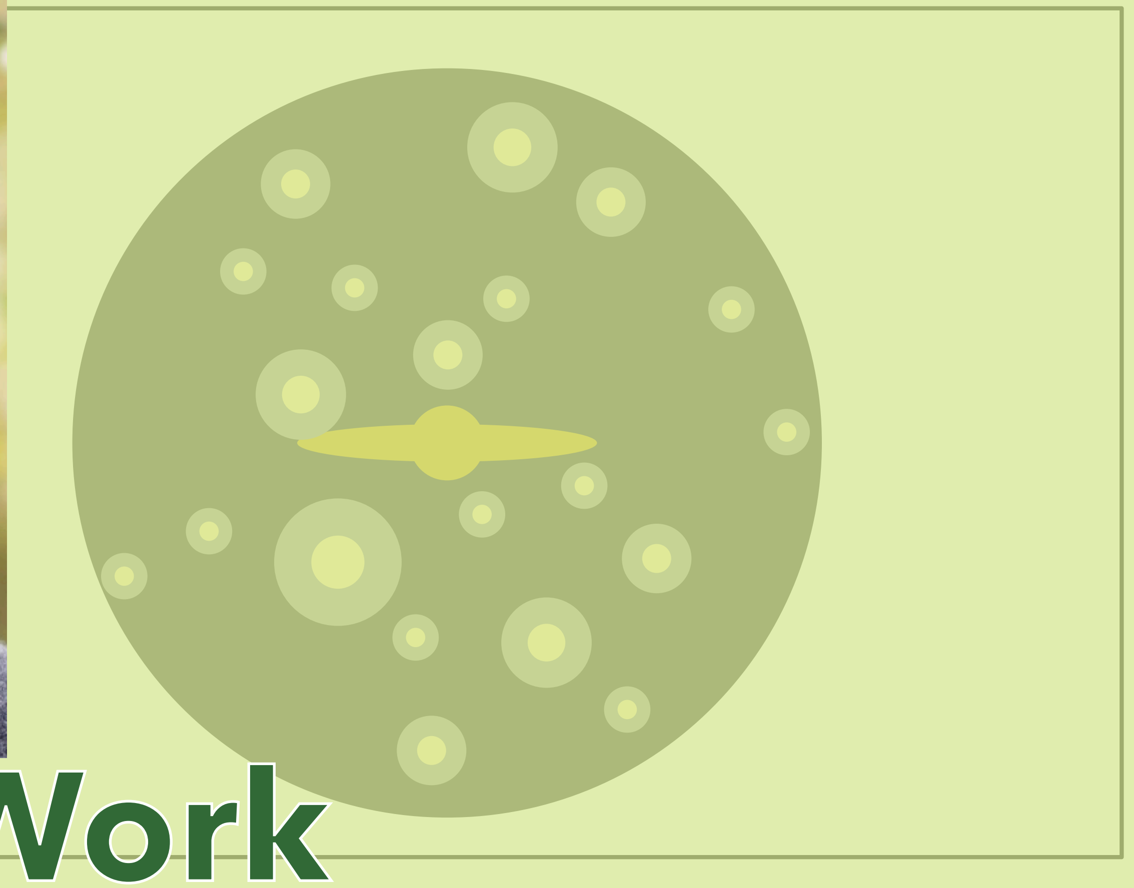
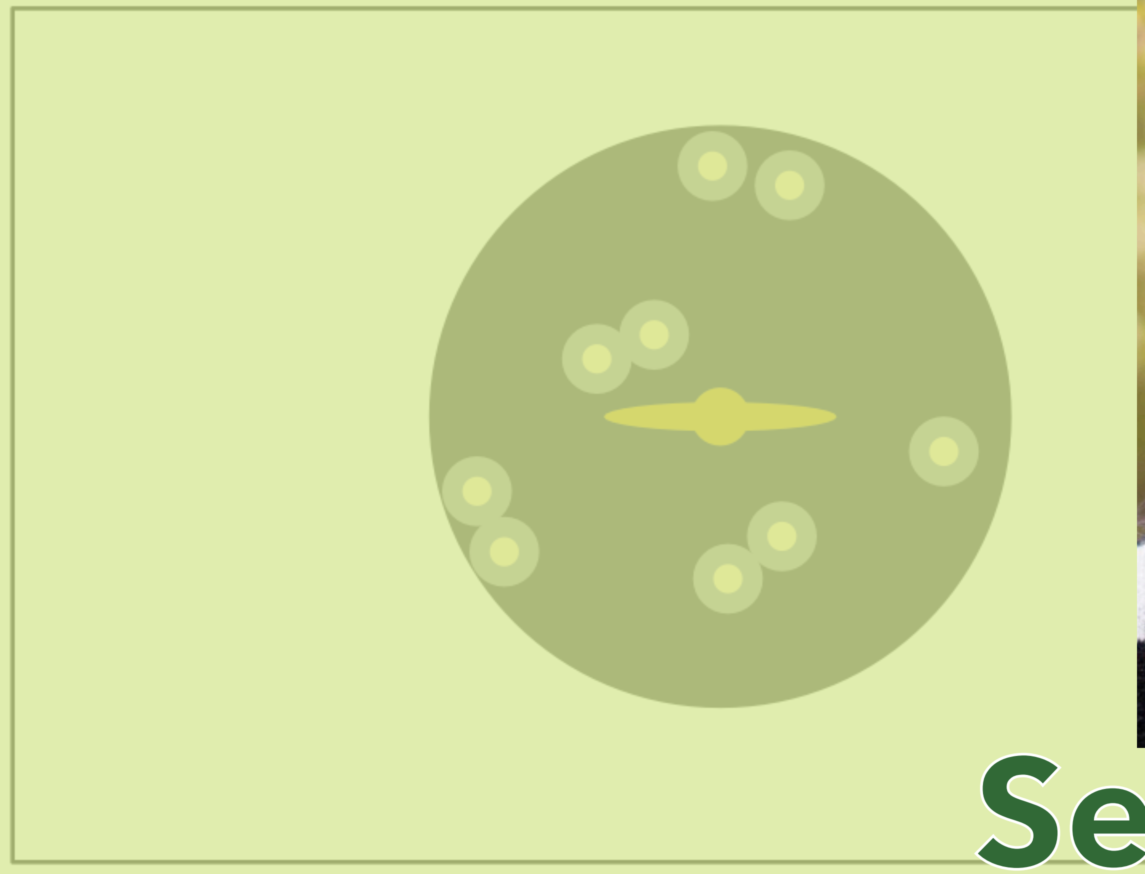


See Jamie's Work

Satellite Pairs



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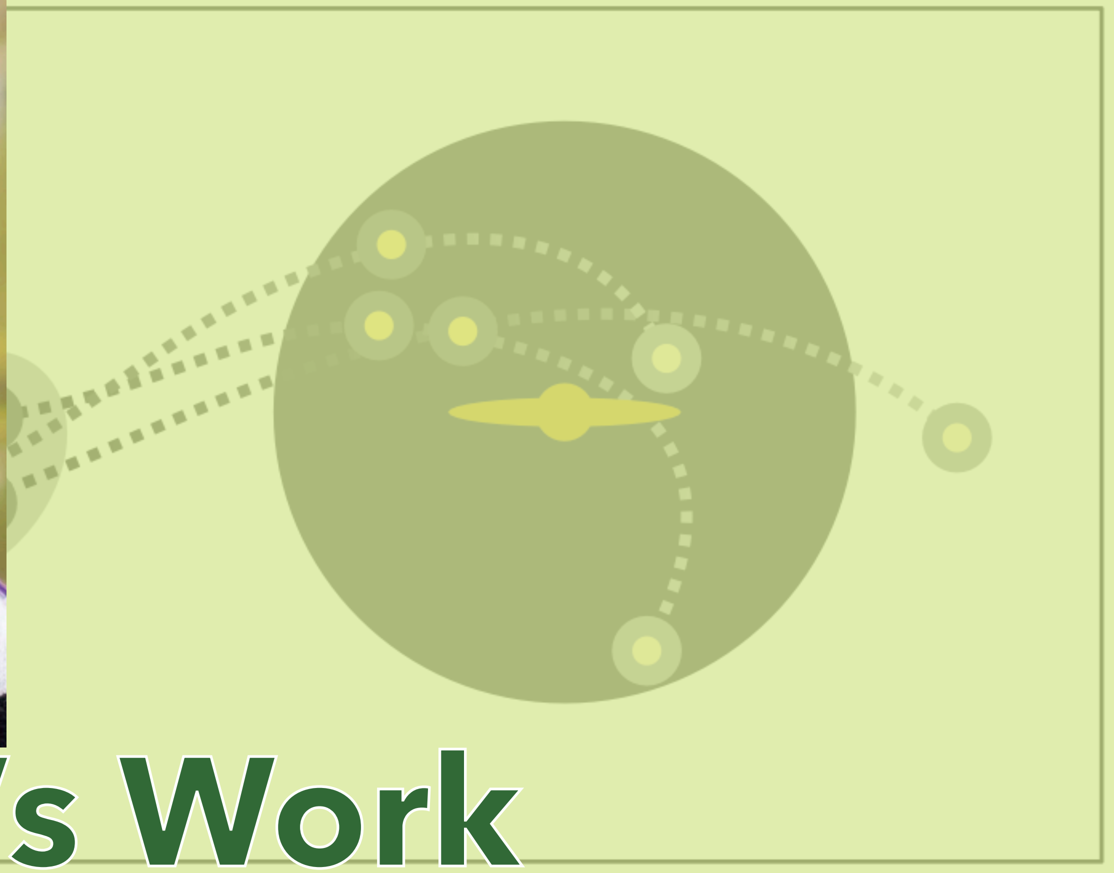
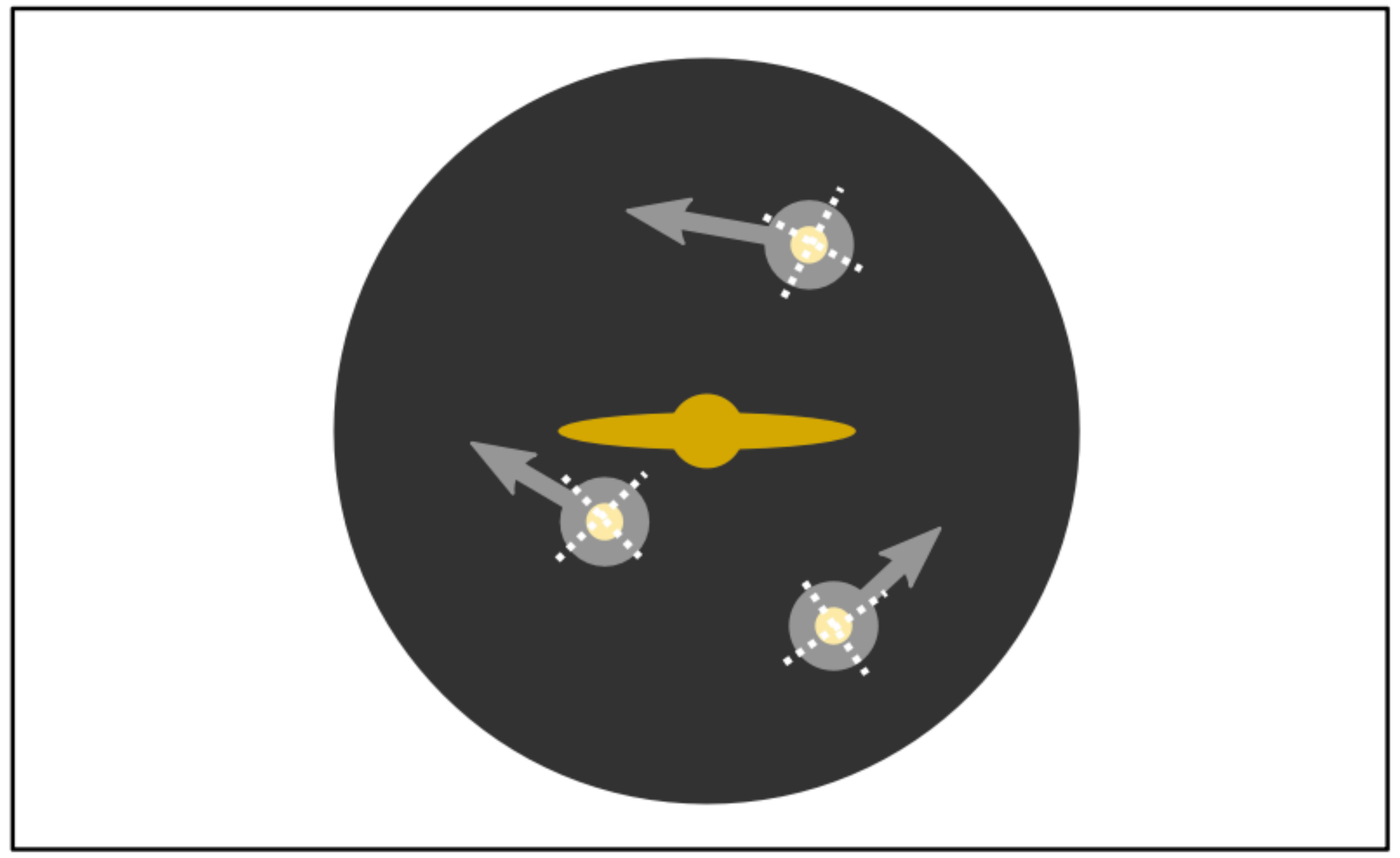
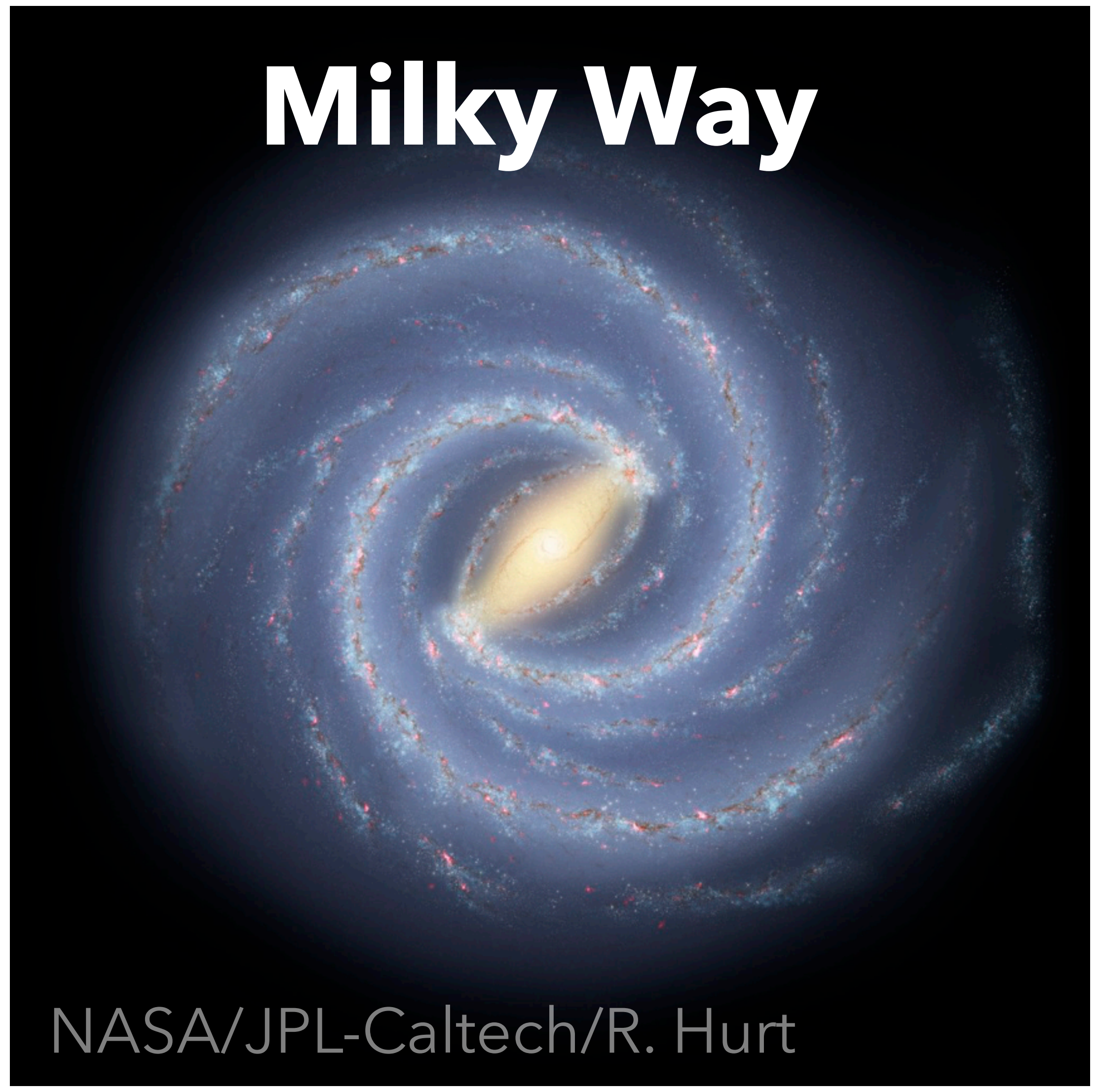


See Mariana's Work

Tangential Velocity Excess



Best-Studied Observed Cases of Satellite Galaxy Planes



Milky Way

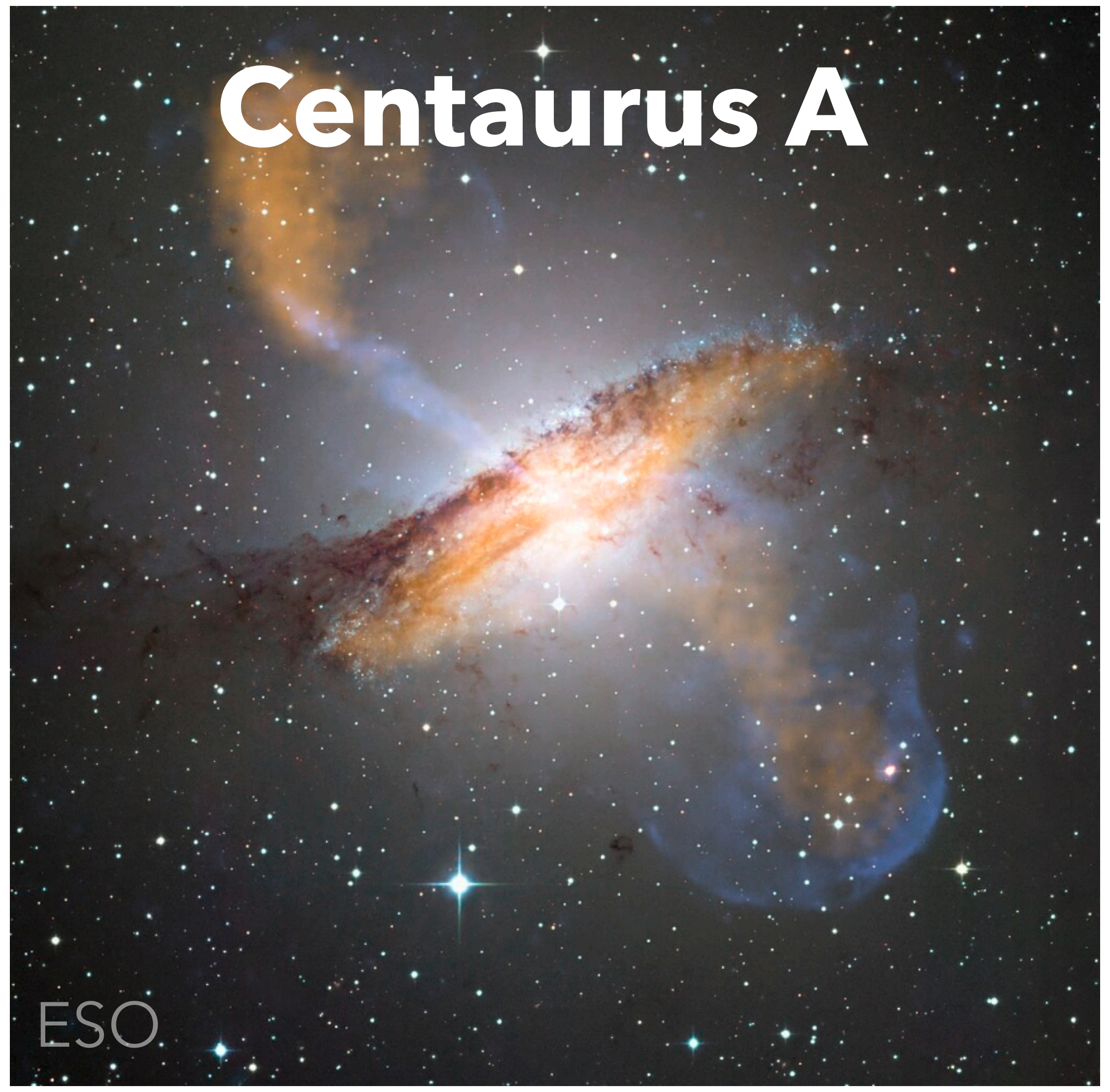
NASA/JPL-Caltech/R. Hurt

From my review (Pawlowski, 2021)

Andromeda

I, Luc Viatour

Casetti-Dinescu, Pawlowski et al. (2025)



Centaurus A

ESO

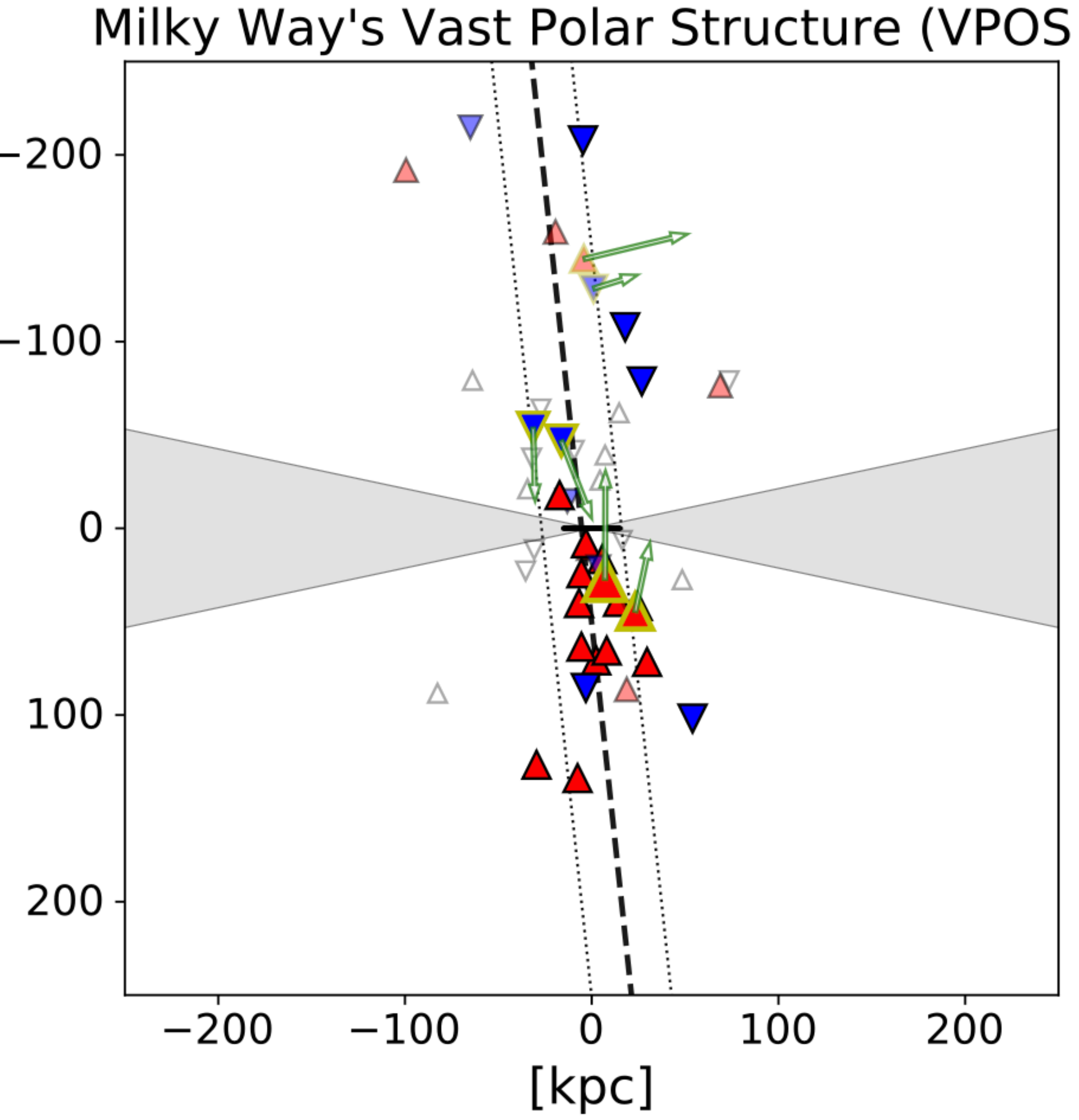
From my review (Pawlowski, 2021)

NGC 4490

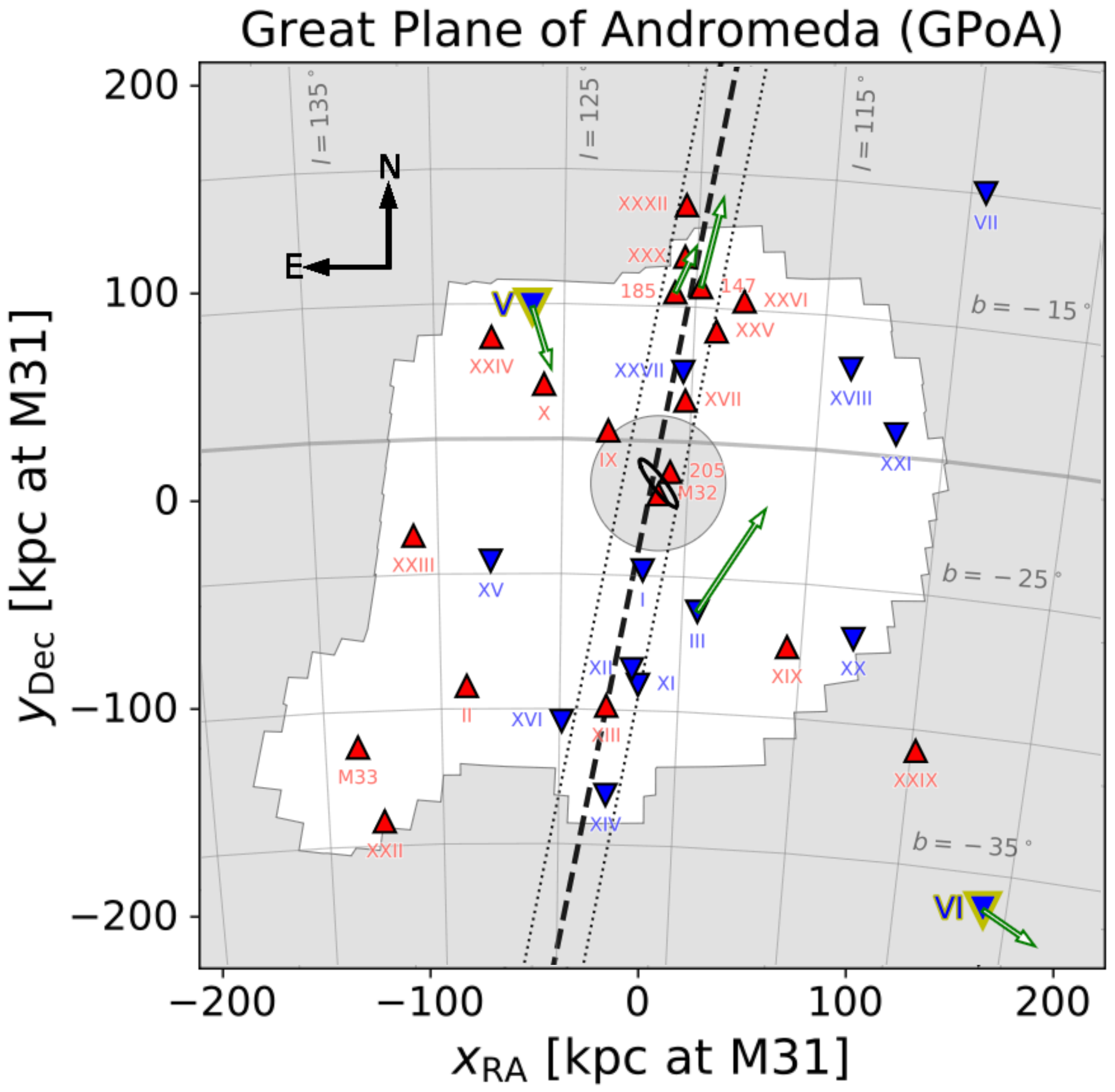
ESA/Hubble

Pawlowski et al. (2024)

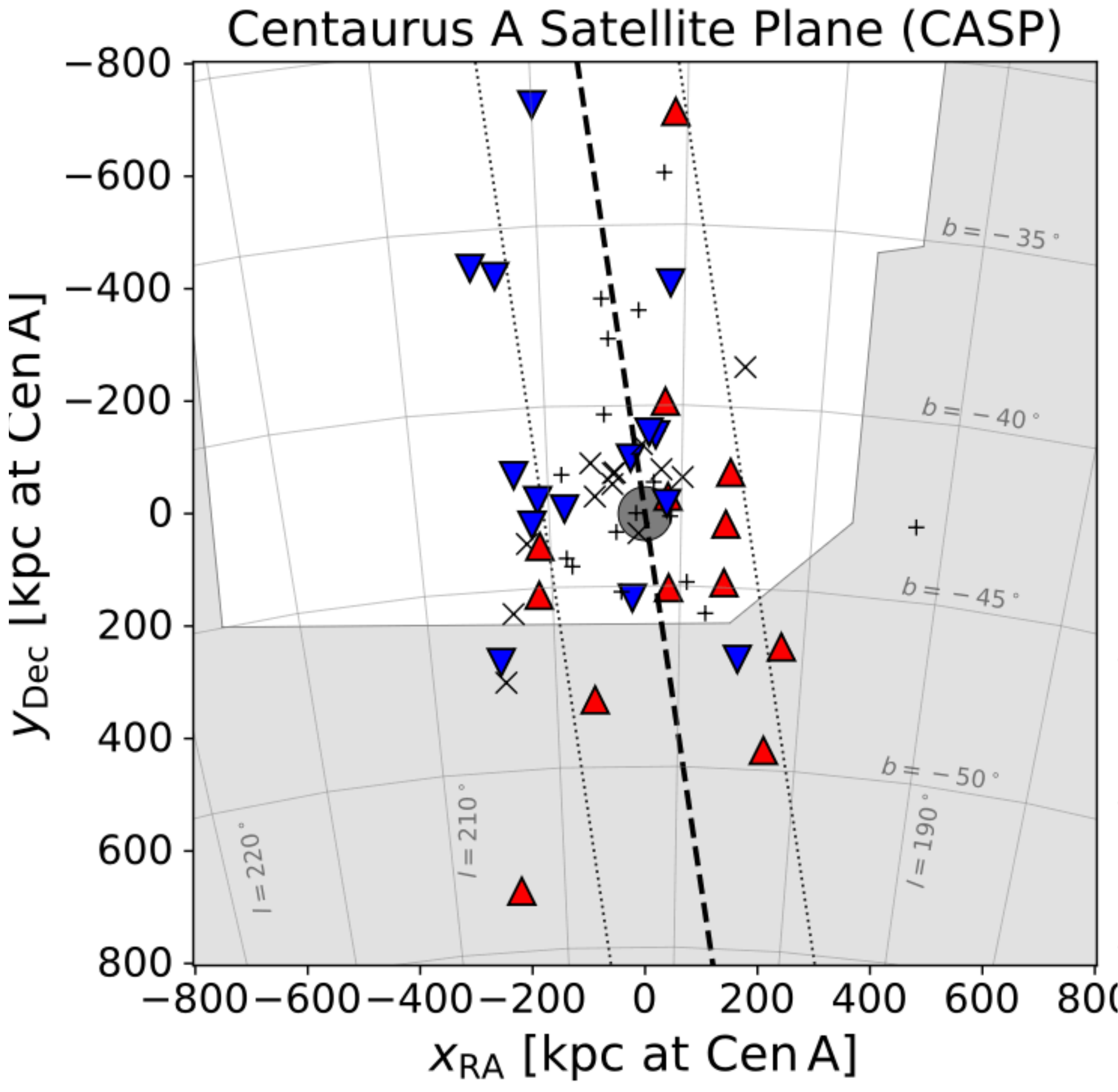
Best-Studied Observed Cases of Satellite Galaxy Planes


Milky Way's Vast Polar Structure (VPOS

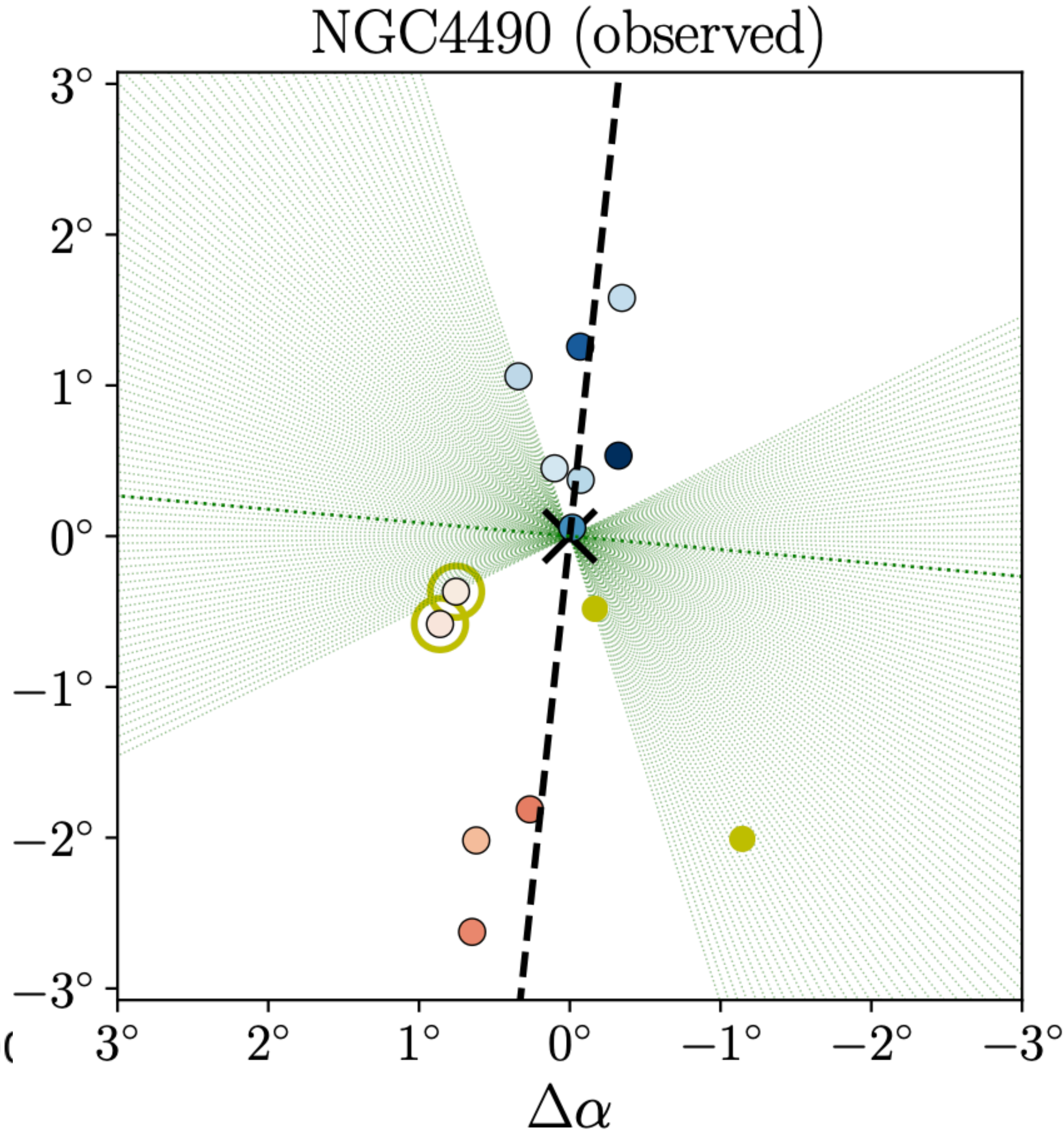
From my review (Pawlowski, 2021)


Great Plane of Andromeda (GPoA)

Casetti-Dinescu, Pawlowski et al. (2025)


Centaurus A Satellite Plane (CASP)

From my review (Pawlowski, 2021)


NGC4490 (observed)

Pawlowski et al. (2024)

proper motions
→ 3D velocities
→ orbital poles align

Tension of current systems with Cold Dark Matter simulations

Observed flattening (horizontal) and orbital coherence (vertical)

From my review (Pawlowski, 2021)

Pawlowski et al. (2024)

Similarly extreme structures are **exceedingly rare in ΛCDM** simulations (~ 1/1000 hosts).

Possible Origins

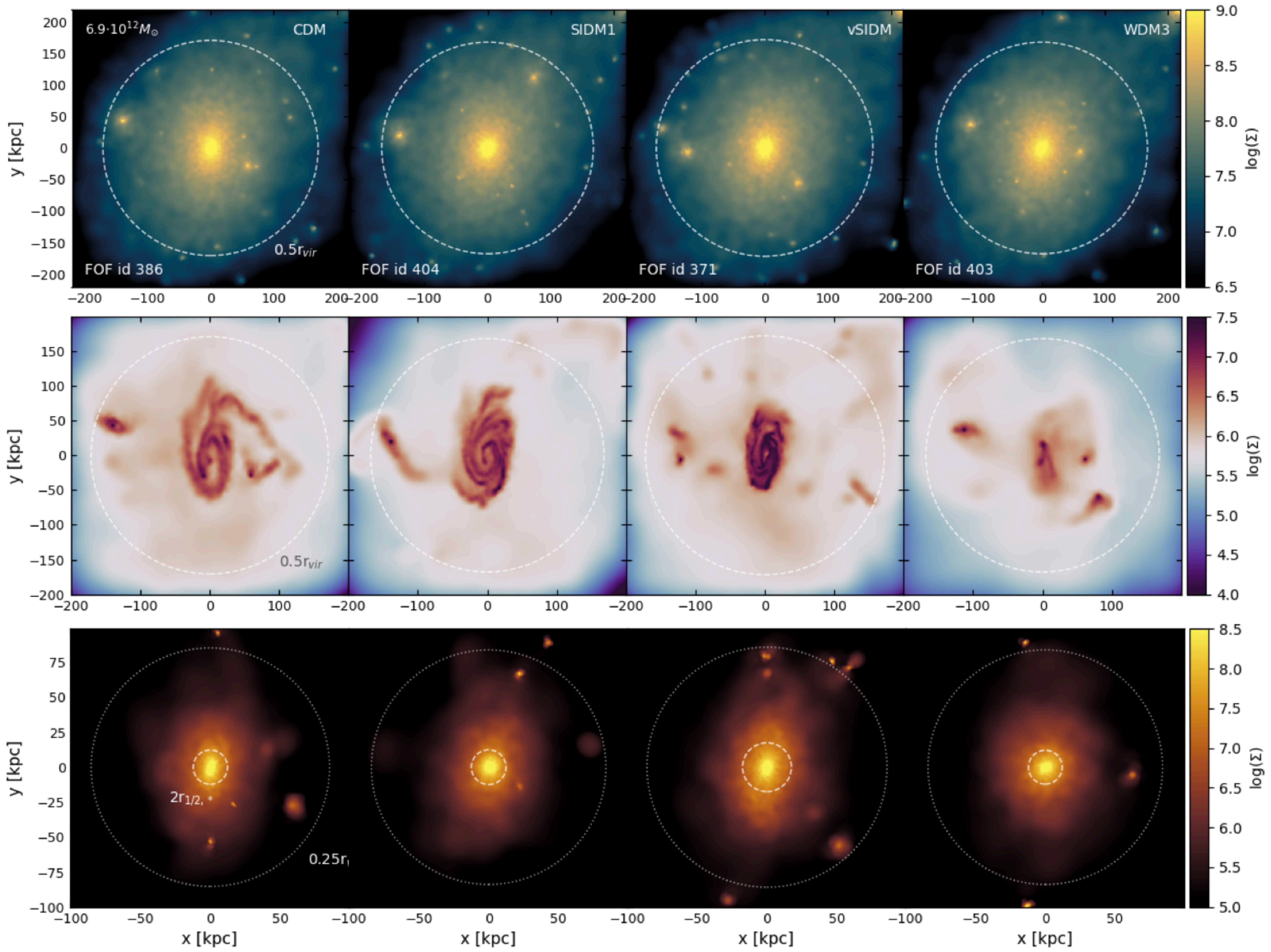
Do Alternative Dark Matter Types help?

Soumya Dhavale

Investigate AIDA TNG simulations (Despali et al. 2025):

- **Self-Interacting Dark Matter (SIDM)** and **Warm Dark Matter (WDM)**
- Otherwise identical initial conditions as **Cold Dark Matter (CDM)** runs

Despali, G., et al.: A&A, 697, A213 (2025)



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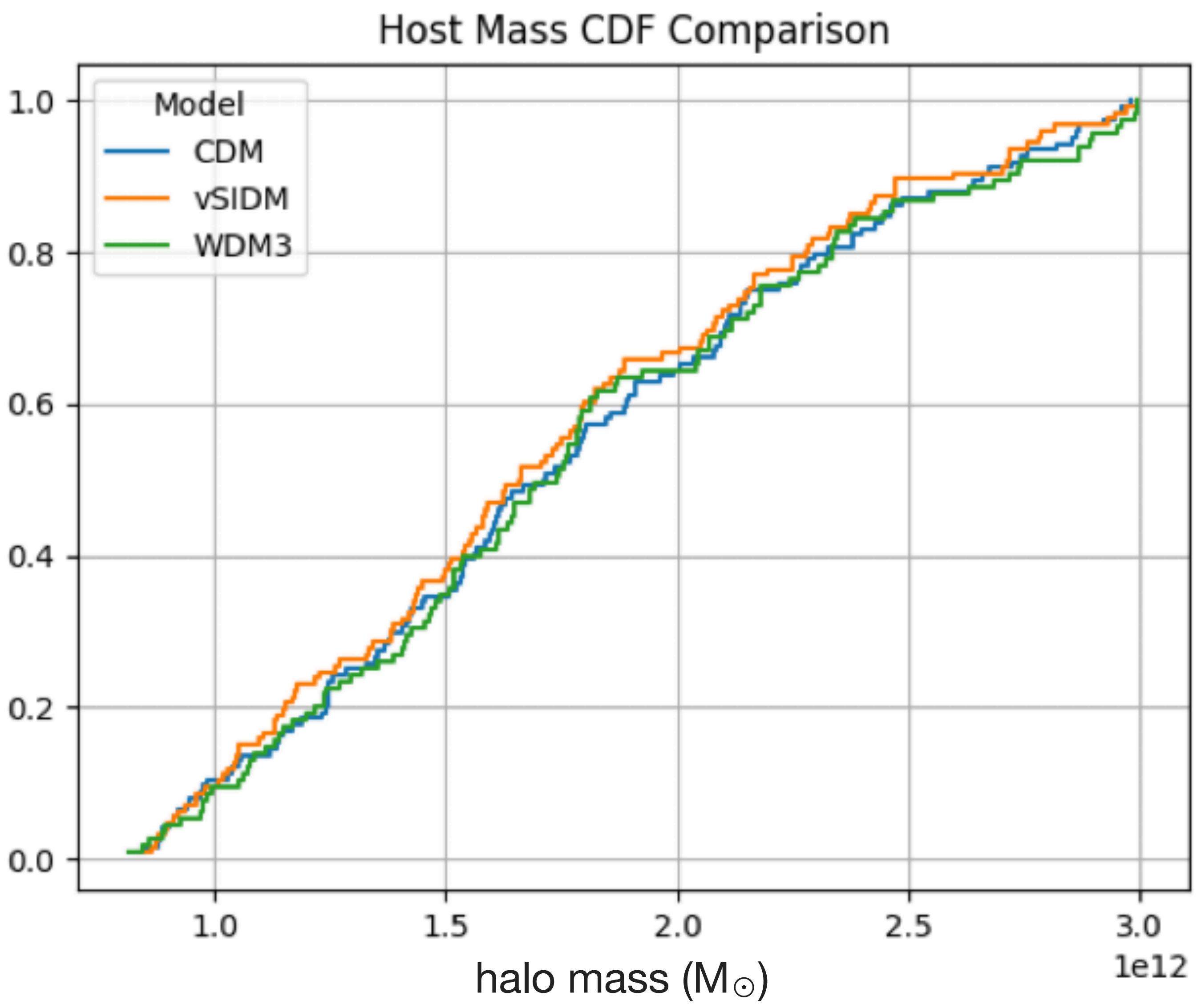

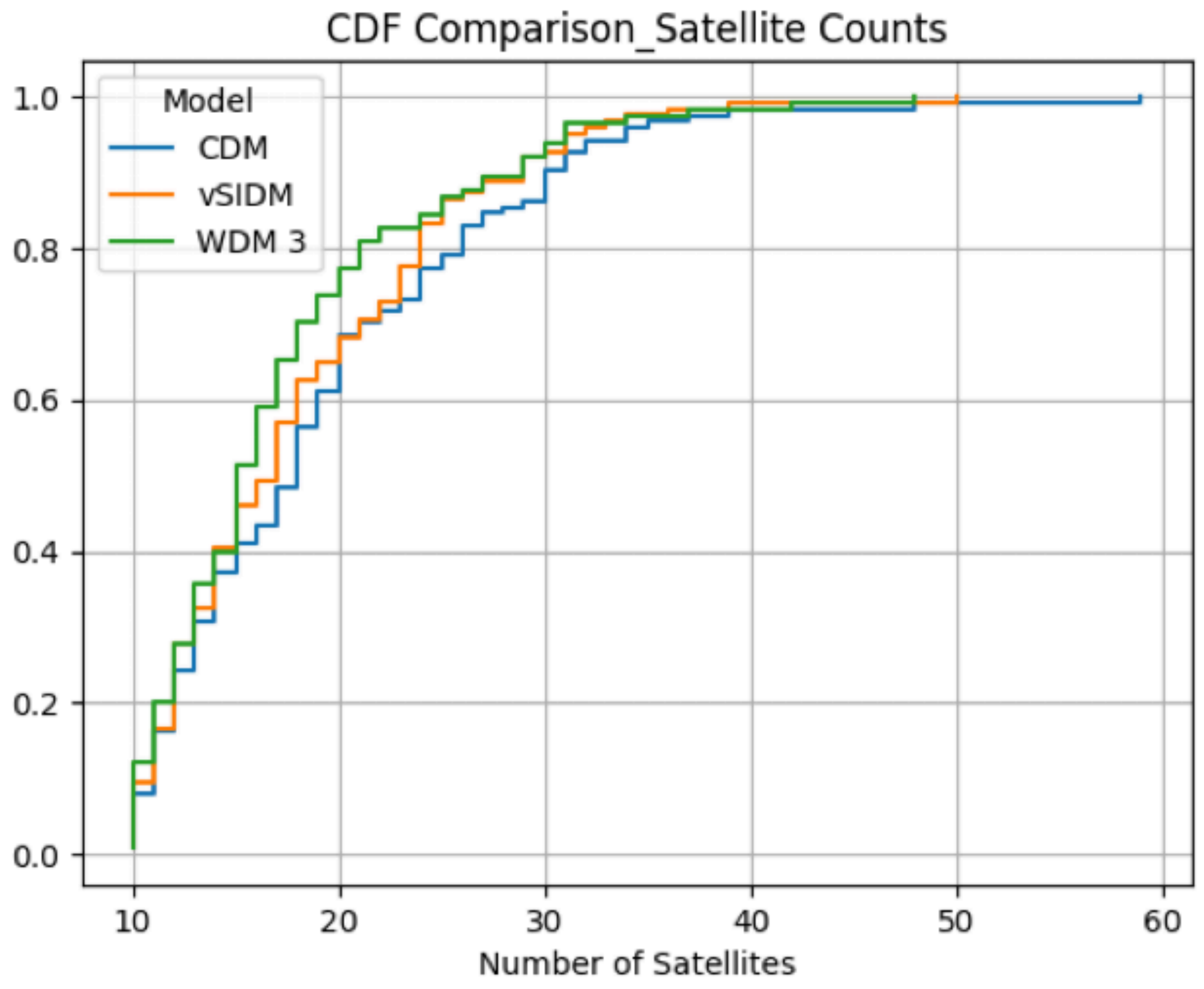

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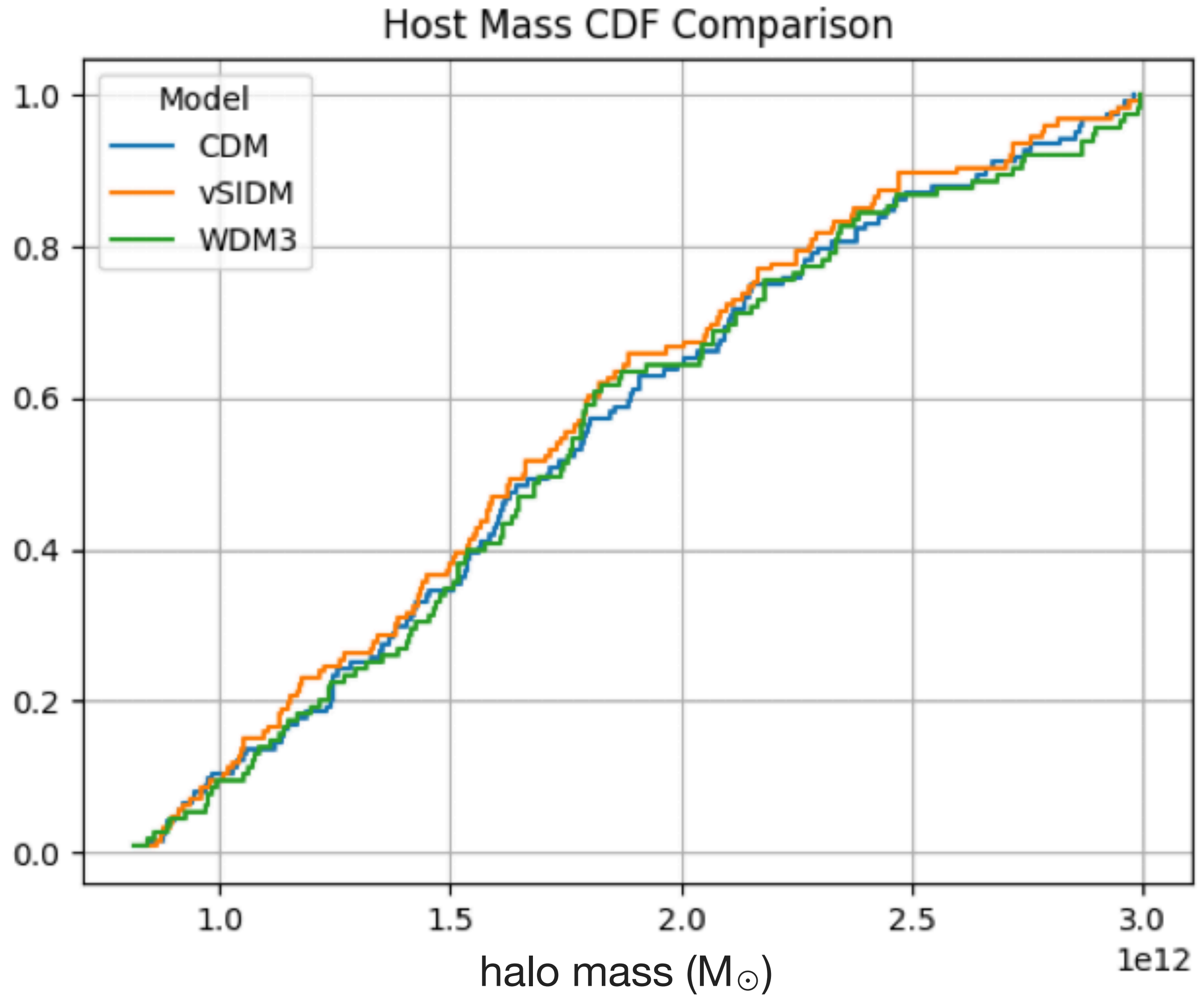

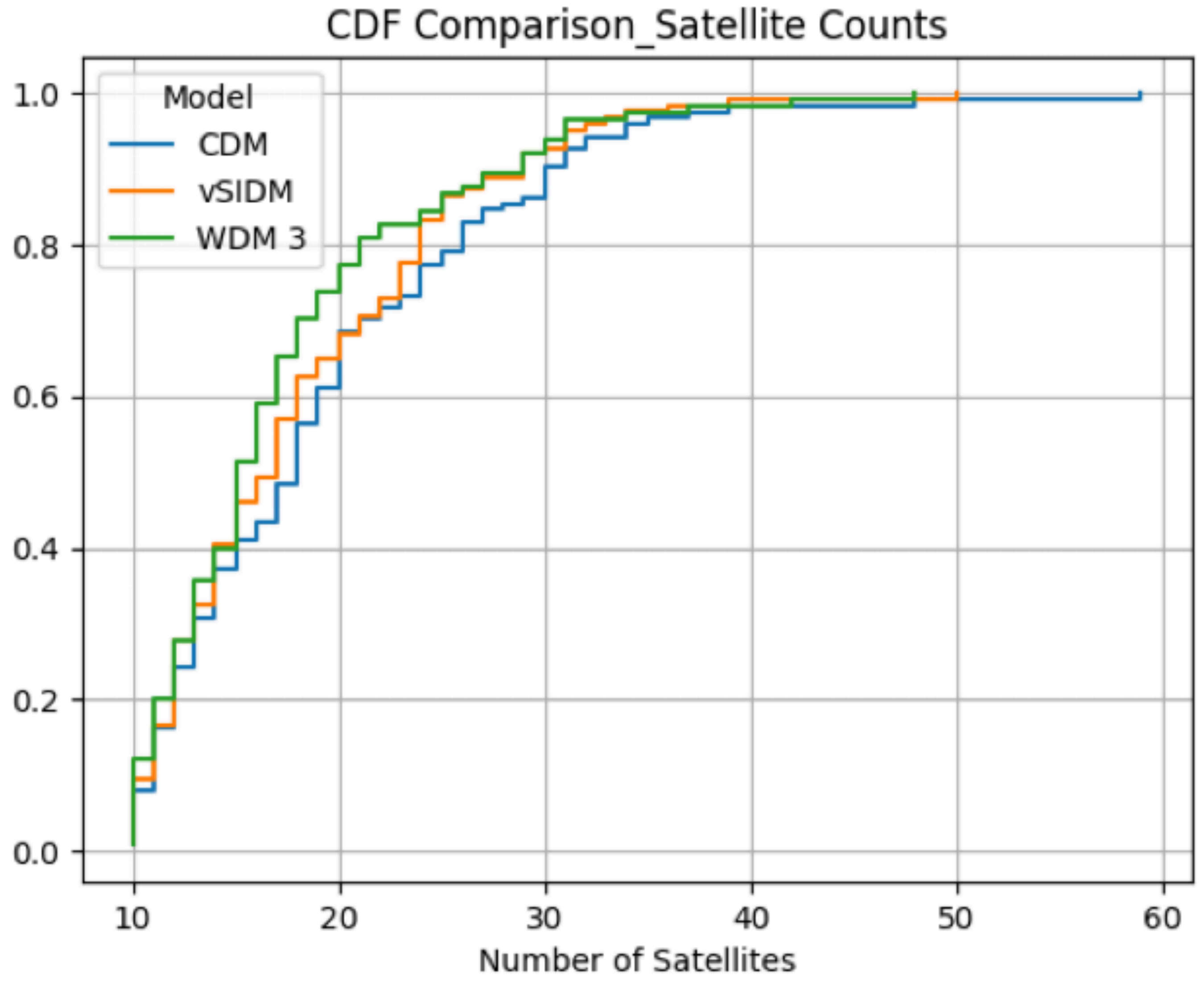

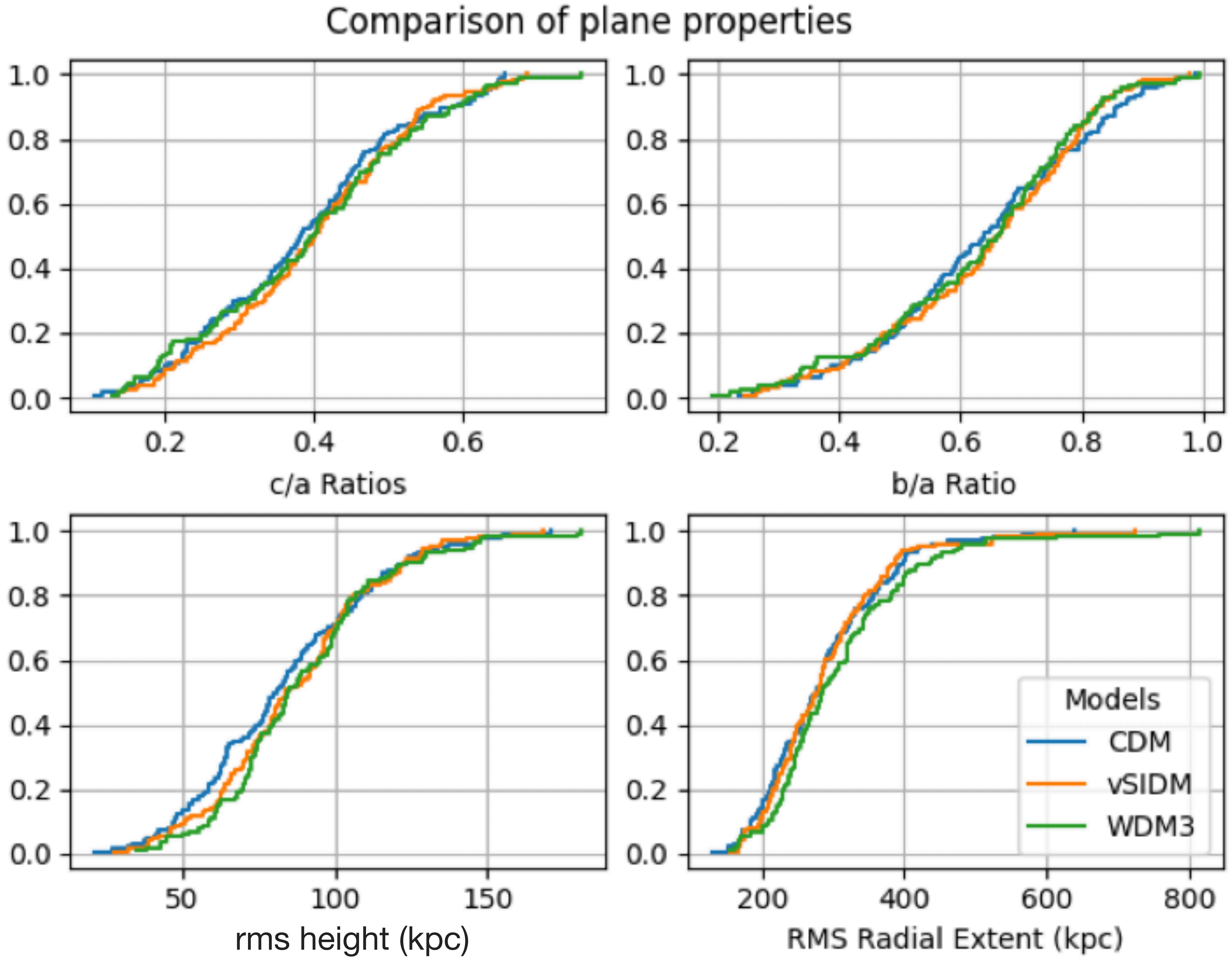

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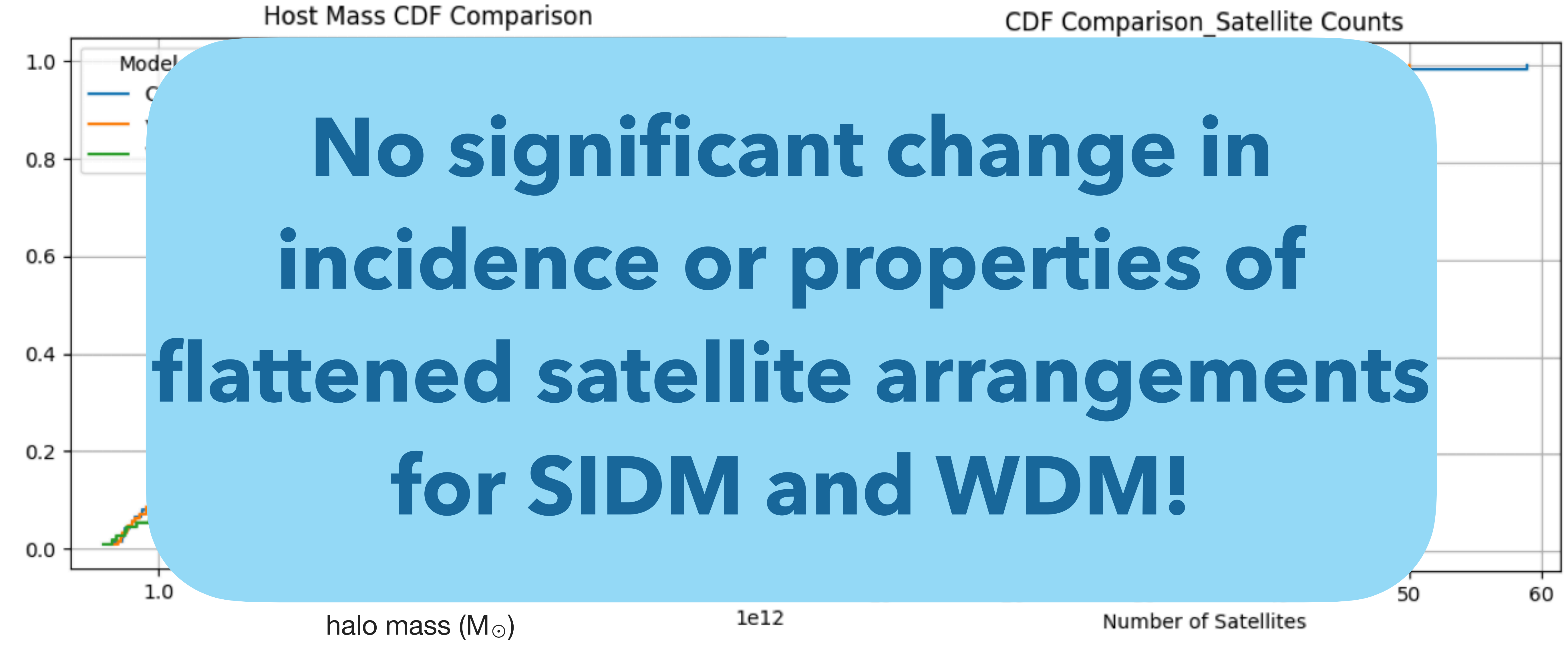
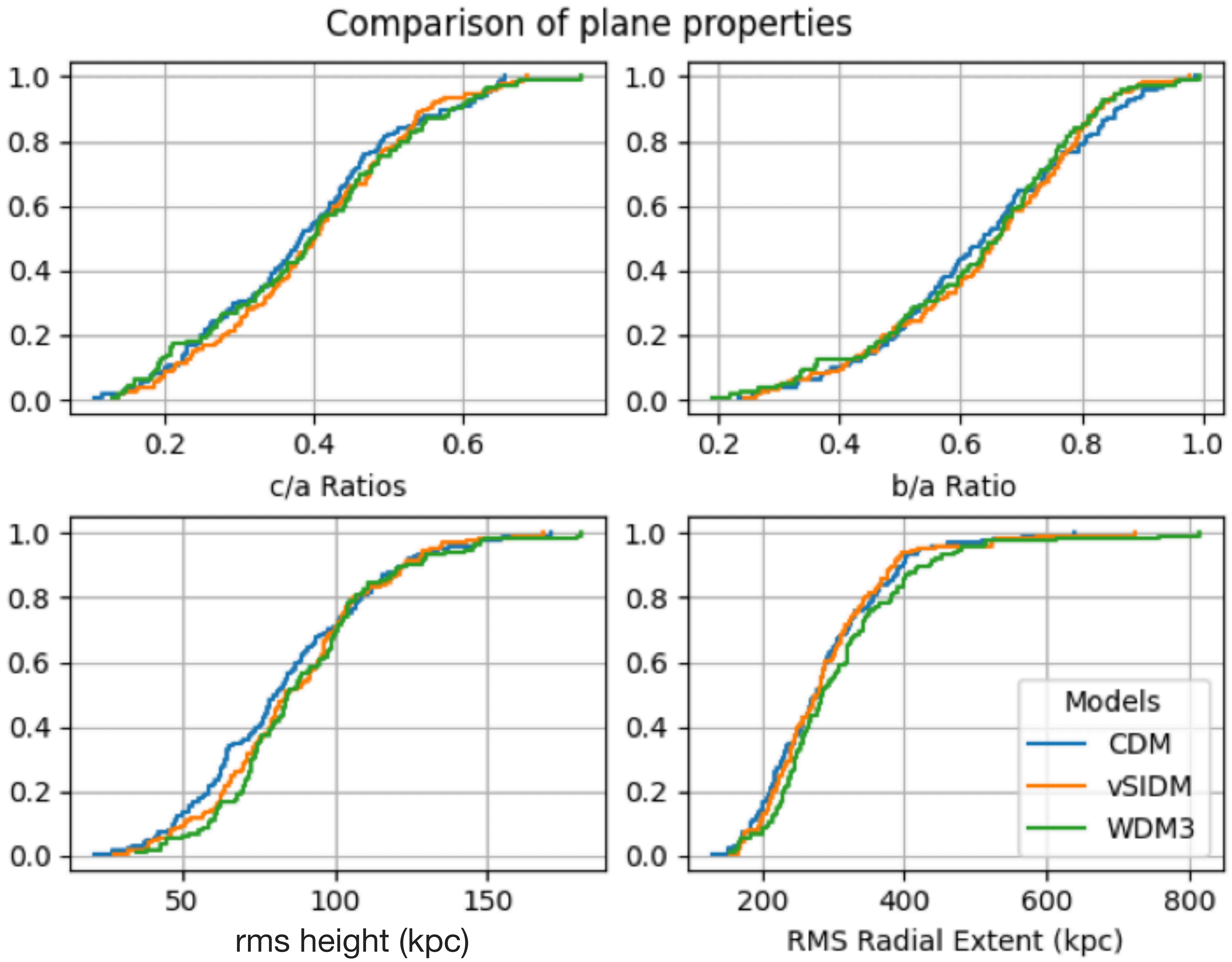


No significant change in incidence or properties of flattened satellite arrangements for SIDM and WDM!

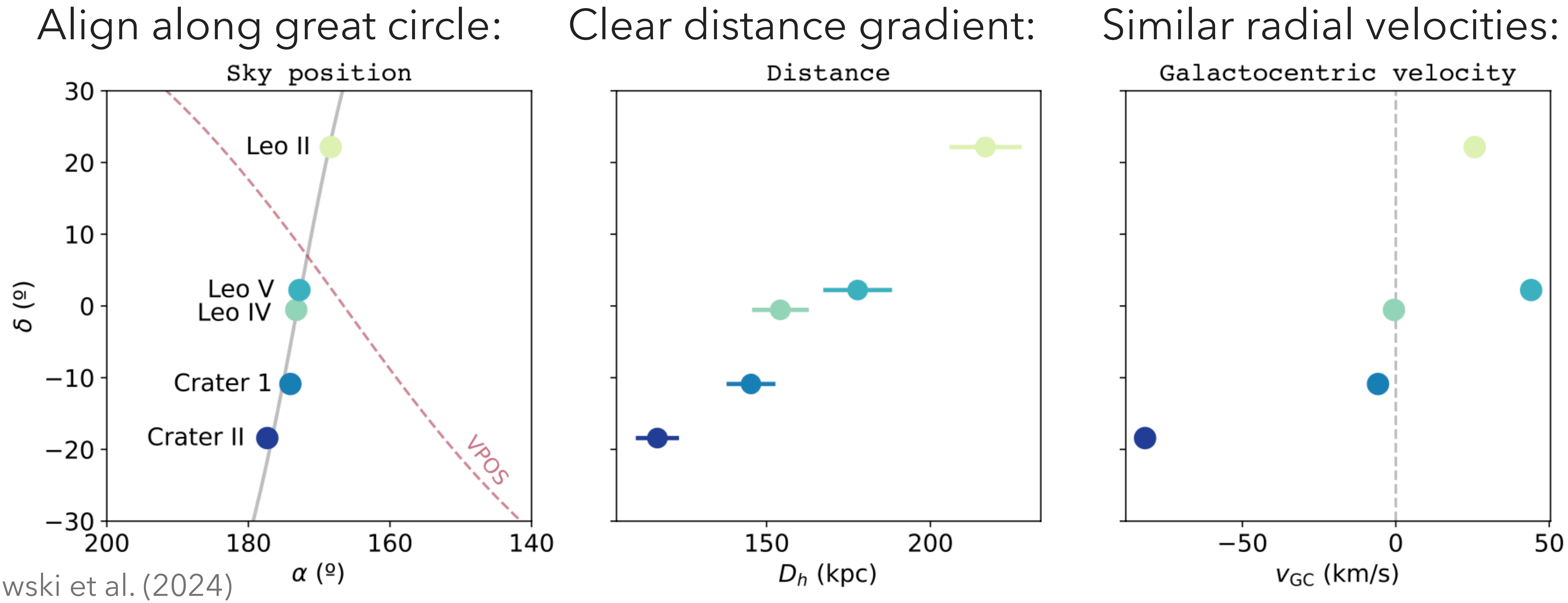


Group Infall: the case of the Crater-Leo Objects

Mariana Pouseiro Júlio

HSTPROMO

- In collaboration with T. Sohn & R. van der Marel:
  We measured new HST proper motions for Leo IV + V.



Align along great circle:

Clear distance gradient:

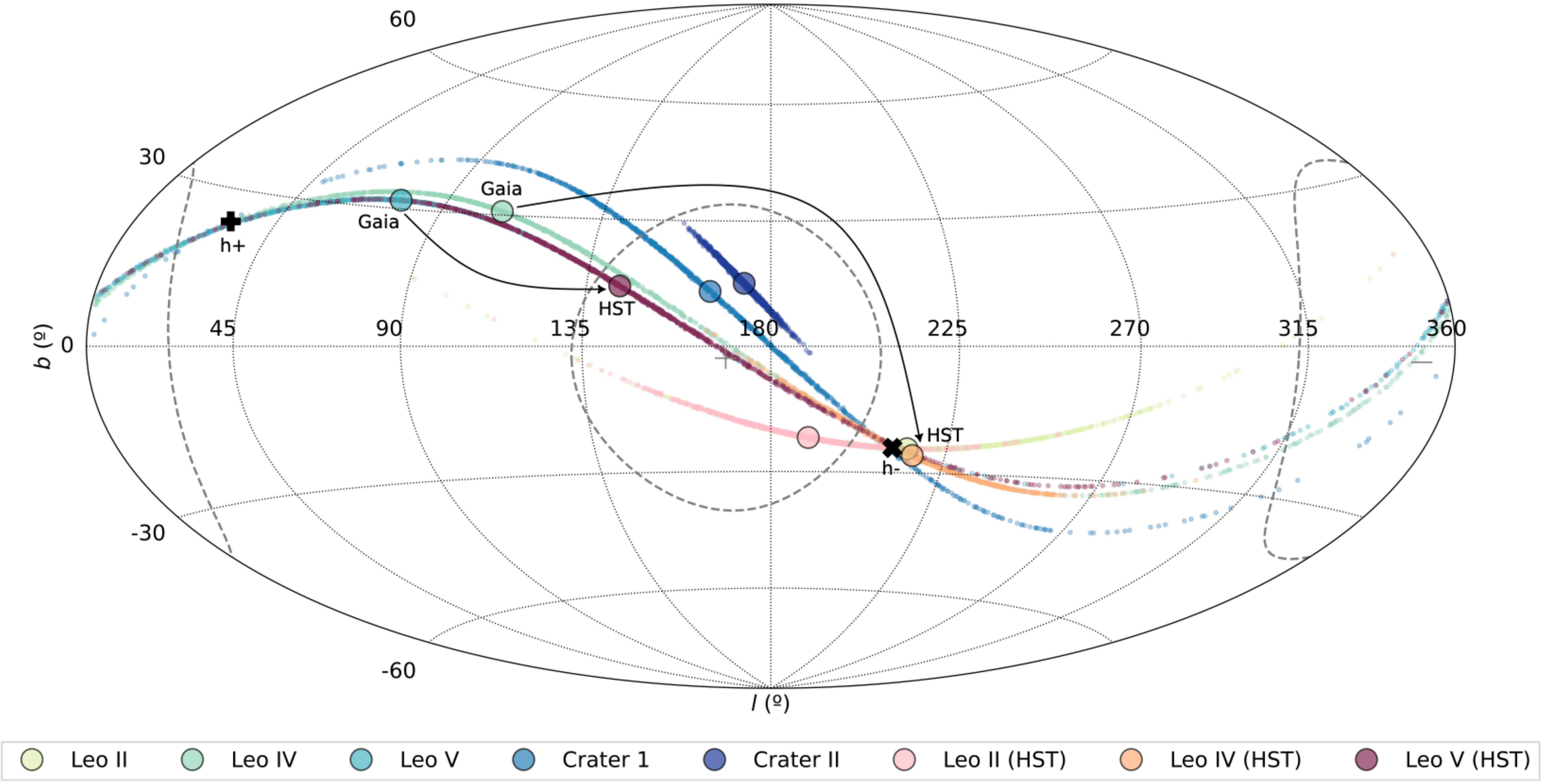
Similar radial velocities:

Júlio, Pawlowski et al. (2024)

Group Infall: the case of the Crater–Leo Objects

- Assume common group (similar energy and angular momentum)
  → predict expected proper motions
  → test with measurements.

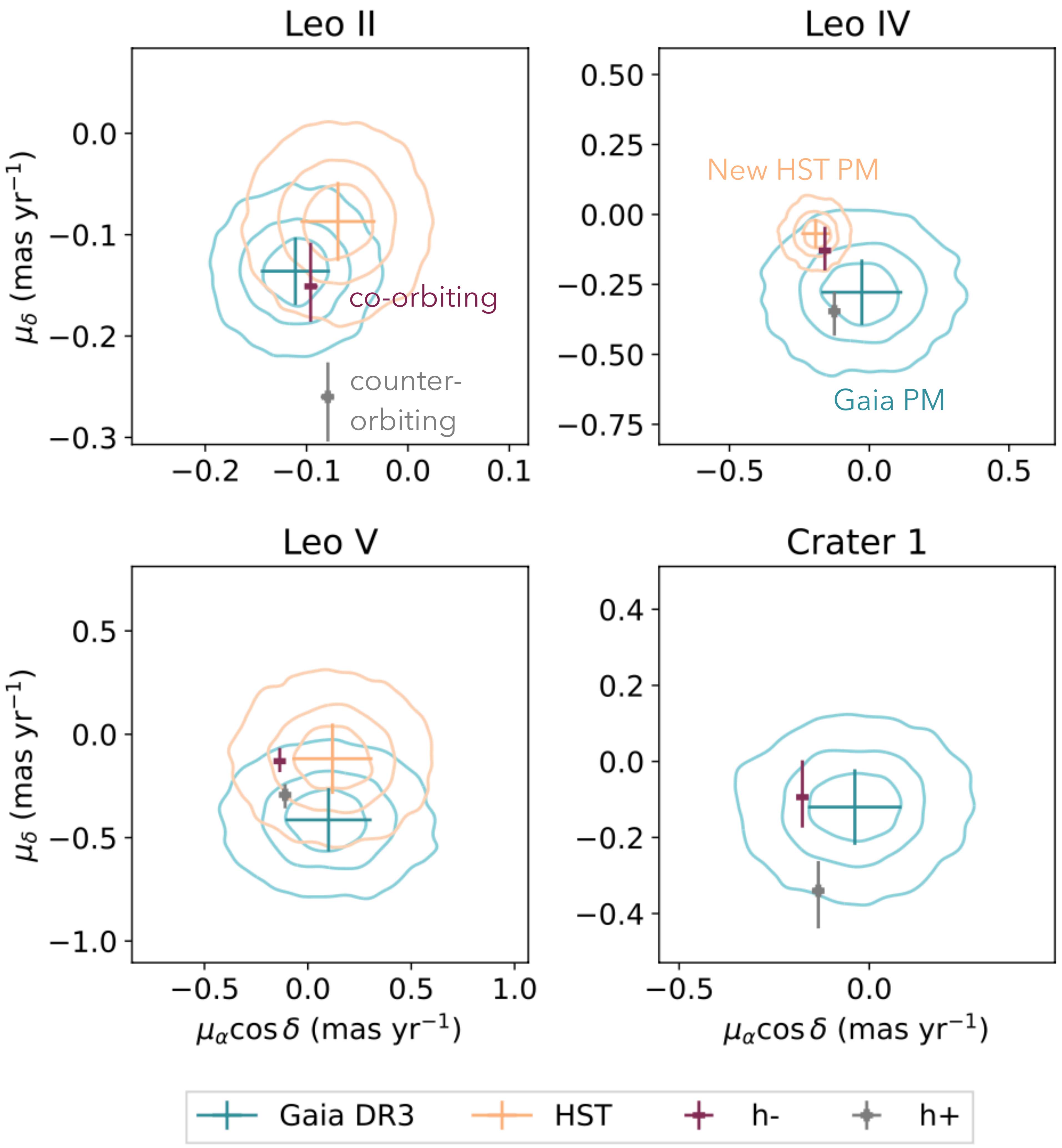
Orbital Poles (= directions of angular momentum)



Pouseiro Júlio et al. (2024)

Group Infall: the case of the Crater-Leo Objects

- Assume common group (similar energy and angular momentum)
  → predict expected proper motions
  → test with measurements.
- **Predictions** consistent within 1-2σ of proper motion measurement. More precise **HST PMs** agree better.
- *First evidence of a more typical group infall event (in contrast to hierarchical LMC satellite system)!*




Mariana Pouseiro Júlio

Pouseiro Júlio et al. (2024)

Not a problem at all?

No problem for ΛCDM after all?

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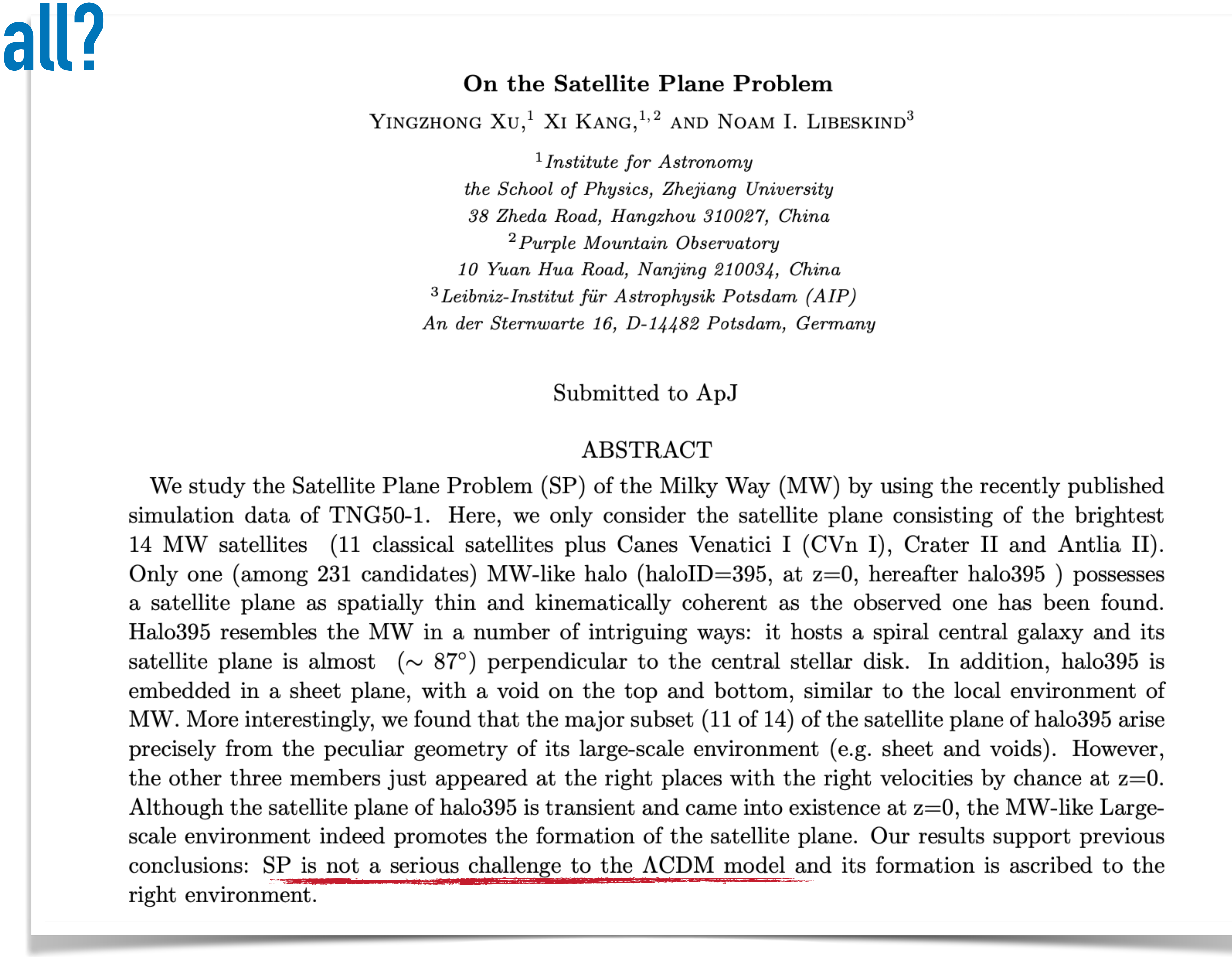

On the Satellite Plane Problem

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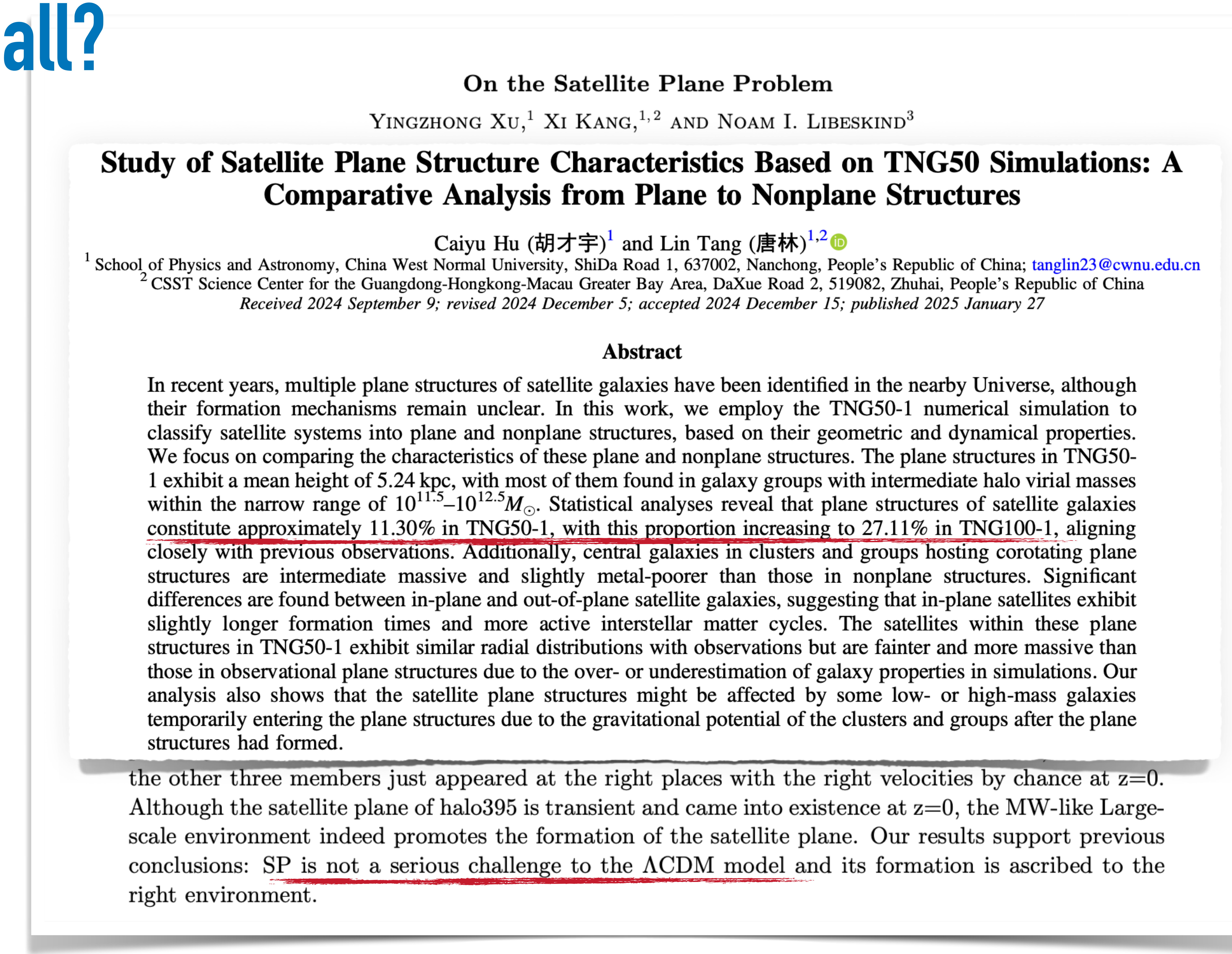
the School of Physics, Zhejiang University
38 Zheda Road, Hangzhou 310027, China
[2] *Purple Mountain Observatory*
10 Yuan Hua Road, Nanjing 210034, China
[3] *Leibniz-Institut für Astrophysik Potsdam (AIP)*
An der Sternwarte 16, D-14482 Potsdam, Germany

Submitted to ApJ

ABSTRACT

We study the Satellite Plane Problem (SP) of the Milky Way (MW) by using the recently published simulation data of TNG50-1. Here, we only consider the satellite plane consisting of the brightest 14 MW satellites (11 classical satellites plus Canes Venatici I (CVn I), Crater II and Antlia II). Only one (among 231 candidates) MW-like halo (haloID=395, at z=0, hereafter halo395) possesses a satellite plane as spatially thin and kinematically coherent as the observed one has been found. Halo395 resembles the MW in a number of intriguing ways: it hosts a spiral central galaxy and its satellite plane is almost (∼ 87°) perpendicular to the central stellar disk. In addition, halo395 is embedded in a sheet plane, with a void on the top and bottom, similar to the local environment of MW. More interestingly, we found that the major subset (11 of 14) of the satellite plane of halo395 arise precisely from the peculiar geometry of its large-scale environment (e.g. sheet and voids). However, the other three members just appeared at the right places with the right velocities by chance at z=0. Although the satellite plane of halo395 is transient and came into existence at z=0, the MW-like Large-scale environment indeed promotes the formation of the satellite plane. Our results support previous conclusions: SP is not a serious challenge to the ΛCDM model and its formation is ascribed to the right environment.

No problem for ΛCDM after all?



On the Satellite Plane Problem

YINGZHONG XU,[1] XI KANG,[1,2] AND NOAM I. LIBESKIND[3]

Study of Satellite Plane Structure Characteristics Based on TNG50 Simulations: A Comparative Analysis from Plane to Nonplane Structures

Caiyu Hu (胡才宇)[1] and Lin Tang (唐林)[1,2]
[1] School of Physics and Astronomy, China West Normal University, ShiDa Road 1, 637002, Nanchong, People's Republic of China; tanglin23@cwnu.edu.cn
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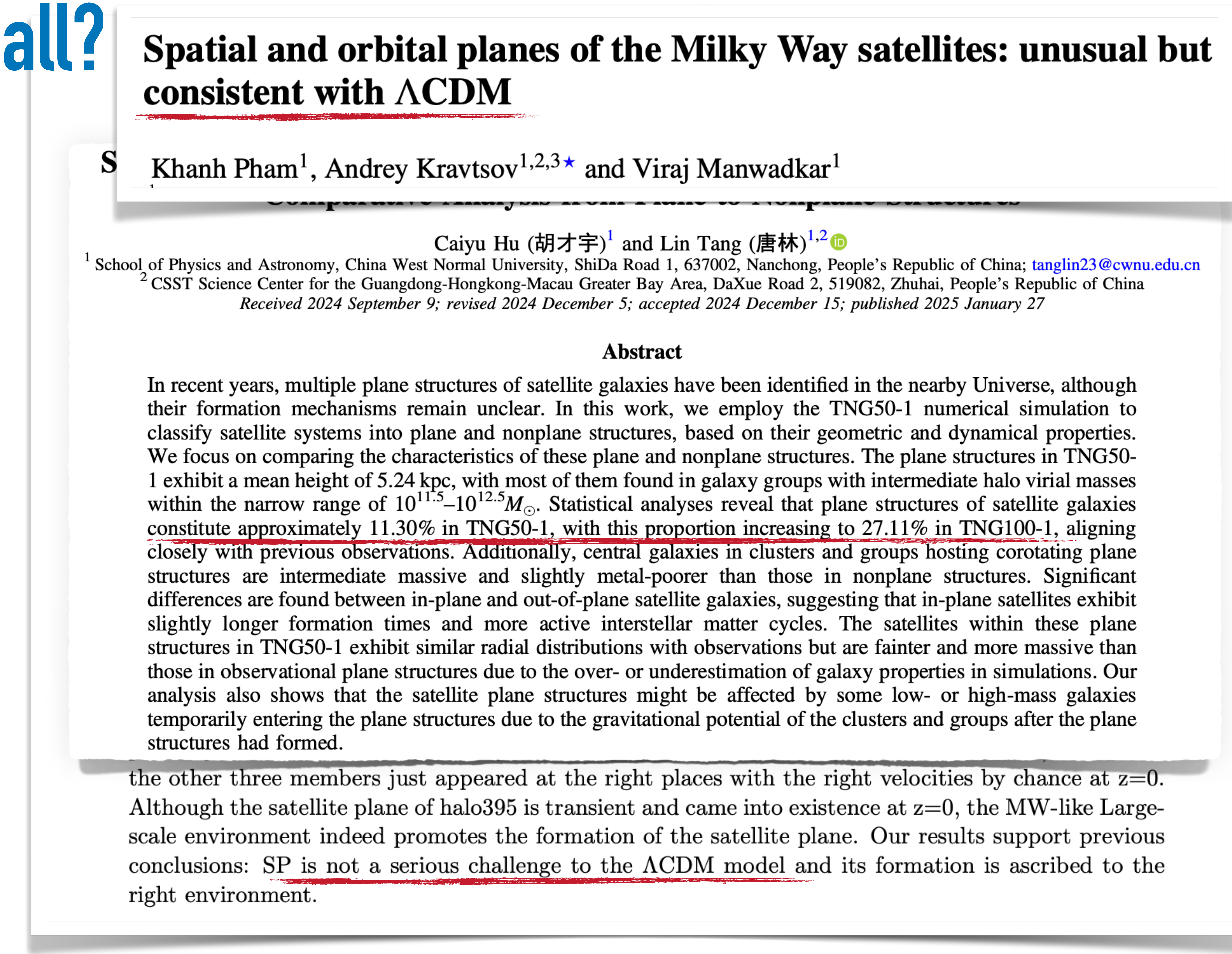

Spatial and orbital planes of the Milky Way satellites: unusual but consistent with ΛCDM

Khanh Pham[1], Andrey Kravtsov[1,2,3]★ and Viraj Manwadkar[1]

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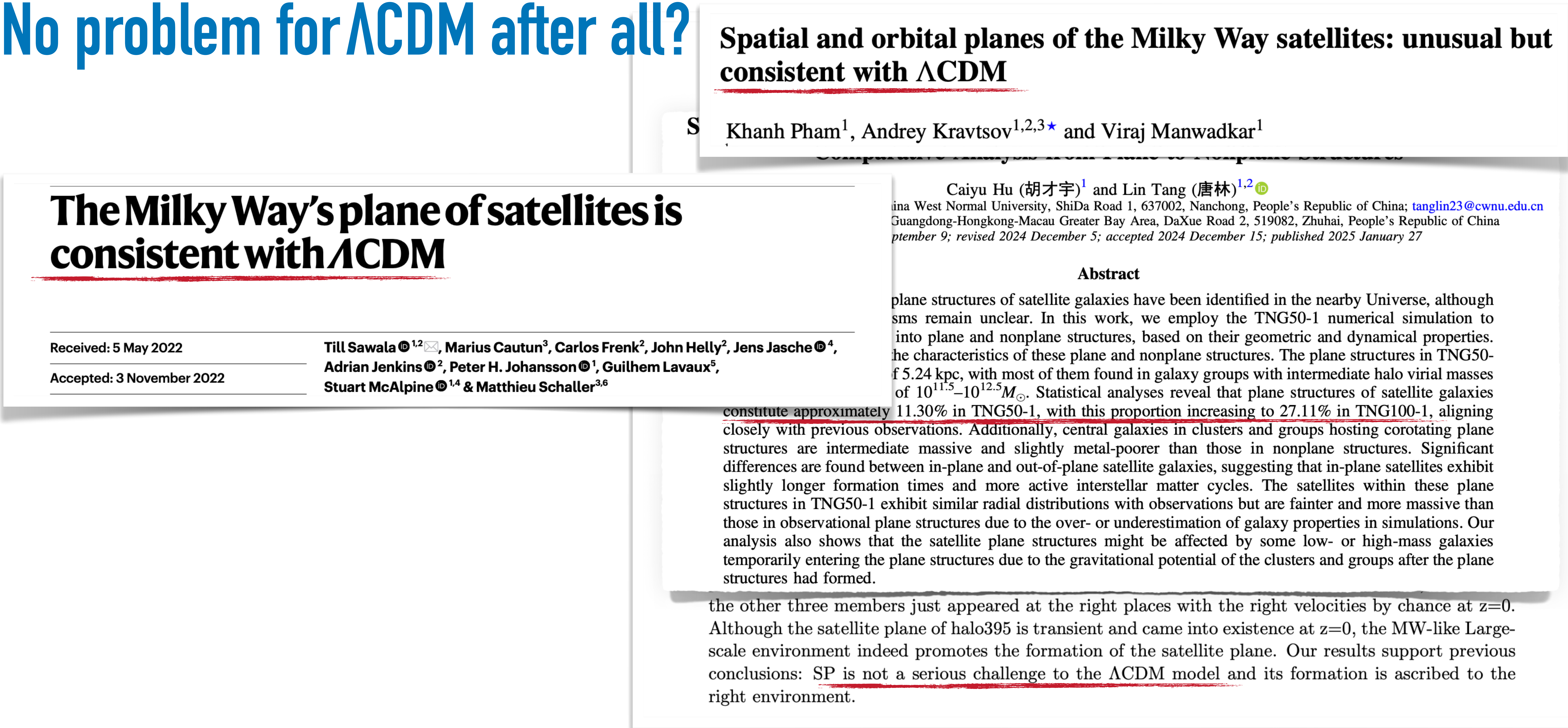

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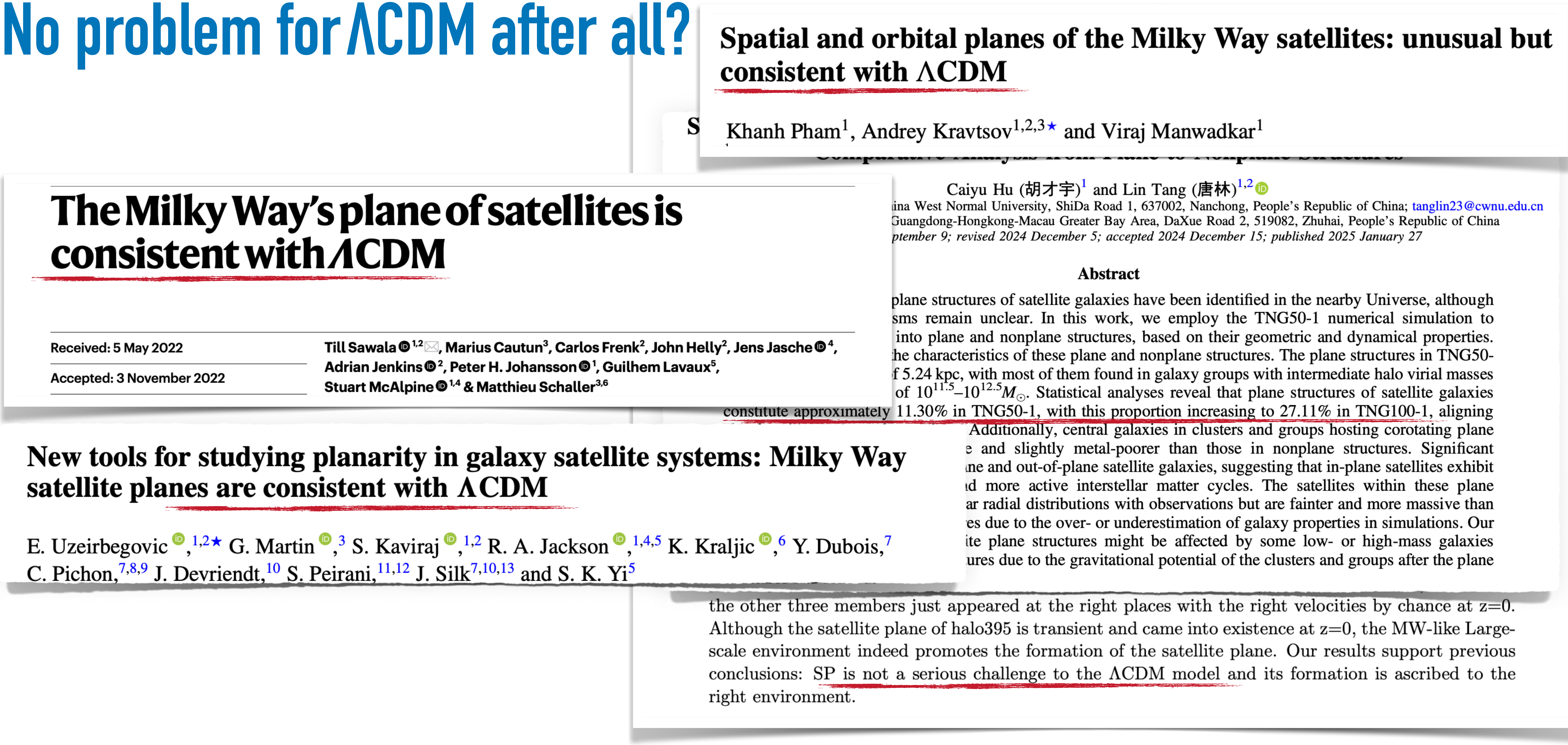

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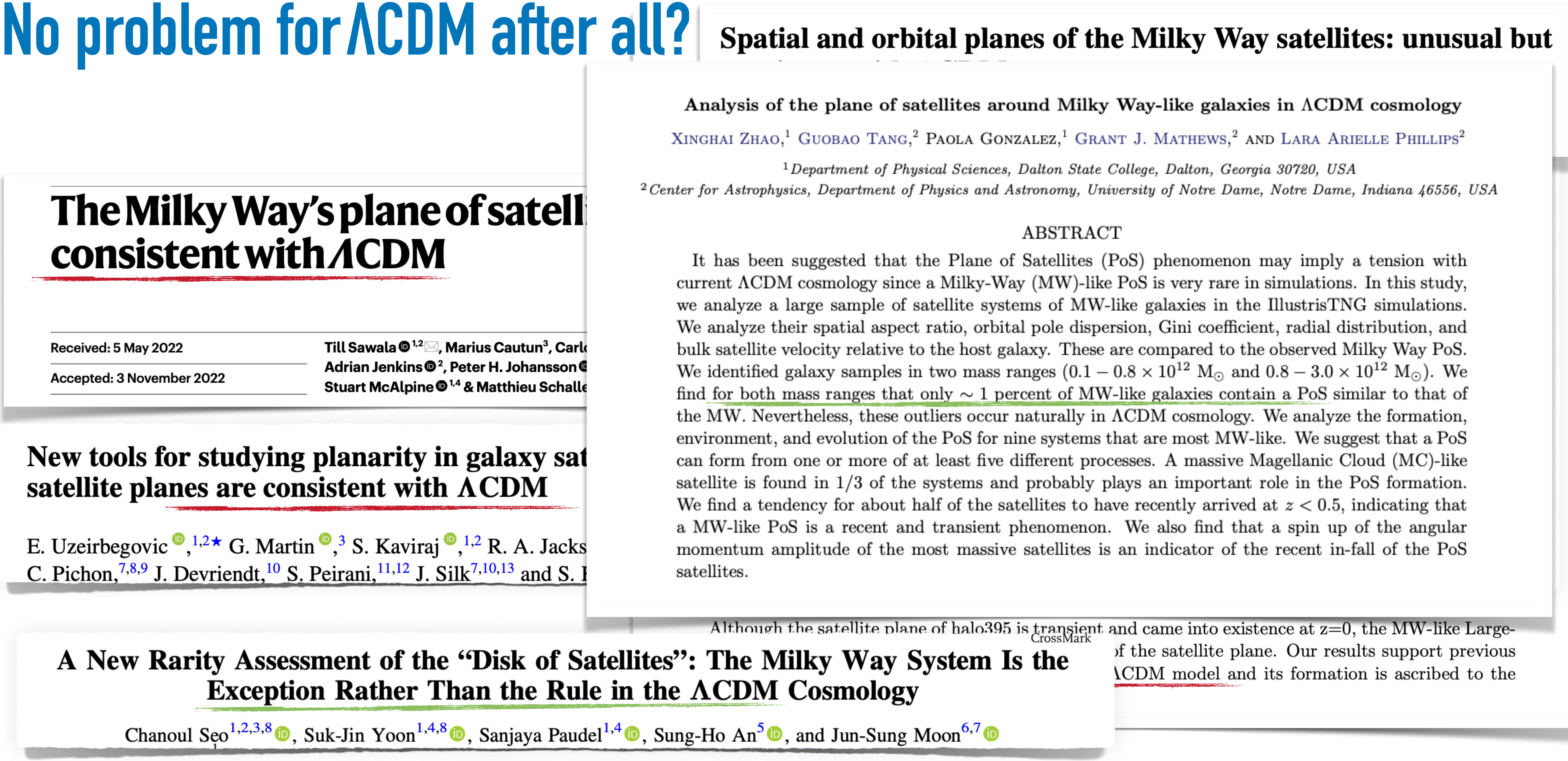

Spatial and orbital planes of the Milky Way satellites: unusual but

Analysis of the plane of satellites around Milky Way-like galaxies in ΛCDM cosmology

Xinghai Zhao,[1] Guobao Tang,[2] Paola Gonzalez,[1] Grant J. Mathews,[2] and Lara Arielle Phillips[2]

[1] *Department of Physical Sciences, Dalton State College, Dalton, Georgia 30720, USA*

[2] *Center for Astrophysics, Department of Physics and Astronomy, University of Notre Dame, Notre Dame, Indiana 46556, USA*

ABSTRACT

It has been suggested that the Plane of Satellites (PoS) phenomenon may imply a tension with current ΛCDM cosmology since a Milky-Way (MW)-like PoS is very rare in simulations. In this study, we analyze a large sample of satellite systems of MW-like galaxies in the IllustrisTNG simulations. We analyze their spatial aspect ratio, orbital pole dispersion, Gini coefficient, radial distribution, and bulk satellite velocity relative to the host galaxy. These are compared to the observed Milky Way PoS. We identified galaxy samples in two mass ranges $(0.1 - 0.8 \times 10^{12}\ M_\odot$ and $0.8 - 3.0 \times 10^{12}\ M_\odot)$. We find for both mass ranges that only ~ 1 percent of MW-like galaxies contain a PoS similar to that of the MW. Nevertheless, these outliers occur naturally in ΛCDM cosmology. We analyze the formation, environment, and evolution of the PoS for nine systems that are most MW-like. We suggest that a PoS can form from one or more of at least five different processes. A massive Magellanic Cloud (MC)-like satellite is found in 1/3 of the systems and probably plays an important role in the PoS formation. We find a tendency for about half of the satellites to have recently arrived at $z < 0.5$, indicating that a MW-like PoS is a recent and transient phenomenon. We also find that a spin up of the angular momentum amplitude of the most massive satellites is an indicator of the recent in-fall of the PoS satellites.

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A New Rarity Assessment of the "Disk of Satellites": The Milky Way System Is the Exception Rather Than the Rule in the ΛCDM Cosmology

Chanoul Seo[1,2,3,8], Suk-Jin Yoon[1,4,8], Sanjaya Paudel[1,4], Sung-Ho An[5], and Jun-Sung Moon[6,7]

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- Most works only focus on MW, but **M31, Cen A, NGC4490 show similar tension.**

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- **Too compact analogs** (e.g. 7 simulated satellites closer than than LMC).
- Gaia PM **systematics ignored** (up to 30x random errors for some classical satellites)
- **Misleading comparisons** to previous works (e.g. Gaia eDR3 vs. combination of Gaia DR2 + other sources, insinuating orbital coherence got worse)

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Flattening + **Kinematic Coherence**

e.g. absolute rms height or
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Rotating (≠ just moving in plane)
→ aligned angular momenta!

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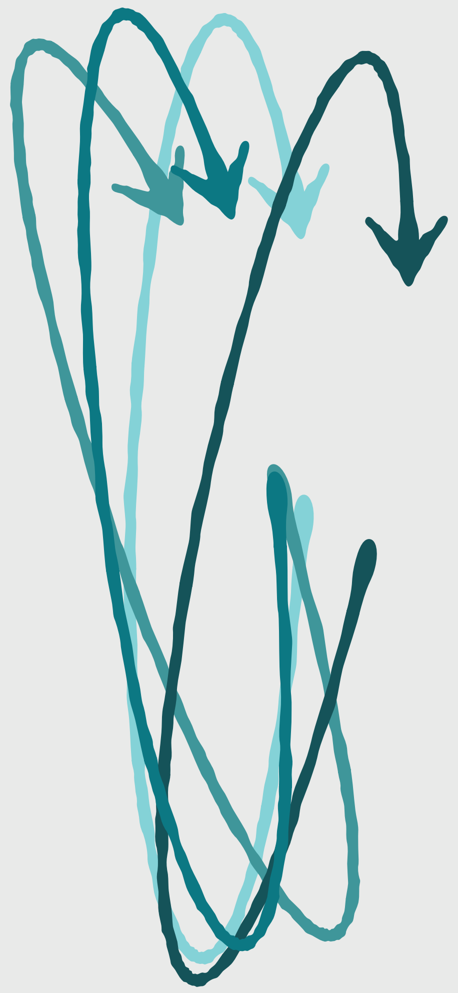

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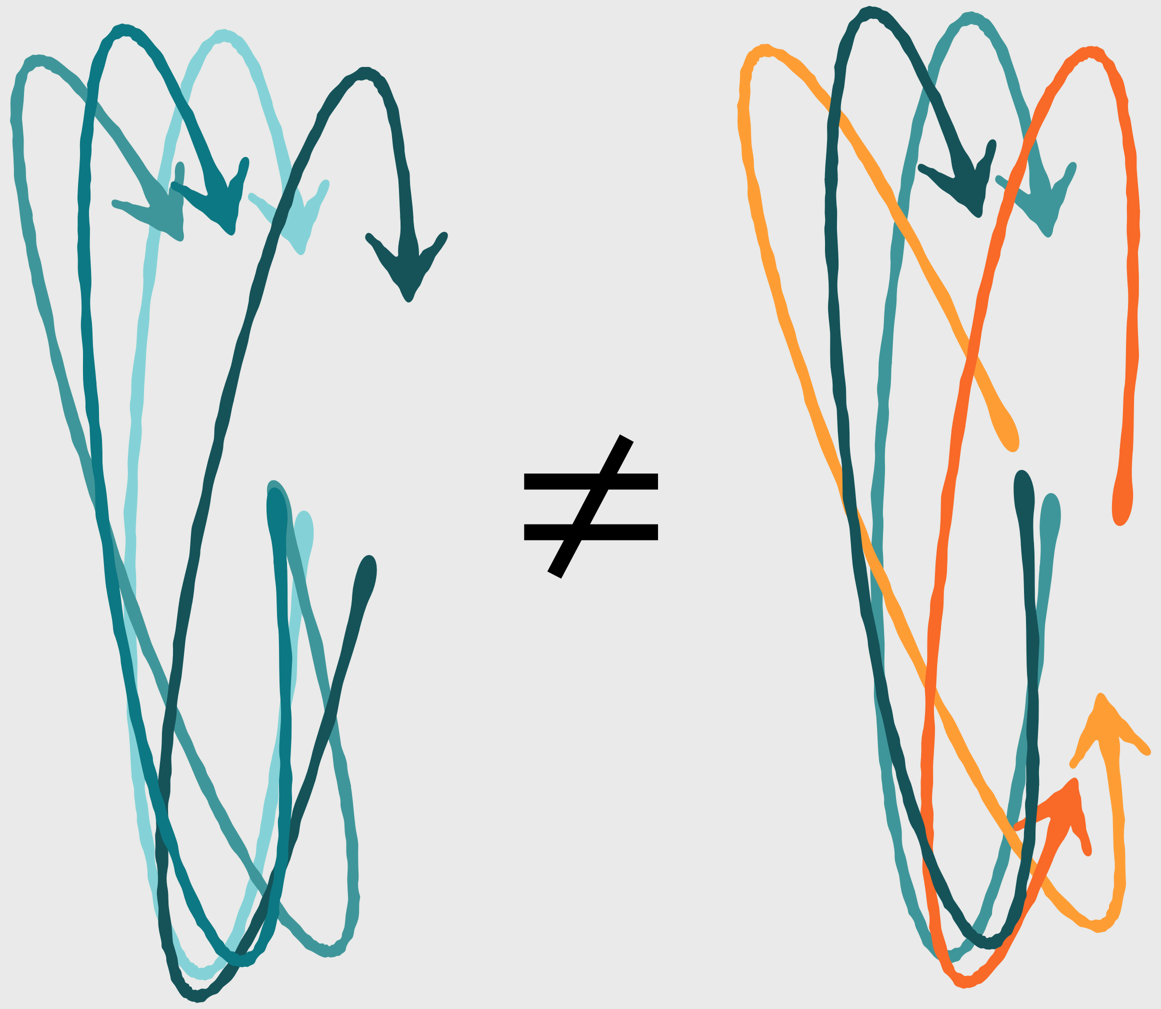

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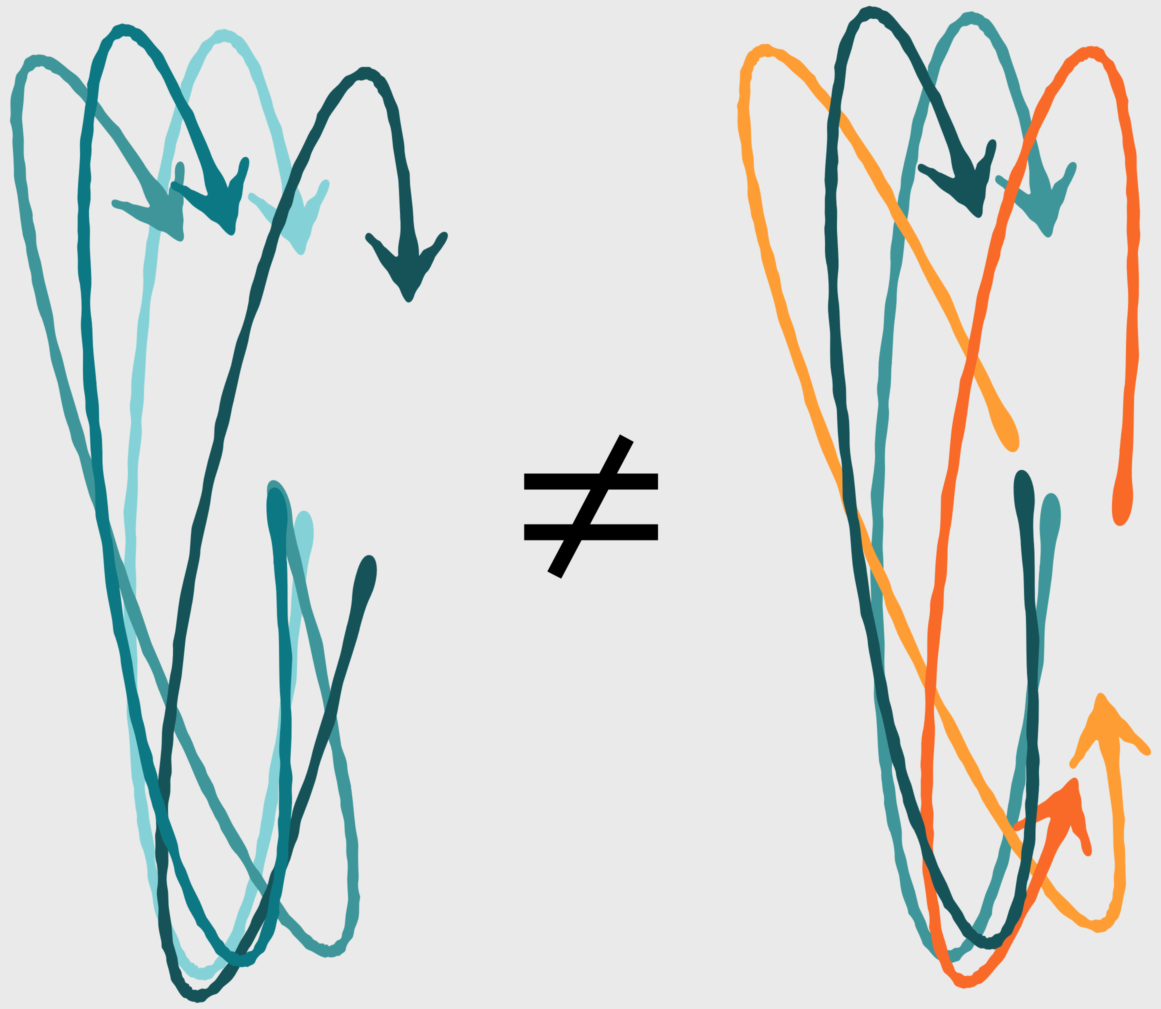
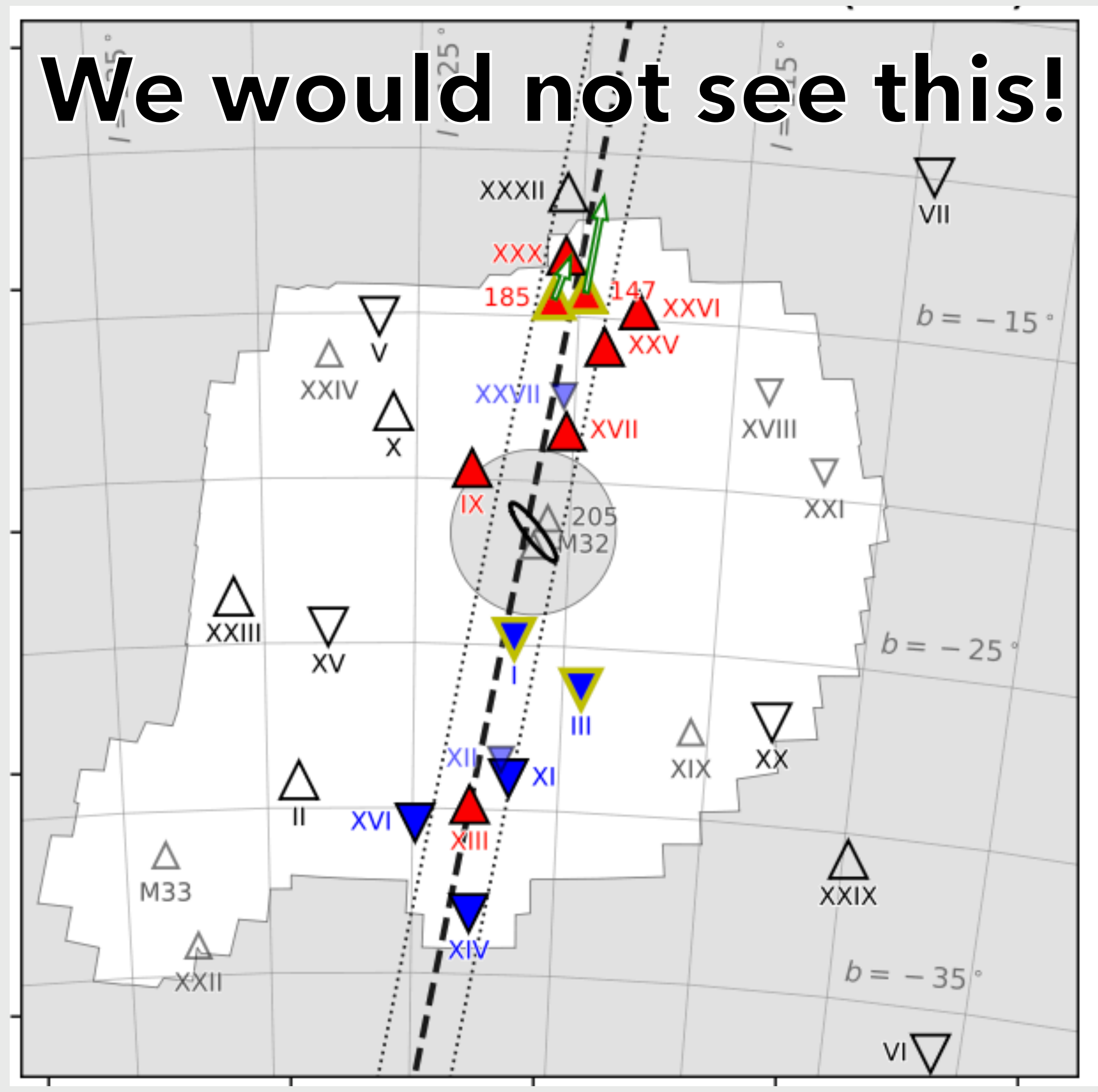
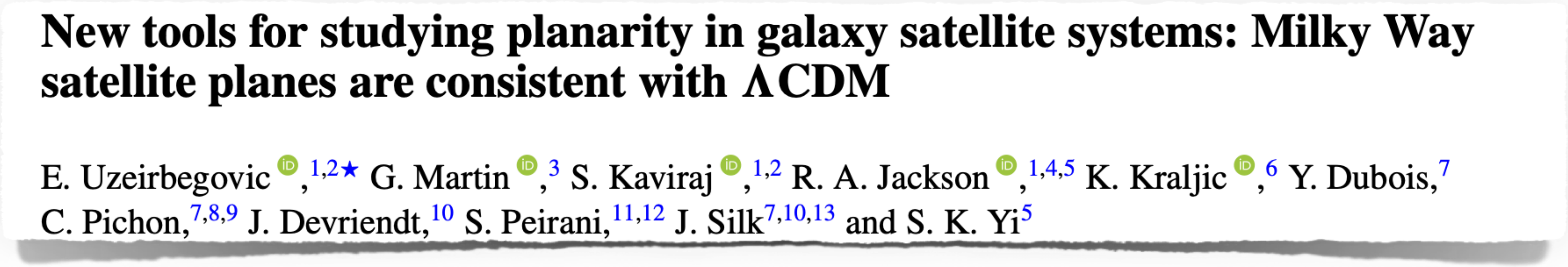



We would not see this!

A new planarity metric for satellite planes?



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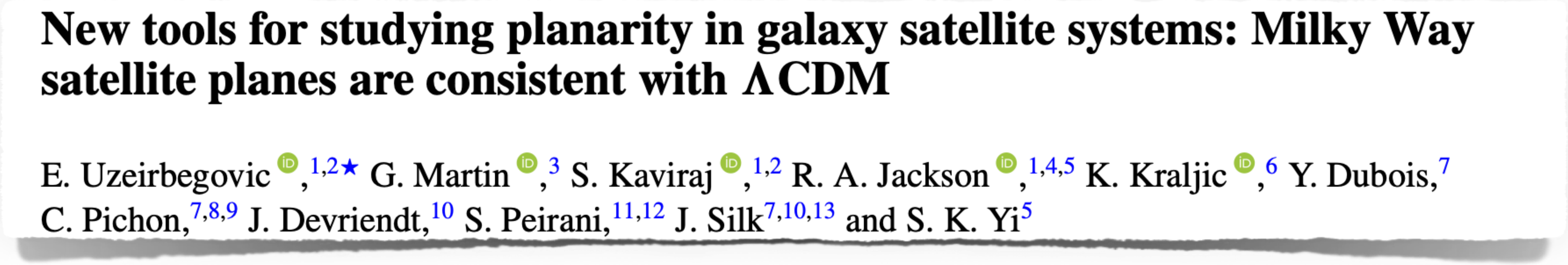

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Testing a proposed planarity tool for studying satellite systems

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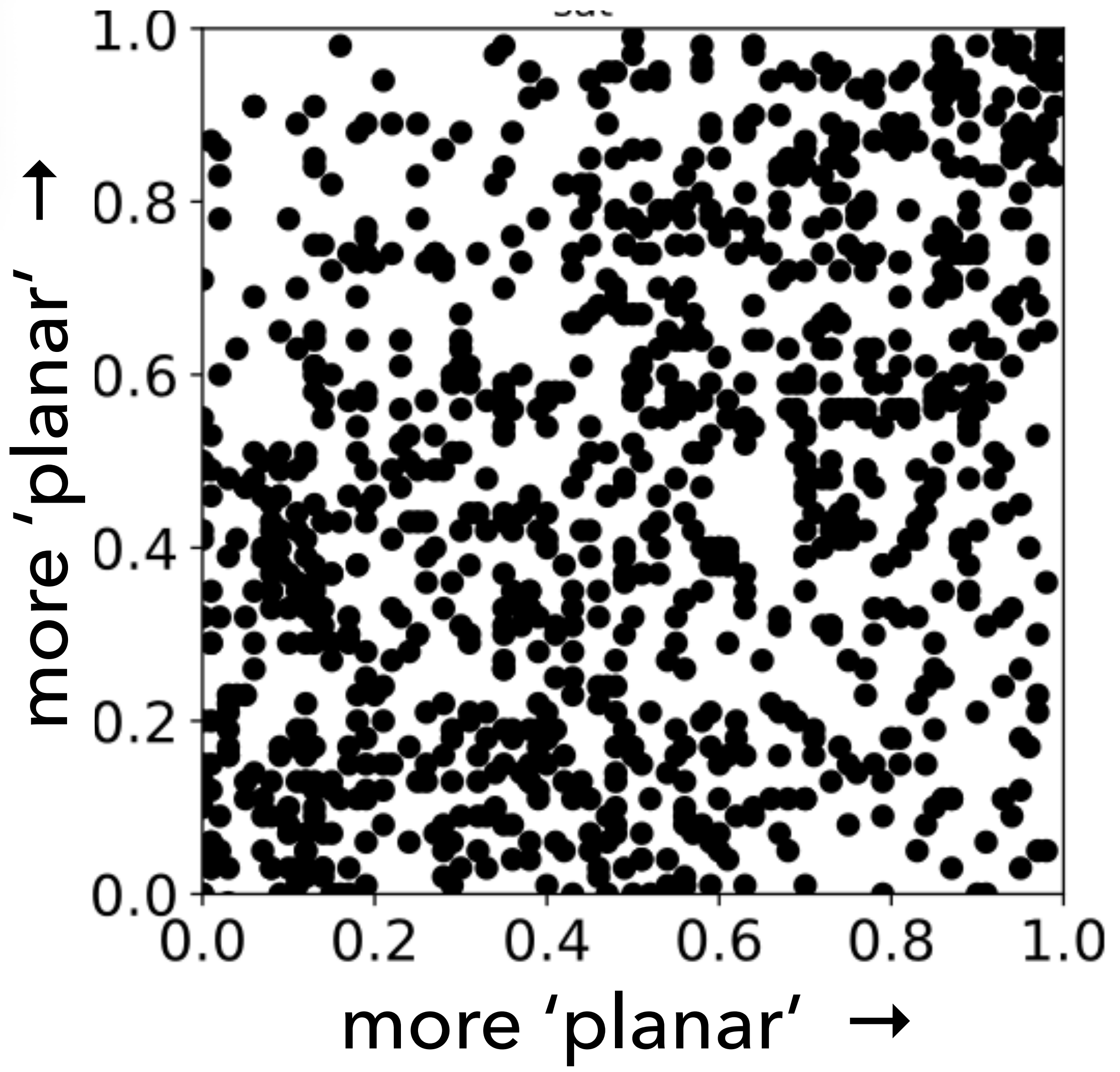
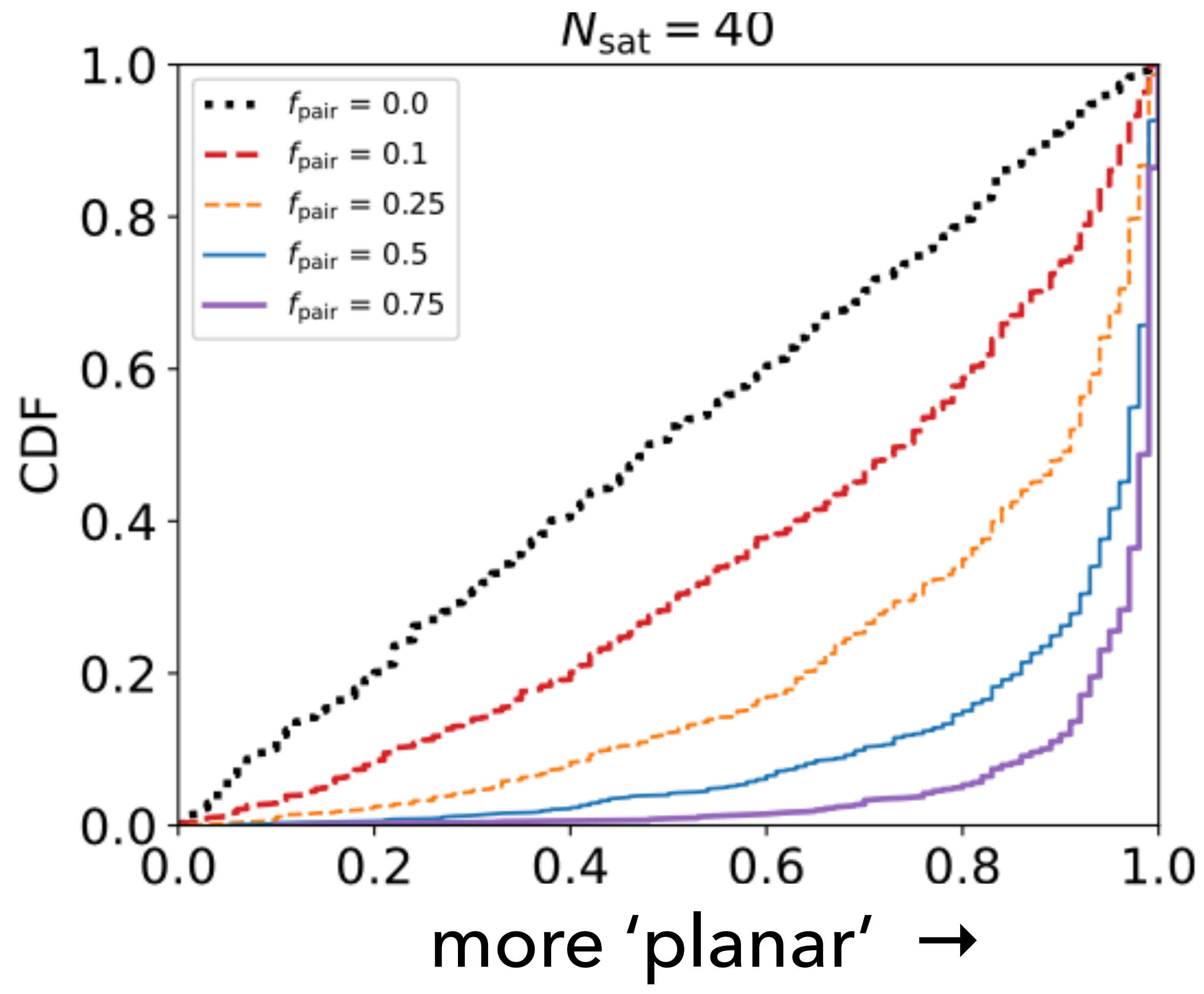


sensitive to e.g. satellite pairs



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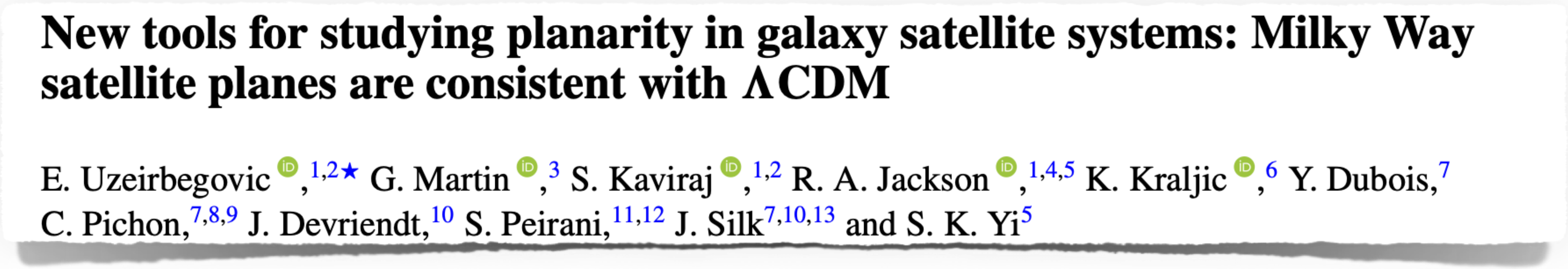

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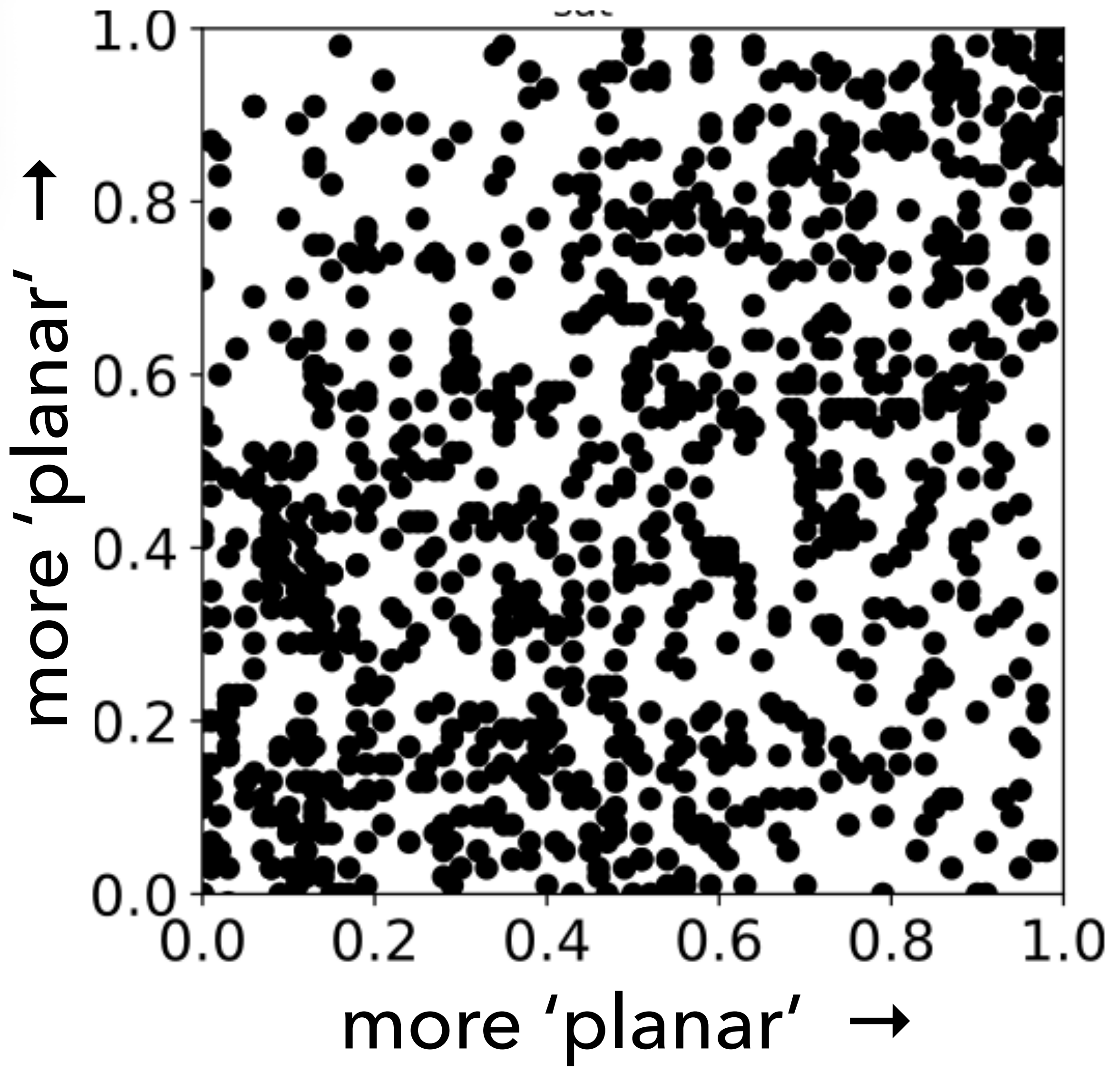

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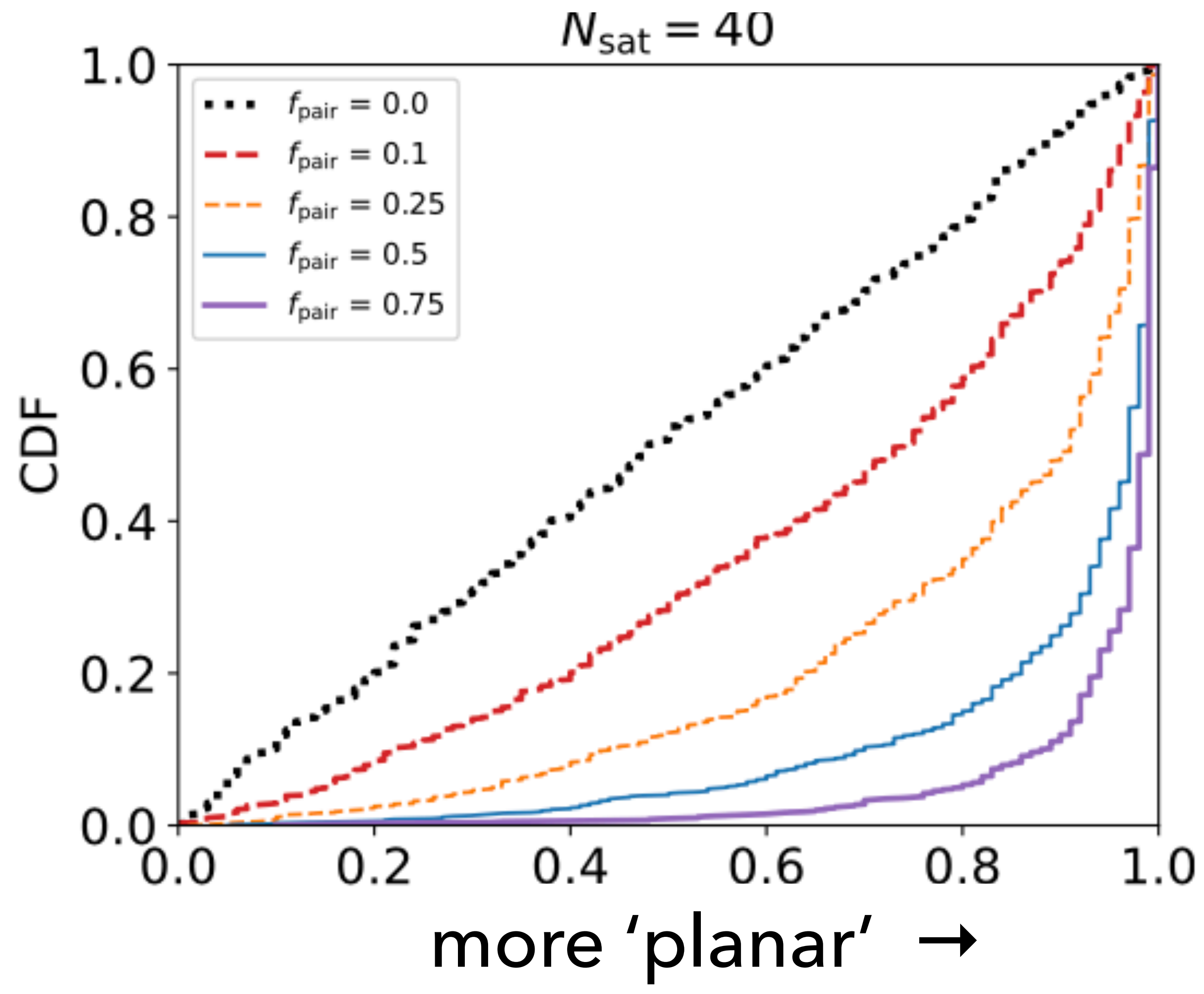
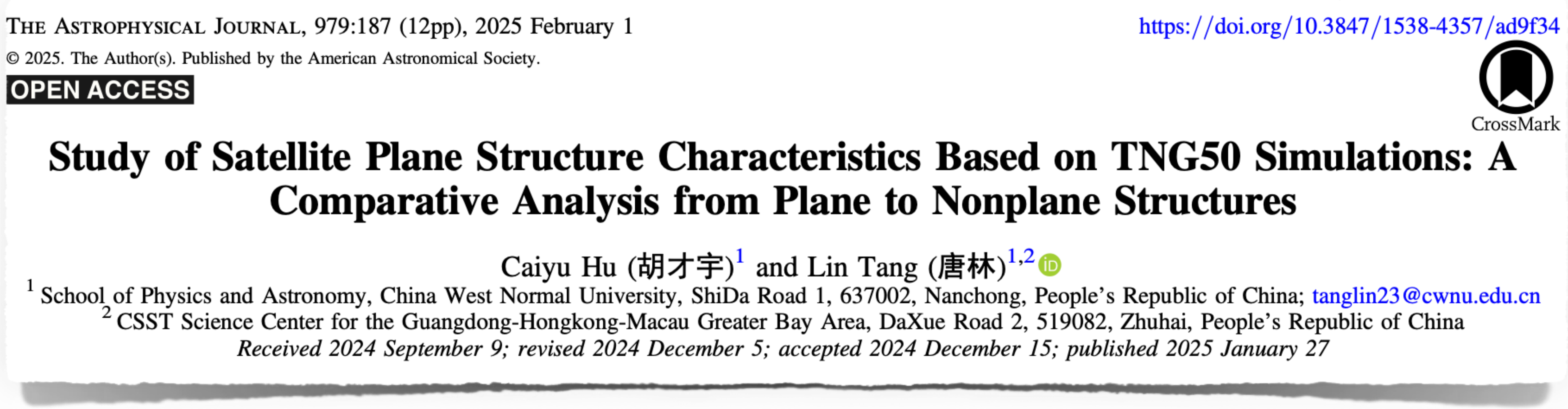


Affected by orientation of coordinate system and lacks specificity.

Rotating Satellite Planes in TNG50?



The Astrophysical Journal, 979:187 (12pp), 2025 February 1 https://doi.org/10.3847/1538-4357/ad9f34

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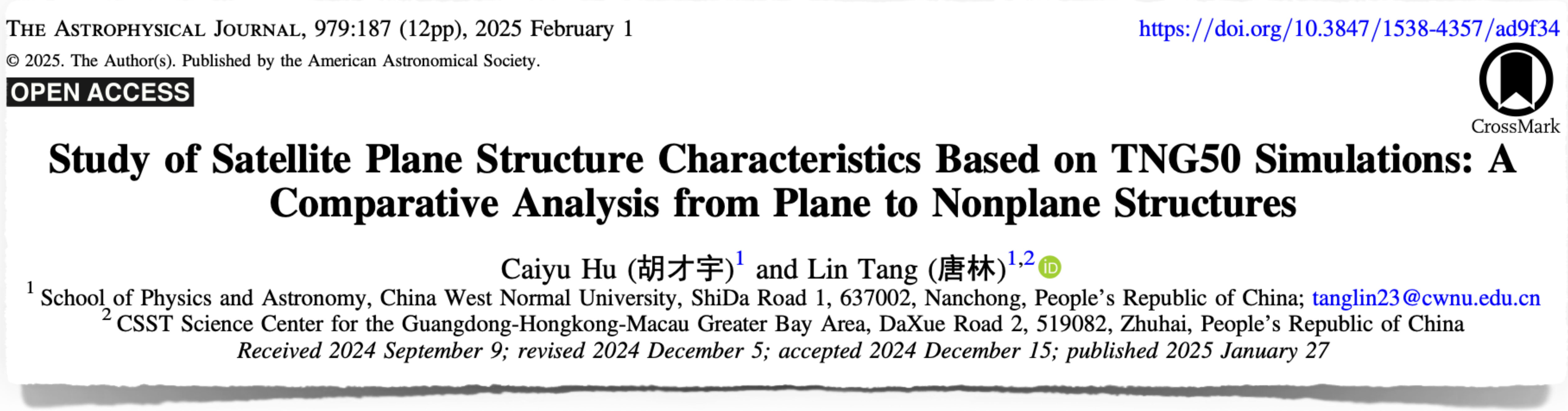

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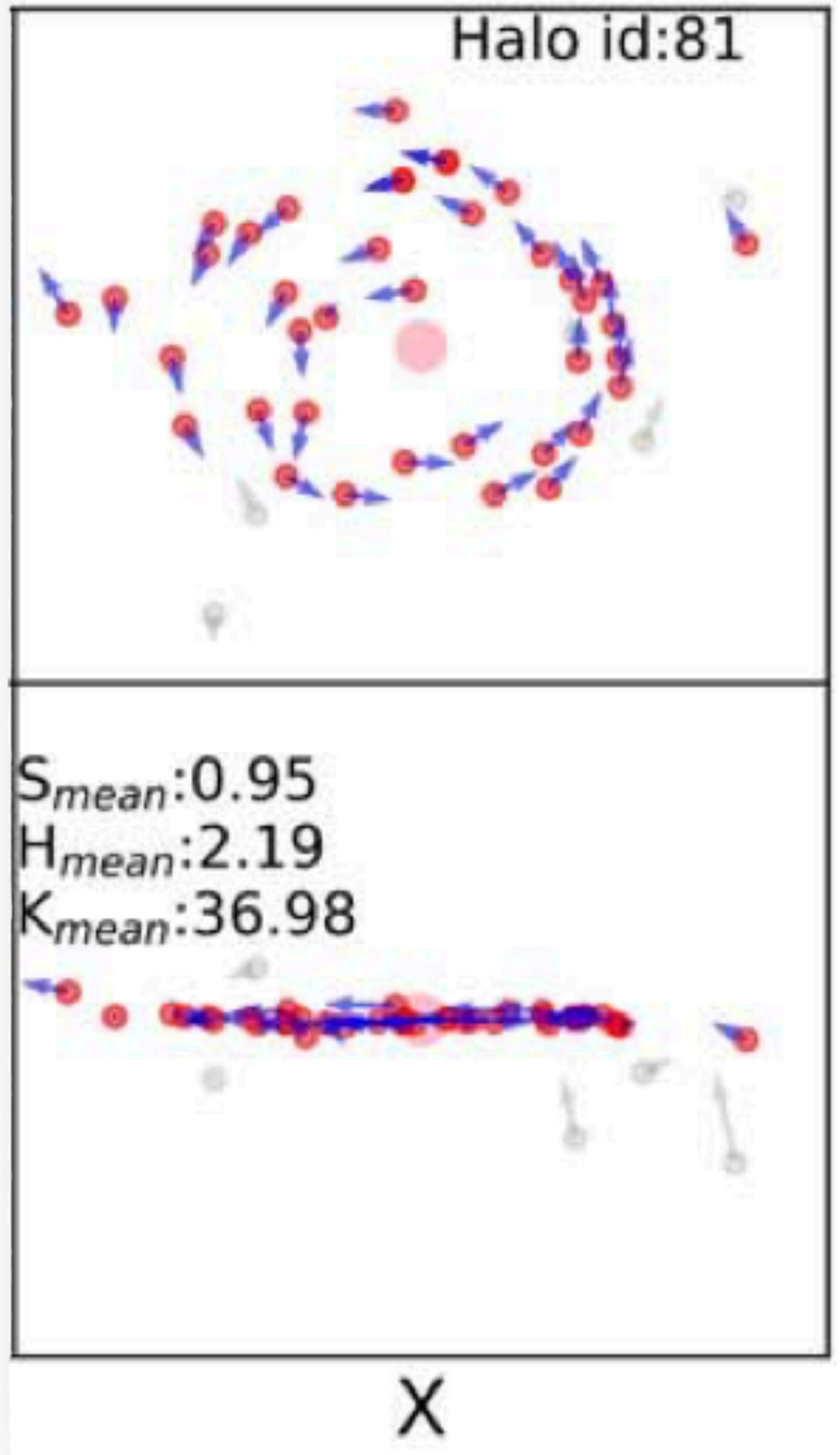
Hu & Tang (2025)



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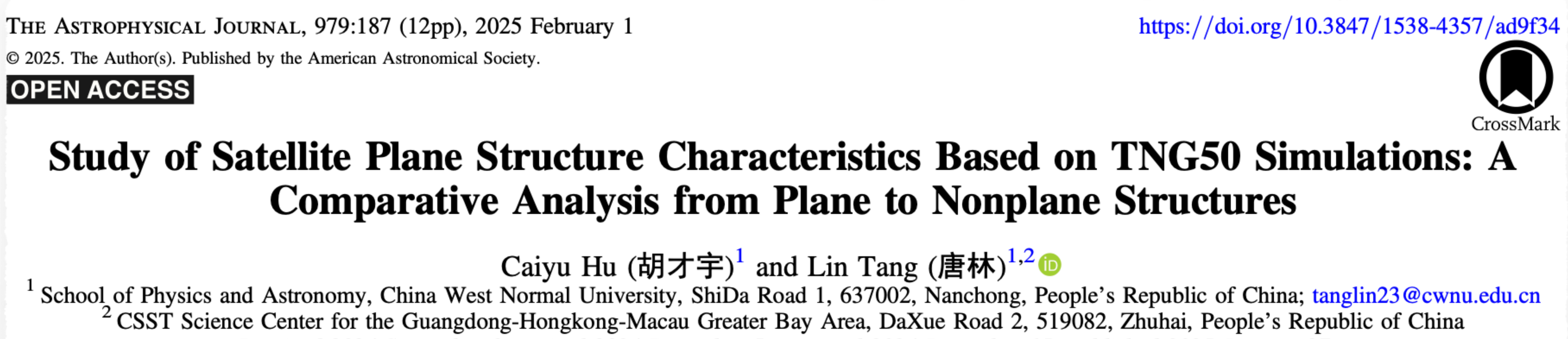

The Astrophysical Journal, 979:187 (12pp), 2025 February 1 https://doi.org/10.3847/1538-4357/ad9f34

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CrossMark

Study of Satellite Plane Structure Characteristics Based on TNG50 Simulations: A Comparative Analysis from Plane to Nonplane Structures

Caiyu Hu (胡才宇)[1] and Lin Tang (唐林)[1,2]

[1] School of Physics and Astronomy, China West Normal University, ShiDa Road 1, 637002, Nanchong, People's Republic of China; tanglin23@cwnu.edu.cn
[2] CSST Science Center for the Guangdong-Hongkong-Macau Greater Bay Area, DaXue Road 2, 519082, Zhuhai, People's Republic of China

Received 2024 September 9; revised 2024 December 5; accepted 2024 December 15; published 2025 January 27

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- Typical plane heights 5 kpc
- Significant differences in on- and off-plane satellites

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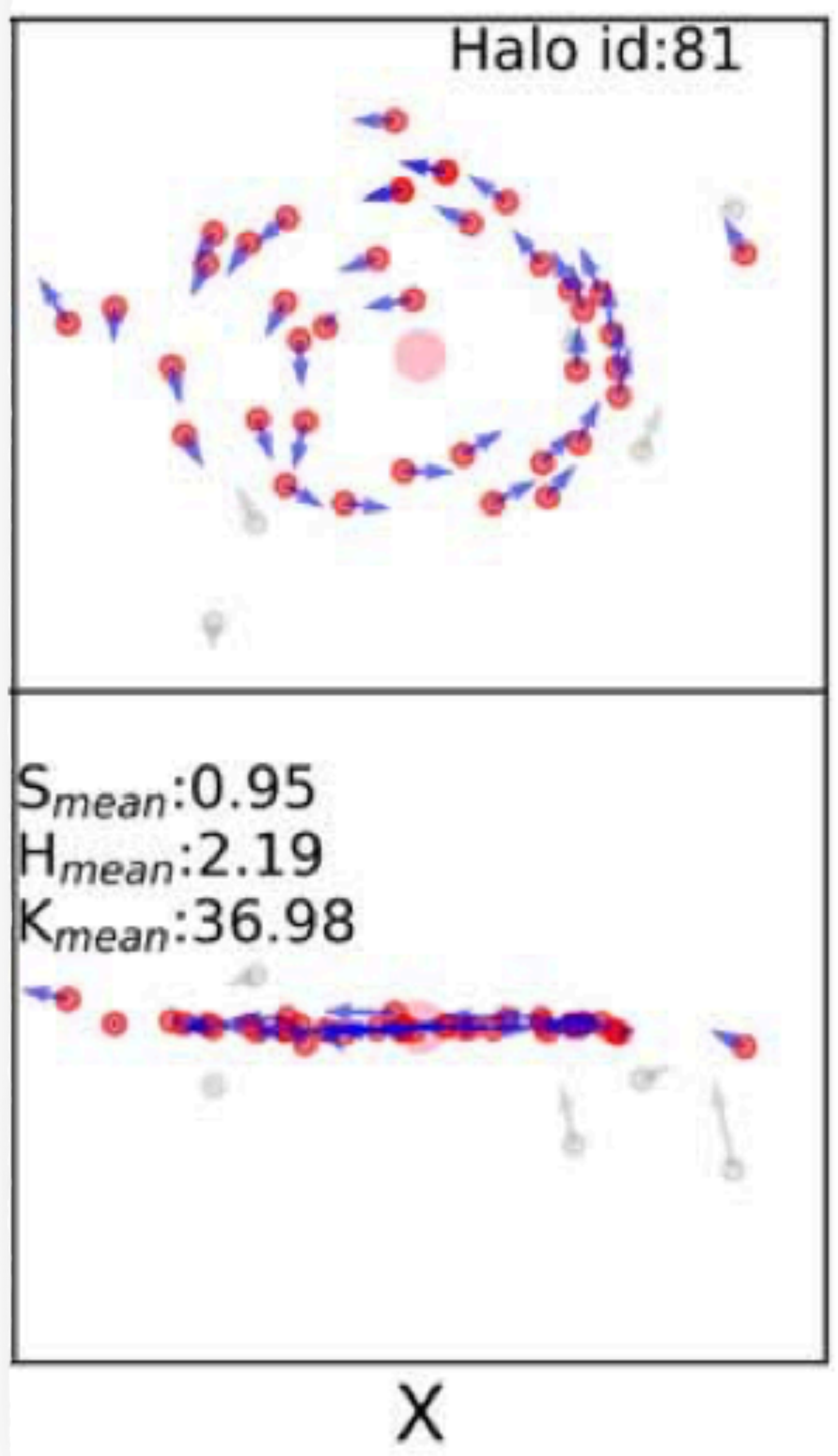

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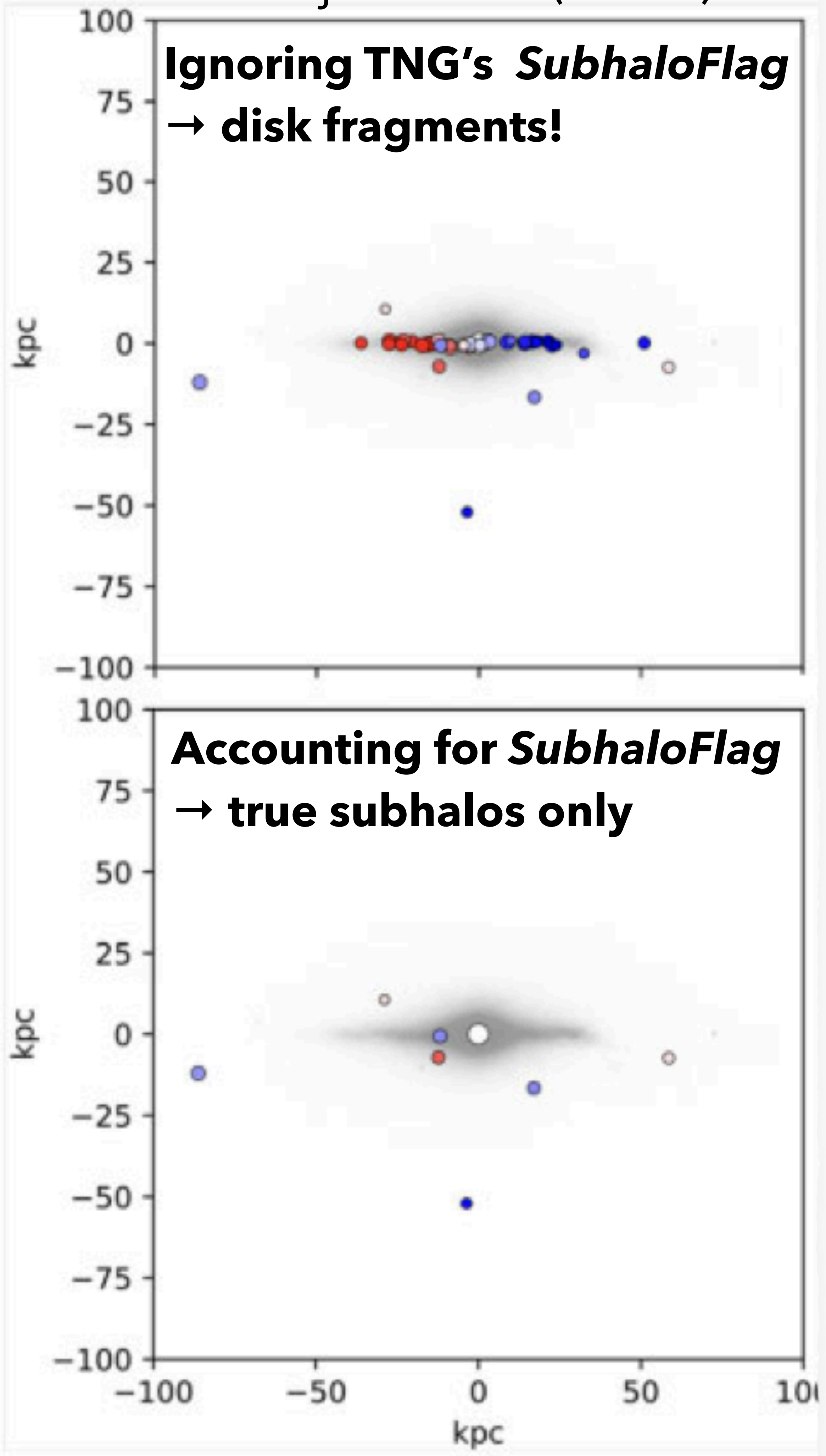
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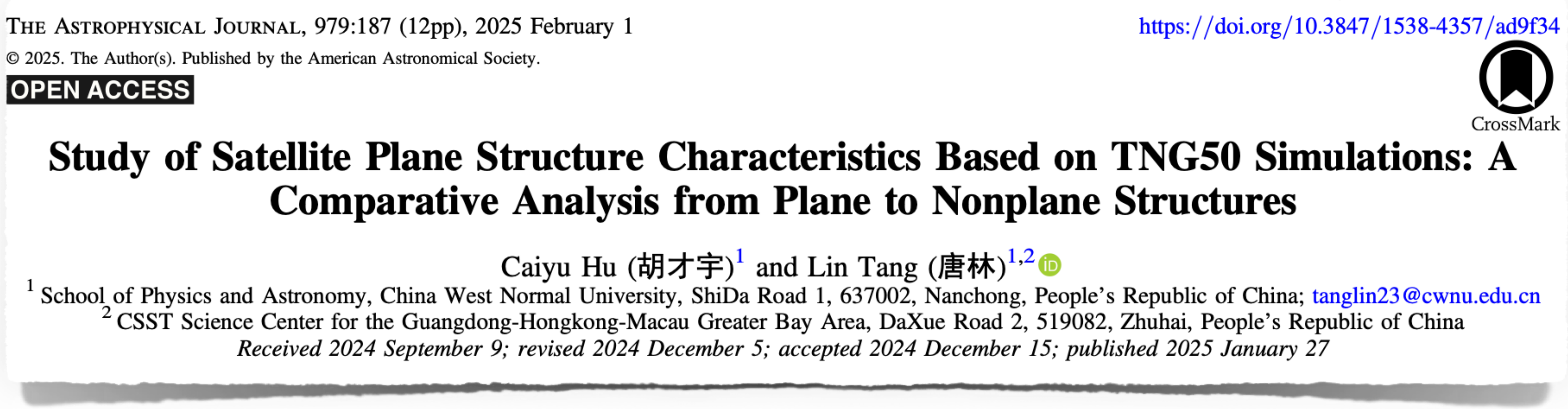

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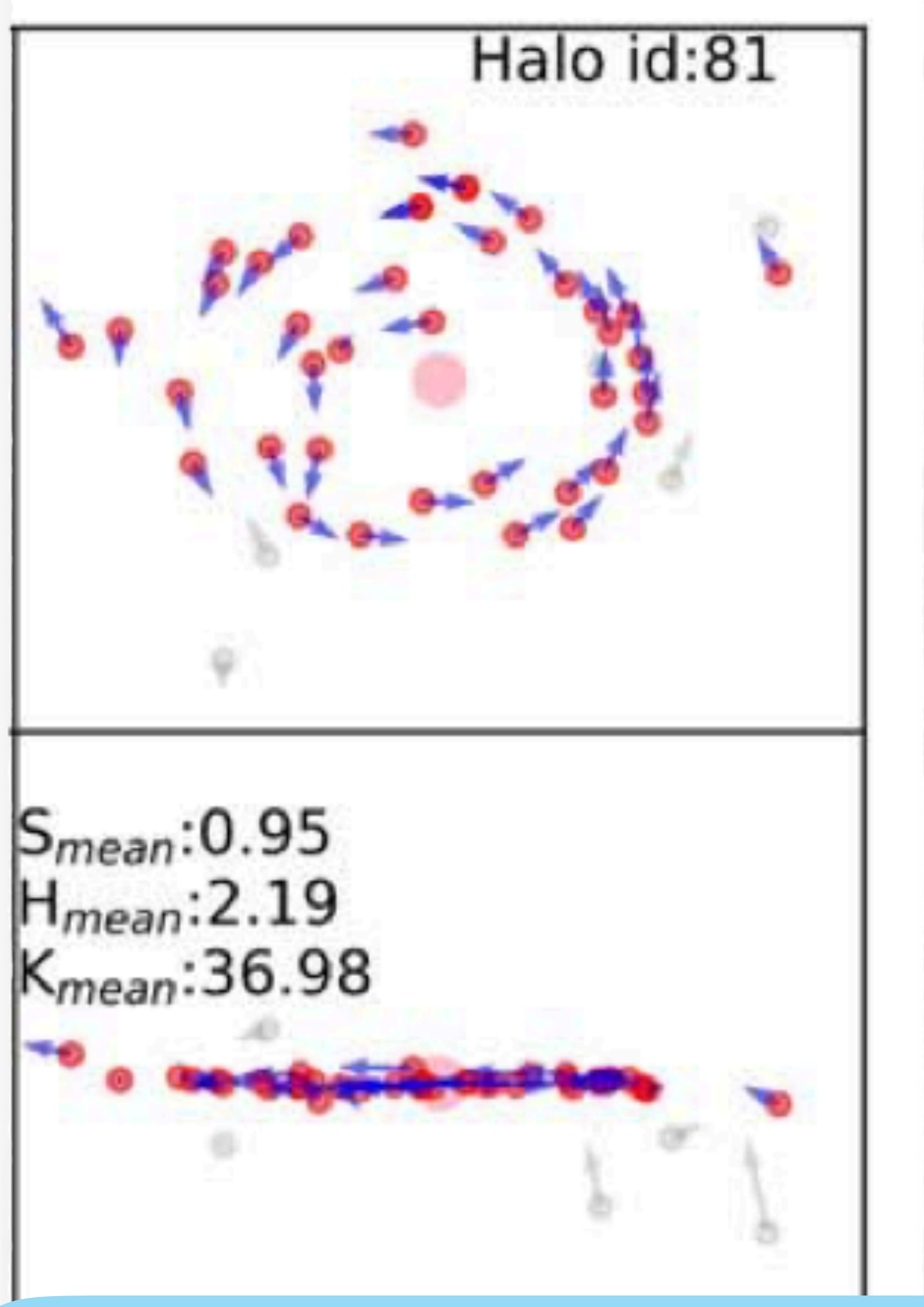

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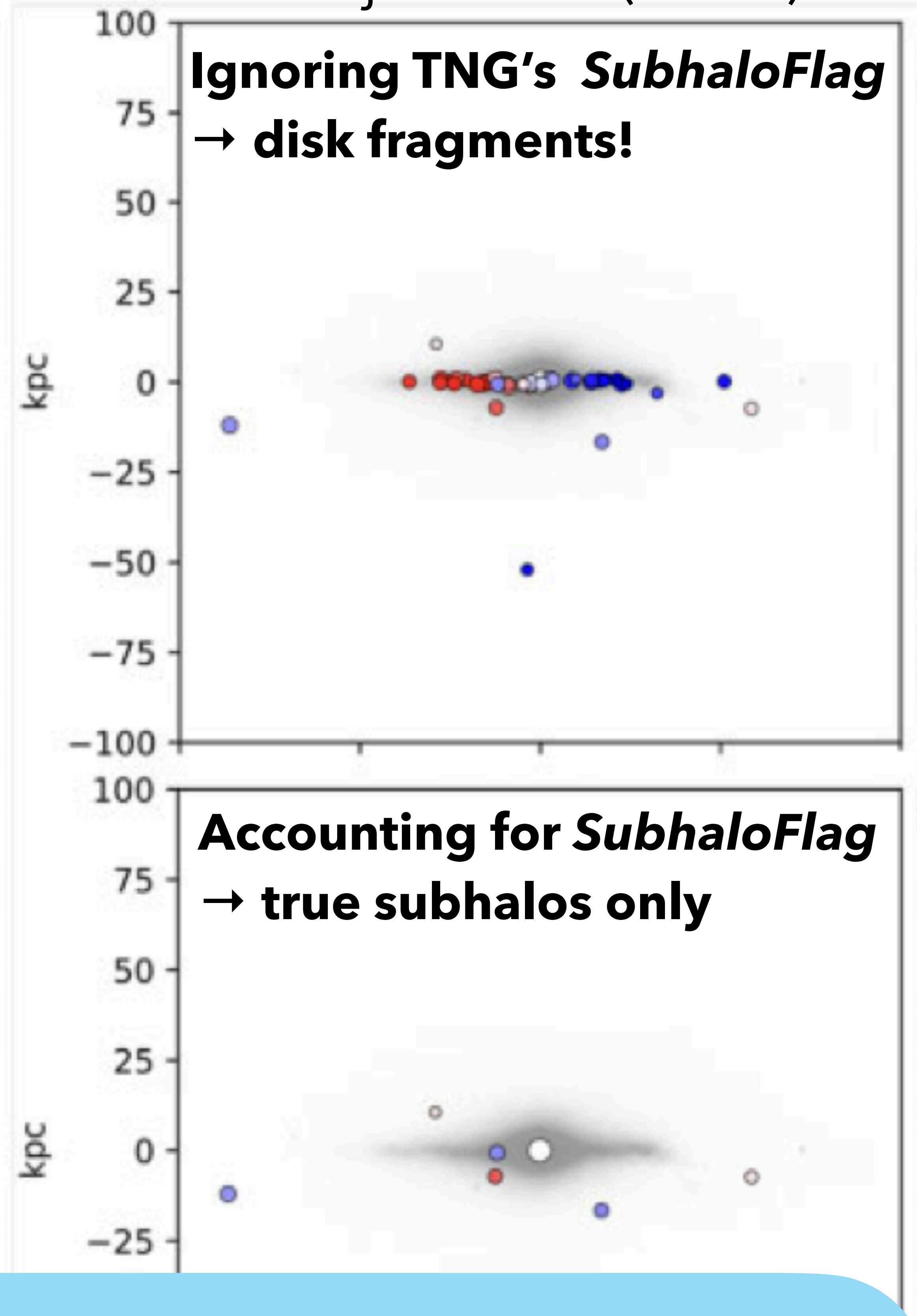

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Fragments of rotating galactic disks incorrectly interpreted as satellite galaxies.

More fundamental Issue:

Single systems epistemologically not very meaningful

What frequency of analogs for an observed system is rare enough to challenge ΛCDM?

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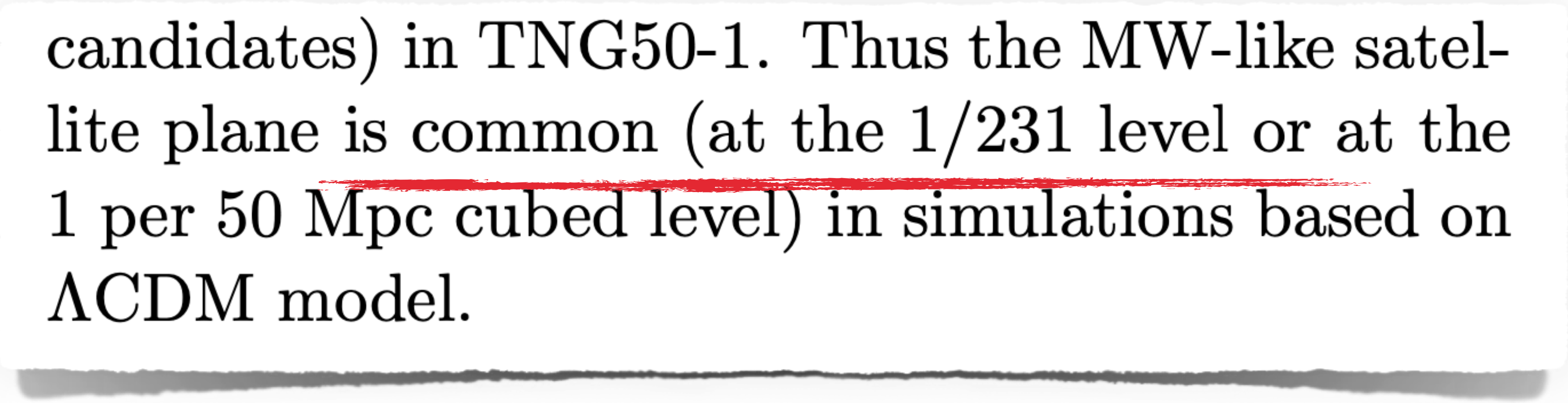

candidates) in TNG50-1. Thus the MW-like satellite plane is common (at the 1/231 level or at the 1 per 50 Mpc cubed level) in simulations based on ΛCDM model.

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Moving from specific systems to demographic samples

Testing phase-space correlations in large samples of satellite systems

Surveys of satellite galaxy systems beyond the Local Group provide increasing amounts of data.

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"Observe" simulations
degrade perfect simulation data to allow fair comparison

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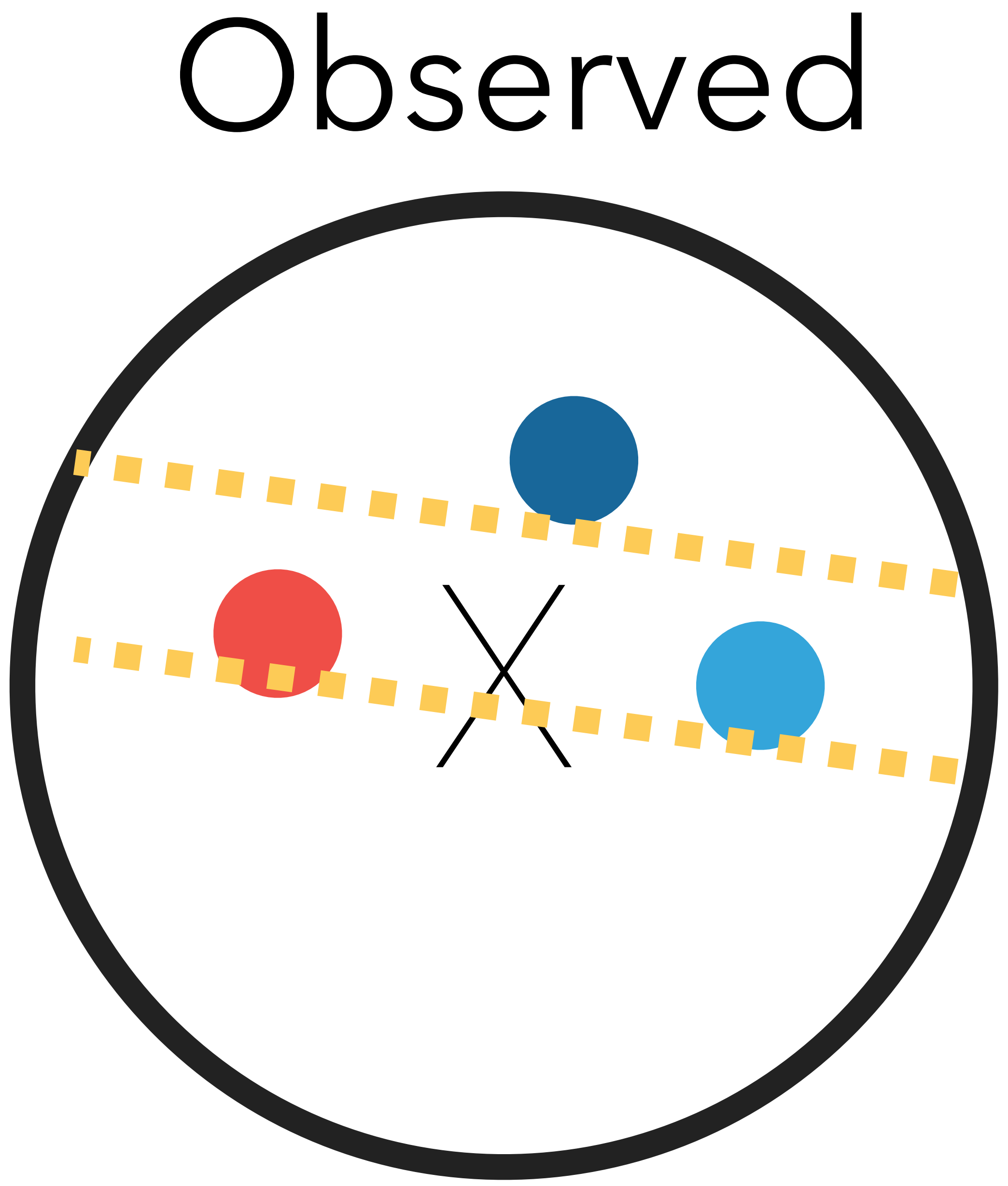

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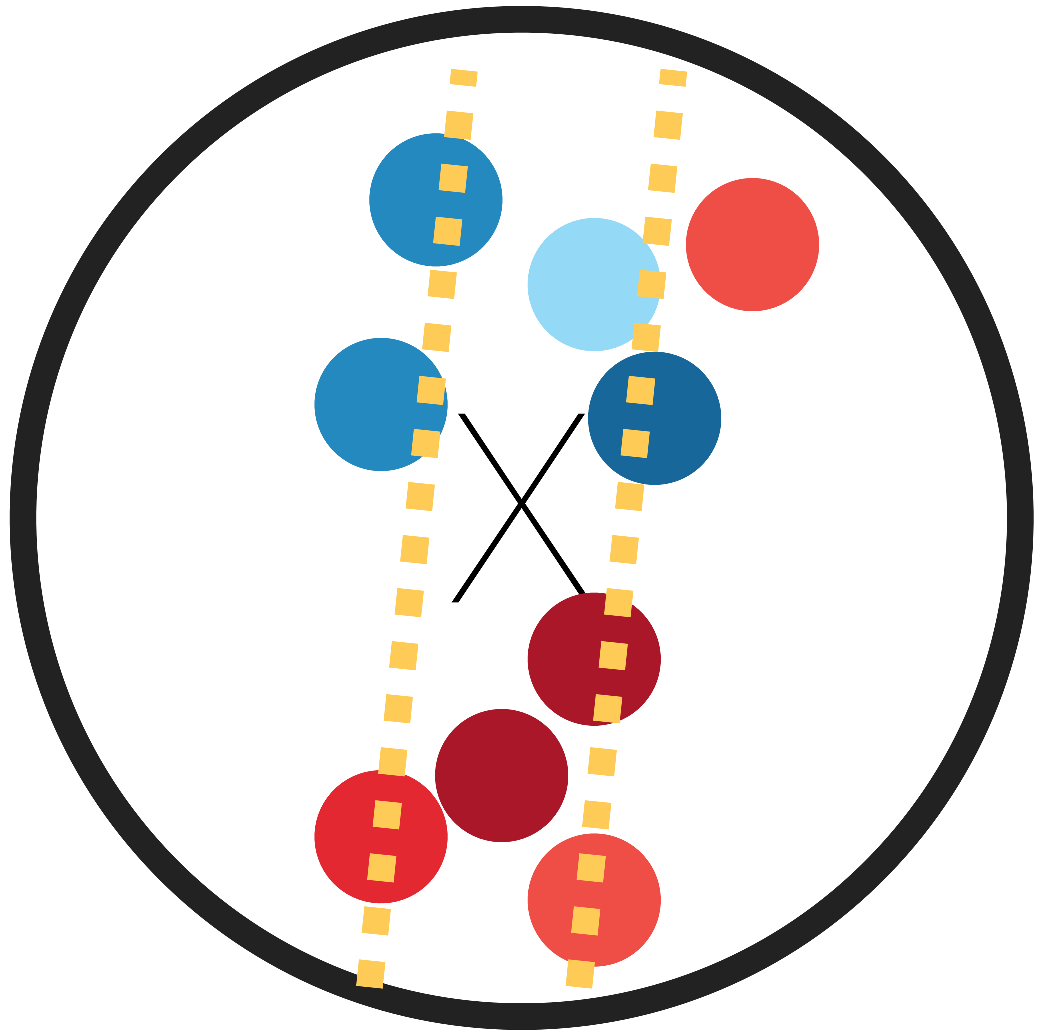

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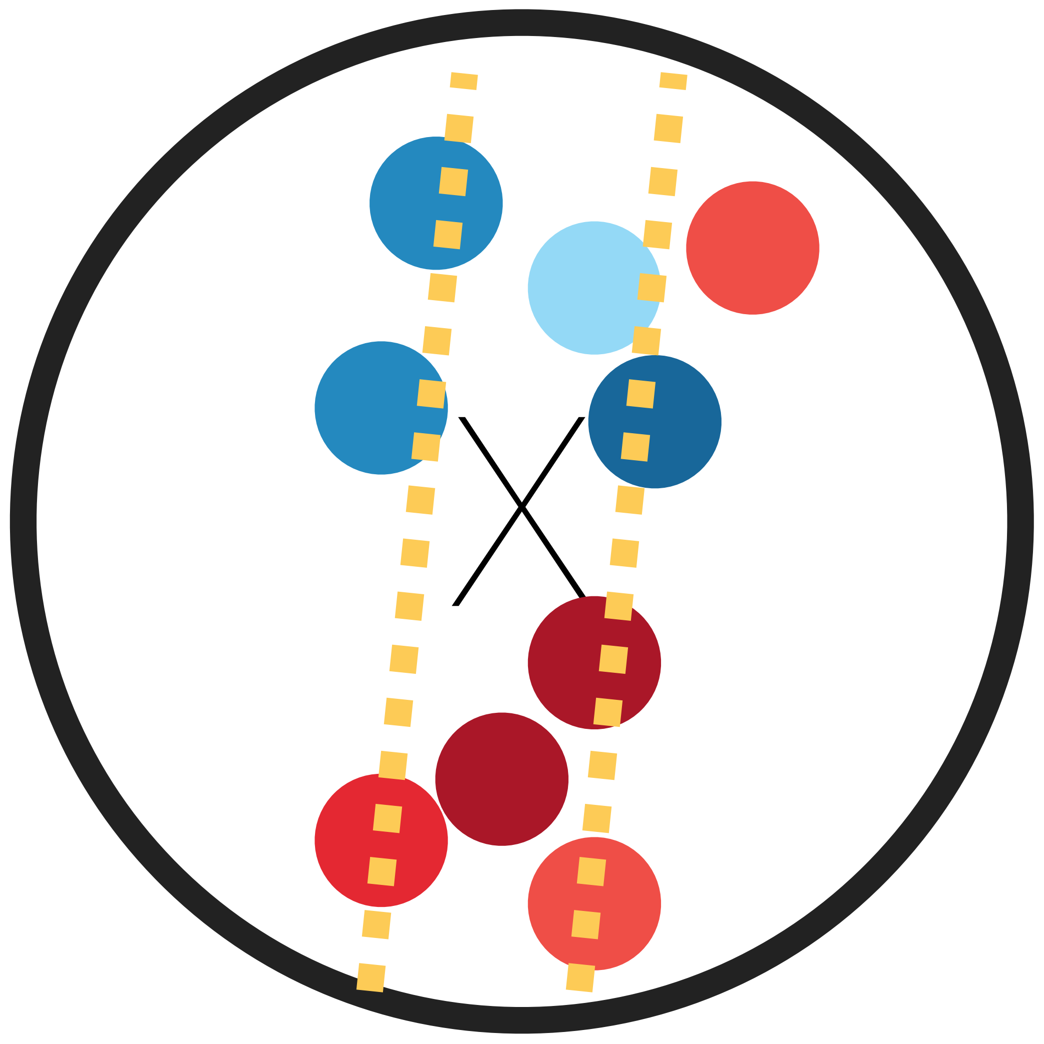
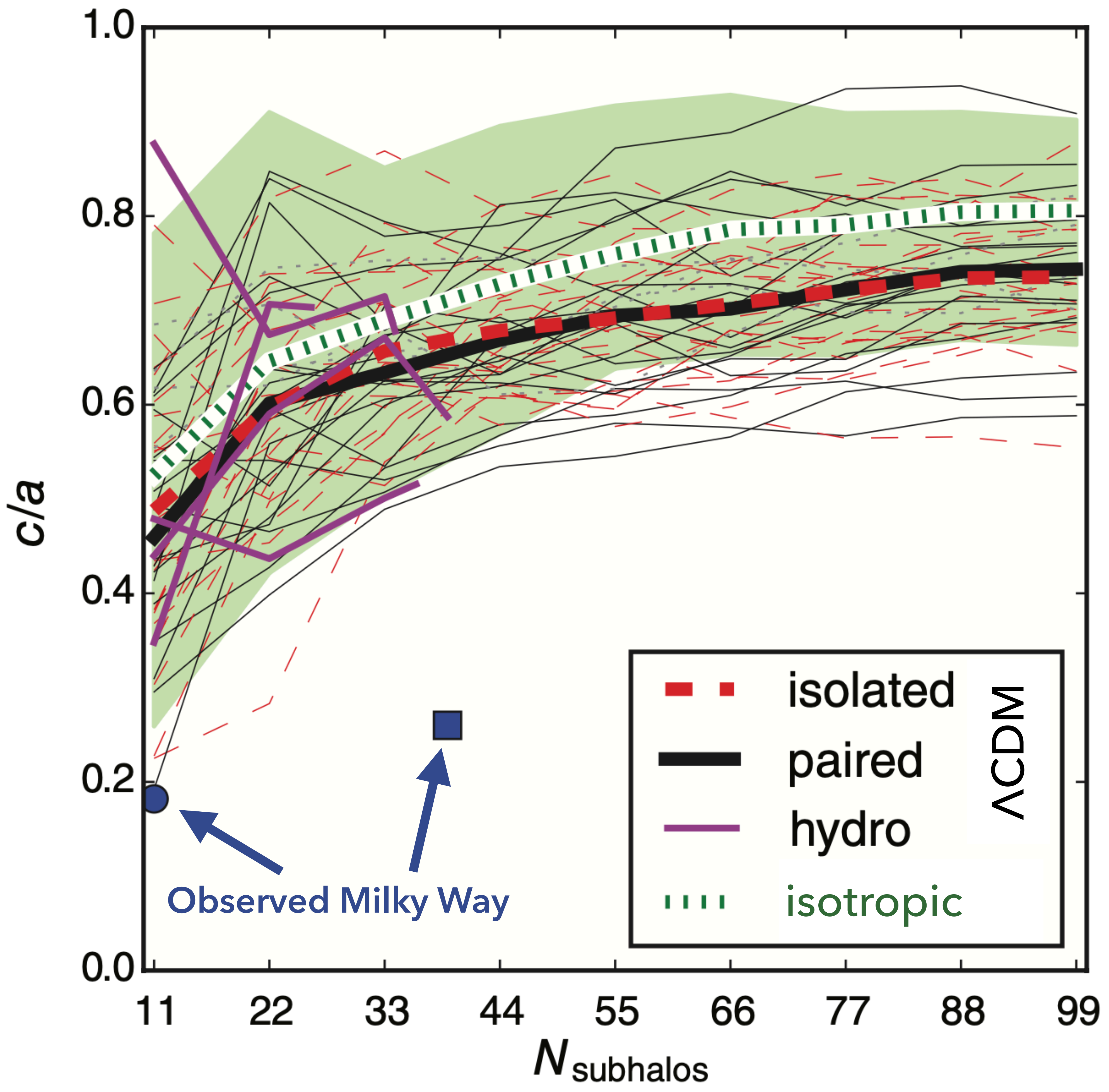


Pawlowski et al. (2017)



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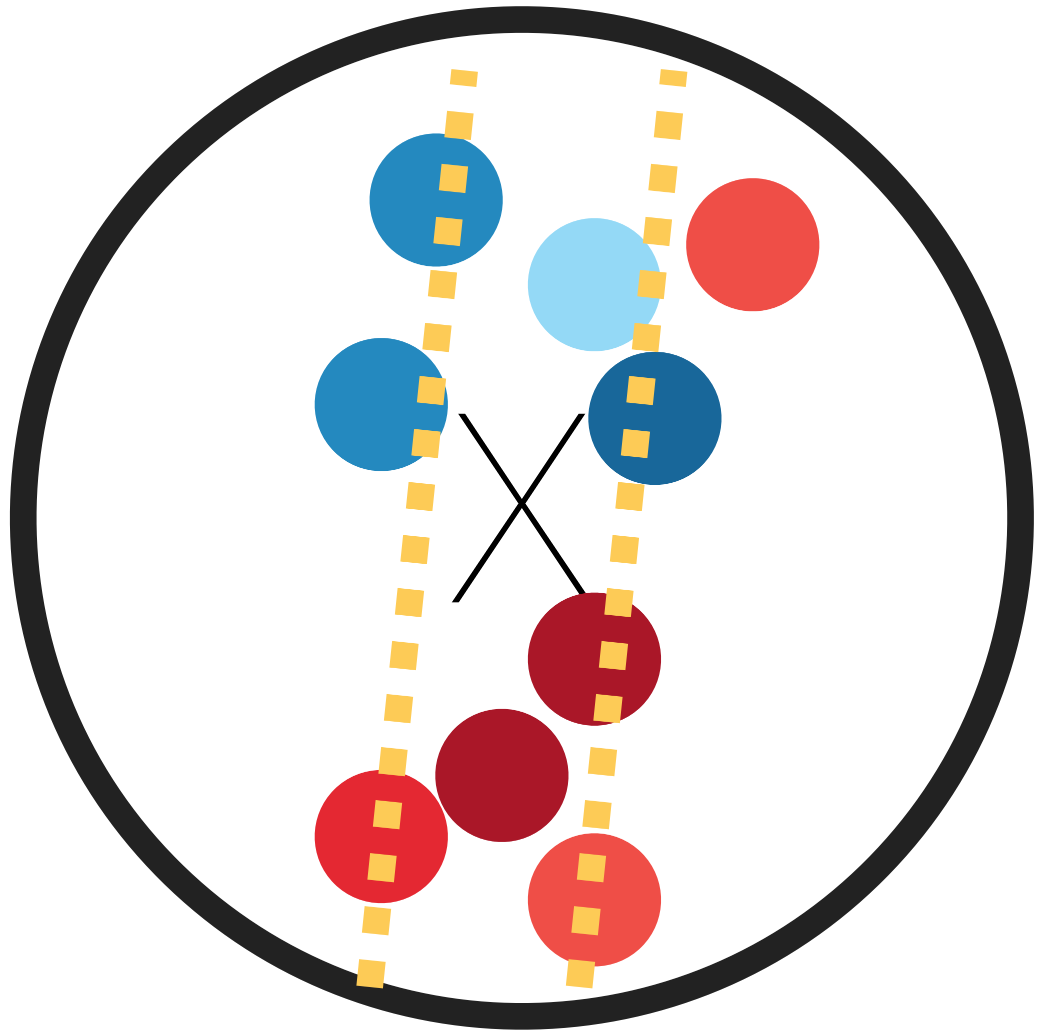

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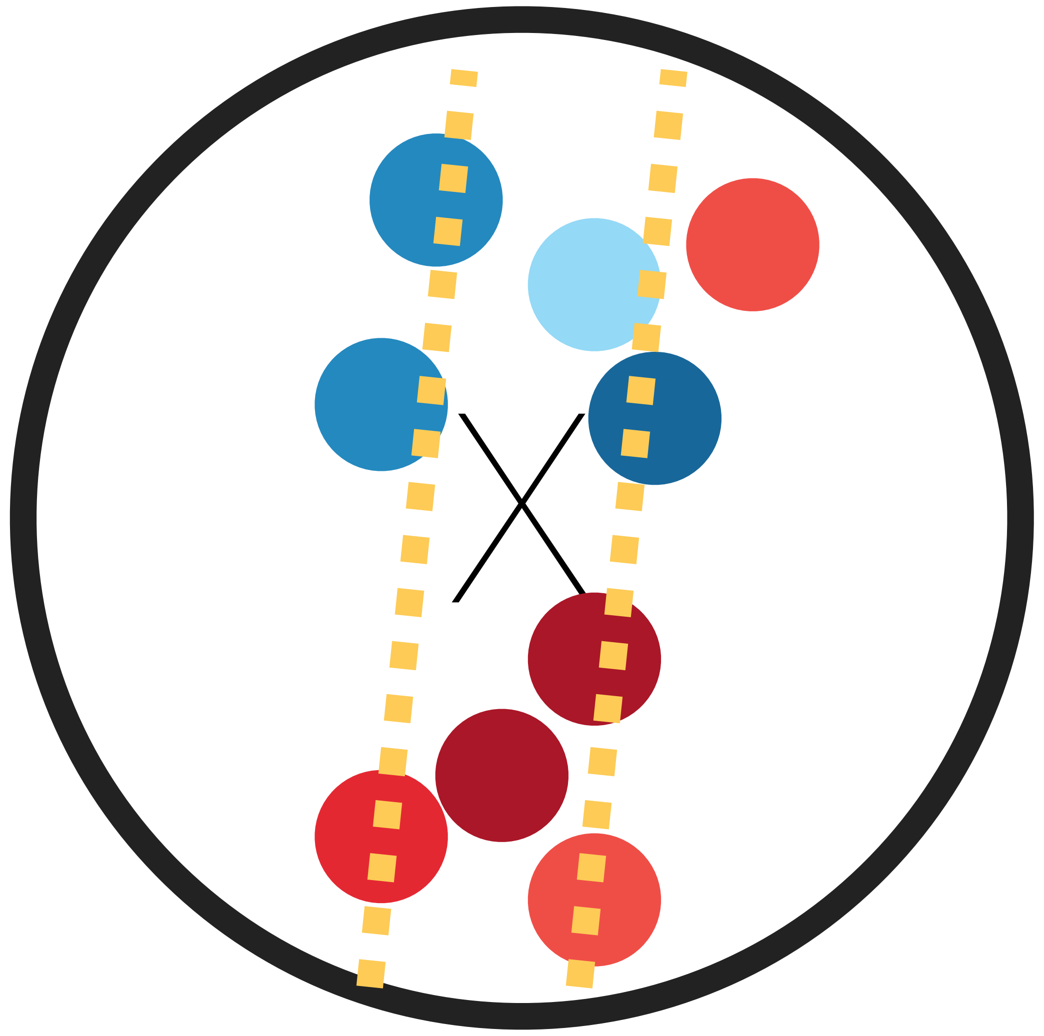

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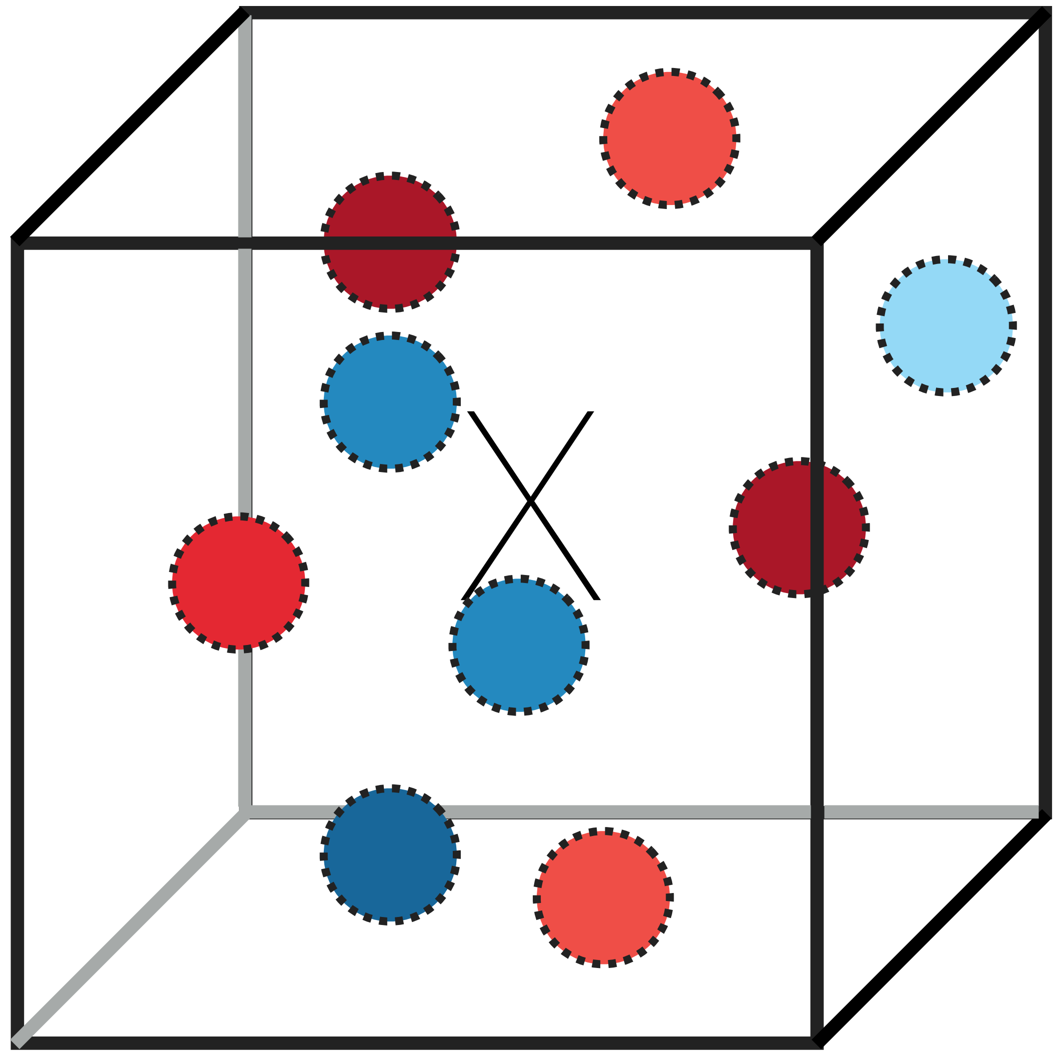

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Quantify systems by how rare analog systems in isotropic distributions are,
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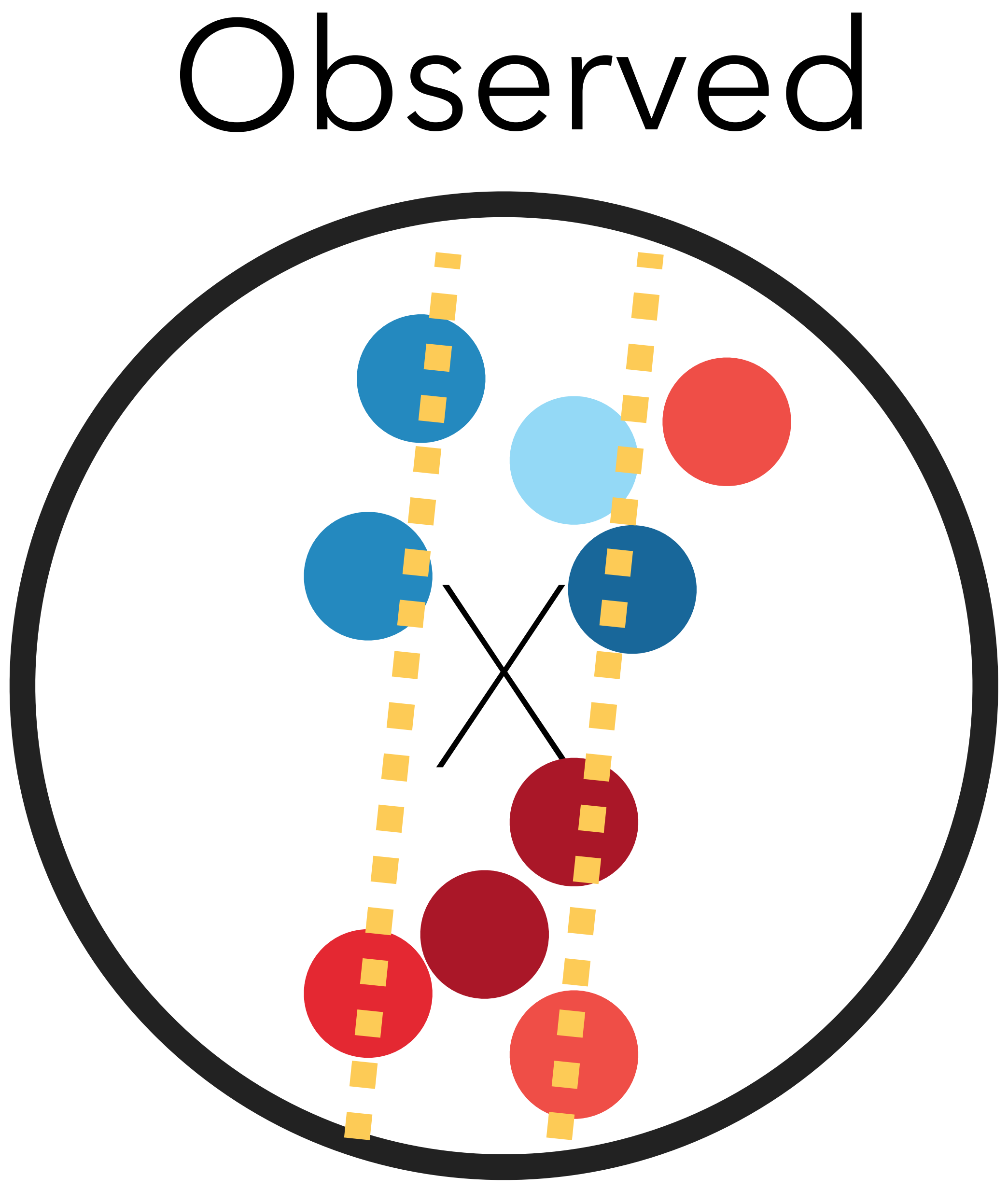

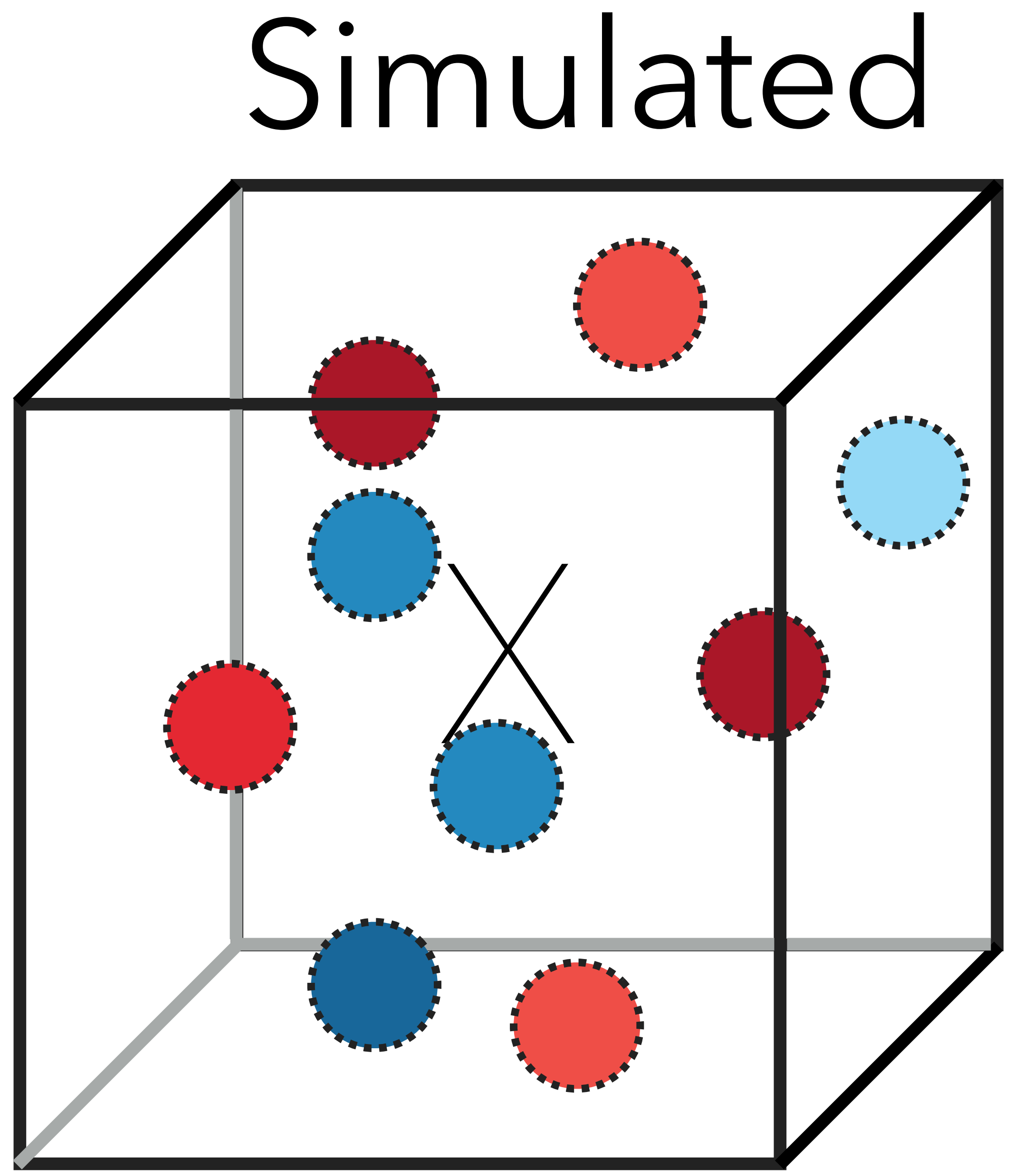

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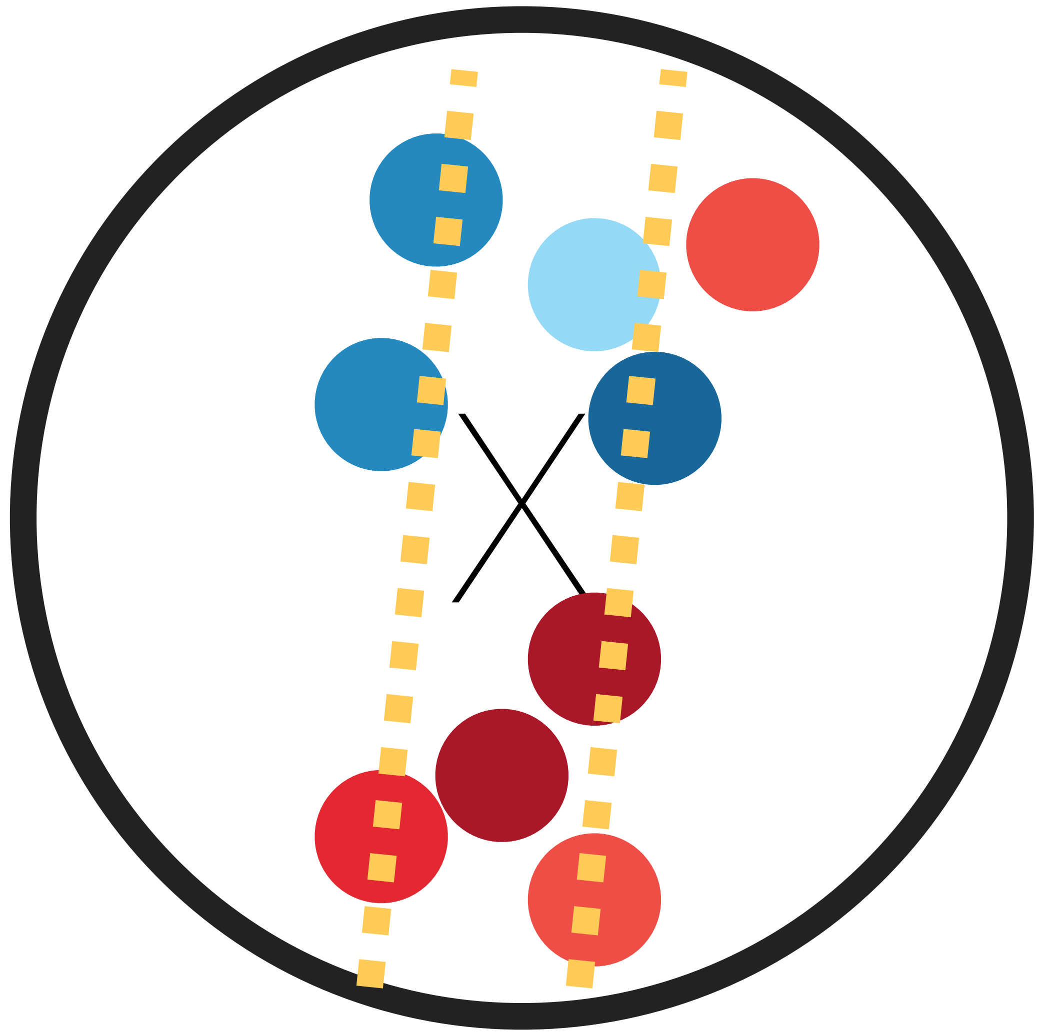
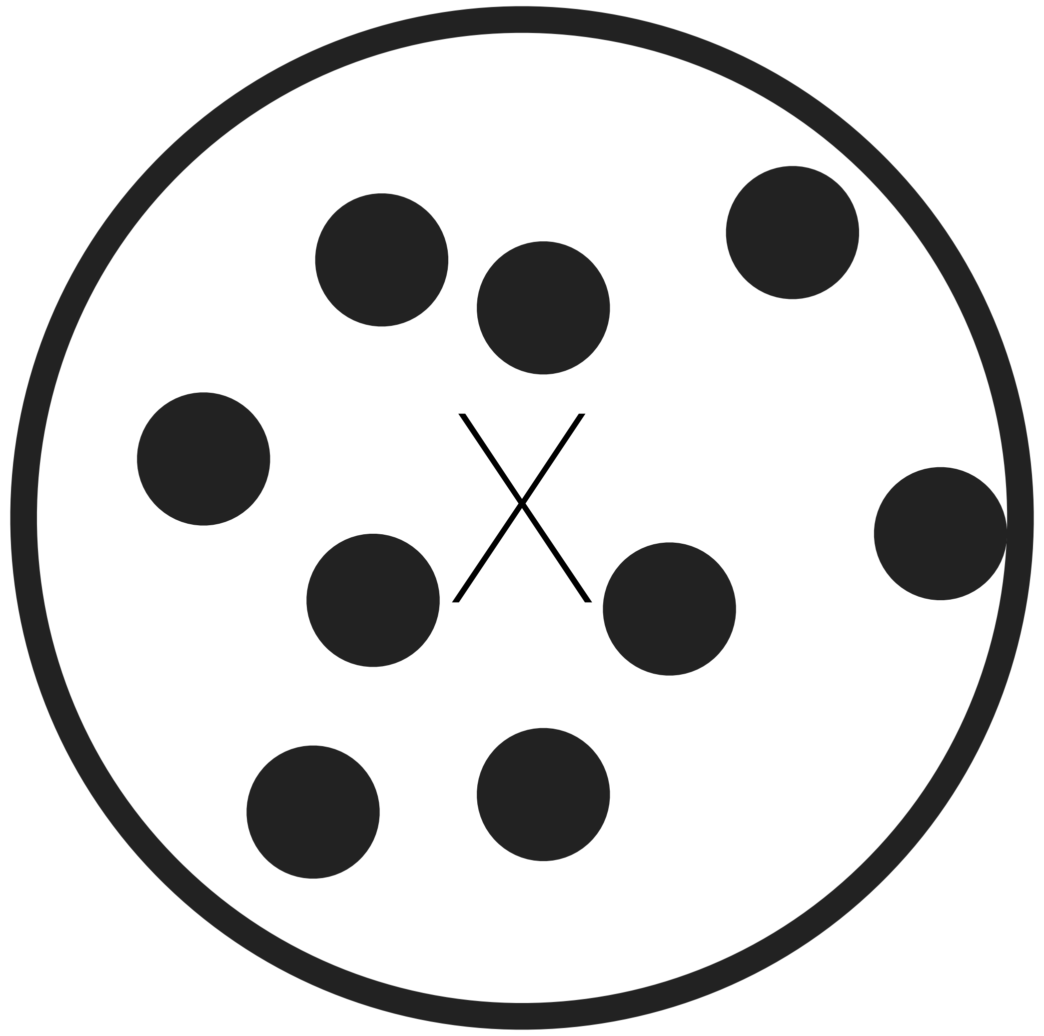


Isotropic Distributions



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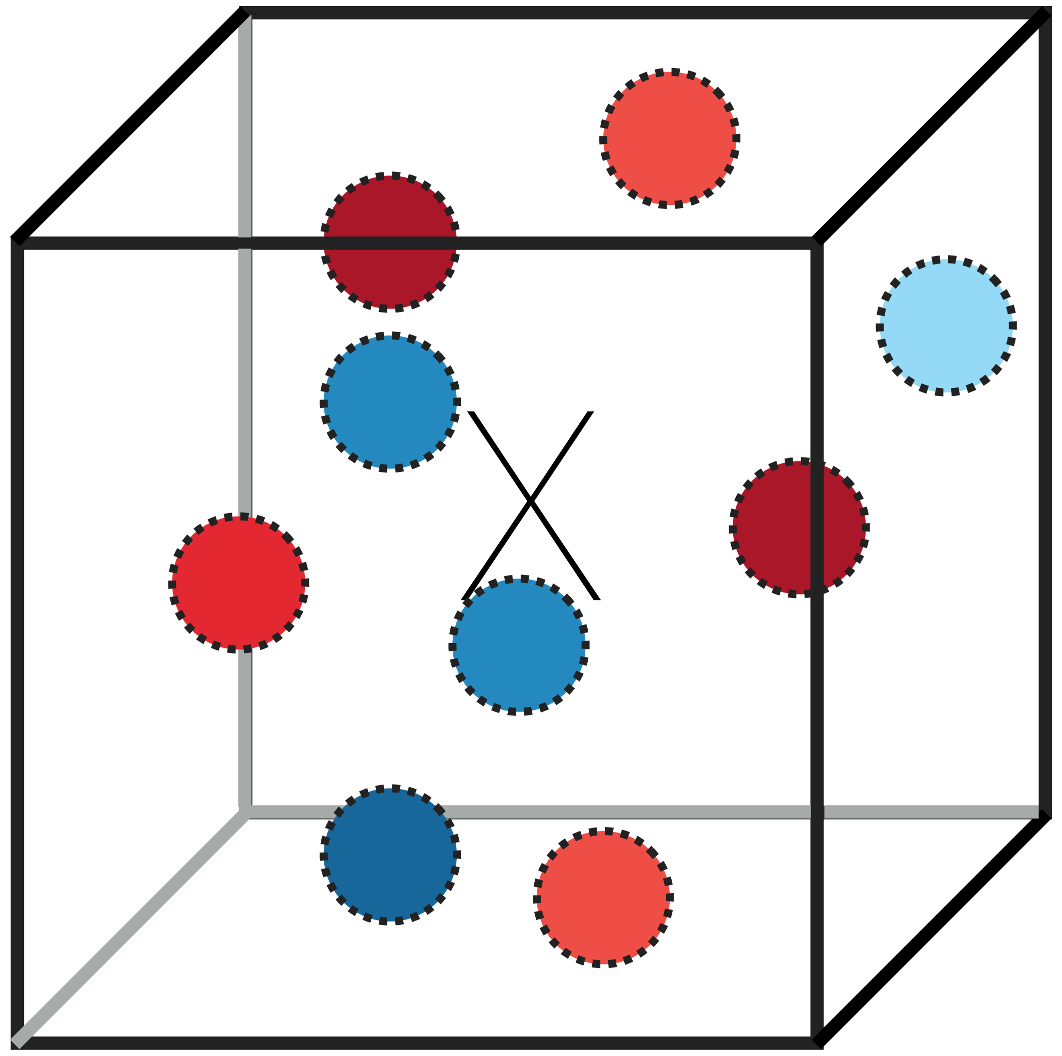

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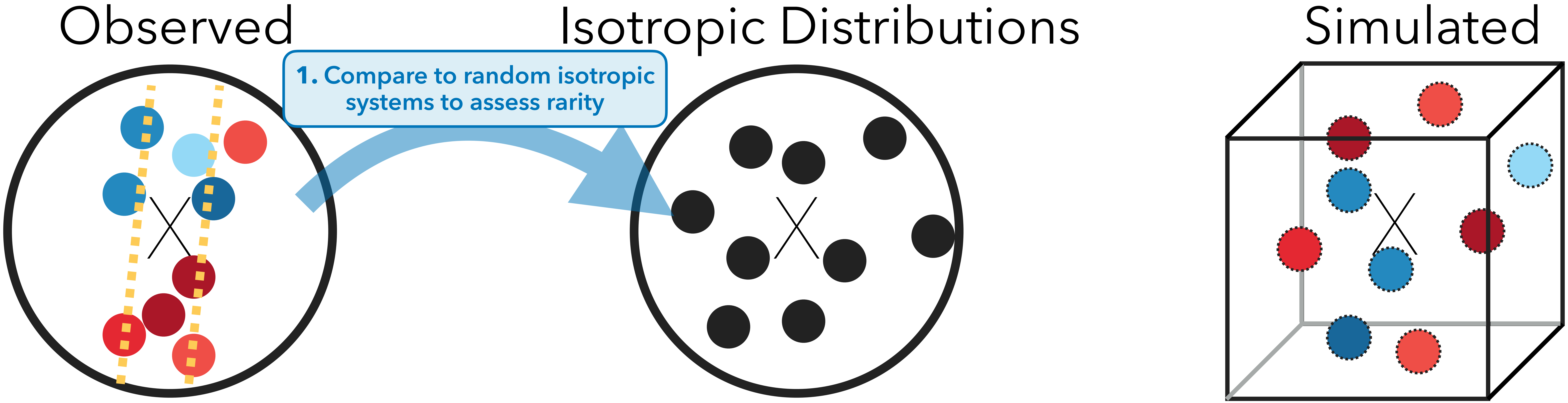

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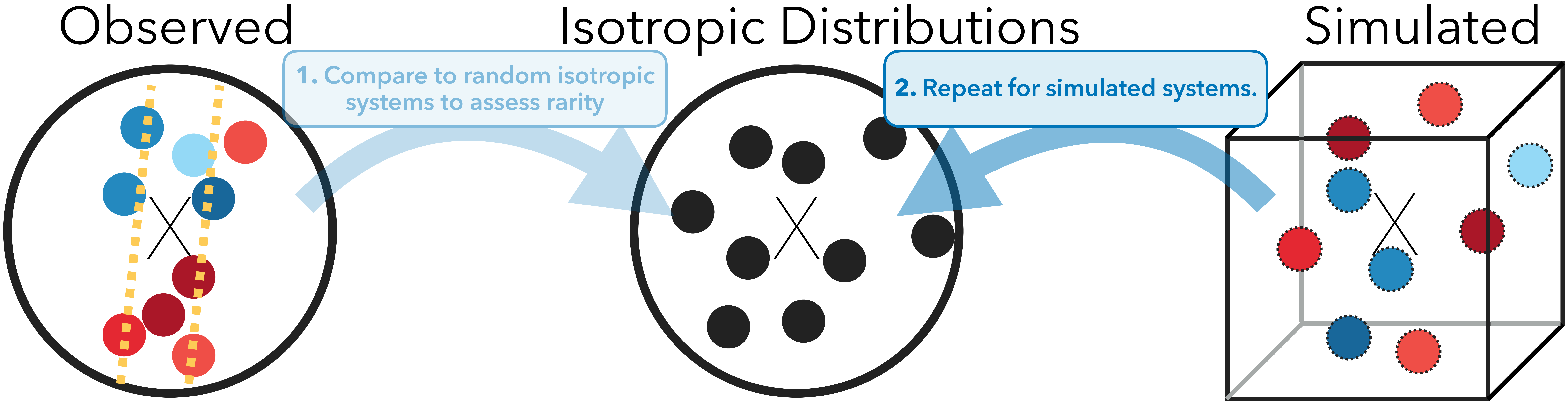

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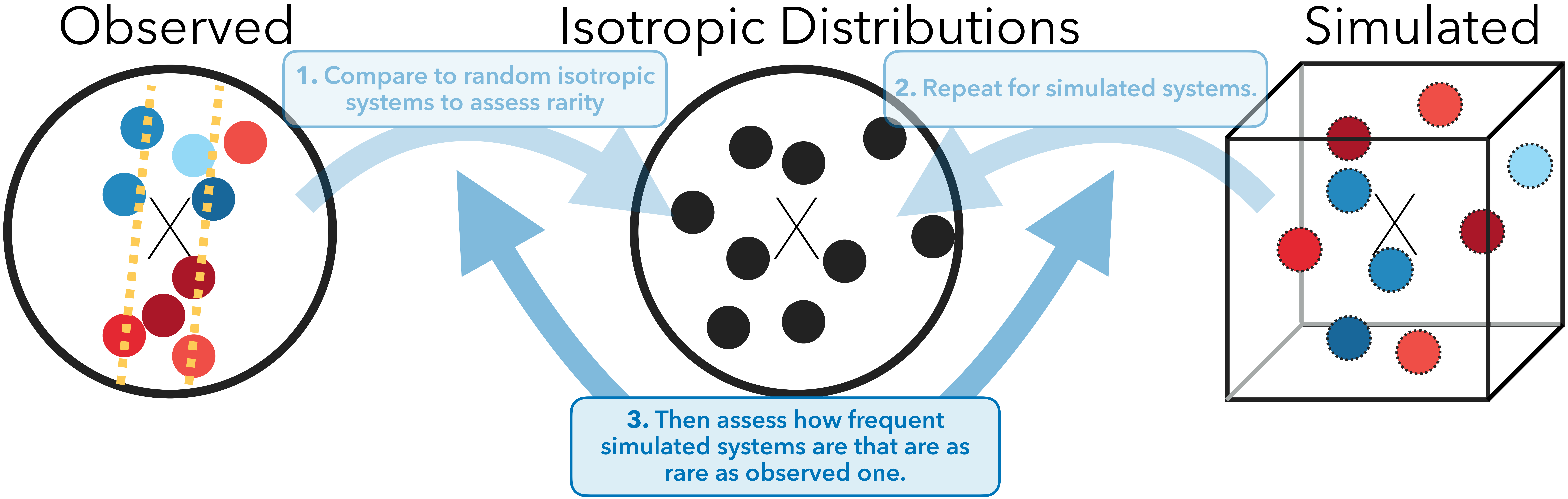
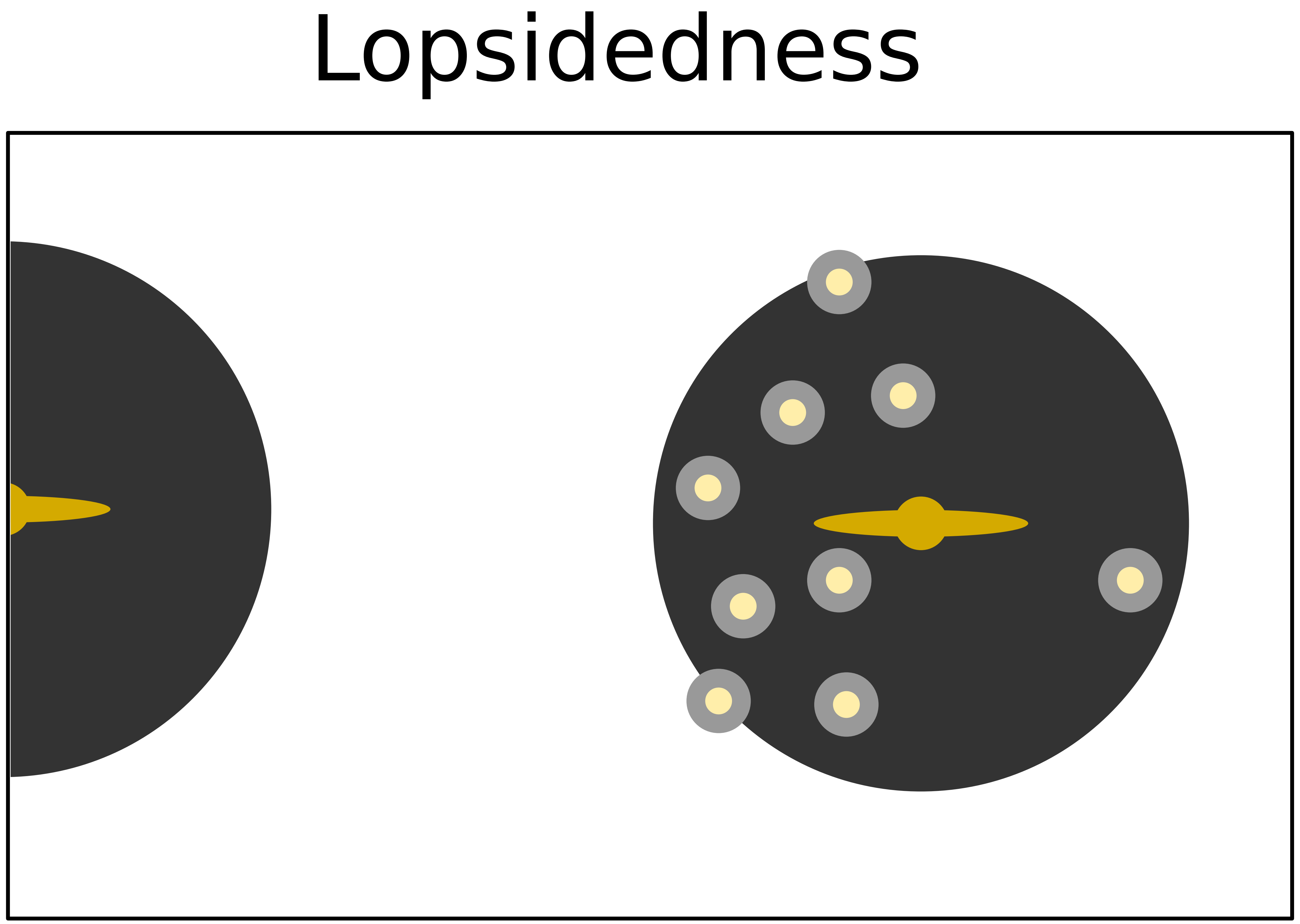


1. Compare to random isotropic systems to assess rarity

2. Repeat for simulated systems.

3. Then assess how frequent simulated systems are that are as rare as observed one.

Lopsided Satellite Systems



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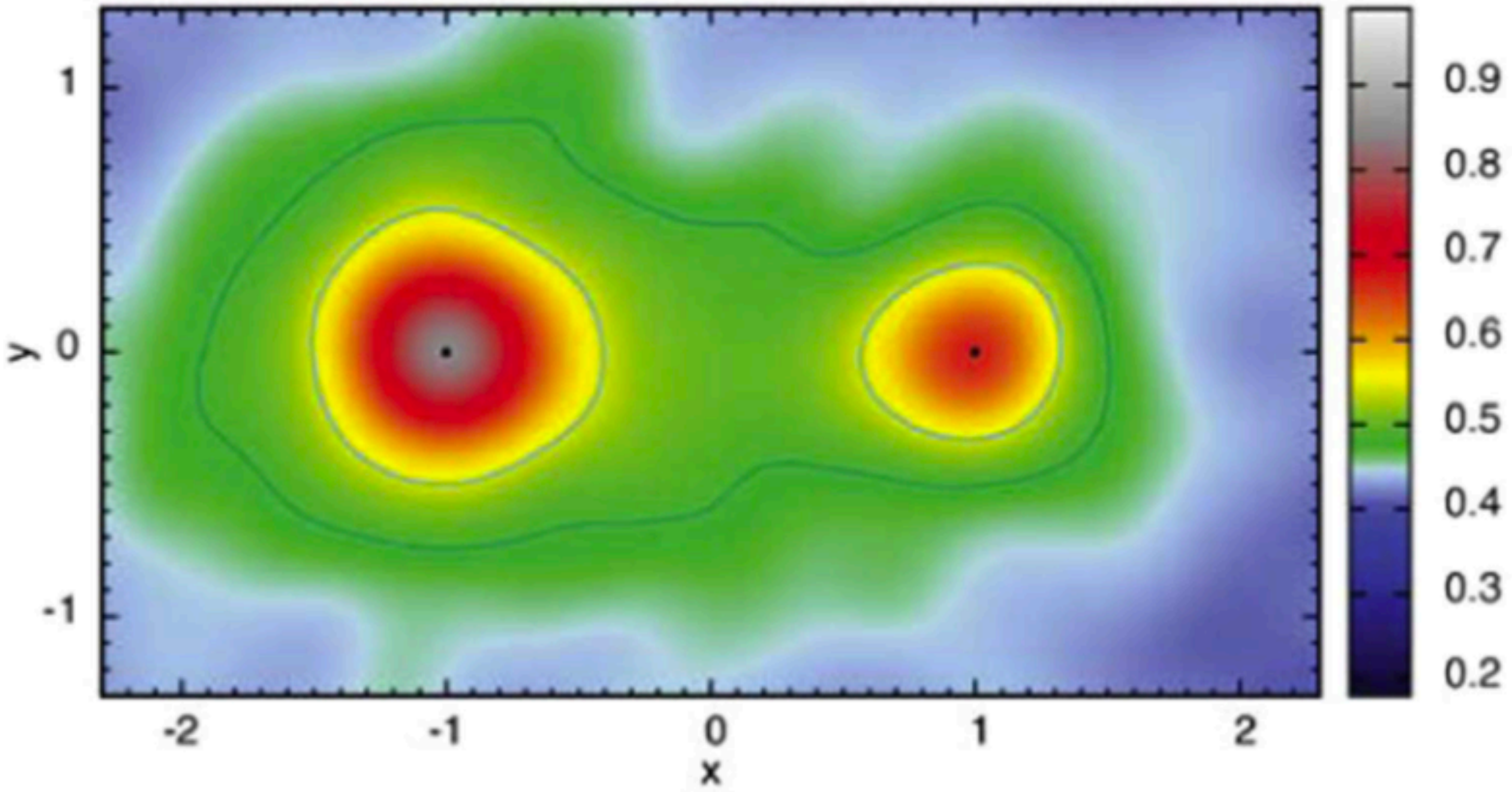

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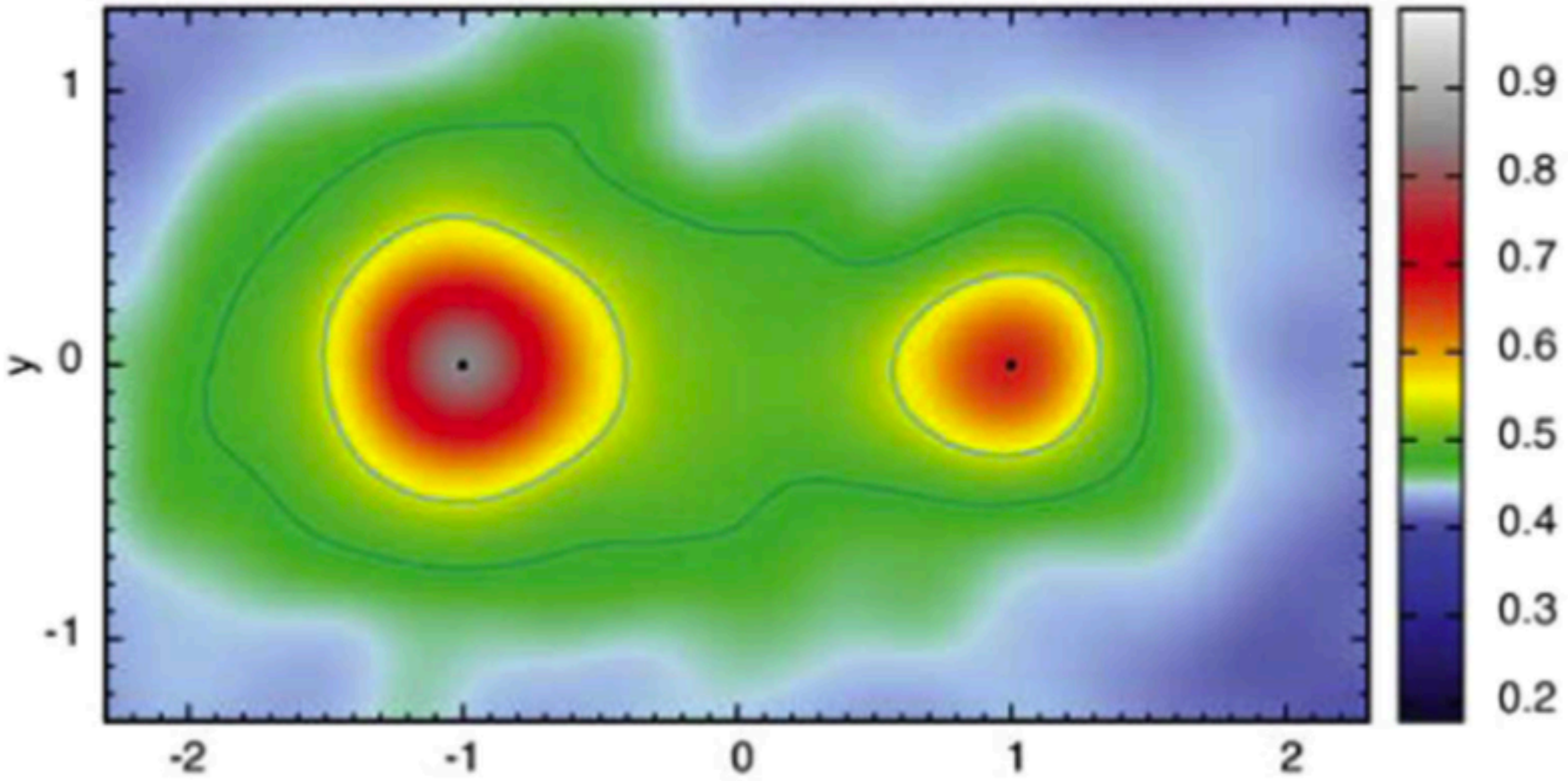

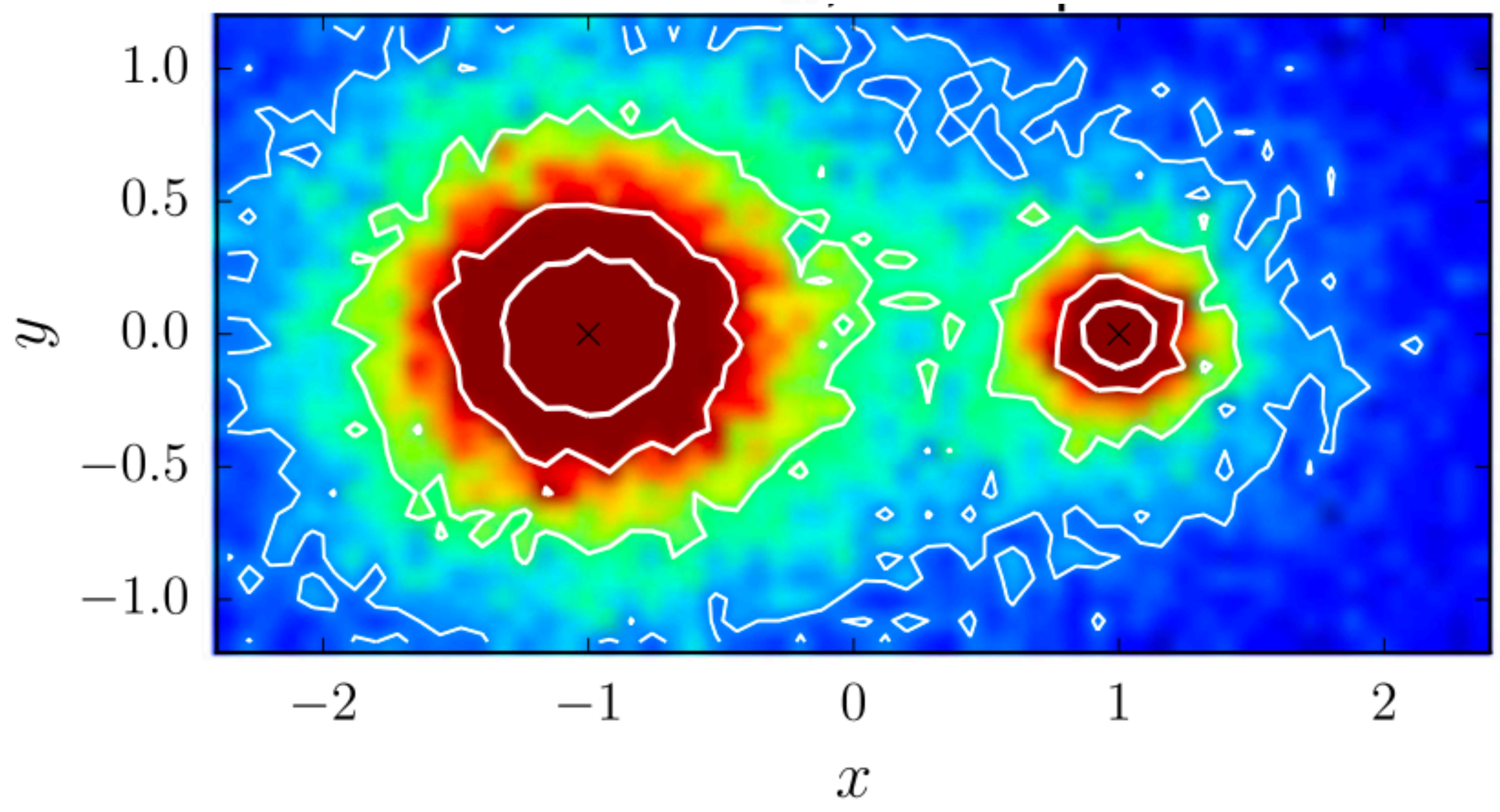

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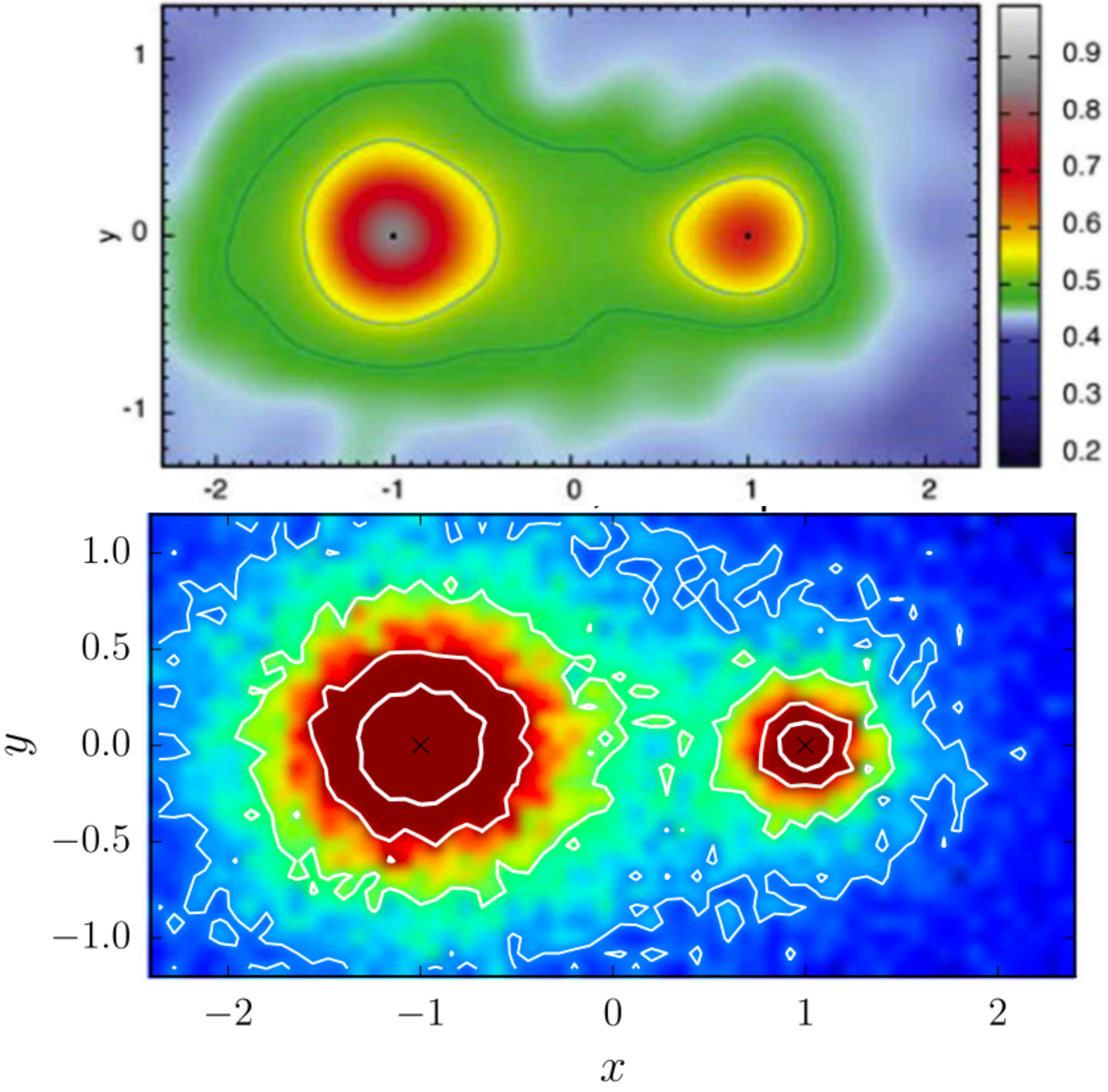
- SDSS **only** allows to **compare a few brightest satellites** and stacked distributions.
What about in-depth comparison of M31 to cosmological expectations?

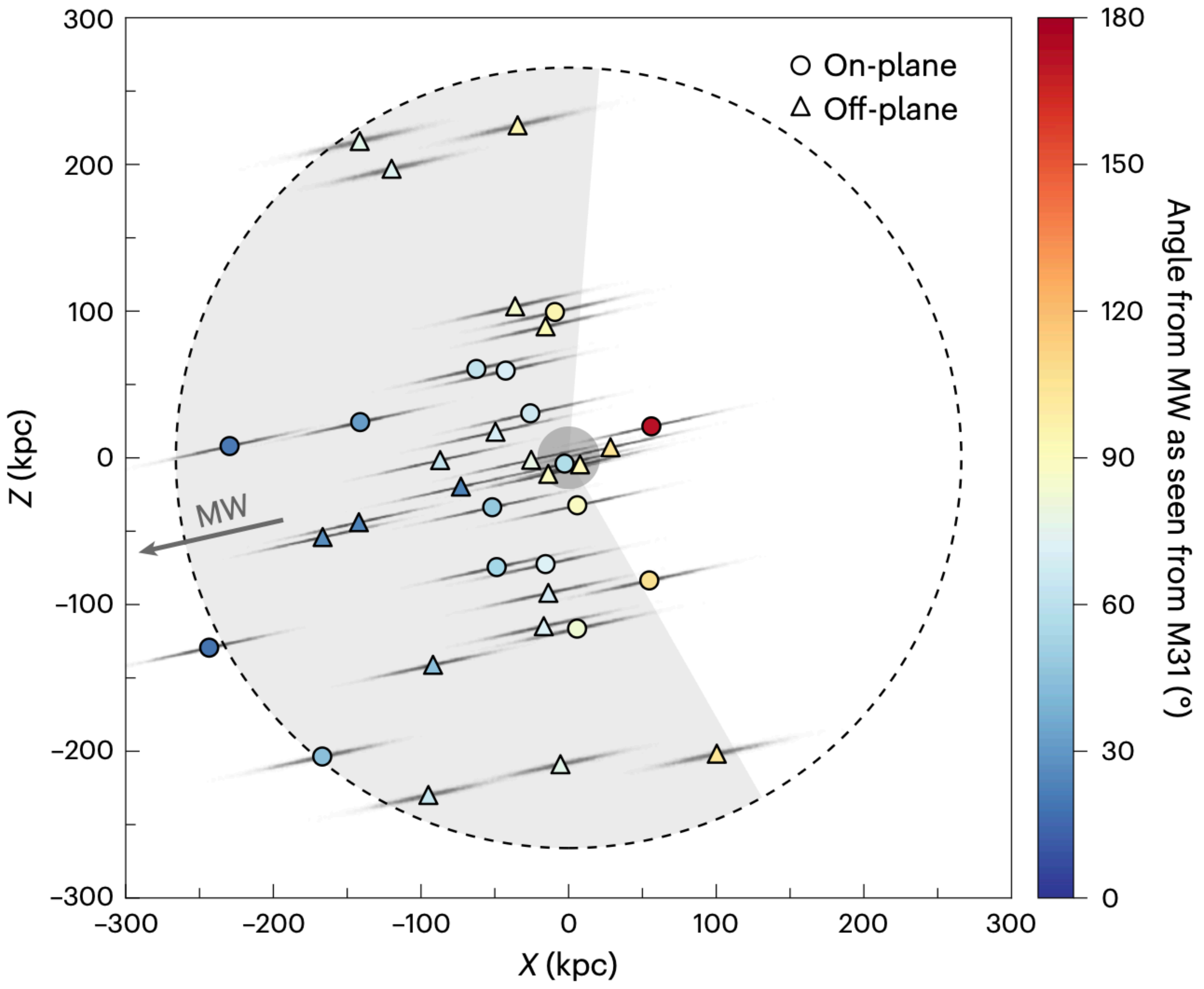


M31 Satellite System

Kanehisa, Pawlowski & Libeskind (2025, *Nature Astronomy*)

Proof of concept: M31 lopsidedness – another problem for ΛCDM

- 36 of 27 M31 satellites are within 107° of direction towards the Milky Way.



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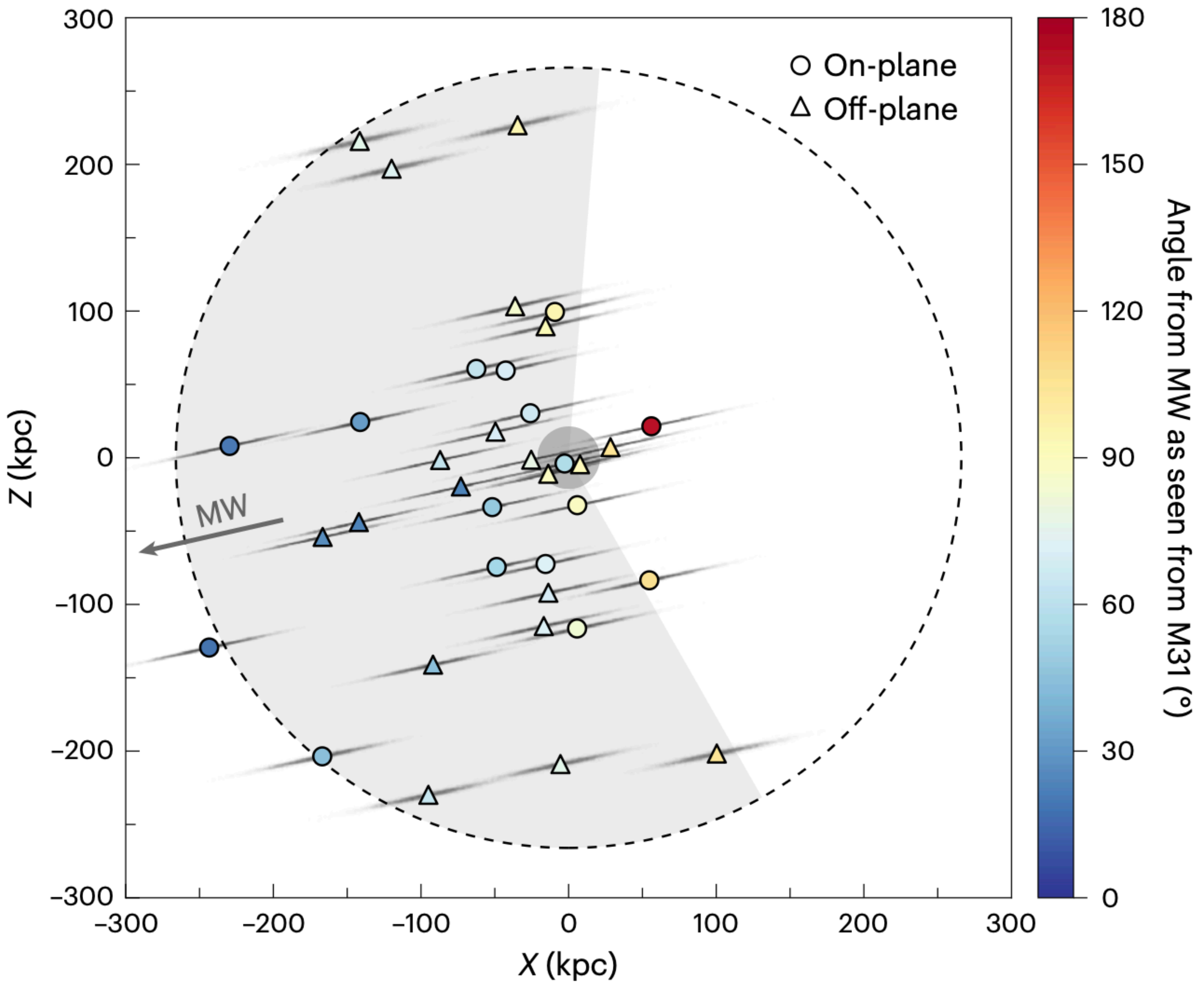

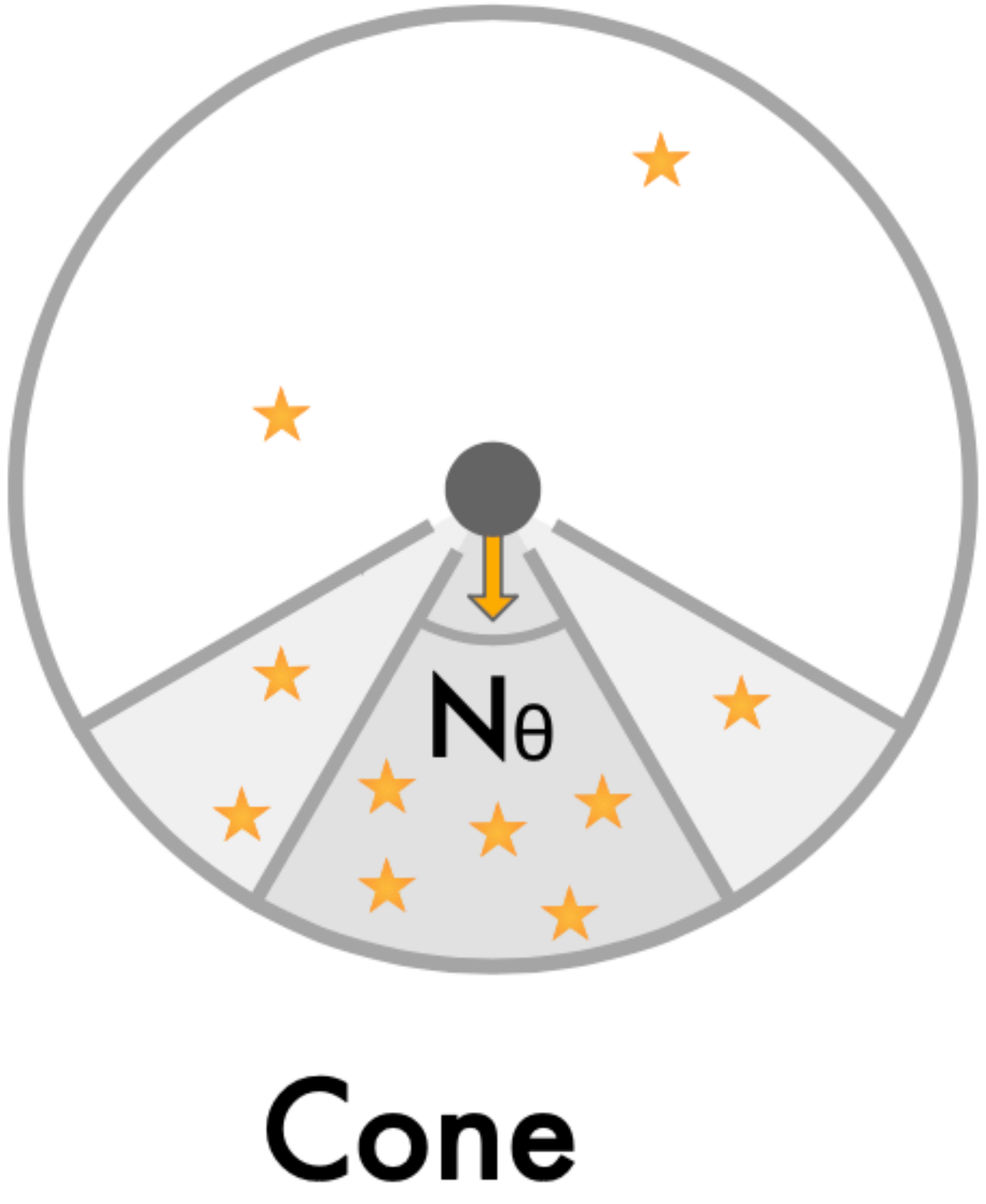

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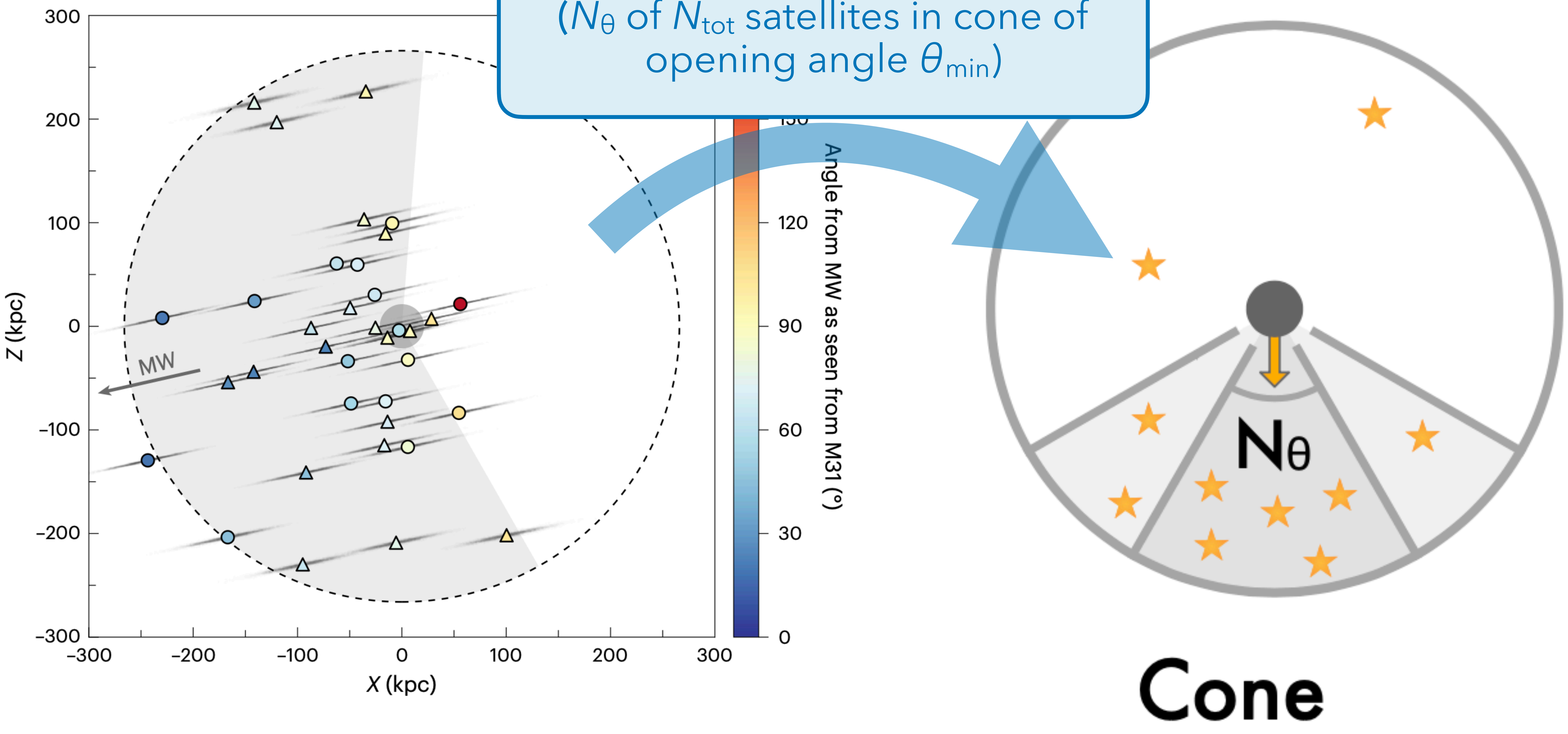

Find most extreme arrangement
(N_θ of N_{tot} satellites in cone of opening angle θ_{min})

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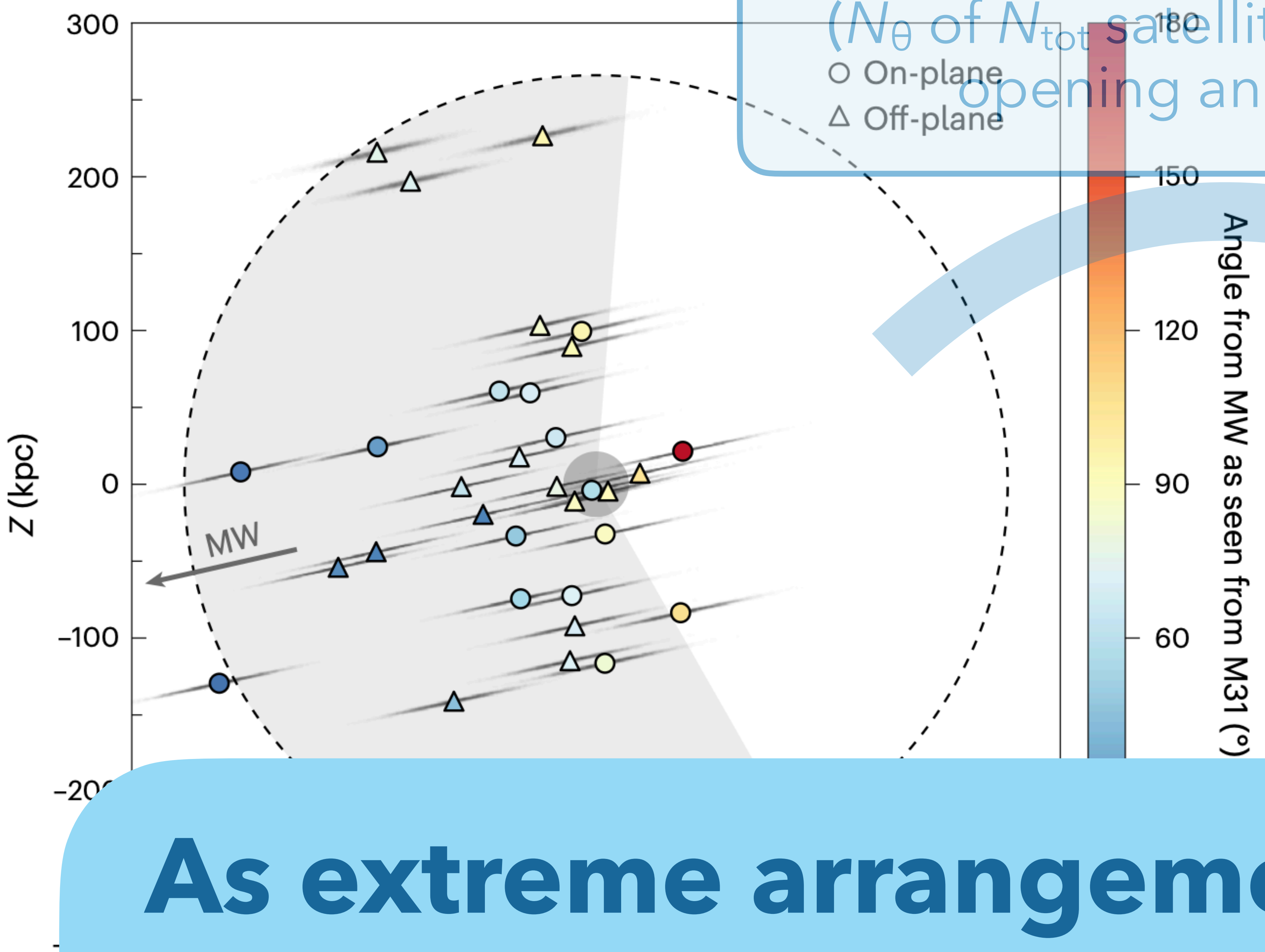

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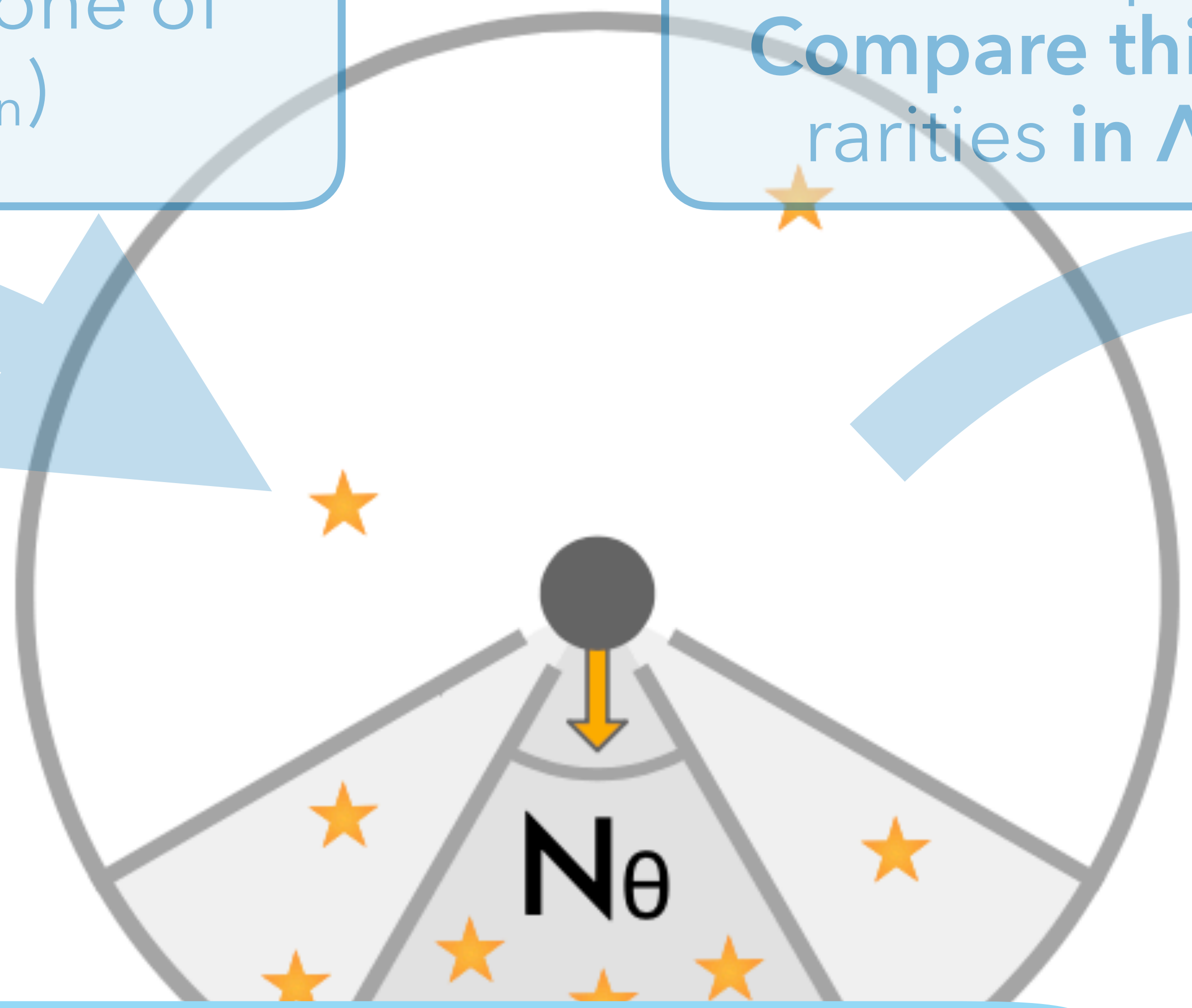

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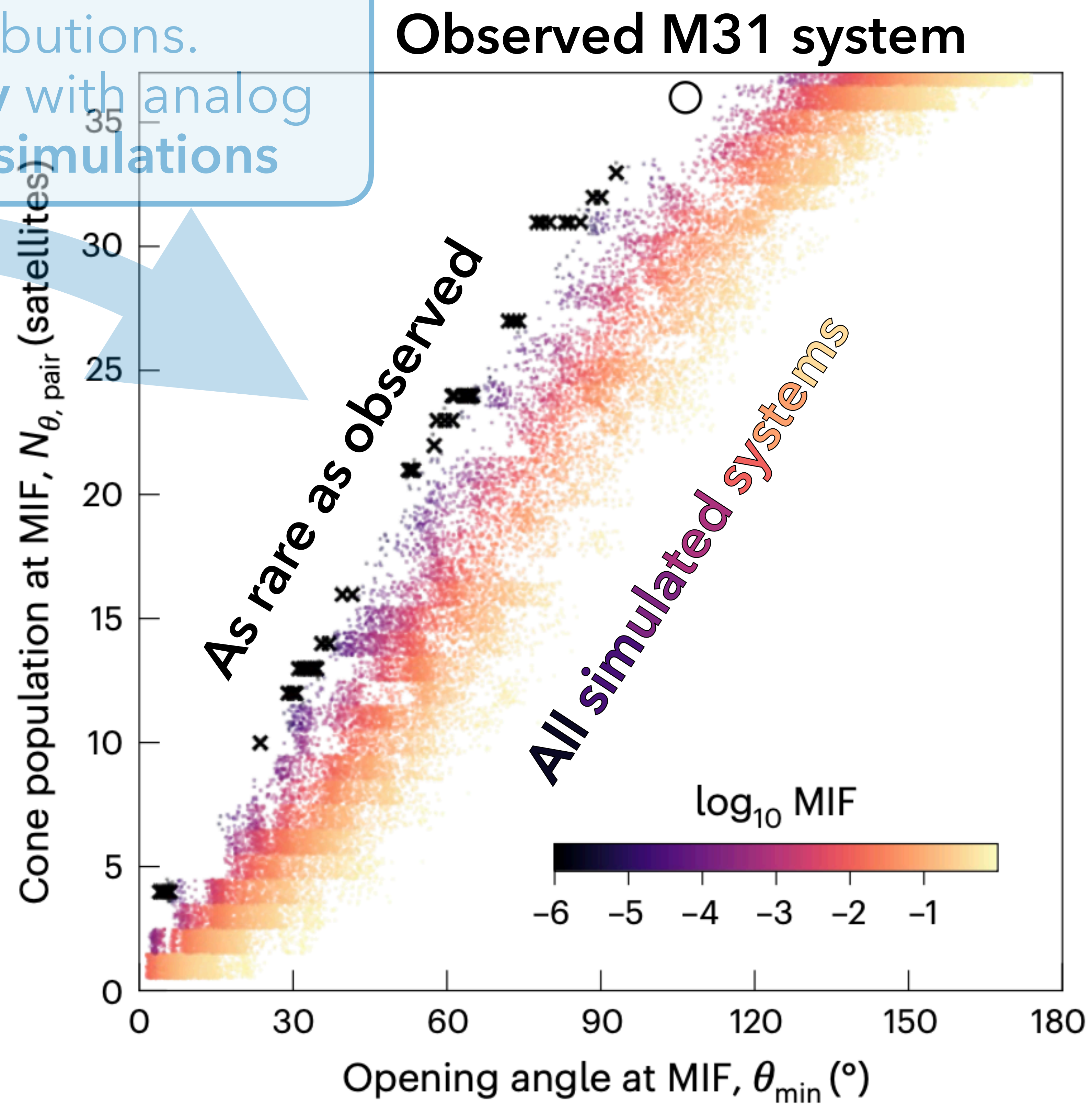

As extreme arrangements are rare (0.3%) in ΛCDM simulations (TNG+Eagle)

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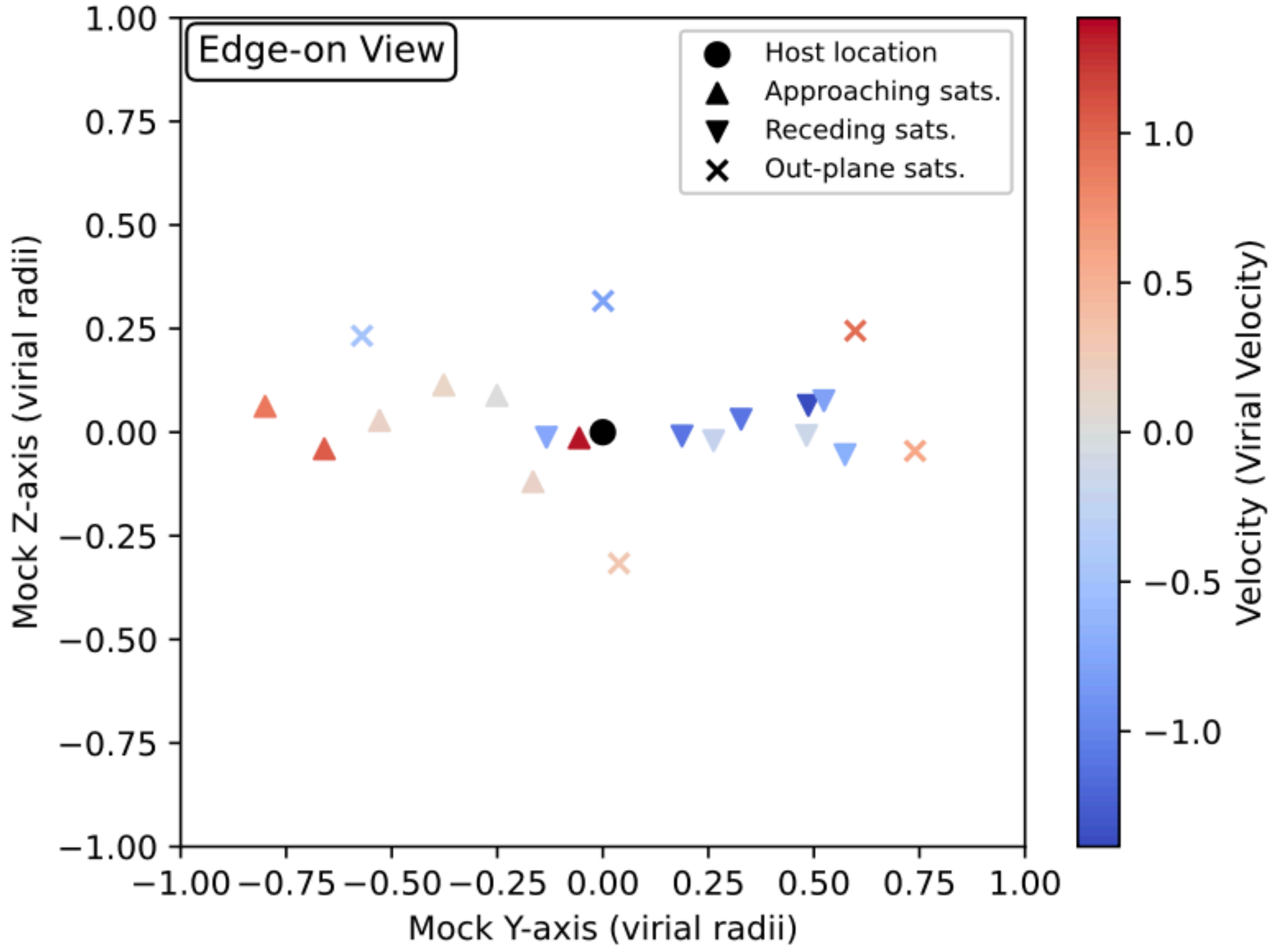
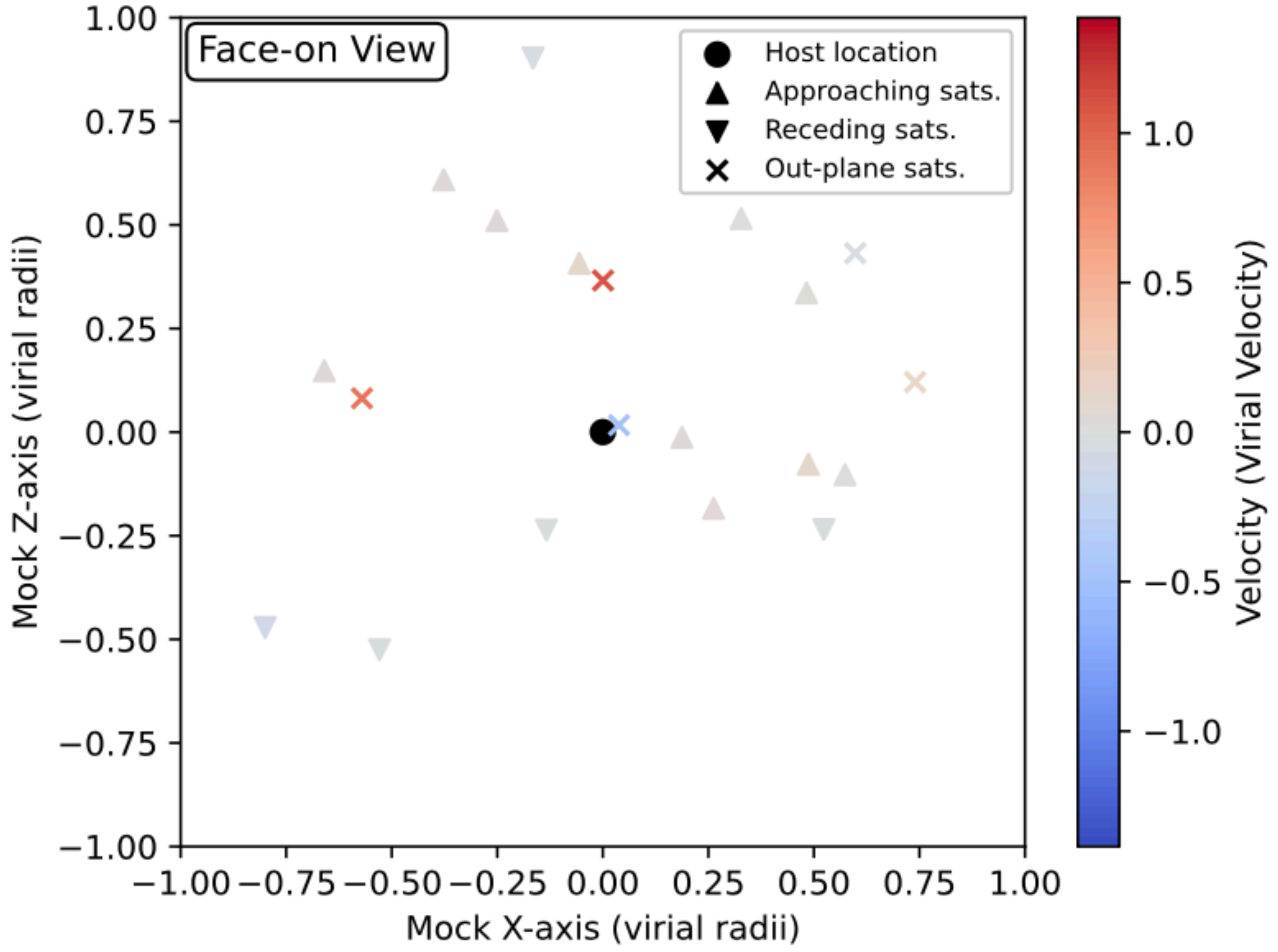
Detectability of satellite planes in mock observations of isolated galaxies

Mock-observe artificial systems with varying (1) numbers of satellites, (2) satellite plane fractions f_p, and (3) orientations θ_rot

Test different diagnostics:





Crosby, Pawlowski, Müller & Jerjen (2026)

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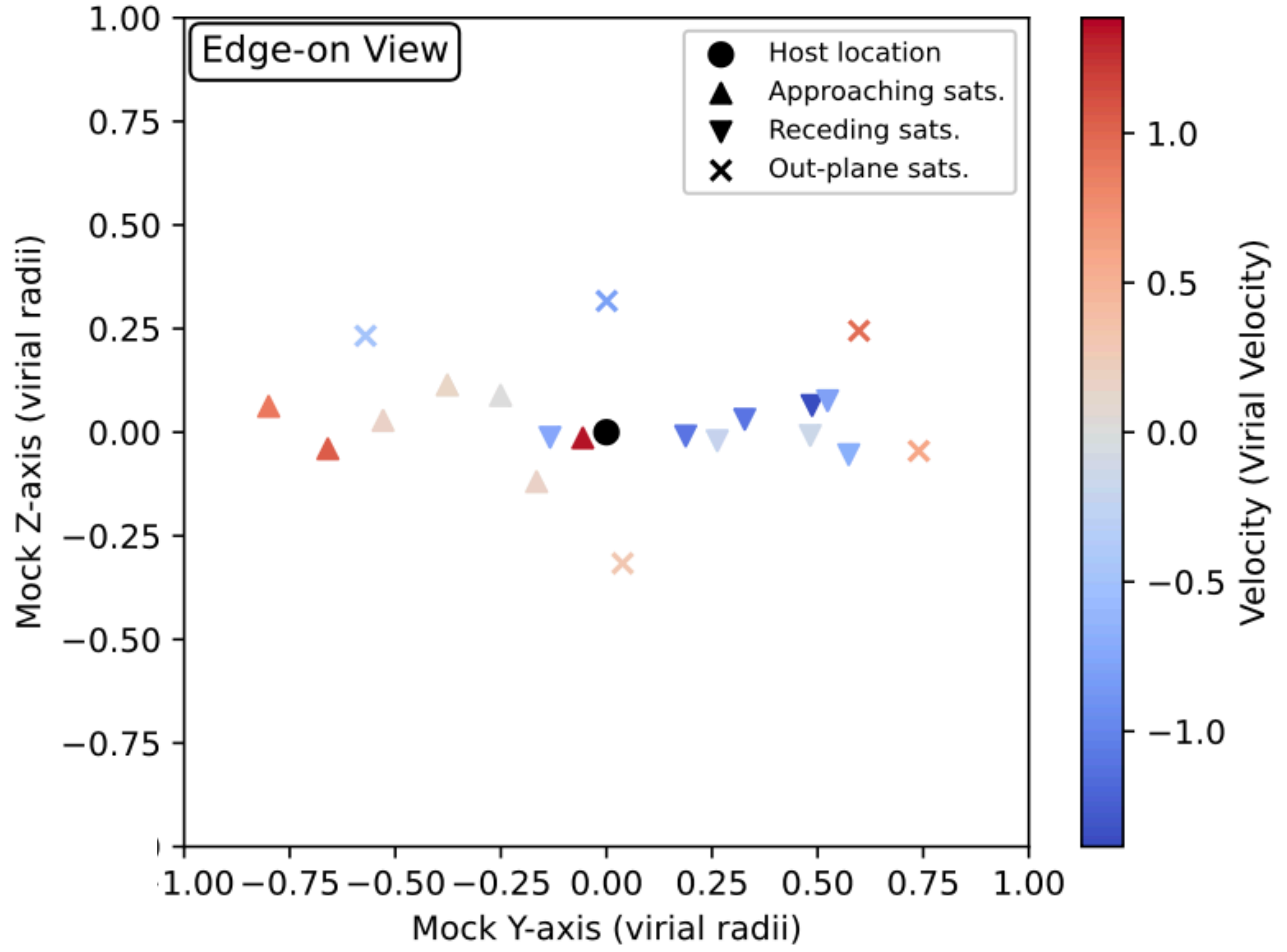

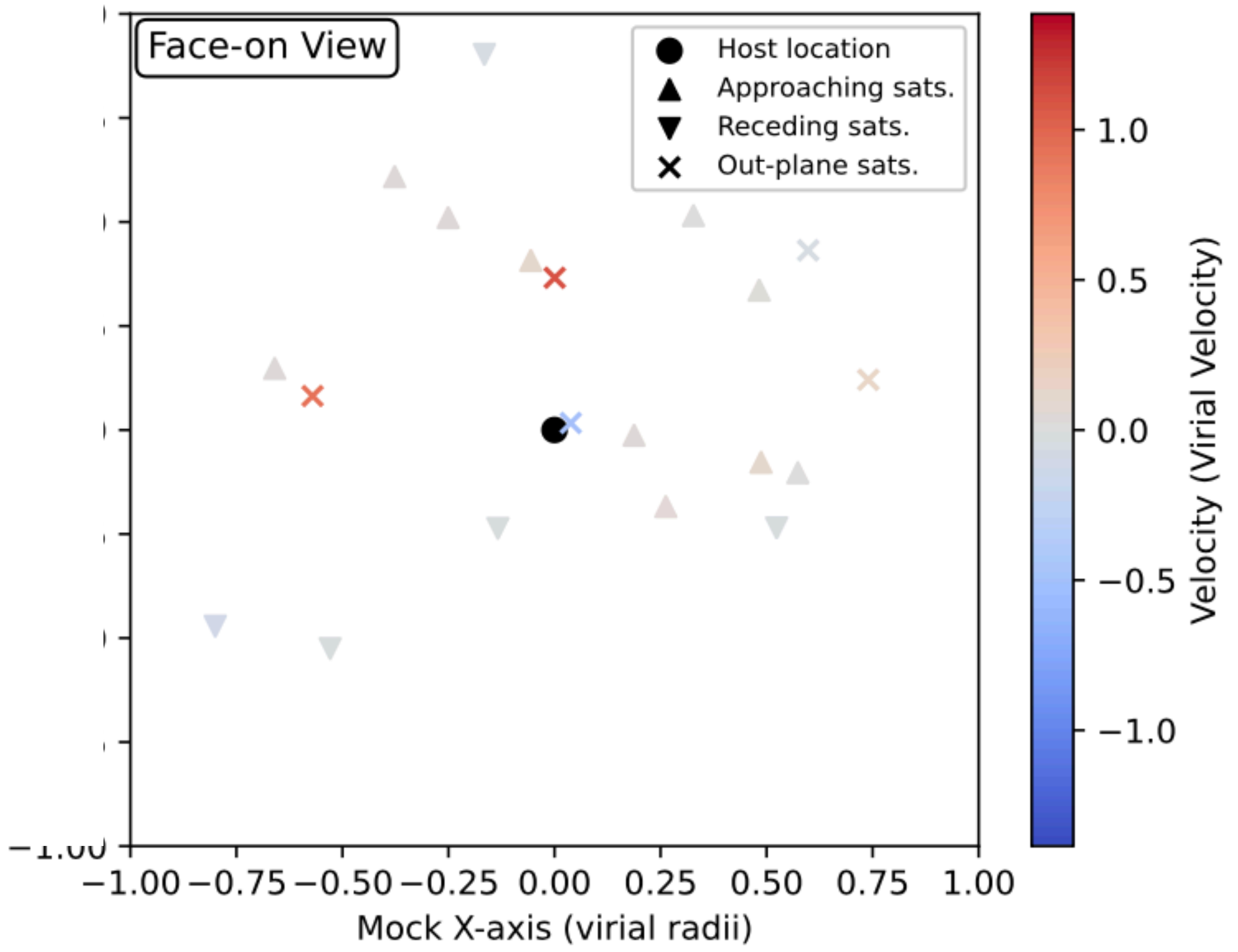

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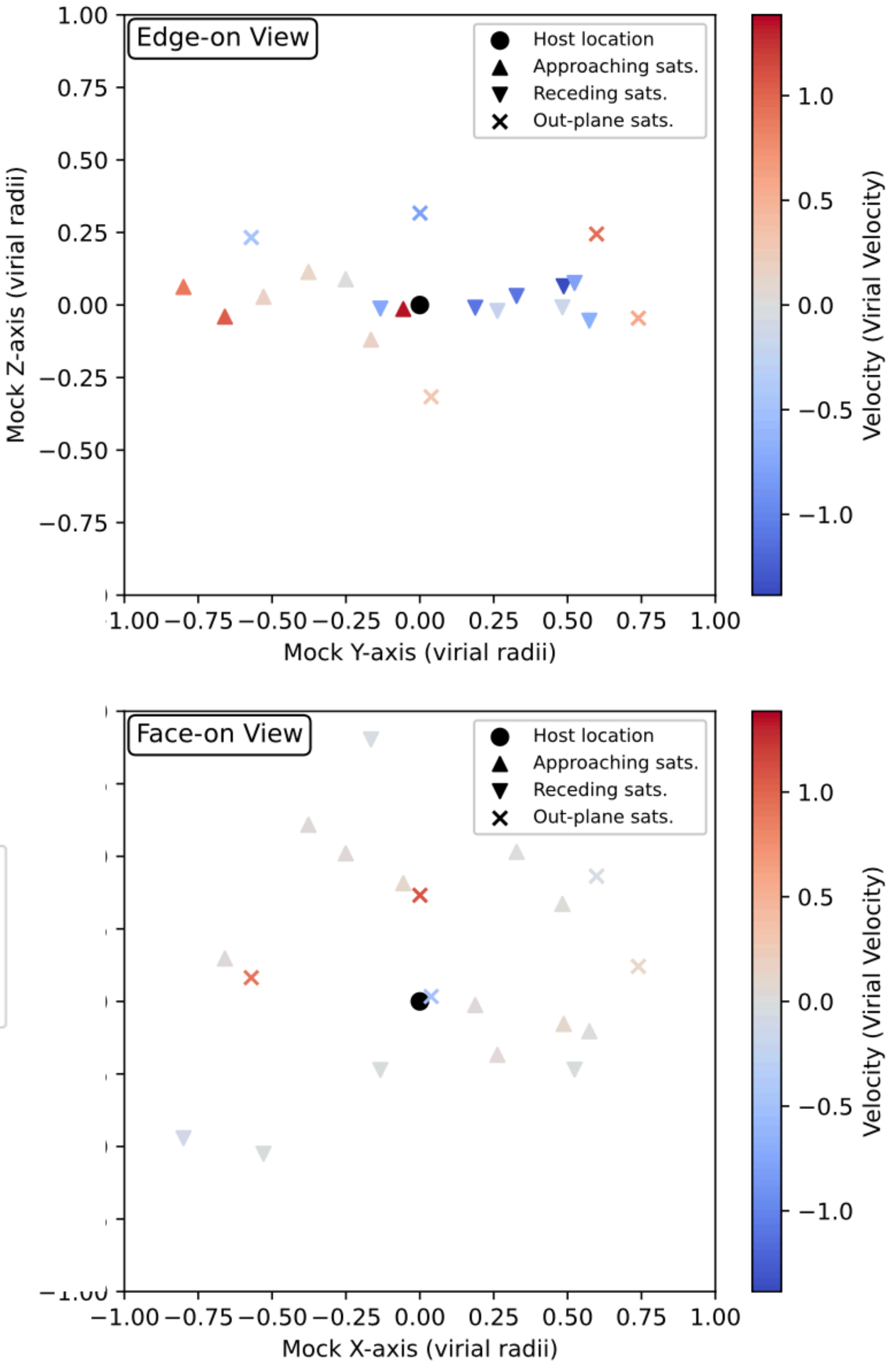

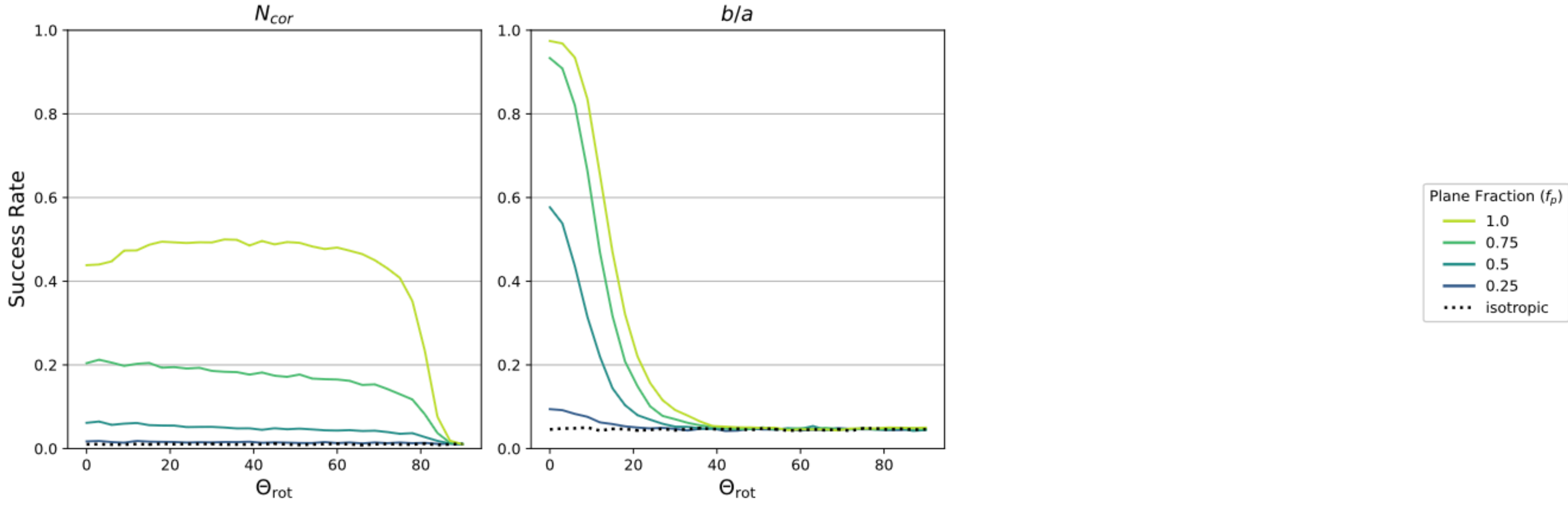

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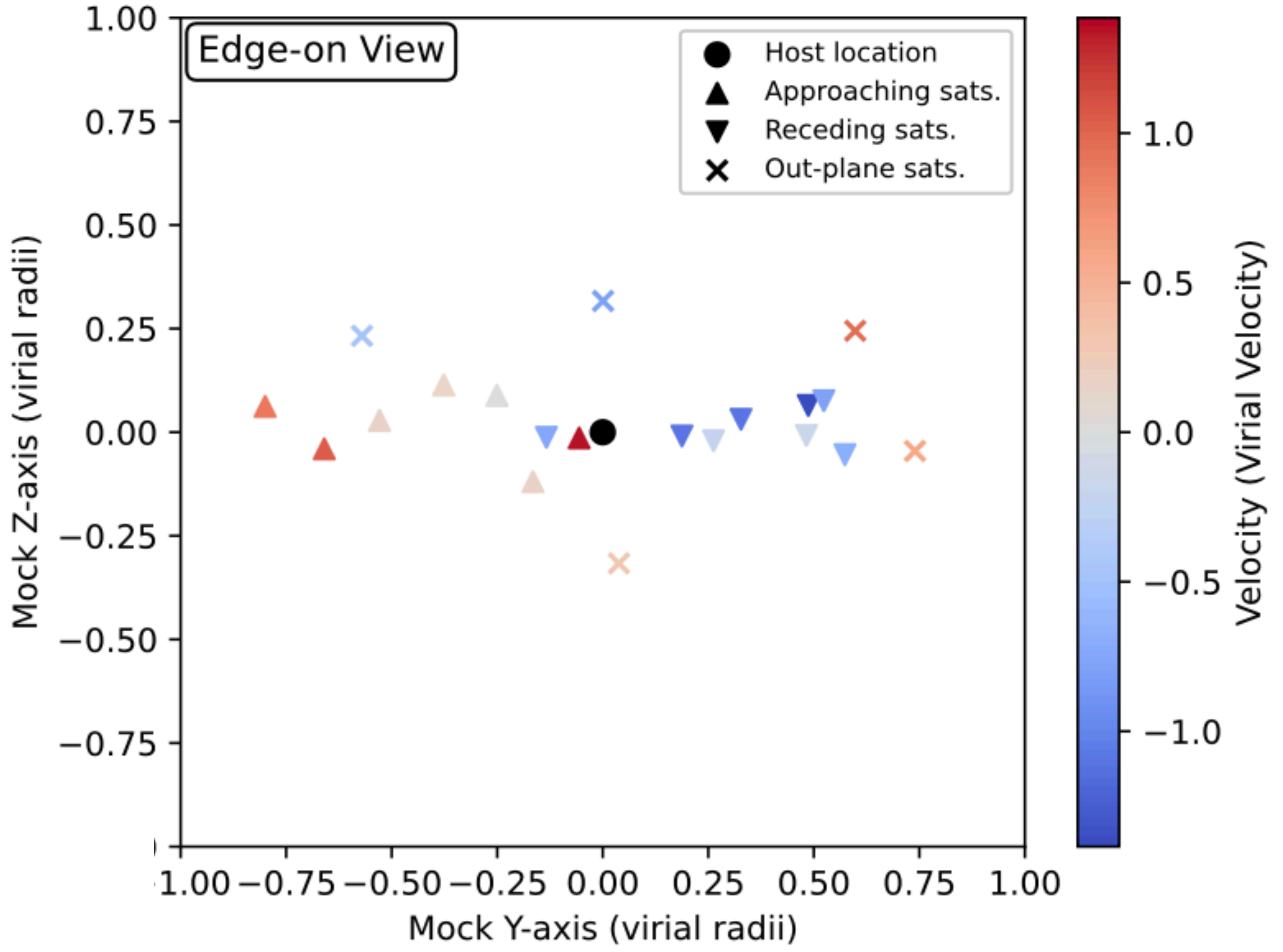
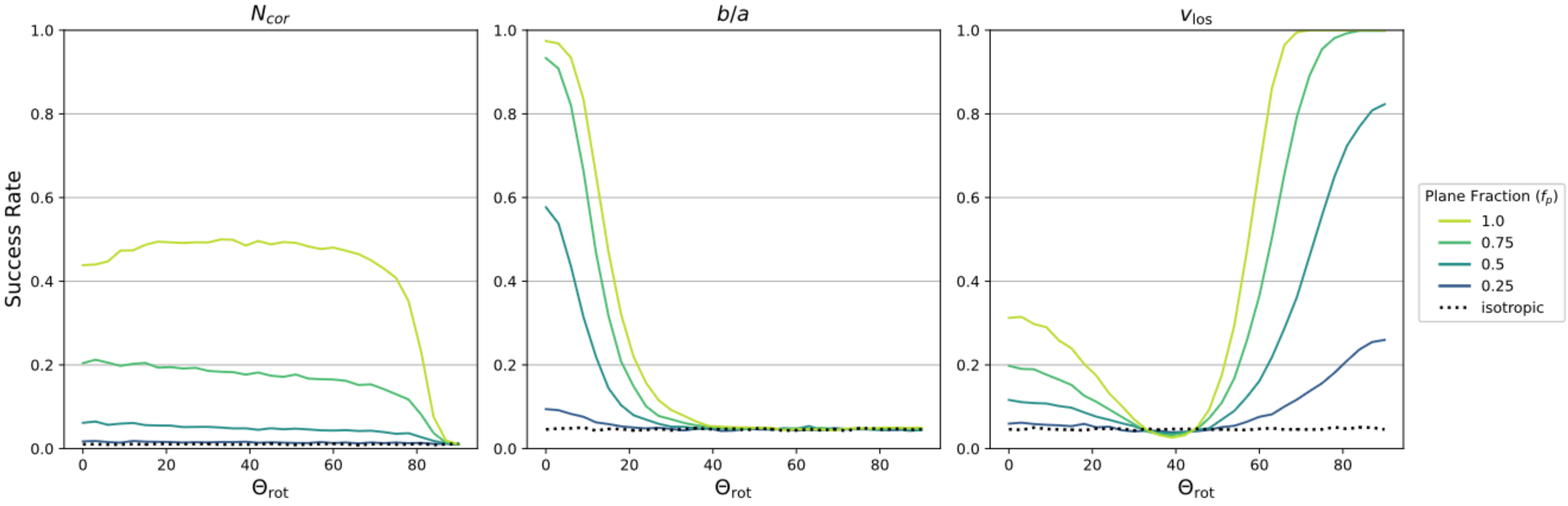
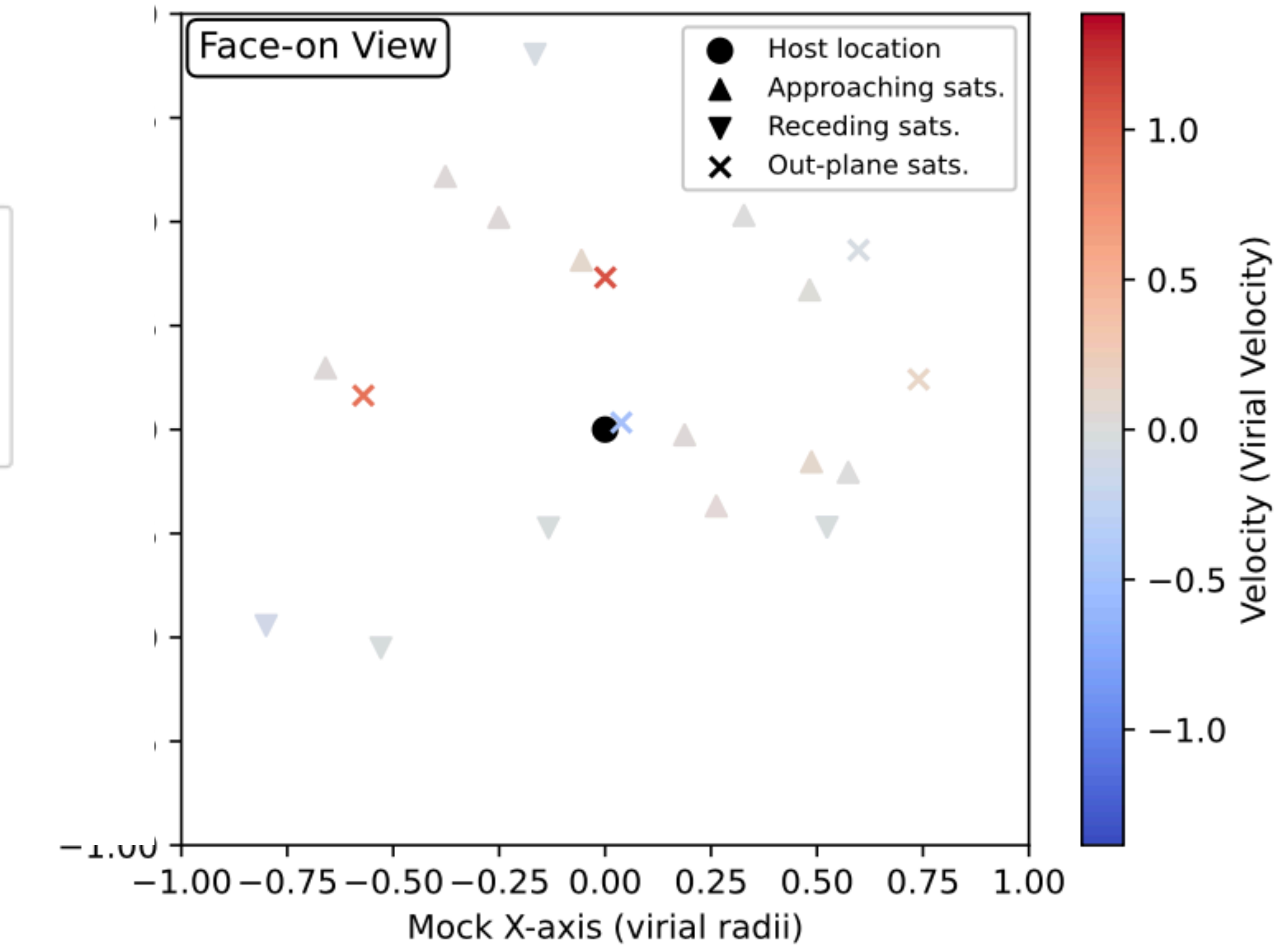
- v_los line-of-sight velocity scatter → highly sensitive to face-on orientations!







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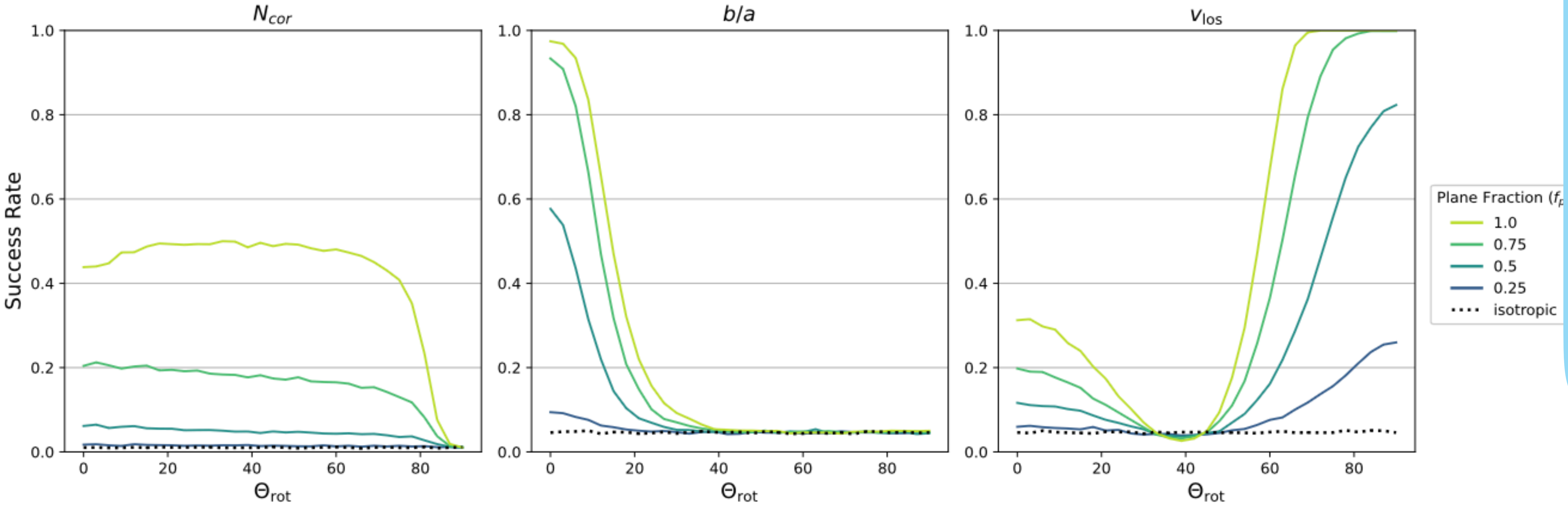
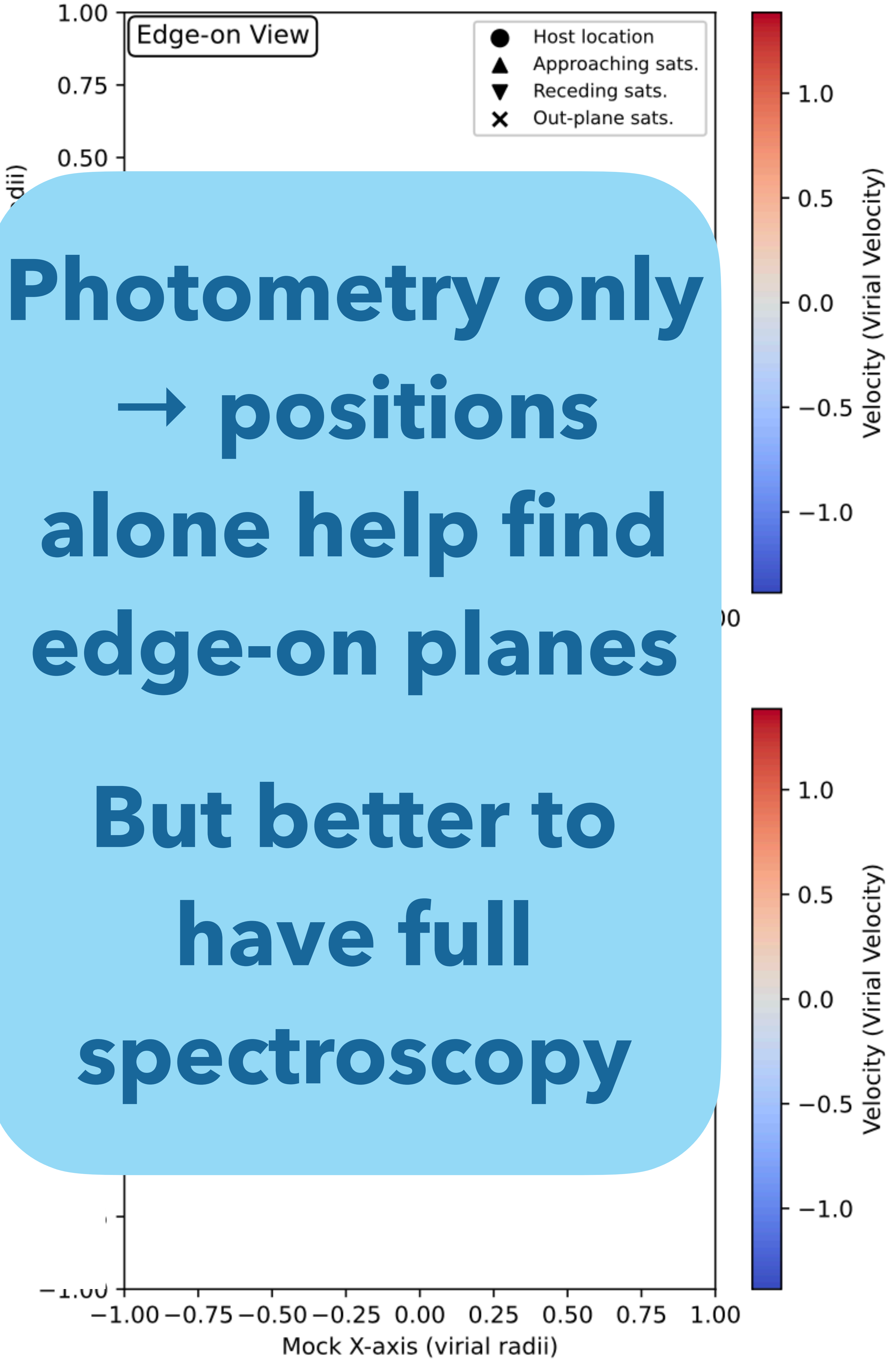
Mock-observe artificial systems with varying (1) numbers of satellites, (2) satellite plane fractions f_p, and (3) orientations θ_rot

Test different diagnostics:

- N_corr line-of-sight velocity correlation → moderately sensitive throughout
- b/a on-sky flattening → highly sensitive to edge-on cases (small θ_rot)
- v_los line-of-sight velocity scatter → highly sensitive to face-on orientations!





Photometry only → positions alone help find edge-on planes

But better to have full spectroscopy

Crosby, Pawlowski, Müller & Jerjen (2026)

Conclusions

- **Satellite planes exist** … not only around the Milky Way but **also around other hosts**.
- **They remain a challenge for ΛCDM.** Claims of consistency often biased or incorrect.
- Alternative DM models do not seem to help.

Next: What do **demographic samples** of satellite systems tell us about phase-space peculiarities?

- Needs careful comparison; accounting for observational limitations, biases, contamination.
- On the way there, we found **other issues**:
  - Highly **lopsided M31** satellite **system** rare **in ΛCDM at** the **0.3% level.**
  - **Too-many-satellites problem** (observed beyond the Local Group vs. simulations).

The End