THE MILKY WAY'S FAINTEST SATELLITES

THE CONTRIBUTION OF "ORPHAN" GALAXIES

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Institute for Computational Cosmology, Durham University

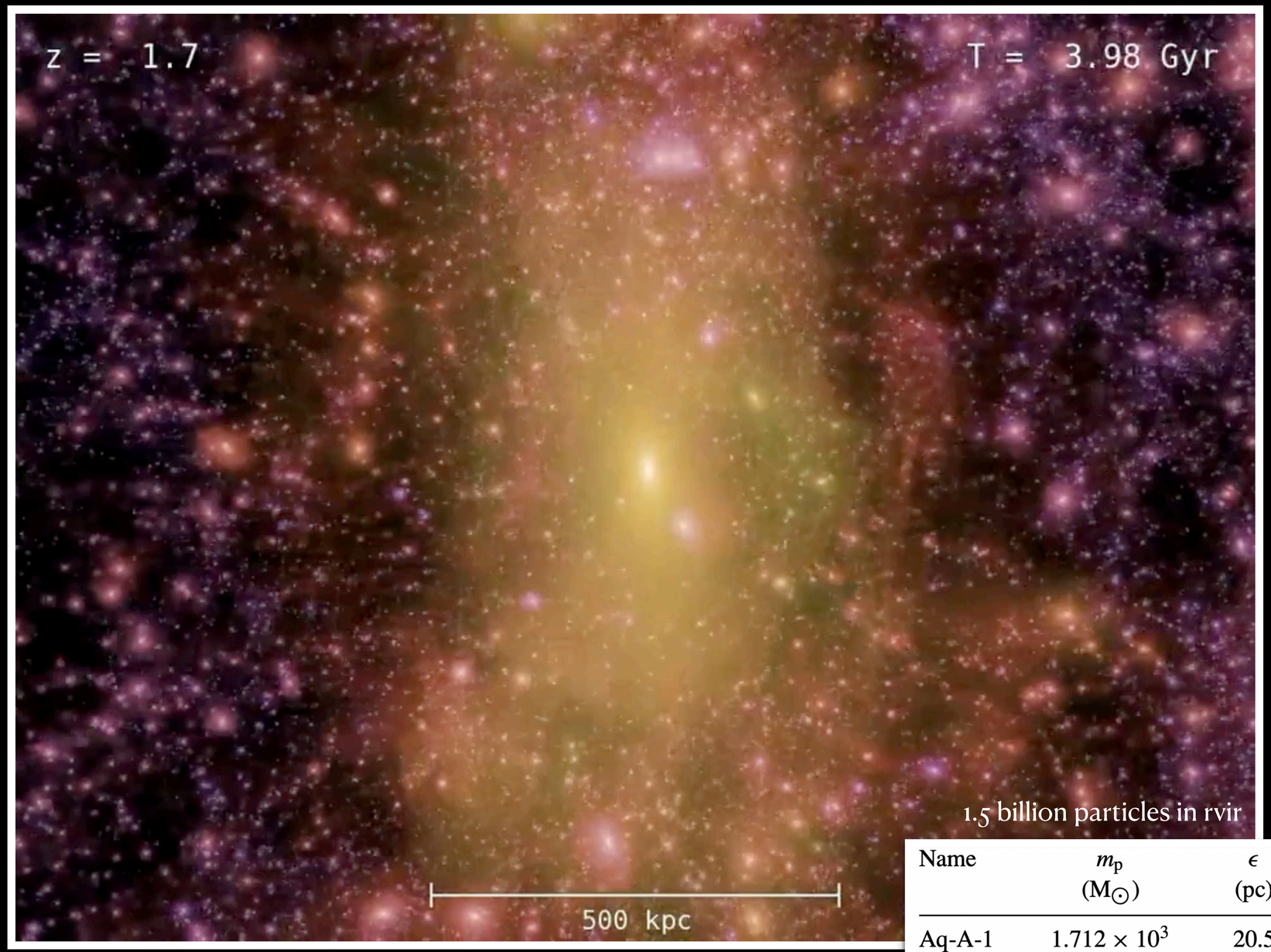
With Carlos Frenk, Julio Navarro, Shaun Cole, John Helly

Self-Interacting Dark Matter and Small-Scale Structure of the Universe - Valencia, June 2025

Image Credit: McAlpine, Flamingo, Colibre

Substructure in Cold Dark Matter

Aquarius MW-mass halo simulation [Springel+08]



1.5 billion particles in rvir

Name	m_p ($M_\odot$)	ϵ (pc)
Aq-A-1	1.712×10^3	20.5

1. Well-defined **mass function**
   –> More small halos than large
2. Self-similar abundance of **substructure**
3. Universal, **"cuspy"** halo density profiles
   –> resilient to tidal effects
4. **Orbits** and accretion histories

[See e.g. Press&Schechter74; Bond+91; White&Rees78; White&Frenk91; NavarroFrenk&White97; Springel+08; Bullock&Boylan-Kolchin17].

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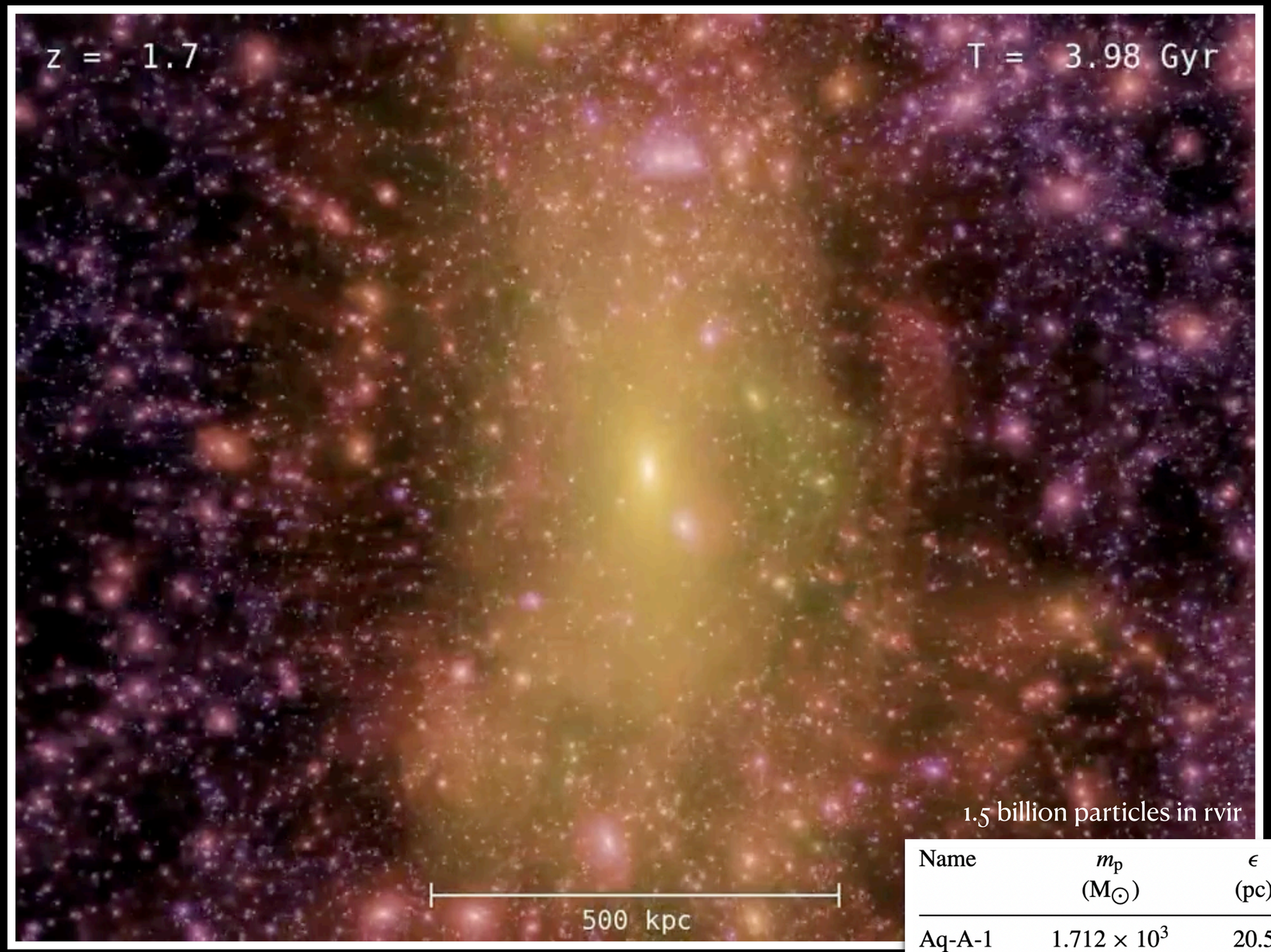

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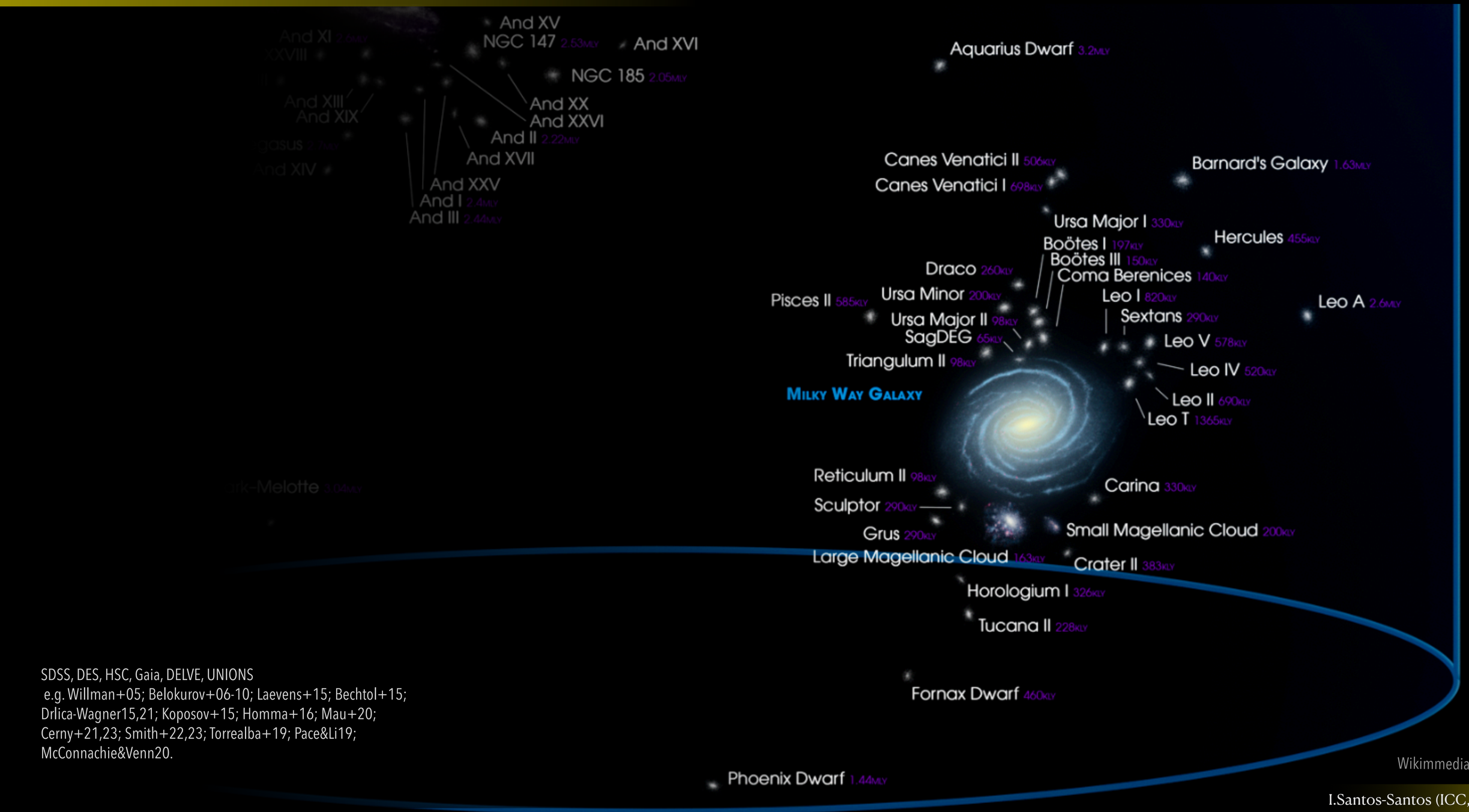
Substructure observed in the MW

**Not up-to-date



SDSS, DES, HSC, Gaia, DELVE, UNIONS
e.g. Willman+05; Belokurov+06-10; Laevens+15; Bechtol+15; Drlica-Wagner15,21; Koposov+15; Homma+16; Mau+20; Cerny+21,23; Smith+22,23; Torrealba+19; Pace&Li19; McConnachie&Venn20.

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I.Santos-Santos (ICC, Durham)

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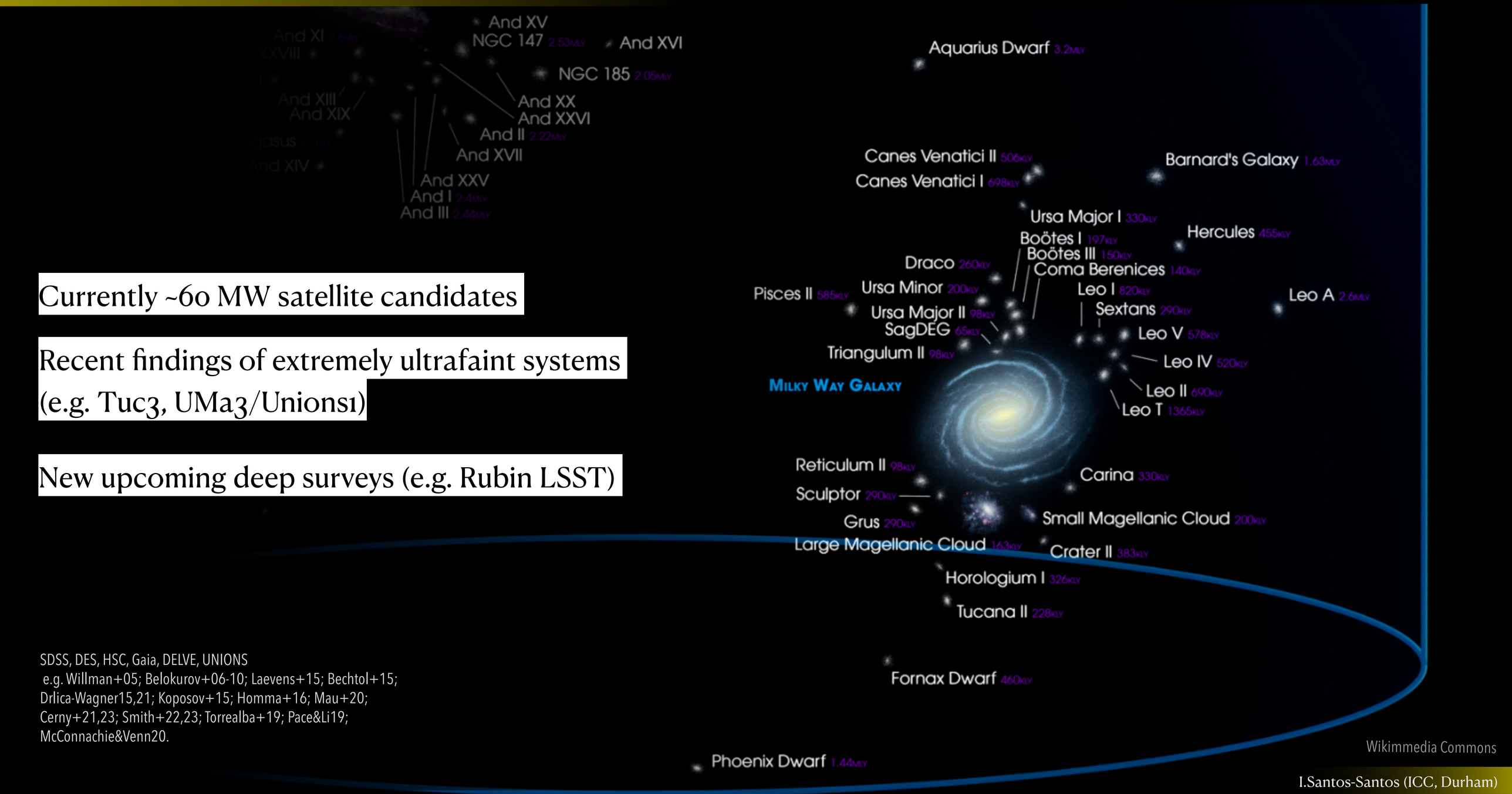

Currently ~60 MW satellite candidates

Recent findings of extremely ultrafaint systems (e.g. Tuc3, UMa3/Unions1)

New upcoming deep surveys (e.g. Rubin LSST)

SDSS, DES, HSC, Gaia, DELVE, UNIONS
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How to model the MW system in CDM?

The unabridged satellite luminosity function of Milky Way-like galaxies in ΛCDM: the contribution of "orphan" satellites

Isabel M.E. Santos-Santos,[1]★ Carlos S. Frenk,[1] Julio F. Navarro,[2] Shaun Cole,[1] John Helly[1]

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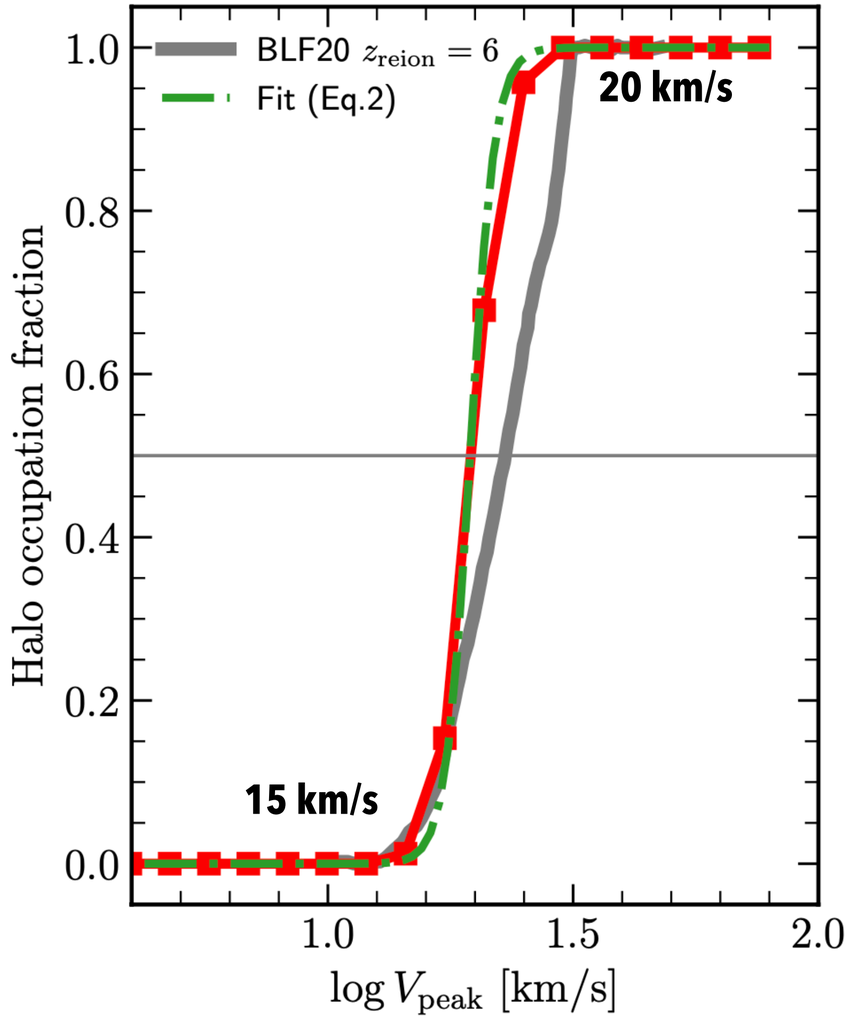
1 Populate subhalos with galaxies



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- ✦A threshold for galaxy formation reflecting the minimum potential well depth needed for Hydrogen to cool $\mathbf{V_{peak}}$**~15-20 km/s**;

[Okamoto&Frenk19, Benitez-Llambay&Frenk20]

- ✦Only halos that reach this potential depth can form stars, rest remain dark.
- ✦Implies number of MW satellites (of any luminosity) cannot be too high (<~300)

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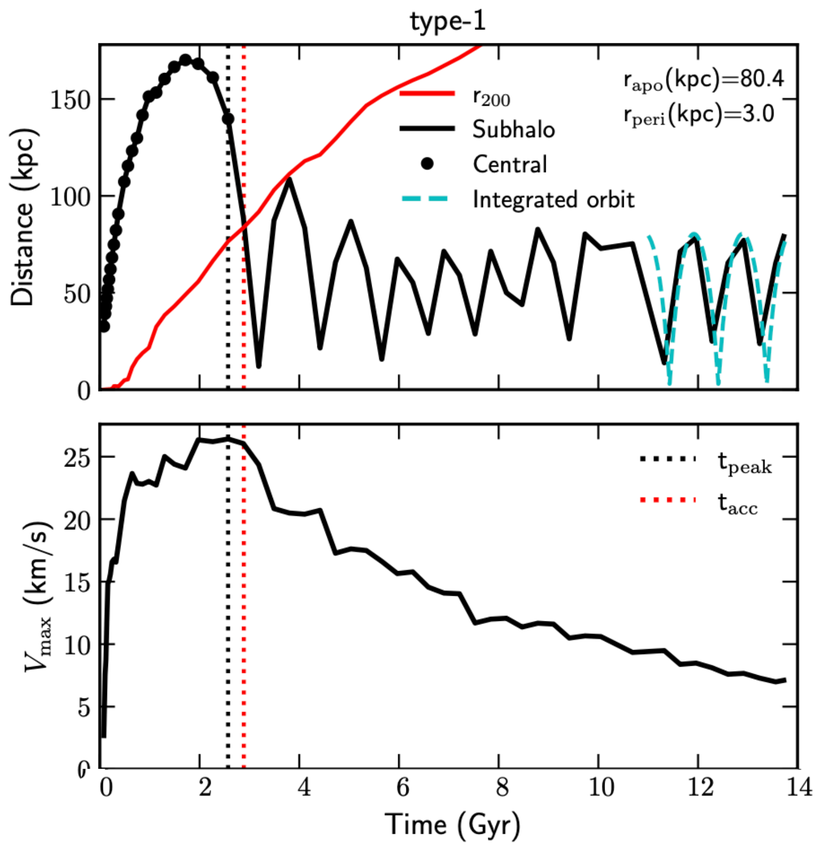
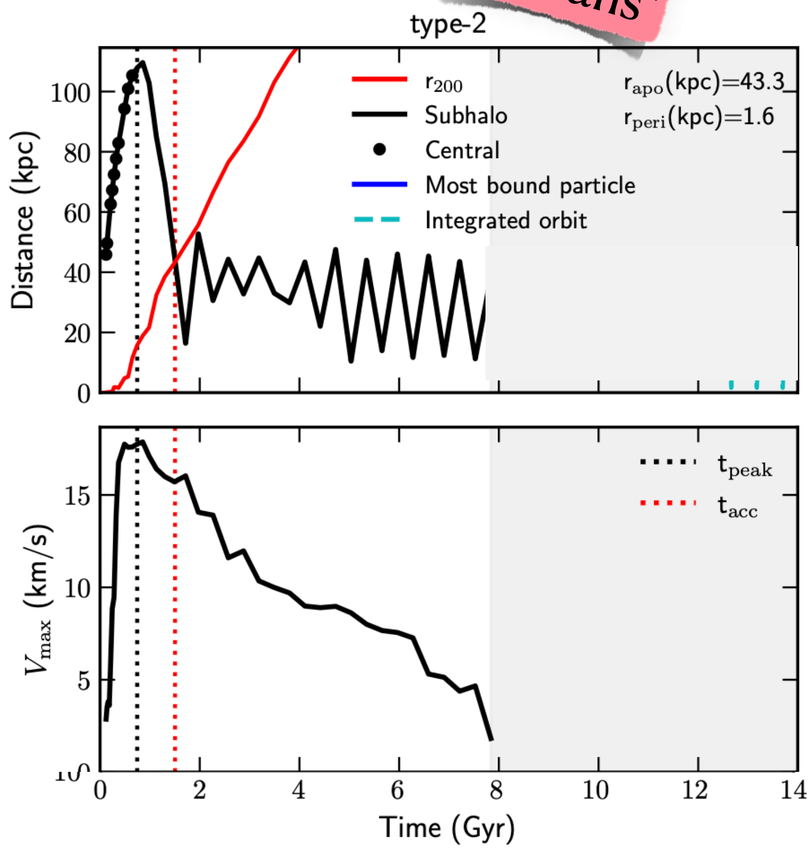
2 Track substructure in time



"Orphans"



- Many subhalos that should host satellites are lost due to numerical issues (artificially disrupt)
- In CDM, every subhalo survives tides, as protected by its cusp
- It is crucial to correct for artificial disruption and track "orphan" satellites

Santos-Santos et al 2025

[see e.g. Peñarrubia+08,10; van den Bosch & Ogiya18; HAn+18; Green&van den Bosch 19; Jiang+21; Stucker+23; He+25; Errani+20,21,22,24]

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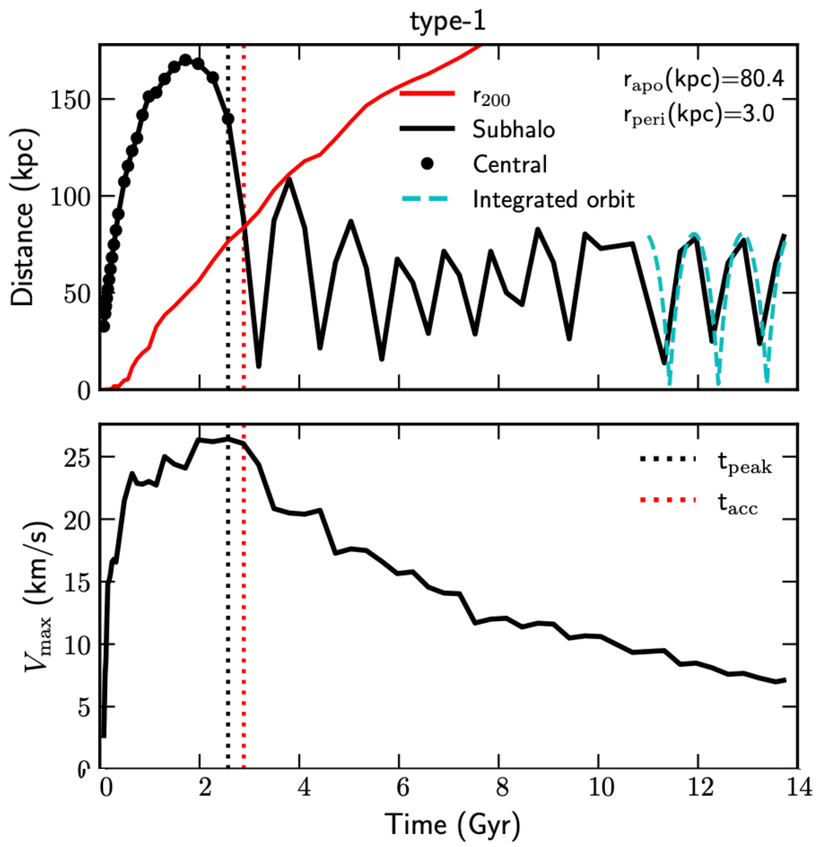

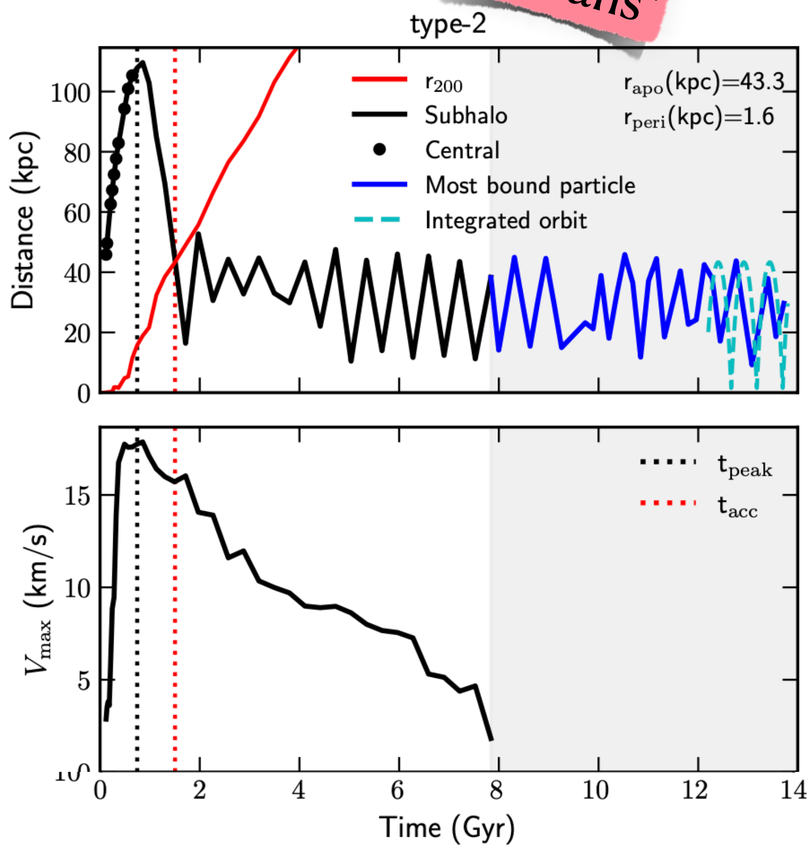

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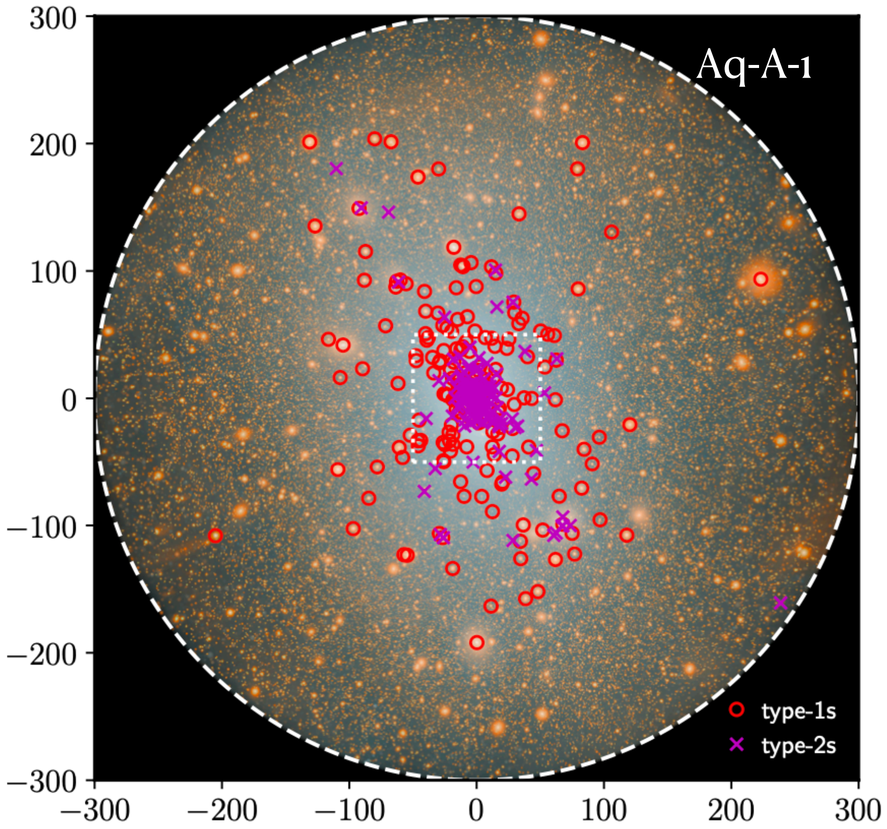

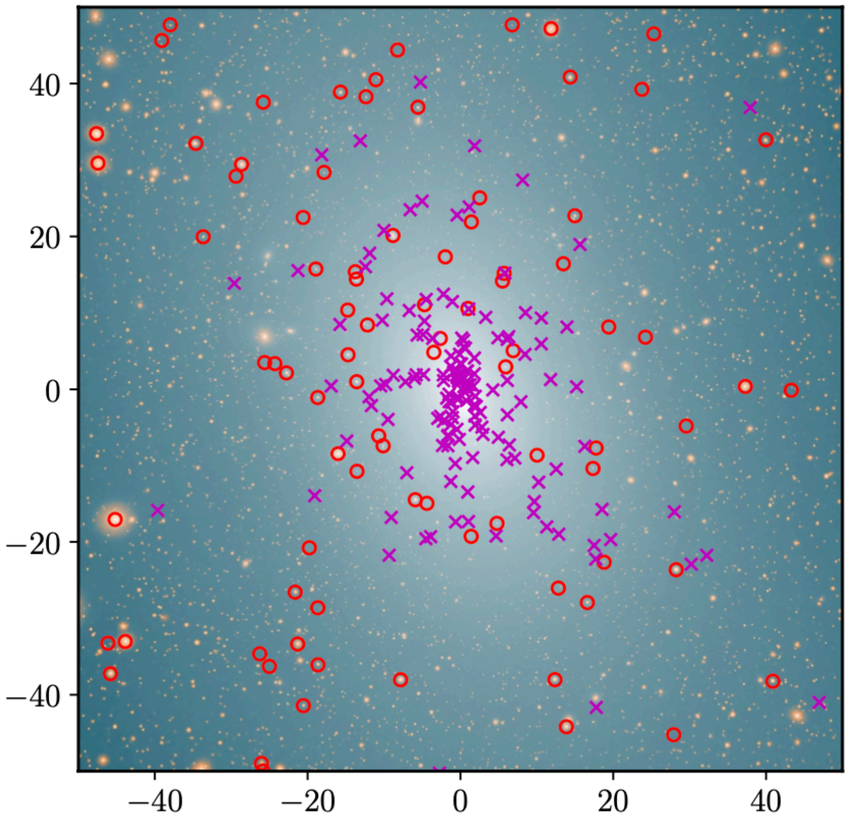

- "Orphans" dominate the inner regions of the MW
- Orphans make up **half** of the total satellite population, even in Aq-A-1

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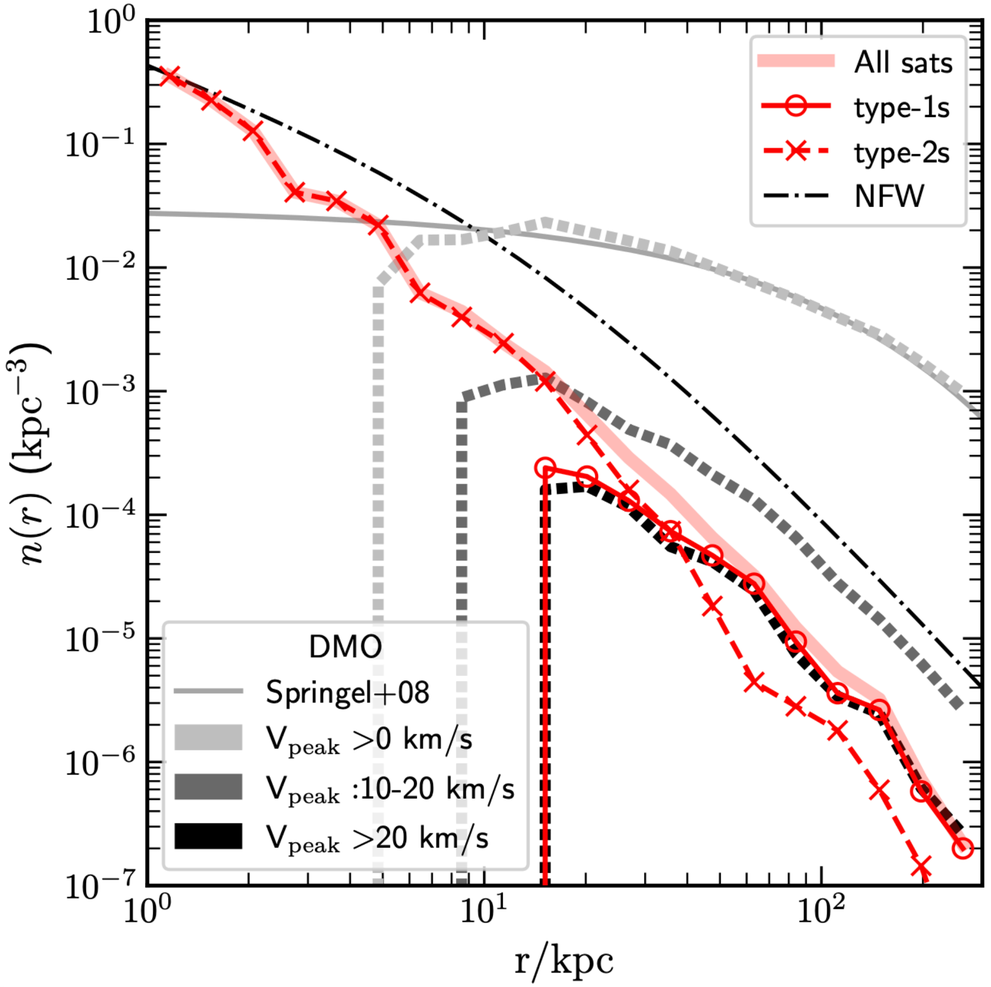

	Particle mass (Msun)	R(kpc)
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L2	1.4e+04	69
L4	4e+05	102
L5	3e+06	150

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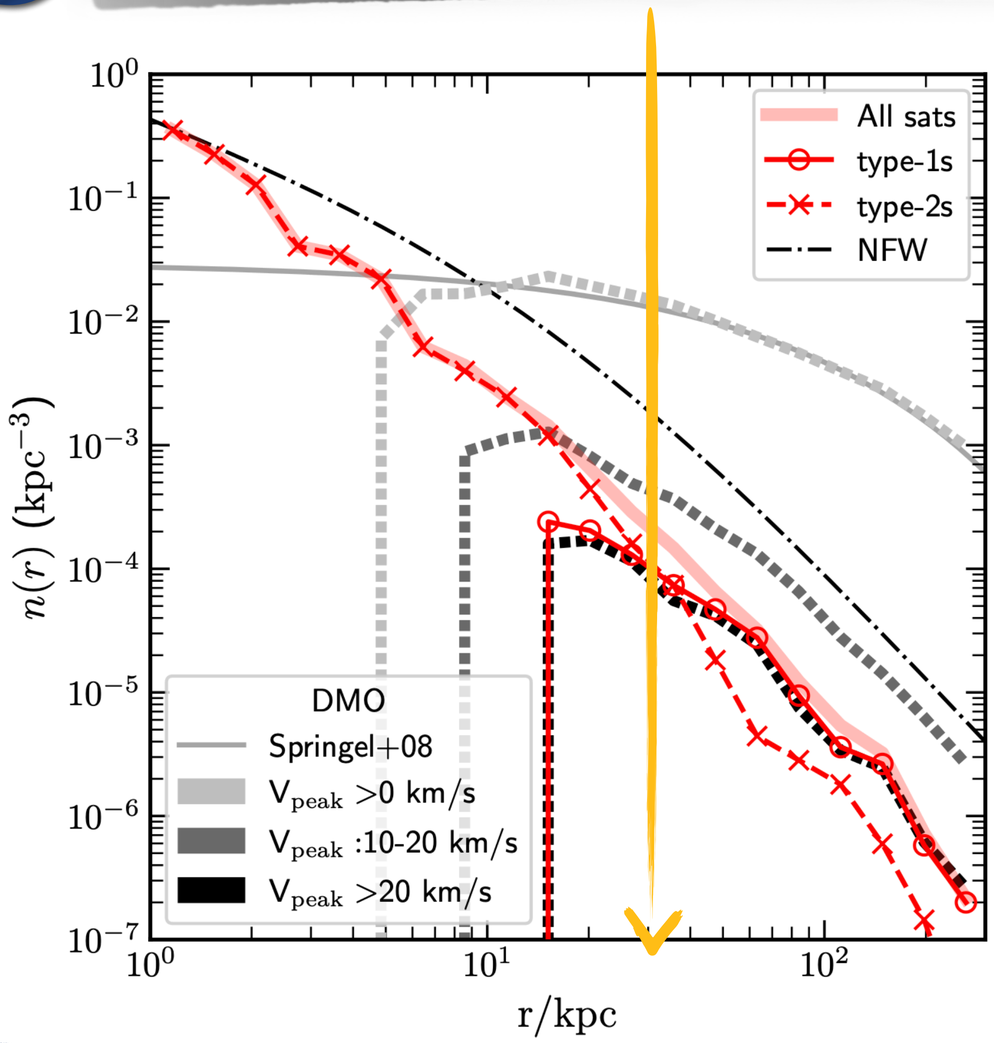

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How to model the MW system in CDM?

GALFORM semi-analytical model
[White&Frenk91, Kauffmann+93, Cole+2000, Lacey+2016]

3 Model observed satellite properties

Initial stellar mass and stellar size

Santos-Santos et al 2025; +in prep

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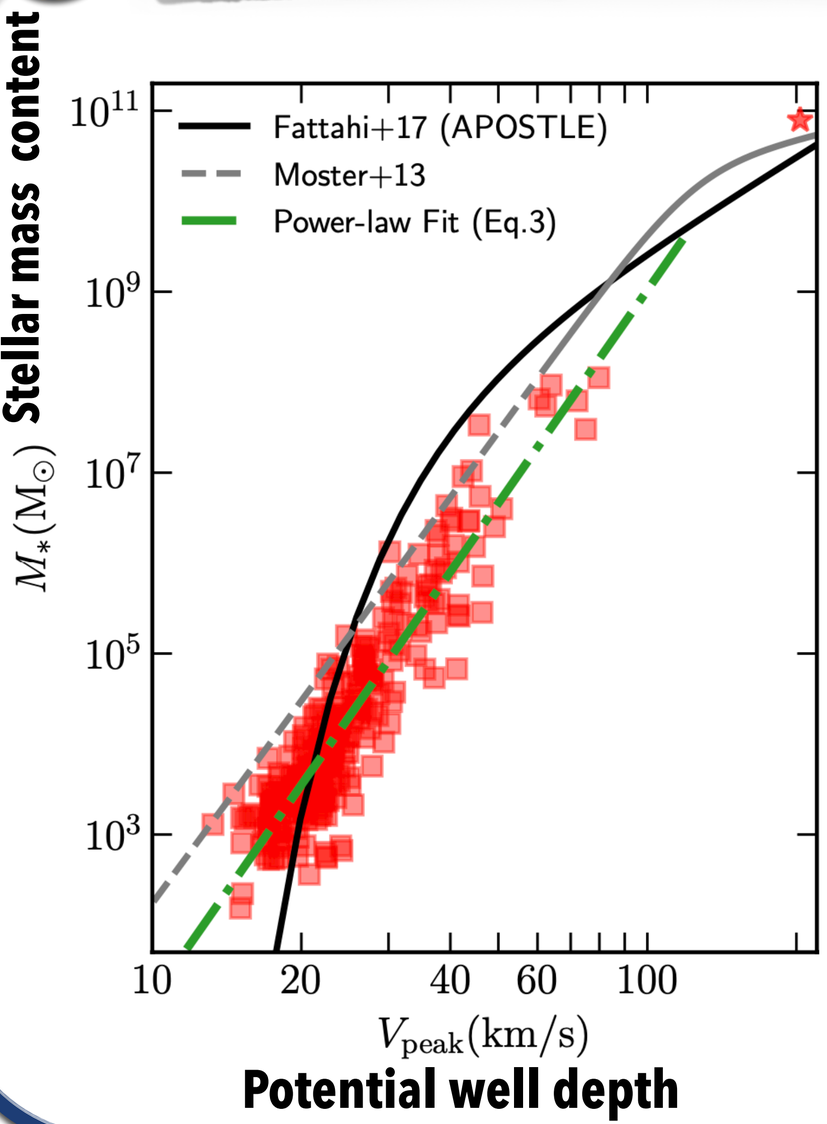

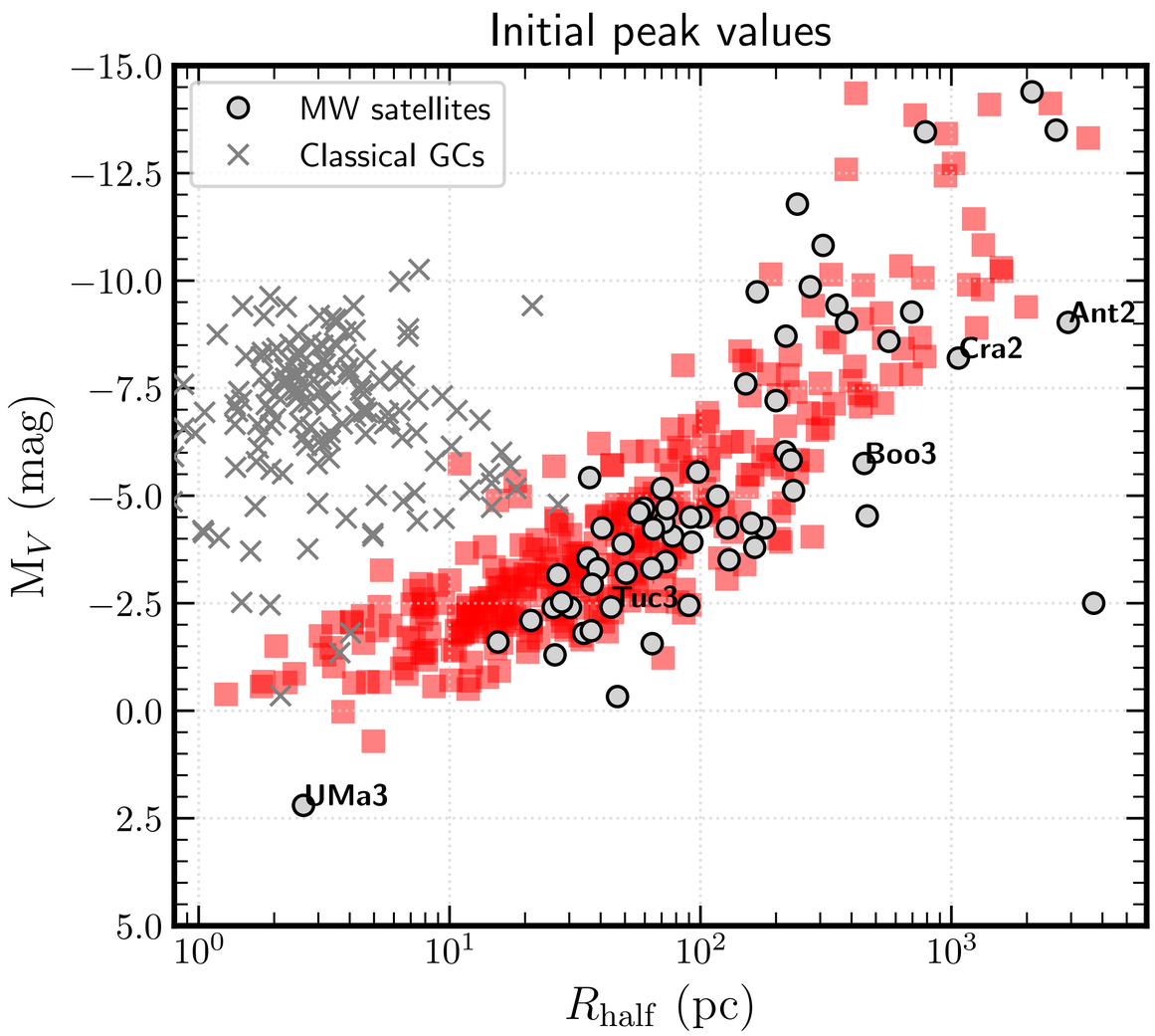

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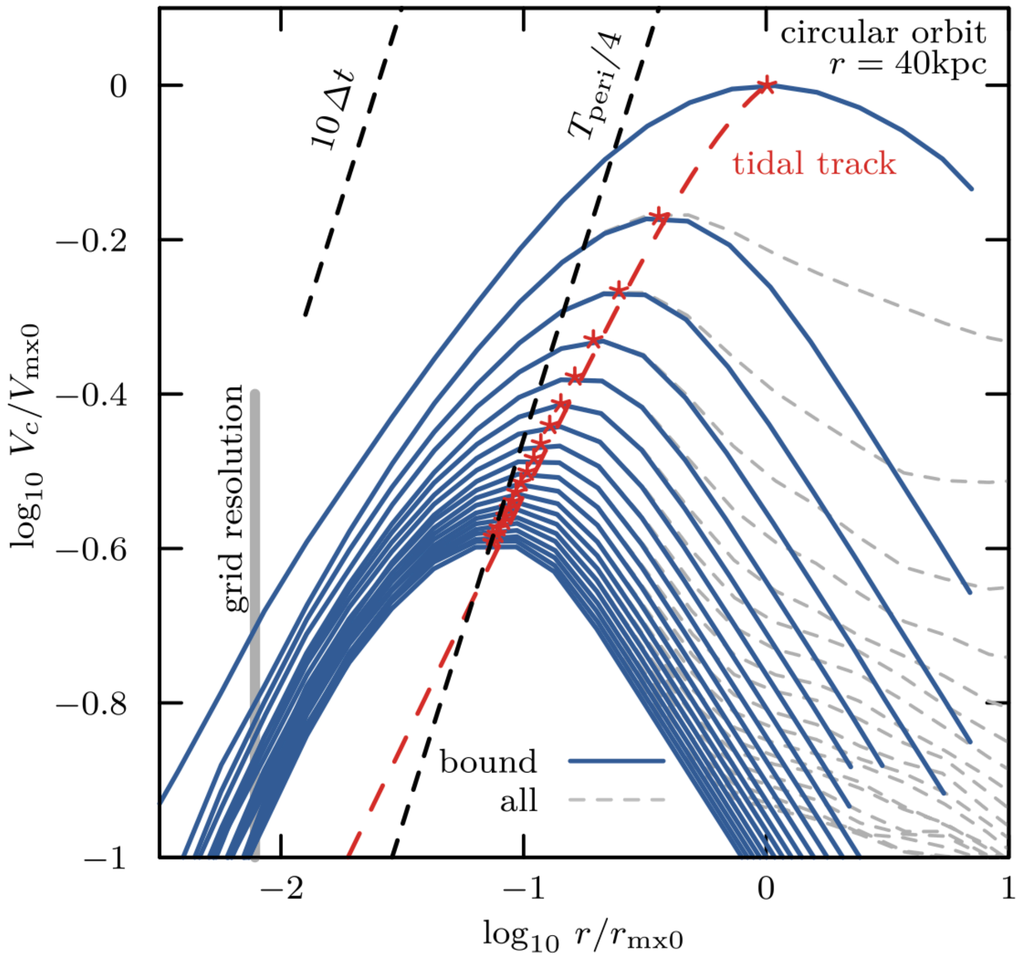
Tidal stripping on Dark Matter and stars



Subhalo tidal evolution in LCDM "Tidal Tracks"

Gives DM mass loss

[Errani+21,22]

Santos-Santos +in prep

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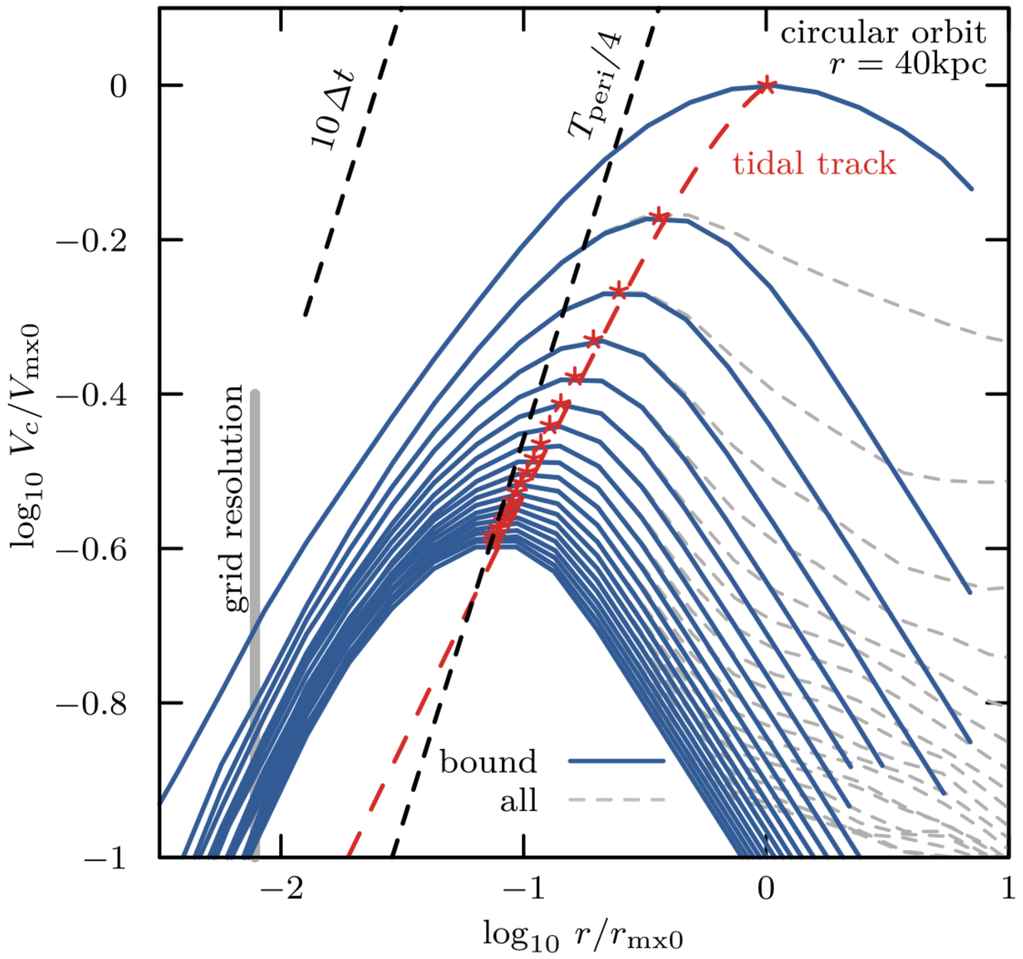

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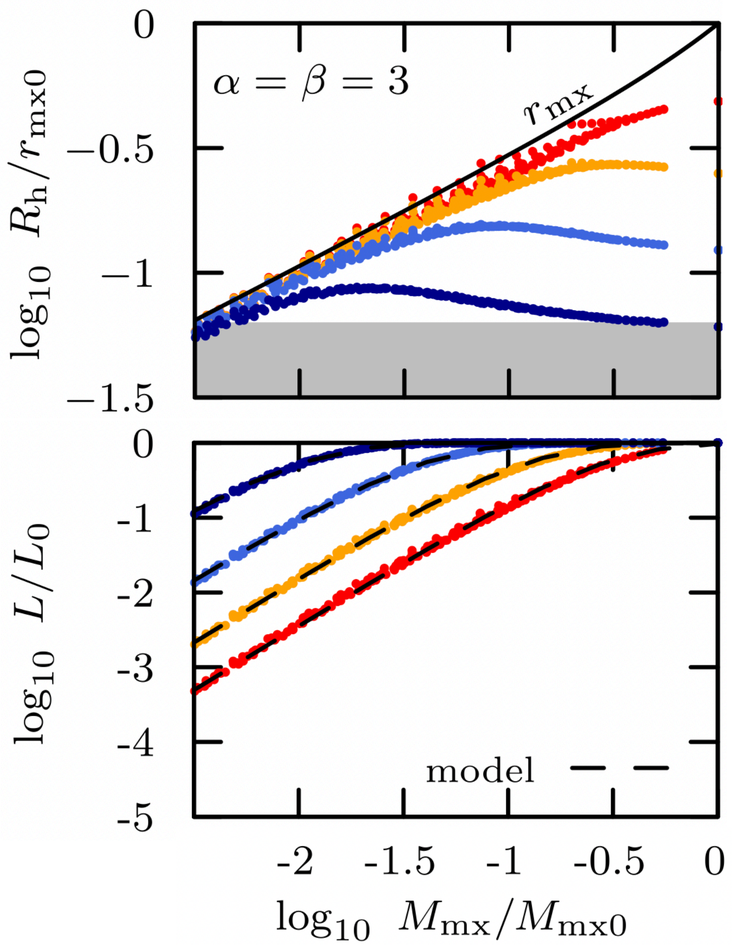

[Errani+21,22]

\+ *Central host disk r=10kpc*

Tidal evolution of the stellar component

Gives change in galaxy luminosity and size

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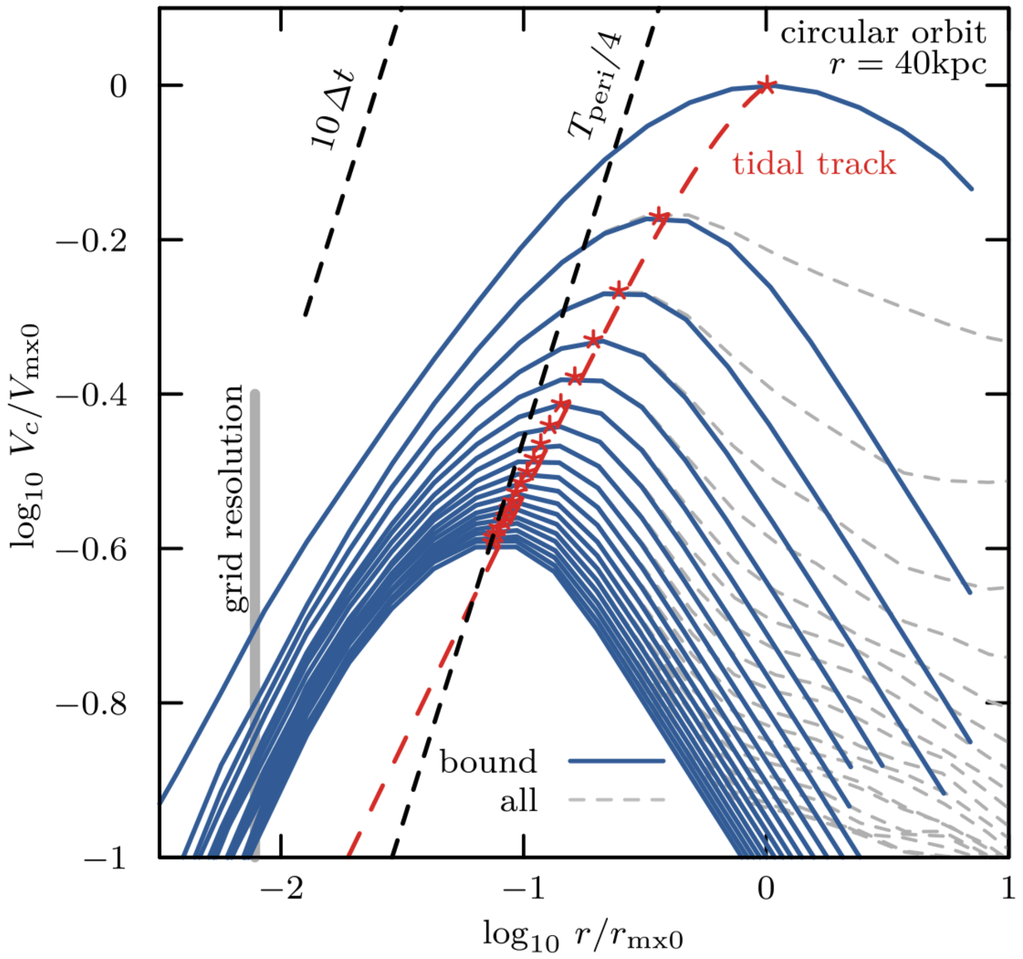

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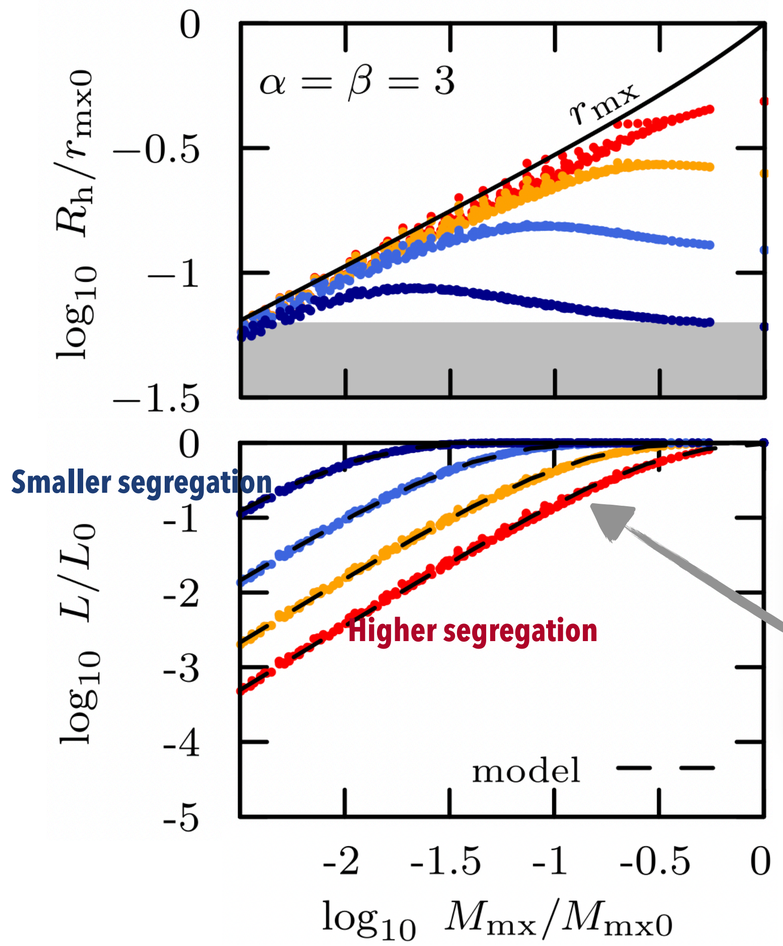

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Depends on **DM mass loss** and "**segregation**", ie. how embbeded stars are relative to DM

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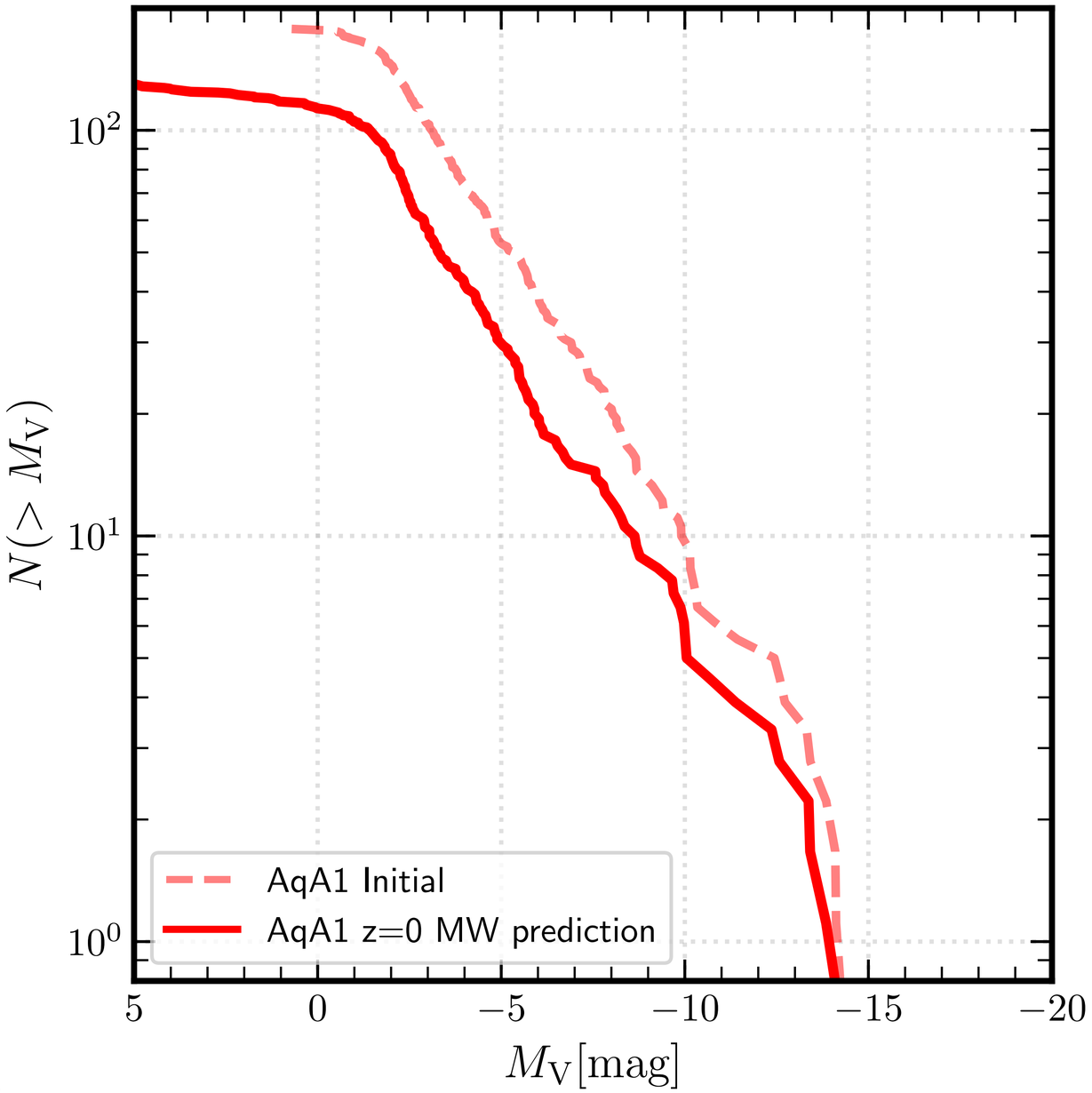
Predictions: MW satellite *luminosity function*

*Santos-Santos er al 2025; +**in prep***



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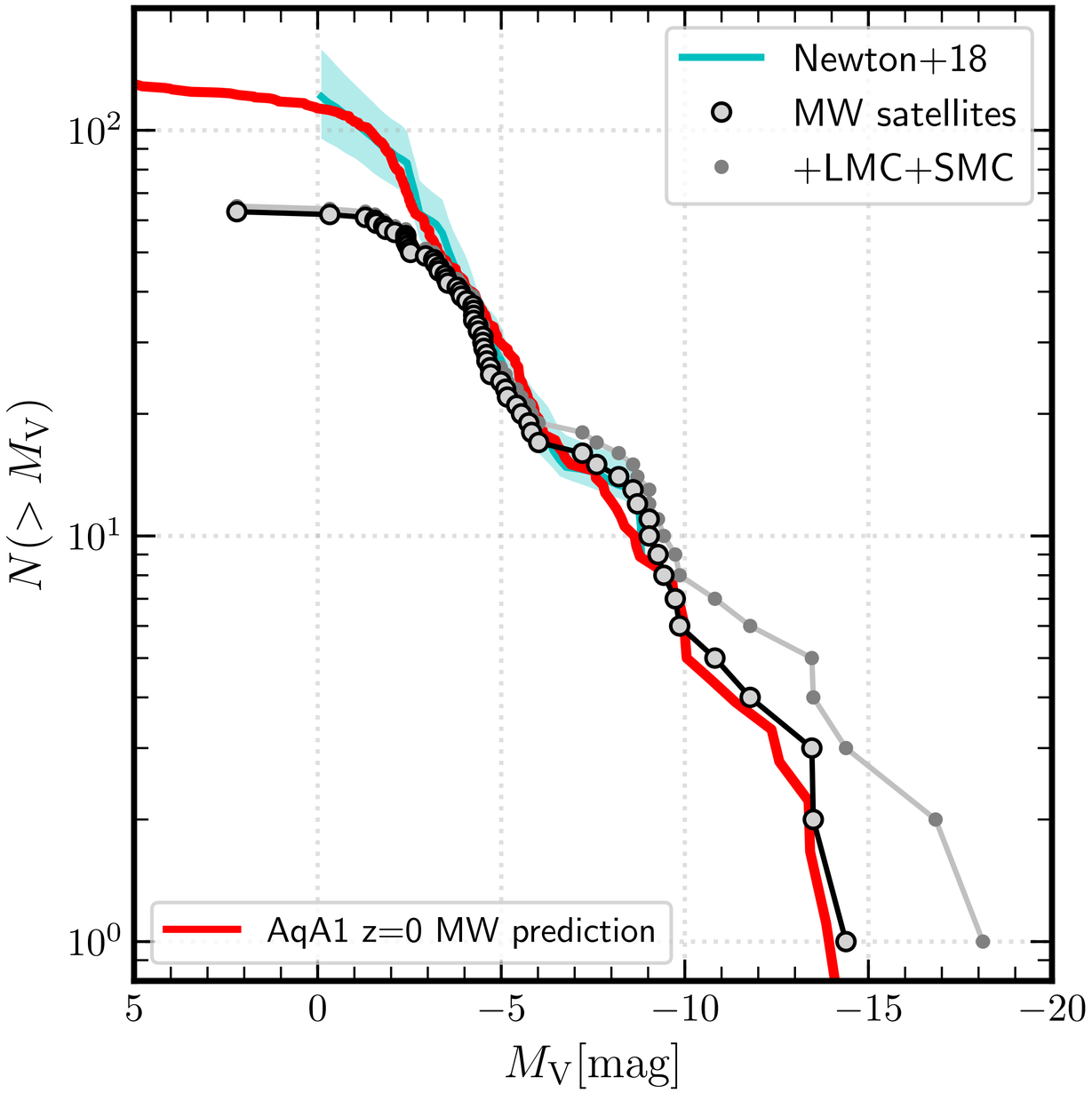

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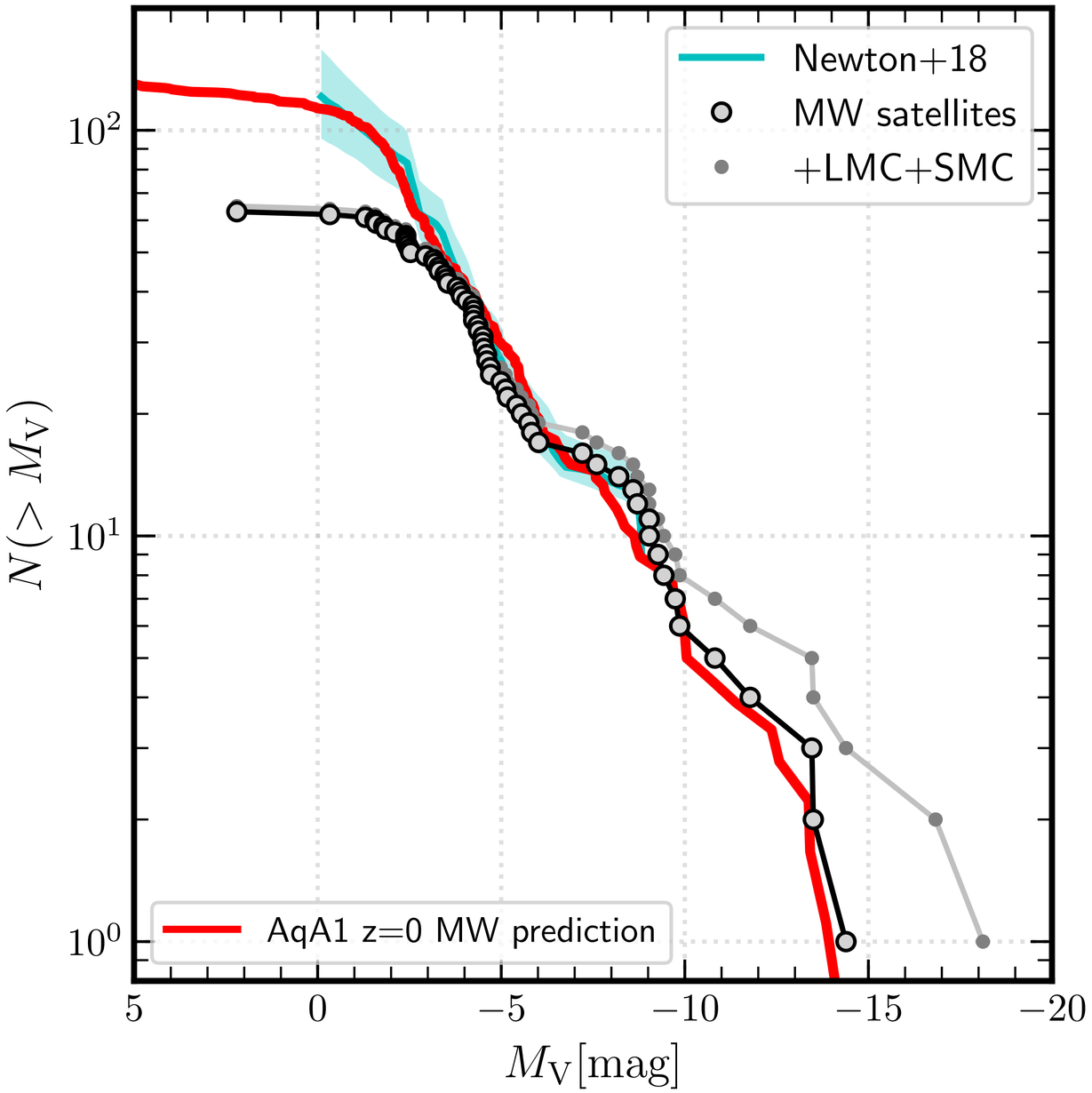

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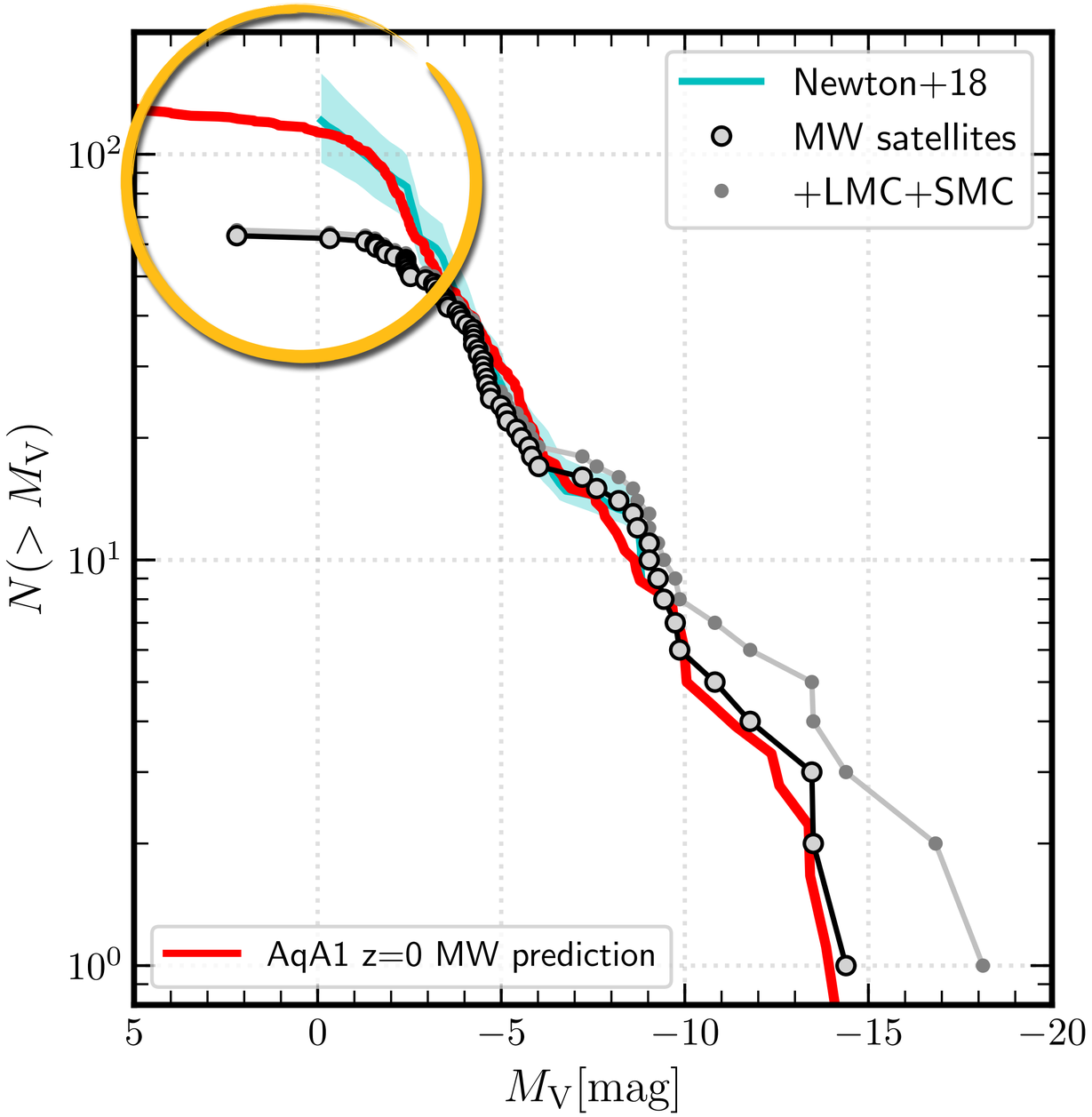

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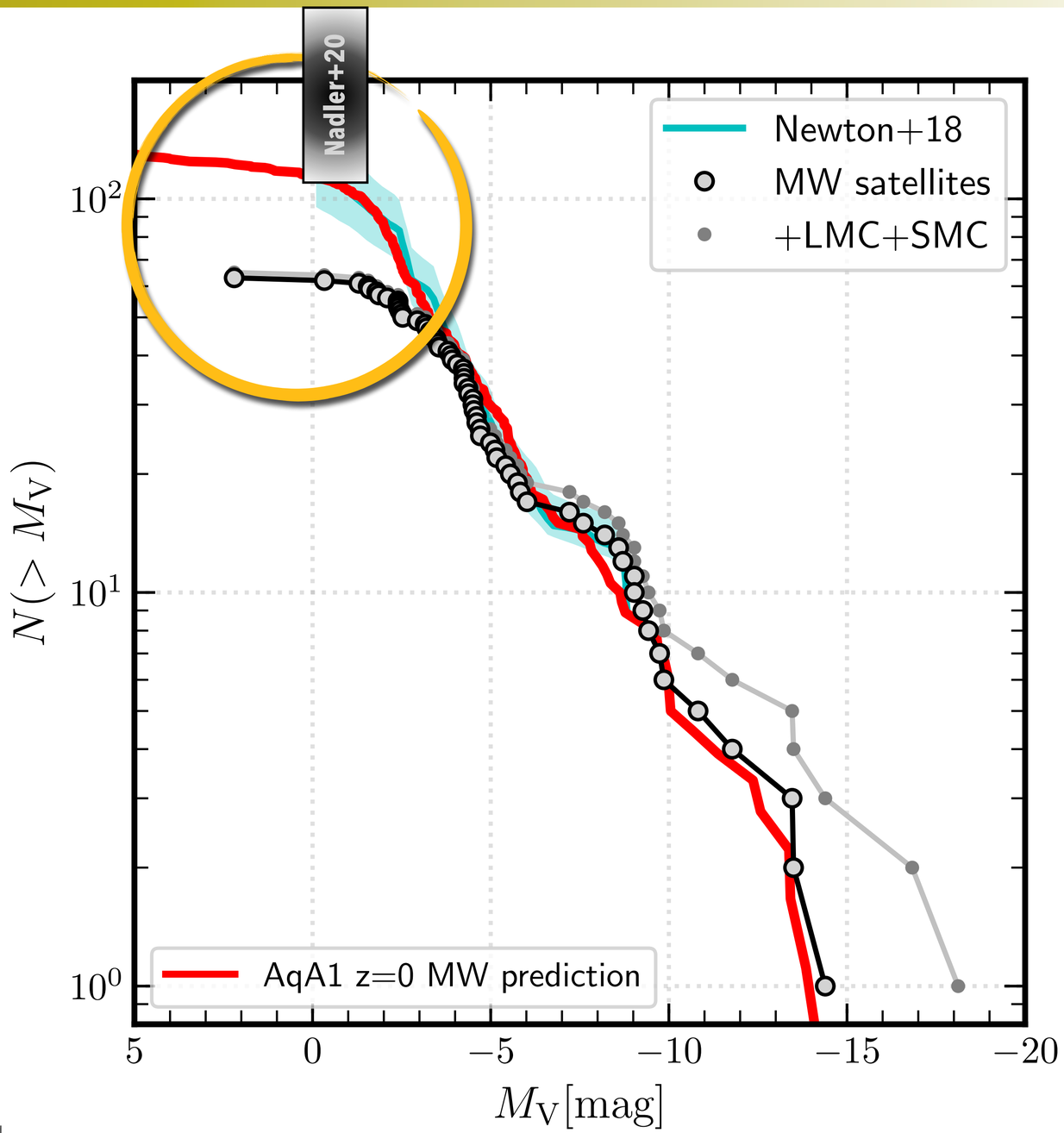

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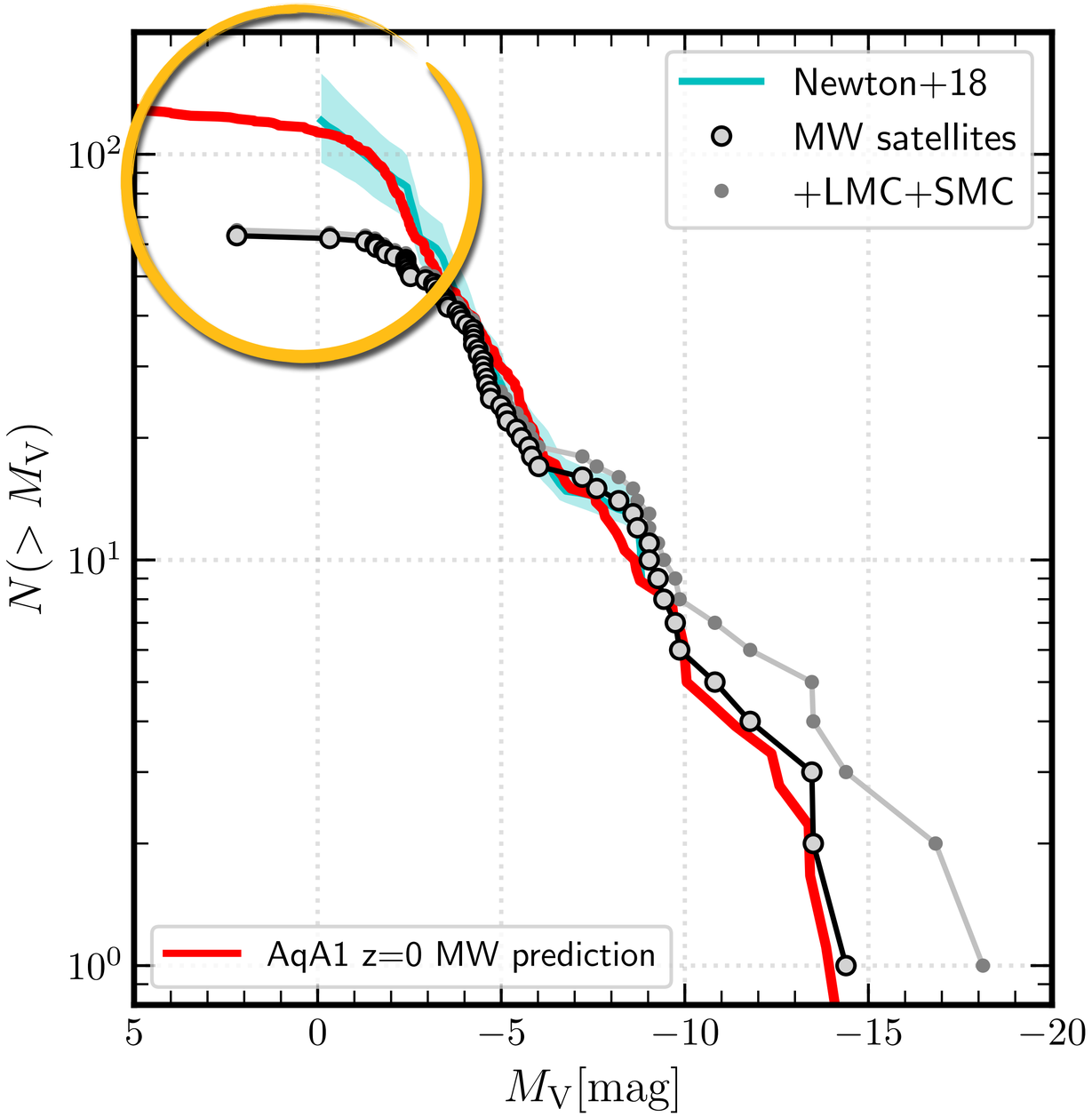

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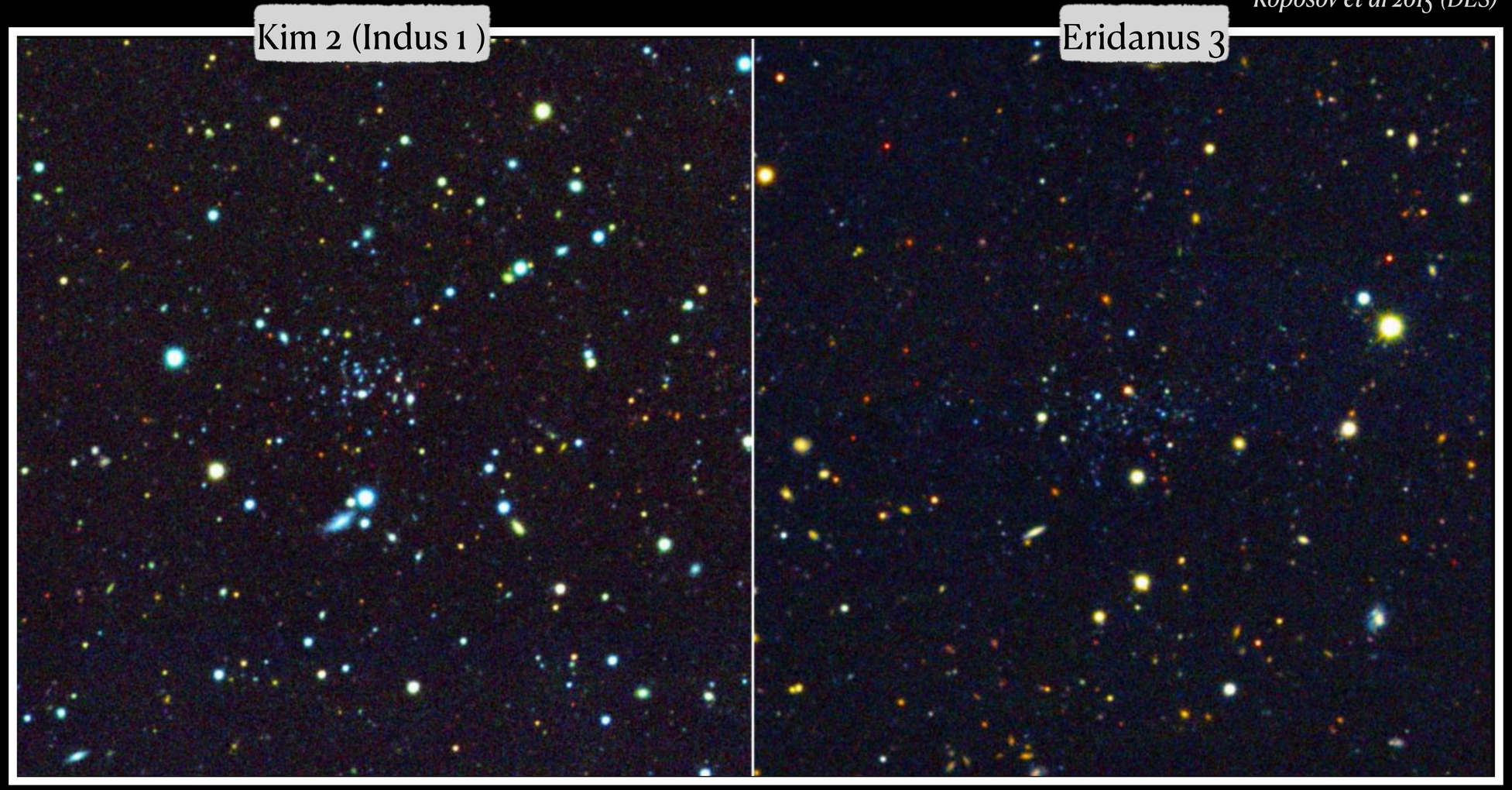
Newly discovered MW "faint ambiguous satellite candidates"

Koposov et al 2015 (DES)



- Found in imaging surveys. Just a few stars
- No line of sight velocities, or large errors. Unclear what is their nature (GCs or dwarfs?)

Koposov 2
Koposov 1
SEGUE 3
Munoz 1
Balbinot 1
Kim 1
Kim 2 (Indus 1)
Draco 2
Crater
SMASH 1
Kim 3
DES J0111-1341
DES J0225+0304
Eridanus 3
DES 1
DES 3
Pictor I
To 1
Laevens 3
DES 4
PS1 1
HSC 1
DES 5
BLISS 1
Gaia 3
DELVE 1
DELVE 2
YMCA-1
DELVE 5
DELVE 3
DELVE 4
DELVE 6
UMa3/Unions 1
...

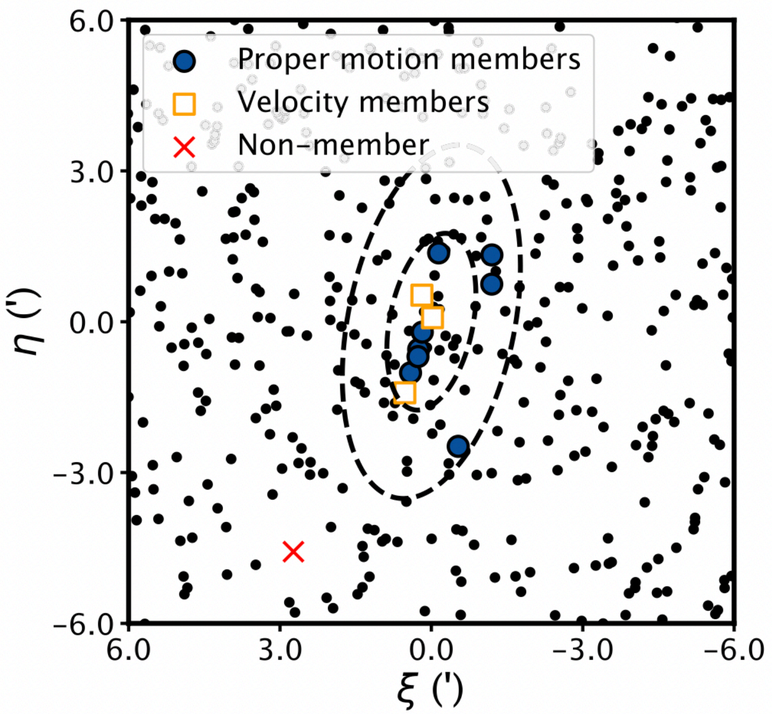
Newly discovered MW "faint ambiguous satellite candidates"

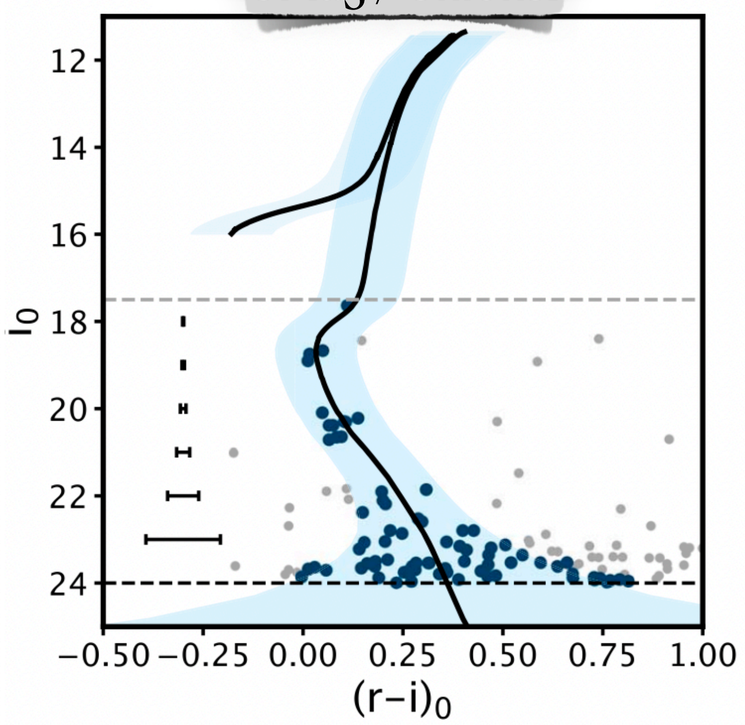
Smith et al 2024 (CFHT Unions Survey)
See also Errani et al 2024

$M_{star} = 16^{+6}_{-5}\ M_\odot$

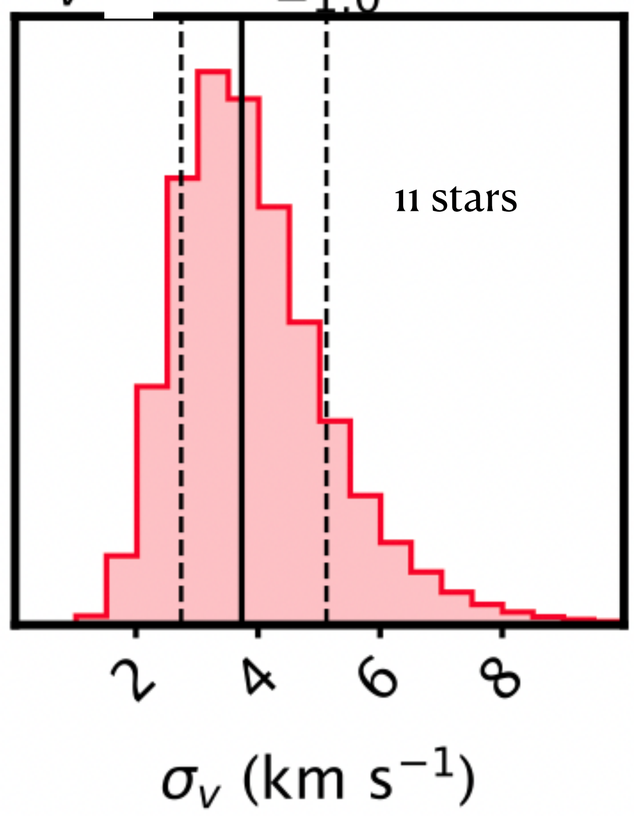
The faintest satellite known!

UMa3 / Unions1





$\sigma_v < 3.7^{+1.4}_{-1.0}$ km s^{-1}



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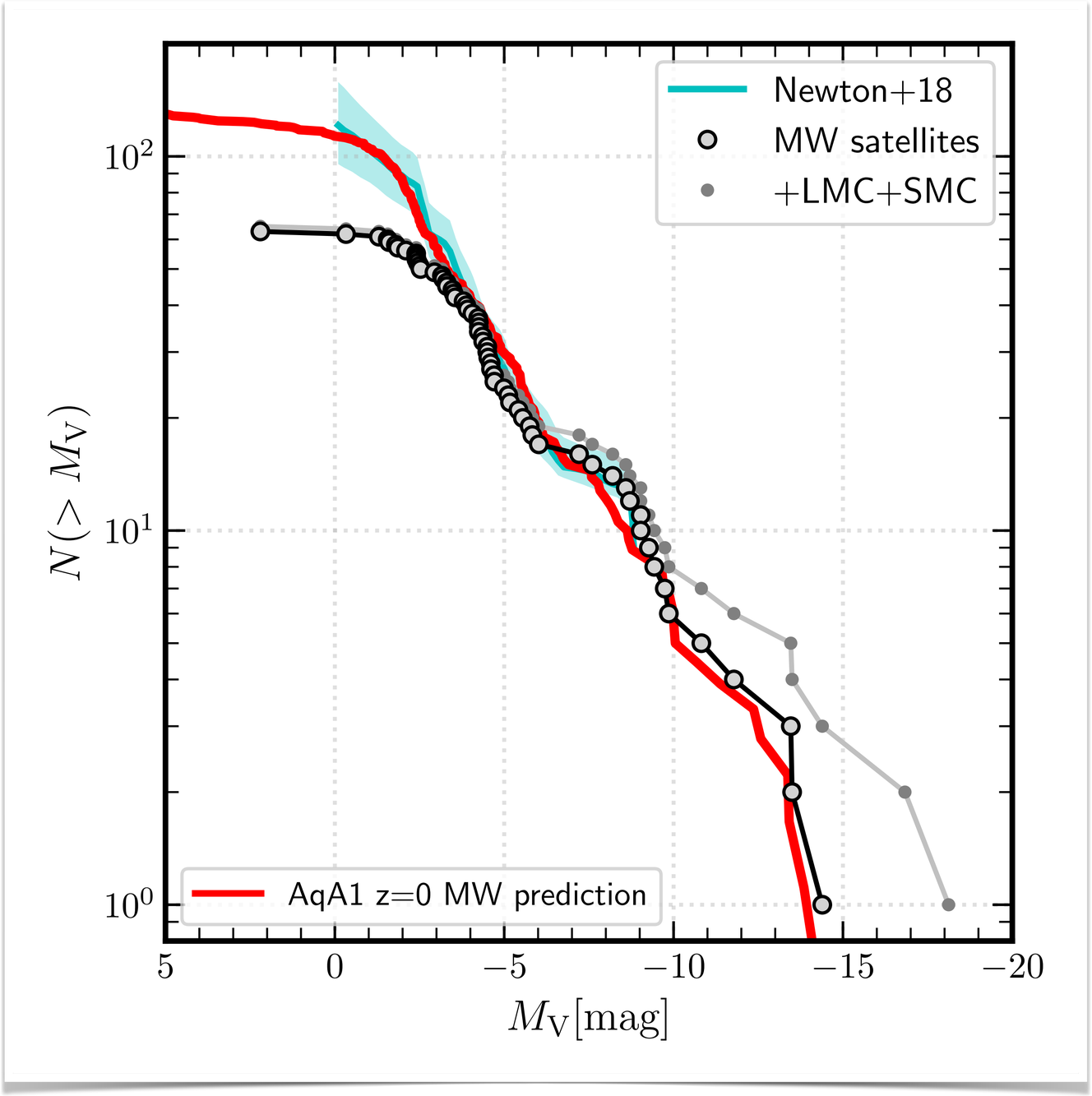

Newly discovered MW "faint ambiguous satellite candidates"

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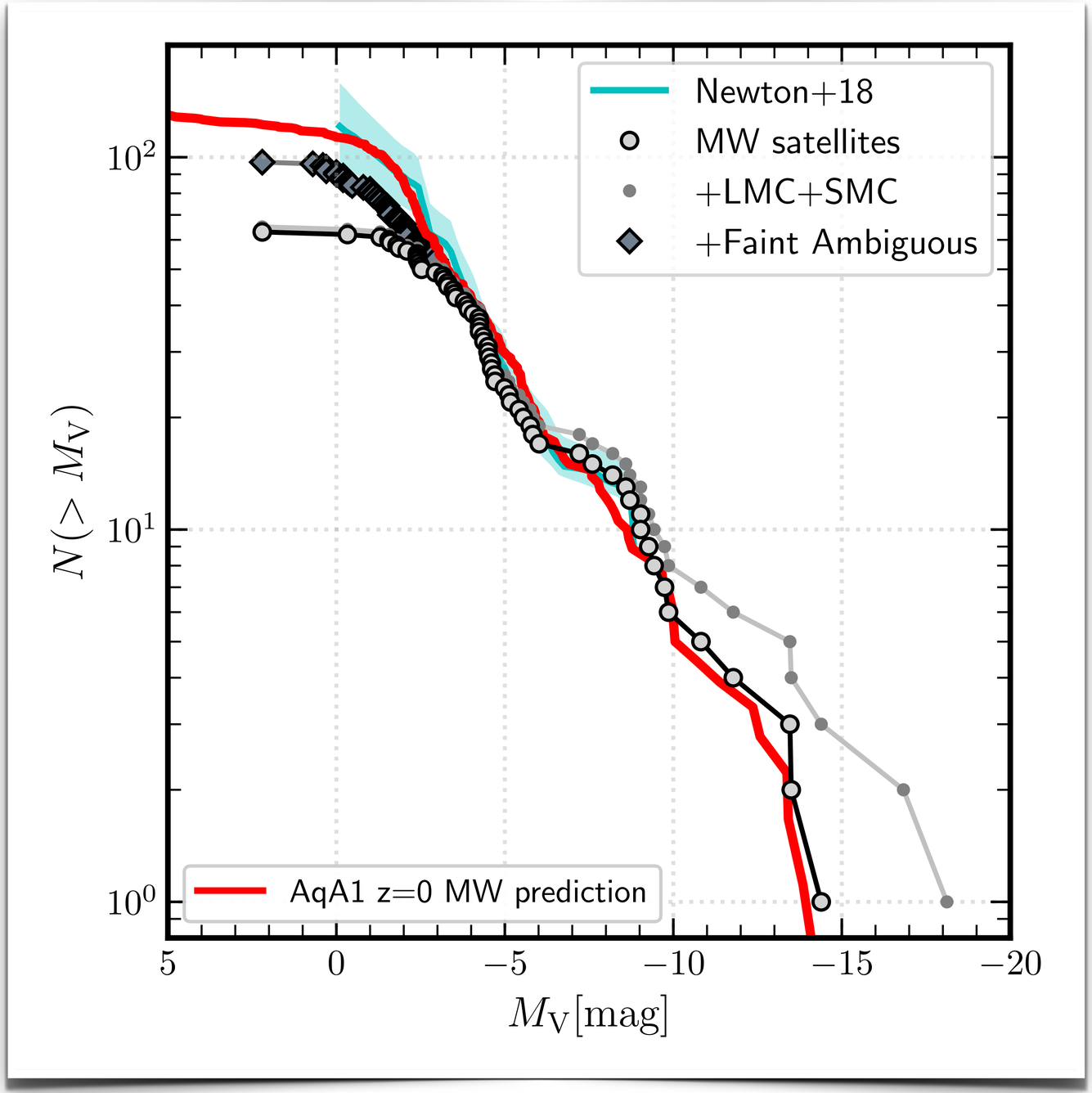
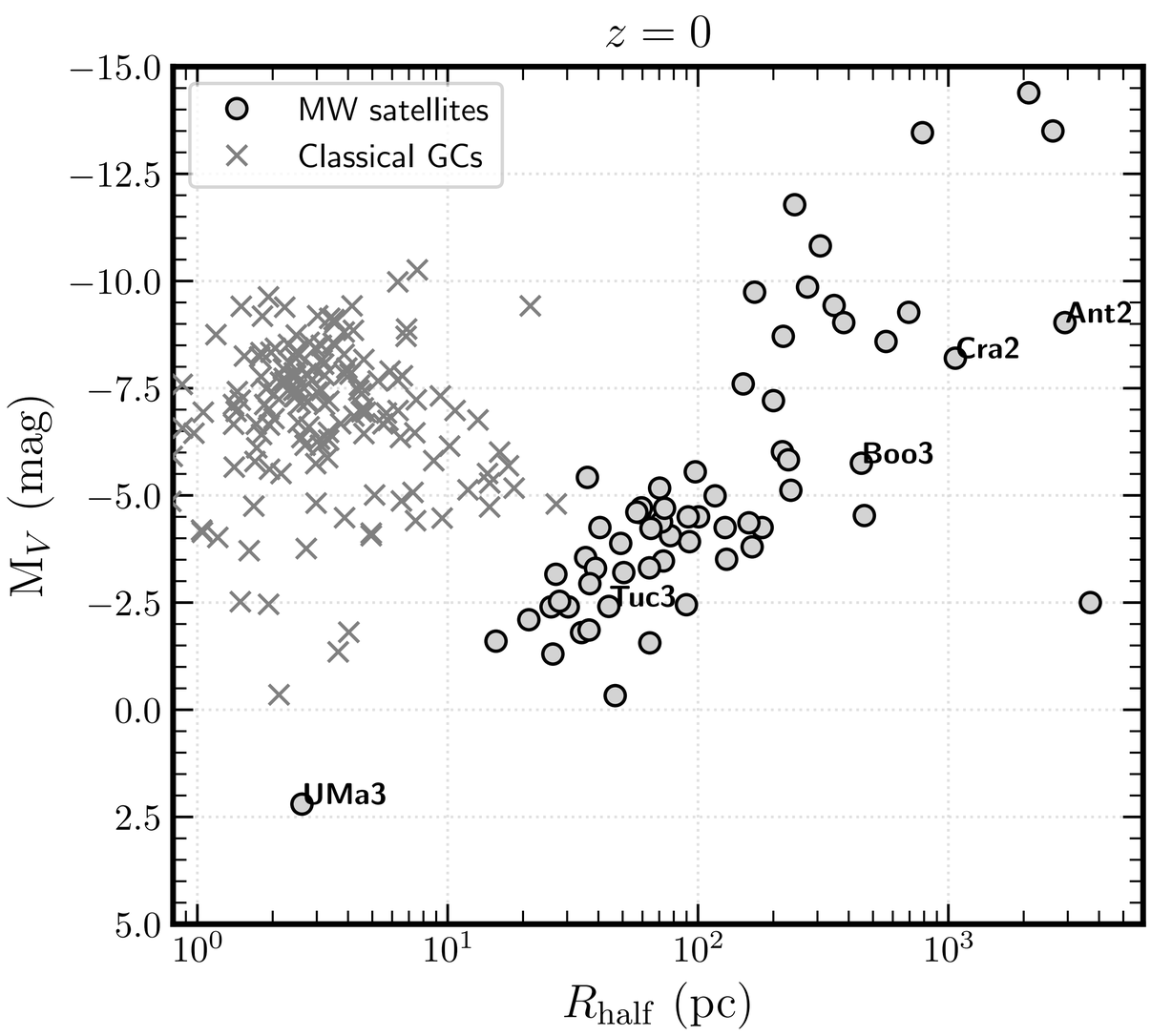
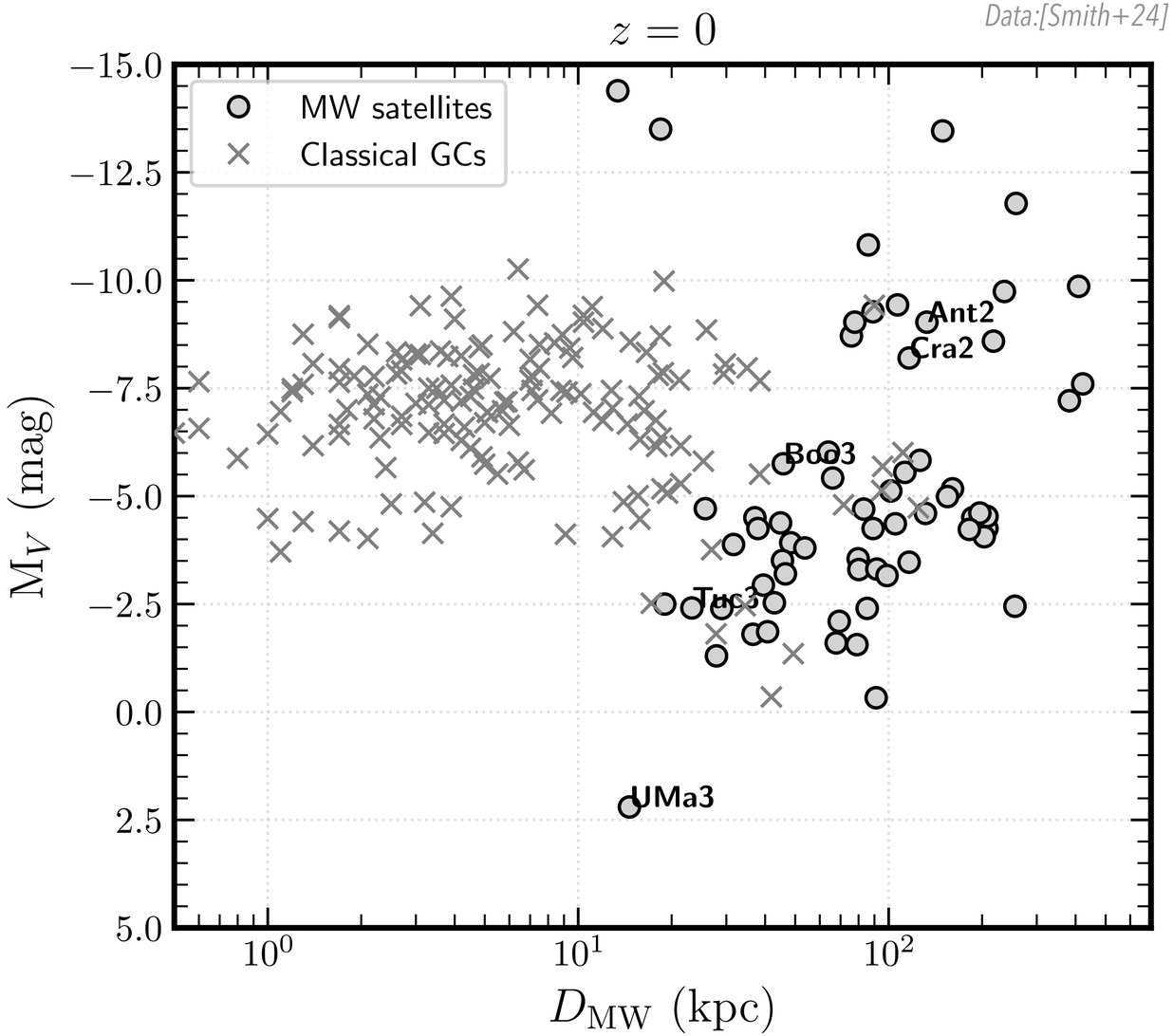


Predictions: MW satellite *luminosities, sizes and distances*

Santos-Santos +*in prep*

Data:[Smith+24]





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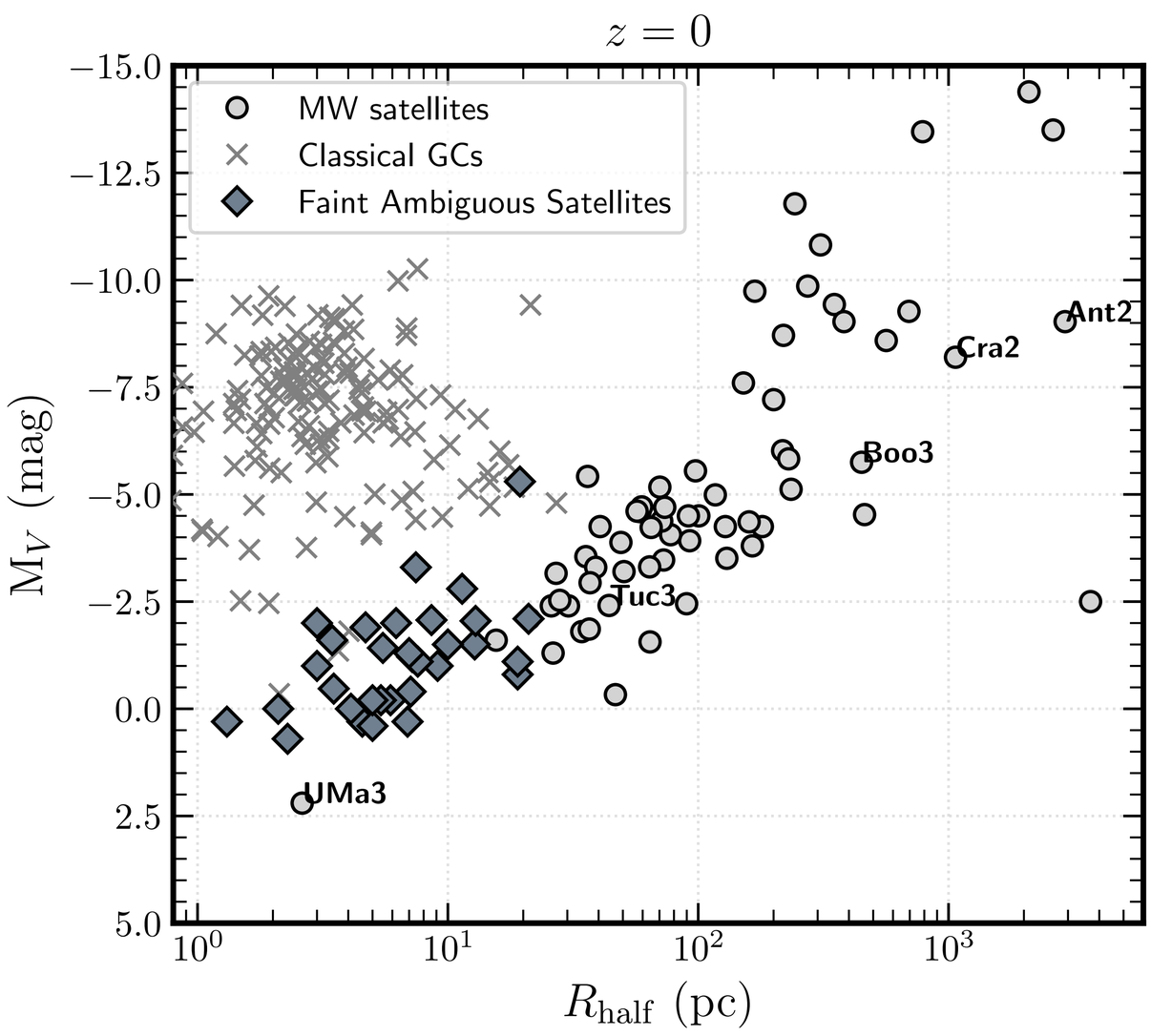

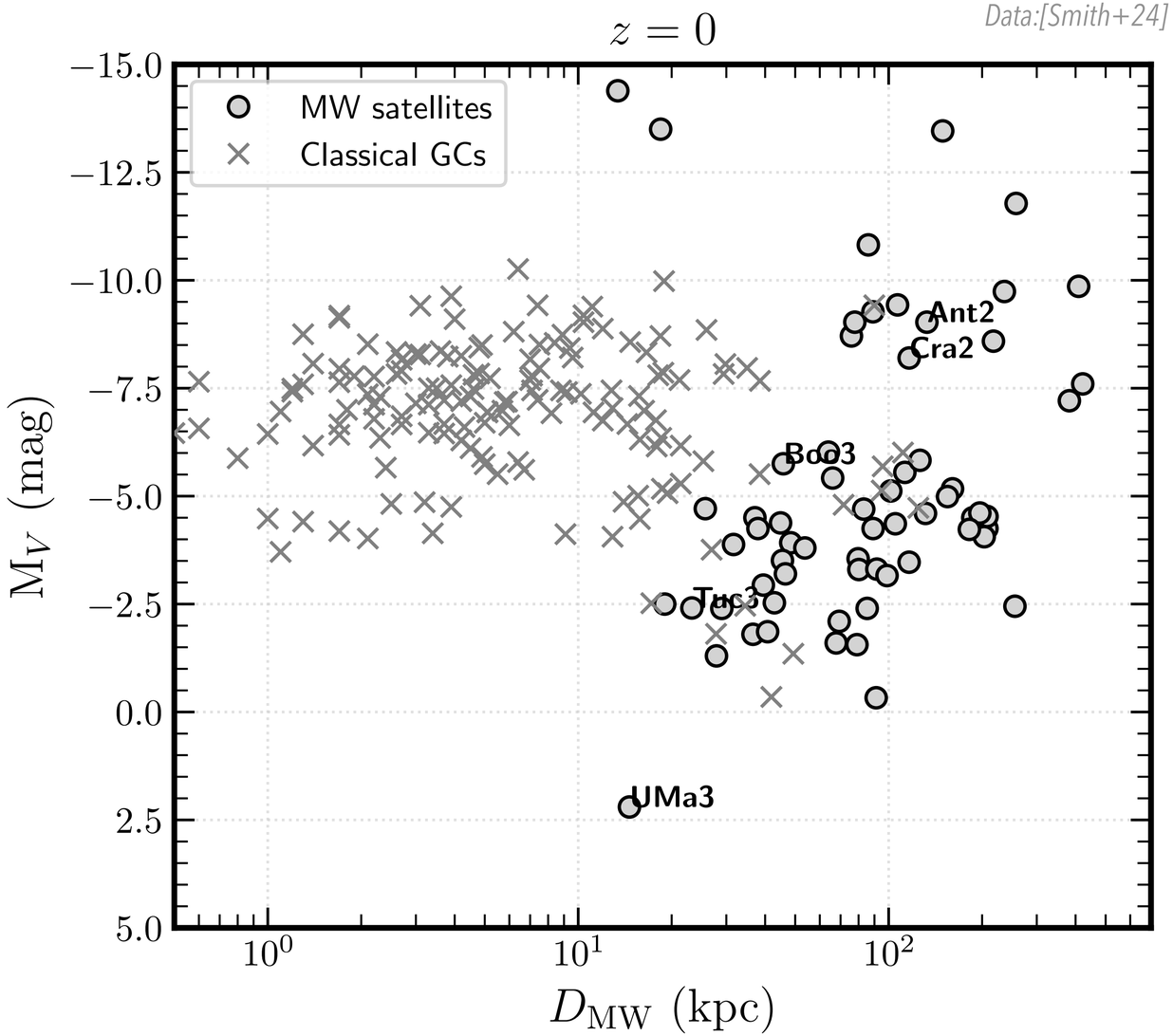

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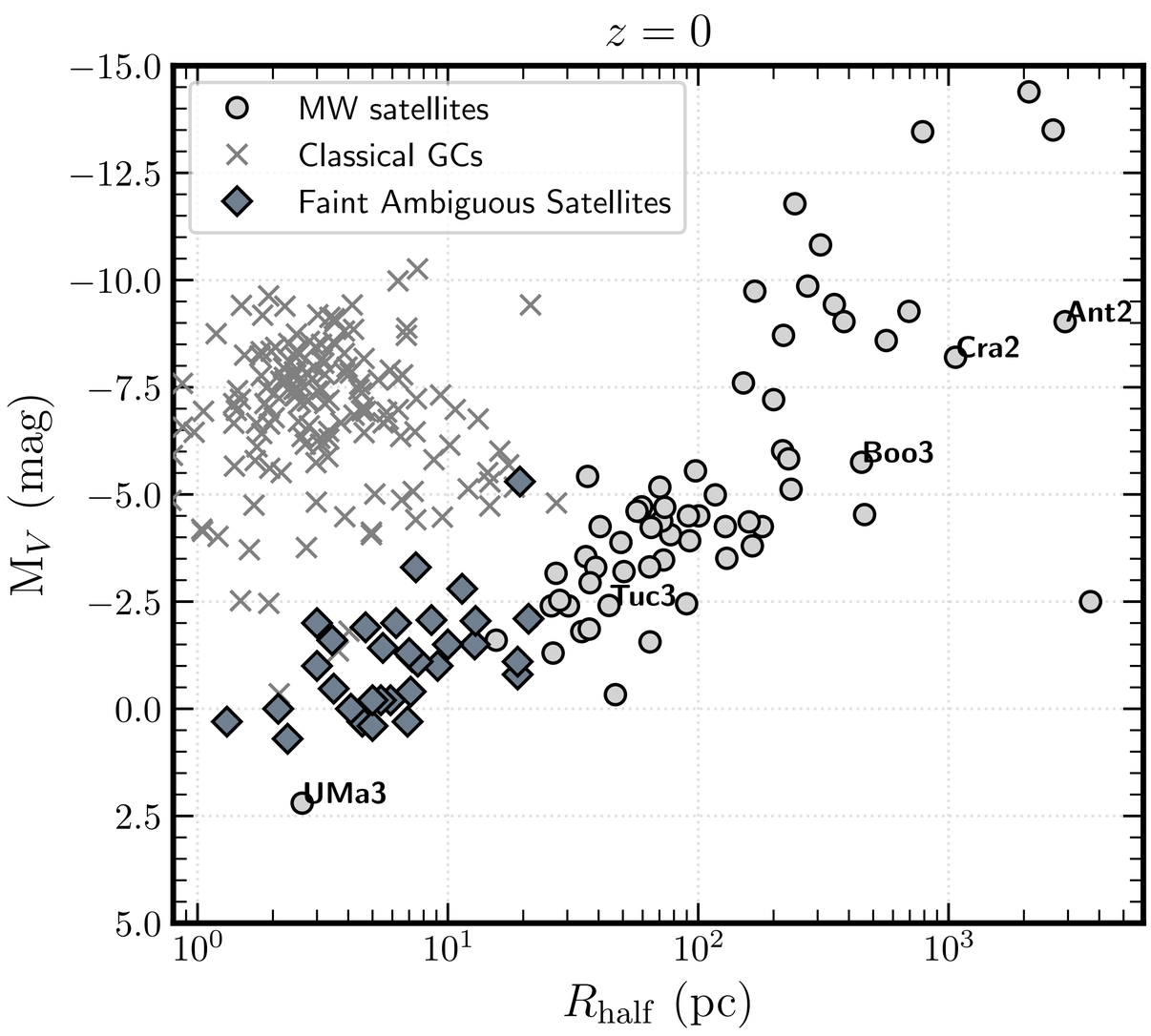

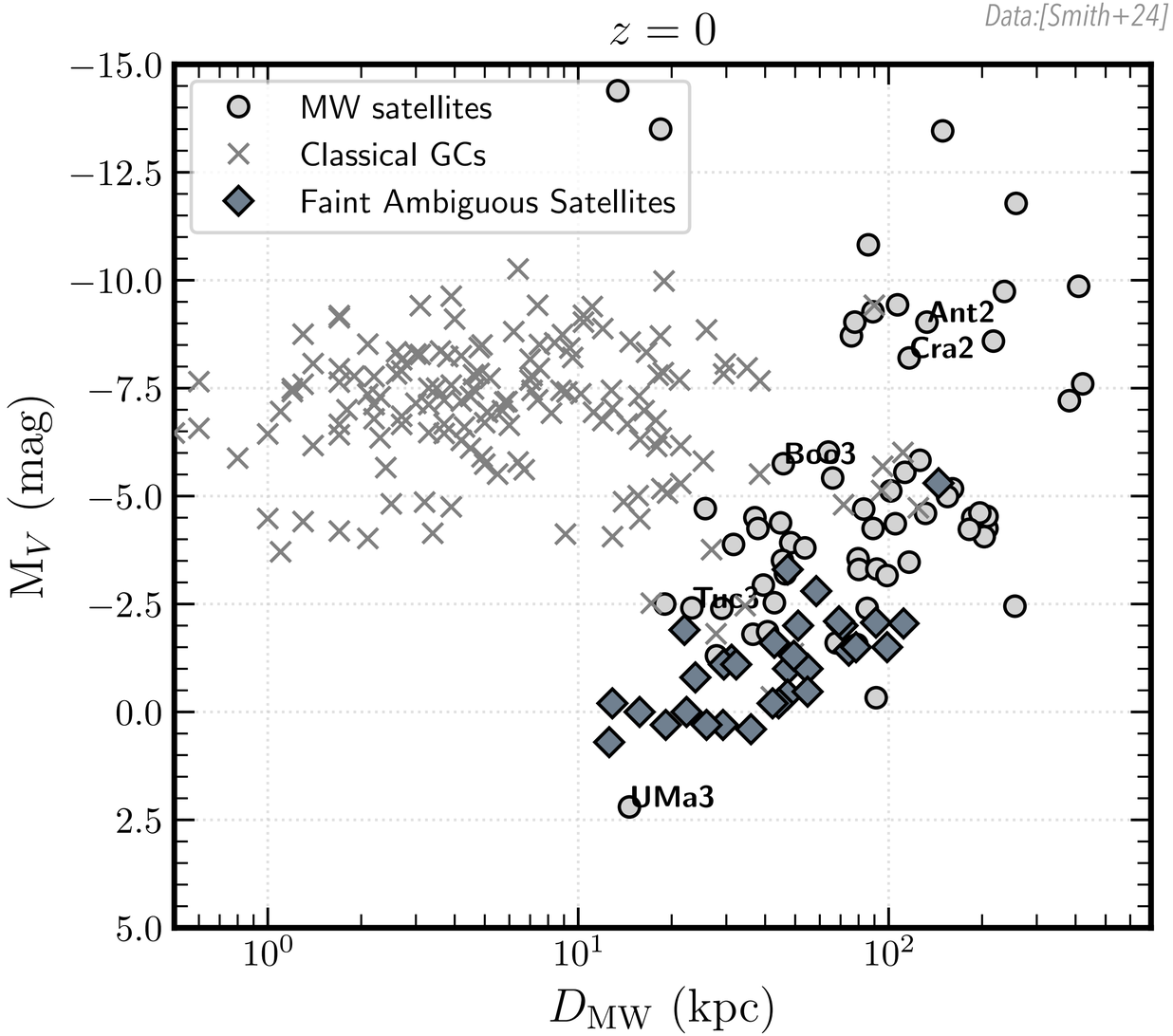

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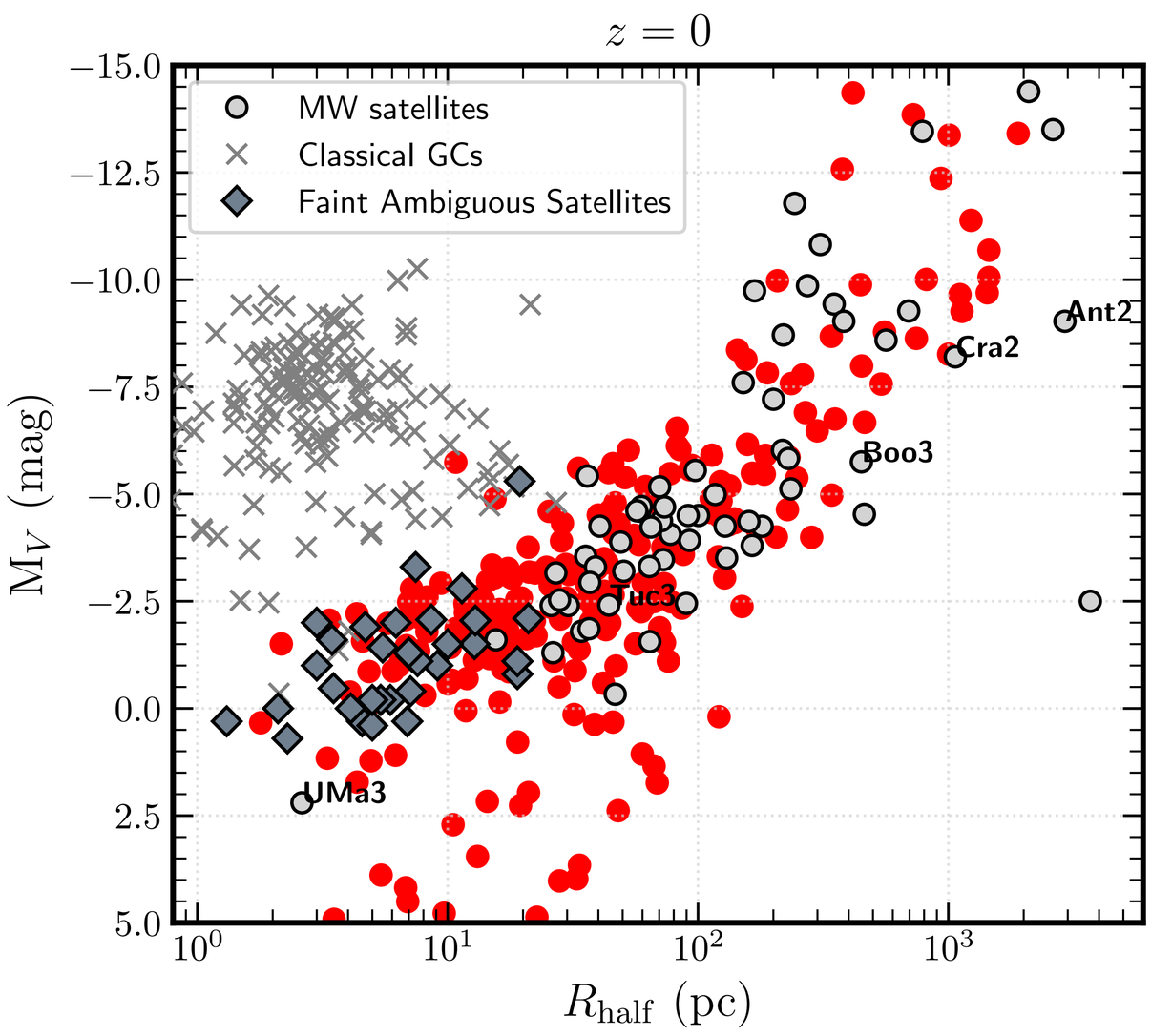
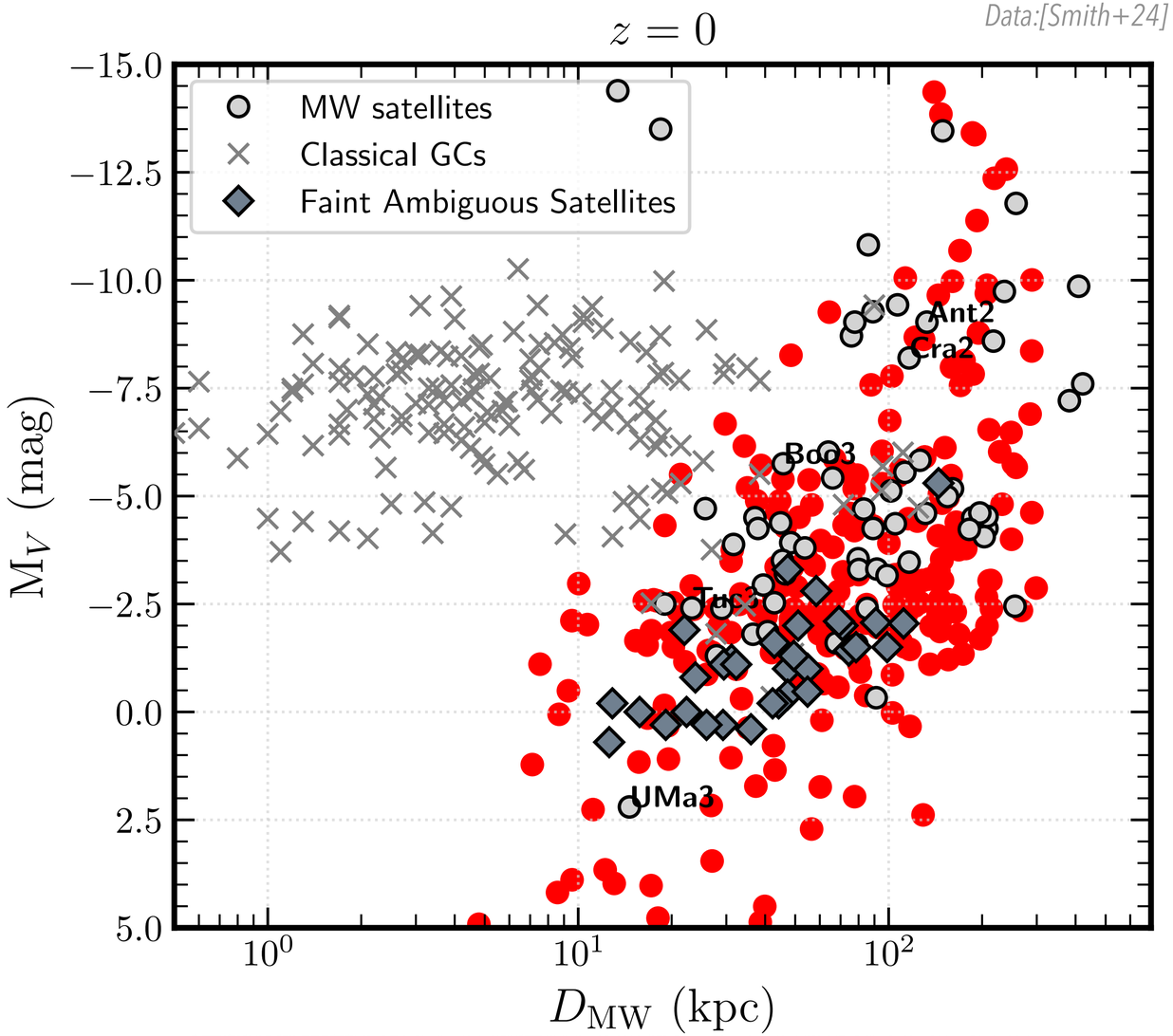


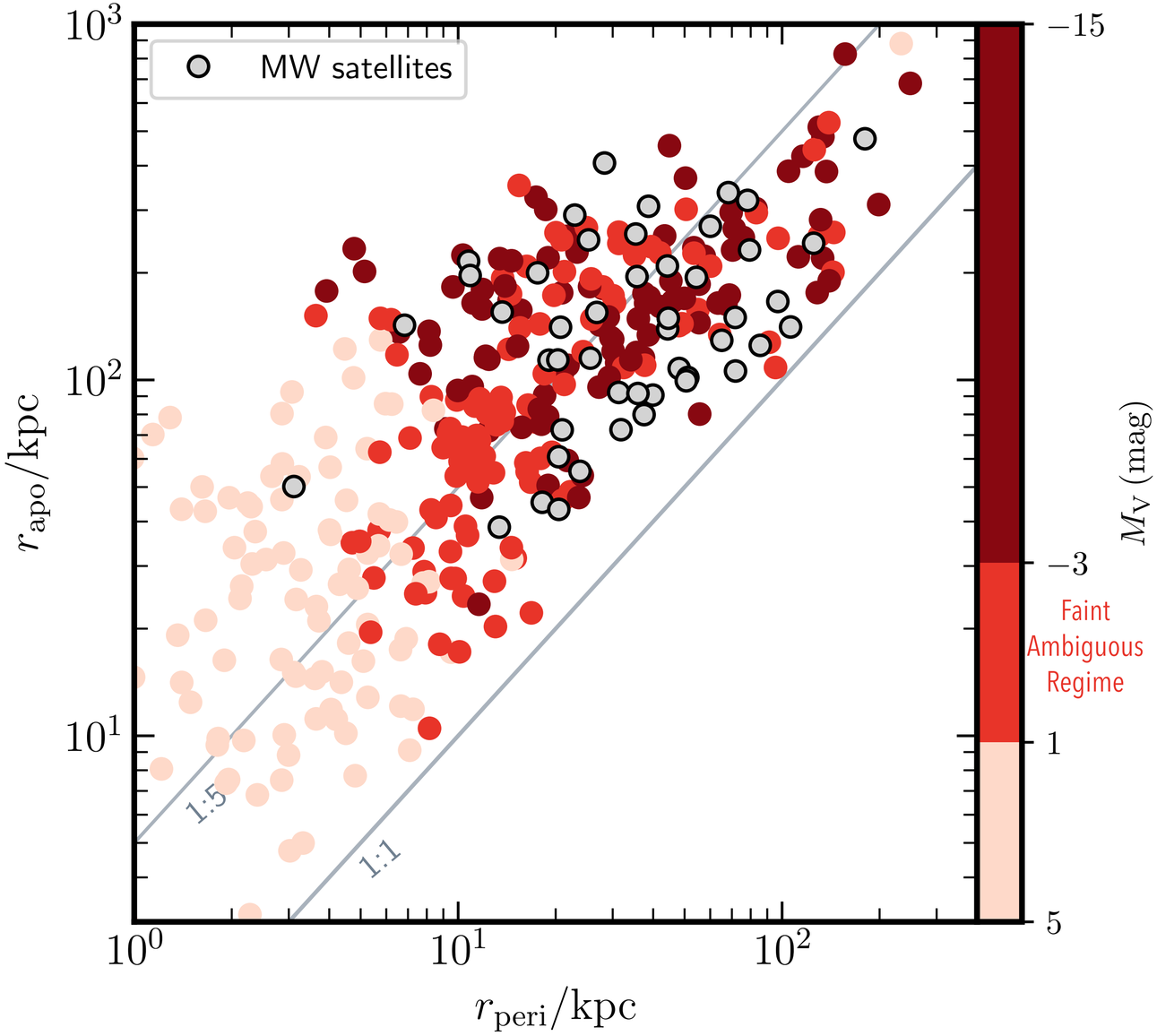


z=0 Luminosities and sizes are consistent with data

No satellite with MV<5 within 10 kpc of the MW centre

Predictions: MW satellite *orbits & accretion times*

*Santos-Santos +**in prep***



[see e.g. Battaglia+22, Pace,Erakal&Li22]

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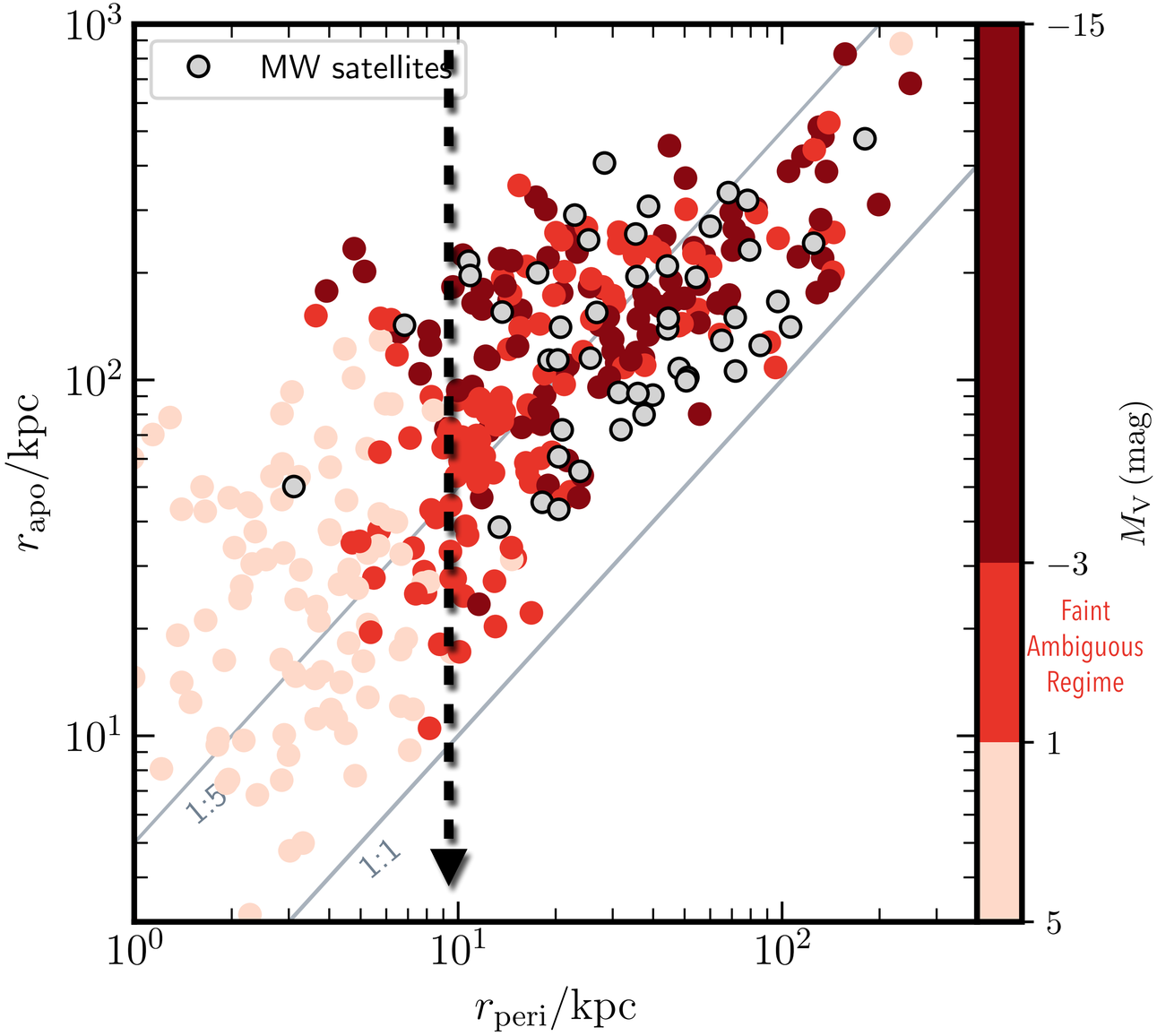

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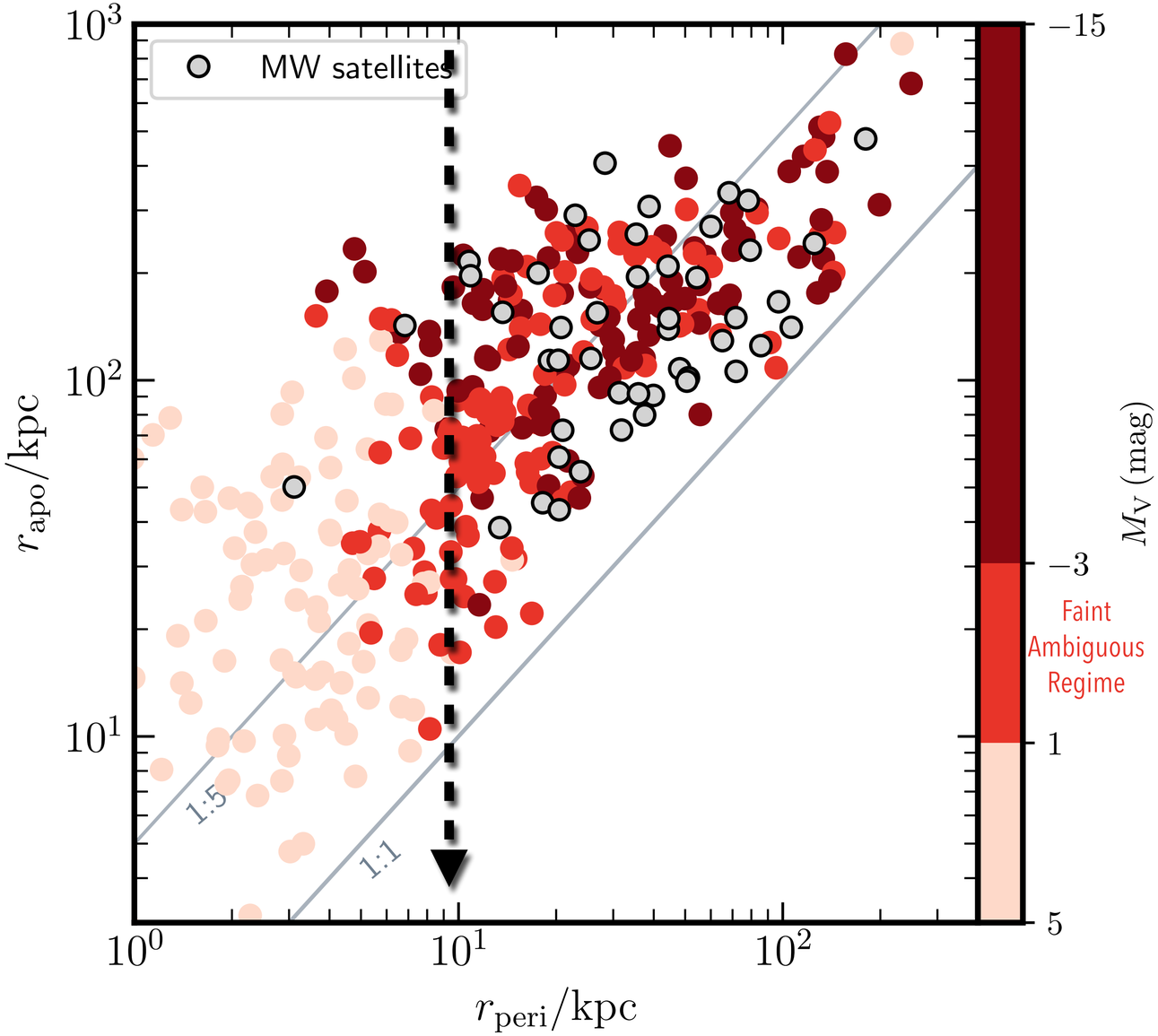
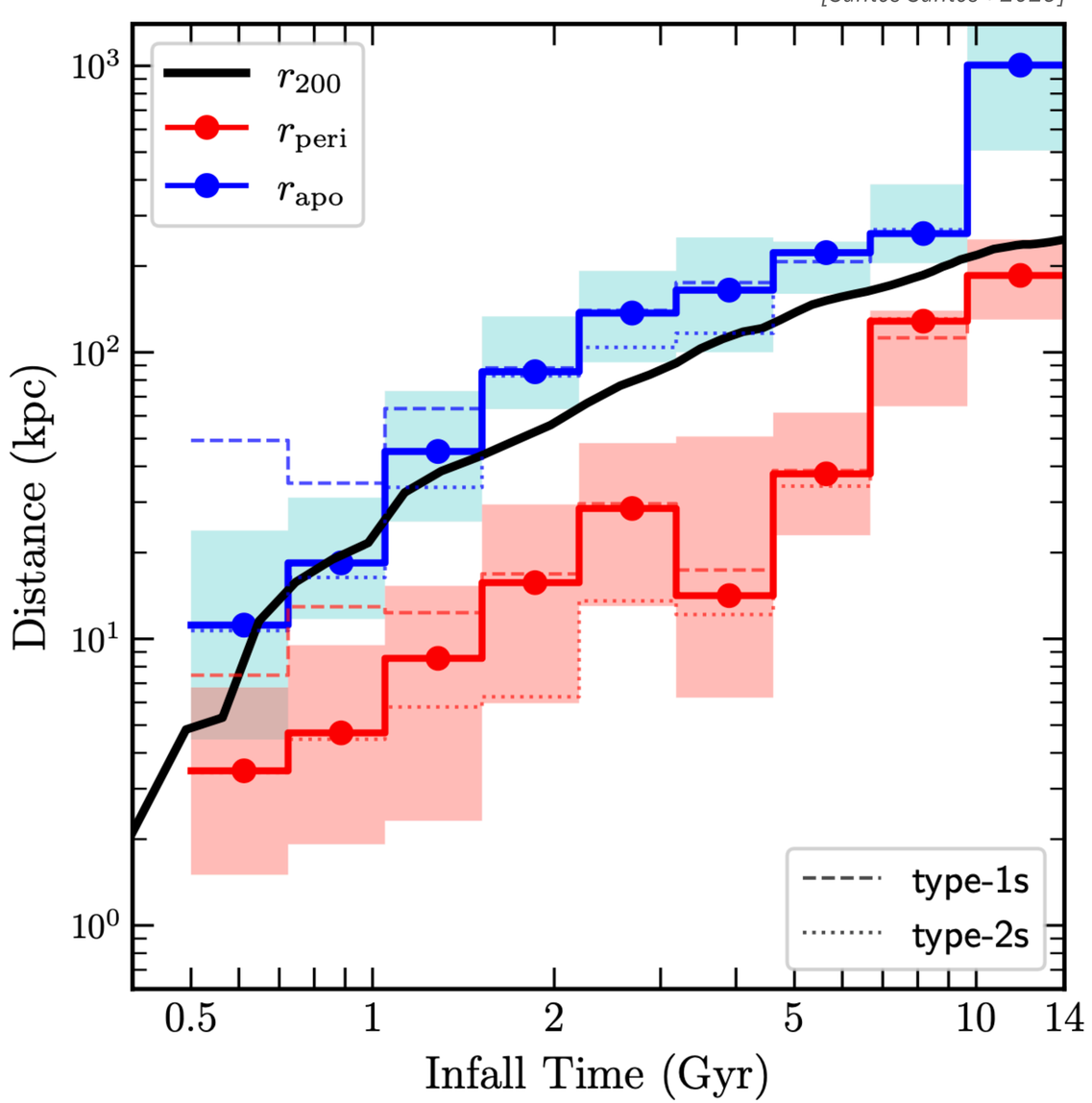
[Santos-Santos+2025]





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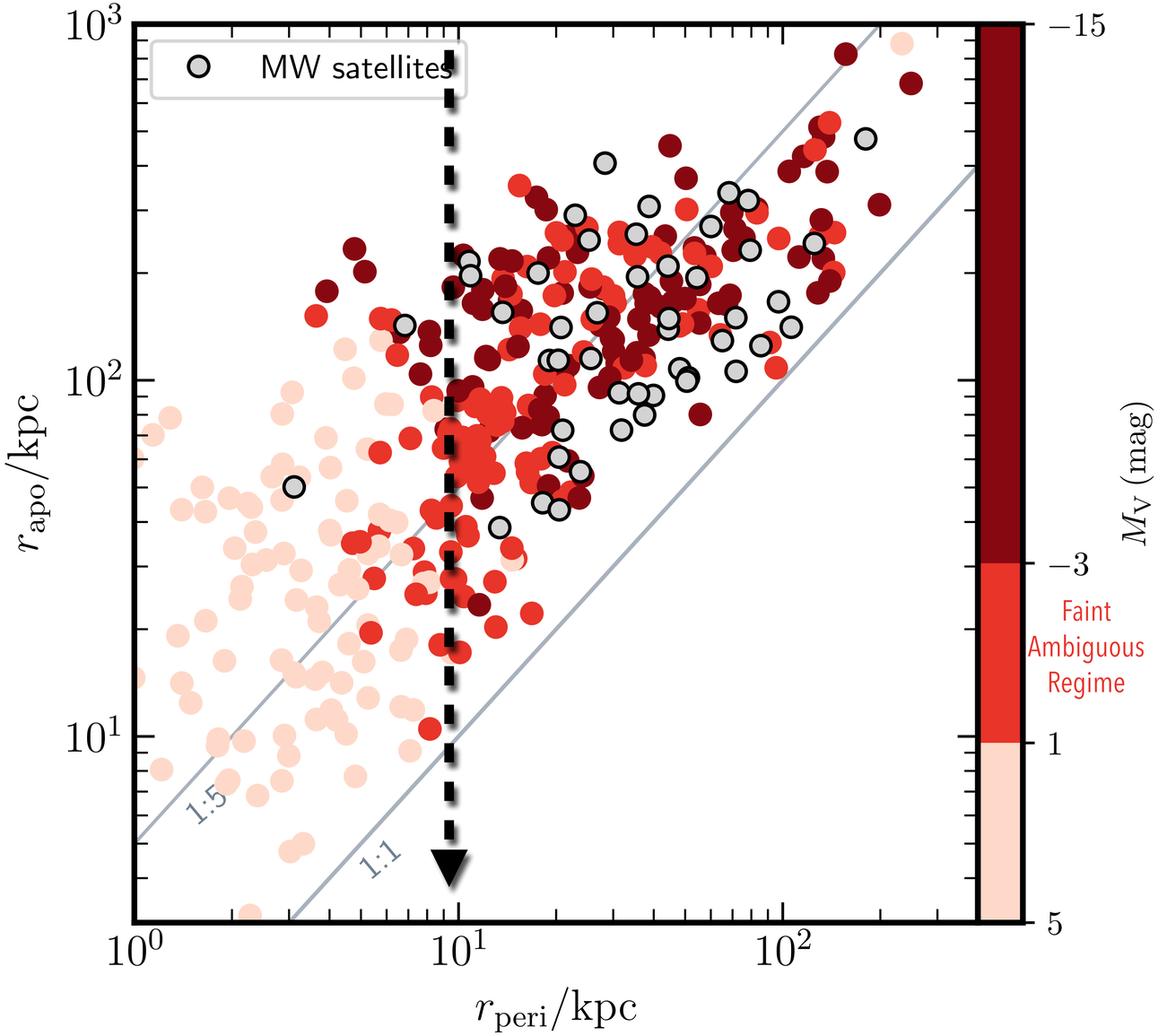

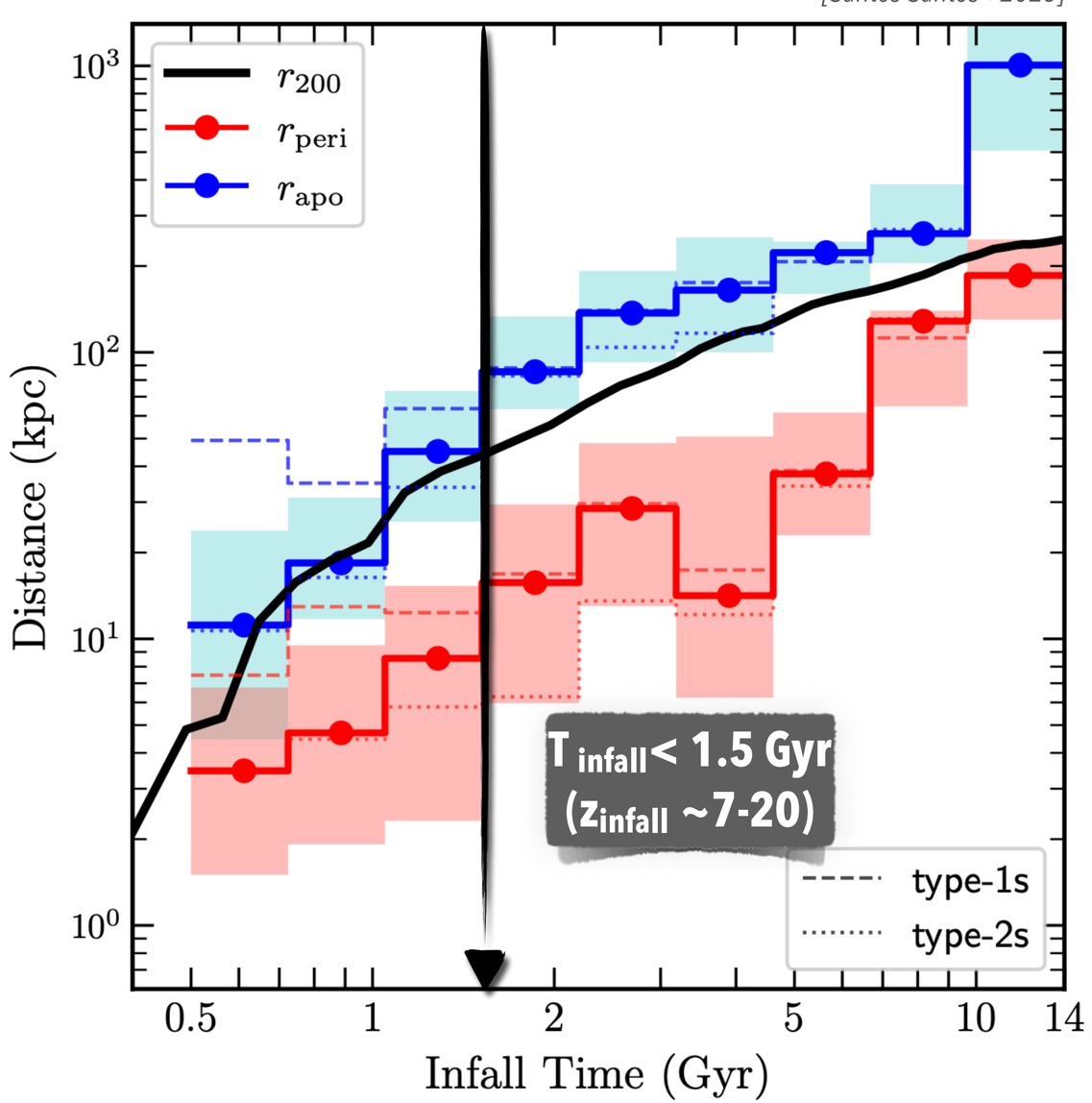

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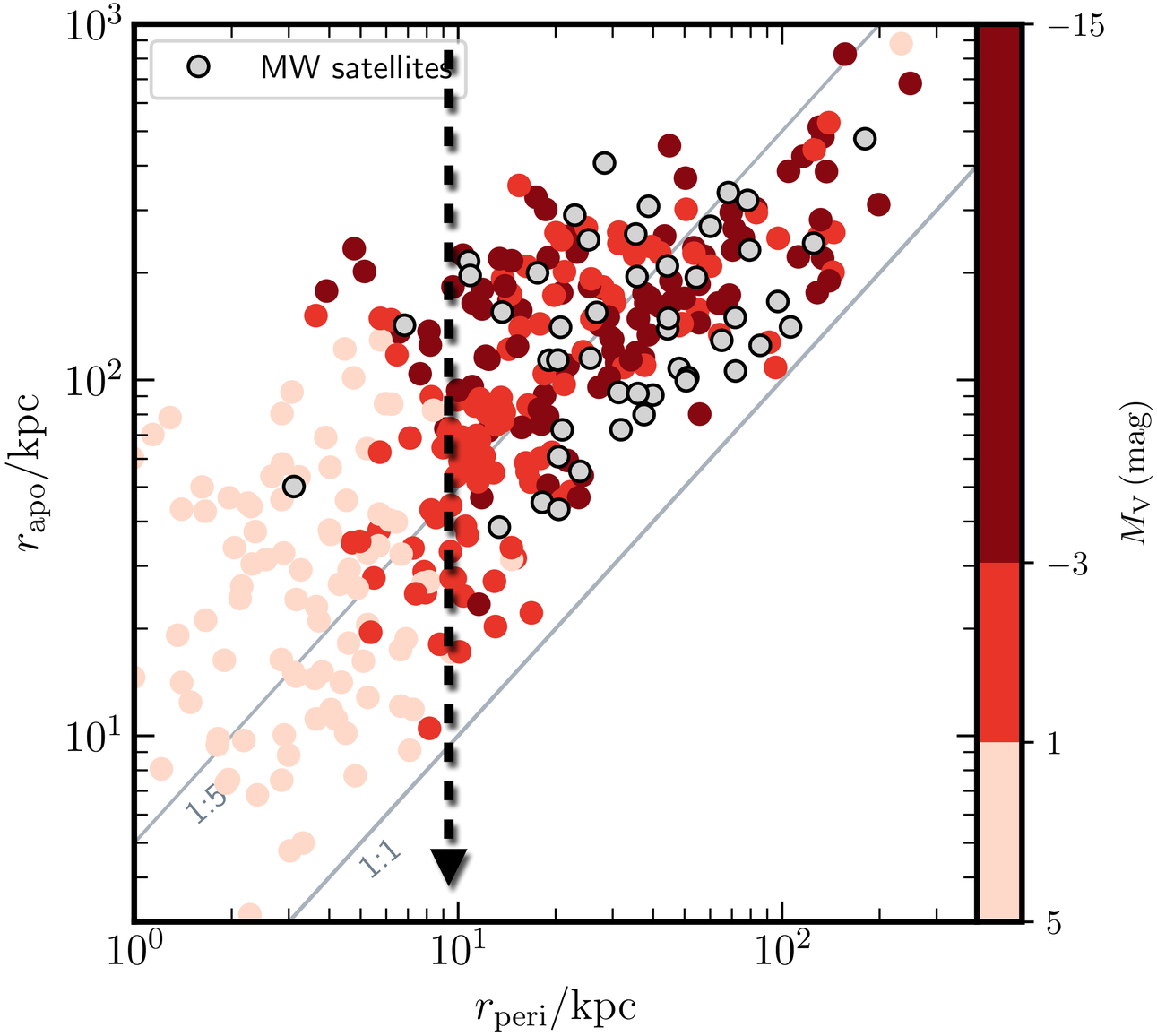
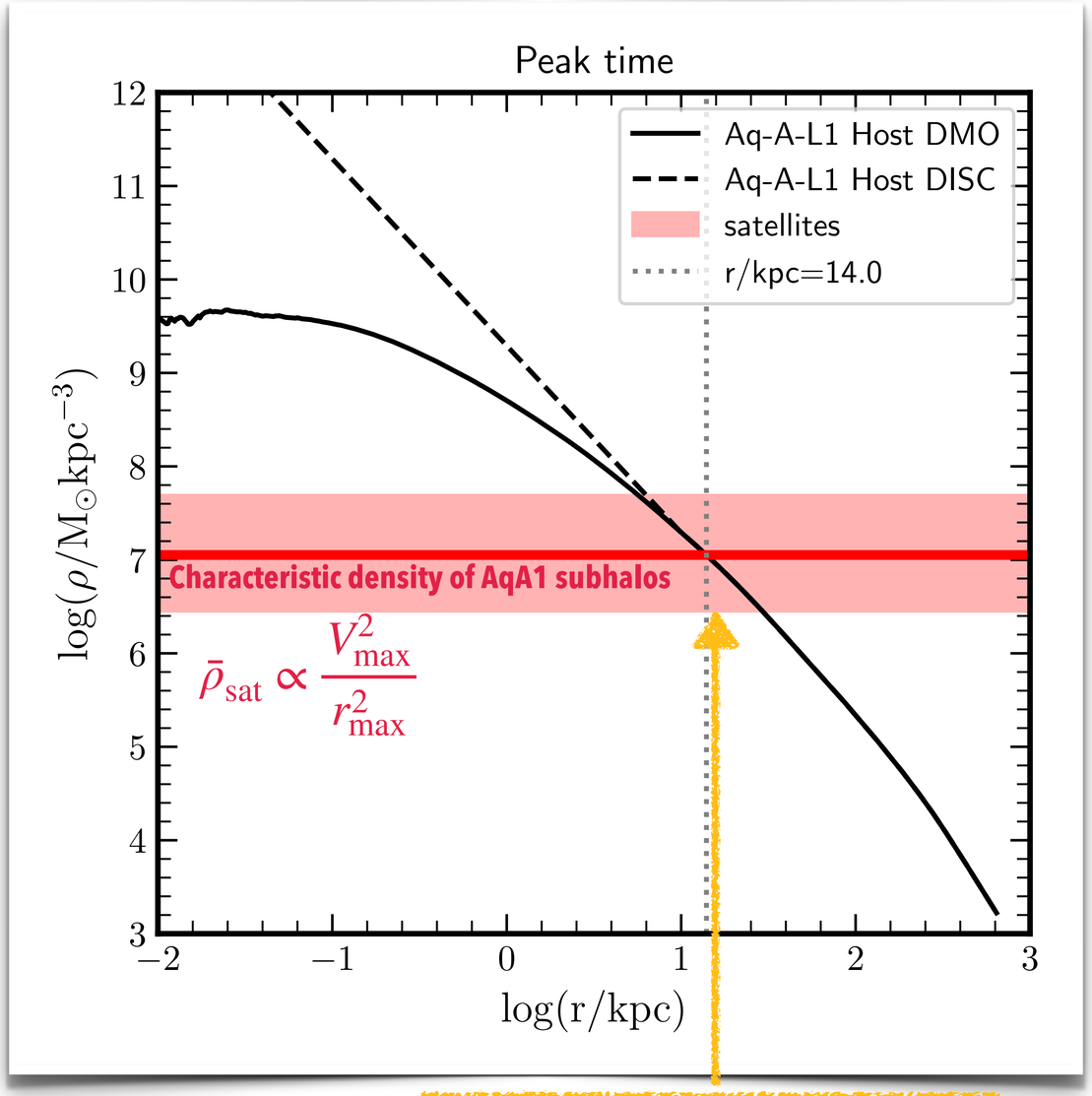




$$\bar{\rho}_{\rm host}(r) \sim \bar{\rho}_{\rm sat}$$

[see e.g. Battaglia+22, Pace,Erakal&Li22]

Predictions: MW satellite *velocity dispersion*

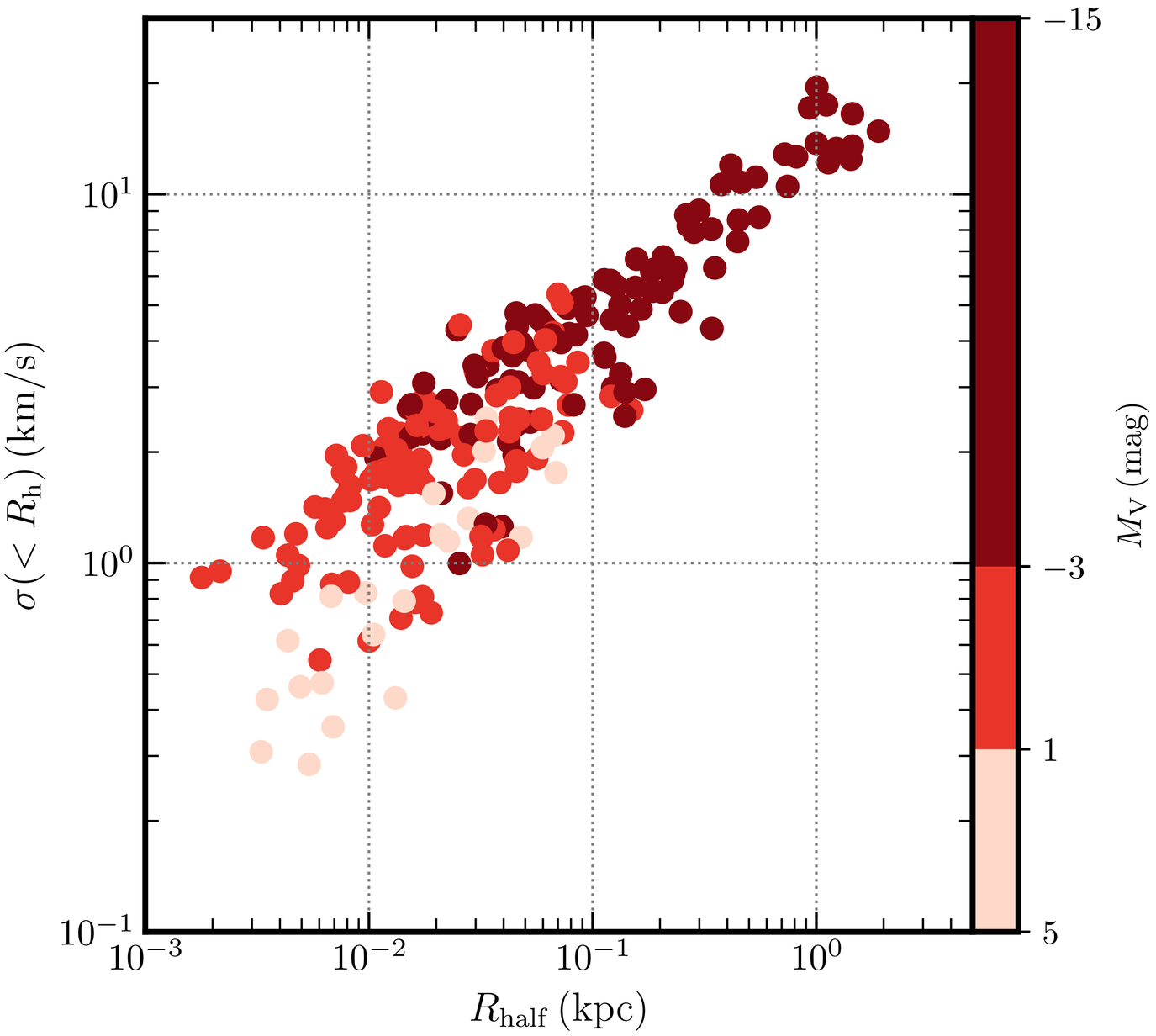
*Santos-Santos +**in prep***

[Errani+21 (Eq.8 & 9)]
Truncated NFW profile.
Depends on mass loss

$$\sigma = \sqrt{\frac{GM(<r_h)}{3r_h}}$$

$$M(<r_h) = (4/3)\pi r_h^3 \bar{\rho}(<r_h)$$

[see also Errani+24]



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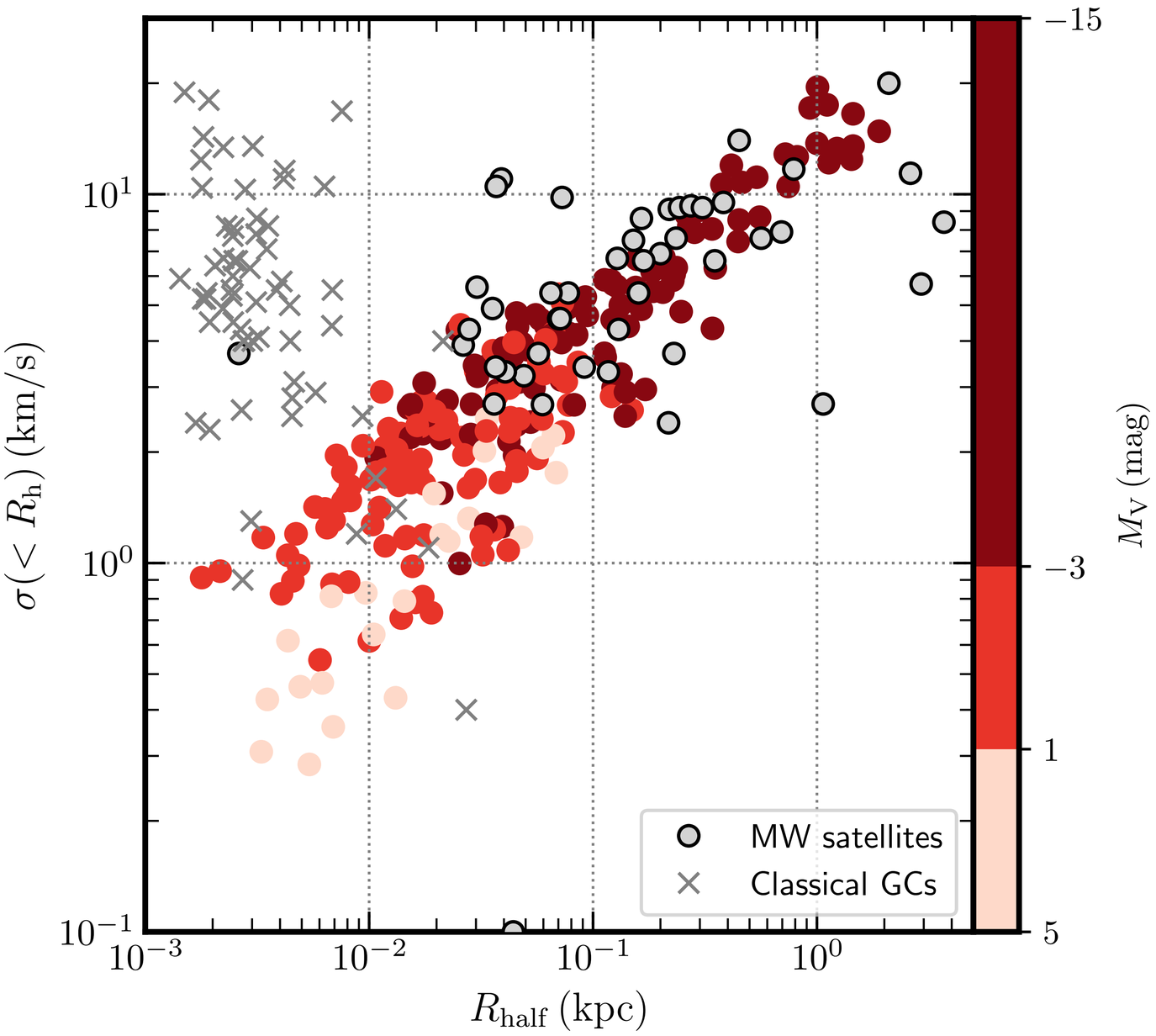

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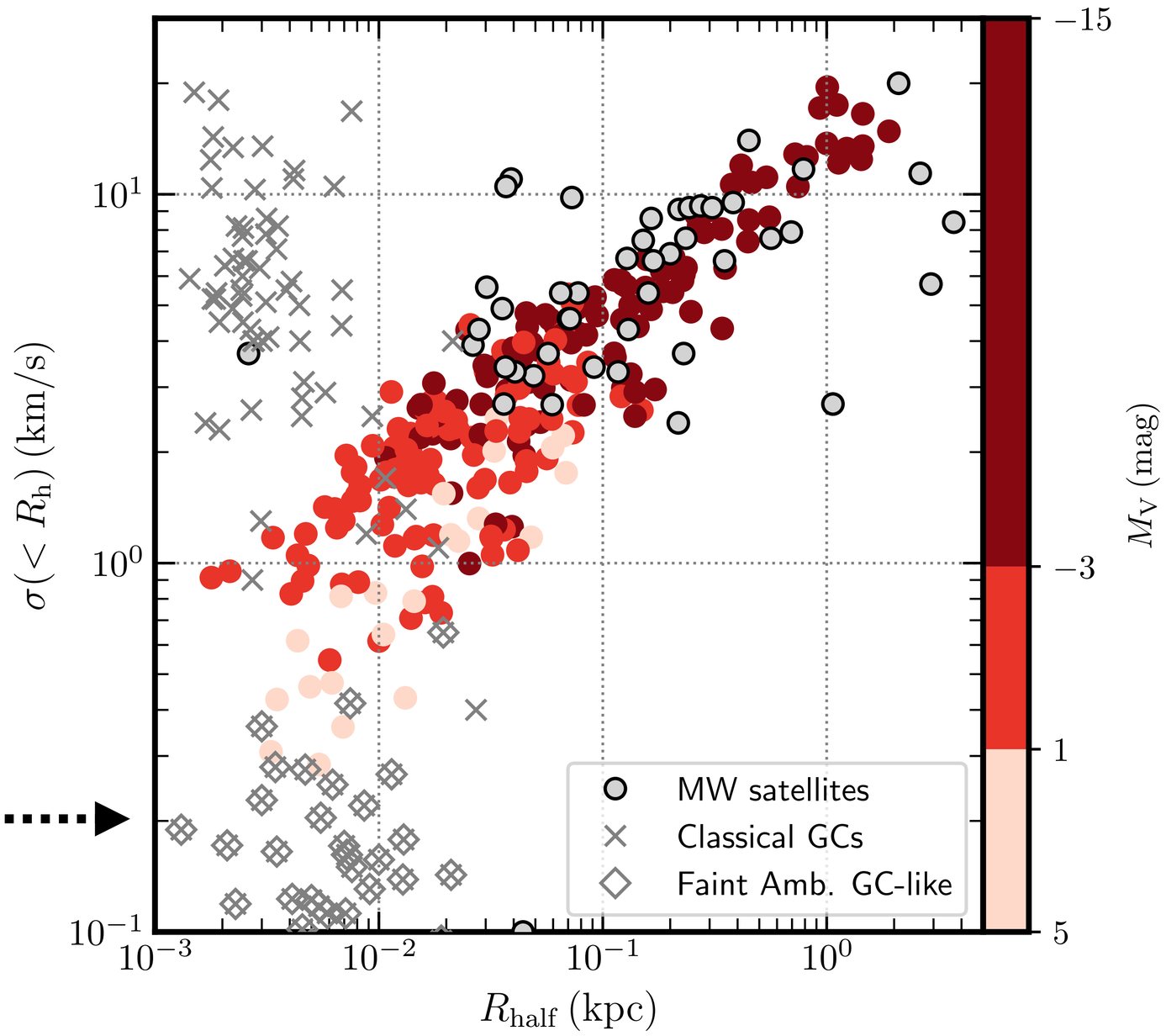
Errani+24 (Eq.2 self-gravitating)

$$\langle \sigma^2_{\rm los} \rangle = \frac{5}{96}\frac{GM_\star}{r_\star}$$



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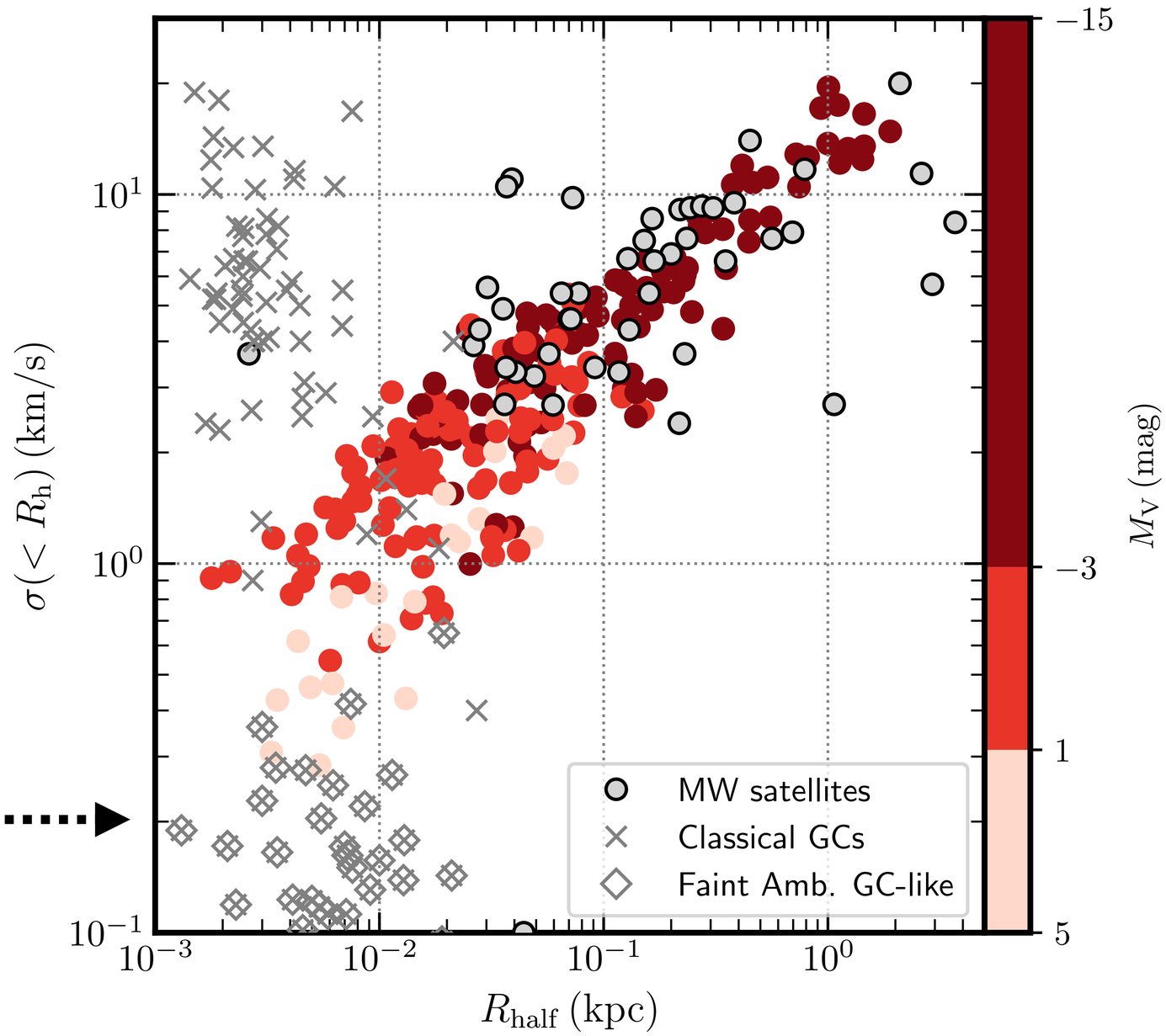


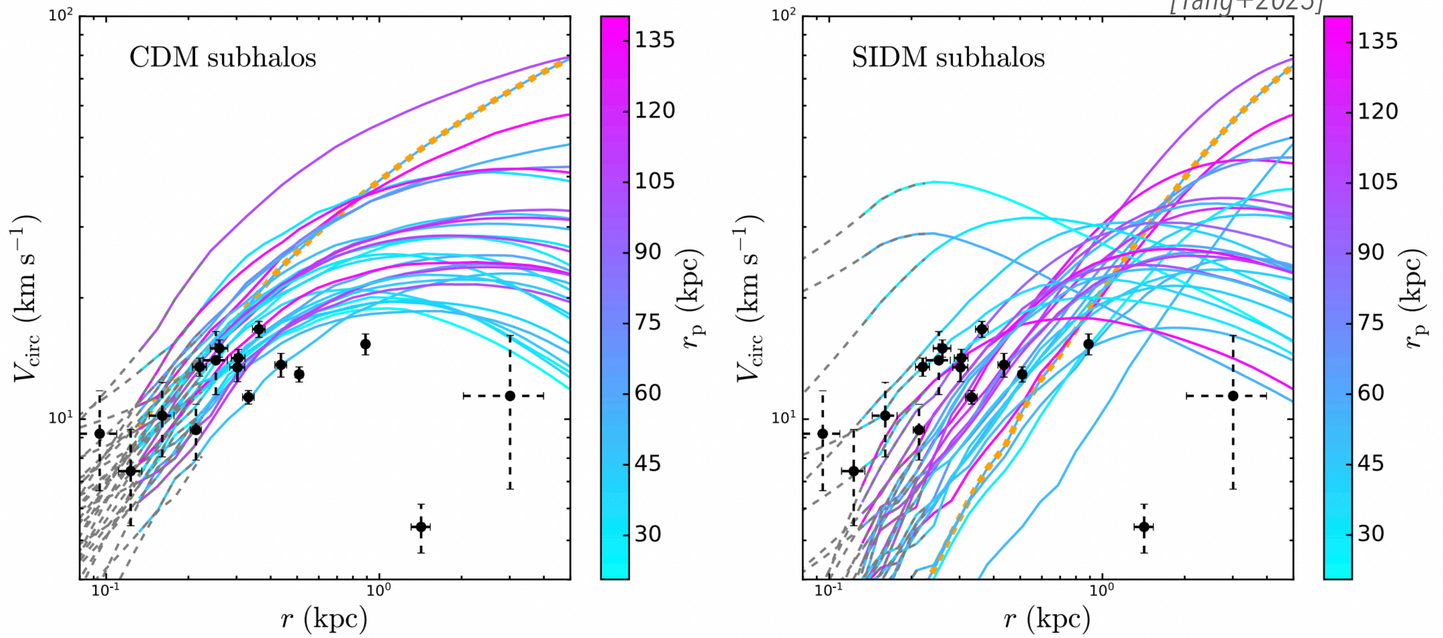
[see also Errani+24]

- Velocity dispersion measurement only way of discriminating conclusively if satellite is a GC or dwarf
- ...But it's difficult

CDM vs SIDM?

[see e.g. Tulin&Yu18; Zavala+19; Turner+21; Correa+22; Nadler+23; Yang+23a; Essig+19; Zeng+23;Hayashi+21; Errani+23; Zhang+24]

[Yang+2023]



A) At first order:

- Heating from self-interactions leads to core formation.
- Subhalos affected by tides, prone to genuine disruption
- Host density profile also changes(!)

B) With small fixed cross-sections (<0.1 cm²/g)

- Very small cores, improving survival of halos –> predictions similar to CDM

C) With velocity-dependent large cross-sections (>10 cm²/g) and "core-collapse":

- **C1)** If $t_{cc} < T_{infall}$ –> subhalo will resist tides –> prediction similar to CDM
- **C2)** If $t_{cc} > T_{infall}$ –> prediction depends on interplay between CC formation and tides

Summary

- In **CDM, subhalos always survive**. Stars may be lost.
- Cosmological simulations suffer subhalo artificial disruption. It is crucial to correct for "orphans".

- LCDM models of the MW system match well the properties of satellite galaxies known so far. They also **predict the existence of numerous faint satellite galaxies at close distances,** with properties
  - σ=1-3 km/s
  - $M_V > -3$ ($M_{star} < 1e3\ M_{sun}$)
  - $r_{peri} > 10$ kpc. ($r_{apo} < \sim 100$ kpc)
- These properties seem to match those of "ambiguous" satellites identified recently with photometric surveys/Gaia
- Some of these predictions are unique to CDM, and may help to discriminate between dark matter models

Gracias!