The "true" radial distribution of satellite galaxies around MW-mass halos in LCDM

Dr Isabel Santos Santos

Institute for Computational Cosmology, Durham University

+ Carlos Frenk, John Helly, Shaun Cole, Julio Navarro et al

The 2nd Shanghai Assembly on Cosmology and Structure Formation - 1 November 2023

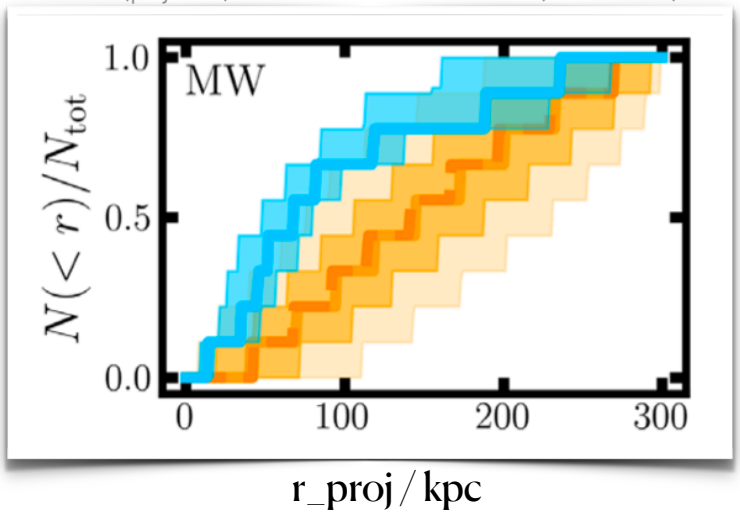
Durham University ICC

Credit: J. Turnbull/K. Oman/APOSTLE Team

A puzzling observation

The observed radial distribution of satellite galaxies in the MW is more concentrated than predicted by cosmological simulations of MW-mass hosts.

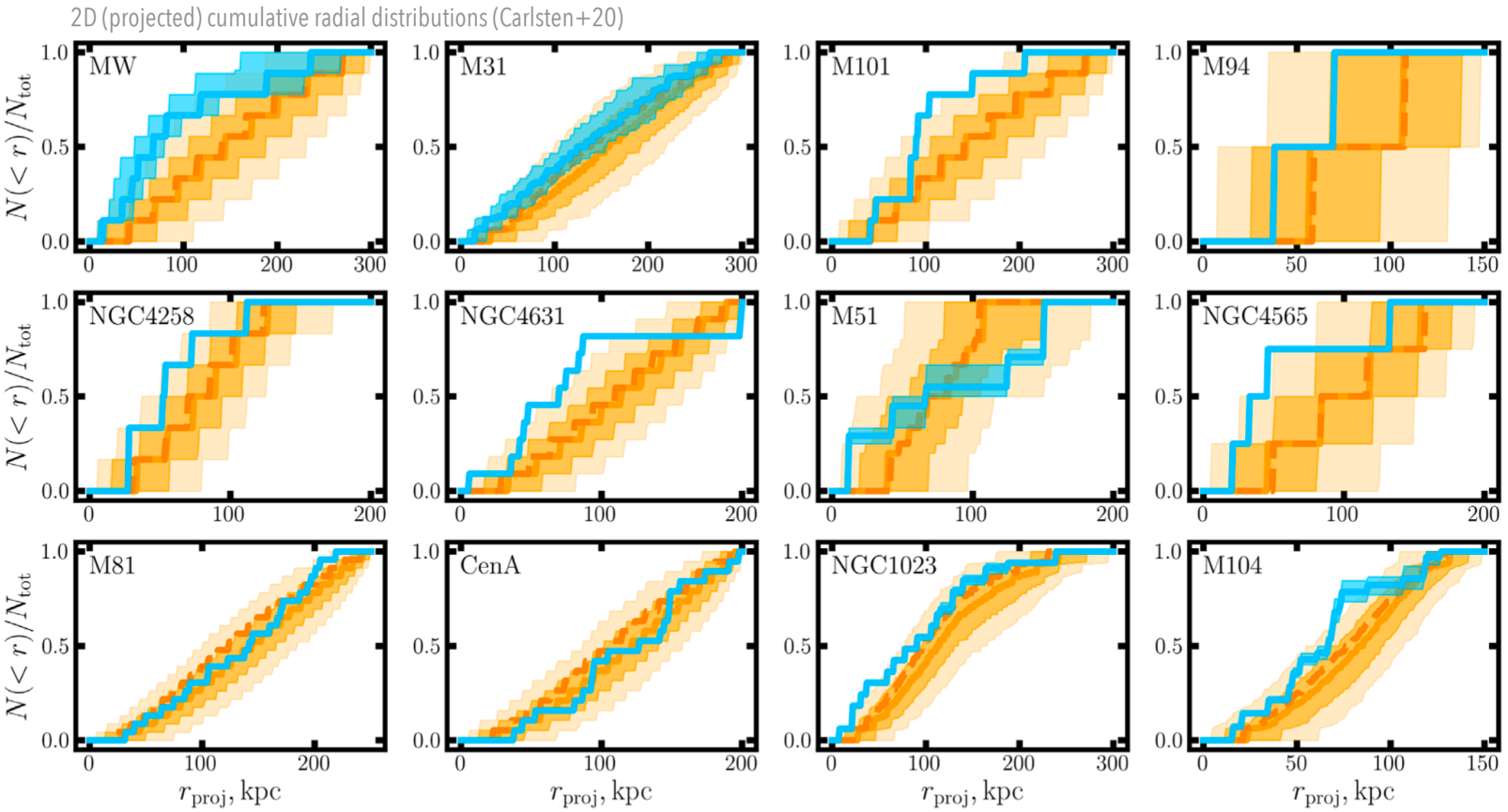
2D (projected) cumulative radial distributions (Carlsten+20)



Observations MW
Simulations

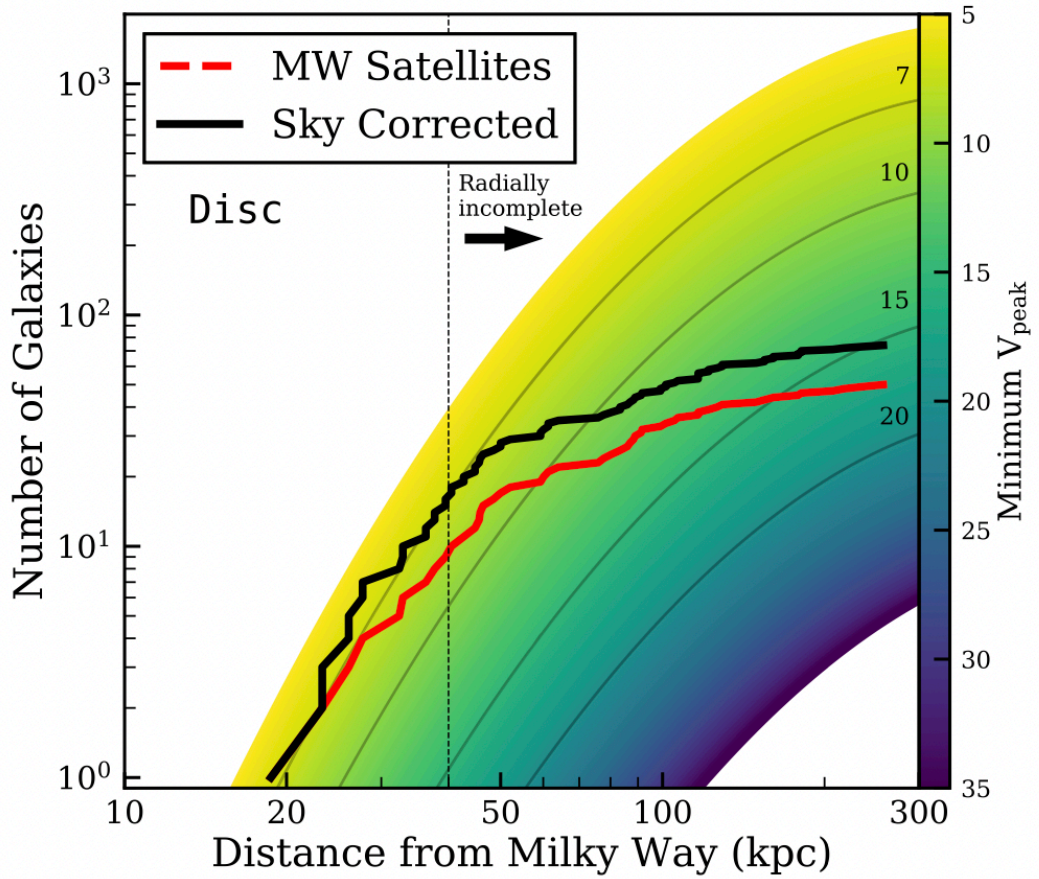
A puzzling observation

The observed radial distribution of satellite galaxies in the MW is more concentrated than predicted by cosmological simulations of MW-mass hosts.



Few nearby subhalos in simulations: A problem for CDM?

Radial distribution of subhalos in ~**"hydro"** simulations (Kelley+19)

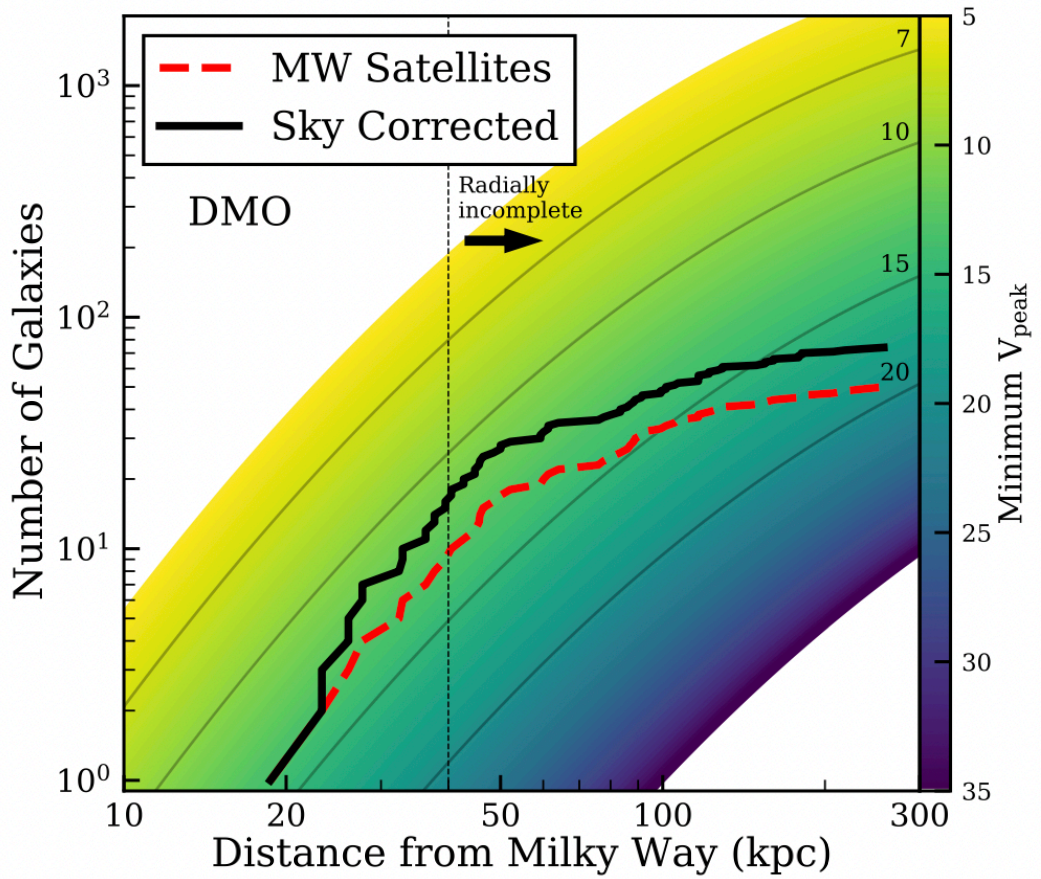


Subhalos with **Vpeak<7 km/s** need to be populated with galaxies to match data

➠ **Not favoured by galaxy formation theory, as is below the H-cooling limit** (Vpeak~19 km/s; Okamoto&Frenk09)

Few nearby subhalos in simulations: A problem for CDM?

Radial distribution of subhalos in **DM-only** simulations (Kelley+19)



Subhalos with Vpeak<12 km/s need to be populated with galaxies to match data

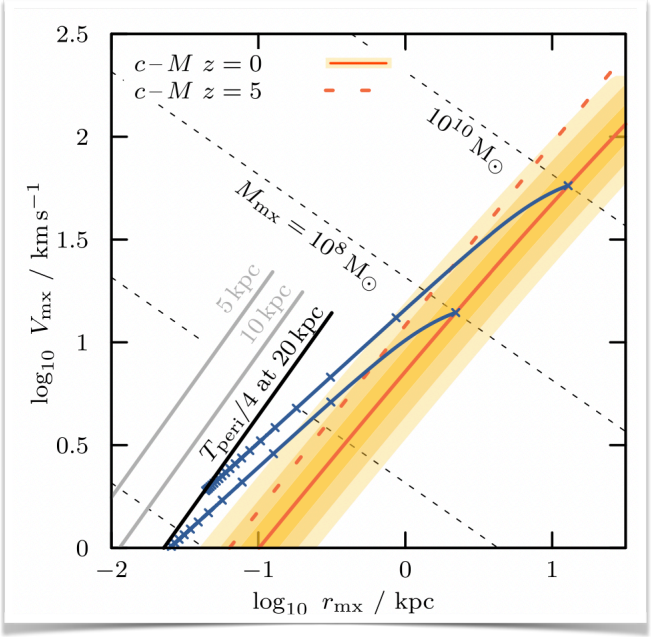
✦**Even in DMO cosmological simulations, there are not enough subhalos at close distances, massive enough to account for observed MW satellites.**

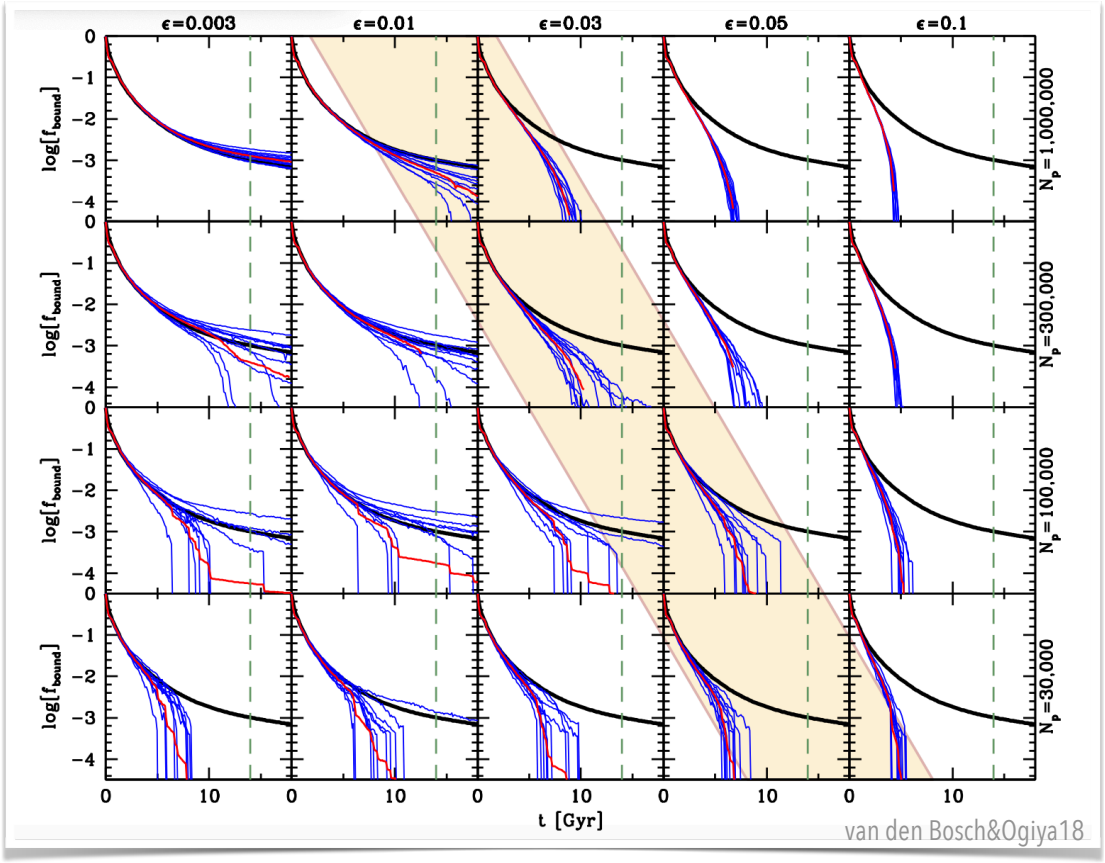
➠ **Not favoured by galaxy formation theory, as is below the H-cooling limit** (Vpeak~19 km/s; Okamoto&Frenk09)

LCDM at infinite resolution: the NFW cusp is indestructible

- Recent works using idealized sims have studied tidal stripping in the limit of very high (infinite) resolution.
- Assuming LCDM (i.e. subhalo starts with an NFW density profile), subhalos lose mass, but never fully disrupt.

Tidal stripping evolution follows a "tidal track"
(Errani&Navarro21, Peñarrubia+08,10)





van den Bosch&Ogiya18

➡ cosmological simulations suffer from artificial disruption of subhalos.

See also Han+16, He+23, Jiang+21, Mansfield+23

This project

- Aim: to correct for the artificially-disrupted subhalos and provide what would be the **"true" abundance and radial distribution of satellite galaxies around a MW-mass galaxy in LCDM**

This project: The *true* radial distribution of MW satellites

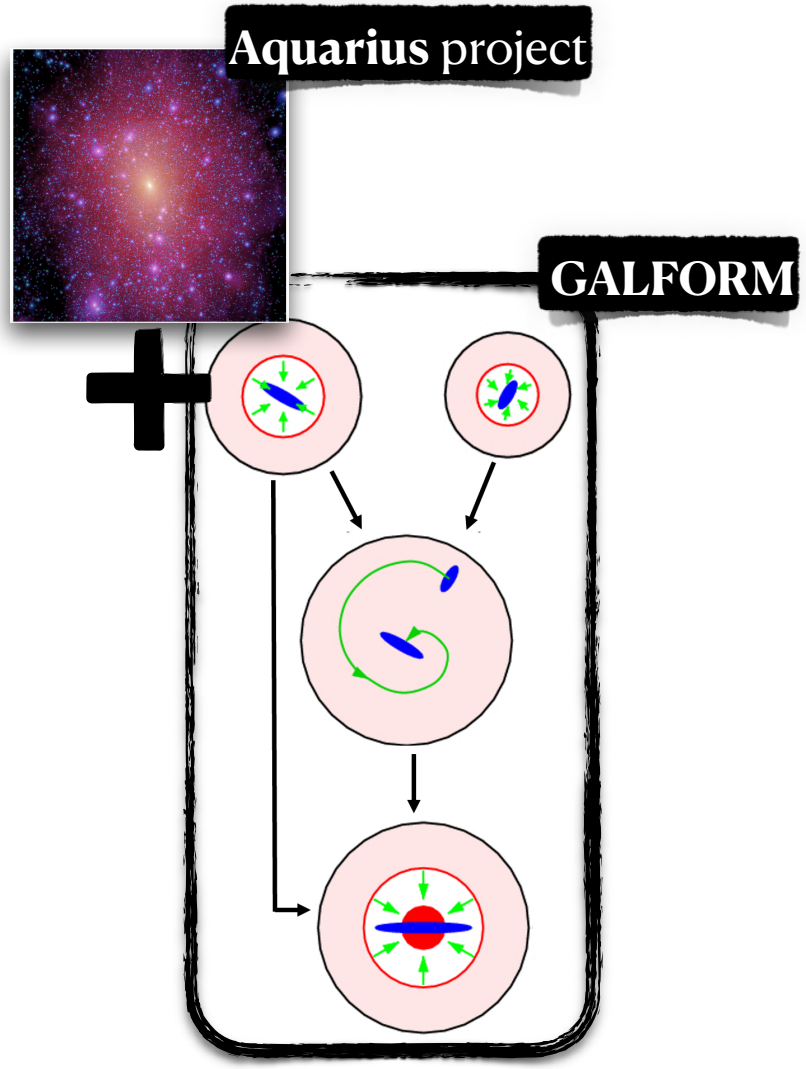
Still highest resolution MW simulation ever run!

Name	m_p ($M_\odot$)	ϵ (pc)
Aq-A-1	1.712×10^3	20.5
Aq-A-2	1.370×10^4	65.8
Aq-A-3	4.911×10^4	120.5
Aq-A-4	3.929×10^5	342.5
Aq-A-5	3.143×10^6	684.9

Aquarius project (Springel+2008)

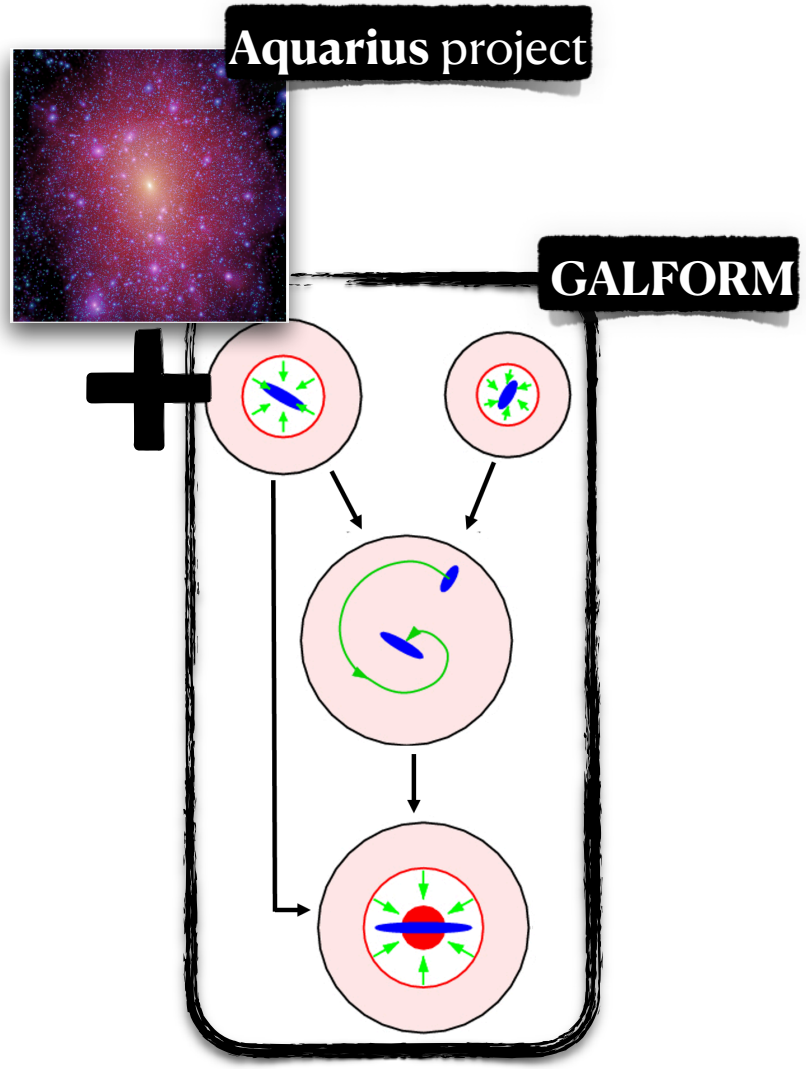
- Aq-A : DM-only MW-mass halo (~10^{12} $M_\odot$)
- Run at 5 resolution levels
- Bound subhalos defined by SUBFIND halo finder.
- Merger trees

This project: The *true* radial distribution of MW satellites



Durham Semianalytical model for galaxy formation
White&Frenk91, Kauffmann+93, Cole+2000, Lacey+2016

This project: The *true* radial distribution of MW satellites



$\dot{M}_\star = (1-R)\psi$

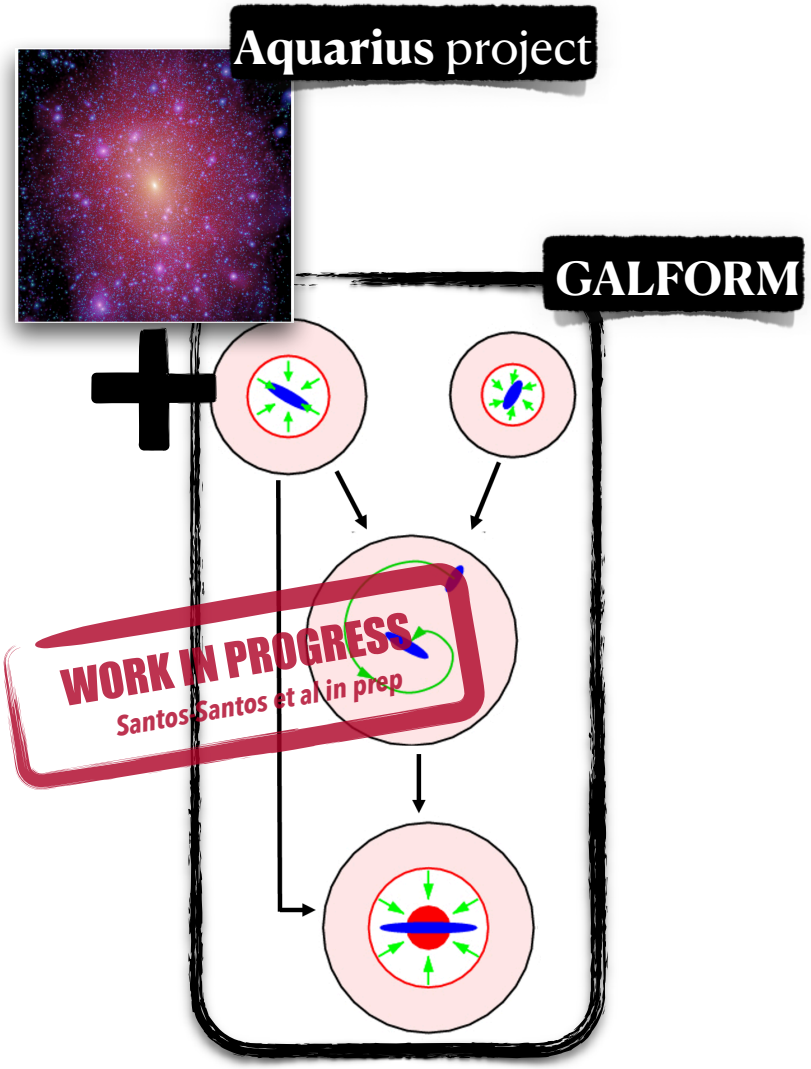
R = recycled fraction

- Infalling gas shock-heated to T_{vir}
- Gas cools radiatively onto central galaxy and forms disk, conserving J?
  → $r_{disk} \sim \lambda_h r_{cool}$
- Stars form in disk
- And give rise to feedback effects
- Satellite sinks by dynamical friction and merges onto central galaxy
- Mergers → starbursts, BH growth
- Major mergers & disk instabilities: stellar disks → spheroids
- New disk may form by gas accretion

AGN feedback $\dot{M}_{BH} = f_{BH}\psi_{burst} + \frac{L_{cool}}{c^2 \varepsilon_{SMBH}}$

Durham Semianalytical model for galaxy formation
White&Frenk91, Kauffmann+93, Cole+2000, Lacey+2016

This project: The *true* radial distribution of MW satellites



- Semianalytical model: defines which subhalos form a galaxy.
- V_{cut}=30 km/s, z_{cut}=6 (for gas cooling after reionization).
- Galform reads Aquarius merger trees and particle data, and is able to **track the evolution of a subhalo after it disrupts (follows most bound particle).**
- "**Type1s**" (satellites in surviving subhalos)
- "**Type2s/orphans**" (satellites in sub-resolution subhalos).

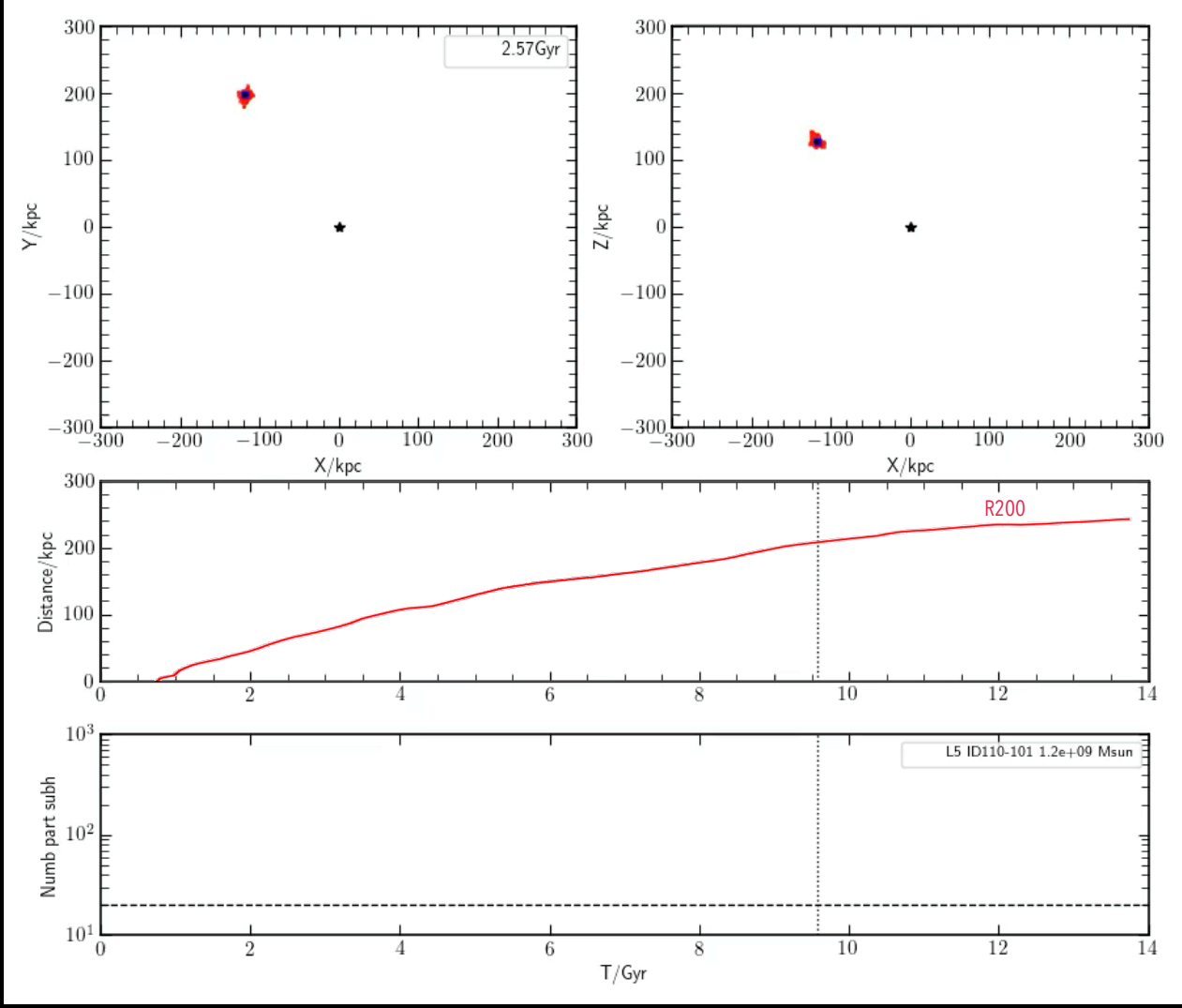
“Type2/Orphans”: sub-resolution subhalos

Galform includes criteria for merging of orphans following Chandrasekhar timescale (see Simha&Cole17)

Starts at time when M=M_{peak}

Subfind data

“Orphan” phase

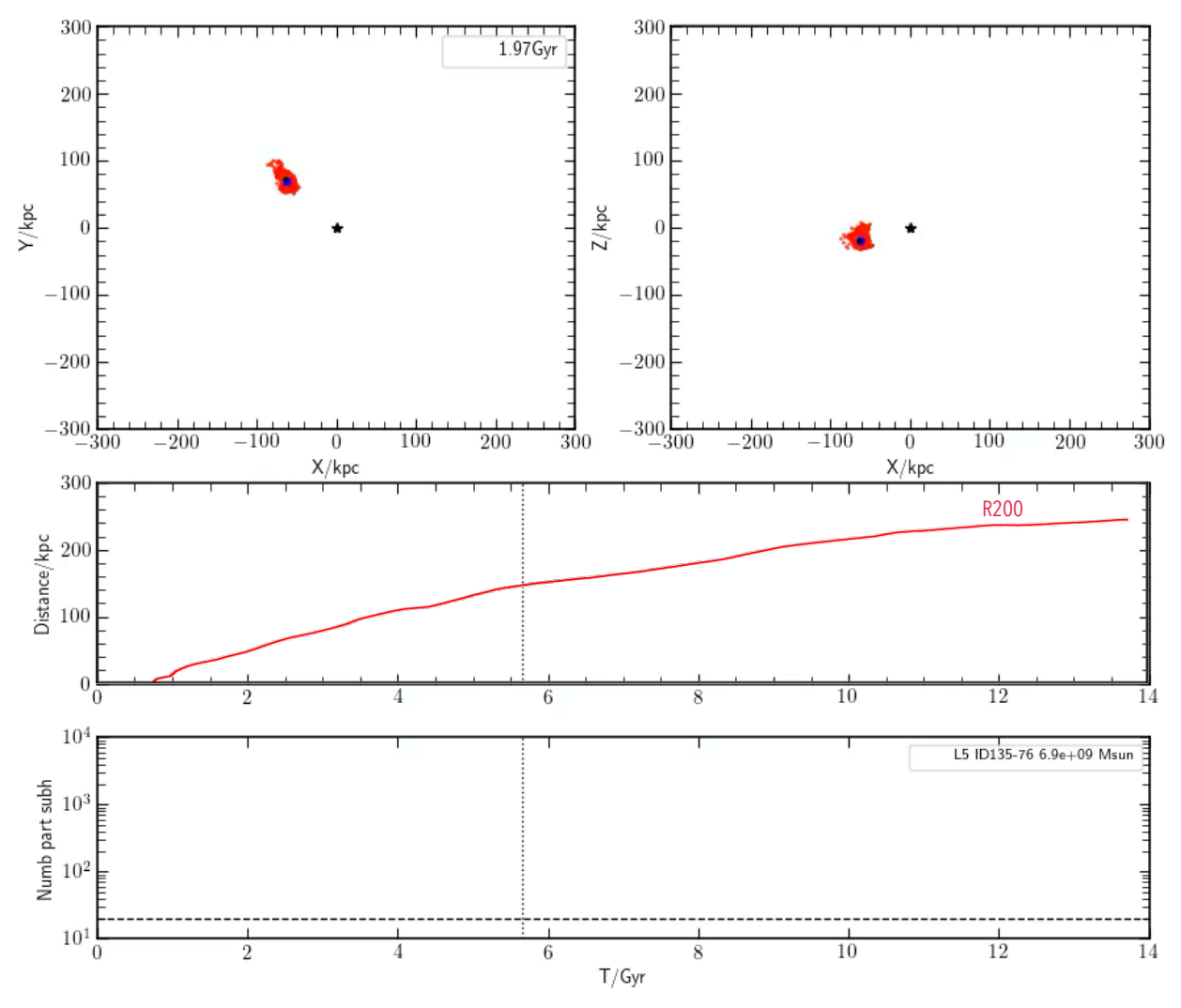


20 particles

“Type2/Orphans”: sub-resolution subhalos

Galform includes criteria for merging of orphans following Chandrasekhar timescale (see Simha&Cole17)

Starts at time when M=M_{peak}
Subfind data
“Orphan” phase

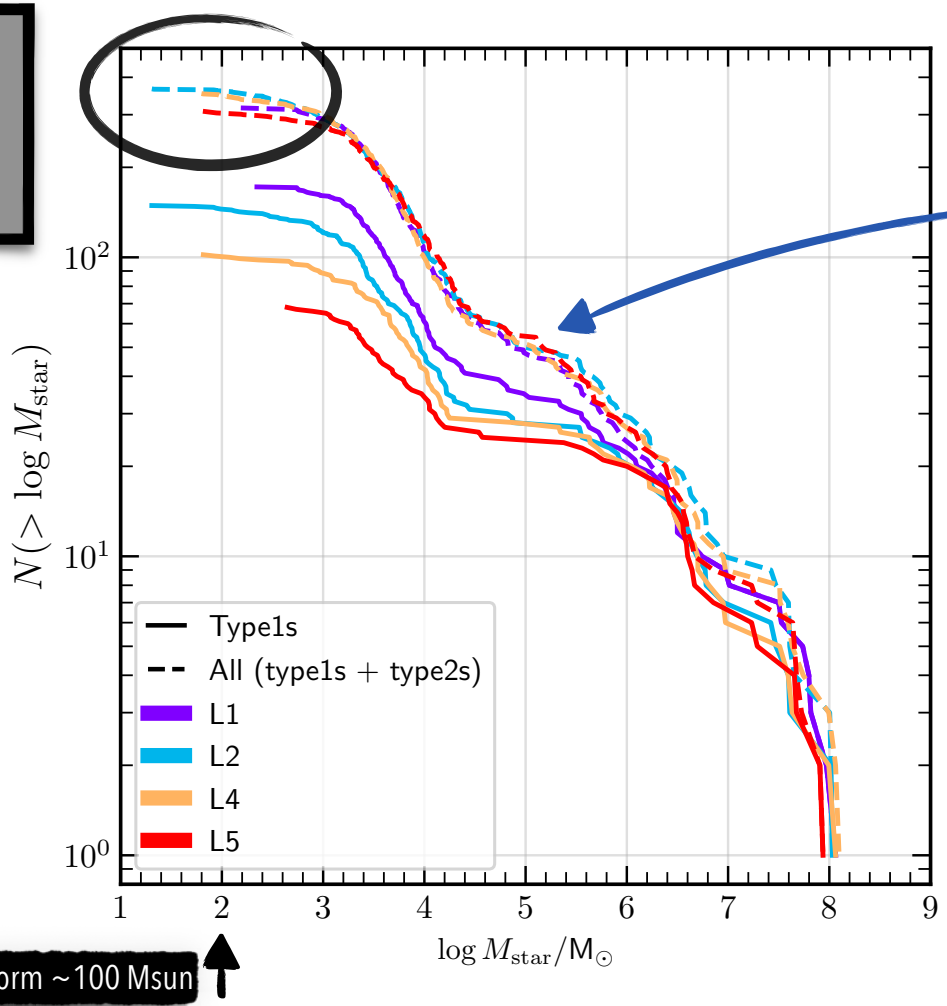


High resolution type2s:
- Very early infall times
- Small pericentres
- Short orbital periods

20 particles

Abundance of MW satellites: luminosity function

Total number of galaxies in 300 kpc converges across resolution levels
$N_T \sim 300$
In L1, 1/2 are orphans



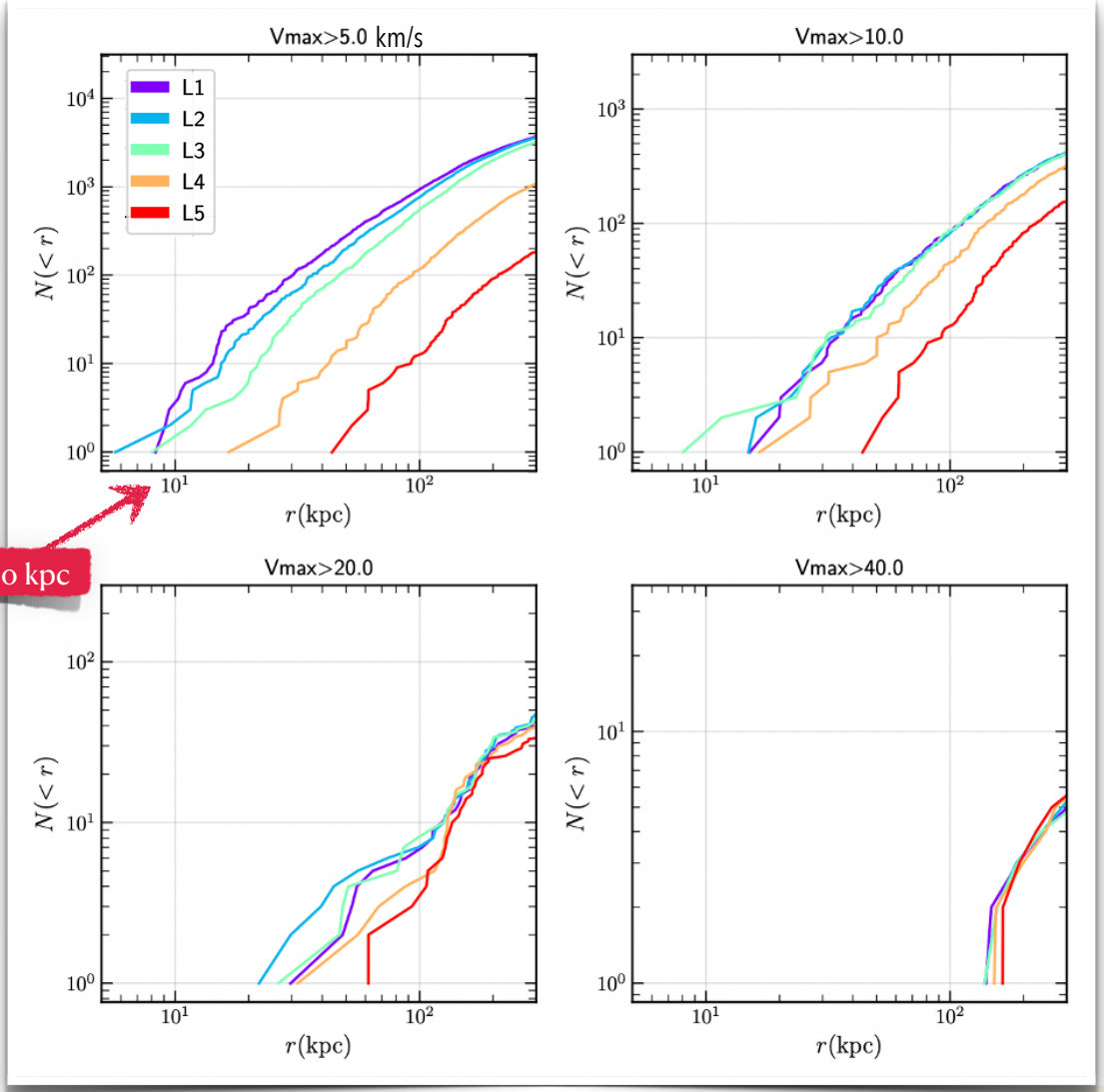
Plateau at Mstar ~10^5 Msun, as a result of reionization (see Bose+18)

Minimum initial M_{star} from Galform ~100 Msun

Radial distribution

Radial distribution: DMO subhalos within 300 kpc of the MW

Aq-A DMO (z=0)



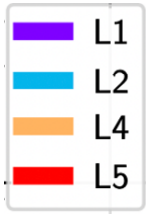
No subhalos below r~10 kpc

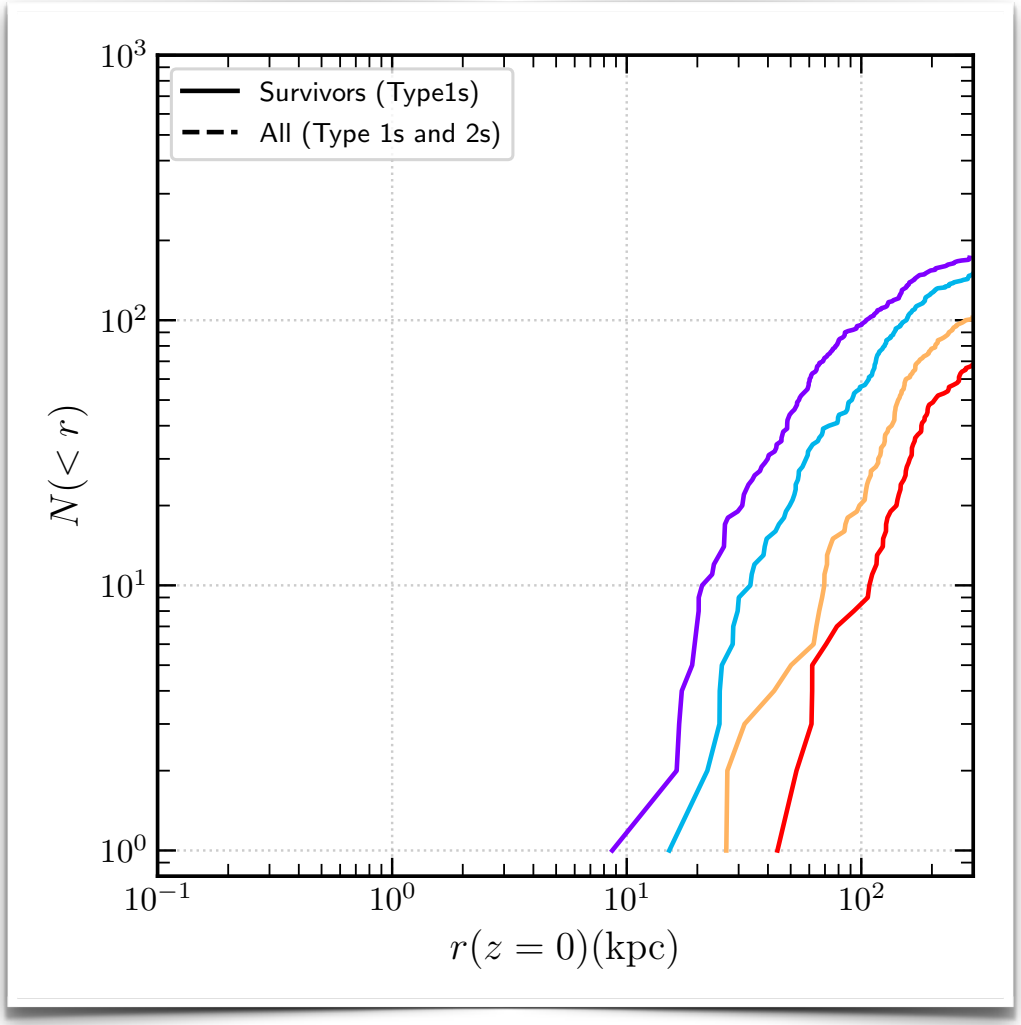
- At higher resolution, more subhalos near the center
- Levels L1,2,3 are converged for Vmax>10 km/s
- (!) But missing disrupted subhalos

Radial distribution: galaxies within 300 kpc of the MW

Aq-A DMO (z=0)
+ GALFORM

- Inclusion of orphans
- Non-linear mapping between subhalos and galaxies

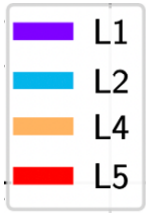


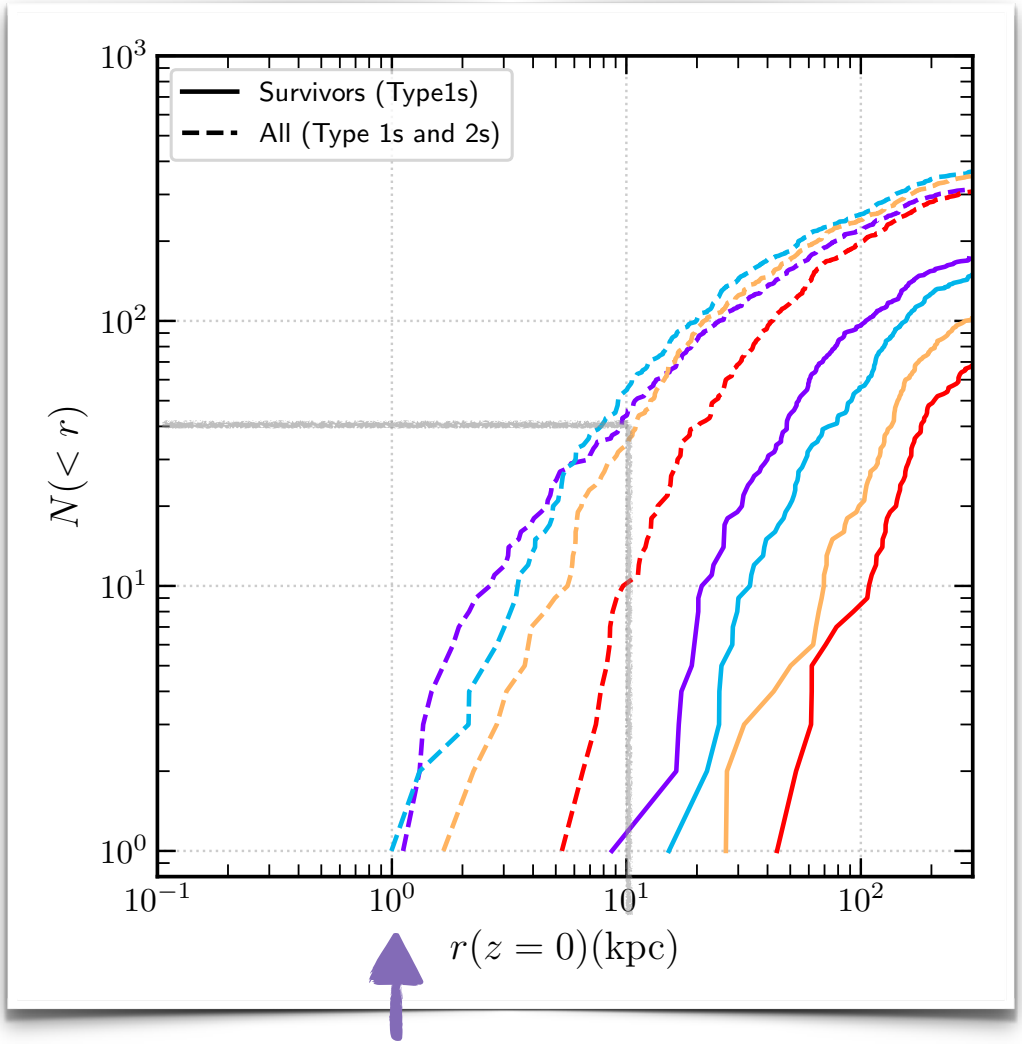


Radial distribution: galaxies within 300 kpc of the MW

Aq-A DMO (z=0)
+ GALFORM

- Inclusion of orphans
- Non-linear mapping between subhalos and galaxies





✦**Orphans are the main contribution to galaxies in the inner regions**

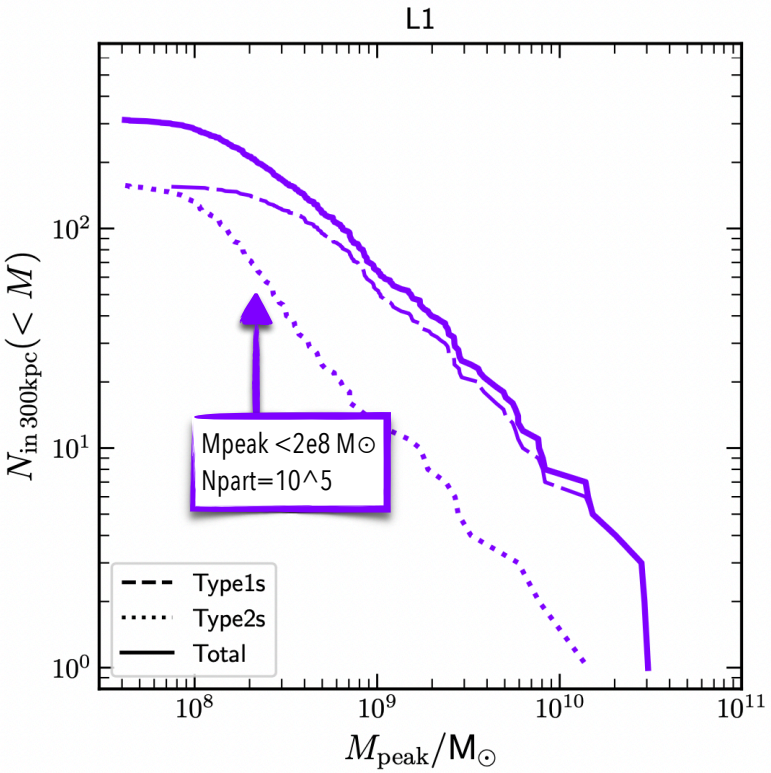
✦~>40 galaxies below r<10 kpc

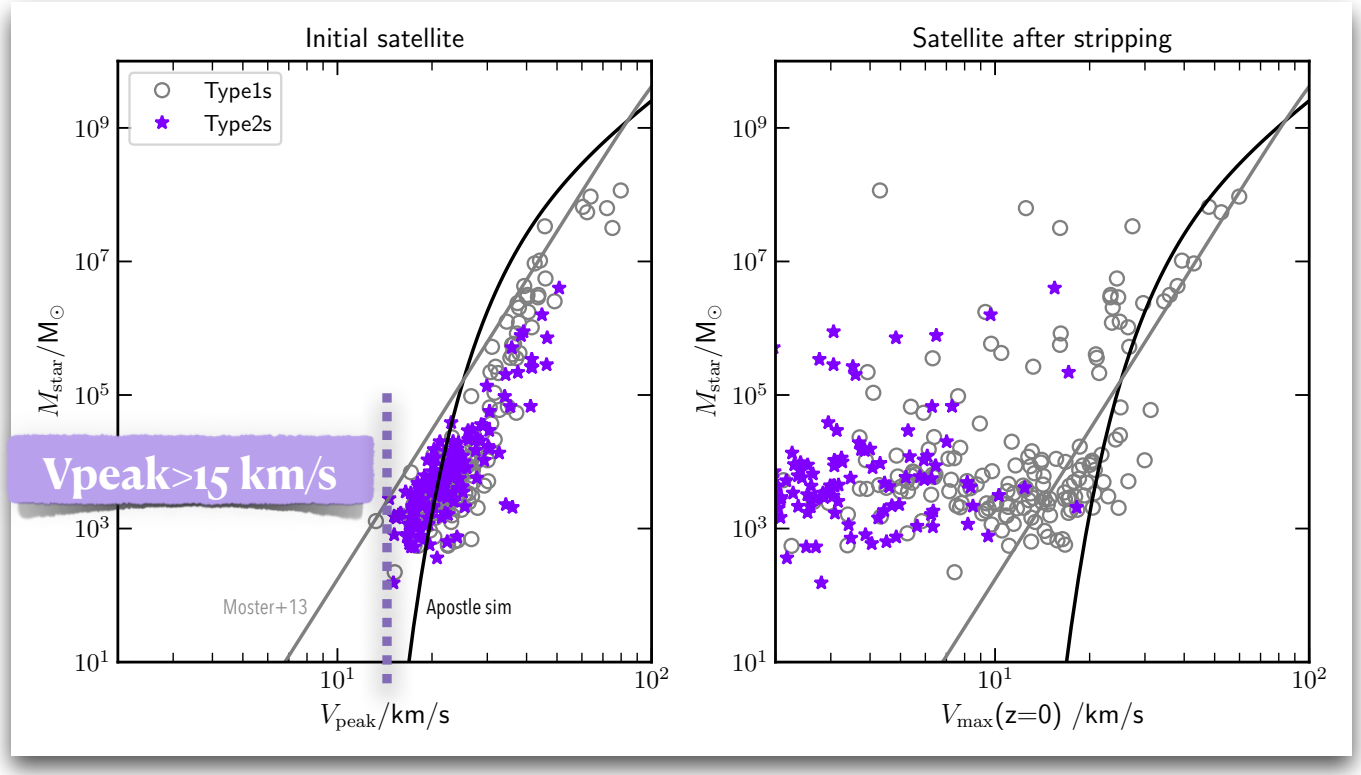
✦Type2s reach r>1 pc.

✦Non-negligible contribution of orphans at all radii

Characteristics of L1 "orphans"

Maximum subhalo mass and circular velocity

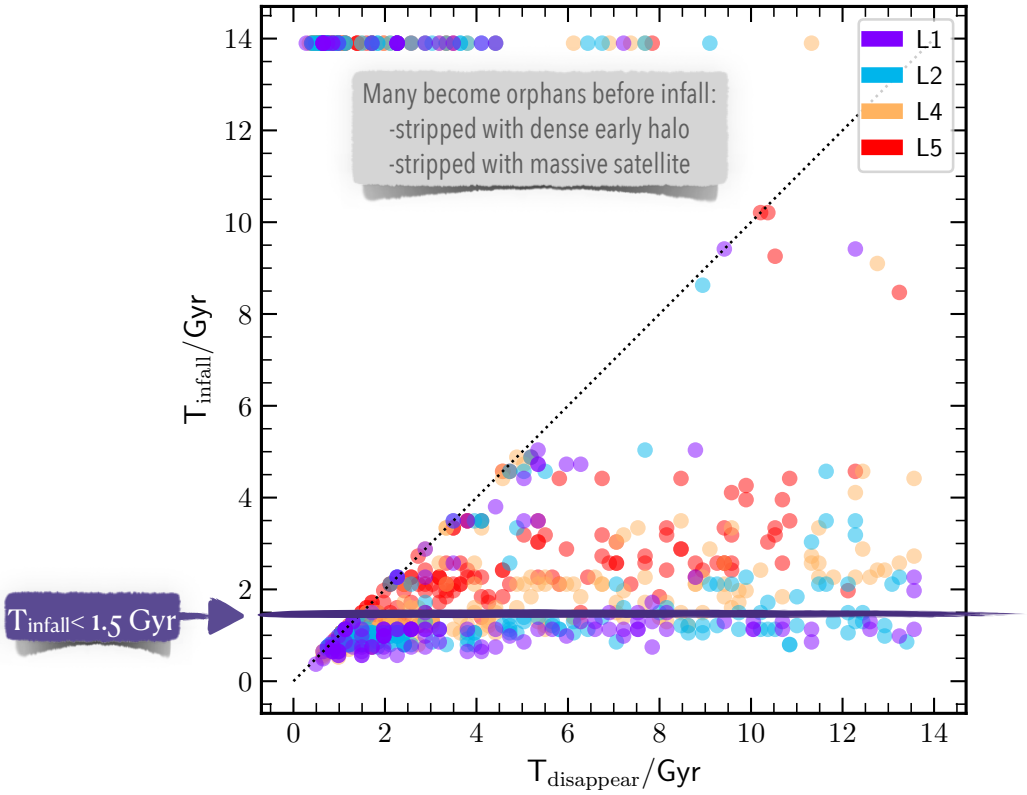




Correction needed in L1 (m_{part}~1e3 M⊙): half of satellite galaxies are orphans

No need to populate very low Vpeak halos to reproduce the MW radial distribution data

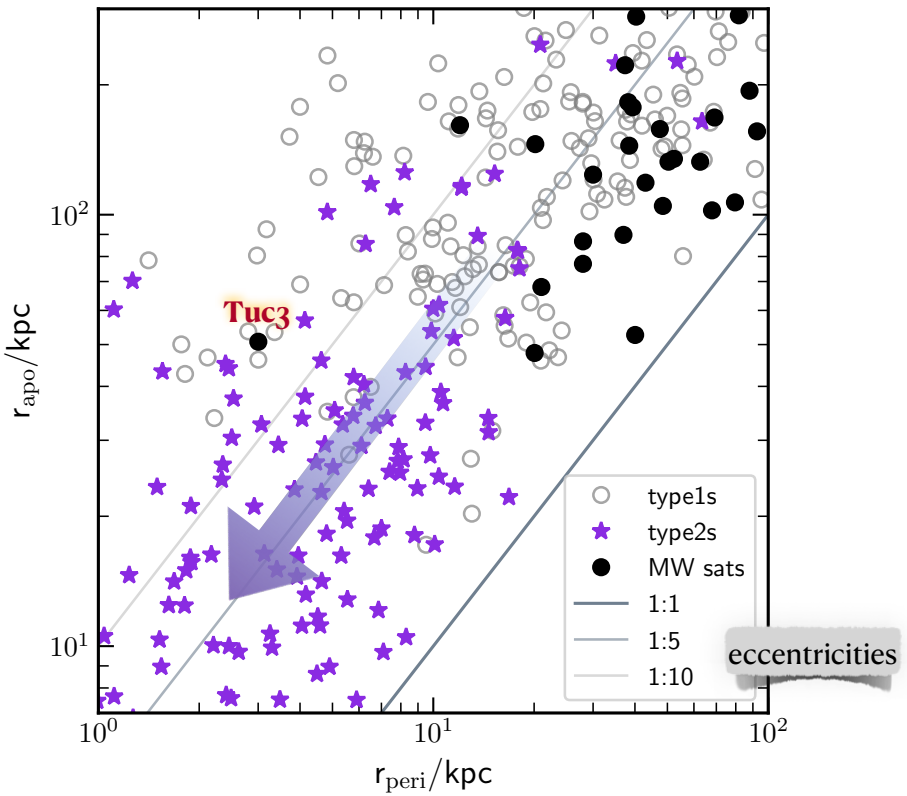
Characteristics of L1 "orphans"



- As resolution increases, orphans are restricted to objects having **earlier infall times**: At HR, objects are more resilient to stripping, and only those that suffer stripping for longer end up artificially disrupted.

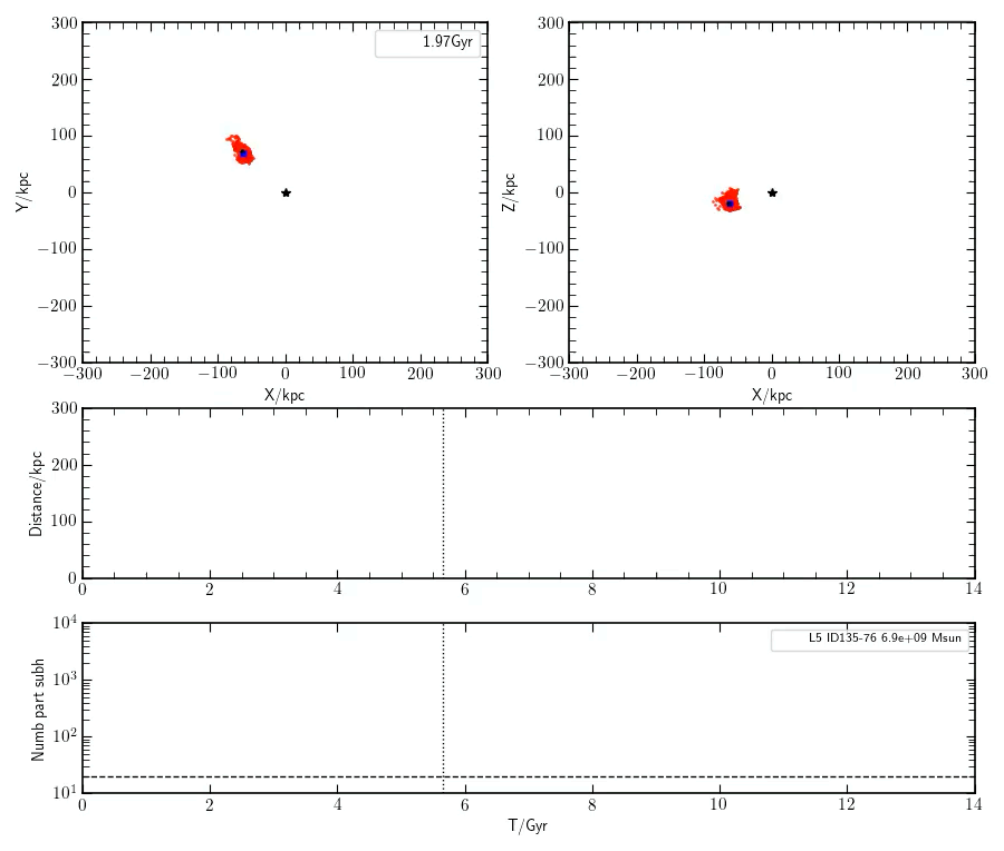
z=0 orbital properties

Approximated peri & apo by integrating orbit in z=0 host potential, starting from most-bound particle pos and vel at z=0



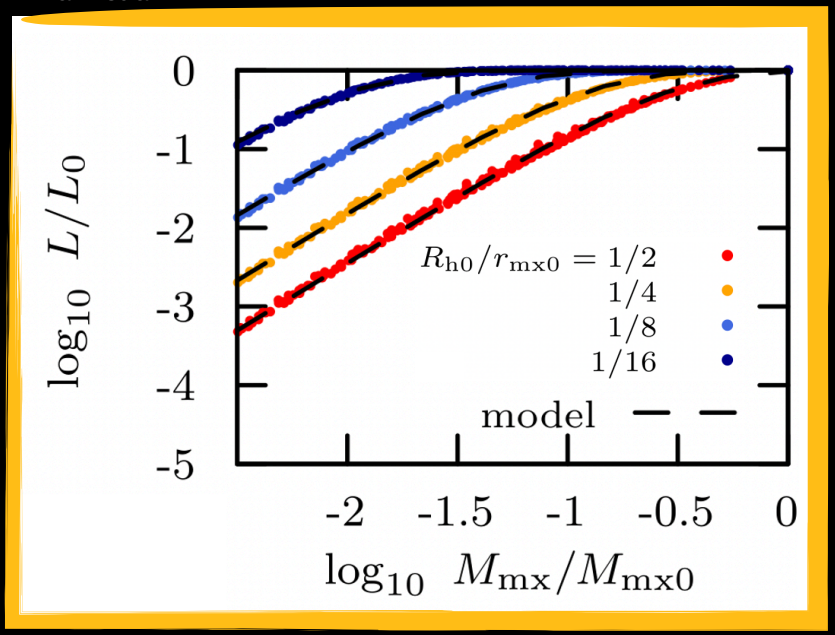
- Predicted nearby MW satellites have very small peri and apocenters.
- Eccentricities similar to known MW sats

Galaxy (stellar component) disruption due to tidal stripping



✦ Although there is always a bound DM remnant, we should consider the stellar mass loss of satellites due to tidal stripping

Errani et al 22

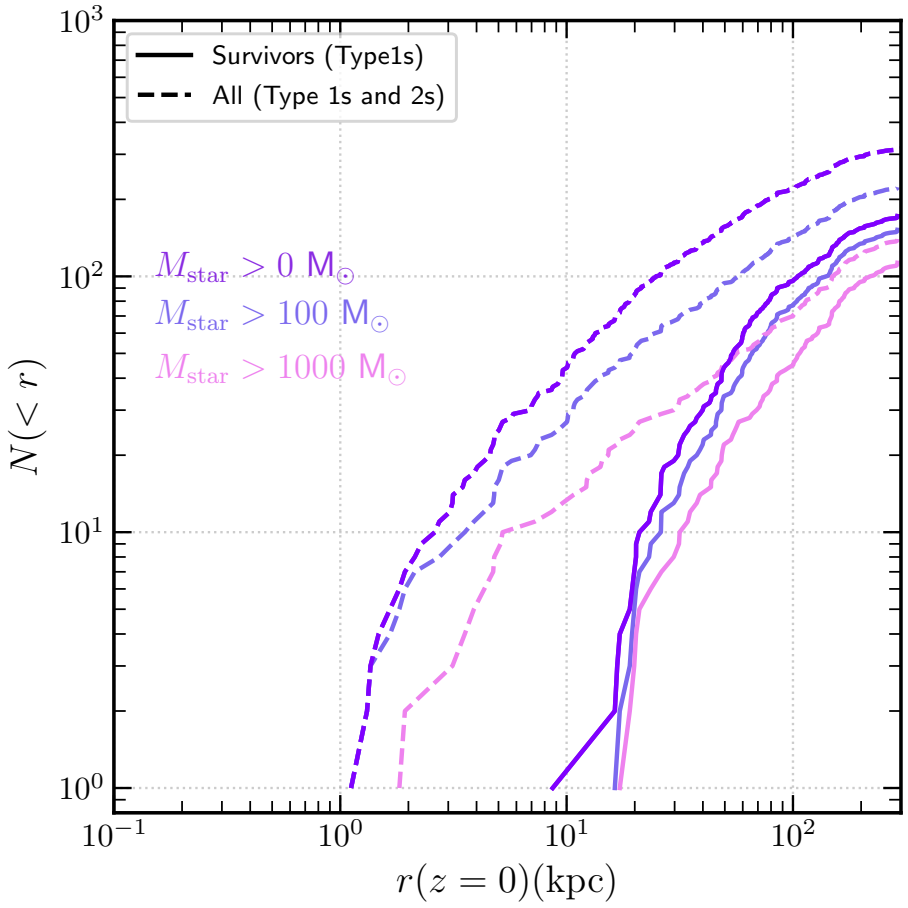


- What happens with the stars during tidal stripping is heavily dependent on the particular energy distribution within the halo.
- Assuming an exponential distribution, there is a relation between bound mass-loss and luminosity loss.
- For the bound mass loss we follow the empirical tidal-track framework from Errani&Navarro21

Predicted "observable" radial distribution of MW satellites

We calculate bound mass loss, and luminosity loss, using the Errani&Navarro21 framework.

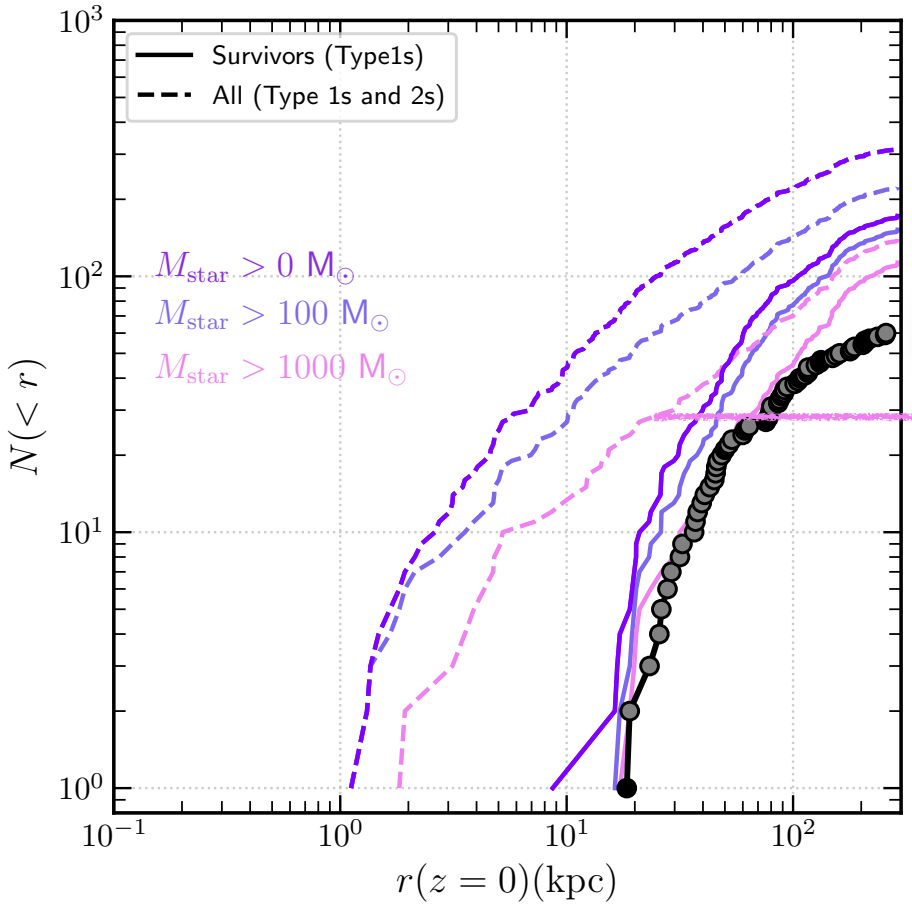
To obtain **final stellar masses after stripping**, we assume M/L ratio =1.6 (dSph, Woo+08)



Predicted "observable" radial distribution of MW satellites

We calculate bound mass loss, and luminosity loss, using the Errani&Navarro21 framework.

To obtain **final stellar masses after stripping**, we assume M/L ratio =1.6 (dSph, Woo+08)



MW

>30 sats with Mstar>1000 Msun within 20 kpc

Caveats:
- GALFORM model (Vcut, zcut)
- Extra stripping due to disk?

Summary

- We need to correct our cosmological simulations for artificial disruption if we want to be able to study the ultrafaint population of MW satellites
- Semi-analytical models like GALFORM represent the best way forward in the study of very small galaxies, given the current computational (hydro) possibilities
- Still much work/understanding needed to reach a proper "model for orphan treatment".
- Reproducing the MW's satellite radial distribution is not a problem for LCDM and galaxy formation models based on H-cooling.
- We predict the discovery of many very faint, nearby (<20kpc) MW satellites

Thank you 谢谢

LCDM at small scales

What is Dark Matter?