Stellar Halos across the Cosmos

controlled and N-body experiments

Nicola C. Amorisco

Inst. for Theory & Computation

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CONTROLLED AND N-BODY EXPERIMENTS

0. HOW TO BUILD A STELLAR HALO WITHOUT RUNNING A COSMOLOGICAL SIMULATION

1. THE DYNAMICS OF MINOR MERGERS: ORBITAL RADIALIZATION

2. L* GALAXIES: STELLAR HALO & ASSEMBLY HISTORY STOCHASTICITY AND TRENDS

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ACCRETED HALO: CONTROLLED AND N-BODY EXP.

or: how to build a stellar halo without running a hydrodynamical cosmological simulation?

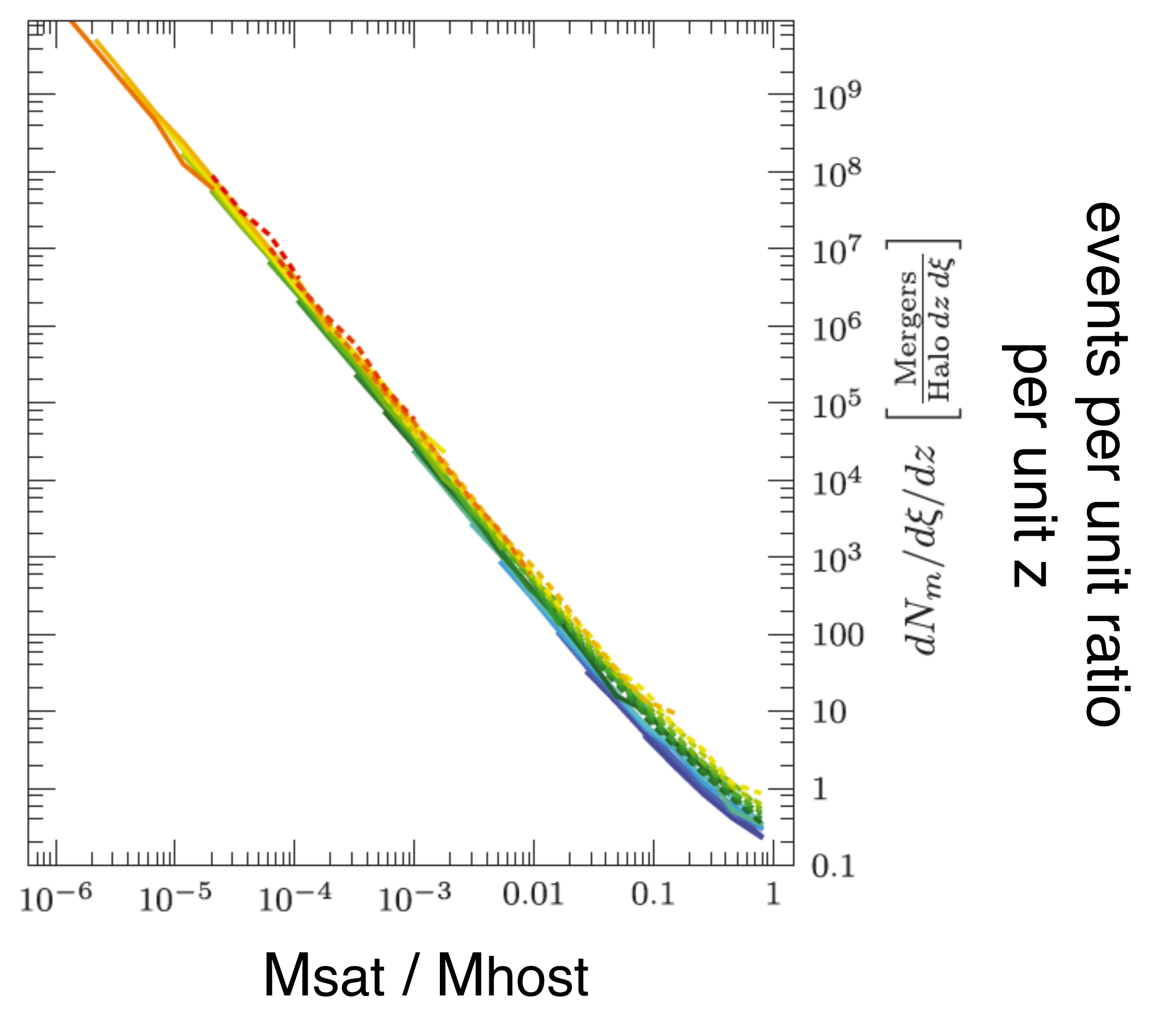
halo accretion history + properties of each accretion event at infall + dynamics of each accretion event after infall → FULL ACCRETED HALO

halo mass growth

accretion events

probability distributions from cosmological simulations

Monte-Carlo **synthetic merger trees**



e.g. Fakhouri et al. (2010)

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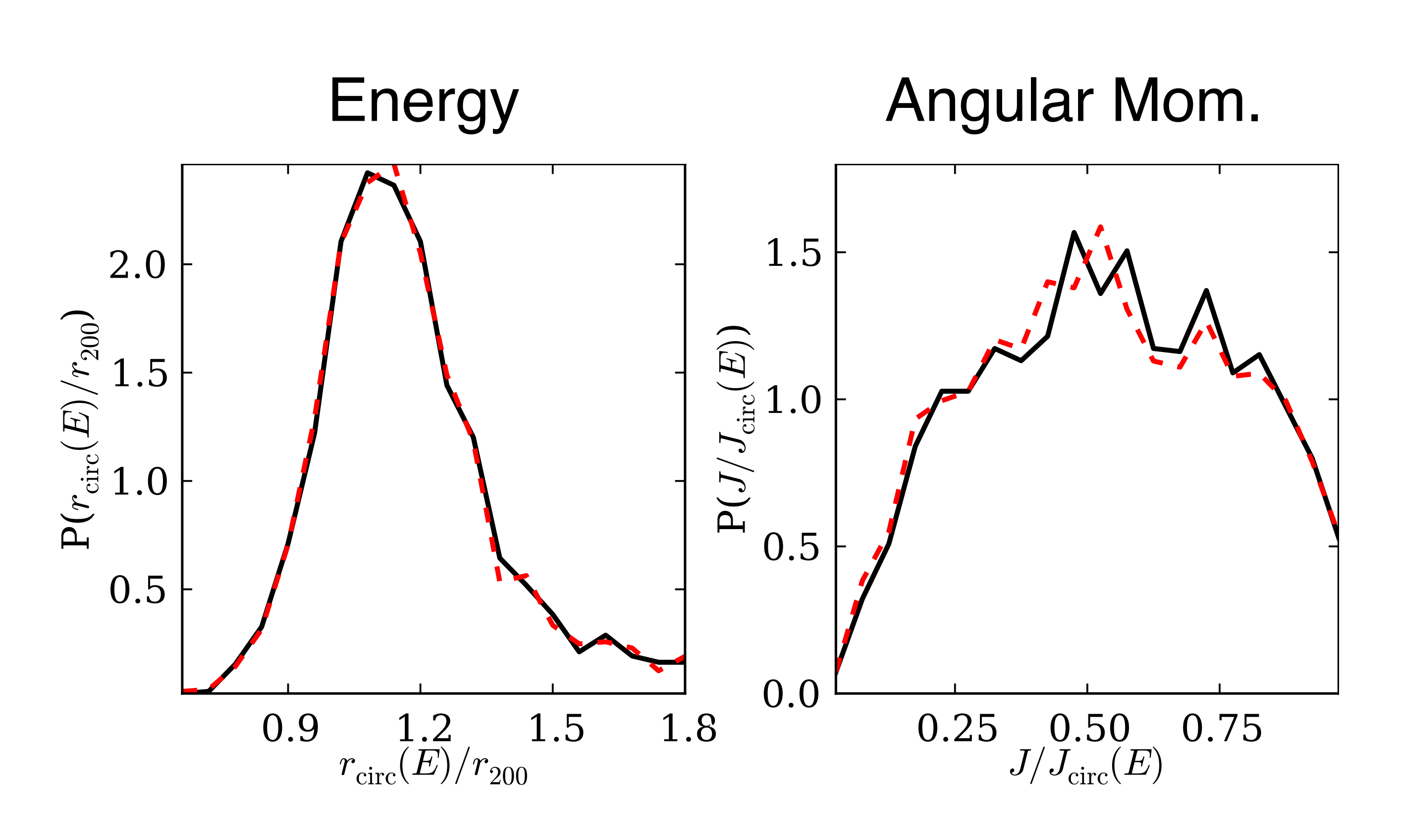
orbital properties at infall

probability distributions from cosmological simulations



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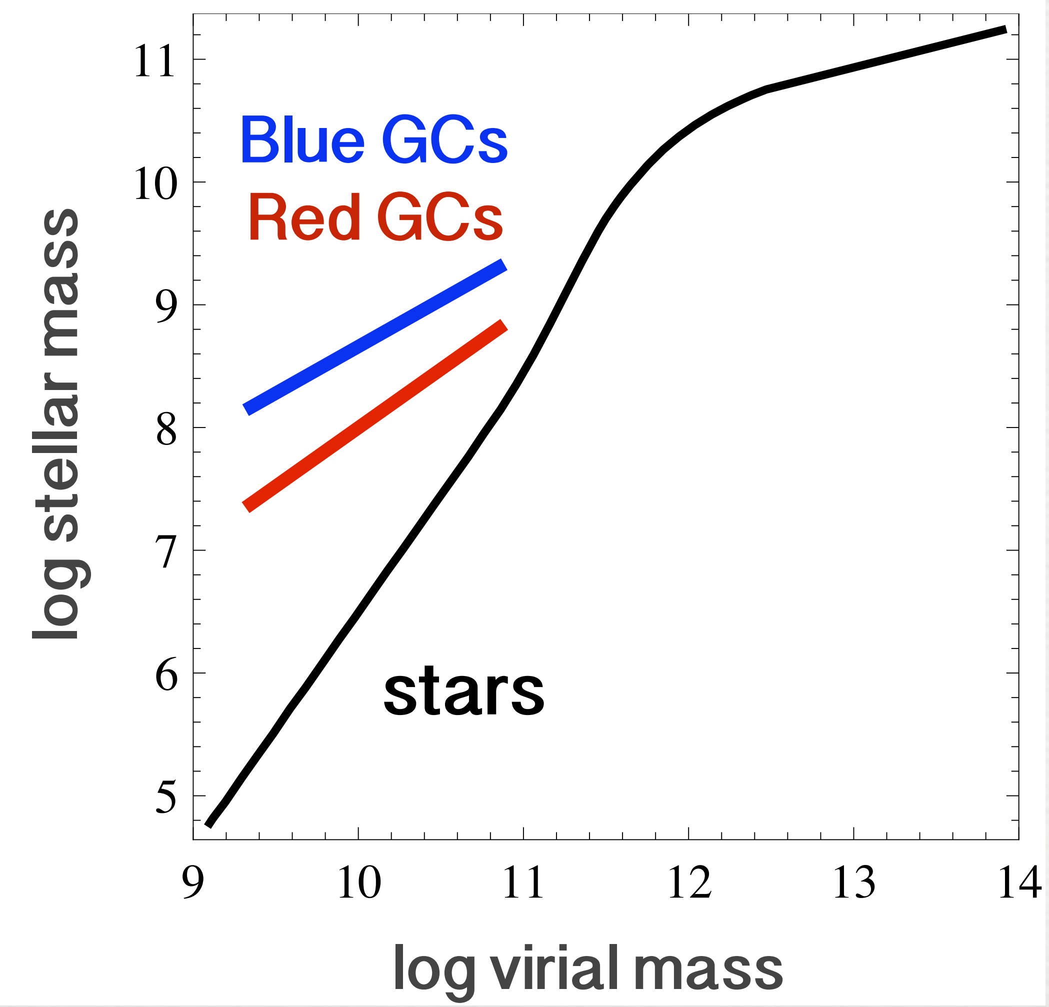
orbital properties at infall

how many stars/tracers at infall

sample from $\mathbf{M^* (M_{halo} , z)}$ / $\mathbf{N_{GC} (M_{halo} , z)}$ with scatters



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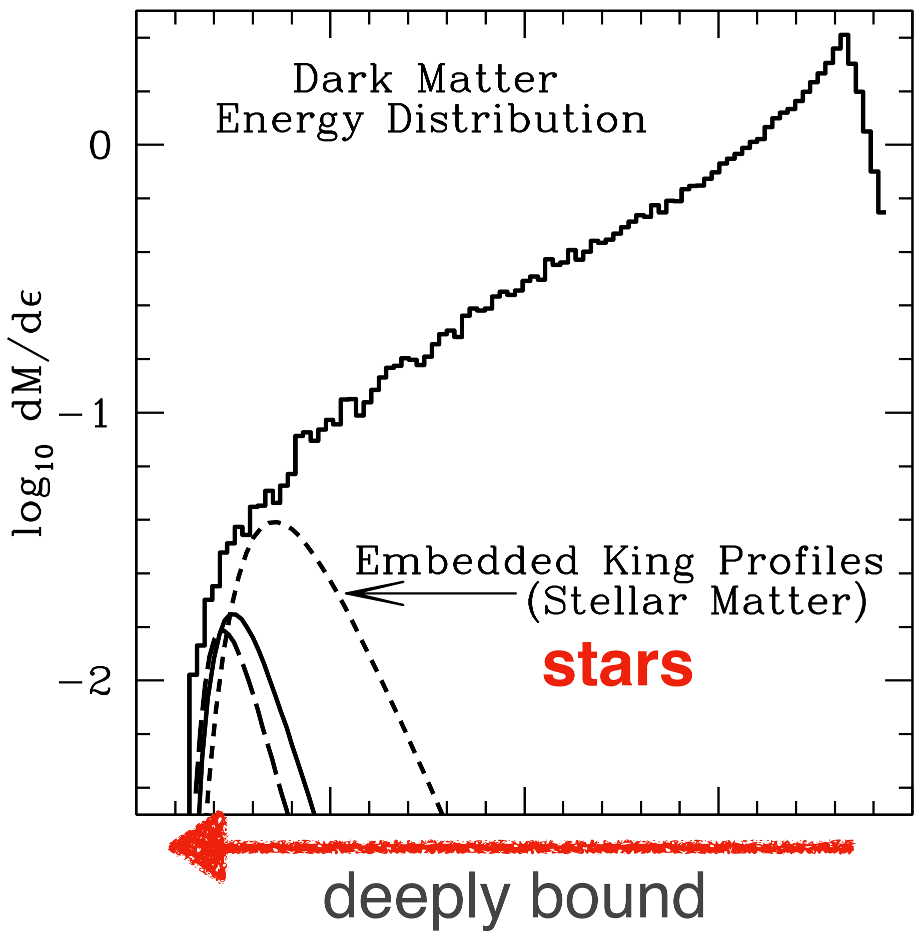
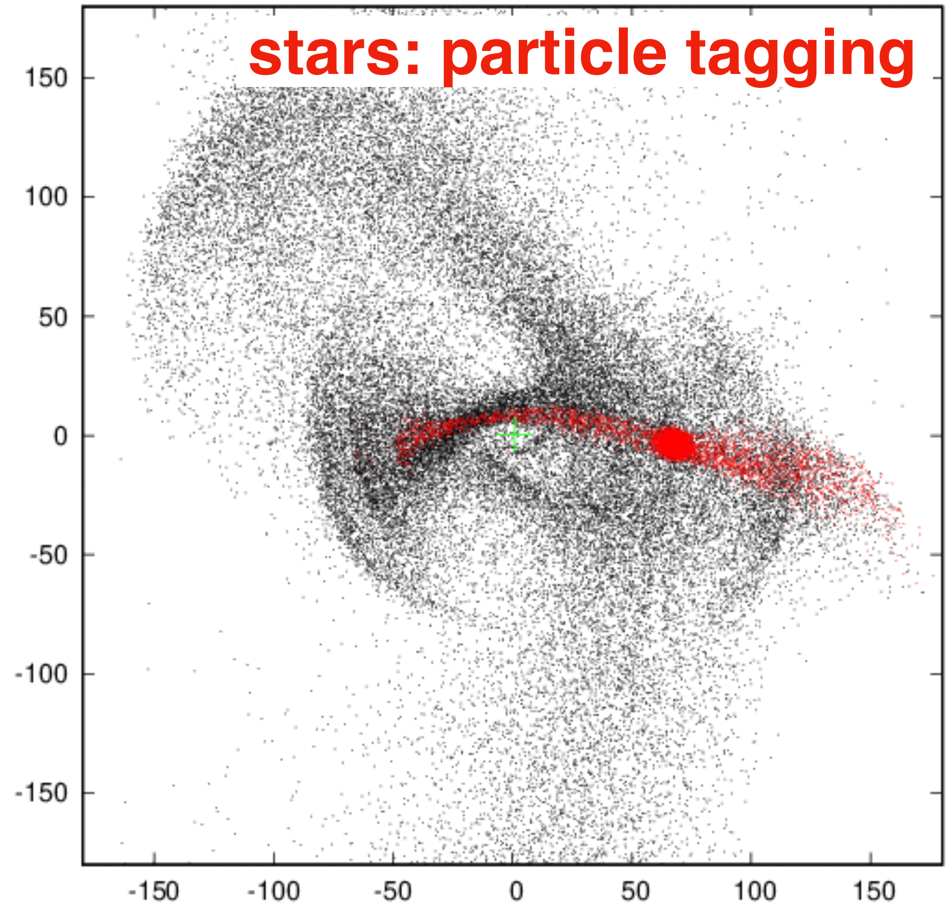
dynamical friction & stripping





choices on host & satellite structure

disk? satellite morphology?

mass - concentration relation

with semi - analytic methods

Bullock, Kravtsov, Weinberg 2001

or controlled N-body simulations

Bullock & Johnston 2005

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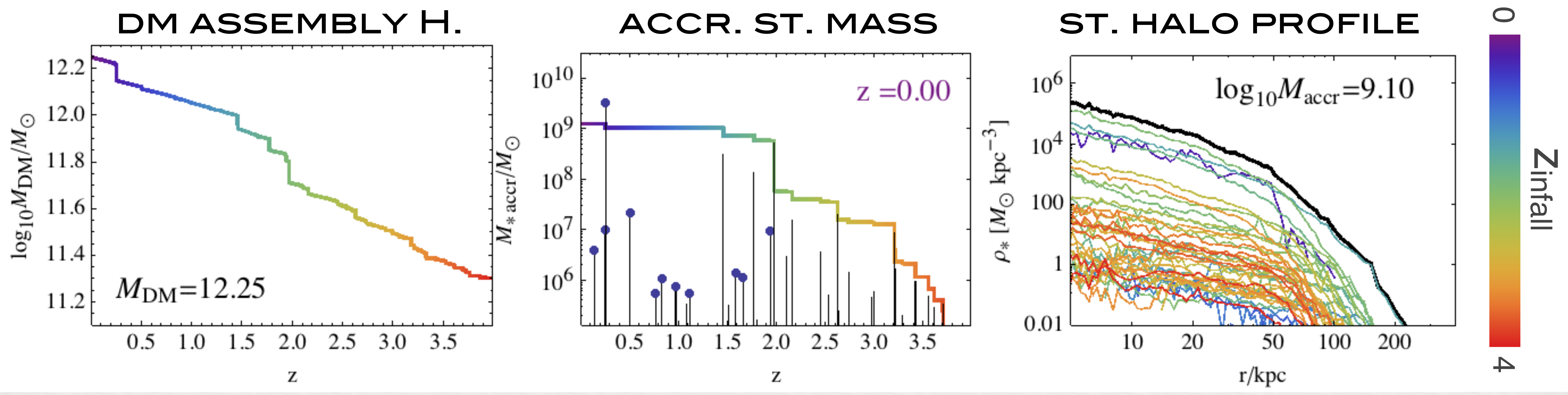

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Limitations:

Bullock & Johnston 2005

Cooper et al. 2010, 2017

Bailin et al. 2014

- no gas or realistic (post-infall) star formation
- accreted halo only

fundamental

- smooth, spherical host DM halo
- particle tagging: no satellite morphology
- no interactions between satellites

depending on specific implementation

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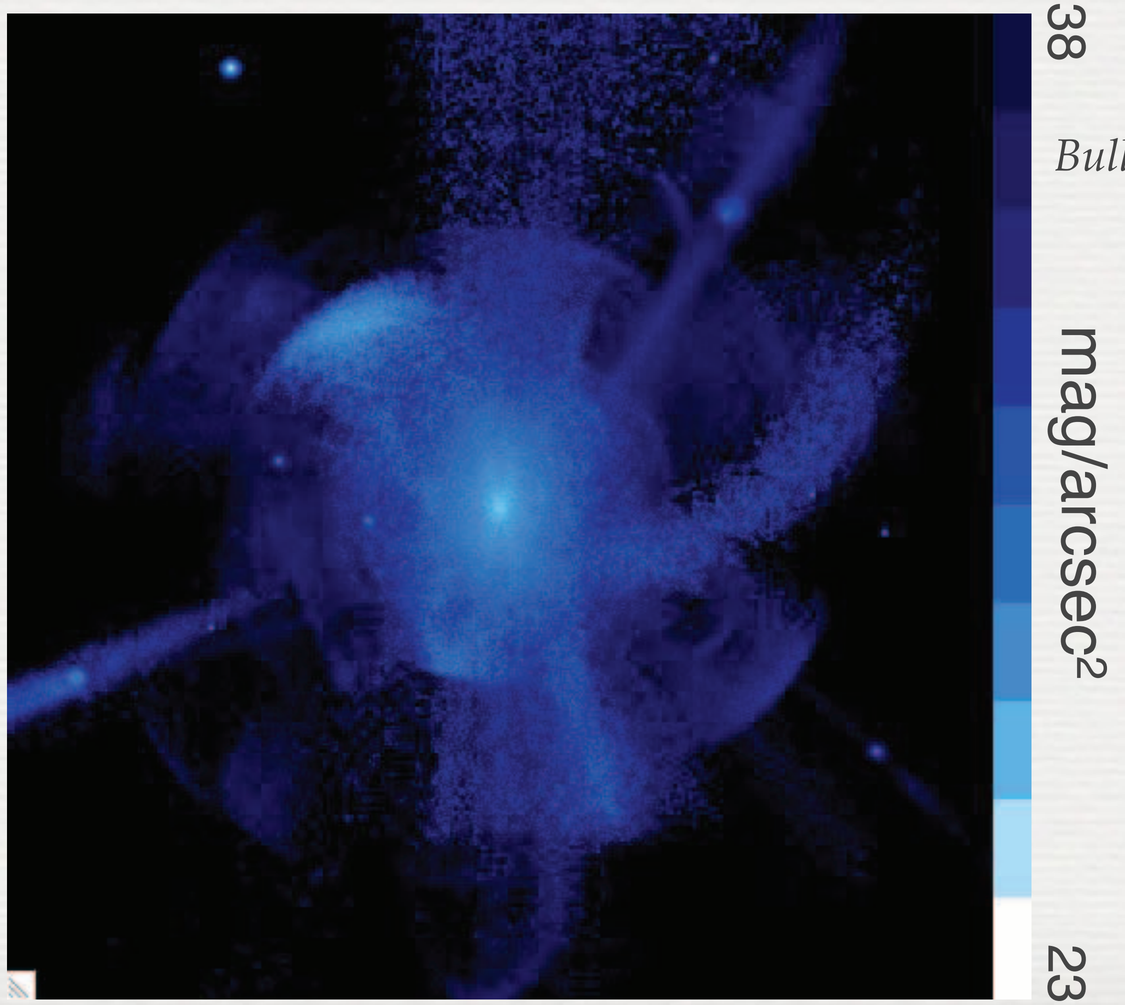
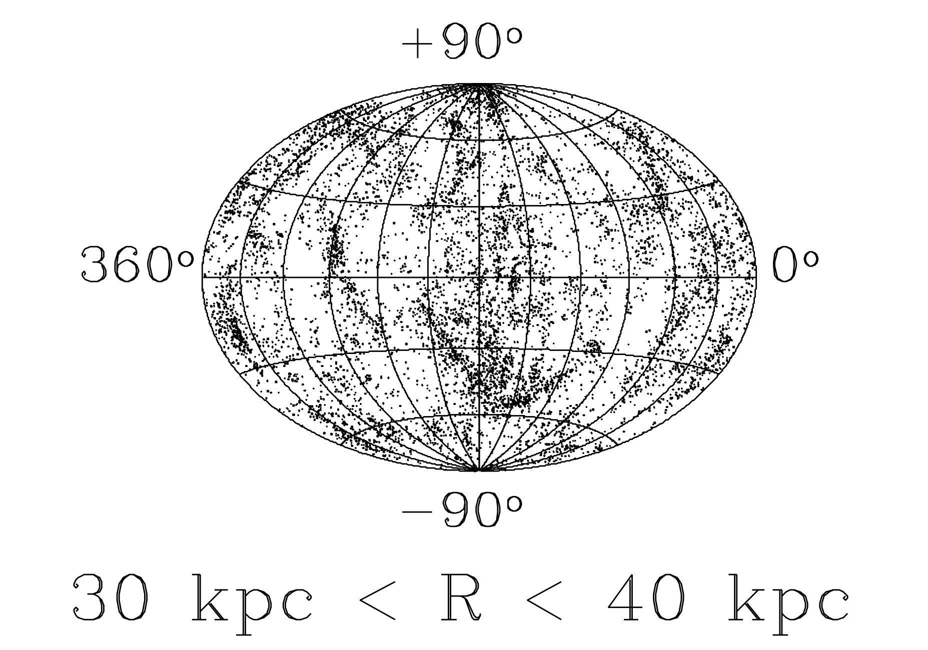
stellar halo in L* galaxies:

- not smooth, substructure



Bullock & Johnston 2005

Bullock, Kravtsov, Weinberg 2001



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stellar halo in L* galaxies:

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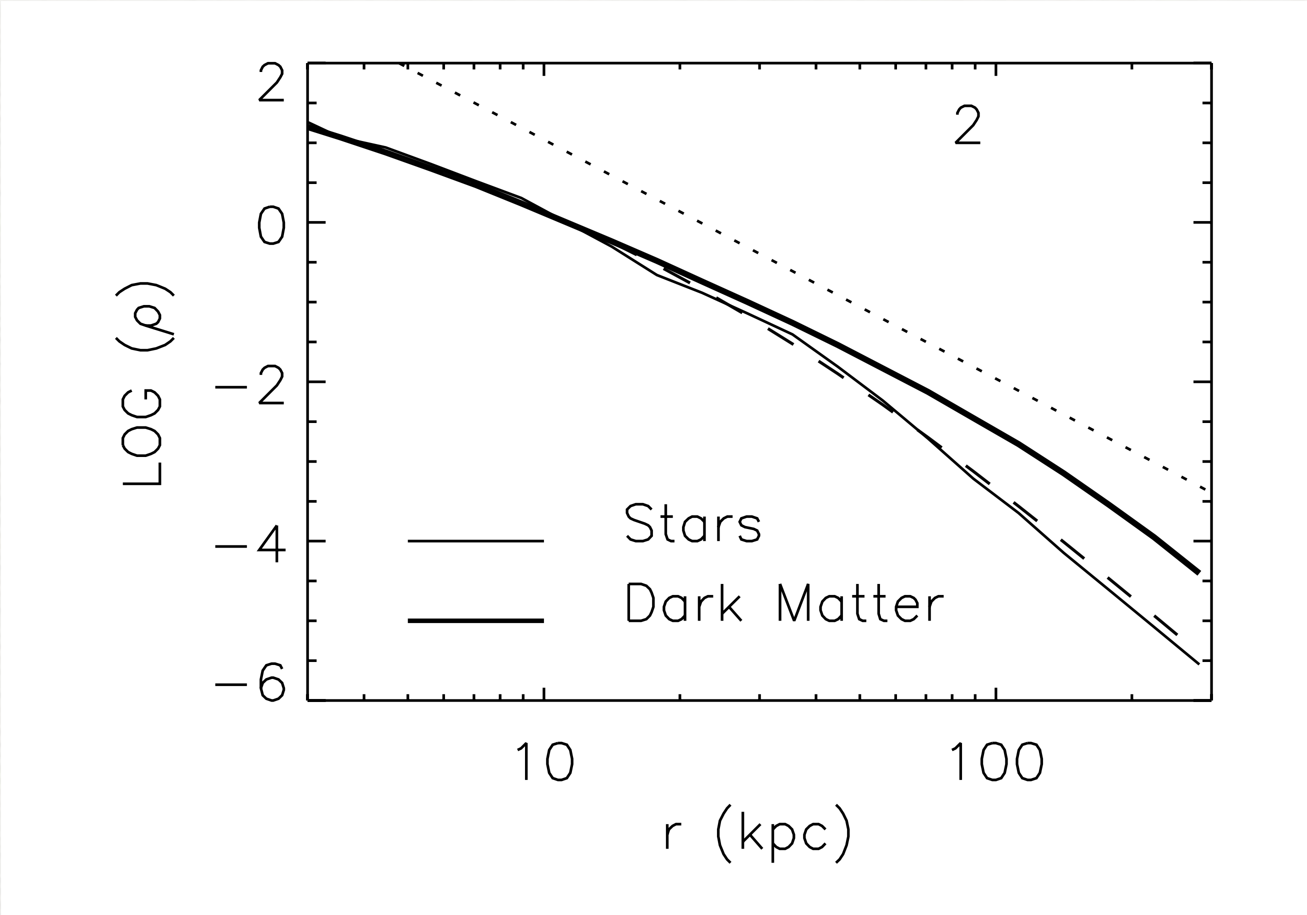

Bullock & Johnston 2005

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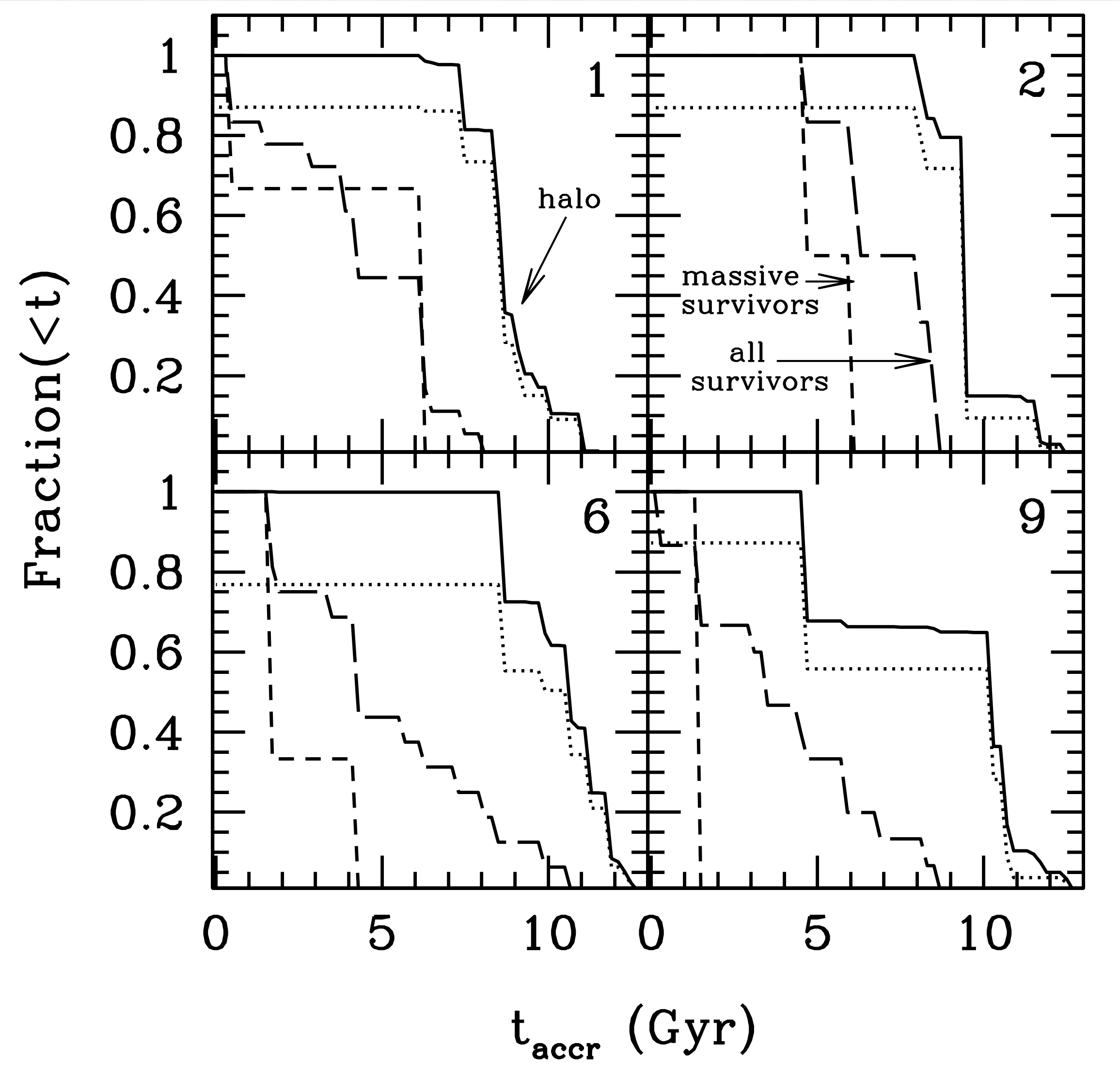
stellar halo in L* galaxies:

- not smooth, substructure
- steeper than DM halo
- only a few major contributions, very stochastic
- different from dSph satellites



Bullock & Johnston 2005

11 assembly histories

ACCRETED HALO: CONTROLLED AND N-BODY EXP.

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stellar halo in L* galaxies:

- not smooth, substructure
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what can controlled & N-body experiments do for you?

minor merger dynamics

from ‘substructure’ in the halo to accretion events

statistics for quantitative inference

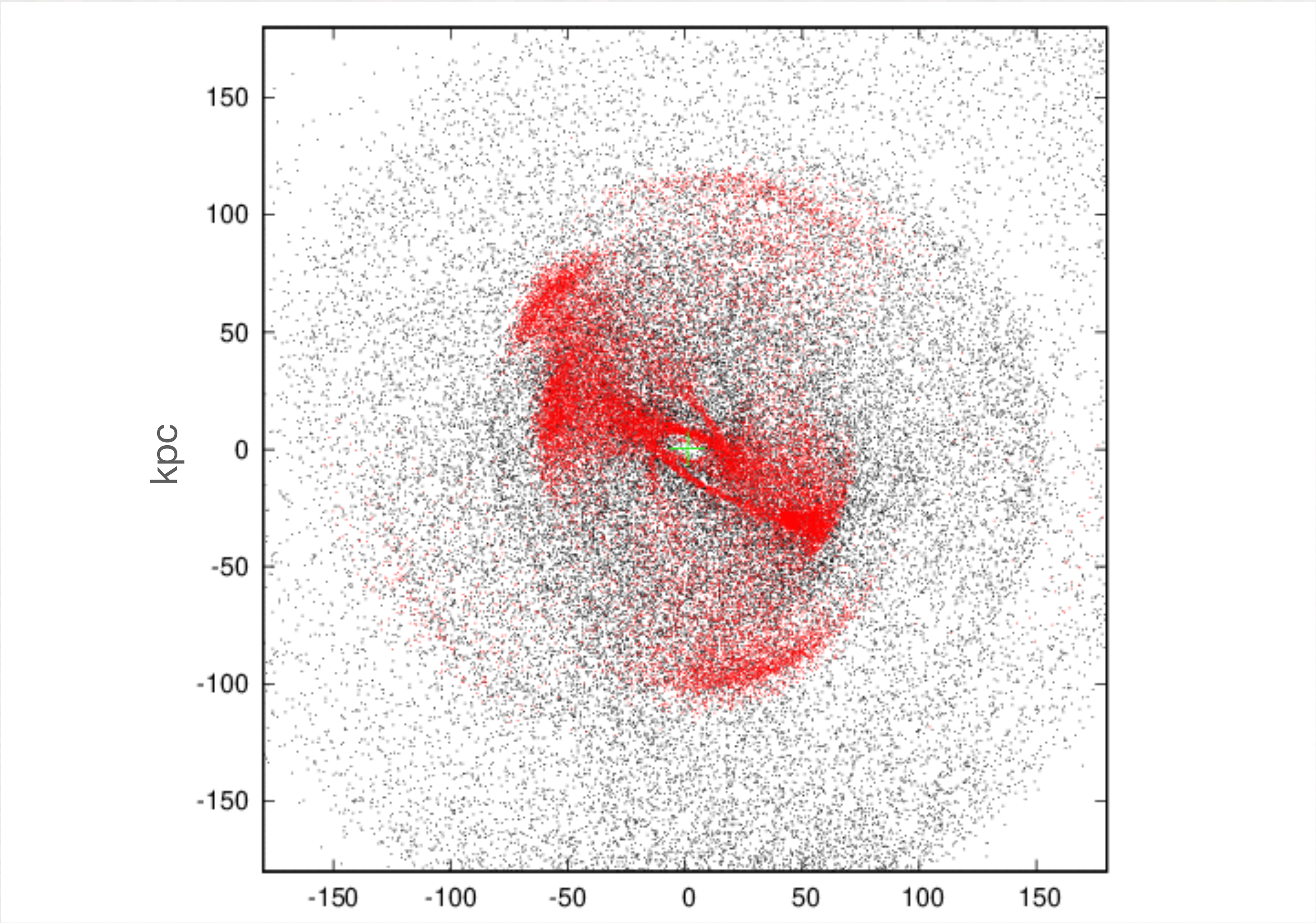
exploring stochasticity to distinguish scatter and trends

DYNAMICS OF MINOR MERGERS

from 'substructure' in the halo to accretion events:

where are stars deposited?

with what kinematics?



if gravity only, spherical symmetry, NFW profiles

4D parameter space

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- structural properties

- **virial mass ratio: Msat / Mhost**
- density contrast: deviations in halo concentration

e.g. Ludlow et al. 2014

- infall orbit

  - energy
  - initial circularity

e.g. Benson et al. 2005, Jiang et al. 2015

HIGHER MASS RATIO ⇒ MORE EFFICIENT SINKING

j_0= 0.5 mean concentrations

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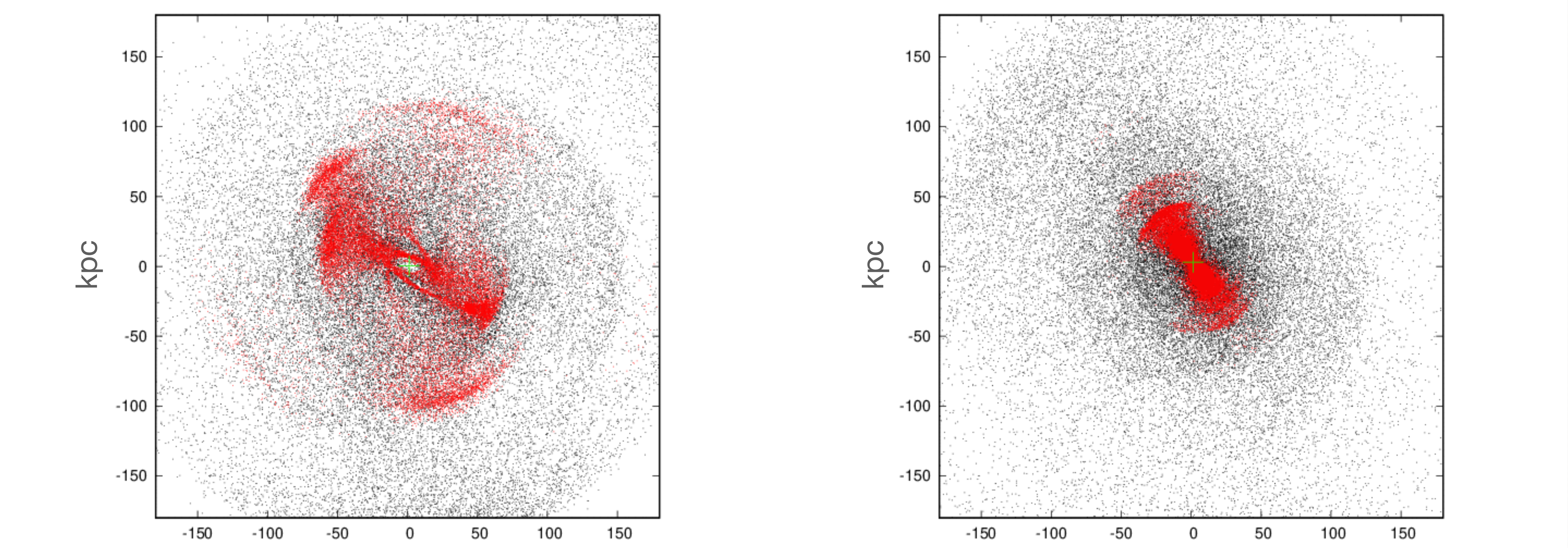
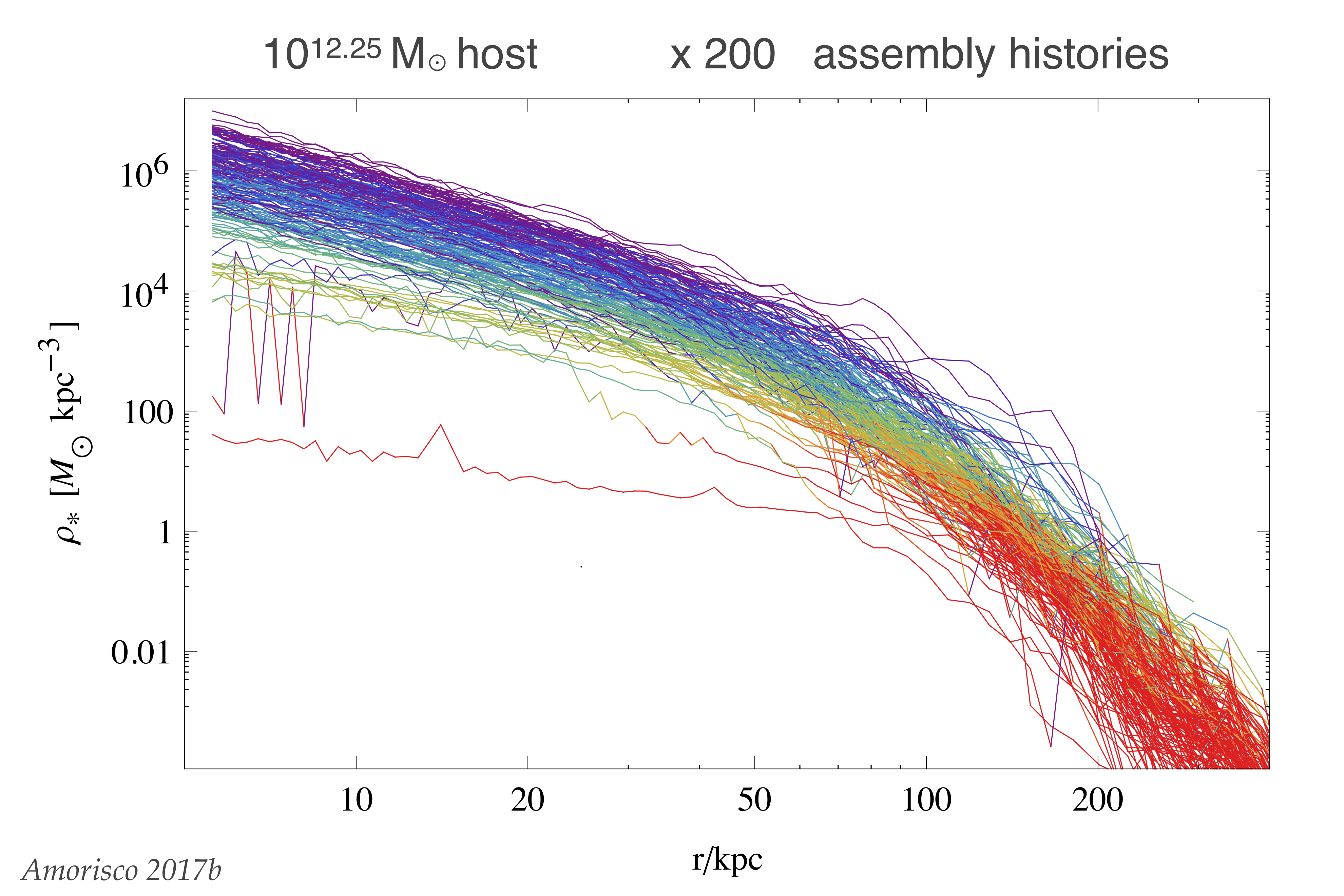


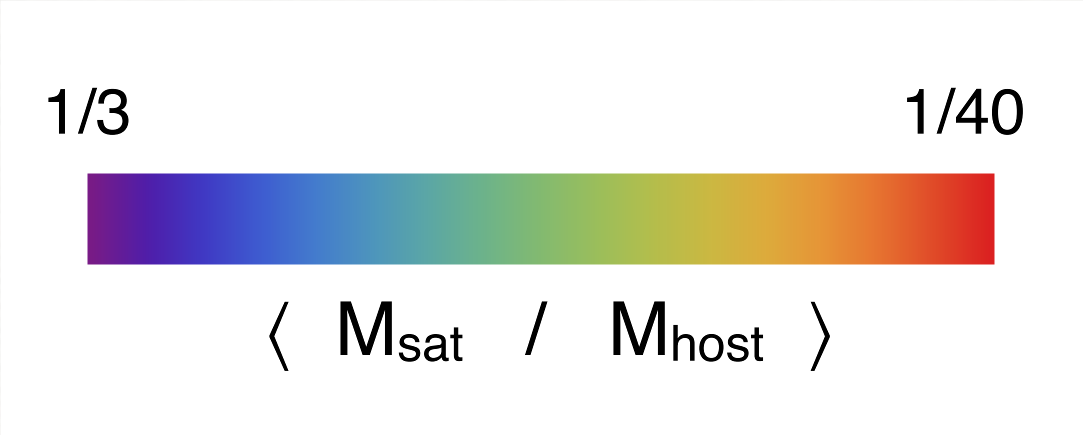
M_{sat} / M_{host} ~ **1/40**

M_{sat} / M_{host} ~ **1/6**

Dynamical friction ➡ more massive satellites deposit stars closer to the centre ➡ **color/metallicity gradients**

HIGHER MASS RATIO ⇒ MORE EFFICIENT SINKING



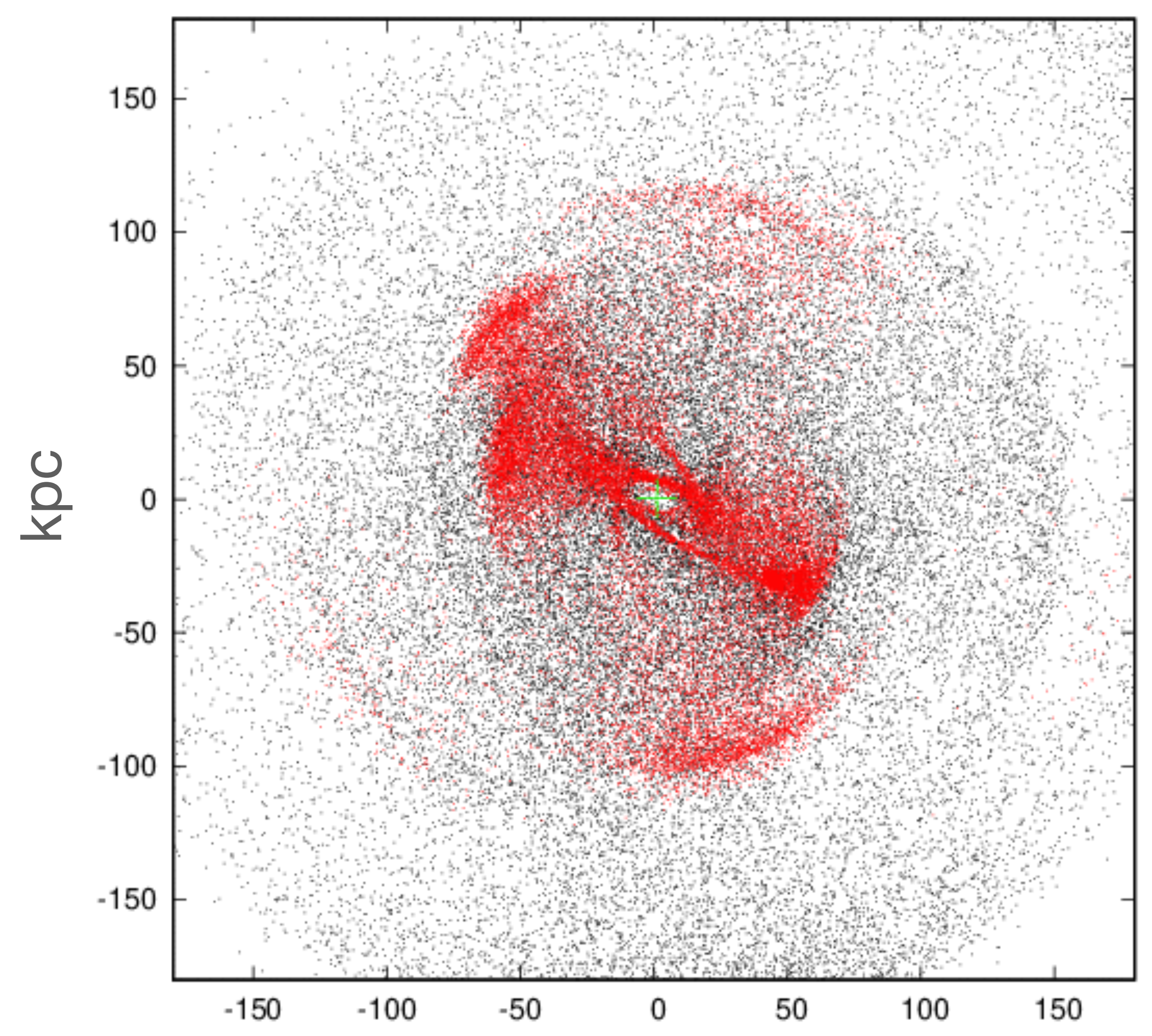


Dynamical friction ➡ more massive satellites deposit stars closer to the centre ➡ **color/metallicity gradients**

DYNAMICAL FRICTION ⇒ ORBITAL CIRCULARIZATION ?

j_0= 0.5 mean concentrations

Amorisco 2017a



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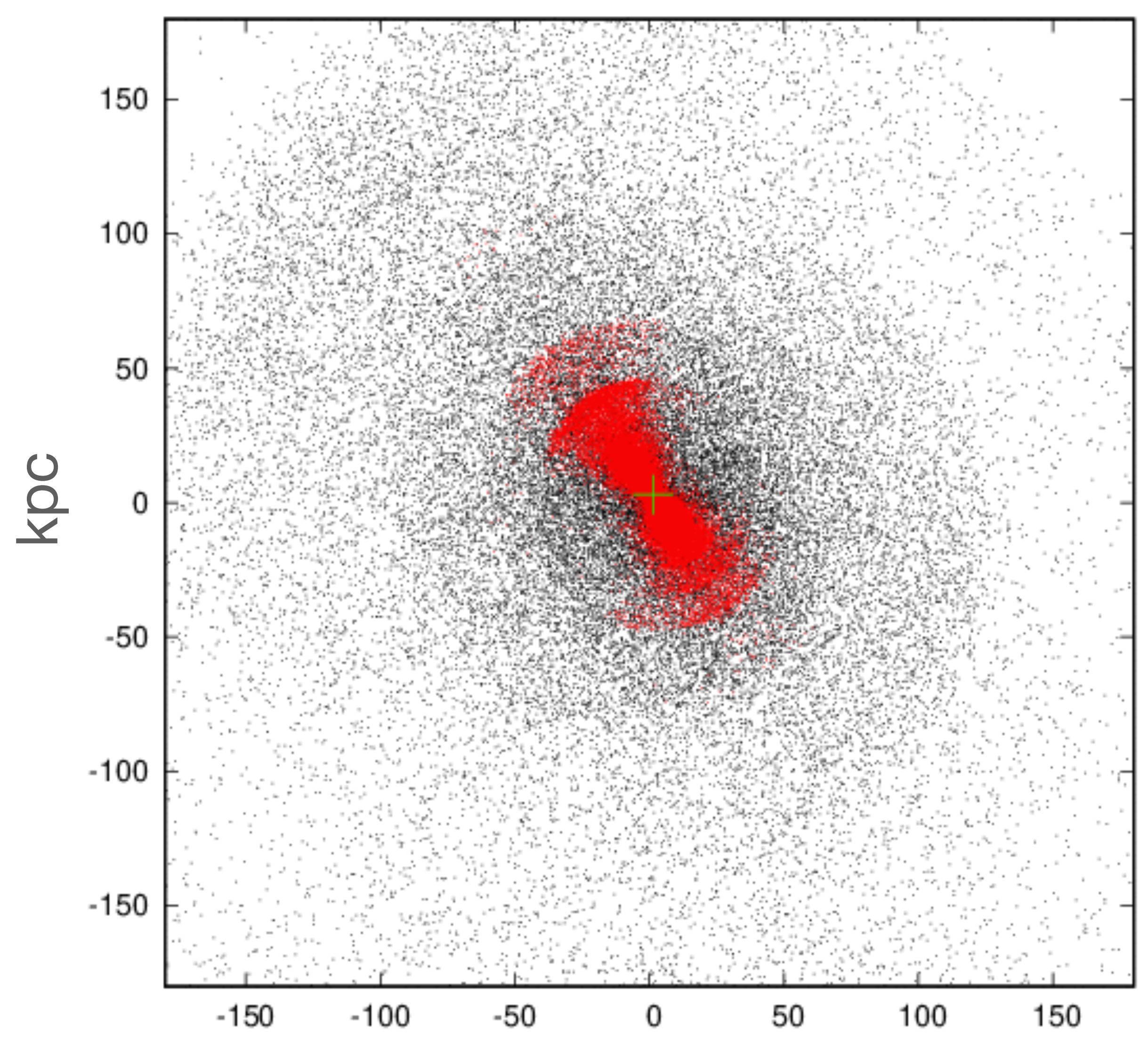
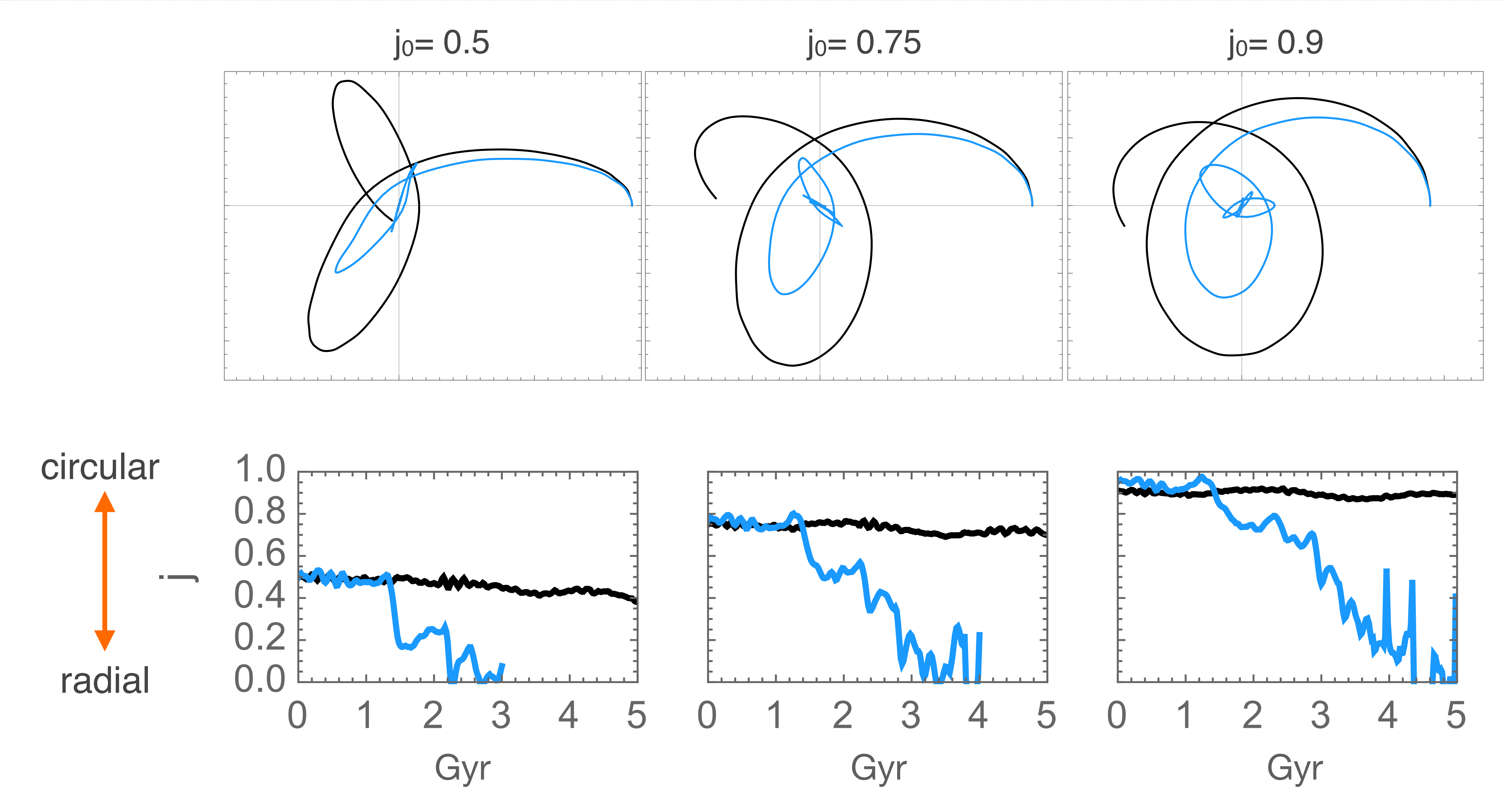


M_{sat} / M_{host} ~ **1/6**

Dynamical friction ➡ **orbital circularization. Right ?!**

HIGHER MASS RATIO ⇒ ORBITAL RADIALIZATION

~~Dynamical friction ⇒ orbital circularization~~



no significant circularization observed

$M_{sat} / M_{host} \sim$ **1/40**

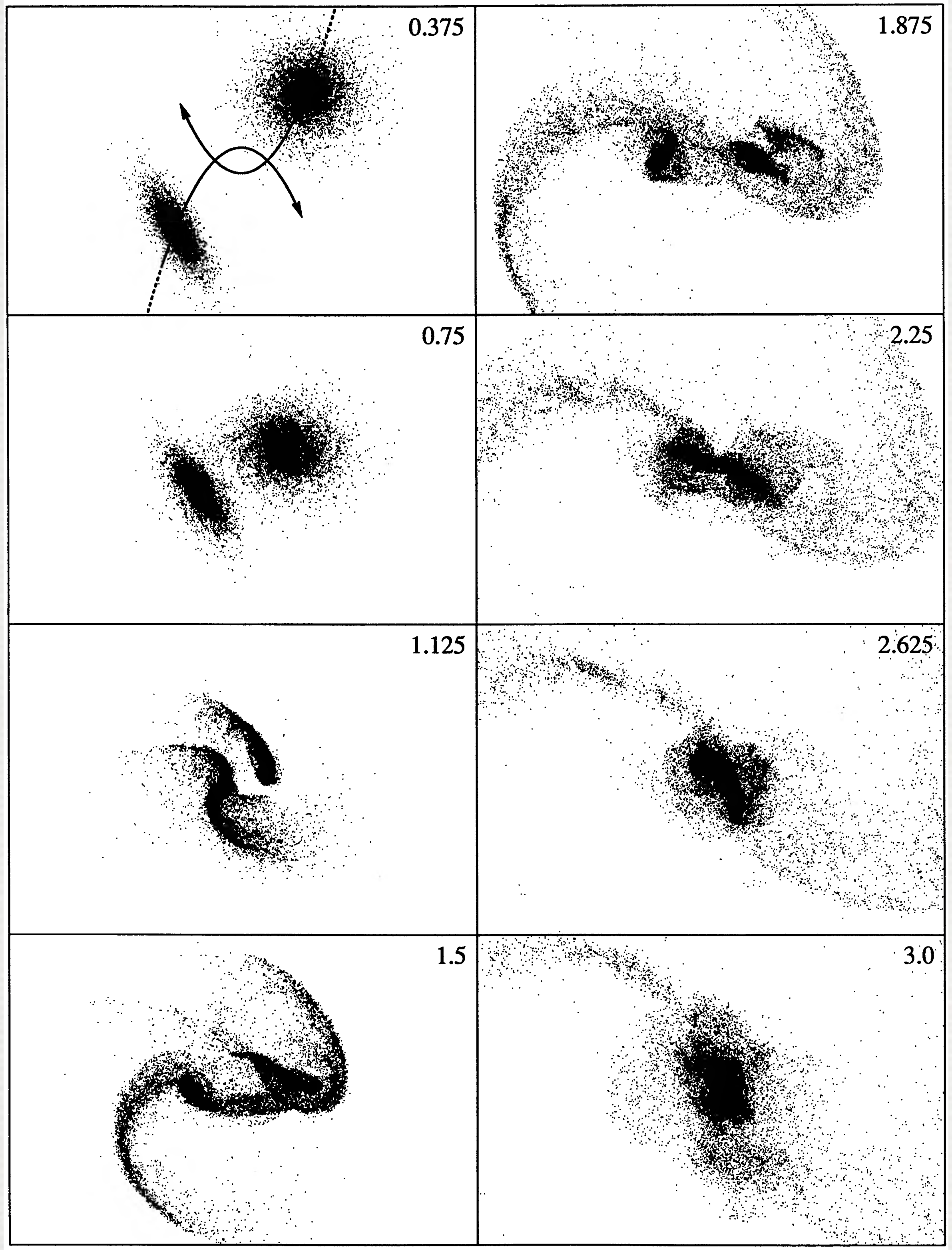
low mass ratios: orbital circularity preserved

$M_{sat} / M_{host} \sim$ 1/6

high mass ratios: quick and efficient **radialization**

Amorisco 2017a, Amorisco in prep.

HIGHER MASS RATIO ⇒ ORBITAL RADIALIZATION



Barnes 1992

White 1978, 1979

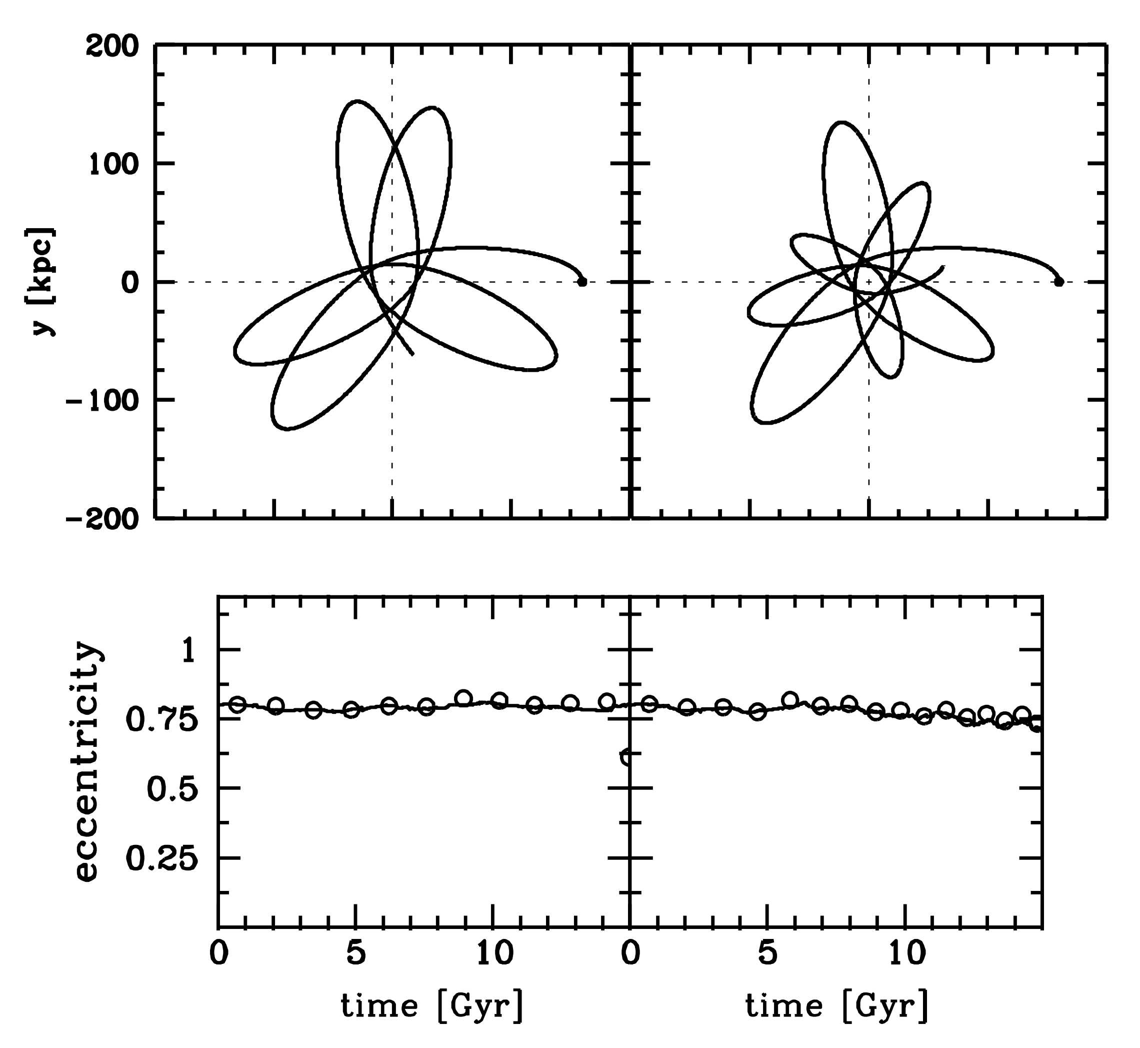
Barnes 1988, 1992

Barnes & Hernquist & 1992

equal-mass parabolic mergers

if halo: 'sticky mergers'

efficient energy transport from central regions out



van den Bosch 1999

Msat / Mhost < 2 × 10^{-2}

minor mergers with
point-mass satellites

constant eccentricity

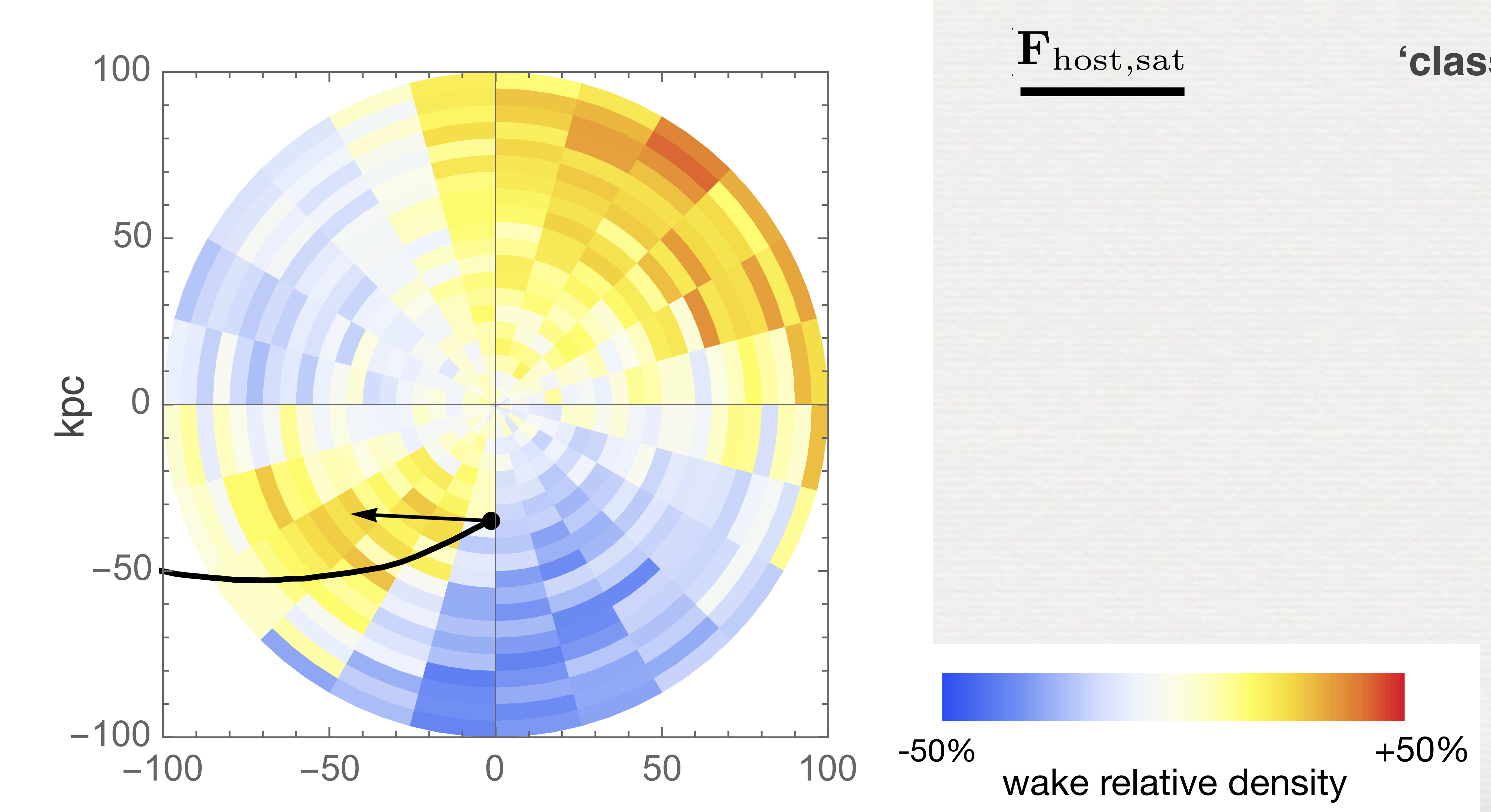
HIGHER MASS RATIO ⇒ ORBITAL RADIALIZATION

$$\dot{L} = (\mathbf{r}_{\rm sat} - \mathbf{r}_{\rm host}) \wedge (\ddot{\mathbf{r}}_{\rm sat} - \ddot{\mathbf{r}}_{\rm host})$$

angular momentum transported from central regions out

$$= (\mathbf{r}_{\rm sat} - \mathbf{r}_{\rm host}) \wedge [(\underline{\mathbf{F}_{\rm host,sat}} + \mathbf{F}_{\rm sat,sat}) - (\mathbf{F}_{\rm sat,host} + \mathbf{F}_{\rm host,host})]$$

Amorisco in prep.



$\underline{\mathbf{F}_{\rm host,sat}}$ **‘classical’ dynamical friction**

HIGHER MASS RATIO ⇒ ORBITAL RADIALIZATION

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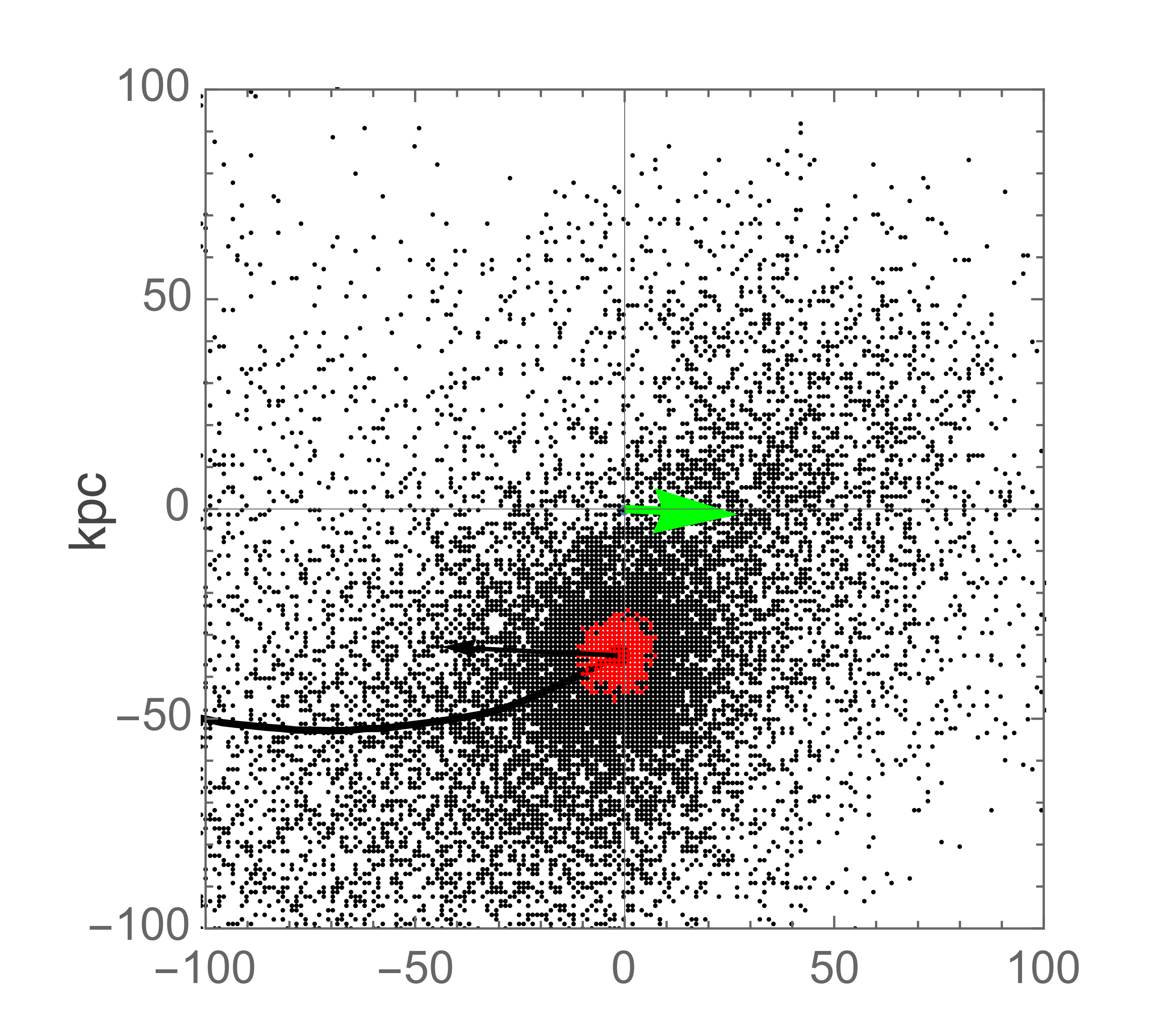

$\underline{\mathbf{F}_{\rm host,sat}}$ **'classical' dynamical friction**

$\underline{\mathbf{F}_{\rm sat,host}}$ symmetric term

if satellite massive enough, it sinks close enough to the centre

HIGHER MASS RATIO ⇒ ORBITAL RADIALIZATION

$$\dot{L} = (\mathbf{r}_{\rm sat} - \mathbf{r}_{\rm host}) \wedge (\ddot{\mathbf{r}}_{\rm sat} - \ddot{\mathbf{r}}_{\rm host})$$

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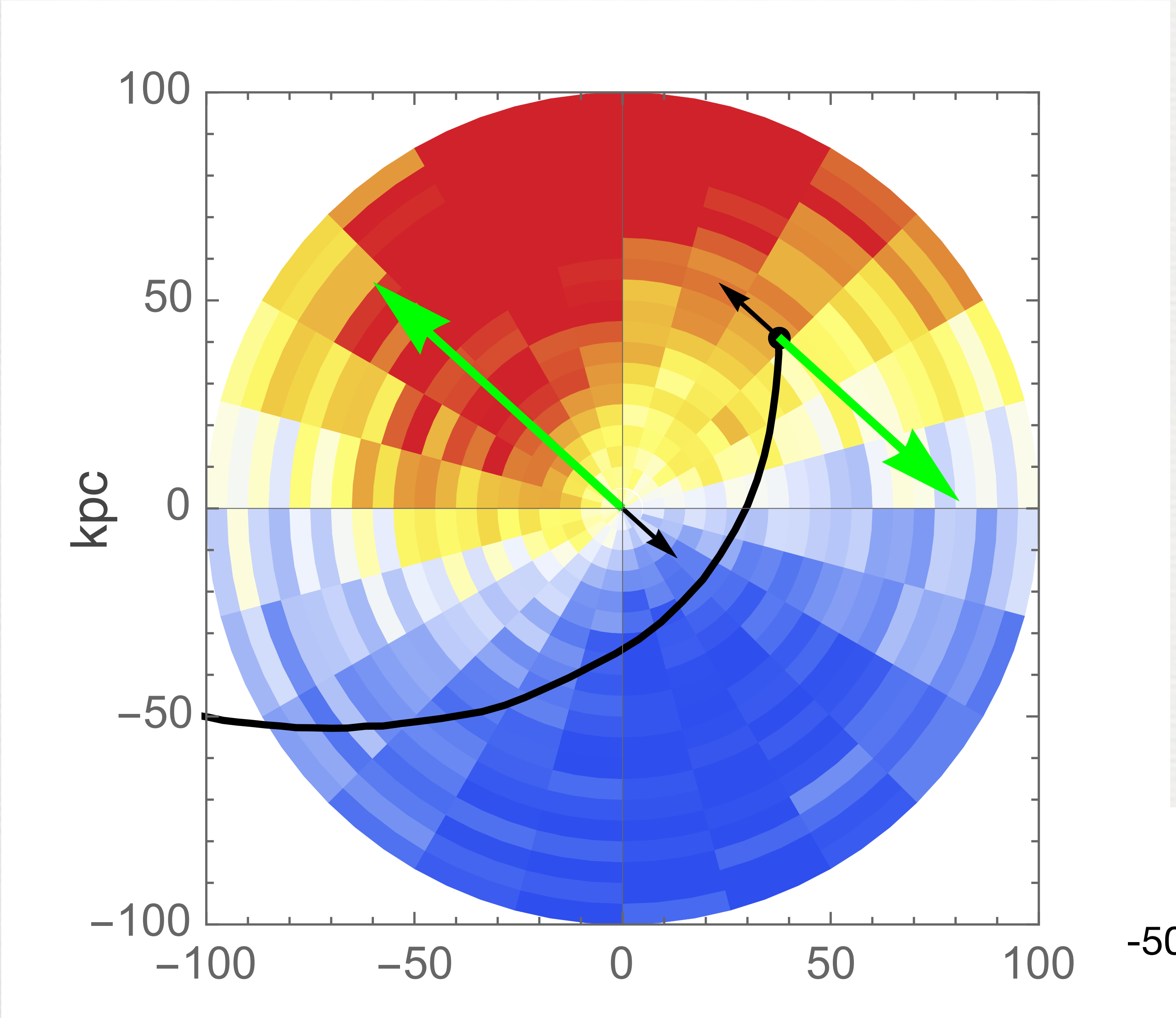


$\mathbf{F}_{\rm host,sat}$ ‘classical’ dynamical friction

$\mathbf{F}_{\rm sat,host}$ symmetric term

tidal terms

$\mathbf{F}_{\rm sat,sat}$ deformed satellite on its own center

$\mathbf{F}_{\rm host,host}$ host on its own center

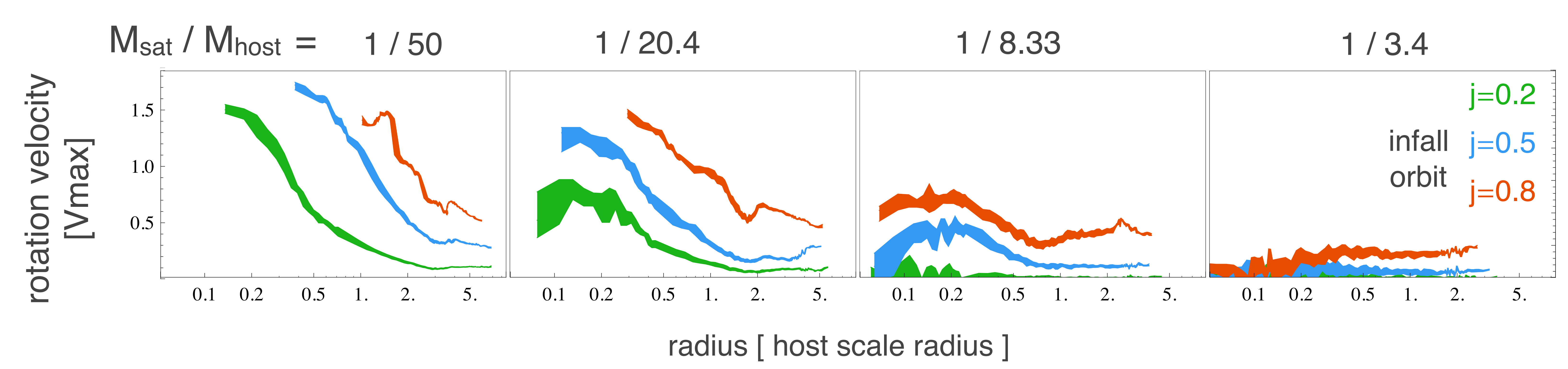
tidal terms dominate for high mass ratio mergers

RADIALIZATION ⇒ CHEMO-DYNAMICAL GRADIENTS

mass ratio increases

color, metallicity

Amorisco 2017a

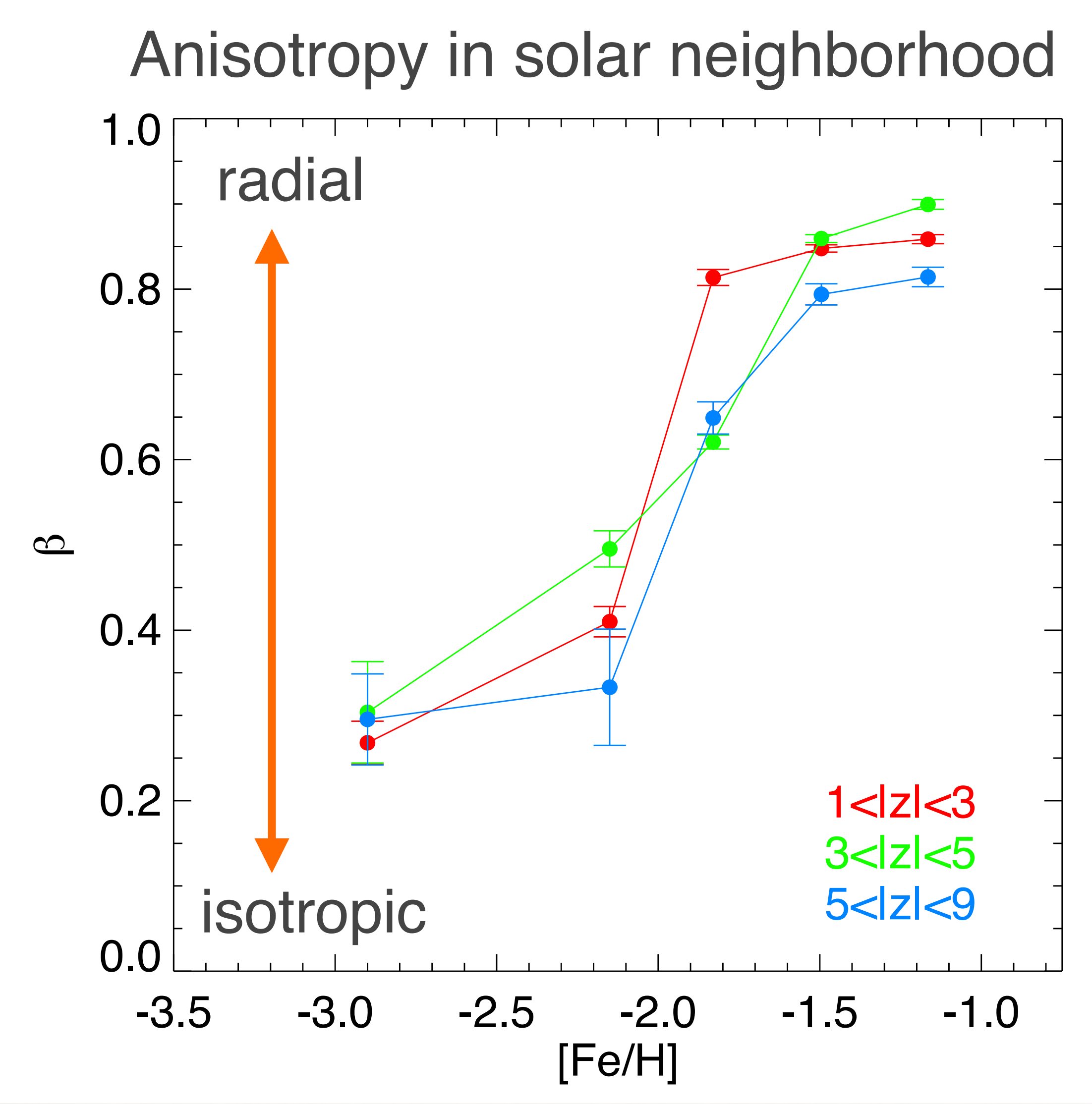


residual angular momentum increases

radial bias increases

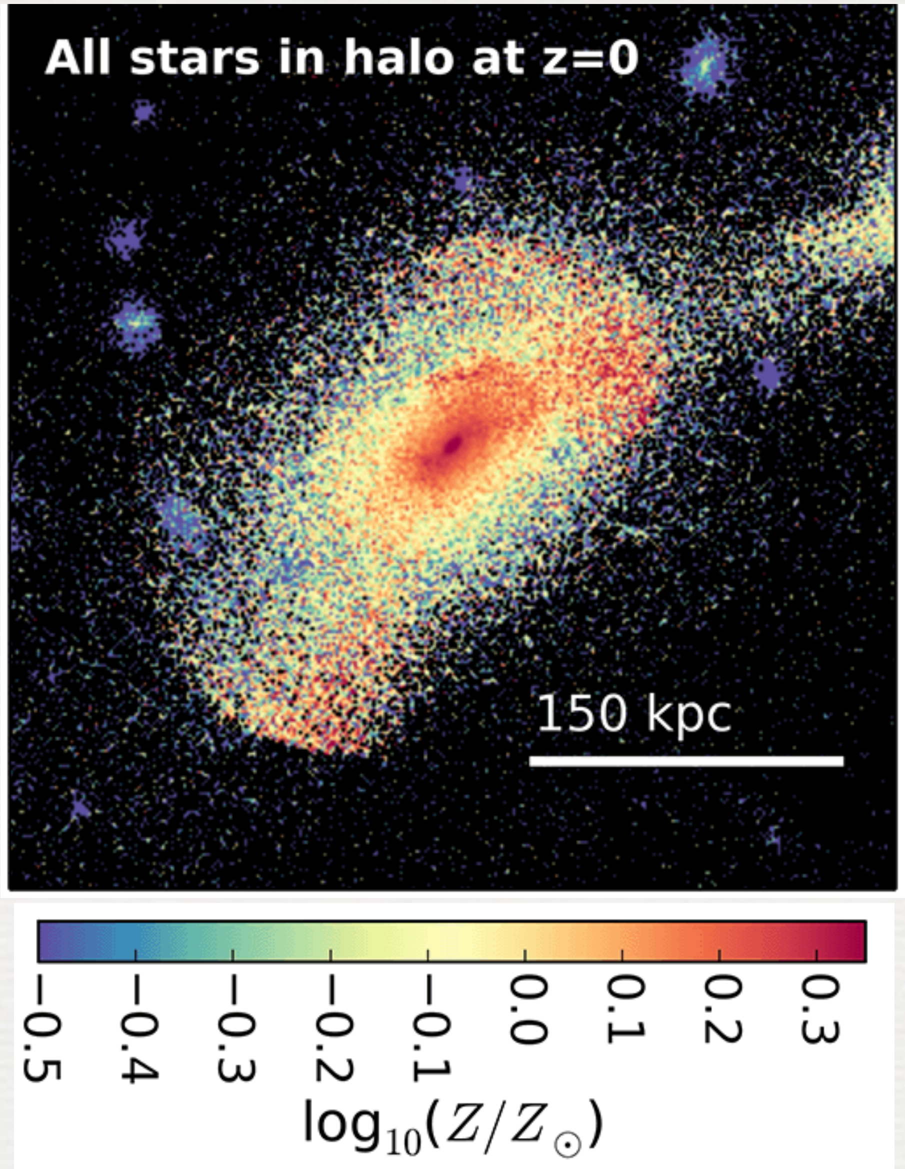
RADIALIZATION ⇒ CHEMO-DYNAMICAL GRADIENTS

Belokurov et al. 2018



chemo-dynamics and kinematical gradients in MW stellar halo

Pop et al. 2017a, 2017b



shells primarily formed by massive satellites

see Roxana's talk on Wed!

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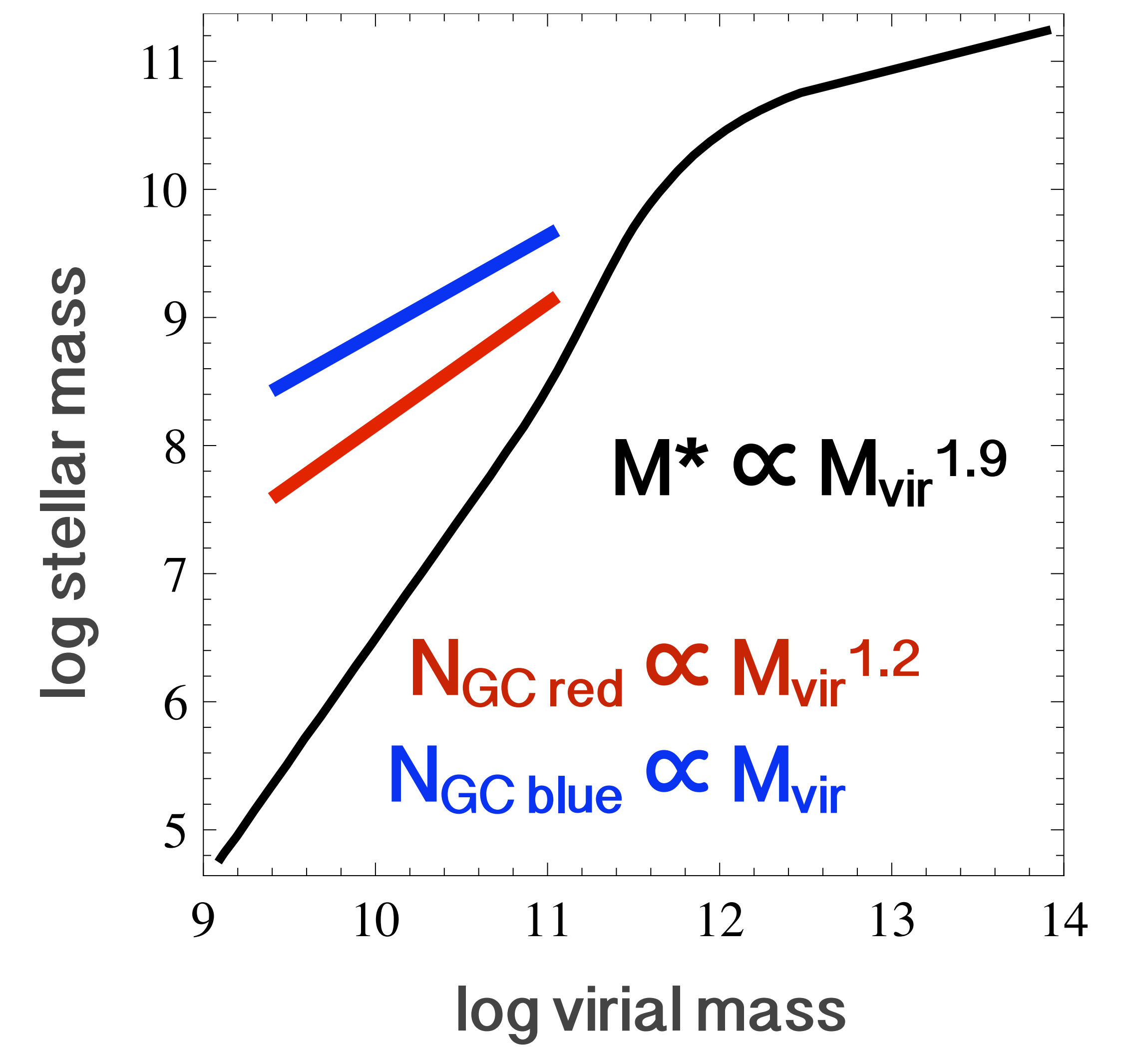


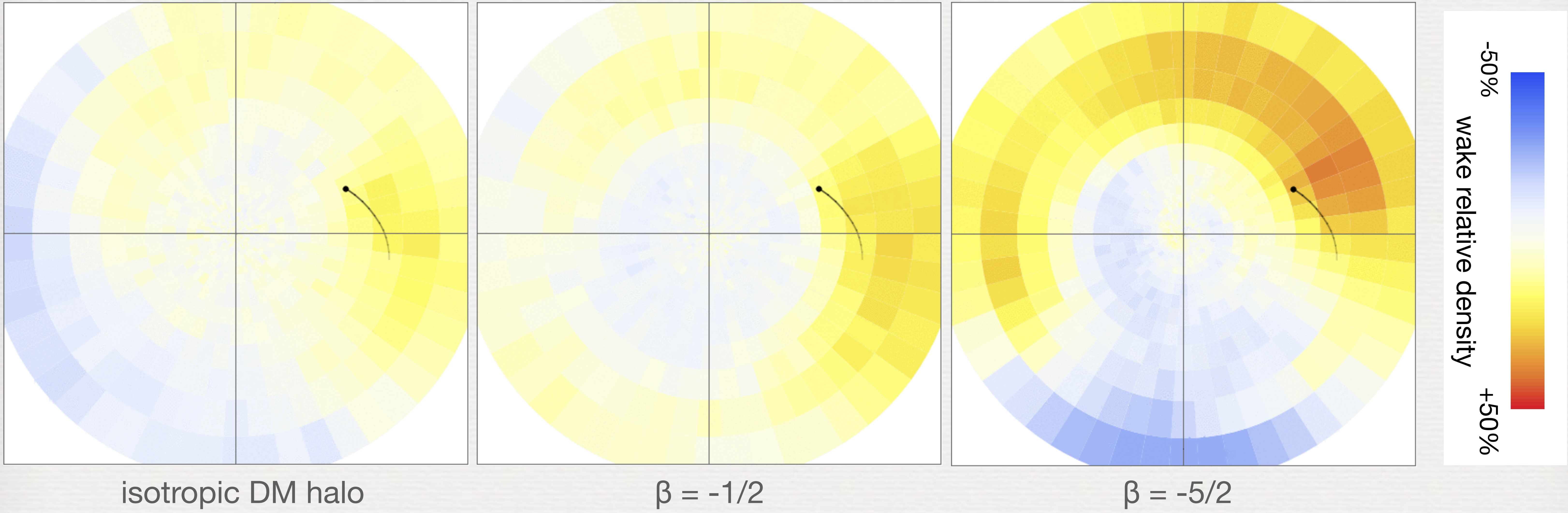
steep M* (M_{halo}) **shallow N_{GC} (M_{halo})**

massive sats vs minor mergers

GC halo ≠ stellar halo

GALACTOSEISMOLOGY: PROBING THE HALO'S NATURE

identical satellites & orbits

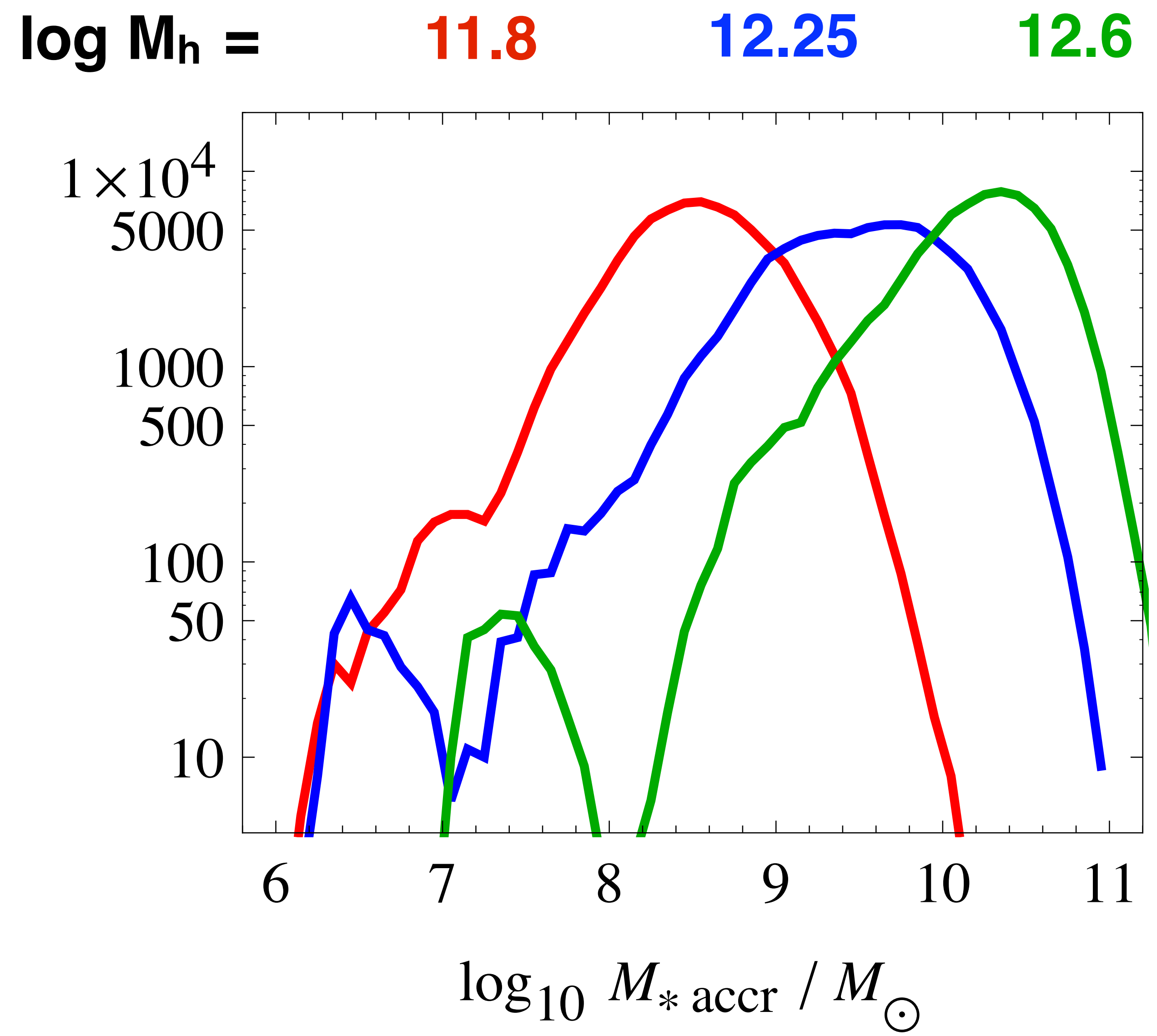


halo anisotropy amplifies the wake

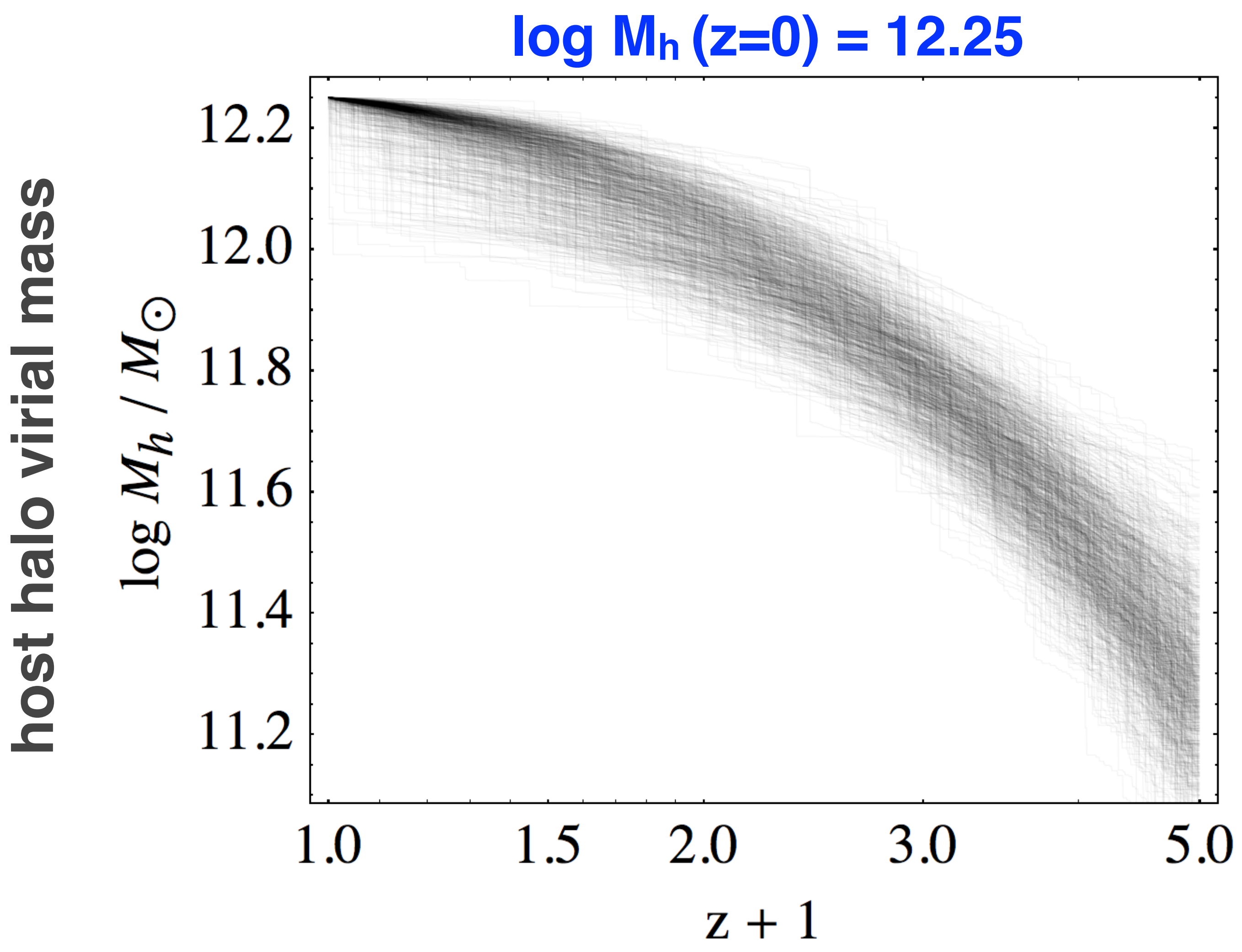
amplifies the disturbances to the disk

Amorisco in prep.

STOCHASTICITY AND TRENDS IN L* GALAXIES



total accreted stellar mass



ΛCDM Monte Carlo assembly histories

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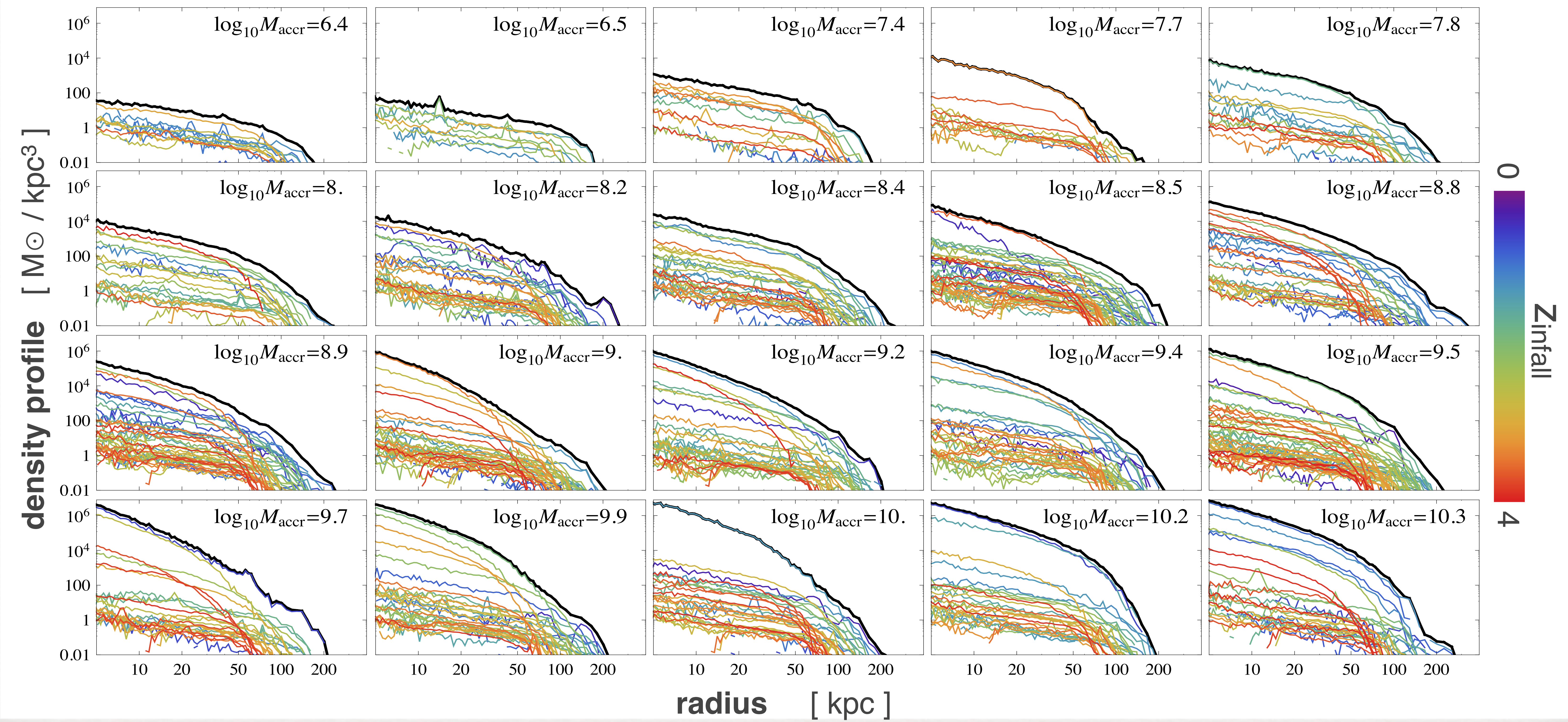
full particle data for

3 host masses x **750 DM assembly histories** x M^* - M_{halo} scatter

STOCHASTICITY AND TRENDS IN L* GALAXIES



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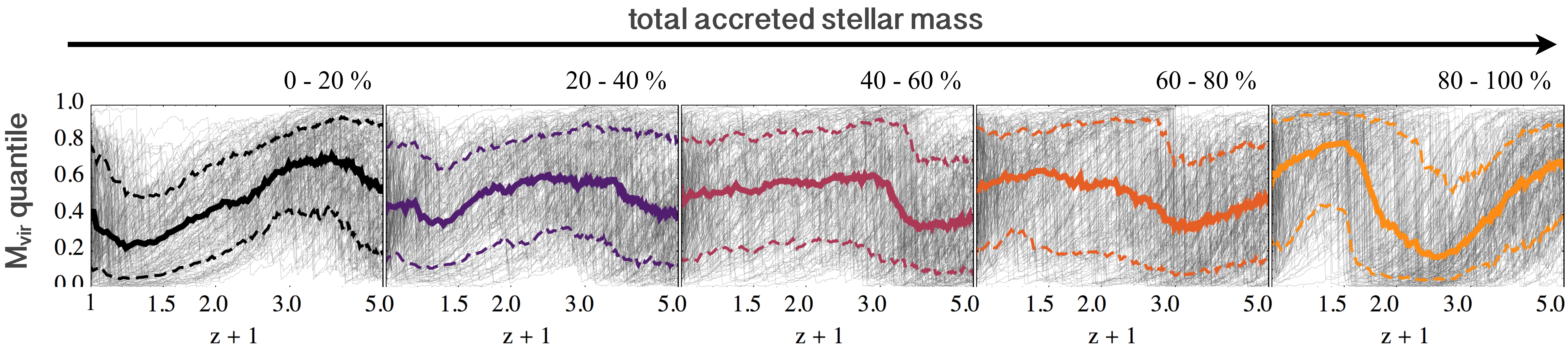
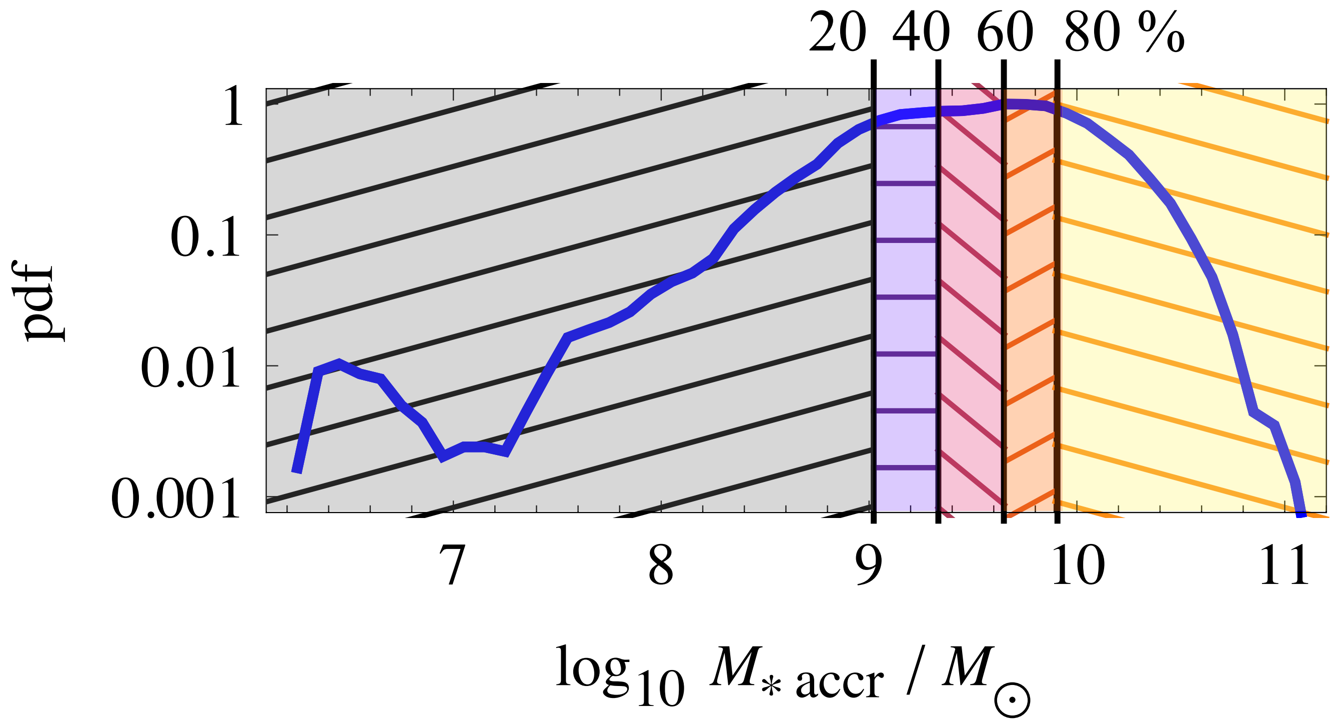
ACCRETED ST. MASS ⇒ ASSEMBLY HISTORY



poor st. haloes

rich st. haloes



total accreted stellar mass

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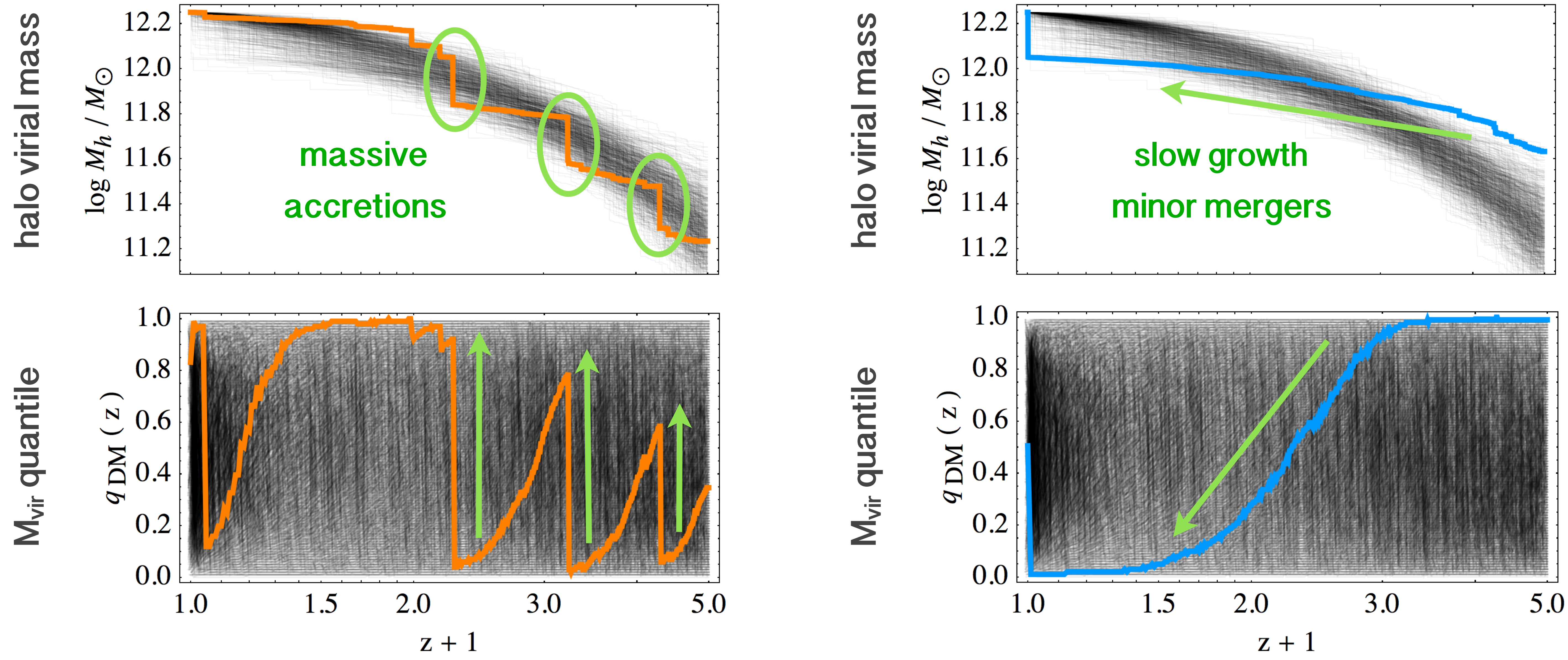
log M_h (z=0) = 12.25

ACCRETED ST. MASS ⇒ ASSEMBLY HISTORY



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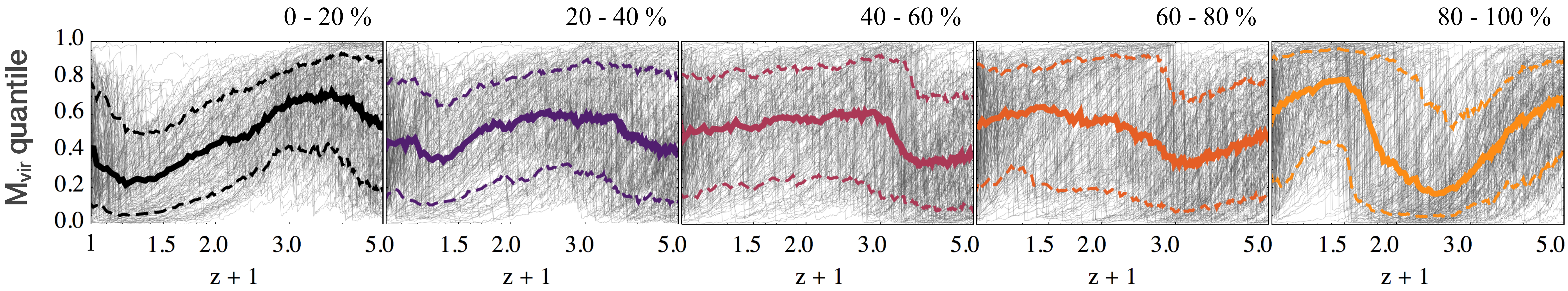
ACCRETED ST. MASS ⇒ ASSEMBLY HISTORY

poor → total accreted stellar mass → **rich**

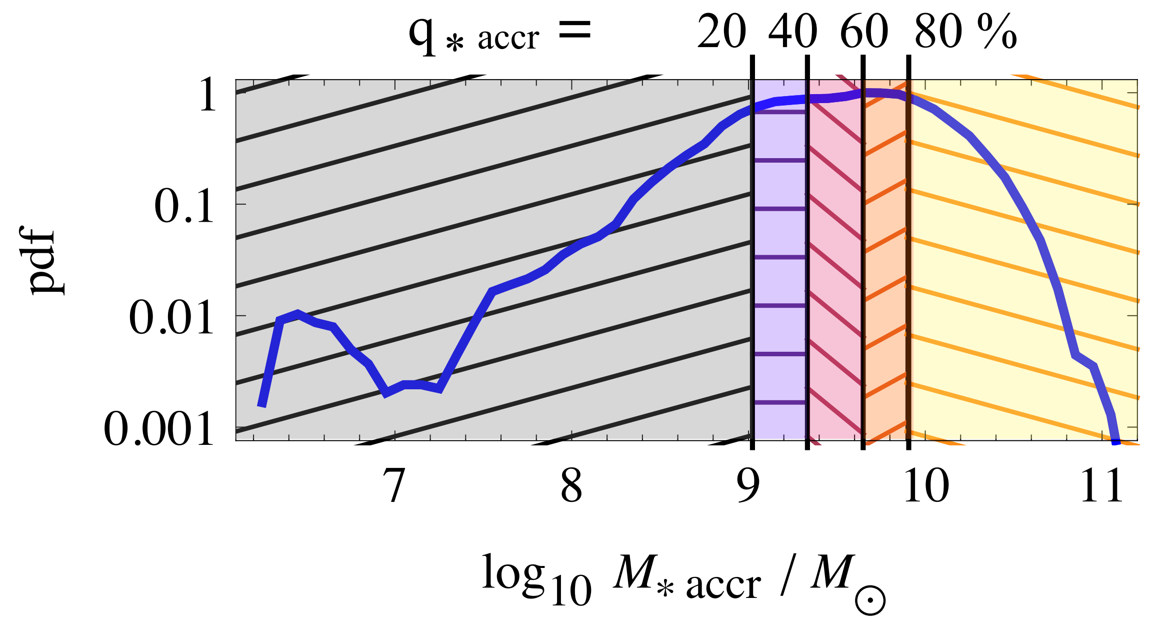


fast - slow - fast

slow - fast - slow

assemble early **z ~ 2.5**

minor mergers alone **0.5 ≲ z ≲ 2.5**



total accreted stellar mass

less massive than average **z ~ 2**

massive accretion events **0.5 ≲ z ≲ 1.5**

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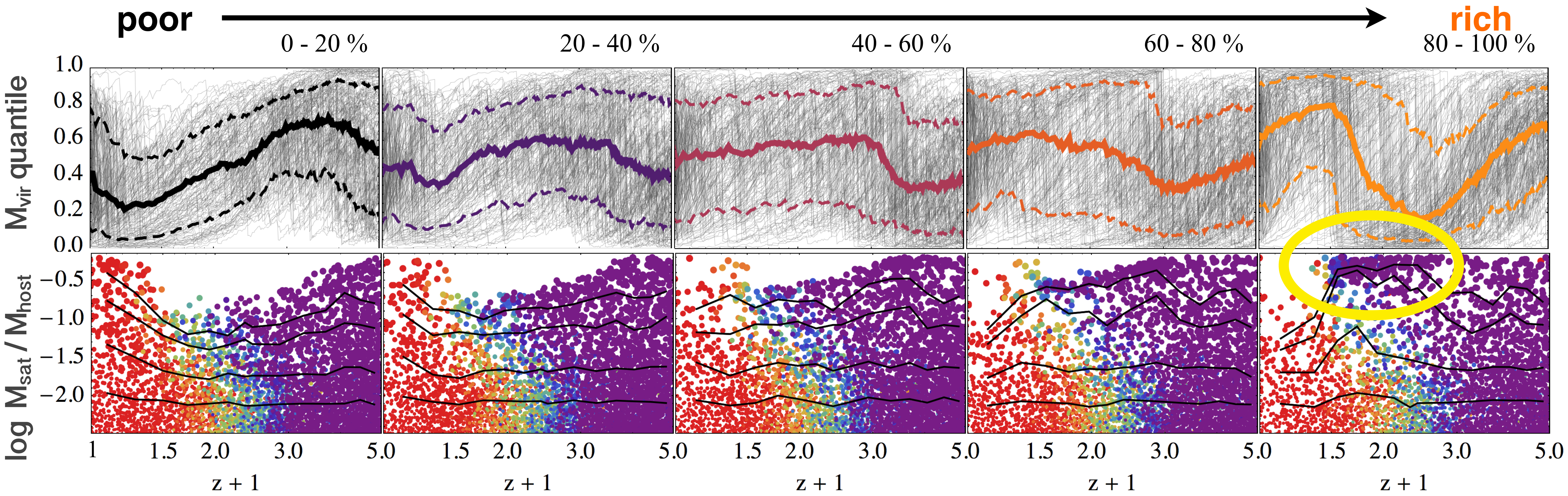
‘RICH’: MASSIVE ACCRET. AT INTERMEDIATE TIMES



NO massive accretions
0.5 ≲ z ≲ 1.5

remnant satellites: stellar fraction
0 — 1
disrupted — **surviving**

massive accretions
0.5 ≲ z ≲ 1.5
⇒ full tidal disruption

massive satellites + intermediate times = **maximize accreted st. mass**

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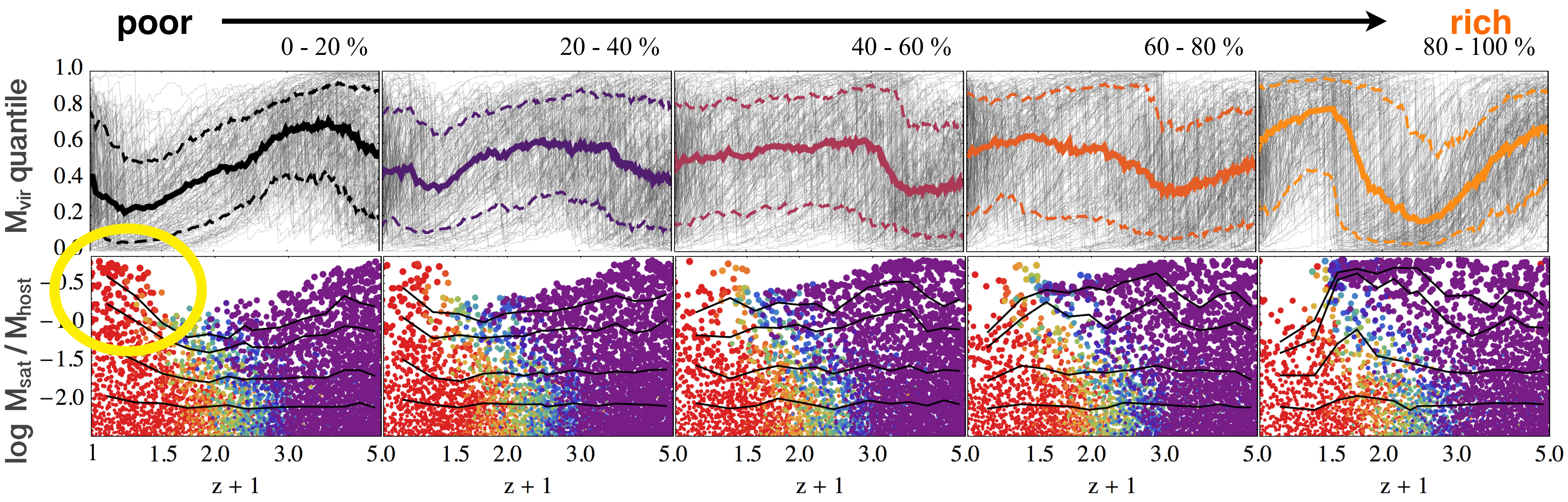
‘POOR’: SURVIVING MASSIVE SATELLITES



massive accretions
at **z ≲ 0.5**

⇒ **survive as satellites**

remnant satellites: stellar fraction

0 **disrupted** 1 **surviving**

massive accretions
0.5 ≲ z ≲ 1.5

⇒ **full tidal disruption**

massive satellites + too late to strip = **minimize accreted st. mass**

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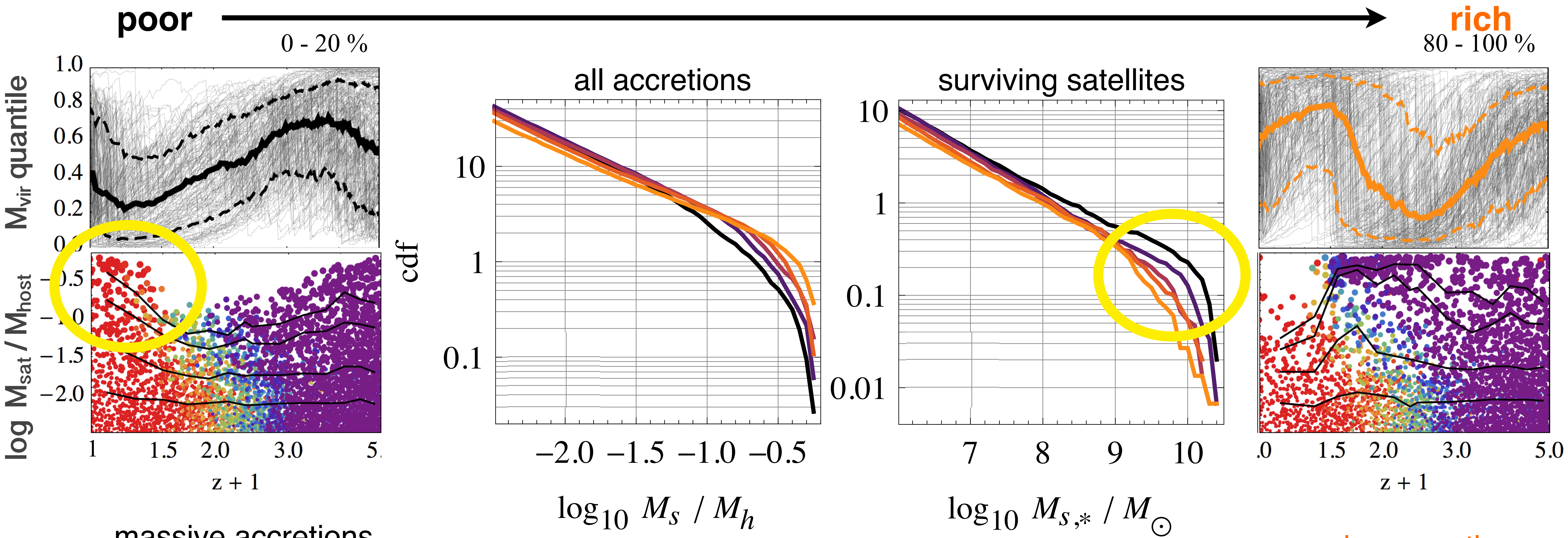
‘POOR’: SURVIVING MASSIVE SATELLITES



massive accretions
at **z ≲ 0.5**

⇒ survive as satellites

massive accretions
0.5 ≲ z ≲ 1.5

⇒ full tidal disruption

poor haloes: larger population of surviving satellites

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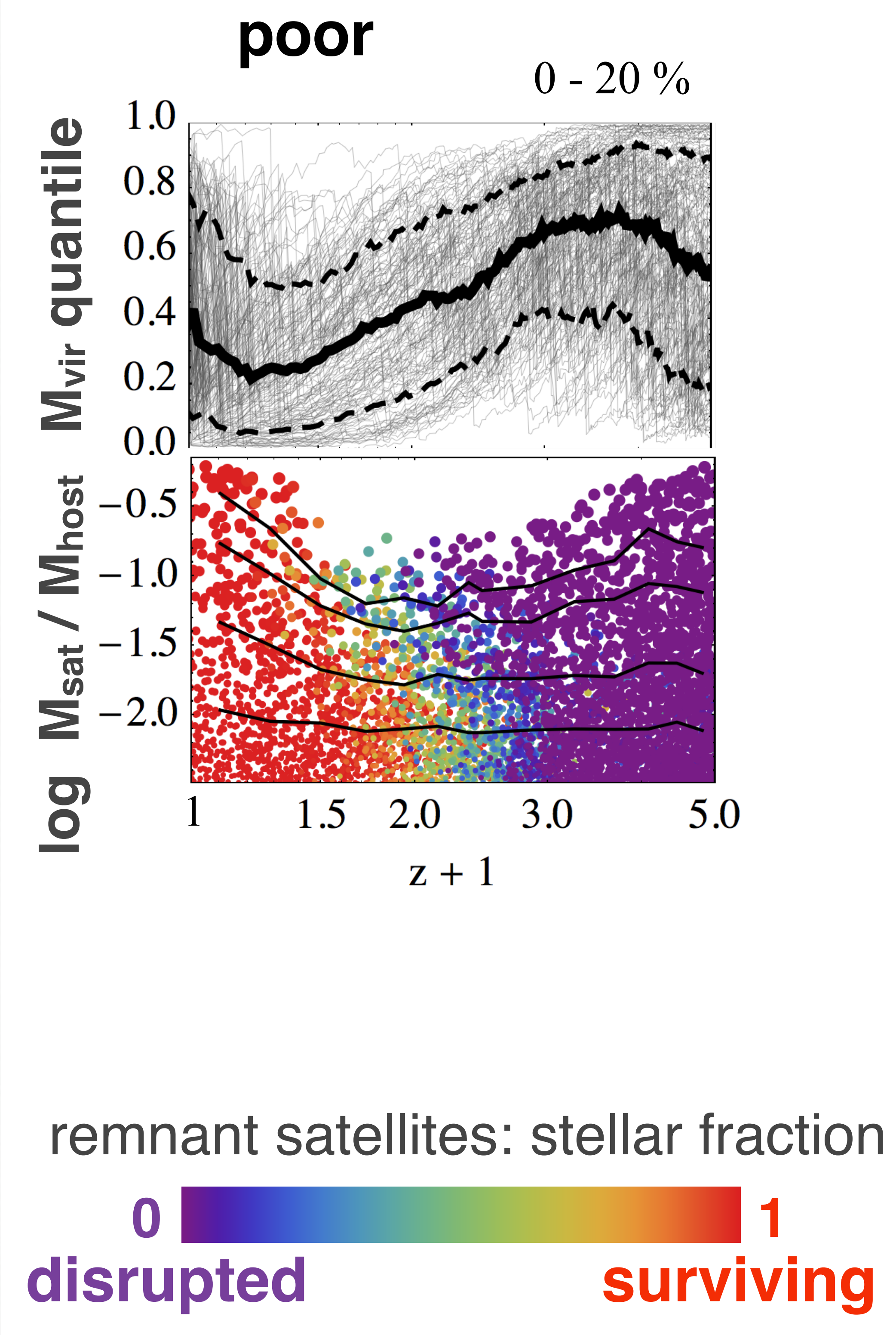
MW: ASSEMBLED AS A 'POOR HALO'



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- surviving logM* ≳ 9 satellites: **Magellanic Clouds, Sagittarius**

- quiet recent past

- 'old' st. halo: **fast chemical enrichment** (faster than dSphs)

$\boldsymbol{\alpha}$ abundances
Tolstoy et al. 2009, Frebel & Norris 2015

RRLyre period distribution
Fiorentino et al. 2015

BHB / BS number ratio
Deason et al. 2015

- early assembly: DM halo **concentration higher than average**

Rashkov et al. 2013, Gibbons et al. 2014, Bovy et al. 2016

CONCLUSIONS

N-body methods

- statistically reproduce DM halo assembly and pre-infall properties
- cannot follow dissipative evolution of gas or model the ‘in-situ’ contribution to the halo
- simplifying assumptions on the post-infall evolution
- **full particle data for thousands of haloes, no minimum ‘star-particle mass’**

Orbital radialization

- high mass ratio mergers **sink deeper & radialize** due to tidal deformations
- ⇒ metallicity gradients and **chemo-dynamical gradients:**
- chemo-dynamics of the stellar halo, plume morphology, differences between GCs & stars

L^* assembly

- **not just scatter**: accreted stellar halo ⇒ pattern in assembly history
- **poor** haloes = **early** assembly & more likely **surviving massive satellites**
- **rich** haloes = **late massive accretions, but just in time to fully disrupt**