Stellar Halos across the Cosmos

CONTROLLED AND N-BODY EXPERIMENTS

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

ACCRETED HALO: CONTROLLED AND N-BODY EXP.

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

orbital properties at infall

probability distributions from cosmological simulations

e.g. Jiang et al. 2015
ACCRETED HALO: CONTROLLED AND N-BODY EXP.

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orbital properties at infall

how many stars/tracers at infall

sample from $M^*(M_{\text{halo}}, z)$ with scatters

$N_{\text{GC}}(M_{\text{halo}}, z)$

$log$ virial mass

log stellar mass

Blue GCs

Red GCs

stars
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

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
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

DM ASSEMBLY H.

ACCR. ST. MASS

ST. HALO PROFILE

\( M_{\text{DM}} = 12.25 \)

\( z = 0.00 \)

\( \log_{10} M_{\text{accr}} = 9.10 \)

Amorisco 2017b
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

Limitations:

- no gas or realistic (post-infall) star formation
- accreted halo only
- smooth, spherical host DM halo
- particle tagging: no satellite morphology
- no interactions between satellites

* fundamental
* depending on specific implementation

Bullock & Johnston 2005
Cooper et al. 2010, 2017
Bailin et al. 2014
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

stellar halo in L* galaxies:

• not smooth, substructure

Bullock & Johnston 2005

Bullock, Krylov, Weinberg 2001

30 kpc < R < 40 kpc

+90°

360°

−90°
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

stellar halo in L\textsuperscript{*} galaxies:

- not smooth, substructure
- steeper than DM halo

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Bullock & Johnston 2005

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Bullock & Johnston 2005
ACCREDITED 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 ACCREDITED HALO

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.

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

stellar halo in L* galaxies:

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

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

• structural properties

• virial mass ratio: $M_{\text{sat}} / M_{\text{host}}$
• density contrast: deviations in halo concentration

• infall orbit

• energy
• initial circularity

Amorisco 2017a

e.g. Ludlow et al. 2014

e.g. Benson et al. 2005, Jiang et al. 2015
**HIGHER MASS RATIO ⇒ MORE EFFICIENT SINKING**

\[ j_0 = 0.5 \quad \text{mean concentrations} \]

\[ \frac{M_{\text{sat}}}{M_{\text{host}}} \sim 1/40 \quad \text{Dynamical friction} \quad \Rightarrow \quad \text{more massive satellites deposit stars closer to the centre} \quad \Rightarrow \quad \text{color/metallicity gradients} \]

\[ \frac{M_{\text{sat}}}{M_{\text{host}}} \sim 1/6 \]
Dynamical friction → more massive satellites deposit stars closer to the centre → color/metallicity gradients

Amorisco 2017b
Dynamical friction $\Rightarrow$ Orbital Circularization?

$$j_0 = 0.5 \quad \text{mean concentrations}$$

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

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

Dynamical friction $\Rightarrow$ orbital circularization. Right ?!
**HIGHER MASS RATIO ⇒ ORBITAL RADIALIZATION**

- **Dynamical friction** → orbital circularization

![Graphs showing orbital circularization and radialization for different mass ratios](image)

- Low mass ratios: orbital circularity preserved.
- High mass ratios: quick and efficient radialization.

\[ \frac{M_{\text{sat}}}{M_{\text{host}}} \sim \frac{1}{40} \]

\[ \frac{M_{\text{sat}}}{M_{\text{host}}} \sim \frac{1}{6} \]

*Amorisco 2017a, Amorisco in prep.*
**HIGHER MASS RATIO ⇒ ORBITAL RADIALIZATION**

White 1978, 1979
Barnes 1988, 1992
Barnes & Hernquist & 1992

- equal-mass parabolic mergers
- if halo: 'sticky mergers'
- efficient energy transport from central regions out

<table>
<thead>
<tr>
<th>Msat / Mhost &lt; 2 × 10⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>minor mergers with point-mass satellites</td>
</tr>
<tr>
<td>constant eccentricity</td>
</tr>
</tbody>
</table>

**Table:**

<table>
<thead>
<tr>
<th>Msat / Mhost</th>
<th>Energy Loss (1)</th>
<th>Angular Momentum Loss (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.6</td>
<td>1.1</td>
</tr>
<tr>
<td>1.0</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>1.2</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>1.4</td>
<td>0.4</td>
<td>0.6</td>
</tr>
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<td>0.2</td>
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</tr>
<tr>
<td>1.8</td>
<td>0.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Figure:**

- The change in energy with time reveals a step-wise behavior.
- The eccentricities are shown only up to a certain point, after which the satellite has virtually reached the central value.

**Notes:**

1. The angular momentum depends on the precise position of the halo's center, which may be poorly determined when the satellite is close to the halo.
2. The eccentricities are plotted only up to a certain point, after which the satellite has virtually reached the central value.

**References:**

- van den Bosch 1999
\[ \dot{L} = (r_{\text{sat}} - r_{\text{host}}) \wedge (\dot{r}_{\text{sat}} - \dot{r}_{\text{host}}) \]

\[ = (r_{\text{sat}} - r_{\text{host}}) \wedge [(\textbf{F}_{\text{host,sat}} + \textbf{F}_{\text{sat,sat}}) - (\textbf{F}_{\text{sat,host}} + \textbf{F}_{\text{host,host}})] \]

angular momentum transported from central regions out

\[ \textbf{F}_{\text{host,sat}} \]

‘classical’ dynamical friction

Amorisco in prep.

HIGHER MASS RATIO ⇒ ORBITAL RADIALIZATION

wake relative density

-50%  0  50  100

-100  -50  0  50  100

kpc
\[ \dot{L} = (\mathbf{r}_{\text{sat}} - \mathbf{r}_{\text{host}}) \wedge (\mathbf{\dot{r}}_{\text{sat}} - \mathbf{\dot{r}}_{\text{host}}) \]

= \left( \mathbf{r}_{\text{sat}} - \mathbf{r}_{\text{host}} \right) \wedge \left[ (\mathbf{F}_{\text{host, sat}} + \mathbf{F}_{\text{sat, sat}}) - (\mathbf{F}_{\text{sat, host}} + \mathbf{F}_{\text{host, host}}) \right]

angular momentum transported from central regions out

\[ F_{\text{host, sat}} \]

‘classical’ dynamical friction

\[ F_{\text{sat, host}} \]

symmetric term

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

Amorisco in prep.
\[ \dot{L} = (\mathbf{r}_{\text{sat}} - \mathbf{r}_{\text{host}}) \wedge (\dot{\mathbf{r}}_{\text{sat}} - \dot{\mathbf{r}}_{\text{host}}) \]

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angular momentum transported from central regions out

Amorisco in prep.

\[ \mathbf{F}_{\text{host, sat}} \quad \text{‘classical’ dynamical friction} \]

\[ \mathbf{F}_{\text{sat, host}} \quad \text{symmetric term} \]

\[ \mathbf{F}_{\text{sat, sat}} \quad \text{deformed satellite on its own center} \]

\[ \mathbf{F}_{\text{host, host}} \quad \text{host on its own center} \]

\[ \text{tidal terms} \]

\[ \text{tidal terms dominate for high mass ratio mergers} \]
RADIALIZATION $\Rightarrow$ CHEMO-DYNAMICAL GRADIENTS

mass ratio increases

color, metallicity

Amorisco 2017a

rotation velocity $\langle V_{\text{max}} \rangle$

radius [host scale radius]

residual angular momentum increases

radial bias increases

$M_{\text{sat}} / M_{\text{host}} = 1 / 50$

$1 / 8.33$

$1 / 3.4$

infall

orbit

Amorisco 2017a
RADIALIZATION ⇒ CHEMO-DYNAMICAL GRADIENTS

Anisotropy in solar neighborhood

- radial
- isotropic

chemo-dynamics and kinematical gradients in MW stellar halo

Top row (columns 1-3): Anisotropy in solar neighborhood vs. [Fe/H].
Bottom row: Anisotropy in solar neighborhood for different vertical distances.

All stars in halo at z=0

shells primarily formed by massive satellites

see Roxana’s talk on Wed!

M* ∝ Mvir\(^{1.9}\)

N_{GC\, red} ∝ Mvir\(^{1.2}\)

N_{GC\, blue} ∝ Mvir

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

Isotropic DM halo

$\beta = -1/2$

$\beta = -5/2$

Halo anisotropy amplifies the wake

Amplifies the disturbances to the disk

Amorisco in prep.
STOCHASTICITY AND TRENDS IN $L^*$ GALAXIES

$\log M_h = 11.8 \quad 12.25 \quad 12.6$

$\log_{10} M_{*\text{acrr}} / M_{\odot}$

total accreted stellar mass

$\Lambda$CDM Monte Carlo assembly histories

$\log M_h (z=0) = 12.25$

full particle data for

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

Amorisco 2018
STOCHASTICITY AND TRENDS IN L* GALAXIES

Amorisco 2017b
The accreted stellar halo (ASH) of a galaxy collects all those stars that were born in less massive galaxy, and that accumulated around their host galaxy during halo assembly.

When considering the global properties of the ASH as a window onto the connection between HAH and ASH, using both global and local properties of the ASH increases in proceeding from massive to less massive galaxy. This has an analogue in dark matter haloes of the ASH. In massive ellipticals, instead, stellar mass accretion dominates the budget of accreted stars (e.g., resulting in a concentrated ASH). At recent times in proceeding from concentrated to extended stellar halo assembly histories, sharing stochasticity provides us with the opportunity of inverting the connection. This Letter shows that both global and local properties of the ASH as a function of halo assembly histories, sharing fundamental dichotomy.

The probability distribution function for the total accreted stellar mass (log $M_{\text{accr}}^*/M_\odot$) at $z=0$ is bimodal, with the rich ASHs (poorer hosts) concentrated at very recent times, hosts with rich ASHs experience more stochasticity in the assembly process, less likely to achieve full tidal disruption by the merger (e.g., Amorisco et al. 2016). The median HAH of these hosts in the left column is the same as what we see in the right column. Comparison with the solid grey lines shows that ordering by $M_\text{vir}$ is effective, while the or-dinary median. The median HAH of these hosts in the left column concur to median HAHs (colored lines) that follow the pattern of the quantile $\bar{z}$; black lines identify the 50, 75, 90, 95% quantiles as a function of $z$. The dial extension of the ASH profile, as quantified by the radial scale $r_\text{ext}$, results in a concentrated ASH. This is shorter in hosts at intermediate phase of slow growth. This is shorter in hosts in the left column. For CDM universe, Amorisco et al. (2016) in prep., this needs to be factored by the number of contributing mergers in their ASHs.

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ACCRETED ST. MASS $\Rightarrow$ ASSEMBLY HISTORY

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INTRODUCTION

Currently, however, a clear bridge between halo assembly histories (ASHs) and accreted stellar haloes (AHs) is lacking. To address this challenge, I introduce an additional ordering, based on the ratio of the quantile $q$ accretion at a fixed time, by means of which it is possible, at least in principle, to systematically compare the AHs of these mode of assembly without comparing ex-situ remnants (e.g., Garrison-Kimmel et al. 2014; Amorisco 2017a; More et al. 2017b; Guo et al. 2017a). Results of both theoretical analyses (e.g., White & Frenk 1991; Fakhouri et al. 2010; Johnston et al. 2017a) are consistent with this picture, despite significant differences in their ASHs.

Columns identify different modes of assembly, which experience HVMR AEs at $z = 0$ - 20% in $M_*$, while the order of the quantile $q$ accretion at a fixed time, by means of which it is possible, at least in principle, to systematically compare the AHs of these mode of assembly without comparing ex-situ remnants (e.g., Garrison-Kimmel et al. 2014; Amorisco 2017a; More et al. 2017b; Guo et al. 2017a). Results of both theoretical analyses (e.g., White & Frenk 1991; Fakhouri et al. 2010; Johnston et al. 2017a) are consistent with this picture, despite significant differences in their ASHs.

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My analysis is divided into different phases of growth, which varies with the host halo mass.

- **Fast - Slow - Fast**: This phase is characterized by a fast growth phase, followed by a slow growth phase, and then another fast growth phase. Hosts with rich ASHs experience more massive accretion events compared to average hosts with $z \approx 2$
- **Slow - Fast - Slow**: This phase is characterized by a slow growth phase, followed by a fast growth phase, and then another slow growth phase. Hosts with rich ASHs experience less massive accretion events compared to average hosts with $z \approx 2$
- **Rich - Poor - Rich**: This phase is characterized by a fast growth phase, followed by a slow growth phase, and then another fast growth phase. Hosts with rich ASHs experience massive accretion events compared to average hosts with $0.5 \leq z \leq 1.5$

For example, $f^*$ - fraction of stellar mass in surviving satellite remnant at $z = 0$ and $t = \tau$.

**Figure 4.** Columns identify different modes of assembly, which experience HVMR AEs at $z = 0$ - 20% in $M_*$, while the order of the quantile $q$ accretion at a fixed time, by means of which it is possible, at least in principle, to systematically compare the AHs of these mode of assembly without comparing ex-situ remnants (e.g., Garrison-Kimmel et al. 2014; Amorisco 2017a; More et al. 2017b; Guo et al. 2017a). Results of both theoretical analyses (e.g., White & Frenk 1991; Fakhouri et al. 2010; Johnston et al. 2017a) are consistent with this picture, despite significant differences in their ASHs.

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NO massive accretions \(0.5 \leq z \leq 1.5\)

remnant satellites: stellar fraction

\[
\begin{array}{c|c|c}
0 & \text{disrupted} & \text{surviving} \\
\hline
1 & \text{massive accretions} & 0.5 \leq z \leq 1.5 \\
\end{array}
\]

⇒ full tidal disruption

massive satellites + intermediate times = maximize accreted st. mass

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shifts: they are more massive than the median at the median. Hosts with equally poor but extended ASHs see the same time, they are early enough to keep growth phases.

However, that ordering by right column. Comparison with the solid grey lines shows, orthogonal pattern preserved: independent of the 'concentration' of their ASHs, the median.

Dial extension of the ASH profile, as quantified by the ratio.

Two families is shown with solid grey lines in all panels of all models. I introduce an additional ordering, based on the ratio.

Columns identify directories. For each column, this ordering defines a set of terciles: hosts with q, moving away from median.

$\bar{r}$

has ASHs that are less (more) extended than $\bar{r}$.

$\bar{r}$

provide very similar results). Within quintiles in total accreted stellar mass, increasing towards the right. Top row: HAHs in terms of different quintiles in total accreted stellar mass, increasing towards the right. Top row: HAHs in terms of different quintiles in total accreted stellar mass, increasing towards the right.

Middle row: infall time and stellar mass of surviving massive satellites. Color-coding represents the fraction of stellar mass in the surviving satellite remnant. Bottom row: infall time and stellar mass. Color-coding identifies the 50, 75, 90, 95% quantiles.

For the quantile $\inf$, resulting in a concentrated ASH. At $\inf$ = 0f or satellites. Color-coding and black lines identify the 50, 75, 90, 95% quantiles. Bottom row: infall time and stellar mass. Color-coding identifies the 50, 75, 90, 95% quantiles.

On average, hosts with rich ASHs experience more distances from the host's center, as the host gradually grows in mass and size over cosmic time. Fundamental differences in these modes lie in the number of filamentary modes of growth which minimise/maximise the total accreted stellar mass, while keeping the final virial mass fixed.

Hosts with poor/rich ASHs assemble following well defined modes of growth which minimise/maximise the total accreted stellar mass, while keeping the final virial mass fixed. For all AEs; color-coding represents the fraction of stellar mass in the surviving satellite remnant.

4 DISCUSSION AND CONCLUSIONS

Massive accretions at $z \approx 0.5$ ⇒ survive as satellites

Remnant satellites: stellar fraction

0 disrupted 1 surviving

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

⇒ full tidal disruption

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This initial phase of fast growth pushes towards higher redshift with concentrated ASHs, which experience HVMR AEs at intermediate phase of slow growth. This is shorter in hosts with diurnal pattern. For references in these modes lie in the number differences in the intensity and timing of these rare HVMRs AEs, while the orthogonal pattern introduces additional bias.

Columns identify different quintiles in total accreted stellar mass, increasing towards the right. Top row: HAHs in terms of the quantile functions in final time. Bottom row: final time and stellar mass all accretions.

For poor satellites: stellar fraction $f^*$ = fraction of stellar mass in surviving satellite remnant at $z = 0$.

Hosts with poor/rich ASHs assemble following well defined growth phases. This Letter shows that both global and local properties of the ASH can be used to constrain HA in MW-like galaxies. Recent times in proceeding from concentrated to extended radii. Symmetrically, the timing of the intermediate phase is earlier in hosts with rich ASHs experience a slower-than-average growth at intermediate times.

The ASH can be used to constrain HA in MW-like galaxies. This Letter shows that both global and local properties of the ASH can be used to constrain HA in MW-like galaxies.

'POOR': SURVIVING MASSIVE SATELLITES

massive accretions at $z \approx 0.5$

⇒ survive as satellites

massive accretions $0.5 \leq z \leq 1.5$

⇒ full tidal disruption

poor haloes: larger population of surviving satellites

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- surviving logM* \( \geq 9 \) satellites: Magellanic Clouds, Sagittarius

- quiet recent past

- ‘old’ st. halo: \textbf{fast chemical enrichment} (faster than dSphs)

\( \alpha \) abundances
\textit{Tolstoy et al. 2009, Frebel & Norris 2015}  \textit{Fiorentino et al. 2015}

\textbf{BHB / BS number ratio}
\textit{Deason et al. 2015}

- early assembly: DM halo \textbf{concentration higher than average}
\textit{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
- $\Rightarrow$ 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 $\Rightarrow$ 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