The Dynamical Lives of High Redshift Galaxies

Greg Poole
...and the rest of the DRAGONS team ...
Stuart Wyithe, Simon Mutch, Paul Geil (Melbourne)
Alan Duffy (Swinburne), Andrei Mesinger (SNS, Pisa)
Paul Angel, Yuxiang Quin, Chuanwu Liu (Melbourne)
Dark Ages Reionization and Galaxy Formation Observables from Simulations

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Halo Structure: Universal Profiles

\[
\frac{\rho(r)}{\rho_c} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}
\]

\[c_{\text{vir}} \equiv \frac{R_{\text{vir}}}{r_s}\]
Halo Structure at Low-z: General Agreement

Prada et al, 2012

Diemer et al, 2015
Halo Structure at High-z: Confusion in the Literature

\[ \log M_{\text{vir}} [M_\odot/h] \]
Halo Structure at Low-z: Depends on Dynamical State

More quiescent halos have higher concentrations
Halo Structure at High-z: Confusion in the Literature

![Graph showing the halo structure at high-z]

The graph illustrates the halo structure at high-redshift (z=5.00) using the NFW profile. The x-axis represents the logarithm of the virial mass in units of $M_{\odot}/h$, while the y-axis shows $C_{\text{vir}}$. The lines represent different studies:

- Dutton (2014)
- Prada (2012)
- Diemer (2014)
Halo Structure at High-z: Confusion in the Literature

- NFW, $z=5.00$
- Full population

- NFW, $z=5.00$
- Relaxed haloes

- $C_{\text{vir}}$ vs. $\log M_{\text{vir}} [M_\odot/h]$
- $C_{\text{vir}}$ vs. $\log M_{\text{vir}} [M_\odot/h]$

- Diemer (2014)
- Dutton (2014)
- Prada (2012)
Suite resolving structures down to $\sim 2 \times 10^6 \ h^{-1} M_\odot$

100 snapshots to $z=5$ (one every 11 Myrs)

Planck-2015 cosmology

Largest run: $2160^3$ particles in a 67.8 $h^{-1}$Mpc box

<table>
<thead>
<tr>
<th>Simulation</th>
<th>$N_p$</th>
<th>$L$ [Mpc/$h$]</th>
<th>$m_p$ [$M_\odot/h$]</th>
<th>$\epsilon$ [kpc/$h$]</th>
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<tr>
<td>Tiamat</td>
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<td>$2.64 \times 10^6$</td>
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<td>0.025</td>
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<tr>
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*Table 1.* Box sizes ($L$), particle counts ($N_p$), particle mass ($m_p$), gravitational softening lengths ($\epsilon$) and integration accuracy parameters ($\eta$) for the Tiamat simulations as well as the cosmology and halo finding codes used for each.
Suite resolving structures down to $\sim 2 \times 10^6 \ h^{-1} M_\odot$

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Table 1. Box sizes ($L$), particle counts ($N_p$), particle mass ($m_p$), gravitational softening lengths ($\epsilon$) and integration accuracy parameters ($\eta$) for the Tiamat simulations as well as the cosmology and halo finding codes used for each.
Quantifying the State of Relaxation

Standard practice: constraints on 3 metrics

1. Centroid Offset
   - $X_{\text{off}} < 7\% R_{\text{vir}}$

2. Virial Ratio
   - $K = \frac{E_{\text{kin}}}{E_{\text{grav}}}$
   - $2K < 1.35|U|$

3. Substructure Fraction
   - $f_{\text{sub}} = \frac{\sum n_{p,i} ; i=1 \text{ to } n-1}{\sum n_{p,i} ; i=0 \text{ to } n-1} < 0.1$

Neto et al, 2007
Quantifying the State of Relaxation

Consider relaxation following 3 dynamical events:

1. \( \frac{1}{2} \)-mass Formation
2. 3:1+ Mergers
3. 10:1+ Mergers
Relaxation Following Formation or Mergers

1. Centroid Offset
2. Virial Ratio
3. Sub. Fraction

Time [units of dynamical time]

DRAGONS I: Poole et al, submitted
Relaxation Following Formation or Mergers

1. Centroid Offset
2. Virial Ratio
3. Sub. Fraction

Time [units of dynamical time]

- $\phi = \frac{2K}{\Pi}$
- $f_{sub}$
- $x_{off}$

10$^{10.5}$ to 10$^{11}$ M⊙

$z \sim 5$

Halos

DRAGONS I: Poole et al, submitted
Quantifying the State of Relaxation

We define a new set of relaxation criteria:

\[ \tau_{\text{relax}} \sim \]

- \( \frac{1}{2} \)-mass Formation
- 3:1+ Mergers
- 10:1+ Mergers
Quantifying the State of Relaxation

We define a new set of relaxation criteria:

\[ \tau_{\text{relax}} > 1.5 \]
\[ \tau_{\text{relax}} > 2 \]

\( \frac{1}{2} \)-mass Formation

10:1+ Mergers
Quantifying the State of Relaxation

We define a new set of relaxation criteria:

Independent of mass!

\[ \tau_{\text{relax}} > 1.5 \]

\[ \tau_{\text{relax}} > 2 \]

½-mass Formation

10:1+ Mergers
Dynamical Ages

Formation is fast; mergers frequent

Time since formation

Time since 3:1+ merger

Time since 10:1+ merger

DRAGONS I: Poole et al., submitted
Relaxed Fractions

Very few halos are relaxed at high-z

Fraction Relaxed from 10:1+ Mergers

Red Fraction meeting the Neto+07 criteria
Blue Fraction meeting our merger criterion

20%
Halo Structure at High-z: Tiamat Results

\[ \log M_{\text{vir}} \left[ M_\odot/h \right] \]

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**NFW, z=5.00**
- Full population
- Diemer (2014)

**NFW, z=5.00**
- Relaxed haloes
- Dutton (2014)
- Prada (2012)
- Ludlow et al (2014)
... an interesting aside ...
Large-Scale Phase Space Substructures at High-$z$

Configuration Space  Velocity Space

ROCKSTAR (phase-space) Subhalos

Subfind (config.-space) Subhalos

Yellow: Most Massive Substructure

Cyan: 2nd Most Massive Substructure
The Dynamical Lives of High Redshift Galaxies

- Structure and dynamical evolution across galactic scales: REMARKABLY invariant at z>5
- Evolution of relaxation metrics: independent of mass
- NFW/Einasto concentrations: insensitive to mass
- Only ~20% of galactic halos are relaxed at z>5
- Large-scale phase-space substructures: ubiquitous