

# Why Do Dark Matter Haloes Die Together?

The Causes of Assembly Bias at Galaxy Masses

Phil Mansfield  
University of Chicago

# Overview

Build an assembly bias “cheatsheet”

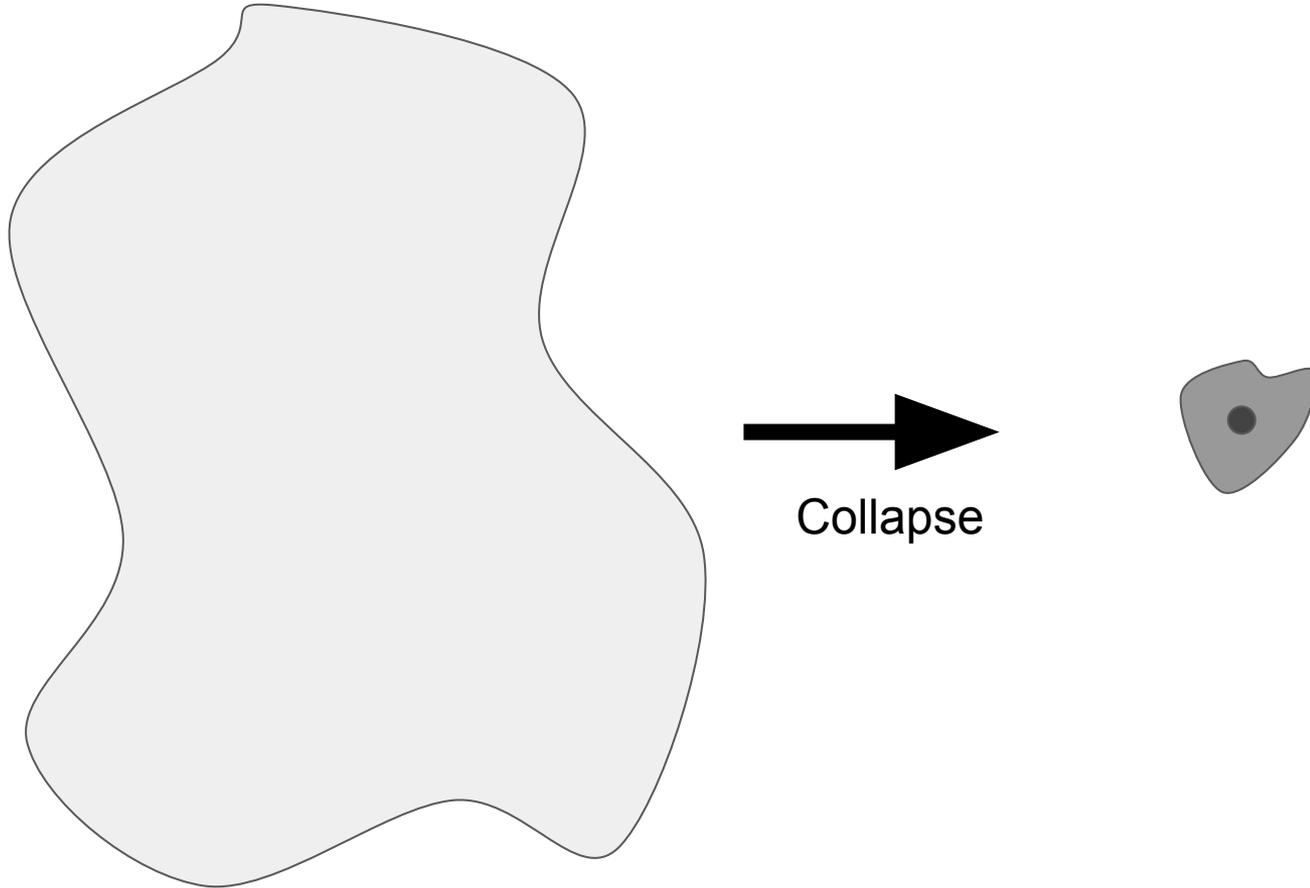
Review explanations for assembly bias

Make those explanations compete with each other

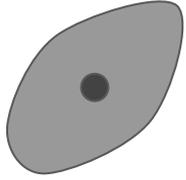
# Building An Assembly Bias Cheatsheet

# The Assembly Bias Cheatsheet

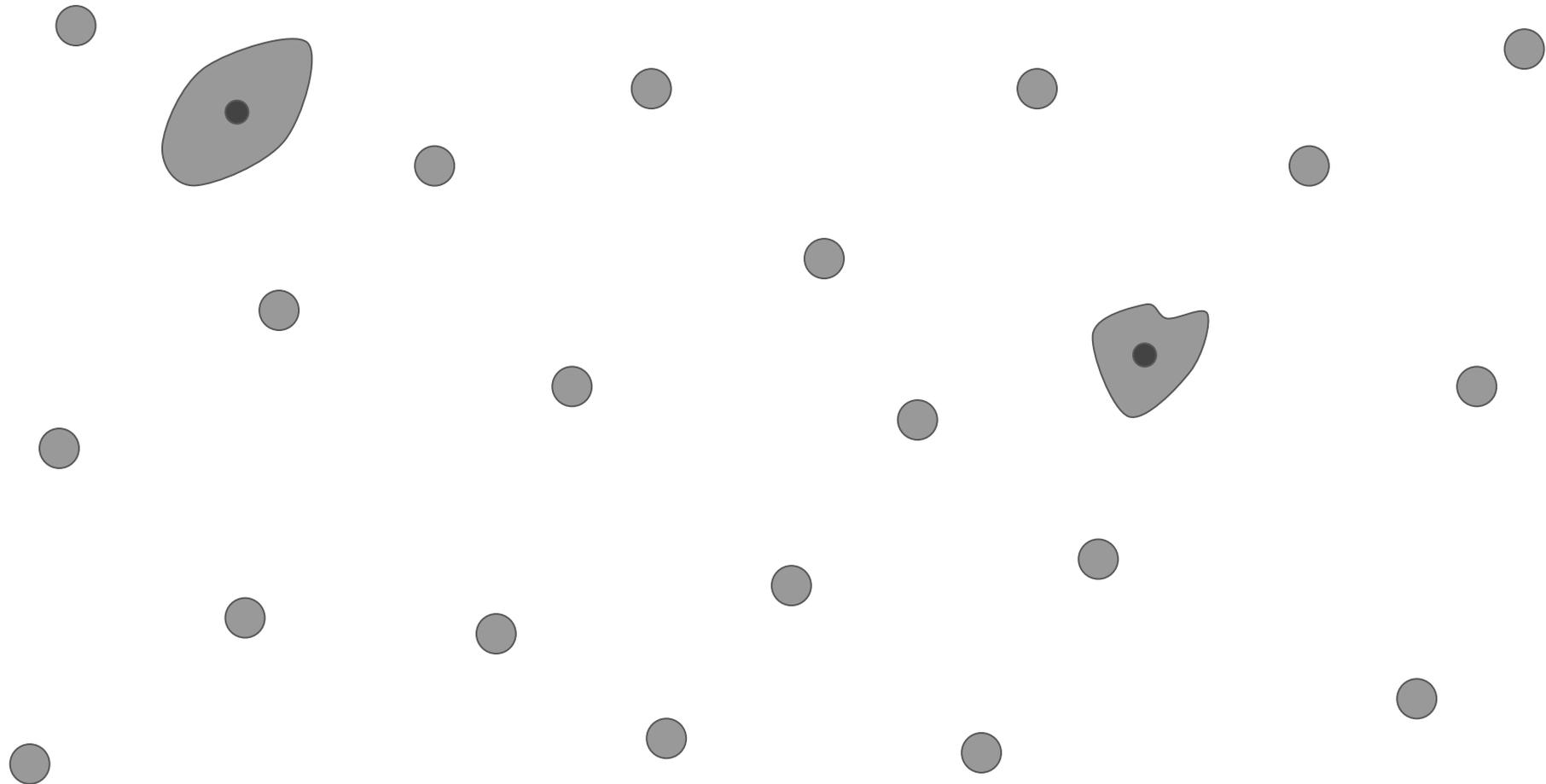
# Dark Matter Lives Inside of Dark Matter Haloes



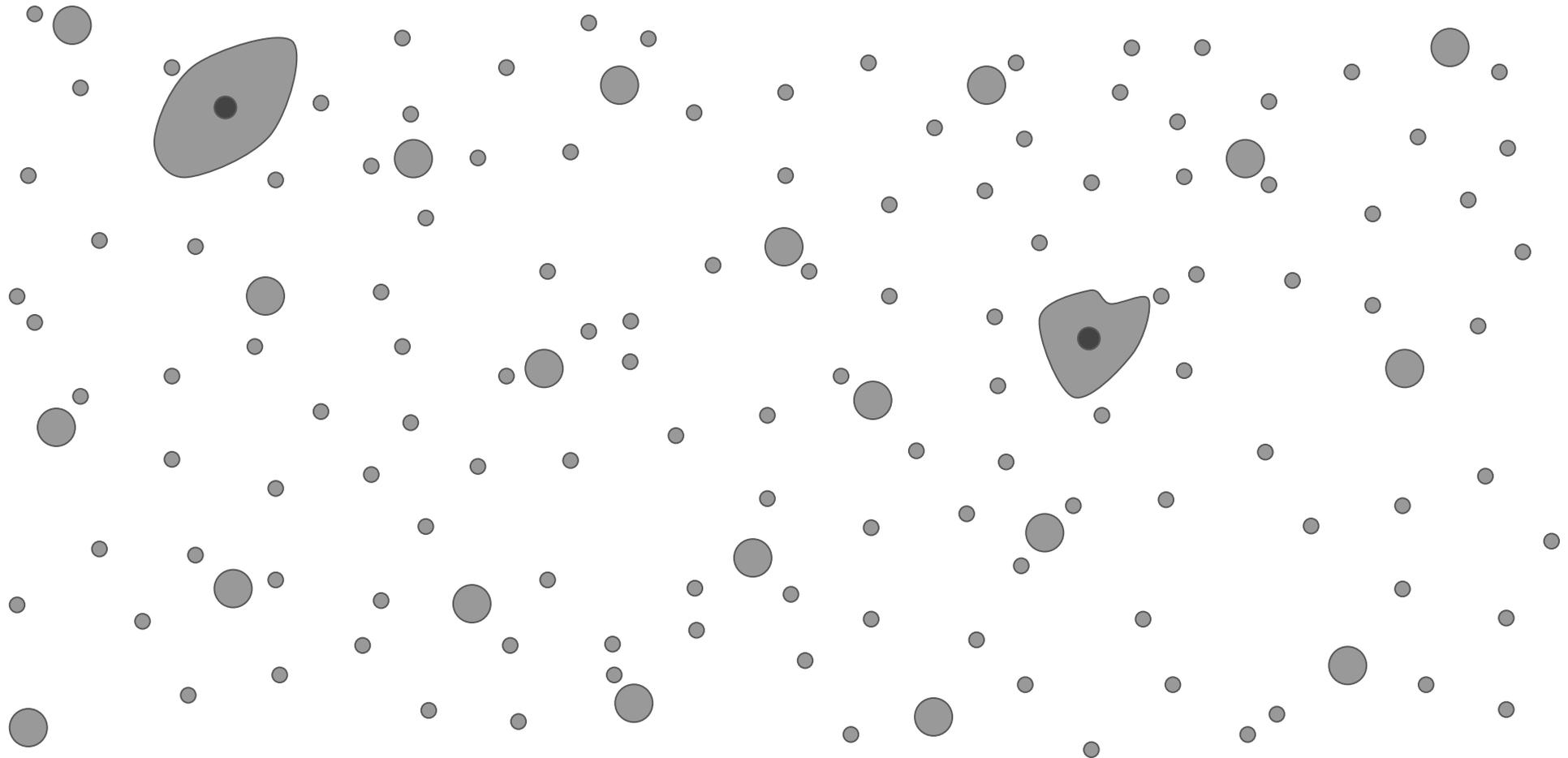
# Dark Matter Lives Inside of Dark Matter Haloes



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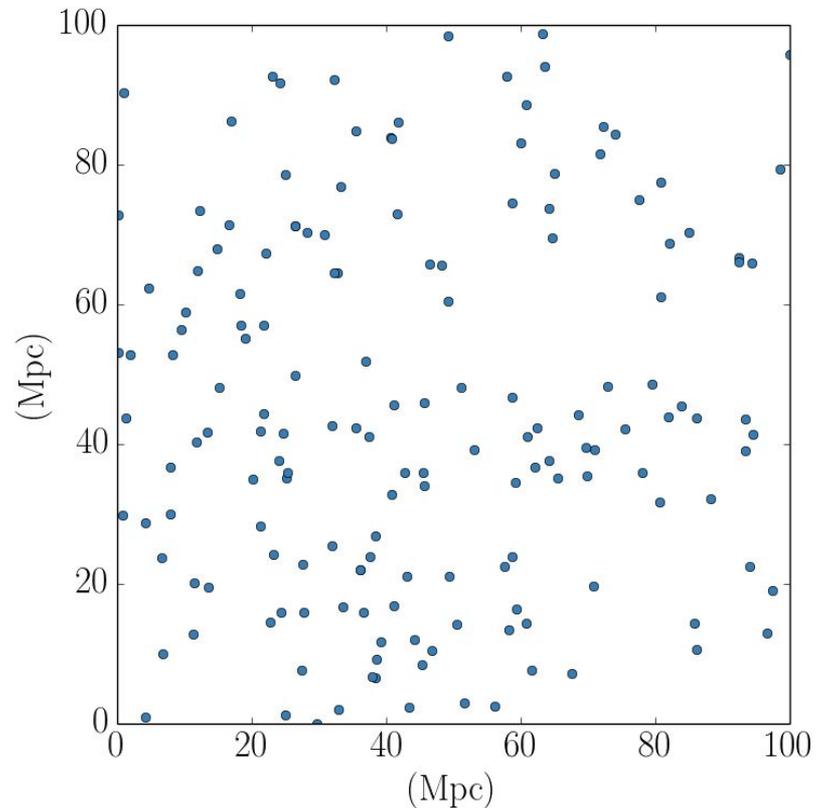
# Dark Matter Lives Inside of Dark Matter Haloes



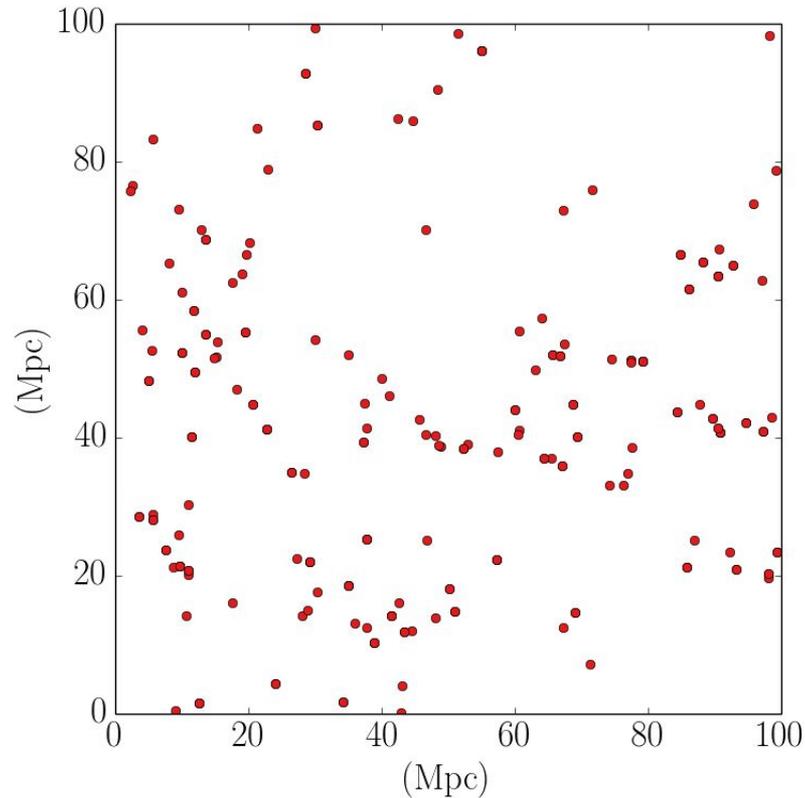
# The Assembly Bias Cheatsheet

1. Dark matter lives inside of dark matter haloes

# Big haloes cluster more than small haloes

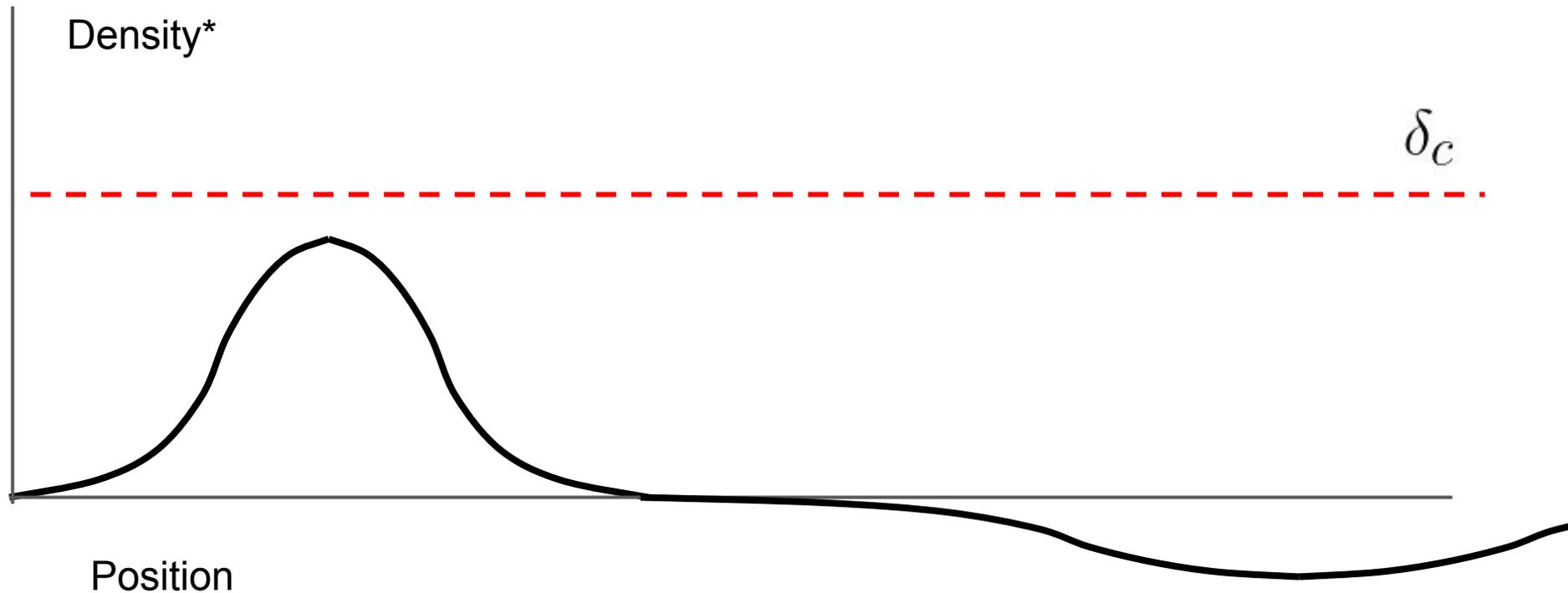


Galaxy-Mass Haloes



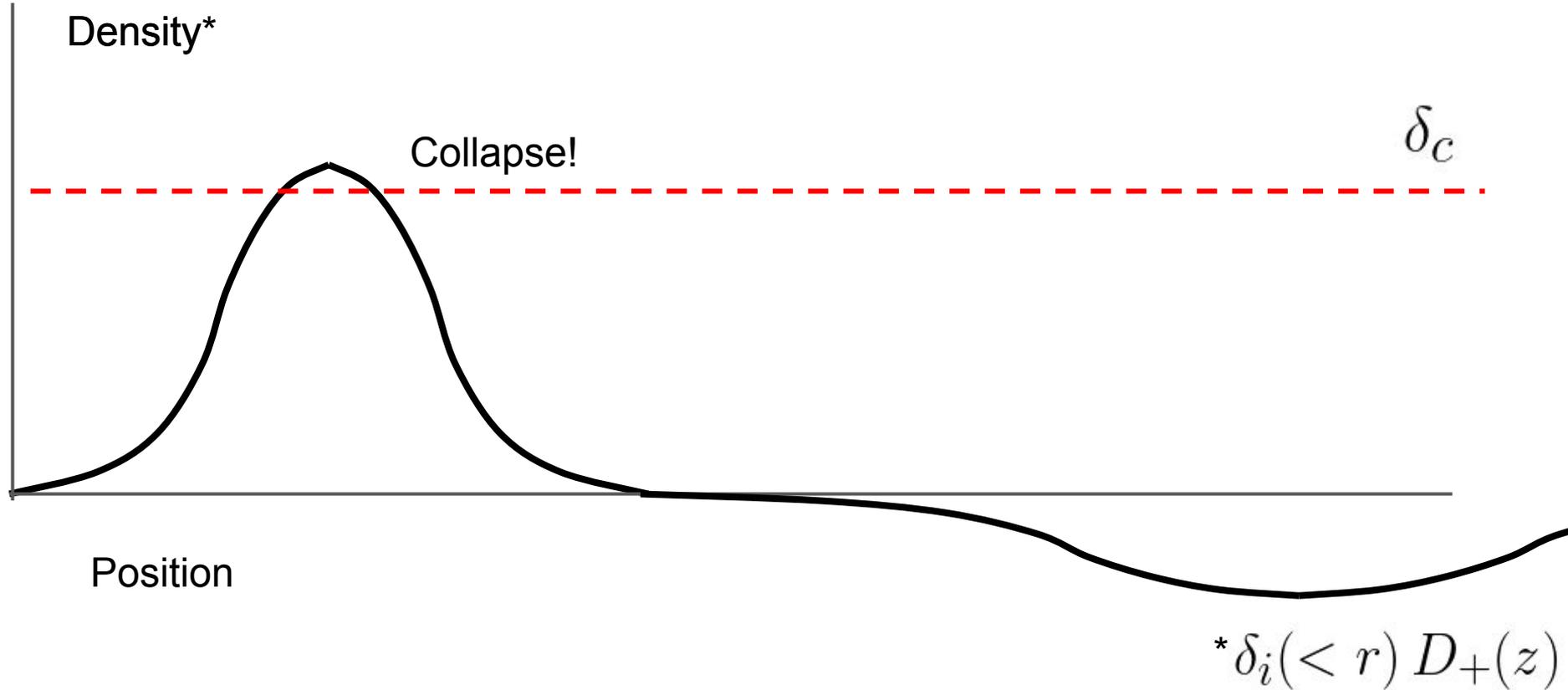
Group-Mass Haloes

# Why do Big Haloes Cluster More Than Small Haloes?

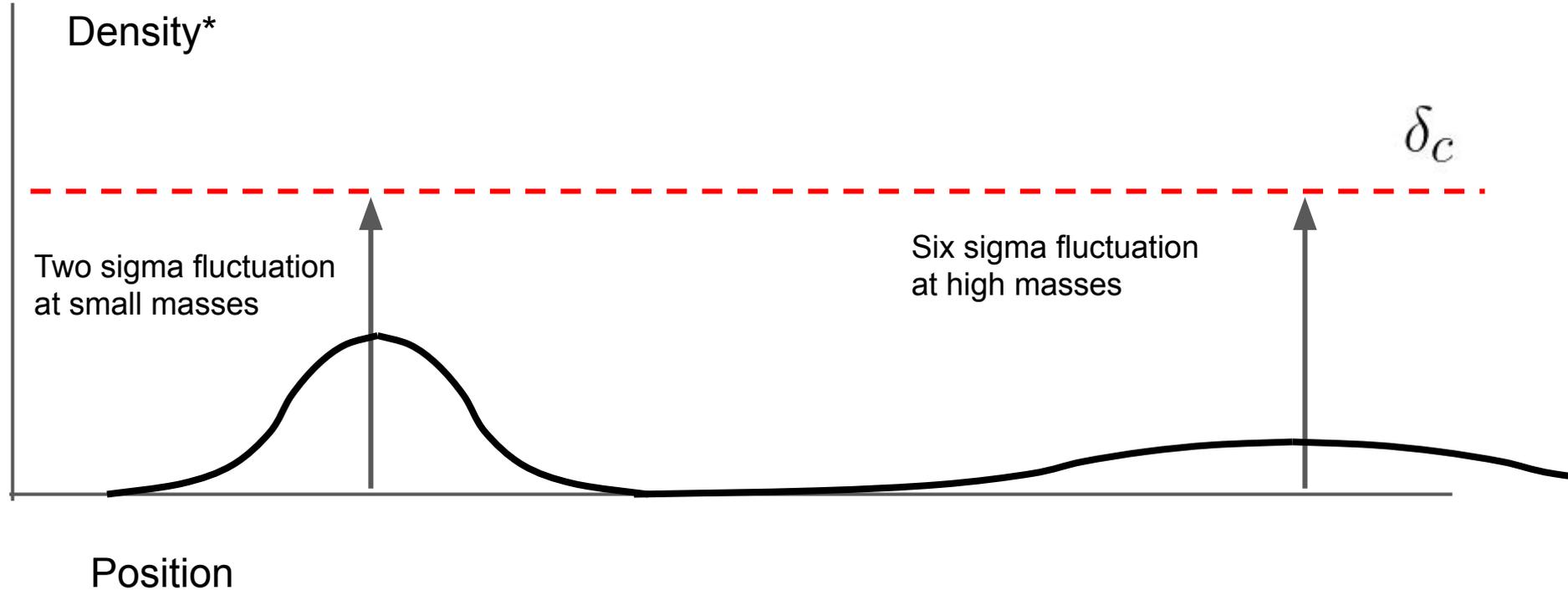


\*  $\delta_i(< r) D_+(z)$

# Why do Big Haloes Cluster More Than Small Haloes?

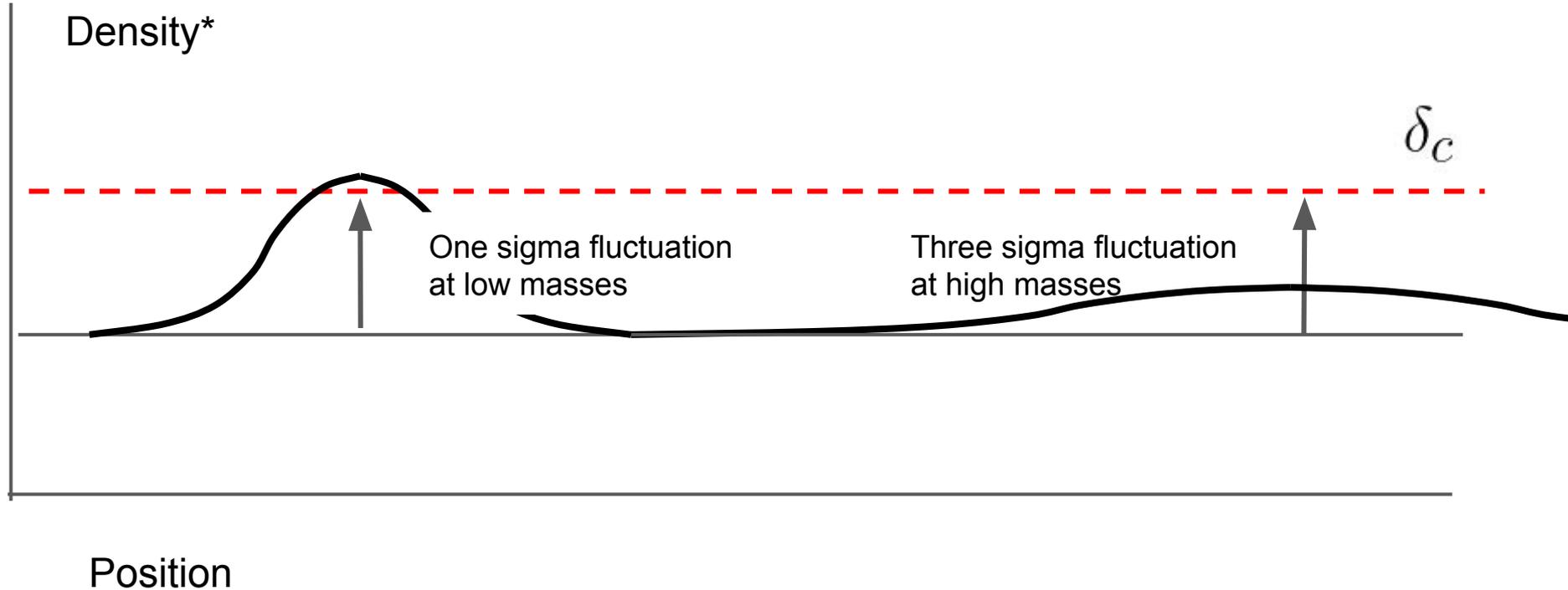


# Why do Big Haloes Cluster More Than Small Haloes?



\*  $\delta_i(< r) D_+(z)$

# Why do Big Haloes Cluster More Than Small Haloes?



\*  $\delta_i(< r) D_+(z)$

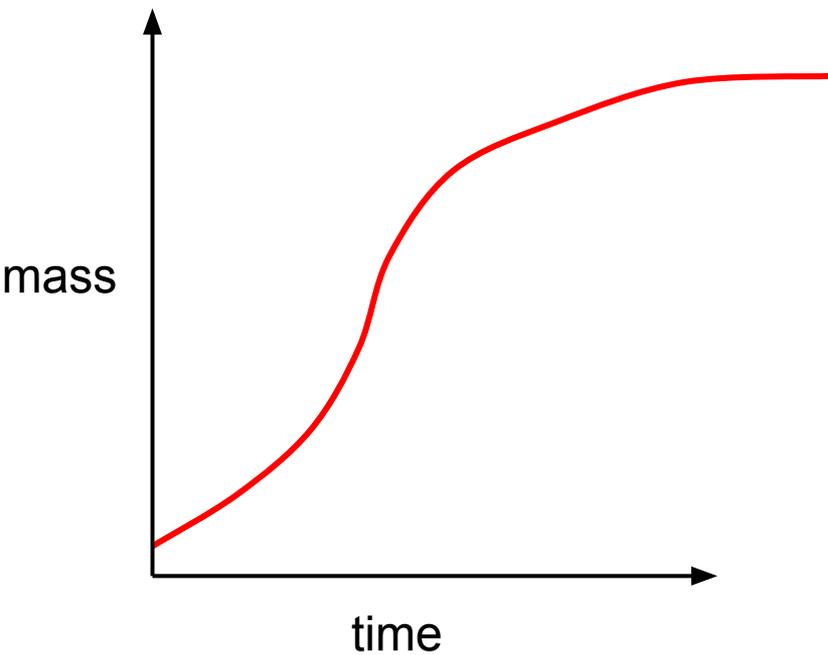
# The Assembly Bias Cheatsheet

1. Dark matter lives inside of dark matter haloes
2. Haloes cluster in a way that depends on mass\*

# Measuring halo age

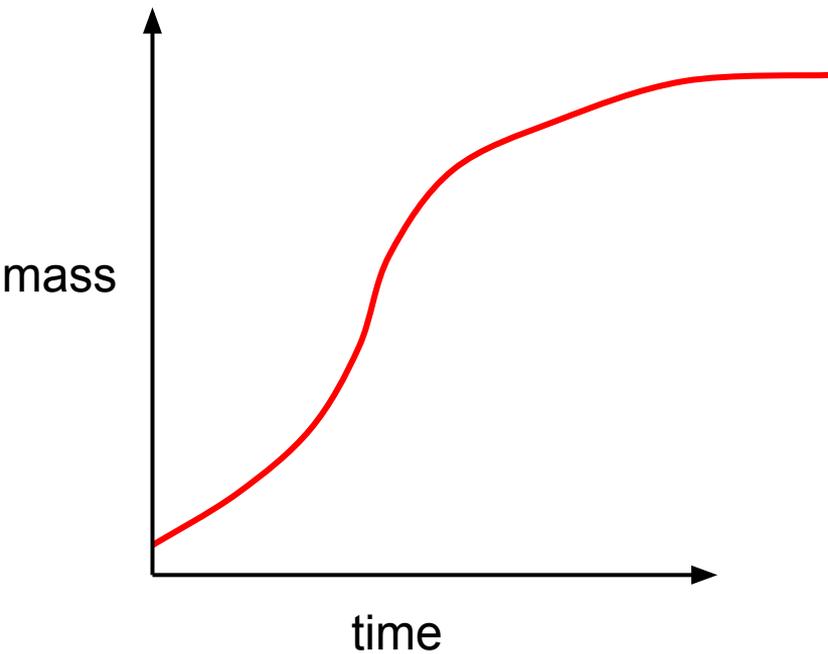
Old/dead halo

Young halo

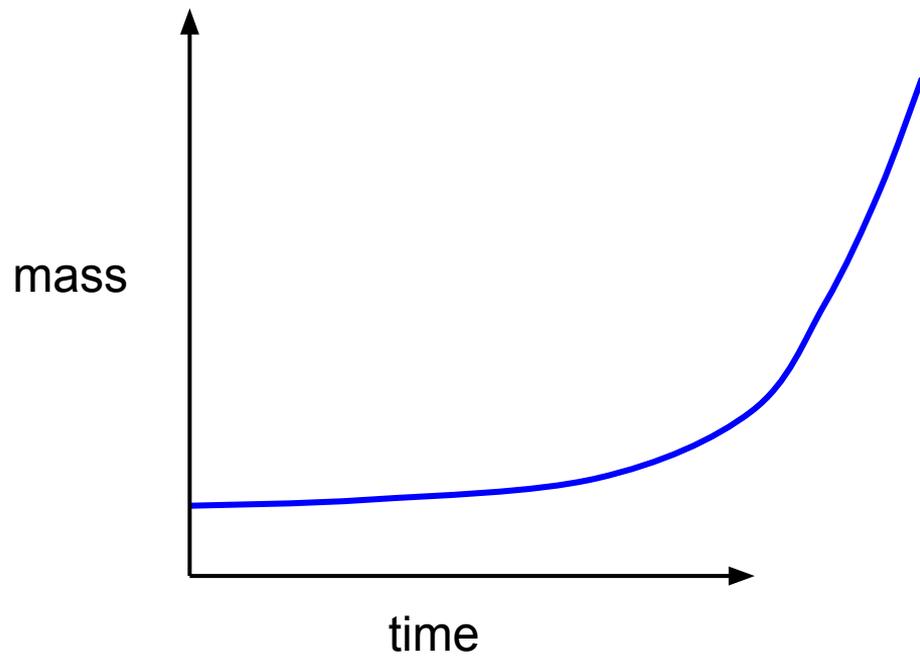


# Measuring halo age

Old/dead halo

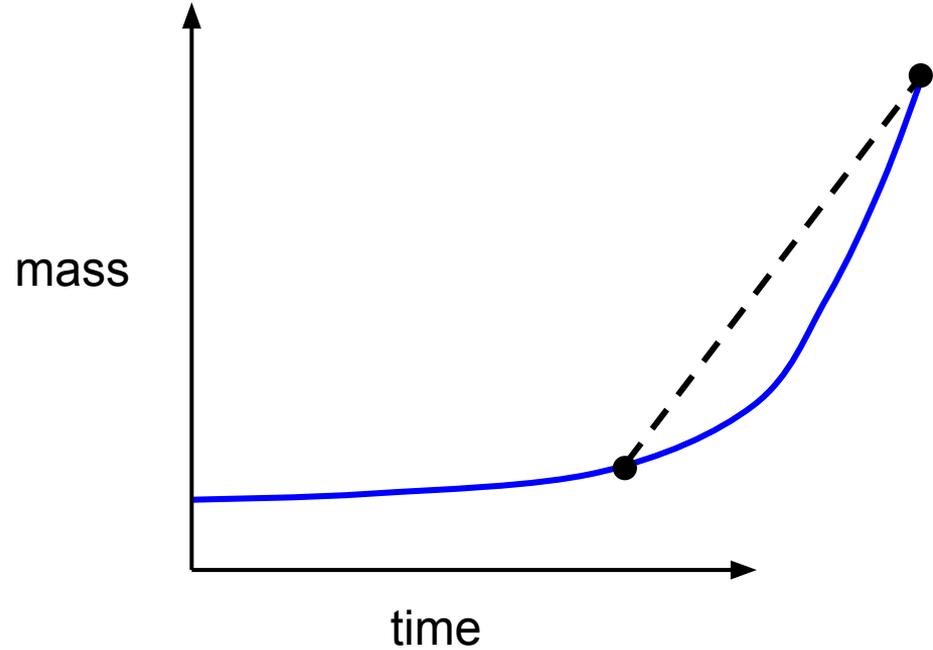


Young halo



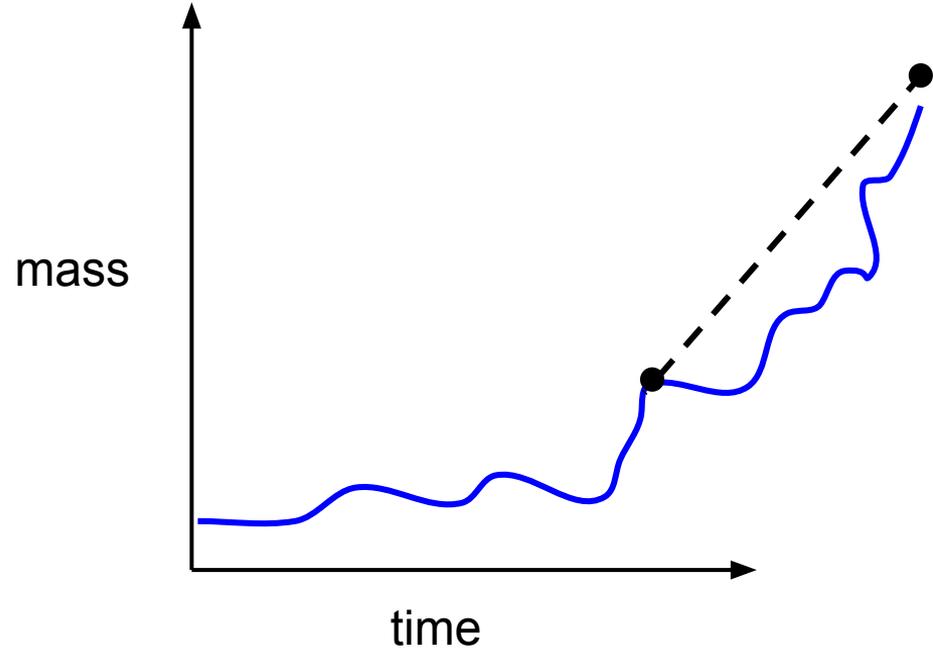
# Measuring halo age

- **Measure the (logarithmic) slope**



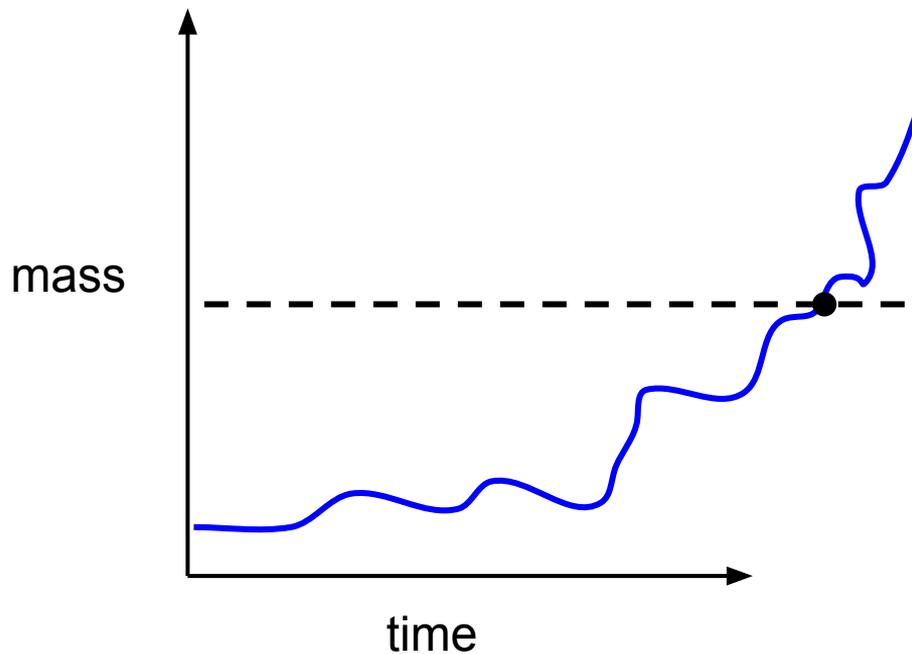
# Measuring halo age

- **Measure the (logarithmic) slope**



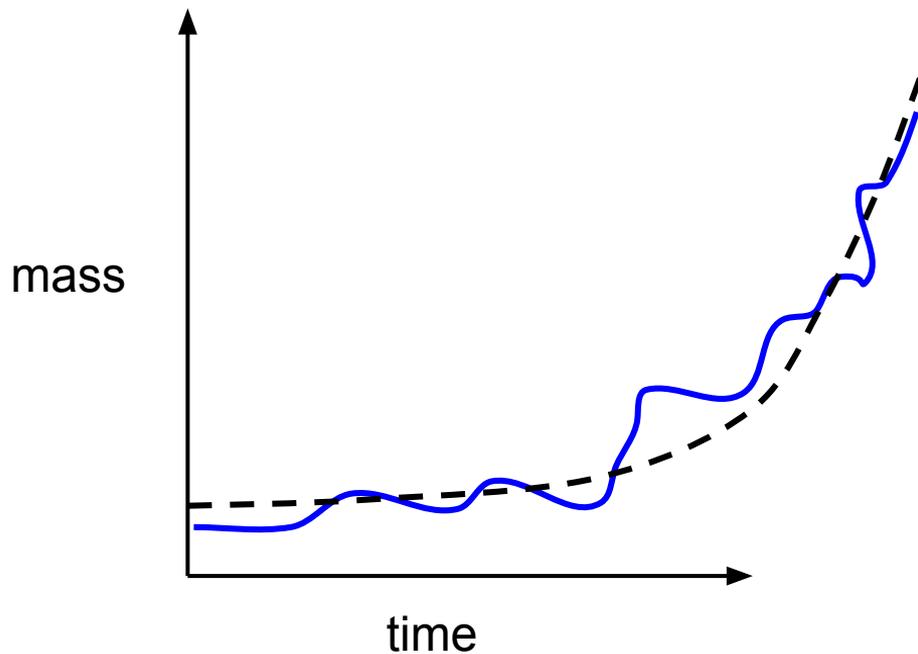
# Measuring halo age

- Measure the (logarithmic) slope
- **Measure when you pass a certain mass threshold**



# Measuring halo age

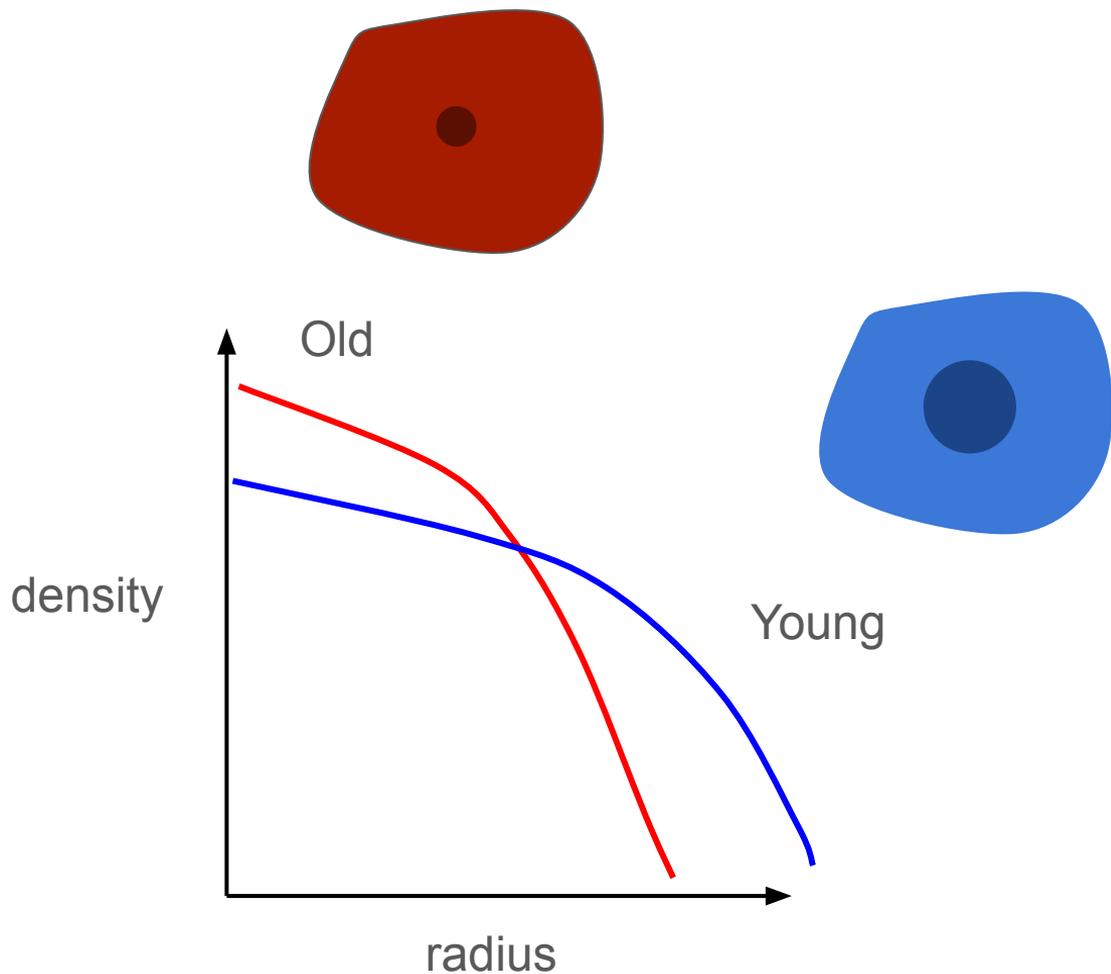
- Measure the (logarithmic) slope
- Measure when you pass a certain mass threshold
- **Fit a functional form to the history and report a parameter**



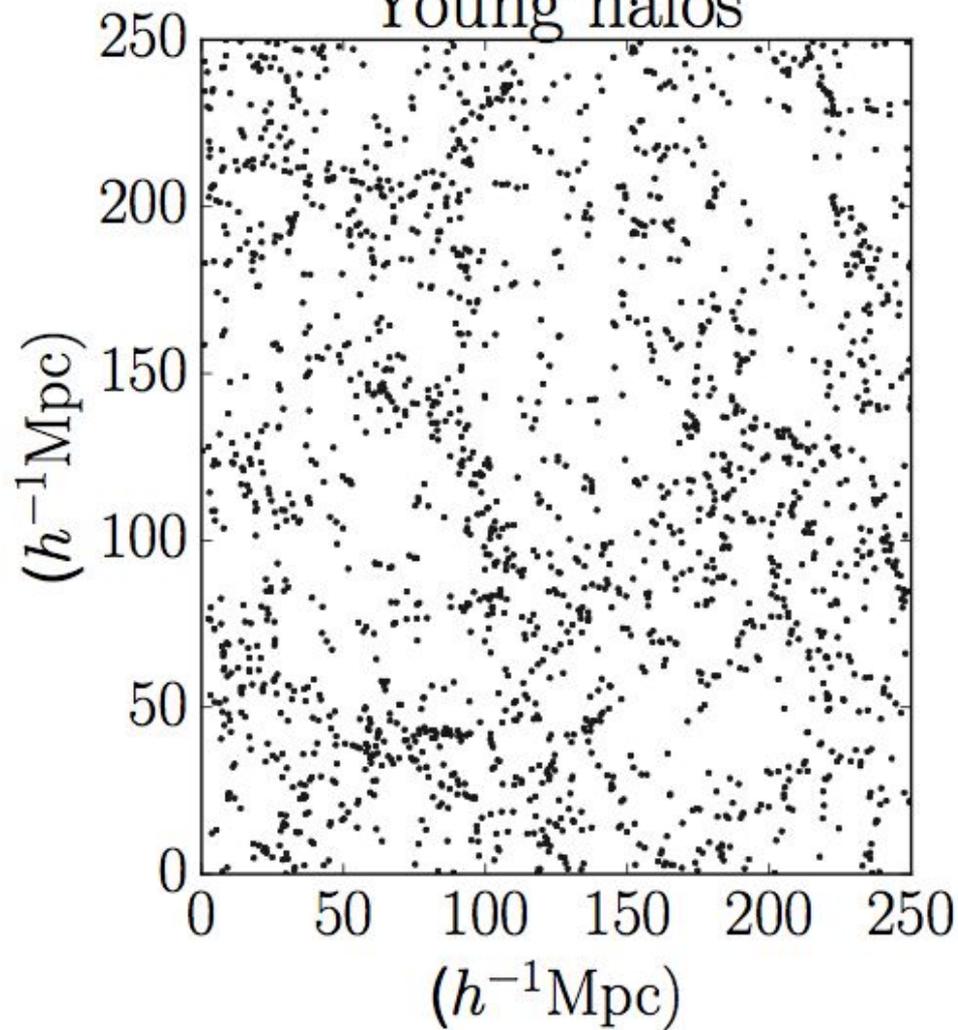
# Measuring halo age

- Measure the (logarithmic) slope
- Measure when you pass a certain mass threshold
- Fit a functional form to the history and report a parameter
- **Use halo concentration**

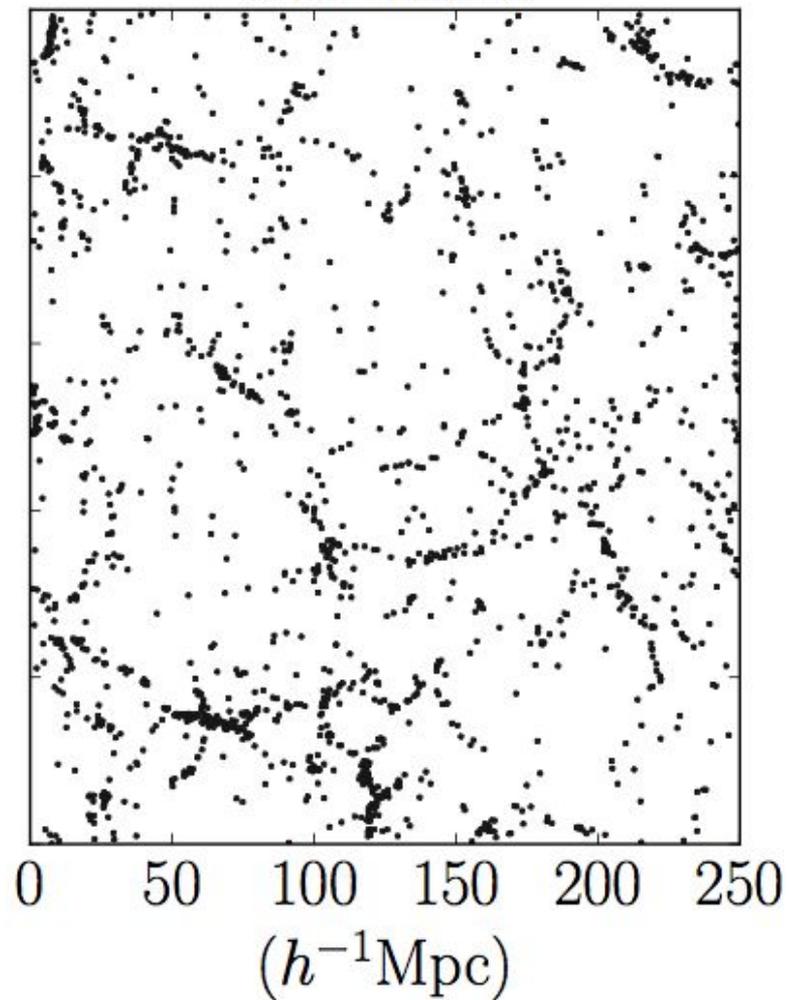
(E.g.: Bullock et al. 2001; Wechsler et al. 2002; Zhao et al. 2003; Lu et al. 2006; Zhao et al. 2009; Dalal et al. 2010; Ludlow et al. 2013, 2014; Diemer & Joyce 2019)



Young halos



Old halos

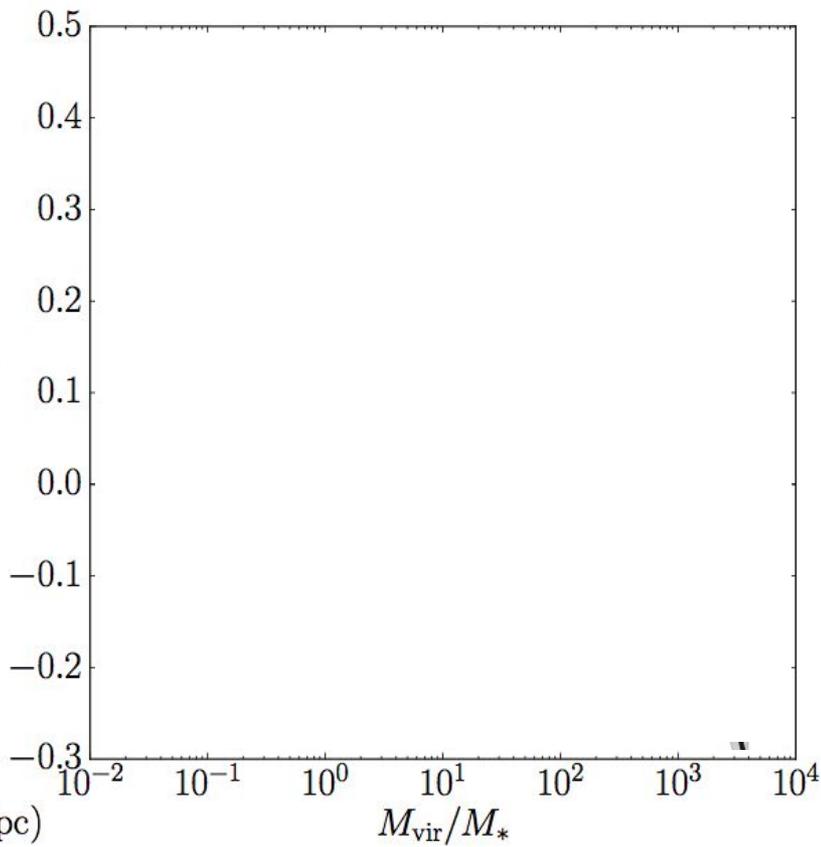


# The Assembly Bias Cheatsheet

1. Dark matter lives inside of dark matter haloes
2. Haloes cluster in a way that depends on mass\*
3. ...but at a constant mass, clustering also depends on age\*\*

# Halo Clustering Depends on Halo Age

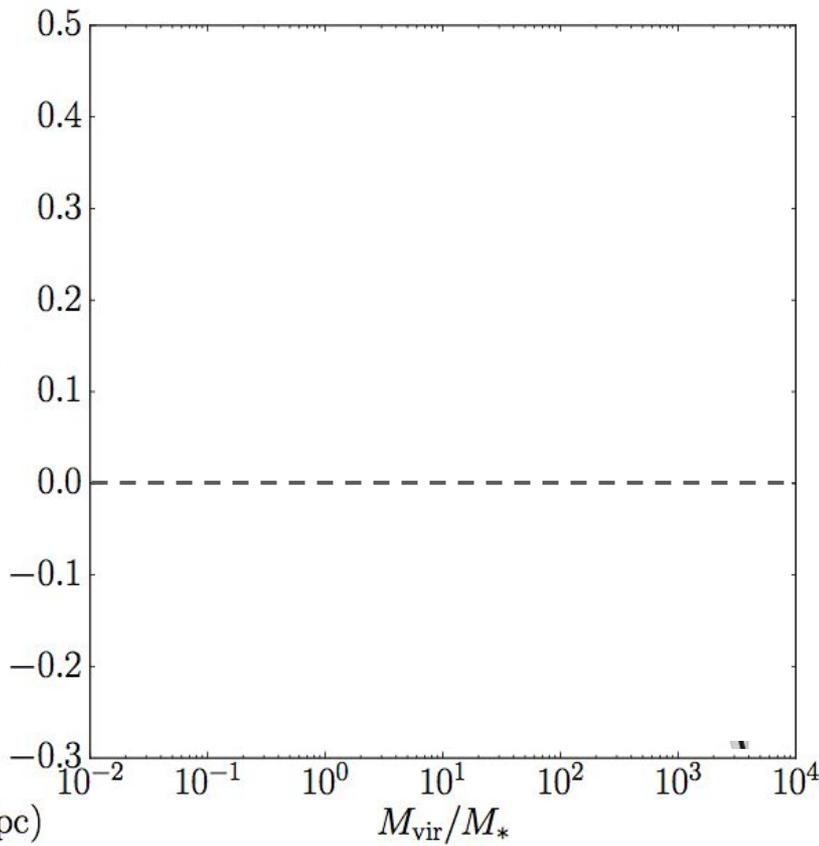
Assembly Bias  
Strength\*



\*  $\text{MCF}(4 h^{-1} \text{ Mpc} < R < 8 h^{-1} \text{ Mpc})$

# Halo Clustering Depends on Halo Age

Assembly Bias  
Strength\*



Older haloes cluster  
more than younger  
haloes

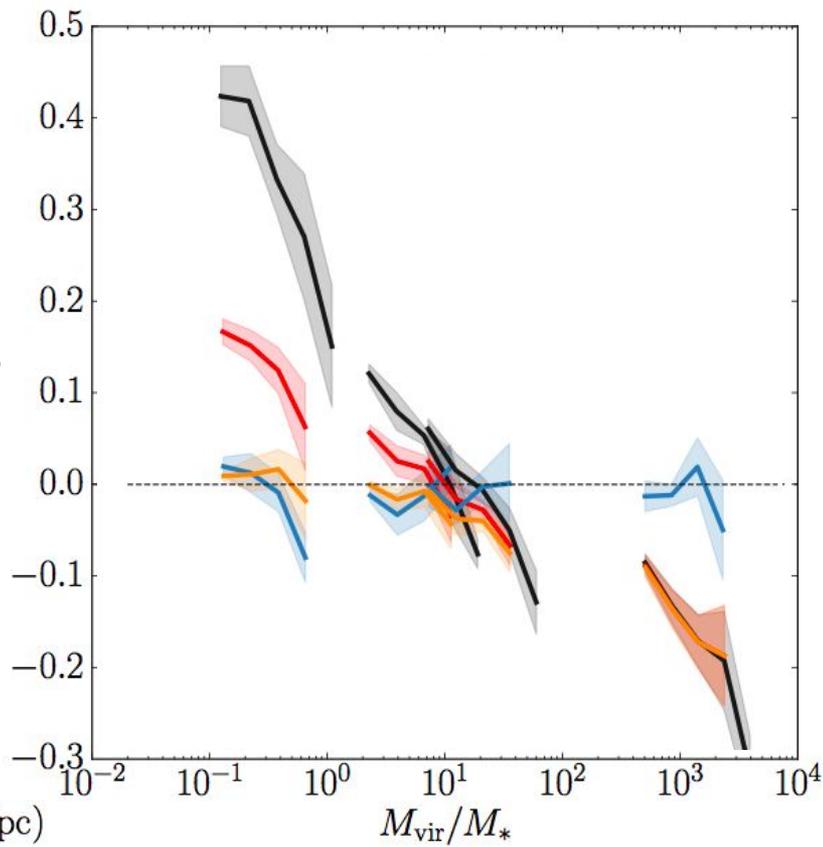
No assembly bias

Younger haloes  
cluster more than  
older haloes

\*  $\text{MCF}(4 h^{-1} \text{ Mpc} < R < 8 h^{-1} \text{ Mpc})$

# Halo Clustering Depends on Halo Age

Assembly Bias  
Strength\*



\*  $\text{MCF}(4 h^{-1} \text{ Mpc} < R < 8 h^{-1} \text{ Mpc})$

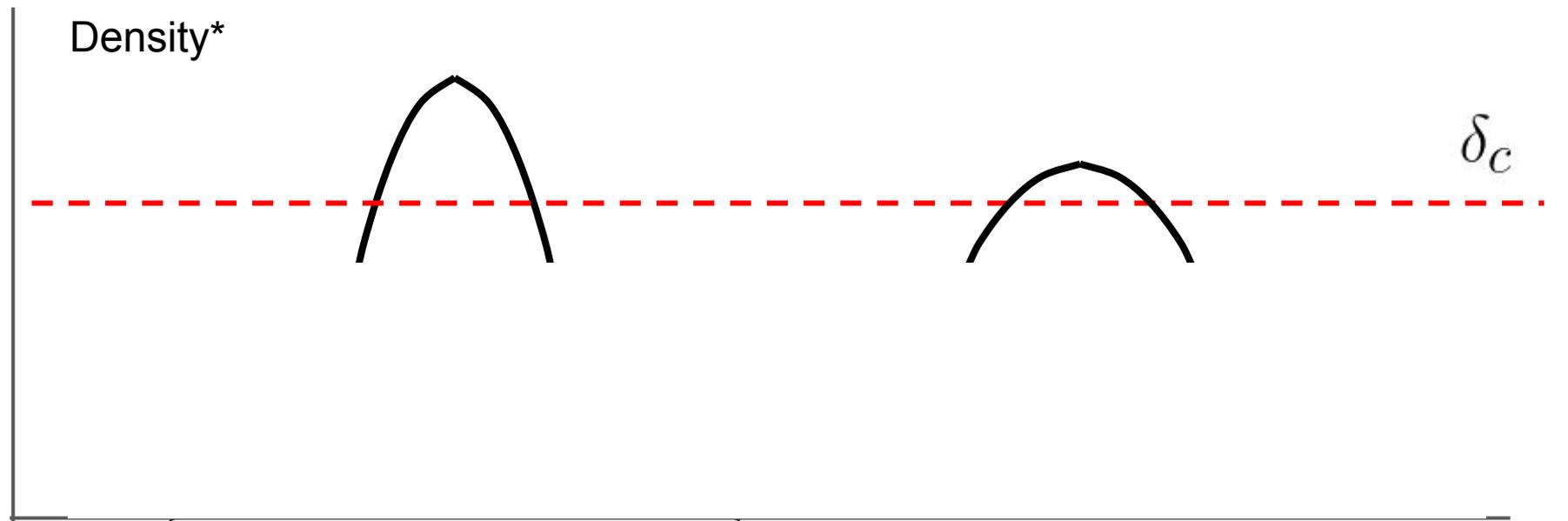
# The Assembly Bias Cheatsheet

1. Dark matter lives inside of dark matter haloes
2. Haloes cluster in a way that depends on mass\*
3. ...but at a constant mass, clustering also depends on age\*\*

At high masses, *young*<sup>\*\*\*</sup> haloes cluster more strongly

At low masses, *old* haloes cluster more strongly

# Why does clustering depend on age?



Position

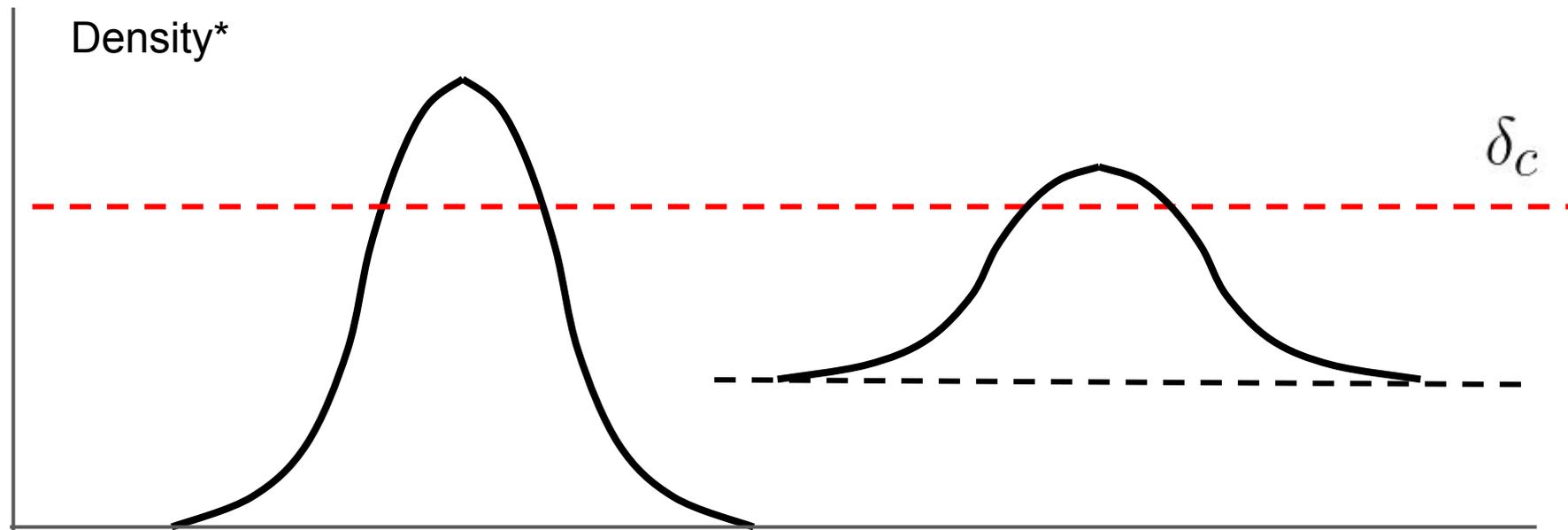
$$* \delta_i(< r) D_+(z)$$

(Dalal et al. 2008)

(See also: Desjacques 2008; Musso & Sheth 2012; Castorina & Sheth 2013)

(See also: Mao et al. 2018; Chue et al. 2018)

# Why does clustering depend on age?



$$* \delta_i(< r) D_+(z)$$

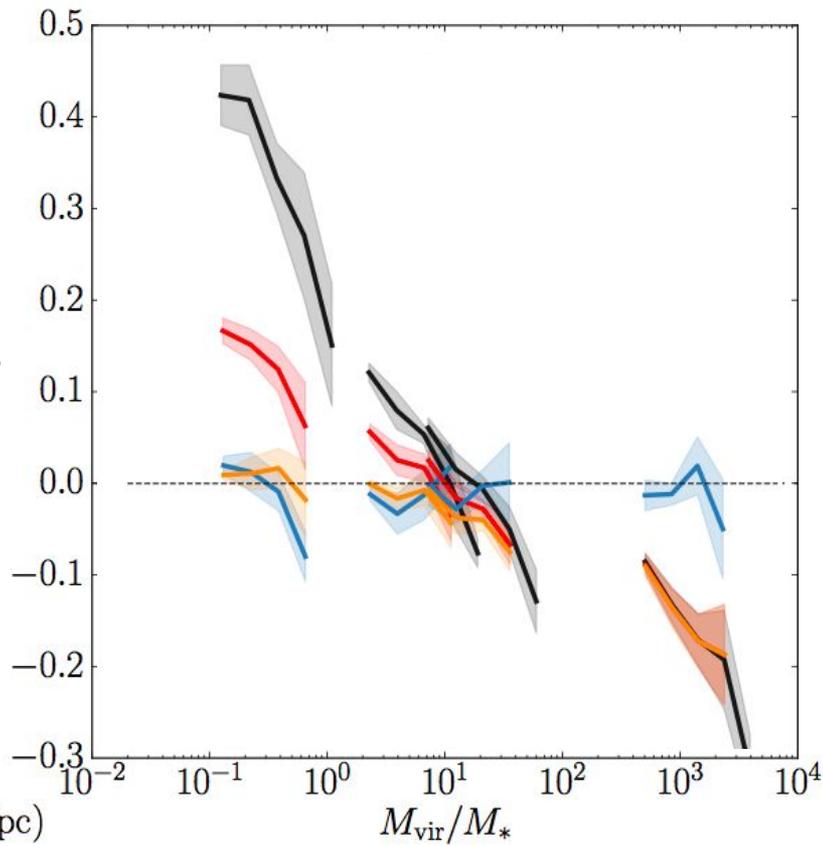
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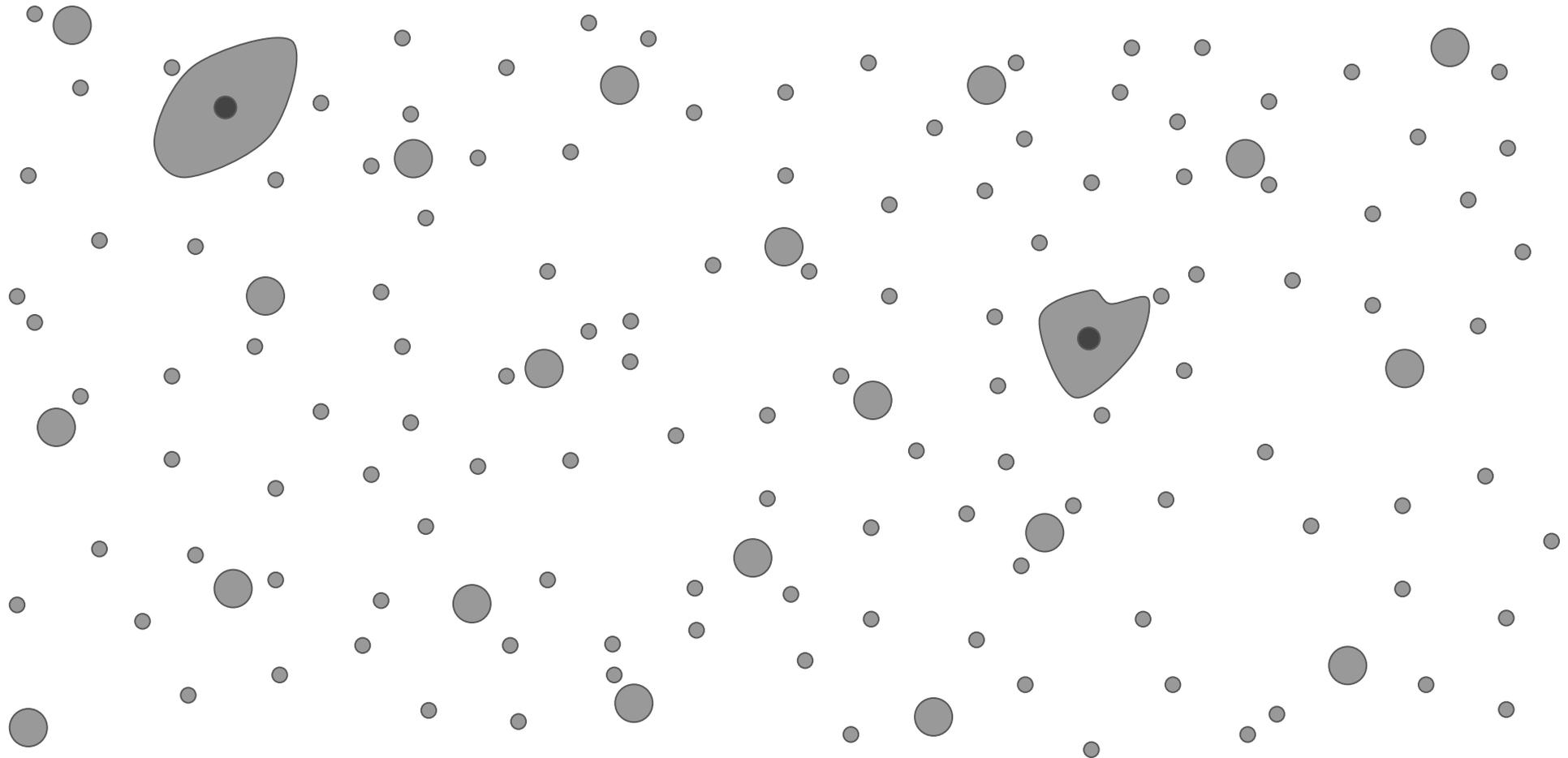
# Why does clustering depend on age?

Assembly Bias  
Strength\*



\*  $\text{MCF}(4 h^{-1} \text{ Mpc} < R < 8 h^{-1} \text{ Mpc})$

# Why does clustering depend on age?



# The Assembly Bias Cheatsheet

1. Dark matter lives inside of dark matter haloes
2. Haloes cluster in a way that depends on mass\*
3. ...but at a constant mass, clustering also depends on age\*\*

At high masses, *young*\*\*\* haloes cluster more strongly because of peak curvature\*\*\*\*

At low masses, *old* haloes cluster more strongly because of  $\sim \sqrt{\rho}$

# The Assembly Bias Cheatsheet

1. Dark matter lives inside of dark matter haloes
2. Haloes cluster in a way that depends on mass\*
3. ...but at a constant mass, clustering also depends on age\*\*

1. Galaxies live at the center of dark matter haloes

At high masses, *young*\*\*\* haloes cluster more strongly because of peak curvature\*\*\*\*

At low masses, *old* haloes cluster more strongly because of  $\sim \sqrt{\rho}$

# The Assembly Bias Cheatsheet

1. Dark matter lives inside of dark matter haloes
2. Haloes cluster in a way that depends on mass\*
3. ...but at a constant mass, clustering also depends on age\*\*

1. Galaxies live at the center of dark matter haloes
2. Halo mass is the main thing that determines galaxy properties

At high masses, *young*<sup>\*\*\*</sup> haloes cluster more strongly because of peak curvature<sup>\*\*\*\*</sup>

At low masses, *old* haloes cluster more strongly because of  $\sim \sqrt{\rho}$

# The Assembly Bias Cheatsheet

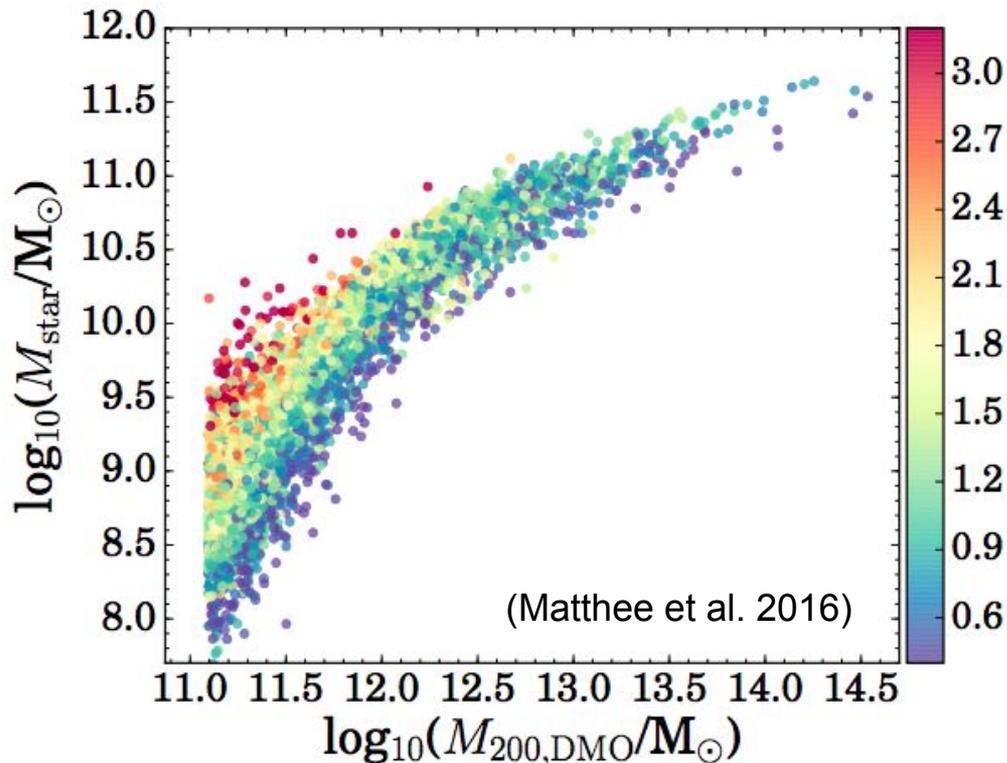
- |  |  |
|--|--|
| 1. Dark matter lives inside of dark matter haloes              | 1. Galaxies live at the center of dark matter haloes             |
| 2. Haloes cluster in a way that depends on mass*               | 2. Halo mass is the main thing that determines galaxy properties |
| 3. ...but at a constant mass, clustering also depends on age** | 3. ...but galaxy properties probably also depend on age          |

At high masses, *young*<sup>\*\*\*</sup> haloes cluster more strongly because of peak curvature<sup>\*\*\*\*</sup>

At low masses, *old* haloes cluster more strongly because of  $\sim \sqrt{\rho}$

# The Assembly Bias Cheatsheet

1. Dark matter
2. Haloes
3. ...but also depend



at the center of dark  
 the main thing that  
 any properties  
 properties probably  
 1 age

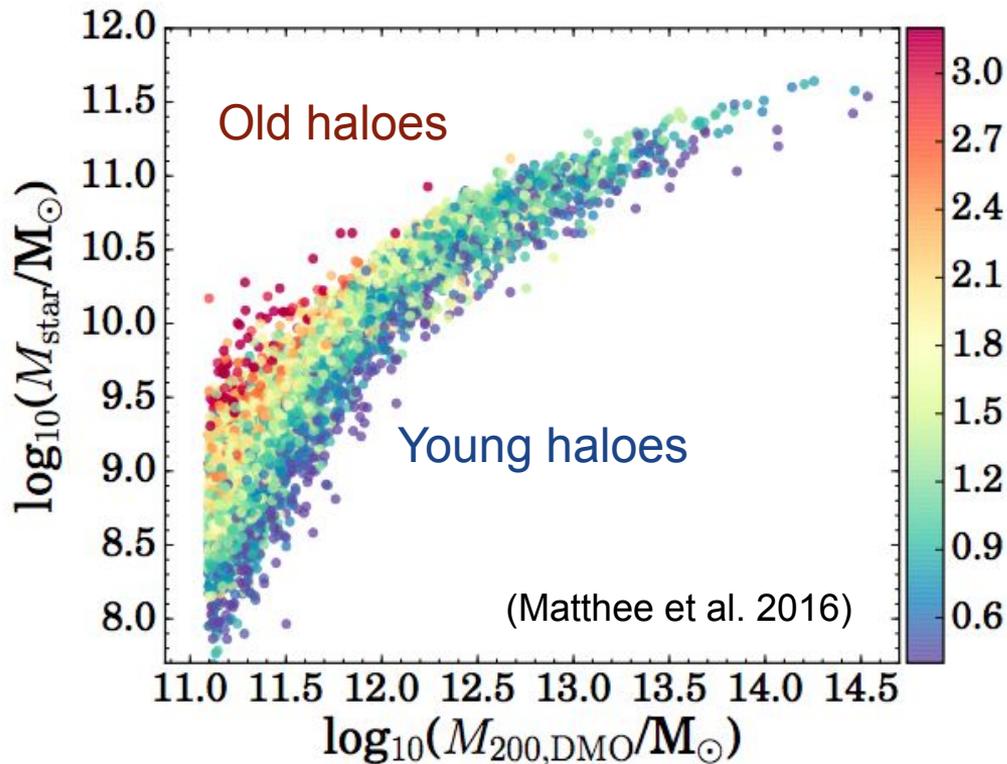
At high masses

size of peak curvature \*\*\*\*

At low masses, old haloes cluster more strongly because of  $\sim \sqrt{\sigma_8}$

# The Assembly Bias Cheatsheet

1. Dark matter halo mass
2. Halo assembly time depends on mass
3. ...but assembly time also depends on environment



At the center of dark matter haloes, the main thing that determines halo properties probably is age.

At high masses:

size of peak curvature \*\*\*\*

At low masses, *old* haloes cluster more strongly because of  $\sim \frac{1}{M}$

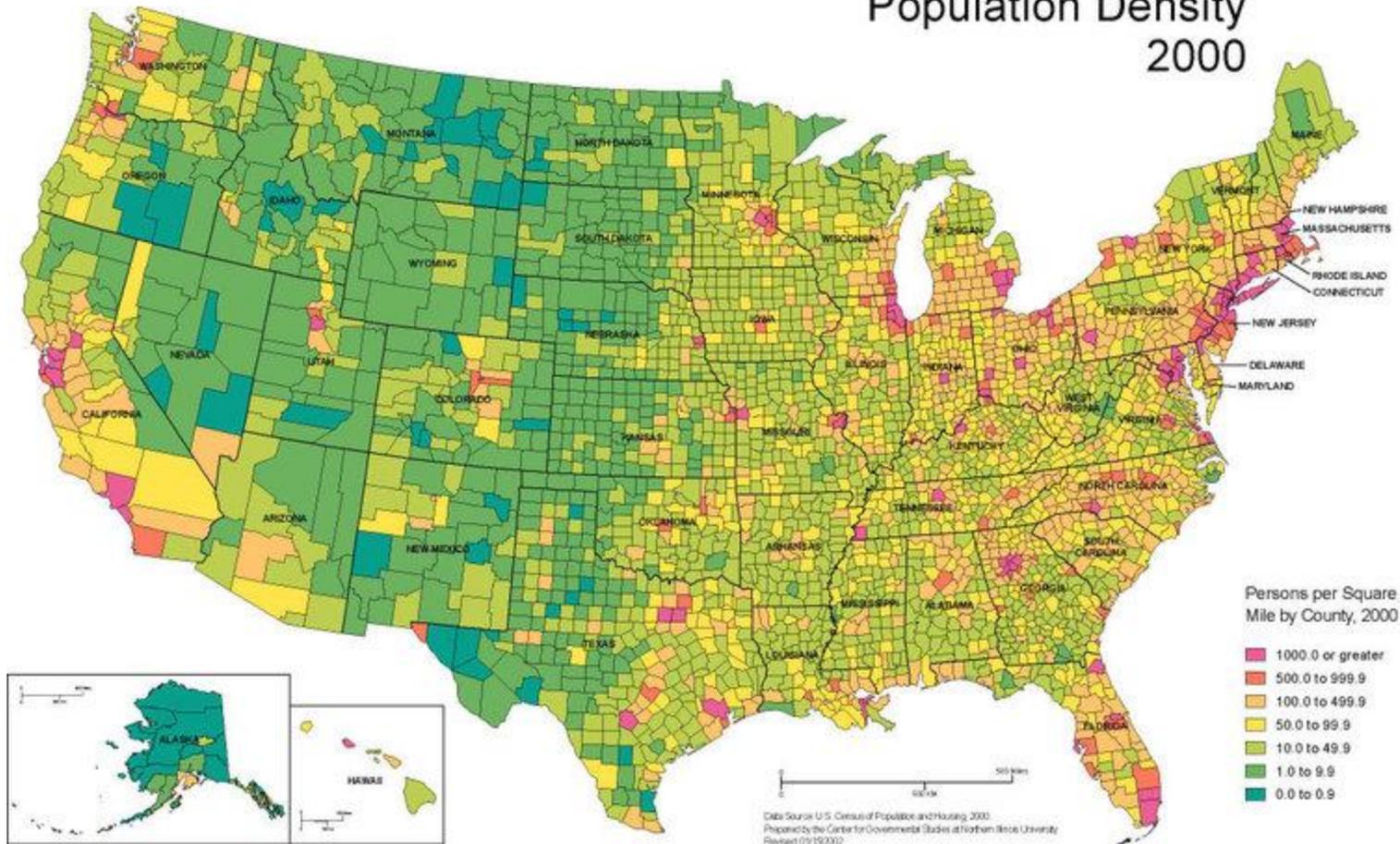
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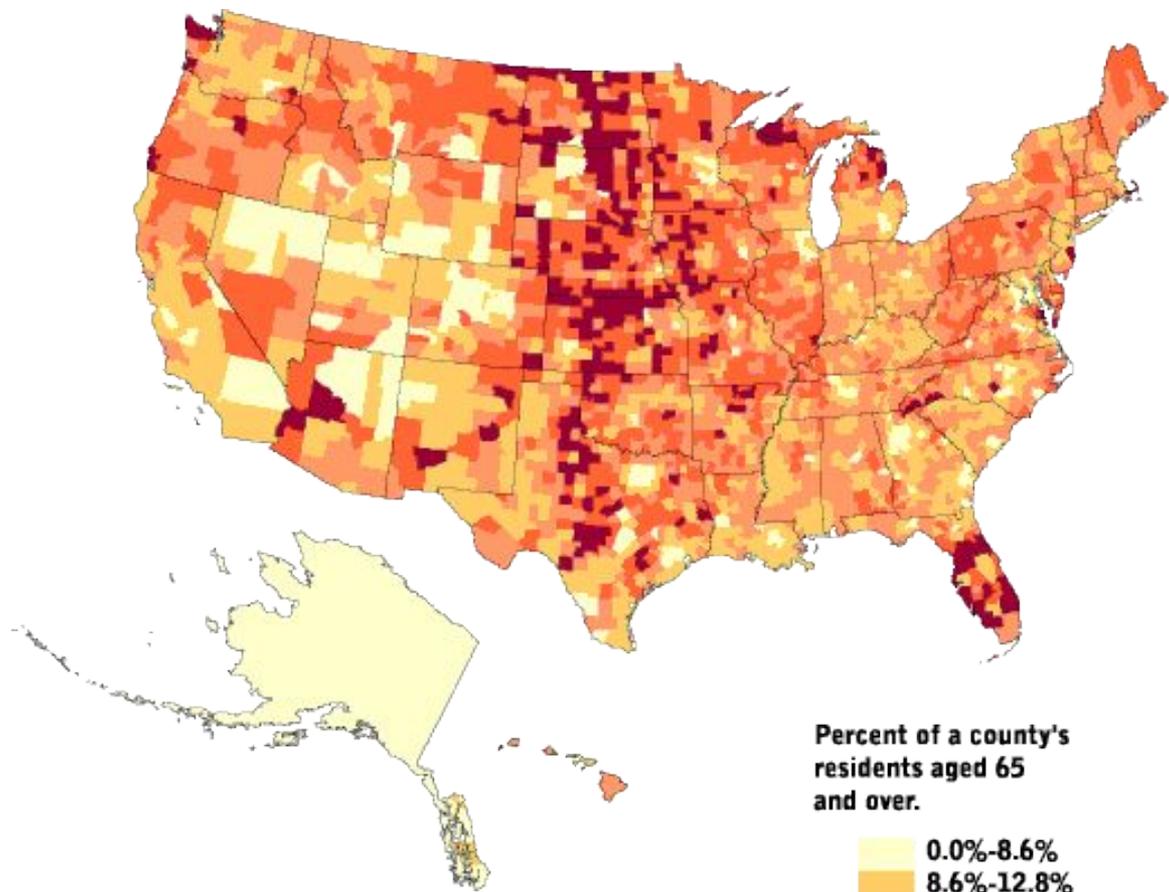
- |   |   |
|---|---|
| <ol style="list-style-type: none"><li>1. Dark matter lives inside of dark matter haloes</li><li>2. Haloes cluster in a way that depends on mass*</li><li>3. ...but at a constant mass, clustering also depends on age**</li></ol> | <ol style="list-style-type: none"><li>1. Galaxies live at the center of dark matter haloes</li><li>2. Halo mass is the main thing that determines galaxy properties</li><li>3. ...but galaxy properties probably also depend on age</li></ol> |
|---|---|

At high masses, *young*<sup>\*\*\*</sup> haloes cluster more strongly because of peak curvature<sup>\*\*\*\*</sup>

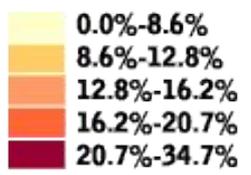
At low masses, *old* haloes cluster more strongly because of  $\sim \sqrt{\rho}$

# Population Density 2000





**Percent of a county's residents aged 65 and over.**



# The Assembly Bias Cheatsheet

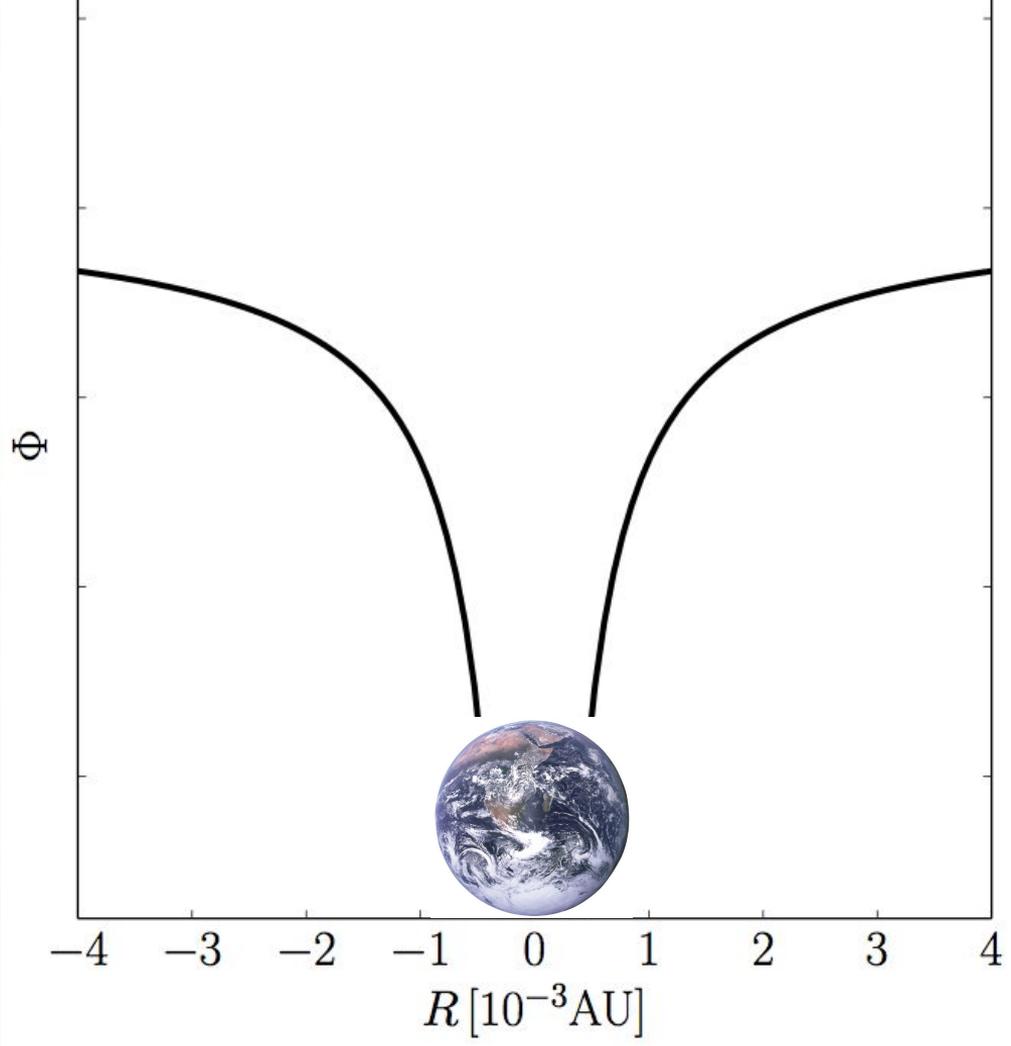
- |  |  |
|--|--|
| 1. Dark matter lives inside of dark matter haloes              | 1. Galaxies live at the center of dark matter haloes             |
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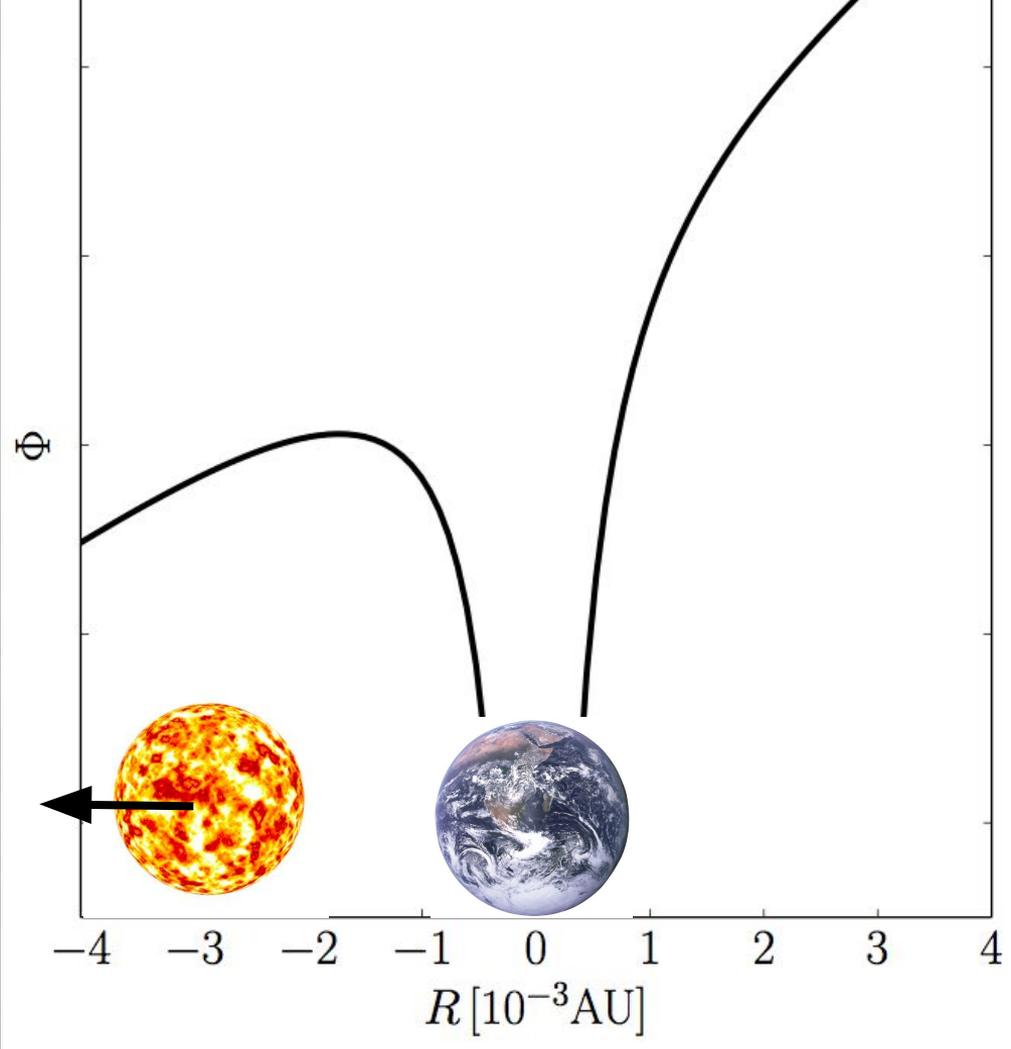
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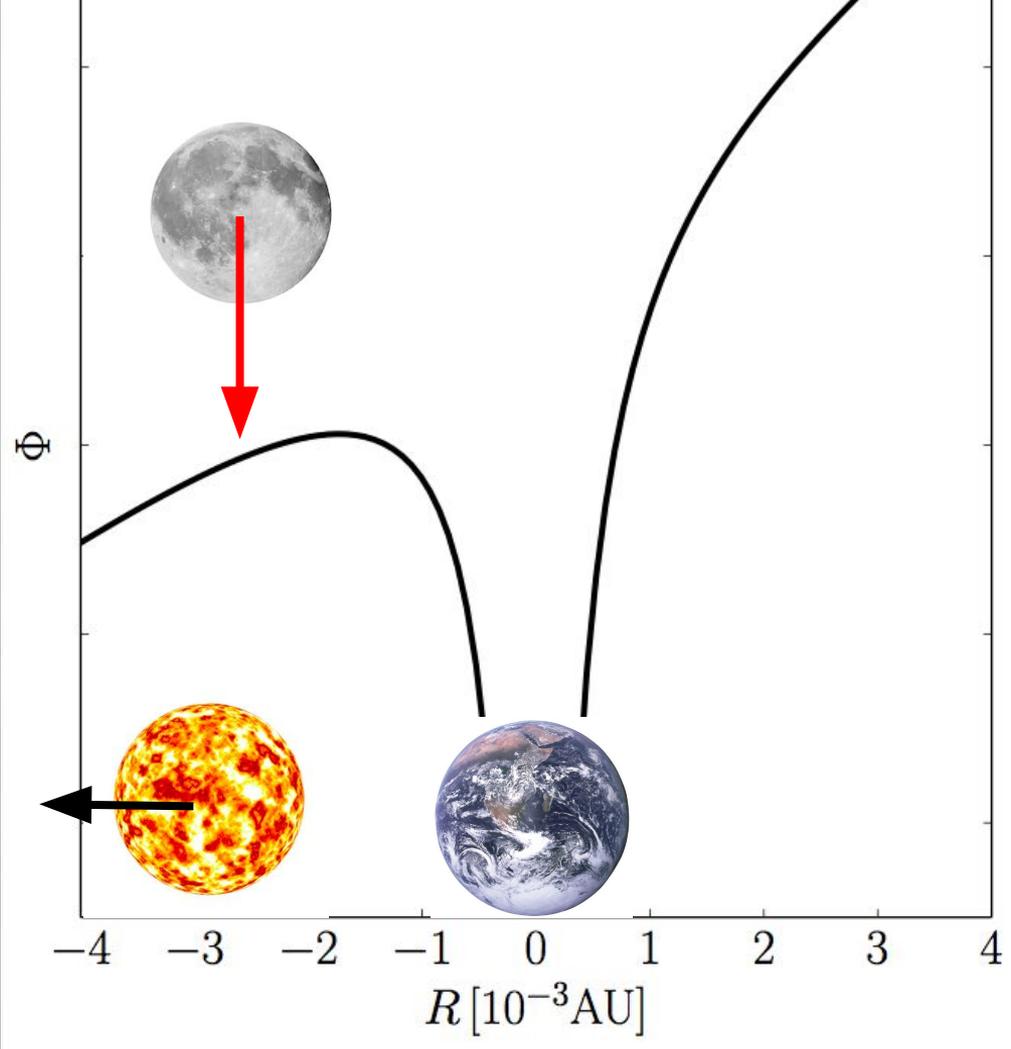
At low masses, *old* haloes cluster more strongly because of  $\sim \sqrt{\rho}$

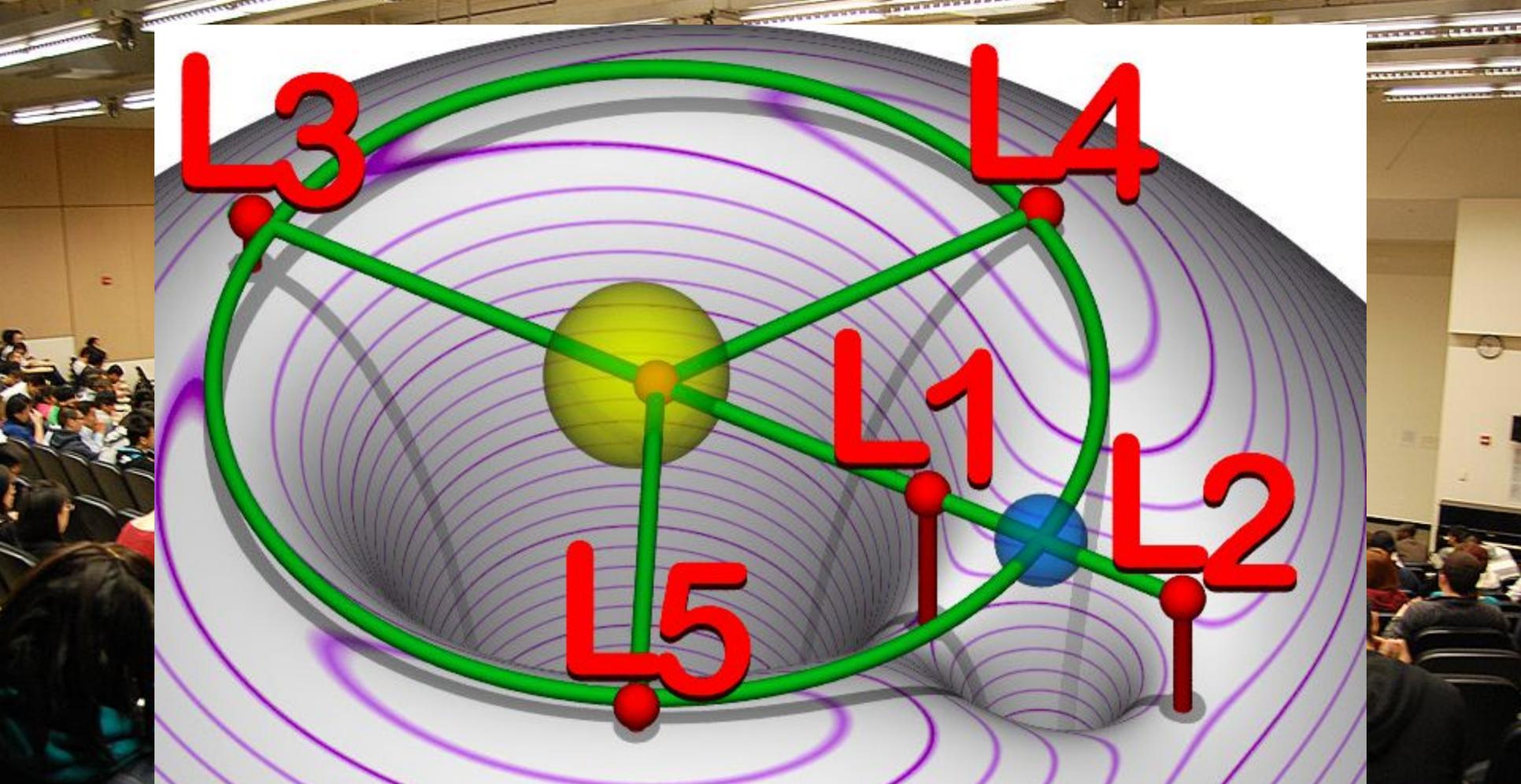
How Do You Make a  
Universe With (Galaxy-  
Mass) Assembly Bias?





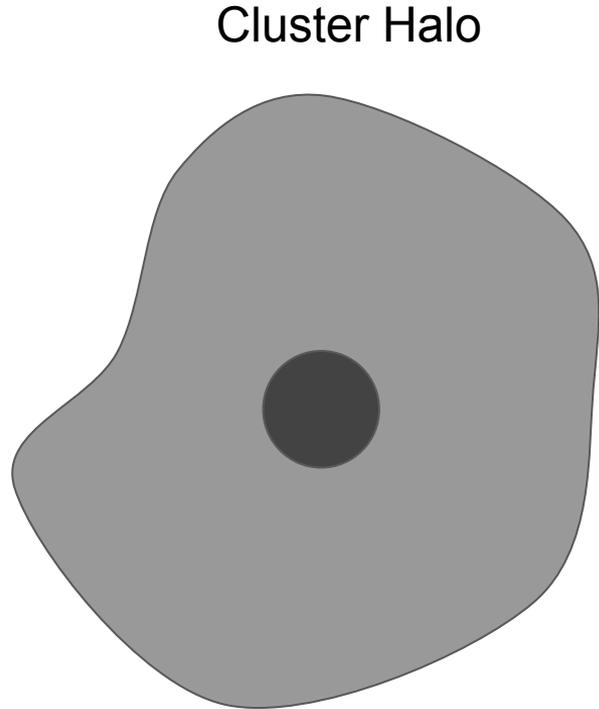






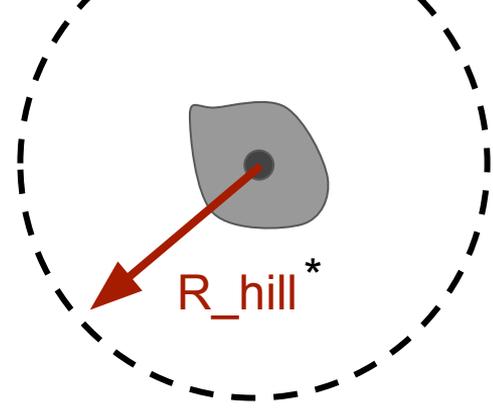
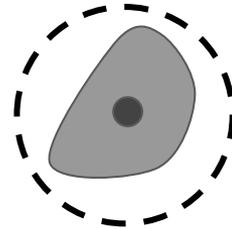
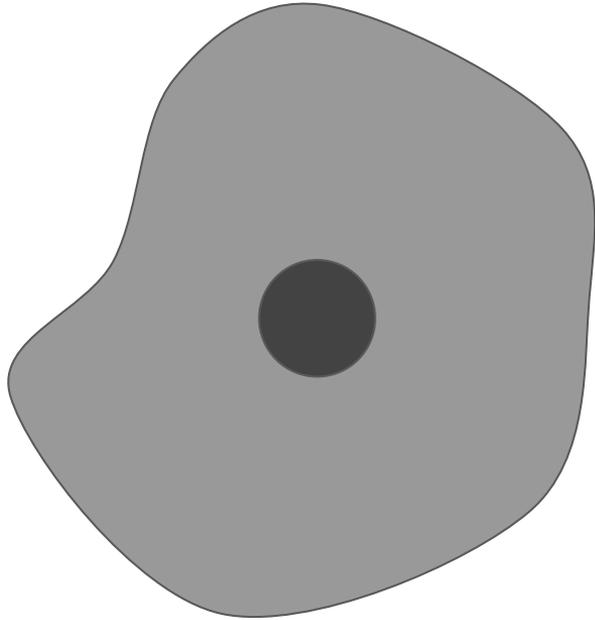
File:Lagrangian points equipotential.jpg. (2018, October 14). Wikimedia Commons, the free media repository. Retrieved 00:27, September 9, 2019 from

# Explanation #1: Single-Halo Tides



(E.g.: Hahn et al. 2009; Behroozi et al. 2014; Hearin et al. 2016; Villarreal et al. 2017; Salcedo et al. 2018).

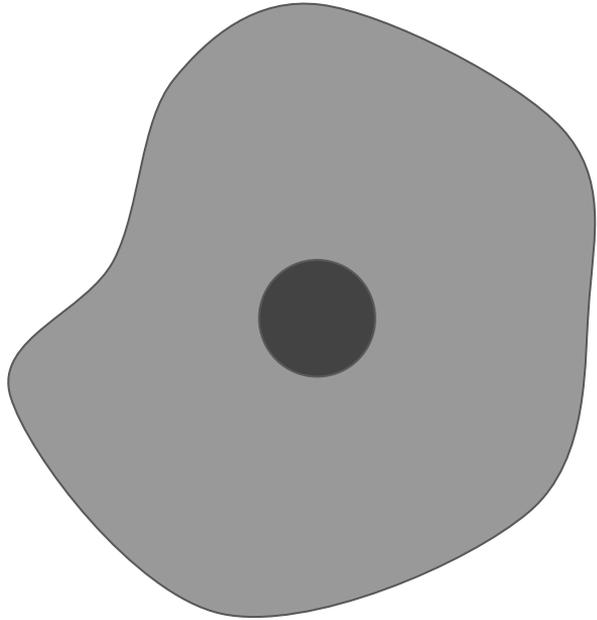
# Explanation #1: Single-Halo Tides



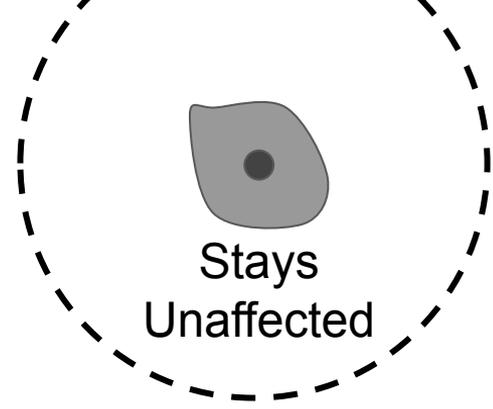
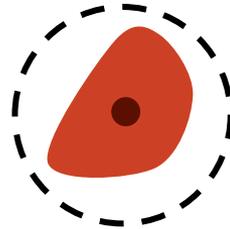
$$* \min_j \left\{ R_{ij} \left( \frac{M_{\text{vir},i}}{3M_{\text{vir},j}} \right)^{1/3} \right\}$$

(E.g.: Hahn et al. 2009; Behroozi et al. 2014; Hearin et al. 2016; Villarreal et al. 2017; Salcedo et al. 2018).

# Explanation #1: Single-Halo Tides



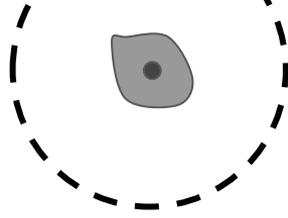
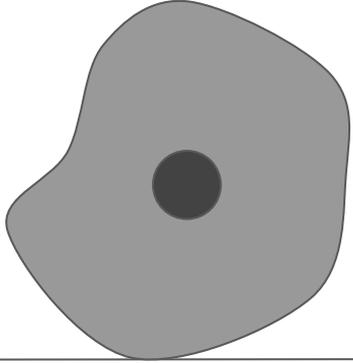
Becomes Old

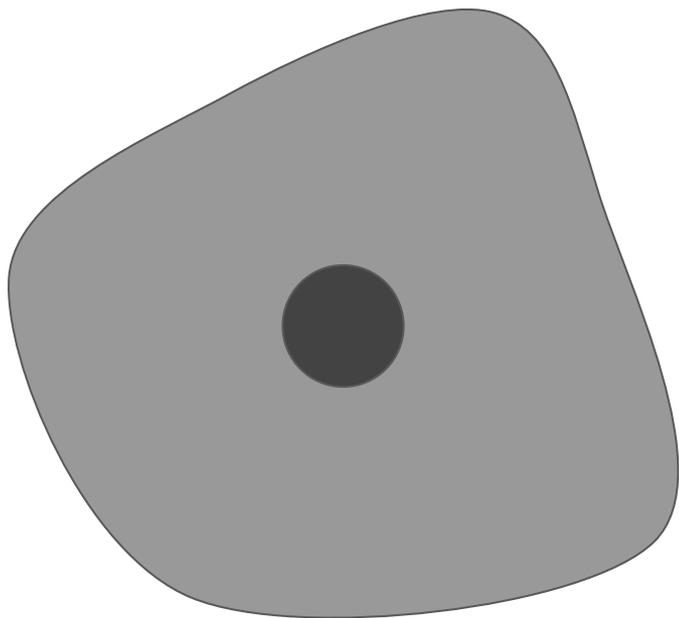


Stays  
Unaffected

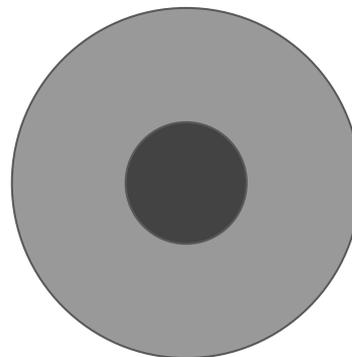
(E.g.: Hahn et al. 2009; Behroozi et al. 2014; Hearin et al. 2016; Villarreal et al. 2017; Salcedo et al. 2018).

Single-halo tidal forces  
Variable:  $R_{\text{hill}}$





Versus



Density



Position

Density



Position

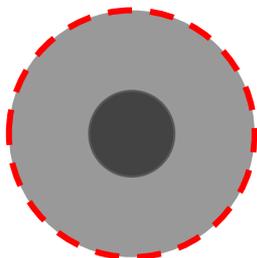
Density



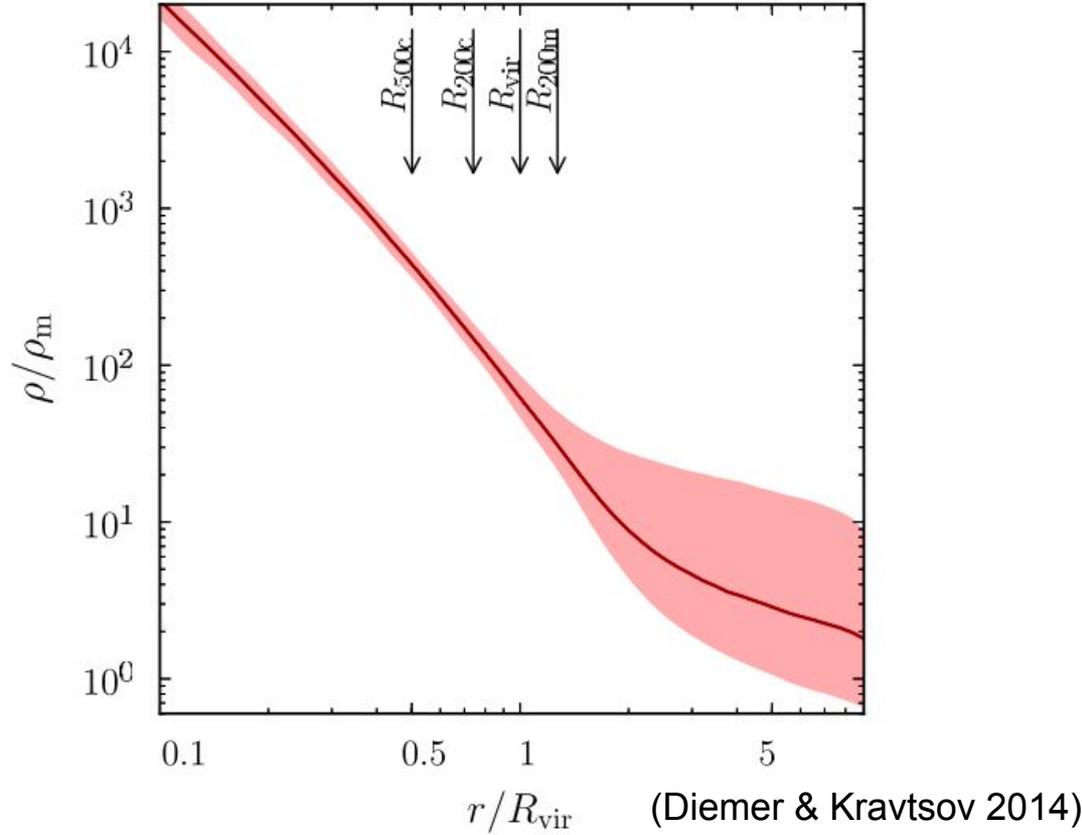
Position



Collapse

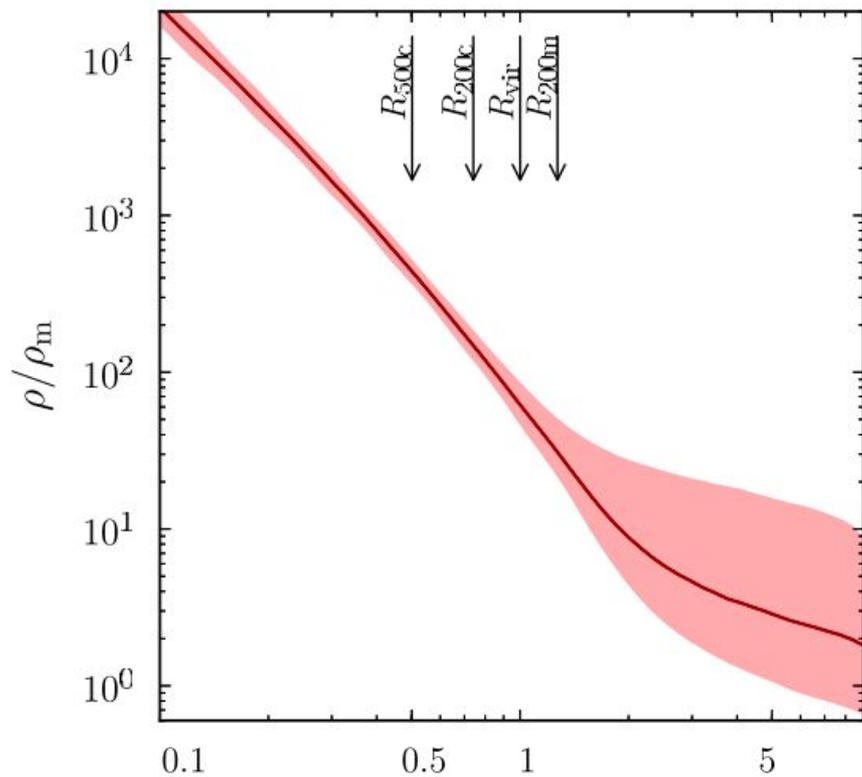


Densit



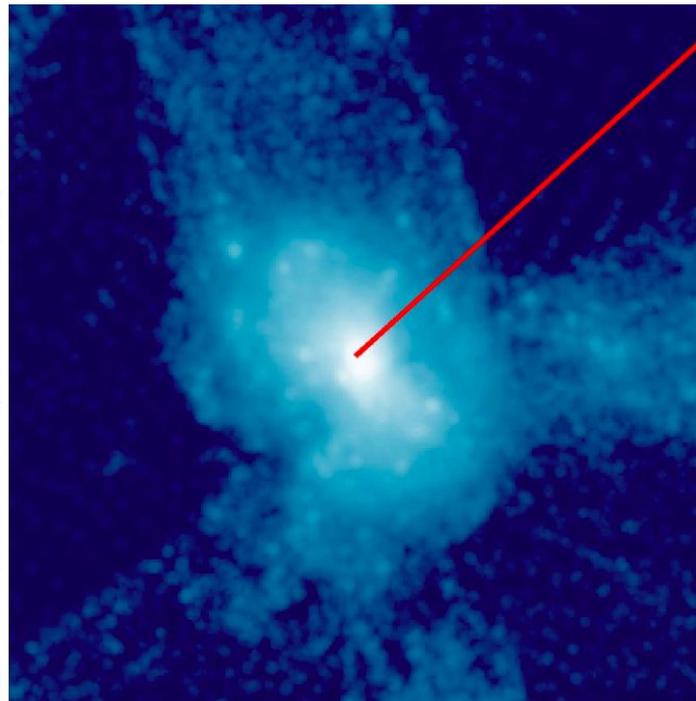
(Diemer & Kravtsov 2014)

Densit



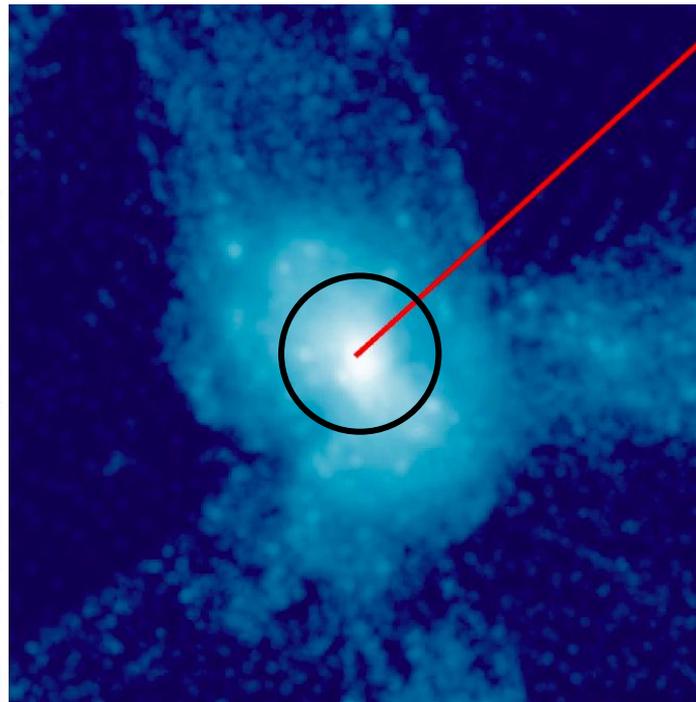
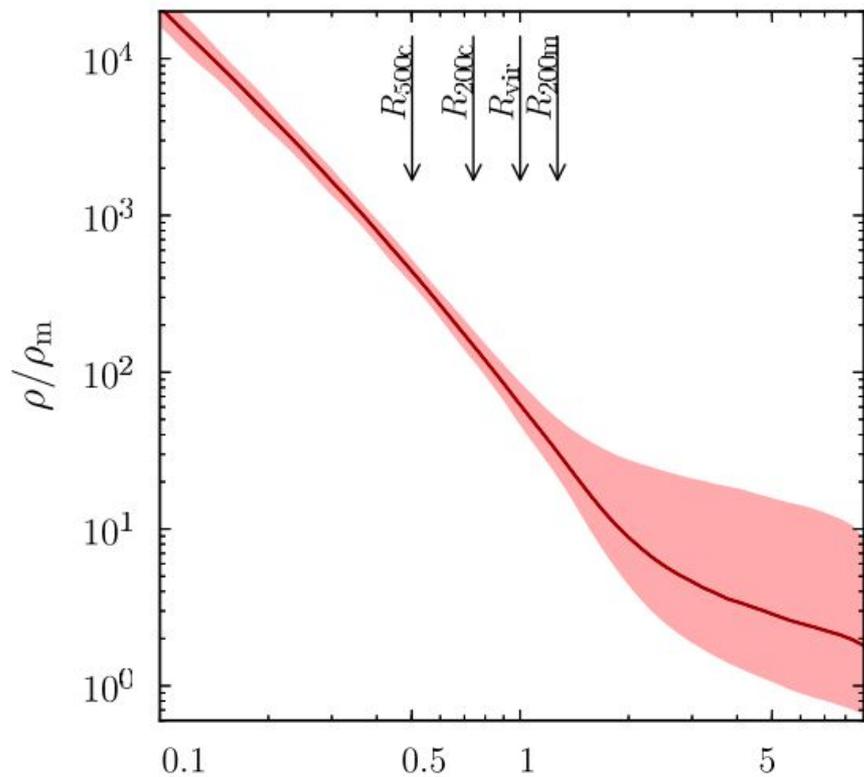
$r/R_{\text{vir}}$

(Diemer & Kravtsov 2014)



(PM, Kravtsov, & Diemer, 2017)

Densit

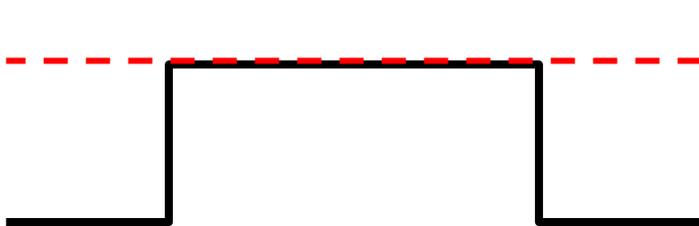


(PM, Kravtsov, & Diemer, 2017)

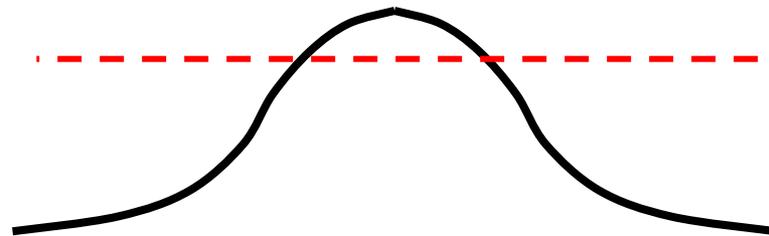
$r/R_{\text{vir}}$  (Diemer & Kravtsov 2014)



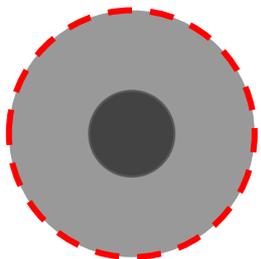
Density



Position



Collapse



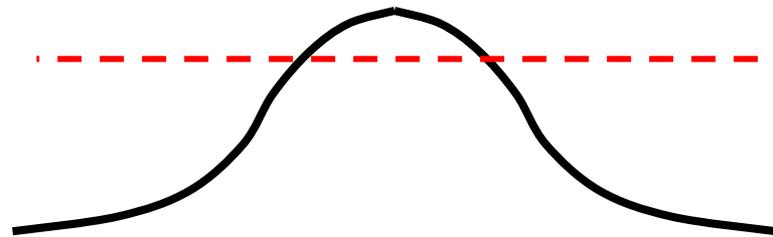
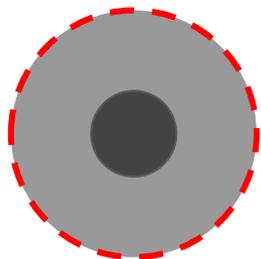
Density



Position



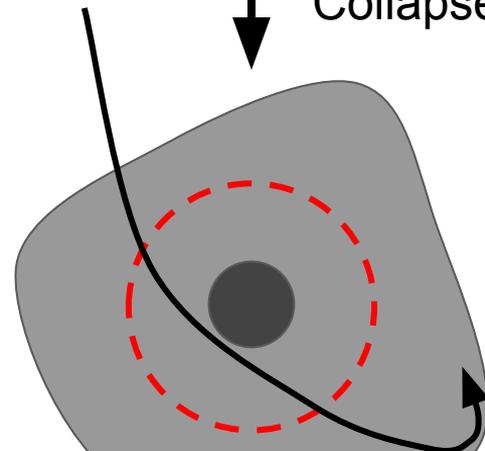
Collapse

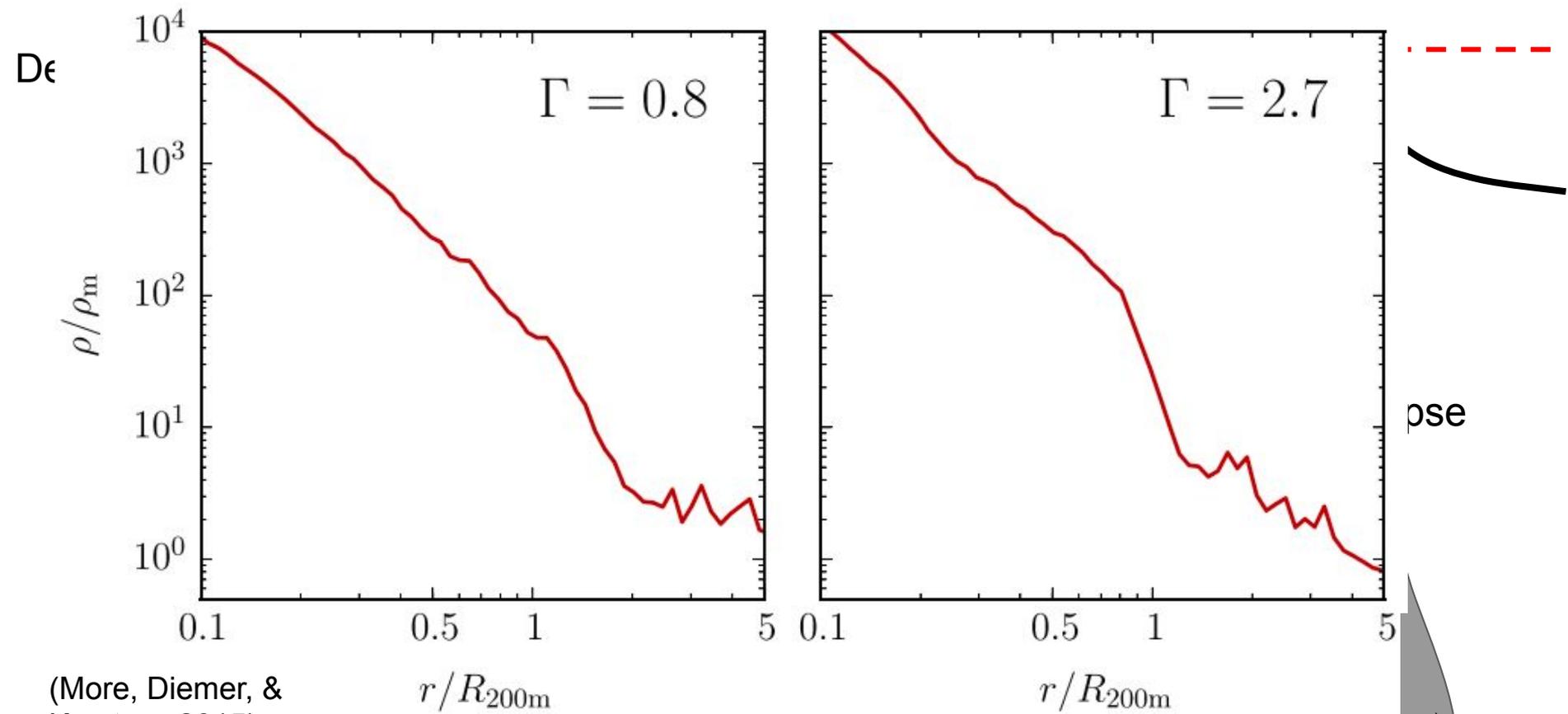


(E.g.: Fillmore & Goldreich 1984;  
Bertschinger 1985; Diemer &  
Kravtsov 2014; Adhikari et al. 2014;  
More et al. 2015)



Collapse

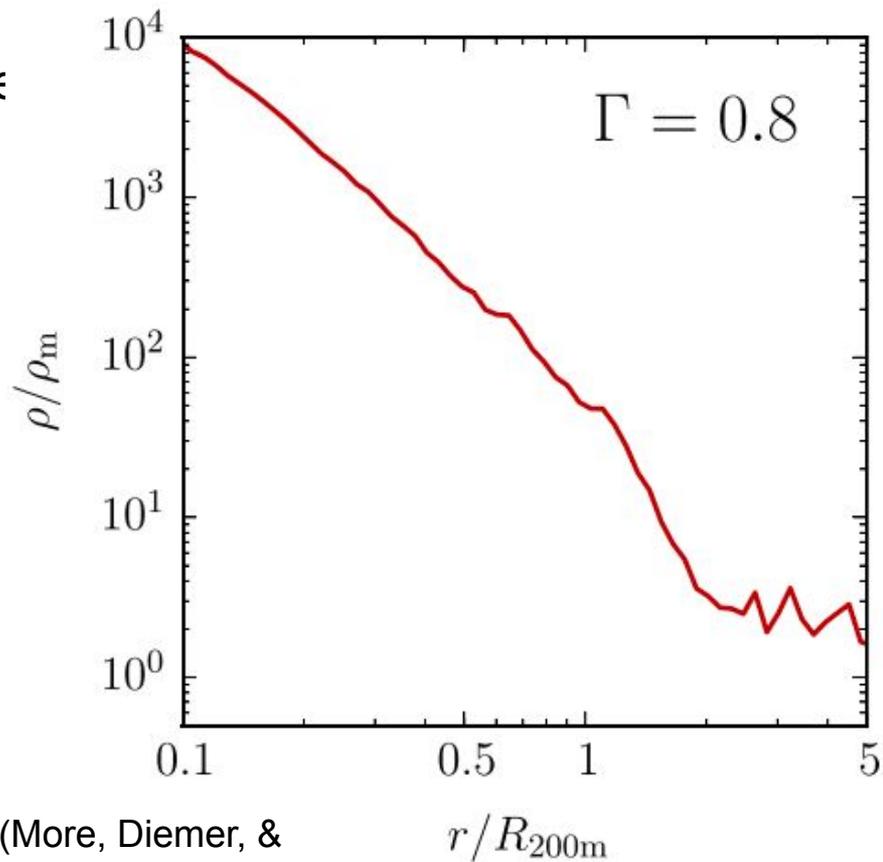




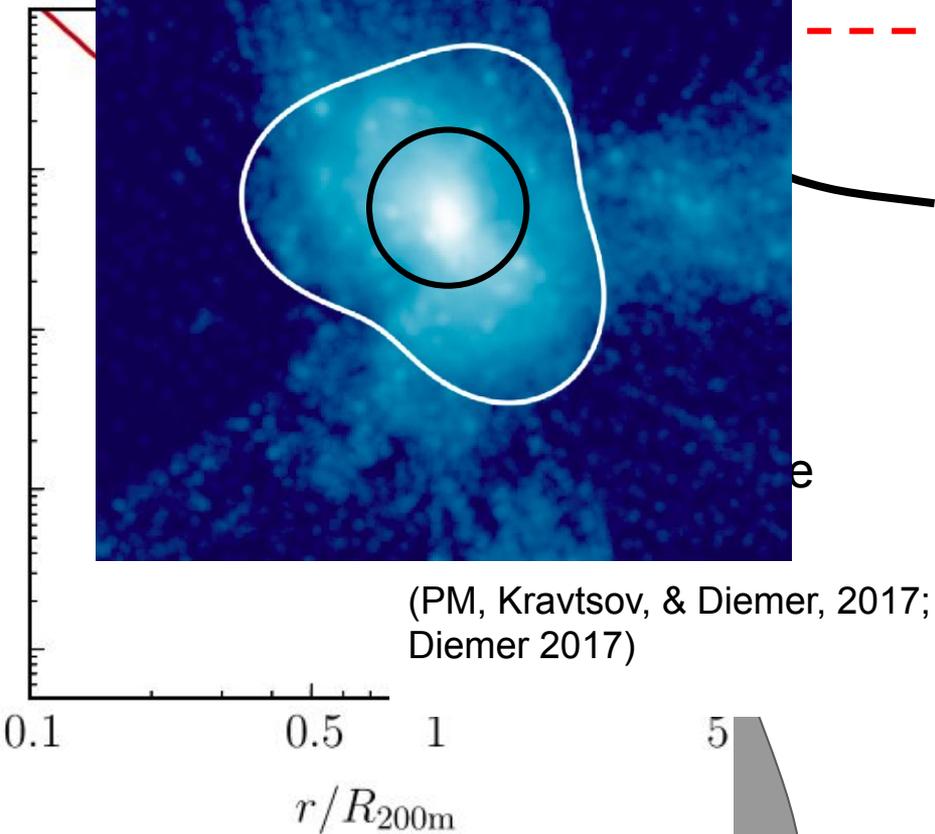
(More, Diemer, &  
Kravtsov 2015)

$r/R_{200m}$

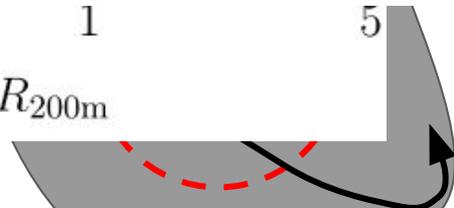
$r/R_{200m}$

$D\epsilon$ 

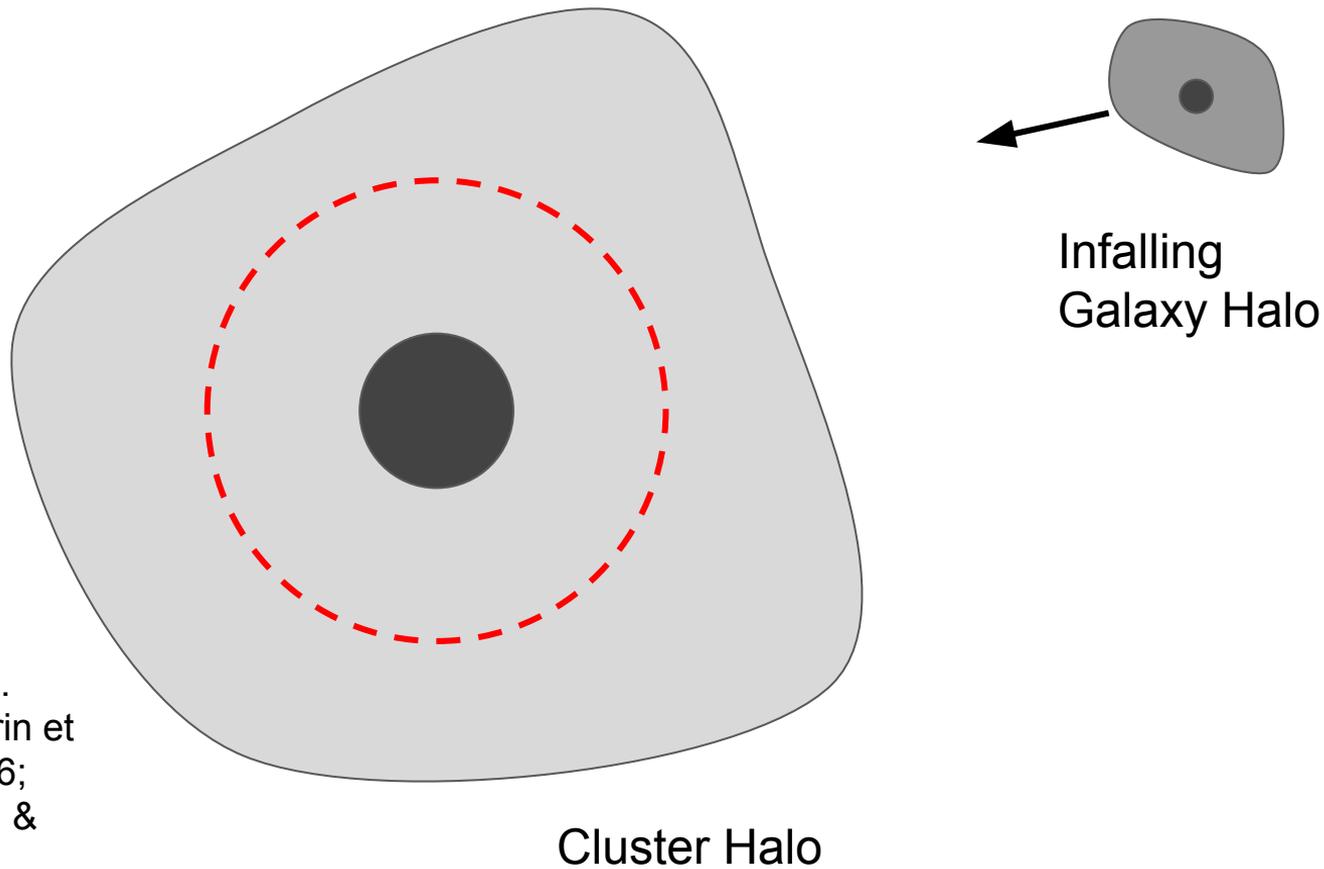
(More, Diemer, &  
Kravtsov 2015)



(PM, Kravtsov, & Diemer, 2017;  
Diemer 2017)

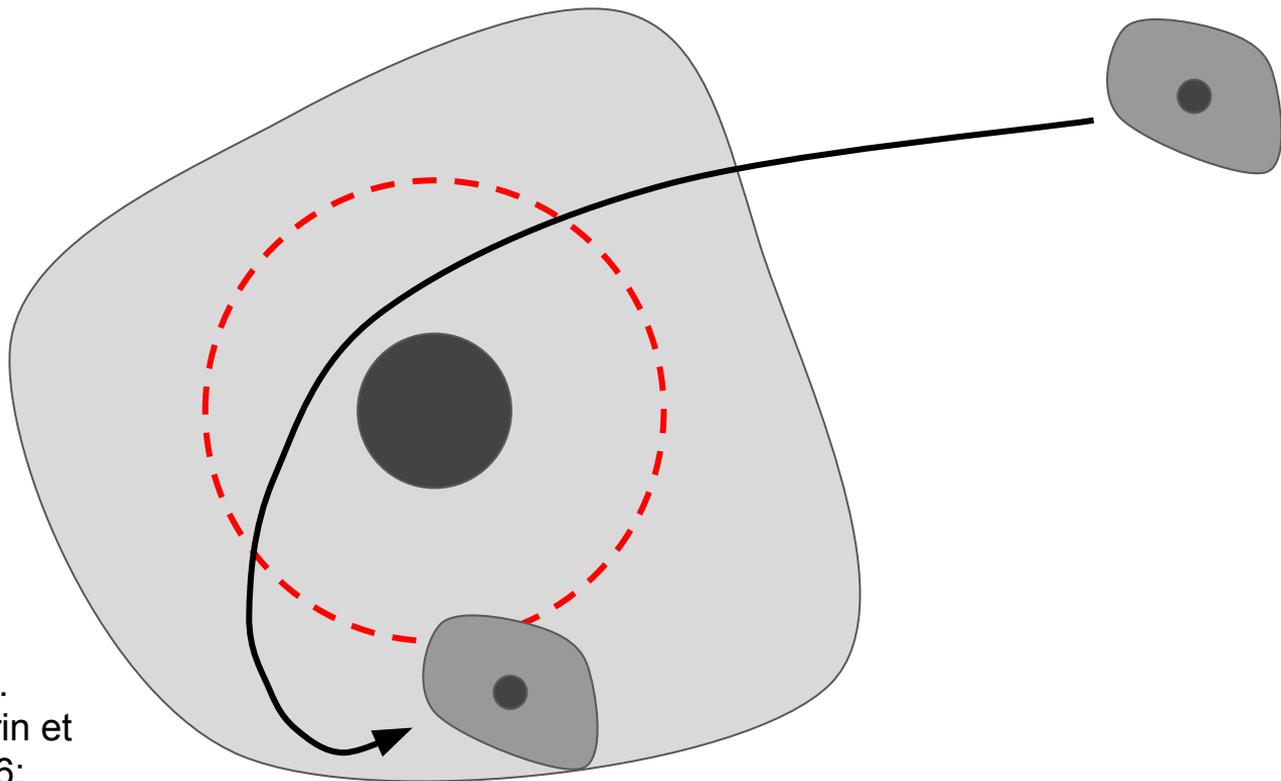


# Explanation #2: Misidentified Splashback Subhaloes



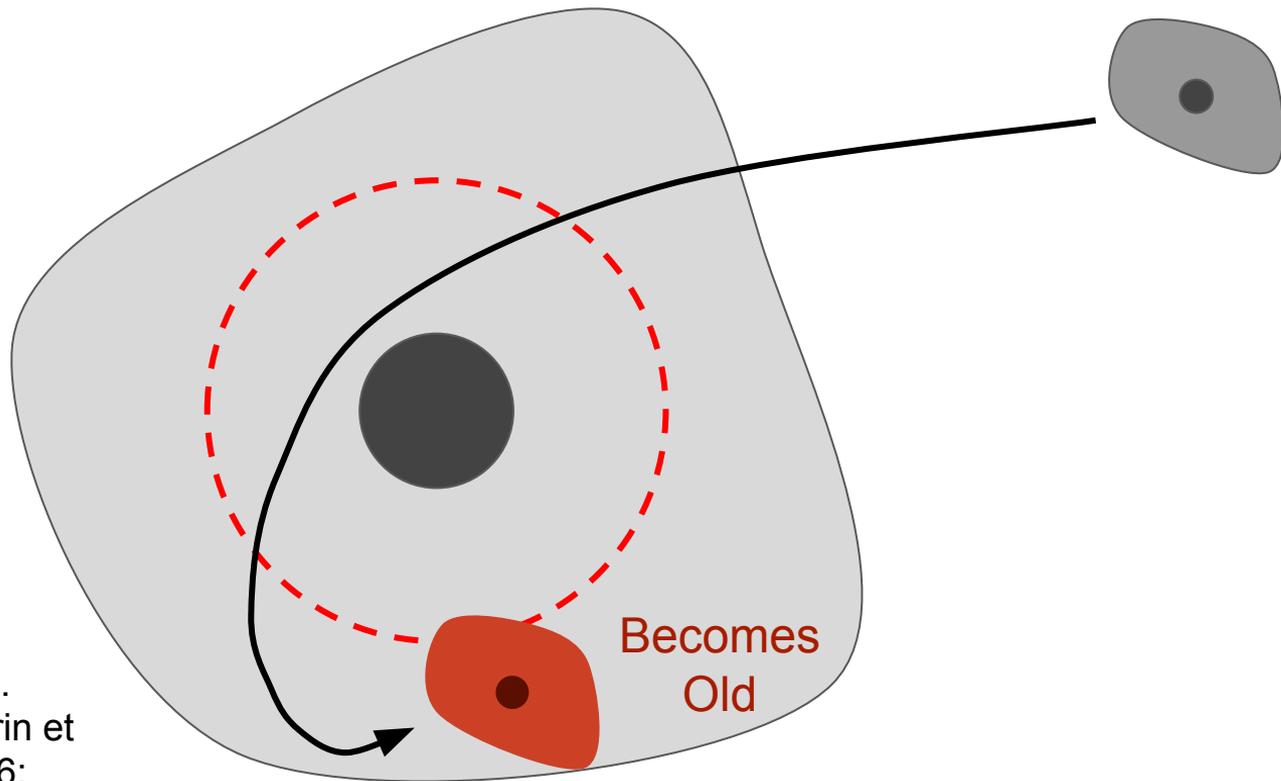
(E.g: Wang et al. 2009; Li et al. 2013; Wetzel et al. 2014; Hearin et al. 2015; Sunayama et al. 2016; Ramakrishnan et al. 2019; PM & Kravtsov 2019)

# Explanation #2: Misidentified Splashback Subhaloes



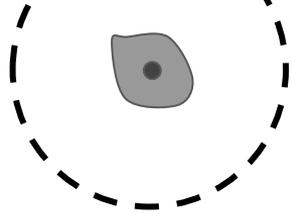
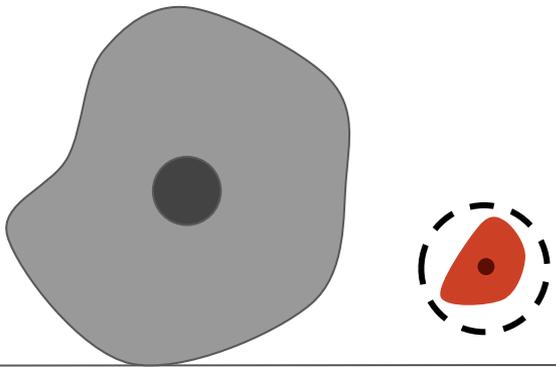
(E.g: Wang et al. 2009; Li et al. 2013; Wetzel et al. 2014; Hearin et al. 2015; Sunayama et al. 2016; Ramakrishnan et al. 2019; PM & Kravtsov 2019)

# Explanation #2: Misidentified Splashback Subhaloes

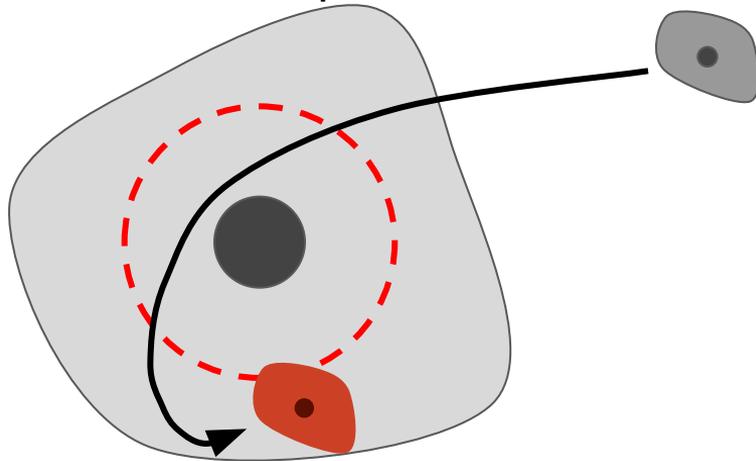


(E.g: Wang et al. 2009; Li et al. 2013; Wetzel et al. 2014; Hearin et al. 2015; Sunayama et al. 2016; Ramakrishnan et al. 2019; PM & Kravtsov 2019)

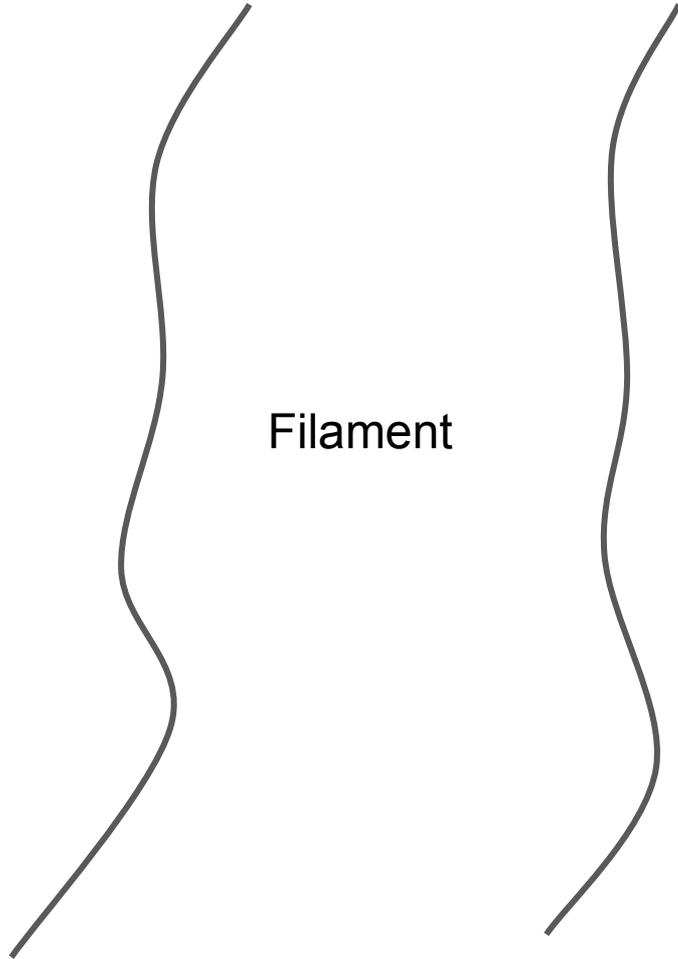
Single-halo tidal forces  
Variable:  $R_{\text{hill}}$



misidentified splashback subhaloes



# Explanation #3: Large-Scale Tidal Fields

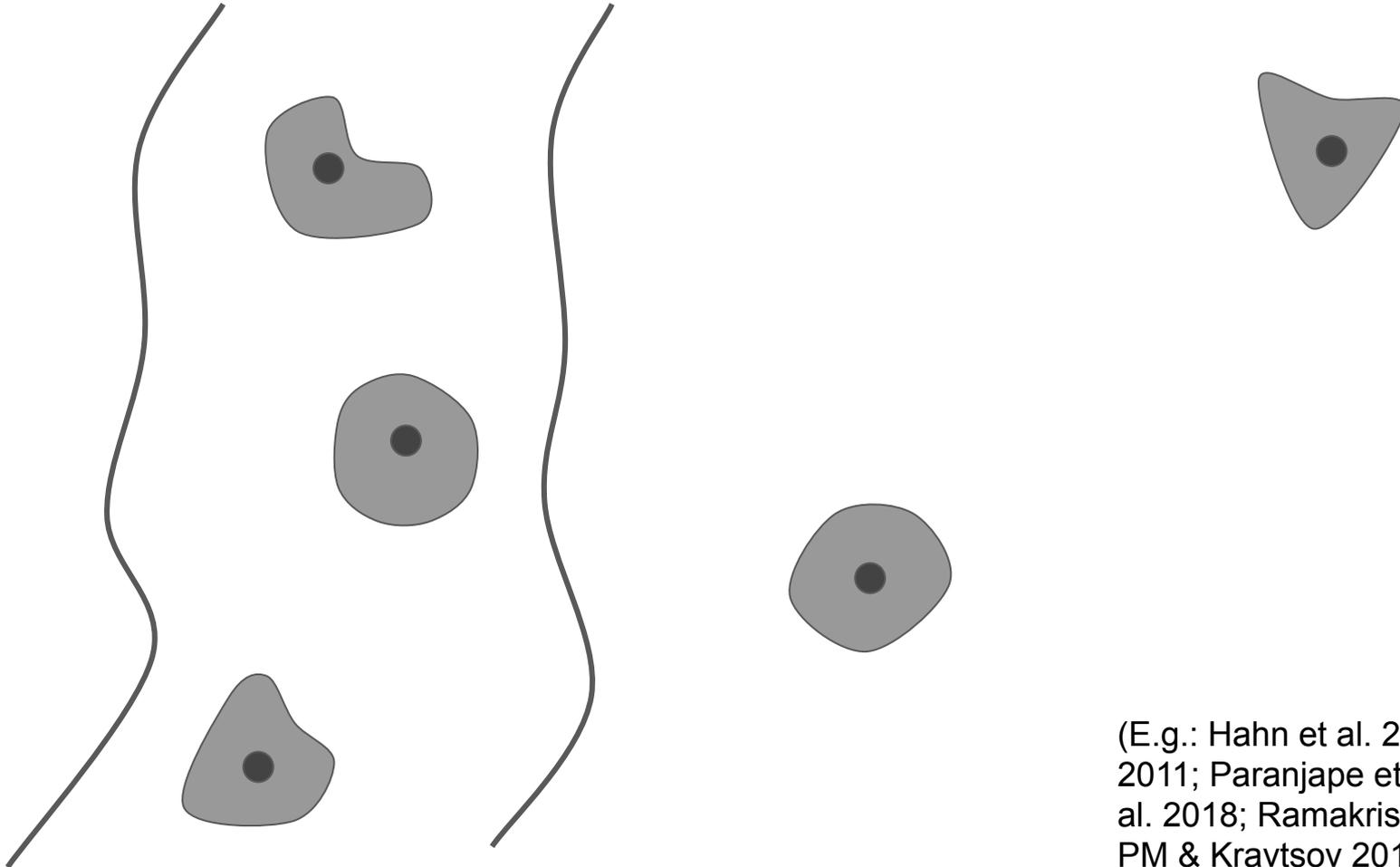


Filament

Void

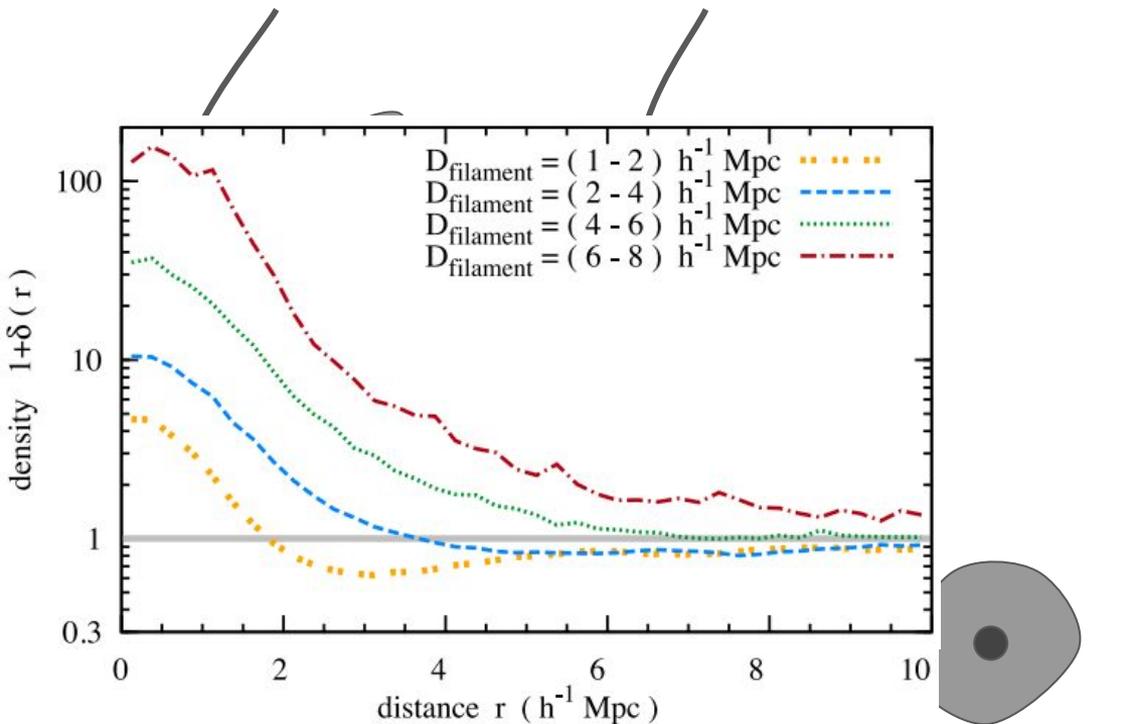
(E.g.: Hahn et al. 2009; Wang et al. 2011; Paranjape et al. 2018; Musso et al. 2018; Ramakrishnan et al. 2019; PM & Kravtsov 2019)

# Explanation #3: Large-Scale Tidal Fields



(E.g.: Hahn et al. 2009; Wang et al. 2011; Paranjape et al. 2018; Musso et al. 2018; Ramakrishnan et al. 2019; PM & Kravtsov 2019)

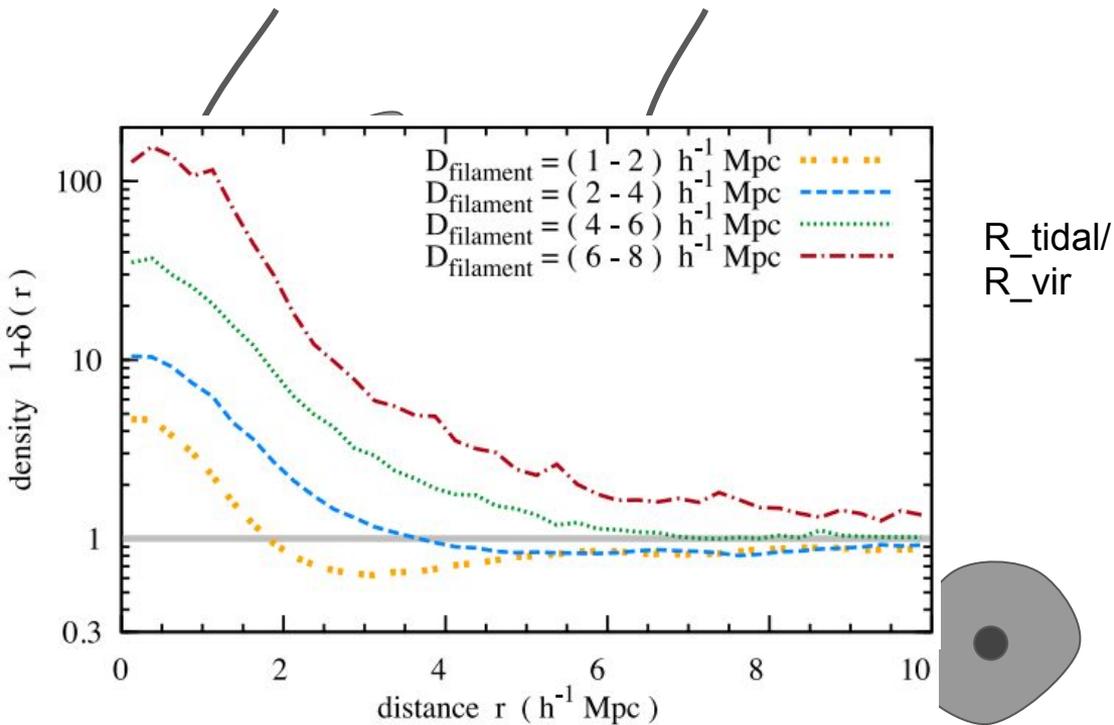
# Explanation #3: Large-Scale Tidal Fields



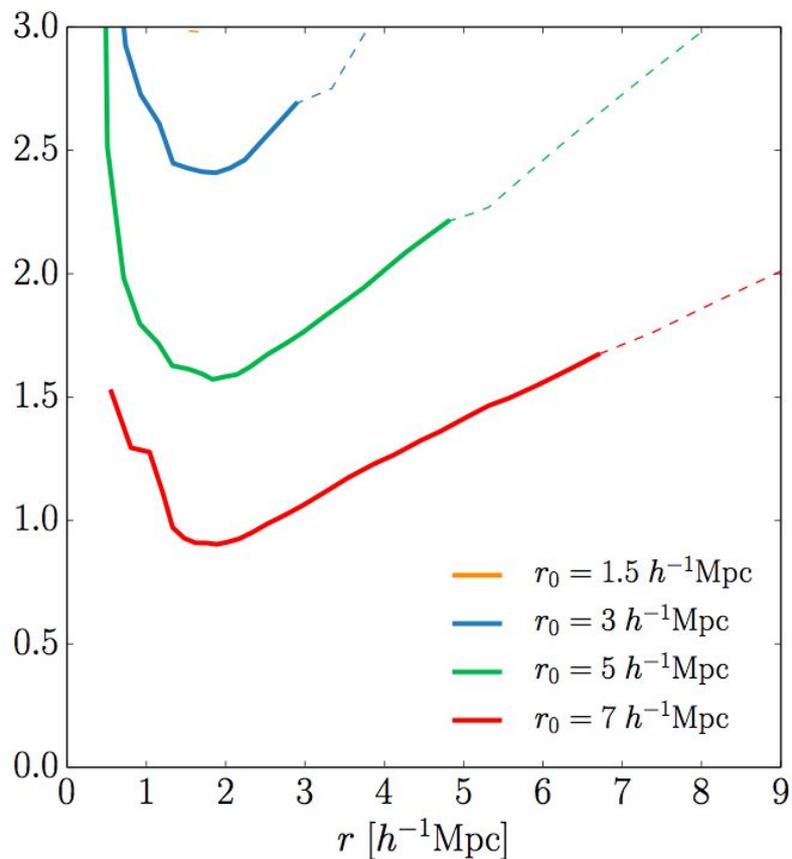
(Cautun et al. 2014)

(E.g.: Hahn et al. 2009; Wang et al. 2011; Paranjape et al. 2018; Musso et al. 2018; Ramakrishnan et al. 2019; PM & Kravtsov 2019)

# Explanation #3: Large-Scale T



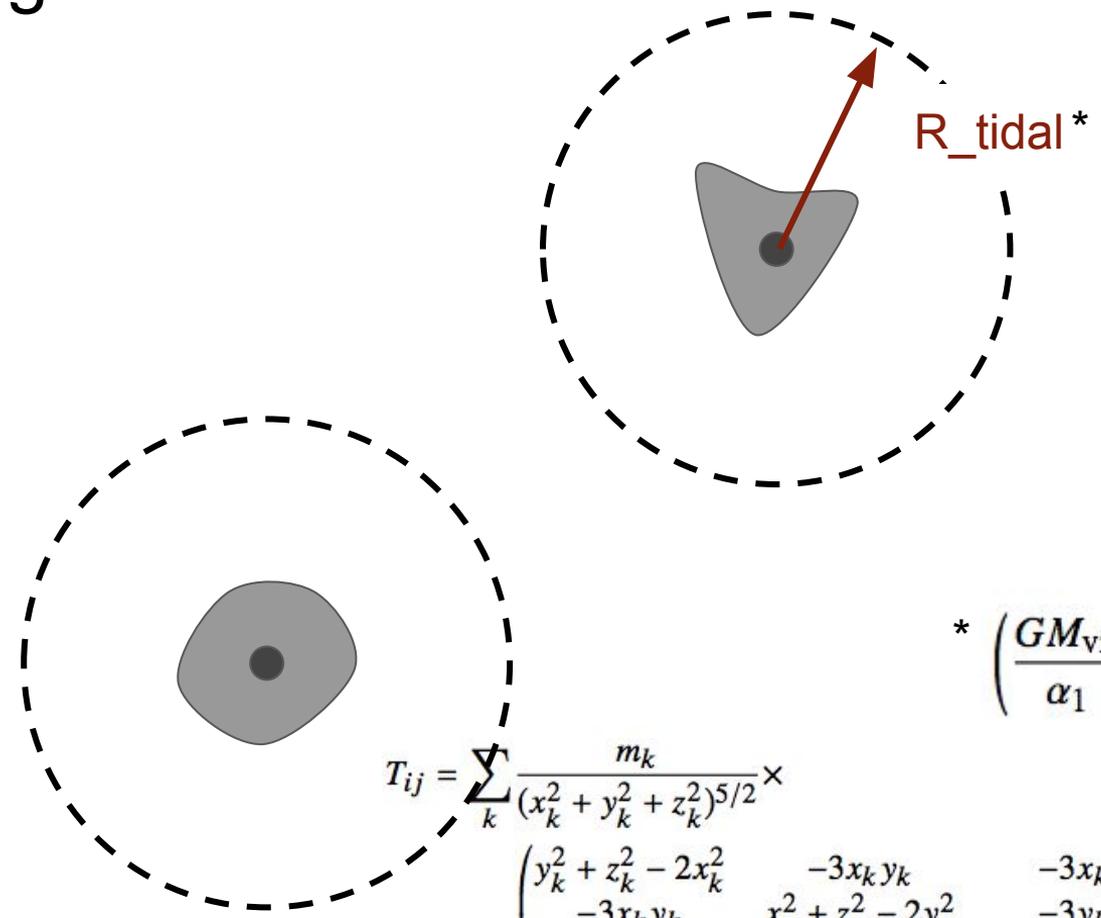
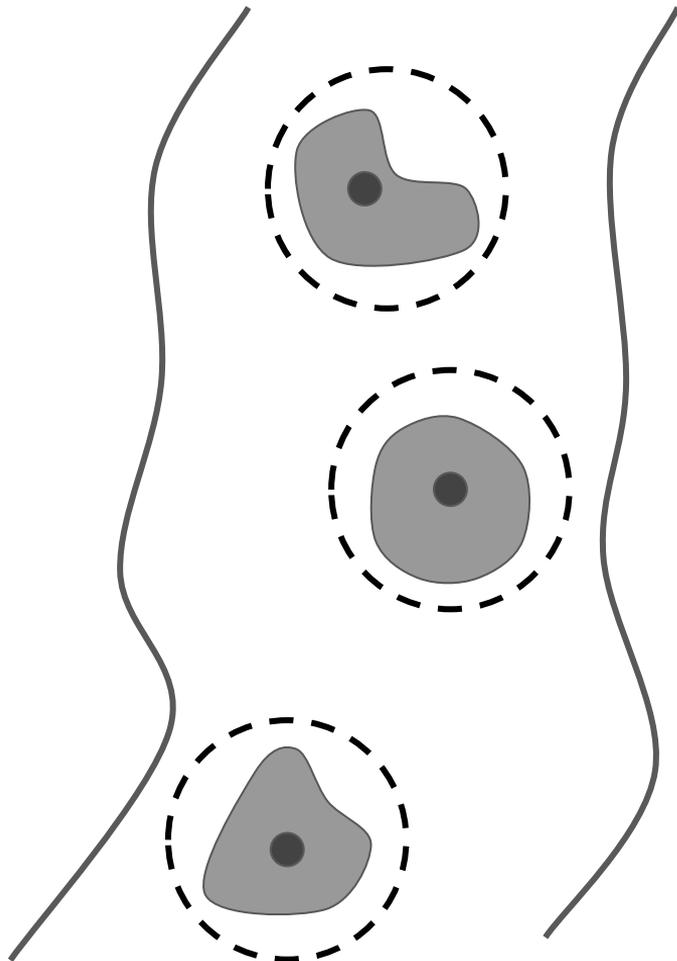
$R_{\text{tidal}}/$   
 $R_{\text{vir}}$



(Cautun et al. 2014)

(E.g.: Hahn et al. 2009; Wang et al. 2011; Paranjape et al. 2018; Musso et al. 2018; Ramakrishnan et al. 2019; PM & Kravtsov 2019)

# Explanation #3: Large-Scale Tidal Fields

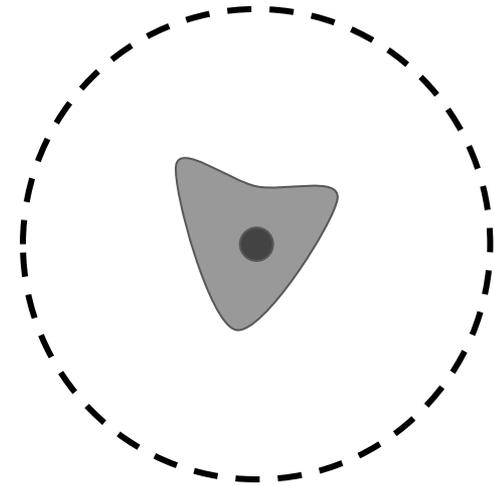
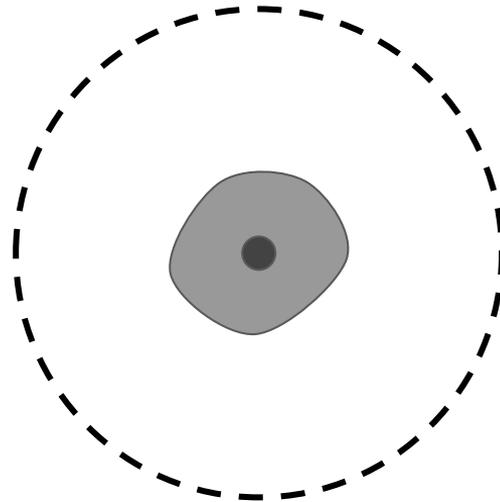
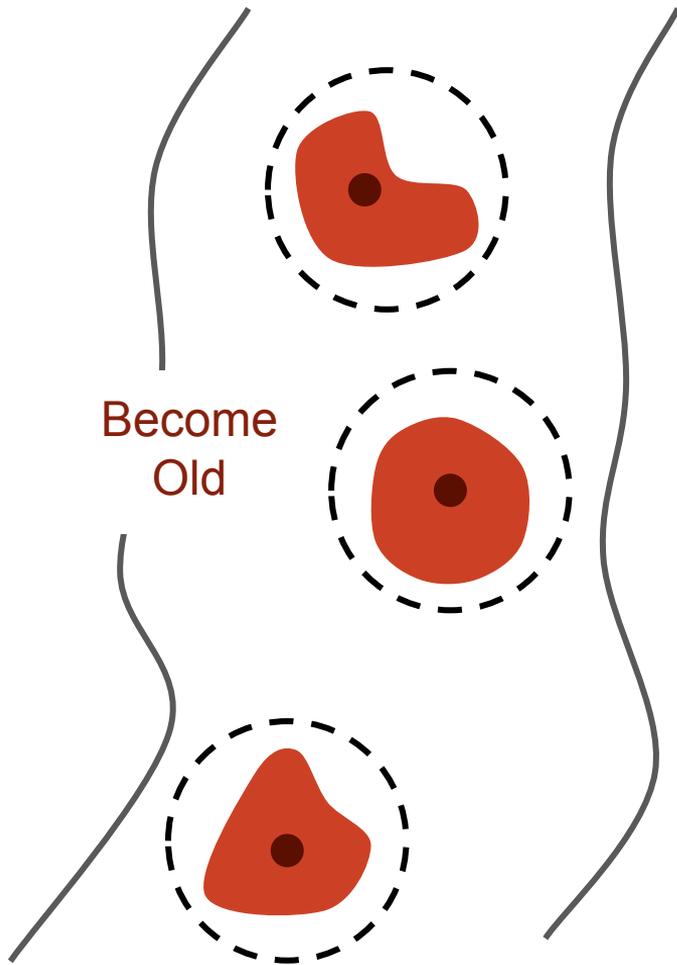


$$T_{ij} = \sum_k \frac{m_k}{(x_k^2 + y_k^2 + z_k^2)^{5/2}} \times$$

$y_k^2 + z_k^2 - 2x_k^2$	$-3x_k y_k$	$-3x_k z_k$
$-3x_k y_k$	$x_k^2 + z_k^2 - 2y_k^2$	$-3y_k z_k$
$-3x_k z_k$	$-3y_k z_k$	$x_k^2 + y_k^2 - 2z_k^2$

\*  $\left( \frac{GM_{\text{vir}}}{\alpha_1} \right)^{1/3}$

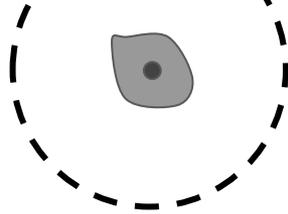
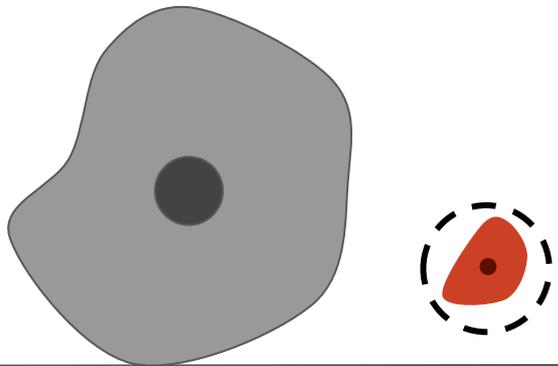
# Explanation #3: Large-Scale Tidal Fields



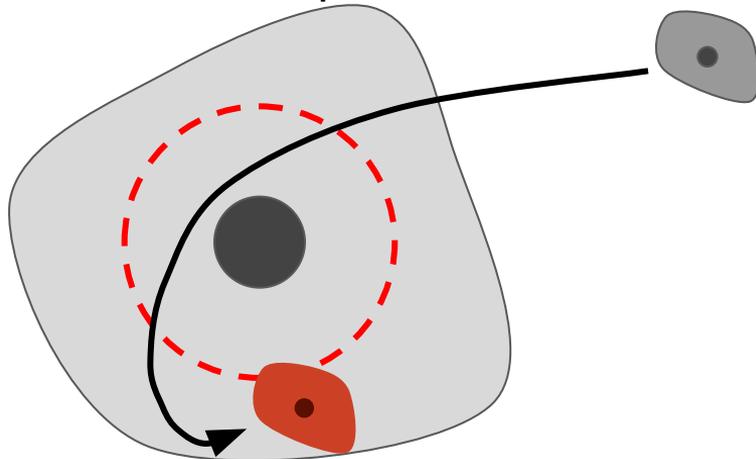
Stay  
Unaffected

(E.g.: Hahn et al. 2009; Wang et al. 2011; Paranjape et al. 2018; Musso et al. 2018; Ramakrishnan et al. 2019; PM & Kravtsov 2019)

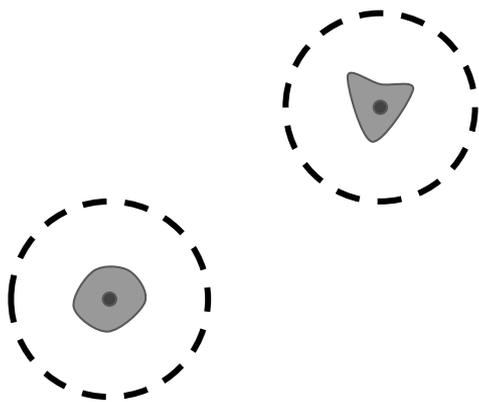
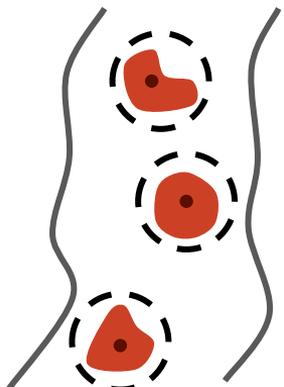
Single-halo tidal forces  
Variable:  $R_{\text{hill}}$

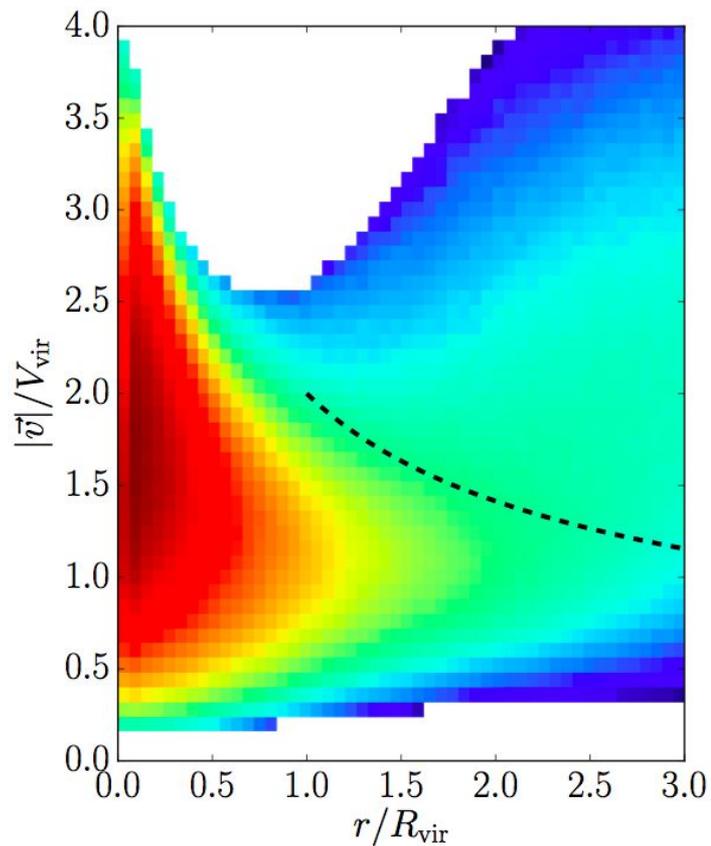


Misidentified splashback subhaloes

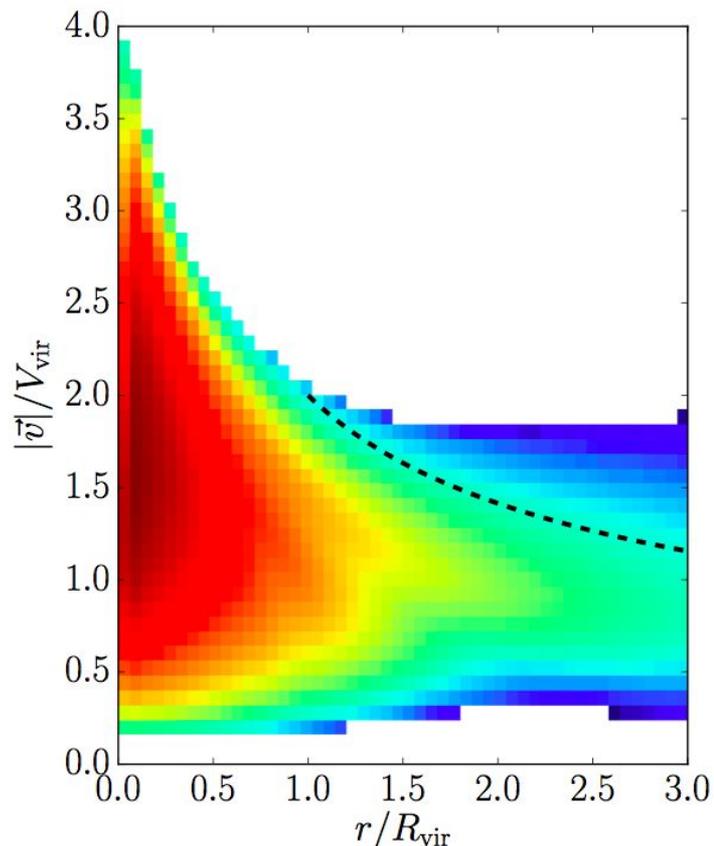


Large-scale tidal forces  
Variable:  $R_{\text{tidal}}$

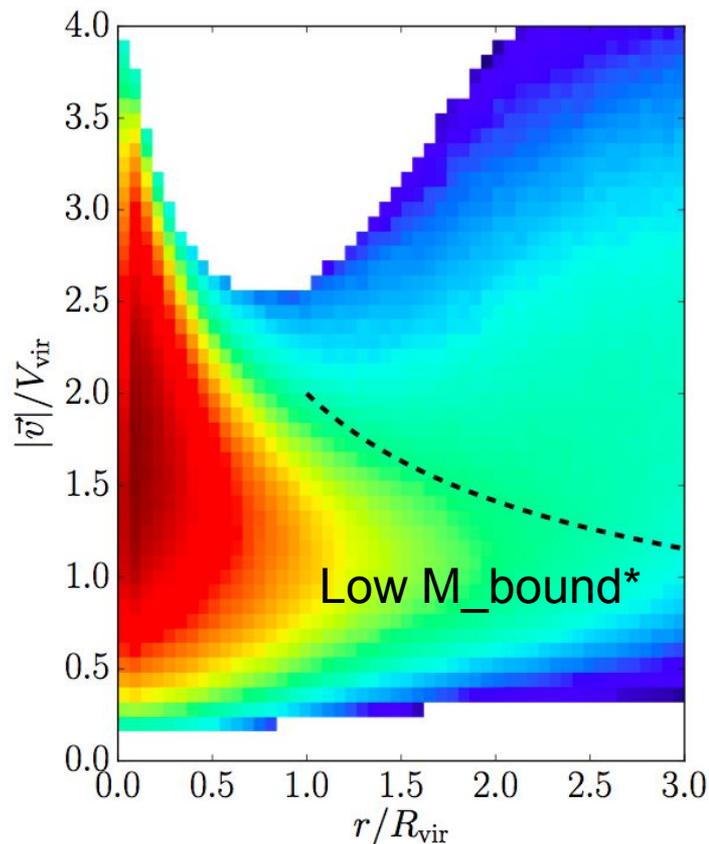




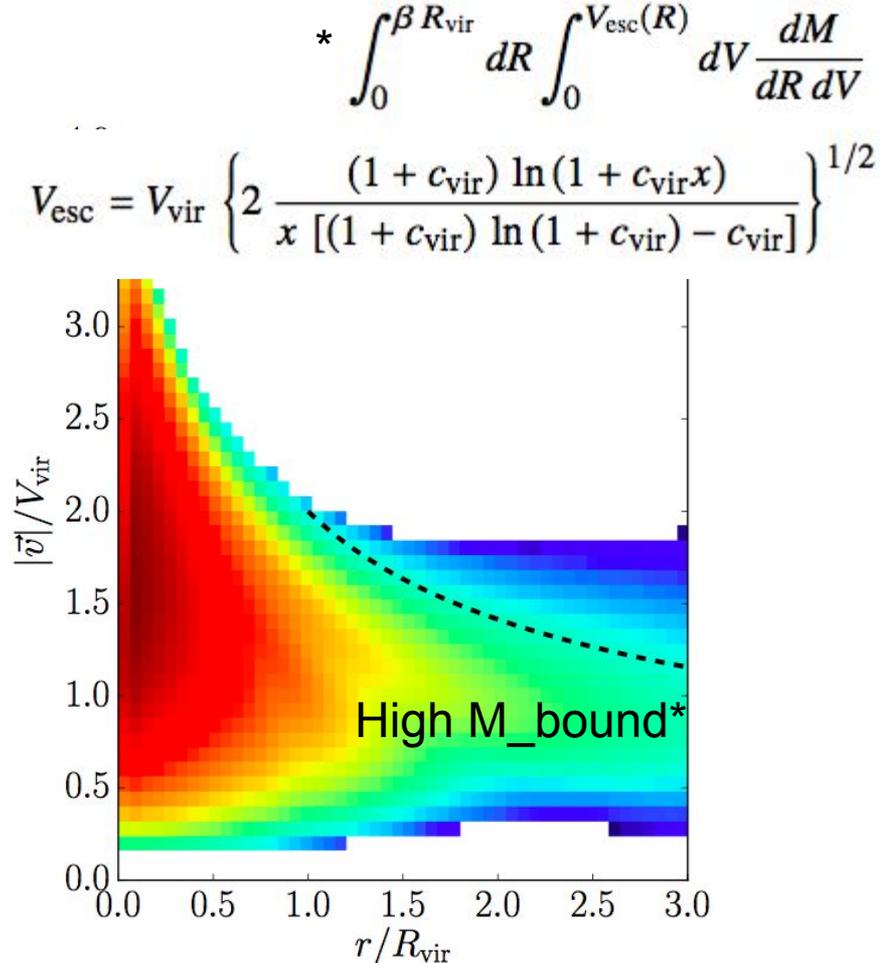
Galaxy-sized haloes in  
dense regions



Galaxy-sized haloes in  
underdense regions

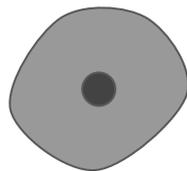
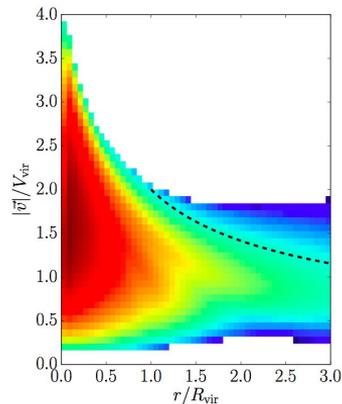
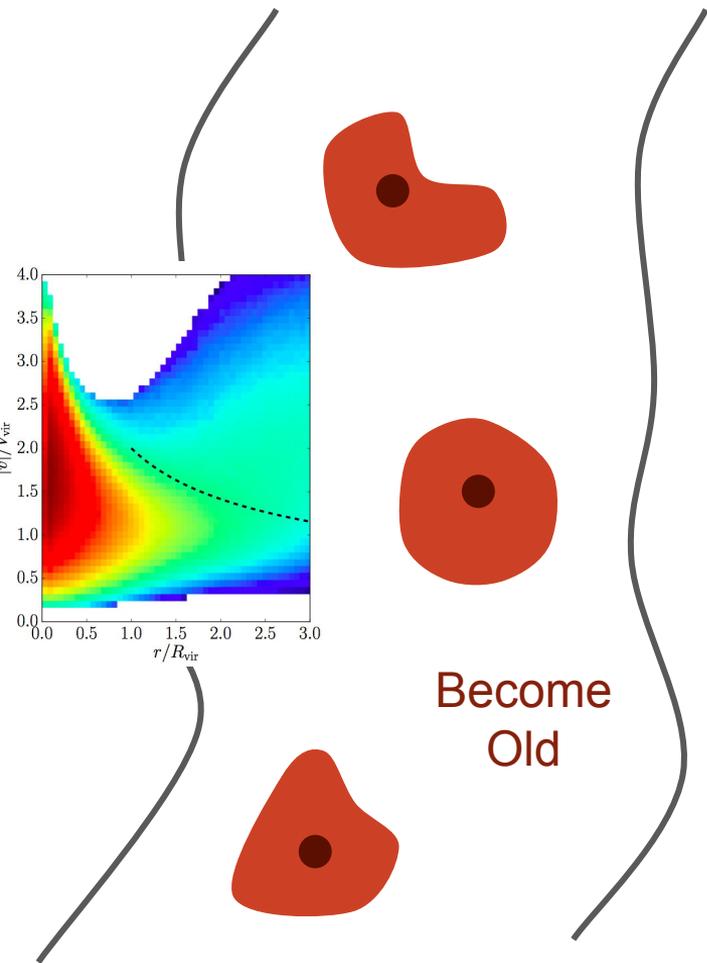


Galaxy-sized haloes in  
dense regions



Galaxy-sized haloes in  
underdense regions

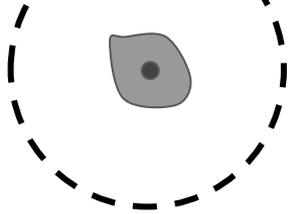
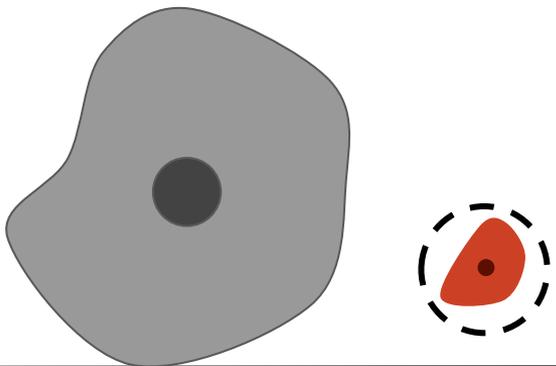
# Explanation #4: Gravitational Heating



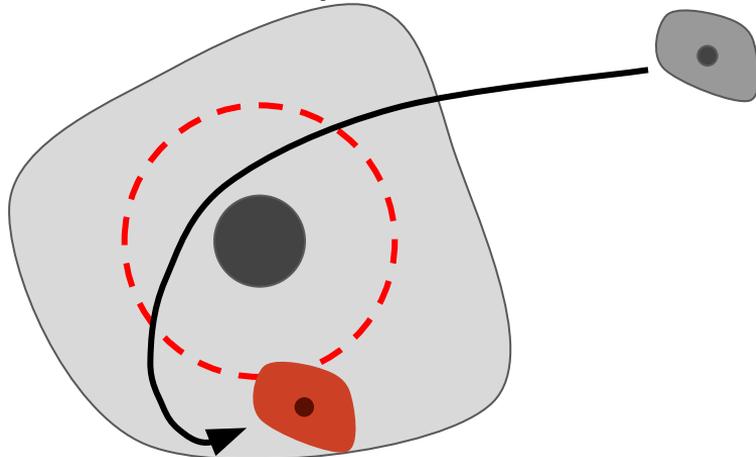
Stay  
Unaffected

(E.g.: Wang et al. 2007; Dalal et al. 2008;  
PM & Kravtsov 2019)

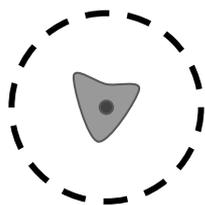
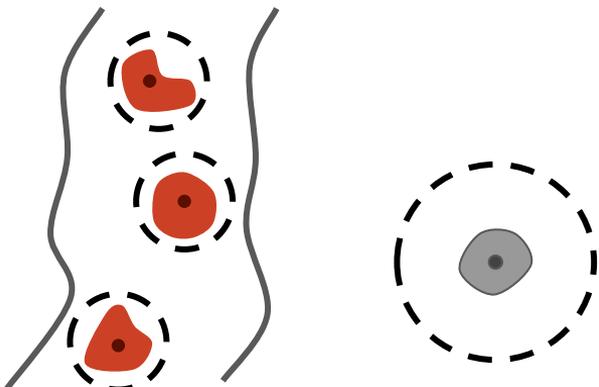
Single-halo tidal forces  
Variable:  $R_{\text{hill}}$



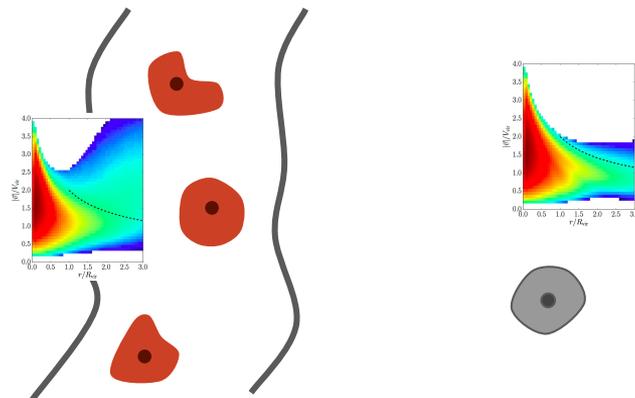
Misidentified splashback subhaloes



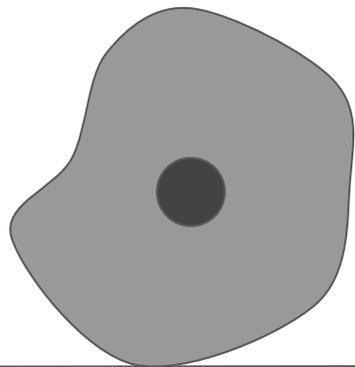
Large-scale tidal forces  
Variable:  $R_{\text{tidal}}$



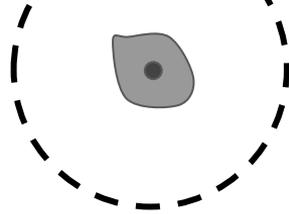
Gravitational heating  
Variable:  $M_{\text{bound}}$



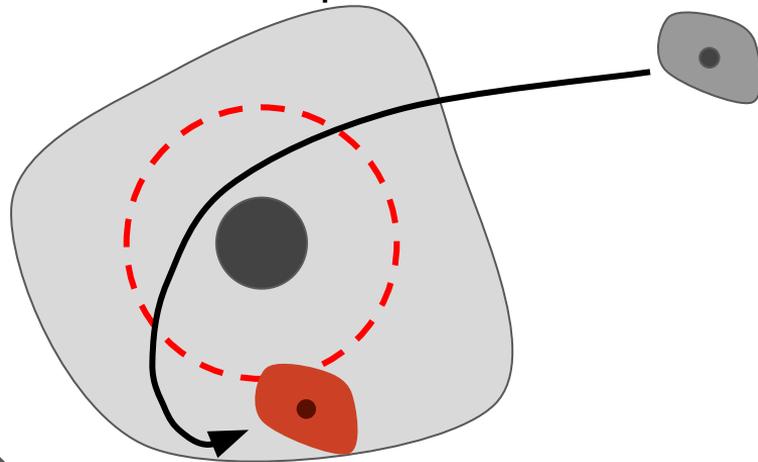
Single-halo tidal forces  
Variable:  $R_{\text{hill}}$



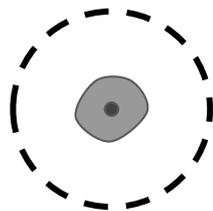
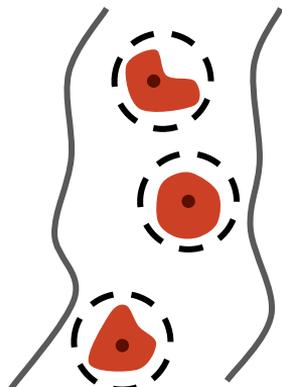
$M_{\text{hill},b}$



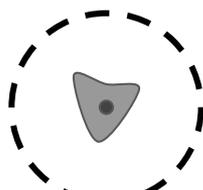
Misidentified splashback subhaloes



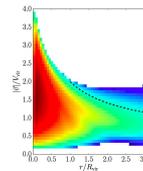
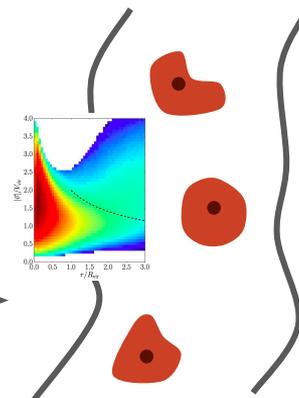
Large-scale tidal forces  
Variable:  $R_{\text{tidal}}$



$M_{\text{tidal},b}$



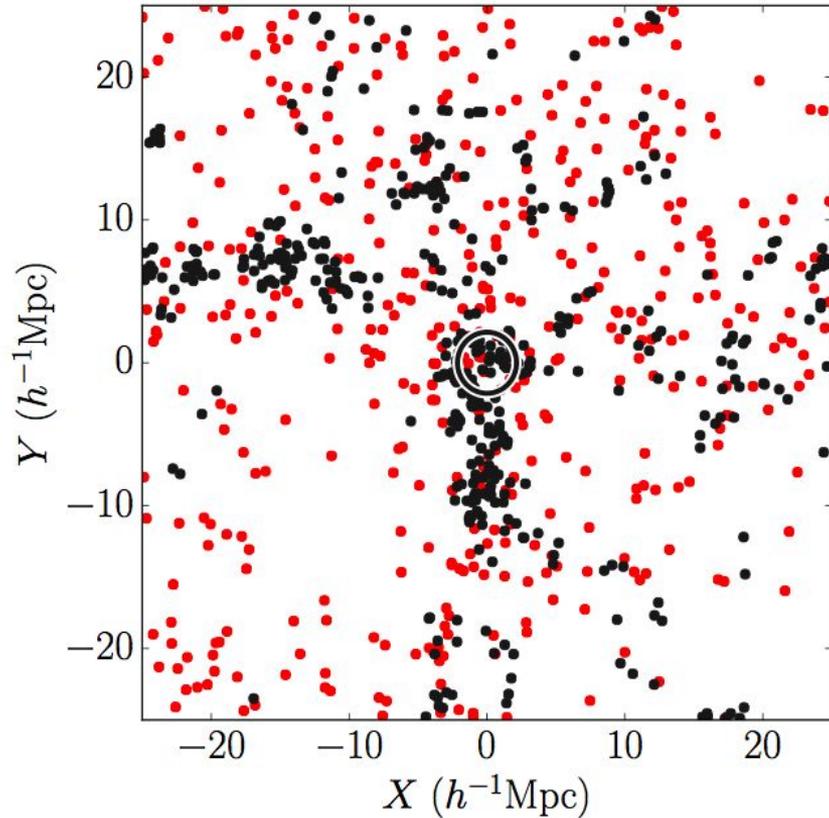
Gravitational heating  
Variable:  $M_{\text{bound}}$



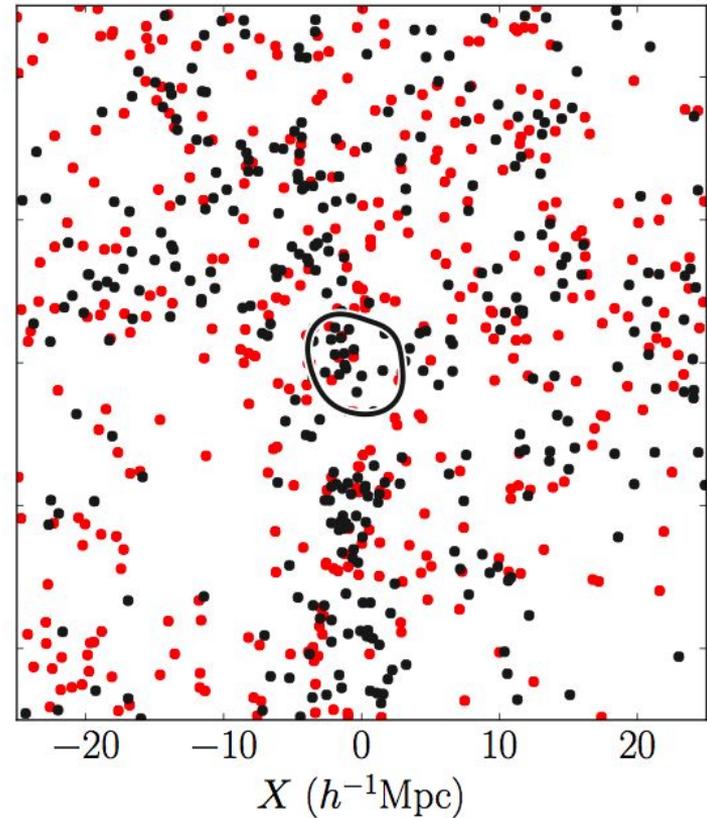
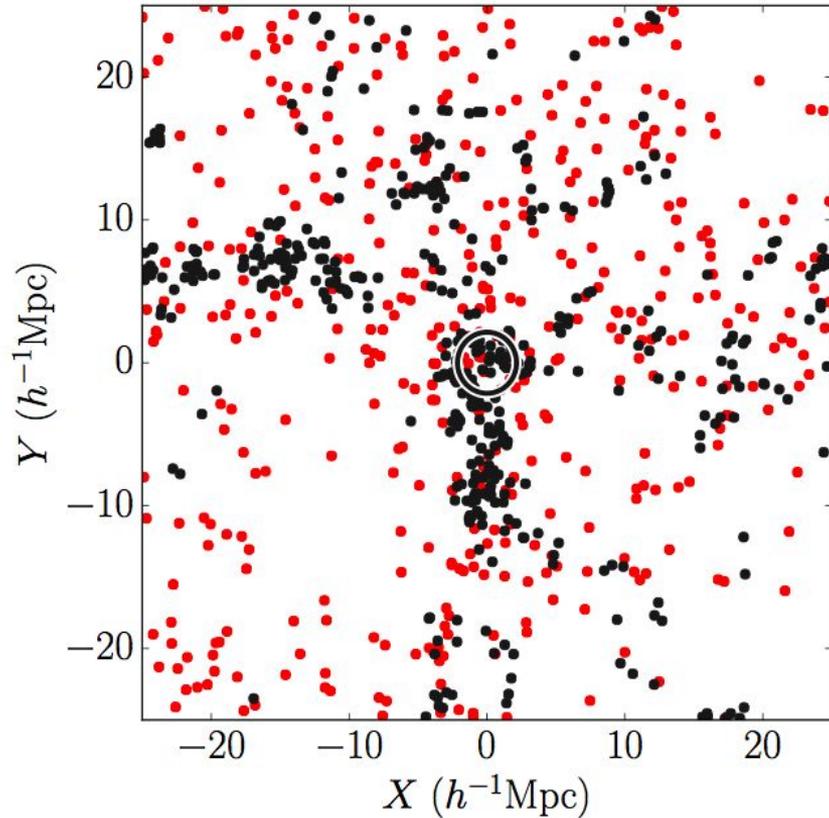
# How Do These Explanations Stack Up?

(Mansfield & Kravtsov 2019)

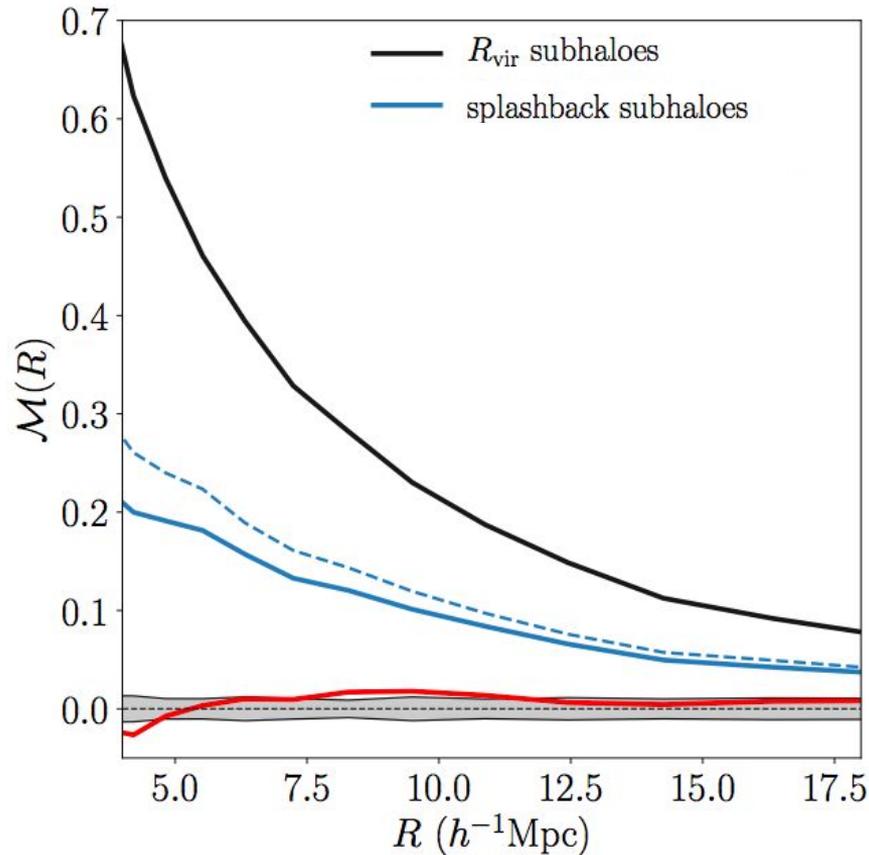
# The Effect of Splashback Subhaloes



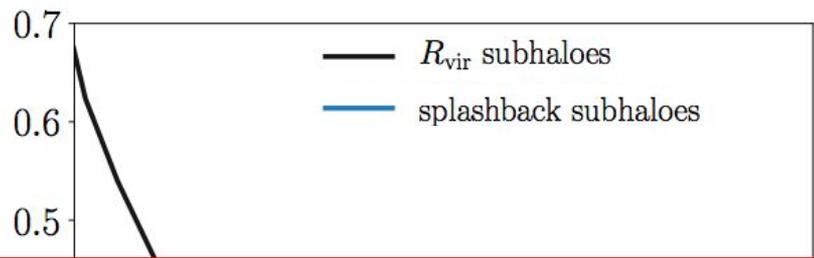
# The Effect of Splashback Subhaloes



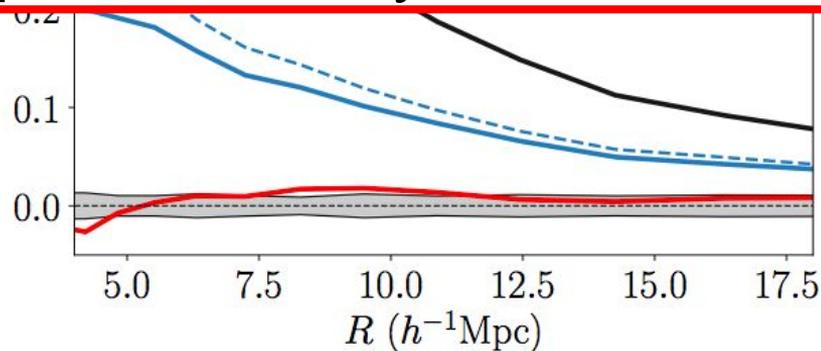
# The Effect of Splashback Subhaloes

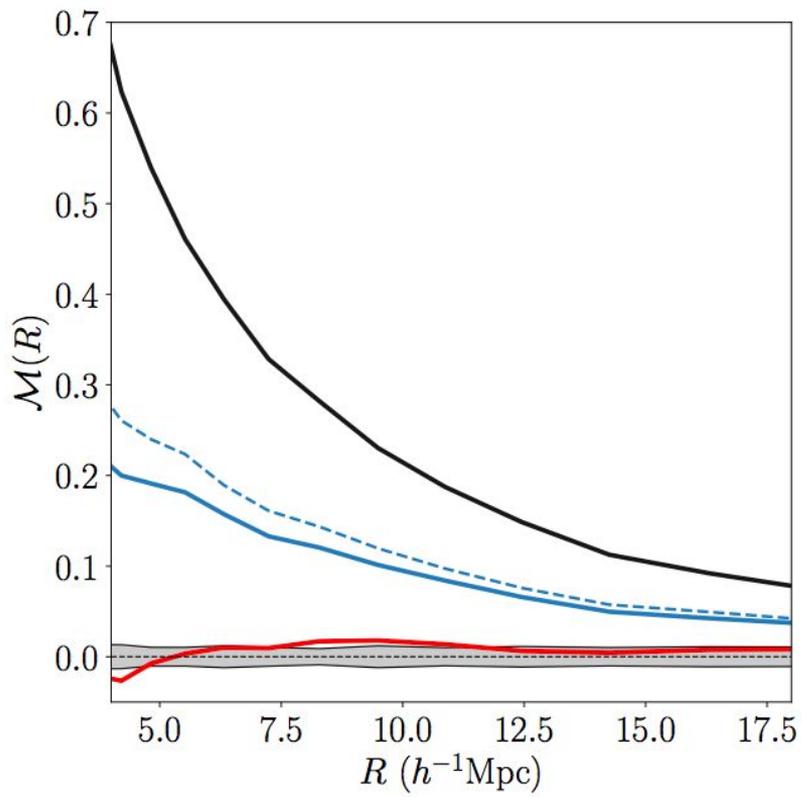


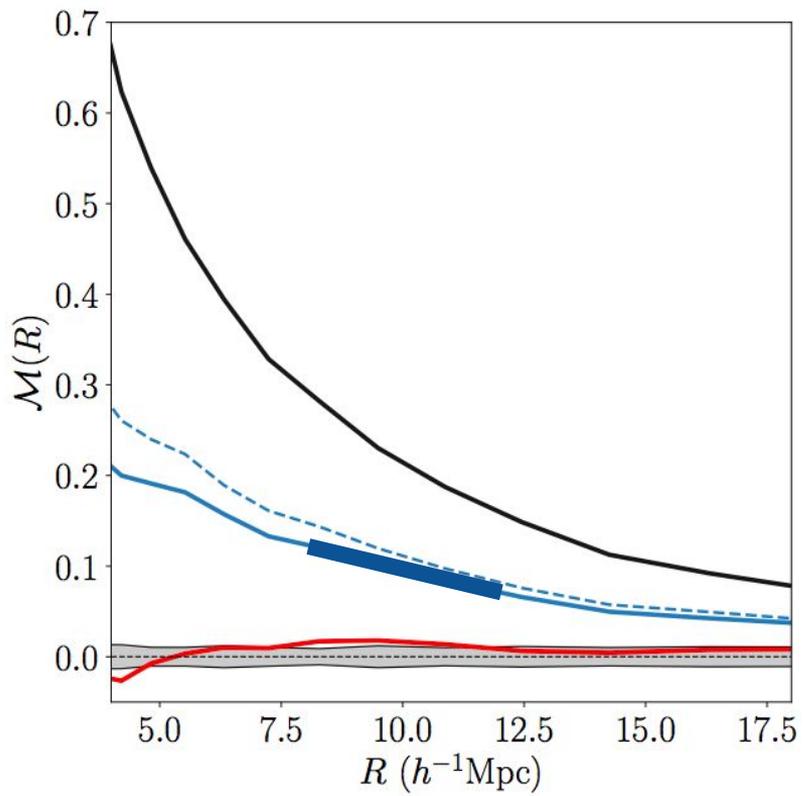
# The Effect of Splashback Subhaloes

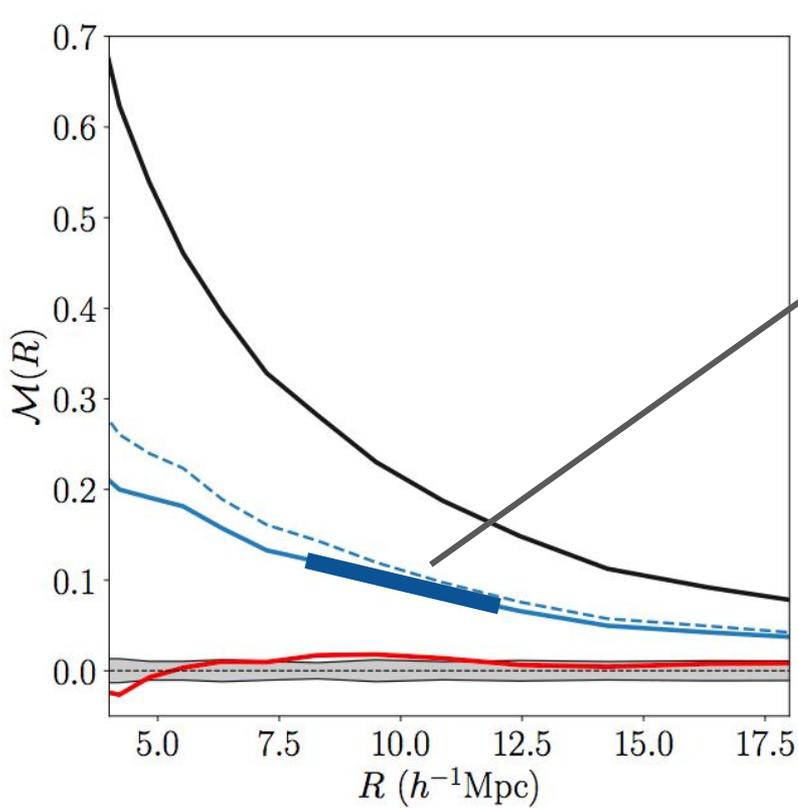


**FACT 1:** Splashback subhaloes cause most (but not all) of  $M_{\text{peak}}$  assembly bias.

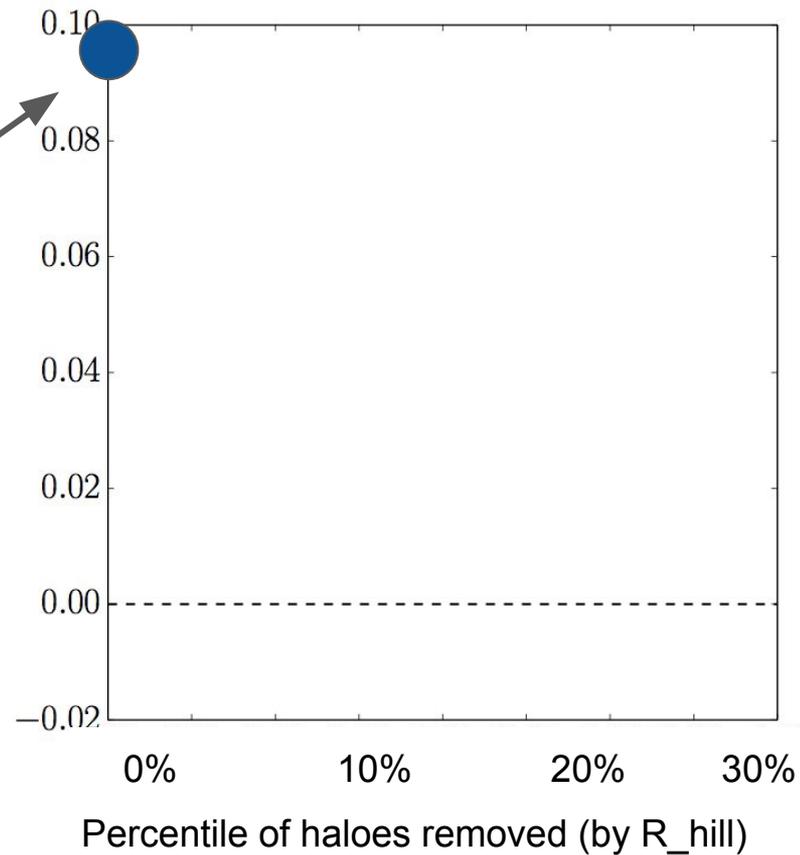


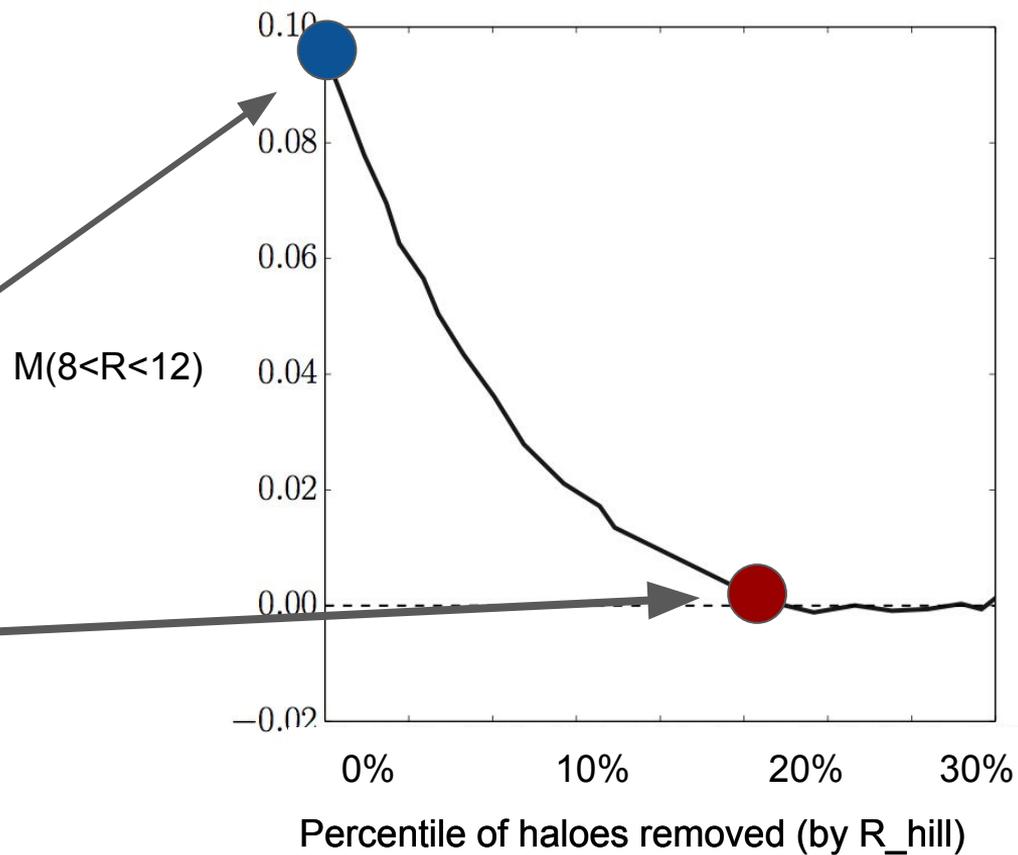
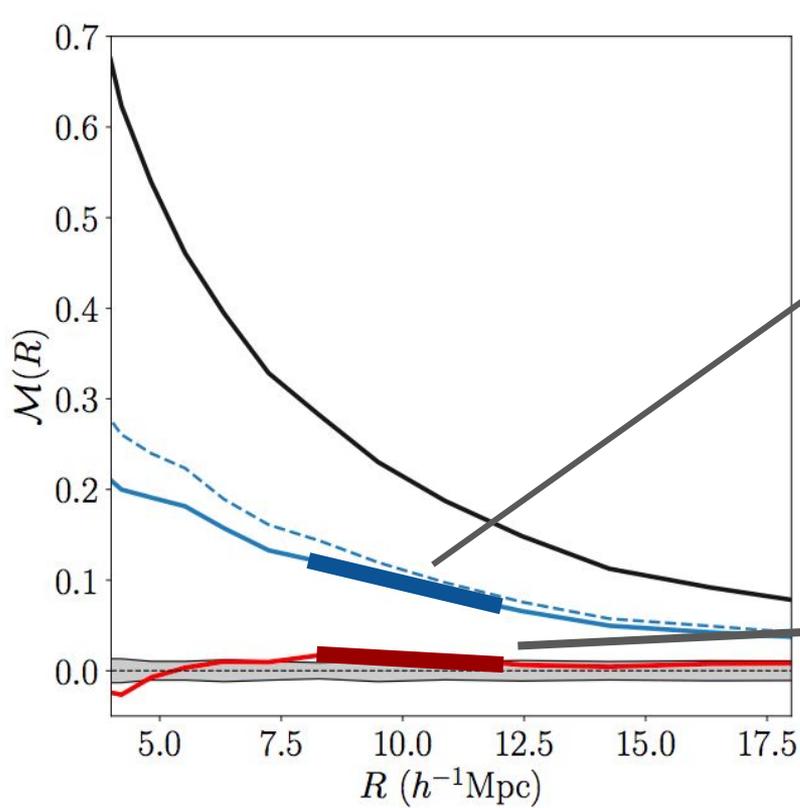


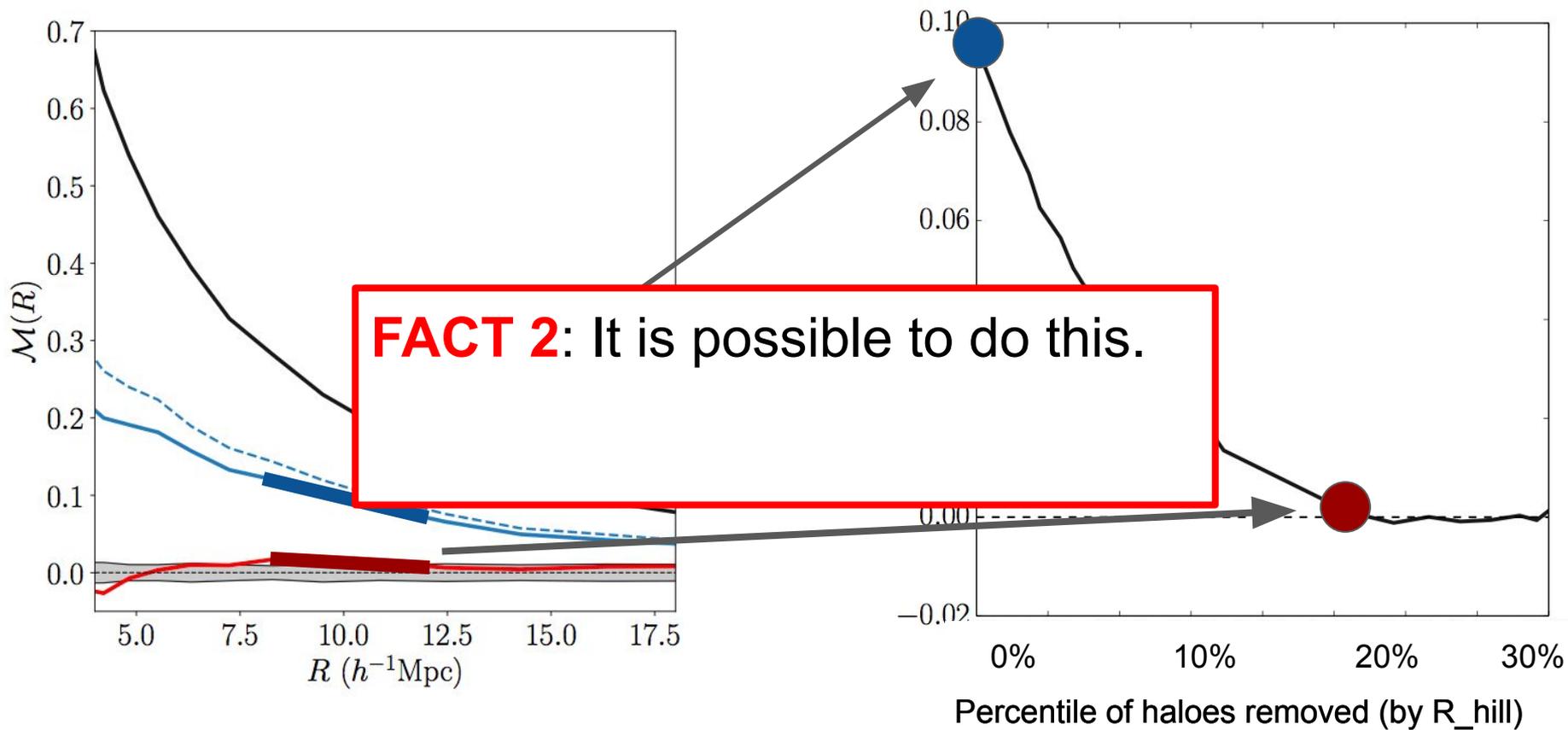




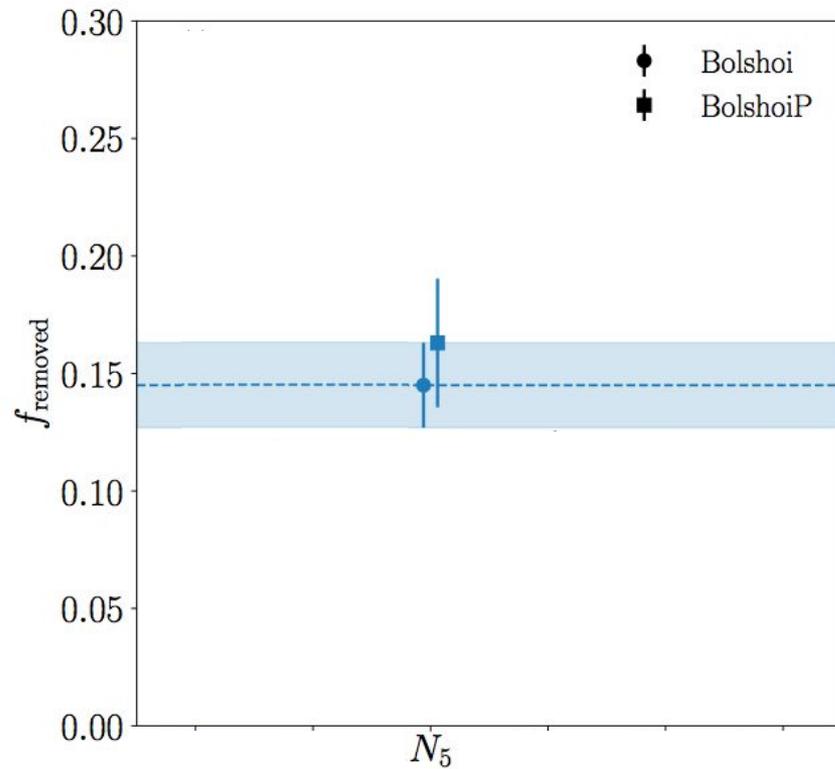
$\mathcal{M}(8 < R < 12)$



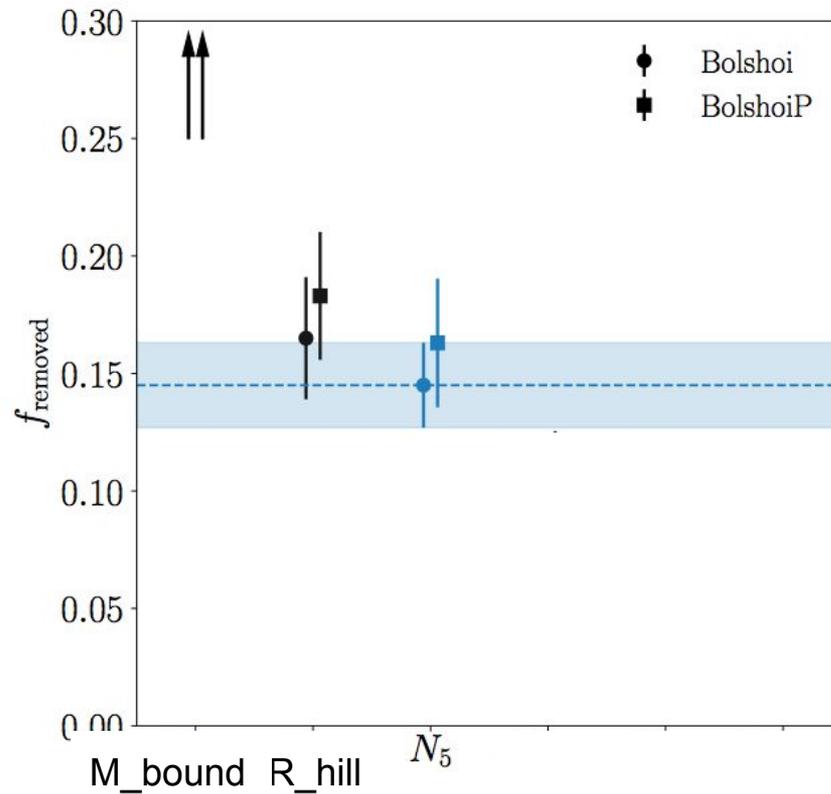




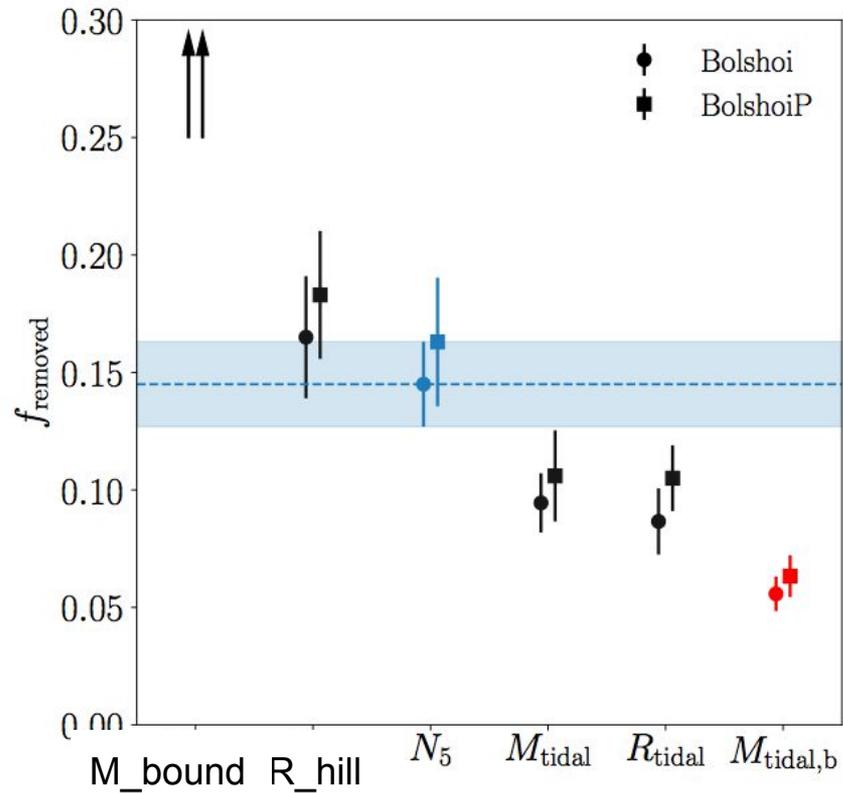
# Which tracers are the most efficient?



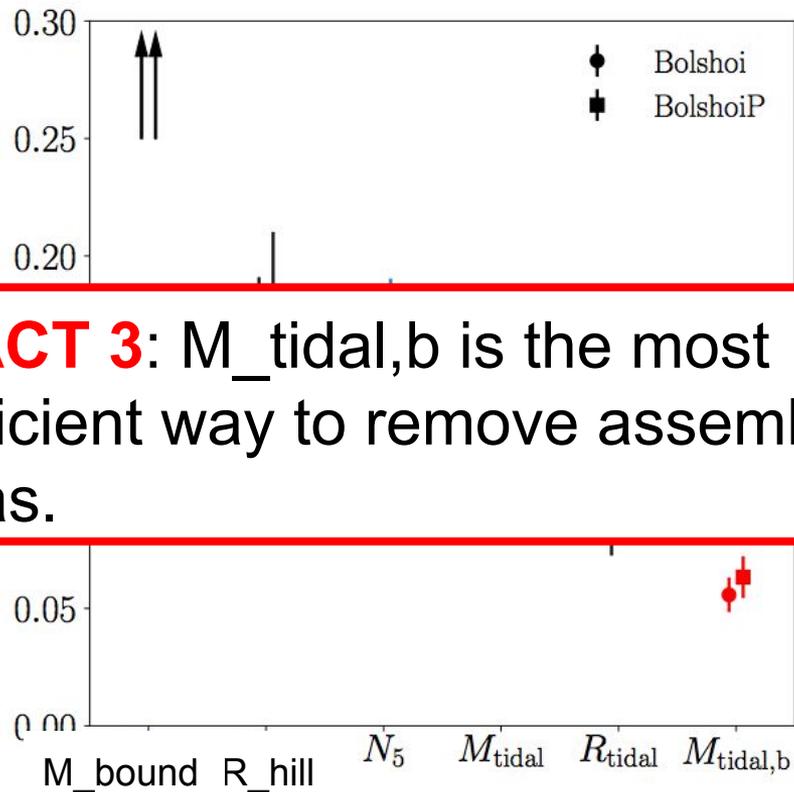
# Which tracers are the most efficient?



# Which tracers are the most efficient?



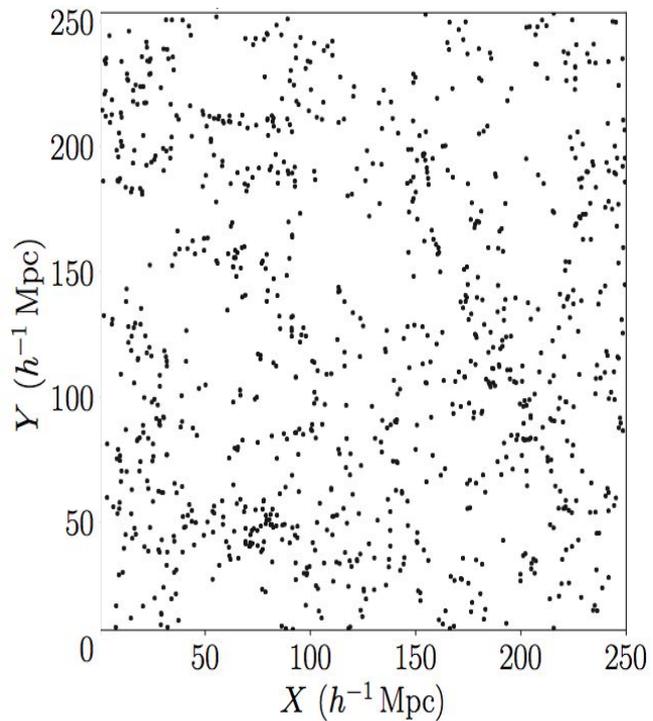
# Which tracers are the most efficient?



**FACT 3:**  $M_{\text{tidal,b}}$  is the most efficient way to remove assembly bias.

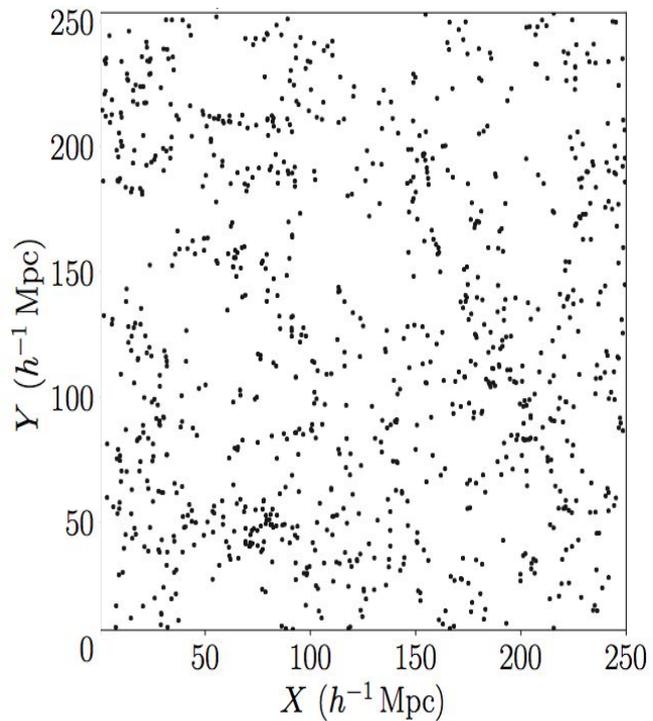
# Where are these haloes?

Remaining Haloes

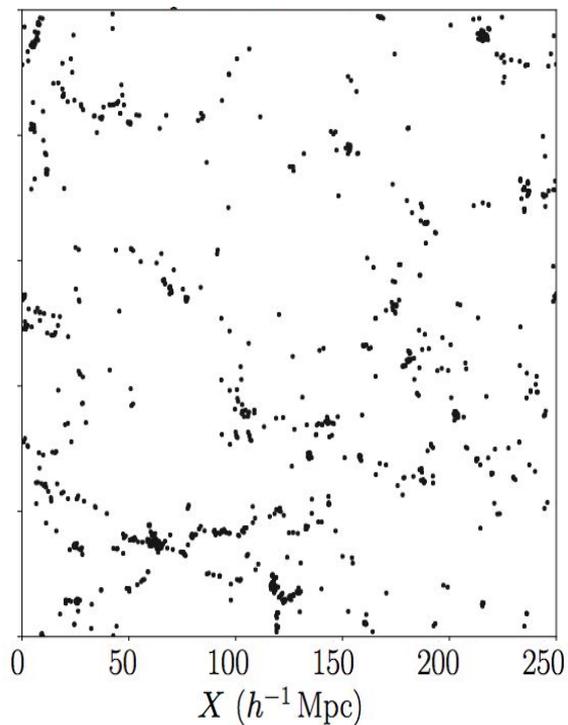


# Where are these haloes?

Remaining Haloes

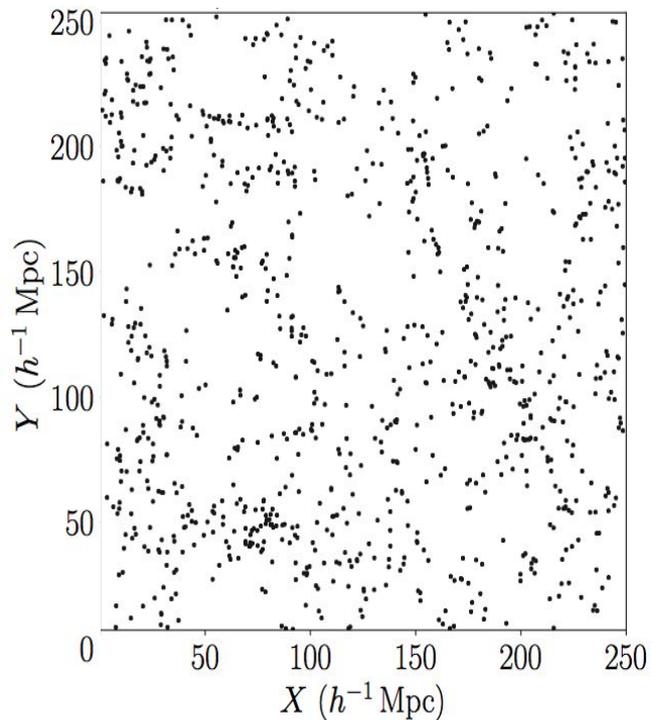


Splashback Subhaloes

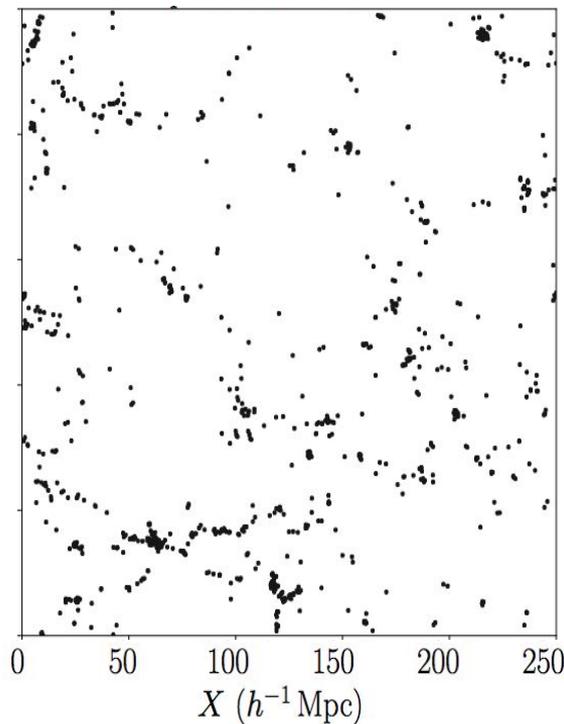


# Where are these haloes?

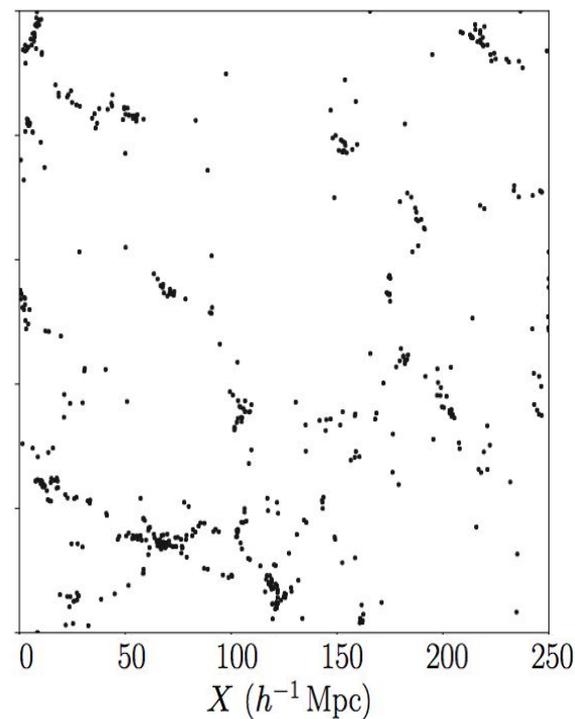
Remaining Haloes



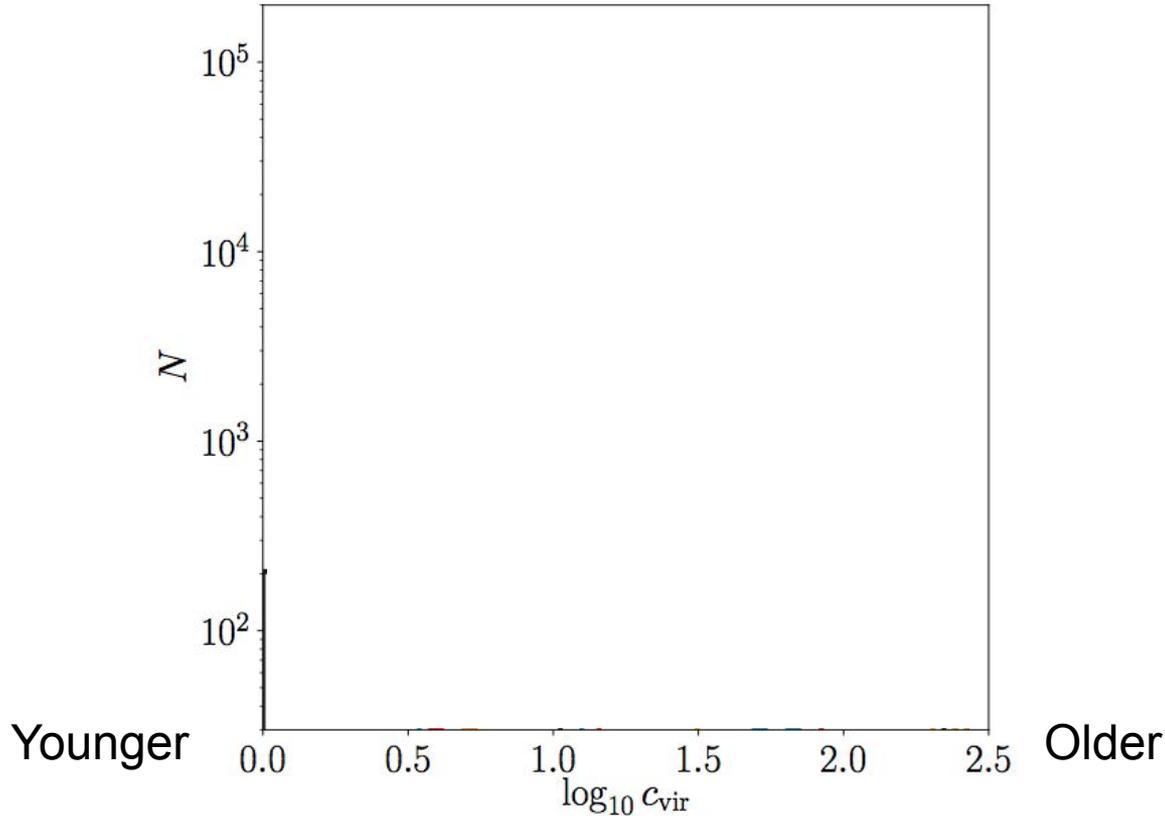
Splashback Subhaloes



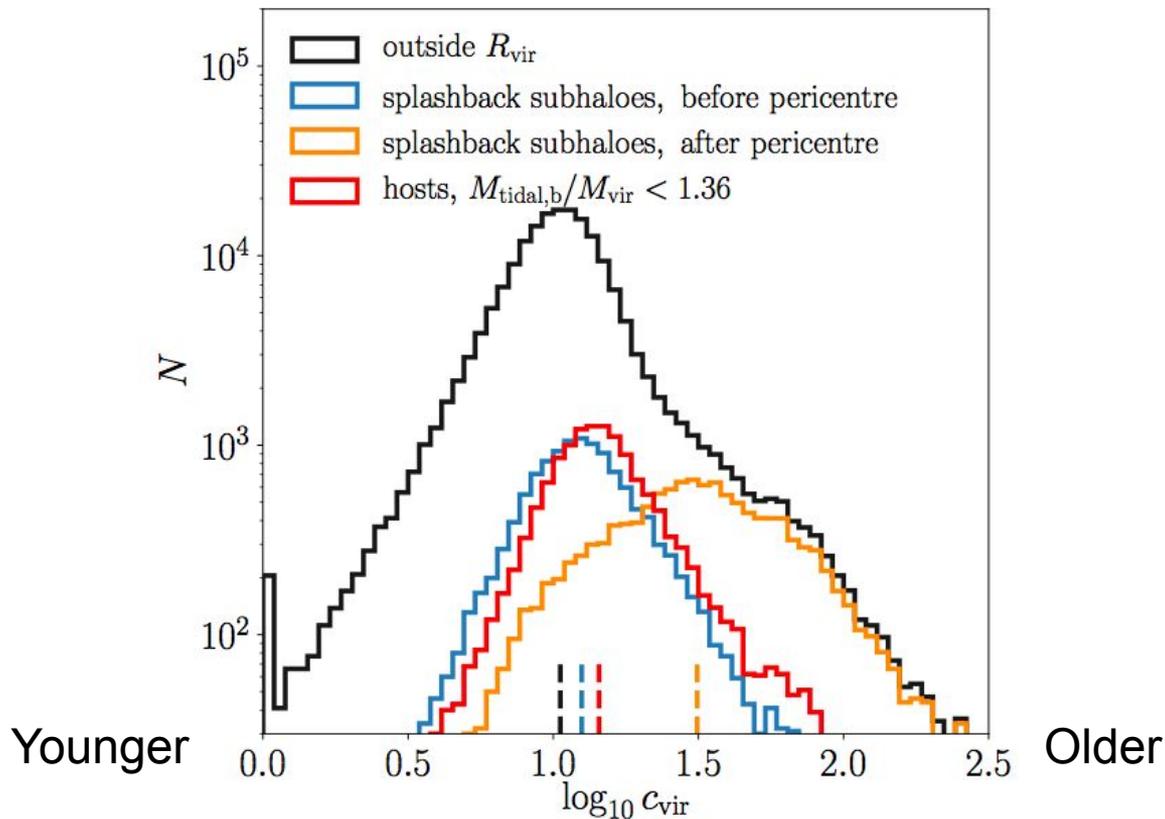
$M_{\text{tidal,b}}$  Haloes



What does  $c_{\text{vir}}$  (age) look like in each of these groups?

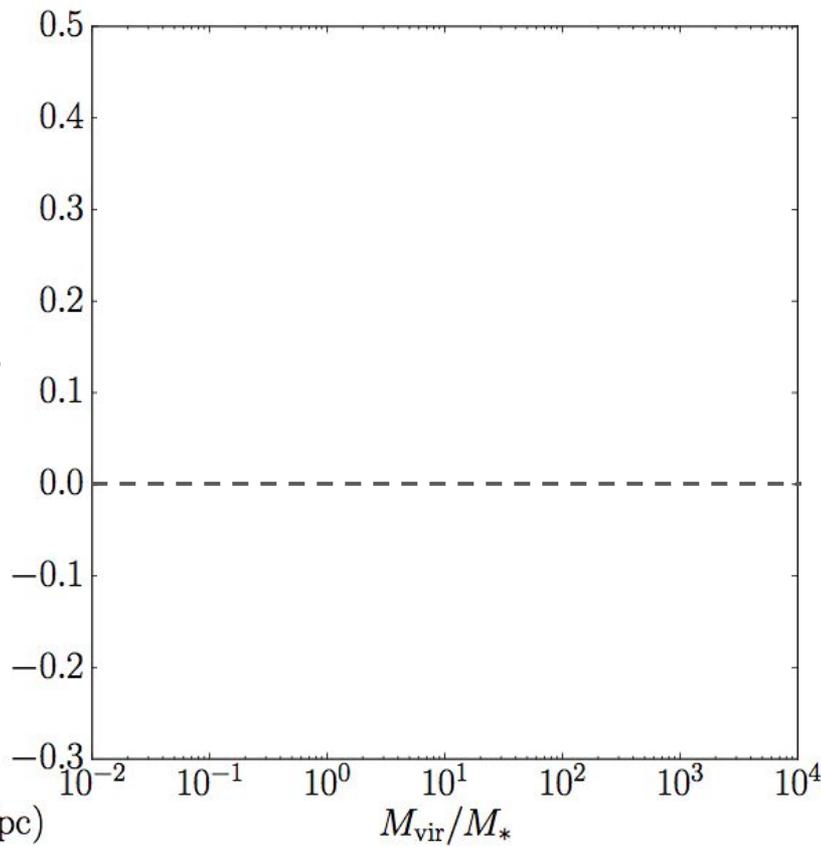


What does  $c_{\text{vir}}$  (age) look like in each of these groups?



# How does this depend on mass?

Assembly Bias  
Strength\*



Older haloes cluster  
more than younger  
haloes

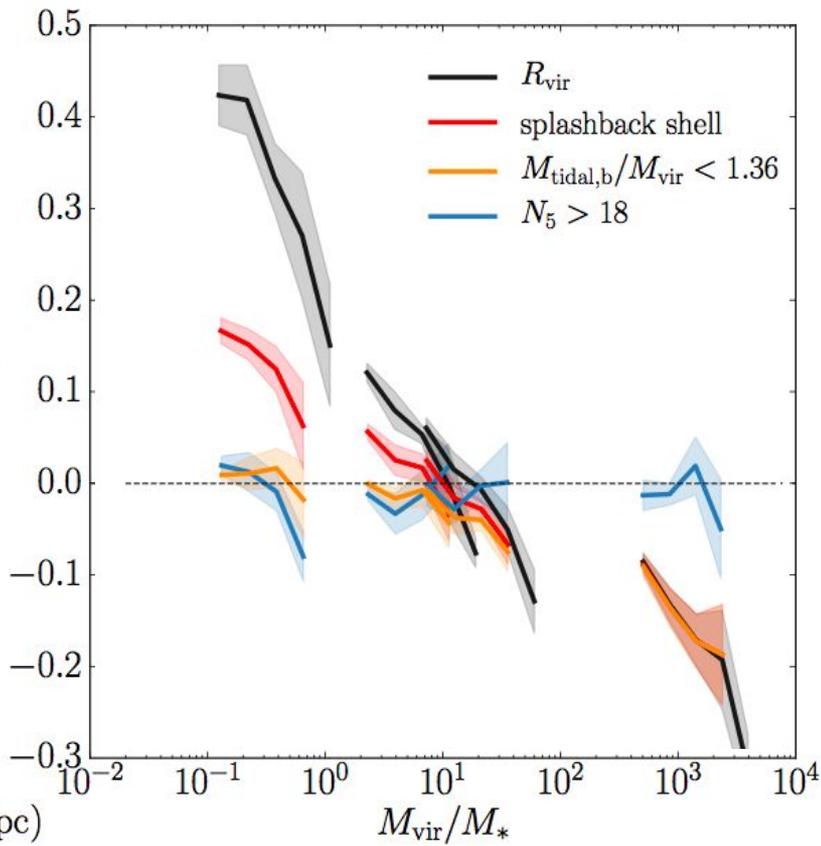
No assembly bias

Younger haloes  
cluster more than  
older haloes

\*  $\text{MCF}(4 h^{-1} \text{ Mpc} < R < 8 h^{-1} \text{ Mpc})$

# How does this depend on mass?

Assembly Bias  
Strength\*



Older haloes cluster  
more than younger  
haloes

No assembly bias

Younger haloes  
cluster more than  
older haloes

\*  $\text{MCF}(4 h^{-1} \text{ Mpc} < R < 8 h^{-1} \text{ Mpc})$

# I'm Working on Other Things, Too

Structure of the Local Volume

The Planes of Satellites Problem

Convergence testing cosmological simulations

Compression algorithms for cosmological simulations

Compression algorithms for surveys and halo catalogues

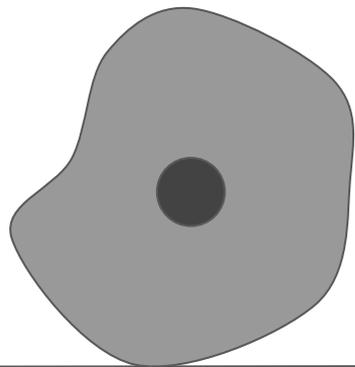
# The Assembly Bias Cheatsheet

- |  |  |
|--|--|
| 1. Dark matter lives inside of dark matter haloes              | 1. Galaxies live at the center of dark matter haloes             |
| 2. Haloes cluster in a way that depends on mass*               | 2. Halo mass is the main thing that determines galaxy properties |
| 3. ...but at a constant mass, clustering also depends on age** | 3. ...but galaxy properties probably also depend on age          |

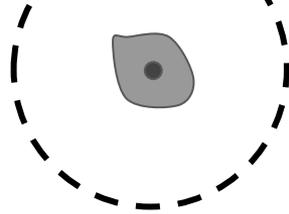
At high masses, *young*<sup>\*\*\*</sup> haloes cluster more strongly because of peak curvature<sup>\*\*\*\*</sup>

At low masses, *old* haloes cluster more strongly because of  $\sim \sqrt{\rho}$

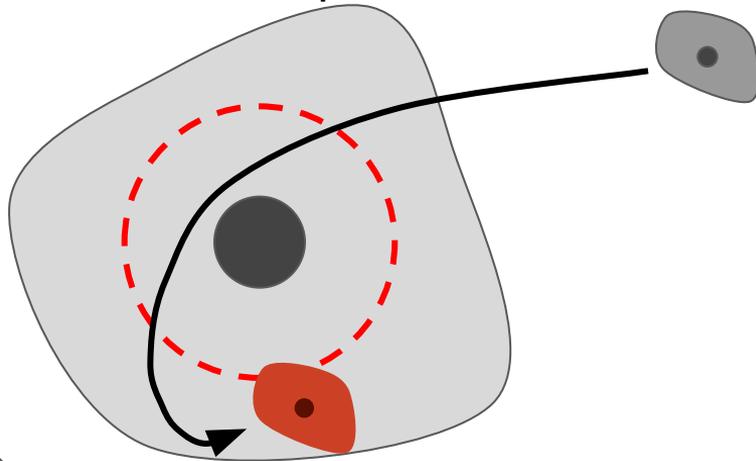
Single-halo tidal forces  
Variable:  $R_{\text{hill}}$



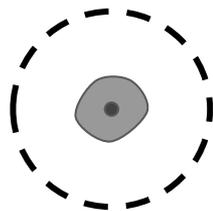
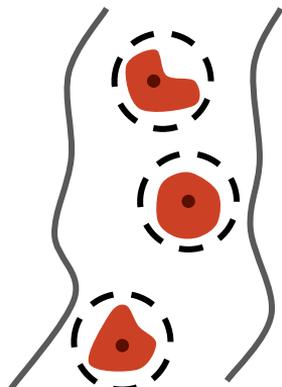
$M_{\text{hill},b}$



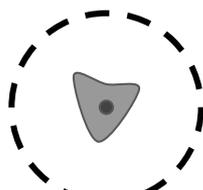
Misidentified splashback subhaloes



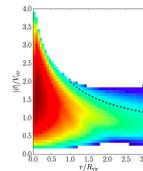
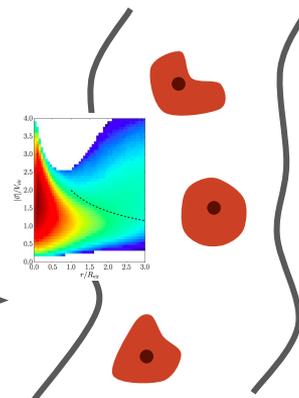
Large-scale tidal forces  
Variable:  $R_{\text{tidal}}$



$M_{\text{tidal},b}$



Gravitational heating  
Variable:  $M_{\text{bound}}$



# Summary

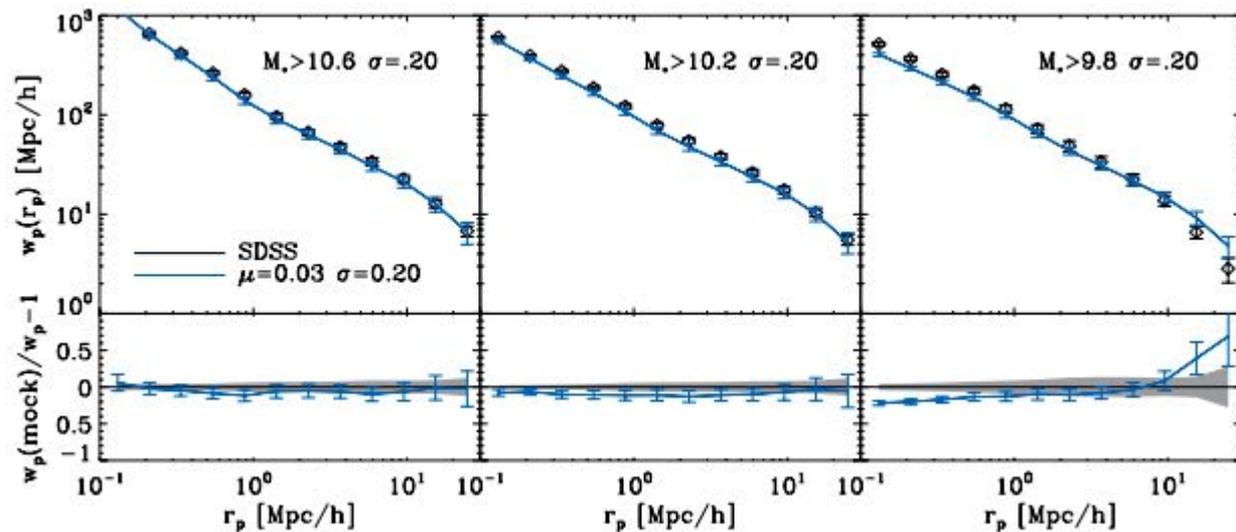
Galaxy-mass assembly bias (in cvir) comes from a small fraction of haloes and it not present in the rest of the sample.

These haloes are a combination of misidentified splashback subhaloes, and haloes with slightly truncated accretion histories due to both large-scale tidal fields and gravitational heating.

Misidentified subhaloes are very old and truncated haloes only see a slight shift in the age distribution.

# Abundance Matching and Observations

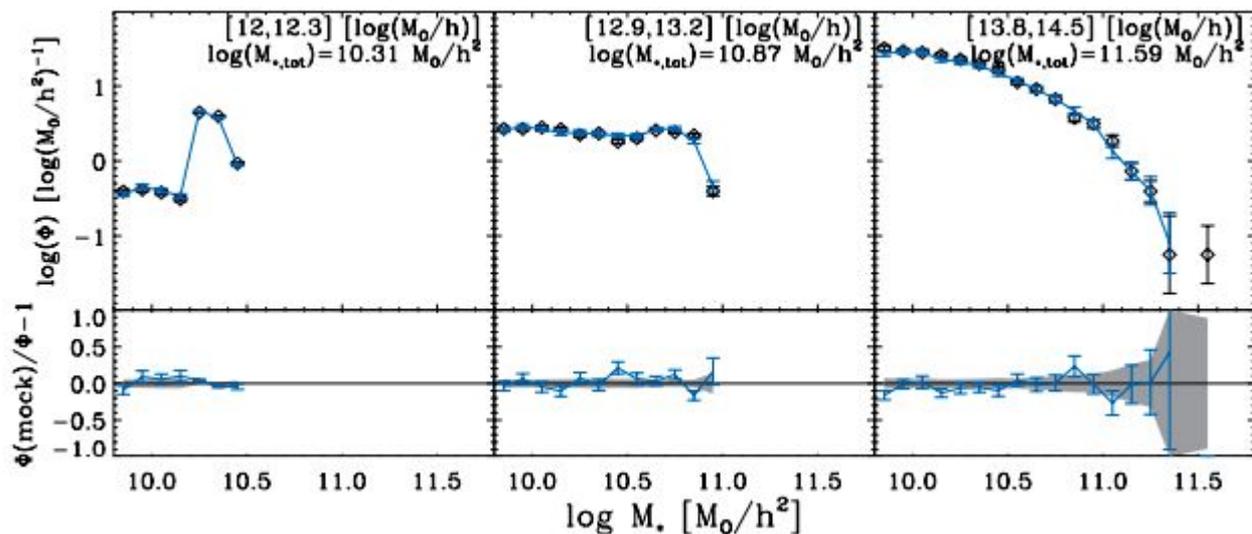
- Clustering strength



(Reddick et al. 2013)

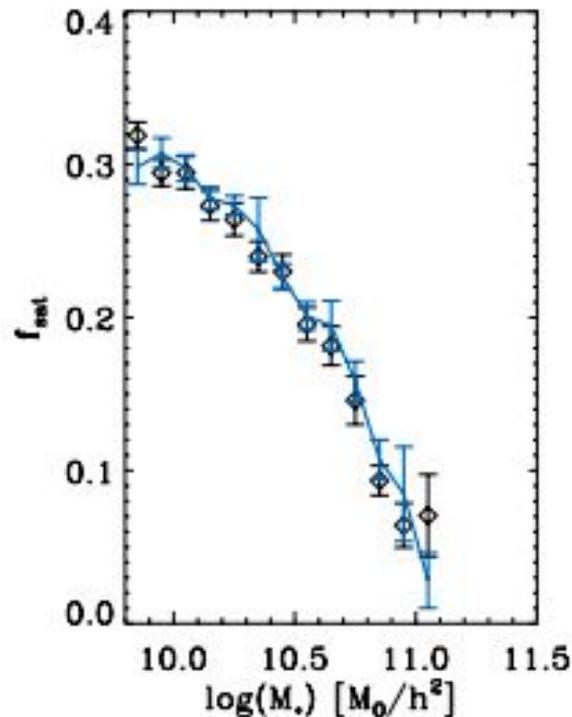
# Abundance Matching and Observations

- Clustering strength
- **Satellite stellar masses**



# Abundance Matching and Observations

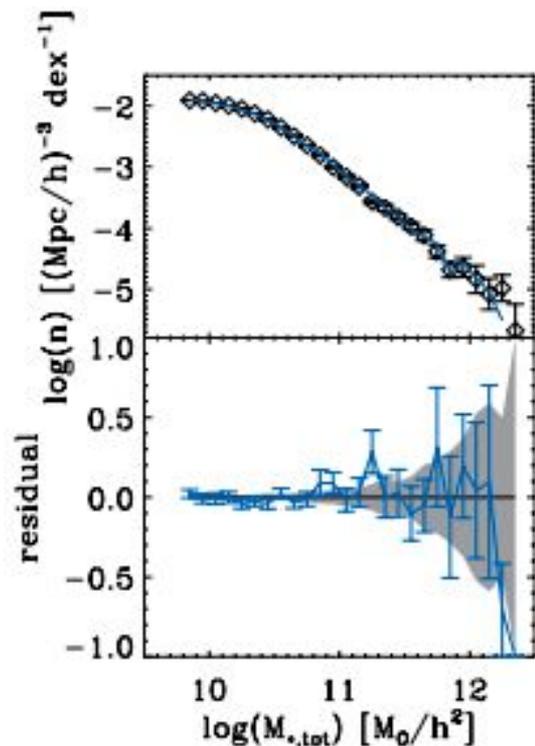
- Clustering strength
- Satellite stellar masses
- **Satellite/central likelihood**



(Reddick et al. 2013)

# Abundance Matching and Observations

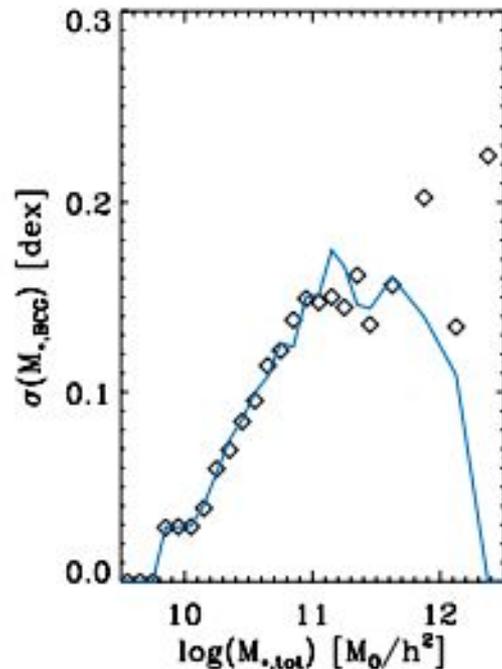
- Clustering strength
- Satellite stellar masses
- Satellite/central likelihood
- **Total stellar masses**



(Reddick et al. 2013)

# Abundance Matching and Observations

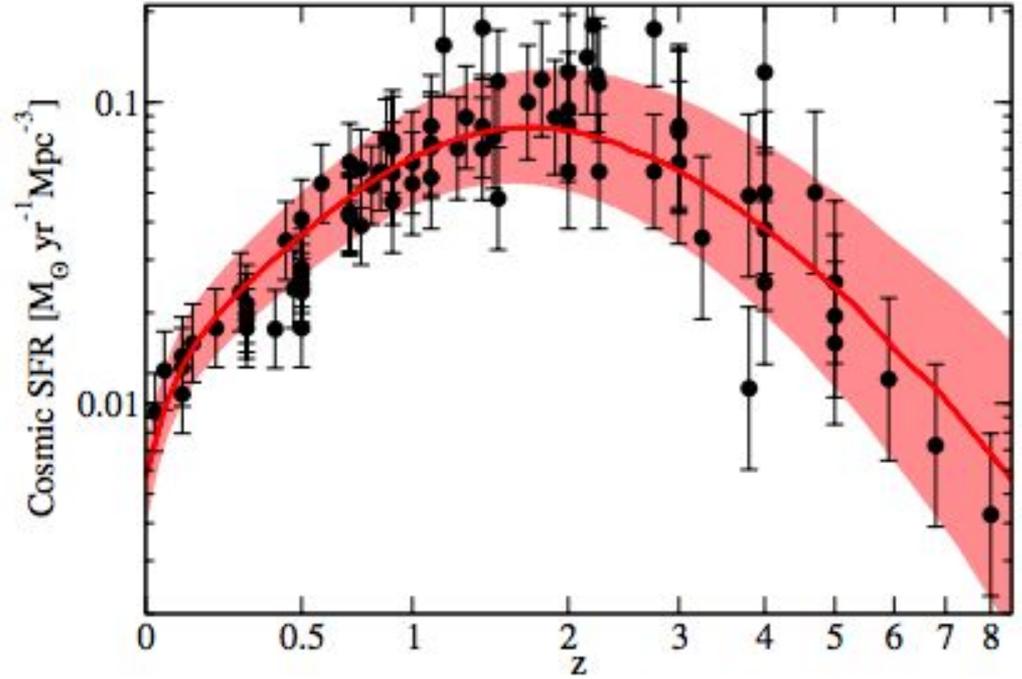
- Clustering strength
- Satellite stellar masses
- Satellite/central likelihood
- Total stellar masses
- **Connection between central and total stellar mass**



(Reddick et al. 2013)

# Abundance Matching and Observations

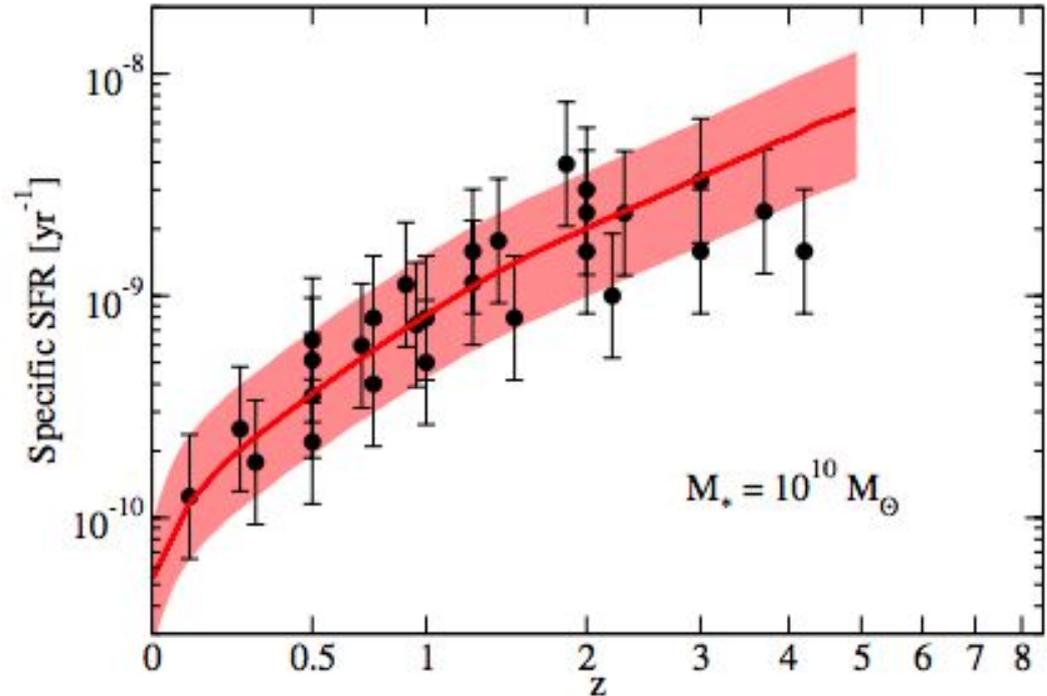
- Clustering strength
- Satellite stellar masses
- Satellite/central likelihood
- Total stellar masses
- Connection between central and total stellar mass
- **Star formation rate**
  - Everywhere



(Behroozi et al. 2013)

# Abundance Matching and Observations

- Clustering strength
- Satellite stellar masses
- Satellite/central likelihood
- Total stellar masses
- Connection between central and total stellar mass
- **Star formation rate**
  - Everywhere
  - **Relative to stellar mass**



(Behroozi et al. 2013)