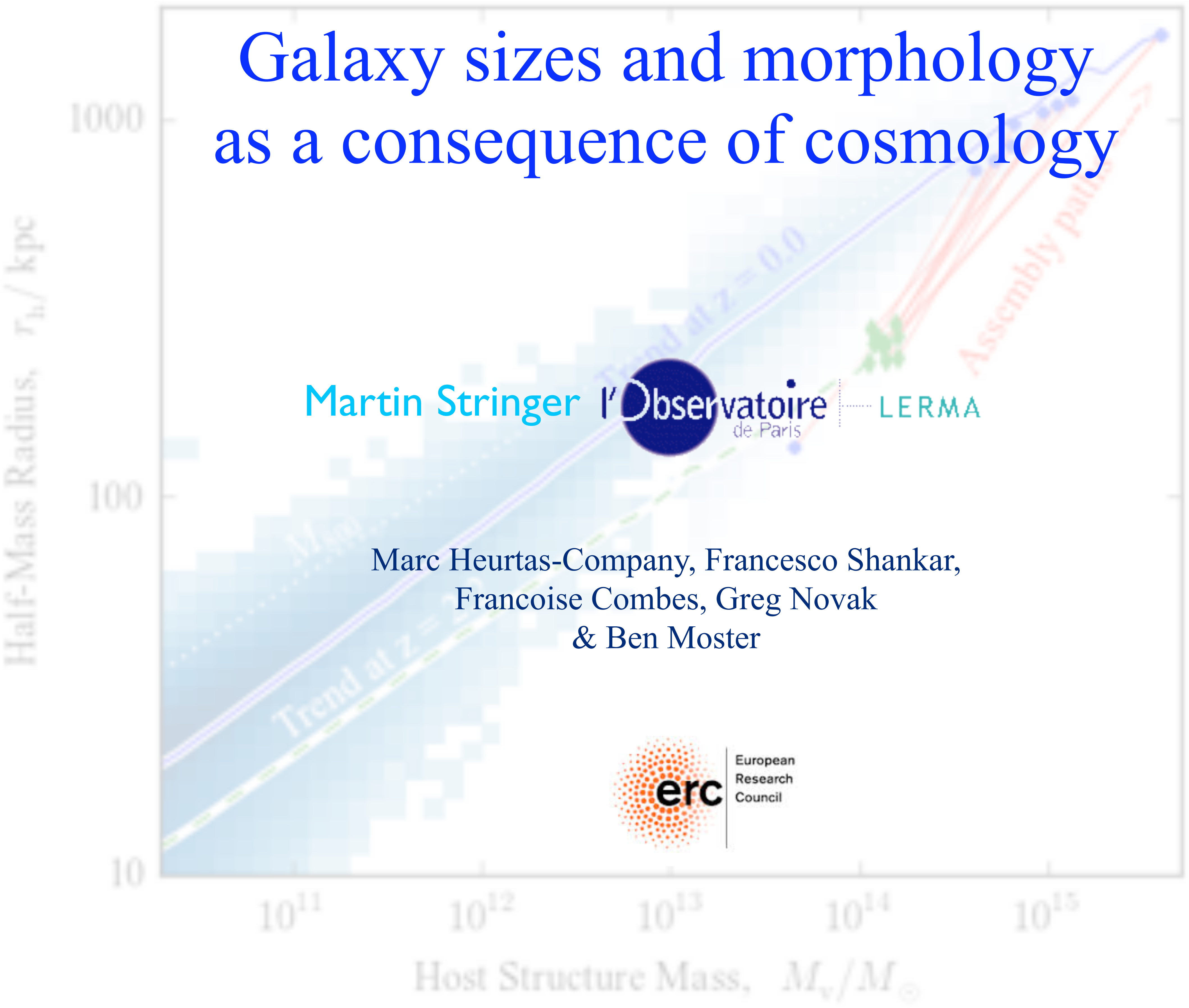
Galaxy sizes and morphology as a consequence of cosmology



Martin Stringer l'Observatoire de Paris | LERMA

Marc Heurtas-Company, Francesco Shankar,
Francoise Combes, Greg Novak
& Ben Moster

erc European Research Council

Complimentary perspectives on galaxy formation

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Archeological

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Evolutionary

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Holistic...

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Galaxy size trends as a consequence of cosmology

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F. Combes[1] and B. P. Moster[4]

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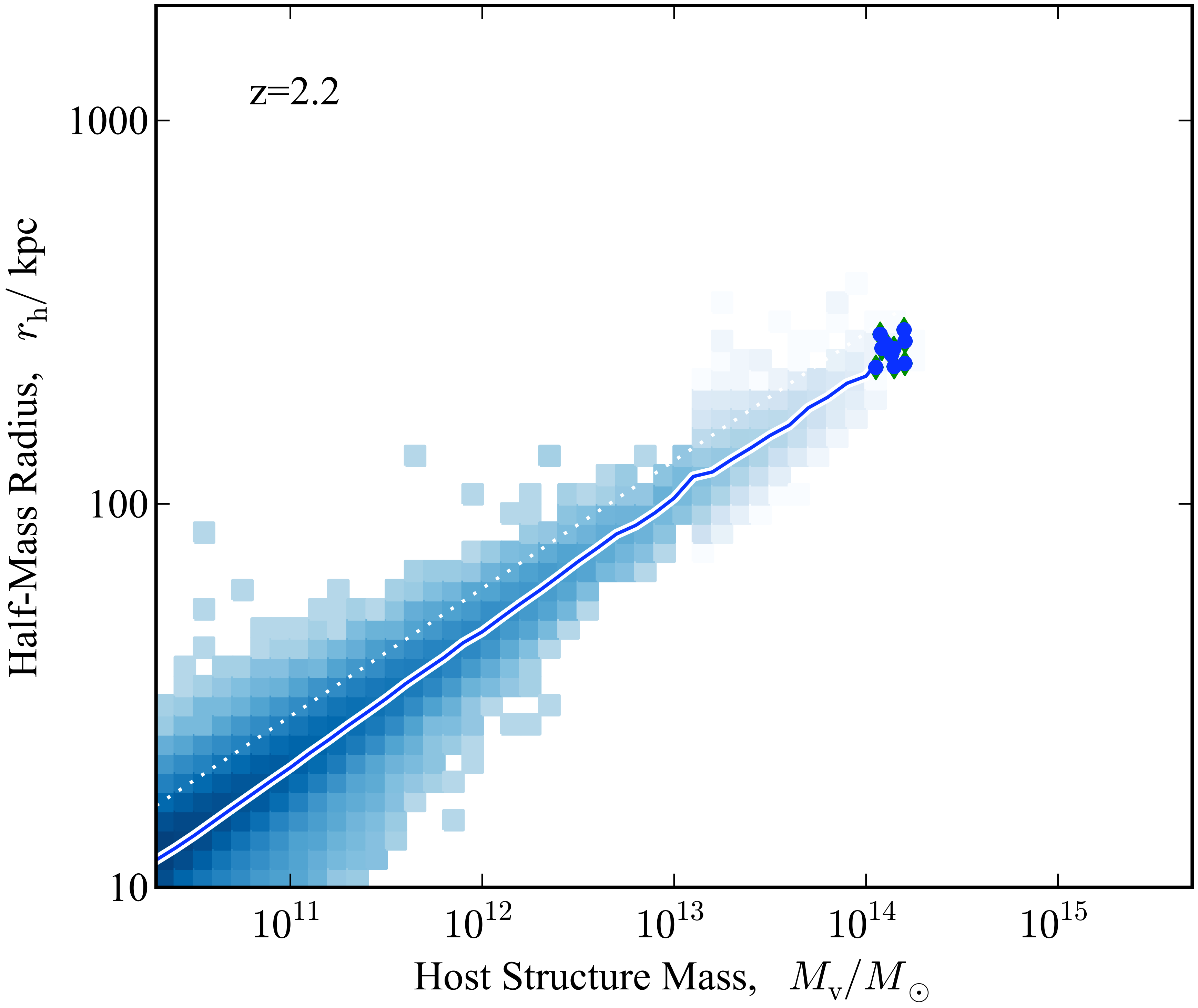
ABSTRACT

We show that the wealth of recent work on trends in galaxy sizes with mass and redshift can be understood in terms of the influence of underlying cosmic evolution; a holistic view which is complimentary to the usual interpretations involving the accumulation of discreet evolutionary processes acting on individual objects. Using analytic predictions from standard cosmology theory, supported with the results of the Millennium simulations, we begin by deriving the size trends in the population of collapsed cosmic structures, and emphasise the important distinction between these trends and the hierarchical assembly of individual structures. Moving on to galaxies, we argue that the observed variation in galactic stellar mass, as a function of inferred host structure mass, can be understood to first order in terms of natural limitations of cooling and feedback. But whilst this fractional stellar mass content varies by orders of magnitude, the characteristic radius of galaxies has been found to correlate strongly and linearly with that of the host structure. Using analytic arguments, illustrated with mock populations generated from the Millennium simulations, we then explain how these two aspects will lead to galaxy sizes that closely follow recently observed trends and their evolution, and verify this with direct comparison to galaxies from the COSMOS and SDSS surveys. Thus we conclude that it may be possible to understand the observed minimum radius for galaxies, the evolving trend in size as a function of mass for intermediate systems, and the observed increase in the sizes of massive galaxies, as being an emergent consequence of the cosmic expansion.

Key words: galaxies: formation – evolution, cosmology: theory

Martin Stringer

Sizes of cosmic structures



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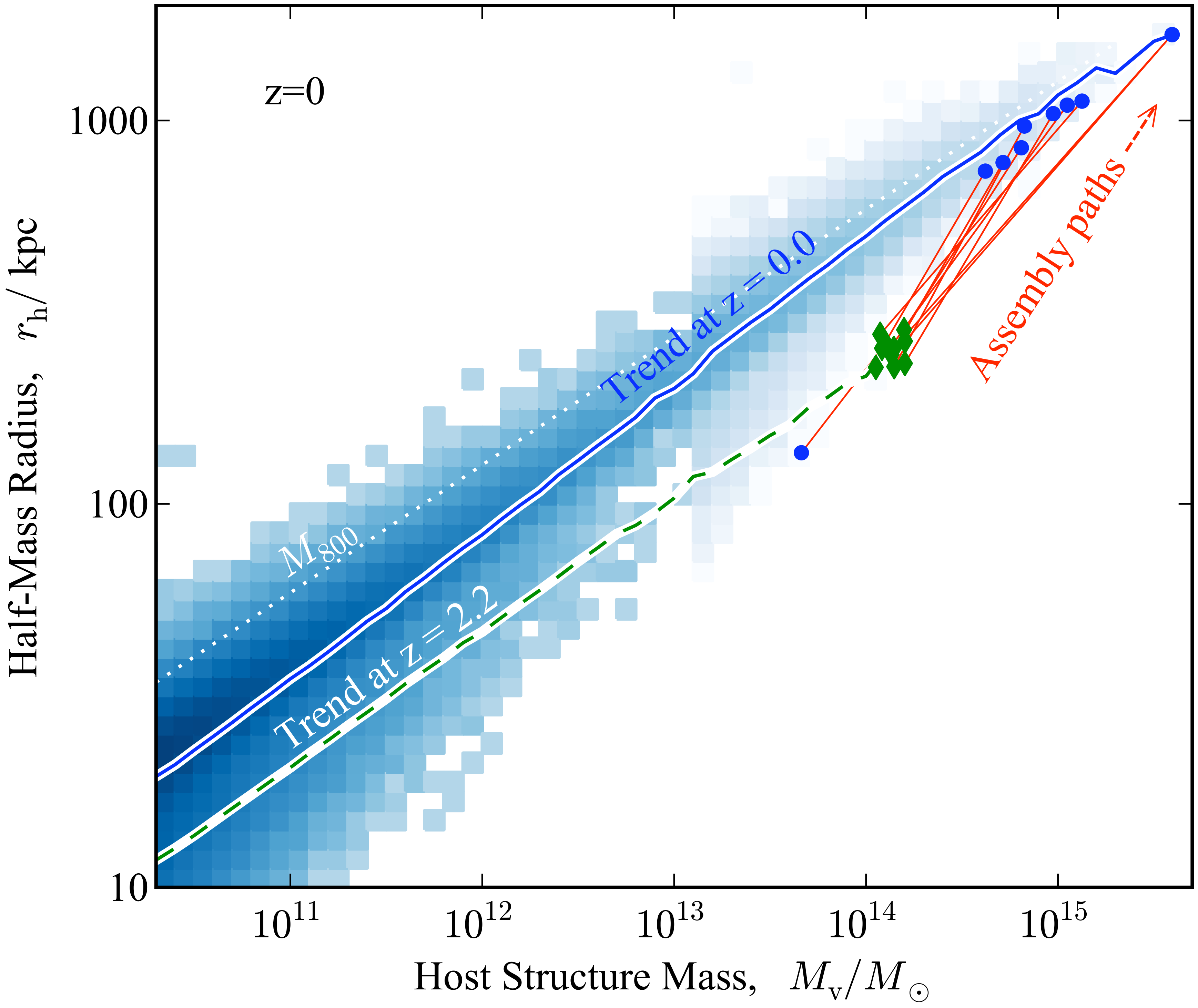


Martin Stringer

The class of z=2.2: Where are they now?

Rank at z=2.2	Rank at z=0
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

The class of z=2.2: Where are they now?

Rank at z=2.2	Rank at z=0
1	1
2	
3	
4	
5	
6	
7	
8	
9	
10	

The class of z=2.2: Where are they now?

Rank at z=2.2	Rank at z=0
1	1
2	53
3	155
4	140
5	
6	
7	
8	
9	
10	

The class of z=2.2: Where are they now?

Rank at z=2.2	Rank at z=0
1	1
2	53
3	155
4	140
5	1
6	
7	
8	
9	
10	

The class of z=2.2: Where are they now?

Rank at z=2.2	Rank at z=0
1	1
2	53
3	155
4	140
5	1
6	250
7	
8	
9	
10	

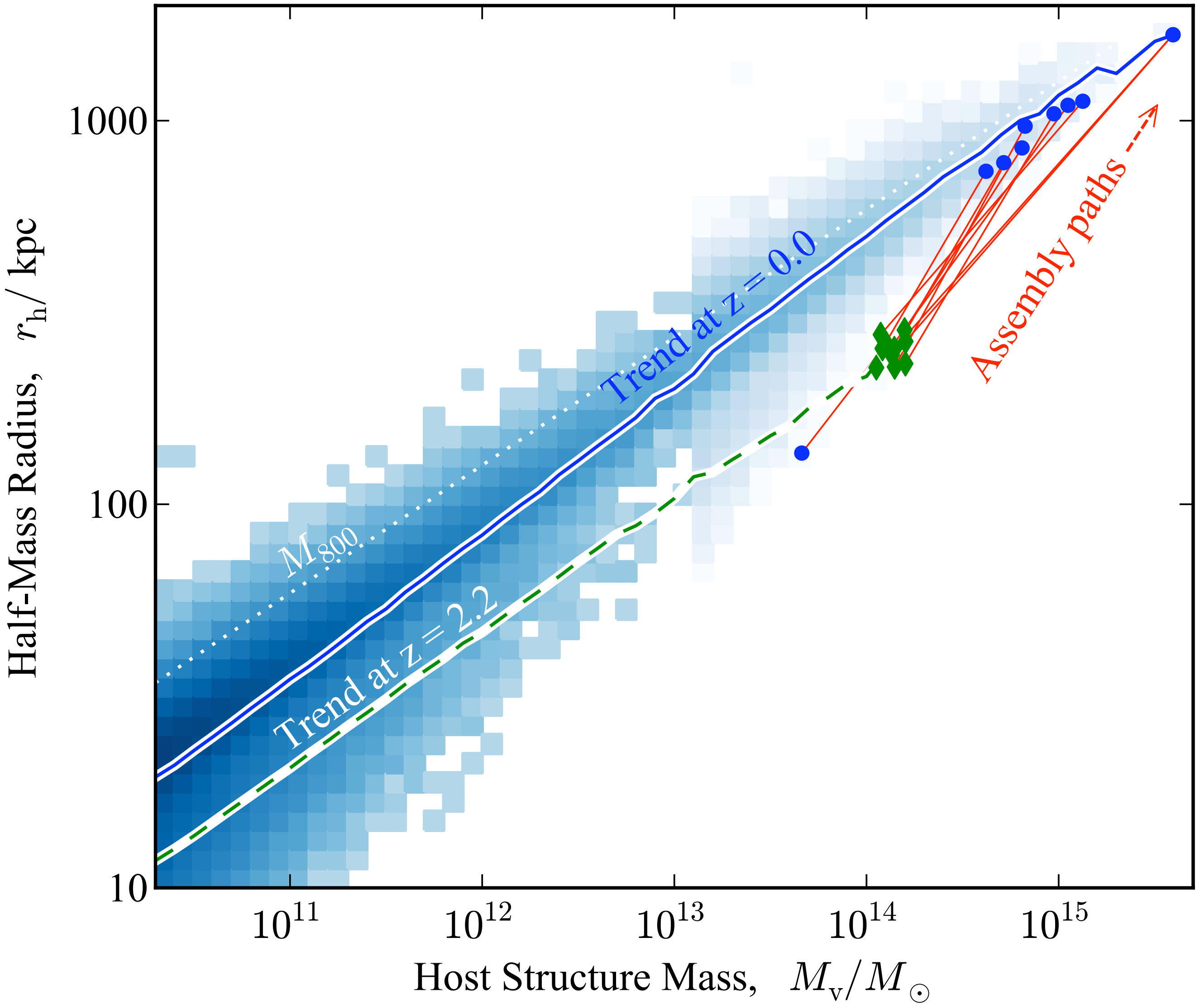
The class of z=2.2: Where are they now?

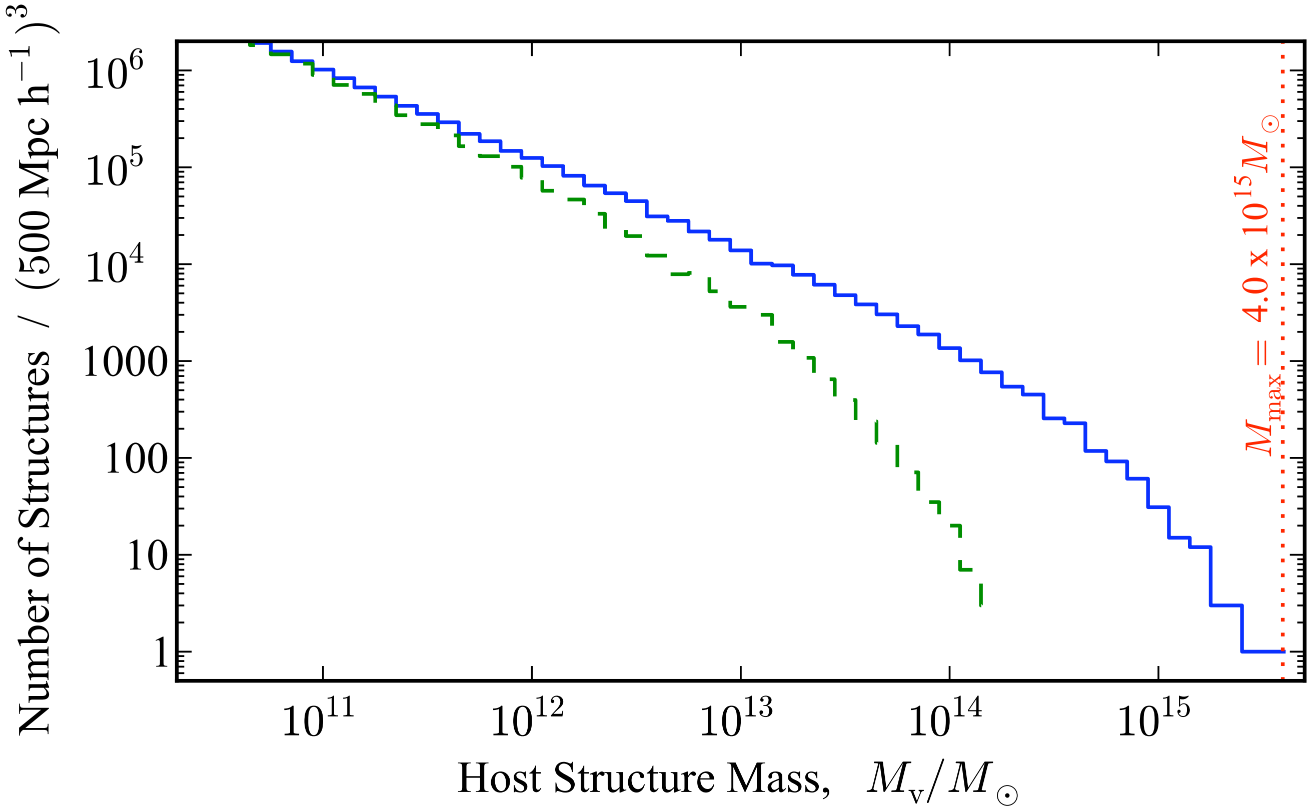
Rank at z=2.2	Rank at z=0
1	1
2	53
3	155
4	140
5	1
6	250
7	11,697
8	
9	
10	

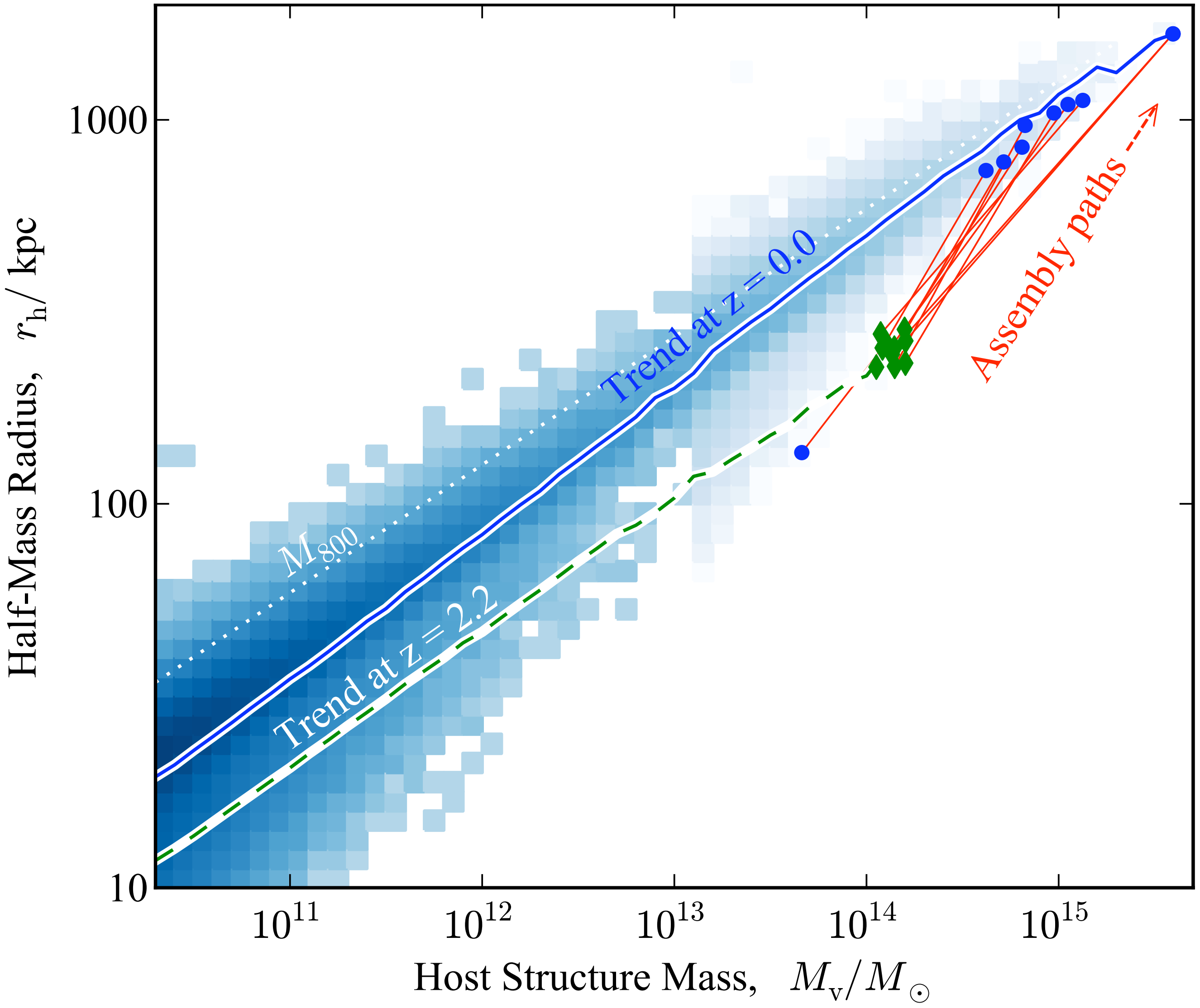
The class of z=2.2: Where are they now?

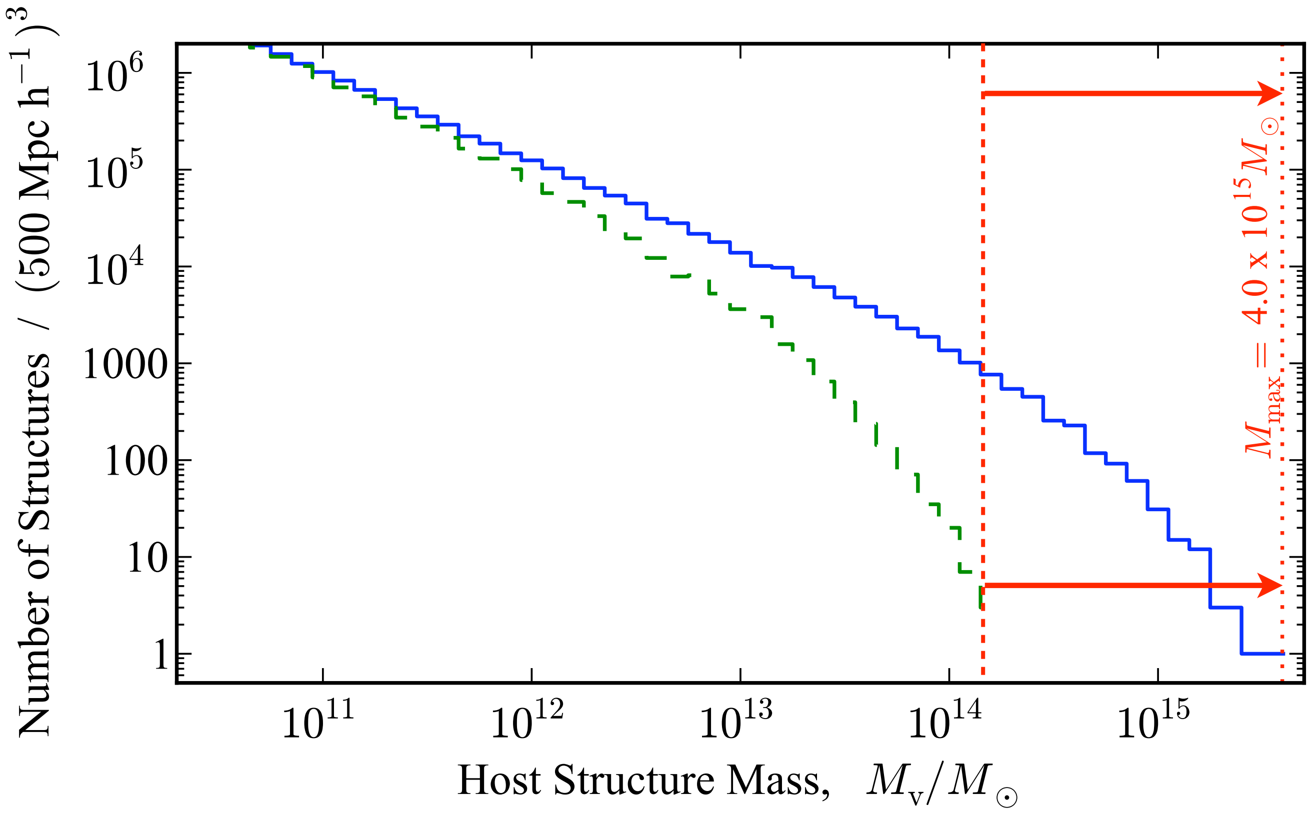
Rank at z=2.2	Rank at z=0
1	1
2	53
3	155
4	140
5	1
6	250
7	11,697
8	385
9	20
10	34

Sizes of cosmic structures




Number of Structures / (500 Mpc h^{-1})^3
10^6
10^5
10^4
1000
100
10
1
$M_{\rm max} = 4.0 \times 10^{15} M_\odot$
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Host Structure Mass, $M_{\rm v}/M_\odot$


Half-Mass Radius, $r_{\rm h}$/ kpc
1000
100
10
Trend at $z = 0.0$
M_{800}
Trend at $z = 2.2$
Assembly paths
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Host Structure Mass, $M_{\rm v}/M_\odot$



Number of Structures / (500 Mpc h^{-1})^3
10^6
10^5
10^4
1000
100
10
1
10^{11}
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10^{15}
Host Structure Mass, $M_\mathrm{v}/M_\odot$
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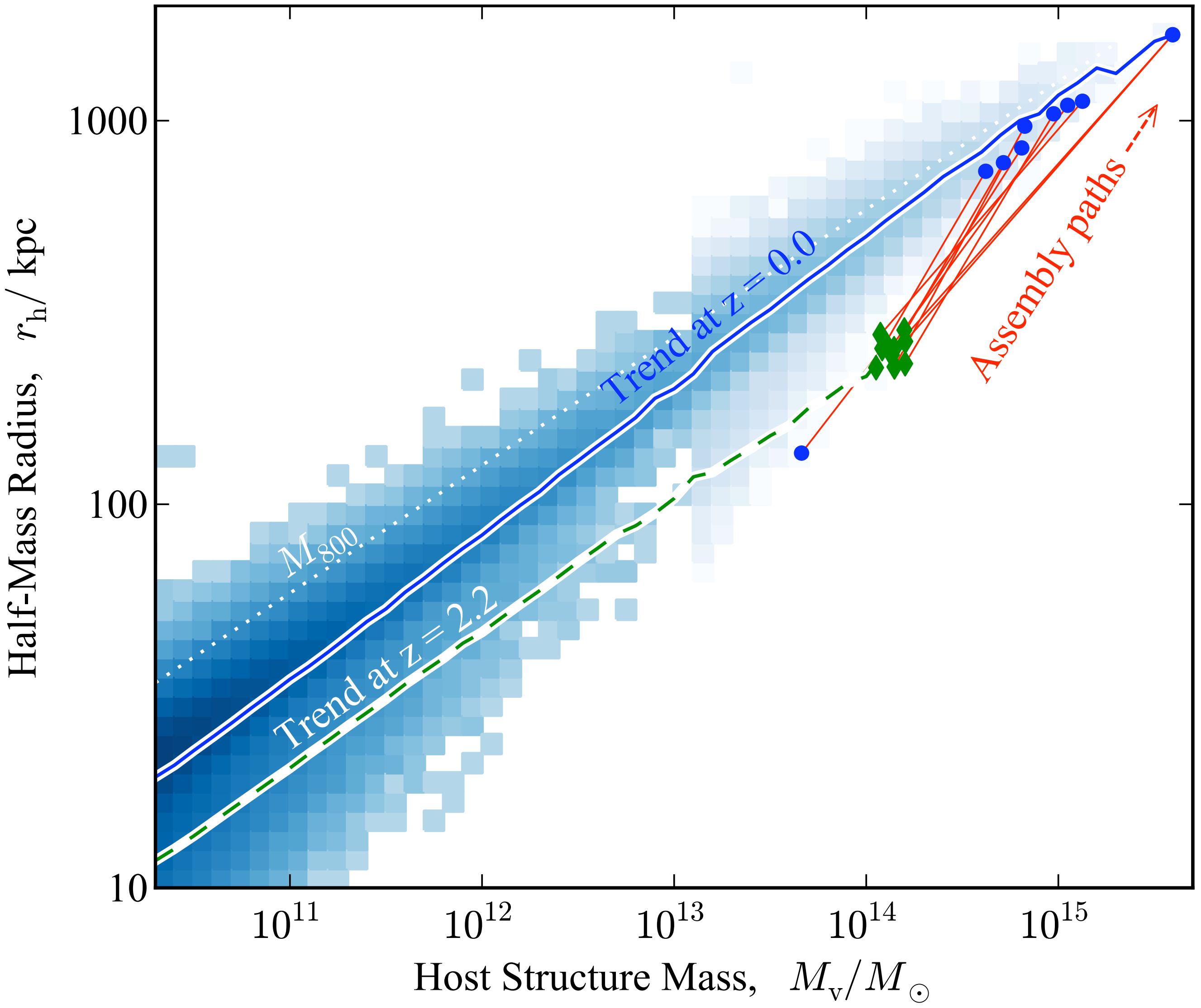
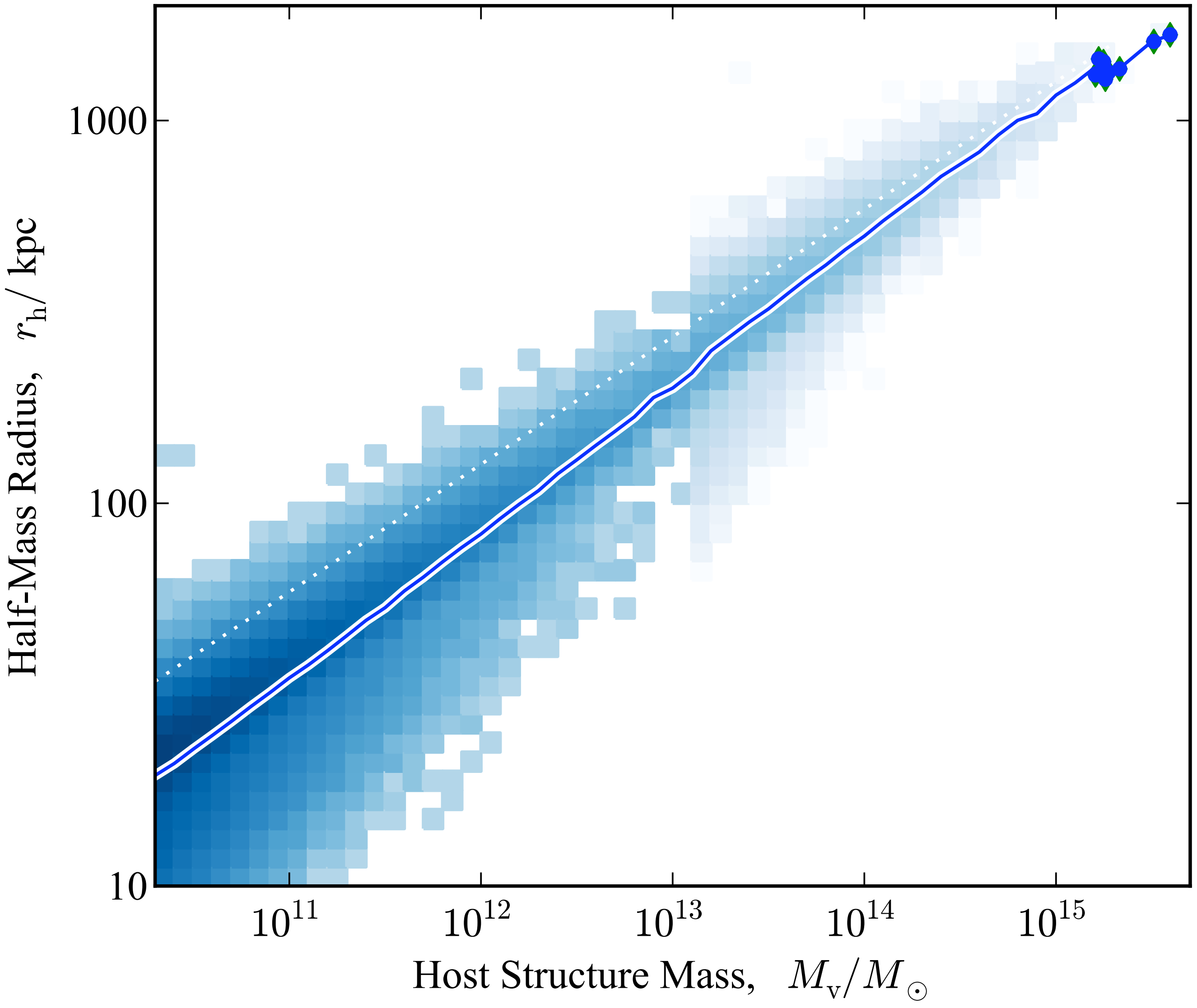
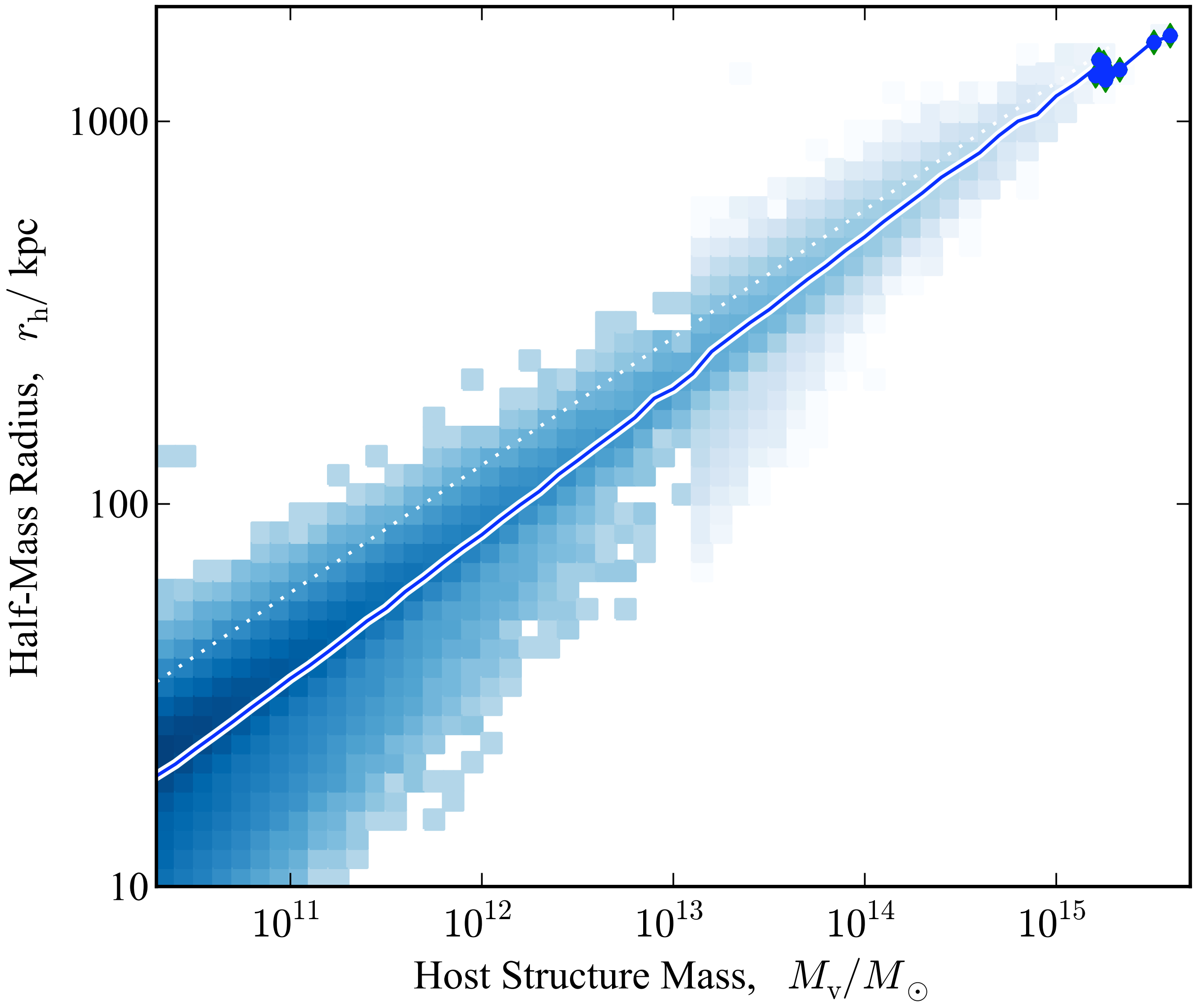


Half-Mass Radius, r_h/ kpc
1000
100
10
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Host Structure Mass, $M_\mathrm{v}/M_\odot$
Trend at $z = 0.0$
Trend at $z = 2.2$
M_{800}
Assembly paths

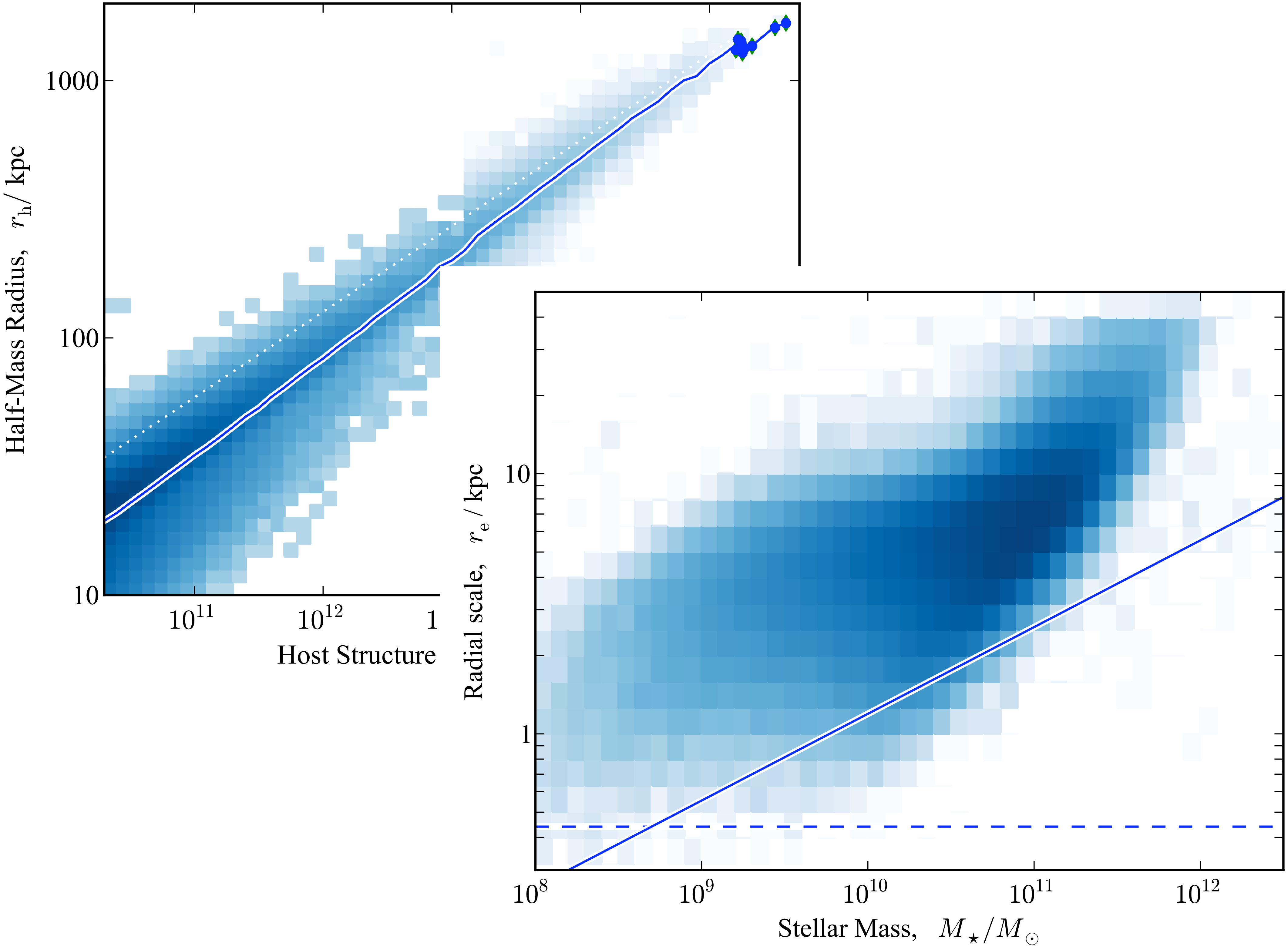
What about galaxies?



What about galaxies?

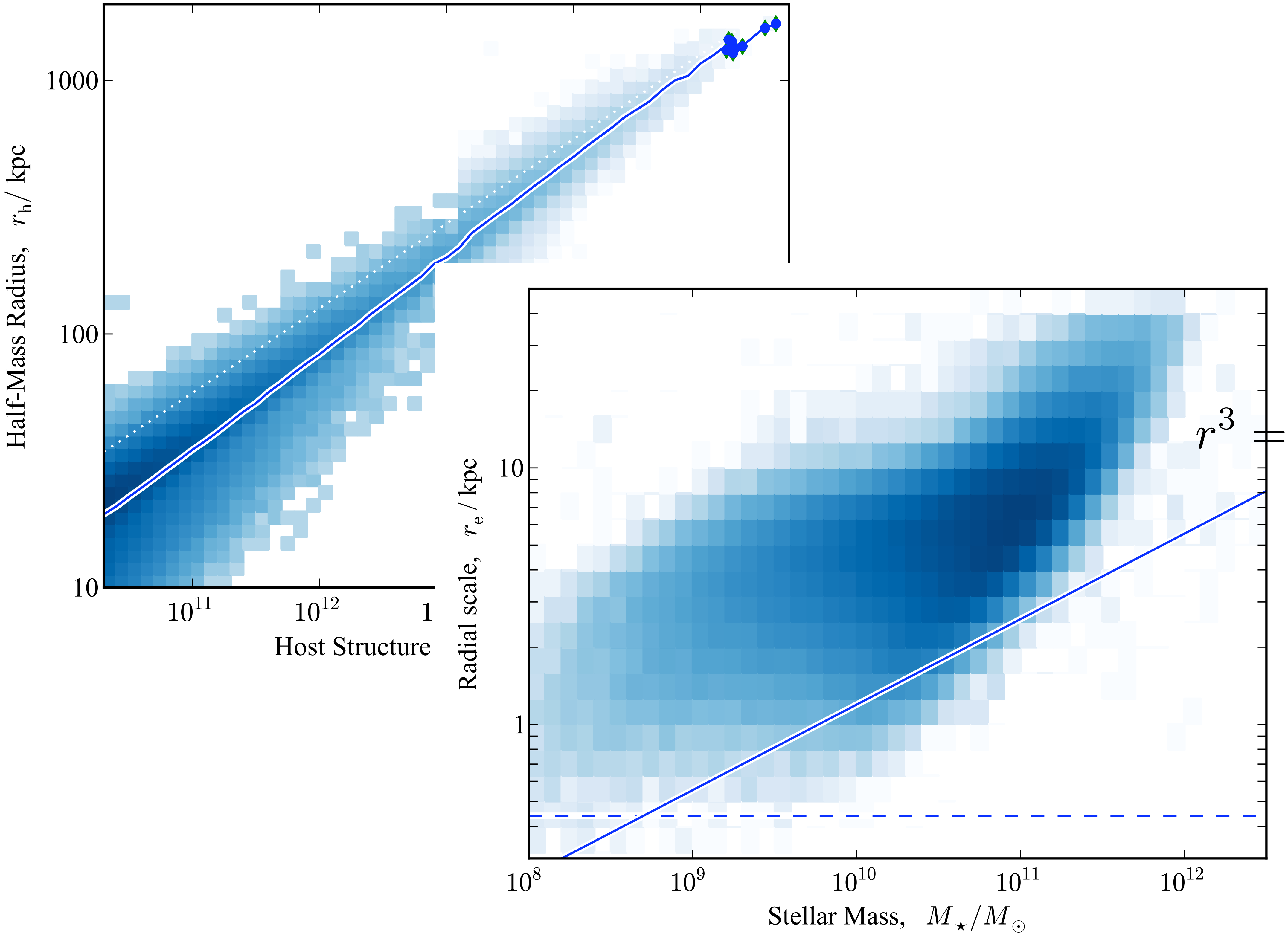


What about galaxies?



Bernardi et al (2013)

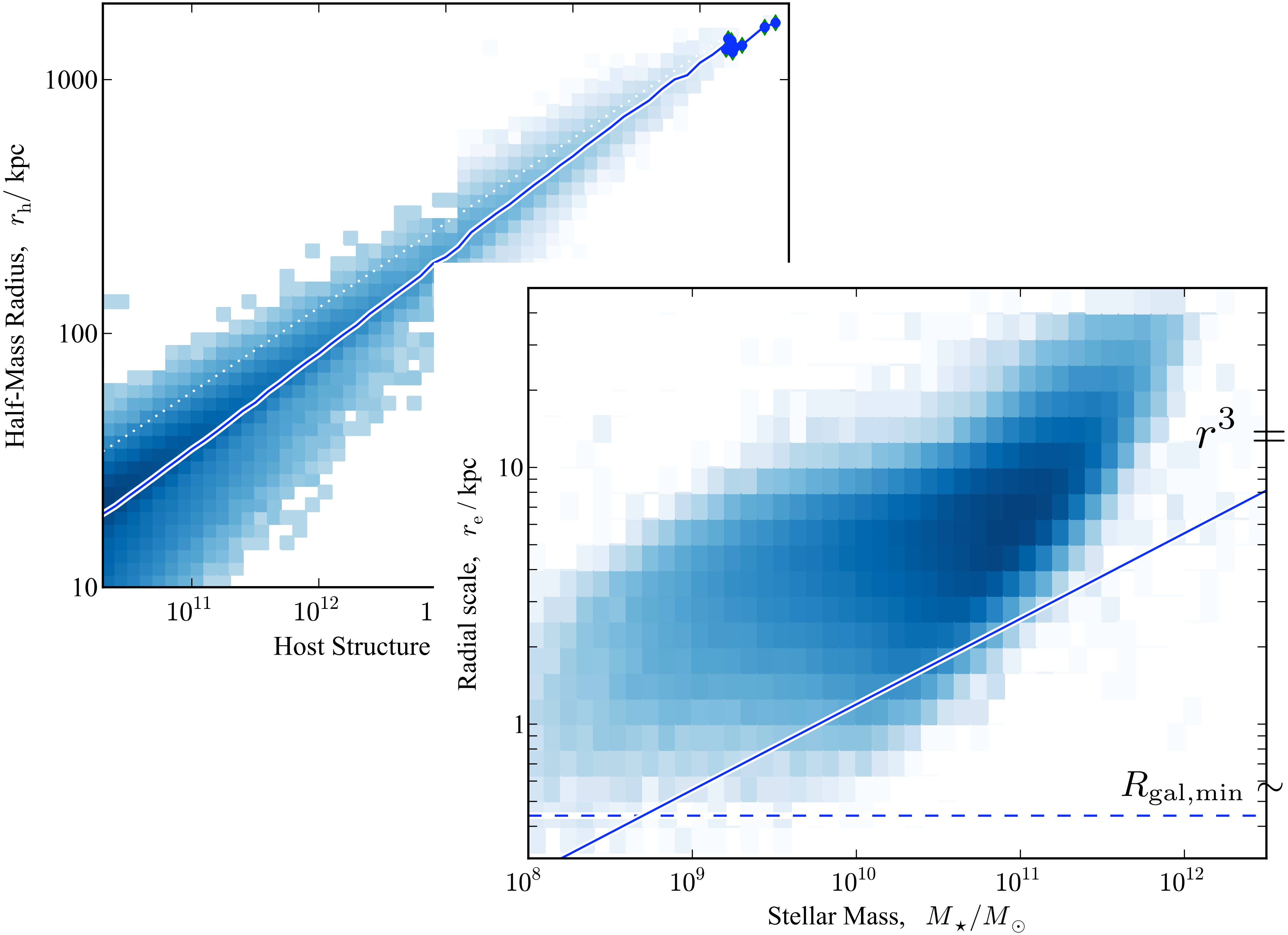
What about galaxies?



$$r^3 = \frac{\lambda G M_\star \Omega_M}{100 H_z^2 \Omega_b}$$

Bernardi et al (2013)

What about galaxies?



$$r^3 = \frac{\lambda G M_\star \Omega_M}{100 H_z^2 \Omega_b}$$

$$R_{\mathrm{gal,min}} \sim \frac{\lambda}{H_z}\left(\frac{6\mathrm{k_B} T_{\mathrm{c}}}{\mu m_{\mathrm{H}} \Delta_z}\right)^{1/2}$$

Bernardi et al (2013)

The Astrophysical Journal, 710:903–923, 2010 February 20 doi:10.1088/0004-637X/710/2/903

CONSTRAINTS ON THE RELATIONSHIP BETWEEN STELLAR MASS AND HALO MASS AT LOW AND HIGH REDSHIFT

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ABSTRACT

We use a statistical approach to determine the relationship between the stellar masses of galaxies and the masses of the dark matter halos in which they reside. We obtain a parameterized stellar-to-halo mass (SHM) relation by populating halos and subhalos in an N-body simulation with galaxies and requiring that the observed stellar mass function be reproduced. We find good agreement with constraints from galaxy–galaxy lensing and predictions of semi-analytic models. Using this mapping, and the positions of the halos and subhalos obtained from the simulation, we find that our model predictions for the galaxy two-point correlation function (CF) as a function of stellar mass are in excellent agreement with the observed clustering properties in the Sloan Digital Sky Survey at $z = 0$. We show that the clustering data do not provide additional strong constraints on the SHM function and conclude that our model can therefore predict clustering as a function of stellar mass. We compute the conditional mass function, which yields the average number of galaxies with stellar masses in the range $m \pm dm/2$ that reside in a halo of mass M. We study the redshift dependence of the SHM relation and show that, for low-mass halos, the SHM ratio is lower at higher redshift. The derived SHM relation is used to predict the stellar mass dependent galaxy CF and bias at high redshift. Our model predicts that not only are massive galaxies more biased than low-mass galaxies at all redshifts, but also the bias increases more rapidly with increasing redshift for massive galaxies than for low-mass ones. We present convenient fitting functions for the SHM relation as a function of redshift, the conditional mass function, and the bias as a function of stellar mass and redshift.

Key words: cosmology: theory – dark matter – galaxies: clusters: general – galaxies: evolution – galaxies: halos – galaxies: high-redshift – galaxies: statistics – galaxies: stellar content – large-scale structure of universe

1. INTRODUCTION

In the standard cold dark matter (CDM) paradigm, the formation of galaxies is driven by the growth of the large-scale structure of the universe and the formation of dark matter halos. Galaxies form by the cooling and condensation of gas in the centers of the potential wells of extended virialized dark matter halos (White & Rees 1978; Fall & Efstathiou 1980; Blumenthal et al. 1984). In this picture, galaxy properties, such as luminosity or stellar mass, are expected to be tightly coupled to the depth of the halo potential and thus to the halo mass.

There are various different approaches to link the properties of galaxies to those of their halos. A first method attempts to derive the halo properties from the properties of its galaxy population using, e.g., galaxy kinematics (Erickson et al. 1987; Zaritsky et al. 1993; Carlberg et al. 1996; More et al. 2009a, 2009b), gravitational lensing (Mandelbaum et al. 2005, 2006; Cacciato et al. 2009), or X-ray studies (Lin et al. 2003; Lin & Mohr 2004).

A second approach is to attempt to model the physics that shapes galaxy formation *ab initio* using either large numerical simulations including both gas and dark matter (Katz et al. 1996; Springel & Hernquist 2003) or semi-analytic models (SAMs) of galaxy formation (e.g., Kauffmann et al. 1993; Cole et al. 1994; Somerville & Primack 1999). In "hybrid" SAMs (e.g., Croton et al. 2006; Bower et al. 2006), dark matter "merger trees" are extracted from a dark matter only N-body simulation, and gas processes are treated with semi-analytic recipes. An advantage of this method is that high-resolution N-body simulations can track the evolution of individual subhalos (Klypin et al. 1999; Springel et al. 2001) and thus provide the precise positions and velocities of galaxies within a halo. However, many of the physical processes involved in galaxy formation (such as star formation and various kinds of feedback) are still not well understood, and in many cases simulations are not able to reproduce observed quantities with high accuracy.

With the accumulation of data from large galaxy surveys over the last decade, a third method has been developed, which links galaxies to halos using a statistical approach. The Halo Occupation Distribution (HOD) formalism specifies the probability distribution for a halo of mass M to harbor N galaxies with certain intrinsic properties, such as luminosity, color, or type (e.g., Peacock & Smith 2000; Seljak 2000; White 2001; Berlind & Weinberg 2002). More complex formulations of this kind of modeling, such as the conditional luminosity function (CLF) formalism (Yang et al. 2003, 2004; van den Bosch et al. 2003) have extended the HOD approach. These methods have the advantage that they do not rely on assumptions about the (poorly understood) physical processes that drive galaxy formation. In this way, it is possible to constrain the relationship between galaxy and halo properties (and thus, indirectly, the underlying physics), and to construct mock catalogs that reproduce in detail a desired observational quantity (such as the luminosity function). One disadvantage of the classical HOD approach was that one had to make assumptions about the distribution of positions and velocities of galaxies within their host halos. In addition, the results of the HOD modeling can be difficult to interpret in terms of the underlying physics of galaxy formation.

In recent years, HOD models have been introduced that make use of information about the positions, velocities, and masses of halos and subhalos extracted from a dissipationless N-body simulation. The (sub)halo mass is then empirically linked to

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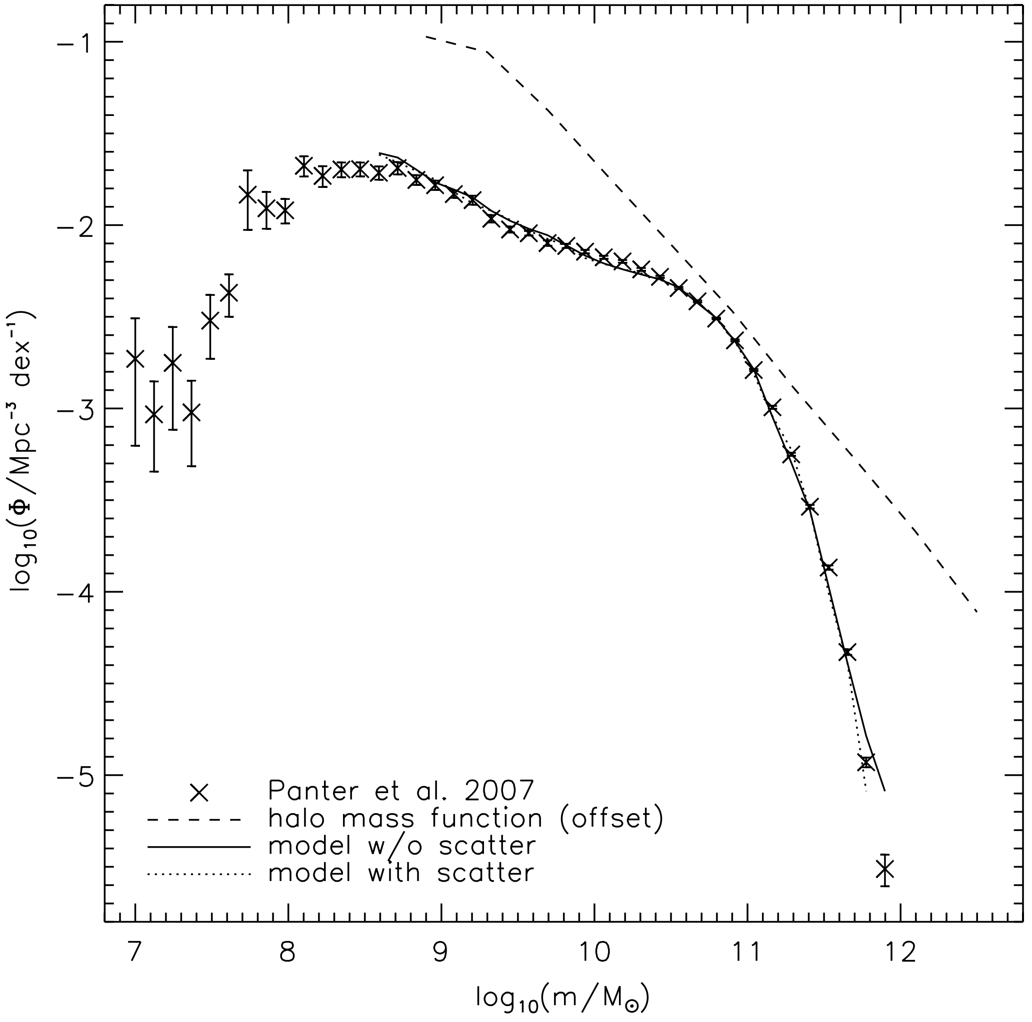

Figure 1. Comparison between the halo mass function offset by a factor of 0.05 (dashed line), the observed galaxy mass function (symbols), our model without scatter (solid line), and our model including scatter (dotted line).We see that the halo and the galaxy mass functions are different shapes, implying that the stellar-to-halo mass ratio m/M is not constant. Our four-parameter model for the halo mass dependent stellar-to-halo mass ratio is in very good agreement with the observations (both including and neglecting scatter).

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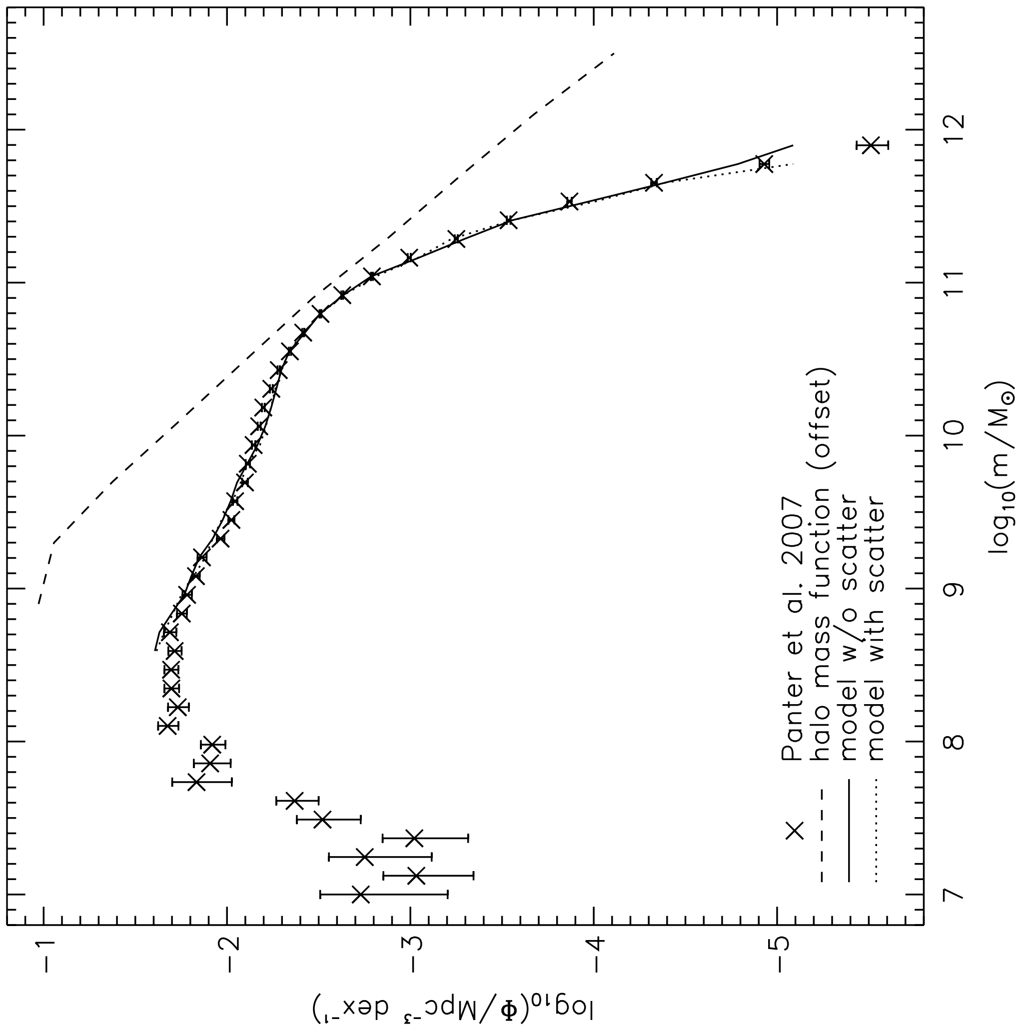

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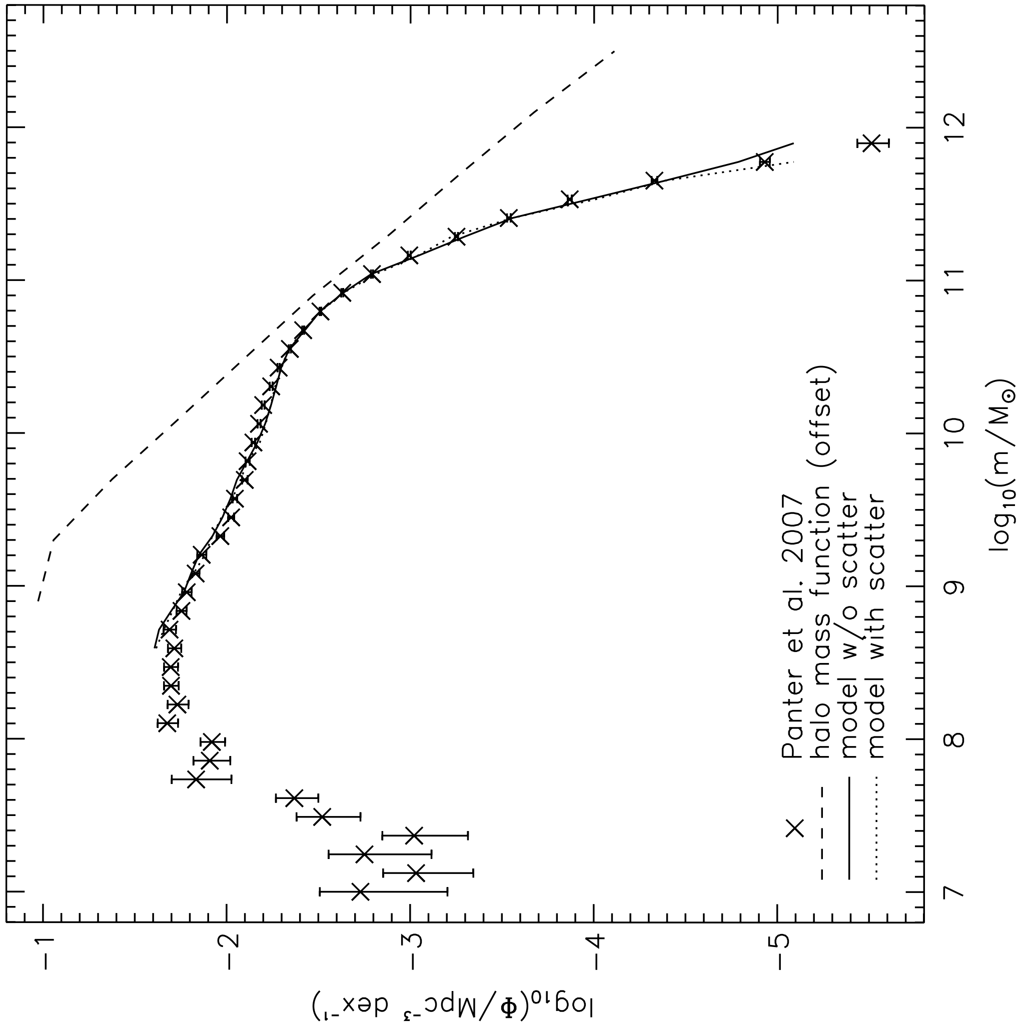

Increasing Halo Mass

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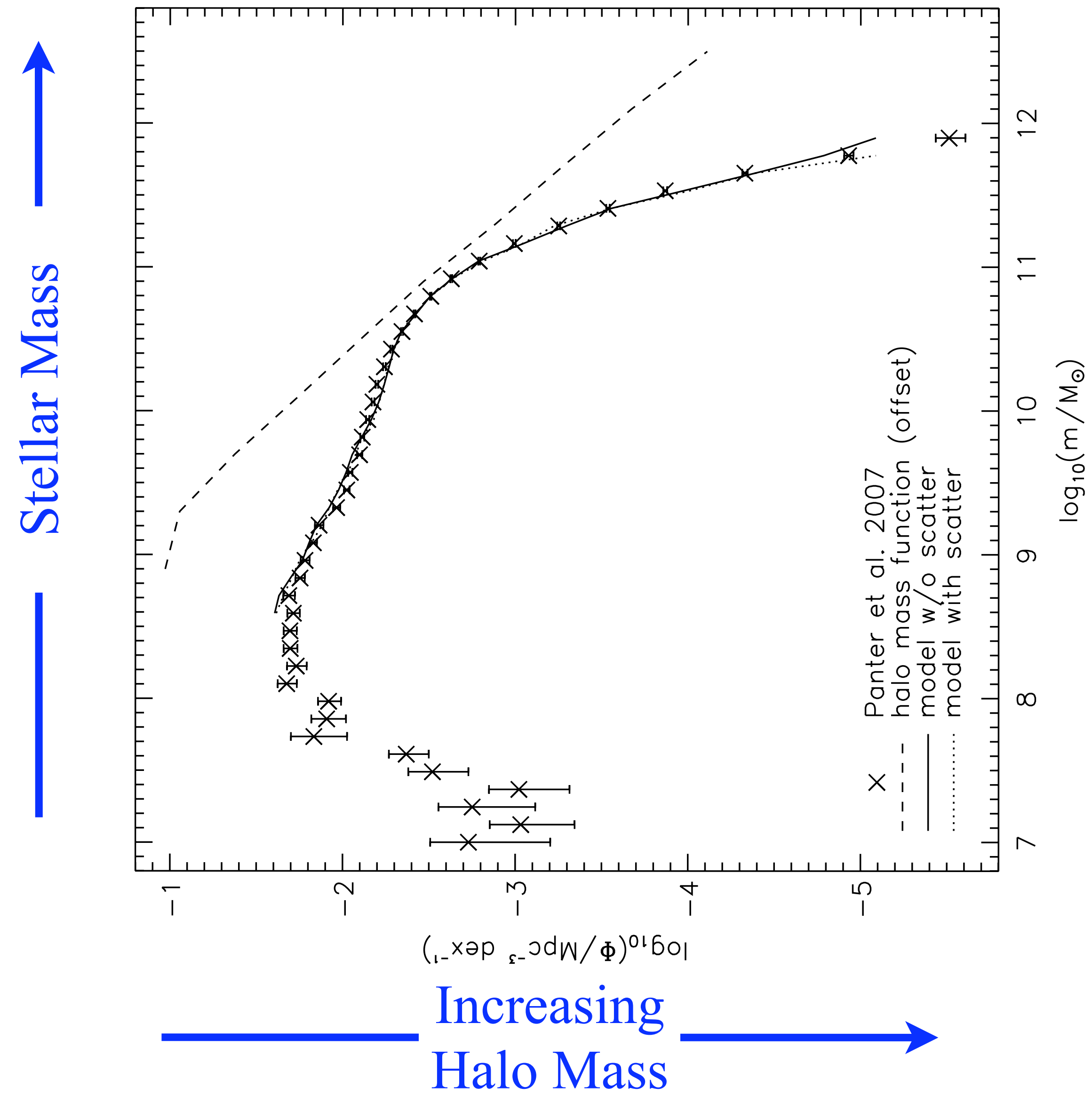

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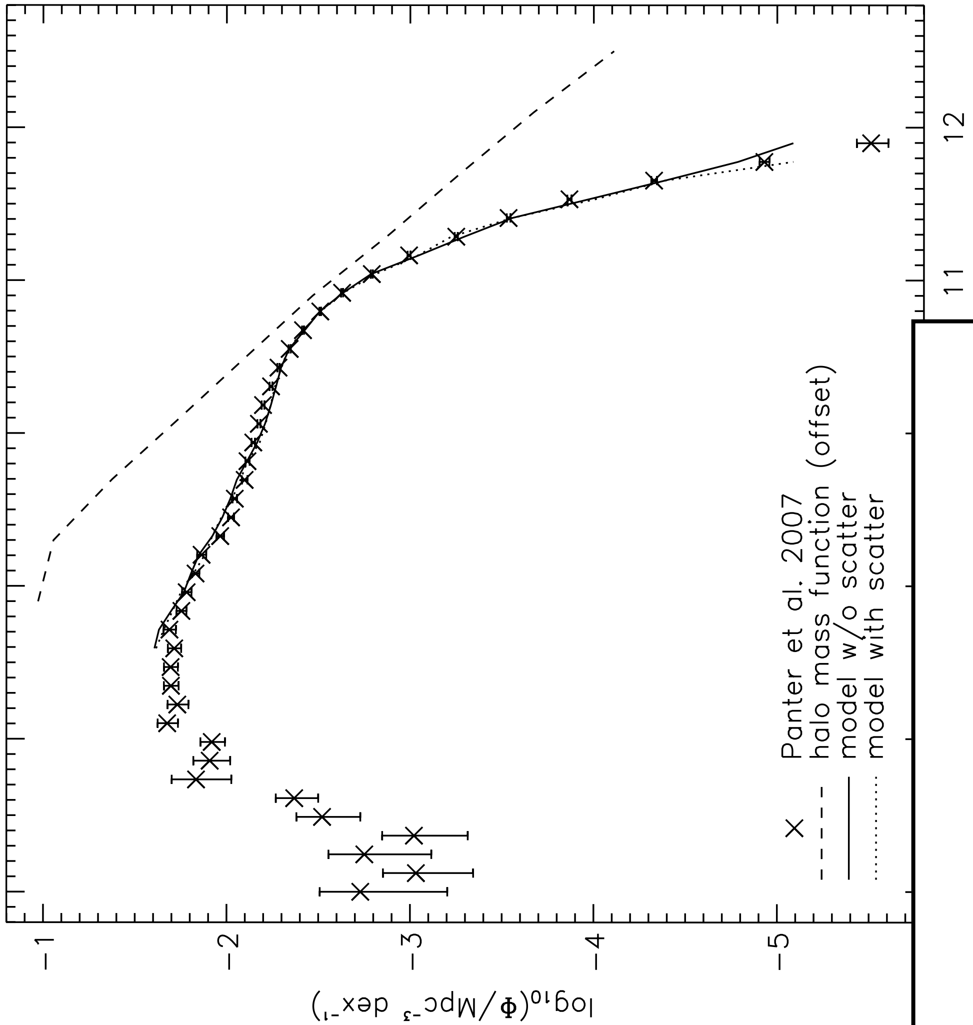


Stellar Mass

Increasing Halo Mass

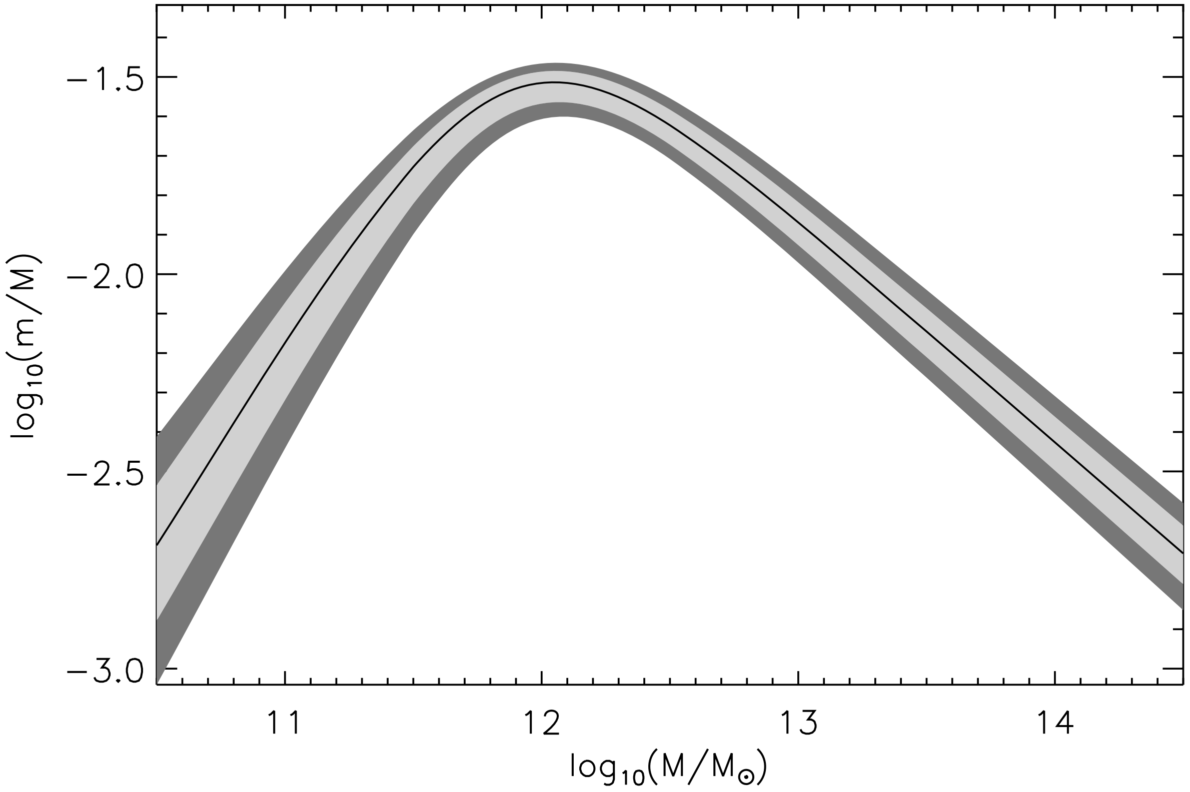
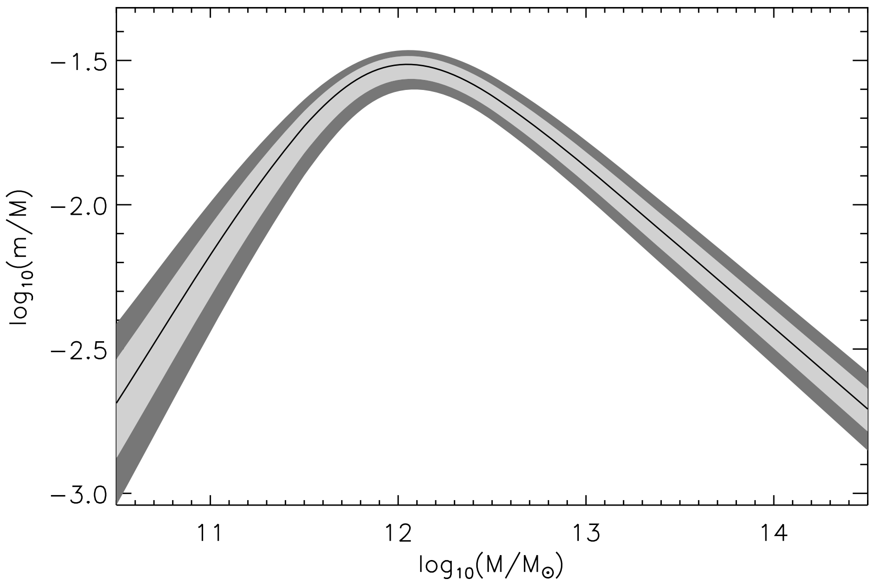


Figure 4. Derived relation between stellar mass and halo mass. The light shaded area shows the 1σ region while the dark and light shaded areas together show the 2σ region. The upper panel shows the SHM relation, while the lower panel shows the SHM ratio.



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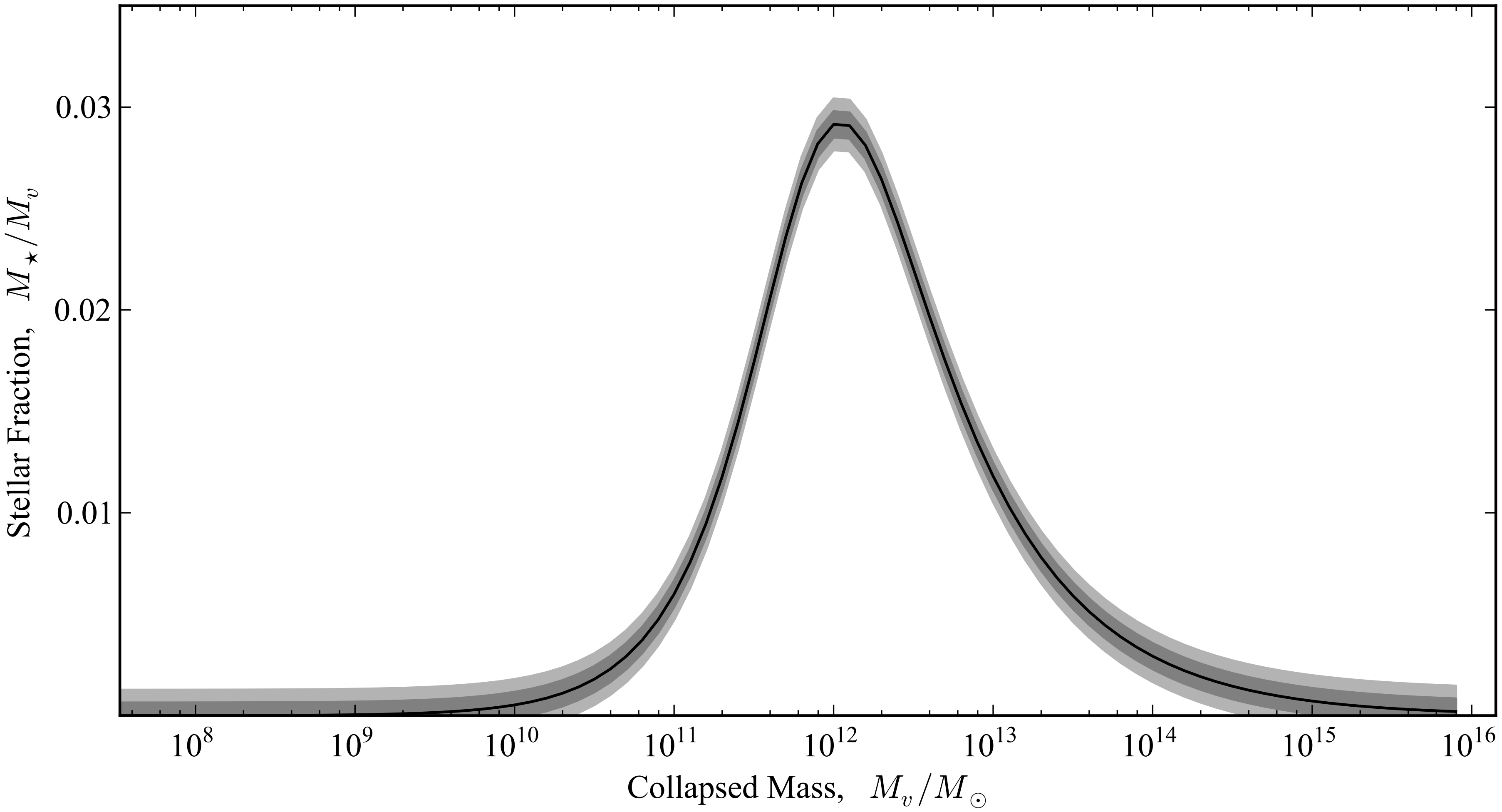

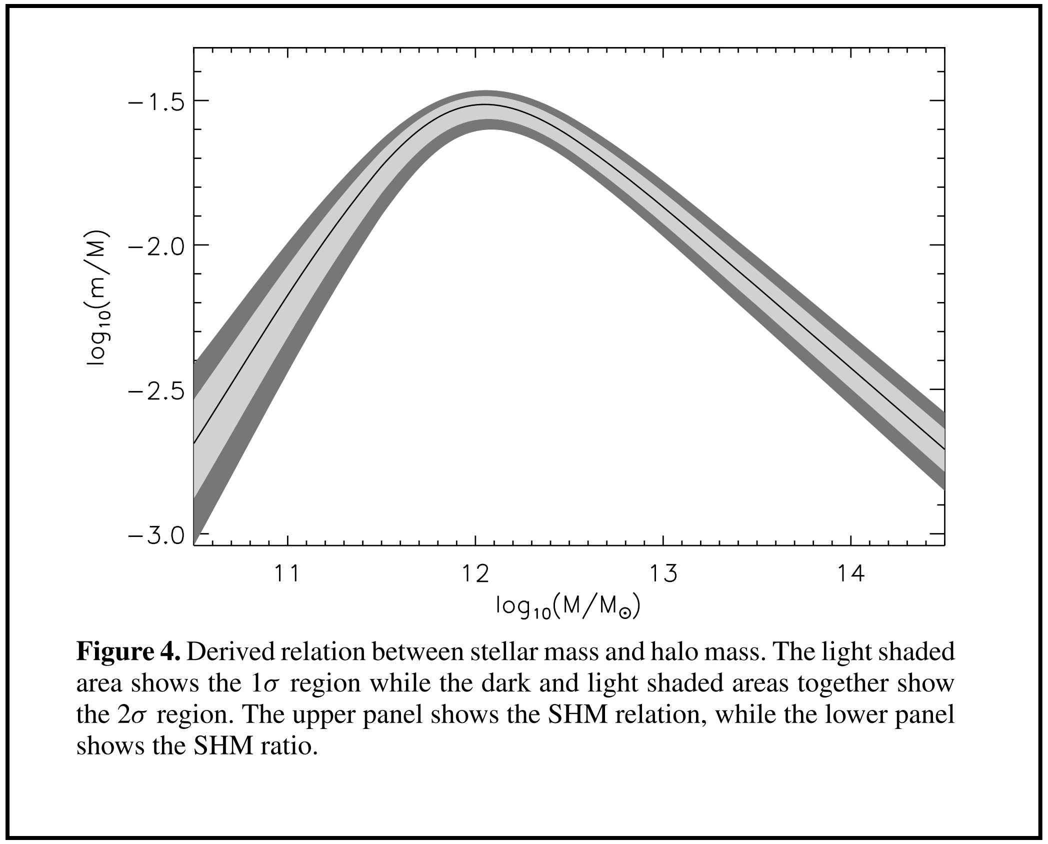

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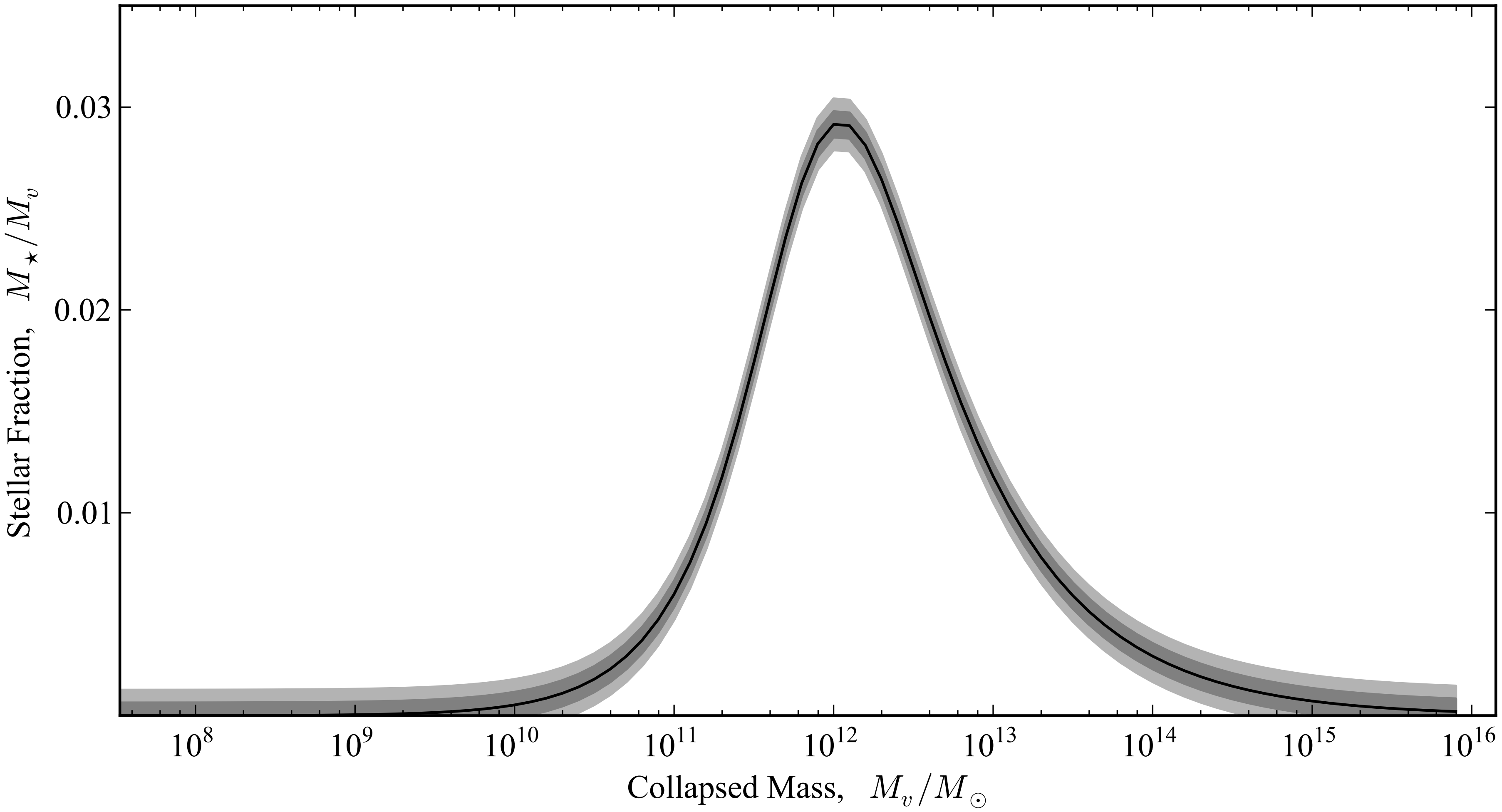
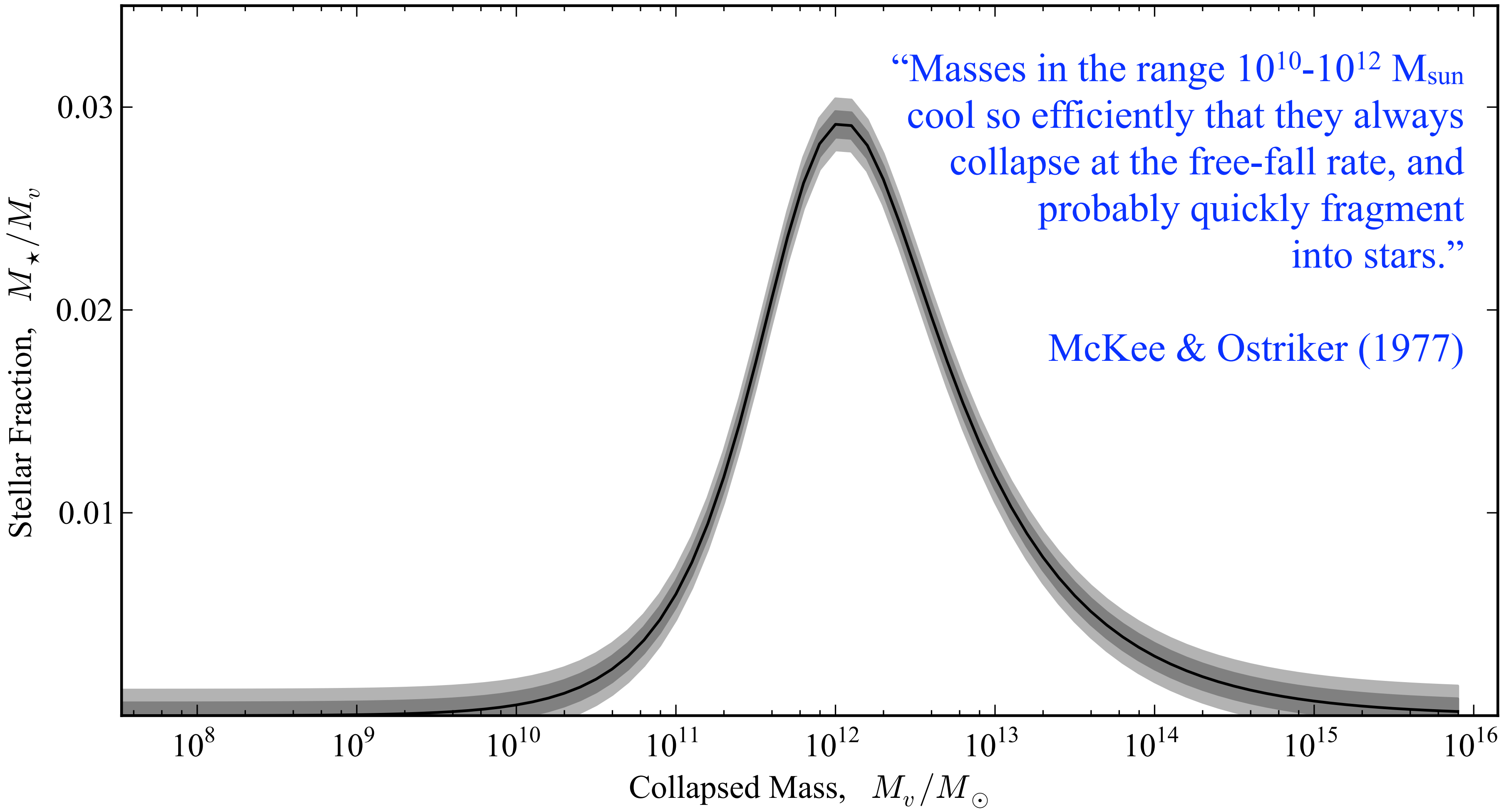
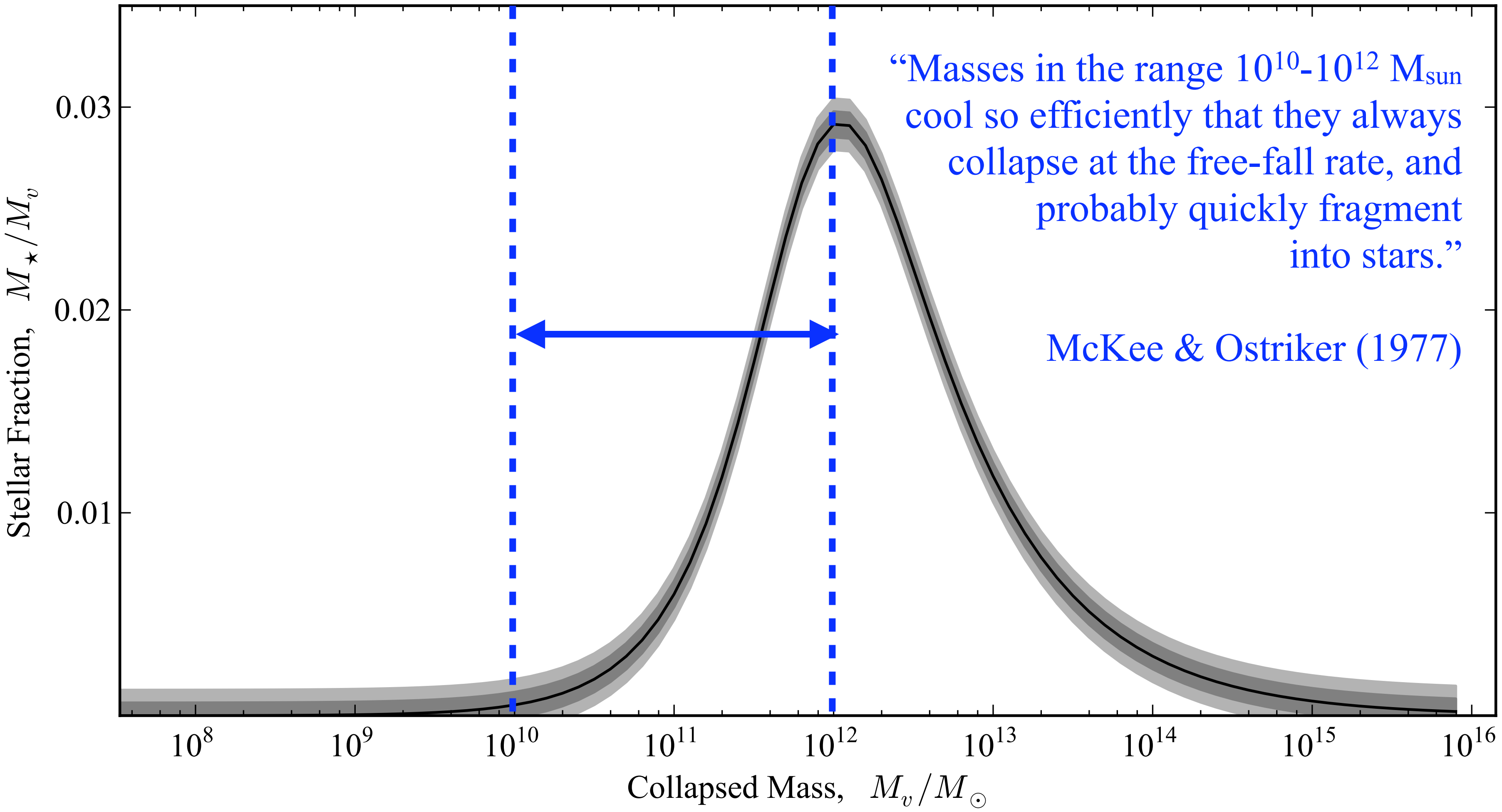

0.03
0.02
0.01
Stellar Fraction, $M_\star/M_v$
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
Collapsed Mass, $M_v/M_\odot$



> “Masses in the range 10^{10}-10^{12} M_{sun}
> cool so efficiently that they always
> collapse at the free-fall rate, and
> probably quickly fragment
> into stars.”
>
> McKee & Ostriker (1977)



"Masses in the range 10^{10}-10^{12} M_{sun} cool so efficiently that they always collapse at the free-fall rate, and probably quickly fragment into stars."

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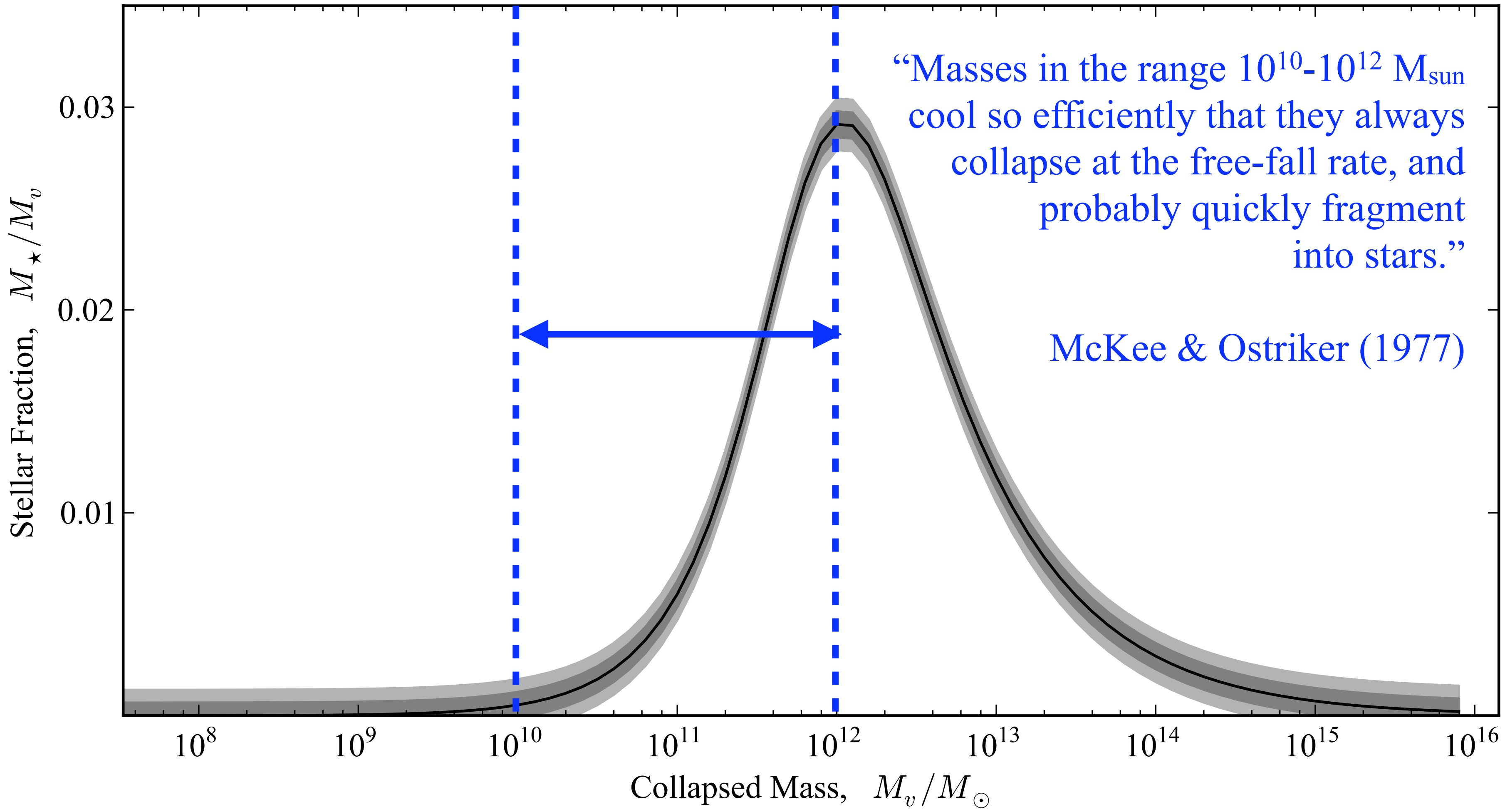

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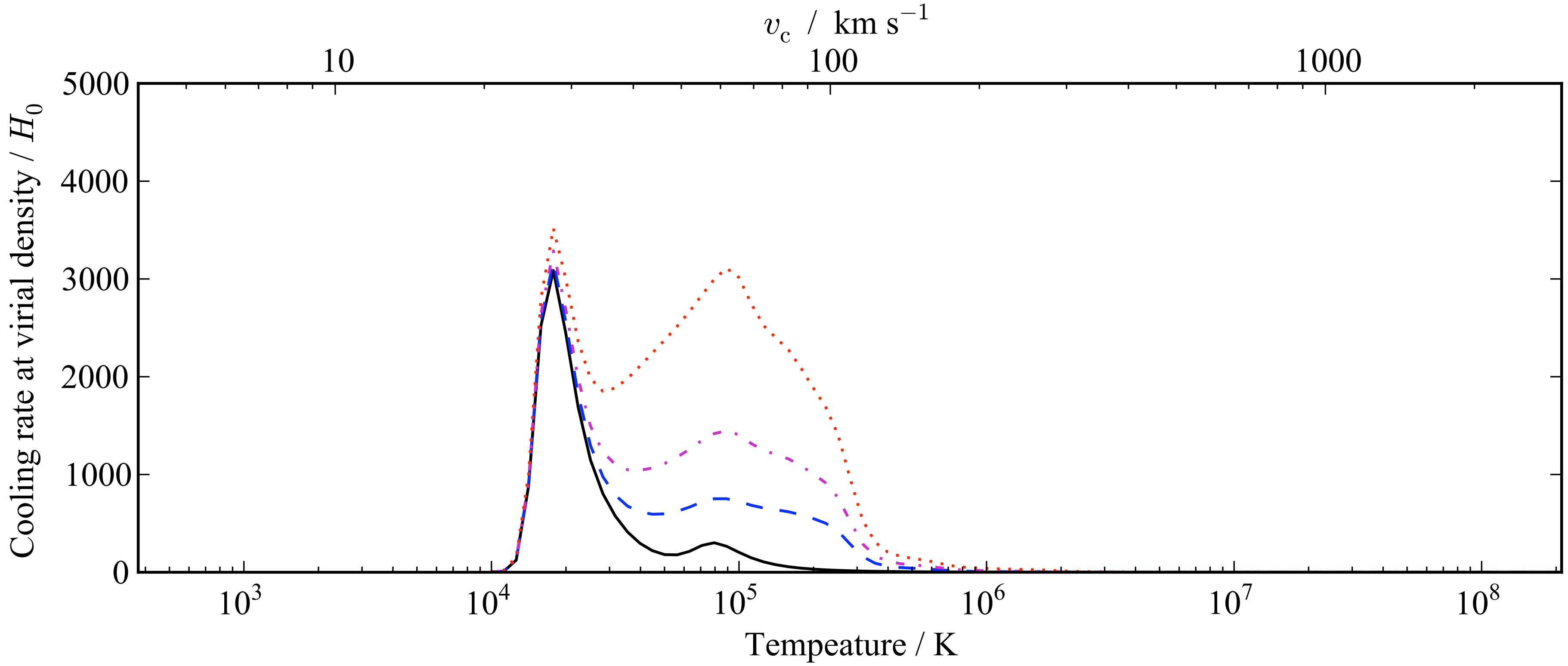

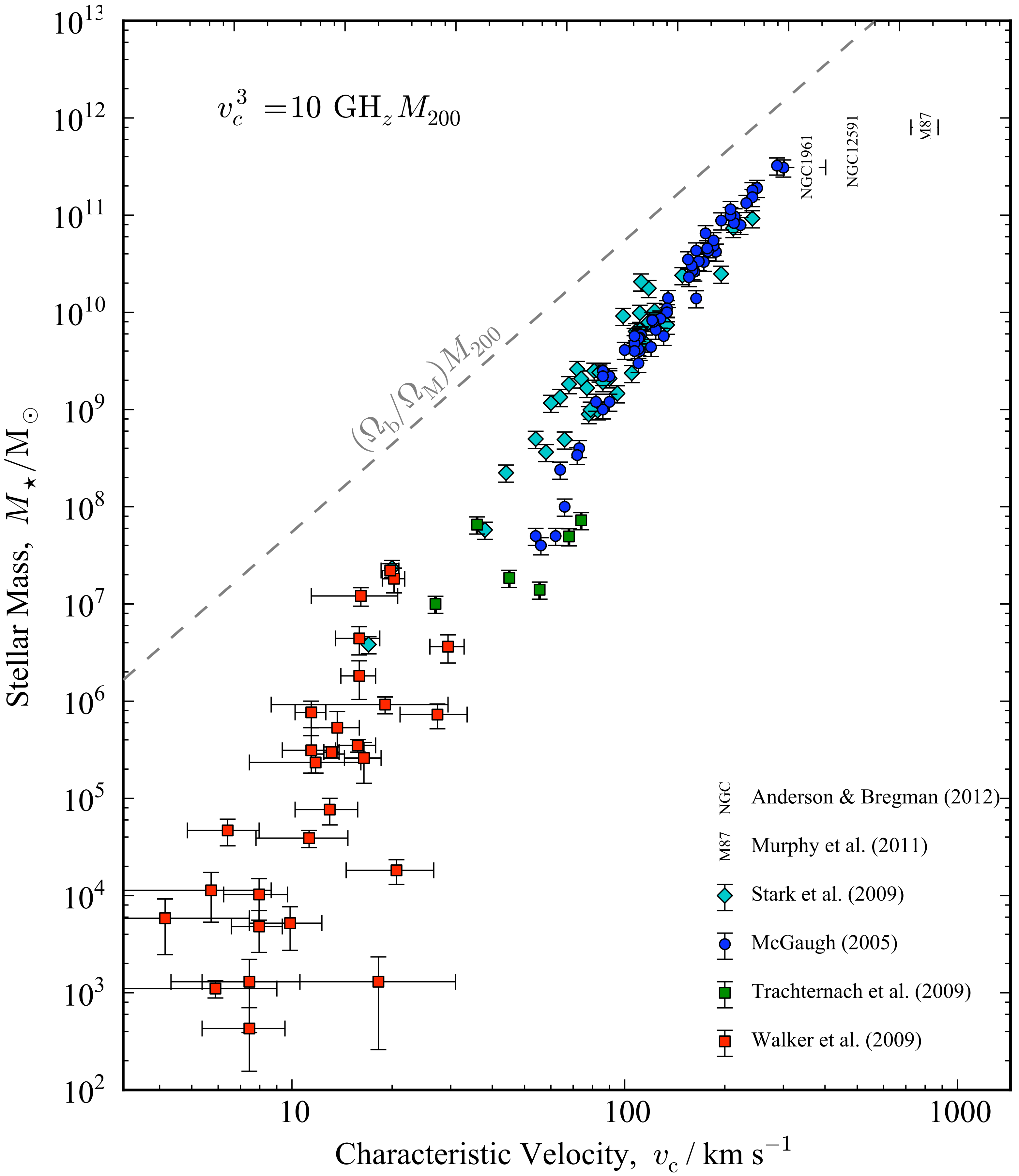
$v_c^3 = 10\ GH_z M_{200}$
$(\Omega_b/\Omega_M) M_{200}$
NGC1961
NGC12591
M87
Stellar Mass, $M_\star / M_\odot$
Characteristic Velocity, v_c / km s^{-1}
10^{13}
10^{12}
10^{11}
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NGC Anderson & Bregman (2012)
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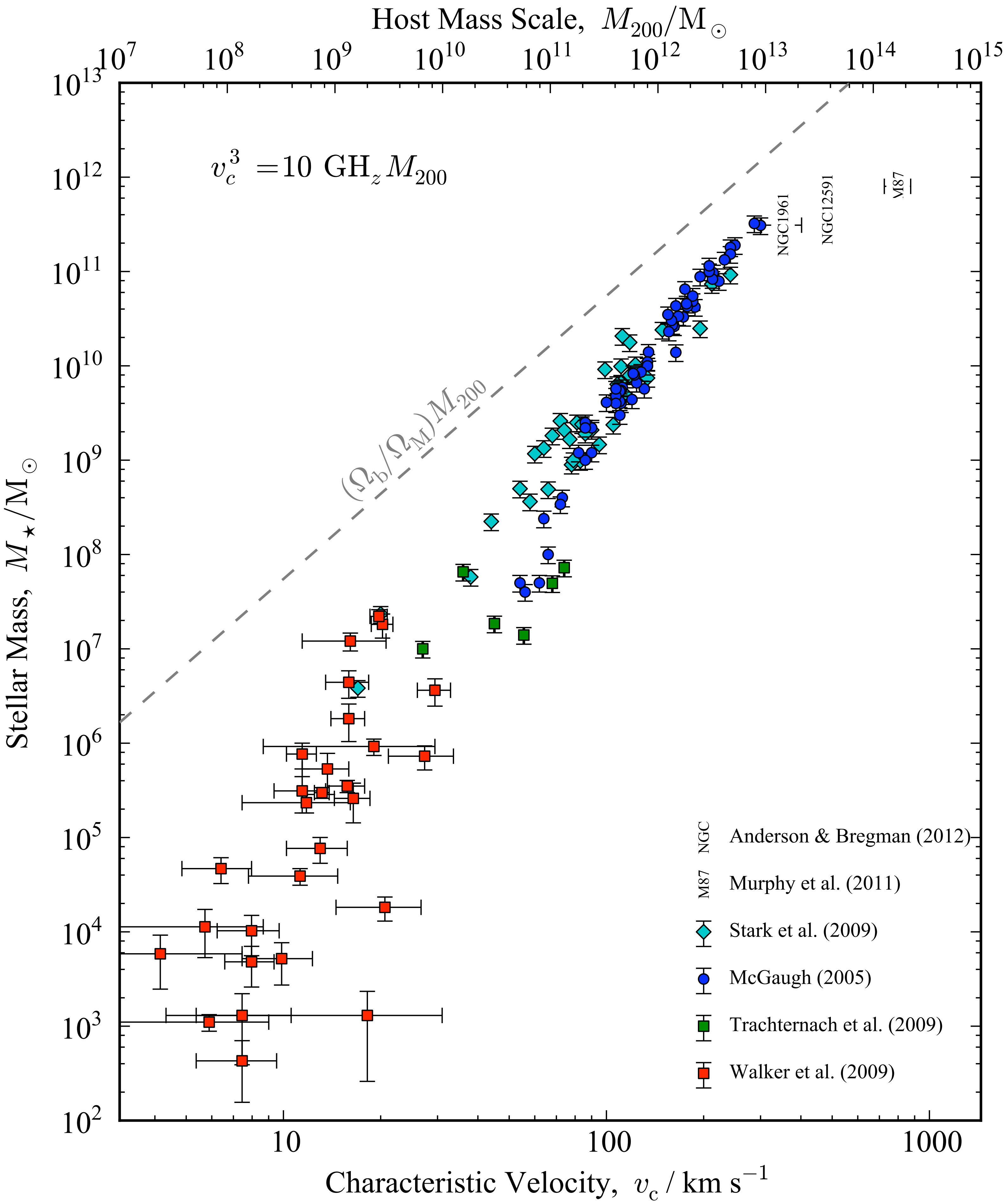
Stark et al. (2009)
McGaugh (2005)
Trachternach et al. (2009)
Walker et al. (2009)


Host Mass Scale, $M_{200}/\mathrm{M}_\odot$
10^7
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$v_c^3 = 10\ \mathrm{G}H_z M_{200}$
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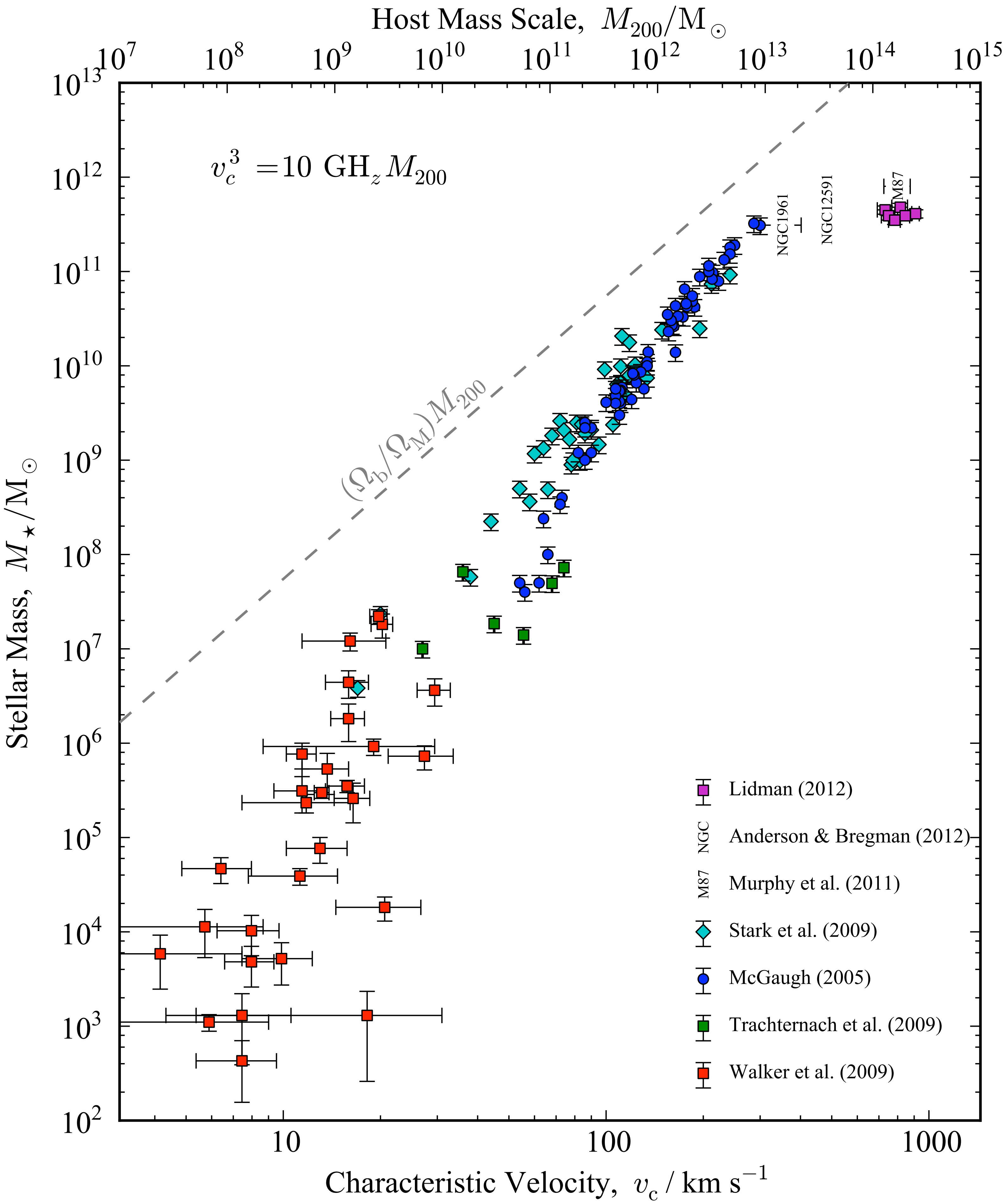
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NGC Anderson & Bregman (2012)
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Stark et al. (2009)
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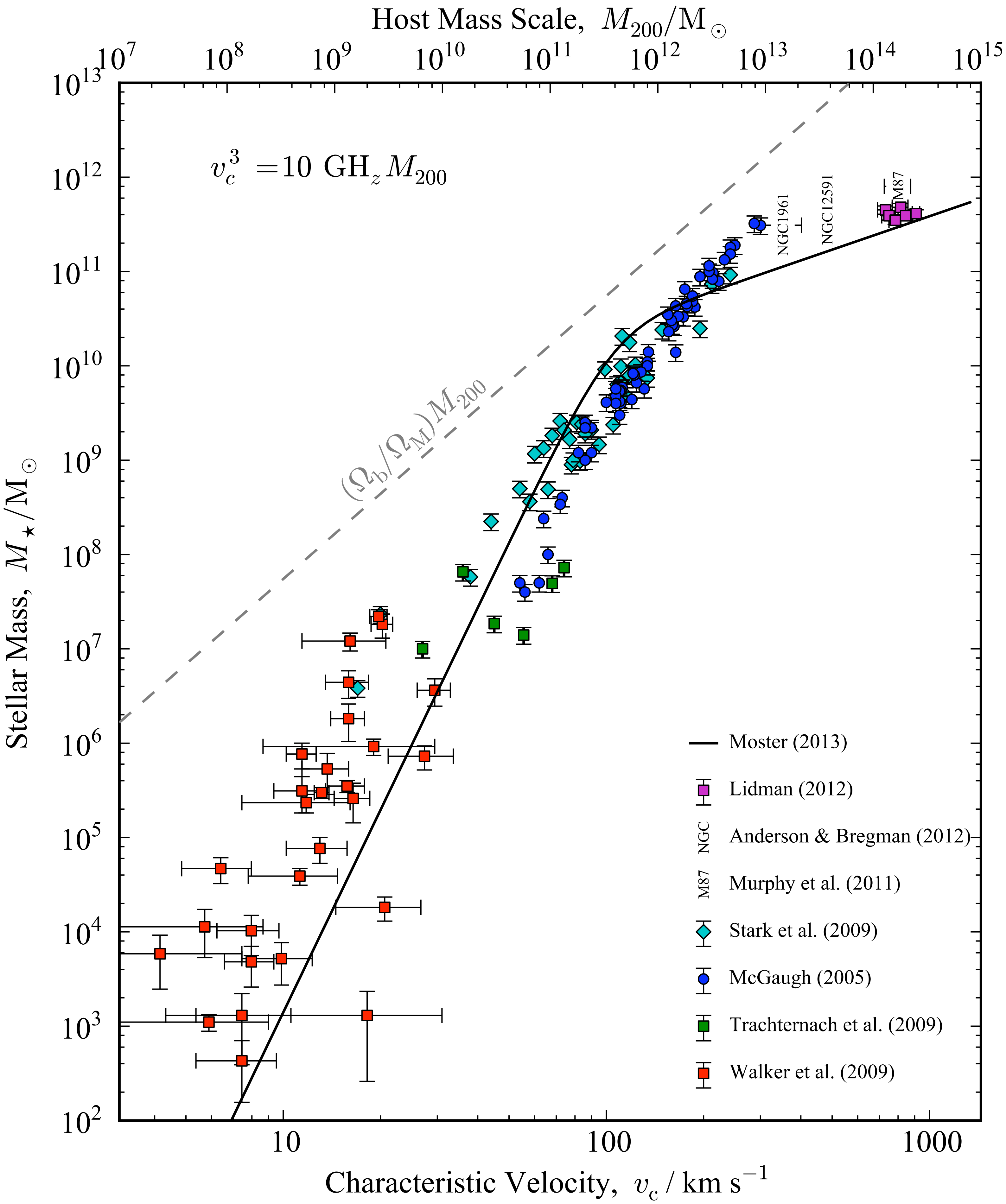
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EFFECTS OF SUPERNOVAE ON THE EARLY EVOLUTION OF GALAXIES

Richard B. Larson

(Received 1974 July 5)

SUMMARY

During the early evolution of an elliptical galaxy, some of the residual interstellar gas is heated to high temperatures by supernova explosions and is driven out of the galaxy in a galactic wind. The energy supplied per supernova is typically reduced about an order of magnitude by radiative cooling of supernova remnants, but the remaining energy is still sufficient to cause significant gas loss, particularly for small galaxies. In galaxies of smaller mass, gas loss begins earlier and carries away a larger fraction of the initial mass, owing to the lower escape velocity. Model collapse calculations show that the effect of early gas loss is to cause galaxies of smaller mass to have less condensed nuclei, smaller average metal abundances, and smaller metal abundance gradients, in qualitative agreement with the observations.

1. INTRODUCTION

In order to explain the absence of observable interstellar matter in most elliptical galaxies, Mathews & Baker (1971) suggested that the gas lost from the stars in an elliptical galaxy is strongly heated by supernova explosions and driven out of the galaxy in a hot ‘ galactic wind ’. An alternative explanation of the general shortage of gas in elliptical galaxies, suggested by Gallagher (1972), is that the gas produced by evolving stars may be efficiently consumed by continuing star formation. However, detailed model calculations for the formation and evolution of elliptical galaxies (Larson 1974, Paper I; Larson & Tinsley 1974, Paper II) show that, while continuing star formation may indeed reduce the gas content below the observed limit, the gas and the young stars formed from it are concentrated toward the centre of the galaxy and give the nucleus a bluer colour than the outer regions, in contradiction to the observations for most elliptical galaxies. Therefore it appears more likely that gas is indeed lost from elliptical galaxies, and it is of interest to consider whether supernova heating in the models of Papers I and II would be sufficient to generate a galactic wind, as proposed by Mathews & Baker (1971). Furthermore, it is of interest to consider when in the evolution of a galaxy a galactic wind might first become important, since there is some evidence that gas loss may occur at a relatively early stage in the evolution of an elliptical galaxy (Paper II).

Another reason for considering the possibility of early gas loss in elliptical galaxies is the fact that the galaxy models of Paper I, which allow no gas loss, do not readily account for the observed correlation between the metal abundances and the masses of elliptical galaxies (Baum 1959; McClure & van den Bergh 1968; Sandage 1972; Faber 1973). This correlation might be explainable if elliptical galaxies lose some of their recycled and metal-enriched gas at an early stage of evolution, and if the amount of gas lost is greater for galaxies of smaller mass. As

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90 per cent of the initial blast energy E_0 of each supernova is radiated away and that the remaining 10 per cent is available for heating the interstellar medium and powering a galactic wind. We also assume that the energy deposited in the interstellar gas by each supernova is stored without further losses until the total energy content of the gas becomes large enough to cause the gas to escape. In the model calculations to be described below, it will be assumed for simplicity that all of the gas in a galaxy is suddenly lost as soon as its total energy content exceeds the escape energy. In reality, the gas is probably not lost all at once, but we would obtain approximately the same prediction for the total amount of gas lost by assuming only that all of the available energy of $\sim 0{\cdot}1\,E_0$ per supernova is expended in removing gas from the galaxy.

If one supernova is produced for every $100\,M_\odot$ of stars formed and if the energy available per supernova for driving a galactic wind is $\approx 10^{50}$ erg, then the total energy available is $\approx 10^{48}$ erg per $M_\odot$ of stars formed. The energy required to cause escape from an elliptical galaxy of mass $10^{11}\,M_\odot$ can be estimated by noting that the escape velocity at the centre of the models of Paper I is about 800 km s^{-1}, which corresponds to an escape energy of about 3×10^{15} erg g^{-1} or 6×10^{48} erg $M_\odot^{-1}$. Hence if $M_{\rm s}$ is the mass ($M_\odot$) of stars formed and $M_{\rm g}$ is the mass remaining in gaseous form, we predict that loss of the remaining gas can occur when the available energy of $\approx 10^{48}\,M_{\rm s}$ erg is equal to the required energy of $\approx 6\times 10^{48}\,M_{\rm g}$ erg, i.e. when $M_{\rm g}/M_{\rm s} \approx 1/6$. Thus, in the models of Paper I, gas loss can occur after roughly 6/7 or 86 per cent of the initial mass has been transformed into stars; the remaining $\approx 1/7$ or 14 per cent of the initial mass is lost in a galactic wind. This result is consistent with the conclusion previously obtained for model D that a galactic wind would have been established by the time that ~ 94 per cent of the initial mass has been converted into stars (Section 3.2). Thus it seems reasonable to conclude that for a galaxy of mass $10^{11}\,M_\odot$ gas loss will become important by the time that roughly 90 per cent of the initial mass has been transformed into stars, and that the remaining ≈ 10 per cent of the mass will be lost in a galactic wind.

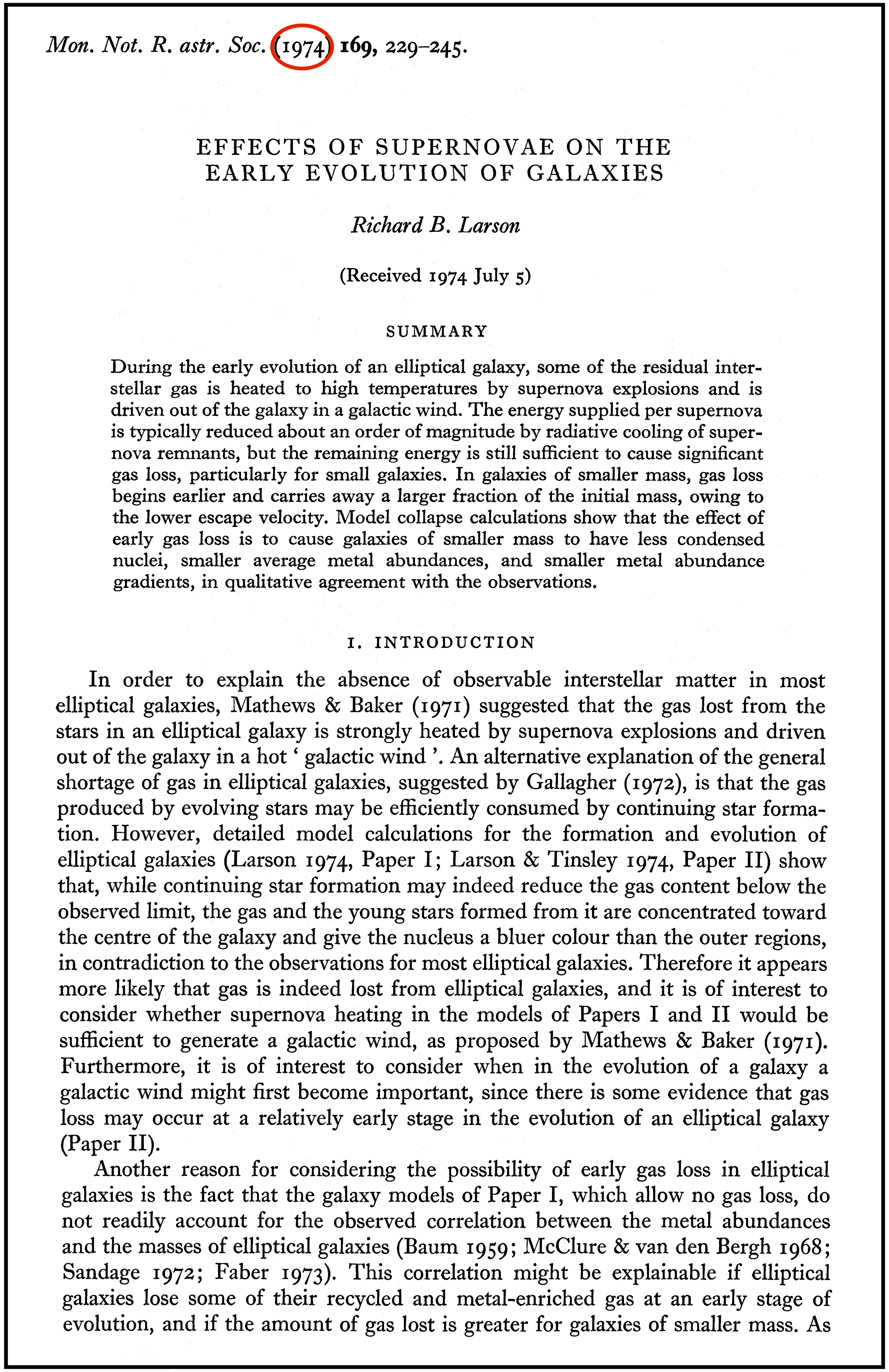
Because of the lower escape velocity of a galaxy of mass less than $10^{11}\,M_\odot$, gas loss will begin earlier in such a galaxy and a larger fraction of the initial mass will be lost. To obtain an estimate of how the escape velocity scales with the total mass M, we assume that protoglaxies of different mass begin with approximately the same initial density, so that $M \propto R^3$ where R is the radius of the protogalaxy. (The results are qualitatively similar for any physically reasonable scaling relationship between M and R.) The escape energy per unit mass then varies as $M/R \propto M^{2/3}$, and for a protogalaxy or galaxy of mass M it is given approximately by

$$E_{\rm esc}/M_{\rm g} \approx 6\times 10^{48}\,(M/10^{11})^{2/3}\ {\rm erg}\ M_\odot^{-1}, \tag{12}$$

where we have made use of the previous estimate of $E_{\rm esc}/M_{\rm g} \approx 6\times 10^{48}$ erg $M_\odot^{-1}$ for a galaxy of mass $10^{11}\,M_\odot$. Equating the available energy $\approx 10^{48}\,M_{\rm s}$ to the energy $E_{\rm esc}$ required to cause escape of the remaining gas, we predict that a protogalaxy of mass M $(=M_{\rm s}+M_{\rm g})$ will lose its remaining gas when

$$M_{\rm g}/M_{\rm s} \approx \tfrac{1}{6}(M/10^{11})^{-2/3} \approx (M/6\times 10^{9})^{-2/3}. \tag{13}$$

For example, if the initial mass M is $6\times 10^{9}\,M_\odot$, we find from equation (13) that gas loss occurs when $M_{\rm g} \approx M_{\rm s} \approx 3\times 10^{9}\,M_\odot$, so that $3\times 10^{9}\,M_\odot$ of gas is lost



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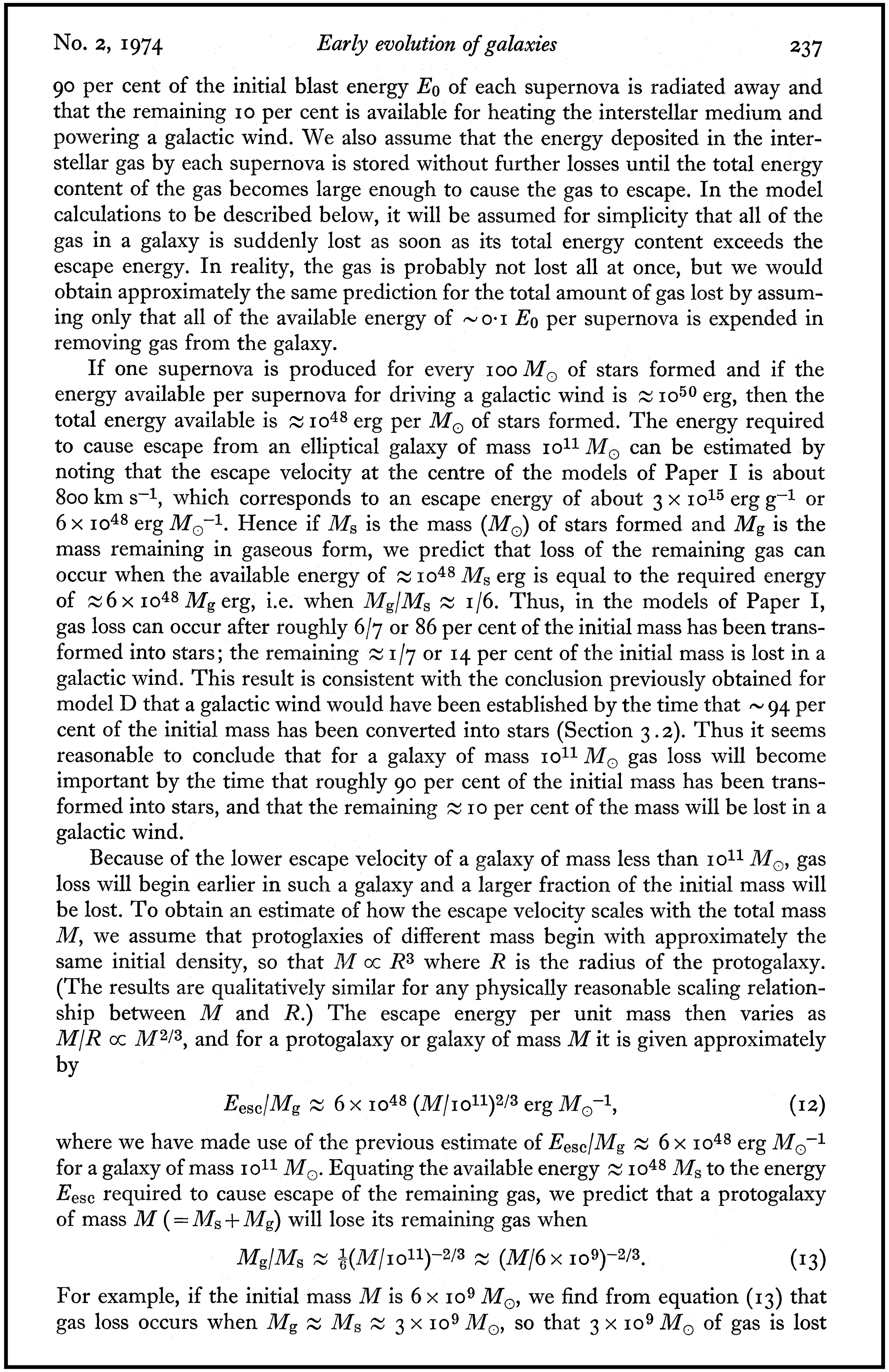

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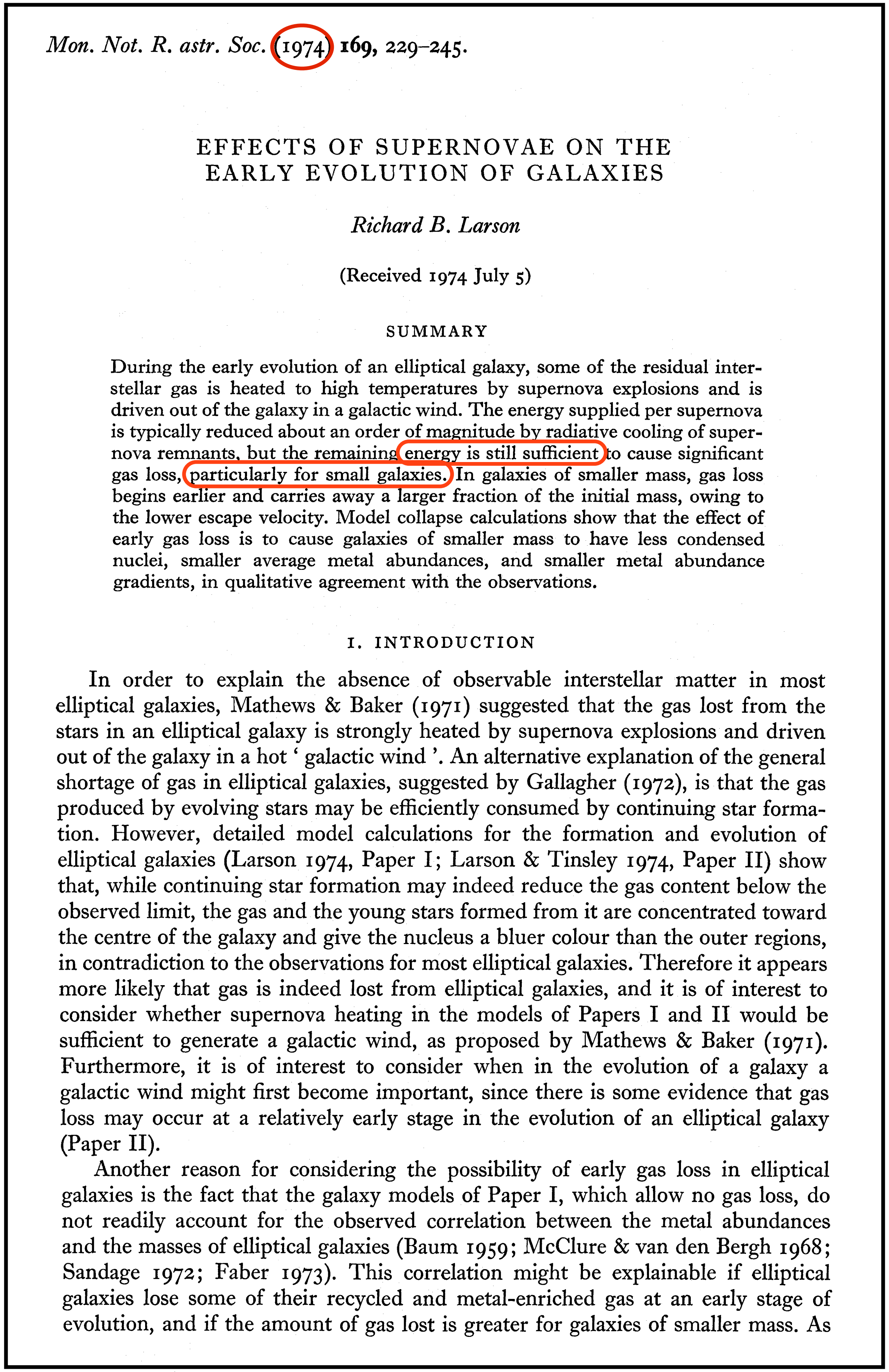

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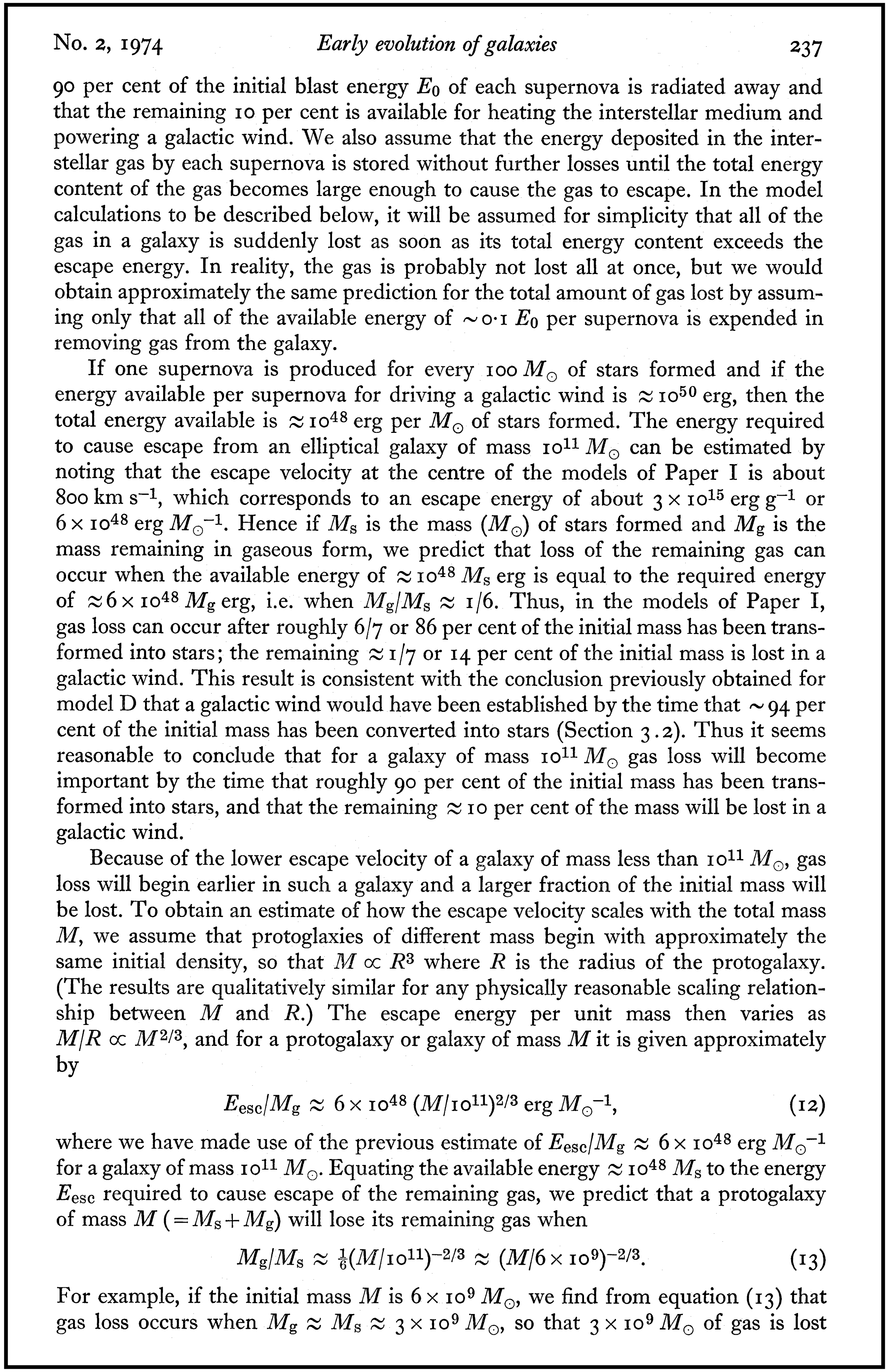

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If one supernova is produced for every 100 $M_\odot$ of stars formed and if the energy available per supernova for driving a galactic wind is $\approx 10^{50}$ erg, then the total energy available is $\approx 10^{48}$ erg per $M_\odot$ of stars formed. The energy required to cause escape from an elliptical galaxy of mass $10^{11}\, M_\odot$ can be estimated by noting that the escape velocity at the centre of the models of Paper I is about 800 km s^{-1}, which corresponds to an escape energy of about 3×10^{15} erg g^{-1} or 6×10^{48} erg $M_\odot^{-1}$. Hence if M_s is the mass ($M_\odot$) of stars formed and M_g is the mass remaining in gaseous form, we predict that loss of the remaining gas can occur when the available energy of $\approx 10^{48}\, M_s$ erg is equal to the required energy of $\approx 6\times 10^{48}\, M_g$ erg, i.e. when $M_g/M_s \approx 1/6$. Thus, in the models of Paper I, gas loss can occur after roughly 6/7 or 86 per cent of the initial mass has been transformed into stars; the remaining $\approx 1/7$ or 14 per cent of the initial mass is lost in a galactic wind. This result is consistent with the conclusion previously obtained for model D that a galactic wind would have been established by the time that ~ 94 per cent of the initial mass has been converted into stars (Section 3.2). Thus it seems reasonable to conclude that for a galaxy of mass $10^{11}\, M_\odot$ gas loss will become important by the time that roughly 90 per cent of the initial mass has been transformed into stars, and that the remaining ≈ 10 per cent of the mass will be lost in a galactic wind.

Because of the lower escape velocity of a galaxy of mass less than $10^{11}\, M_\odot$, gas loss will begin earlier in such a galaxy and a larger fraction of the initial mass will be lost. To obtain an estimate of how the escape velocity scales with the total mass M, we assume that protoglaxies of different mass begin with approximately the same initial density, so that $M \propto R^3$ where R is the radius of the protogalaxy. (The results are qualitatively similar for any physically reasonable scaling relationship between M and R.) The escape energy per unit mass then varies as $M/R \propto M^{2/3}$, and for a protogalaxy or galaxy of mass M it is given approximately by

$$E_{\rm esc}/M_g \approx 6\times 10^{48}\,(M/10^{11})^{2/3}\ {\rm erg}\ M_\odot^{-1}, \tag{12}$$

where we have made use of the previous estimate of $E_{\rm esc}/M_g \approx 6\times 10^{48}$ erg $M_\odot^{-1}$ for a galaxy of mass $10^{11}\, M_\odot$. Equating the available energy $\approx 10^{48}\, M_s$ to the energy $E_{\rm esc}$ required to cause escape of the remaining gas, we predict that a protogalaxy of mass M $(=M_s+M_g)$ will lose its remaining gas when

$$M_g/M_s \approx \tfrac{1}{6}(M/10^{11})^{-2/3} \approx (M/6\times 10^9)^{-2/3}. \tag{13}$$

For example, if the initial mass M is $6\times 10^9\, M_\odot$, we find from equation (13) that gas loss occurs when $M_g \approx M_s \approx 3\times 10^9\, M_\odot$, so that $3\times 10^9\, M_\odot$ of gas is lost

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EFFECTS OF SUPERNOVAE ON THE EARLY EVOLUTION OF GALAXIES

Richard B. Larson

(Received 1974 July 5)

SUMMARY

During the early evolution of an elliptical galaxy, some of the residual interstellar gas is heated to high temperatures by supernova explosions and is driven out of the galaxy in a galactic wind. The energy supplied per supernova is typically reduced about an order of magnitude by radiative cooling of supernova remnants, but the remaining energy is still sufficient to cause significant gas loss, particularly for small galaxies. In galaxies of smaller mass, gas loss begins earlier and carries away a larger fraction of the initial mass, owing to the lower escape velocity. Model collapse calculations show that the effect of early gas loss is to cause galaxies of smaller mass to have less condensed nuclei, smaller average metal abundances, and smaller metal abundance gradients, in qualitative agreement with the observations.

1. INTRODUCTION

In order to explain the absence of observable interstellar matter in most elliptical galaxies, Mathews & Baker (1971) suggested that the gas lost from the stars in an elliptical galaxy is strongly heated by supernova explosions and driven out of the galaxy in a hot ‘ galactic wind ’. An alternative explanation of the general shortage of gas in elliptical galaxies, suggested by Gallagher (1972), is that the gas produced by evolving stars may be efficiently consumed by continuing star formation. However, detailed model calculations for the formation and evolution of elliptical galaxies (Larson 1974, Paper I; Larson & Tinsley 1974, Paper II) show that, while continuing star formation may indeed reduce the gas content below the observed limit, the gas and the young stars formed from it are concentrated toward the centre of the galaxy and give the nucleus a bluer colour than the outer regions, in contradiction to the observations for most elliptical galaxies. Therefore it appears more likely that gas is indeed lost from elliptical galaxies, and it is of interest to consider whether supernova heating in the models of Papers I and II would be sufficient to generate a galactic wind, as proposed by Mathews & Baker (1971). Furthermore, it is of interest to consider when in the evolution of a galaxy a galactic wind might first become important, since there is some evidence that gas loss may occur at a relatively early stage in the evolution of an elliptical galaxy (Paper II).

Another reason for considering the possibility of early gas loss in elliptical galaxies is the fact that the galaxy models of Paper I, which allow no gas loss, do not readily account for the observed correlation between the metal abundances and the masses of elliptical galaxies (Baum 1959; McClure & van den Bergh 1968; Sandage 1972; Faber 1973). This correlation might be explainable if elliptical galaxies lose some of their recycled and metal-enriched gas at an early stage of evolution, and if the amount of gas lost is greater for galaxies of smaller mass. As

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90 per cent of the initial blast energy E_0 of each supernova is radiated away and that the remaining 10 per cent is available for heating the interstellar medium and powering a galactic wind. We also assume that the energy deposited in the interstellar gas by each supernova is stored without further losses until the total energy content of the gas becomes large enough to cause the gas to escape. In the model calculations to be described below, it will be assumed for simplicity that all of the gas in a galaxy is suddenly lost as soon as its total energy content exceeds the escape energy. In reality, the gas is probably not lost all at once, but we would obtain approximately the same prediction for the total amount of gas lost by assuming only that all of the available energy of $\sim 0{\cdot}1\,E_0$ per supernova is expended in removing gas from the galaxy.

If one supernova is produced for every $100\,M_\odot$ of stars formed and if the energy available per supernova for driving a galactic wind is $\approx 10^{50}$ erg, then the total energy available is $\approx 10^{48}$ erg per $M_\odot$ of stars formed. The energy required to cause escape from an elliptical galaxy of mass $10^{11}\,M_\odot$ can be estimated by noting that the escape velocity at the centre of the models of Paper I is about $800\ \mathrm{km\,s^{-1}}$, which corresponds to an escape energy of about $3\times10^{15}\ \mathrm{erg\,g^{-1}}$ or $6\times10^{48}\ \mathrm{erg}\ M_\odot^{-1}$. Hence if M_s is the mass ($M_\odot$) of stars formed and M_g is the mass remaining in gaseous form, we predict that loss of the remaining gas can occur when the available energy of $\approx 10^{48}\,M_s$ erg is equal to the required energy of $\approx 6\times10^{48}\,M_g$ erg, i.e. when $M_g/M_s \approx 1/6$. Thus, in the models of Paper I, gas loss can occur after roughly 6/7 or 86 per cent of the initial mass has been transformed into stars; the remaining $\approx 1/7$ or 14 per cent of the initial mass is lost in a galactic wind. This result is consistent with the conclusion previously obtained for model D that a galactic wind would have been established by the time that ~ 94 per cent of the initial mass has been converted into stars (Section 3.2). Thus it seems reasonable to conclude that for a galaxy of mass $10^{11}\,M_\odot$ gas loss will become important by the time that roughly 90 per cent of the initial mass has been transformed into stars, and that the remaining ≈ 10 per cent of the mass will be lost in a galactic wind.

Because of the lower escape velocity of a galaxy of mass less than $10^{11}\,M_\odot$, gas loss will begin earlier in such a galaxy and a larger fraction of the initial mass will be lost. To obtain an estimate of how the escape velocity scales with the total mass M, we assume that protoglaxies of different mass begin with approximately the same initial density, so that $M \propto R^3$ where R is the radius of the protogalaxy. (The results are qualitatively similar for any physically reasonable scaling relationship between M and R.) The escape energy per unit mass then varies as $M/R \propto M^{2/3}$, and for a protogalaxy or galaxy of mass M it is given approximately by

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Principles of supernova-driven winds

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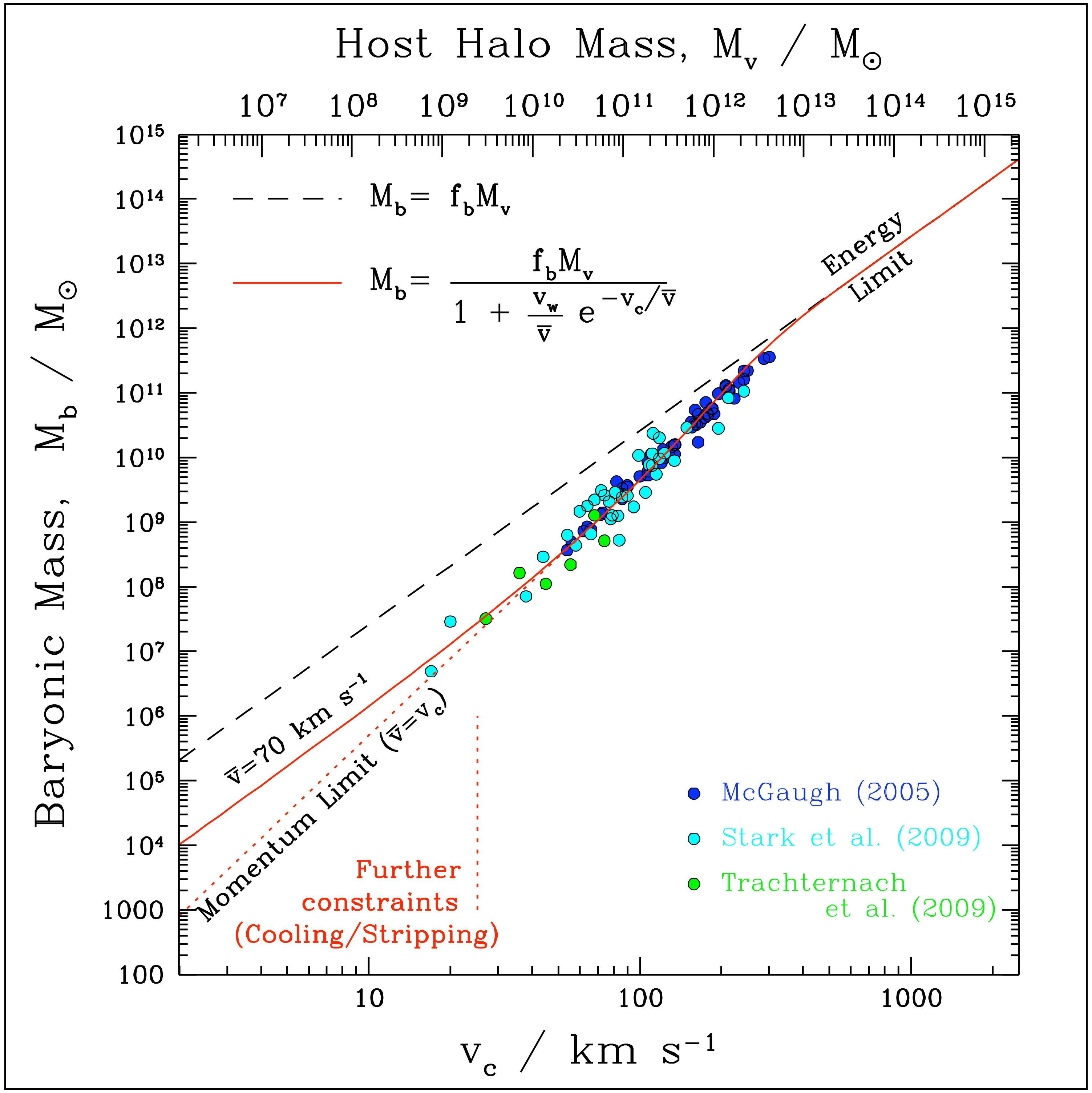
ABSTRACT

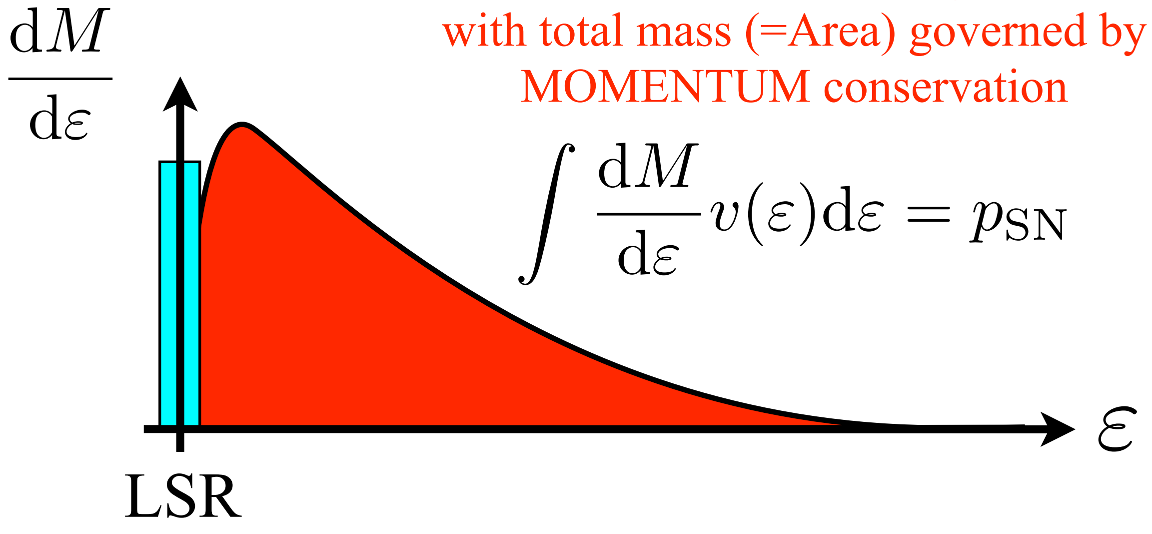
The formation of galaxies is regulated by a balance between the supply of gas and the rate at which it is ejected. Traditional explanations of gas ejection equate the energy required to escape the galaxy or host halo to an estimate for the energy yield from supernovae. This yield is usually assumed to be a constant fraction of the total available from the supernova, or is derived from the assumption of a consistent momentum yield. By applying these ideas in the context of a cold dark matter cosmogony, we derive a first-order analytic connection between these working assumptions and the expected relationship between baryon content and galaxy circular velocity, and find that these quick predictions straddle recent observational estimates. To examine the premises behind these theories in more detail, we then explore their applicability to a set of gasdynamical simulations of idealized galaxies. We show that different premises dominate to differing degrees in the simulated outflow, depending on the mass of the system and the resolution with which it is simulated. Using this study to anticipate the emergent behaviour at arbitrarily high resolution, we motivate more comprehensive analytic model which allows for the range of velocities with which the gas may exit the system, and incorporates both momentum and energy-based constraints on the outflow. Using a trial exit velocity distribution, this is shown to be compatible with the observed baryon fractions in intermediate-mass systems, but implies that current estimates for low-mass systems cannot be solely accounted for by supernova winds under commonly held assumptions.

Key words: supernovae: general – ISM: supernova remnants – galaxies: evolution – galaxies: formation.

Martin Stringer l'Observatoire de Paris LERMA

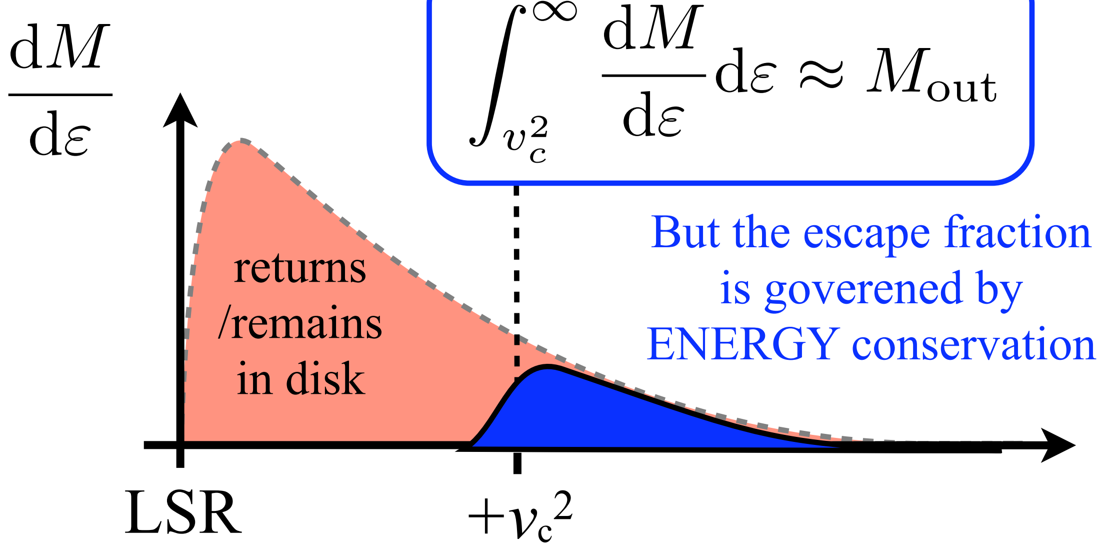
Alternative picture





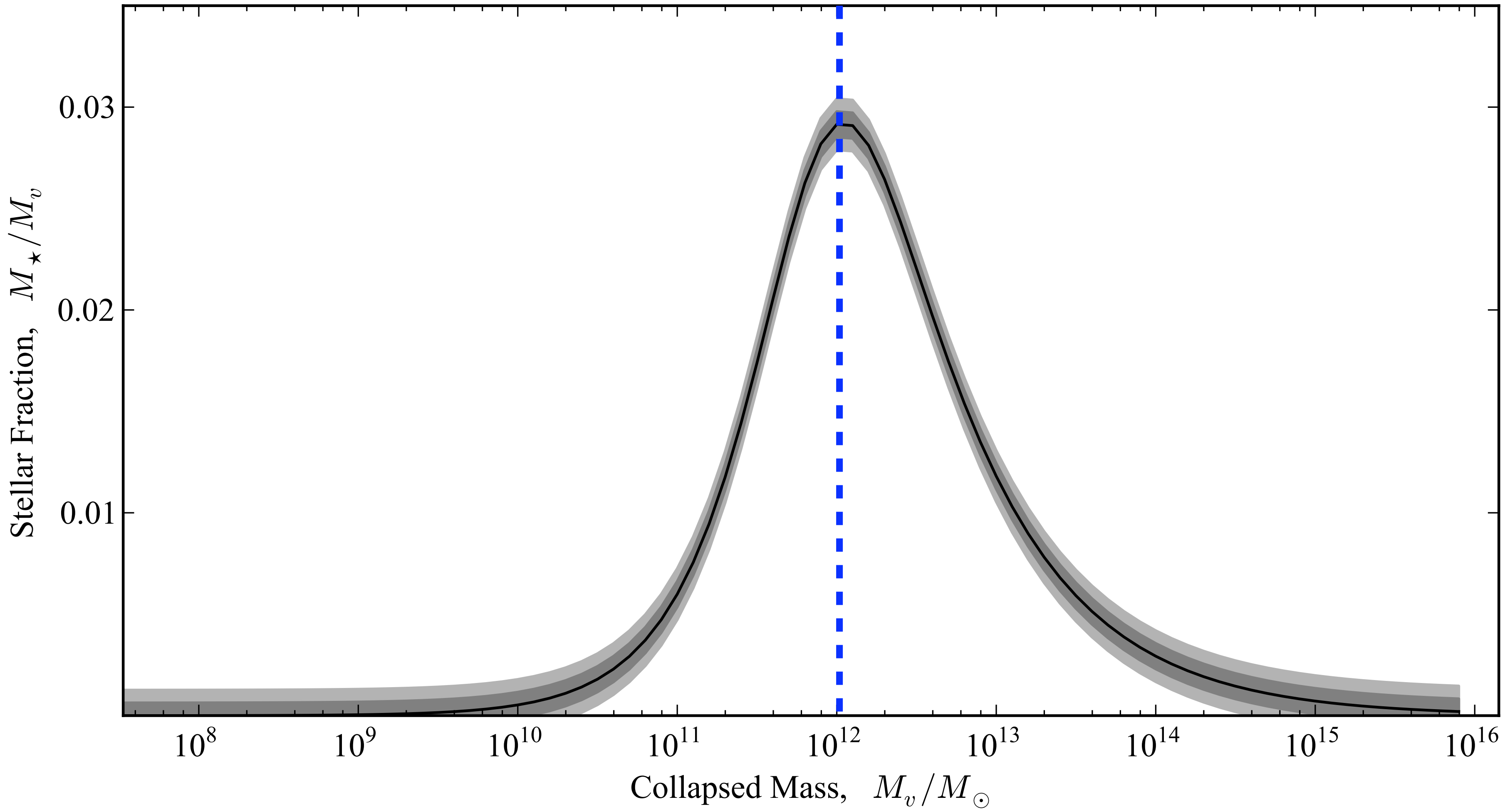
<u>Distribution</u> of energies
with total mass (=Area) governed by
MOMENTUM conservation

$$\int \frac{dM}{d\varepsilon} v(\varepsilon) d\varepsilon = p_{\rm SN}$$



$$\int_{v_c^2}^{\infty} \frac{dM}{d\varepsilon} d\varepsilon \approx M_{\rm out}$$

But the escape fraction
is goverened by
ENERGY conservation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0.02
0.01
10^8
10^9
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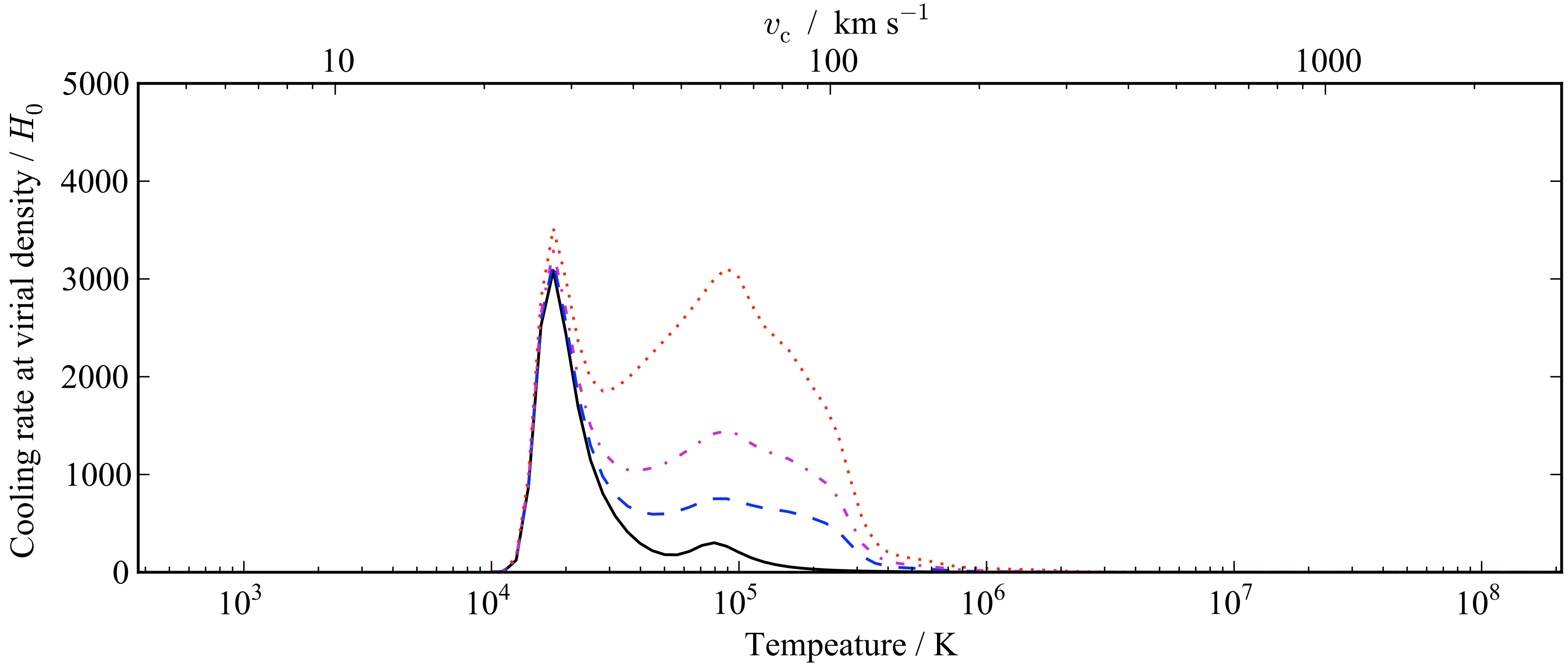
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
Collapsed Mass, $M_v/M_\odot$


v_c / km s^{-1}
10
100
1000
Cooling rate at virial density / H_0
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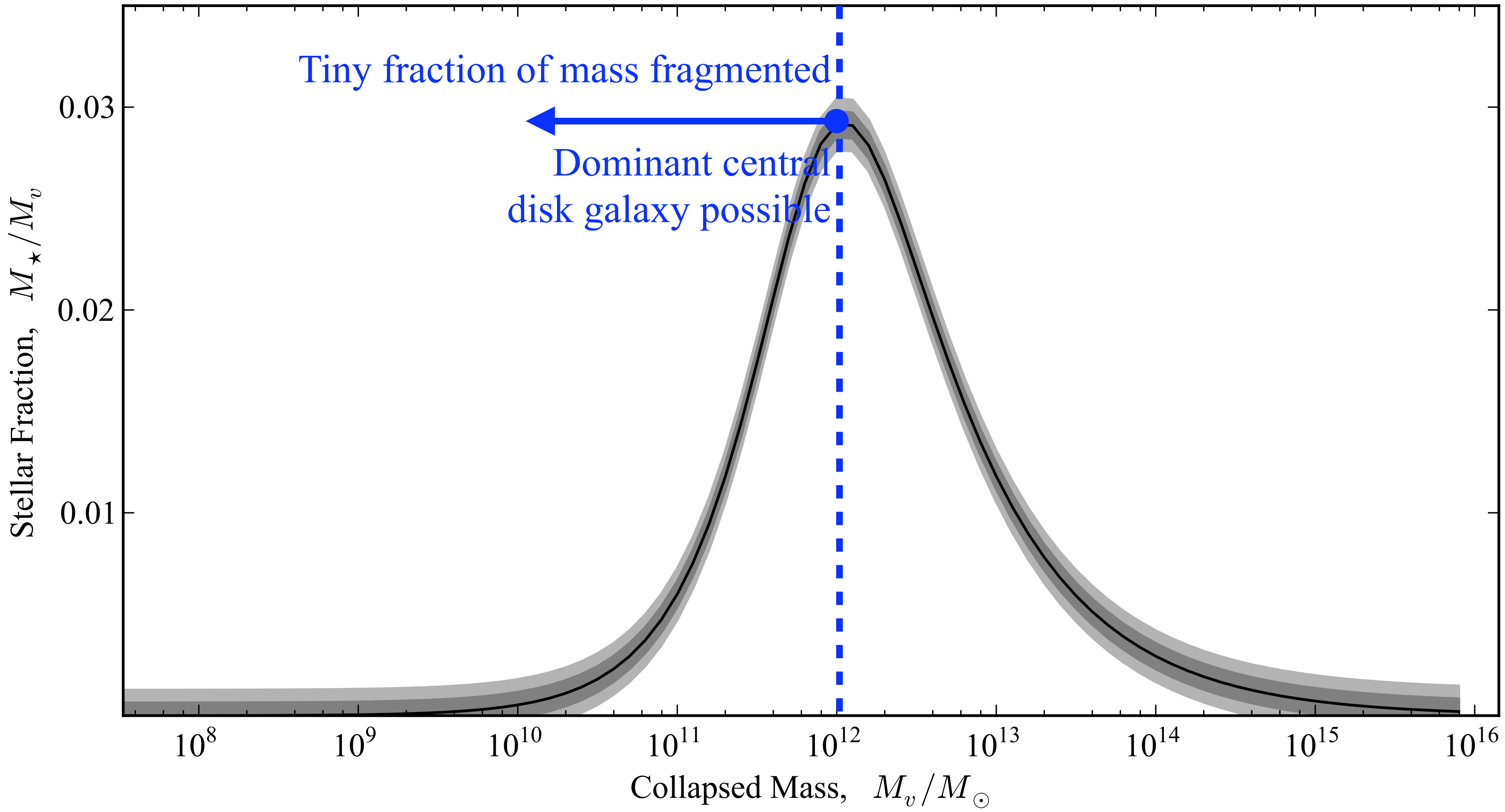
4000
3000
2000
1000
0
10^3
10^4
10^5
10^6
10^7
10^8
Tempeature / K


Tiny fraction of mass fragmented
Dominant central disk galaxy possible
Stellar Fraction, $M_\star/M_v$
0.03
0.02
0.01
10^8
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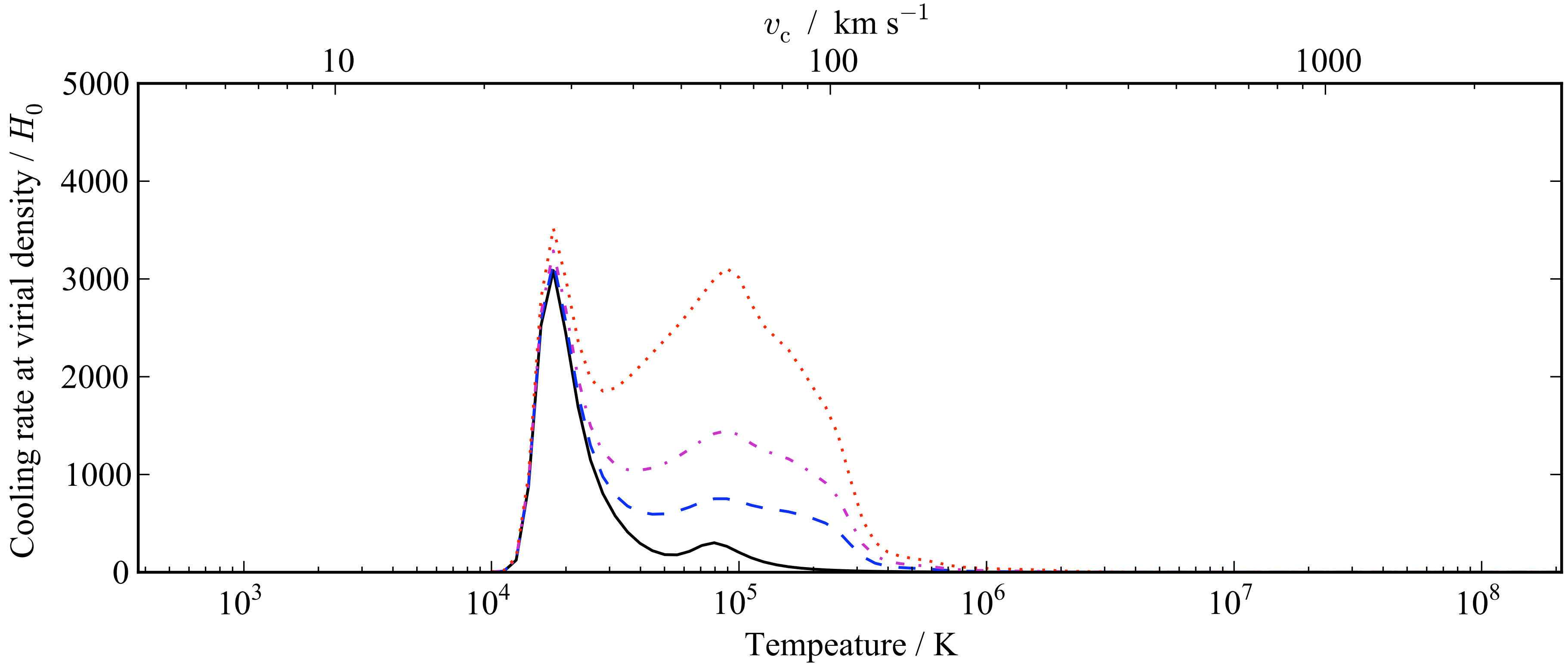
Collapsed Mass, $M_v/M_\odot$


v_c / km s^{-1}
10
100
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Cooling rate at virial density / H_0
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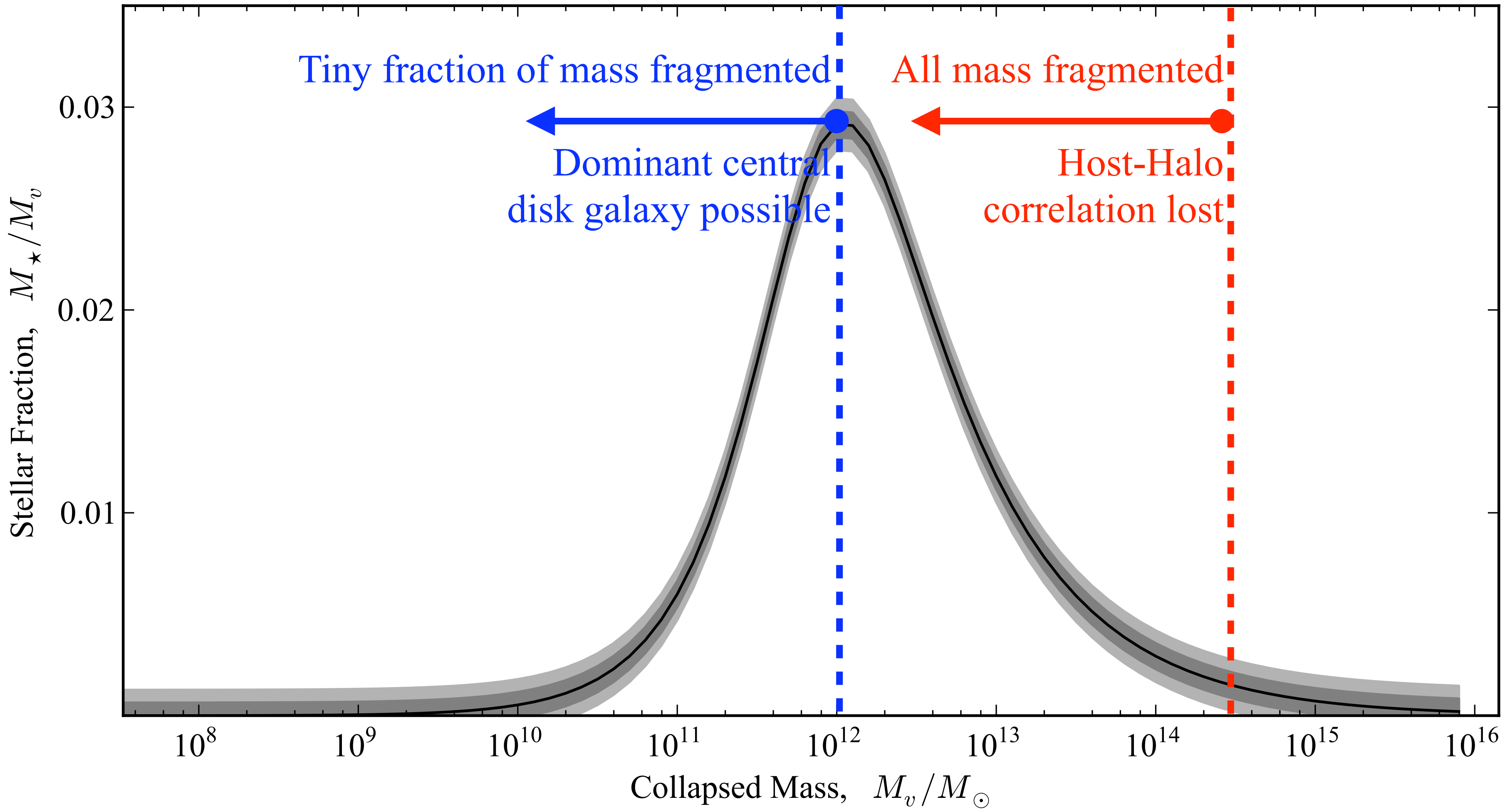
10^8
Tempeature / K


Tiny fraction of mass fragmented
All mass fragmented
Dominant central disk galaxy possible
Host-Halo correlation lost
Stellar Fraction, $M_\star/M_v$
0.03
0.02
0.01
10^8
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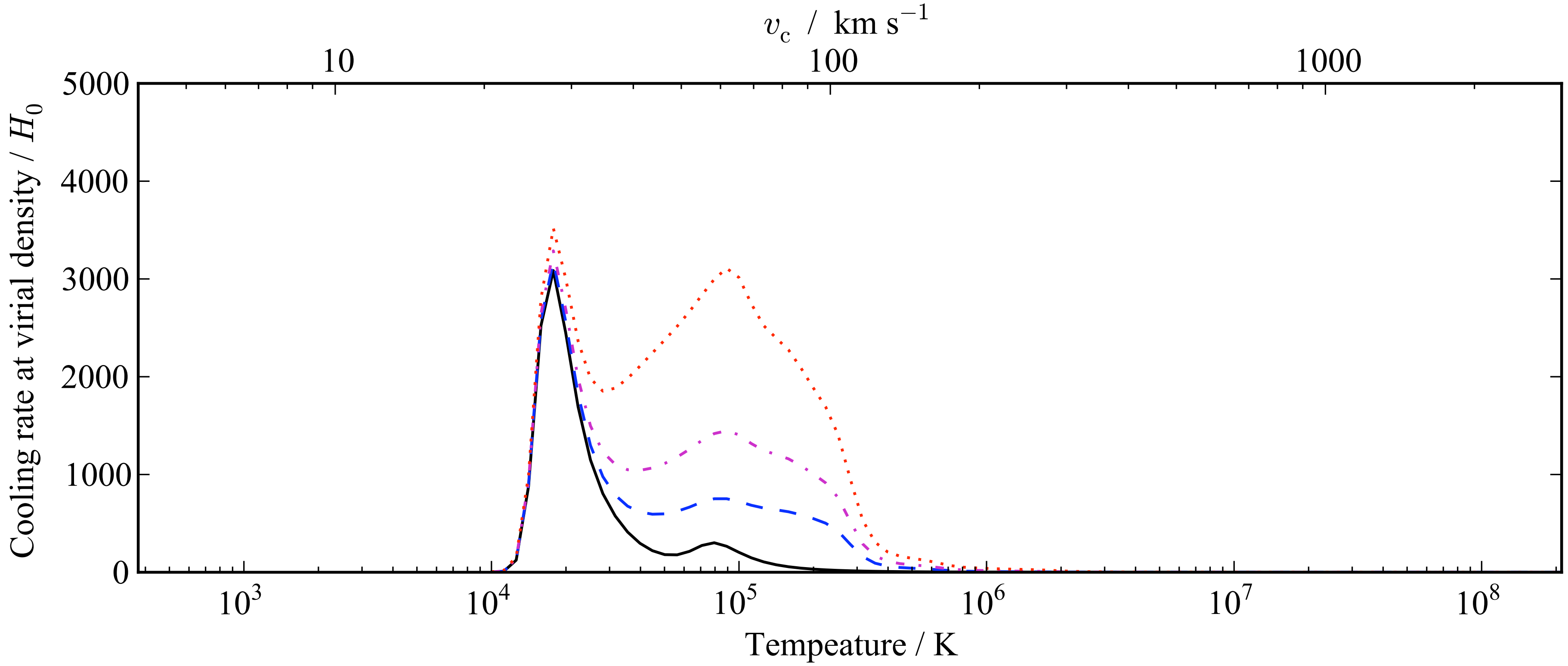
Collapsed Mass, $M_v/M_\odot$


v_c / km s^{-1}
10
100
1000
Cooling rate at virial density / H_0
5000
4000
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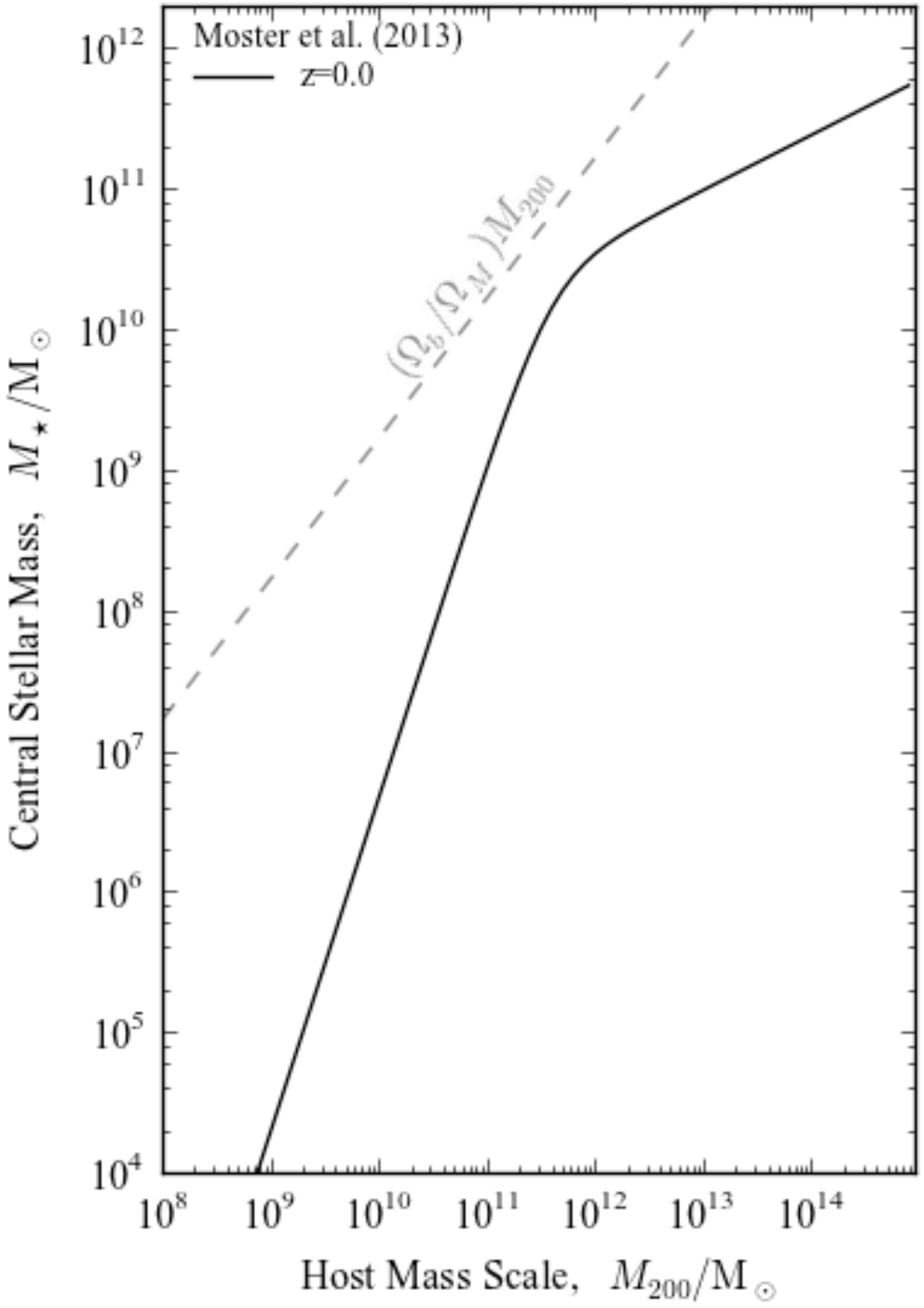
10^3
10^4
10^5
10^6
10^7
10^8
Tempeature / K

From host structures to galaxies



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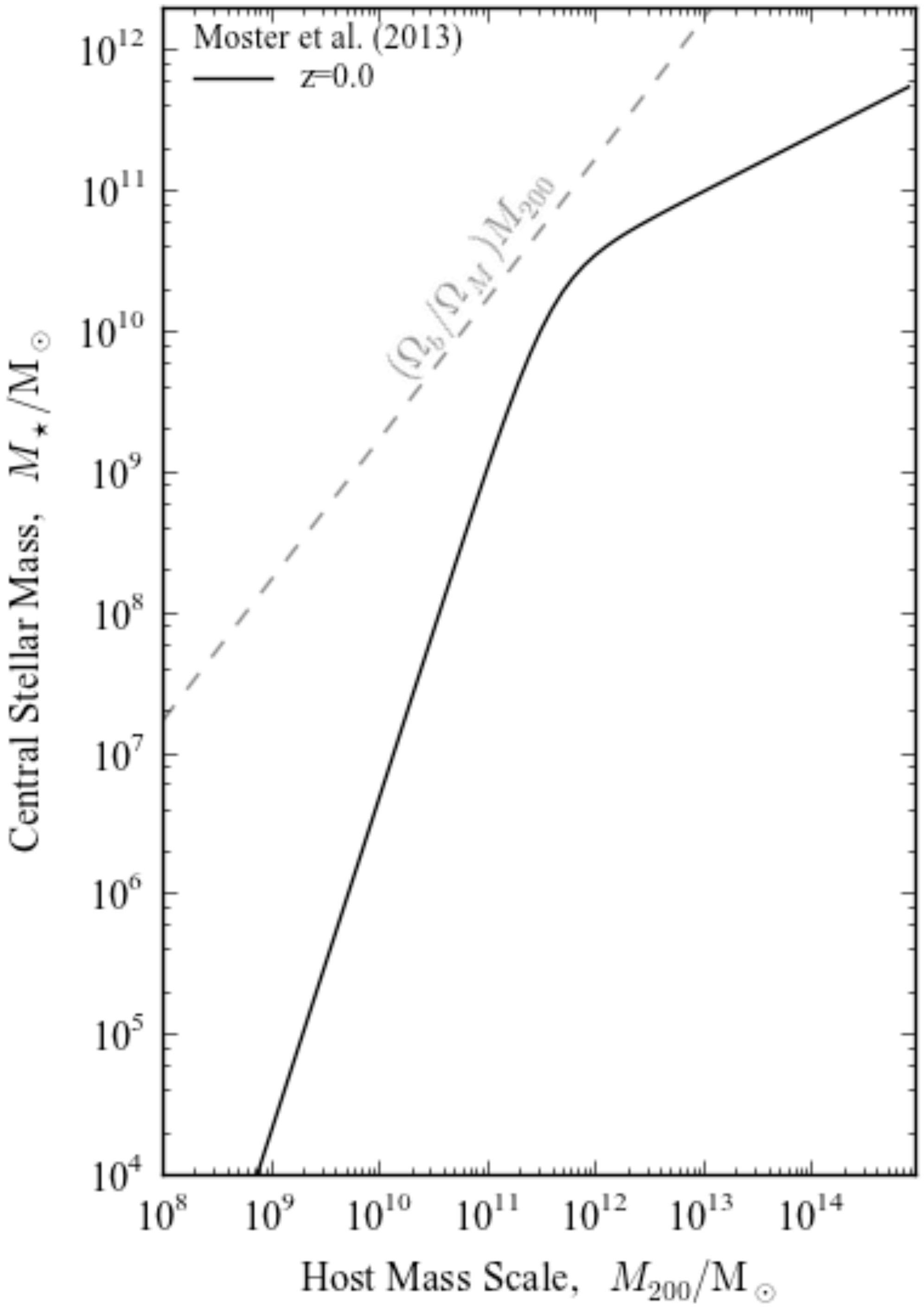

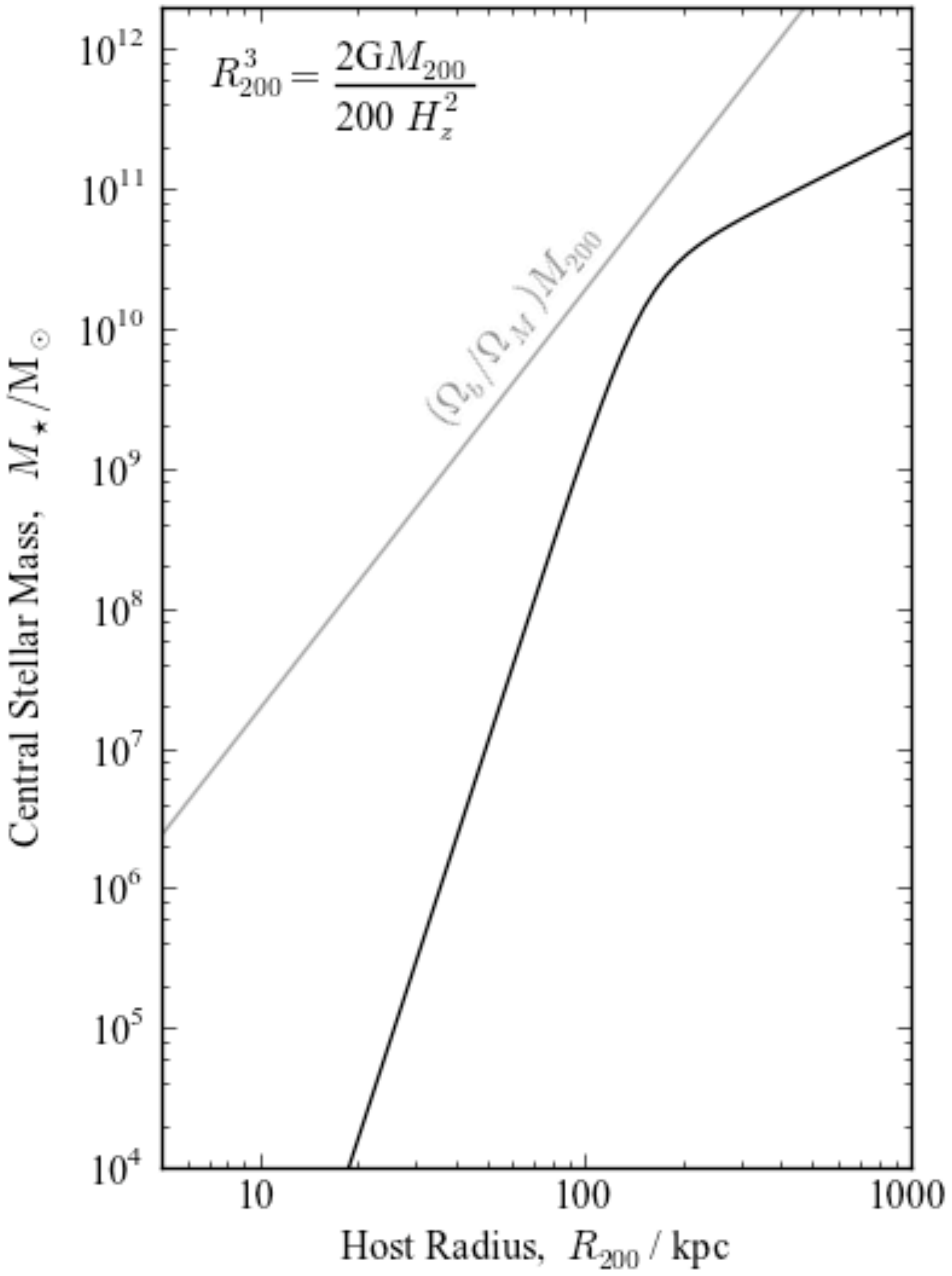

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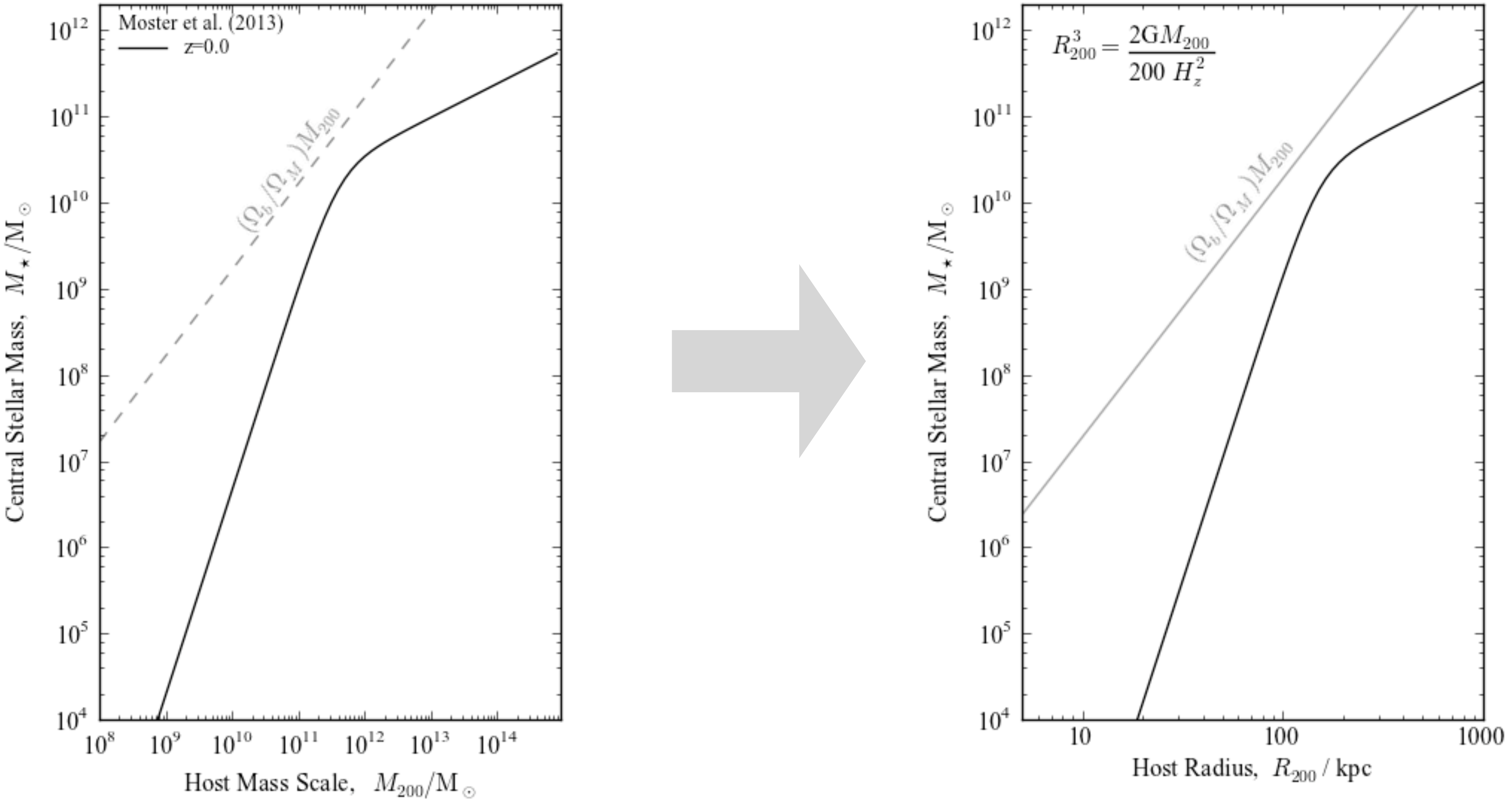

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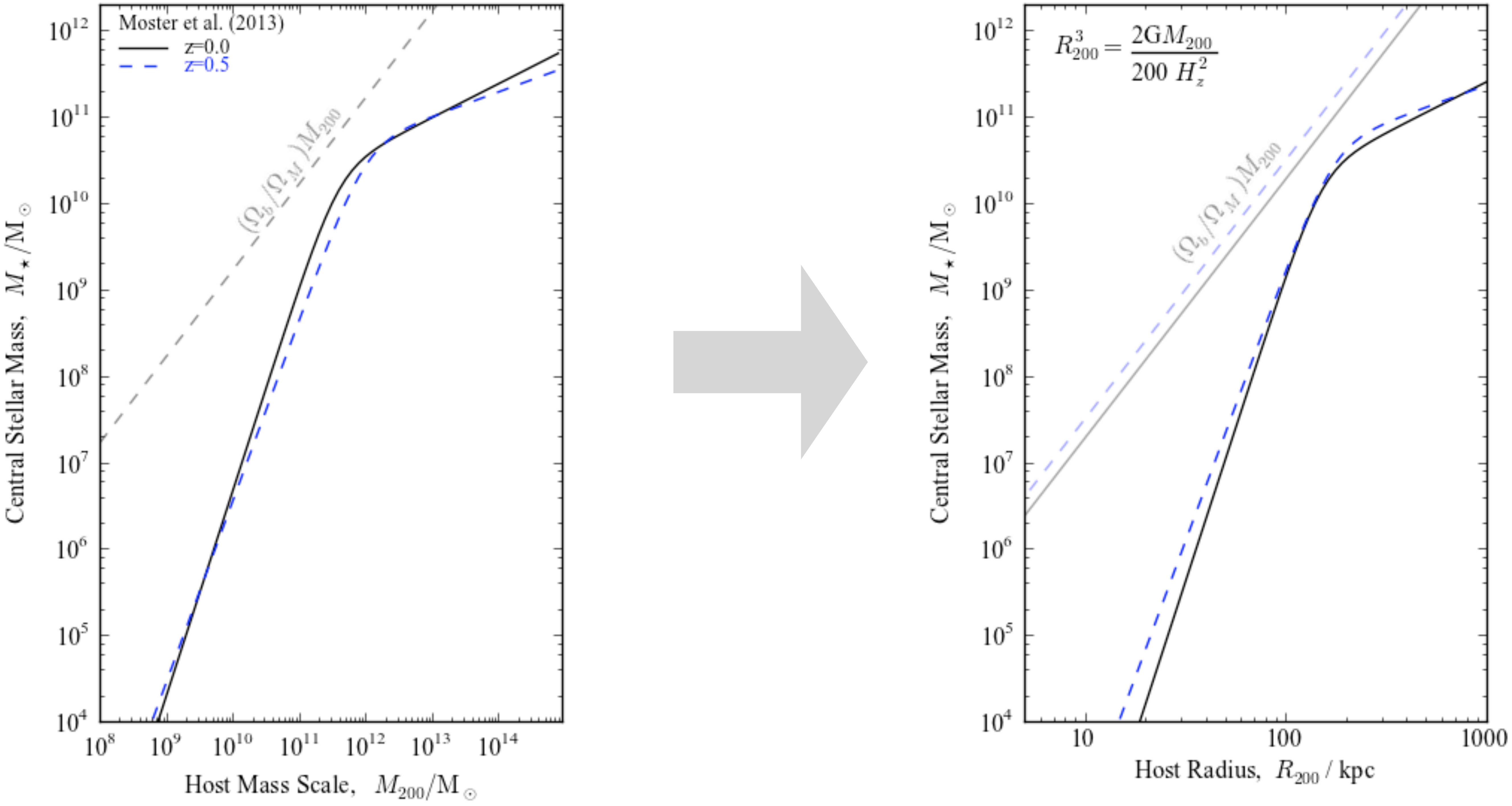

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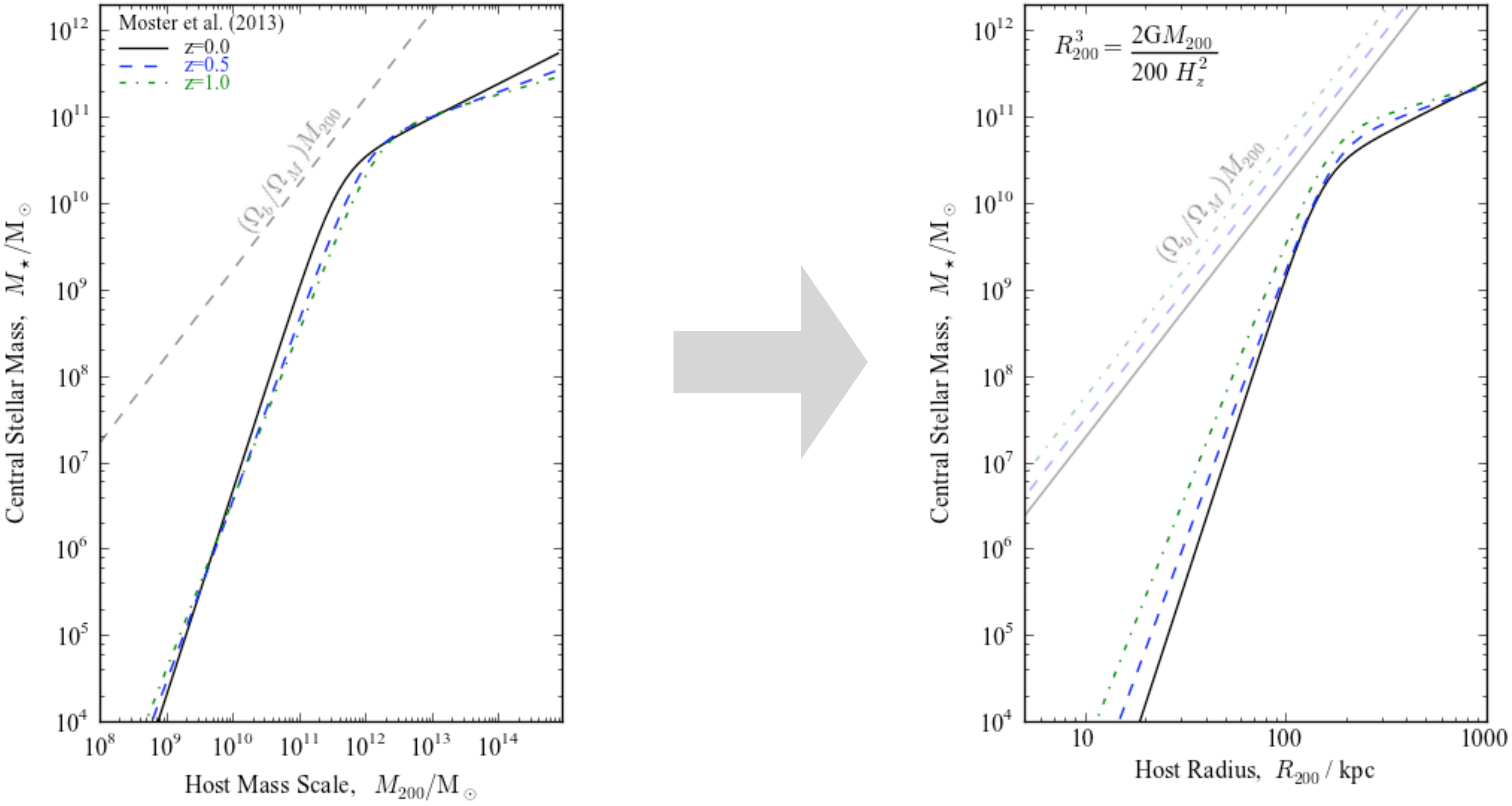
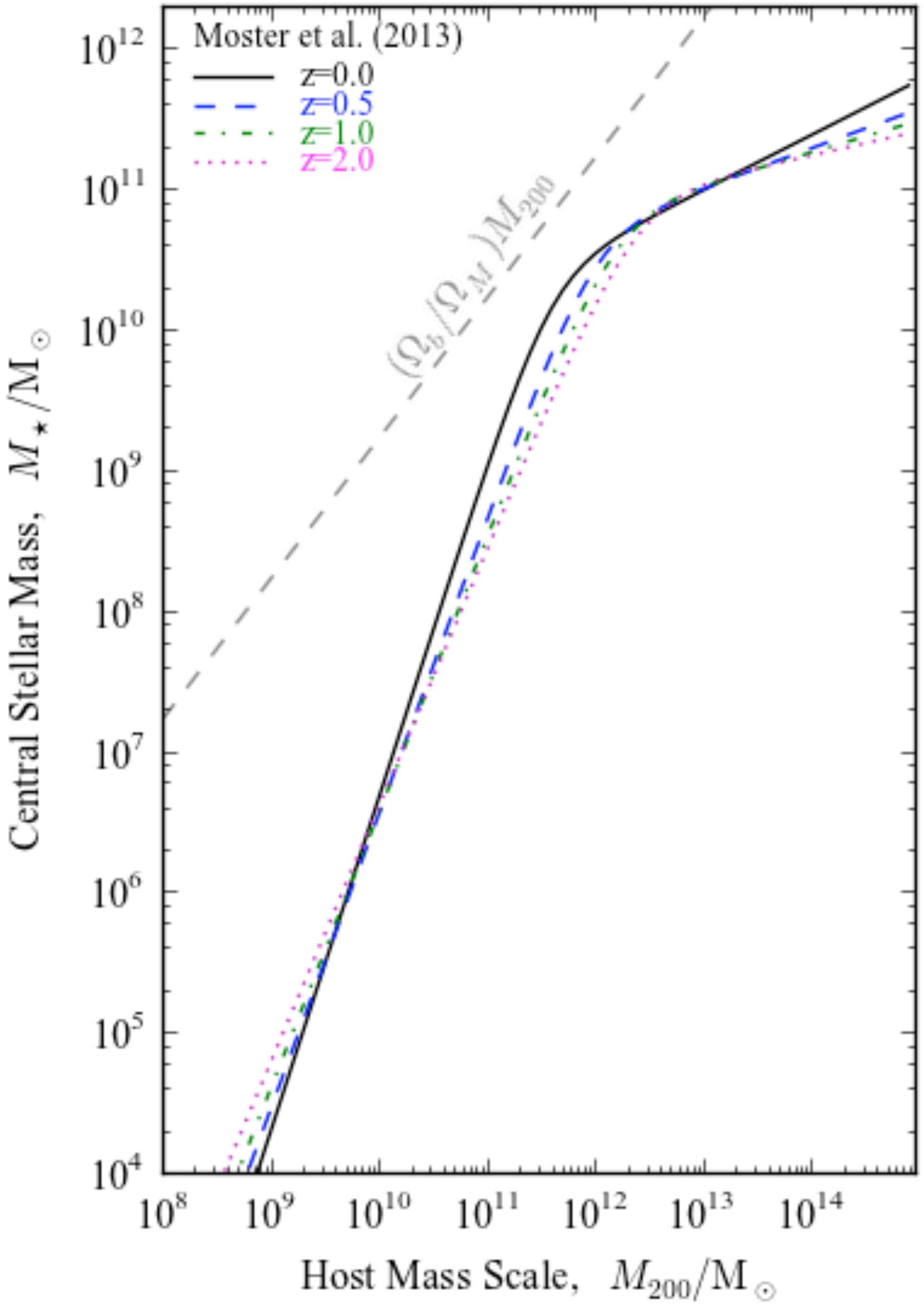
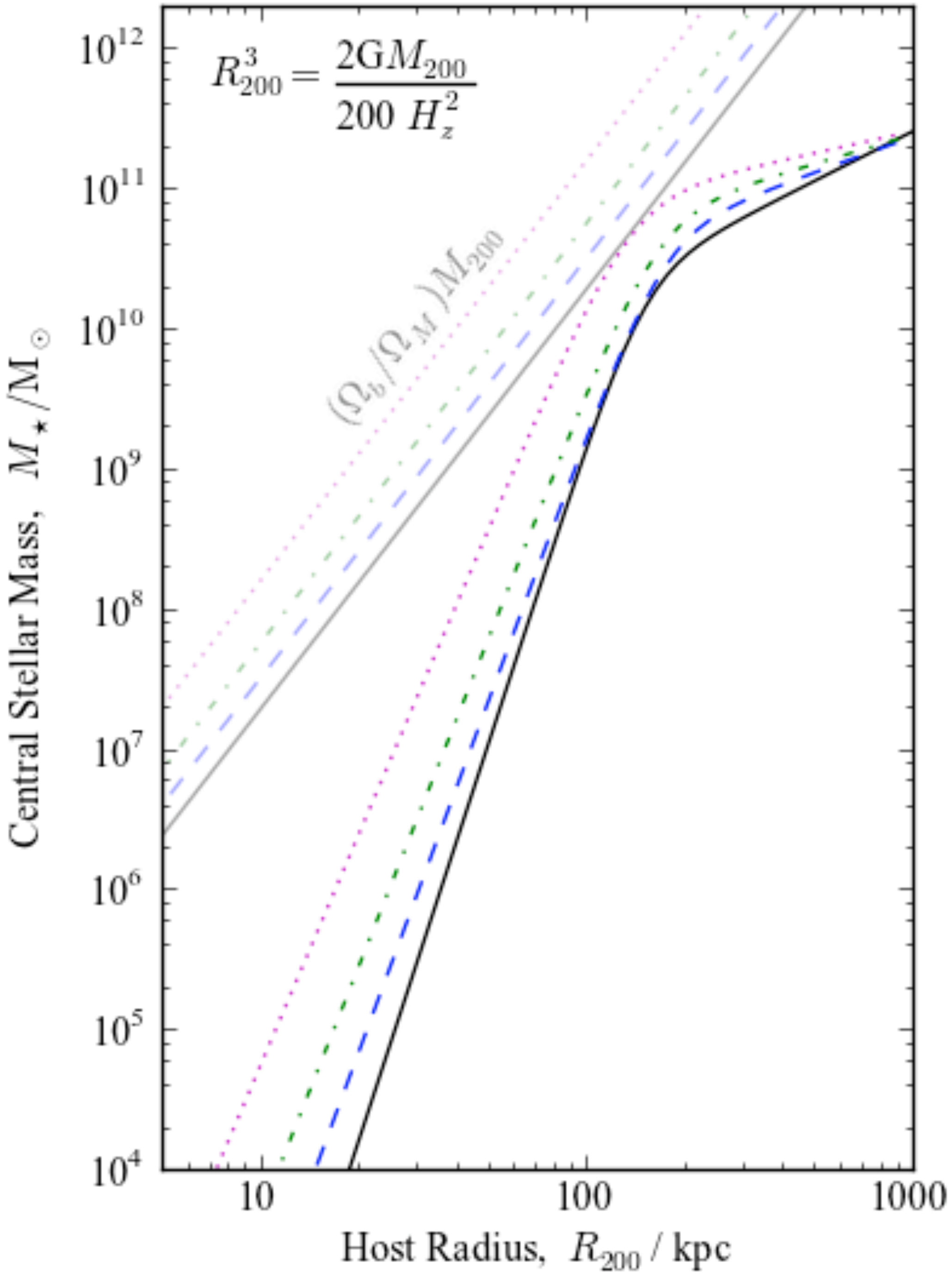


Martin Stringer

From host structures to galaxies





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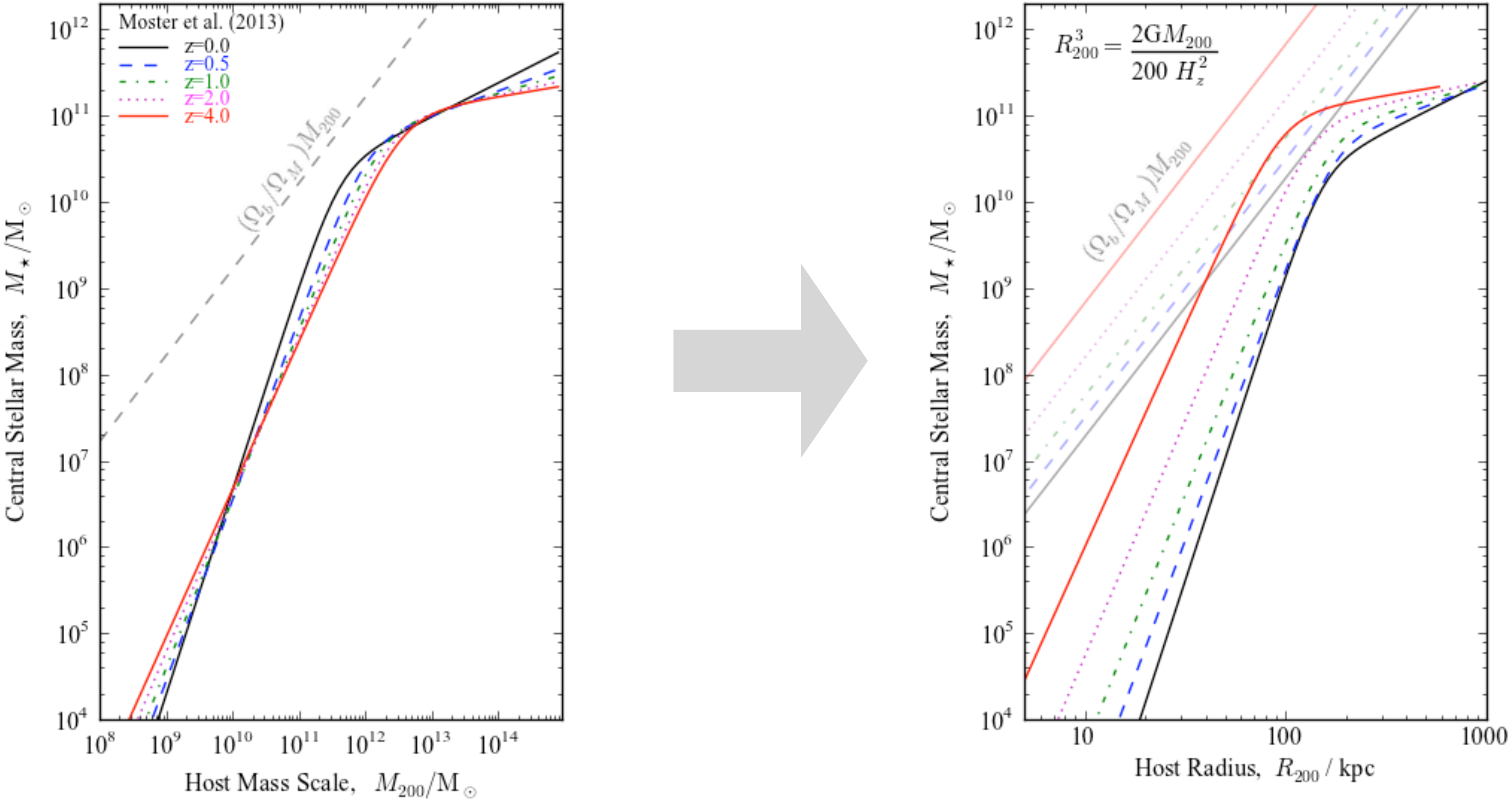

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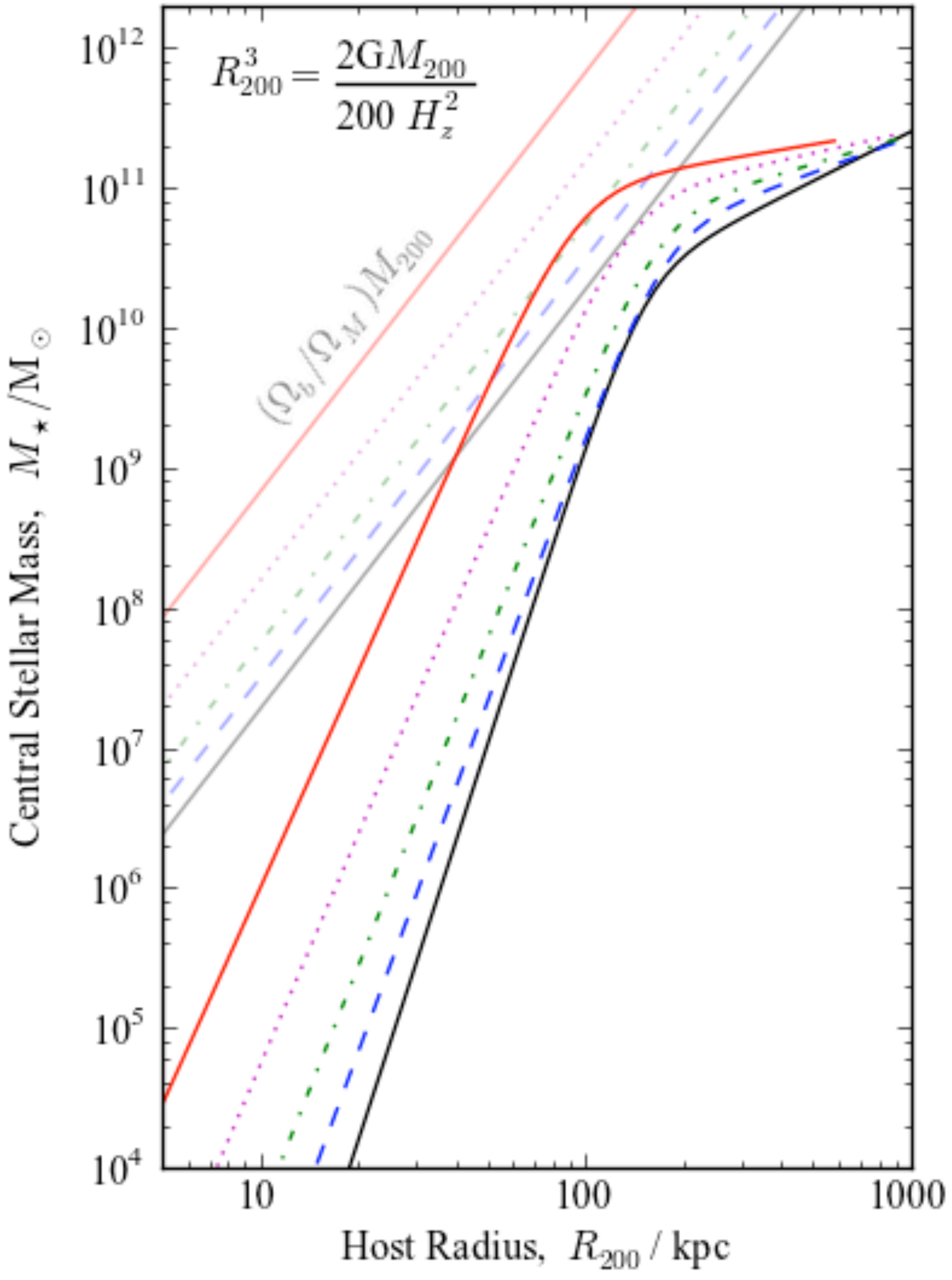

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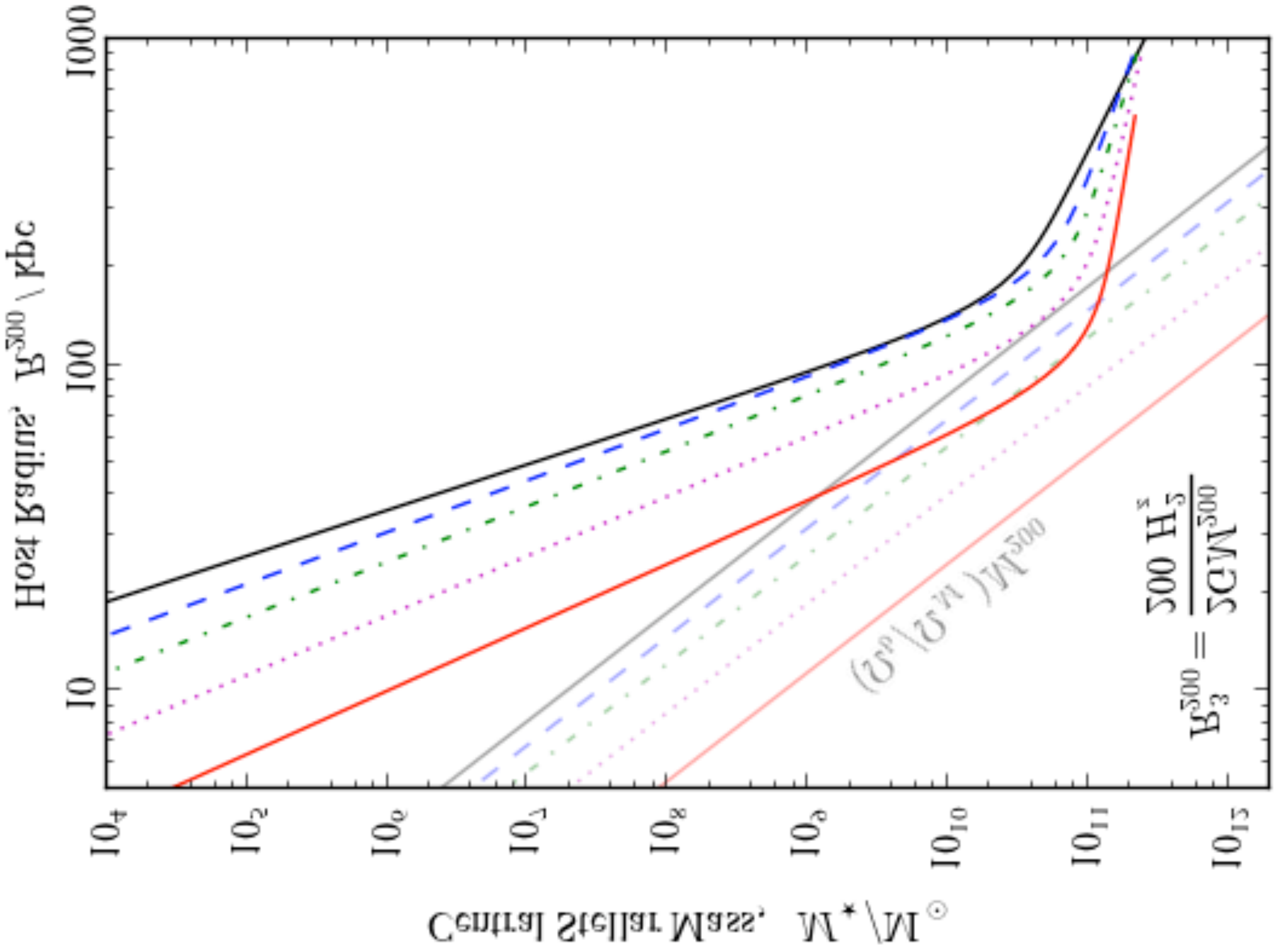

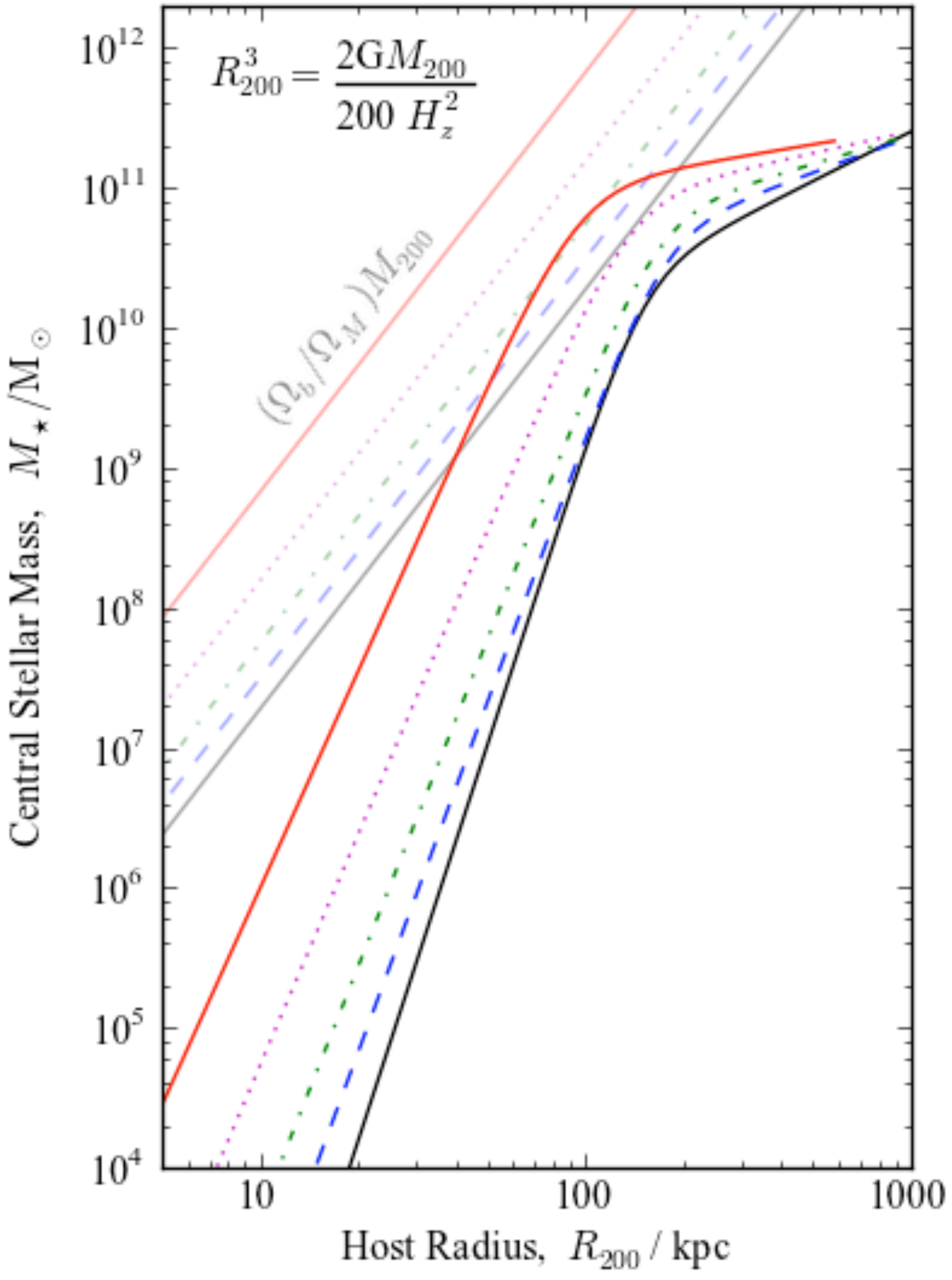

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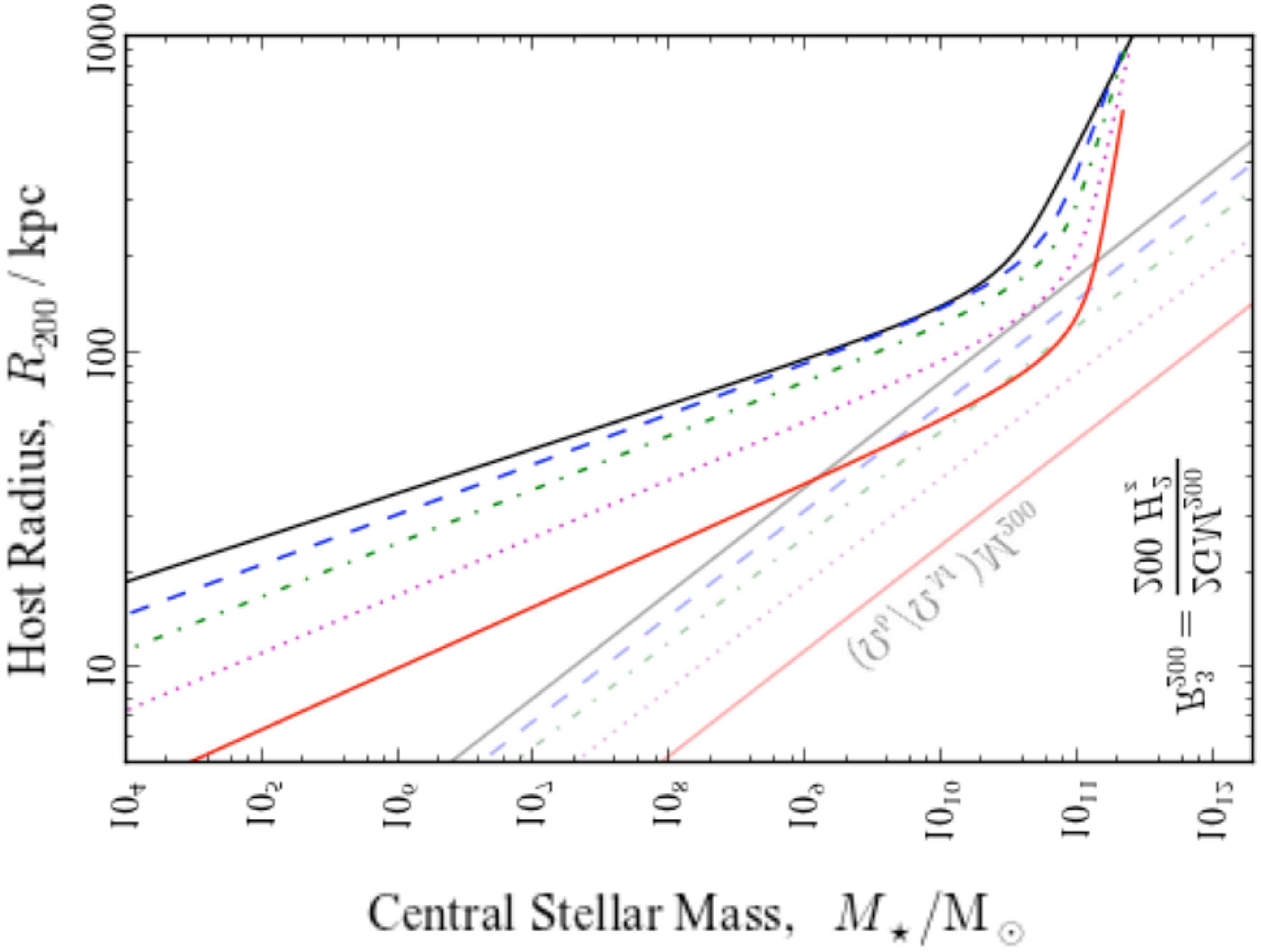

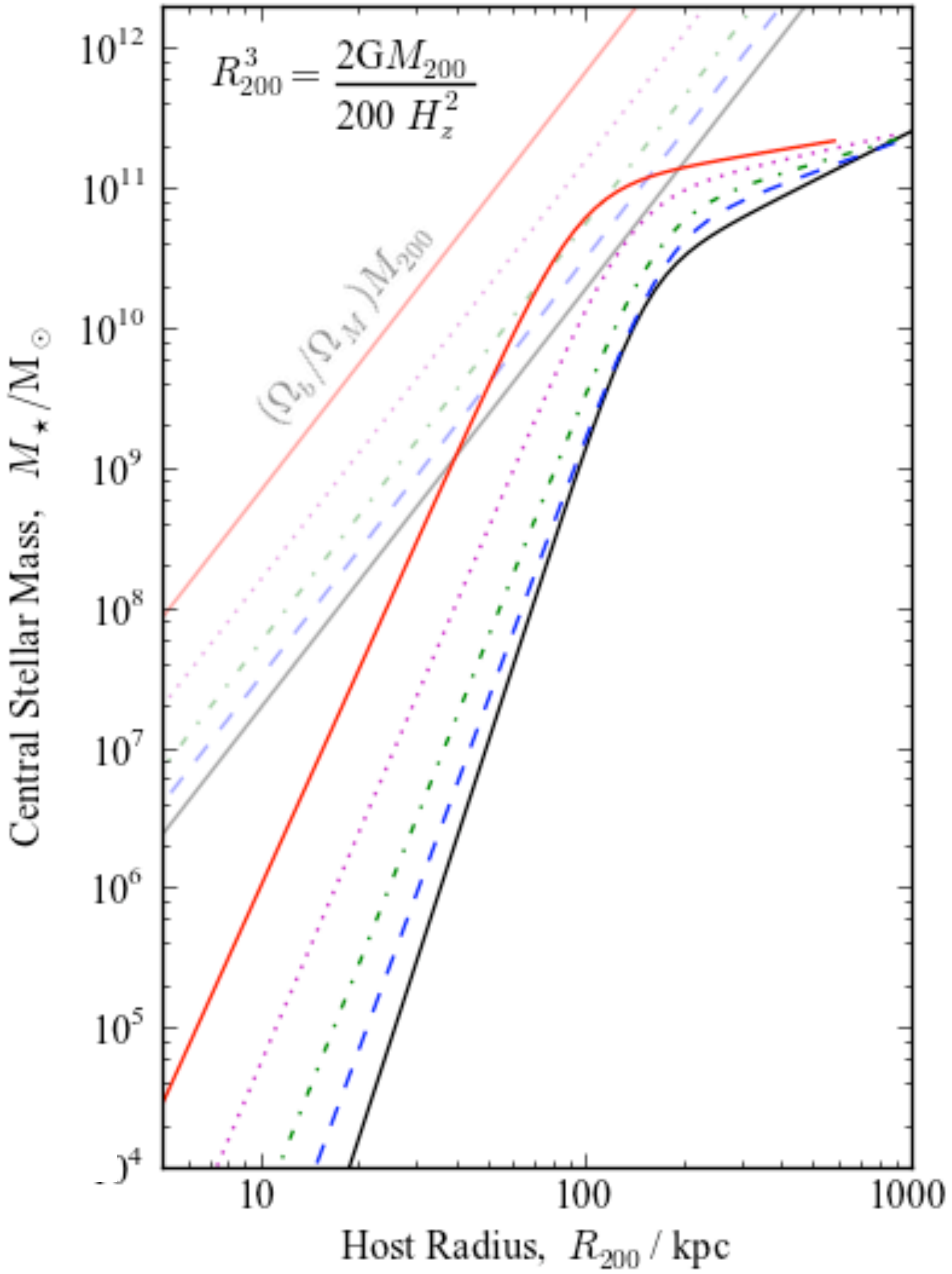

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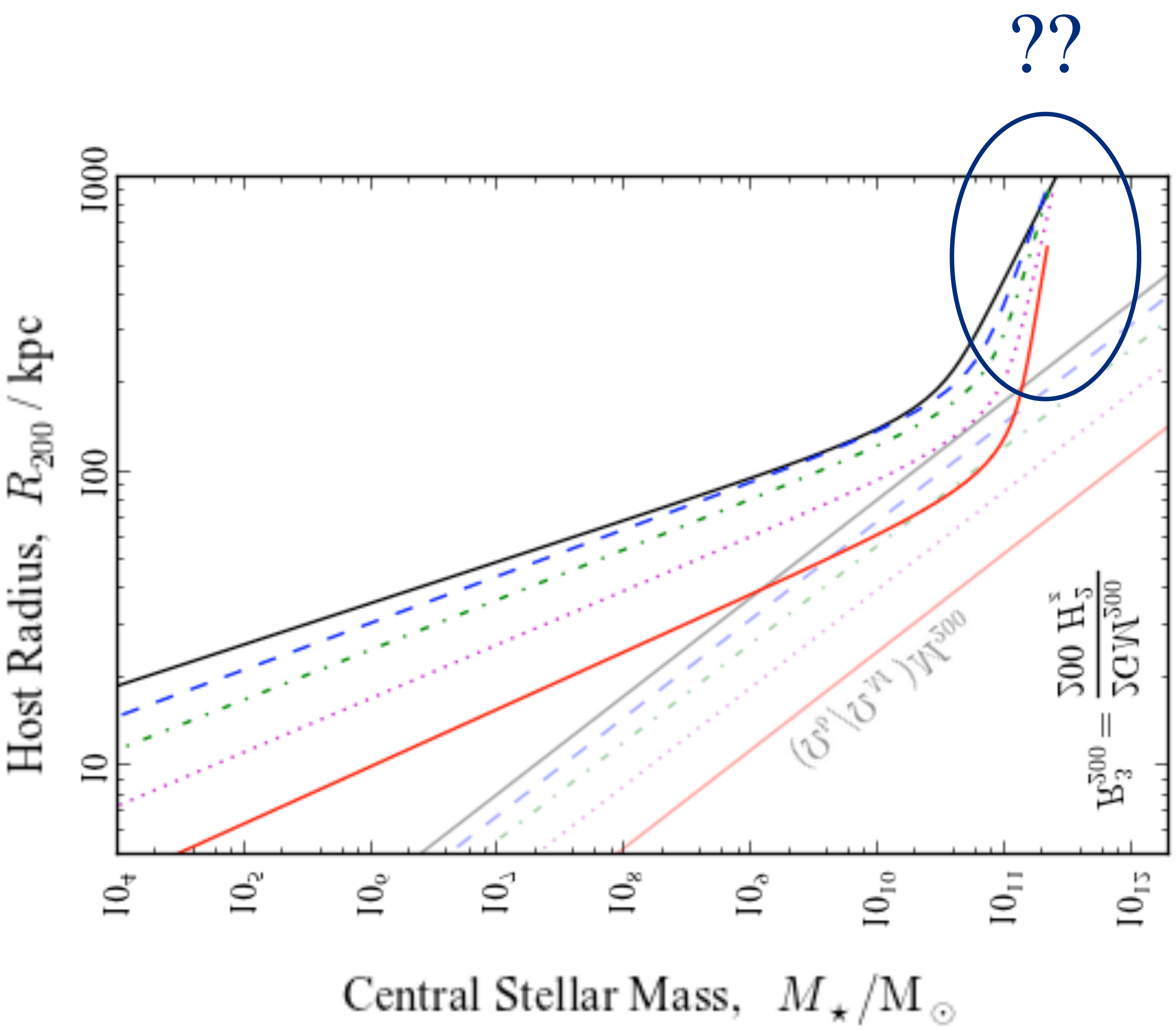

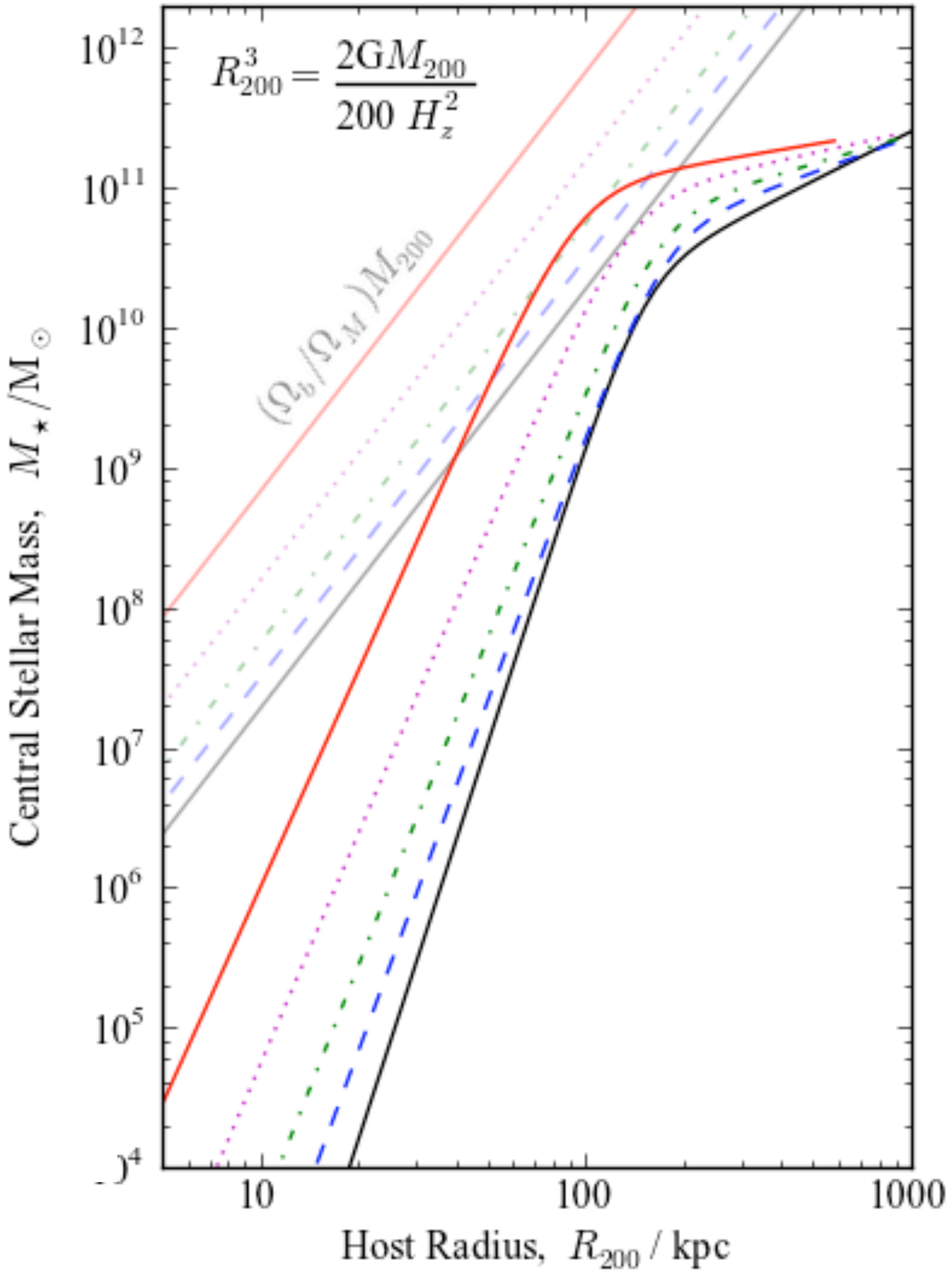

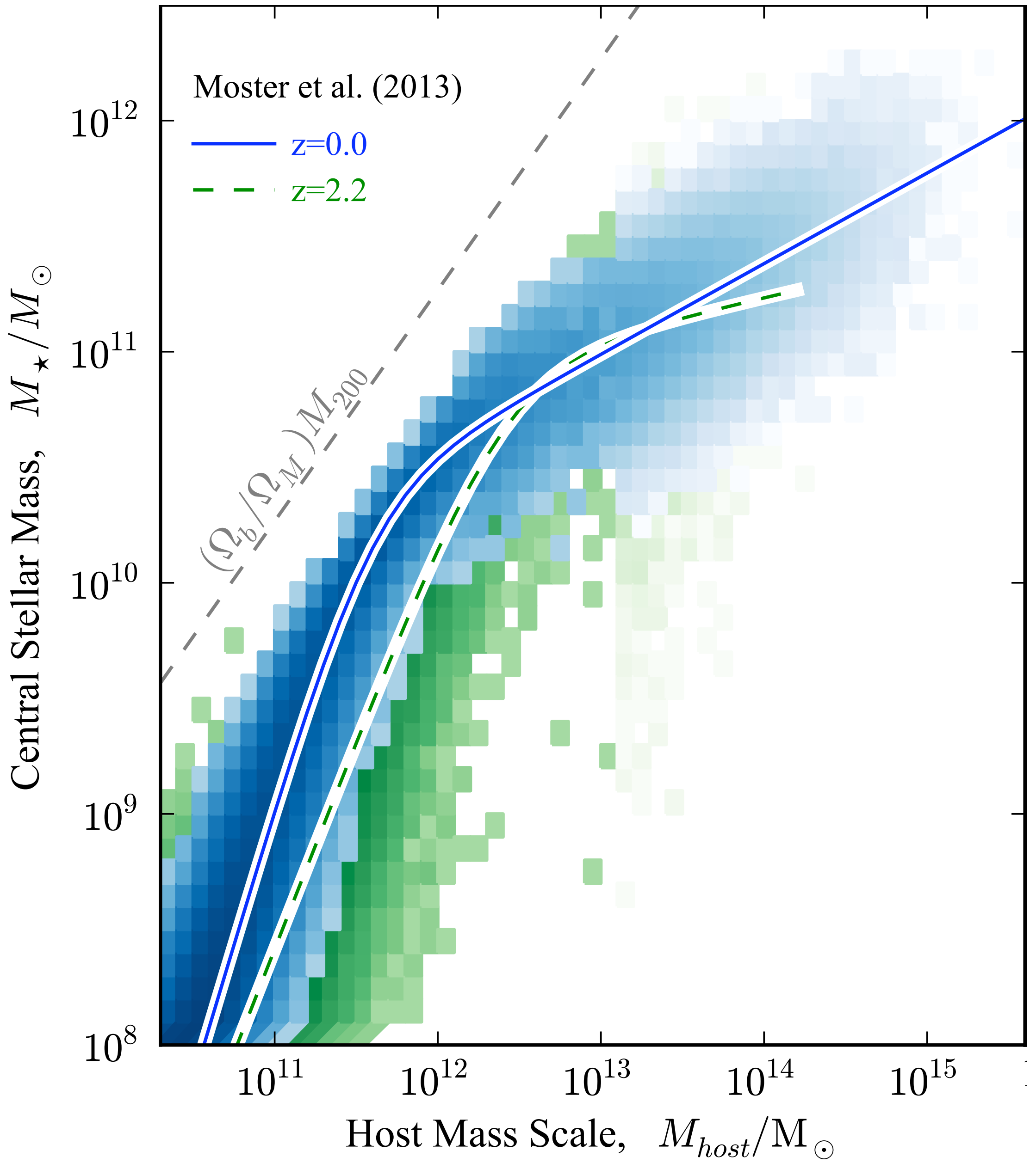
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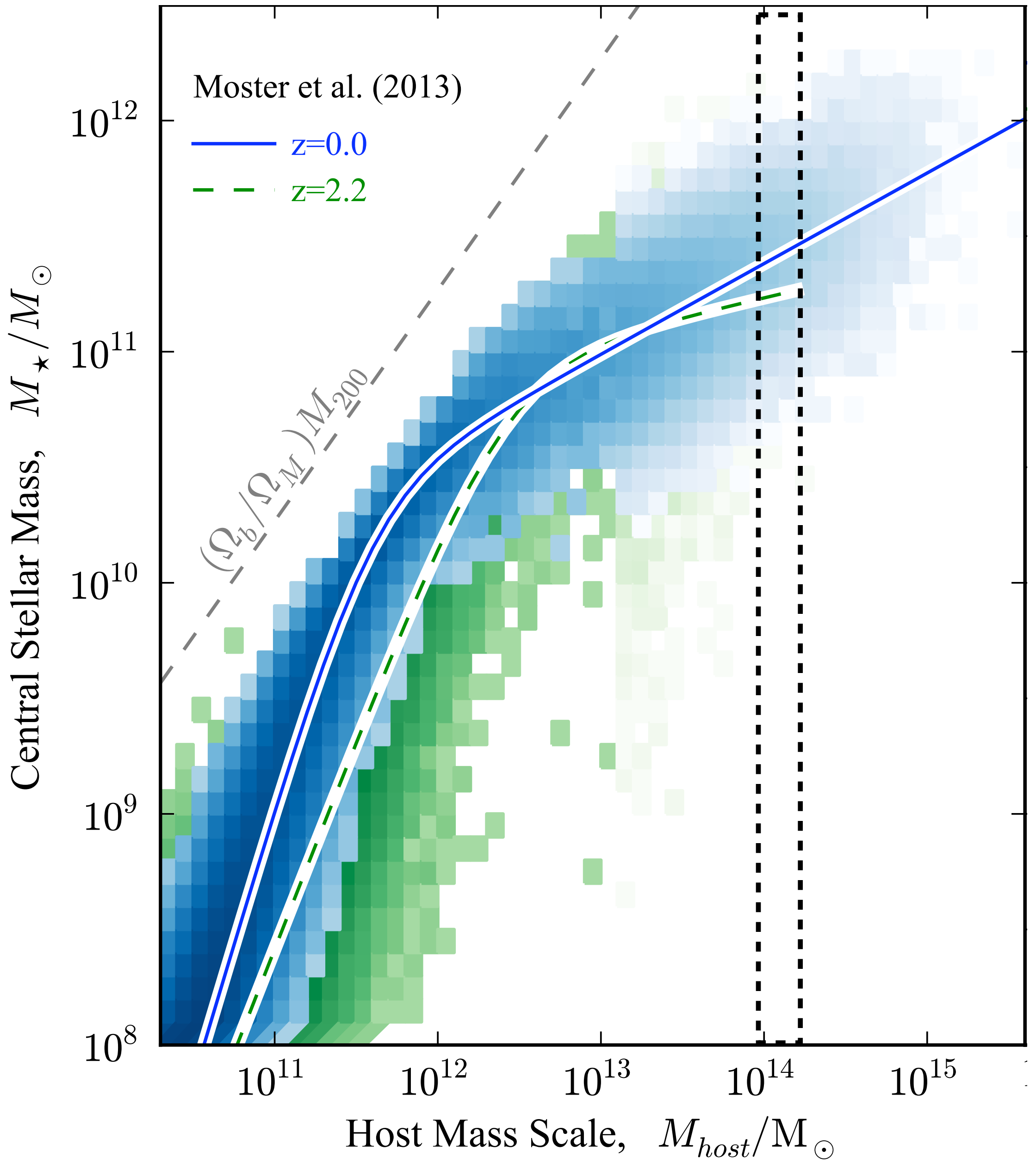
10^{15}
Host Mass Scale, $M_{host}/\mathrm{M}_\odot$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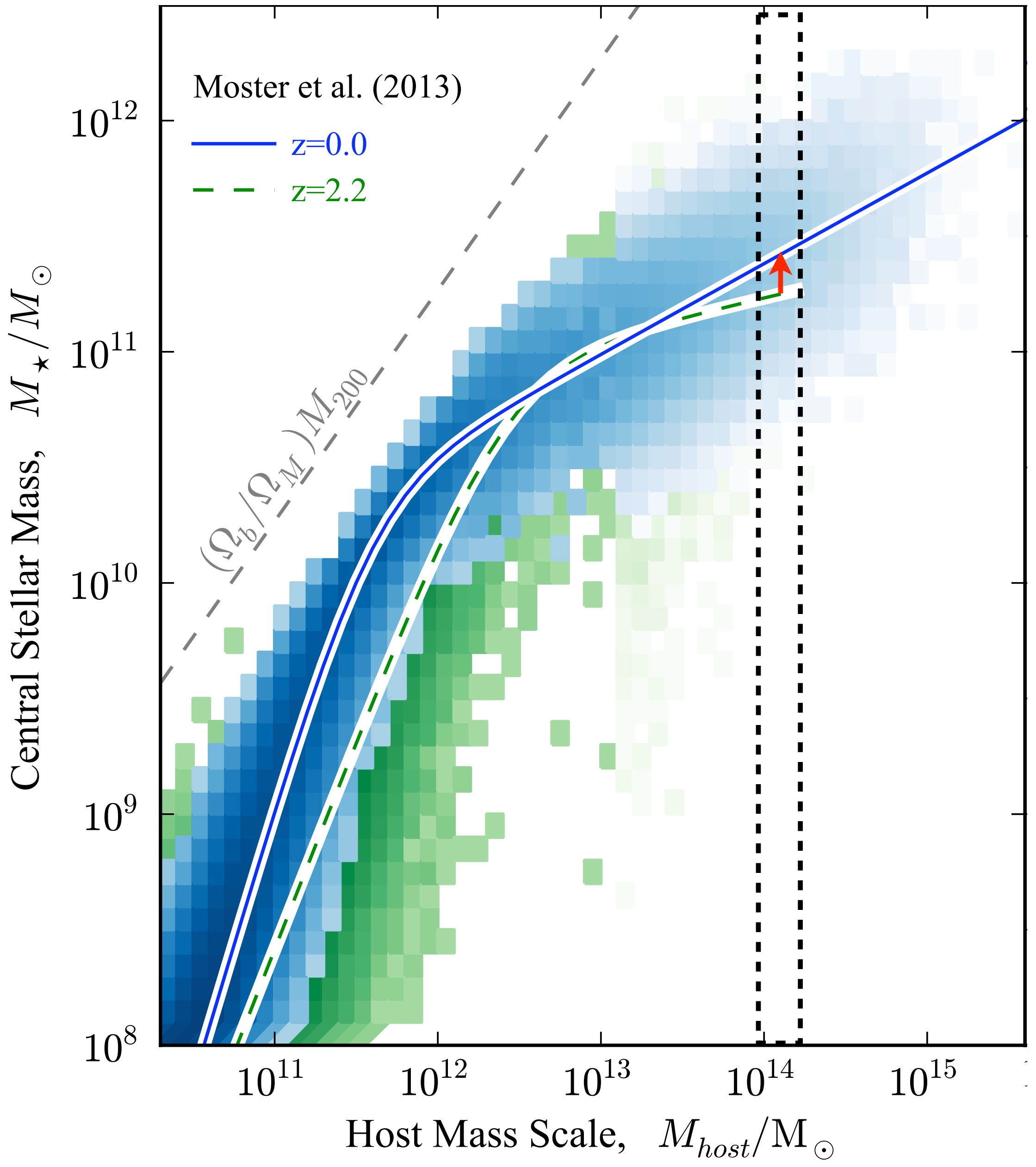
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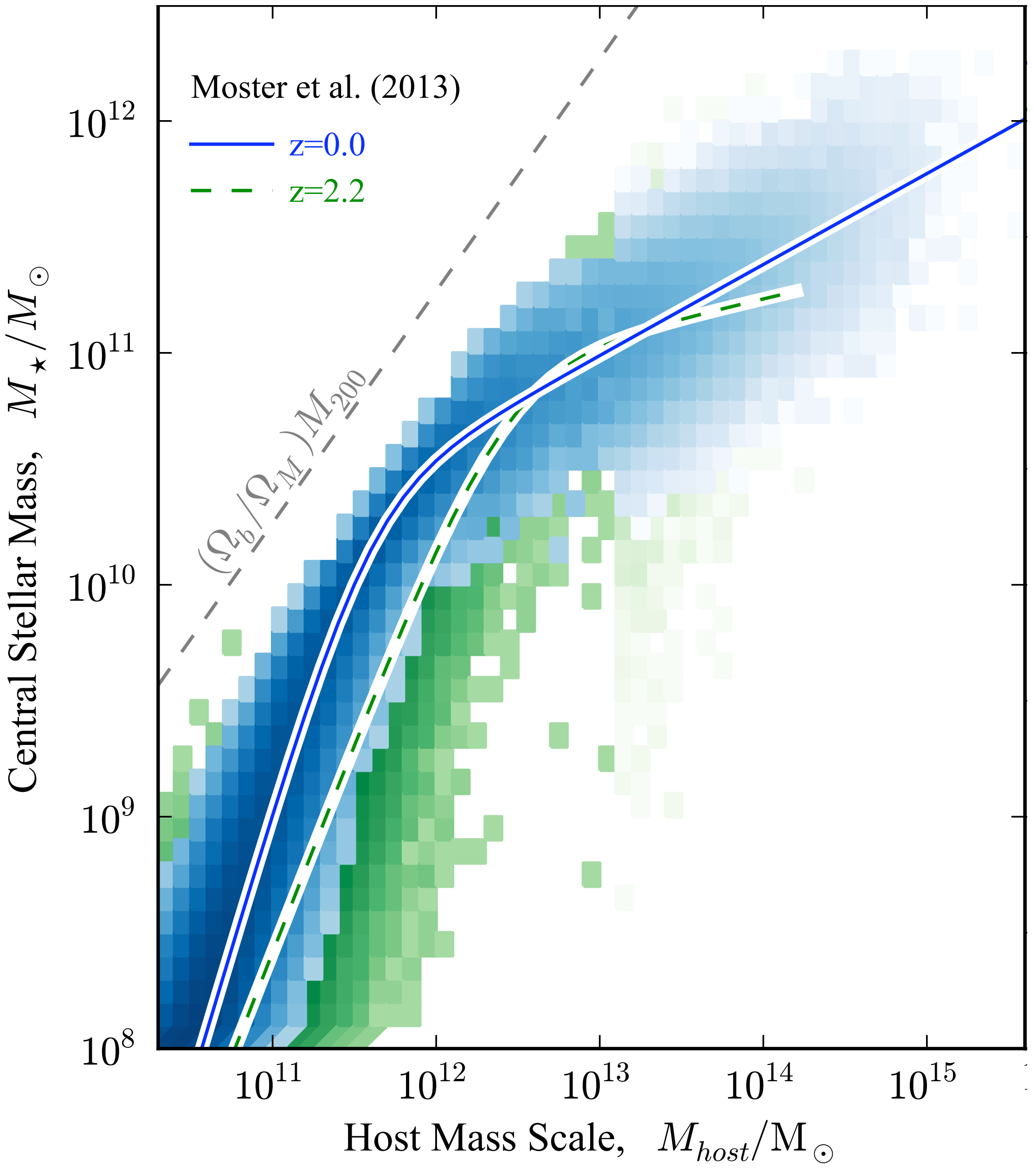
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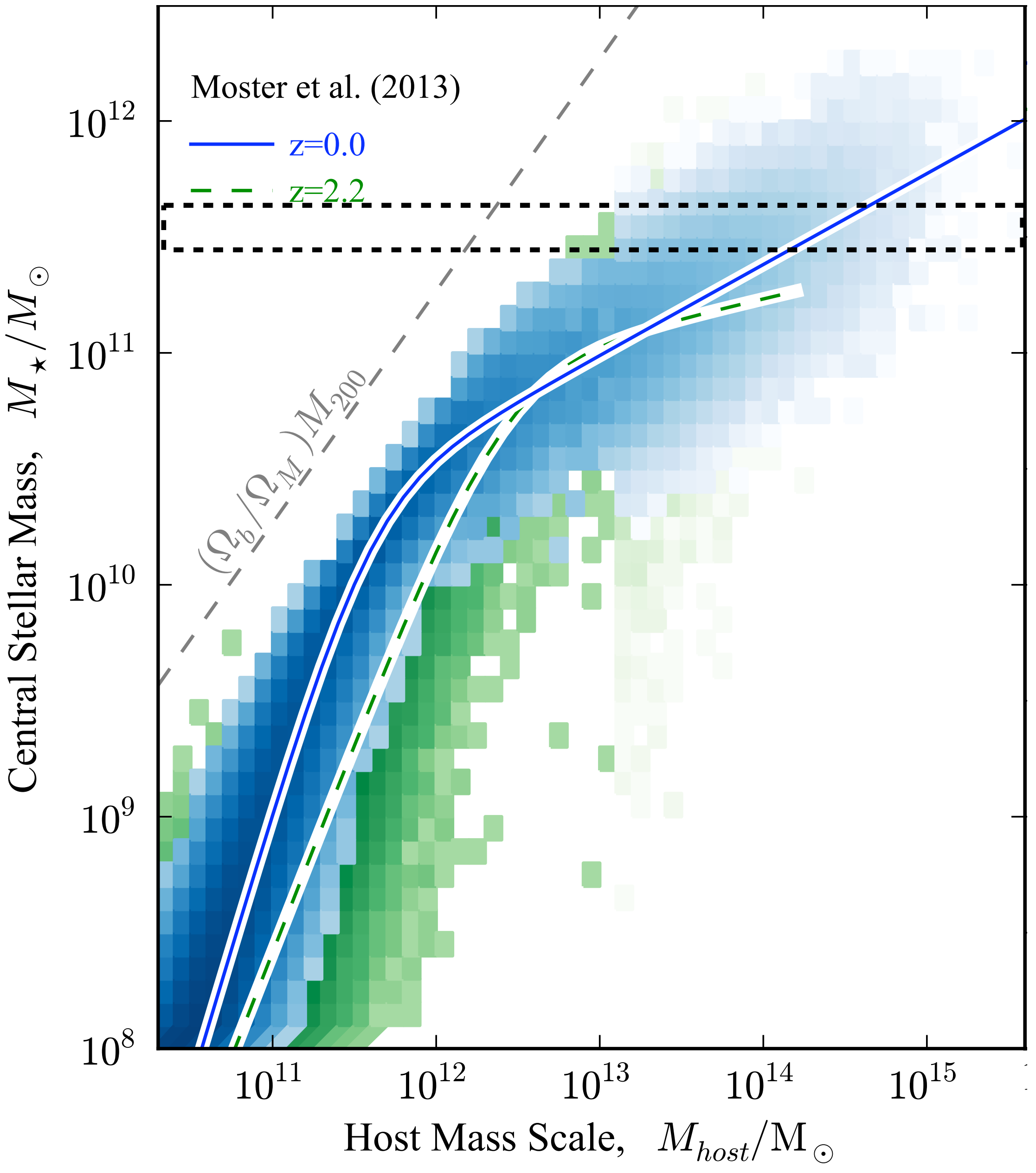
Host Mass Scale, $M_{host}/\mathrm{M}_\odot$



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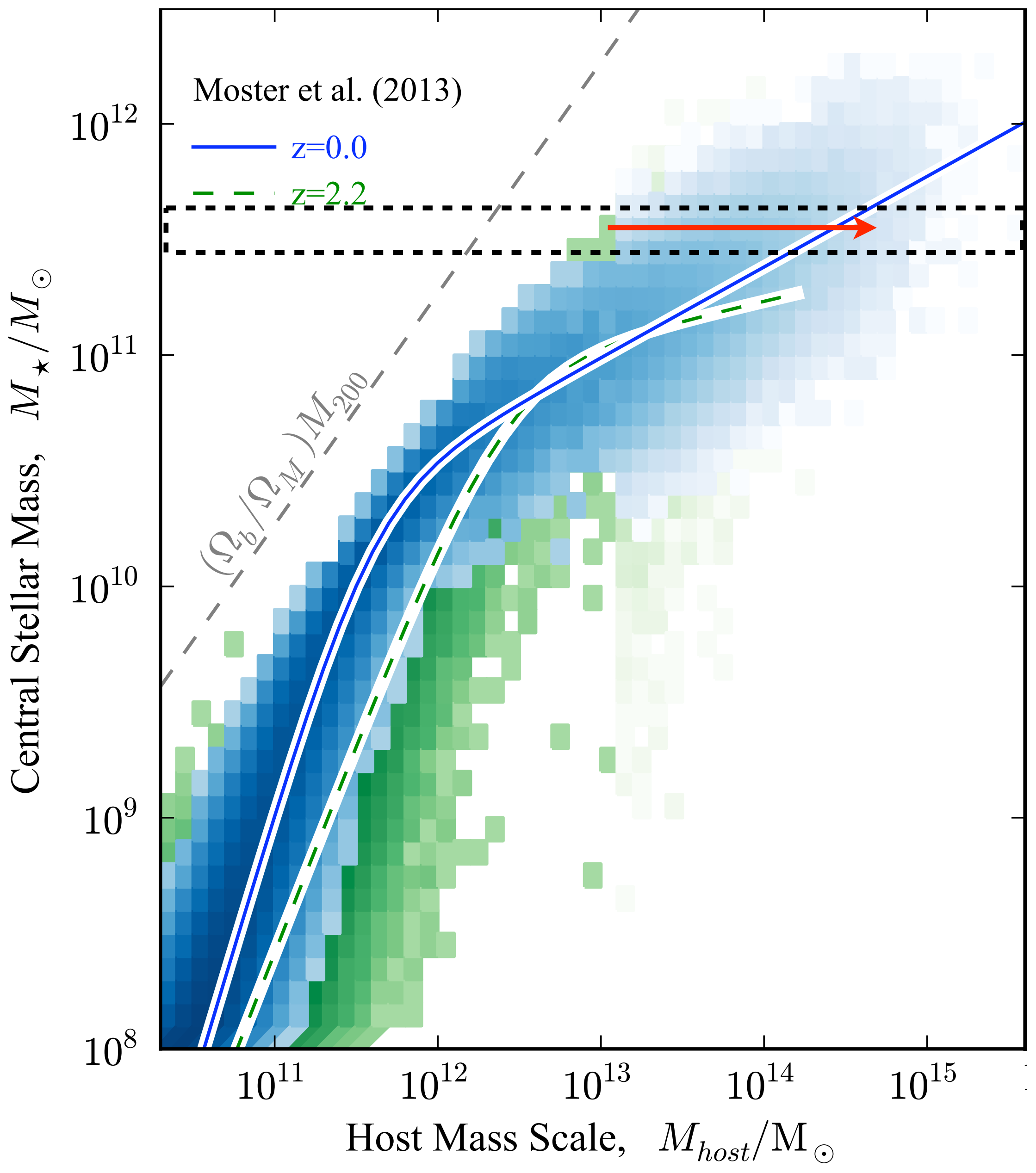
Host Mass Scale, $M_{host}/\mathrm{M}_\odot$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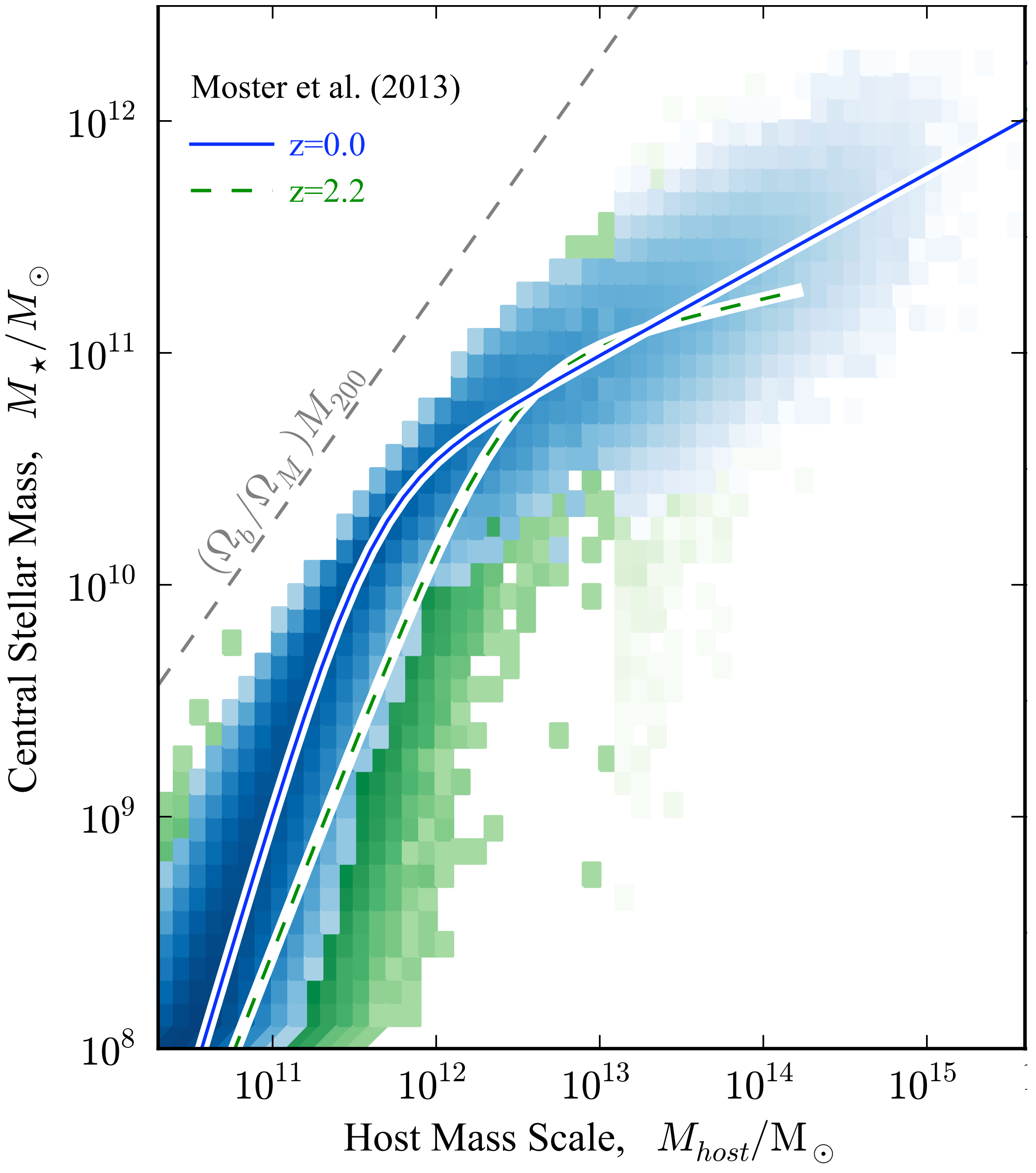
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Host Mass Scale, $M_{host}/\mathrm{M}_\odot$


Moster et al. (2013)
z=0.0
z=2.2
$(\Omega_b/\Omega_M)M_{200}$
Central Stellar Mass, $M_\star/M_\odot$
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
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10^{13}
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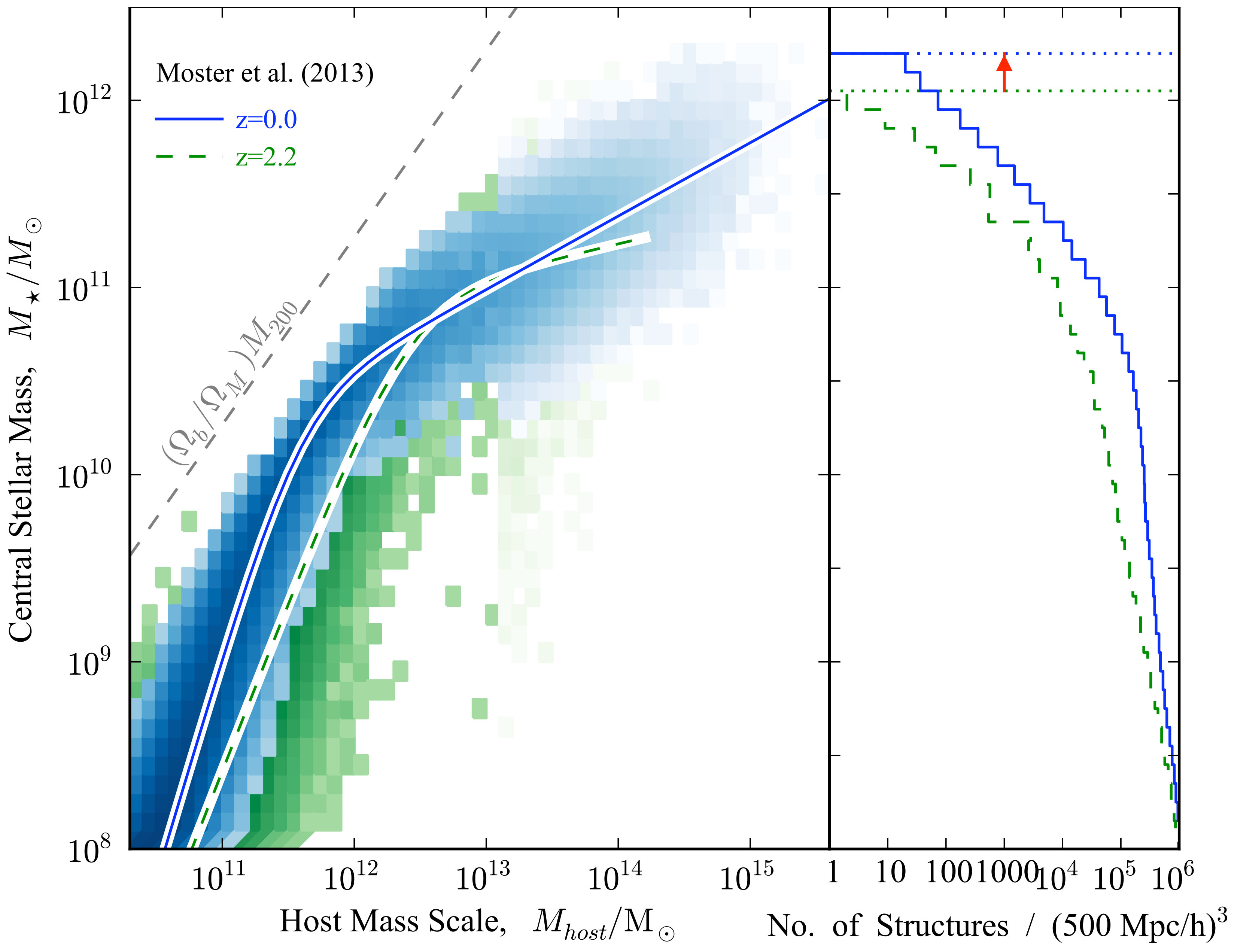
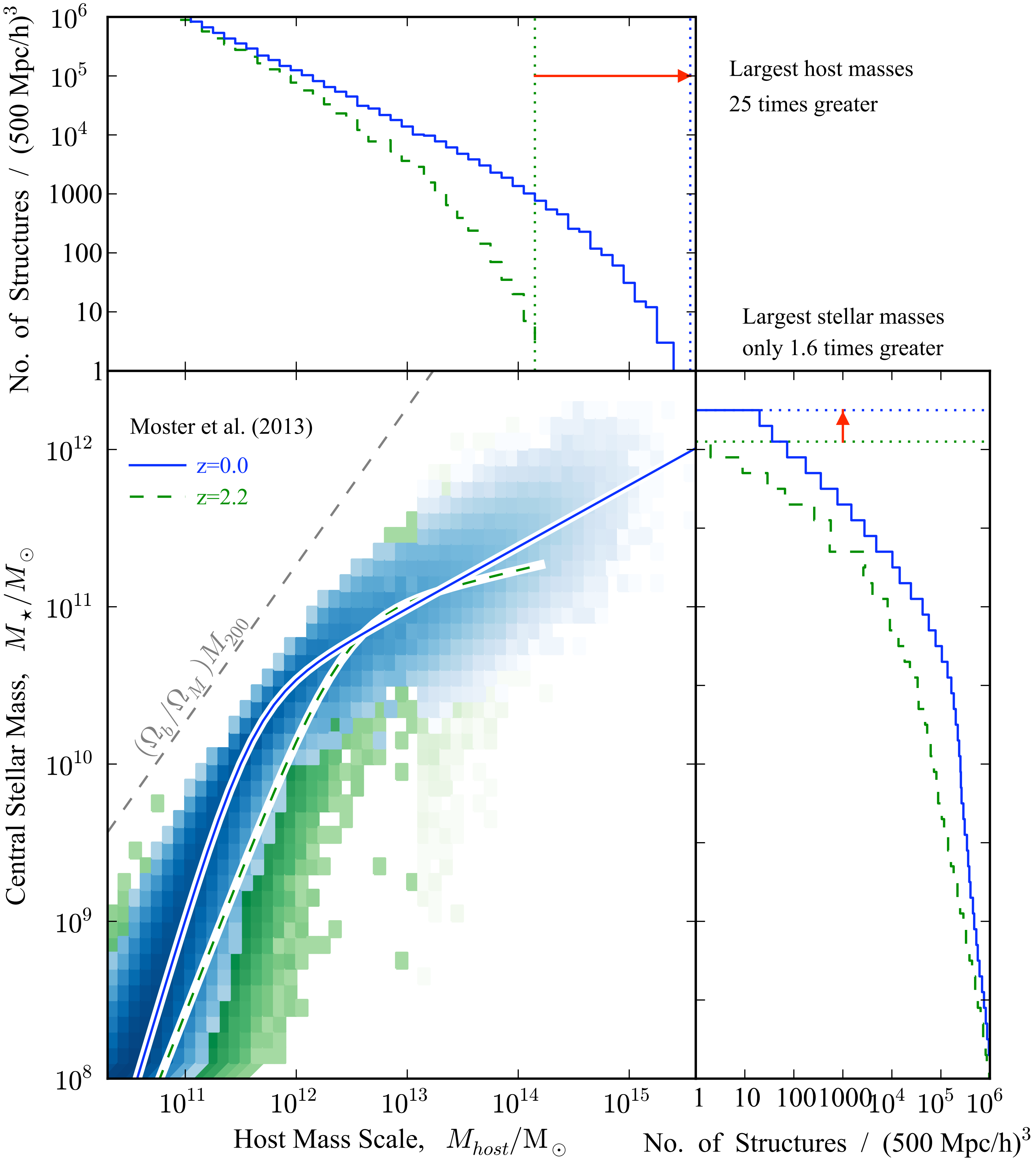

Moster et al. (2013)
z=0.0
z=2.2
$(\Omega_b/\Omega_M)M_{200}$
Central Stellar Mass, $M_\star/M_\odot$
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Host Mass Scale, $M_{host}/M_\odot$
1
10
100
1000
10^4
10^5
10^6
No. of Structures / $(500\ \mathrm{Mpc/h})^3$


Largest host masses
25 times greater
Largest stellar masses
only 1.6 times greater
No. of Structures / (500 Mpc/h)^3
10^6
10^5
10^4
1000
100
10
1
Moster et al. (2013)
z=0.0
z=2.2
$(\Omega_b/\Omega_M)M_{200}$
Central Stellar Mass, $M_\star/M_\odot$
10^{12}
10^{11}
10^{10}
10^9
10^8
10^{11}
10^{12}
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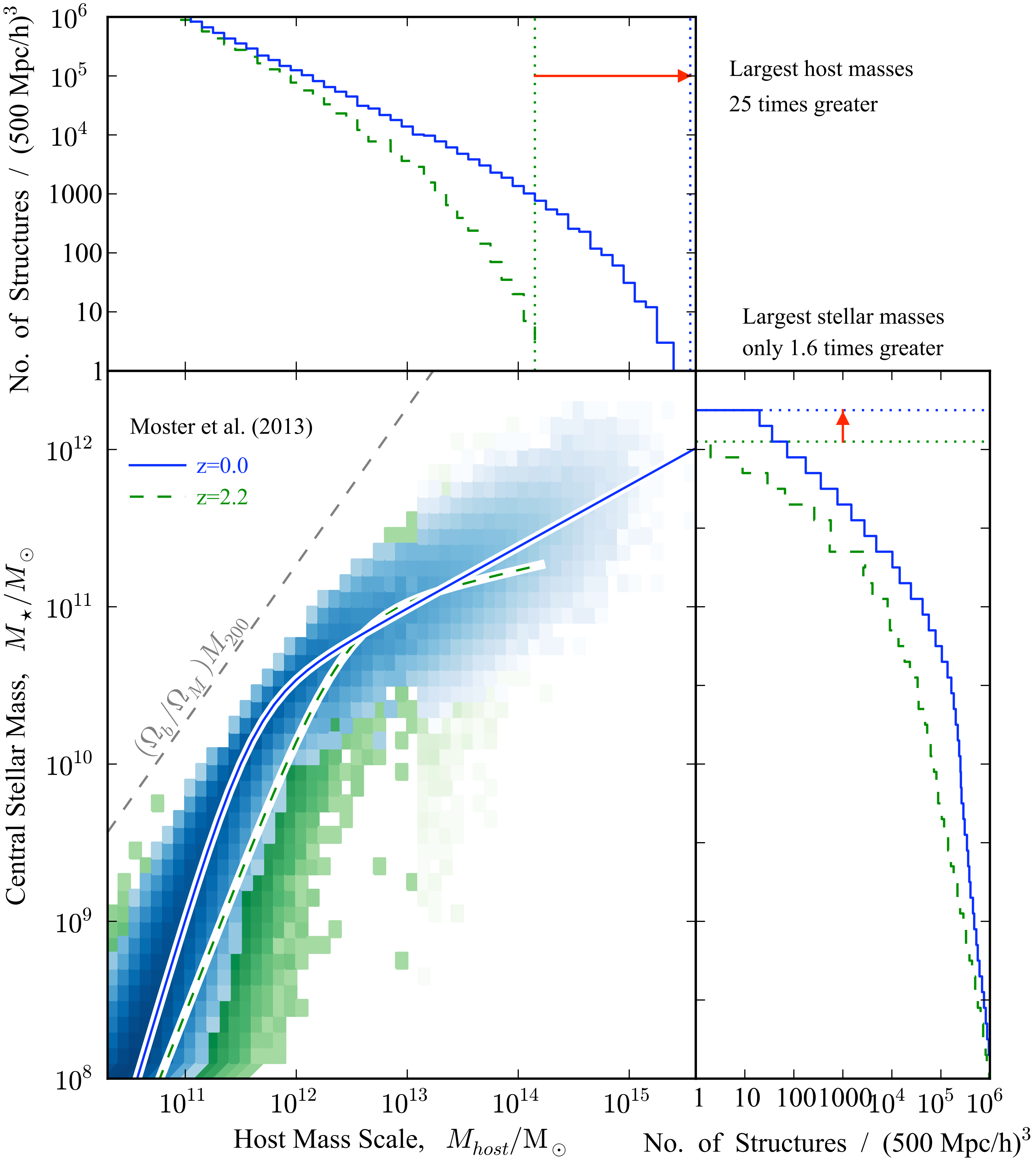
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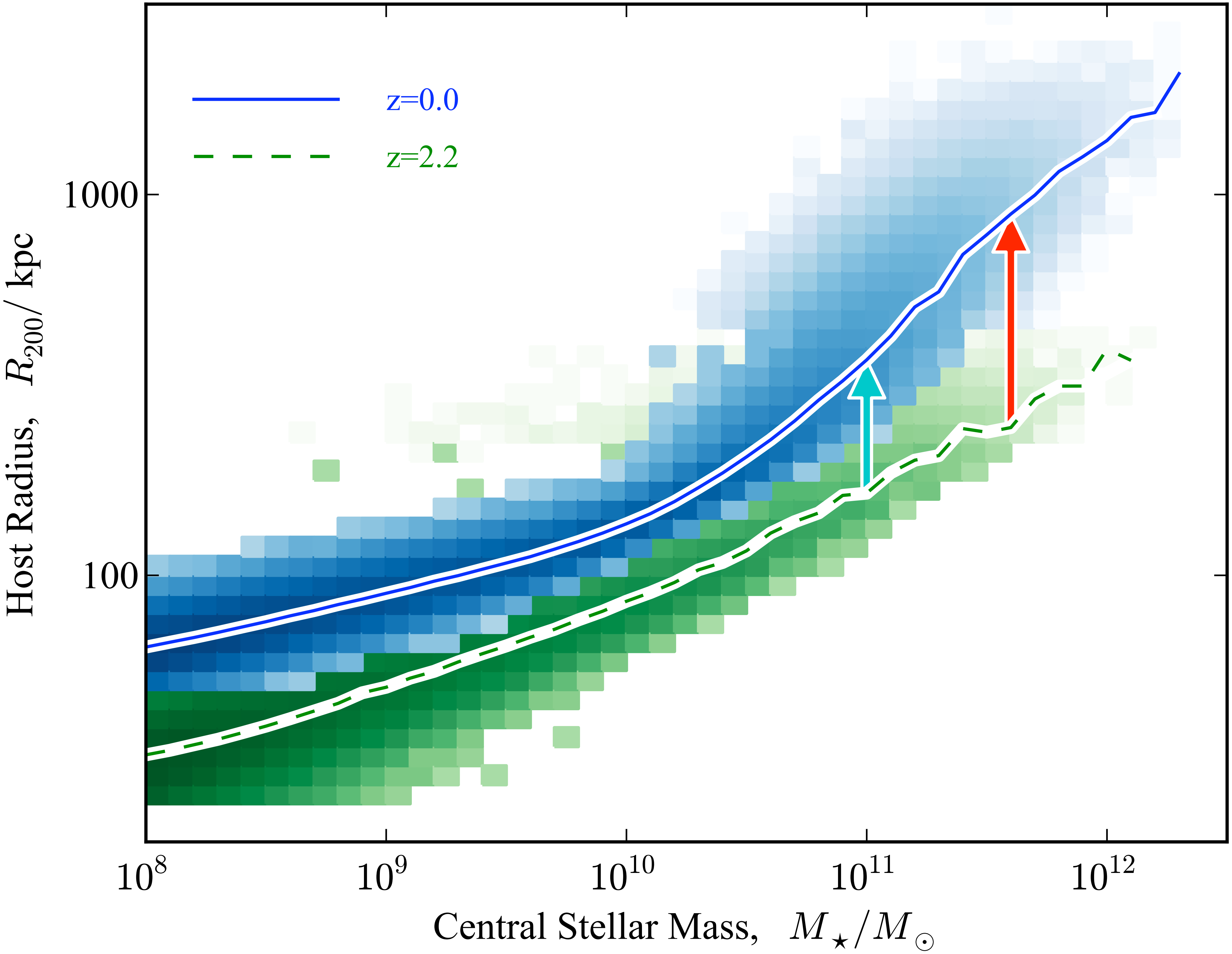
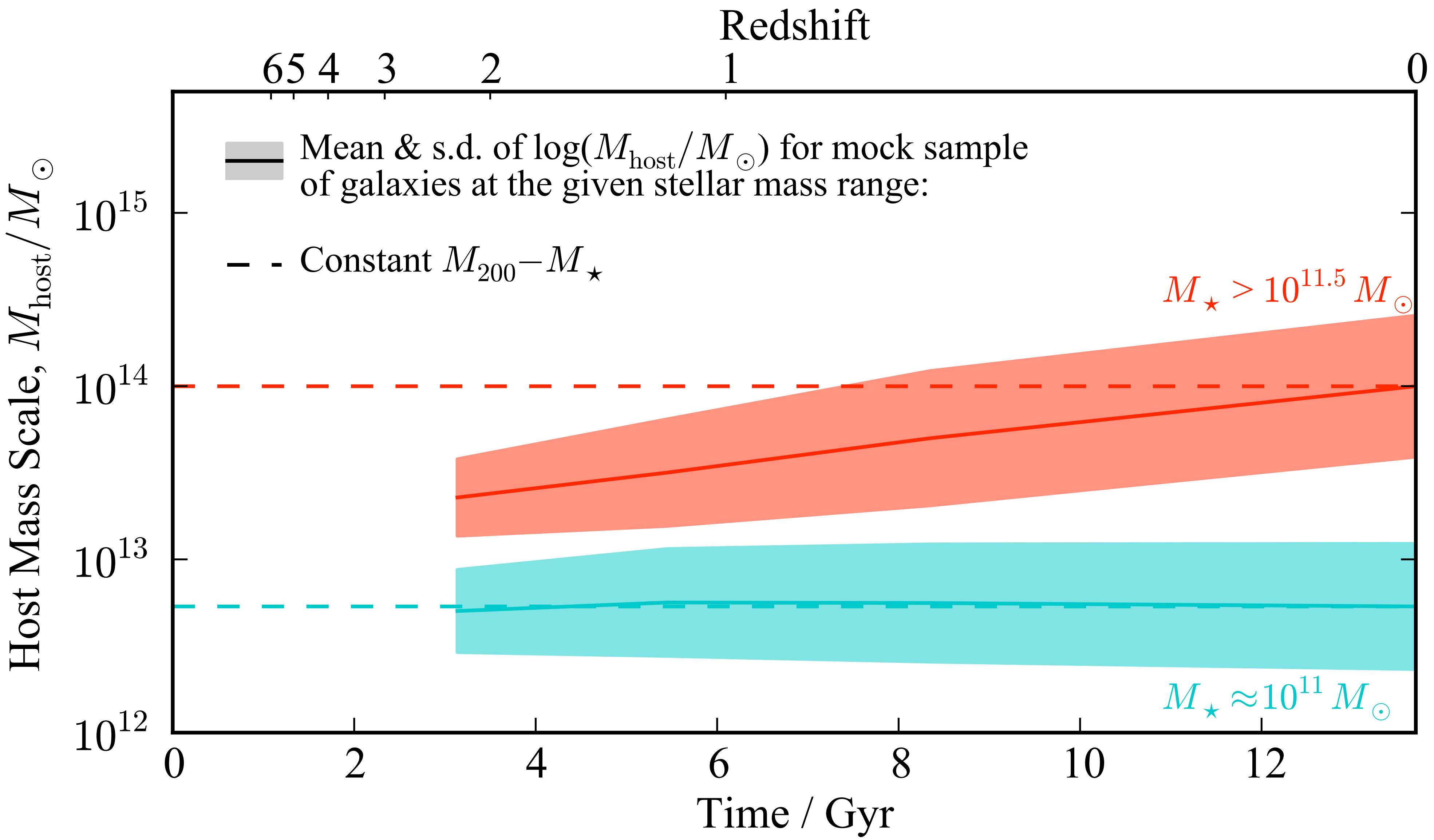
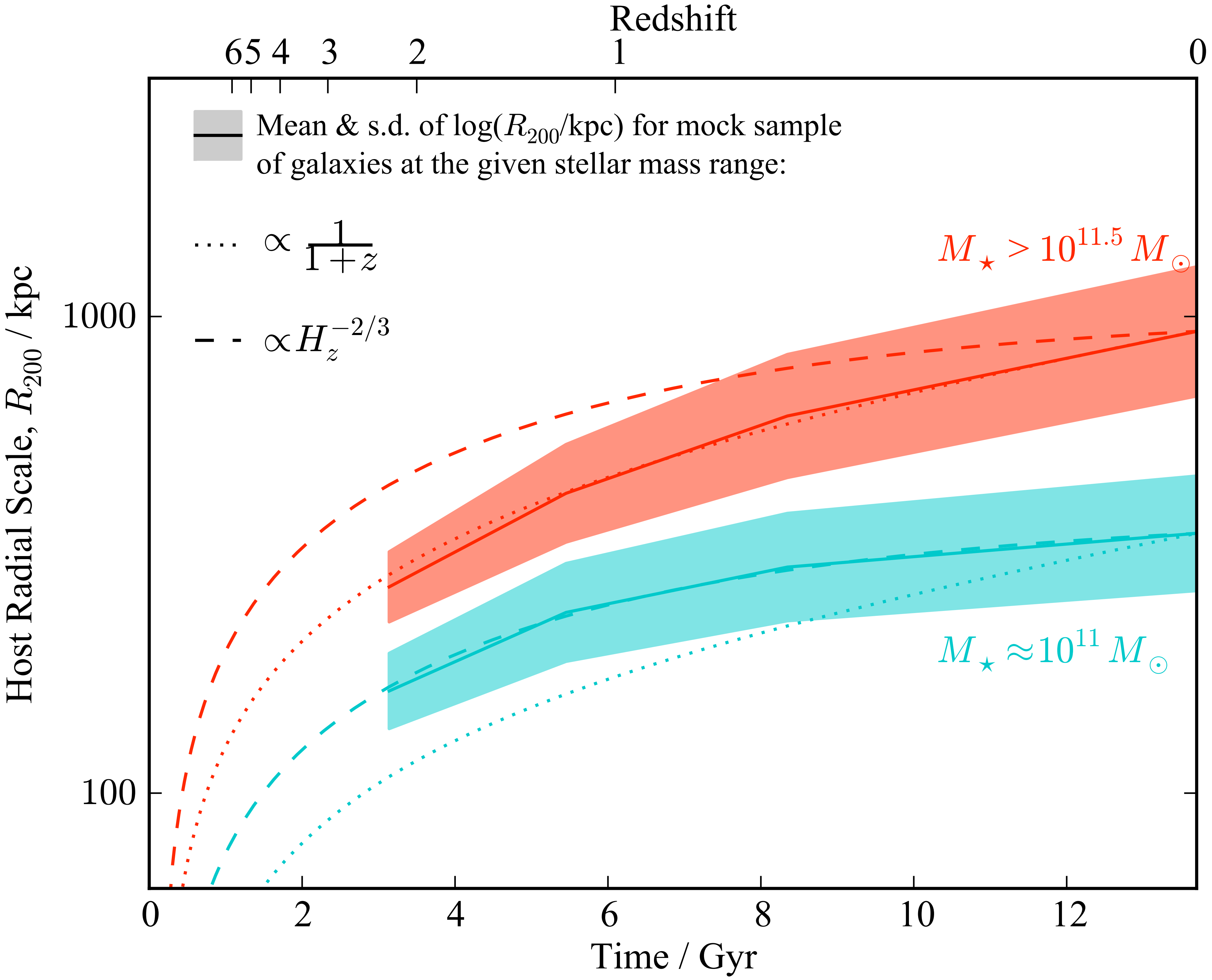


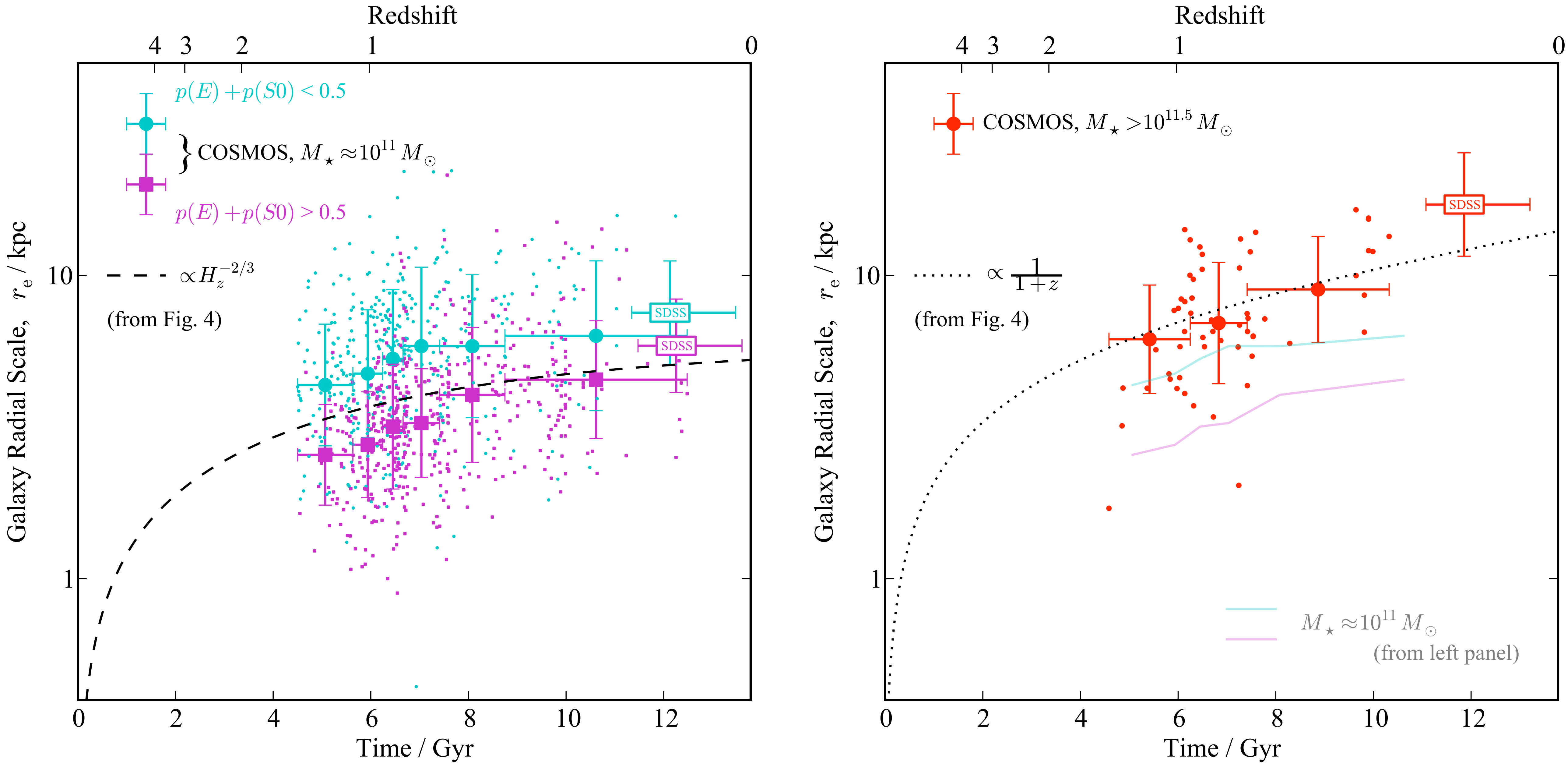
Martin Stringer l'Observatoire de Paris LERMA


Redshift
6
5
4
3
2
1
0
10^{15}
10^{14}
10^{13}
10^{12}
Host Mass Scale, $M_{\rm host}/M_\odot$
Mean & s.d. of $\log(M_{\rm host}/M_\odot)$ for mock sample
of galaxies at the given stellar mass range:
Constant M_{200}–$M_\star$
$M_\star > 10^{11.5}\,M_\odot$
$M_\star \approx 10^{11}\,M_\odot$
0
2
4
6
8
10
12
Time / Gyr



Martin Stringer

Observational Comparison



Martin Stringer

Complimentary perspectives on galaxy formation

Archeological

Evolutionary

Holistic...

“If the genome wants to swim in the ocean, it makes itself a fish;

if the genome wants to fly in the air, it makes itself a bird.

If it wants to go to Harvard, it makes itself a human”

George Wald (1906-1997)

From host structures to galaxies: Radii

From host structures to galaxies: Radii

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 195:4 (17pp), 2011 July doi:10.1088/0067-0049/195/1/4

THE OVERDENSITY AND MASSES OF THE FRIENDS-OF-FRIENDS HALOS AND UNIVERSALITY OF HALO MASS FUNCTION

SURHUD MORE[1], ANDREY V. KRAVTSOV[1,2,3], NEAL DALAL[4], AND STEFAN GOTTLÖBER[5]
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[2] Department of Astronomy & Astrophysics, The University of Chicago, Chicago, IL 60637, USA
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ABSTRACT

The friends-of-friends algorithm (hereafter FOF) is a percolation algorithm which is routinely used to identify dark matter halos from *N*-body simulations. We use results from percolation theory to show that the boundary of FOF halos does not correspond to a single density threshold but to a range of densities close to a critical value that depends upon the linking length parameter, b. We show that for the commonly used choice of $b = 0.2$, this critical density is equal to 81.62 times the mean matter density. Consequently, halos identified by the FOF algorithm enclose an average overdensity which depends on their density profile (concentration) and therefore changes with halo mass, contrary to the popular belief that the average overdensity is $\sim$180. We derive an analytical expression for the overdensity as a function of the linking length parameter b and the concentration of the halo. Results of tests carried out using simulated and actual FOF halos identified in cosmological simulations show excellent agreement with our analytical prediction. We also find that the mass of the halo that the FOF algorithm selects crucially depends upon mass resolution. We find a percolation-theory-motivated formula that is able to accurately correct for the dependence on number of particles for the mock realizations of spherical and triaxial Navarro–Frenk–White halos. However, we show that this correction breaks down when applied to the real cosmological FOF halos due to the presence of substructures. Given that abundance of substructure depends on redshift and cosmology, we expect that the resolution effects due to substructure on the FOF mass and halo mass function will also depend on redshift and cosmology and will be difficult to correct for in general. Finally, we discuss the implications of our results for the universality of the mass function.

Key words: cosmology: theory – dark matter – methods: numerical

Online-only material: color figures

From host structures to galaxies: Radii

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Xiv:1205.0253v1 [astro-ph.CO] 1 May 2012

The radius of baryonic collapse in disc galaxy formation

Susan A. Kassin,[1⋆†] Julien Devriendt,[2] S. Michael Fall,[3] Roelof S. de Jong,[4]
Brandon Allgood,[5,6] & Joel R. Primack[5]
[1] *Astrophysics Science Division, Goddard Space Flight Center, Code 665, Greenbelt, MD 20771, USA*
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3 May 2012

ABSTRACT
In the standard picture of disc galaxy formation, baryons and dark matter receive the same tidal torques, and therefore approximately the same initial specific angular momentum. However, observations indicate that disc galaxies typically have only about half as much specific angular momentum as their dark matter haloes. We argue this does not necessarily imply that baryons lose this much specific angular momentum as they form galaxies. It may instead indicate that galaxies are most directly related to the inner regions of their host haloes, as may be expected in a scenario where baryons in the inner parts of haloes collapse first. A limiting case is examined under the idealised assumption of perfect angular momentum conservation. Namely, we determine the density contrast Δ, with respect to the critical density of the Universe, by which dark matter haloes need to be defined in order to have the same average specific angular momentum as the galaxies they host. Under the assumption that galaxies are related to haloes via their characteristic rotation velocities, the necessary Δ is ~ 600. This Δ corresponds to an average halo radius and mass which are $\sim 60\%$ and $\sim 75\%$, respectively, of the virial values (i.e., for $\Delta = 200$). We refer to this radius as the radius of baryonic collapse R_{BC}, since if specific angular momentum is conserved perfectly, baryons would come from within it. It is not likely a simple step function due to the complex gastrophysics involved, therefore we regard it as an effective radius. In summary, the difference between the predicted initial and the observed final specific angular momentum of galaxies, which is conventionally attributed solely to angular momentum loss, can more naturally be explained by a preference for collapse of baryons within R_{BC}, with possibly some later angular momentum transfer.

Key words: galaxies – formation, galaxies – evolution, galaxies – kinematics and dynamics, galaxies – fundamental properties.

From host structures to galaxies: Radii

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THE SIZE-VIRIAL RADIUS RELATION OF GALAXIES

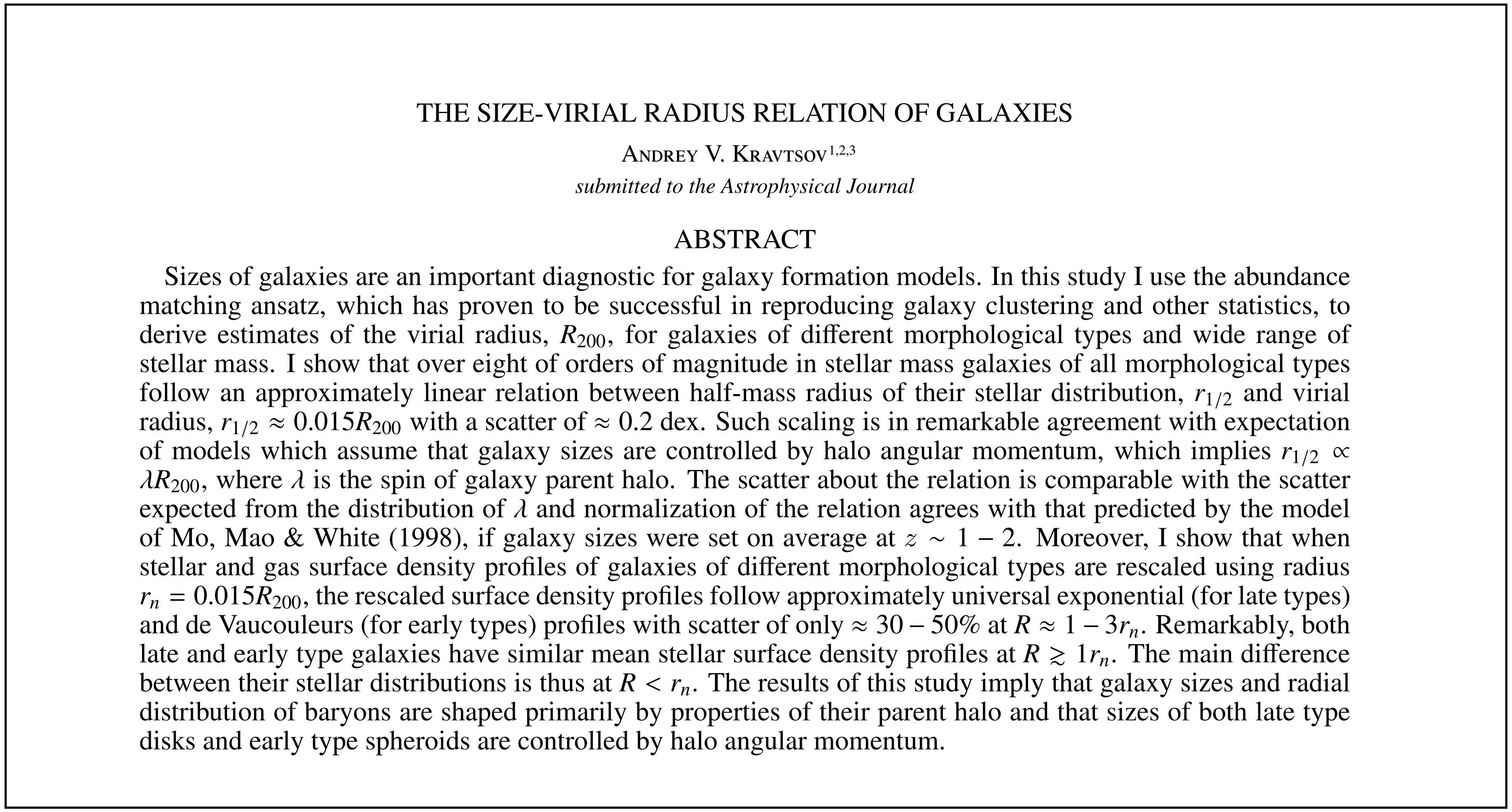
ANDREY V. KRAVTSOV[1,2,3]

submitted to the Astrophysical Journal

ABSTRACT

Sizes of galaxies are an important diagnostic for galaxy formation models. In this study I use the abundance matching ansatz, which has proven to be successful in reproducing galaxy clustering and other statistics, to derive estimates of the virial radius, R_{200}, for galaxies of different morphological types and wide range of stellar mass. I show that over eight of orders of magnitude in stellar mass galaxies of all morphological types follow an approximately linear relation between half-mass radius of their stellar distribution, $r_{1/2}$ and virial radius, $r_{1/2} \approx 0.015R_{200}$ with a scatter of ≈ 0.2 dex. Such scaling is in remarkable agreement with expectation of models which assume that galaxy sizes are controlled by halo angular momentum, which implies $r_{1/2} \propto \lambda R_{200}$, where λ is the spin of galaxy parent halo. The scatter about the relation is comparable with the scatter expected from the distribution of λ and normalization of the relation agrees with that predicted by the model of Mo, Mao & White (1998), if galaxy sizes were set on average at $z \sim 1-2$. Moreover, I show that when stellar and gas surface density profiles of galaxies of different morphological types are rescaled using radius $r_n = 0.015R_{200}$, the rescaled surface density profiles follow approximately universal exponential (for late types) and de Vaucouleurs (for early types) profiles with scatter of only $\approx 30-50\%$ at $R \approx 1-3r_n$. Remarkably, both late and early type galaxies have similar mean stellar surface density profiles at $R \gtrsim 1r_n$. The main difference between their stellar distributions is thus at $R < r_n$. The results of this study imply that galaxy sizes and radial distribution of baryons are shaped primarily by properties of their parent halo and that sizes of both late type disks and early type spheroids are controlled by halo angular momentum.

From host structures to galaxies: Radii



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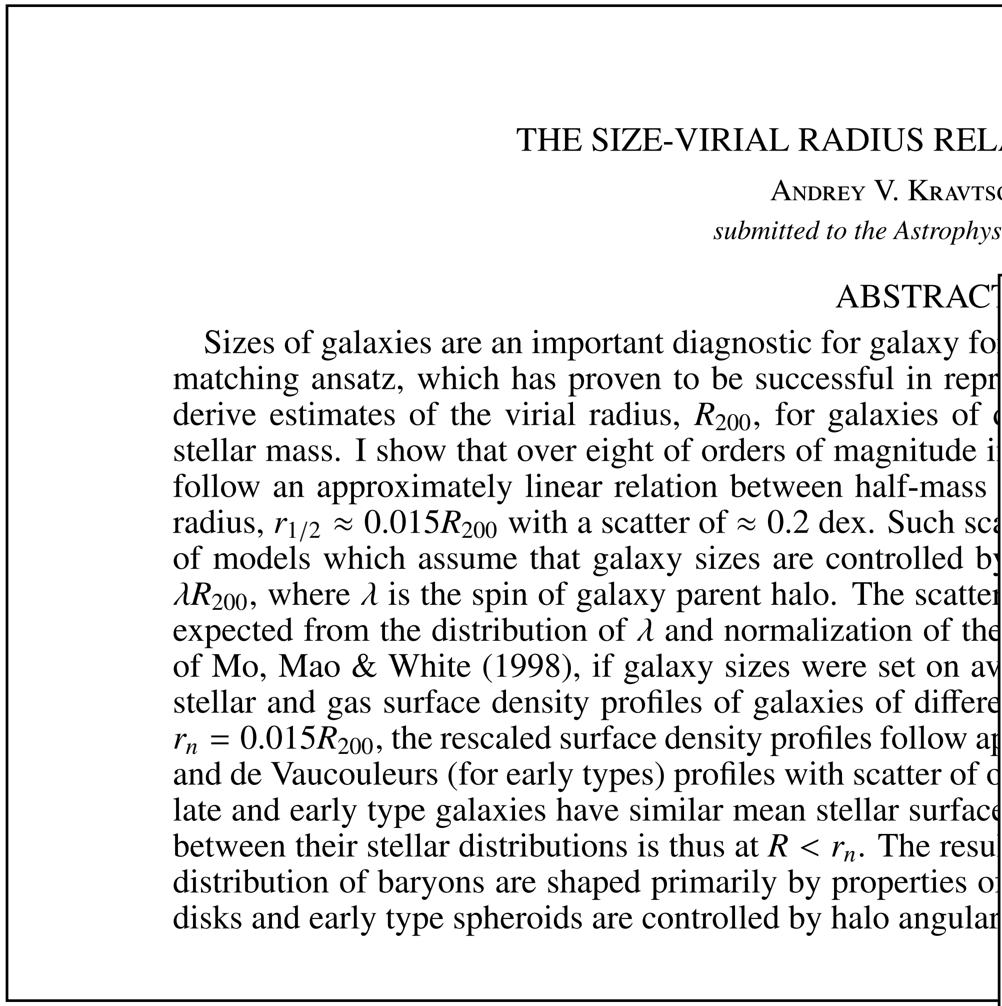

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