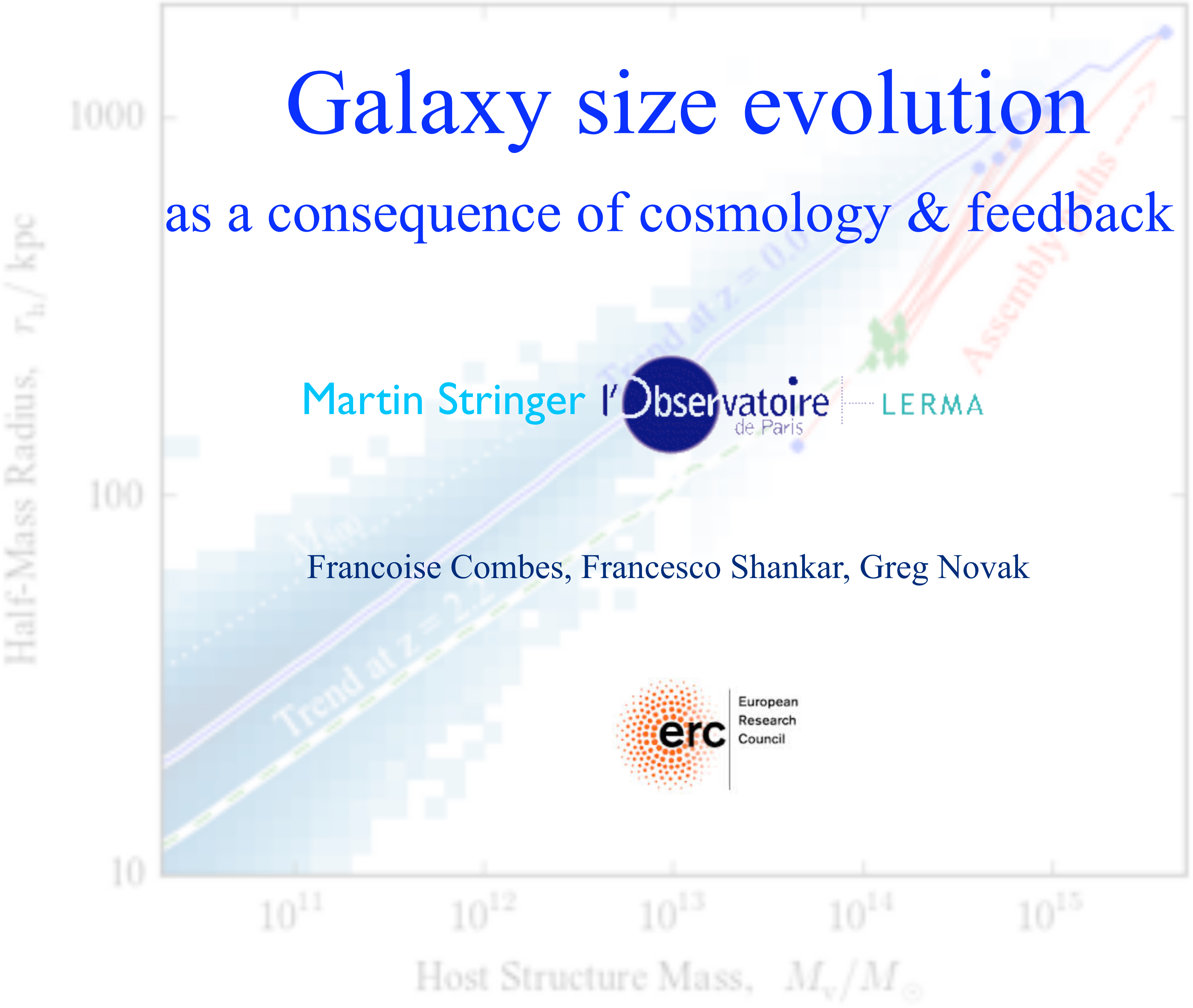

Galaxy size evolution

as a consequence of cosmology & feedback

Martin Stringer l'Observatoire de Paris LERMA

Francoise Combes, Francesco Shankar, Greg Novak

erc European Research Council

Complimentary perspectives on galaxy formation

Complimentary perspectives on galaxy formation

Archeological

Complimentary perspectives on galaxy formation

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Holistic...

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"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)

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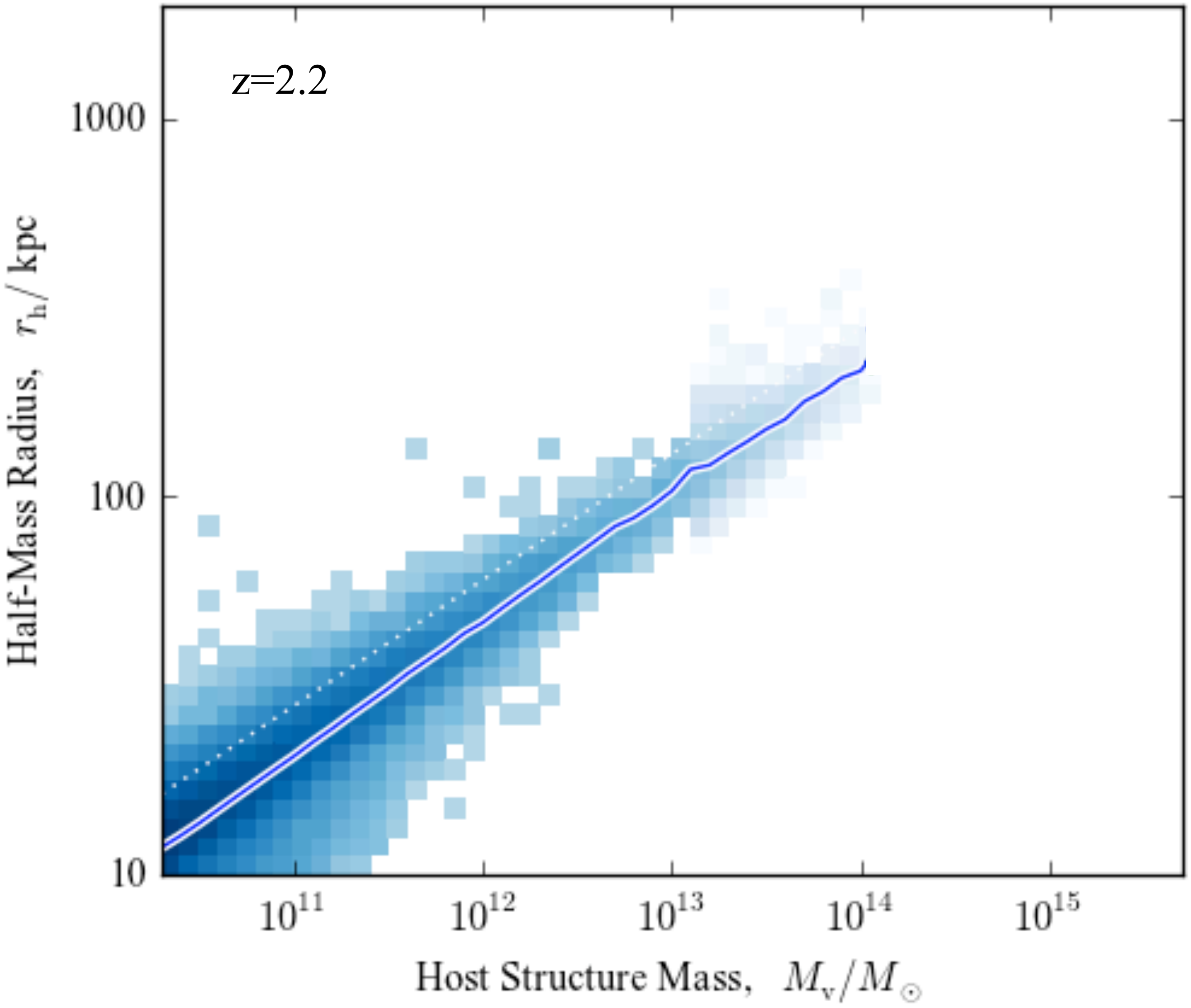
Sizes of cosmic structures



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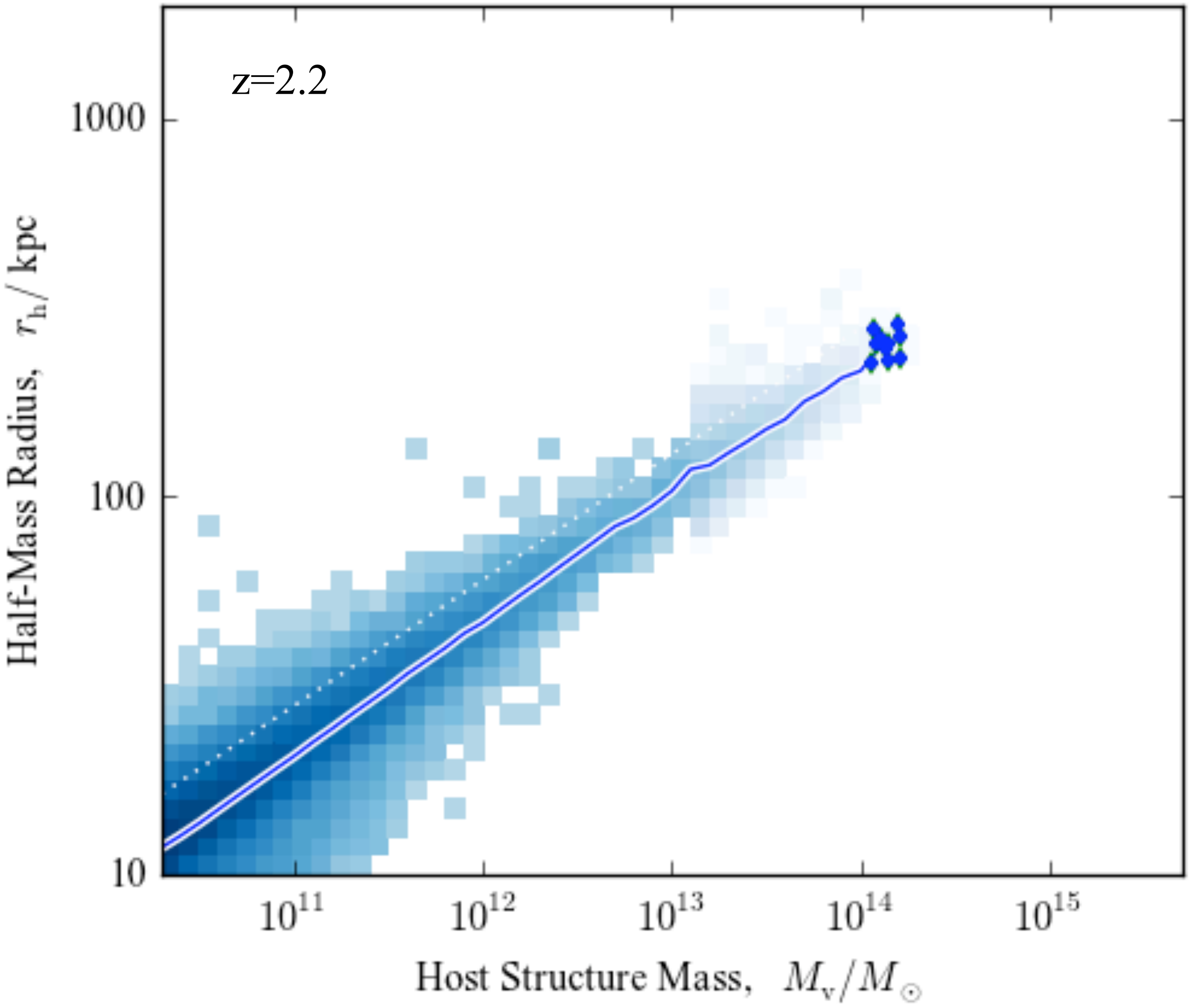

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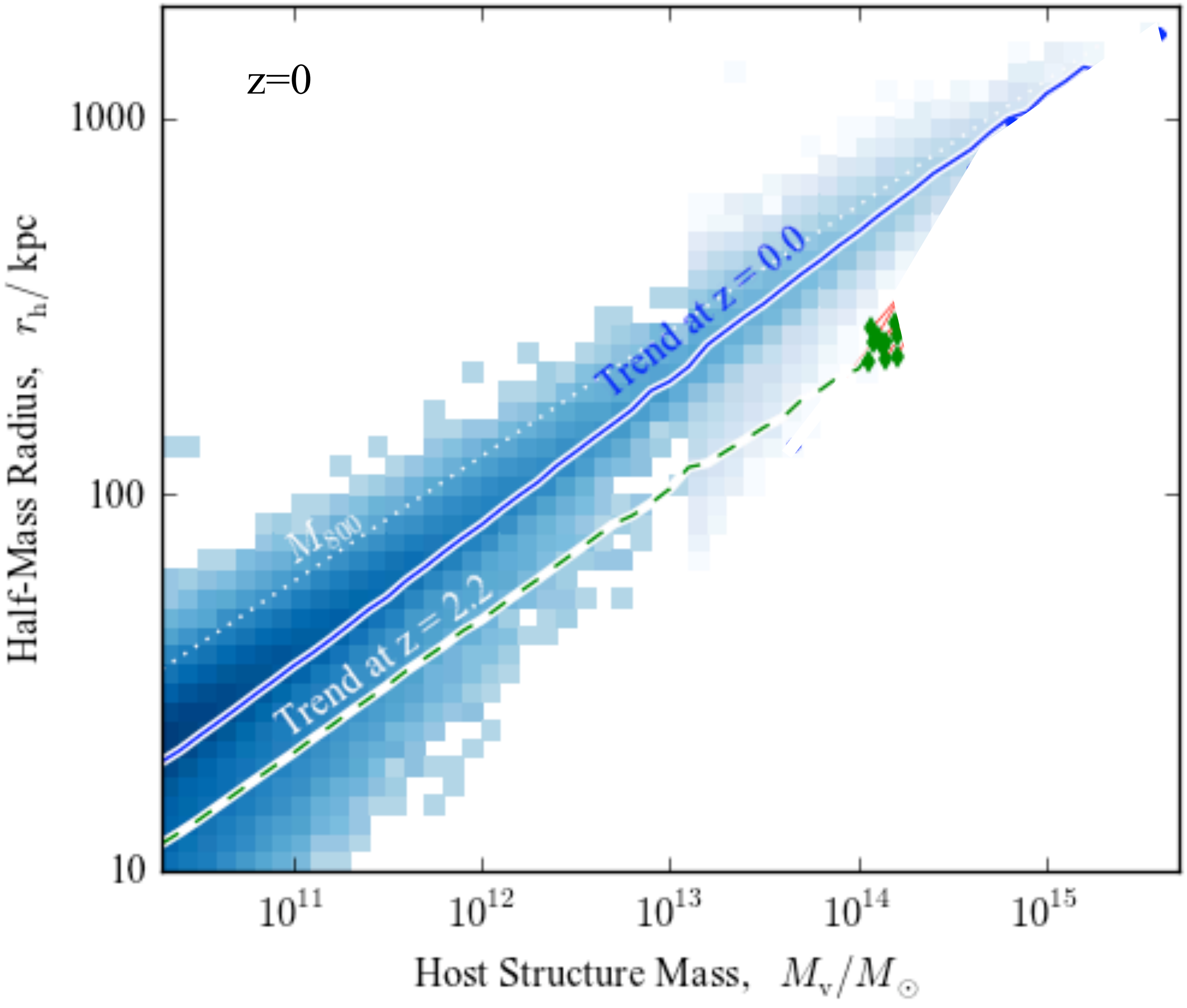

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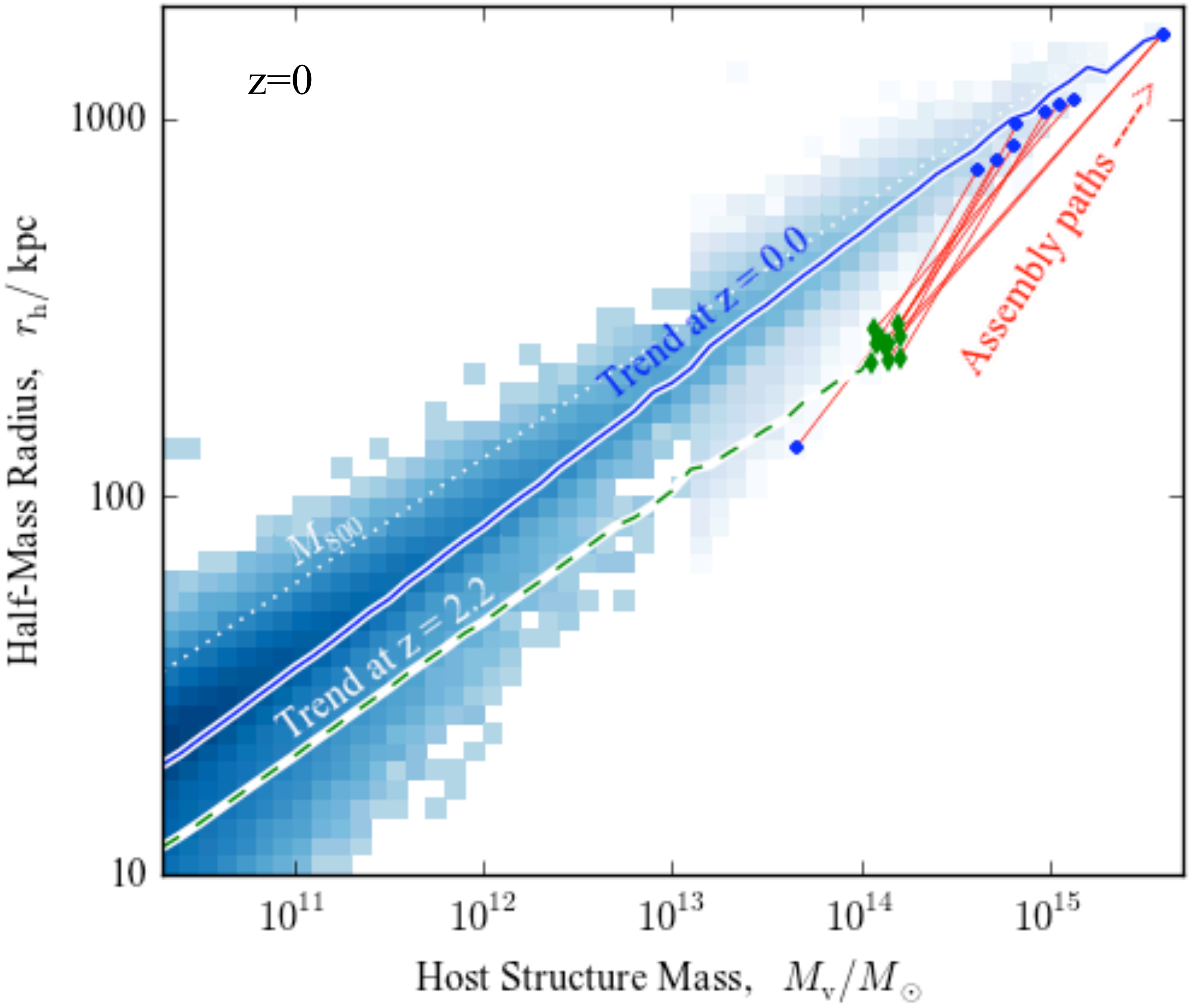


Martin Stringer l'Observatoire de Paris LERMA

Aside: Preservation of mass order?

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

Aside: Preservation of mass order?

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

Aside: Preservation of mass order?

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

Aside: Preservation of mass order?

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

Aside: Preservation of mass order?

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	

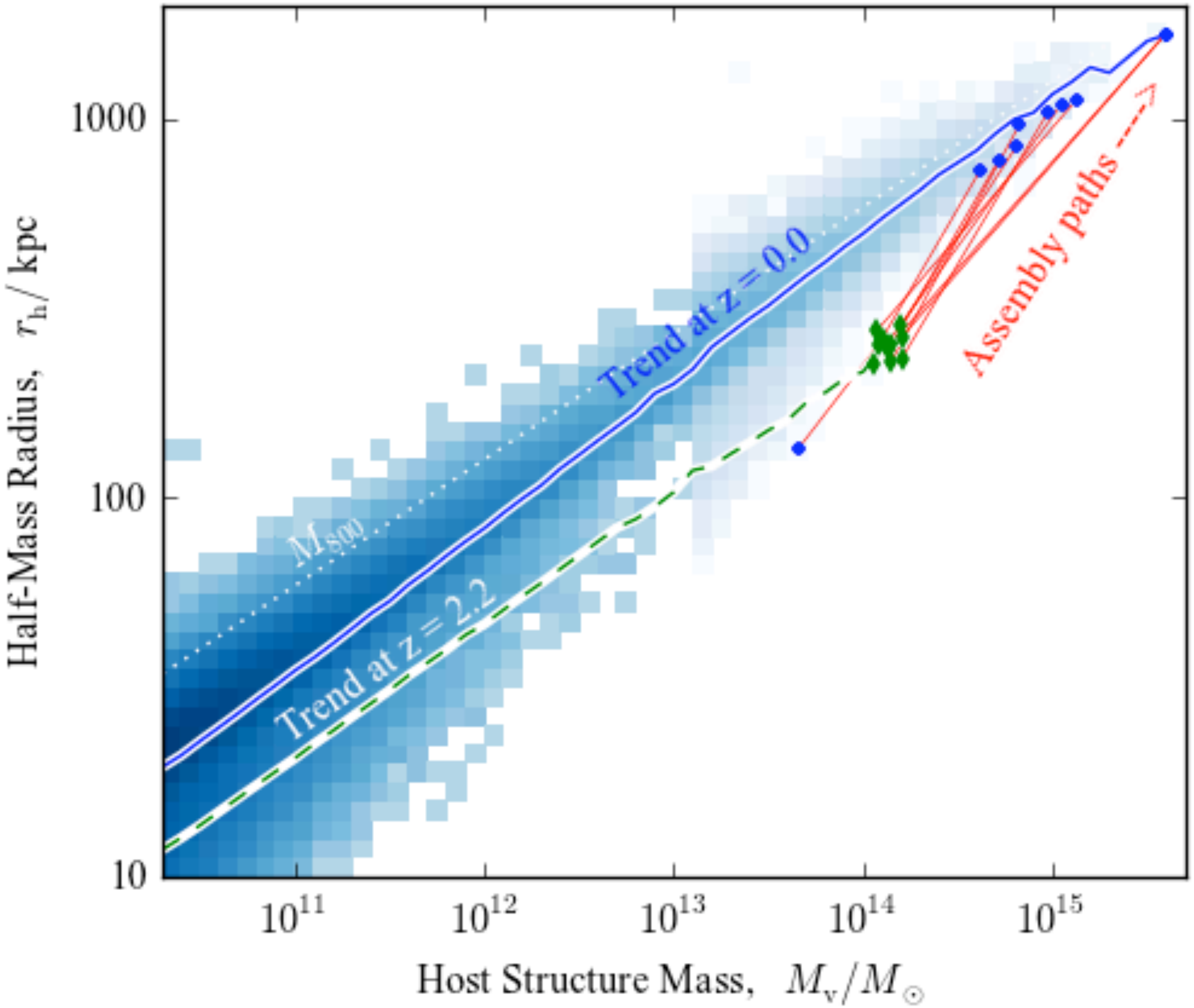
Aside: Preservation of mass order?

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	

Aside: Preservation of mass order?

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



Martin Stringer l'Observatoire de Paris LERMA

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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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*
[2] *Sub-Department of Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK*
[3] *Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*
[4] *Astrophysikalisches Institut Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany*
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[6] *currently at: Numerate Inc., 1150 Bayhill Drive, San Bruno, CA 94066, USA*

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

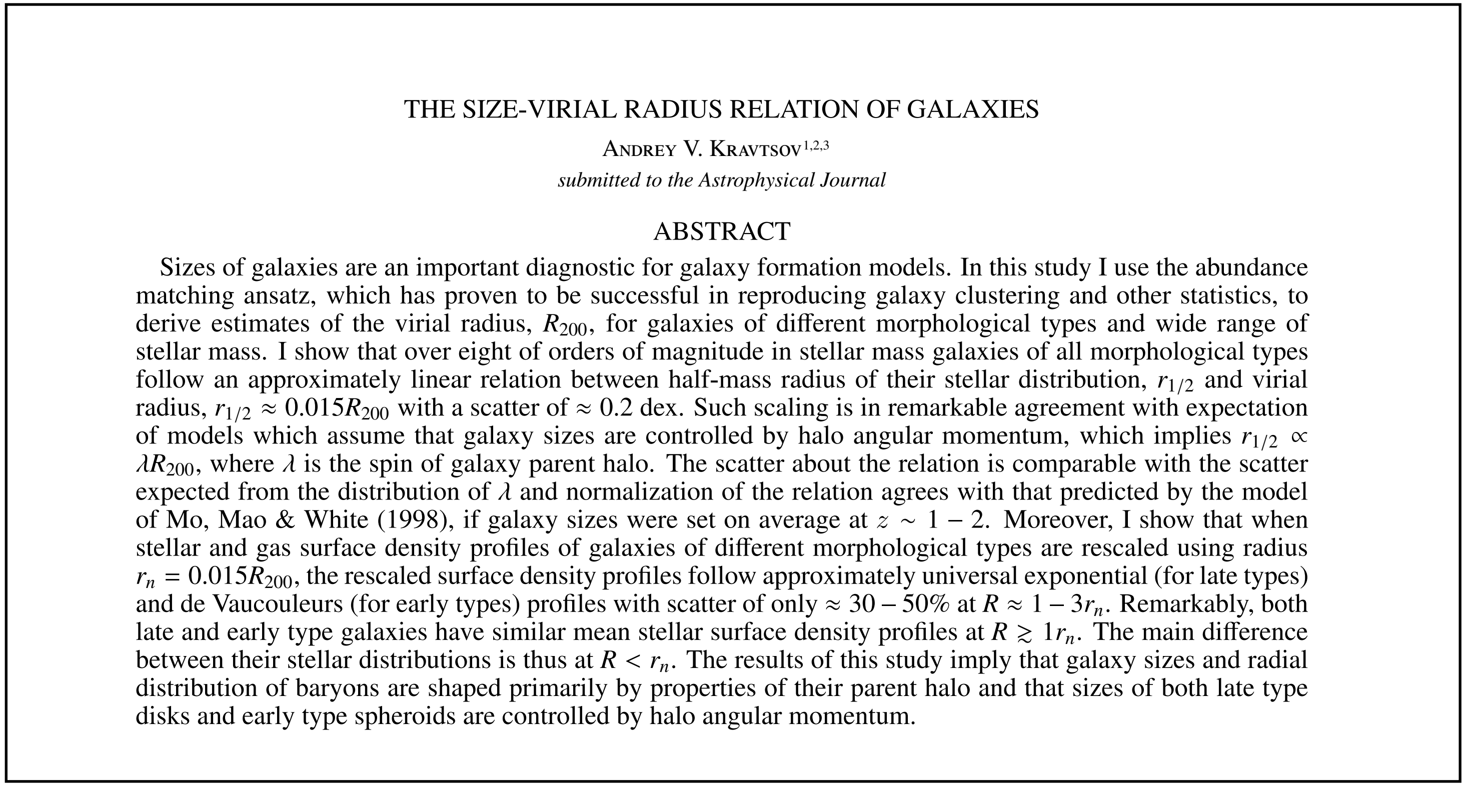
Andrey V. Kravtsov[1,2,3]

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, $r_{1/2} \approx 0.015 R_{200}$ 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 $r_n = 0.015 R_{200}$, 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 $R \approx 1-3 r_n$. Remarkably, both late and early type galaxies have similar mean stellar surface density profiles at $R \gtrsim 1 r_n$. 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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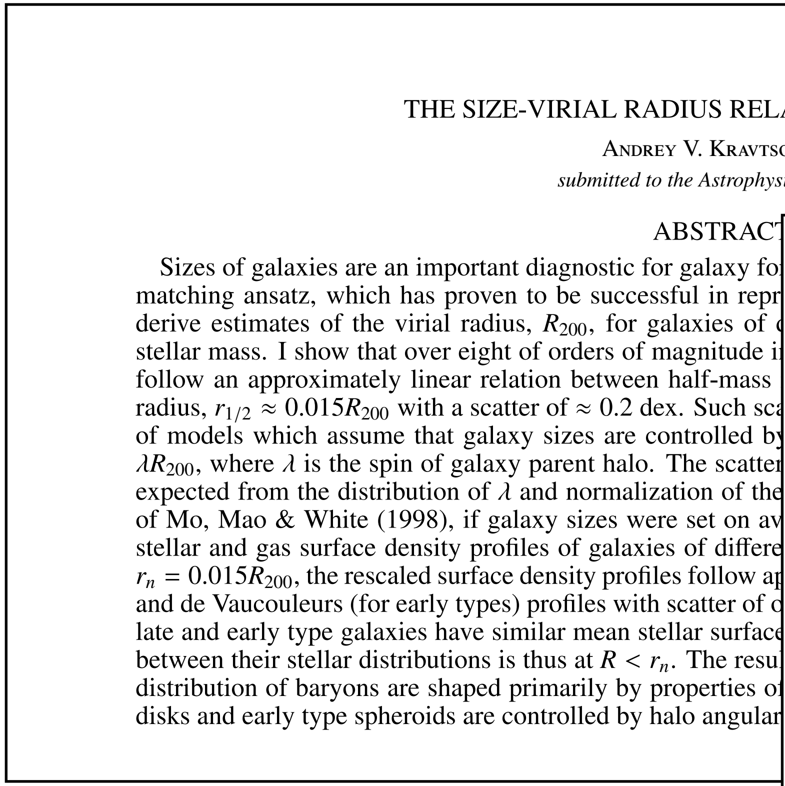

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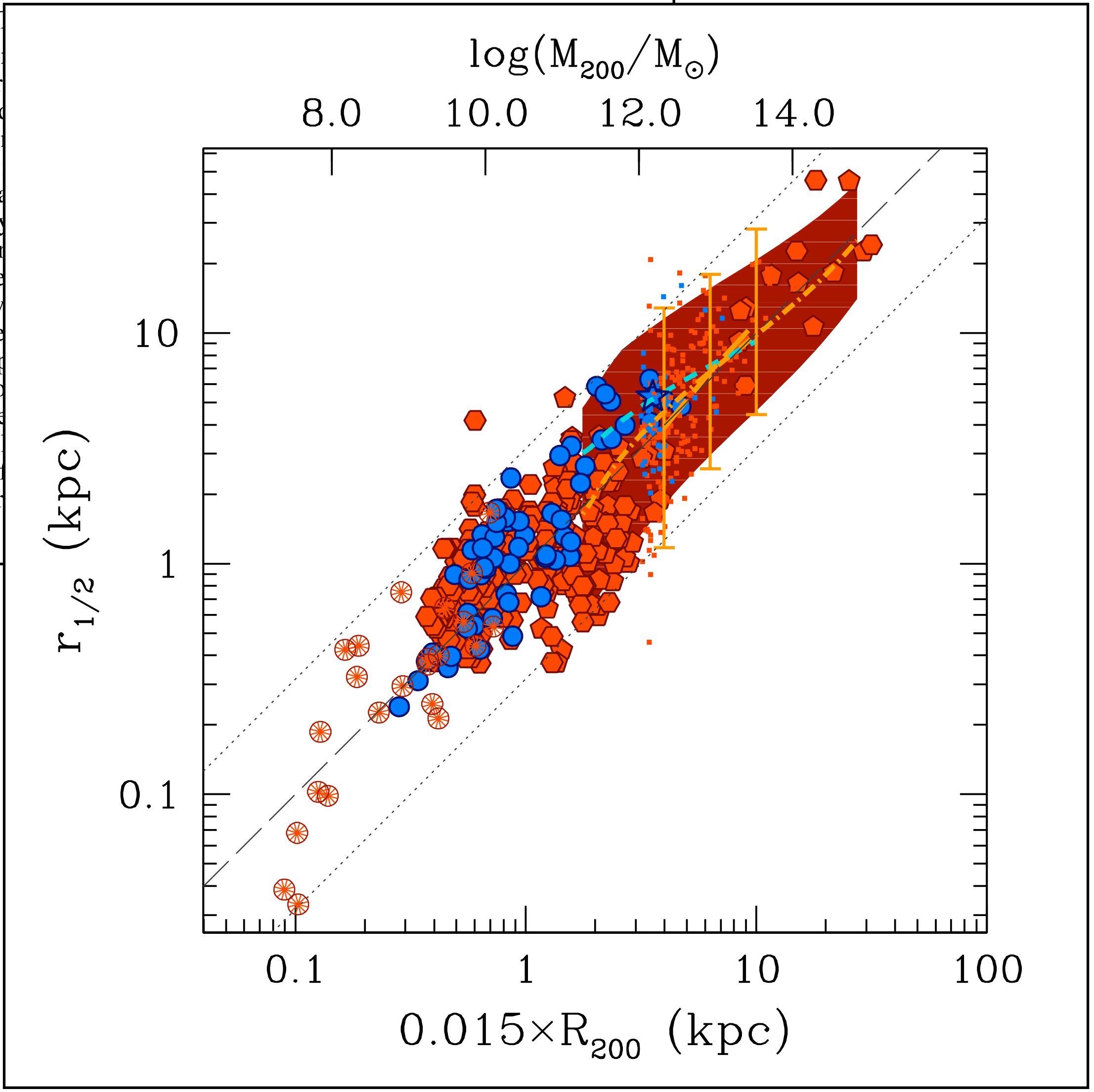

From host structures to galaxies: Stellar Mass

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Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **428,** 3121–3138 (2013) doi:10.1093/mnras/sts261

Galactic star formation and accretion histories from matching galaxies to dark matter haloes

Benjamin P. Moster,* Thorsten Naab and Simon D. M. White
Max-Planck Institut für Astrophysik, Karl-Schwarzschild Straße 1, D-85748 Garching, Germany

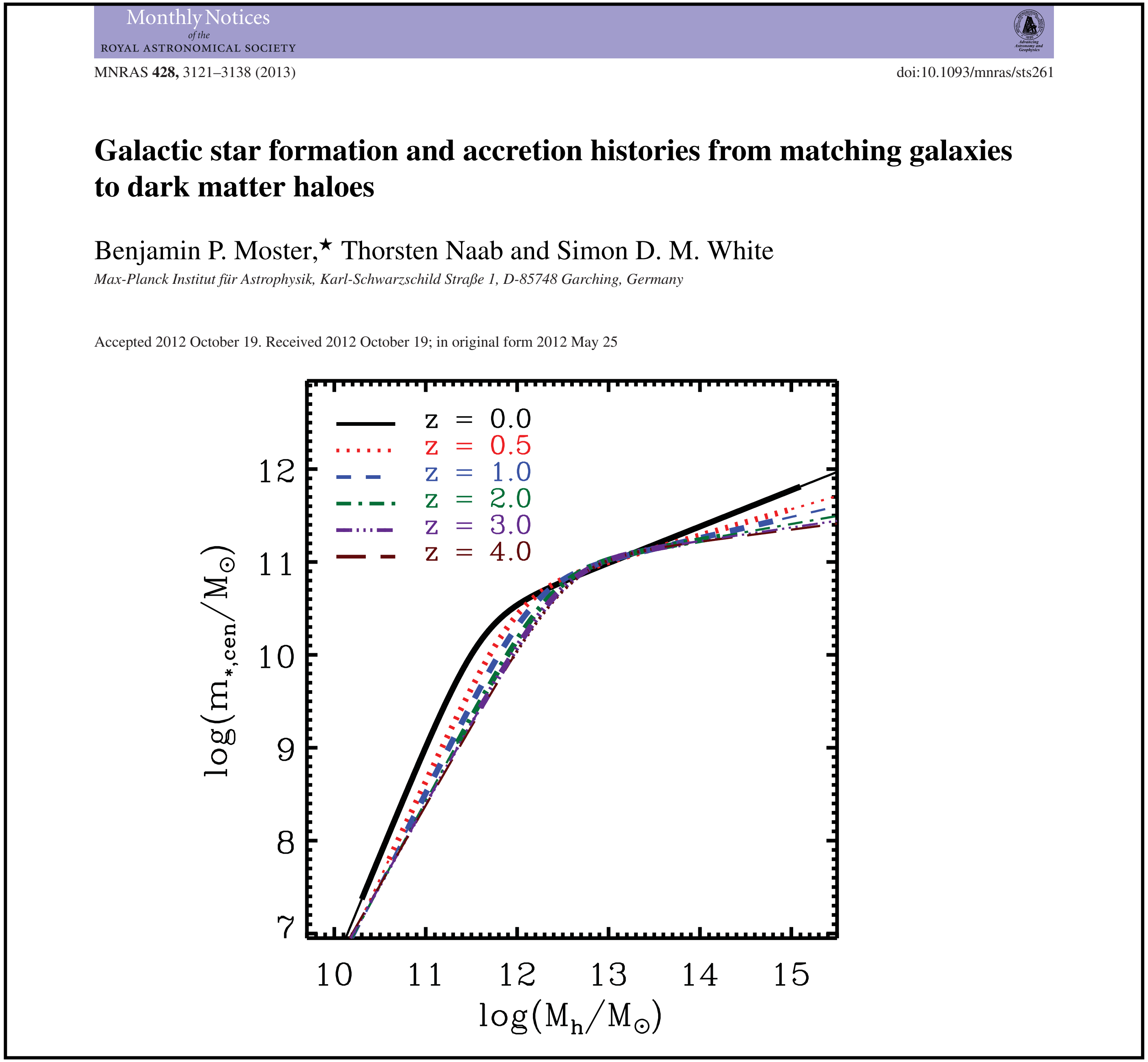
Accepted 2012 October 19. Received 2012 October 19; in original form 2012 May 25

ABSTRACT

We present a new statistical method to determine the relationship between the stellar masses of galaxies and the masses of their host dark matter haloes over the entire cosmic history from $z \sim 4$ to the present. This multi-epoch abundance matching (MEAM) model self-consistently takes into account that satellite galaxies first become satellites at times earlier than they are observed. We employ a redshift-dependent parametrization of the stellar-to-halo-mass relation to populate haloes and subhaloes in the Millennium simulations with galaxies, requiring that the observed stellar mass functions at several redshifts are reproduced simultaneously. We show that physically meaningful growth of massive galaxies is consistent with these data only if observational mass errors are taken into account. Using merger trees extracted from the dark matter simulations in combination with MEAM, we predict the average assembly histories of galaxies, separating into star formation within the galaxies (in situ) and accretion of stars (ex situ). Our main results are the peak star formation efficiency decreases with redshift from 23 per cent at $z = 0$ to 9 per cent at $z = 4$ while the corresponding halo mass increases from $10^{11.8}$ to $10^{12.5}$ $\mathrm{M}_{\odot}$. The star formation rate of central galaxies peaks at a redshift which depends on halo mass; for massive haloes this peak is at early cosmic times while for low-mass galaxies the peak has not been reached yet. In haloes similar to that of the Milky Way about half of the central stellar mass is assembled after $z = 0.7$. In low-mass haloes, the accretion of satellites contributes little to the assembly of their central galaxies, while in massive haloes more than half of the central stellar mass is formed ex situ with significant accretion of satellites at $z < 2$. We find that our method implies a cosmic star formation history and an evolution of specific star formation rates which are consistent with those inferred directly. We present convenient fitting functions for stellar masses, star formation rates and accretion rates as functions of halo mass and redshift.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: statistics – galaxies: stellar content – cosmology: theory – dark matter.

From host structures to galaxies: Stellar Mass



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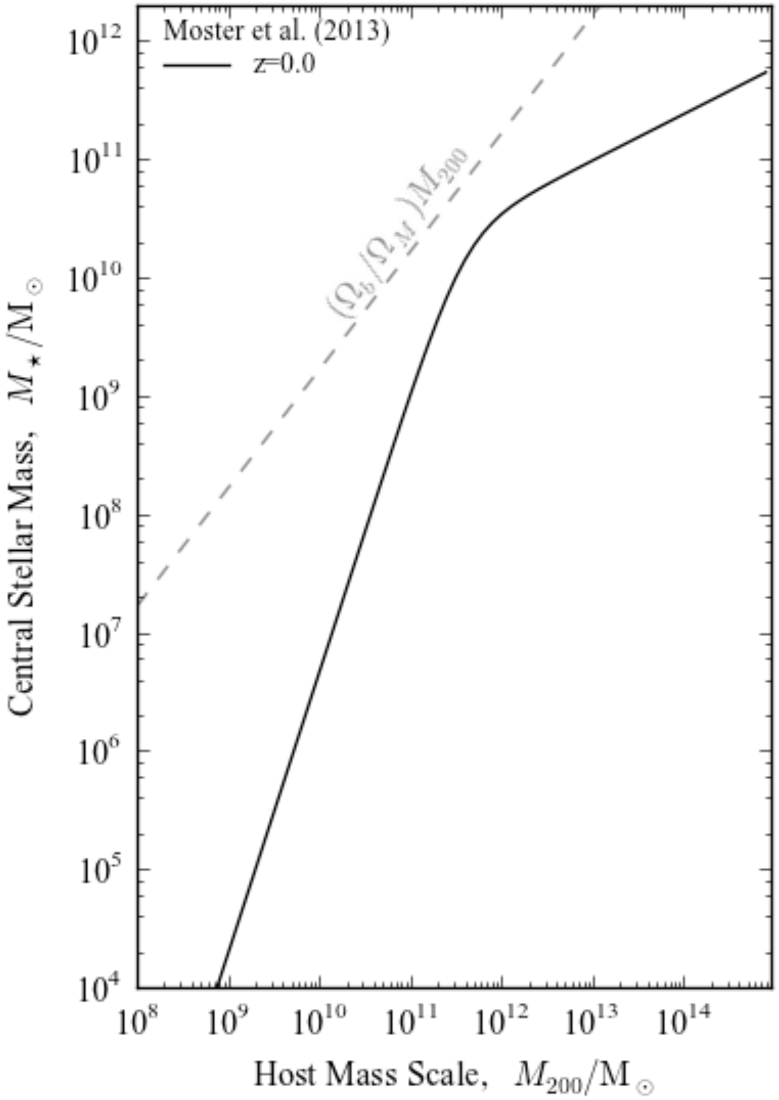

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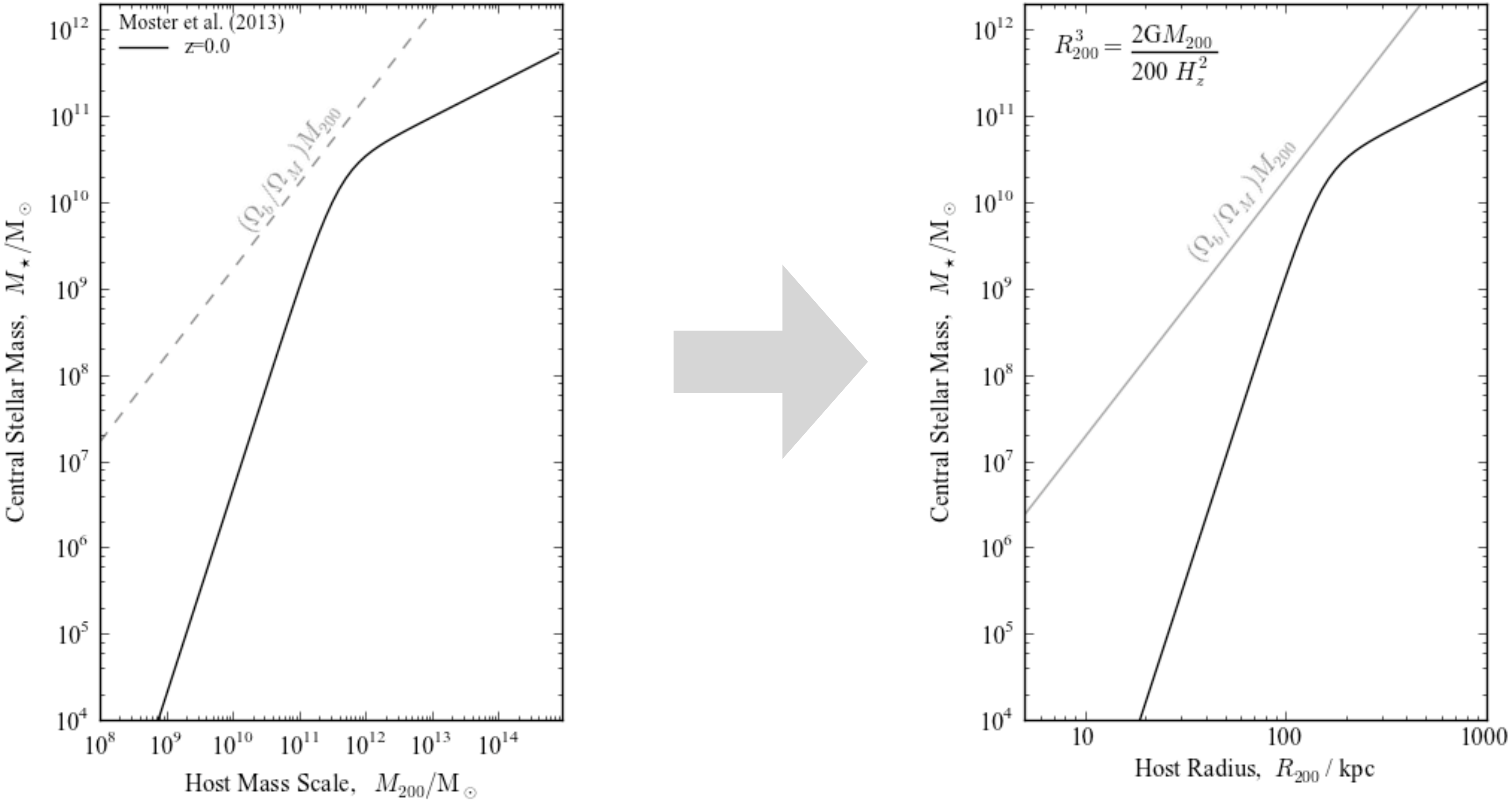

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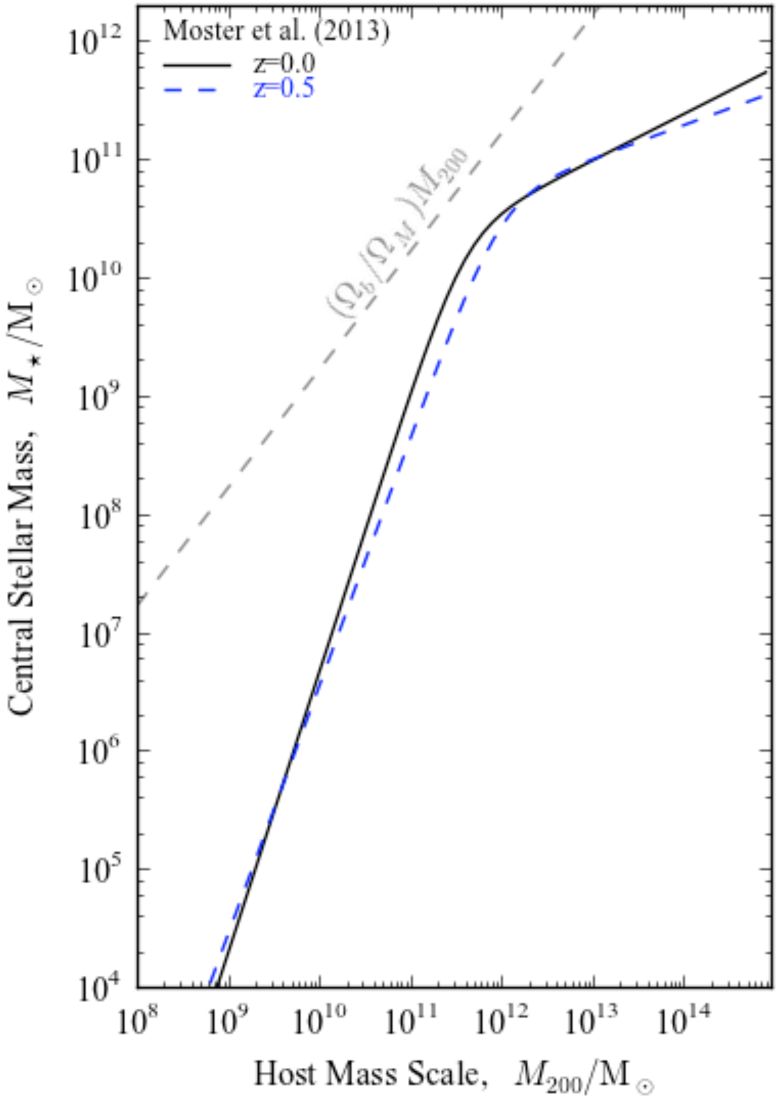

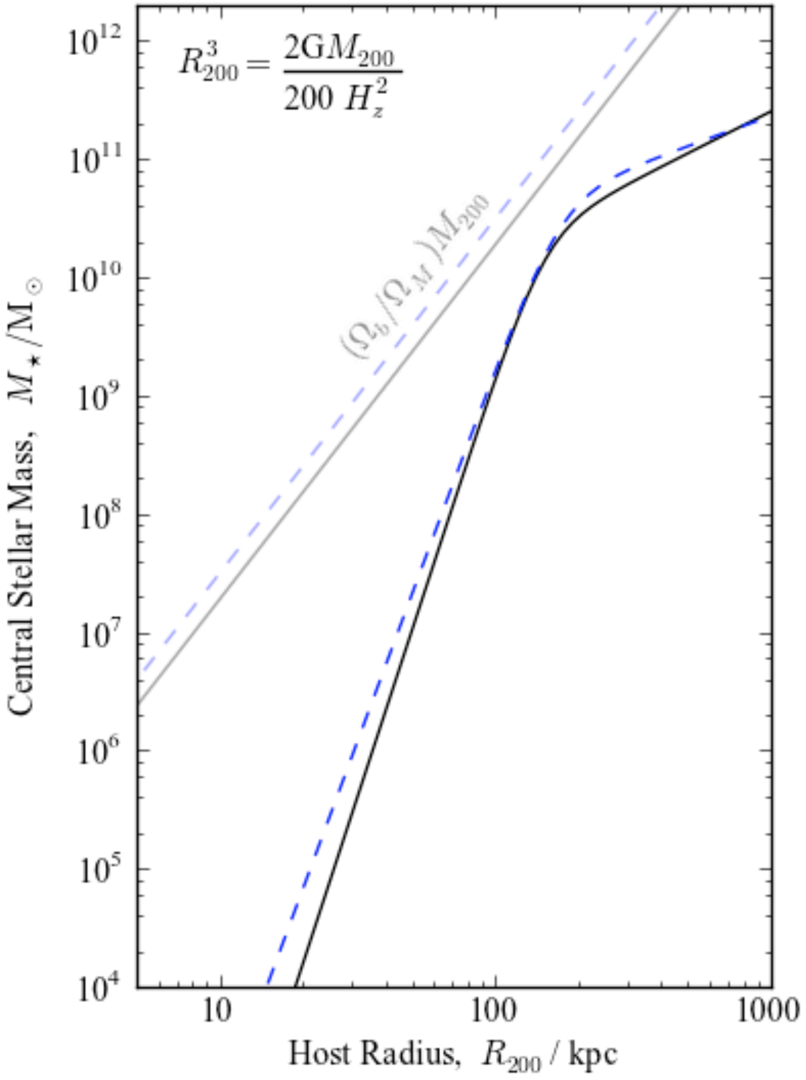

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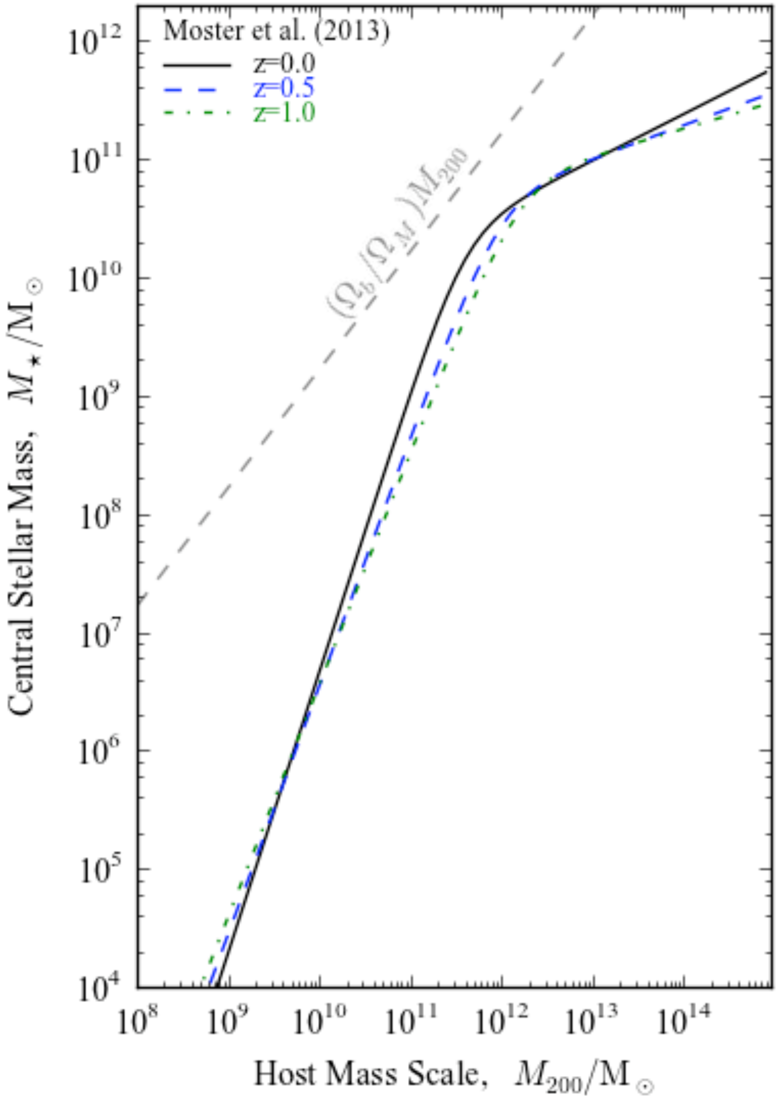

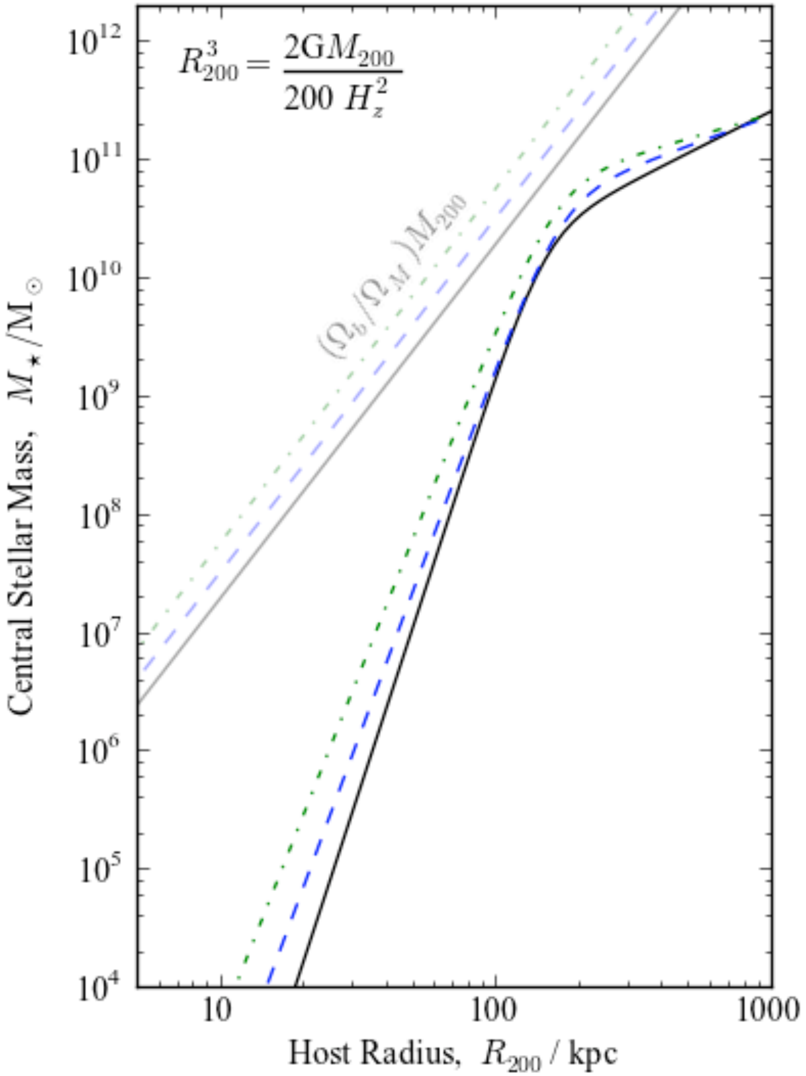

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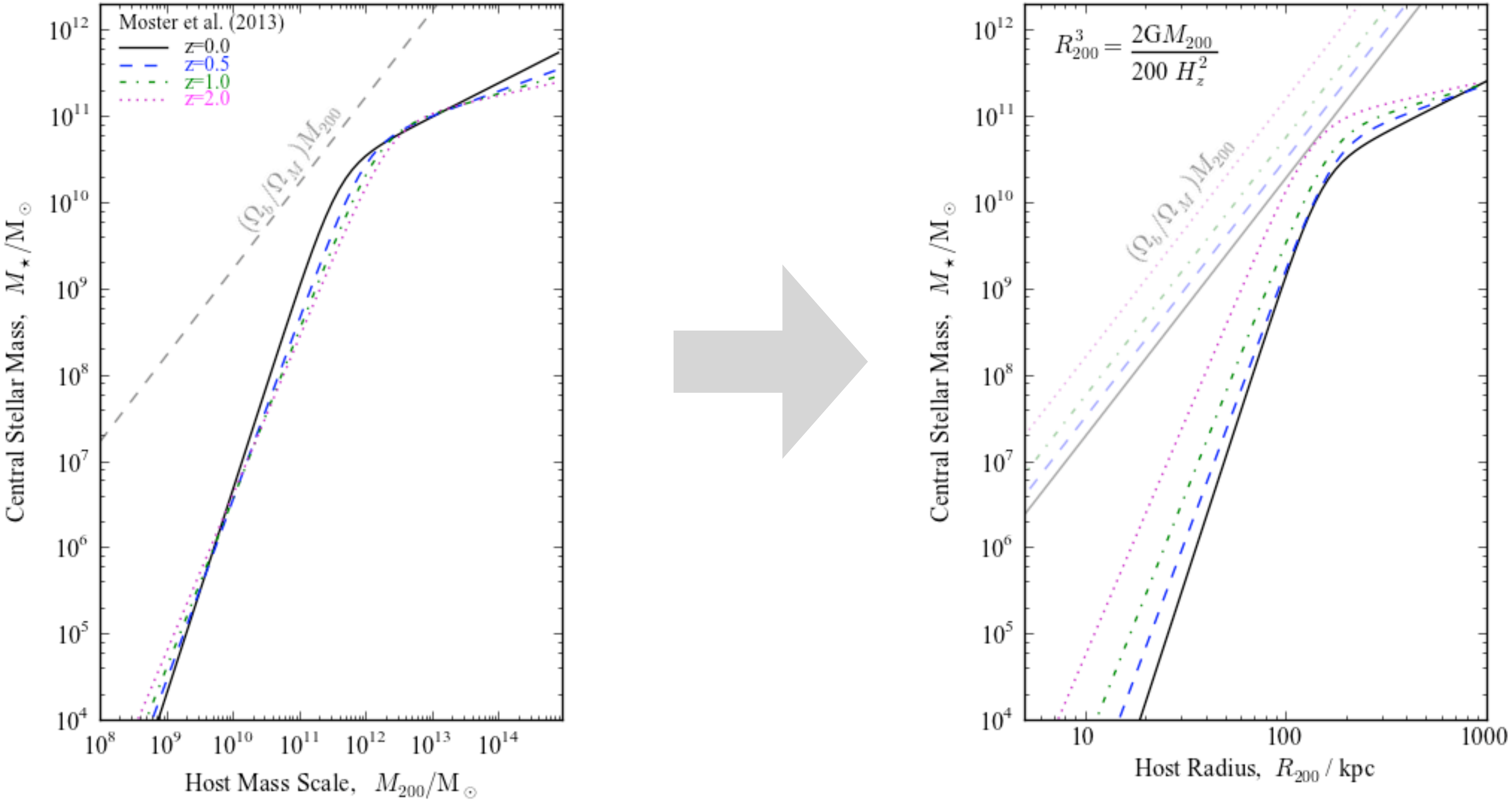

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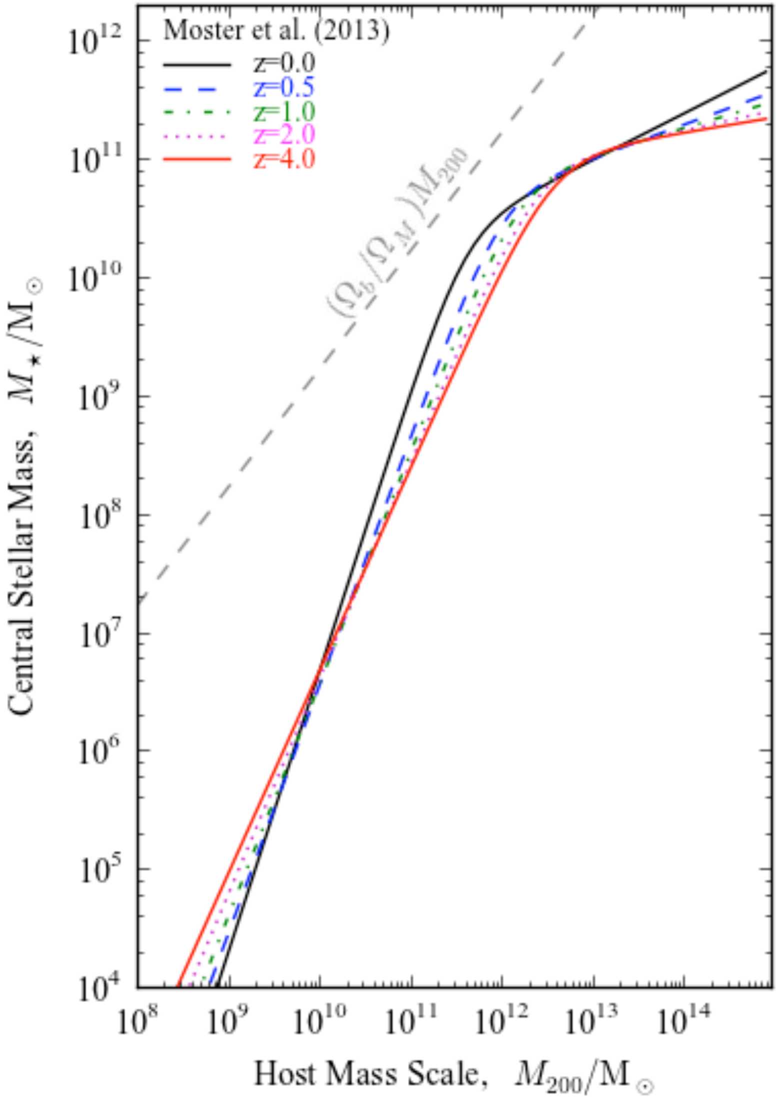

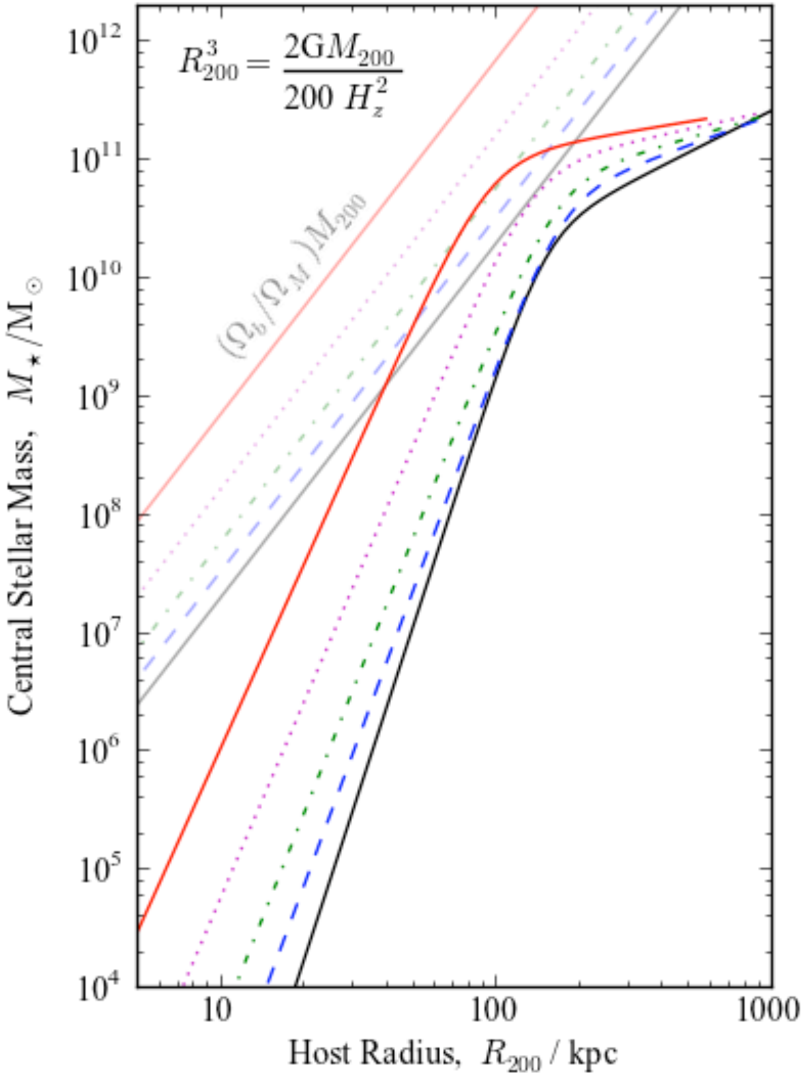

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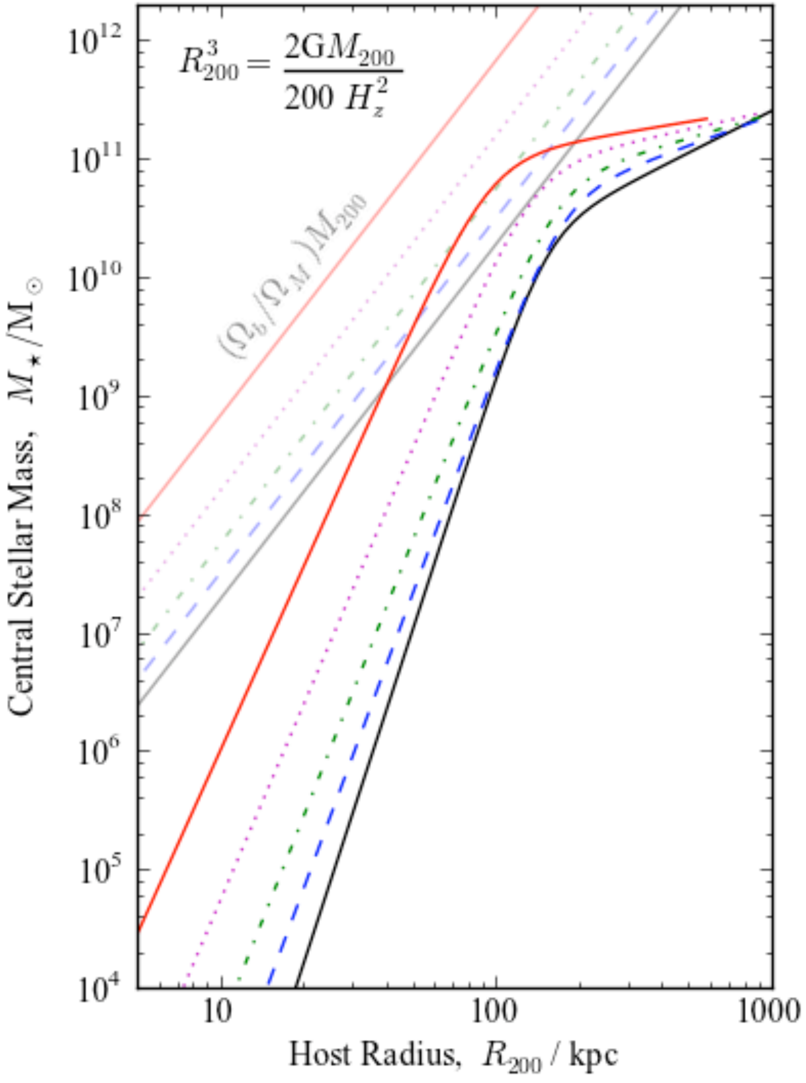

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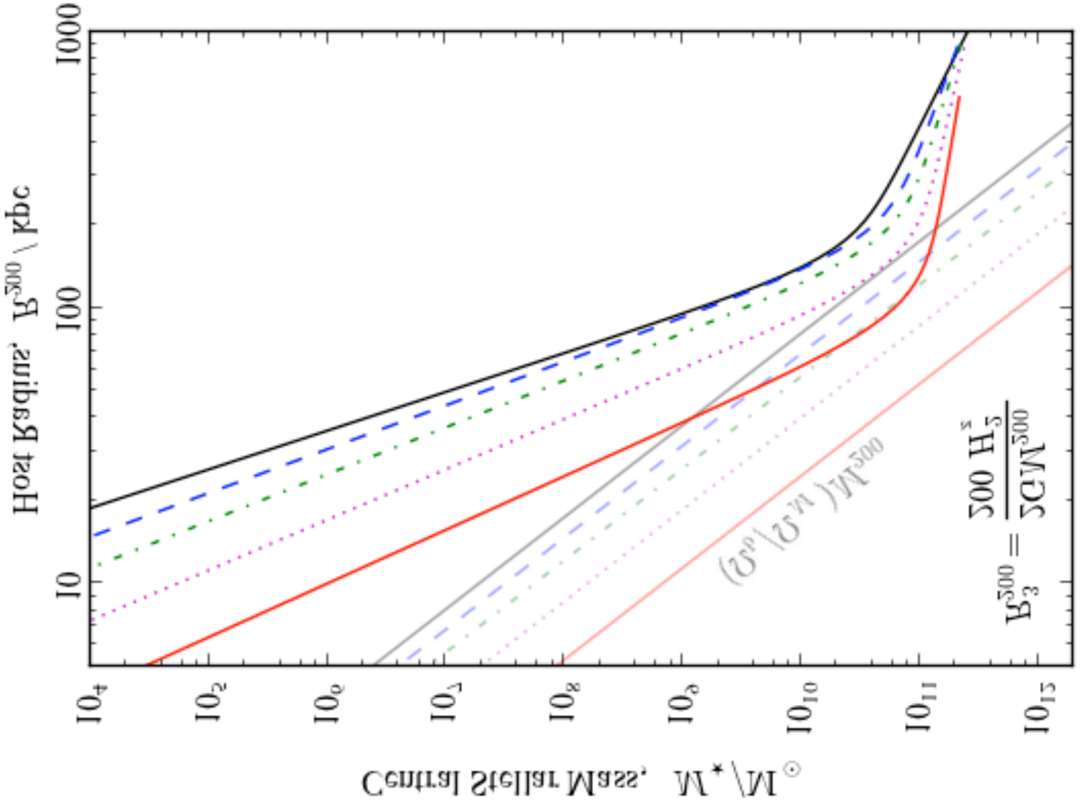

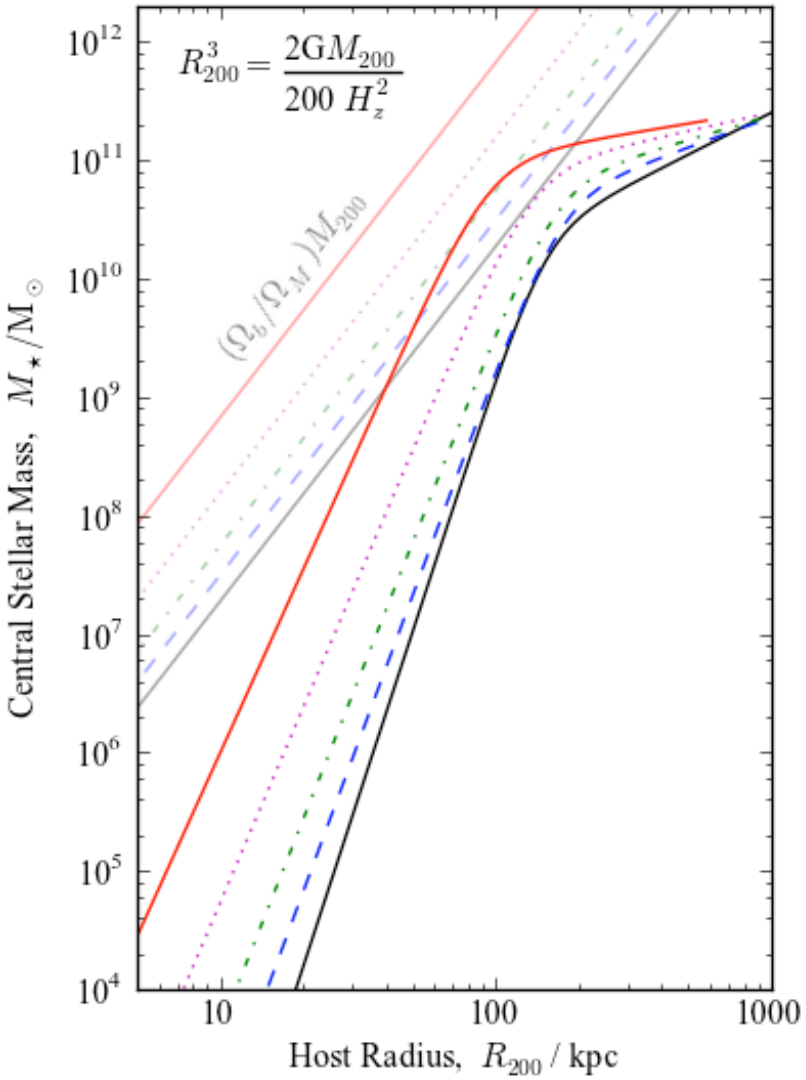

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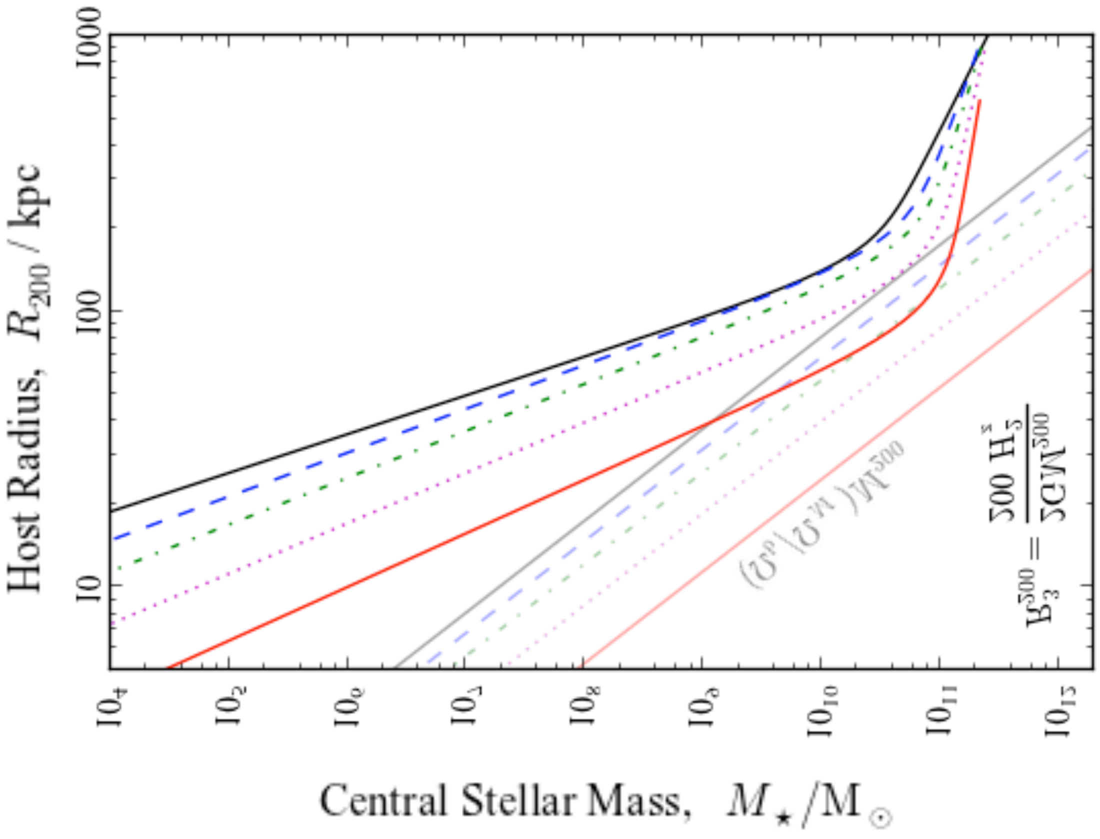

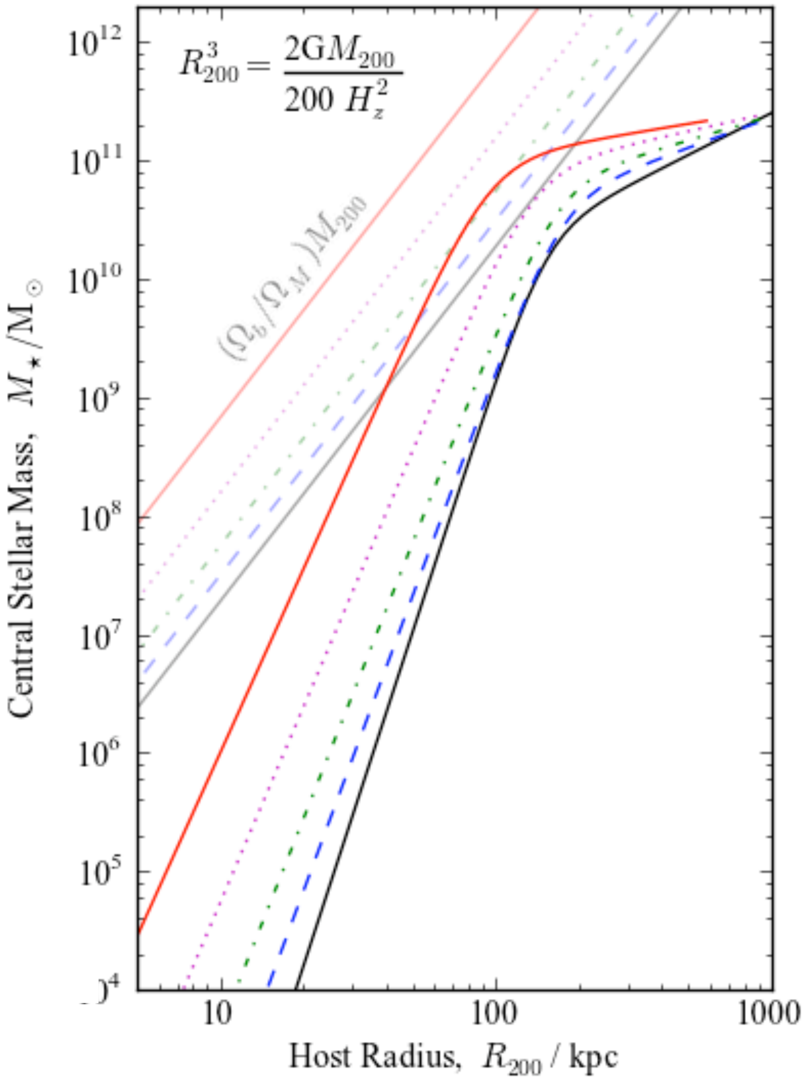

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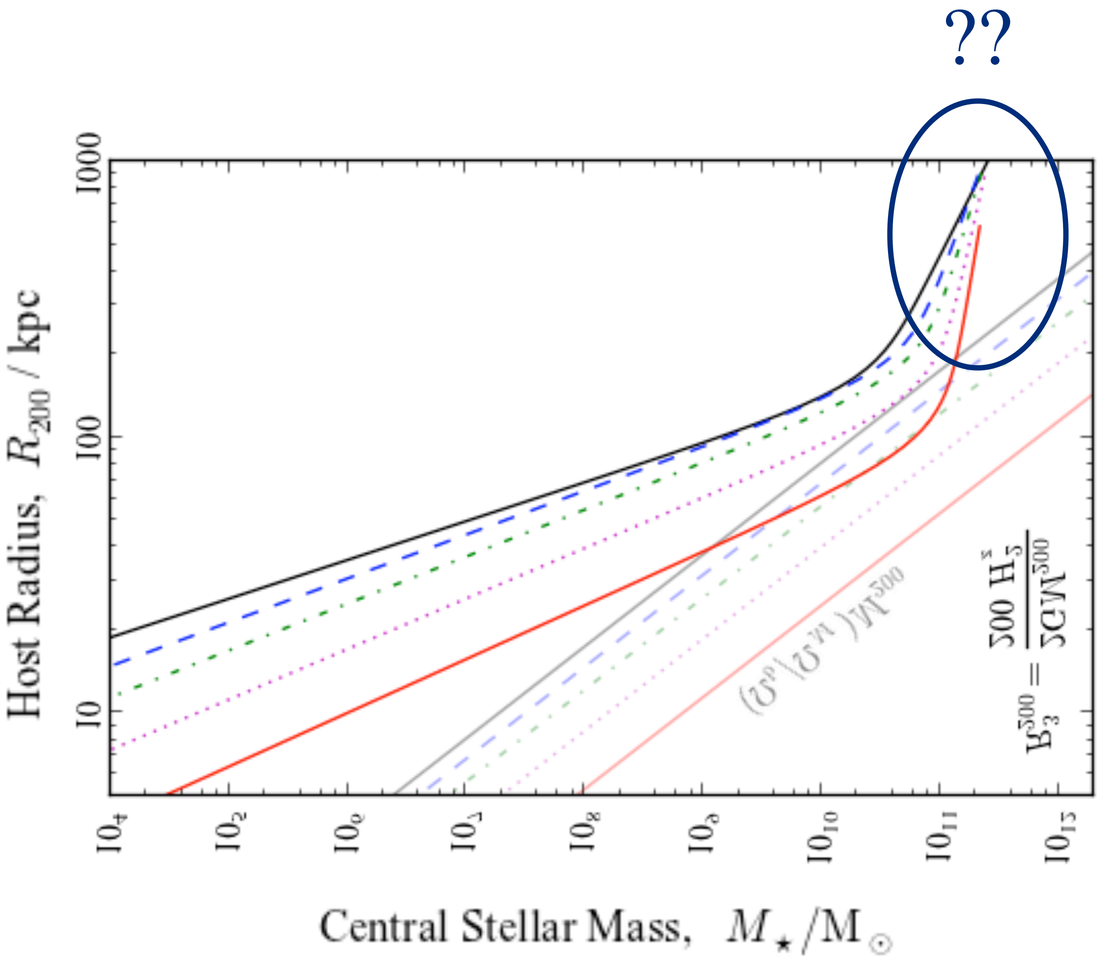
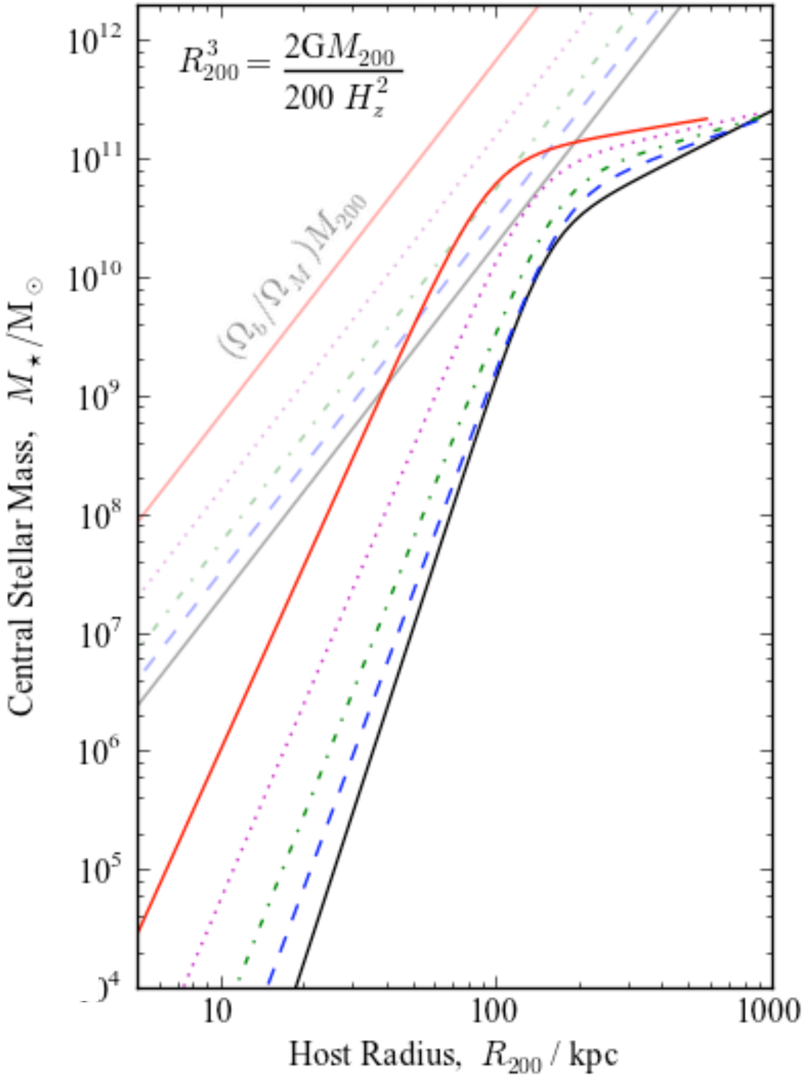
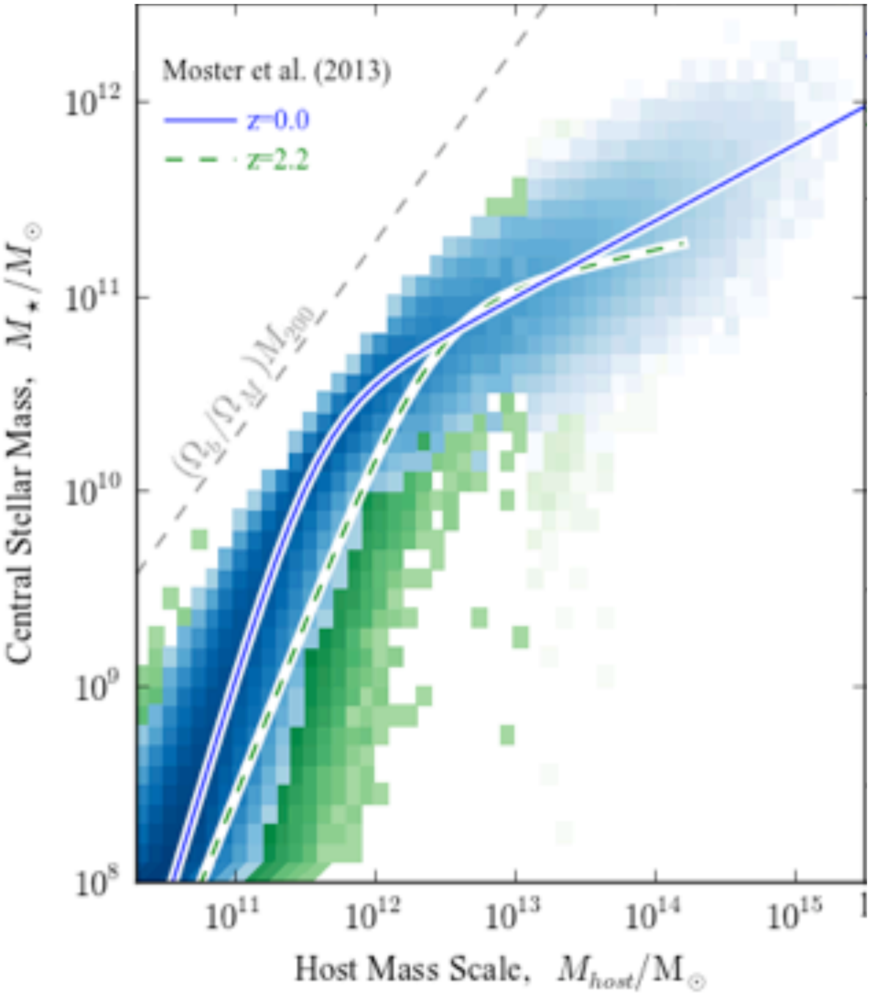
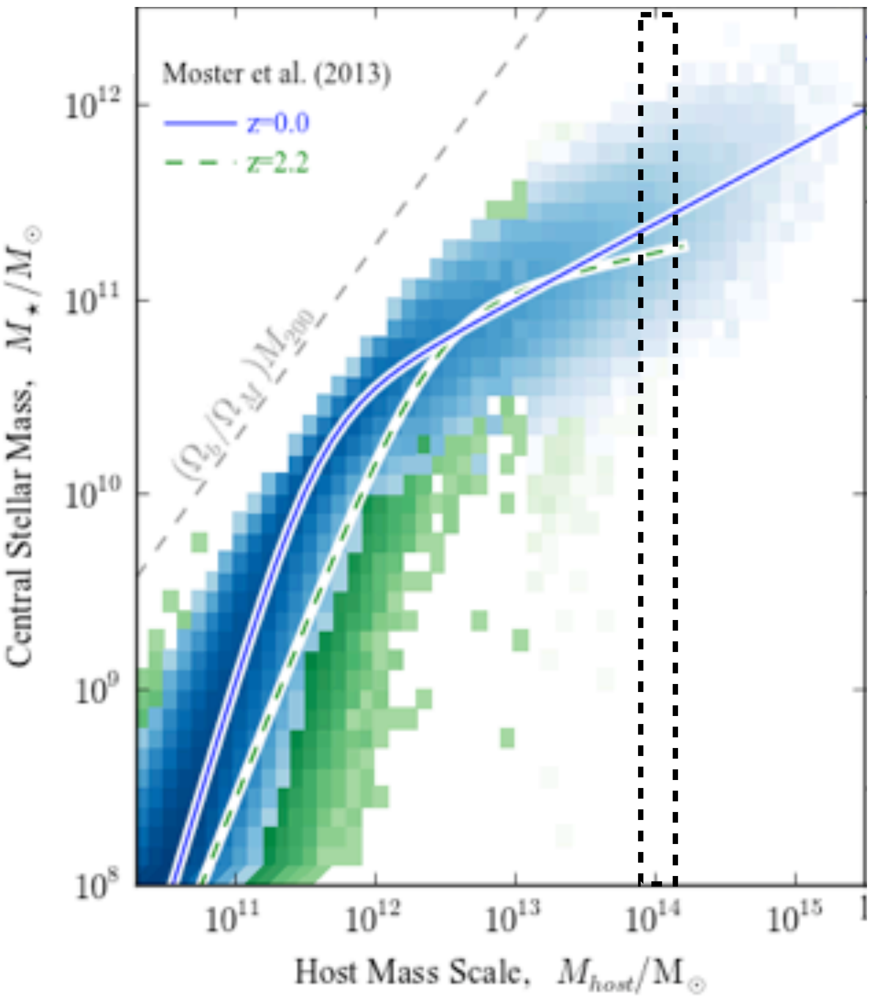
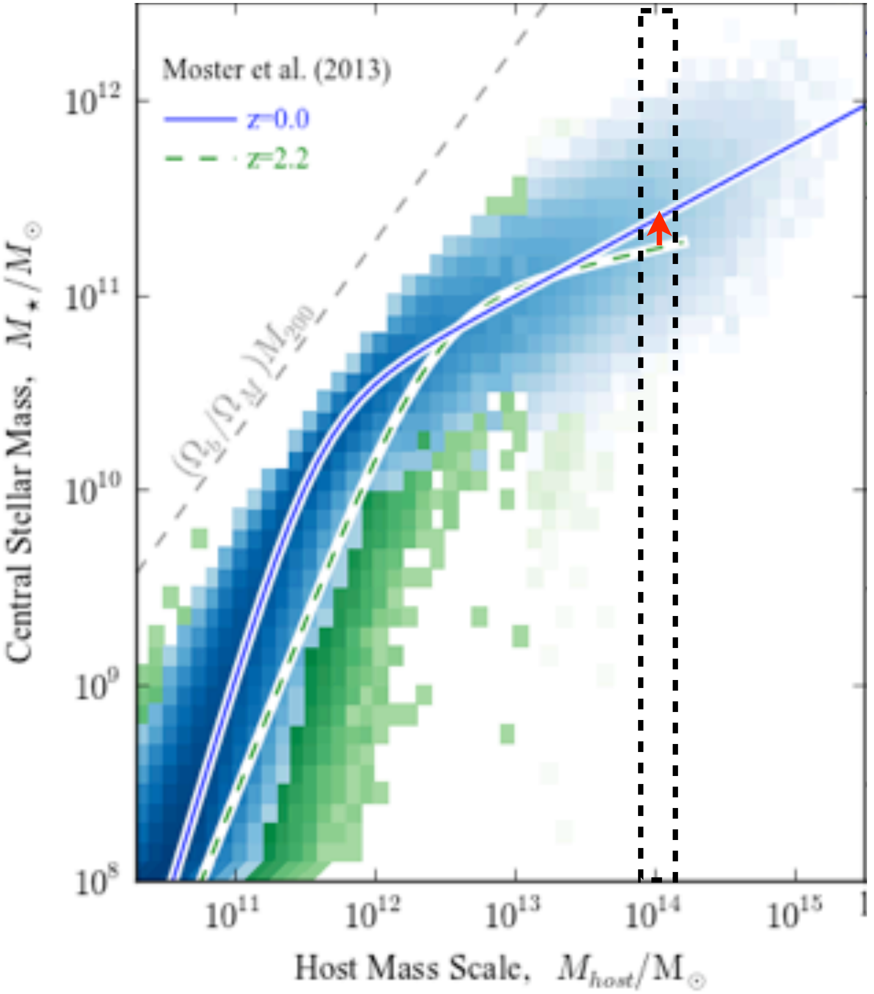





Moster et al. (2013)
z=0.0
z=2.2
$(\Omega_b/\Omega_M)M_{200}$
Central Stellar Mass, $M_\star/M_\odot$
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Host Mass Scale, $M_{host}/\mathrm{M}_\odot$


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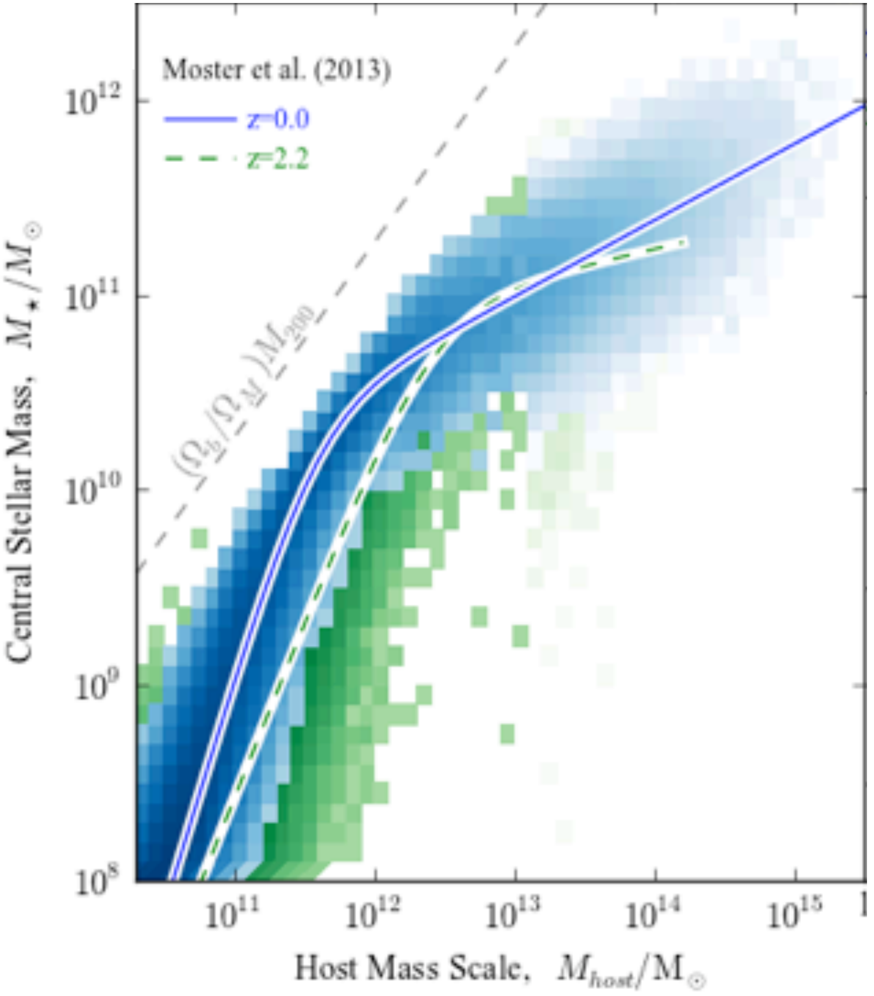
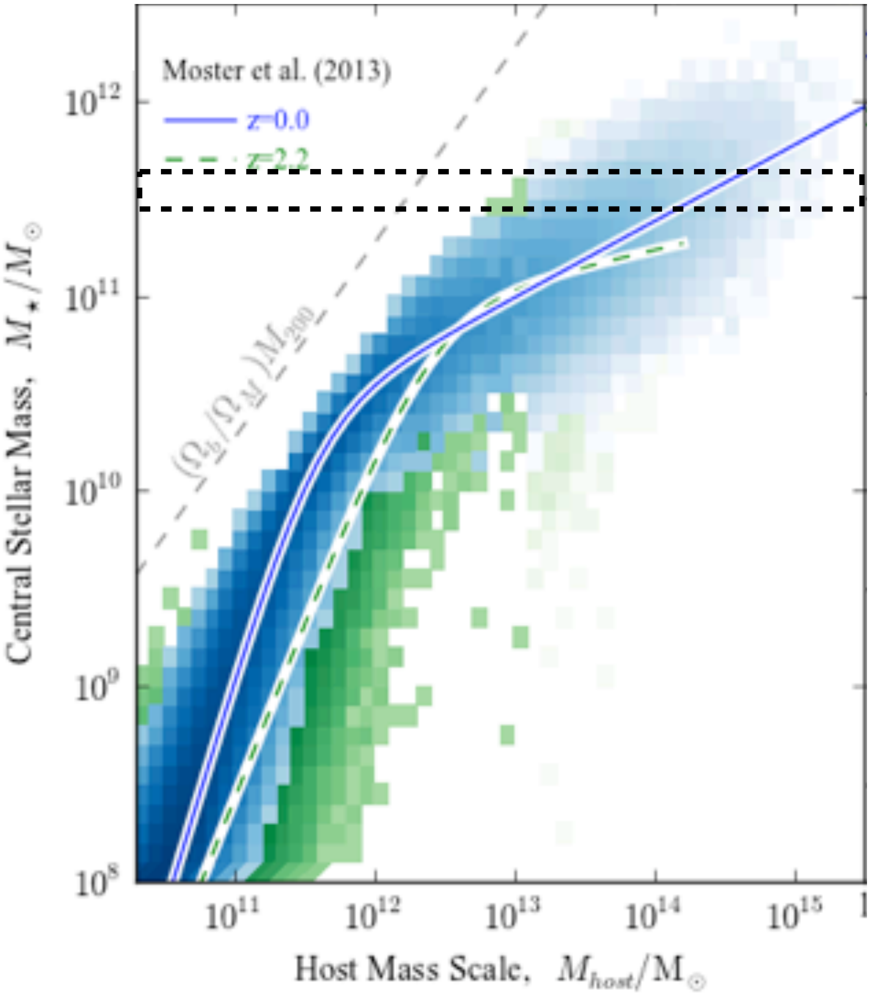
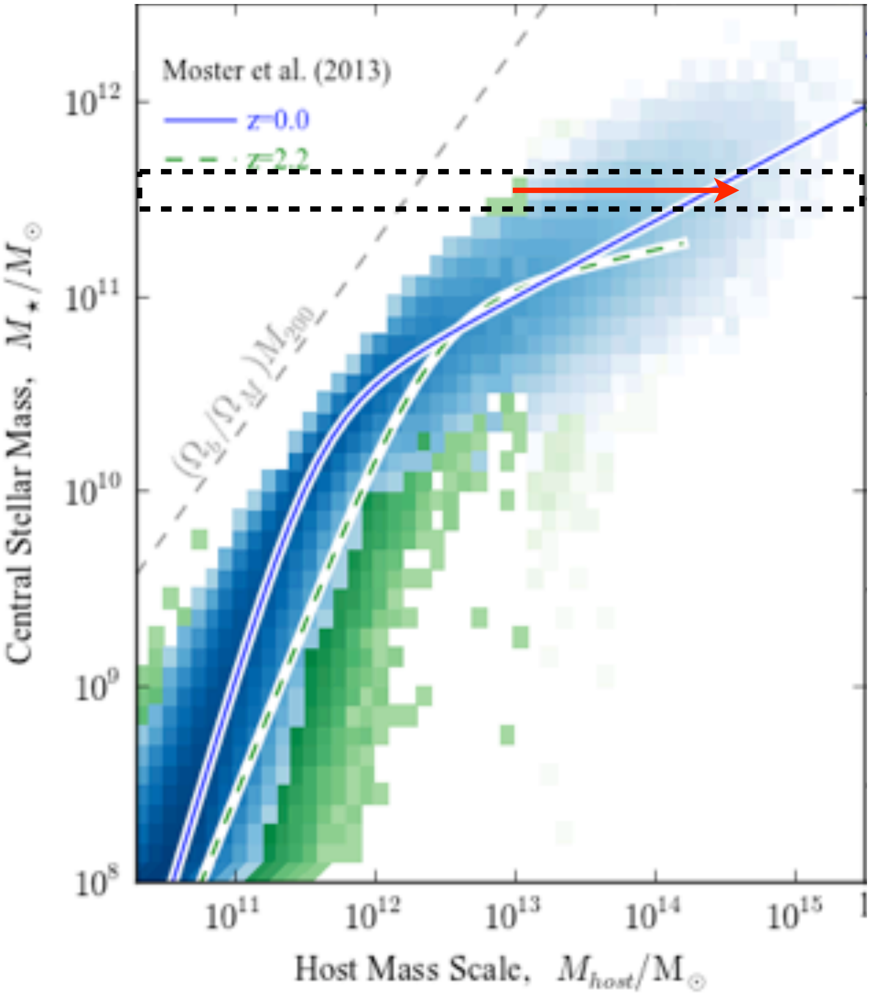
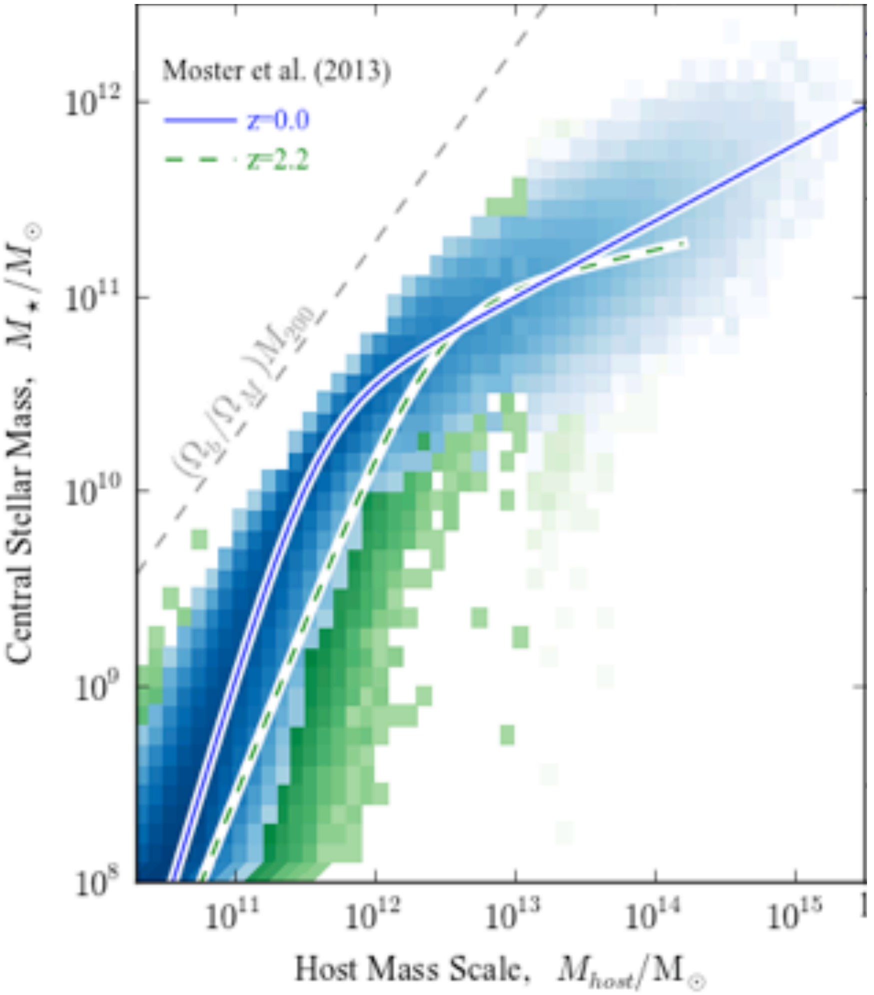
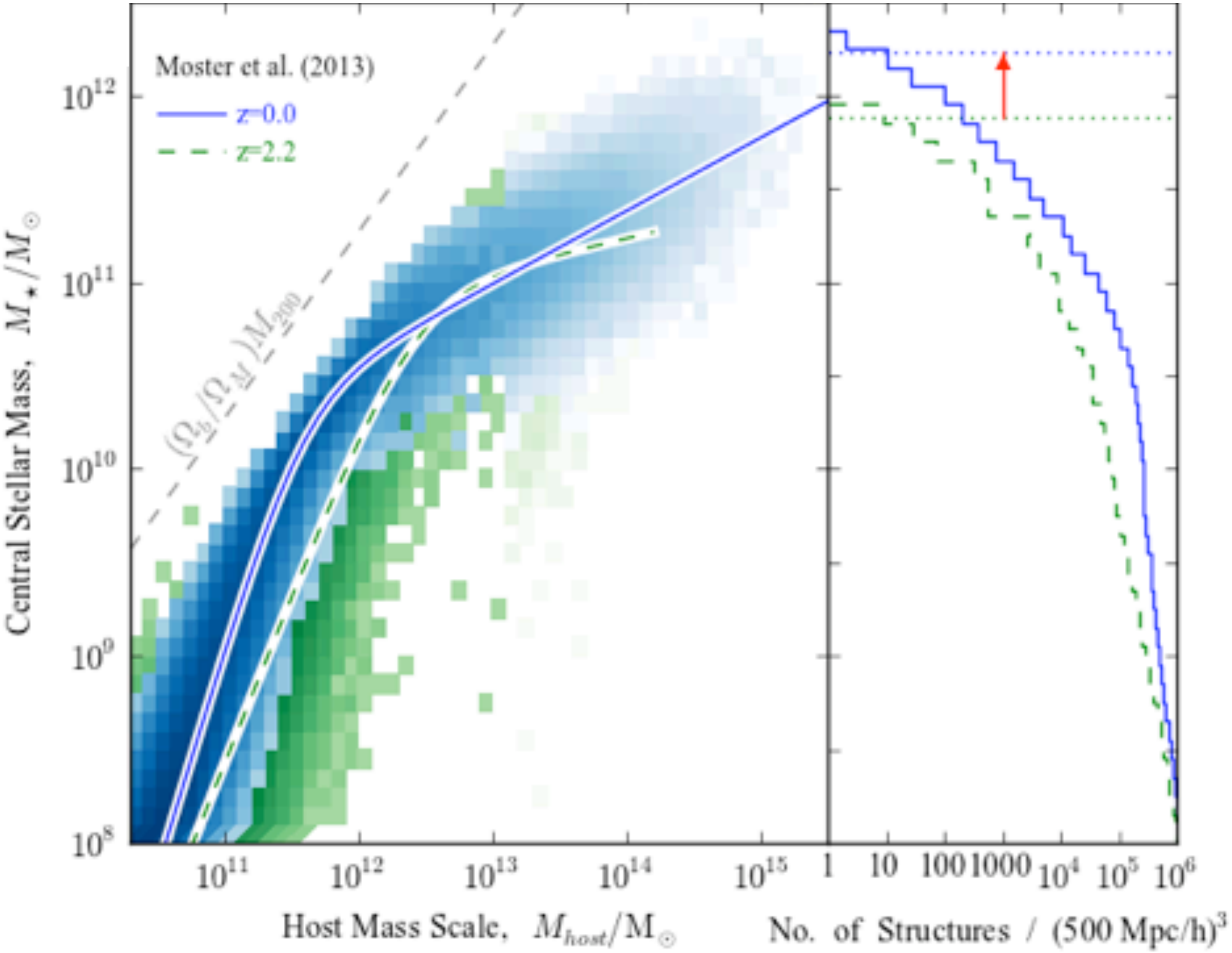
10^{10}
10^{9}
10^{8}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Host Mass Scale, $M_{host}/\mathrm{M}_\odot$

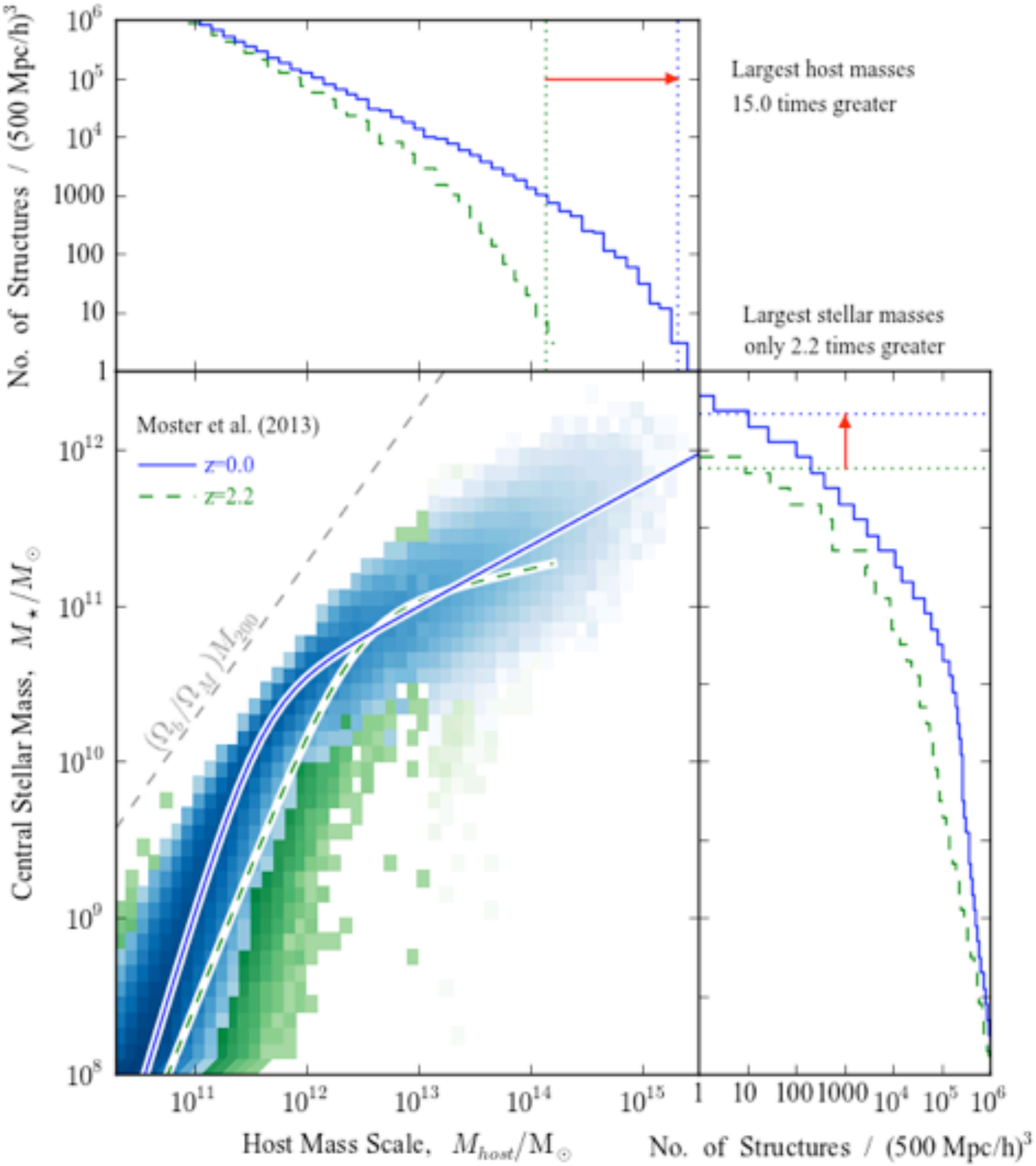

Moster et al. (2013)
z=0.0
z=2.2
$(\Omega_b/\Omega_M)M_{200}$
Central Stellar Mass, $M_\star/M_\odot$
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Host Mass Scale, $M_{host}/\mathrm{M}_\odot$

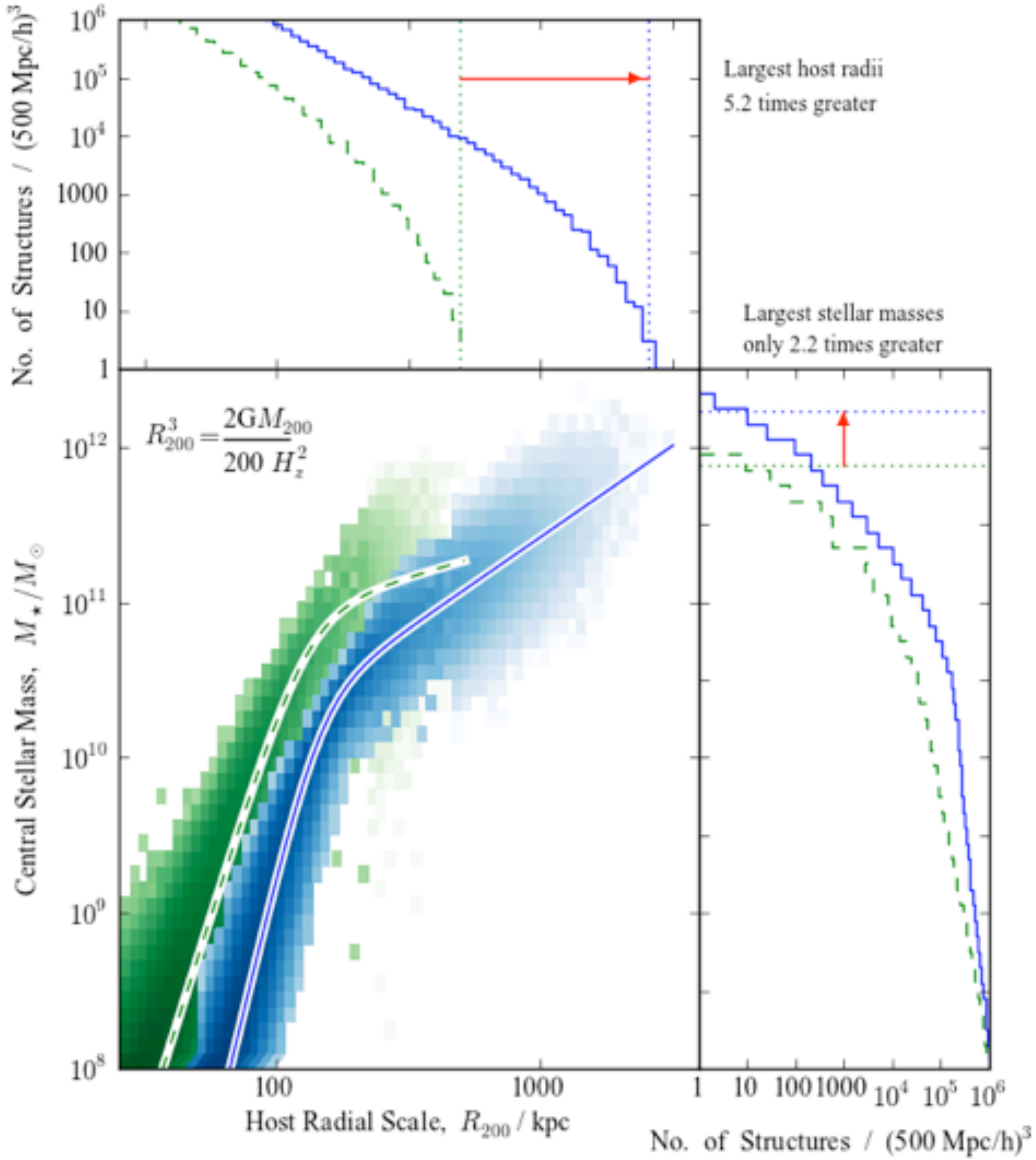

Moster et al. (2013)
z=0.0
z=2.2
$(\Omega_b/\Omega_M)M_{200}$
Central Stellar Mass, $M_\star/M_\odot$
10^{12}
10^{11}
10^{10}
10^9
10^8
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Host Mass Scale, $M_{host}/\mathrm{M}_\odot$


Moster et al. (2013)
z=0.0
z=2.2
$(\Omega_b/\Omega_M)M_{200}$
Central Stellar Mass, $M_\star/M_\odot$
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Host Mass Scale, $M_{host}/M_\odot$


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

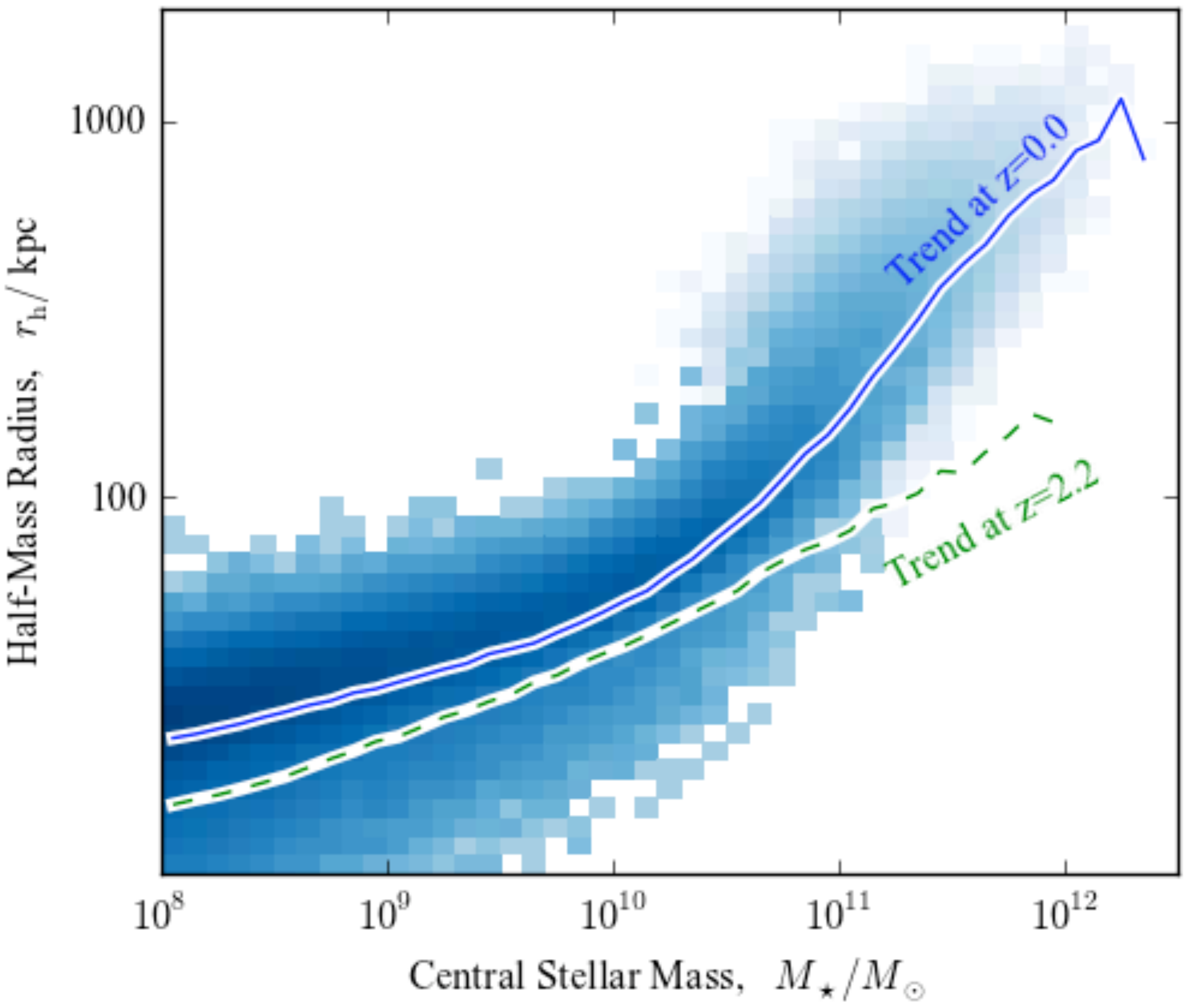

Moster et al. (2013)
z=0.0
z=2.2
$(\Omega_b/\Omega_M)M_{200}$
Central Stellar Mass, $M_\star/M_\odot$
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Host Mass Scale, $M_{host}/\mathrm{M}_\odot$
1
10
100
1000
10^4
10^5
10^6
No. of Structures / (500 Mpc/h)^3


Largest host masses
15.0 times greater
Largest stellar masses
only 2.2 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}
10^{13}
10^{14}
10^{15}
Host Mass Scale, $M_{host}/\mathrm{M}_\odot$
1
10
100
1000
10^4
10^5
10^6
No. of Structures / (500 Mpc/h)^3



Largest host radii
5.2 times greater

Largest stellar masses
only 2.2 times greater



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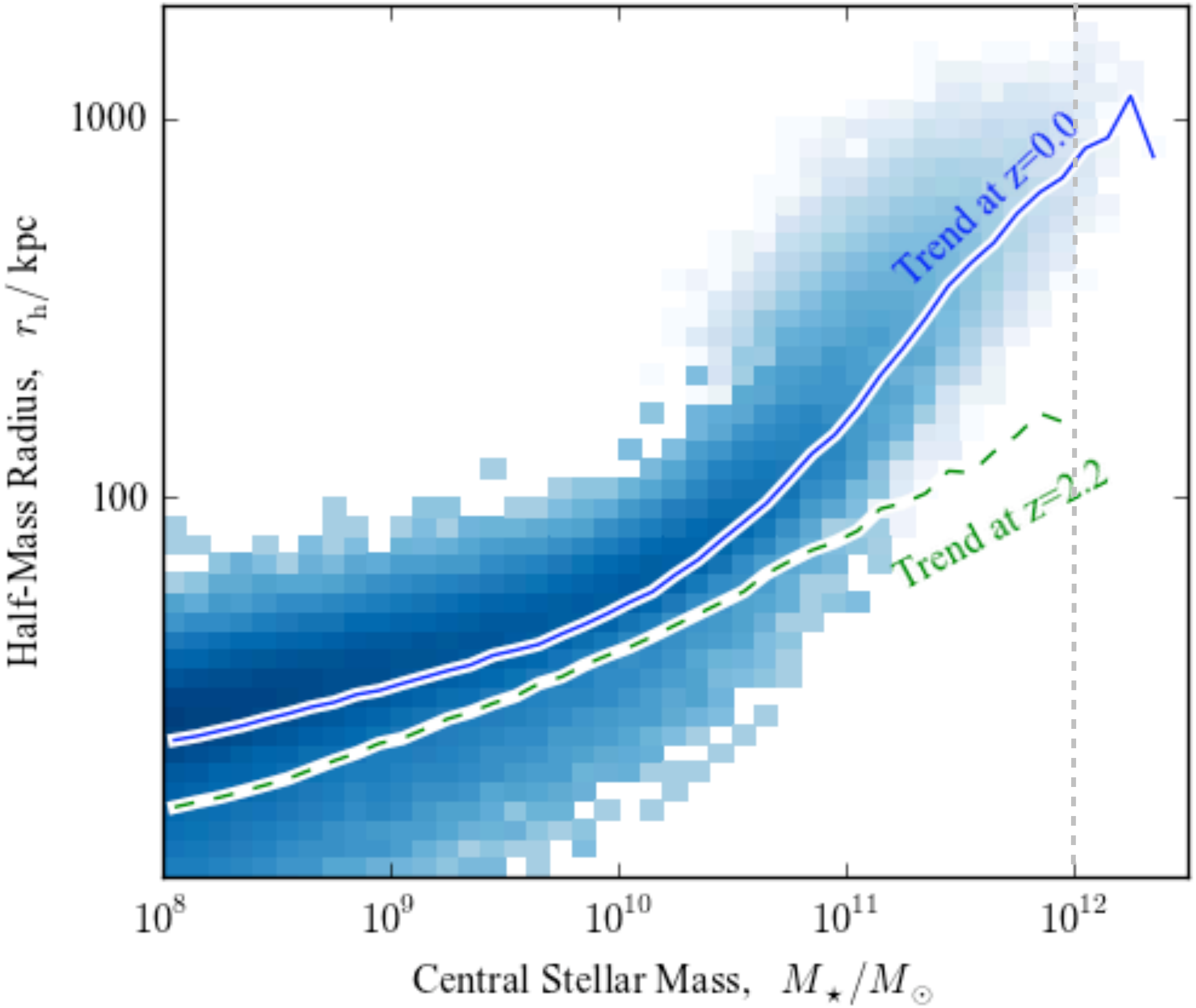
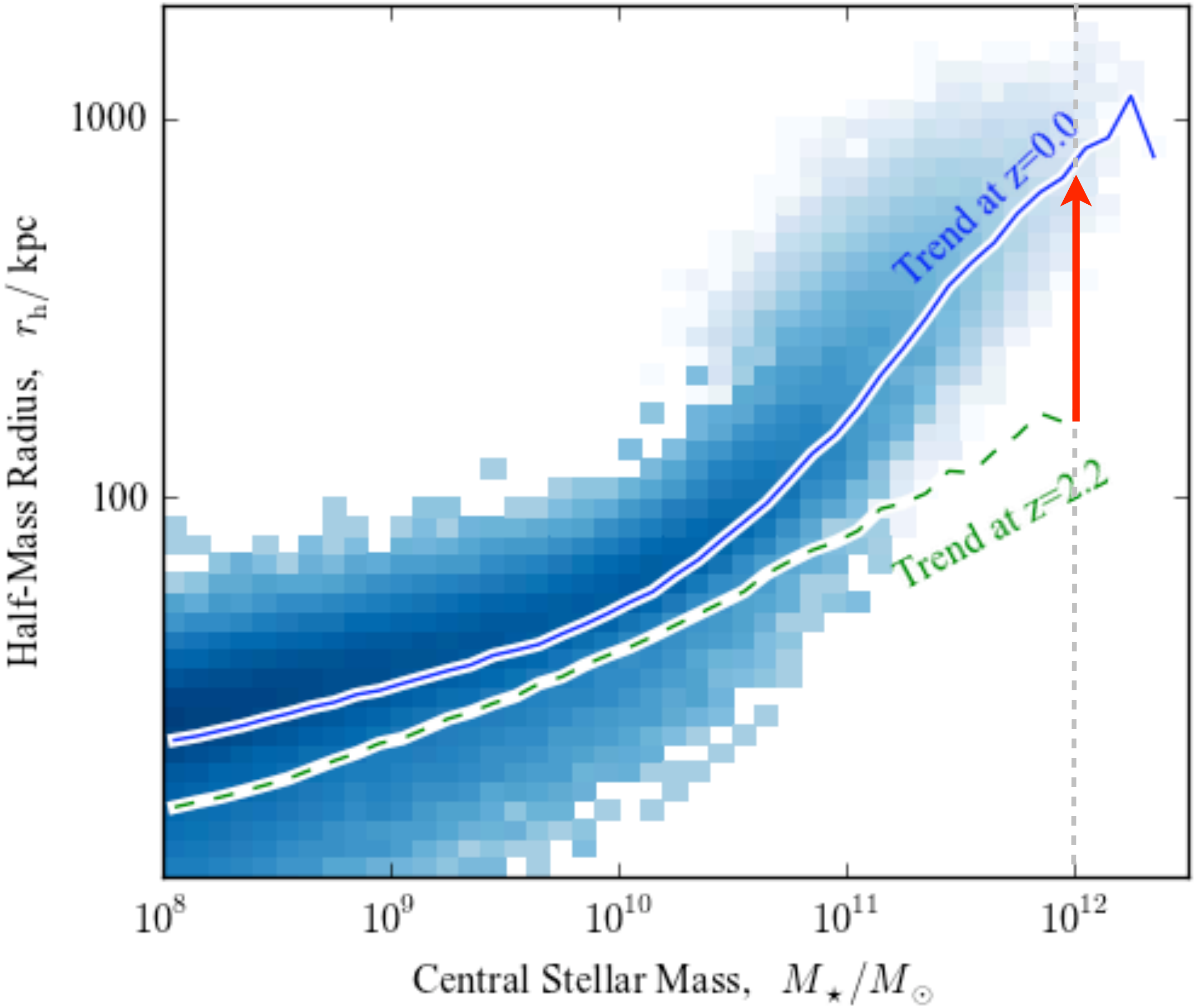
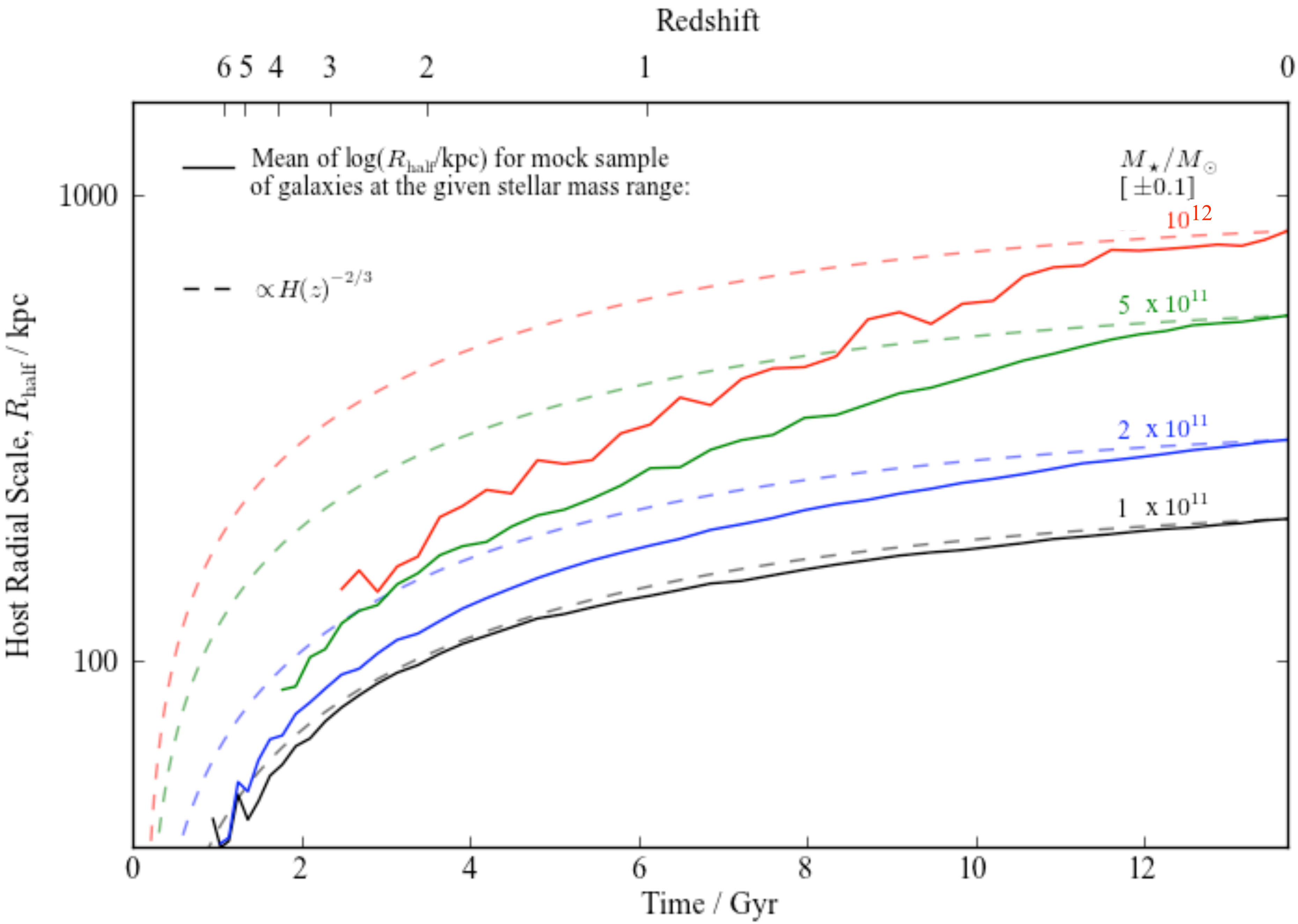

1000
100
Half-Mass Radius, $r_{\rm h}$ / kpc
Trend at z=0.0
Trend at z=2.2
10^8
10^9
10^{10}
10^{11}
10^{12}
Central Stellar Mass, $M_\star / M_\odot$



Strong evolution in trend at high mass due to dramatically different host populations



Martin Stringer

Comparison with surveys

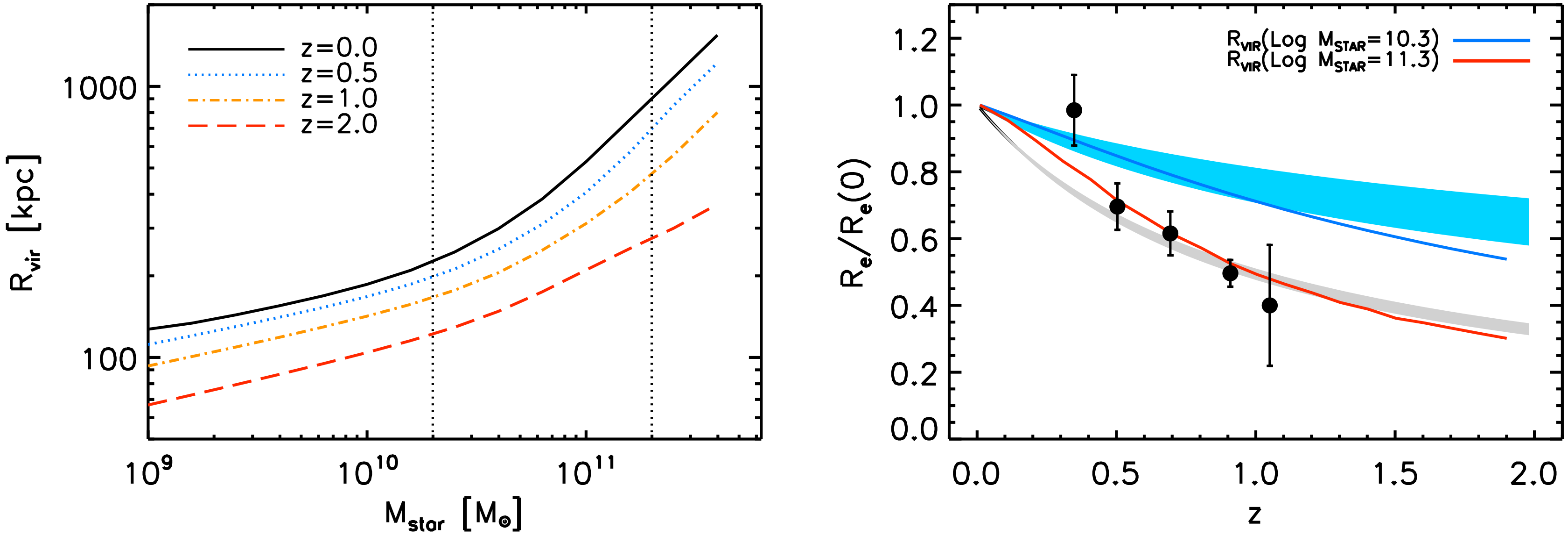


Figure 3. *Left panel*: Relation between median virial radius and stellar mass at different redshifts, as labelled, empirically calibrated by applying the Moster et al. (2013) stellar mass-halo mass relation on large mock halo catalogs. *Right panel*: Predicted virial size evolution, normalized at the value at $z = 0$, for hosts with galaxies at fixed stellar mass of 2×10^{10} and 2×10^{11} (*blue* and *red*, *solid* lines). The models are compared with data for the size evolution of disc galaxies at fixed stellar mass collected by Hopkins et al. (2009; *blue* region), and for the size evolution at fixed stellar mass for early-type galaxies with stellar mass $\gtrsim (1-2) \times 10^{11}$, by van de Sande et al. (2012; *grey* region), and Huertas-Company et al. (2013; *filled circles*).

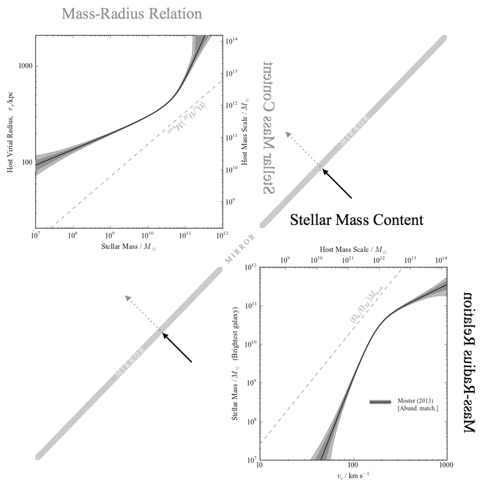
Galaxy Properties

as a fingerprint of cosmology & fundamental physics

Martin Stringer

l'Observatoire de Paris | LERMA

Stellar masses and radii



This sketch shows how stellar mass - radius trends can be understood as emerging from the familiar variation of stellar mass content within cosmic structures. The lower right panel is the well known plot of stellar mass content as a function of host mass (shown here is the content deduced from abundance matching techniques by Moster et al. 2013). By appealing to the close mapping between virial mass, velocity and radius in standard cosmology, a diagonal reflection of this well-known plot, in the plane shown, yields a plot of *virial radius* vs. stellar mass (top left panel) and hence provides an understanding of the observed size trends in galaxies.

The argument:

If galaxy sizes correlate linearly with those of their host structure (as recently reenforced by Kravstov 2013)

and this is indeed due to conservation of specific angular momentum (Fall & Efstathiou 1980; Kassin et al. 2012),

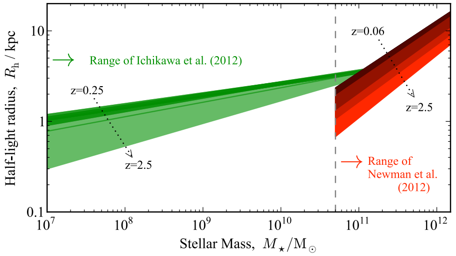
then the observed trends in galaxy size as a function of stellar mass, and their evolution, can be understood as:

1. Collapsed structures carrying an imprint of the cosmology,

2. with stellar mass content that varies strongly with host mass,

3. but mean scalar specific angular momentum that remains directly correlated.

Observational Summary



$$R_{\rm gal} \approx \lambda R_{\rm v}$$

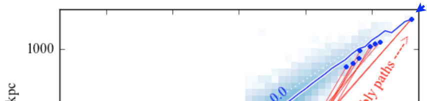
Strong evolution in the *trend* at high stellar mass is due to new galaxies having formed in much larger host structures.

Start from sizes of pure CDM structures

$$\boxed{\frac{\mathrm{G}M_{\rm v}}{r_{\rm v}^3} = \frac{\Delta}{2}H_z^2}$$

Where z is the collapse redshift. Since high density fluctuations, more often found in smaller regions, collapse earlier, this leads to a slope slightly *steeper* than

$r_v \propto M_v^{1/3}$



Star formation rates

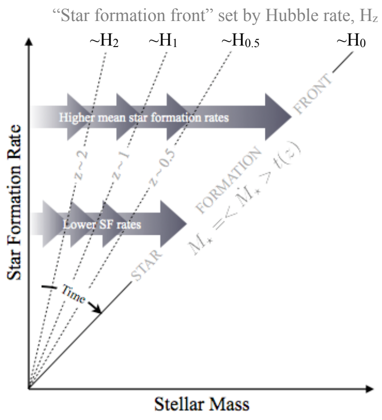


Fig. 2. An illustration of the case where star formation rates at any given time $\dot M_\star(t)$ do not greatly differ from the mean star formation rate over cosmic time, $< M_\star >_t$ of that same system (or more generally, the sum over all its progenitors). Arrows indicate evolutionary paths for galaxies in this scenario: regions with high star formation rates accumulate large stellar masses, regions with lower average star formation rates will, at the same epoch, have lower stellar masses. Mathematically this means that the population, as observed at any given time, will fall on and around a "formation front" given simply by $< M_\star >=< \dot M_\star > t_z$, where t_z is approximately equal to the age of the universe at the observed redshift. Both axes here are linear; in a log – log plot the dotted lines would be parallel.

Sketch uses linear scale

Data on same diagram but using logarithmic scale

Stellar mass, $M_\star = \int_{t_f}^{t_z} \dot M_\star dt \quad (\approx \ < \dot M_\star > t_z)$

so galaxies scatter about the locus $\dot M_\star = M_\star / t(z) \quad (\sim M_\star H_z)$

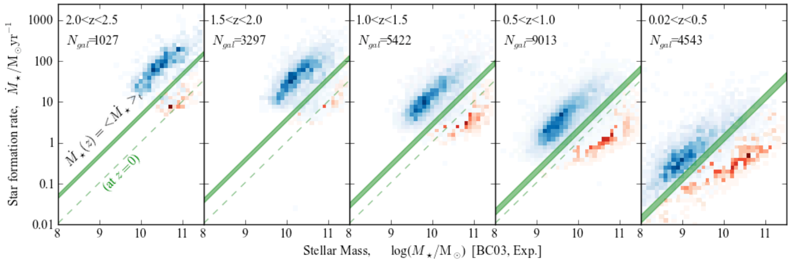
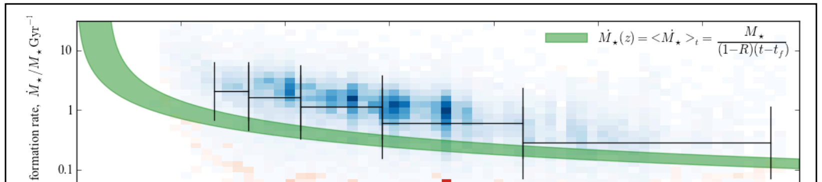
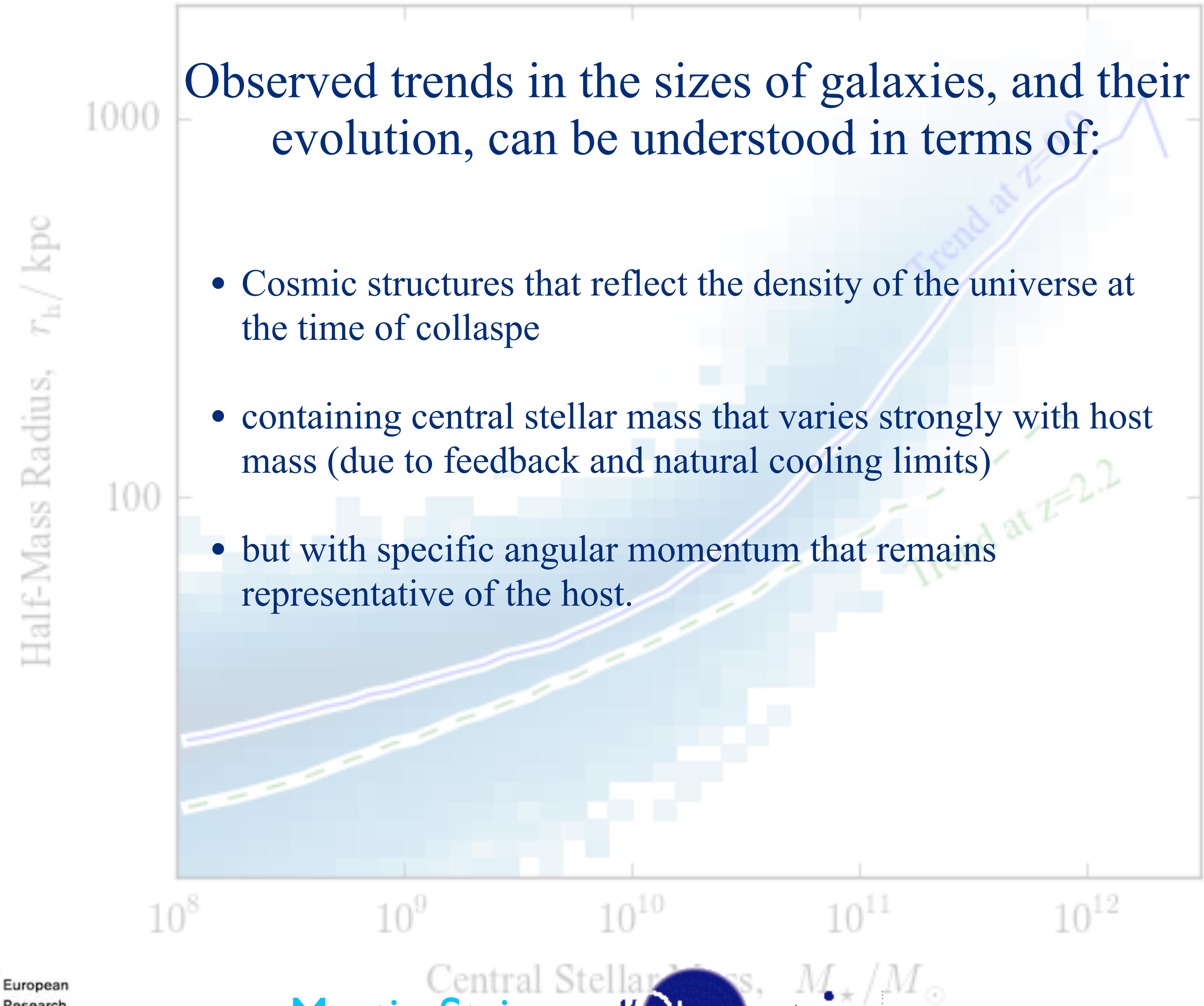


Fig. 1. Distribution of estimated star formation rates and stellar masses from Whitaker et al. (2012), for a set of photometrically determined redshift ranges. "quiescent" and "star forming" systems are shown in red and blue respectively, having been categorised according to their rest frame U, V & J-band magnitudes. The green shaded area shows the locus where the current star formation rate is equal to the average rate (given initial formation times in the range $0 < t_f < 0.6$ Gyr, and recycling fractions $0.3 < R < 0.5$).

This can also be seen from specific star formation rates, $\dot M_\star / M_\star$ vs. time...



Summary



Observed trends in the sizes of galaxies, and their evolution, can be understood in terms of:

- Cosmic structures that reflect the density of the universe at the time of collaspe
- containing central stellar mass that varies strongly with host mass (due to feedback and natural cooling limits)
- but with specific angular momentum that remains representative of the host.