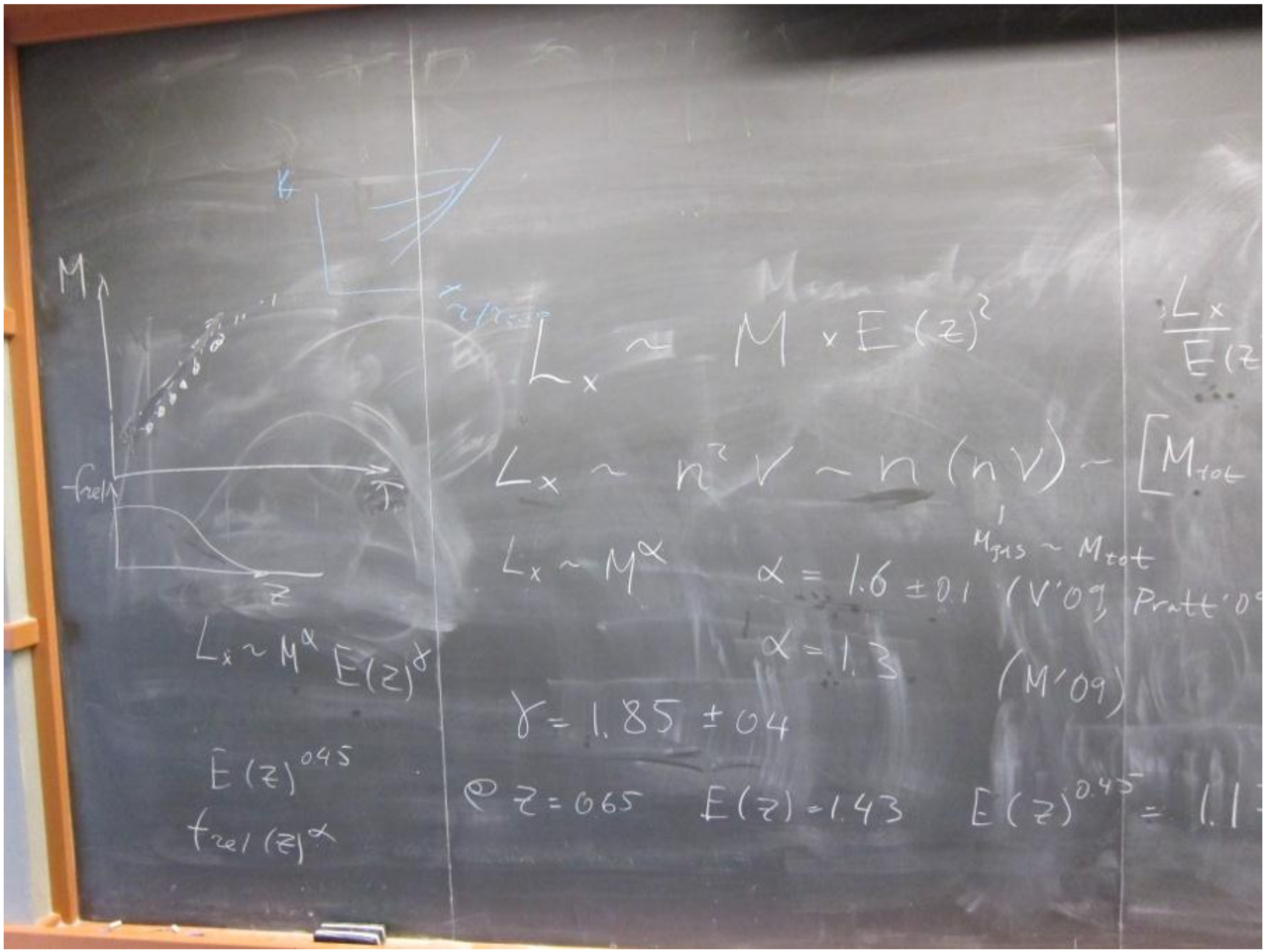
pseudo-evolution of halo mass and observable-mass relations



Andrey Kravtsov
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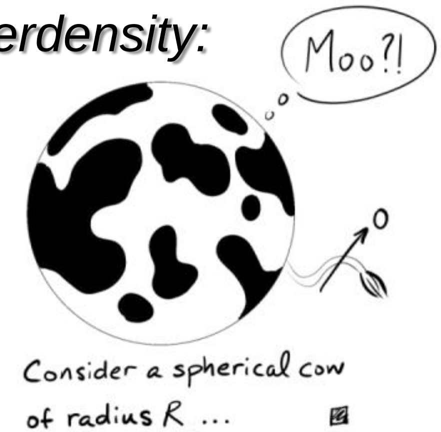
Baseline model for cluster scaling relations

Kaiser 1986, 1991

- *If mass is defined within a spherical radius ecnlosing a given overdensity:*



$$M = \frac{4\pi}{3} \Delta \rho_{\rm cr}(z) R_\Delta^3$$

$$\rho_{\rm cr}(z) \equiv \frac{3H^2(z)}{8\pi G} \equiv \frac{3H_0^2}{8\pi G} E^2(z) \equiv \rho_{\rm cr,0}\, E^2(z)$$

- *Radial density profiles of intracluster gas and dark matter are assumed to be identical, which implies*

$$M_{\rm gas,\Delta} = f_{\rm gas} M_\Delta \qquad f_{\rm gas} = {\rm const}$$

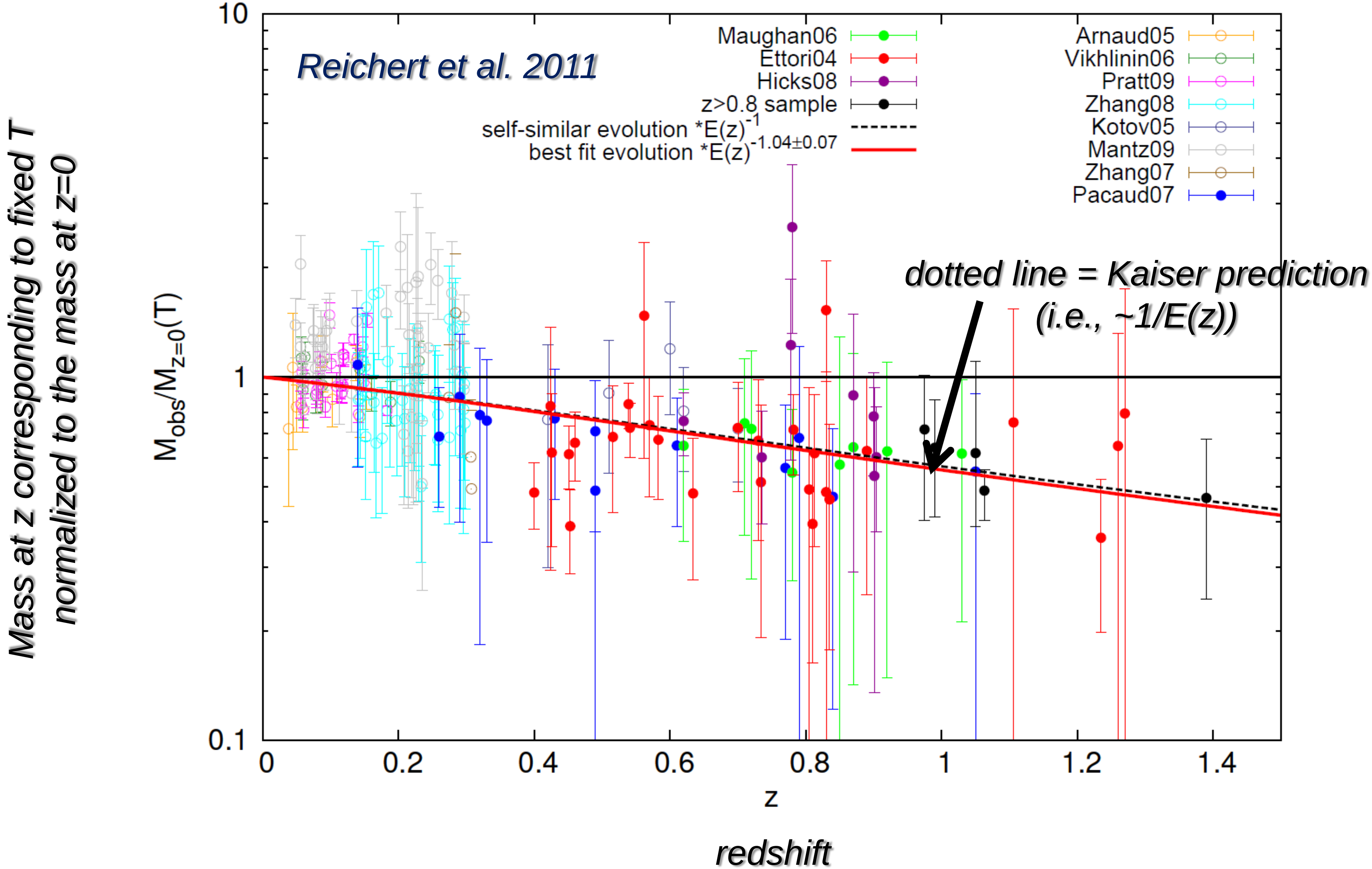
- *temperature scaling based on dimensional grounds*

$$T \propto \frac{M_\Delta}{R_\Delta} \propto (\Delta \rho_{\rm cr})^{\frac{1}{3}} M_\Delta^{\frac{2}{3}} \propto E^{\frac{2}{3}}(z) M_\Delta^{\frac{2}{3}} \longrightarrow M_\Delta \propto E^{-1}(z)\, T^{3/2}$$

$$Y \equiv M_{\rm gas,\Delta} T \propto E(z)^{\frac{2}{3}} M_\Delta^{\frac{5}{3}} \longrightarrow M_\Delta \propto E(z)^{-\frac{2}{5}} Y^{\frac{3}{5}}$$

Observed evolution of the M-T relation

appears to be roughly consistent with the Kaiser model expectation, although current observational uncertainties are large

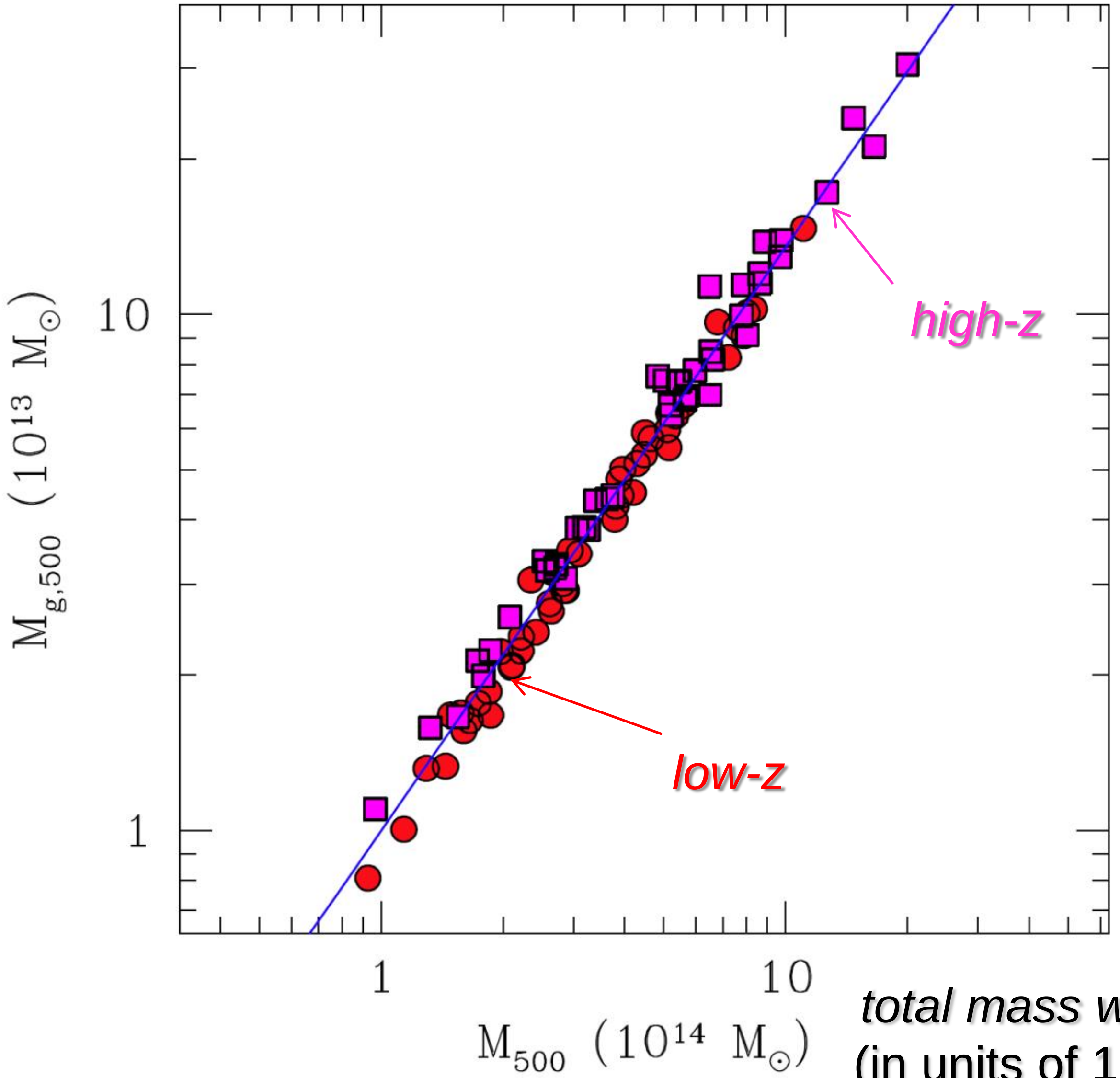


Relation of M_{gas} with total mass M_{500}

Is both nonlinear and evolves with redshift

$$M_g \propto M^{s_3}(1+z)^{\gamma_3} \qquad \gamma_3 = 0.41 \pm 0.06 \quad s_3 = 1.13 \pm 0.01$$

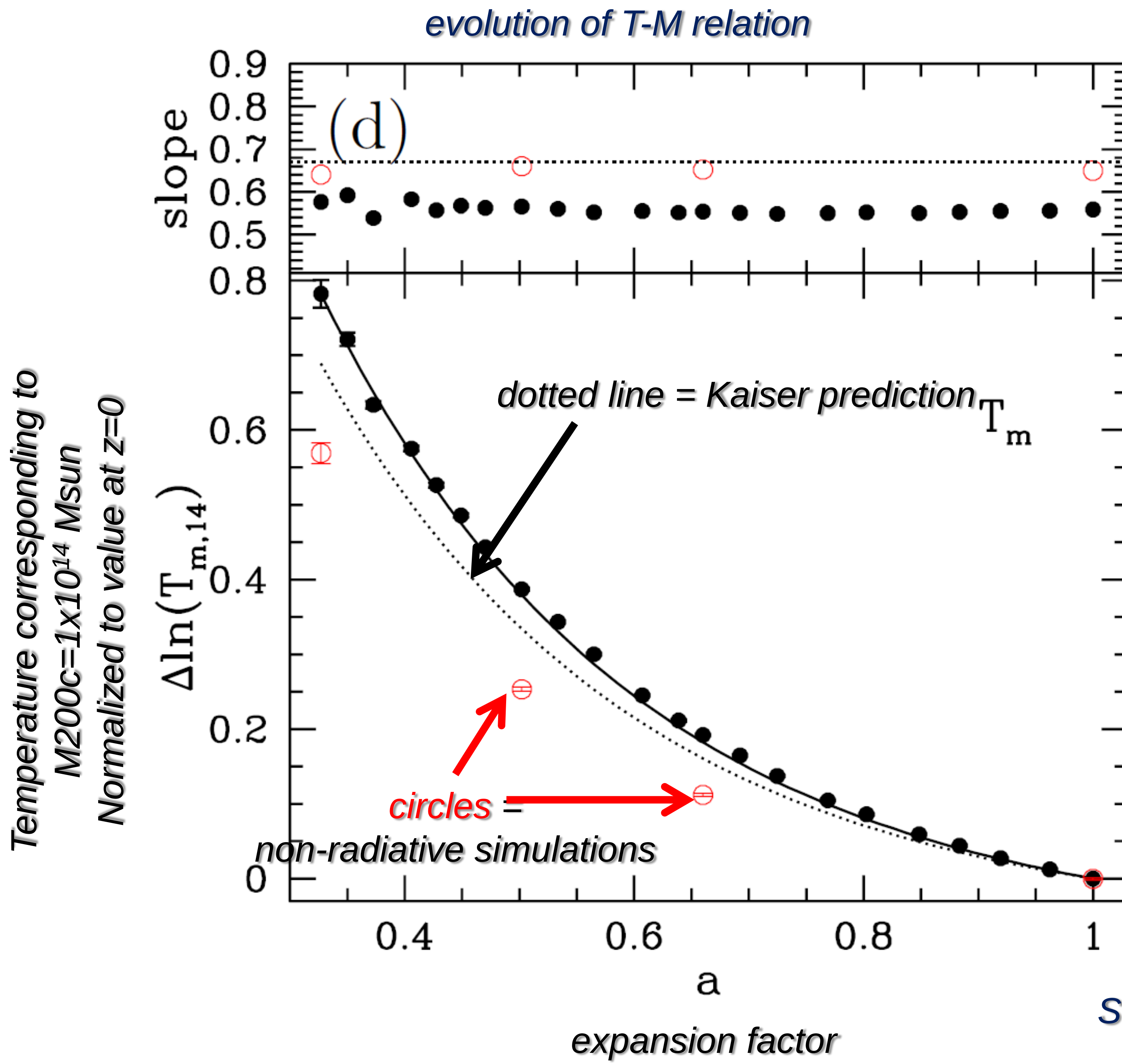
gas mass within R_{500}
(in units of 10^{13} Msun)



total mass within R_{500}
(in units of 10^{14} Msun)

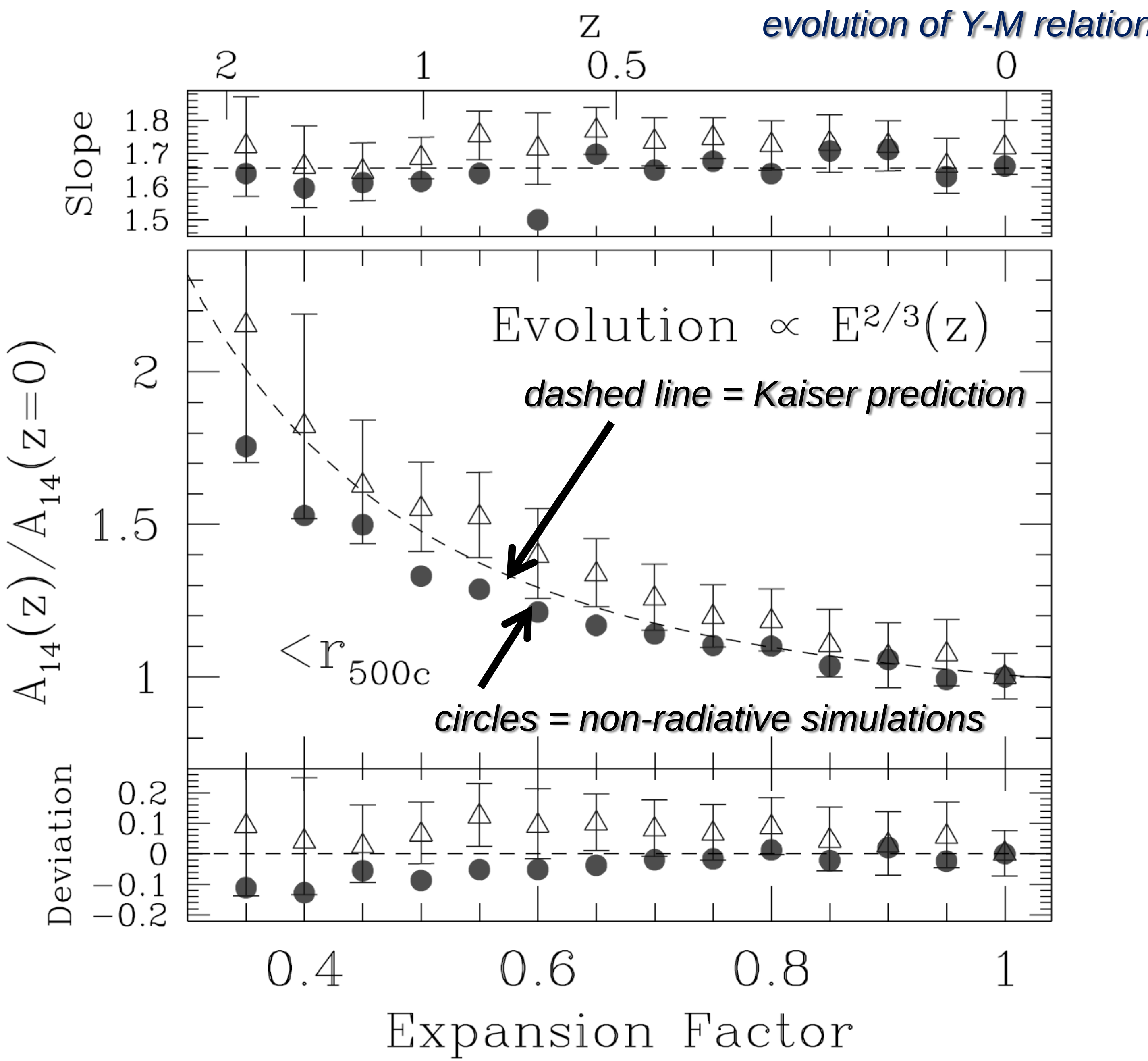
Lin et al. 2012
ApJL 745, L3
+
Vikhlinin et al. 2009

Some deviations from the Kaiser model have been observed in cluster simulations



Stanek et al. 2010

Some deviations from the Kaiser model have been observed in cluster simulations



Nagai et 2006

Revisiting assumptions of the Kaiser model

for details, see Kravtsov & Borgani 2012, ARAA in press (arXiv/1205.5556)

The baseline model of Kaiser (1986) makes a number of important assumptions. For example, consider relation between gas mass and total mass. The Kaiser model assumes that this relation is linear and does not evolve.

However, this does not necessarily mean that evolution over the redshift range probed by current observations is not self-similar.

For non-linear relation self-similar expectation is

$$M_{\rm g} = C_{\rm g} M^{1+\alpha_{\rm g}} \qquad f_{\rm g} \equiv \frac{M_{\rm g}}{M} = C_{\rm g} M^{\alpha_{\rm g}}$$

$$f_{\rm g}(M,z) = {\rm const} \times \left(\frac{M}{M_{\rm NL}(z)}\right)^{\alpha_{\rm g}} \qquad \begin{array}{l} \rightarrow \alpha_{\rm g} = {\rm const} \neq \alpha_{\rm g}(z) \\ \rightarrow C_{\rm g} \propto M_{\rm NL}(z)^{-\alpha_{\rm g}} \end{array}$$

nonlinear mass

$$\sigma(M_{\rm NL}) = D_+(z)\sigma(M_{\rm NL}, z=0) = \delta_c \approx 1.69$$

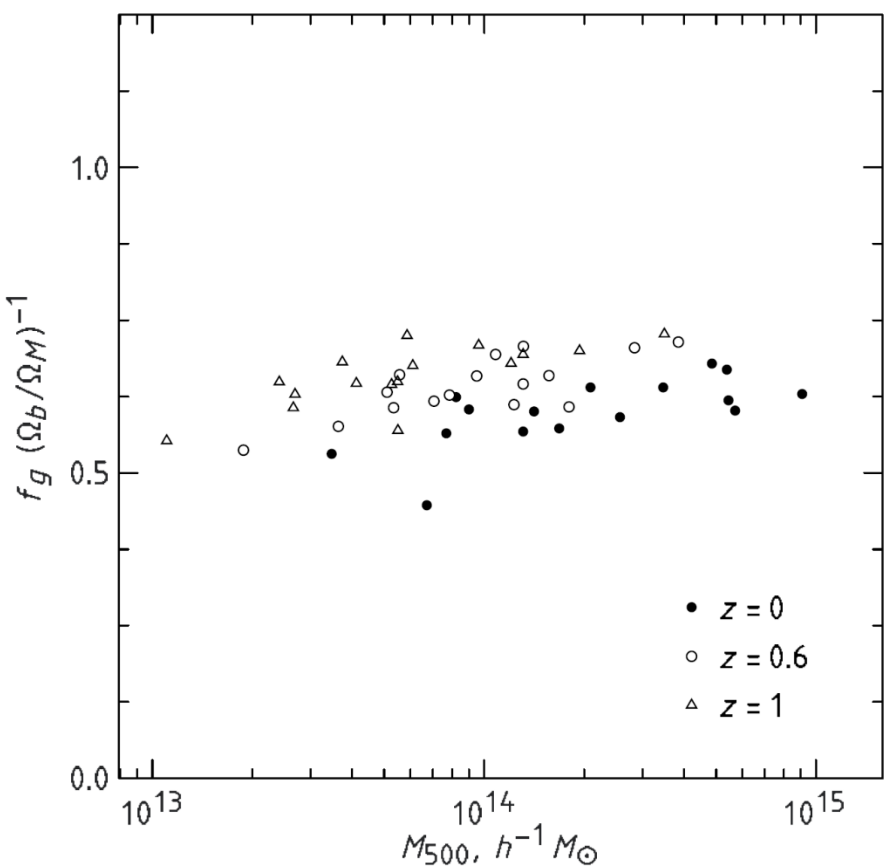
Does this work in simulations?

evolution of gas fractions at low redshifts in simulated clusters is quite self-similar (in the sense just discussed)

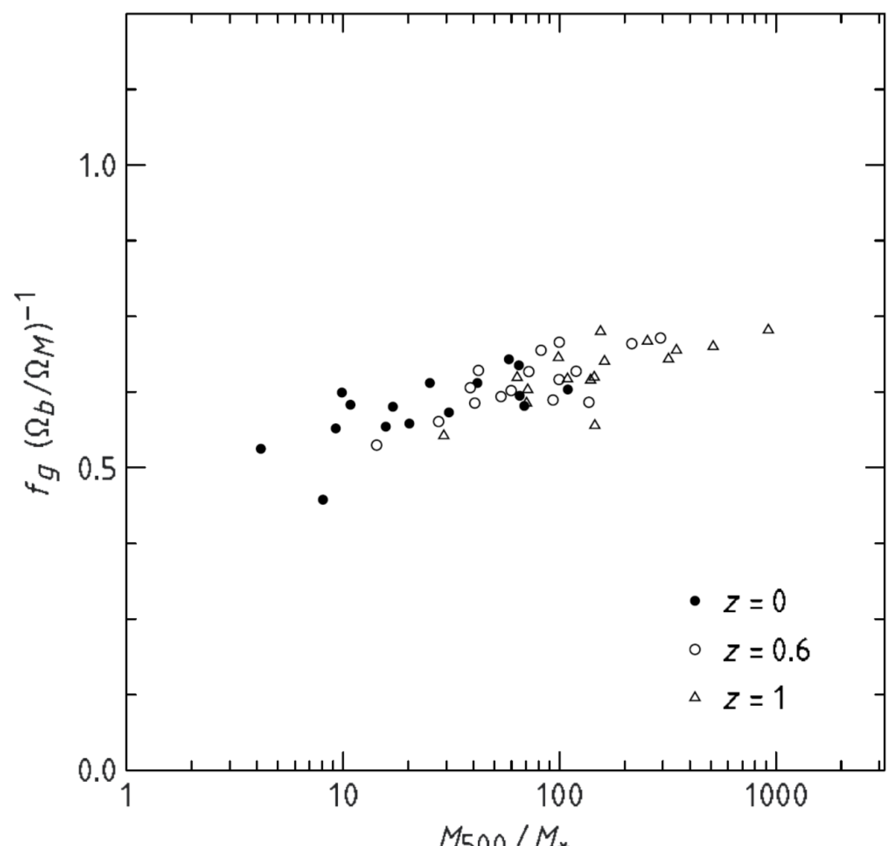
this makes sense if the main effects of non-self-similar processes are confined to high z and cluster evolution at lower z is driven mainly by gravity and is self-similar

Figure adopted from Vikhlinin et al. 09, used simulations of Nagai et al. 07

gas fraction in units of universal baryon fraction



physical mass M_{500}



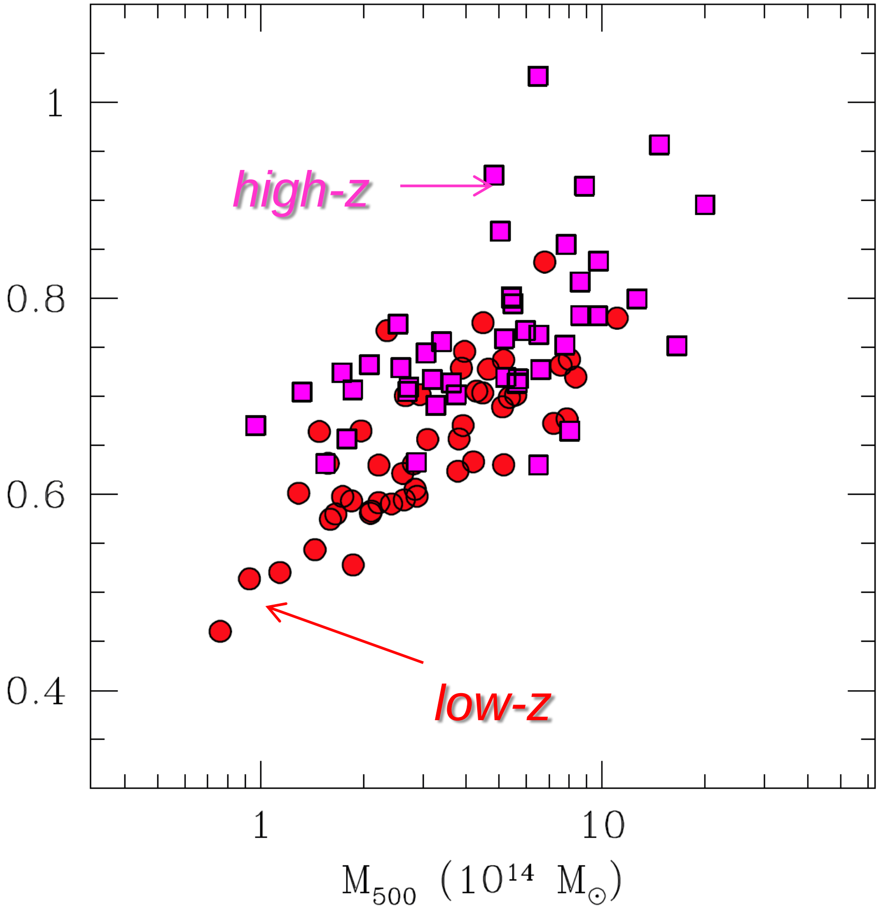
M_{500} scaled by nonlinear mass M_{NL} at each redshift

Does this work for observed clusters?

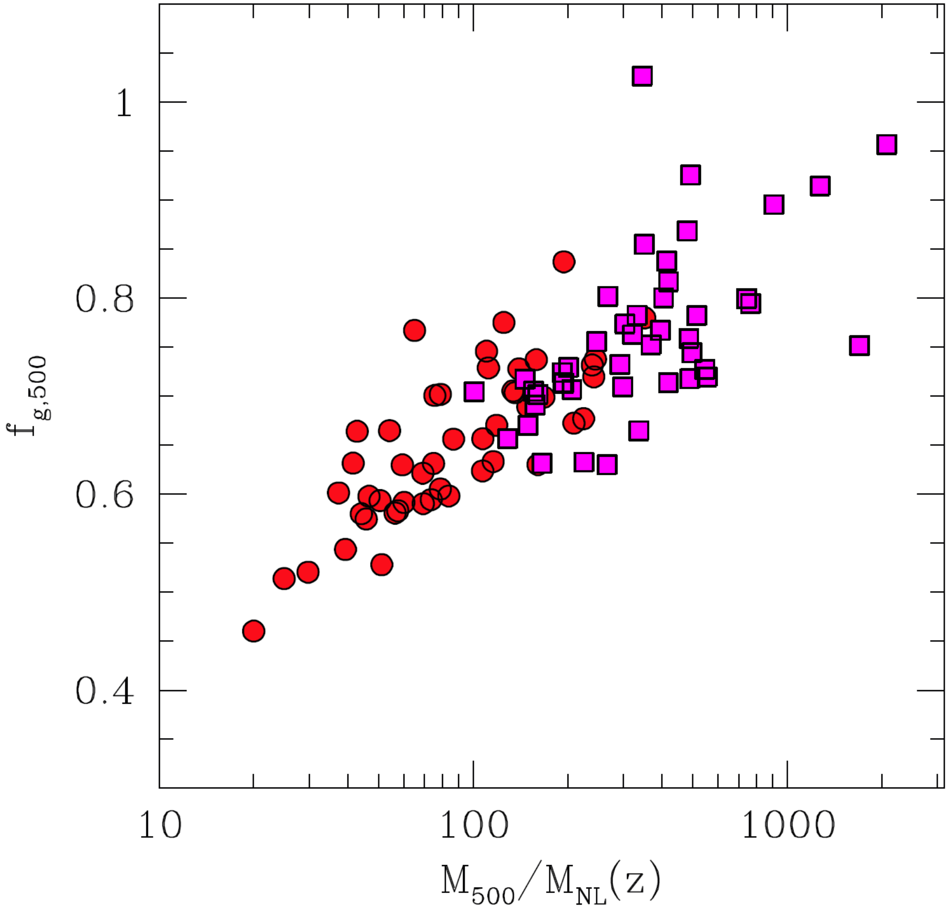
evolution of fgas from z~0 to ~0.4 is consistent
with the expected M/M_{NL} scaling

Observational cluster samples from Lin, Y.-T. et al. 2012, ApJL 745, L3

gas fraction in units of universal baryon fraction



physical mass M_{500}



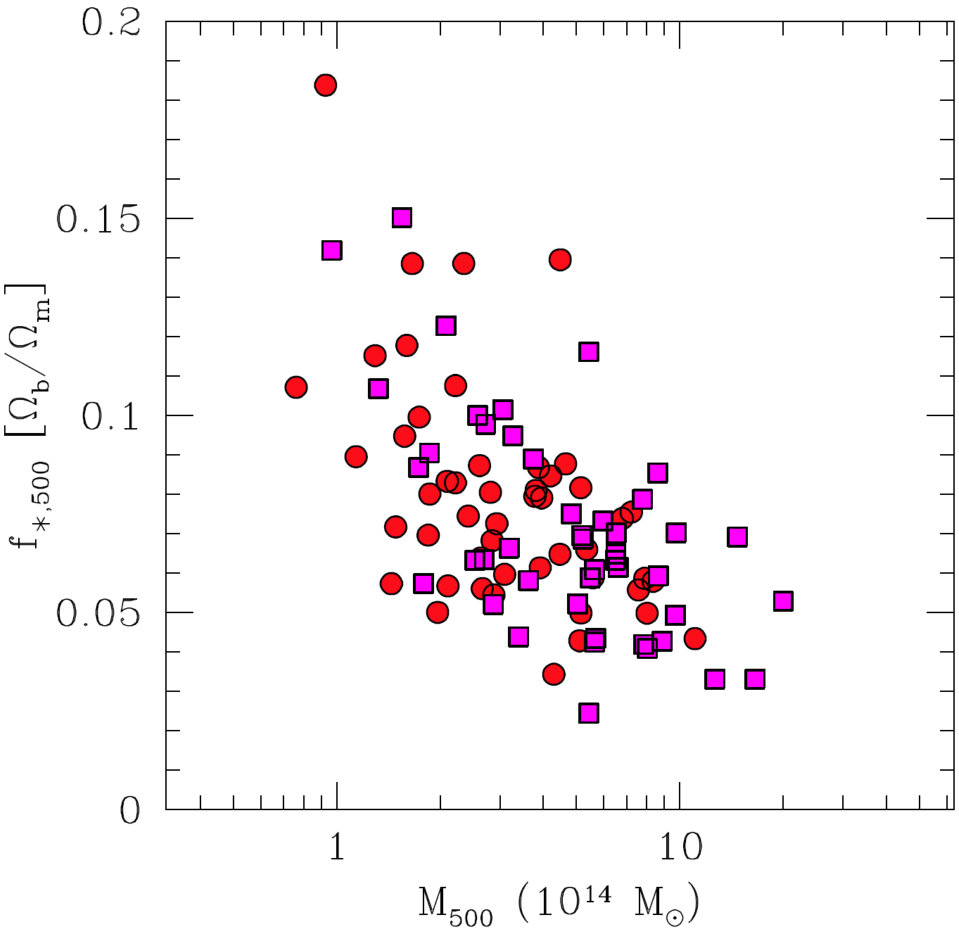
M_{500} scaled by nonlinear mass M_{NL} at each redshift

However, observed $f_{*,500}$ evolution

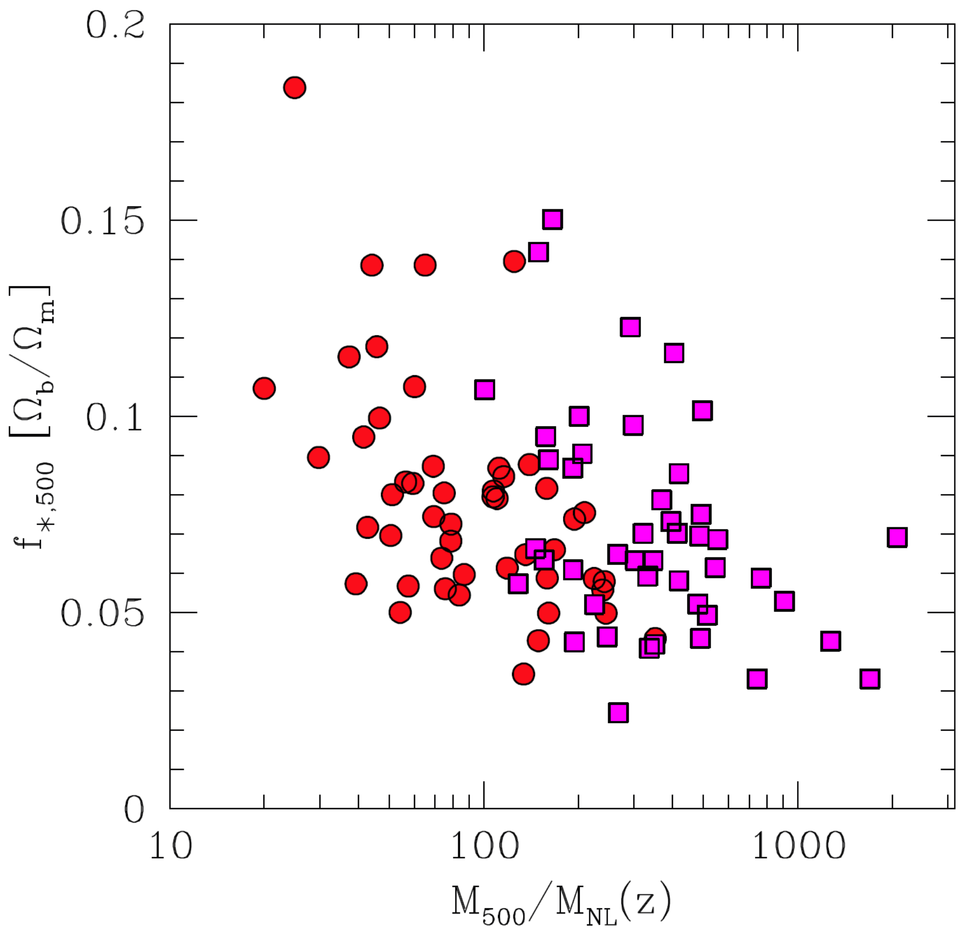
from z~0 to ~0.4 is <u>inconsistent</u> with self-similar expectation

therefore, it appears that stars and hot gas evolve differently with respect to the total cluster mass. Why?...

stellar fraction in units of universal baryon fraction



physical mass M_{500}



M_{500} scaled by nonlinear mass M_{NL} at each redshift

Let's revisit halo mass definition

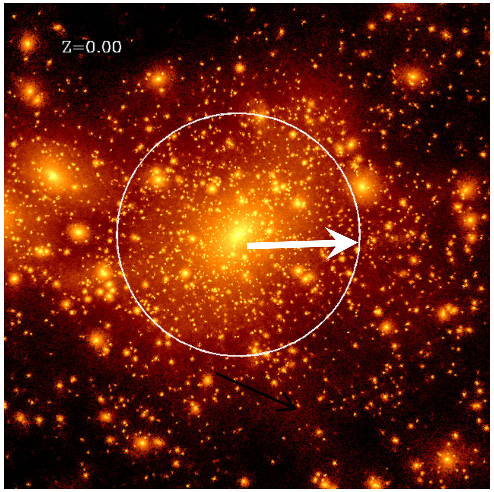
analytic models:

$$M = \frac{4\pi}{3}\bar{\rho}_{\rm m}\, R^3 \longleftarrow \textit{filter radius}$$

non-linear characteristic mass:

$$\sigma(M_{\rm NL}) = D_+(z)\sigma(M_{\rm NL}, z=0) = \delta_c \approx 1.69$$

simulations:

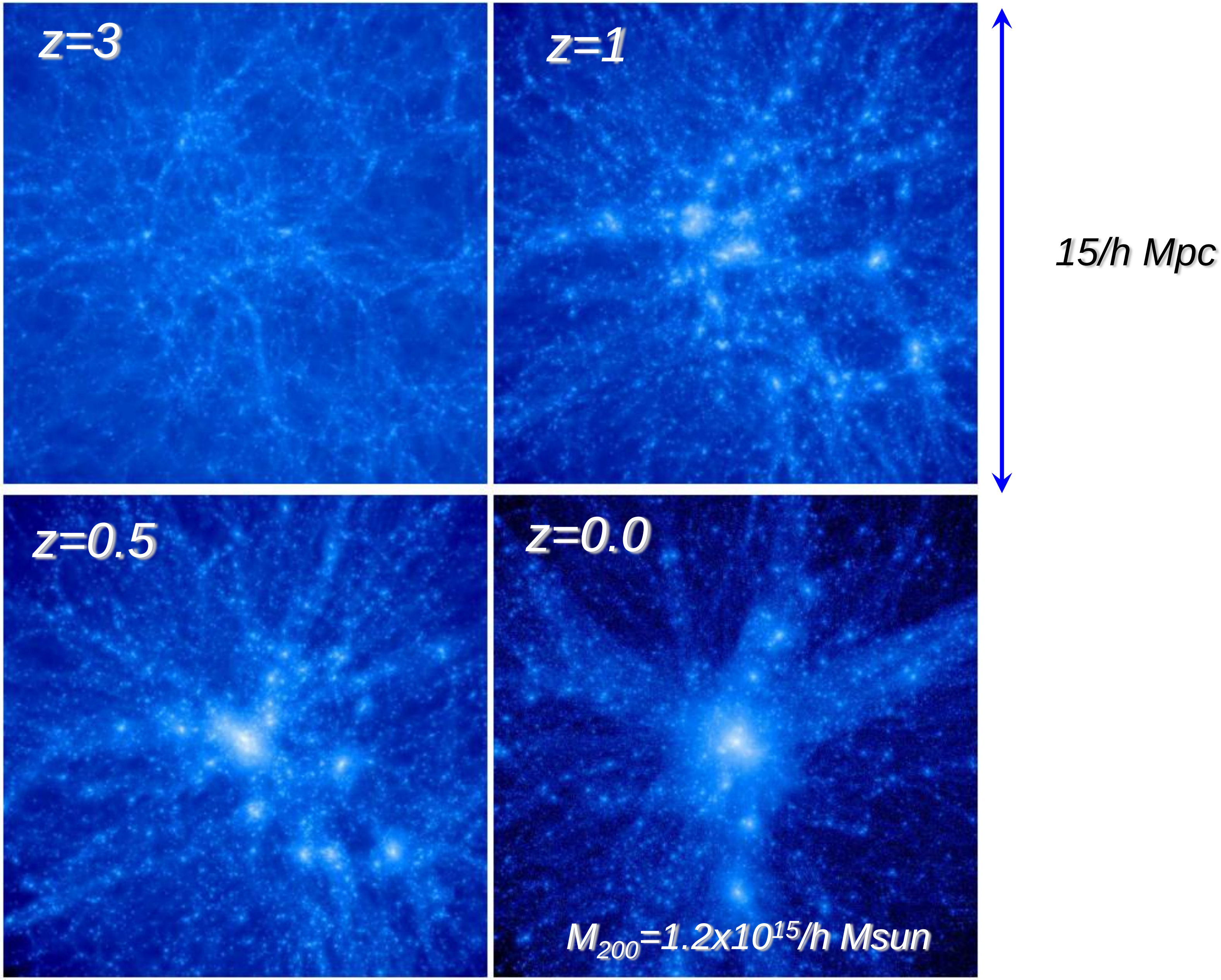


spherical overdensity (SO) mass

$$M_\Delta = \frac{4\pi}{3}\Delta\,\rho_{\rm cr} R_\Delta^3$$

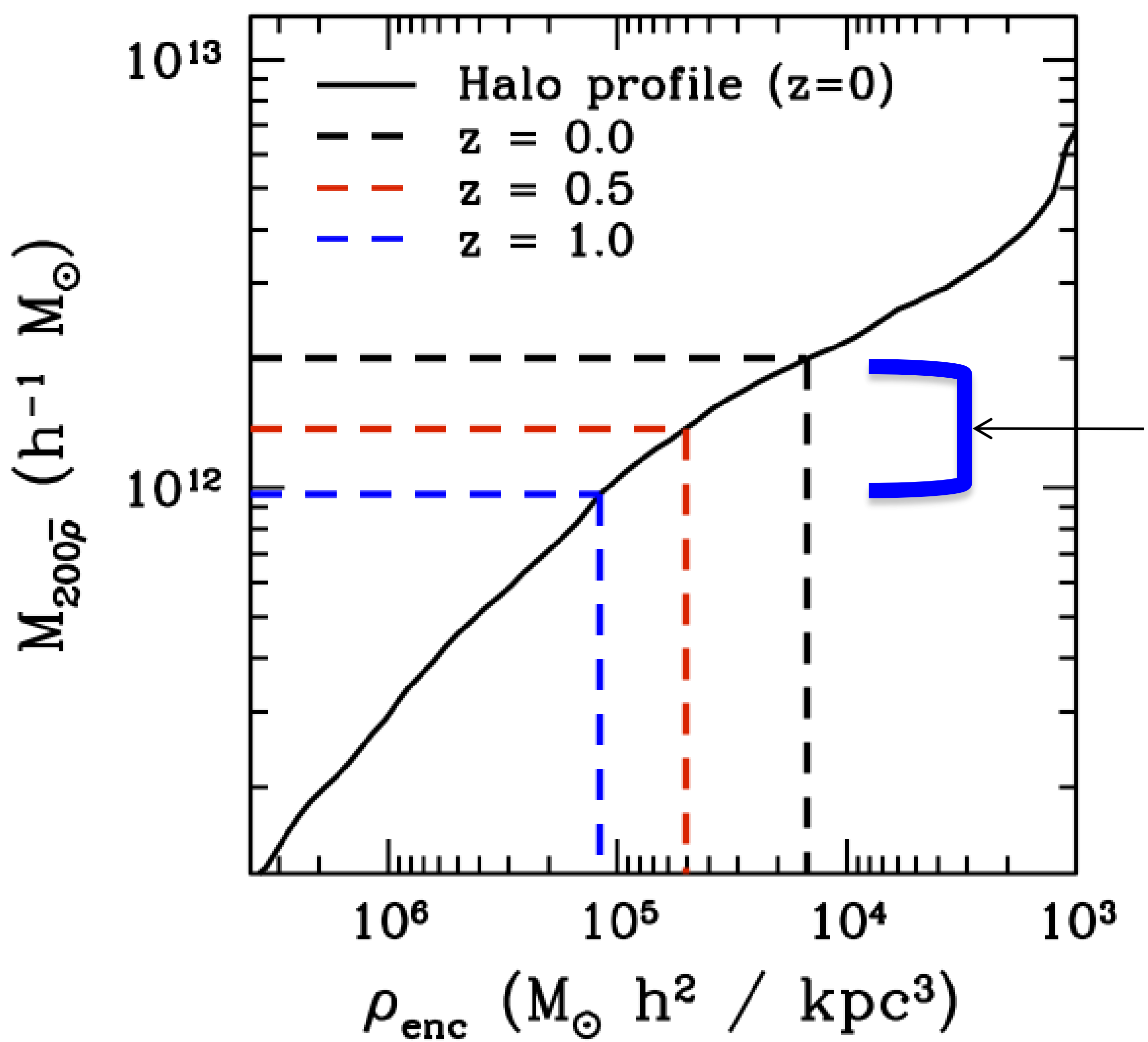
radius of sphere enclosing overdensity Δ wrt reference density

The actual collapse is considerably more complex than idealized spherical or ellipsoidal collapse



Real halos often do not have a well-defined boundary

For the standard mass definitions (SO or FoF) mass evolves due to evolving critical or background density of the Universe, even if object itself does not evolve
This was noted by Diemand et al. 2007 for the MW-sized halo (VL simulation)

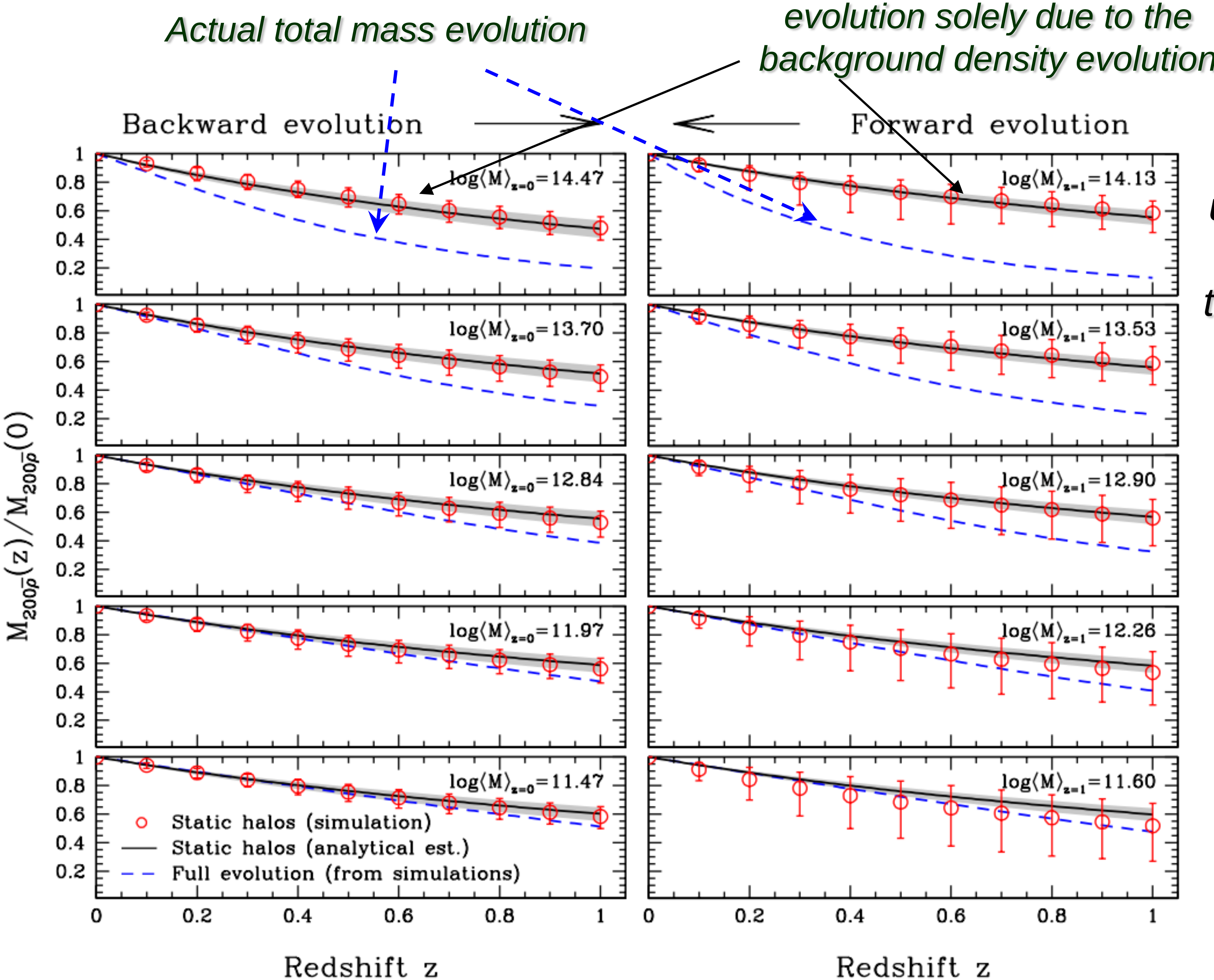


mass within radius enclosing overdensity 200 x the mean density

Pseudo-evolution

enclosed density

This "artificial" evolution can be dominant source of mass evolution at low z even for cluster-mass objects



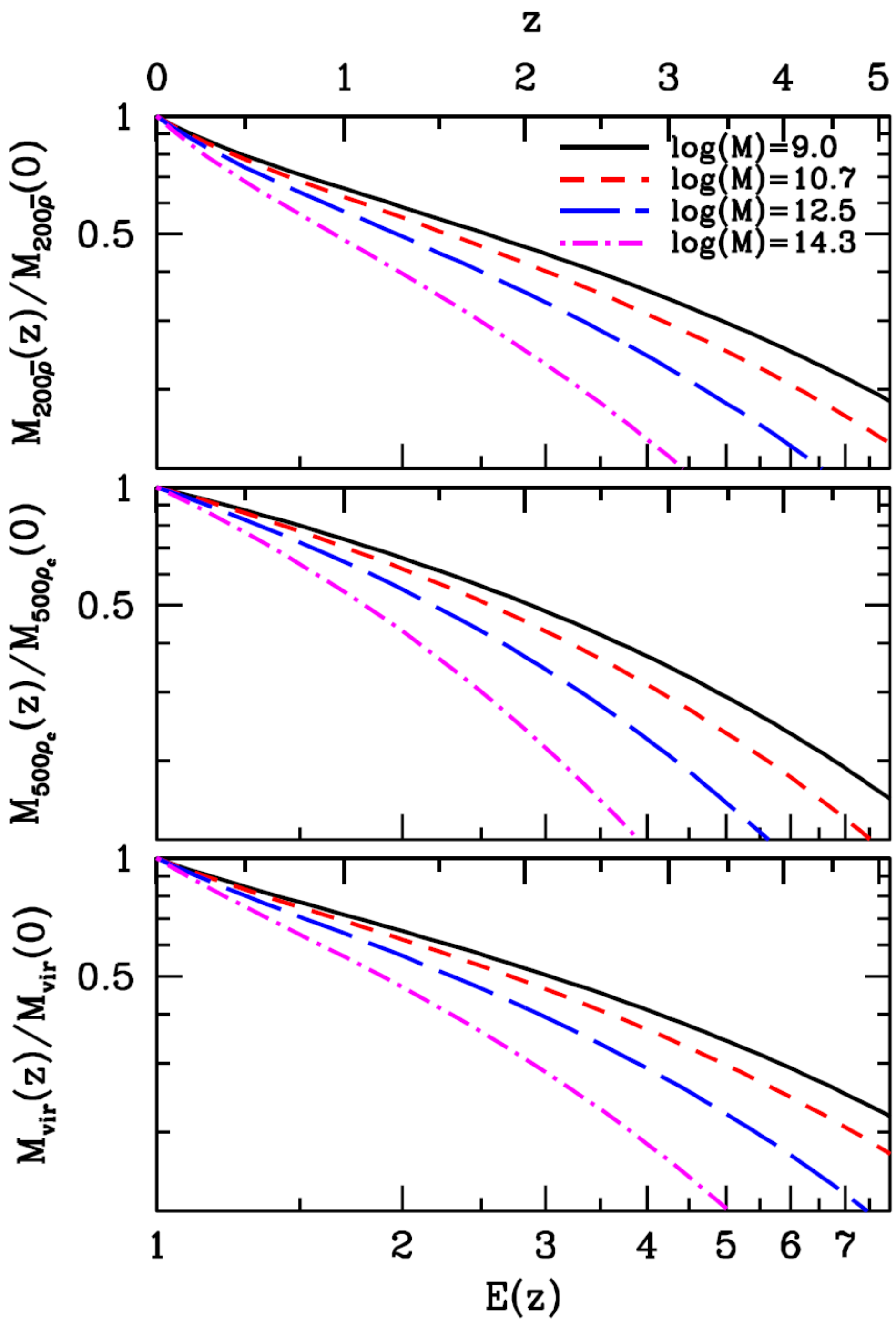
analysis was done using halo populations extracted from the Bolshoi simulations

red points – actual measurements from simulation (error bars show scatter)

solid line – predicted evolution assuming that halos can be described by NFW profile at z=0 or z=1 and do not evolve

Diemer, More & Kravtsov 2012, ApJ submitted (arXiv/1207.0816)

Pseudo-evolution of halo mass for different mass definitions

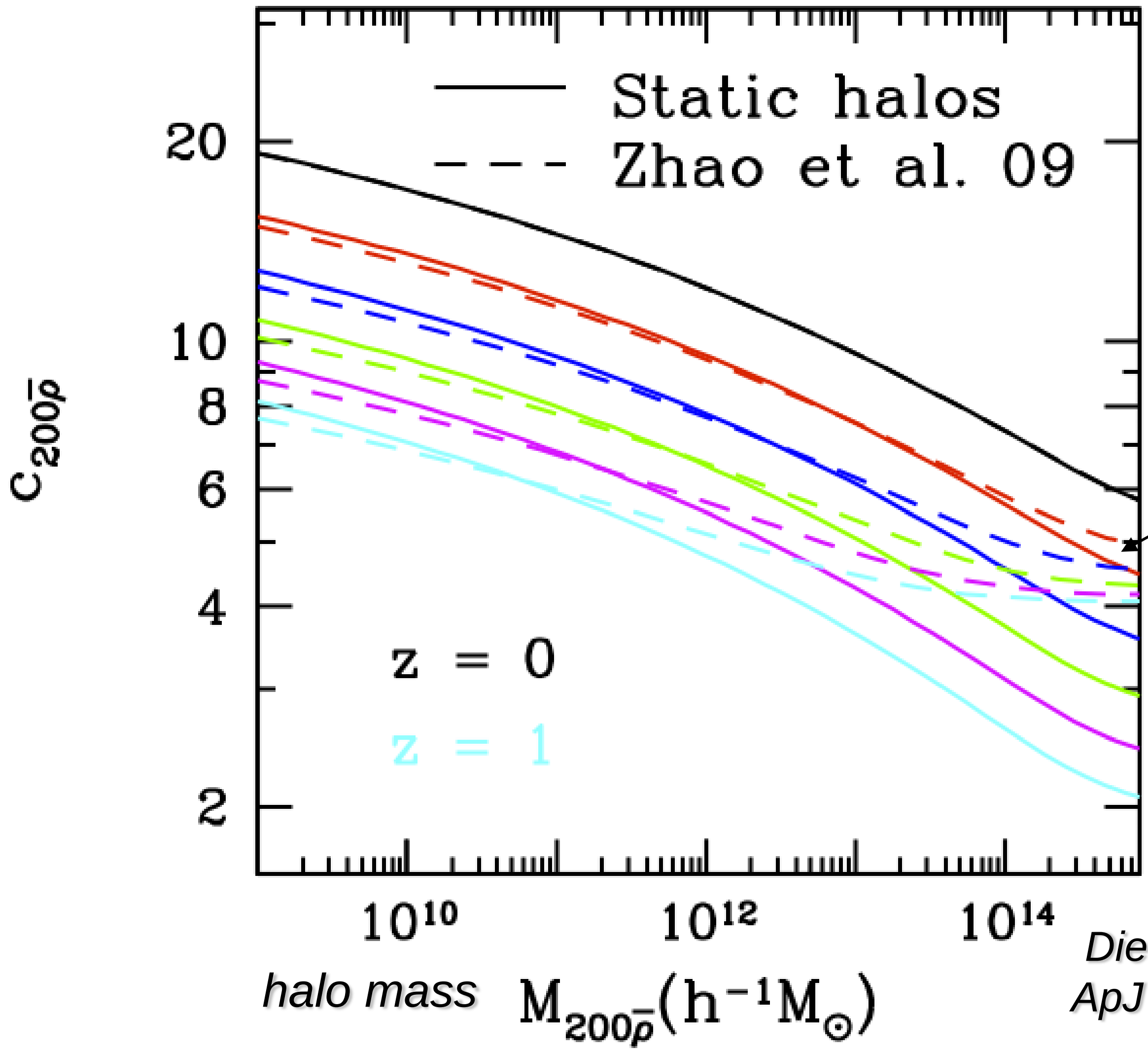


Diemer, More & Kravtsov 2012,
ApJ submitted (arXiv/1207.0816)

Implication for the evolution of halo concentration-mass relation

Evolution of concentration at late times in halos of M<10^{13}-10^{14} Msun is almost entirely due to the pseudo-evolution of mass (i.e., just reflects expansion of the universe and not physical evolution of halos)

halo concentratio = virial radius/ scale radius



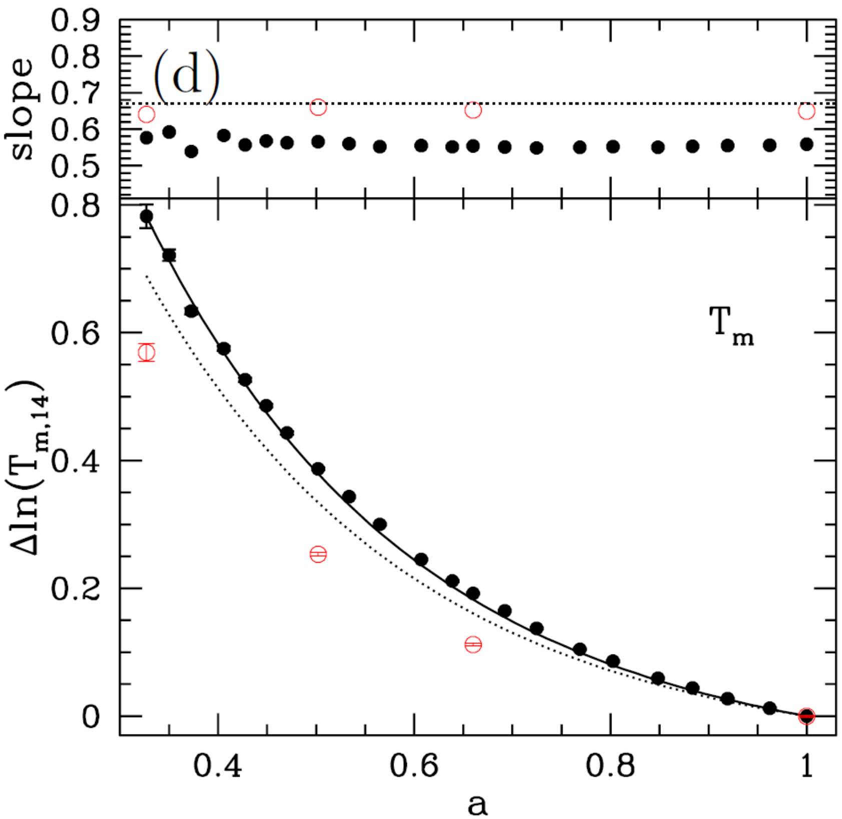
halo mass

the only real evolution here is non-evolution of concentrations at high masses

Diemer, More & Kravtsov 2012, ApJ submitted (arXiv/1207.0816)

Implication for the evolution of M–T relation

Temperature corresponding to M200c=1x10[14] Msun
Normalized to value at z=0



expansion factor

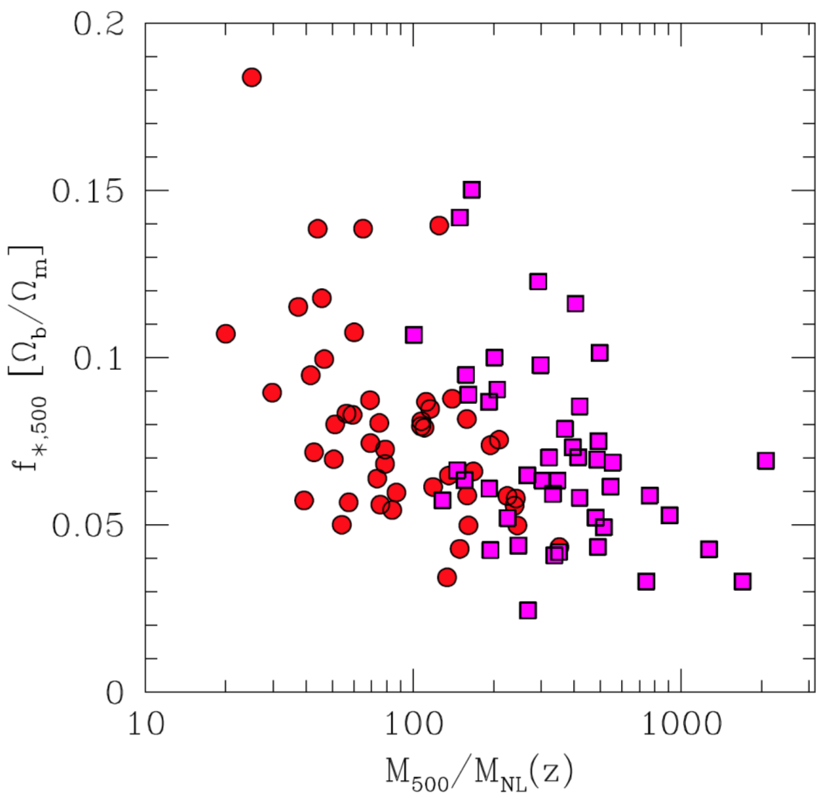
- *Temperature and total mass profiles are significantly different (much more so than gas and total mass profiles) and thus pseudo-evolution of T and M_{500} will be very different (T is almost insensitive to it).*

- *This contributes to the evolution of T -M_{500} relation: for a given T, M_{500} evolves faster than it should (or, for a given M_{500}, T evolves slower than it should).*

- *Such pseudo-evolution needs to be taken into account in baseline model for evolution of cluster scaling relations or, better yet, we need to switch to a better definition of mass or potential proxy.*

Implication for the evolution of $M_{*,500}$ -M_{500} relation

stellar fraction in units of universal baryon fraction



M_{500} scaled by nonlinear mass M_{NL} at each redshift

- Stellar mass and total mass profiles are significantly different (much more so than gas and total mass profiles) and thus pseudo-evolution of $M_{*,500}$ and M_{500} will be different.

- This contributes to the evolution of $M_{*,500}$ -M_{500} relation (pseudo-evolution of M500 is larger than $M_{*,500}$ and thus amplitude of the relation will decrease with decreasing redshift due to pseudo-evolution) and can explain why this relation evolves differently from the $M_{gas,500}$-M_{500} relation

- Such pseudo-evolution needs to be taken into account in baseline model for evolution of cluster scaling relations or, better yet, we need to switch to a better definition of mass or potential proxy.

summary

- *Kaiser model for baseline evolution of cluster scaling relations relies on a number of assumptions. Some of these may not be correct and thus deviations from this model do not always imply deviations from self-similar behavior! Extensions to this model can be developed*

  Kravtsov & Borgani 2012, ARAA in press (arXiv/1205.5556)

- *Significant fraction of halo mass evolution during late epochs observed in simulations is due simply to the evolution of the reference density used to define halo radius and not due to real physical accretion*

  Diemer, More, Kravtsov ApJ submitted (arXiv/1207.0816)

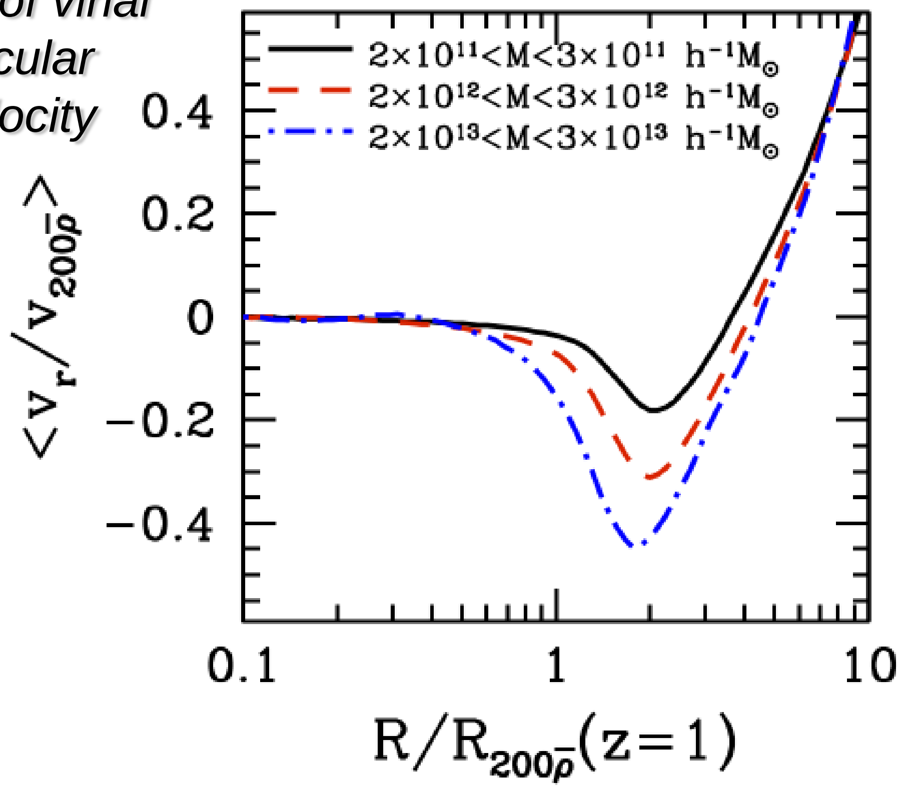
- *The pseudo-evolution of halo mass needs to be taken into account when interpreting evolution of galaxy and cluster scaling relations or comparing analytical models to simulations*

- *Ultimately, we need a better definition of mass that does not suffer from pseudo-evolution or come up with an alternative to mass.*

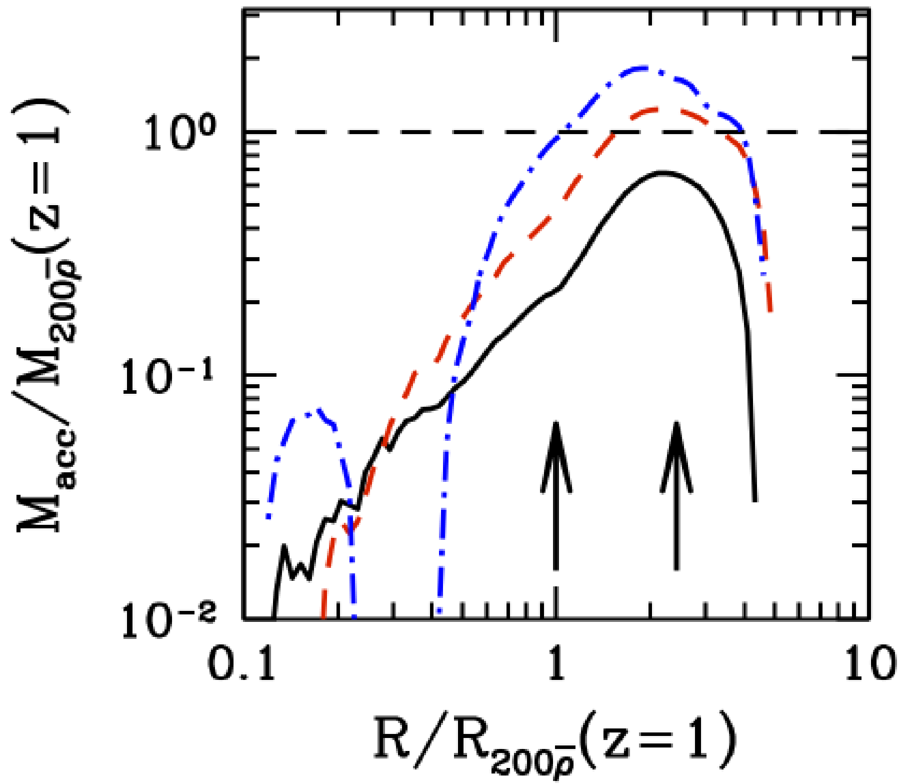
estimates of the actual accretion based on average radial infall velocities of matter around R_Δ

see also Prada et al. 2006, Cuesta et al. 2008, Anderhalden & Diemand 2011

mean radial velocity of matter in units of virial circular velocity



estimate of mass that would be accreted within a certain R from z=1 and z=0



Radius in units ov R200 at z=1