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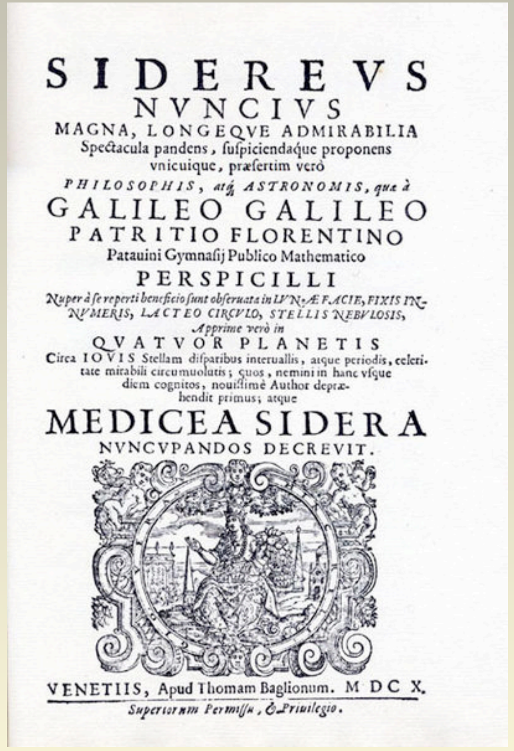
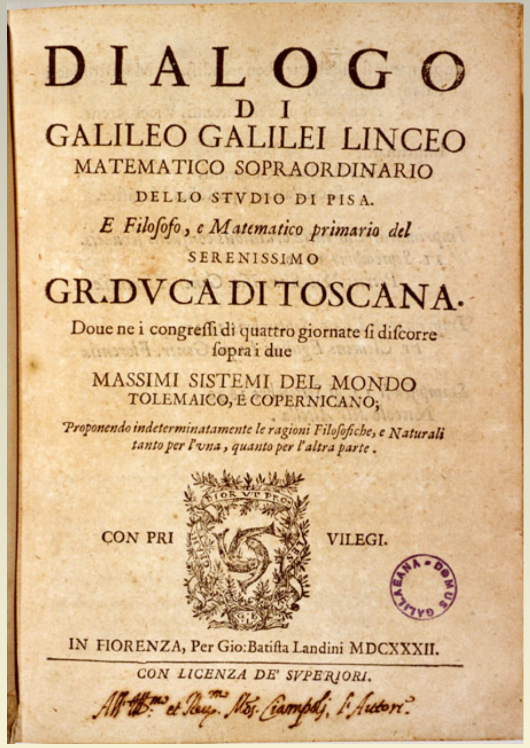
N-body Simulations of Interacting Dark Energy Models

[arXiv:0812.3901 in collaboration with V. Pettorino, G. Robbers, V. Springel]

Dark Energy Conference - Galileo Galilei Institute for Theoretical Physics
Florence - 02 III 2009

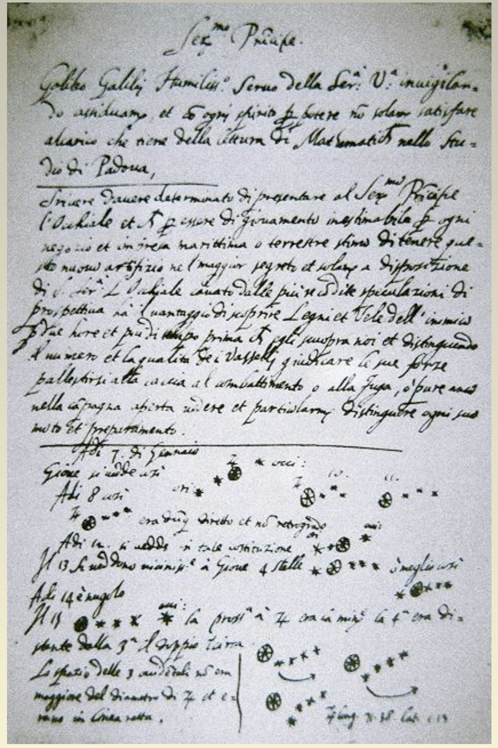

SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vsque diem cognitos, nouissimè Author depræhendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

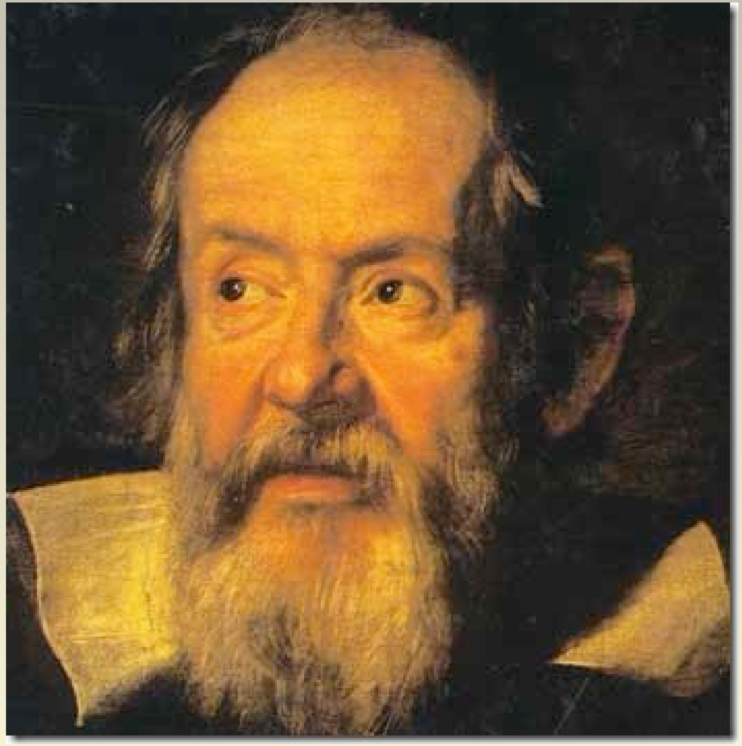
VENETIIS, Apud Thomam Baglionum. M D C X.
Superiorum Permissu, & Priuilegio.


DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filosofo, e Matematico primario del
SERENISSIMO
GR. DVCA DI TOSCANA.
Doue ne i congressi di quattro giornate si discorre
sopra i due
MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;
Proponendo indeterminatamente le ragioni Filosofiche, e Naturali
tanto per l'vna, quanto per l'altra parte.

CON PRI VILEGI.

IN FIORENZA, Per Gio: Batista Landini MDCXXXII.
CON LICENZA DE' SVPERIORI.





Outline

Basic equations and main features of coupled quintessence models

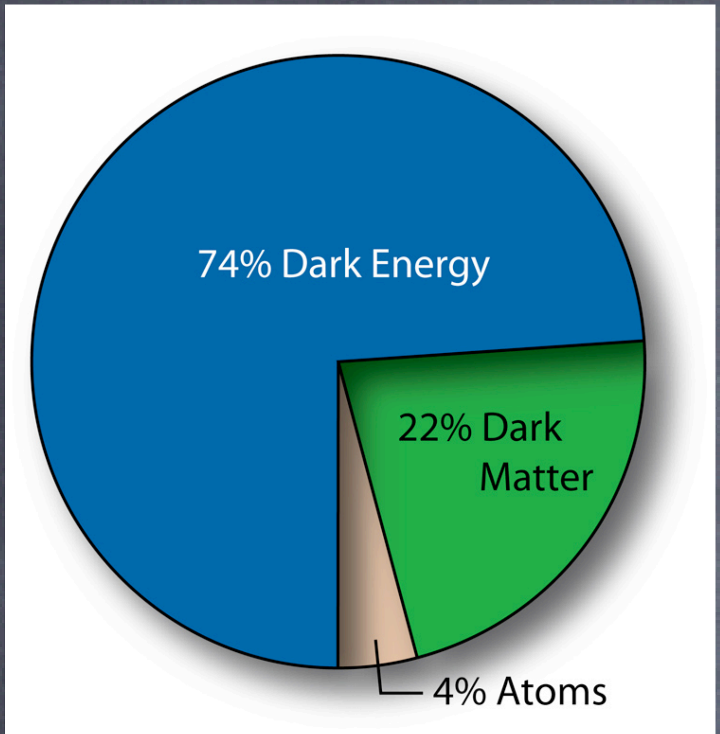
Numerical implementation in an N-body code

Numerical tests of the implemented physics

High resolution simulations results:

- Baryon-CDM bias
- Halo baryon fraction
- Density profiles
- Halo concentrations
- Physical interpretation of the results

our framework...



from the WMAP team

According to the presently established set of cosmological parameters, we assume the dark energy to be given by a quintessence scalar field:

$$\rho_{de} = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

[C. Wetterich, 1988]

[P. J. E. Peebles and B. Rhatra, 1988]

and we introduce a coupling between the dark energy and the cold dark matter fluid (baryons are uncoupled) in the form:

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV(\phi)}{d\phi} = \kappa\beta(\phi)\rho_c$$

$$\dot{\rho}_c + 3H\rho_c = -\kappa\beta(\phi)\rho_c\dot{\phi}$$

$$\dot{\rho}_b + 3H\rho_b = 0$$

[C. Wetterich, 1995]

[L. Amendola, 2004]

The parameters of our models

We consider a series of quintessence models with inverse power potential:

$$V(\phi) = \frac{\Lambda^{4+\alpha}}{\phi^{\alpha}}$$

with constant coupling to CDM and no coupling to baryons, and with the cosmological parameters set according to the WMAP5 results:

Model's parameters

Model	Slope α	Coupling to CDM βc
ΛCDM	0	0
RP1	0.143	0.04
RP2	0.143	0.08
RP3	0.143	0.12
RP4	0.143	0.16
RP5	0.143	0.2
RP6	2.0	0.12

The same models as in Macciò et al (2004)

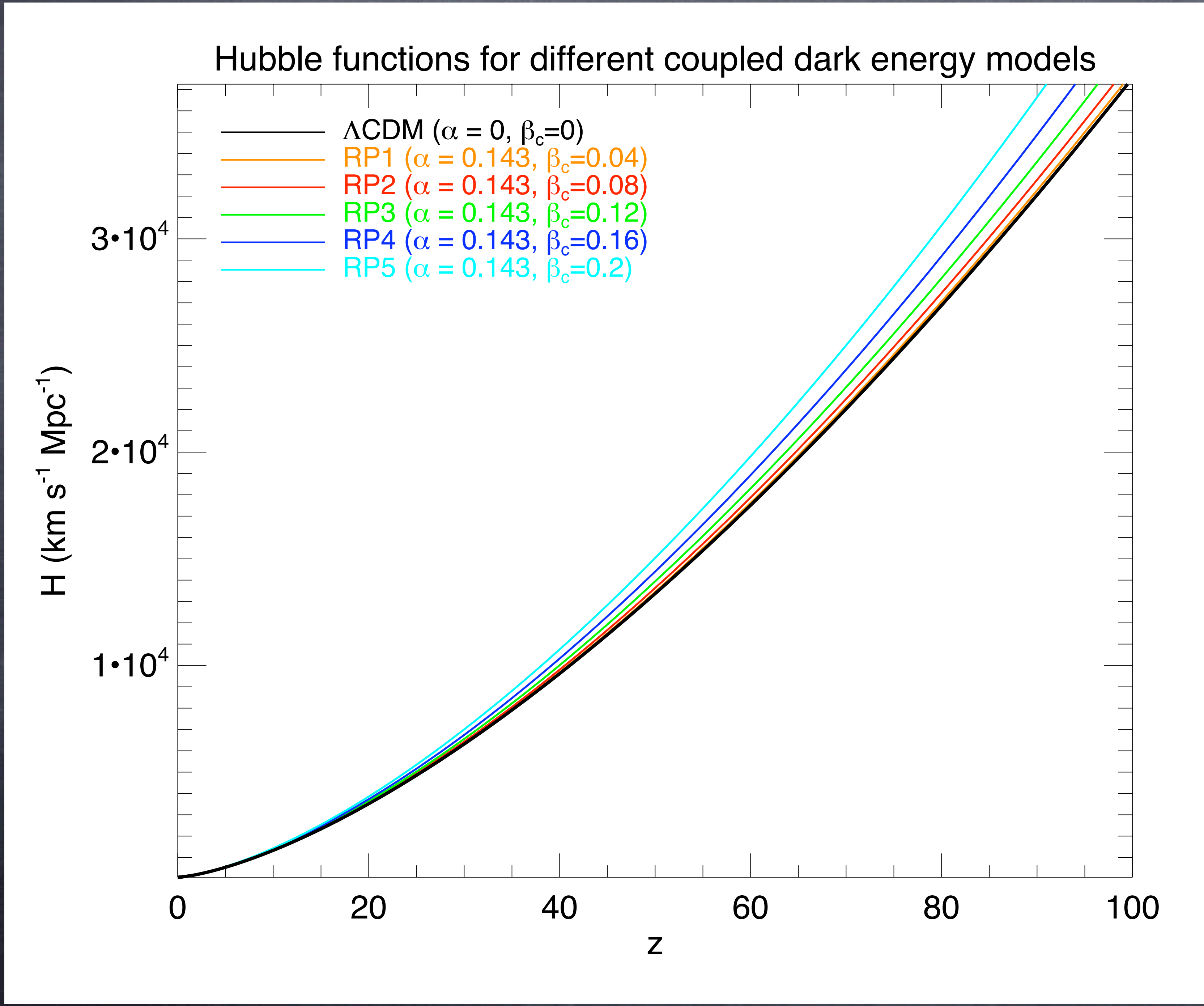
Cosmological parameters

Ω_{CDM}	0.213
Ω_{DE}	0.743
Ω_b	0.044
H_0	71.9 $\mathrm{km\ s^{-1}\ Mpc^{-1}}$
σ_8	0.769
n	0.963

[Komatsu et al. (2008)]

CDE features: the effect on the expansion

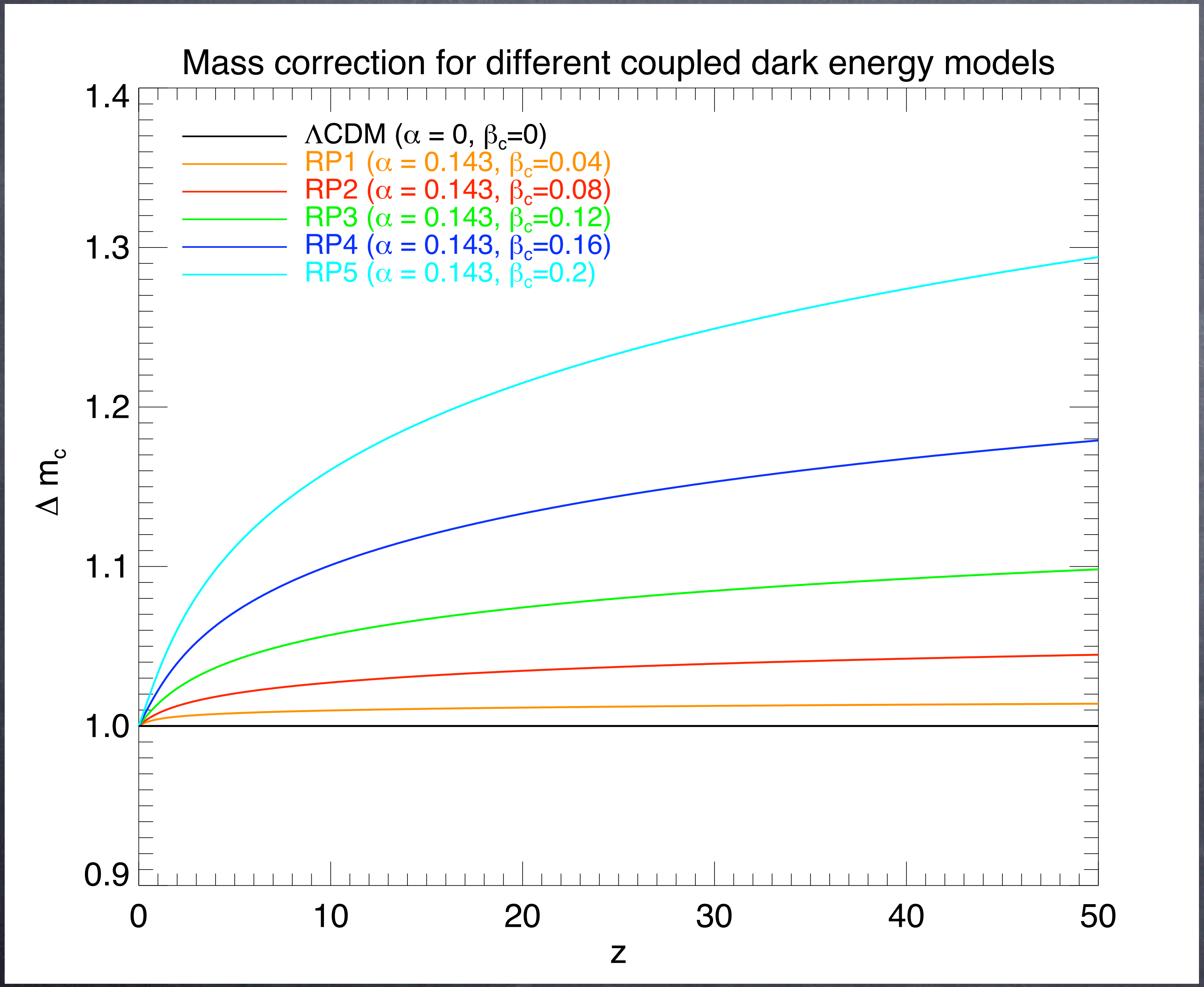
The presence of a DE-CDM coupling changes the expansion history of the Universe. A larger coupling means a larger DE fraction at high redshift, and therefore a faster expansion...



needs to be taken into account in N-body simulations

CDE features: mass variation

$$m(\phi) = m_0 \exp\left[\kappa \int_{\phi}^{\phi_0} \beta(\phi')d\phi'\right] = m_0 \Delta m_c(\phi)$$



needs to be taken into account in N-body simulations

CDE perturbations in the Newtonian limit

If we perturb the coupled dynamic equations to linear order, we find for the small scale limit in the Newtonian gauge the evolution equation:

$$\ddot{\delta}_c + \left(2H - 2\beta\frac{\dot{\phi}}{M}\right)\dot{\delta}_c - \frac{3}{2}H^2\left[(1+2\beta^2)\,\Omega_c\delta_c + \Omega_b\delta_b\right] = 0$$

extra-friction term

modified gravitational interaction

varying DM particle mass

FIFTH FORCE - VIOLATION OF WEP

[Nusser, Gubser, Peebles (2005)]

[Kesden & Kamionkowski (2006)]

[Keselman, Nusser, Peebles (arXiv:0902.3452)]

[Macciò et al., (2004)]

CDE perturbations in the Newtonian limit

If we perturb the coupled dynamic equations to linear order, we find for the small scale limit in the Newtonian gauge the acceleration equation:

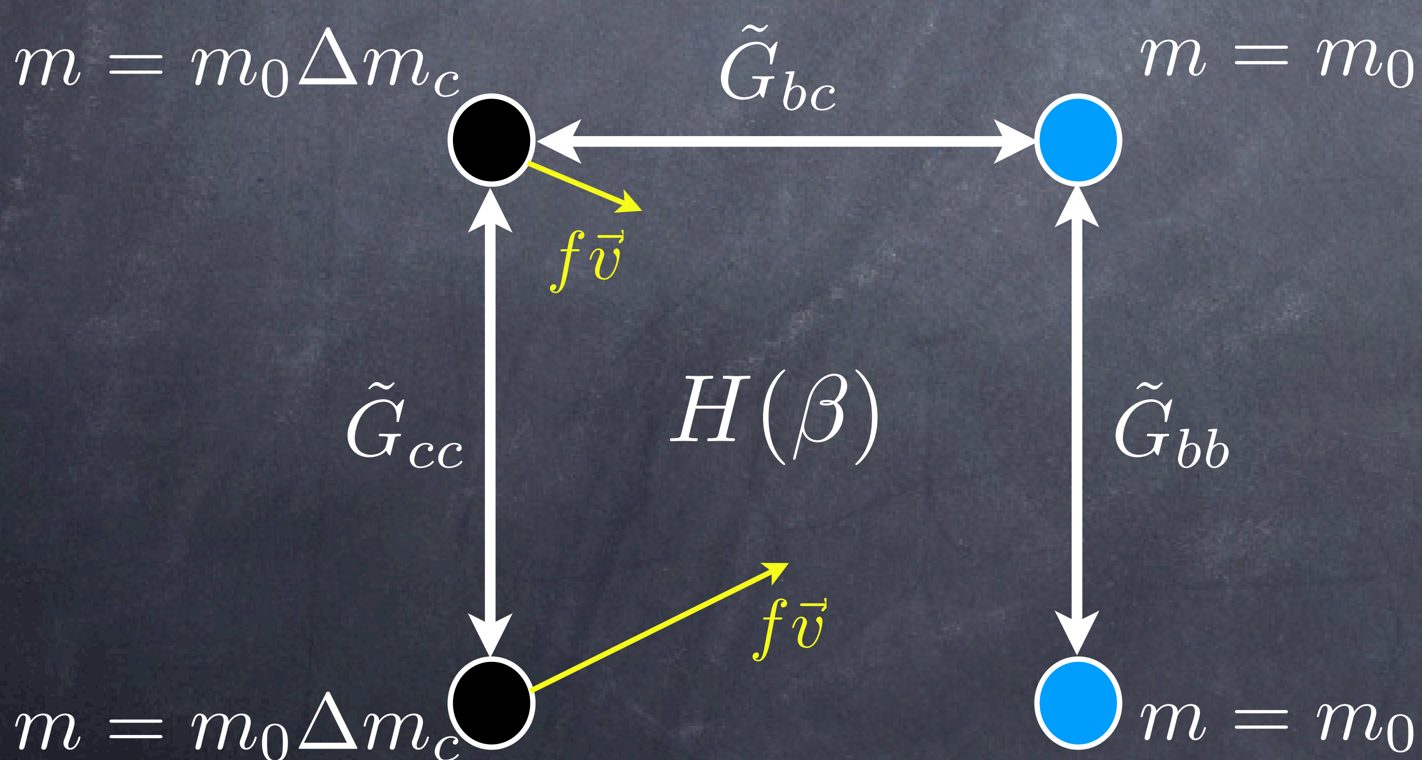
varying DM particle mass

$$\dot{\vec{v}} = -\left[H - \beta\frac{\dot{\phi}}{M}\right]\vec{v} - G\left[(1+2\beta^2)\frac{\vec{\nabla}\Phi_c}{a} + \frac{\vec{\nabla}\Phi_b}{a}\right]$$

extra-friction term

modified gravitational interaction

We implement these new features in GADGET [V. Springel, 2005]



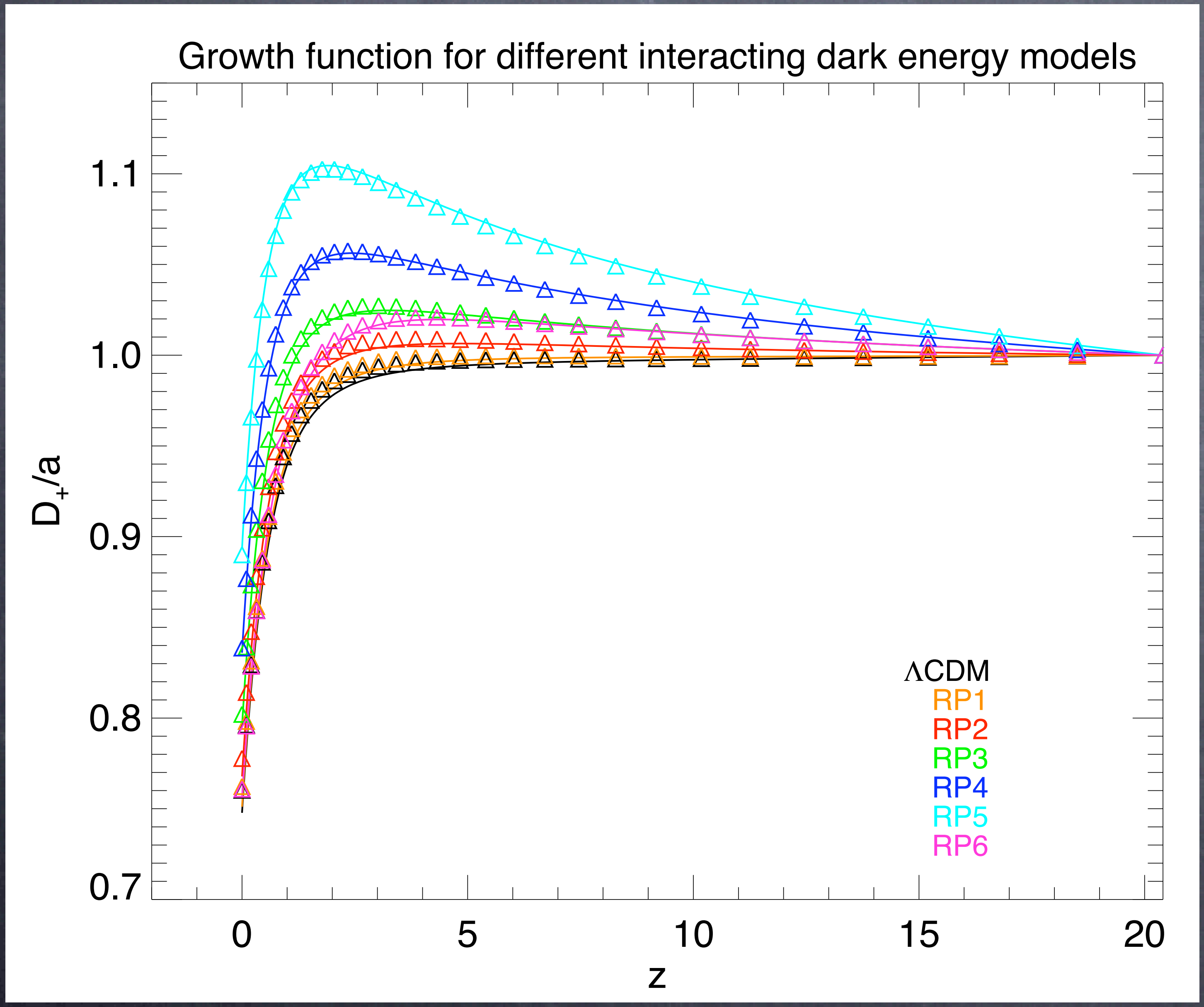
$$\tilde{G}_{ij} = G_N(1 + 2\beta_i\beta_j)$$

[L. Amendola, 2004]

$$f = \beta_i \frac{\dot{\phi}}{M}$$

Numerical tests - the Growth Factor

With a set of low resolution simulations we test the linear growth of density fluctuations by computing the evolution of the matter power spectrum amplitude on large scales at different redshifts.



$$L_{box} = 320h^{-1}Mpc$$

$$N = 2 \times 128^3$$

$$m_b \sim 1.9 \cdot 10^{11}\mathrm{h}^{-1}M_{\odot}$$

$$m_c(z=0) \sim 9.2 \cdot 10^{11}\mathrm{h}^{-1}M_{\odot}$$

the accuracy is at the percent level for all the values of the coupling.

The Simulations

For four of the models discussed before (ΛCDM, RP1, RP2, RP5) we run high resolution hydrodynamical simulations including all the modifications described above, normalizing density fluctuations with the same σ_8 today.

$L_{\rm box} = 80\,{\rm h}^{-1}{\rm Mpc}$	$m_c(z=0) \sim 2\cdot 10^8\,{\rm h}^{-1}{\rm M}_{\odot}$
$N = 2\times 512^3$	$m_b \sim 5\cdot 10^7\,{\rm h}^{-1}{\rm M}_{\odot}$
$\epsilon_g = 3.5\,{\rm h}^{-1}{\rm kpc}$	$z_i = 60$

In addition, we run other two simulations with the same numerical settings but switching off the hydrodynamic forces acting on baryons (ΛCDM NO SPH, RP5 NO SPH).

Finally, we ran a last simulation with the largest coupling value but with the same initial conditions as the ΛCDM one (RP5 NO GF).

ALL the simulations have the same random phases.

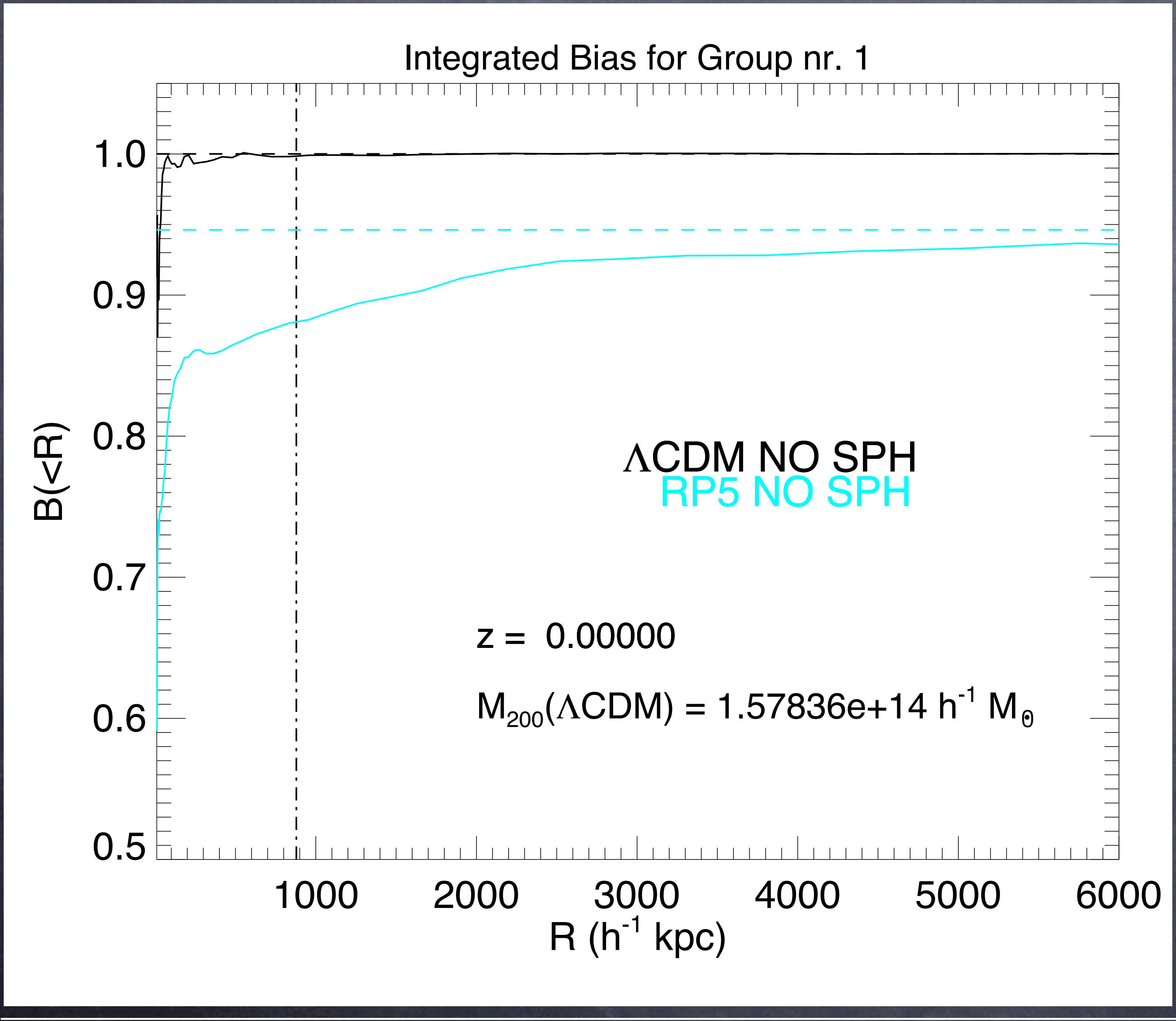
All the simulations ran on 64 processors on the OPA cluster @RZG

And now the results...

Results : Baryon-CDM bias [M.Baldi et al., arXiv:0812.3901]

Integrated bias (as defined in Macciò et al. [2004]):

$$B(<R) \equiv \frac{\rho_b(<R) - \bar{\rho}_b}{\bar{\rho}_b} \cdot \frac{\bar{\rho}_c}{\rho_c(<R) - \bar{\rho}_c}$$



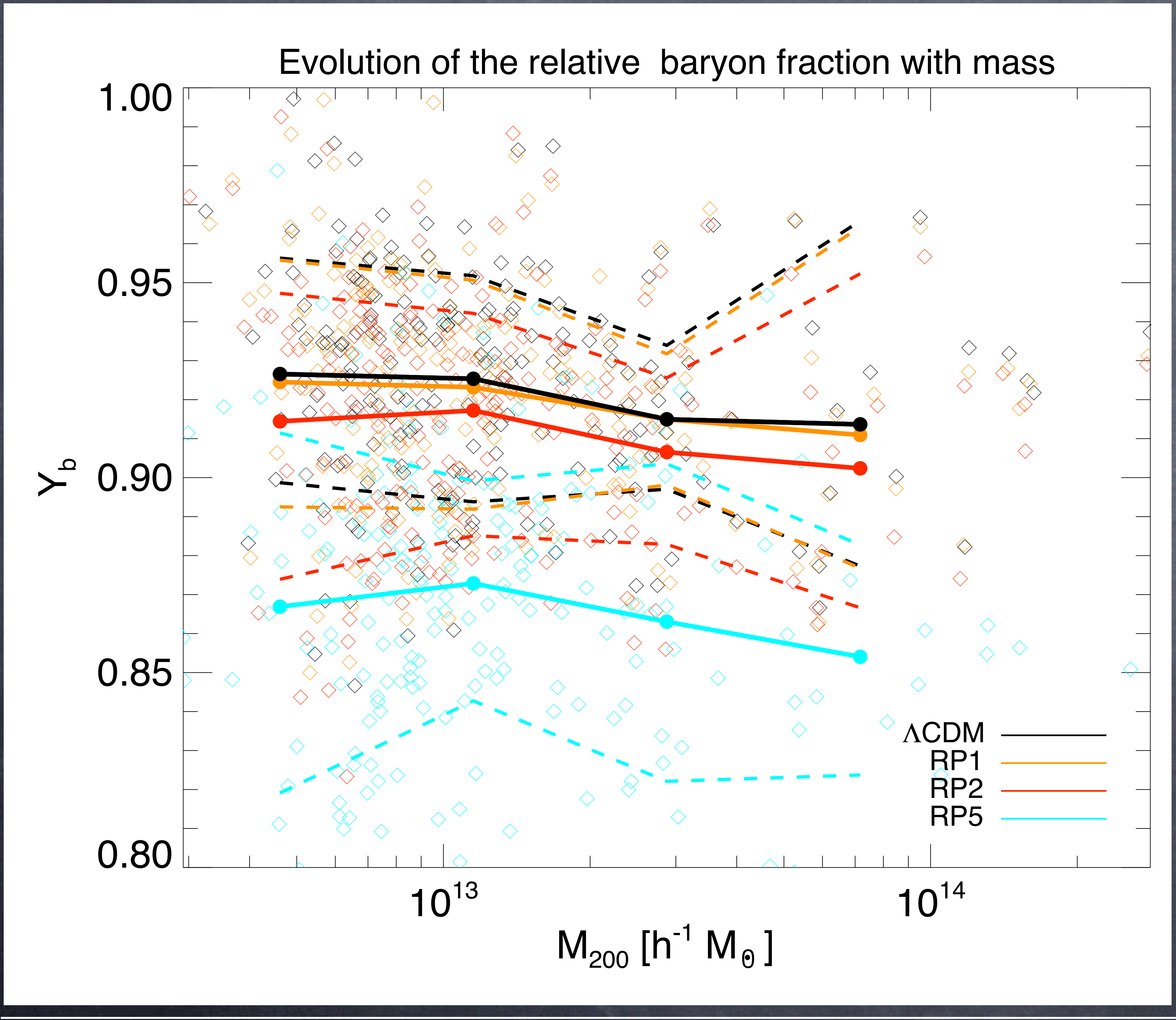
-At large radii the linear bias is recovered

-The bias is enhanced in the inner region both by hydrodynamic effects and by the extra scalar interaction

-The scalar field effect is clearly visible in case of purely collisionless simulations

Results : Halo baryon fraction [M.Baldi et al., arXiv:0812.3901]

As a consequence of the linear (and non-linear) bias between baryons and CDM the baryon fraction in halos is reduced proportionally to the coupling strength:

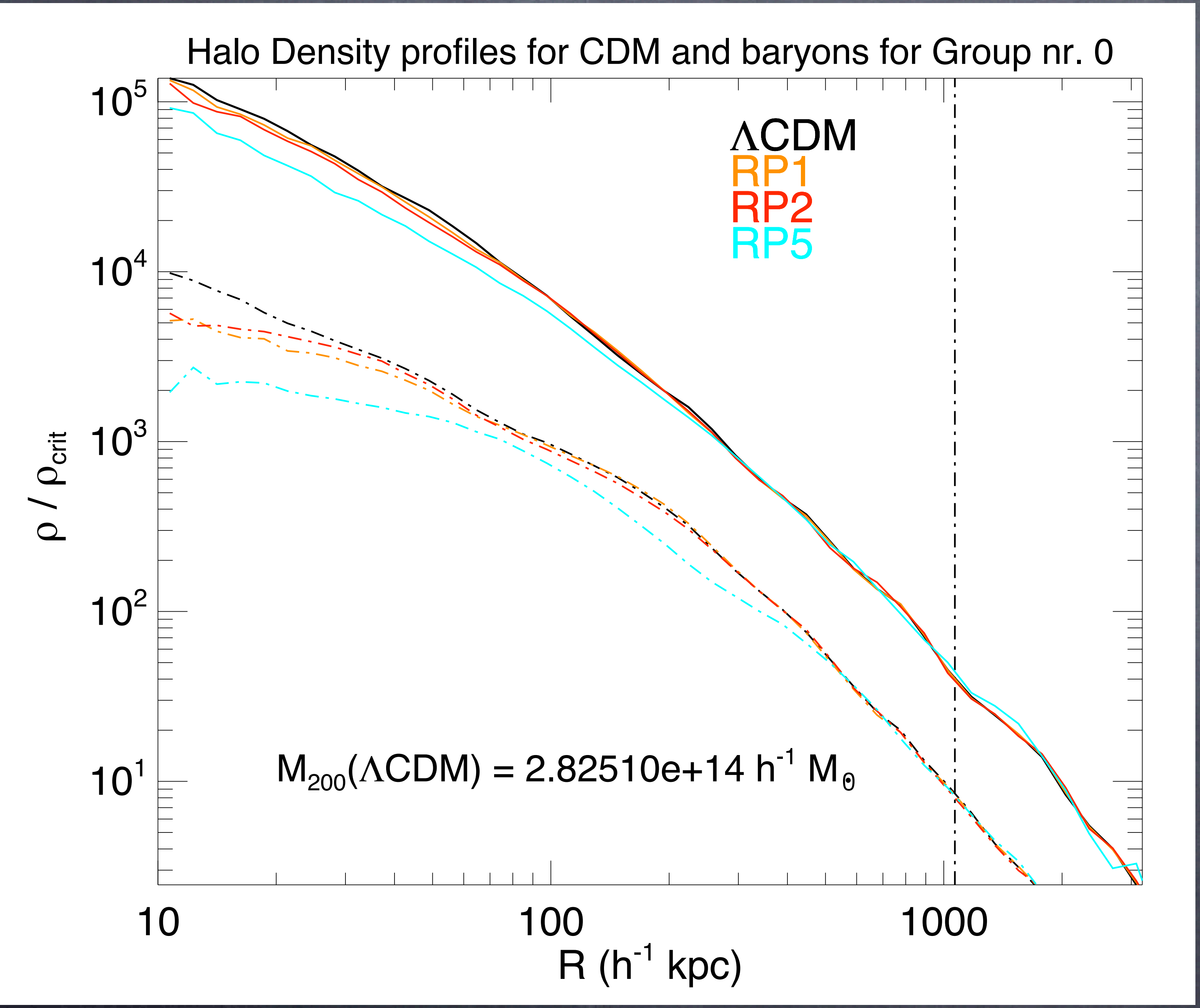


$$f_b \equiv \frac{M_b(< r_{200})}{M_{tot}(< r_{200})}$$

$$Y_b \equiv \frac{f_b}{\Omega_b/\Omega_M}$$

Results : Halo density profiles [M.Baldi et al., arXiv:0812.3901]

We compare density profiles of baryons and CDM for those halos in our group catalogue that can be identified as being the same object in the four different simulations.

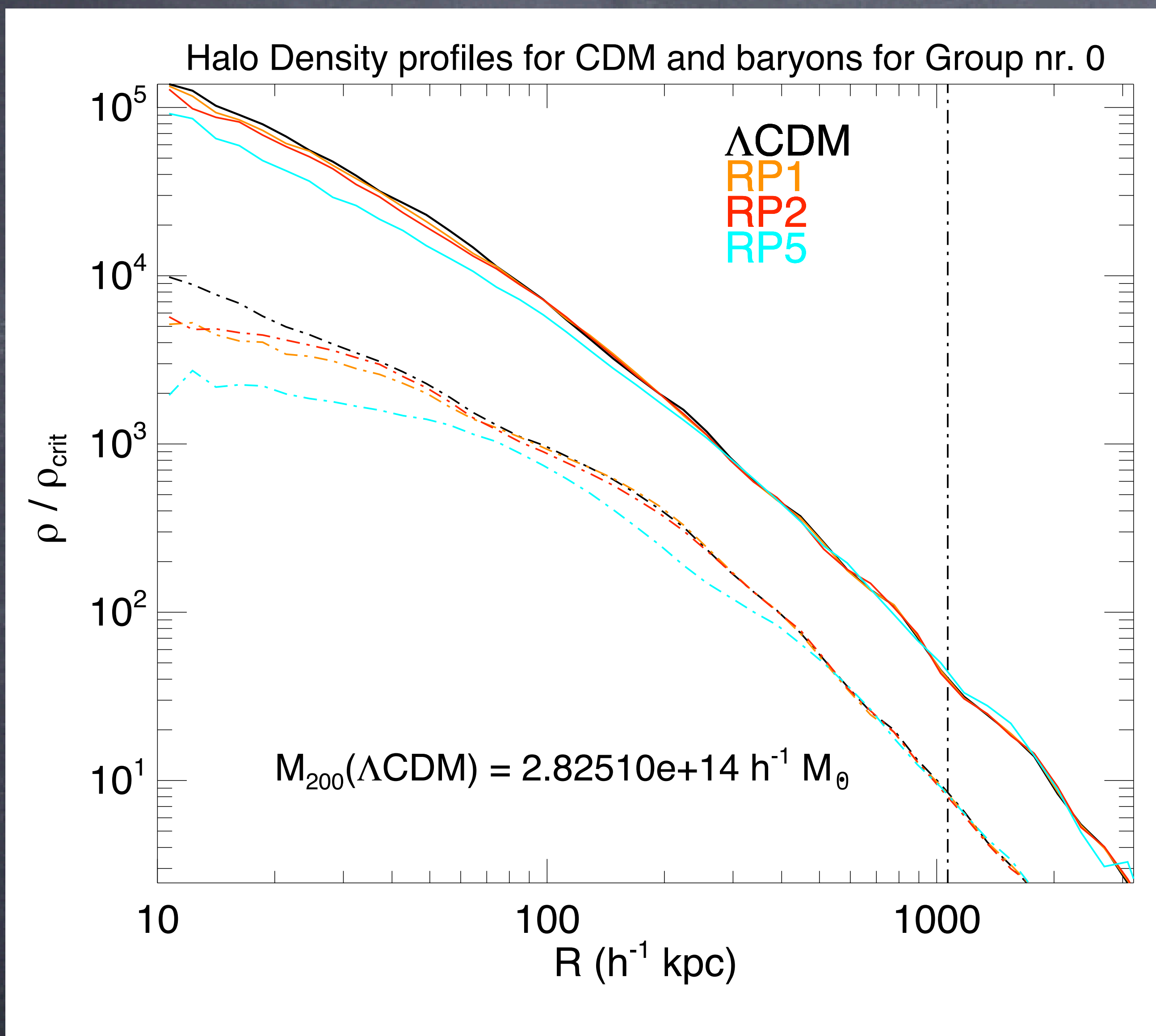


- The inner density of both baryons and CDM decreases with increasing coupling;

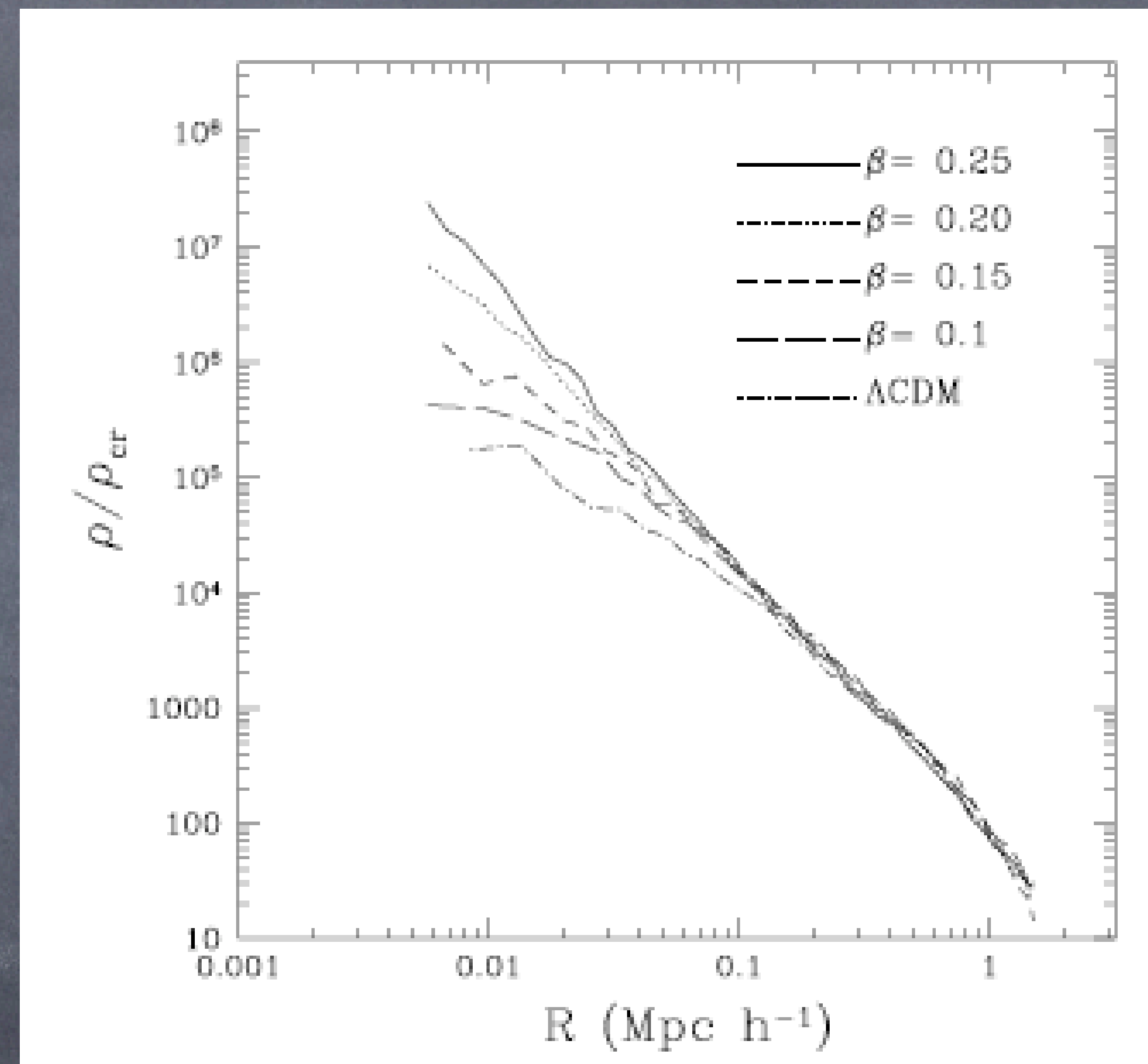
- The same trend appears in the vast majority of the halos in our sample;

- This result is in sharp contrast with Macciò et al [2004]

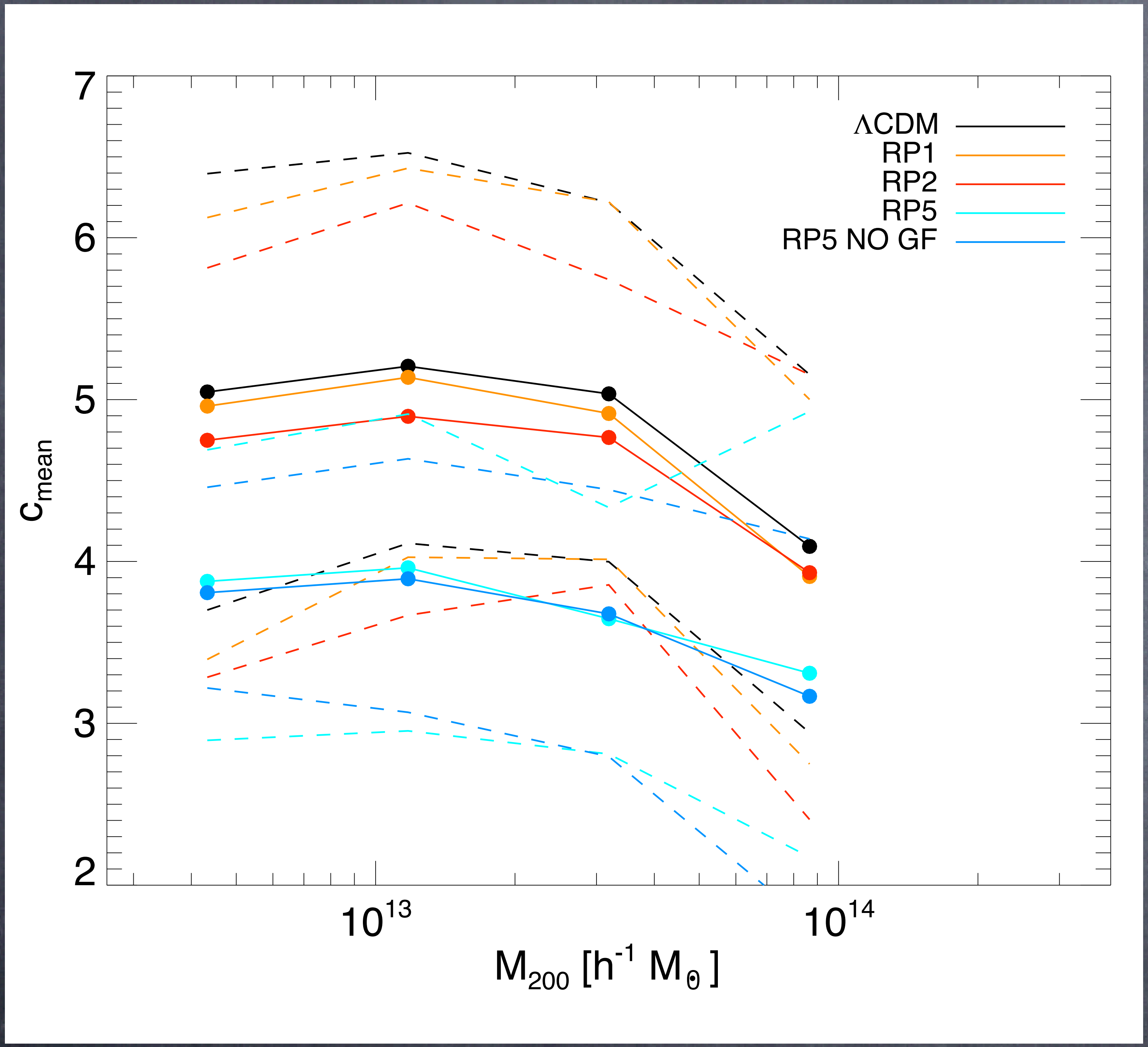
[M.Baldi et al., arXiv:0812.3901]



Macciò et al., 2004



Results : Halo concentrations [M.Baldi et al., arXiv:0812.3901]



We can fit all our density profiles with an NFW shape:

$$\left(\frac{\rho(r)}{\rho_{crit}}\right)_{NFW} = \frac{\delta^*}{\frac{r}{r_s}(1+\frac{r}{r_s})^2}$$

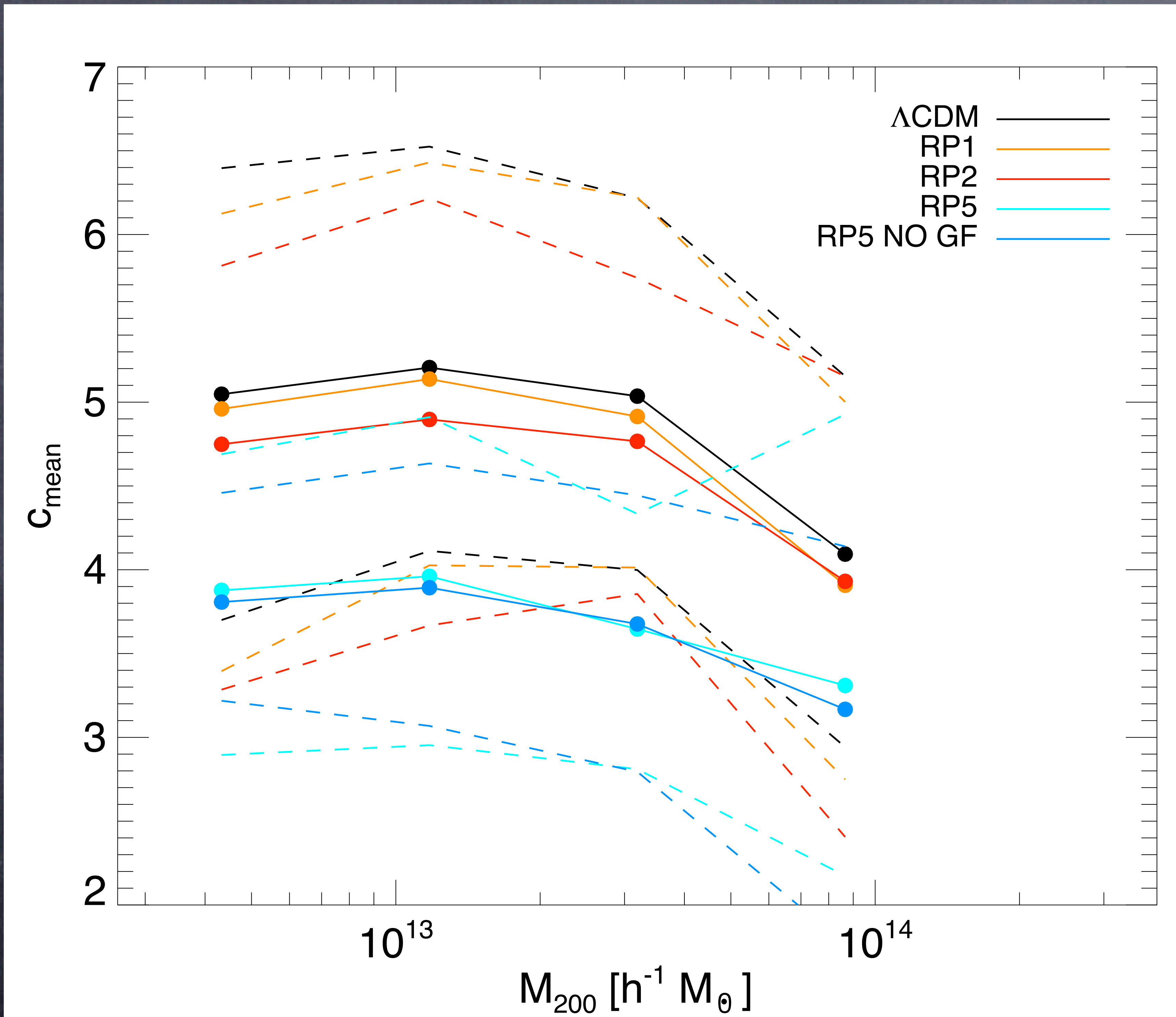
and we compute halo concentrations for the 200 most massive halos in our group catalogue

$$c = \frac{r_{200}}{r_s}$$

The mean halo concentration decreases with increasing coupling

Coupling & Halo concentrations [M.Baldi et al., arXiv:0812.3901]

What determines the decrease of halo concentrations with coupling?



Could it be the lower initial amplitude of density fluctuations?

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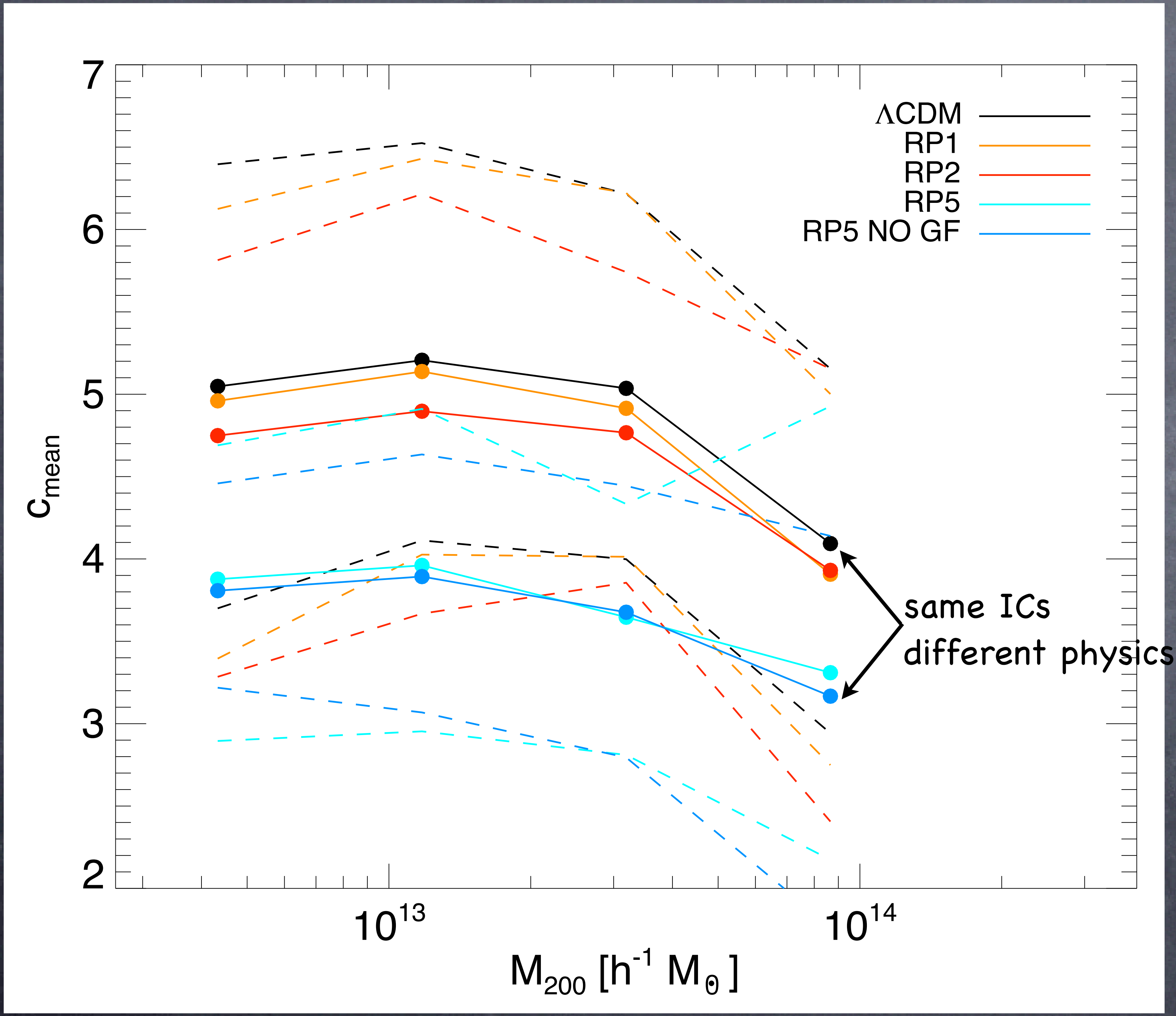

Could it be the lower initial amplitude of density fluctuations?

NO

Could it be the decrease of mass that reduces the internal potential energy of halos?

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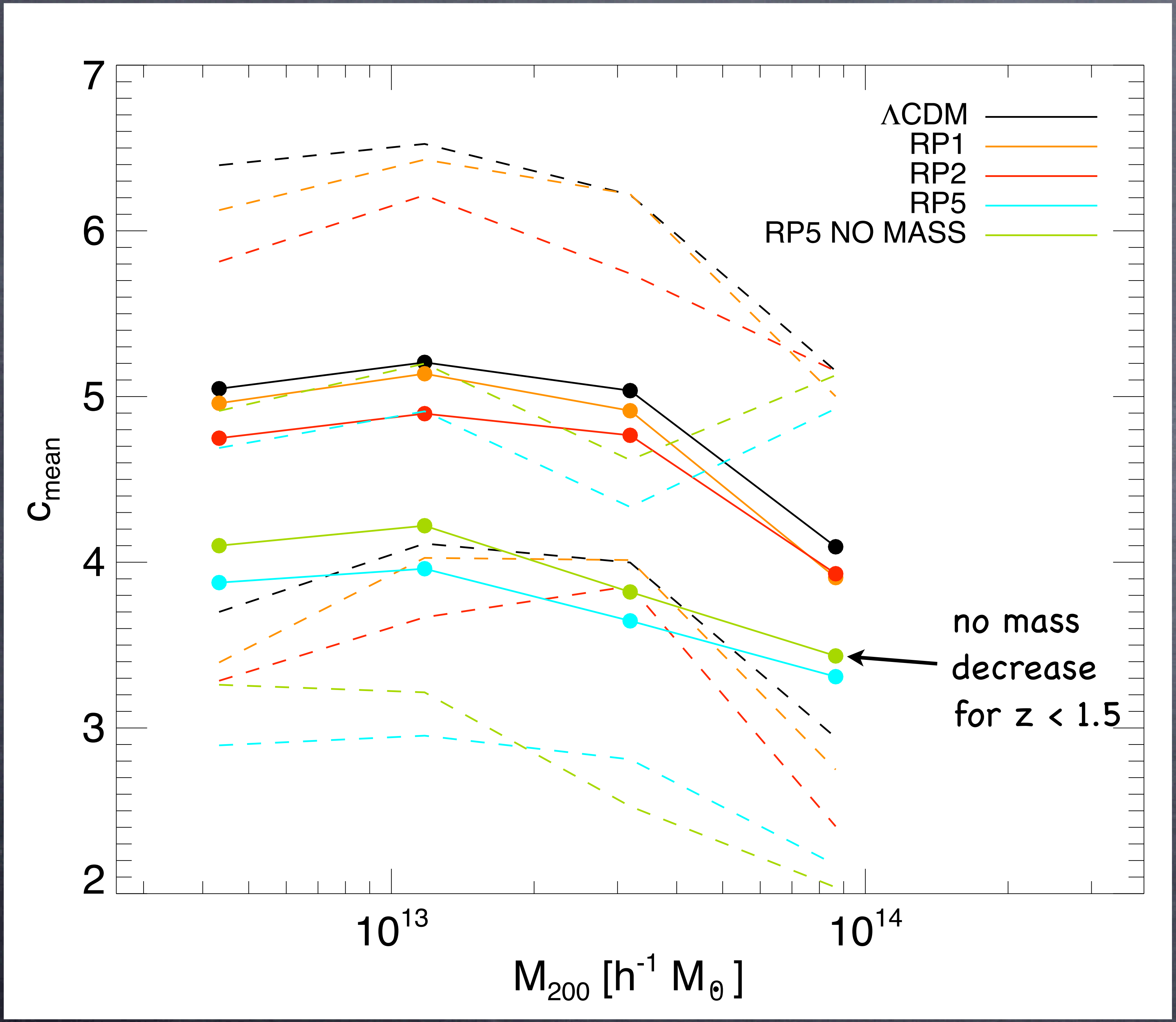

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YES, PARTLY

Could it be the friction term that "heats up" the halo by increasing particles' kinetic energy?

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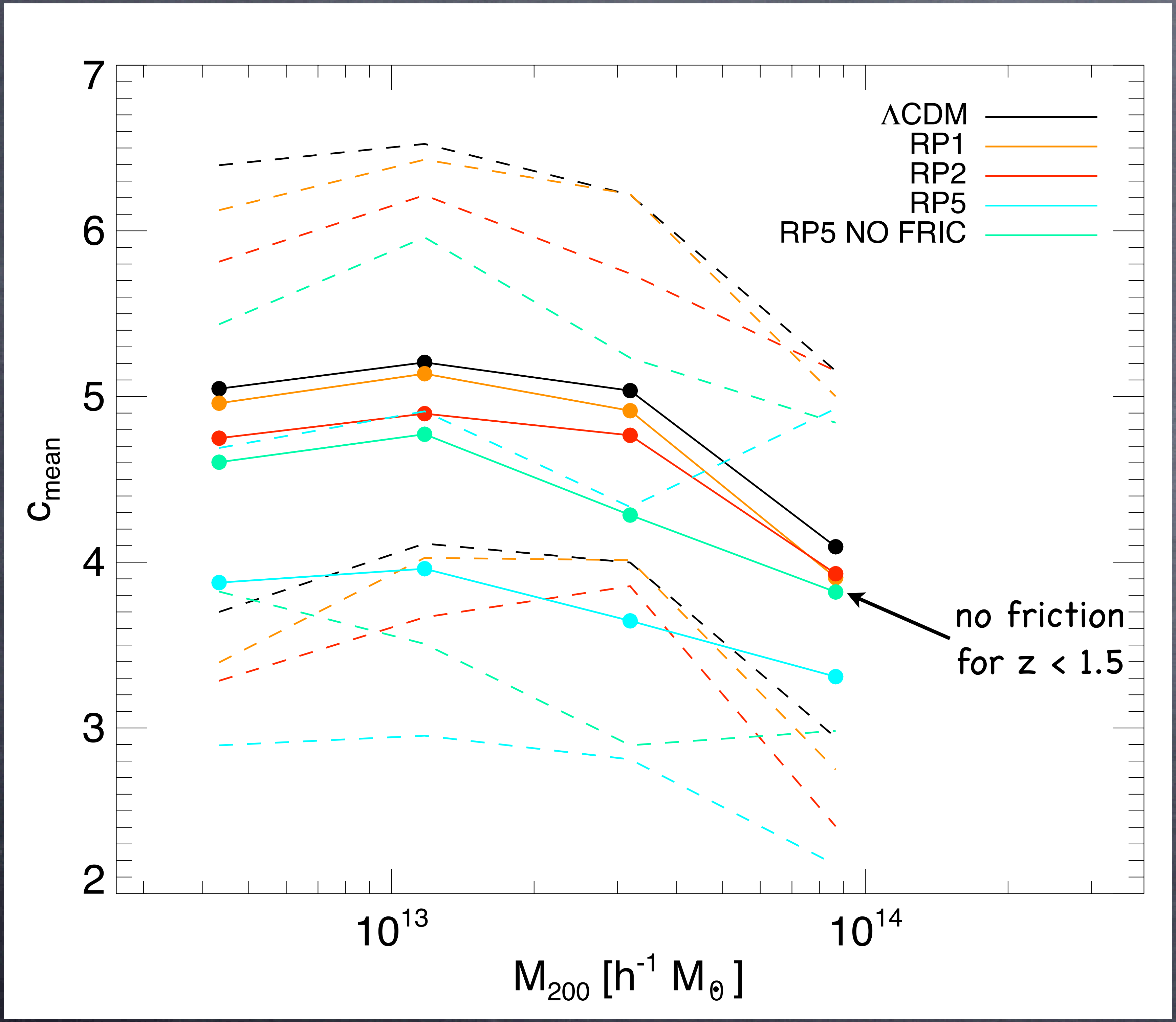

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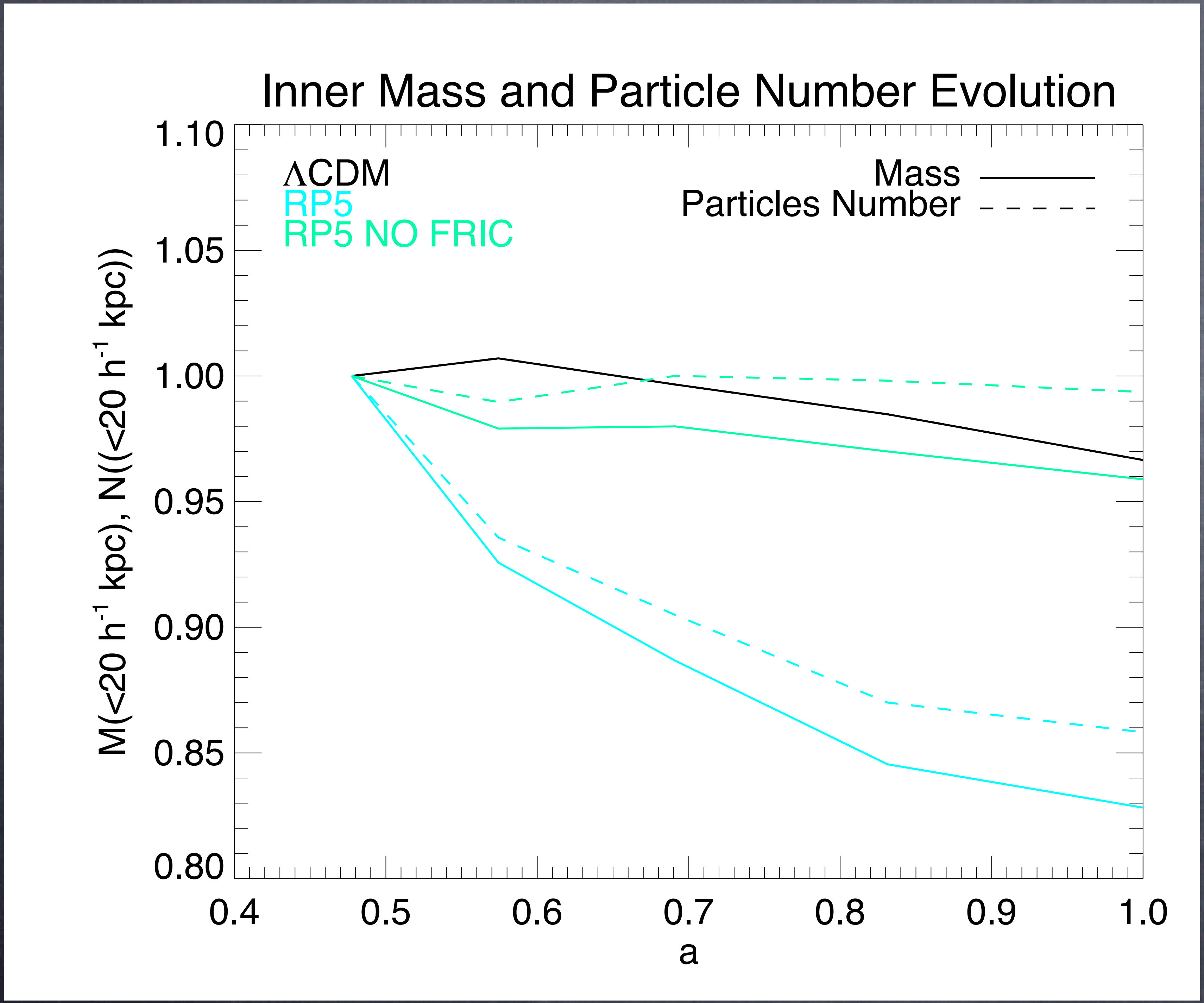
Coupling & Halo expansion [M.Baldi et al., arXiv:0812.3901]

The mass and the particle number in the core of the halos decrease much more for the interacting DE model than for ΛCDM... and if you switch off the friction term...



Bottom line:

The injection of energy in the virialised structures (coming from the friction term) **induces an adiabatic expansion of the halos**

Concluding...

We tested coupled dark energy cosmologies with constant coupling to CDM for a range of possible coupling values by means of cosmological N-body simulations of structure formation, improving statistics and extending the analysis of simulations outputs with respect to previous works.

1) The coupling imprints a universal linear bias between baryon and CDM density fluctuations. This bias is enhanced inside nonlinear structures. As a consequence, halo baryon fraction is reduced.

2) Halo density profiles get shallower in the inner part of massive halos with increasing value of the coupling (in contrast with previous claims).

3) Halo concentrations at z=0 are significantly reduced with respect to ΛCDM, proportionally to the value of the coupling.

4) The decrease of concentrations is mainly due to the particle mass variation and to the friction term that induce an adiabatic expansion of the halos.

Our code is way more general than the simple models presented here. If you want to know more about it:

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Thank you...