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# NUMERICAL SIMULATIONS OF GALAXY CLUSTERS IN DARK ENERGY COSMOLOGIES: *c-M* RELATION

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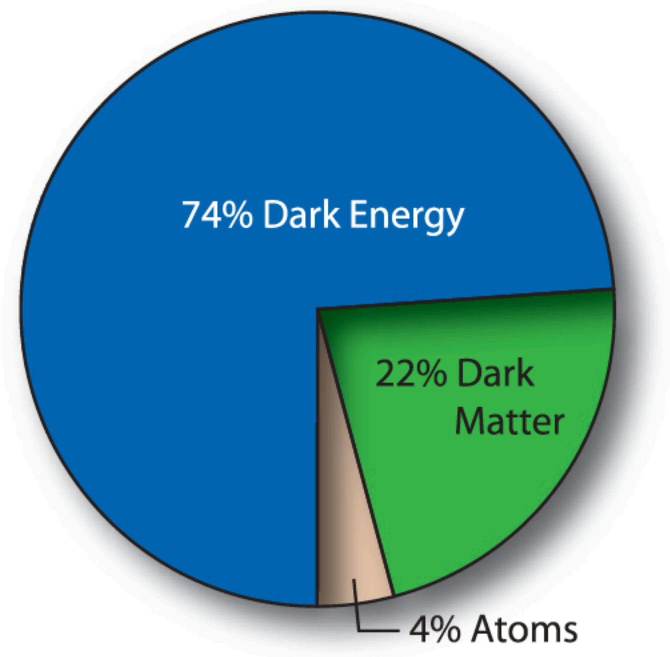
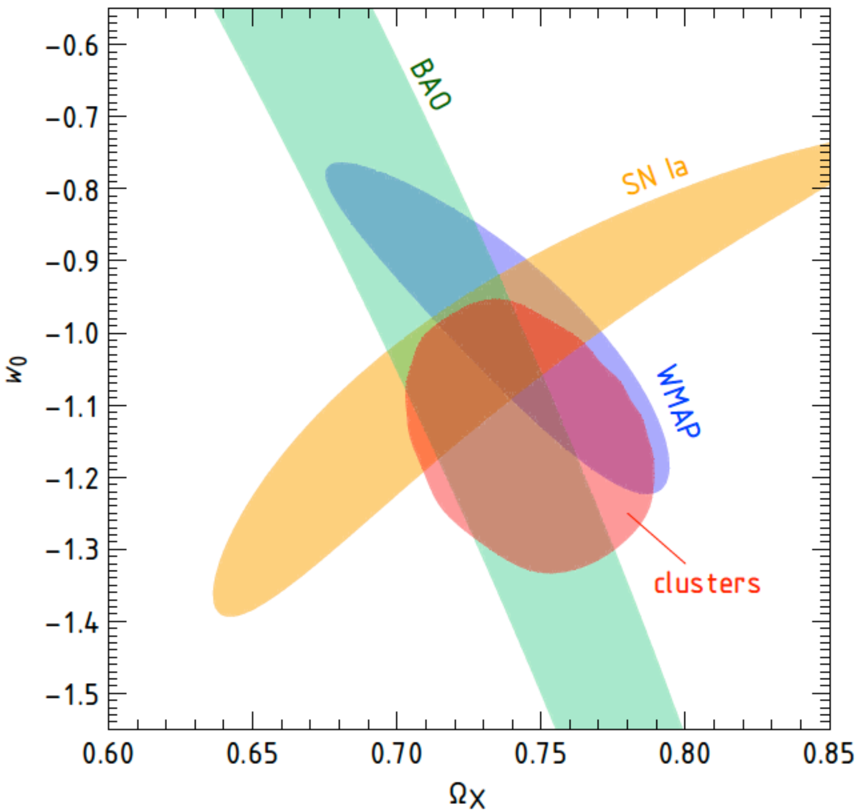
# OUTLINE

- Introduction
- Dark energy models
- Numerical simulations
- *c-M* relation

# INTRODUCTION




(NASA)




(Vikhlinin et al. 2009)

# INTRODUCTION

Largest bound objects in the Universe:

$M \sim 10^{14} - 10^{15}\, M_{\odot}$
$R \sim 1$ Mpc
$T_X \sim 1 - 10$ keV
$L_X \sim 10^{43} - 10^{44}$ erg/s
$\sigma \sim 700 - 800$ km/s

(NASA)

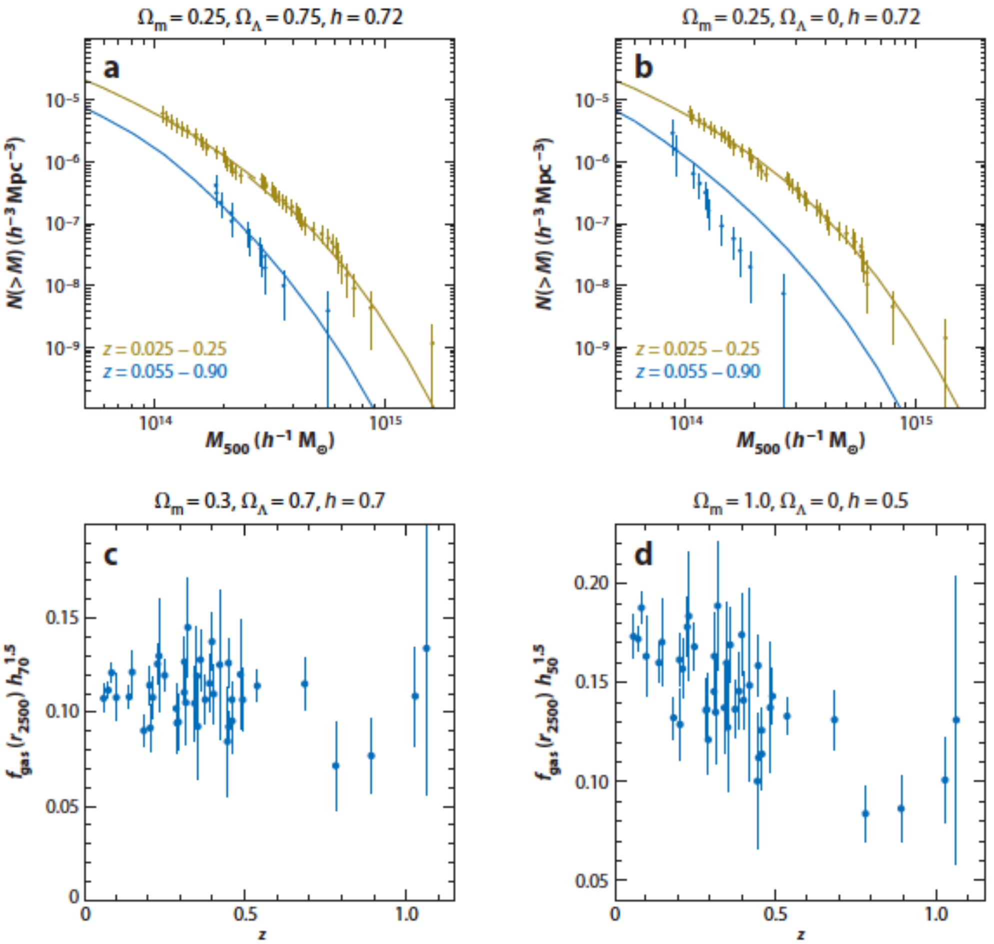
Galaxies ~ 5% of the total mass.

Only 15-20% in form of visible matter.

# INTRODUCTION

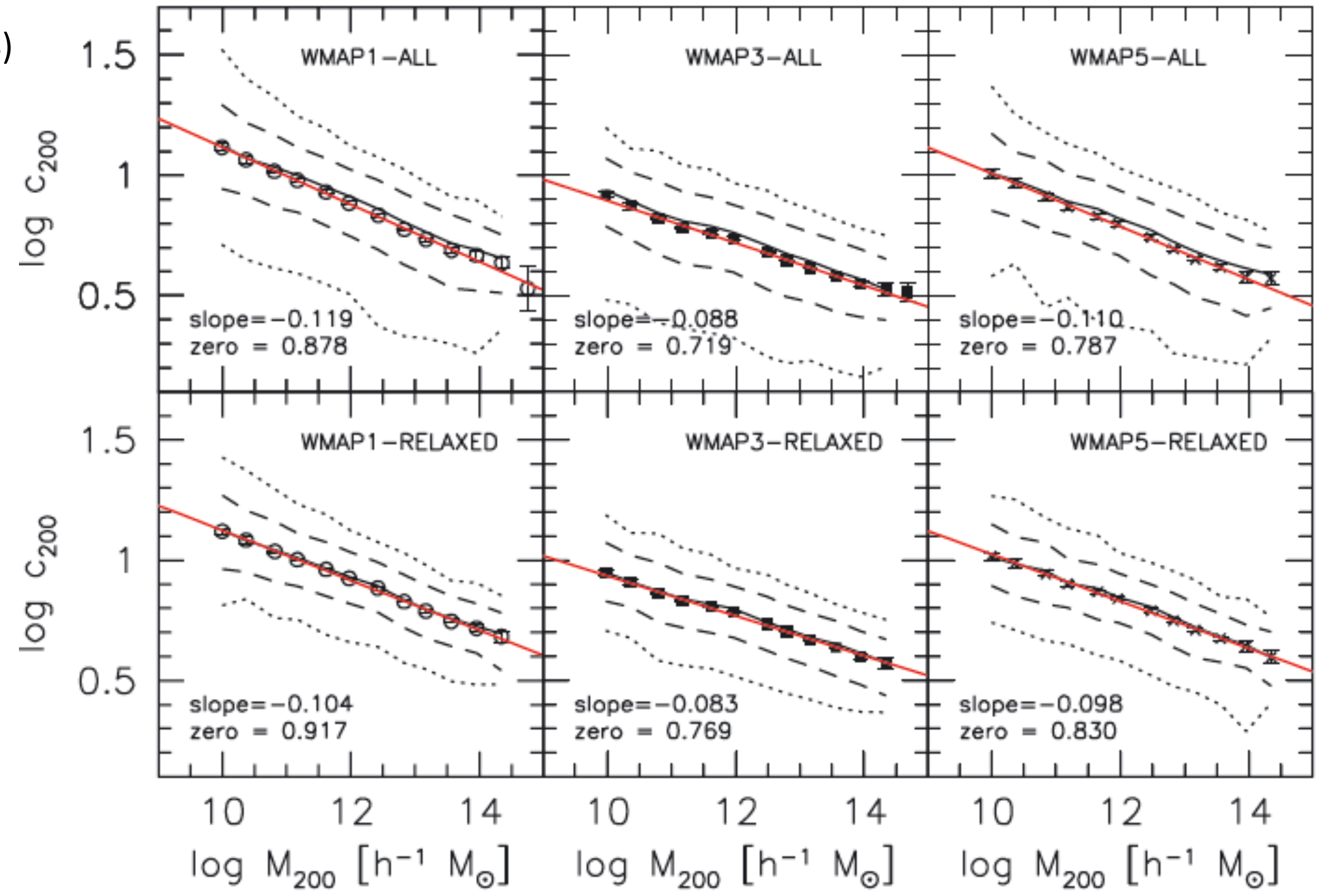
(Vikhlinin et al. 2009)

(Allen et al. 2008)



# INTRODUCTION

(Macciò et al. 2008)



# INTRODUCTION

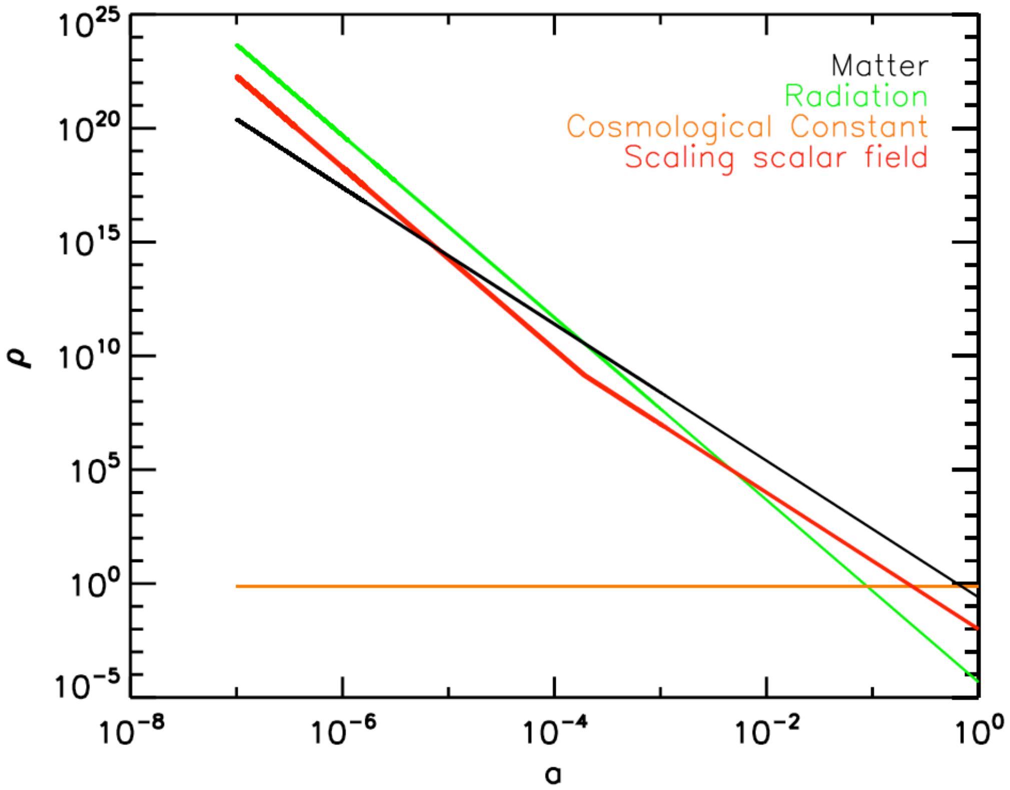
- What is the influence of dark energy on structure formation?
- Is the *c-M* relation affected in some way by dark energy?
- How is the *c-M* relation influenced by the dynamical state of the sample?
- Simulations must be used to study galaxy clusters properties in cosmological context with different dark energy models

# DARK ENERGY MODELS

- $w = -1$ → cosmological constant
- $w = w(z)$ → dynamical dark energy (quintessence)

$w = p/\rho$ dark energy equation of state

# DARK ENERGY MODELS




(courtesy of Marco Baldi)

# DARK ENERGY MODELS

- $w = -1$ → cosmological constant
- $w = w(z)$ → dynamical dark energy (quintessence)

Minimally coupled quintessence:

minimal coupling between quintessence scalar field and gravity, inverse power-law potential (RP)

(Ratra & Peebles 1988)

# DARK ENERGY MODELS

- $w = -1$ → cosmological constant
- $w = w(z)$ → dynamical dark energy (quintessence)

Minimally coupled quintessence:

minimal coupling between quintessence scalar field and gravity, inverse power-law potential with exponential term (SUGRA)

(Brax & Martin 1999)

# DARK ENERGY MODELS

- $w = -1$ → cosmological constant
- $w = w(z)$ → dynamical dark energy (quintessence)

Scalar-tensor theories:

non-minimal positive/negative coupling between quintessence scalar field and gravity, extended quintessence (EQp/EQn)

(Pettorino & Baccigalupi 2008)

# DARK ENERGY MODELS

$$\frac{\tilde{G}}{G_*} \sim 1 - 8\pi G_* \xi(\phi^2 - \phi_0^2)$$

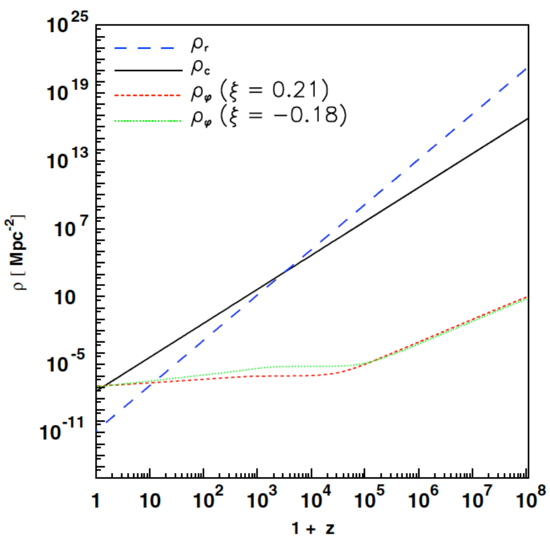
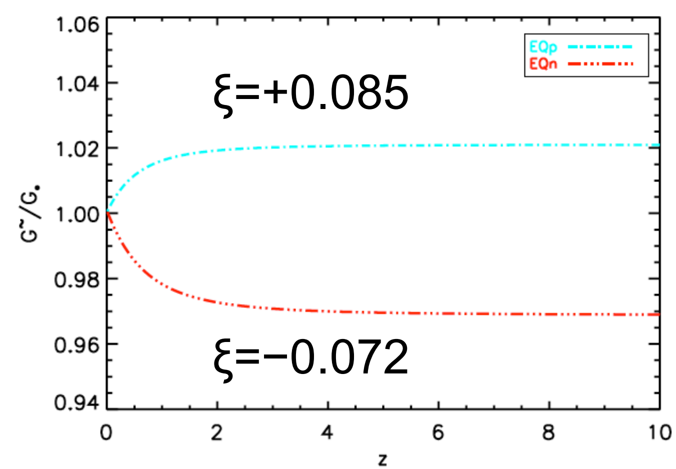



TABLE I. Summary of corrections required to run N-body simulations in CQ and EQ scenarios.

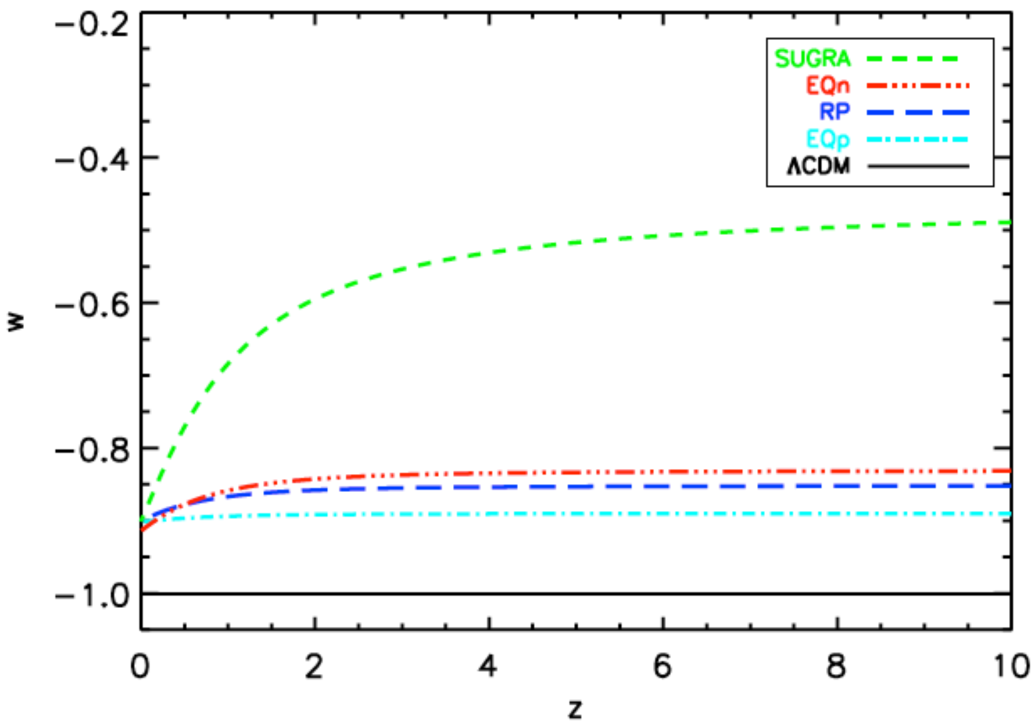
| Correction type | CQ | EQ |
|---|---|---|
| Gravity $(\Delta G/G_*)$ DM-DM | $1+2C_c^2$ | $\tilde{G}/G_*$ |
| Gravity $(\Delta G/G_*)$ B-DM | 1 | $\tilde{G}/G_*$ |
| Gravity $(\Delta G/G_*)$ B-B | 1 | $\tilde{G}/G_*$ |
| Friction $(\Delta\mathcal{H}/\mathcal{H})$ | $1-\frac{C_c\phi'}{\mathcal{H}}$ | 1 |
| Mass $(\Delta m/m)$ DM | $e^{-C_c(\phi-\phi_0)}$ | 1 |
| Mass $(\Delta m/m)$ B | 1 | 1 |




(Pettorino & Baccigalupi 2008)

# DARK ENERGY MODELS

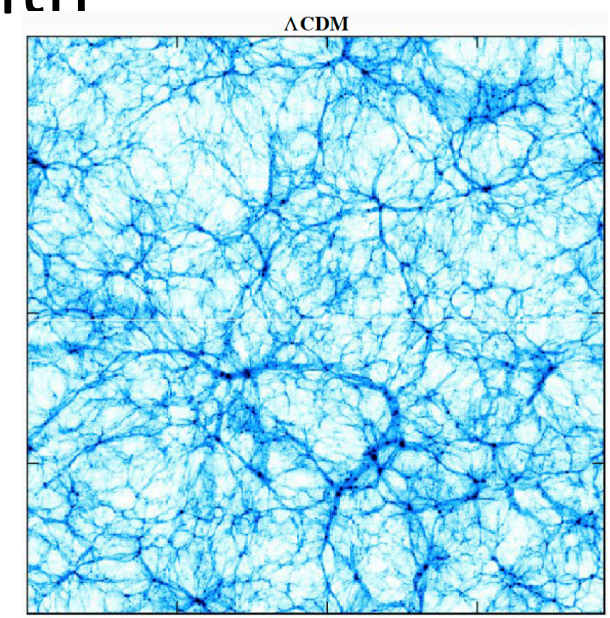
- ΛCDM (cosmological constant)
- RP
- SUGRA
- EQp
- EQn



# PADME SIMULATION

## DM-ONLY RUN

- GADGET-3 cosmological N-body simulation
- $(300 \text{ Mpc}/h)^3$ box resolved with $(768)^3$ particles
- $m_{DM} = 4.4 \times 10^9\ M_{\odot}/h$

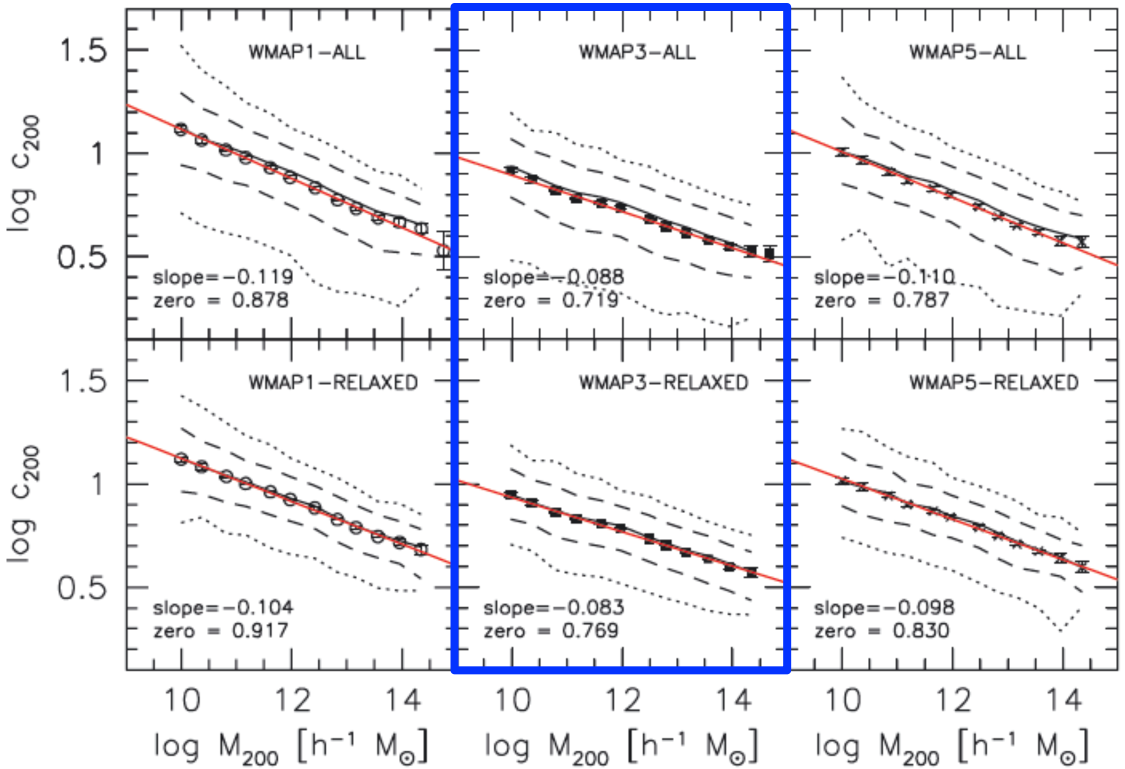



(K. Dolag)

# PADME SIMULATION

Background cosmology (WMAP3)

- $\Omega_{0m} = 0.268$
- $\Omega_{0\Lambda} = 0.732$
- $\Omega_{0b} = 0.044$
- $H_0 = 0.704$
- $\sigma_8 = 0.776$
- $n_s = 0.947$



# PADME SIMULATION

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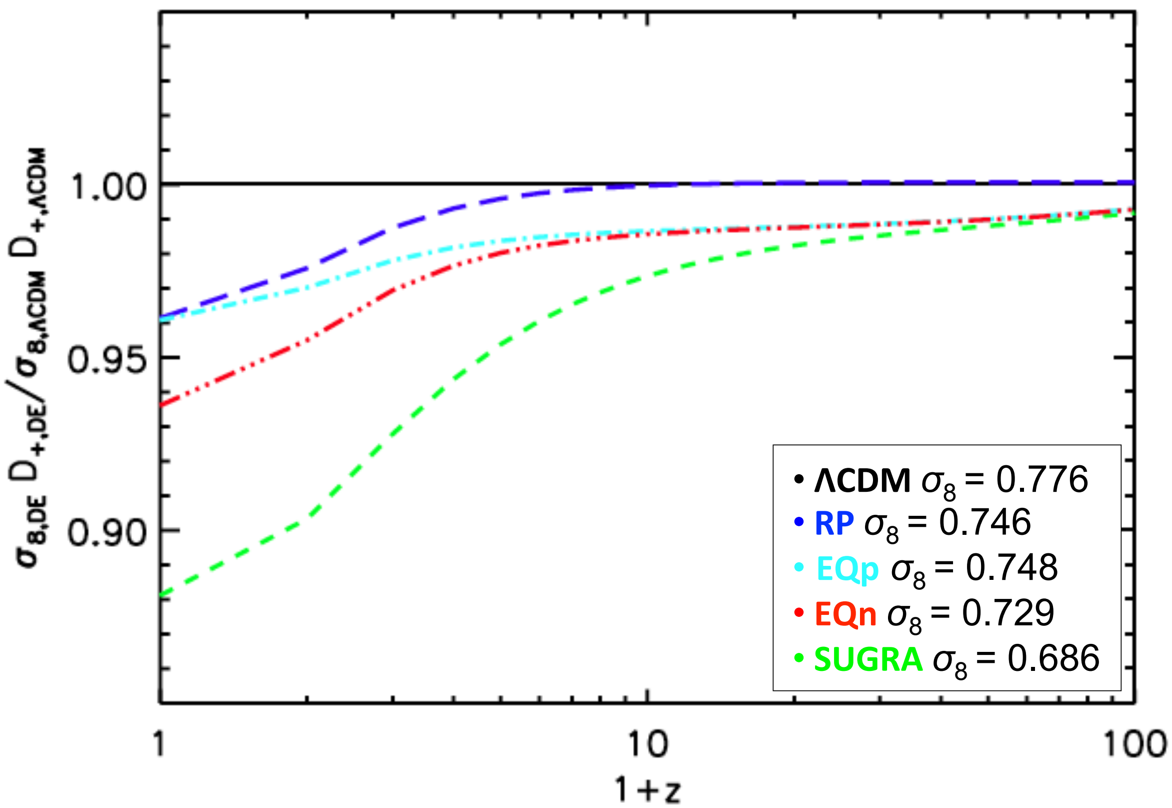
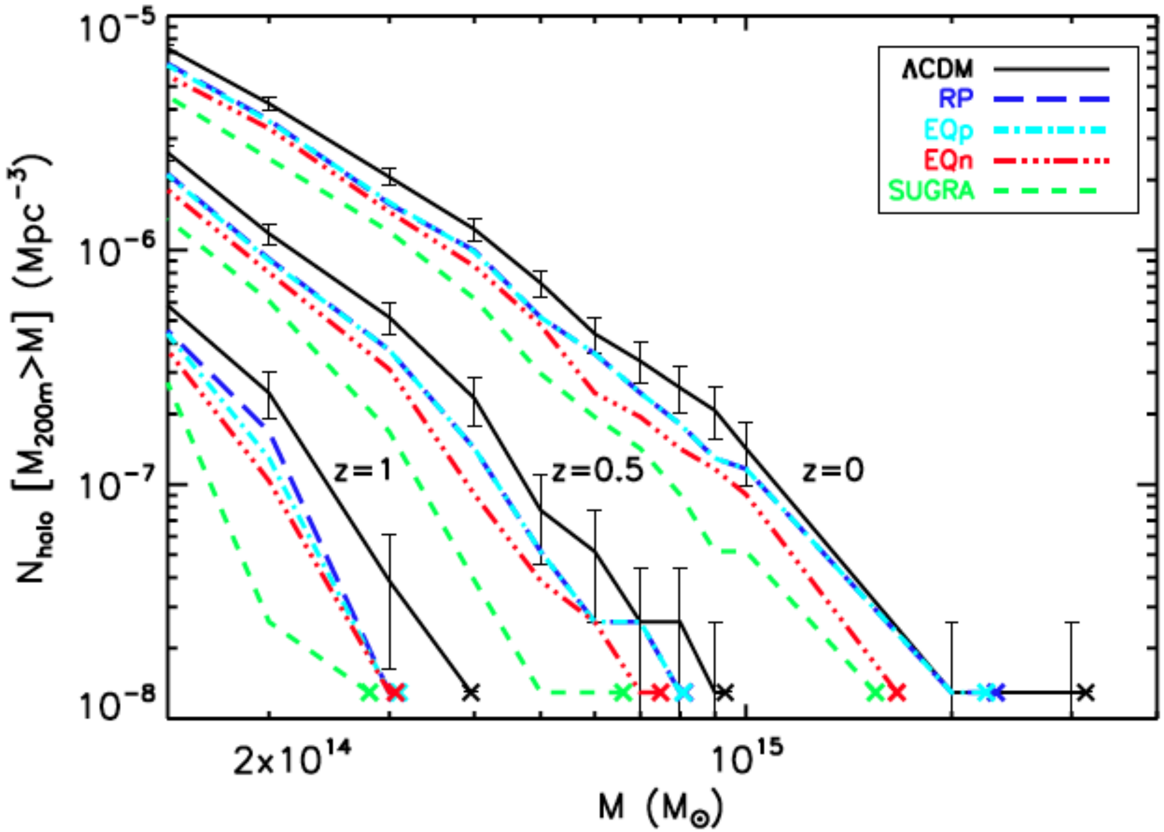
- $n_s = 0.947$

All the dark energy models are consistent with WMAP3 data, and $\sigma_8$ is always recalculated to agree with the CMB

# PADME SIMULATION



# PADME SIMULATION




(De Boni et al. 2011)

# CONCENTRATION

Fit of a NFW profile in the range [0.1-1]$R_{200}$

$$\frac{\rho(r)}{\rho_c} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(Poissonian errors)

$$\delta_c = \frac{200}{3}\frac{c_{200}^3}{\left[\ln(1+c_{200}) - \frac{c_{200}}{1+c_{200}}\right]}$$

$$c_{200} = R_{200}/r_s$$

$$\log_{10} c_{200} = \log_{10} A + B\ \log_{10}\left(\frac{M_{200}}{10^{14}\mathrm{M}_\odot}\right)$$

# THE SAMPLE

All the objects with $M_{200m} \geq 10^{14}\ \mathrm{M}_{\odot}/h$

The 200 objects with $M_{200m}$ closest to

$7 \times 10^{13}\ \mathrm{M}_{\odot}/h$

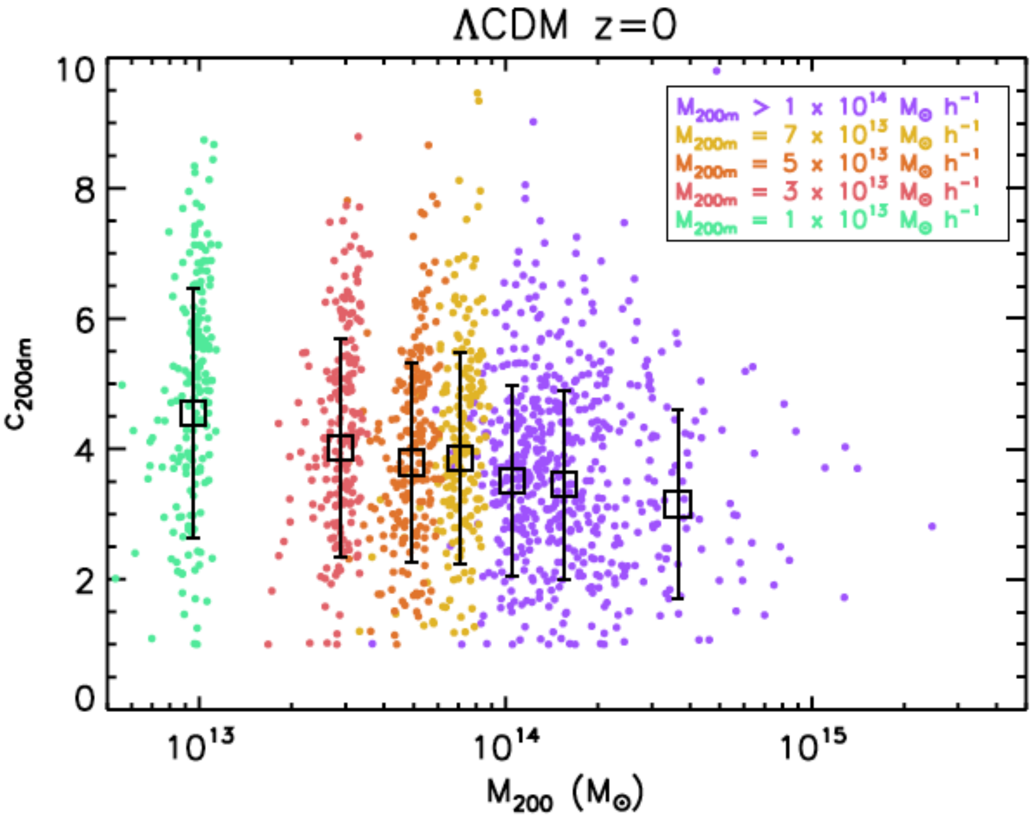
$5 \times 10^{13}\ \mathrm{M}_{\odot}/h$

$3 \times 10^{13}\ \mathrm{M}_{\odot}/h$

$10^{13}\ \mathrm{M}_{\odot}/h$

We bin the objects with $M_{200m} \geq 10^{14}\ \mathrm{M}_{\odot}/h$ in groups of 200 starting from the less massive ones

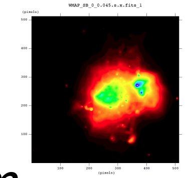
# THE SAMPLE



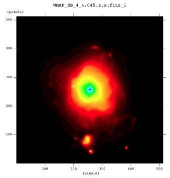
ΛCDM z=0
$M_{200m} > 1 \times 10^{14}$ $M_\odot$ $h^{-1}$
$M_{200m} = 7 \times 10^{13}$ $M_\odot$ $h^{-1}$
$M_{200m} = 5 \times 10^{13}$ $M_\odot$ $h^{-1}$
$M_{200m} = 3 \times 10^{13}$ $M_\odot$ $h^{-1}$
$M_{200m} = 1 \times 10^{13}$ $M_\odot$ $h^{-1}$
$c_{200dm}$
0
2
4
6
8
10
$10^{13}$
$10^{14}$
$10^{15}$
$M_{200}$ ($M_\odot$)

# THE SAMPLE

Complete sample: all the objects inside a bin



Relaxed sample: objects with $x_{off} < 0.07R_{200m}$

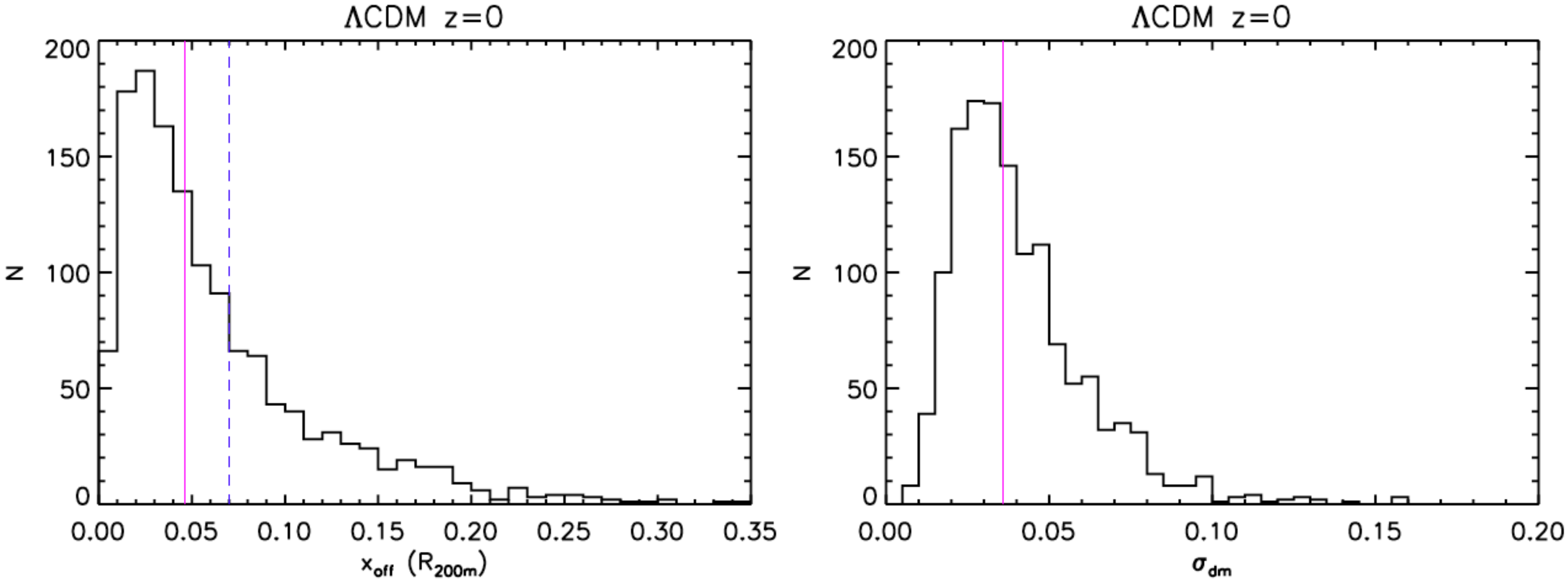


Super-relaxed sample: objects with

$x_{off}$ < median($x_{off}$) and $\sigma_{rms}$ < median($\sigma_{rms}$)

$$\sigma^2_{rms} = \frac{1}{N_{bins}} \sum_{i=1}^{N_{bins}} [\log_{10}\rho_i - \log_{10}\rho_{NFW}]^2$$

# THE SAMPLE

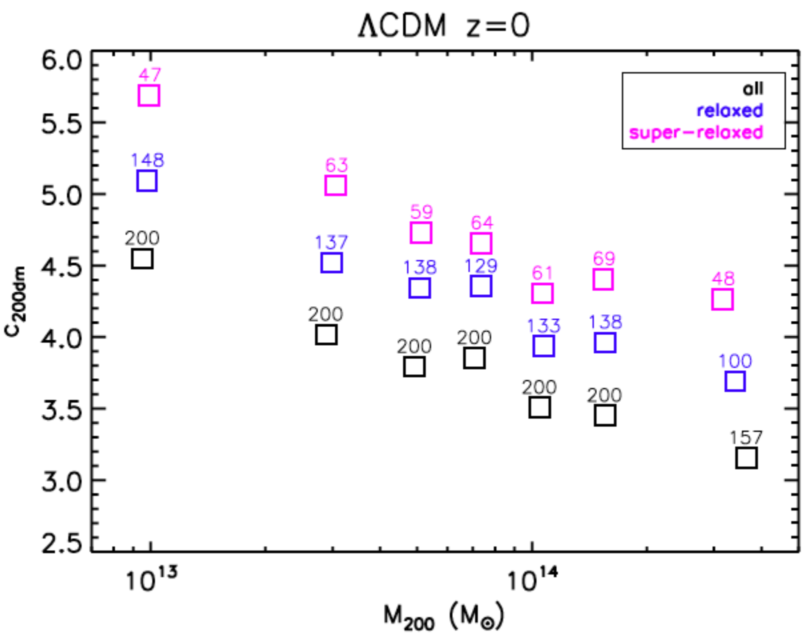


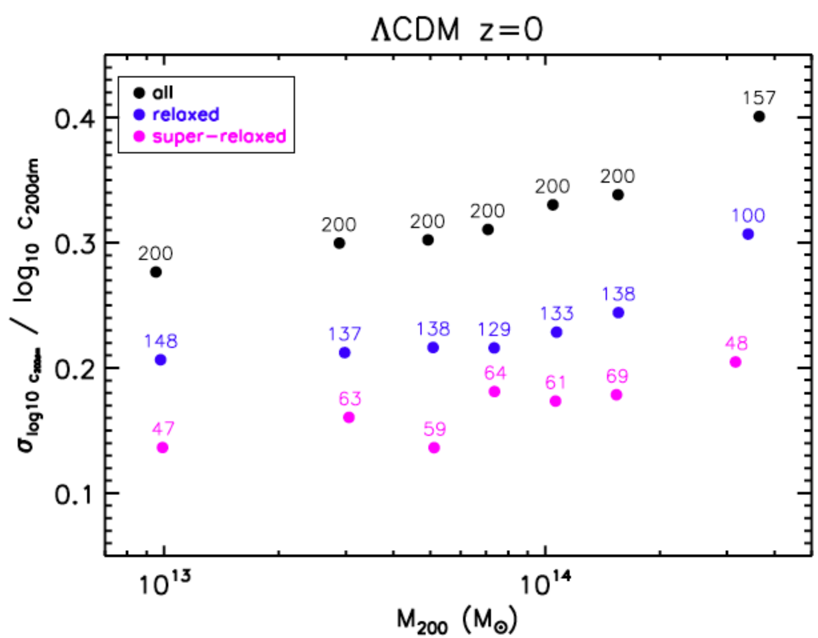
ΛCDM z=0
200
150
100
50
0
N
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
$x_{off}$ ($R_{200m}$)
ΛCDM z=0
200
150
100
50
0
N
0.00
0.05
0.10
0.15
0.20
$\sigma_{dm}$

# RESULTS

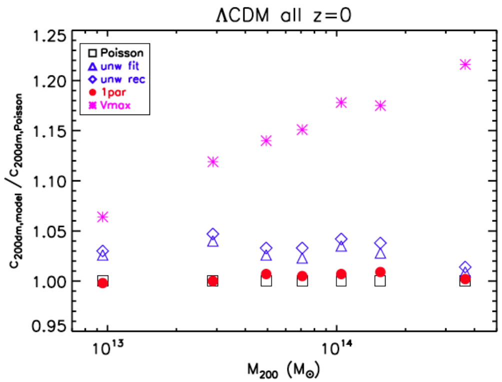
## *c-M* relation in ΛCDM @ *z*=0

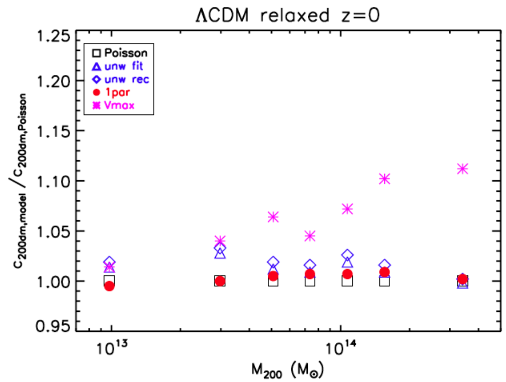
A=3.59/4.09/4.52 B=−0.099/−0.092/−0.091

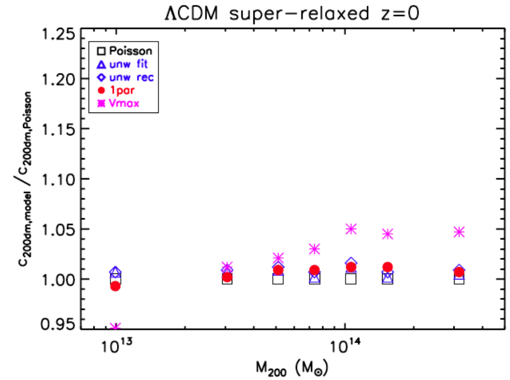


# RESULTS




$$\frac{\rho(r)}{\rho_c} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

$$\delta_c = \frac{200}{3}\frac{c_{200}^3}{\left[\ln(1+c_{200}) - \frac{c_{200}}{1+c_{200}}\right]}$$

unw fit

$$c_{200} = R_{200}/r_s$$

unw rec

one-parameter fit with Poissonian errors

1 par

$$\frac{V_{max}}{V_{200}} = \left(\frac{0.216\ c}{f(c)}\right)^{1/2}$$

$$f(c) = \ln(1+c) - \frac{c}{1+c}$$

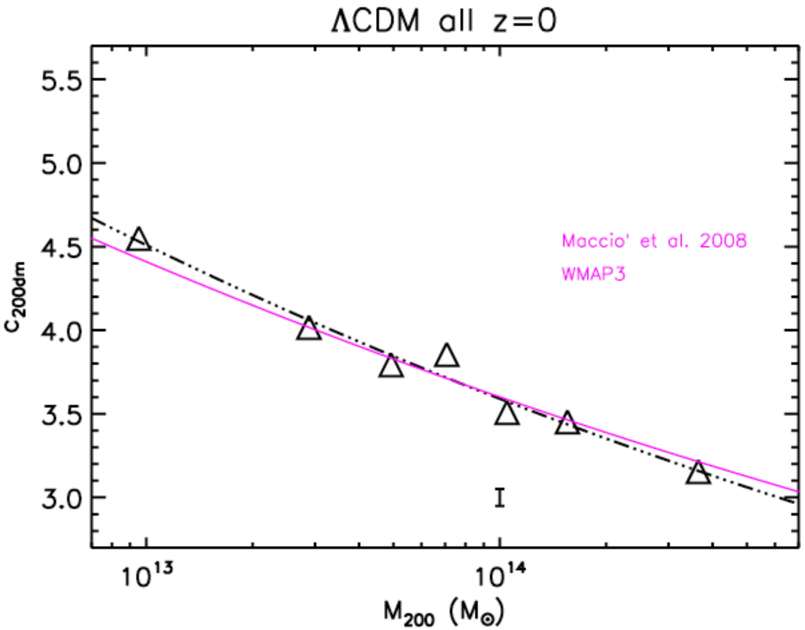
$$V_{max}^2 = \max\left[\frac{GM(<r)}{r}\right]$$

$$V_{200} = \left(\frac{GM_{200}}{R_{200}}\right)^{1/2}$$

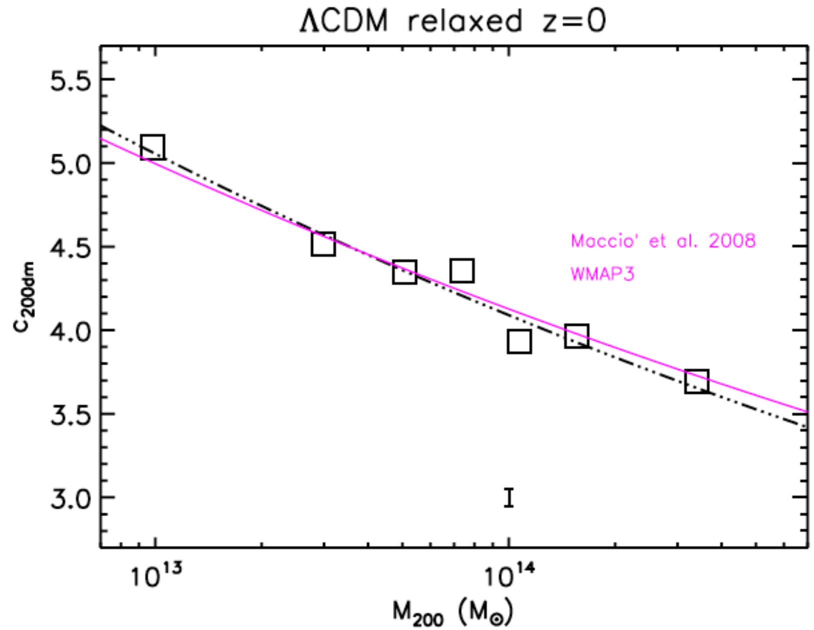
Vmax

# RESULTS COMPARISON

A=3.59/3.60
B=−0.099/−0.088

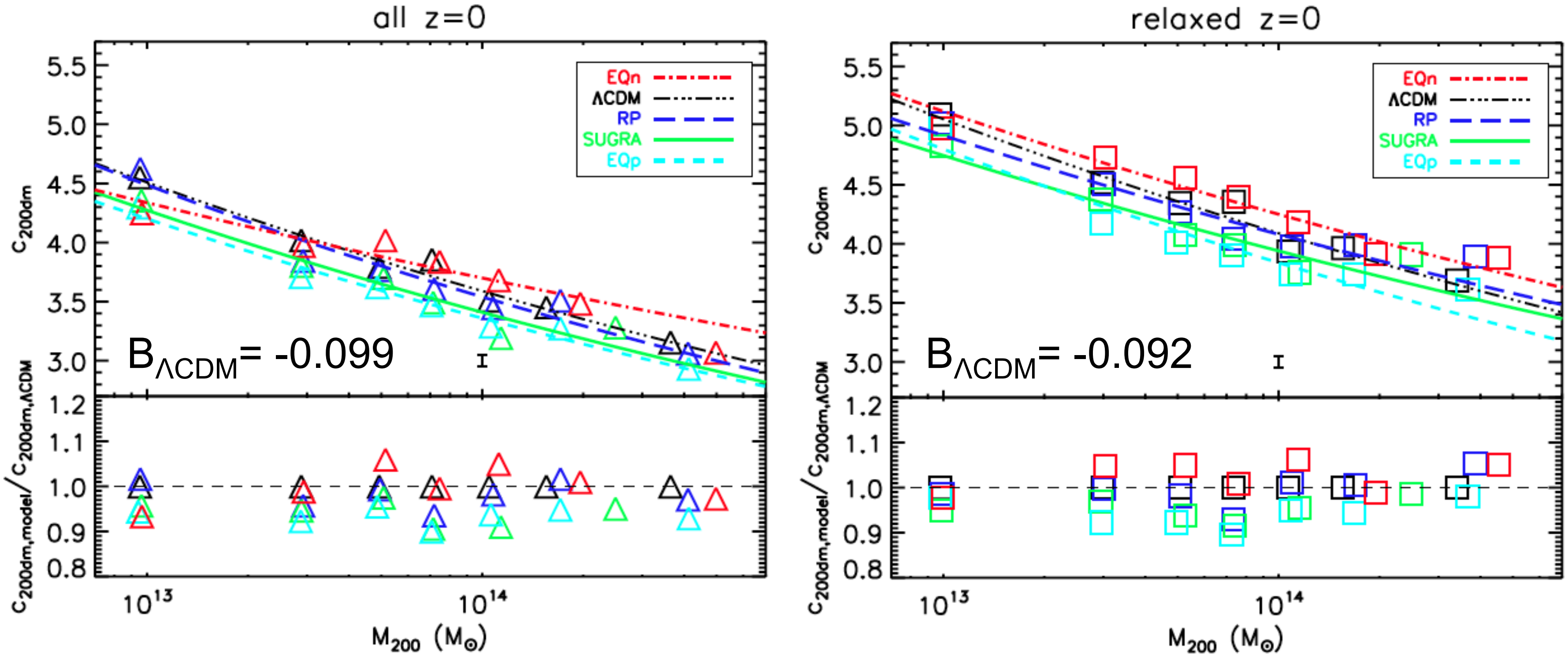



A=4.09/4.13
B=−0.092/−0.083



# RESULTS

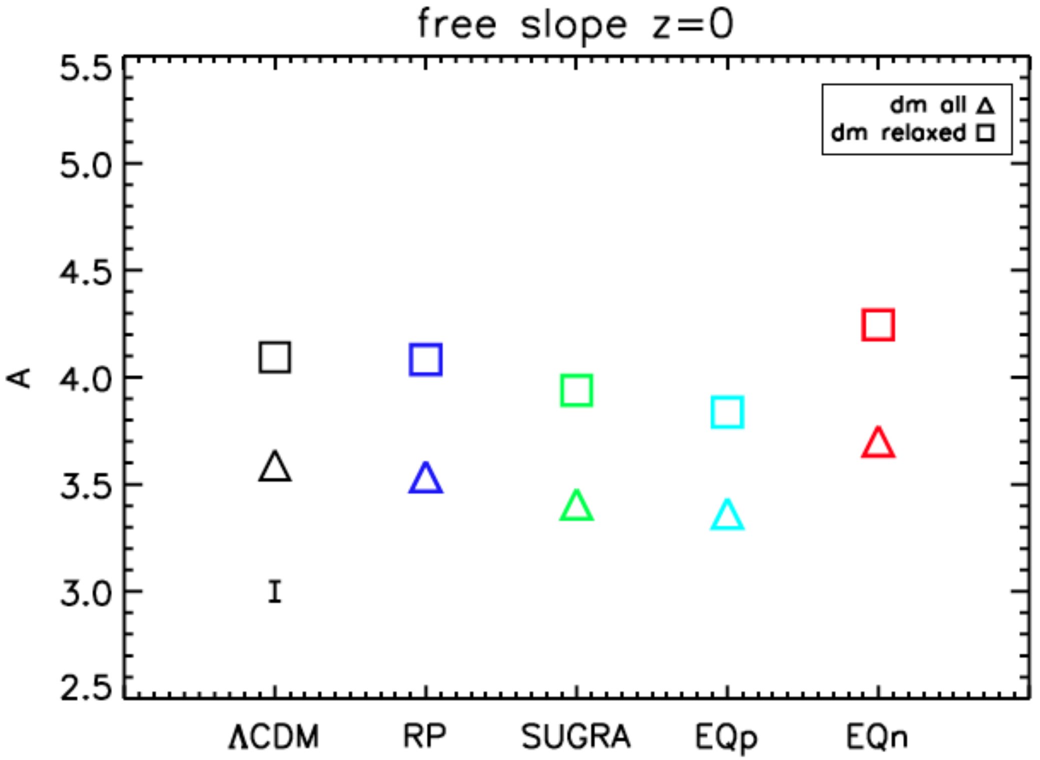
dark matter *c-M* relation @ *z*=0




1σ error on ΛCDM normalization

# RESULTS

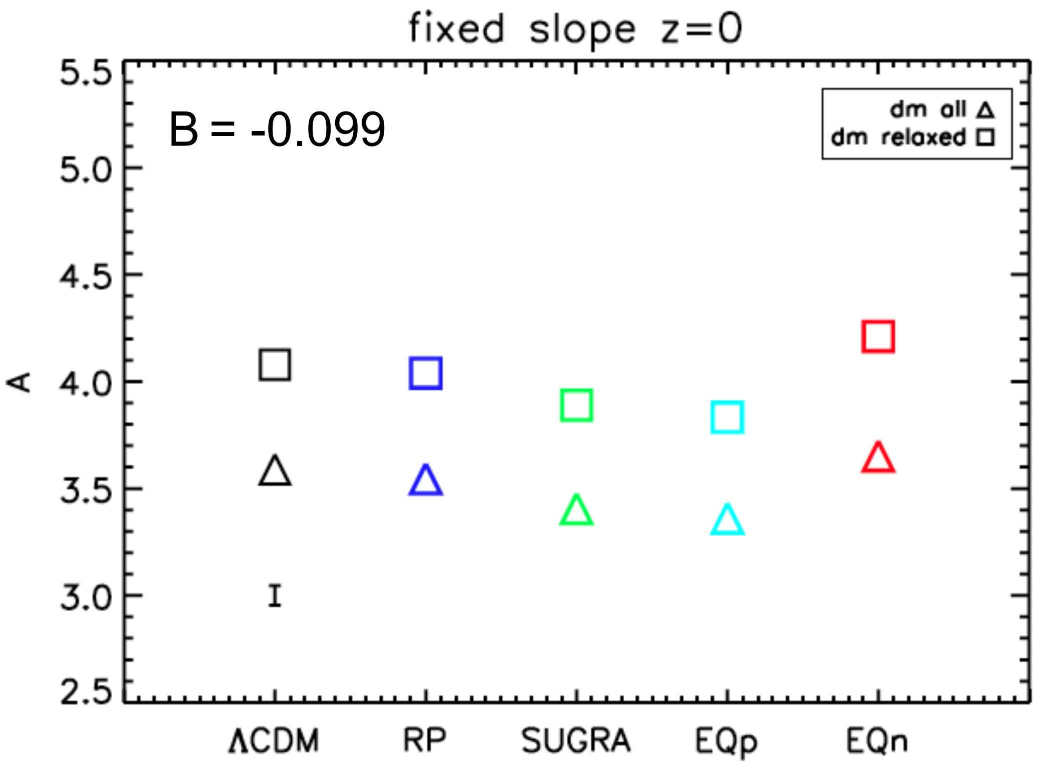
*c*-*M* normalization @ *z*=0



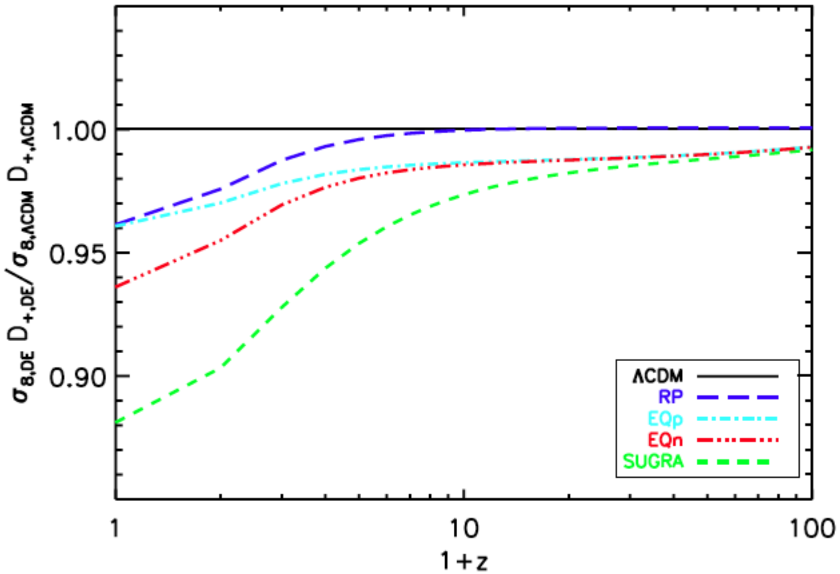

1σ error on dm all normalization

# RESULTS

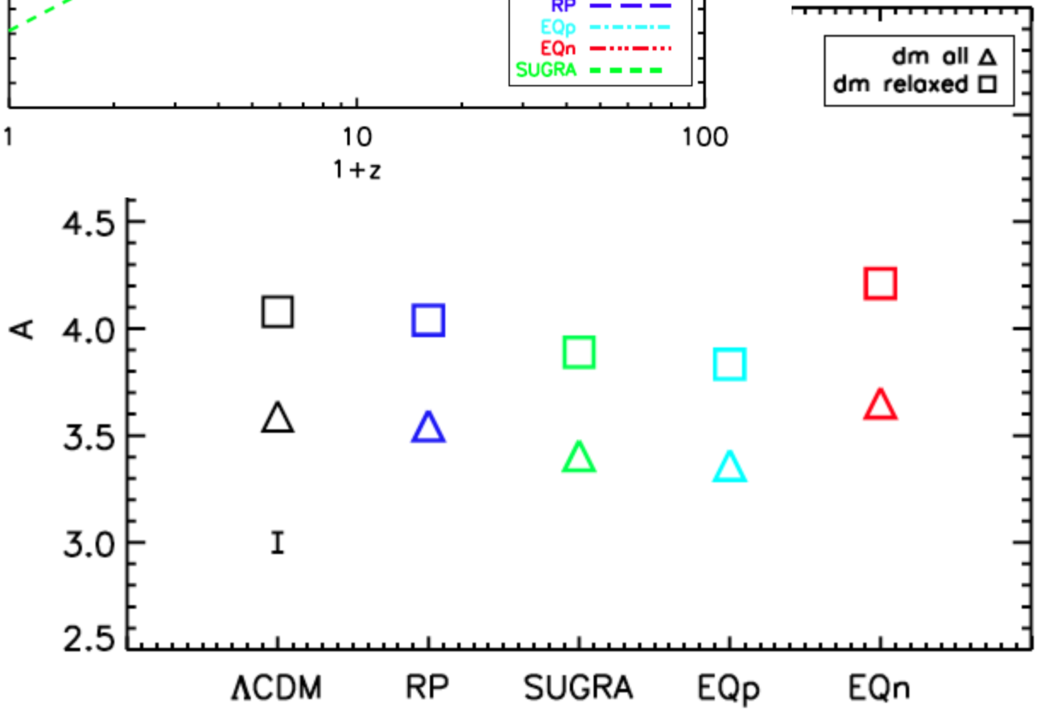
*c*-*M* normalization @ *z*=0



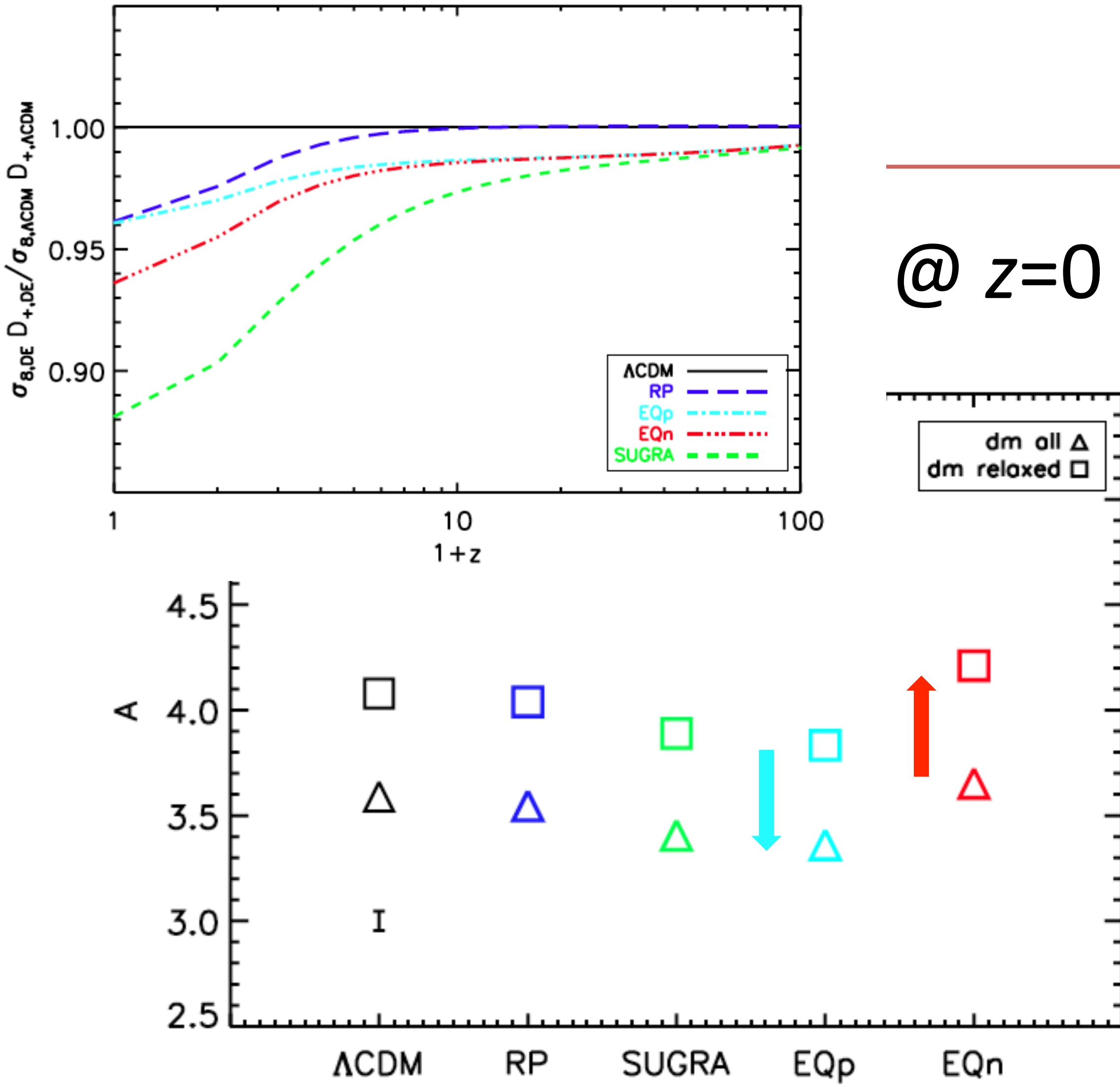

1σ error on dm all normalization




@ $z$=0

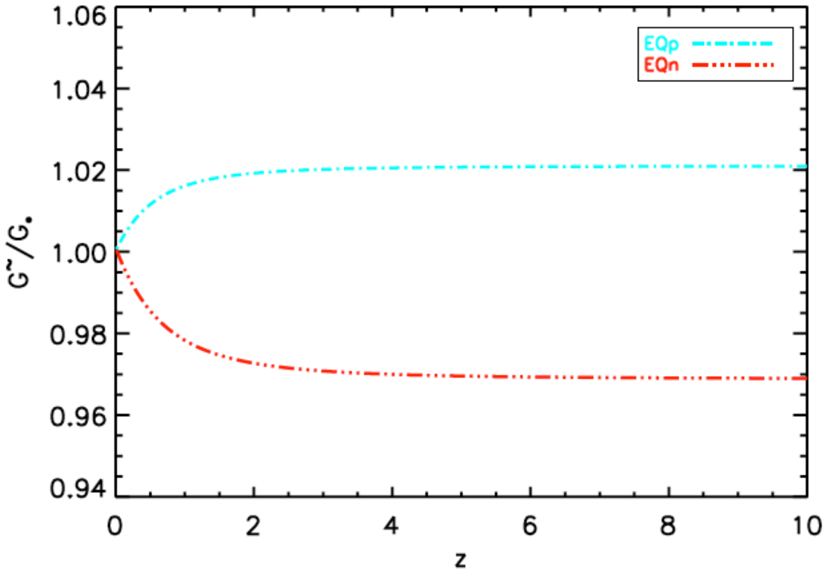



1σ error on dm all normalization

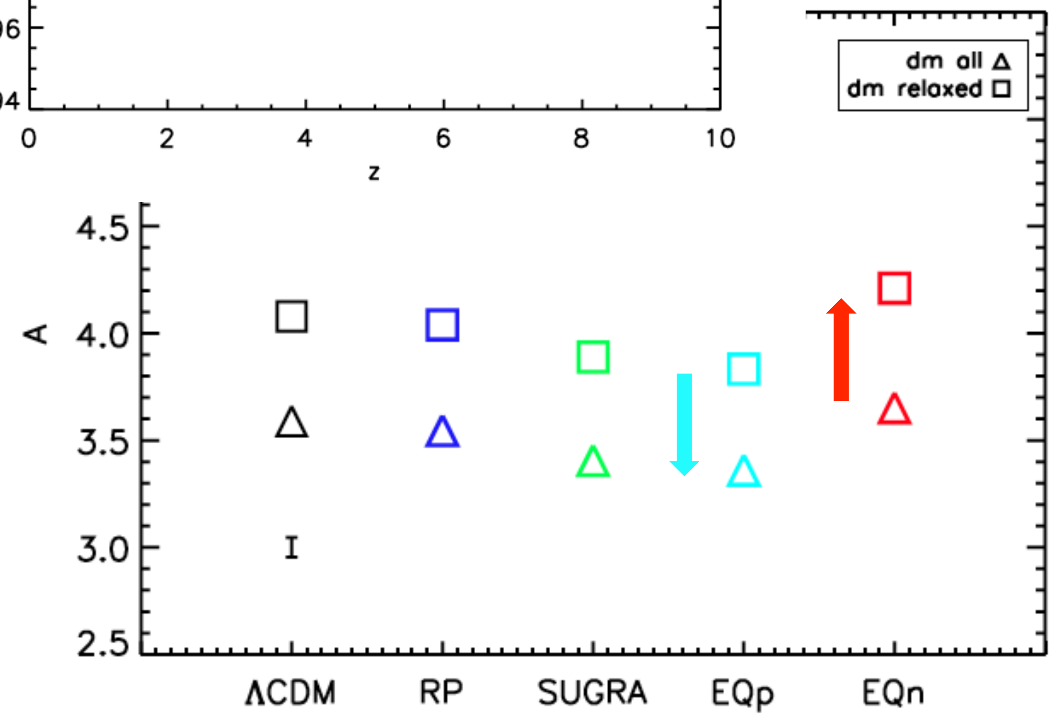



@ $z$=0

1σ error on dm all normalization




@ $z$=0




1σ error on dm all normalization

# CONCLUSIONS

- The dynamical state of the sample dominates the normalization and the intrinsic scatter
- For ΛCDM, RP and SUGRA the normalization of the *c-M* relation follows $\sigma_8 D_+$
- For EQp and EQn the effect of the coupling is to decrease the normalization of EQp and to increase the one of EQn

(De Boni et al. 2012)