MARCO BALDI
EXCELLENCE CLUSTER UNIVERSE, GARCHING

SIMULATING DARK ENERGY MODELS

THE QUEST FOR DARK ENERGY: WHEN THEORY MEETS SIMULATIONS
RINGBERG CASTLE, 25 VI 2012

OUTLINE

Classification of Dark Energy and Modified Gravity models

N-body simulations of homogeneous Dark Energy

N-body simulations of interacting Dark Energy

- Non-Universal couplings: coupled quintessence and growing neutrinos
- Universal couplings: screening mechanisms (the case of f(R) theories)

Other models and open issues

Summary and conclusions

DARK ENERGY AND N-BODY SIMULATIONS

The first observational hint of a DE-dominated Universe came from the comparison of the APM galaxy survey with N-body simulations ~ 10 years before the detection of acceleration
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The cosmological constant and cold dark matter

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Department of Physics, University of Oxford, Oxford OX1 3RH, UK

THE cold dark matter (CDM) model[1–4] for the formation and distribution of galaxies in a universe with exactly the critical density is theoretically appealing and has proved to be durable, but recent work[5–8] suggests that there is more cosmological structure on very large scales ($l > 10\,h^{-1}$ Mpc, where h is the Hubble constant H_0 in units of 100 km s^{-1} Mpc^{-1}) than simple versions of the CDM theory predict. We argue here that the successes of the CDM theory can be retained and the new observations accommodated in a spatially flat cosmology in which as much as 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.

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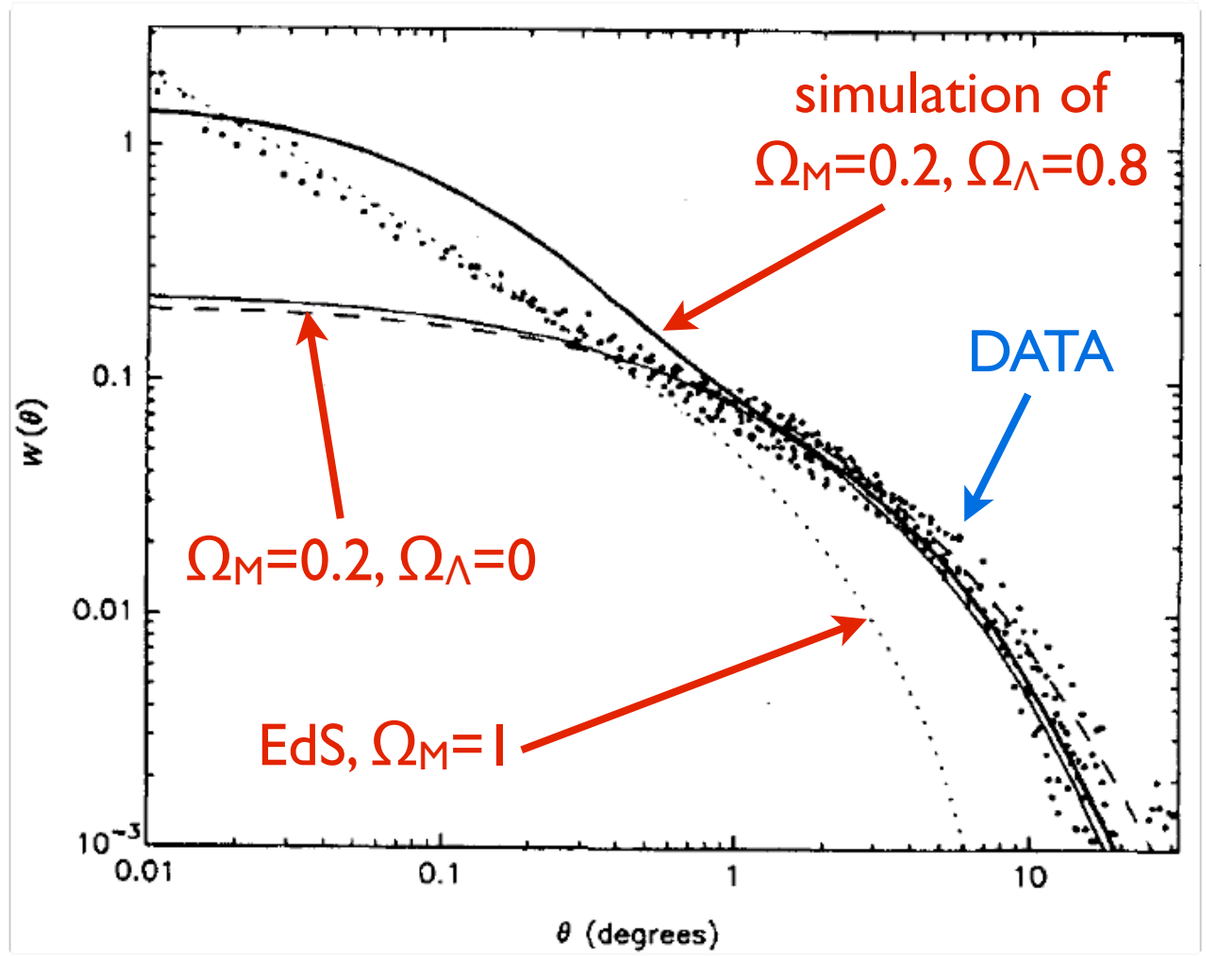

CLASSIFICATION OF DARK ENERGY MODELS

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	time evolution	spatial fluctuations	interactions
Λ	✗	✗	✗
Dynamical DE (quintessence, k-essence, EDE)	✔ a dynamical (scalar) degree of freedom	✗ no clustering at sub-horizon scales	✗ minimally-coupled to matter fields

DYNAMICAL DARK ENERGY

Scalar field models

A scalar degree of freedom $\phi(t)$ evolving in a self-interaction potential

$$\rho_{\rm DE} = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad c_\phi^2 \approx 1$$

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

Wetterich 1988; Ratra & Peebles 1988
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Dark Energy Parametrizations

A parametrization of the time evolution of DE

Time-dependent equation of state:

$$w_{\rm DE}(a) = w_0 + w_a(1-a)$$ Chevallier & Polarski 2001; Linder 2003

Early Dark Energy:

$$w_{\rm DE}(a) = \frac{w_0}{1 + b\ln(1/a)} \qquad b = -\frac{3w_0}{\ln\frac{1-\Omega_{\rm EDE}}{\Omega_{\rm EDE}} + \ln\frac{1-\Omega_M}{\Omega_M}}$$

Wetterich 2004

DYNAMICAL DARK ENERGY

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A homogeneous and minimally-coupled DE scalar field will affect structure formation only through the background expansion history of the Universe:

$$\left(\frac{H}{H_0}\right)^2 = \Omega_M a^{-3} + (1-\Omega_M)\exp\left(-3\int_1^a \frac{1+w(a')}{a'}da'\right)$$

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DYNAMICAL DARK ENERGY

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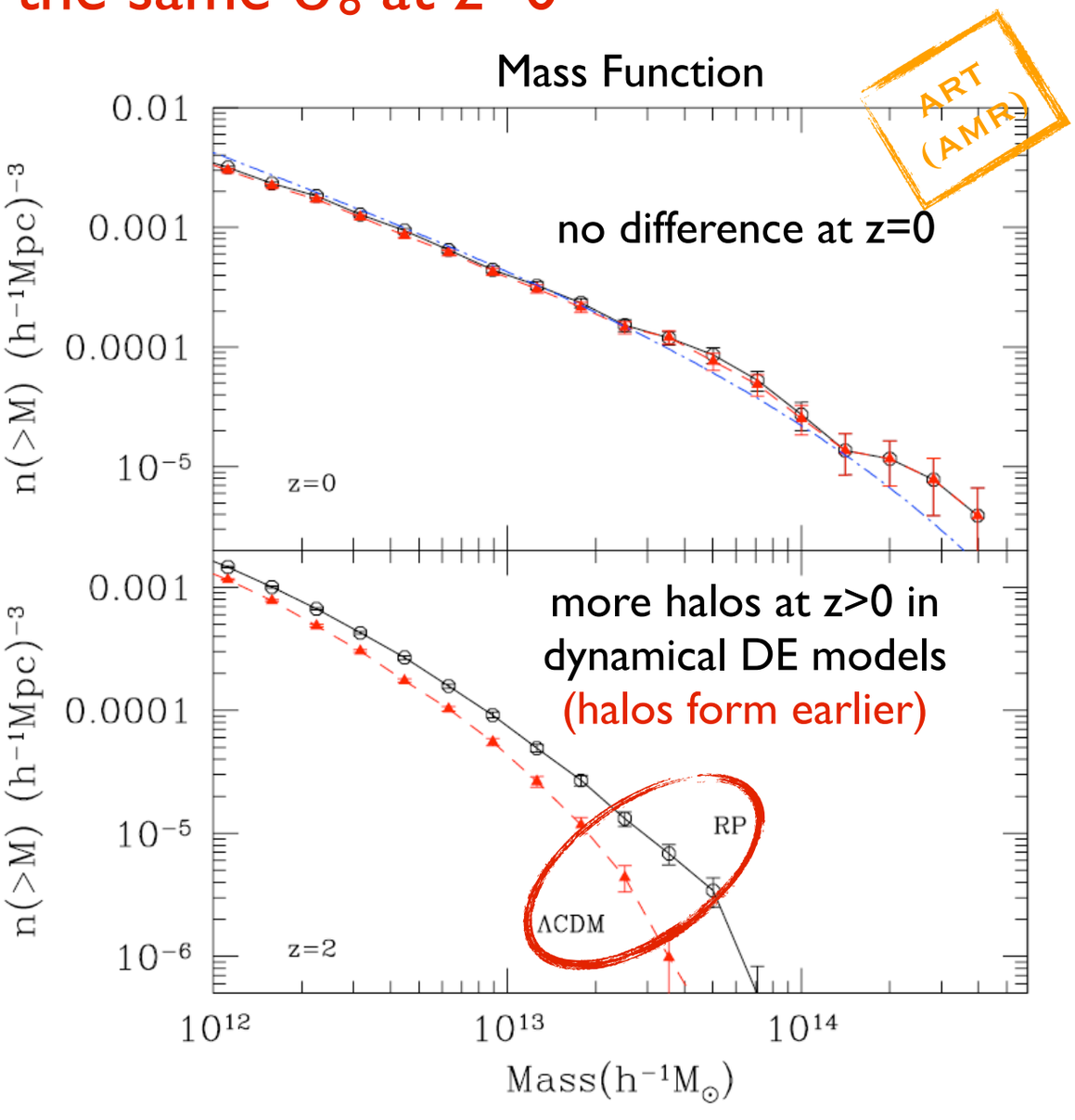

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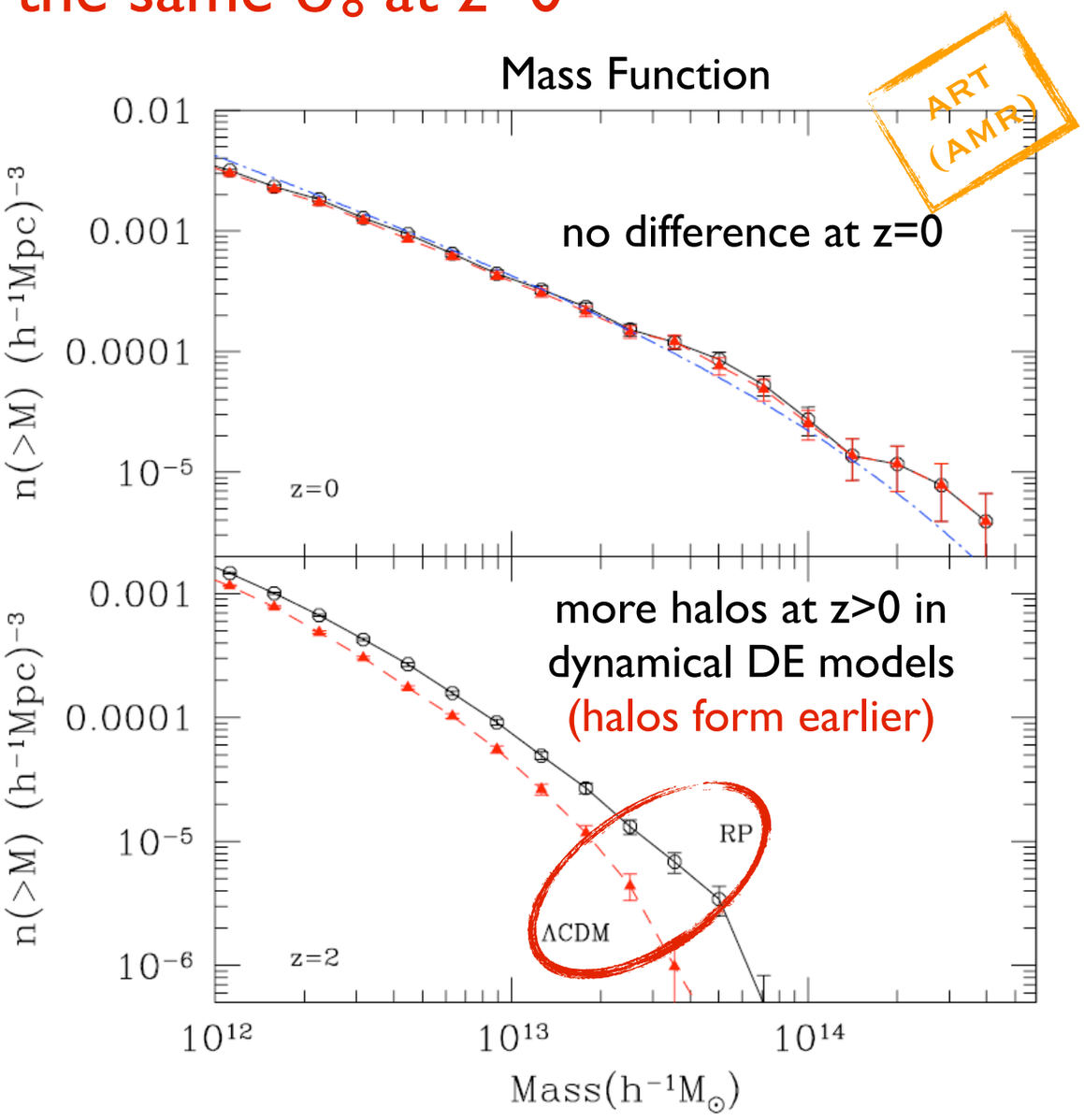

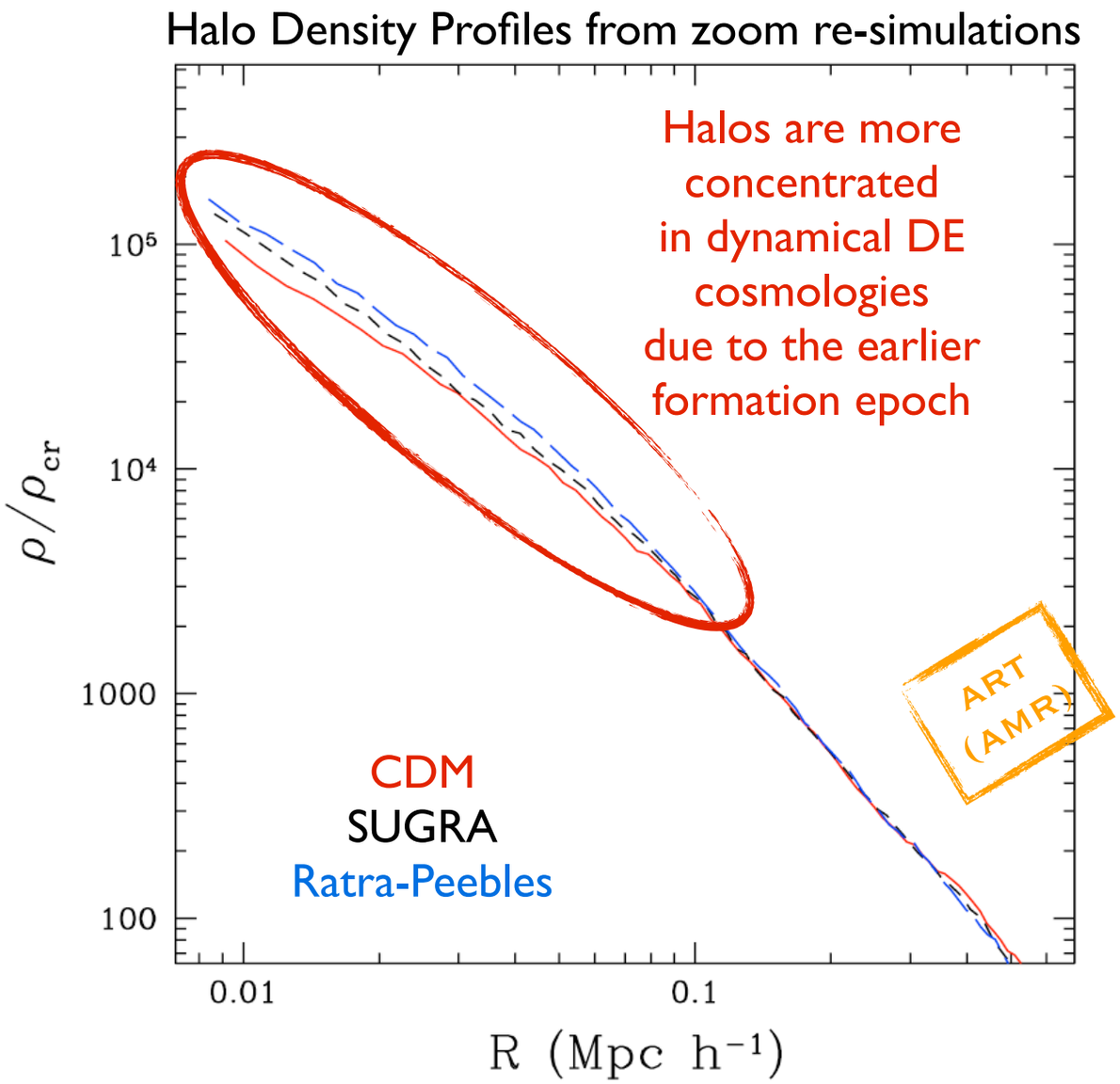

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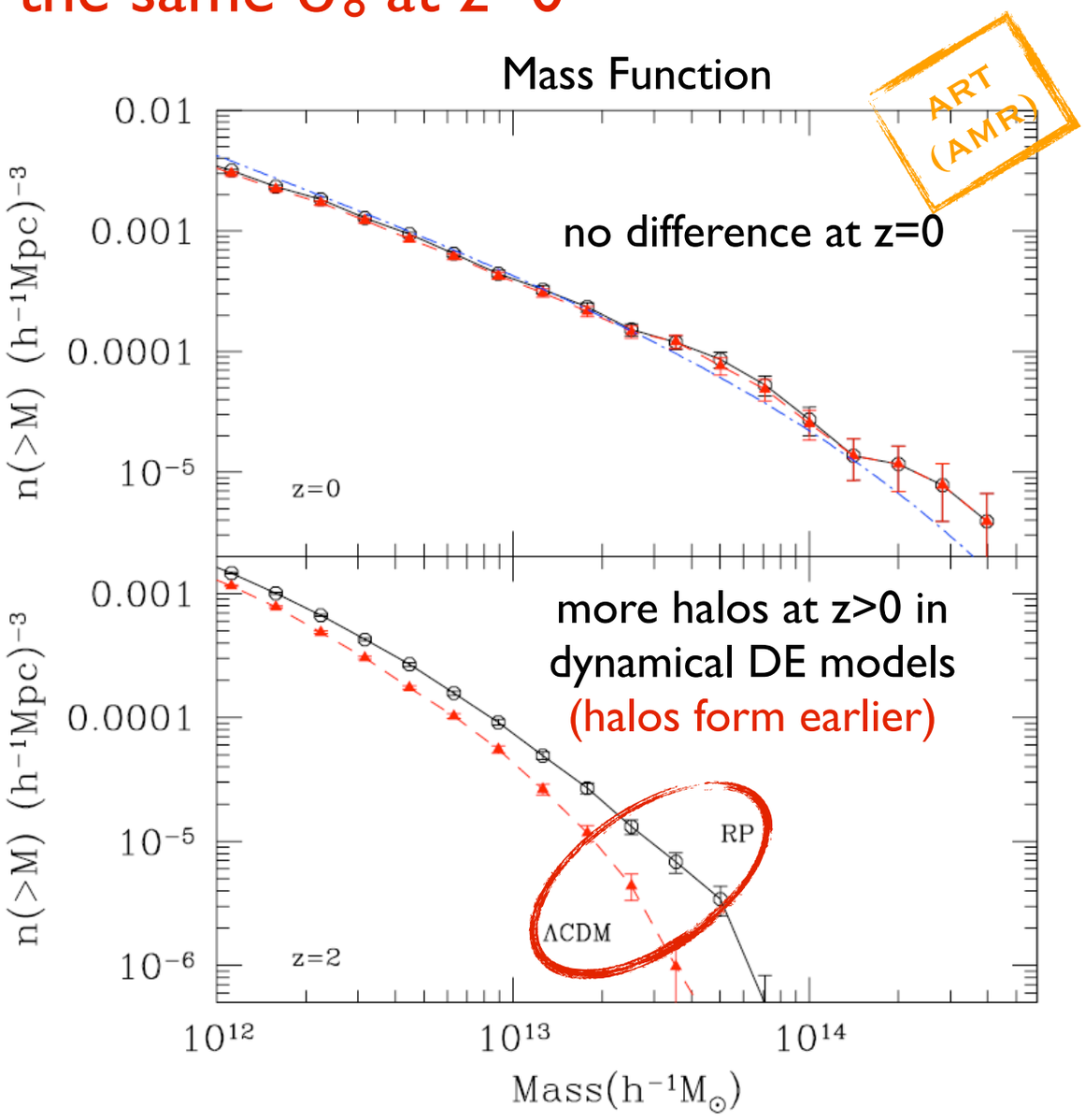

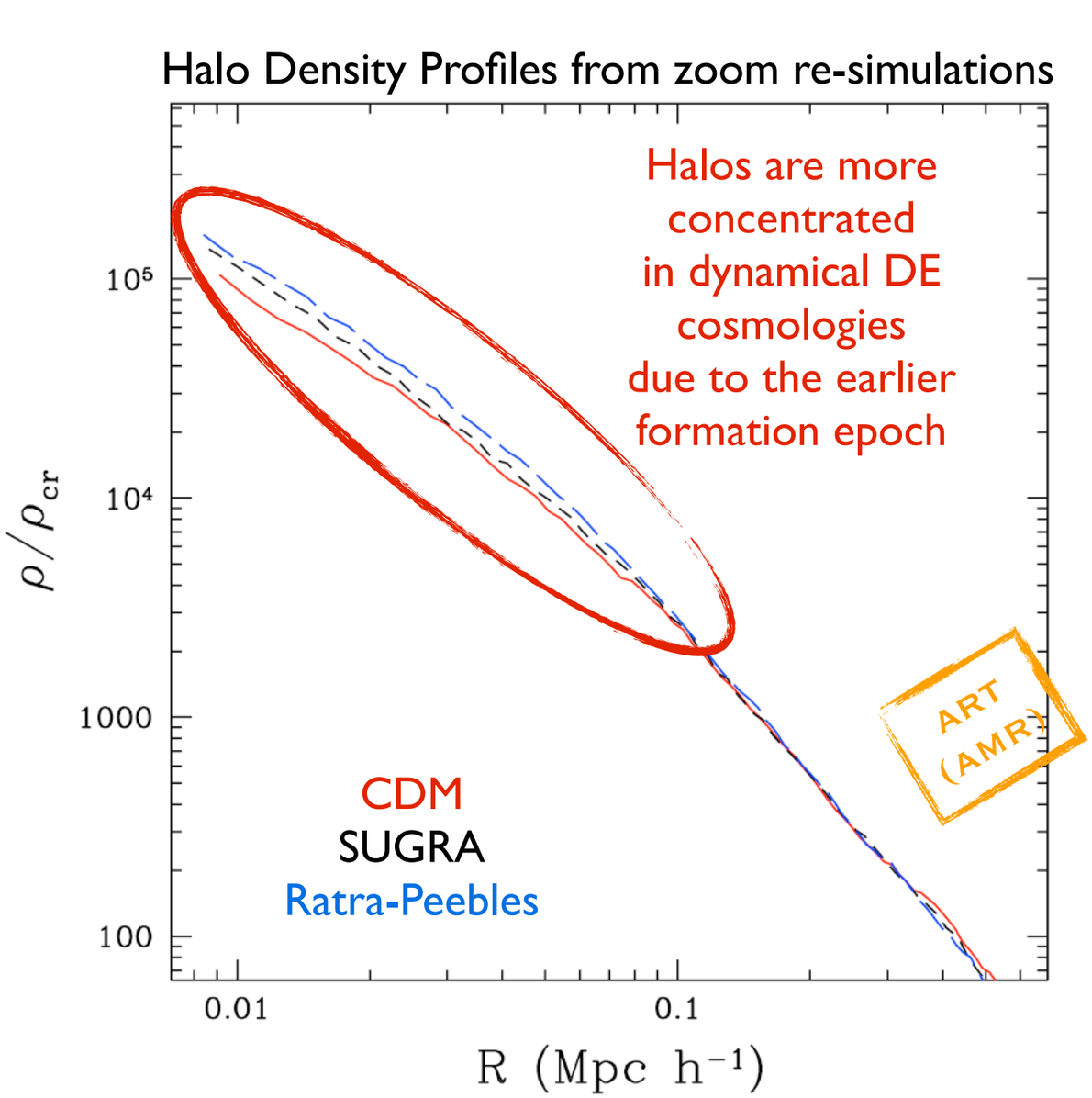

Results confirmed by: Linder & Jenkins 2003 (Gadget); Lokas, Bode, Hoffman 2004 (TreePM); Dolag et al. 2004 (Gadget);

DYNAMICAL DARK ENERGY

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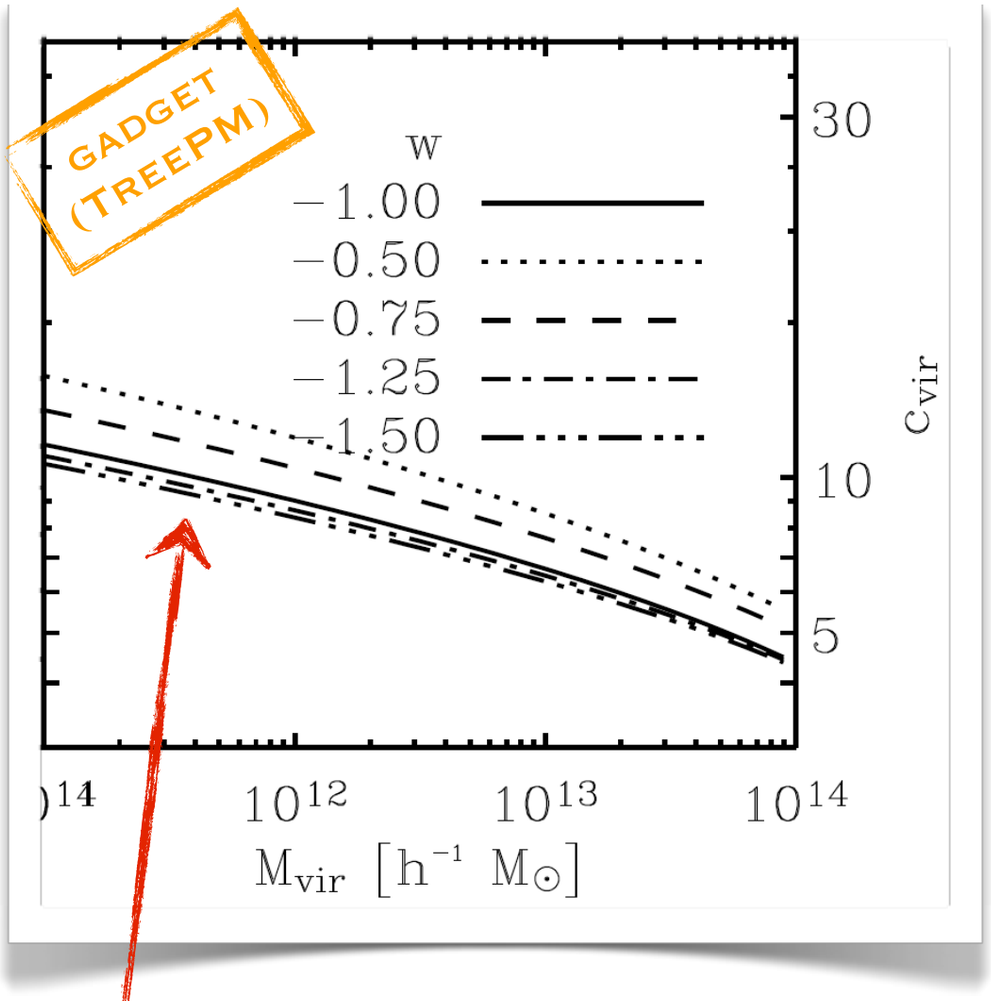

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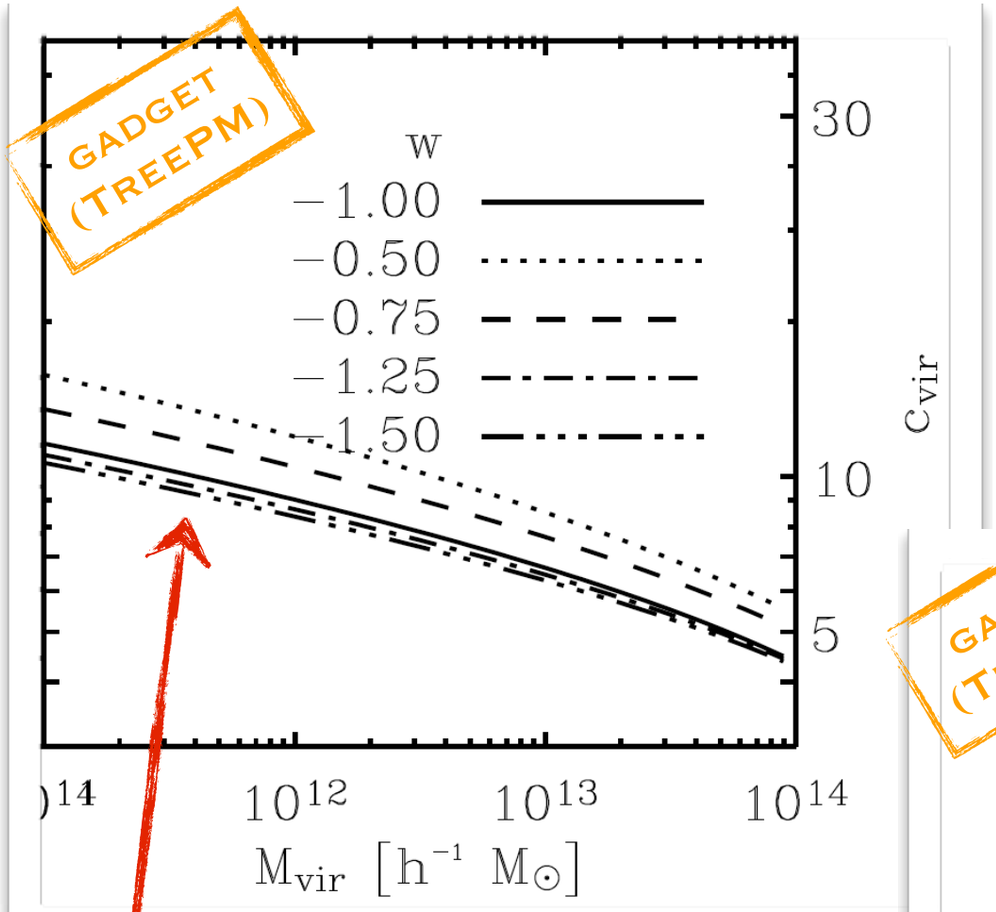

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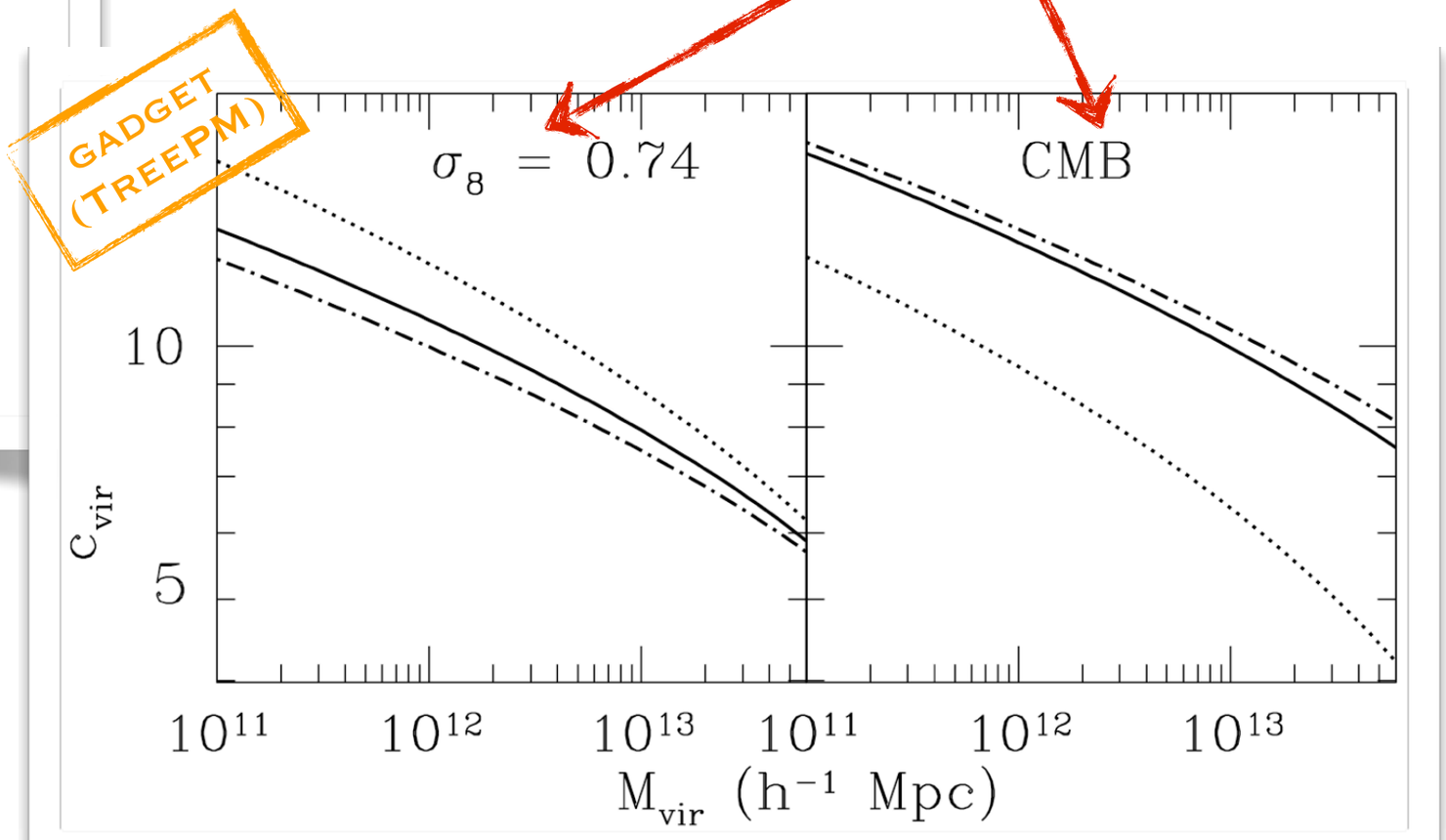
The role of the normalization of perturbations amplitude is crucial: normalizing at CMB instead of z=0 one finds the opposite effect:
The impact of dynamical (homogeneous) DE on structure formation is degenerate with σ_8



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The impact of dynamical DE on BAO (Jennings et al. 2010)

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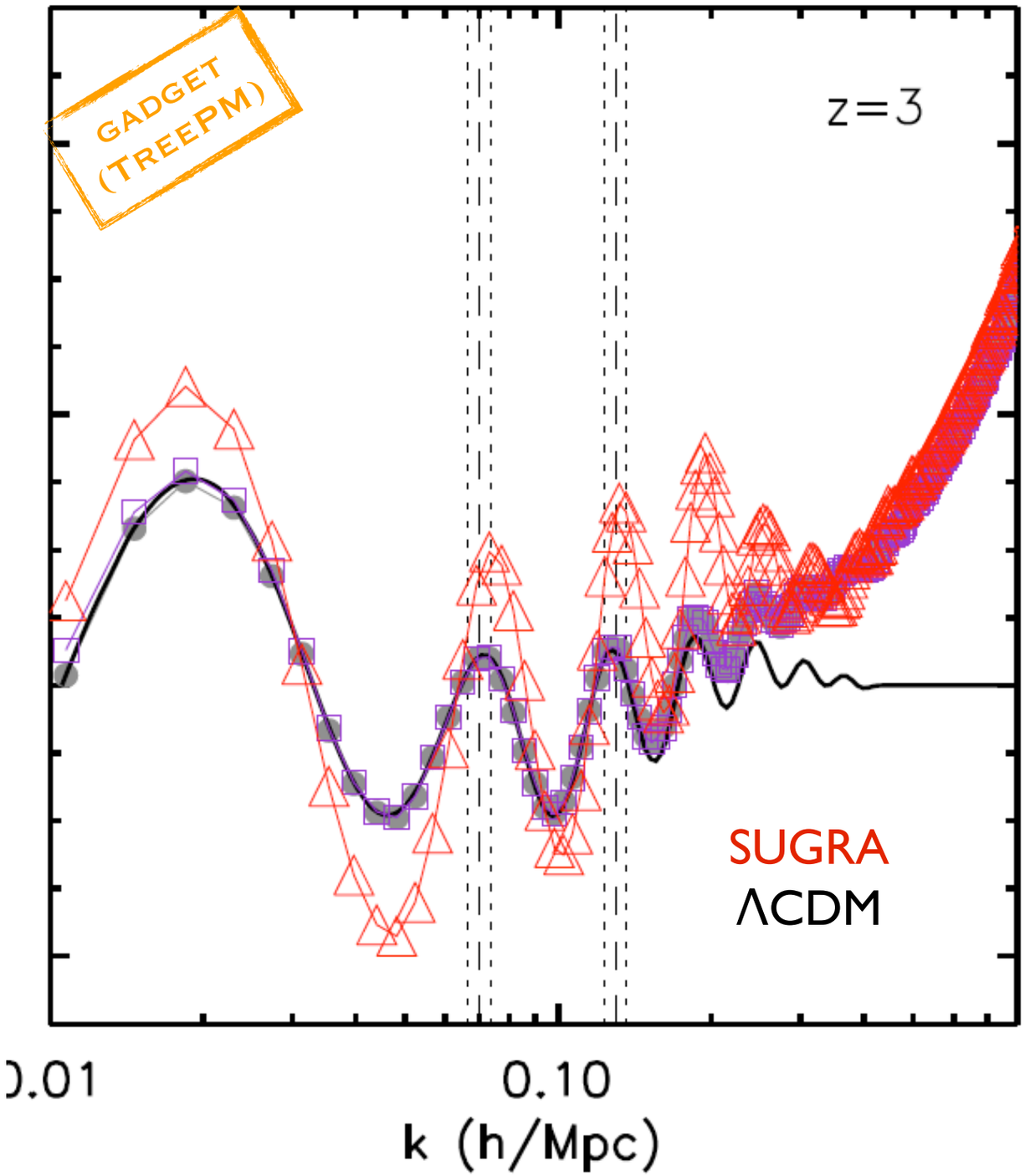

While dynamical DE models have a higher halo abundance at high z when normalized with σ_8 at z=0, their BAO peaks positions can be identical to those of ΛCDM, which makes it difficult to detect a time variation of w with BAO

DYNAMICAL DARK ENERGY

Early Dark Energy (Francis, Lewis, Linder 2008; Grossi & Springel 2009)

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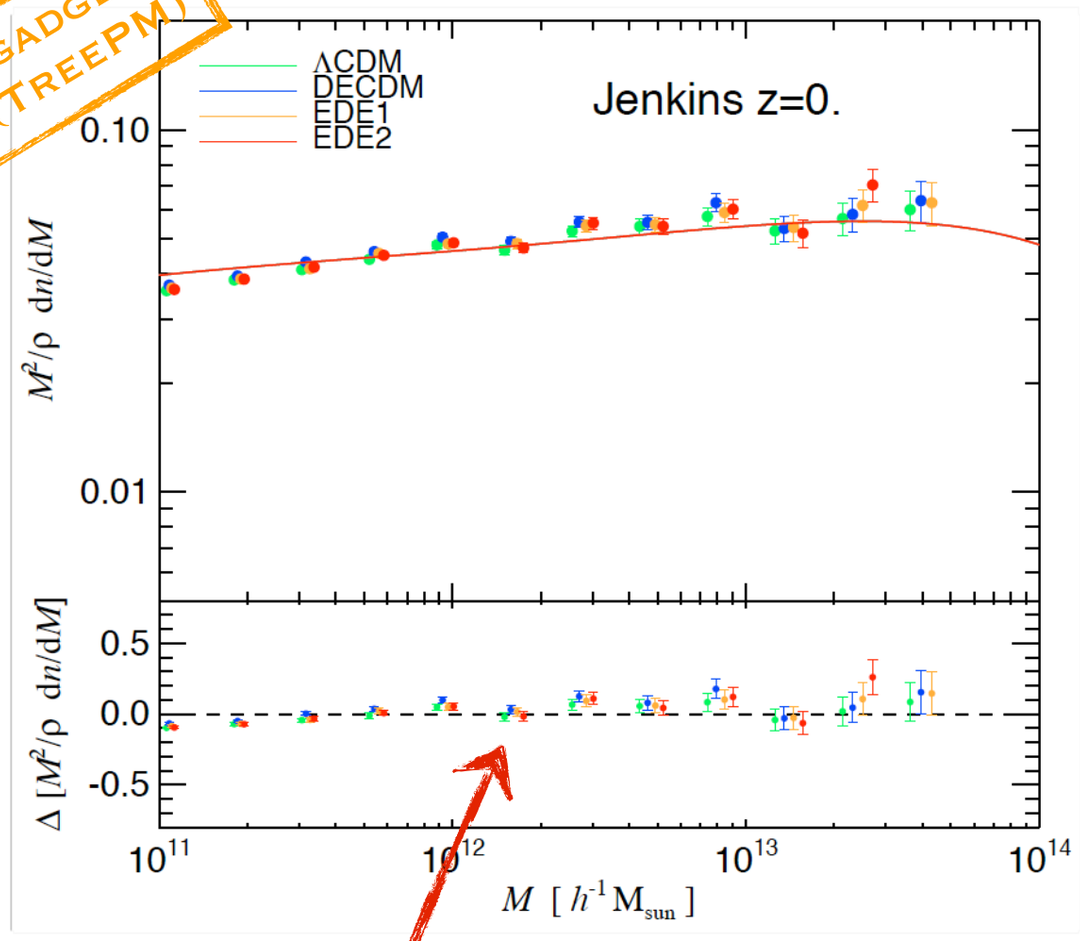
GADGET (TREEPM)



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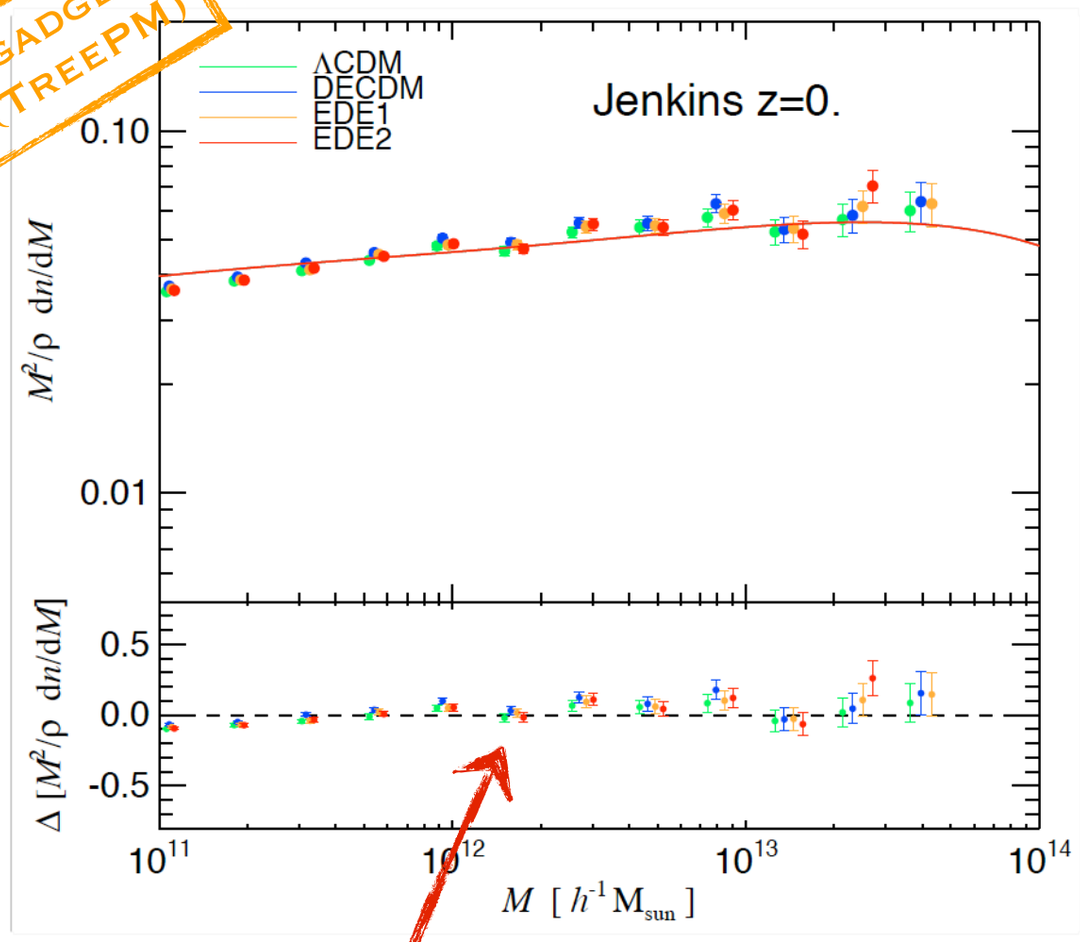

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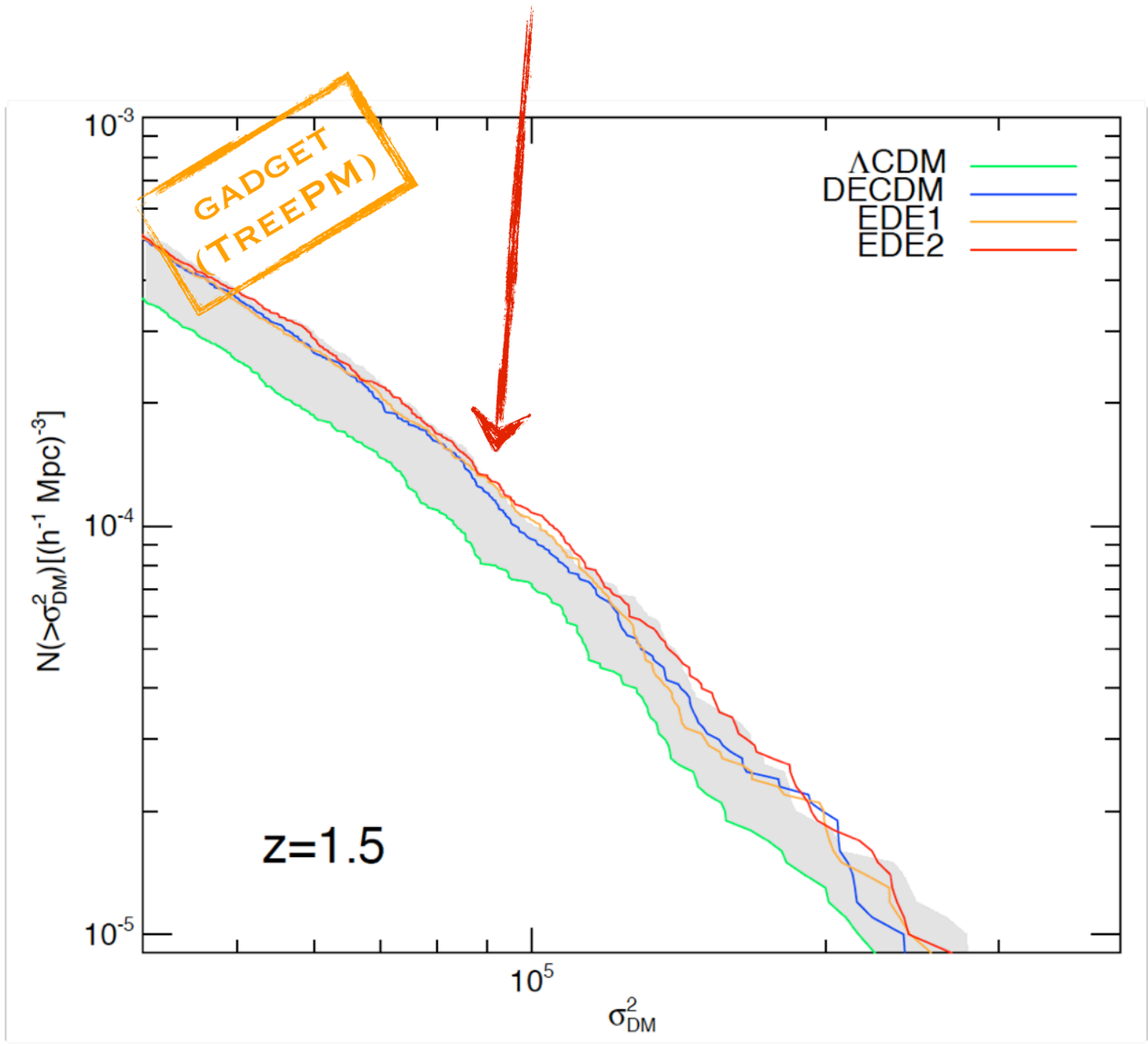
Counting EDE halos by l.o.s. velocity dispersion (rather than by mass) would imply a higher σ_8 normalization if interpreted in terms of ΛCDM



DYNAMICAL DARK ENERGY

Many other relevant works on...

The impact of dynamical DE on the nonlinear matter power spectrum
(e.g. Francis, Lewis, Linder 2007; Ma 2007; Casarini, Macciò, Bonometto 2009; Alimi et al. 2010; Fedeli, Dolag, Moscardini 2012)

The impact of dynamical DE on Strong Lensing statistics
(e.g. Meneghetti et al. 2005)

The impact of dynamical DE on reionization
(e.g. Maio et al. 2006)

The impact of dynamical DE on clusters properties and scaling relations
(e.g. Dolag et al. 2004; Aghanim et al. 2009; De Boni et al. 2011, 2012)

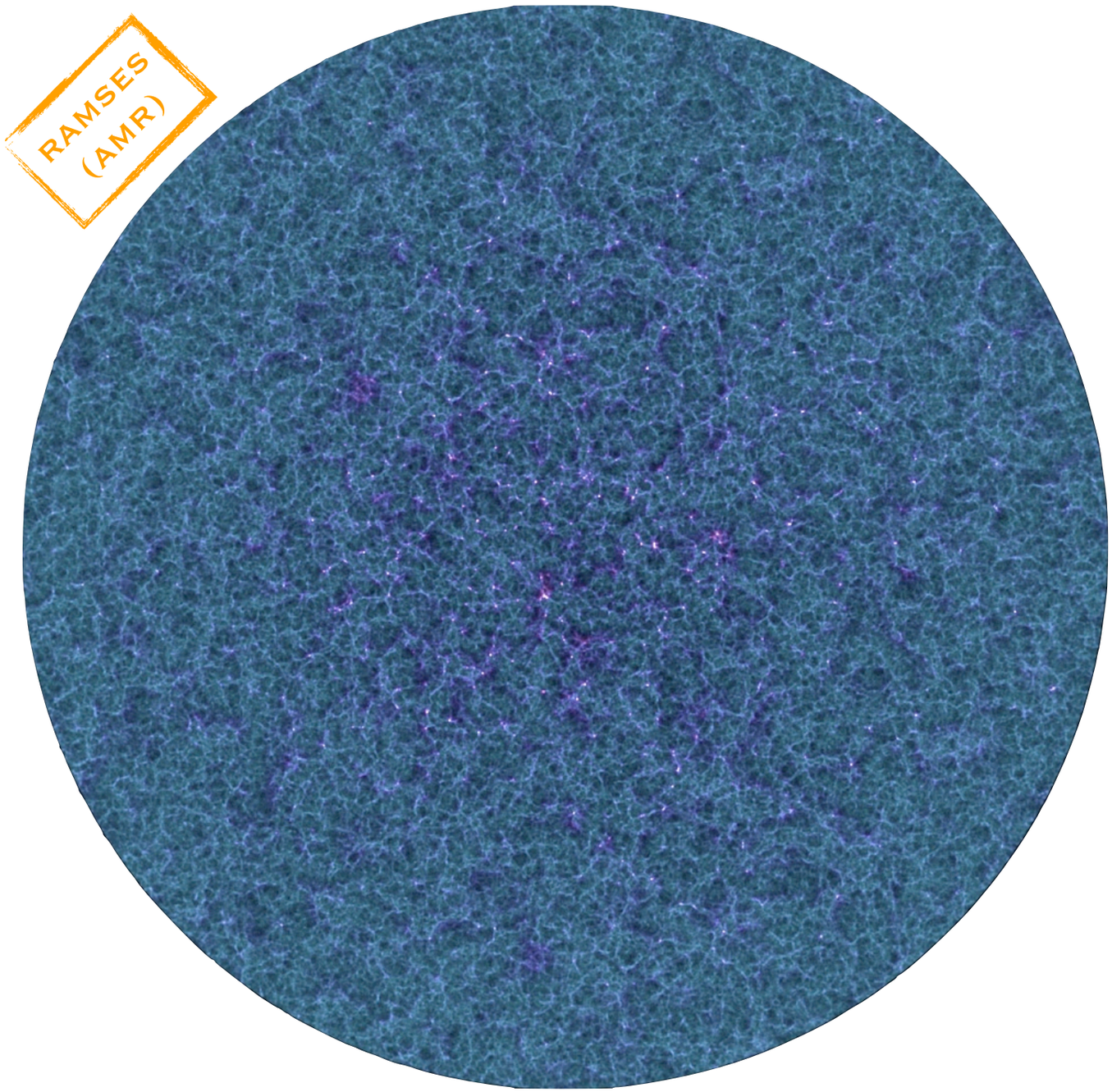
The impact of dynamical DE on cosmic voids
(e.g. Patrick Bos et al. 2012)

Testing the universality of the halo mass function
(e.g. Courtin et al. 2011)

DYNAMICAL DARK ENERGY

Towards extremely large simulations of DE cosmologies

(Rasera et al. 2010; Alimi et al. 2012)



The Dark Energy Universe Simulation Series (DEUSS)

The Dark Energy Universe Simulation Full Universe Run (DEUS FUR)

21 Gpc/h
5.5×10^{11} particles
10^7 CPU hours

So far only ΛCDM,
soon also for a quintessence DE and a phantom DE models

See Pier Stefano Corasaniti's talk in a few minutes

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A scalar filed with time-depending equation of state and $c_\phi^2 \approx 0$

(Creminelli et al. 2009; Creminelli et al. 2010; Sefusatti & Vernizzi 2011)

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Simulations on the way

(work in progress with F. Vernizzi, P. Creminelli, S. Borgani)

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Clustering DE ("cold" DE models)	✓ a dynamical (scalar) degree of freedom	✓ small sound speed, clustering at sub-H	✗ minimally coupled to matter
Interacting DE (Coupled and Extended Quintessence, Modified Gravity)	✓ a dynamical (scalar) degree of freedom	✓ fluctuations sourced by the interaction	✓ non-minimally coupled to matter

INTERACTING DARK ENERGY

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A coupling between a scalar field and matter (or gravity) would source perturbations at sub-horizon scales and mediate a fifth-force.

$$\nabla^2\Phi_g = -4\pi G\left(\delta\rho_M + \delta\rho_{\rm DE}\right) \qquad \vec{a} = -\vec{\nabla}\Phi_g - 2\beta(\phi)e^{-m_\phi r}\vec{\nabla}\delta\phi$$

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How to evade such constraints?

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Non-Universal Couplings

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If the field interacts with CDM only, solar system constraints do not apply, and the main bounds come from cosmology.

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UNIVERSAL COUPLING + SCREENING MECHANISM

(Khoury & Weltman 2004; Vainshtein1972)

If the fifth-force is screened (suppressed) in our local environment solar system constraints can be evaded

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$$\nabla^2\delta\phi \approx \beta(\phi)\delta\rho_M \Rightarrow \delta\phi \approx \beta(\phi)\Phi_g$$

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For universal couplings one needs to suppress the fifth-force in our local environment, i.e. in high-density regions. This can be achieved by, e.g.:

A density-dependent scalar mass (e.g. Chameleon)

$e^{-m_\phi r} \ll 1$ in high-density regions (Khoury & Weltman 2004; Brax et al 2004)

A density-dependent coupling (e.g. Symmetron)

$\beta(\phi) \ll 1$ in high-density regions (Hinterbichler & Khoury 2010)

INTERACTING DARK ENERGY

Non-universal couplings: Coupled Quintessence

$$\vec{a}_{\rm CDM} = -\vec{\nabla}\Phi_g(1+2\beta^2(\phi))+\beta(\phi)\dot{\phi}\vec{v} \qquad \vec{a}_{\rm b} = -\vec{\nabla}\Phi_g$$

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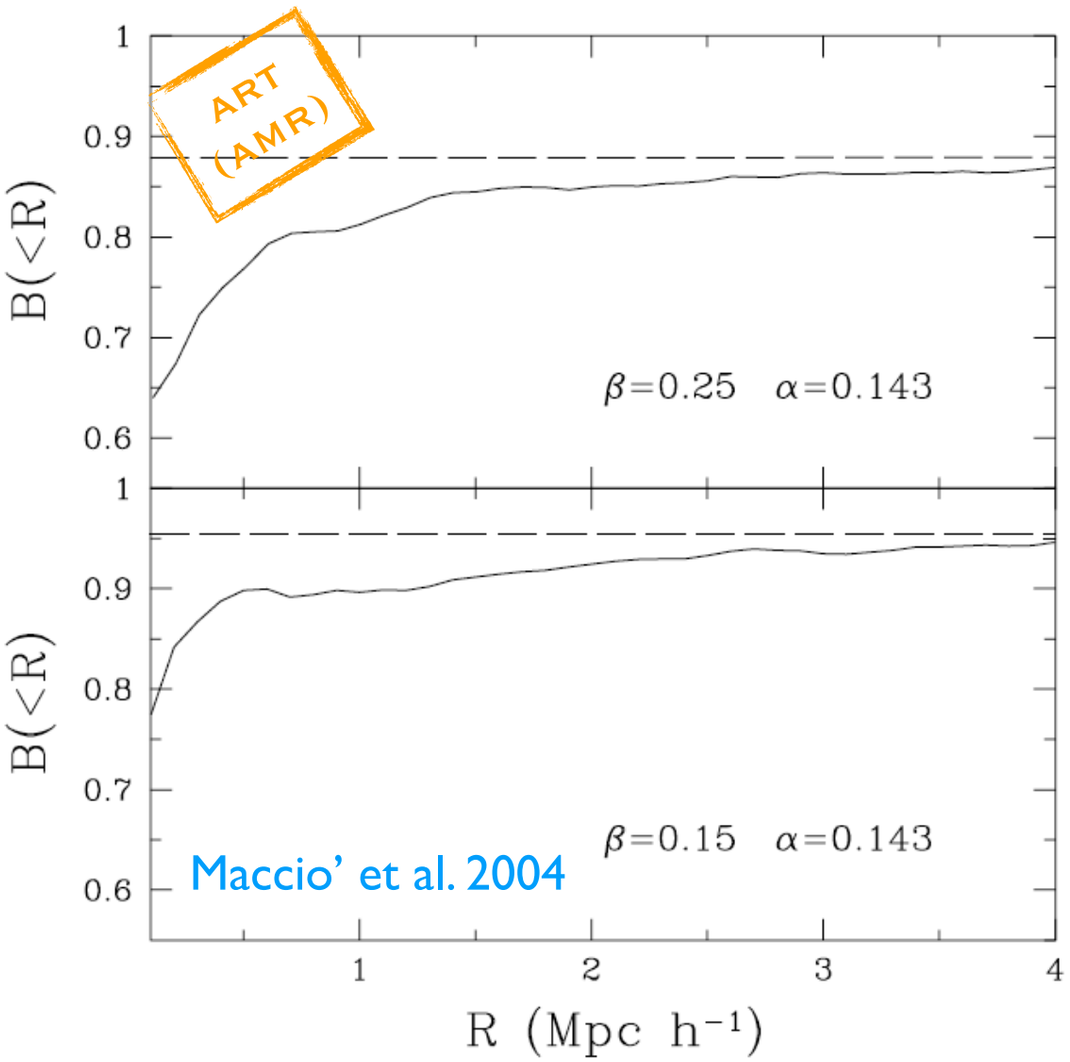

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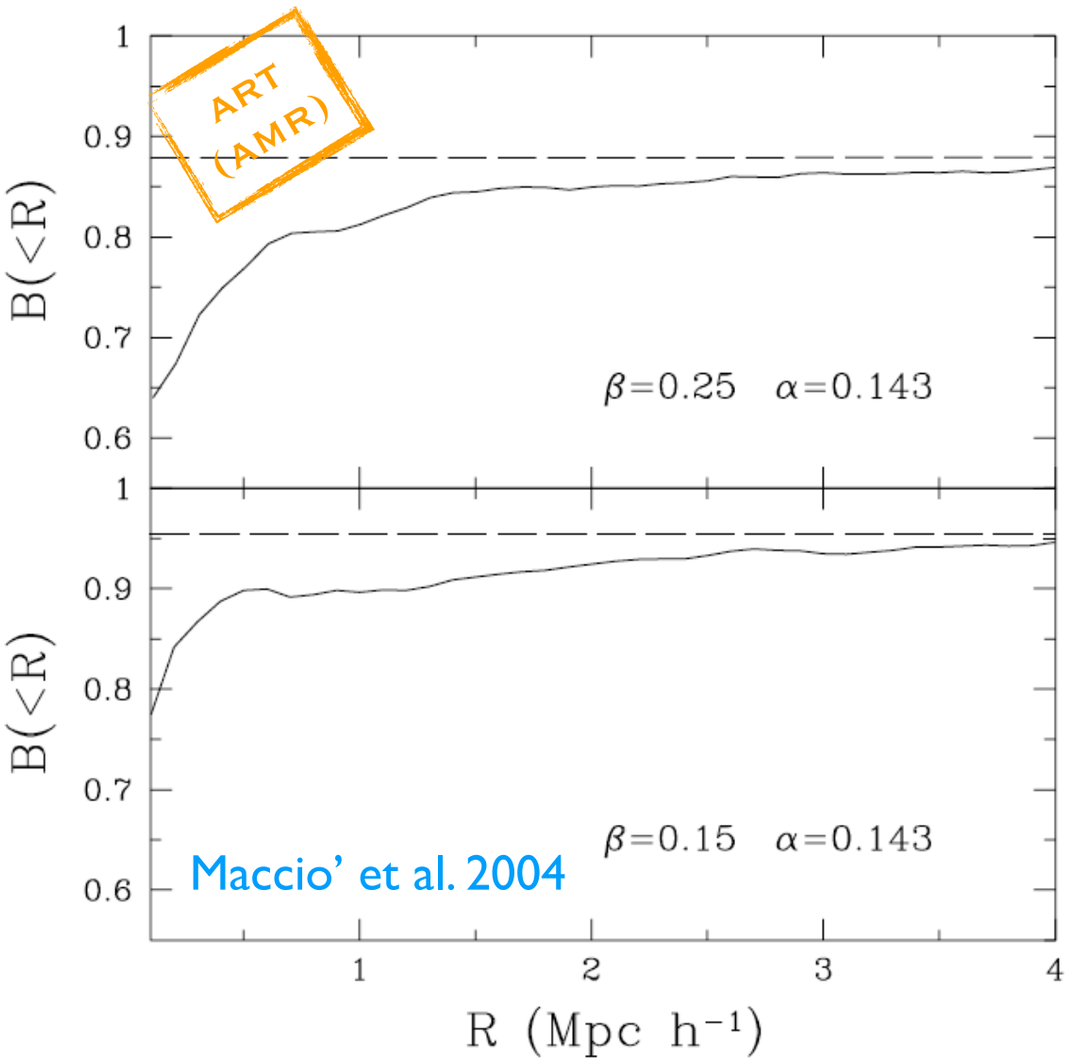
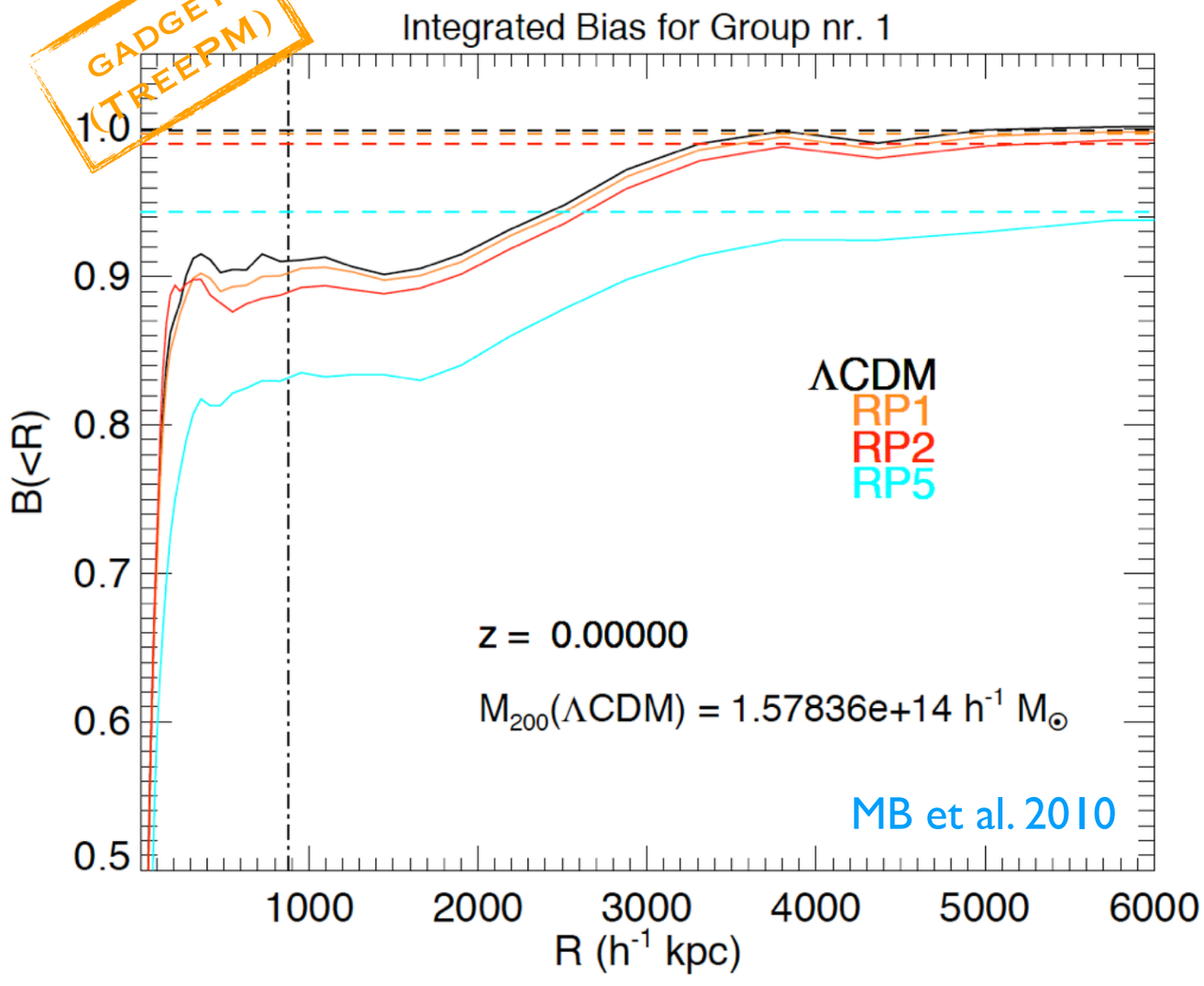
First N-body simulations by Macciò et al. 2004 using ART

First Hydro simulations by MB et al. 2010 using GADGET





INTERACTING DARK ENERGY

Maccio' et al. 2004

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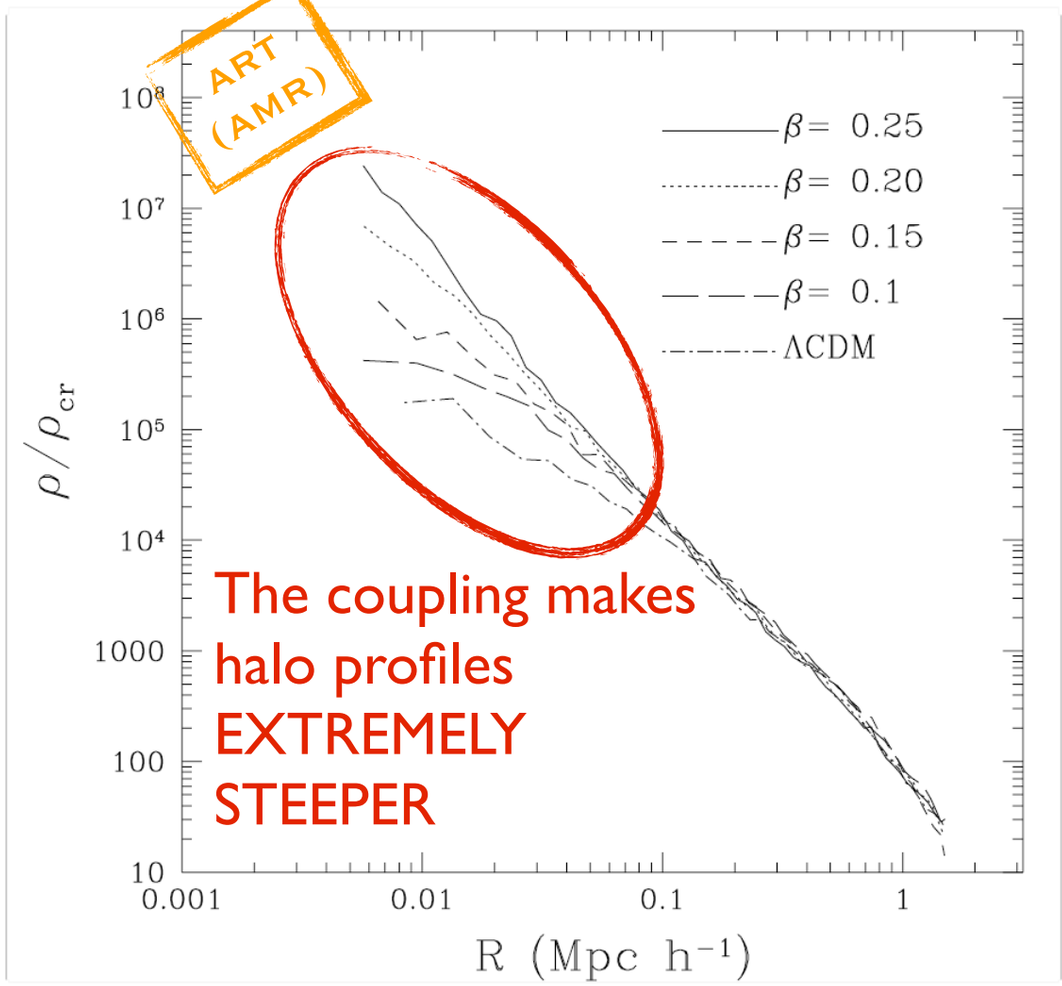

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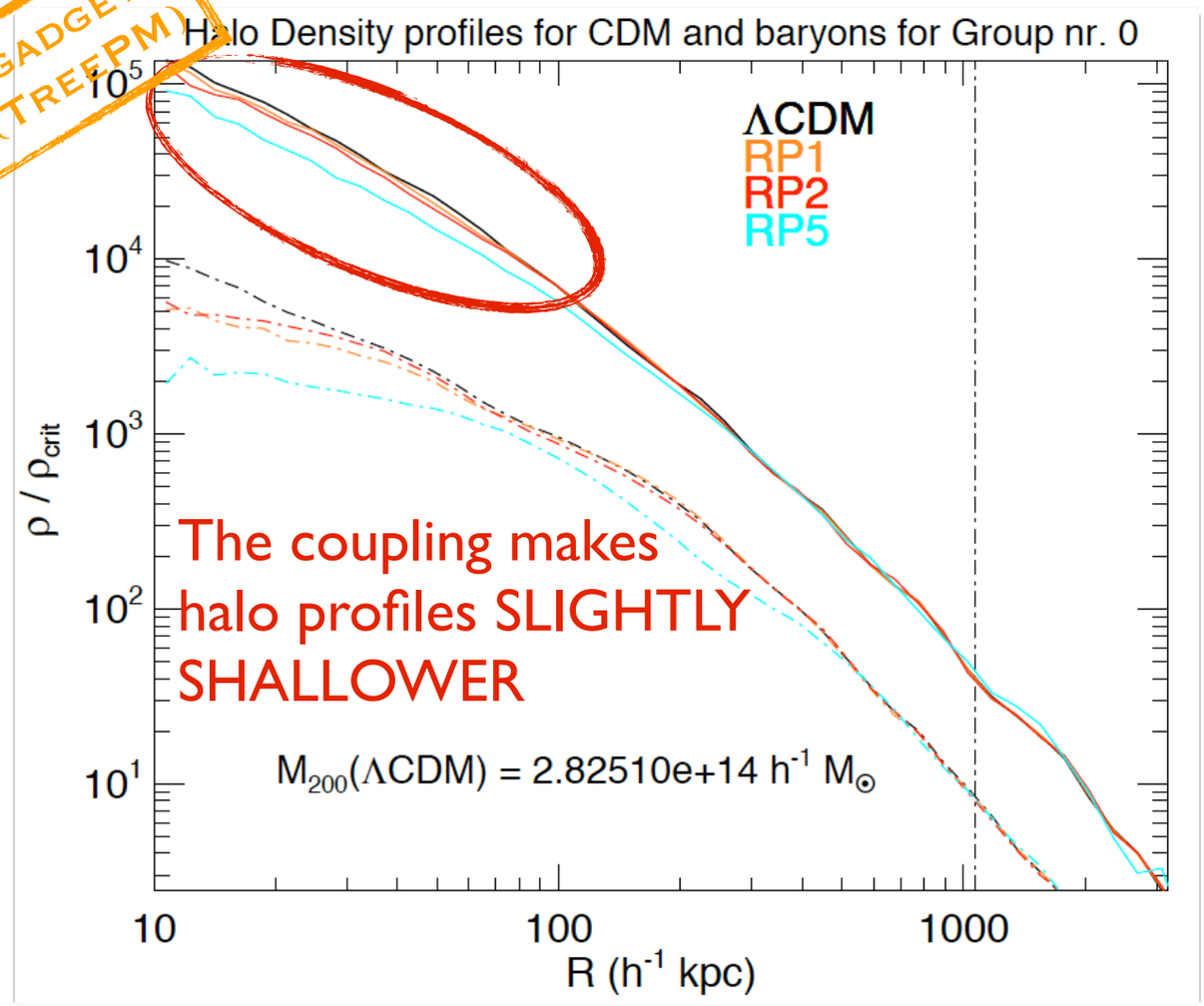

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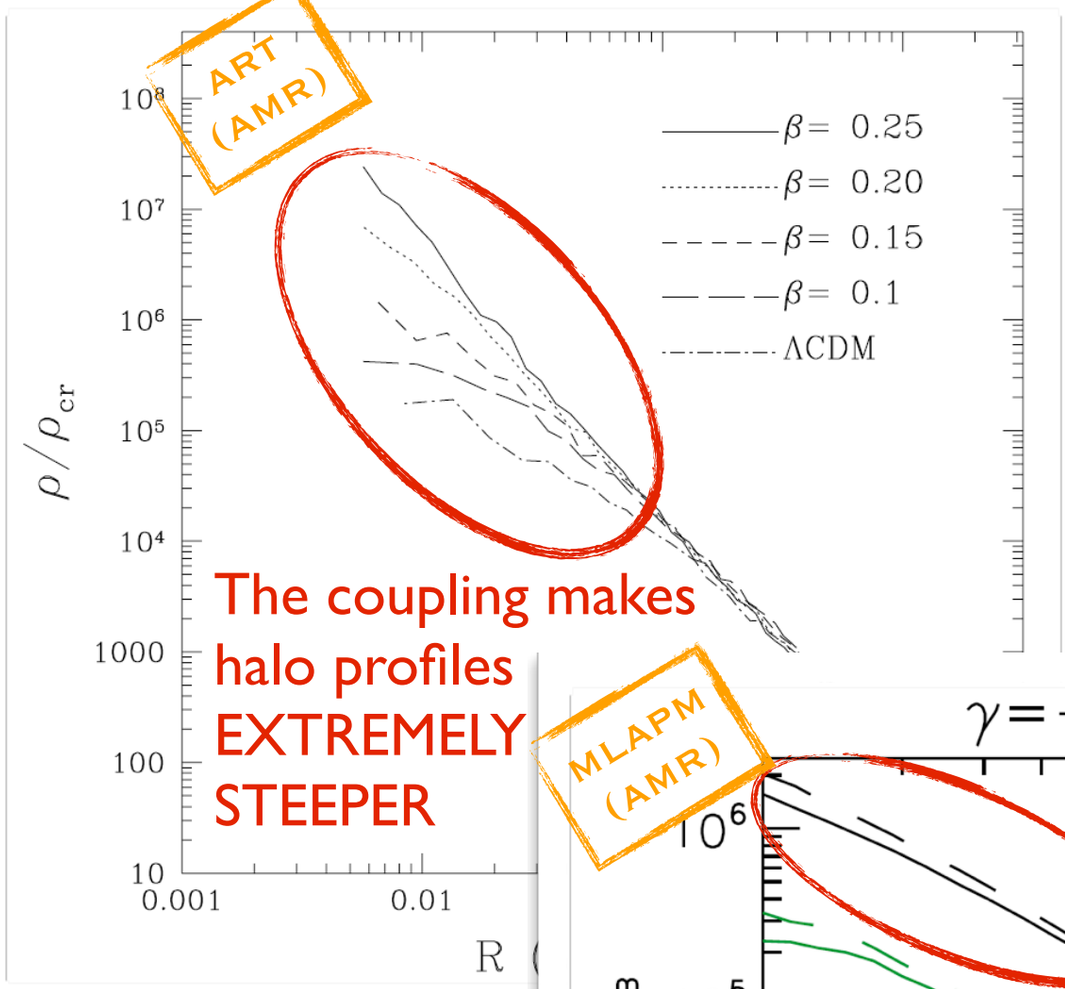

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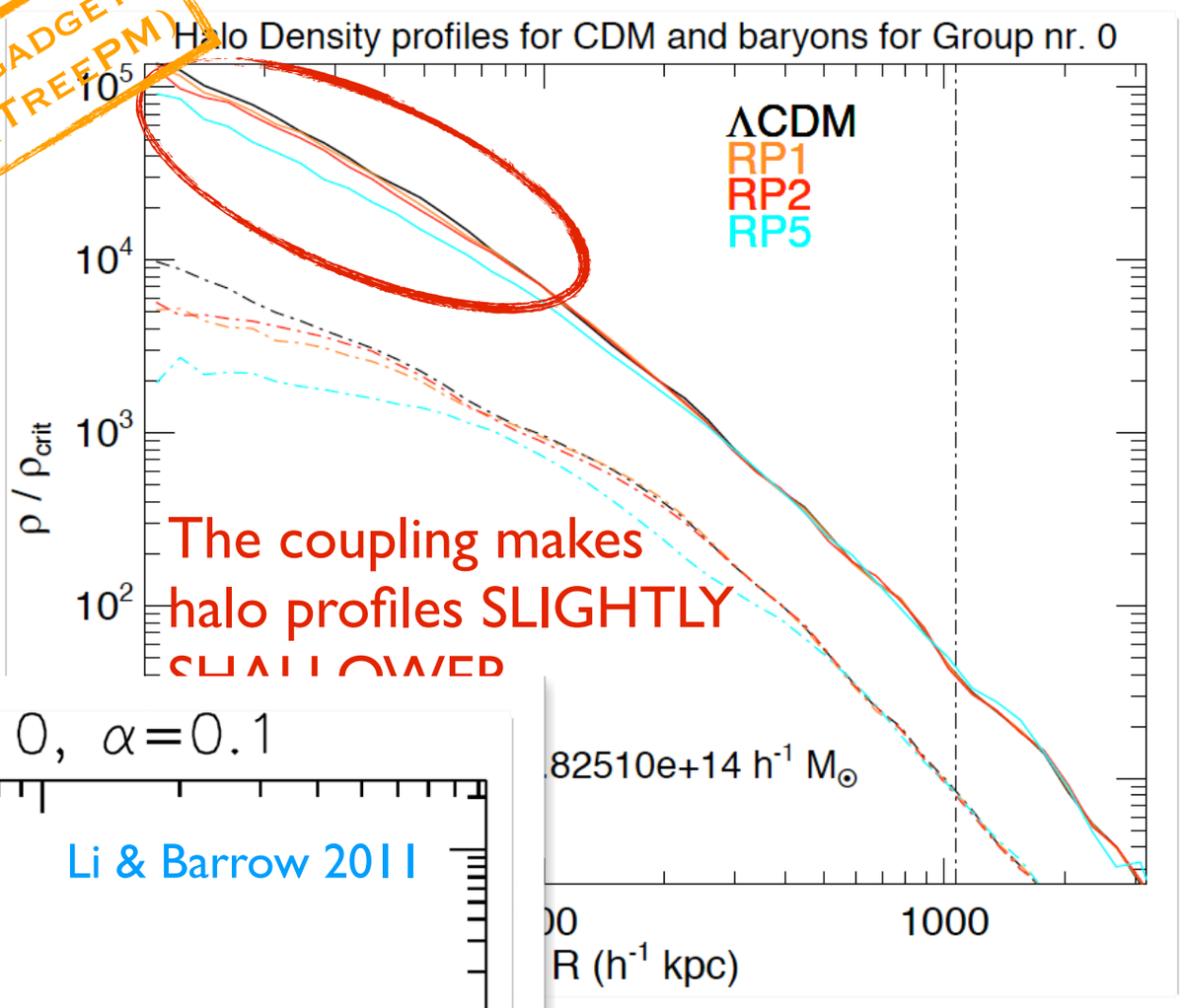

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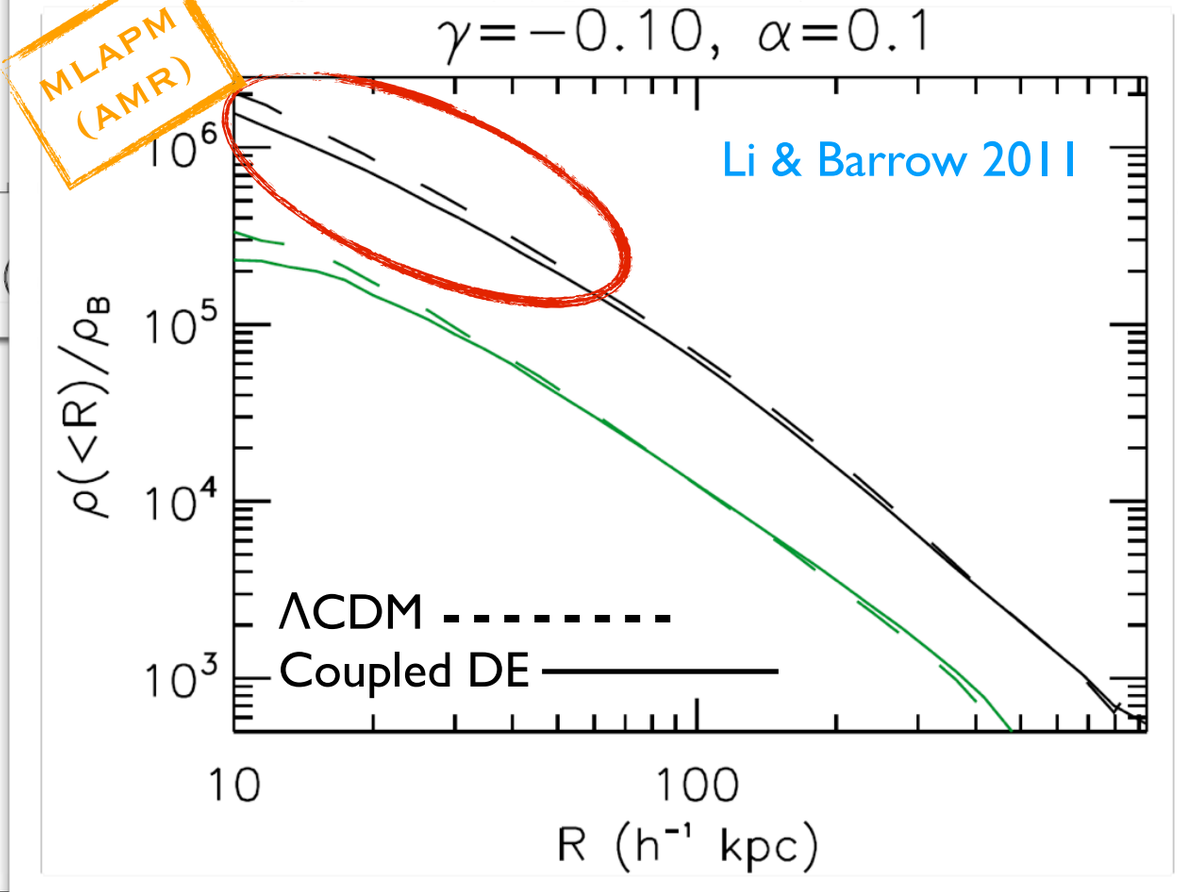

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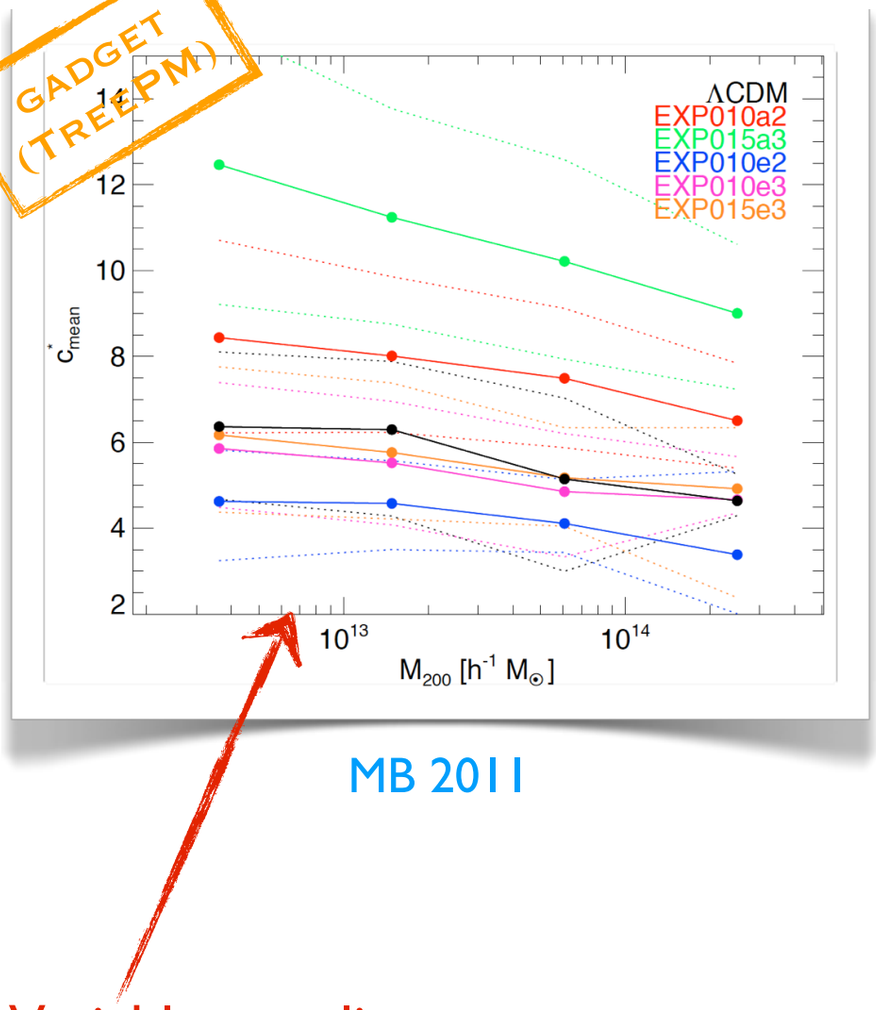

Variable couplings can produce opposite effects with respect to constant couplings on the nonlinear matter power spectrum, the density profiles, and the c-M relation

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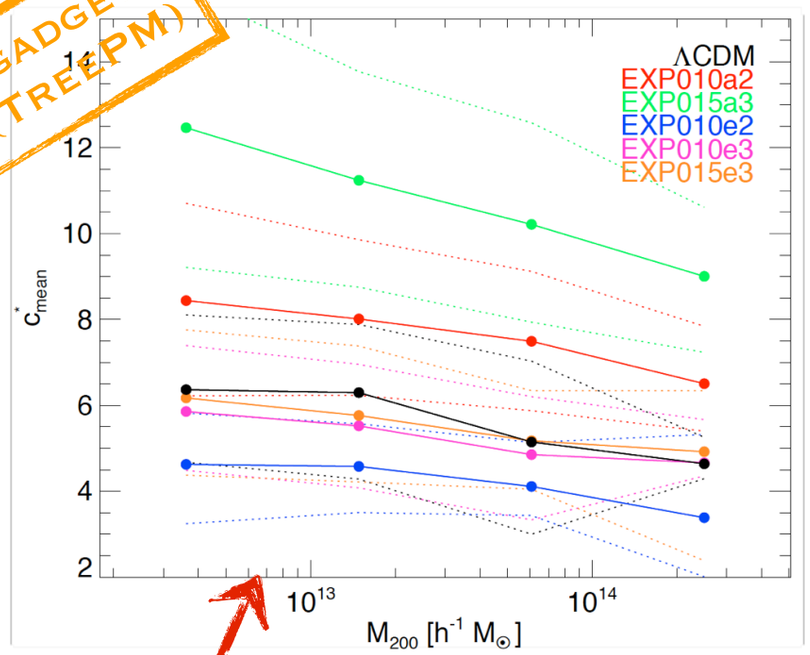

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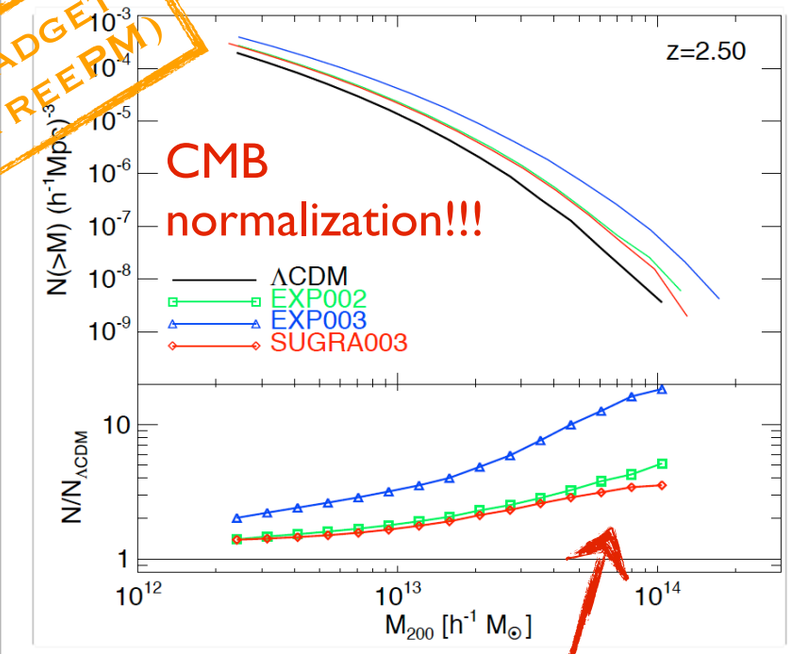

MB & Pettorino 2011; MB 2012

cDE can increase the number of high-z massive clusters even for CMB normalization, and for the case of a SUGRA potential, even for a simultaneous CMB and z=0 normalization

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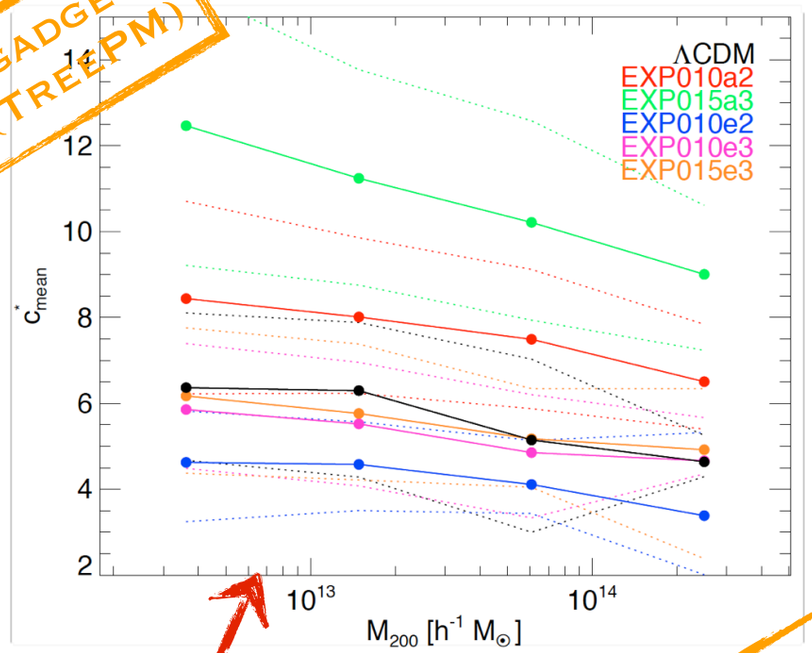

MB 2011

Large N-body simulations of several different cDE models are now publicly available through the CoDECS Project

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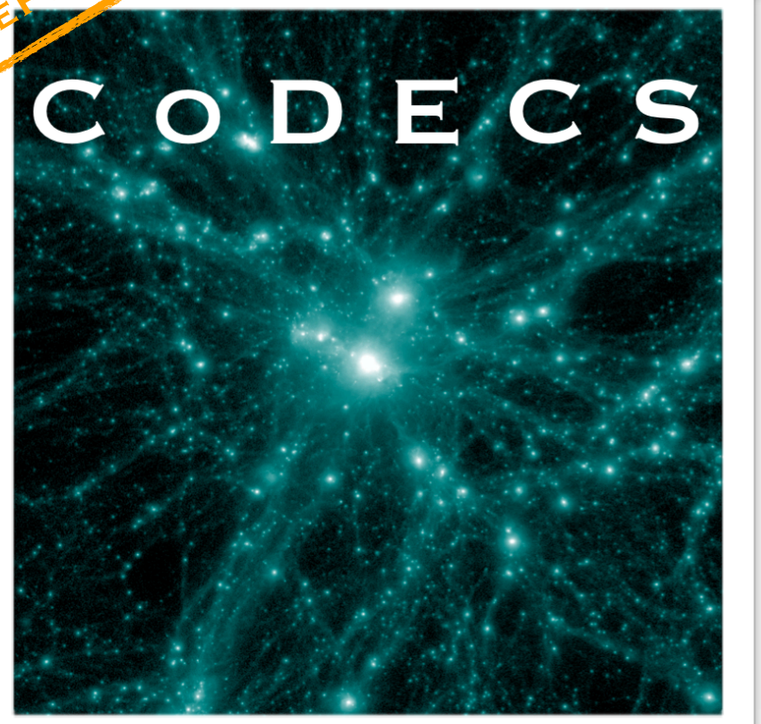

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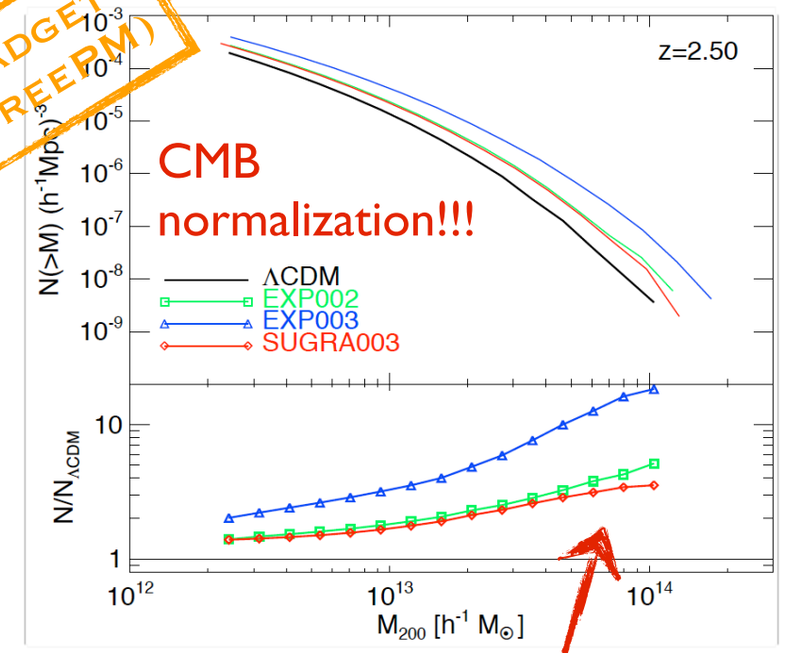

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http://www.usm.lmu.de/~mbaldi/CoDECS

INTERACTING DARK ENERGY

Non-universal couplings: Growing Neutrinos (Amendola, MB, Wetterich 2007)

The type of fifth-force is the same as for coupled quintessence, but involves massive neutrinos, and requires a much larger coupling such that the scalar force results orders of magnitude larger than gravity

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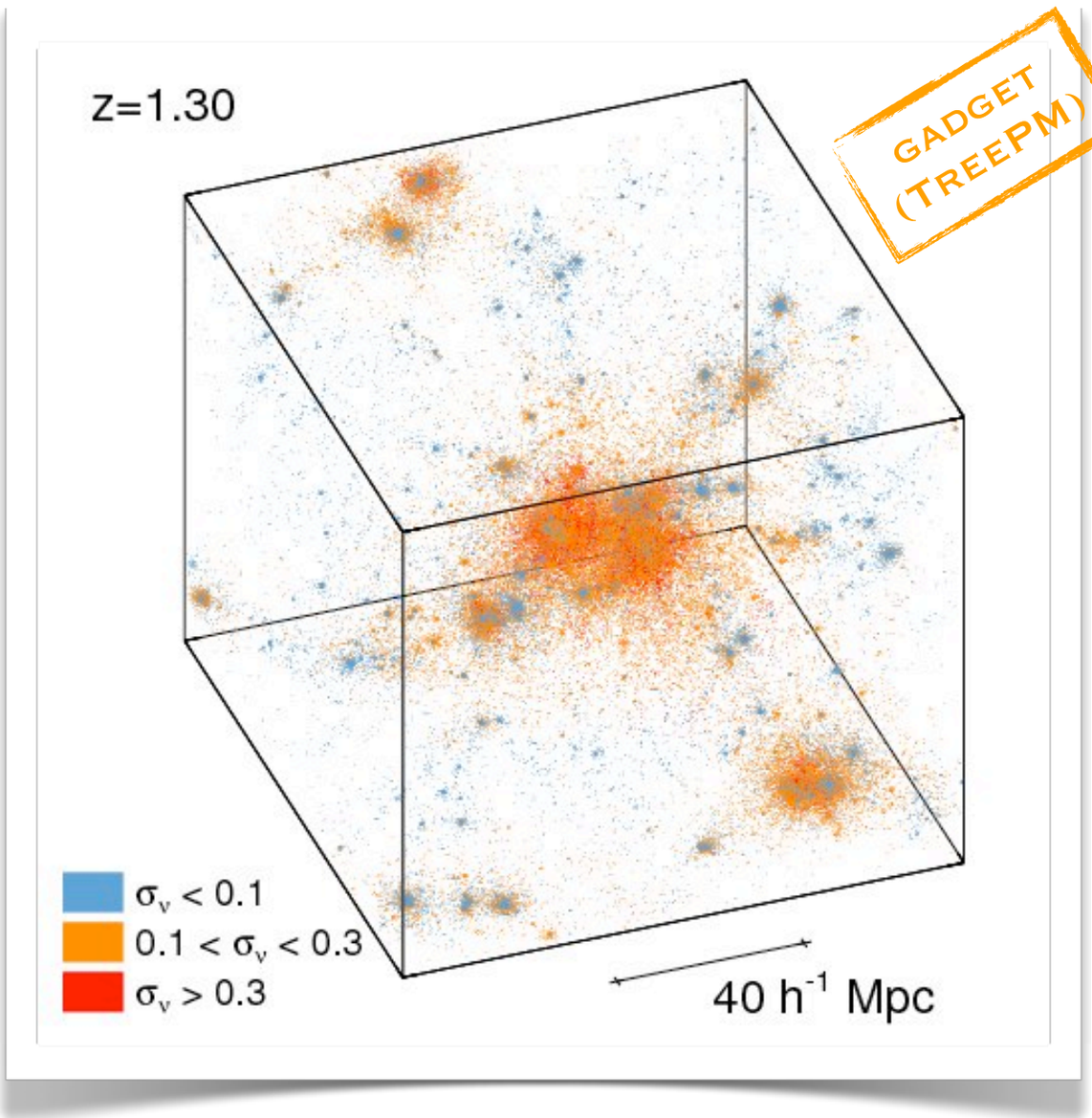

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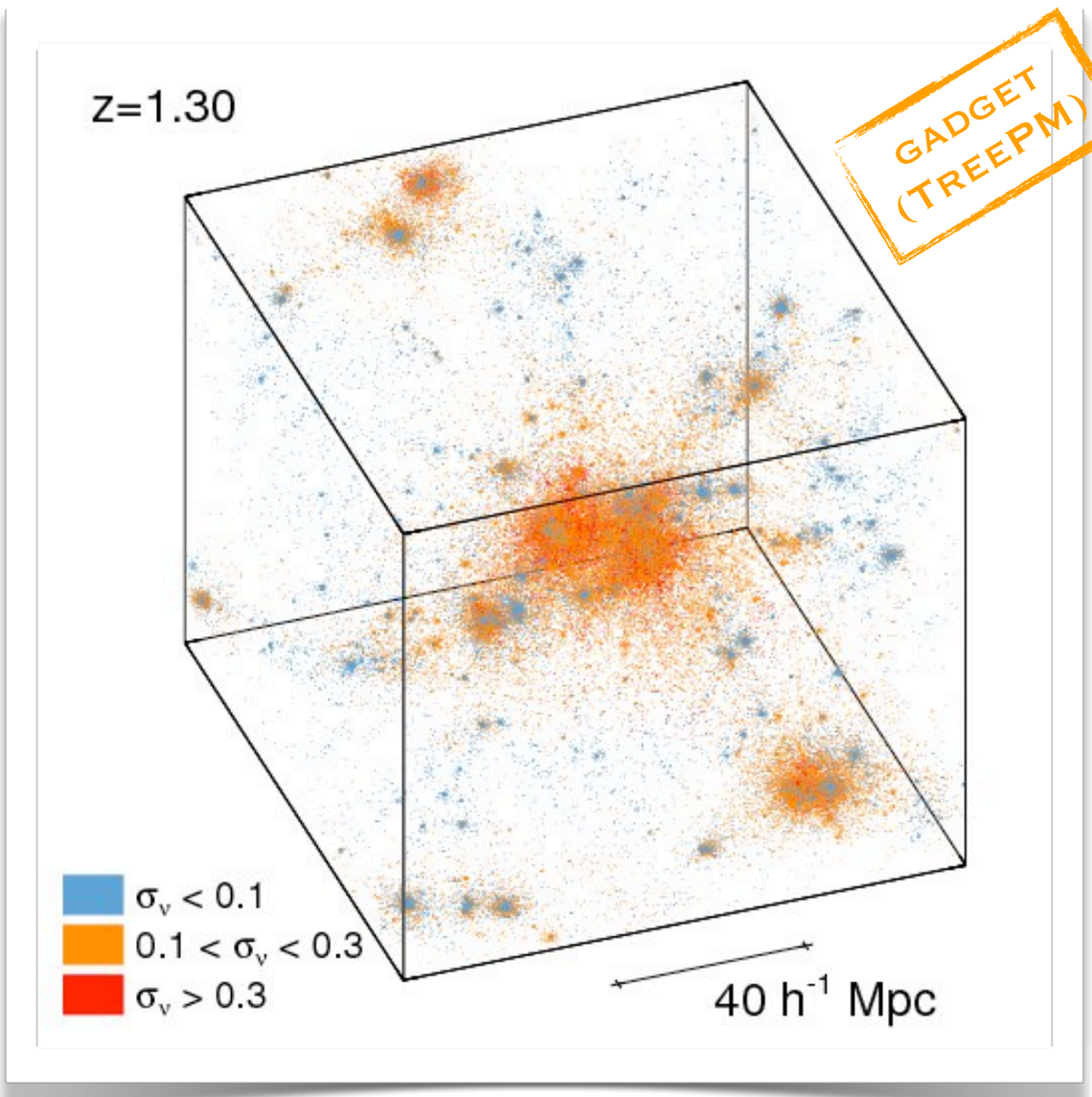

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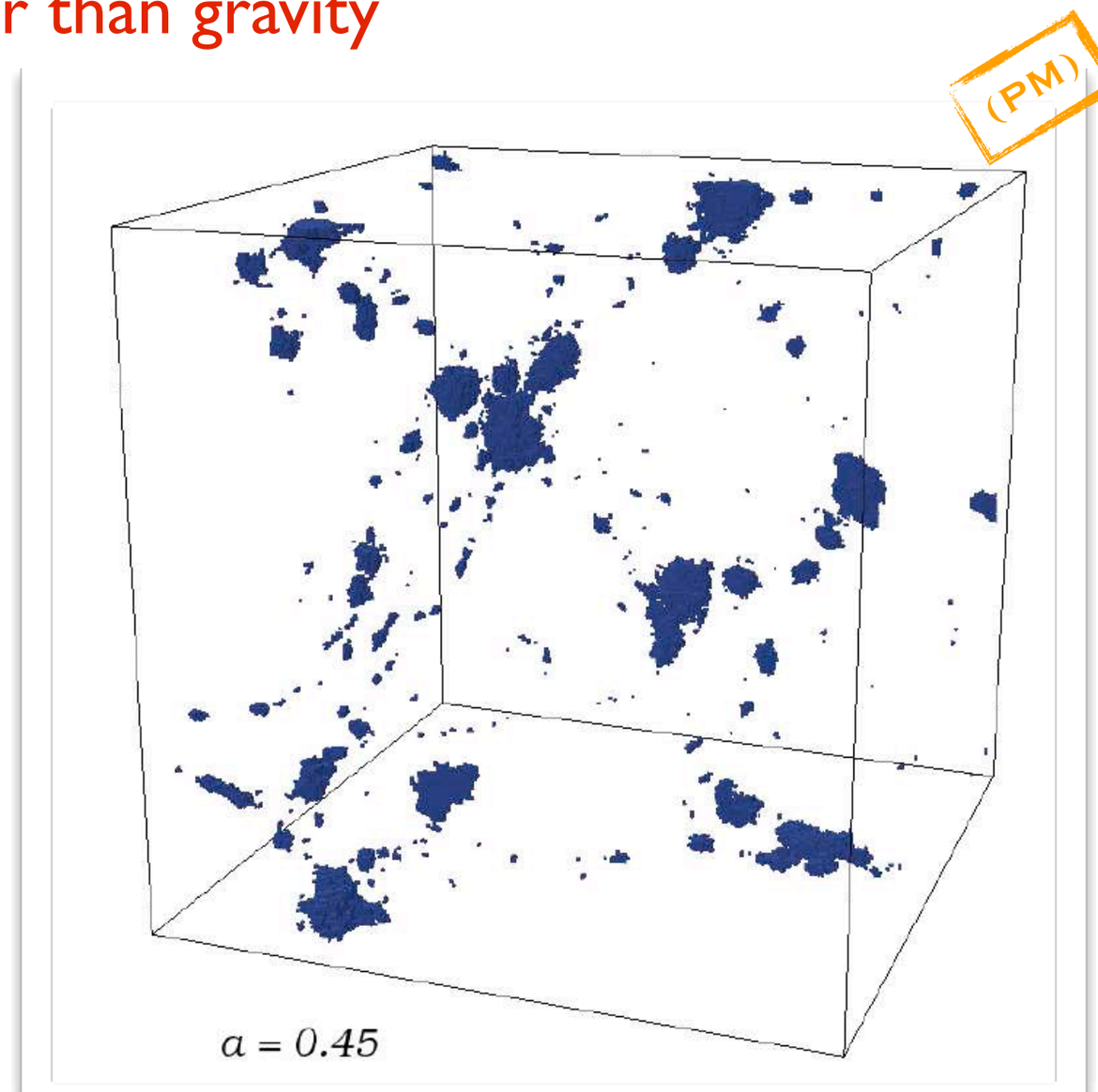

Ayaita, Weber, Wetterich 2011

INTERACTING DARK ENERGY

Universal couplings: Extended Quintessence, f(R), Symmetron, Dilaton, et al.

$$\nabla^2 \delta\phi = F(\delta\phi) + \beta(\phi)\delta\rho_M$$

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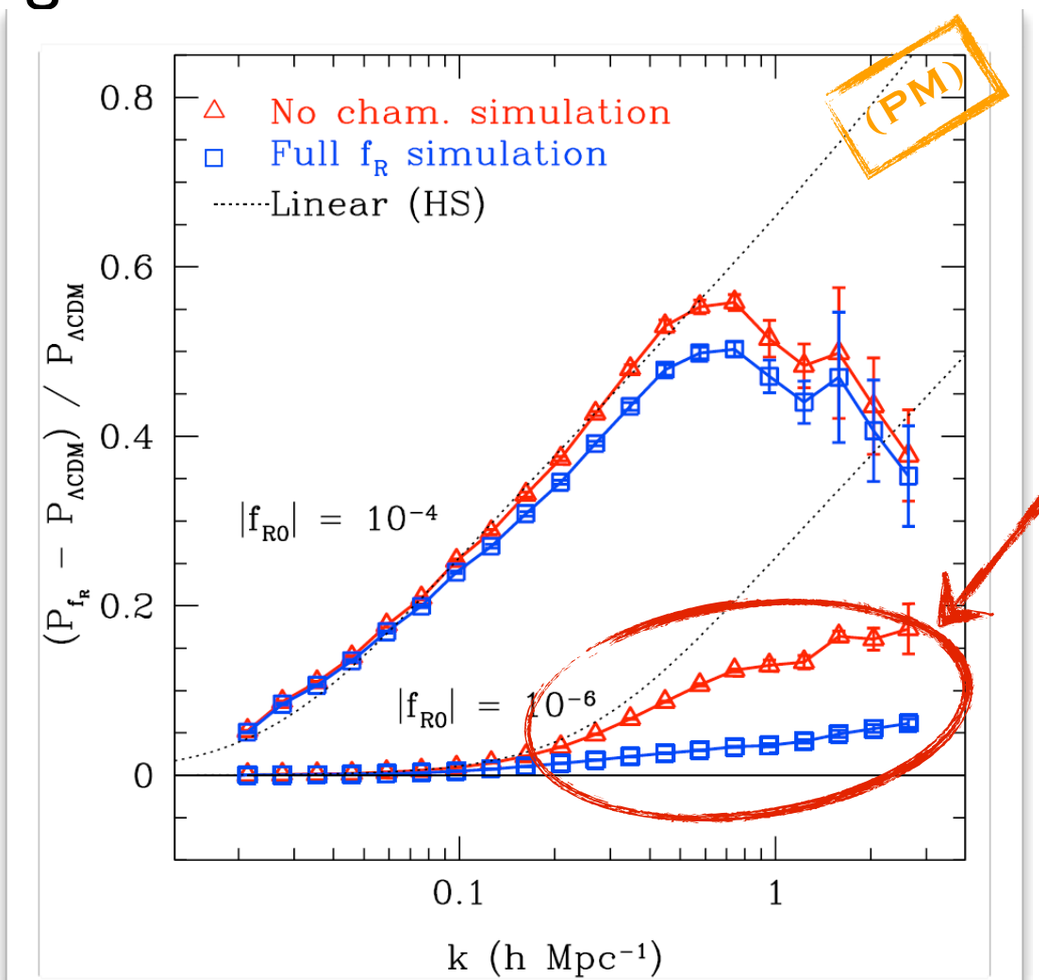
First simulations by Oyaizu 2008; Oyaizu, Lima, Hu 2008; Schmidt et al 2009 using an iterative scheme within a fix-grid PM code



The scalar fifth-force is suppressed in high-density regions according to the solution of the nonlinear Poisson equation for $\delta\phi$. The screening mechanism (in this case a Chameleon effect) is more efficient for lower values of $|f_{R0}|$

INTERACTING DARK ENERGY

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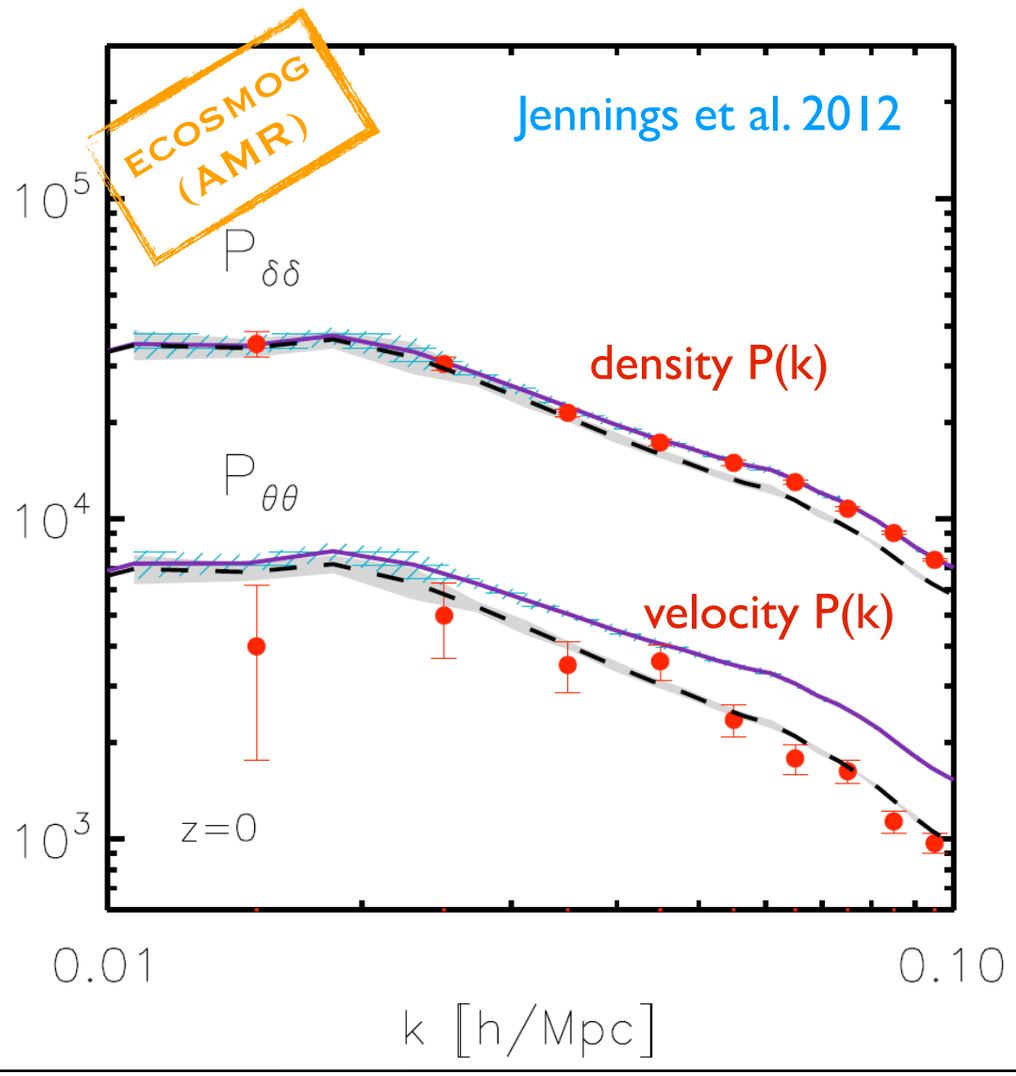
Li et al 2012 implemented a similar iterative solver in the AMR ECOSMOG (based on RAMSES), which has been used to investigate f(R) models and simulate other types of screening mechanisms as the Symmetron and the Dilaton (Jennings et al 2012; Davis et al. 2012; Brax et al 2012; Li et al 2012)



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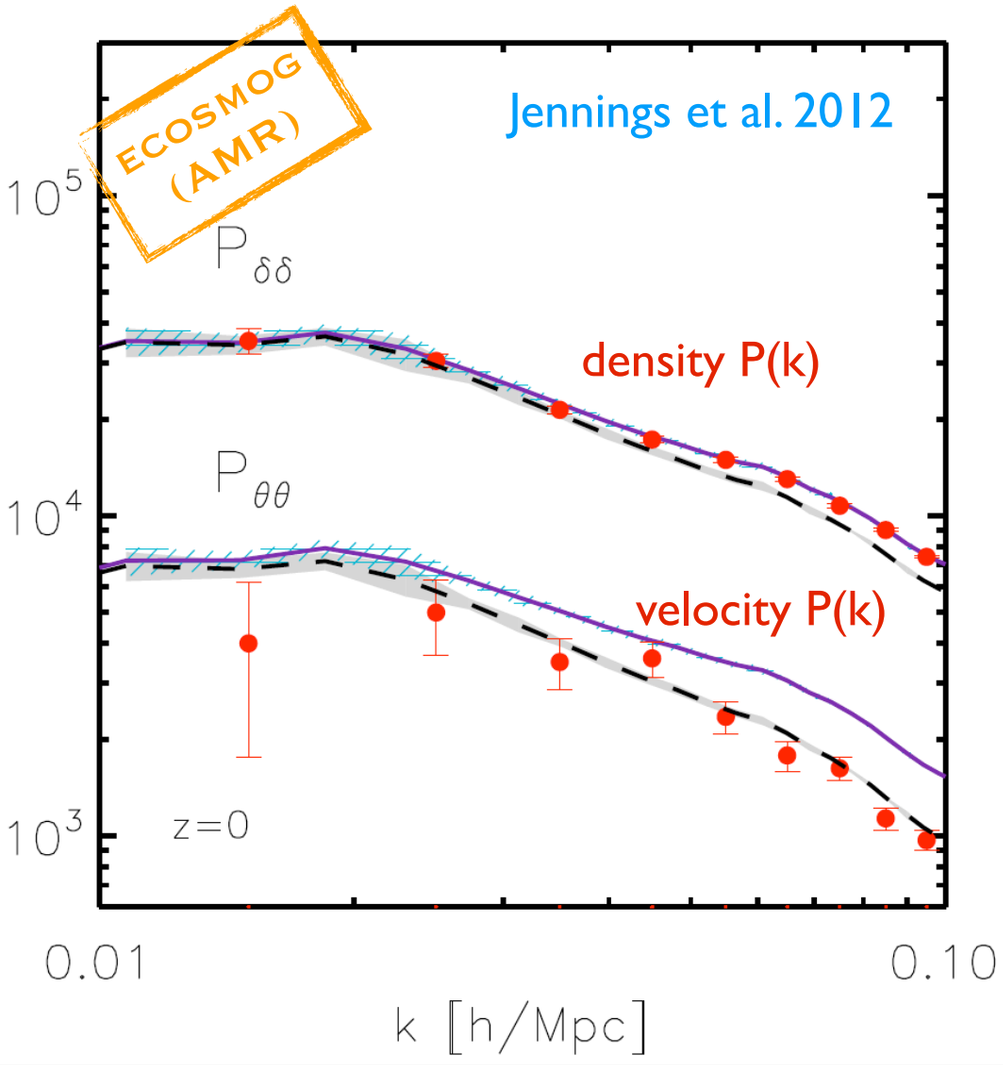
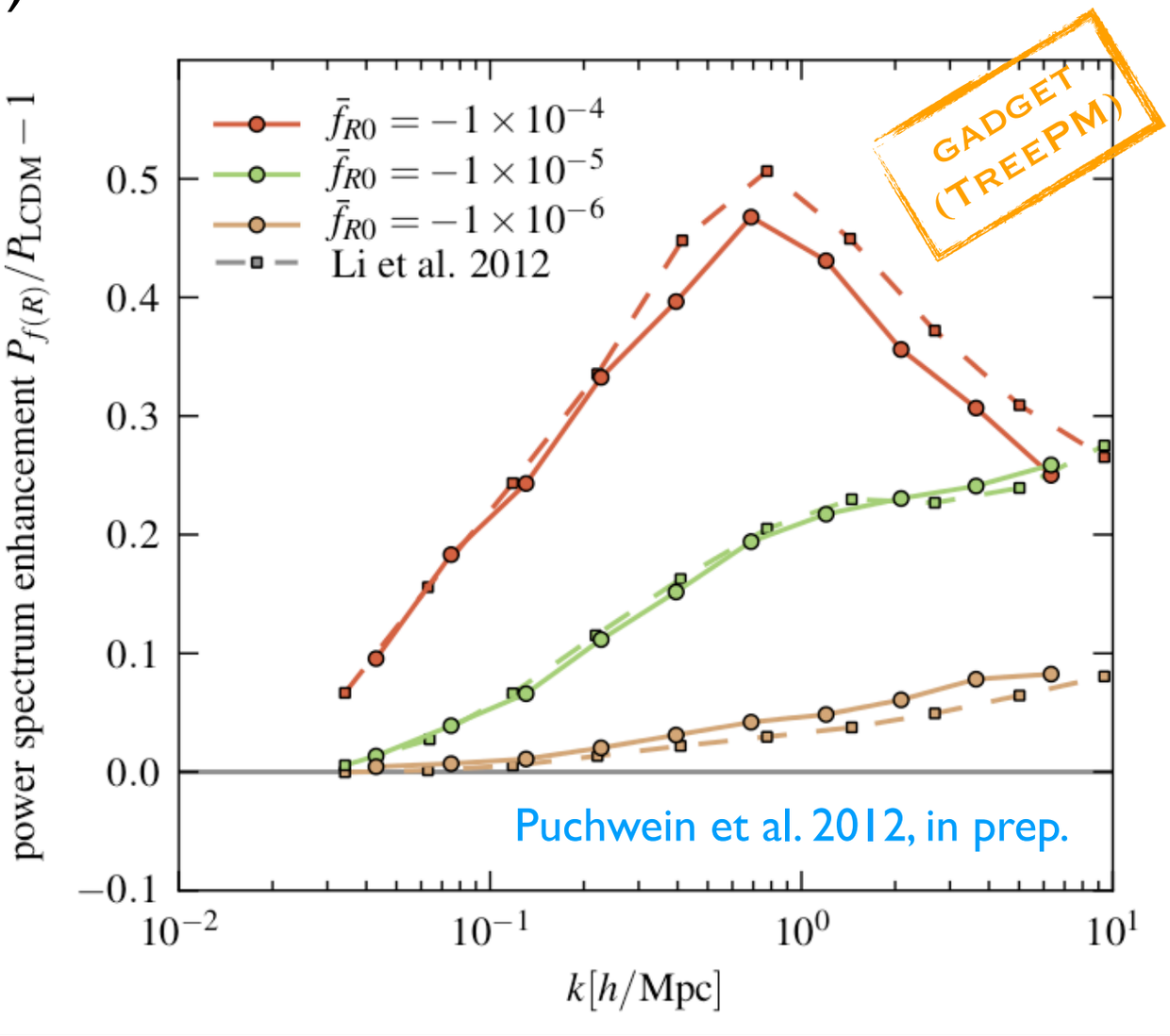
An alternative implementation has been recently developed for GADGET (see Ewald Puchwein's talk on wednesday)





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Maybe more...?
Keep it in mind for the discussion session!!

SUMMARY

Dark Energy is simply a label for any conceivable physical mechanism capable to explain the observed cosmic acceleration and to fit presently available data

The concept of DE can be realized introducing new degrees of freedom with different levels of spatial fluctuations and/or interactions

Various different DE models can have a very diverse impact on structure formation and related observable quantities, in particular in the non-linear regime

N-body algorithms for these different theoretical realizations of the DE phenomenon (smooth scalar fields, clustering DE, interacting DE and Modified Gravity) have been developed and applied in the last years.

The field of Dark Energy simulations has now reached a sufficient maturity to provide competitive constraints on the nature of the cosmic acceleration.

Enjoy the meeting!