N-Body Simulations of DARK ENERGY DOMINATED COSMOlogies

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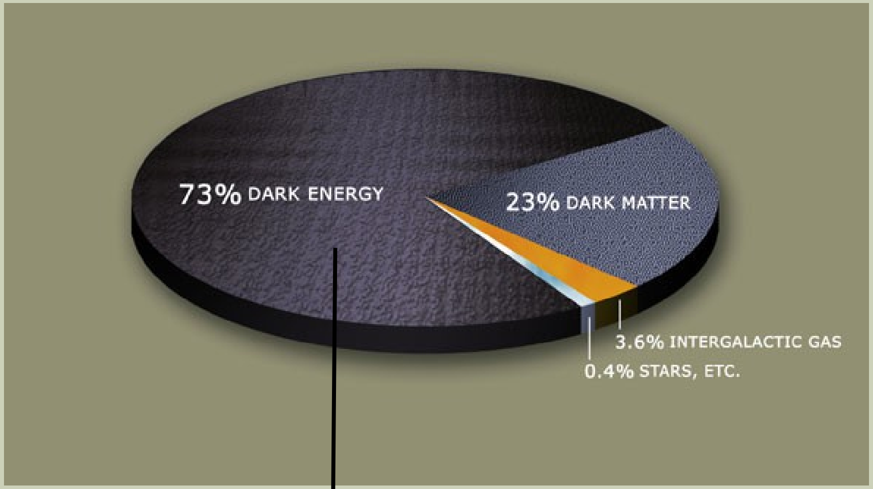
EDECS

Exploring Dark Energy Cosmic Structures

OUTLINE

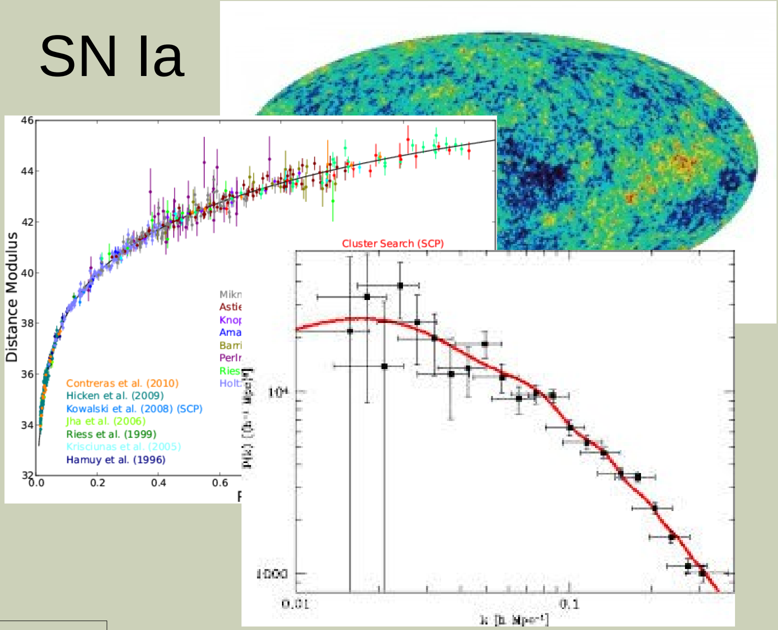
- Dark Energy Quest – (why not just Λ)
- Dark Energy and Linear Collapse
- Imprints on Non-Linear Scales
  - Matter Power Spectrum
  - Mass Function
  - Halo Density Profiles
- Baryonic Processes and Dark Energy

The Quest for Dark Energy



CMB

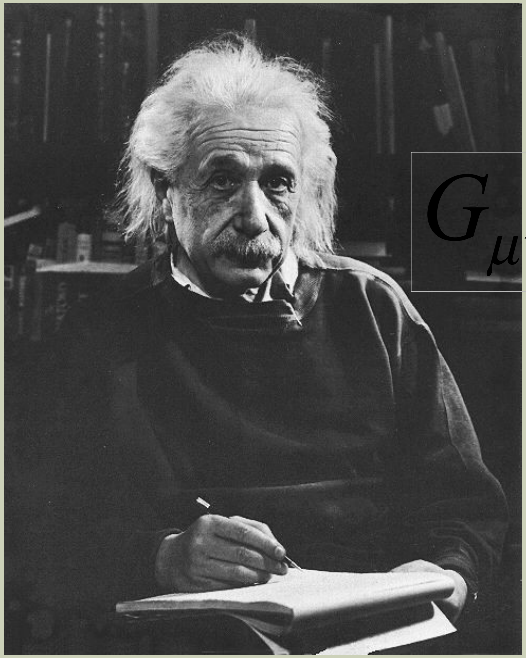
SN Ia



LSS

Λ fits them all!

Cosmological constant



$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

$$p_\Lambda = -\rho_\Lambda$$

EUREKA?

Vacuum Energy Puzzle

…what is it?

- Case 1: Λ =

However,

$$\Lambda_{QFT} >>>>>>>> \Lambda$$

Unsolved QFT problem

UNNATURAL CONSTANT

- Case 2: $$S = \int d^4x \sqrt{-g} \left[\frac{c^4}{16\pi G} (R - 2\Lambda) + L_M \right]$$

Gravity ruled locally by coupling constant G and globally by geometrical constant Λ…

…the only additive (non-coupling) constant of Physics

Historical Diversion I

"It cannot be denied that the introduction of the constant detracts from the simplicity and elegance of the original theory….one of whose great charms was that it embraced so much without introducing a new empirical constant"

De Sitter's letter to Einstein (1917)

"In any case, one thing stands. The general theory of relativity allows the addition of the [cosmological constant] in the field equations. One day our actual knowledge of the composition of the fixed-star sky, the apparent motions of the fixed stars, the position of the spectral lines as function of distance, will probably have come far enough for us to be able to decide empirically the question of whether or not vanishes."

Einstein's letter to De Sitter (1917)

Historical Diversion II

"Einstein was soon aware of these new possibilities and completely rejected the cosmological term as superfluous and no longer justified. I fully accept this new standpoint of Einstein's"

Pauli's note to 1958 translation of *Die Relativitatstheorie* (1921)

"The introduction of such a constant implies a considerable renunciation of the logical simplicity of the theory… Since I introduced this term, I had always a bad conscience… I am unable to believe that such an ugly thing should be realized in nature."

Einstein's letter to Lemaitre (1947)

Beyond Λ

New « exotic » matter sector

$$S = \int d^4x\sqrt{-g}\left[\frac{c^4}{16\pi G}R + L_M + L_\phi\right]$$

or

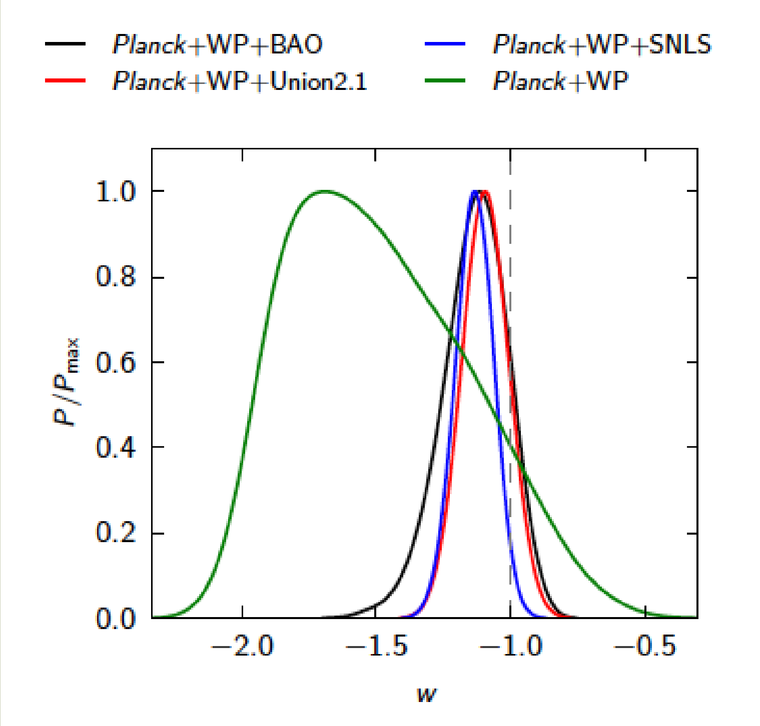
New gravitational sector

$$S = \int d^4x\sqrt{-g}\left[\frac{c^4}{16\pi G}f(R) + L_M\right]$$

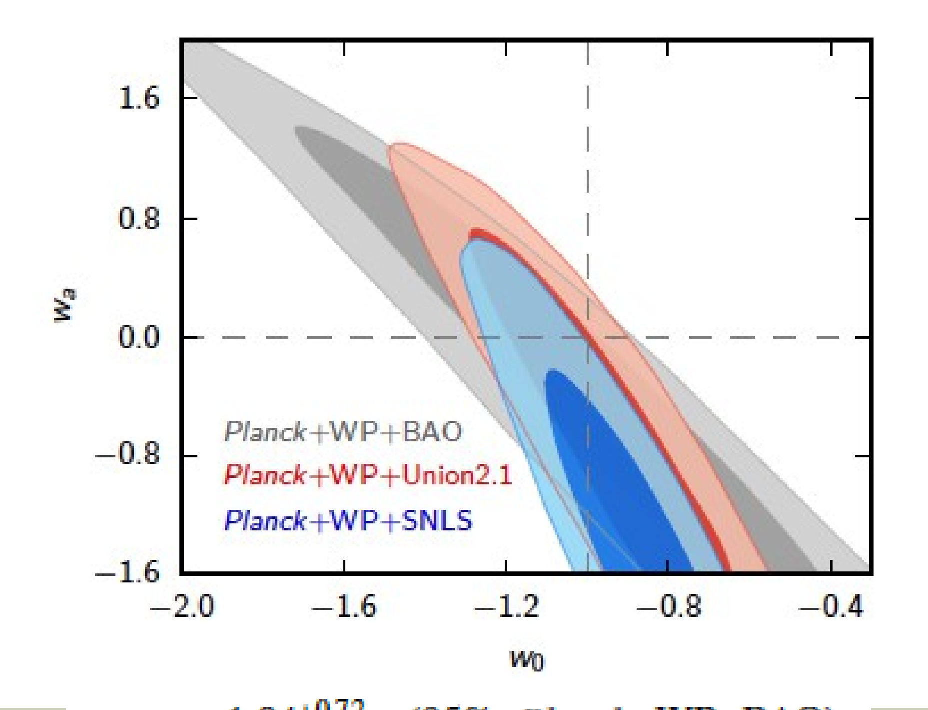
Phenomenologically :

$$w_{DE} = w_{DE}(t)$$ → DE dynamical phenomenon

Unconstrained DE Dynamics



$$w = -1.13^{+0.24}_{-0.25}$$



$$w_0 = -1.04^{+0.72}_{-0.69} \quad (95\%; \textit{Planck}\text{+WP+BAO}),$$
$$w_a < 1.32 \quad (95\%; \textit{Planck}\text{+WP+BAO}).$$

PLANCK 2013 results. XVI. Cosmological Parameters, *arXiv:1303.5076*

DE Dynamics & COSMIC STRUCTURES

The dawn of N-body Simulations of DE models

THE MASS POWER SPECTRUM IN QUINTESSENCE COSMOLOGICAL MODELS

CHUNG-PEI MA,[1] R. R. CALDWELL,[2] PAUL BODE,[3] AND LIMIN WANG[4]

Received 1999 May 10; accepted 1999 June 9; published 1999 June 25

L= 100 Mpc *h*-1
Np = 1283

L= 1 Gpc *h*-1
Np = 5123

EVOLUTION OF THE CLUSTER MASS FUNCTION: Gpc^3 DARK MATTER SIMULATIONS

PAUL BODE, NETA A. BAHCALL, ERIC B. FORD, AND JEREMIAH P. OSTRIKER
Princeton University Observatory, Princeton, NJ 08544-1001

Received 2000 August 30; accepted 2000 November 21

A&A 416, 853–864 (2004)
DOI: 10.1051/0004-6361:20031757
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Numerical study of halo concentrations in dark-energy cosmologies

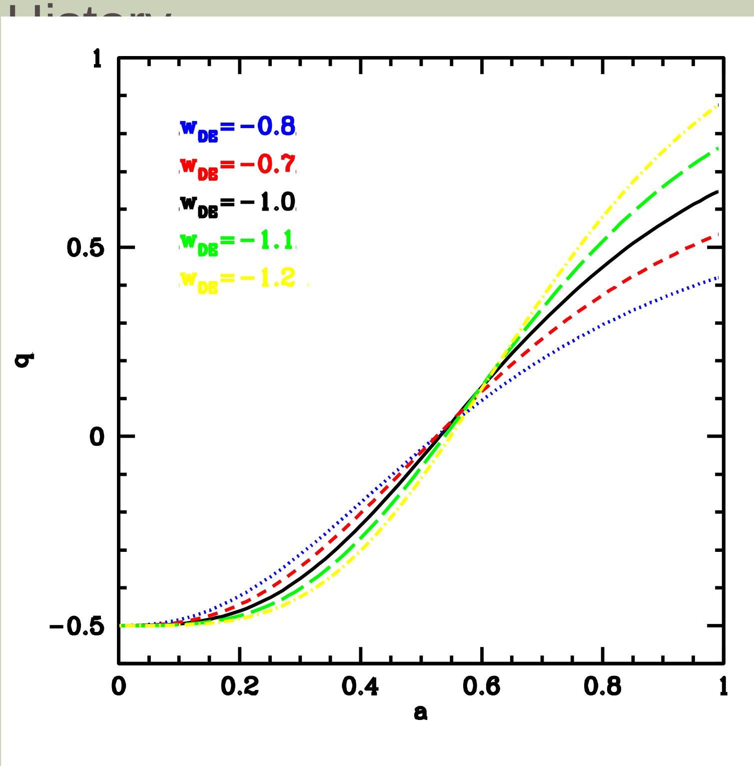
K. Dolag[1], M. Bartelmann[2], F. Perrotta[3,4], C. Baccigalupi[3,4], L. Moscardini[5], M. Meneghetti[1], and G. Tormen[1]

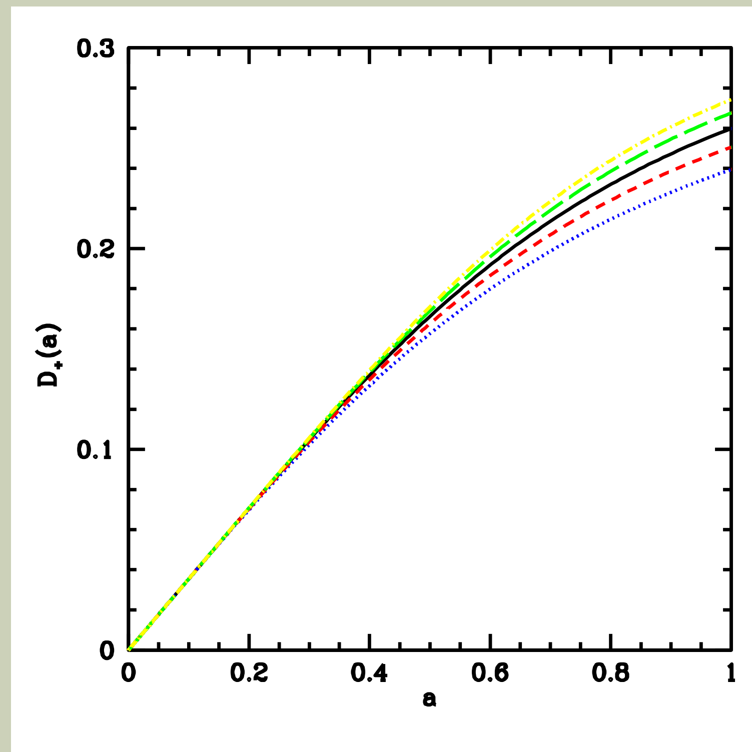
Zoom
Simul.
17 Clust.

EffecTs on Linear Clustering

Scalar Field-like DE fluid

Cosmic Expansion History → Linear growth function





EffecTs on Linear Clustering

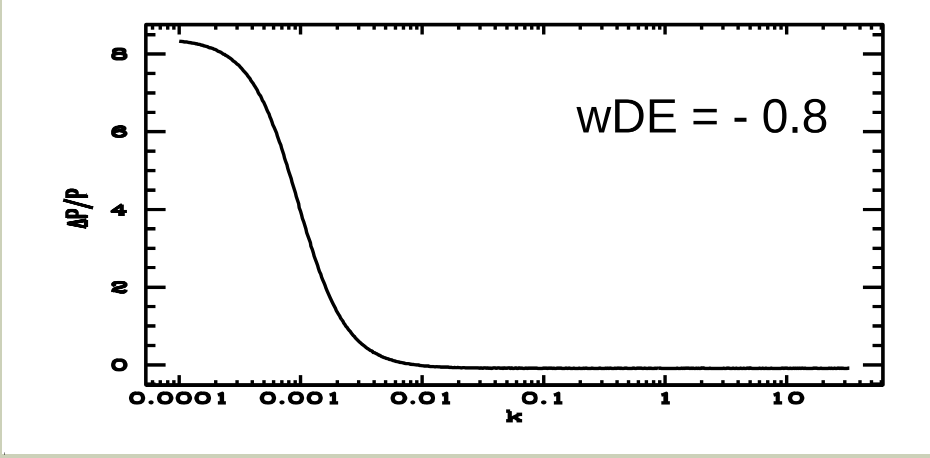
Scalar Field-like DE fluid

DE perturbations $w_{DE} \neq -1 \longrightarrow \delta\rho_{DE}, \delta p_{DE}$

Jeans-like scale $k_{DE} \approx \frac{3H}{c}\sqrt{(1-w_{DE})[2+w_{DE}+w_{DE}\Omega_{DE}(a)]}$

Modes

$$\delta\rho_{DE} \approx cst. \quad k < k_{DE}$$
$$\delta\rho_{DE} \approx dec. \quad k > k_{DE}$$



DE N-body SIMULATIONS

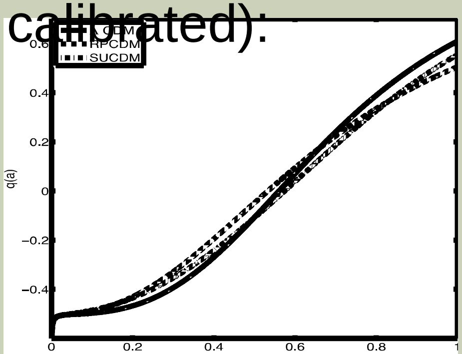
N-Body Initial Conditions

- CAMB Plin(k)
- MPGRAFIC (DE modif.)

N-Body Code:

- RAMSES (DE dyn.)

DE Models (CMB+SN+SDSS calibrated):



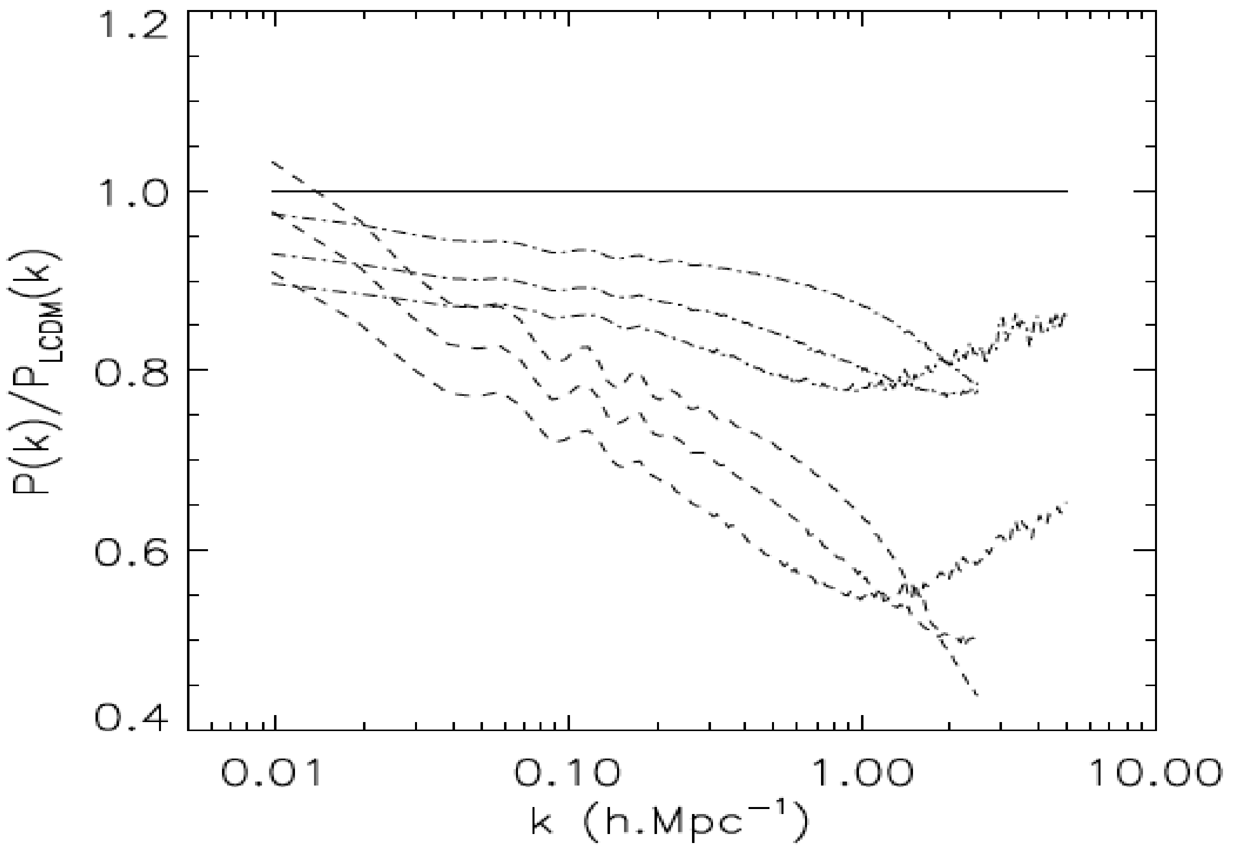
LARGE SET OF UNIVERSE VOLUMES (+ 25 SIMULATIONS)

HIGH SPATIAL RESOLUTION AND MASS: 2.5 h^{-1} kpc to 10.4 h^{-1} Gpc, 2.5 10^{8} h^{-1} $M_\odot$ to 10^{16} h^{-1} $M_\odot$

INITIAL REDSHIFT DEEP IN LINEAR REGIME

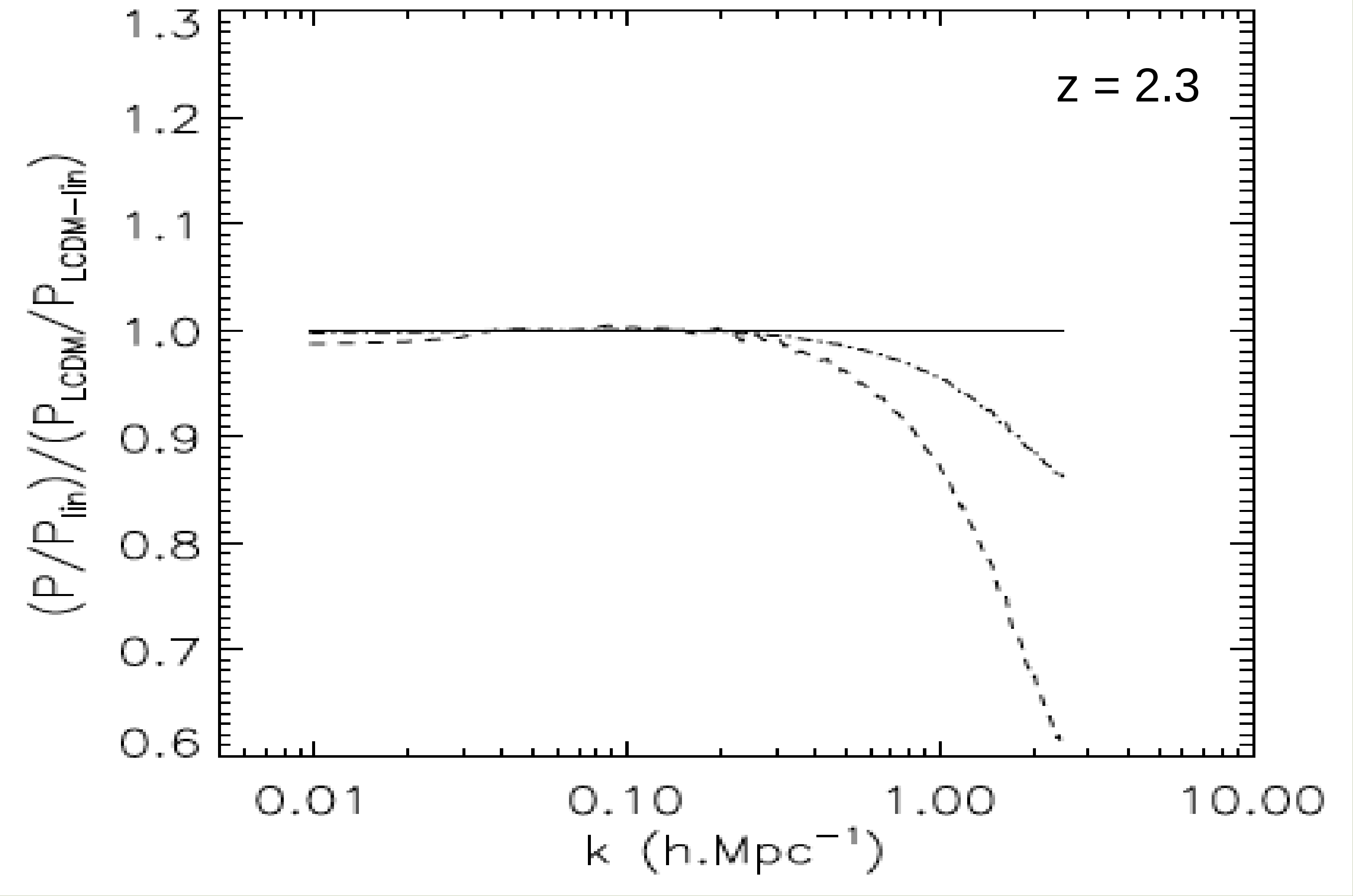
Box Size	Force Resolution	Mass Resolution	Number of Particles	Initial Redshift	Cosmological Models	Supercomputer (Nb of Proc)
162 h^{-1} Mpc	2.5 h^{-1} kpc	~2. 10^{9} h^{-1} $M_\odot$	512^3	~90	ΛCDM, SUCDM, RPCDM	Titane (64)
162 h^{-1} Mpc	2.5 h^{-1} kpc	~2.5 10^{8} h^{-1} $M_\odot$	1024^3	~130	ΛCDM, SUCDM, RPCDM	Blue Gene/P(4096)
648 h^{-1} Mpc	20 h^{-1} kpc	~1.5 10^{11} h^{-1} $M_\odot$	512^3	~55	ΛCDM, SUCDM, RPCDM	-
648 h^{-1} Mpc	10 h^{-1} kpc	~1.75 10^{10} h^{-1} $M_\odot$	1024^3	~90	ΛCDM, SUCDM, RPCDM	Blue Gene/P(4096)
648 h^{-1} Mpc	5 h^{-1} kpc	~2. 10^{9} h^{-1} $M_\odot$	2048^3	~90	ΛCDM, RPCDM	Blue Gene/P(32768)
1296 h^{-1} Mpc	40 h^{-1} kpc	~1. 10^{12} h^{-1} $M_\odot$	512^3	~40	ΛCDM, SUCDM, RPCDM	-
2592 h^{-1} Mpc	40 h^{-1} kpc	~1. 10^{12} h^{-1} $M_\odot$	1024^3	~55	ΛCDM, SUCDM, RPCDM	Blue Gene/P(4096)
2592 h^{-1} Mpc	20 h^{-1} kpc	~1.5 10^{11} h^{-1} $M_\odot$	2048^3	~55	ΛCDM, RPCDM	Blue Gene/P(24576)
5184 h^{-1} Mpc	40 h^{-1} kpc	~1. 10^{12} h^{-1} $M_\odot$	2048^3	~40	ΛCDM, RPCDM	Blue Gene/P(24576)
10368 h^{-1} Mpc	40 h^{-1} kpc	~1. 10^{12} h^{-1} $M_\odot$	4096^3	~40	ΛCDM	Curie Fat Nodes (9728)

Non-Linear Matter POWER SPECTRUM



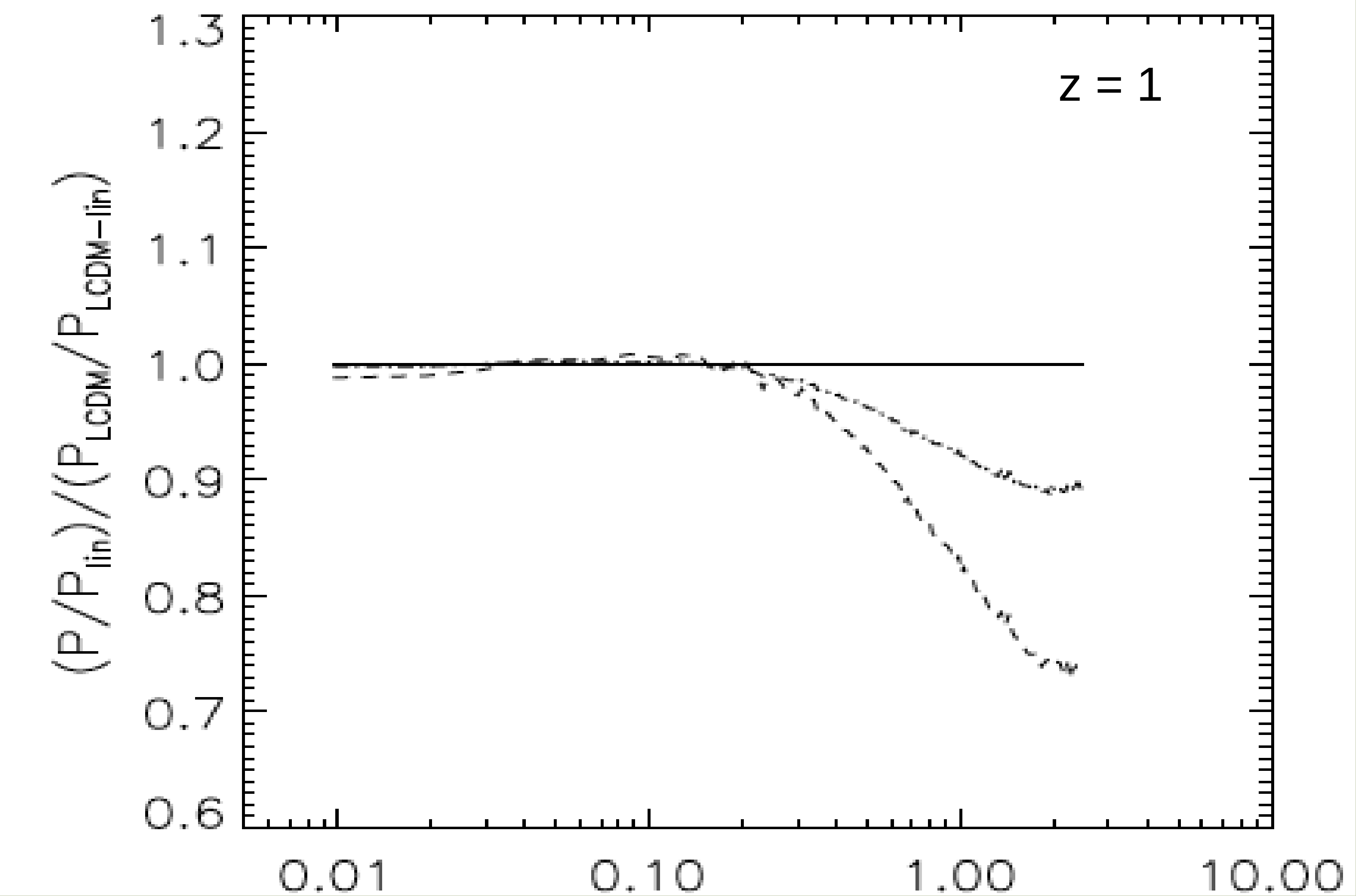
J.-M. Alimi et al., MNRAS 401, 775 (2010)

Non-Linear Matter POWER SPECTRUM



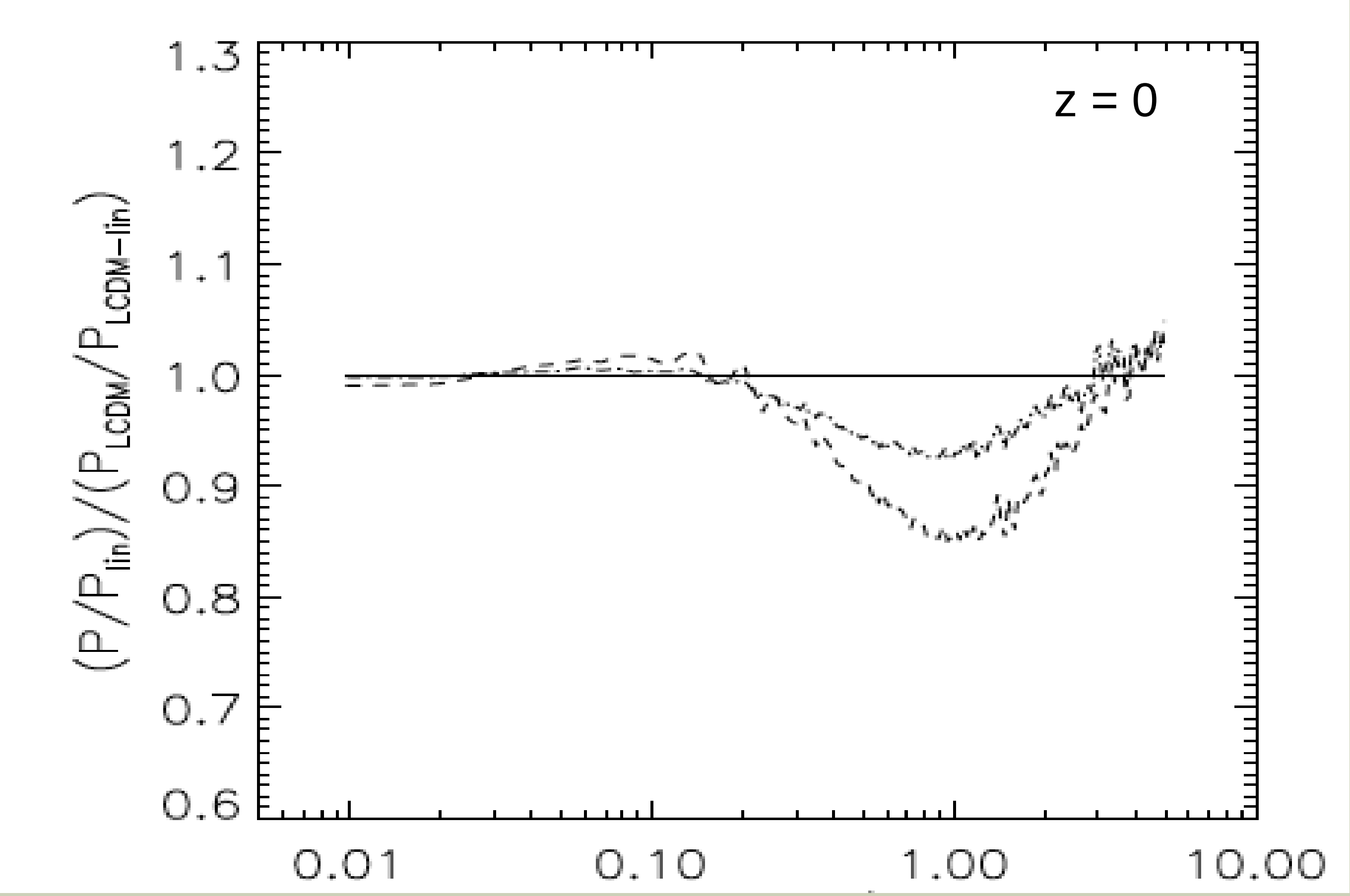
J.-M. Alimi et al., MNRAS 401, 775 (2010)

Non-Linear Matter POWER SPECTRUM



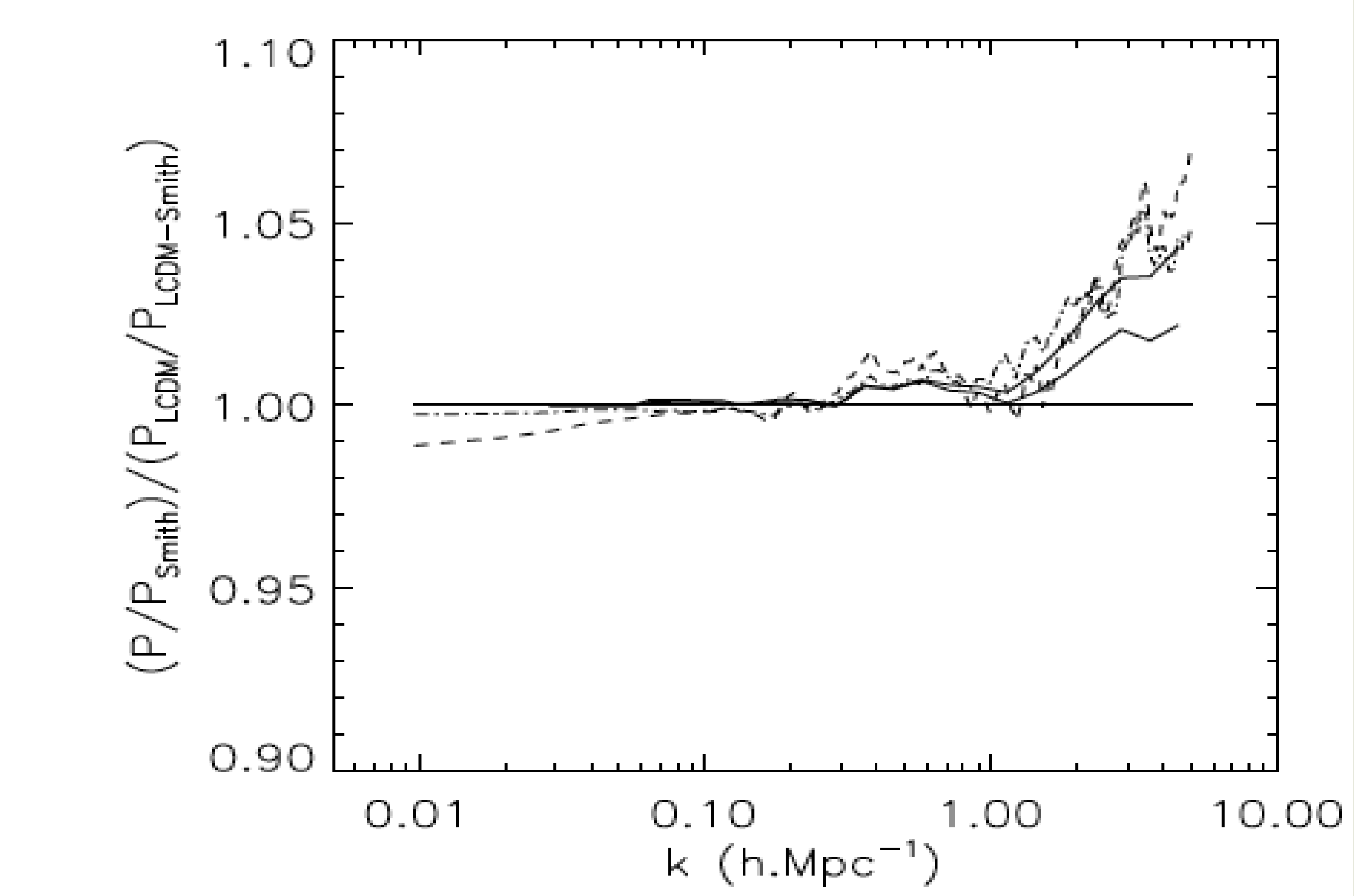
J.-M. Alimi et al., MNRAS 401, 775 (2010)

Non-Linear Matter POWER SPECTRUM



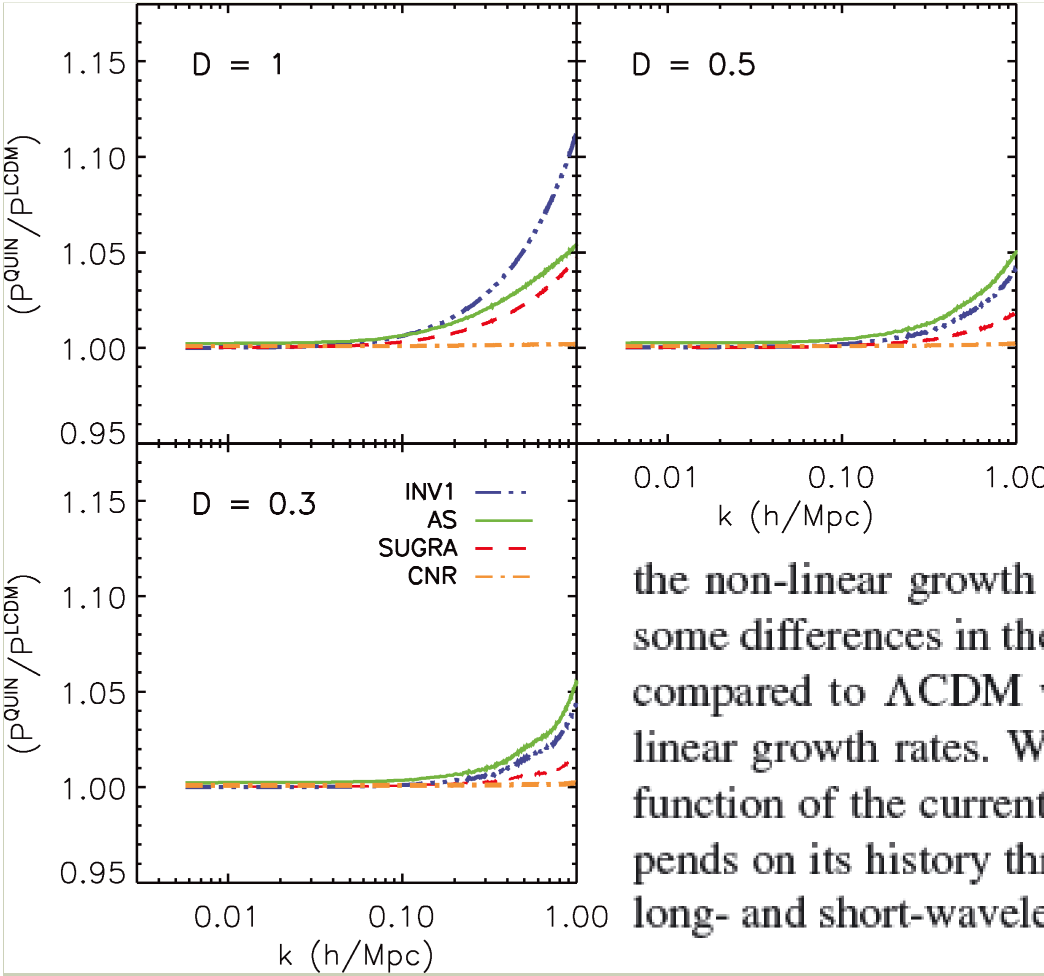
J.-M. Alimi et al., MNRAS 401, 775 (2010)

BEYOND D+(z) Dependence



J.-M. Alimi et al., MNRAS 401, 775 (2010)

BEYOND D+(z) Dependence



- NL does not completely erase traces of the linear regime
- Small clustering maintains a fossil record of past evolution

the non-linear growth at early redshifts. In Fig. 10, there are still some differences in the small-scale growth in quintessence models compared to ΛCDM which cannot be explained by the different linear growth rates. We find that non-linear evolution is not just a function of the current value of the linear growth rate but also depends on its history through the evolution of the coupling between long- and short-wavelength modes.

E. Jennings et al., MNRAS 401,2181 (2010)

A Simple OLD ARGUMENT

Equation of Motion

$$\frac{d\,\mathrm{v}}{dt} + 2H\,\mathrm{v} = -\frac{3}{2}\Omega_m H^2 \nabla\phi \quad \text{with} \quad \Delta\phi = \delta$$

Time variable = Linear Growing mode $\tau = \ln D(t)$

$$\frac{d\,\mathrm{v}}{d\tau} + \frac{1}{f^2}\left[\frac{df}{d\ln a} + (1-q)f\right]\mathrm{v} = -\frac{3}{2f^2}\Omega_m \nabla\Phi$$

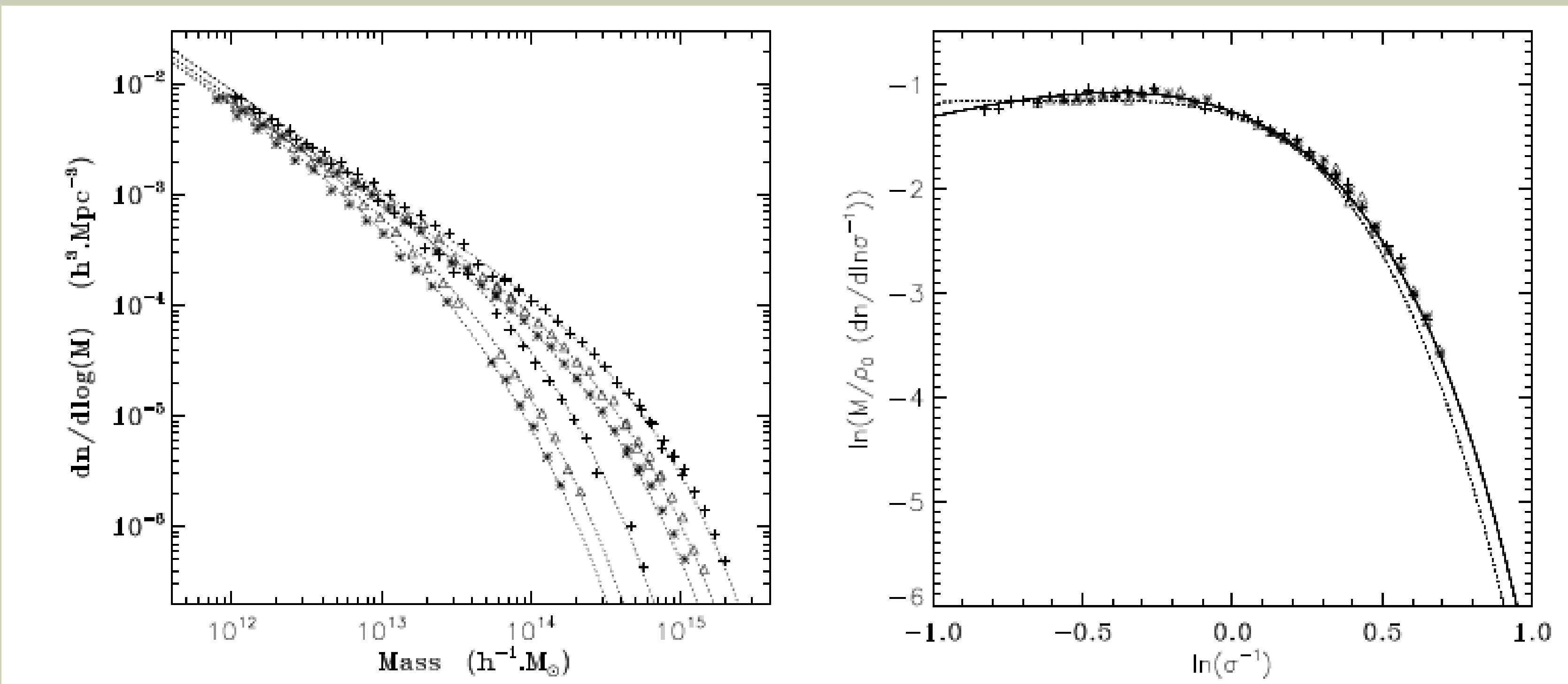
A. Nusser & J. Colberg, MNRAS. 294, 457 (1998)

Halo Mass Function

Questioning Universality

$$\frac{dn}{dM} = \frac{\bar{\rho}}{M^2}\frac{d\ln\sigma^{-1}}{d\ln M}\left[2\sigma^2\frac{dF}{dS}\right]$$

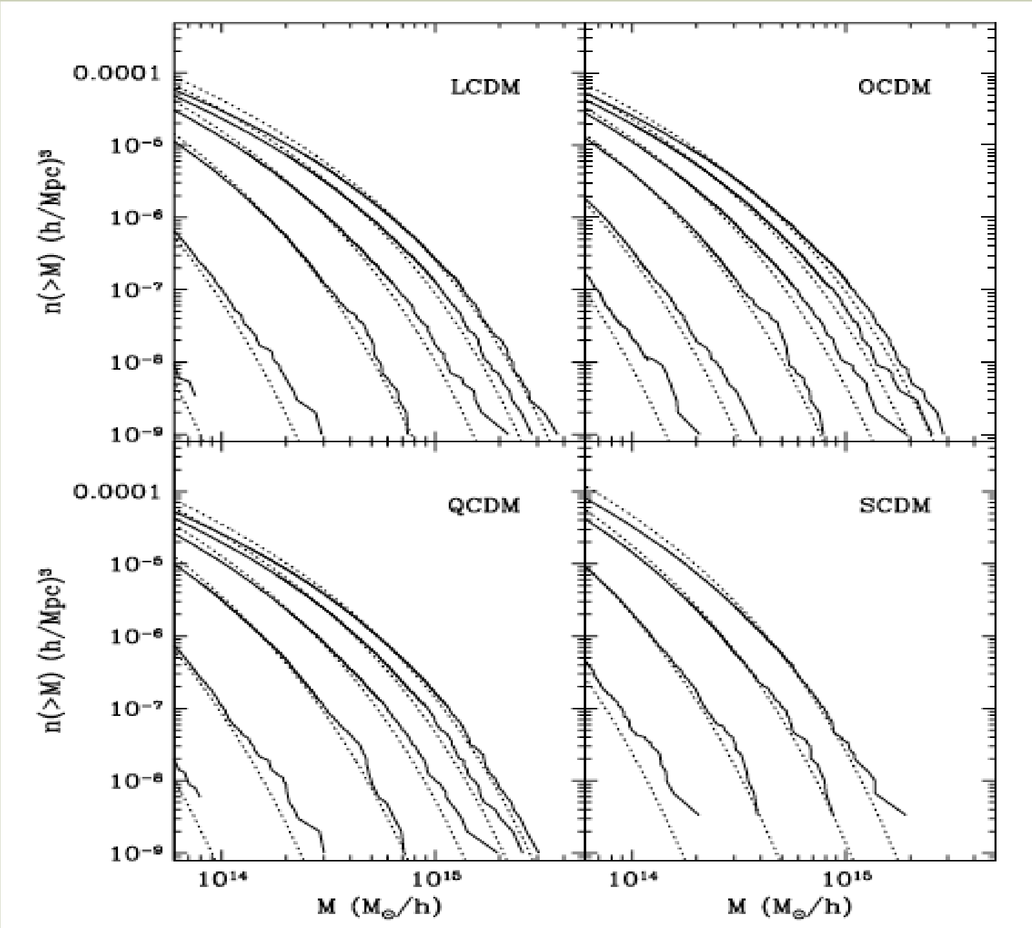
- Reabsorbing Ωm and σ8
- f(σ)=2σ2dF/dS universal (?)



plot from J. Courtin et al., MNRAS 410, 1911 (2011)

Halo Mass Function

Early Hints



$$f_{EPS}(\sigma) = \sqrt{\frac{2}{\pi}}\frac{\delta_c}{\sigma} e^{-\delta_c^2/(2\sigma^2)}$$

- Over-estimates low mass halos
- Under-estimates high mass halos
- Under-estimates mass function at higher z
- Better when adjusting δc

P. Bode, N.A. Bahcall, E.R. Ford & J. Ostriker, ApJ 551, 15 (2001)

Halo Mass Function

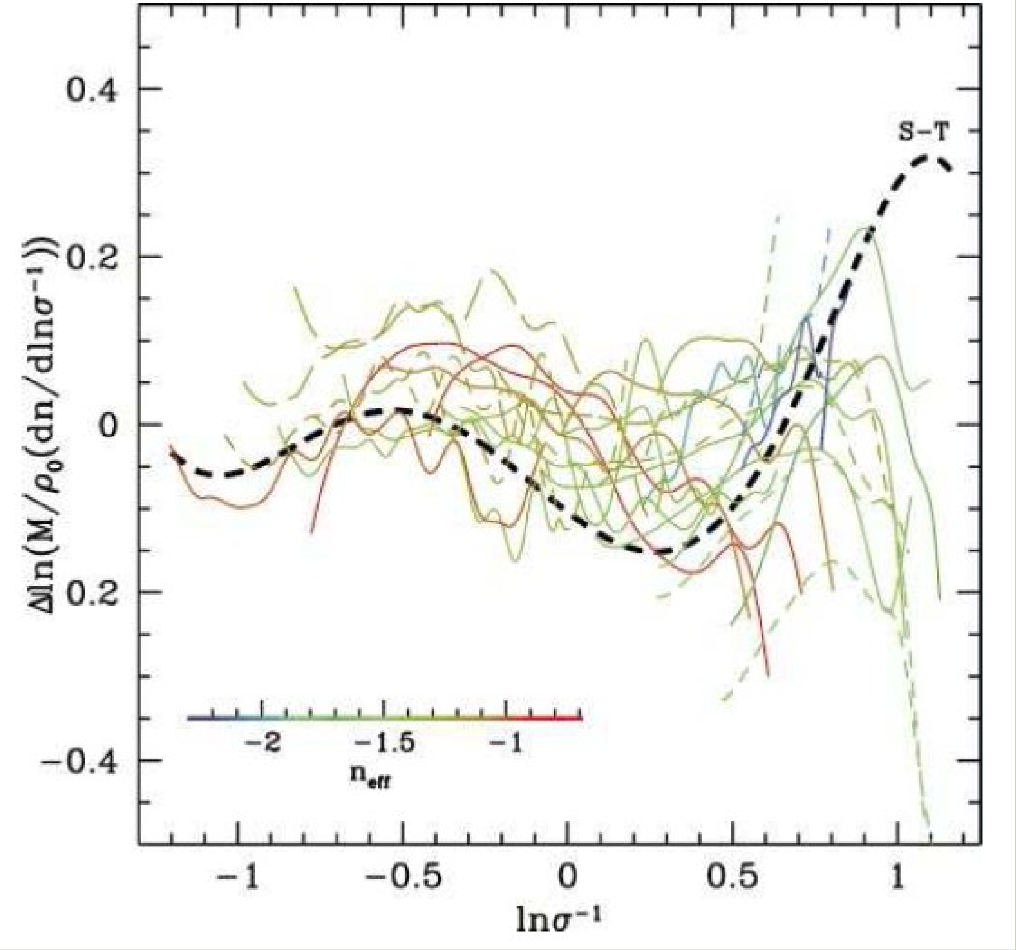
Universality

$$f(\sigma) = 0.315 \exp\left(-\left|\ln \sigma^{-1} + 0.61\right|^{3.8}\right)$$

- FoF(b=0.2)
- different cosmologies:

|Δf/f|< 20%

- Multiplicity function independent of cosmological details



A. Jenkins et al., MNRAS 312, 372 (2001)

Halo Mass Function

LIMITS OF UNIVERSALITY

$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right] e^{-c/\sigma^2}$$

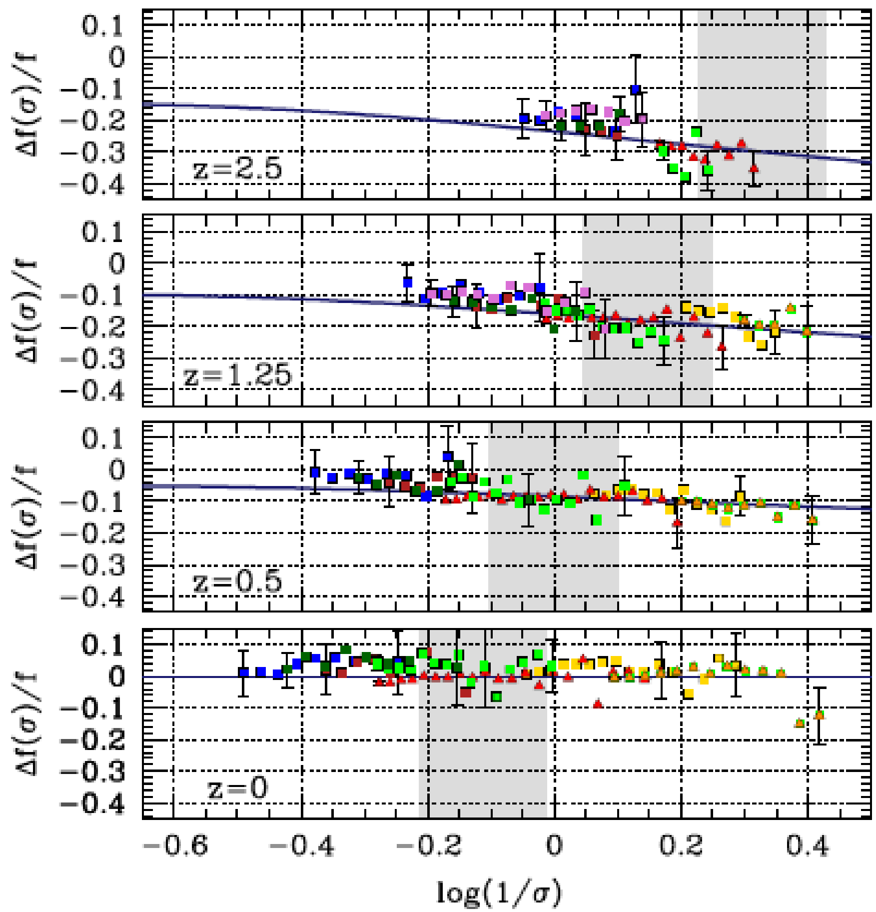
$$A(z) = A_0\,(1+z)^{-0.14},$$

$$a(z) = a_0\,(1+z)^{-0.06},$$

$$b(z) = b_0\,(1+z)^{-\alpha},$$

$$\log \alpha(\Delta) = -\left(\frac{0.75}{\log(\Delta/75)}\right)^{1.2},$$

- WMAP1 & WMAP3 cosmologies
- SOD(Δ)



J. Tinker et al., ApJ 688, 709 (2008)

Halo Mass Function

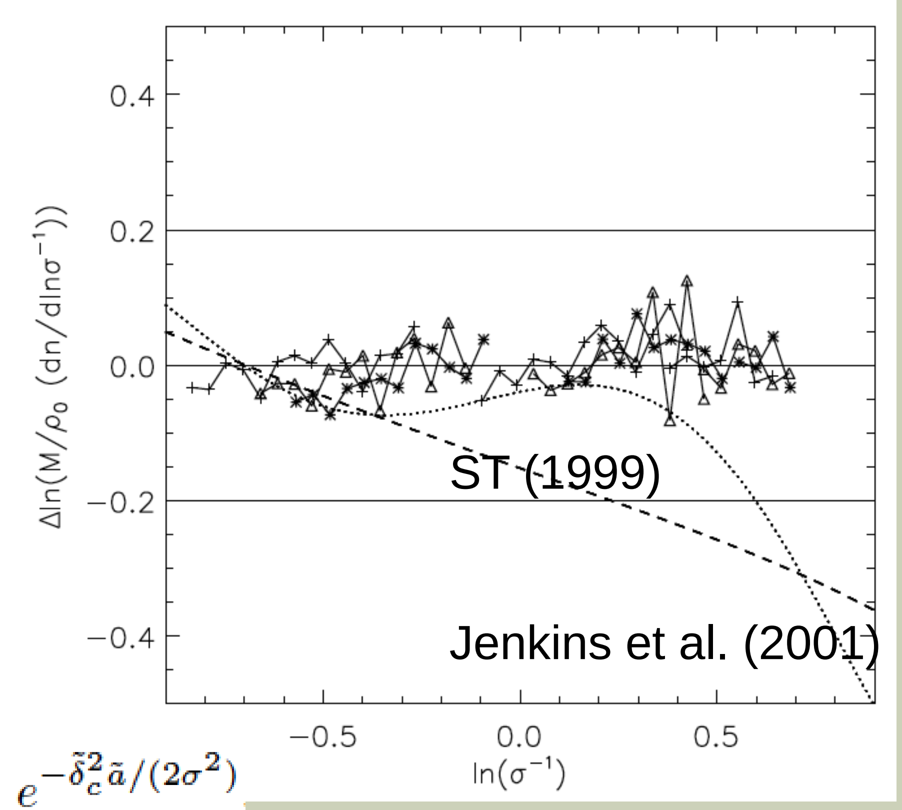
MULTIPLICITY FUNCTION & Cosmology

ΛCDM-WMAP Models:

Model	Ω_{DE}	h	σ_8	n_s	Ω_b
ΛCDM-W5	0.74	0.72	0.79	0.963	0.044
ΛCDM-W3	0.76	0.73	0.74	0.951	0.042
ΛCDM-W1	0.71	0.72	0.90	0.99	0.047

Universality valid (to numerical precision) only for cosmologies with ≈ D+(z) (≈ δc (z))

$$f(\sigma) = \tilde{A}\left(\frac{2\tilde{a}}{\pi}\right)^{1/2}\frac{\tilde{\delta}_c}{\sigma}\left[1+\left(\frac{\tilde{\delta}_c}{\sigma\sqrt{\tilde{a}}}\right)^{-2\tilde{p}}\right]e^{-\tilde{\delta}_c^2\tilde{a}/(2\sigma^2)}$$



J. Courtin et al., MNRAS 410, 1911 (2011)

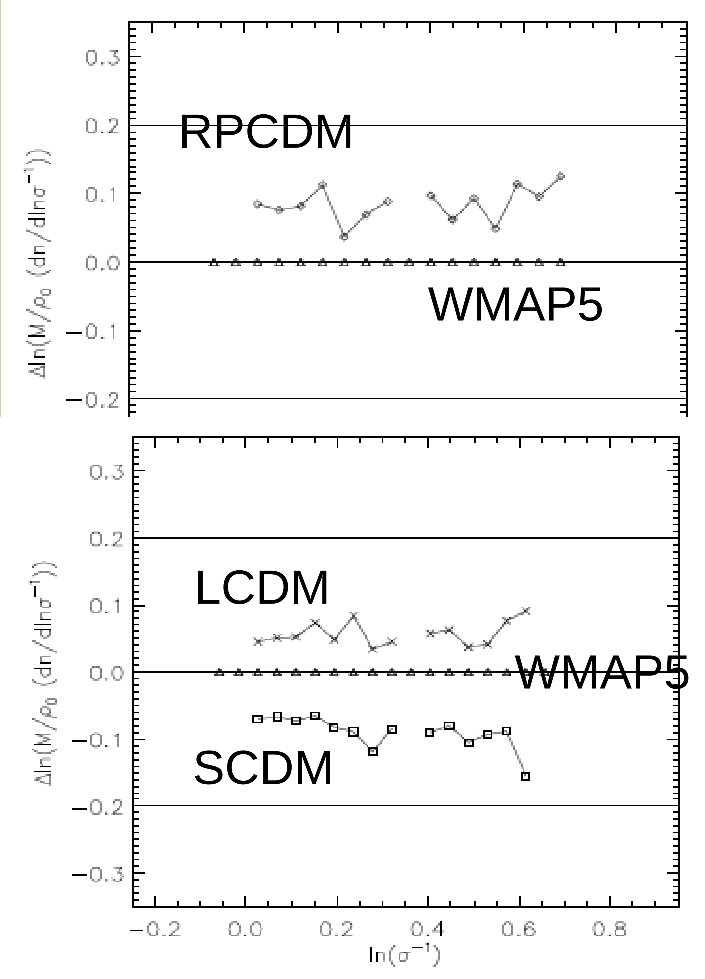
Halo Mass Function

NON-UNIVERSALITY

Non-Standard DE Models:

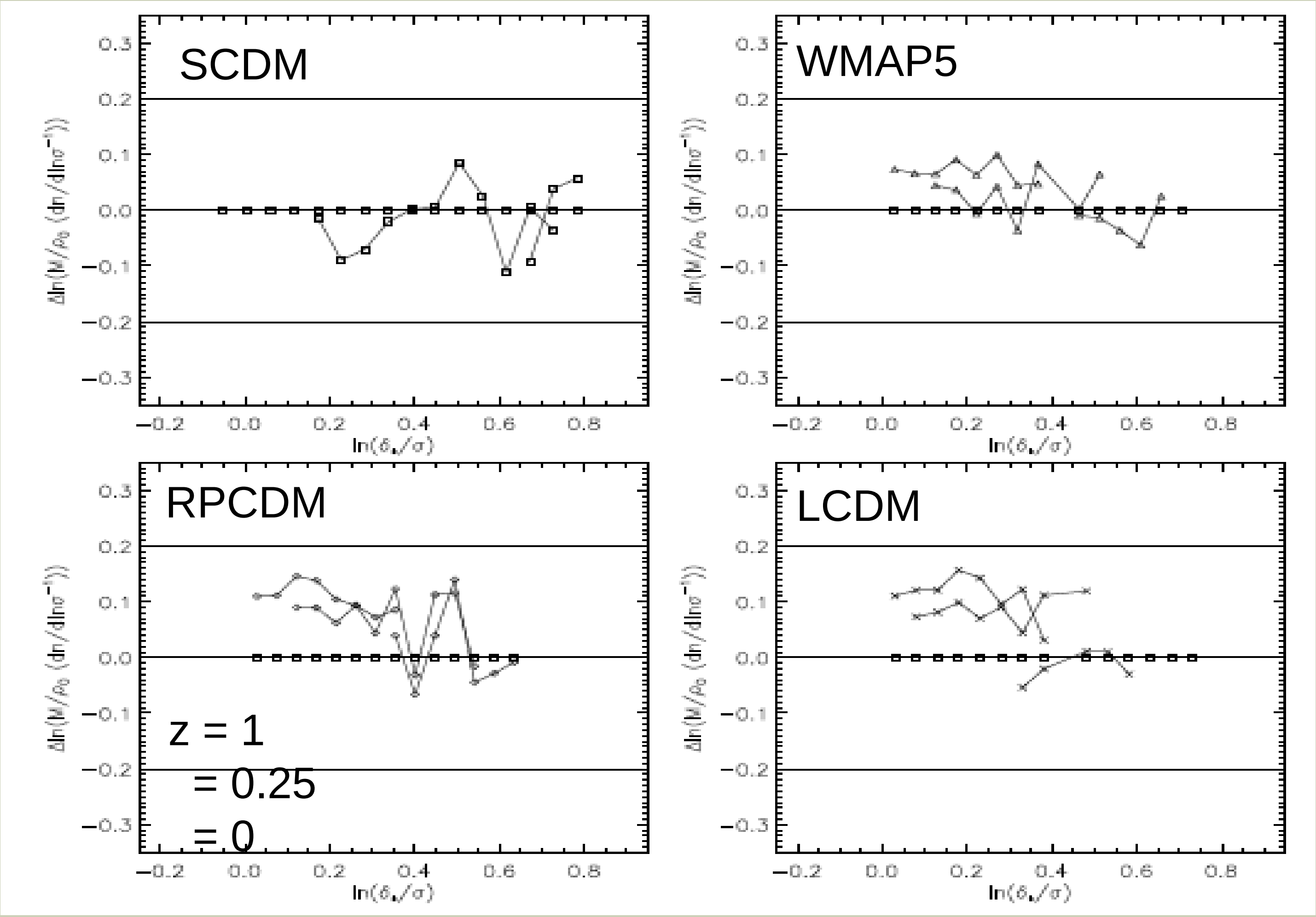
Model	Ω_{DE}	α	P(k)
L-RPCDM	0.74	10	ΛCDM-W5
L-ΛCDM	0.9	-	ΛCDM-W5
SCDM*	0	-	ΛCDM-W5

- Extreme models deviates from universal behavior
- Deviations are correlated with δc as expected from the PS approach



Halo Mass Function

Non-Universality ENCODED IN Spherical Collapse



Halo DENSITY PROFILES

NFW Formula

- Universal profile
- Halo Concentration
- c – M relation

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

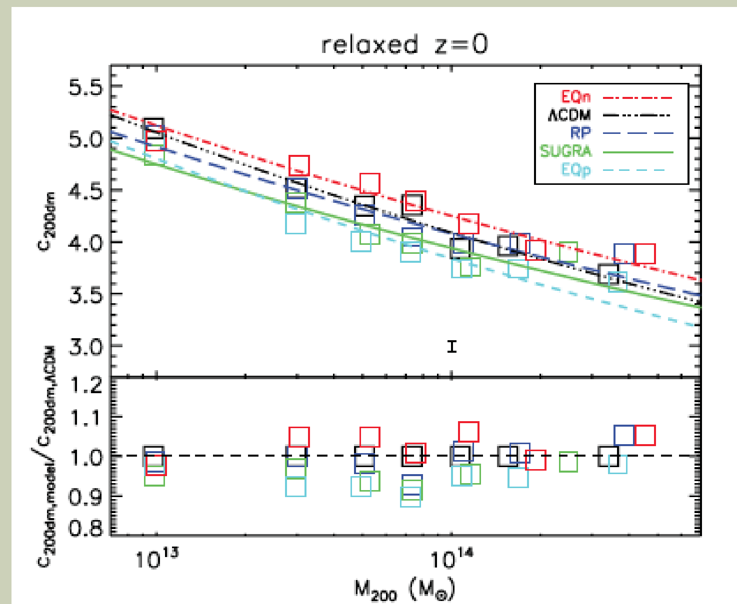
$$c = \frac{r_{200}}{R_s}$$

DE Imprint

- Normalization c – M relation

$$c_0 \rightarrow c_0^{\Lambda CDM} \frac{D_+(z_{coll})}{D_+^{\Lambda CDM}(z_{coll})}$$

Dolag et al., A&A 416, 853 (2004)



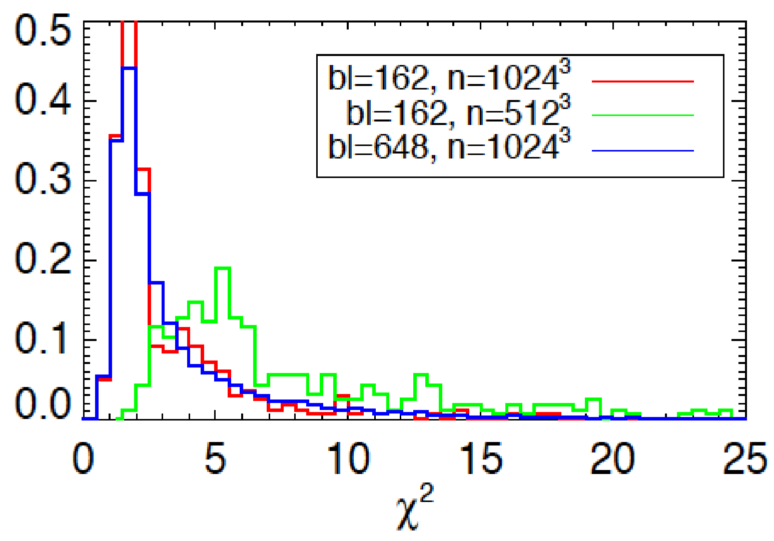
C. De Boni et al., MNRAS 428, 2921 (2013)

Halo DENSITY PROFILES

Goodness-of-fit and Mass Resolution

NFW Goodness-of-fit

$$\chi^2 = \frac{1}{N_{\rm bins}} \sum_{i=1}^{N_{\rm bins}} \frac{[\rho_i - \rho_{\rm NFW}(r_i)]^2}{2\sigma_i^2}$$



N=5123 L=162 Mpc/h
mp~ 2.3x109 Msun

N=10243 L=648 Mpc/h
mp= 1.8x1010 Msun

N=2563 L=162 Mpc/h
mp~ 1.8x1010 Msun

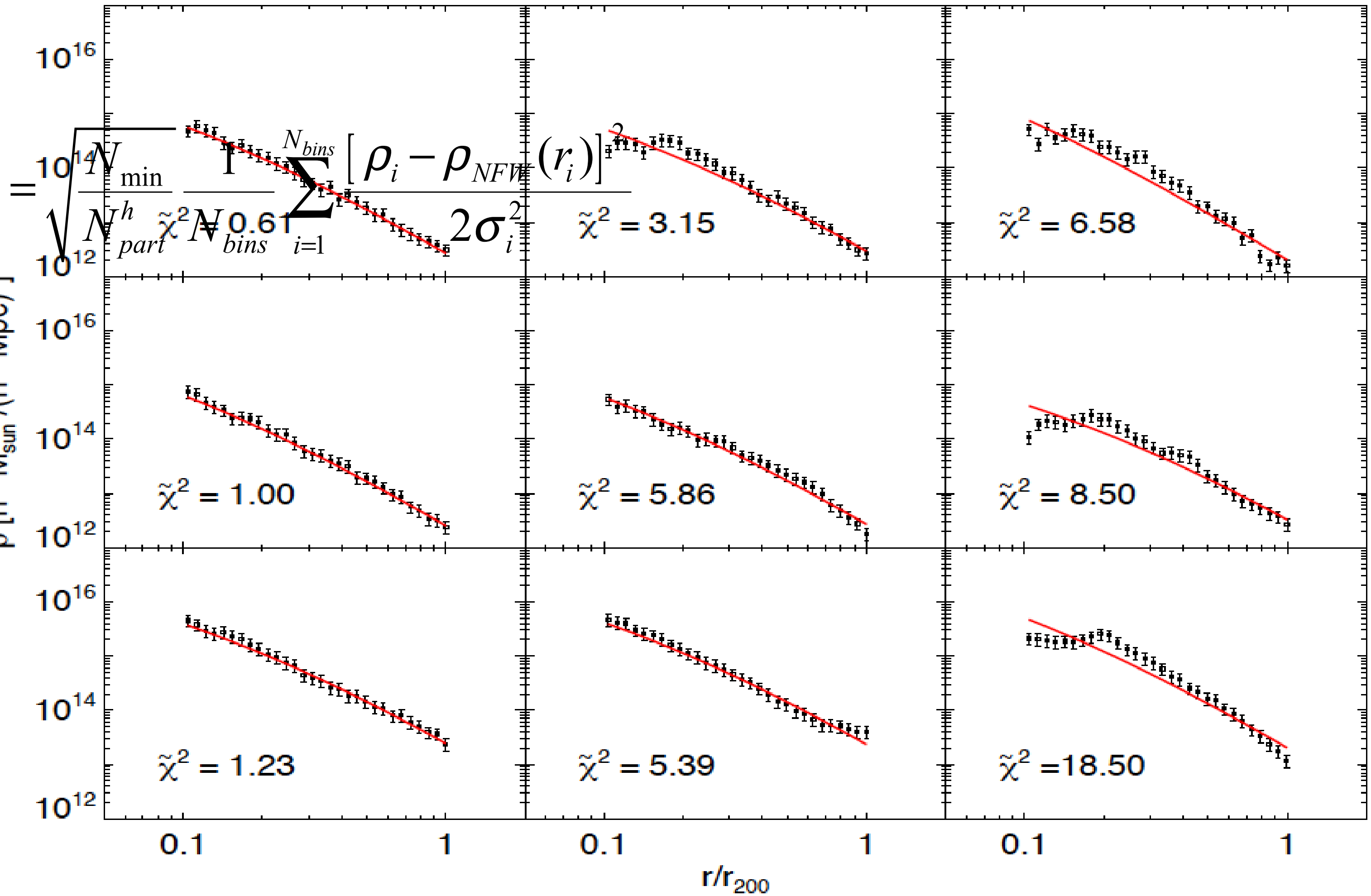
I. Balmes et al., MNRAS 437, 2328 (2014)

Halo DENSITY PROFILES

DEVIATIONS FROM NFW

NI

$$\tilde{\chi}^2 = \sqrt{\frac{N_{min}}{N^h_{part}}} \frac{1}{N_{bins}} \sum_{i=1}^{N_{bins}} \frac{[\rho_i - \rho_{NFW}(r_i)]^2}{2\sigma_i^2}$$



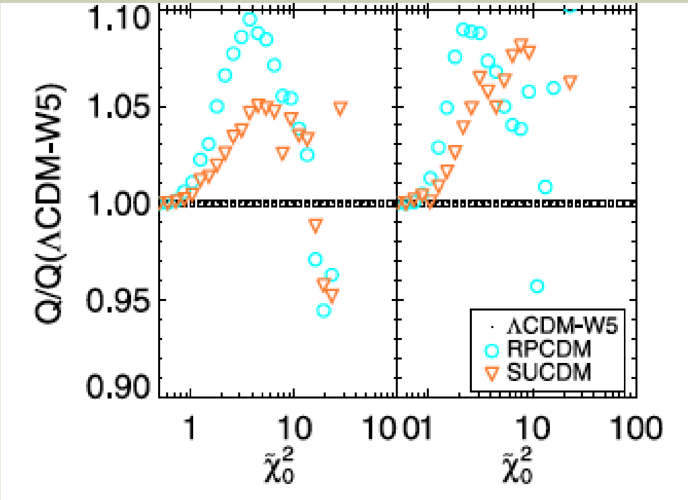
(2014)

Halo DENSITY PROFILES

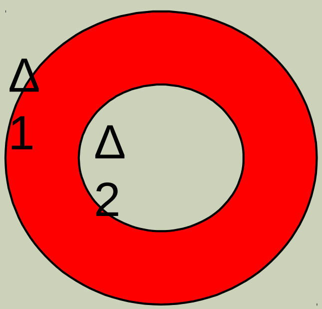
Cosmology dependence non-NFW Halos

Halo populations

- Fraction of halos >2σ from NFW varies with cosmology



Halo Sparsity

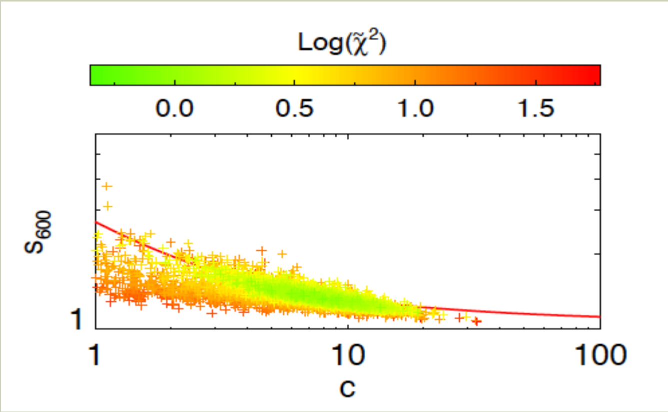


$$s_{\Delta_1\Delta_2} = M_{\Delta_1} / M_{\Delta_2}$$

$$\Delta_2 > \Delta_1$$

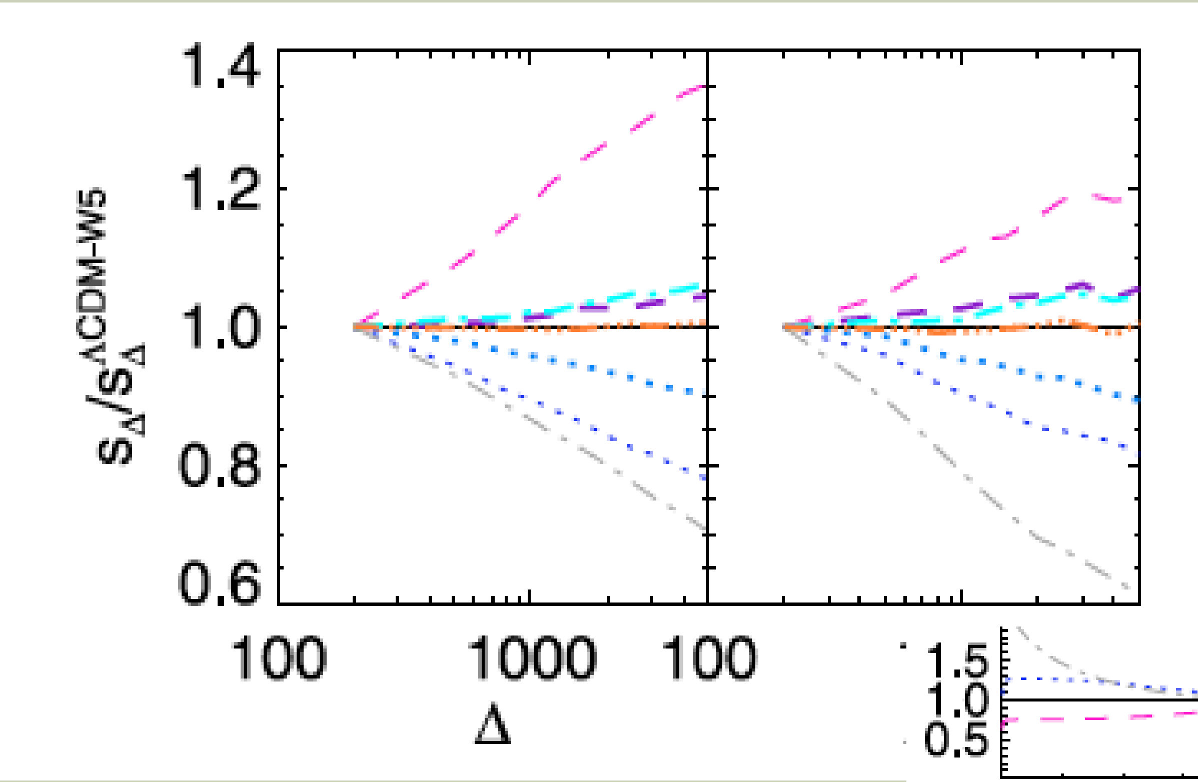
for NFW halos

$$s_\Delta = \frac{200}{x^3\Delta}$$ & $$x^3 \frac{\Delta}{200} = \frac{\ln(1+cx) - \frac{cx}{1+cx}}{\ln(1+c) - \frac{c}{1+c}}$$

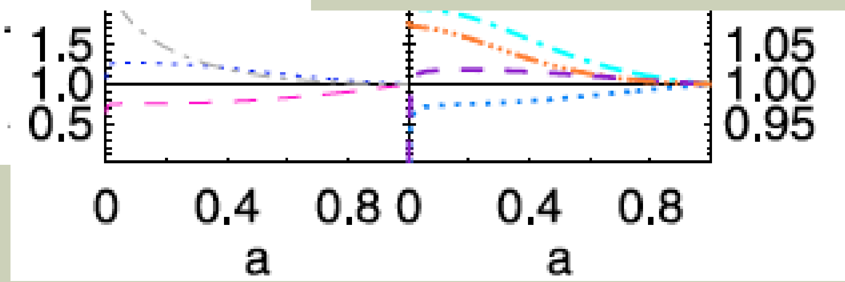


Halo DENSITY PROFILES

Linear Growth FActor



Structures form later for D+ < D+LCDM thus smaller mass assembled at larger Δ



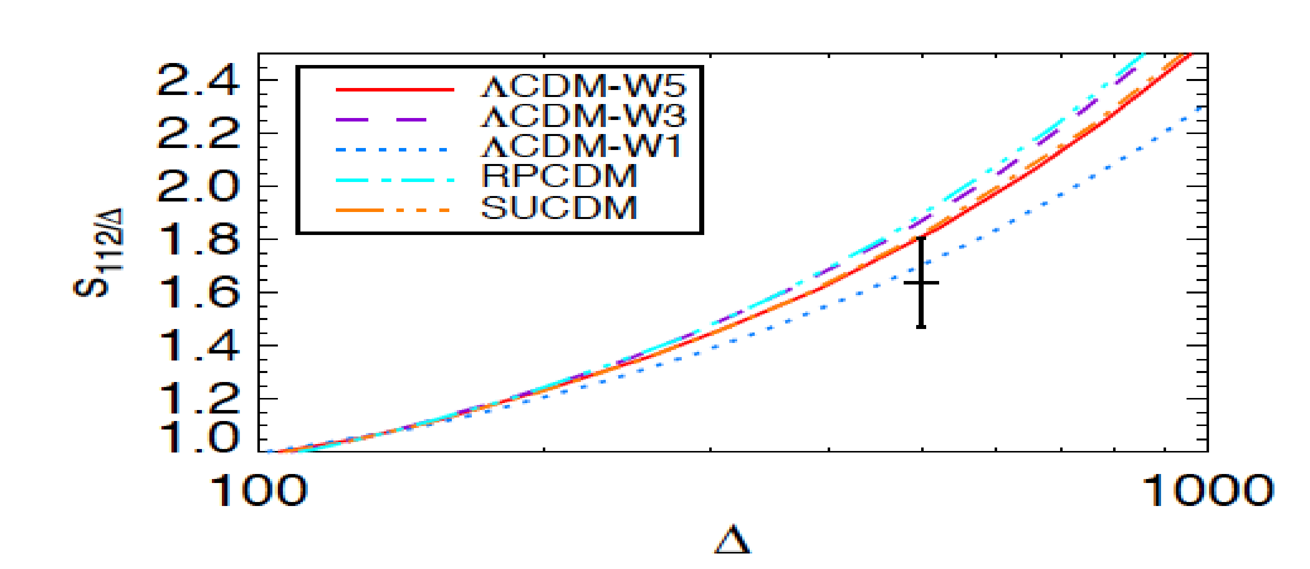
Even the mass distribution of perturbed halos carry a trace of DE dynamics through D+(z) dependence

Observational PRobe

Cluster Sparsity

LoCuSS Clusters

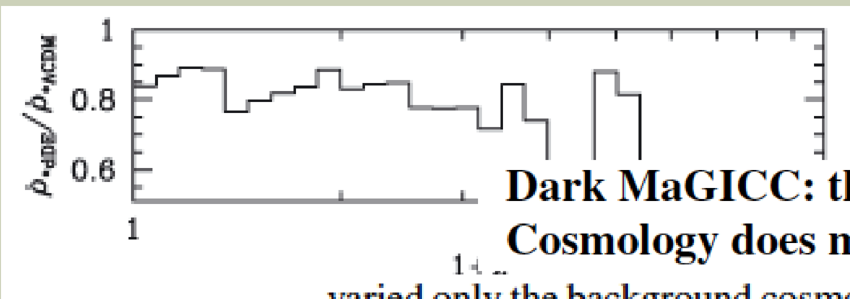
- ~20 Clusters at z~0.2 (Okabe et al. 2012)
- 2D Lensing Masses (no NFW assumption) at Δc=112 & Δc=500
- For simplicity we compare to z=0 catalog



Baryonic PROCESSES & DARK ENERGY

What relation between DE effects on DM non-linear scales & Gas Physics?

e.g. Star Formation:



L. Casarini et al., MNRAS 412, 911 (2011)

Dark MaGICC: the effect of dark energy on disc galaxy formation. Cosmology does matter

varied only the background cosmology. We find that the DE parametrization has a surprisingly important impact on galaxy evolution and on structural properties of galaxies at $z = 0$, in striking contrast with predictions from pure N-body simulations. The different background evolutions can (depending on the behaviour of the DE equation of state) either enhance or quench star formation with respect to a Λ cold dark matter model, at a level similar to the variation of the stellar feedback parametrization, with strong effects on the final galaxy rotation curves. While overall stellar feedback is still the driving force in shaping galaxies, we show that the effect of the DE parametrization plays a larger role than previously thought, especially at lower redshifts. For this reason, the influence of DE parametrization on galaxy formation must be taken into account, especially in the era of precision cosmology.

C. Penzo, et al., MNRAS 442, 176 (2014)

MORALE

- Dark Energy leaves an imprint on Dark Matter clustering at all scales
- Dark Matter collapse carries integrated signature of linear regime (cosmology dependent)
- Amplitude of baryonic processes (may be) not independent of underlying DE model assumptions