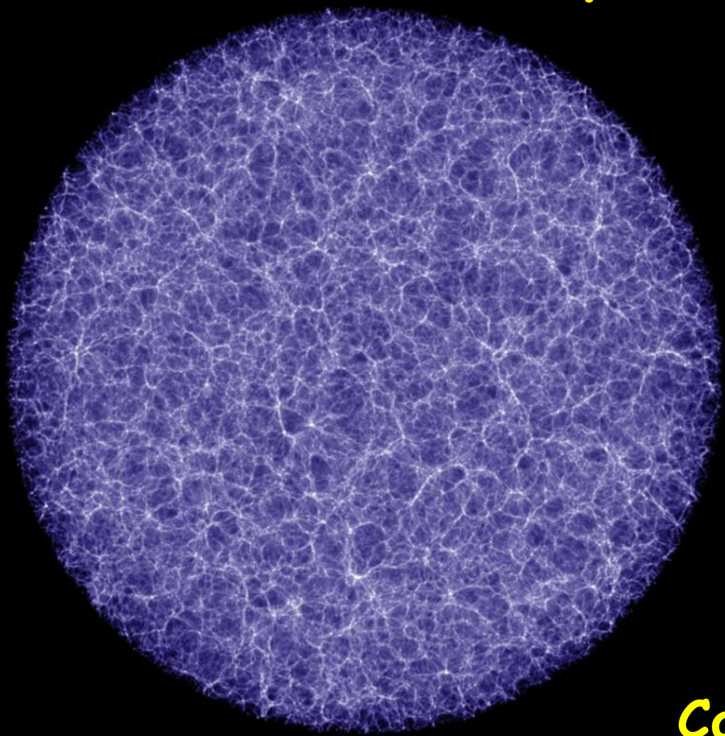
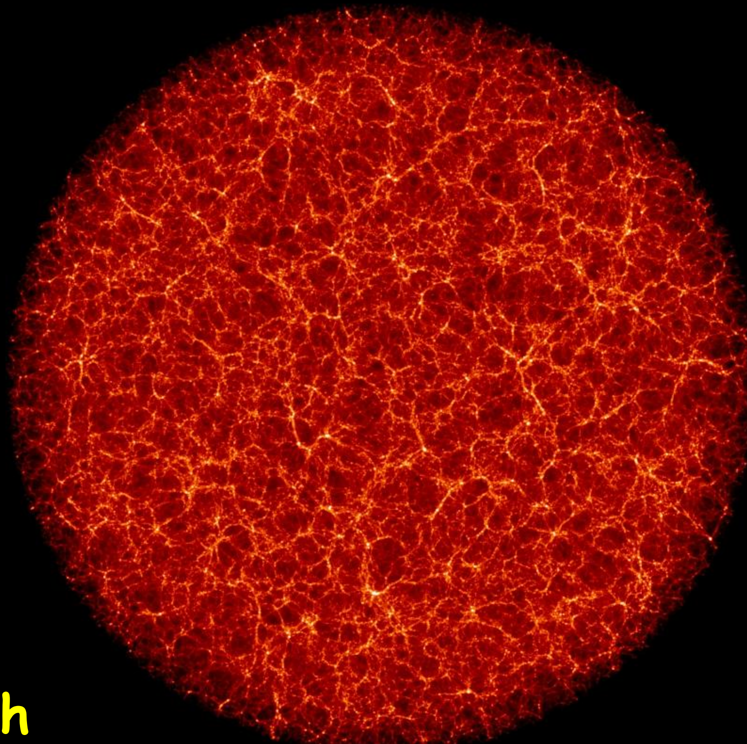
Simulating quintessence cosmologies: growth of structure and redshift space distortions





Carlton Baugh

Institute for Computational Cosmology

Durham University

Benasque 2010 Modern Cosmology: Early Universe, CMB and LSS

Outline: two main topics

- Quintessence N-body simulations
  Jennings et al. 2010 MNRAS, 401, 2181

- Redshift-space distortions
  Jennings et al. 2010, arXiv:1003.4282 in press

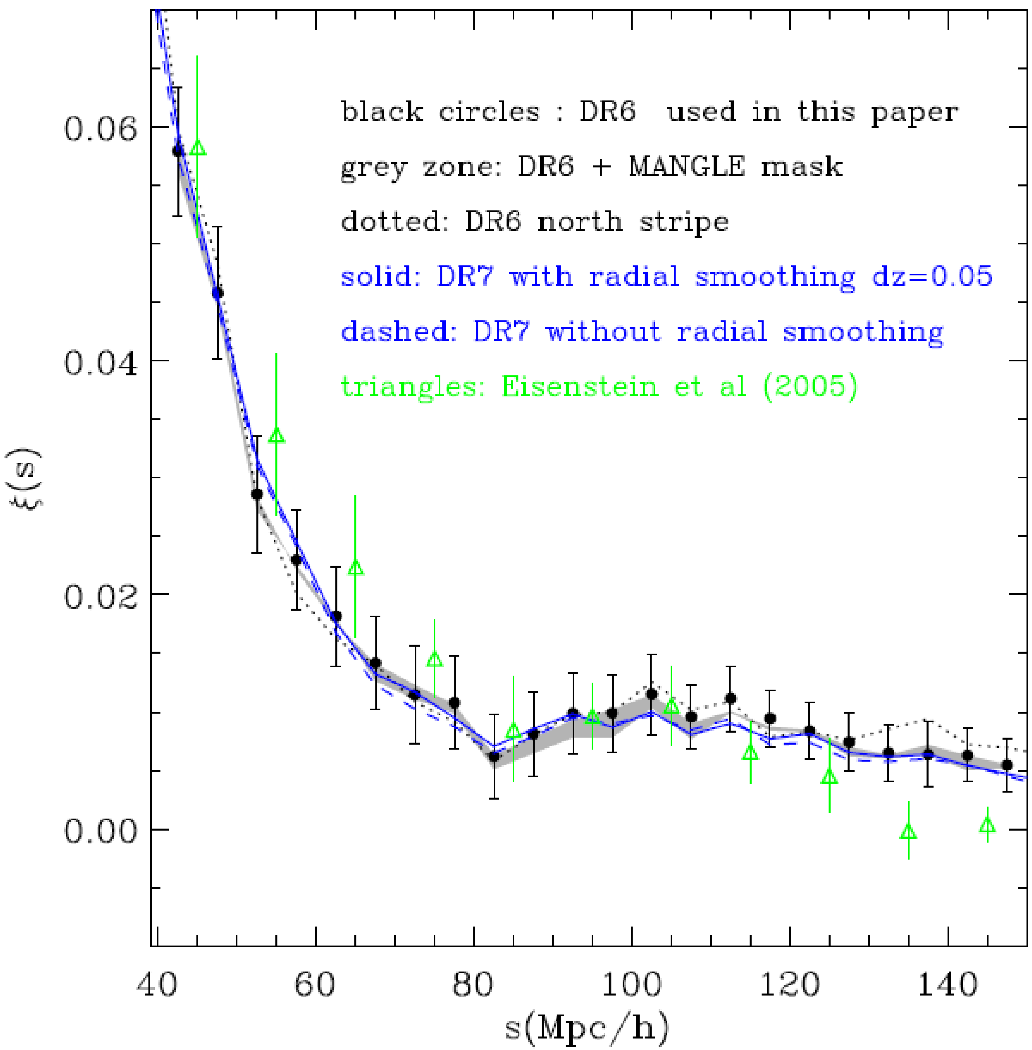
Collaborators:

Elise Jennings, Silvia Pascoli, Raul Angulo (MPA)

Durham University

ICC

The BAO signal in galaxy clustering



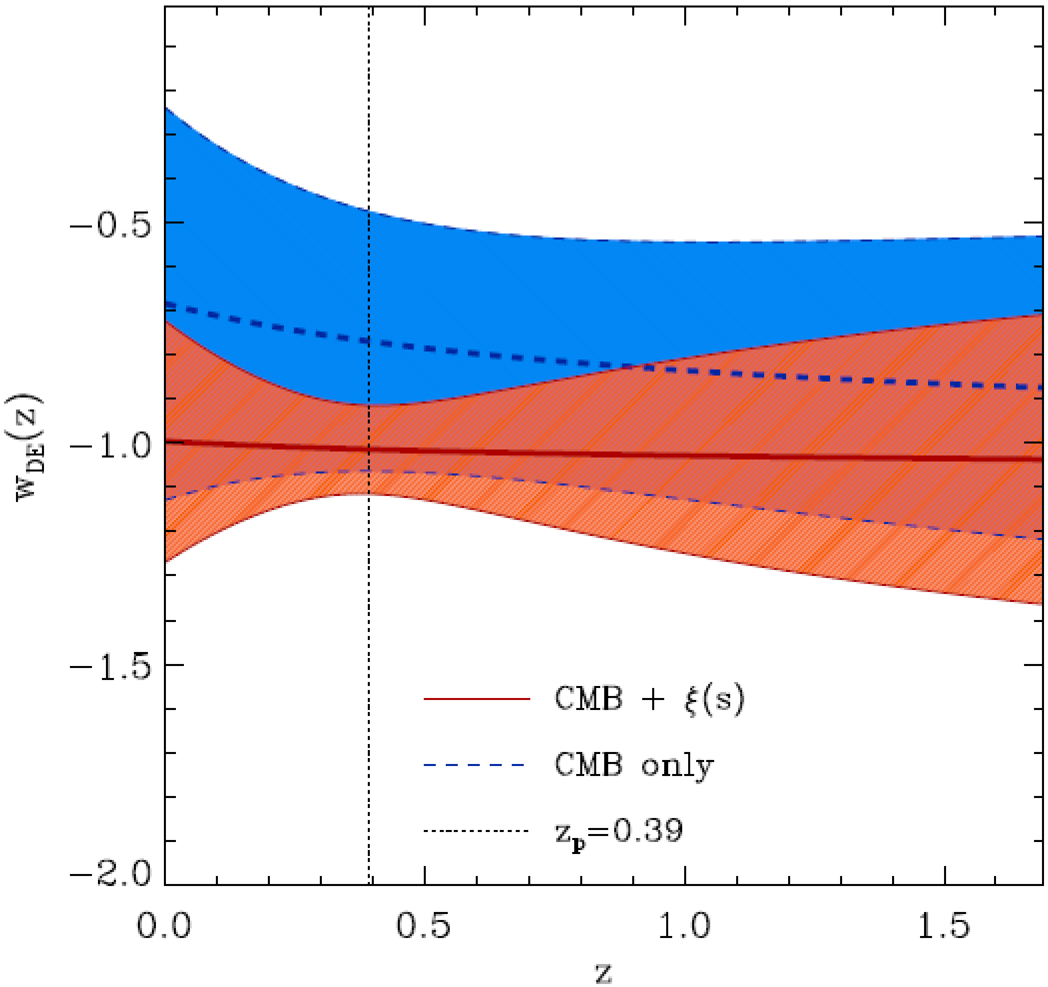
SDSS Luminous Red Galaxy

Cabre & Gaztanaga 2009
Gaztanaga et al 2009

Sanchez et al. 2009

Evolution in the DE eqn of state?

EFFECTIVE EQUATION OF STATE



REDSHIFT

Equation of state parameter:

$$w = \frac{P}{\rho}$$

Cosmological constant:

w = -1

Sanchez et al. 2009

Modelling the Gigaparsec Universe

- Why do we need simulations?
- Modelling quintessence dark energy
- Redshift space distortions

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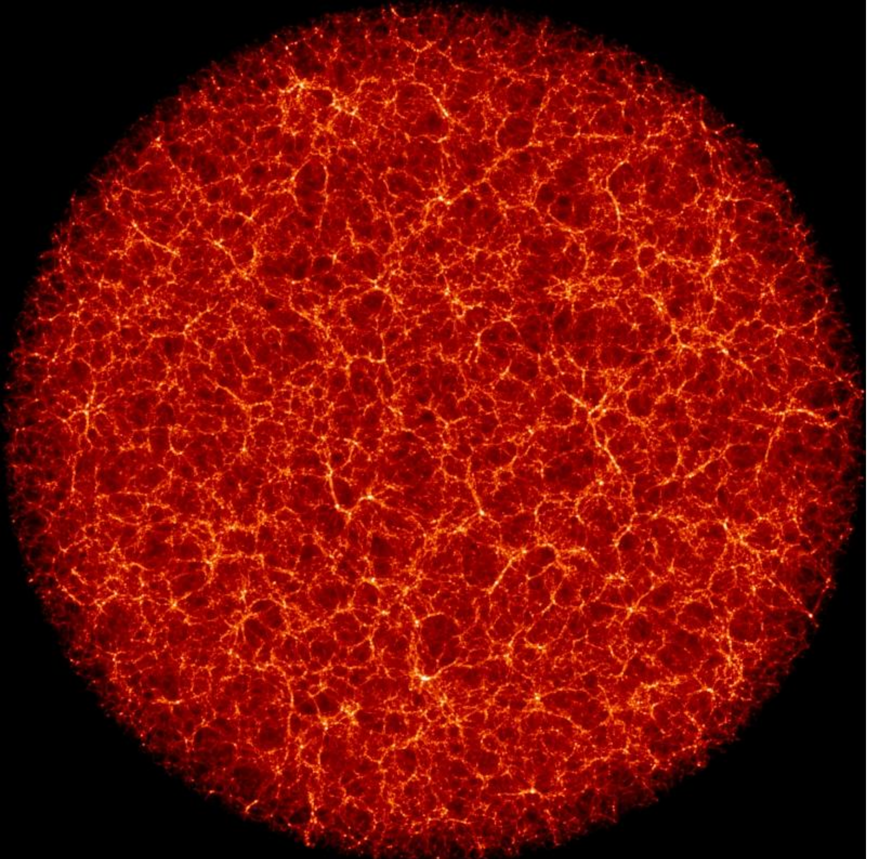
Why do we need simulations?

- Dark energy/modified gravity tests use LSS
- Isn't linear perturbation theory good enough?
- Need high precision measurements as models give similar predictions
- Need high precision theory too!



Baryonic Acoustic Simulations at the ICC
BASICC

L = 1340/h Mpc V=2.4/h^3 Gpc^3

(20 x Millennium volume)

N=1448^3 (>3 billion particles)

Can resolve galactic haloes

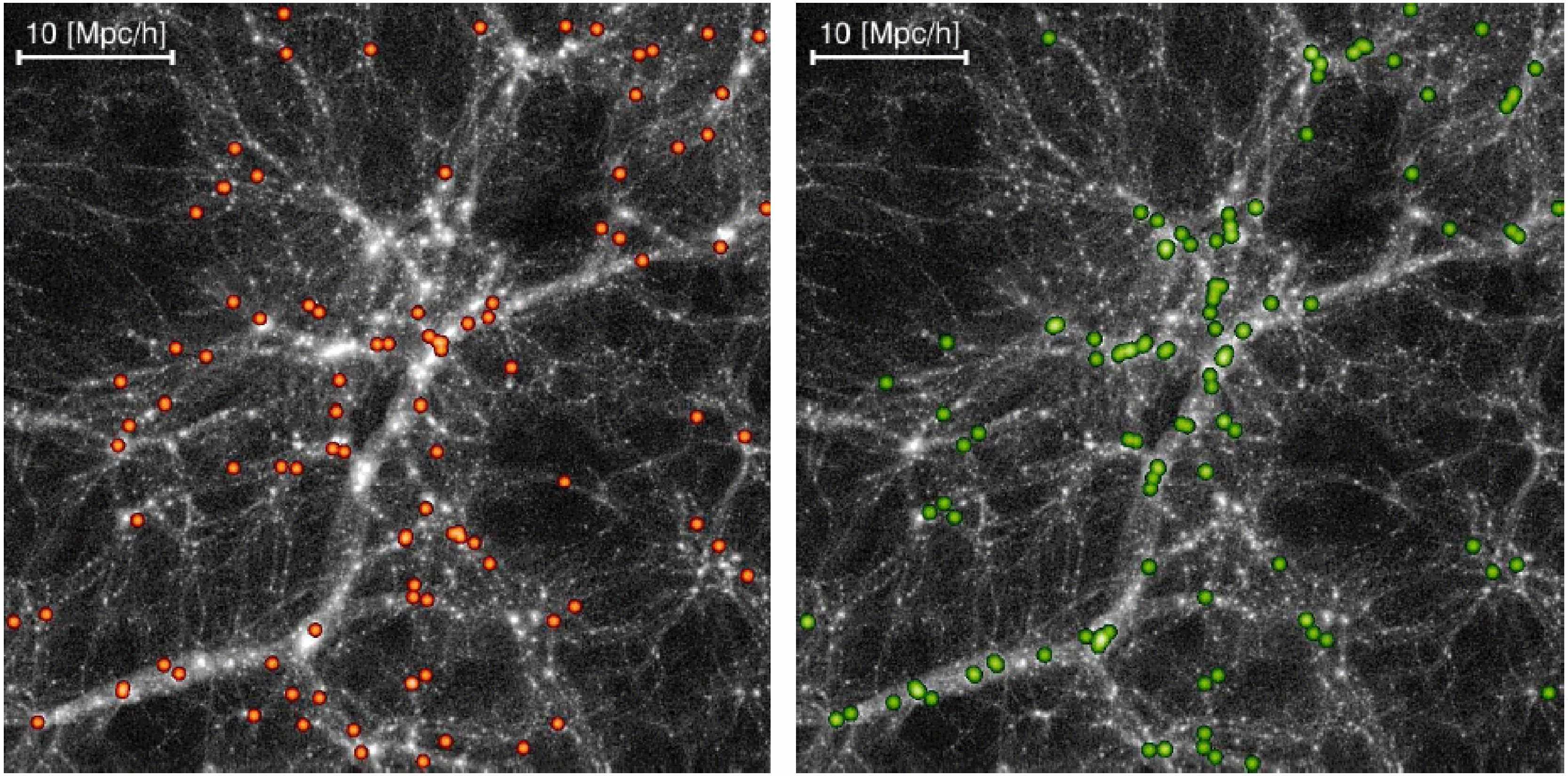
130,000 hours CPU on Cosmology Machine

Combine with semi-analytical galaxy formation model GALFORM

50 low-res BASICC runs for errors
(= 1000 Millenniums!)

Angulo et al. 2008

Combine with galaxy formation model



H-alpha emitters

z=1

H-band selection

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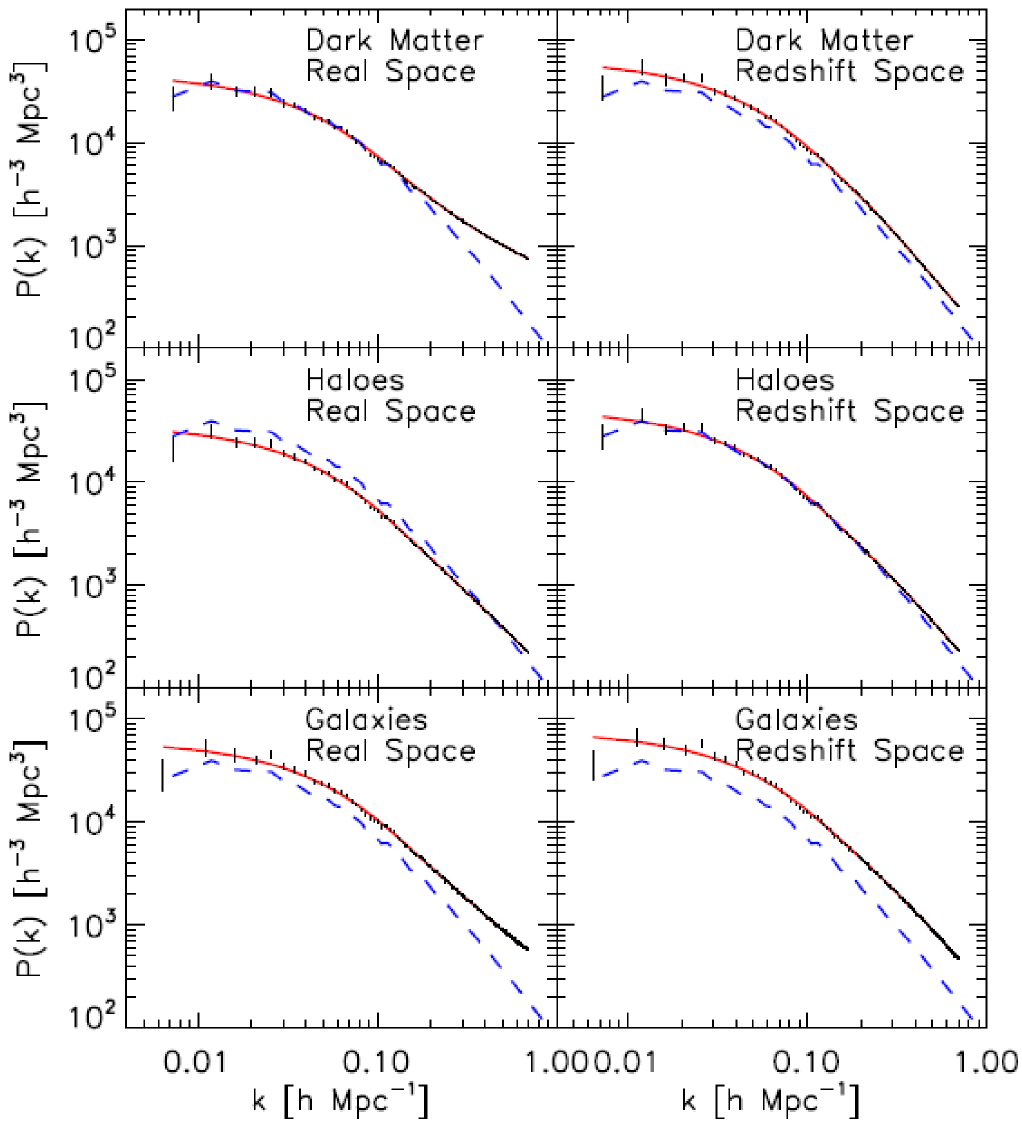
Alvaro Orsi et al. 2009

ICC

So, is linear theory good enough?

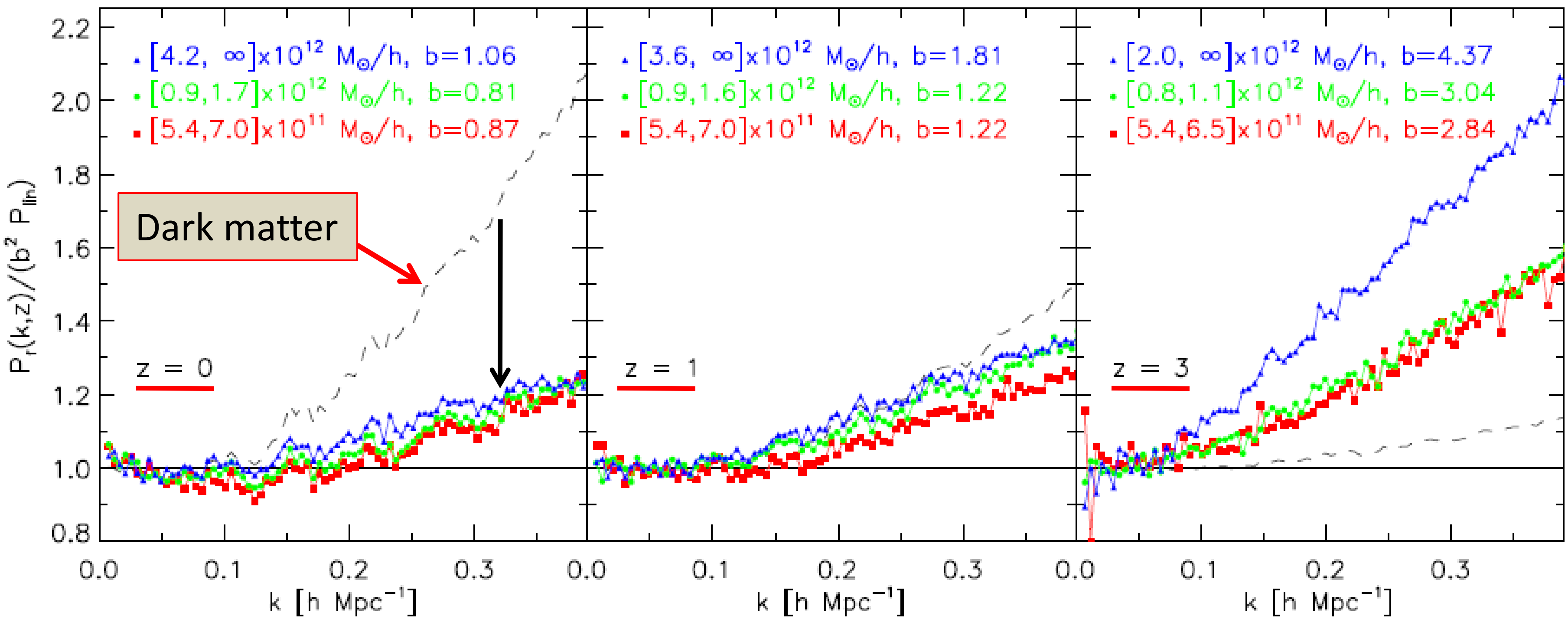


No! Because of .....

- Nonlinear growth of fluctuations
- Redshift space distortions
- Scale dependent halo and galaxy bias

Angulo et al. 2008

Scale dependent bias



Remove asymptotic bias: Scale dependent halo bias

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Angulo et al. 2008

ICC

Quintessence Dark Energy

- Alternative to cosmological constant
- Solves fine tuning and coincidence problems
- Dynamical scalar field

Scalar Fields in Cosmology

$$H^2 = \frac{8\pi G}{3}[\rho_m + \rho_r + \frac{\dot{\varphi}^2}{2} + V(\varphi)]$$

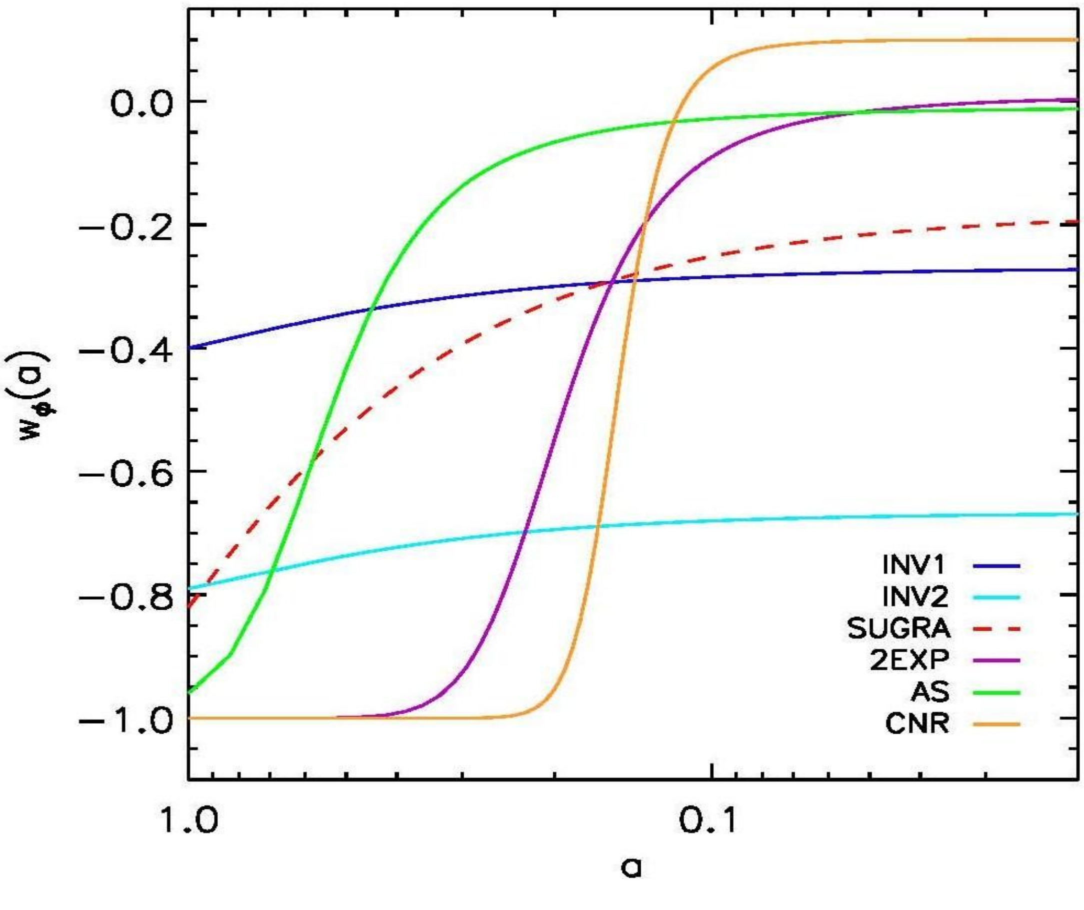
Dark Energy equation of state:

$$w(\varphi) = \frac{P_\varphi}{\rho_\varphi} = \frac{\dot{\varphi}^2/2 - V(\varphi)}{\dot{\varphi}^2/2 + V(\varphi)}$$

Lots of choice for potential V !

- Inverse (INV) (Zlatev et al. 1999) $$V(\varphi) \sim M^{(4+\alpha)}\varphi^{-\alpha}$$
- Albrecht-Skordis (AS) $$V(\varphi) \sim V_p(\varphi)e^{-\lambda\varphi} \qquad V_p(\varphi) = (\varphi - B)^\alpha + A$$
- SUGRA (Brax & Martin 1999) $$V(\varphi) \sim 1/\varphi^\alpha e^{\varphi^2/2}$$

How can we describe this range of models?

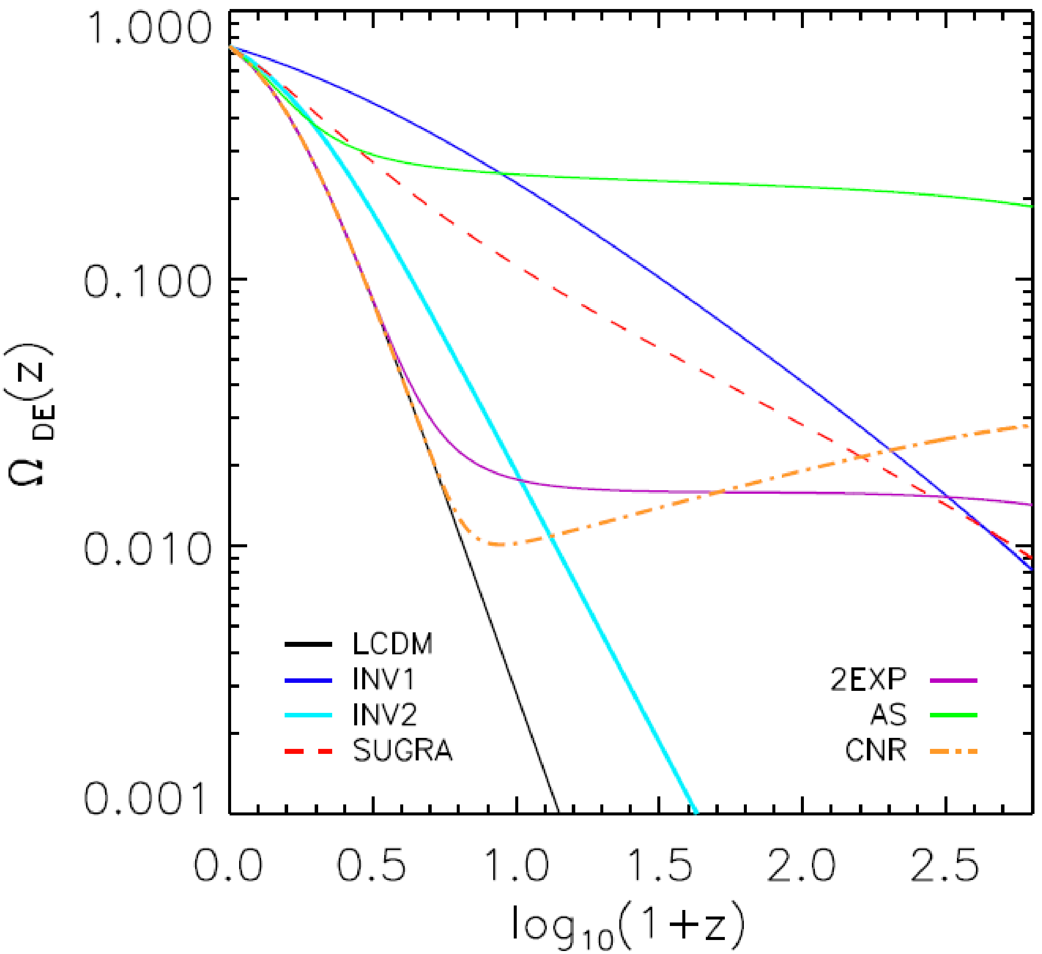


- Rich variety of w(z)
- Need to describe this accurately to z>100 in an N-body simulation
- Two parameter models out by 10% already at z=1
- Use 4 parameter model Corasaniti & Copeland
- Accurate to <5% to z=1000

Jennings et al. 2010 MNRAS, 401, 2181

Simulating quintessence DE

Dark energy density parameter



- Models have different expansion histories to LCDM
- Structure grows at different rates

Jennings et al 2010

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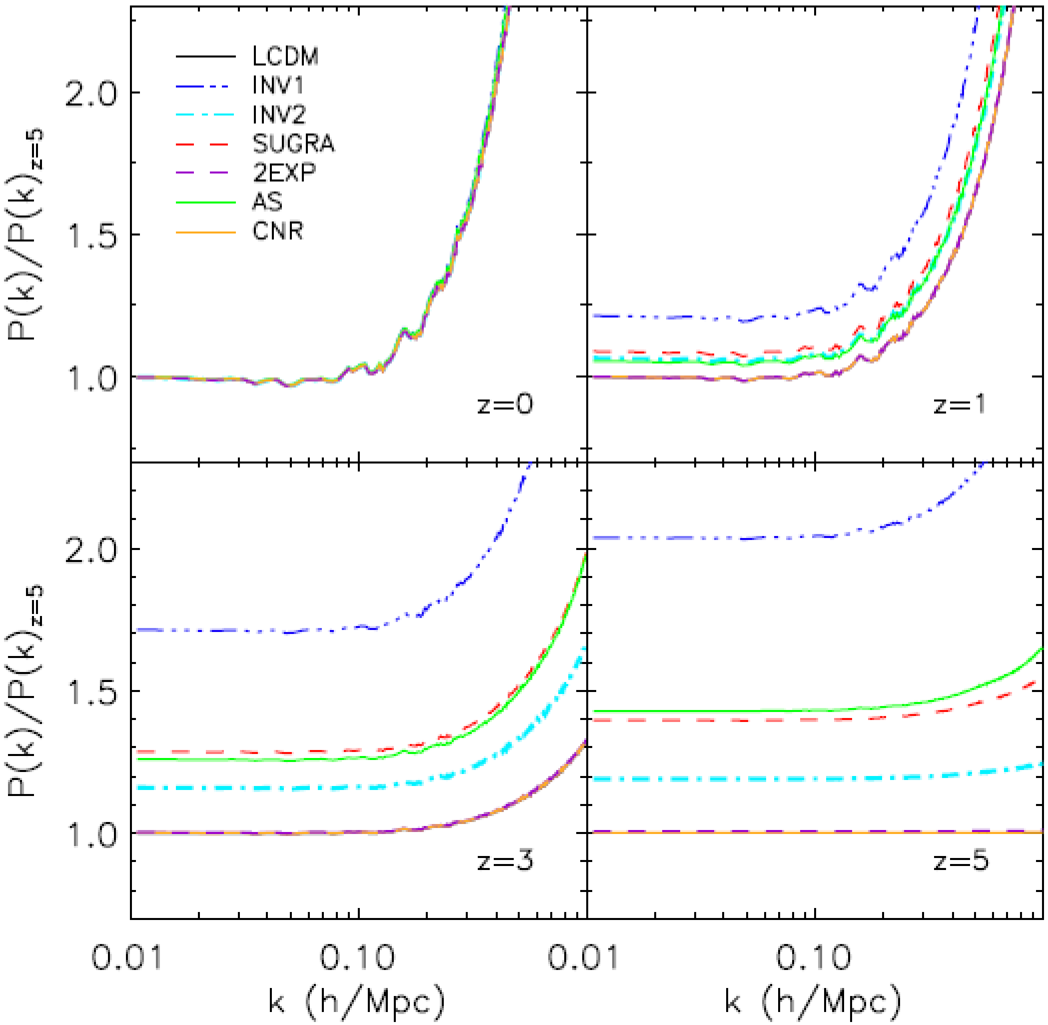
Stage I: The growth of structure



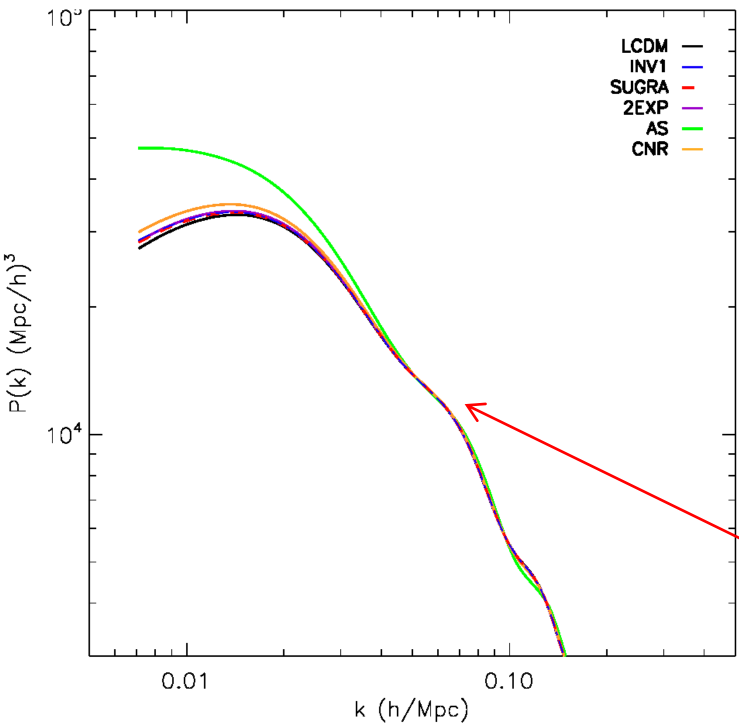
- LCDM input P(K)
- Change expansion history using w(z)

Stage II : Quintessence and linear theory power

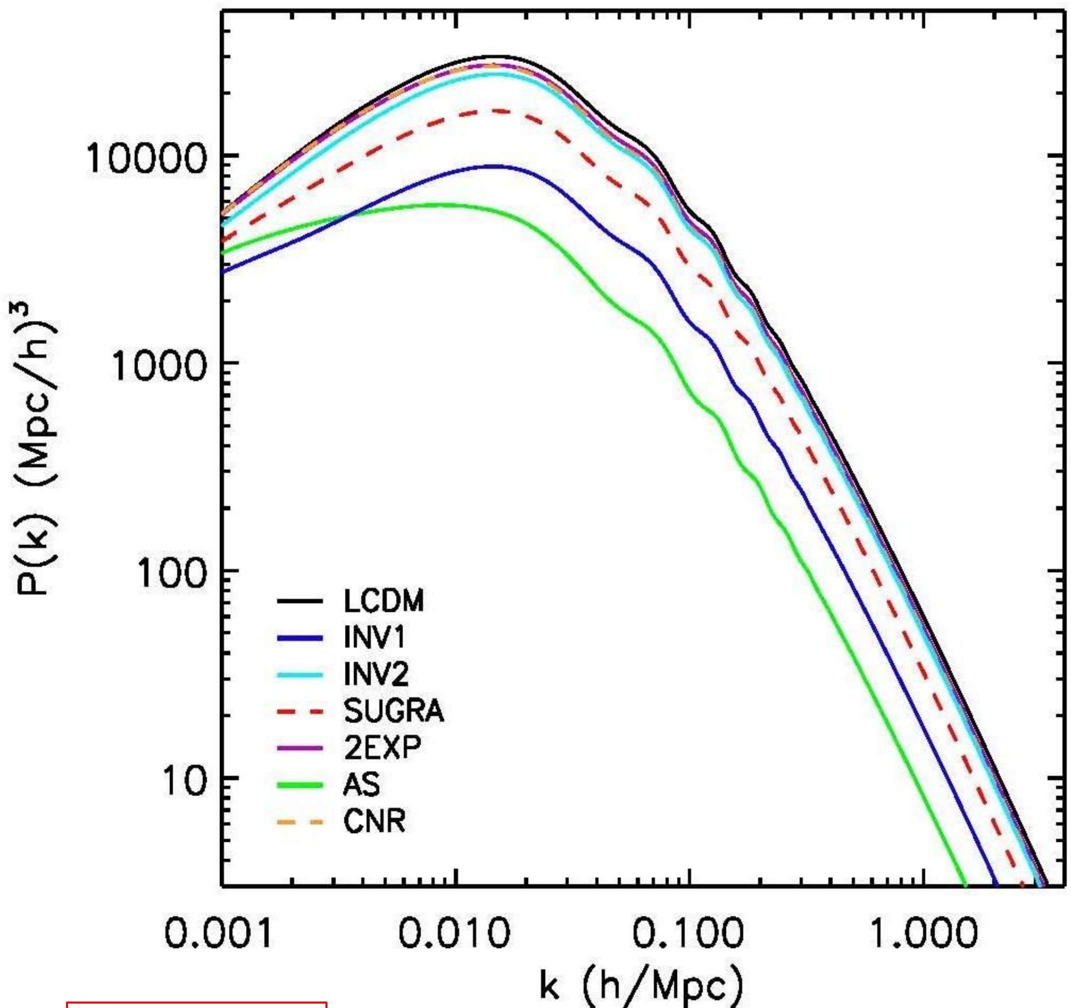
Growth of δ_m during matter dominated era

- Negligible dark energy $\delta_m \propto a$
- With appreciable dark energy:

$$\delta_m \propto a^{[\sqrt{25-24\Omega_{DE}}-1]/4}$$



Normalise to σ_8=0.8



Jennings et al 2010

Stage Ⅲ : Consistency with observational data

Cosmological distance priors

'Acoustic Scale'

$$l_A(z_*) = (1+z_*)\pi \frac{D_A(z_*)}{r_s(z_*)}$$

'Shift parameter'

(Bond et al. 1997)

$$R_{conc}(z_*) = \frac{\sqrt{\Omega_m H_0^2}}{c}(1+z_*)D_A(z_*)$$

Redshift at decoupling

(Hu & Sugiyama 1996)

$$z_* = z_*(\Omega_m h^2, \Omega_B h^2)$$

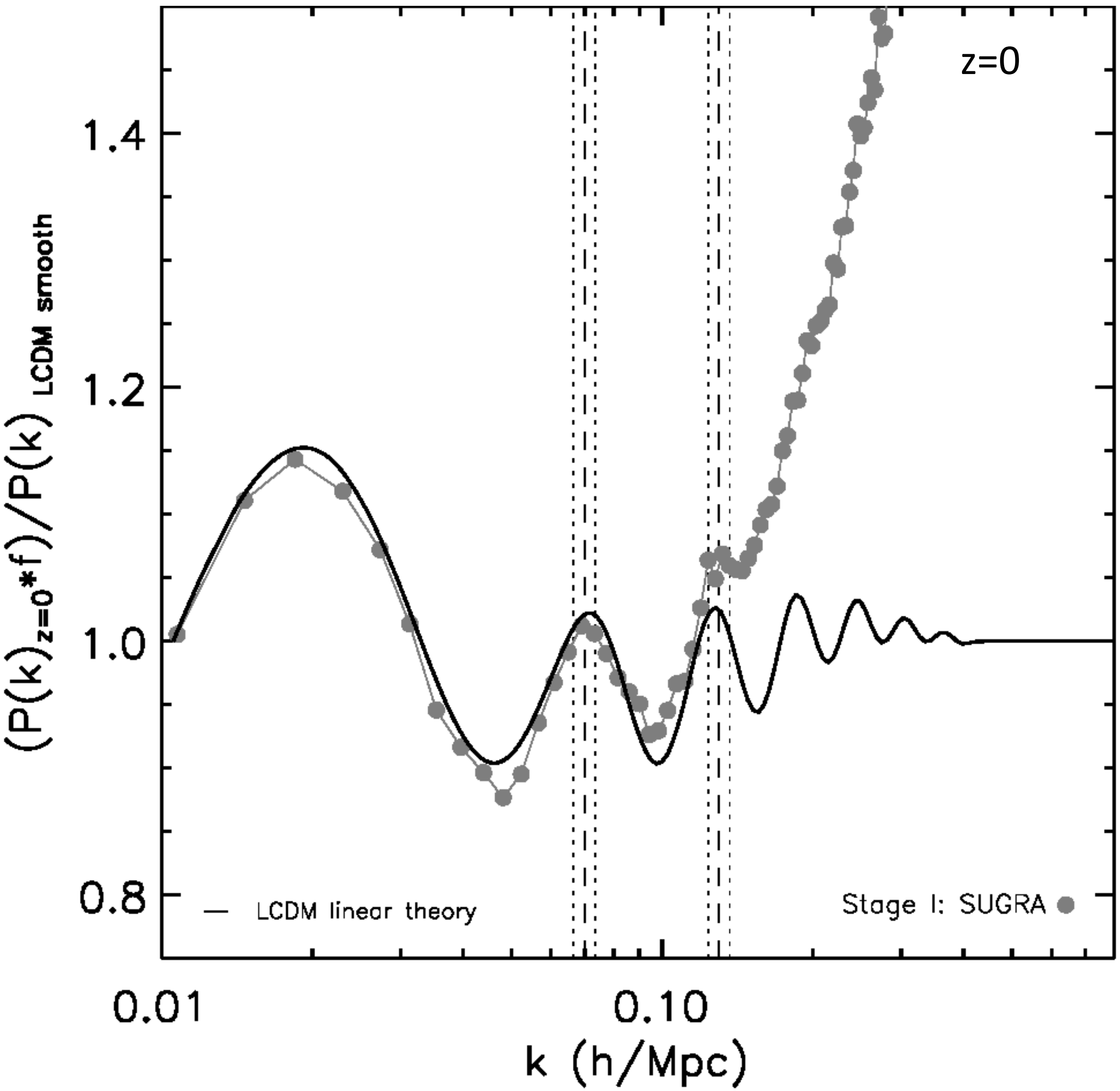
	$z*$	$l_A(z*)$	$R(z*)$
WMAP 5-yr ML	1090.51 $\pm$0.95	302.10 $\pm$ 0.86	1.710 $\pm$ 0.019

Fit to the distance priors for each quintessence model using ΛCDM parameters

	$\chi^2_{\rm total}/\nu$
INV1	15.34
INV2	1.81
SUGRA	3.88
2EXP	1.09
AS	2.04
CNR	1.37

Jennings et al 2010

Baryon acoustic oscillations



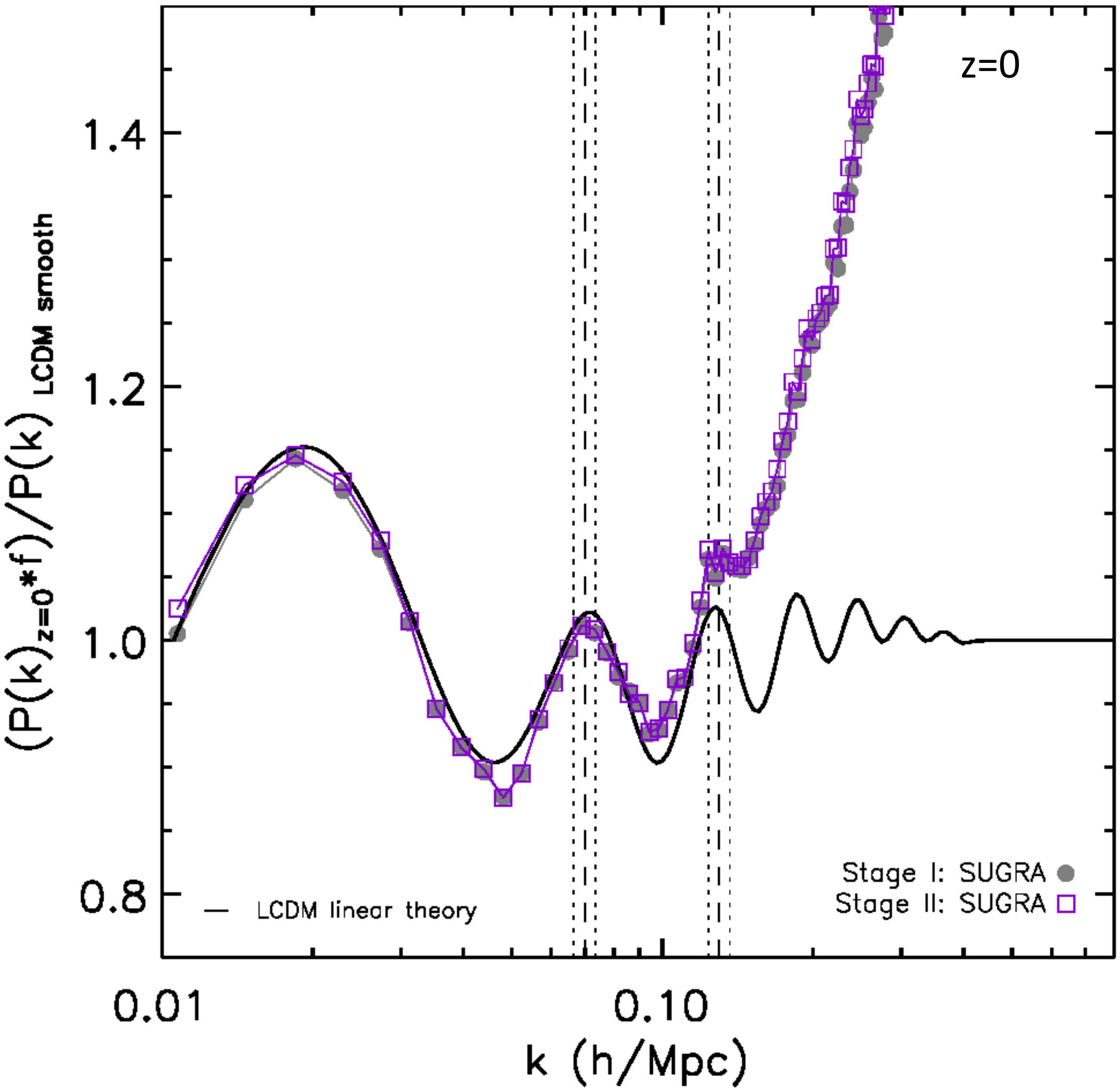
SUGRA

Stage I : SUGRA linear growth factor

Multiplicative factor f corrects the scatter of the measured power from the expected linear theory

Jennings et al. 2010

Baryon acoustic oscillations

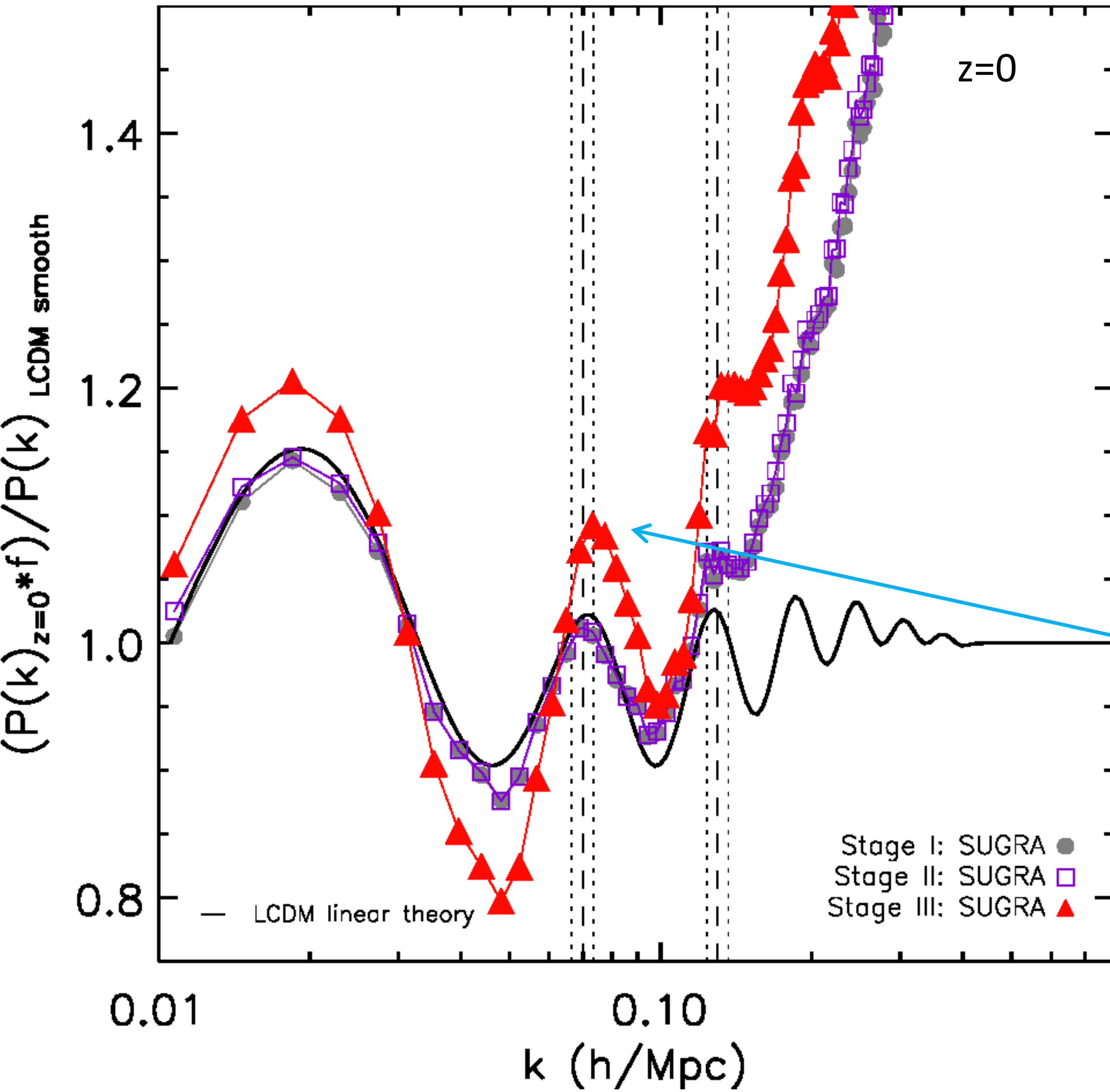


SUGRA

Stage I : SUGRA linear growth factor
Stage II : SUGRA linear theory

Jennings et al. 2010

Baryon acoustic oscillations



SUGRA

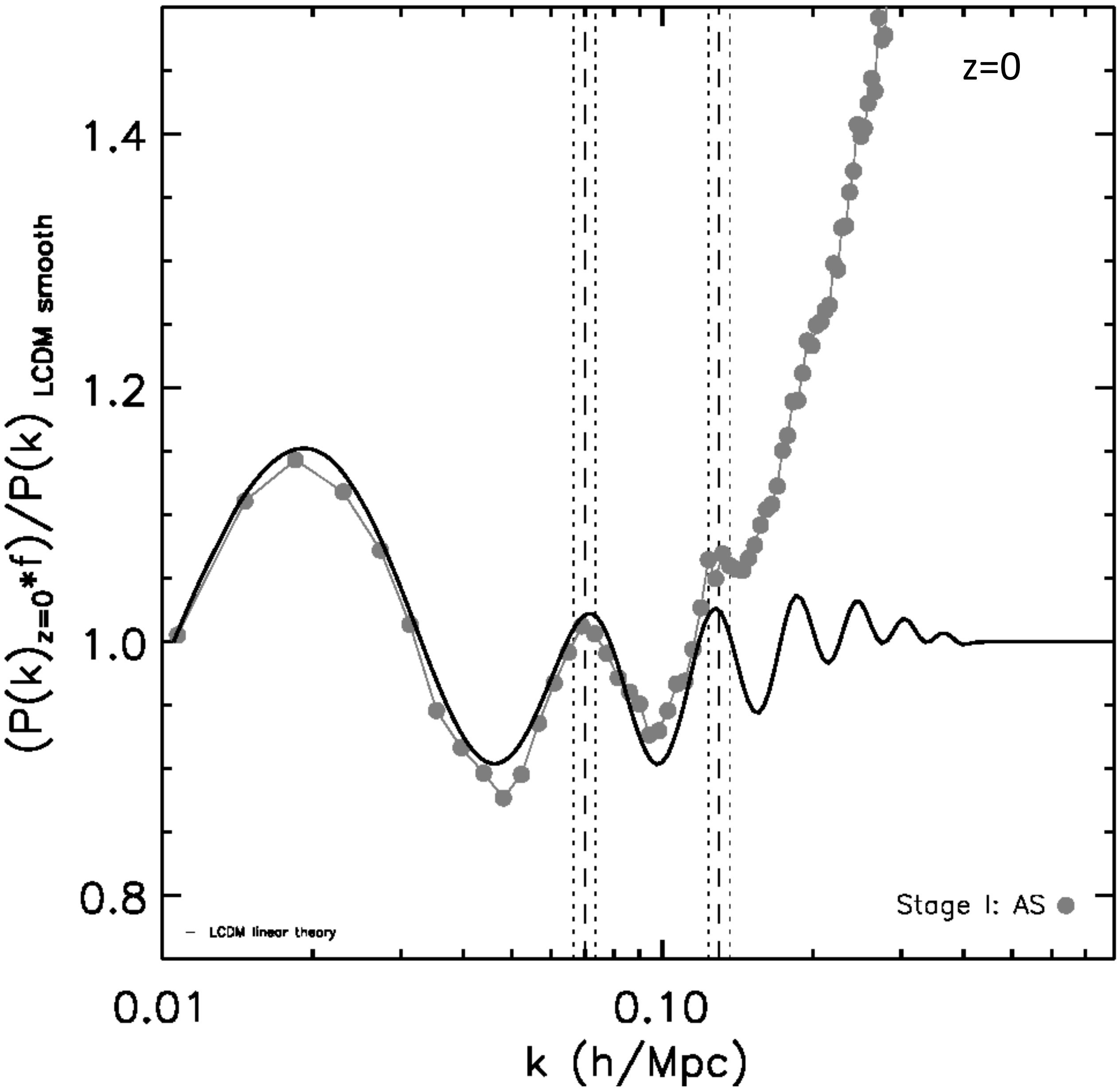
Stage I : SUGRA linear growth factor

Stage II : SUGRA linear theory

Stage III: SUGRA best fit parameters

Jennings et al. 2010

Baryon acoustic oscillations

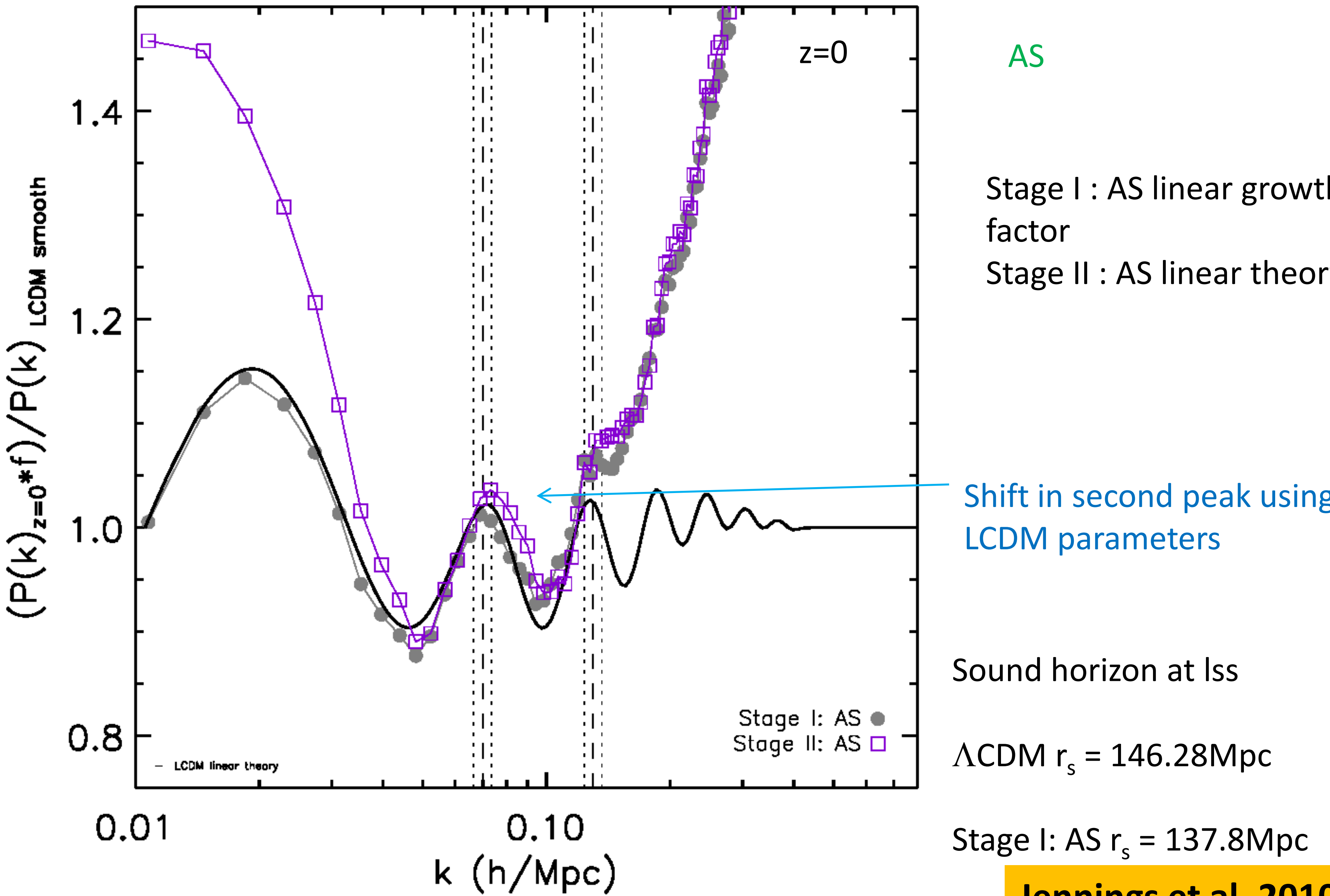


AS

Stage I : AS linear growth factor

Jennings et al. 2010

Baryon acoustic oscillations



AS

Stage I : AS linear growth factor

Stage II : AS linear theory

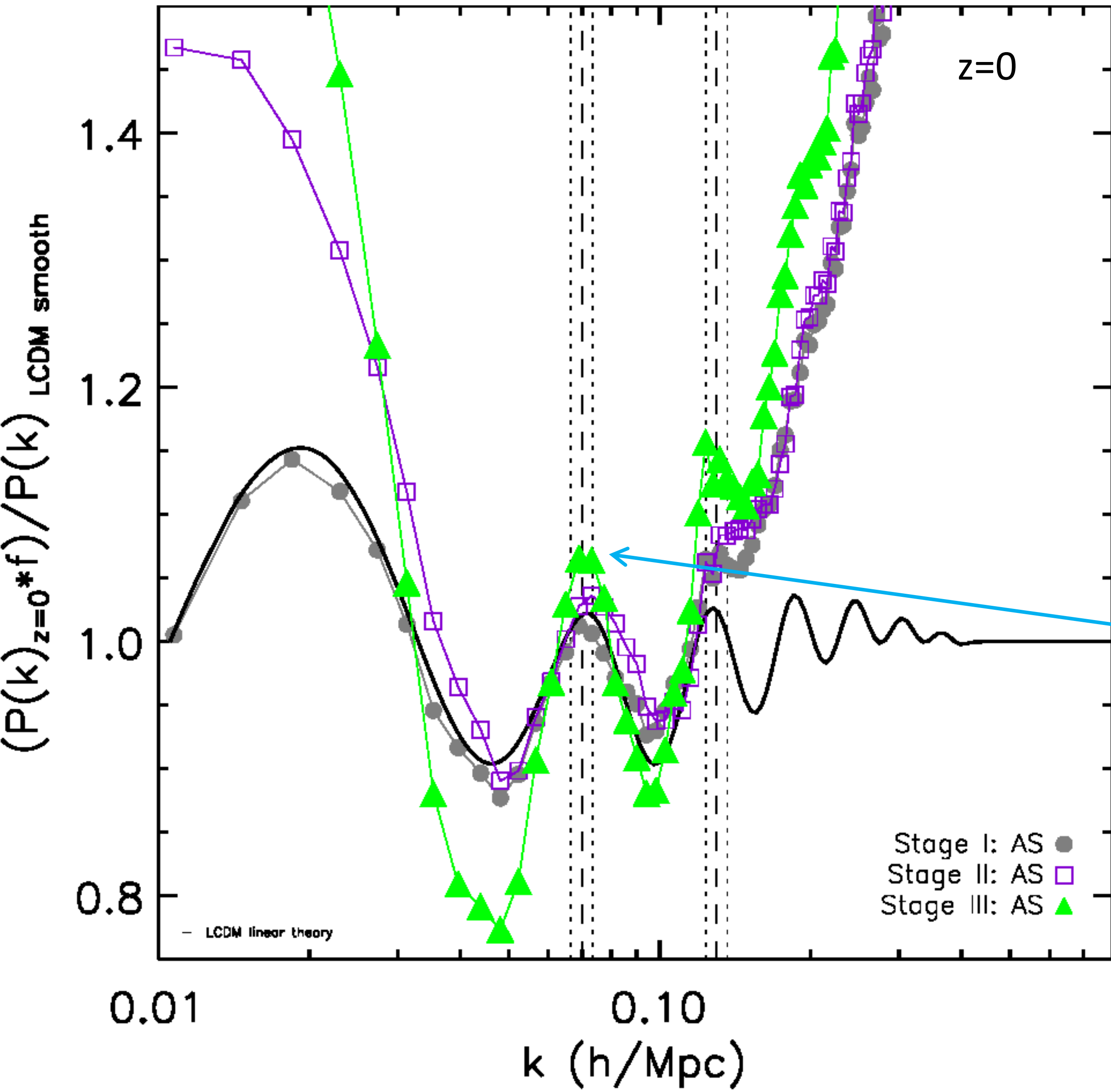
Sound horizon at lss

ΛCDM r_s = 146.28Mpc

Stage I: AS r_s = 137.8Mpc

Jennings et al. 2010

Baryon acoustic oscillations



AS

Stage I : AS linear growth factor

Stage II : AS linear theory

Stage III: AS best fit parameters

<1% shift in second peak compared to ΛCDM

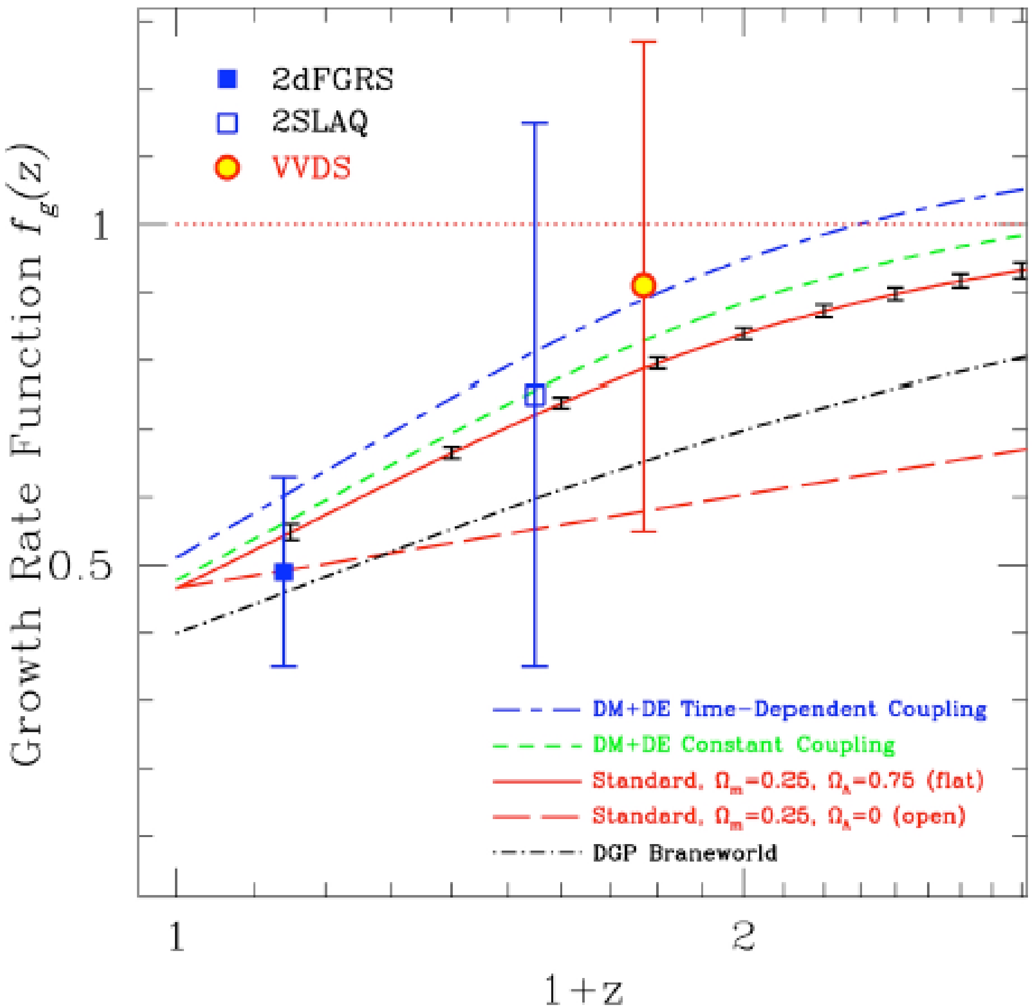
Sound horizon at lss

ΛCDM r_s = 146.8Mpc

Stage III: AS r_s = 149.8Mpc

Jennings et al. 2010

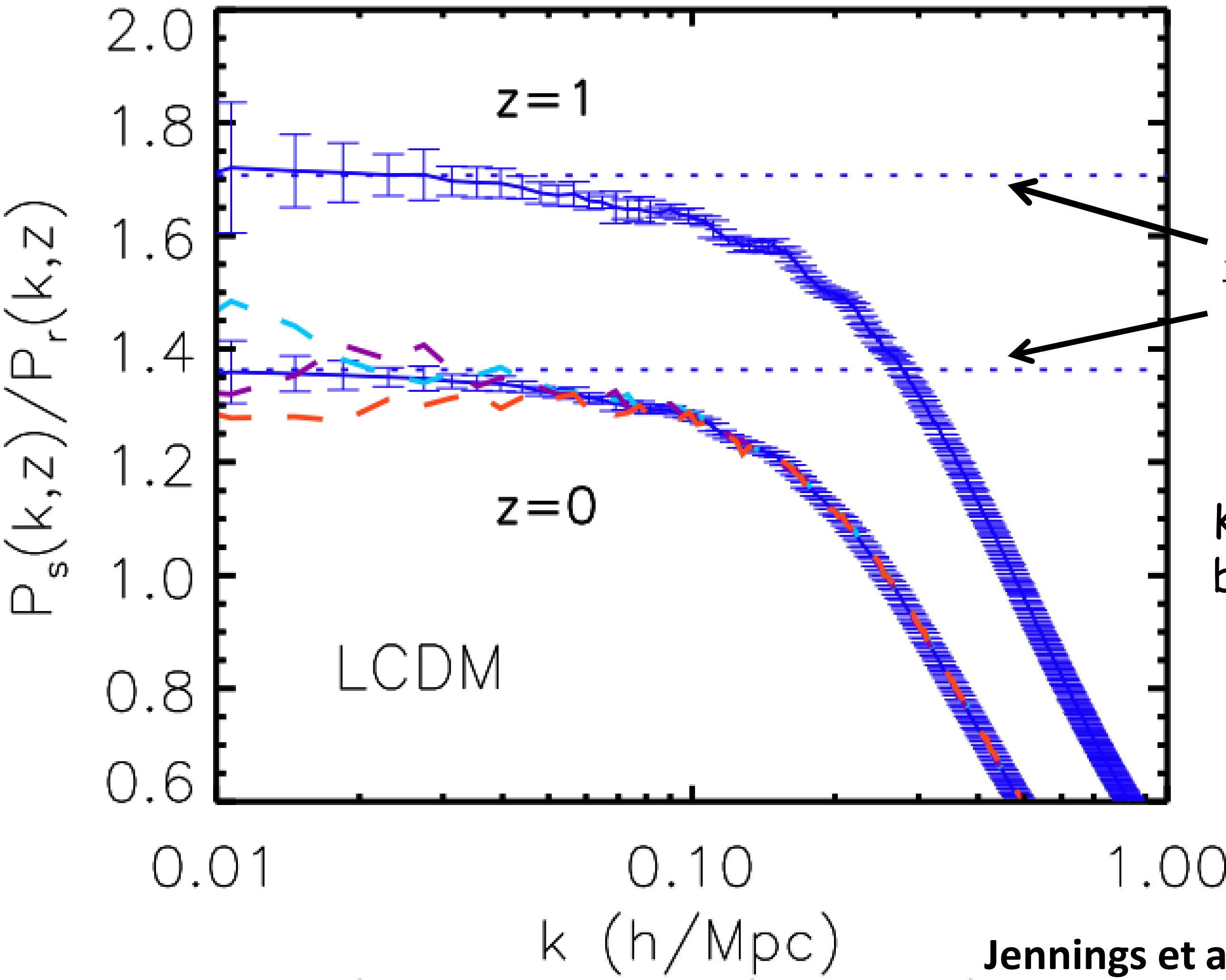
Growth rate of structure



- Expansion history a(t) influences growth of structure
- Compare a(t) from z-space distortions with independent estimate derived from H(z)
- Distinguish dark energy and modified gravity

Guzzo et al. 2008

Measuring the growth factor: redshift space distortions of P(K)



$$\frac{P_0^s(k)}{P_r(k)} = 1 + \frac{2}{3}f + \frac{1}{5}f^2$$

Kaiser effect: coherent bulk flows

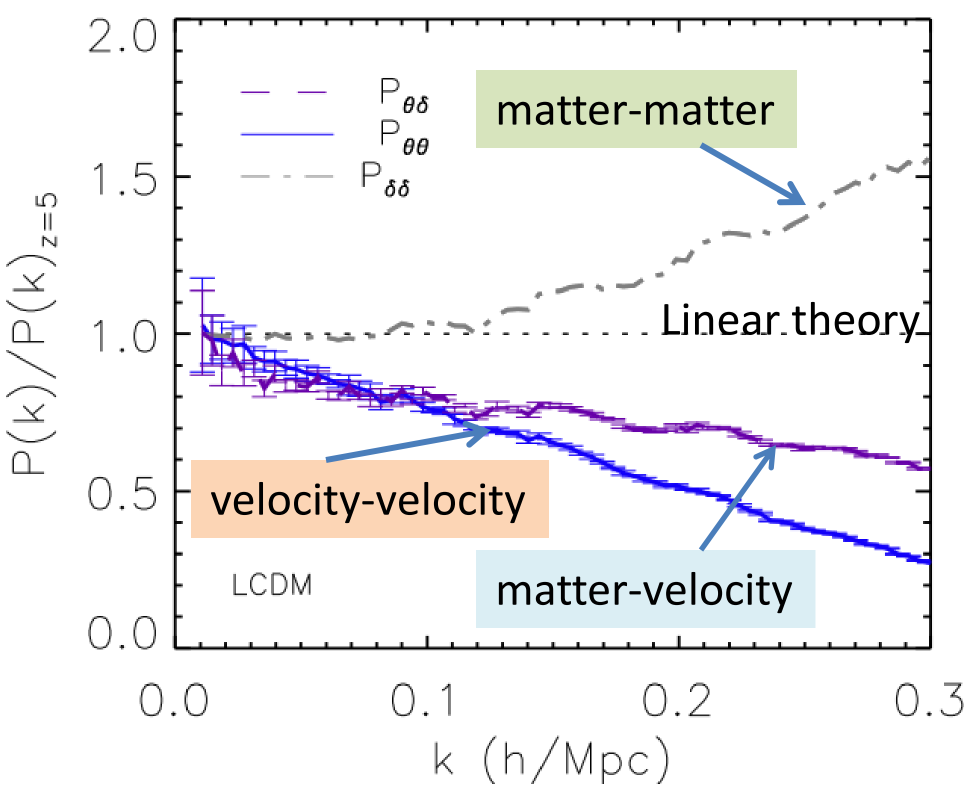
Jennings et al 2010 arXiv:1003.4282

Redshift space distortions: The Kaiser (1987) model

$$\frac{P_0^s(k)}{P^r(k)} = 1 + \frac{2}{3}f + \frac{1}{5}f^2 \qquad f = \mathrm{dln}D/\mathrm{dln}a$$

1. The small scale velocity dispersion can be neglected.
2. The velocity gradient $|\mathrm{d}\vec{\mathrm{u}}/\mathrm{dr}| \ll 1$.
3. The velocity and density perturbations satisfy the linear continuity equation.
4. The real space density perturbation is assumed to be small, $|\delta(r)| \ll 1$, so that higher order terms can be neglected.

Accurate redshift space distortions



Kaiser formula: linear theory

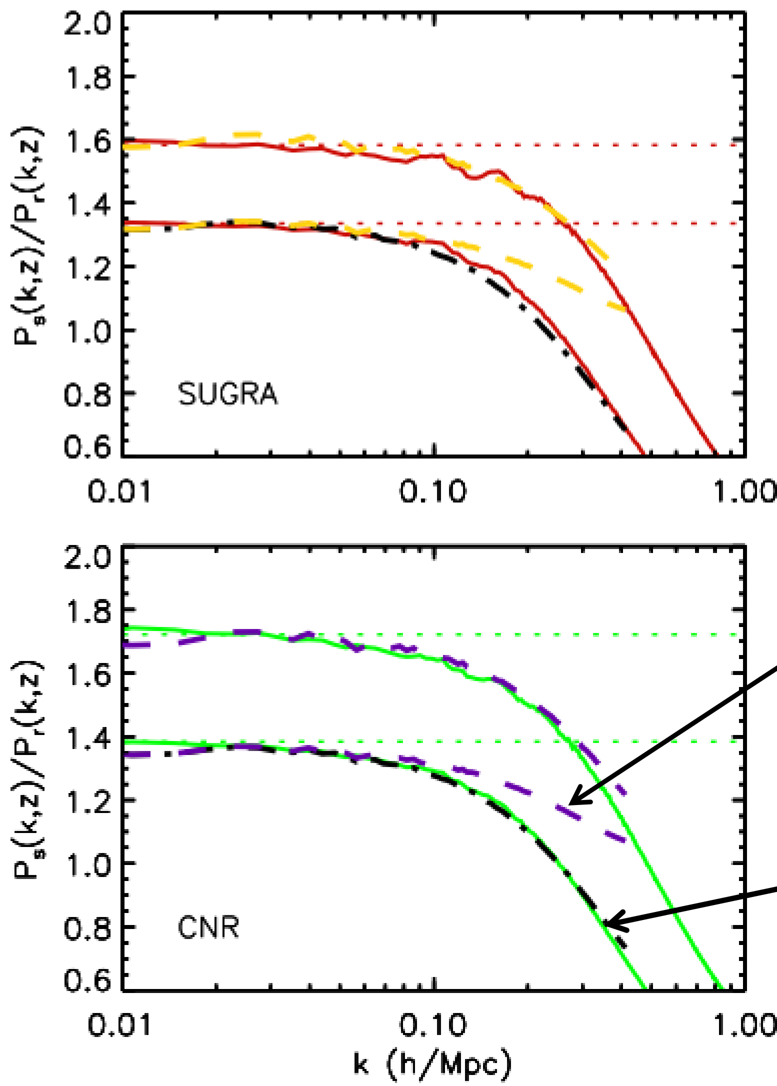
$$\frac{P_0^s(k)}{P_r(k)} = 1 + \frac{2}{3}f + \frac{1}{5}f^2$$

Nonlinear terms: Scoccimarro 2004

$$P_0^s(k) = P_{\delta\delta}(k) + \frac{2}{3}fP_{\delta\theta}(k) + \frac{1}{5}f^2P_{\theta\theta}(k)$$

Jennings et al 2010 arXiv:1003.4282

Accurate redshift space distortions

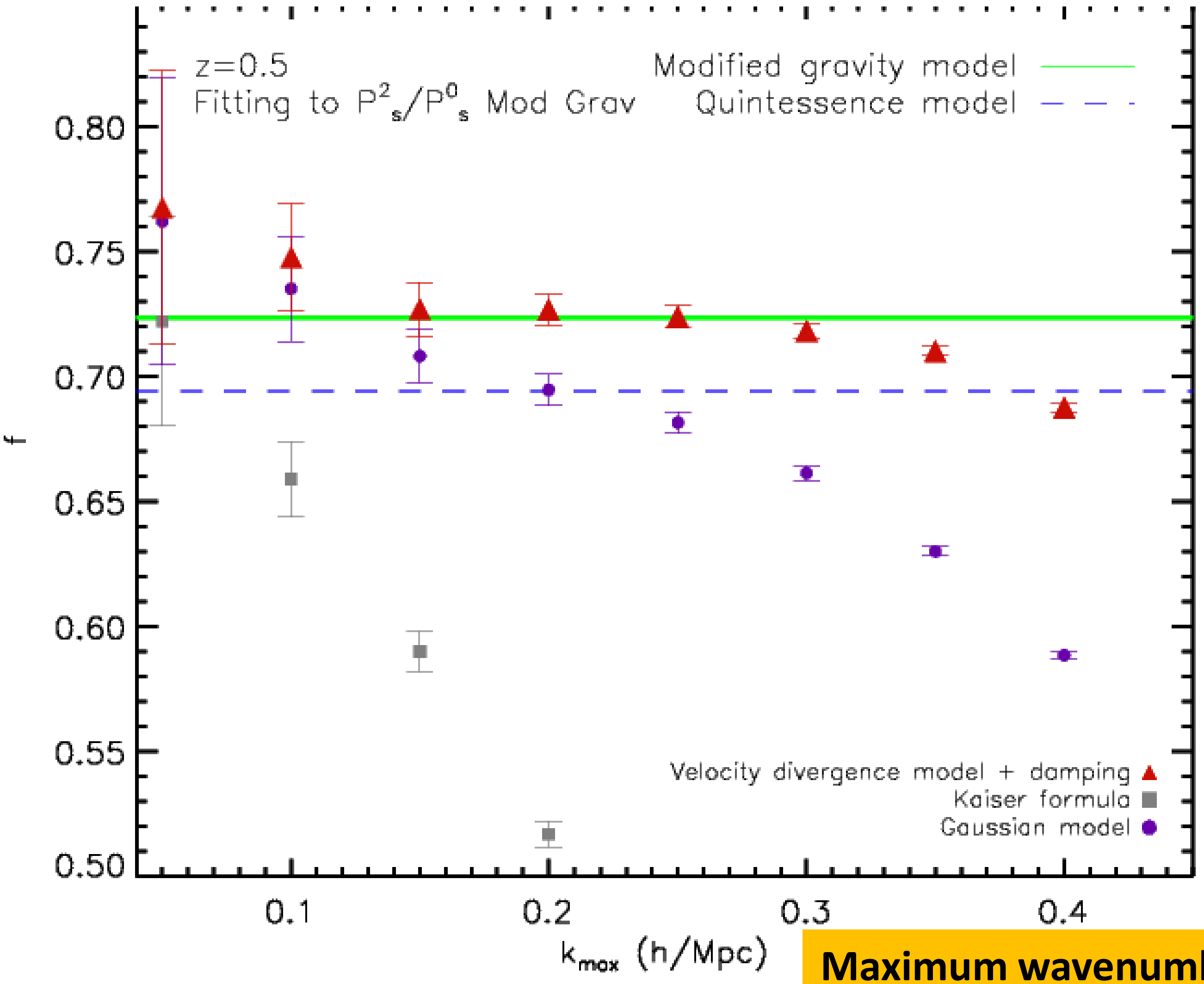


$$P_0^s(k) = P_{\delta\delta}(k) + \frac{2}{3} f P_{\delta\theta}(k) + \frac{1}{5} f^2 P_{\theta\theta}(k)$$

Including velocity dispersion

Jennings et al 2010 arXiv:1003.4282

Impact on recovered growth factor



Growth factor

Maximum wavenumber used in fit

Summary

- Linear perturbation theory is not accurate enough even on surprisingly large scales
- Simulations DM + galaxies reveal: scale dependent bias and scale dependent redshift space distortions
- Quintessence simulations:
  - alter expansion rate
  - early dark energy: change linear P(k) shape
  - alter best fit parameters for consistency with obs.
- BAO (and mass function) cannot distinguish all quintessence models from cosmological constant
- Redshift space distortions more complicated than generally thought – but better models do exist

"QUICC" Quintessence at the ICC

L-Gadget2 (Springel 2005)

N_p = 2.69 x 10^8 particles
L_{box} = 1500 h^{-1} Mpc

Softening: ϵ=50 h^{-1} kpc
Starting redshift: z_i =200

Mass resolution:
M_p=9.067 x 10^{11} $h^{-1}M_\odot$
r_{mean} ~2.3 h^{-1} Mpc

ΛCDM Cosmological parameters (A. Sánchez at al. 2009)

$$\Omega_m = 0.261 \qquad \Omega_B = 0.044$$
$$h = 0.715 \qquad n_s = 0.96$$
$$\sigma_8 = 0.8$$