Title: Early Dark Energy

Date: Oct 28, 2008 02:00 PM

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Abstract: The Dark Energy might constitute an observable fraction of the total energy density of our Universe as far back as the time of matter radiation equality or even big bang nucleosynthesis. In this talk, I will review the cosmological implications of such an \'Early Dark Energy\' component, and discuss how it might - or might not - be detected by observations. In particular, I will show how assuming the early dark energy to be negligible will bias the interpretation of cosmological data.

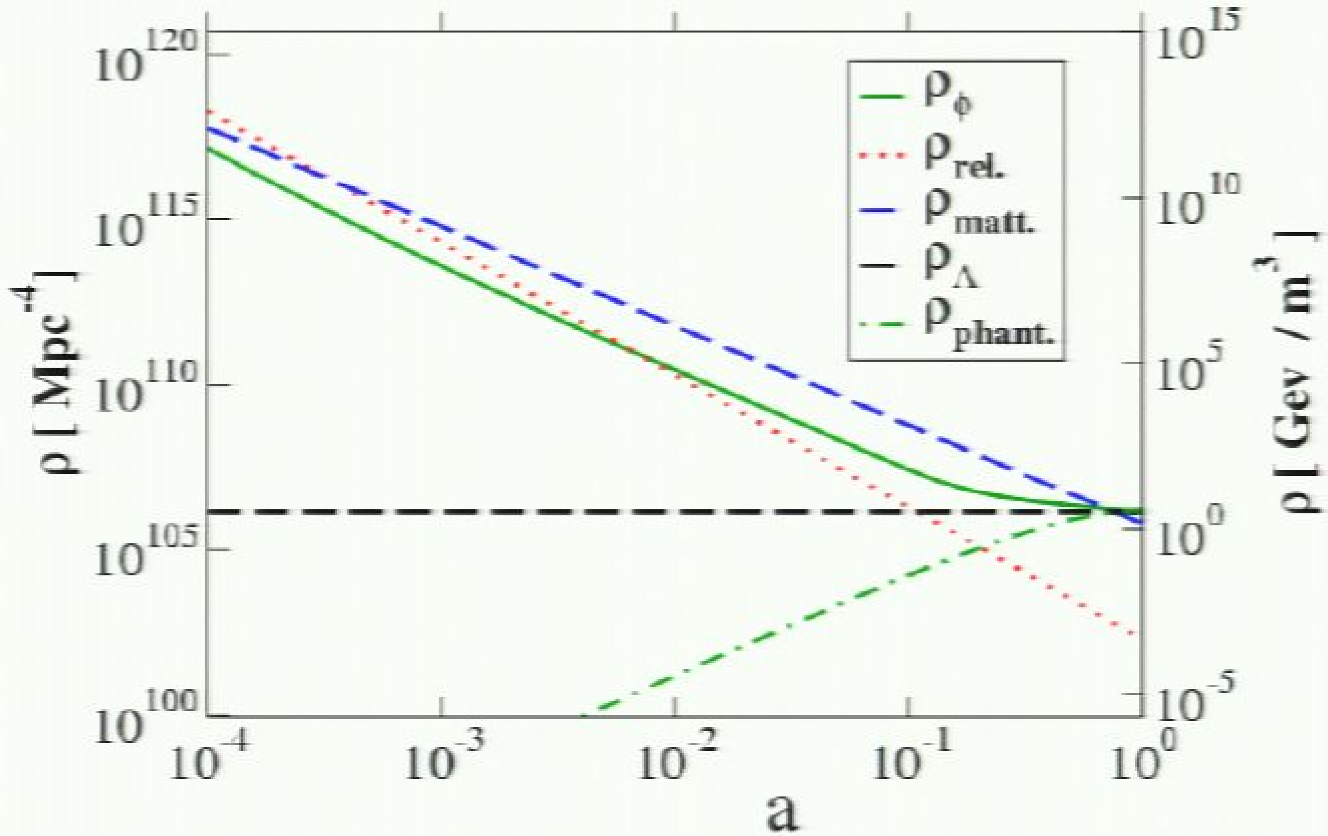
Early Dark Energy

Georg Robbers

Institut für Theoretische Physik, Uni Heidelberg

Perimeter Institute, Oct 28, 2008

energy densities



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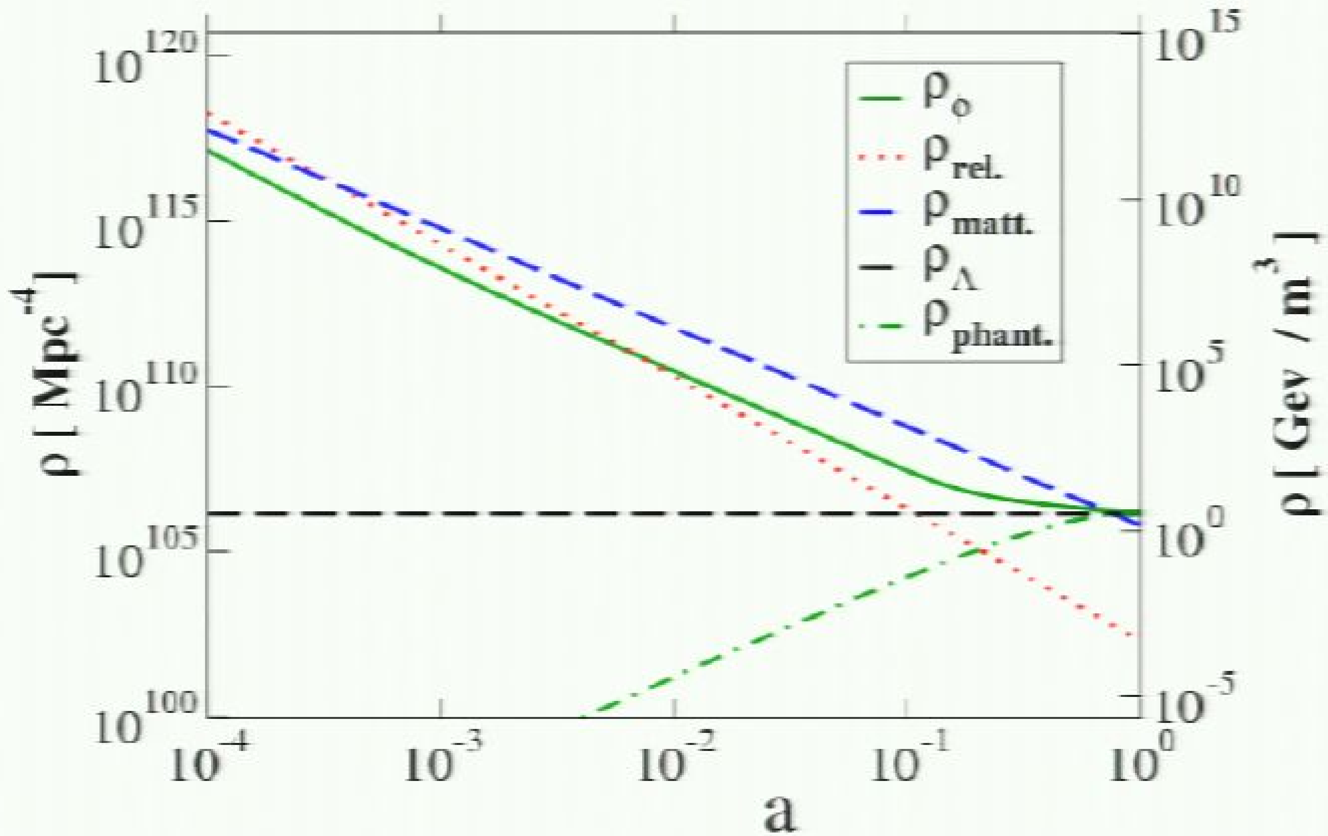

exponential potential

- scalar field, exponential potential, $V(\phi) = M^4 exp(-\alpha \frac{\phi}{M})$
- $\Omega_{de}^{early} = \frac{n}{\alpha^2}$, $n = 3(4)$ for matter (radiation) domination
- how to get out of attractor?

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Growing Neutrinos

Amendola, Baldi, Wetterich 2007

Ingredients:

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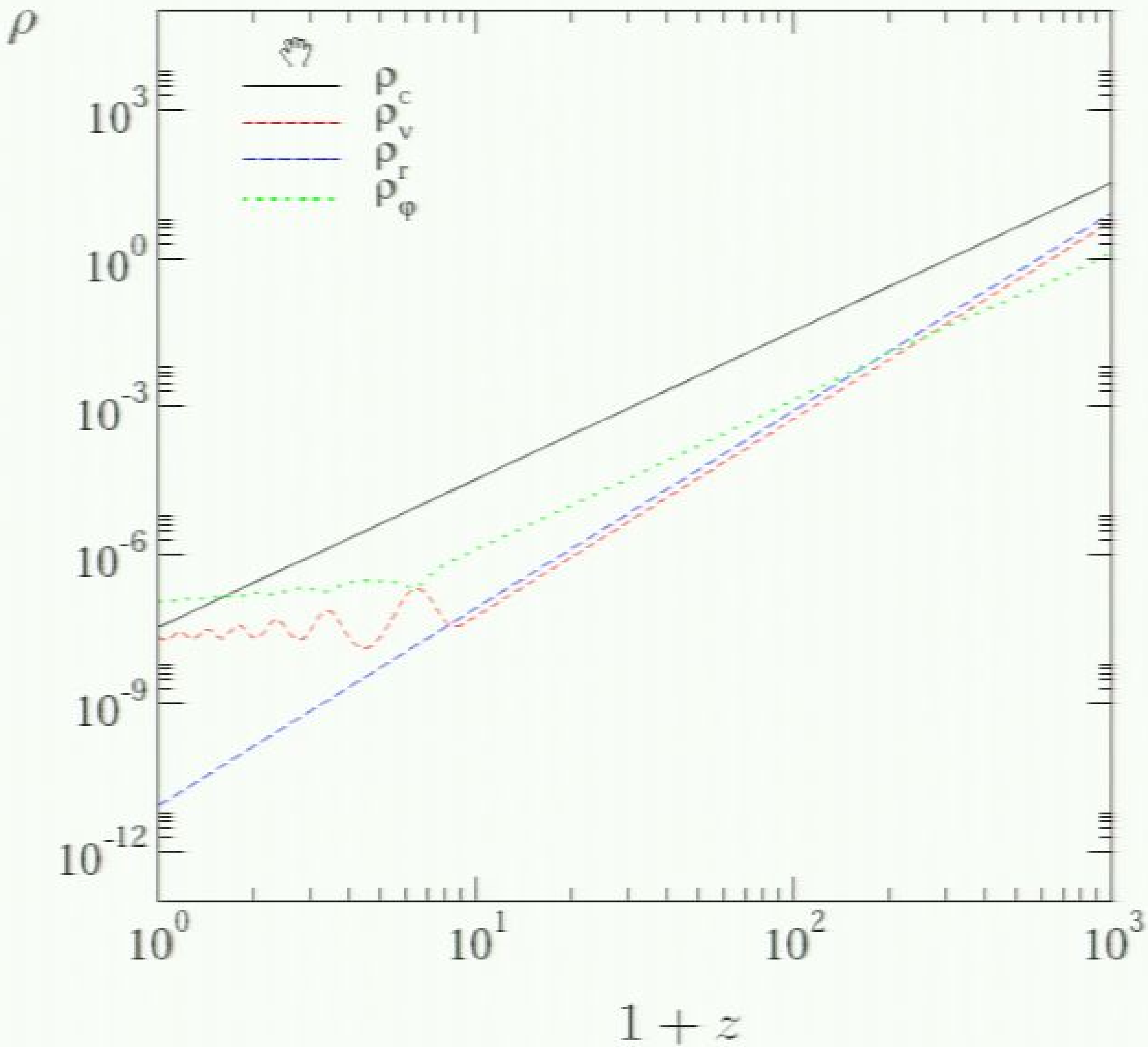

background evolution for constant $\beta = -52$ $\alpha = 10$ and large neutrino mass $m_\nu = 2.11\,eV$

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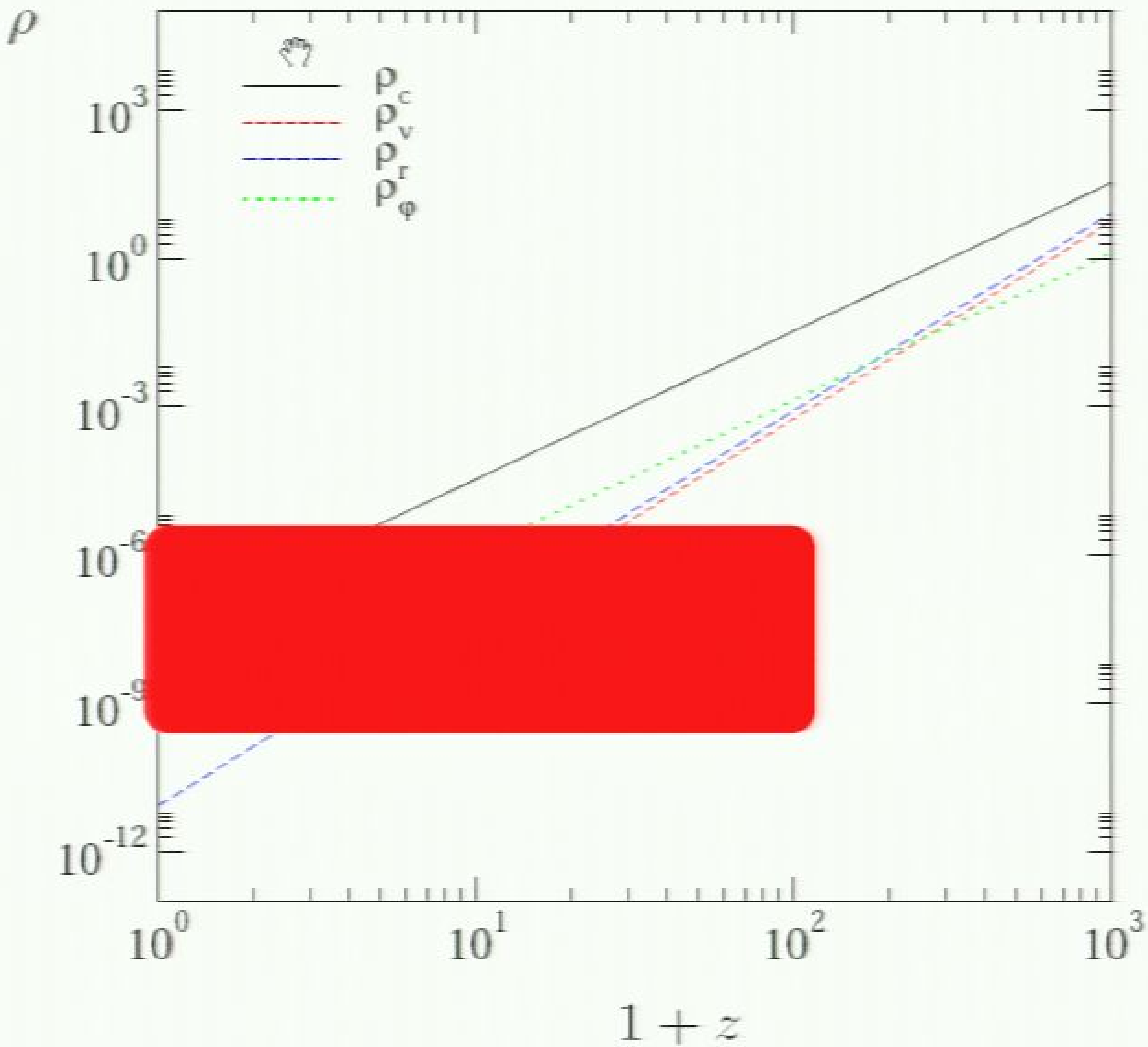

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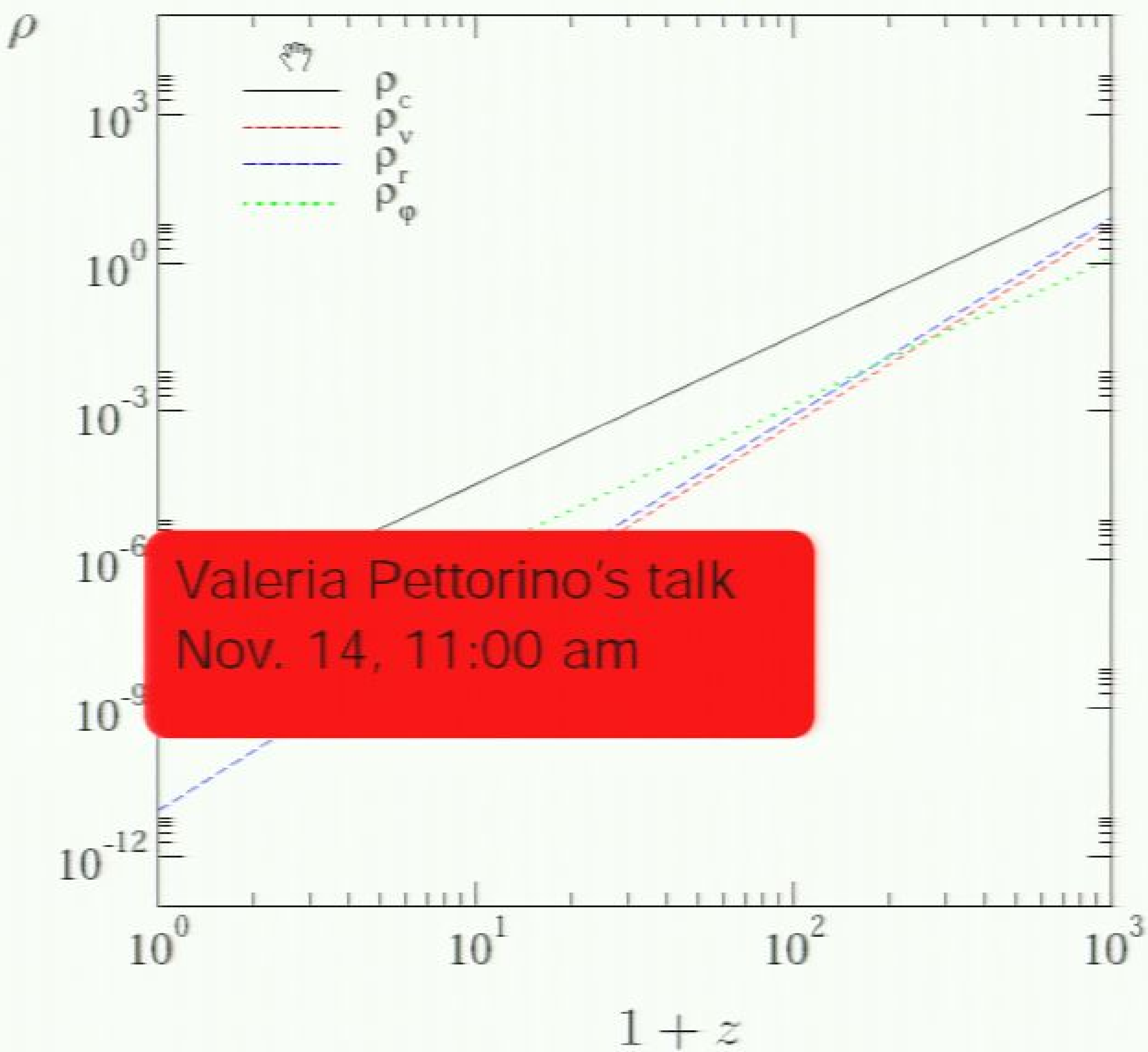
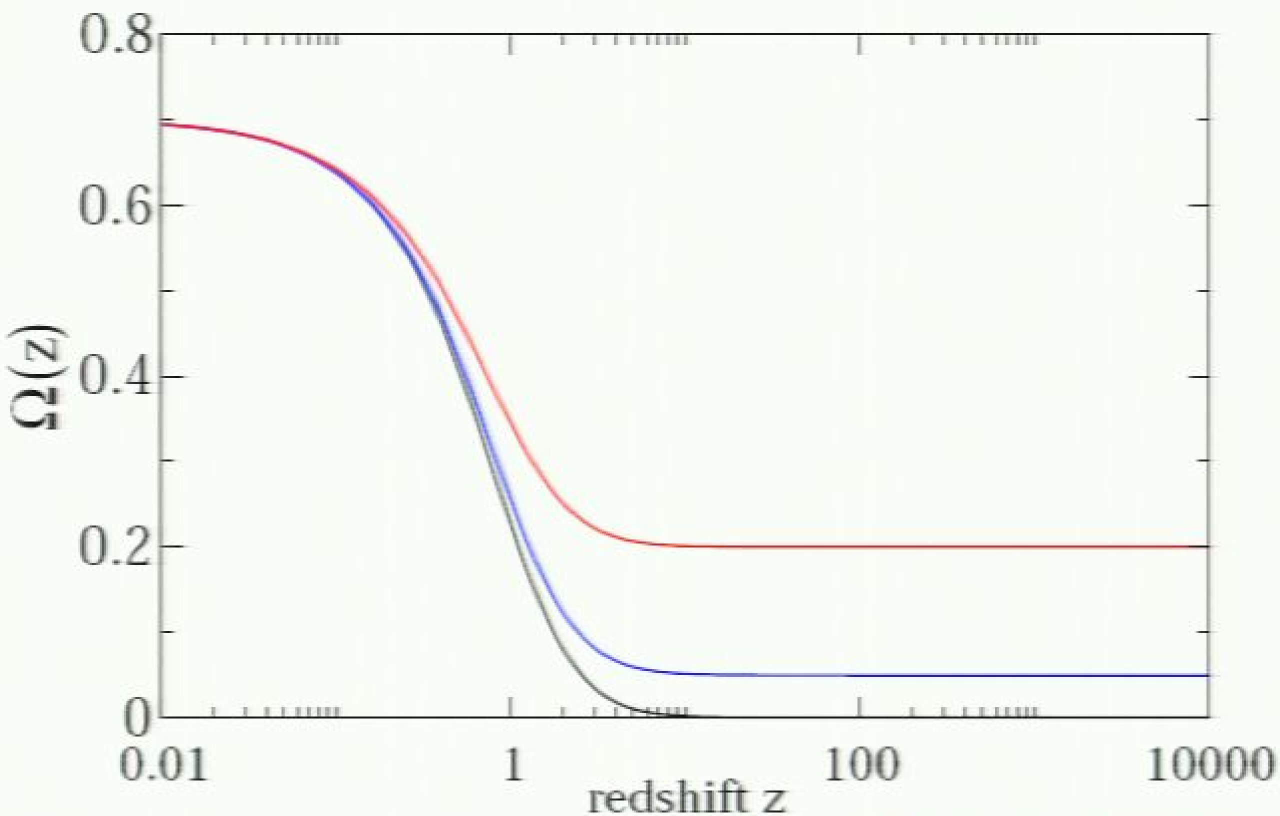


background evolution for constant $\beta = -52$ $\alpha = 10$ and large neutrino mass $m_\nu = 2.11\,eV$

One Model of Early Dark Energy

$$\Omega_{de}(a) = \frac{\Omega_{de}^0 - (1 - a^{-3w_0})\Omega_{de}^{early}}{\Omega_{de}^0 + (1 - \Omega_{de}^0)a^{3w_0}} + \Omega_{de}^{early}(1 - a^{-3w_0})$$



M. Doran and GR, JCAP 0606 (2006) 026

geometric distances

- horizon

$$\tau_0 \approx \frac{2}{H_0\sqrt{\Omega_m}}\, {}_2F_1\left(\frac{1}{2}, -\frac{1}{6w_0}; 1-\frac{1}{6w_0}; -\frac{\Omega^0_{de}}{\Omega_m}\right)$$
$$-C(w_0)\frac{2\Omega^{early}_{de}}{H_0\sqrt{\Omega_m}}\, {}_2F_1\left(\frac{1}{2}, -\frac{1}{6w_0}; 3-\frac{1}{6w_0}; -\frac{\Omega^0_{de}}{\Omega_m}\right)\frac{1}{\left(2-\frac{1}{6w_0}\right)\left(1-\frac{1}{6w_0}\right)}$$

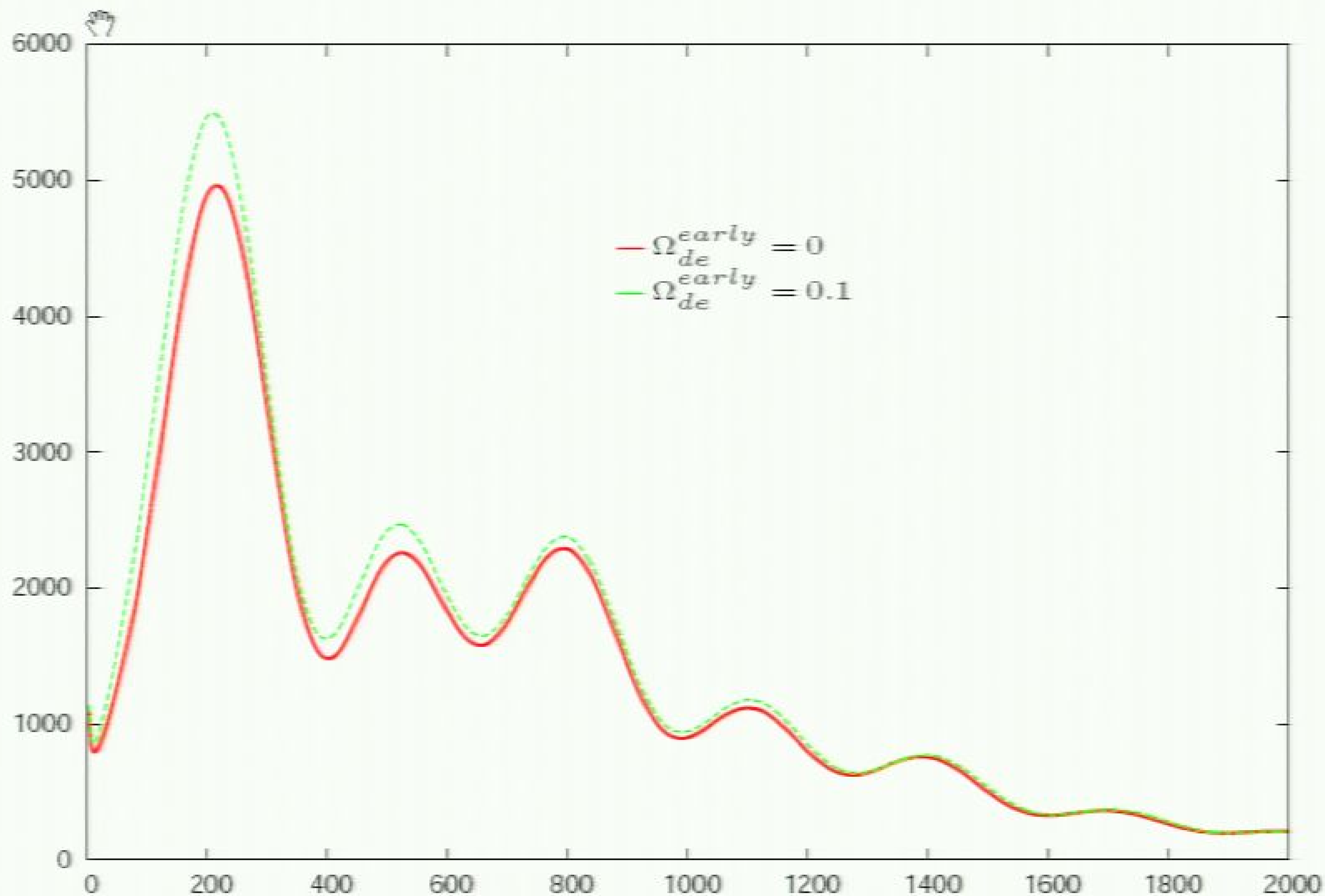
- last scattering

$$\tau_{ls} = \frac{2}{H_0}\left(\frac{1-\Omega^{early}_{de}}{\Omega^0_m}\right)^{1/2}\left[\sqrt{a_{ls}+\frac{\Omega_{rel}}{\Omega^0_m}} - \sqrt{\frac{\Omega_{rel}}{\Omega^0_m}}\right]$$

- sound horizon

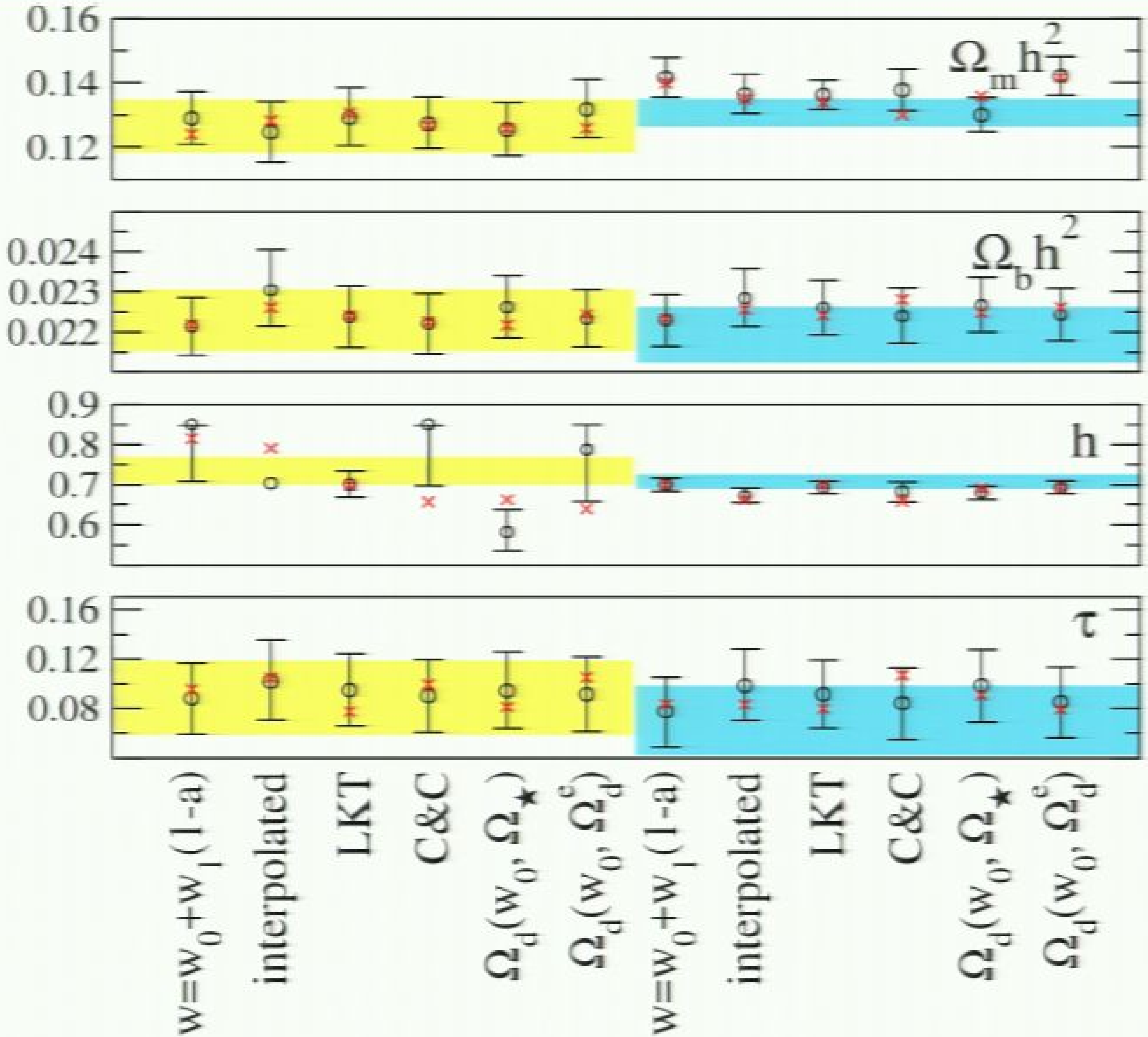
$$s_*(\Omega^{early}_{de}) = \sqrt{1-\Omega^{early}_{de}}\; s_*(\Omega^{early}_{de} \approx 0)$$

CMB spectra



$\Omega_{de}^{early} = 0$
$\Omega_{de}^{early} = 0.1$
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000

WMAP 3-year



0.16
0.14
0.12
$\Omega_m h^2$
0.024
0.023
0.022
$\Omega_b h^2$
0.9
0.8
0.7
0.6
h
0.16
0.12
0.08
τ
$w=w_0+w_1(1-a)$
interpolated
LKT
C&C
$\Omega_d(w_0, \Omega_\star)$
$\Omega_d(w_0, \Omega_d^e)$
$w=w_0+w_1(1-a)$
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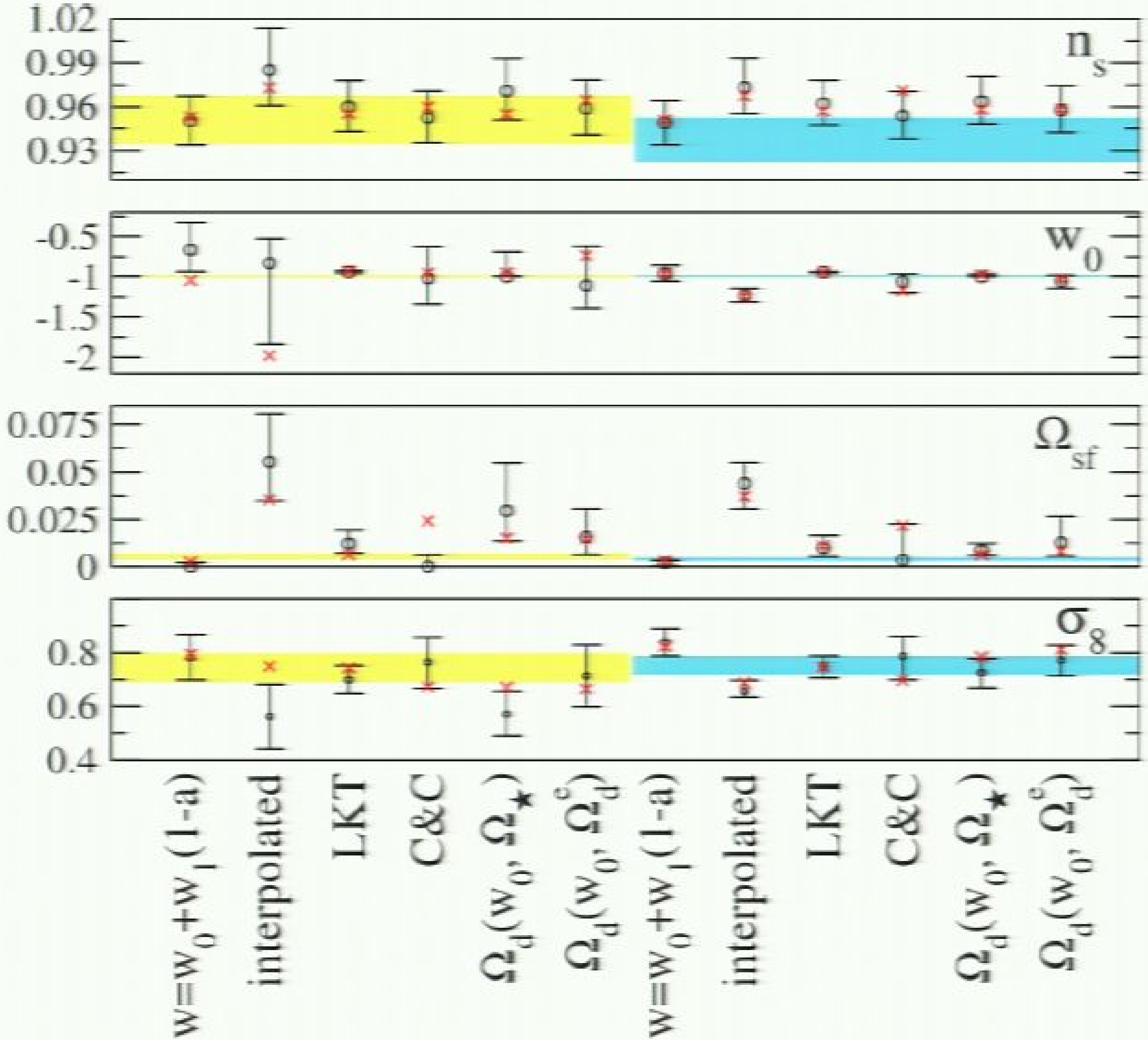

n_s
w_0
Ω_sf
σ_8
1.02
0.99
0.96
0.93
-0.5
-1
-1.5
-2
0.075
0.05
0.025
0
0.8
0.6
0.4
w=w_0+w_1(1-a)
interpolated
LKT
C&C
Ω_d(w_0, Ω_★)
Ω_d(w_0, Ω_d^e)
w=w_0+w_1(1-a)
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Ω_d(w_0, Ω_d^e)

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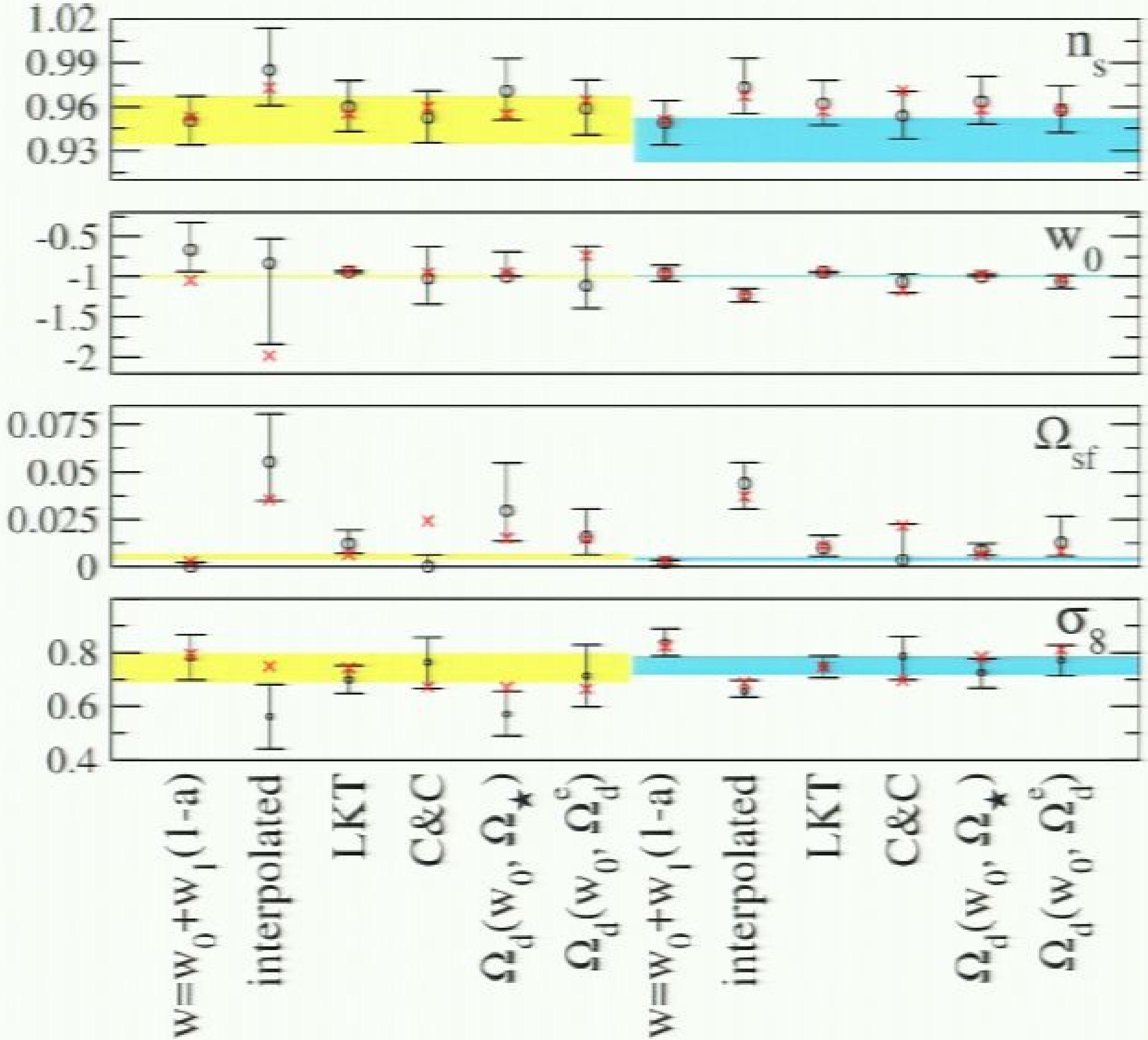

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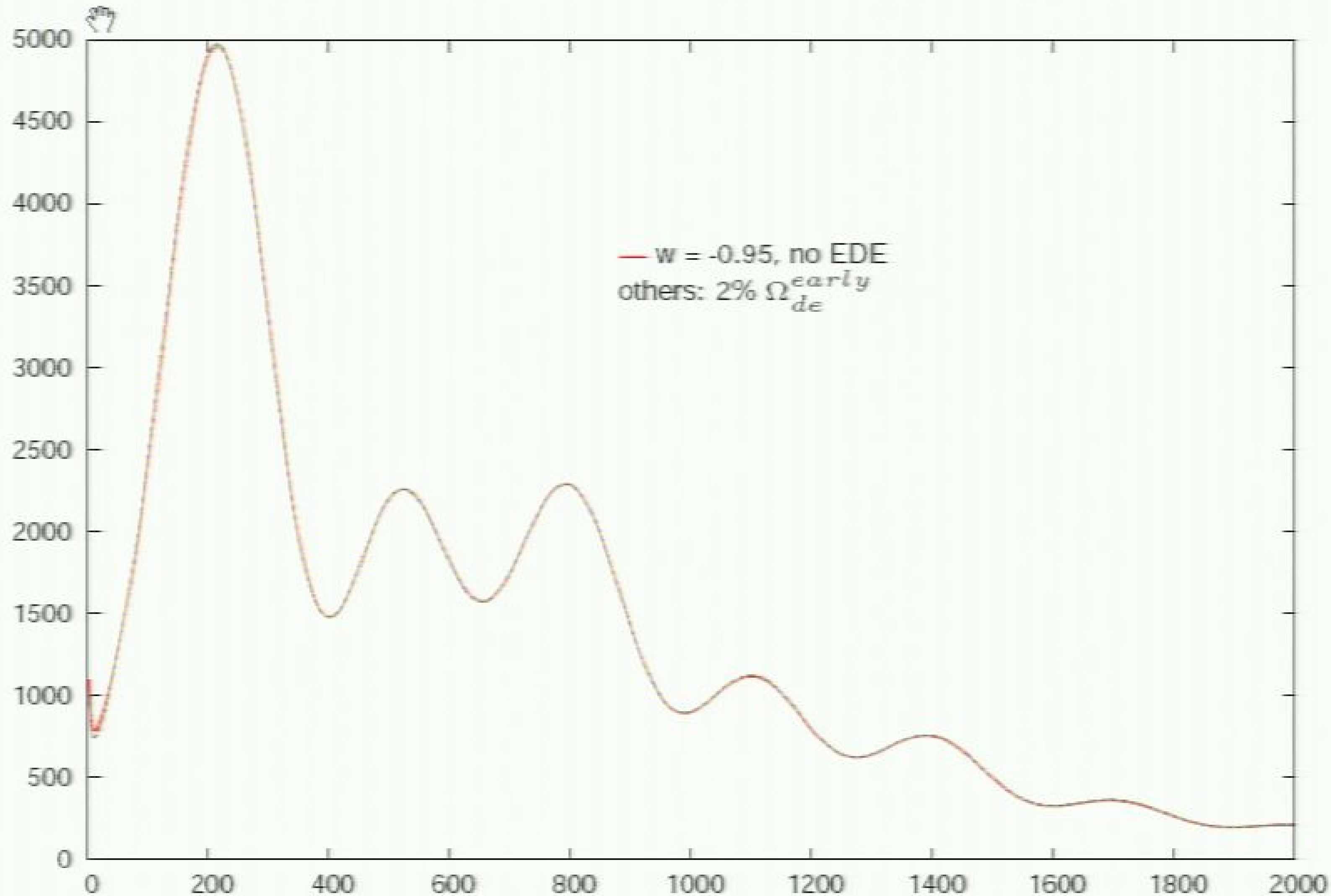
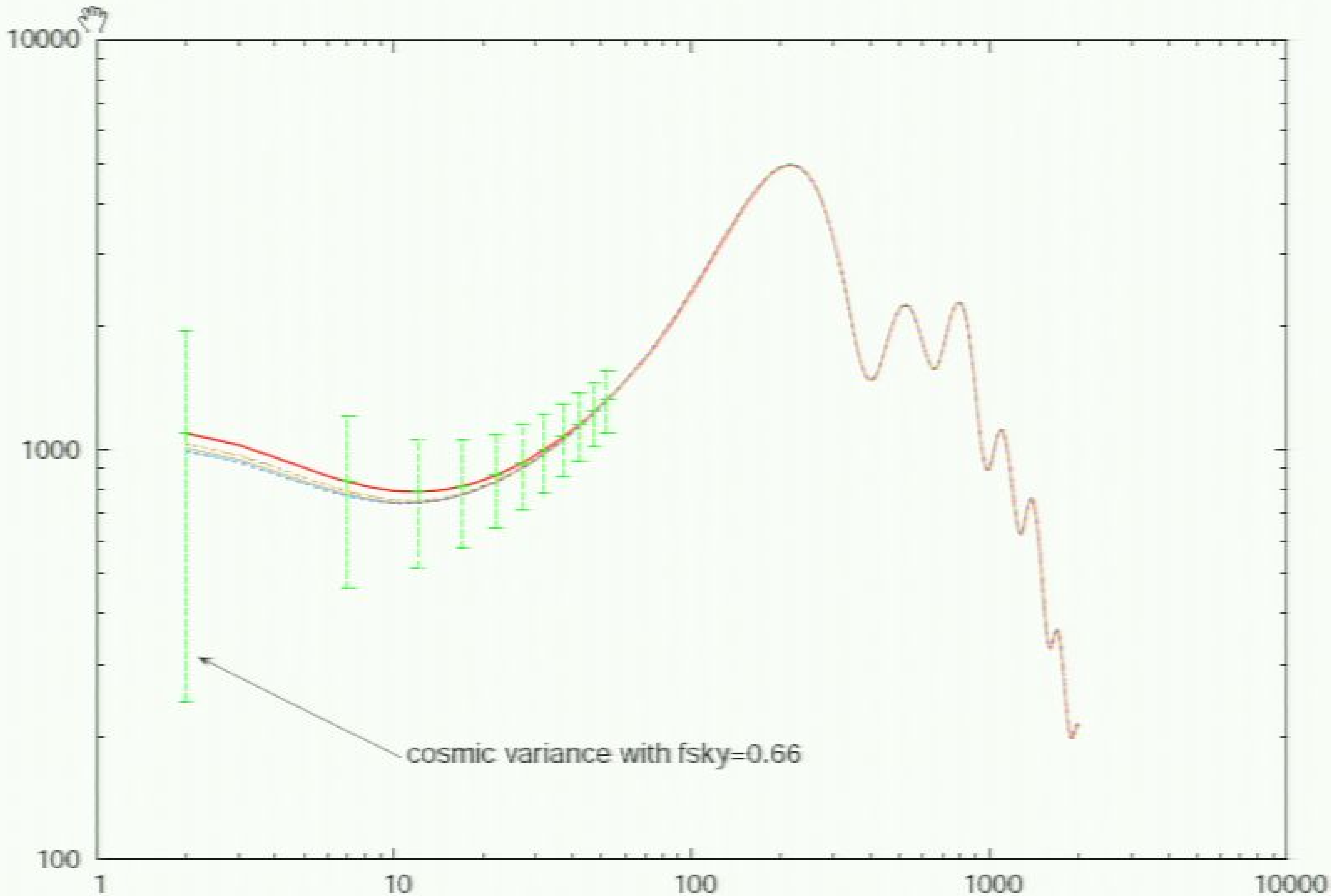


5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
— w = -0.95, no EDE
others: 2% Ω_{de}^{early}

CMB spectra

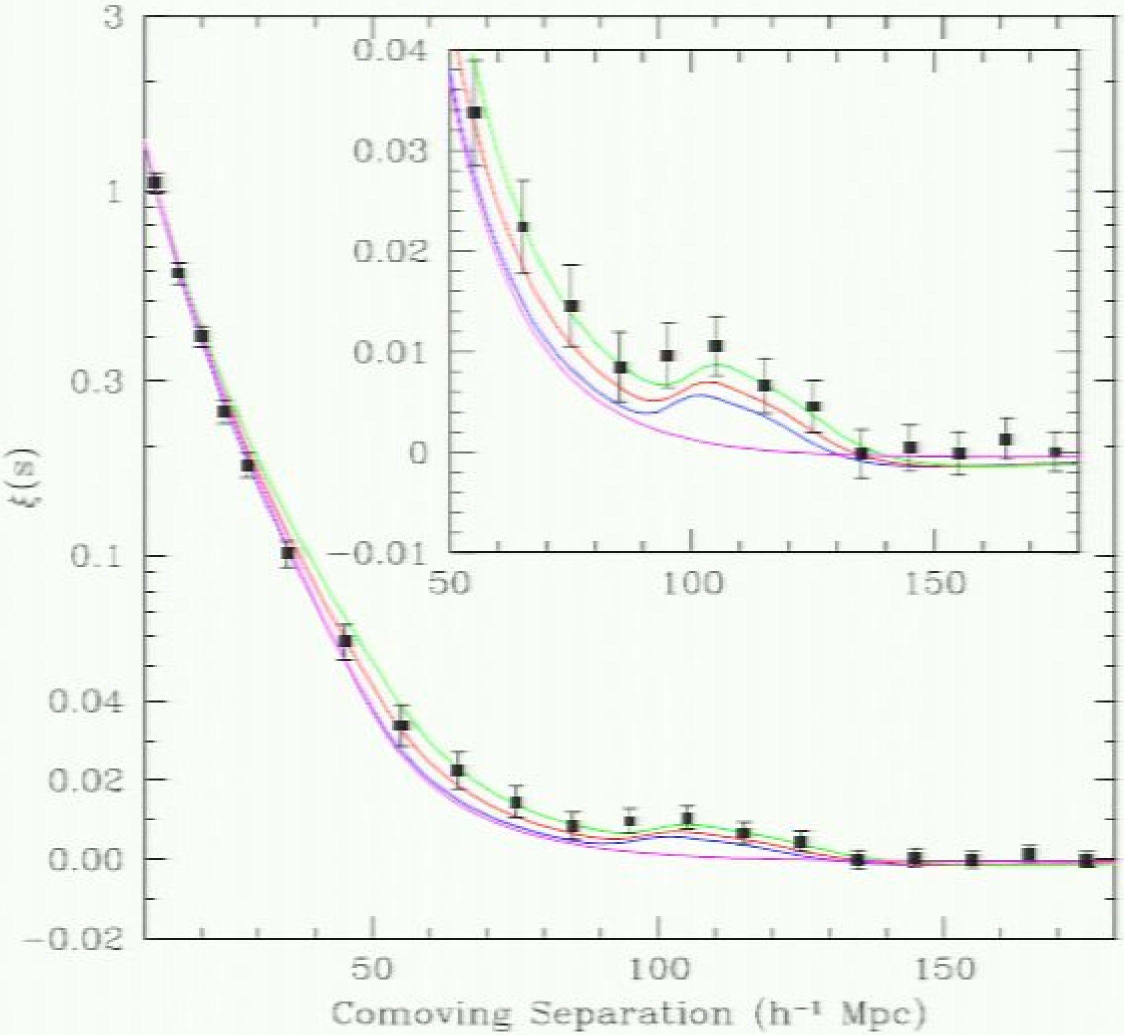


10000
1000
100
1
10
100
1000
10000
cosmic variance with fsky=0.66

Baryon accoustic oscillations

Baryon accoustic oscillations

Eisenstein et al. '05, arXiv:astro-ph/0501171v1



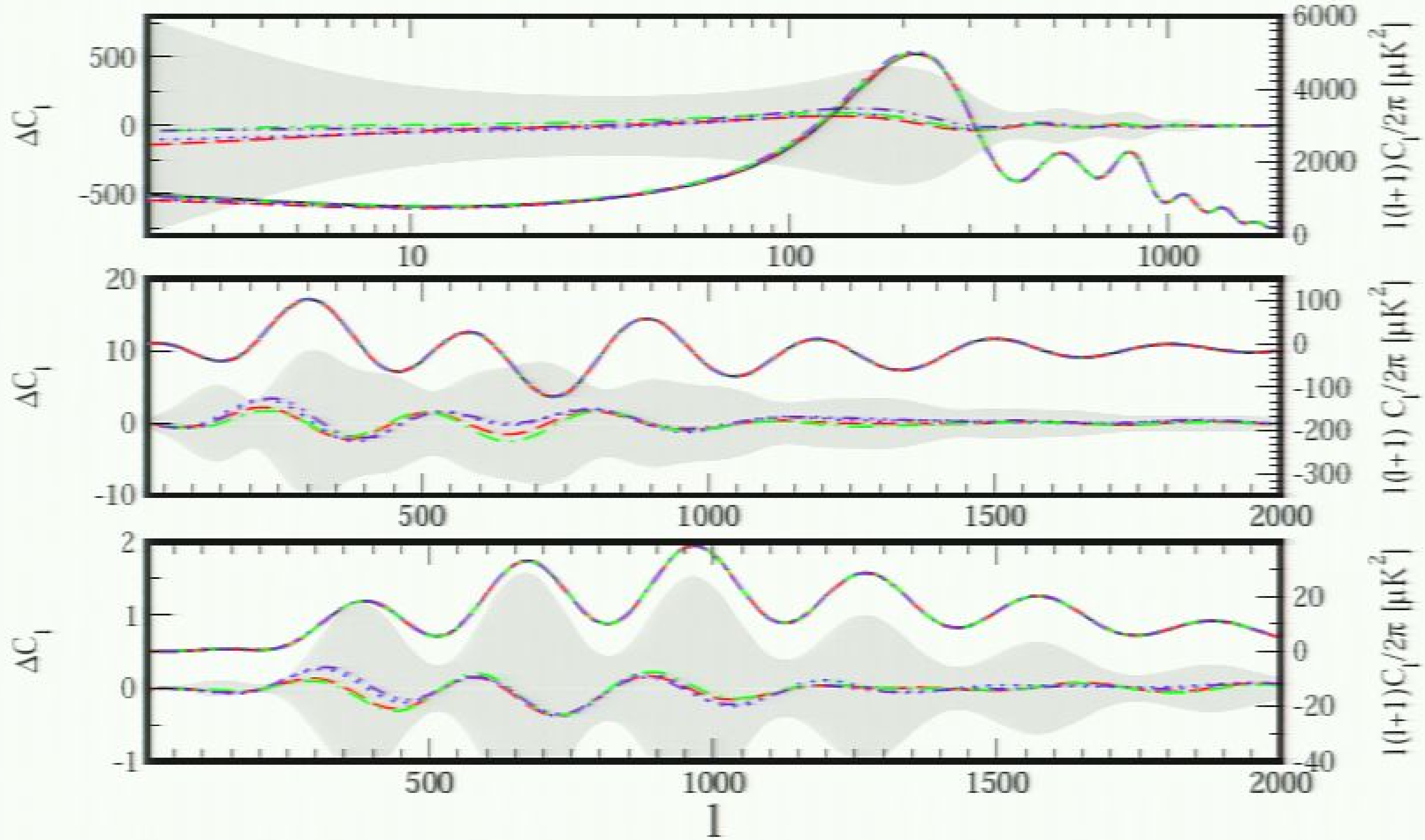
EDE and BAO measurements E. V. Linder & GR, 08

What happens if we assume a wrong cosmology?

- take a fiducial $(w_0 = -0.95, w_a = -0.1)$ cosmology, no EDE
- can we really match CMB spectra?

EDE and BAO measurements E. V. Linder & GR, 08

Yes, we can:



EDE and BAO measurements

E. V. Linder & GR, 08

- Accoustic peak measures geometric shift factor, i.e. $d_{\rm lss}/s$
- compare cmb-spectra of $\Omega_{de}^{early} = 0.03$ cosmologies to fiducial $(w_0 = -0.95, w_a = -0.1)$ model

$$w(a) = w_0 + w_a(1 - a)$$

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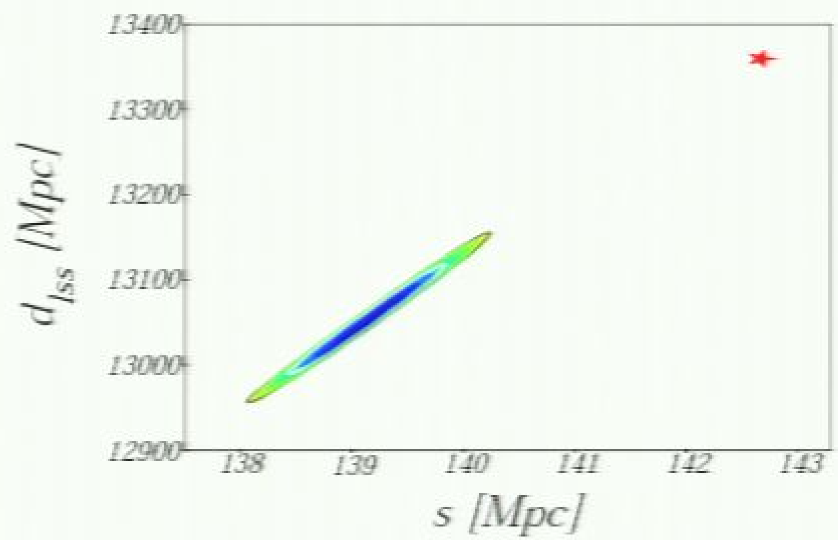

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- CMB data from Planck

EDE and BAO measurements

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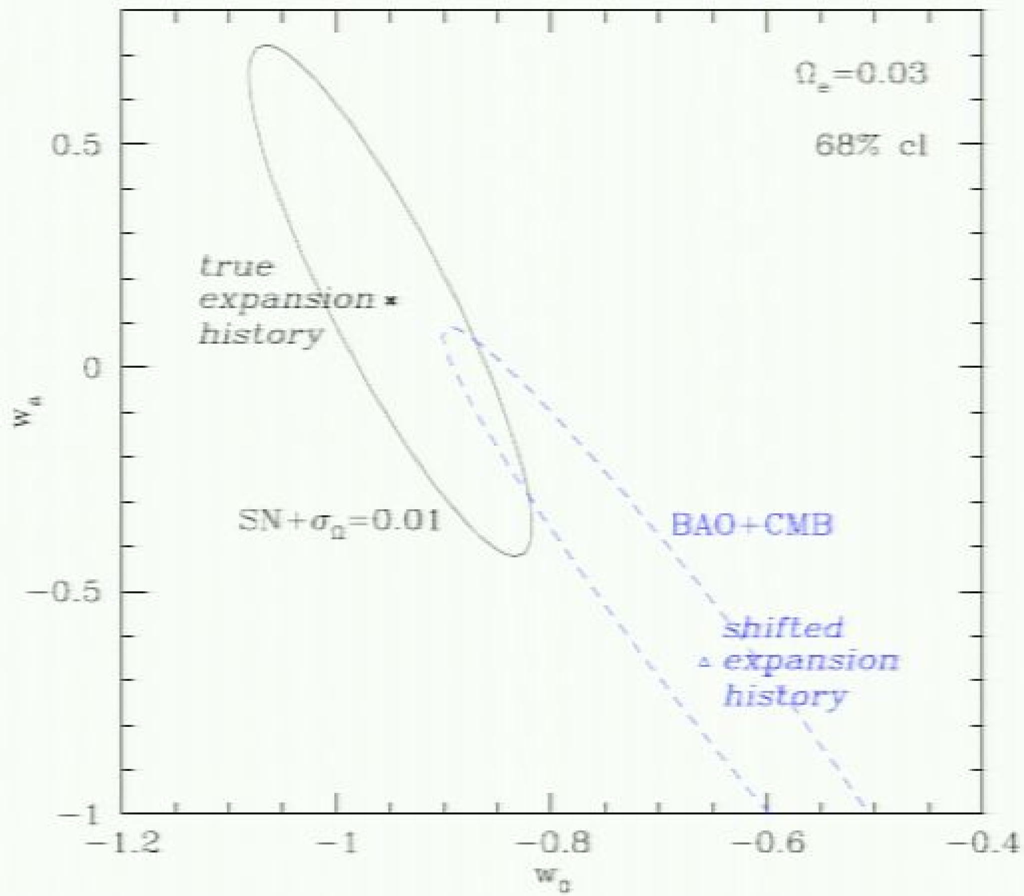

EDE and BAO measurements E. V. Linder & GR, 08

Possible way out:

- introduce calibration parameter S

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EDE and BAO measurements E. V. Linder & GR, 08

Possible way out:

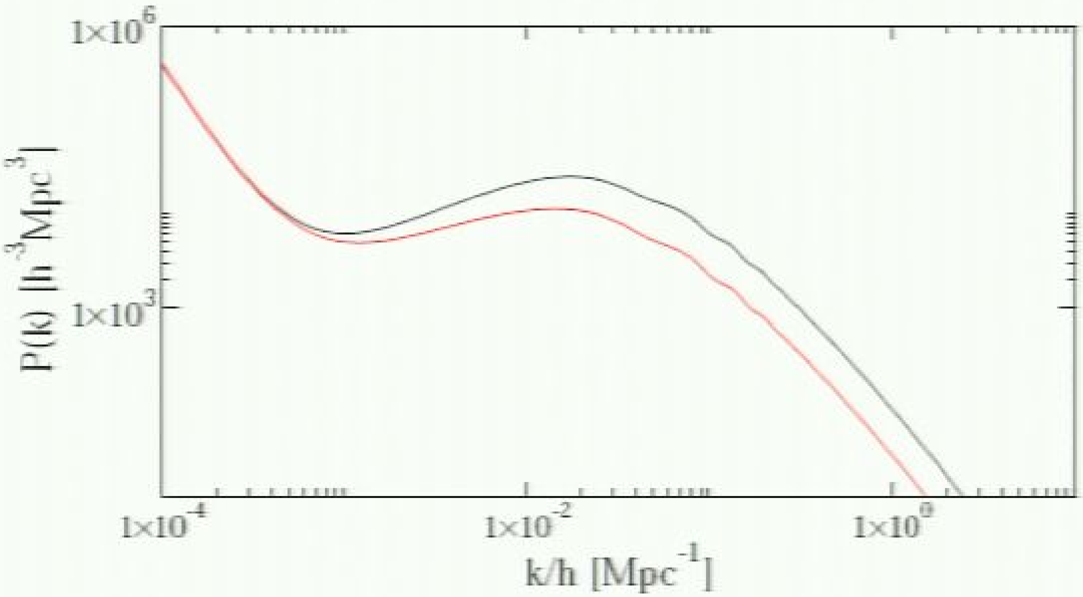
- introduce calibration parameter $\mathcal{S}$
- decrease in the area "figure of merit" by a factor 2.3
- or prior constraint on $\mathcal{S}$ (to better than 0.5%)

Effects on Structure Formation

Effects on Structure

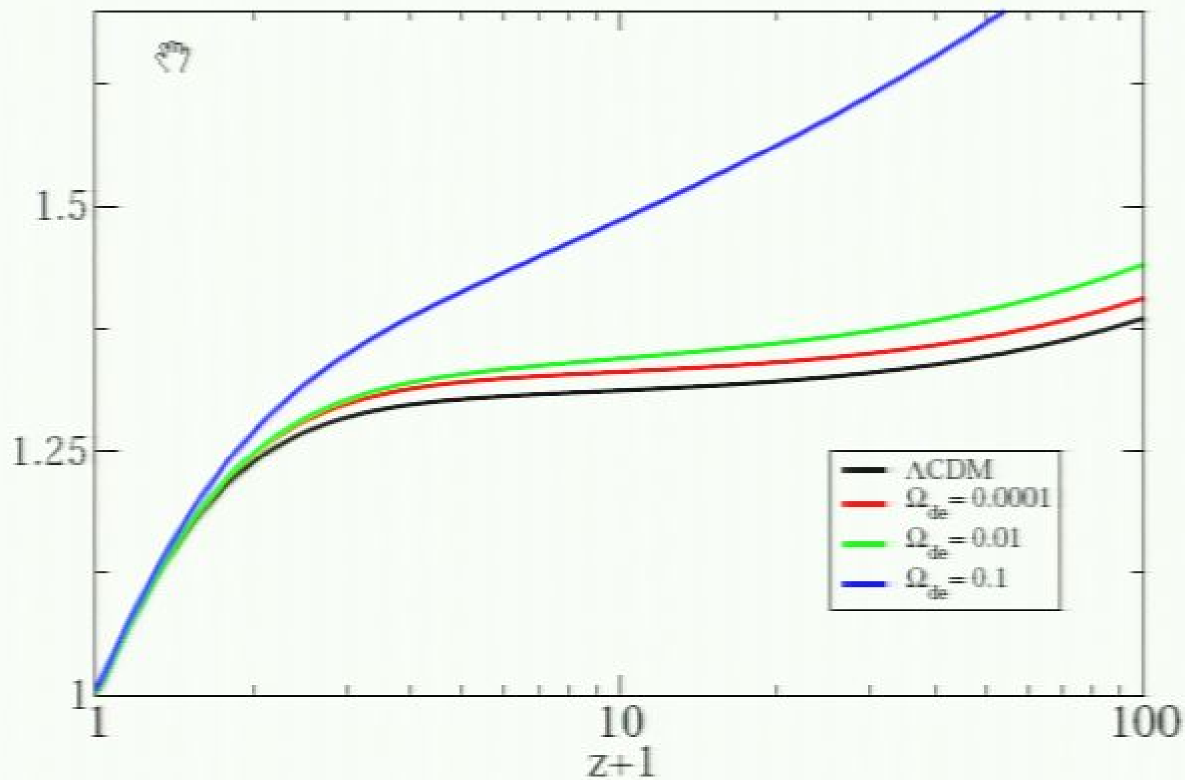
- linear structure growth is slowed

  Ferreira & Joyce '97, Schwindt '01, Doran et al. '01



- $\frac{\sigma_8(EDE)}{\sigma_8(noEDE)} \approx (a_{eq})^{3\Omega_{de}^{sf}/5}(1-\Omega_{de}^{early})^{-(1+\bar{w}^{-1})/5}\sqrt{\frac{\tau_0(EDE)}{\tau_0(noEDE)}}$
- Increase $\bar{\Omega}_{de}^{sf}$ by $0.1 \rightarrow \sigma_8 \searrow 50\%$

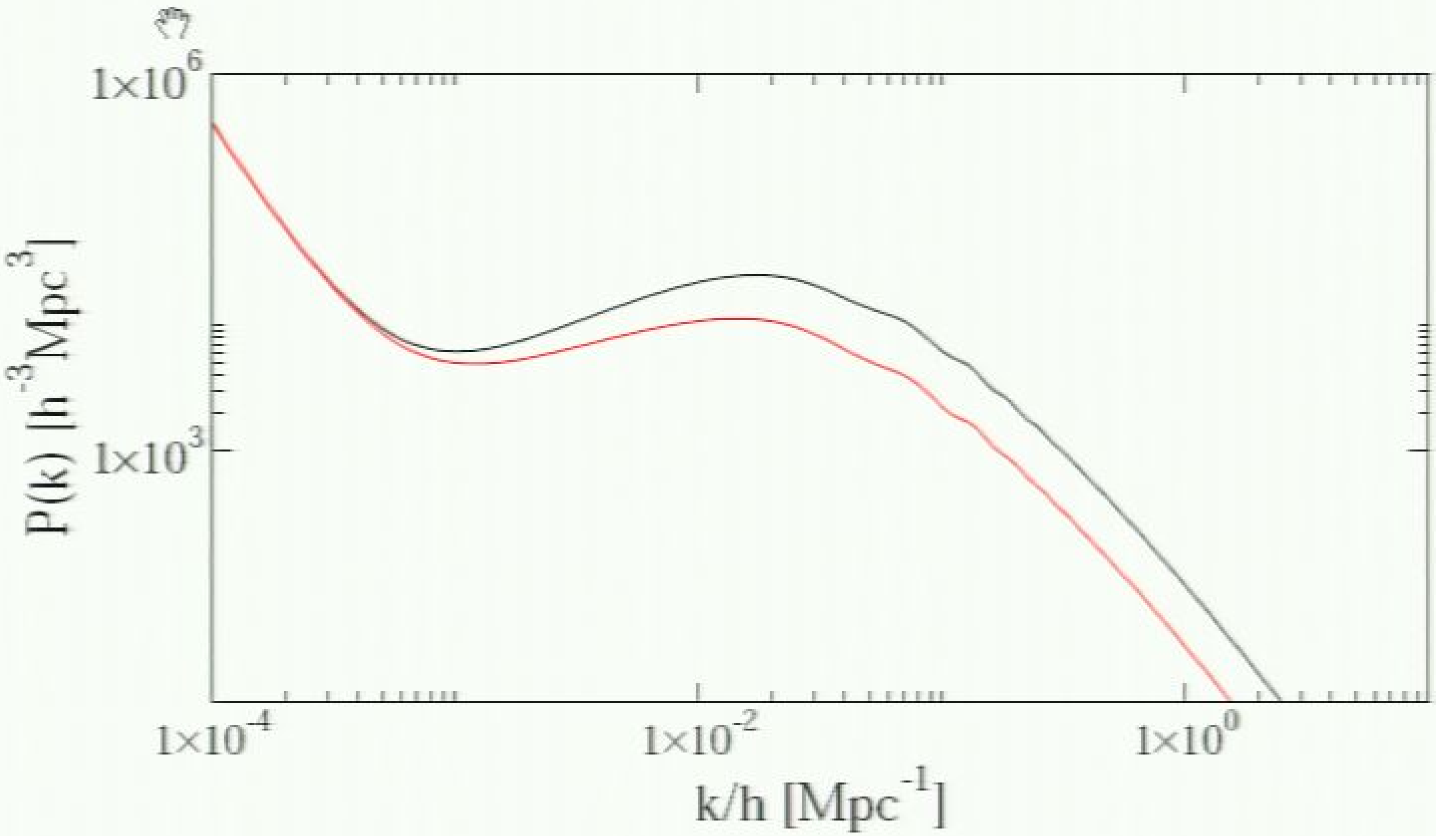
cdm-growthfactors



$$\ddot{\delta}_m + \frac{\dot{a}}{a}\dot{\delta}_m - \frac{3}{2}\left(\frac{\dot{a}}{a}\right)^2 \Omega_m \delta_m = 0$$

$$\delta_m \propto a^{[\sqrt{25-24\Omega_{de}}-1]/4} \approx a^{1-3\Omega_{de}/5}.$$

Ly-α-forest Afshordi et al., astro-ph/0702002



- linear powerspectrum amplitude and slope at $z \approx 3$, $k \simeq 1\mathrm{Mpc}^{-1}$

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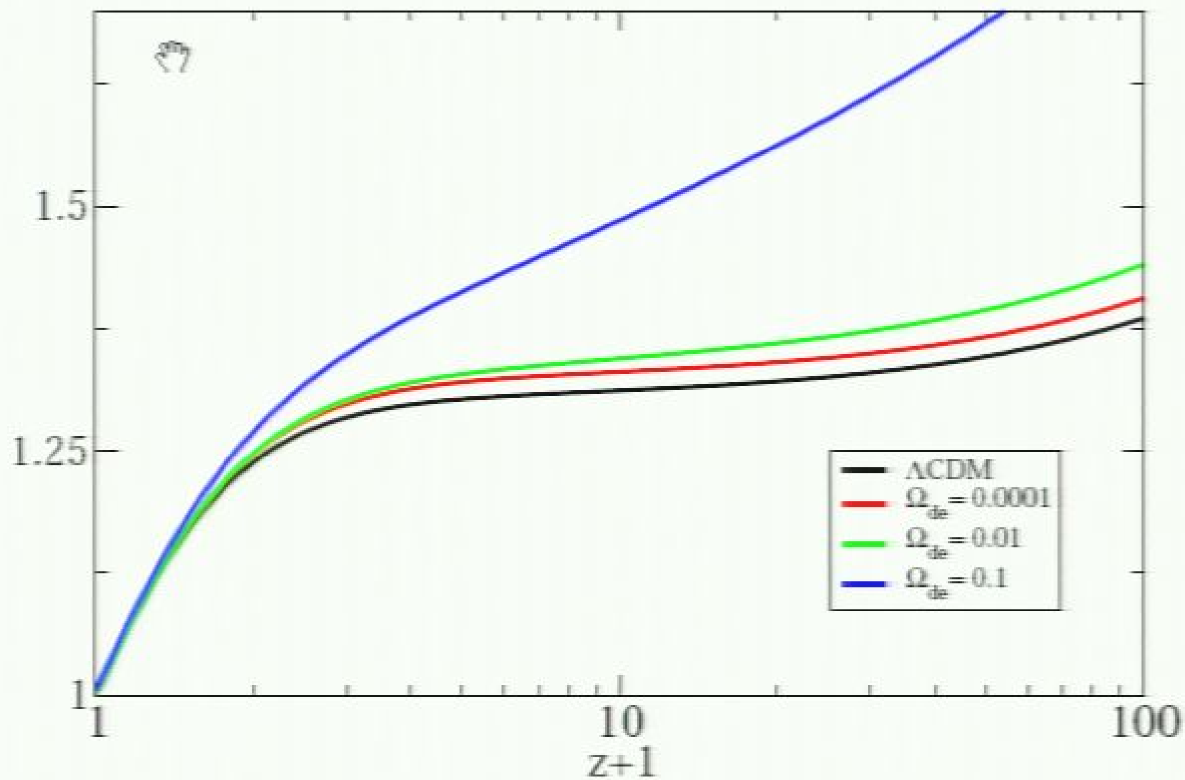

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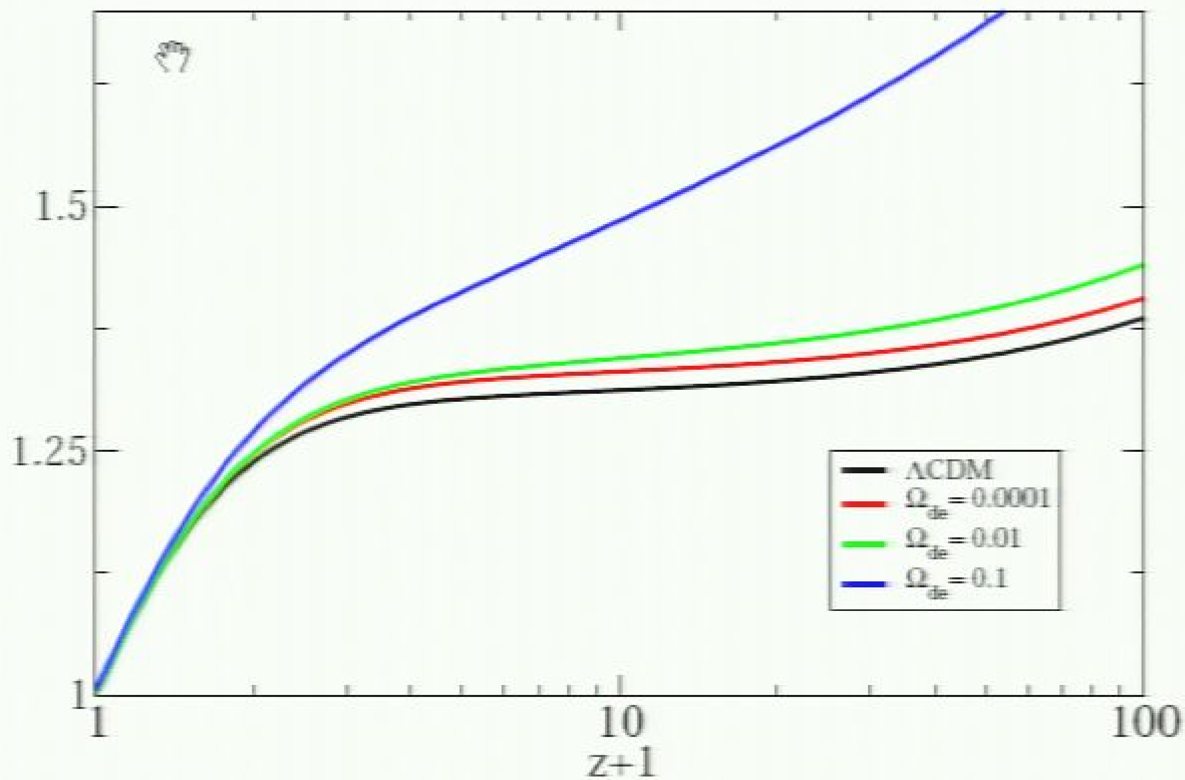

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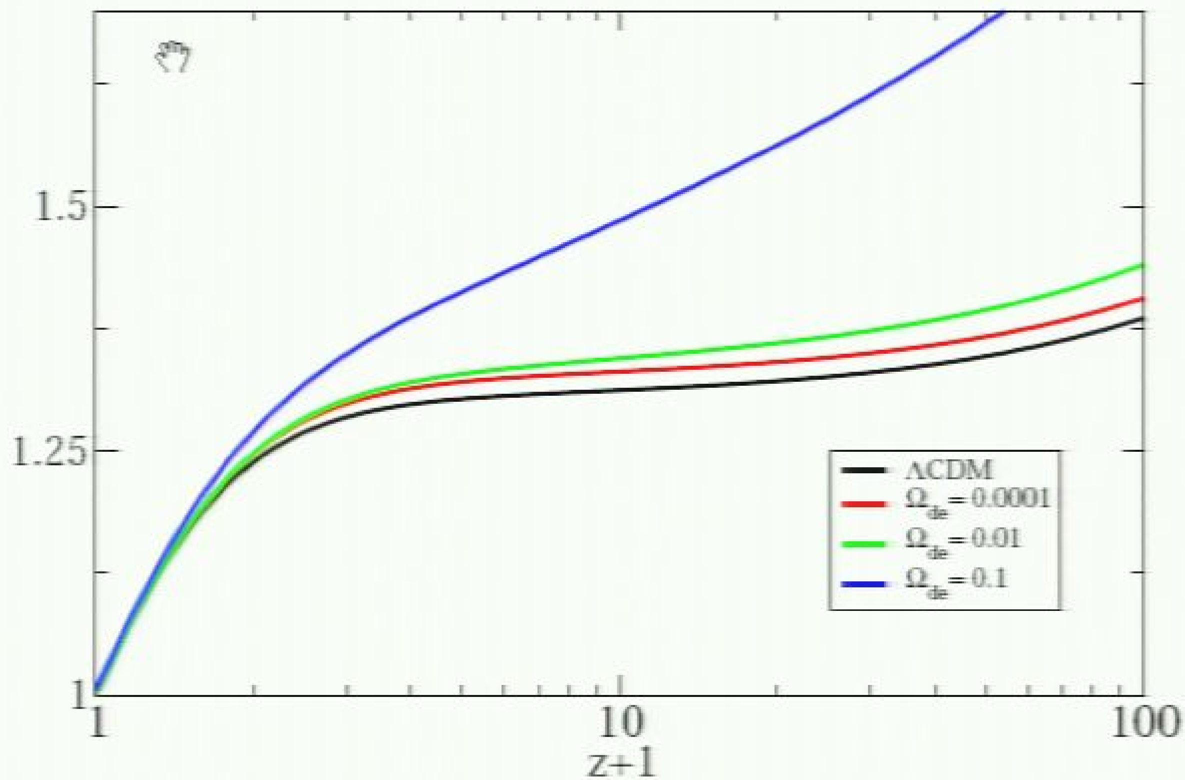

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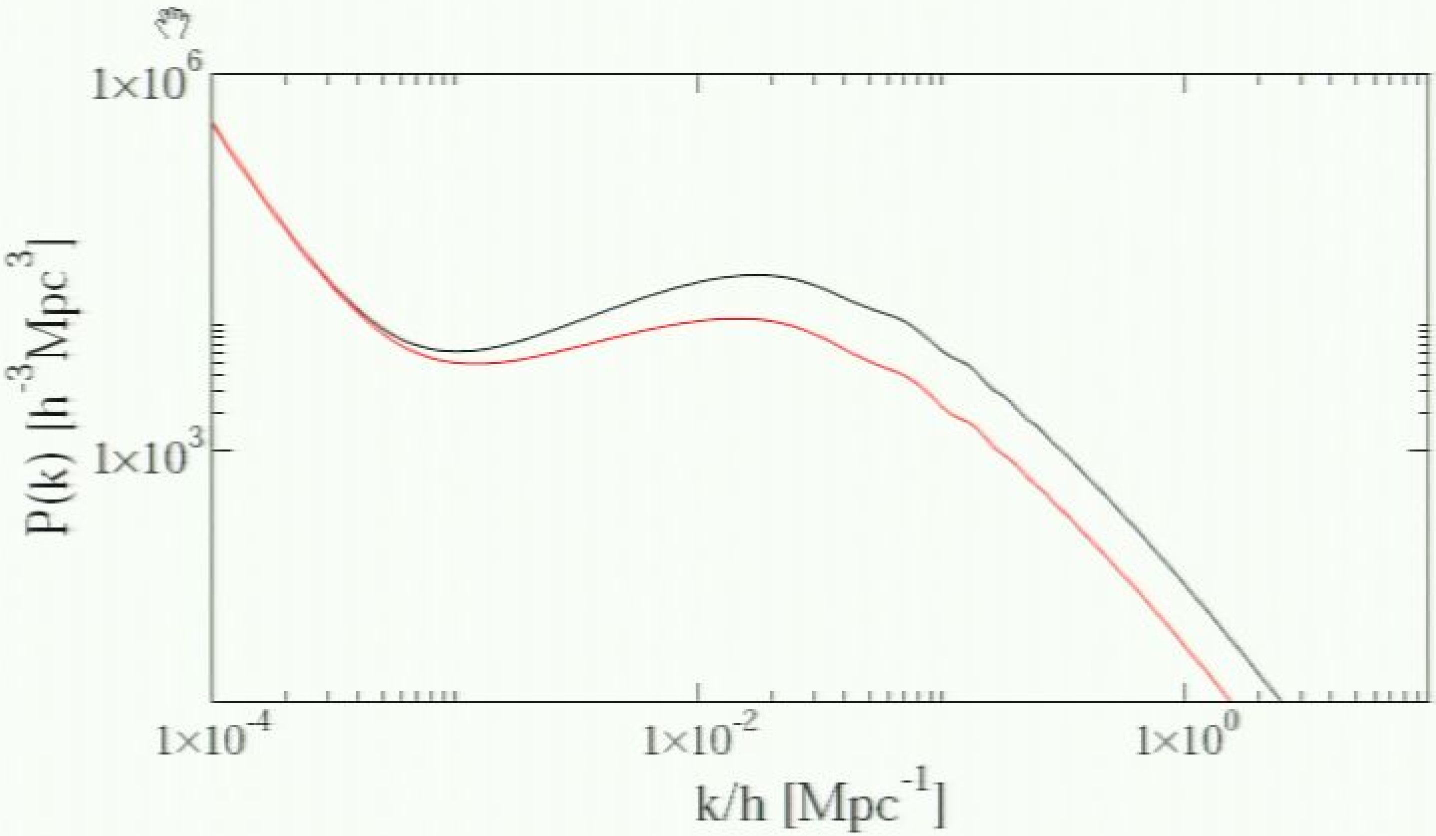

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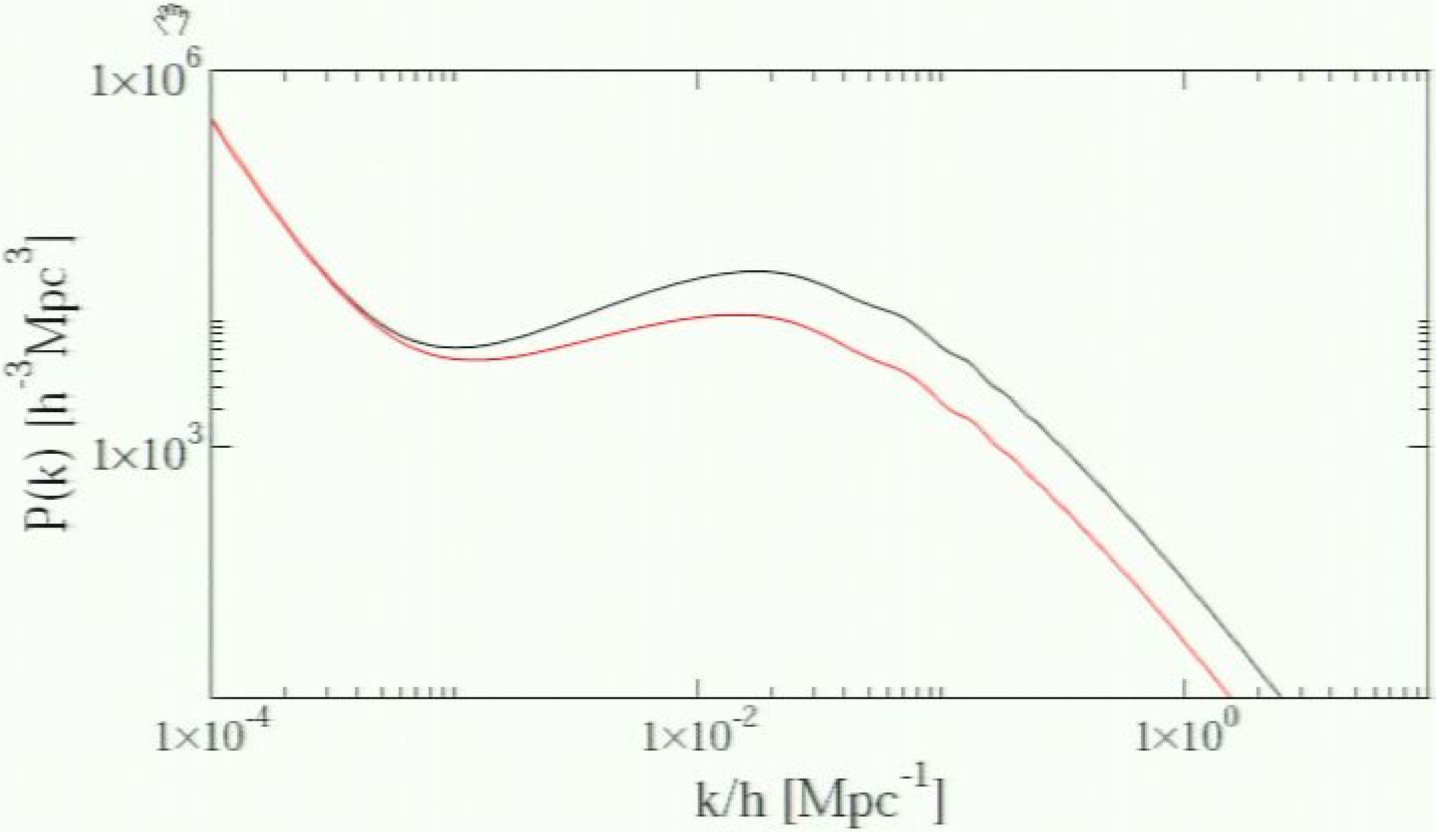
Nonlinear structure

spherical collapse model

Bartelmann et al, 2005

Ly-α-forest Afshordi et al., astro-ph/0702002



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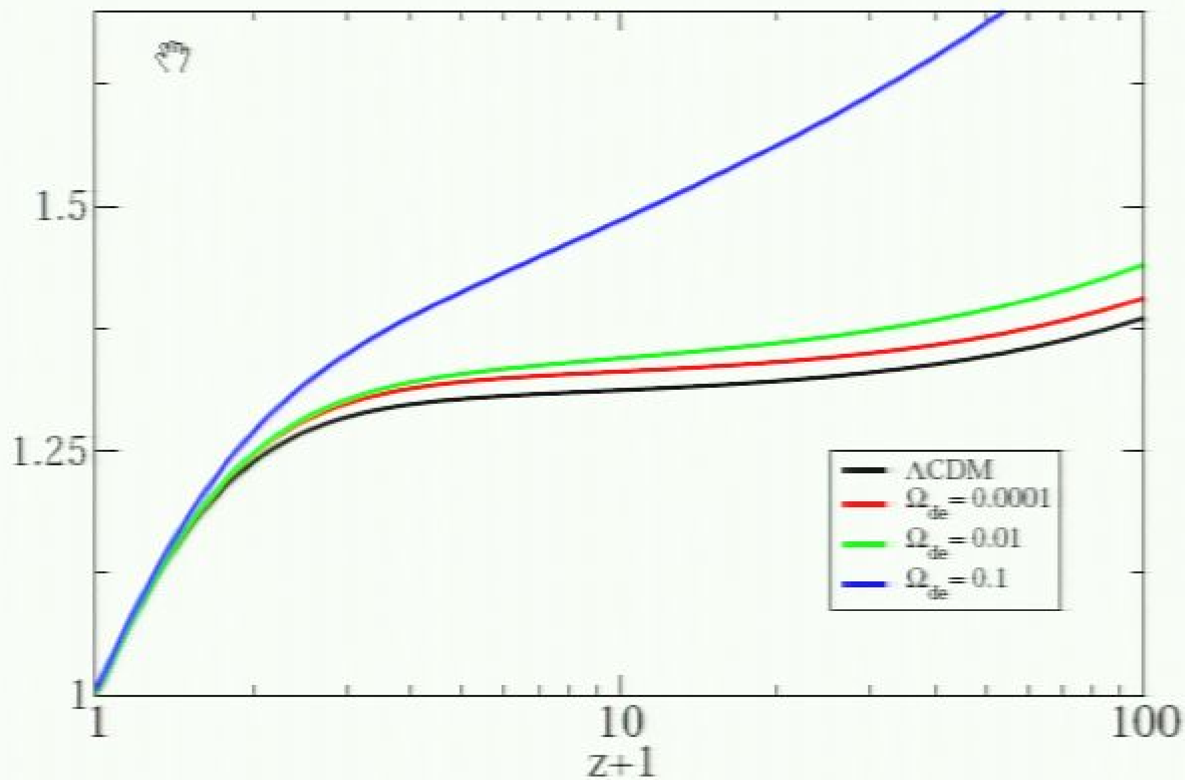

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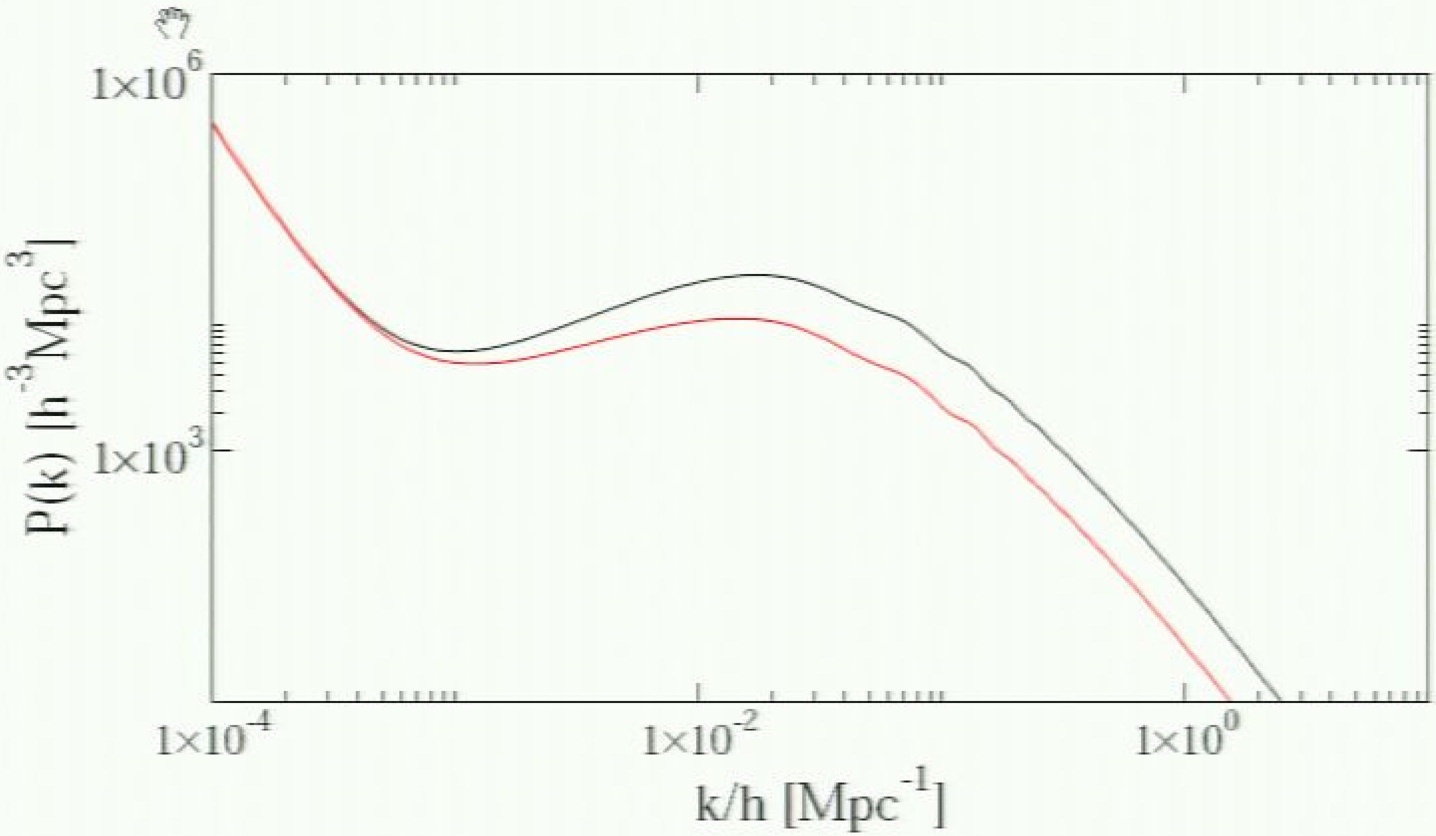

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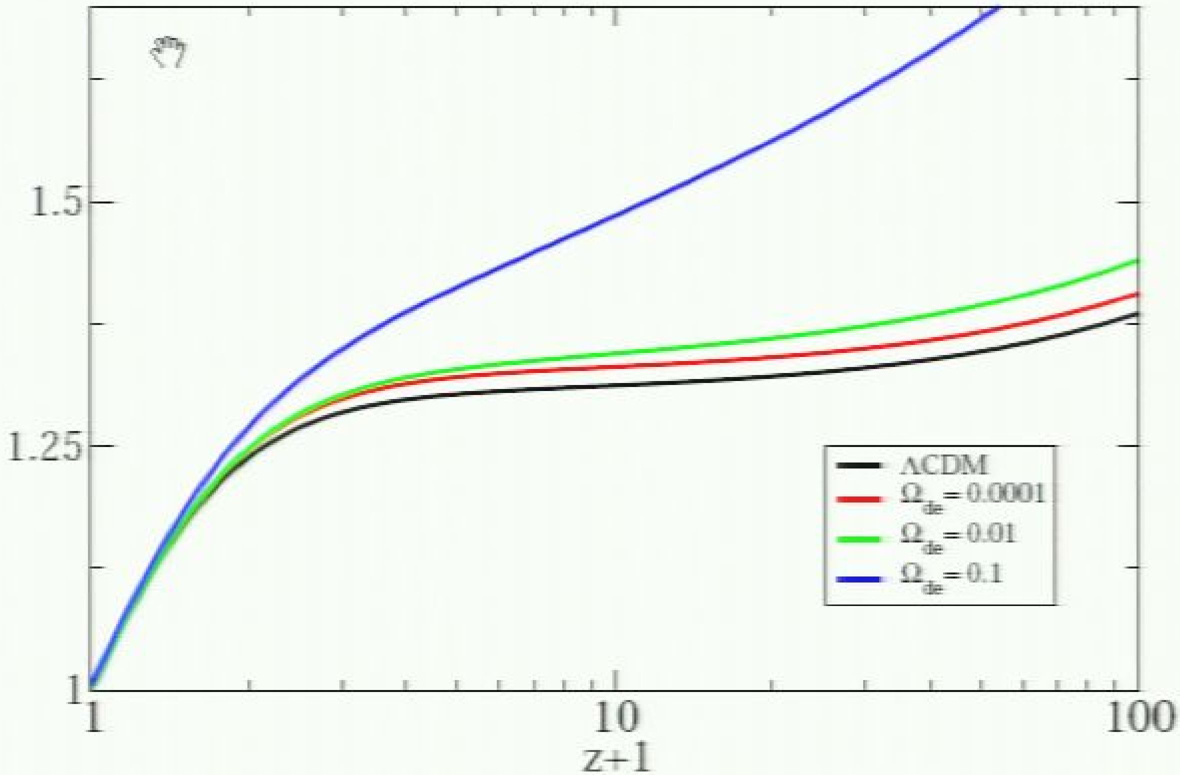

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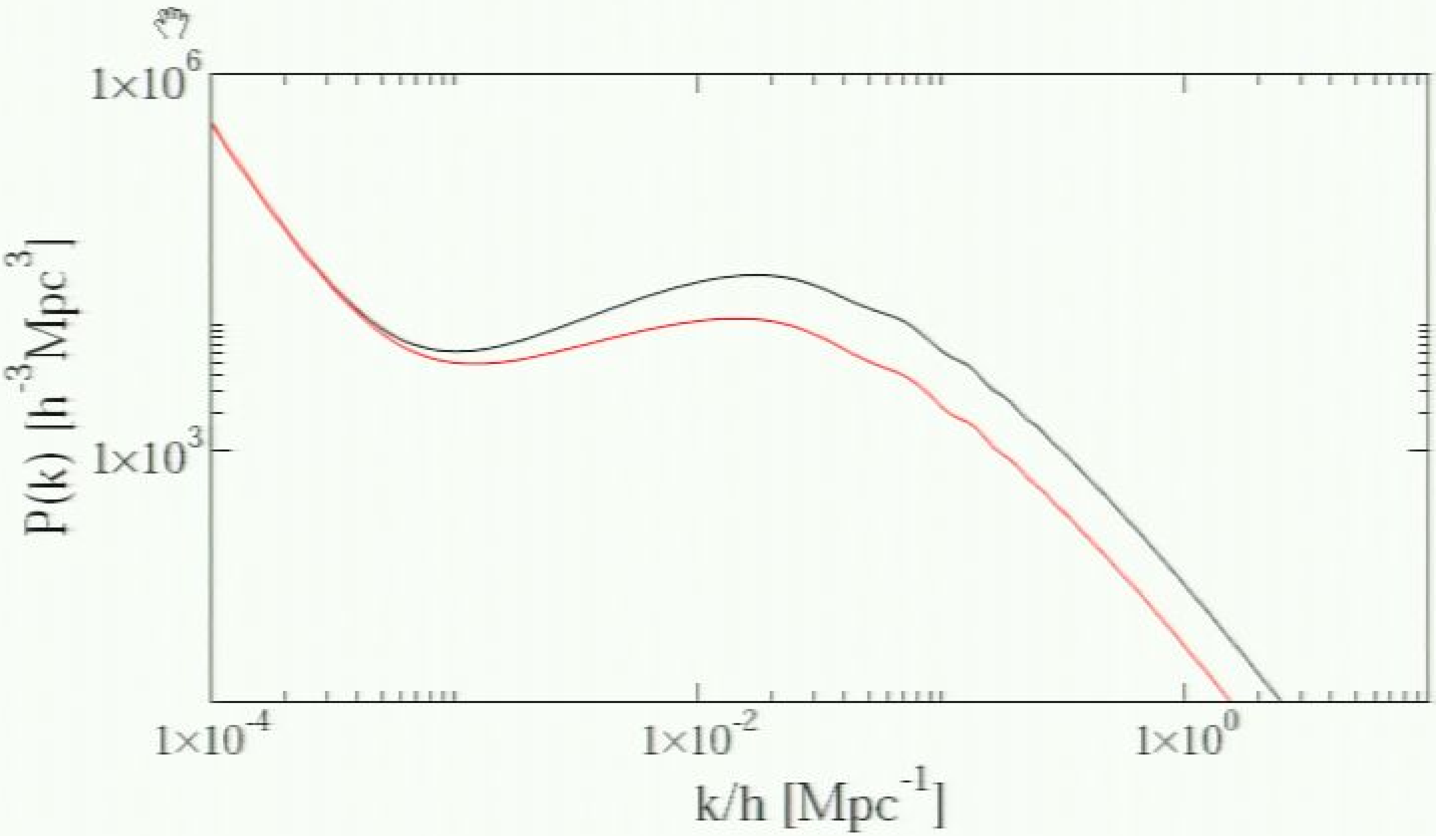

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spherical collapse model

Bartelmann et al, 2005

Nonlinear structure

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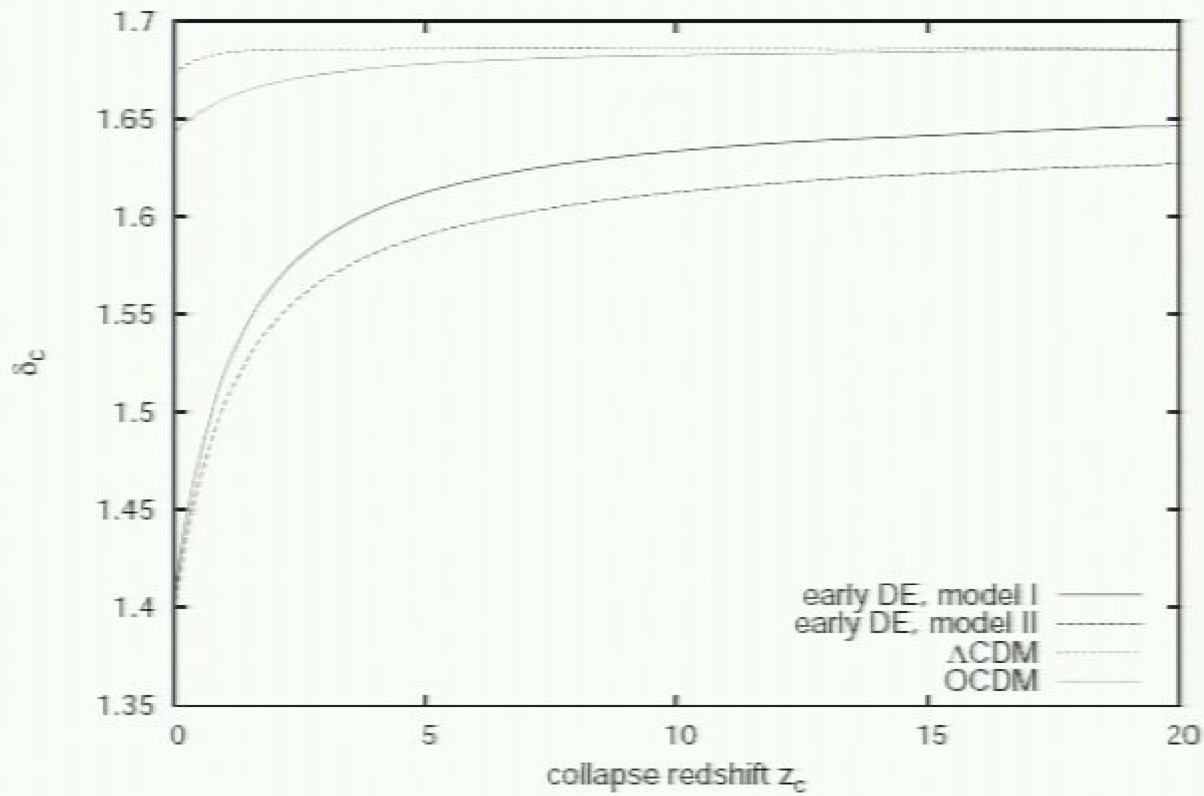
Bartelmann et al, 2005

analytic estimate of linear density contrast at collapse time, δ_c

canonical value $\delta_c = 1.686$



Nonlinear structure Bartelmann et al. '05

Consequences:

- halos are more concentrated (since they form earlier)
- number density of massive halos today: galaxy-sized: about the same, cluster-sized 40% higher than in ΛCDM
- prediction for thermal Sunyaev-Zel'dovich surveys: *Planck* should find about $10\times$ more clusters above redshift one than in a ΛCDM-universe

Planck SZ cluster sample J.-C. Waizmann et al. '08

Parameter	ΛCDM	EDE2	EDE3	EDE4
$\Omega_{\rm m}$	0.265	0.364	0.284	0.282
$\Omega_{\rm DE}$	0.735	0.636	0.716	0.718
$\bar{\Omega}_{\rm DE,sf}$	-	0.04	0.033	0.048
h	0.71	0.62	0.686	0.684
σ_8	0.8	0.78	0.715	0.655
$n_{\rm s}$	0.948	0.99	0.978	0.976
w_0	-1	-0.99	-0.942	-0.934

N-body simulations

N-body simulation results Francis et al., '08

- non-linear large scale structure (including abundance of clusters) relatively insensitive to presence of EDE

N-body simulation results Grossi & Springel, arXiv:0809.3404

- somewhat higher mass resolution than Francis et al., '08

Conclusions

- $\Omega_{de}^{sf} \lesssim$ few percent
- changes scale of “standard” rulers
- expected signatures in nonlinear structure formation
- not seen by nbody simulations
- future prospect: probe linear growth (ISW, b-modes...)