Unified Dark Matter models with fast transition and observational constraints

Marco Bruni
ICG, Portsmouth

Credits

- Ananda & Bruni, PRD, 74, 023523 (2006). astro-ph/0512224
- Ananda & Bruni, PRD, 74, 023524 (2006). gr-qc/0603131
- Balbi, Bruni & Quercellini, PRD 76, 103519 (2007). astro-ph/0702423
- Quercellini, Balbi & Bruni, CQG 24, 5413 (2007). astro-ph/0706.3667
- Quercellini, Bruni, Balbi & Pietrobon, PRD 78, 063527 (2008). astro-ph/0803.1976
- Pietrobon, Balbi, Bruni & Quercellini, PRD 78, 083510 (2008). astro-ph/0807.5077
- Piattella, Bertacca, Bruni & Pietrobon, JCAP 01 (2010) 014. arXiv:0911.2664

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Outline

- ΛCDM, alternatives, and UDM motivations
- UDM affine EoS: simple 2-parameter model with constant speed of sound
- UDM models with fast transition
- Outlook

ΛCDM and beyond

- CDM has been with us for more than 25 years (almost a 1/3 of modern cosmology) and is still a mystery, adding Λ is nice and simple, but considered unsatisfactory in many respects. At the very least, we want to test ΛCDM by generalising it.
- ΛCDM can be seen as a form of Unified Dark Matter (UDM) with vanishing speed of sound, $c_s^2 = dP/d\rho = 0$

UDM: Motivations

- Simplicity + Skepticism:
  - use GR and a phenomenological approach to the dark sector, with a simple parametric EoS for a single dark component;
  - background: same barotropic EoS $P=P(\rho)$ for fluid, Quintessence or K-essence fields;
  - perturbations: in general different for fluid and fields, because of different effective speed of sound c^2_{eff}
- Assuming a flat Universe, what can we learn adding one/few extra parameter for the background model?

UDM models

- Assume just GR, flat RW dynamics and a single UDM component:

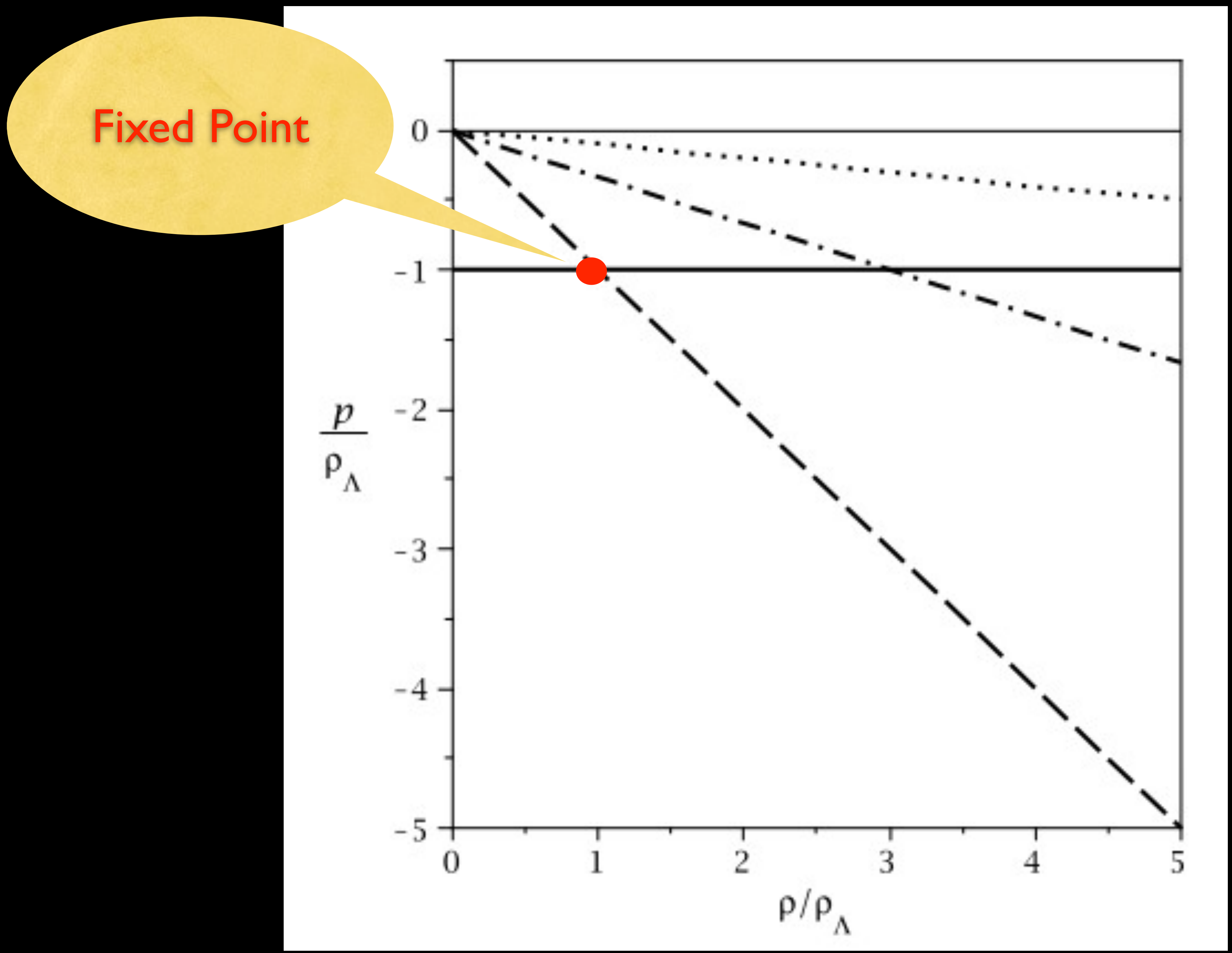
$$H^2 = \frac{8\pi G}{3}(\rho_r + \rho_b + \rho_X)$$

- Assume UDM is barotropic, P=P(ρ), and violates SEC, in order to source acceleration. Then also assuming a non negative c_s^2 =dP/dρ leads to a sort of cosmic no-hair theorem: from energy conservation

$$\dot{\rho}_X = -3H(\rho_X + P_X)$$

- an effective Λ follows: $p_\Lambda = -\rho_\Lambda$, fixed point of dynamics: de Sitter.

p-ρ plane



UDM "affine" model

- Simplest model for barotropic UDM:
  - assume constant "speed of sound": $c_s^2 = dP/d\rho = \alpha$
  - from this it follows an affine EoS:

$$P_X \simeq p_0 + \alpha \rho_X$$

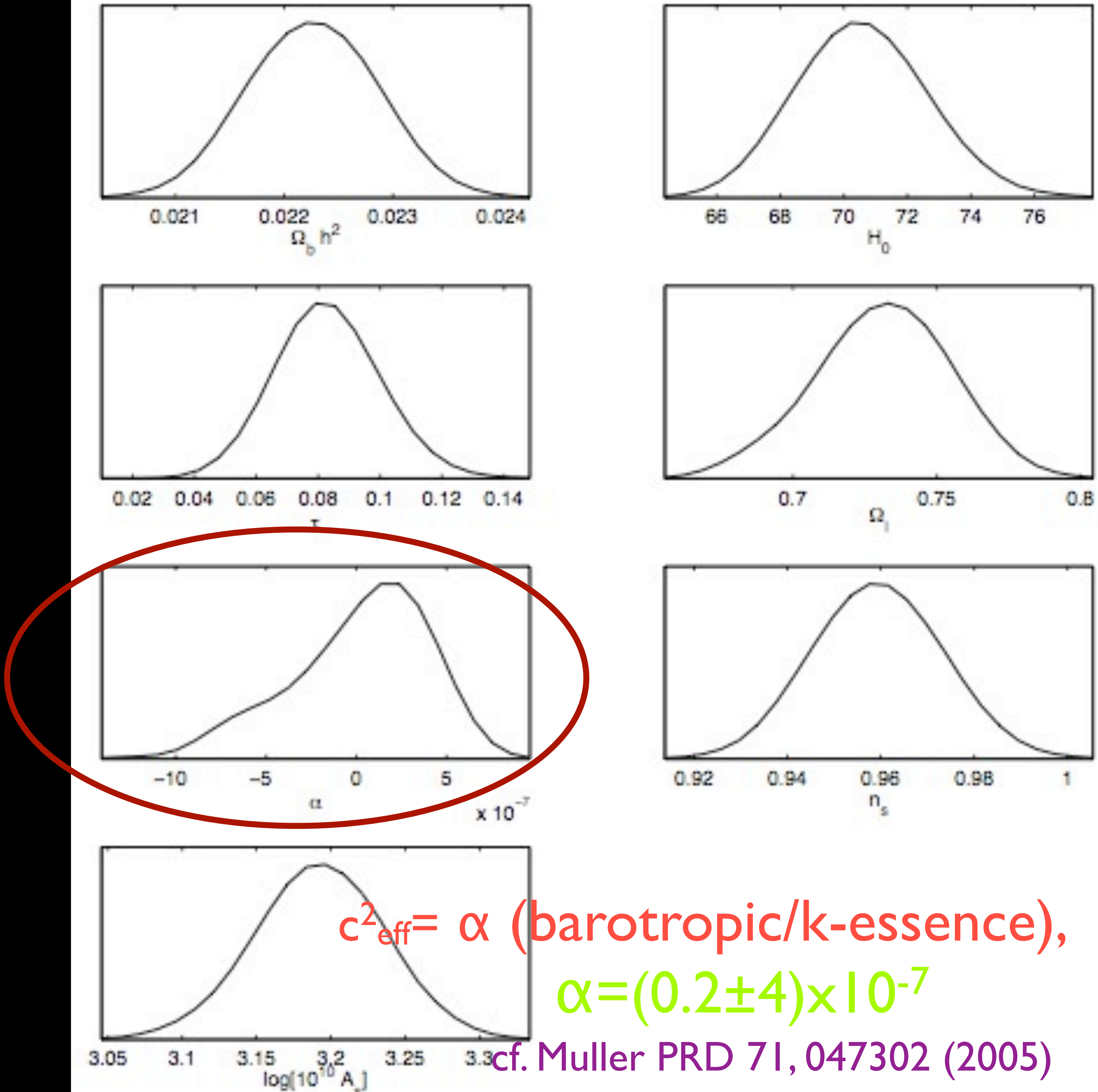
- can be seen as first order in a Taylor expansion. Extrapolate to any time: with $\rho_\Lambda = -(1+\alpha)p_o$ we get

$$\rho_X(a) = \rho_\Lambda + (\rho_{Xo} - \rho_\Lambda) a^{-3(1+\alpha)}$$

- $\alpha=0$ formally gives ΛCDM (horizontal line $p=-\rho_\Lambda$)

affine EoS UDM: constraints from WMAP5 and SDSS LRG4

- assumption/Gaussian prior: H_0=72±8 km/s/Mps (HST 1σ)

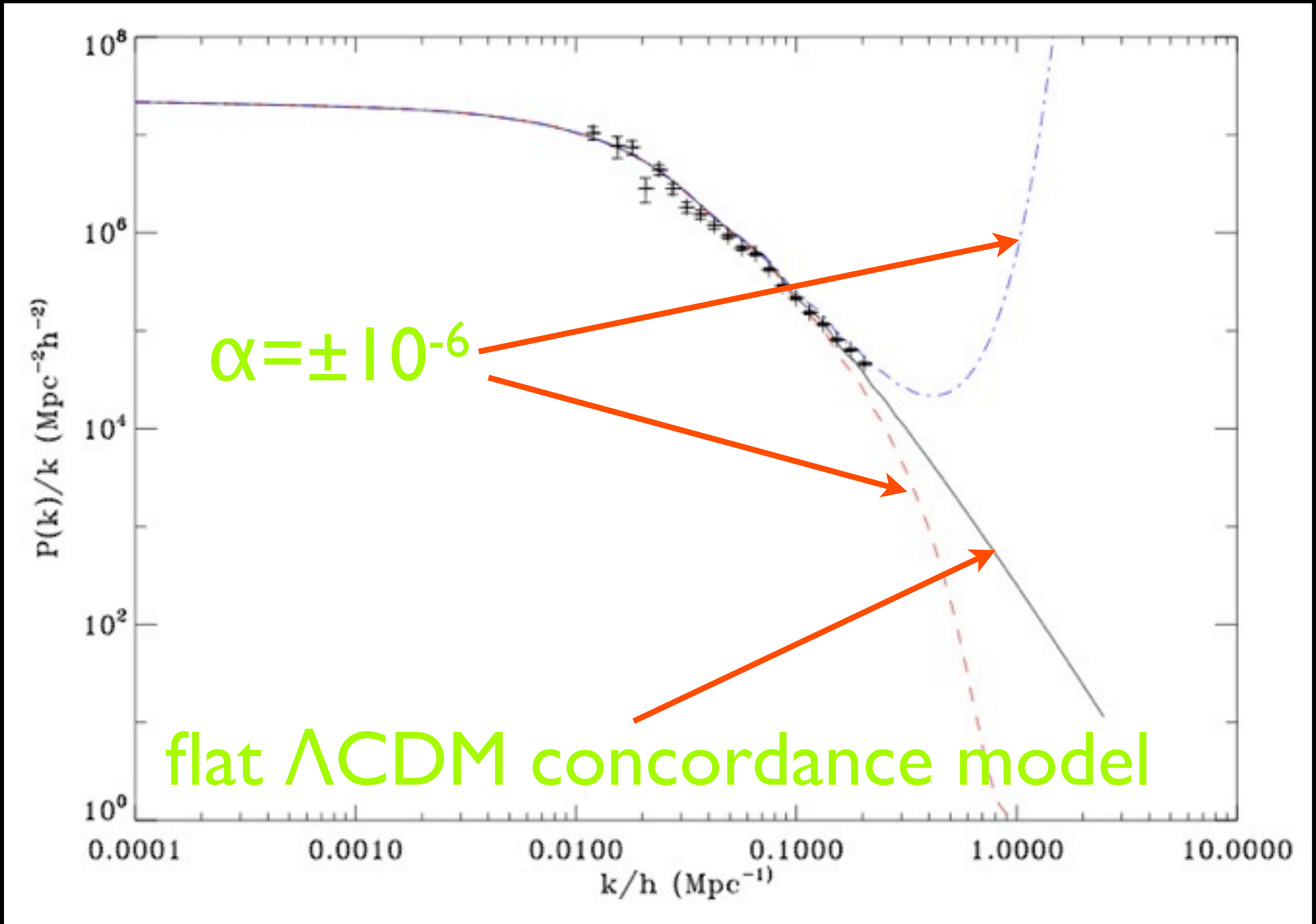


$c^2_{eff}= \alpha$ (barotropic/k-essence),

$\alpha=(0.2\pm4)\times10^{-7}$

cf. Muller PRD 71, 047302 (2005)

UDM with $c^2_{eff} = \alpha$ (barotropic/k-essence)



- EoS parameter α is strongly constrained by the matter power spectrum (galaxy survey: SDSS data)
- Other parameters are fully consistent with the results of WMAP5

UDM models with fast transition

- can we build UDM models that are not forced to be almost indistinguishable from ΛCDM?
- clearly the problem of building working models is related to the speed of sound, which typically gives a non negligible Jeans scale
- we want bild models such that:
  - pressure is negligible at early times (EdS);
  - pressure is negligible at late times, so as to avoid a strong ISW effect and to avoid big changes in structure formation

Jeans Scale

$$k_J^2 = \frac{3}{2}\frac{\rho}{(1+z)^2}\frac{(1+w)}{c_s^2}\left|\frac{1}{2}(c_s^2 - w) - \rho\frac{dc_s^2}{d\rho} + \frac{3(c_s^2-w)^2 - 2(c_s^2-w)}{6(1+w)} + \frac{1}{3}\right| .$$

- Jeans wave number inversely proportional to c_s^2. The Jeans length is negligible when the speed of sound is vanishingly small, e.g. as for standard CDM.
- We can make k_j^2 large also if the rate of change of the speed of sound is large, i.e. if we have a fast transition.

Jeans Scale

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Jeans Scale

$$k_{\rm J}^2 = \frac{3}{2}\frac{\rho}{(1+z)^2}\frac{(1+w)}{c_{\rm s}^2}\left|\frac{1}{2}(c_{\rm s}^2 - w) - \rho\frac{dc_{\rm s}^2}{d\rho} + \frac{3(c_{\rm s}^2 - w)^2 - 2(c_{\rm s}^2 - w)}{6(1+w)} + \frac{1}{3}\right| .$$

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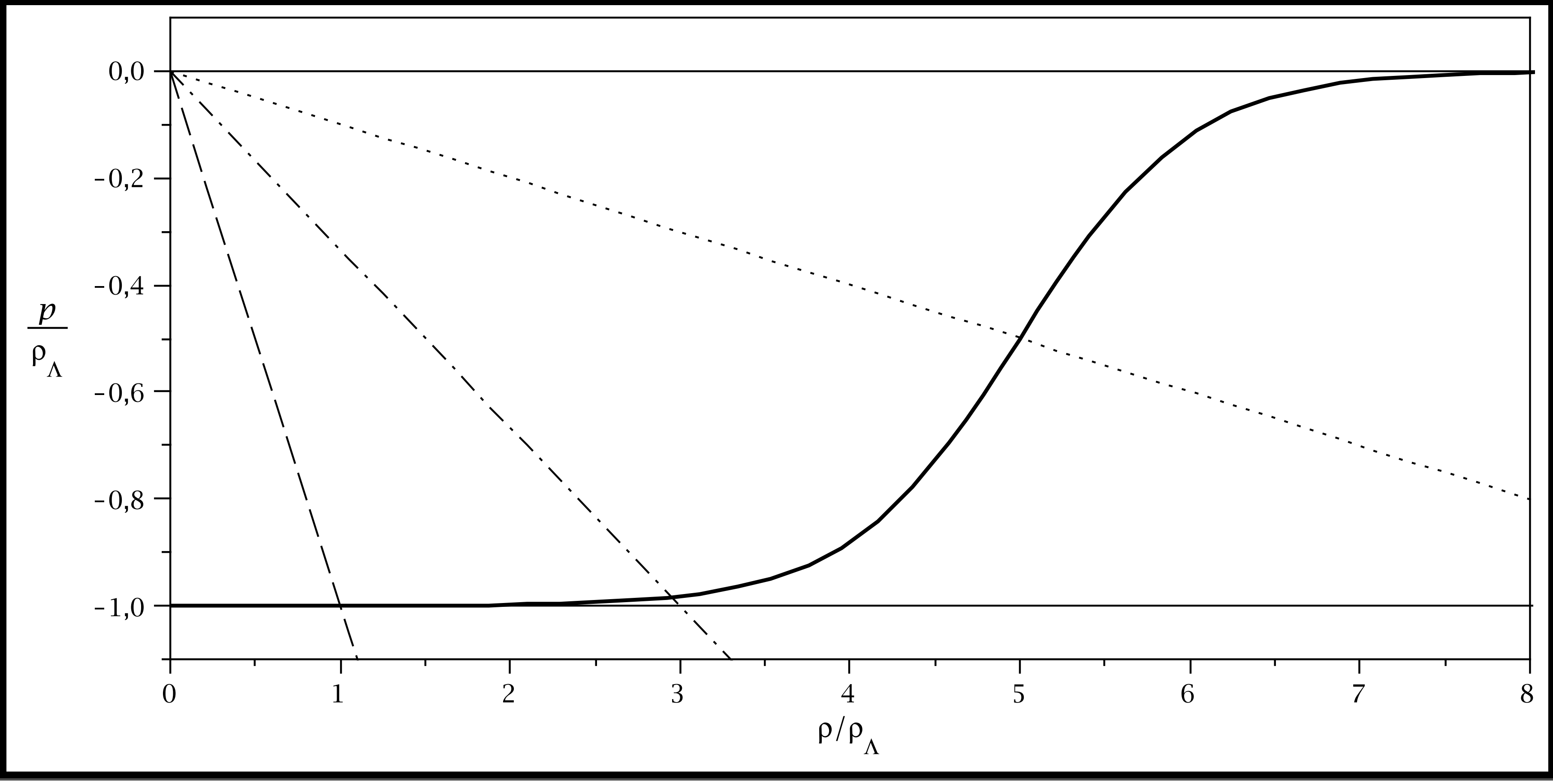
A toy model

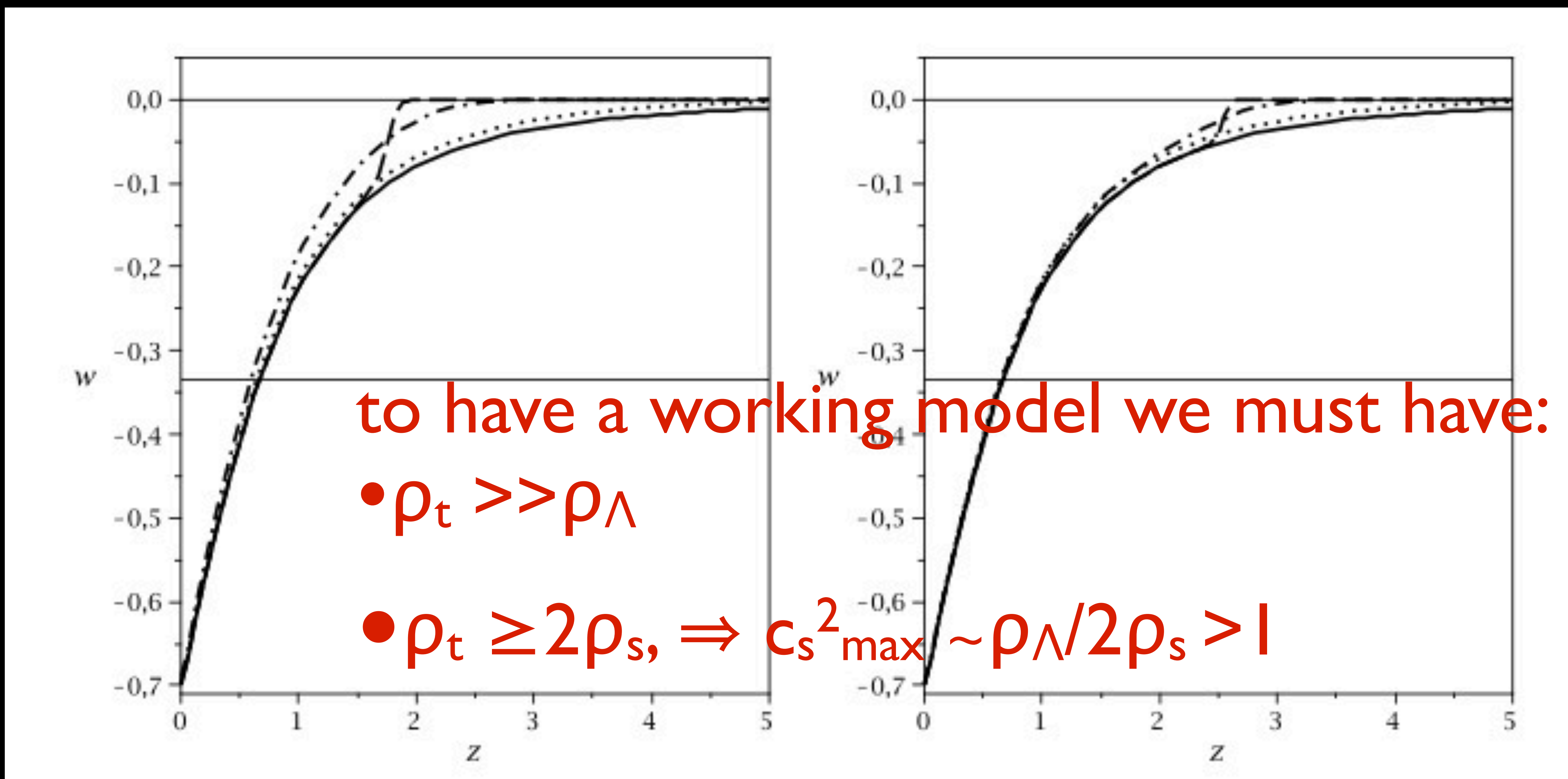
- we assume the 3-parameters barotropic EoS

$$p = -\rho_\Lambda \left[\frac{1 - \tanh\left(\frac{\rho - \rho_t}{\rho_s}\right)}{1 - \tanh\left(\frac{\rho_\Lambda - \rho_t}{\rho_s}\right)} \right]$$



Evolution of the EoS w(z)

- interpolation between EdS (CDM) and ΛCDM



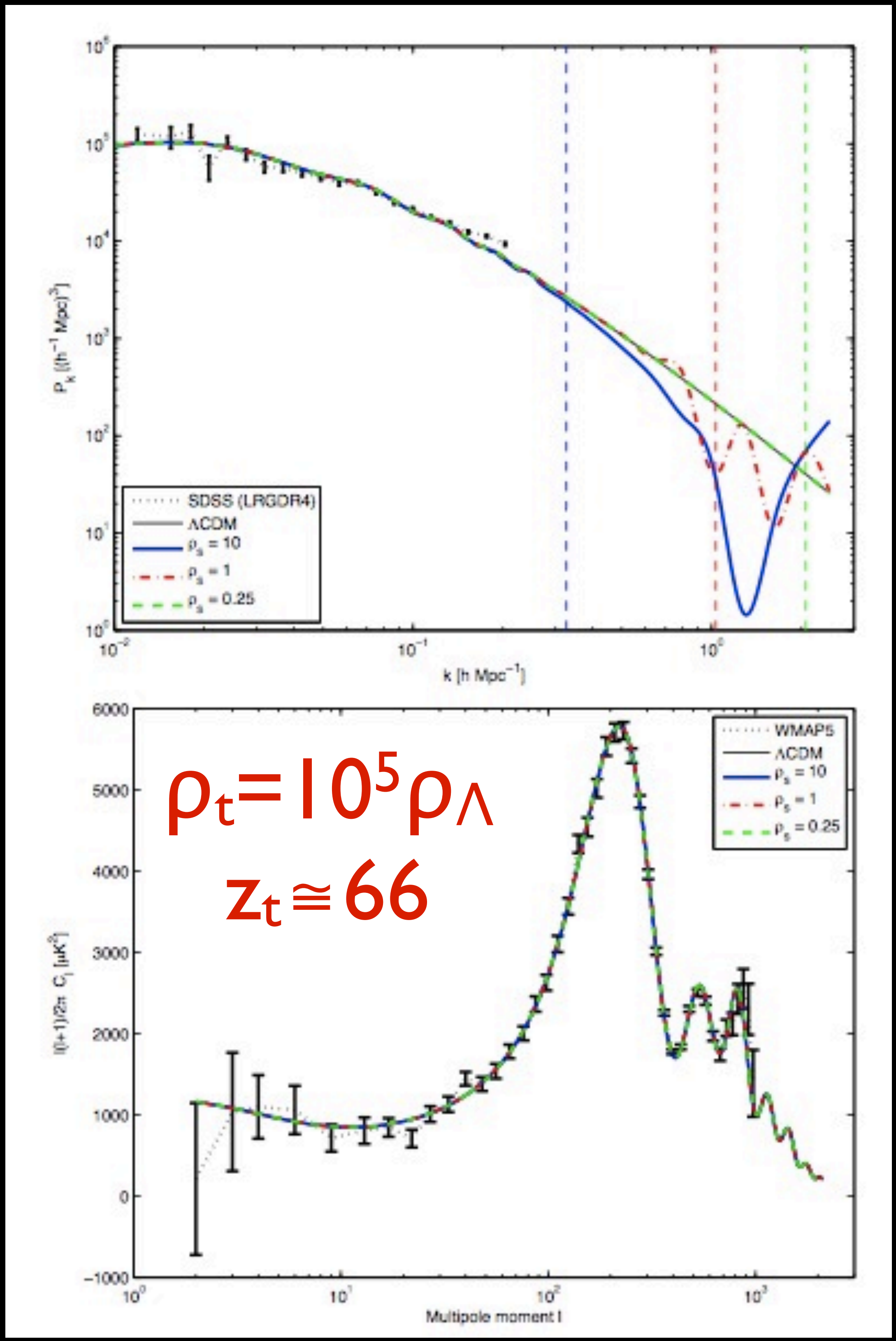
to have a working model we must have:

- $\rho_t >> \rho_\Lambda$
- $\rho_t \geq 2\rho_s, \Rightarrow c_s{}^2{}_{max} \sim \rho_\Lambda / 2\rho_s > 1$

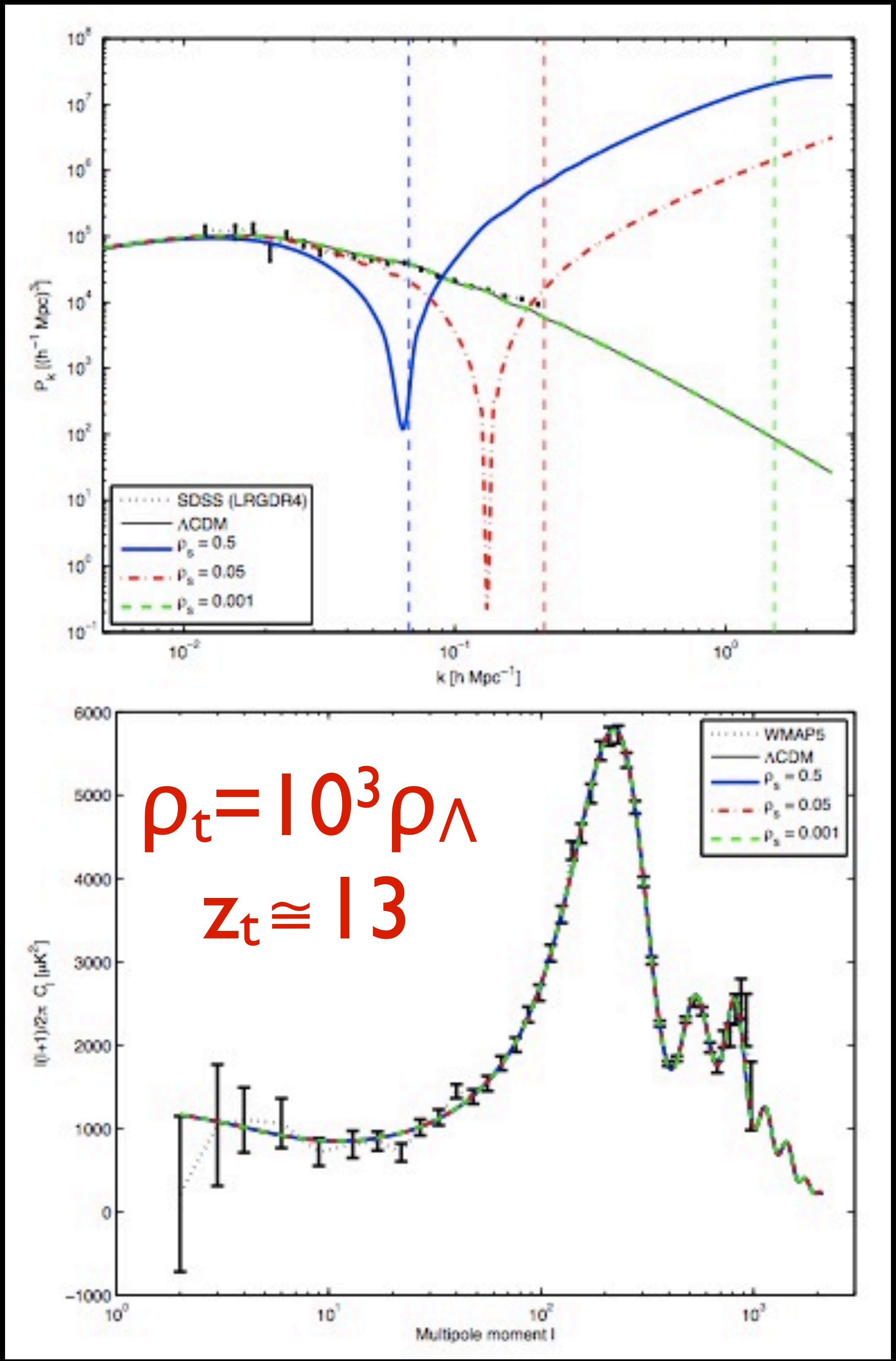
Comparison with Observables

- two main observables:
  - WMAP5 data for CMB fluctuations
  - SDSS data (galaxy survey) for matter power spectrum
- ΛCDM reference model: combined best fit of WMAP5, BAO and Type Ia SNs, with Ω_Λ=0.721±0.015 etc...
- choice of parameters: careful analysis defines criteria for the choice of reasonable parameter values that lead to the desired behaviour of the Jeans scale k_j
- definition of a reference k_j

results

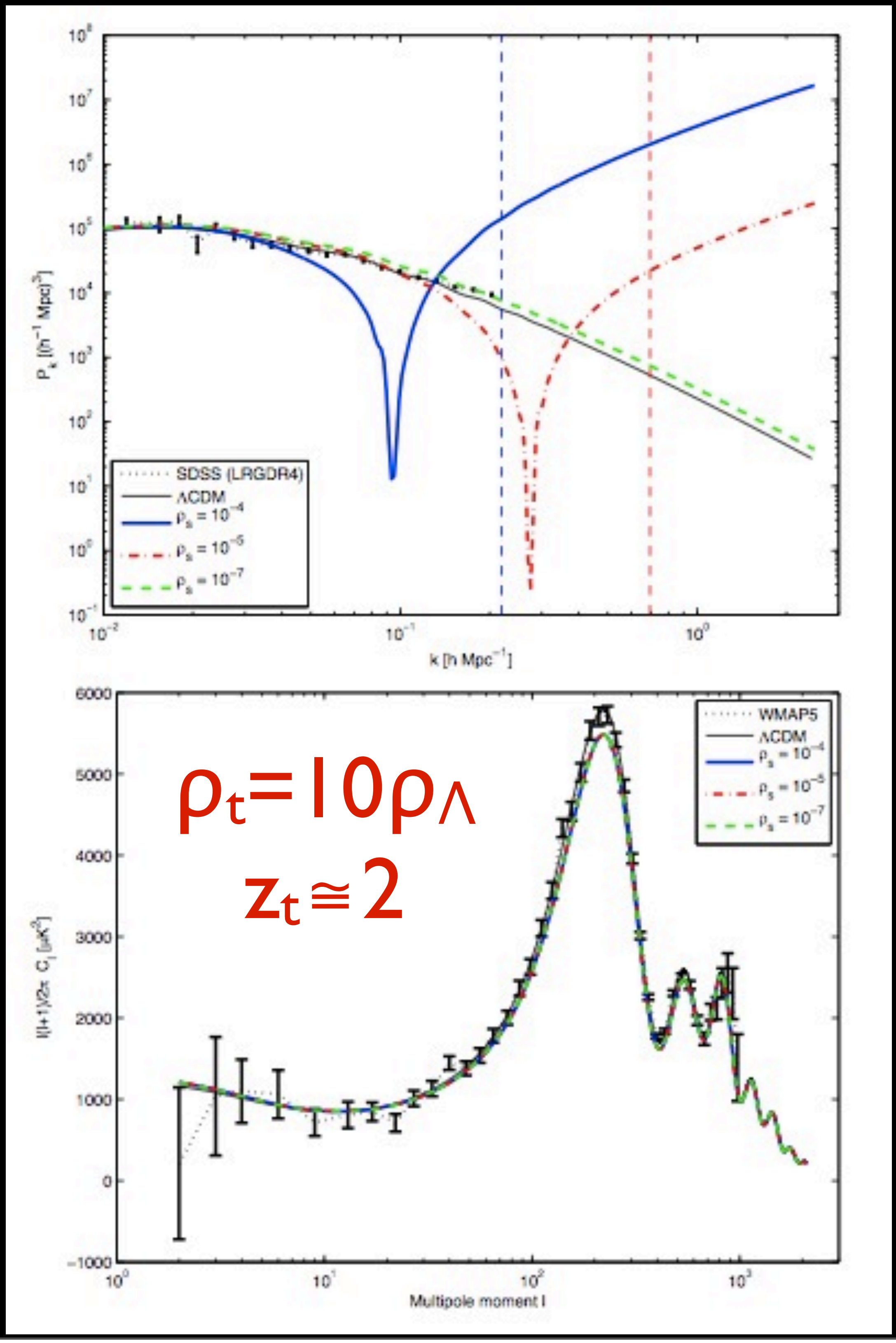


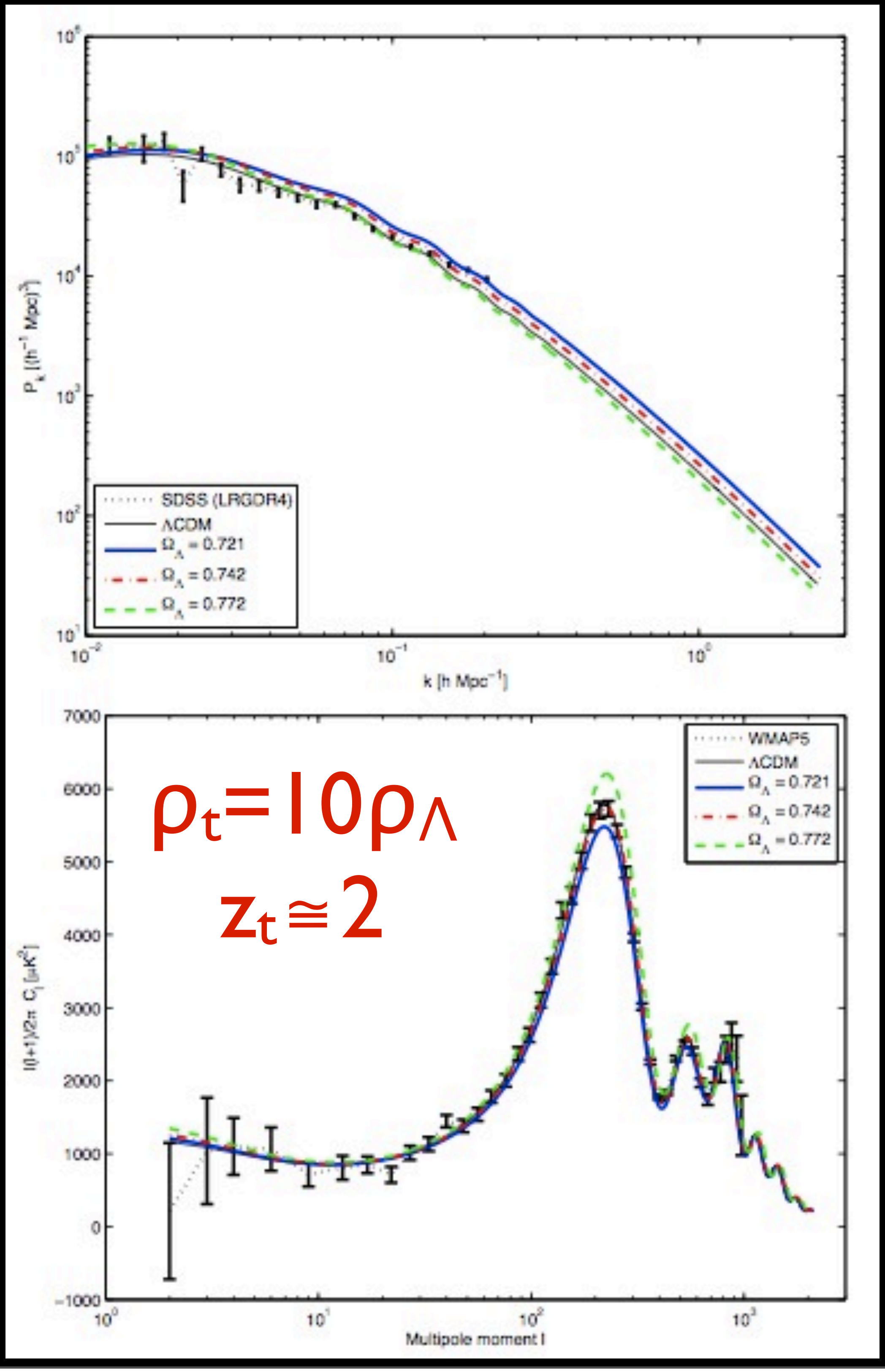
SDSS (LRGDR4)
ΛCDM
ρs = 10
ρs = 1
ρs = 0.25
k [h Mpc⁻¹]
WMAP5
Multipole moment l
$\rho_t = 10^5 \rho_\Lambda$
$z_t \cong 66$



SDSS (LRGDR4)
ΛCDM
ρs = 0.5
ρs = 0.05
ρs = 0.001
k [h Mpc⁻¹]
WMAP5
Multipole moment l
$\rho_t = 10^3 \rho_\Lambda$
$z_t \cong 13$

results


SDSS (LRGDR4)
ΛCDM
$\rho_s = 10^{-4}$
$\rho_s = 10^{-5}$
$\rho_s = 10^{-7}$
P_k [(h^{-1} Mpc)^3]
k [h Mpc^{-1}]
WMAP5
ΛCDM
$\rho_s = 10^{-4}$
$\rho_s = 10^{-5}$
$\rho_s = 10^{-7}$
$l(l+1)/2\pi$ C_l [μK^2]
Multipole moment l
$\rho_t = 10\rho_\Lambda$
$z_t \cong 2$


SDSS (LRGDR4)
ΛCDM
$\Omega_\Lambda = 0.721$
$\Omega_\Lambda = 0.742$
$\Omega_\Lambda = 0.772$
P_k [(h^{-1} Mpc)^3]
k [h Mpc^{-1}]
WMAP5
ΛCDM
$\Omega_\Lambda = 0.721$
$\Omega_\Lambda = 0.742$
$\Omega_\Lambda = 0.772$
$l(l+1)/2\pi$ C_l [μK^2]
Multipole moment l
$\rho_t = 10\rho_\Lambda$
$z_t \cong 2$

Conclusions

- The universe seems to be best described by:
  - a totally standard CDM-based evolution at early times (EdS-like);
  - a background ΛCDM-like model at low red-shifts.
- Standard UDM models like Chaplygin or the "affine" have to be indistinguishable from ΛCDM to fit the data;
  - key point: the problem is to have the right clustering, which requires a vanishing small effective speed of sound and Jeans lenght.
- Fast transition UDM models fit observations if the transition is fast enough, depending on the redshift of the transition;
  - key point: if the transition is fast enough, the effective speed of sound becomes very large but for an extremely short time and we can fit the matter power spectrum

Outlook

- next steps:
  - scalar fields;
  - likelyhood analysis and best fit; other data;
  - Bayesian comparison;
  - non-linear small-scales evolution and clustering;
  - predictions: e.g. scale dependent bias?