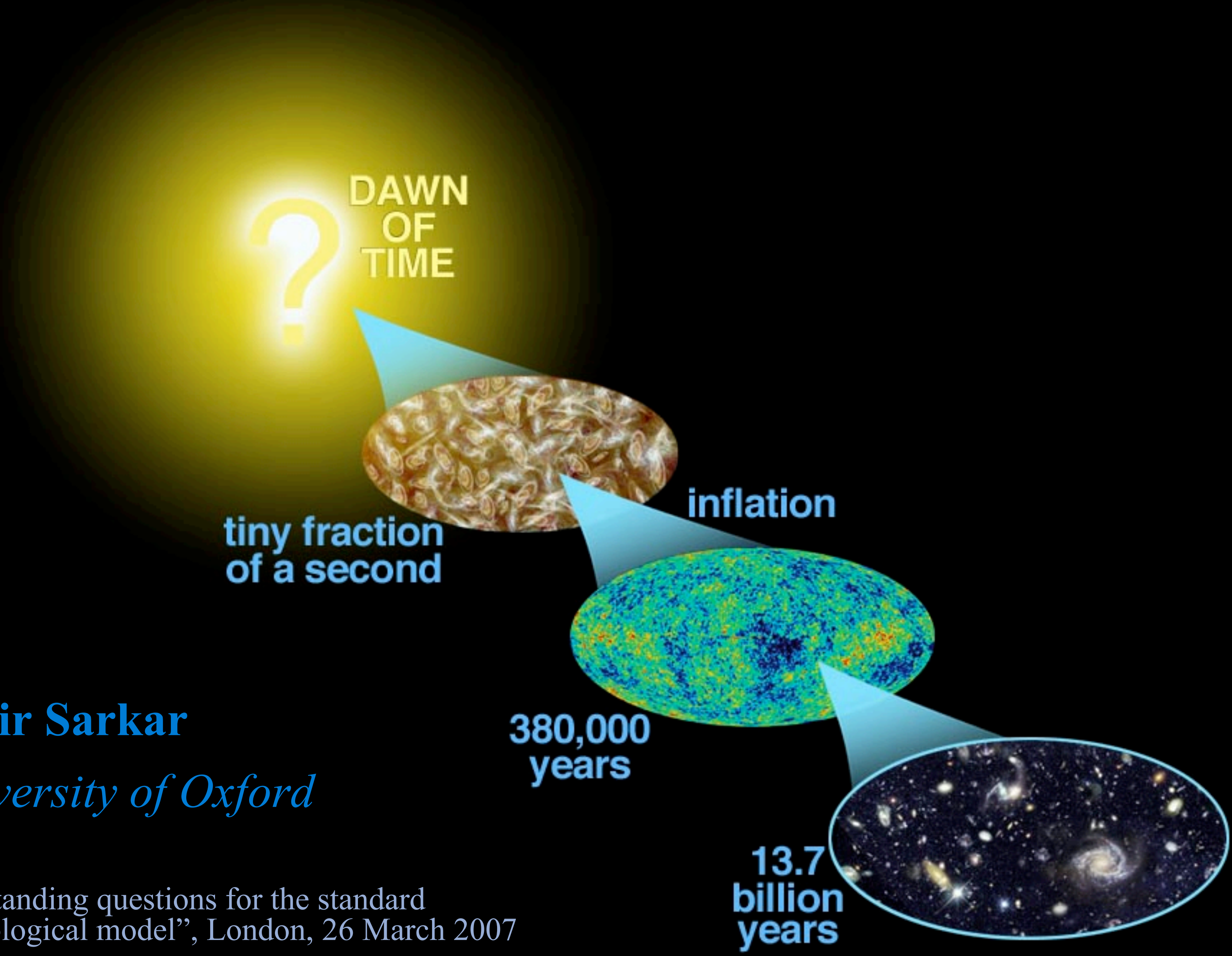
Do CMB & LSS data require dark energy?



Courtesey: NASA/WMAP Science Team

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University of Oxford

"Outstanding questions for the standard cosmological model", London, 26 March 2007

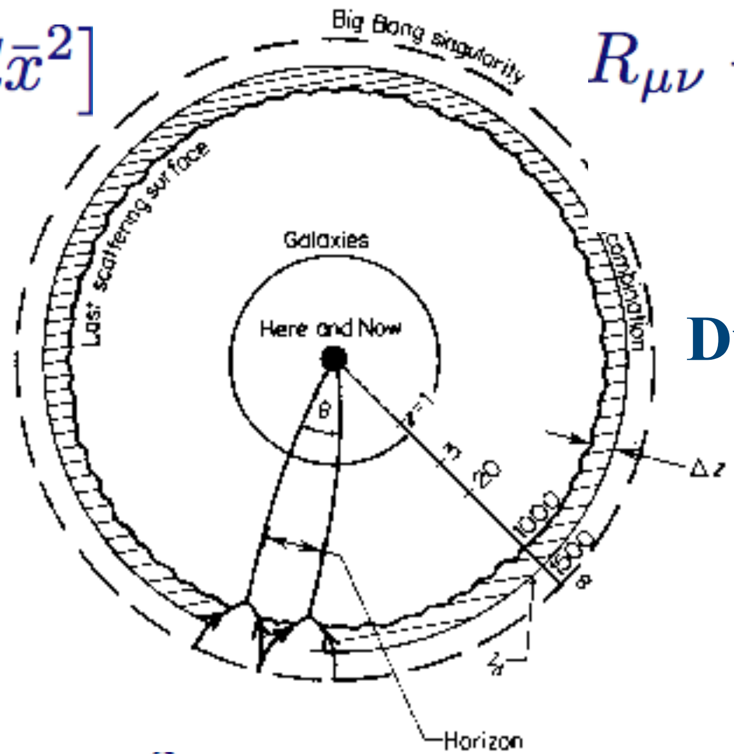
The standard cosmological model

… maximally symmetric, simply connected space-time
containing ideal fluids (dust, radiation …)

$$ds^2 = a^2(\eta)\left[d\eta^2 - d\bar{x}^2\right]$$

$$a^2(\eta) \equiv dt^2$$

Space-time metric:
Robertson-Walker



$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu}$$
$$= 8\pi G_{\rm N} T_{\mu\nu}$$

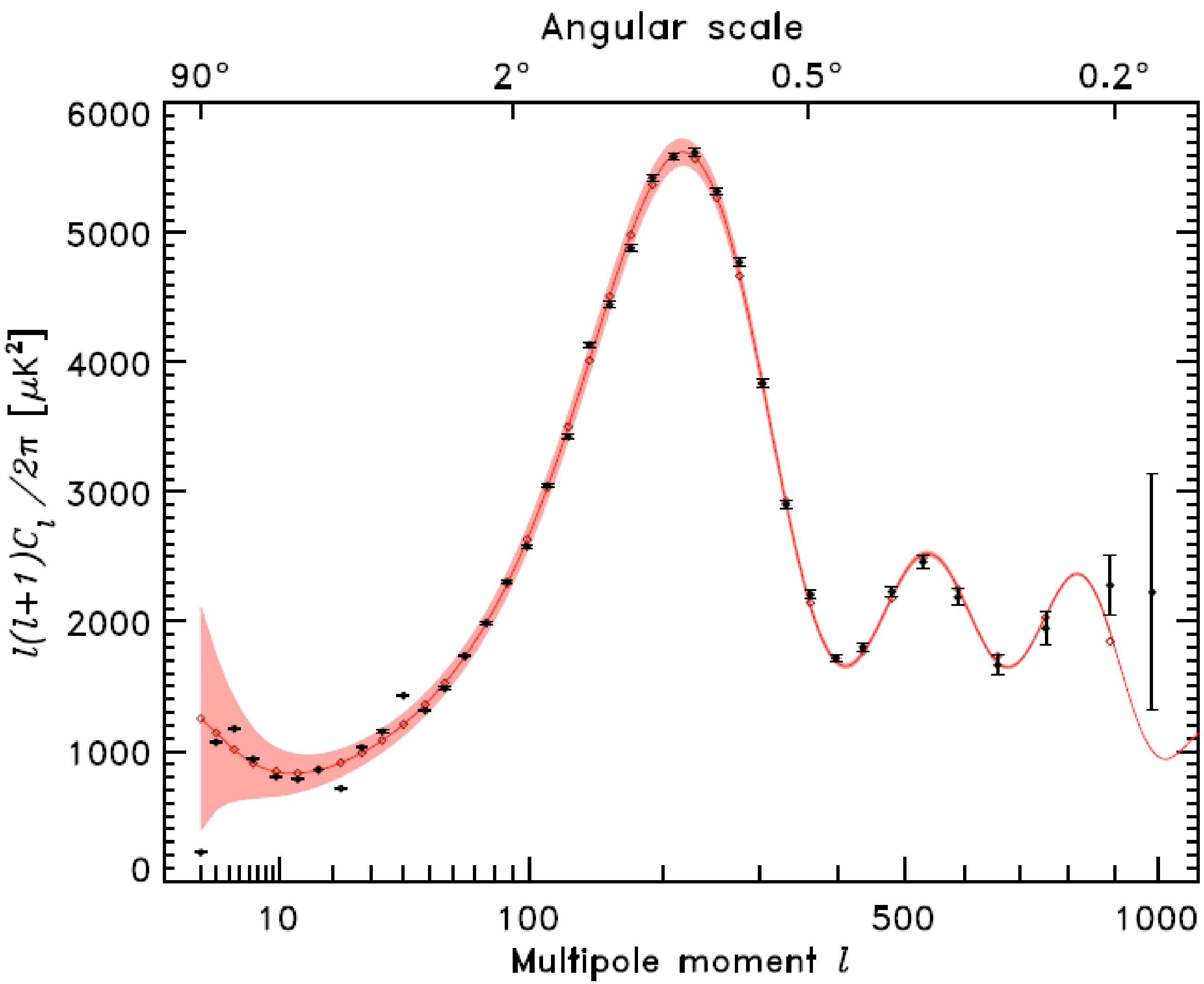
Dynamics: Einstein

$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\rm N}\rho_{\rm m}}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\equiv {H_0}^2\left[\Omega_{\rm m}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

The 3-yr *WMAP* data is said to *confirm* the 'power-law ΛCDM model'

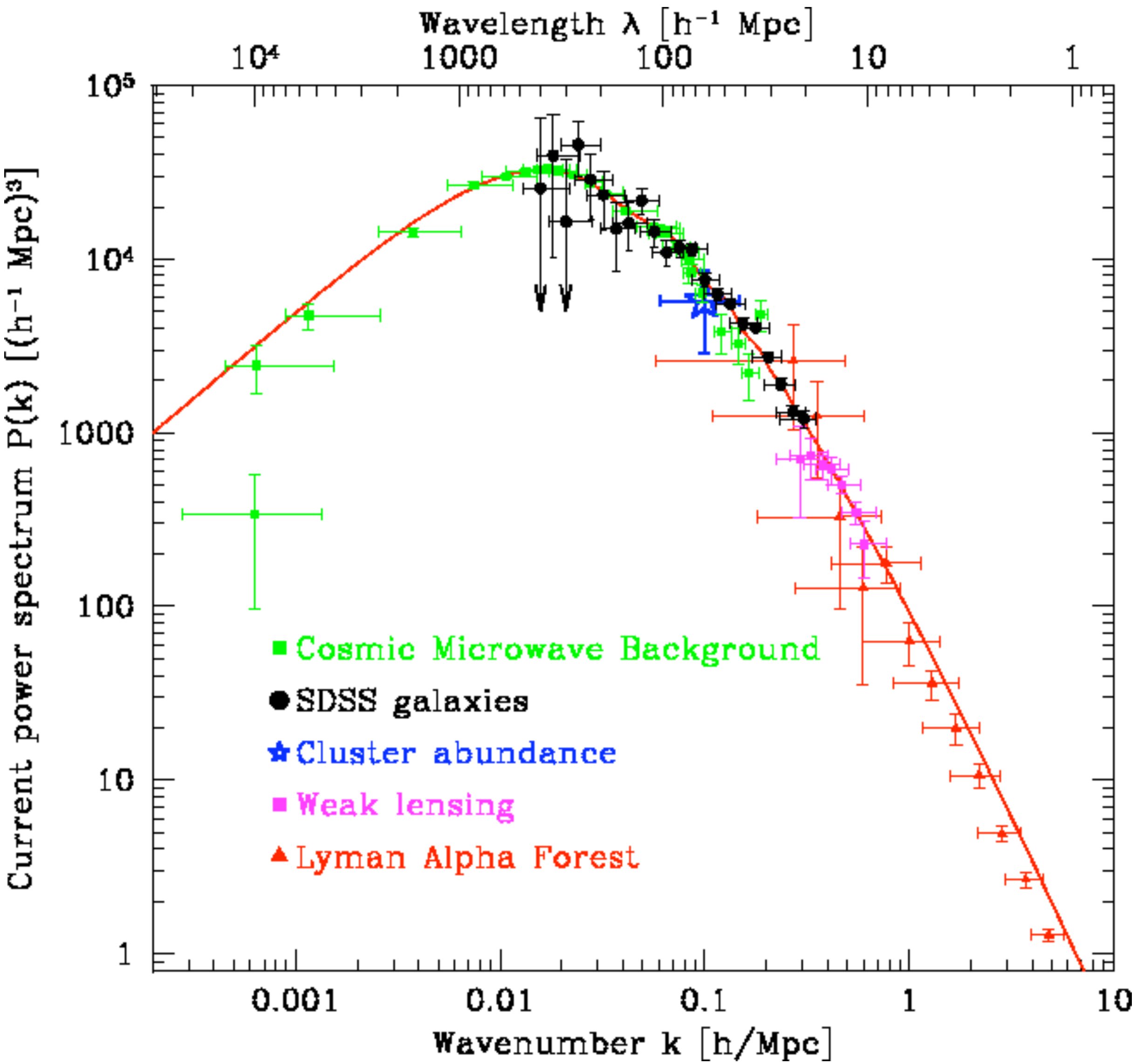
Best-fit: $\Omega_m h^2 = 0.13 \pm 0.01$, $\Omega_b h^2 = 0.022 \pm 0.001$, $h = 0.73 \pm 0.05$, $n = 0.95 \pm 0.02$



But the χ^2/dof = 1049/982 ⇒ probability of only ~7% that this model is correct!

Observations of large-scale structure too are *consistent* with the ΛCDM model if the primordial fluctuations are *adiabatic* and ~*scale-invariant*

(as is apparently "expected in the simplest models of inflation")



Why is a vacuum energy of $\Lambda \sim 10^{-3}$ eV physically ridiculous?

Our present description of matter is an *effective* field theory
… valid up to some cutoff energy Λ

Consider the Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model Lagrangian

Cosmological constant — *Higgs mass correction*

$$\mathcal{L}_{eff} = \Lambda^4 + \Lambda^2\Phi^2$$ **super-renormalisable**

$$+ (D\Phi)^2 + \overline{\Psi}\, \not{D}\Psi + F^2 + \overline{\Psi}\Psi\Phi + \Phi^4$$ **renormalisable**

$$+ \frac{\overline{\Psi}\Psi\Phi\Phi}{\Lambda} + \frac{\overline{\Psi}\Psi\overline{\Psi}\Psi}{\Lambda^2} + \ldots,$$ **non-renormalisable**

The effects of new physics beyond the SM (neutrino masses, nucleon decay, FCNC …) are suppressed by powers of the cutoff so 'decouple' as $\Lambda \rightarrow M_P$

But as Λ increases, the effects of the d < 4 operators are exacerbated!

Solution for 2nd term → softly broken' supersymmetry at $\Lambda \sim 1$ TeV ($\Rightarrow$ ~100 new parameters)

The 1st term couples *only* to gravity – must be cancelled order by order to reduce it from its *minimum* value of ~1 TeV^4 down to cosmologically indicated value - **fine tuning by ~10^{60}**

The formation of large-scale structure is akin to a scattering experiment

The **Beam: inflationary density perturbations**

No 'standard model' – usually *assumed* to be adiabatic and ~scale-invariant

The **Target: dark matter (+ baryonic matter)**

Identity unknown - usually taken to be cold (sub-dominant 'hot' component?)

The **Detector: the universe**

Modelled by a 'simple' FRW cosmology with parameters h, Ω_{CDM} , Ω_b , Ω_Λ , Ω_k ...

The **Signal: CMB anisotropy, galaxy clustering …**

measured over scales ranging from ~ 1 – 10000 Mpc ($\Rightarrow$ ~8 e-folds of inflation)

We cannot simultaneously determine the properties of *both* the **beam** *and* the **target** with an unknown **detector**

… hence need to adopt suitable 'priors' on h, Ω_{CDM}, etc in order to break inevitable parameter *degeneracies*

Astronomers have traditionally *assumed* a Harrison-Zeldovich spectrum:

$$P(k) \propto k^n, \ n = 1$$

But models of inflation generally predict departures from scale-invariance

In **single-field slow-roll models**: $n = 1 + 2V''/V - 3\,(V'/V)^2$

Since the potential $V(\Phi)$ steepens towards the end of inflation, there will be a *scale-dependent spectral tilt* on cosmologically observable scales:

e.g. in model with *cubic* leading term: $V(\Phi) \simeq V_o - \beta^3 + \ldots \Rightarrow n \simeq 1 - 4/N_* \sim 0.94$

where $N_* \approx 50 + \ln\,(k^{-1}/3000h^{-1}\ \mathrm{Mpc})$ is the # of e-folds from the *end* of inflation

This agrees with the best-fit value power-law index inferred from the *WMAP* data

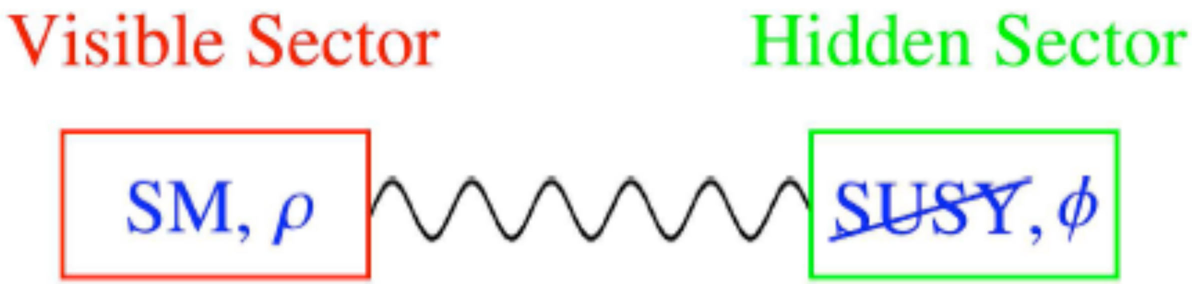
In **hybrid models**, inflation is ended by the ‘waterfall’ field, *not* due to the steepening of $V(\Phi)$, so spectrum is generally closer to scale-invariant …

In general there would be *many* other fields present, whose own dynamics may *interrupt* the inflaton’s slow-roll evolution (rather than terminate it altogether)

→ can generate features in the spectrum (‘steps’, ‘oscillations’, ‘bumps’ …)

Consider inflation in context of *effective* field theory: N =1 SUGRA

(successful description of gauge coupling unification, EW symmetry breaking, …)



The visible sector could be important during inflation if gauge symmetry breaking occurs

Supersymmetric theories contain 'flat directions' in field space where the potential vanishes in the limit of unbroken SUSY

This is due to various symmetries and non-renormalisation theorems

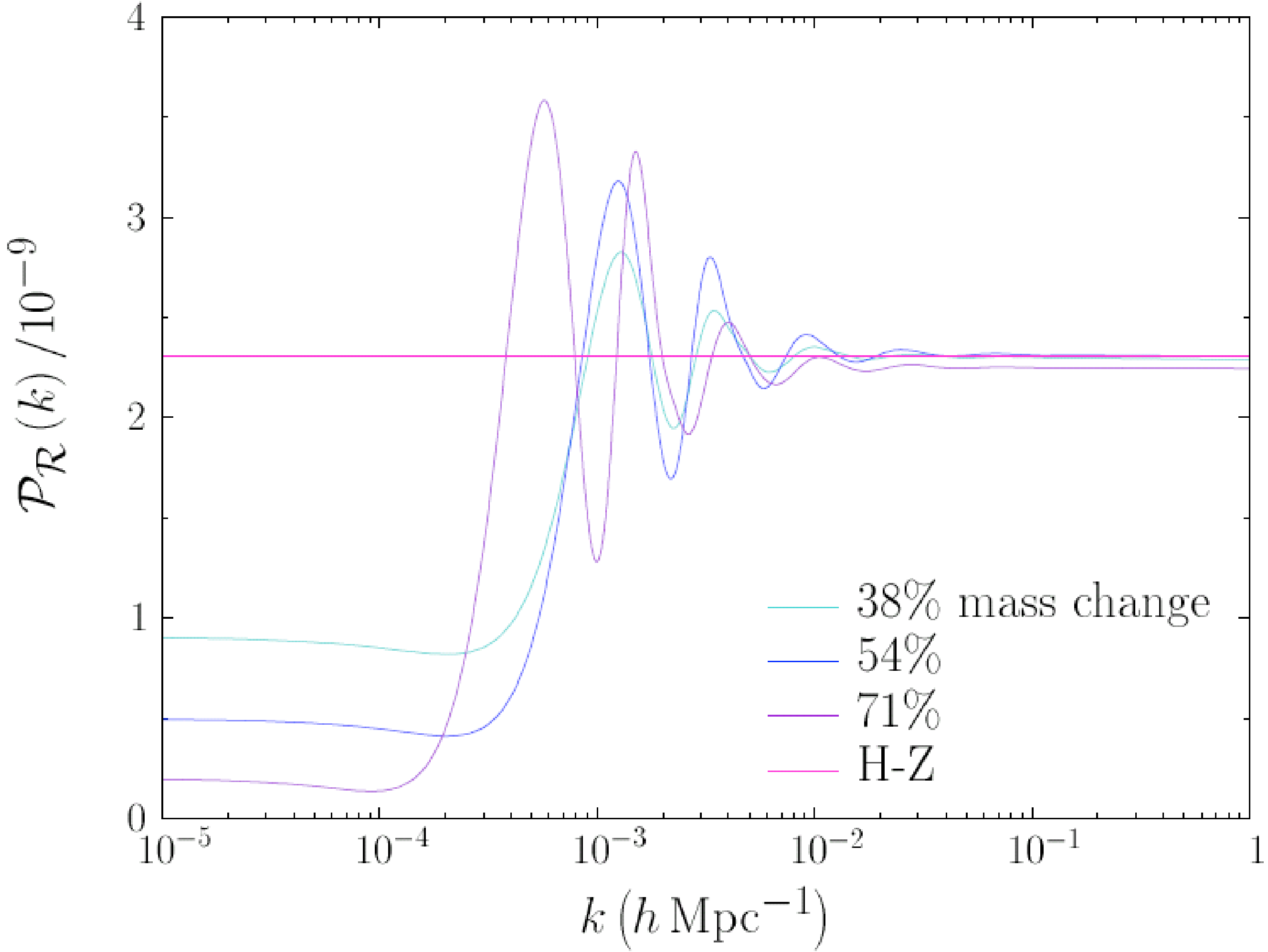
Flat directions are lifted by

- ~~SUSY~~ .
- Higher dimensional operators $\rho^n/M_{\rm P}^{n-4}$ which appear after integrating out heavy degrees of freedom

These fields undergo phase transitions *during* inflation, causing the inflaton mass to change

(Adams, Ross & Sarkar 1997)

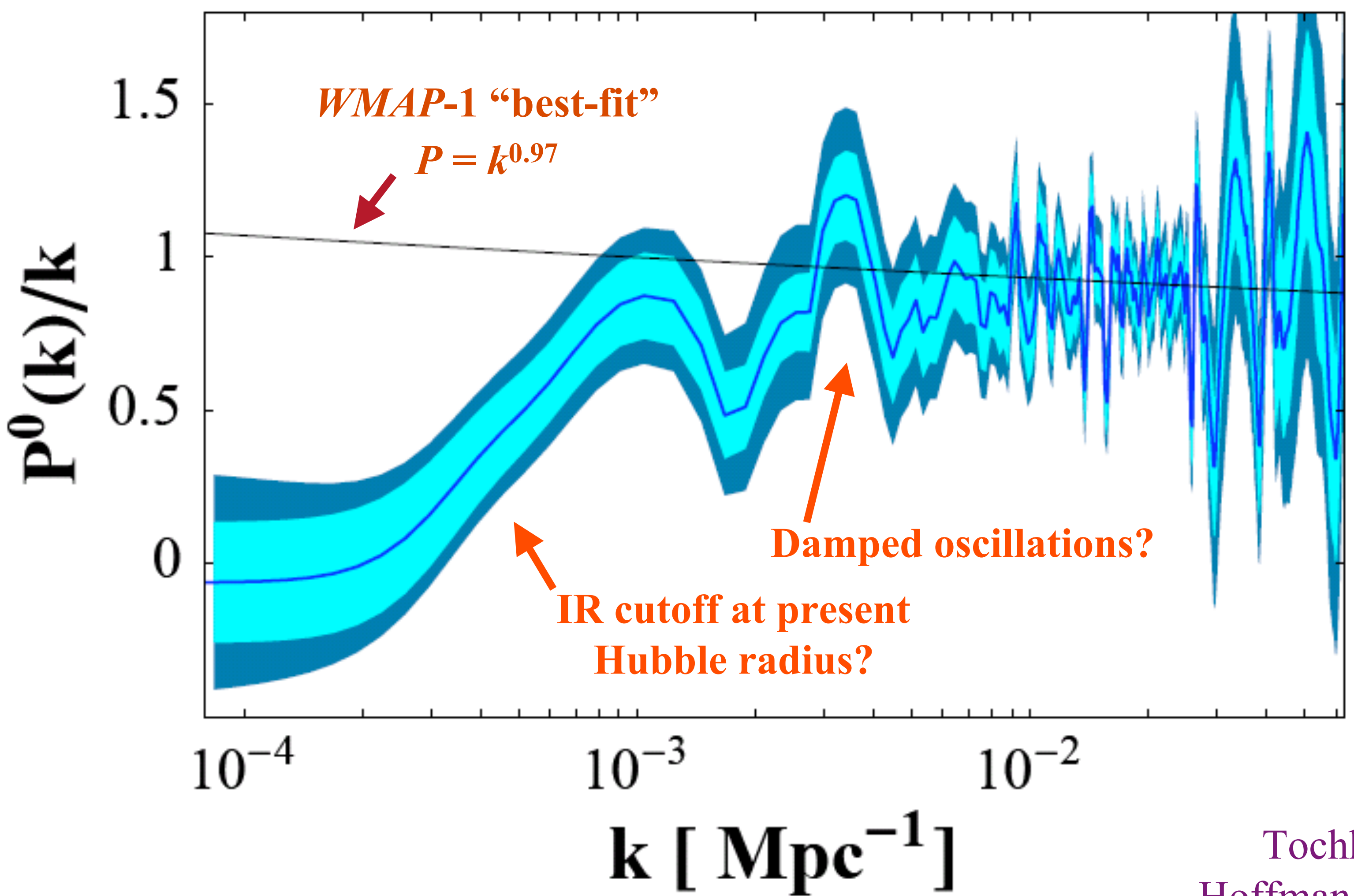
If this happens as cosmologically interesting scales 'exit the horizon' (likely if last phase of inflation did not last much longer than 50 e-folds) then 'step' like features with 'ringing' can be imprinted on the spectrum



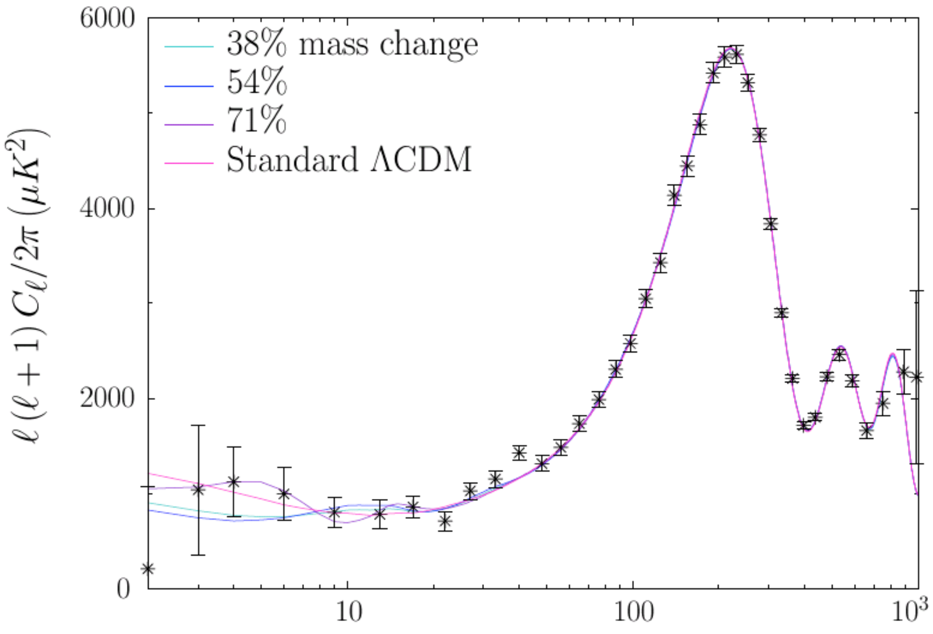
Hunt & Sarkar (2005)

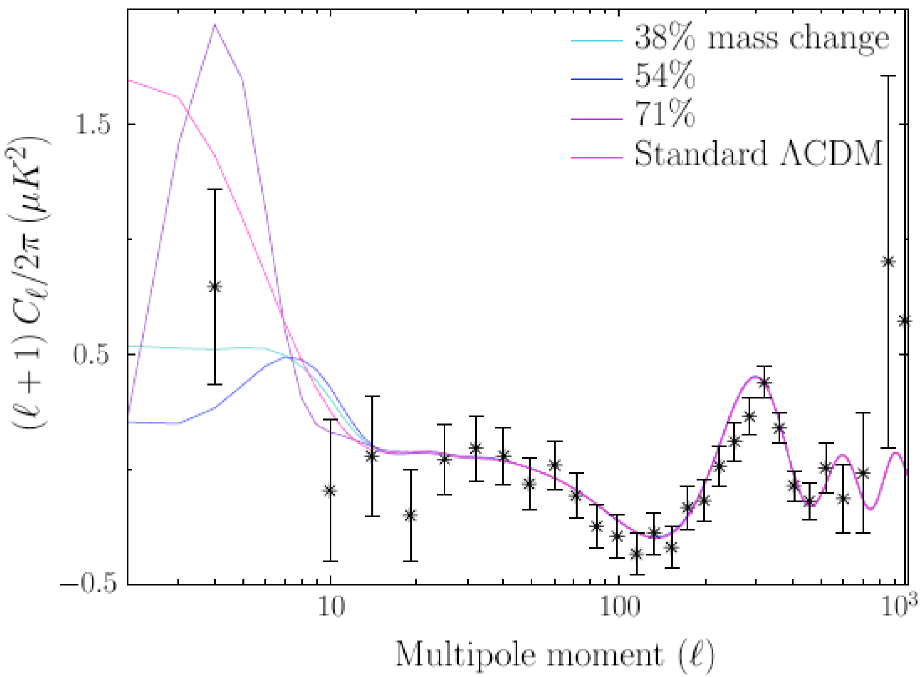
This is just what is seen by reconstructing the primordial spectrum (using *non*-parametric methods) *assuming* ΛCDM

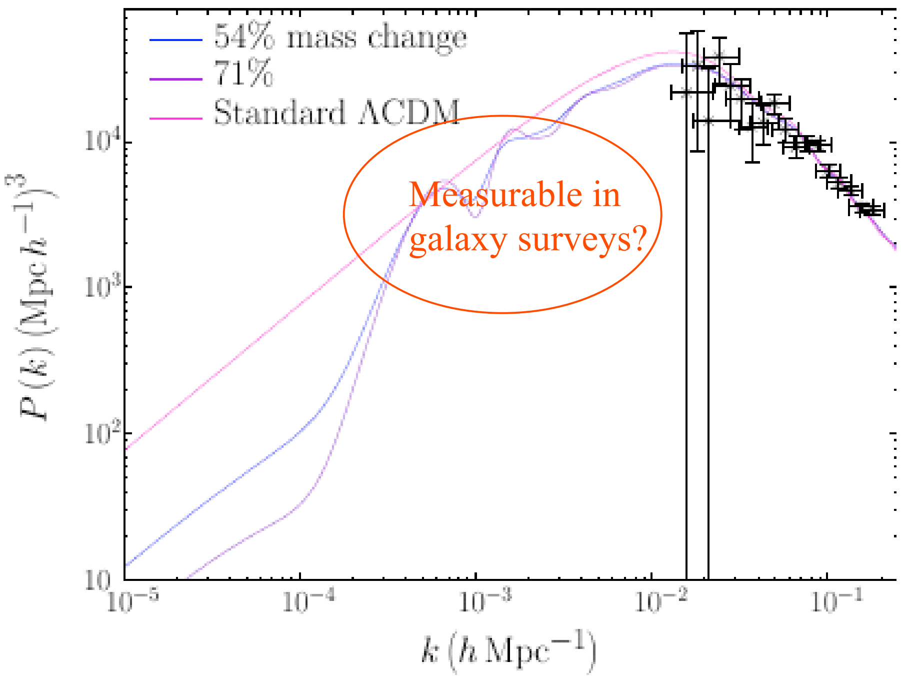
(Shafieloo & Souradeep 2004)



Tochhini-Valentini,
Hoffman & Silk (2005)







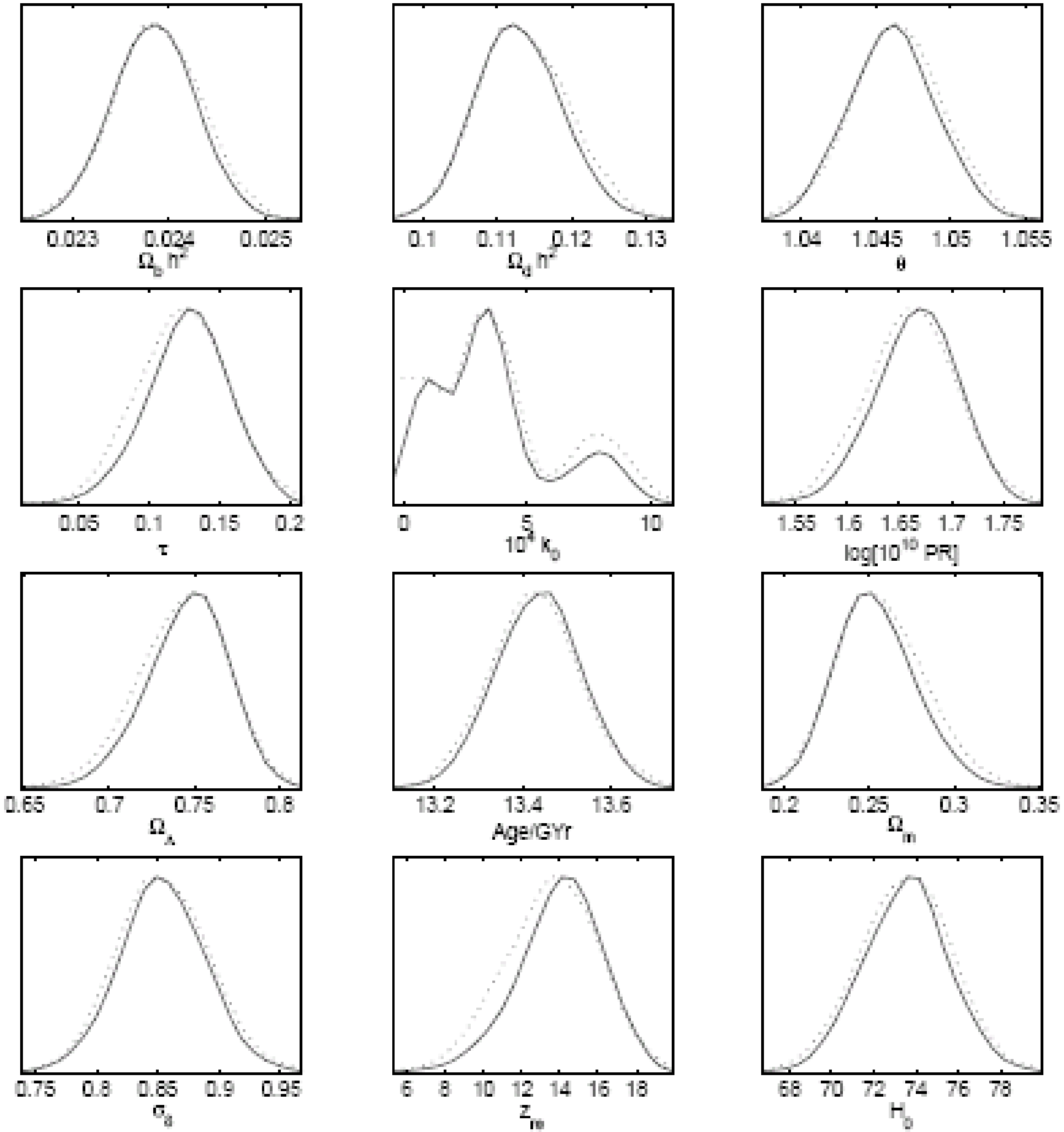
Fits are *all* acceptable … but fit parameters change little except for large-scale amplitude

n	χ^2	$\frac{\Delta m_\phi^2}{m^2}$	$\Omega_b h^2$	$\Omega_c h^2$	H_0	τ	$10^4 k_0$	$10^{10} A_s$
15	5628.9	0.38	0.0237 ±0.0010	0.0982 ±0.0204	78.9 ±8.1	0.150 ±0.076	8.04 ±5.84	9.54 ±1.09
16	5629.4	0.54	0.0236 ±0.0011	0.0992 ±0.0217	78.8 ±8.5	0.150 ±0.075	7.89 ±5.16	5.23 ±0.49
17	5629.6	0.71	0.0238 ±0.0011	0.1010 ±0.0233	78.0 ±9.2	0.131 ±0.075	3.62 ±4.74	2.21 0.20

***WMAP* does *not* require the primordial density perturbation to be scale-free**

Hunt & Sarkar (2007)

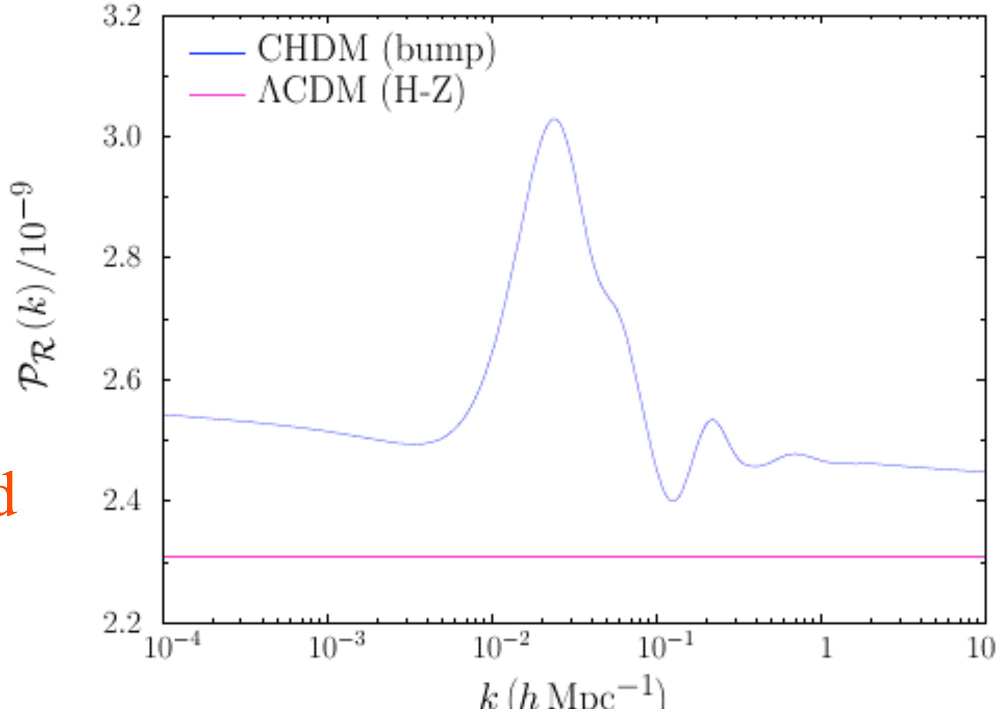
MCMC likelihood distributions for ΛCDM (‘step’ spectrum)



… not too different from ‘power law ΛCDM’

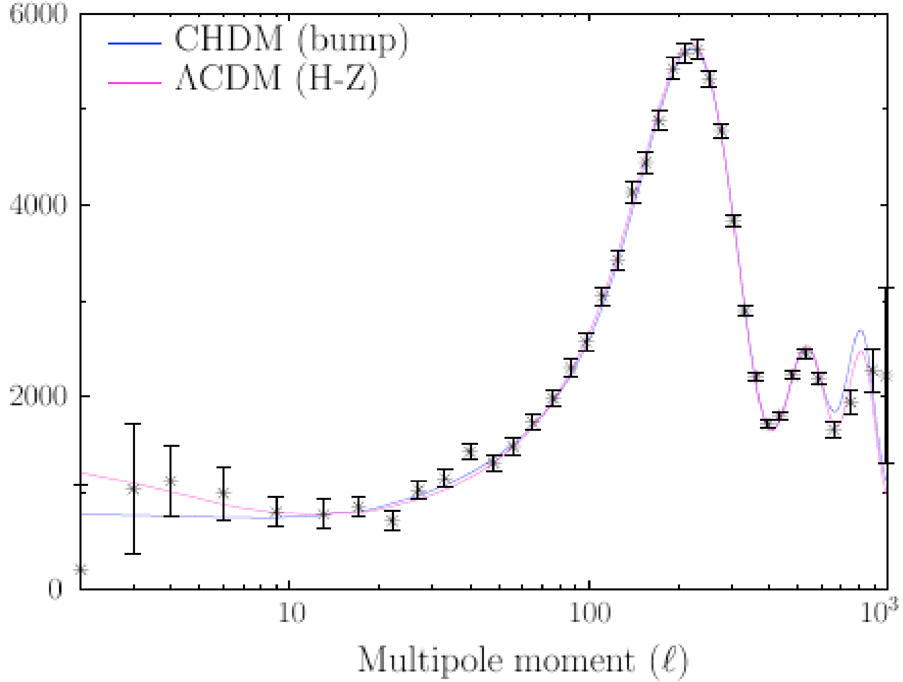
Hunt & Sarkar (2007)

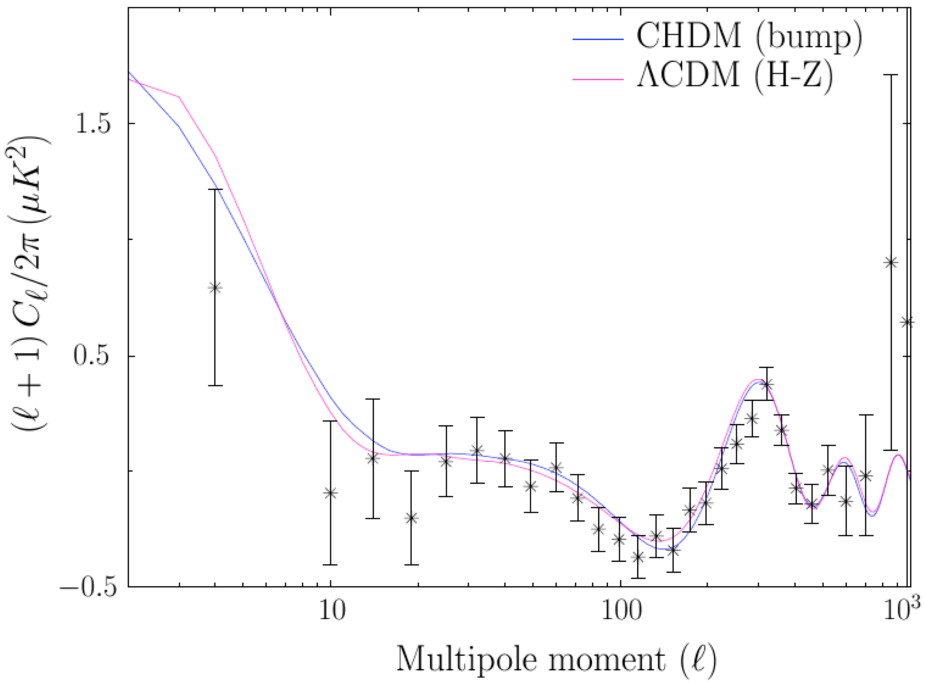
Since there are *many* flat directions fields, two phase transitions may occur in quick succession, creating a 'bump' in the primordial spectrum on cosmologically relevant scales



The *WMAP* data can then be fitted just as well with ***no dark energy***

$(\Omega_m = 1, \ \Omega_\Lambda = 0, \ h = 0.46)$

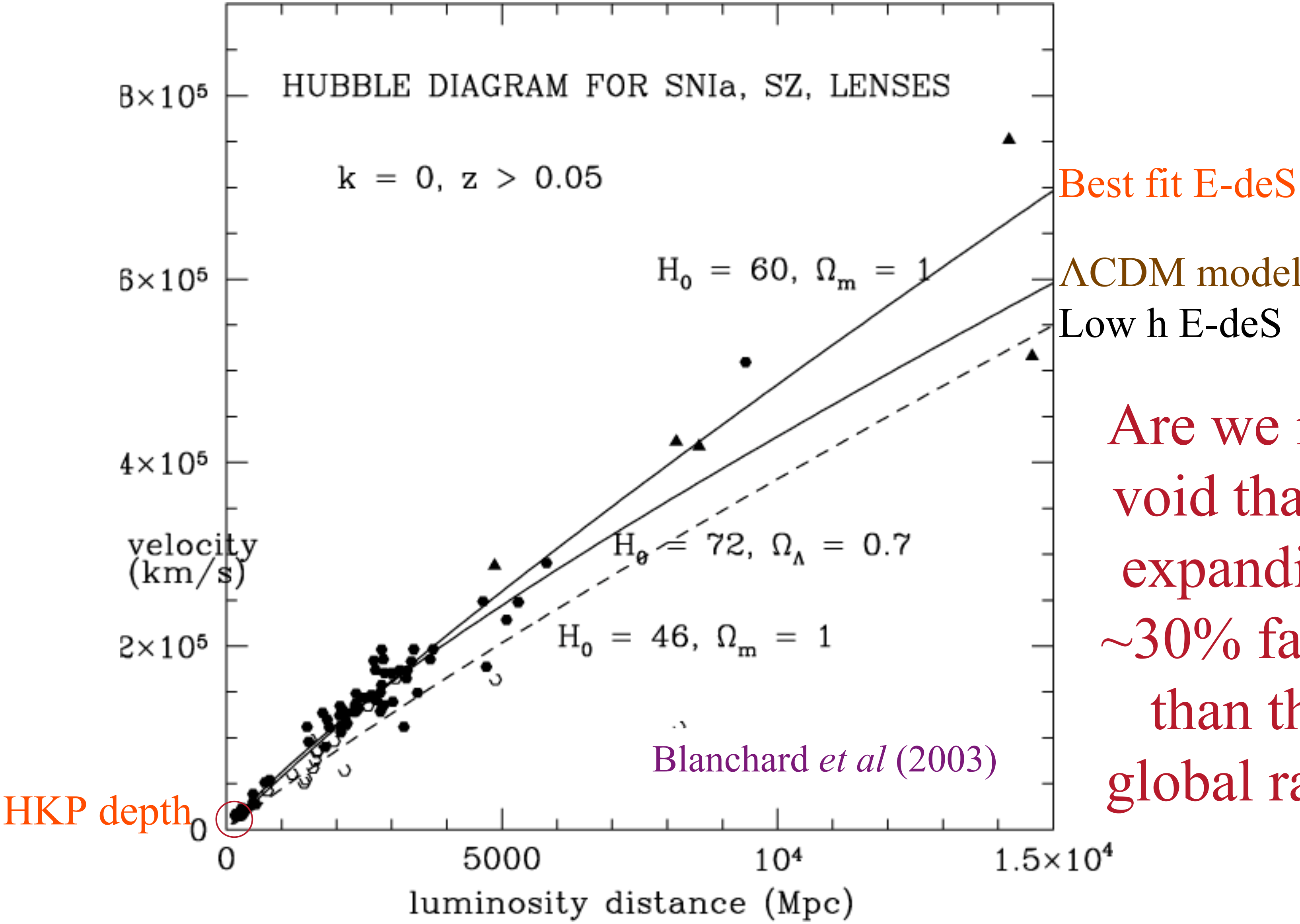




$h = 0.46$ is inconsistent with Hubble Key Project value ($h = 0.72 \pm 0.08$)

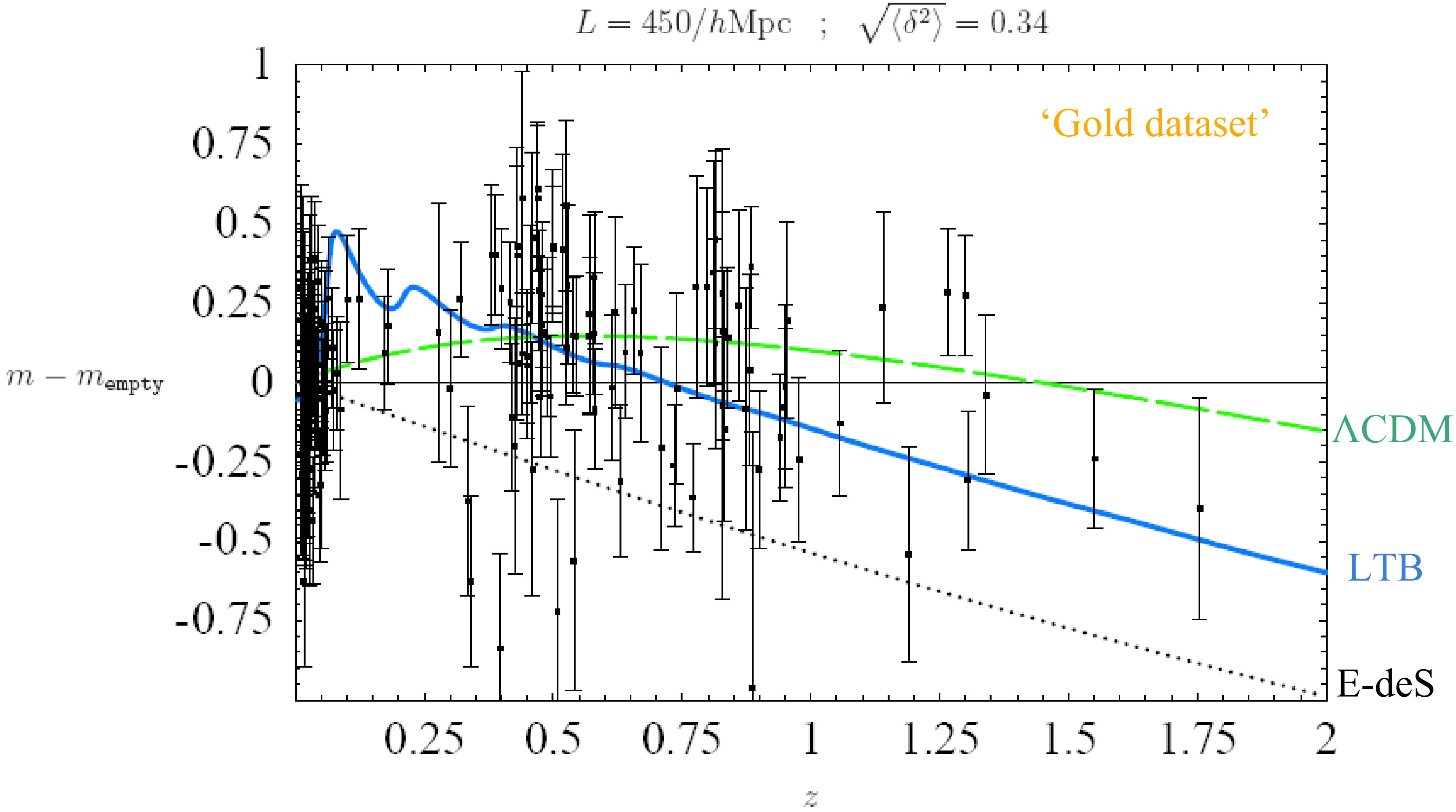
but is in fact *indicated* by direct (and much deeper) determinations

e.g. gravitational lens time delays ($h = 0.48 \pm 0.03$)



Are we in a void that is expanding ~30% faster than the global rate?

The Lemaitré-Tolman-Bondi model may even explain the SNIa Hubble diagram *without* acceleration!

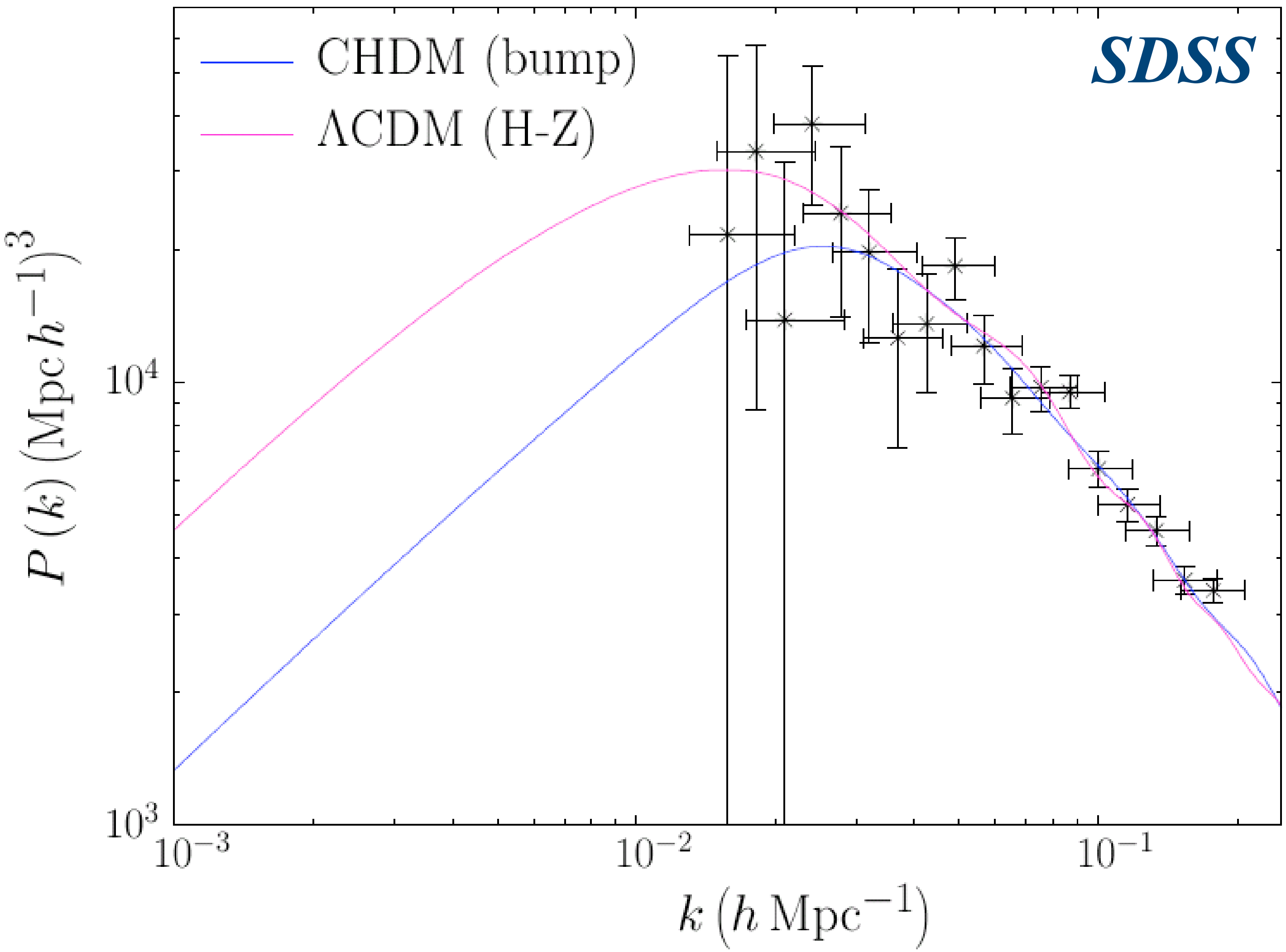


Biswas, Mansouri & Notari (2006)

The small-scale power would be excessive unless damped by free-streaming

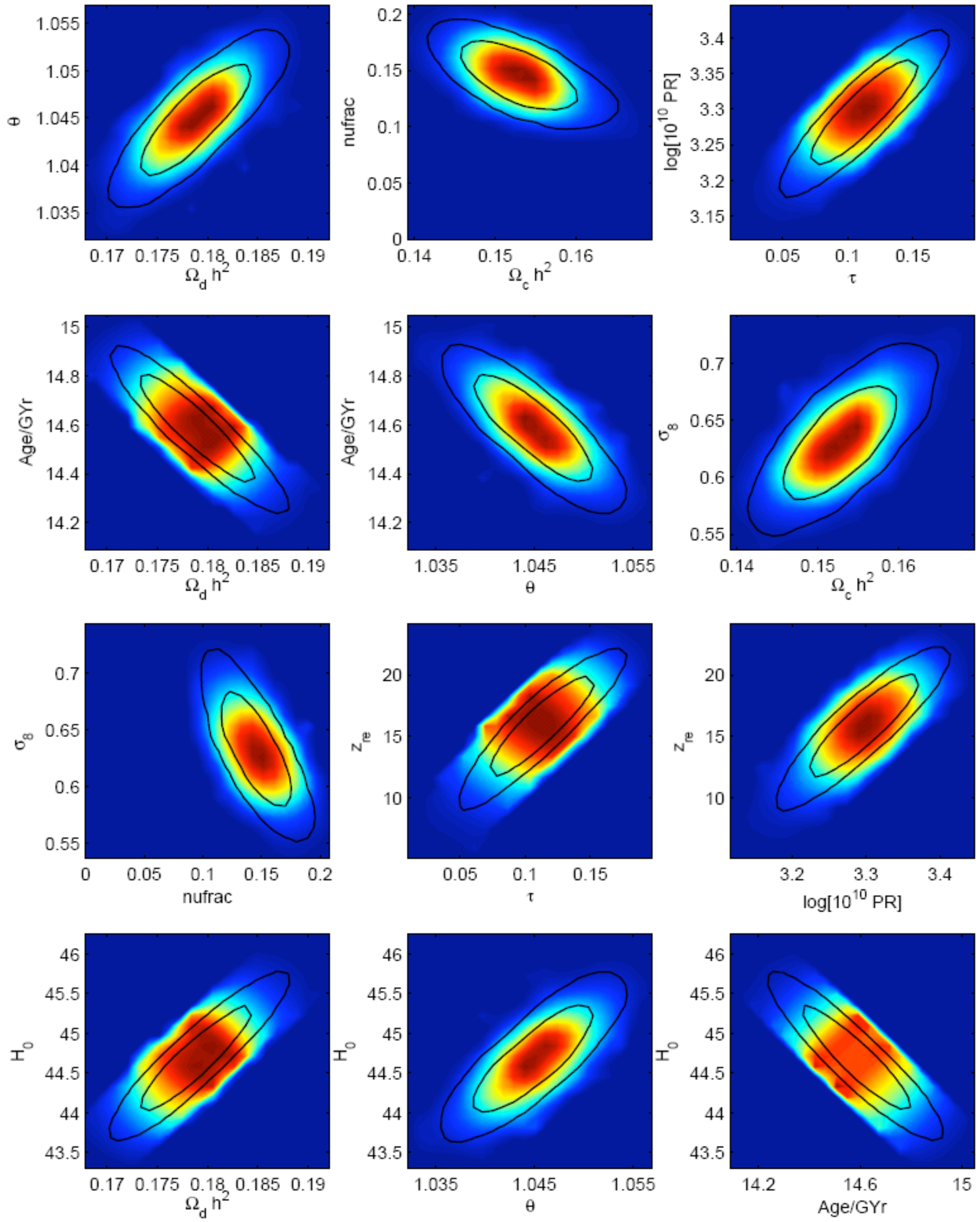
But adding 3 νs of mass 0.8 eV ($\Rightarrow \Omega_\nu \approx 0.14$) gives *good* match to large-scale structure

(note that $\Sigma m_\nu \approx 2.4$ eV – well above '*WMAP* bound')



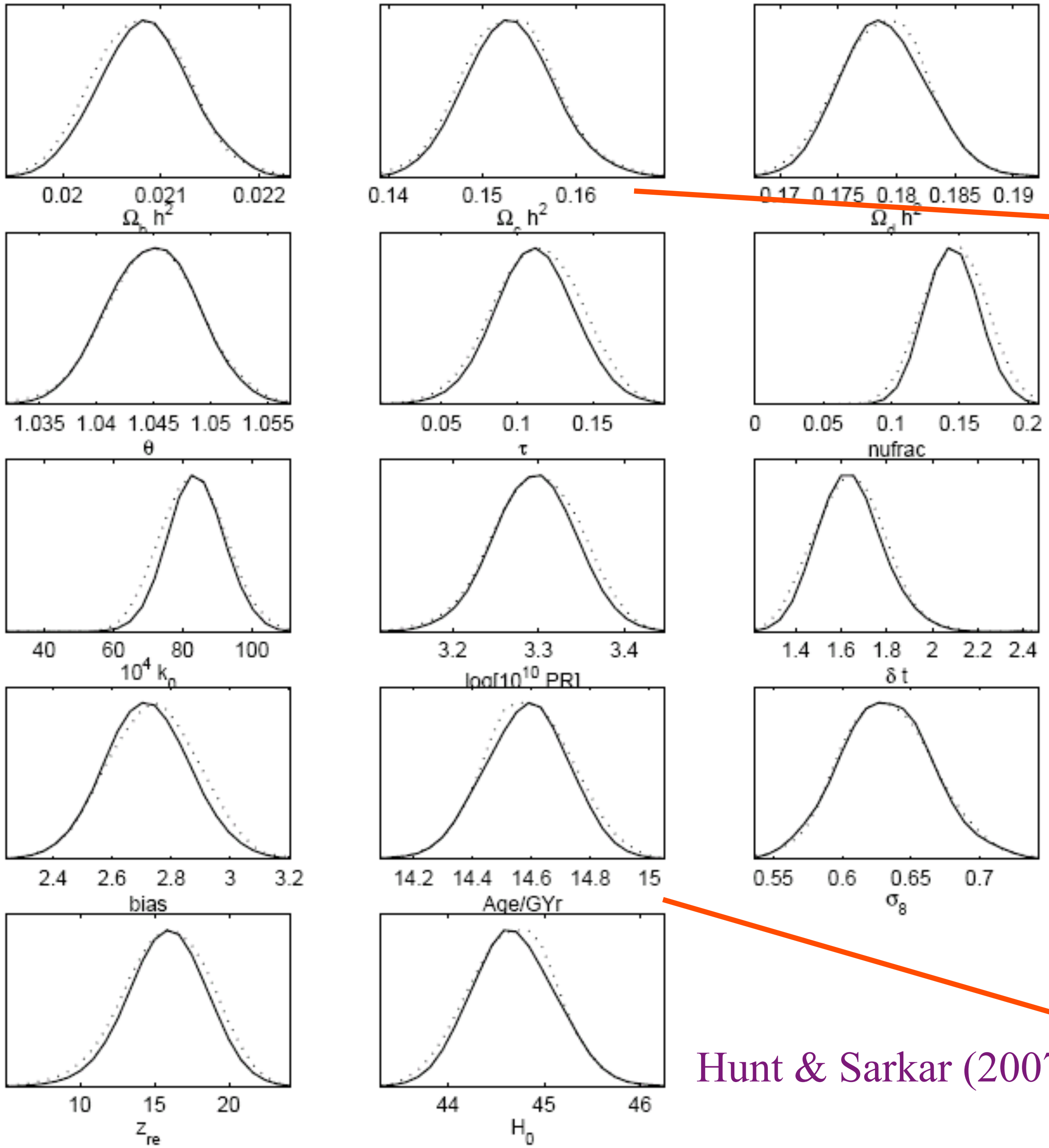
Fit gives $\Omega_b h^2 \approx 0.021 \rightarrow$ BBN √ $\Rightarrow$ baryon fraction in clusters predicted to be ~11% √

Parameter degeneracies - CHDM universe ('bump' spectrum)



Hunt & Sarkar (2007)

MCMC likelihoods - CHDM universe ('bump' spectrum)



This is ~50% higher than the 'WMAP value' used widely for CDM abundance

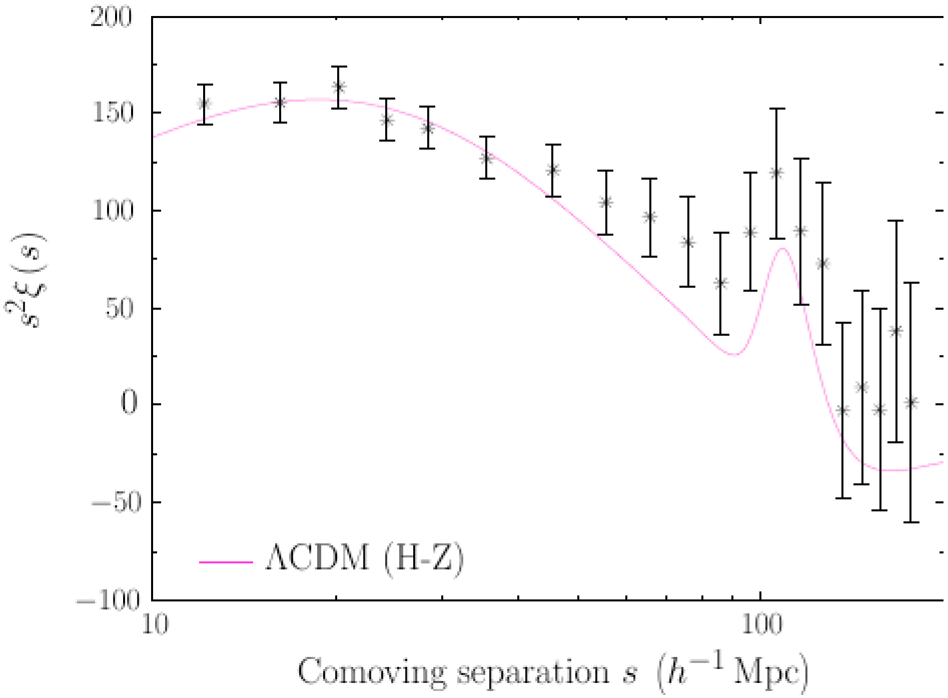
To fit the large-scale structure data *requires* ~eV mass neutrinos

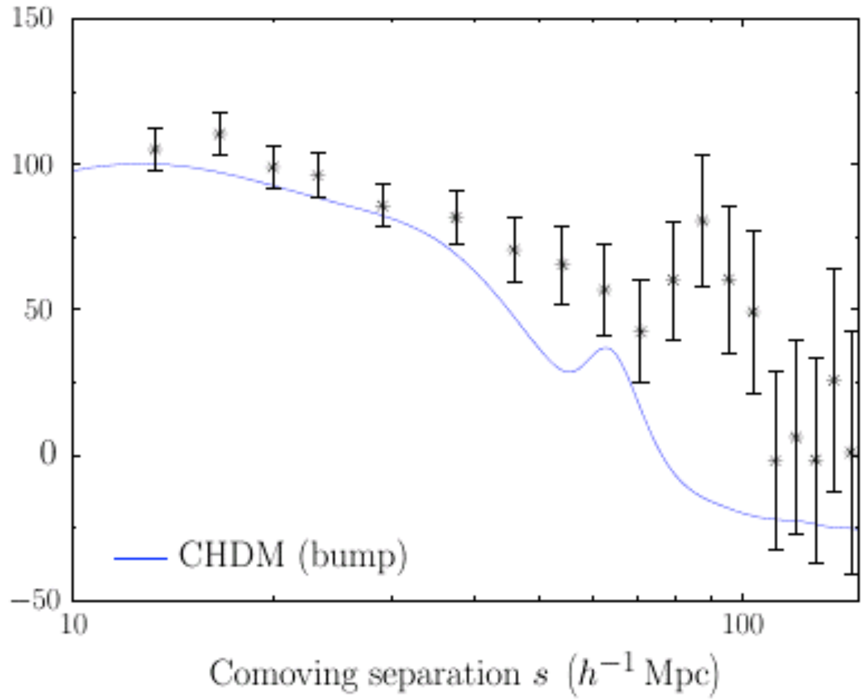
Consistent with data on clusters and weak lensing

Consistent age for the universe

Hunt & Sarkar (2007)

However in the E-deS model, the 'baryon acoustic peak', although at the ~same *physical* scale, is displaced in observed (redshift) space …





We *can* match the angular size of the 1st acoustic peak at $z \sim 1100$ by taking $h \sim 0.5$, but we *cannot* then also match the angular size of the baryonic feature at $z \sim 0.35$

But for inhomogeneous LTB model ($h \sim 0.7$ for $z < 0.08$, then $h \to 0.5$) **angular diameter distance @ z = 0.35 is similar to ΛCDM**

Biswas, Mansouri, Notari (2006)

Conclusions

WMAP data have supposedly confirmed the need for a dominant component of dark energy from precision observations of the CMB

- But we cannot simultaneously determine *both* the primordial spectrum and the cosmological parameters from just CMB (and LSS) data

We do not know the physics behind inflation hence cannot just assume that the generated scalar density perturbation is scale-free … and then conclude that the data confirm the power-law ΛCDM model

The data provides intriguing hints for features in the primordial spectrum … this has crucial implications for parameter extraction e.g. a 'bump' in the spectrum allows the data to be well-fitted *without dark energy*!

- Given the unacceptable degree of fine-tuning required to accommodate dark energy, we should explore if the SNIa Hubble diagram, BAO etc can be equally well accounted for in inhomogeneous cosmolgical models

The FRW model may be *an oversimplified* description of the universe