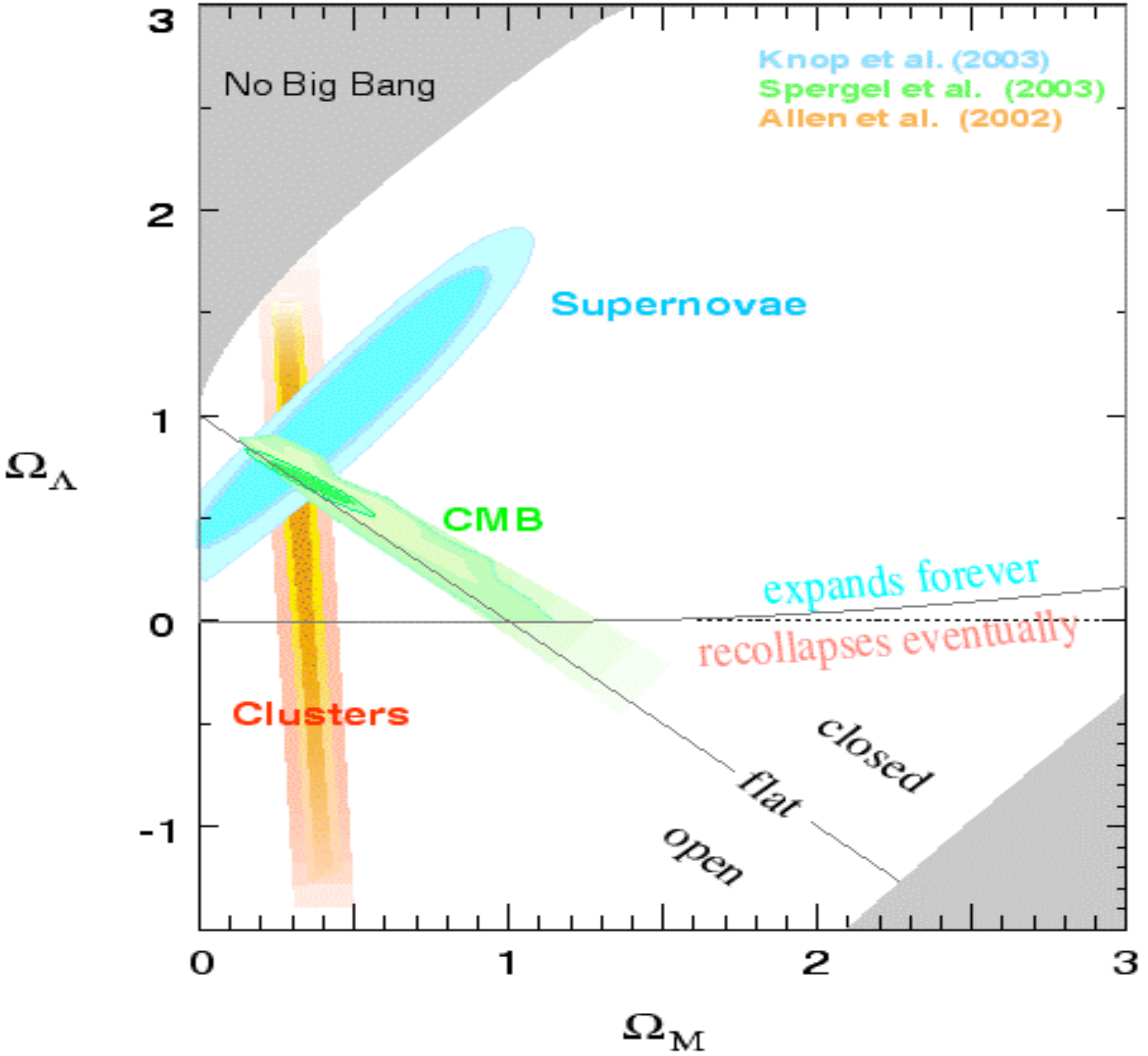
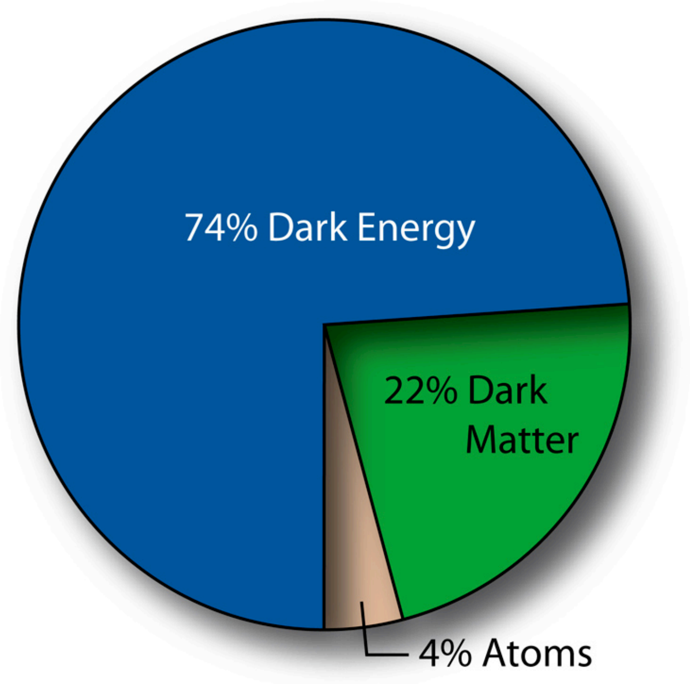
Does dark energy exist?





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Cosmology, Strings & Phenomenology

Alba Nova, 11-20 June 2007

The standard cosmological model

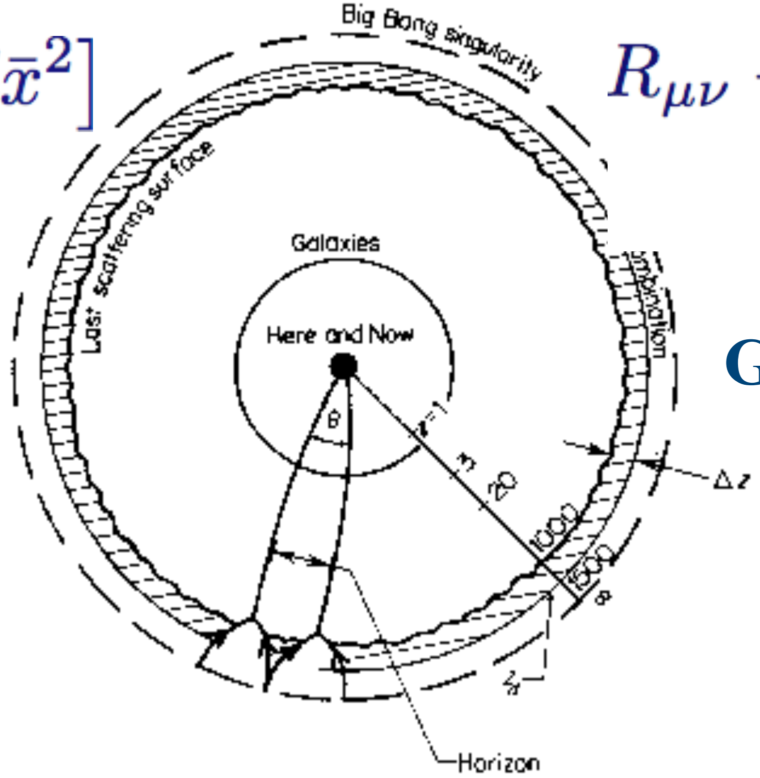
(maximally symmetric space-time containing ideal fluids)

… necessarily exhibits dark energy!

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

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

Space-time metric:
Robertson-Walker



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

Geometrodynamics:
Einstein

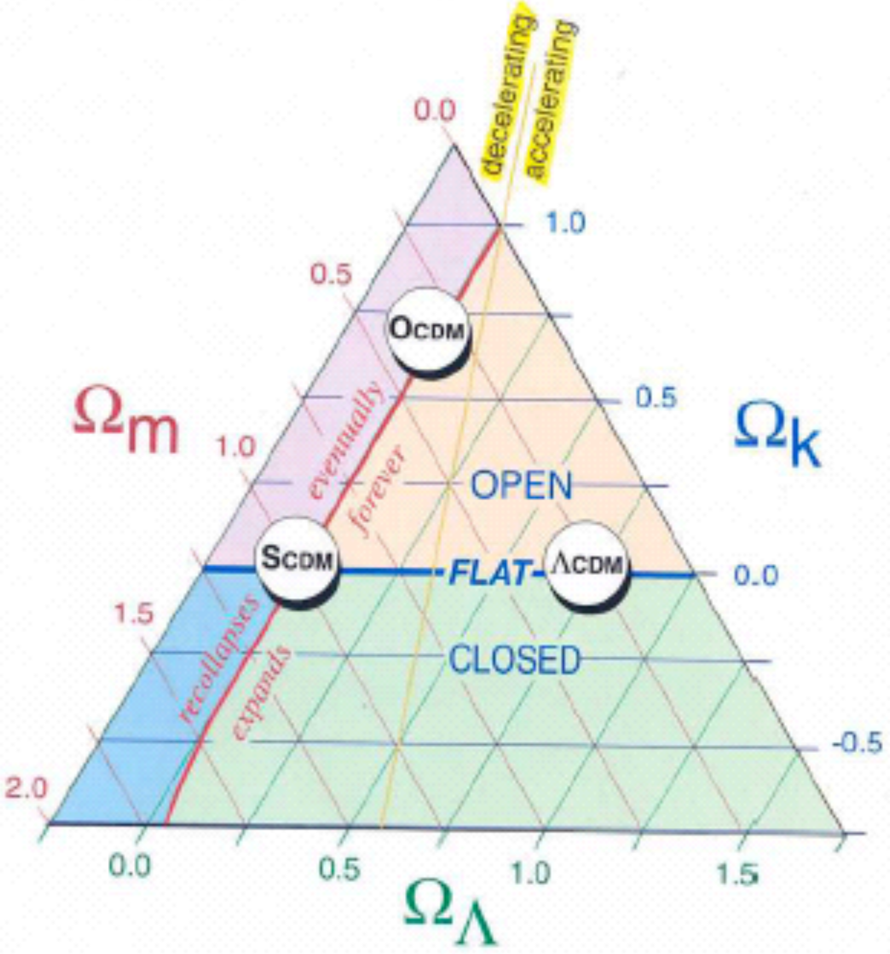
$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\mathrm{N}}\rho_{\mathrm{m}}}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

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

The Cosmic Triangle

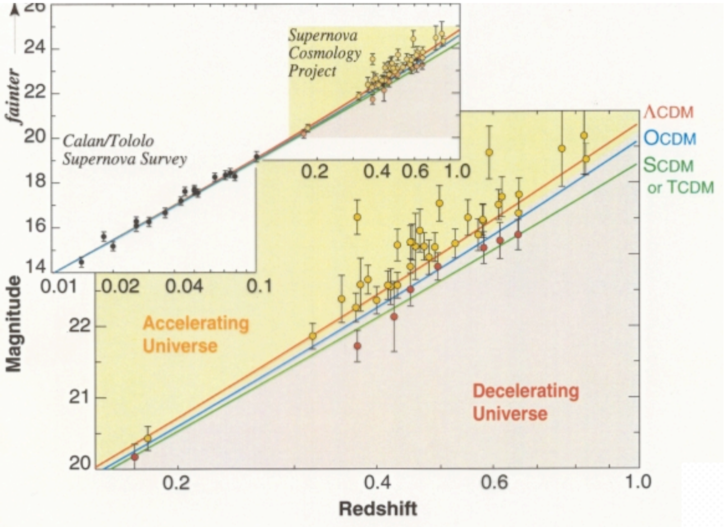
Sum rule: $\Omega_m + \Omega_k + \Omega_\Lambda = 1$

$\rho_m / \frac{3H_0^2}{8\pi G}$ $\quad -k/a_0^2 H_0^2 \quad$ $\Lambda/3H_0^2$

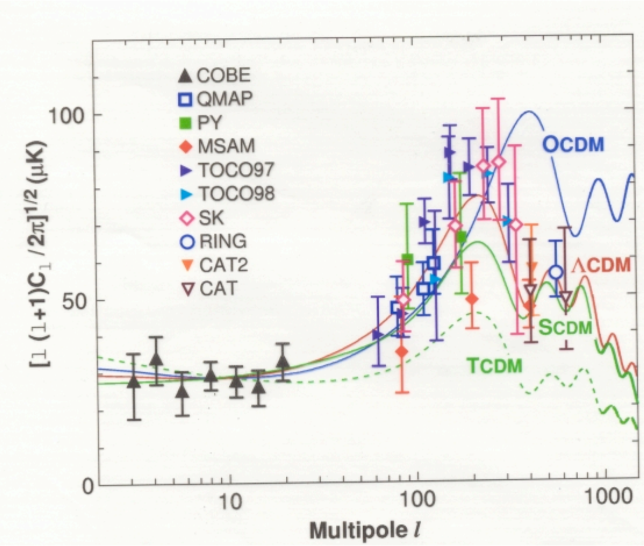


Estimating Ω_Λ from this **sum rule** is *likely* to yield a non-zero value, given the inevitable uncertainties in measuring Ω_m and Ω_k …

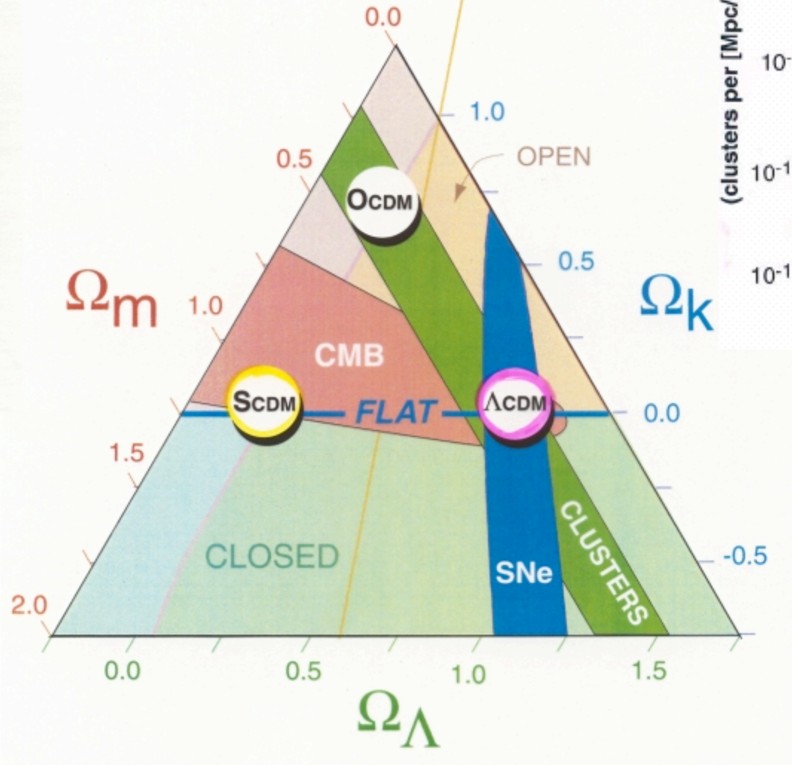
Even so it was claimed that 'Cosmic Concordance' *requires* dark energy

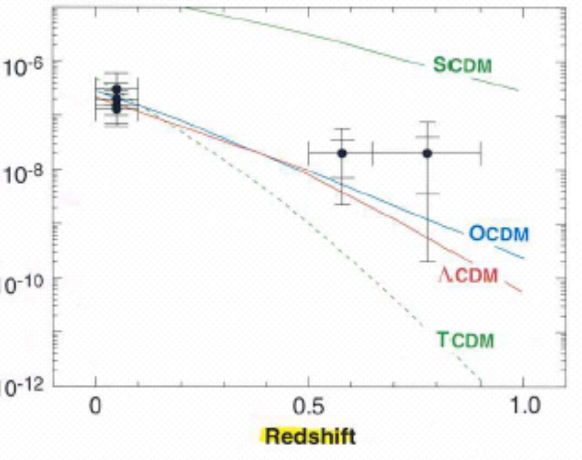


$0.8\Omega_m - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$



$\Omega_m + \Omega_\Lambda \approx 1.0 \pm 0.03$





$\Omega_m \sim 0.3$

Bahcall *et al* (2000)

$\Omega_\Lambda \sim O(1) \Rightarrow$ vacuum energy: $\rho_\Lambda \sim (10^{-12}\,\text{GeV})^4$

- ► if $\Omega_\Lambda = 0$ … then must explain how different contributions to ρ_Λ (ranging possibly up to $\sim M_P^4$) cancel *exactly*?
- ► if $\Omega_\Lambda \approx \Omega_m$ … then must explain also why is $\rho_\Lambda \approx \rho_m$ *today*?

Models of evolving scalar fields ('**quintessence**') address the second problem *only* … this requires $V(\Phi)^{1/4} \sim 10^{-12}$ GeV but $\sqrt{d^2V/d\Phi^2} \sim H_0^{-1} \sim 10^{-42}$ GeV to ensure slow-roll

Similar fine-tuning in models, where gravity is modified on the scale of the present Hubble radius H_0^{-1} (e.g. '**DGP brane-world**'), as an alternative to vacuum energy

Would seem **natural** to have $\Lambda \sim O(H^2)$ *always*, but this is just a redefinition of G_N! … **ruled out** by Big Bang nucleosynthesis (requires G_N to be within 5% of lab value)

Thus there can be no 'natural' explanation for the coincidence problem

Do we see $\Lambda \sim O(H_0^2)$ because that is the observational sensitivity?

Why is $\Omega_\Lambda \sim 0.7 \Rightarrow \rho_\Lambda^{1/4} \sim 10^{-3}$ eV physically ridiculous?

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

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

Cosmological constant

Higgs mass correction

super-renormalisable

renormalisable

non-renormalisable

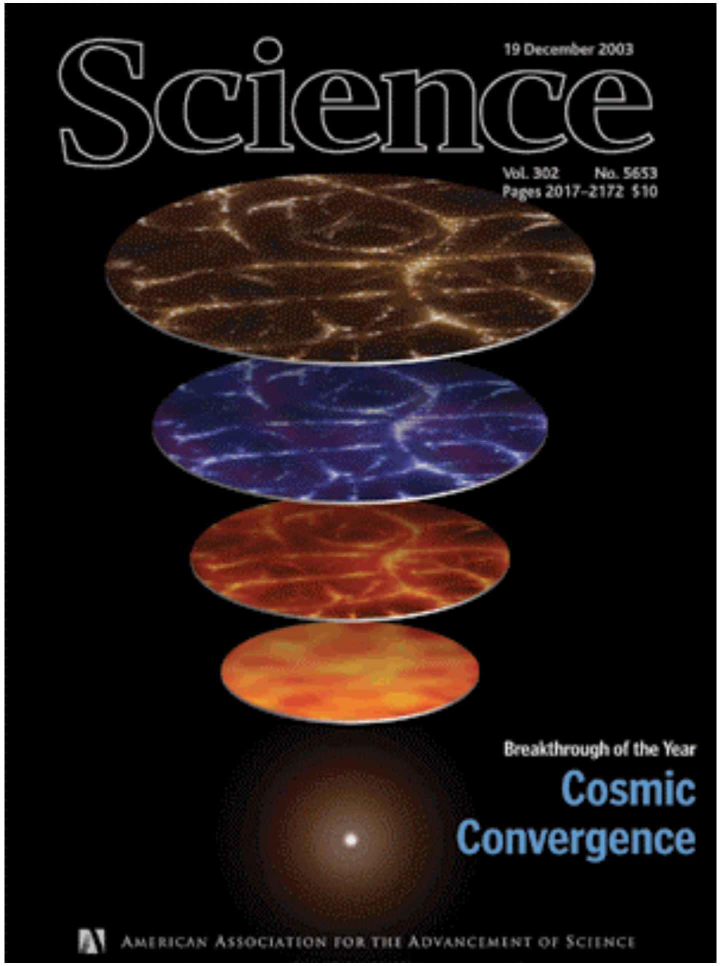
$$
\begin{aligned}
\mathcal{L}_{eff} &= \boxed{\Lambda^4} + \boxed{\Lambda^2 \Phi^2} \\
&+ (D\Phi)^2 + \overline{\Psi}\, \not{D} \Psi + F^2 + \overline{\Psi}\Psi\Phi + \Phi^4 \\
&+ \frac{\overline{\Psi}\Psi\Phi\Phi}{\Lambda} + \frac{\overline{\Psi}\Psi\overline{\Psi}\Psi}{\Lambda^2} + \dots ,
\end{aligned}
$$

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 Λ ~ 1 TeV (⇒ 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 $\times 10^{60}$!



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Pages 2017–2172 $10

Breakthrough of the Year
Cosmic Convergence

American Association for the Advancement of Science

Breakthrough Online
For an expanded version of this section, with references and links, see www.sciencemag.org/content/vol302/issue5653/#special

Breakthrough

#1 The Winner

Portraits of the earliest universe and the lacy pattern of galaxies in today's sky confirm that the universe is made up largely of mysterious dark energy and dark matter. They also give the universe a firm age and a precise speed of expansion.

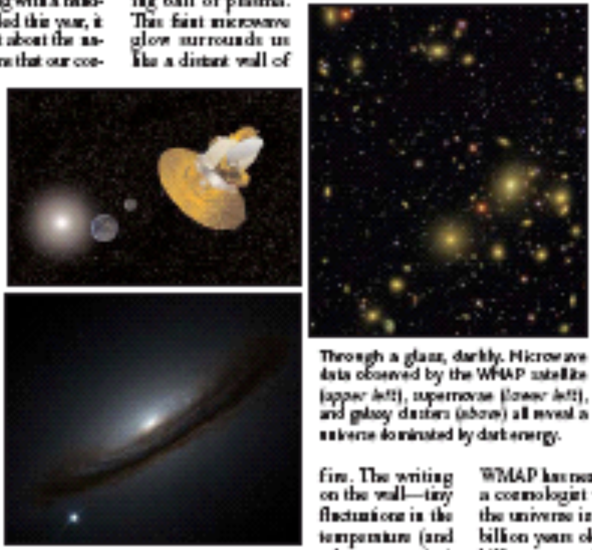
Illuminating the Dark Universe

A lonely satellite spinning slowly through the void has captured the very essence of the universe. In February, the Wilkinson Microwave Anisotropy Probe (WMAP) produced an image of the infant cosmos, of all of creation when it was less than 400,000 years old. The brightly colored picture marks a turning point in the field of cosmology: Along with a handful of other observations revealed this year, it ends a decades-long argument about the nature of the universe and confirms that our cosmos is much, much stranger than we ever imagined.

Five years ago, *Science*'s cover sported the visage of Albert Einstein looking shocked by 1998's Breakthrough of the Year: the accelerating universe. Two teams of astronomers had seen the faint imprint of a ghostly force in the death rattles of dying stars. The apparent brightness of a certain type of supernova gave cosmologists a way to measure the expansion of the universe at different times in its history. The scientists were surprised to find that the universe was expanding ever faster, rather than decelerating, as general relativity—and common sense—had led astrophysicists to believe. This was the first sign of the mysterious "dark energy," an unknown force that counteracts the effects of gravity and flings galaxies away from each other.

Although the supernova data were compelling, many cosmologists hesitated to embrace the bizarre idea of dark energy. Teams of astronomers across the world rushed to test the existence of this invisible force in independent ways. That quest ended this year. No longer are scientists trying to confirm the existence of dark energy; now they are trying to find out what it's made of, and what it tells us about the birth and evolution of the universe.

Lingering doubts about the existence of dark energy and the composition of the universe dissolved when the WMAP satellite took the most detailed picture ever of the cosmic microwave background (CMB). The CMB is the most ancient light in the universe, the radiation that streamed from the newborn universe when it was still a glowing ball of plasma. This faint microwave glow surrounds us like a distant wall of fire. The writing on the wall—tiny fluctuations in the temperature (and other properties) of the ancient light—reveals what the universe is made of.



Through a glass, darkly. Microwave data observed by the WMAP satellite (*upper left*), supernovae (*lower left*), and galaxy clusters (*above*) all reveal a universe dominated by dark energy.

Long before there were stars and galaxies, the universe was made of a hot, glowing plasma that roiled under the competing influences of gravity and light. The big bang had set the entire cosmos ringing like a bell, and pressure waves rattled through the plasma, compressing and expanding and compressing clouds of matter. Hot spots in the background radiation are the images of compressed, dense plasma in the cooling universe, and cold spots are the signatures of rarefied regions of gas.

Just as the tone of a bell depends on its shape and the material it's made of, so does the "sound" of the early universe—the relative abundances and sizes of the hot and cold spots in the microwave background—depend on the composition of the universe and its shape. WMAP is the instrument that finally allowed scientists to hear the celestial music and figure out what sort of instrument our cosmos is.

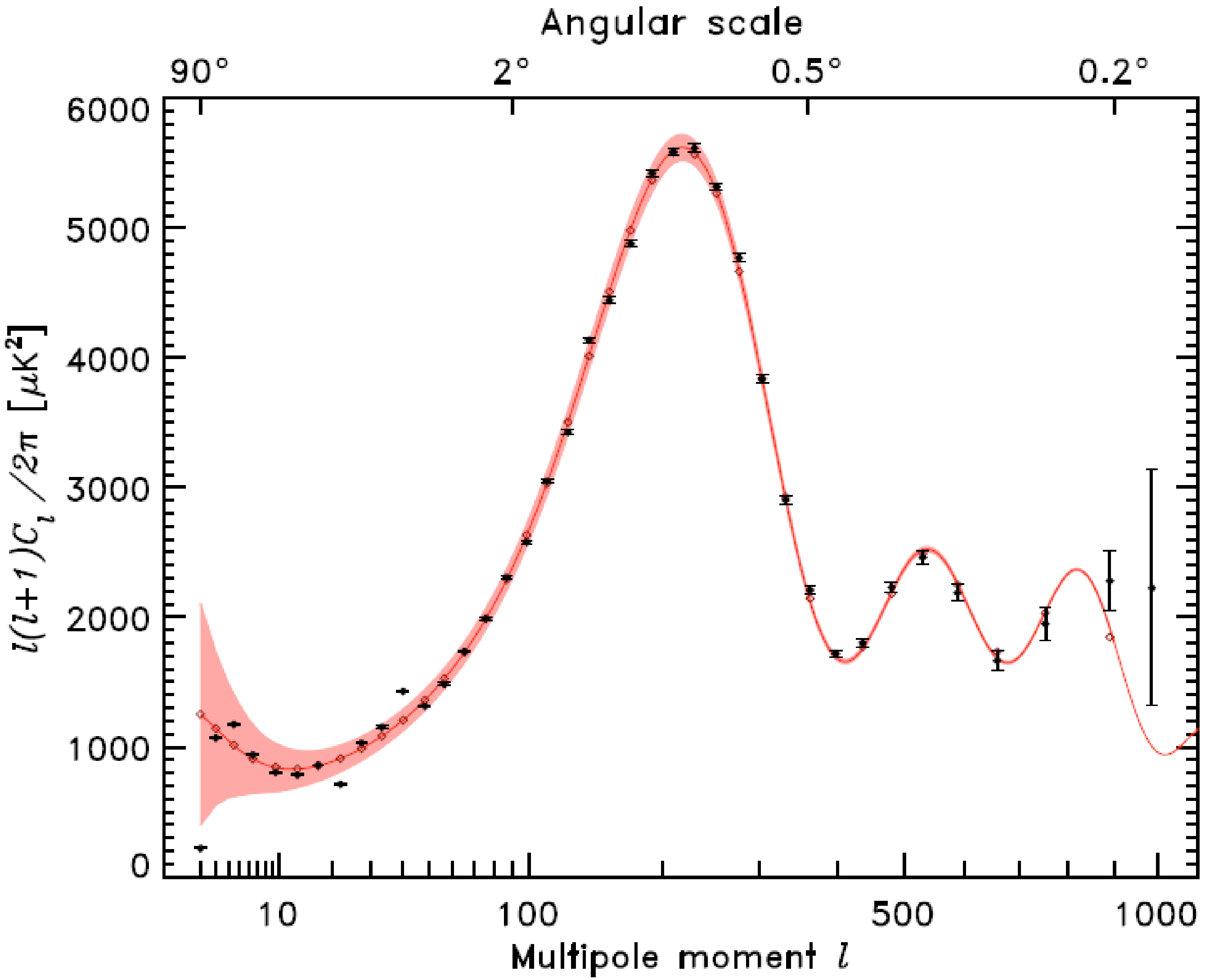
The answer was disturbing and comforting at the same time. The WMAP data confirmed the incredibly strange picture of the universe that other observations had been painting. The universe is only 4% ordinary matter, the stuff of stars and trees and people. Twenty-three percent is exotic matter: dark mass that astrophysicists believe is made up of an as-yet-undetected particle. And the remainder, 73%, is dark energy.

The tone of the cosmic bell also reveals the age of the cosmos and the rate at which it is expanding, and WMAP has nearly perfect pitch. A year ago, a cosmologist would likely have said that the universe is between 12 billion and 15 billion years old. Now the estimate is 13.7 billion years, plus or minus a few hundred thousand. Similar calculations based on WMAP data have also pinned down the rate of the universe's expansion—71 kilometers per second per megaparsec, plus or minus a few hundredths—and the universe's "shape": slate flat. All the arguments of the last few decades about the basic properties of the universe—its age, its expansion rate, its composition, its density—have been settled in one fell swoop.

As important as WMAP is, it is not this year's only contribution to cosmologists' understanding of the history of the universe. The Sloan Digital Sky Survey (SDSS) is mapping out a million galaxies. By analyz-

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

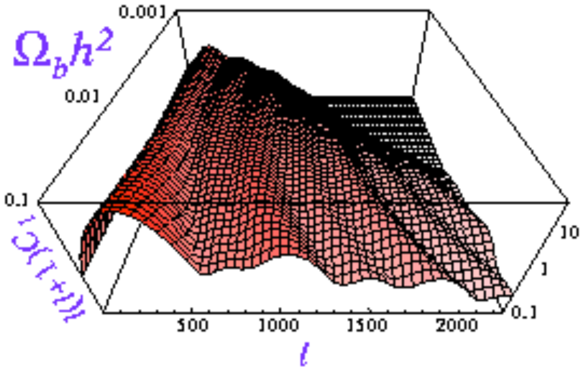
Best-fit: $\Omega_m h^2 = 0.13 \pm 0.01$, $\Omega_b h^2 = 0.022 \pm 0.001$, $h = 0.73 \pm 0.05$, $n = 0.95 \pm 0.02$



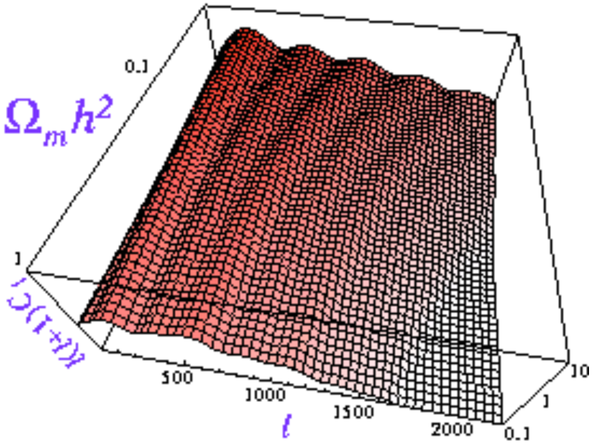
But the χ^2/dof = 1049/982 ⇒ probability of only ~7% that this model is correct!

Cosmological parameters in the CMB

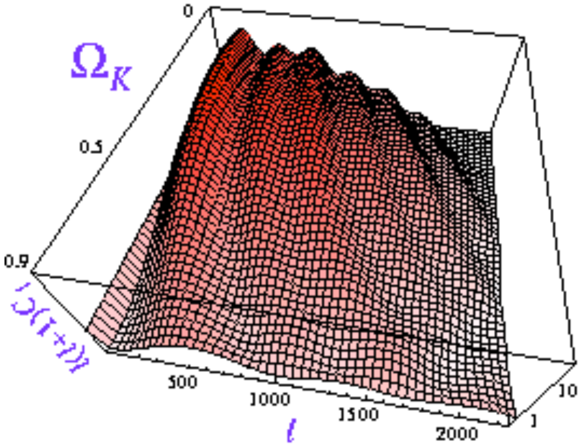
Baryon–Photon Ratio



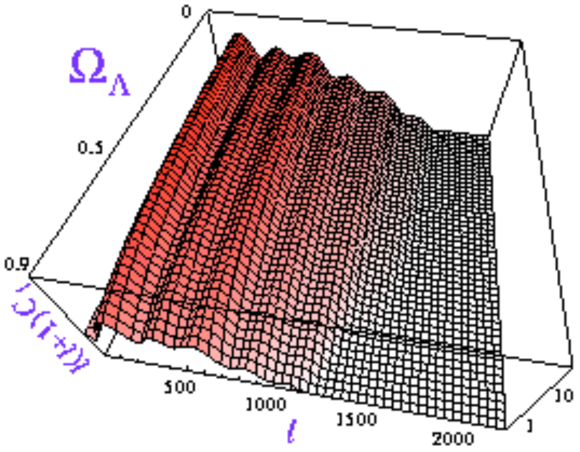
Matter–Radiation Ratio



Curvature



Cosmological Constant



Cosmological constant has (a rather mild) effect on distance to last scattering surface

So must use other data in conjunction …

Large-scale structure:

Autocorrelation of galaxies measures $\Omega_m h$ and $\Omega_b h$

Three-point correlation sensitive to bias ($\sim 1/\sigma_8$)

Peculiar velocity field measures $\sigma_8 \Omega_m^{0.6}$

… but these 'measurements', especially at small scales (Lyman-α forest), are sensitive to *deviation of primordial spectrum from scale-invariant form* and possible *hot dark matter* component

SN Ia Hubble Diagram

… measures d_L, with local calibration, so sensitive to assumption of *homogeneity*

Baryon 'acoustic peak'

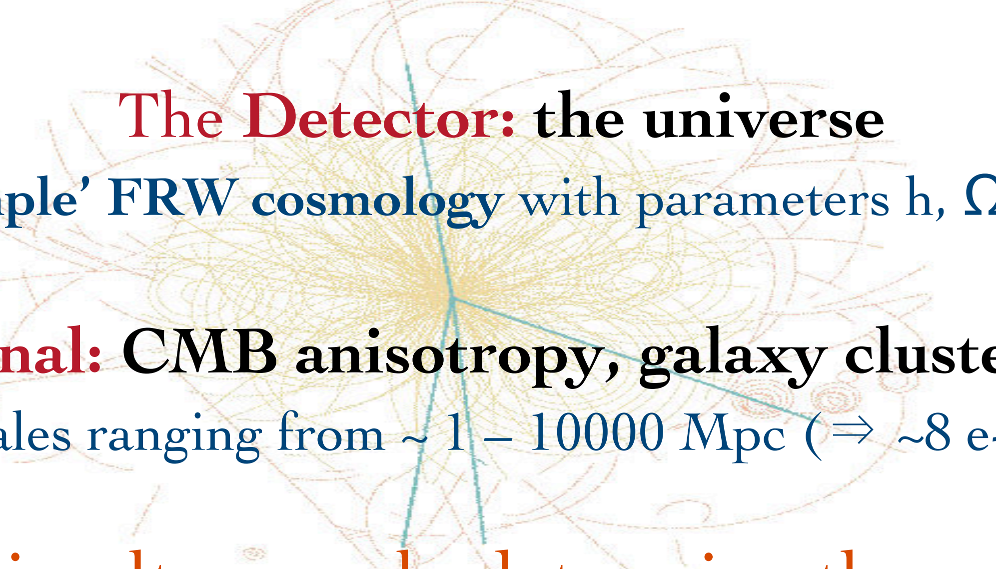
… measures d_A, and is also sensitive to assumption of *homogeneity*

Clusters:

Evolution of number density with redshift, baryon fraction

… assumed cluster scaling relations found to be *violated* - needs further study

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:

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

But models of inflation generally predict departures from scale-invariance

e.g. 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: $V(\Phi) \simeq V_o - \beta\Phi^3 + \ldots \Rightarrow n \simeq 1 - 4/N_* \sim 0.92$

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

Such a 'tilt' is consistent with the *WMAP* data but the model fit is poor ('glitches')

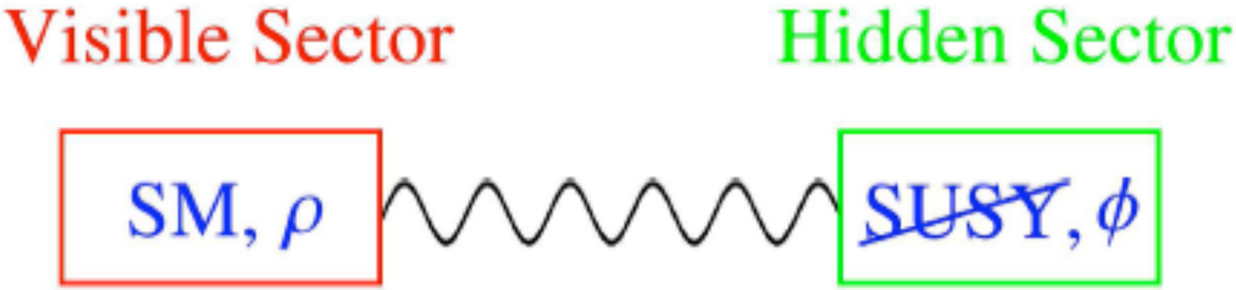
In **hybrid models**, inflation is ended by the 'waterfall' field, *not* due to the steepening of $V(\Phi)$, so spectrum can be closer to scale-invariant …

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, ⋯)



Visible Sector

Hidden Sector

SM, ρ

~~SUSY~~, ϕ

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

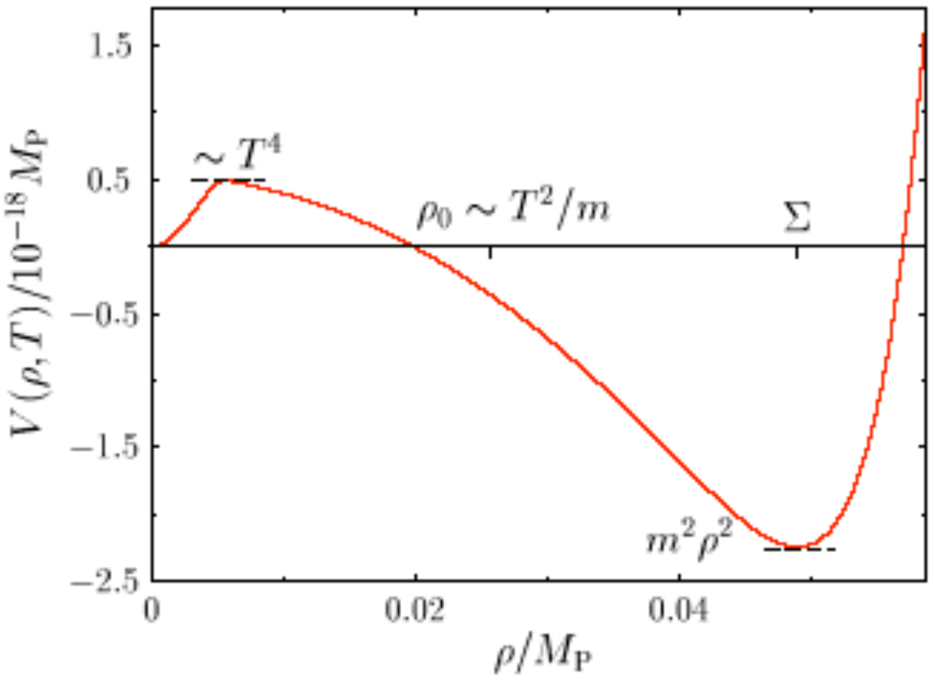
Flat directions are lifted by

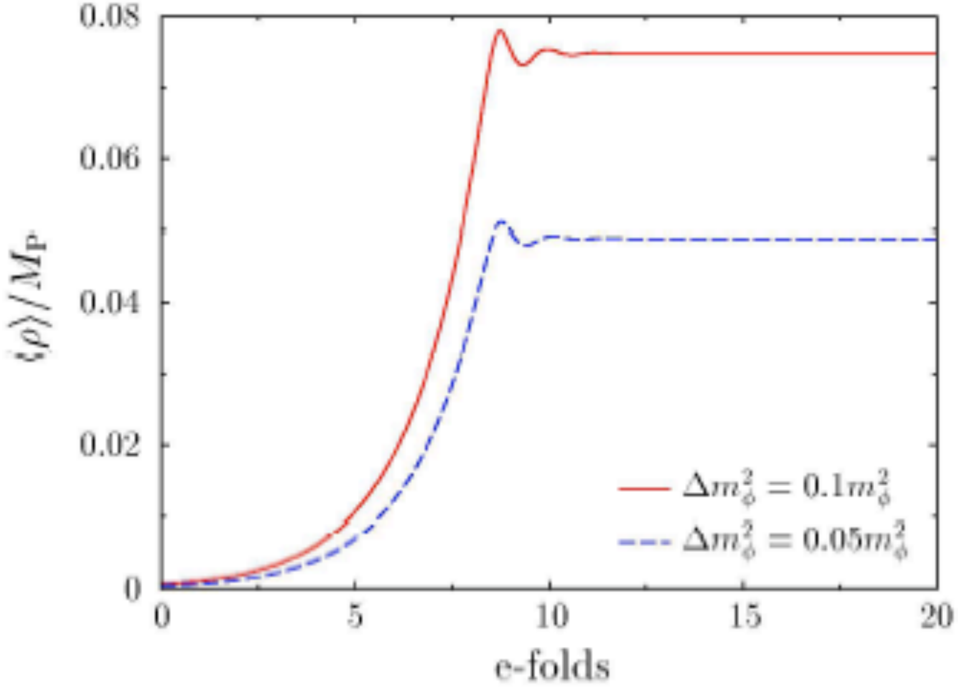
- ~~SUSY~~ .
- Higher dimensional operators $\rho^n/M_{\mathrm{P}}^{n-4}$ which appear after integrating out heavy degrees of freedom

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

(Adams, Ross & Sarkar 1997)

These fields will evolve rapidly to their minima (and thus acquire a large mass) as the universe *cools* during inflation

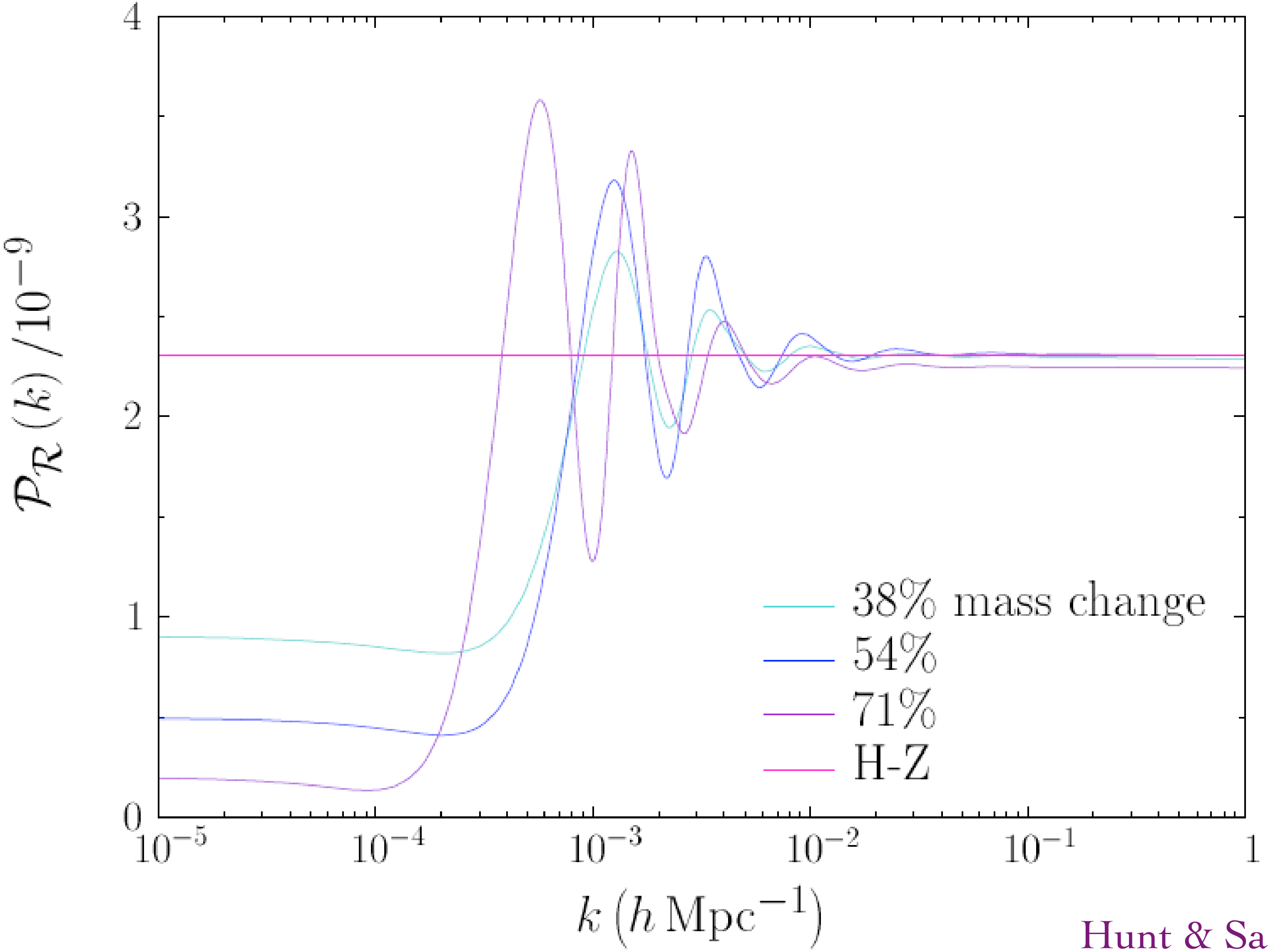




The inflaton field couples to these fields hence its own mass will change *suddenly* ⇒ 'features' in the perturbation spectrum

The phase transition(s) will occur if the initial conditions are thermal … the 'features' will be visible if this (last) phase of inflation lasts just long enough to create present Hubble volume

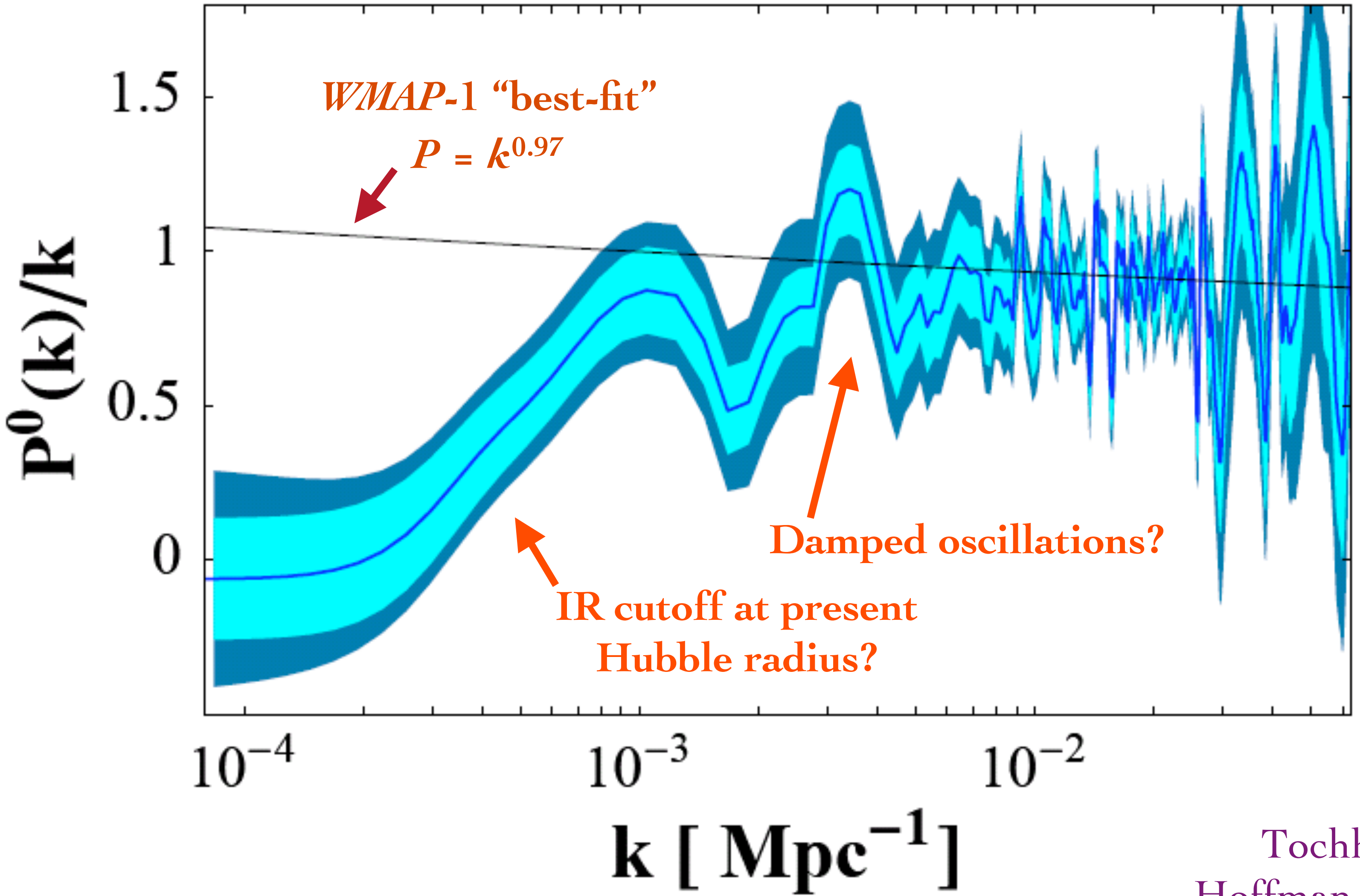
If this happens as cosmologically interesting scales ‘exit the horizon’
(likely if last phase of inflation did not last longer than 50 e-folds)
then the observed fluctuations will *not* be scale-free …



Hunt & Sarkar (2005)

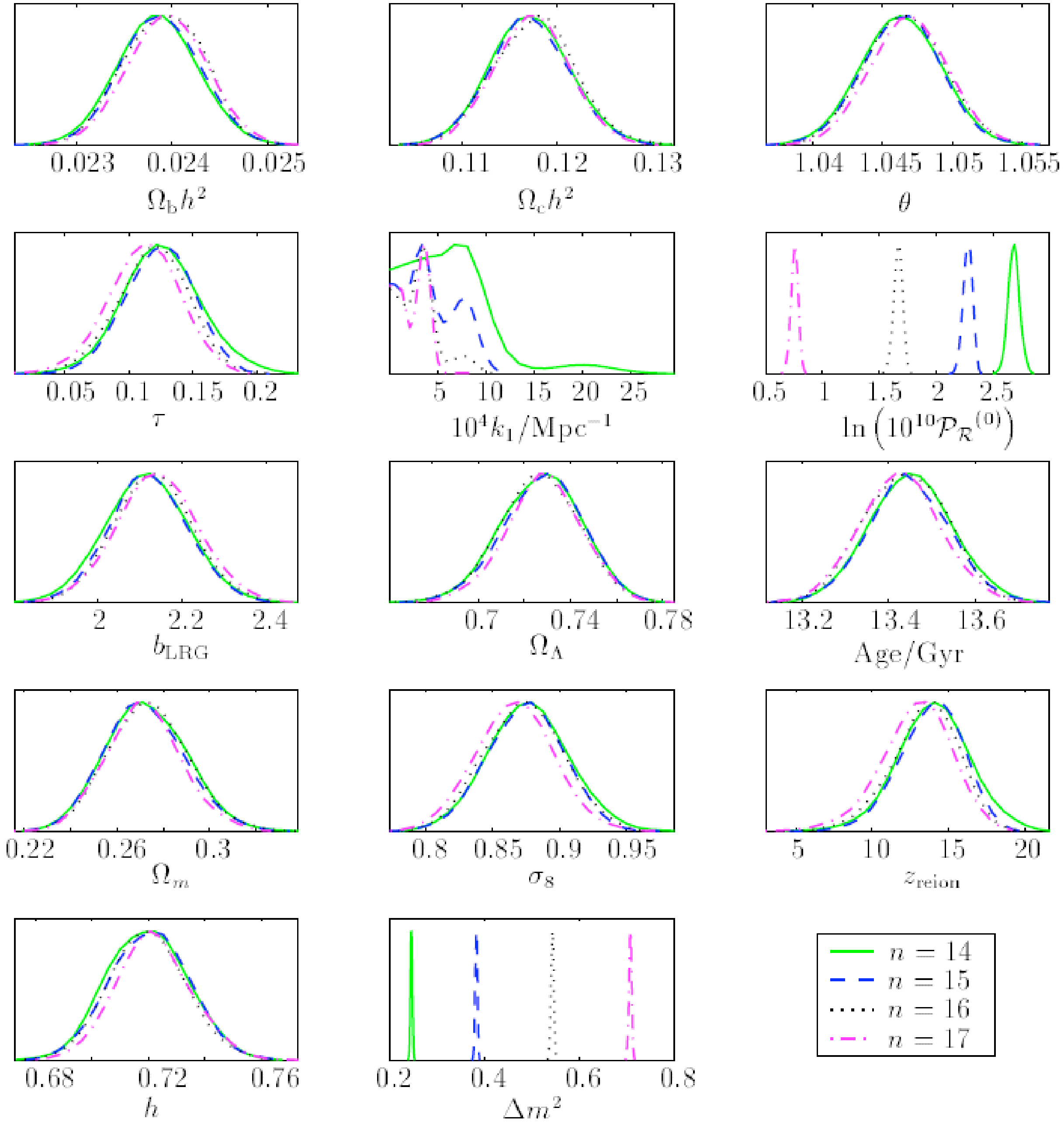
This is just what is seen when the primordial spectrum is reconstructed *assuming* ΛCDM

(Shafieloo & Souradeep 2004, 2006)



Tochhini-Valentini, Hoffman & Silk (2005)

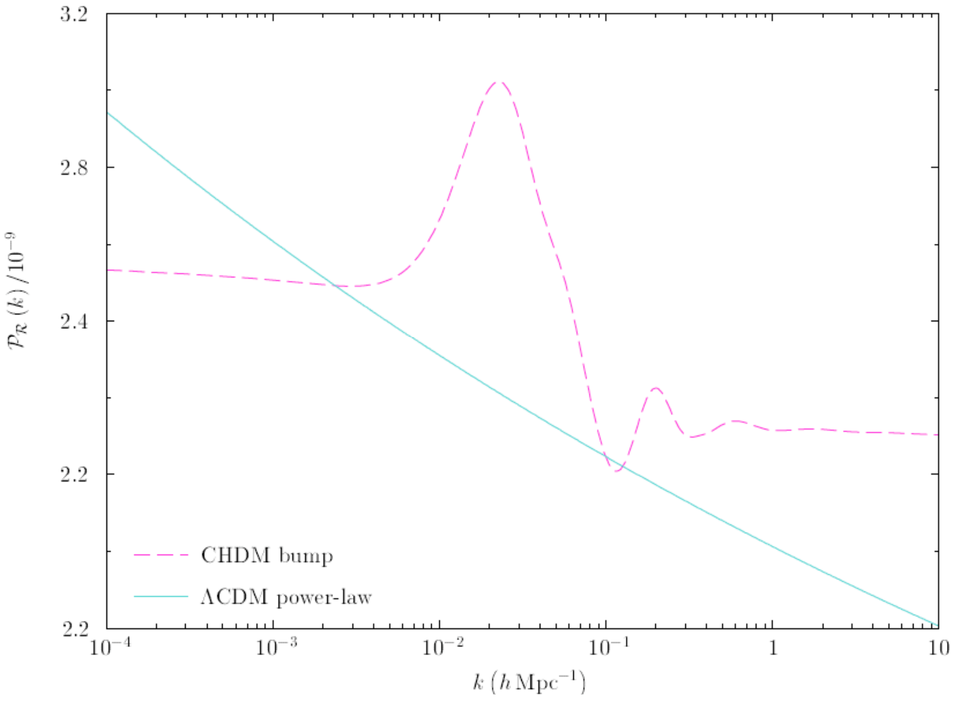
MCMC likelihood distributions for ΛCDM ‘step’ model



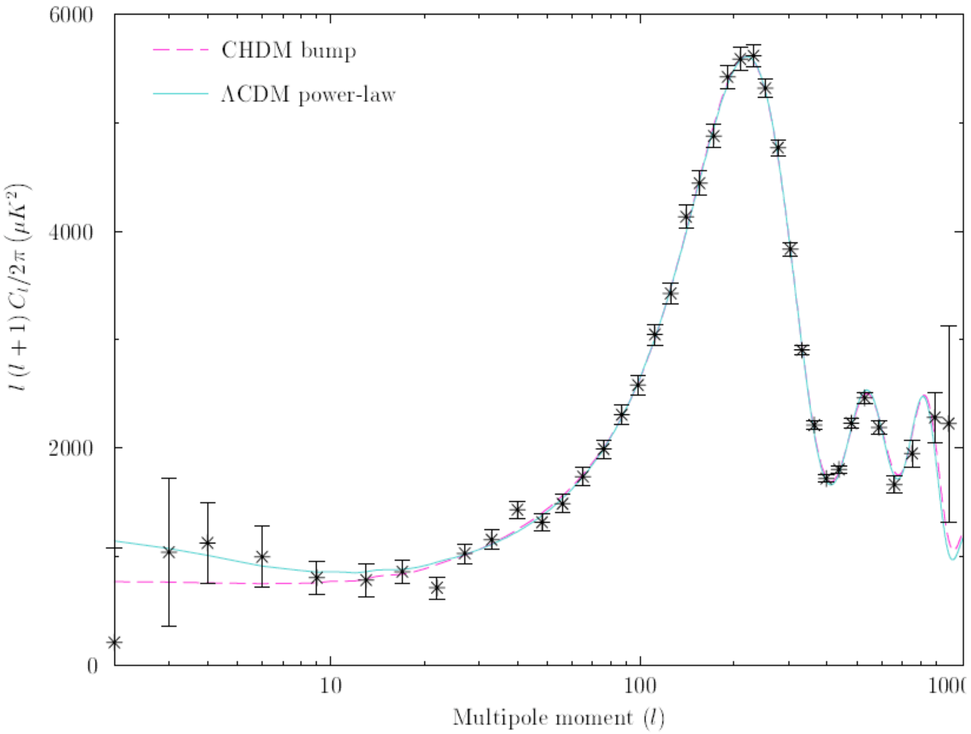
… not too different from ‘power law ΛCDM’

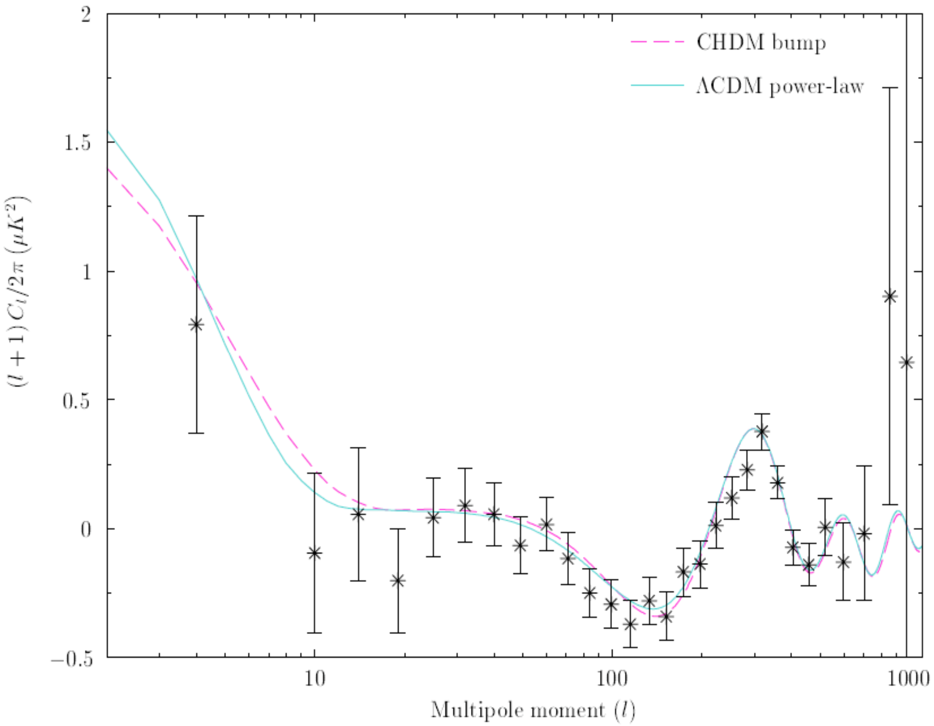
Hunt & Sarkar
(arXiv: 0706.2443)

Since there are *many* flat direction 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 well-fitted with *no dark energy* ($\Omega_m = 1$, $\Omega_\Lambda = 0$, $h = 0.44$)

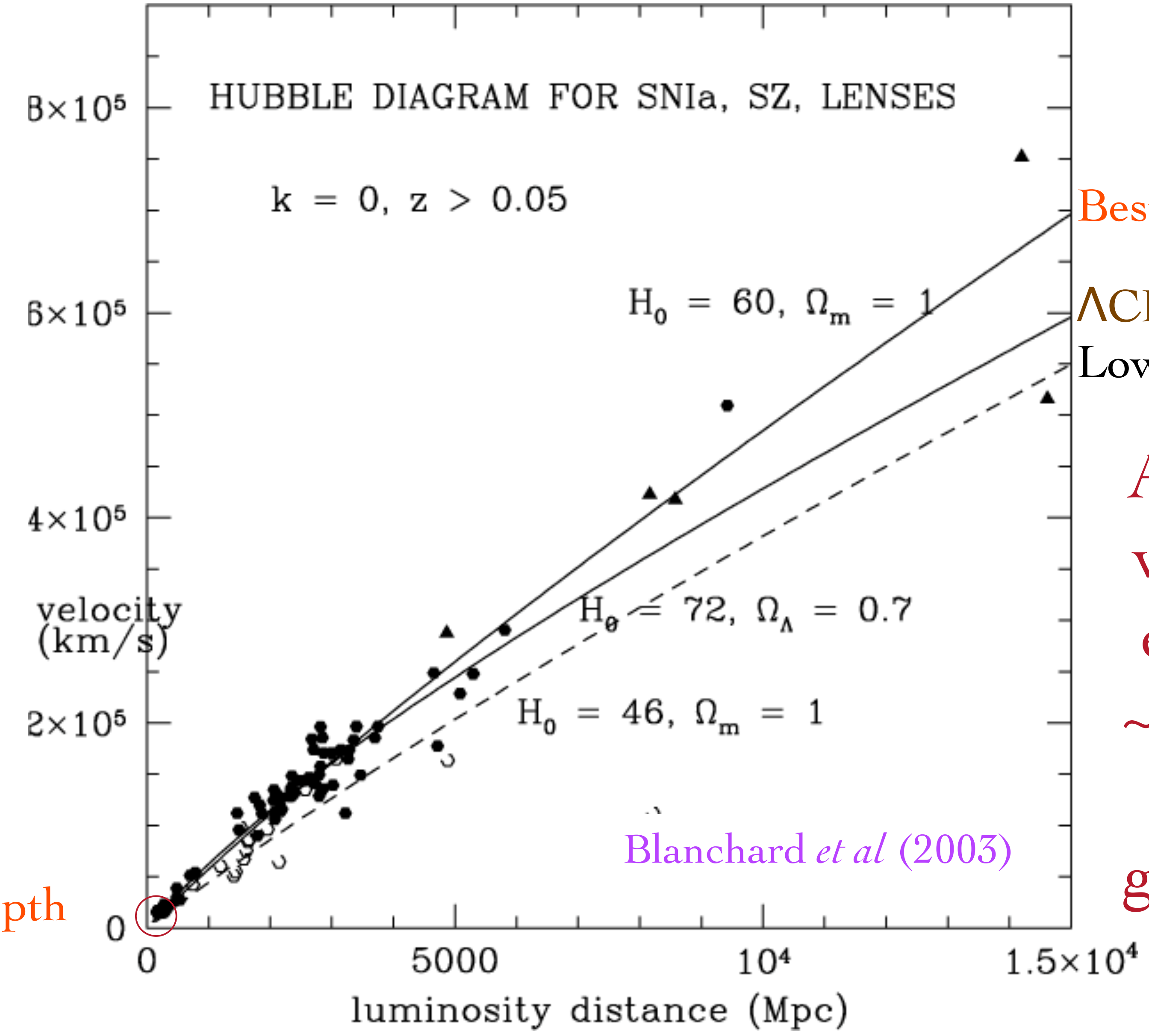




$h = 0.44$ is inconsistent with Hubble Key Project value ($h = 0.72 \pm 0.08$)

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

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



Best fit E-deS

ΛCDM model

Low h E-deS

HKP depth

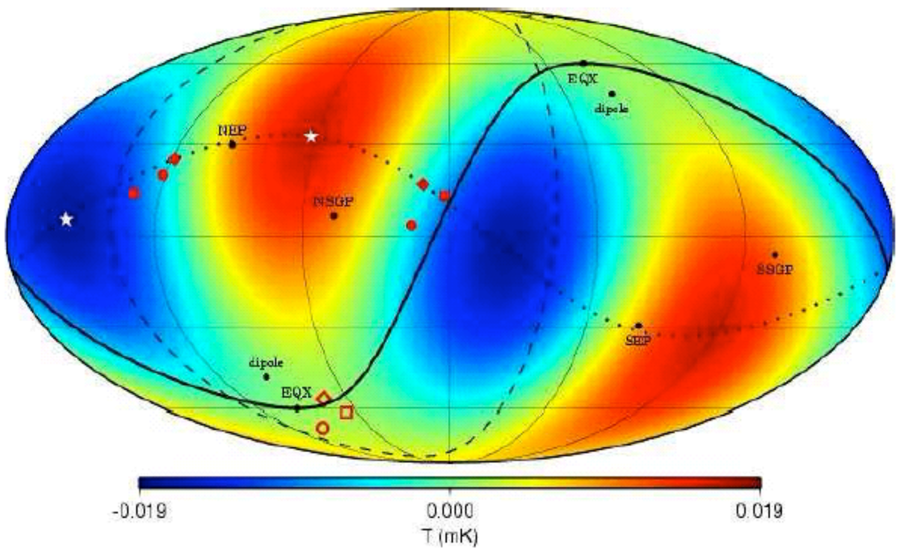
Blanchard *et al* (2003)

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

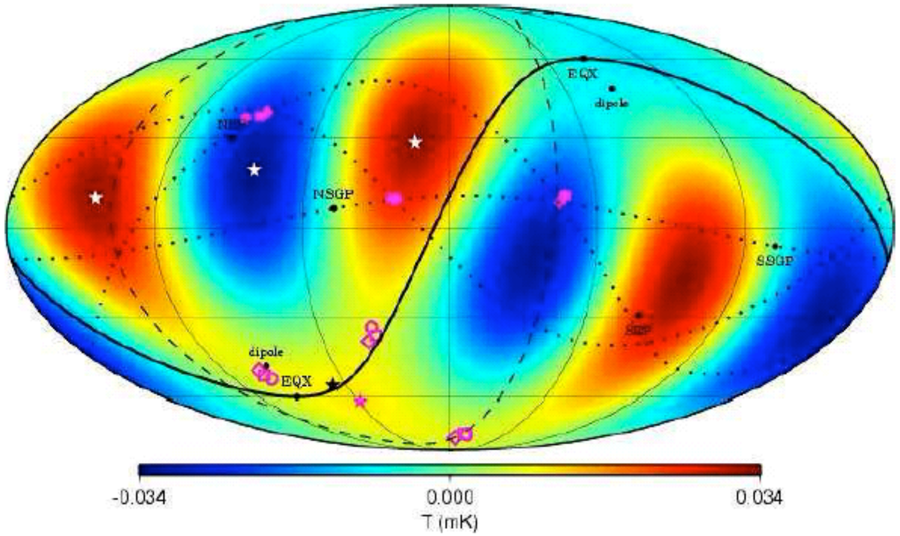
A Local ‘Hubble Bubble’ from Type Ia Supernovae?

A local void has been proposed as one way to reconcile the age of the universe based on the Hubble expansion with the ages of globular clusters within the framework of the Einstein–de Sitter cosmology (e.g., Turner, Cen, & Ostriker 1992; Bartlett et al. 1995). Measurements of the Hubble constant within the void would overestimate the universal value by $\delta\rho/\rho \sim -3\delta H/H$. Indeed, the values obtained for the Hubble constant from the longest-range distance indicators, the SNe Ia (Jacoby et al. 1992; Sandage & Tammann 1993; Tammann & Sandage 1995; Hamuy et al. 1995, 1996b; Riess, Press, & Kirshner 1995a, 1996; Branch, Nugent, & Fisher 1997) and the gravitational lenses (Falco et al. 1997; Keeton & Kochanek 1997) are typically smaller than values obtained more locally using Tully-Fisher (TF) distance indicators (Kennicutt, Freedman, & Mould 1995; Mould et al. 1995; Freedman et al. 1994; Freedman 1997, Giovanelli et al. 1997). A local void would also imply that local estimates of Ω underestimate the global value of Ω. Finally, a local outflow would reduce the distances derived from TF peculiar velocities for features such as the Great Attractor, bringing them into better agreement with the positions derived from redshift surveys (Sigad et al. 1998).

Zehavi, Riess, Kirshner & Dekel (1998)

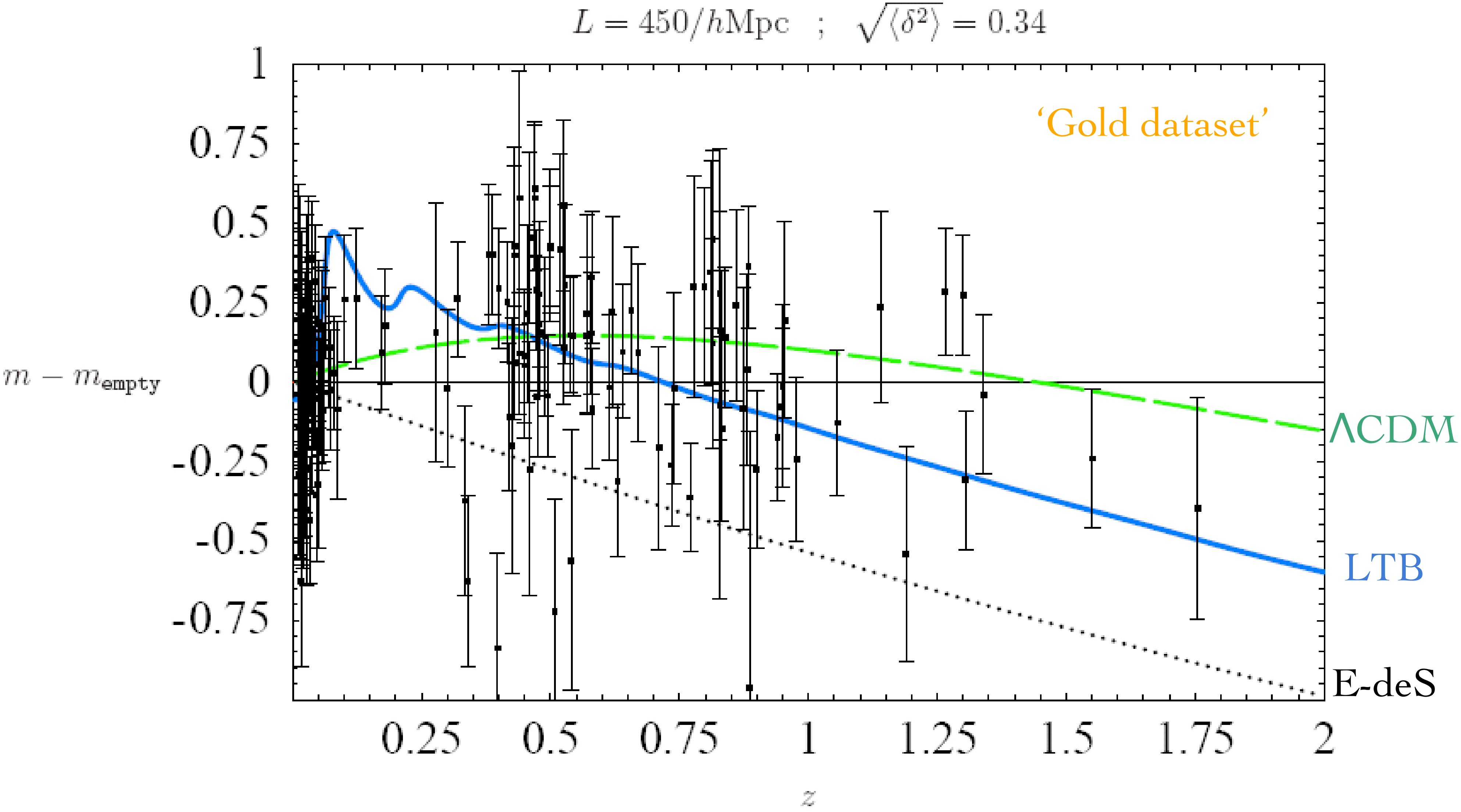


The Rees-Sciama effect due to our *local* inhomogeneity may explain the observed mysterious alignment of the quadrupole and octupole



(Inoue & Silk 2006)

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

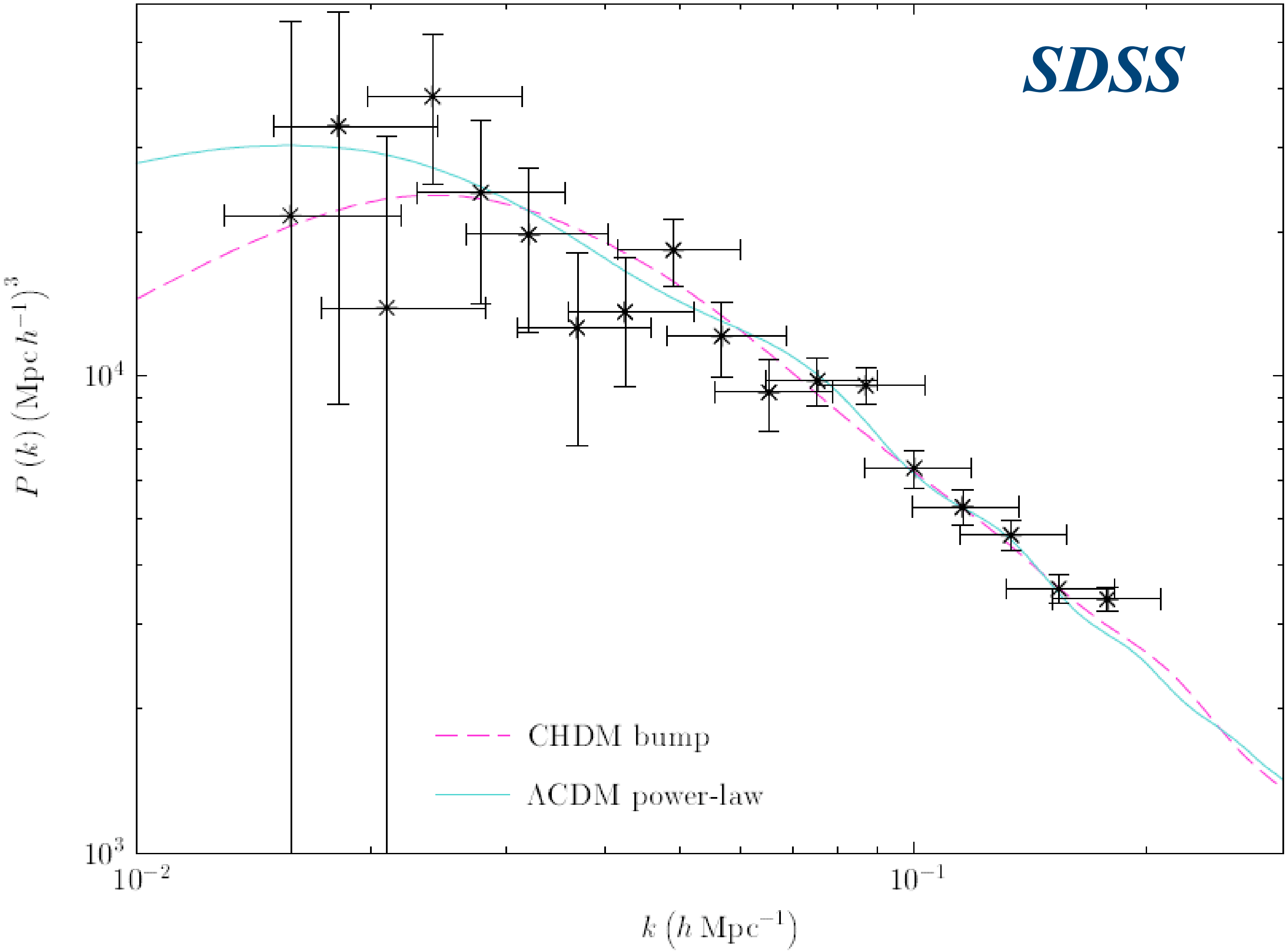


Biswas, Mansouri & Notari (2006)

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

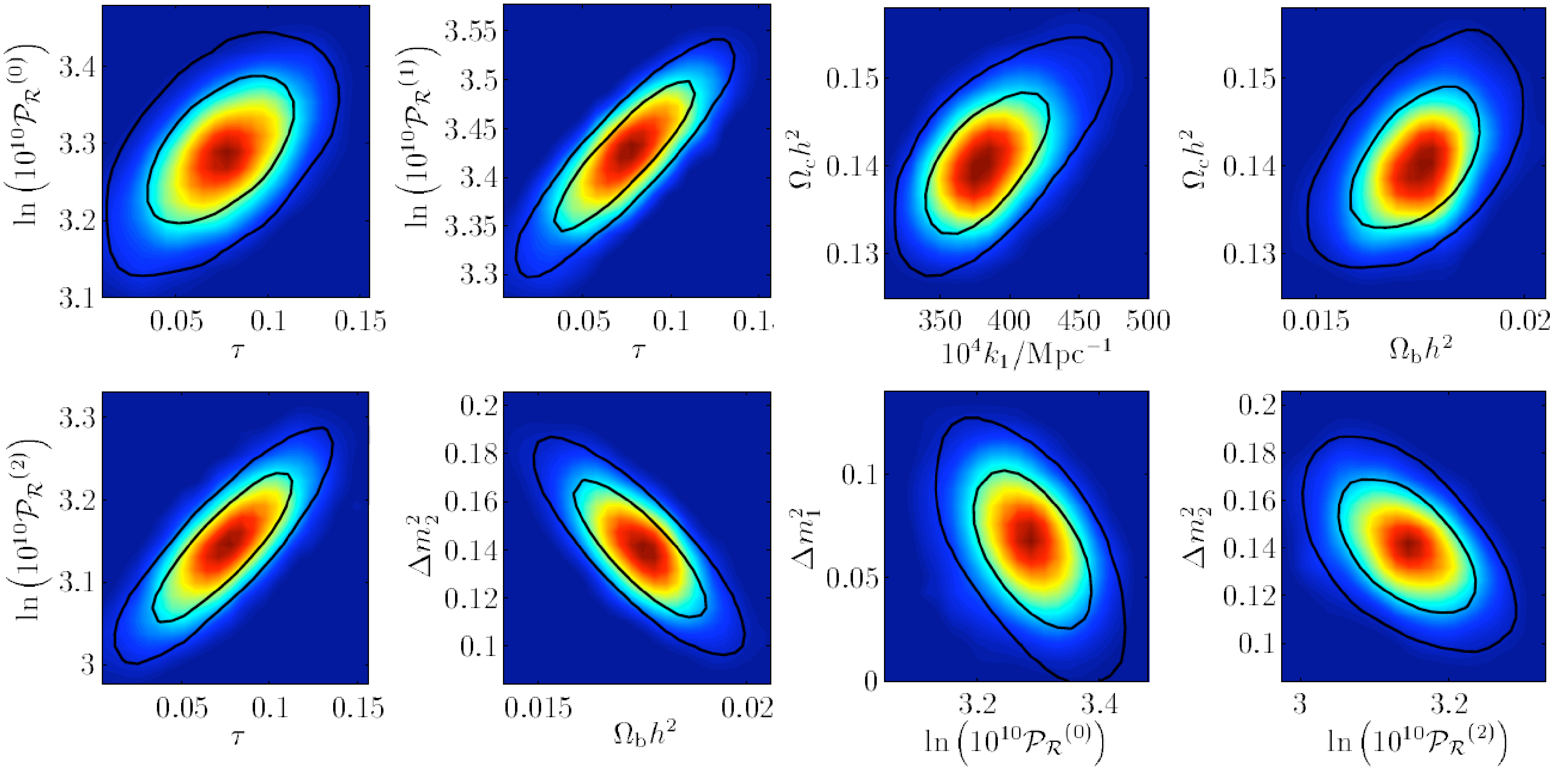
But adding 3 ν of mass 0.5 eV ($\Rightarrow \Omega_\nu \sim 0.1$) gives *good* match to large-scale structure

(note that $\Sigma\ m_\nu \approx 1.5$ eV … well above 'WMAP bound')



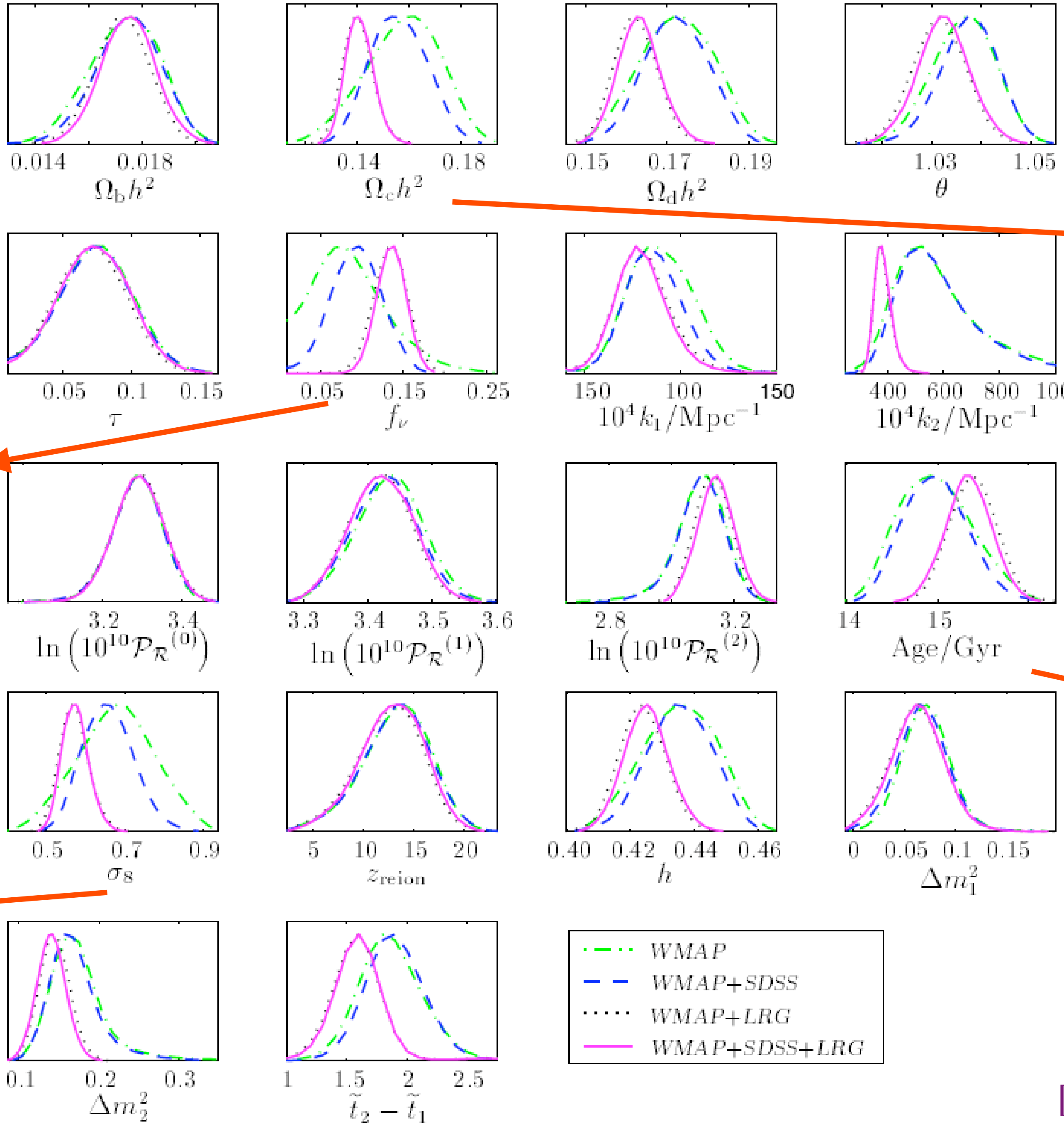
Fit gives $\Omega_b h^2 \approx 0.018$ → BBN √ ⇒ baryon fraction in clusters ~10% √

Parameter degeneracies: CHDM model (‘bump’ spectrum)



Hunt & Sarkar
[arXiv: 0706.2443]

MCMC likelihoods: CHDM model (‘bump’ spectrum)



This is ~50% higher than the ‘WMAP value’ used for CDM abundance

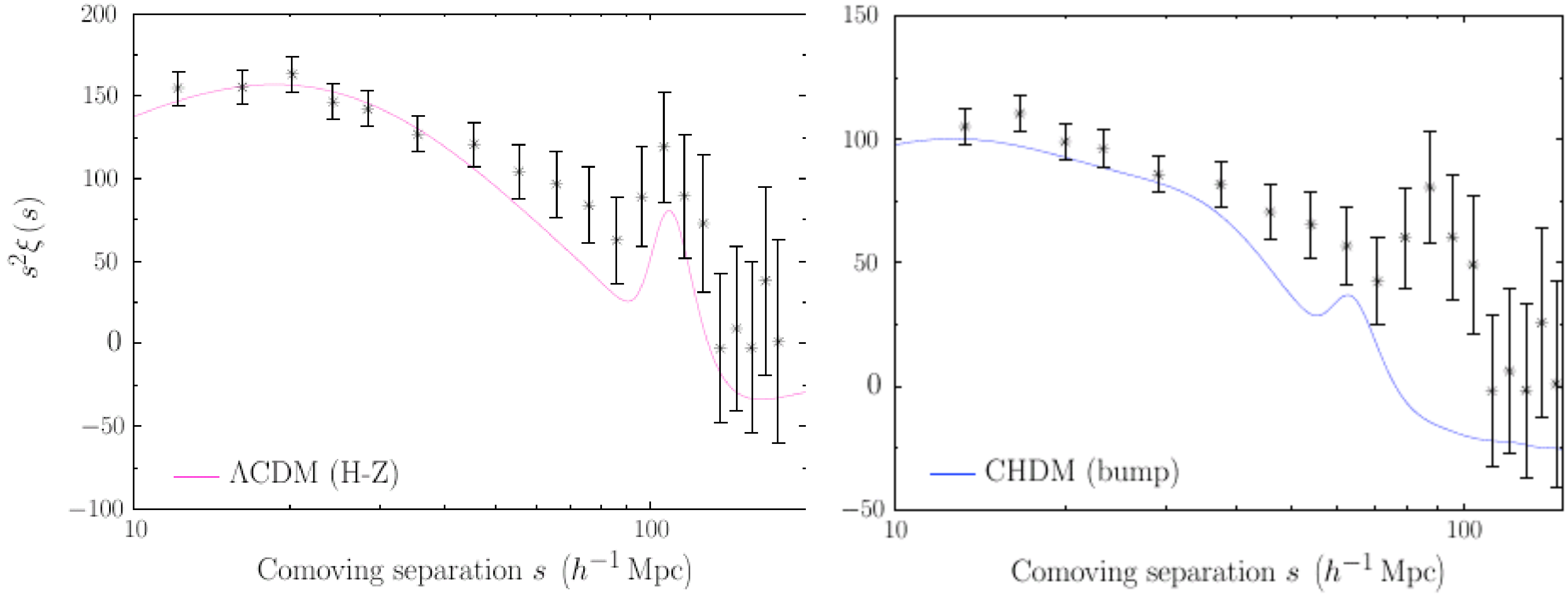
To fit the large-scale structure data *requires* 0.5 eV mass neutrinos

Consistent age for the universe

Consistent with data on clusters and weak lensing

Hunt & Sarkar
[arXiv: 0706.2443]

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 ~ 1100 by taking h ~ 0.5, but we *cannot* then also match the angular size of the baryonic feature at z ~ 0.35

But for inhomogeneous LTB model (h ~ 0.7 for $z < 0.08$, then h →0.5) **angular diameter distance @ z = 0.35 is similar to that for 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 an inhomogeneous cosmology

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