Cosmology beyond the Standard Model

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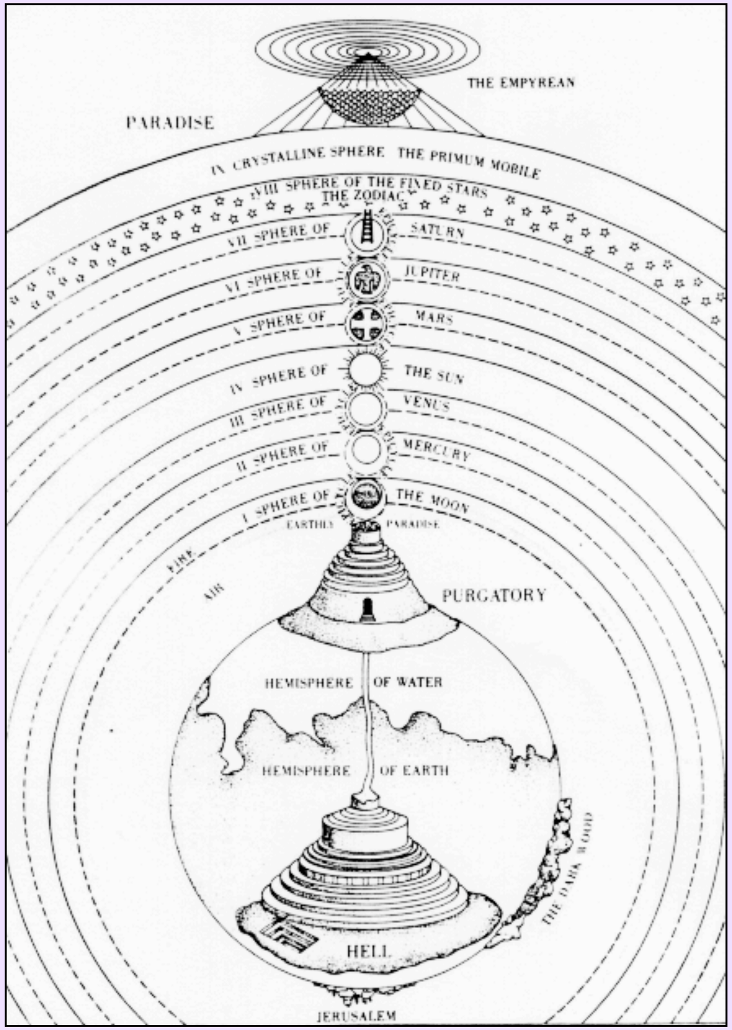
In the Aristotlean 'standard model' of cosmology (circa 350 BC) the universe was *static* and *finite* and *centred on the Earth*

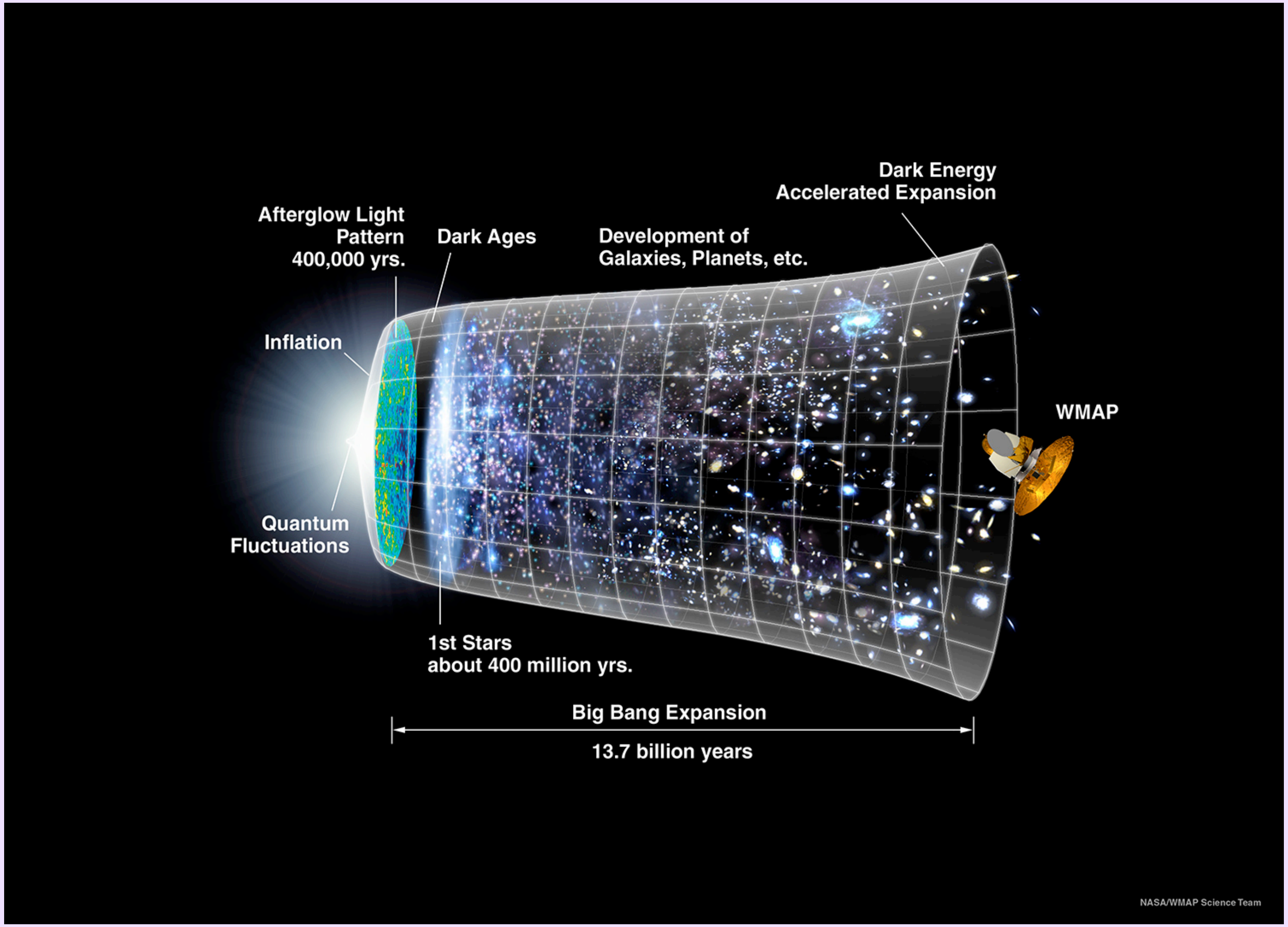


The Divine Comedy, Dante Allighieri (1321)

This was a 'simple' model and fitted all the observational data
… but the underlying dynamical principle was un*physical*

Today we have a new 'standard model' of the universe …

dominated by dark energy and undergoing accelerated expansion



Courtesey: NASA/WMAP Science Team (2007)

It too is 'simple' and fits all the observational data but lacks an underlying physical basis

The **Standard $SU(3)_c$ x $SU(2)_L$ x $U(1)_Y$ Model** provides an exact description of all *microphysics* (up to some high energy cut-off scale *M*)

Cosmological constant — *Higgs mass correction*

$$\mathcal{L}_{\text{eff}} = M^4 + M^2\Phi^2 \quad \textbf{super-renormalisable}$$

$$+ \; (D\Phi)^2 + \bar{\Psi} \, \not{D}\Psi + F^2 + \bar{\Psi}\Psi\Phi + \Phi^2 \quad \textbf{renormalisable}$$

$$+ \; \frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \ldots \quad \textbf{non-renormalisable}$$

The effects of new physics beyond the SM (neutrino mass, nucleon decay, FCNC …)
⇒ Non-renormalisable operators suppressed by M^n … so 'decouple' as $M \to M_P$

But as *M* is raised, the effects of the super-renormalisable operators are *exacerbated*

Solution for 2nd term → 'softly broken' supersymmetry at *M* ~ 1 TeV (100 new parameters)

This suggests possible mechanisms for **dark matter**, **baryogenesis**, **inflation** …
(as do other proposed extensions of the SM, e.g. new dimensions @ TeV scale)

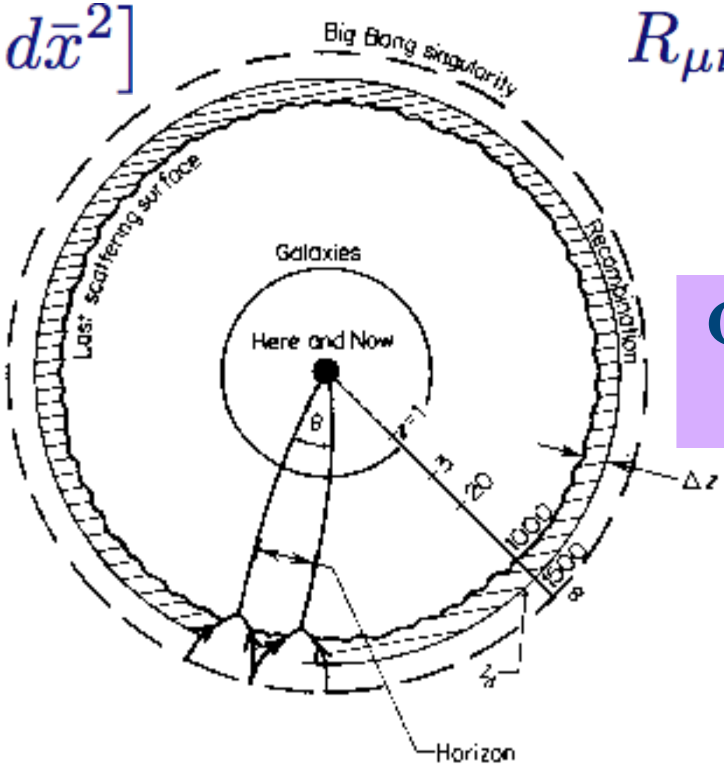
The 1st term *couples to gravity* so the SM predicts $\rho_\Lambda \sim (1 \text{ TeV})^4$ i.e. the universe should have been inflating since ~ 10^{-12} s! As this is not the case, there *must* be some dynamical reason why the cosmological constant →0

The **standard cosmological model** is based on several key assumptions:
maximally symmetric space-time + general relativity + *ideal fluids*

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

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

Space-time metric
Robertson-Walker



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

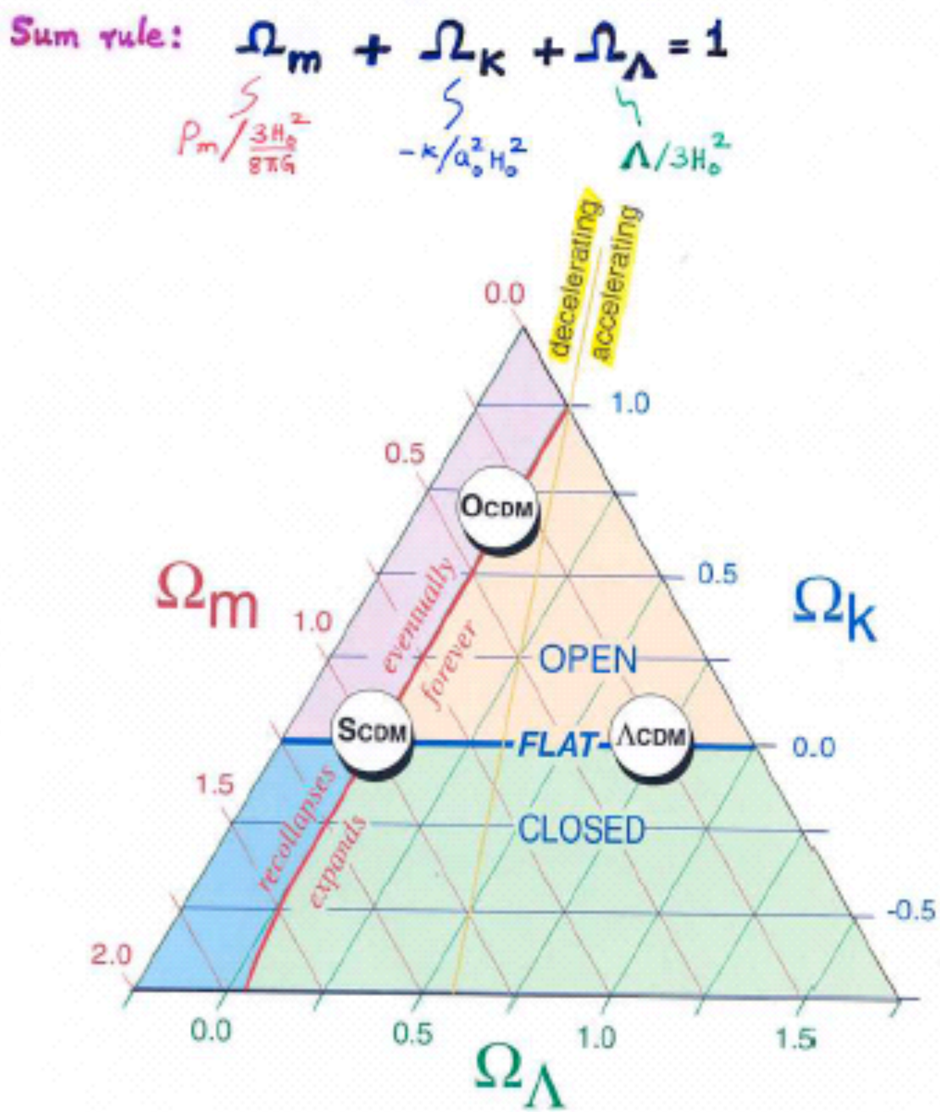
Geometrodynamics
Einstein

$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho_m}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

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

… so *naturally* exhibits 'dark energy' at late times!

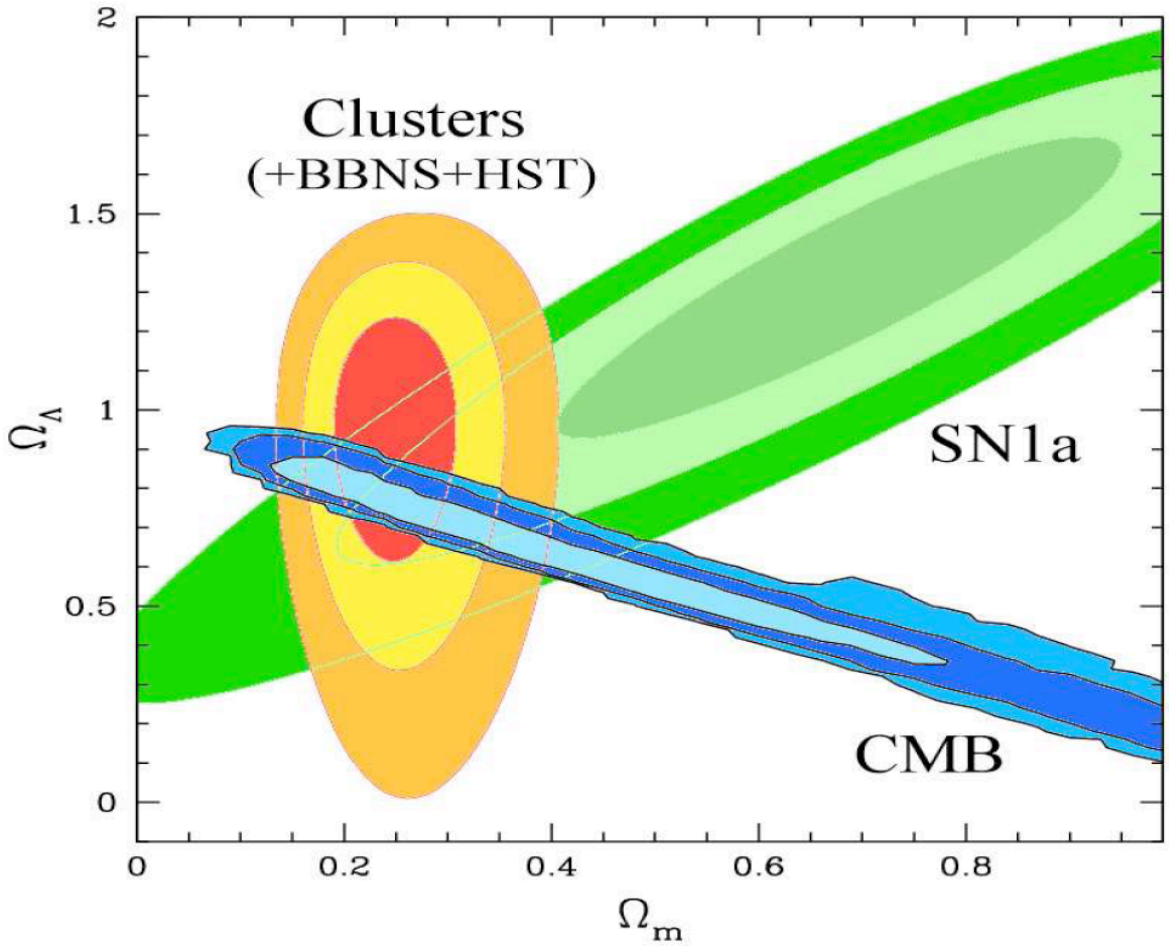
Hence interpretation of data in this framework is *likely* to yield $\Lambda \sim H_0^2$



… e.g. would typically infer Ω_Λ (= $\Lambda/3H_0^2$) to be of $O(1)$ from the **cosmic sum rule**, given the uncertainties in measuring Ω_m and Ω_k

We believe now that $\Omega_k = 0$ is natural because of dynamics (inflation)

but there is no plausible dynamical reason for $\Omega_\Lambda = 0$



Then 'cosmic concordance' implies dark energy: **$\Omega_\Lambda \sim 0.75$, $\Omega_m \sim 0.25$**

If it is just a cosmological *constant*, why is $\rho_\Lambda \approx \rho_m$ *today*?

An evolving ultralight scalar field ('**quintessence**') can display 'tracking' behaviour: this requires $V(\Phi)^{1/4} \sim 10^{-12}$ GeV but $\sqrt{d^2V/d\Phi^2} \sim H_0 \sim 10^{-42}$ GeV to ensure slow-roll

… *i.e. just as much fine-tuning as a bare cosmological constant*

A similar comment applies to models (e.g. '**DGP brane-world**') wherein gravity is modified on the scale of the present Hubble radius so as to mimic vacuum energy

…this scale is simply *put in by hand*

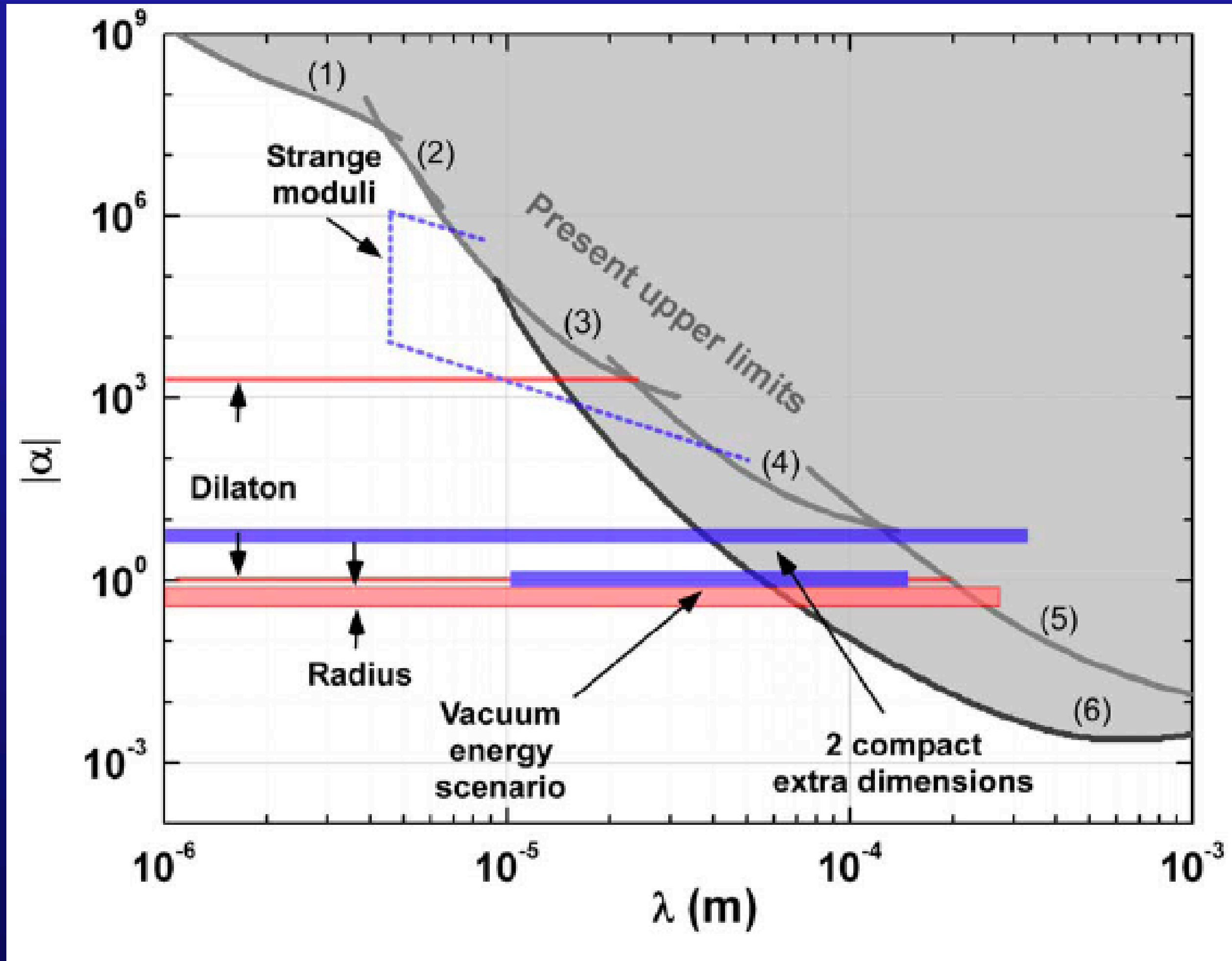
Would seem natural to have $\Lambda \sim H^2$ *always*, but this just means a redefinition of G_N

… *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

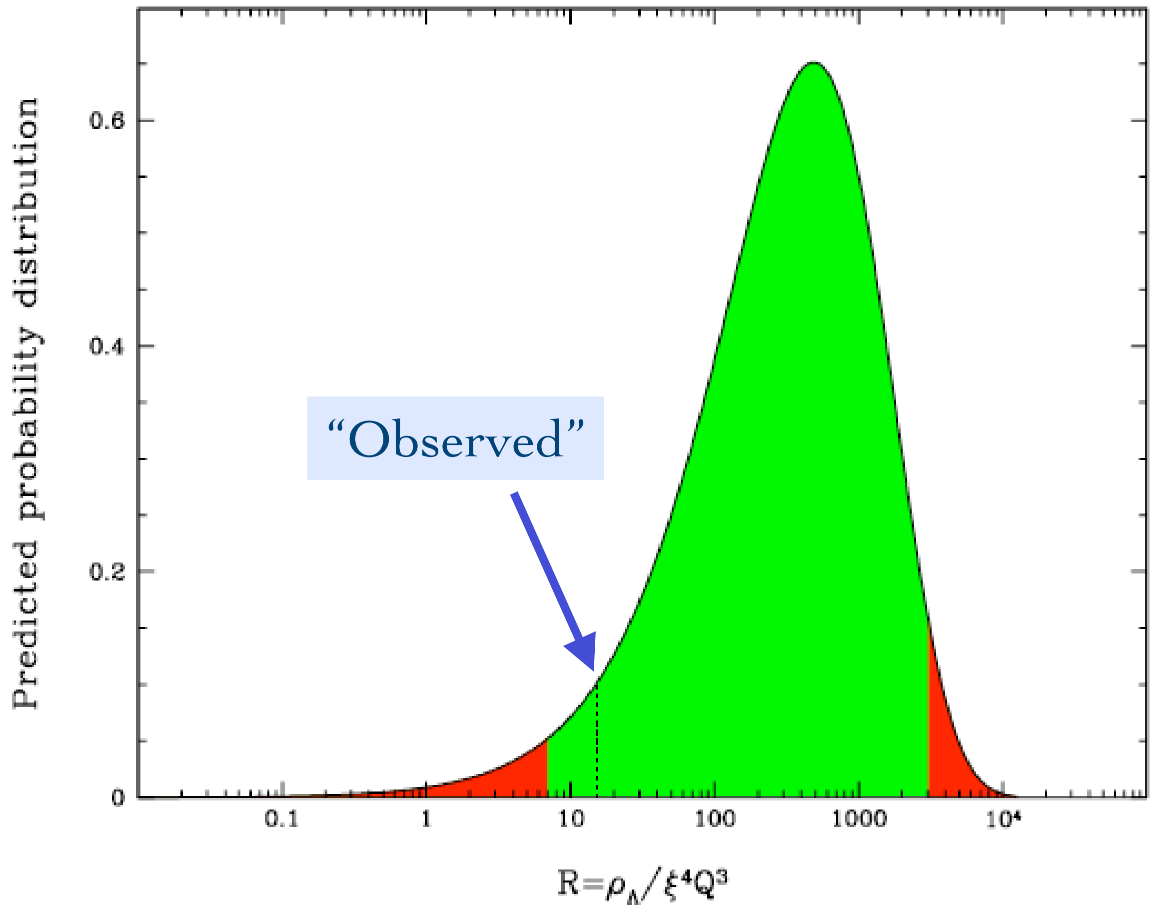
Do we see $\Lambda \sim H_0^2$ because that is just the **observational sensitivity?**

Current constraints to violations of the ISL



No evidence for change in inverse-square law at 'dark energy' scale
$\rho_\Lambda^{-1/4} \sim (H_0 M_P)^{-1/2} \sim 0.1$ mm

‘Anthropic prediction’ of Λ from considerations of galaxy formation



But this *assumes* the prior distribution of ρ_Λ is *flat* in the range $0 \rightarrow 10^{-120}\,M_P^4$

Since we have no physical understanding of Λ this may not be reasonable

If the relevant physical variable is in fact *log* ρ_Λ, then $\rho_\Lambda = 0$ would be the favoured possibility!

So it is not clear if Λ has an anthropic explanation

(Efstathiou 1995, Martel, Shapiro & Weinberg 1998, … Tegmark, Aguirre, Rees & Wilczek 2006)

FIG. 11: Probability distribution for the quantity $R \equiv \rho_\Lambda/\xi^4 Q^3$ measured from a random $10^{12} M_\odot$ halo, using a uniform prior for R and ignoring other selection effects. This is equivalent to treating ξ and Q as fixed. Green/light shading indicates the 95% confidence interval, the dotted line indicates the observed value $R \approx 15$.

New H-band Galaxy Number Counts

Are we located in an underdense region in the galaxy distribution?

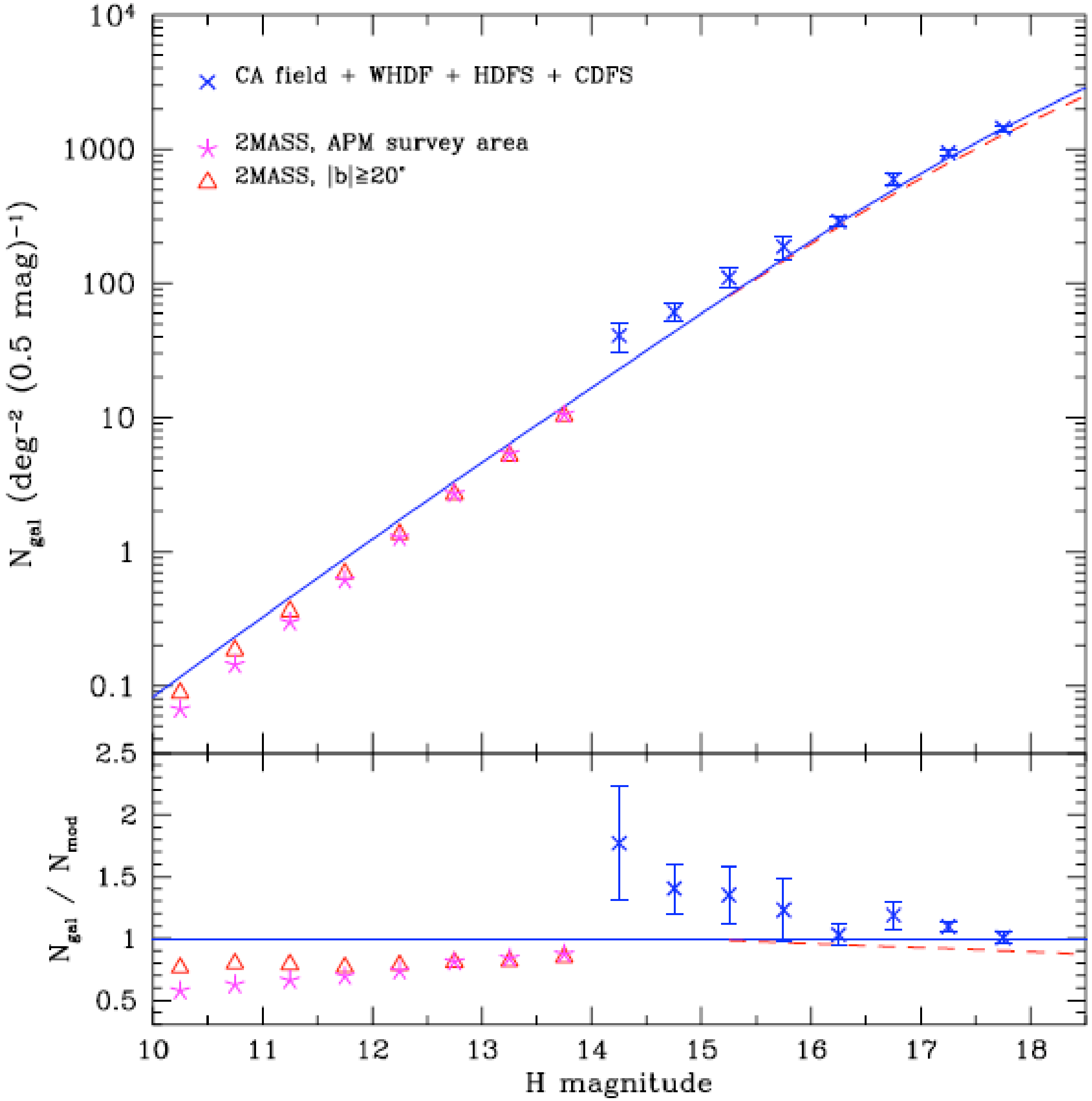
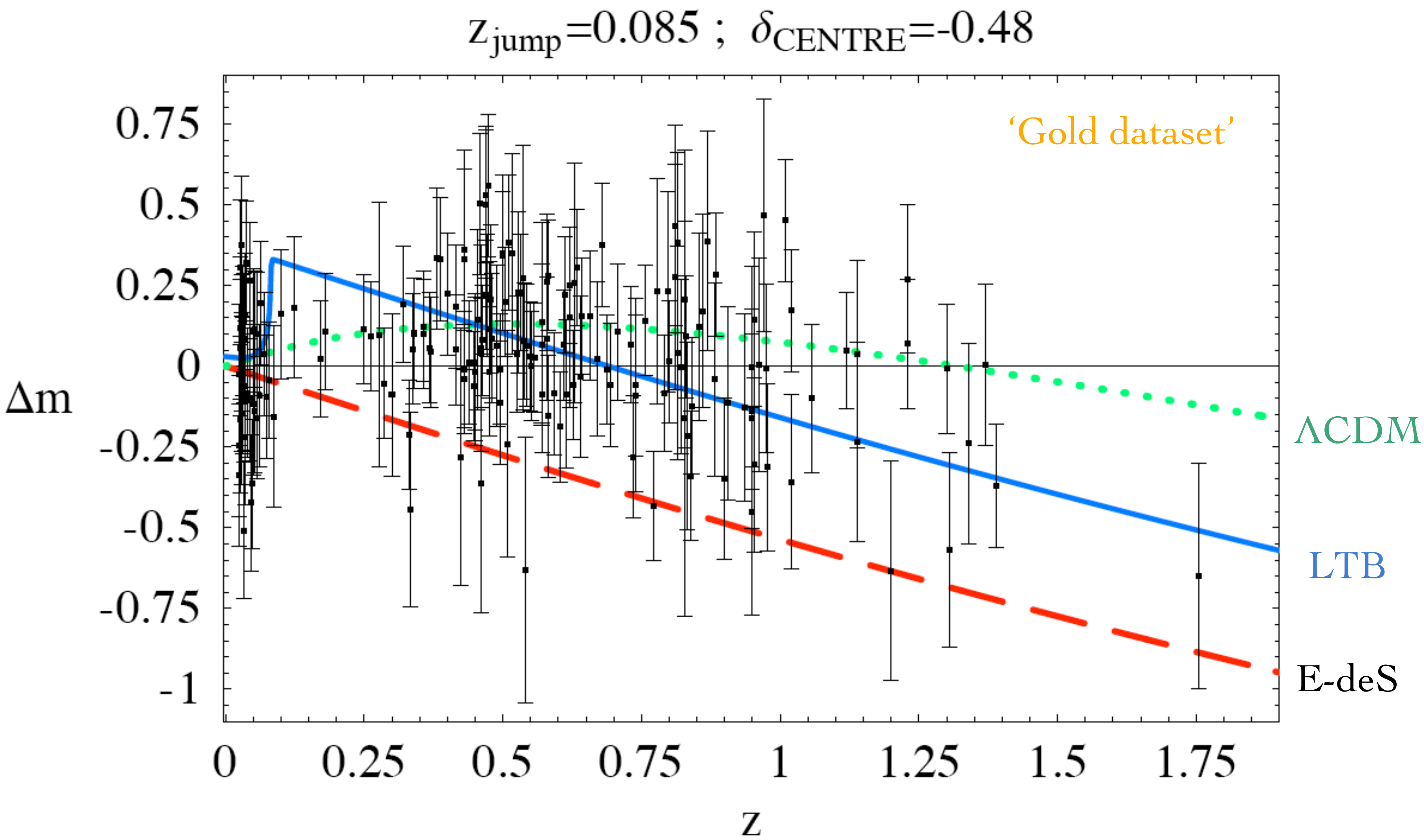


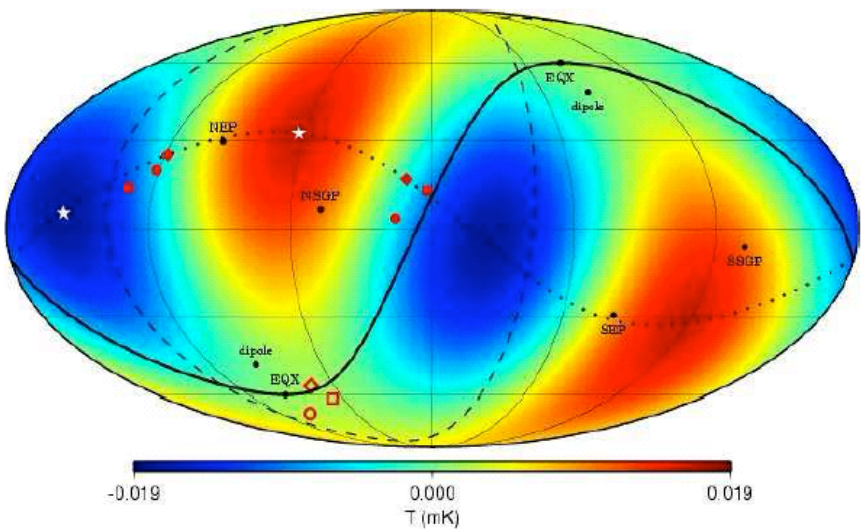
Figure 8. Here we show the faint H-band data from the two fields presented in this work (CA field and WHDF) and the two fields published by the LCIRS (HDFS and CDFS; Chen et al. 2002) applying a zeropoint to the LCIRS data consistent with the bright H-band 2MASS data (and hence the CA field and WHDF also), as shown in Fig. 7. The errorbars at faint magnitudes indicate the field-to-field error, weighted in order to account for the different solid angles of each field. Bright H-band counts extracted from 2MASS for the APM survey area and for |b| >20° are shown as previously. In the lower panel, the counts are divided through by the pure luminosity evolution homogeneous prediction as before.

Frith, Metcalfe & Shanks (2006)

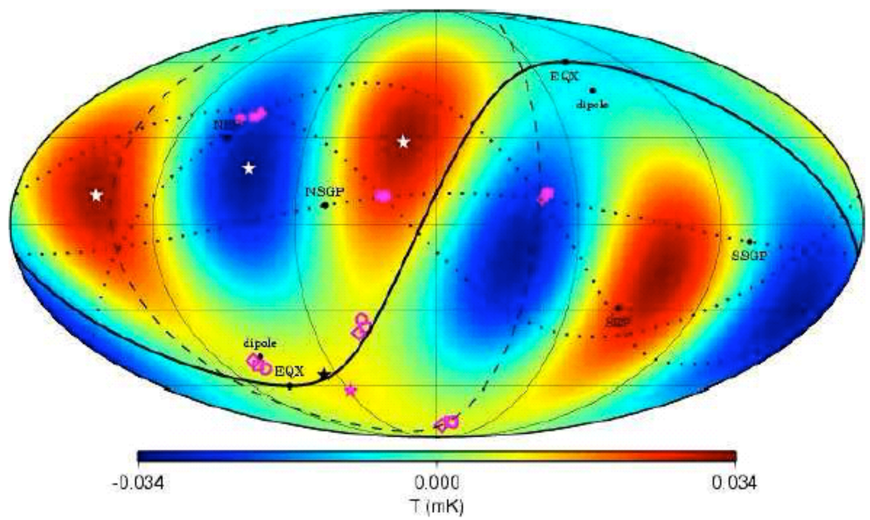
If so the SN Ia Hubble diagram may be explained *without* invoking acceleration, in a Lemaitré-Tolman-Bondi model



Alexander, Biswas,Notari & Vaid (2007)



The CMB quadrupole and octupole are surprisingly well-aligned - could this be the 'Rees-Sciama effect' of the local inhomogeneity?



(Inoue & Silk 2006)

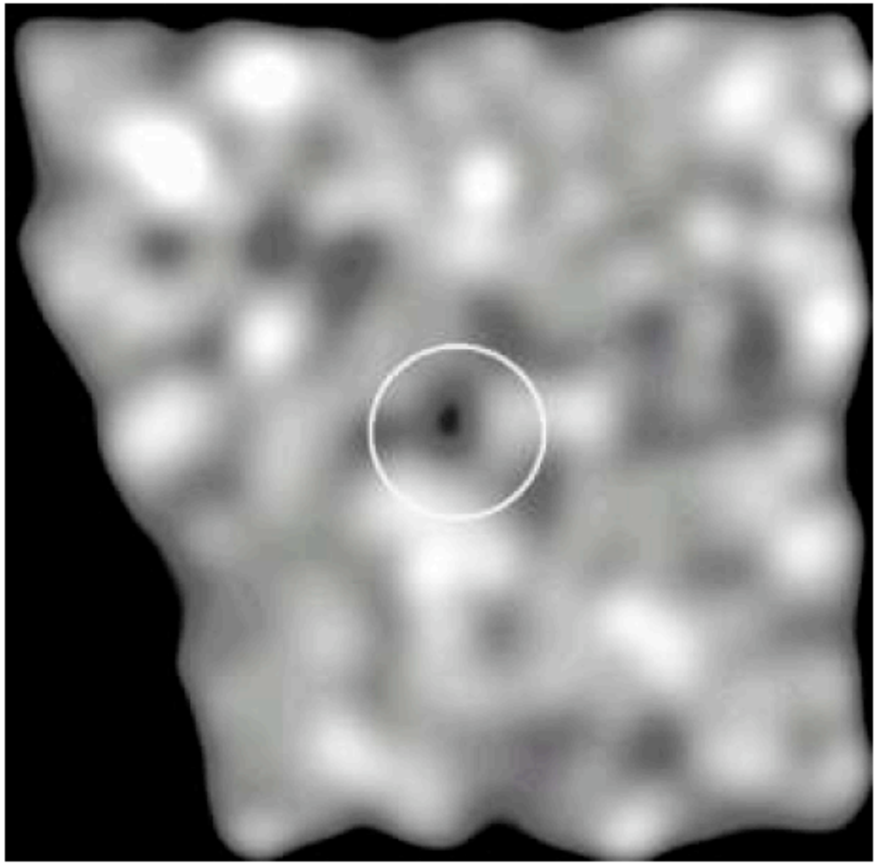


Fig. 1.— 50° field from smoothed NVSS survey at 3.4° resolution, centered at l_{II}, b_{II} = 209°, -57°. Values range from black: 9.3 mJy/beam to white: 21.5 mJy/beam. A 10° diameter circle indicates the position and size of the WMAP cold spot.

A similar void at $z \sim 1$ may be responsible for the 'cold spot' in the *WMAP* sky

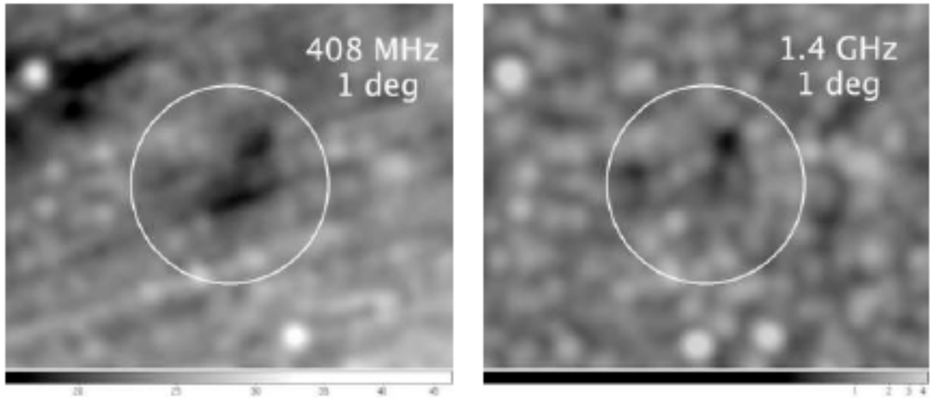
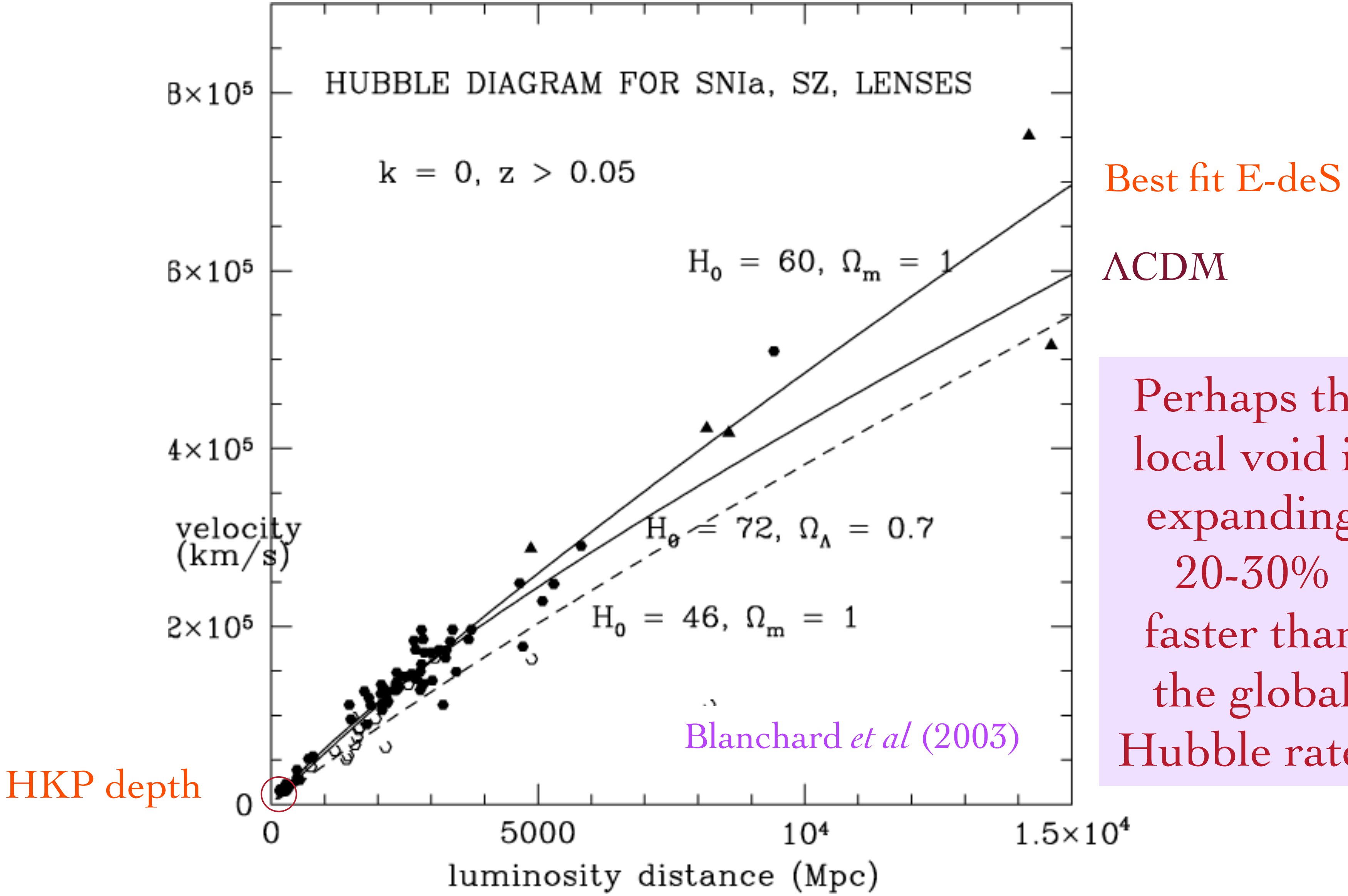


Fig. 4.— 18° fields, with 1° resolution, centered at l_{II}, b_{II} = 209°, -57°. Left: 408 MHz (Haslam et al. 1981). Right: 1.4 GHz (Condon et al. 1998). A 10° diameter circle indicates the position and size of the WMAP cold spot.

(Rudnick, Brown & Williams 2007)

Deep determinations of the Hubble constant e.g. gravitational lens time delays yield h = 0.48 ± 0.03 (Kochanek & Schechter 2004) - much smaller than the *local* measurement by the Hubble Key Project (h = 0.72 ± 0.08)



Perhaps the local void is expanding 20-30% faster than the global Hubble rate?

Uncertainty in Hubble parameter determination comes from lens model

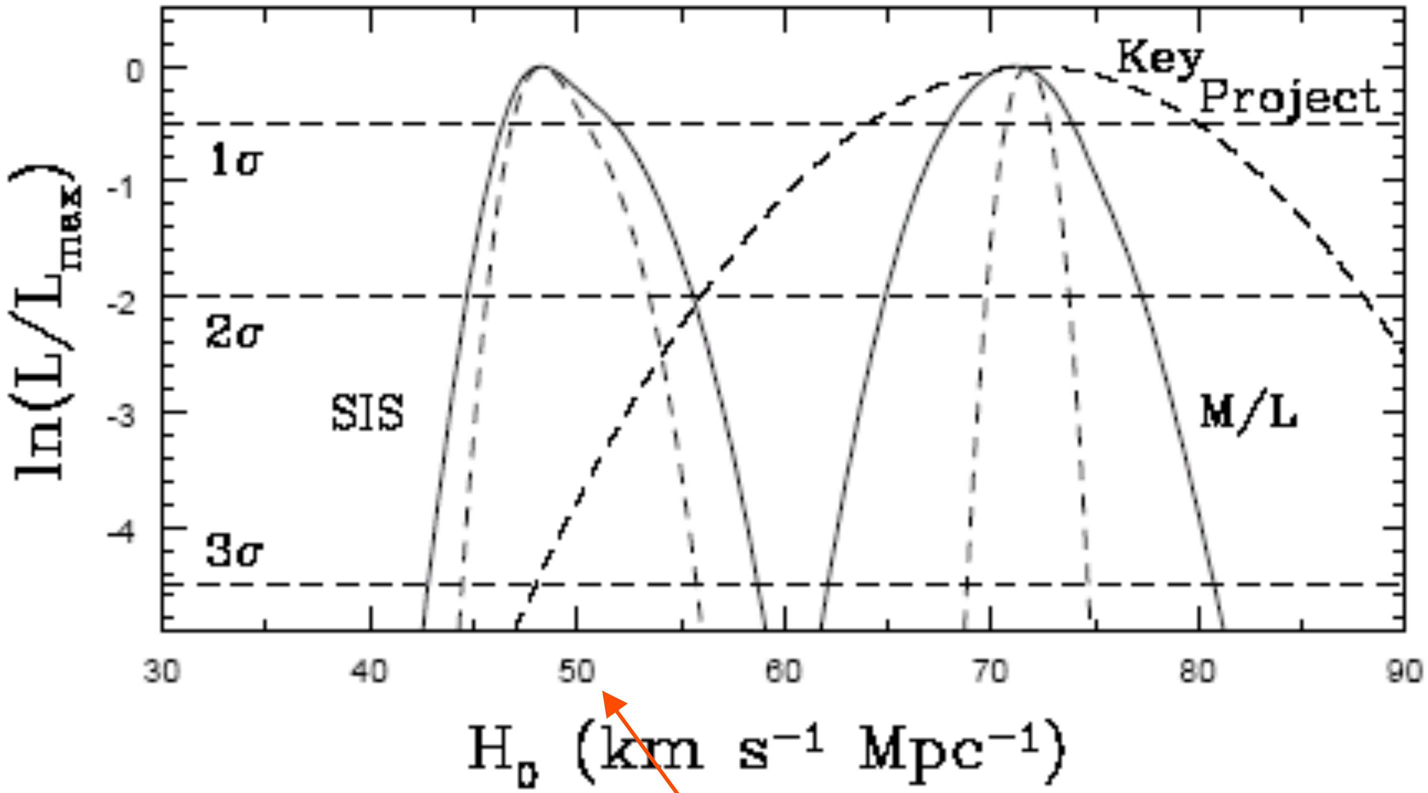


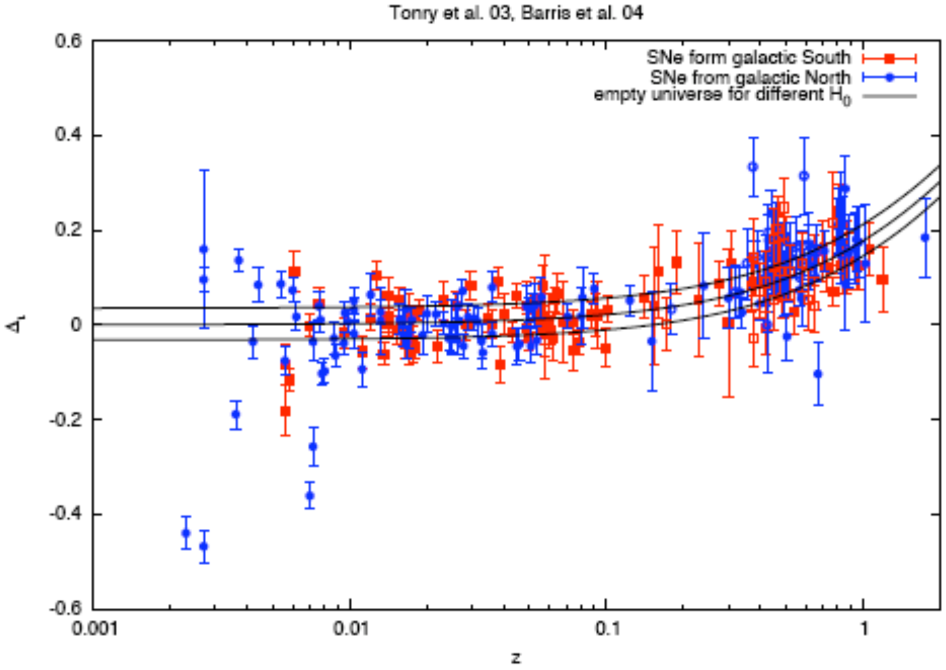
Fig. 1.4. H_0 likelihood distributions. The curves show the joint likelihood functions for H_0 using the four simple lenses PG1115+080, SBS1520+530, B1600+434, and HE2149–2745 and assuming either an SIS model (high $\langle\kappa\rangle$, flat rotation curve) or a constant M/L model (low $\langle\kappa\rangle$, declining rotation curve). The heavy dashed curves show the consequence of including the X-ray time delay for PG1115+080 from Chartas (2003) in the models. The light dashed curve shows a Gaussian model for the Key Project result that $H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1}.

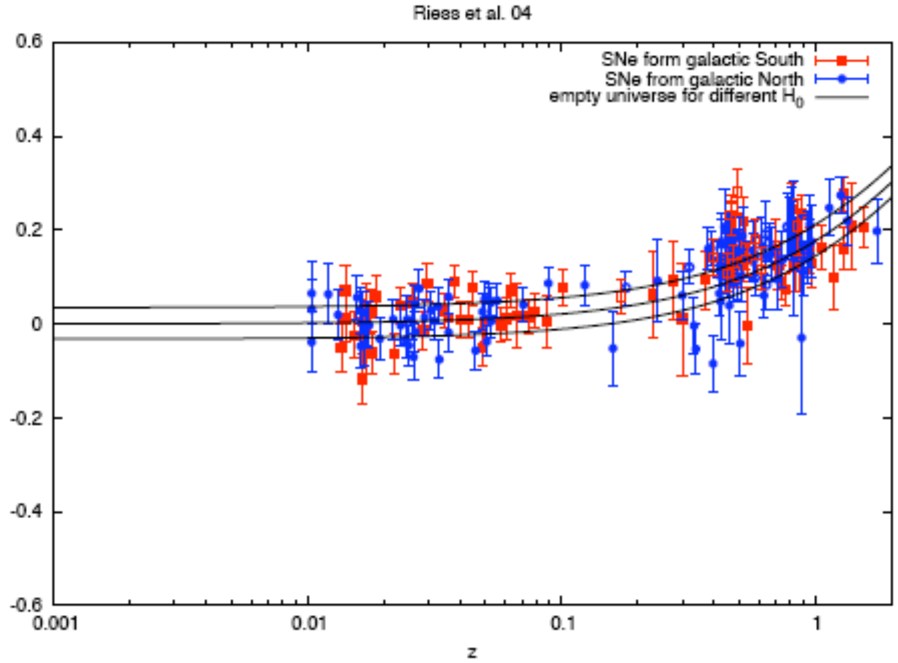
If lensing galaxies have dark matter halos then $h \approx 0.5$ (Kochanek & Schechter 2004)

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).

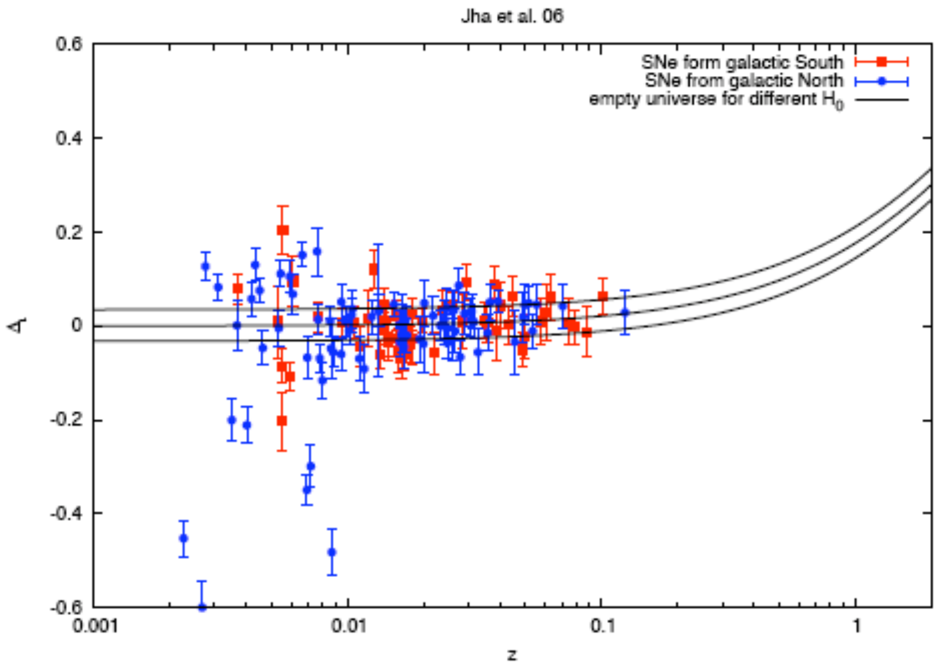
Zehavi, Riess, Kirshner & Dekel (1998)





"A statistically significant anisotropy of the Hubble diagram at redshifts $z < 0.2$ is discovered … The discrepancy between the equatorial North and South hemispheres shows up in the SN calibration."

(Schwarz & Weinhorst 2007)



"… our model independent test cannot exclude the case of the deceleration of the expansion at a statistically significant level"

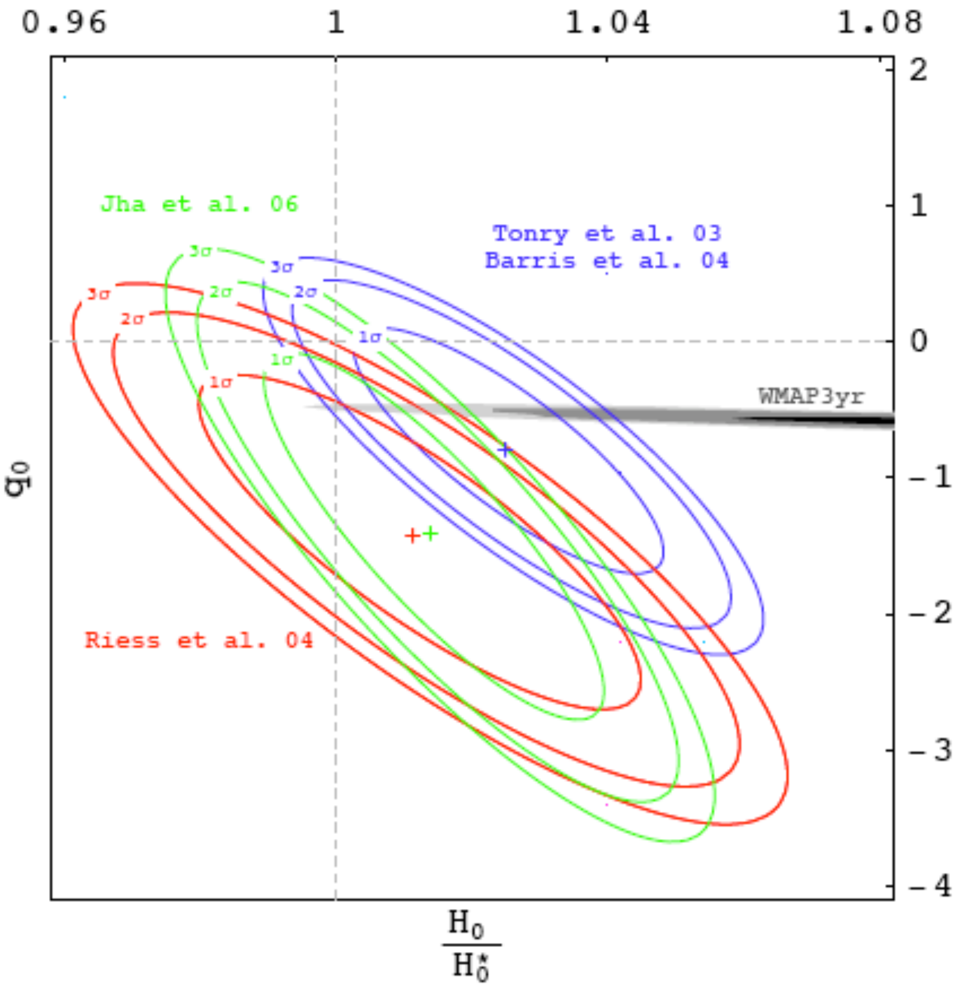
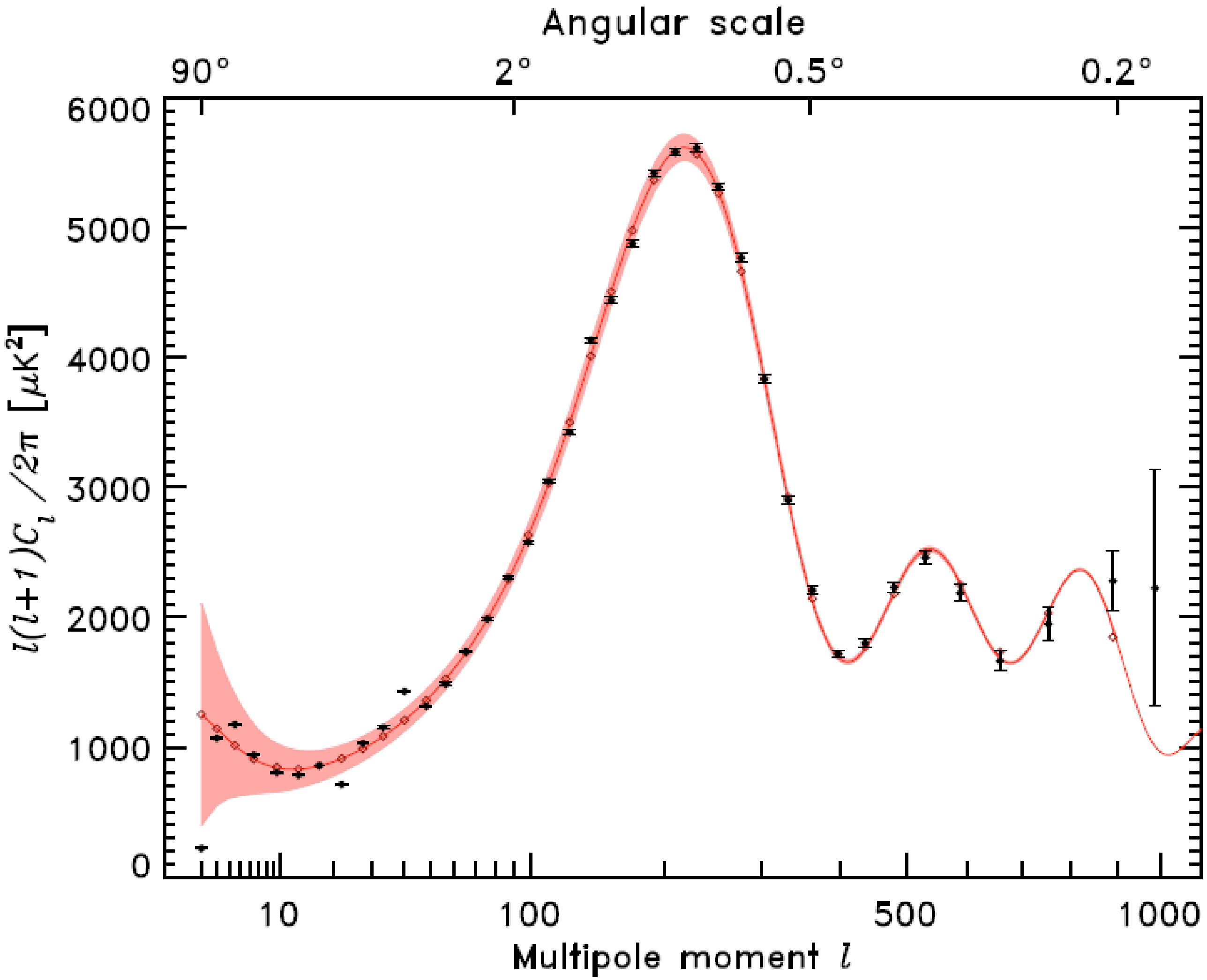


Fig. 3. Confidence contours for a model-independent full-sky fit to the Hubble law at second order for three SNe Ia data sets. SNe up to redshift $z = 0.2$ are included in the fits. (Schwarz & Weinhorst 2007)

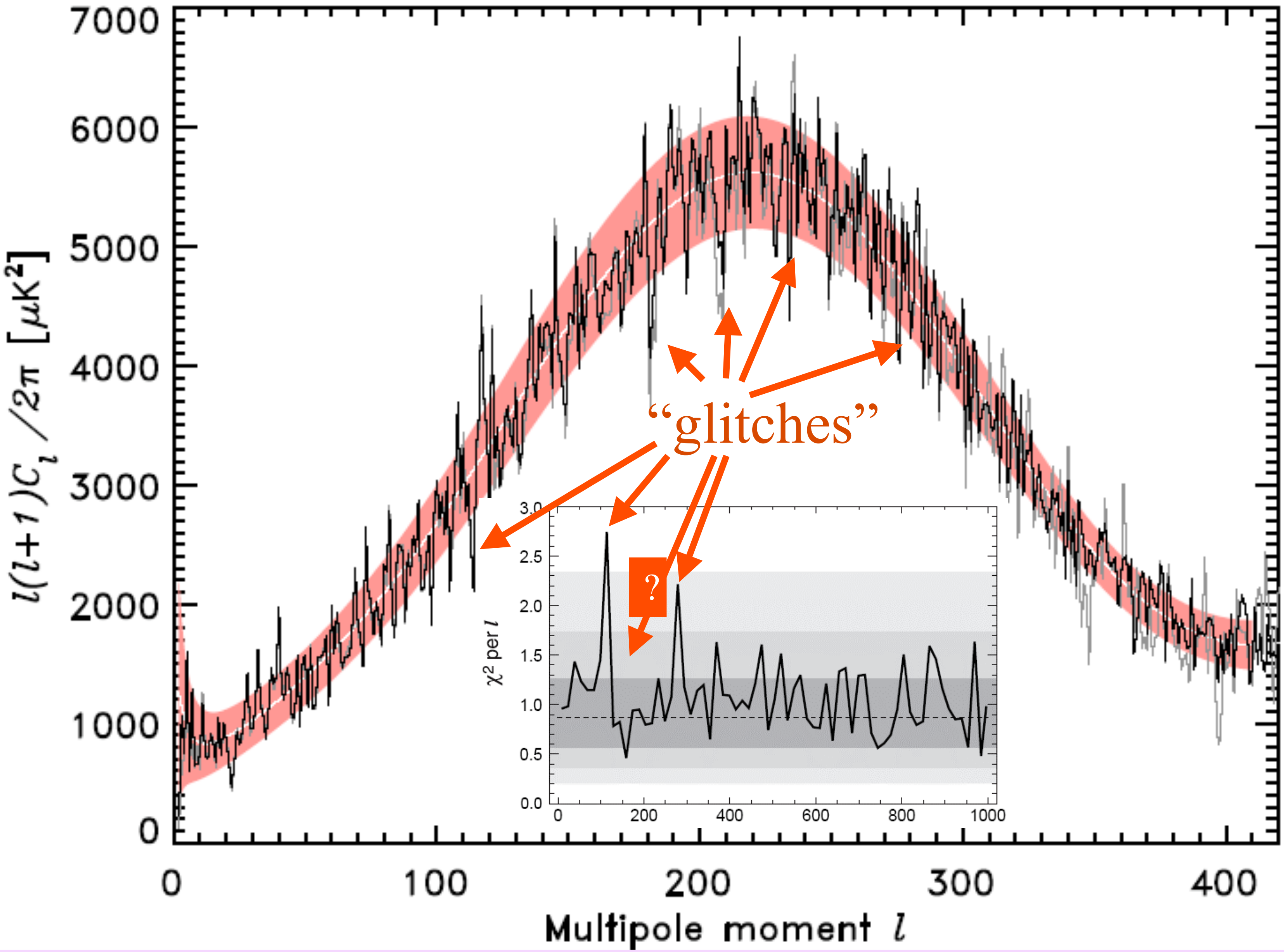
The ‘power-law ΛCDM model’ is believed to be *confirmed* by *WMAP*

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!

The excess χ^2 comes mostly from the *outliers* in the TT spectrum



Is the primordial density perturbation really **scale-free**?

"In the absence of an established theoretical framework in which to interpret these glitches … they will likely remain curiosities"

Hinshaw *et al* (2006)

Then why not also say:

"In the absence of an established theoretical framework in which to interpret *dark energy* … the *apparent acceleration of the universe* will likely remain a curiosity"

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 …**

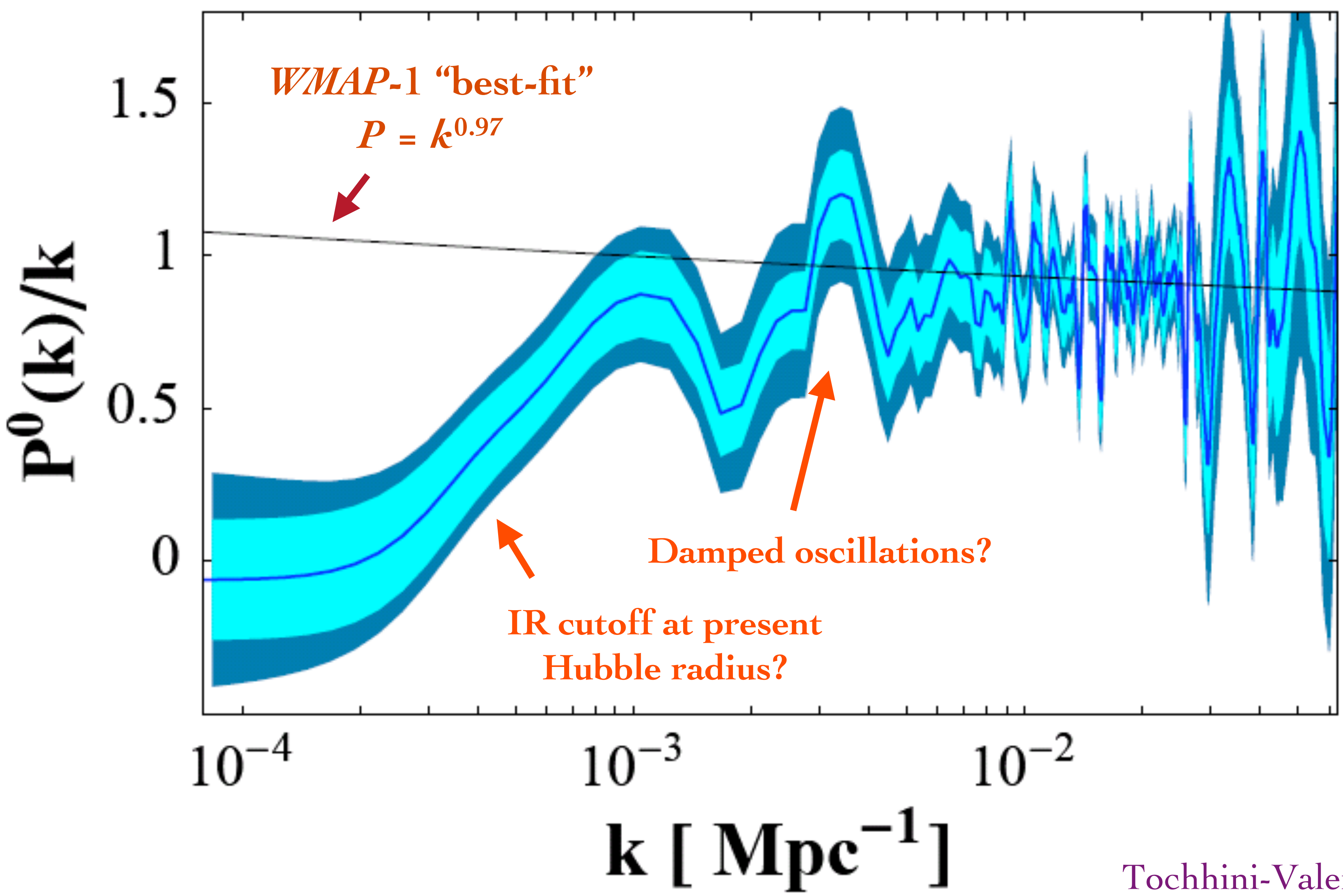
measured over scales ranging from ~ 1 – 10000 Mpc ($\Rightarrow$ ~8 e-folds of inflation)

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*

Many attempts made to reconstruct the primordial spectrum (*assuming* ΛCDM)

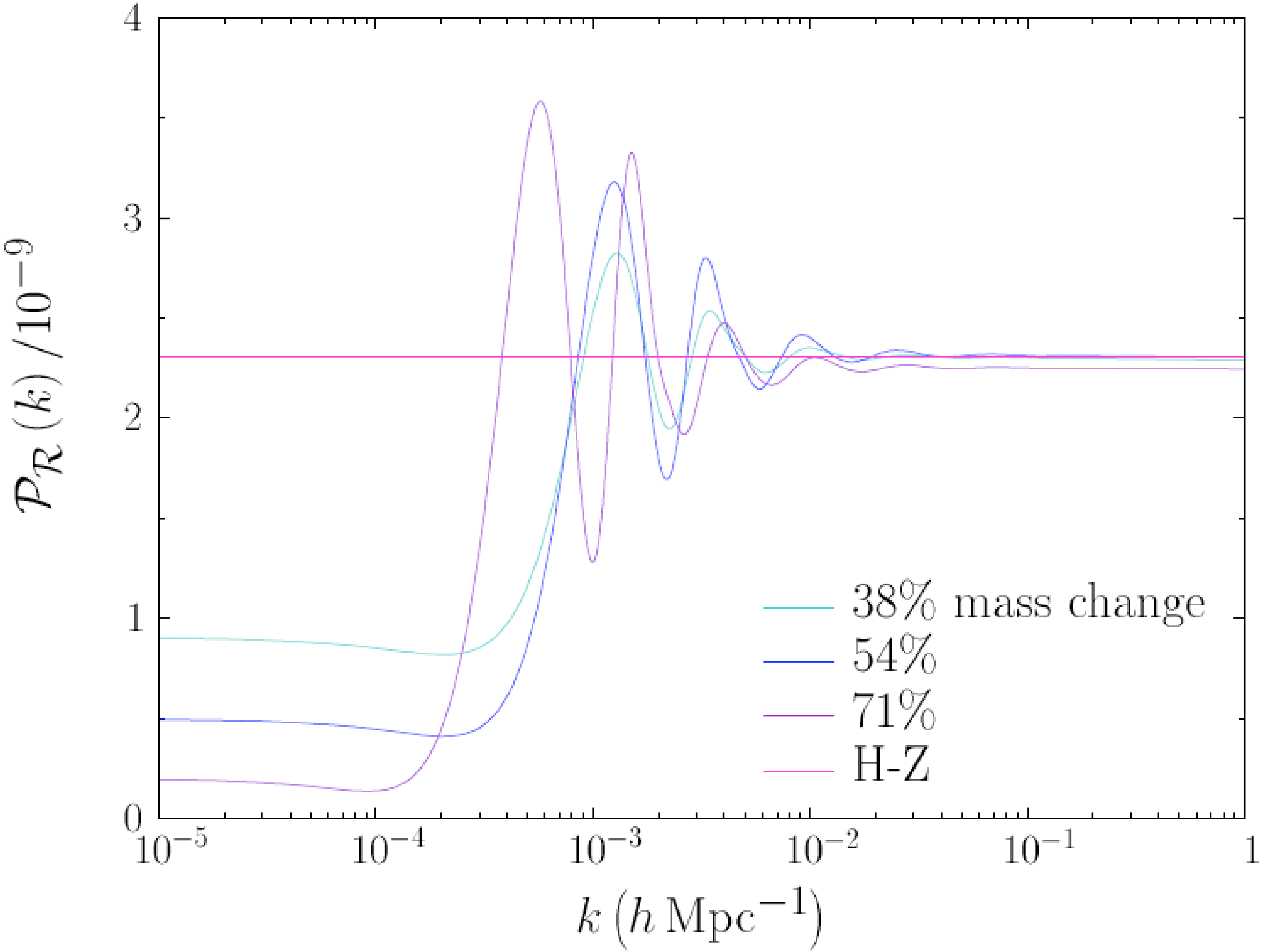
… recent work suggests departures from a power-law spectrum



Tochhini-Valentini,
Hoffman & Silk (2005)

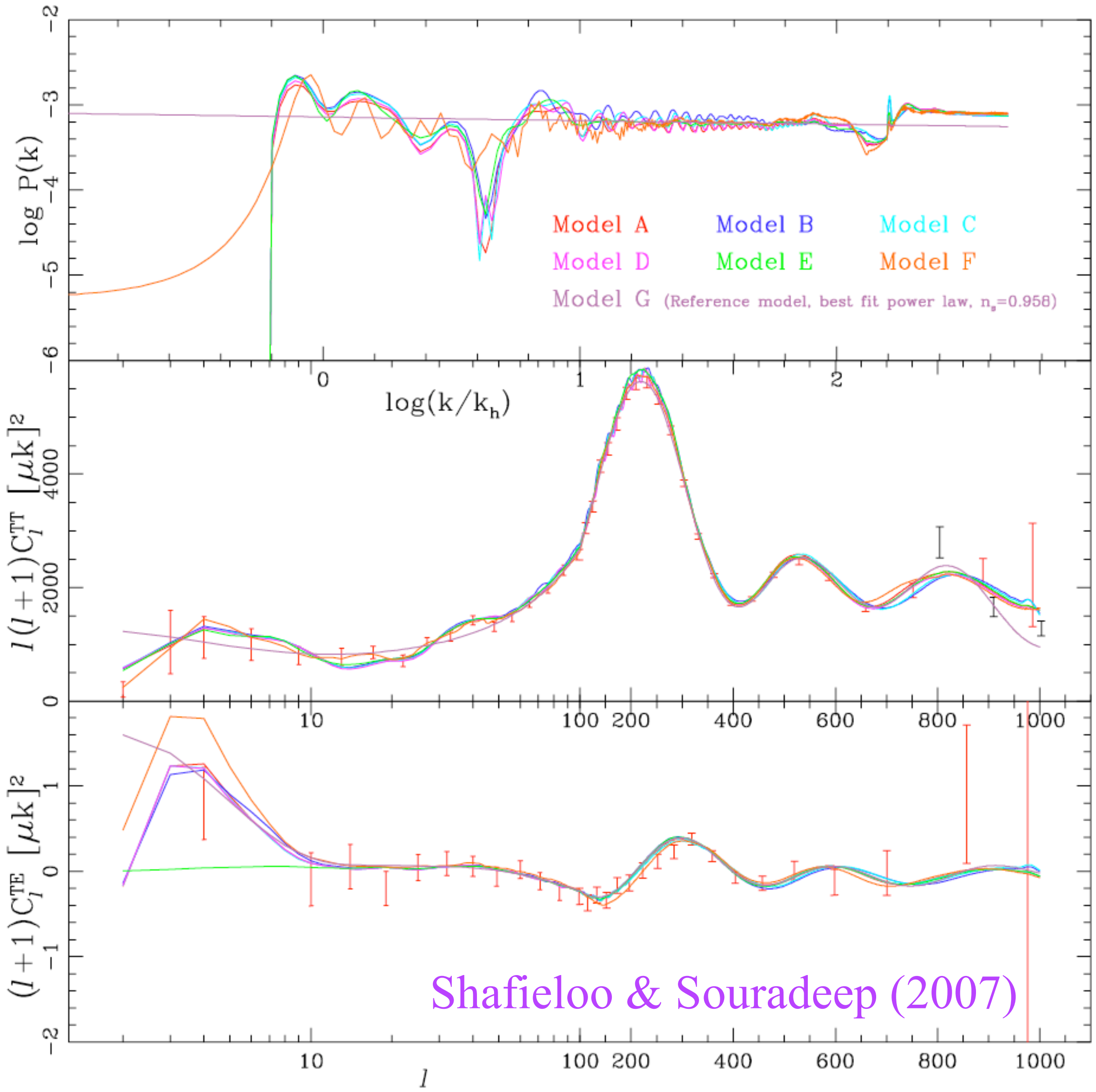
Such spectra arise *naturally* if the inflaton mass changes suddenly, e.g. due to its coupling (through gravity) to a field which undergoes a fast symmetry-breaking phase transition in the rapidly cooling universe

(Adams, Ross & Sarkar 1997)



Hunt & Sarkar (2005)

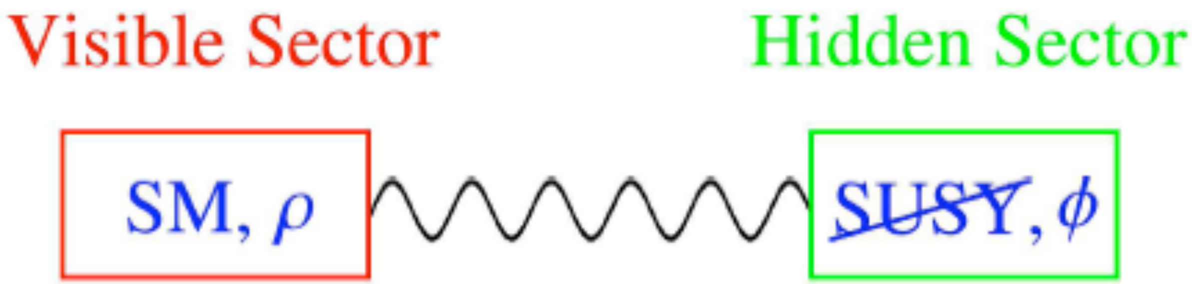
For different priors on cosmological parameters, infer *∂ifferent* primordial spectra



Conversely infer *∂ifferent* cosmological parameters for different primordial spectra!

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

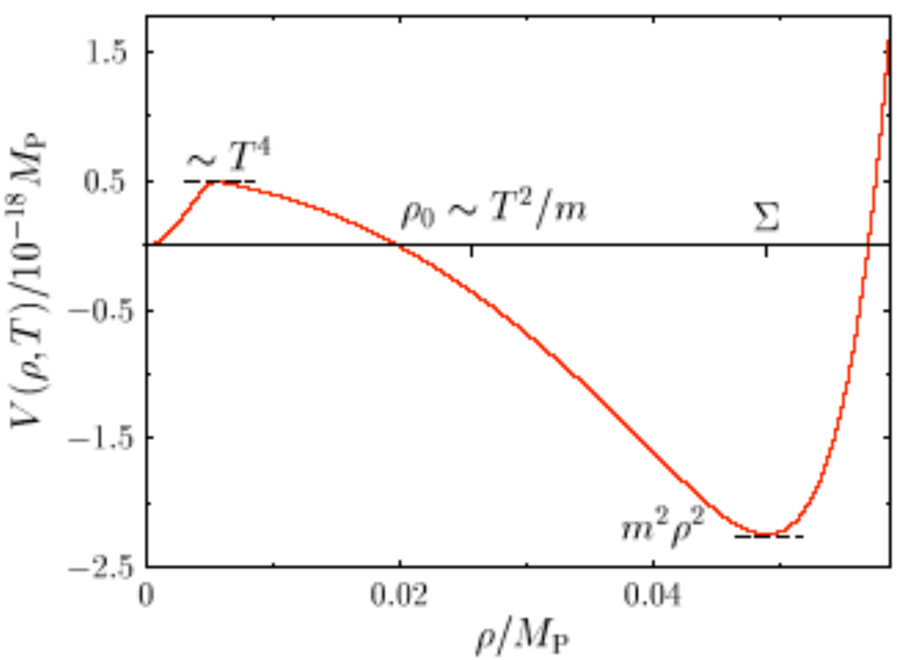
This is due to various symmetries and non-renormalisation theorems

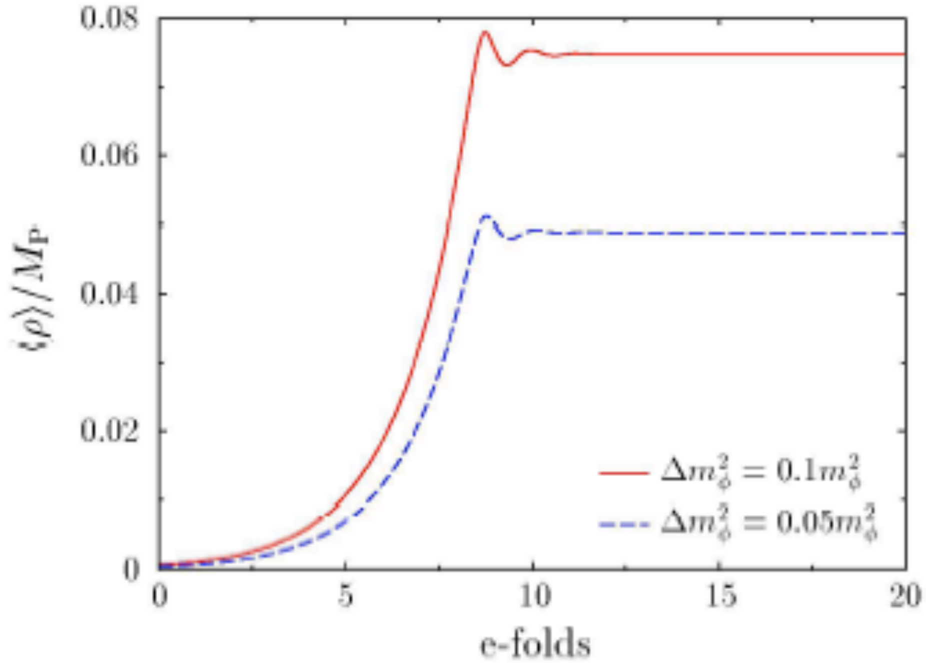
Flat directions are lifted by

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

These fields get a large mass ($m^2 \approx \pm H^2$) *during* inflation, since vacuum energy breaks SUSY

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





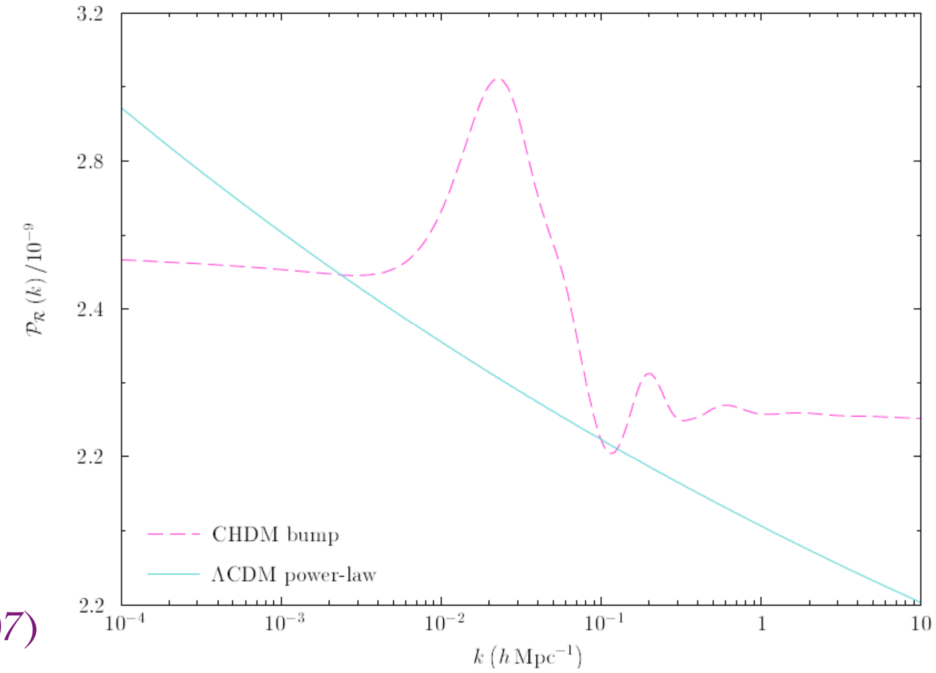
The inflaton field couples to these fields hence its own mass will change *suddenly* $\Rightarrow$ 'features' in the perturbation spectrum

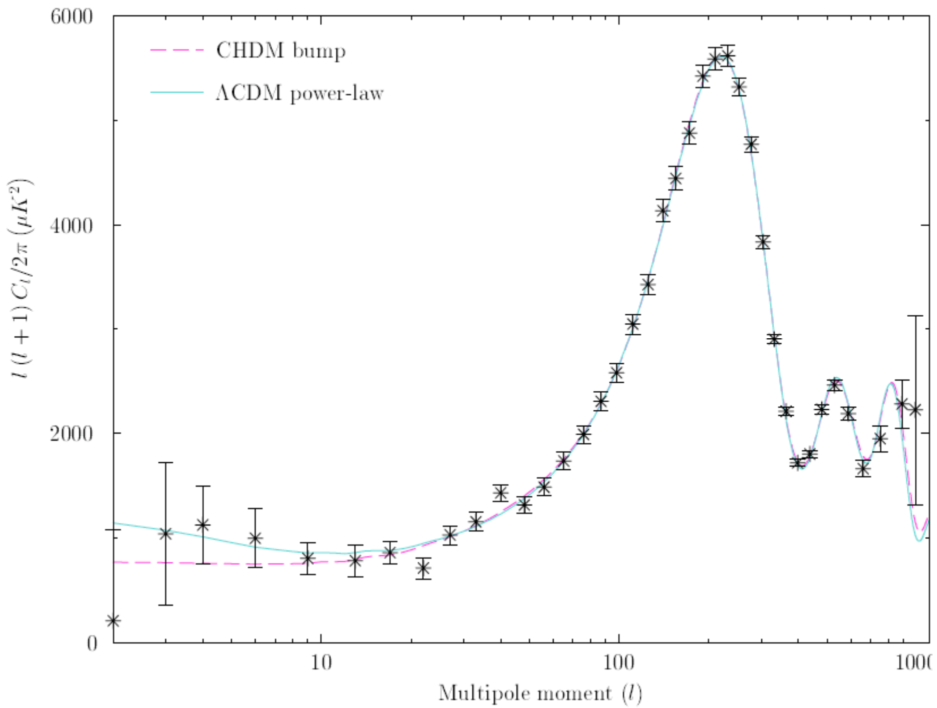
The phase transition(s) will occur if the initial conditions are thermal … the 'features' will be visible if this (last) phase of inflation lasts just long enough to create present Hubble volume

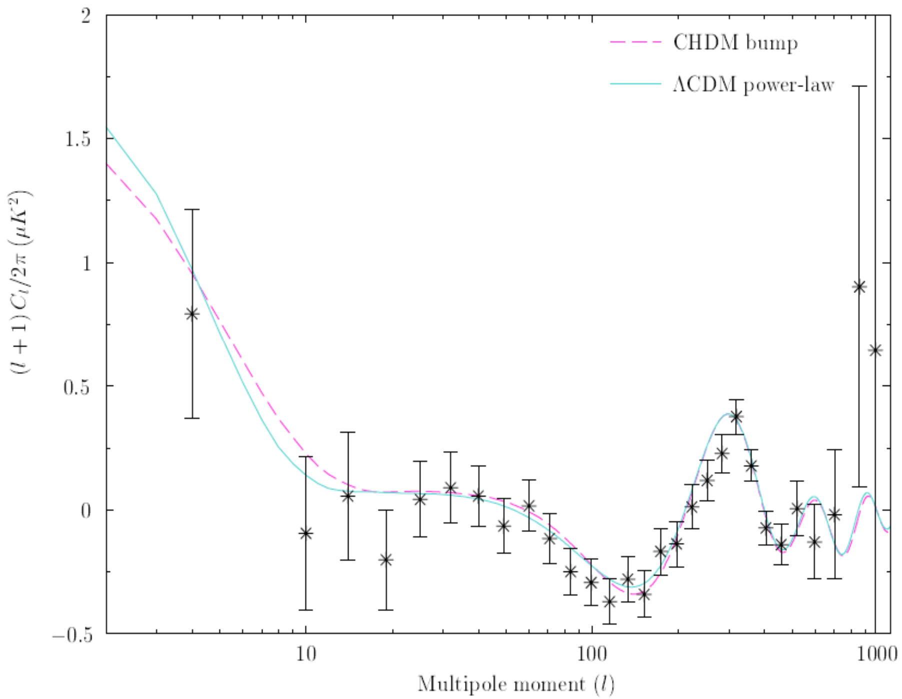
The primordial perturbation spectrum need not be scale-free as is commonly *assumed*

If there is a 'bump' in the spectrum, the WMAP data can be fitted with *no dark energy*
($\Omega_m = 1$, $\Omega_\Lambda = 0$) if $h \sim 0.44$

(Hunt & Sarkar 2007)

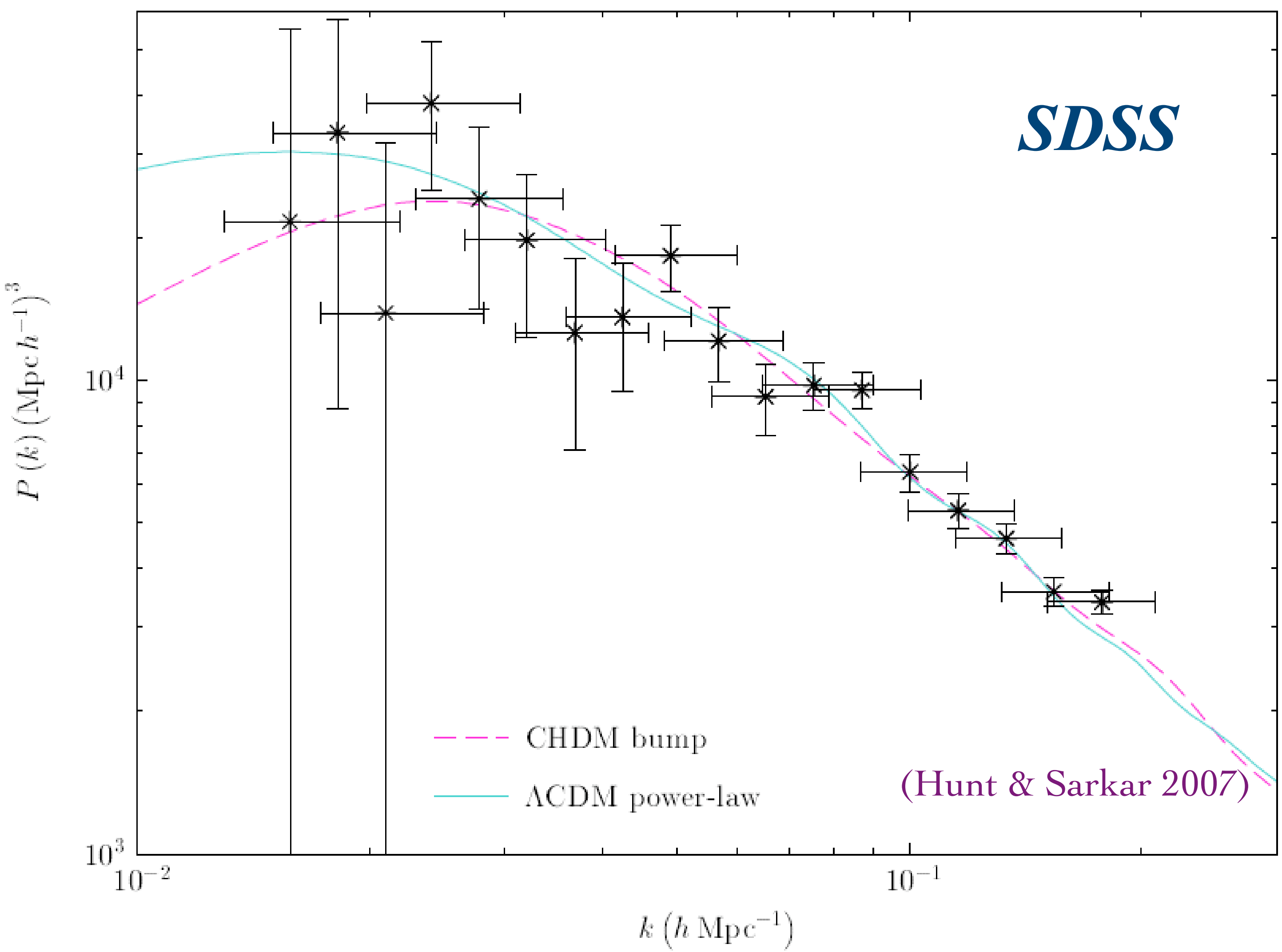






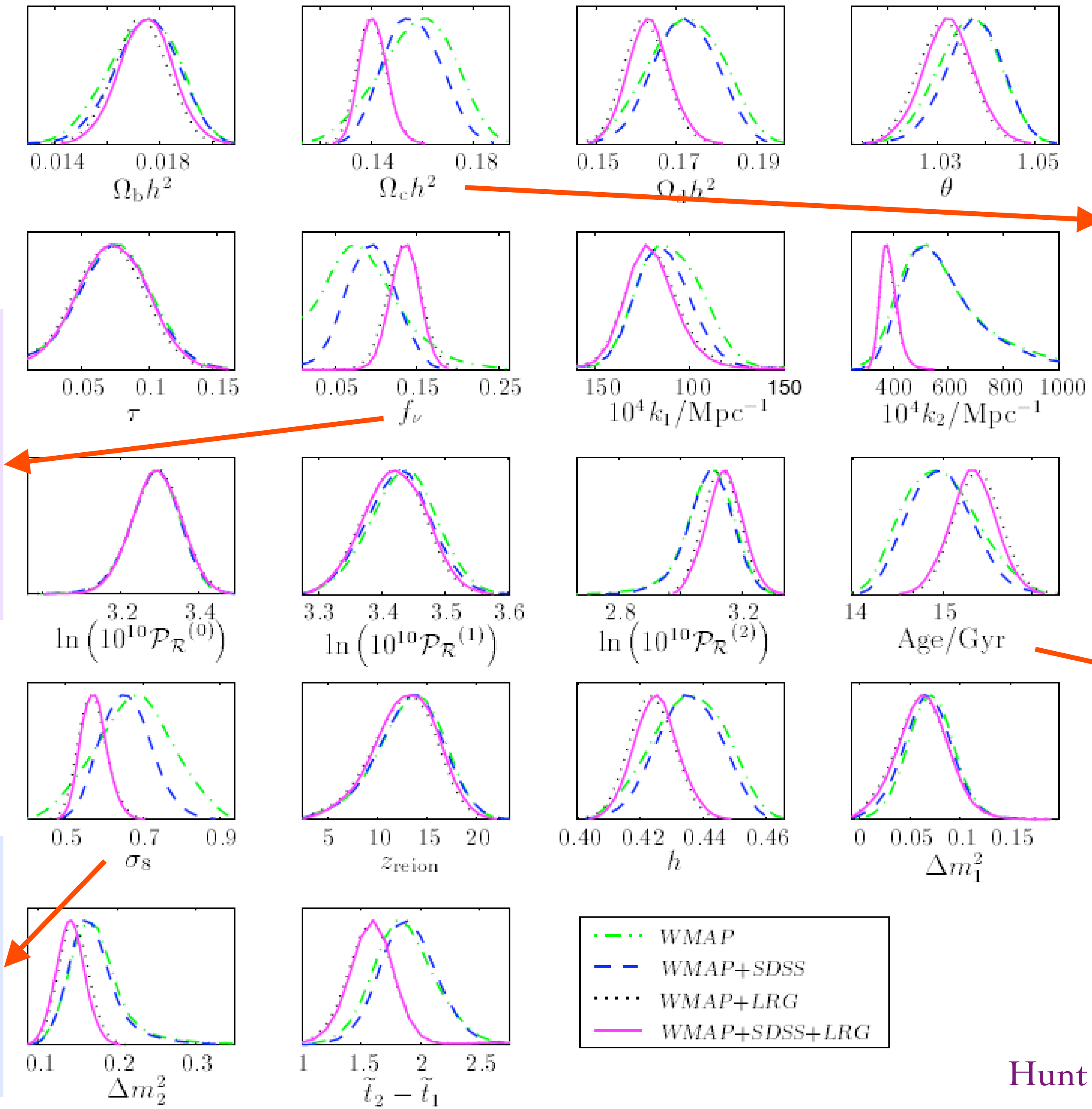
The small-scale power would be excessive unless damped by free-streaming

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



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

MCMC likelihoods: CHDM model ('bump' spectrum)



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

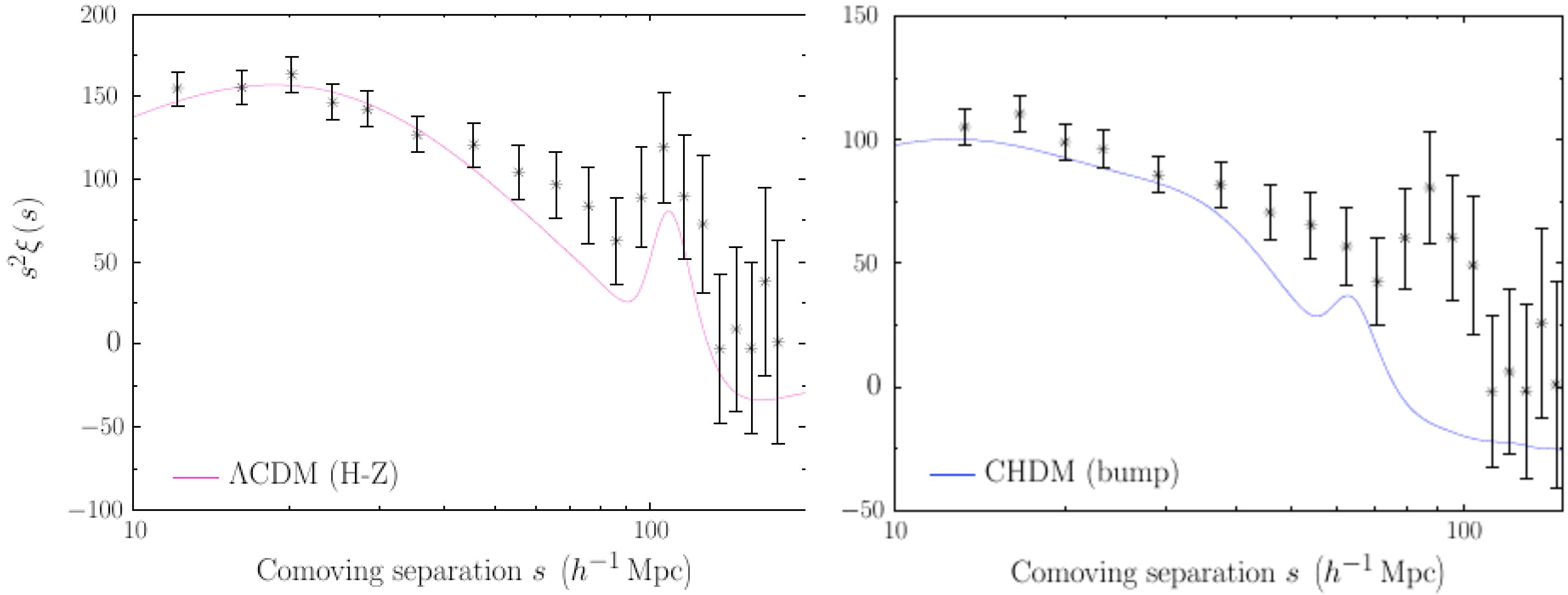
To fit the large-scale structure data *requires* 0.5 eV mass neutrinos

Consistent age for the universe

Consistent with data on clusters and weak lensing

Hunt & Sarkar (2007)

However the E-deS model is *ruled out* by the 'baryon acoustic peak' (present at the ~same *physical* scale, but displaced in redshift space)



But can get angular diameter distance @ z = 0.35 similar to ΛCDM in *inhomogeneous* LTB model - so crucial to measure *z dependence of BAO*!

Must find direct *dynamical* evidence for Λ (e.g. the 'late integrated Sachs-Wolfe effect' @ 5σ) to establish that dark energy really exists

Conclusions

There has been a renaissance in cosmology but modern data is still interpreted in terms of an *idealised* model whose basic assumptions have not been rigorously tested

The standard FRW model naturally admits $\Lambda \sim H_0^2$

… and this is being *interpreted* as dark energy with $\rho_\Lambda \sim H_0^2 M_P^2$

More realistic models of our *inhomogeneous* universe may account for the SNIa Hubble diagram without acceleration

The CMB and LSS data can be equally well fitted if the primordial perturbations are *not* scale-free and $m_\nu \sim 0.5$ eV

“We must know, we will know”

“Wir müssen wissen. Wir werden wissen”
David Hilbert (Lecture in Königsberg, 1930)