Cosmology beyond the Standard Model

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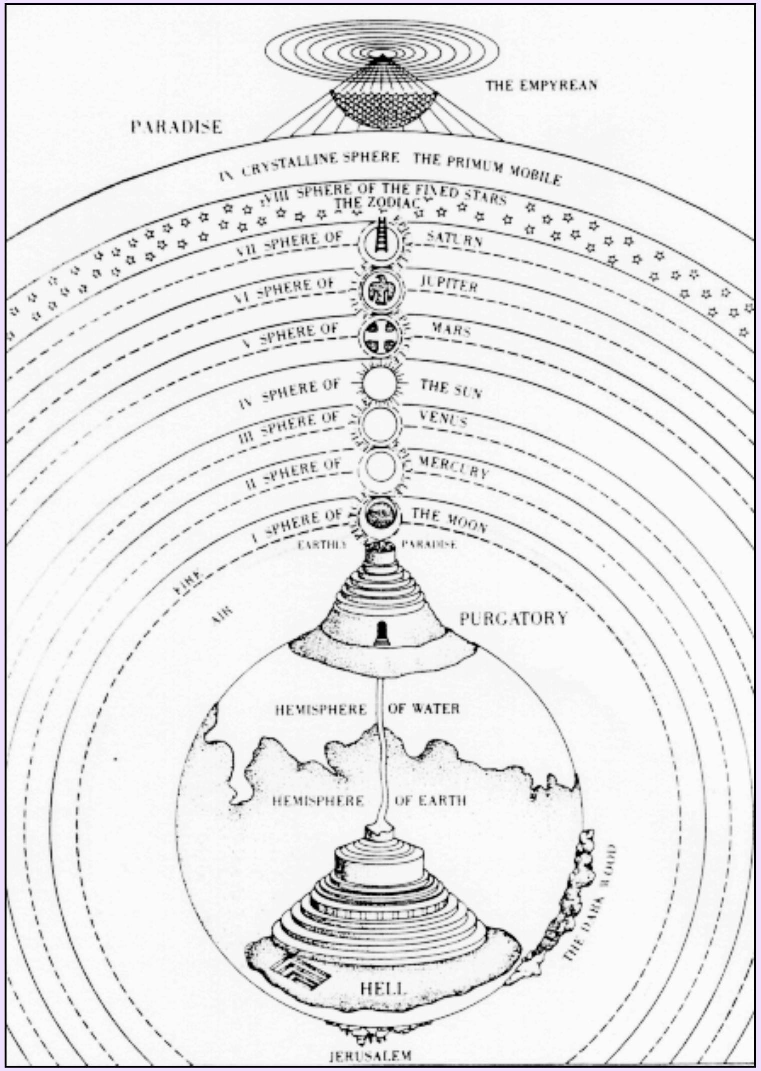
In the Aristotlean 'standard model' of cosmology (circa 350 BC)
the universe was *static* and *finite* and *centred on the Earth*

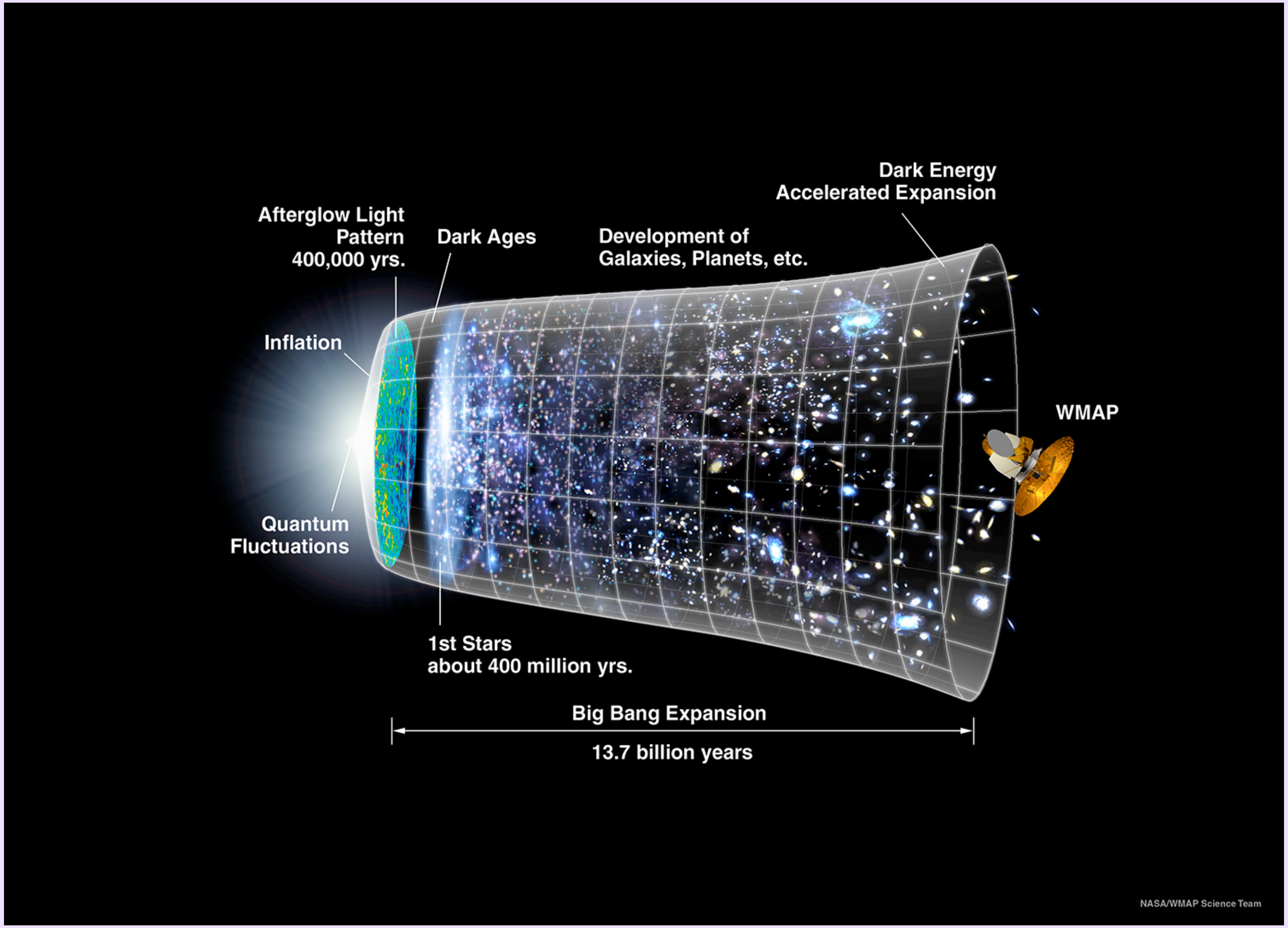


The Divine Comedy, Dante Allighieri (1321)

This was a 'simple' model and fitted all the observational data
… but the underlying principle was unphysical

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

dominated by dark energy and undergoing accelerated expansion



Courtesy: 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*

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

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

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

The effects of *new* physics beyond the SM (neutrino mass, nucleon decay, FCNC ...)
⇒ **non-renormalisable operators** suppressed by M^n … which '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 (10^2 new parameters)

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

The 1st term **couples to gravity** so the *natural* expectation is $\rho_\Lambda \sim (1\ \text{TeV})^4$
i.e. the universe should have been inflating since $t \sim 10^{-12}$ s!

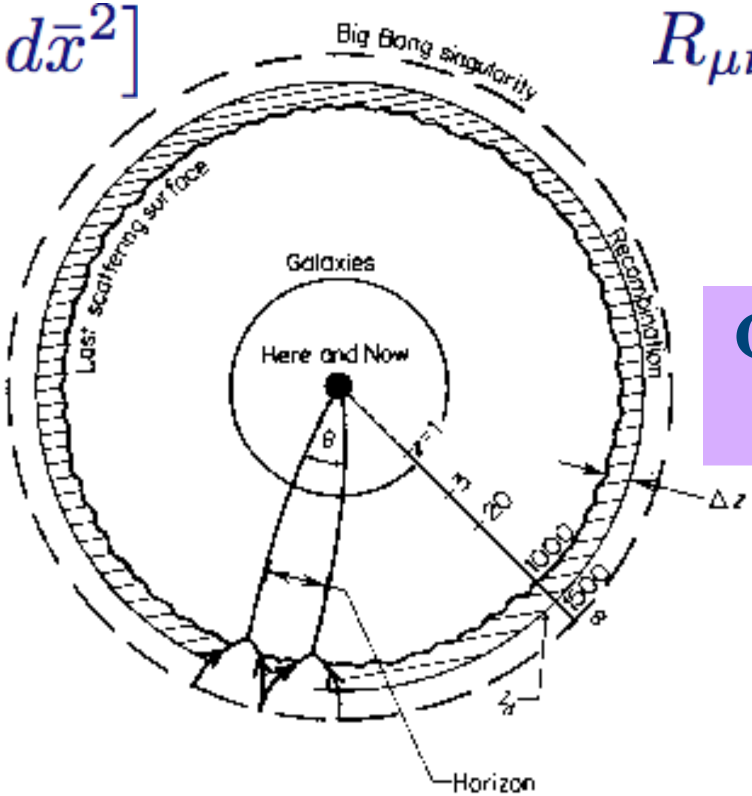
There *must* be some reason why this did not happen ($\Lambda \to 0$?)

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



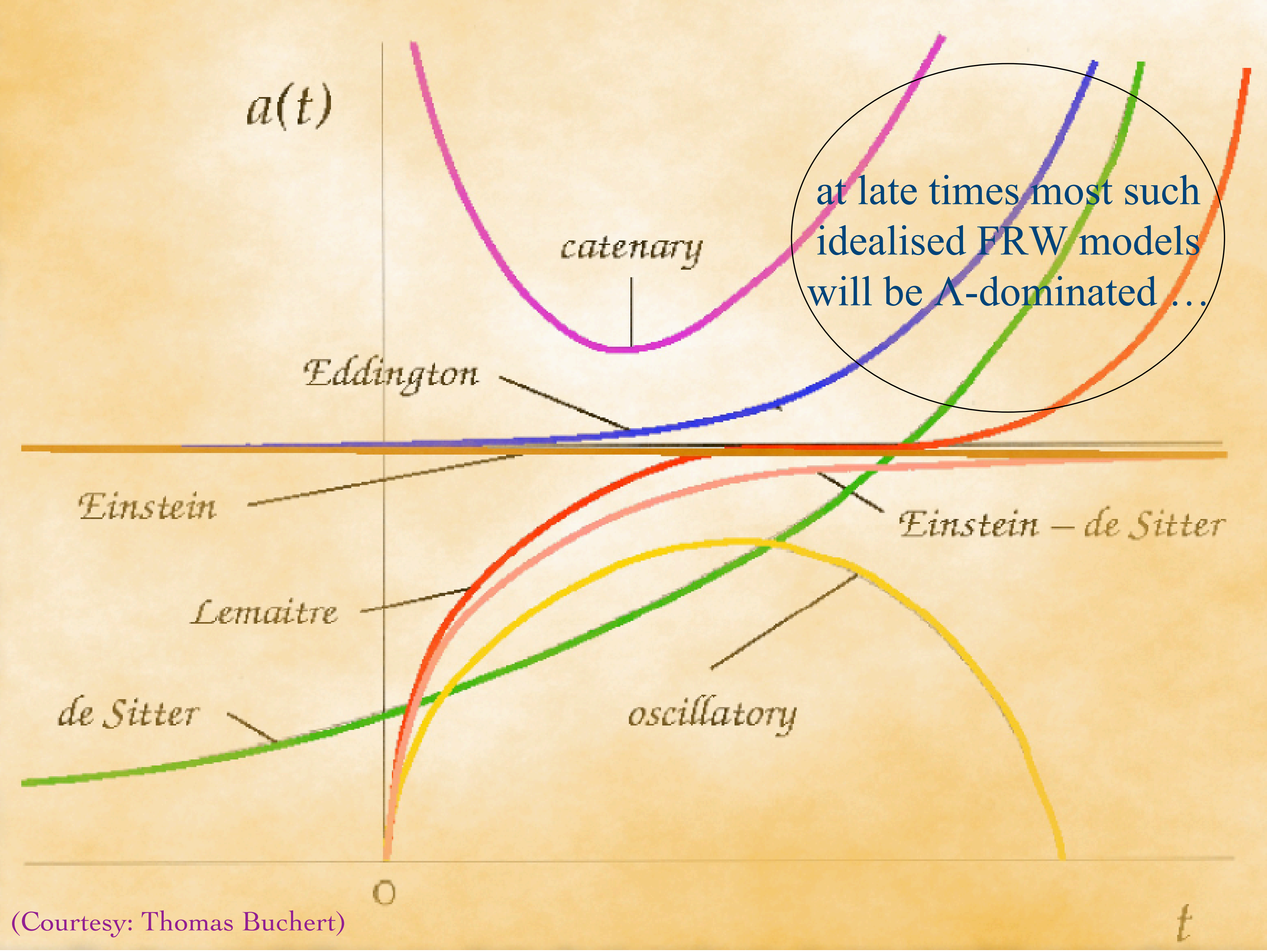
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_{\rm N}T_{\mu\nu}$$

Geometrodynamics
Einstein

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

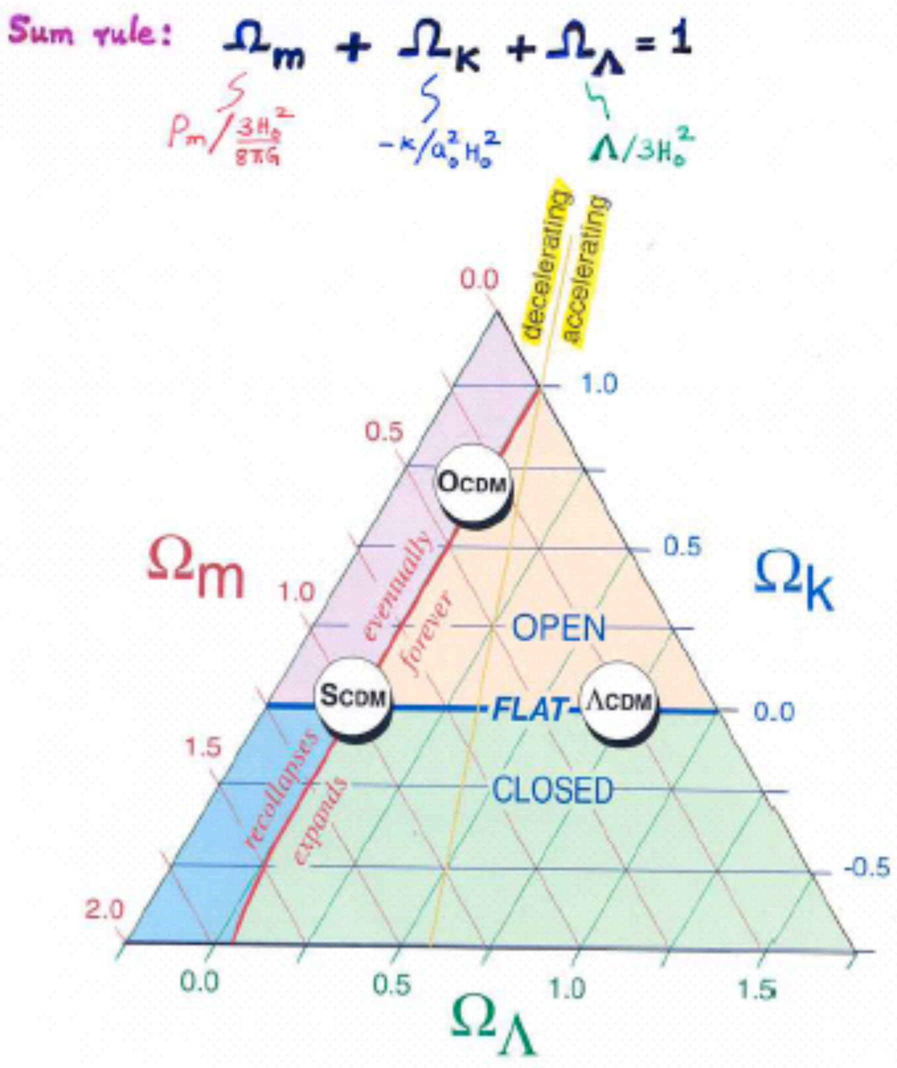
$$\equiv {H_0}^2\left[\Omega_{\rm m}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

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



(Courtesy: Thomas Buchert)

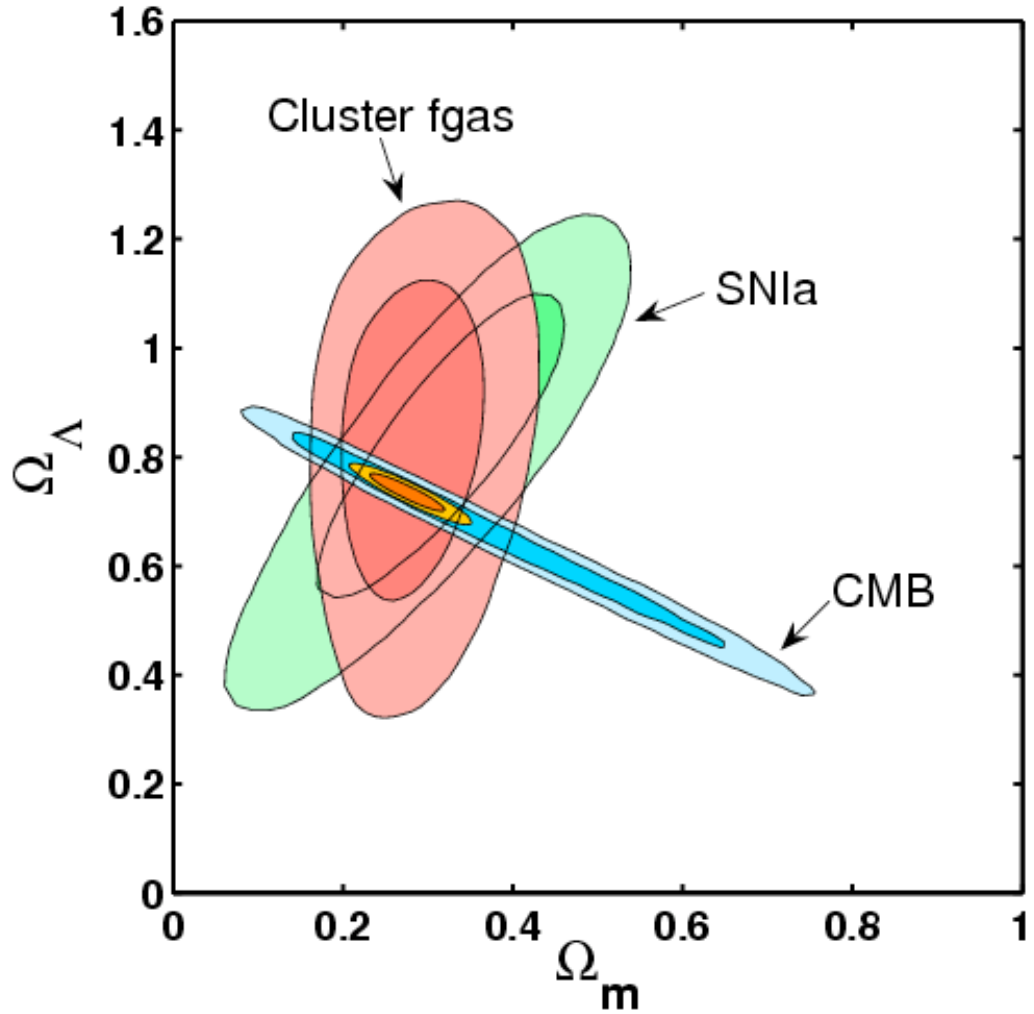
It is *natural* for data interpreted in this *idealised* model to yield $\Lambda \sim H_0^2$



Bahcall, Ostriker, Perlmutter & Steinhardt (1999)

… *not* surprising that we usually 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 and the possibility of other components (Ω_x) which are *unaccounted* for

Observations indicate $\Omega_k \approx 0$ so the FRW model is simplified further, leaving only two free parameters (Ω_Λ and Ω_m) to be fitted to data



Allen *et al* (2008)

If we *underestimate* Ω_m, or if there is a Ω_x ("back reaction") which the FRW model does not account for, then we will *necessarily* infer $\Omega_\Lambda \neq 0$

Quantities averaged over a domain $\mathcal{D}$ obey modified Friedmann equations Buchert 1999:

$$
\begin{aligned}
3\frac{\ddot{a}_{\mathcal{D}}}{a_{\mathcal{D}}} &= -4\pi G\langle\rho\rangle_{\mathcal{D}} + \mathcal{Q}_{\mathcal{D}} \, , \\
3\left(\frac{\dot{a}_{\mathcal{D}}}{a_{\mathcal{D}}}\right)^2 &= 8\pi G\langle\rho\rangle_{\mathcal{D}} - \frac{1}{2}\langle^{(3)}R\rangle_{\mathcal{D}} - \frac{1}{2}\mathcal{Q}_{\mathcal{D}} \, ,
\end{aligned}
$$

where $\mathcal{Q}_{\mathcal{D}}$ is the backreaction term,

$$
\mathcal{Q}_{\mathcal{D}} = \frac{2}{3}(\langle\theta^2\rangle_{\mathcal{D}} - \langle\theta\rangle_{\mathcal{D}}^2) - \langle\sigma^{\mu\nu}\sigma_{\mu\nu}\rangle_{\mathcal{D}} \, .
$$

Variance of the expansion rate.

Average shear.

If $\mathcal{Q}_{\mathcal{D}} > 4\pi G\langle\rho\rangle_{\mathcal{D}}$ then $a_{\mathcal{D}}$ accelerates.

Can mimic a cosmological constant if $\mathcal{Q}_{\mathcal{D}} = -\frac{1}{3}\langle^{(3)}R\rangle_{\mathcal{D}} = \Lambda_{\text{eff}}$.

Whether the backreaction can be sufficiently large is an *open question* …
hard to compute in general because spatial averaging and time evolution along our past light cone do *not* commute (Ellis 1982)

Interpreting Λ as vacuum energy raises the coincidence problem:

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 unnatural in a fundamental theory and is simply put in by hand

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

(recall: $H^2 = 8\pi G_N\rho/3 + \Lambda/3$)

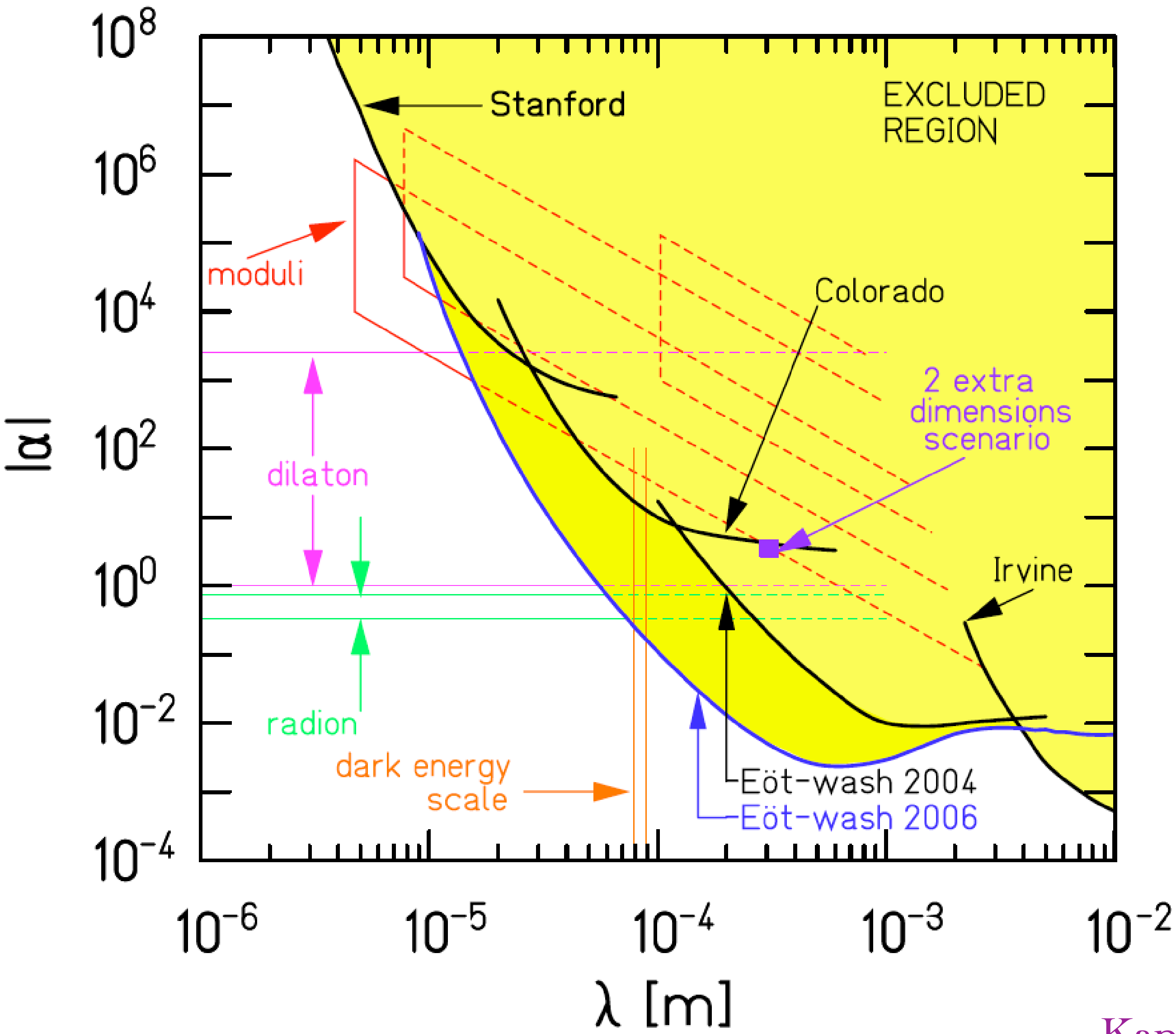
… *ruled out* by Big Bang nucleosynthesis (requires G_N to be within 5% of lab value)

There cannot be a *natural* explanation for the coincidence problem

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

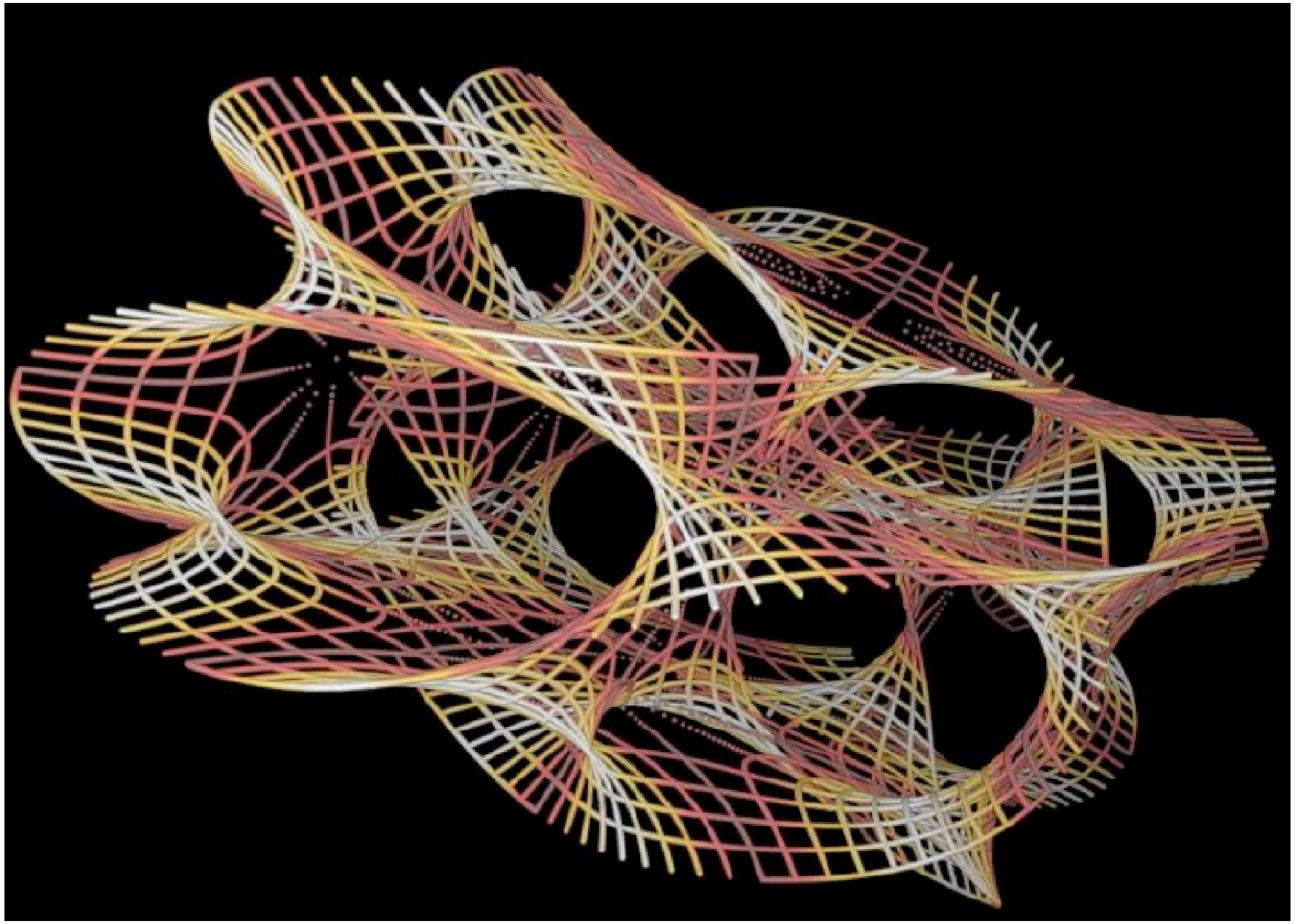
If this is 'dark energy', why is there is *no* evidence for a change in the inverse-square law at the scale $\rho_\Lambda^{-1/4} \sim (H_0 M_P)^{-1/2} \sim 0.1$ mm ?

$$V(r) = -G\frac{m_1 m_2}{r}[1 + \alpha \exp(-r/\lambda)]$$



Kapner *et al* (2007)

In string/M-theory, the sizes and shapes of the extra dimensions ('moduli') must be stabilised … e.g. by turning on background 'fluxes'

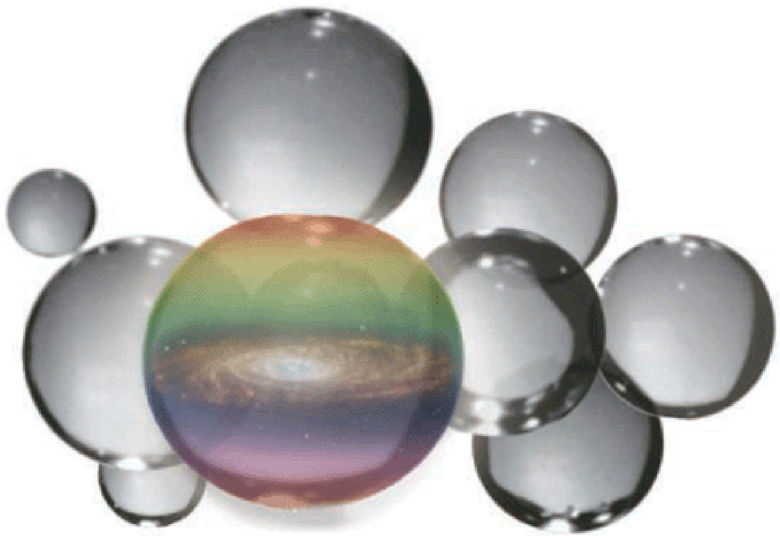


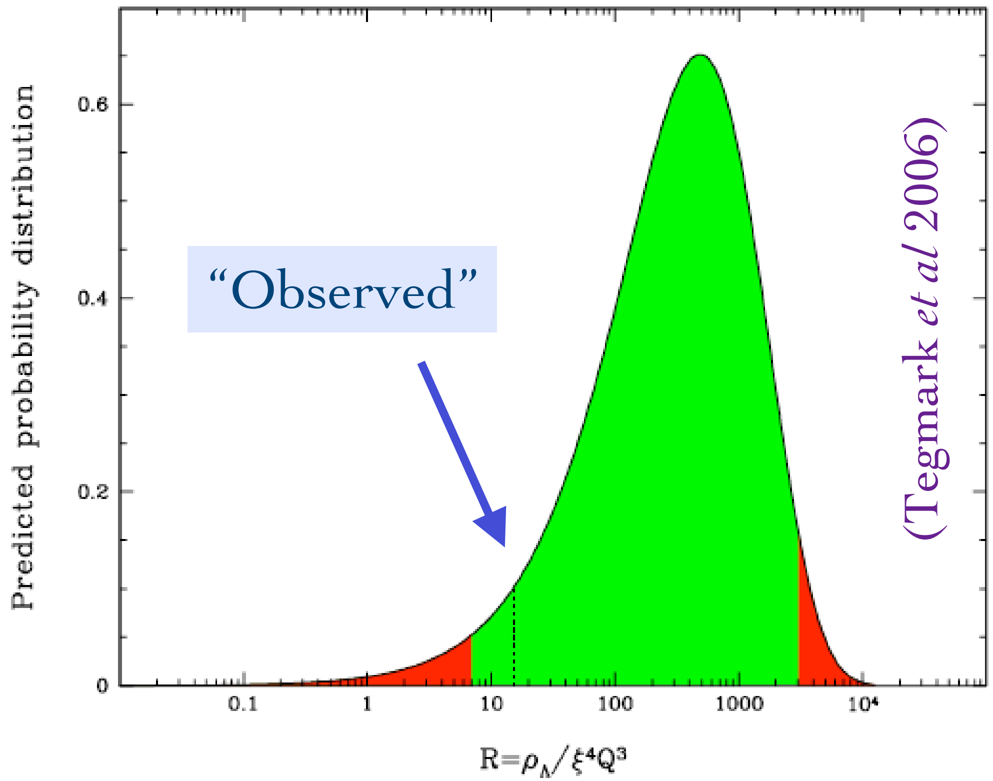
Given the variety of flux choices and the number of local minima in the flux potential, the total number of vacuua is *very* large - perhaps 10^{500}!

The existence of the huge *landscape* of possible vacuua in string theory (with moduli stabilised through background fluxes) has remotivated **attempts at an 'anthropic' explanation for $\rho_\Lambda \sim \rho_m$**

Perhaps it is just "observer bias" … galaxies would not have formed for *higher* Λ
(Weinberg 1989, Efstathiou 1995, Martel, Shapiro, Weinberg 1998 …)

(Credit: K. Buckheit Krause/Science)



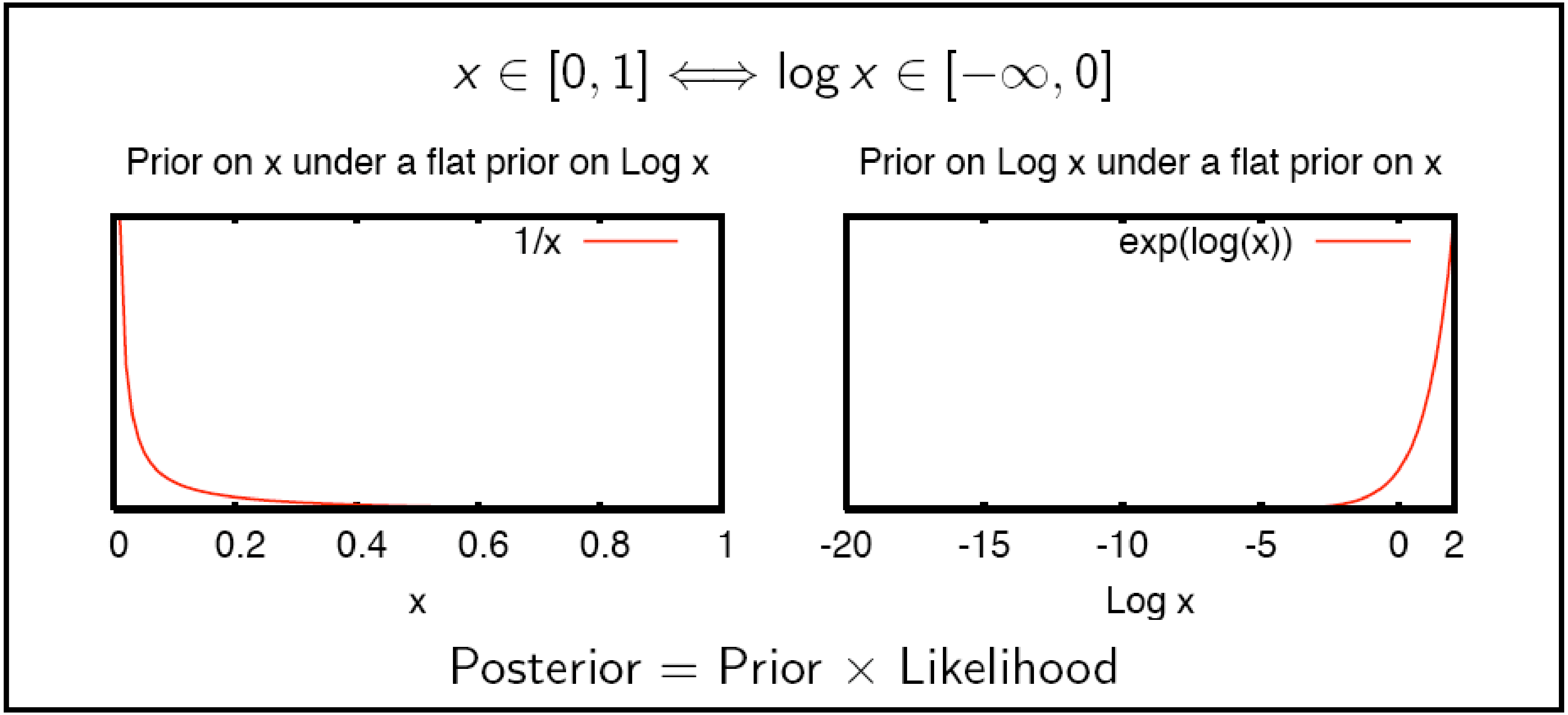


But the 'anthropic prediction' of Λ from considerations of galaxy formation is much *higher* than the observationally inferred value

Moreover this assumes the prior distribution to be *flat* in the range $0 \rightarrow 10^{-120}\ M_P^4$

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

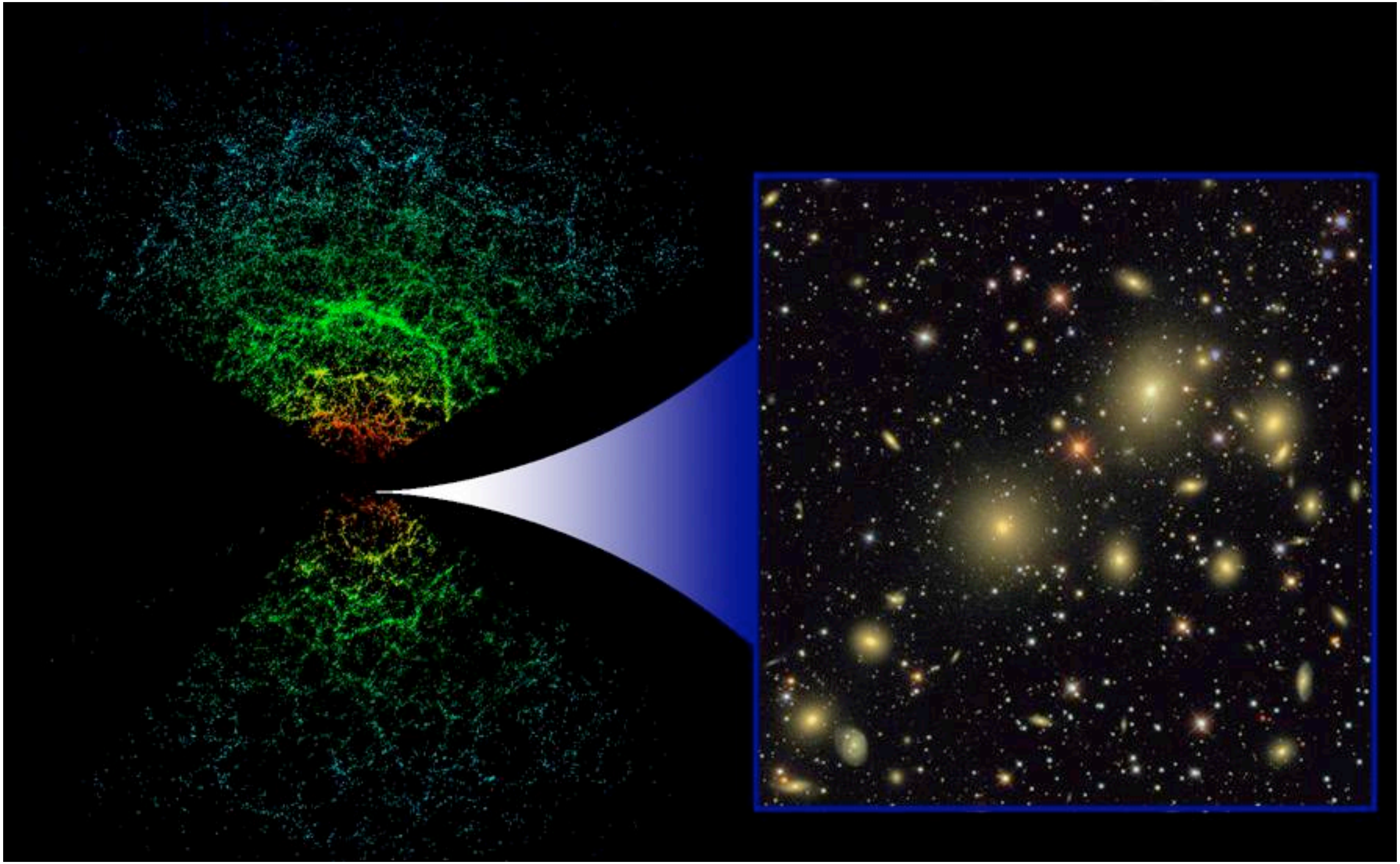
If the relevant physical variable is e.g. *log* ρ_Λ, then $\rho_\Lambda = 0$ would be favoured!



(Courtesey: W Valkenburg)

So it is far from clear that $\Lambda \sim H_0^2$ has an anthropic explanation

Galaxies are seen to trace out a cosmic 'web' of filamentary structure



Averaged on *large* scales the universe is presumably homogeneous but how would it bias cosmological inferences if we are located in a void?

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

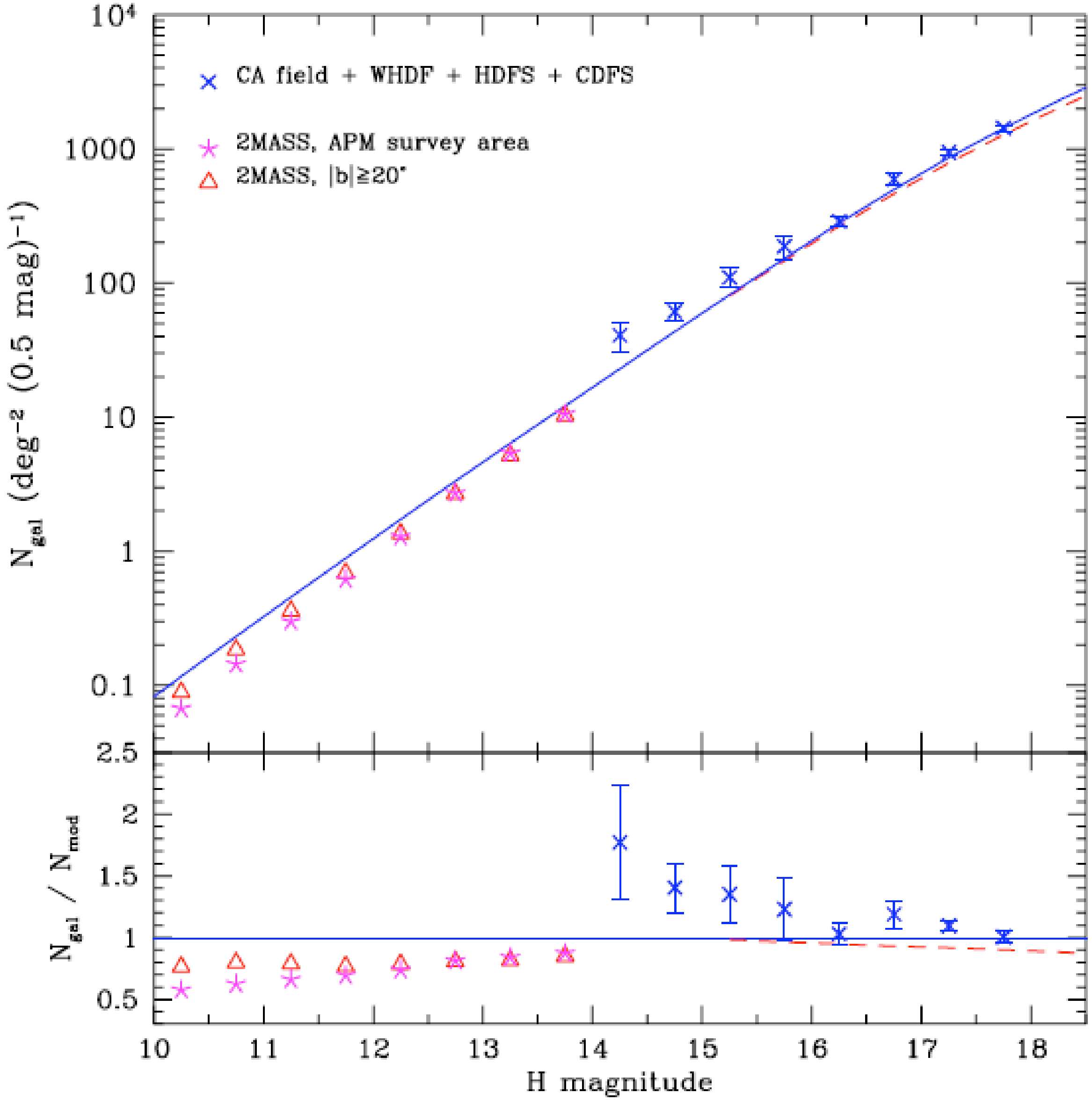
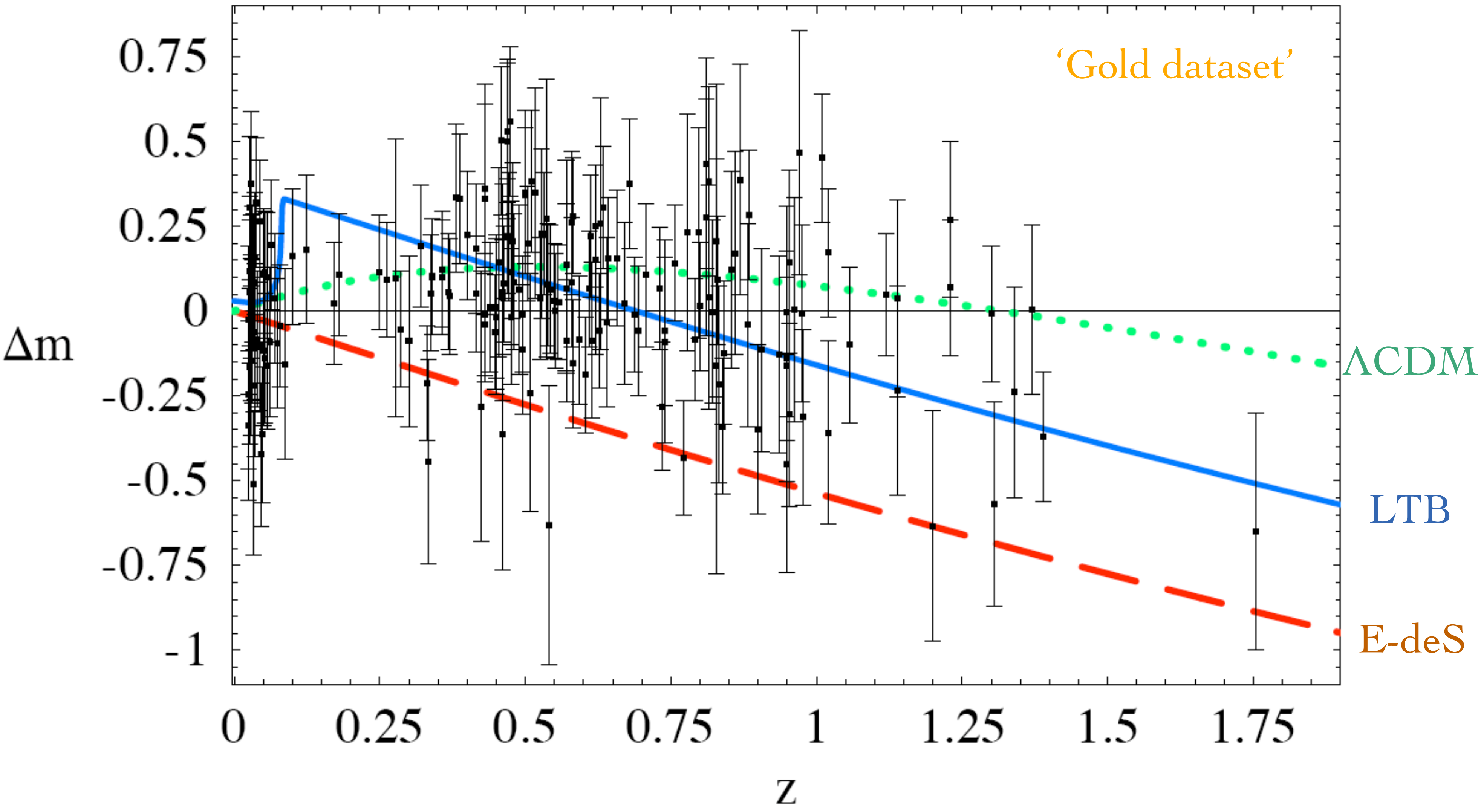


Figure 8. Here we show the faint H-band data from the two fields presented in this work (CA field and WHDF) and the two fields published by the LCIRS (HDFS and CDFS; Chen et al. 2002) applying a zeropoint to the LCIRS data consistent with the bright H-band 2MASS data (and hence the CA field and WHDF 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.

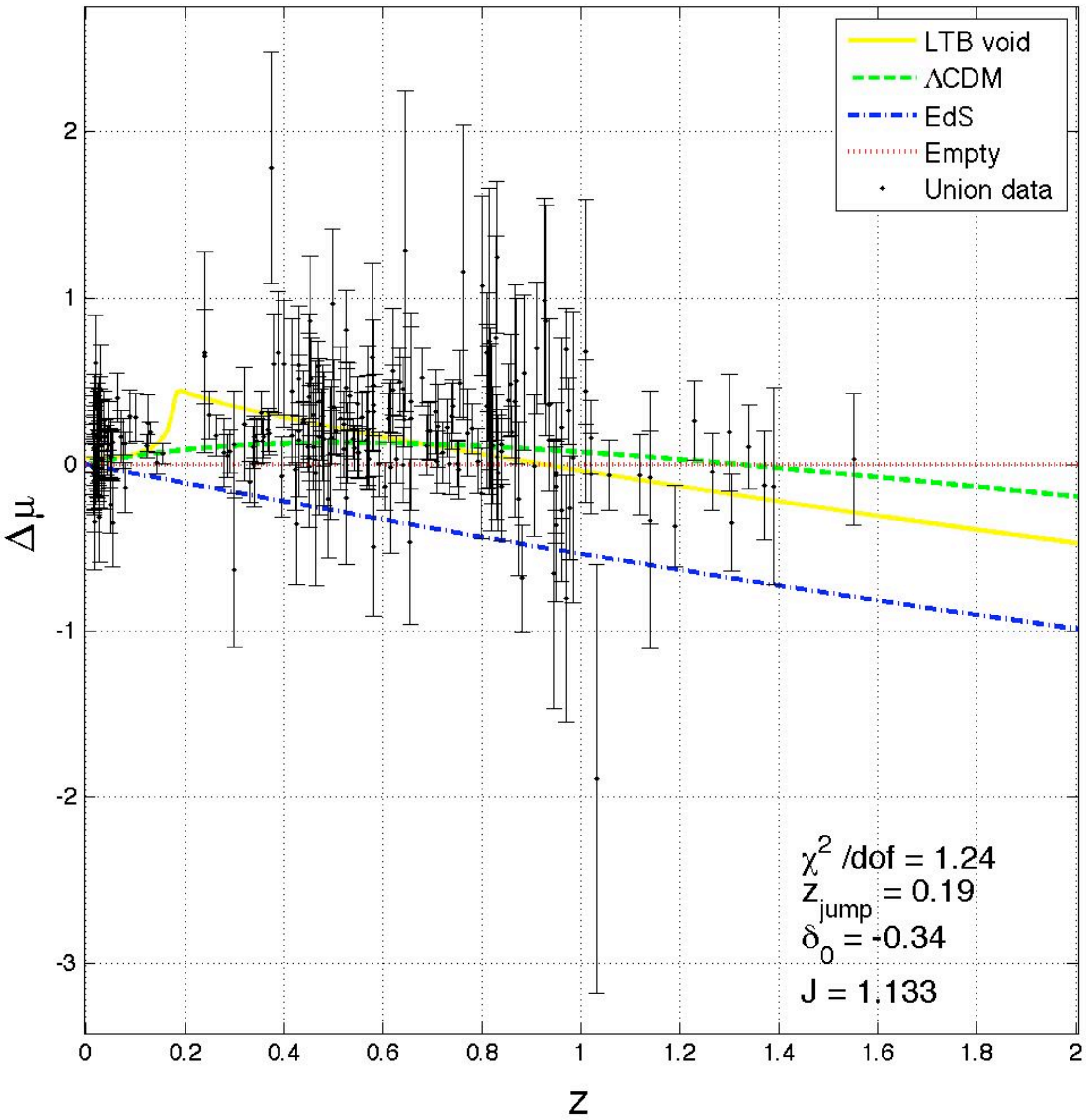
Frith, Metcalfe & Shanks (2006)

If so, the SN Ia Hubble diagram may be explained *without invoking acceleration*, since distant supernovae would be in a *slower* Hubble flow than the nearby ones within the local void (**Lemaitré-Tolman-Bondi inhomogeneous model**)

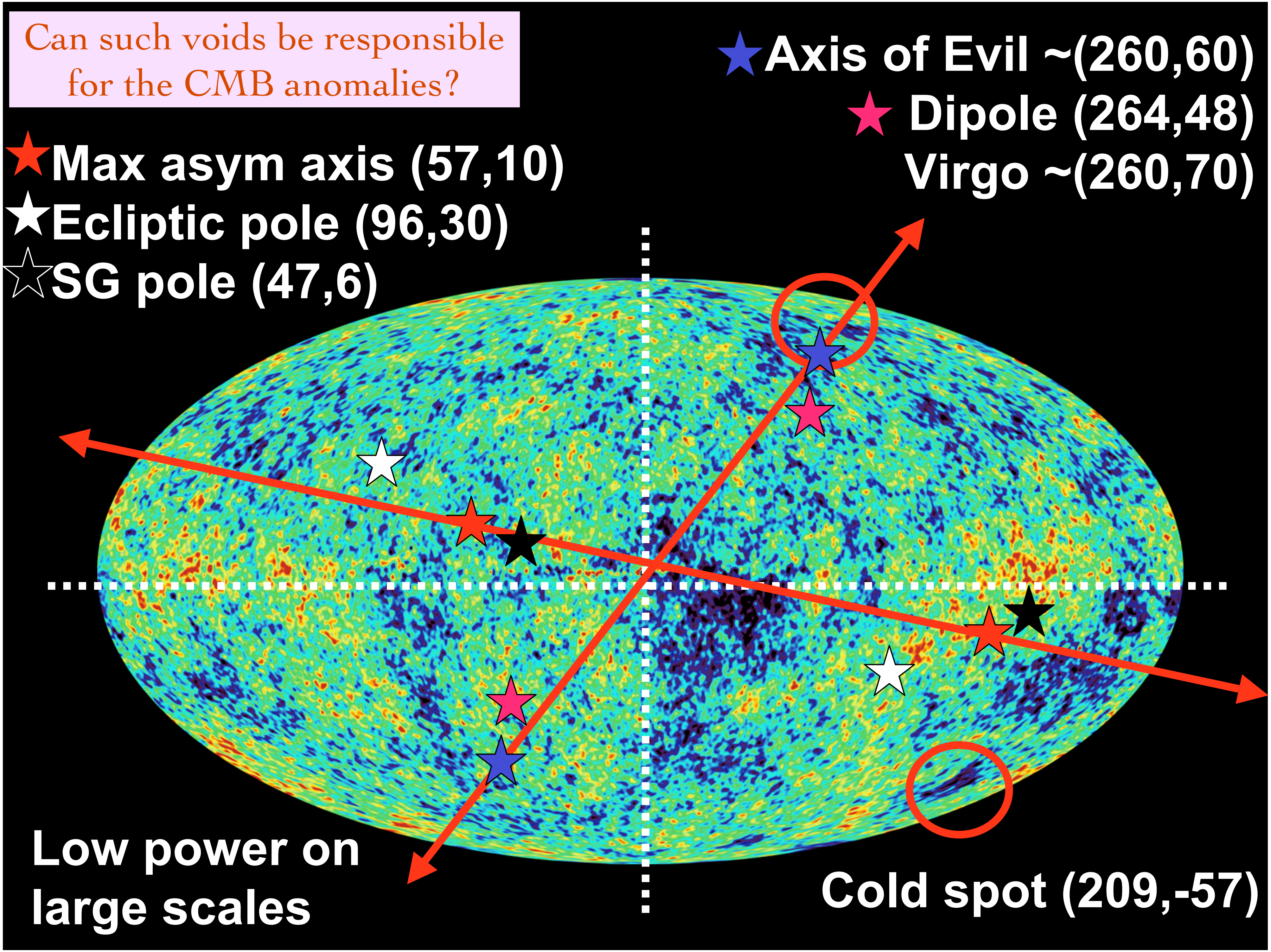


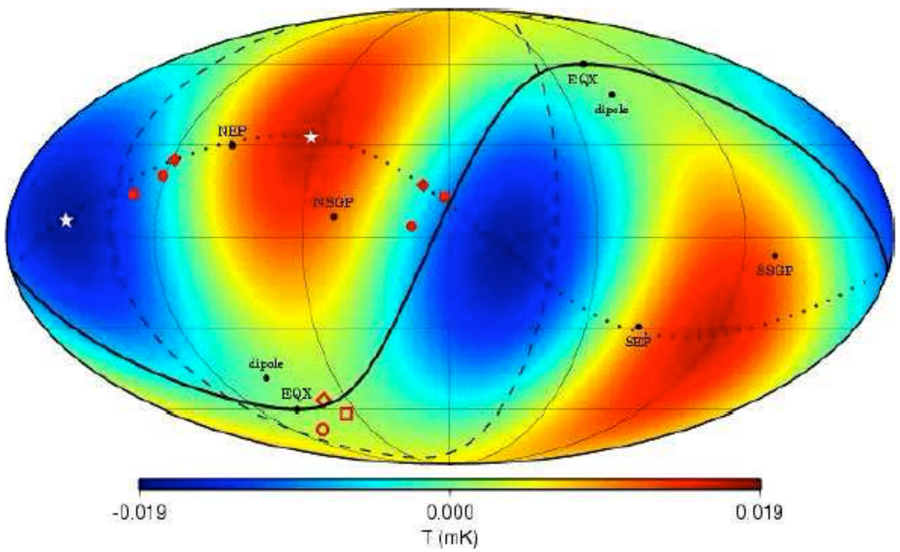
Alexander, Biswas,Notari & Vaid (2007)

Even adding recent data, the gap at z ~ 0.1-0.3 remains so a ~200-400 Mpc size local void is not yet ruled out



… but the SDSS II data will fill this gap and test this model


Can such voids be responsible
for the CMB anomalies?
Axis of Evil ~(260,60)
Dipole (264,48)
Virgo ~(260,70)
Max asym axis (57,10)
Ecliptic pole (96,30)
SG pole (47,6)
Low power on
large scales
Cold spot (209,-57)

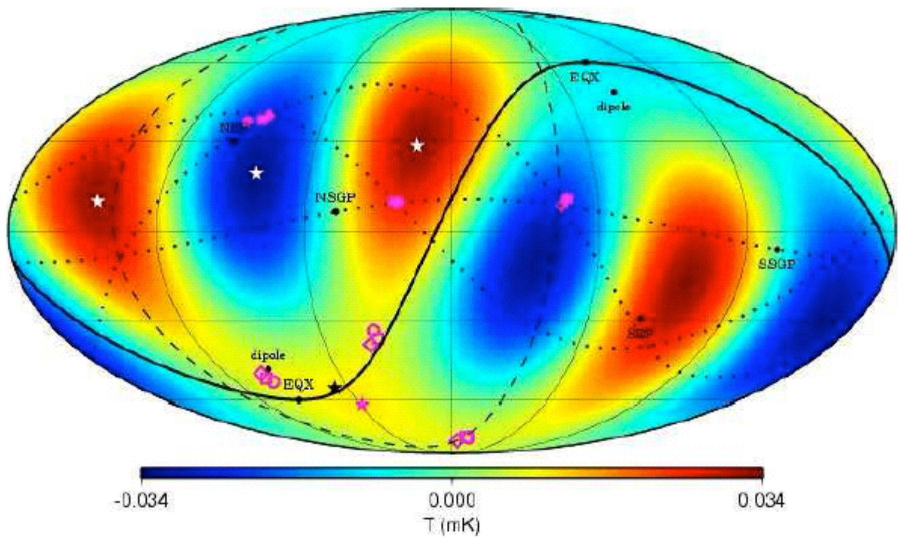


The local void need not be exactly spherical … nor would we expect to be *exactly* at its centre

So might expect (low *l*) CMB anisotropies to be generated by the **'Rees-Sciama effect'** (must be within 10% of centre to *not* generate excessive dipole)

The CMB quadrupole and octupole are indeed very well-aligned!

This however requires us to be located at the boundary between two voids (to yield the observed *planar* alignment)
Inoue & Silk (2006)



These authors suggested that a similar void at $z \sim 1$ may be responsible for the 'cold spot' in the southern *WMAP* sky

(Cruz *et al* 2007)

… this void has subsequently been seen in radio surveys

(Rudnick, Brown, Williams 2007)

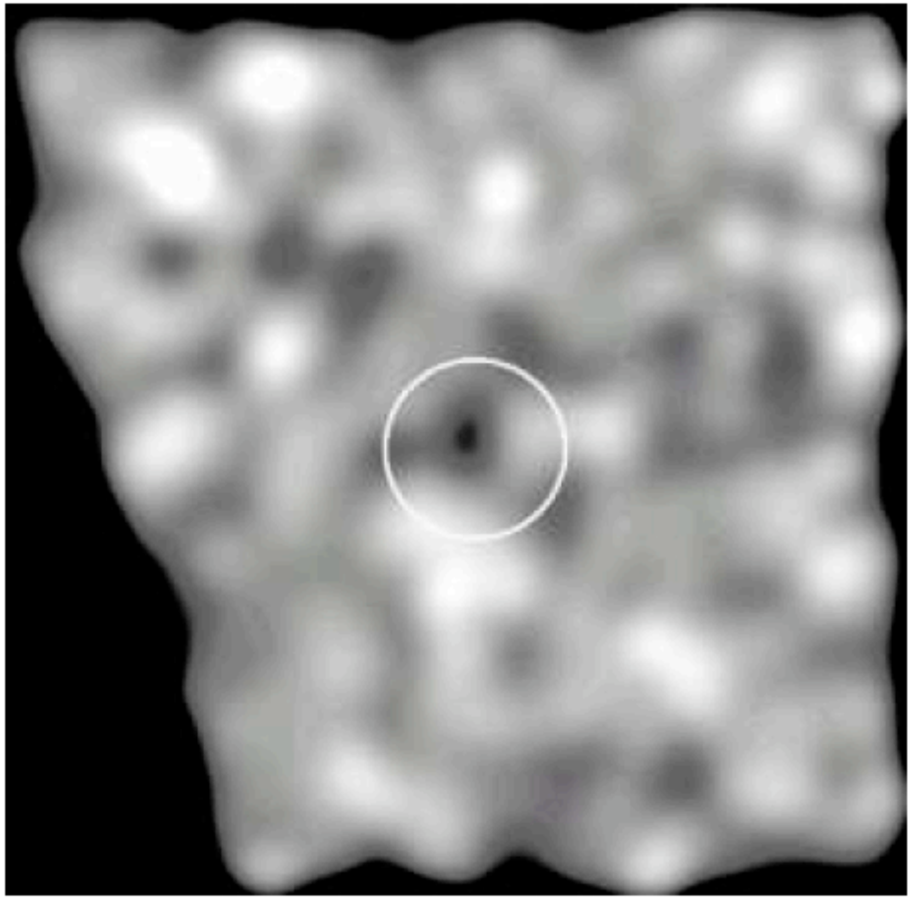


Fig. 1.— 50° field from smoothed NVSS survey at 3.4° resolution, centered at l_{II}, b_{II} = 209°, -57°. Values range from black: 9.3 mJy/beam to white: 21.5 mJy/beam. A 10° diameter circle indicates the position and size of the WMAP cold spot.

Some have argued (Naselsky *et al* 2007, Smith & Huterer 2008) that there is *no* such localised feature … but Swarup *et al* (2008) confirm it

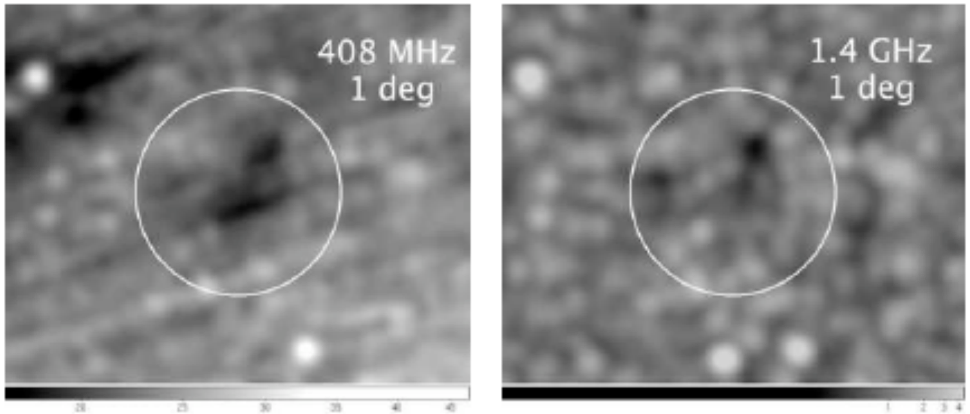
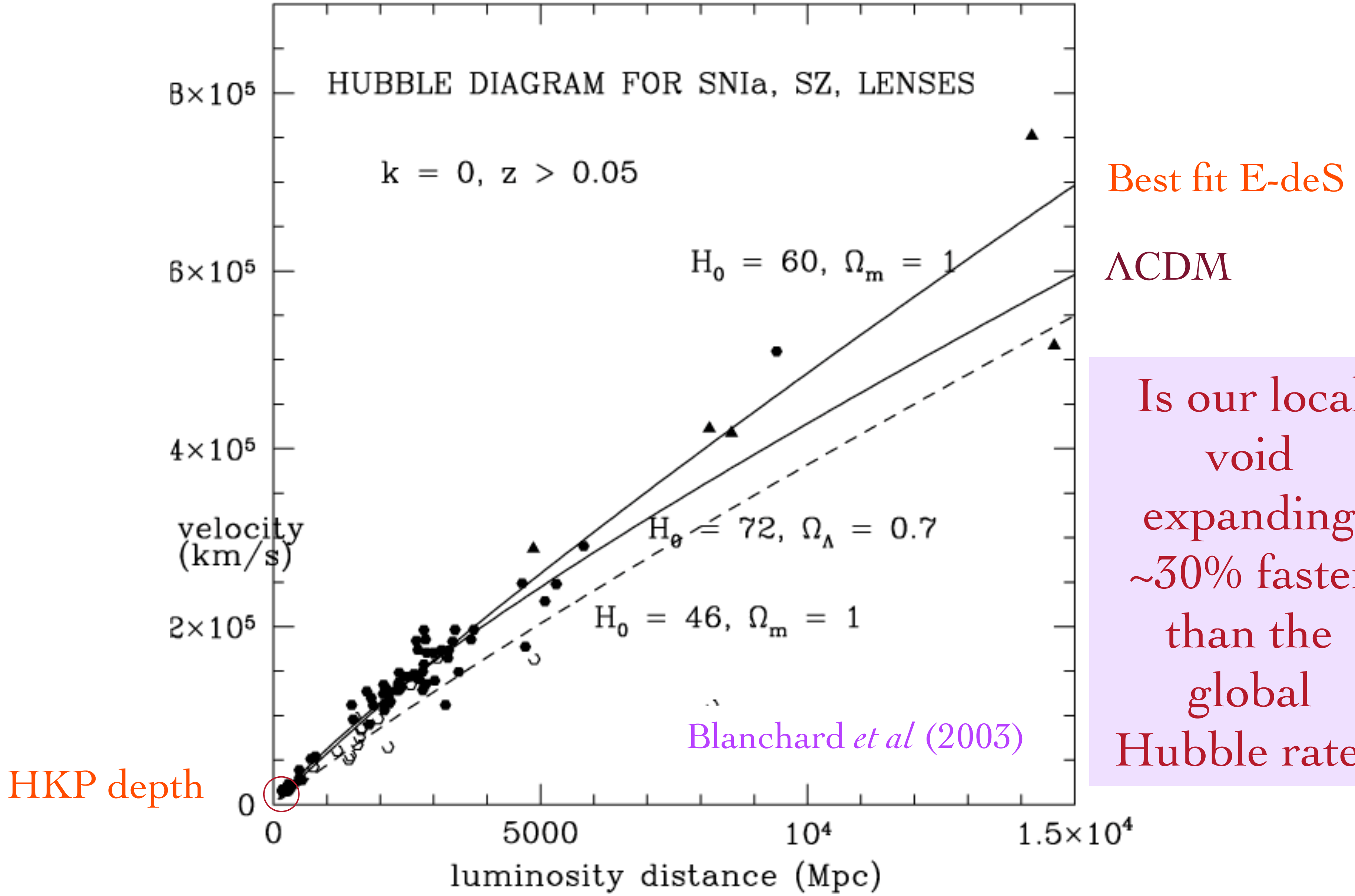


Fig. 4.— 18° fields, with 1° resolution, centered at l_{II}, b_{II} = 209°, -57°. Left: 408 MHz (Haslam et al. 1981). Right: 1.4 GHz (Condon et al. 1998). A 10° diameter circle indicates the position and size of the WMAP cold spot.

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



Is our local void expanding ~30% faster than the global Hubble rate?

Uncertainty in Hubble parameter determination comes from lens model

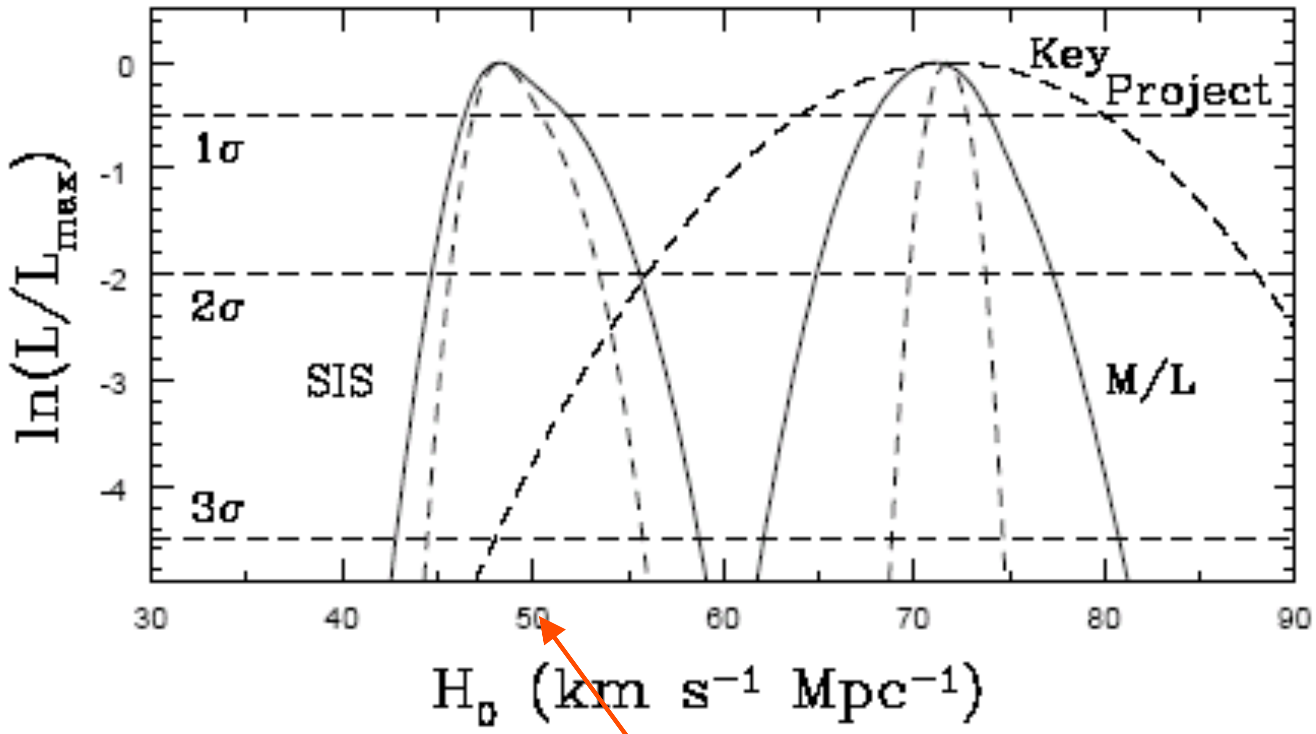


Fig. 1.4. H_0 likelihood distributions. The curves show the joint likelihood functions for H_0 using the four simple lenses PG1115+080, SBS1520+530, B1600+434, and HE2149–2745 and assuming either an SIS model (high $\langle\kappa\rangle$, flat rotation curve) or a constant M/L model (low $\langle\kappa\rangle$, 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}.

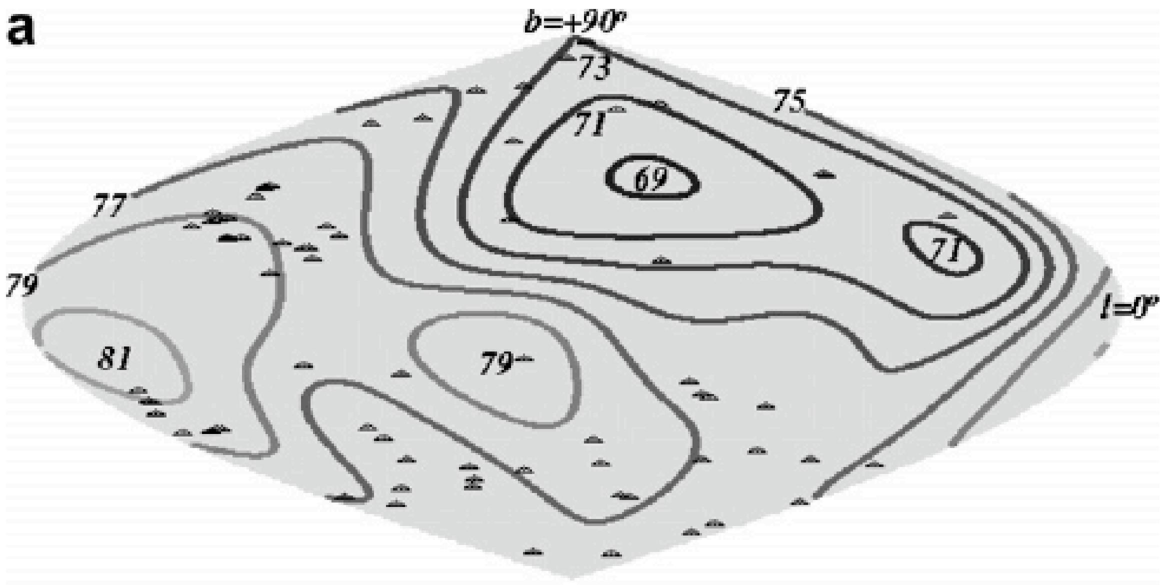
If lensing galaxies have dark matter halos then $h \approx 0.5$ (Kochanek & Schechter 2004)

A Local 'Hubble Bubble' from Type Ia Supernovae?

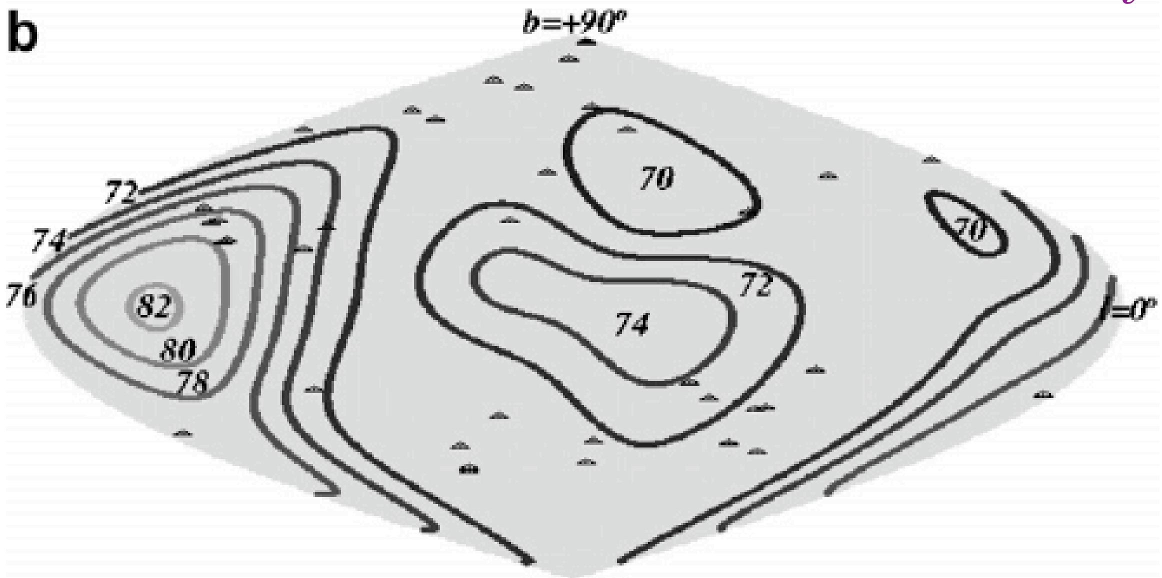
A local void has been proposed as one way to reconcile the age of the universe based on the Hubble expansion with the ages of globular clusters within the framework of the Einstein–de Sitter cosmology (e.g., Turner, Cen, & Ostriker 1992; Bartlett et al. 1995). Measurements of the Hubble constant within 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)

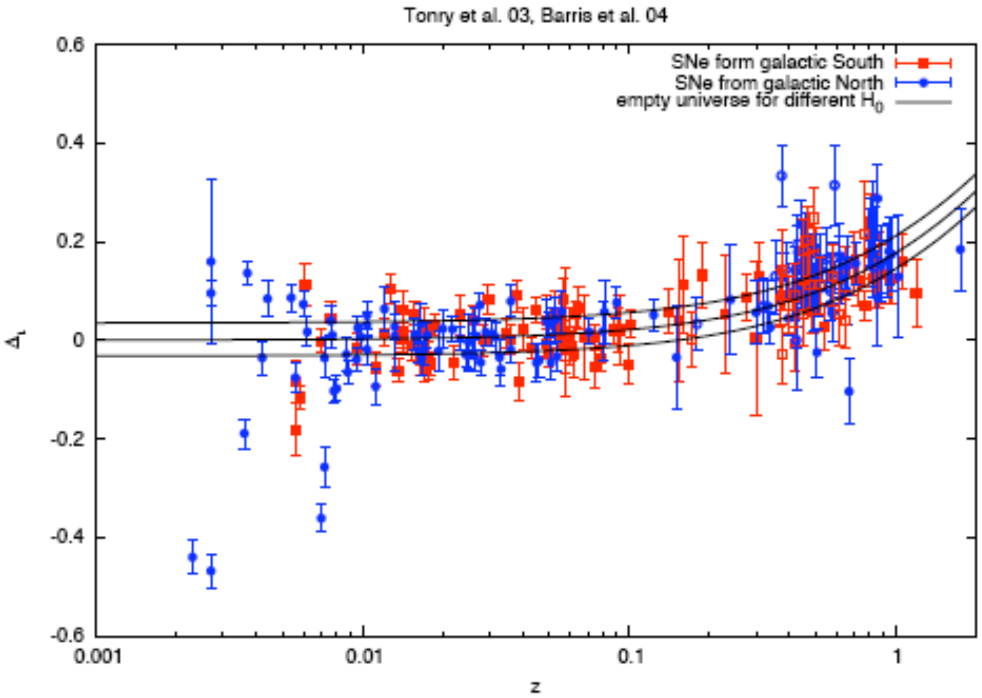
There are *significant* variations in H_0 of up to 9 km/s/Mpc across the sky in HKP data

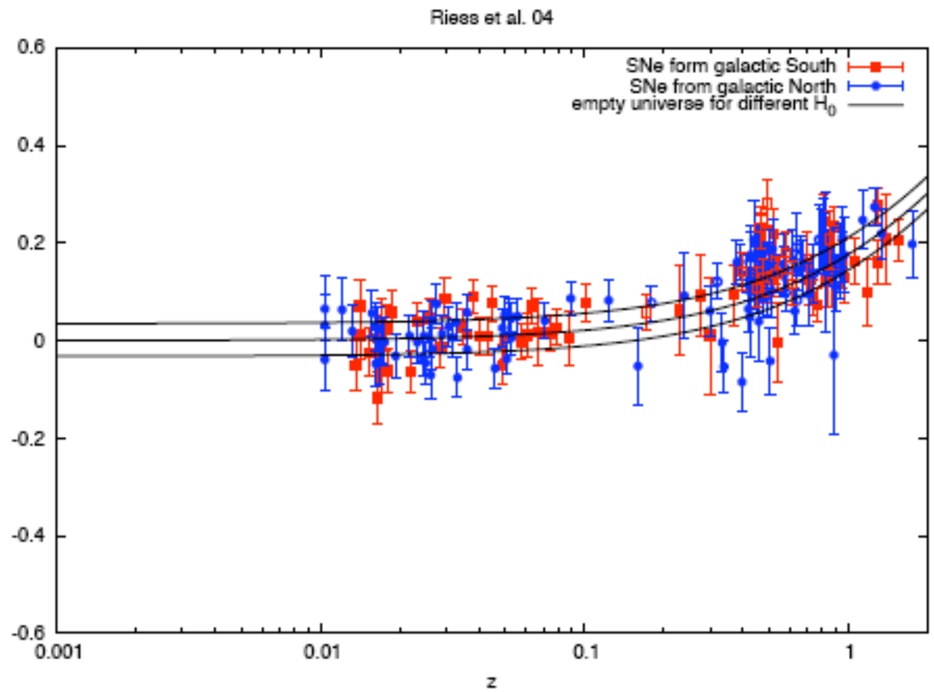


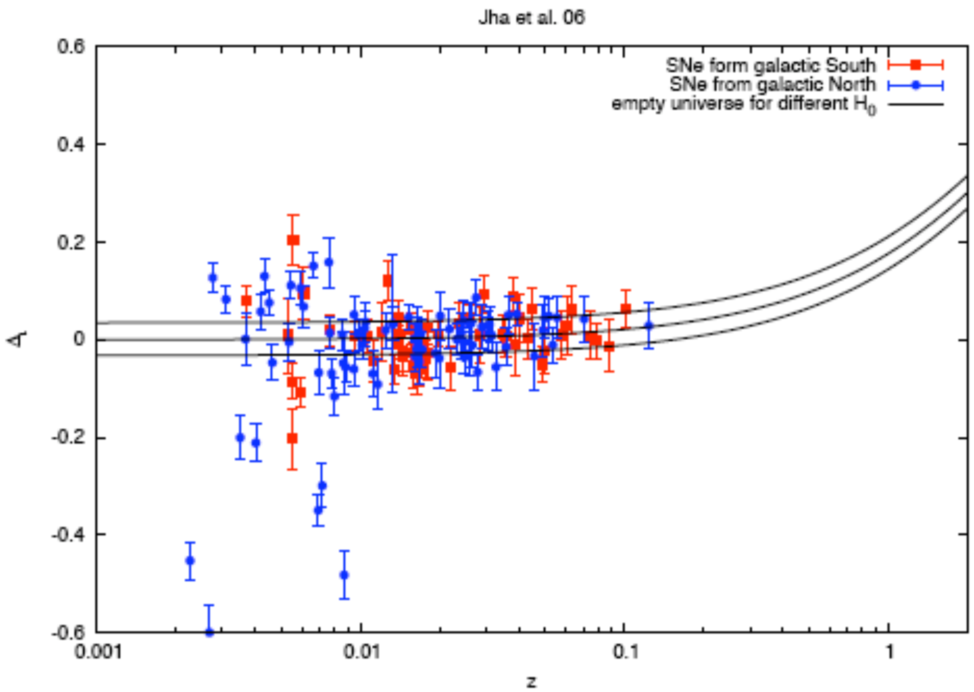
McLure & Dyer (2007)



… and also in an *independent* sample of objects







"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"

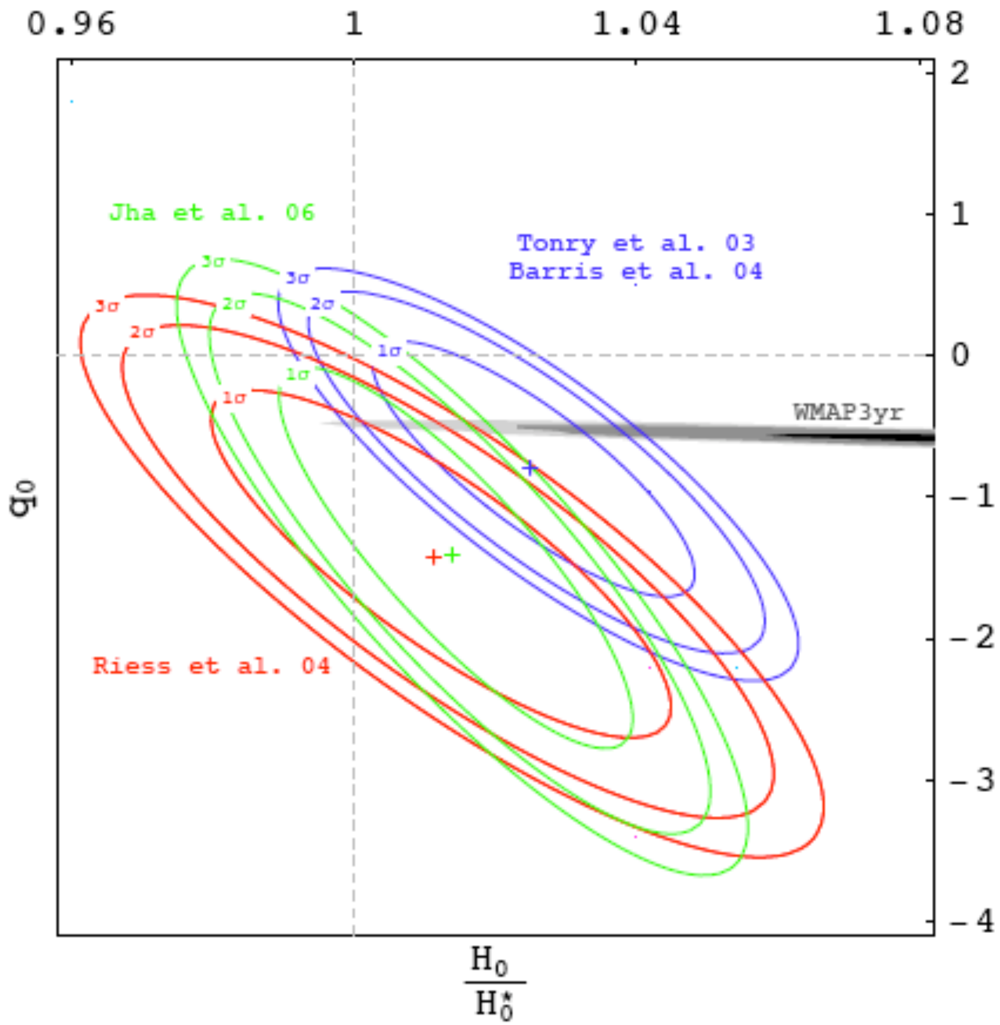
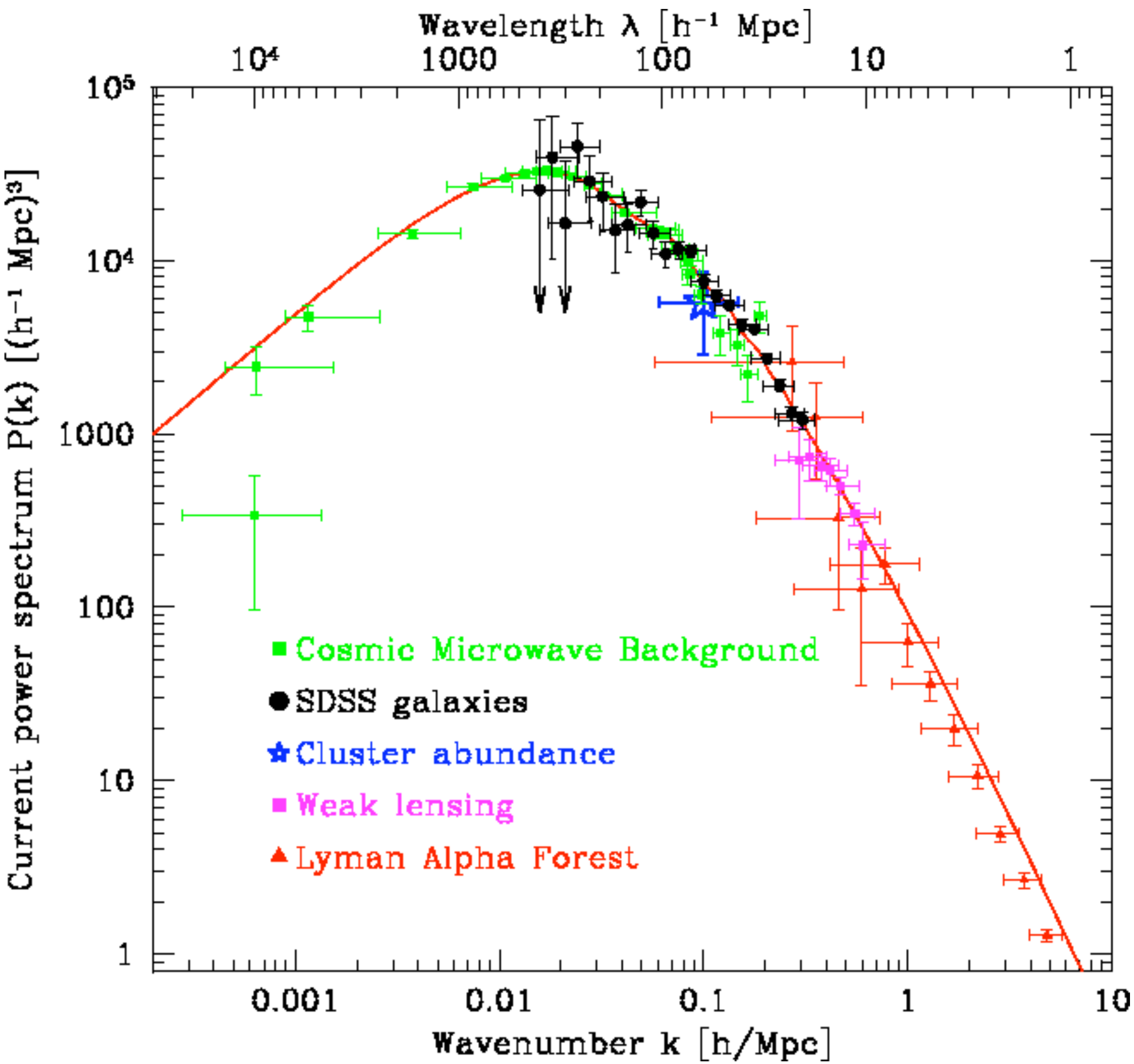


Fig. 3. Confidence contours for a model-independent full-sky fit to the Hubble law at second order for three SNe Ia data sets. SNe up to redshift $z = 0.2$ are included in the fits. (Schwarz & Weinhorst 2007)

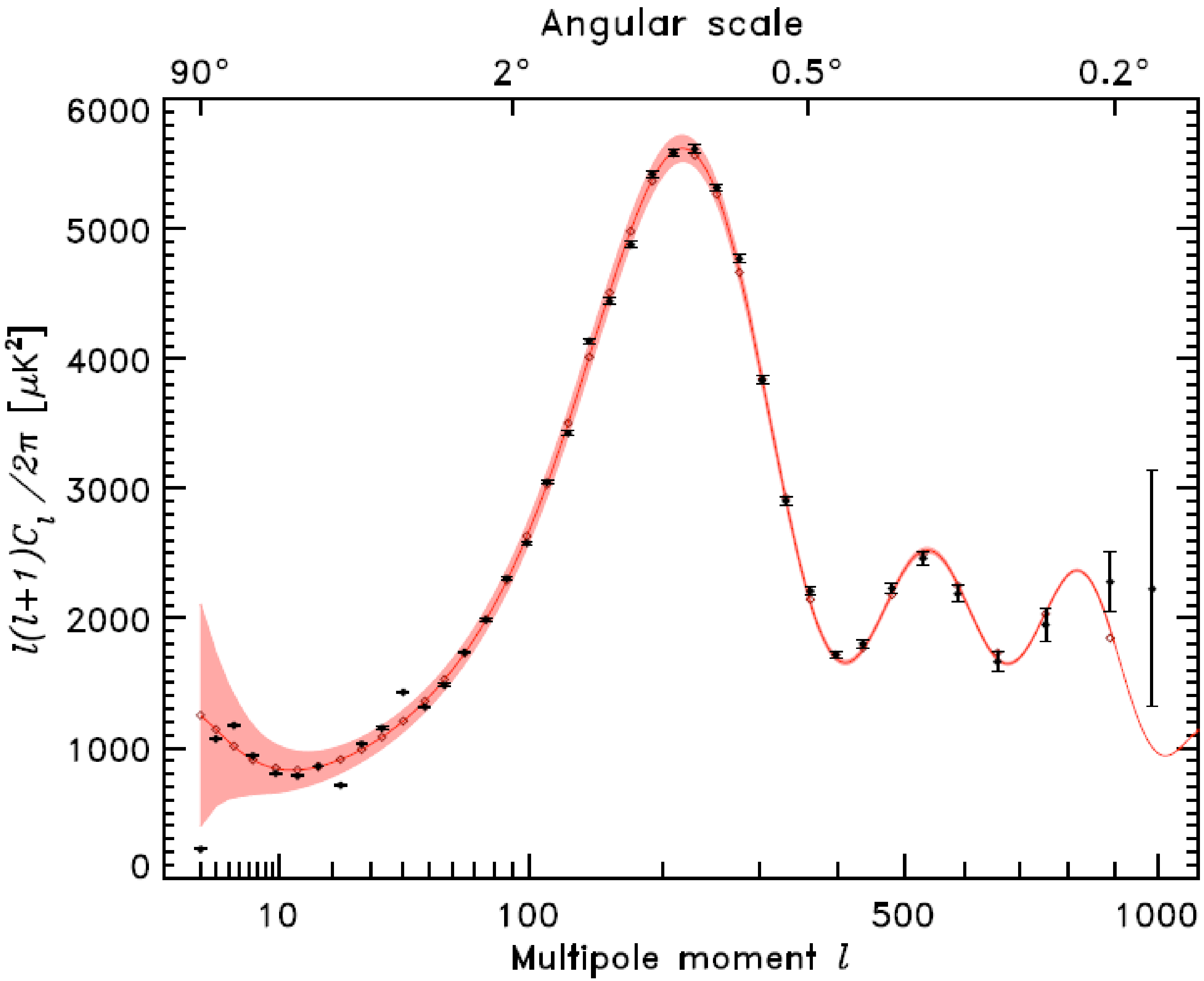
Observations of large-scale structure are *consistent* with the ΛCDM model if the primordial fluctuations are ***adiabatic*** and ~***scale-invariant*** (as is apparently "expected in the simplest models of inflation")



Tegmark (2004)

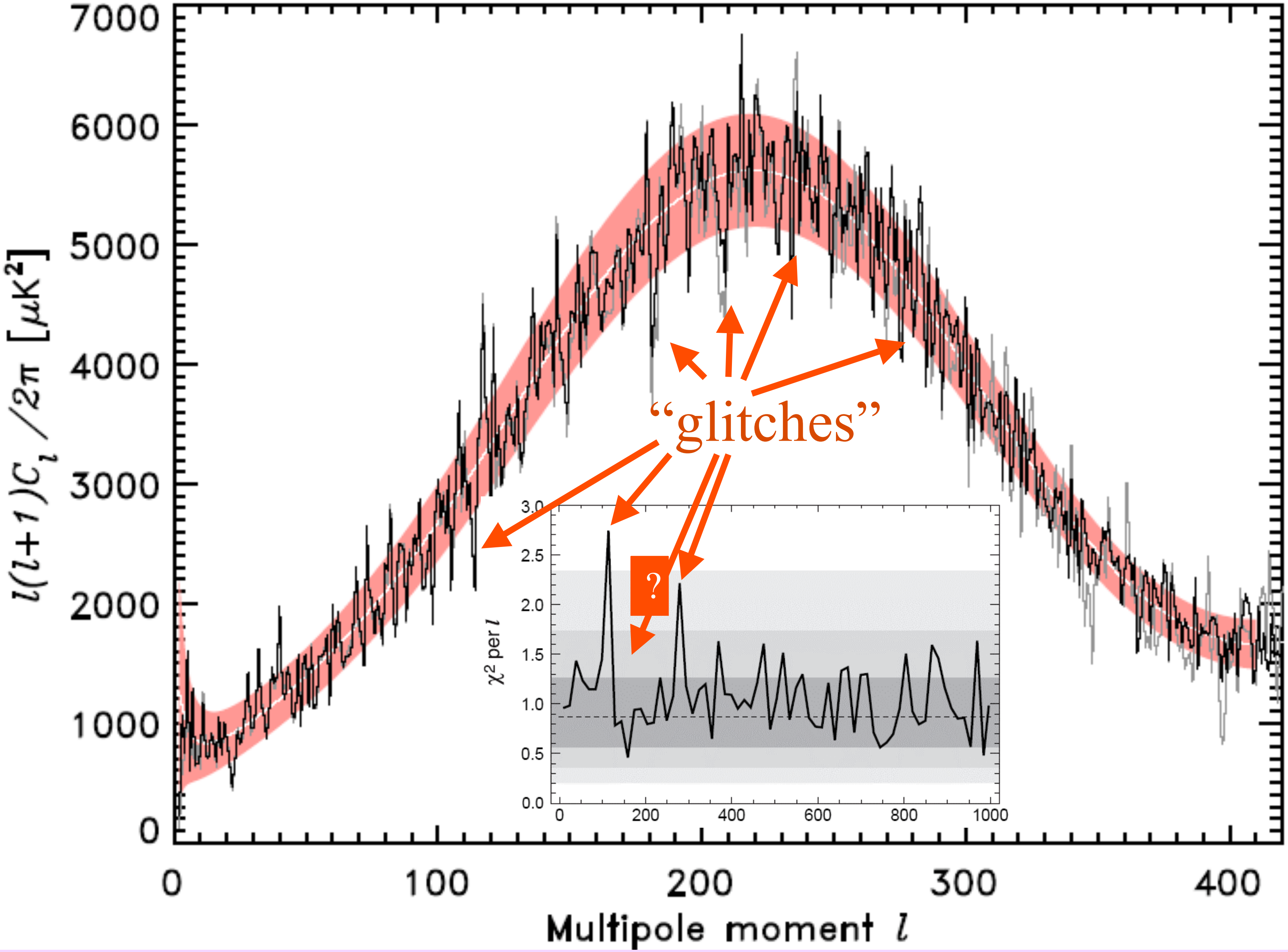
The ‘power-law ΛCDM model’ is believed to be *confirmed* by *WMAP*

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 χ^2/dof = 1049/982 ⇒ probability of ~7% that this model describes the data!

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



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

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, $\Omega_{\rm CDM}$, $\Omega_{\rm b}$, Ω_{Λ} , Ω_{k} …

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

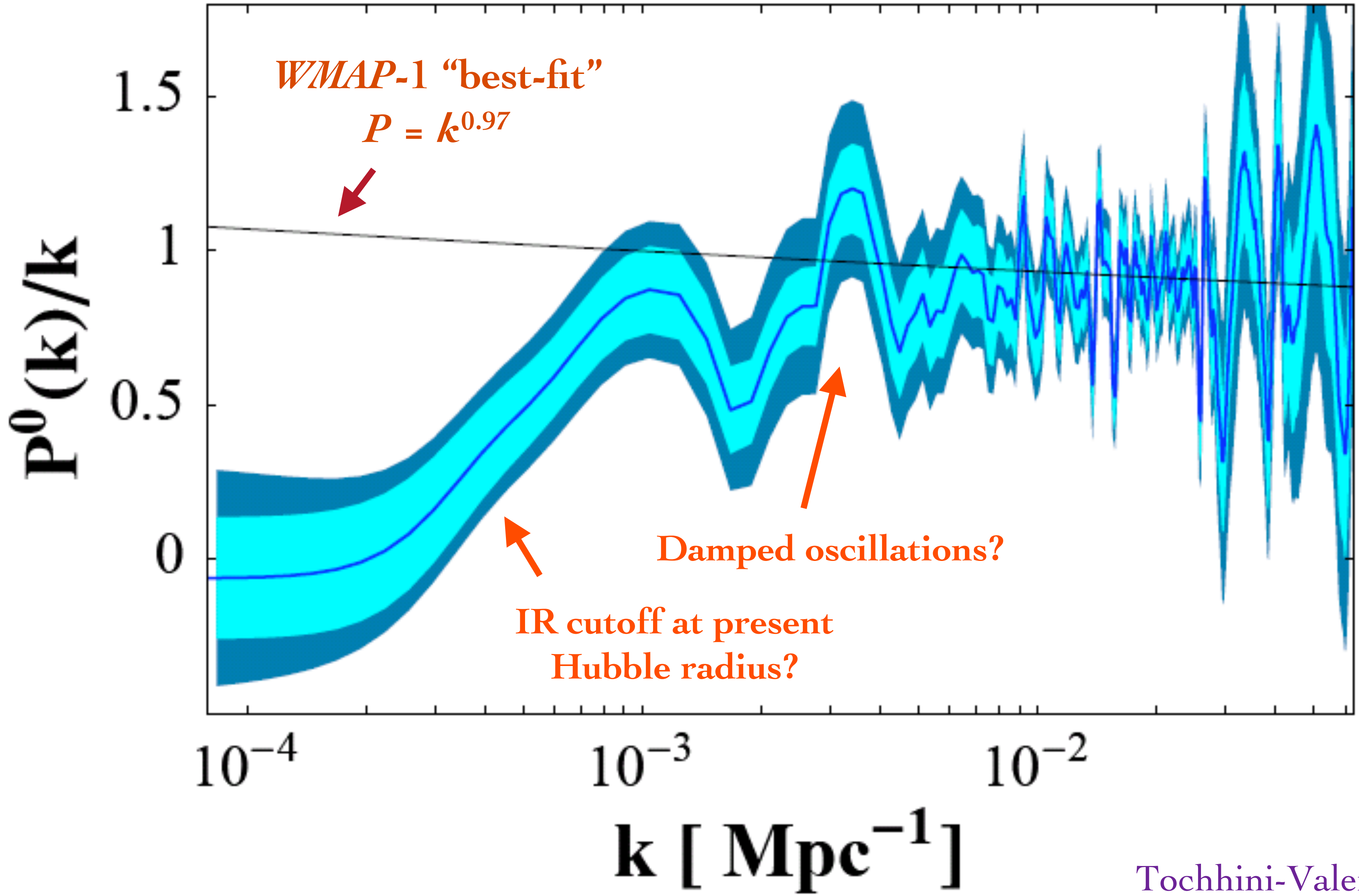
measured over scales ranging from ~ 1 – 10000 Mpc ($\Rightarrow$ ~8 e-folds of inflation)

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, $\Omega_{\rm CDM}$, etc in order to break inevitable parameter *degeneracies*

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

➜ evidence for departures from a power-law spectrum

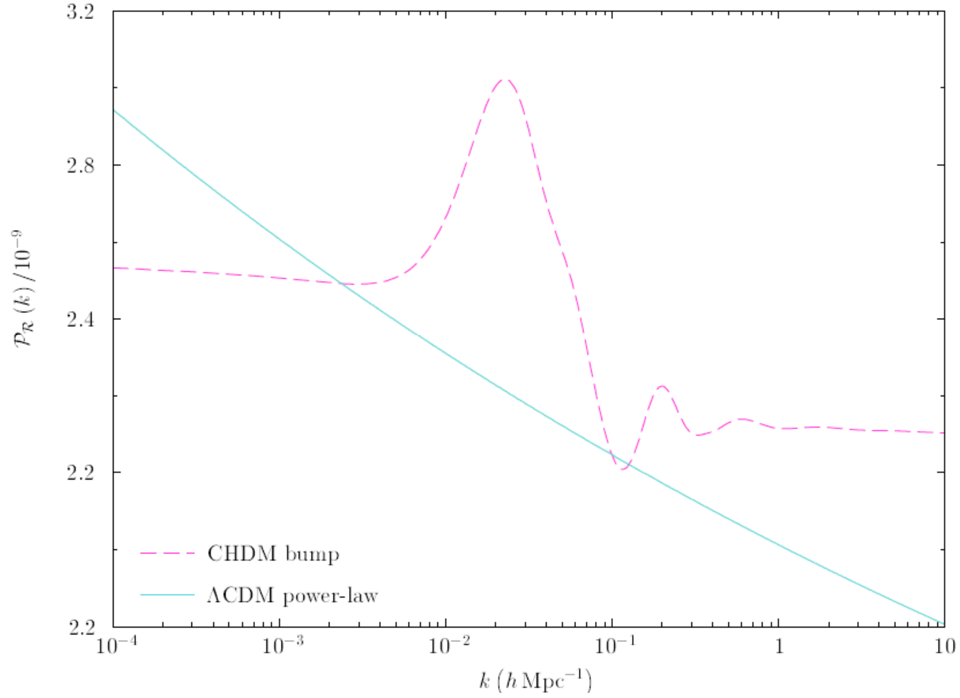


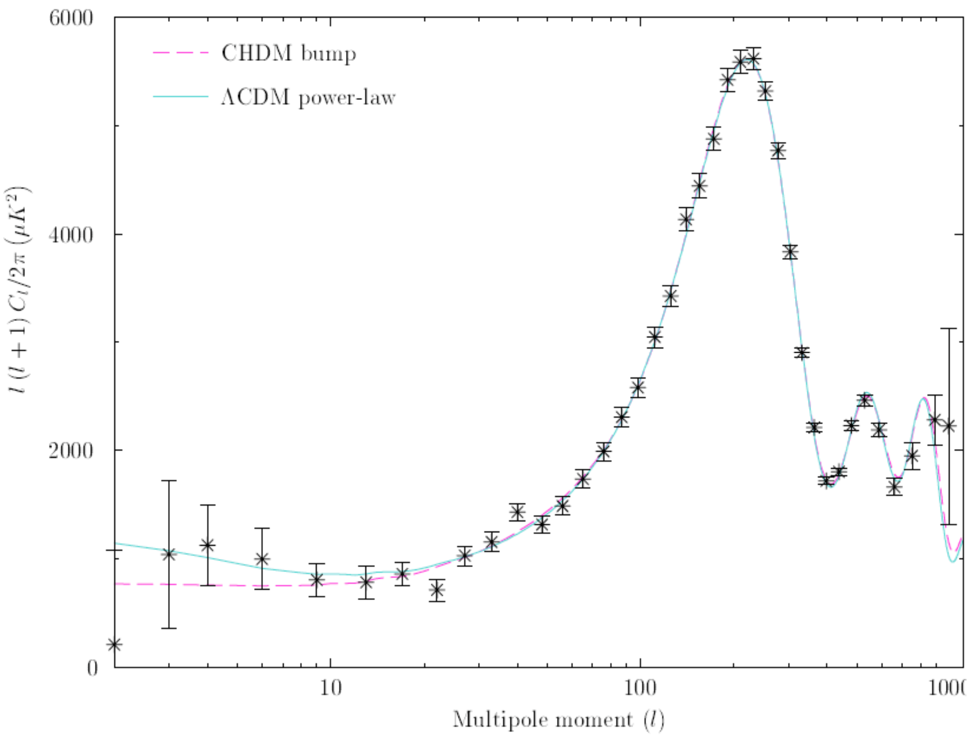
Tochhini-Valentini,
Hoffman & Silk (2005)

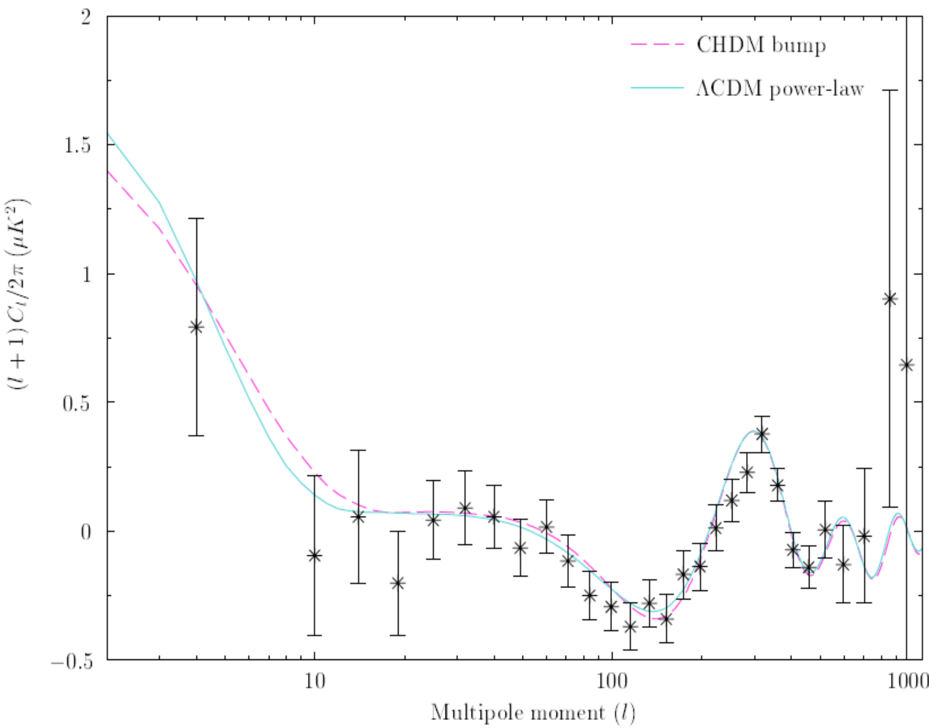
The primordial perturbation spectrum need not be scale-free as is commonly *assumed*

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)

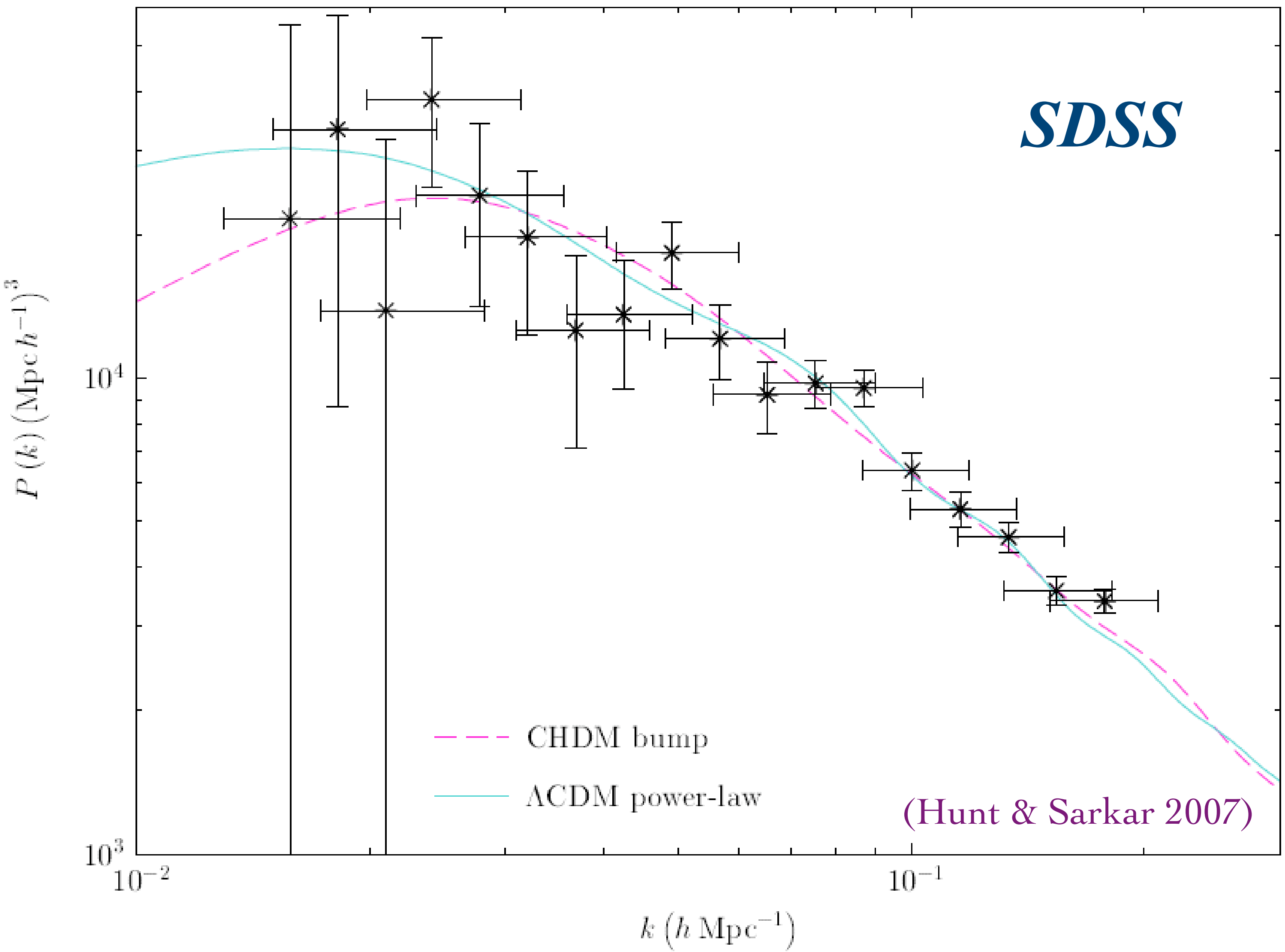






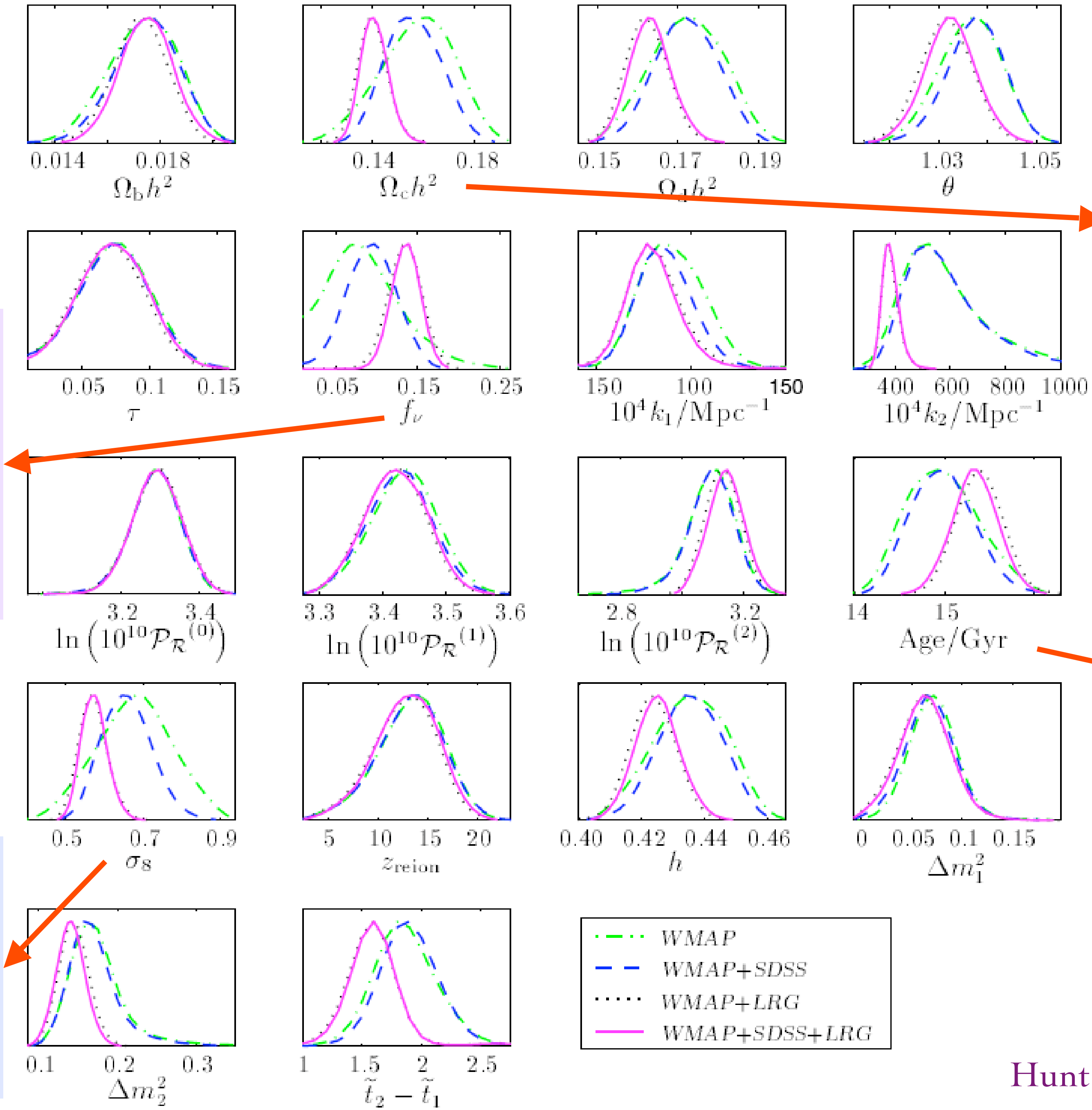
The small-scale power would be excessive unless damped by free-streaming

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

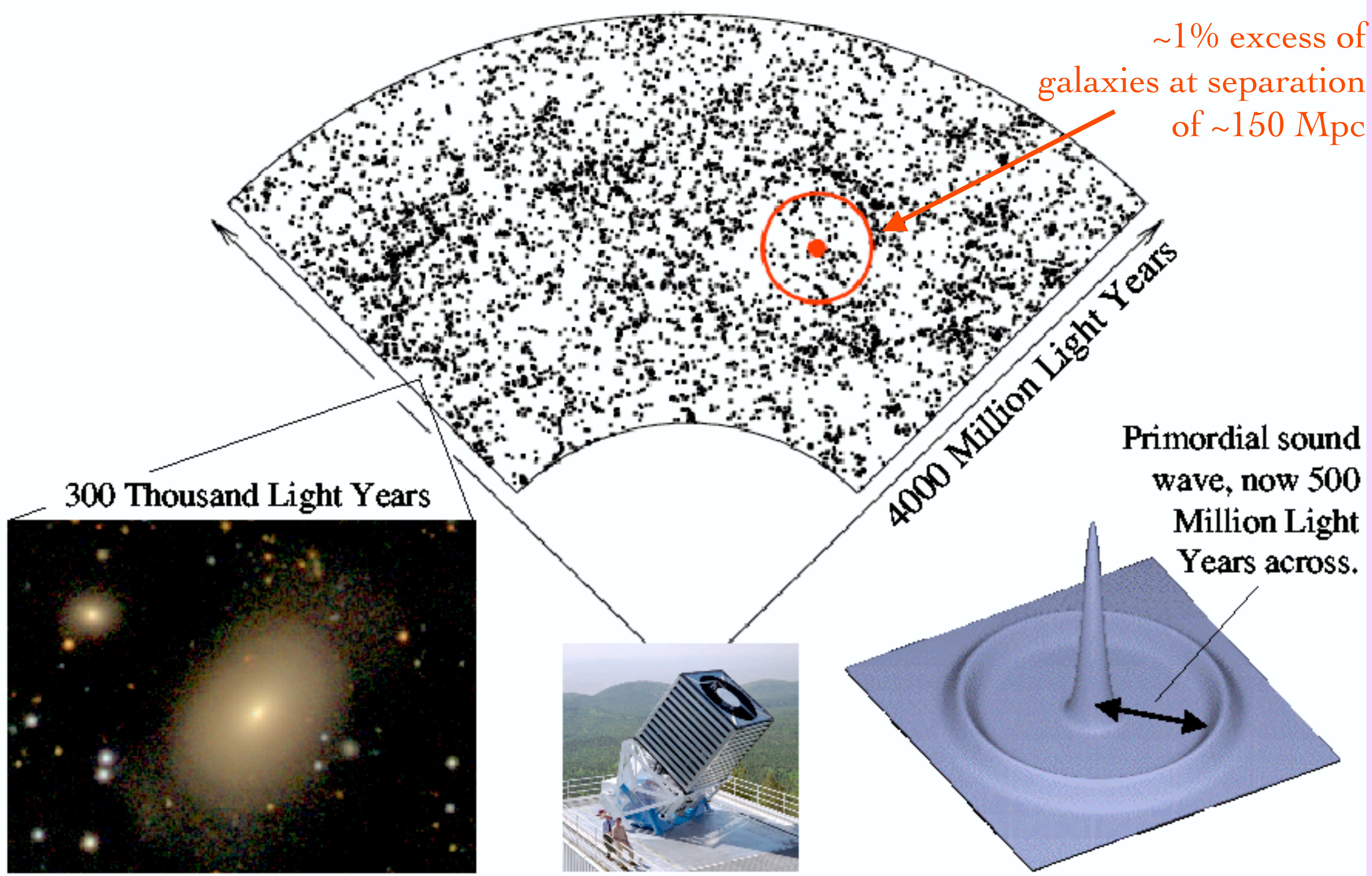
To fit the large-scale structure data *requires* 0.5 eV mass neutrinos

Consistent age for the universe

Consistent with data on clusters and weak lensing

Hunt & Sarkar (2007)

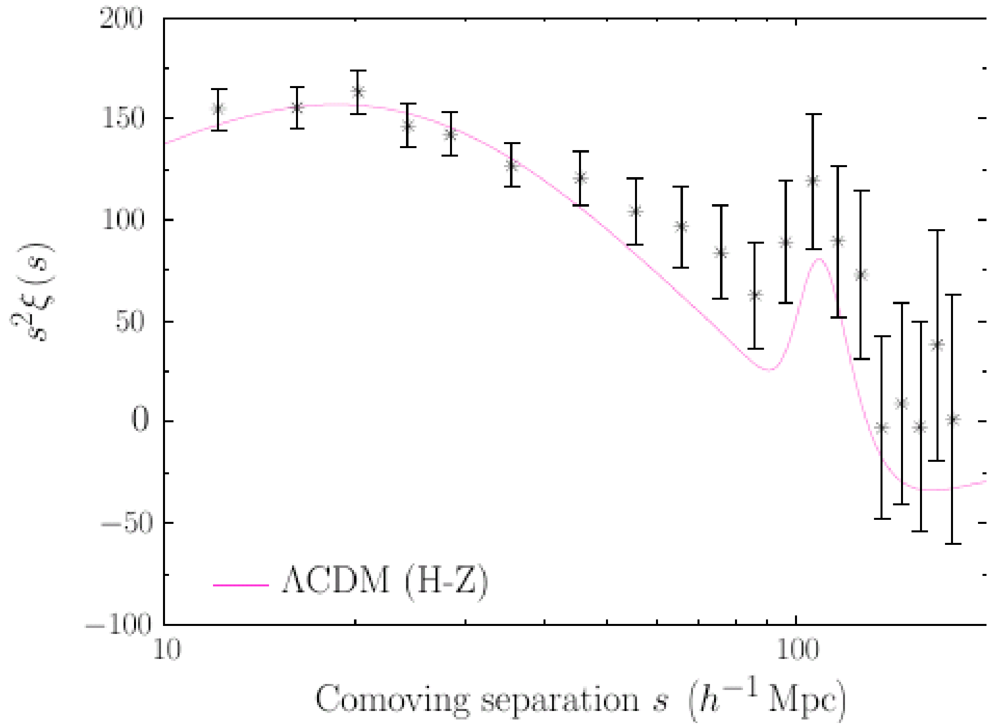
New Test: Baryon Acoustic Peak in the Large-Scale Correlation Function of *SDSS* Luminous Red Galaxies

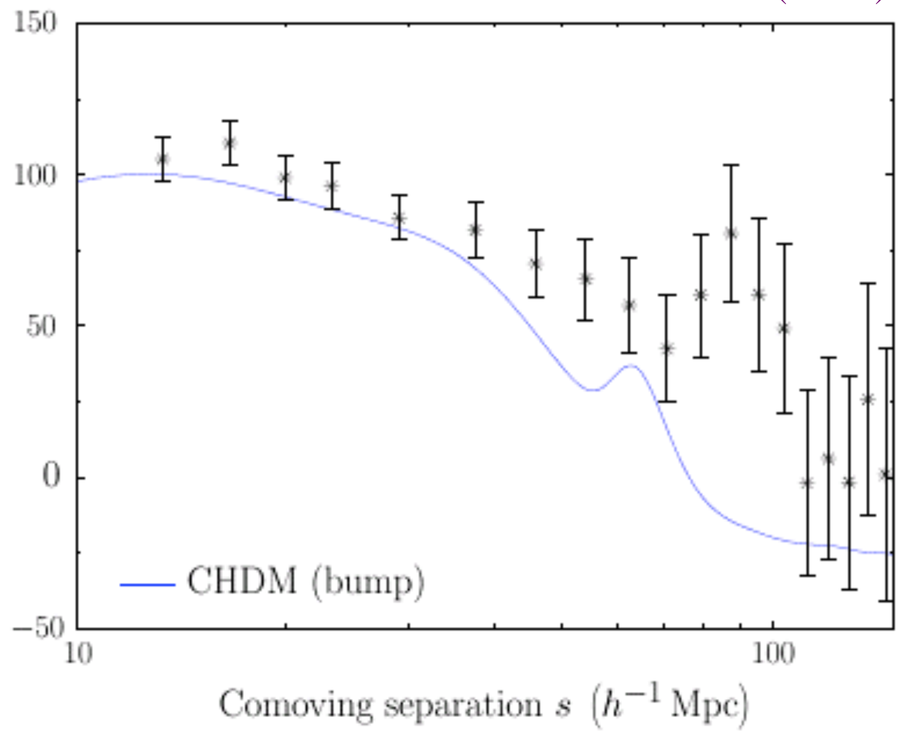


Eisenstein (2005)

The E-deS model is however *disfavoured* by the 'baryon acoustic peak' … present at the ~same *physical* scale, but displaced in redshift space

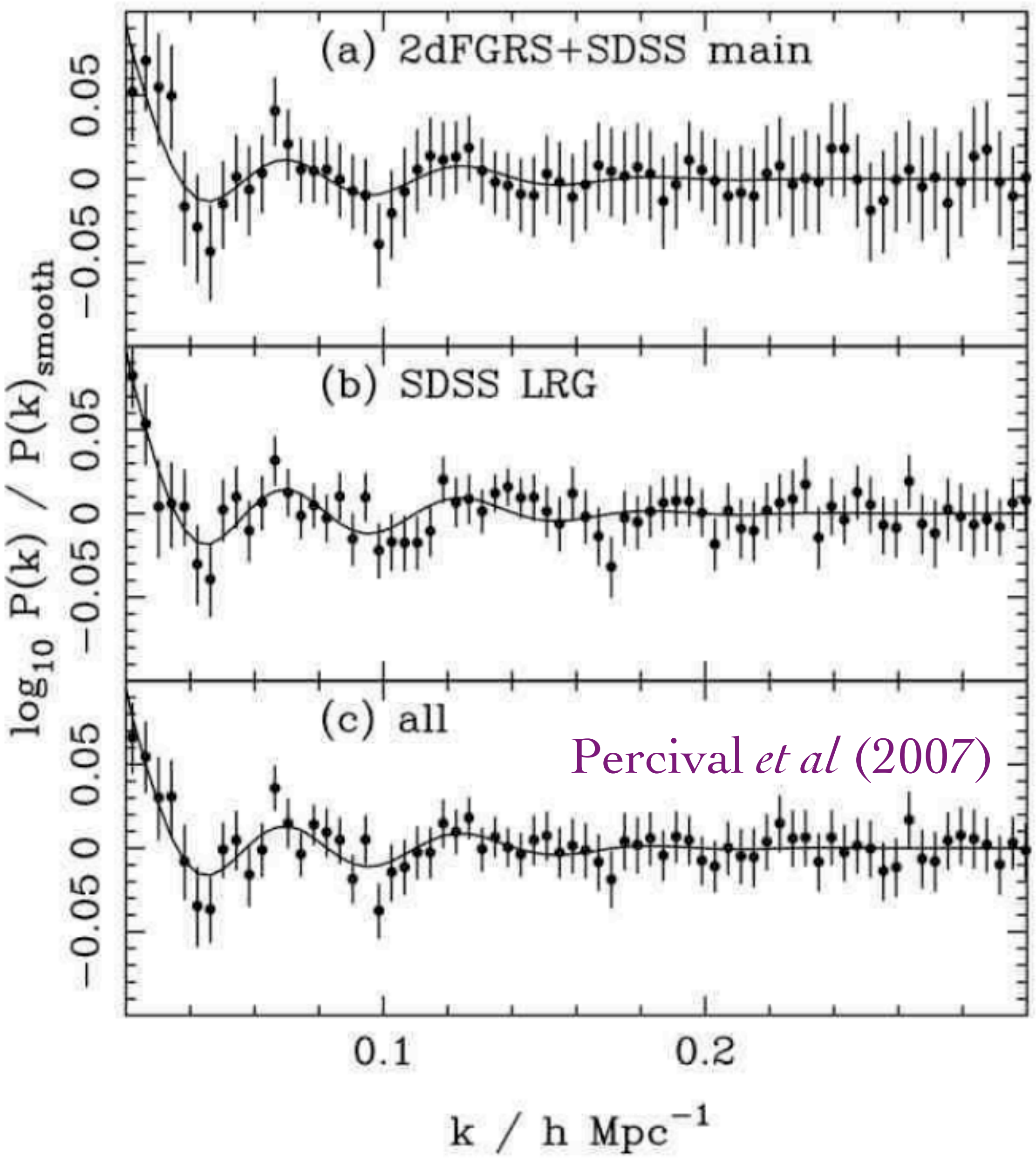
Blanchard *et al* (2006)





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

A *very large* void will however distort the CMB spectrum (Goodman 1995, Caldwell & Stebbins 2008) … also constrained by kinetic Sunyaev-Zeldovich effect (Haugboelle & Garcia-Bellido 2008)



143k + 466k galaxies

78k galaxies

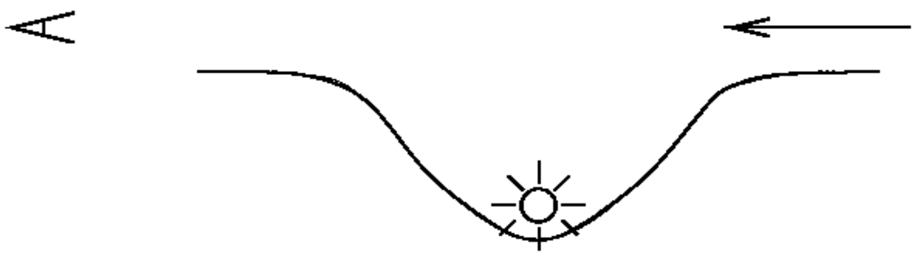
Percival *et al* (2007)

In fact $D_v(z=0.35)/D_v(z=0.2) = 1.812 \pm 0.060$ is *higher* by 2.4σ than the expected ratio of 1.67 for the concordance ΛCDM model!

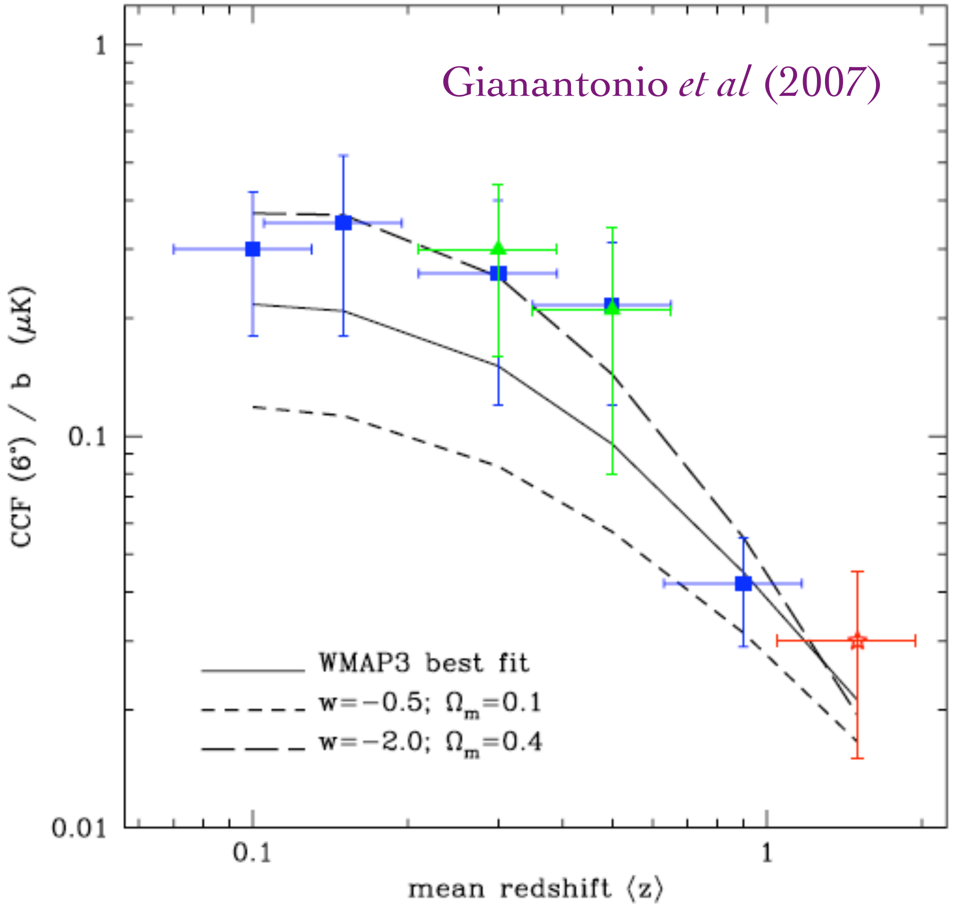
Is there direct *dynamical* evidence for Λ?

('late integrated Sachs-Wolfe effect')

gravitational potential traced by galaxy counts



potential depth changes as CMB photons pass through



Present detections are of *low* significance (2-3 σ) … moreover the observed amplitude/z-dependence is *higher/steeper* than expected for Λ

It has been noted that there are *many* voids in the SDSS LRG sample

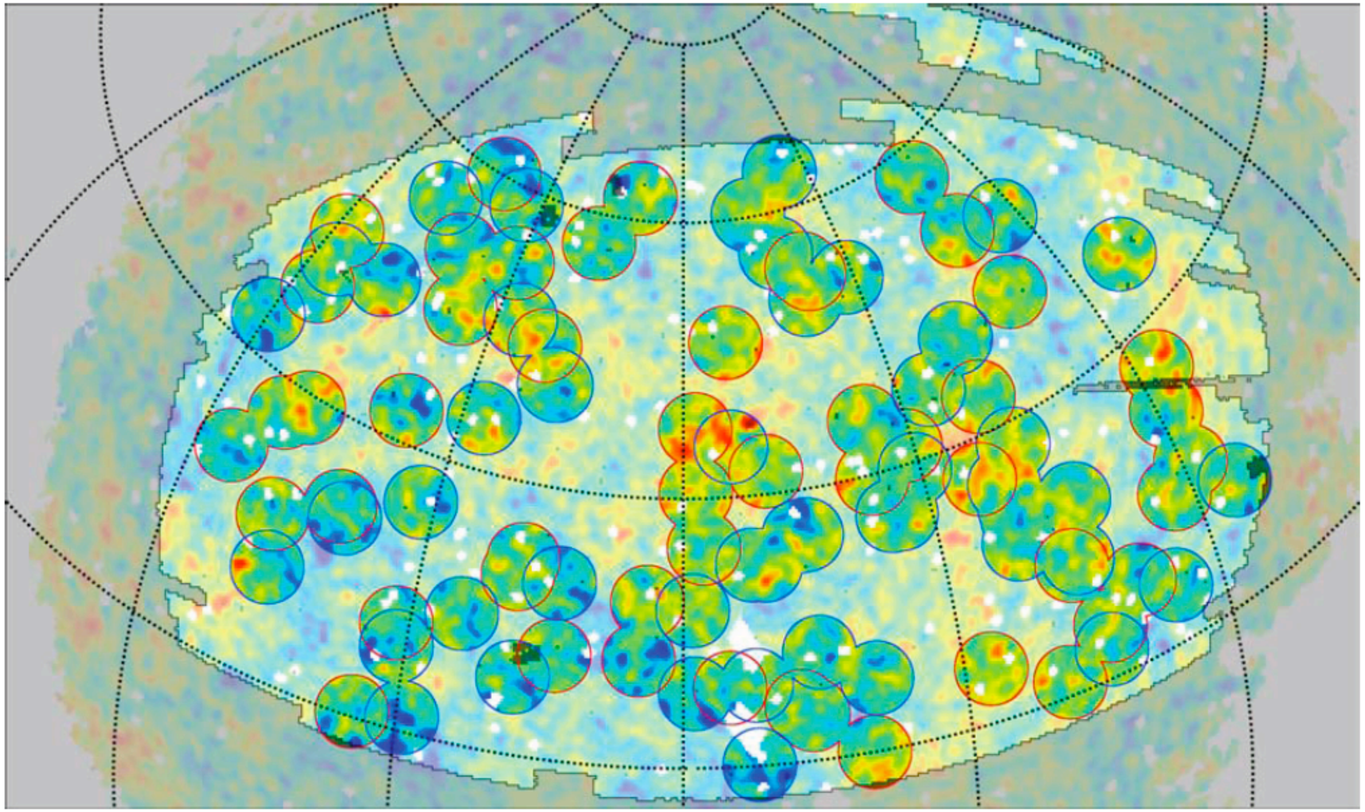


Figure 1: A map of the microwave sky over the SDSS area. The supervoids and superclusters used in our analysis are highlighted and outlined at a radius of 4°, blue for supervoids and red for superclusters. The compensated filter we use in our analysis approximately corrects for the large-angular-scale temperature variations that are visible across the map. The SDSS DR6 coverage footprint is outlined. Holes in the survey, *e.g.* due to bright stars, are displayed in black. Additionally, the WMAP Galactic foreground and point source mask is plotted (white holes). The disk of the Milky Way, which extends around the left and right border of the figure, is also masked. The map is in a Lambert azimuthal equal-area projection, centred at right ascension 180 and declination 35. The longitude and latitude lines are spaced at 30° intervals.

Granett *et al* [arXiv:0805.2974]

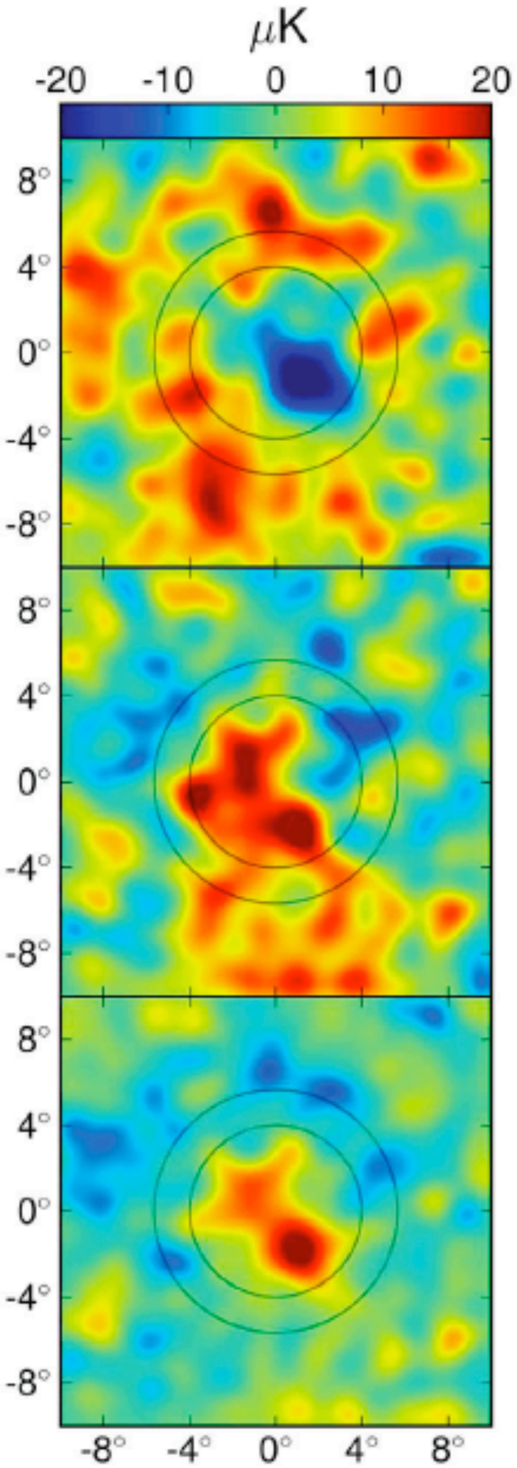


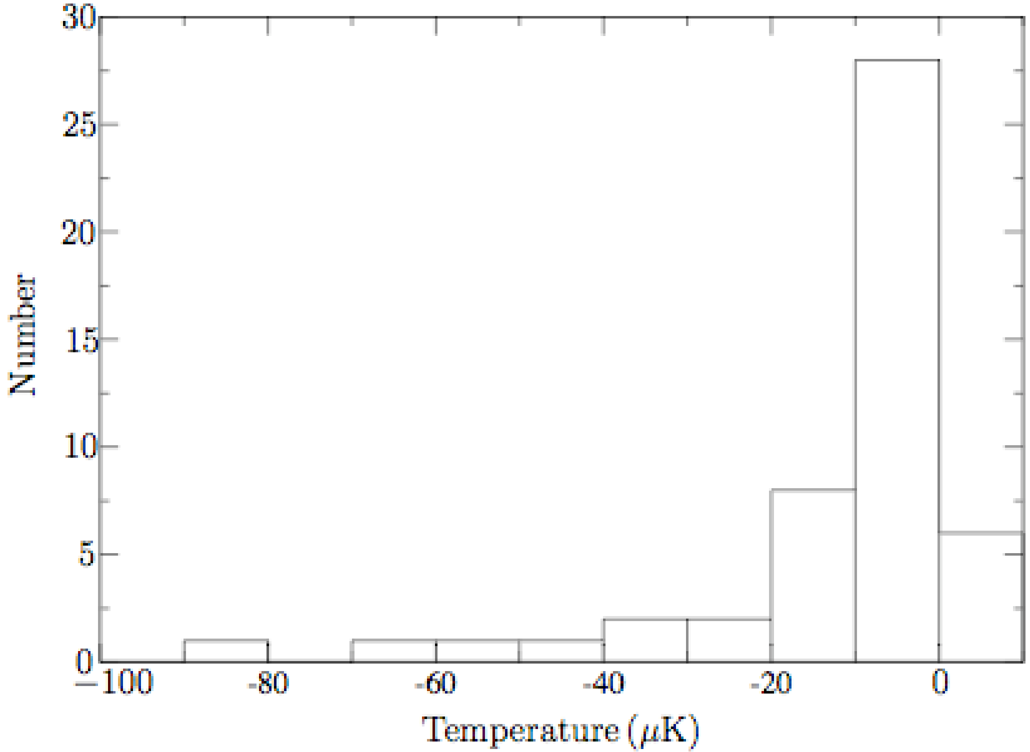
Figure 2: We stack regions on the CMB corresponding to supervoid and supercluster structures identified in the Sloan Digital Sky Survey. We averaged CMB cut-outs around 50 supervoids (top) and 50 superclusters (middle), and differenced these two samples (bottom). The individual cutouts from the CMB were aligned vertically in the image based on the measured orientations of the clusters and voids, but we do not scale or apply weights to the images. Although our statistical analysis uses the raw image, for this figure we smooth the images with a Gaussian kernel with width 0.5°. A hot spot and a cold spot are immediately recognizable in the cluster and void stacks, respectively, with a characteristic radius of 4°, corresponding to spatial scales of 100 h^{-1} Mpc. The inner circle (4° radius) and equal-area outer ring mark the extent of the compensated filter used in our analysis. The measured signal from these large structures is consistent with the ISW effect. There is a tantalizing hint of a hot ring around the cold spot. The observed morphology is consistent with the 'cosmic web'[30] picture in which voids are typically surrounded with 'walls' of higher density regions, while clusters fade gradually into the surrounding with filaments originating from them. Given the somewhat arbitrary rotations of each image in the stack, and the noise level, small-scale features should be interpreted cautiously.

Granett *et al* claim to detect the **late ISW effect due to dark energy** by *cross-correlating* with the WMAP sky

However the temperature decrement is >10 times *more* than expected in the ΛCDM model …

So the voids must be *bigger* and *emptier* than indicated by the LRG counts

Hunt & Sarkar [arXiv:0807.4508]

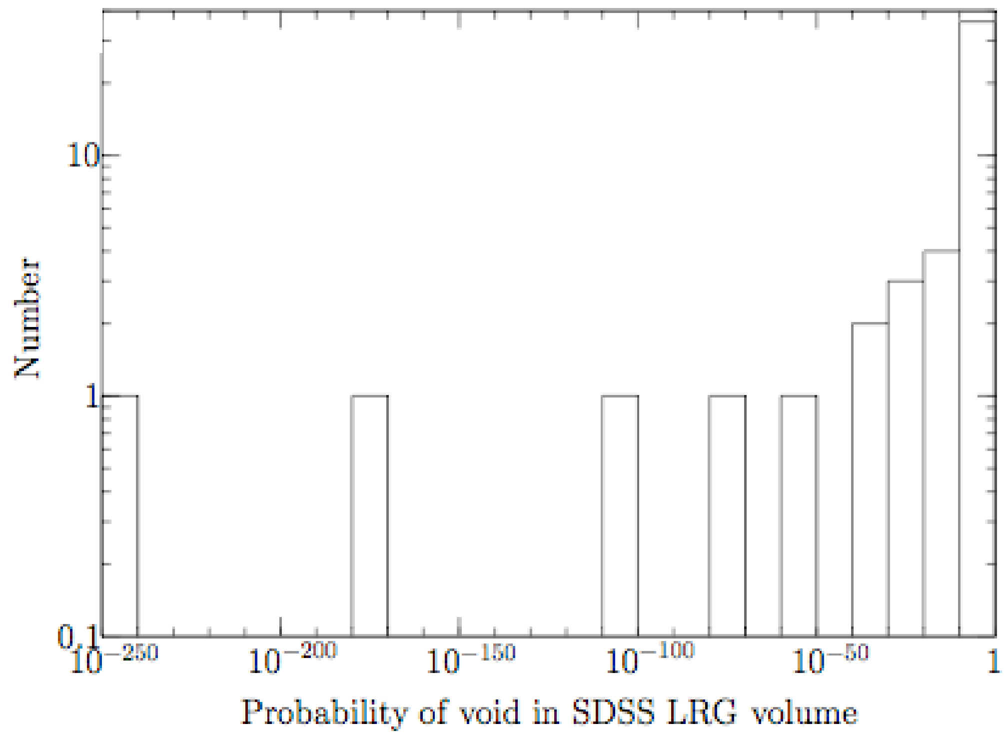


To yield the observed temperature decrements (*if* these are due to the ISW effect), the voids must have underdensities δ ~ - 0.7-0.9 and radii ~ 100-200 h^{-1} Mpc

$$\frac{\Delta T}{T} = -\frac{\Omega_{\rm m}}{2}\left(\frac{R}{c/H_0}\right)^3 \frac{(1+2z)^{1/2}}{(1+z)^2}\delta$$

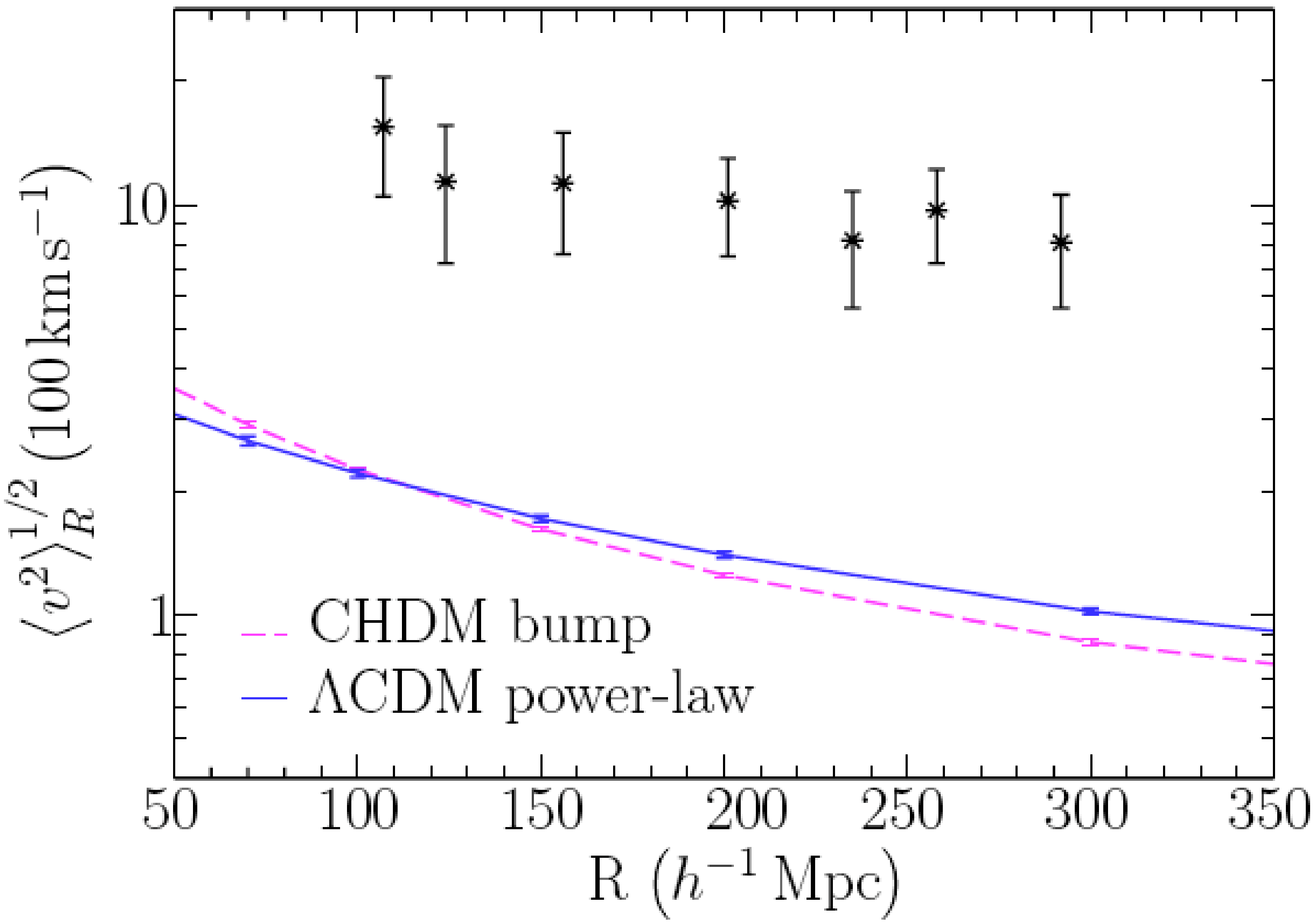
The probability of finding such huge underdense regions in the ΛCDM model normalised to WMAP is *vanishingly* small

Hunt & Sarkar [arXiv:0807.4508]



Unexpectedly large peculiar velocities have been detected recently

Kashlinsky *et al* [arXiv:0809.3734], Watkins et al [arXiv:0809.4041]



This *cannot* be accounted for in the standard theory of structure formation (assuming gaussian adiabatic density fluctuations)

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: $\rho_\Lambda \sim H_0^2 M_P^2$

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

Dark energy may just be an artifact of an oversimplified cosmological model