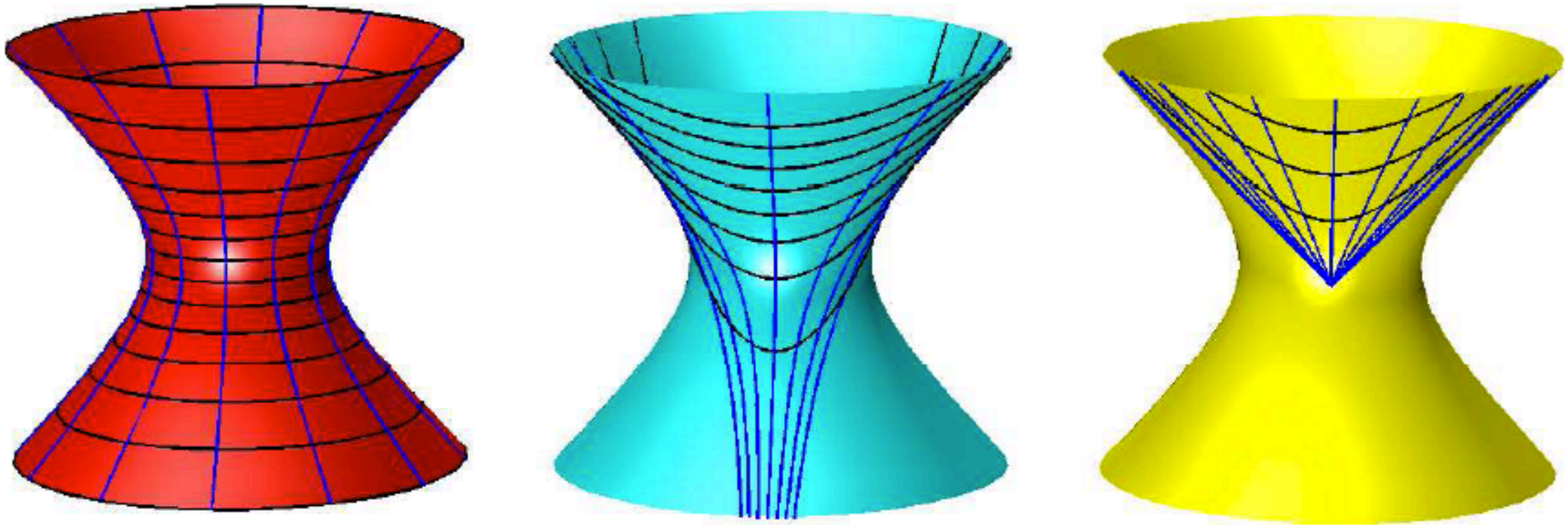
Is our universe in a De Sitter phase?



http://www.bourbaphy.fr/moschella.pdf

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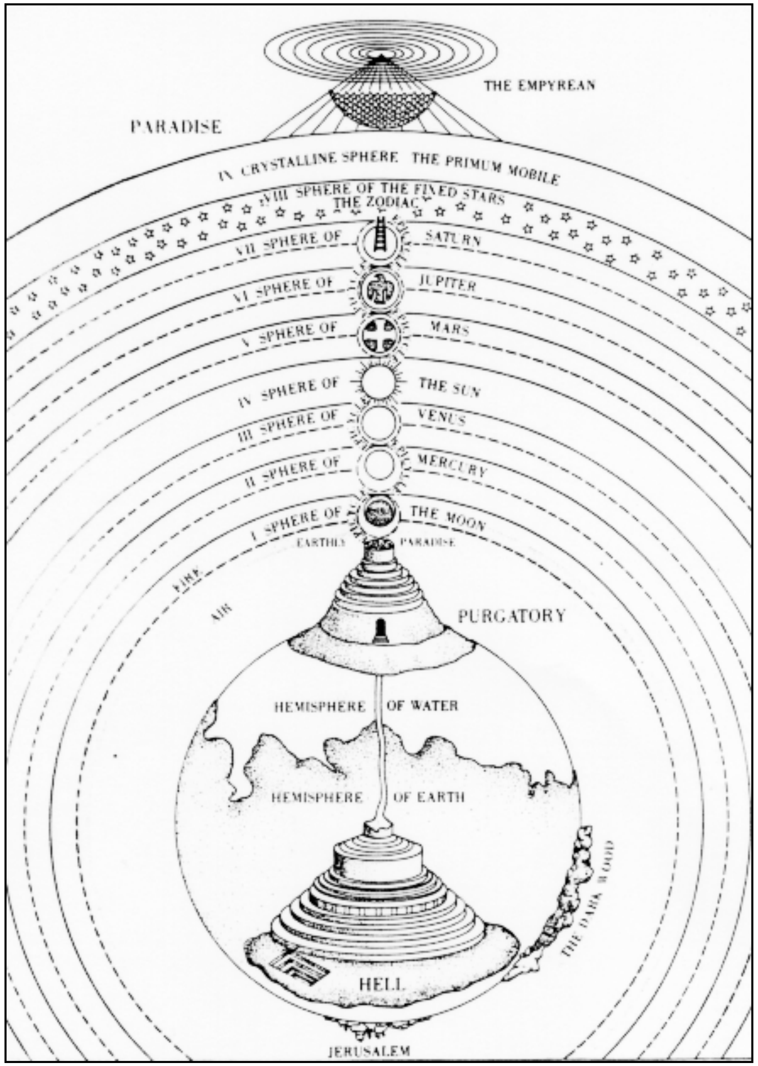
“The Physics of De Sitter Space-time”, Albert Einstein Institute, Hannover, 11-14 September 2012

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

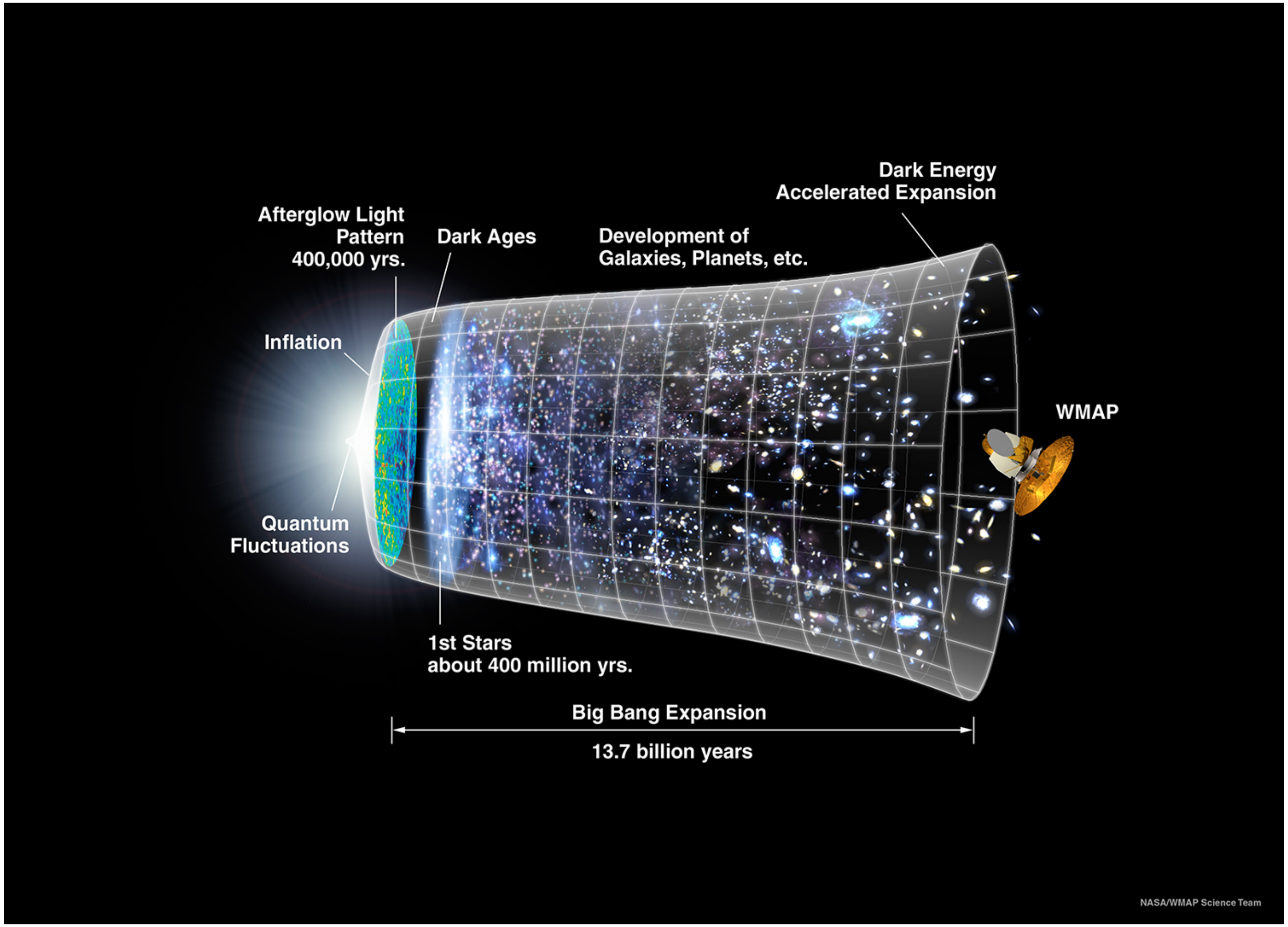


The Divine Comedy, Dante Allighieri (1321)

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 (upto some cut-off M, when viewed as an *effective field theory*)

Cosmological constant

Higgs mass divergence

$$\begin{aligned} &+M^4 + M^2\Phi^2 && \textbf{super-renormalisable}\\ \mathcal{L}_{\text{eff}} = {}& F^2 + \bar{\Psi}\,\not{D}\Psi + \bar{\Psi}\Psi\Phi + (D\Phi)^2 + \Phi^2 && \textbf{renormalisable}\\ &+\frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \ldots && \textbf{non-renormalisable} \end{aligned}$$

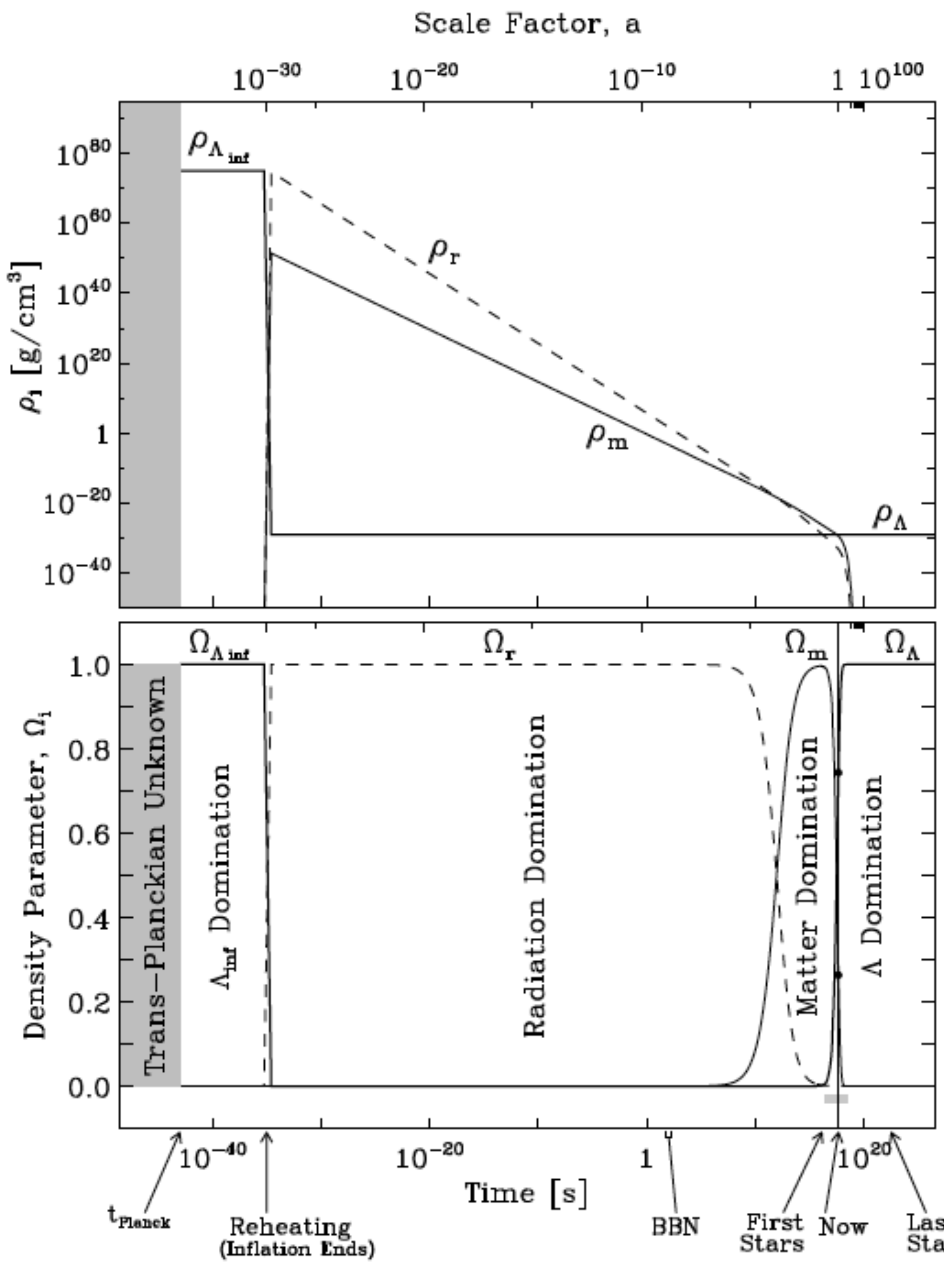
New physics beyond the SM (neutrino mass, nucleon decay, FCNC …) ⇒ **non-renormalisable operators** suppressed by M^n … which 'decouple' as $M \rightarrow M_{\mathrm{P}}$

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

There are possible solutions for the Higgs mass divergence, e.g. 'softly broken' supersymmetry at $M \sim 1$ TeV (or perhaps the Higgs is composite e.g. as in **technicolour**)

But 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 (or collapsed at) $t \sim 10^{-12}$ s

Why did this *not* happen … did $\Lambda \rightarrow 0$ or does vacuum energy *not* couple to gravity?



Egan, arXiv:1005.0745

Either way this also raises the question of whether primordial inflation was really driven by the vacuum energy of a scalar field (fine-tuned at its potential minimum)

We are fascinated by De Sitter space-time … but have no real understanding of the physical mechanism which can generate it … and get us out of it!

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

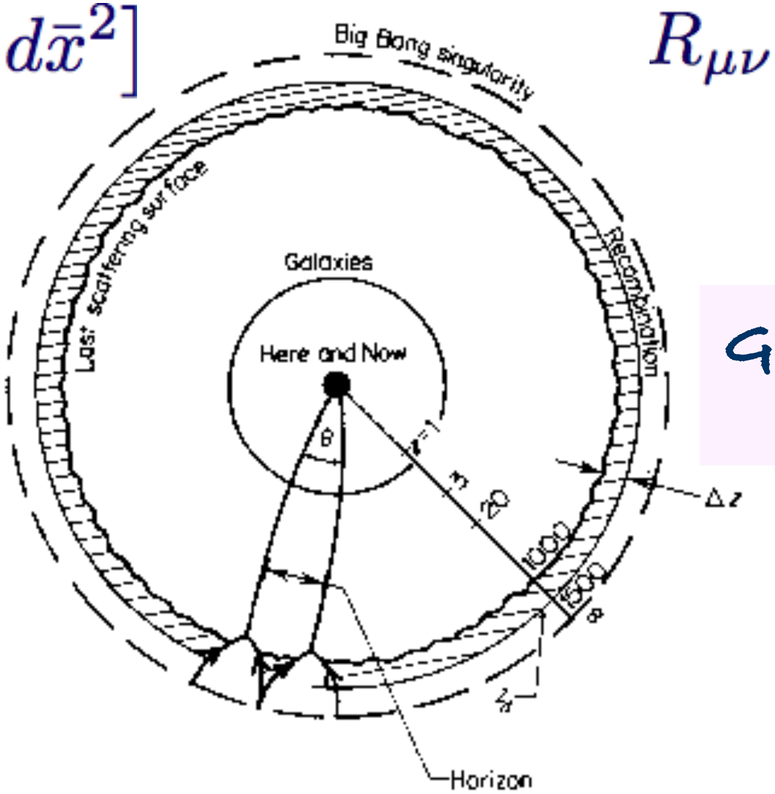
$$ds^2 = a^2(\eta)\left[d\eta^2 - d\bar{x}^2\right]$$

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

Space-time metric
Robertson-Walker

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

Geometrodynamics
Einstein



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

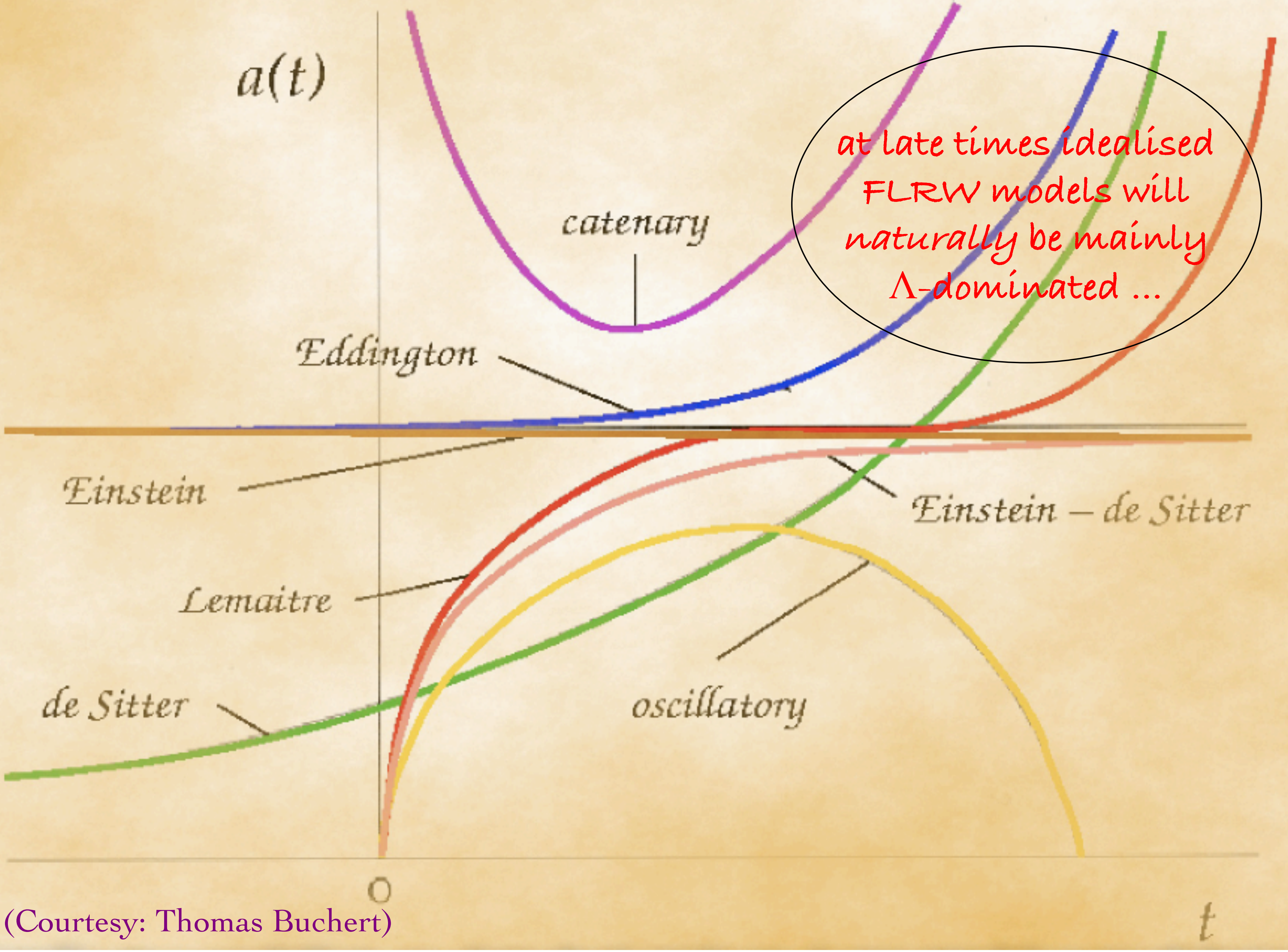
$$\equiv {H_0}^2\left[\Omega_{\mathrm{m}}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

$$\boxed{\Omega_{\mathrm{m}} \equiv \rho_{\mathrm{m}_0} / \frac{3H_0^2}{8\pi G_{\mathrm{N}}}}$$

$$\boxed{\Omega_k \equiv -k/a_0^2 H_0^2}$$

$$\boxed{\Omega_\Lambda \equiv \Lambda/3H_0^2}$$

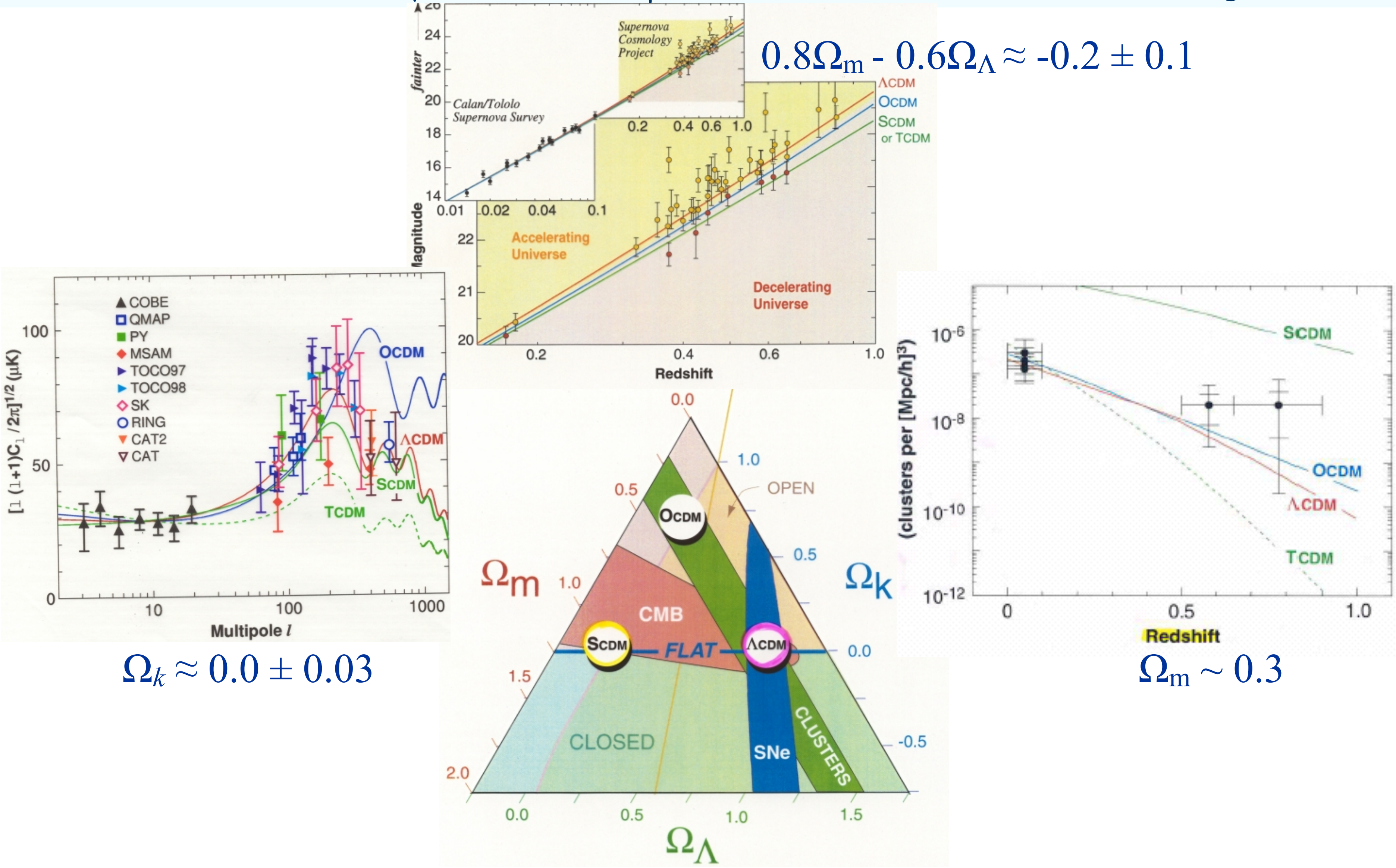
... so has apparent late-time acceleration built into it!



at late times idealised FLRW models will naturally be mainly Λ-dominated ...

(Courtesy: Thomas Buchert)

It is almost inevitable for data interpreted in this idealised model to give $\Lambda \sim H_0^2$



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

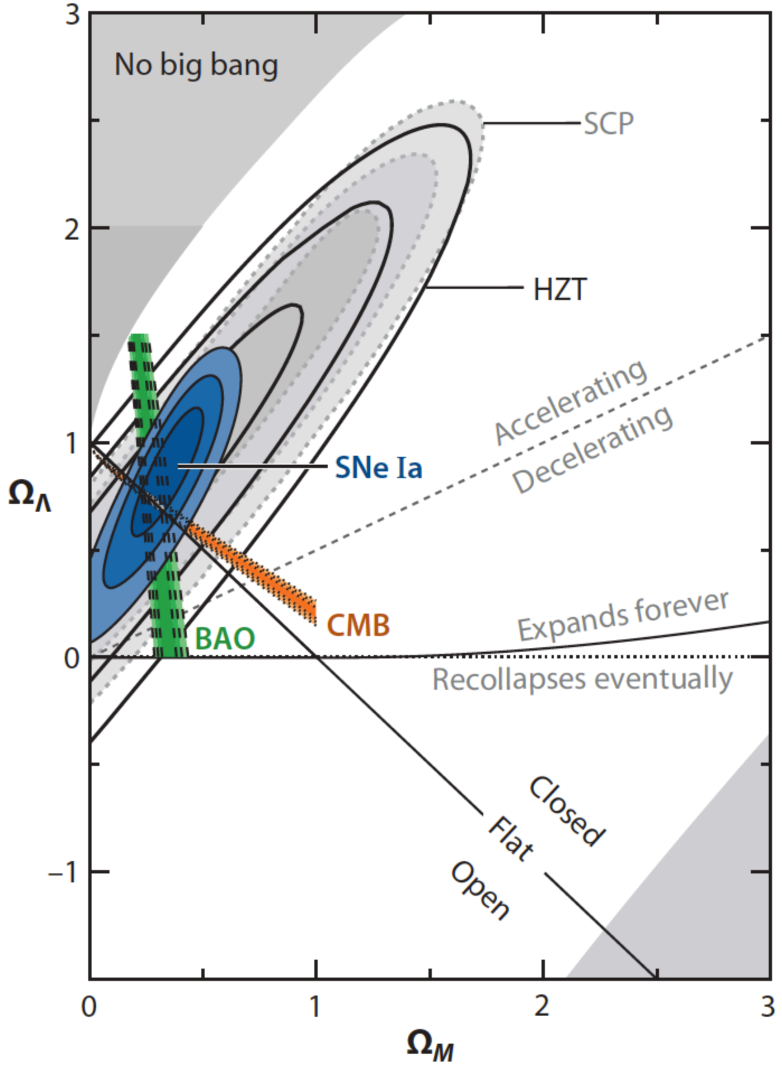
$\Omega_k \approx 0.0 \pm 0.03$

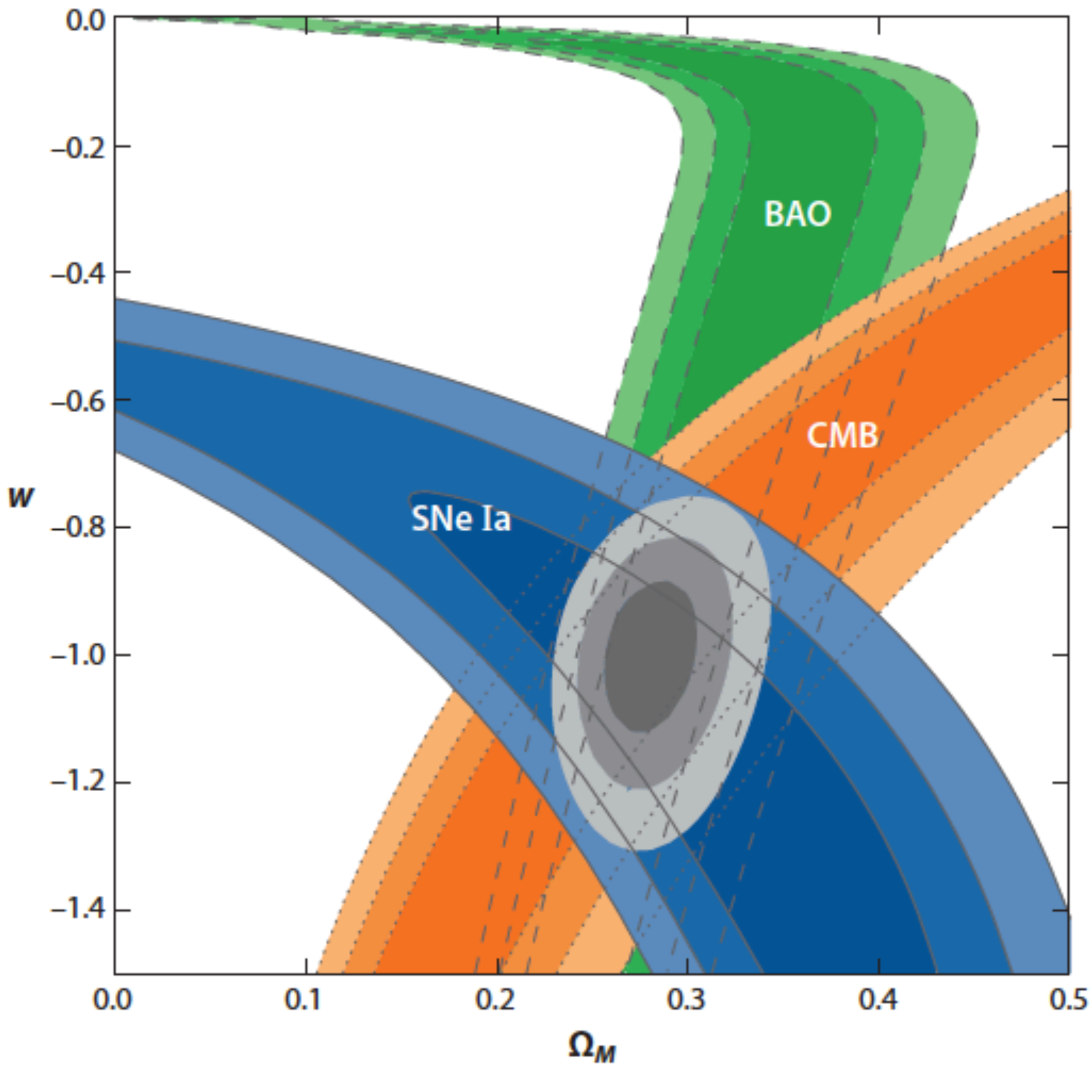
$\Omega_m \sim 0.3$

Bahcall *et al*, Science 284:1481,1999

… Is it then so surprising that we infer $\Omega_\Lambda (\equiv \Lambda/3H_0^2)$ 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 not accounted for?

The 'concordance' of evidence for a Cosmological Constant today with $\Lambda \simeq 2H_0^2 \Rightarrow$ $\Omega_\Lambda \simeq 0.7$ is based entirely on geometrical measures (luminosity distance, angular diameter distance) which are interpreted *assuming* exact homogeneity





Goobar, Leibundgut, ARNPS 61:251,2011

The data have been *interpreted* more generally as implying 'dark energy' with *negative* pressure ($w = p/\rho \simeq$ -1) but there is no direct evidence yet (late ISW effect) for this property

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,

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

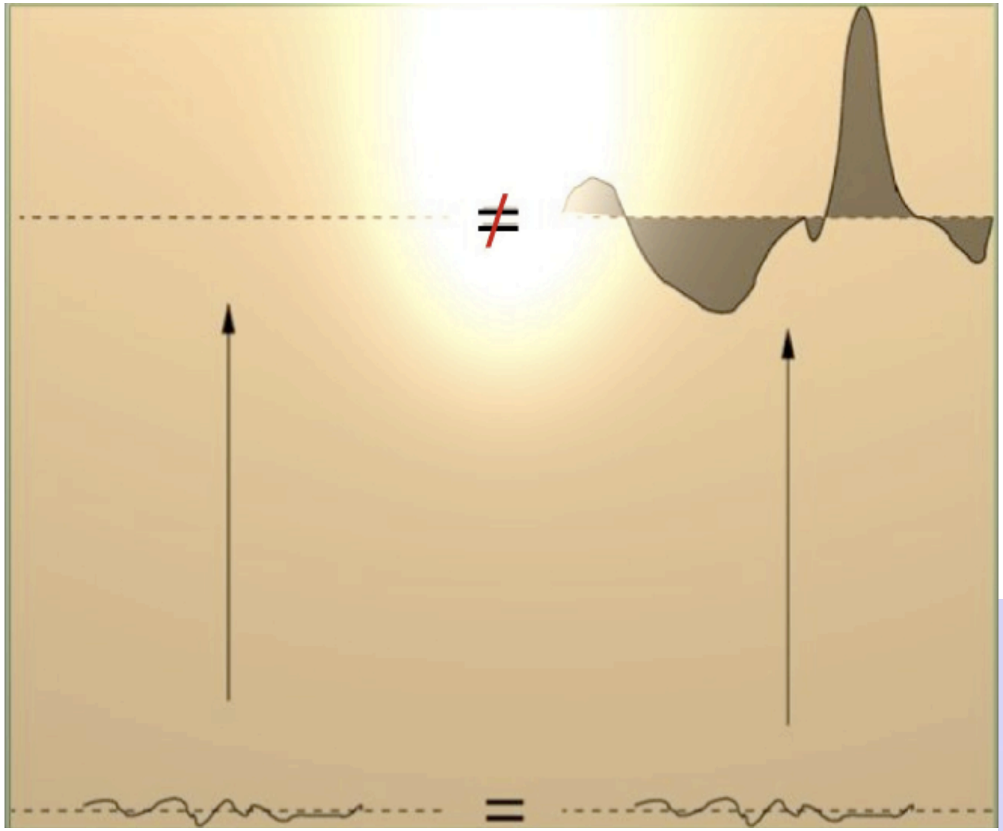
Variance of the expansion rate.

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 $\mathcal{Q}_{\mathcal{D}} = -\frac{1}{3}\langle{}^{(3)}R\rangle_{\mathcal{D}} = \Lambda_{\text{eff}}$.

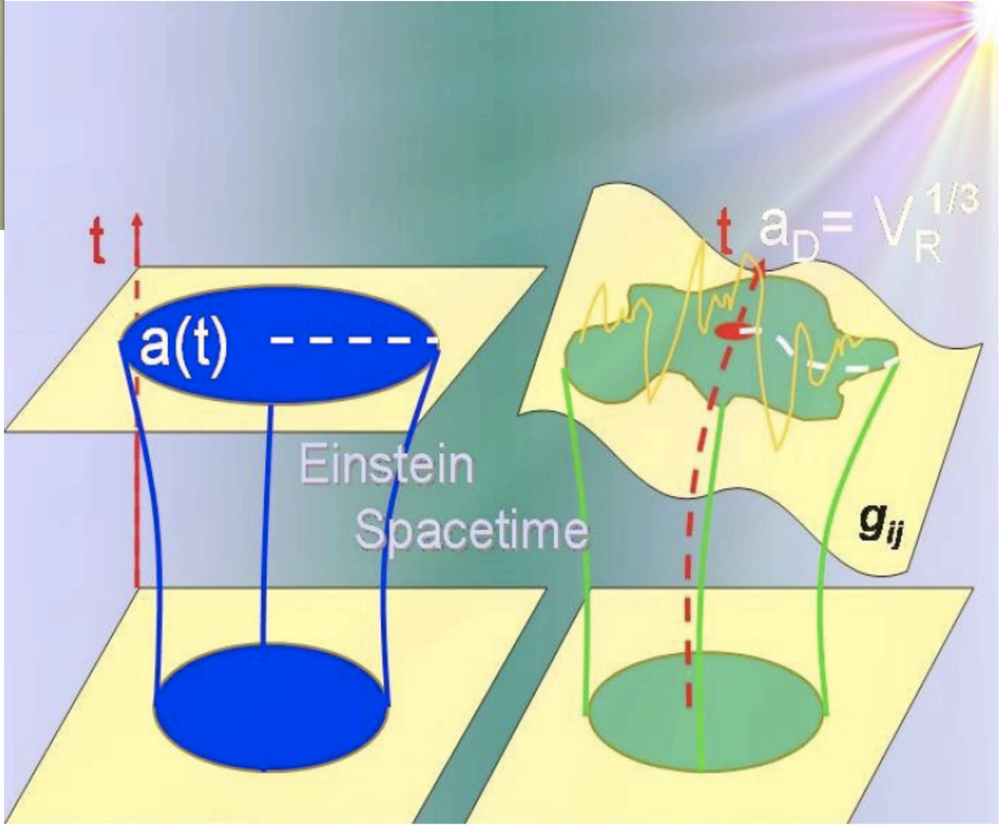
Whether the backreaction can be sufficiently large is an *open question*



'Back reaction' is hard to compute because spatial averaging and time evolution (along our past light cone) do not commute (Ellis 1982) … hence the ongoing controversy

(Buchert & Rasanen, arXiv:1112.5335)

Due to structure formation, the homogeneous solution of Einstein's eqs. is distorted - its average must be taken over the *actual geometry* … the result is *different from* the standard FLRW model



Courtesy: Thomas Buchert

Interpreting Λ as vacuum energy raises the coincidence problem: *why is $\Omega_\Lambda \approx \Omega_m$ today?*

Option 1: invent an ultralight scalar field (**'quintessence'**) with $V(\varphi)^{1/4} \sim 10^{-12}$ GeV but $\sqrt{d^2V/d\varphi^2} \sim H_0 \sim 10^{-42}$ GeV, which displays 'tracking' behaviour

… but this is just as much fine-tuning as a bare cosmological constant

Option 2: Modify gravity on the scale of the present Hubble radius so as to mimic vacuum energy (**'DGP brane-world'**) taking care to avoid instabilities

… this scale is unnatural in a fundamental theory and is just put in by hand

Option n>>1: **chameleon/$f(R)$ models, symmetron fields, massive gravity** …

All 'explanations' for cosmic accn. insert the scale $H_0 \sim 10^{-42}$ GeV by hand!

The only *natural* option is if $\Lambda \sim H^2$ always (as attempted in e.g. causal set models), but this is just a renormalisation of G_N (recall: $H^2 = 8\pi G_N/3 + \Lambda/3$)

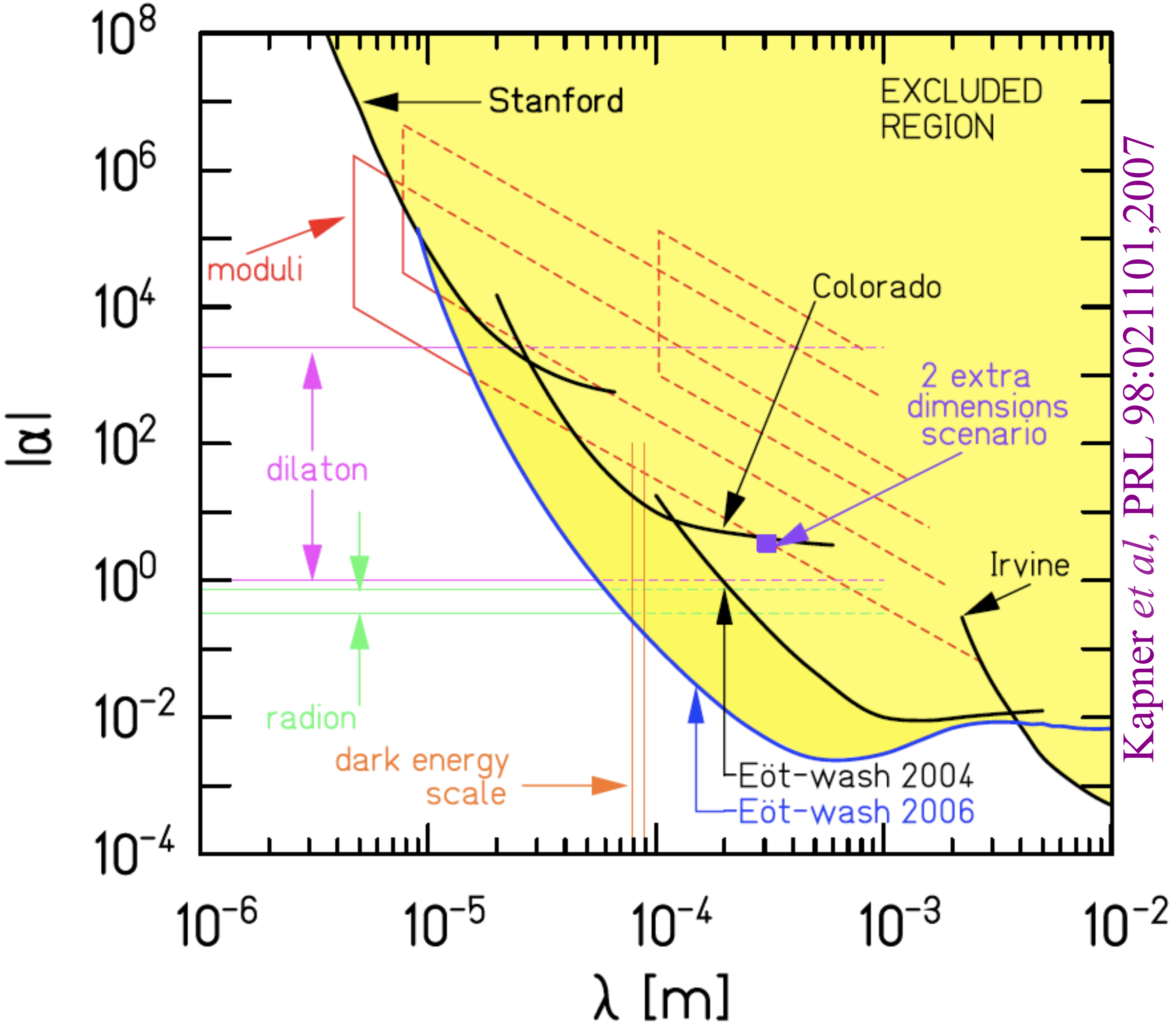
(*ruled out* by Big Bang nucleosynthesis which requires G_N to be within few% of its laboratory value … and in any case this will not yield accelerated expansion)

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

Do we infer $\Lambda \sim H_0^2$ simply because H_0 is the only scale in the FLRW model and enters in every observation (through the distance scale)?

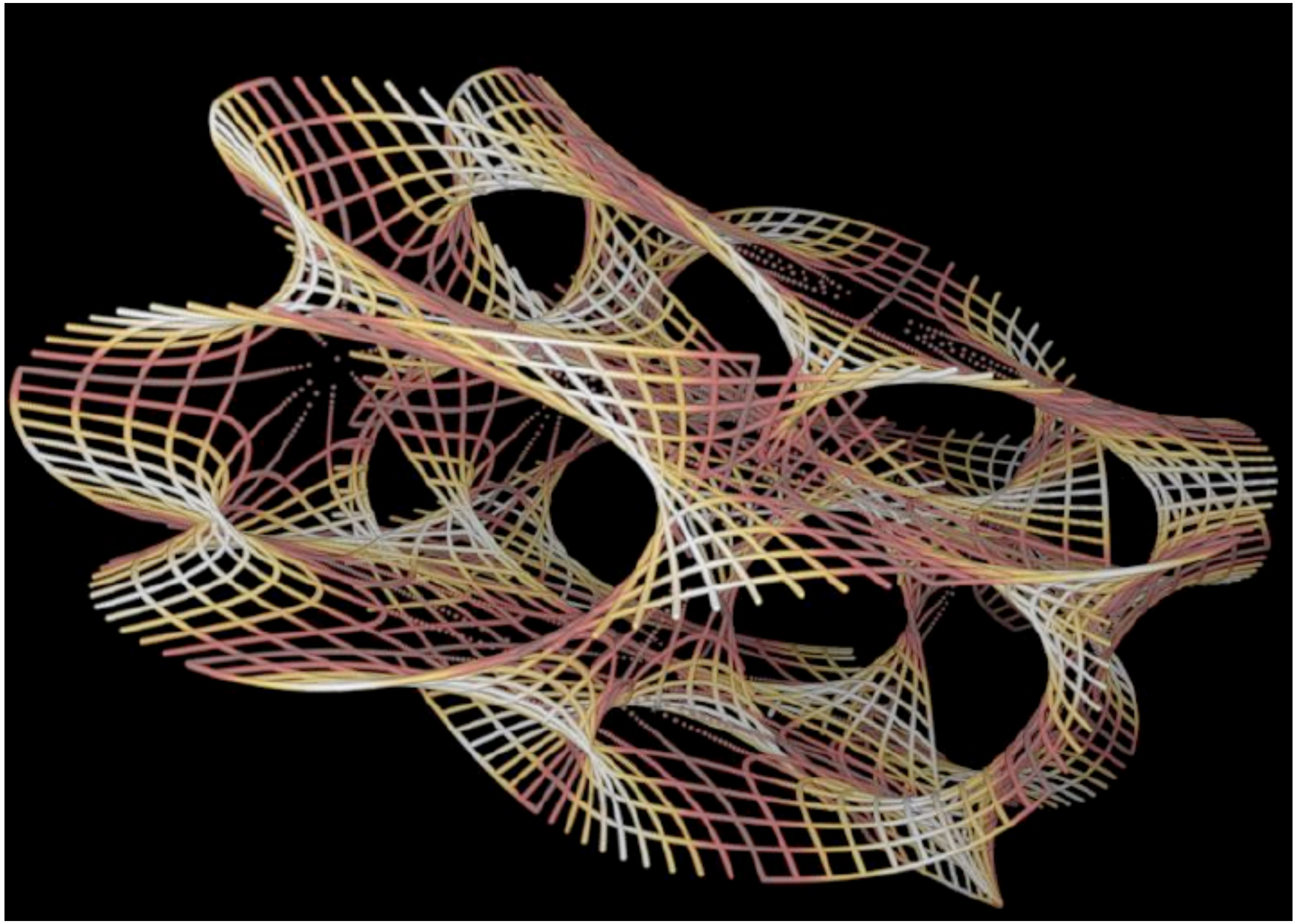
There is *no* evidence for any change in the inverse-square law of gravitation at the ‘dark energy’ scale: $\Omega_\Lambda^{-1/4} \sim (H_0 M_P)^{-1/2} \sim 0.1$ mm

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



Kapner *et al*, PRL 98:021101,2007

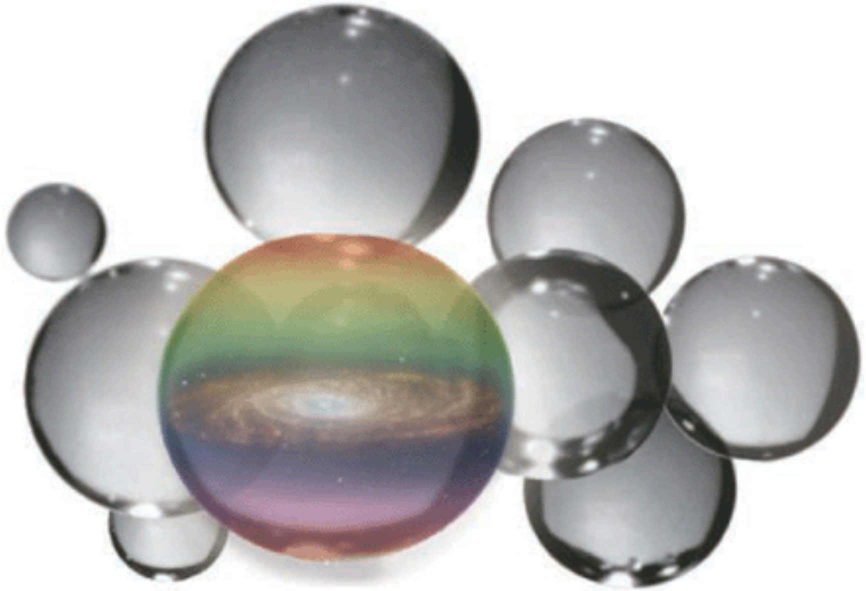
In string/M-theory, the sizes and shapes of the extra dimensions ('moduli') must be stabilised ... e.g. by turning on background 'fluxes'

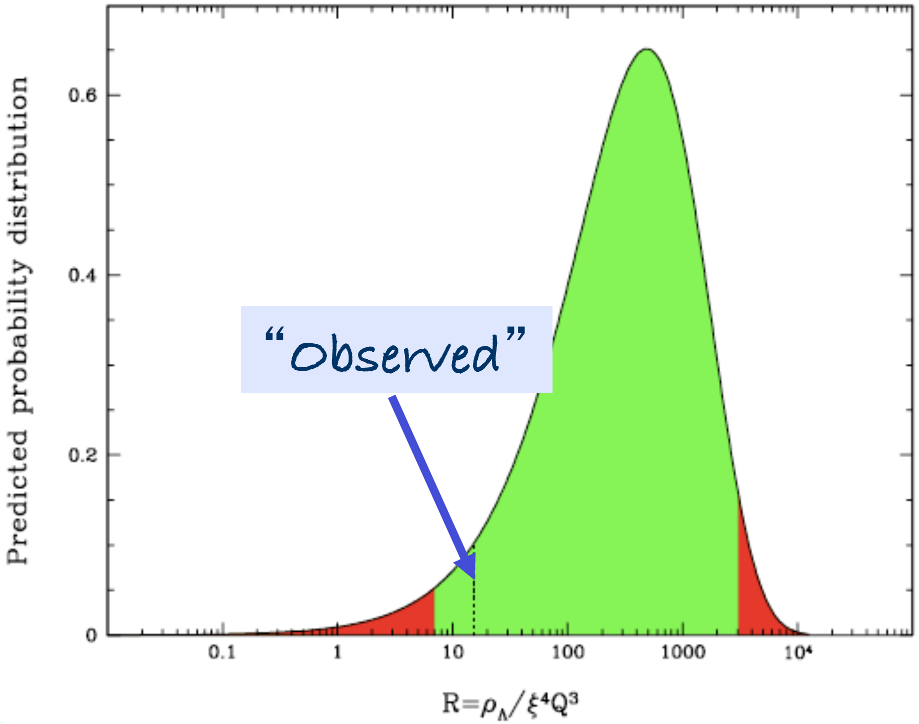


Given the variety of flux choices and the number of local minima in the flux potential, the total number of vacuua is very large - perhaps 10^{500}

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 $\Omega_\Lambda \sim \Omega_m$**

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





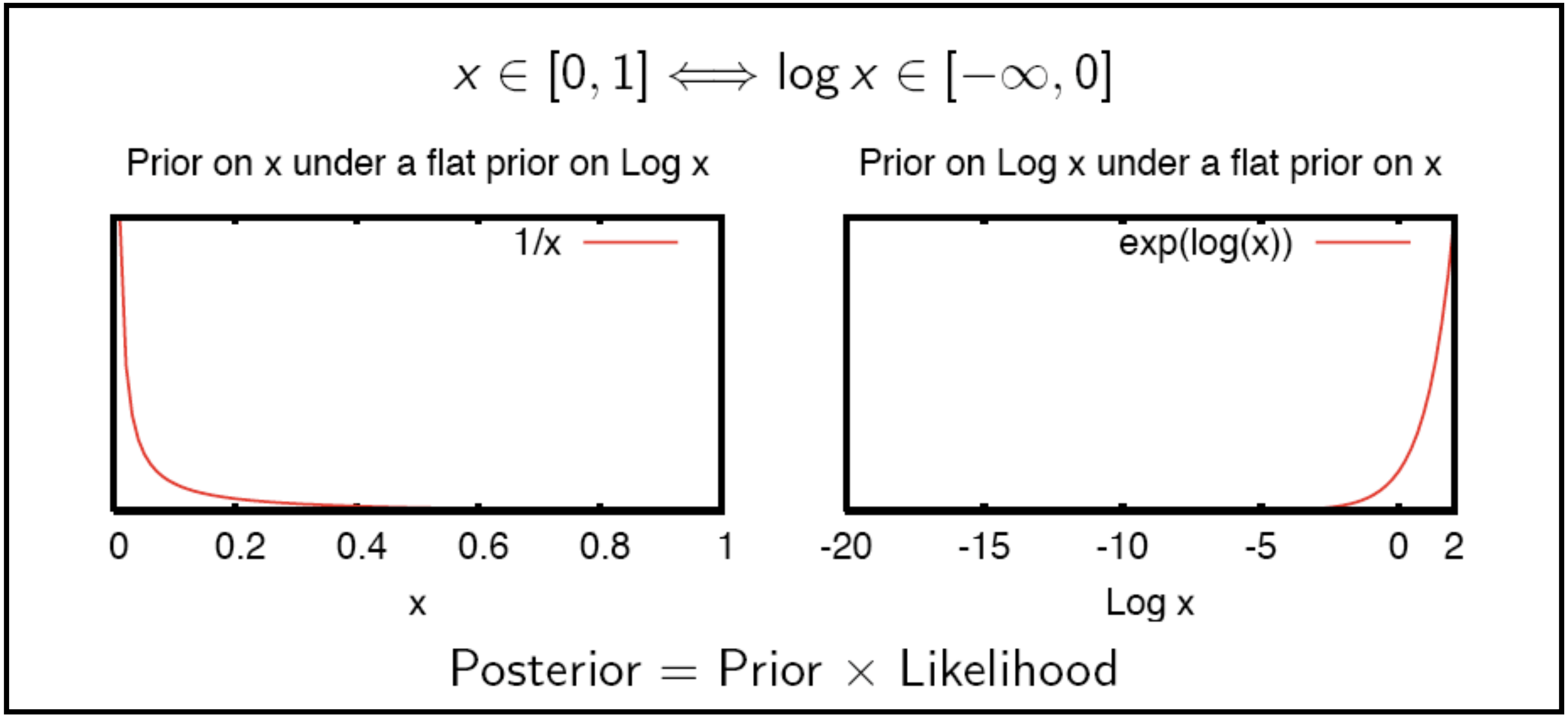
Tegmark, Aguirre, Rees, Wilczek, Phys.Rev. D73:023505, 2006

But the 'anthropic prediction' of Λ from considerations of galaxy formation is significantly *higher* than the observationally inferred value … not surprising since galaxy formation occurred at redshift $z \sim 3\text{-}5$ when the matter density was $(1+z)^3$ times higher

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

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

If the relevant physical variable is e.g. *log* Ω_Λ, then $\Omega_\Lambda = \mathbf{0}$ would be favoured!



$$x \in [0,1] \Longleftrightarrow \log x \in [-\infty, 0]$$

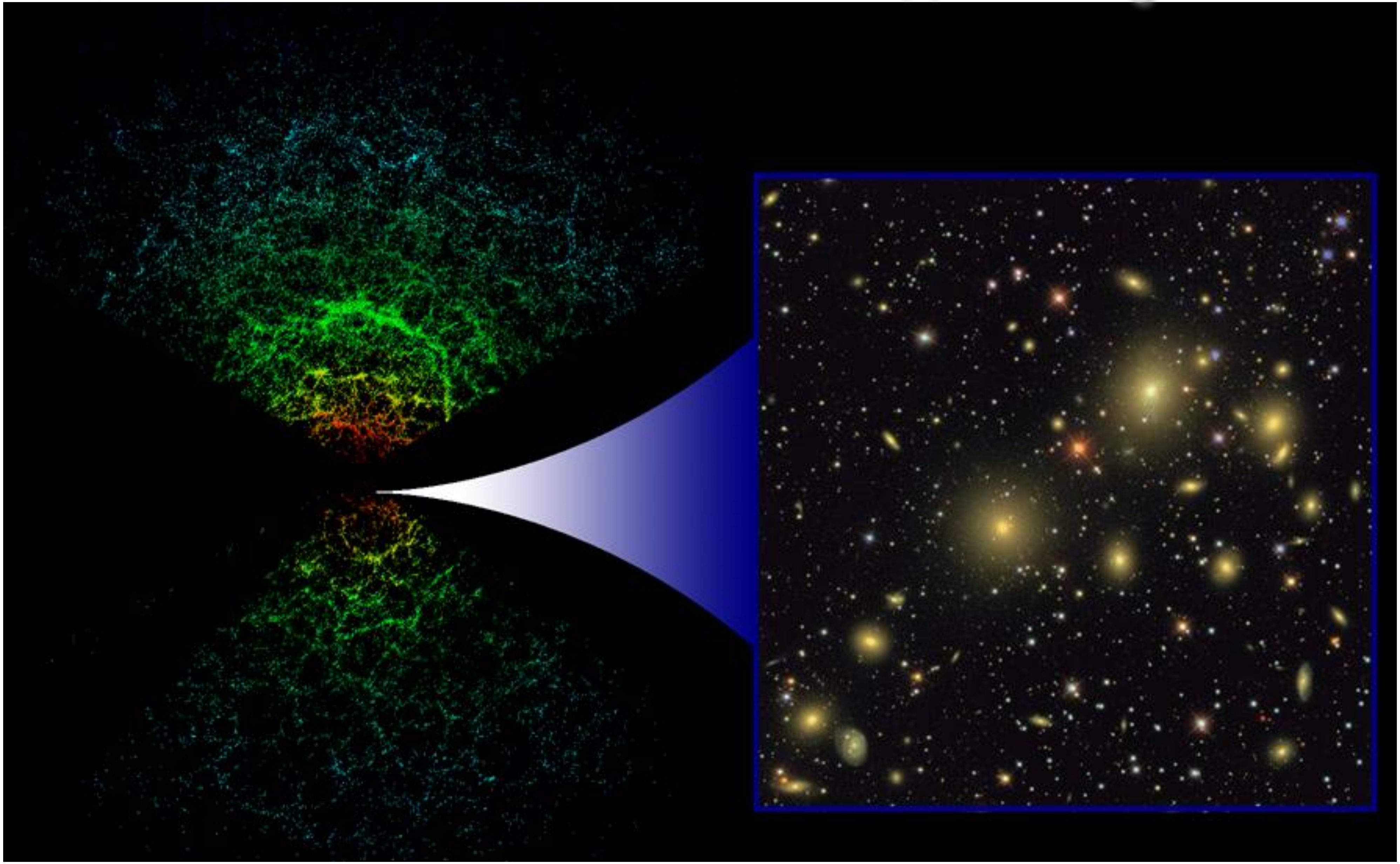
Prior on x under a flat prior on Log x

Prior on Log x under a flat prior on x

$$\text{Posterior} = \text{Prior} \times \text{Likelihood}$$

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

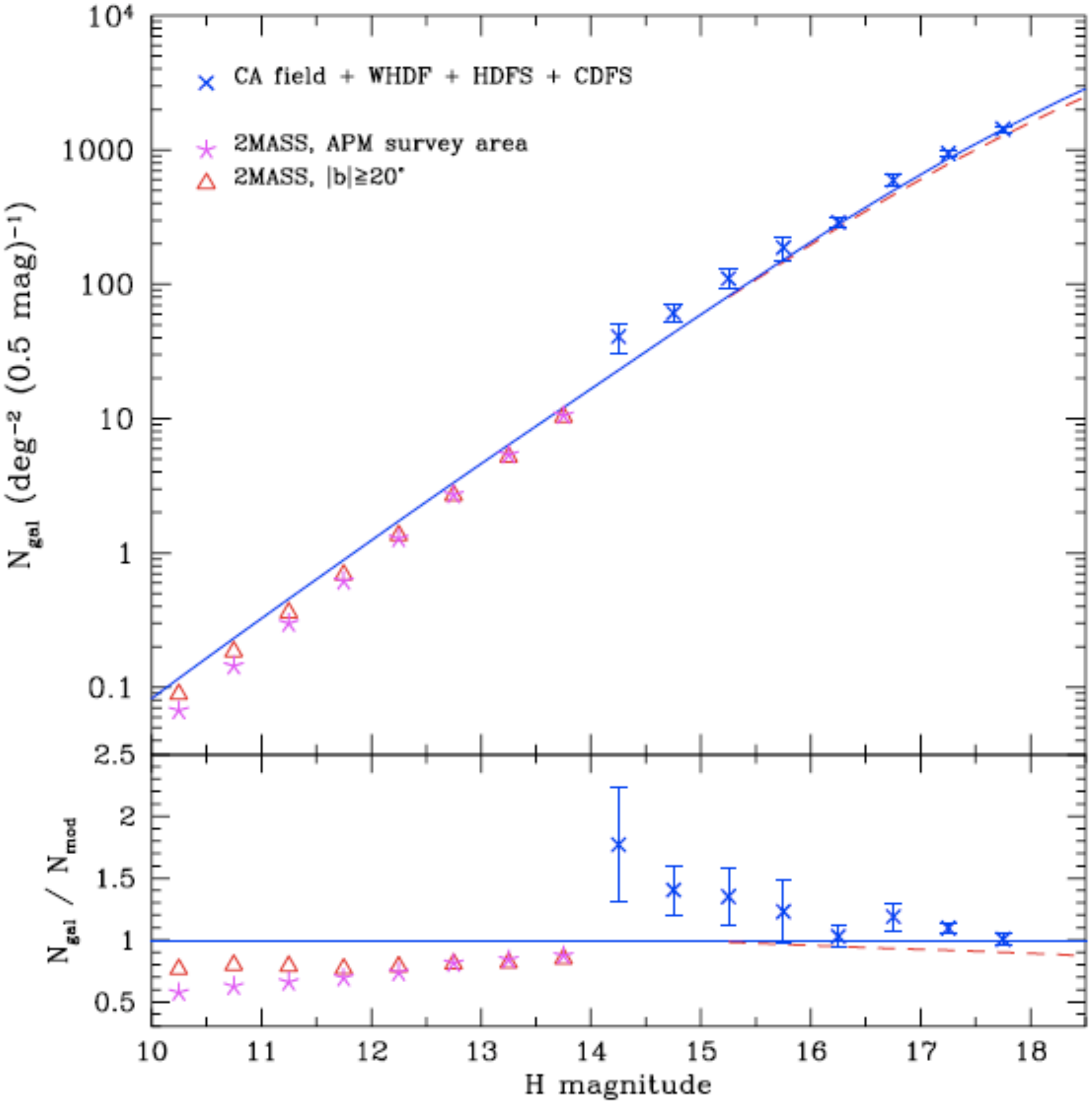
Galaxies are seen to trace out a cosmic ‘web’ of filamentary structure



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

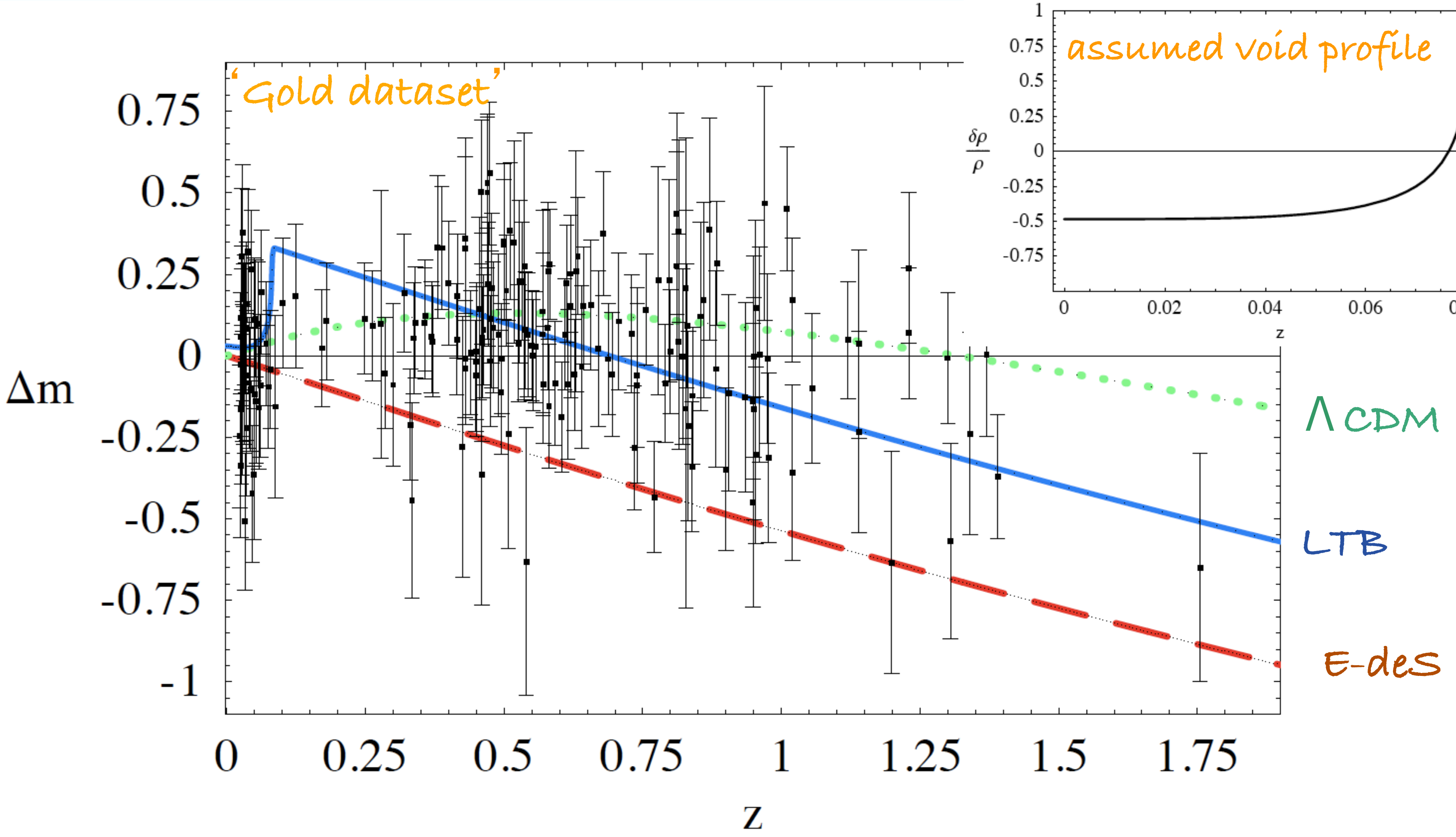
New H-band Galaxy Number Counts

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



Frith, Metcalfe & Shanks (2006)

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



Alexander, Biswas, Notari & Vaid, JCAP 09:025,2009

Fits the SN data with $h_{\mathrm{out}} \sim 0.45$, $0.51 < h_{\mathrm{in}} < 0.59$, void radius ~ 150-250 Mpc h_{in}^{-1}

However subsequent SN data has filled in the gap at z ~ 0.1-0.4 and may have ruled out this model … so now one needs to consider a larger void of ~Gpc size

Toy model that fits the SN Ia Hubble diagram *without* cosmic acceleration/dark energy

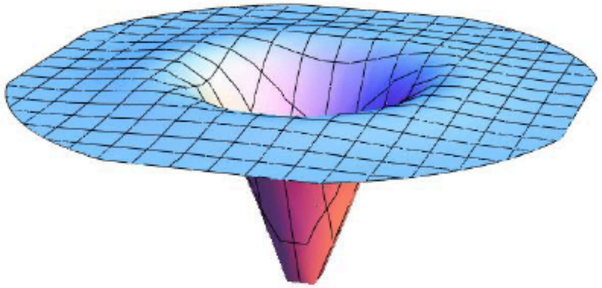
LTB metric: $ds^2 = -c^2dt^2 + \frac{A'^2(r,t)}{1+K(r)}dr^2 + A^2(r,t)d\Omega^2$

Two Hubble rates: $H_T(r,t) \equiv \frac{\dot{A}}{A}$ and $H_L(r,t) \equiv \frac{\dot{A}'}{A'}$

Obtain modified version of Friedmann equation -

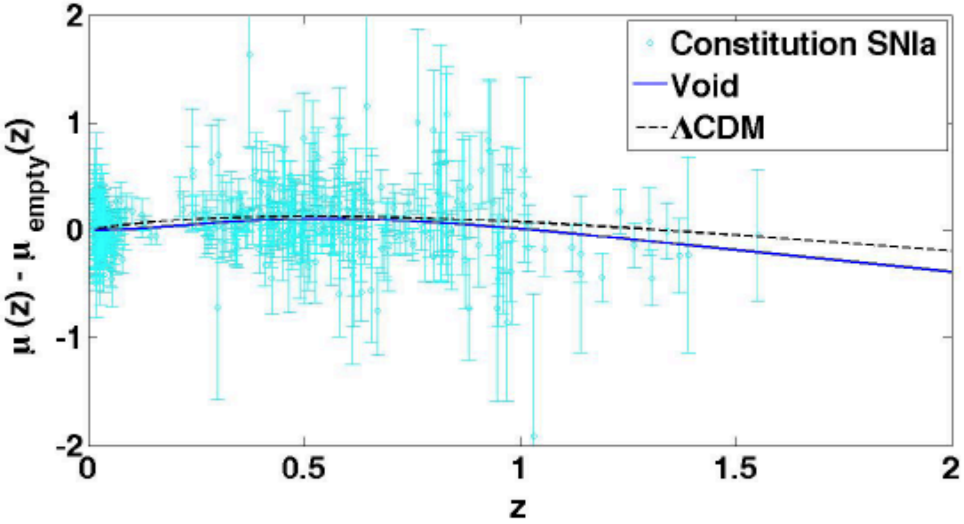
$$H_T^2(r,t) = H_0^2(r)\left[\Omega_m(r)\left(\frac{A_0(r)}{A(r,t)}\right)^3 + \Omega_K(r)\left(\frac{A_0(r)}{A(r,t)}\right)^2\right]$$

Choose a density profile

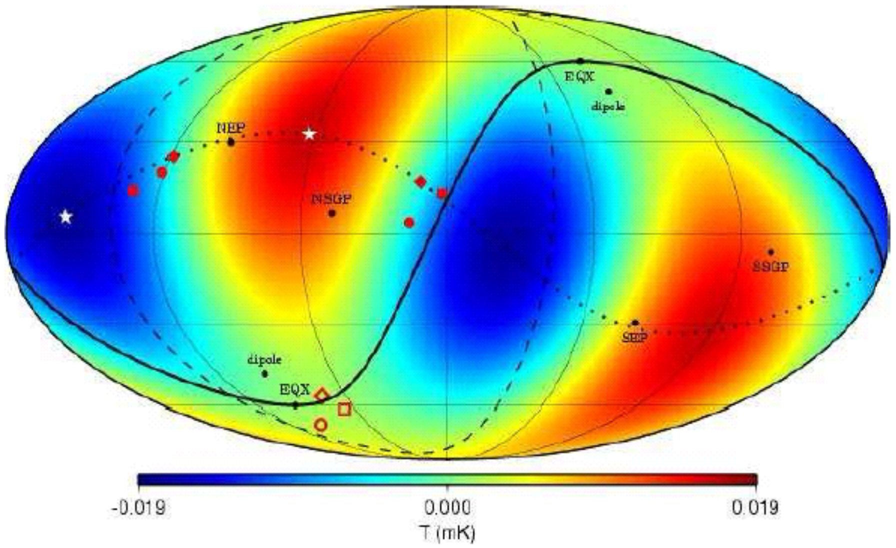


- Solve modified Friedmann equation numerically for $A(r,t)$
- Luminosity distance $D_L(z) = (1+z)^2A(r,t)$

Can get a very good fit to supernovae data:



e.g. Nadathur & Sarkar, Phys. Rev. D83:063506,2011

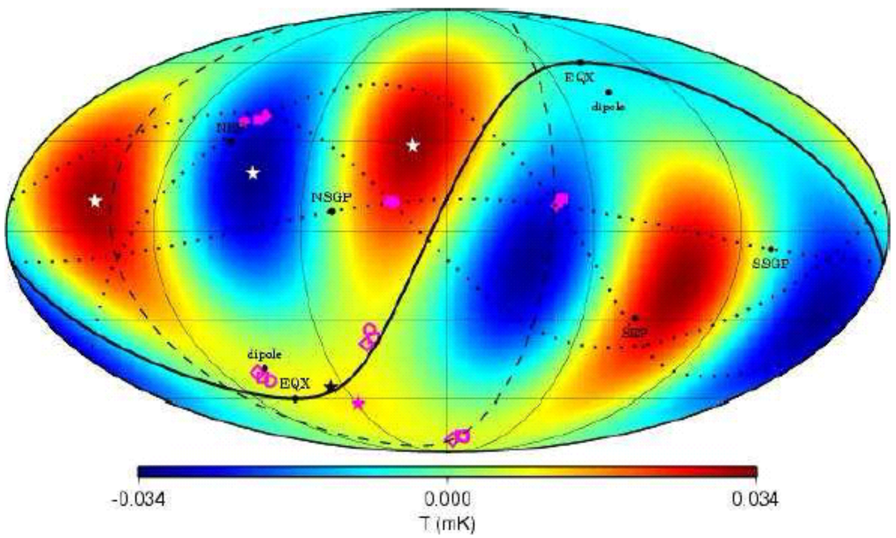


The local void need not be exactly spherical … nor would we expect to be *exactly* at its centre

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

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

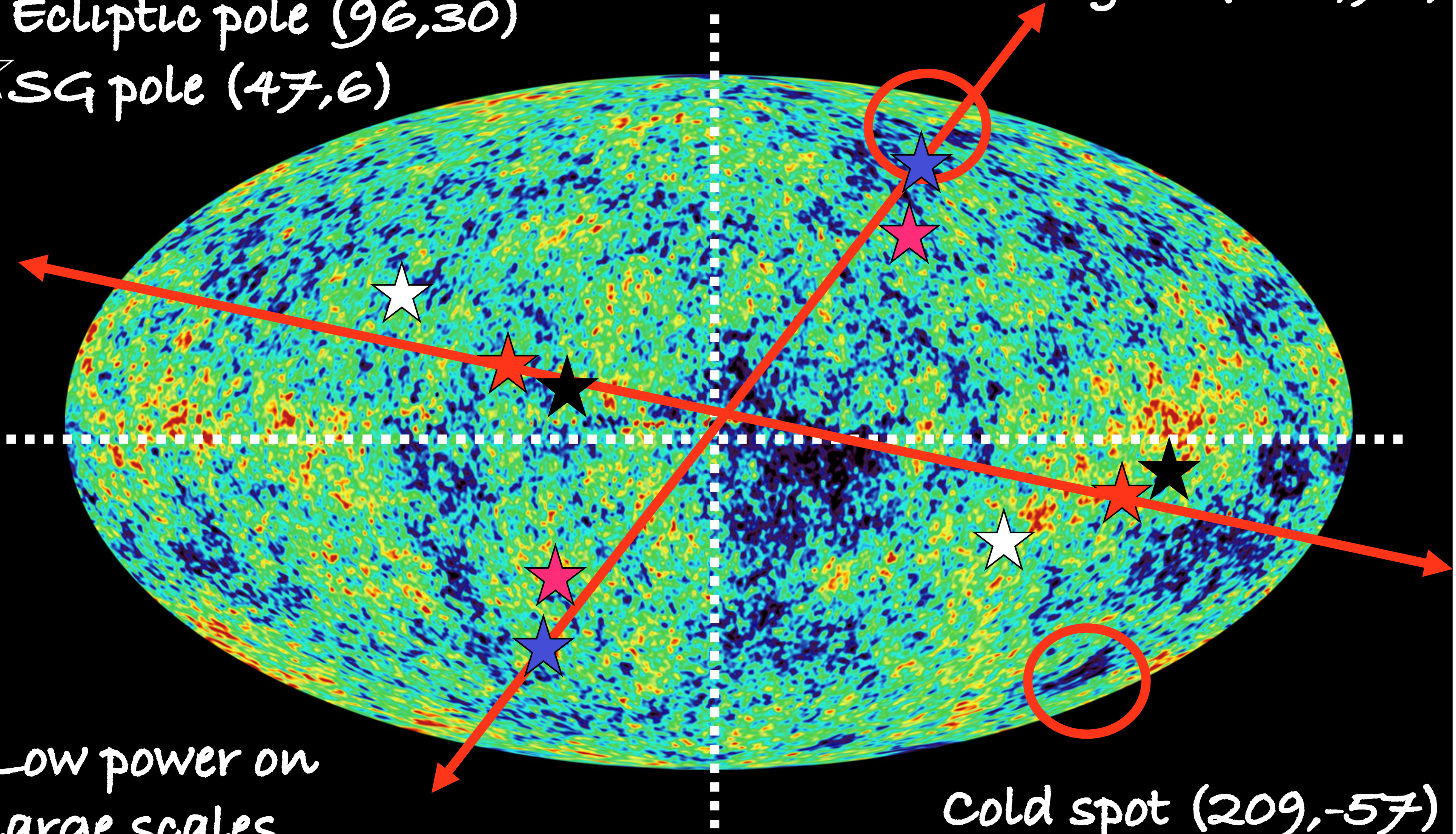
This requires us to be located at the boundary between two voids (to yield the observed *planar* – rather than linear – alignment)
Inoue & Silk, ApJ 648:23,2006



Can such a void be responsible for the CMB 'cold spot'?

★ Axis of Evil ~ (260,60)
★ Dipole (264,48)

★ Max asym axis (57,10)
★ Ecliptic pole (96,30)
☆ SG pole (47,6)

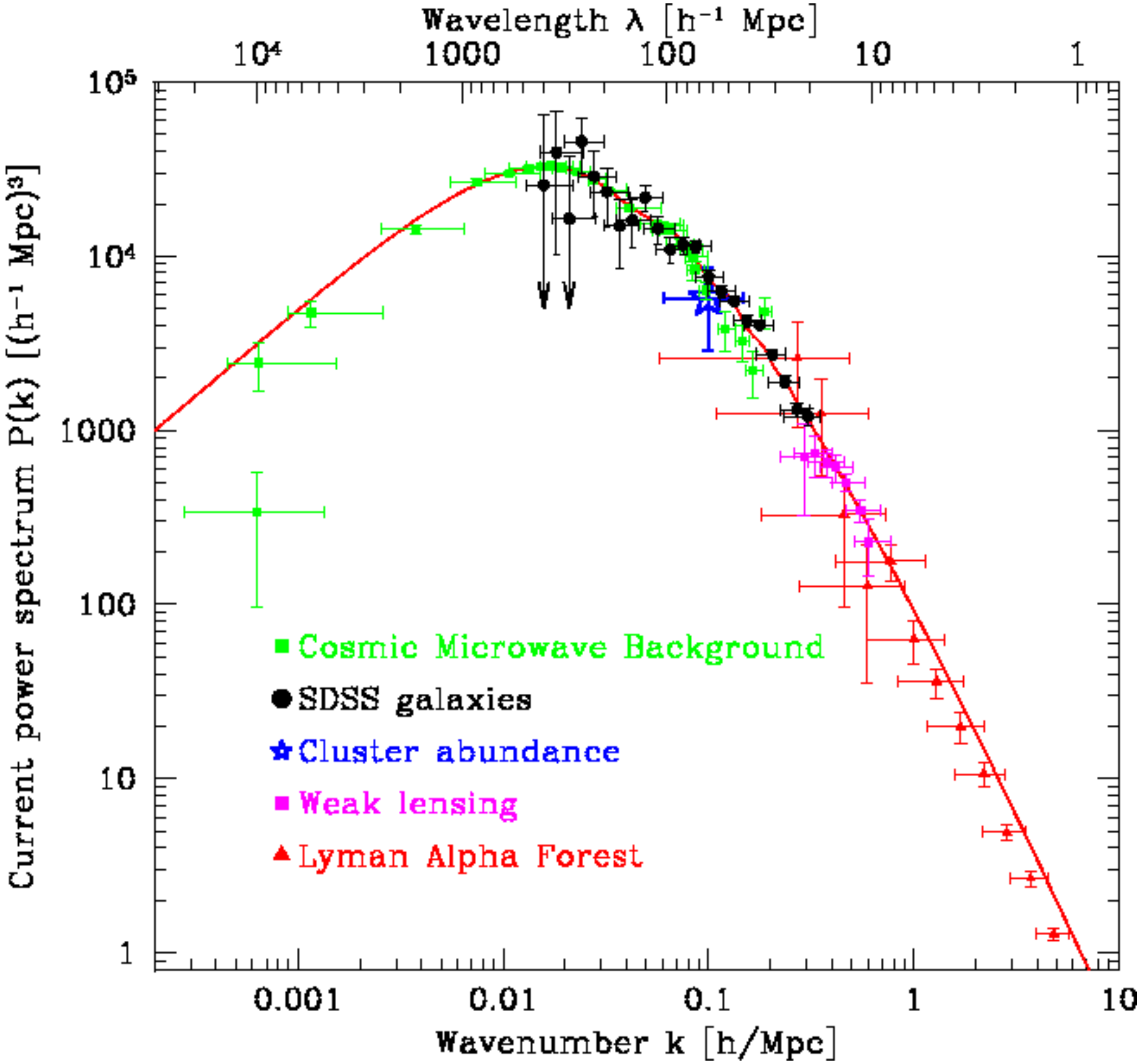


Virgo ~ (260,70)

Low power on large scales

Cold spot (209,-57)

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



Tegmark (2004)

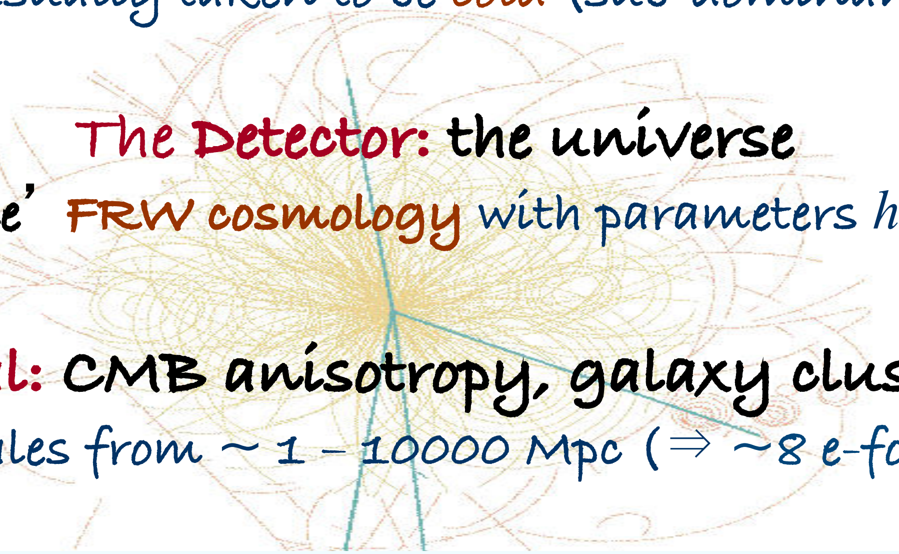
The formation of large-scale structure is akin to a scattering experiment

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} …

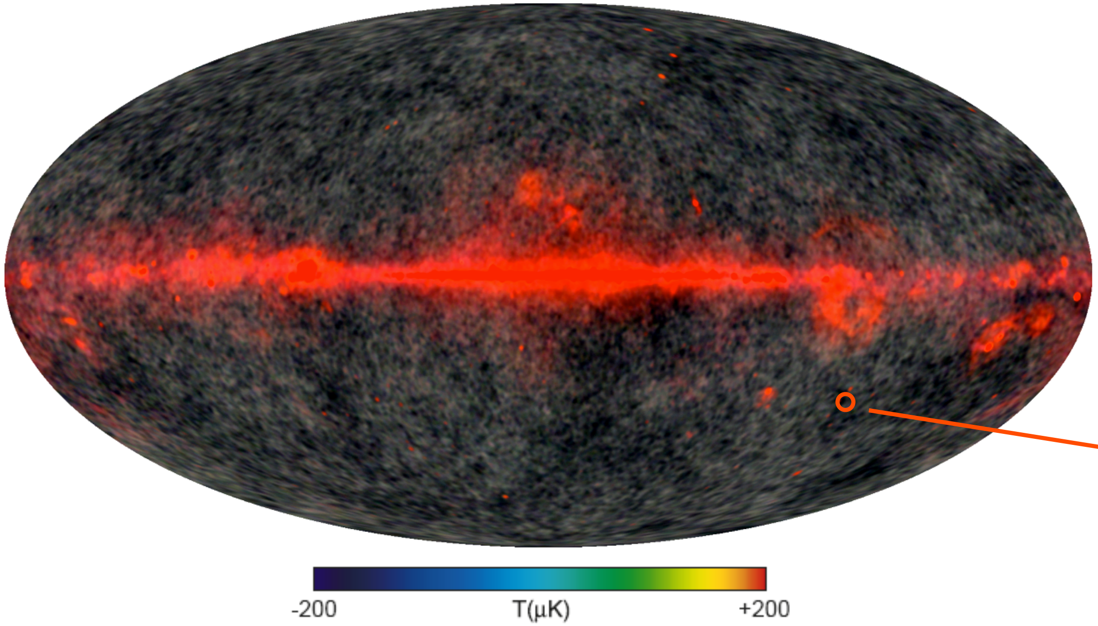
The Signal: CMB anisotropy, galaxy clustering …

measured over scales from ~ 1 – 10000 Mpc (⇒ ~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*

‘Internal Linear Combination’ map



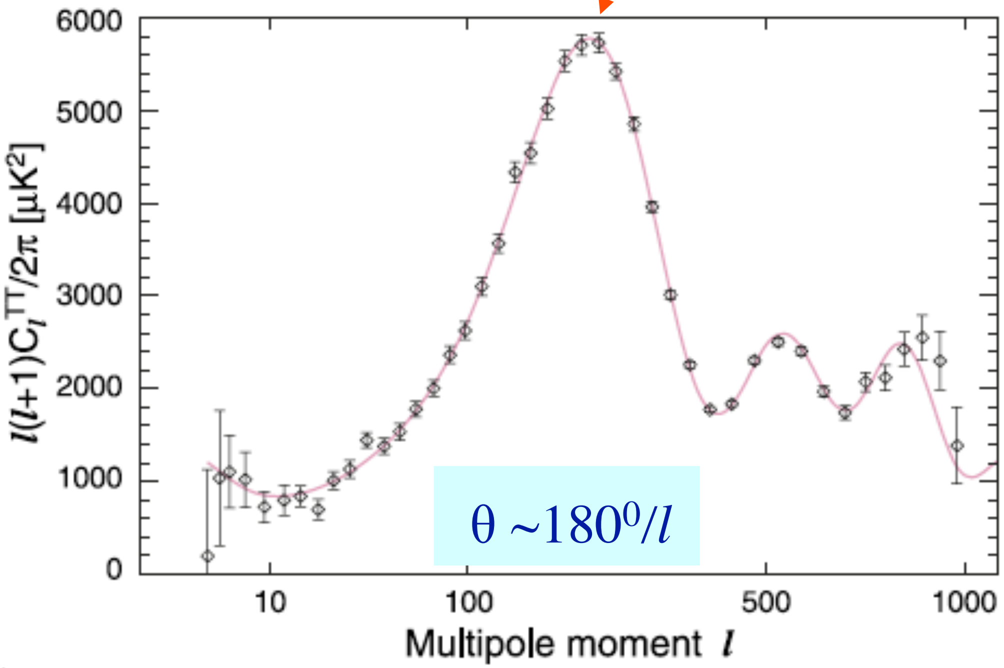
Coherent oscillations
in photon-baryon
plasma, excited by
primordial density
perturbations on
super-horizon scales …

(Hubble radius at t_{rec})

$$\Delta T(\mathbf{n}) = \sum a_{lm} Y_{lm}(\mathbf{n})$$

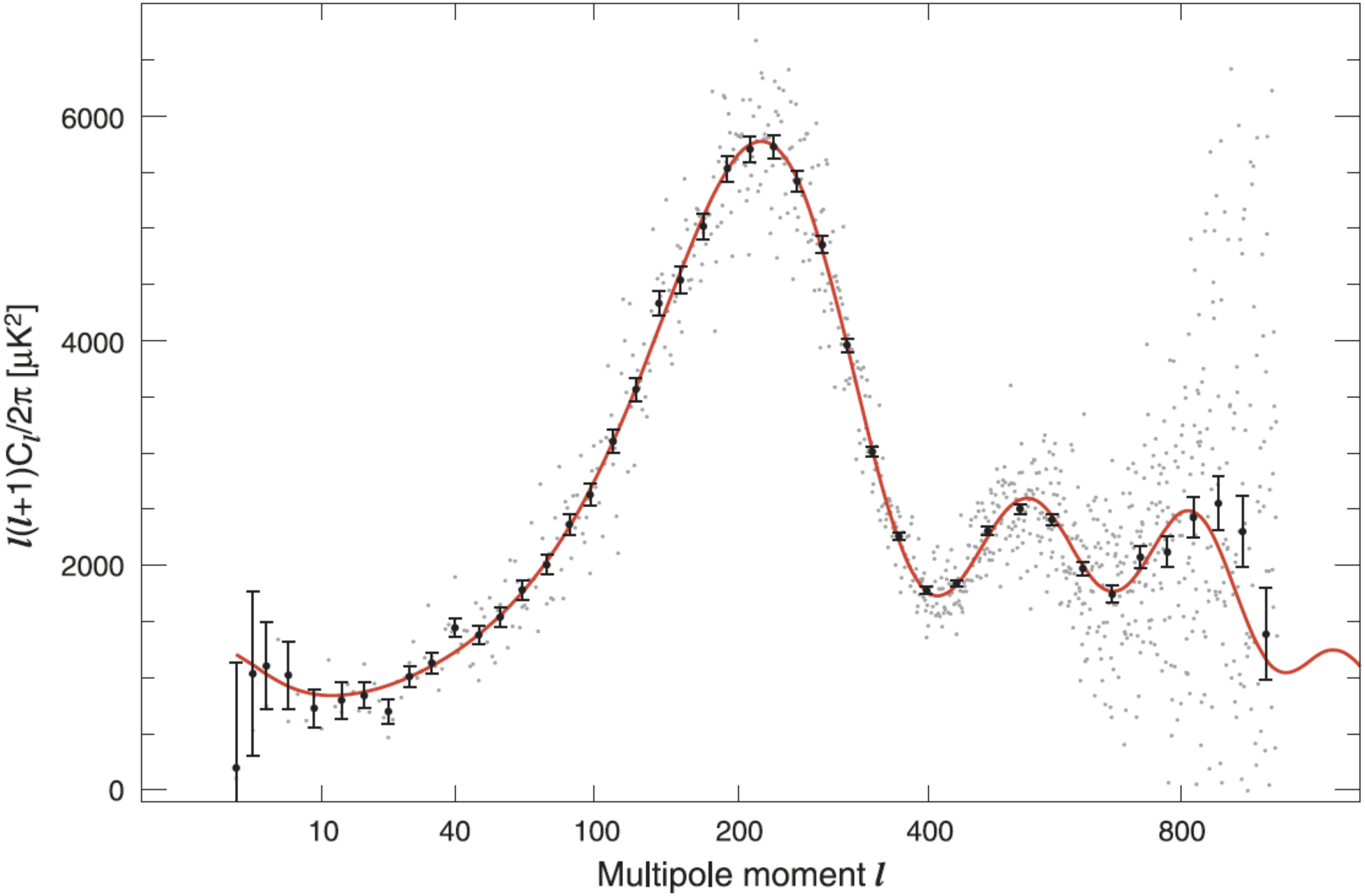
$$C_l \equiv \frac{1}{2l+1} \sum |a_{lm}|^2$$

C_l’s mildly correlated since
(due to Galactic foreground)
only ~85% of sky can be used



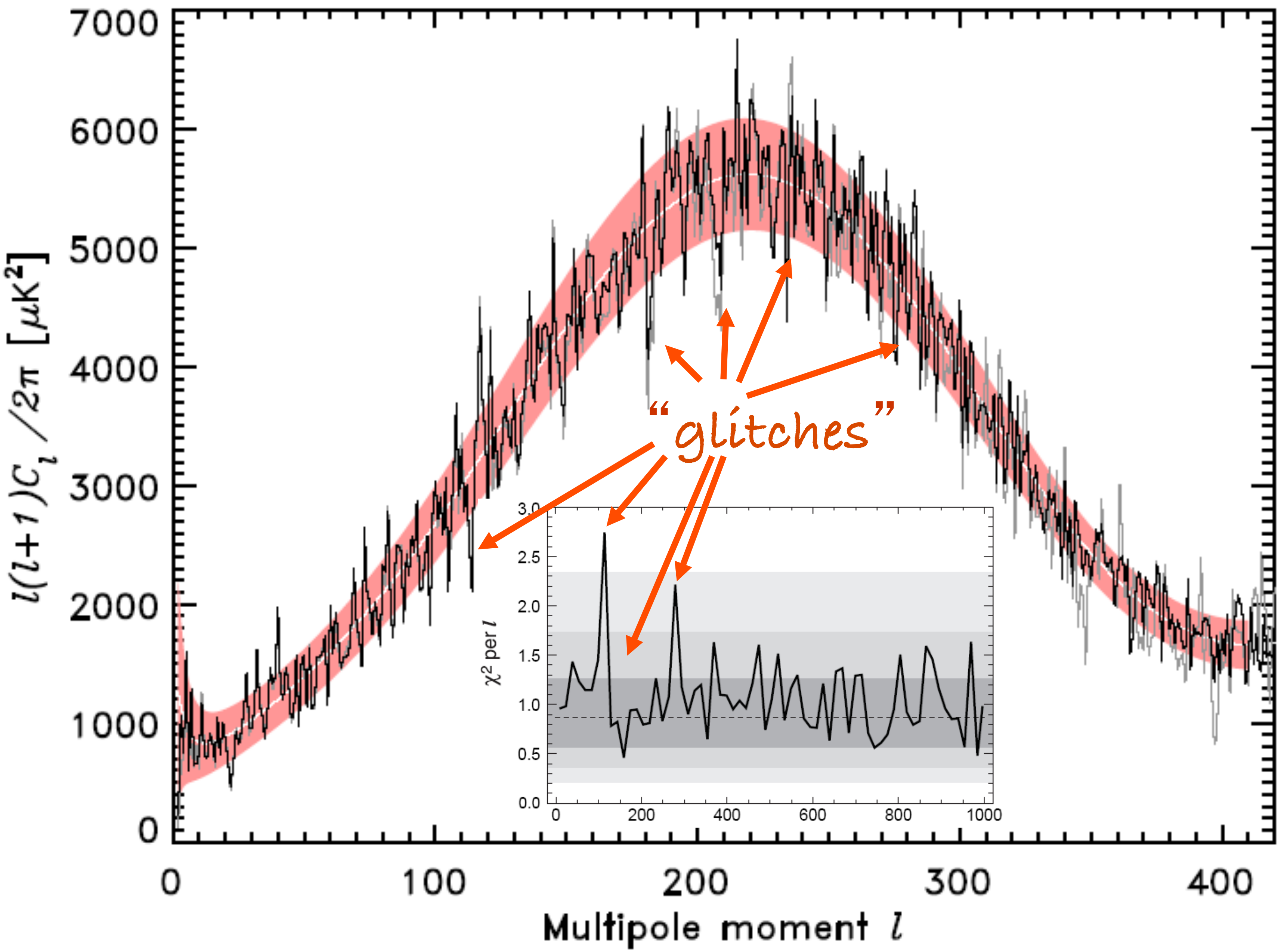
The 'power-law ΛCDM model' is believed to be confirmed by WMAP

Best-fit: $\Omega_m h^2 = 0.11 \pm 0.01$, $\Omega_b h^2 = 0.023 \pm 0.001$, $h = 0.72 \pm 0.03$, $n = 0.96 \pm 0.02$



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

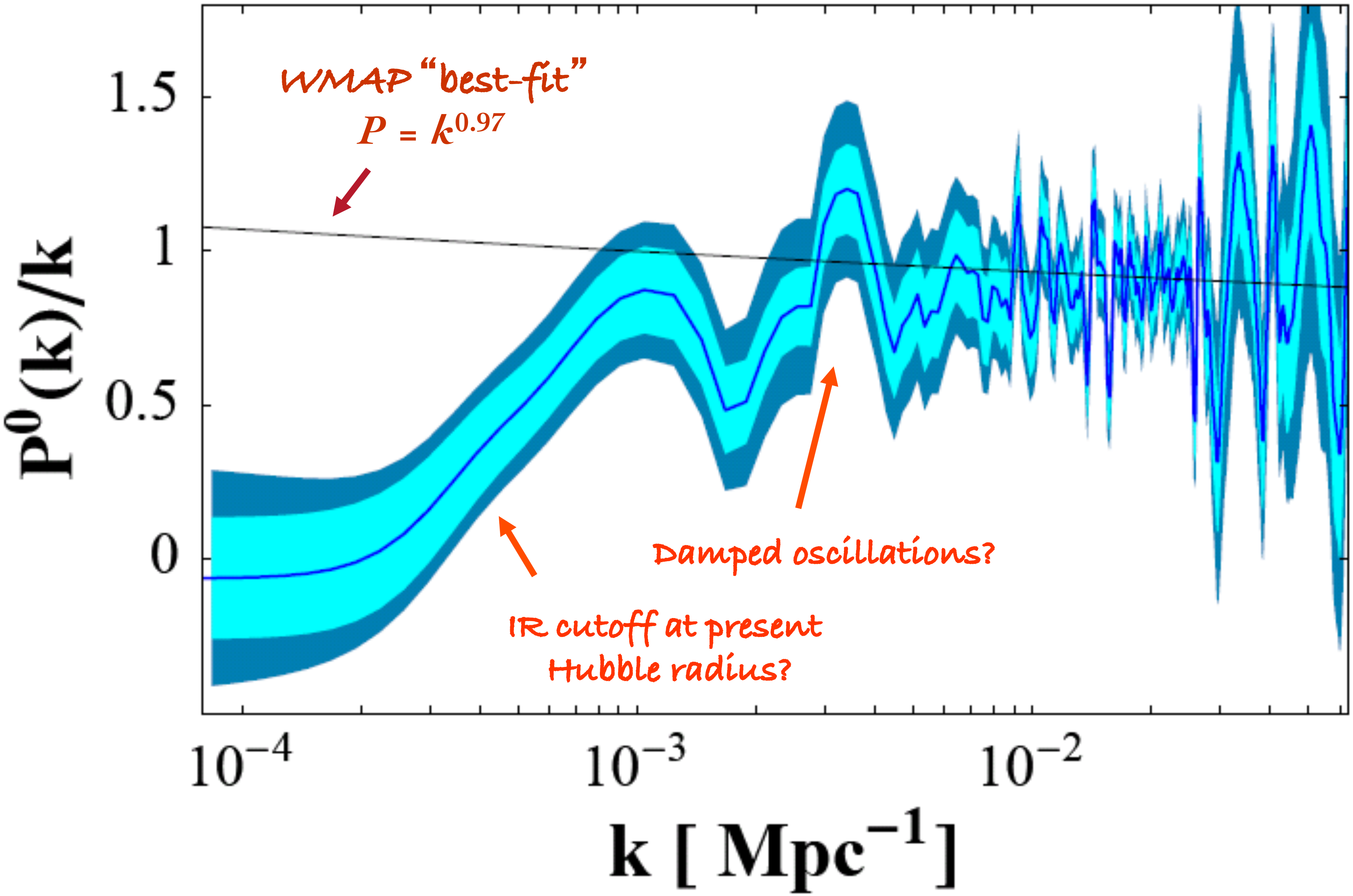
The excess χ^2 comes mostly from the *outliers* in the TT spectrum



“glitches”

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

Many attempts made to reconstruct the primordial spectrum (assuming ΛCDM) ➜ indications for departures from a power-law spectrum



WMAP "best-fit"
$P = k^{0.97}$

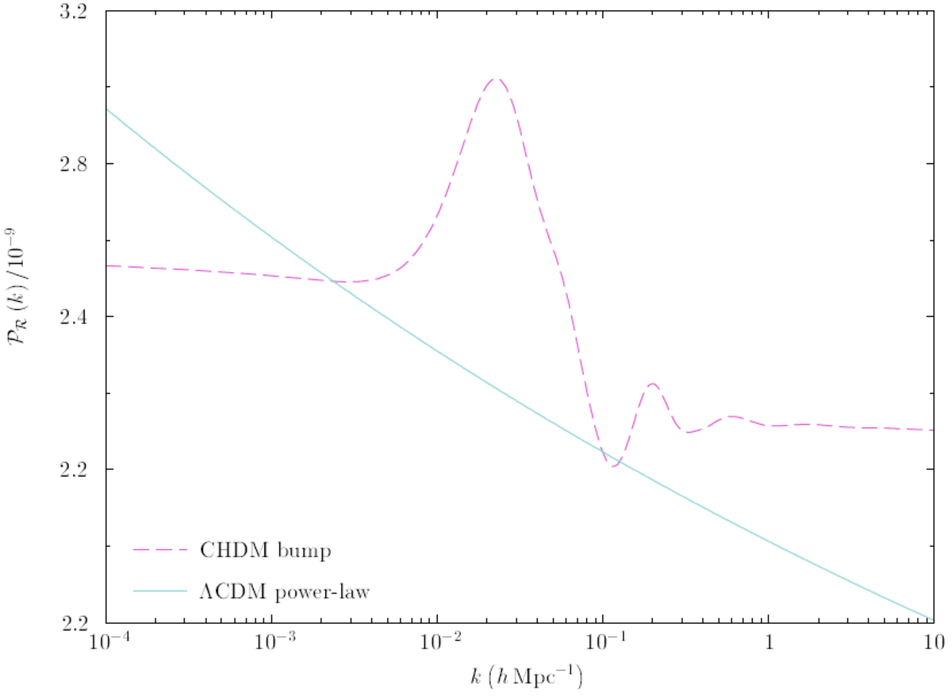
Damped oscillations?

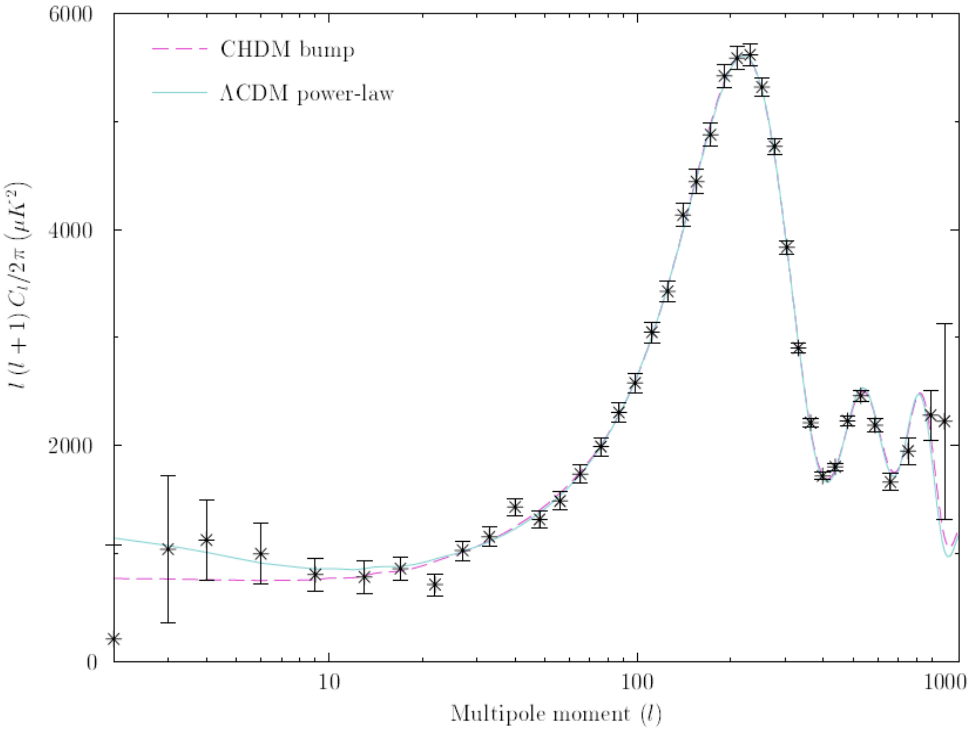
IR cutoff at present Hubble radius?

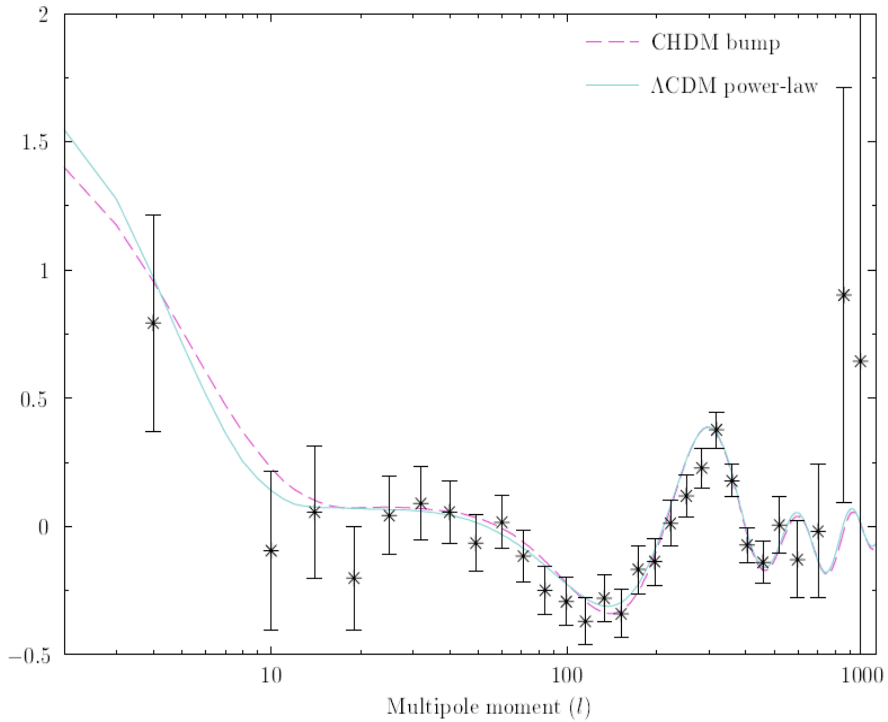
Tochhini-Valentini, Hoffman & Silk (2005)

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 $h \sim 0.44$



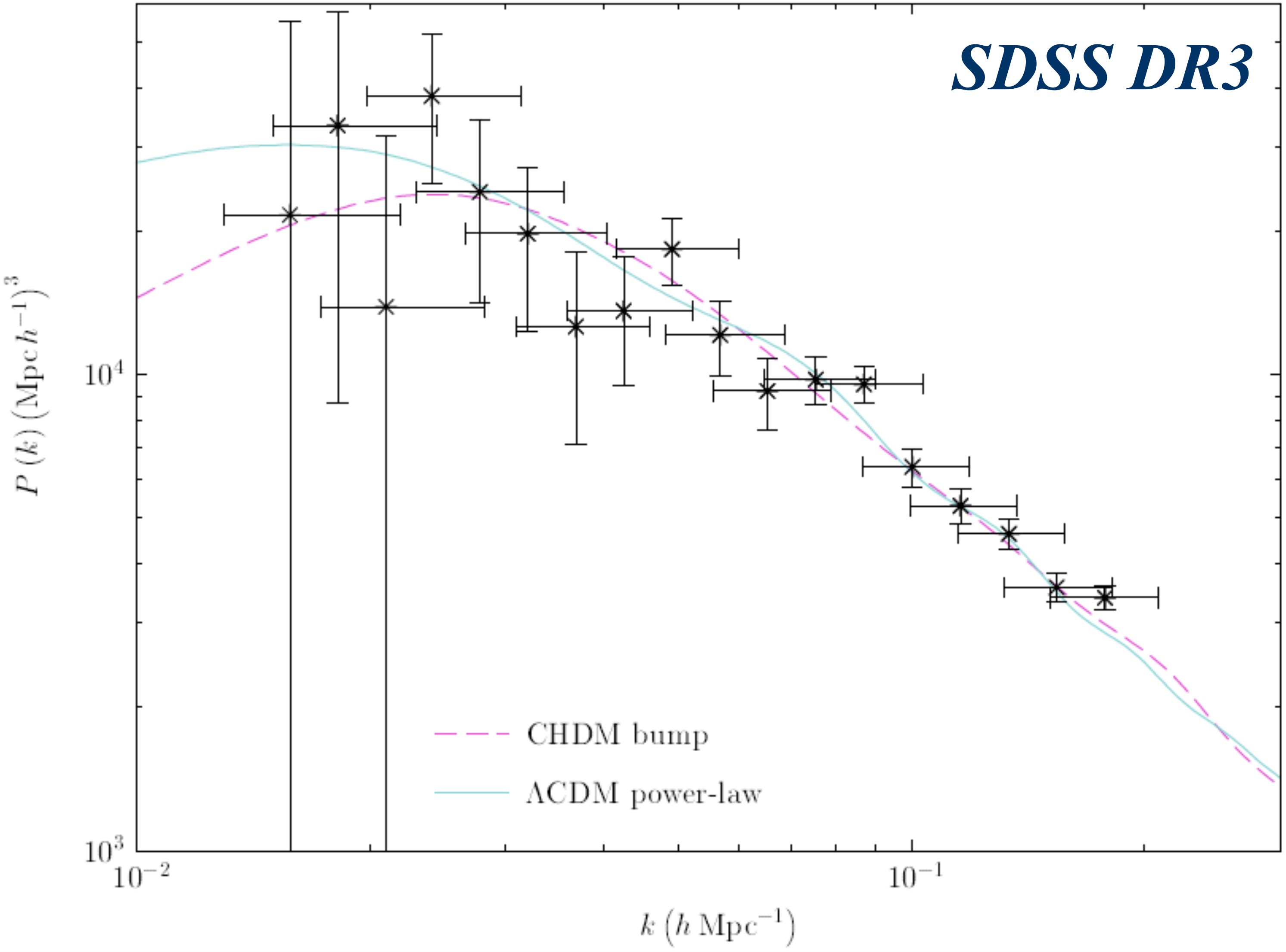




(Hunt & Sarkar, Phys. Rev. D76:123504,MNRAS, 401:547,2010)

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

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



(Hunt & Sarkar, Phys. Rev. D76:123504,2007)

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

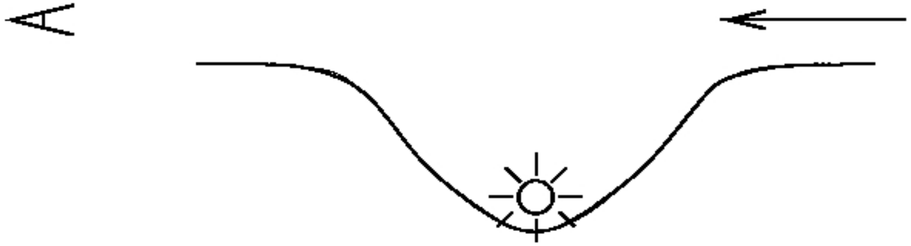
… also excellent match to gravitational lensing signal in CMB

Is there direct *dynamical* evidence for Λ?

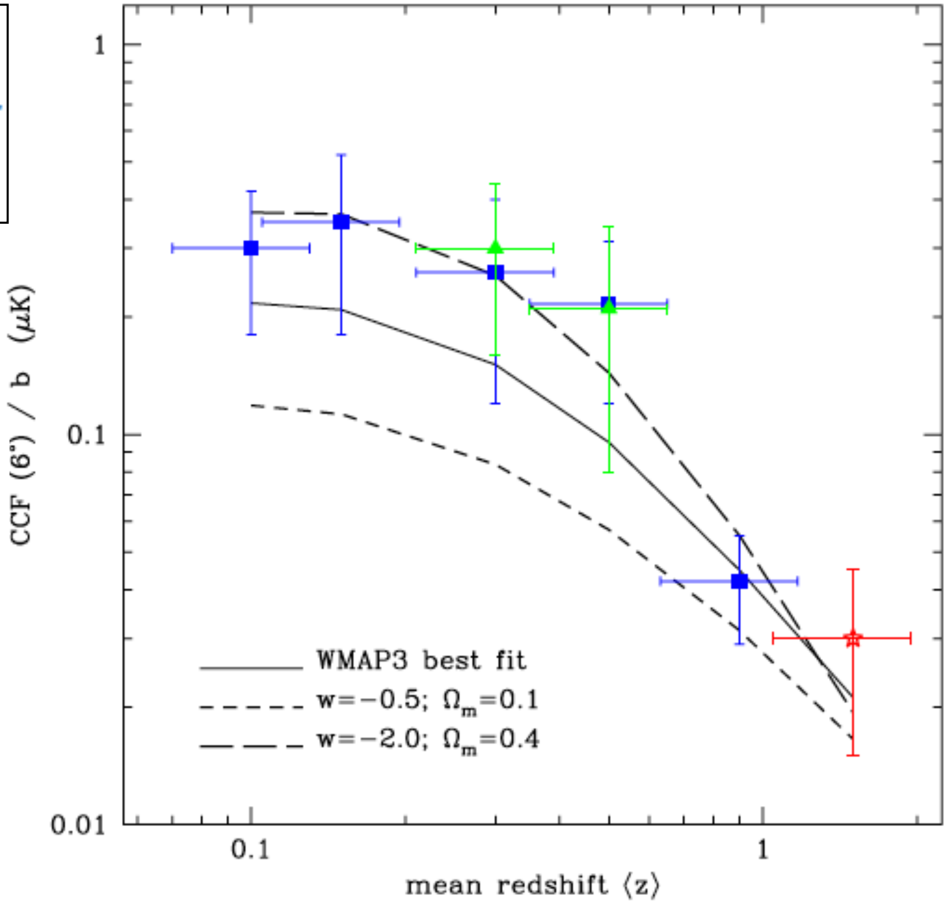
('late integrated Sachs-Wolfe effect')

$$\frac{\Delta T(\hat{n})}{T_0} = \frac{2}{c^3}\int_0^{r_L} \dot{\Phi}(r, z, \hat{n})\, a\, dr$$

gravitational potential traced by galaxy counts



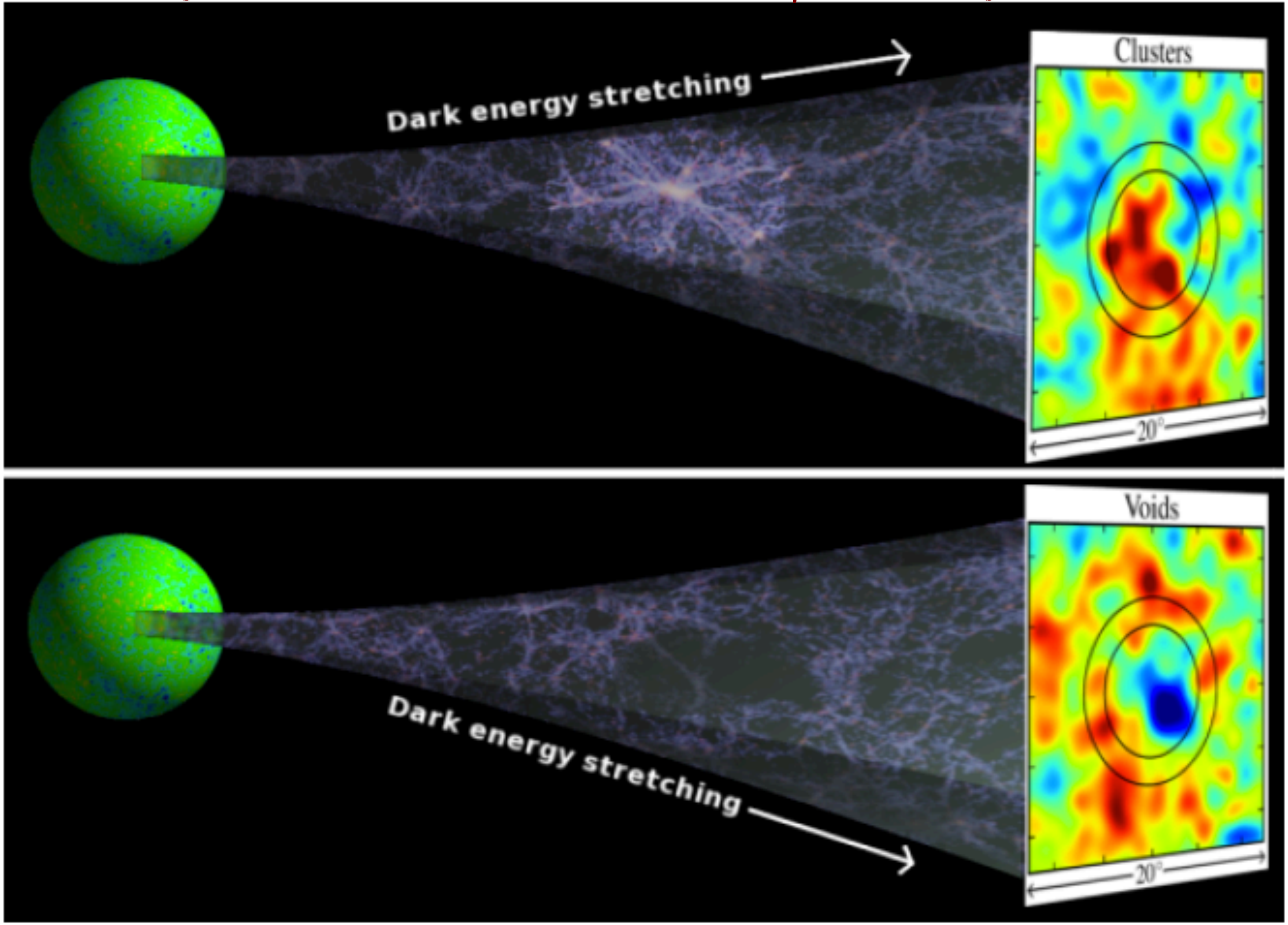
potential depth changes as CMB photons pass through



Gianantonio *et al* (2007)

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

So it was big news when a >4σ detection was reported using SDSS DR6 LRGs



$\Delta T = -11.3 \pm 3.1\ \mu\text{K}$ for voids, $\Delta T = 7.9 \pm 3.0\ \mu\text{K}$ for clusters

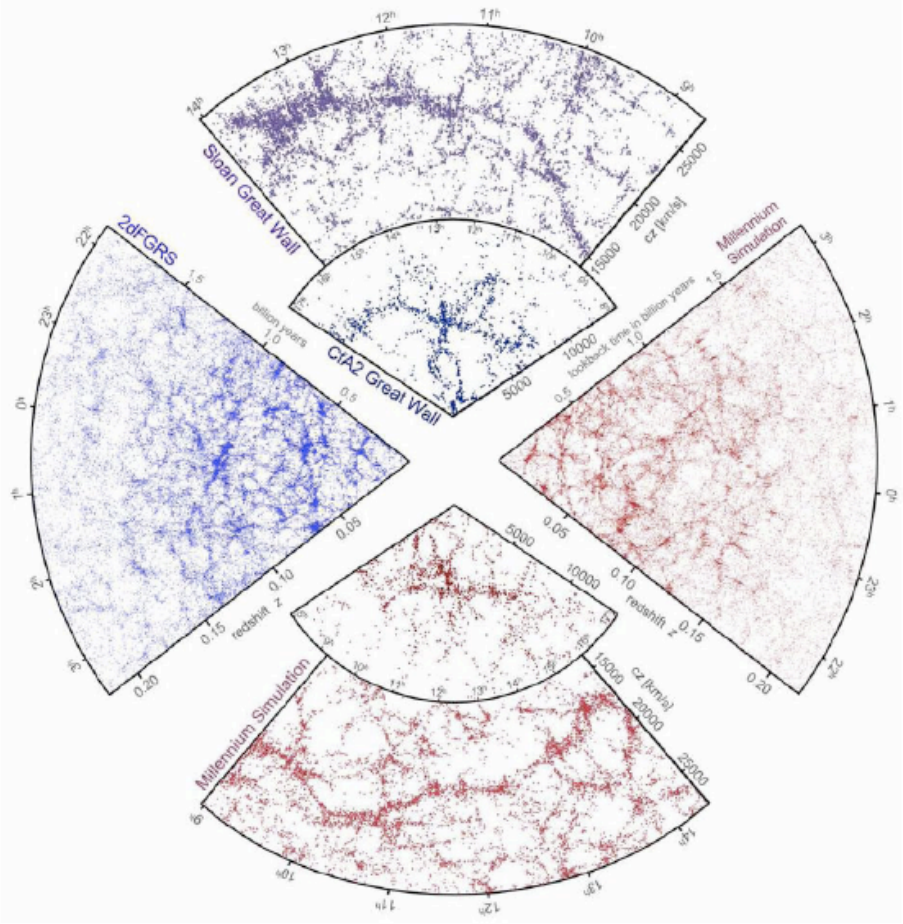
Grannet, Neyrink, Szapudi, arXiv:0805.2974, 0805.3695

However expected signal (using compensated top-hat profile as expected for asymptotic evolution of large void) is only $\Delta T \sim 0.1\,\mu K$ … to yield the observed signal the voids would have to be essentially empty - *very unlikely in Gaussian density field!* (Hunt & Sarkar, MNRAS, 401:547,2010)

More sophisticated treatement (using BBKS formalism for linear perturbations in Gaussian field) increases expectation somewhat but there is still $>3\sigma$ discrepancy with observations (Nadathur *et al*, JCAP06:042,2012)

Although simulations of structure formation in ΛCDM are generally in good agreement with observations, the abundance of rare structures (rich clusters, giant voids) does seem to be a problem … peculiar velocities too are higher than expected.

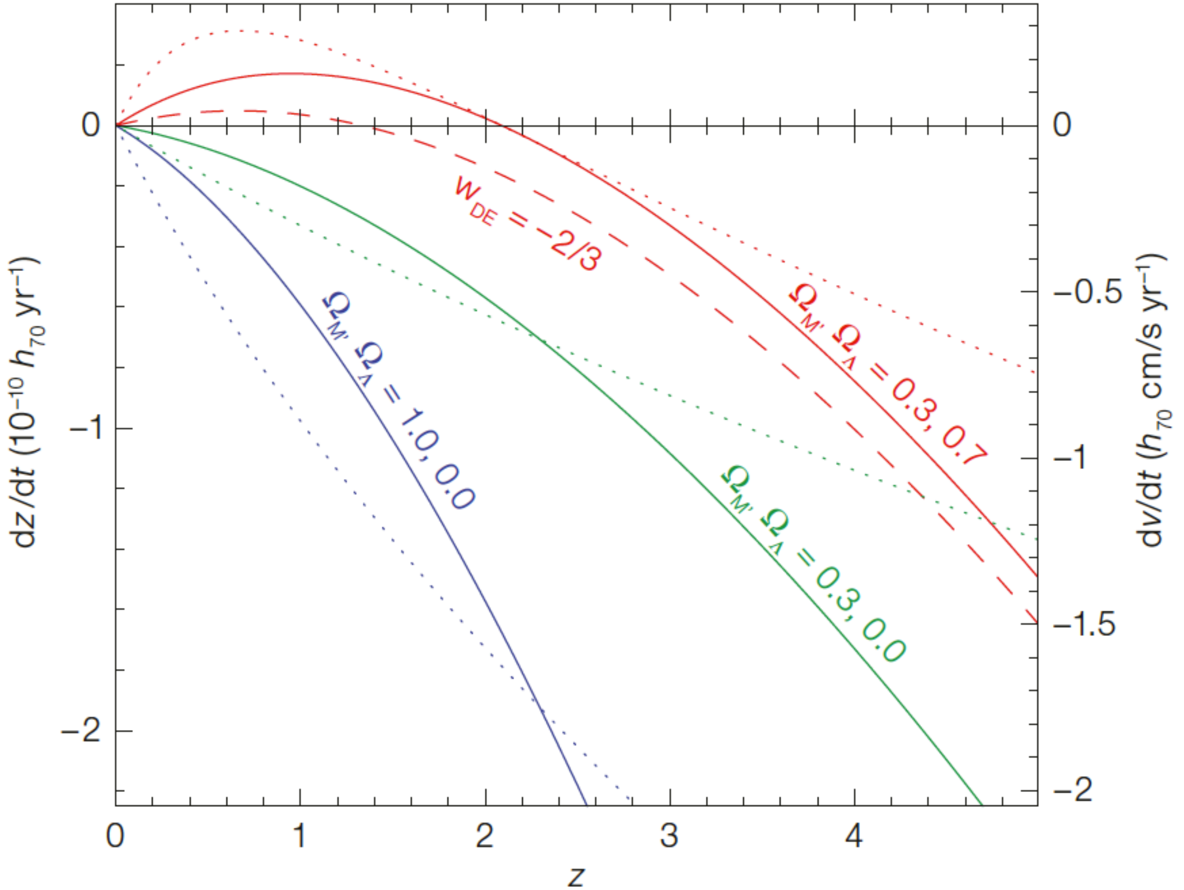
Forthcoming observations by Euclid of e.g. variations in the growth rate of structure with redshift will be crucial.

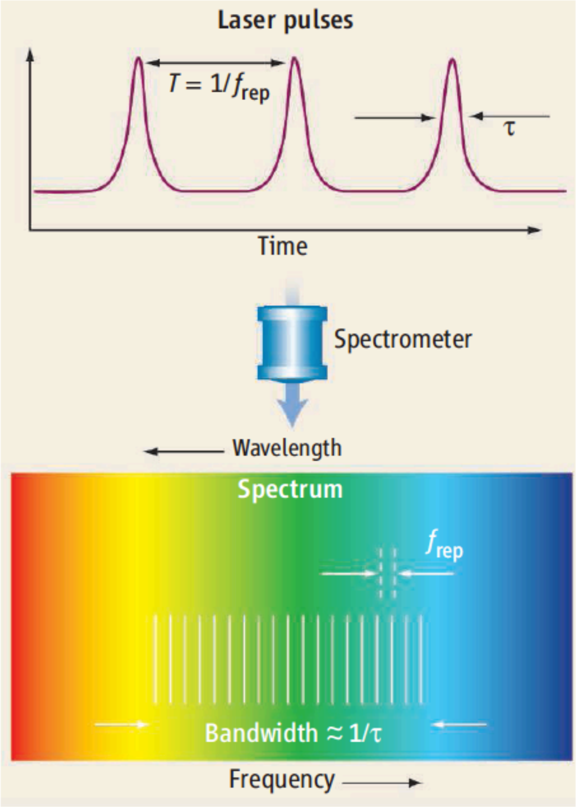


(Springel, Frenk, White 2007)

The evolution of the expansion rate can in principle be measured *directly* by monitoring the 'redshift drift' over time (Sandage, 1962): $\dot{z} = (1+z)H_0 - H(z)$ … however *"With present optical techniques there is apparently no hope of detecting such small changes in redshifts for time intervals smaller than 10^7 years"*

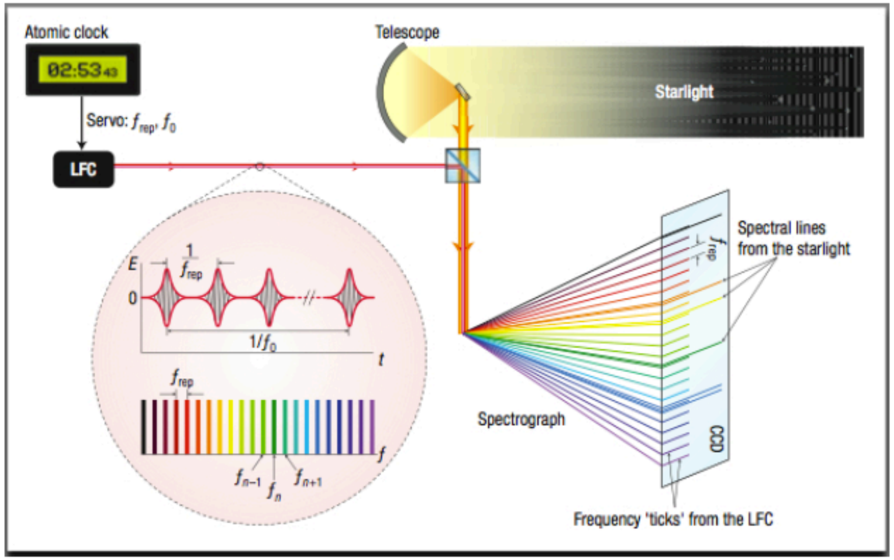
The development of the 'Laser Frequency Comb' for very accurate wavelength measurements has opened up the possibility of doing this in just ~10-20 yrs!

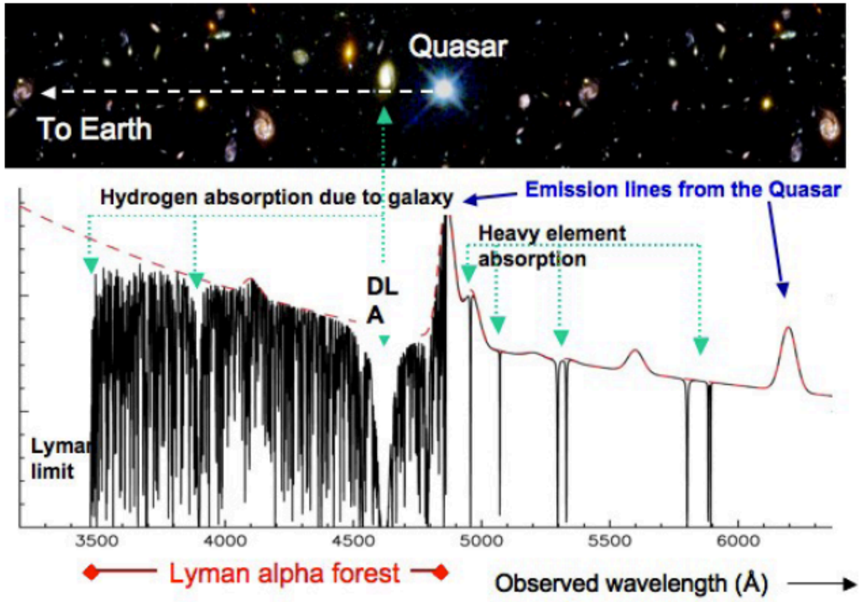


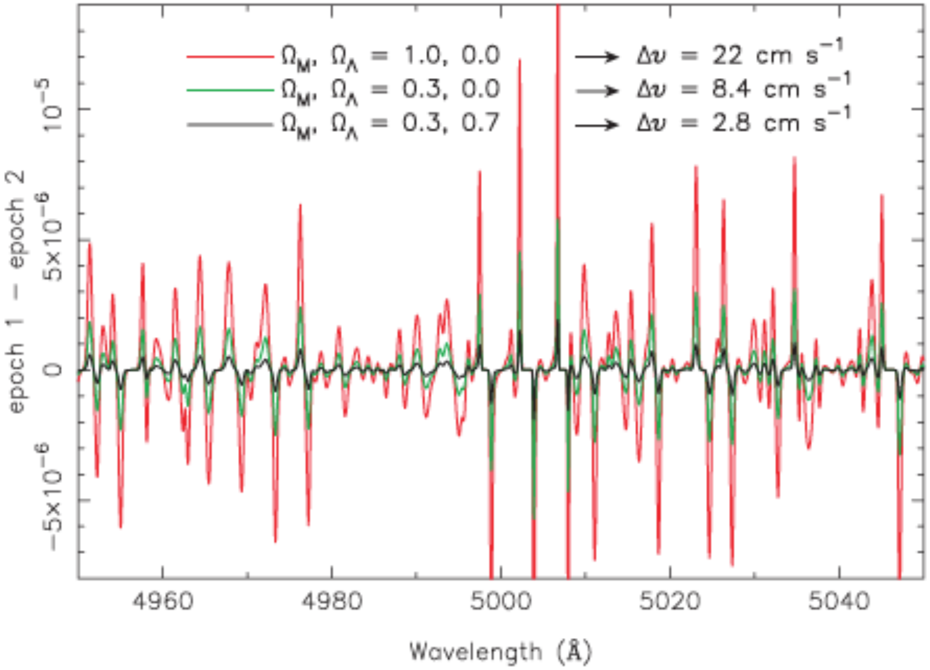


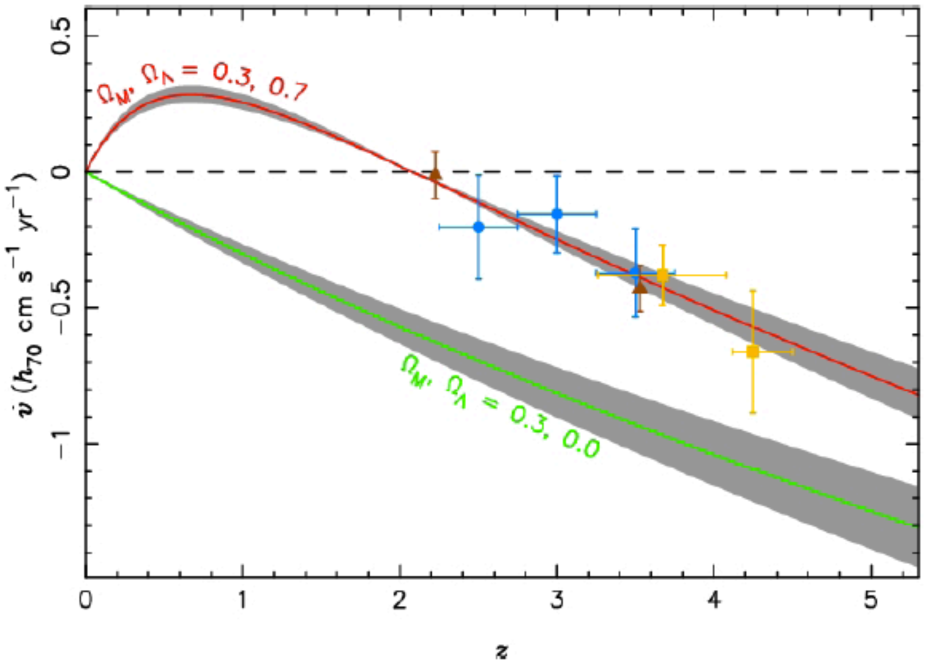
Loeb (1998) suggested that the 'Lyman-alpha forest' of absorpion lines in the spectra of distant quasars provide the best target (peculiar motions are small)

Whether the expansion rate is indeed accelerating will be tested *directly* with the CODEX spectrograph on the European-Extremely Large Telescope









Liske *et al*, MNRAS 386:1192,2008

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

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