

# Is there evidence for cosmic acceleration?

Subir Sarkar



Scientific Reports **6**:35596 (2016), <http://www.nature.com/articles/srep35596>

with: Jeppe Trøst Nielsen & Alberto Guffanti, Niels Bohr Institute Copenhagen

+

Astron. & Astrophys. **412**:35 (2003), **449**:925 (2006)

(with: Alain Blanchard, Marian Douspis & Michael Rowan-Robinson)

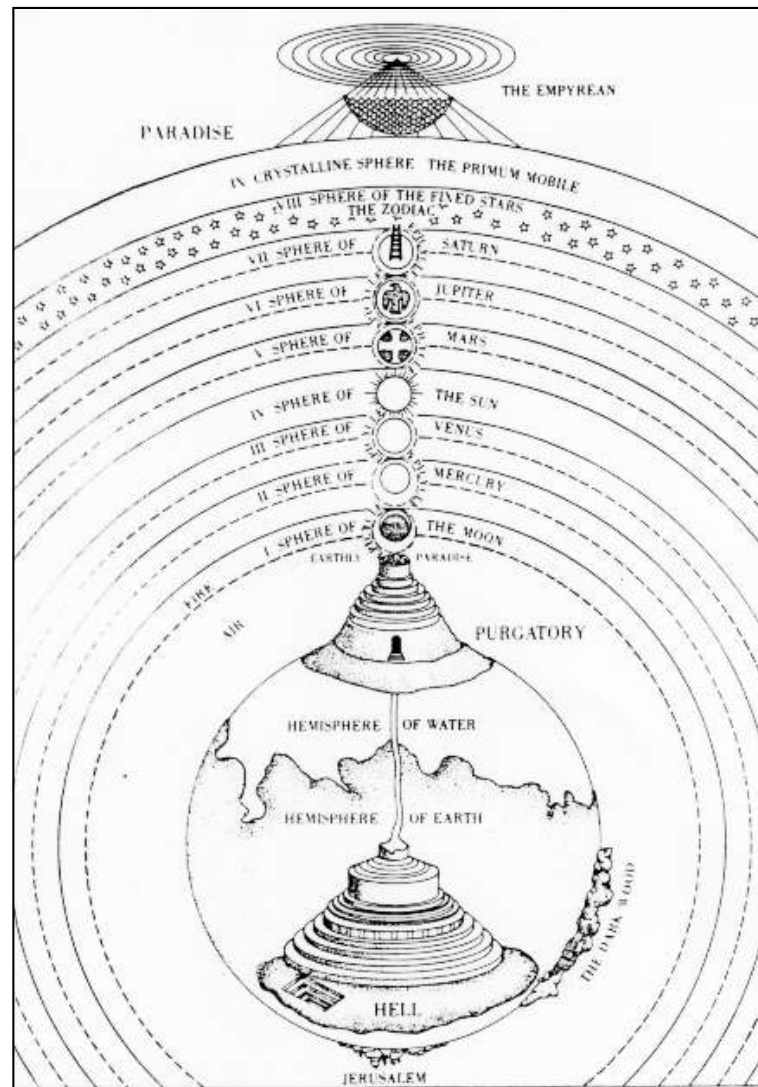
PRD **76**:123504 (2007); MNRAS **401**:547 (2010); JCAP **01**:025 (2014), **12**:052 (2015)

(with: Paul Hunt)

Review: Gen. Rel. & Grav. **40**:269 (2008)

*Joint Stony Brook / Brookhaven Cosmology Seminar, 30 March 2017*

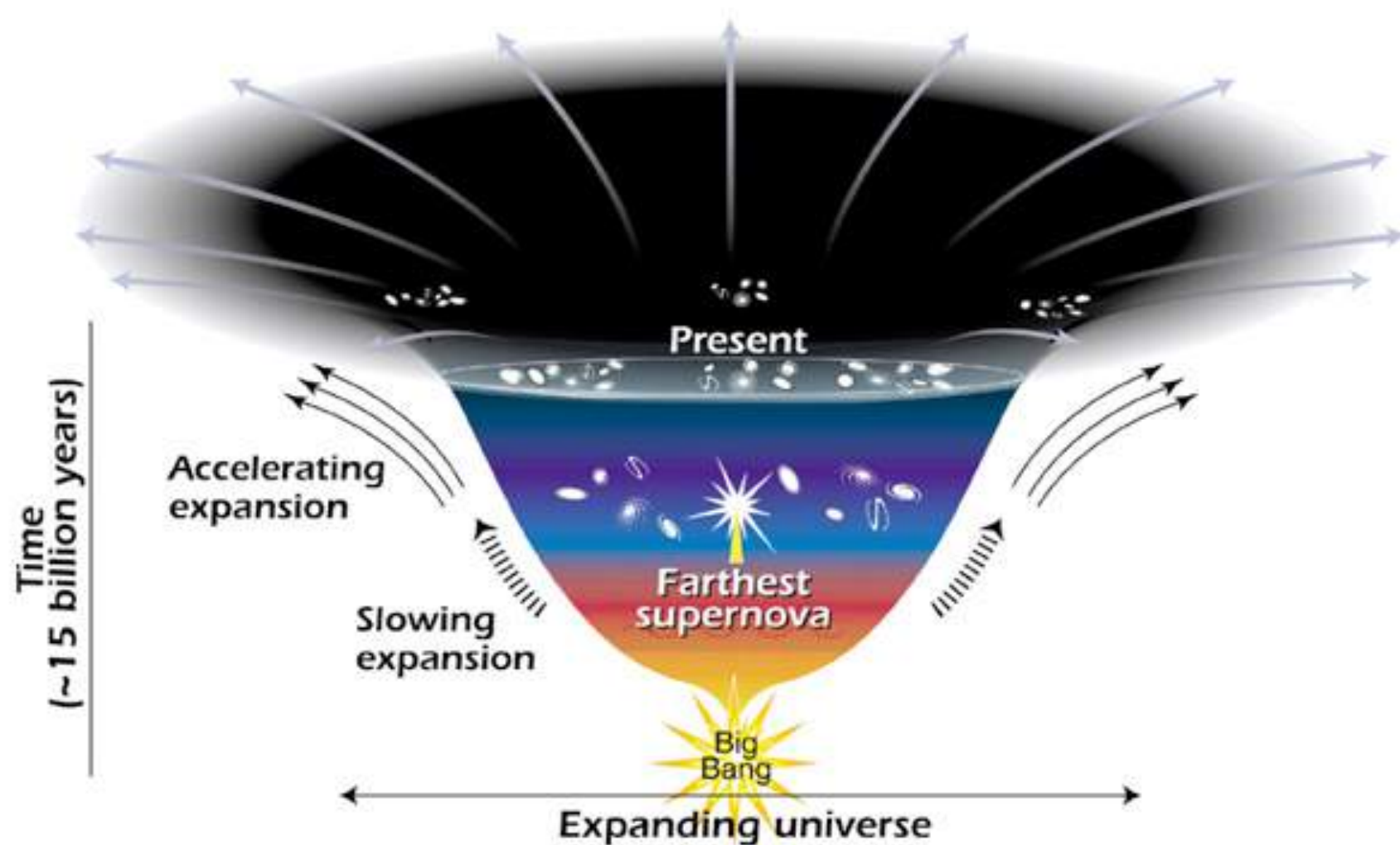
In the Ptolemaic/Aristotelean standard cosmology (350 BC → 1600 AD) the universe was *static* and *finite* and centred on the Earth



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



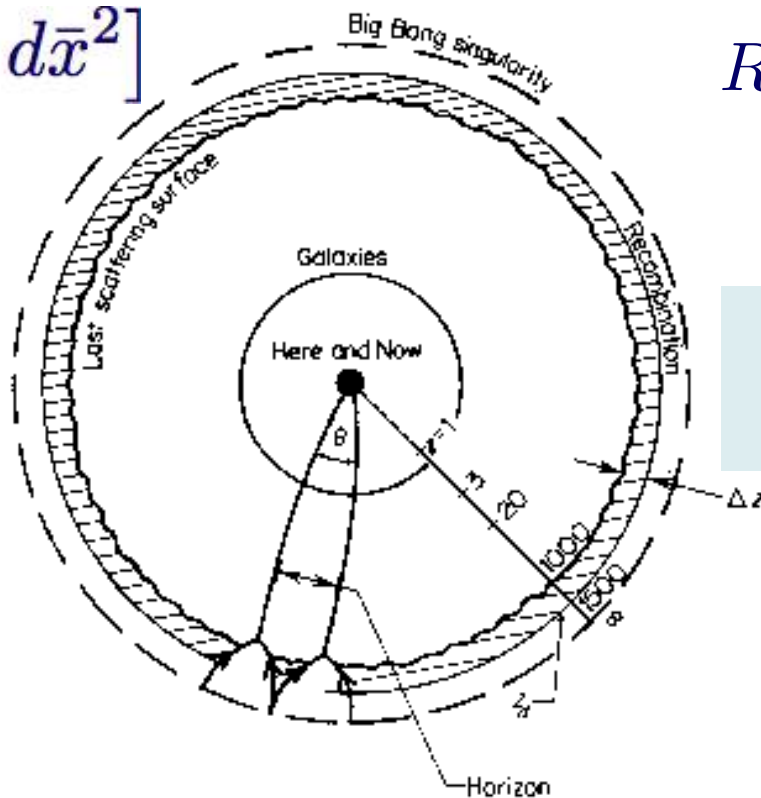
It too is '*simple*' and fits *all* the observational data  
but lacks a *physical* foundation

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

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

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

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

$$T_{\mu\nu} = -\langle \rho \rangle_{\text{fields}} g_{\mu\nu}$$

$$\Lambda = \lambda + 8\pi G_N \langle \rho \rangle_{\text{fields}}$$

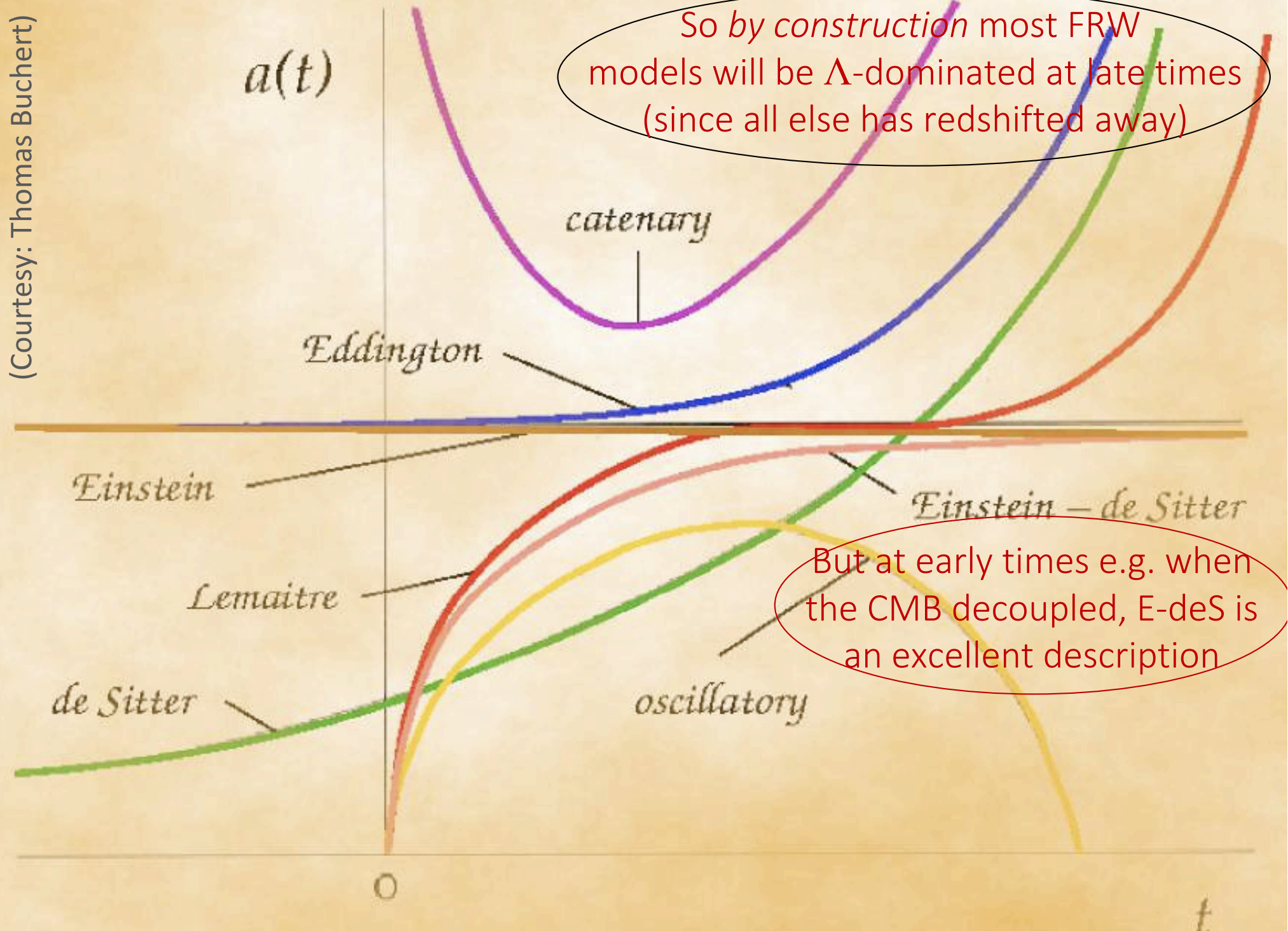
$$\Rightarrow H^2 = \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G_N \rho_m}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

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

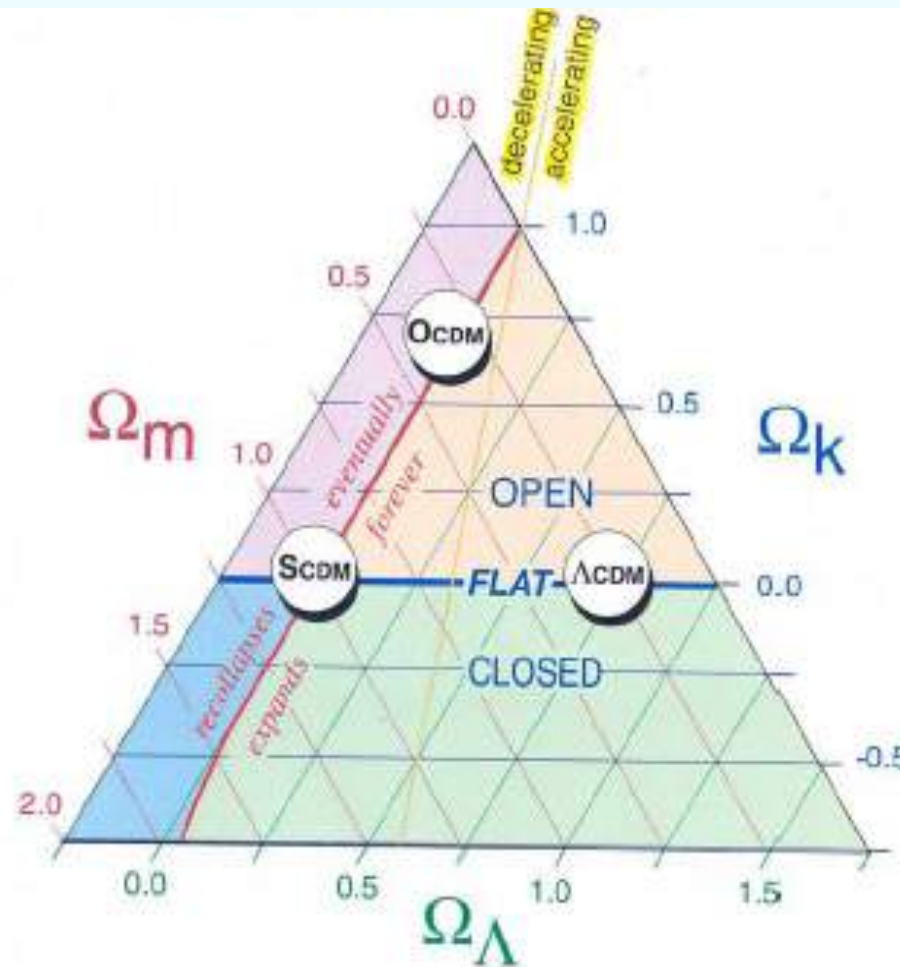
where :  $z \equiv \frac{a_0}{a} - 1$ ,  $\Omega_m \equiv \frac{\rho_m}{3H_0^2/8\pi G_N}$ ,  $\Omega_k \equiv \frac{k}{a_0^2 H_0^2}$ ,  $\Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2}$

This implies the 'sum rule':  $1 \equiv \Omega_m + \Omega_k + \Omega_\Lambda$





It is natural for data interpreted in this idealised model to suggest that  $\Omega_\Lambda (\equiv 1 - \Omega_m - \Omega_k)$  is non-zero, i.e.  $\Lambda$  is of  $O(H_0^2)$ , given the inevitable uncertainties in measuring  $\Omega_m$  and  $\Omega_k$  and the possibility of other components ( $\Omega_x$ ) which are *unaccounted* for in the Hubble equation



Bahcall, Ostriker, Perlmutter & Steinhardt (1999)

This has however been *interpreted* as evidence for vacuum energy

$$\Rightarrow \rho_\Lambda = 8\pi G\Lambda \sim H_0^2 M_p^2 \sim (10^{-12} \text{ GeV})^4$$

The Standard  $SU(3)_c \times SU(2)_L \times U(1)_Y$  Model (viewed as an effective field theory up to some high energy cut-off scale  $M$ ) describes *all* of microphysics

$$\begin{aligned}
 & + \underbrace{M^4}_{\text{super-renormalisable}} + \underbrace{M^2 \Phi^2}_{\text{super-renormalisable}} \quad m_H^2 \simeq \frac{h_t^2}{16\pi^2} \int_0^{M^2} dk^2 = \frac{h_t^2}{16\pi^2} M^2 \\
 & - \mu^2 \phi^\dagger \phi + \frac{\lambda}{4} (\phi^\dagger \phi)^2, m_H^2 = \lambda v^2 / 2 \\
 \mathcal{L}_{\text{eff}} = & F^2 + \bar{\Psi} \not{D} \Psi + \bar{\Psi} \Psi \Phi + (D\Phi)^2 + \underbrace{V(\Phi)}_{\text{renormalisable}} \\
 & + \underbrace{\frac{\bar{\Psi} \Psi \Phi \Phi}{M}}_{\text{neutrino mass}} + \underbrace{\frac{\bar{\Psi} \Psi \bar{\Psi} \Psi}{M^2}}_{\text{proton decay, FCNC ...}} + \dots \quad \text{non-renormalisable}
 \end{aligned}$$

New physics beyond the SM  $\Rightarrow$  non-renormalisable operators suppressed by  $M^n$  which decouple as  $M \rightarrow M_p \dots$  so neutrino mass is small, proton decay is slow *et cetera*

But as  $M$  is raised, the effects of the super-renormalisable operators are *exacerbated*  
 (One solution for Higgs mass divergence  $\rightarrow$  ‘softly broken’ *supersymmetry* at  $O(\text{TeV})$   
 $\dots$  or the Higgs could be *composite* – a pseudo Nambu-Goldstone boson)

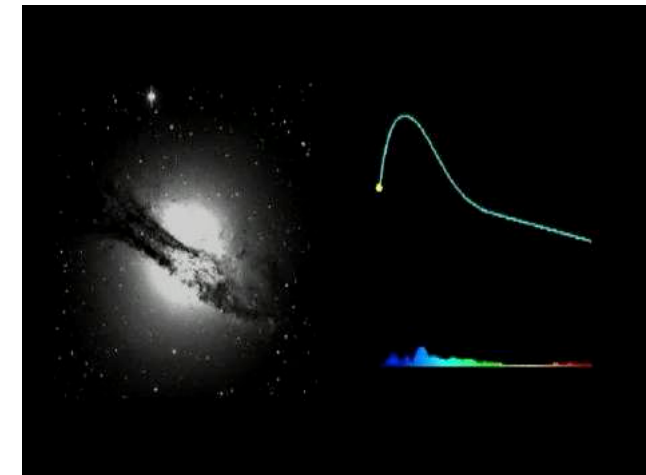
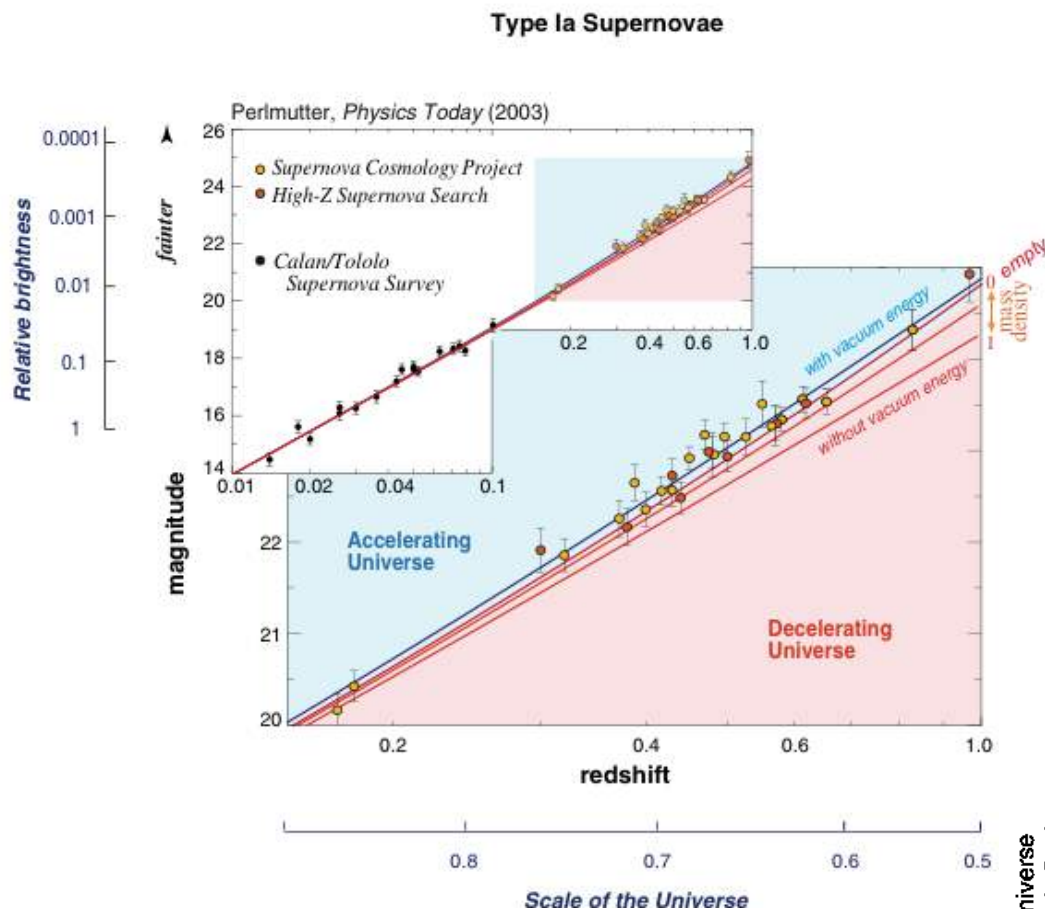
1<sup>st</sup> SR term **couples to gravity** so the *natural* expectation is  $\rho_\Lambda \sim (1 \text{ TeV})^4 \gg (1 \text{ meV})^4$   
 $\dots$  *i.e.* the universe should have been inflating since (or collapsed at):  $t \sim 10^{-12} \text{ s}$ !

**There must be some reason why this did *not* happen!**

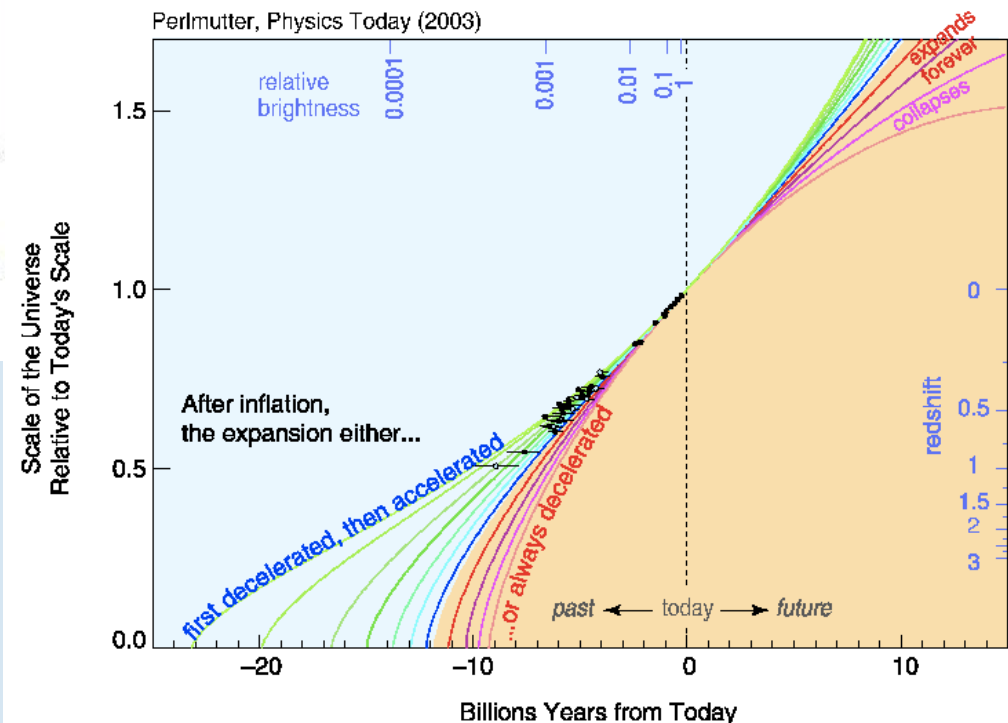
*“Also, as is obvious from experience, the [zero-point energy] does not produce any gravitational field”* - Wolfgang Pauli

Die allgemeinen Prinzipien der Wellenmechanik, Handbuch der Physik, Vol. XXIV, 1933

Distant SNIa appear fainter than expected for “standard candles” in a decelerating universe  $\Rightarrow$  accelerated expansion below  $z \sim 0.5$ :



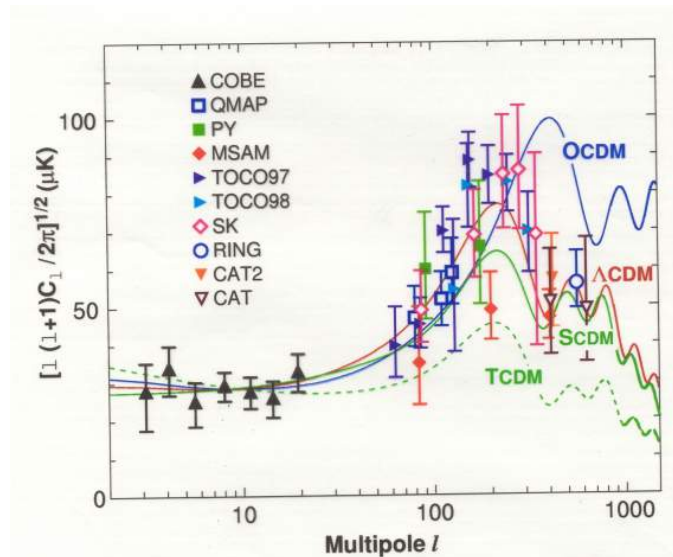
### Expansion History of the Universe



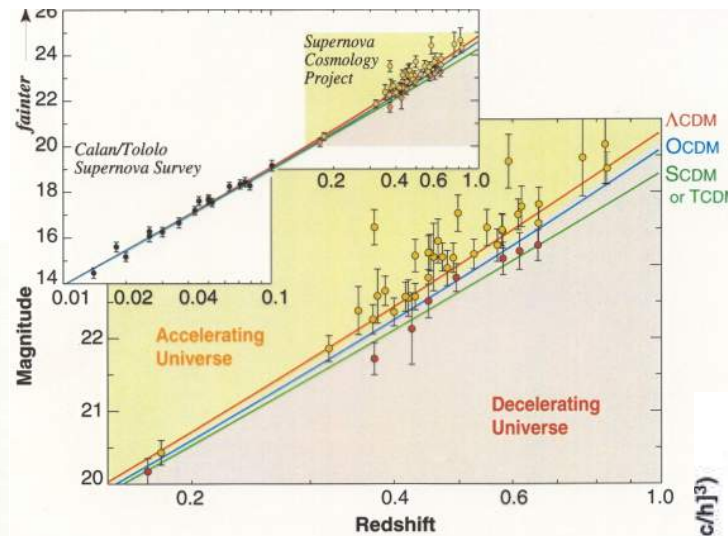
The observations are made at *one* instant (the redshift is taken as a proxy for time) so this is not quite a *direct* measurement of acceleration ... nevertheless it is presently the most direct evidence



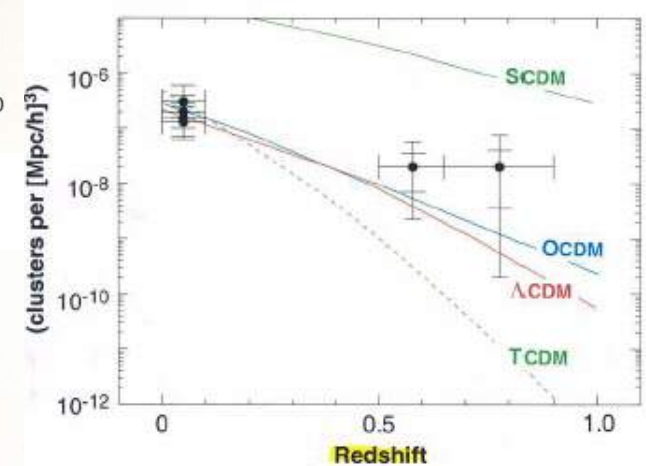
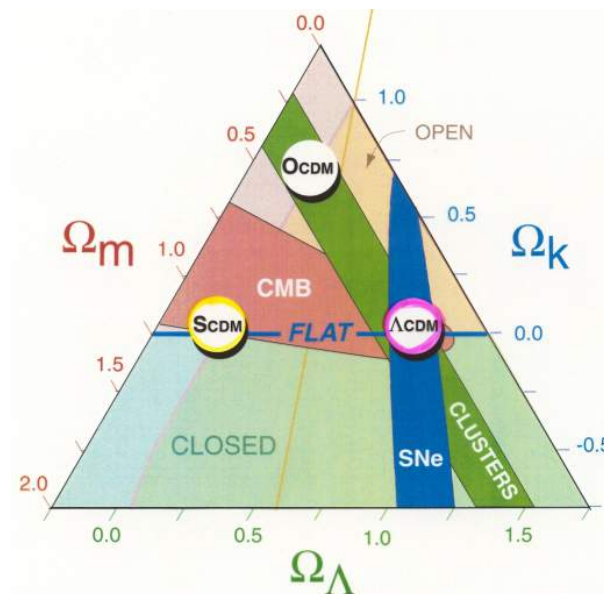
Assuming the sum rule, complementary observations implied:  $\Omega_\Lambda \sim 0.7$ ,  $\Omega_m \sim 0.3$



$$\Omega_k \approx 0.0 \pm 0.03$$



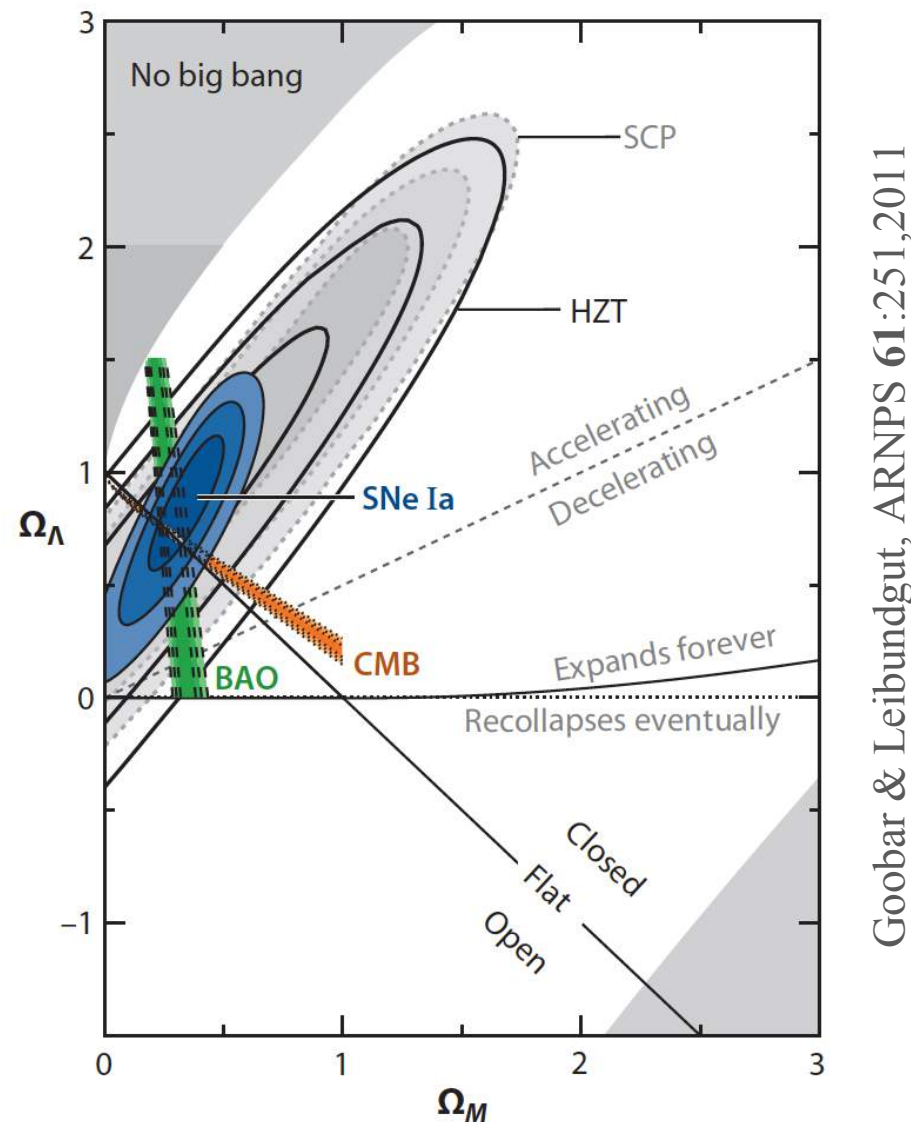
$$0.8\Omega_m - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$$



$$\Omega_m \sim 0.3$$

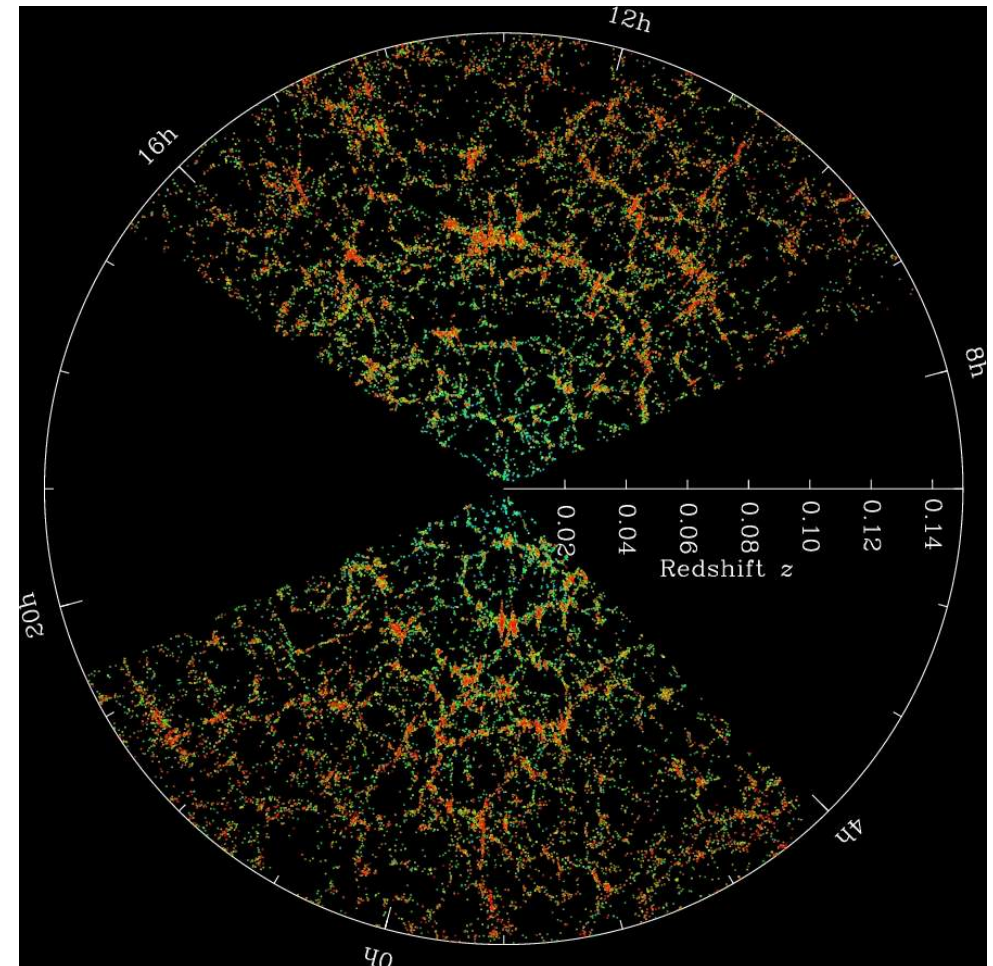
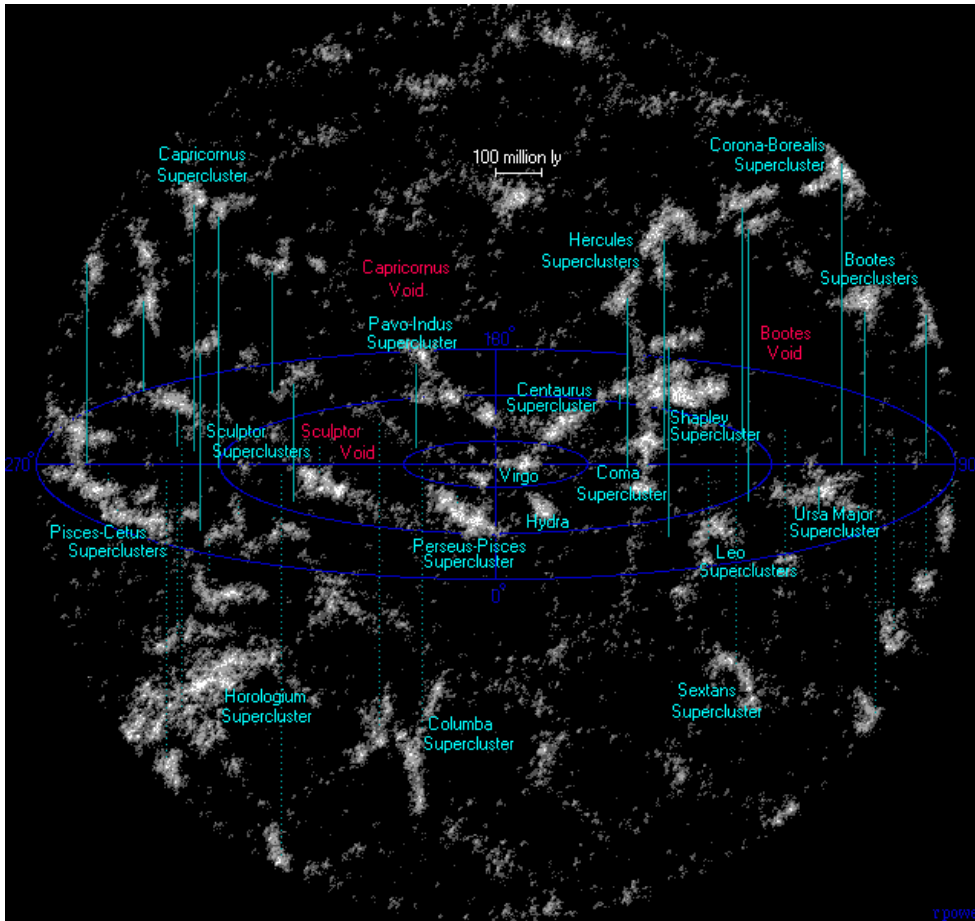
Estimates of  $\Omega_m$  are the most uncertain ... there is no direct measurement of  $\Omega_\Lambda$  alone

CMB data indicate  $\Omega_k \approx 0$  so the FRW model is simplified further, leaving only two free parameters ( $\Omega_\Lambda$  and  $\Omega_m$ ) to be fitted to data



But e.g. if we underestimate  $\Omega_m$ , or if there is a  $\Omega_x$  (e.g. “back reaction”) which the FRW model does *not* include, then we will *necessarily* infer  $\Omega_\Lambda \neq 0$

This is what our universe  
*actually* looks like ...  
locally and on large-scales



Is it justified to approximate it as  
exactly homogeneous?

To assume that we are a 'typical'  
observer?

To assume that all directions are  
equivalent?

Could dark energy be an artifact of approximating the universe as homogeneous?

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

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

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

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

Variance of the expansion rate.

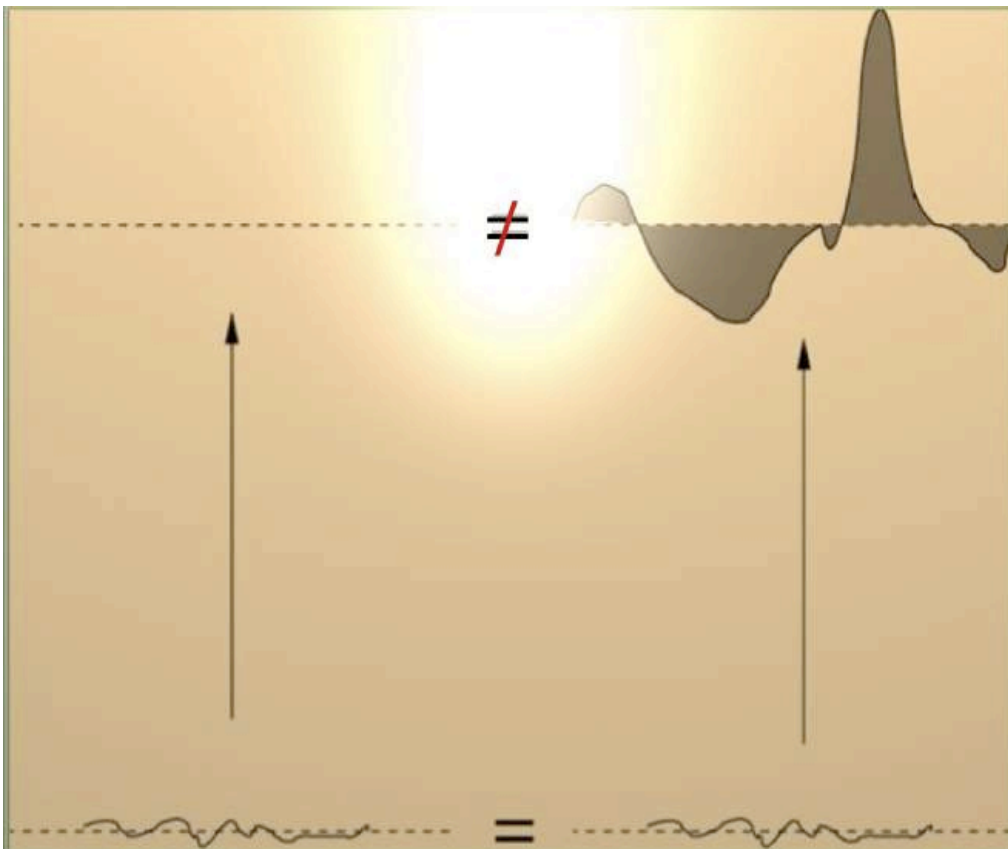
Average shear.

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

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

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

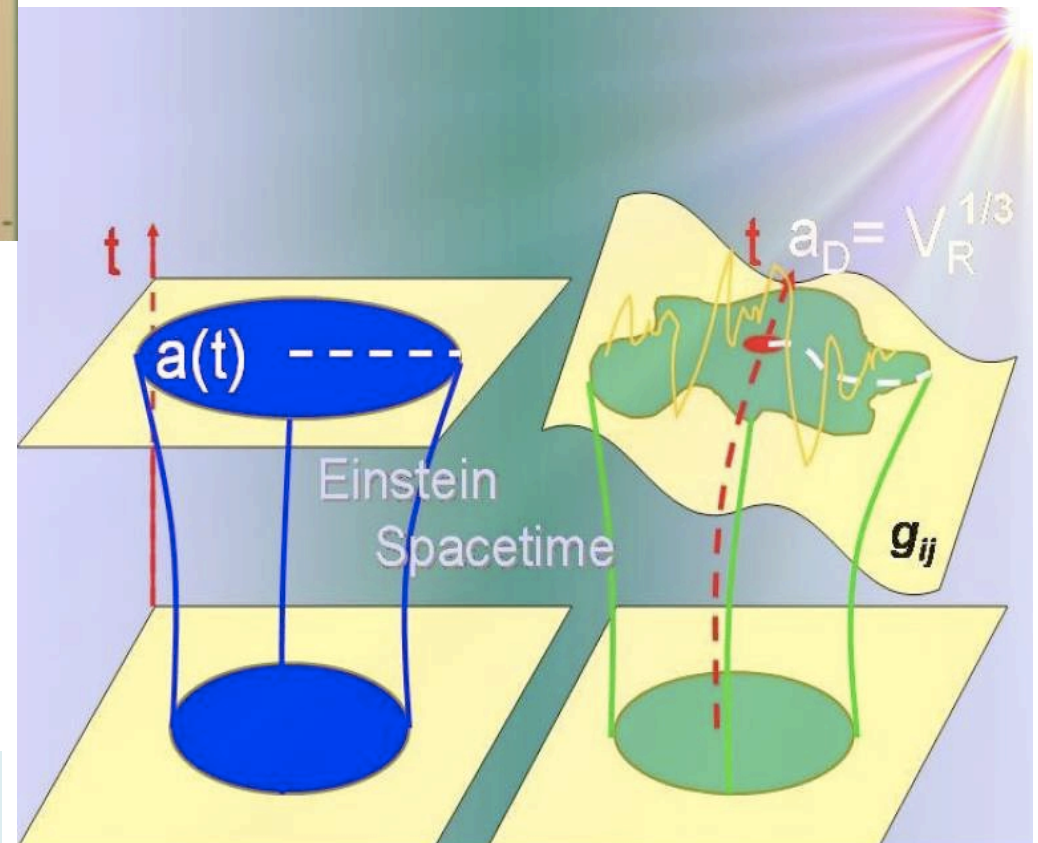




'Back reaction' is hard to compute because spatial averaging and time evolution (along our past light cone) do *not* commute

Due to structure formation, the homogeneous solution of Einstein's equations is distorted - its average must be taken over the *actual* geometry

*Relativistic* numerical simulations of structure formation have just begun to be performed



Courtesy: Thomas Buchert

Interpreting  $\Lambda$  as vacuum energy raises the coincidence problem:

why is  $\Omega_\Lambda \approx \Omega_m$  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*

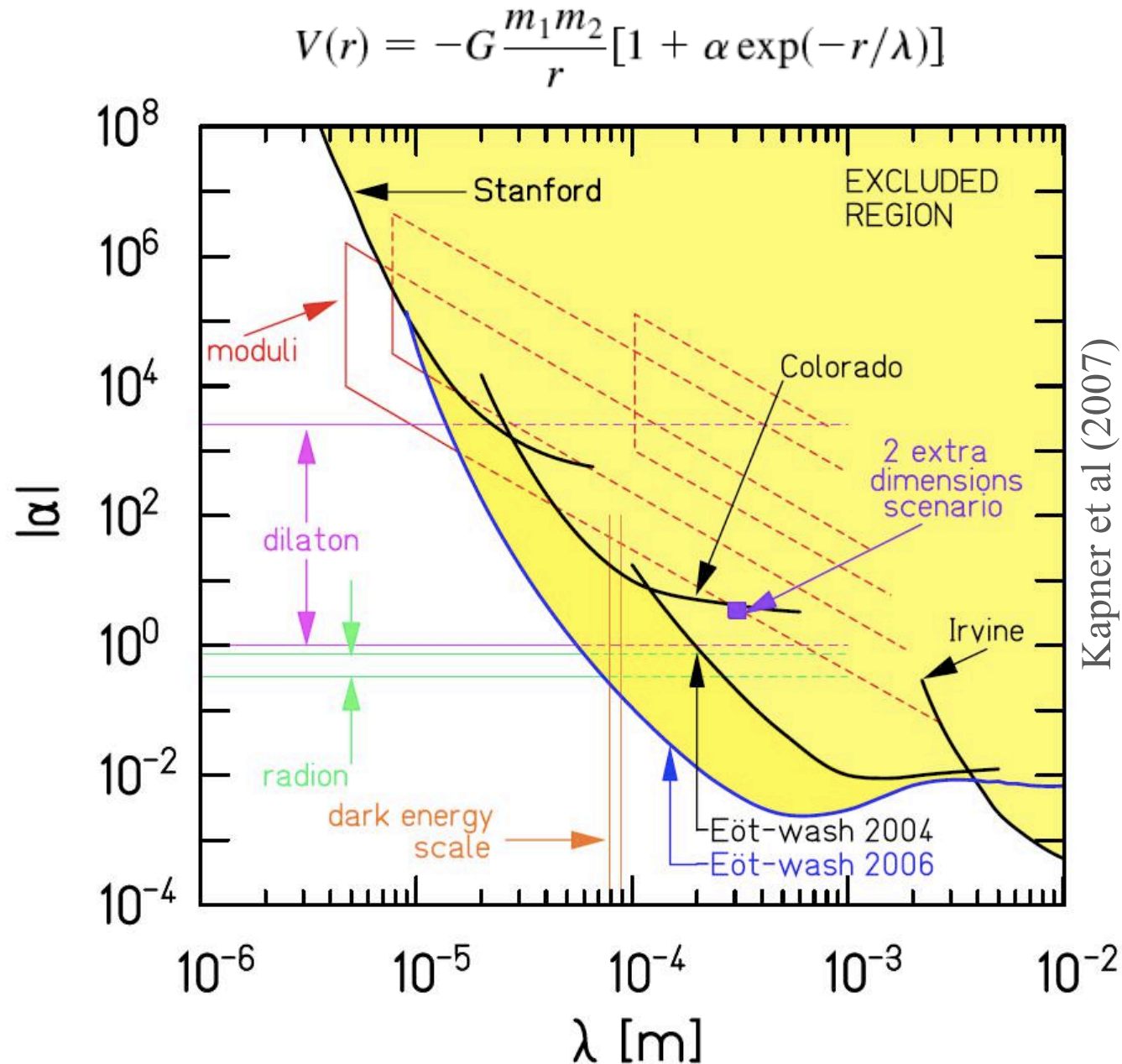
A similar comment applies to models (e.g. 'DGP brane-world') wherein gravity is modified on the scale of the present Hubble radius so as to mimic vacuum energy ...  
*this scale is absent in a fundamental theory and is simply put in by hand*  
**(similar fine-tuning in every alternative – massive gravity, chameleon fields ...)**

The only natural option is if  $\Lambda \sim H^2$  *always*, but this is just a renormalisation of  $G_N$  (recall:  $H^2 = 8\pi G_N/3 + \Lambda/3$ )  $\rightarrow$  ruled out by Big Bang nucleosynthesis (requires  $G_N$  to be within 5% of lab value) ... in any case this will not yield accelerated expansion

**Thus there can be no physical explanation for the coincidence problem**

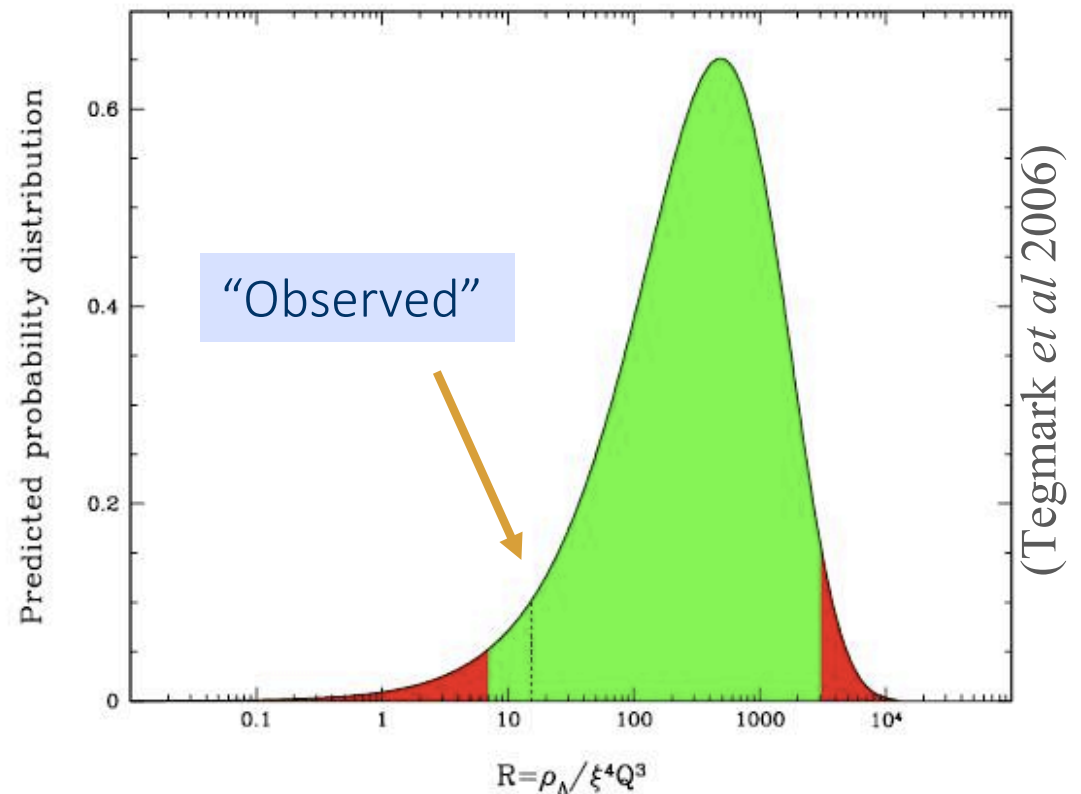
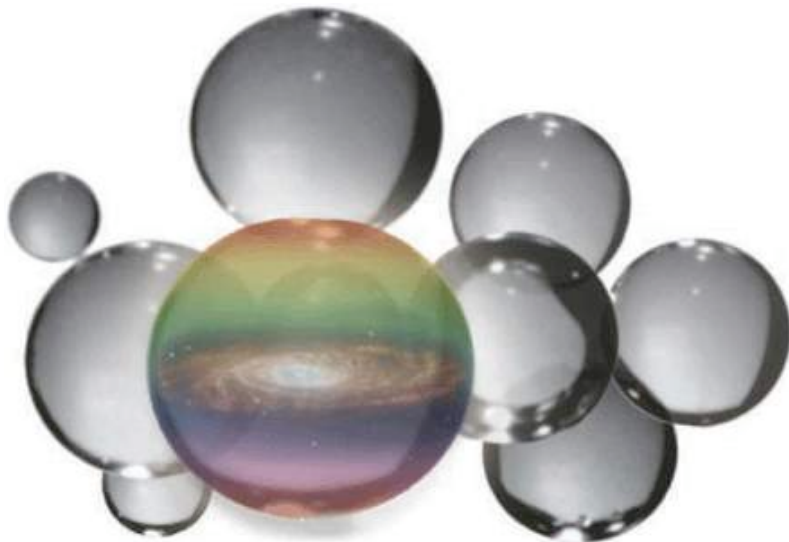
Do we infer  $\Lambda \sim H_0^2$  because that is just the observational sensitivity?  
... just how strong is the evidence for accelerated expansion?

Note that there is *no* evidence for any change in the inverse-square law of gravitation at the 'dark energy' scale:  $\rho_\Lambda^{-1/4} \sim (H_0 M_P)^{-1/2} \sim 0.1 \text{ mm}$



The existence of the huge landscape of possible vacua 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  $\Lambda$  had been much higher (Weinberg 1989, Efstathiou 1995, Martel, Shapiro, Weinberg 1998 ...)



But the ‘anthropic prediction’ of  $\Lambda$  from considerations of galaxy formation is significantly *higher* than the observationally inferred value





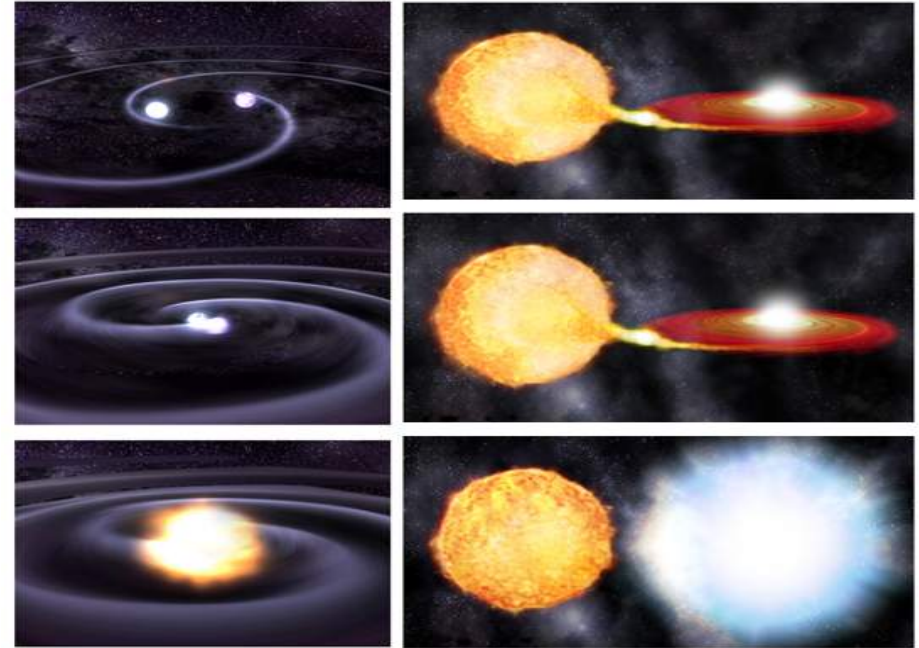
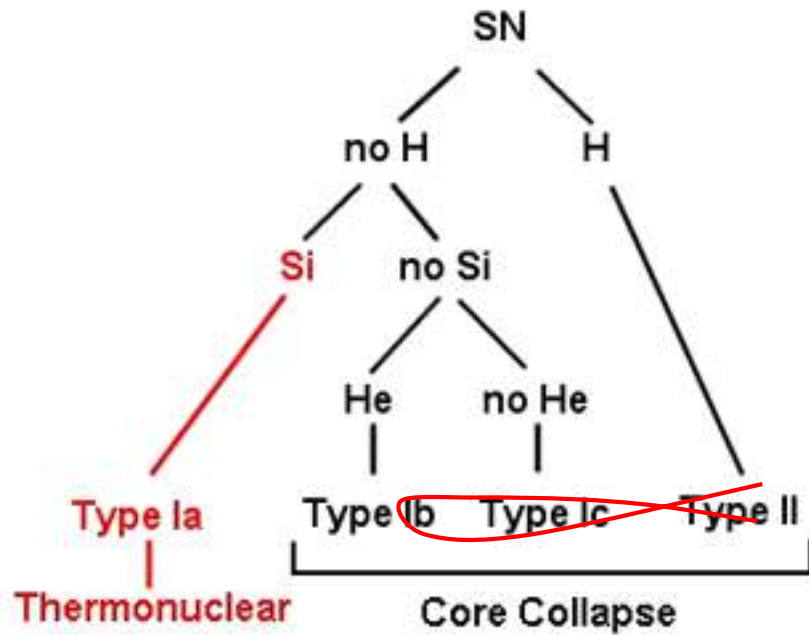
*Shaw Prize 2006 "for discovering that the expansion rate of the universe is accelerating"*

*2007 Gruber Cosmology Prize to two teams who discovered the accelerating universe*

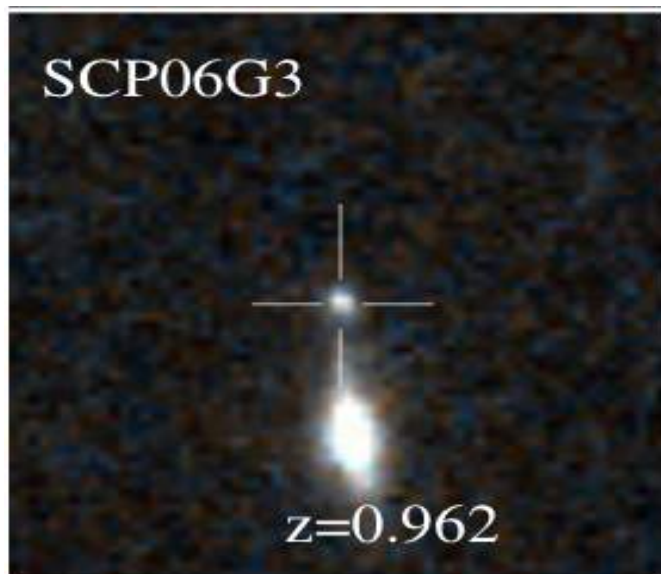
*Discovery of accelerating universe Wins 2011 Nobel Prize in Physics*

*The 2015 Breakthrough Prize in Fundamental Physics for the most unexpected discovery that the expansion of the universe is accelerating ...*

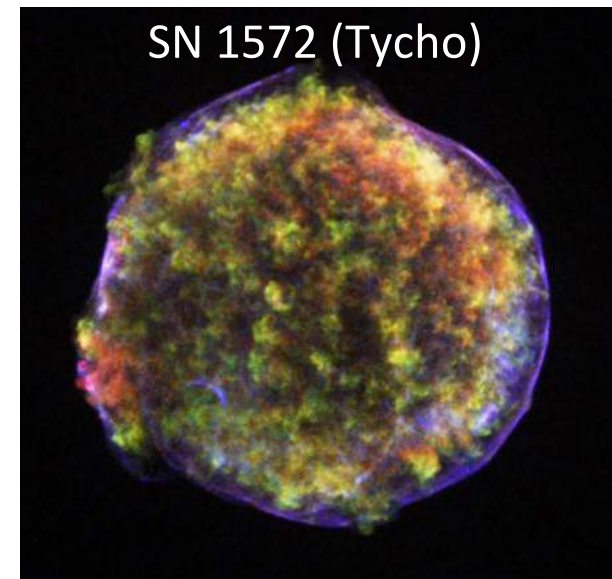
# What are Type Ia supernovae?



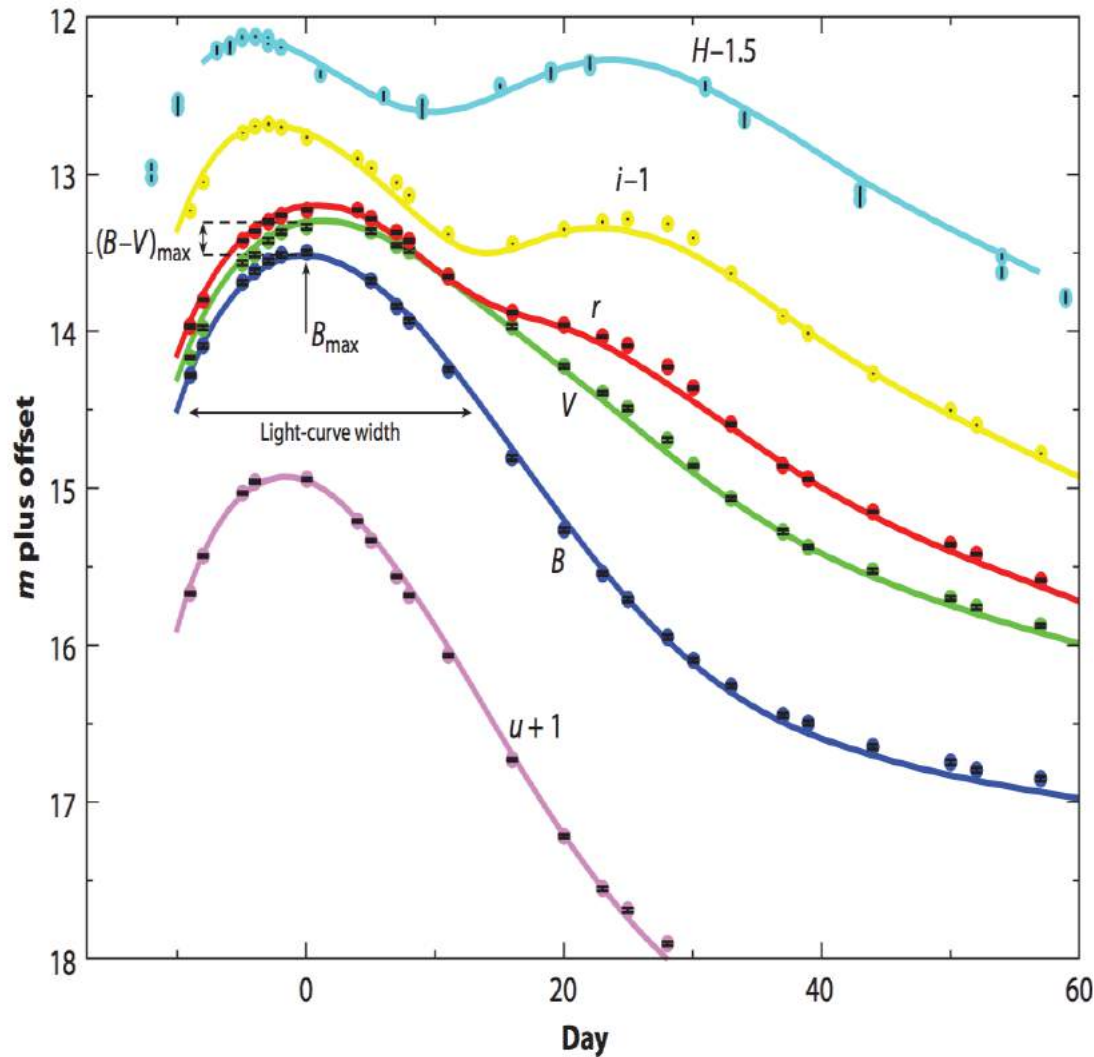
Suzuki et al, 1105.3470



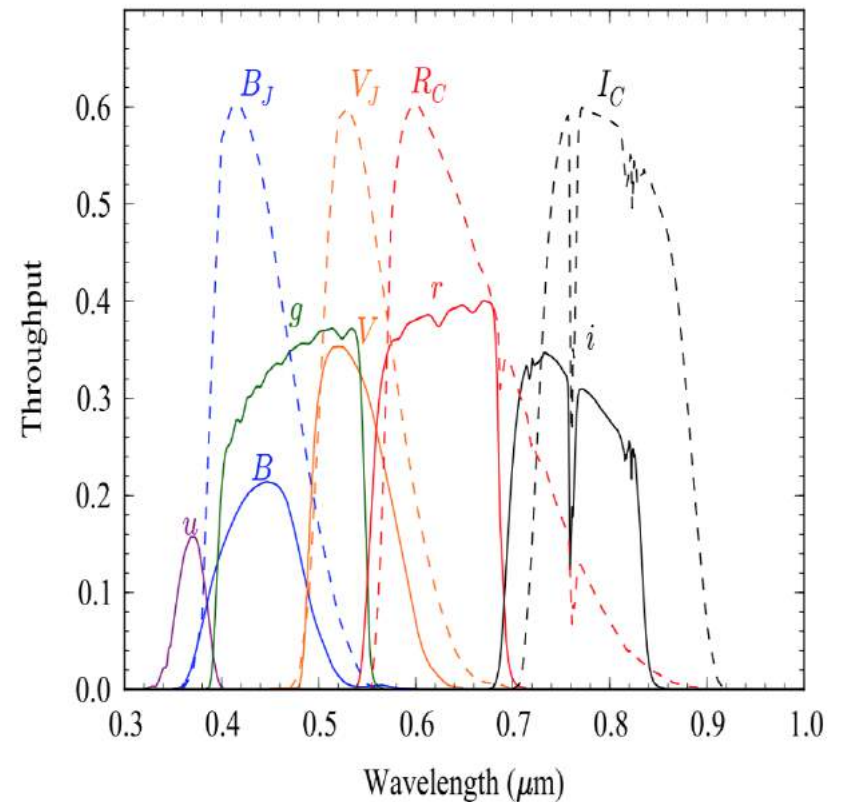
~500 years



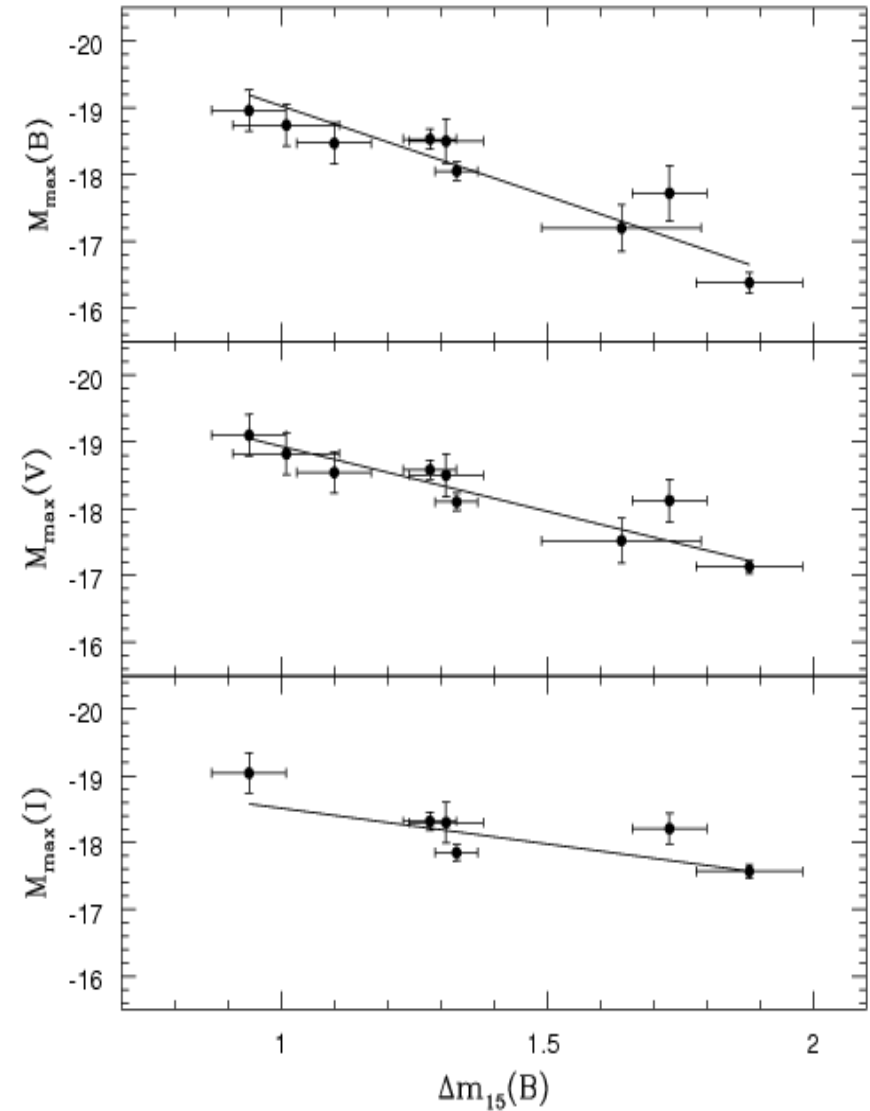
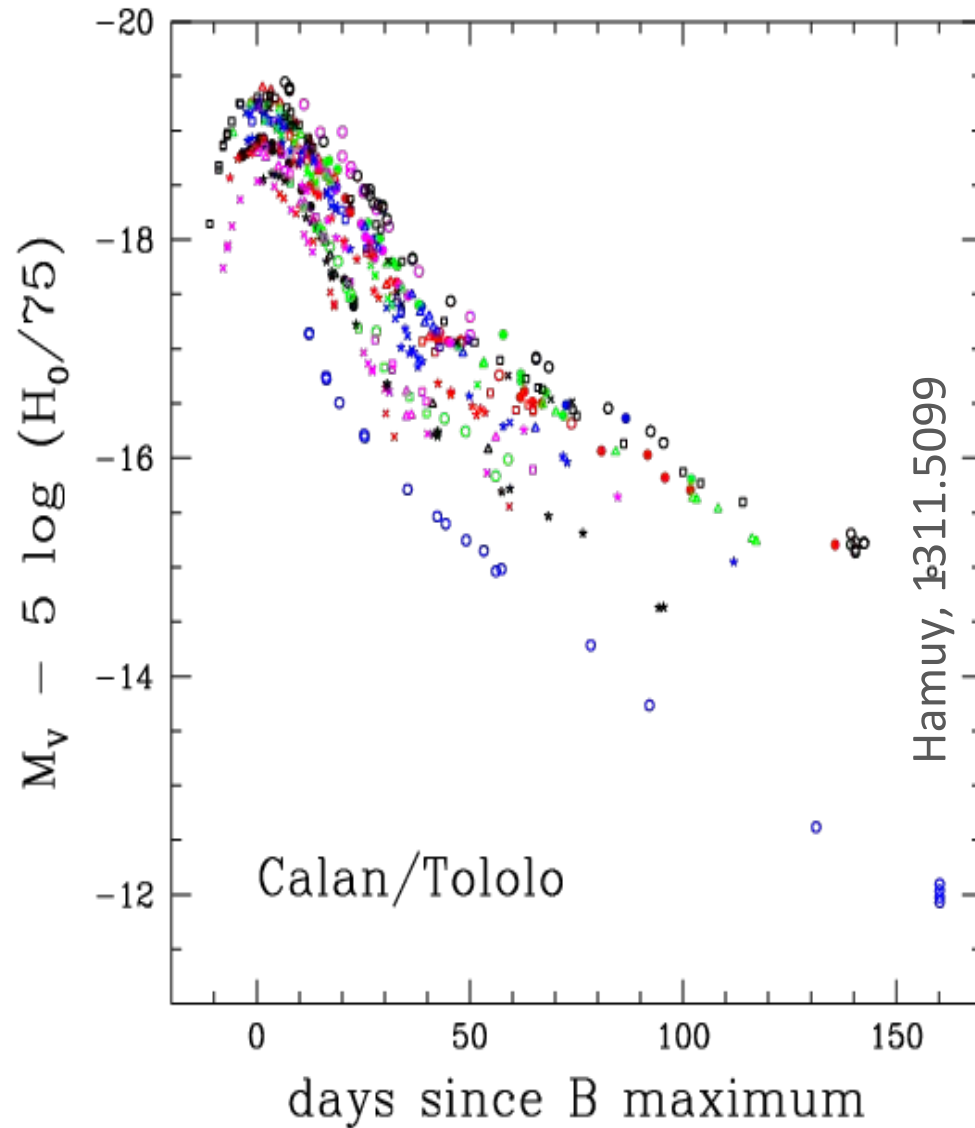
# What are Type Ia supernovae?



$$m = -2.5 \log(F/F_{\text{ref}})$$



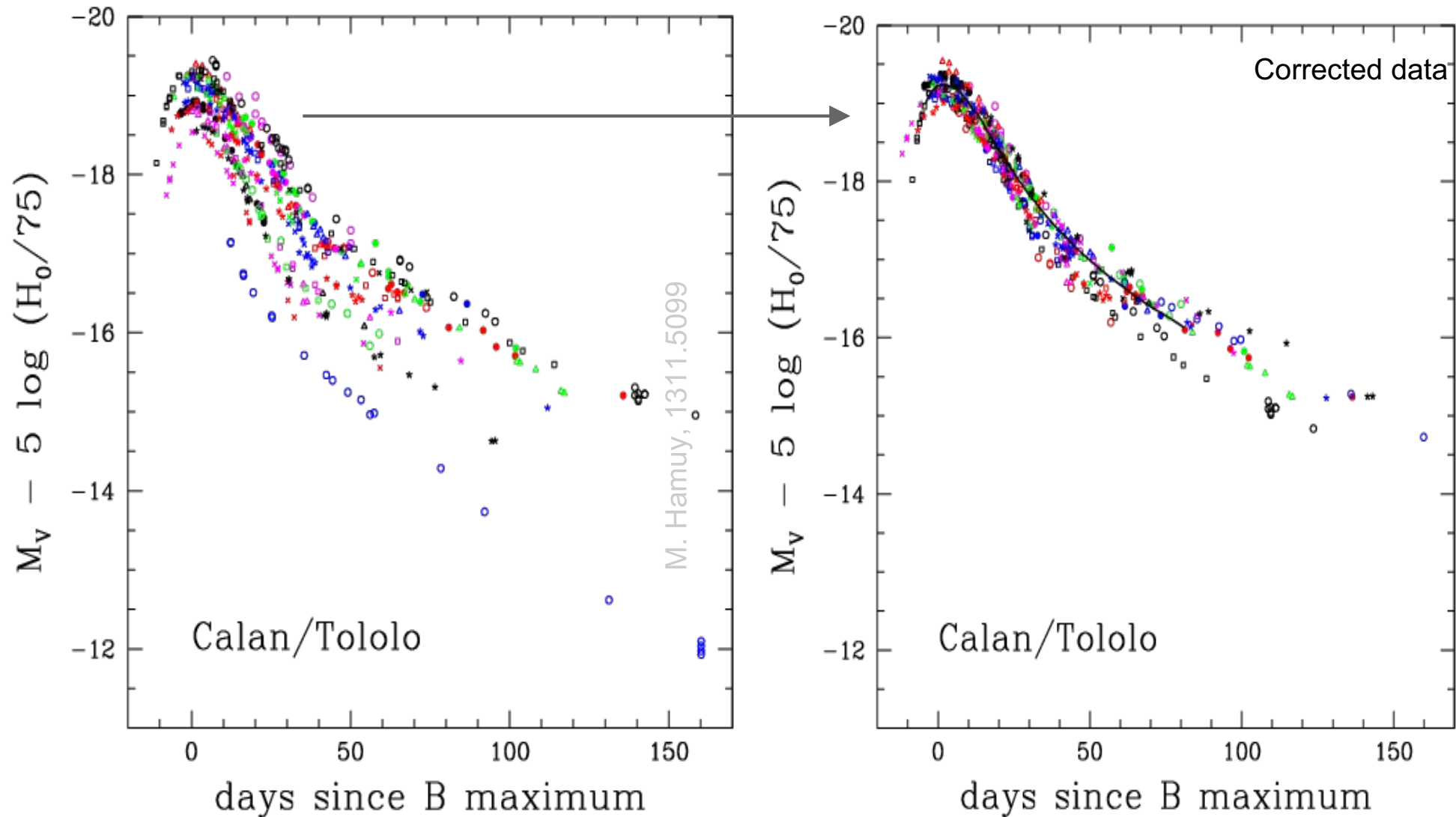
# What are Type Ia supernovae?



Phillips, 1993



# What are Type Ia supernovae?



# What are Type Ia supernovae?

SALT 2 parameters

Betoule *et al.*, 1401.4064

Name	$z_{\text{cmb}}$	$m_B^*$	$X_1$	$C$	$M_{\text{stellar}}$	?
03D1ar	0.002	$23.941 \pm 0.033$	$-0.945 \pm 0.209$	$0.266 \pm 0.035$	$10.1 \pm 0.5$	?
03D1au	0.503	$23.002 \pm 0.088$	$1.273 \pm 0.150$	$-0.012 \pm 0.030$	$9.5 \pm 0.1$	?
03D1aw	0.581	$23.574 \pm 0.090$	$0.974 \pm 0.274$	$-0.025 \pm 0.037$	$9.2 \pm 0.1$	?
03D1ax	0.495	$22.960 \pm 0.088$	$-0.729 \pm 0.102$	$-0.100 \pm 0.030$	$11.6 \pm 0.1$	?
03D1bp	0.346	$22.398 \pm 0.087$	$-1.155 \pm 0.113$	$-0.041 \pm 0.027$	$10.8 \pm 0.1$	?
03D1co	0.678	$24.078 \pm 0.098$	$0.619 \pm 0.404$	$-0.039 \pm 0.067$	$8.6 \pm 0.3$	?
03D1dt	0.611	$23.285 \pm 0.093$	$-1.162 \pm 1.641$	$-0.095 \pm 0.050$	$9.7 \pm 0.1$	
03D1ew	0.866	$24.354 \pm 0.106$	$0.376 \pm 0.348$	$-0.063 \pm 0.068$	$8.5 \pm 0.8$	
03D1fc	0.331	$21.861 \pm 0.086$	$0.650 \pm 0.119$	$-0.018 \pm 0.024$	$10.4 \pm 0.0$	
03D1fq	0.799	$24.510 \pm 0.102$	$-1.057 \pm 0.407$	$-0.056 \pm 0.065$	$10.7 \pm 0.1$	
03D3aw	0.450	$22.667 \pm 0.092$	$0.810 \pm 0.232$	$-0.086 \pm 0.038$	$10.7 \pm 0.0$	
03D3ay	0.371	$22.273 \pm 0.091$	$0.570 \pm 0.198$	$-0.054 \pm 0.033$	$10.2 \pm 0.1$	
03D3ba	0.292	$21.961 \pm 0.093$	$0.761 \pm 0.173$	$0.116 \pm 0.035$	$10.2 \pm 0.1$	
03D3bl	0.356	$22.927 \pm 0.087$	$0.056 \pm 0.193$	$0.205 \pm 0.030$	$10.8 \pm 0.1$	

$$\mu_B = m_B^* - M + \alpha X_1 - \beta C$$

# Cosmology

$$\begin{aligned}\mu &\equiv 25 + 5 \log_{10}(d_L/\text{Mpc}), \quad \text{where:} \\ d_L &= (1+z) \frac{d_H}{\sqrt{\Omega_k}} \text{sinn} \left( \sqrt{\Omega_k} \int_0^z \frac{H_0 dz'}{H(z')} \right), \\ d_H &= c/H_0, \quad H_0 \equiv 100h \text{ km s}^{-1} \text{Mpc}^{-1}, \\ H &= H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda},\end{aligned}$$

$\text{sinn} \rightarrow \sinh$  for  $\Omega_k > 0$  and  $\text{sinn} \rightarrow \sin$  for  $\Omega_k < 0$

## What is measured

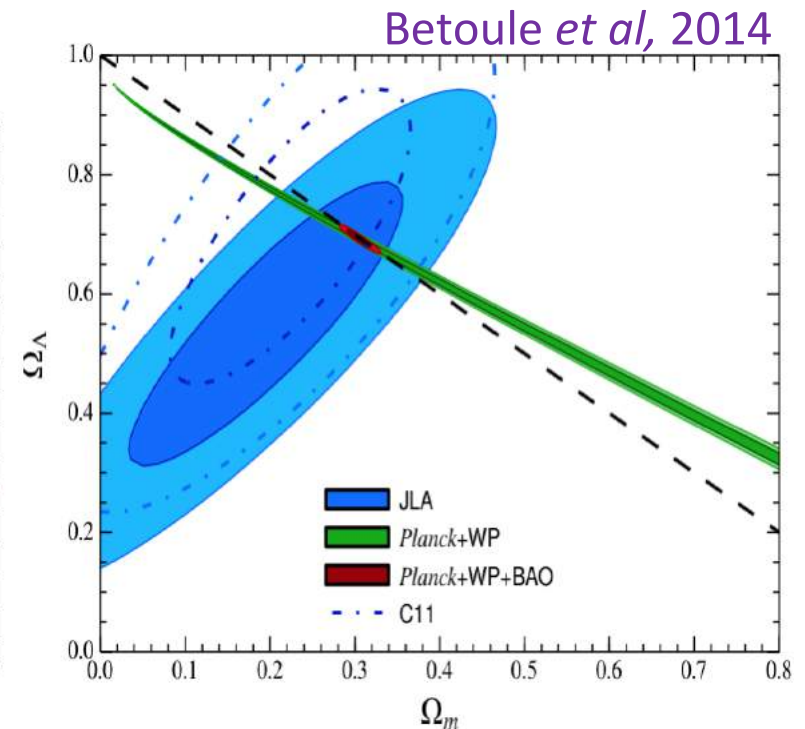
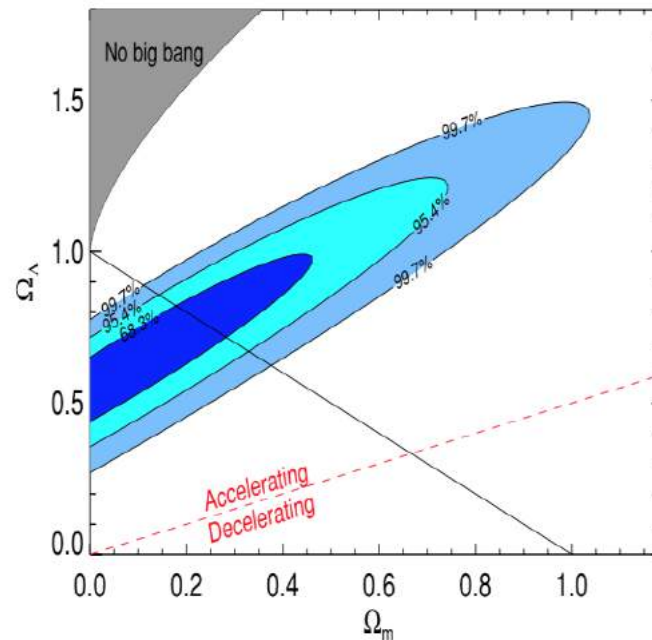
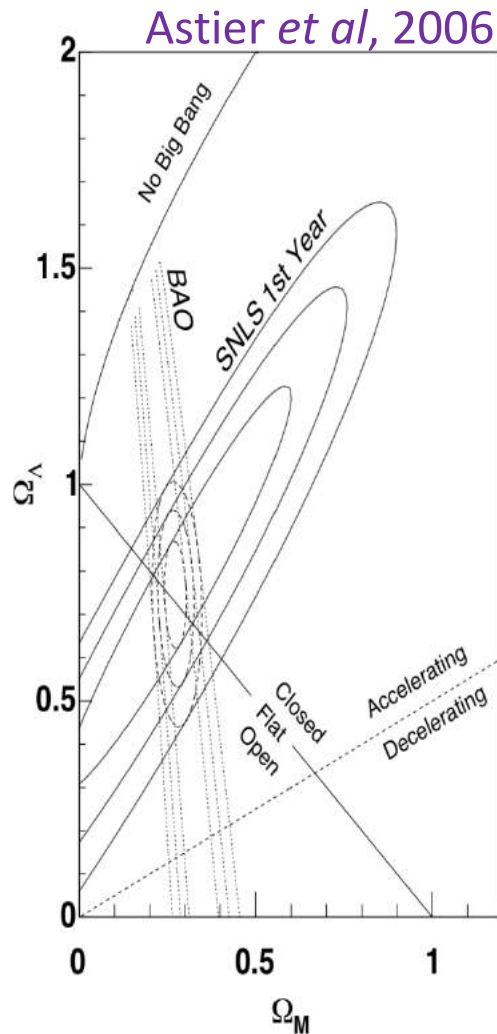
$$\mu_C = m - M = -2.5 \log \frac{F/F_{\text{ref}}}{L/L_{\text{ref}}} = 5 \log \frac{d_L}{10 \text{ pc}}$$

$$\mu_B = m_B^* - M + \alpha X_1 - \beta C$$

# How strong is the evidence for cosmic acceleration?

“SN data alone require\*  
cosmic acceleration at  
>99.999% confidence,  
including systematic  
effects” (Conley *et al*, 2011)

\*from the magnitude-redshift plot

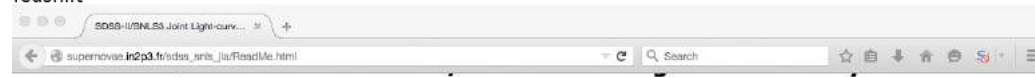
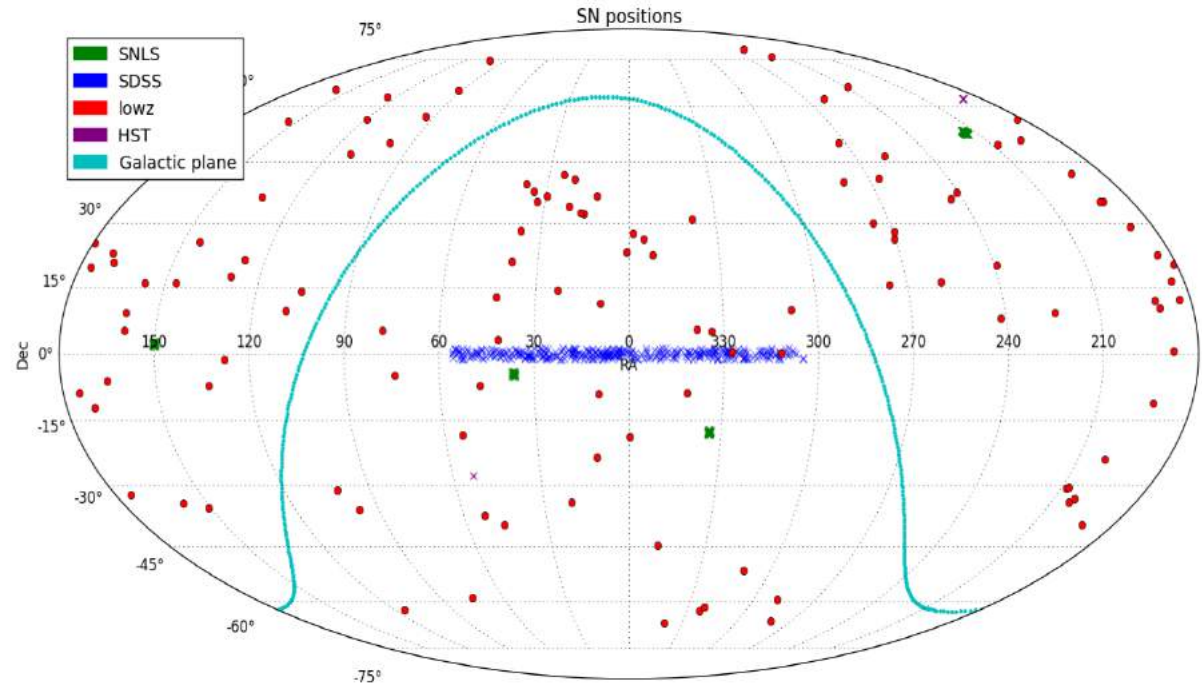
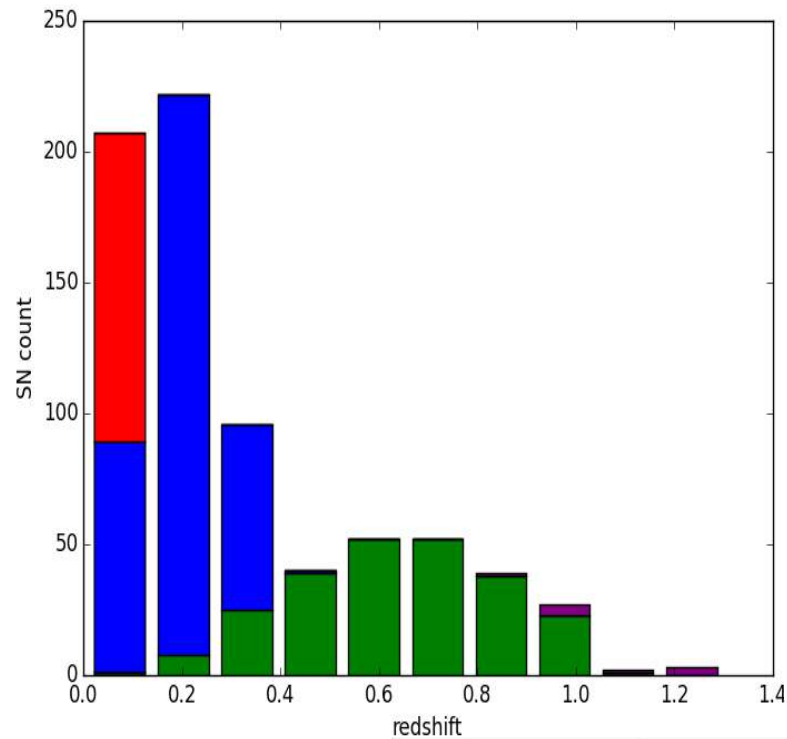


$$\chi^2 = \sum_{\text{objects}} \frac{(\mu_B - 5 \log_{10}(d_L(\theta, z)/10 \text{ pc}))^2}{\sigma^2(\mu_B) + \sigma_{\text{int}}^2}$$

But they *assume*  $\Lambda$ CDM and adjust  $\sigma_{\text{int}}$  to get chi-squared of 1 per d.o.f. for the fit!



# Joint Lightcurve Analysis data (740 SNe)



This page contains links to data associated with the SDSS-II/SNLS3 Joint Light-Curve Analysis (Betoule et al. 2014, submitted to A&A).

The release consists in:

1. The end products of the analysis and a C++ code to compute the likelihood of this data associated to a cosmological model. The code enables both evaluations of the *complete* likelihood, and *fast* evaluations of an *approximate* likelihood (see Betoule et al. 2014, Appendix E).
2. The version 2.4 of the SALT2 light-curve model used for the analysis plus 200 random realizations usable for the propagation of model uncertainties.
3. The exact set of Supernovae light-curves used in the analysis.

We also deliver presentation material.

Since March 2014, the JLA likelihood plugin is included in the official release of *cosmomc*. For older versions, the plugin is still available (see below: *Installation of the cosmomc plugin*).

To analyze the JLA sample with SNANA, see \$SNDATA\_ROOT/sample\_input\_files/JLA2014/AAA\_README.

## 1 Release history

**V1 (January 2014, paper submitted):**

First arxiv version.

**V2 (March 2014):**

Same as v1 with additional information (R.A., Dec. and bias correction) in the file of light-curve parameters.

**V3 (April 2014, paper accepted):**

Same as v2 with the addition of a C++ likelihood code in an independant archive (jla\_likelihood\_v3.tgz).

**V4 (June 2014):**

### 1. Release history

V1 (January 2014, paper submitted):  
V2 (March 2014):  
V3 (April 2014, paper accepted):  
V4 (June 2014):  
V5 (March 2015):  
V6 (March 2015):

### 2. Installation of the C++ likelihood code

Installation of the cosmomc plugin

### 3. SALT2 model

### 4. Error propagation

Error decomposition  
SALT2 light-curve model  
uncertainties

Data publicly available now

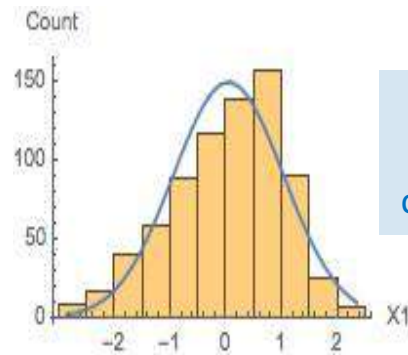
Betoule et al, 1401.4064

# Construct a Maximum Likelihood Estimator

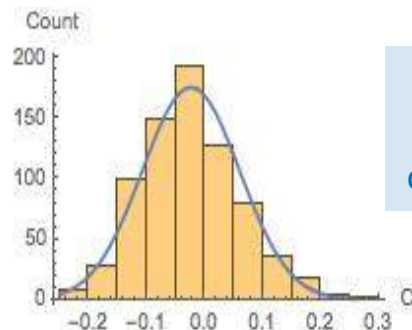
$\mathcal{L}$  = probability density(data|model)

$$\begin{aligned}\mathcal{L} &= p[(\hat{m}_B^*, \hat{x}_1, \hat{c})|\theta] \\ &= \int p[(\hat{m}_B^*, \hat{x}_1, \hat{c})|(M, x_1, c), \theta_{\text{cosmo}}] \\ &\quad \times p[(M, x_1, c)|\theta_{\text{SN}}] dM dx_1 dc\end{aligned}$$

Well-approximated as Gaussian



JLA data  
'Stretch'  
corrections



JLA data  
'Colour'  
corrections

$$p[(M, x_1, c)|\theta] = p(M|\theta)p(x_1|\theta)p(c|\theta),$$

$$p(M|\theta) = \frac{1}{\sqrt{2\pi\sigma_M^2}} \exp\left(-\left[\frac{M - M_0}{\sigma_{M0}}\right]^2 / 2\right)$$

$$p(x_1|\theta) = \frac{1}{\sqrt{2\pi\sigma_{x0}^2}} \exp\left(-\left[\frac{x_1 - x_{10}}{\sigma_{x0}}\right]^2 / 2\right)$$

$$p(c|\theta) = \frac{1}{\sqrt{2\pi\sigma_{c0}^2}} \exp\left(-\left[\frac{c - c_0}{\sigma_{c0}}\right]^2 / 2\right)$$

# Likelihood

$$p(Y|\theta) = \frac{1}{\sqrt{|2\pi\Sigma_l|}} \exp \left[ -\frac{1}{2}(Y - Y_0)\Sigma_l^{-1}(Y - Y_0)^T \right]$$

$$p(\hat{X}|X, \theta) = \frac{1}{\sqrt{|2\pi\Sigma_d|}} \exp \left[ -\frac{1}{2}(\hat{X} - X)\Sigma_d^{-1}(\hat{X} - X)^T \right]$$

$$\mathcal{L} = \frac{1}{\sqrt{|2\pi(\Sigma_d + A^T\Sigma_l A)|}} \times \exp \left( -\frac{1}{2}(\hat{Z} - Y_0 A)(\Sigma_d + A^T\Sigma_l A)^{-1}(\hat{Z} - Y_0 A)^T \right)$$

intrinsic distributions

cosmology
SALT2

# Confidence regions

Nielsen et al, Sci.Rep.6:35596,2016

$$p_{\text{cov}} = \int_0^{-2 \log \mathcal{L} / \mathcal{L}_{\text{max}}} \chi^2(x; \nu) dx$$

$$\mathcal{L}_p(\theta) = \max_{\phi} \mathcal{L}(\theta, \phi)$$

1,2,3-sigma

solve for Likelihood value

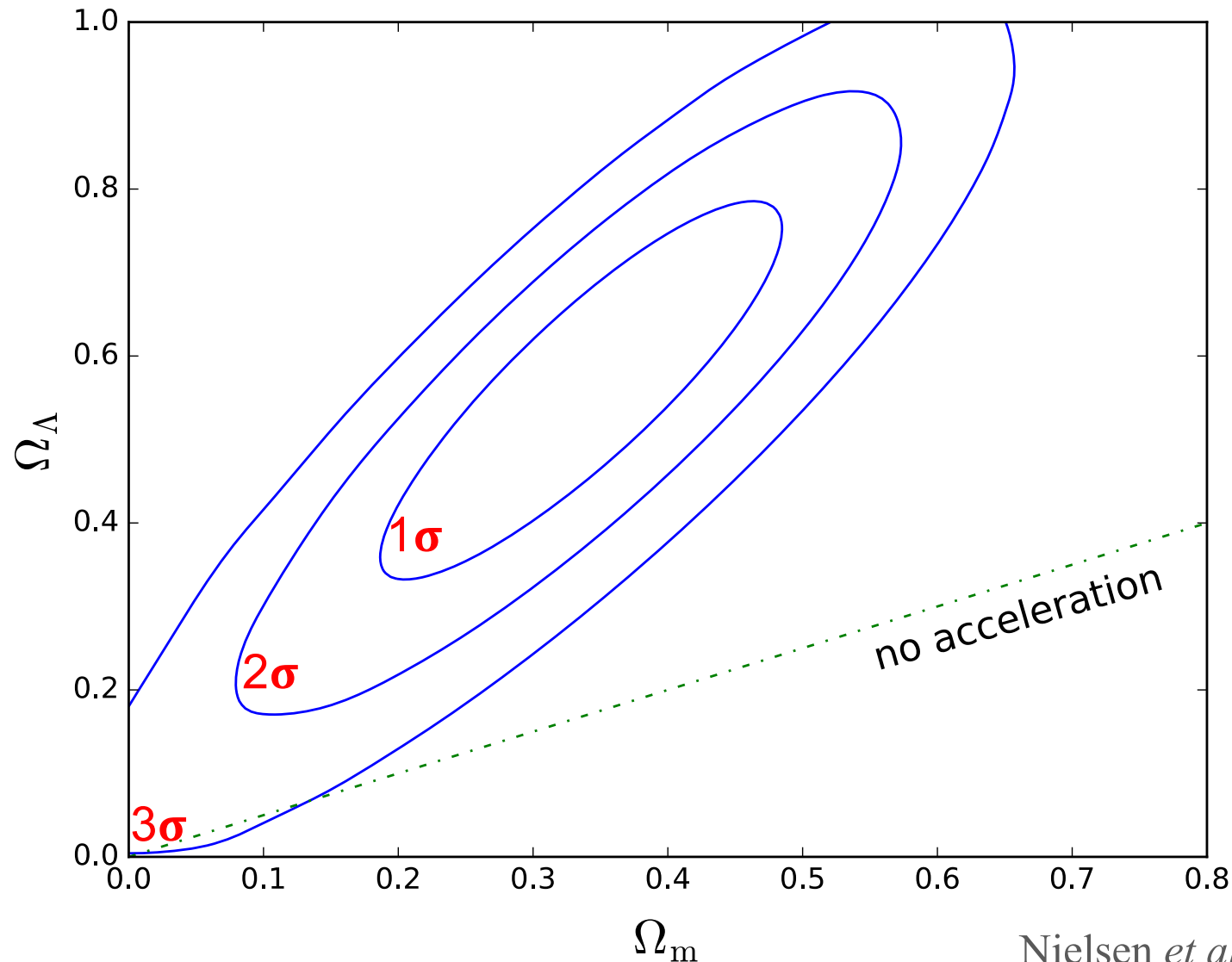
# Data consistent with *uniform expansion* @ $3\sigma$ !

Opens up interesting possibilities e.g. could the cosmic fluid be viscous – perhaps associated with structure formation (e.g. Floerchinger *et al*, PRL **114**:091301,2015)

profile likelihood

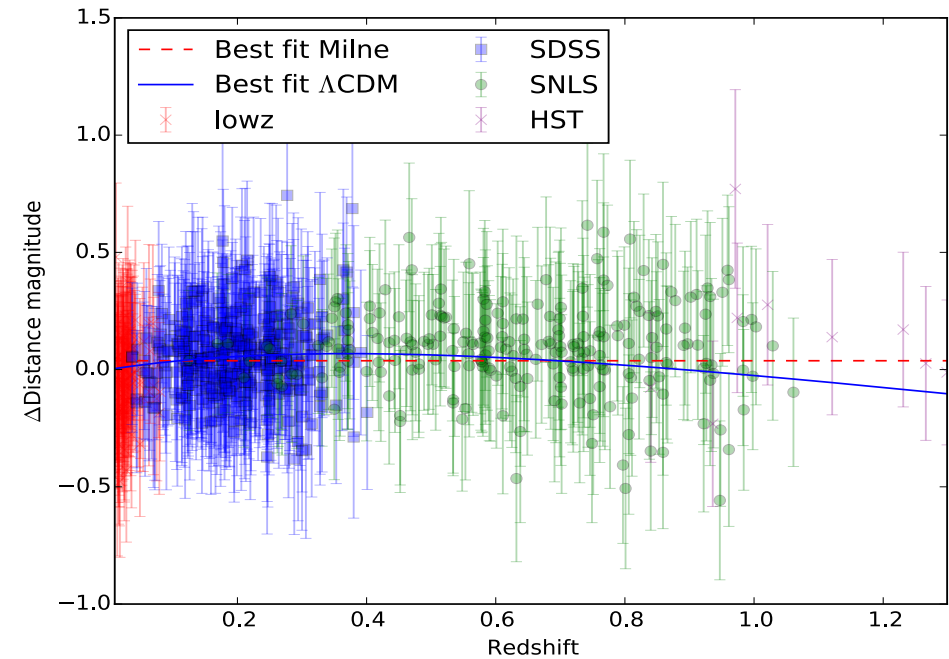
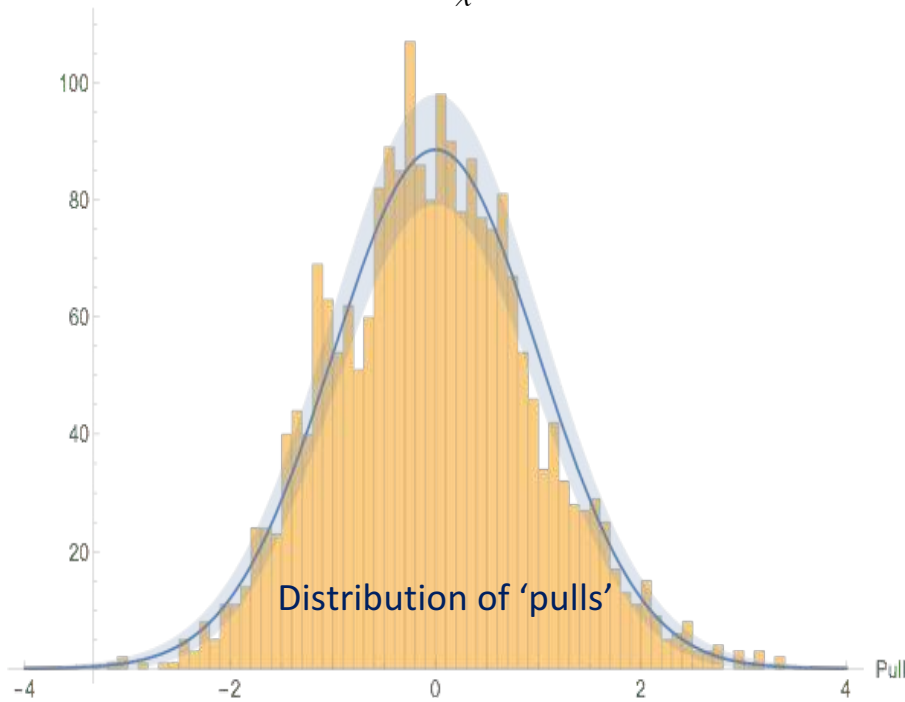
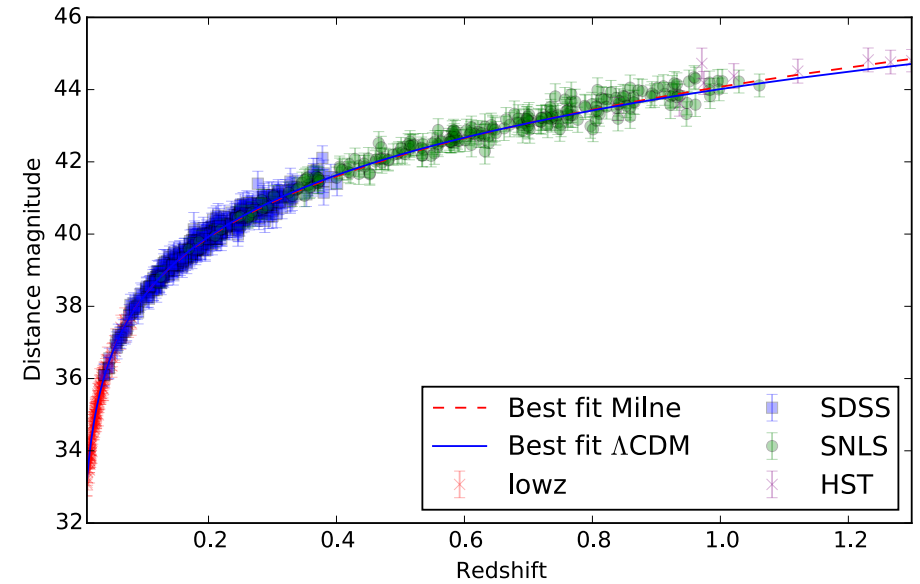
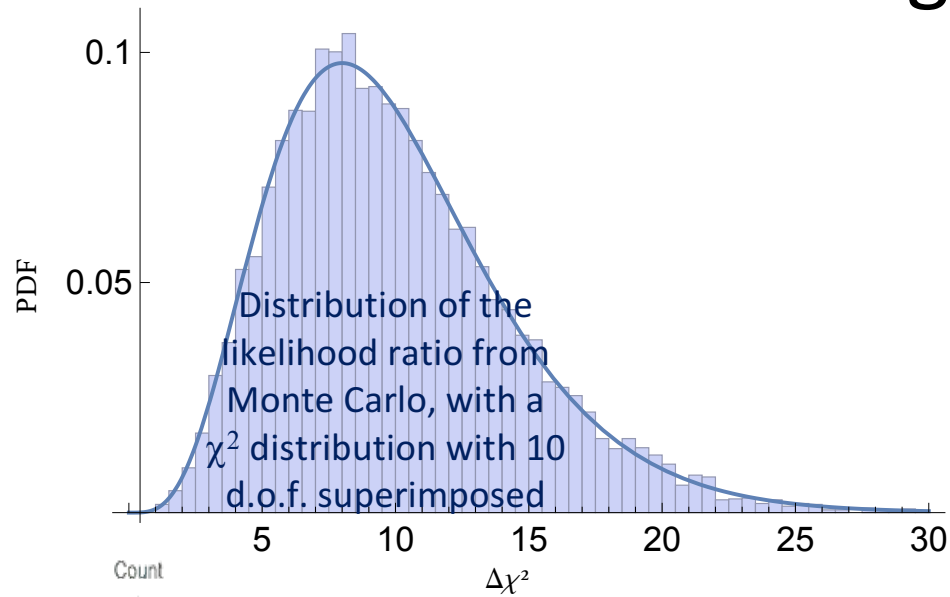
MLE, best fit

$\Omega_M$	0.341
$\Omega_\Lambda$	0.569
$\alpha$	0.134
$x_0$	0.038
$\sigma_{x0}^2$	0.931
$\beta$	3.058
$c_0$	-0.016
$\sigma_{c0}^2$	0.071
$M_0$	-19.05
$\sigma_{M0}^2$	0.108



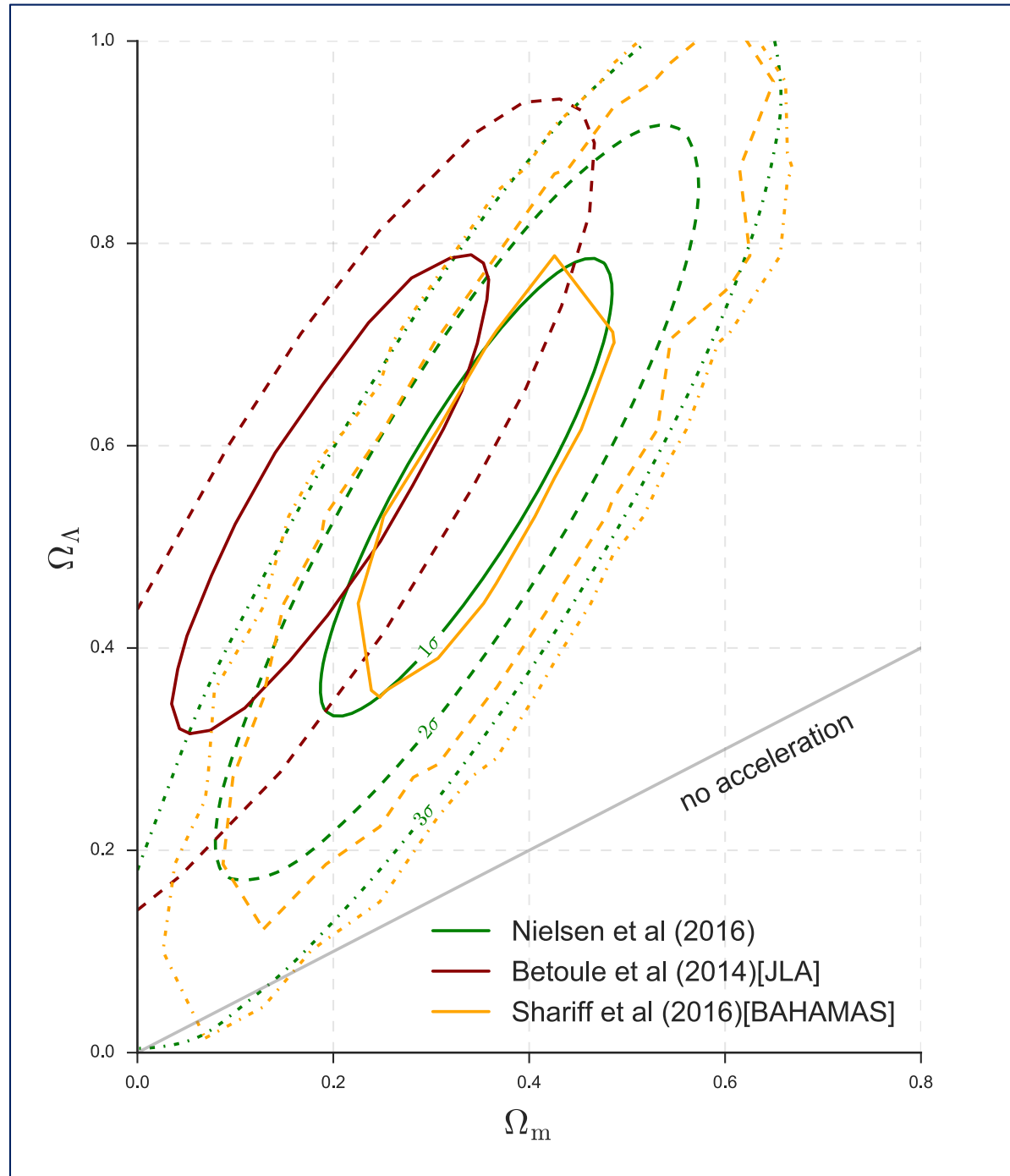


# Is it a good fit ?



$$\text{pull} = (\Sigma_d + A^T \Sigma_l A)^{-1/2} (\hat{Z} - Y_0 A)$$

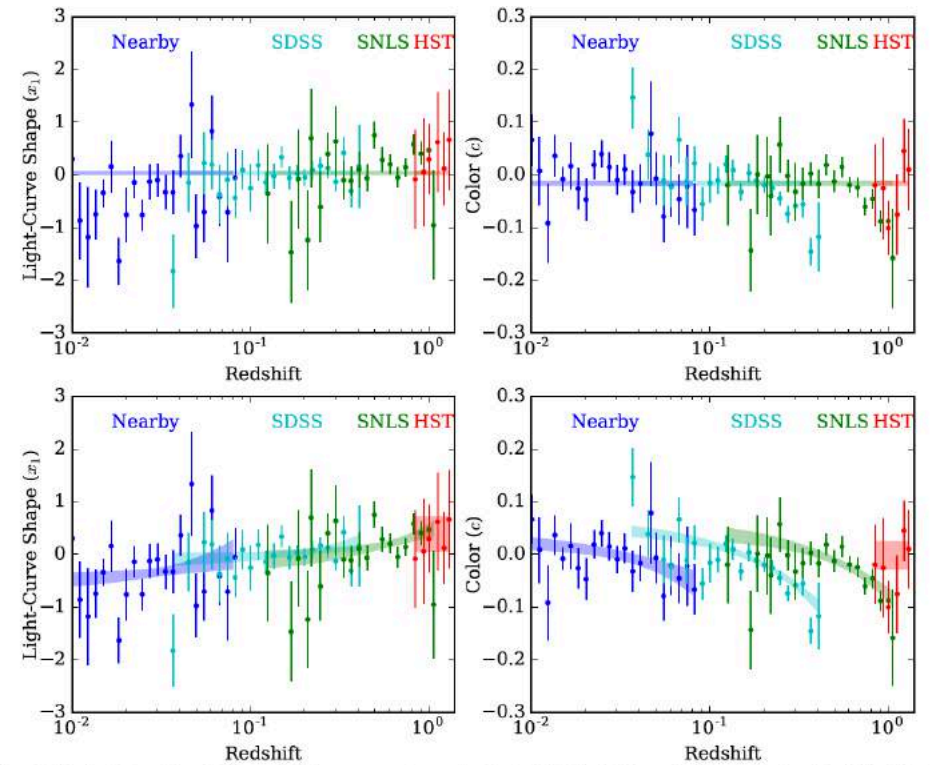
Our result has been confirmed by a subsequent *Bayesian* analysis



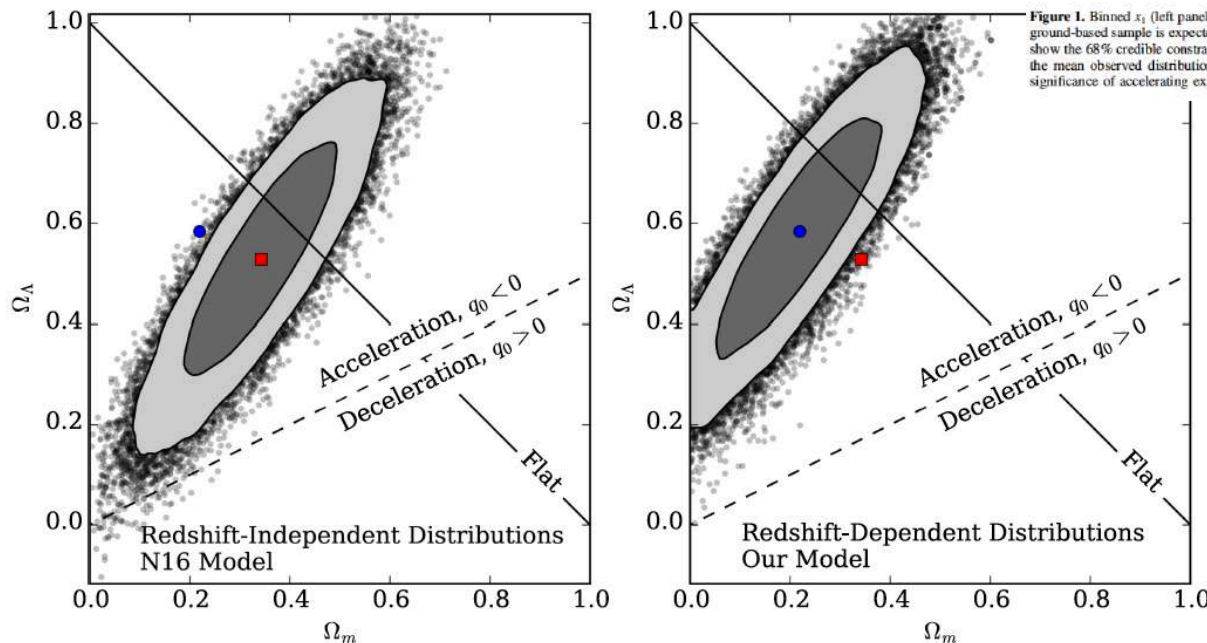
Shariff, Jiao, Trota & van Dyk, ApJ 827:1, 2016

# Epilogue

Rubin & Hayden (ApJ 833:L30,2016) say that our model for the distribution of the light curve fit parameters should have included a dependence on redshift (to allow for ‘Malmqvist bias’ which JLA had in fact already corrected for) ... they add 12 more parameters to our (10 parameter) model to describe this



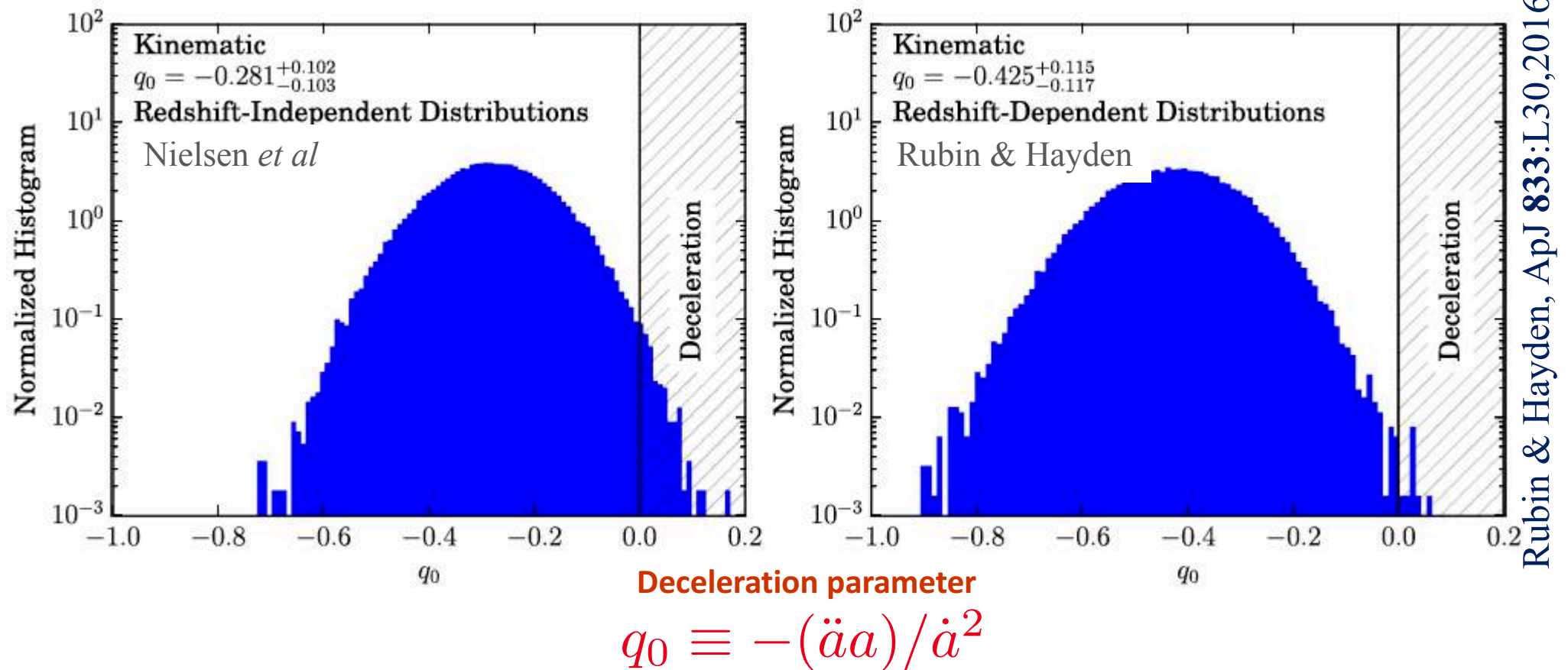
**Figure 1.** Binned  $x_1$  (left panels) and  $c$  (right panels) light curve parameters as a function of redshift for the JLA sample. The trend of color with redshift within each ground-based sample is expected due to the combination of the color-luminosity relation combined with redshift-dependent luminosity detection limits. The top panels show the 68% credible constraints on a constant-in-redshift model, as was used in N16. The bottom panels show our proposed revision. Failing to model the drift in the mean observed distributions demonstrated by the bottom panels will tend to cause high-redshift SNe to appear brighter on average, therefore reducing the significance of accelerating expansion.



**Figure 2.**  $\Omega_m$ - $\Omega_\Lambda$  constraints enclosing 68.3% and 95.4% of the samples from the posterior. Underneath, we plot all samples. The left panel shows the constraints obtained with  $x_1$  and  $c$  distributions that are constant in redshift, as in the N16 analysis; the right panel shows the constraints from our model. The red square and blue circle show the location of the median of the samples from the respective posteriors.

Even if this is justified, the significance with which a non-accelerating universe is rejected is raised (back!) to  $\sim 4\sigma$  ... still inadequate to claim a ‘discovery’ (even though the dataset has increased from 50 to 740 SNe Ia in the past 20 yrs)

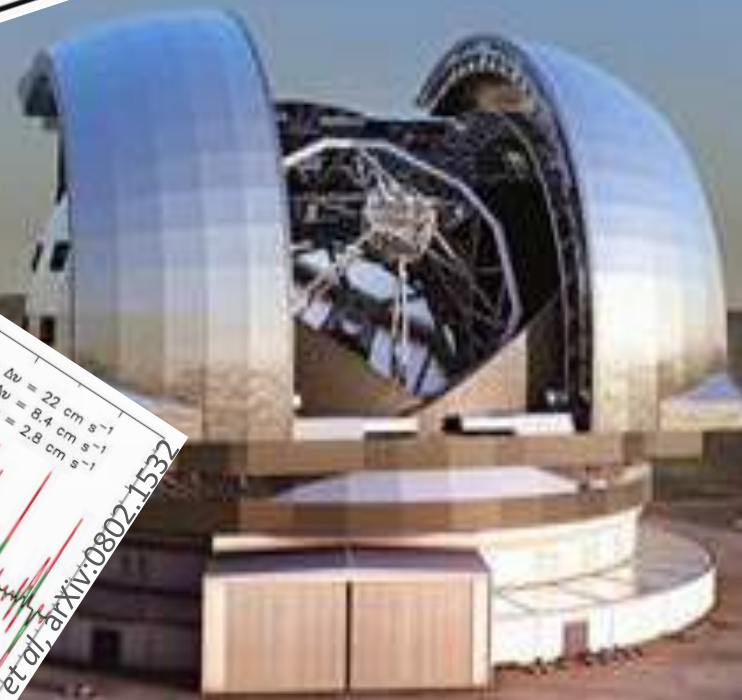
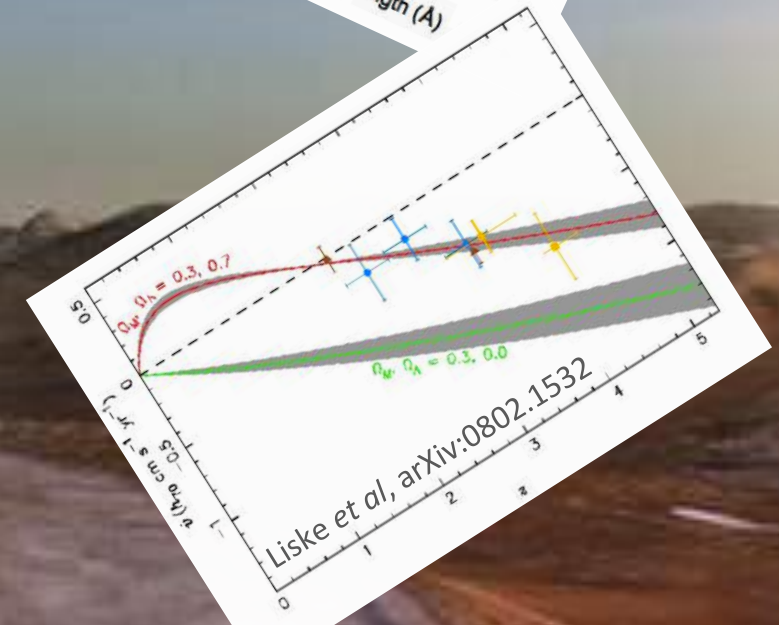
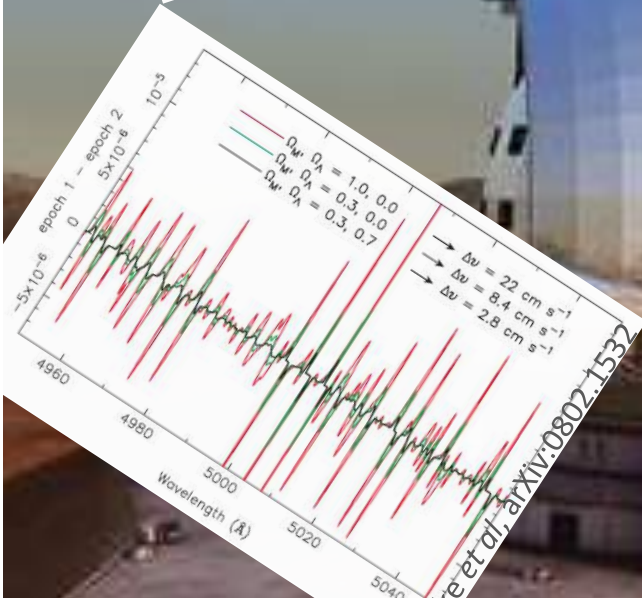
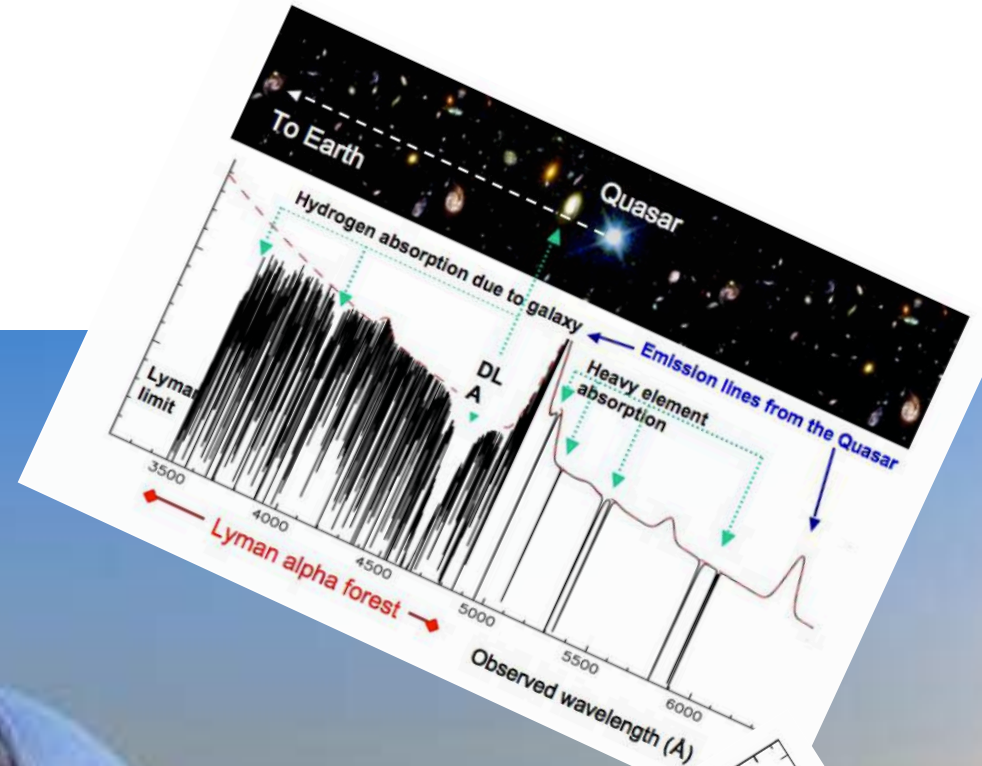
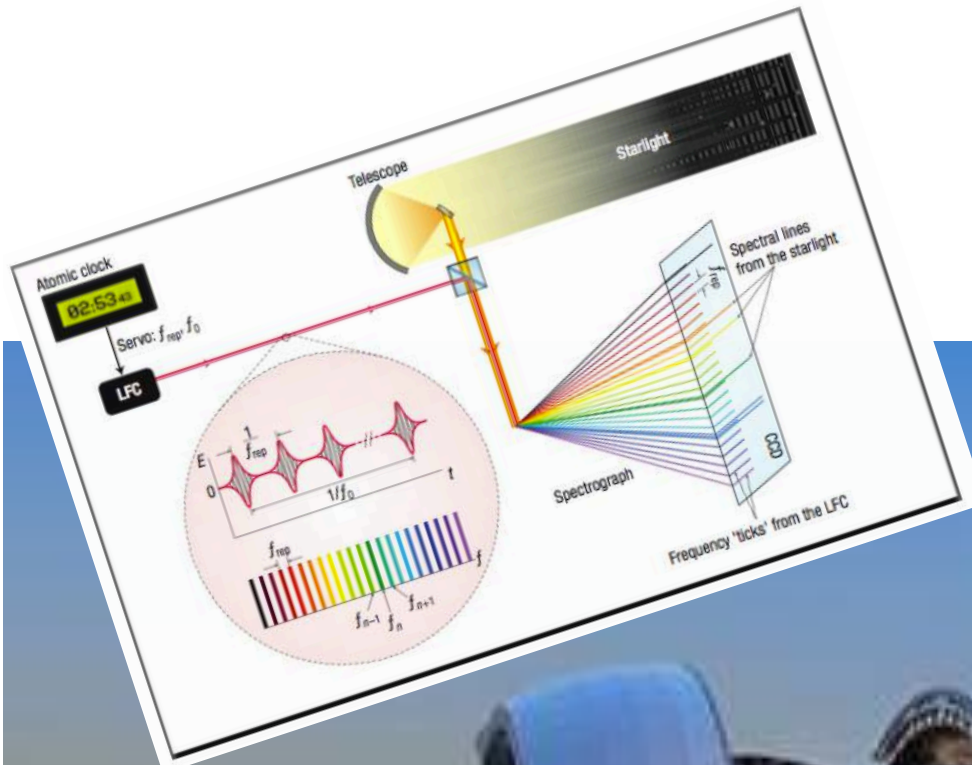
Acceleration is a *kinematic* quantity so the data can be analysed simply by expanding the time variation of the scale factor in a Taylor series, without reference to a dynamical model (e.g. Visser, CQG **21**:2603,2004)



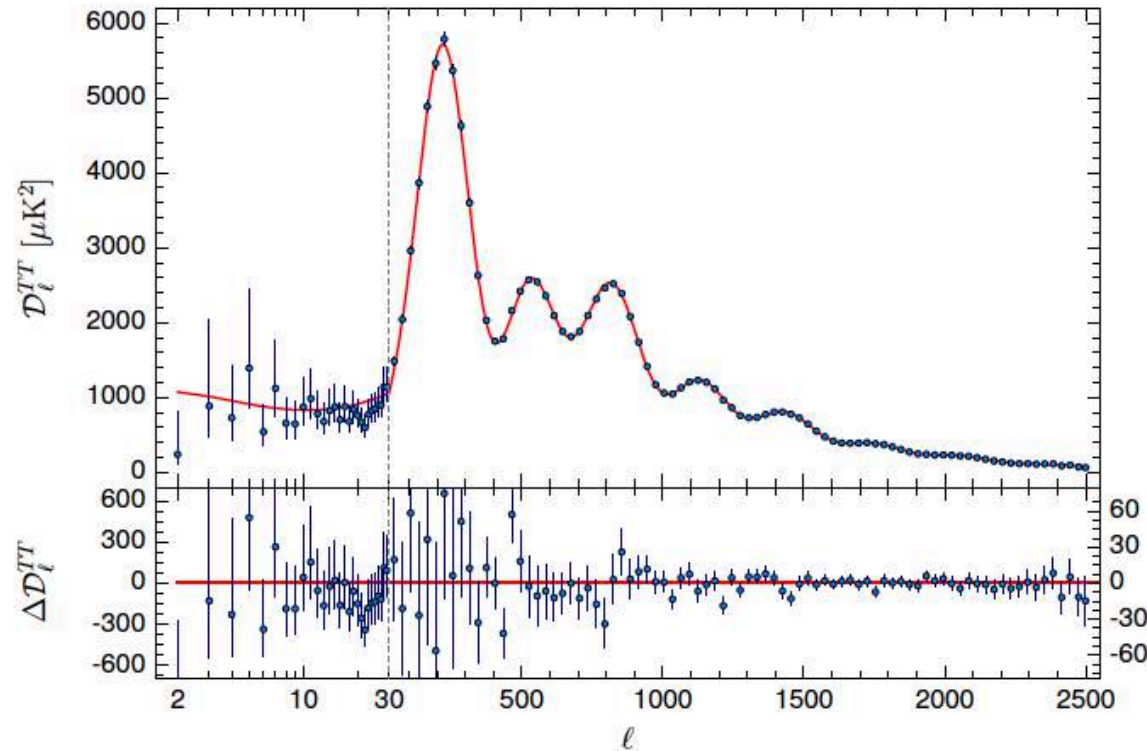
This yields  $2.8\sigma$  evidence for acceleration in our approach  
 ... increasing to only  $3.6\sigma$  when an *ad-hoc* redshift-dependence is allowed in the light-curve fitting parameters



# A direct test of cosmic acceleration (using a 'Laser Comb' on the European Extremely Large Telescope) to measure the redshift drift of the Lyman-a forest over 15 years



# What about the precision data on CMB anisotropies?



Parameter	[1] <i>Planck</i> TT+lowP	[2] <i>Planck</i> TE+lowP	[3] <i>Planck</i> EE+lowP	[4] <i>Planck</i> TT,TE,EE+lowP
$\Omega_b h^2$ . . . . .	$0.02222 \pm 0.00023$	$0.02228 \pm 0.00025$	$0.0240 \pm 0.0013$	$0.02225 \pm 0.00016$
$\Omega_c h^2$ . . . . .	$0.1197 \pm 0.0022$	$0.1187 \pm 0.0021$	$0.1150^{+0.0048}_{-0.0055}$	$0.1198 \pm 0.0015$
$100\theta_{MC}$ . . . . .	$1.04085 \pm 0.00047$	$1.04094 \pm 0.00051$	$1.03988 \pm 0.00094$	$1.04077 \pm 0.00032$
$\tau$ . . . . .	$0.078 \pm 0.019$	$0.053 \pm 0.019$	$0.059^{+0.022}_{-0.019}$	$0.079 \pm 0.017$
$\ln(10^{10} A_s)$ . . . . .	$3.089 \pm 0.036$	$3.031 \pm 0.041$	$3.066^{+0.046}_{-0.041}$	$3.094 \pm 0.034$
$n_s$ . . . . .	$0.9655 \pm 0.0062$	$0.965 \pm 0.012$	$0.973 \pm 0.016$	$0.9645 \pm 0.0049$
$H_0$ . . . . .	$67.31 \pm 0.96$	$67.73 \pm 0.92$	$70.2 \pm 3.0$	$67.27 \pm 0.66$
$\Omega_m$ . . . . .	$0.315 \pm 0.013$	$0.300 \pm 0.012$	$0.286^{+0.027}_{-0.038}$	$0.3156 \pm 0.0091$
$\sigma_8$ . . . . .	$0.829 \pm 0.014$	$0.802 \pm 0.018$	$0.796 \pm 0.024$	$0.831 \pm 0.013$
$10^9 A_s e^{-2\tau}$ . . . . .	$1.880 \pm 0.014$	$1.865 \pm 0.019$	$1.907 \pm 0.027$	$1.882 \pm 0.012$

Where is the entry for  $\Lambda$ ?!

There is no direct sensitivity of the CMB to dark energy ... it is all inferred (in the framework of  $\Lambda$ CDM model)



Is not dark energy (cosmic acceleration) independently established from combining CMB & large-scale structure observations? Answer: No!

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

**The Beam:** inflationary density perturbations

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

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

**Identity unknown** - usually taken to be **cold** and **collisionless**

**The Detector:** the universe

**Modelled by a 'simple' FRW cosmology** with parameters  $h, \Omega_{\text{CDM}}, \Omega_{\text{B}}, \Omega_{\Lambda}, \Omega_k$

**The Signal:** CMB anisotropy, galaxy clustering, weak lensing ...

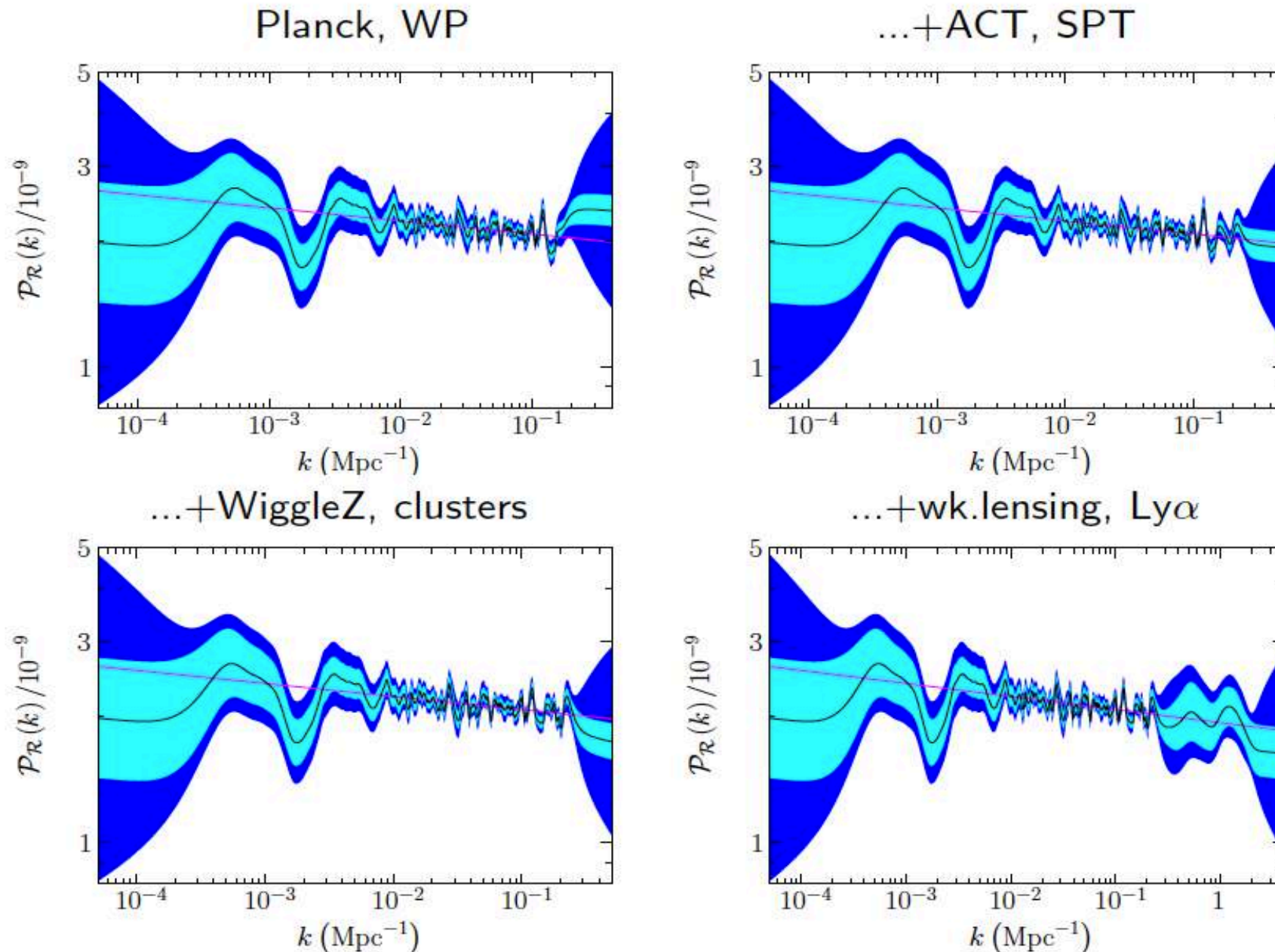
measured over scales ranging from  $\sim 1 - 10000$  Mpc ( $\Rightarrow \sim 8$  e-folds of inflation)

But we *cannot* uniquely determine the properties of the **detector**  
with an unknown **beam and target!**

... hence need to adopt 'priors' on  $h, \Omega_{\text{CDM}}$  ..., and *assume* a primordial power-law spectrum, in order to break inevitable **parameter degeneracies**

Hence evidence for  $\Lambda$  is *indirect* (can match same data without it e.g. arXiv:0706.2443)

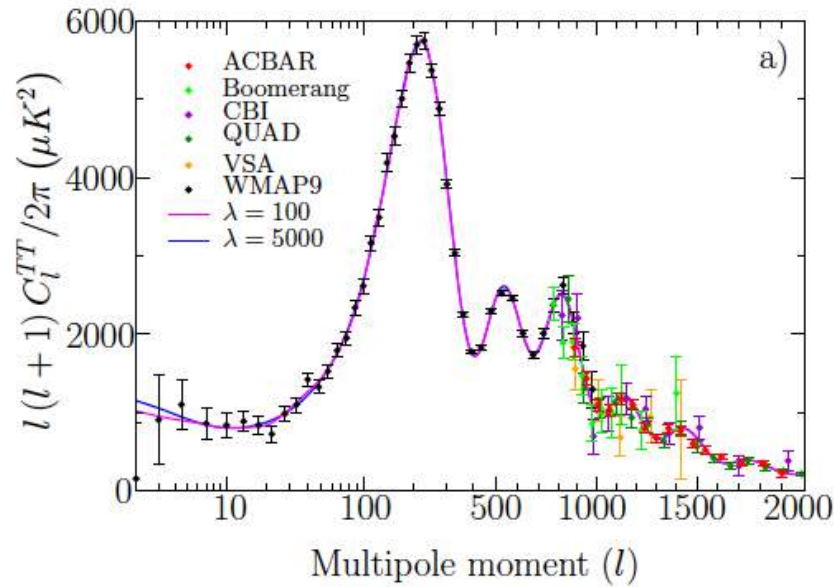
The ‘inverse problem’ of inferring the primordial spectrum of perturbations generated by inflation is necessarily “ill-conditioned” ... ‘Tikhonov regularisation’ can be used to do this in a non-parametric manner (Hunt & Sarkar, JCAP **01**:025,2014, **12**:052,2015)



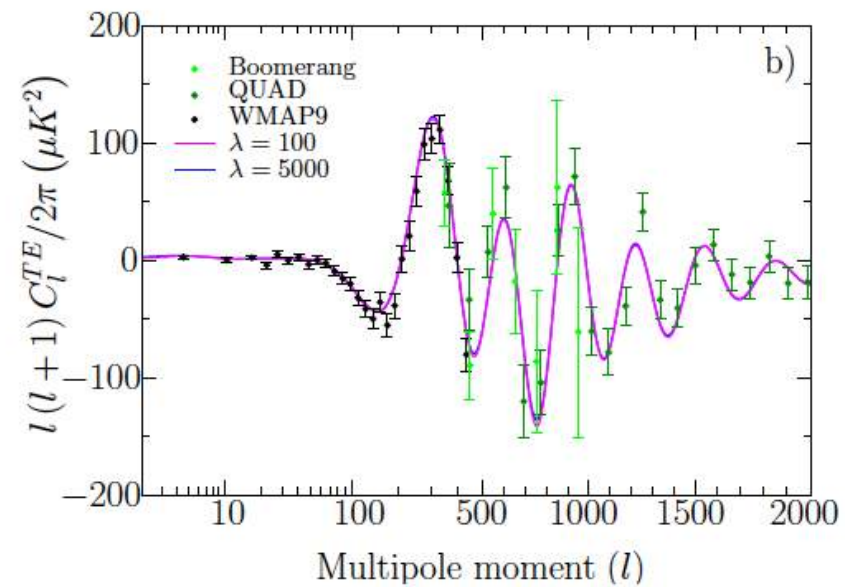


The fit to all the data is *just as good* as the usually (assumed) power-law spectrum ... but the inferred cosmological parameters are *different* if there are spectral features

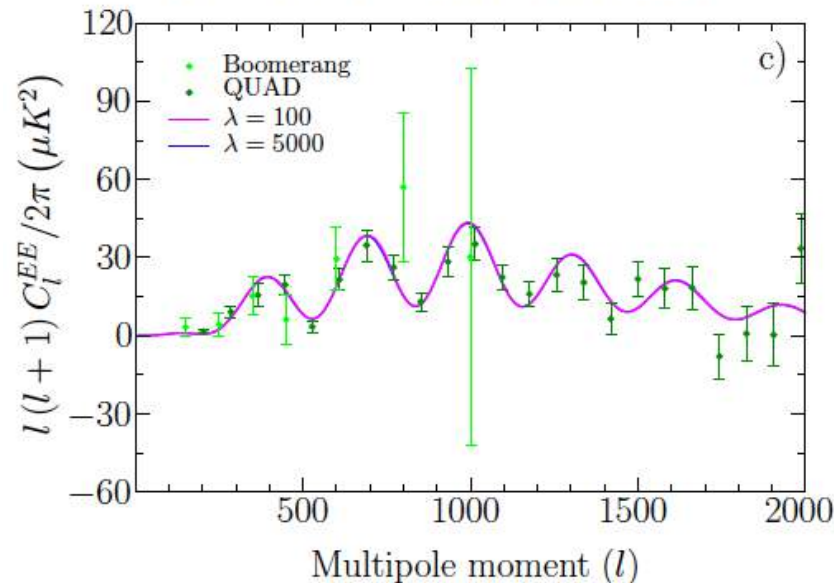
The fit to CMB TT data



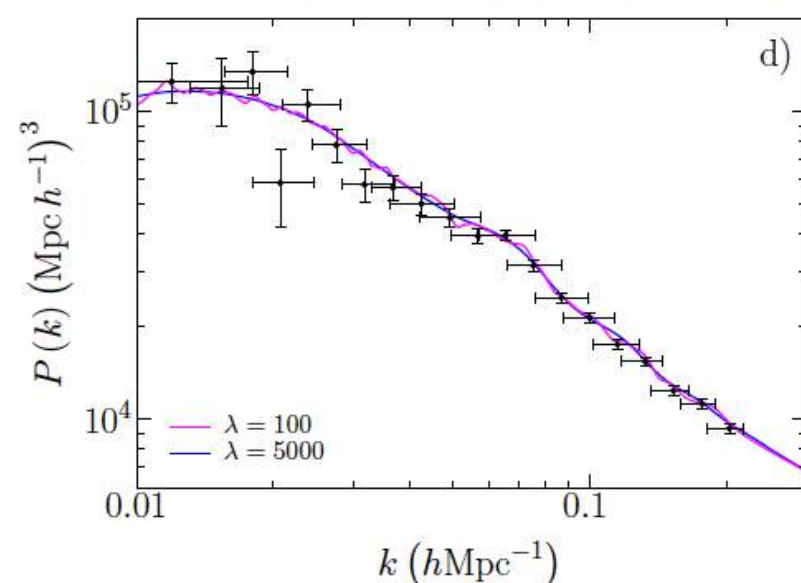
The fit to CMB TE data



The fit to CMB EE data

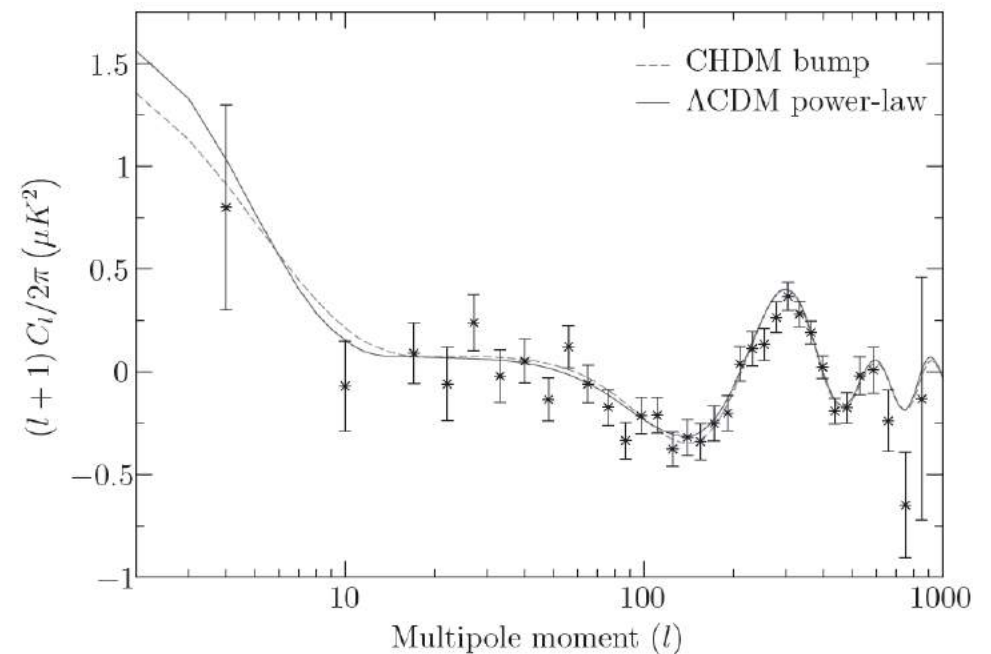
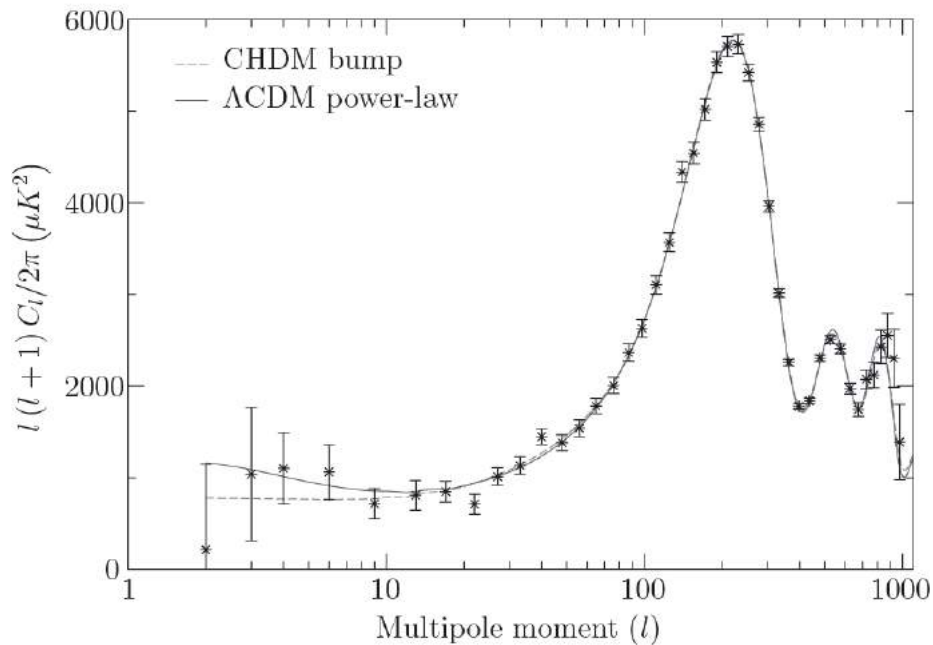
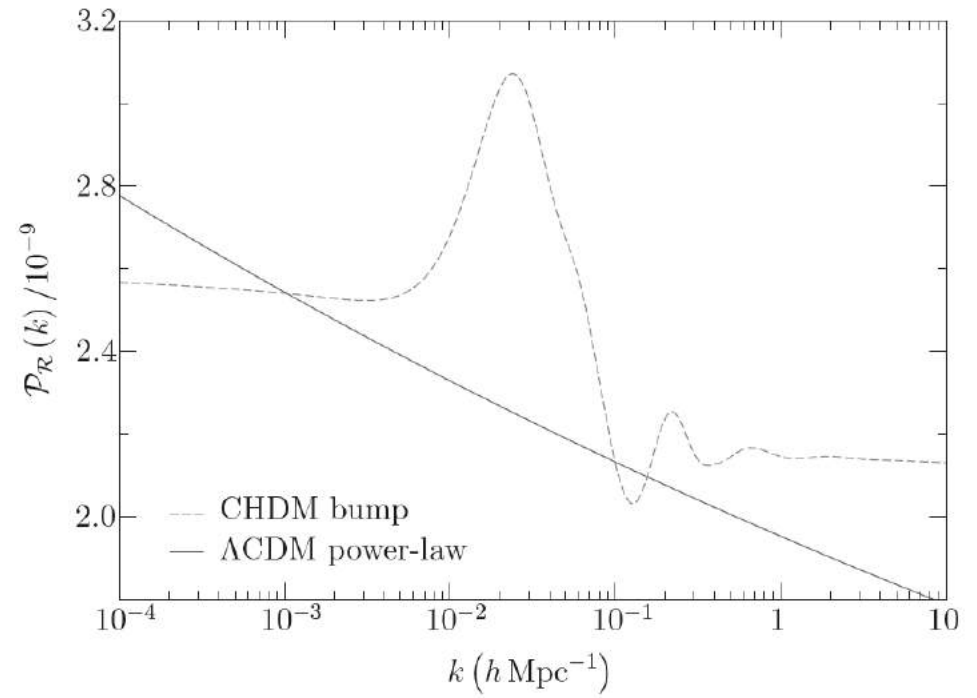


The fit to SDSS LRG data



E.g. if there is a ‘bump’ in the spectrum (around the first acoustic peak), the CMB data can be fitted *without dark energy* ( $\Omega_m = 1$ ,  $\Omega_\Lambda = 0$ ) if  $h \sim 0.45$  (Hunt & Sarkar arXiv:0706.2443, 0807.4508)

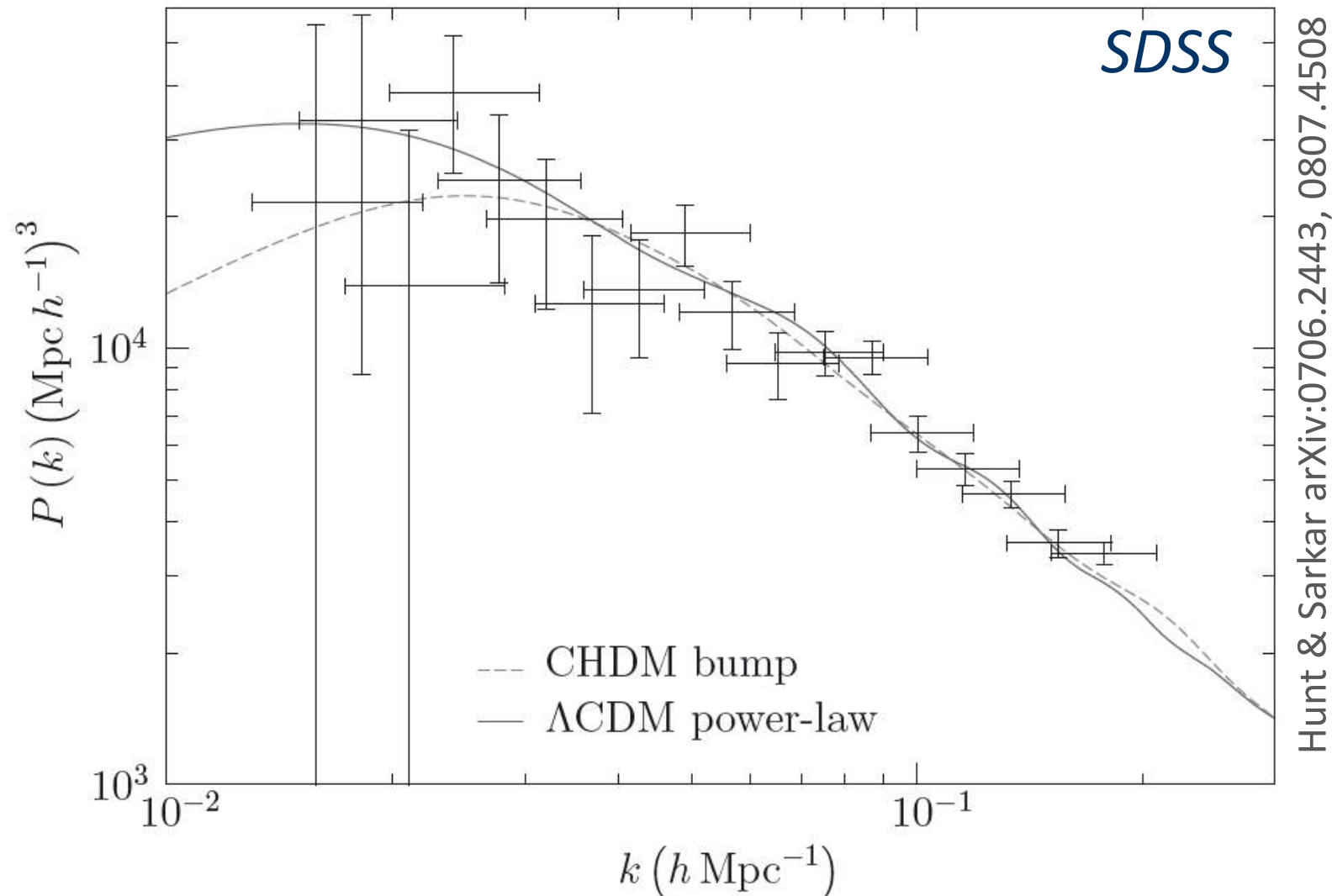
While significantly below the local value of  $h \sim 0.7$  this is *consistent* with its ‘global’ value in the effective EdeS relativistic inhomogeneous model matching  $H(z)$  data (Roukema *et al*, arXiv:1608.06004)



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

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

(note that  $\Sigma m_\nu \approx 1.5$  eV ... well above 'CMB bound' – but detectable by KATRIN!)



Fit gives  $\Omega_b h^2 \approx 0.021 \rightarrow \text{BBN} \color{red}{\nabla} \Rightarrow \text{baryon fraction in clusters predicted to be } \sim 11\% \color{red}{\nabla}$

# Summary

- The ‘standard model’ of cosmology was established long before there was any observational data ... and its empirical foundations (homogeneity, ideal fluids) have never been rigorously tested.  
*Now that we have data, it should be a priority to test the model assumptions ... not simply measure its parameters*
- It is *not* simply a choice between a cosmological constant (‘dark energy’) and ‘modified gravity’ – there are other interesting possibilities (e.g. ‘back-reaction’ and ‘effective viscosity’)
- The fact that the standard model implies an unnatural value for the cosmological constant,  $\Lambda \sim H_0^2$ , ought to motivate further work on *developing and testing alternative models* ... rather than pursuing “precision cosmology” of what may well turn out to be an illusion