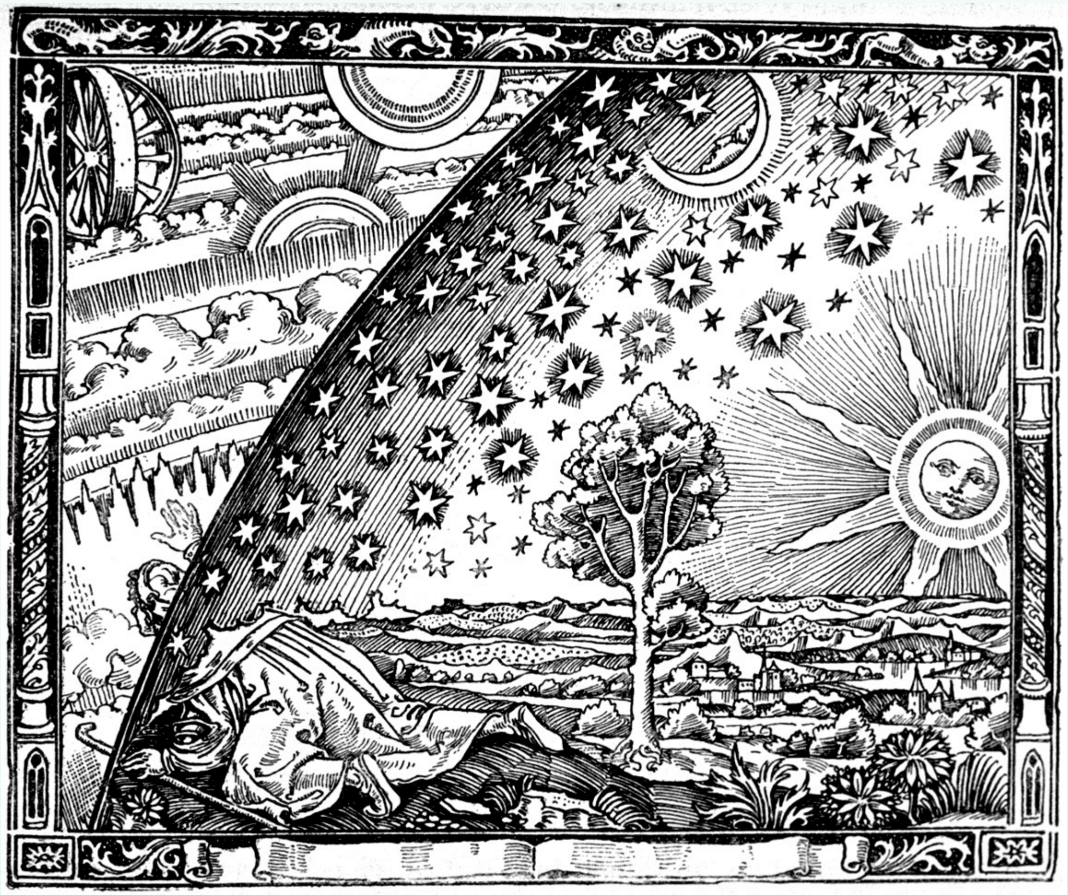
Cosmology Beyond the Standard Model



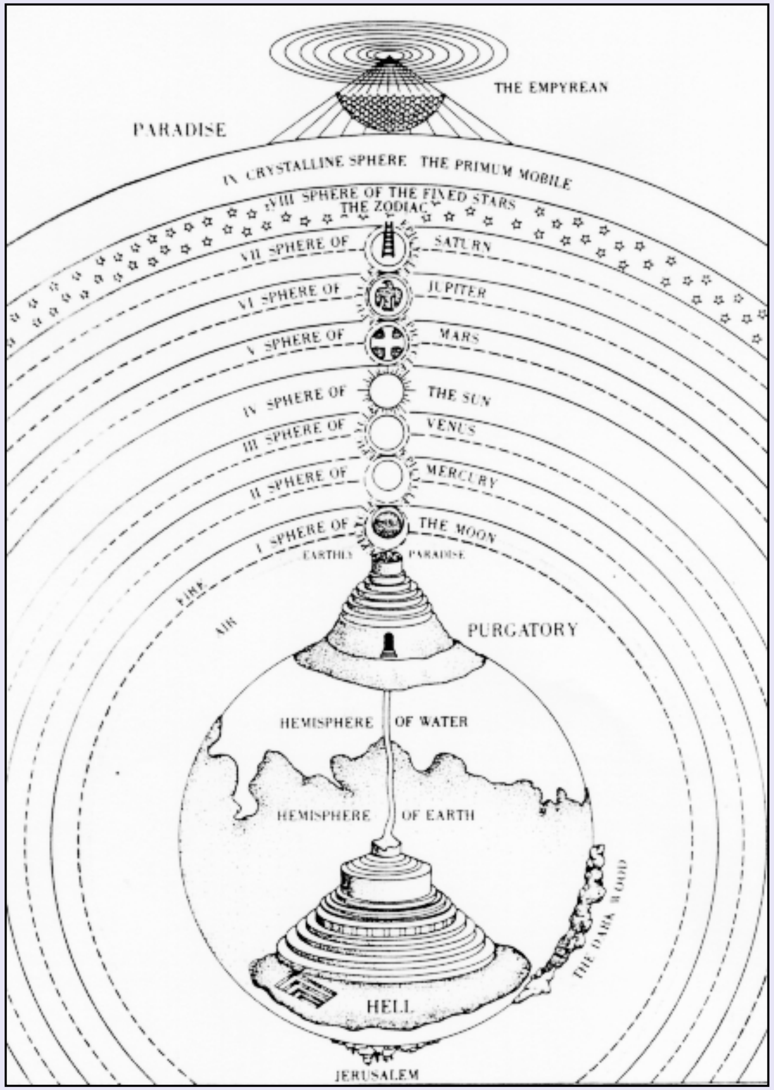
Subir Sarkar

Rudolf Peierls Centre for Theoretical Physics, University of Oxford

Niels Bohr Institute, University of Copenhagen

Elizabeth Spreadbury Lecture, UCL, 22nd March 2017

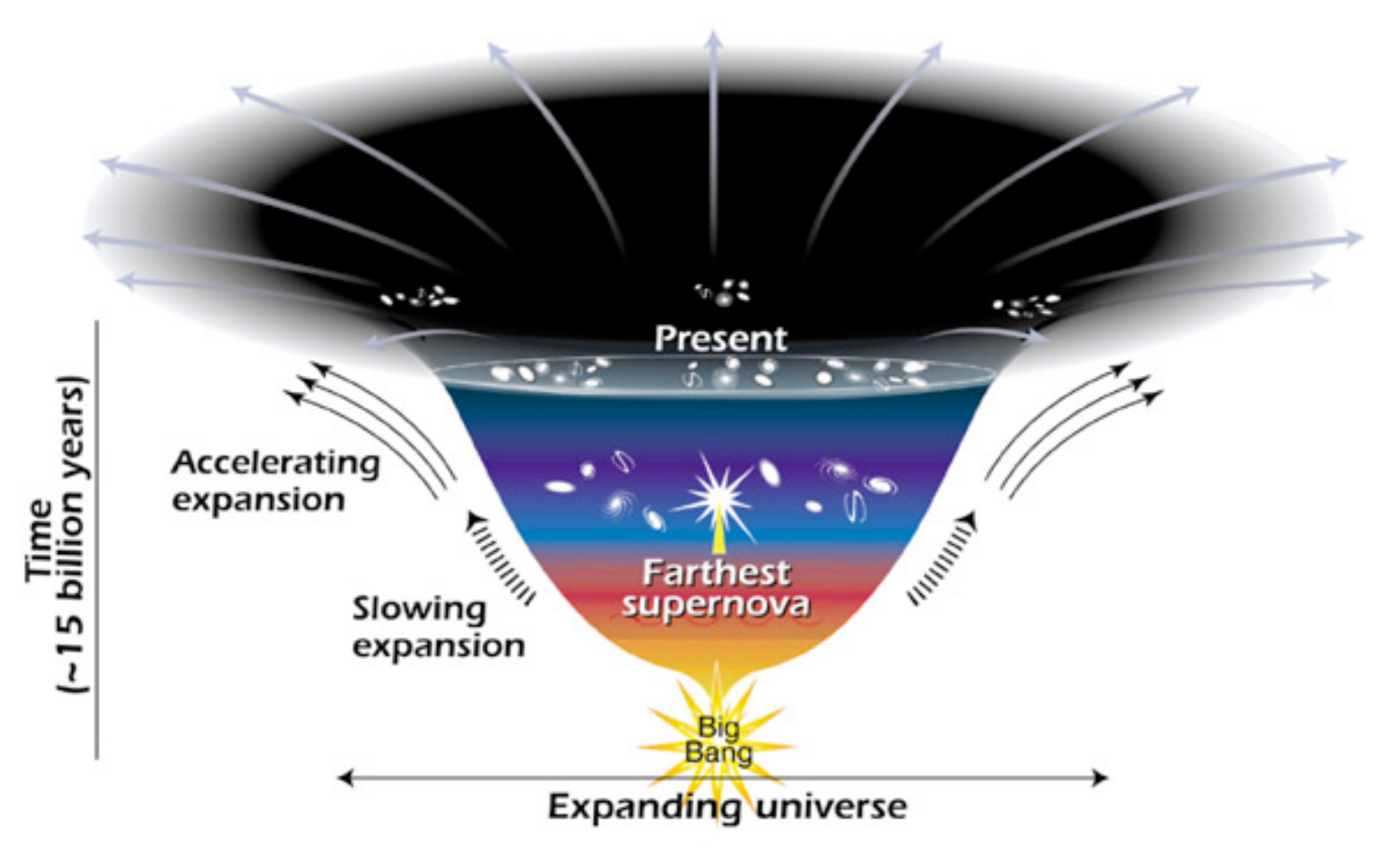
In the Aristotlean ‘standard model’ of cosmology (350 BC➛~1600 AD) the universe was *static* and *finite* and centred on the Earth



The Divine Comedy, Dante Allighieri (1321)

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

Today we have a new 'standard model' of the universe …
dominated by dark energy and undergoing accelerated expansion



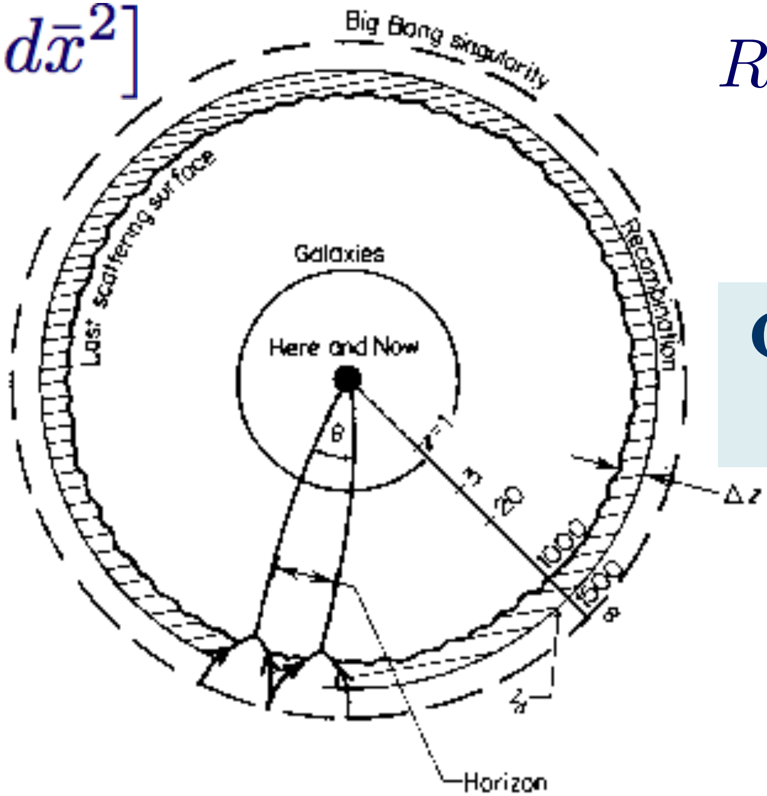
It too is '*simple*' and fits *all* the observational data
but lacks a *physical* foundation

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

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

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

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

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

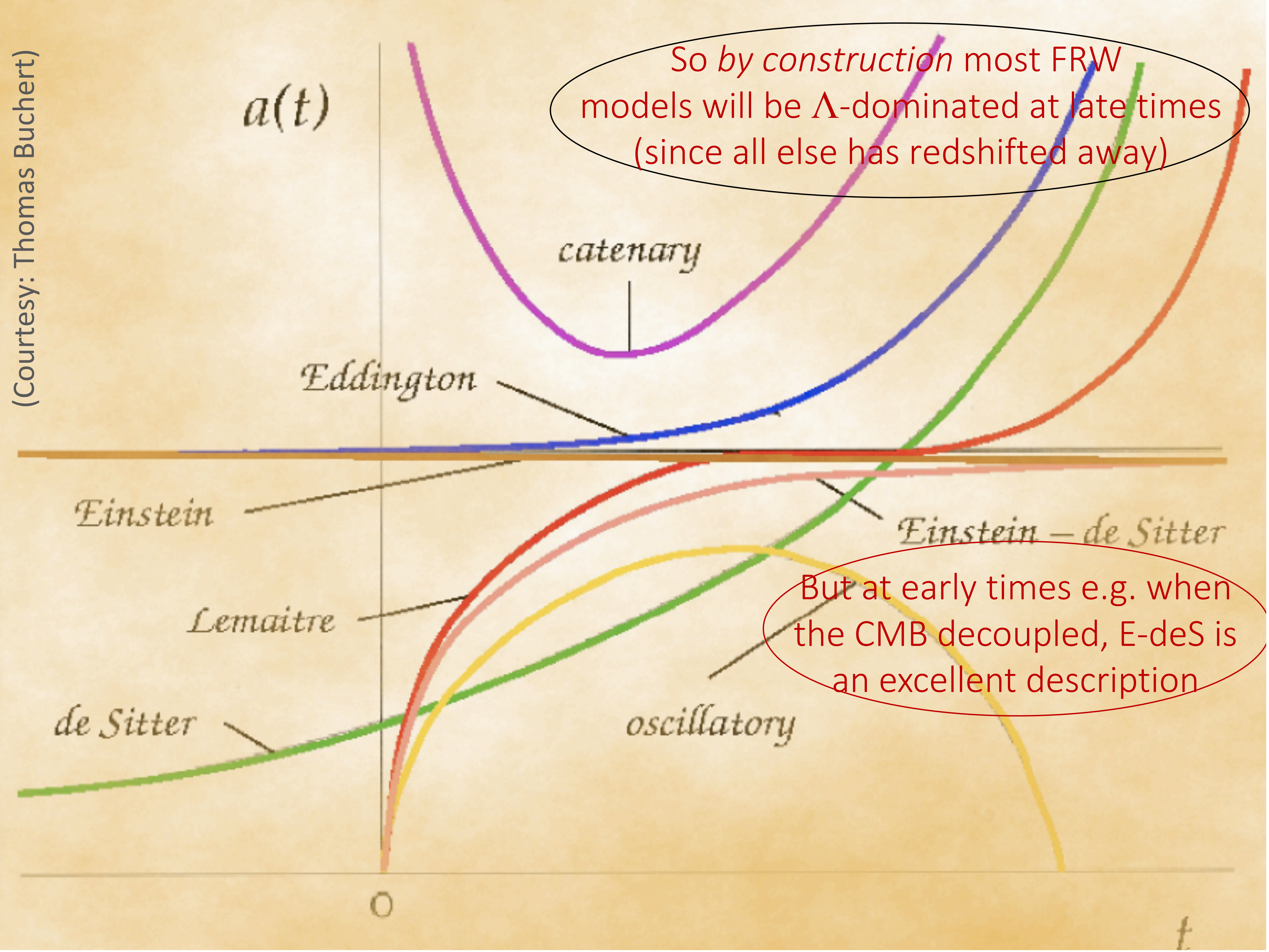
$$\Lambda = \lambda + 8\pi G_{\mathrm{N}}\langle\rho\rangle_{\text{fields}}$$

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

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

where : $z \equiv \frac{a_0}{a} - 1, \Omega_{\mathrm{m}} \equiv \frac{\rho_{\mathrm{m}}}{3H_0^2/8\pi G_{\mathrm{N}}}, \Omega_k \equiv \frac{k}{a_0^2 H_0^2}, \Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2}$

This implies the 'sum rule': $1 \equiv \Omega_{\mathrm{m}} + \Omega_k + \Omega_\Lambda$


(Courtesy: Thomas Buchert)
a(t)
So *by construction* most FRW models will be Λ-dominated at late times (since all else has redshifted away)
catenary
Eddington
Einstein
Einstein – de Sitter
But at early times e.g. when the CMB decoupled, E-deS is an excellent description
Lemaitre
de Sitter
oscillatory
0
t

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

$$+M^4 + M^2\Phi^2 \quad m_H^2 \simeq \frac{h_t^2}{16\pi^2}\int_0^{M^2} \mathrm{d}k^2 = \frac{h_t^2}{16\pi^2}M^2$$

super-renormalisable

$$-\mu^2\phi^\dagger\phi + \frac{\lambda}{4}(\phi^\dagger\phi)^2, m_H^2 = \lambda v^2/2$$

$$\mathcal{L}_{\rm eff} = F^2 + \bar{\Psi}\,\not{D}\Psi + \bar{\Psi}\Psi\Phi + (D\Phi)^2 + V(\Phi)$$

renormalisable

$$+\frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \dots$$

non-renormalisable

neutrino mass — proton decay, FCNC …

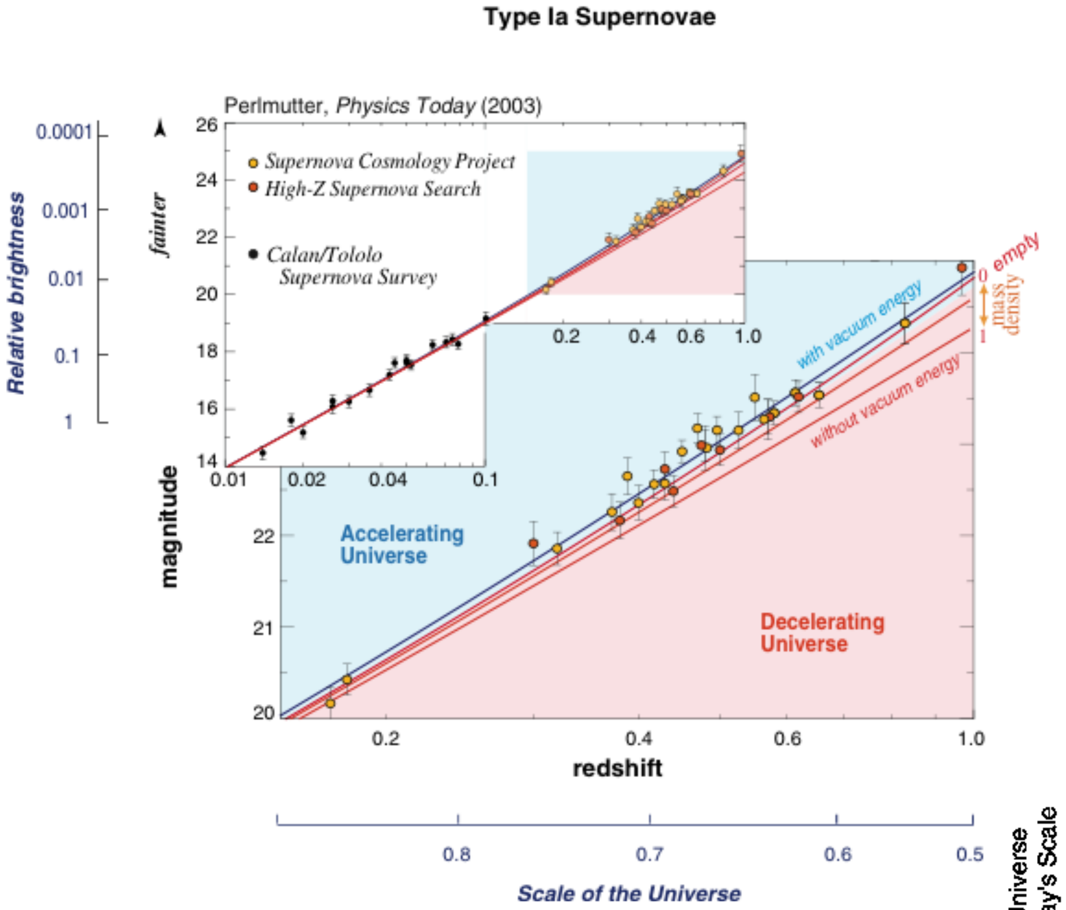
New physics beyond the SM ⇒ non-renormalisable operators suppressed by M^n which decouple as $M \to M_P$ … so neutrino mass is small, proton decay is slow

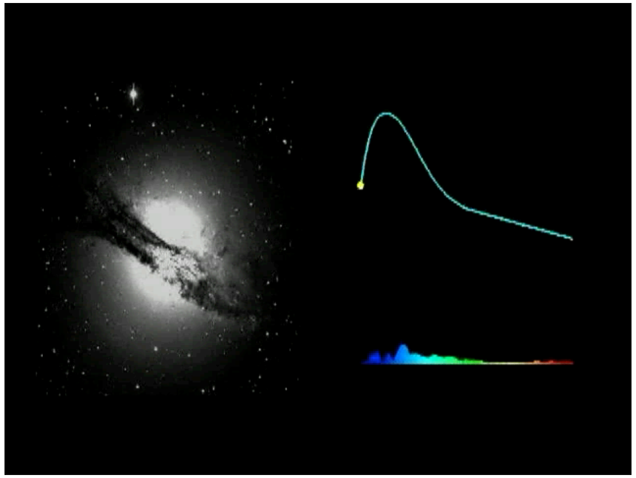
But as M is raised, the effects of the super-renormalisable operators are *exacerbated*
(One solution for Higgs mass divergence → 'softly broken' *supersymmetry* at O(TeV)
… or the Higgs could be *composite* – a pseudo Nambu-Goldstone boson)

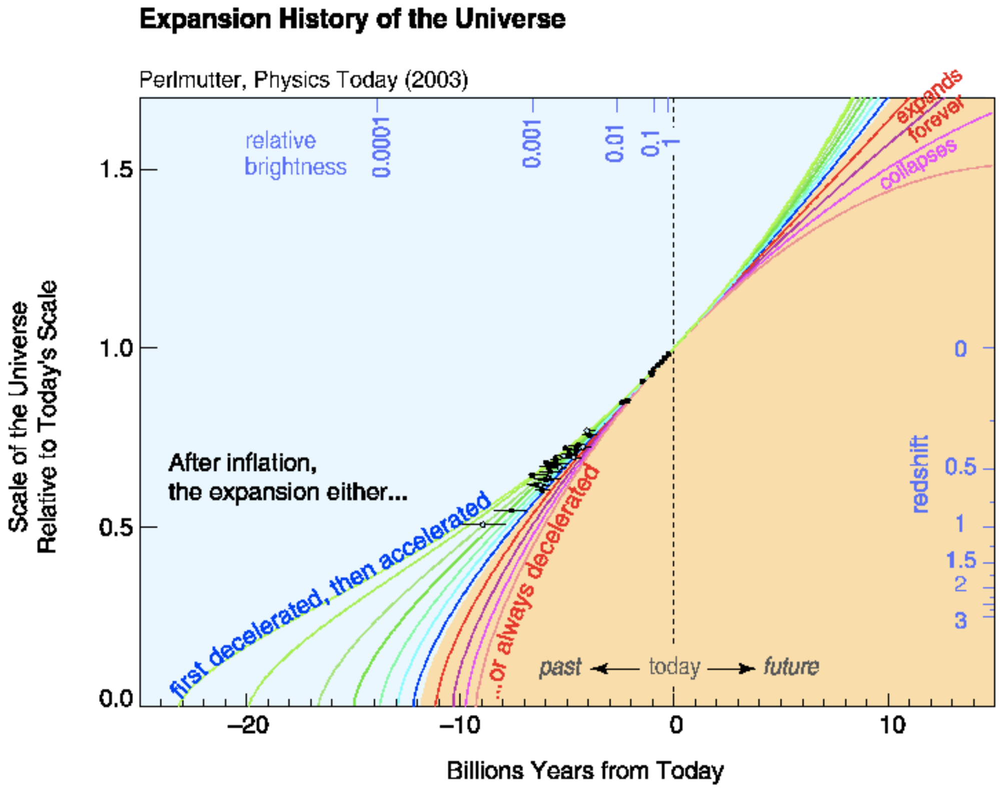
1st SR term **couples to gravity** so the *natural* expectation is $\rho_\Lambda \sim (1\ \text{TeV})^4 >> (1\ \text{meV})^4$
… *i.e.* the universe should have been inflating since (or collapsed at): $t \sim 10^{-12}$ s!
There must be some reason why this did *not* happen!

"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 $z \sim 0.5$

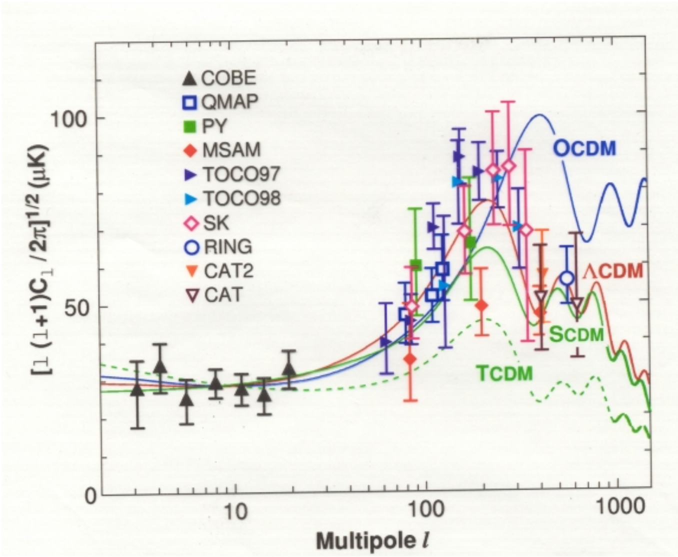




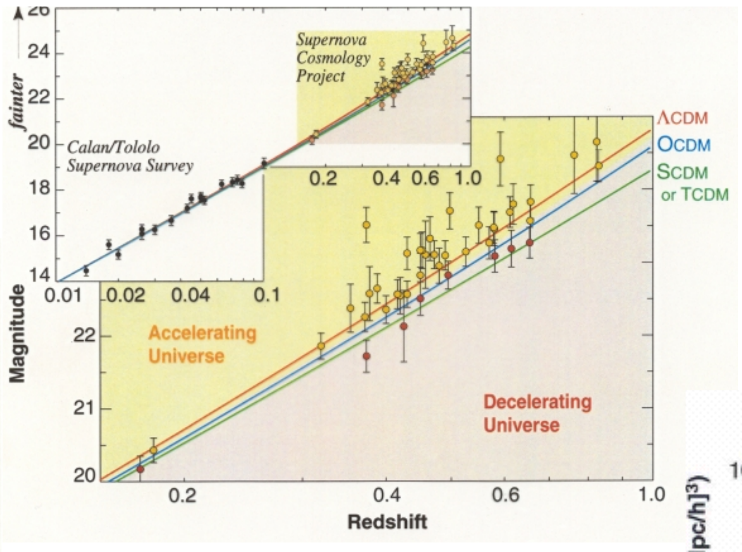


Note that the observations are actually made at *one* instant in time (the redshift is taken to be a proxy for time) … so it is not a *direct* measurement of acceleration

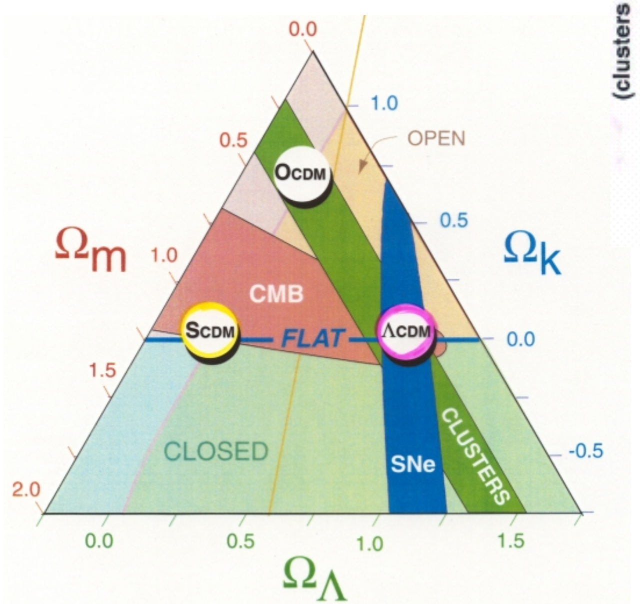
This has been interpreted as due to the effect of 'dark (vacuum) energy'

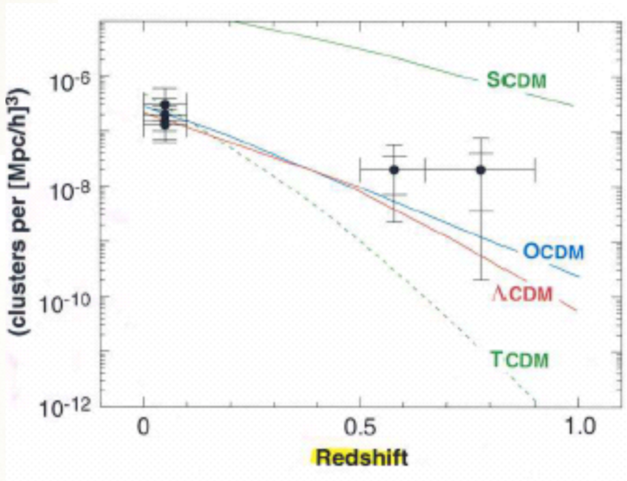


$\Omega_k \approx 0.0 \pm 0.03$



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



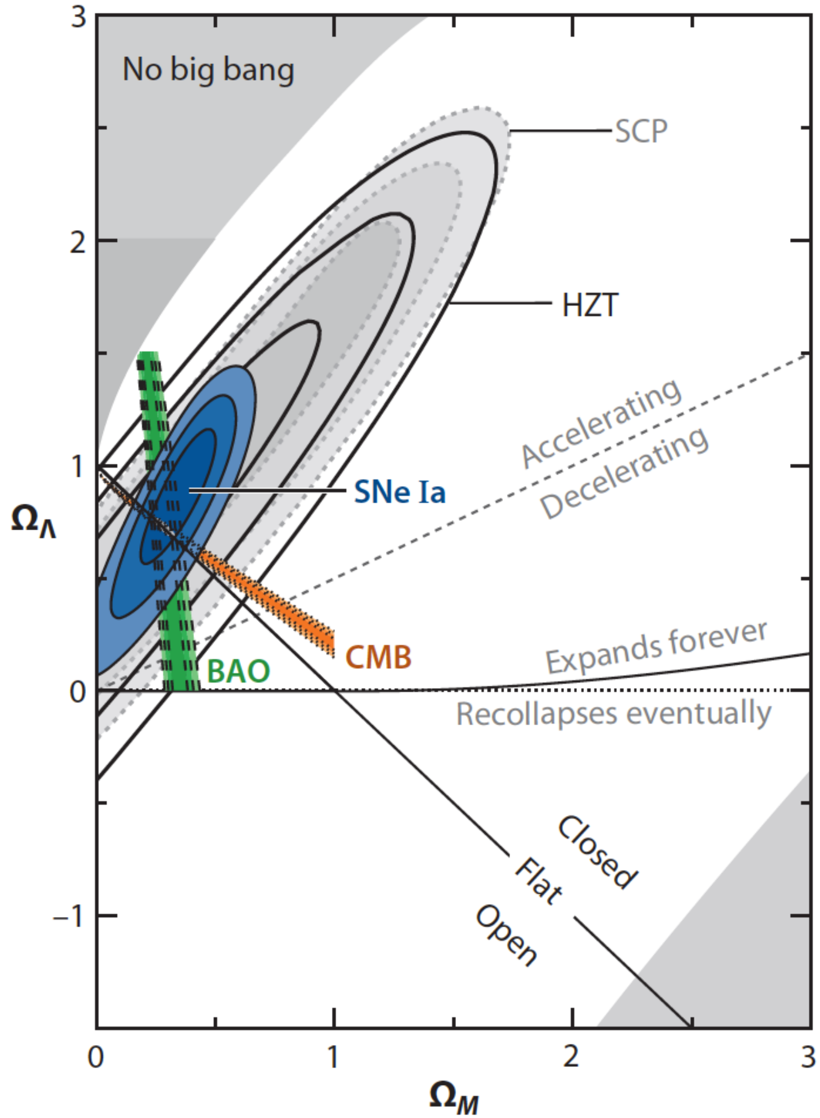


$\Omega_m \sim 0.3$

Bahcall, Ostriker, Perlmutter, Steinhardt (1999)

... because complementary observations suggest $\Omega_\Lambda \sim 0.7$, *using* $\Omega_m + \Omega_k + \Omega_\Lambda = 1$

CMB data 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



Goobar & Leibundgut, ARNPS 61:251,2011

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

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:

$$3\frac{\ddot{a}_{\mathcal{D}}}{a_{\mathcal{D}}} = -4\pi G\langle\rho\rangle_{\mathcal{D}} + \mathcal{Q}_{\mathcal{D}} ,$$

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

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

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

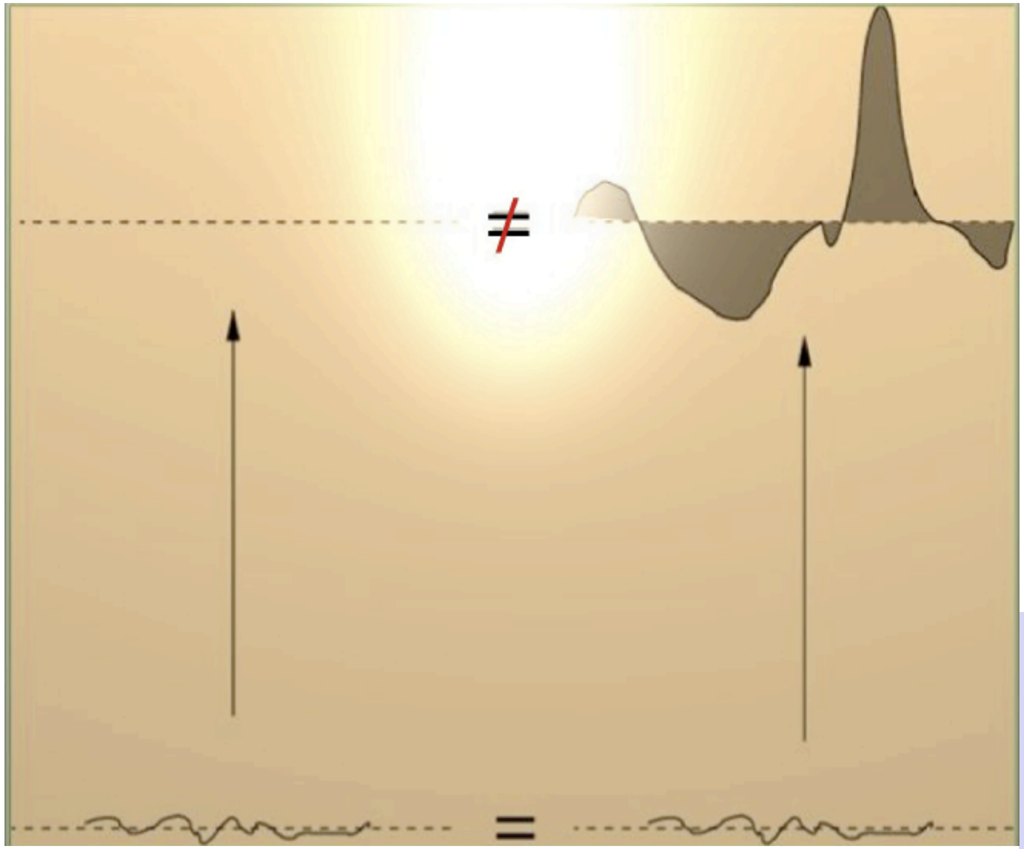
Variance of the expansion rate.

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

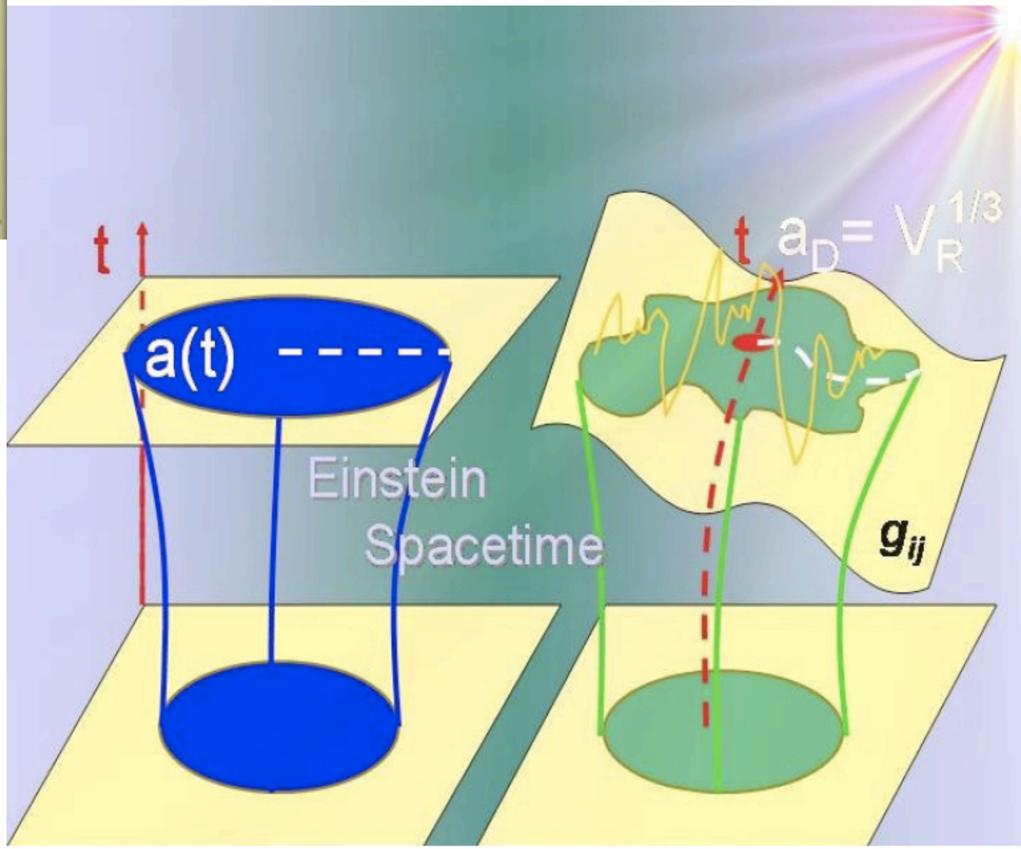
Whether the backreaction can be sufficiently large is an ***open question***



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

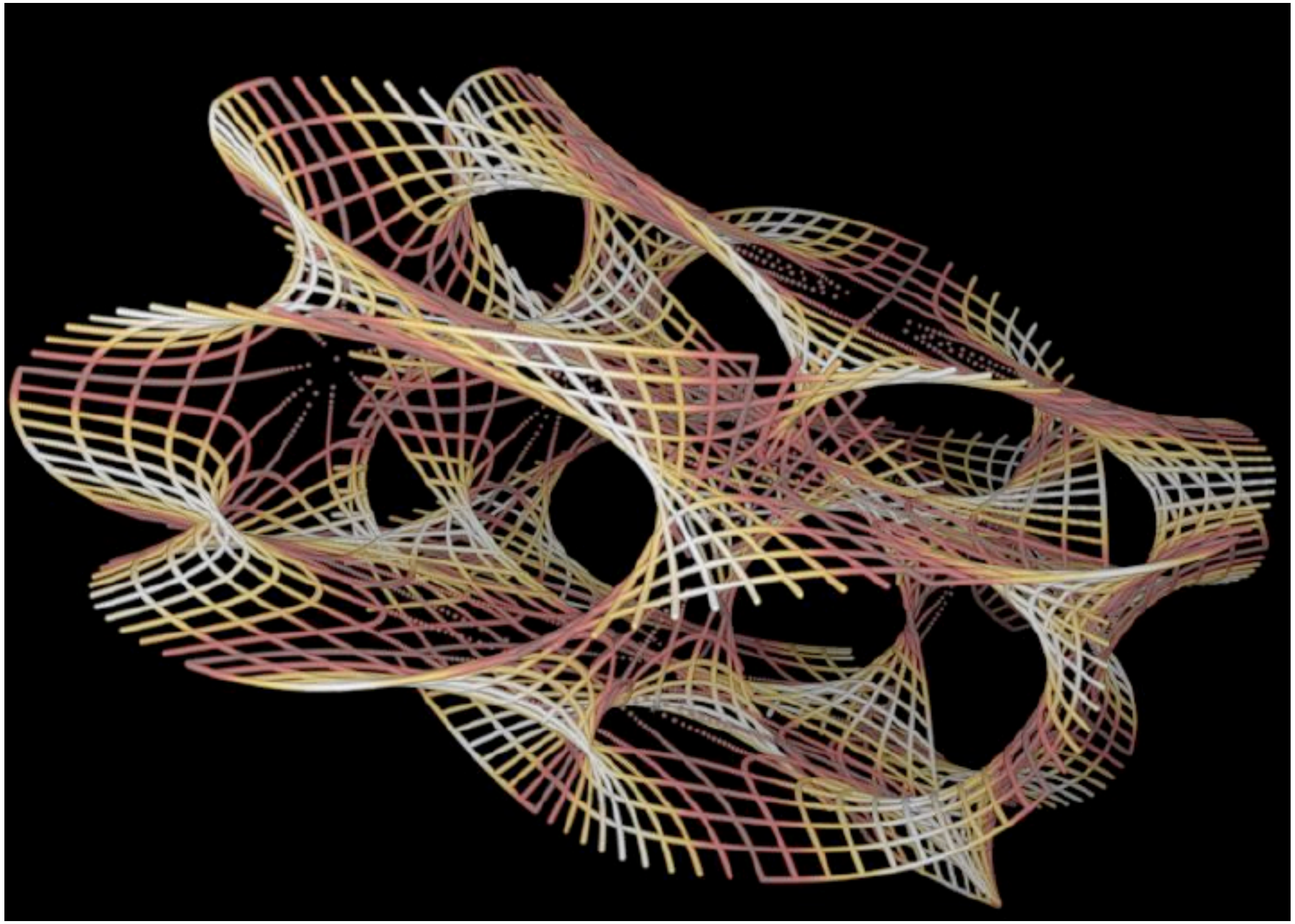
Due to structure formation, the homogeneous solution of Einstein's equations is distorted - its average must be taken over the *actual* geometry

This can be done using *relativistic* numerical simulations of structure formation which have just begun to be performed



Courtesy: Thomas Buchert

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



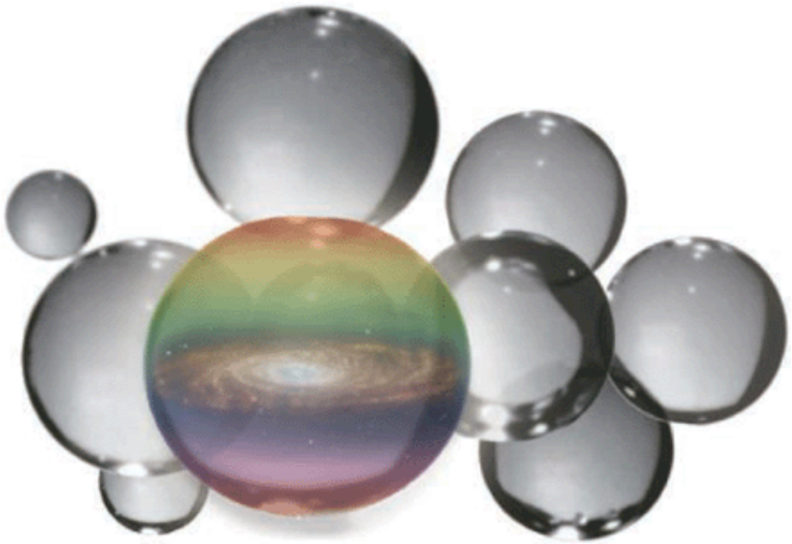
Given the variety of flux choices and the number of local minima in the flux potential, the total number of vacuua is *very* large - perhaps 10^{500}

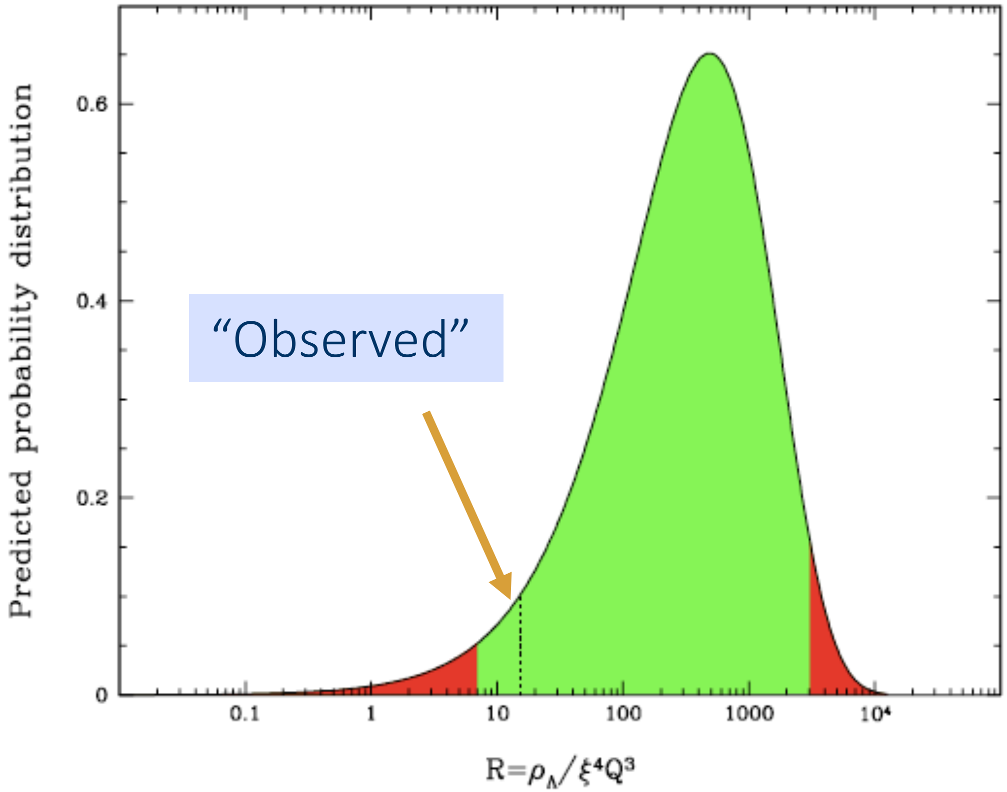
The existence of the huge landscape of possible vacuua in string theory (with moduli stabilised through background fluxes) has remotivated attempts at an 'anthropic' explanation for $\Omega_\Lambda \sim \Omega_m$

Is it "observer bias"? … galaxies would not have formed if Λ had been much higher

(Weinberg 1989, Efstathiou 1995, Martel, Shapiro, Weinberg 1998 …)

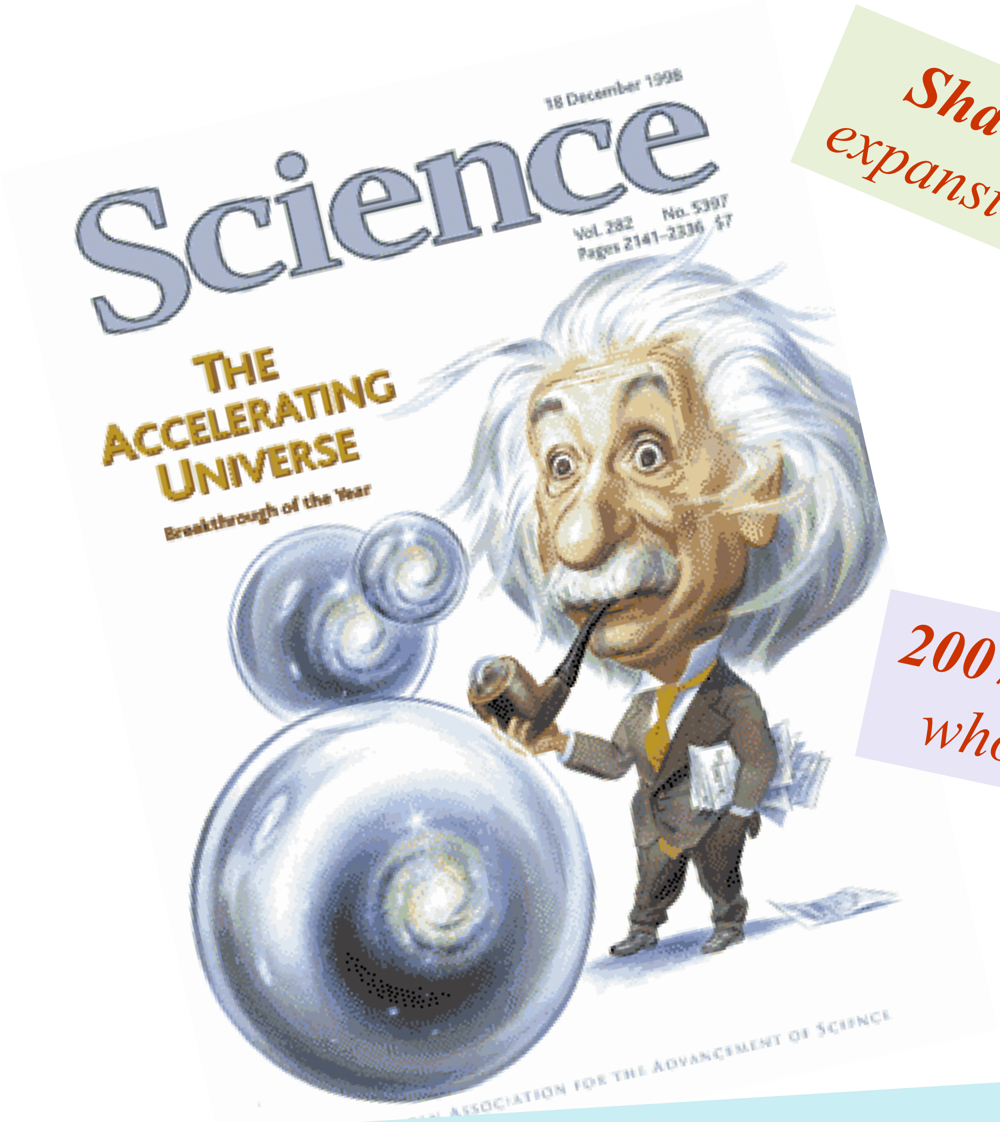
(Courtesey: *Science*)





(Tegmark *et al* 2006)

But the 'anthropic prediction' of Λ from considerations of galaxy formation is significantly *different* than the observationally inferred value (since galaxies formed at redshift $z \sim 5$ when ρ_m was ~100 times higher!)



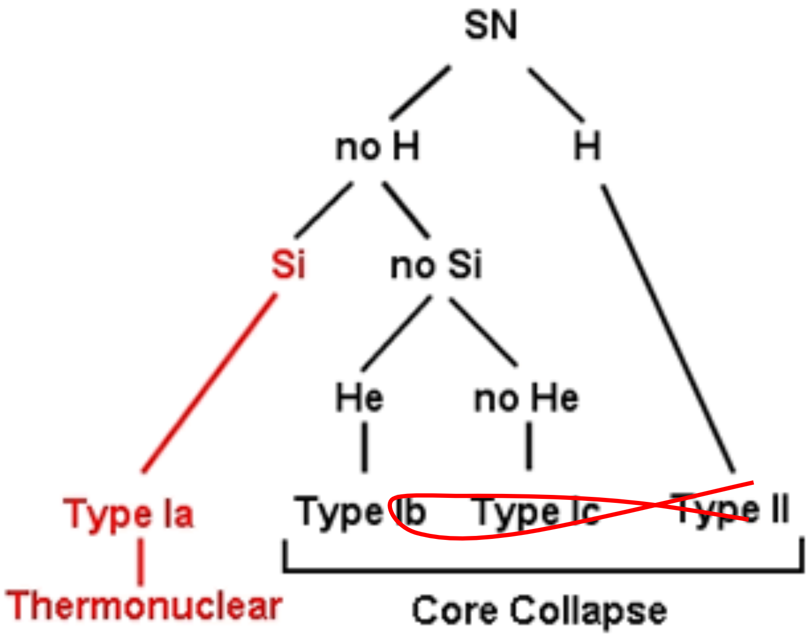
Shaw Prize 2006 "*for discovering that the expansion rate of the universe is accelerating*"

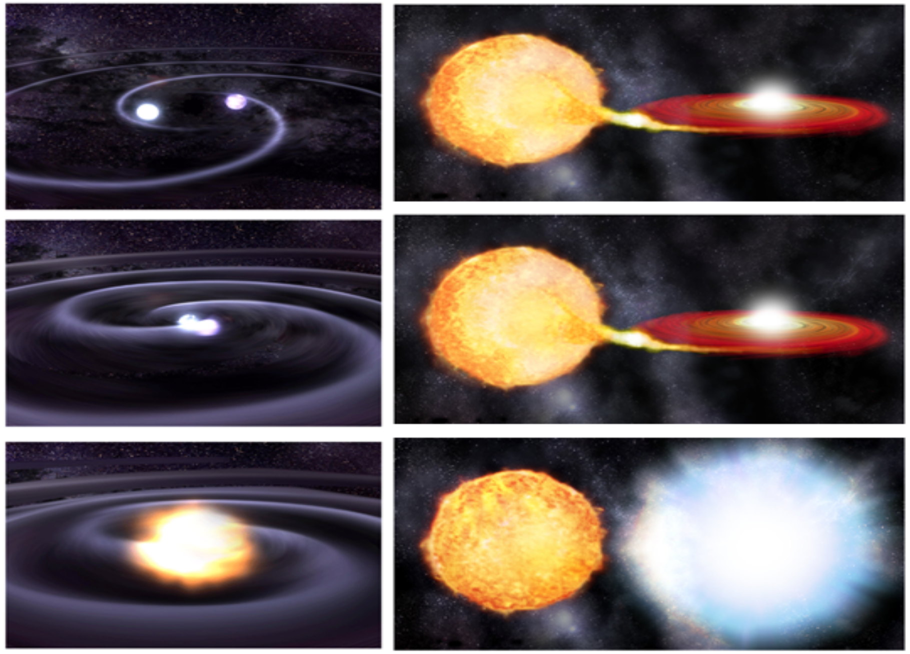
2007 Gruber Cosmology Prize *to two teams who discovered the accelerating universe*

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

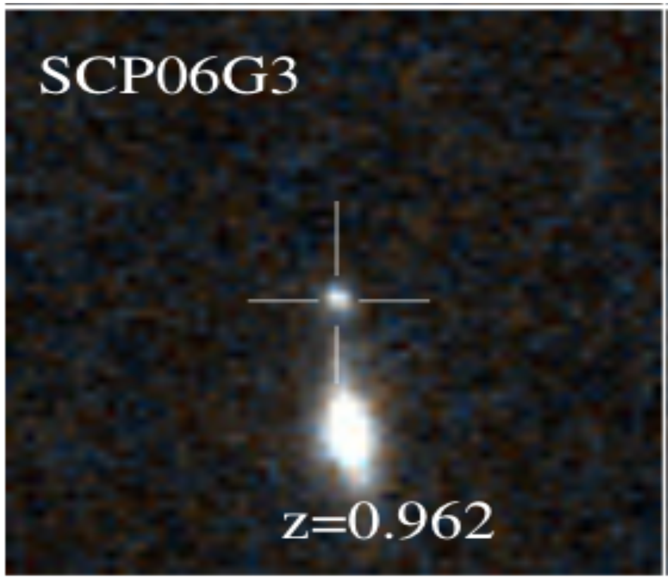
The ***2015 Breakthrough Prize in Fundamental Physics*** *for the most unexpected discovery that the expansion of the universe is accelerating ...*

What are Type Ia supernovae?

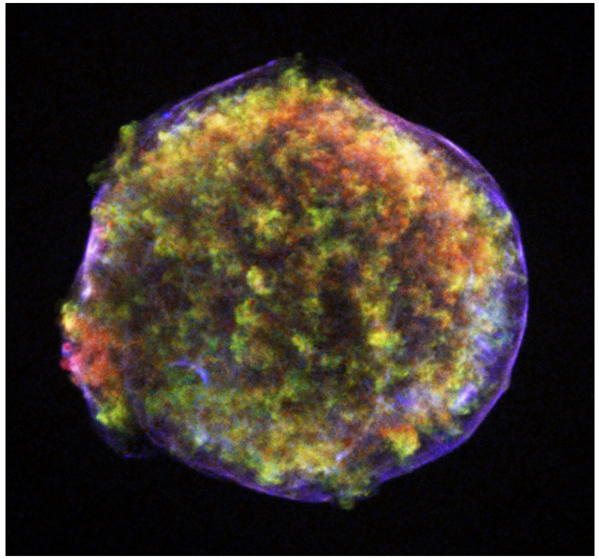




Suzuki *et al*, 1105.3470

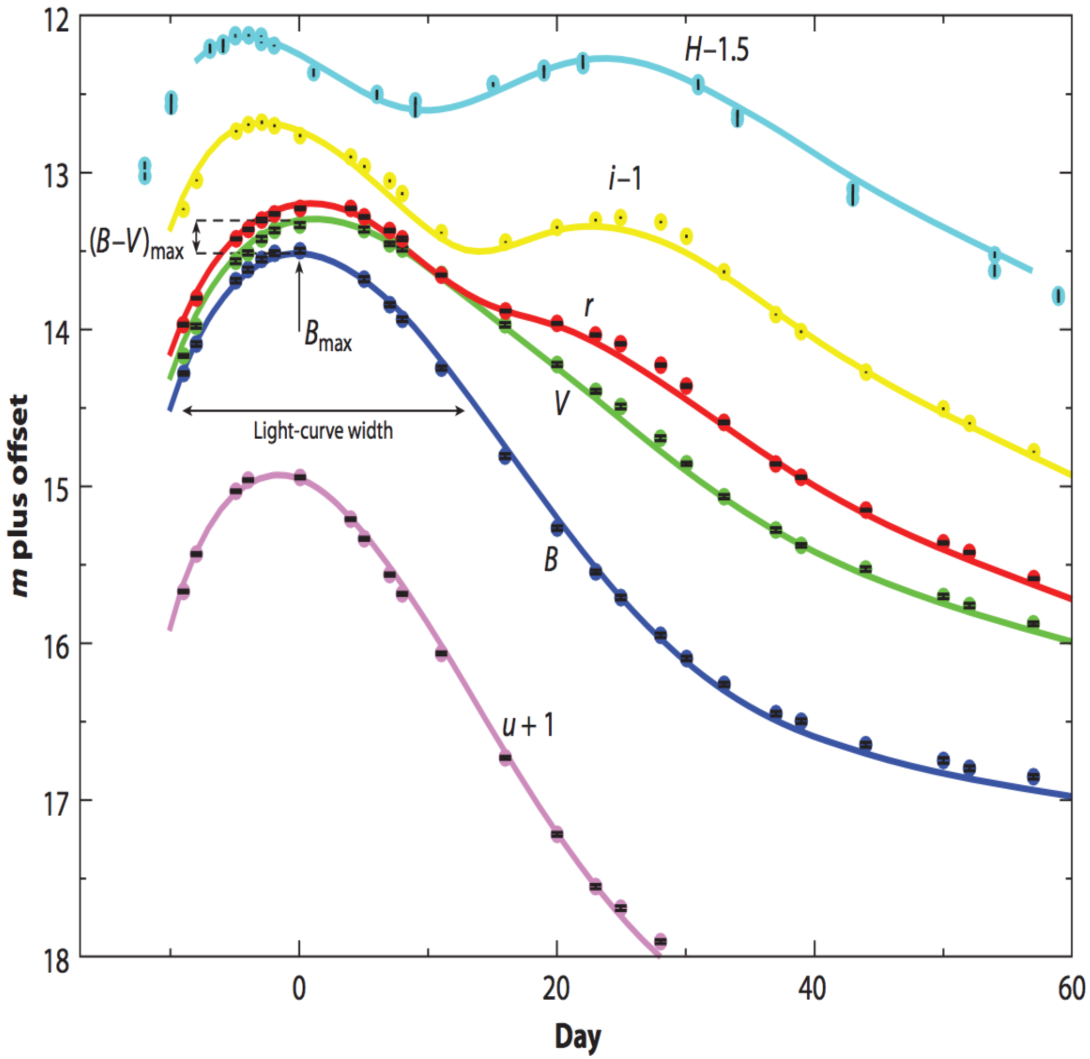


~500 years

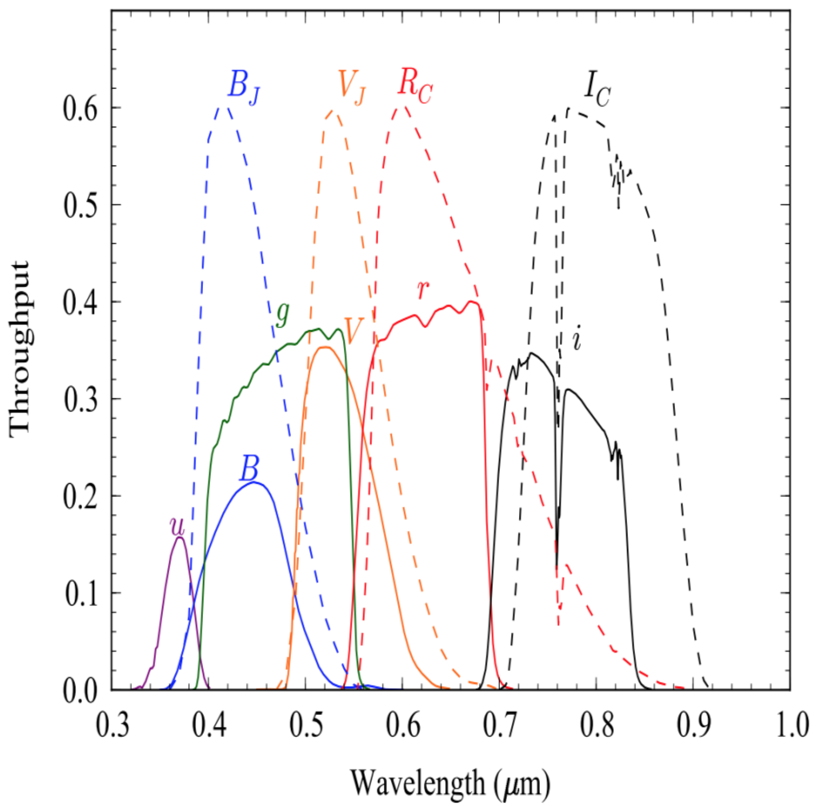


SN 1572 (Tyccho)

What are Type Ia supernovae?



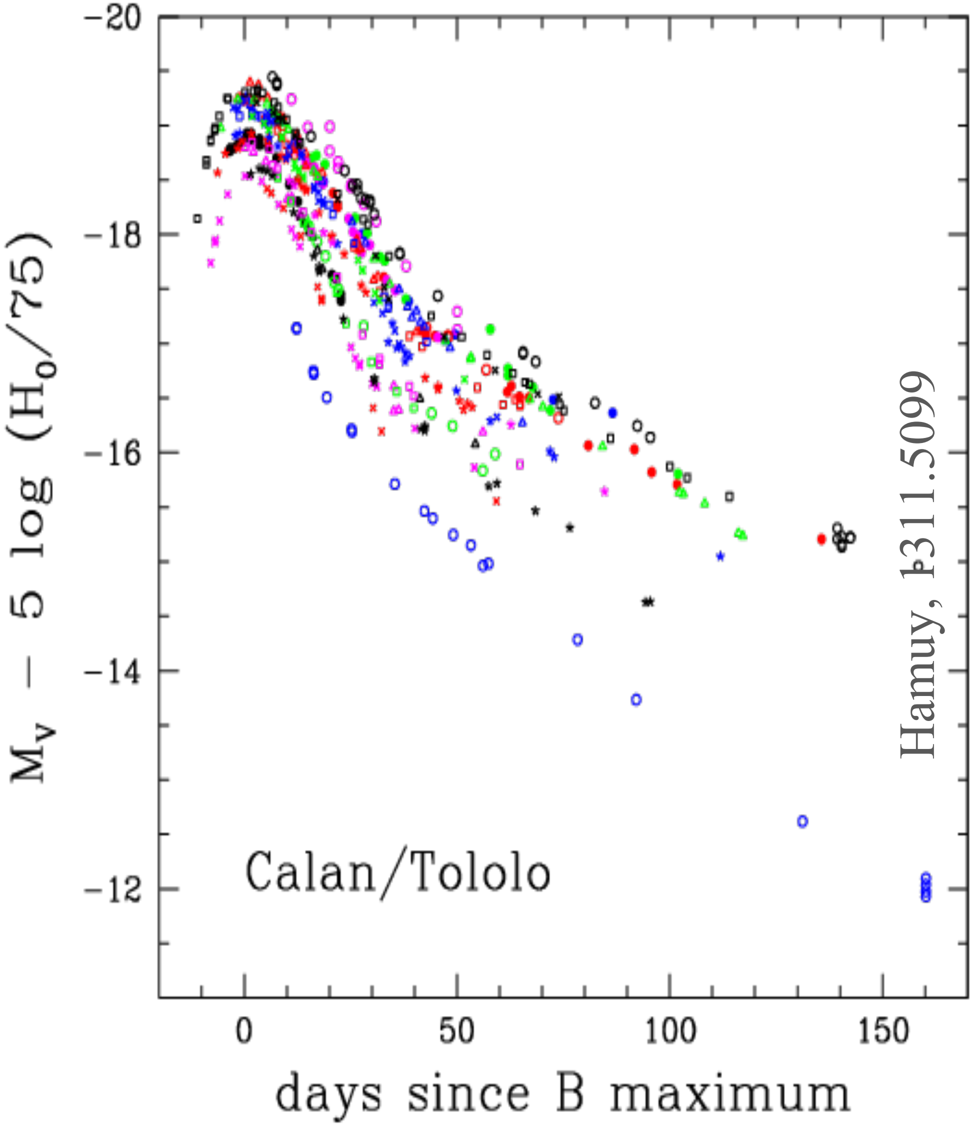
$$m = -2.5\log(F/F_{\mathrm{ref}})$$

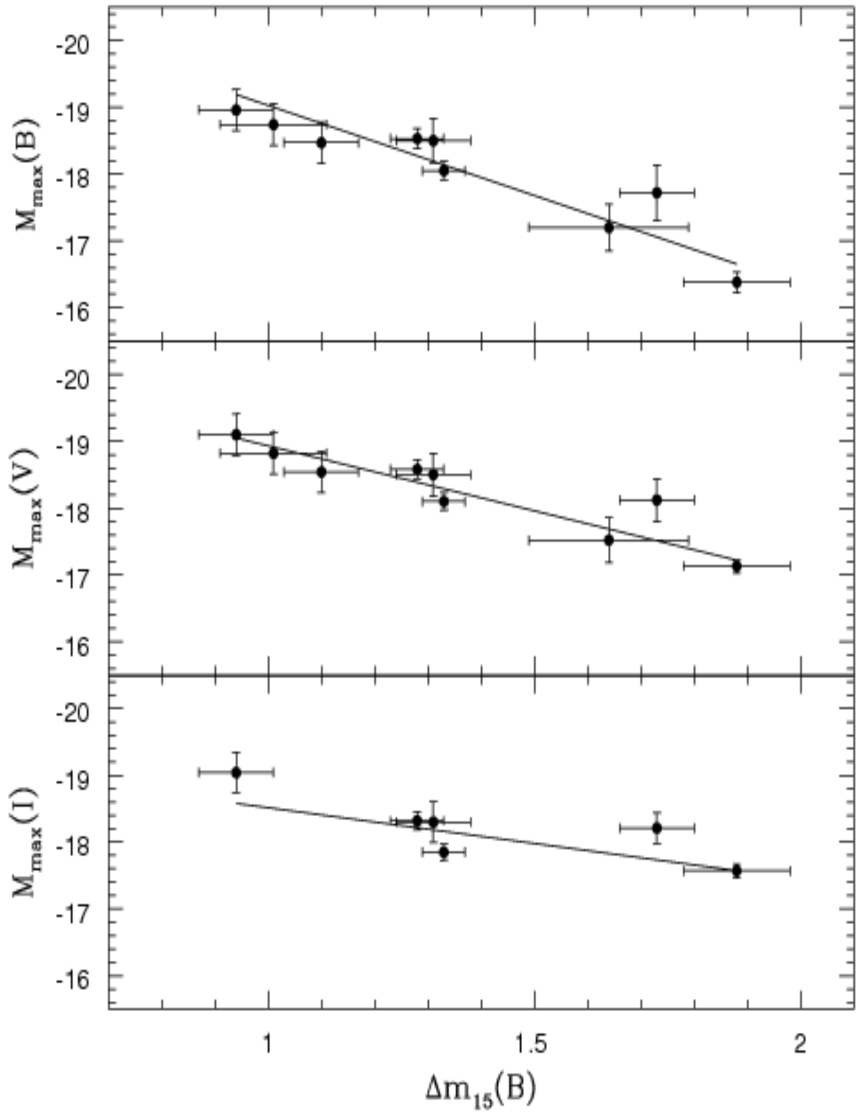


Goobar & Leibundgut, ARNPS 61:251,2011

What are Type Ia supernovae?

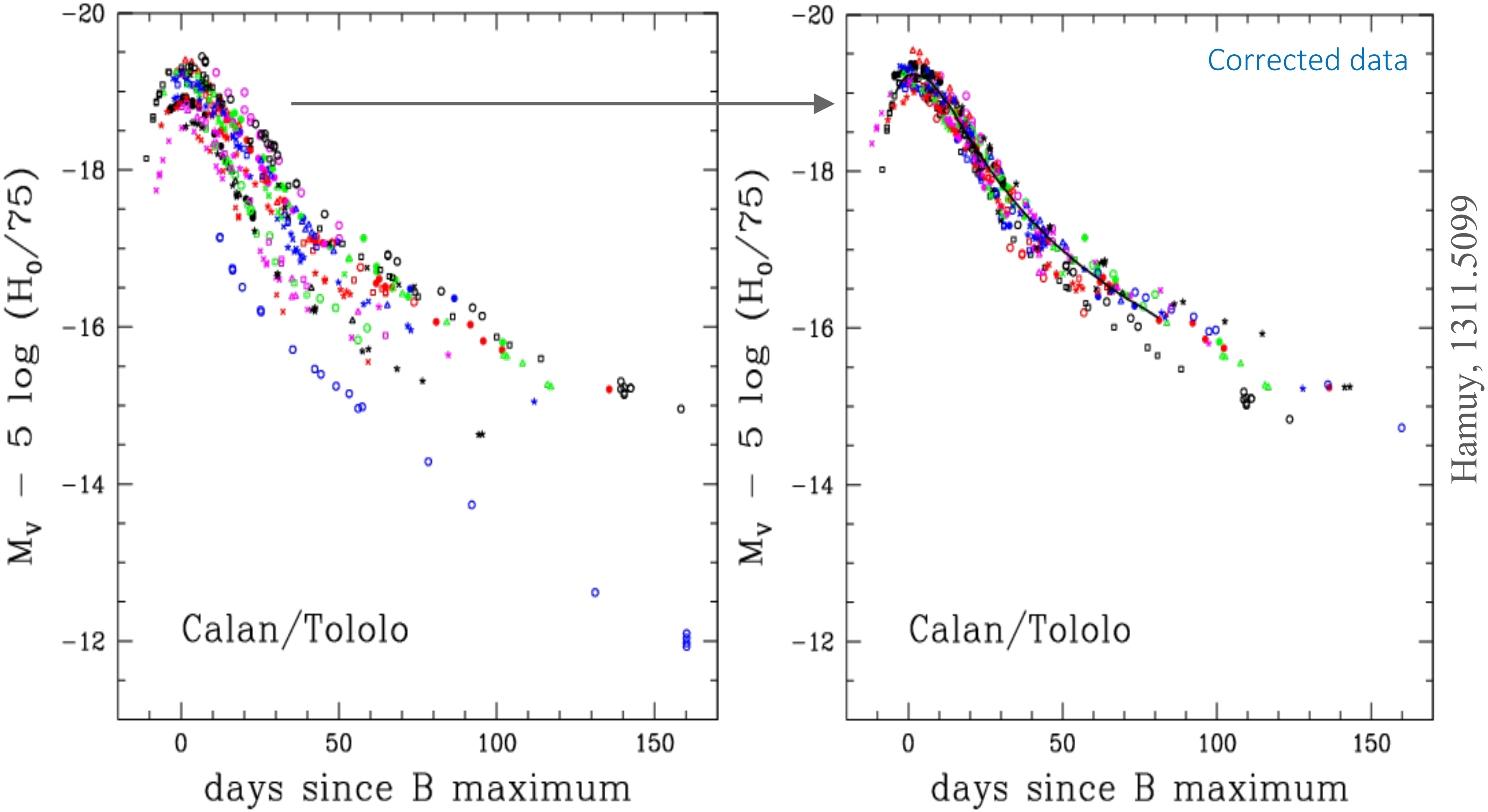
Not standard candles … but peak luminosity correlated with width of light curve (and colour)





Phillips, 1993

Type Ia supernovae as 'standardisable candles'



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

Use a standard template (e.g. SALT 2) to make 'stretch' and 'colour' corrections …

What are Type Ia supernovae?

SALT 2 parameters

Betoule *et al*., A&A568:A22,2014

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

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

Cosmology

$$\mu \equiv 25 + 5\log_{10}(d_{\rm L}/{\rm Mpc}), \quad \text{where:}$$

$$d_{\rm L} = (1+z)\frac{d_{\rm H}}{\sqrt{\Omega_k}}\,{\rm sinn}\left(\sqrt{\Omega_k}\int_0^z \frac{H_0{\rm d}z'}{H(z')}\right),$$

$$d_{\rm H} = c/H_0, \quad H_0 \equiv 100h\ {\rm km\,s^{-1}Mpc^{-1}},$$

$$H = H_0\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda},$$

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

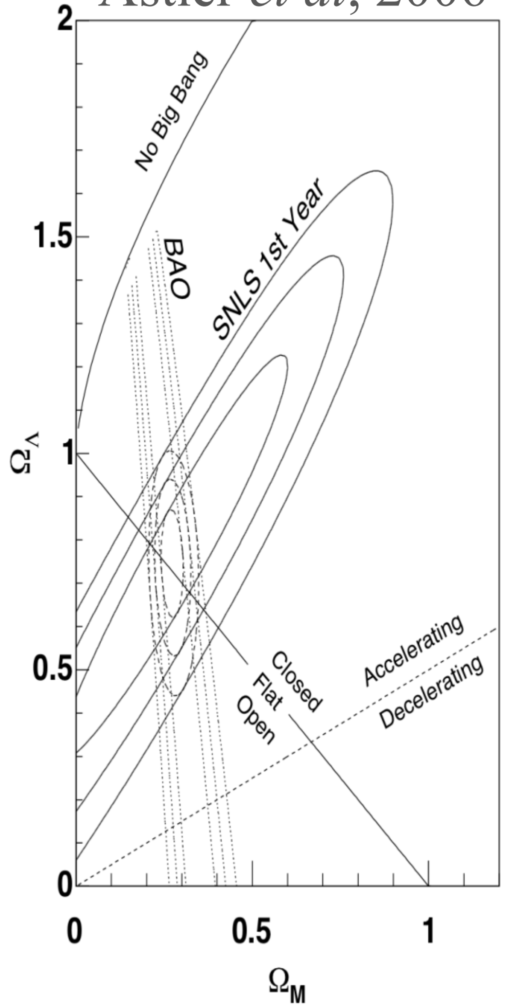
What is measured?

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

values?

How strong is the evidence for cosmic acceleration?

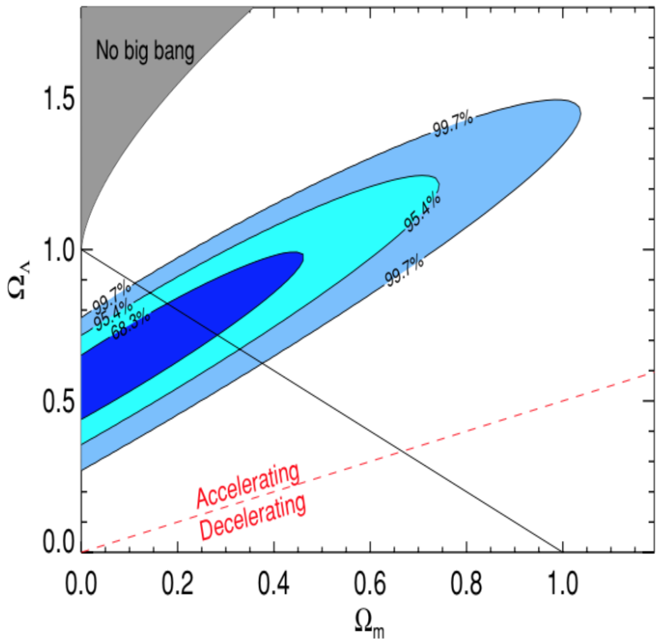
Astier *et al*, 2006



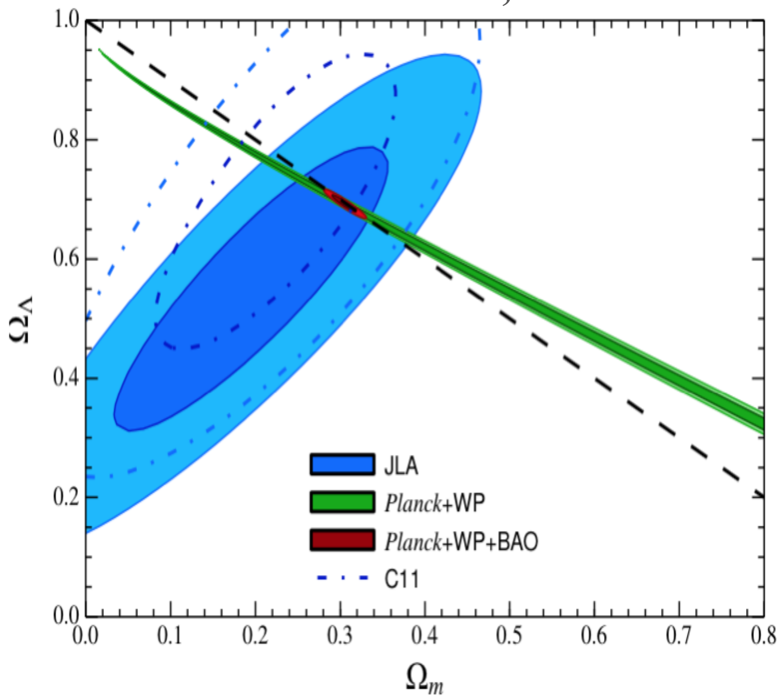
"SN data alone require* cosmic acceleration at >99.999% confidence, including systematic effects"

Conley *et al*, 2011

*from the magnitude-redshift plot



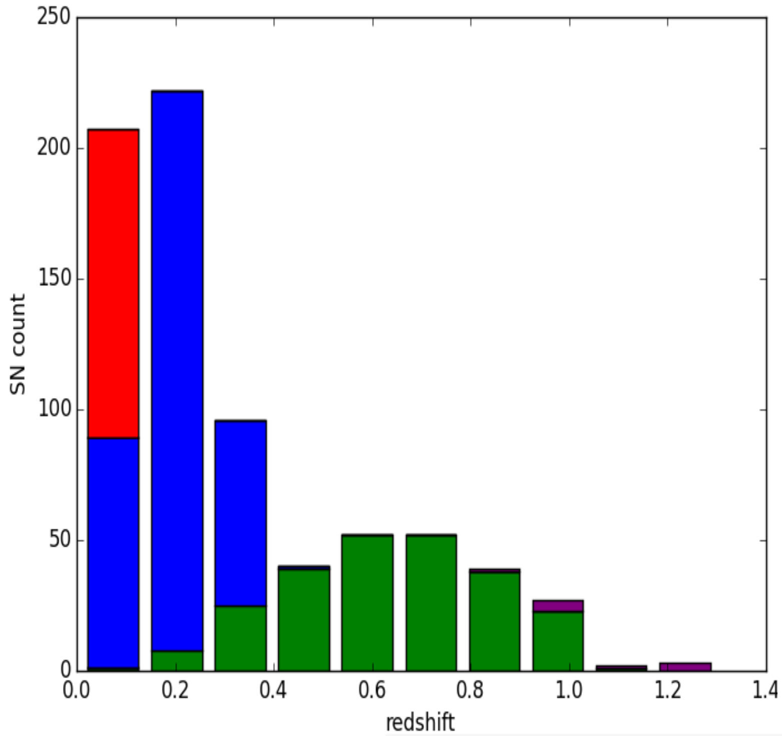
Betoule *et al*, 2014

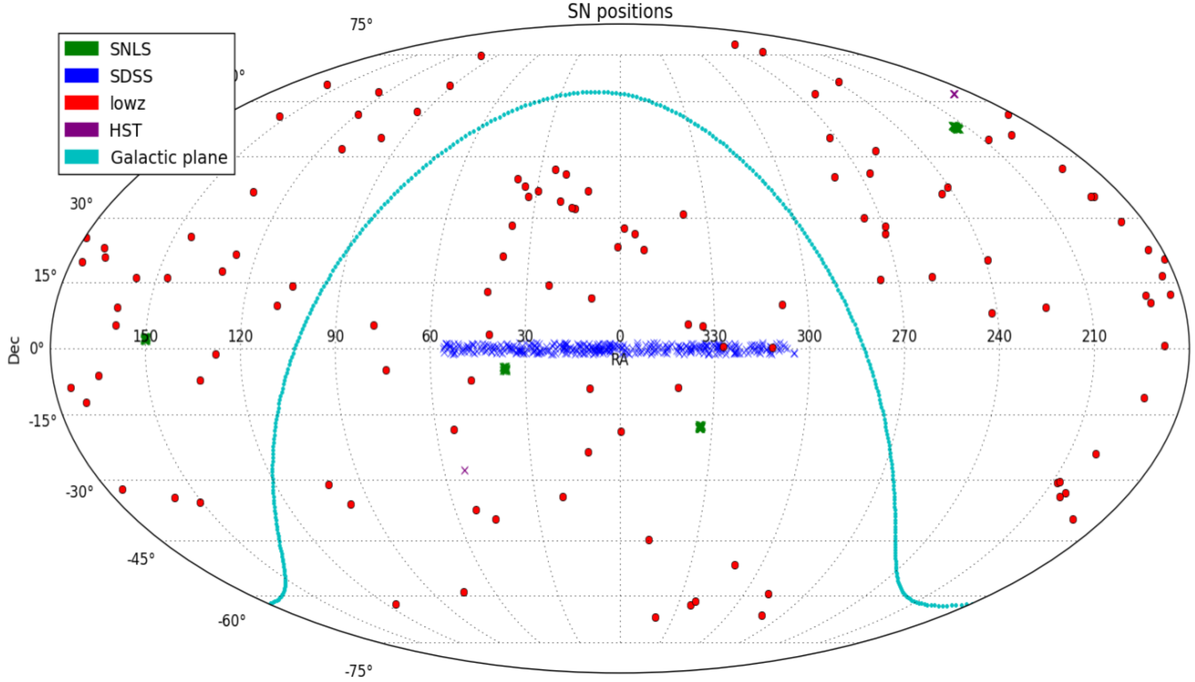


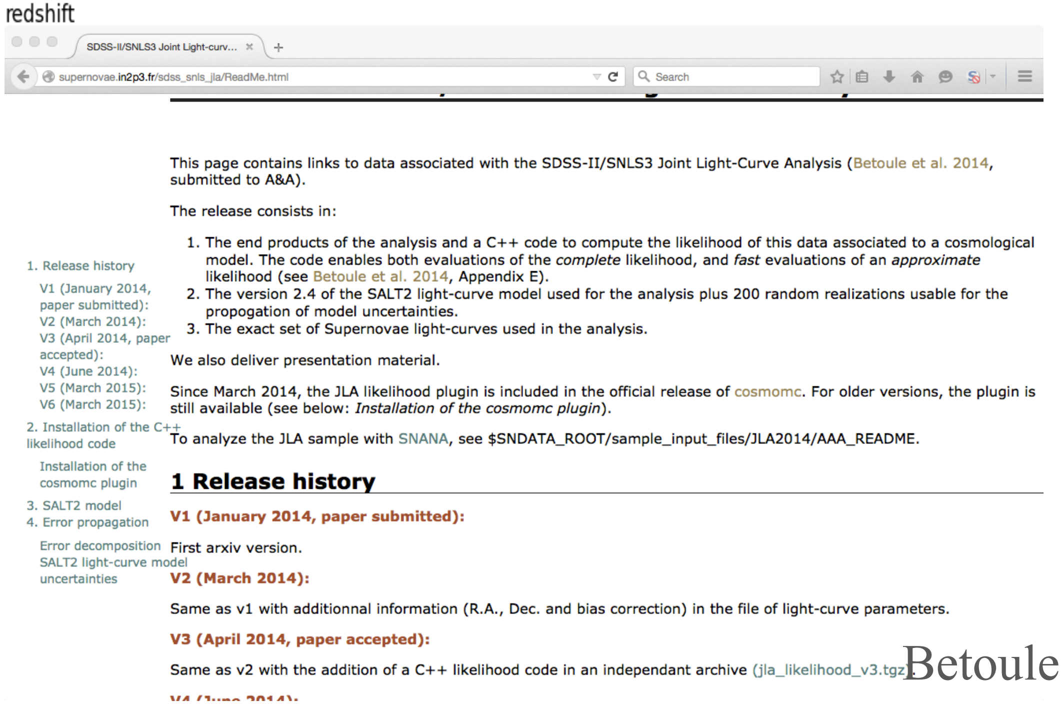
$$\chi^2 = \sum_{objects} \frac{(\mu_B - 5\log_{10}(d_L(\theta,z)/10pc))^2}{\sigma^2(\mu_B) + \sigma_{int}^2}$$

But they *assume* ΛCDM and adjust σ_{int} to get a 'constrained' χ^2 of 1/d.o.f. for the fit!

Joint Lightcurve Analysis data (740 SNe)






SDSS-II/SNLS3 Joint Light-curv...

supernovae.in2p3.fr/sdss_snls_jla/ReadMe.html

Search

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

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 propogation 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 additionnal 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

Data is now *publicly* available

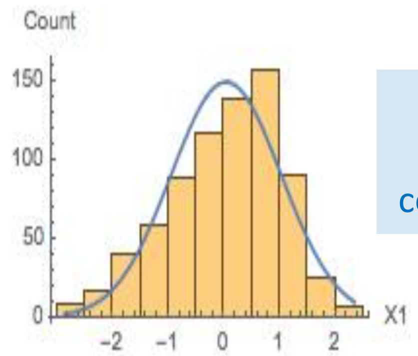
Betoule *et al*, A&A568:A22,2014

Construct a Maximum Likelihood Estimator

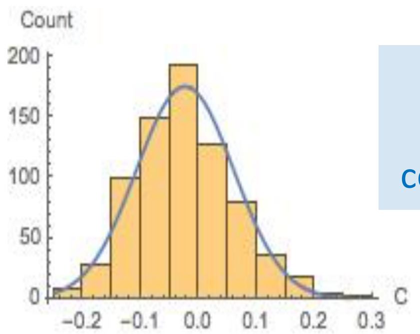
$$\mathcal{L} = \text{probability density}(\text{data}|\text{model})$$

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

Well-approximated as Gaussian



JLA data
'Stretch'
corrections



JLA data
'Colour'
corrections

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

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

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

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

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

Likelihood

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

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

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

intrinsic distributions

cosmology

SALT2

Confidence regions

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

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

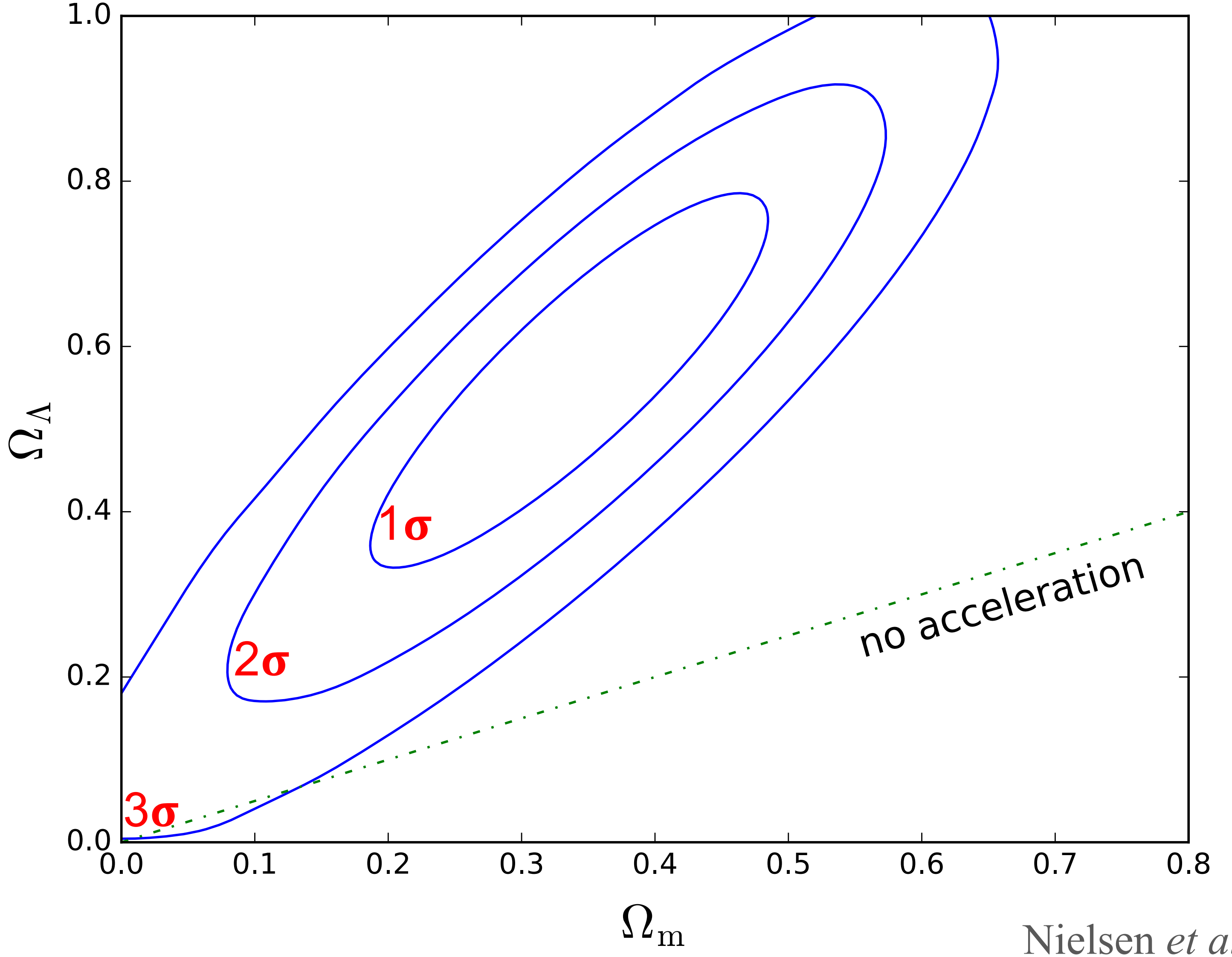
$$\mathcal{L}_p(\theta) = \max_{\phi} \mathcal{L}(\theta,\phi)$$

1,2,3-sigma

solve for Likelihood value

Data consistent with uniform expansion @3σ!

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)



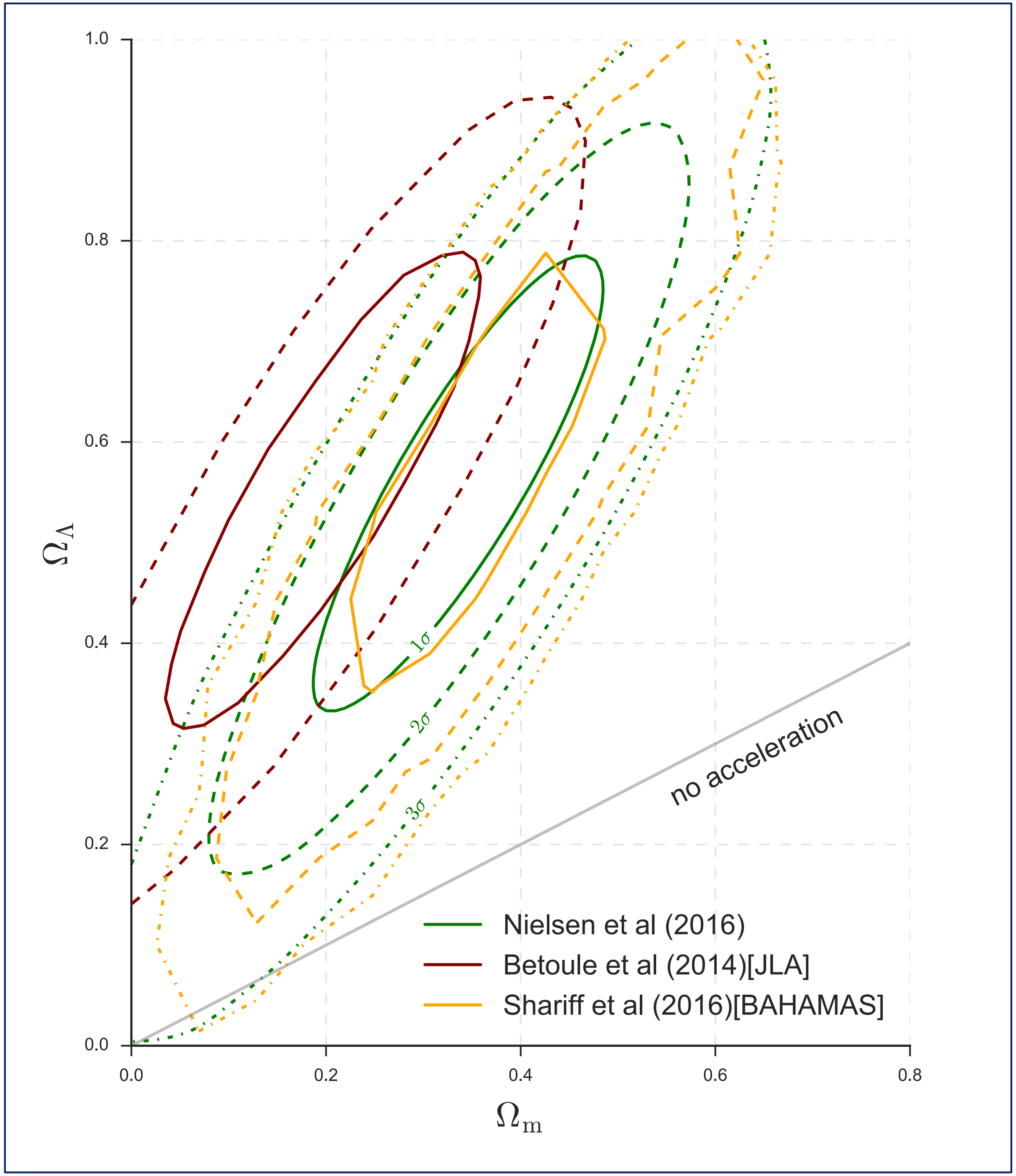
profile likelihood

<u>MLE, *best fit*</u>

Ω_M	0.341
Ω_Λ	0.569
α	0.134
x_0	0.038
σ^2_{x0}	0.931
β	3.058
c_0	-0.016
σ^2_{c0}	0.071
M_0	-19.05
σ^2_{M0}	0.108

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

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



Shariff, Jiao, Trotta & 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

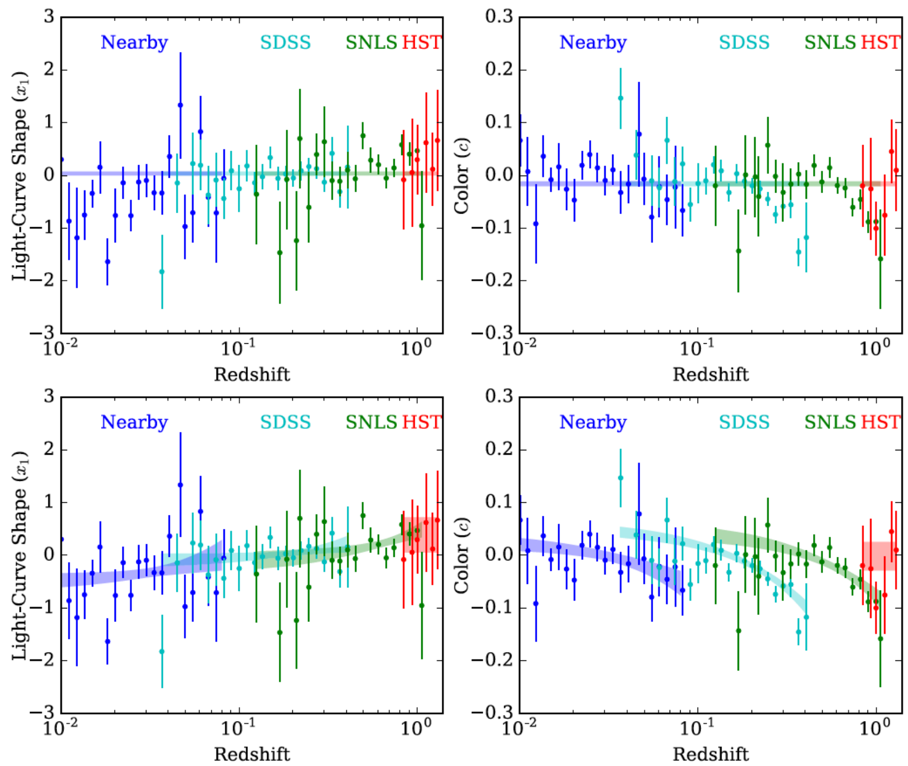


Figure 1. Binned x_1 (left panels) and c (right panels) light curve parameters as a function of redshift for the JLA sample. The trend of color with redshift within each ground-based sample is expected due to the combination of the color-luminosity relation combined with redshift-dependent luminosity 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.

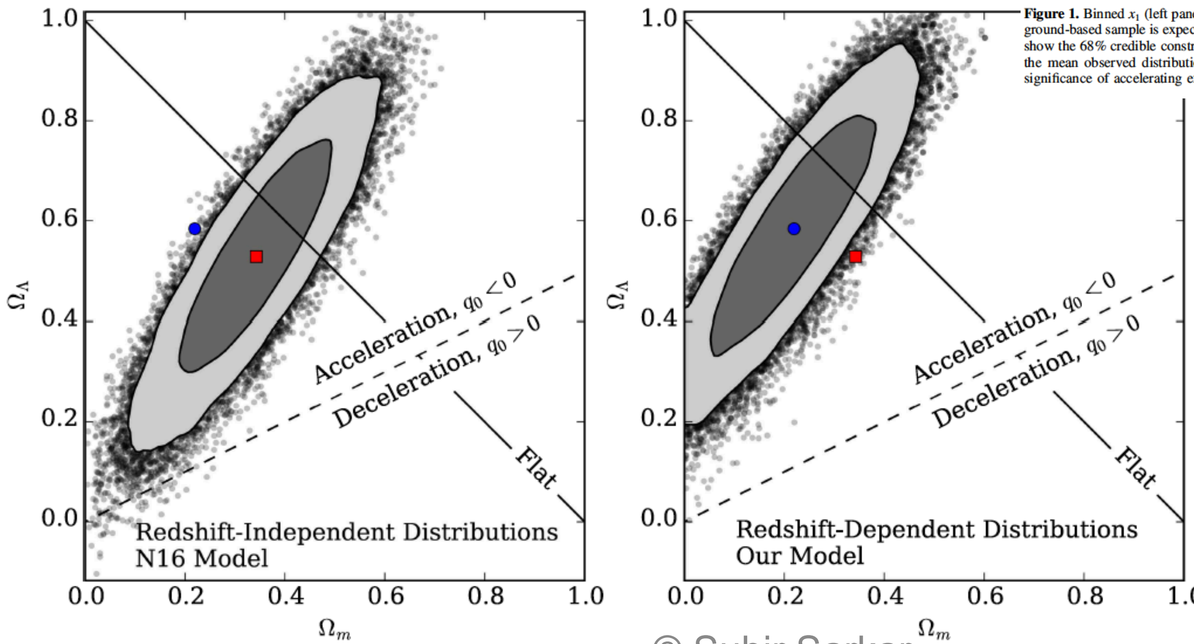
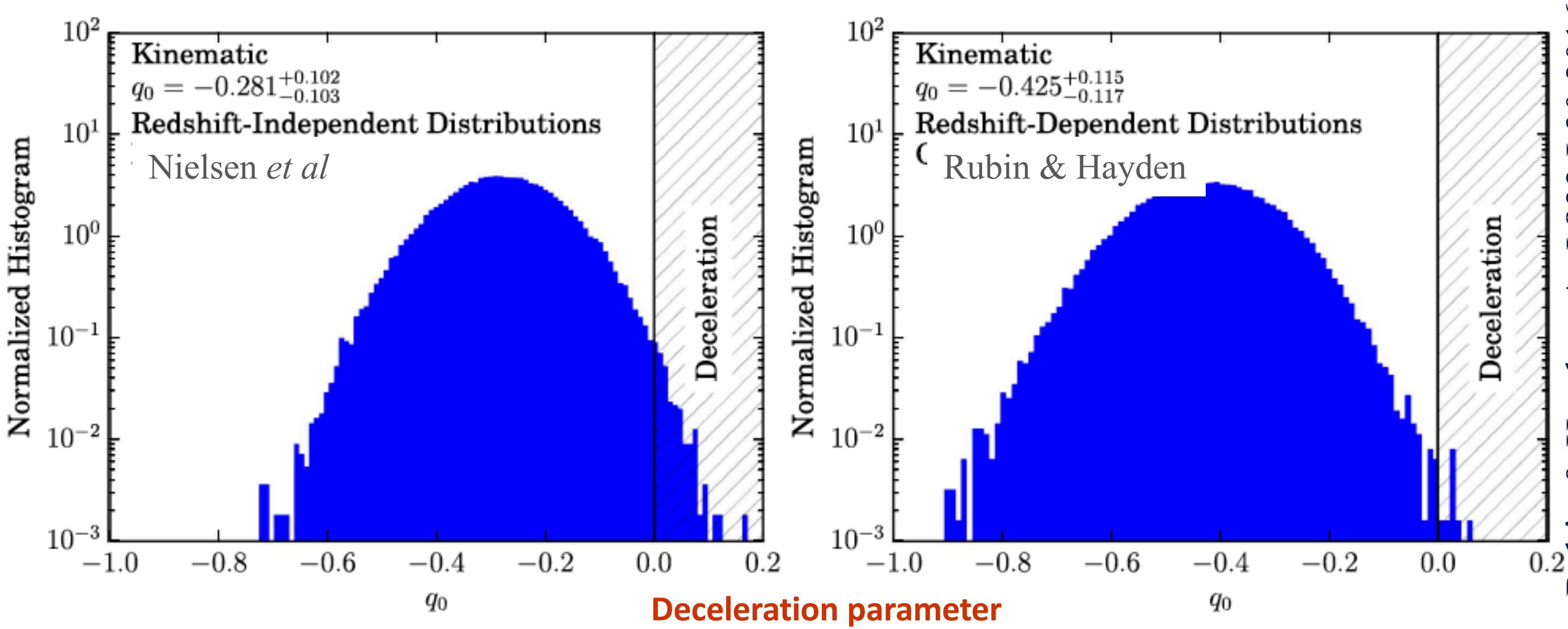


Figure 2. Ω_m–Ω_Λ constraints enclosing 68.3% and 95.4% of the samples from the posterior. Underneath, we plot all samples. The left panel shows the constraints obtained with x_1 and c distributions that are constant in redshift, as in the N16 analysis; the right panel shows the constraints from our 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 rises only to ~4σ … still inadequate to claim a 'discovery' (even though the dataset has increased from 50 to 740 SNe Ia in ~20 yrs)

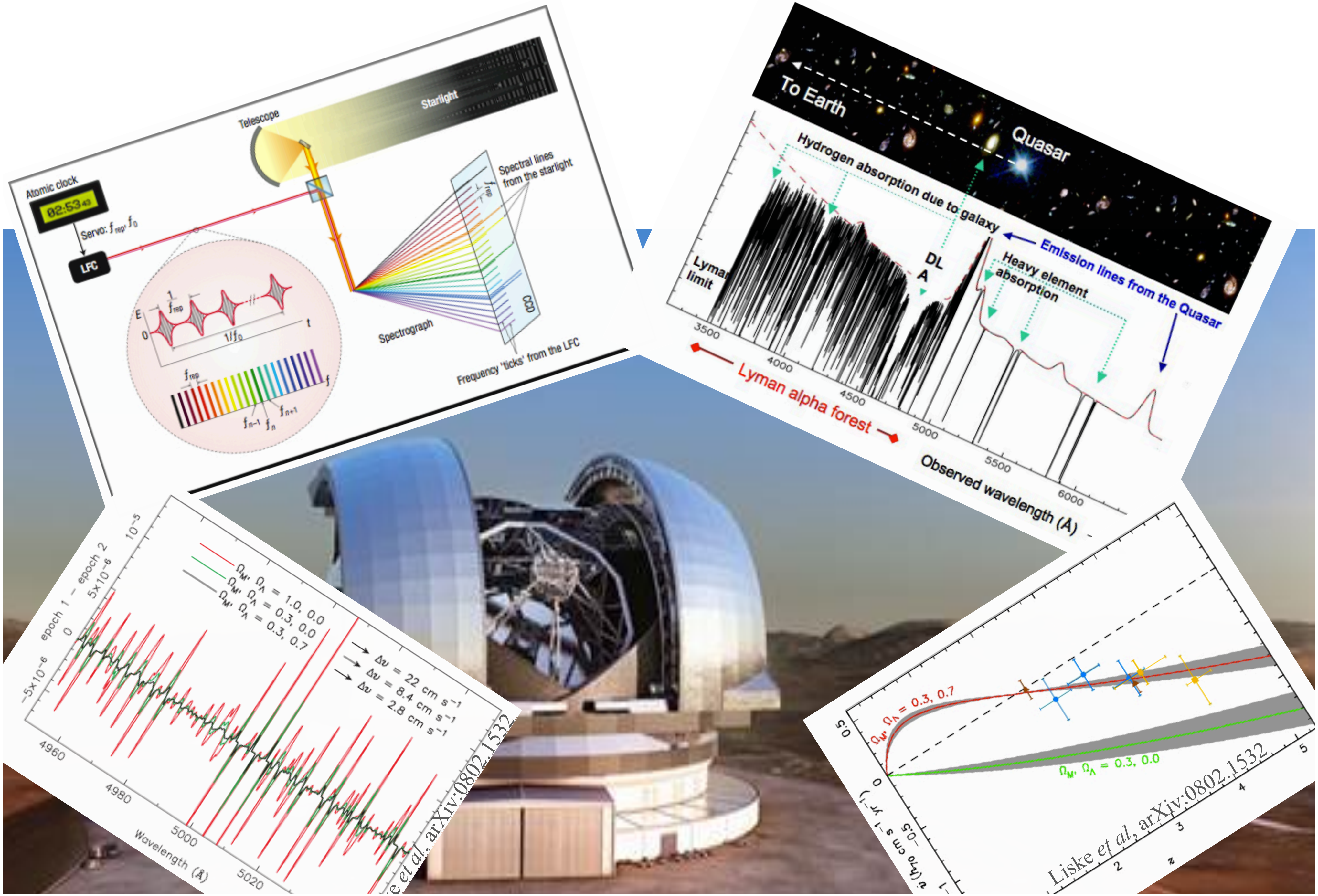
Acceleration is a *kinematic* quantity so the data can be analysed simply by expanding the time variation of the scale factor in a Taylor series, without reference to a dynamical model (e.g. Visser, CQG **21**:2603,2004)



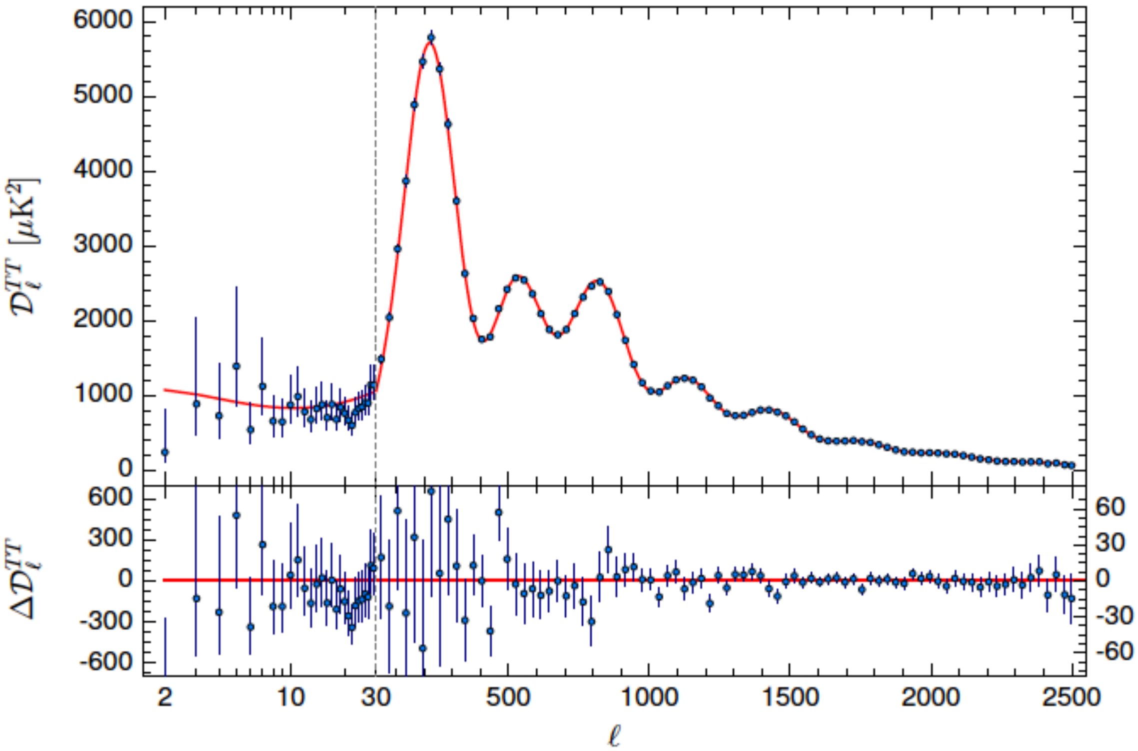
Rubin & Hayden, ApJ **833**:L30,2016

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

Whether the expansion rate is accelerating can be directly tested using a 'Laser Comb' on the European Extremely Large Telescope to measure redshift drift of the Lyman-α forest over ~15 yr



What about the precision data on CMB anisotropies?



Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012

Where is the entry for Λ?!

There is no *direct* sensitivity of the CMB to dark energy … it is all inferred (in the framework of ΛCDM model)

Is not dark energy (cosmic acceleration) independently established from combining CMB and 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, Ω_{CDM} , Ω_{B} , Ω_{Λ} , Ω_k

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

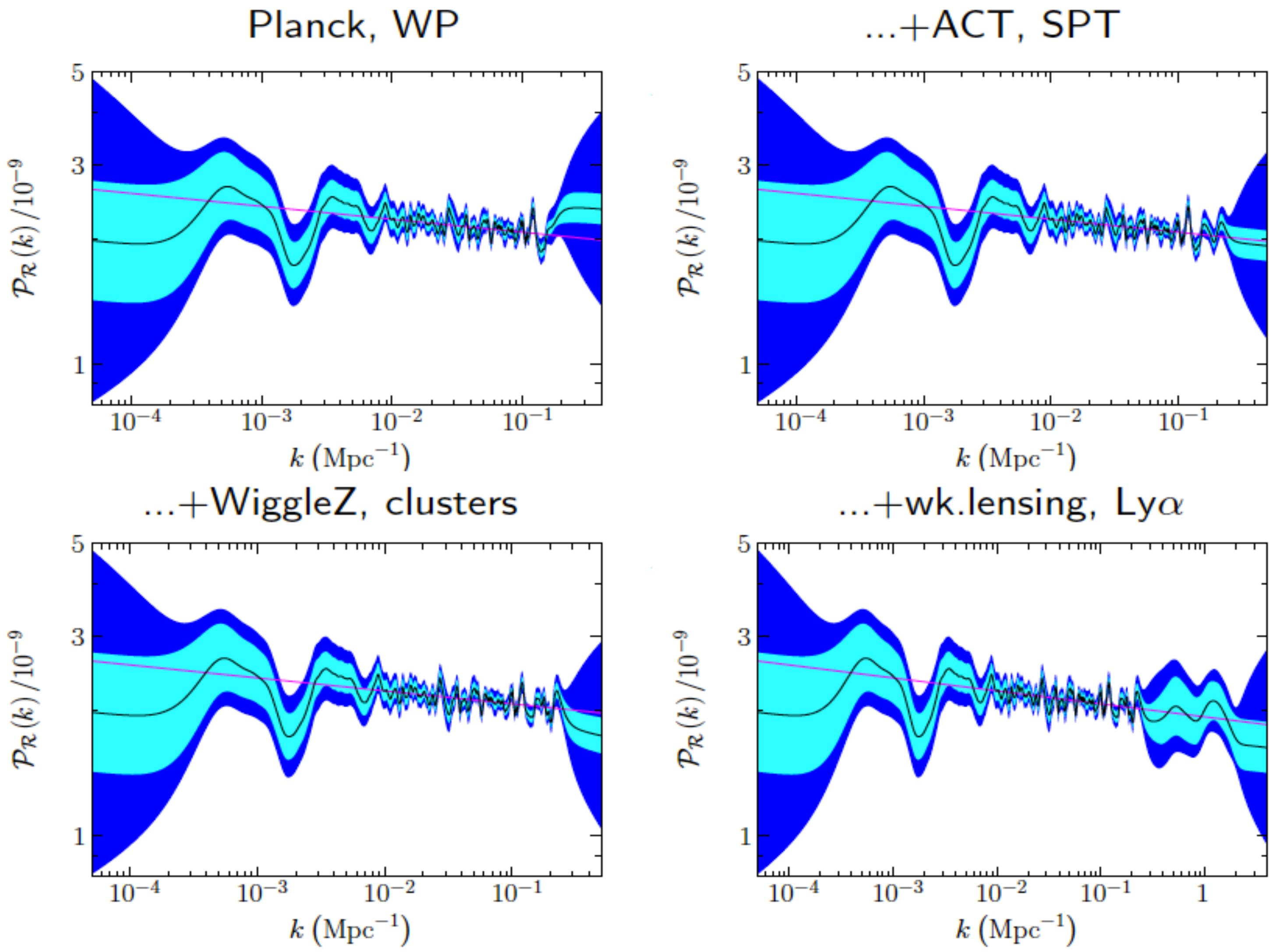
measured over scales ranging from ~1 – 10000 Mpc ($\Rightarrow$ only ~8 e-folds of inflation)

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

… hence need to adopt 'priors' on h, Ω_{CDM} …, and *assume* an initial power-law fluctuation spectrum, in order to break inevitable **parameter degeneracies**

Hence evidence for Λ is *indirect* – can match same data without it (arXiv:0706.2443)

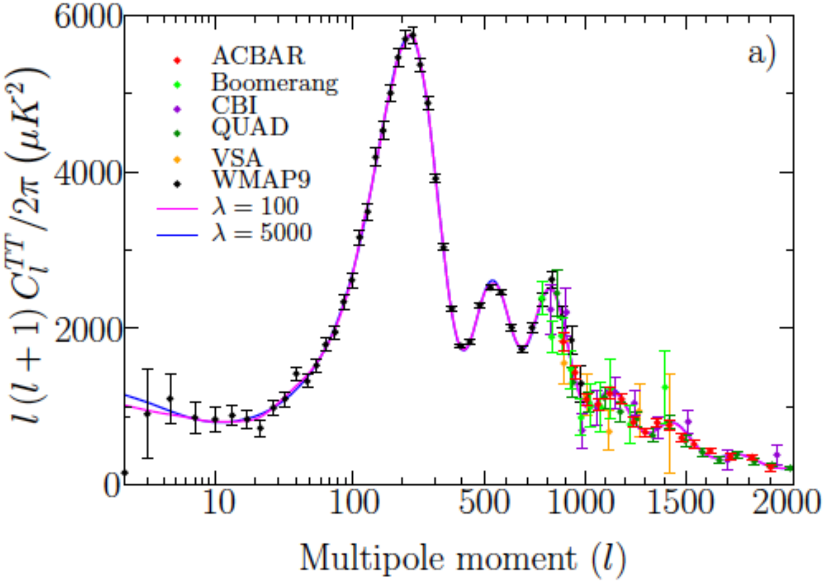
The ‘inverse problem’ of inferring the primordial spectrum of perturbations generated by inflation is necessarily “ill-conditioned” … ‘Tikhonov regularisation’ can be used to do this in a non-parametric manner (Hunt & Sarkar, JCAP **01**:025,2014, **12**:052,2015)



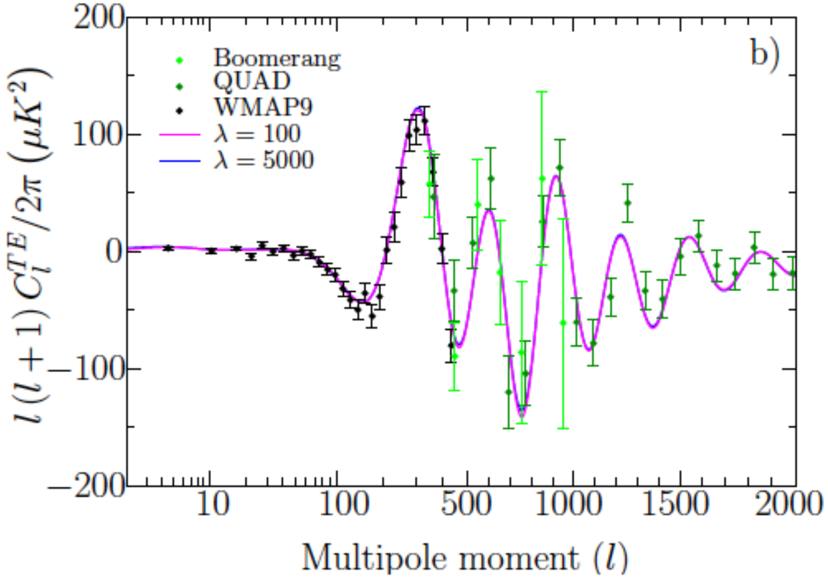
While the data is *consistent* with a power-law, it does allow for deviations (‘features’) and this can have a *significant* impact on the values of extracted parameters …

The spectrum deviates from usually (assumed) power-law and the fit to data is marginally better … but the inferred cosmological parameters can be very different

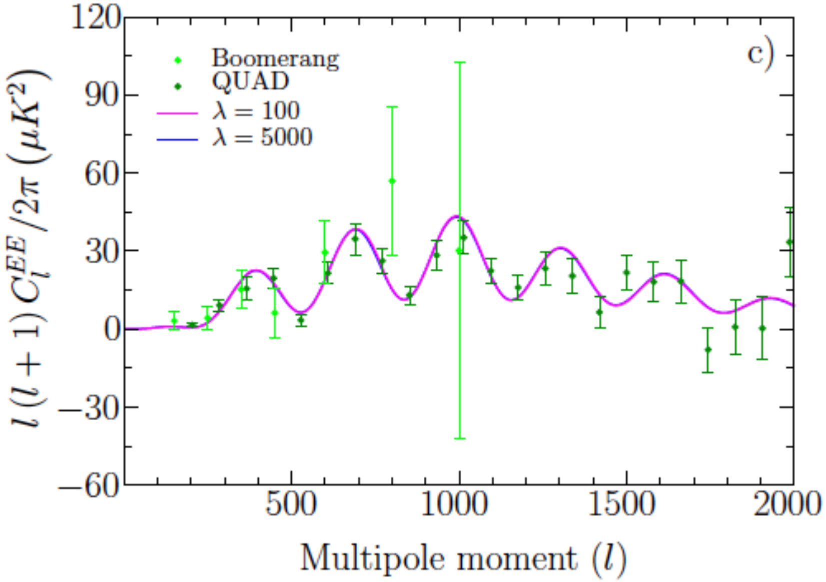
The fit to CMB TT data



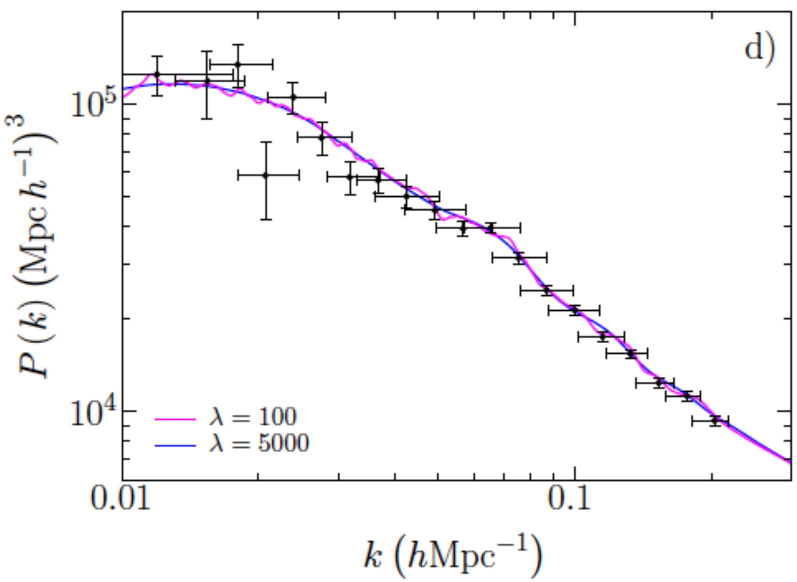
The fit to CMB TE data



The fit to CMB EE data



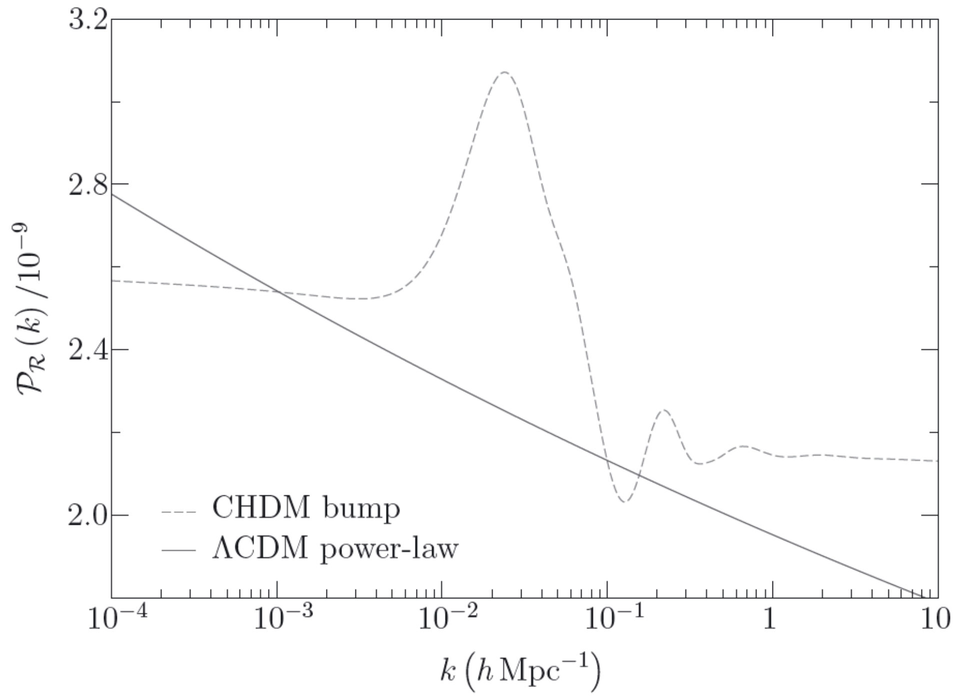
The fit to SDSS LRG data



Hunt & Sarkar, JCAP **01**:025,2014

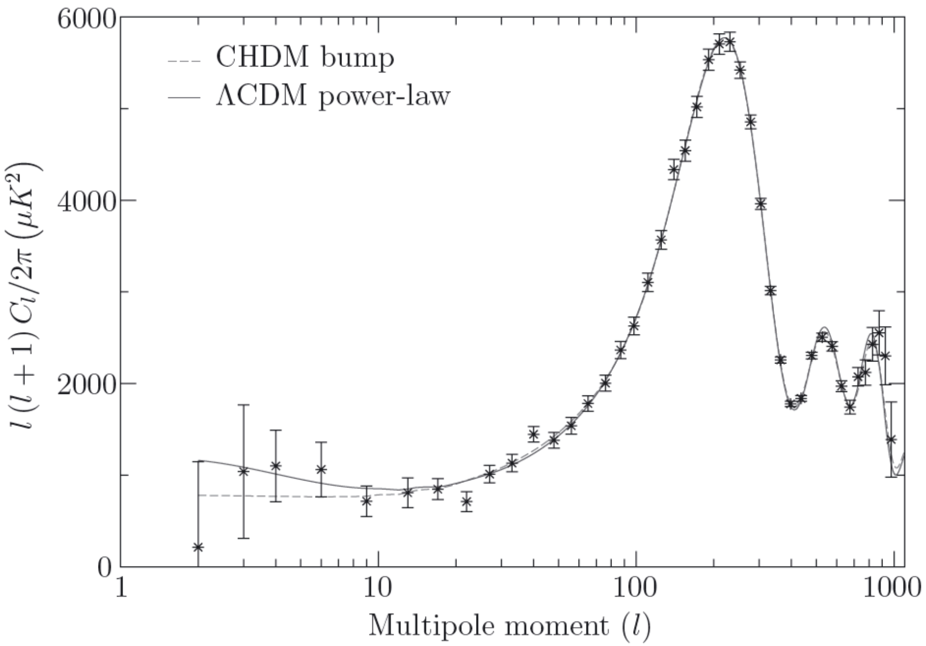
E.g. if there is a 'bump' in the spectrum (around the first acoustic peak), the CMB data can be fitted *without dark energy* ($\Omega_m = 1$, $\Omega_\Lambda = 0$) if $h \sim 0.45$

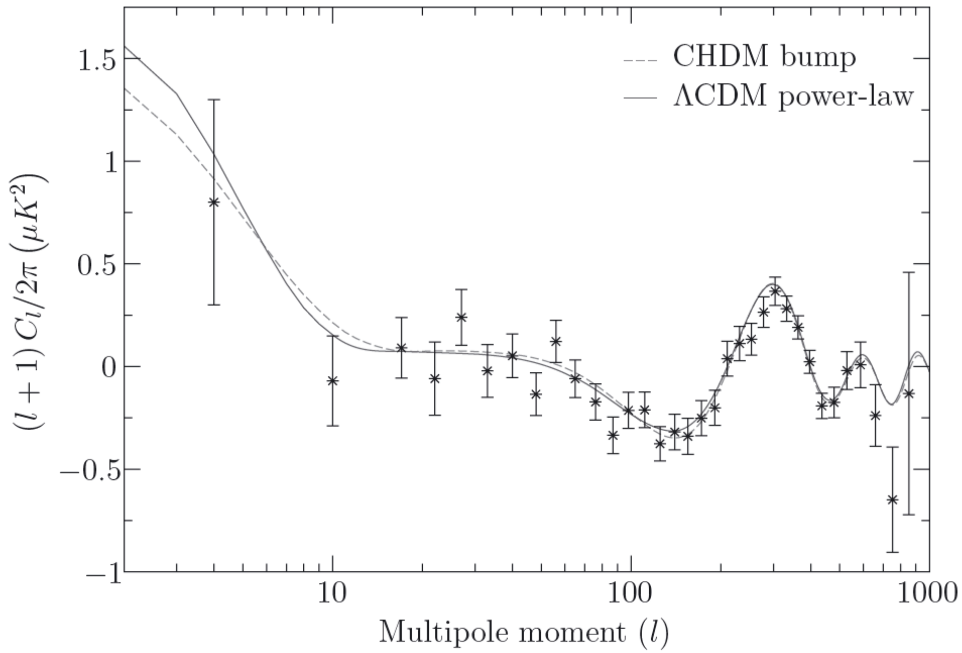
(Hunt & Sarkar arXiv:0706.2443, 0807.4508)



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)

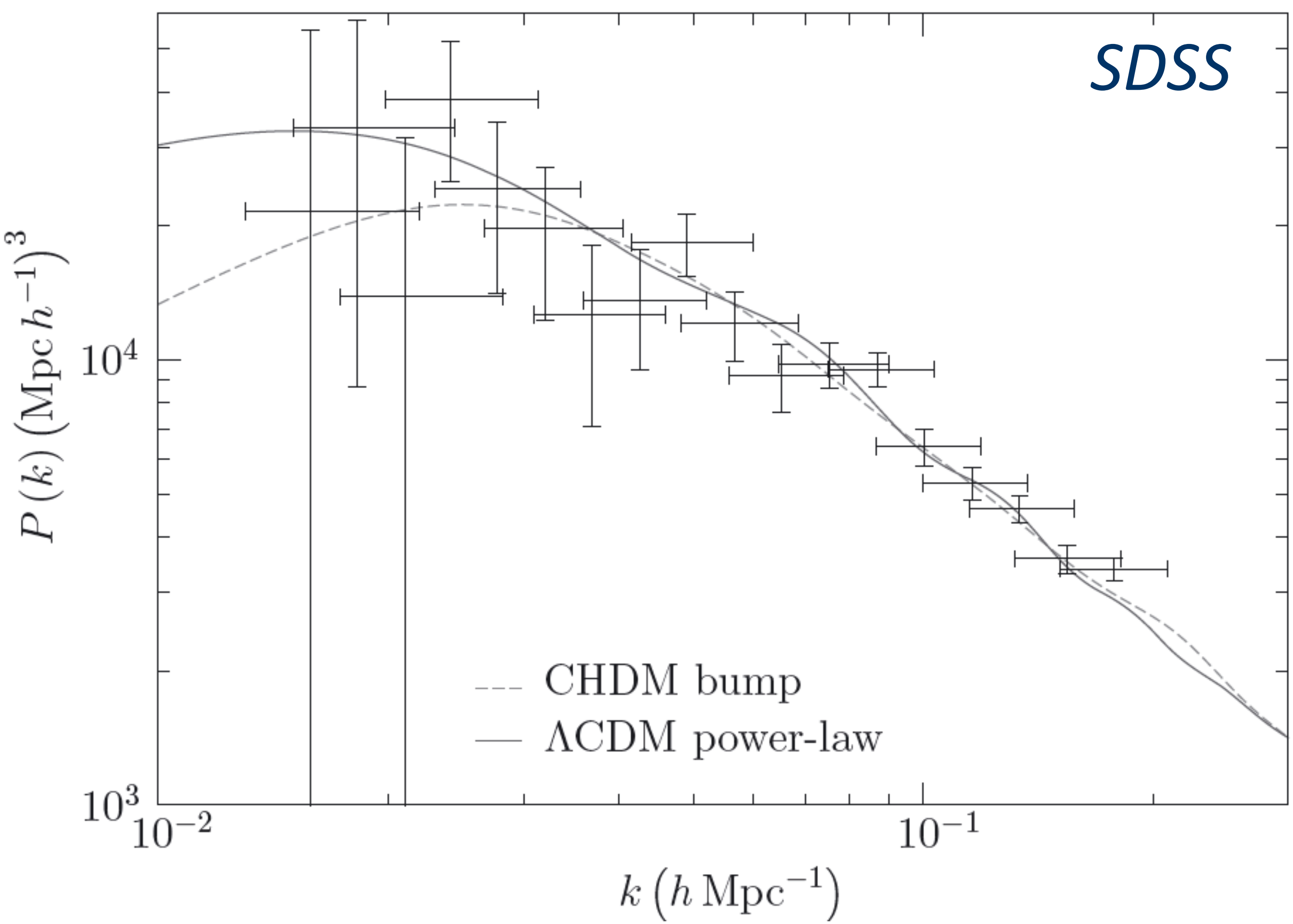




The small-scale power would be excessive unless damped by free-streaming

But adding 3 νs of mass ~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 soon detectable by KATRIN!



Hunt & Sarkar arXiv:0706.2443, 0807.4508

Fit gives $\Omega_b h^2 \approx 0.021 \rightarrow$ BBN √ $\Rightarrow$ baryon fraction in clusters predicted to be ~11% √

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

"Wir müssen wissen. Wir werden wissen"

David Hilbert (Lecture in Königsberg, 1930)