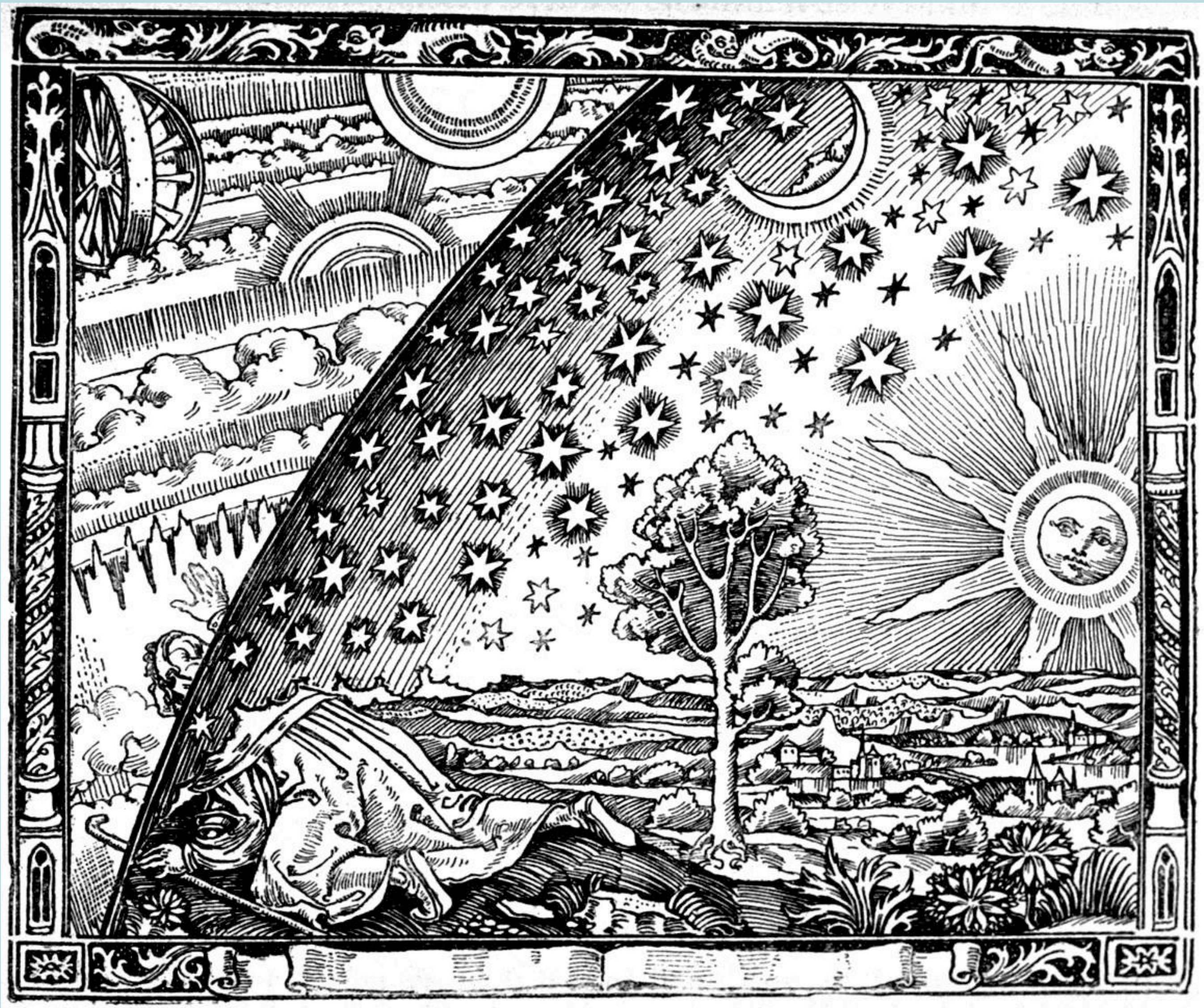


Beyond the cosmological standard model

Prof Subir Sarkar

University of Oxford, and

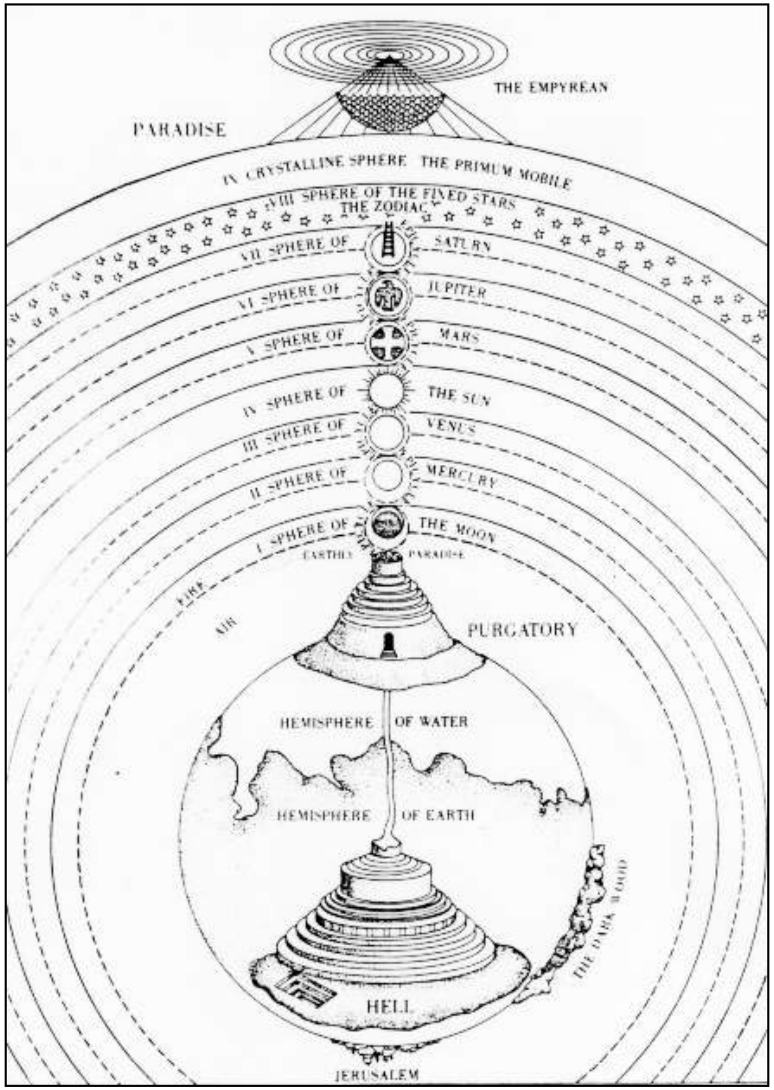
Niels Bohr Institute Copenhagen

Freitag, 27.11.2017 17:15

Uhr Kirchhoff-Institut, INF 227

Otto-Haxel-Hörsaal

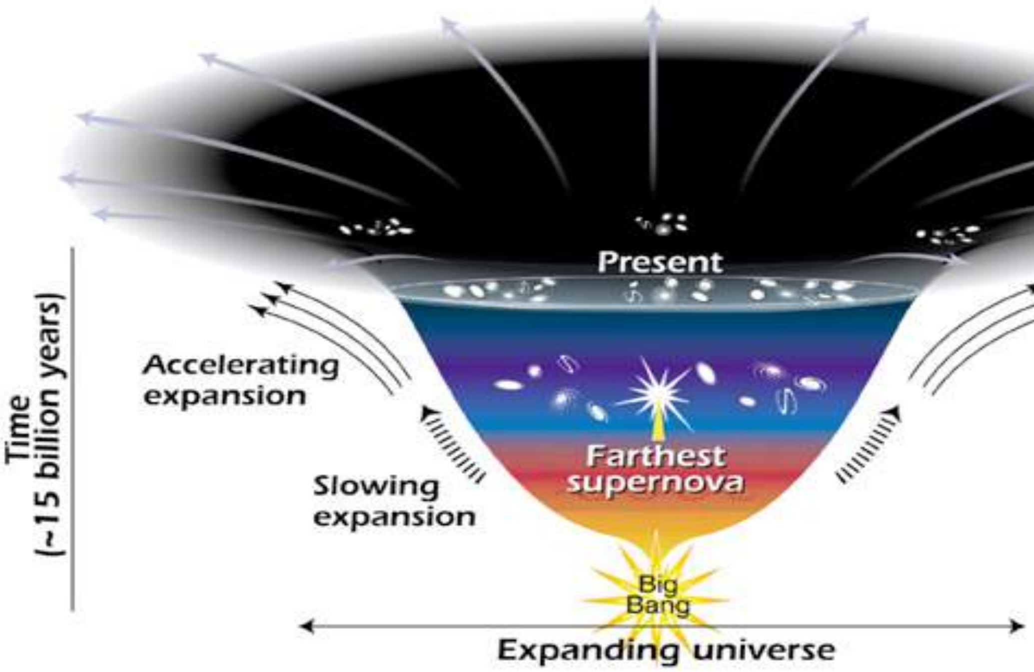
In the Ptolemic/Aristotlean standard cosmology (350 BC➛1600 AD) the universe was *static* and *finite* and centred on the Earth

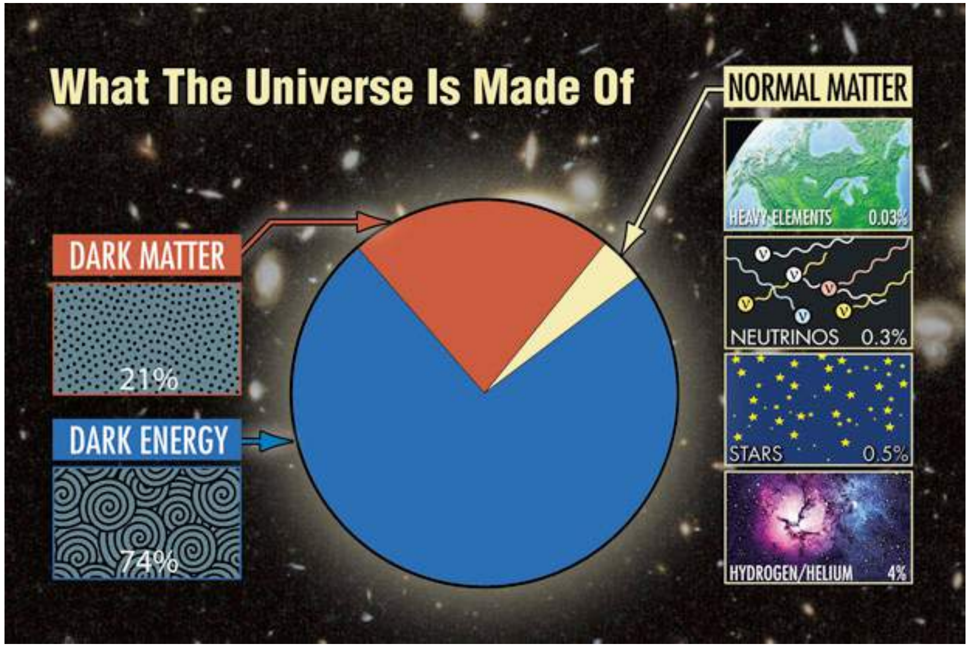


The Divine Comedy, Dante Allighieri (1321)

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

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





It too is '*simple*' (counting Λ as one parameter) and fits all the observational data but lacks a *physical* foundation

The standard cosmological model is based on several key assumptions:

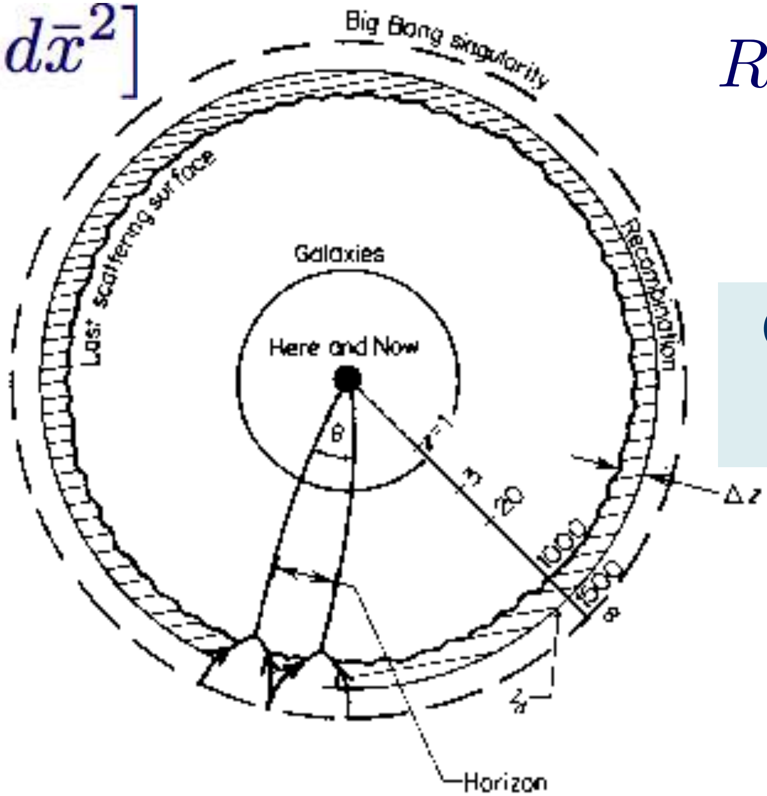
maximally symmetric space-time + general relativity + ideal fluids

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

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

Space–time metric

Robertson–Walker



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

Geometrodynamics

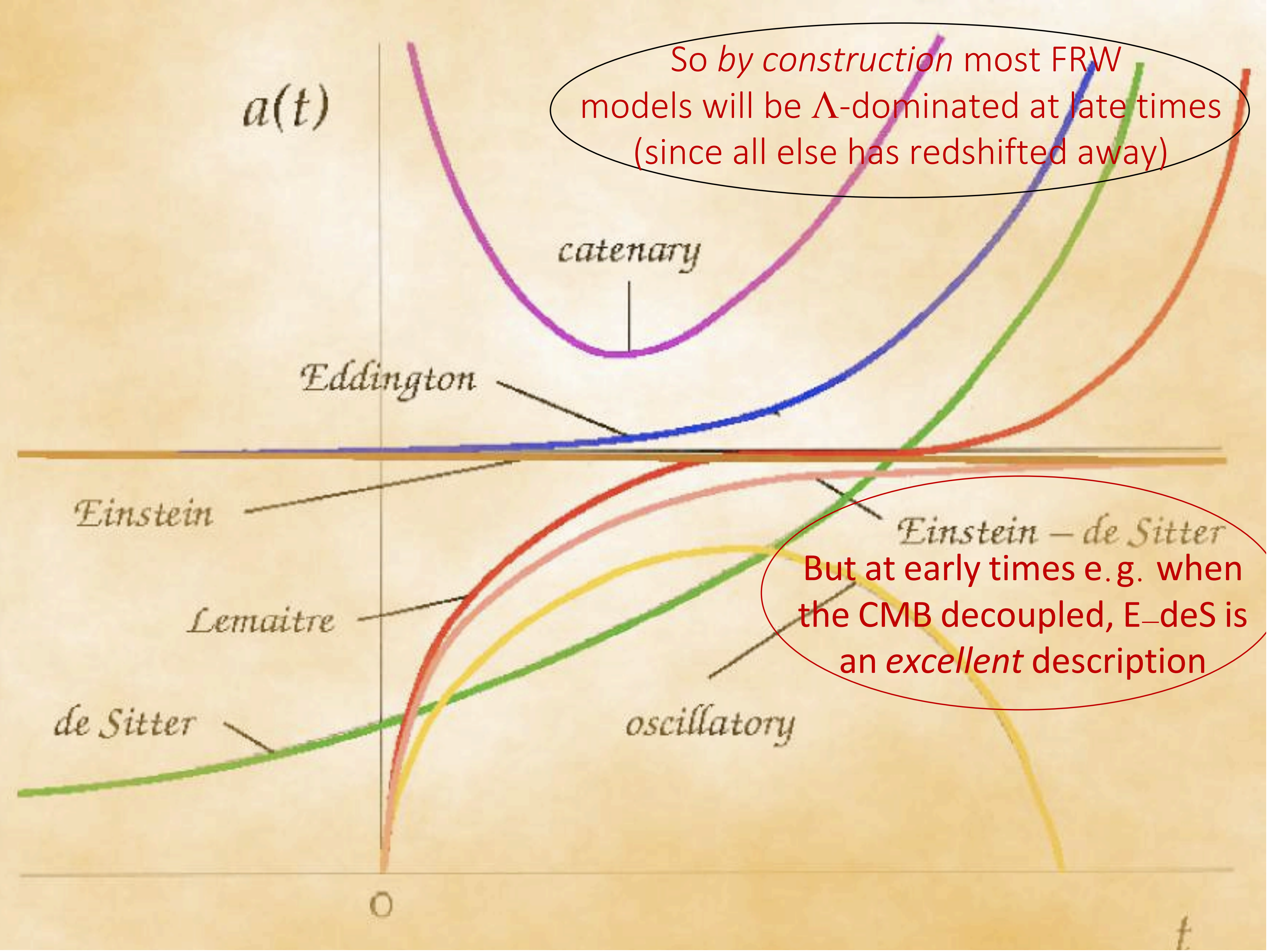
Einstein

$$T_{\mu\nu} = -\langle\rho\rangle_{\text{fields}}\ g_{\mu\nu}$$
$$\Lambda = \lambda + 8\pi G_N \langle\rho\rangle_{\text{fields}}$$

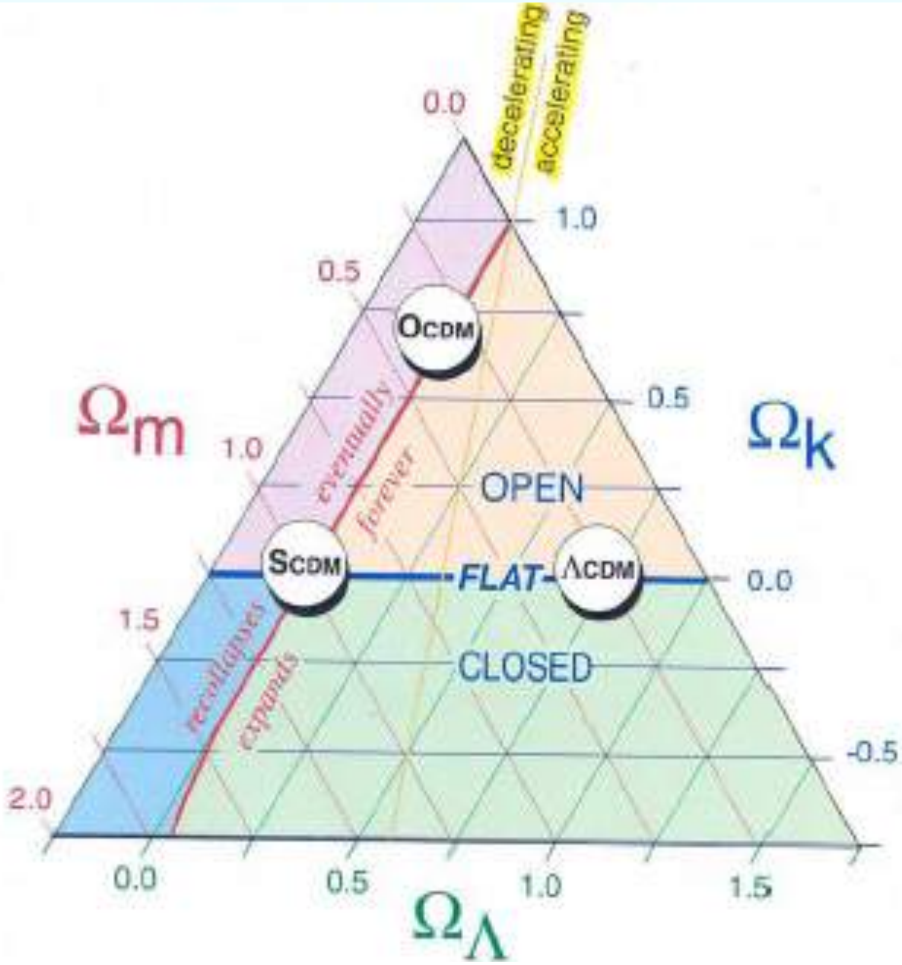
$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho_m}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$
$$\equiv {H_0}^2\left[\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

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': $1 \equiv \Omega_m + \Omega_k + \Omega_\Lambda$


So *by construction* most FRW models will be Λ-dominated at late times (since all else has redshifted away)
a(t)
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
O
t

It is thus *natural* for data interpreted in this idealised model to imply that Ω_Λ ($\equiv 1 - \Omega_m - \Omega_k$) is non-zero, i.e. Λ is of $O(H_0^2)$ … given the inevitable uncertainties in measuring Ω_m and Ω_k and the possibility of other components (Ω_x) which are *unaccounted* for in the Hubble equation



Bahcall, Ostriker, Perlmutter & Steinhardt, astro-ph/9906463

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

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

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 $\boldsymbol{M}$) describes *all* of microphysics

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

Vacuum energy Higgs mass correction

super-renormalisable

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

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

renormalisable

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

non-renormalisable

neutrino mass proton decay, FCNC …

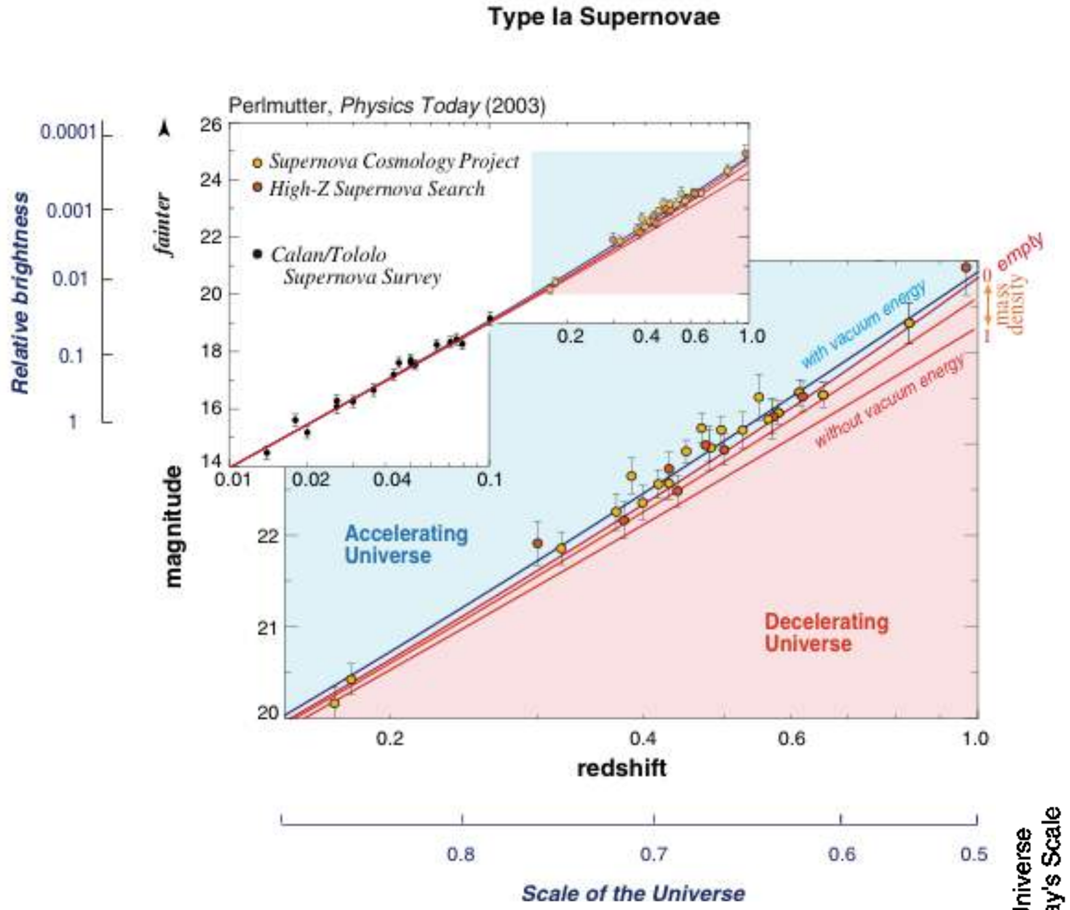
New physics beyond the SM $\Rightarrow$ non-renormalisable operators suppressed by M^n which *decouple* as $M \to M_P$ … so neutrino mass is naturally small, proton decay is very slow *etc*

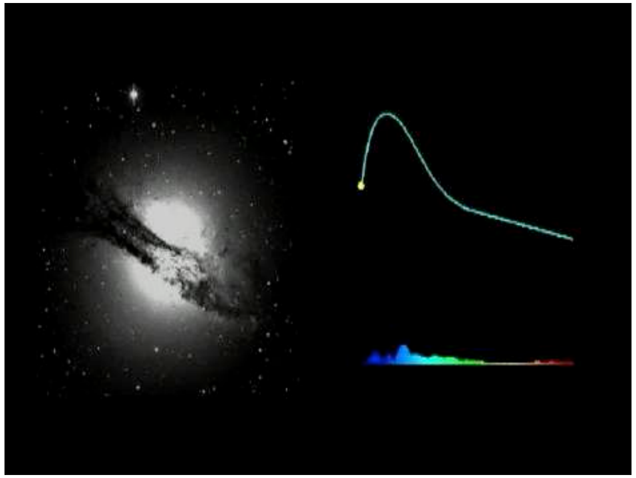
But as M is raised, the effects of the super-renormalisable operators are exacerbated
(One solution for Higgs mass divergence $\rightarrow$ 'softly broken' supersymmetry at O(TeV)
… or the Higgs could be *composite* – a pseudo Nambu-Goldstone boson)

1st SR term couples to gravity so the *natural* expectation is $\rho_\Lambda \sim (1\ \text{TeV})^4 \Rightarrow 10^{60}$ x $(1\ \text{meV})^4$
… i.e. the universe should have been inflating since (or collapsed at): $t \sim 10^{-12}$ s after BB
There must be a good reason why this did *not* happen!

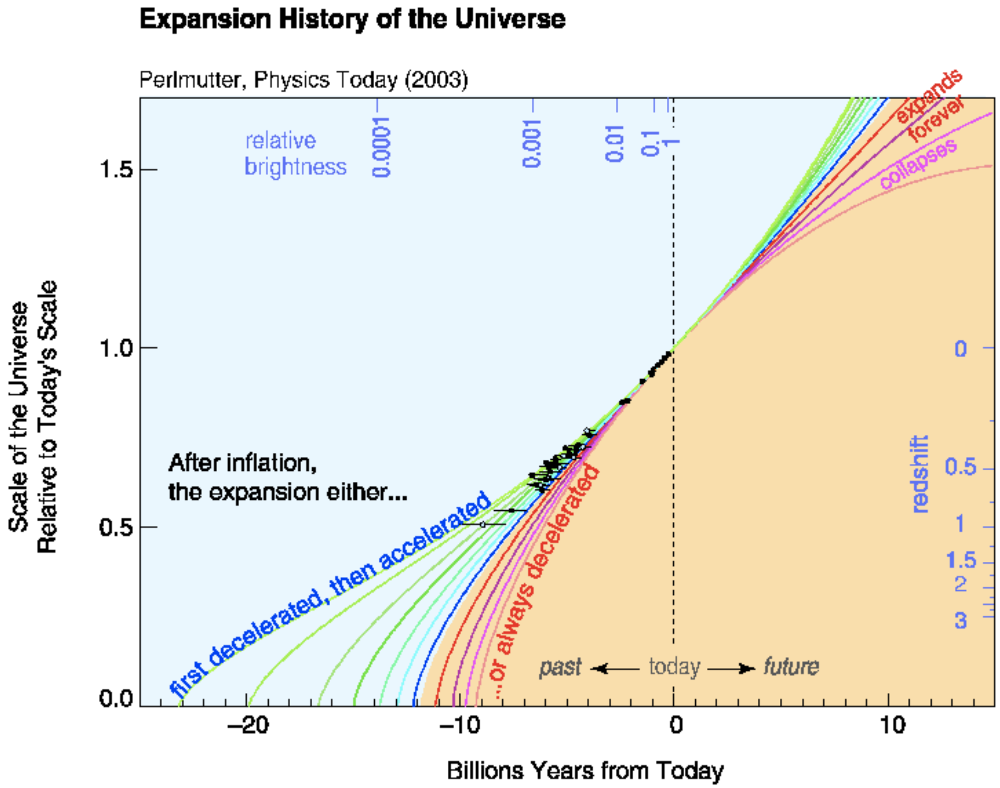
"Also, as is obvious from experience, the [zero–point energy] does not produce any gravitational field" – Wolfgang Pauli
Die allgemeinen Prinzipien der Wellenmechanik, Handbuch der Physik, Vol. XXIV, 1933

1998: Distant SNIa appear fainter than expected for "standard candles" in a decelerating universe ... interpreted as $\Rightarrow$ accelerated expansion below $z \sim 0.5$

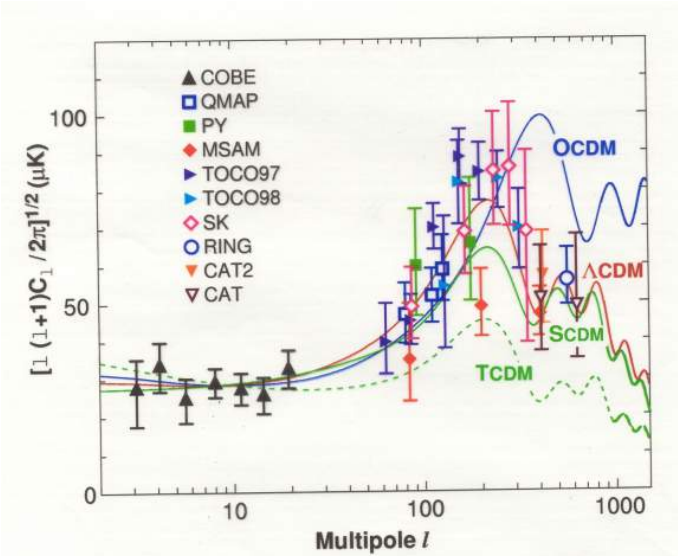




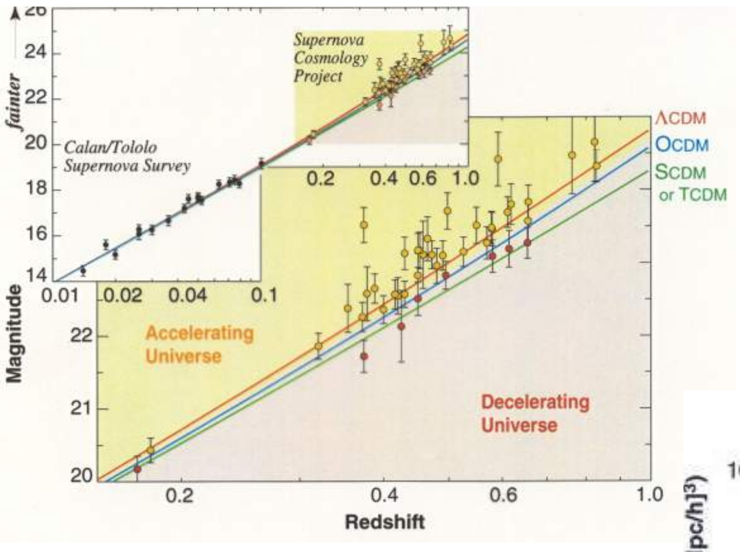
The observations are made at *one* instant (the redshift is taken as a proxy for time) so this is not a *direct* measurement of acceleration, nevertheless it is presently more direct than all other 'evidence'



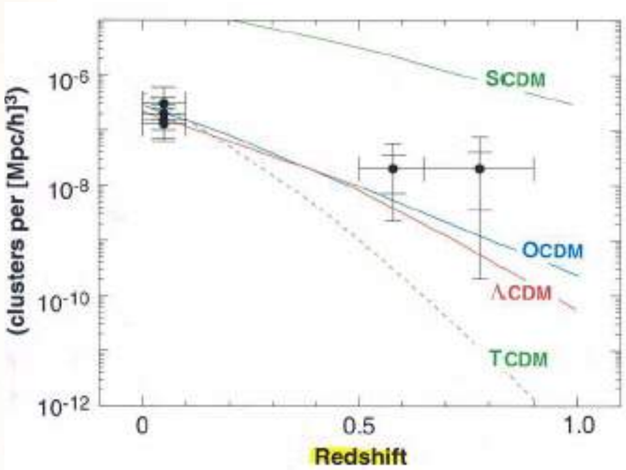
Assuming the sum rule, complementary observations implied: $\Omega_\Lambda \sim 0.7$, $\Omega_m \sim 0.3$



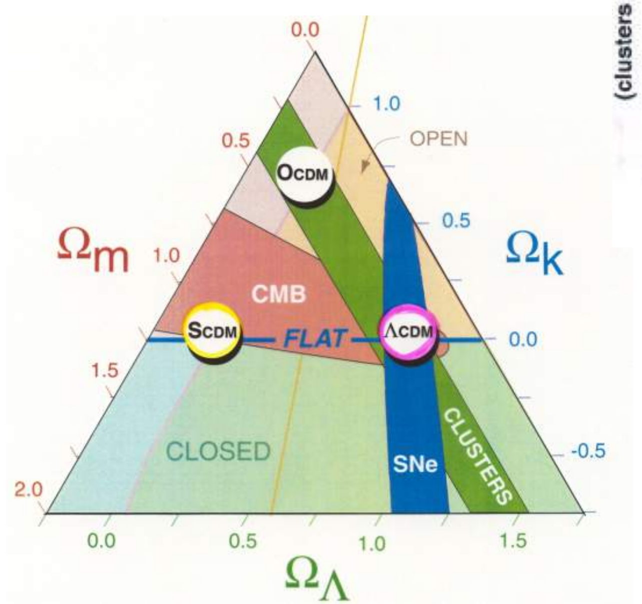
$\Omega_k \approx 0.0 \pm 0.03$



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



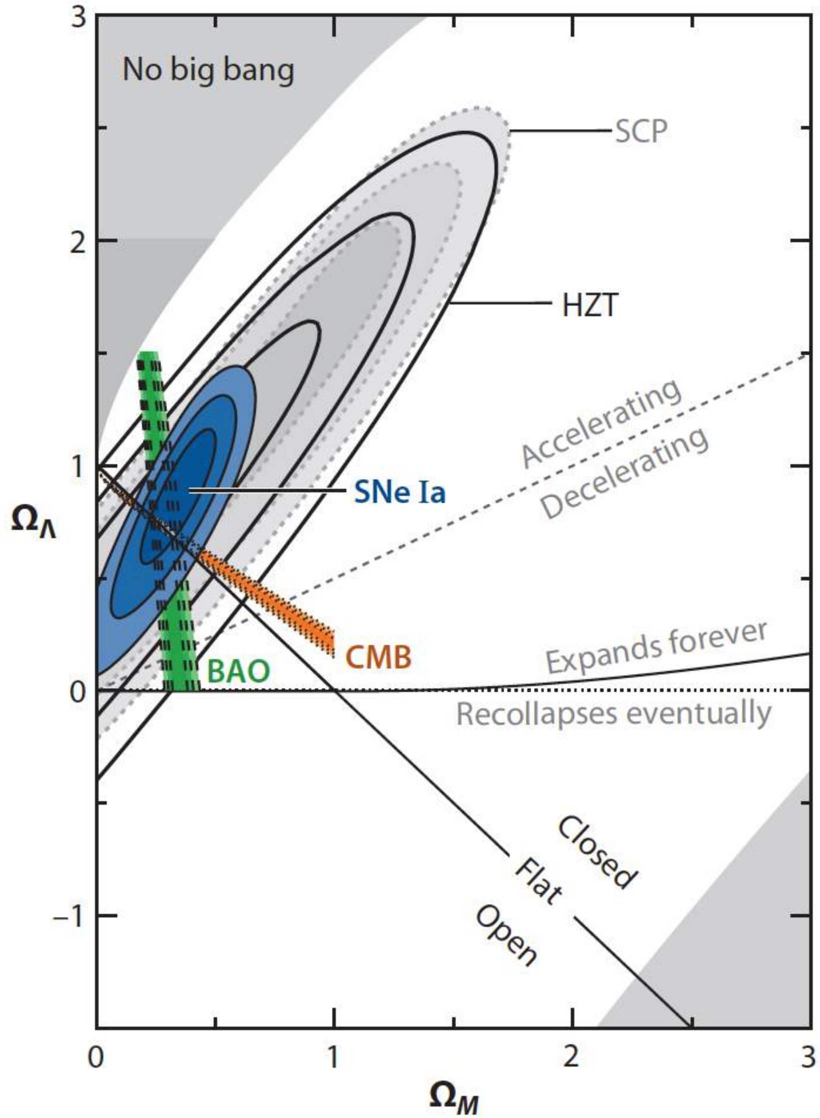
$\Omega_m \approx 0.3$



Bahcall, Ostriker, Perlmutter & Steinhardt, astro-ph/9906463

Estimates of Ω_m are rather uncertain … moreover there is *no* measurement of Ω_Λ *alone*

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



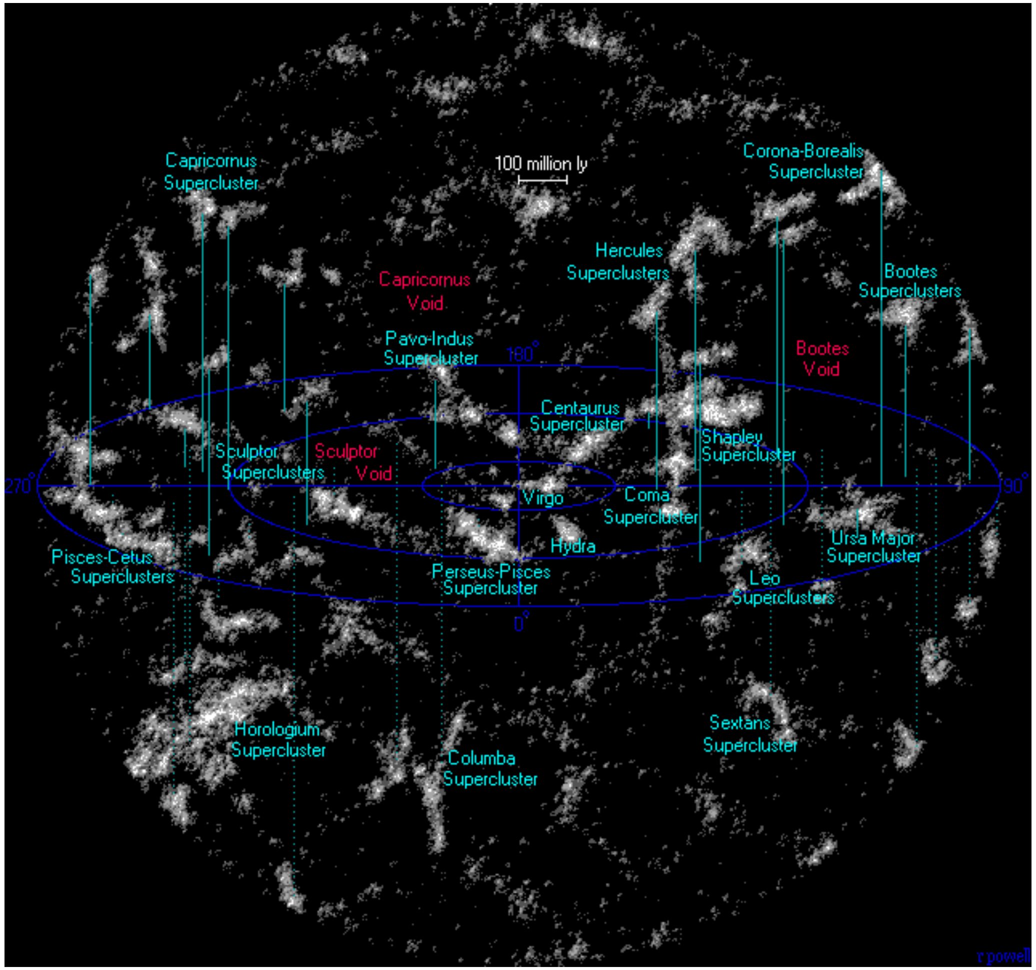
Goobar & Leibundgut, arXiv:1102.1431

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

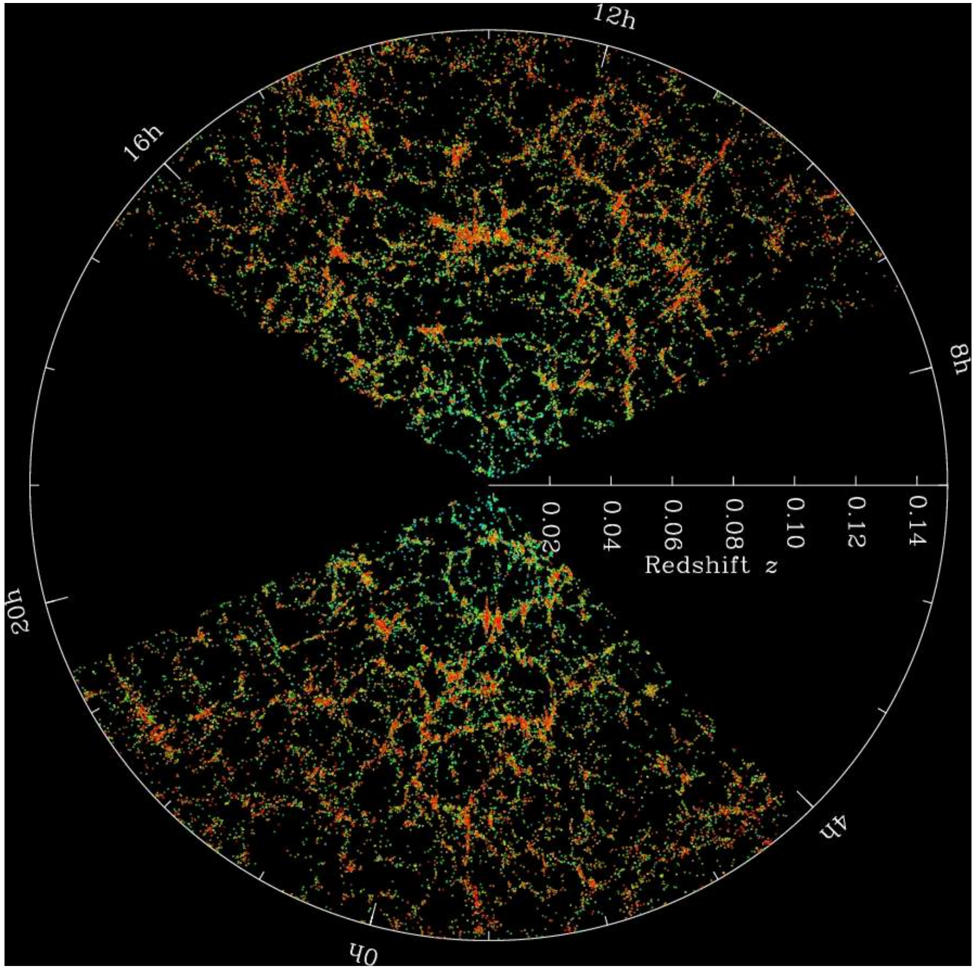
Is it justified to approximate it as *exactly* homogeneous?

... To assume that we are a '*typical*' observer?

... To assume that all observed directions are *equivalent*?



This is what our universe *actually* looks like …
locally (out to ~300 Mpc)
and on larger (SDSS) scales



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,

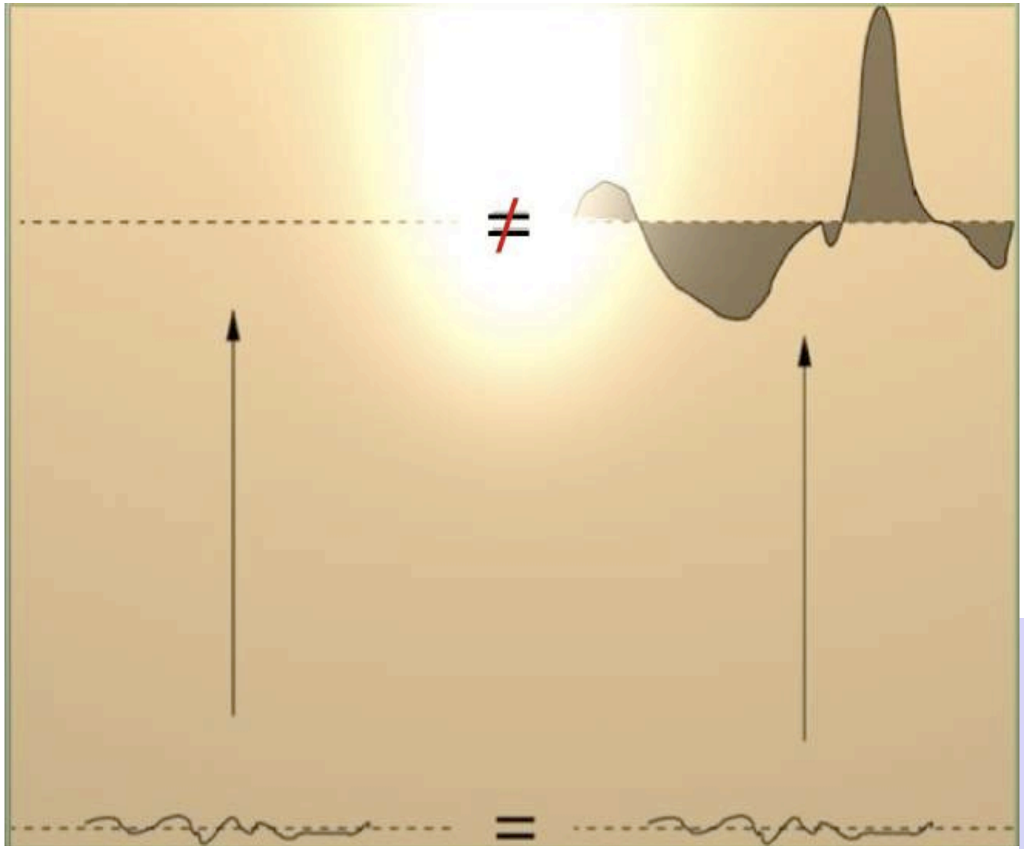
$$\mathcal{Q}_{\mathcal{D}} = \frac{2}{3}\left(\langle\theta^2\rangle_{\mathcal{D}} - \langle\theta\rangle^2_{\mathcal{D}}\right) - \langle\sigma^{\mu\nu}\sigma_{\mu\nu}\rangle_{\mathcal{D}} .$$

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

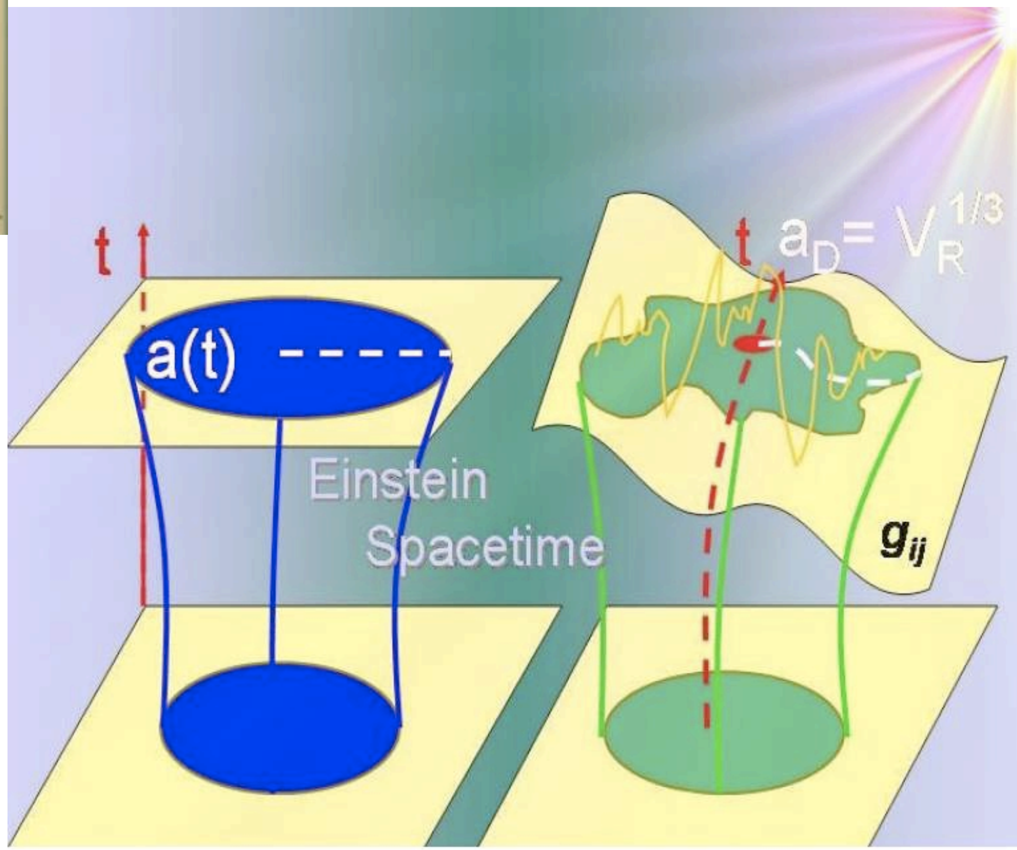
Whether the backreaction can be sufficiently large is still an *open* question



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

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

Relativistic numerical simulations of structure formation have just begun to be performed … and indicate significant backreaction effects



Courtesy: Thomas Buchert

Interpreting Λ 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 $V(\varphi)^{1/4} \sim 10^{-12}$ GeV but $\sqrt{d^2V/d\varphi^2} \sim H_0 \sim 10^{-42}$ GeV to ensure slow–roll … i.e. *just as much fine–tuning as a bare cosmological constant*

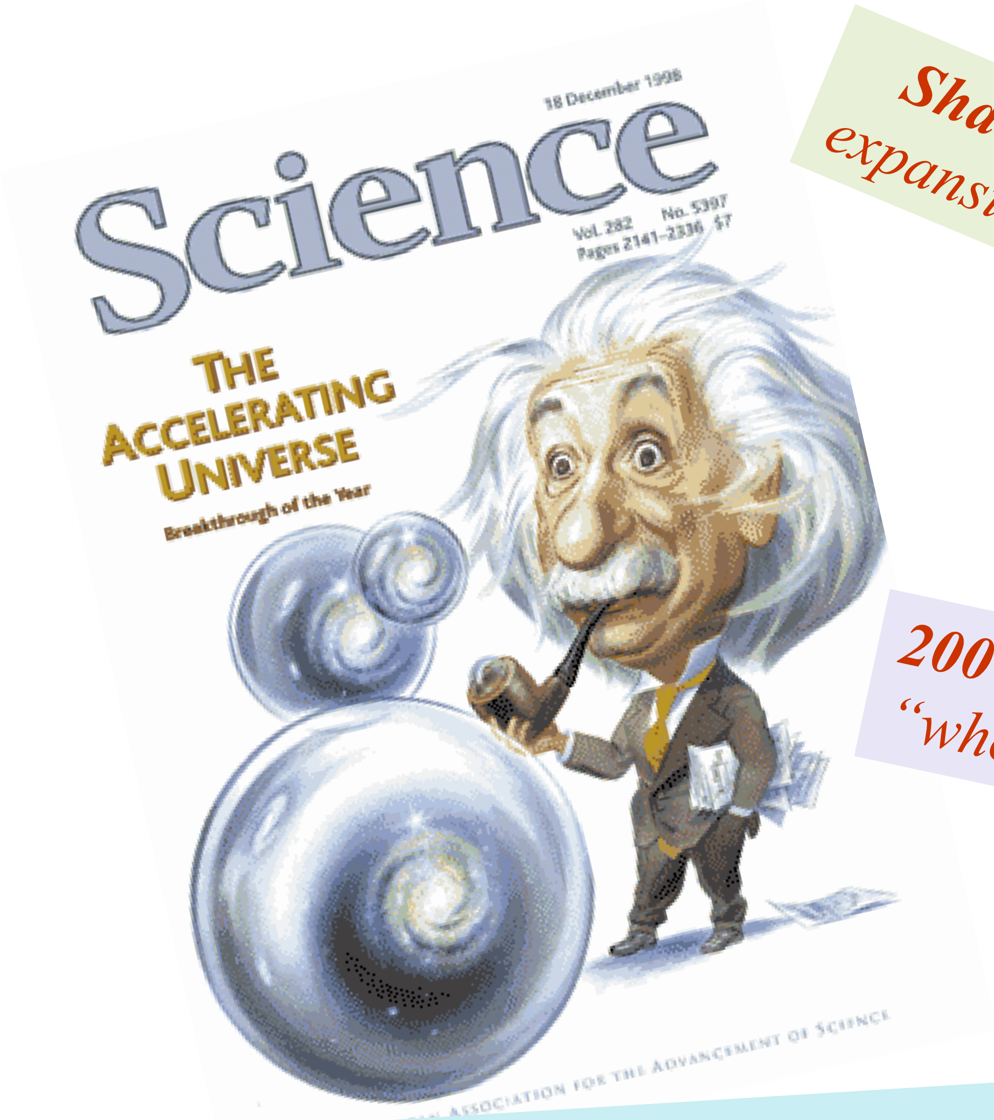
A similar comment applies to models (e.g. 'DGP brane–world') wherein gravity is modified on the scale of the present Hubble radius $1/H_0$ so as to mimic vacuum energy … this scale is *absent* in a fundamental theory and is just put in by hand

(**similar fine–tuning in *every* proposal** – e.g. 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: $H^2 = 8\pi G_N/3 + \Lambda/3$) ➞ 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 (in the FRW cosmology framework) … just how strong is the evidence for accelerated expansion?



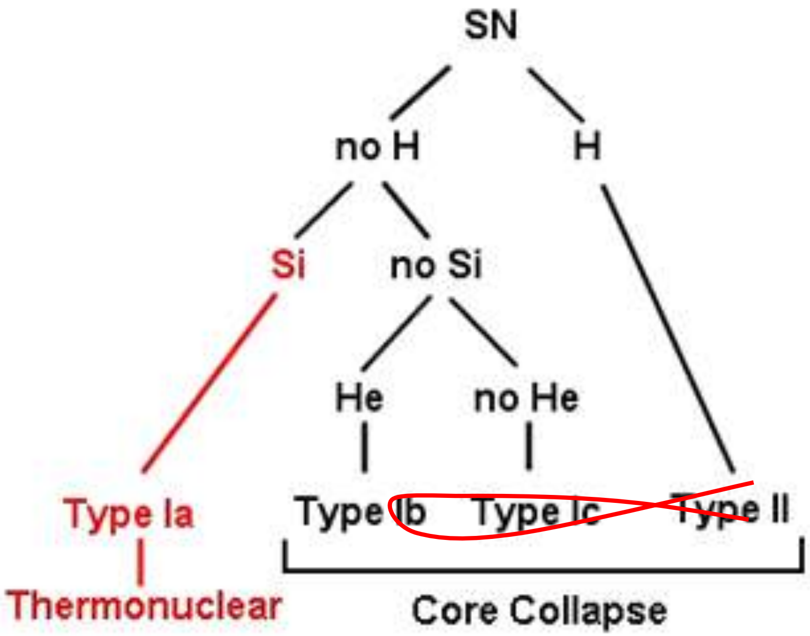
Shaw Prize 2006 *"for discovering that the expansion rate of the universe is accelerating"*

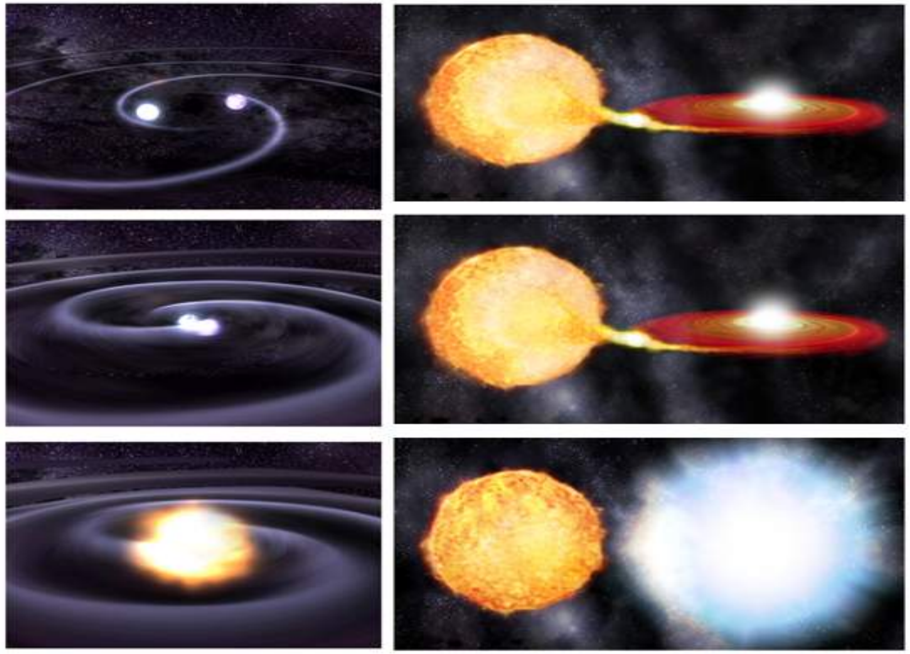
2007 Gruber Cosmology Prize *to two teams "who discovered the accelerating universe"*

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

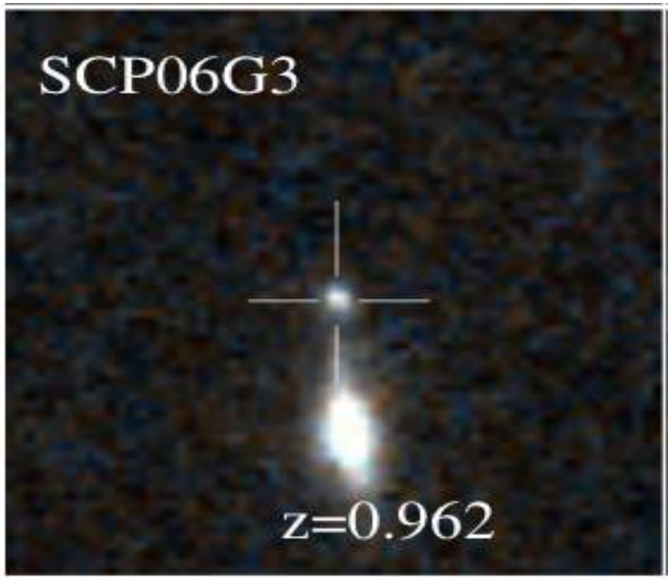
The ***2015 Breakthrough Prize in Fundamental Physics*** *"for the most unexpected discovery that the expansion of the universe is accelerating"*

What are Type Ia supernovae?

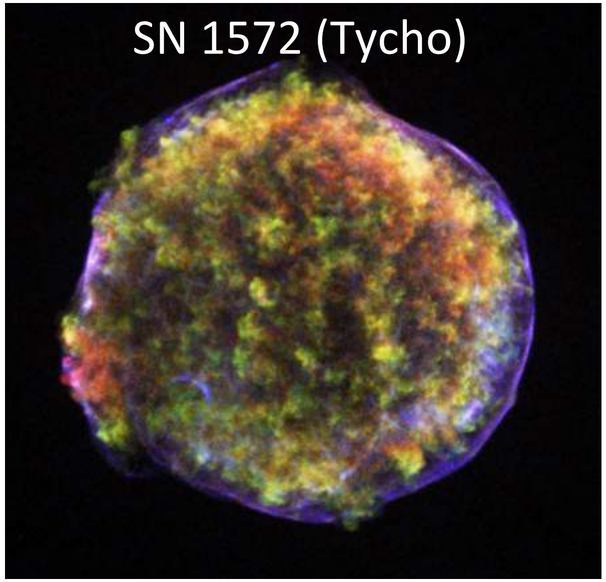




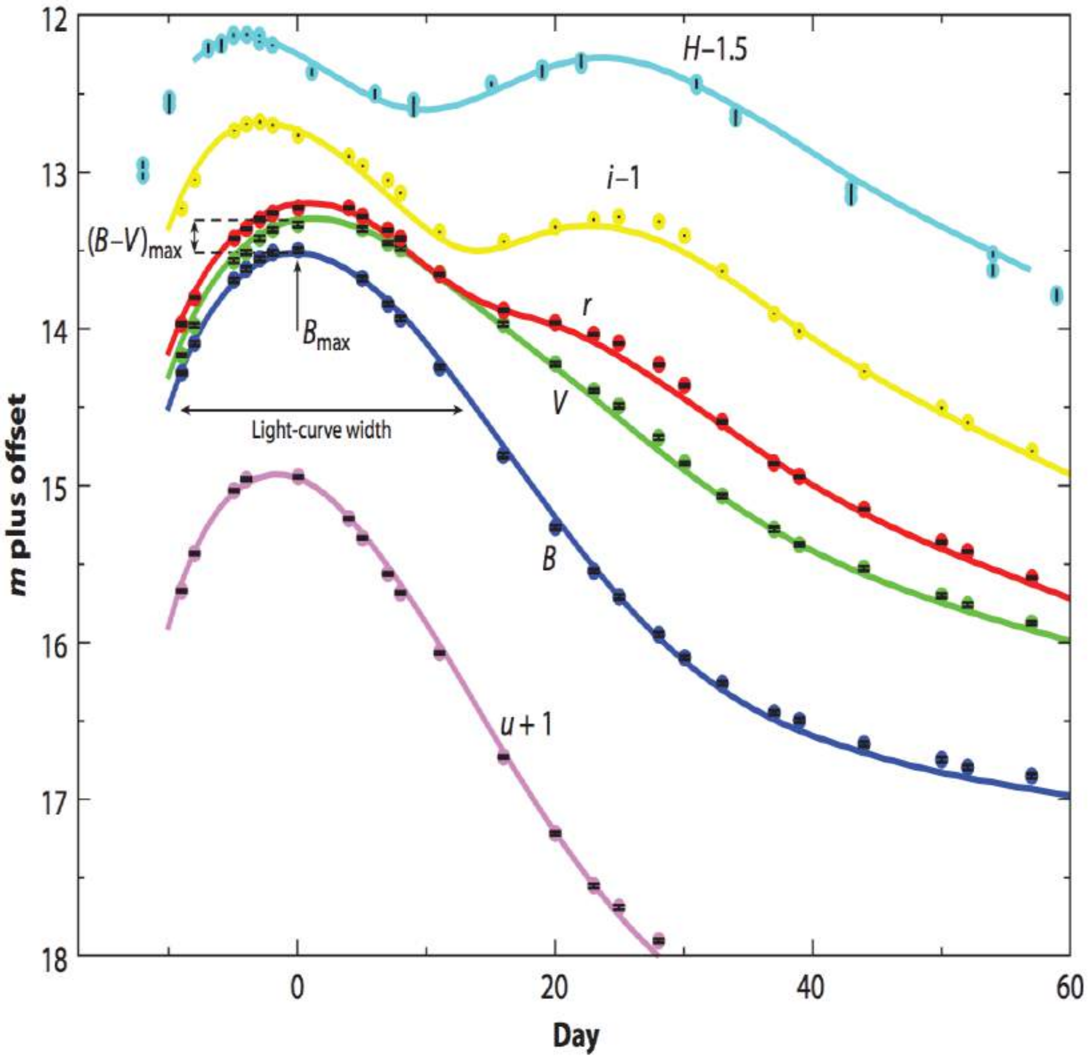
Suzuki *et al*, arXiv:105.3470



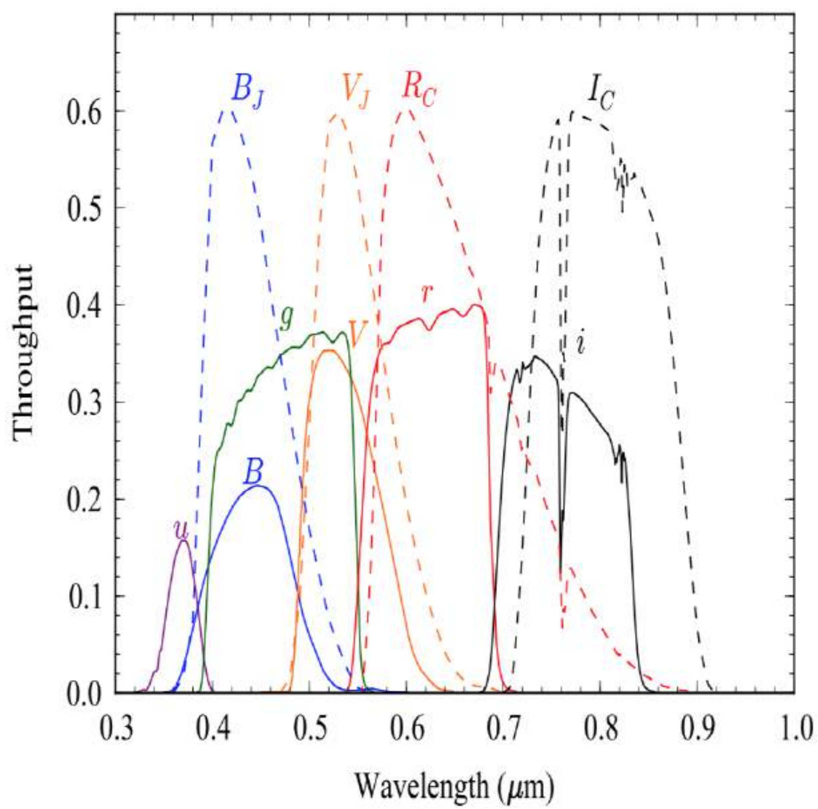
~500 years



What are Type Ia supernovae?



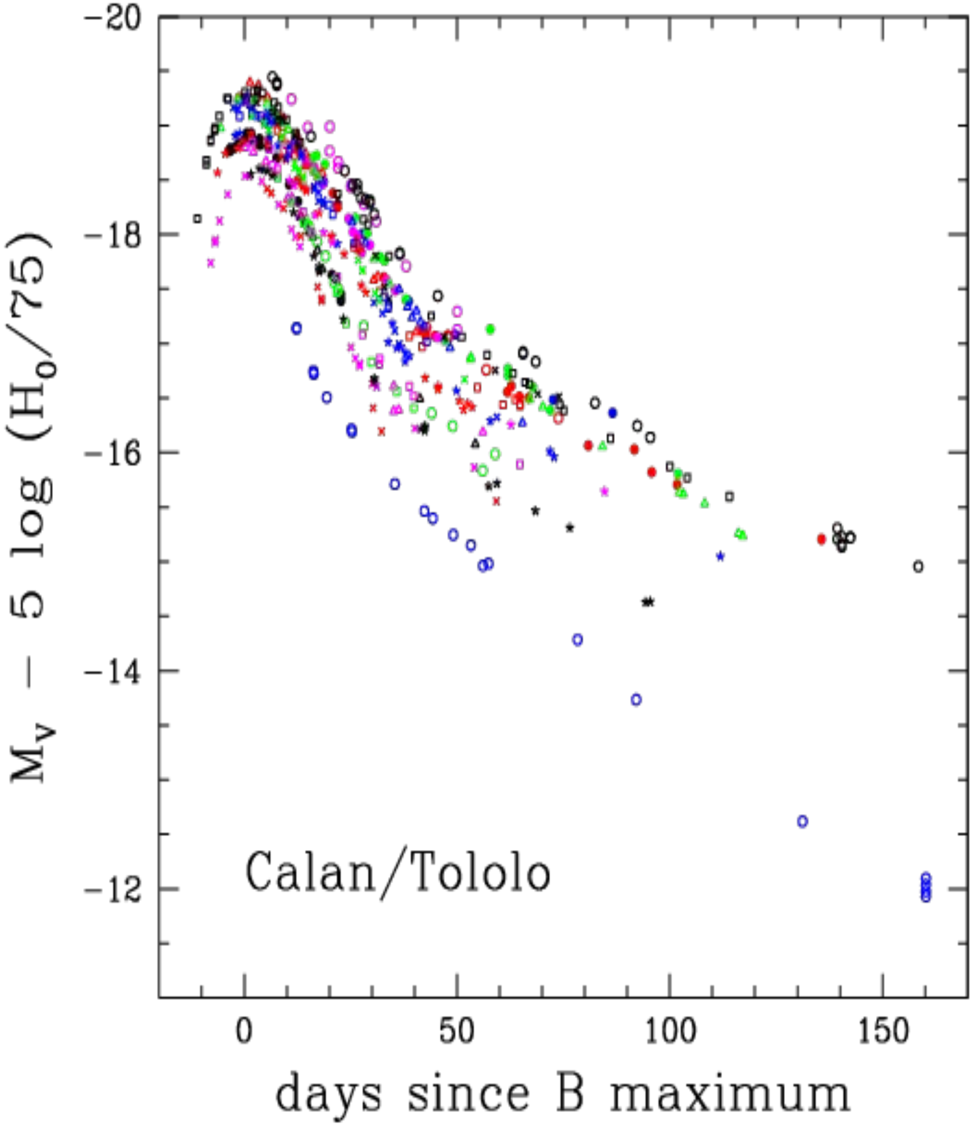
$$m = -2.5 \log(F/F_{\rm ref})$$



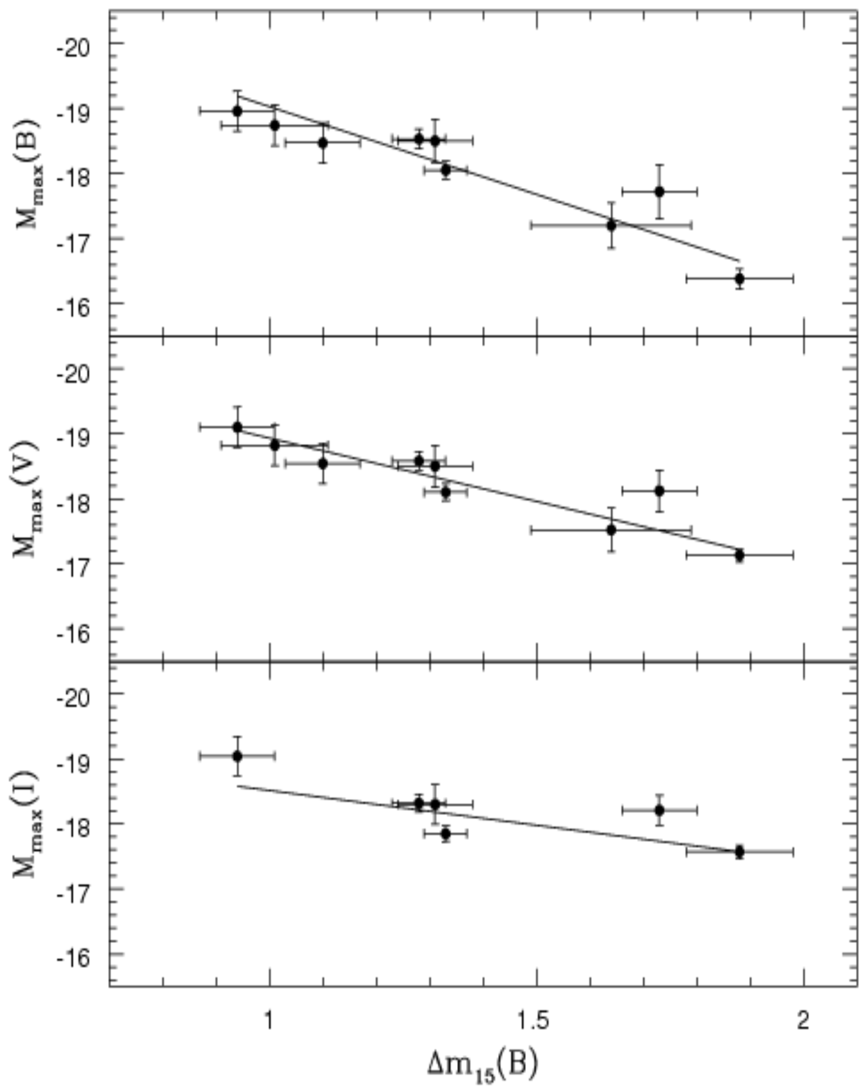
Goobar & Leibundgut, arXiv:1102.1431

They are certainly *not* 'standard candles'

What are Type Ia supernovae?



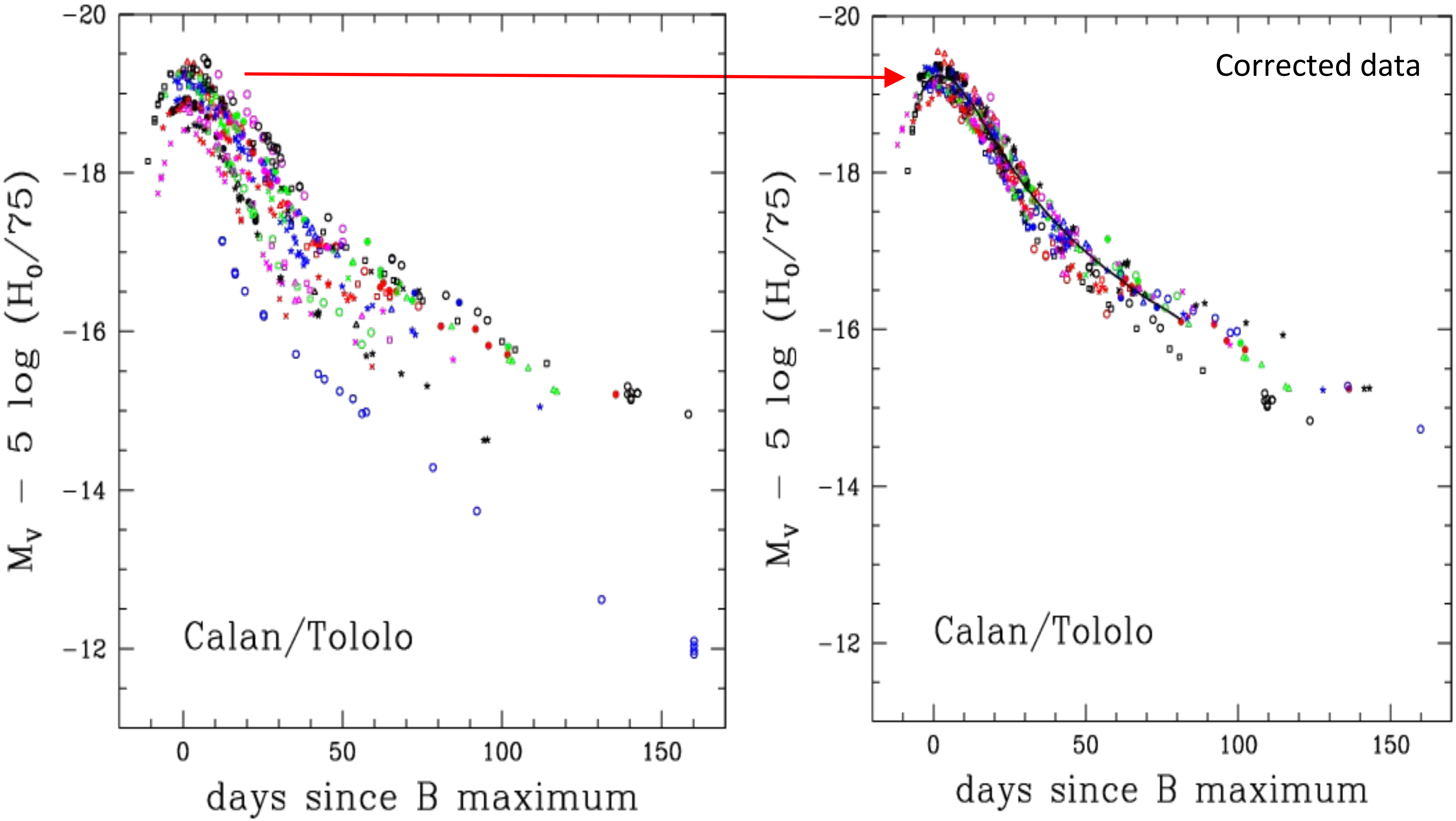
Hamuy, arXiv:311.5099



Phillips, ApJ **413**:L105, 1993

But they can be 'standardised' using the observed correlation between their peak magnitude and light–curve width (NB: this is *not* understood theoretically)

What are Type Ia supernovae?



Hamuy, arXiv:1311.5099

The scatter is thus reduced from a factor of ~10 to a factor of ~2

(NB: This requires observing the rise of the light curve *before* the SN peaks!)

Spectral Adaptive Lightcurve Template

(For making 'stretch' and 'colour' corrections to the observed lightcurves)

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

B-band

SALT 2 parameters

Betoule *et al.*, arXiv:1401.4064

Name	$z_{\rm cmb}$	$m_B^\star$	X_1	C	$M_{\rm stellar}$	?
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	

There may well be other variables that the magnitude correlates with …

Cosmology

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

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

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

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

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

Distance modulus

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

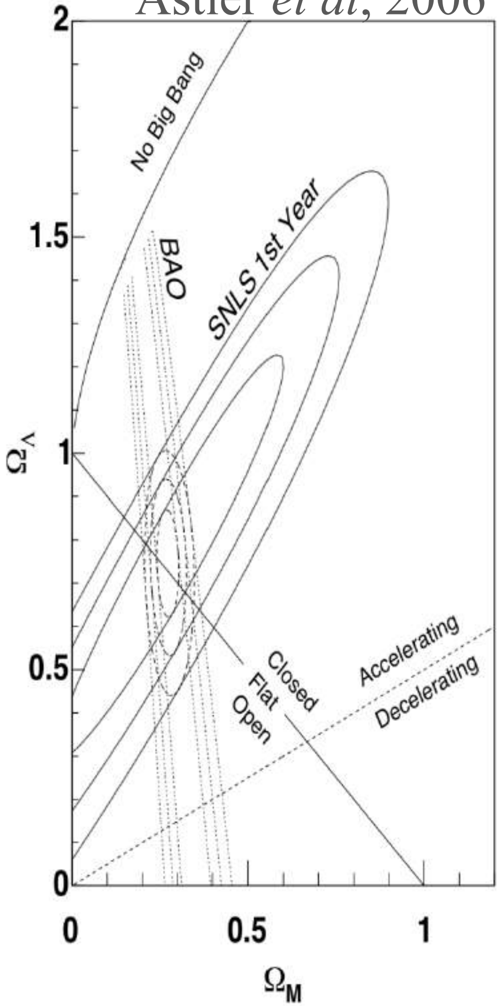
What is measured?

Redshift z and apparent magnitude (at maximum) m^*_B … then fit to SALT–2 template

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

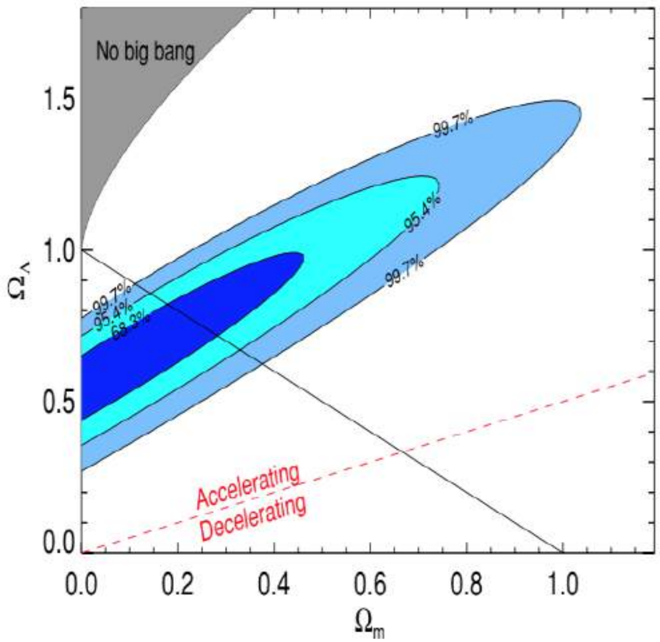
How strong is the evidence for cosmic acceleration?

Astier *et al*, 2006

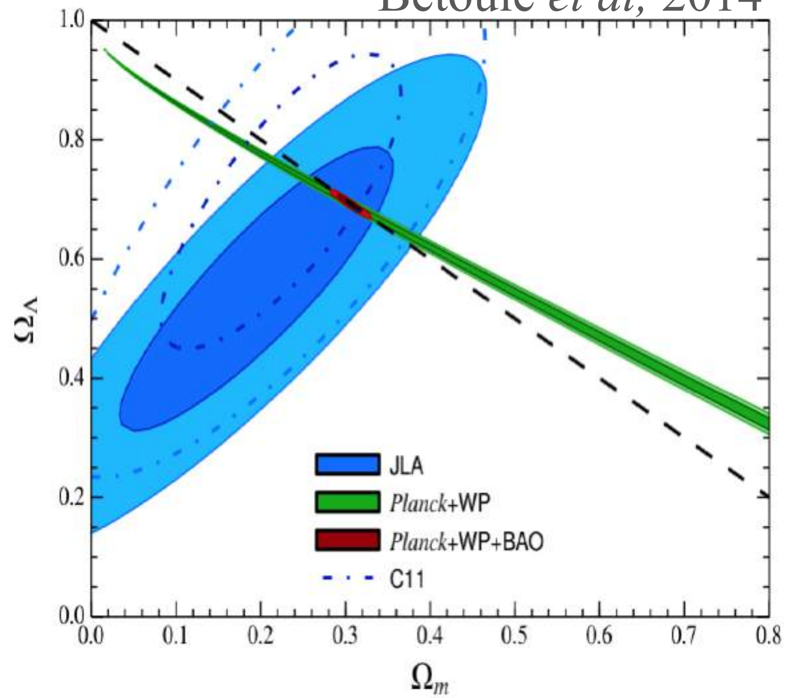


"SN data alone require* cosmic acceleration at >99.999% confidence, including systematic effects" (Conley *et al*, 2011)

*from the magnitude-redshift plot



Betoule *et al*, 2014

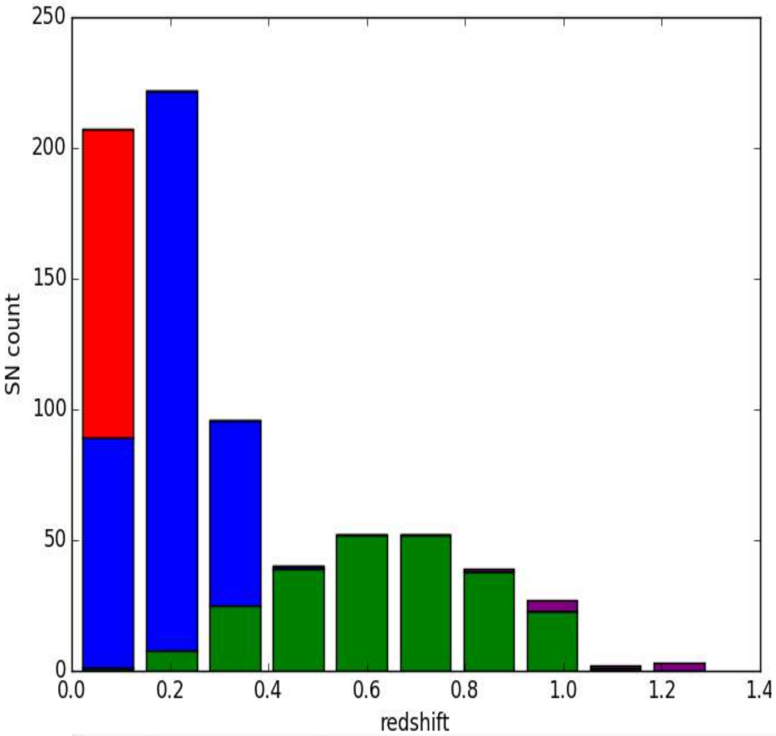


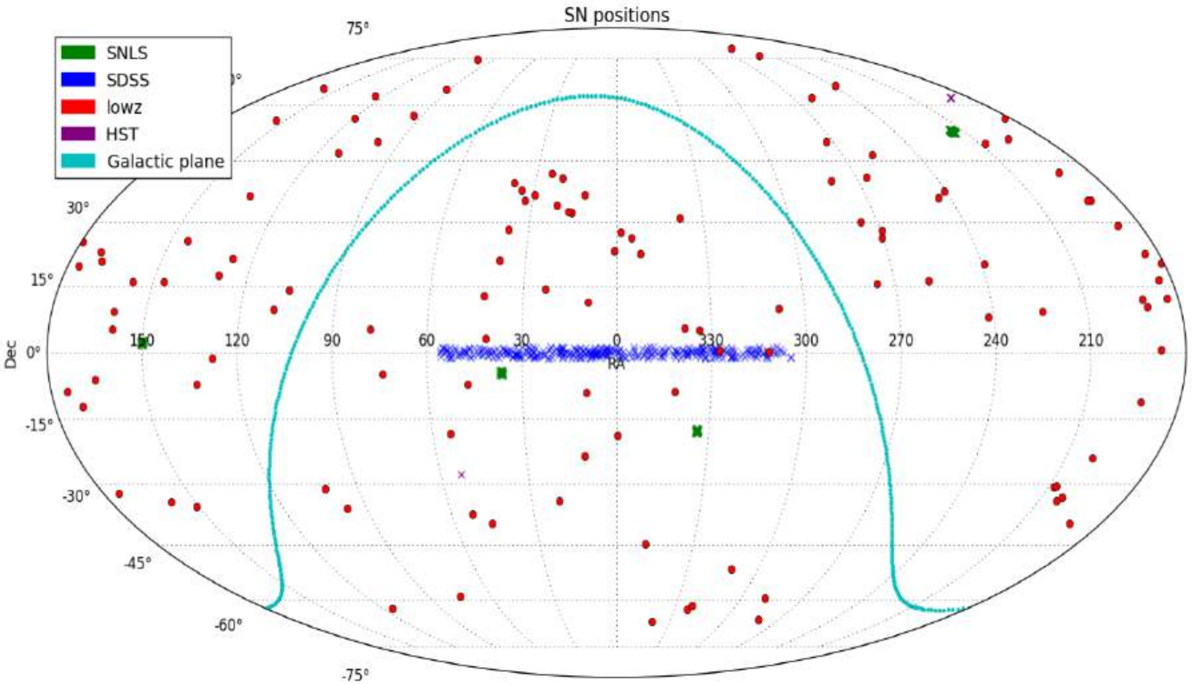
$$\chi^2 = \sum_{objects} \frac{(\mu_B - 5\log_{10}(d_L(\theta, z)/10pc))^2}{\sigma^2(\mu_B) + \sigma^2_{int}}$$

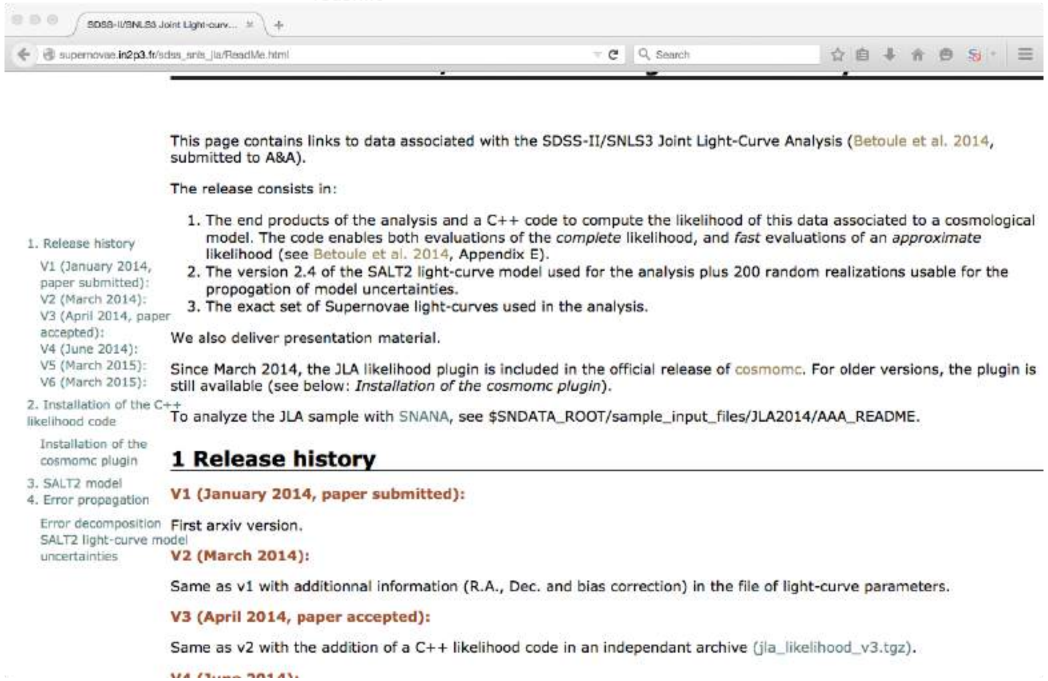
But they *adjust* σ_{int} to get χ^2 of 1/d.o.f. for the fit to the *assumed* ΛCDM model!

Joint Lightcurve Analysis data (740 SNe)

Betoule *et al*, arXiv:1401.4064







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 *publicly* available

http://supernovae.in2p3.fr/sdss_snls_jla/

... has been *corrected* for Malmqvist bias

We use *exactly* the same dataset but apply a *principled* statistical analysis

Nielsen *et al*, arXiv:1506.01354

Construct a Maximum Likelihood Estimator

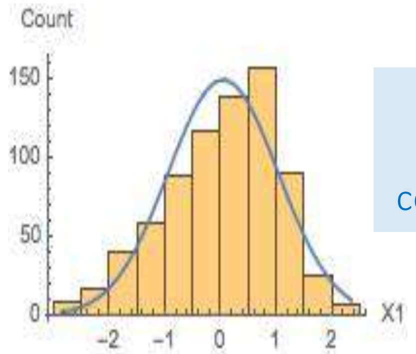
$$\mathcal{L} = \text{probability density}(\text{data}|\text{model})$$

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

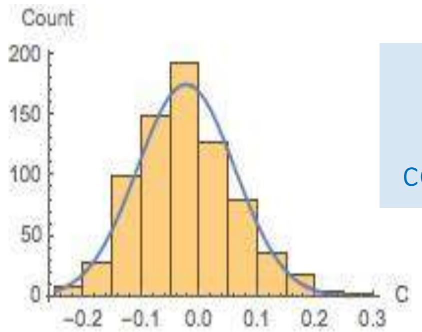
Cosmological model

Supernova model

Well–approximated as Gaussian



JLA data
'Stretch'
corrections



JLA data
'Colour'
corrections

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

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

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

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

Nielsen, Guffanti & Sarkar, arXiv:1506.01354

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, Guffanti & Sarkar, arXiv:1506.01354

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

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

1,2,3-sigma

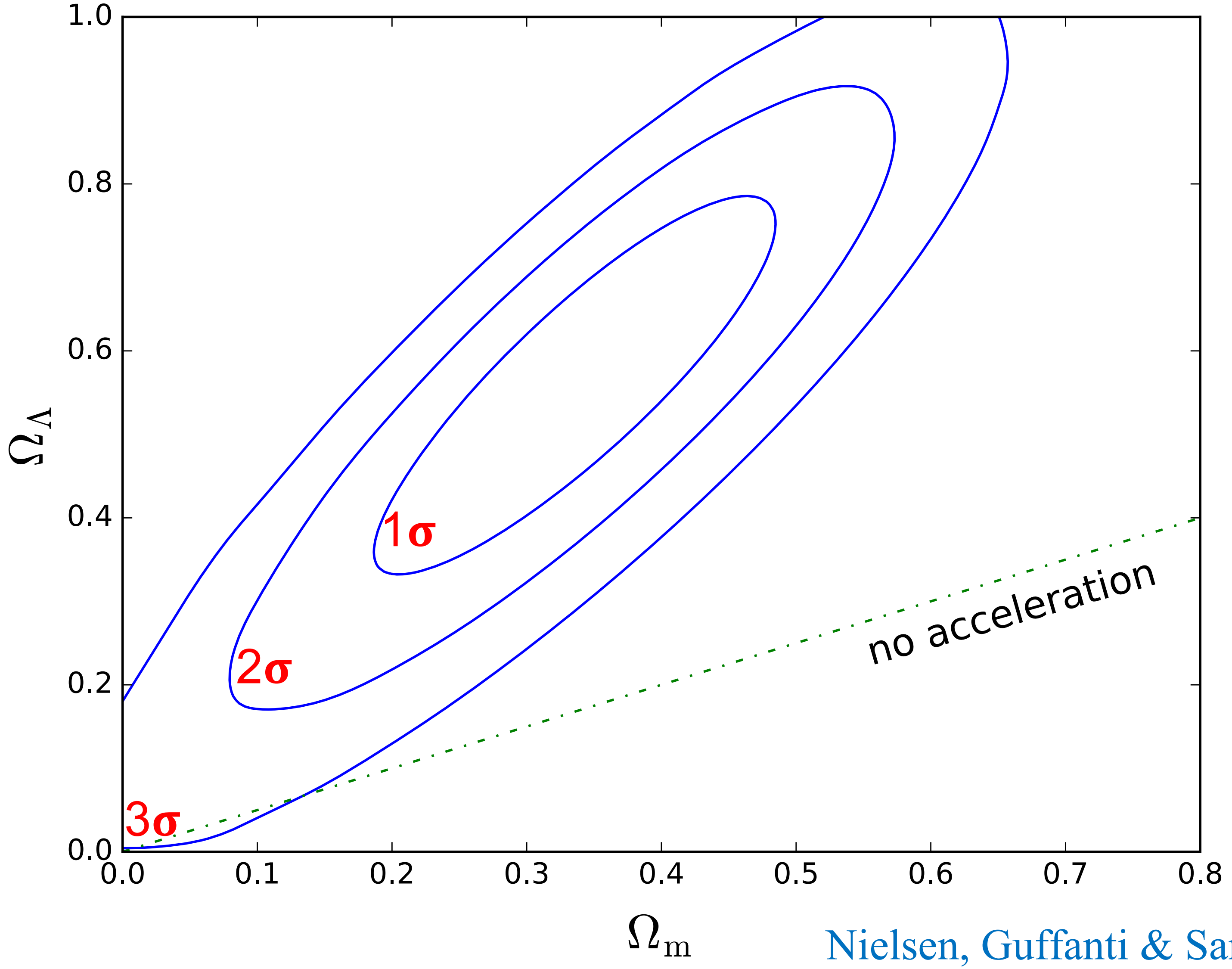
solve for Likelihood value

Data consistent with *uniform* expansion rate @ <3σ!

Raises interesting questions e.g. could an effective EOS of $p \sim -\rho/3$ arise from shear/bulk viscosity of dark matter during structure formation (Floerchinger *et al*, arXiv:1411.3280)?

Profile Likelihood

10 parameters
(8 SNIa + 2 cosmology)

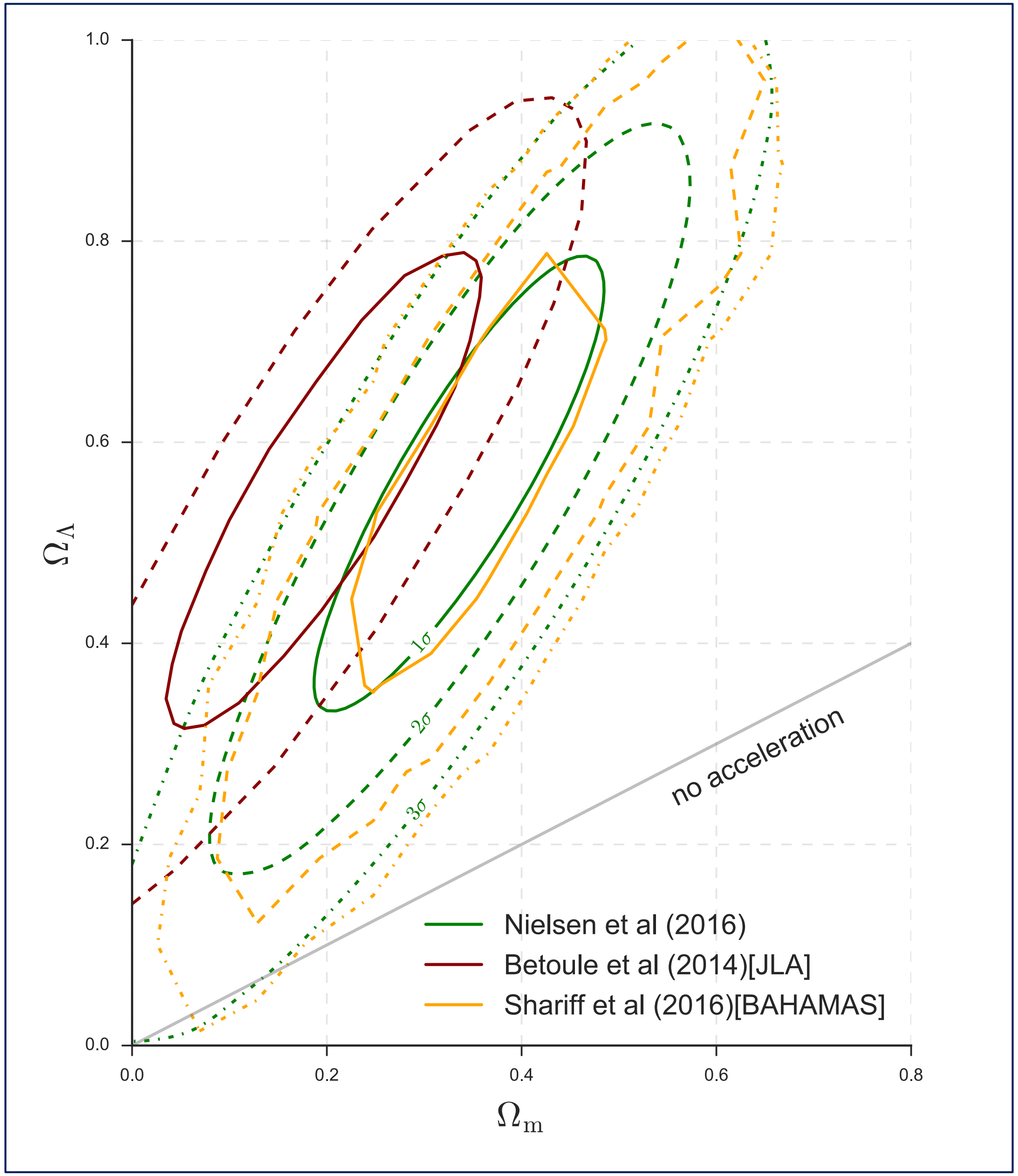


MLE, *best fit*

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, Guffanti & Sarkar, arXiv:1506.01354

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



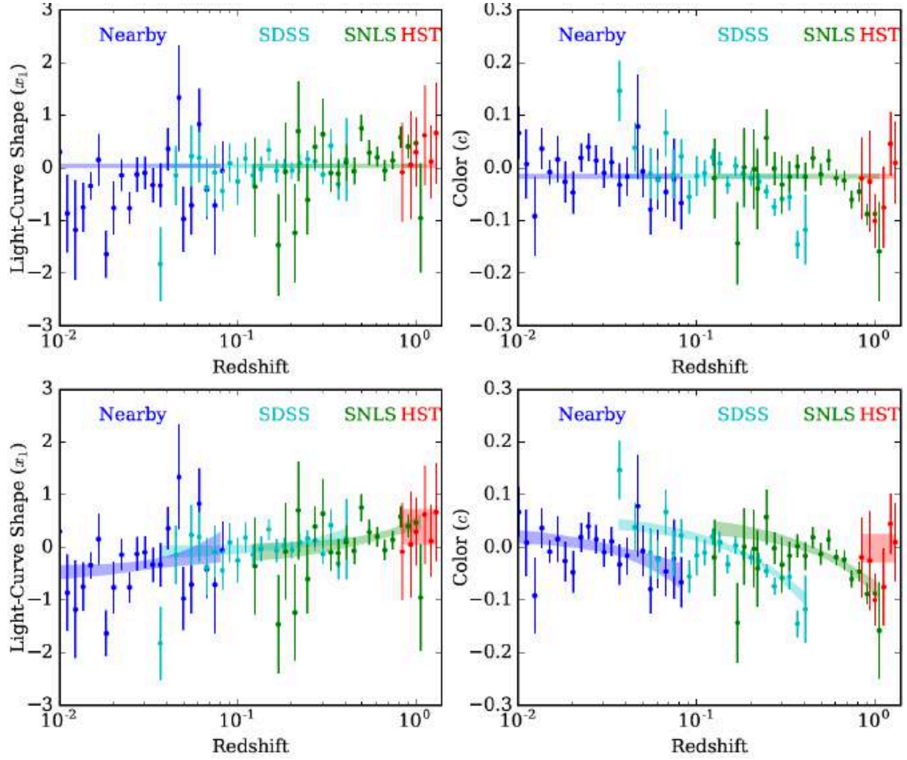
Shariff, Jiao, Trotta & van Dyk, arXiv:1510.05954

… much more computationally intensive (MCMC scan) hence contours are ragged

Epilogue

Rubin & Hayden (arXiv:1610.08972) 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 say they have *already* corrected for)

... they describe this by **adding 12 more parameters** to our (10 parameter) model



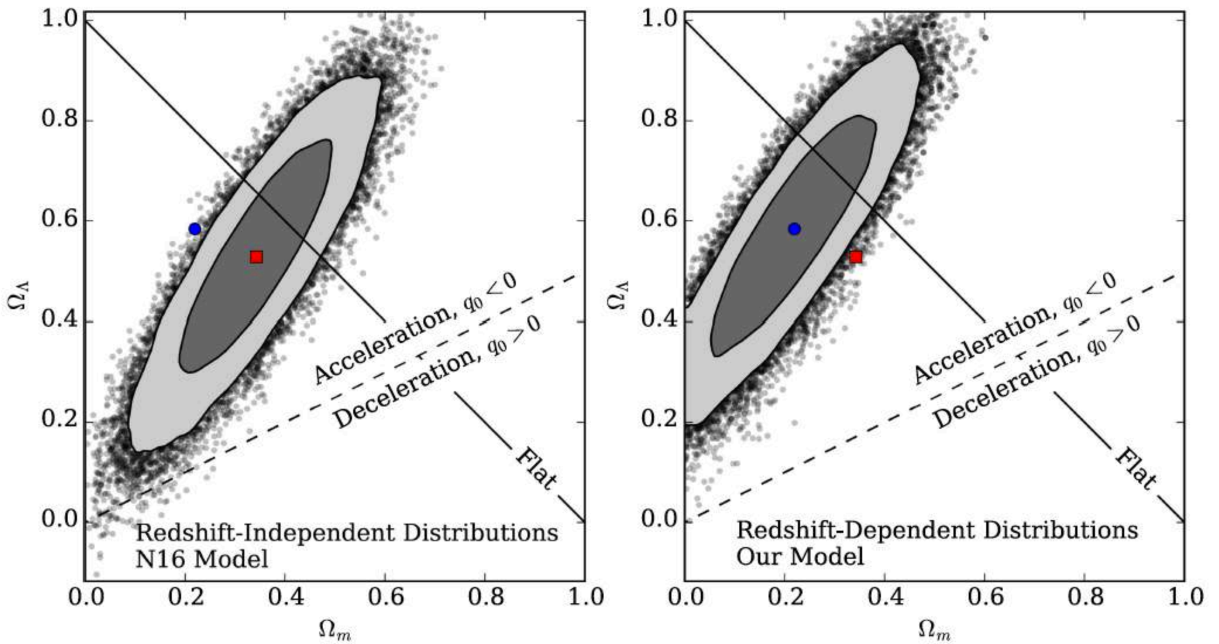
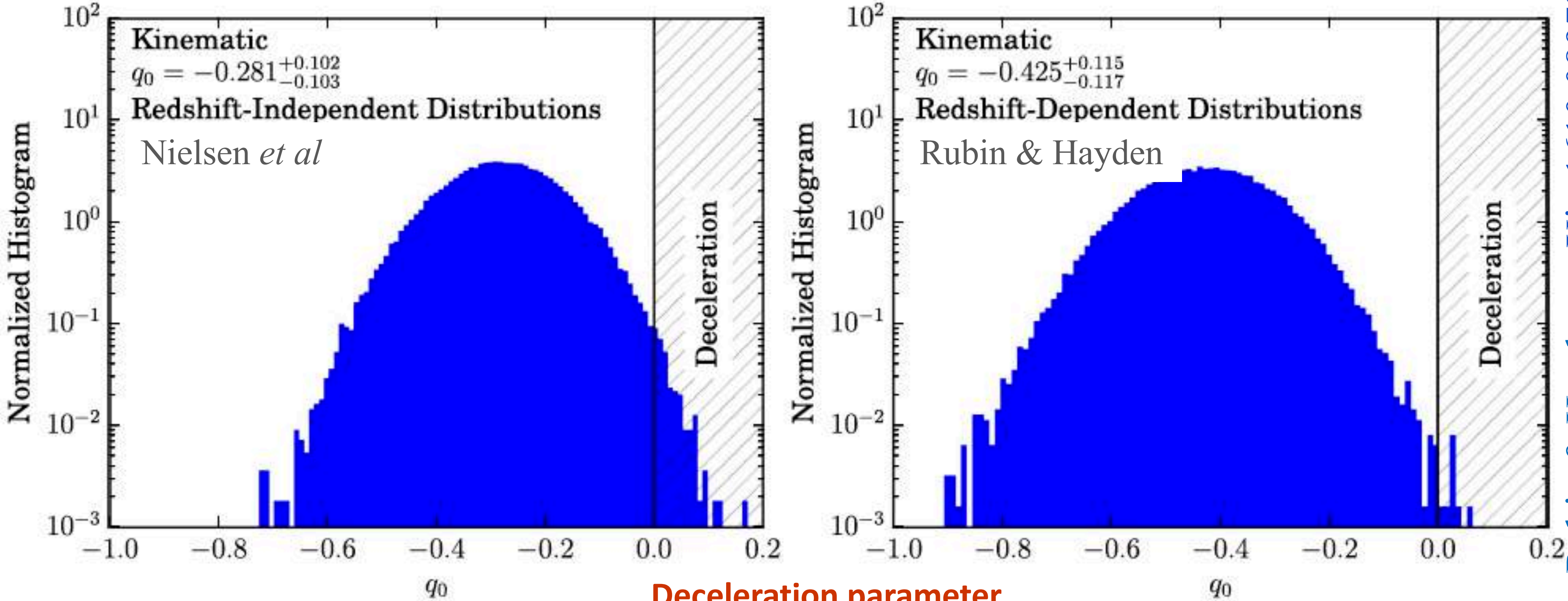


Figure 2. Ω_m–Ω_Λ constraints enclosing 68.3% and 95.4% of the samples from the posterior. Underneath, we plot all samples. The left panel shows the constraints obtained with x_1 and c distributions that are constant in redshift, as in the N16 analysis; the right panel shows the constraints from our 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 is raised to only $\lesssim 4\sigma$ ... 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, arXiv:gr-qc/0309109)



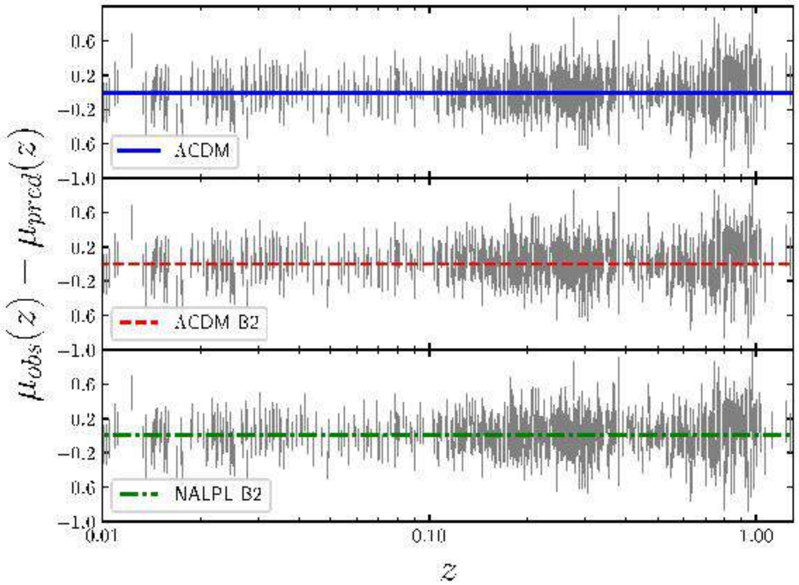
Rubin & Hayden, arXiv:1610.08972

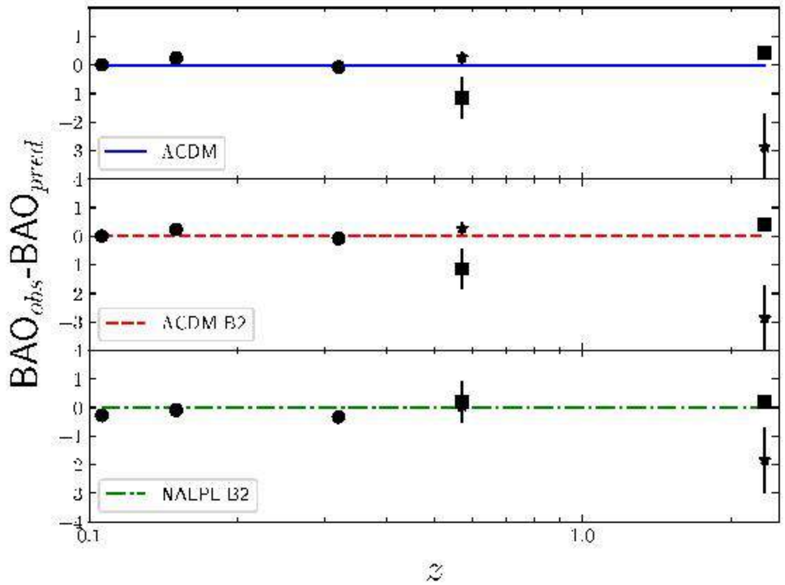
Deceleration parameter

$$q_0 \equiv -(\ddot{a}a)/\dot{a}^2$$

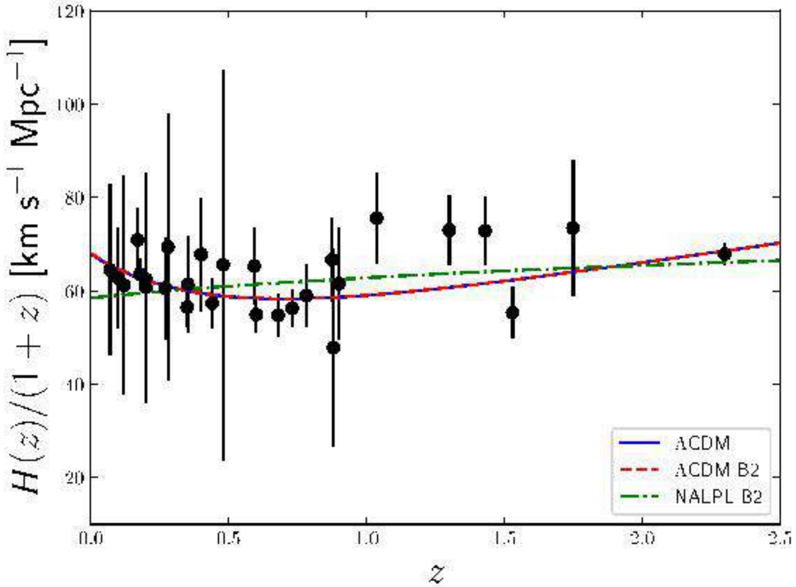
This yields 2.8σ evidence for acceleration in our approach … increasing to only 3.7σ when an *ad-hoc* redshift-dependence is allowed in the light-curve fitting parameters

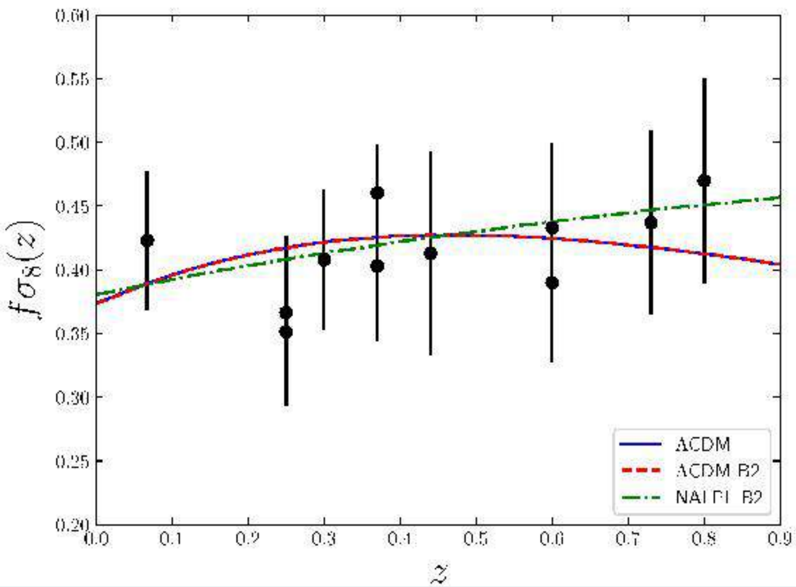
What about the evidence from BAO, *H*(*z*), growth of structure, …?





The ’independent’ lines of evidence are usually obtained using ΛCDM templates!

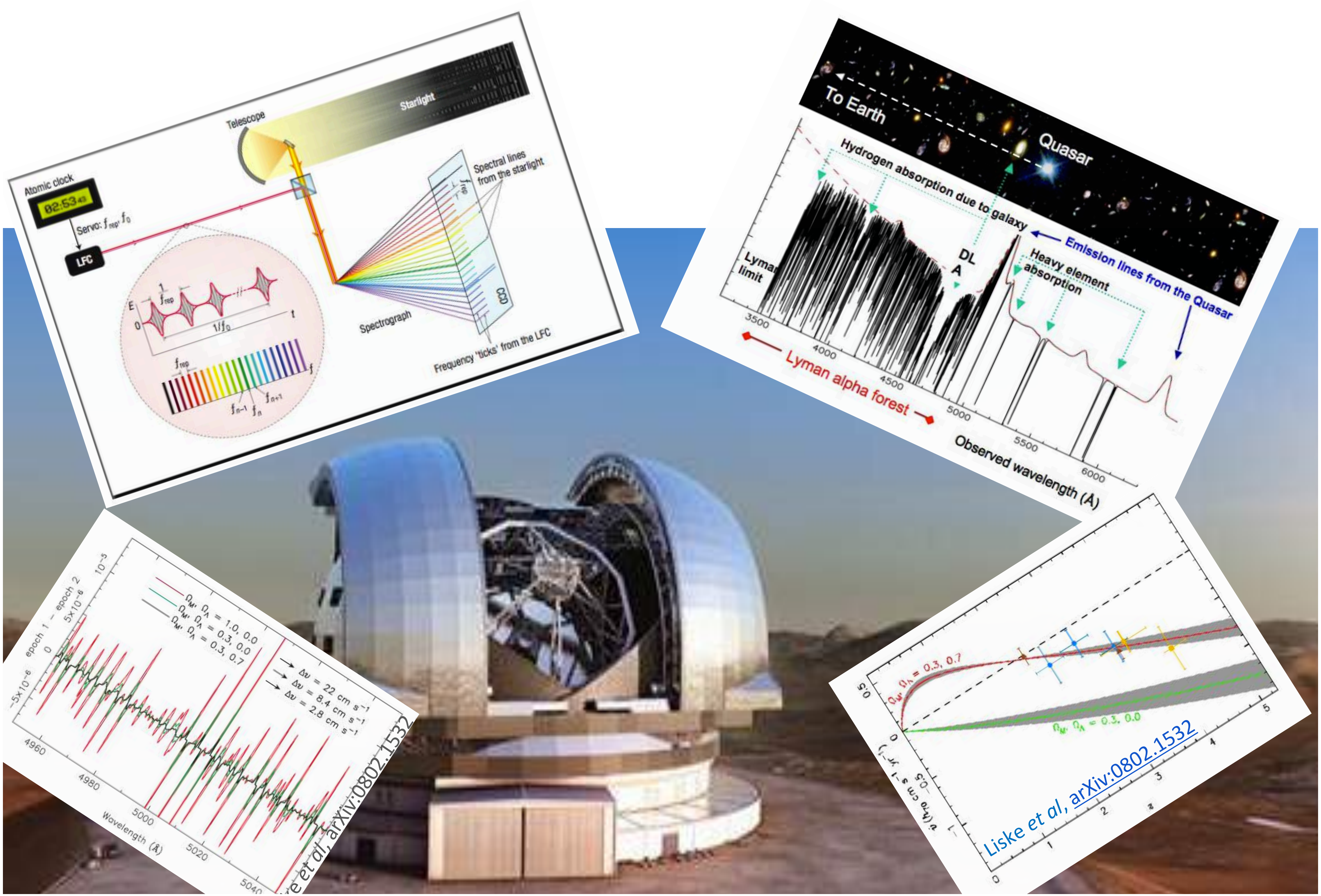




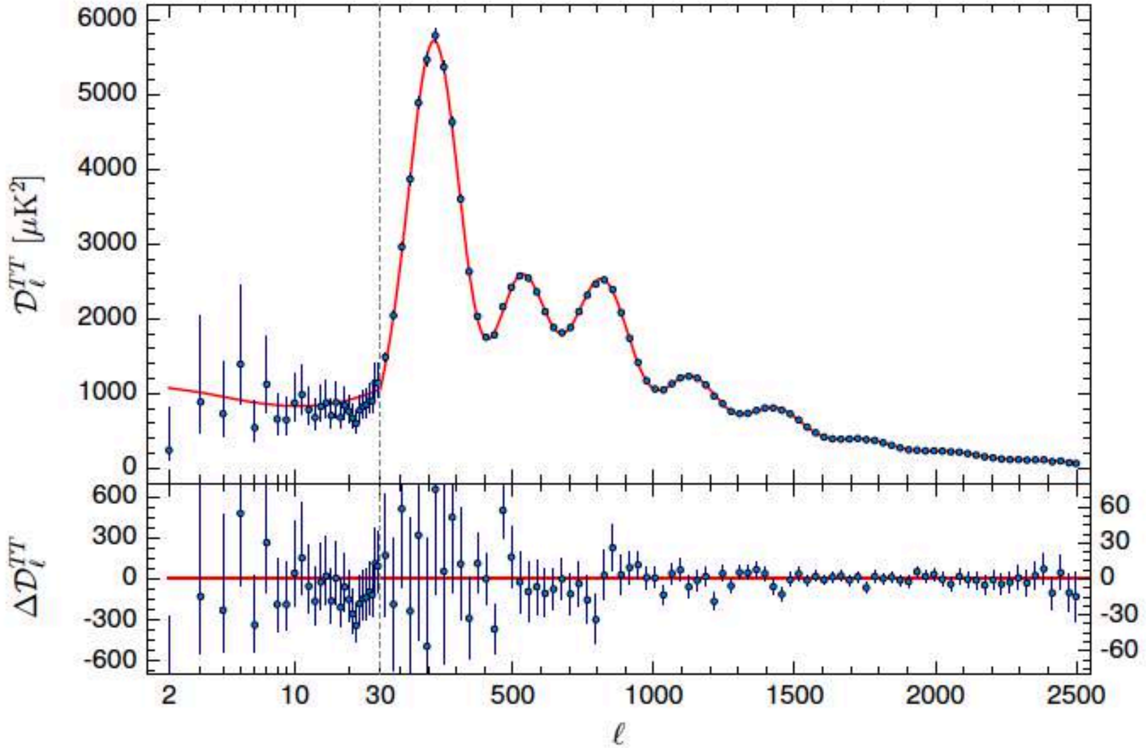
Tutusaus, Lamine, Dupays & Blanchard, arXiv:1706.05036

All data are *equally consistent* with *non*–accelerated expansion

Whether the expansion rate is accelerating needs to 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 & 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 (⇒ ~8 e-folds of inflation)

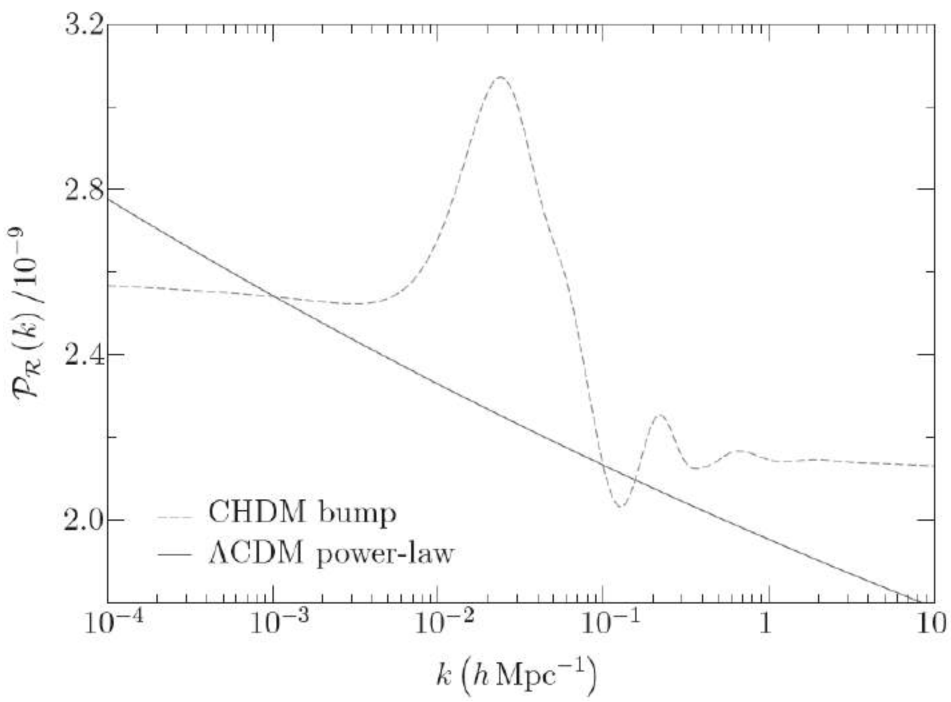
But we *cannot* uniquely determine the properties of the **detector** as well as of the (unknown) **beam** *and* **target**, from their convolution!

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

With different assumptions can match *same* data *without* Λ (Hunt & Sarkar, arXiv:0706.2443)

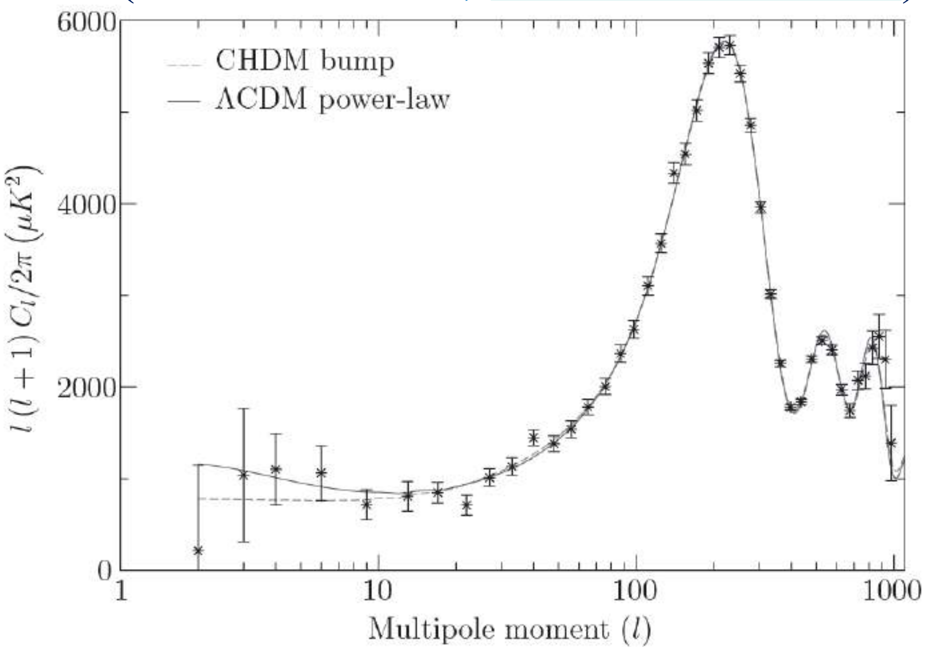
E.g. if there is a 'bump' in the spectrum (around the first acoustic peak), the CMB data can be fitted *without dark energy* ($\Omega_m = 1$, $\Omega_\Lambda = 0$) if $h \sim 0.43$

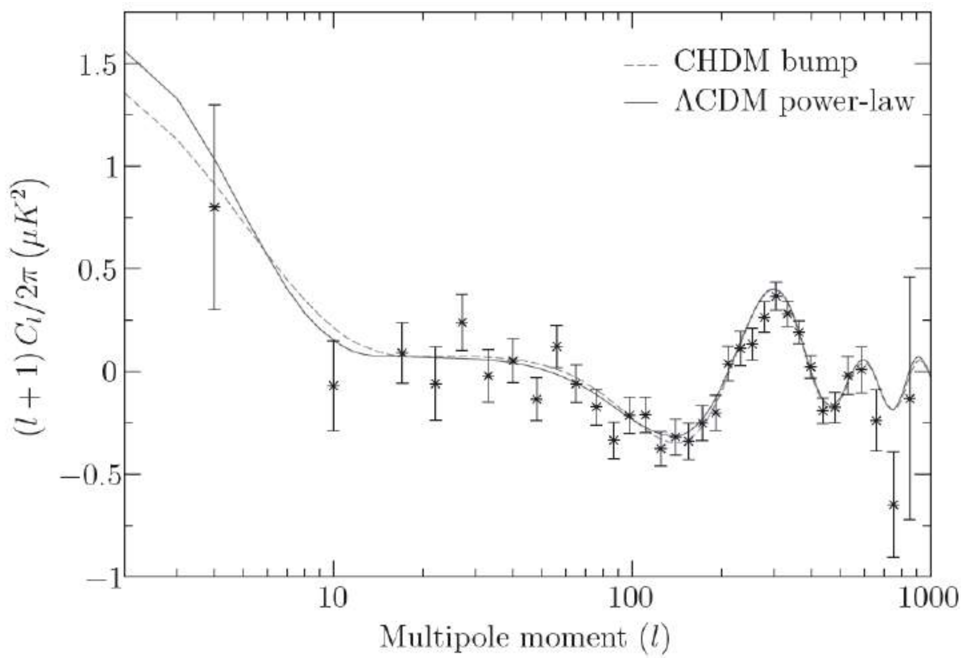
Hunt & Sarkar, arXiv:0706.2443, 0807.4508



While significantly below the *local* value of *h* ~ 0.67, this agrees with its value in the effective E-deS relativistic inhomogeneous model that matches stellar ages (*H*(*z*) data)

(Roukema *et al*, arXiv:1608.06004)

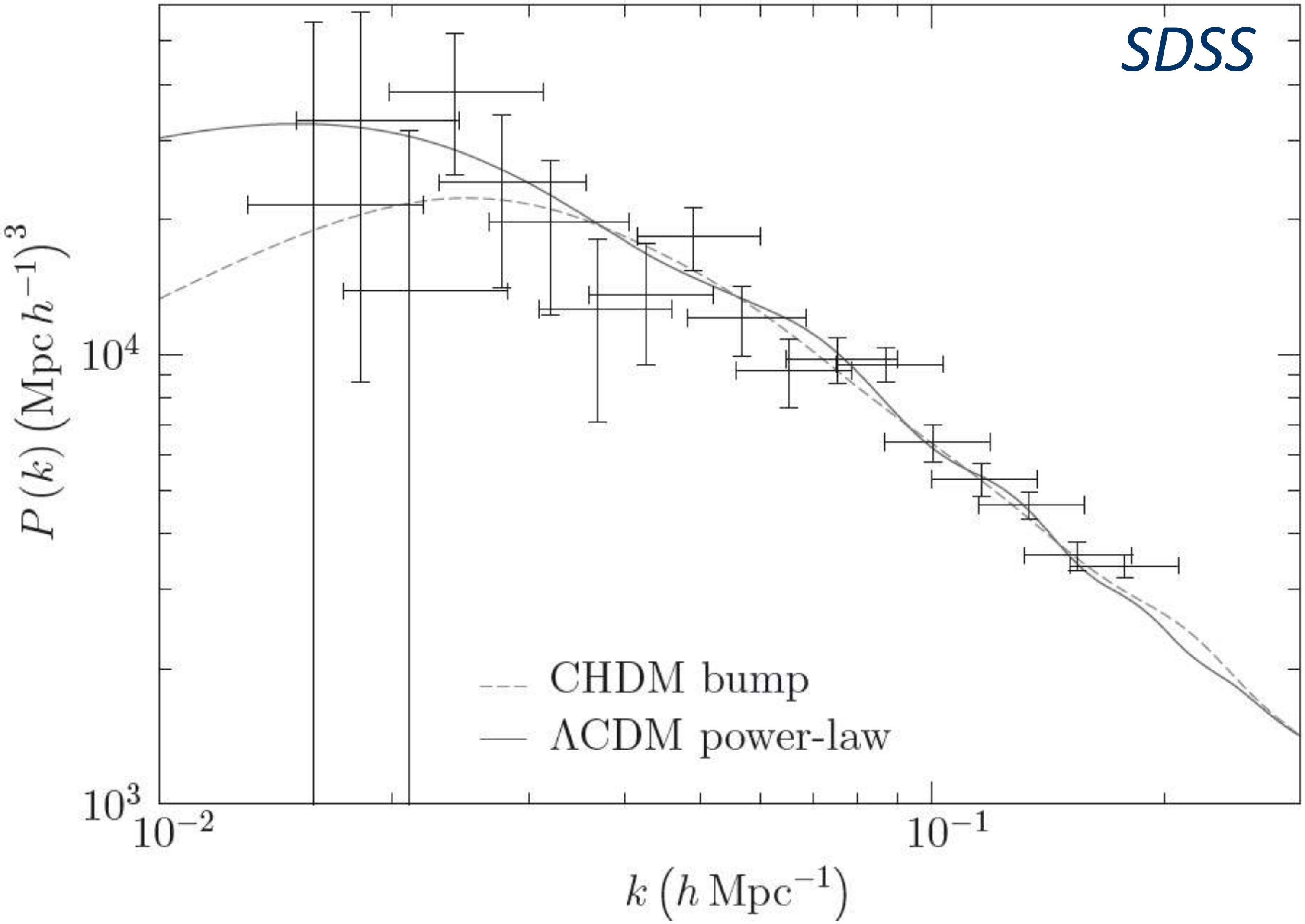




The small-scale power would be excessive unless damped by free-streaming

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 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 ... moreover these should be *'blind' analyses* (i.e. not assuming the answer beforehand!)

- 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