Is there evidence for cosmic acceleration?

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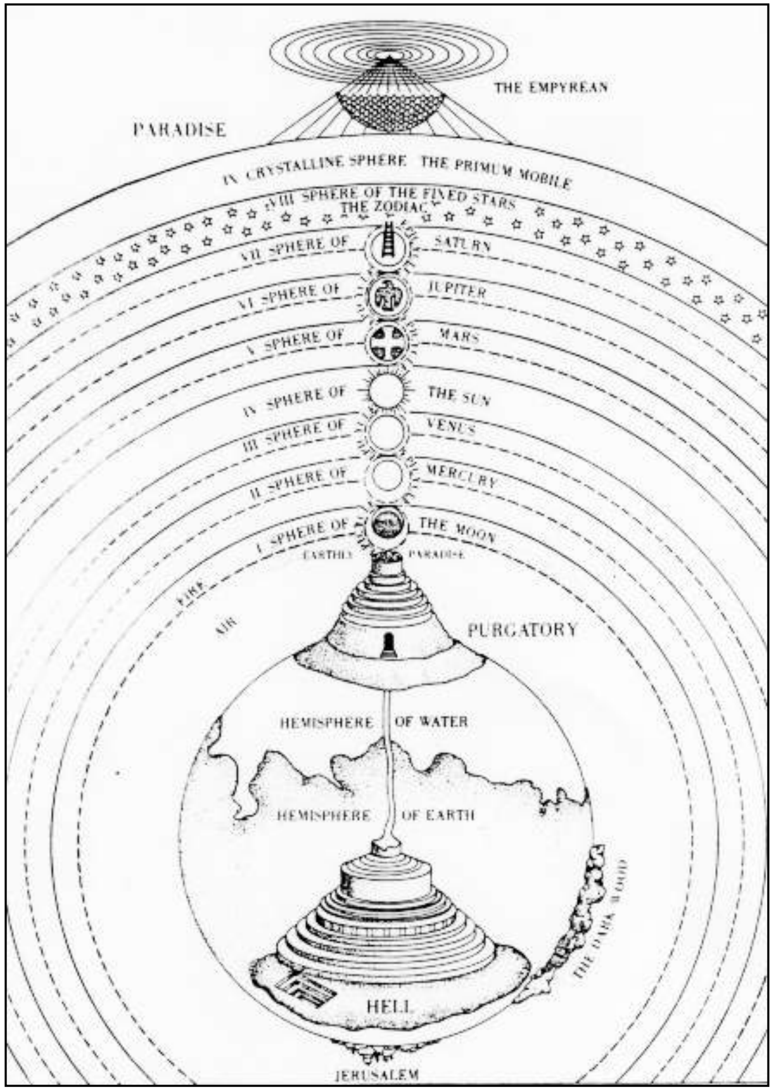
Scientific Reports **6**:35596 (2016), http://www.nature.com/articles/srep35596

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

Fysiska institutionen, University of Lund, 10th January 2017

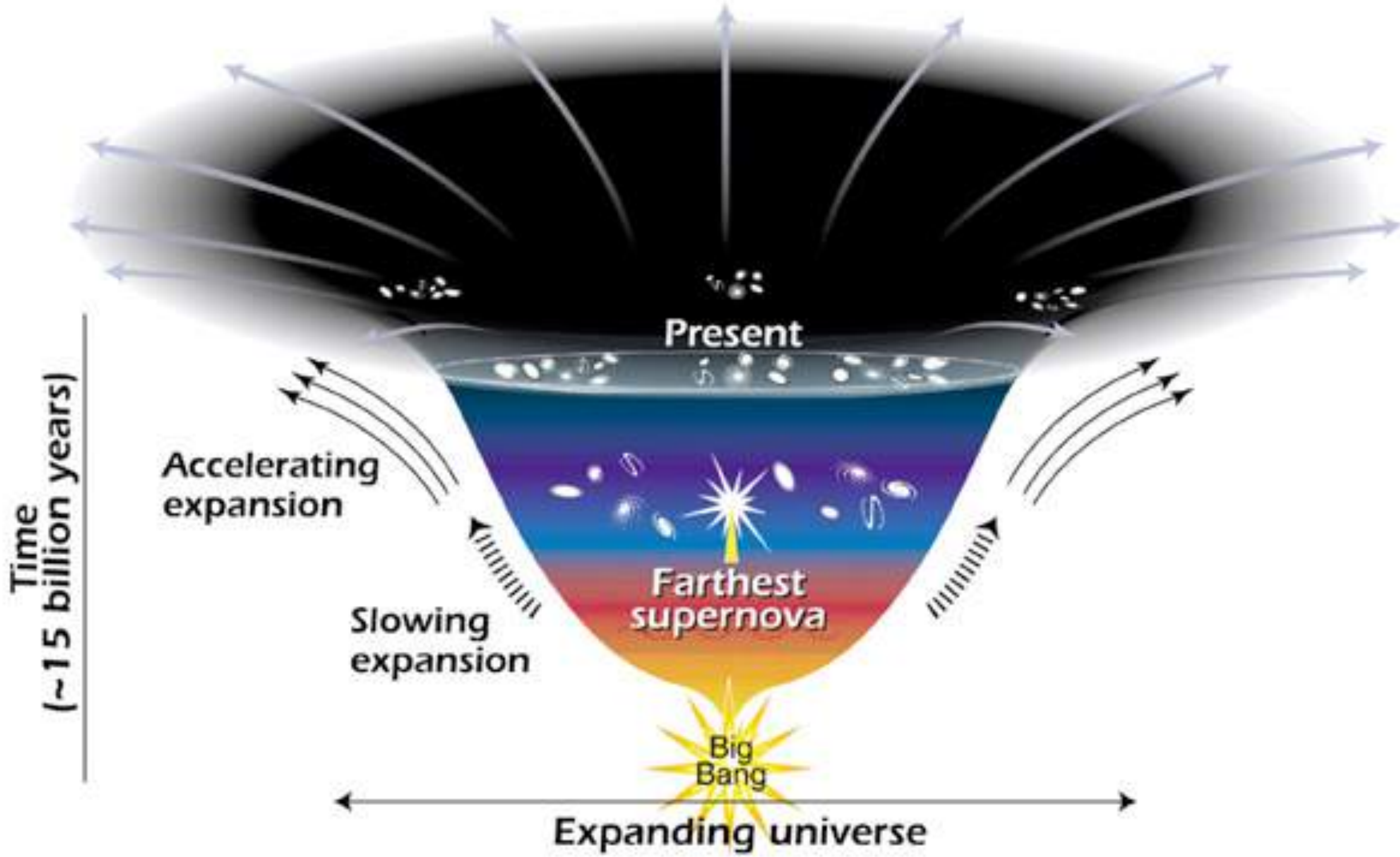
In the Aristotlean ‘standard model’ of cosmology (350 BC ➛ ~1600 AD) the universe was static and finite and centred on the Earth



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



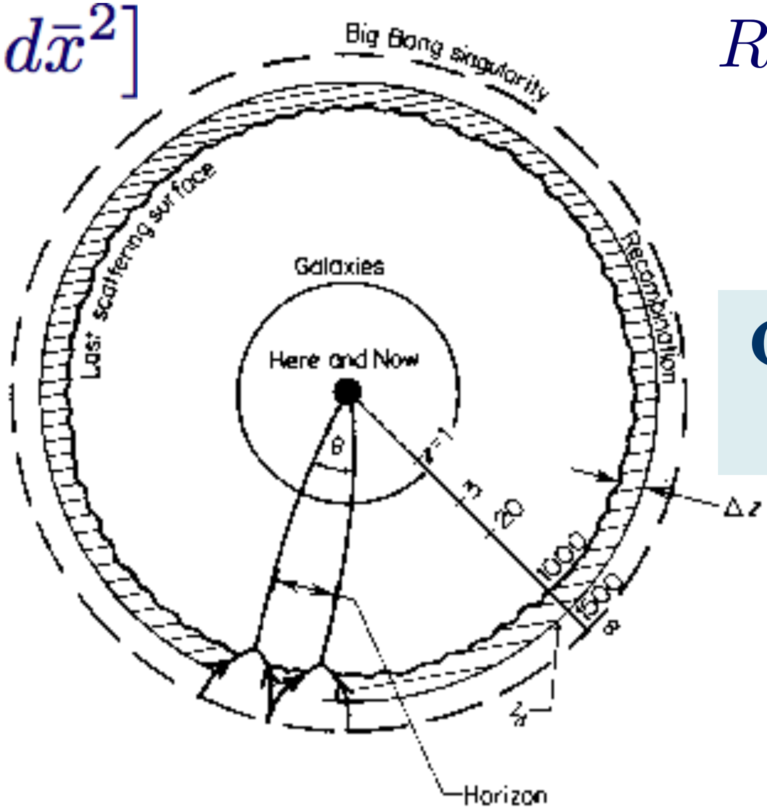
It too is 'simple' and fits all the observational data but lacks an underlying *physical* basis

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



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

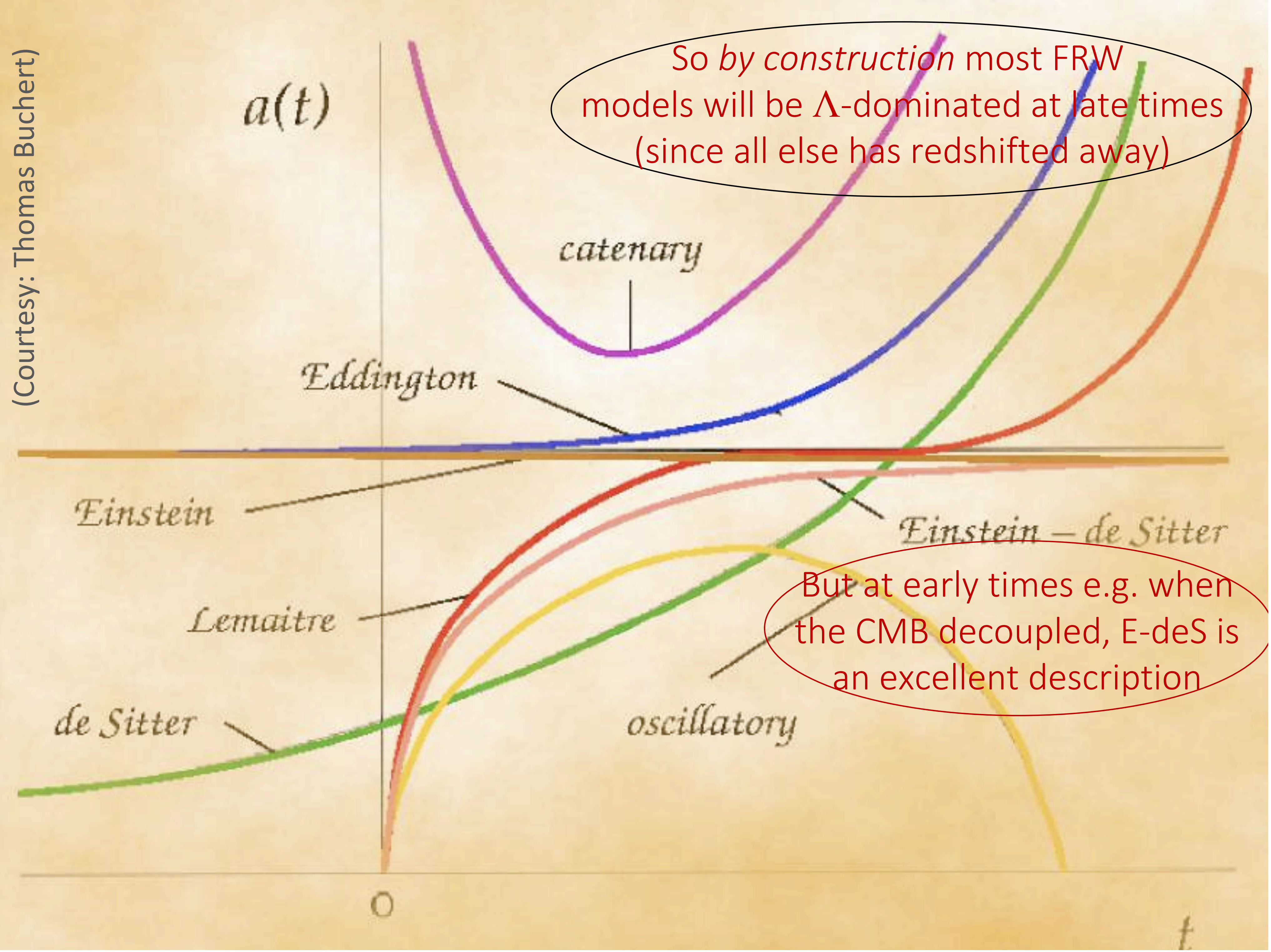
Geometrodynamics
Einstein

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

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

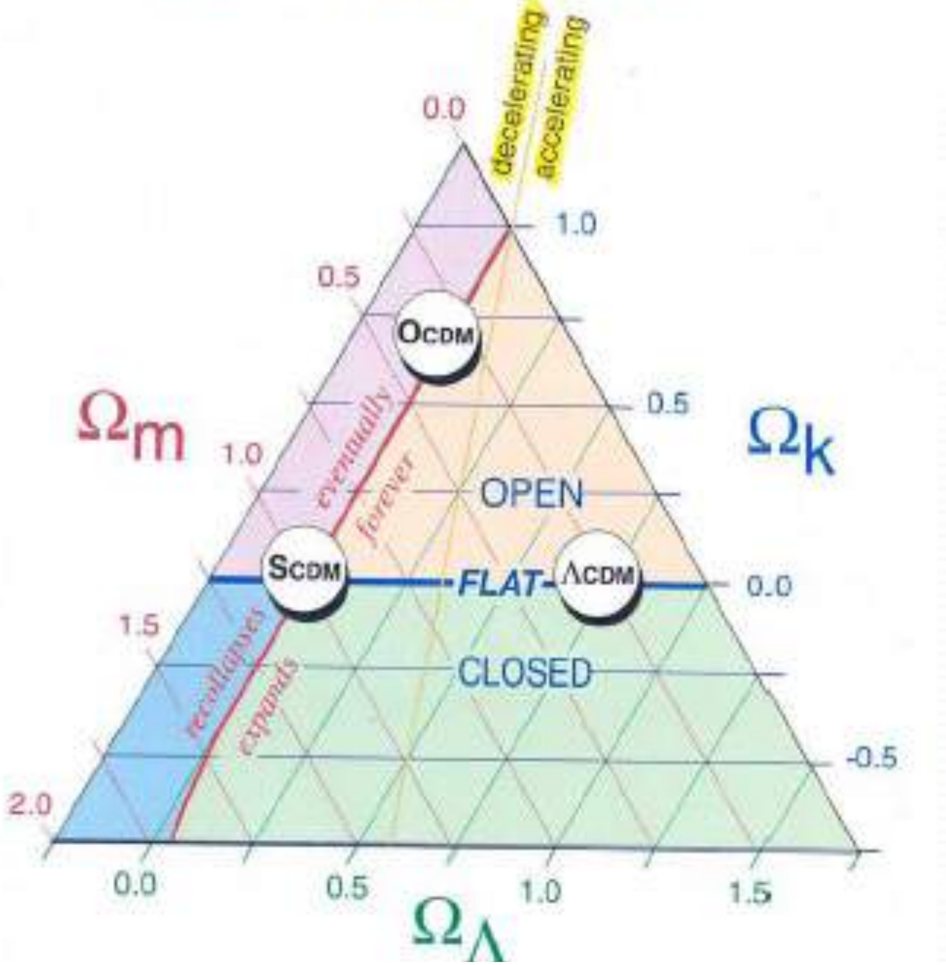
$$\equiv {H_0}^2\left[\Omega_{\mathrm{m}}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

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


(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

This yields the sum rule $1 \equiv \Omega_m + \Omega_k + \Omega_\Lambda$, using which Ω_Λ is *inferred* … but any uncertainties in measurements of Ω_m and Ω_k would then imply a *non-zero* Ω_Λ i.e. $\Lambda \sim O(H_0^2)$ – as has happened several times in recent history

There may also be other components Ω_x which are *not* included in the sum rule



Bahcall, Ostriker, Perlmutter & Steinhardt (1999)

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

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

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 ***M***) describes *all* of microphysics

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

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

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

neutrino mass

proton decay, FCNC …

non-renormalisable

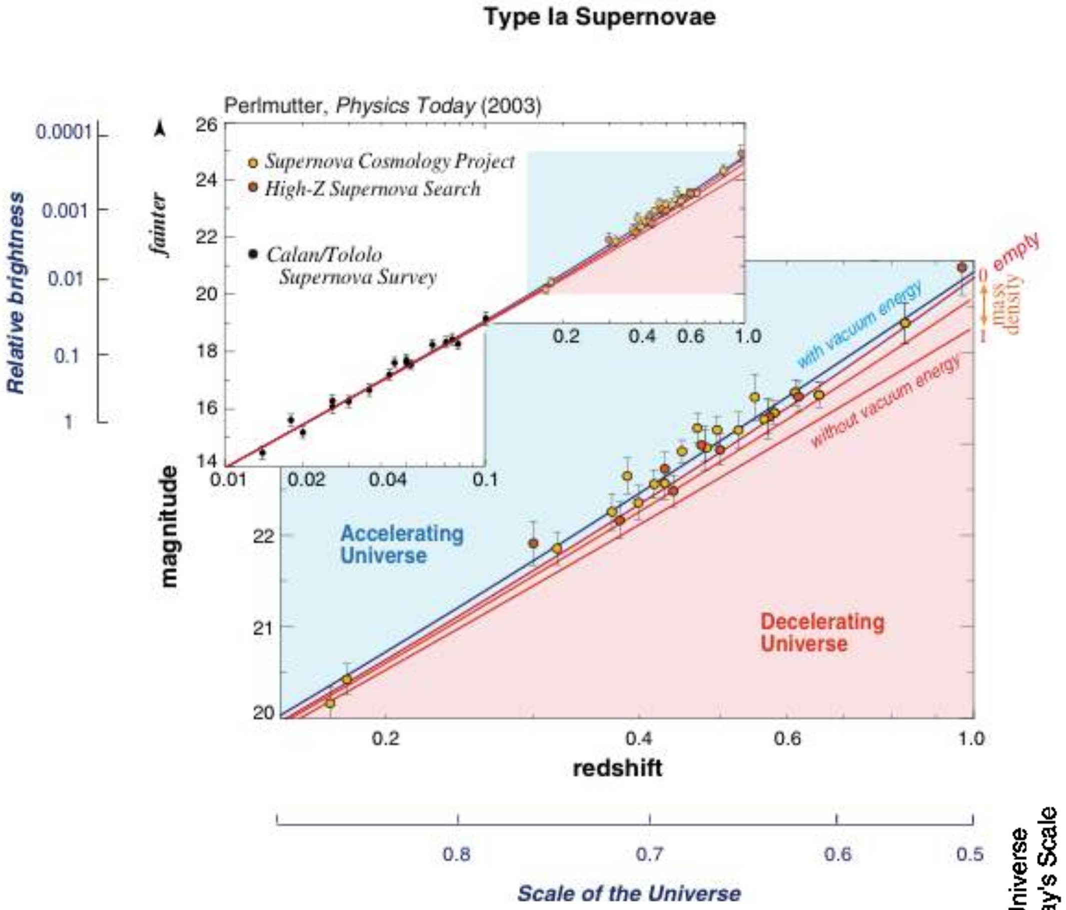
New physics beyond the SM ⇒ non-renormalisable operators suppressed by M^n which decouple as $M \to M_P$ … so neutrino mass is small, proton decay is slow

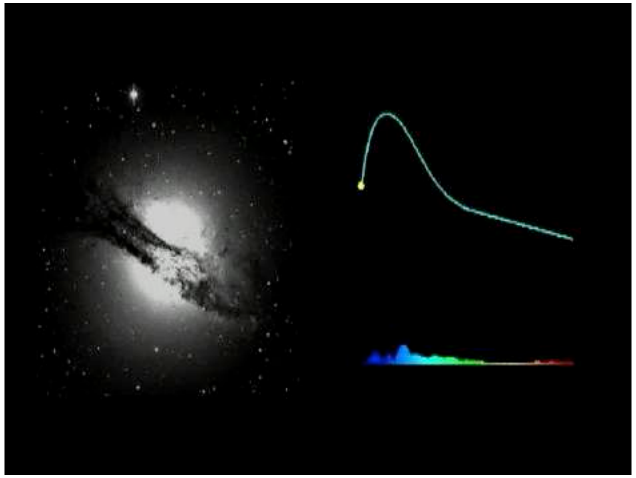
But as M is raised, the effects of the super-renormalisable operators are *exacerbated*
(One solution for Higgs mass divergence → 'softly broken' *supersymmetry* at O(TeV)
… or the Higgs could be *composite* – a pseudo Nambu-Goldstone boson)

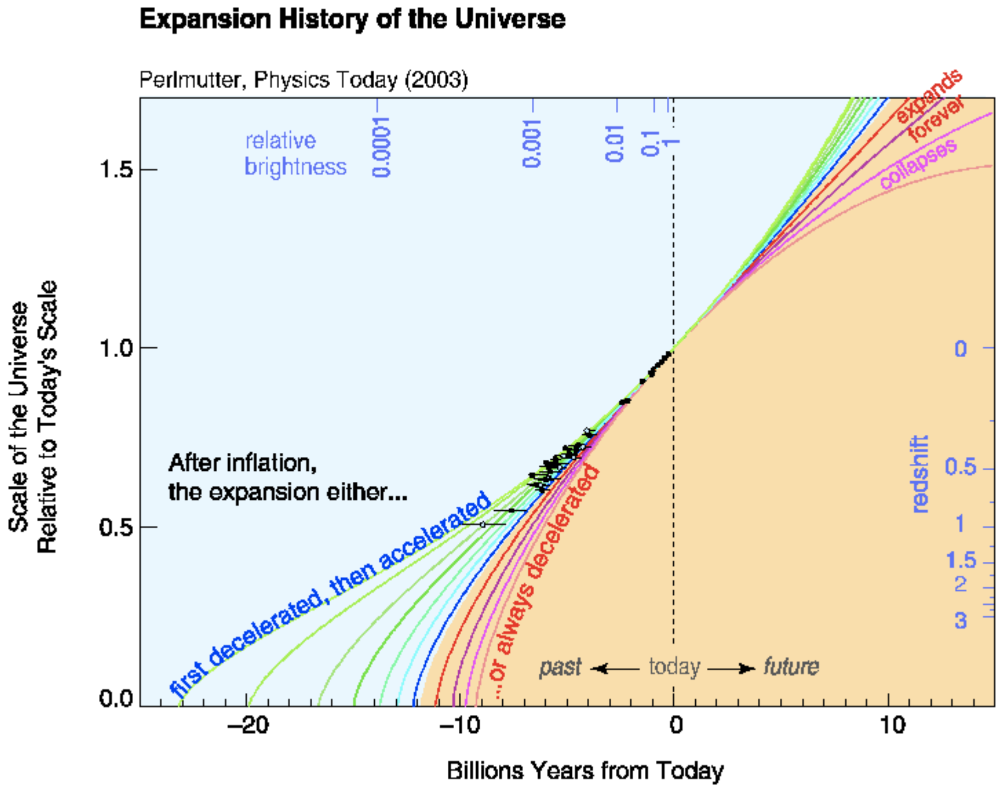
1st SR term **couples to gravity** so the *natural* expectation is $\rho_\Lambda \sim (1\ \text{TeV})^4 >> (1\ \text{meV})^4$
… *i.e.* the universe should have been inflating since (or collapsed at): $t \sim 10^{-12}$ s!
There must be some reason why this did *not* happen!

"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 $z \sim 0.5$:

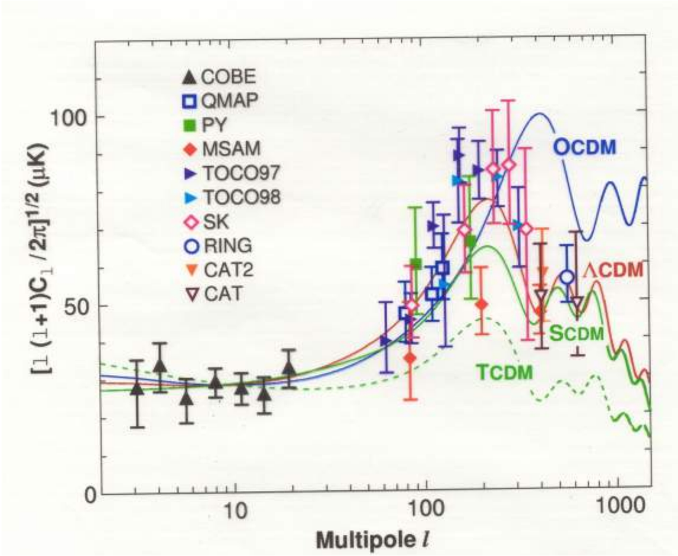




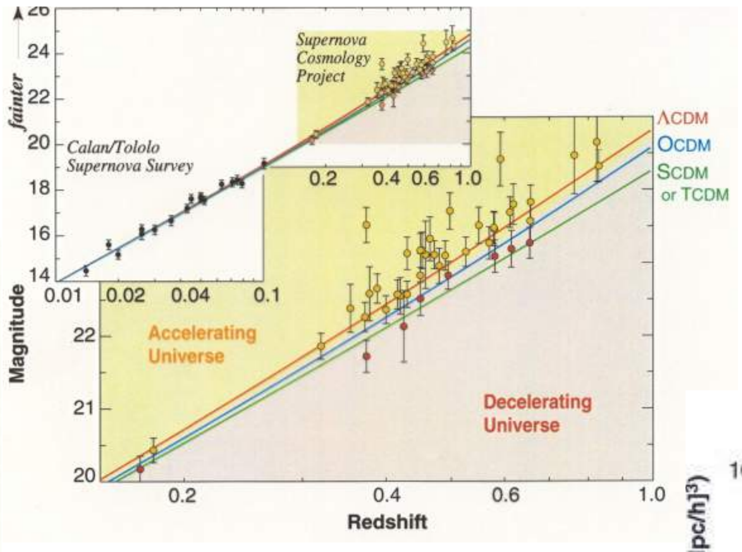


Note that the observations are actually made at *one* point in time (the redshift is assumed to be a proxy for time) …
so it is not quite a *direct* measurement

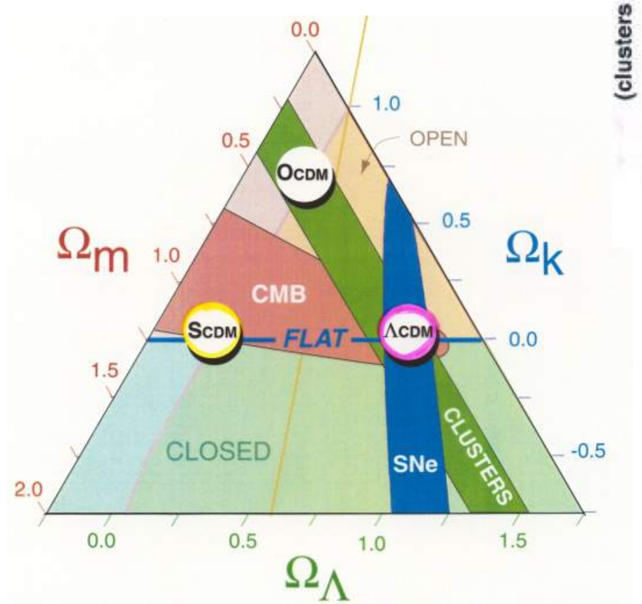
This was interpreted as due to the effect of ‘dark (vacuum) energy’

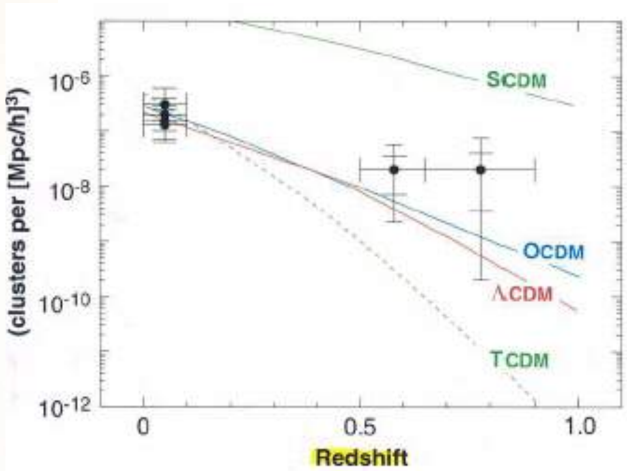


$\Omega_m + \Omega_\Lambda \approx 1.0 \pm 0.03$



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



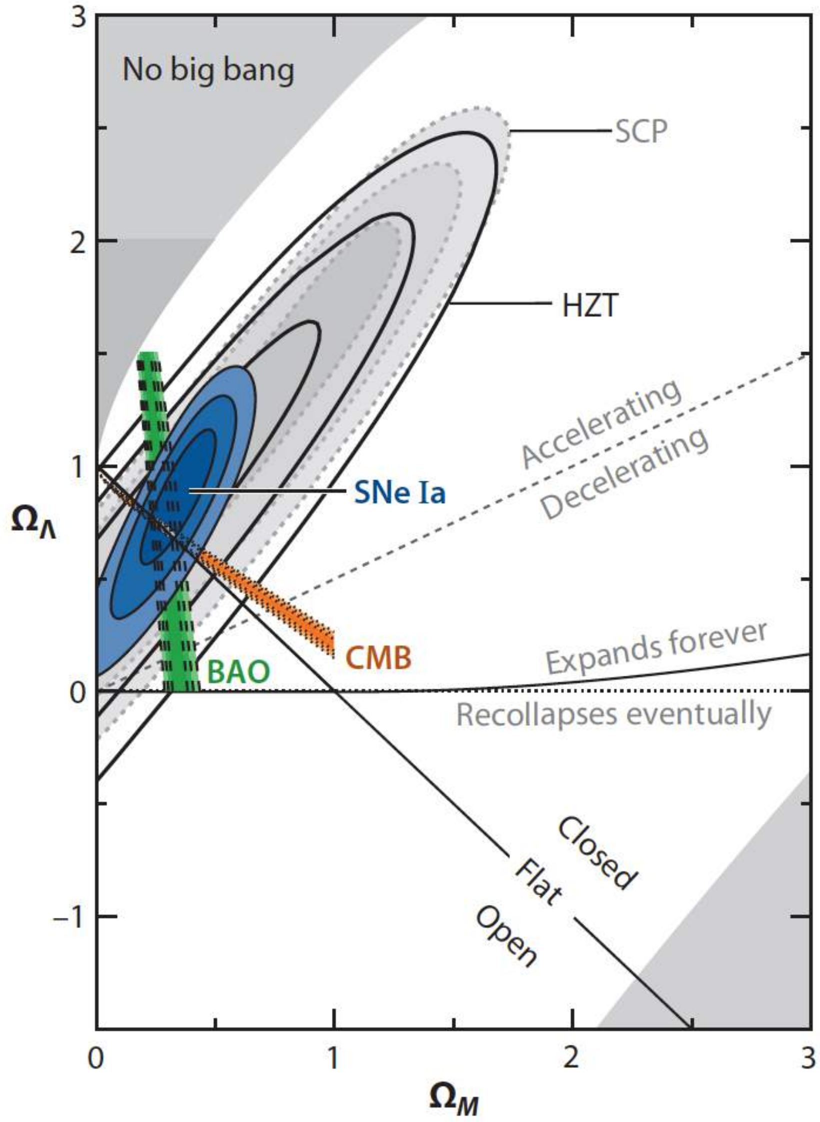


$\Omega_m \sim 0.3$

Bahcall, Ostriker, Perlmutter, Steinhardt (1999)

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

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 e.g. 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:

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

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

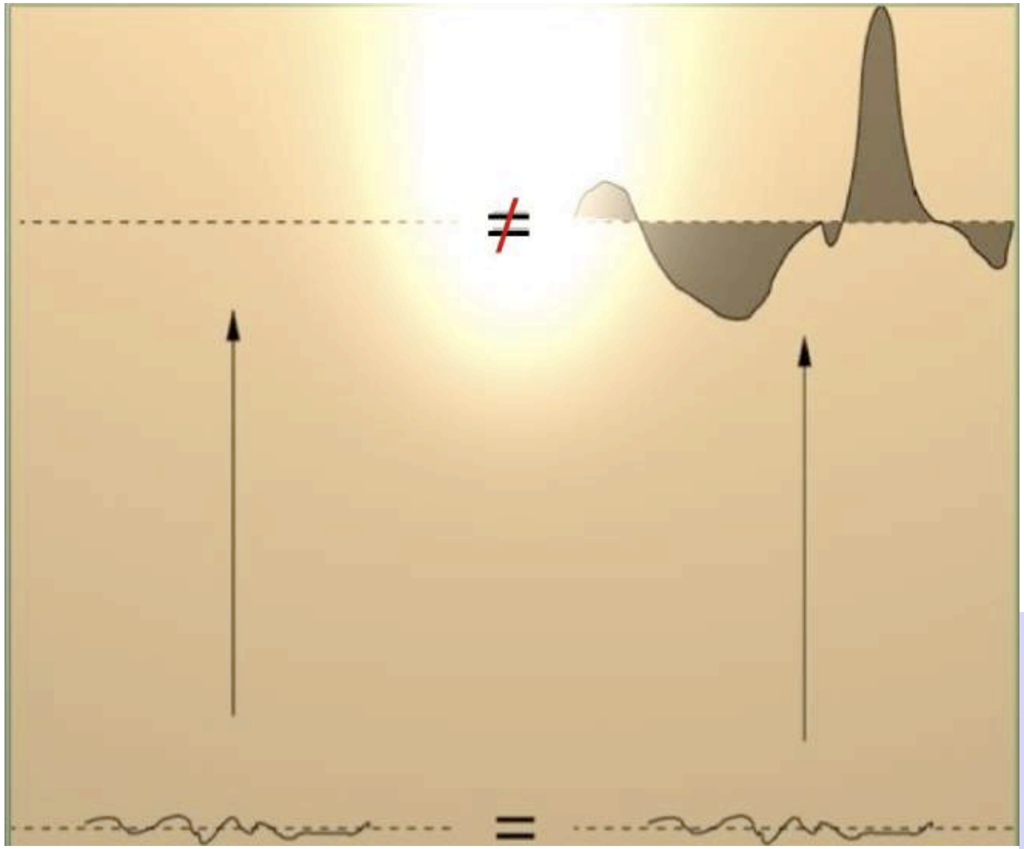
$$
\mathcal{Q}_{\mathcal{D}} = \frac{2}{3}\left(\langle\theta^2\rangle_{\mathcal{D}} - \langle\theta\rangle^2_{\mathcal{D}}\right) - \langle\sigma^{\mu\nu}\sigma_{\mu\nu}\rangle_{\mathcal{D}} \ .
$$

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.

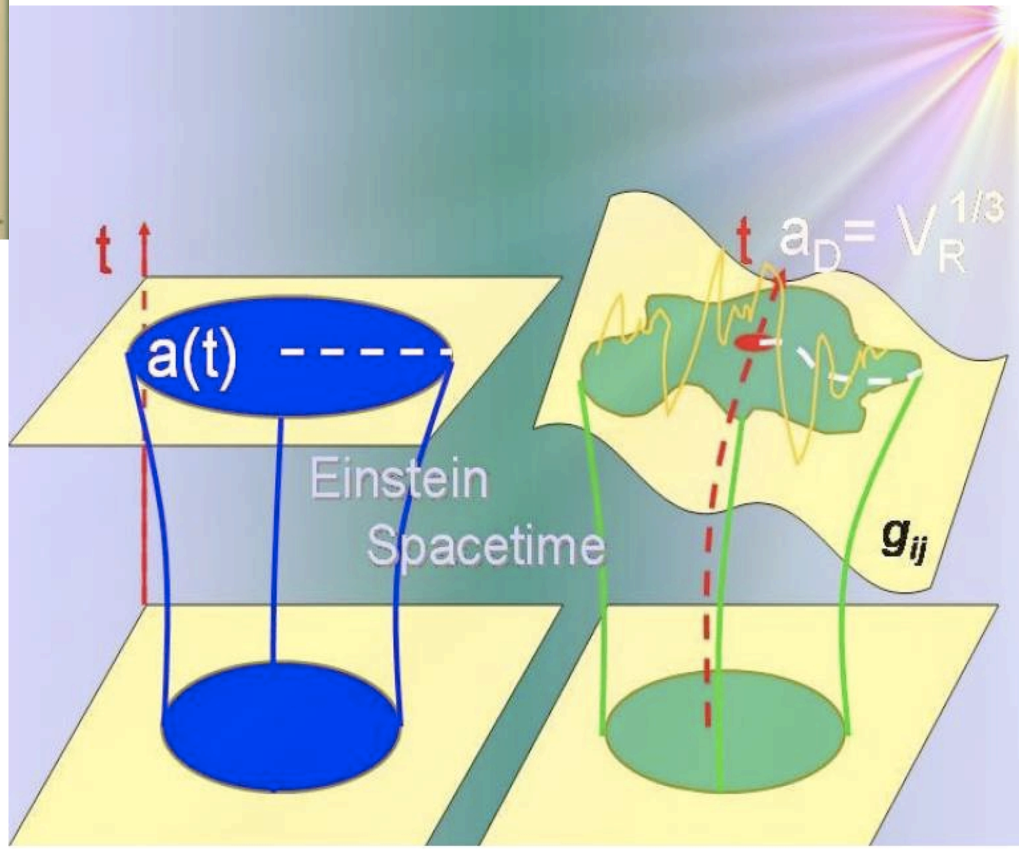
Can mimic a cosmological constant if $\mathcal{Q}_{\mathcal{D}} = -\frac{1}{3}\langle{}^{(3)}R\rangle_{\mathcal{D}} = \Lambda_{\text{eff}}$.

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



'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 … the result is different from the standard FRW model



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 so as to mimic vacuum energy … this scale is unnatural in a fundamental theory and is simply put in by hand

(similar fine-tuning in every other attempt – 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: $H^2 = 8\pi G_N/3 + \Lambda/3$ – and in any case this will not yield accelerated expansion

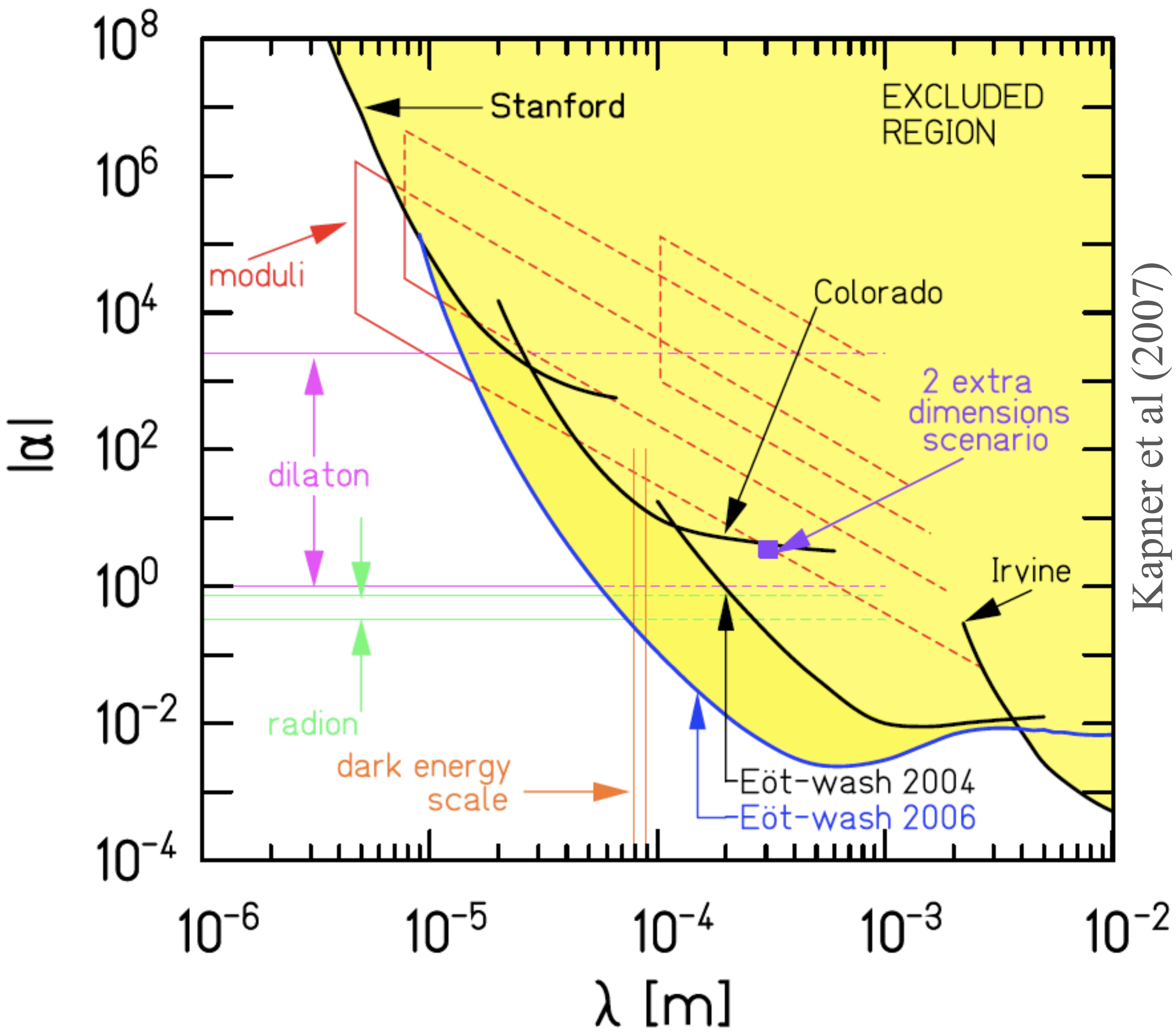
→ ruled out by Big Bang nucleosynthesis (requires G_N to be within 5% of lab value)

There is no physical explanation for the coincidence problem

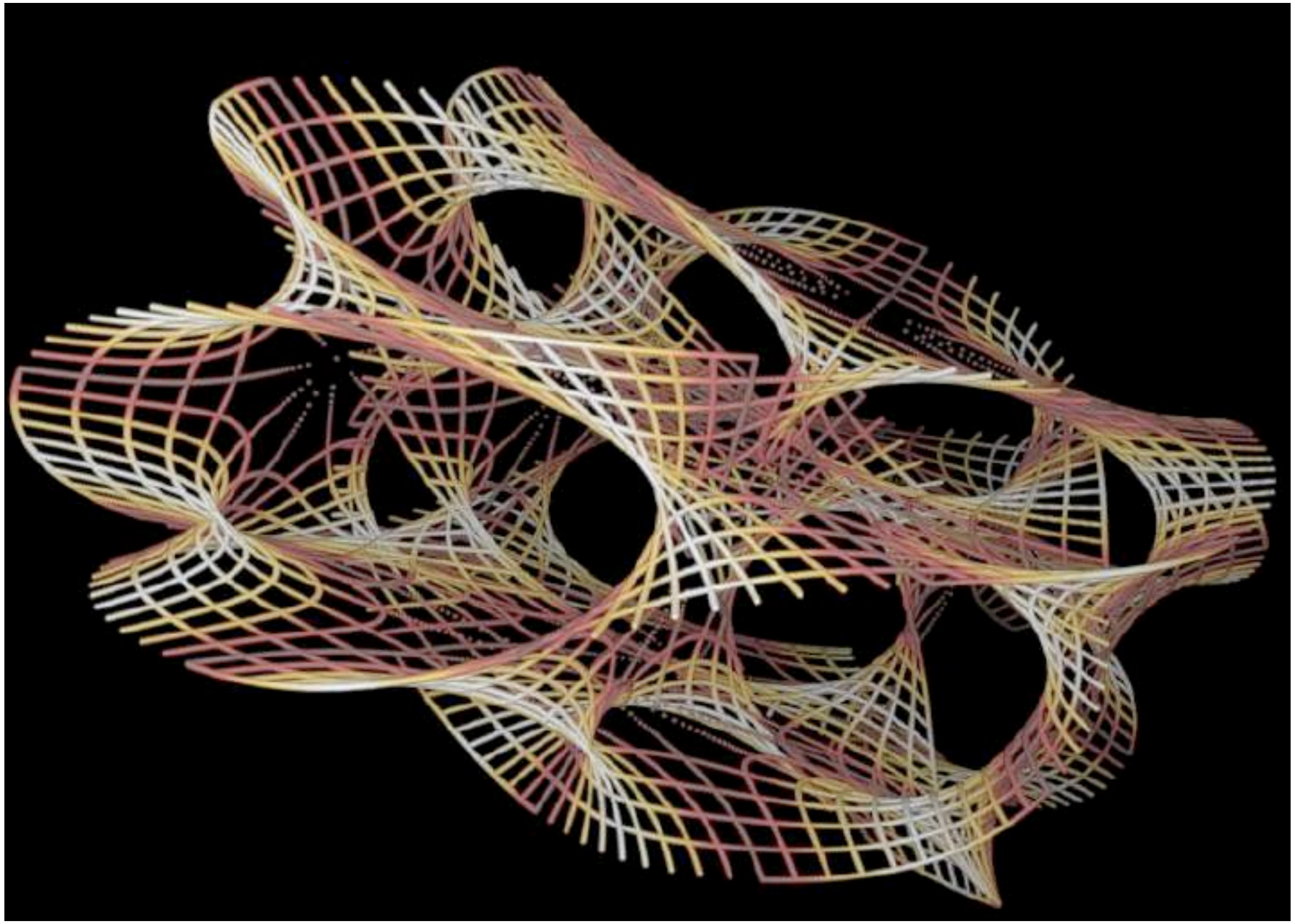
Do we infer $\Lambda \sim H_0^2$ because that is just the observational sensitivity?
… just how strong is the evidence for accelerated expansion?

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

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



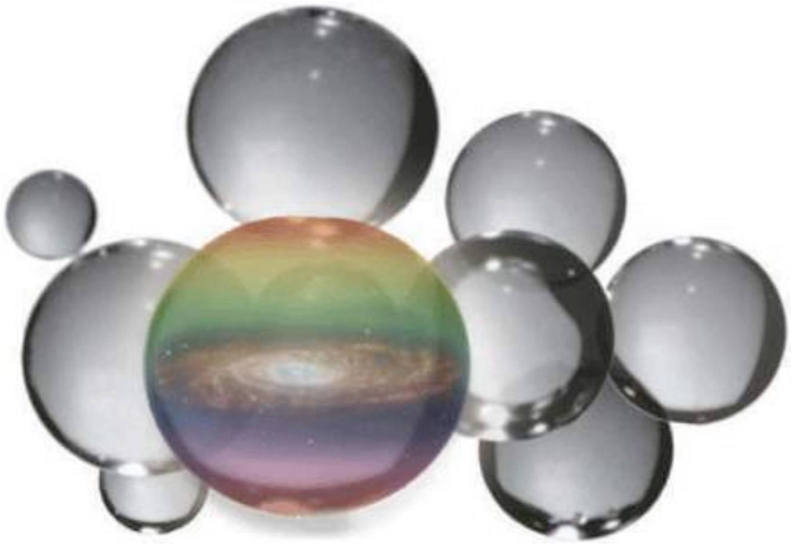
In string/M-theory, the sizes and shapes of the extra dimensions ('moduli') must be stabilised … e.g. by turning on background 'fluxes'

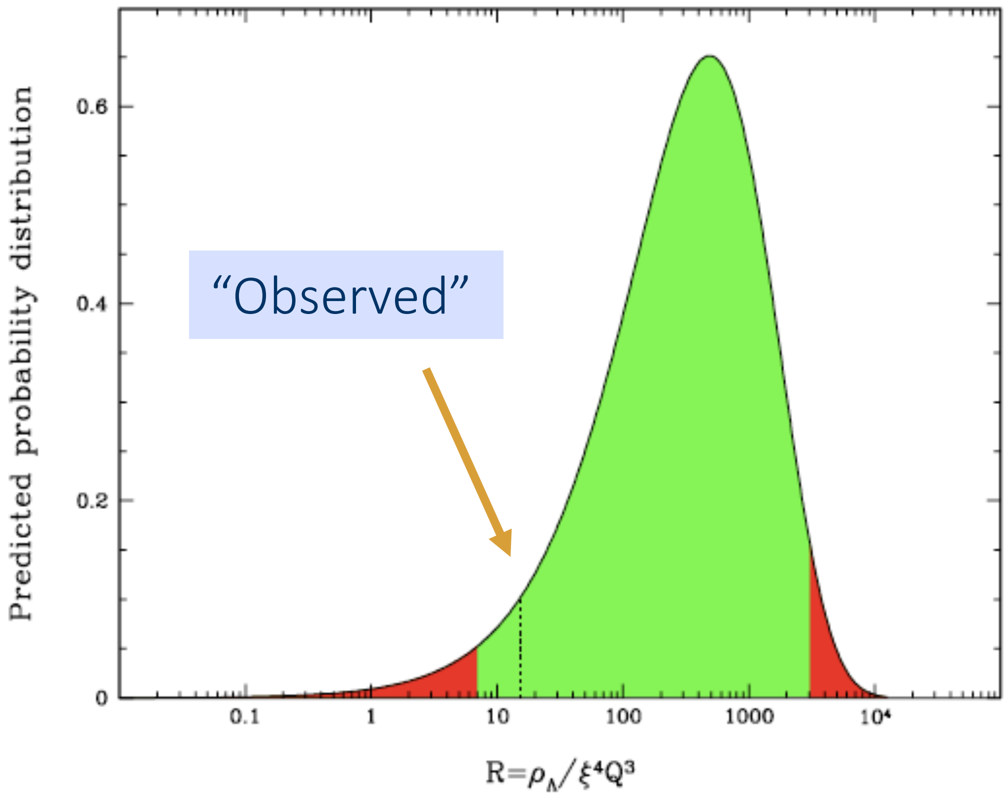


Given the variety of flux choices and the number of local minima in the flux potential, the total number of vacuua is *very* large - perhaps 10^{500}

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

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

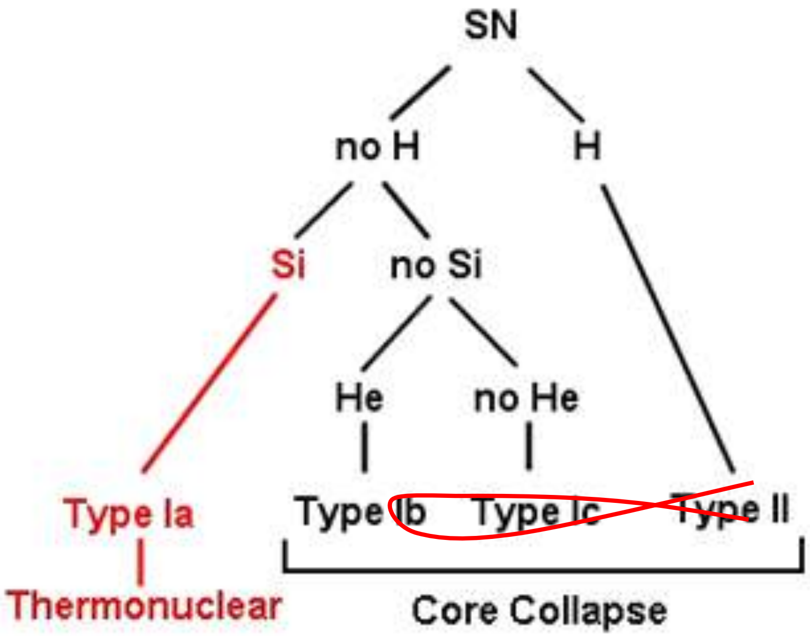


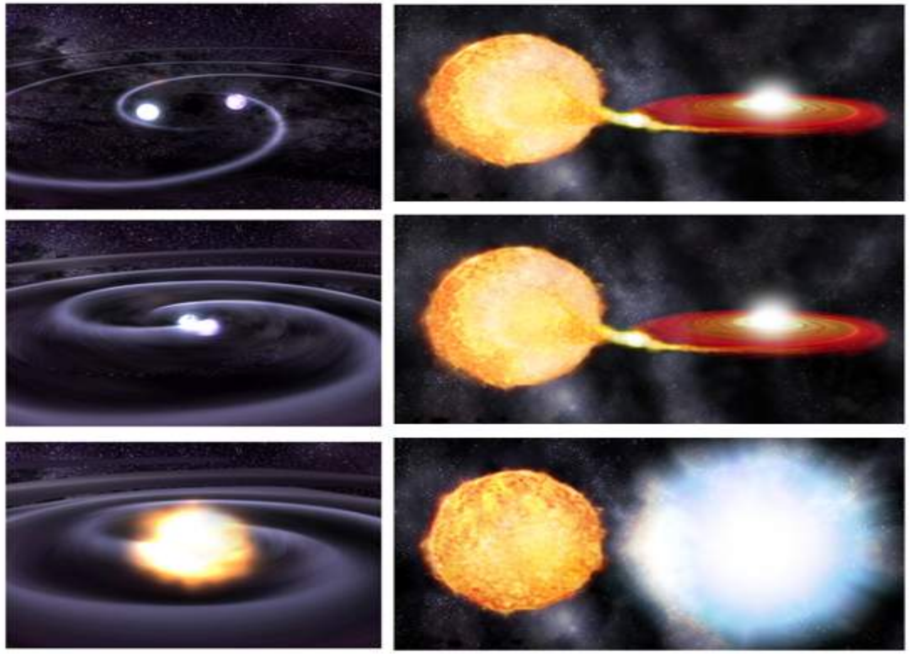


(Tegmark *et al* 2006)

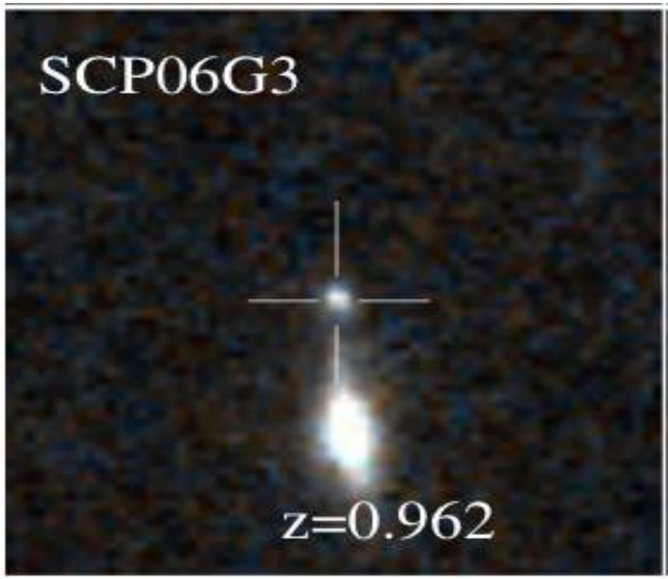
But the 'anthropic prediction' of Λ from considerations of galaxy formation is significantly *higher* than the observationally inferred value

What are Type Ia supernovae?

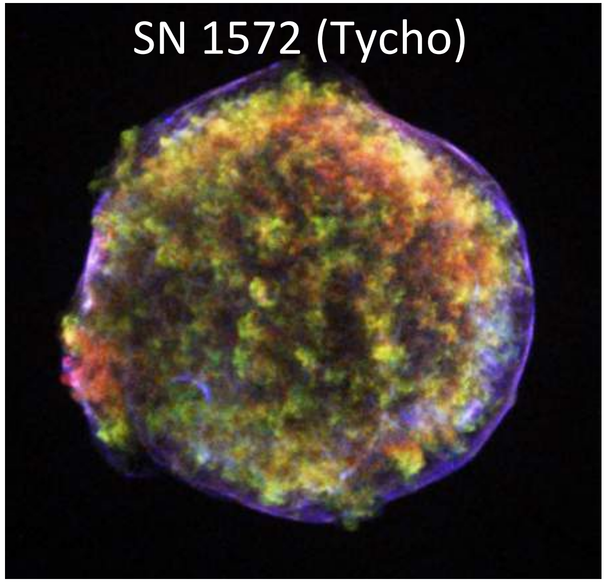




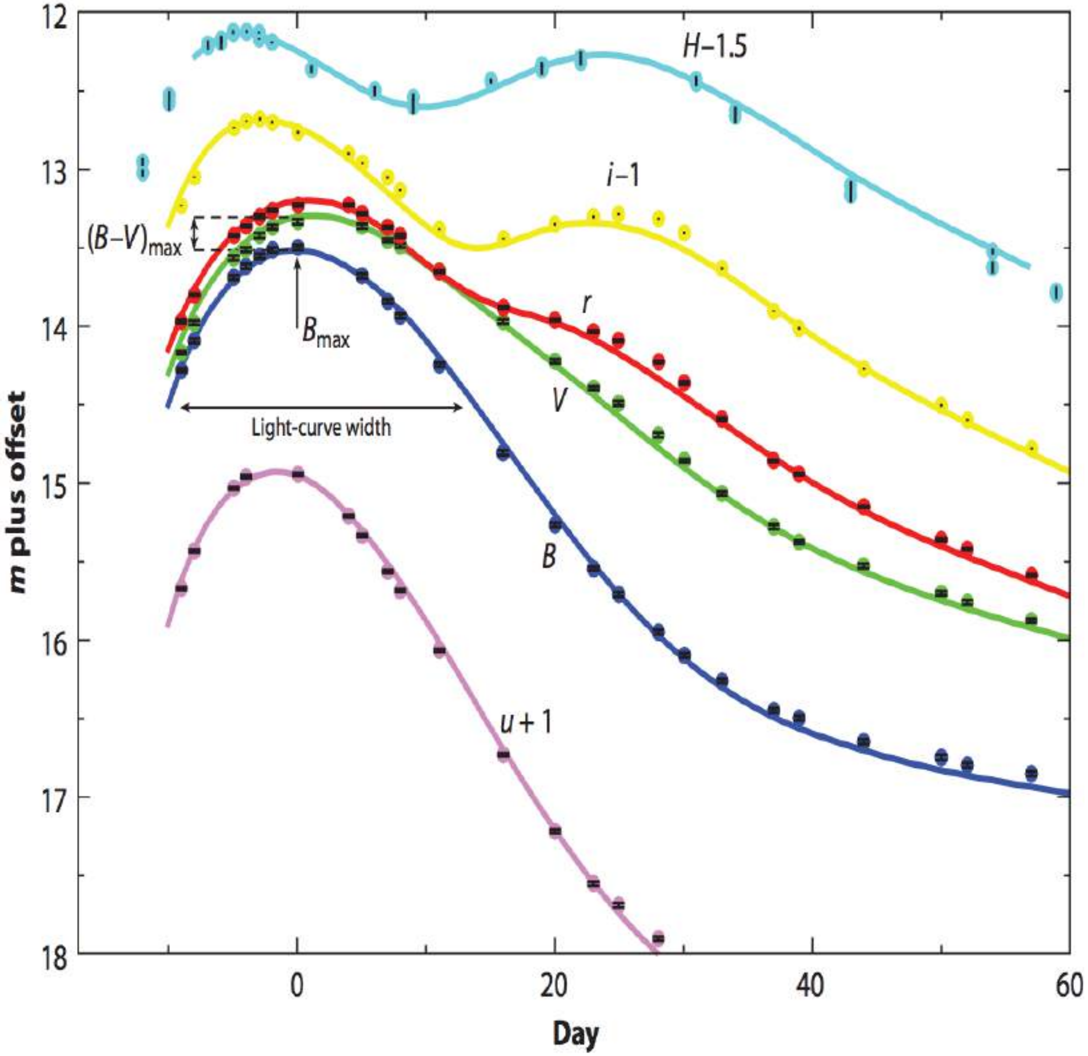
Suzuki *et al*, 1105.3470



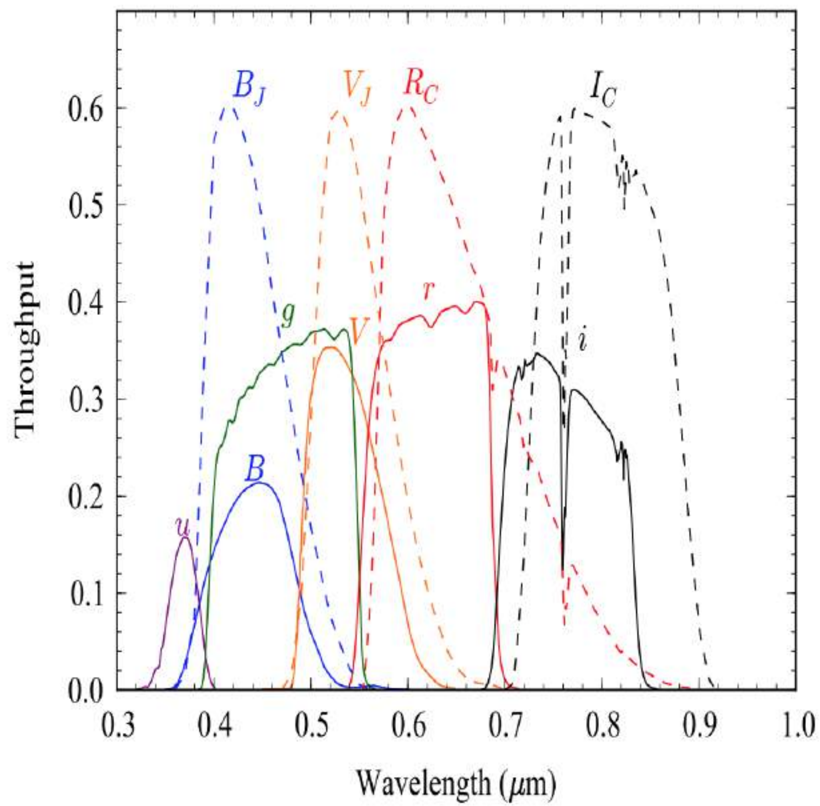
~500 years



What are Type Ia supernovae?

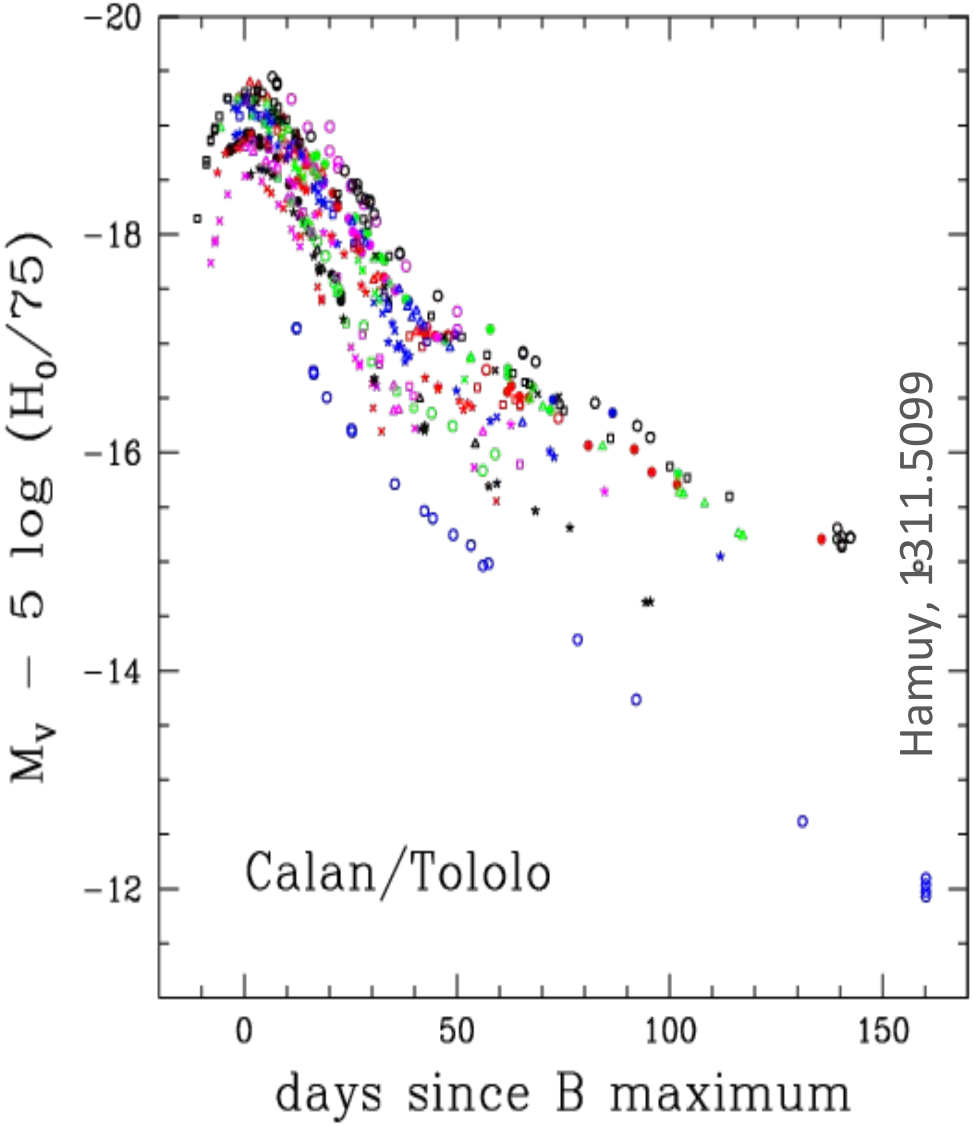


$$m = -2.5 \log(F/F_{\mathrm{ref}})$$

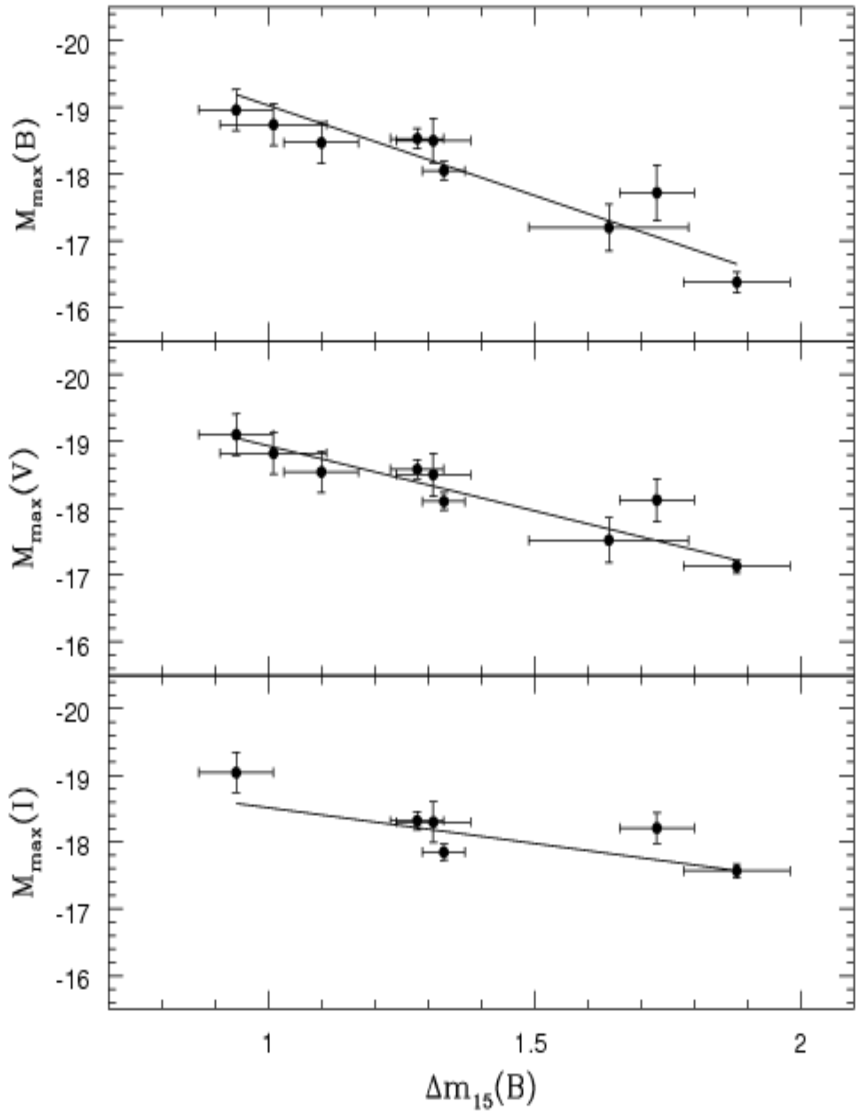


Goobar & Leibundgut, 1102.1431

What are Type Ia supernovae?

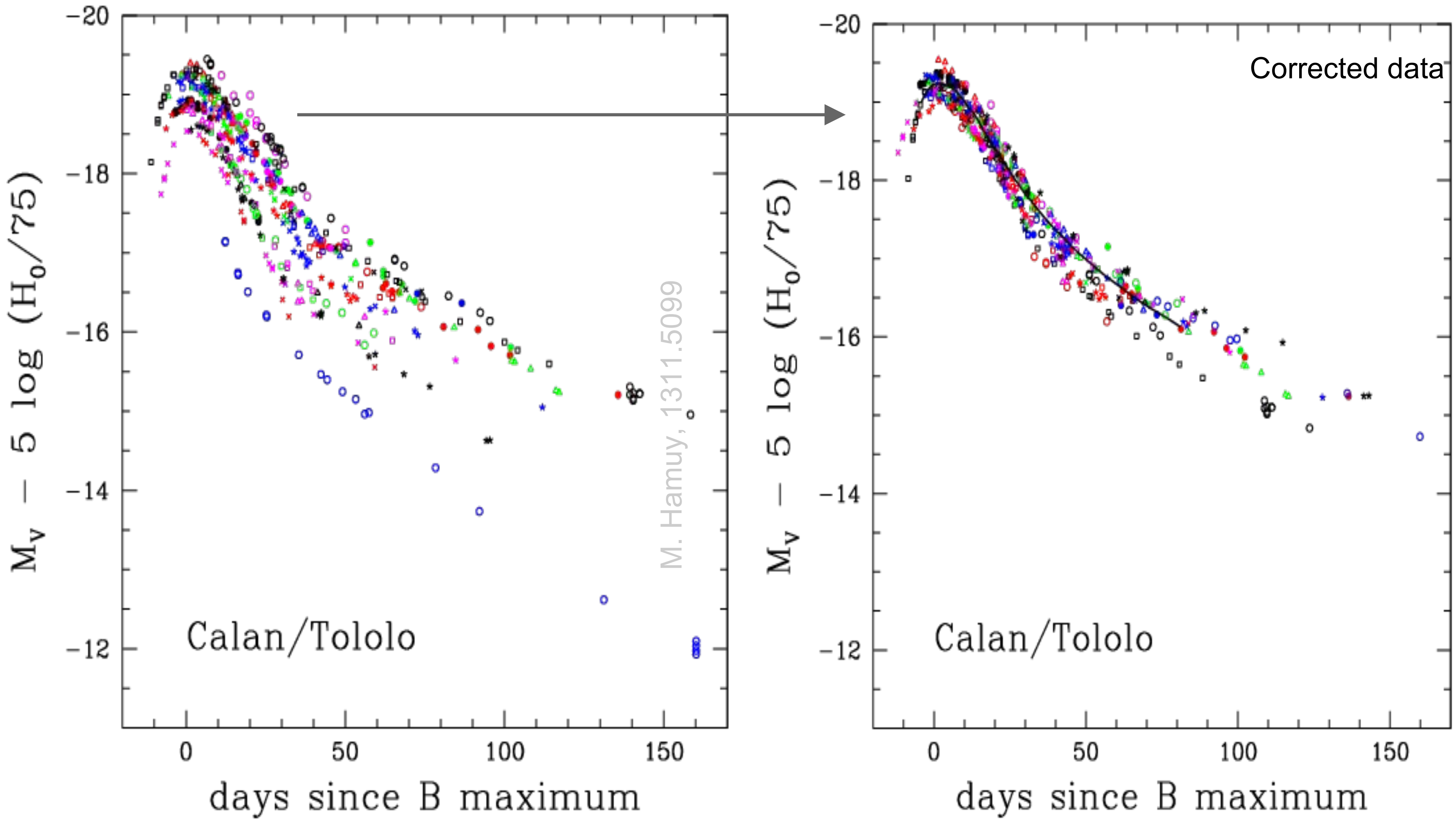


Hamuy, 1311.5099



Phillips, 1993

What are Type Ia supernovae?



What are Type Ia supernovae?

SALT 2 parameters

Betoule *et al.*, 1401.4064

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	

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

Cosmology

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

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

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

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

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

What is measured

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

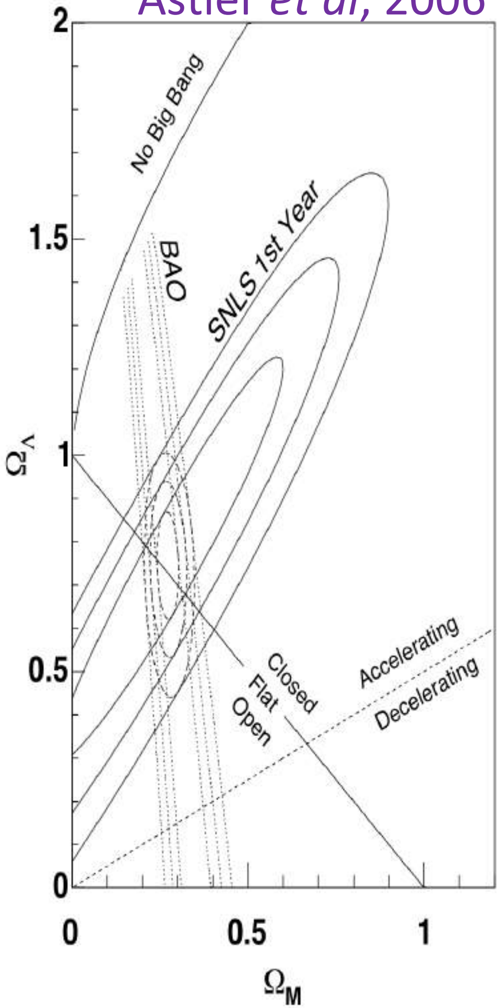
$$\mu_B = m_B^* - M + \alpha X_1 - \beta\mathcal{C}$$

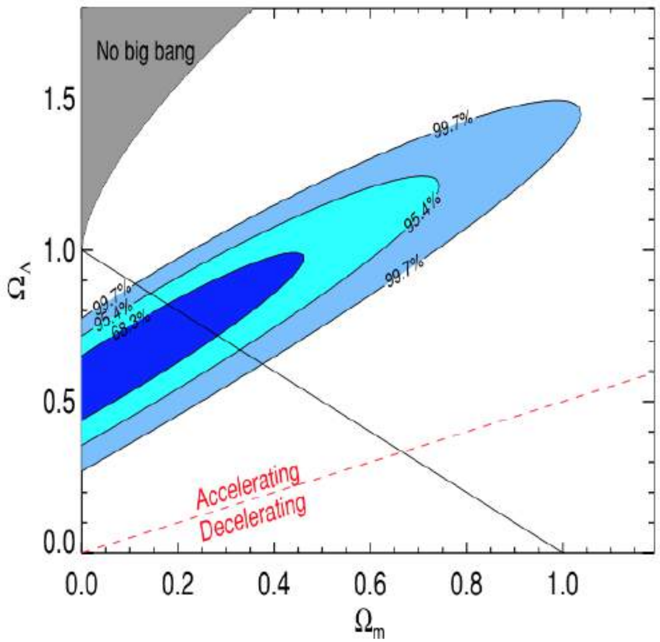
How strong is the evidence for cosmic acceleration?

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

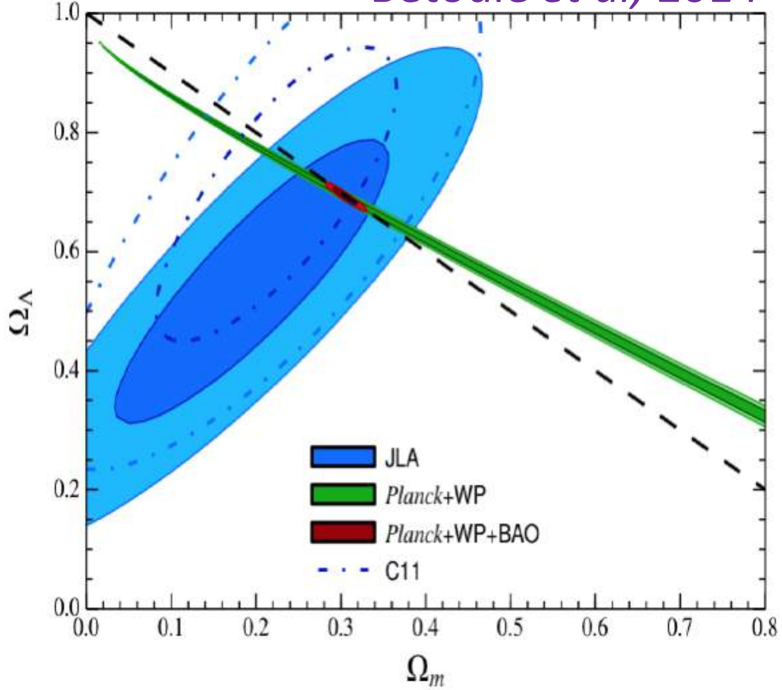
*from the magnitude-redshift plot

Astier *et al*, 2006





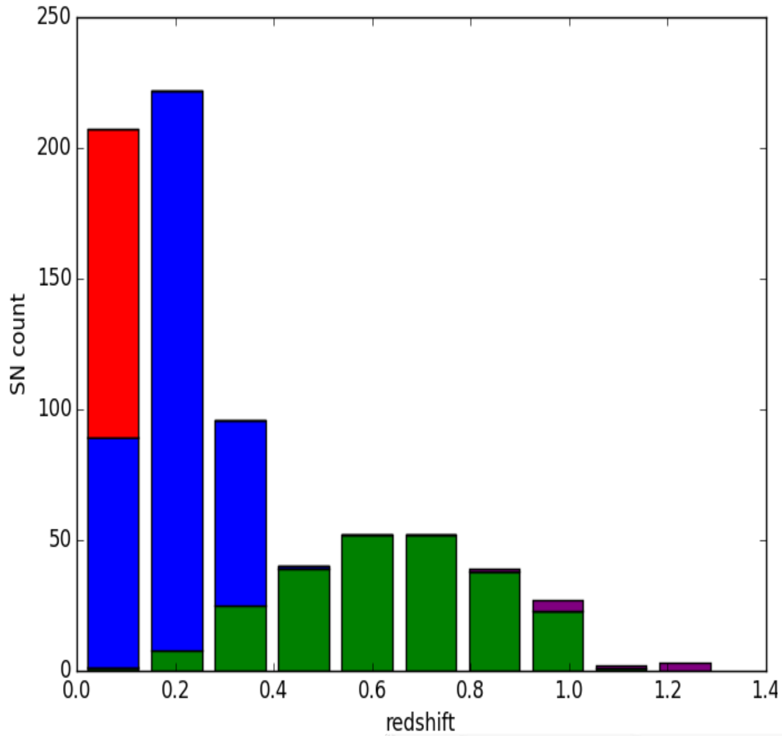
Betoule *et al*, 2014

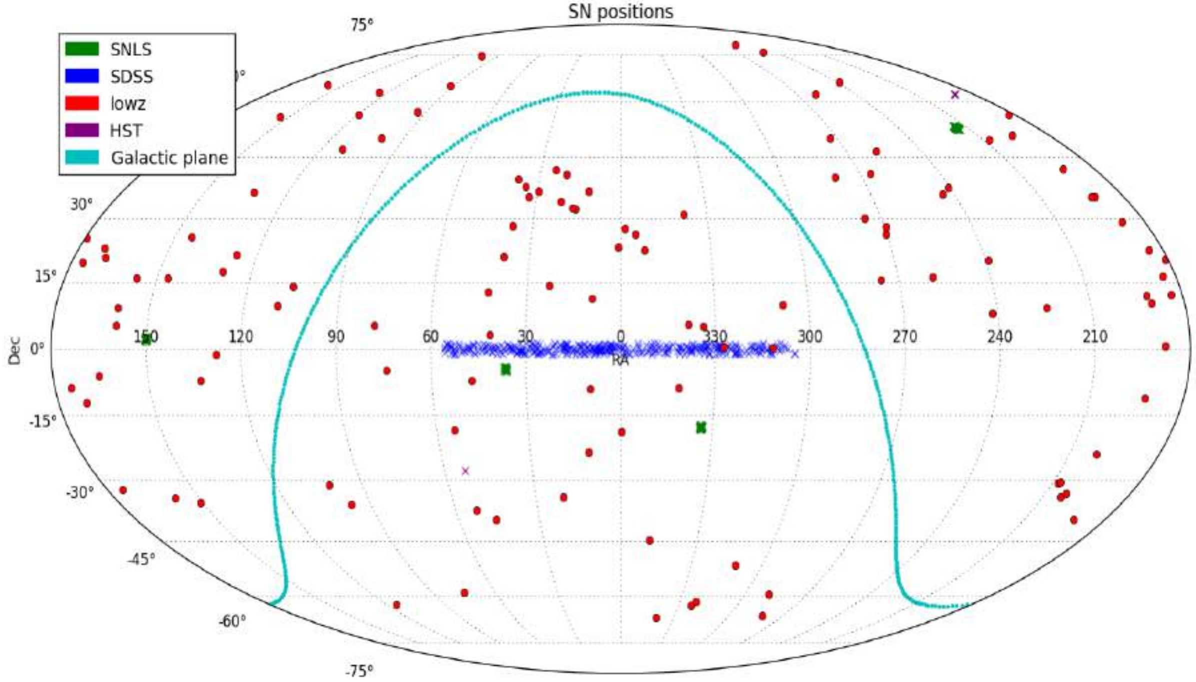


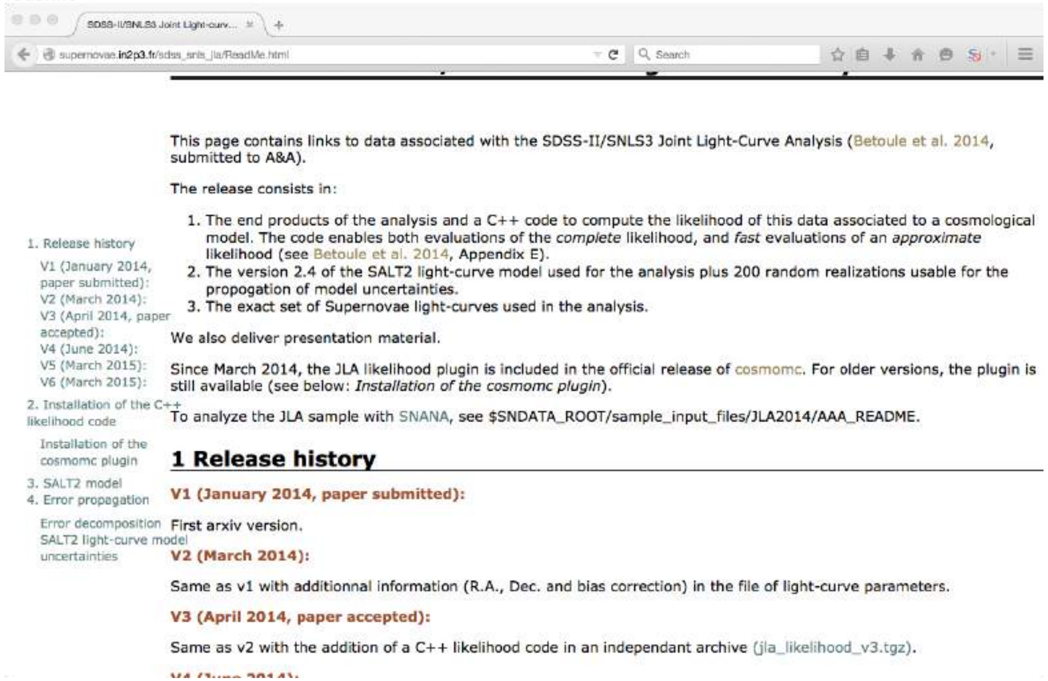
$$\chi^2 = \sum_{objects} \frac{(\mu_B - 5\log_{10}(d_L(\theta, z)/10pc))^2}{\sigma^2(\mu_B) + \sigma_{int}^2}$$

But they *assume* ΛCDM and adjust σ_{int} to get chi-squared of 1 per d.o.f. for the fit!

Joint Lightcurve Analysis data (740 SNe)







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 now

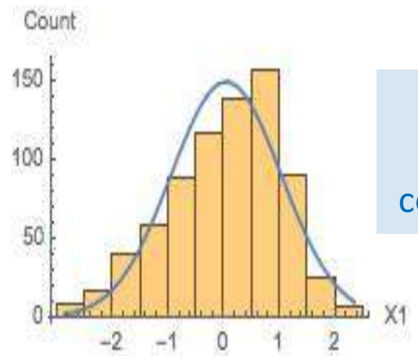
Betoule *et al*, 1401.4064

Construct a Maximum Likelihood Estimator

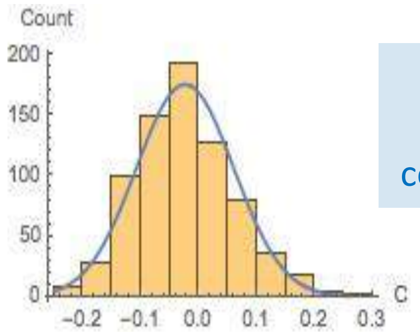
$$\mathcal{L} = \text{probability density}(\text{data}|\text{model})$$

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

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*, 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

Nielsen *et al*, arXiv: 1506.01354

Confidence regions

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

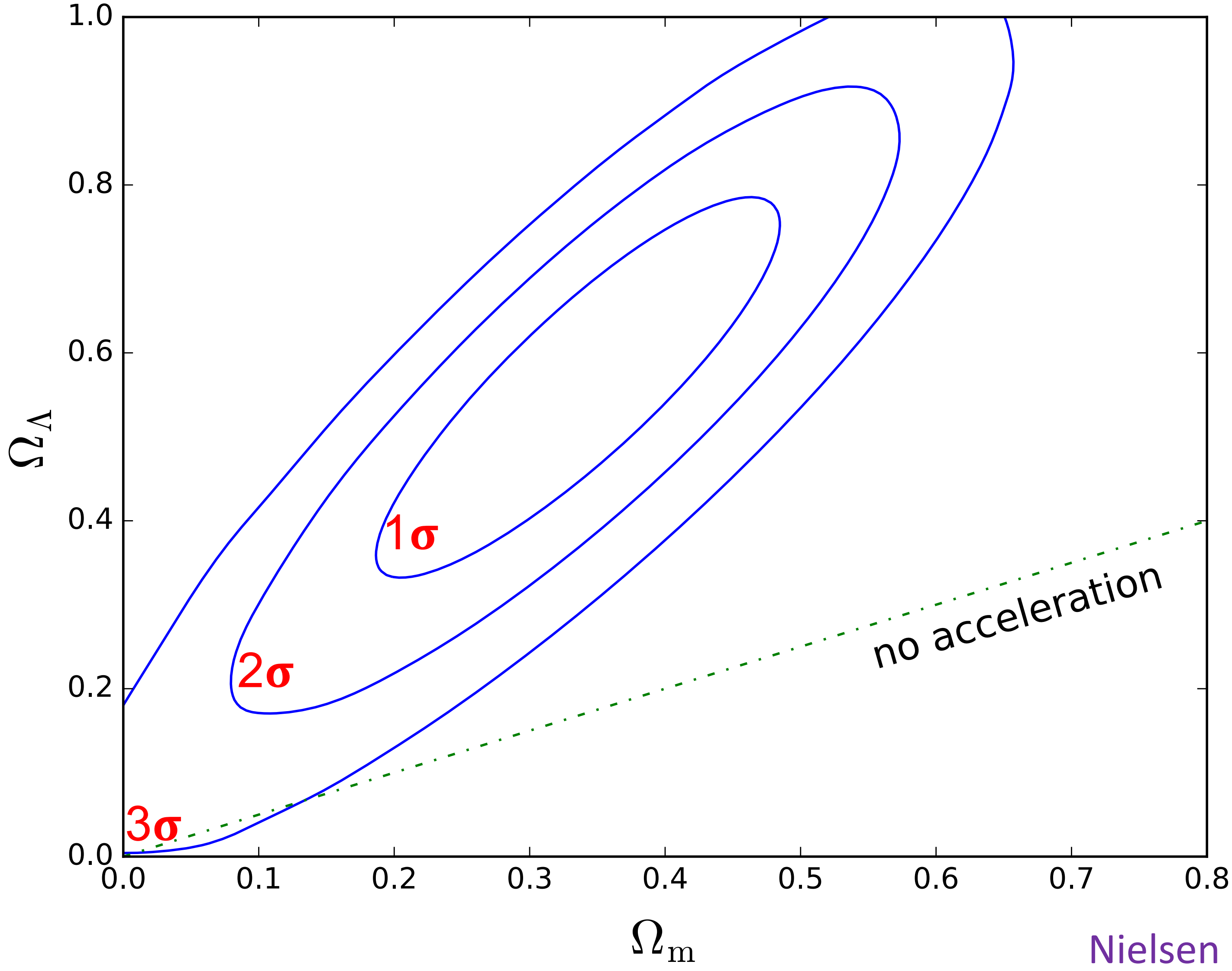
$$\mathcal{L}_p(\theta) = \max_{\phi} \mathcal{L}(\theta, \phi)$$

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*, arXiv:1411.3280)



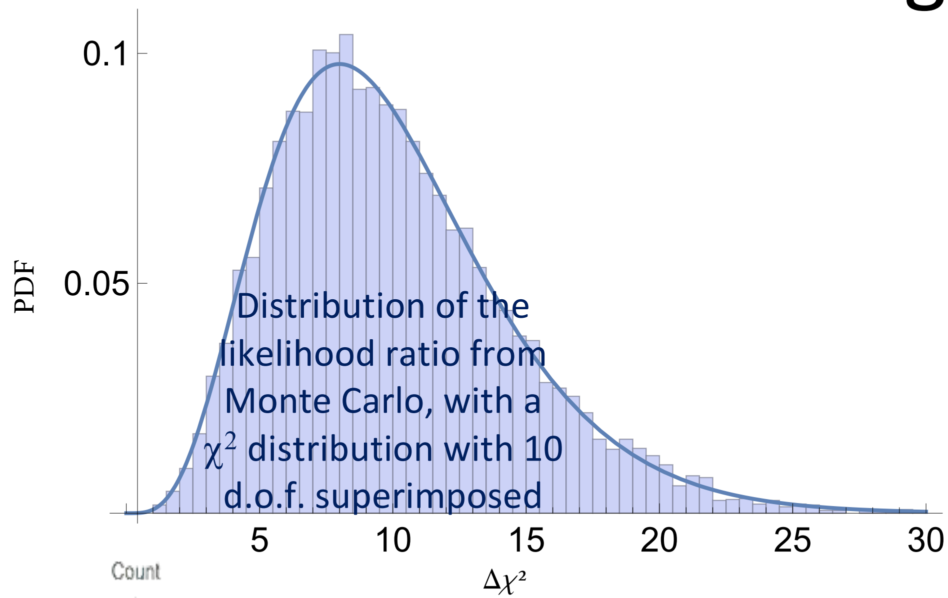
profile likelihood

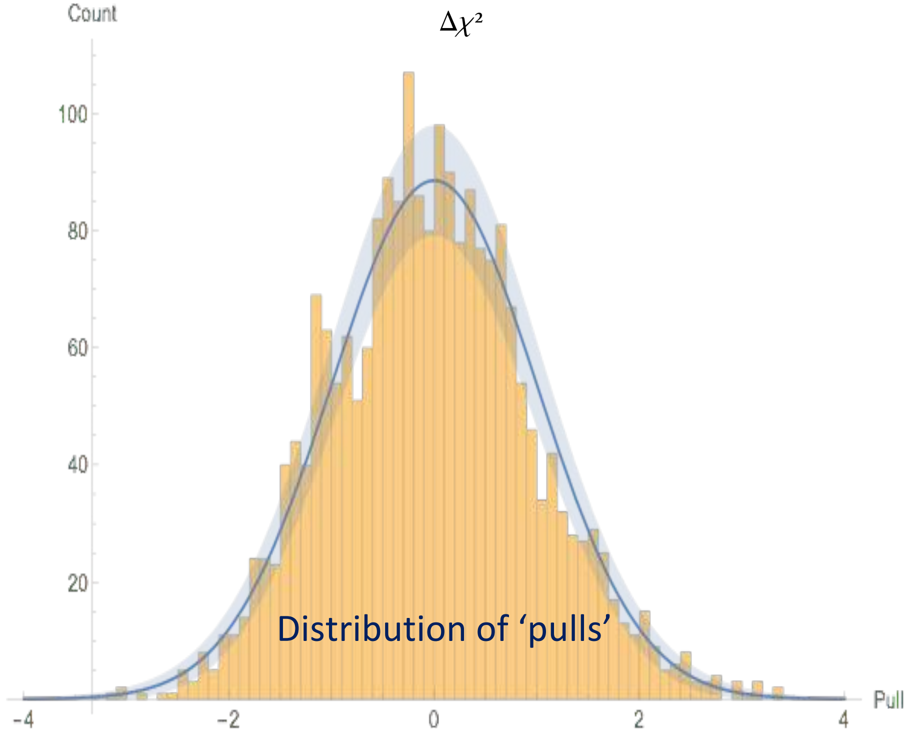
<u>MLE, *best fit*</u>

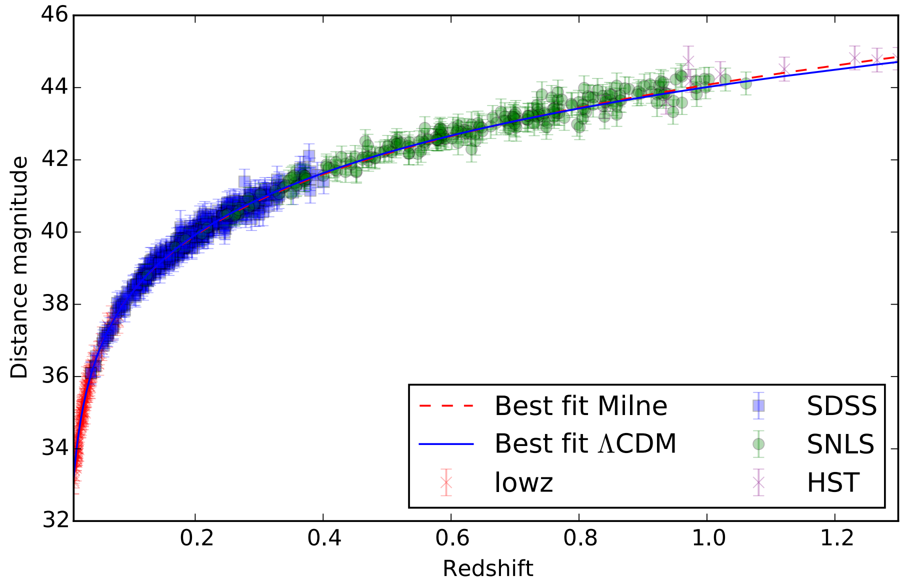
Ω_M	0.341
Ω_Λ	0.569
α	0.134
x_0	0.038
σ^2_{x0}	0.931
β	3.058
c_0	-0.016
σ^2_{c0}	0.071
M_0	-19.05
σ^2_{M0}	0.108

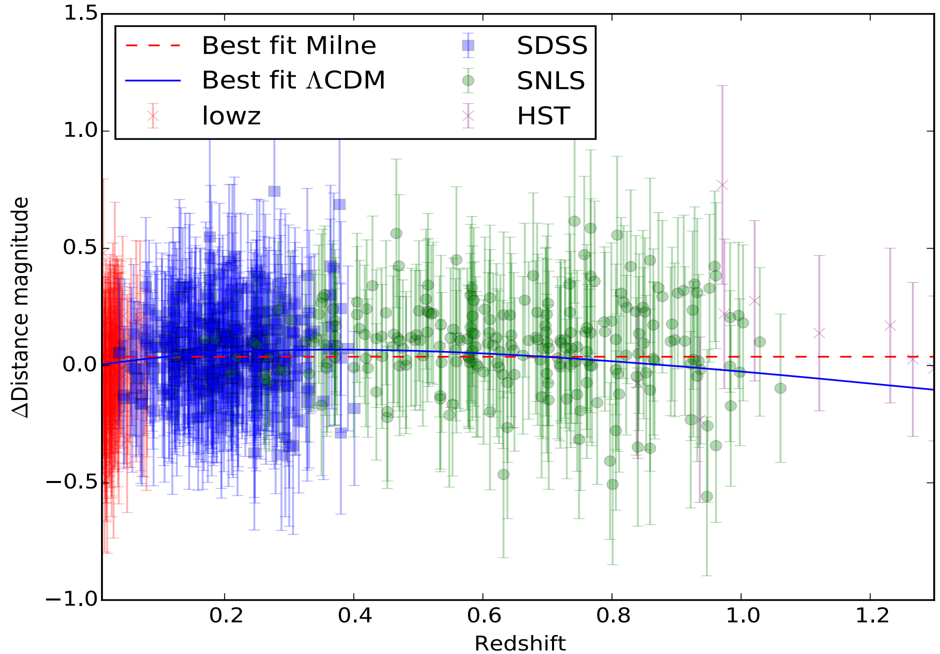
Nielsen *et al*, arXiv: 1506.01354

Is it a good fit ?





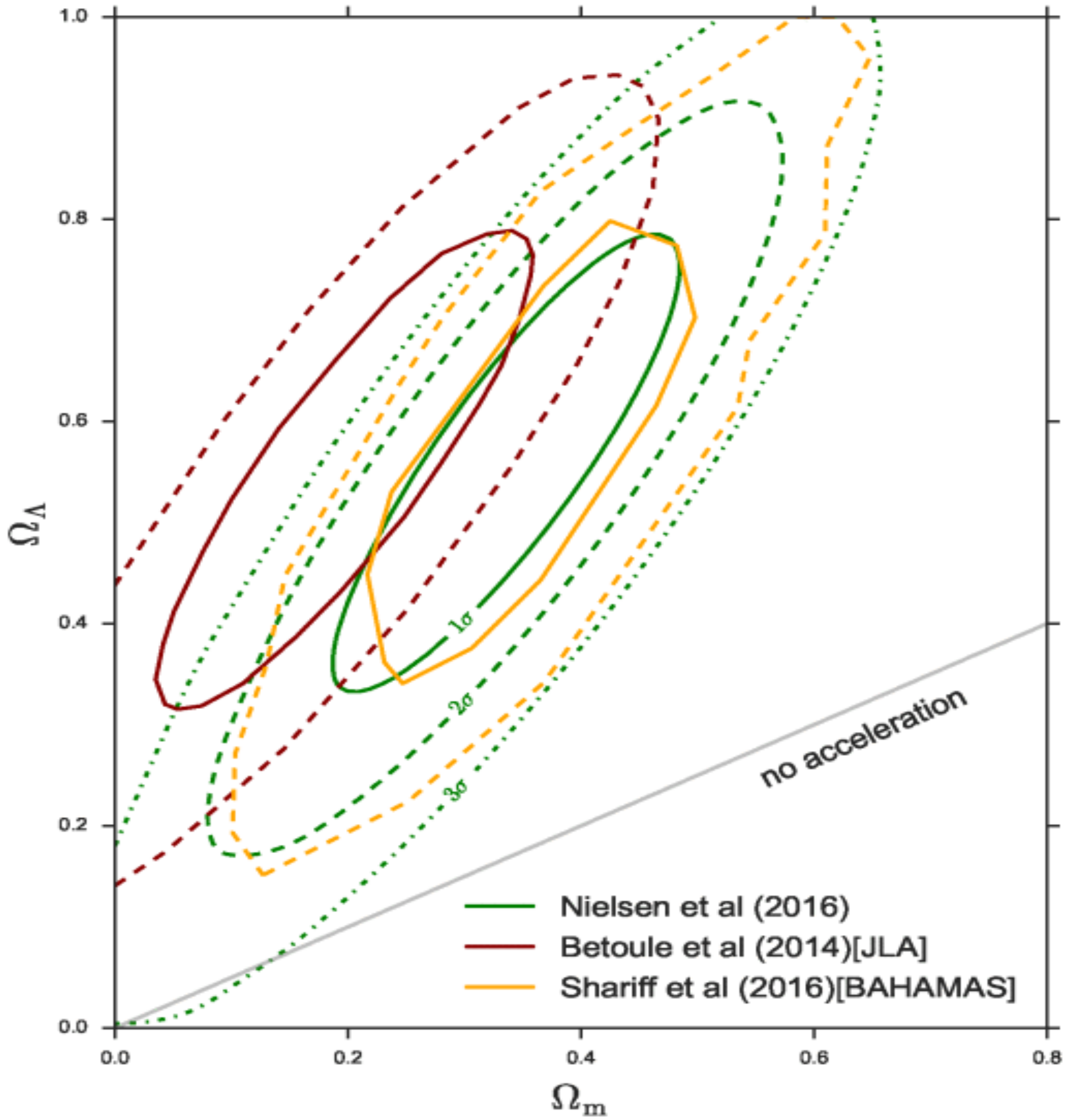




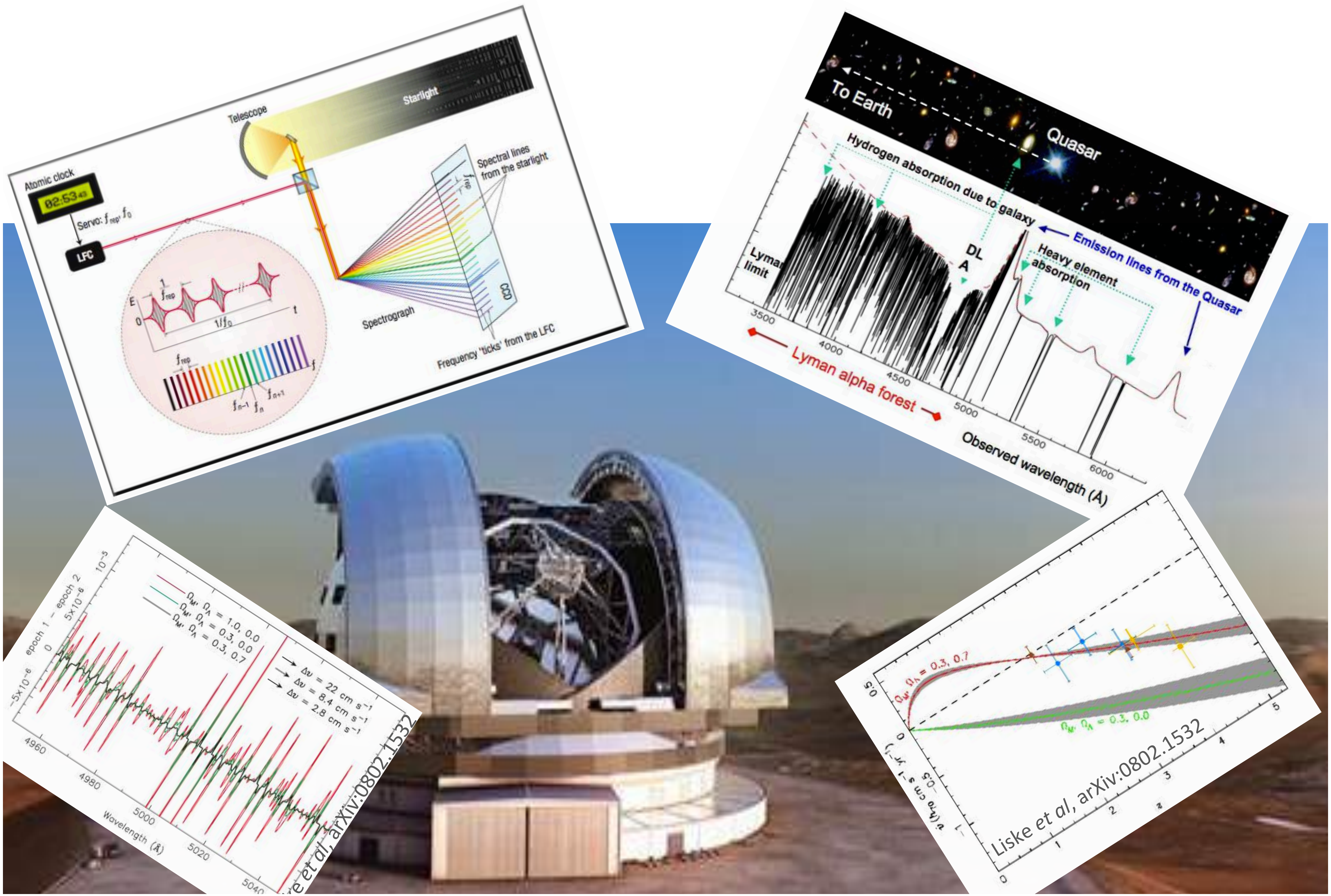
$$\text{pull} = (\Sigma_d + A^{\mathrm{T}}\Sigma_l A)^{-1/2}(\hat{Z} - Y_0 A)$$

Nielsen *et al*, arXiv: 1506.01354

Our result (arXiv: 1506.01354) has been *confirmed* by a subsequent independent Bayesian analysis (arXiv: 1510.05954) up to the 2σ contour



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



But is not dark energy (cosmic acceleration) independently established from 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, $\Omega_{\rm CDM}$, $\Omega_{\rm B}$, Ω_Λ , Ω_k

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

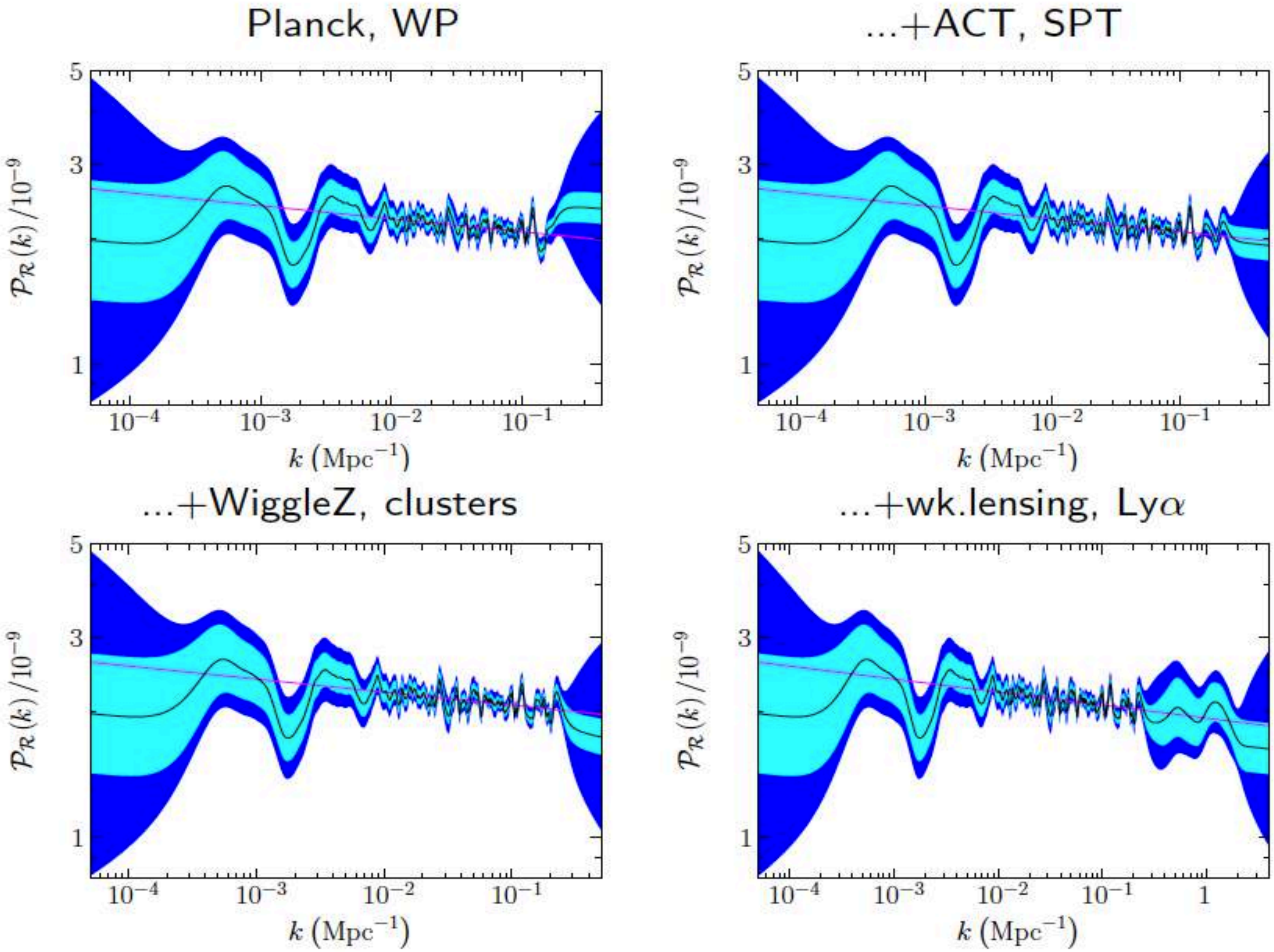
measured over scales ranging from ~1 – 10000 Mpc ($\Rightarrow$ ~8 e-folds of inflation)

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

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

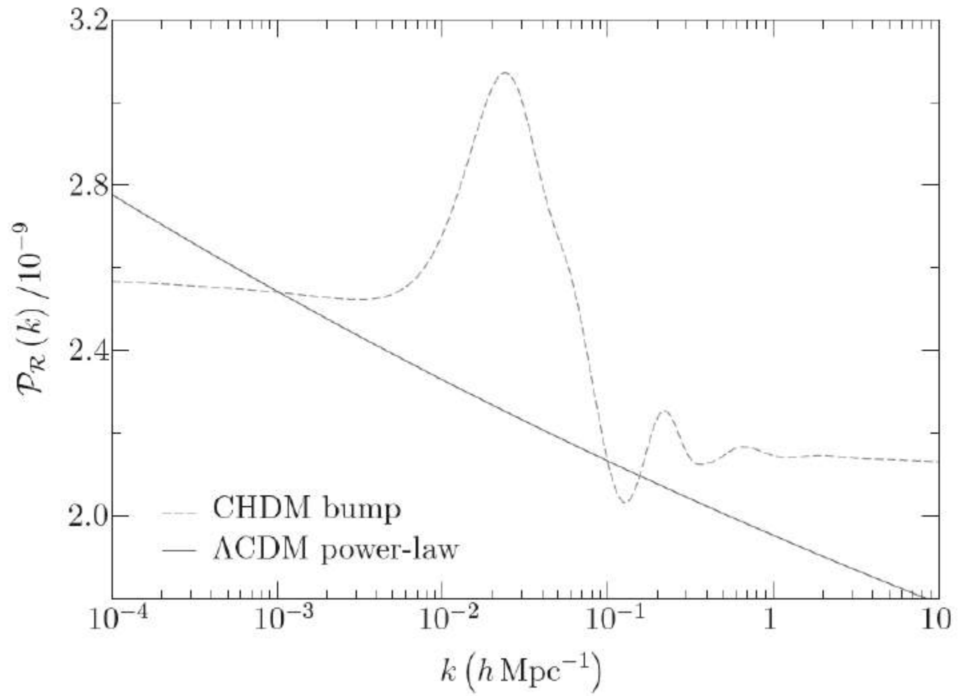
Hence evidence for Λ is *indirect* (can match same data without it e.g. arXiv:0706.2443)

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)



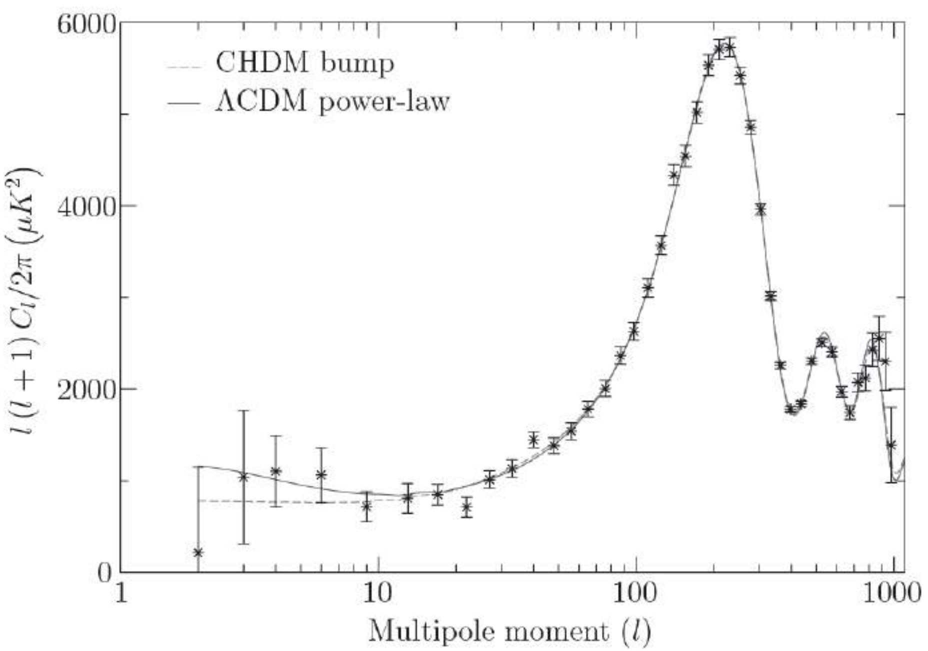
E.g. if there is a 'bump' in the spectrum (around the first acoustic peak), the CMB data can be fitted *without dark energy* ($\Omega_m = 1$, $\Omega_\Lambda = 0$) if $h \sim 0.45$

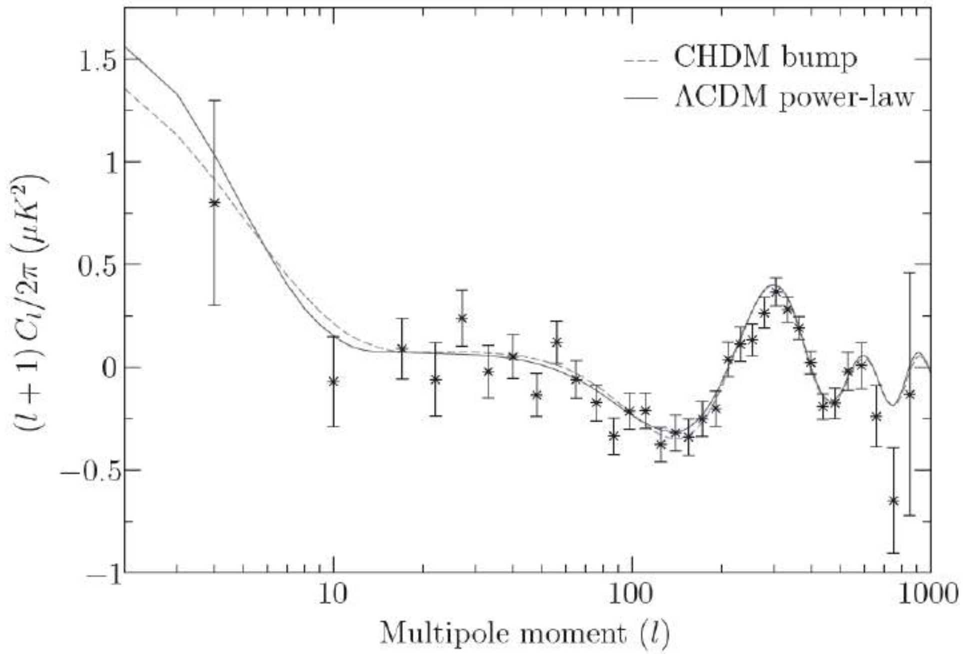
(Hunt & Sarkar arXiv:0706.2443, 0807.4508)



While significantly below the local value of $h \sim 0.7$ this is consistent with its 'global' value in the *effective* EdeS model fitted to an inhomogeneous, relativistic cosmology

(Roukema *et al*, arXiv:1608.06004)

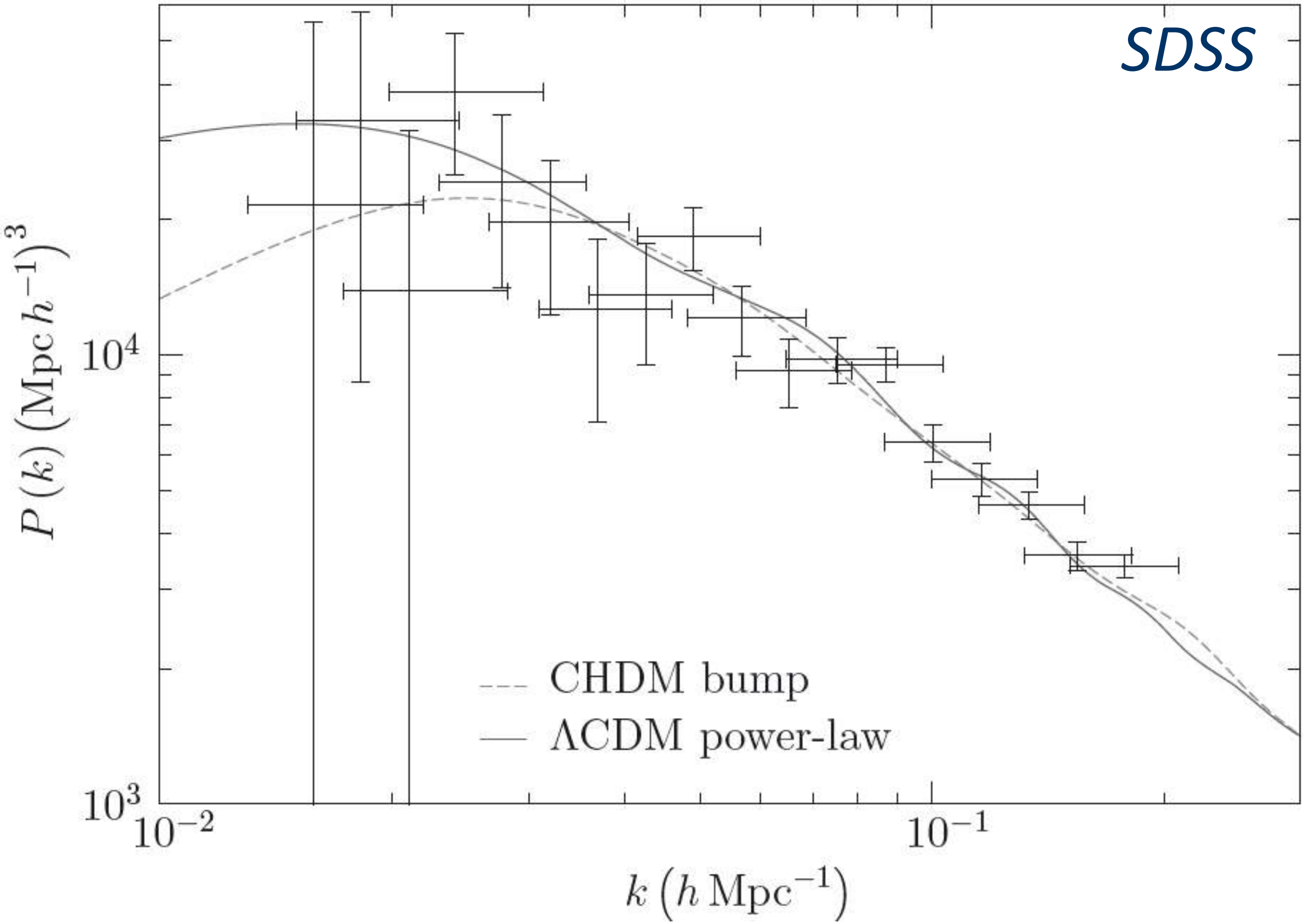




The small-scale power would be excessive unless damped by free-streaming

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

- It is *not* simply a choice between a cosmological constant (‘dark energy’) and ‘modified gravity’ – there are other interesting possibilities (e.g. effective viscosity during structure formation)

- 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