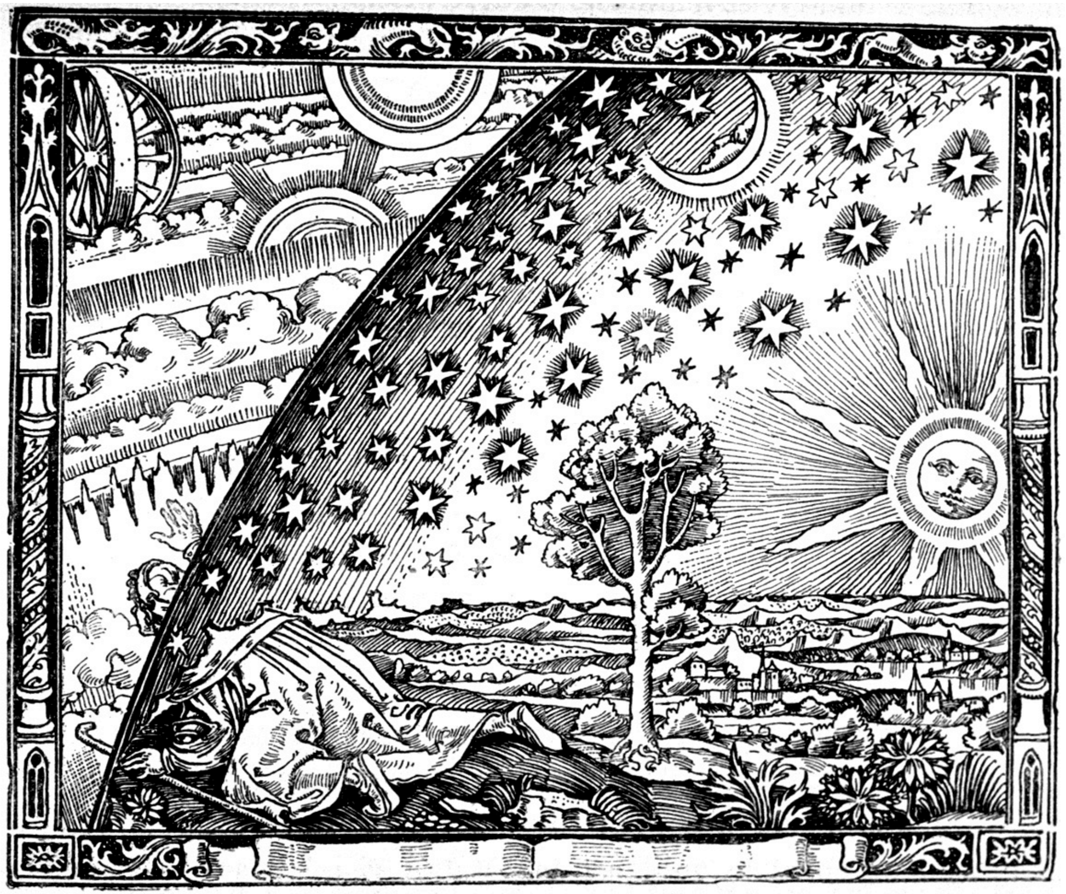
Current Problems in Cosmology

Response to the APPEC roadmap



Subir Sarkar

Department of Physics, University of Oxford & Niels Bohr Institute, Copenhagen

APPEC Town Meeting, Paris-Sorbonne, 6 April 2016

3. Probing the acceleration of the expansion of the Universe: Dark Energy (DE)

DE findings and tasks

The study of the history of the expansion rate of the Universe, using supernovae as distant standard candle processes led to the discovery by S. Perlmutter, A. Riess and B. Schmidt (Nobel Prize 2011) of the accelerated expansion of the Universe, dubbed Dark Energy (DE). At the end of this decade, next-generation DE projects currently in construction, both on ground (LSST and DESI) and in space (Euclid) will accomplish detailed large galaxy spectroscopic and photometric surveys with unprecedented precision and extension providing a breakthrough in our knowledge of the history of the expansion rate of the Universe and of the rate of growth of cosmic structures. Spectroscopic galaxy surveys, provide a precise determination of the galaxies' redshifts, and hence a true 3D picture of the galaxy distribution, but they are costly in time and resources, and may suffer from limited depth, incompleteness and selection effects. On the other hand, imaging (also called photometric) galaxy surveys are more efficient and usually deeper, more complete and nearly unbiased, but do not provide a complete 3D view of the Universe, due to their limited resolution in the galaxy positions along the line of sight. It is fair to say that currently the USA leads the research on DE performed from the ground through large galaxy surveys: DESI a spectroscopic survey starting in 2018 and DES a photometric survey in operation and LSST a photometric survey starting in 2021 while Europe will have the leadership on DE studies from space with the Euclid ESA mission launched around 2020. Euclid combines a weak-lensing imaging survey like LSST with a spectroscopic survey like DESI. Taking advantage of its position in space, outside the Earth's atmosphere, Euclid will be able to take the weak-lensing technique to its limit. On the other hand, it will still need a significant amount of data from imaging surveys on the ground in order to both estimate the (photometric) redshifts of the over 1 billion galaxies it will measure and mitigate some of the leading systematic errors. In contrast the ground surveys will rely on the better knowledge of systematics in space due to the absence of atmospheric distortion.

- ***DE Consideration 1***. Europe should support the construction data analysis of Euclid which will dominate dark energy science from space in the next decade, providing clear European leadership in that area.
- ***DE Consideration 2***. Europe should support the key contributions of European groups to the ground program, in particular LSST that will be deeper, wider and faster than any ground based optical survey to date.
- ***DE Consideration 3***. Europe should encourage data exchange between Euclid and LSST as this will enhance the scientific output of both missions.

DE prospects

Both the history of the expansion rate of the Universe and of the rate of growth of cosmic structures depend on the DE properties, although in different ways. By measuring both rates, with the above program, we will be able to disentangle kinematic effects from dynamic effects and therefore eventual modifications of gravity theories from theories postulating e.g. new fields of the particle physics type. Furthermore the studies of correlations between the "recent" (redshift < 3) large scale structures probed by the large scale surveys of DE and the primordial CMB fluctuations studied by CMB serves as a testing ground of the standard models of cosmology and particle physics (possibilities of sterile neutrinos, new particles etc.). Last but not least, the indirect measurements of the sum of neutrino masses that they provide, when compared to direct measurement of neutrino masses from ground experiments, constitute a sensitive probe of New Physics again (non-constant DE, non-Gaussianities, new radiation/particle species, etc.).

However …

- The evidence for **cosmic acceleration** from Type Ia supernovae is still ***marginal***!
  It is necessary to do *real-time* cosmology – measure the 'redshift drift' with E-ELT.

- There is as yet ***no consistent and convincing evidence*** for the ***'late ISW effect'***
  (*dynamical* effect of the negative pressure of dark energy).

- There are observations which *conflict* with the expectations in the standard ΛCDM cosmology, e.g. there are *too many* **colliding clusters of galaxies** [arXiv:1412.7719].

- There are still *many* ***parameter degeneracies*** in extracting information from CMB and large-scale structure data (e.g. ν mass from gravitational lensing).

2. Probing inflation and the formation of of cosmic structures: Cosmological Microwave Background (CMB)

CMB findings and tasks

The Planck satellite gave the ultimate measurement of cosmological microwave background fluctuations of temperature discovered by Smoot and Mather (Nobel Prize 2006). The importance of these measurements, as well as the measurement of the fluctuations in the polarisation modes E and B cannot be overestimated since besides the precision measurements of the cosmological parameters they also provide precise measurements of the number of neutrinos and the sum of their masses as well as the first complete map, through gravitational lensing, of the clusters of matter (including dark matter) intervening between the recombination era and the present era of the Universe. The USA has a clear leadership on ground and balloon detection, as is testified by the plethora of experiments either now taking data or planned for the near future in the Atacama, at the South pole and long and ultra-long duration balloons. Nevertheless, there are also ambitious third (G3) generation CMB programs in Europe: QUBIC, QIJOTE and NIKA2 and the balloons LSPE and OLIMPO. The task at hand is now to work towards the measurement of the B-modes of polarisation of the cosmological background with the same type of ultimate precision as obtained in the temperature (scalar) fluctuations. At large angles the B-modes are primordial and bear the imprints of the gravitational waves (tensor modes) produced during the inflation era. The ratio of the amplitudes of the tensor to scalar modes, gives access to the scale of inflation. Furthermore, in the future, the measurement of specific relationships between relevant cosmological quantities should be able to provide unmistakable proof of a signature of inflation. At small angles the B-modes are produced through the lensing of E-modes by the intervening matter and give therefore access to the large scale distribution of matter (including dark matter), the number and masses of neutrinos and/or other exotic particles with precisions that will give, by 2025-2030, conclusive tests of coherence of earth-bound and cosmic measurements. Another domain of research, whose feasibility with current technologies is under investigation, is the measurement with very high precision of the distortions in the CMB black-body spectrum. This could reveal resonant peaks due to standard transitions e.g. from nucleons to the nuclei era (nucleosynthesis), or even dark matter annihilation or any other new physics injections.

- ***CMB Consideration 1***. The next generation of experiments should aim at per mil sensitivities for the tensor to scalar ratio r and also at the largest coverage of the angular spectrum. Ground- and space based experiments play a complementary role in this study since ground-based experiments permit the deployment of very large arrays and therefore high angular resolution, while space-born experiments can probe a sufficient number of frequencies that permit an unsurpassed (and probably very much needed) parametrisation and subtraction of the foregrounds.
- ***CMB Consideration 2***. Europe should participate in a G4 ground programme in synergy/complementarity with the CMB-S4 CMB-currently in development in the USA, aiming at a precision on the tensor to scalar ratio of order one per mil, ca 2025, as well as unprecedented precision on the mass of light neutrinos, in synergy with the neutrino programme.
- ***CMB Consideration 3***. Europe should lead a CMB space programme (e.g. CORE+ as a M5 ESA mission, launch 2029-2030), in close discussion with space programs in development in Japan (LiteBird) and the USA (Pixie).
- ***CMB Consideration 4***. Technology wise, Europe should support R&D and TRL (Technology Readiness Level) upgrade of new detection technologies using cryogenic Transition Edge Sensors (TES) and Kinetic Inductance Detectors (KIDs).
- ***CMB Consideration 5***. APPEC should promote the global coordination of the field.

CMB prospects

The current and future CMB program sets the stage for major thematic unifications. Firstly the prospect of measurement of the inflation parameters, associated with the discovery of Higgs and possibly more massive particles at the LHC, will provide the glimpse of a unified description of physics from the electroweak scale to this of inflation. Secondly the comparison of the neutrino related cosmological measurements with the experimental values measured on ground will become a portal of discoveries of New Physics surpassing the standard models of particle physics and cosmology. Thirdly the study of correlations between the cosmological background primordial fluctuations and the large scale cosmological structures in the Universe, in particular these studied in large Dark Energy surveys, will provide the possibility of a unified description of the totality of visible (and invisible) Universe.

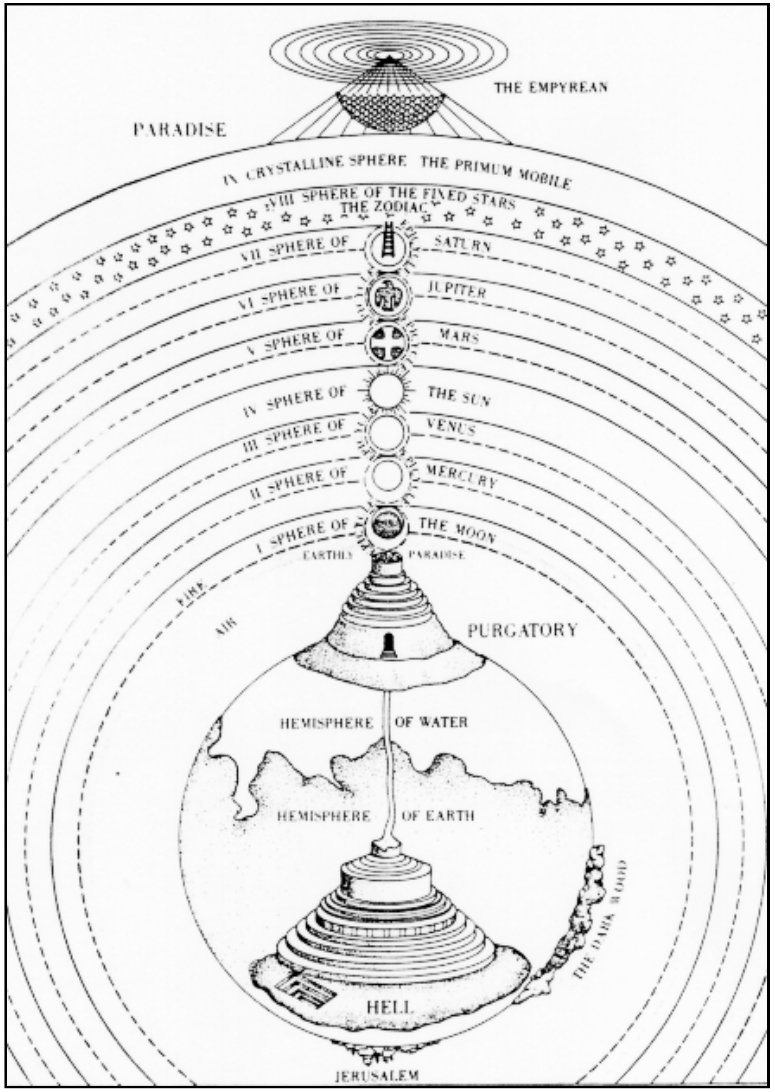
However …

- There is *no* mention of the most important issue for progress in CMB studies, *viz.* a *better* understanding of ***Galactic foregrounds*** (have we forgotten the 'discovery' by BICEP2 of ~~primordial inflationary gravitational waves~~ emission by Galactic dust?)

- There is no *physical* theory of (scalar field vacuum energy driven) inflation so no set of "inflation parameters" to be measured … apart from the energy scale to which the gravitational wave amplitude is sensitive.

- Whereas cosmology provides stronger 'bounds' on neutrinos than the laboratory, if the neutrino mass measured by e.g. KATRIN conflicts with cosmology this will surely indicate a *failure* of the ΛCDM model, rather than a "*portal of discoveries of New Physics surpassing the standard models of particle physics and cosmology*"!

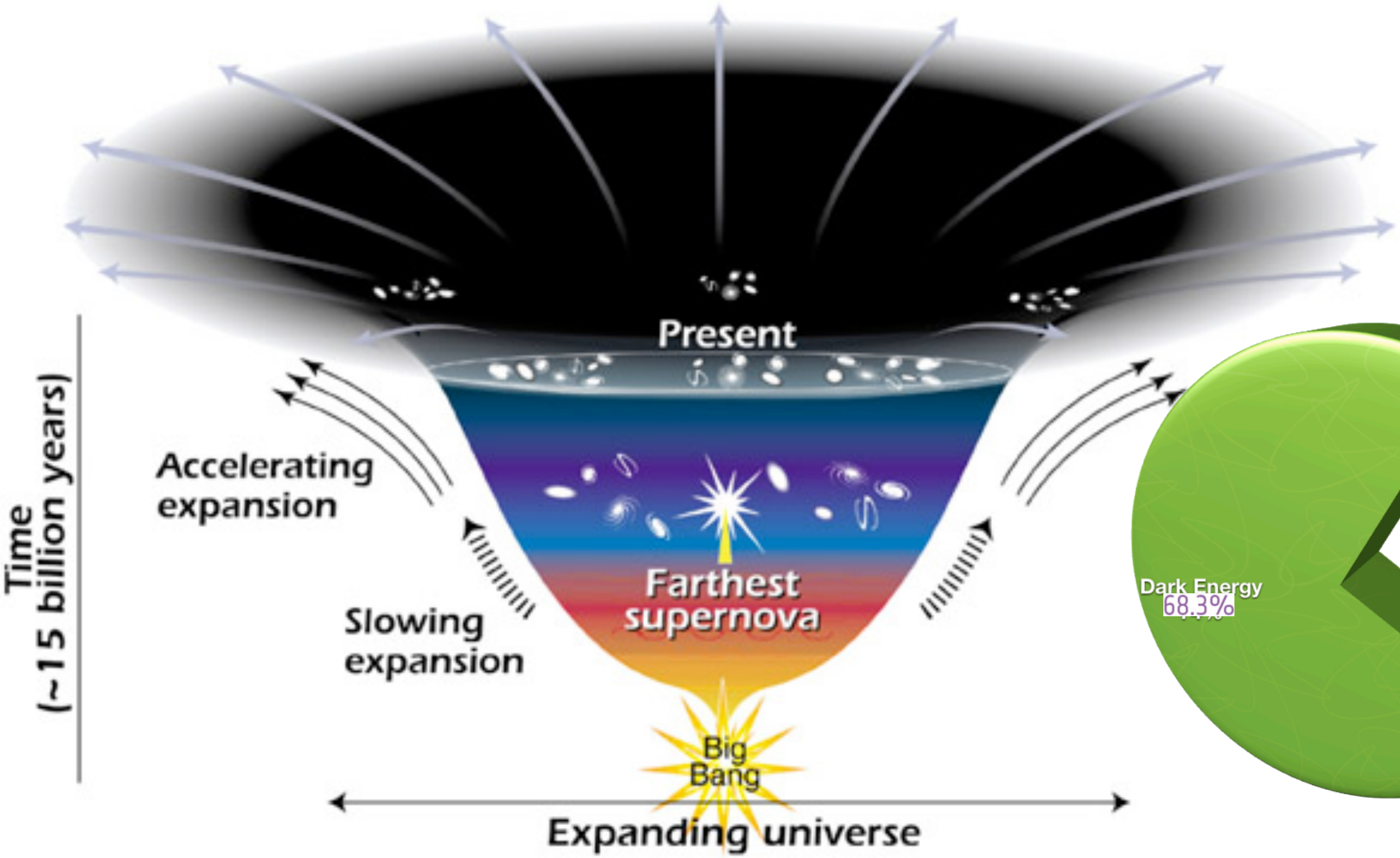
In the Aristotlean 'standard model' of cosmology (~350 BC→1600 AD) the universe was *static* and *finite* and *centred on the Earth*

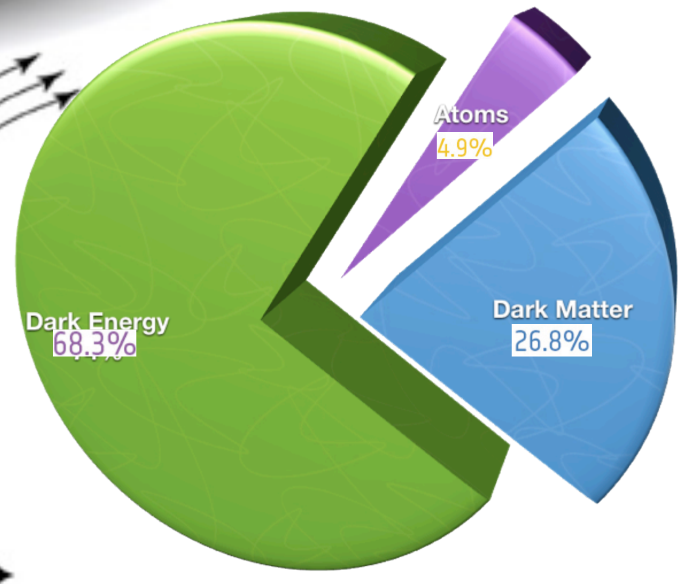


The Divine Comedy, Dante Allighieri (1321)

Recall that this was a 'simple' model and fitted all the observational data … however it had no *dynamical* basis

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





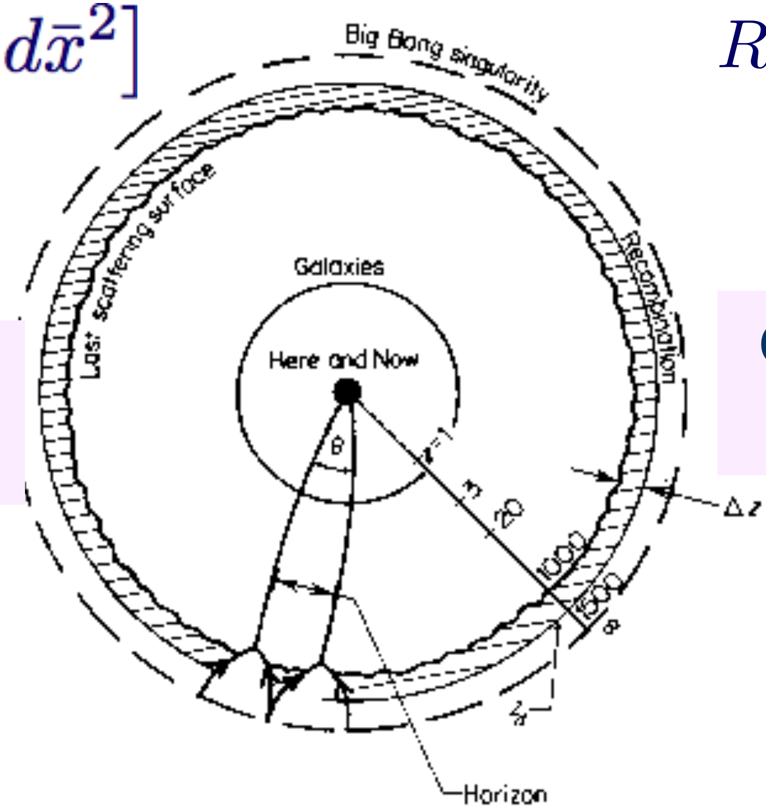
Because it is 'simple' and fits "all the observational data" does *not* make it any better ... when we lack a *physical* understanding of Λ

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

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

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

Classical *and* quantum contributions

Friedmann
Lemaitre

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

Hubble
equation

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

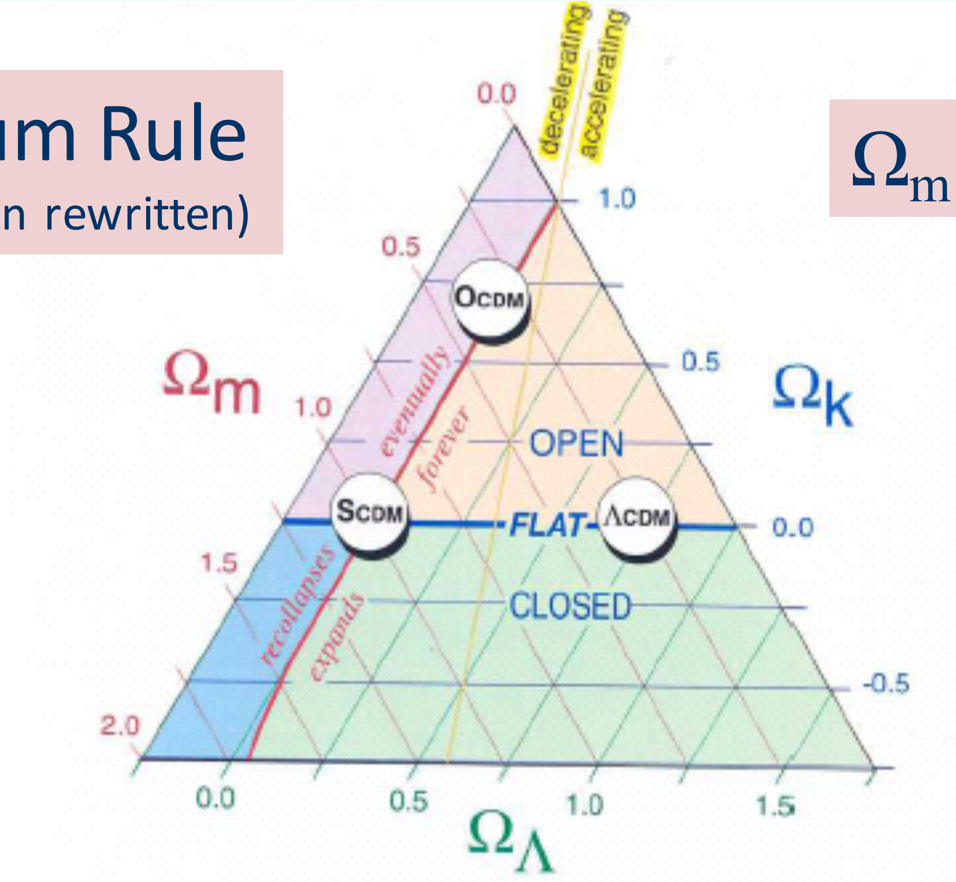
$$\text{where}: z \equiv \frac{a_0}{a} - 1,\ \Omega_{\mathrm{m}} \equiv \frac{\rho_{\mathrm{m}}}{3H_0^2/8\pi G_{\mathrm{N}}},\ \Omega_k \equiv \frac{k}{a_0^2H_0^2},\ \Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2}$$

So it is *natural* for data interpreted in this idealised model to imply that $\Omega_\Lambda\,(\equiv 1-\Omega_\mathrm{m}-\Omega_k)$ is of $O(1)$, i.e. $\Lambda \sim H_0^{\,2}$, given the uncertainty in measuring Ω_m and the possibility of other components (Ω_x) e.g. the 'back reaction' of inhomogeneities which are *unaccounted* for in the standard Hubble equation

Cosmic Sum Rule

(Hubble equation rewritten)

$$\Omega_\mathrm{m} + \Omega_k + \Omega_\Lambda \equiv 1$$



Bahcall, Ostriker, Perlmutter & Steinhardt (1999)

Nevertheless this has been interpreted as evidence for vacuum energy!

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

(NB: The *real* energy scale of the problem is: $H_0 \sim 10^{-42}\,\mathrm{GeV}$)

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

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

hierarchy problem

super-renormalisable

vacuum energy problem

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

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

renormalisable

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

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 a small Majorana ν mass, metastable proton etc is *natural*

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 $\rho_\Lambda \sim (1\ \mathrm{TeV})^4 >> (1\ \mathrm{meV})^4$

… *i.e.* the universe should have been inflating since (or collapsed at): $t \sim 10^{-12}$ s!

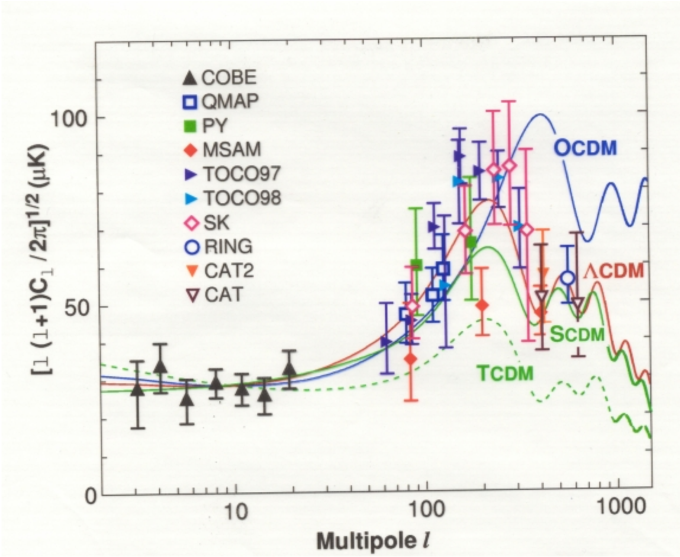
There must be some reason why this did *not* happen ($\Lambda \to 0$?)

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

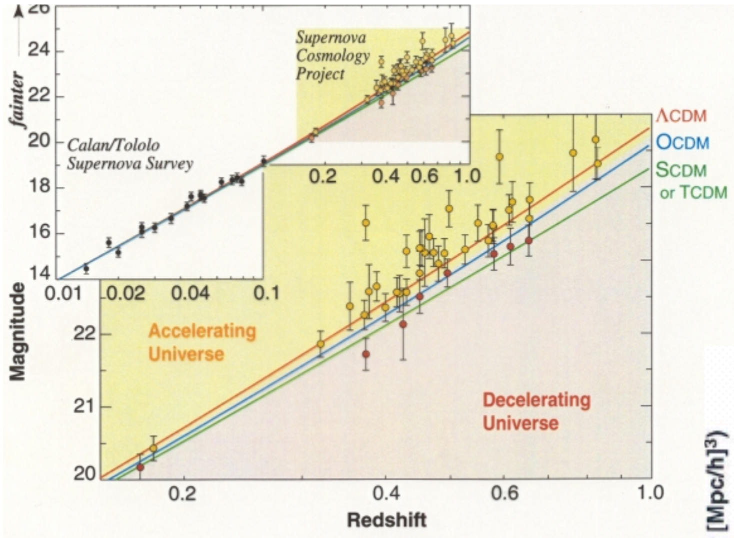
Die allgemeinen Prinzipien der Wellenmechanik, Handbuch der Physik, Vol. XXIV, 1933

However complementary observations indicated that: $\Omega_\Lambda \sim 0.7$, $\Omega_m \sim 0.3$

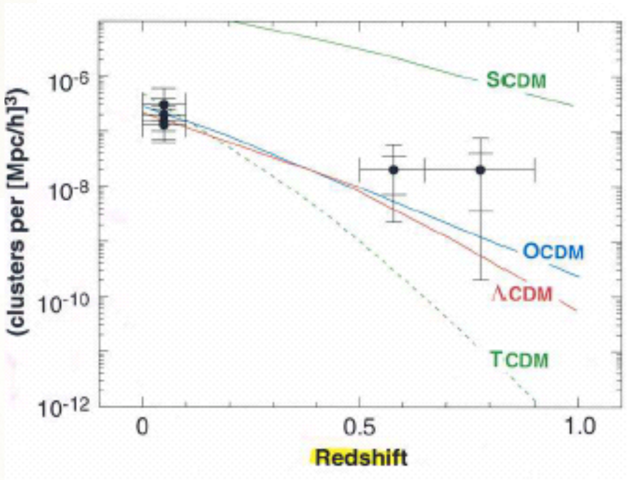
(*assuming* the 'Cosmic Sum Rule': $\Omega_m + \Omega_k + \Omega_\Lambda \equiv 1$)



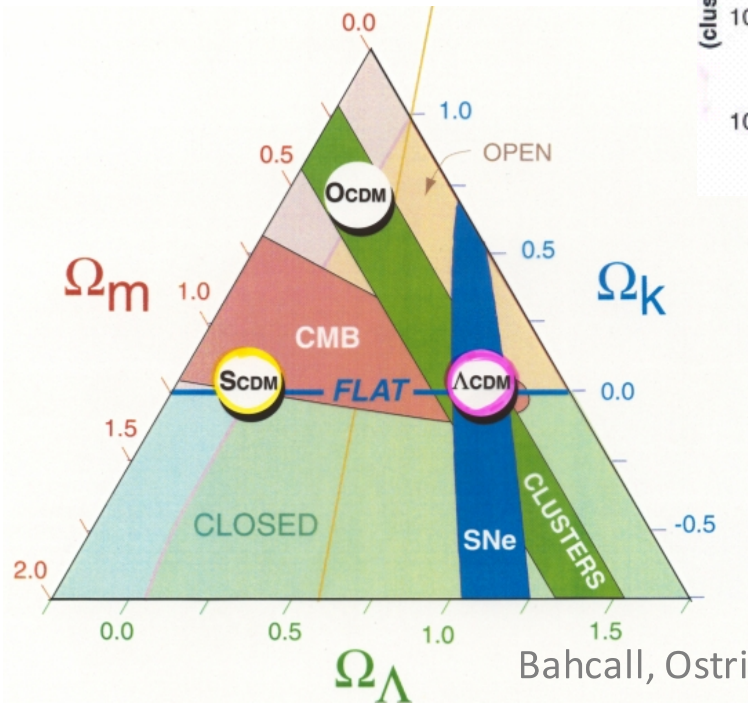
$\Omega_m + \Omega_\Lambda \approx 1.0 \pm 0.03$



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

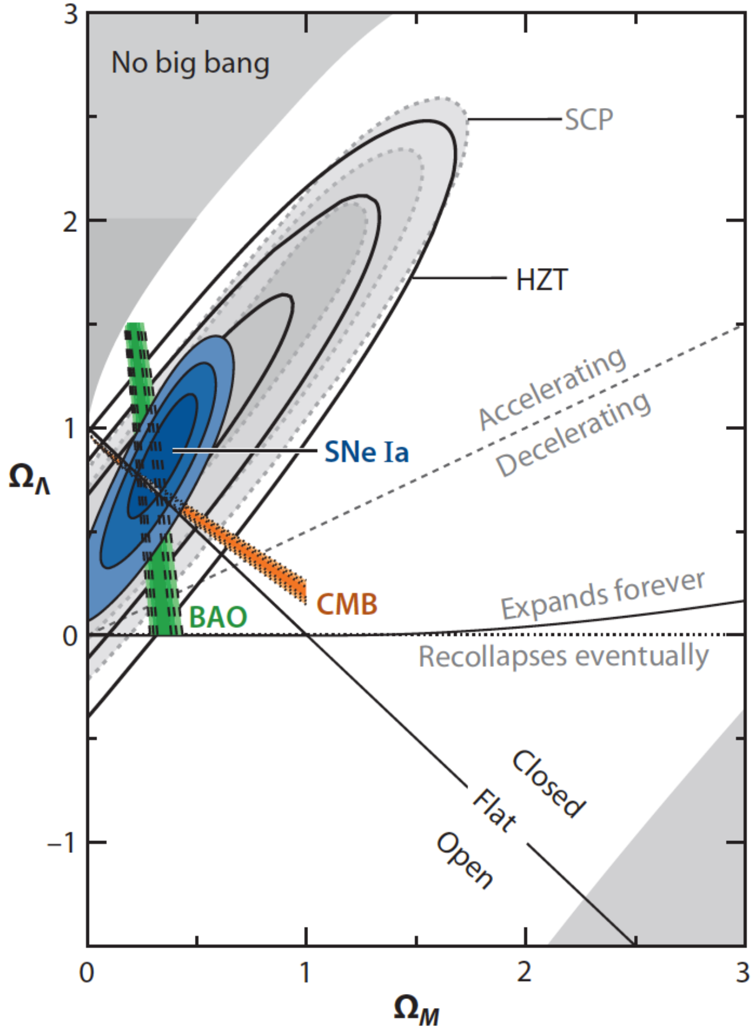


$\Omega_m \approx 0.3$



Bahcall, Ostriker, Perlmutter, Steinhardt (1999)

CMB data indicate $\Omega_k \approx 0$ so the FLRW 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 Cosmic Sum Rule does *not* include, then we will *necessarily* infer $\Omega_\Lambda \neq 0$ (and the plot above will be misleading since flatness now $\Rightarrow \Omega_\Lambda + \Omega_m + \Omega_x = 1$)

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,

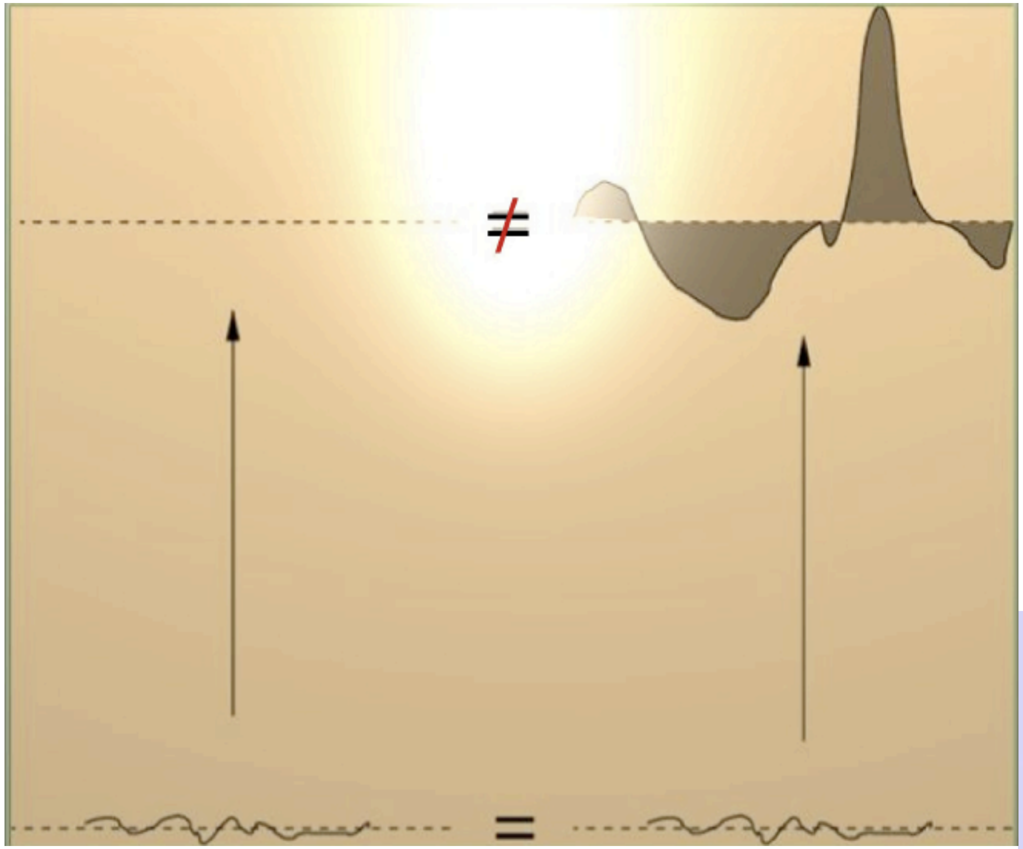
$$
\mathcal{Q}_{\mathcal{D}} = \frac{2}{3}\left(\langle\theta^2\rangle_{\mathcal{D}} - \langle\theta\rangle_{\mathcal{D}}^2\right) - \langle\sigma^{\mu\nu}\sigma_{\mu\nu}\rangle_{\mathcal{D}} \ .
$$

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.

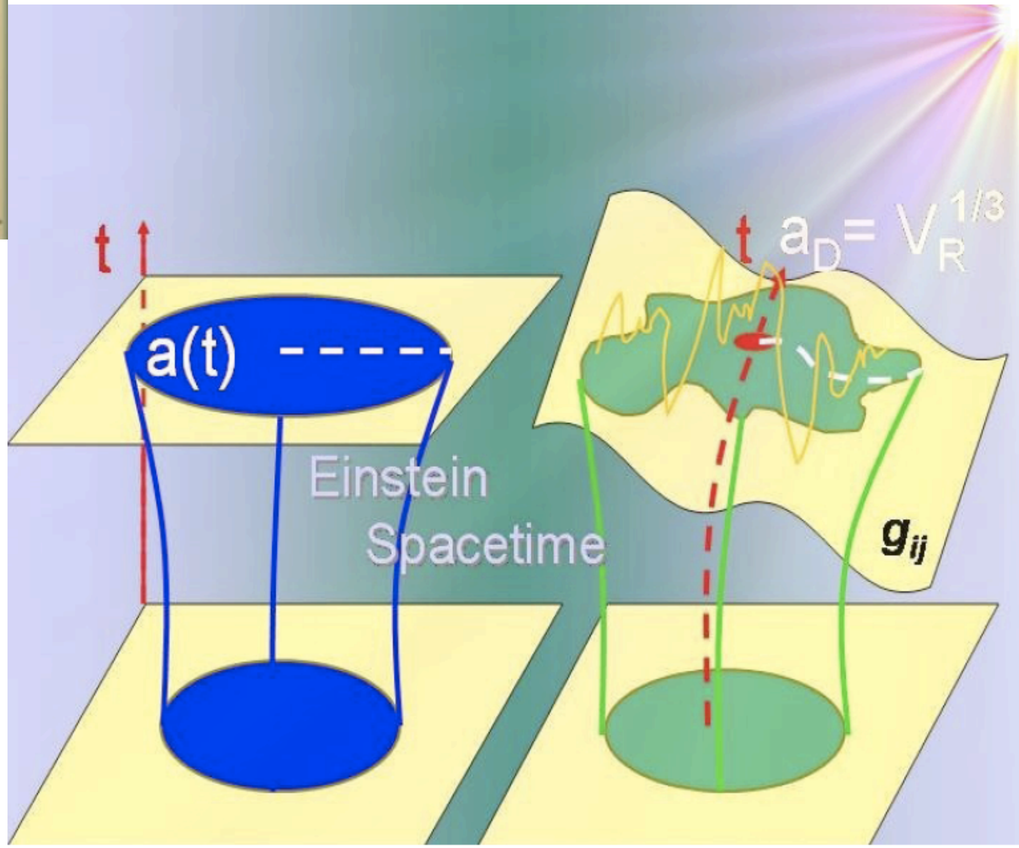
Can mimic a cosmological constant if $\mathcal{Q}_{\mathcal{D}} = -\frac{1}{3}\langle{}^{(3)}R\rangle_{\mathcal{D}} = \Lambda_{\text{eff}}$.

Whether the backreaction can be sufficiently large is 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 eqs. is distorted - its average must be taken over the *actual* geometry … the result is *different* from the standard FRW model



Courtesy: Thomas Buchert

Does it make sense to interpret Λ as vacuum energy?

"The interpretation, we feel, should be left to you and the very few others who are competent to discuss the matter with authority"

Edwin Hubble in letter to Wilhelm De Sitter (1931)

(concerning interpretation of cosmological redshifts … after he had mistakenly fitted the redshift-distance data to a *quadratic* relationship: $z \propto r^2$ – 'the De Sitter effect')

For a clock in De Sitter space, $\mathrm{d}s^2 = \left(1 - \frac{r^2}{\mathcal{R}^2}\right)\mathrm{d}t^2 - \mathrm{d}r^2/\left(1 - \frac{r^2}{\mathcal{R}^2}\right) - r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2)$, at rest ($\mathrm{d}r = \mathrm{d}\theta = \mathrm{d}\varphi = 0$), the time-like interval, $\mathrm{d}s^2 = \mathrm{d}t^2(1 - r^2/R^2)$, depends on radial distance, becoming smaller as r increases $\Rightarrow$ redshift of light from distant sources with: $\frac{\mathrm{d}t}{\mathrm{d}t_0} = \sqrt{1 - \frac{r^2}{\mathcal{R}^2}} = \frac{\lambda}{\lambda_0} = 1 + \frac{\Delta\lambda}{\lambda_0} \Rightarrow z \simeq \frac{1}{2}\frac{r^2}{\mathcal{R}^2}, \text{ for } r \ll \mathcal{R}$

(NB: This is misleading because there are in fact no inertial observers in De Sitter space!)

"Raffiniert ist der Herrgott, aber boshaft ist er nicht!"

(*Subtle is the Lord, but malicious He is not!*)

Albert Einstein (1921)

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 $\mathbf{V(\varphi)^{1/4} \sim 10^{-12}}$ **GeV,** but $\sqrt{\mathbf{d^2V/d\varphi^2}} \sim H_0 \sim \mathbf{10^{-42}}$ **GeV** to ensure slow-roll **...**
i.e. exactly 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

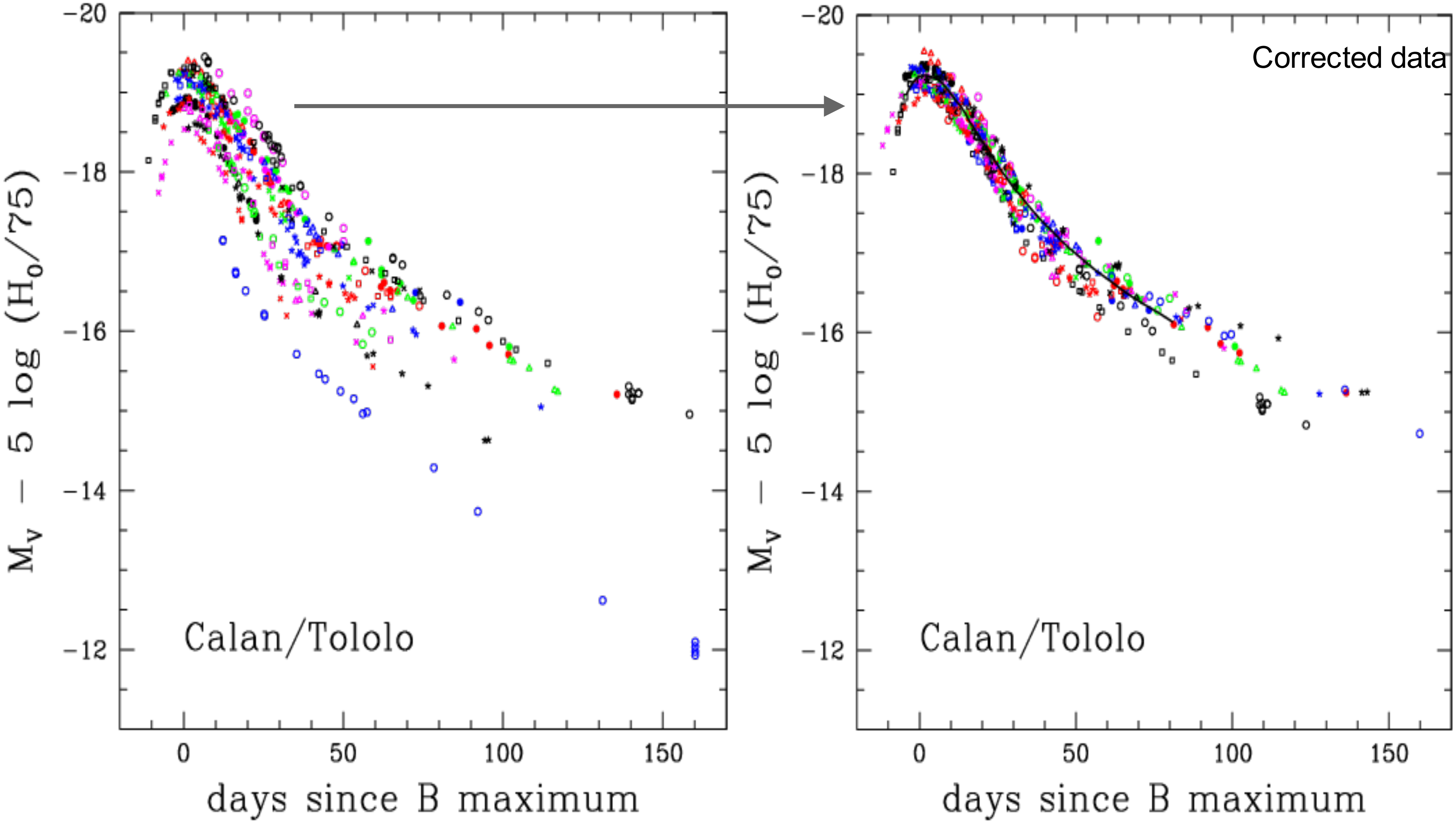
(Similar fine-tuning in *every* other attempt: **massive gravity**, **chameleon fields** …)

The only *natural* option is if $\Lambda \sim H^2$ *always*, but this is just a renormalisation of G_N! Recall: $H^2 = 8\pi G_N/3 + \Lambda/3$ … this is *ruled out* by e.g. Big Bang nucleosynthesis (which requires $G_N^{\text{cosmic}} \sim G_N^{\text{laboratory}}$) and in any case does *not* yield accelerated expansion

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**?
(if $\Lambda << H_0^2$ we would not measure it, if $\Lambda >> H_0^2$ we would not be here!)

Type Ia supernovae as ‘standardisable candles’



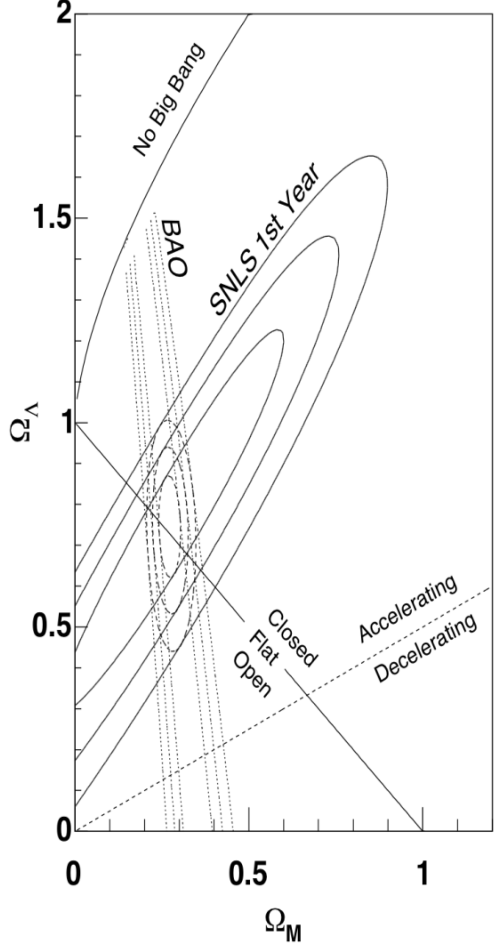
Hamuy, 1311.5099

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

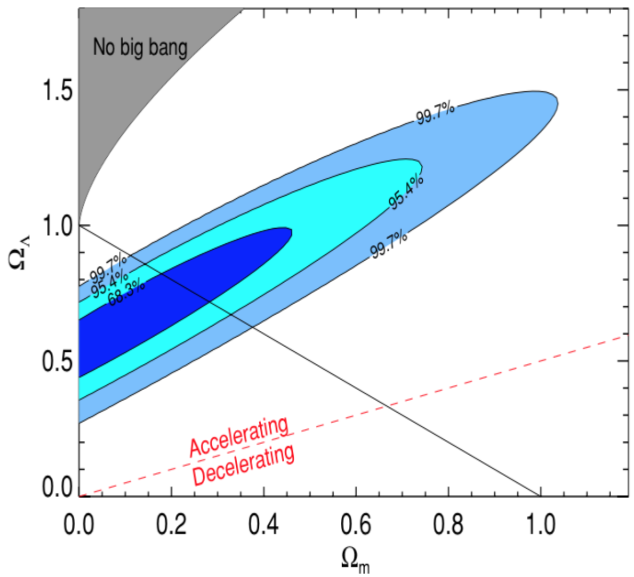
Use a standard template (e.g. SALT 2) to make ‘stretch’ and ‘colour’ corrections …

How strong is the evidence for cosmic acceleration?

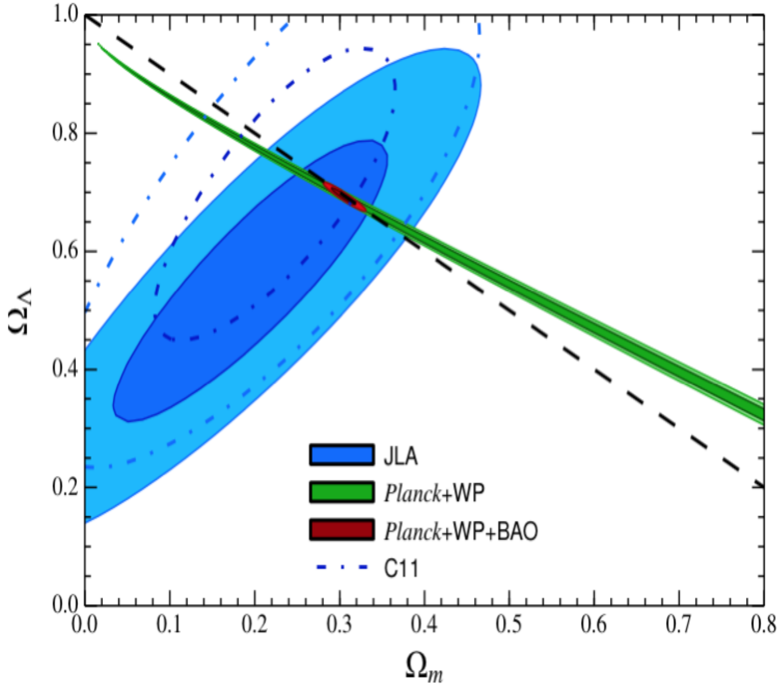
Astier *et al*, 2006



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



Betoule *et al*, 2014

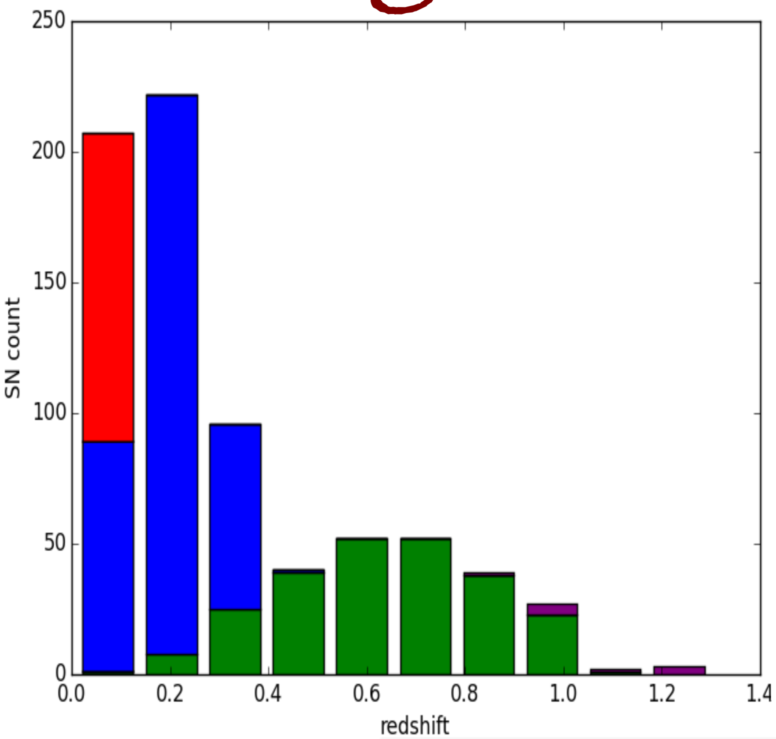


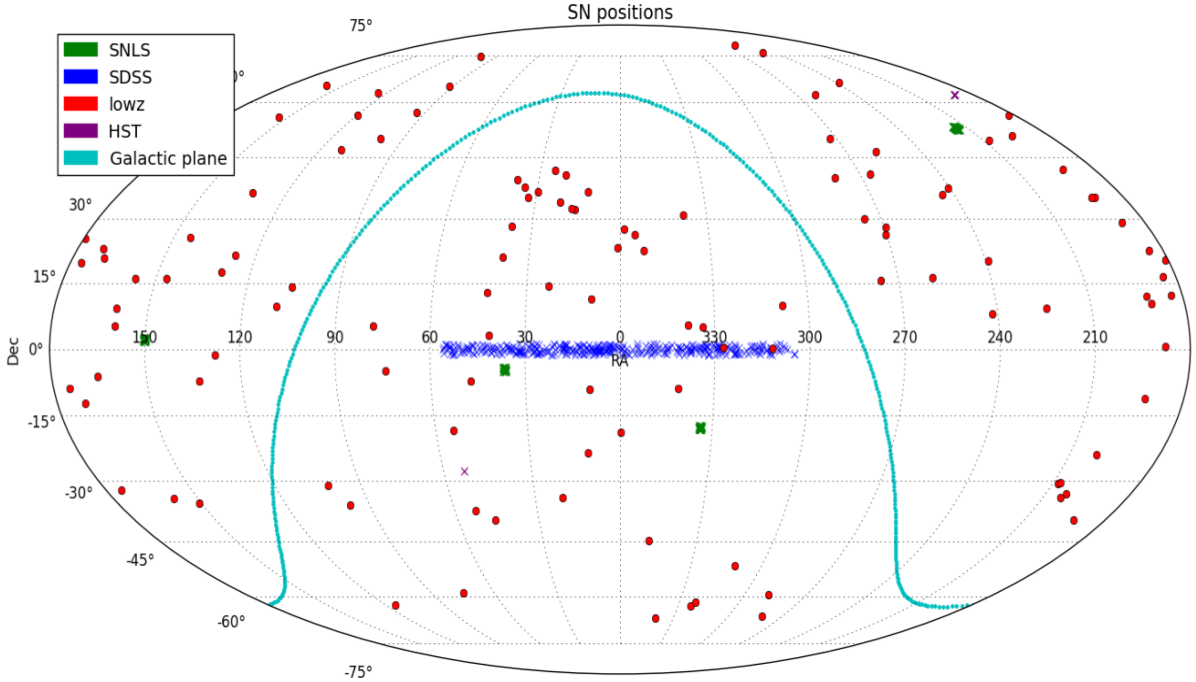
$$\boxed{\mu_B = m_B^* - M + \alpha X_1 - \beta \mathcal{C}}$$

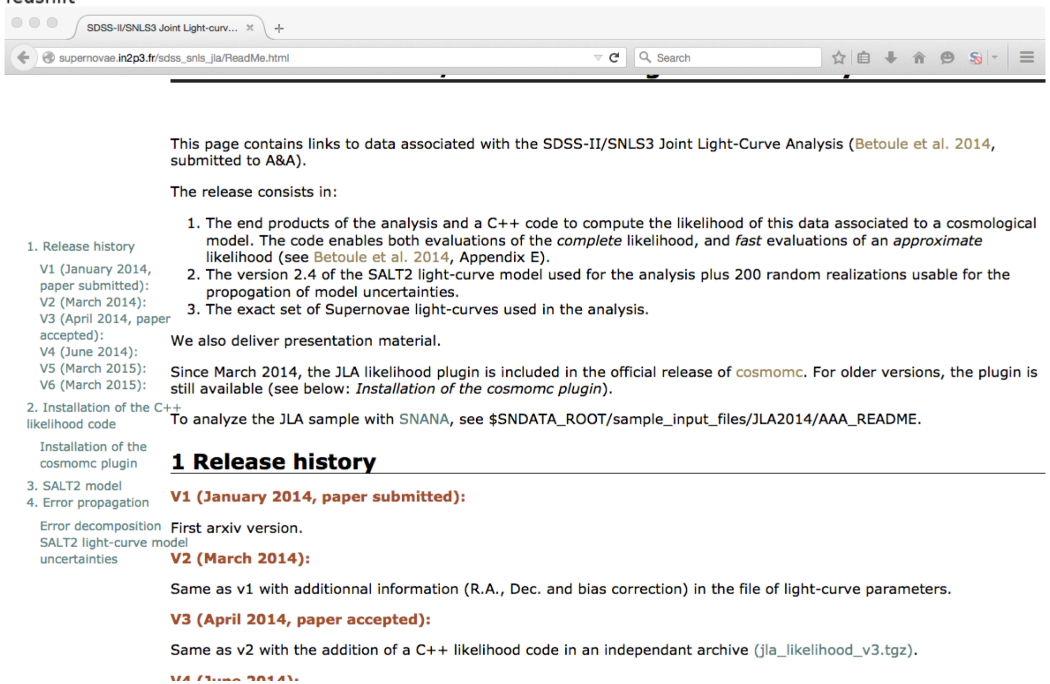
$$\chi^2 = \sum_{objects} \frac{(\mu_B - 5\log_{10}(d_L(\theta, z)/10pc))^2}{\sigma^2(\mu_B) + \sigma^2_{int}}$$

But they *assume* ΛCDM and adjust $\sigma_{\rm int}$ 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 (thanks!)

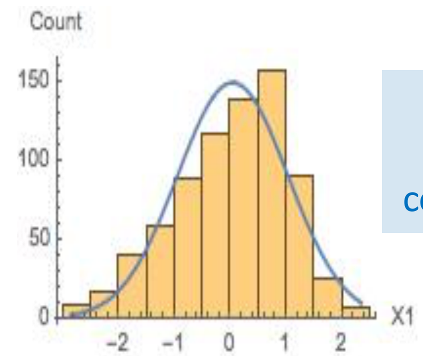
Betoule *et al*, 1401.4064

Construct a Maximum Likelihood Estimator!

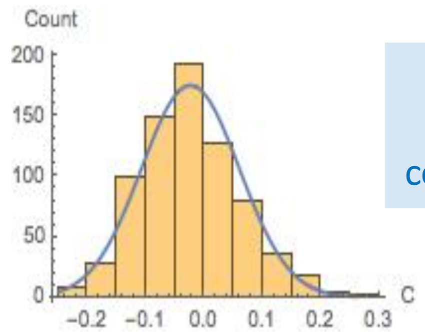
$$\mathcal{L} = \text{probability density}(\text{data}|\text{model})$$

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

Well-approximated as Gaussian



JLA data
'Stretch'
corrections



JLA data
'Colour'
corrections

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

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

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

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

Nielsen *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

Confidence regions

Nielsen *et al*, arXiv: 1506.01354

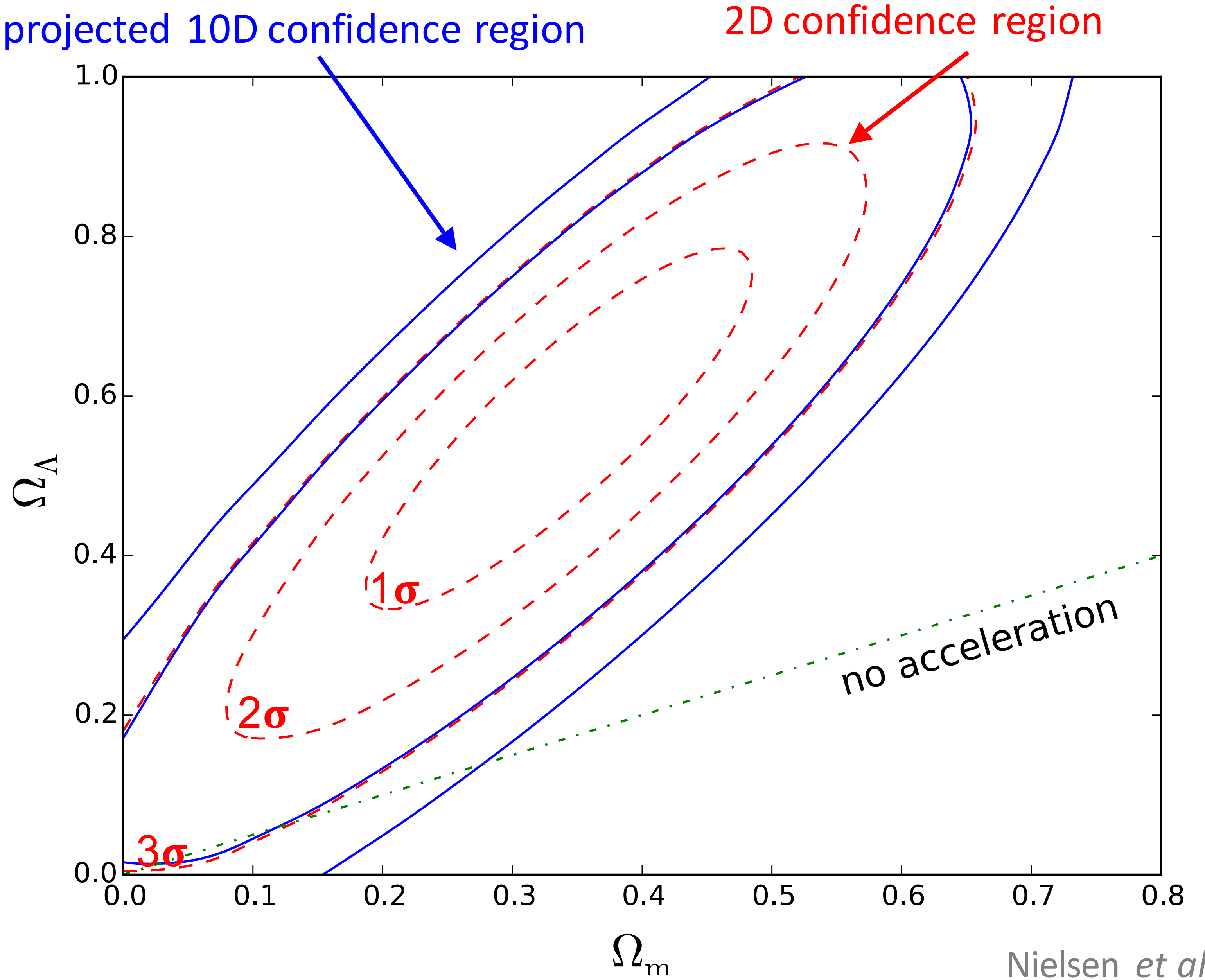
$$p_{\mathrm{cov}} = \int_0^{-2\log\mathcal{L}/\mathcal{L}_{\max}} \chi^2(x;\nu)dx$$

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

1,2,3-sigma

solve for Likelihood value

Data consistent with *uniform expansion* @3σ!



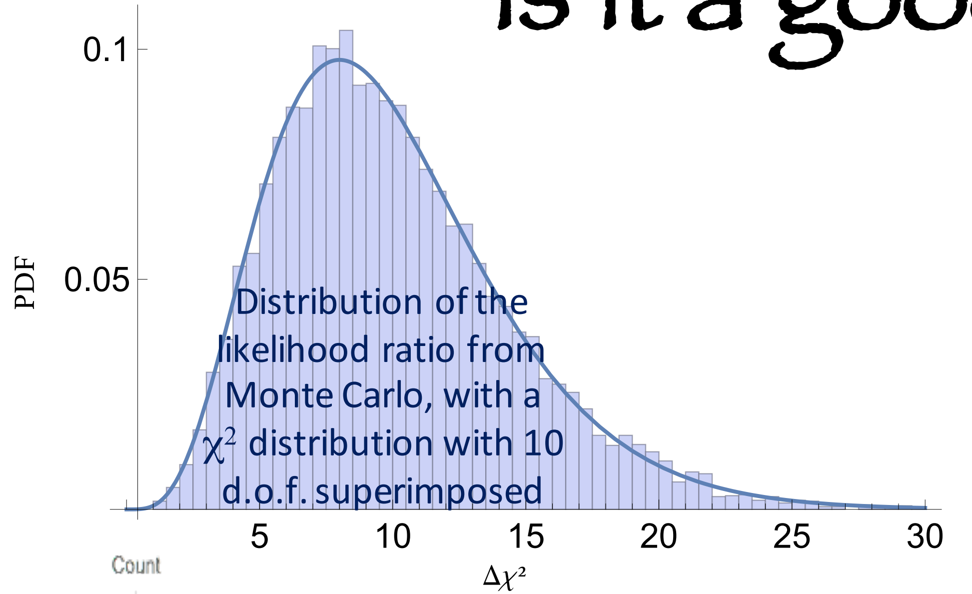
profile likelihood

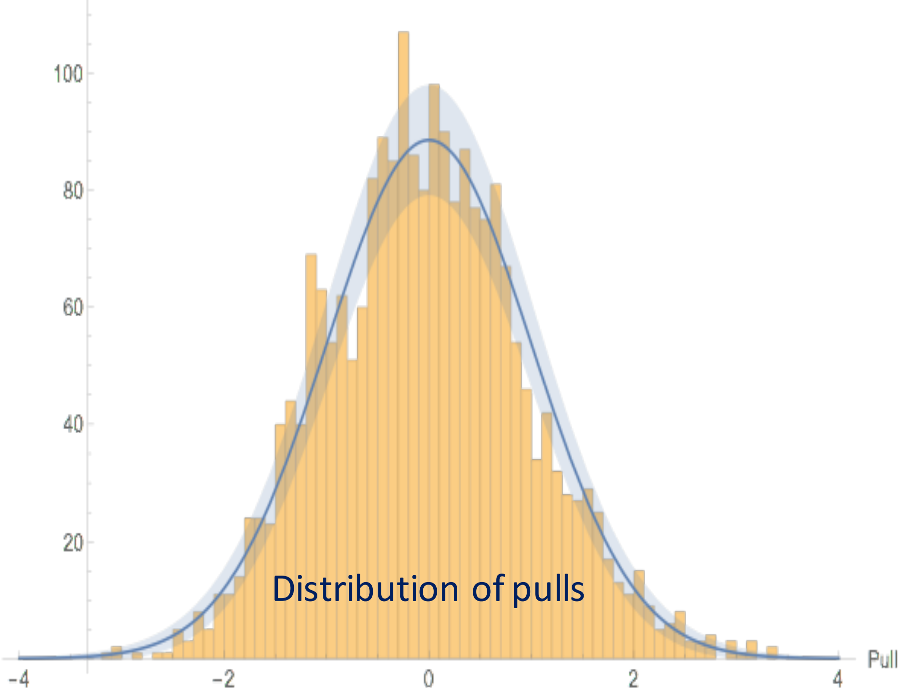
<u>MLE, *best fit*</u>

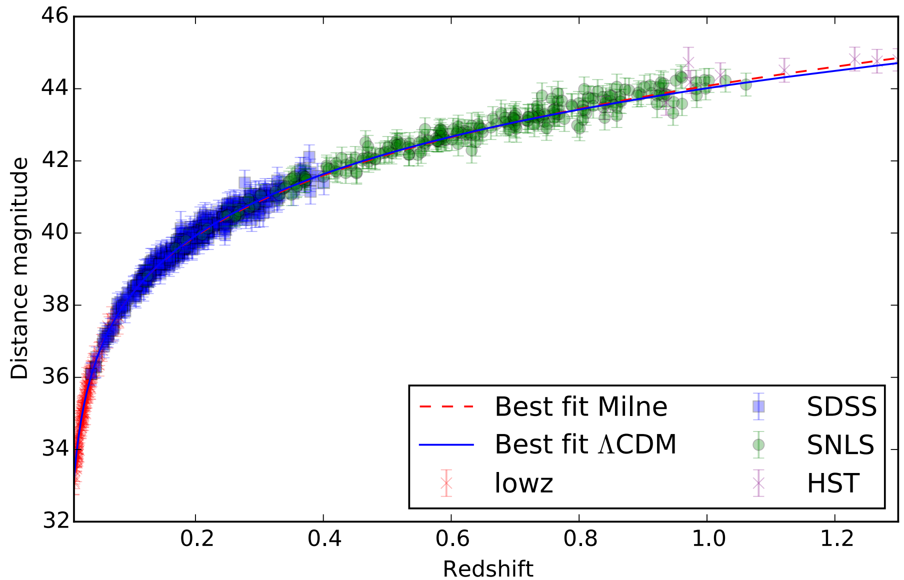
Ω_M	0.341
Ω_Λ	0.569
α	0.134
x_0	0.038
σ^2_{x0}	0.931
β	3.058
c_0	-0.016
σ^2_{c0}	0.071
M_0	-19.05
σ^2_{M0}	0.108

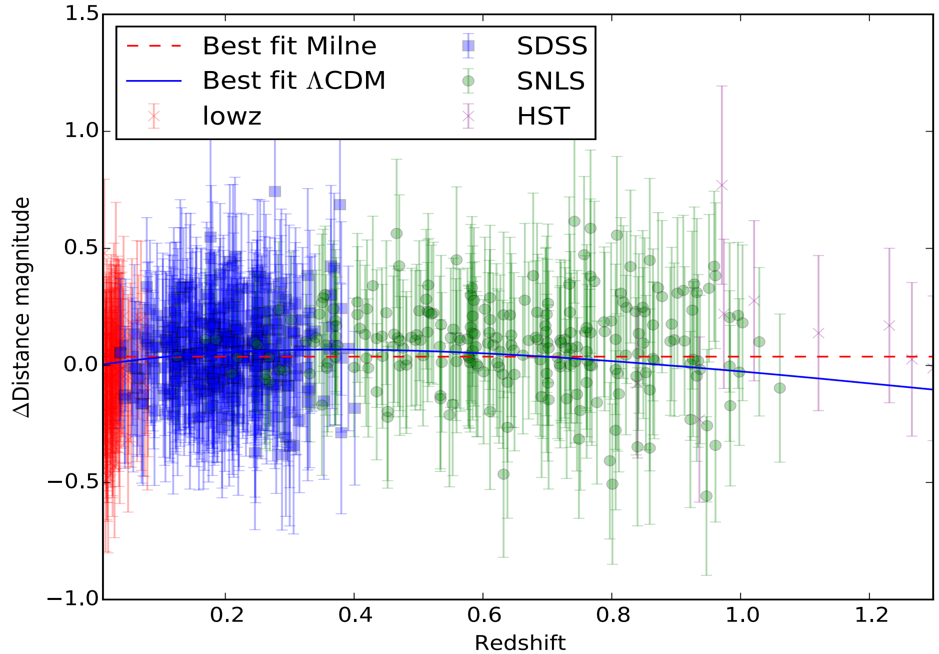
Nielsen *et al*, arXiv: 1506.01354

Is it a good fit ?





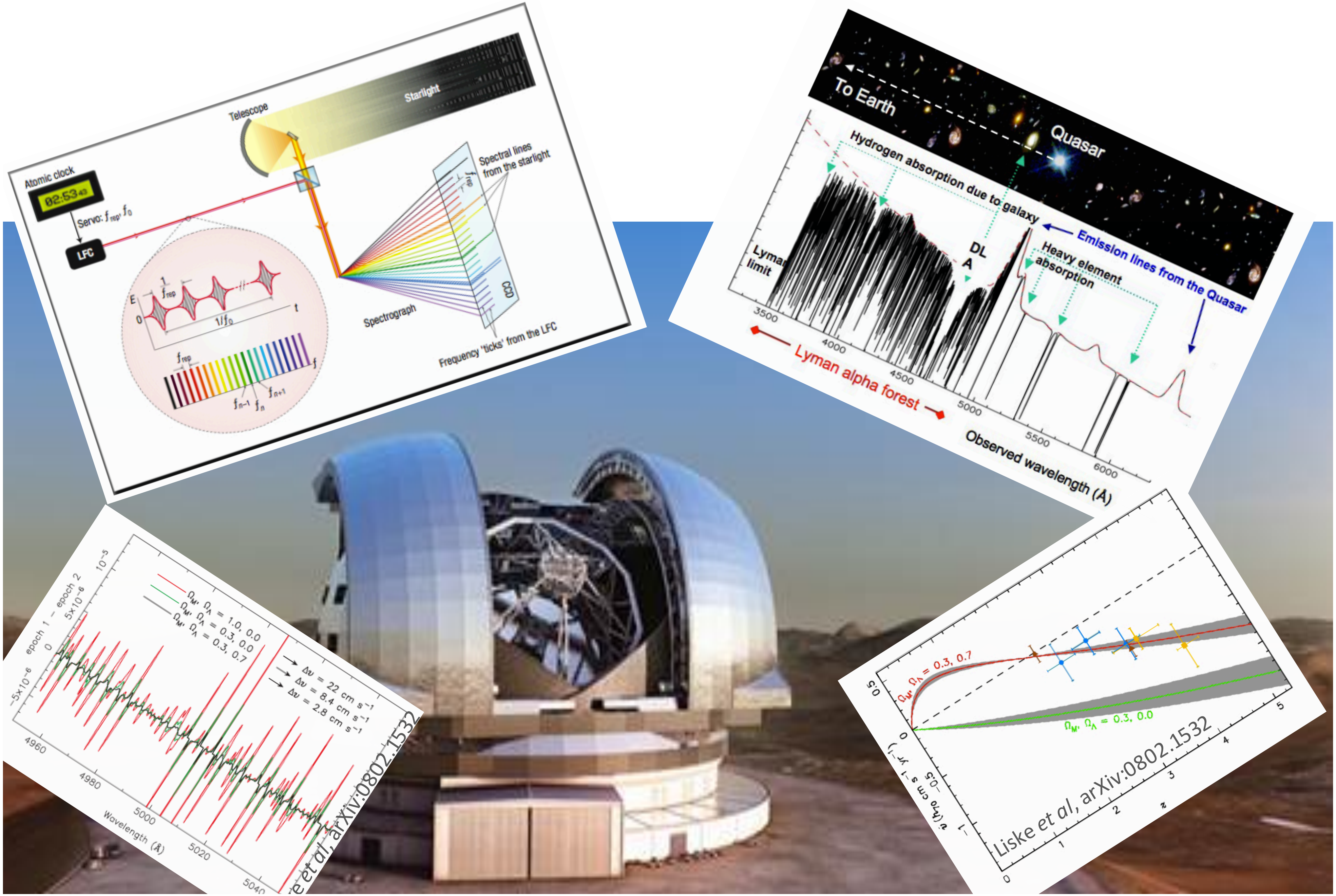




$$\boxed{\mathrm{pull} = (\Sigma_d + A^{\mathrm{T}}\Sigma_l A)^{-1/2}(\hat{Z} - Y_0 A)}$$

Nielsen *et al*, arXiv: 1506.01354

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?

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 ($\Rightarrow$ ~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 $\boldsymbol{h}$, $\boldsymbol{\Omega_{\mathrm{CDM}}}$ …, assume a primordial power-law spectrum, *etc* in order to break inevitable parameter degeneracies

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

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 this should be a priority!

- It is *not* simply a choice between a cosmological constant ('dark energy') and 'modified gravity' – there are other possibilities which should be explored (exact solutions of Einstein's equations are hard to find unless a great deal of symmetry is assumed … so alternative models are not as easy to formulate and confront with observations - but that does not make them less plausible as a description of nature)

- 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