Ian Hinchcliffe (Berkeley), DPhil in Theoretical Physics, Oxford (1975)

Hinchcliffe's rule: If the title of a scholarly article is a yes-no question, the answer is '*no*'!

Is Hinchliffe's Rule True?

Boris Peon

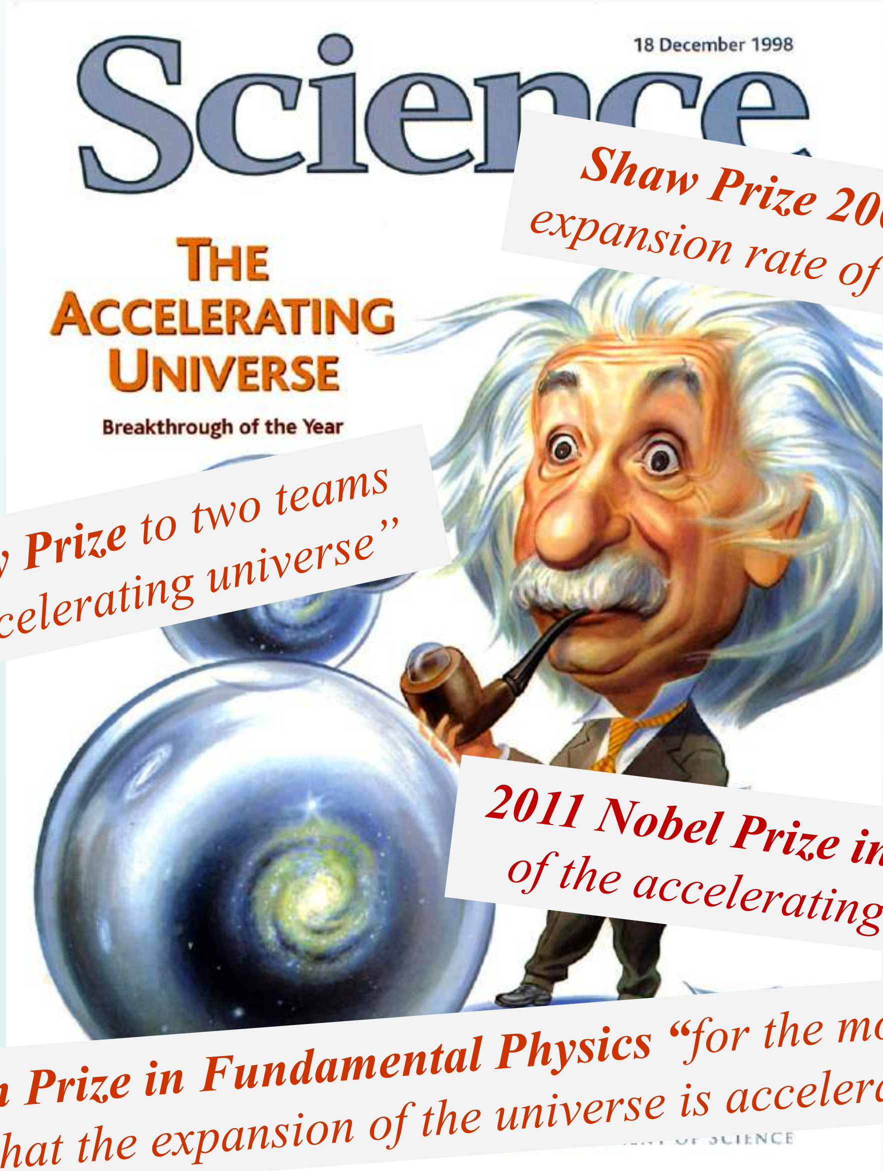
Aug 4, 1988 - 1 pages
Submitted to: Annals Gnosis

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that **Hinchliffe's assertion is false, but only if it is true.**

Cosmic acceleration revealed by Type Ia supernovae ?

Subir Sarkar
Rudolf Peierls Centre for Theoretical Physics



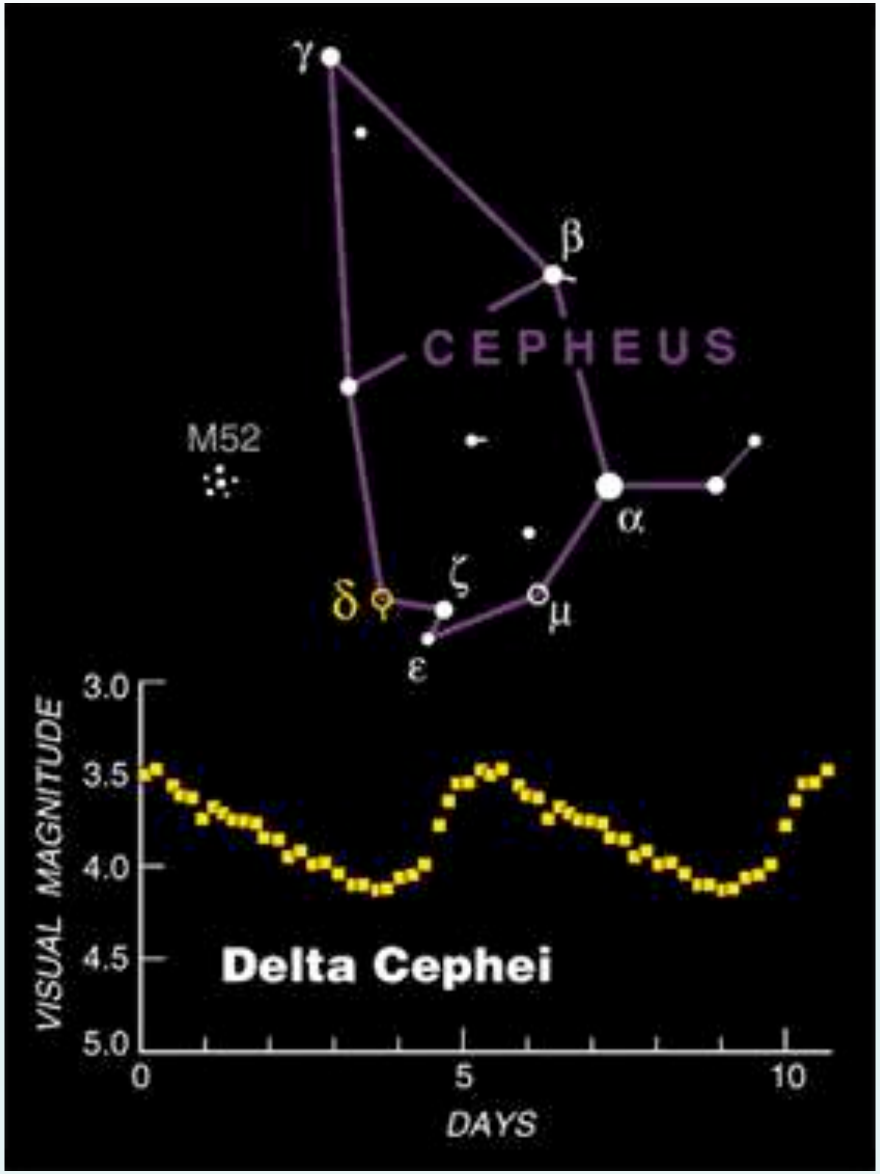
Shaw Prize 2006 *"for discovering that the expansion rate of the universe is accelerating"*

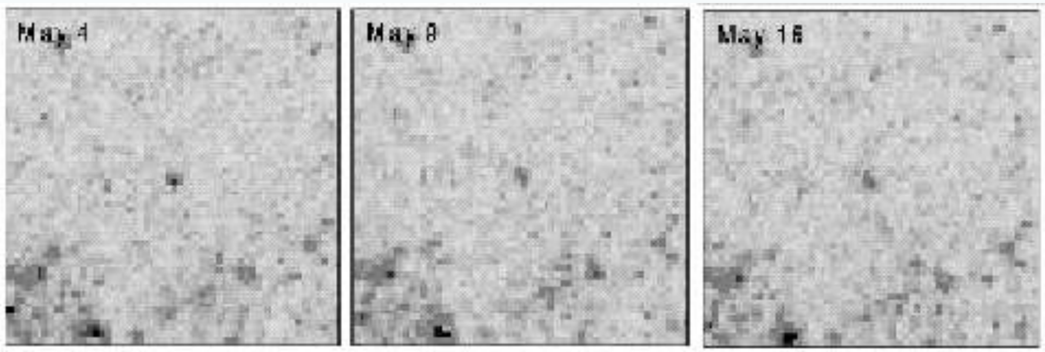
2007 Gruber Cosmology Prize *to two teams "who discovered the accelerating universe"*

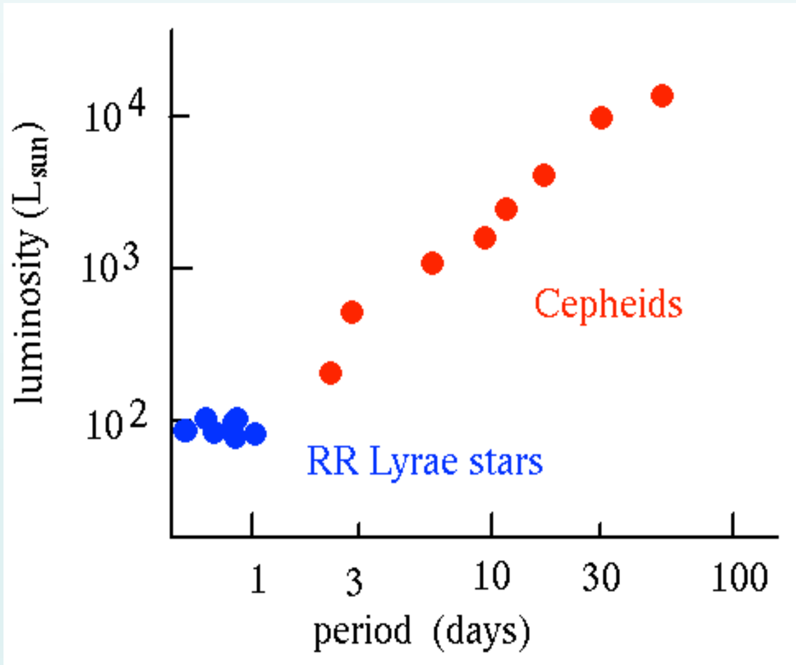
2011 Nobel Prize in Physics *"for their discovery of the accelerating expansion of the universe"*

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

To measure distances we need "standard candles" – astronomical sources whose *absolute* luminosity is known from its correlation with some other property

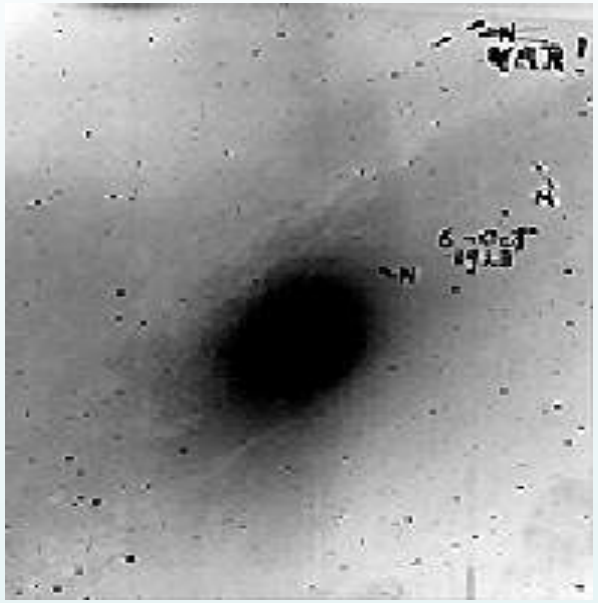






… e.g. pulsation period in the case of **Cepheid variable** stars

In 1923 Edwin Hubble used the 100” Mt Wilson telescope to determine the distance to the Andromeda Nebula

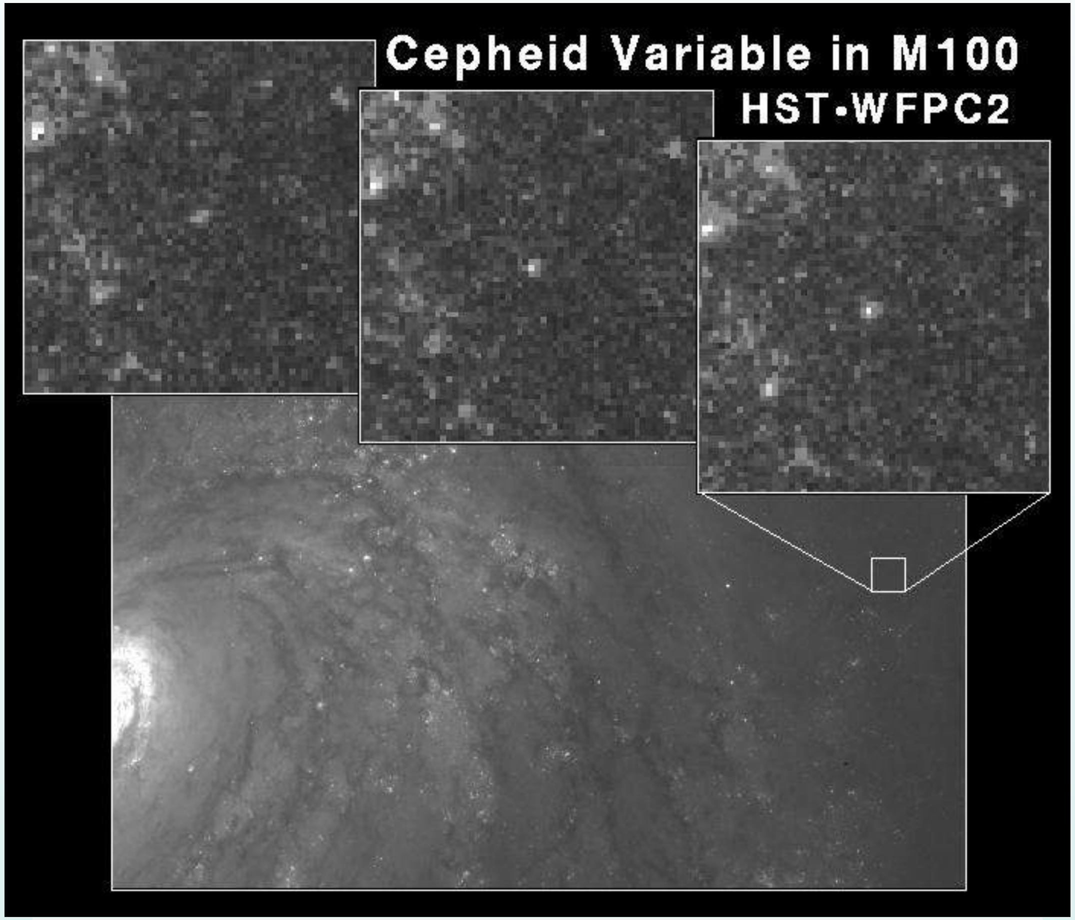


He was actually searching for ‘novae’ … instead he found a ‘Cepheid variable’, which **Henrietta Leavitt** had shown (in 1912) to be a good distance indicator

Hubble discovered that Andromeda (M31) is not a cloud of stars and gas in our Milky Way, but a galaxy similar to our own at a very substantial distance … 2.5 million light years ($\Rightarrow$ 0.8 Mpc)!

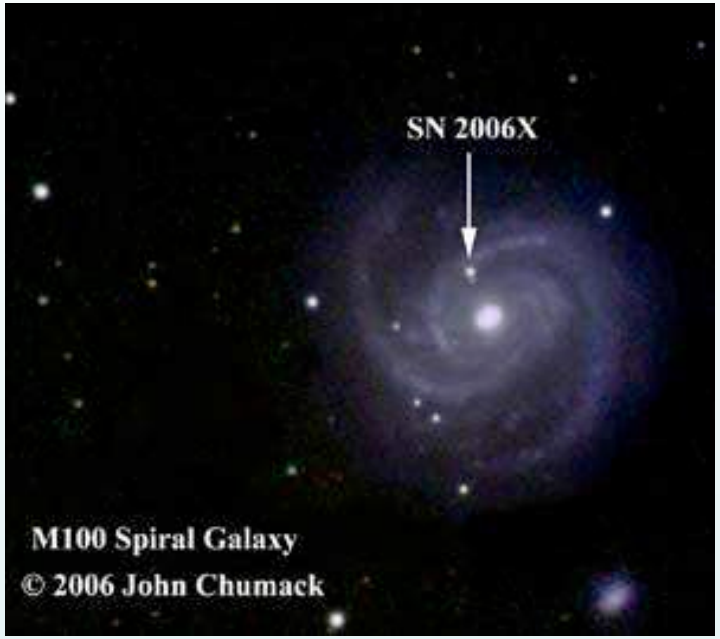
The Universe suddenly became a *lot* bigger … and so began modern cosmology

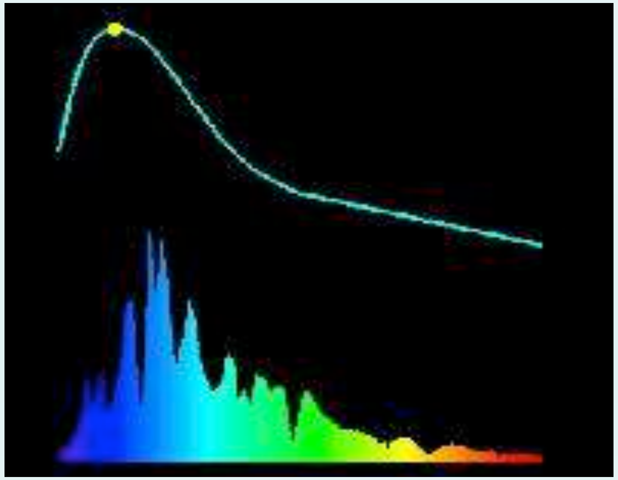
The Hubble Space Telescope (1990-) can resolve Cepheids in galaxies *much* further away

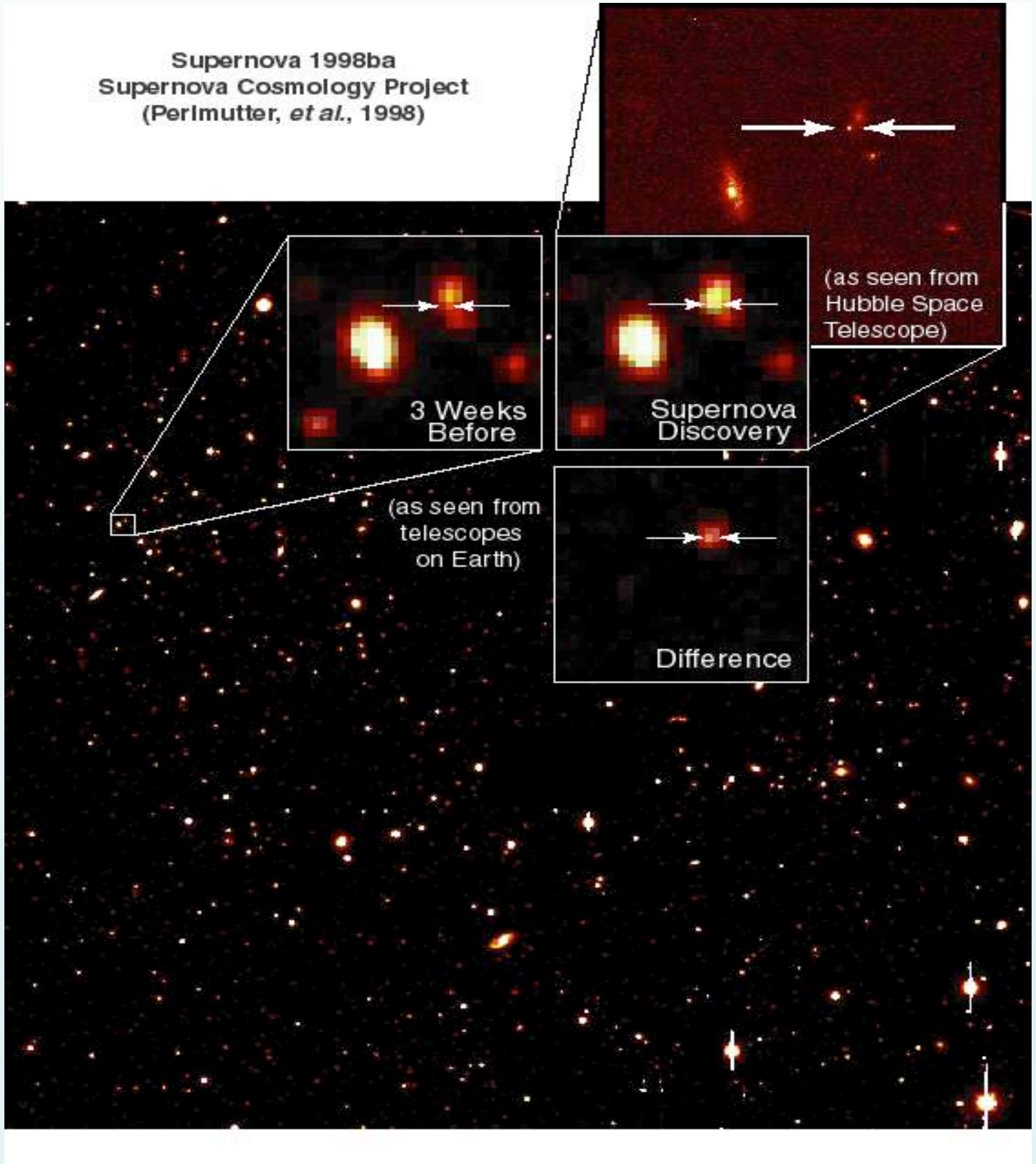


M100 is a galaxy in the **Virgo cluster** at a distance of 54 million light years (16.4 Mpc)

Cepheids can be used to 'calibrate' other sources such as supernovae – exploding stars which are bright enough to be seen *even* further away

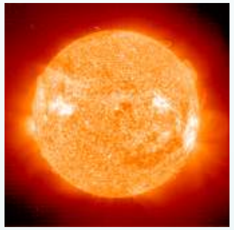






... using supernovae we can now measure distances of *billions* of light-years

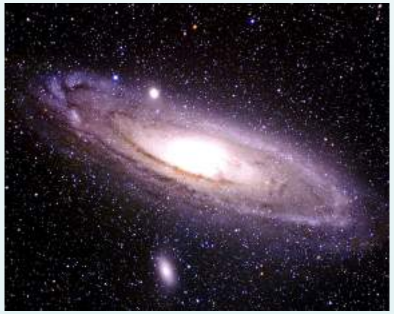
Looking far away is the same as looking back into our past …



We see the
Sun as it was
8 minutes ago

We see the nearest star
Proxima Centauri,
as it was 4 years ago

We see the Galactic
centre as it was
30,000 years ago



We see our nearest
galaxy Andromeda as
it was 2.5 million
years ago

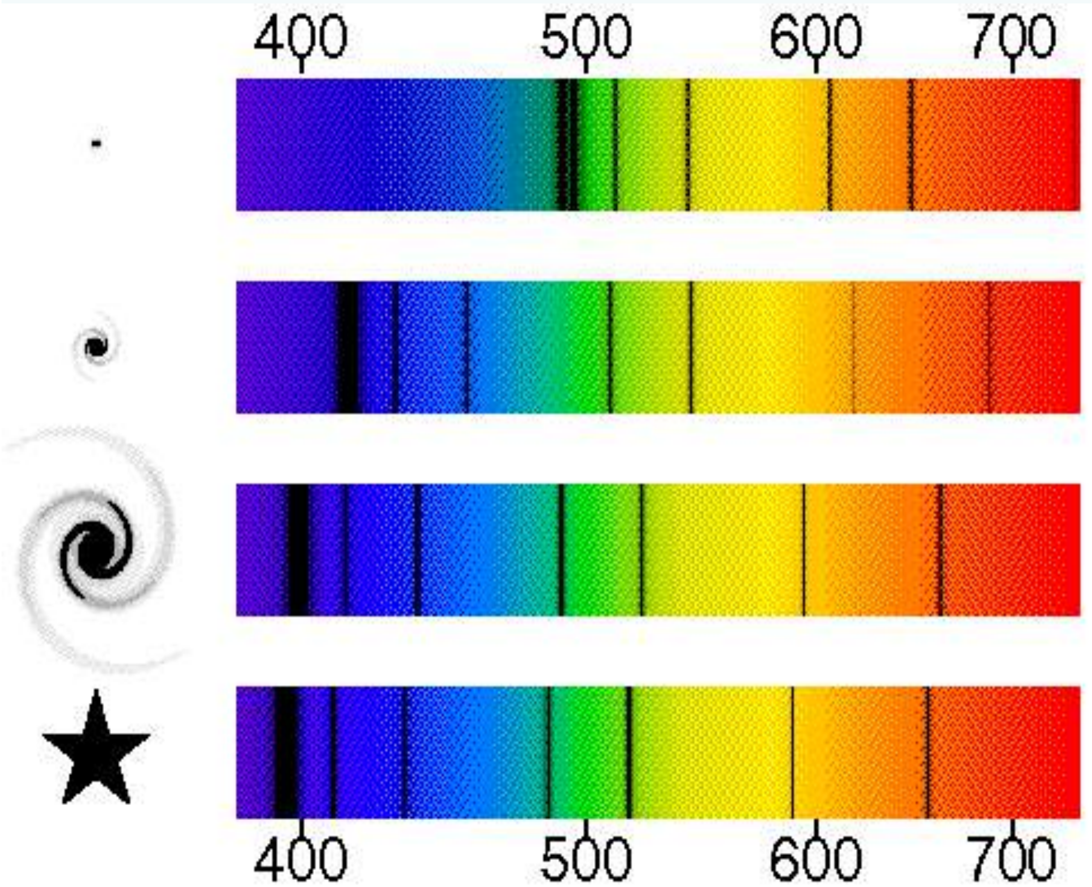
We see the Virgo
cluster as it was
54 million years ago

We see galaxies in
the Hubble Ultra
Deep Field
as they were - up to
12 billion years ago

But there is something *odd* about the spectra of distant galaxies …

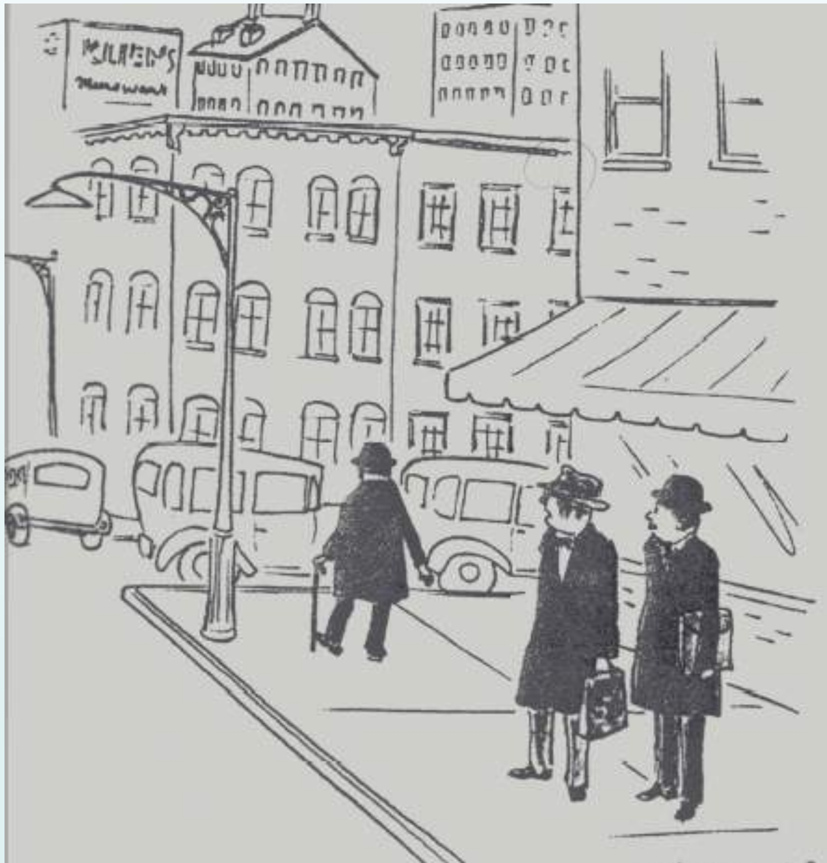
… they are shifted towards the red (longer wavelengths)

as if they are travelling away from us - Doppler effect?



Red Shift: $z = \frac{\lambda_{\mathrm{emitted}} - \lambda_{\mathrm{observed}}}{\lambda_{\mathrm{emitted}}}$

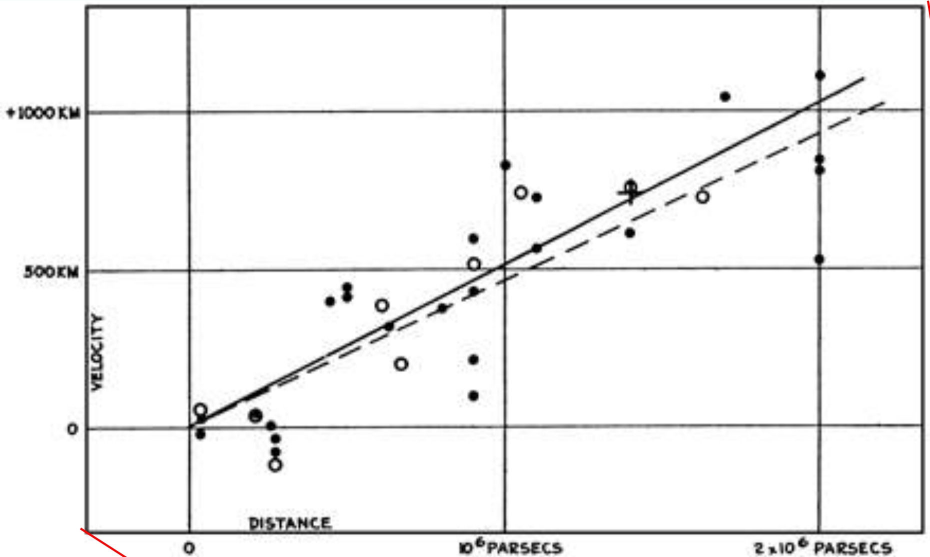
$\simeq v/c$, for $z \ll 1$



The New Yorker

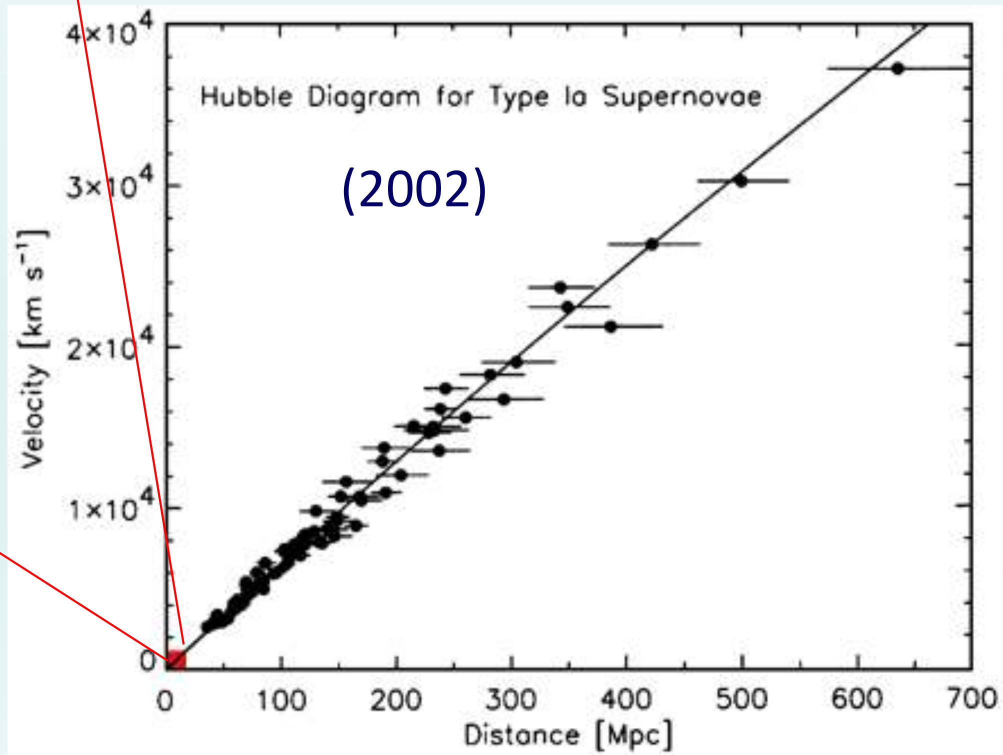
"Every time I see Edwin Hubble, he is moving rapidly away from me!"

The 'expansion' of the universe



Hubble's data (1929)

Hubble (1931) to De Sitter:
"The interpretation, we feel, should be left to you and the very few others who are competent to discuss the matter with authority".

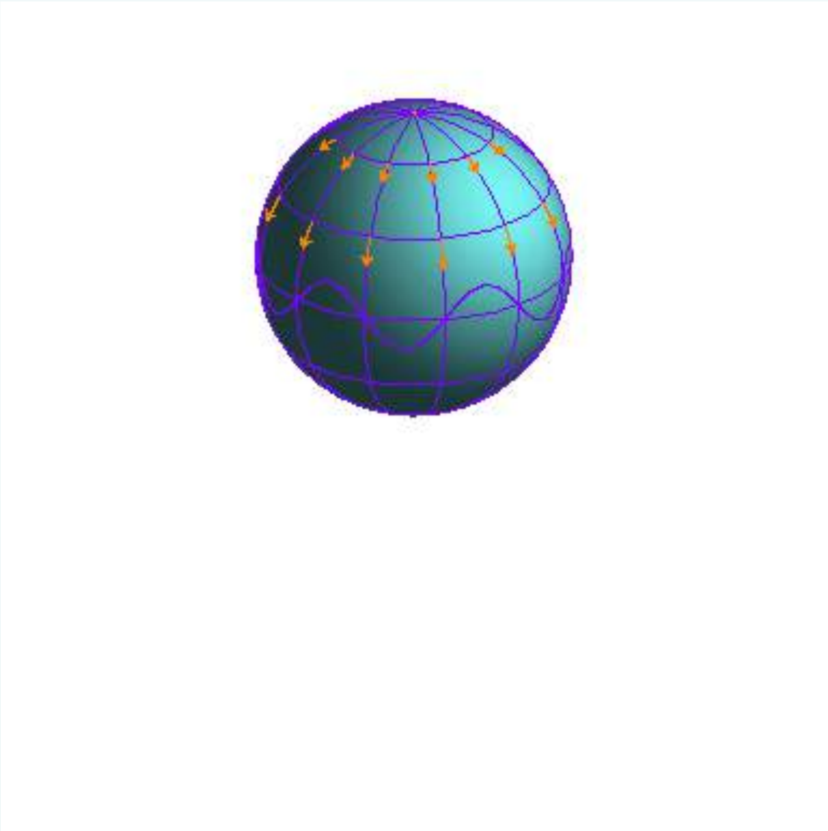


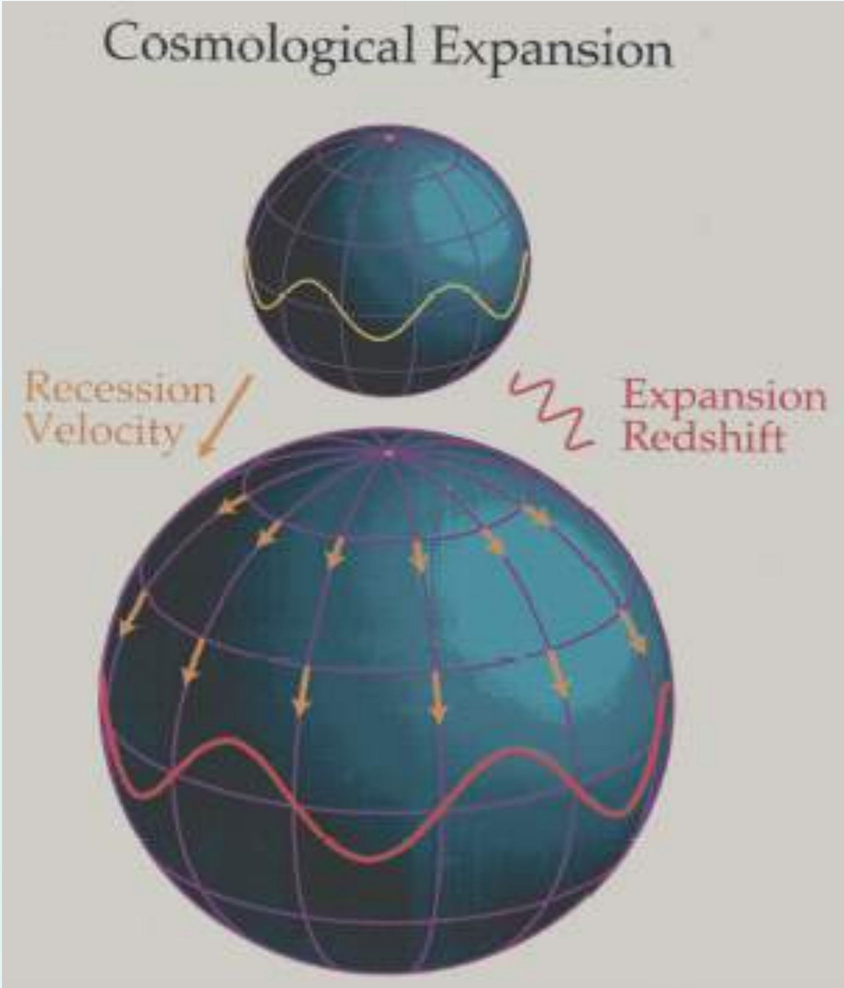
(2002)

The redshift of distant galaxies is *not* a Doppler effect

… it occurs because the wavelength of light is apparently increased by the stretching of space-time (aka 'expansion of the universe')

$$\lambda_{observed}/\lambda_{emitted} = 1 + z = r_{observed}/r_{emitted}$$

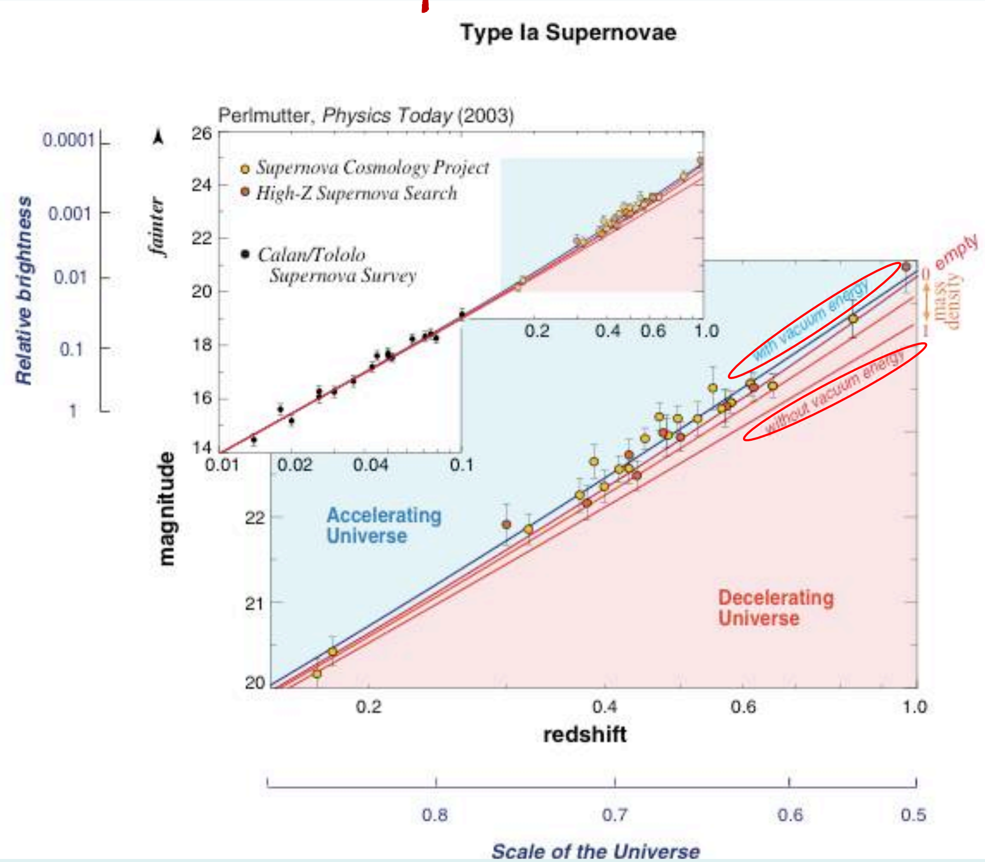


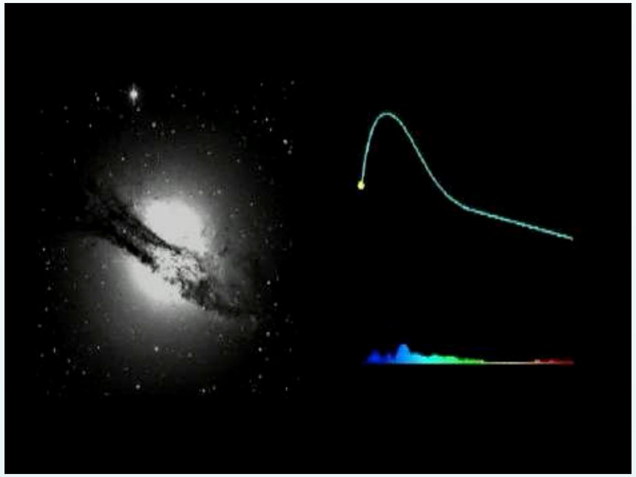


This picture also makes it clear that the expansion has *no* 'centre'

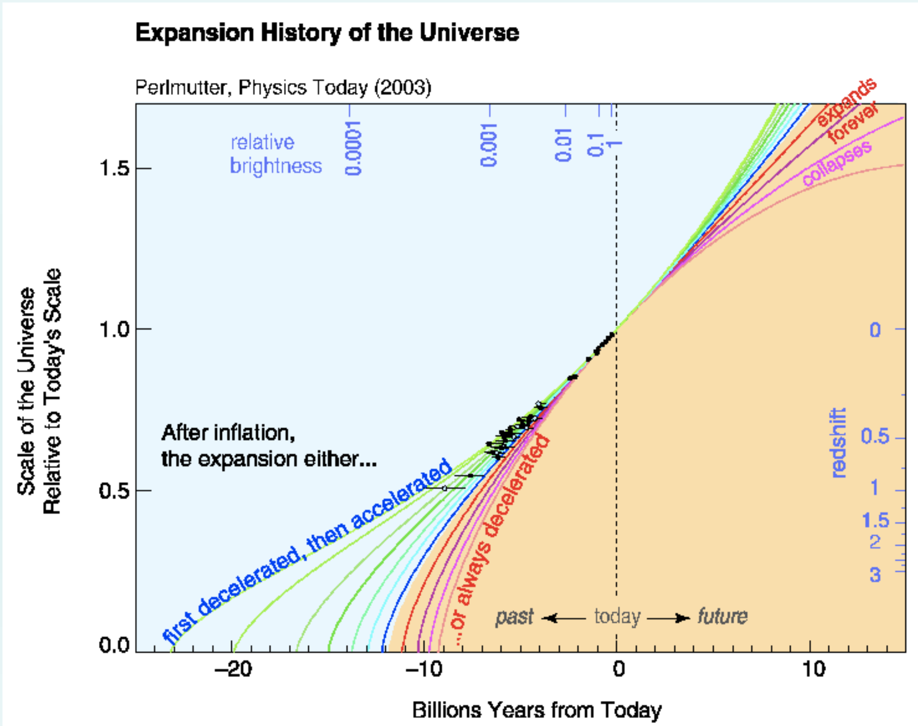
1998: Distant SNIa appear fainter than expected for "standard candles" in a decelerating universe

… interpreted as ⇒ 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 such 'evidence'



Standard cosmological model

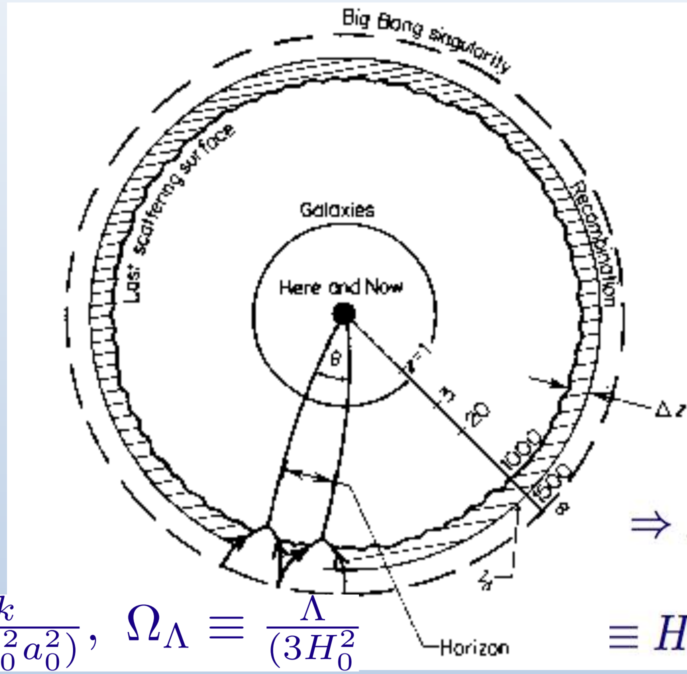
The universe is isotropic + homogeneous (when averaged on ‘large’ scales)

⇒ Maximally-symmetric space-time + ideal fluid energy-momentum tensor

$$ds^2 \equiv g_{\mu\nu} dx^\mu dx^\nu$$
$$= a^2(\eta)\left[d\eta^2 - d\bar{x}^2\right]$$
$$a^2(\eta) d\eta^2 \equiv dt^2$$

Robertson-Walker

$$\ddot{a} = -\frac{4\pi G}{3}(\rho + 3P)\, a$$



$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \lambda g_{\mu\nu}$$

Einstein $= 8\pi G_{\rm N} T_{\mu\nu}$

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

$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\rm N}\rho_{\rm m}}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$
$$\equiv H_0{}^2\left[\Omega_{\rm m}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

$$\Omega_{\rm m} \equiv \frac{\rho_{\rm m}}{(3H_0^2/8\pi G_{\rm N})},\quad \Omega_k \equiv \frac{k}{(3H_0^2 a_0^2)},\quad \Omega_\Lambda \equiv \frac{\Lambda}{(3H_0^2}$$

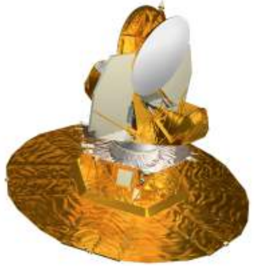
So the **Friedmann-Lemaitre equation** ⇒ ‘cosmic sum rule’: $\mathbf{\Omega_m + \Omega_k + \Omega_\Lambda = 1}$

We observe ~zero curvature (CMB) + insufficient matter to make up critical density ($\Omega_{\rm m} \sim 0.3$)

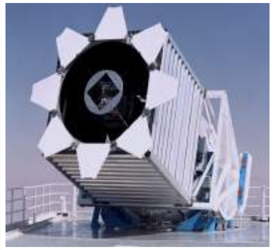
➞ infer universe is *dominated* by **dark energy**: $\mathbf{\Omega_\Lambda = 1 - \Omega_m - \Omega_k \sim 0.7 \Rightarrow \Lambda \sim 2H_0^2}$

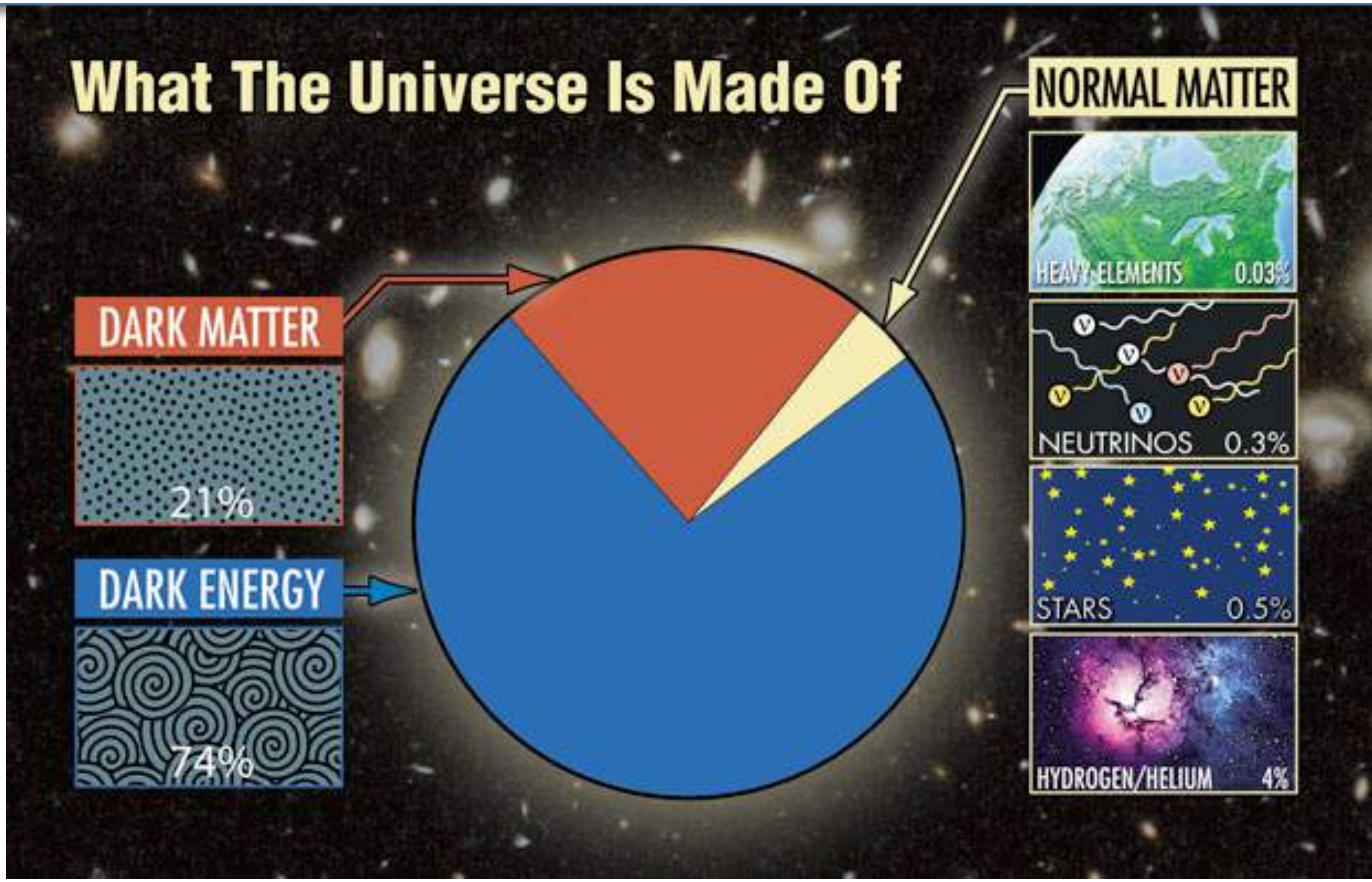
To drive *accelerated* expansion requires the pressure to be *negative* ($P < -\rho/3$) so this is interpreted as *vacuum* energy at the scale $(\rho_\Lambda)^{1/4} = (H_0^2/8\pi G_{\rm N})^{1/4} \sim 10^{-12}$ GeV << $G_{\rm F}^{-1/2} \sim 10^2$ GeV

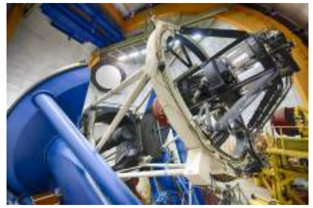
This makes *no* physical sense … exacerbates the (old) Cosmological Constant problem!

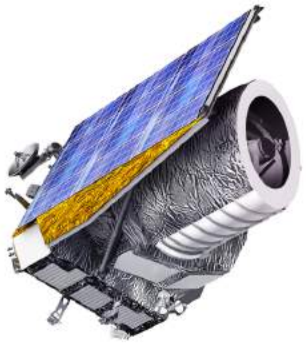


Since 1998 (Riess *et al.*[1], Perlmutter *et al.*[2]), surveys of cosmologically distant Type Ia supernovae (SNe Ia) have indicated an acceleration of the expansion of the Universe, distant SNe Ia being dimmer that expected in a decelerating Universe. With the assumption that the Universe can be described on average as isotropic and homogeneous, this acceleration implies either the existence of a fluid with negative pressure usually called "Dark Energy", a constant in the equations of general relativity or modifications of gravity on cosmological scales.

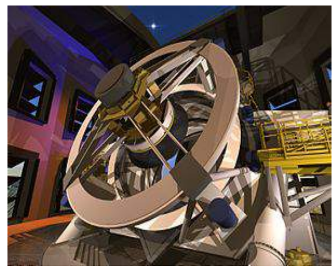




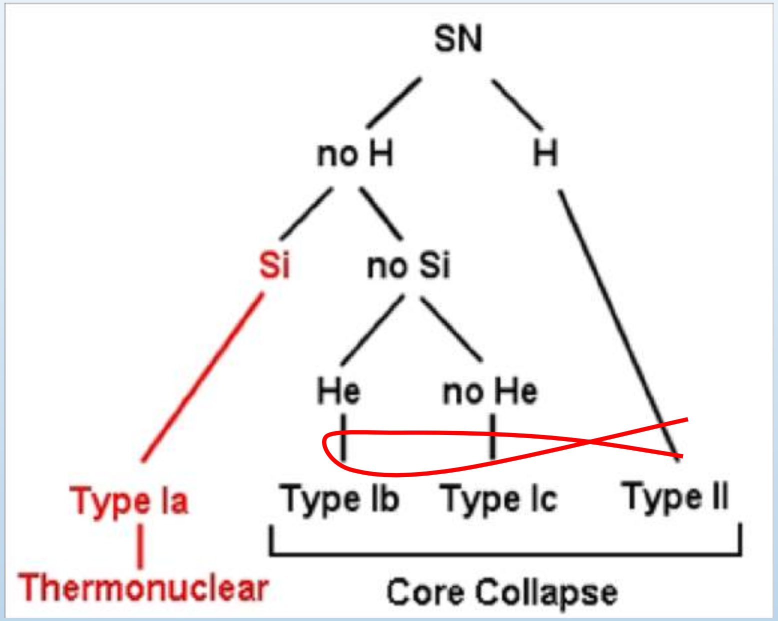


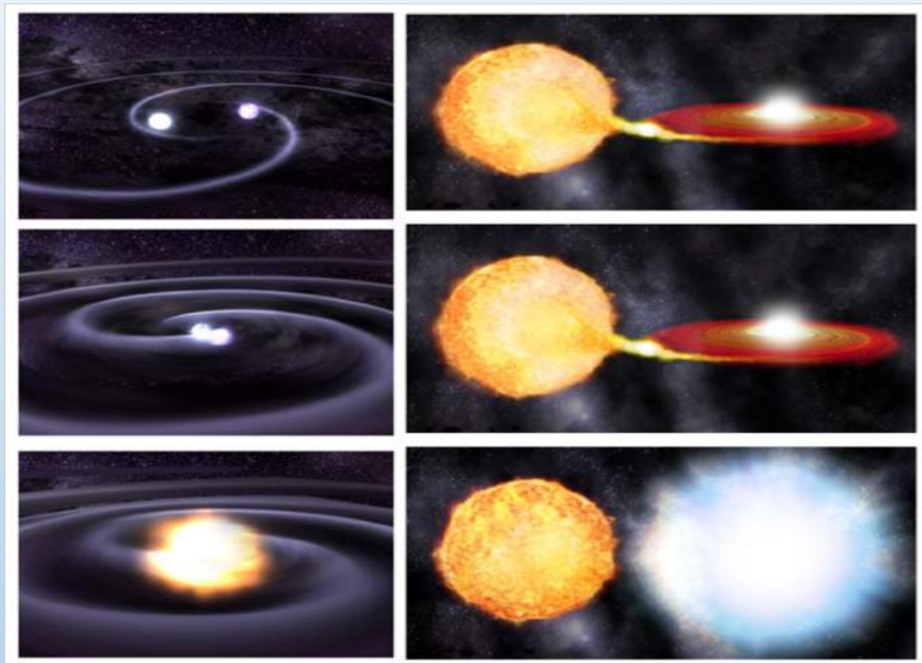


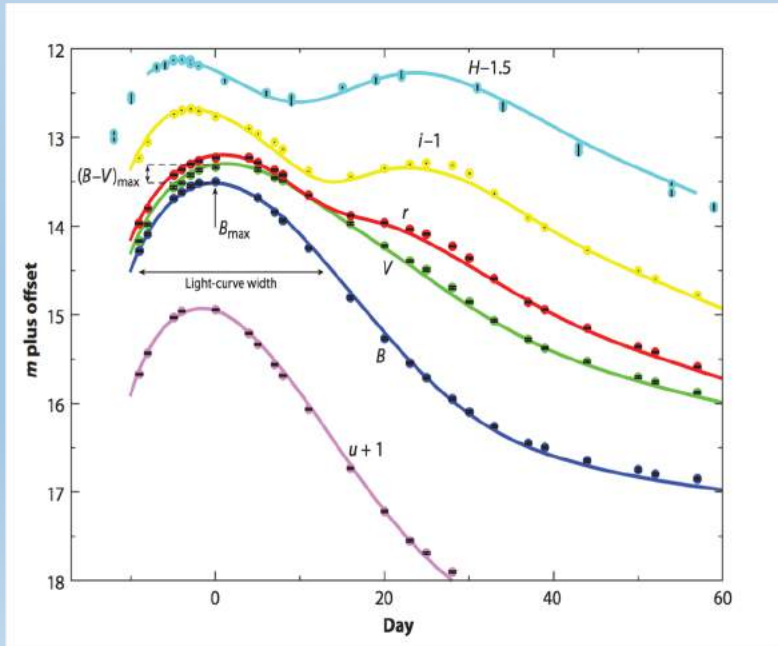
There has been substantial investment in major satellites and telescopes to *measure the parameters* of the 'standard cosmological model' with increasing 'precision'… but surprisingly little work on ***testing its foundational assumptions***



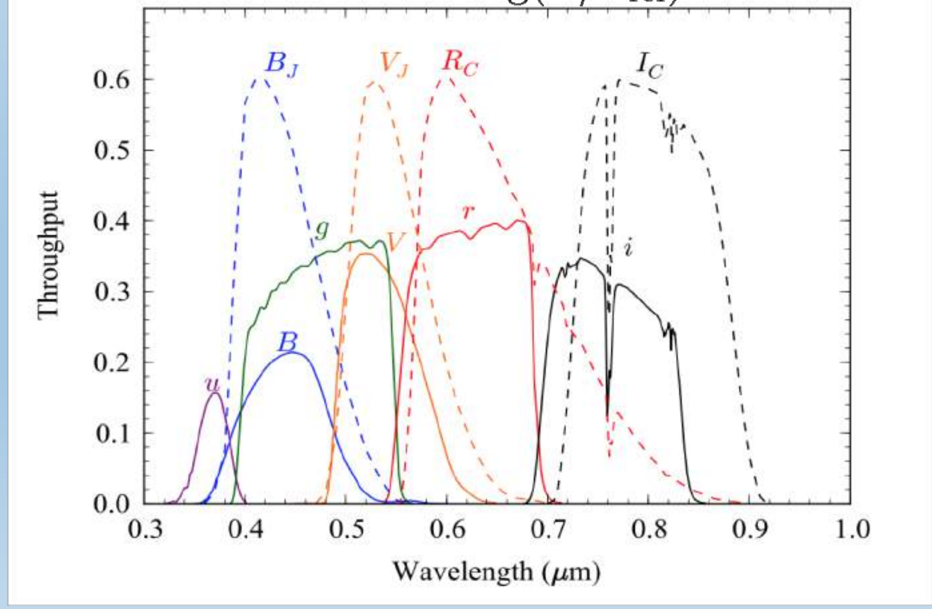
What are Type Ia supernovae?





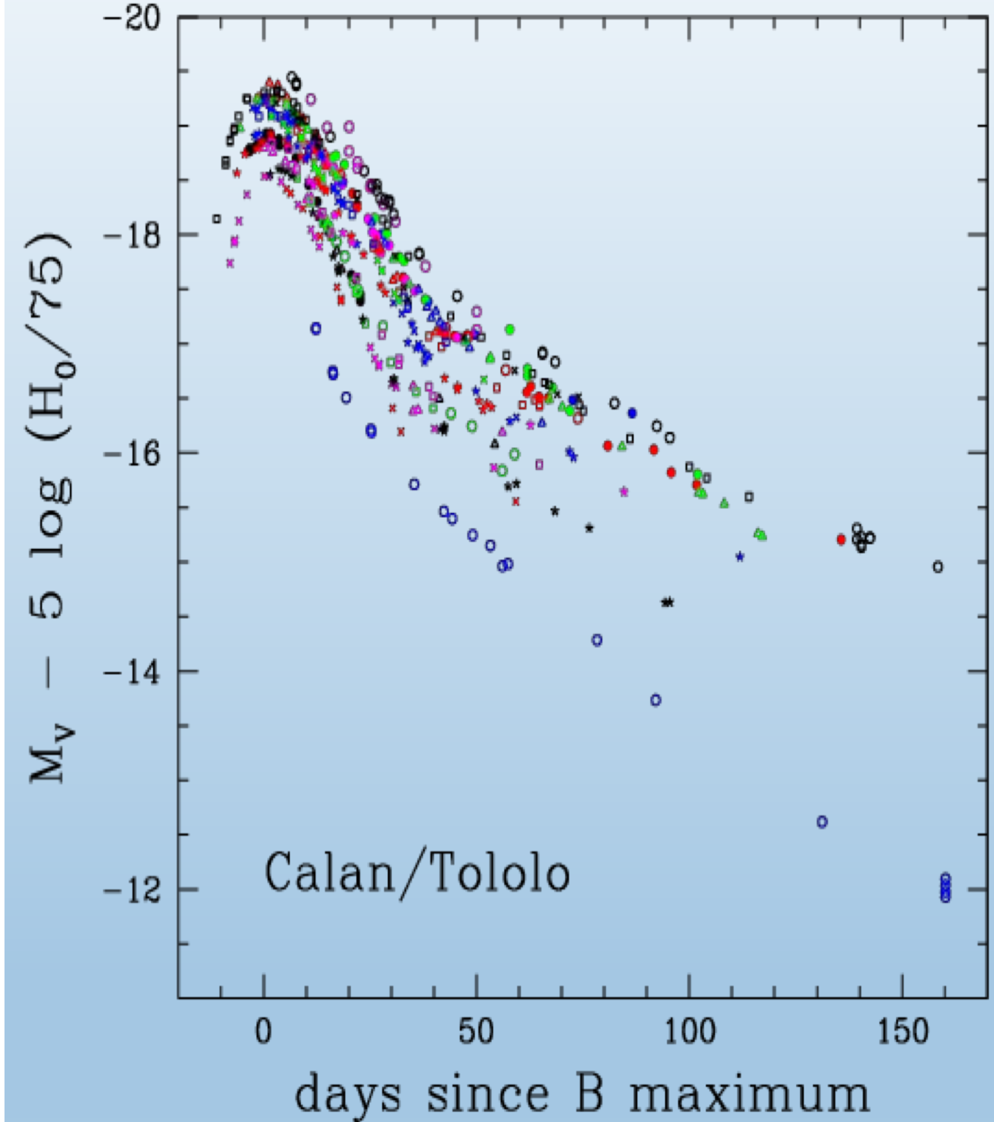


$$m = -2.5 \log(F/F_{\rm ref})$$

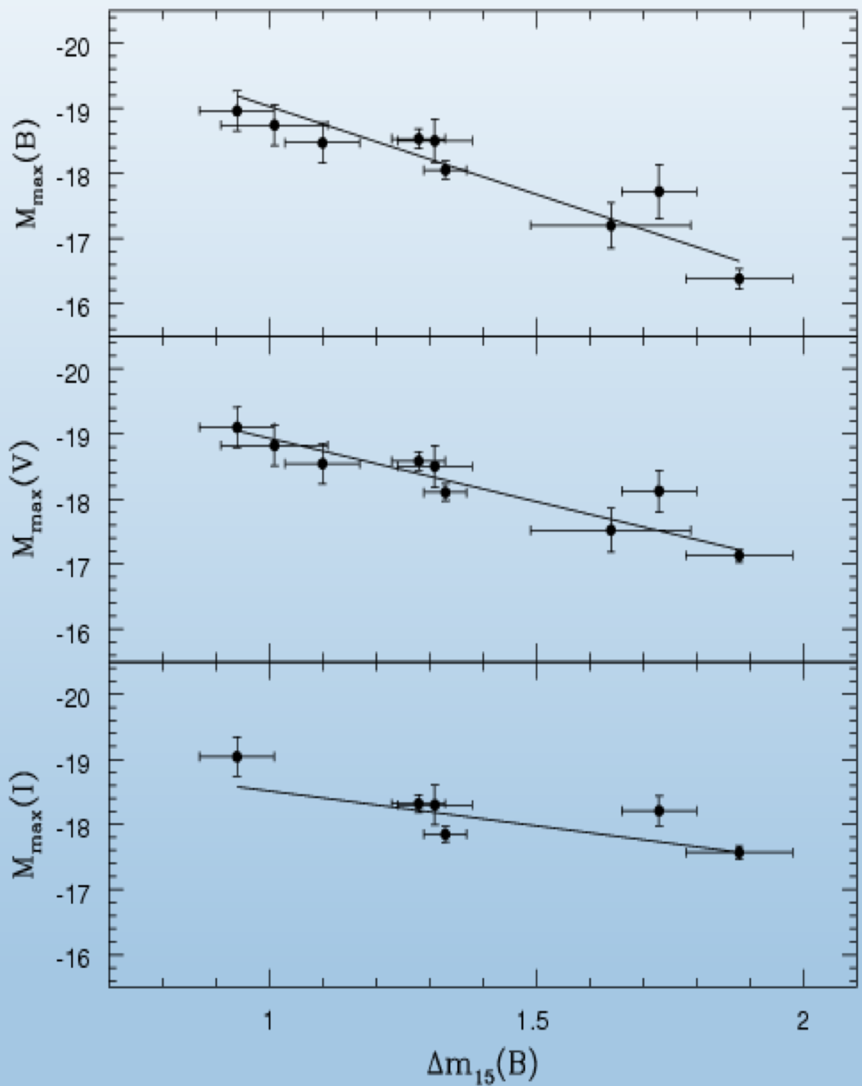


Goobar & Leibundgut, arXiv:1102.1431

They are certainly *not* 'standard candles'



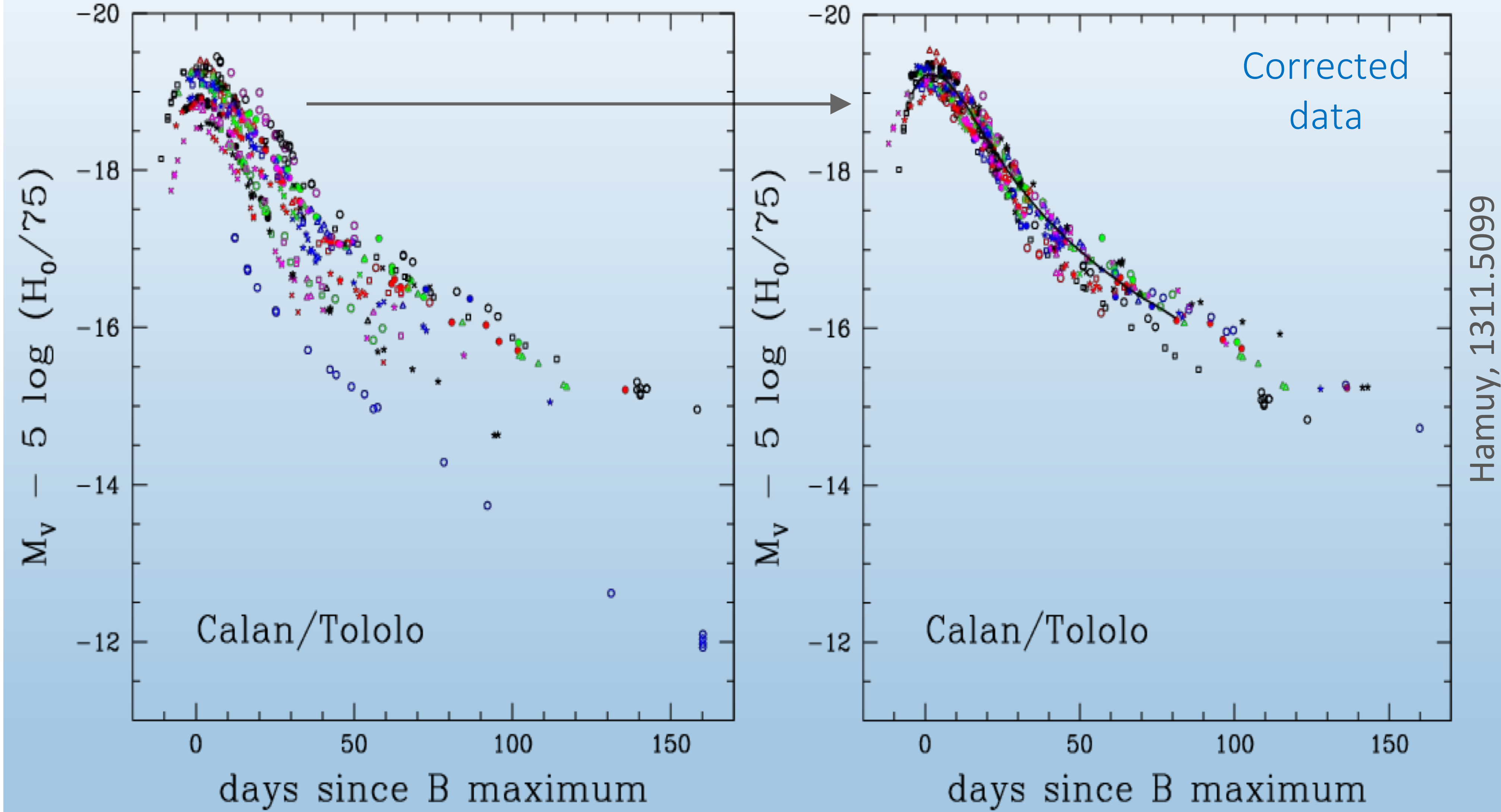
Hamuy, arXiv:311.5099



Phillips, ApJ 413:L105, 1993

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

Type Ia supernovae as 'standardisable candles'



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

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

Cosmology with Type Ia supernovae

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

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

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

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

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

Distance modulus

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

So can extract cosmological parameters from the **magnitude-redshift relationship**

Acceleration is a *kinematic* quantity so can also analyse the data without assuming a model, by expanding the time variation of the scale factor in a Taylor series:

$q_0 \equiv -(\ddot{a}a)/\dot{a}^2$ $\quad$ $j_0 \equiv (\dddot{a}/a)(\dot{a}/a)^{-3}$ $\quad$ (e.g. Visser, CQG **21**:2603,2004)

$$d_L(z) = \frac{c\,z}{H_0}\left\{1 + \frac{1}{2}[1-q_0]\,z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 + \frac{kc^2}{H_0^2\,a_0^2}\right]z^2 + O(z^3)\right\}$$

Spectral Adaptive Lightcurve Template

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

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

B-band

SALT 2 parameters

Betoule et al., A&A **568**:A22,2014

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

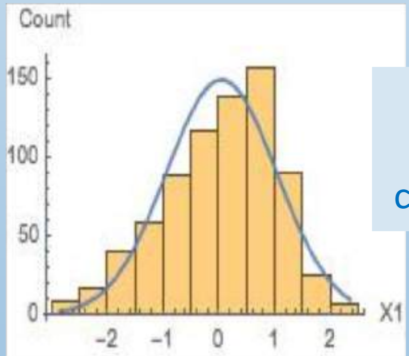
The host galaxy mass turns out not to be relevant in the fitting exercise …
but there may well be other variables that the magnitude correlates with

Construct a Maximum Likelihood Estimator

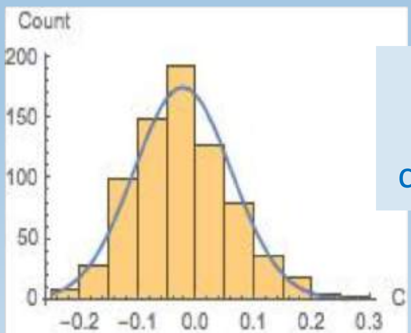
$$\mathcal{L} = \text{probability density}(\text{data}|\text{model})$$

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

Well-approximated as Gaussian



JLA data 'Stretch' corrections



JLA data 'Colour' corrections

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

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

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

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

Nielsen, Guffanti & Sarkar, Sci.Rep. **6**:35596,2016

Likelihood

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

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

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

Intrinsic distributions

cosmology

SALT2

Confidence regions

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

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

1,2,3 σ

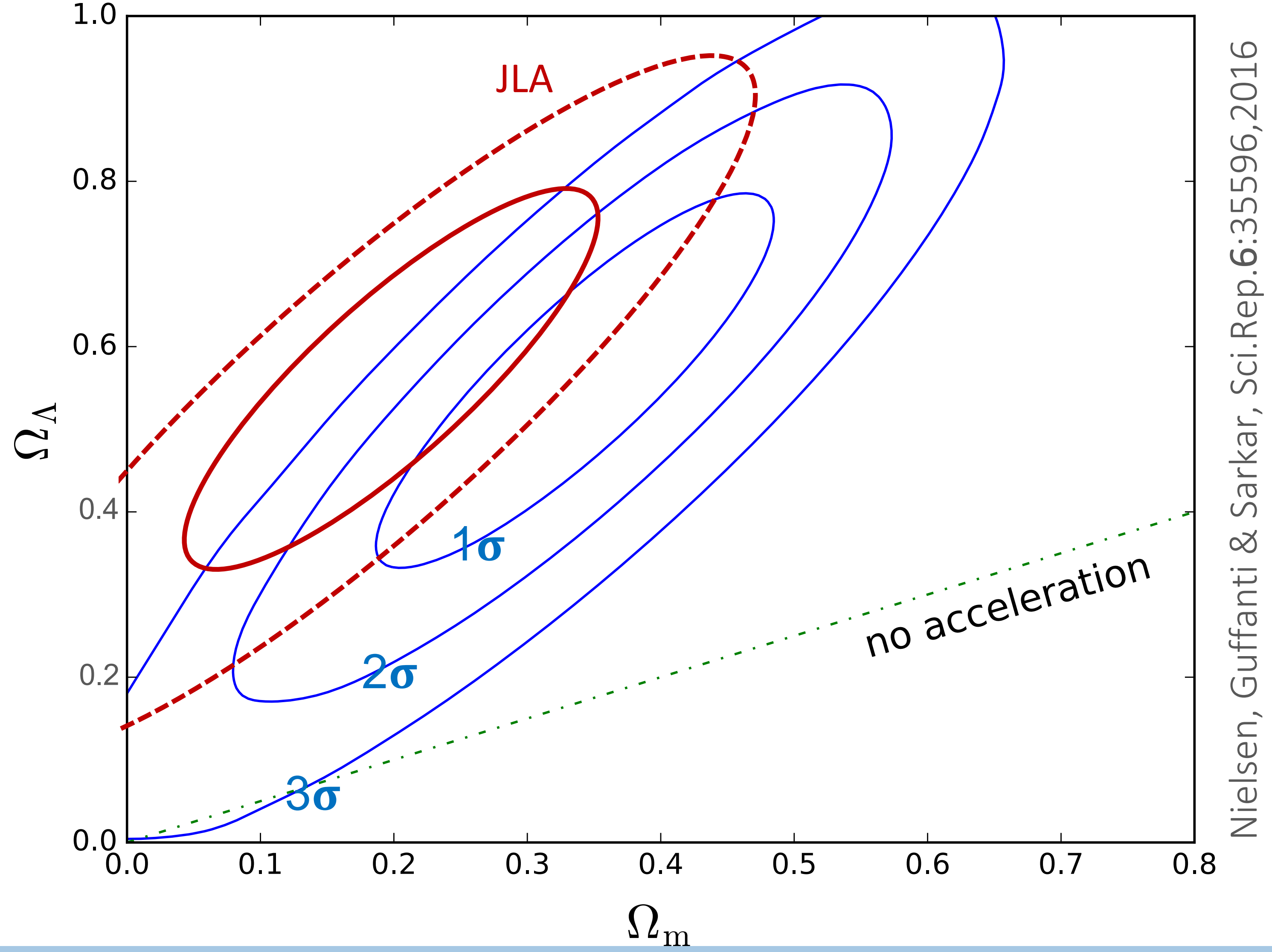
solve for Likelihood value

Nielsen, Guffanti & Sarkar,
Sci.Rep. **6**:35596,2016

But what previous authors (e.g. Betoule *et al* 2014) have done is to adjust σ_{int} to get chi-squared of 1 per d.o.f. for the fit to ΛCDM! So we get a rather different result …

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

Data is consistent with *no* acceleration @2.8σ!



Profile Likelihood

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

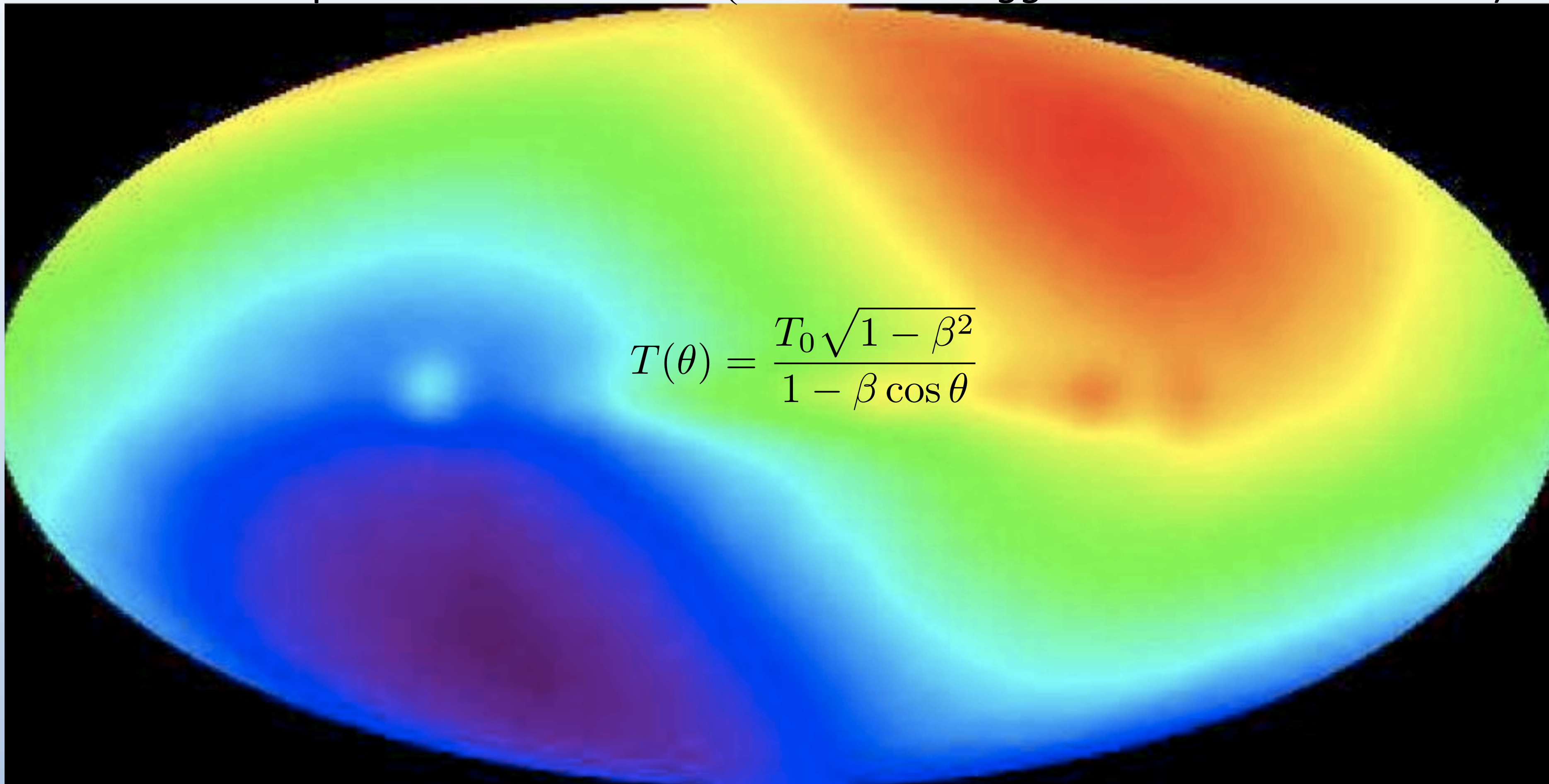
Ω_M	0.341
Ω_Λ	0.569
α	0.134
x_0	0.038
σ^2_{x0}	0.931
β	3.058
c_0	-0.016
σ^2_{c0}	0.071
M_0	-19.05
σ^2_{M0}	0.108

NB: We show the result in the Ω_m-Ω_Λ plane for comparison with previous results (JLA) simply to emphasise that the statistical analysis has *not* been done correctly earlier

(Other constraints e.g. $\Omega_M \gtrsim 0.2$ or $\Omega_M + \Omega_\Lambda \simeq 1$ are relevant *only* to the ΛCDM model)

We have assumed isotropy but the CMB sky is in fact quite anisotropic

There is a a dipole with $\Delta T/T \sim 10^{-3}$ (~100 times *bigger* than the fluctuations)



$$T(\theta) = \frac{T_0\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$

Stewart & Sciama 1967, Peebles & Wilkinson 1968

This is *interpreted* as due to our motion at 370 km/s wrt the frame in which the CMB is truly isotropic ⇒ motion of the Local Group at 620 km/s towards *l*=271.9°, *b*=29.6°

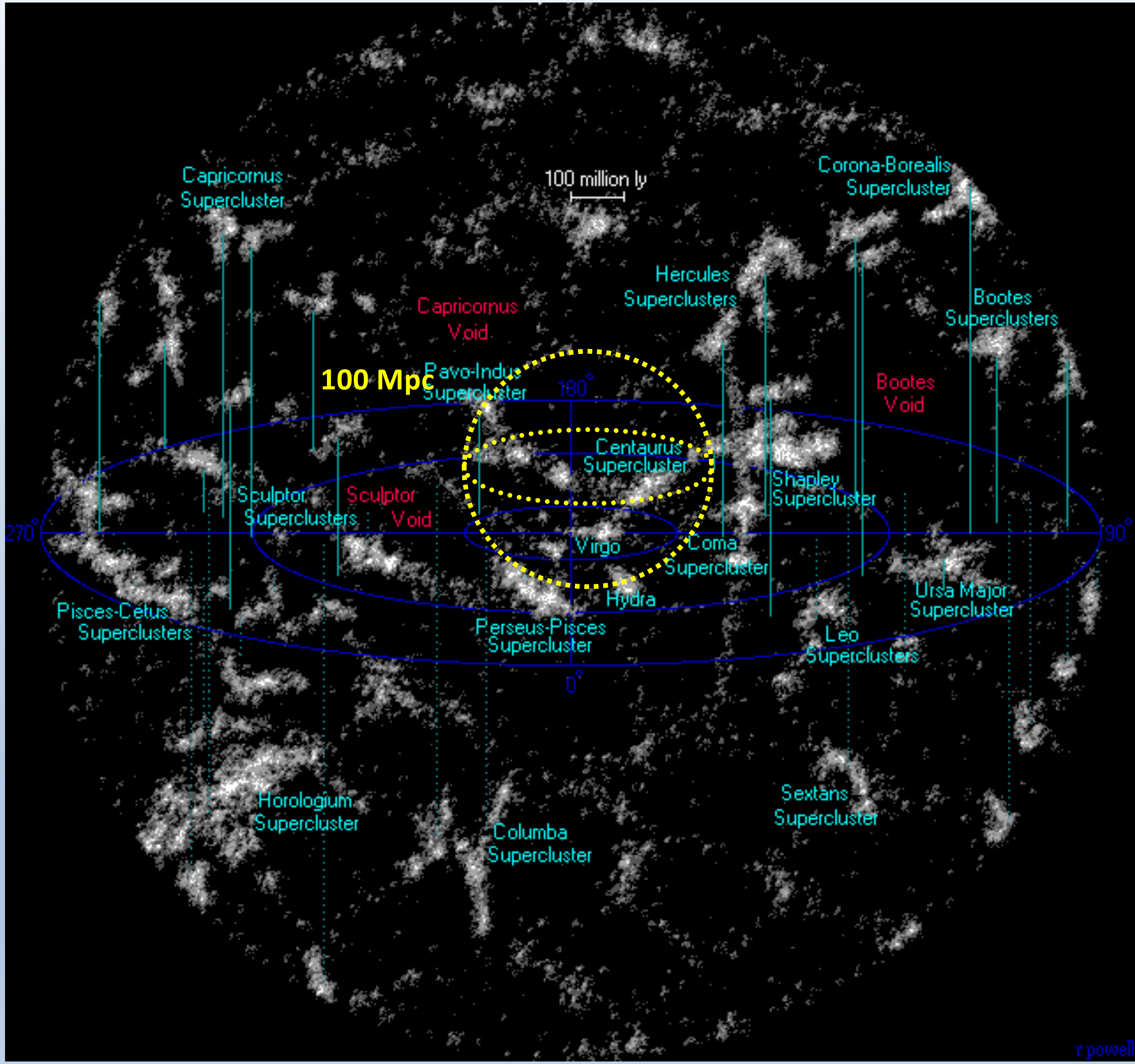
This motion is *presumed* to be due to local inhomogeneity in the matter distribution

Its scale – beyond which we converge to the CMB frame – is supposedly of *O*(100) Mpc

(Counts of galaxies in the SDSS & WiggleZ surveys are said to scale as r^3 on larger scales)

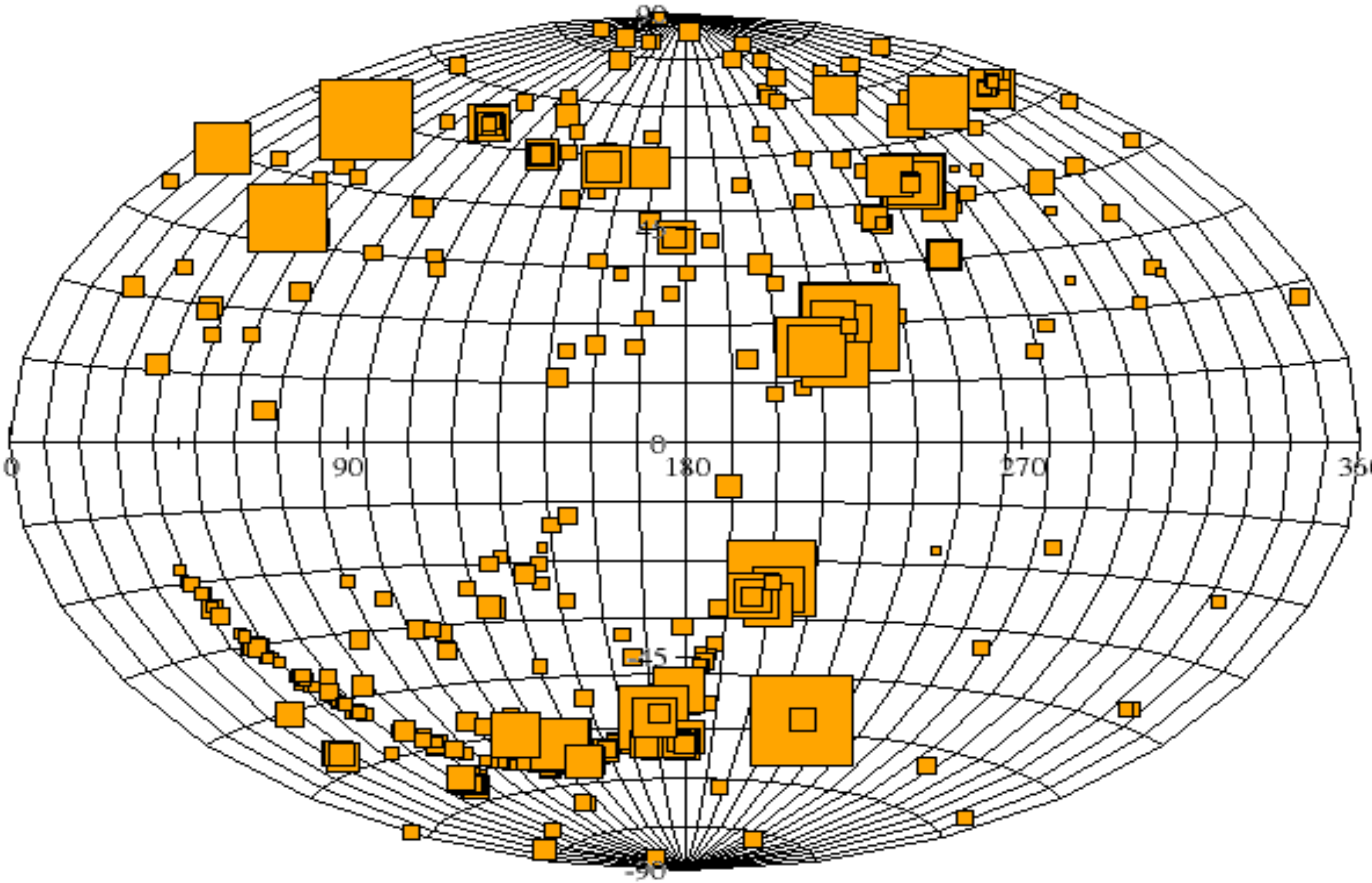
This is what our universe *actually* looks like locally (out to ~300 Mpc)

We are moving towards the Shapley supercluster supposedly due to a 'Great Attractor'



We are *not* comoving ('Copernican') observers .. as is generally assumed

Union 2 compilation of 557 SNe Ia



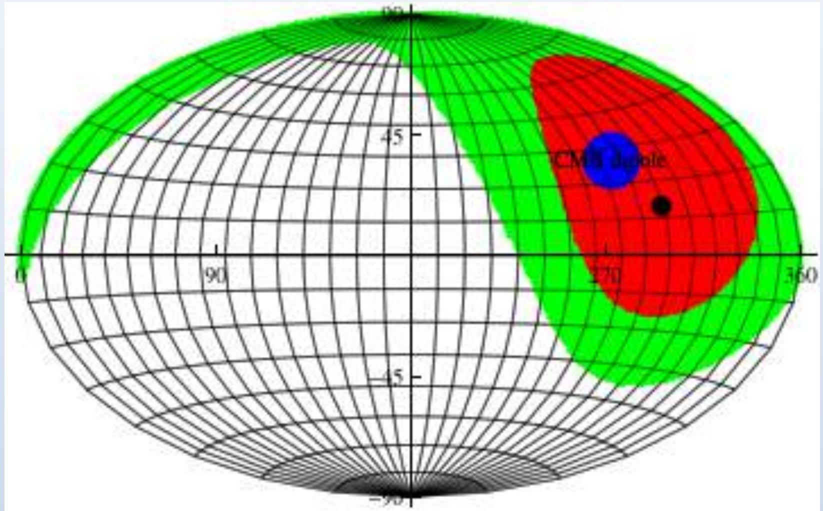
Aitoff-Hammer plot, Galactic coordinates

We perform *tomography* of the Hubble flow by testing if the supernovae are at the expected Hubble distances: **Residuals ⇒ 'peculiar velocity' flow in local universe**

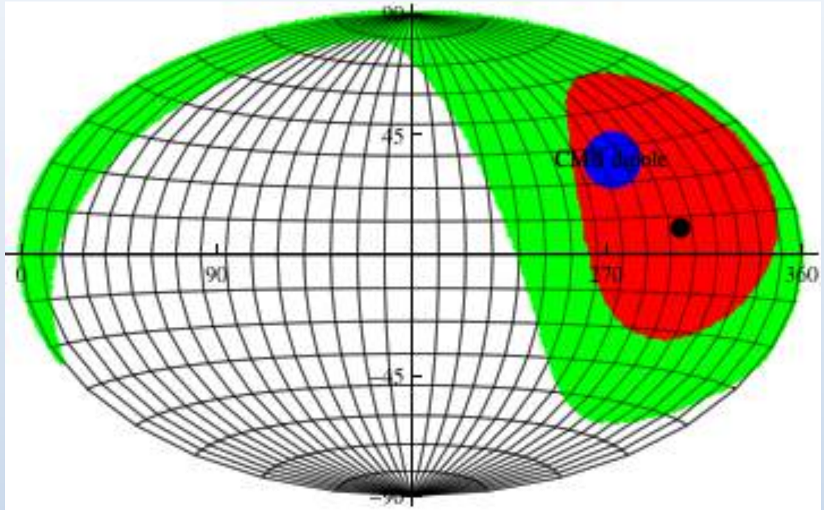
Colin, Mohayaee, Sarkar & Shafieloo, MNRAS **414**:264,2011

This reveals a dipole in the SN Ia velocity field *aligned* with the CMB Dipole

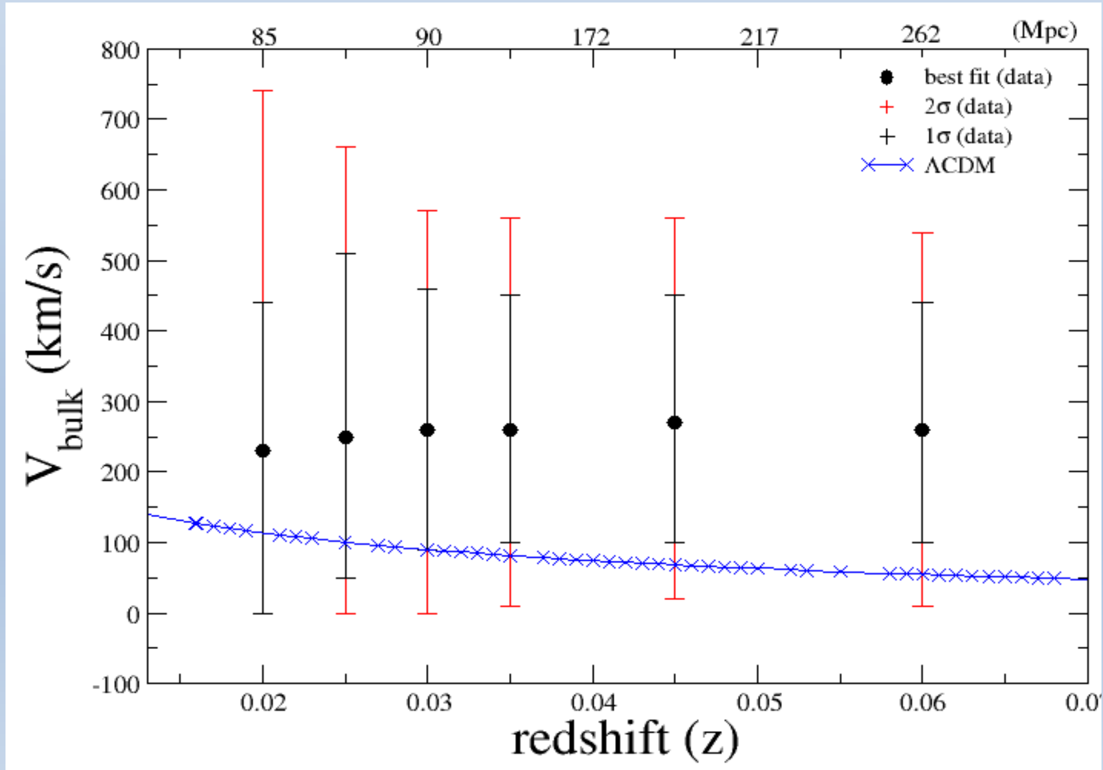
$0.015 < z < 0.045$, $v = 270$ km/s, $l = 291$, $b = 15$



$0.015 < z < 0.06$, $v = 260$ km/s, $l = 298$, $b = 8$



Colin *et al*, MNRAS **414**:264,2011

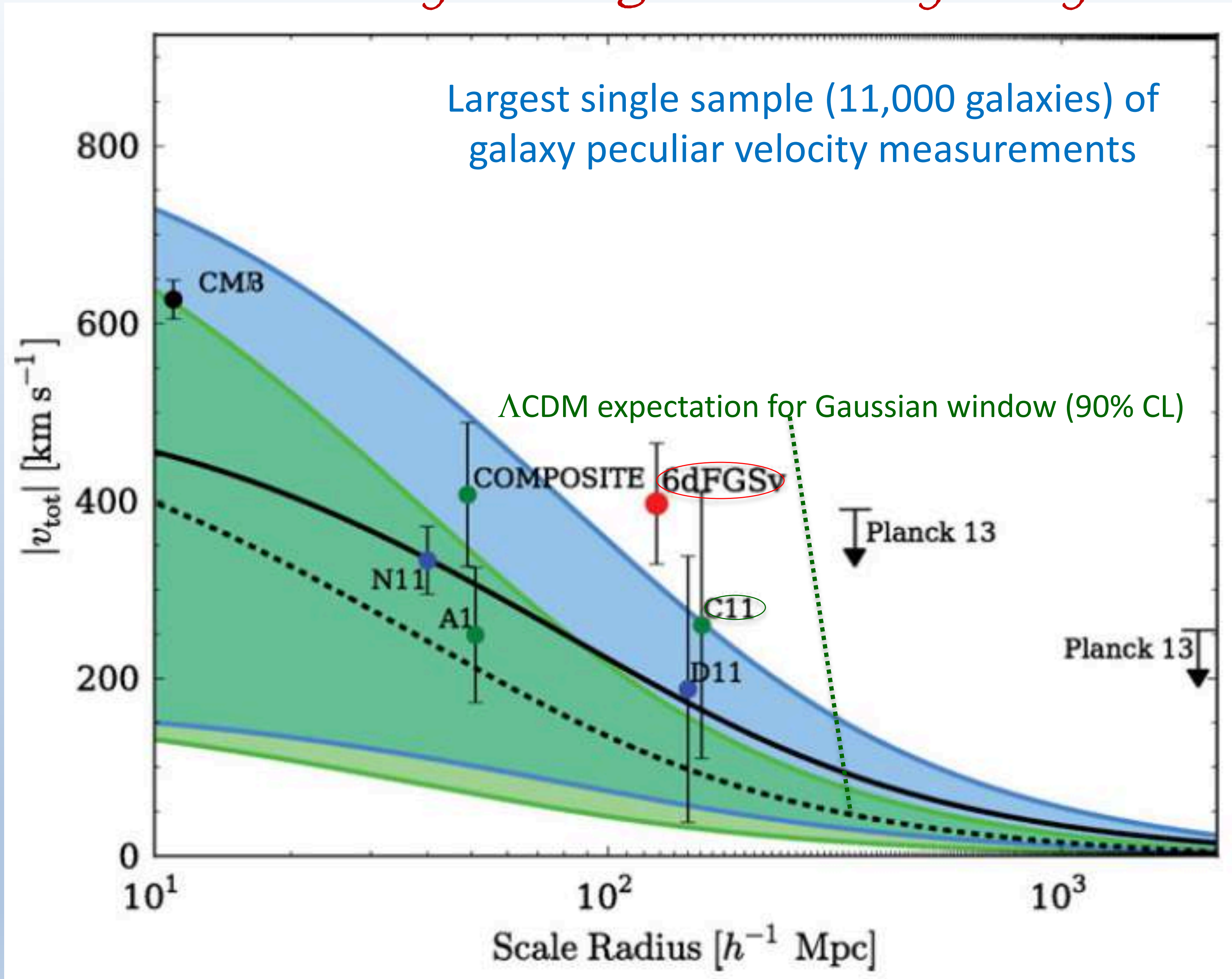


This is ≳1σ higher than expected for the standard ΛCDM model … and extends *beyond* Shapley (at 260 Mpc)

… consistent with Watkins *et al* (2009) who found a bulk flow of 416±78 km/s towards $b = 60 \pm 6^0$, $l = 282 \pm 11^0$ extending up to ~100 h^{-1} Mpc

No convergence to CMB frame, even well beyond 'scale of homogeneity'

Our result is confirmed by the 6-degree Field Galaxy Survey (6dFGSv)



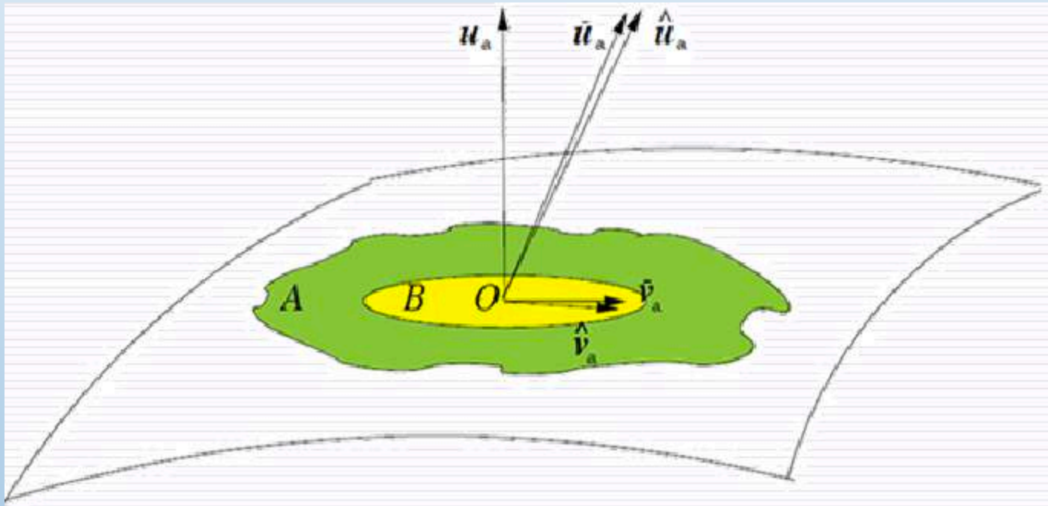
Magoulas, Springbob, Colless, Mould, et al (2016)

According to the 'Dark Sky' ΛCDM Hubble Volume simulations, *less than 1%* of Milky Way–like observers should experience a bulk flow as large as is observed, extending out as far as is seen

Do we infer acceleration even though the expansion is actually decelerating … because we are *inside* a local 'bulk flow'?

(Tsagas 2010, 2011, 2012; Tsagas & Kadiltzoglou 2015)

… if so then we would expect to see a dipole asymmetry in the inferred deceleration parameter in the same direction – i.e. *aligned* with the CMB dipole



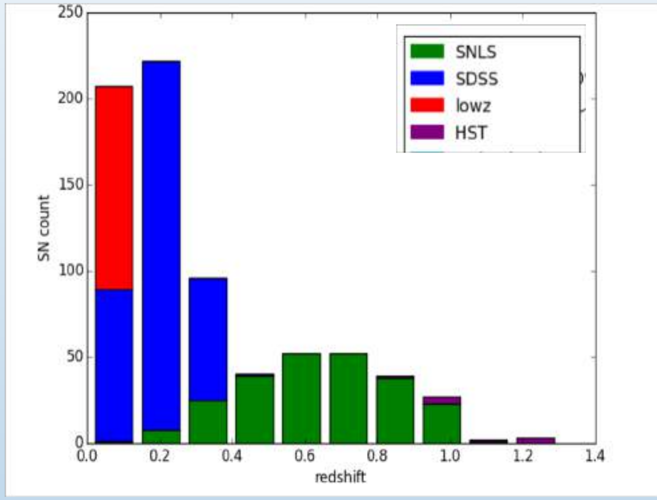
The patch A has mean peculiar velocity $\tilde{v}_a$ with $\vartheta = \tilde{\mathrm{D}}^a v_a \gtrless 0$ and $\dot{\vartheta} \gtrless 0$
(the sign depending on whether the bulk flow is faster or slower than the surroundings)

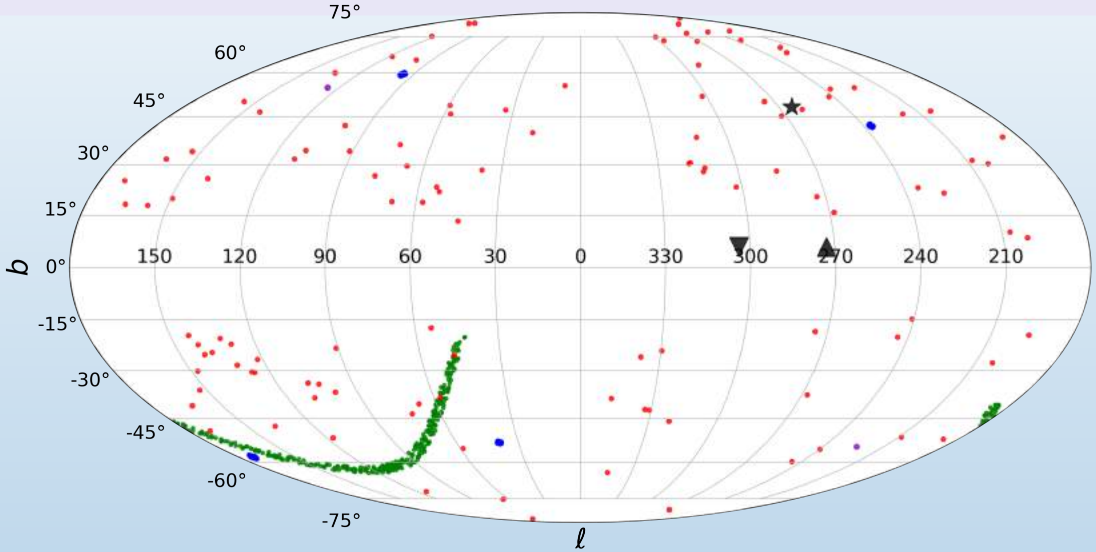
Inside region B, the r.h.s. of the expression

$$1 + \tilde{q} = (1+q)\left(1 + \frac{\vartheta}{\Theta}\right)^{-2} - \frac{3\dot{\vartheta}}{\Theta^2}\left(1 + \frac{\vartheta}{\Theta}\right)^{-2}, \qquad \tilde{\Theta} = \Theta + \vartheta,$$

drops below 1 and the comoving observer 'measures' *negative* deceleration parameter

Sky distribution of the 4 sub-samples of the JLA catalogue in Galactic coordinates:
SDSS (red dots), SNLS (blue dots), low redshift (green dots) and HST (black dots).
CMB dipole (star), SMAC bulk flow (triangle), 2M++ bulk flow (inverted triangle)

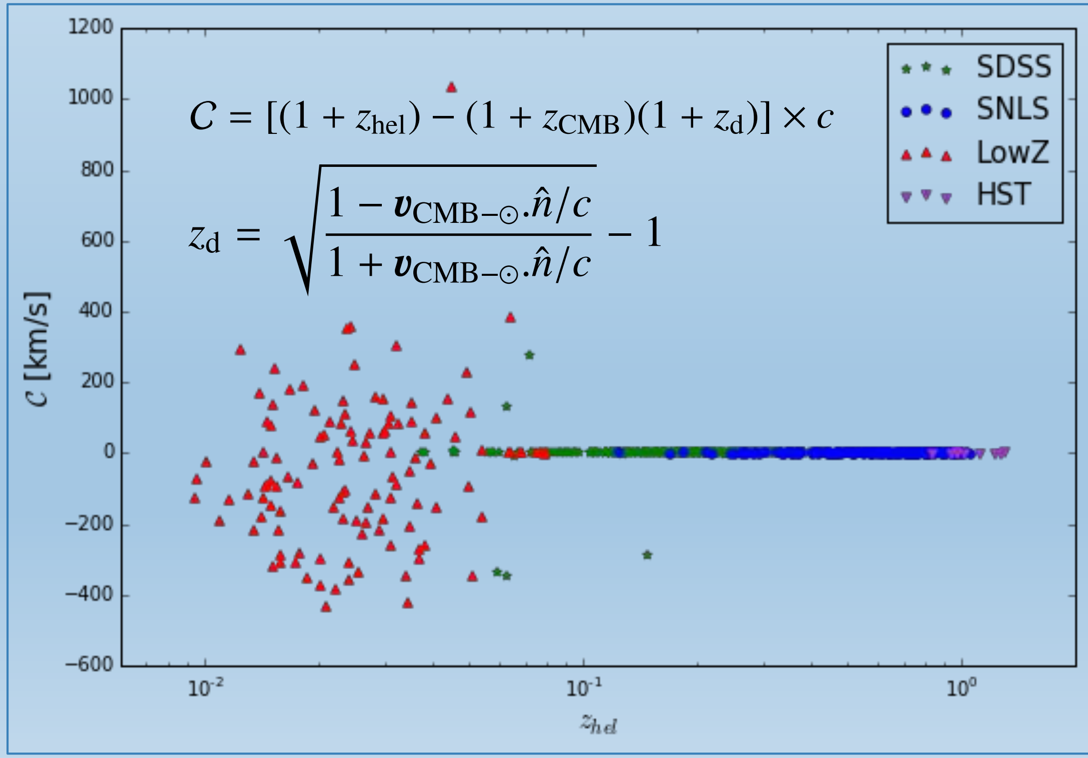




Subsequently we realised that the peculiar velocity `corrections' applied to the JLA catalogue are suspect … the bulk flow had been assumed to drop to zero at ~150 Mpc - although it is observed to continue to > 300 Mpc.

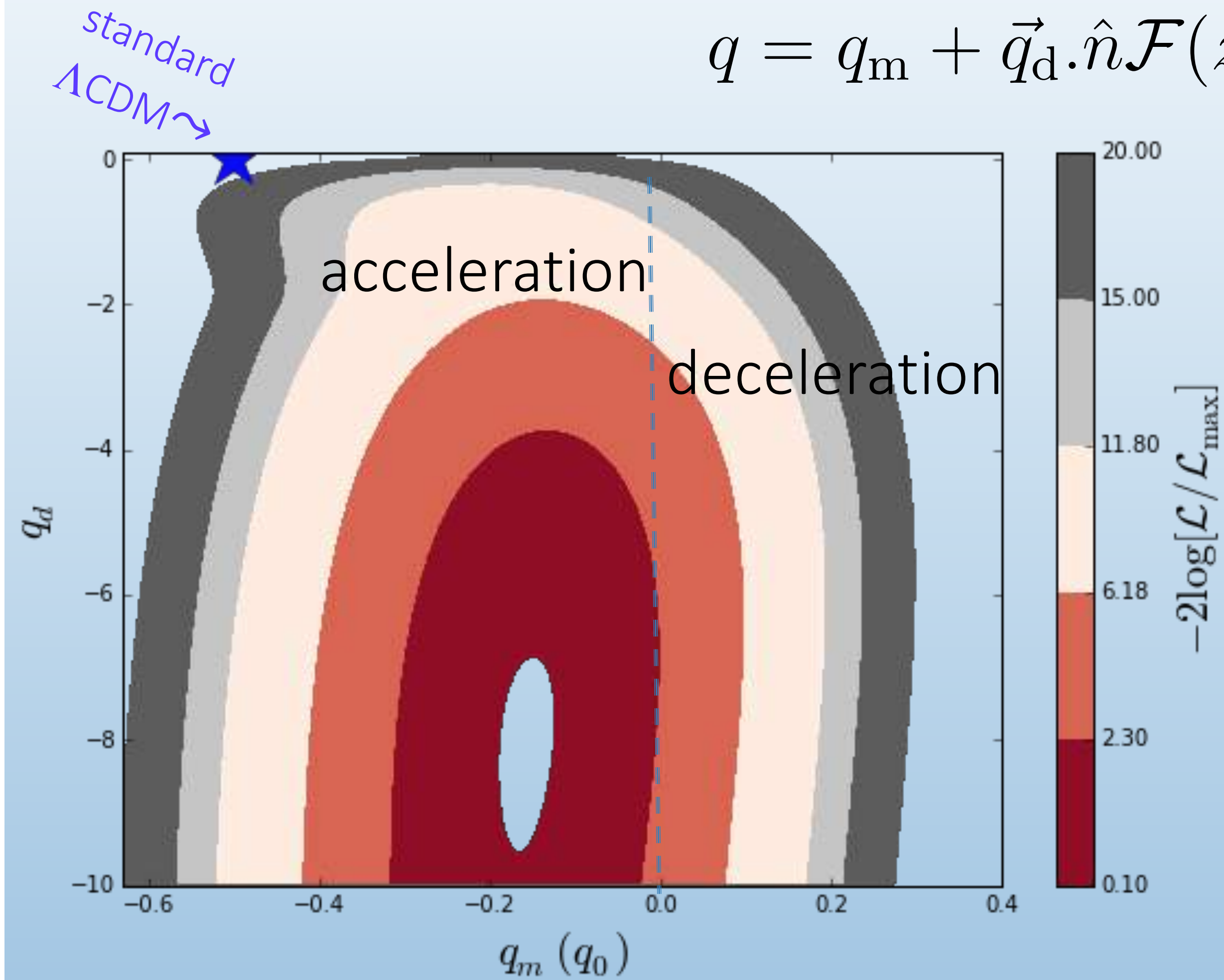
So we *undid* the corrections to recover the original data and test for isotropy … with some rather surprising findings

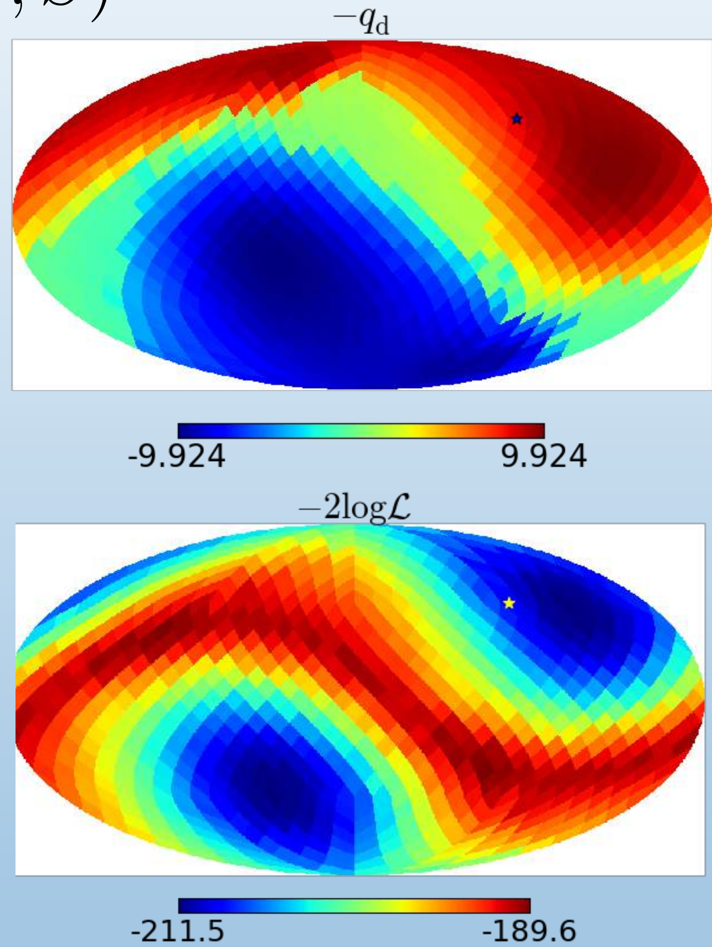
Colin *et al*, arXiv:1808.04597



If we now analyse the JLA catalogue allowing for a dipole, we find the MLE *prefers* one (50 times *bigger* than the monopole) … in the direction of the CMB dipole

$$q = q_{\mathrm{m}} + \vec{q}_{\mathrm{d}}.\hat{n}\mathcal{F}(z, S)$$





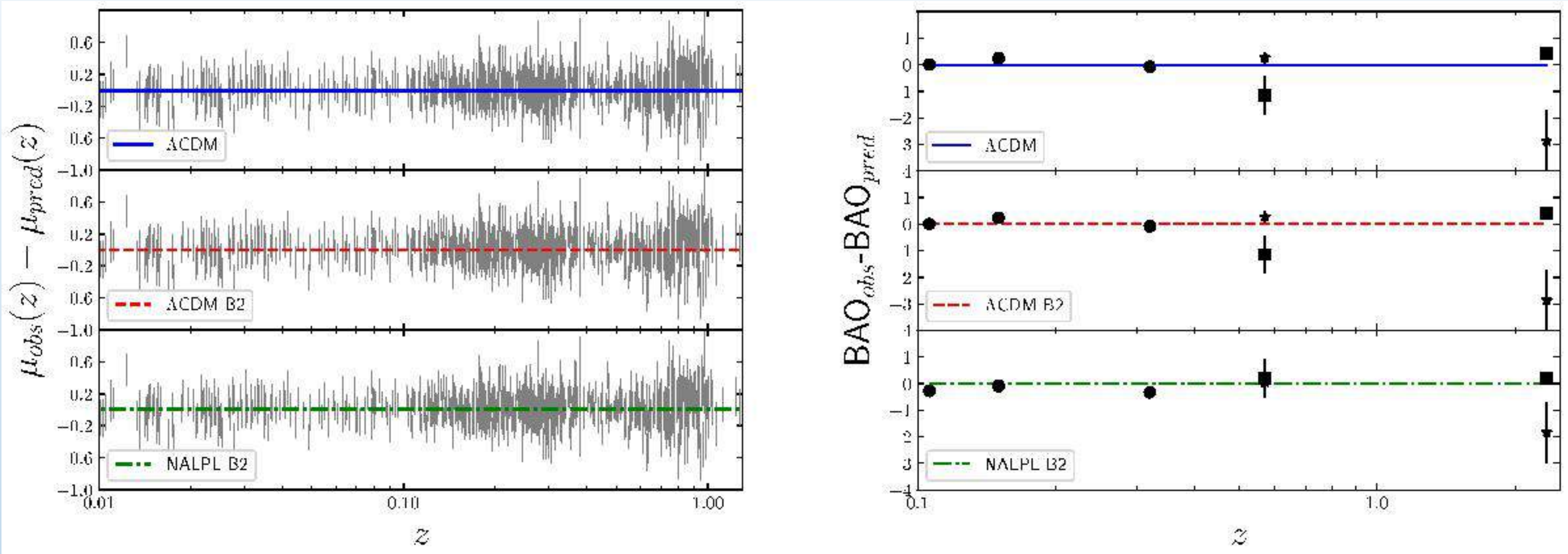
Colin, Mohayaee, Rameez & Sarkar, arXiv:1808.04597, A&A in press

The significance of q_{m} being negative has now *decreased* to only 1.4σ

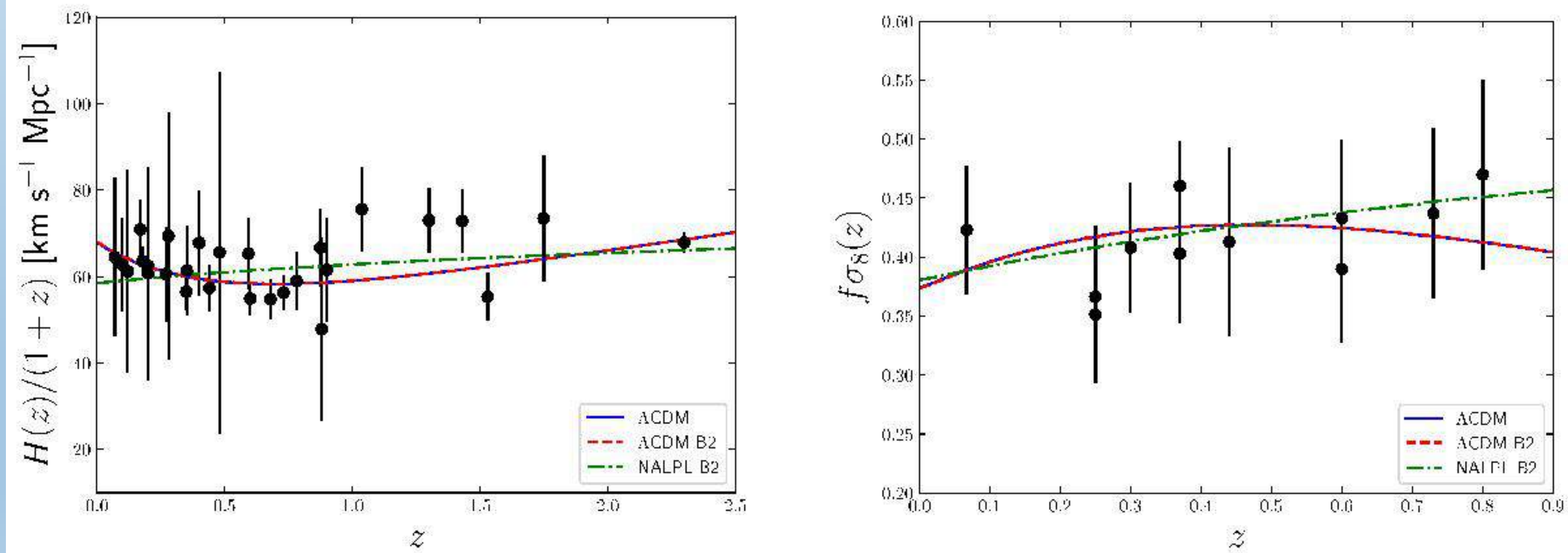
(in fact the best-fit by the Bayesian information criterion is $q_{\mathrm{m}} = 0$)

This suggests that cosmic acceleration is an artefact of our being located inside a local 'bulk flow' (which includes ~3/4 of the observed SNe Ia)

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



The 'independent' lines of evidence are obtained **using ΛCDM templates**!

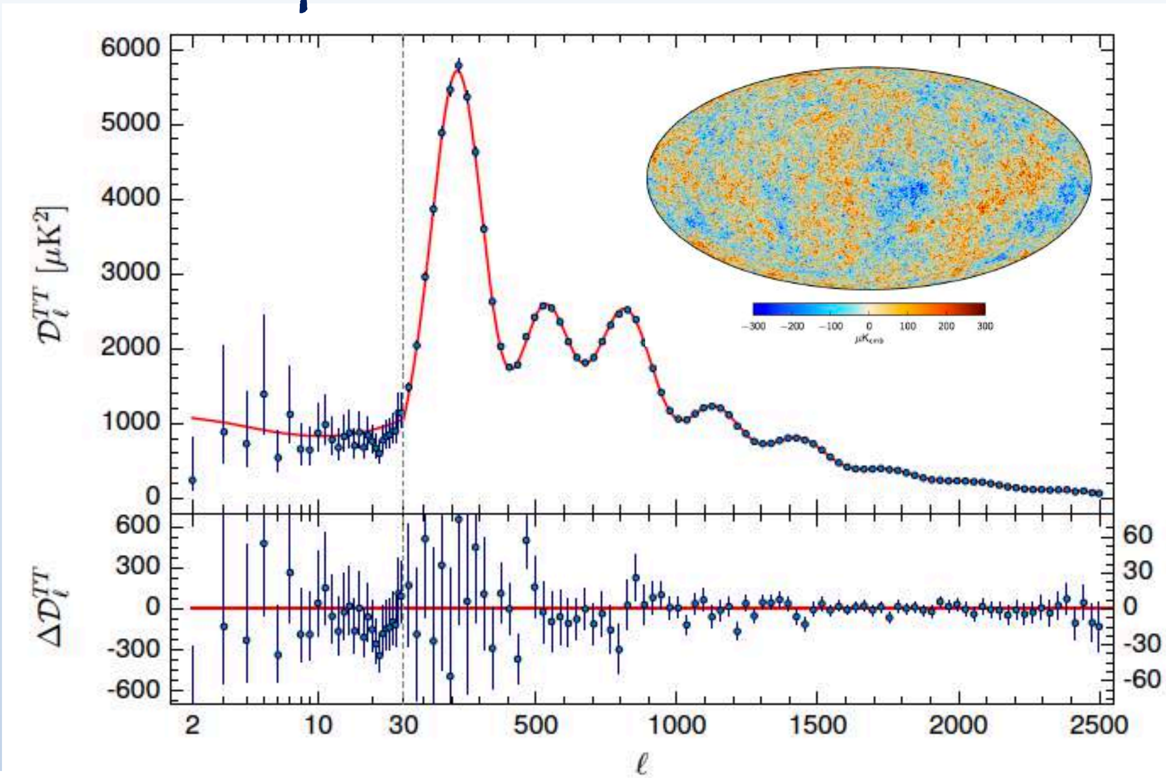


Tutusaus, Lamine, Dupays & Blanchard, A&A **602**:A73,2017

In fact all data are *equally consistent* with *no* acceleration (best fit: $a \sim t^{0.92}$)

… will need ~5x10^6 galaxy redshifts to see BAO peak *without* assuming a model

What about the precision data on CMB anisotropies?

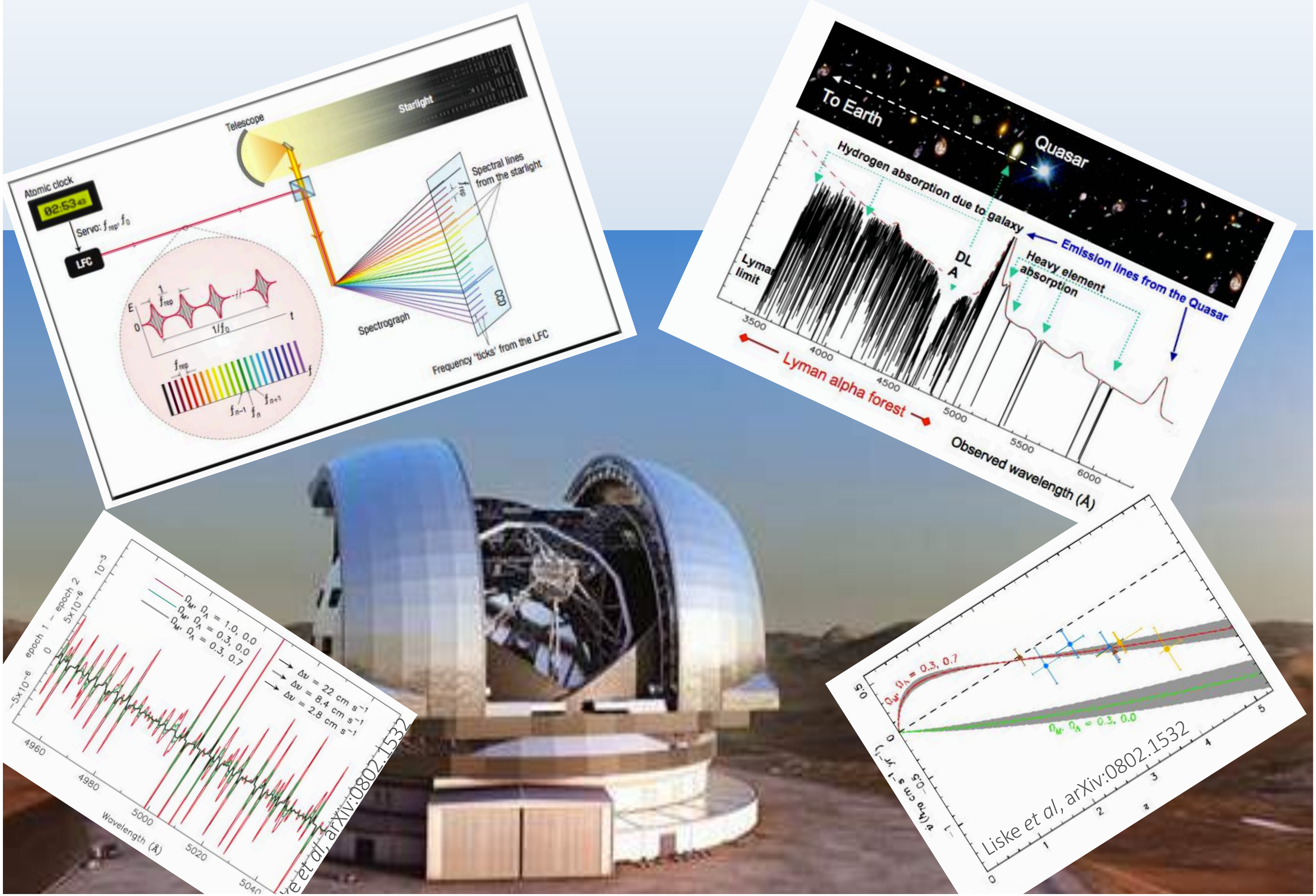


Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 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 CMB anisotropy to dark energy … it is all *inferred* (in the framework of ΛCDM)

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

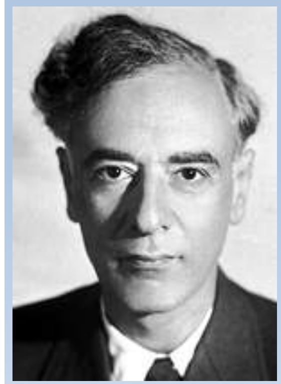


A 'tilted' Universe?

- There is a dipole in the recession velocities of host galaxies of supernovae ⇒ we are in a 'bulk flow' stretching out well *beyond* the scale at which the universe *supposedly* becomes statistically homogeneous.
- The inference that the Hubble expansion rate is accelerating may be an illusion … in fact the acceleration is found to be mainly a dipole (at 3.9σ) aligned with the flow, and the monopole is *consistent with zero* at 1.4σ

The 'standard' assumptions of isotropy & homogeneity are questionable … forthcoming surveys (Euclid, LSST, SKA) will enable *definitive* tests

Meanwhile whether the universe is dominated by 'dark energy' is open to question



Cosmologists are often in error but seldom in doubt
Lev Landau

It is not even wrong!
Wolfgang Pauli