Tracking the Hubble expansion on cosmological scales

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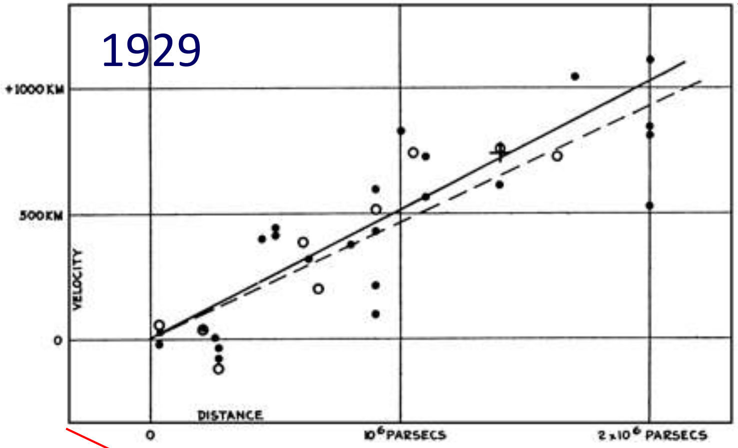
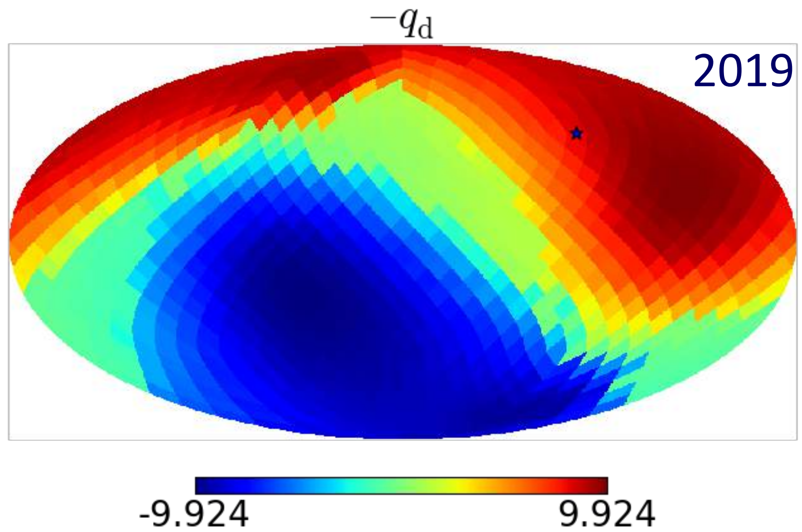
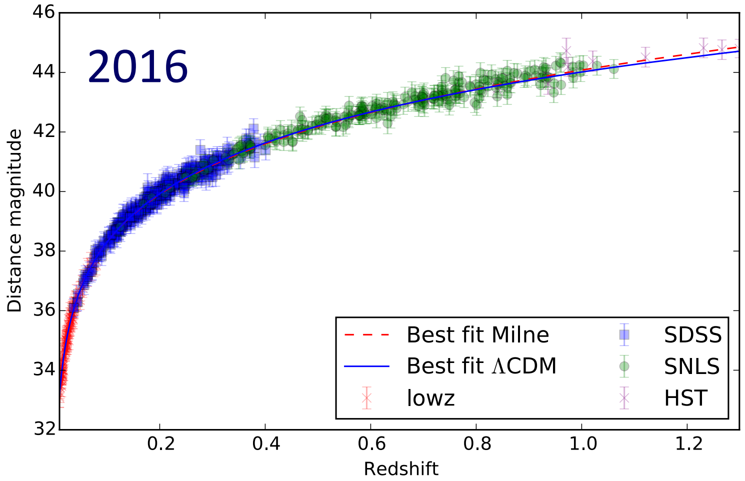
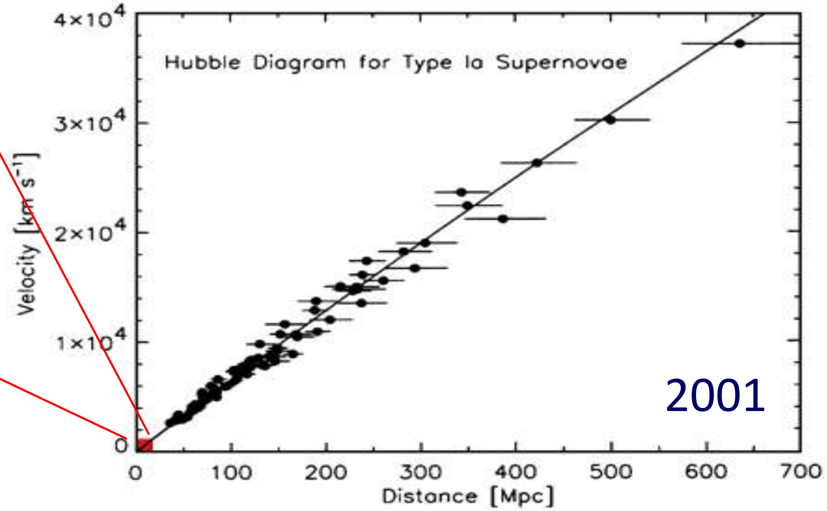
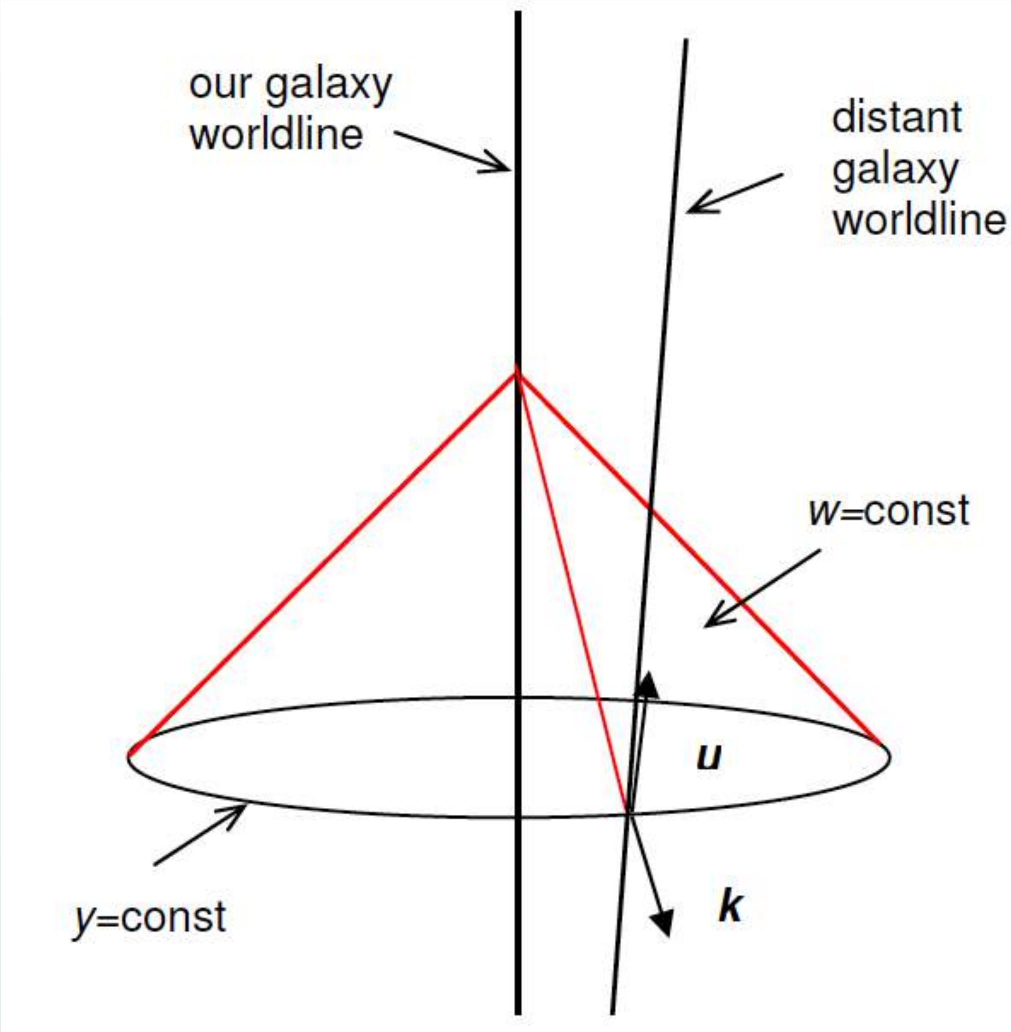








All we can *ever* learn about the universe is contained within our past light cone



We *cannot* move over cosmological distances and check if the universe looks the same from 'over there' as it does from here … so there are ***limits* to what we can know (cosmic variance)**

Standard cosmological model

The universe is **isotropic** + **homogeneous** (when averaged on 'large' scales)

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

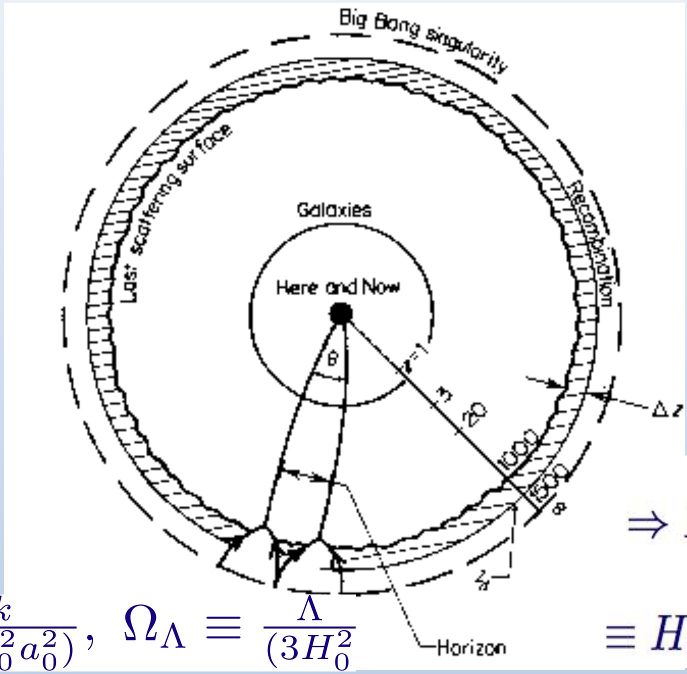
$$ds^2 \equiv g_{\mu\nu} dx^\mu dx^\nu$$

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

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

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 $= 8\pi G_N T_{\mu\nu}$

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

$$\Lambda = \lambda + 8\pi G_N \langle\rho\rangle_{\text{fields}}$$

$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho_m}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\Omega_m \equiv \frac{\rho_m}{(3H_0^2/8\pi G_N)},\quad \Omega_k \equiv \frac{k}{(3H_0^2 a_0^2)},\quad \Omega_\Lambda \equiv \frac{\Lambda}{(3H_0^2}$$

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

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

We observe: $0.8\Omega_m - 0.6\Omega_\Lambda \approx -0.2$ (Supernovae), $\Omega_k \approx 0.0$ (CMB), $\Omega_m \sim 0.3$ (Clusters)

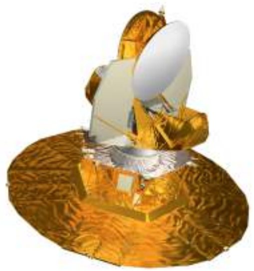
➞ infer universe is dominated by **dark energy**: $\Omega_\Lambda = 1 - \Omega_m - \Omega_k \sim 0.7 \Rightarrow \mathbf{\Lambda \sim 2H_0^2}$

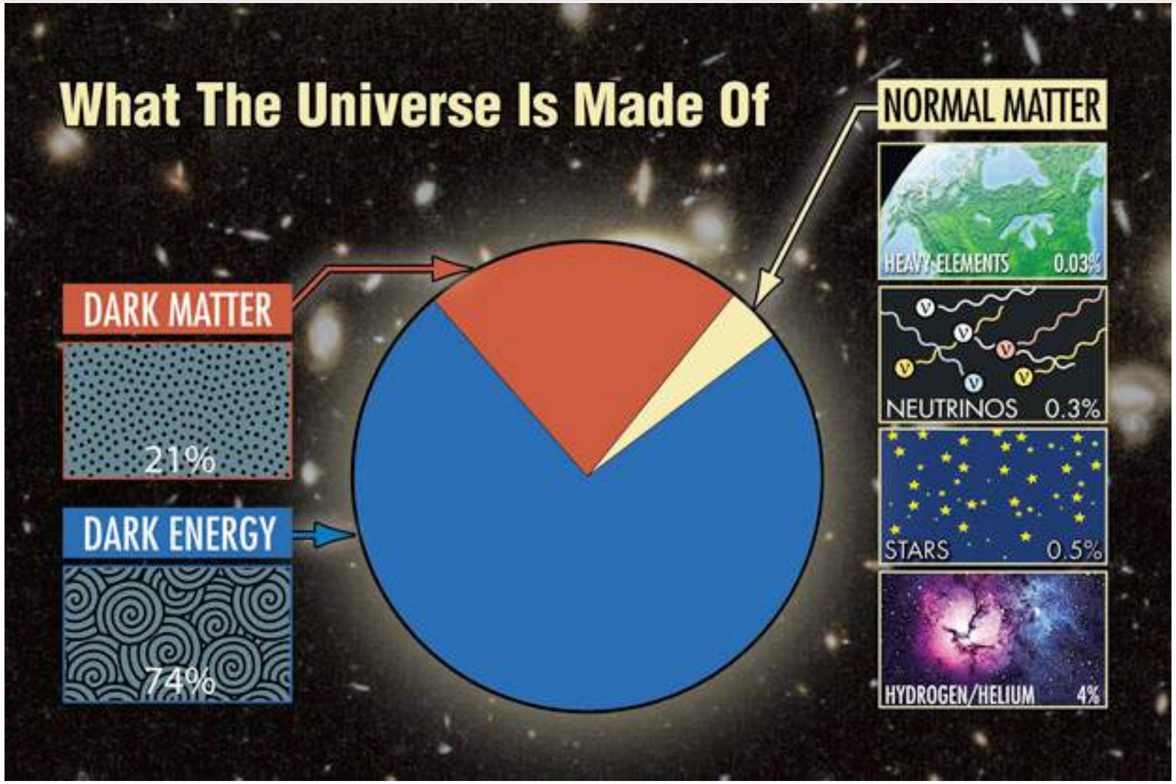
The scale is set by the *only* dimensionful parameter: $H_0 \sim 10^{-42}$ GeV

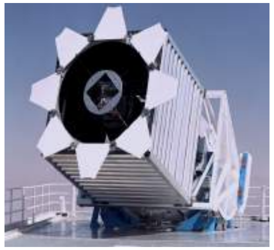
To drive *accelerated* expansion requires the pressure to be ***negative*** ($P < -\rho/3$) so this is interpreted as *vacuum* energy at the scale $(\rho_\Lambda)^{1/4} = (H_0^2/8\pi G_N)^{1/4} \sim 10^{-12}$ GeV << $G_F^{-1/2} \sim 10^2$ GeV

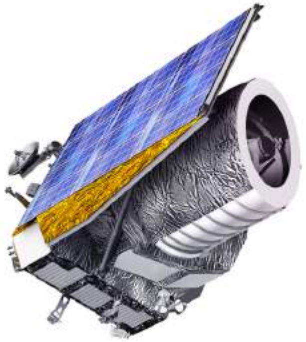
This makes *no* physical sense … exacerbates the (old) Cosmological Constant problem!

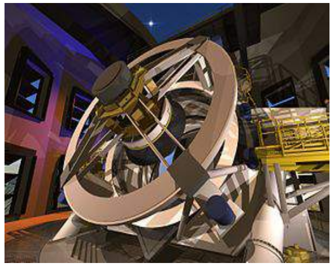
Since 1998 (Riess *et al.*[1], Perlmutter *et al.*[2]), surveys of cosmologically distant Type Ia supernovae (SNe Ia) have indicated an acceleration of the expansion of the Universe, distant SNe Ia being dimmer that expected in a decelerating Universe. With the assumption that the Universe can be described 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.





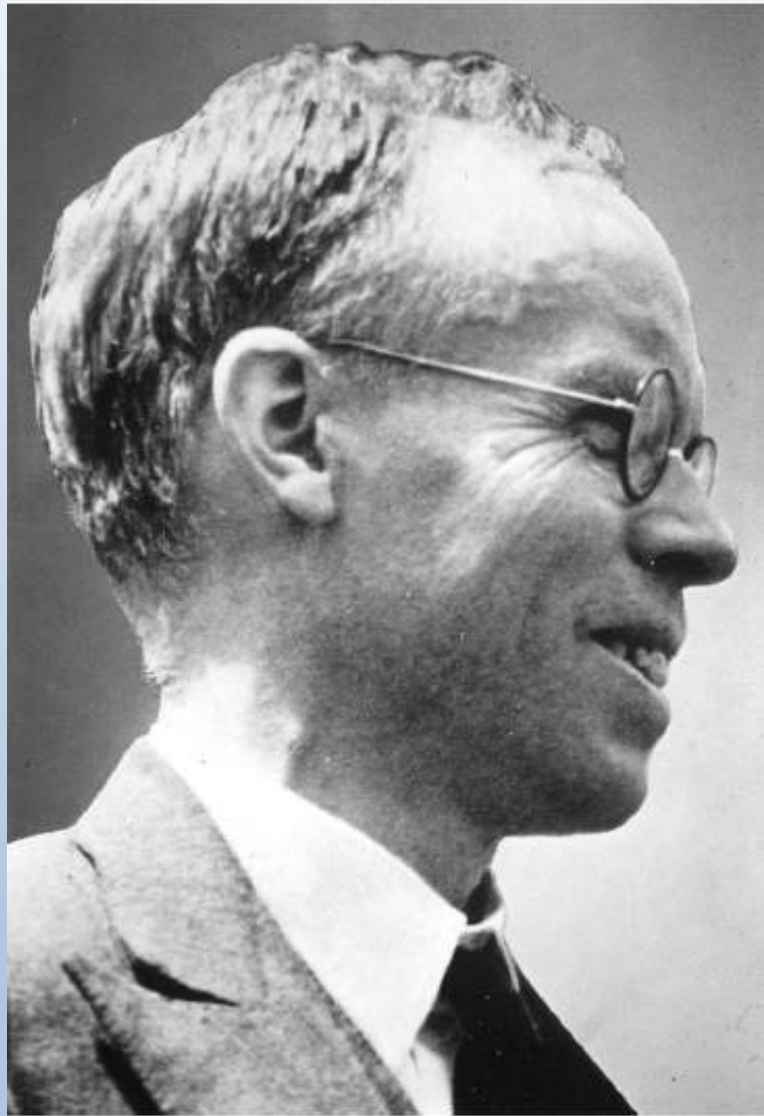






There has been substantial investment in major satellites and telescopes to *measure the parameters* of the 'standard cosmological model' with increasing 'precision'… but surprisingly little work on ***testing its foundational assumptions***

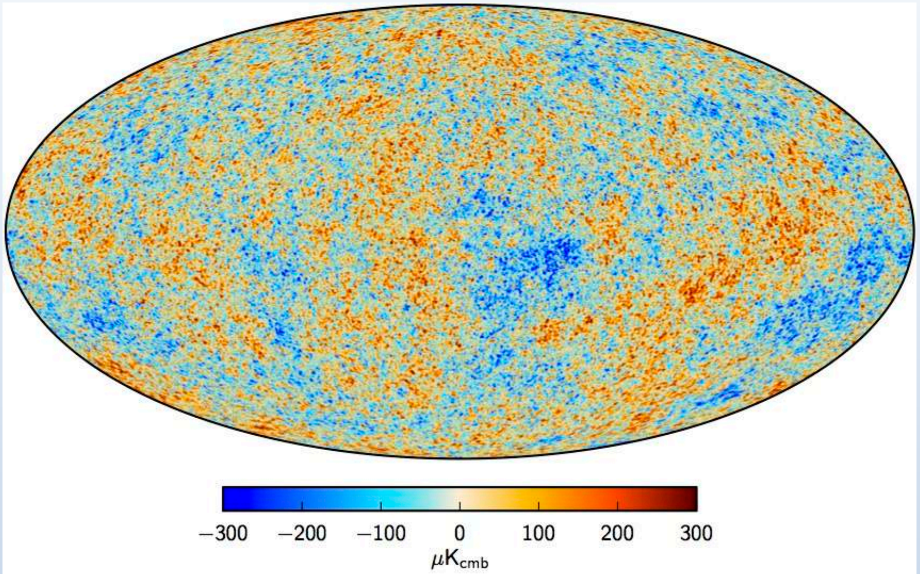
The Universe must appear to be the same to all observers wherever they are
*This ‘**cosmological principle**’ …*

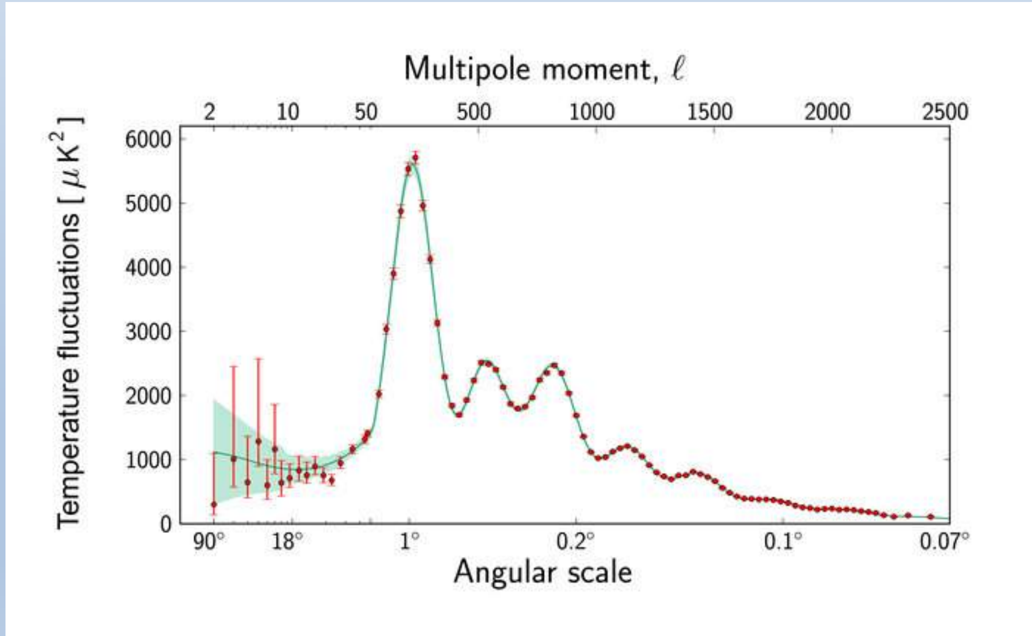


Edward Arthur Milne (1896-1950)

Rouse Ball Professor of Mathematics & Fellow of Wadham College, Oxford, 1928-

"Data from the Planck satellite show the universe to be highly isotropic" (Wikipedia)

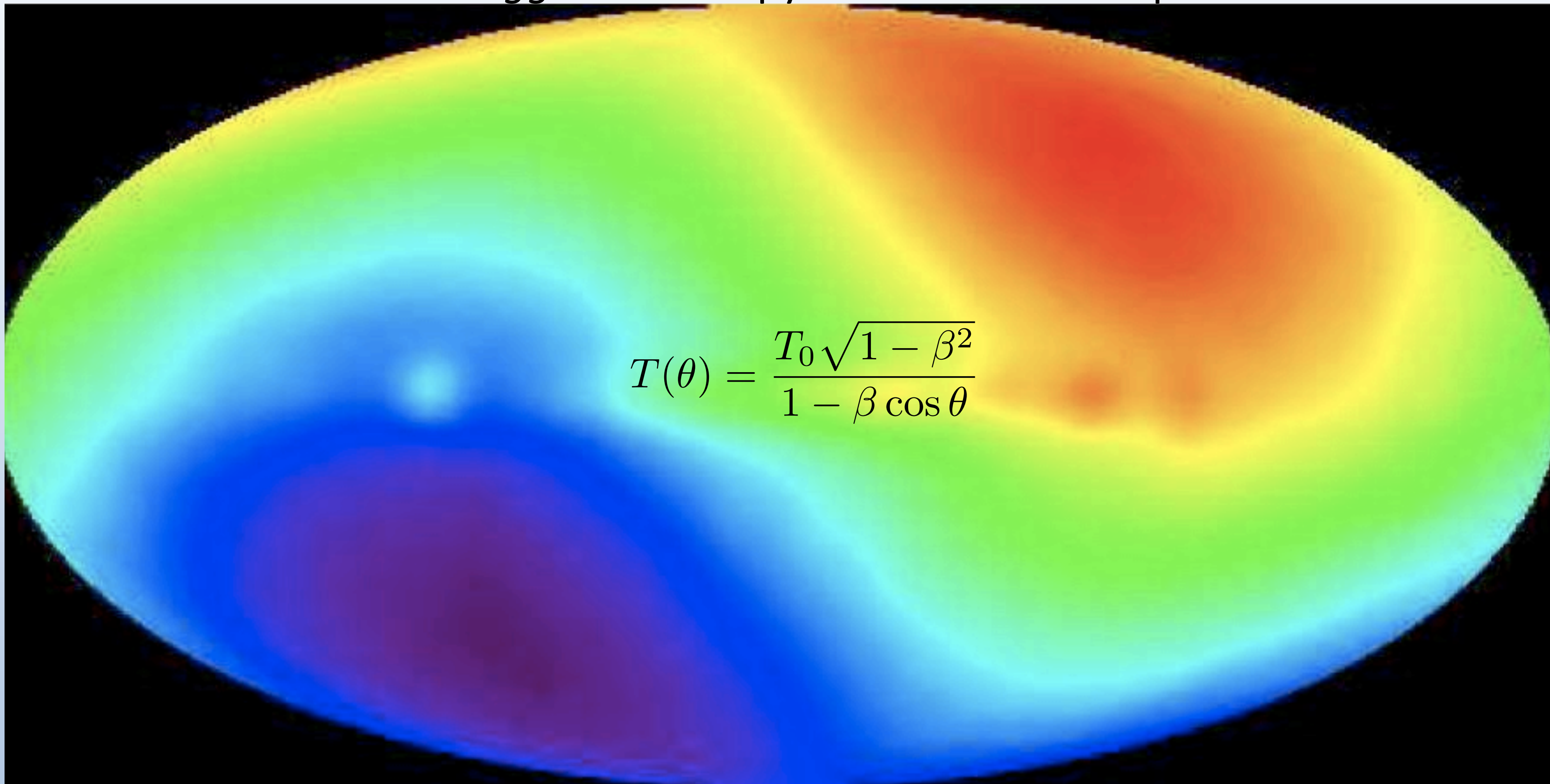




We observe a statistically isotropic Gaussian random field of small temperature fluctuations (fully quantified by the 2-point correlations ➛ angular power spectrum)

But the CMB sky is in fact quite anisotropic

There is a ~100 times *bigger* anisotropy in the form of a dipole with $\Delta T/T \sim 10^{-3}$



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

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°

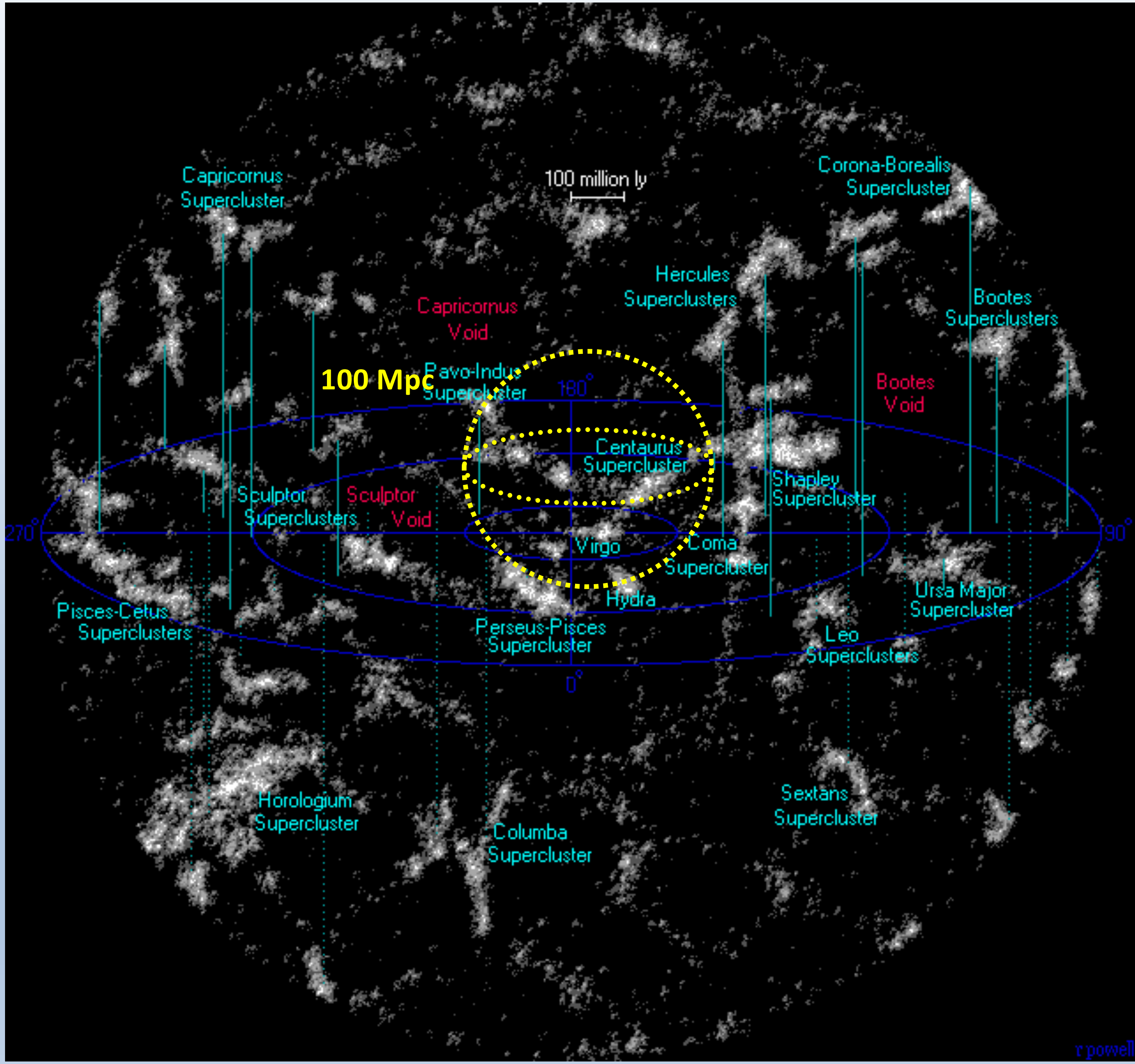
This motion is *presumed* to be due to local inhomogeneity in the matter distribution

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'



If so, our 'peculiar velocity' should fall off as $\sim 1/r$ so we "converge to the CMB frame"

Theory of peculiar velocity fields

In linear perturbation theory, the growth of the density contrast $\delta(x) = [\rho(x) - \bar{\rho}]/\bar{\rho}$ as a function of commoving coordinates and time is governed by:

$$\frac{\partial^2 \delta}{\partial t^2} + 2H(t)\frac{\partial \delta}{\partial t} = 4\pi G_{\mathrm{N}} \bar{\rho} \delta$$

We are interested in the 'growing mode' solution – the density contrast grows self-similarly and so does the perturbation potential and its gradient … so the direction of the acceleration (and its integral – the peculiar velocity) remains *unchanged*.

The peculiar velocity field is related to the density contrast as:

$$v(\mathbf{x}) = \frac{2}{3H_0} \int \mathrm{d}^3 y \frac{\mathbf{x} - \mathbf{y}}{|\mathbf{x} - \mathbf{y}|^3} \delta(\mathbf{y}),$$

So the peculiar Hubble flow, $\boldsymbol{\delta} H(\boldsymbol{x}) = H_{\mathrm{L}}(\boldsymbol{x}) - H_0$ ($\Rightarrow$ trace of the shear tensor), is:

$$\delta H(\mathbf{x}) = \quad \mathrm{d}^3\mathbf{y}\ \mathbf{v}(\mathbf{y}) \cdot \frac{\mathbf{x} - \mathbf{y}}{|\mathbf{x} - \mathbf{y}|^2} W(\mathbf{x} - \mathbf{y}),$$

where $H_{\mathrm{L}}(\mathbf{x})$ is the *local* value of the Hubble parameter and $W(\mathbf{x} - \mathbf{y})$ is the 'window function' (e.g. $\theta(R - |\mathbf{x} - \mathbf{y}|)\ (4\pi R^3/3)^{-1}$ for a volume-limited survey, out to distance R)

Theory of peculiar velocity fields (cont.)

Rewrite in terms of the Fourier transform $\delta(\mathbf{k}) \equiv (2\pi)^{3/2} \int d^3x\, \delta(\mathbf{x}) e^{i\mathbf{k}\cdot\mathbf{x}}$:

$$\frac{\delta H}{H_0} = \int \frac{d^3k}{(2\pi)^{3/2}} \delta(k) \mathcal{W}_H(kR) e^{ik.x}, \quad \mathcal{W}_H(x) = \frac{3}{x^3}\left(\sin x - \int_o^x dy \frac{\sin y}{y}\right)$$

Window function

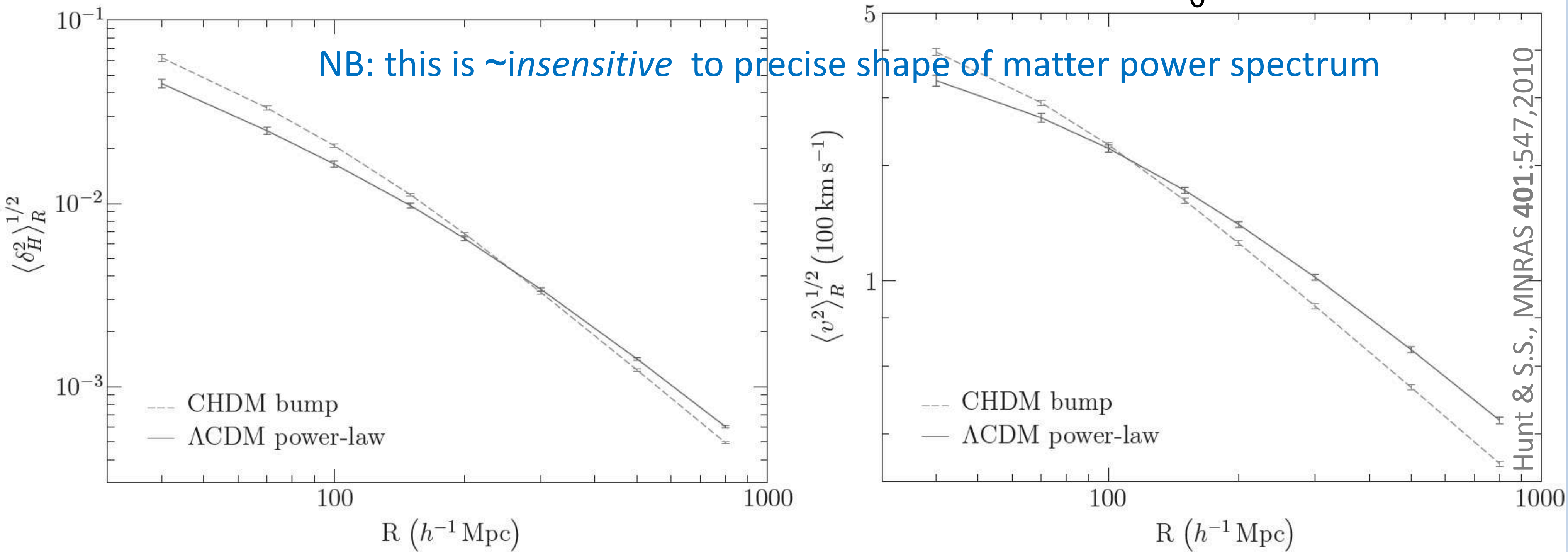
Then the RMS fluctuation in the local Hubble constant $\delta_H \equiv \langle (\delta H/H_0)^2 \rangle^{1/2}$ is:

$$\delta_{\rm H}^2 = \frac{f^2}{2\pi^2} \int_0^\infty k^2 dk\; P(k) \mathcal{W}^2(kR), \quad P(k) \equiv |\delta(k)^2|, \quad f \simeq \Omega_{\rm m}^{4/7} + \frac{\Omega_\Lambda}{70}\left(1 + \frac{\Omega_{\rm m}}{2}\right)$$

Power spectrum of matter fluctuations — Growth rate

Similarly the variance of the peculiar velocity is: $\langle v^2 \rangle_R = \frac{f^2 H_0^2}{2\pi^2} \int_0^\infty dk P(k) \mathcal{W}^2(kR)$

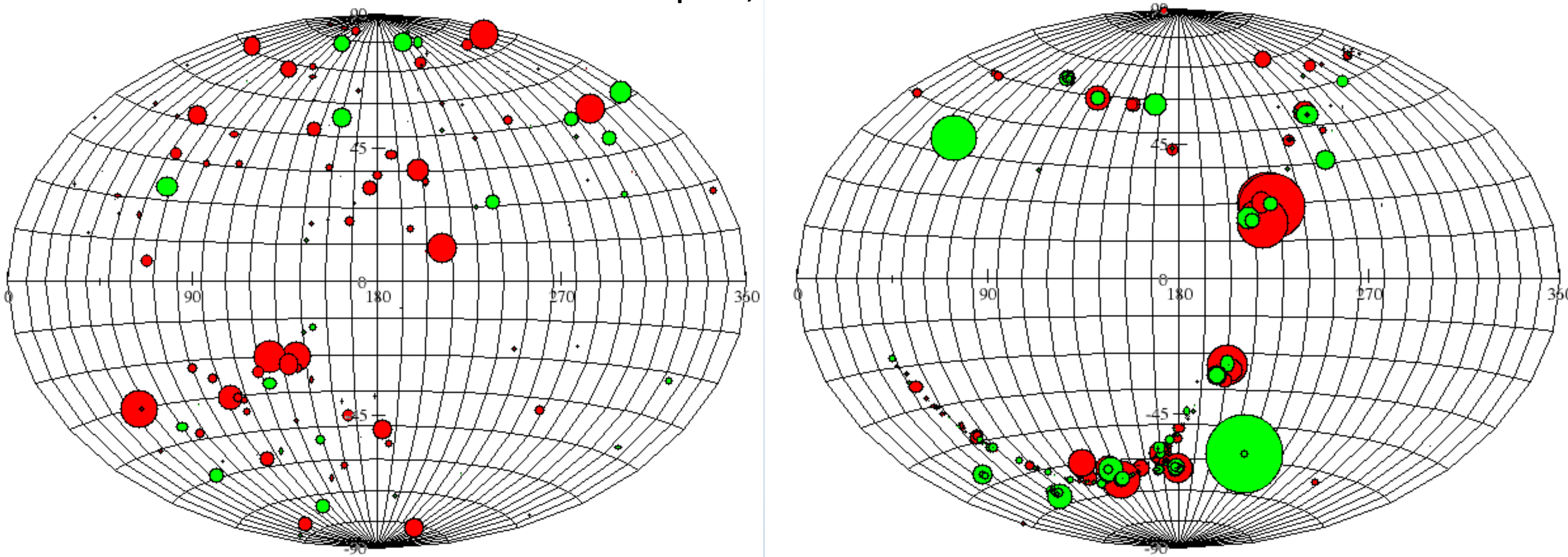
NB: this is ~*insensitive* to precise shape of matter power spectrum



Hunt & S.S., MNRAS **401**:547,2010

Union 2 compilation of 557 SNe Ia

Aitoff-Hammer plot, Galactic coordinates

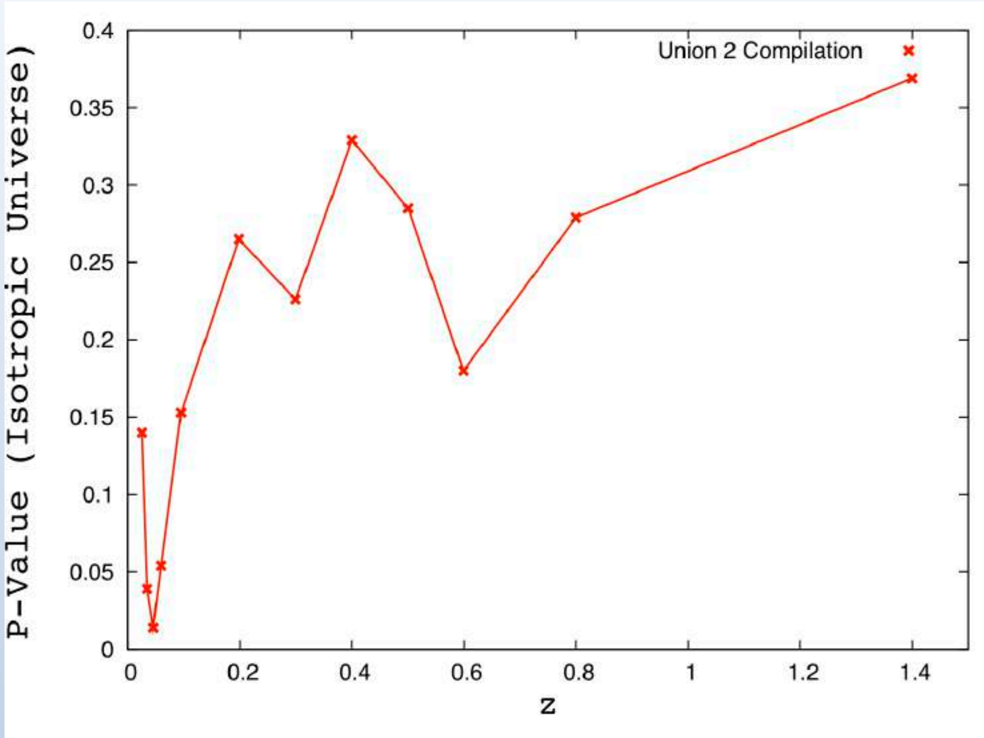


Left panel: The red spots represent the data points for $z < 0.06$ with distance moduli μ_{data} bigger than the values μ_{CDM} predicted by ΛCDM, and the green spots are those with μ_{data} less than μ_{CDM}; the spot size is a relative measure of the discrepancy. A dipole anisotropy is visible around the direction $b = -30^\circ$, $l = 96^\circ$ (red points) and its opposite direction $b = 30^\circ$, $l = 276^\circ$ (small green points), which is the direction of the CMB dipole. **Right panel**: Same plot for $z > 0.06$

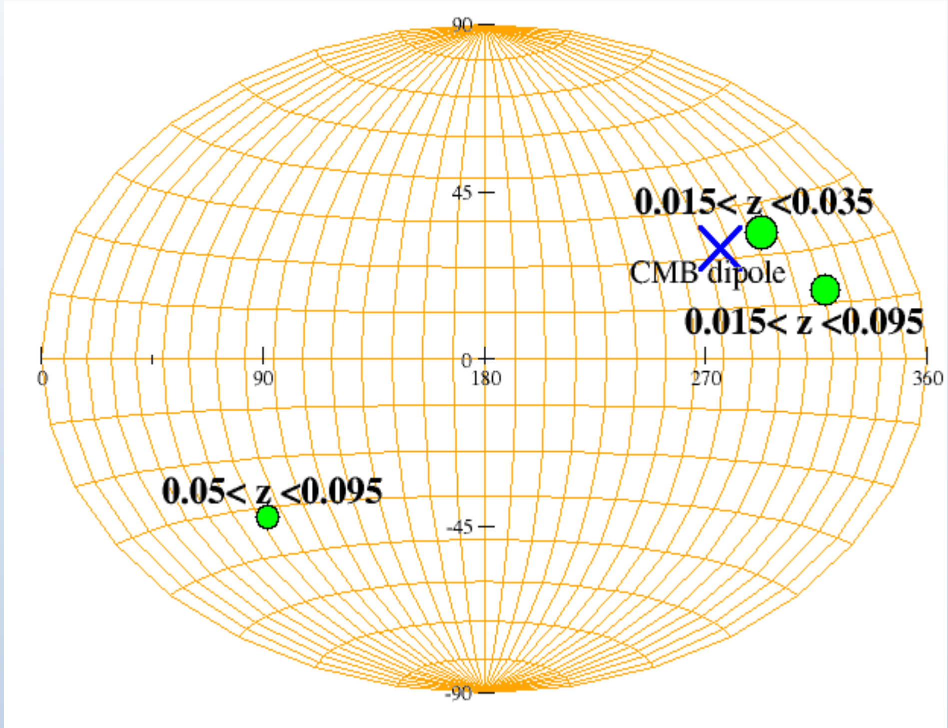
Colin, Mohayaee, S.S. & Shafieloo, MNRAS **414**:264,2011

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**

IS THE UNIVERSE ISOTROPIC?



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



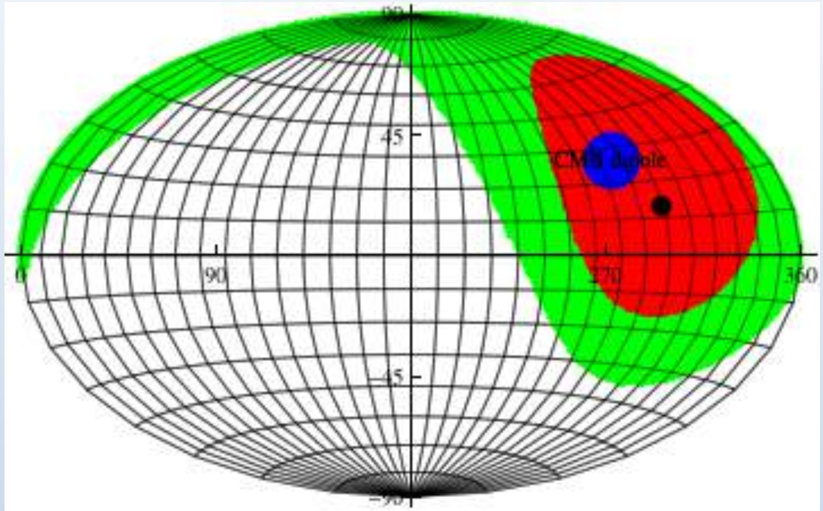
Left panel: P-value for the consistency of the isotropic universe with the data versus redshift. At $z \approx 0.05$ (~200 Mpc) the P-value drops to 0.014 showing that isotropy is *excluded* at 3σ … i.e. we have *not* converged to the CMB rest frame.

Right panel: Cumulative analysis shows that at low redshift, $0.015 < z < 0.06$, isotropy is excluded at 2–3 σ with P = 0.054; but at higher redshift, $0.15 < z < 1.4$ the data is consistent with isotropy within 1σ (P = 0.594).

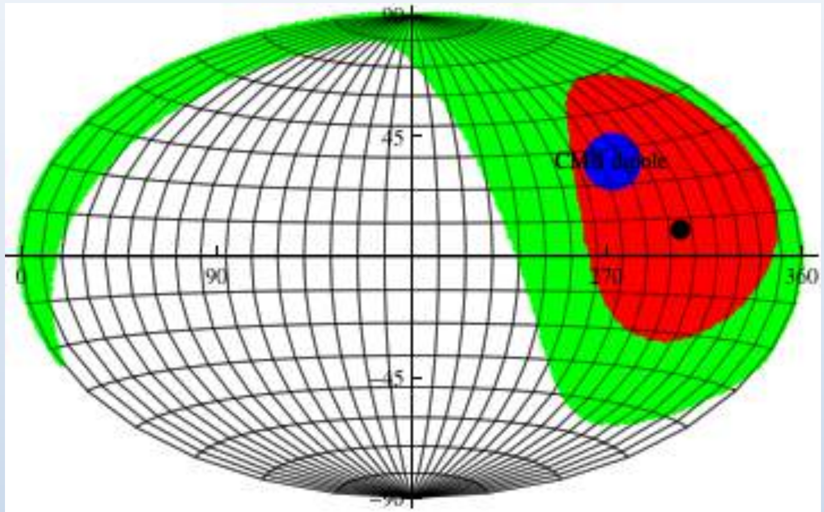
Maximum likelihood analysis can now be used to estimate the bulk flow at low redshifts where the velocities are not yet dominated by the cosmic expansion

DIPOLE IN THE SN IA VELOCITY FIELD *ALIGNED* WITH THE CMB DIPOLE

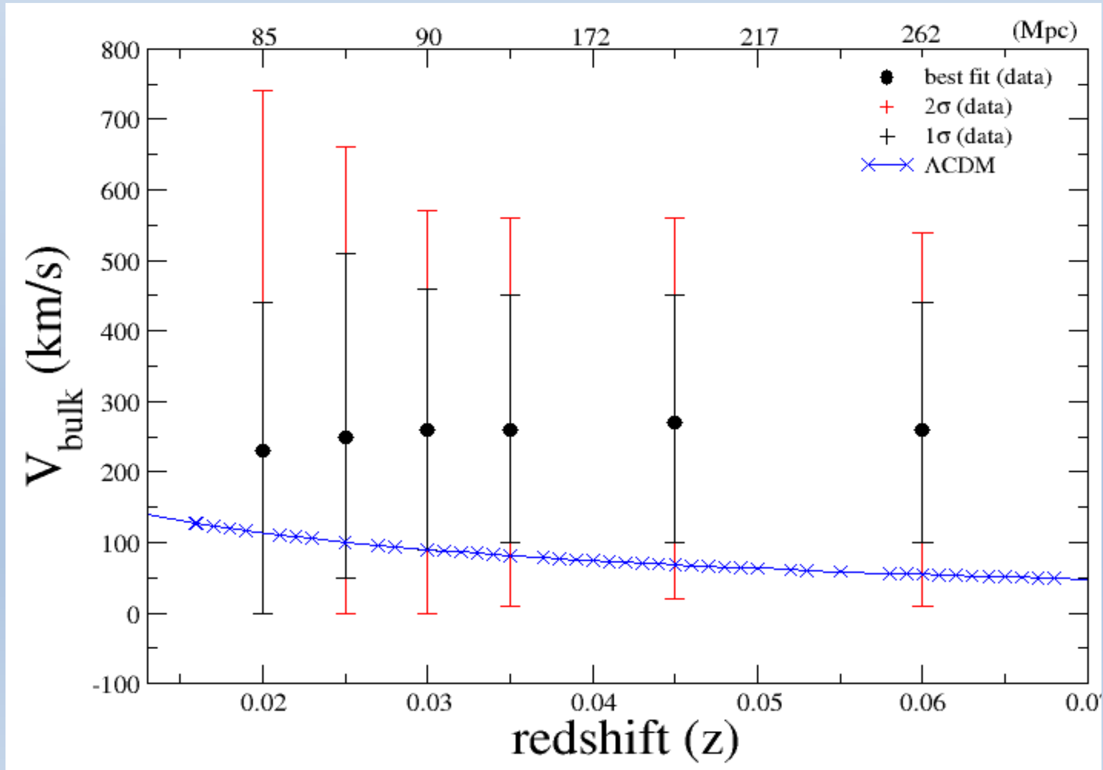
$0.015 < z < 0.045$, $v = 270$ km/s, $l = 291$, $b = 15$



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



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

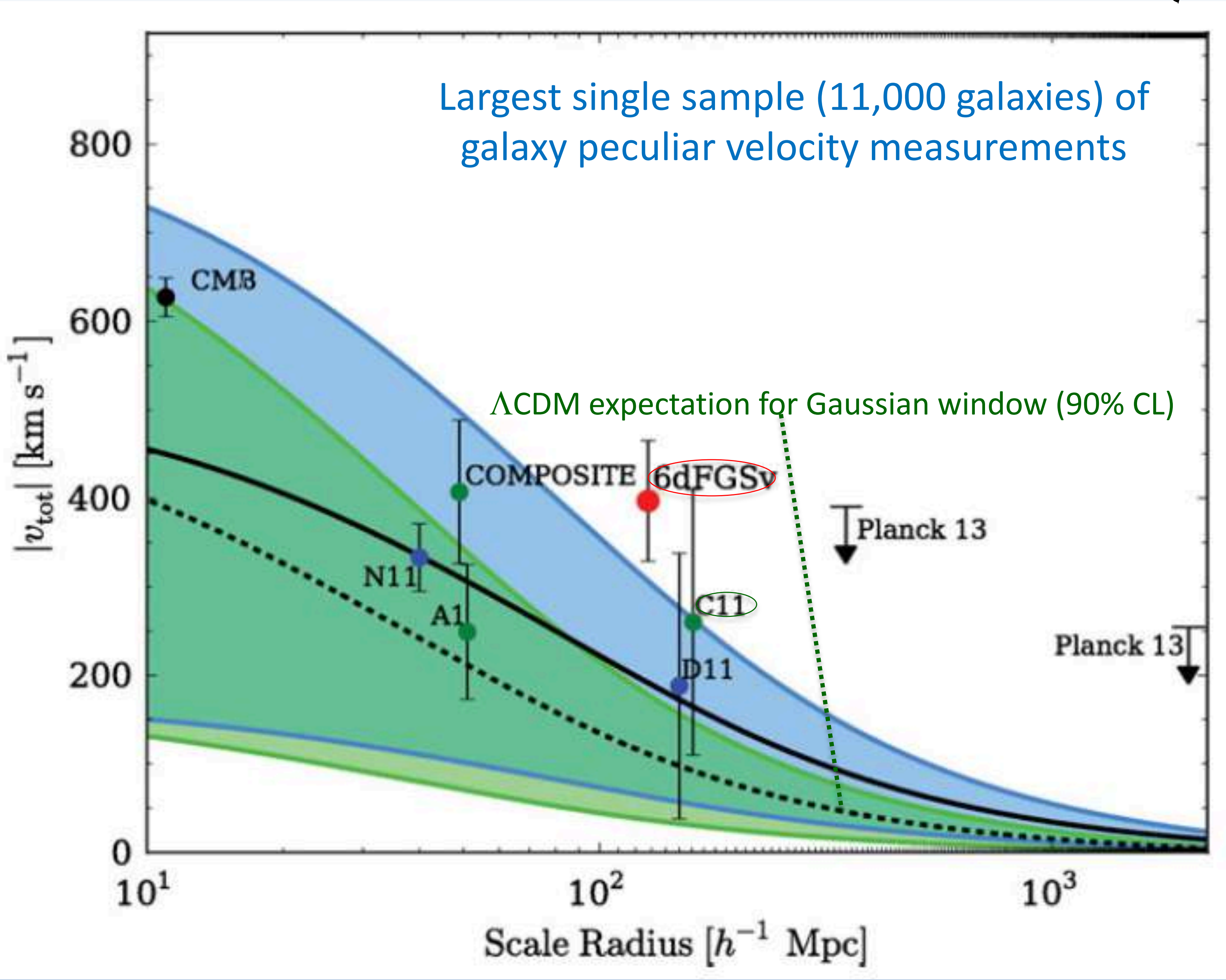


This is ≳1σ higher than expected for the standard ΛCDM model … and extends *beyond* Shapley (at 260 Mpc)

… 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)



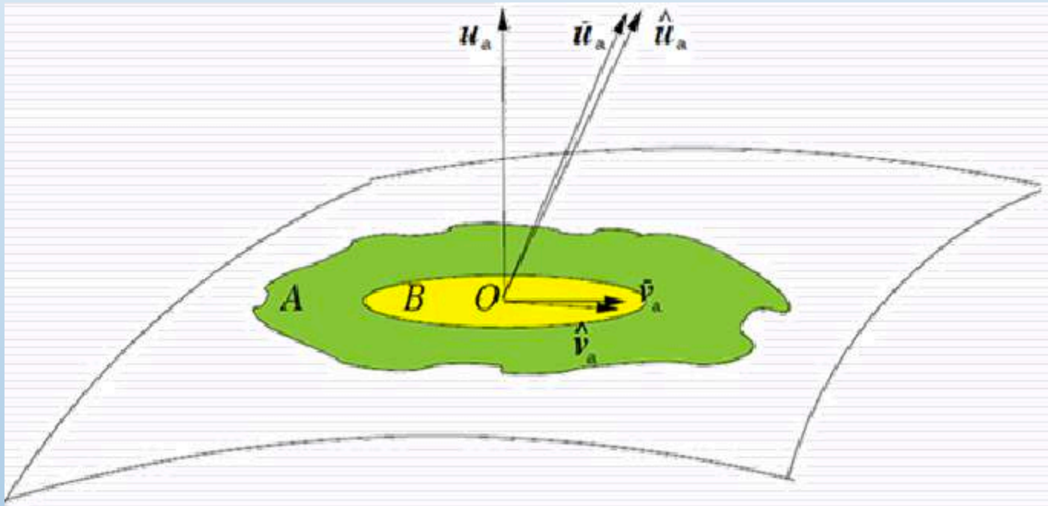
Magoulas, Springbob, Colless, Mould, *et al* (2016)

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, there should be 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)

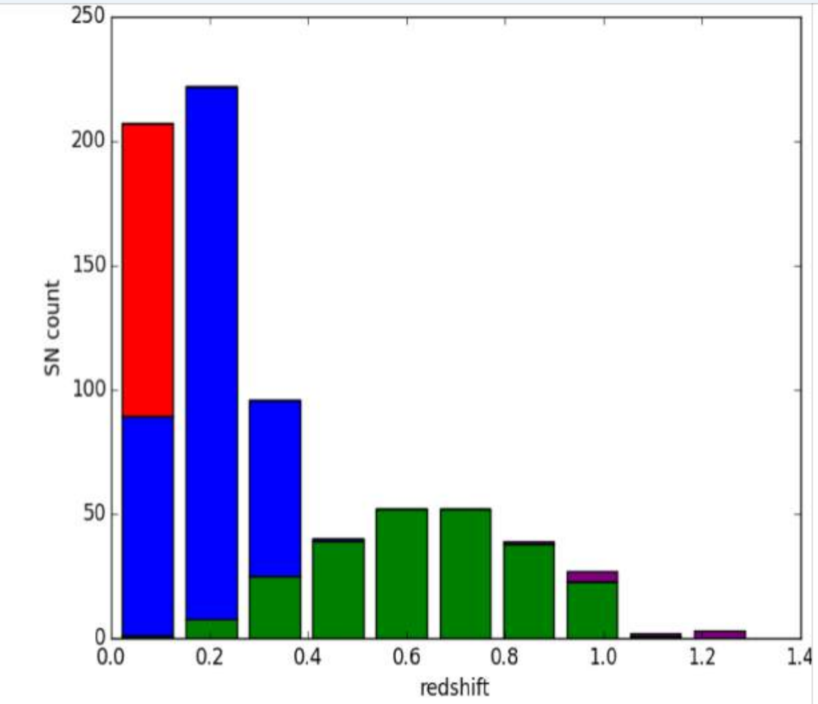
Inside region B, the r.h.s. of the expression

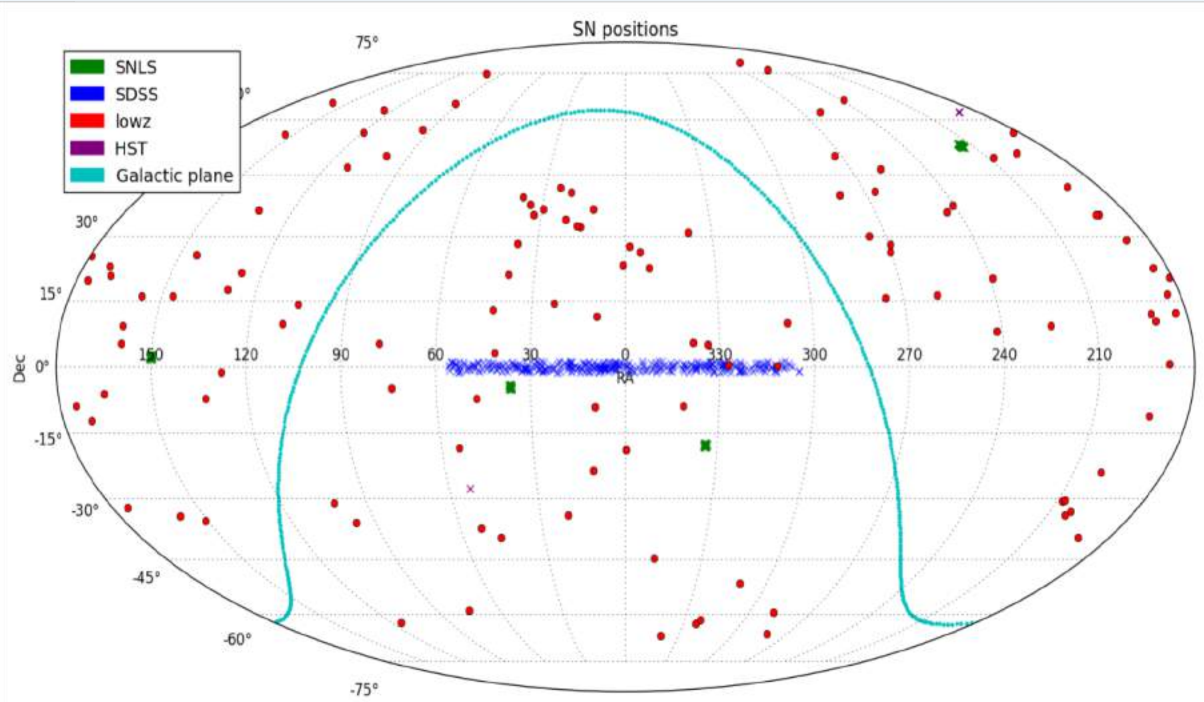
$$1 + \tilde{q} = (1+q)\left(1 + \frac{\vartheta}{\Theta}\right)^{-2} - \frac{3\dot{\vartheta}}{\Theta^2}\left(1 + \frac{\vartheta}{\Theta}\right)^{-2},$$

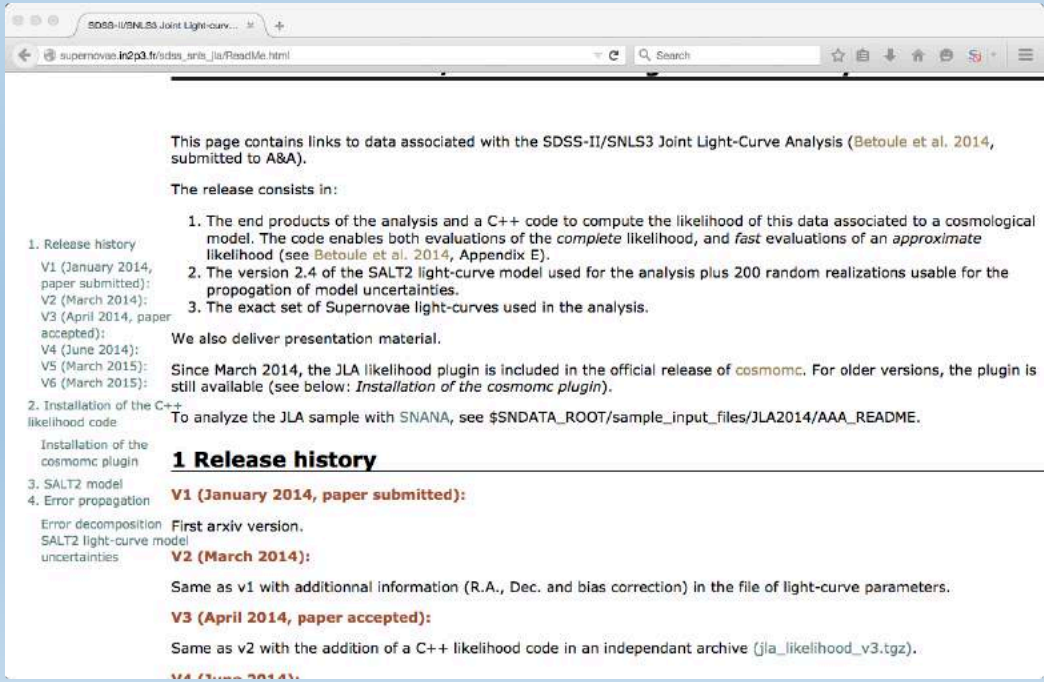
$$\tilde{\Theta} = \Theta + \vartheta,$$

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

Joint Lightcurve Analysis data (740 SNe Ia)






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

supernovae.in2p3.fr/sdss_snls_jla/ReadMe.html

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):

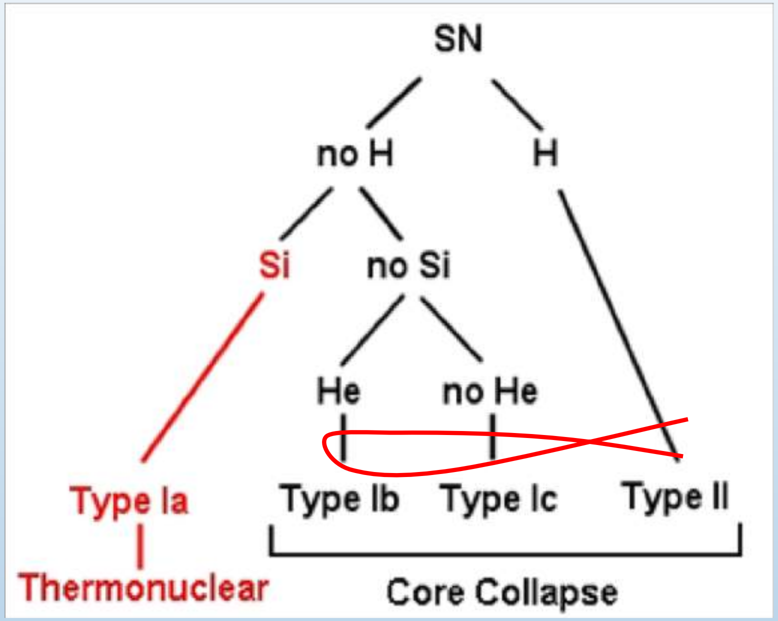
Same as v2 with the addition of a C++ likelihood code in an independant archive (jla_likelihood_v3.tgz).

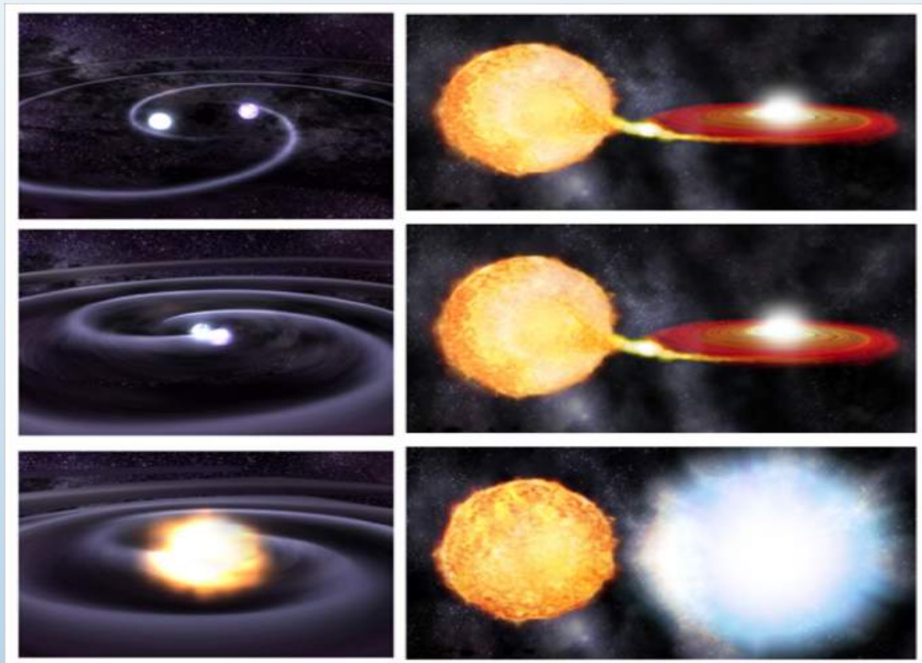
Betoule *et al*, A&A **568**:A22,2014
http://supernovae.in2p3.fr/sdss_snls_jla/

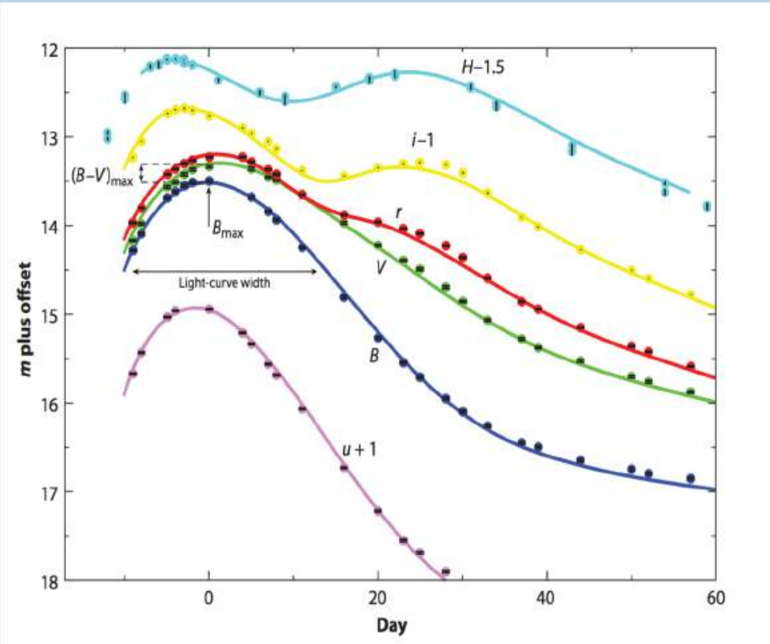
In contrast to previous analyses (which assumed ΛCDM and *adjusted* the errors to get a good fit) we apply a *principled* statistical analysis (Maximum Likelihood) … and obtain rather different results

Nielsen, Guffanti & S.S., Sci.Rep. 6:35596,2016

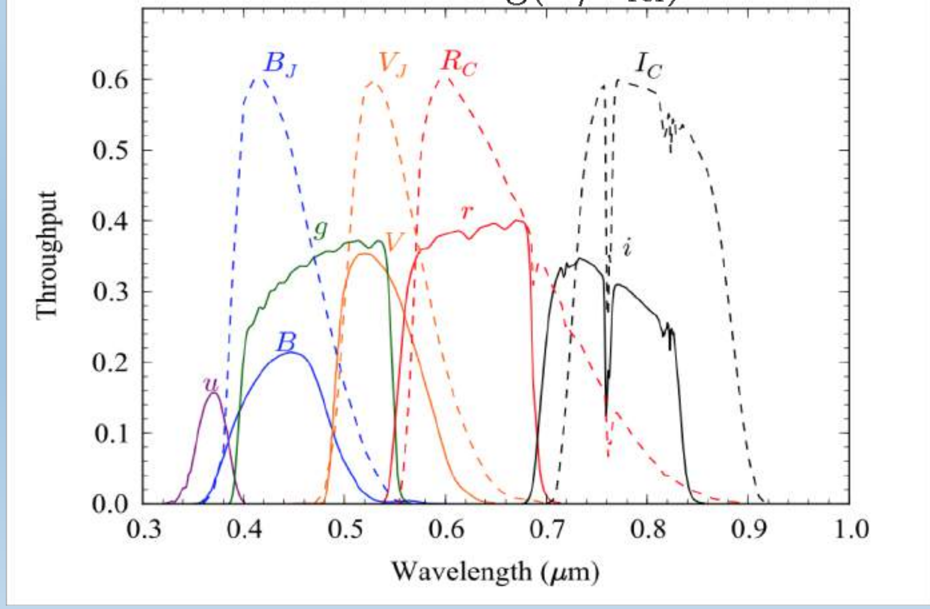
What are Type Ia supernovae?





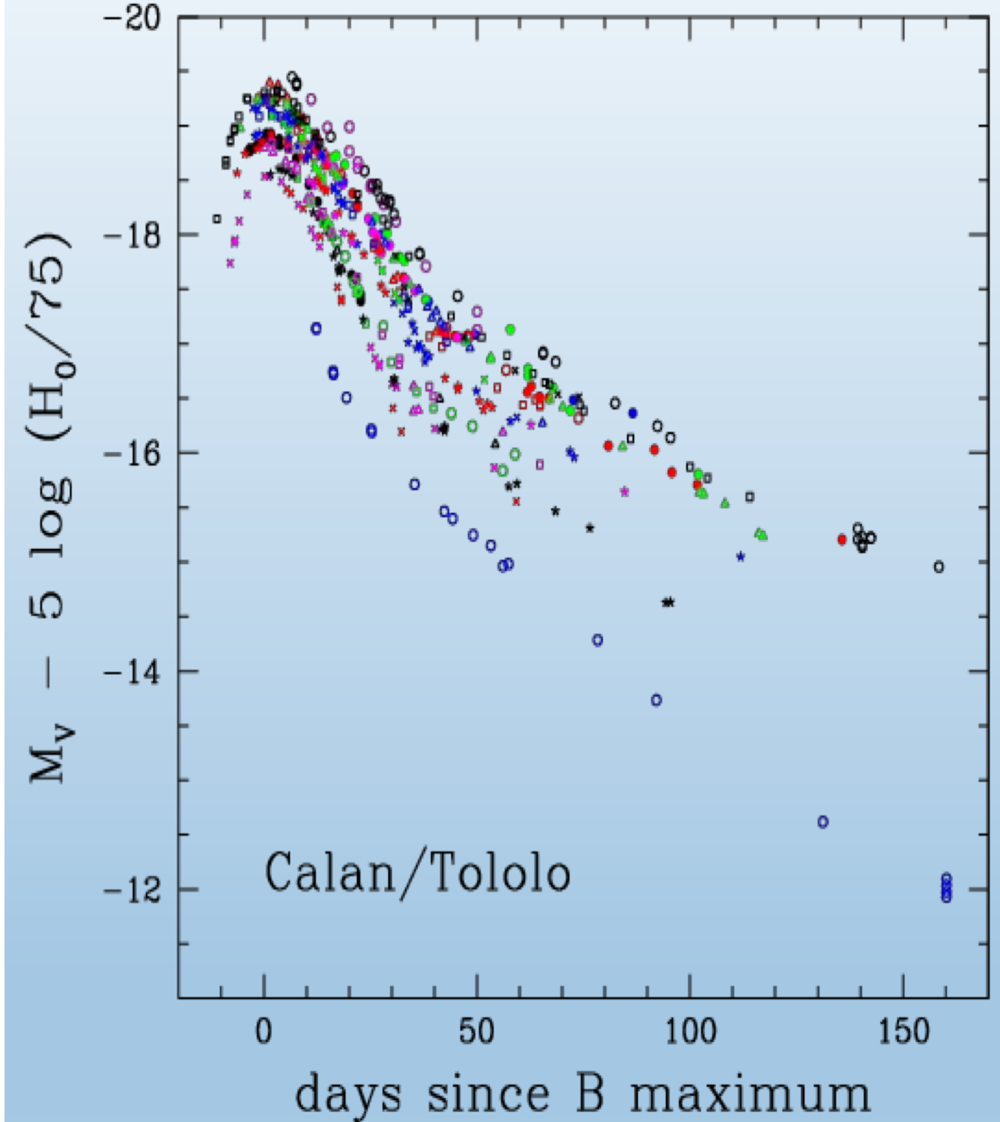


$$m = -2.5 \log(F/F_{\mathrm{ref}})$$

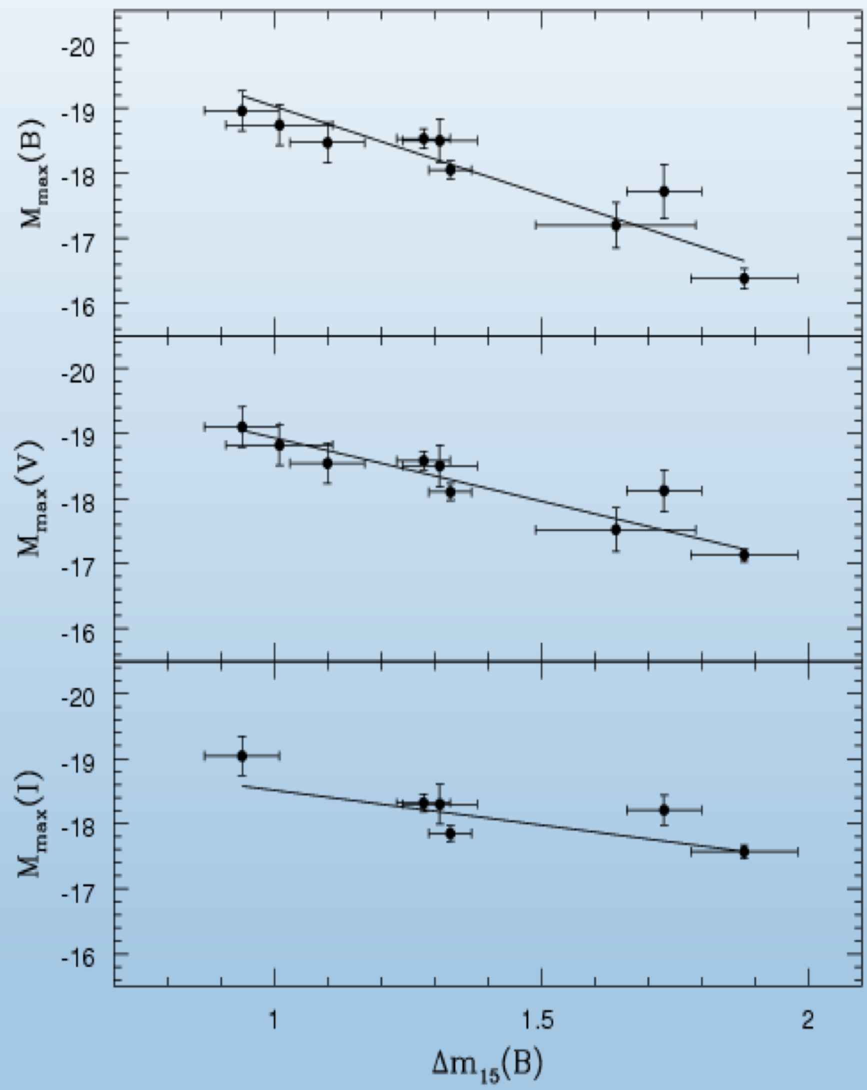


Goobar & Leibundgut, ARAA **61**:251,2011

They are certainly *not* ‘standard candles’



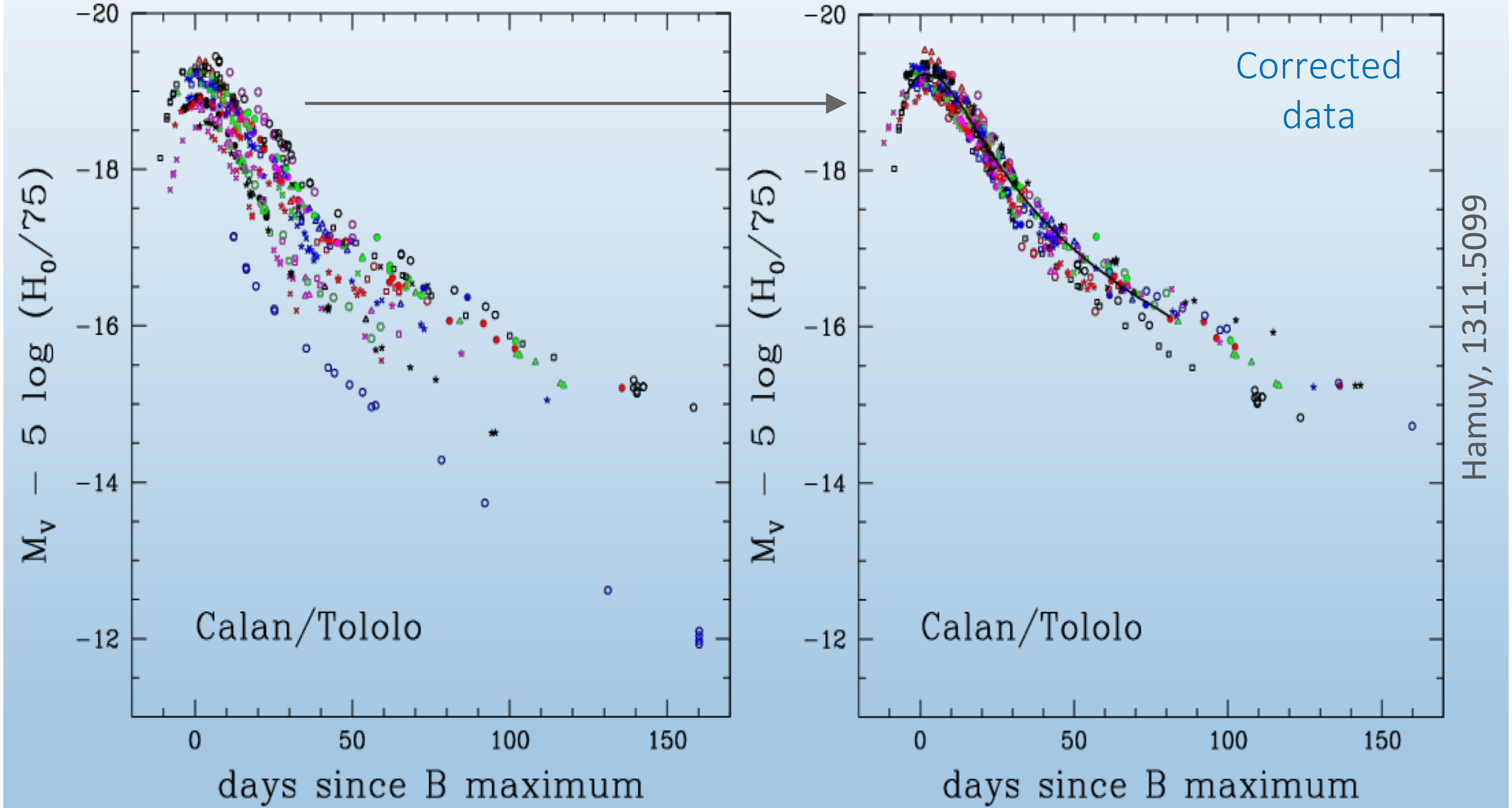
Hamuy, arXiv:311.5099



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 …

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 appears not to be relevant … but there may well be other variables that the magnitude correlates with …

Cosmology

$$\mu \equiv 25 + 5\log_{10}(d_{\rm L}/{\rm Mpc}), \quad \text{where:}$$
$$d_{\rm L} = (1+z)\frac{d_{\rm H}}{\sqrt{\Omega_k}}\,{\rm sinn}\left(\sqrt{\Omega_k}\int_0^z \frac{H_0 {\rm d}z'}{H(z')}\right),$$
$$d_{\rm H} = c/H_0, \quad H_0 \equiv 100h\ {\rm km\,s^{-1}Mpc^{-1}},$$
$$H = H_0\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda},$$

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

Distance modulus

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

Acceleration is a *kinematic* quantity so the data can be analysed without assuming any dynamical 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)

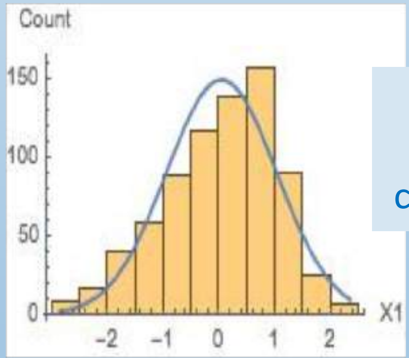
$$d_L(z) = \frac{c\,z}{H_0}\left\{1 + \frac{1}{2}[1-q_0]\,z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 + \frac{kc^2}{H_0^2\,a_0^2}\right]z^2 + O(z^3)\right\}$$

Construct a Maximum Likelihood Estimator

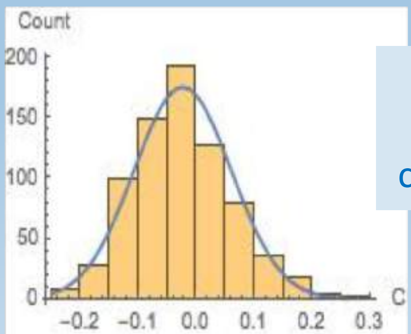
$$\mathcal{L} = \text{probability density}(\text{data}|\text{model})$$

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

Well-approximated as Gaussian



JLA data
'Stretch'
corrections



JLA data
'Colour'
corrections

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

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

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

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

Nielsen, Guffanti & S.S., 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

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

1,2,3-sigma

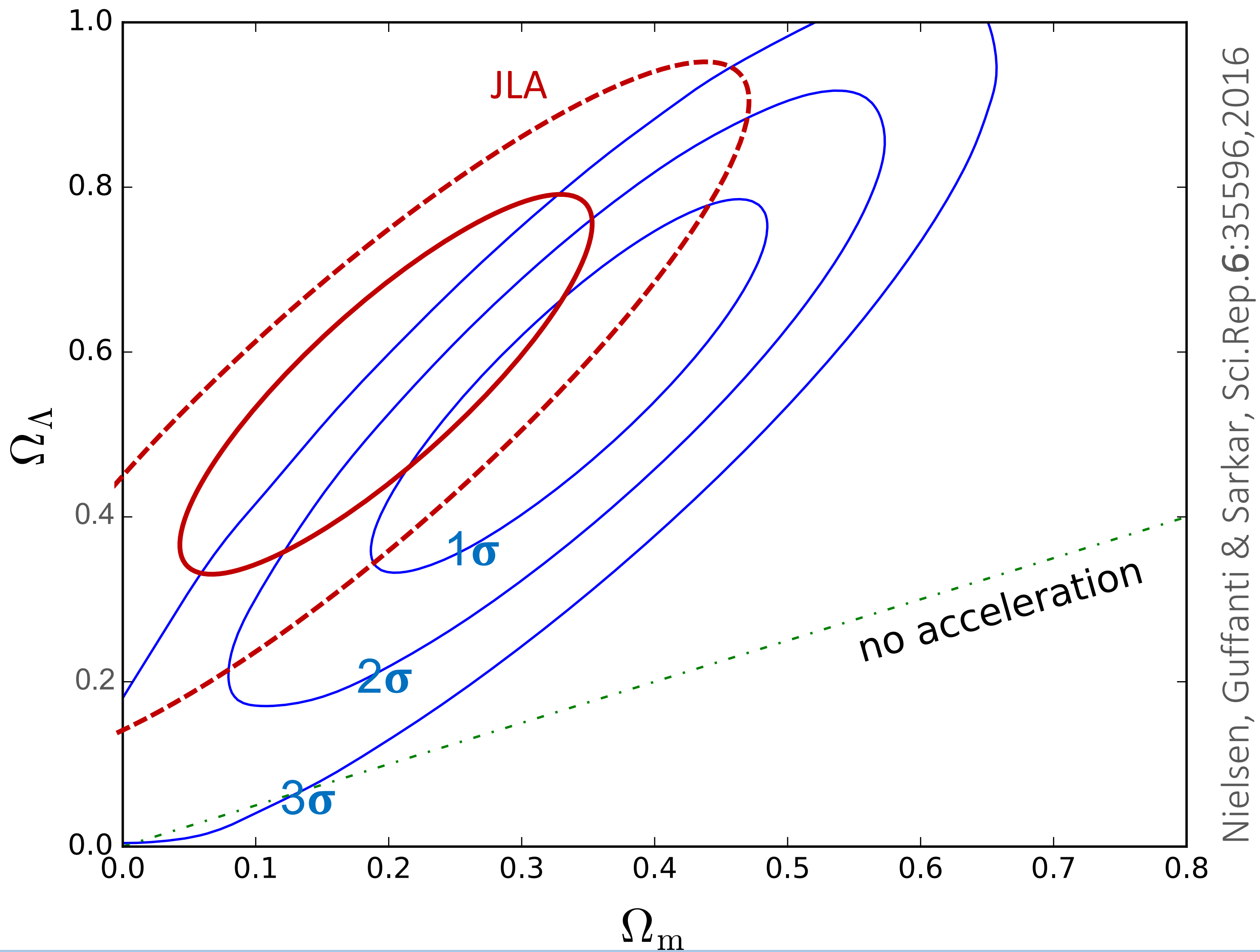
solve for Likelihood value

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

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

... it is clear that previous analyses overestimated the significance of acceleration because they adjusted σ_{int} to get χ^2 of 1/d.o.f. for the fit to the *assumed* ΛCDM model!

Data consistent with *uniform* rate of expansion @ 3σ ($\Rightarrow \rho + 3p = 0$)



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)

Rubin & Hayden (ApJ **833**:L30,2016) say that our model for the distribution of the JLA light curve fit parameters should have included a dependence on sample and redshift (to allow for 'Malmqvist bias'- which the JLA collab. had *corrected* for) ... they added 12 more parameters to our (10 parameter) model to describe this

This *a posteriori* modification is not justified by the Bayesian Information criterion

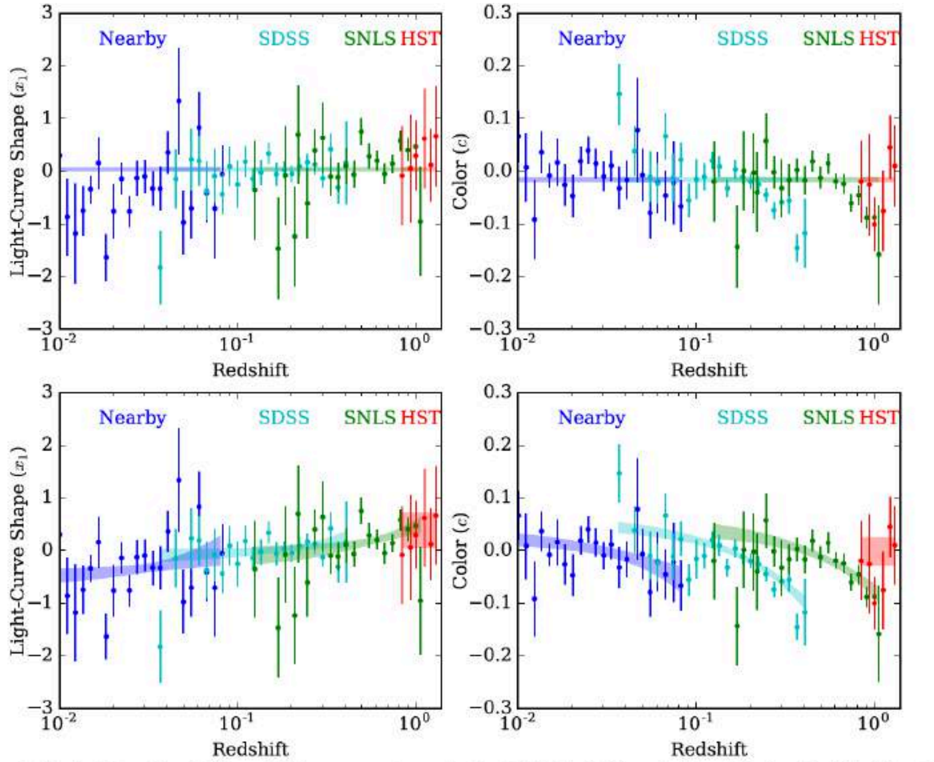


Figure 1. Binned x_1 (left panels) and c (right panels) light curve parameters as a function of redshift for the JLA sample. The trend of color with redshift within each ground-based sample is expected due to the combination of the color-luminosity relation combined with redshift-dependent luminosity detection limits. The top panels show the 68% credible constraints on a constant-in-redshift model, as was used in N16. The bottom panels show our proposed revision. Failing to model the drift in the mean observed distributions demonstrated by the bottom panels will tend to cause high-redshift SNe to appear brighter on average, therefore reducing the significance of accelerating expansion.

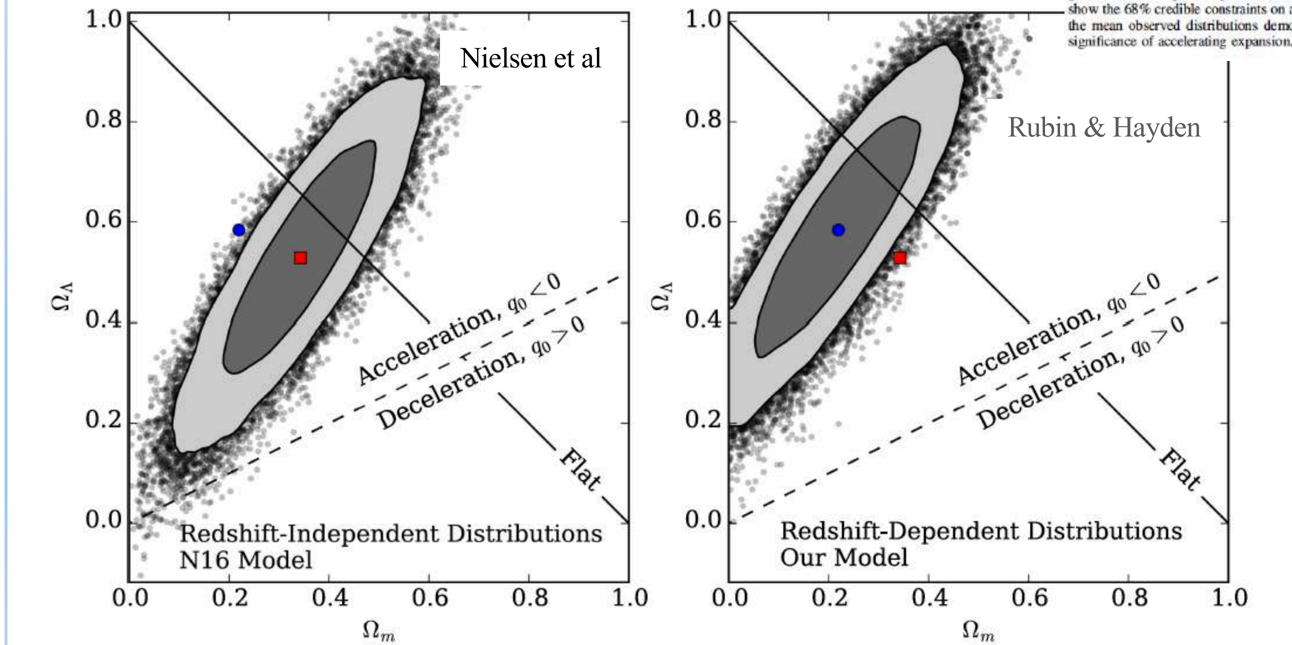
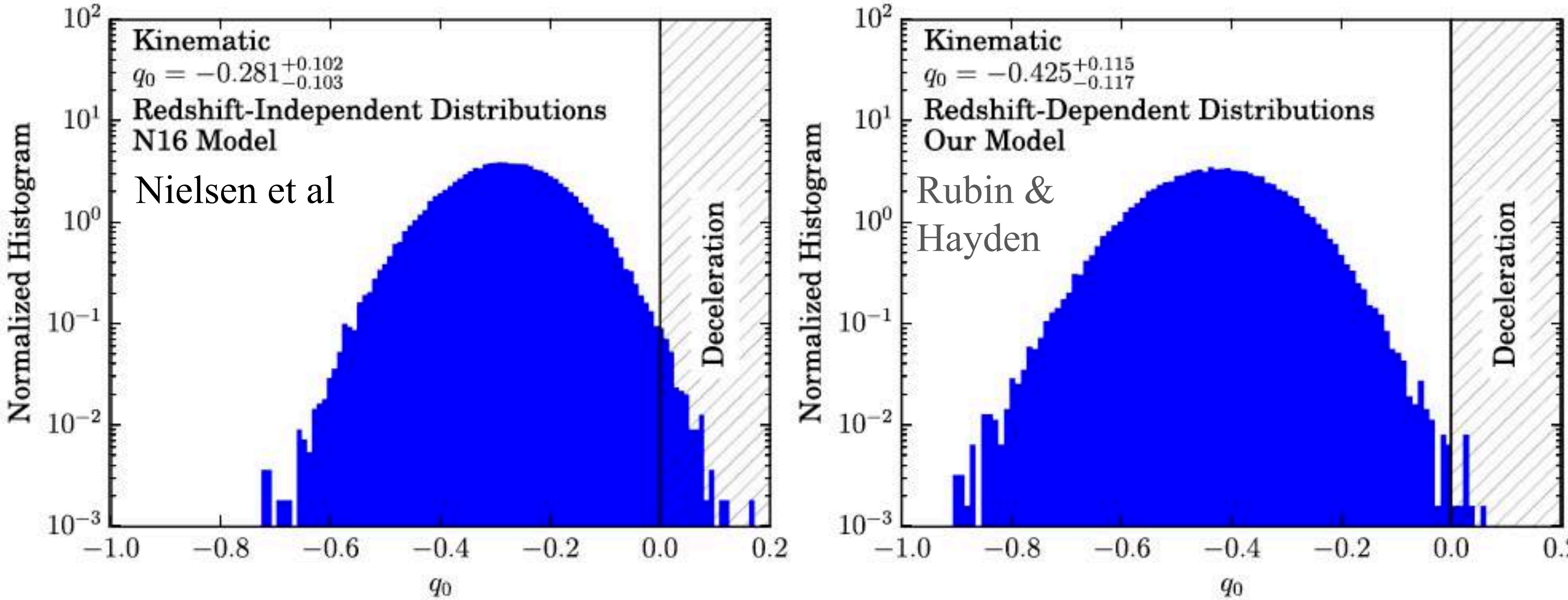


Figure 2. Ω_m–Ω_Λ constraints enclosing 68.3% and 95.4% of the samples from the posterior. Underneath, we plot all samples. The left panel shows the constraints obtained with x_1 and c distributions that are constant in redshift, as in the N16 analysis; the right panel shows the constraints from our model. The red square and blue circle show the location of the median of the samples from the respective posteriors.

In any case this raises the significance with which a non-accelerating universe is rejected to only ≲4σ ... still inadequate to claim a 'discovery' (even though the dataset has increased from ~100 to 740 SNe Ia in 20 yrs)

The data can be analysed by expanding the time variation of the scale factor in a Taylor series, *without* reference to the ΛCDM model



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

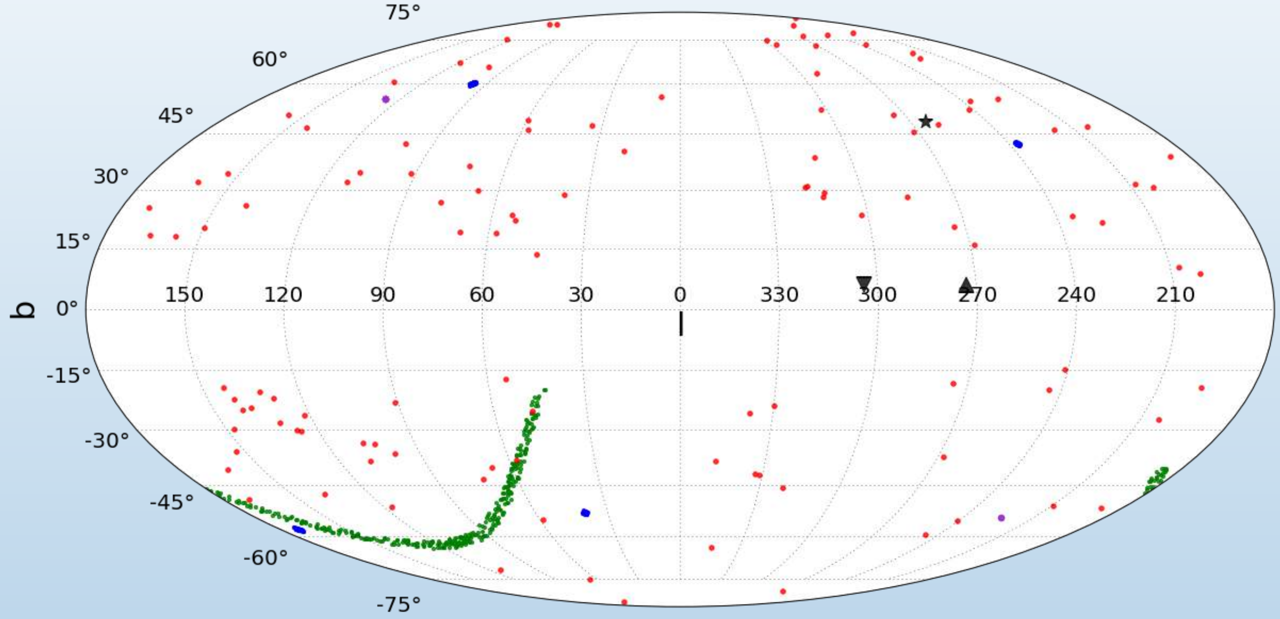
$$d_L(z) = \frac{c\,z}{H_0}\left\{1 + \frac{1}{2}\left[1 - q_0\right] z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 + \frac{kc^2}{H_0^2\,a_0^2}\right] z^2 + O(z^3)\right\}$$

Deceleration parameter

$$q_0 \equiv -(\ddot{a}a)/\dot{a}^2 \qquad j_0 \equiv (\dddot{a}/a)(\dot{a}/a)^{-3}$$

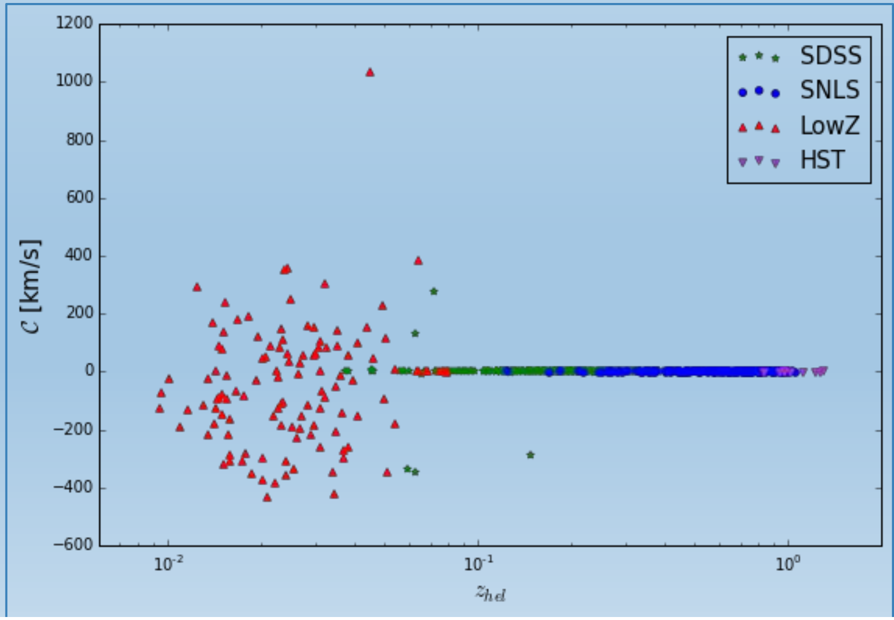
This yields 2.8σ evidence for acceleration in our approach … increasing to 3.7σ when an *ad-hoc* redshift-dependence is allowed in the light-curve parameters

The 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). Note that the 4 big blue dots are clusters of many individual SNe Ia. The directions of the CMB dipole (star), the SMAC bulk flow (triangle) and the 2M++ bulk flow (inverted triangle) are shown.



Subsequently we realised that the peculiar velocity `corrections' applied to the JLA catalogue are suspect … so *undid* them to recover the original data and test for isotropy

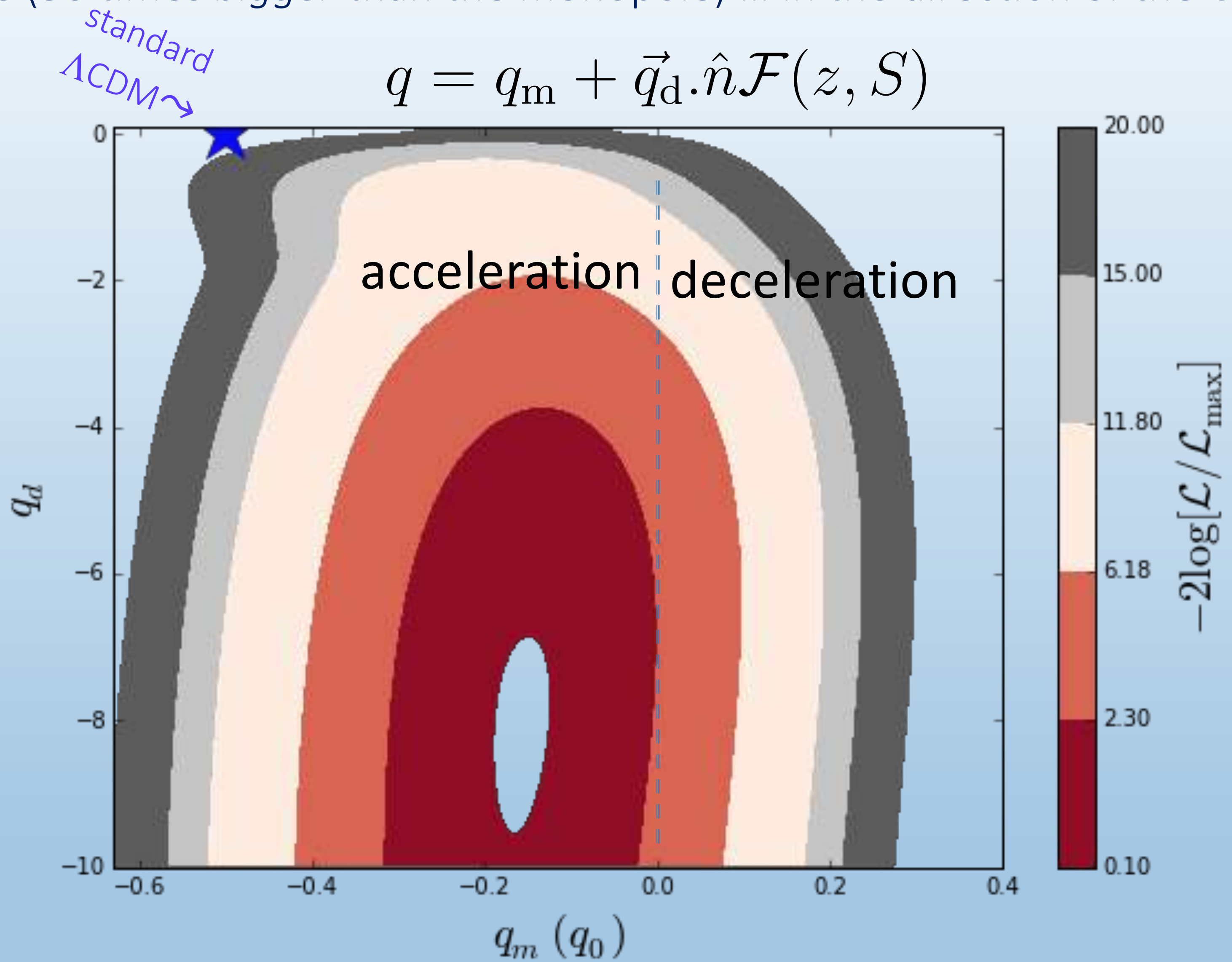
$$C = [(1 + z_{\rm hel}) - (1 + z_{\rm CMB})(1 + z_{\rm d})] \times c$$



$$z_{\rm d} = \sqrt{\frac{1 - \boldsymbol{v}_{\rm CMB-\odot}.\hat{n}/c}{1 + \boldsymbol{v}_{\rm CMB-\odot}.\hat{n}/c}} - 1$$

Moreover when the JLA catalogue is analysed allowing for a dipole, we find the MLE *prefers* one (50 times *bigger* than the monopole) … in the direction of the CMB dipole

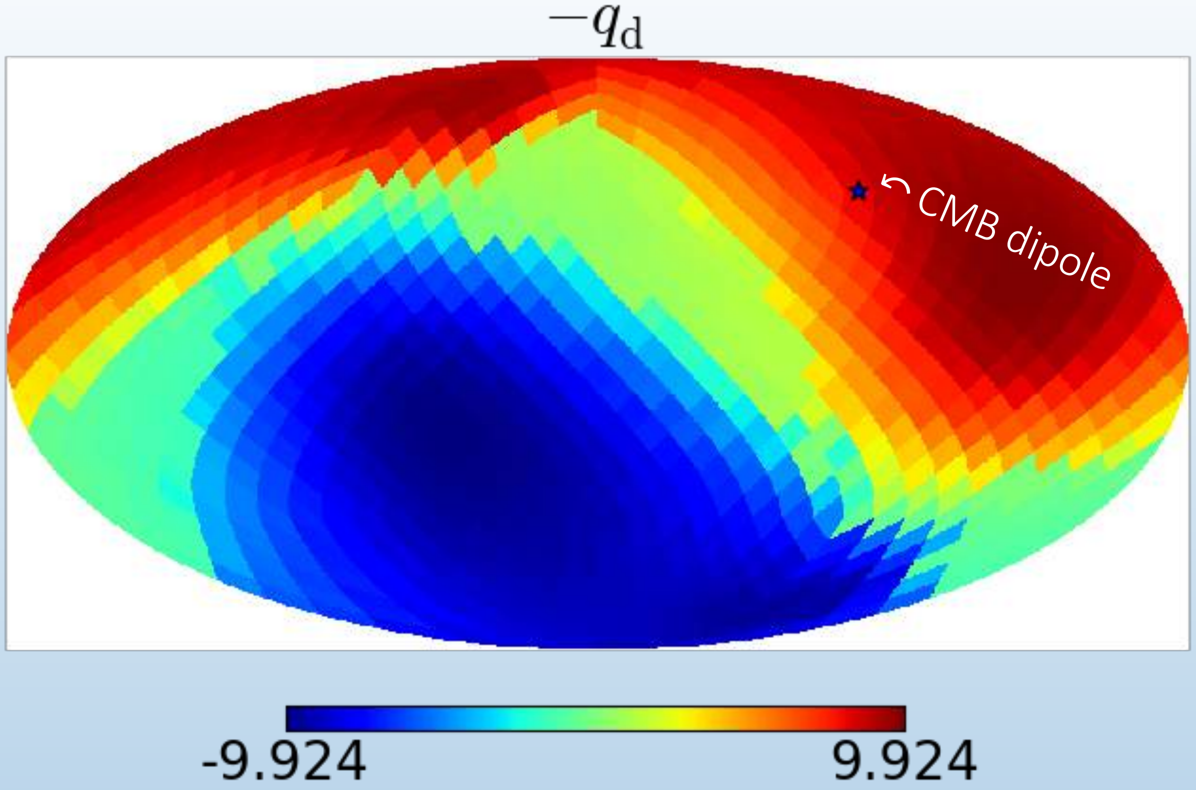
$$q = q_{\rm m} + \vec{q}_{\rm d}.\hat{n}\mathcal{F}(z,S)$$



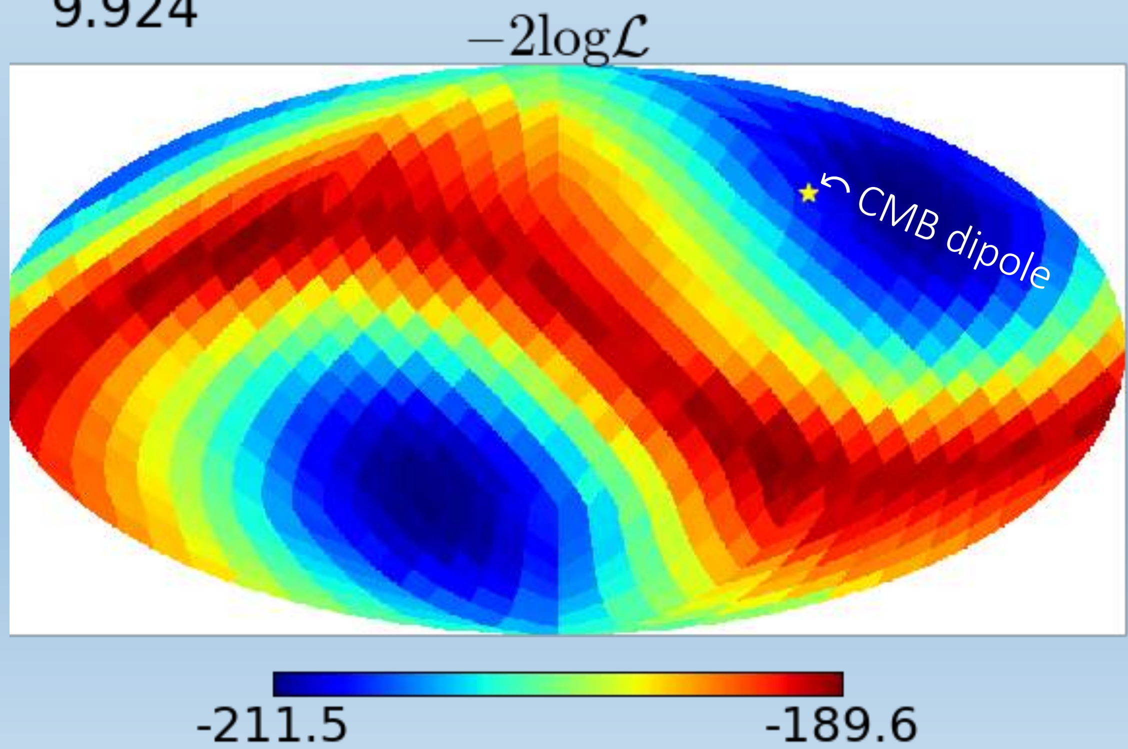
Colin, Mohayaee, Rameez & Sarkar, A&A **631**:L13,2019

The significance of q_o being negative has now *decreased* to only 1.4σ

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



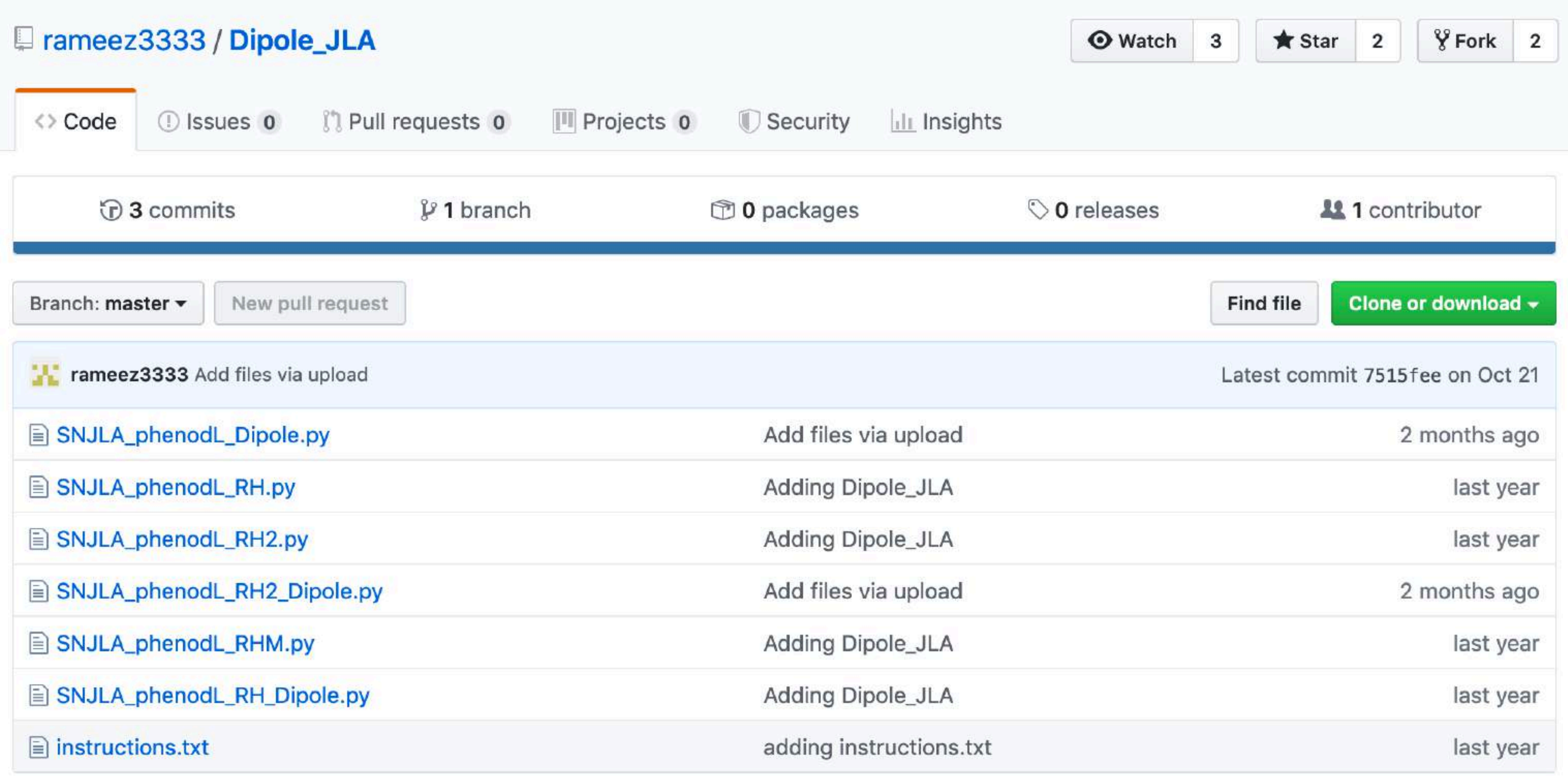
There is not enough data to do an *a priori* scan of the best-fit direction of q_d … but if done *a posteriori* it is found to be within 23^0 of the CMB dipole



The log-likelihood changes by just 3.2 between the two directions i.e. the direction of the acceleration

Colin, Mohayaee, Rameez & Sarkar, A&A **631**:L13,2019

All results may be reproduced using the *public* JLA catalogue and our code available at:
https://github.com/rameez3333/Dipole_JLA



Don’t take anyone’s word for it!

"For the Pantheon catalogue (Scolnic et al. 2018) the z_{hel} values and individual contributions to the covariance are not public, and moreover there are unresolved concerns about the accuracy of the data therein (Rameez 2019) so we cannot use it" - Colin *et al*, A&A **631**:L13,2019

Scolnic et al. Supernova Catalog

You can download the Pantheon catalog of supernovae parameters, as well as simulated or input/statistics files, from the table below. Consult the PS1COSMO homepage for information on what types of files are located in each directory.

Pantheon SN Parameters (.txt)	Pantheon Systematic Error Matrix (.txt)	binned_data/	data_fitres/	sim_fitres/	spec_summary/

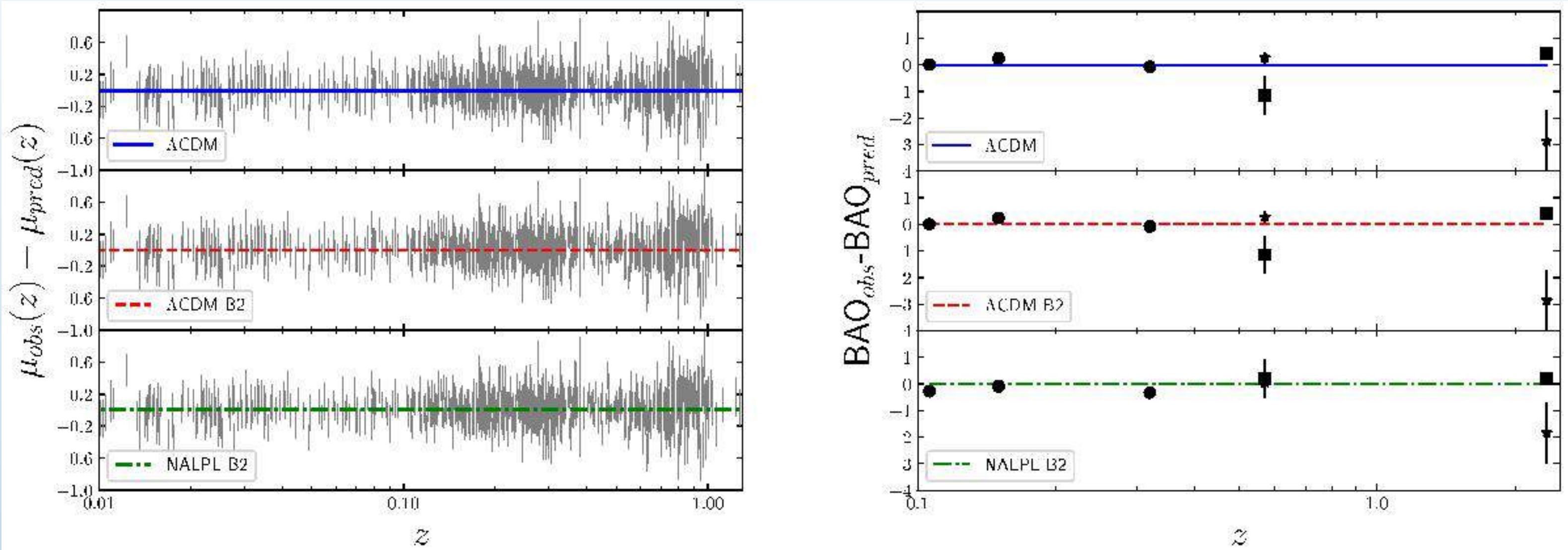
The interactive table below contains the supernovae parameters from the Scolnic et al. catalog. Some of the columns are sortable, by clicking on the column headers. Below some headers are text boxes that allow for filtering as well. These support basic text and numerical expressions. For example, if you want to filter the table to on include supernovae with zhel greater than 0.5, type "> 0.5" (without the quotes) under the "ZHEL" column. Note you can still sort the column with a filter applied.

1 to 100 of 1048 rows **Rows Per Page:** 100 **Jump To Page:** 1

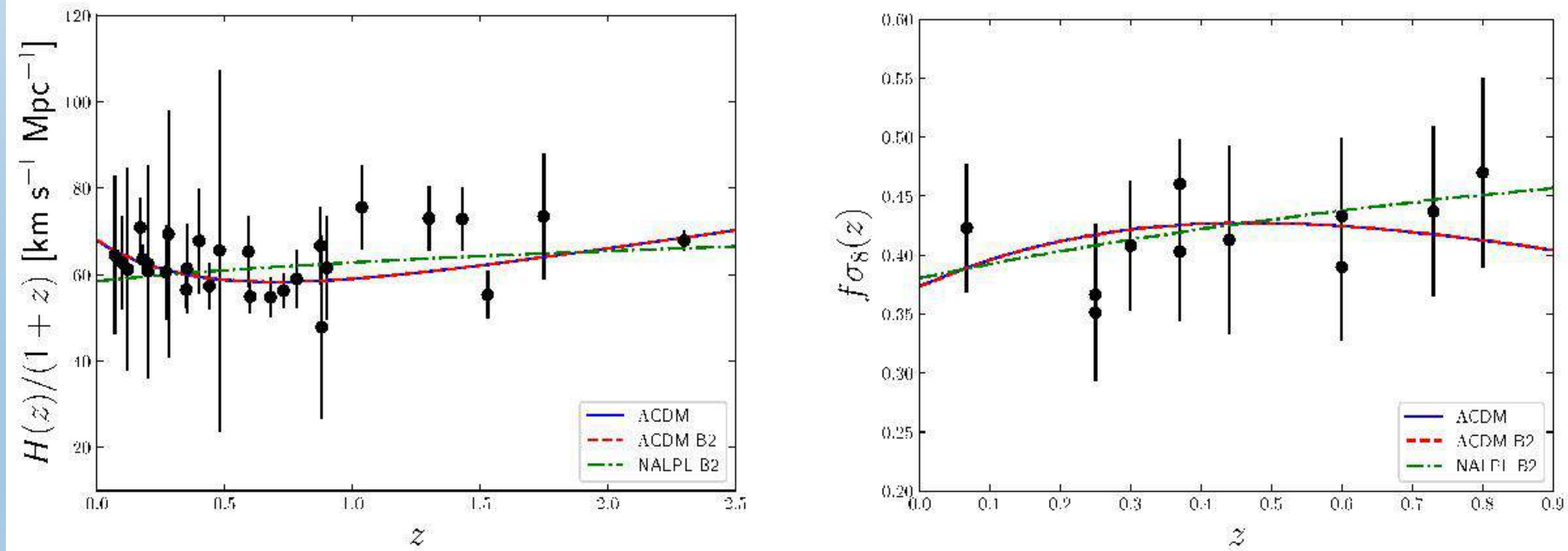
Target ID (sortable)	ZCMB (sortable)	ZHEL (sortable)	DZ (sortable)	MB (sortable)	DMB (sortable)
Type filter...	Type filter...	Type filter...	Type filter...	Type filter...	
03D1au	0.50309	0.50309	0.0	22.93445	0.12605
03D1aw	0.58073	0.58073	0.0	23.52355	0.1372
03D1ax	0.4948	0.4948	0.0	22.8802	0.11765
03D1bp	0.34593	0.34593	0.0	22.11525	0.111
03D1co	0.67767	0.67767	0.0	24.0377	0.2056
03D1ew	0.8665	0.8665	0.0	24.34685	0.17385
03D1fc	0.33094	0.33094	0.0	21.7829	0.10685
03D1fq	0.79857	0.79857	0.0	24.3605	0.17435
03D3aw	0.44956	0.44956	0.0	22.78895	0.14135
03D3ay	0.37144	0.37144	0.0	22.28785	0.1245
03D3ba	0.29172	0.29172	0.0	21.47215	0.12535
03D3bl	0.35582	0.35582	0.0	22.05915	0.12645
03D3cd	0.46127	0.46127	0.0	22.62945	0.13775

https://archive.stsci.edu/prepds/ps1cosmo/scolnic_datatable.html

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



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

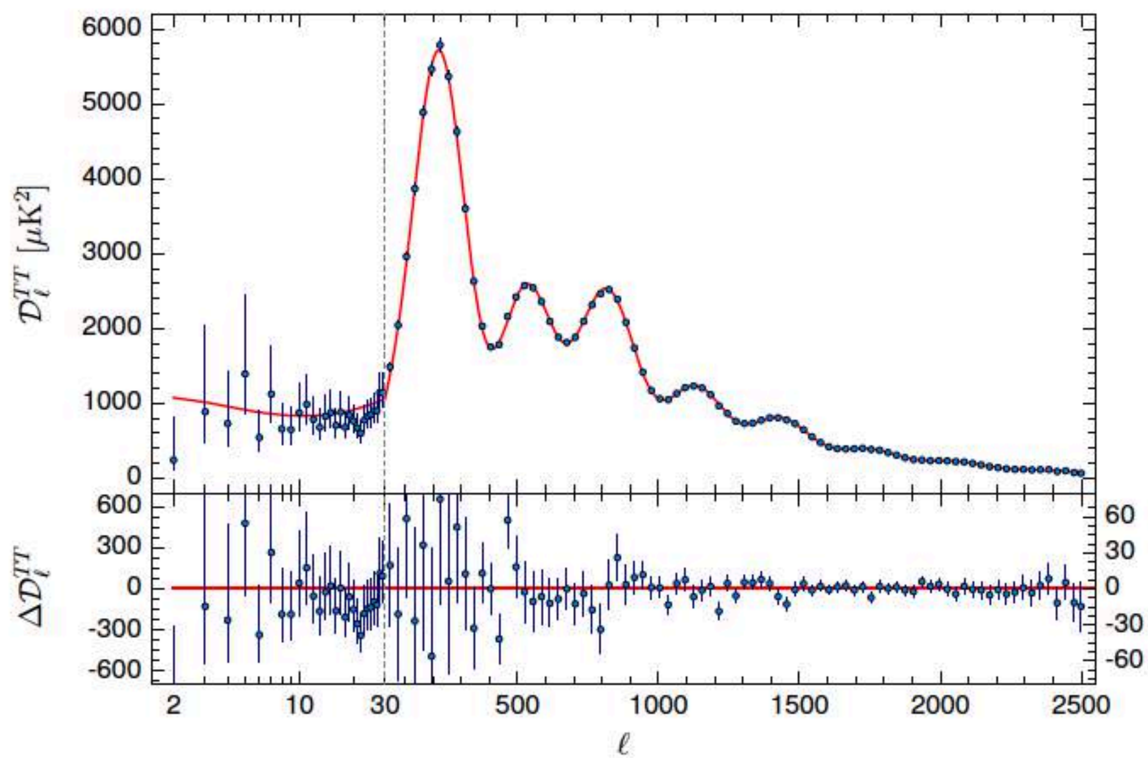


Tutusaus, Lamine, Dupays & Blanchard, A&A **602**:A73,2017

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?

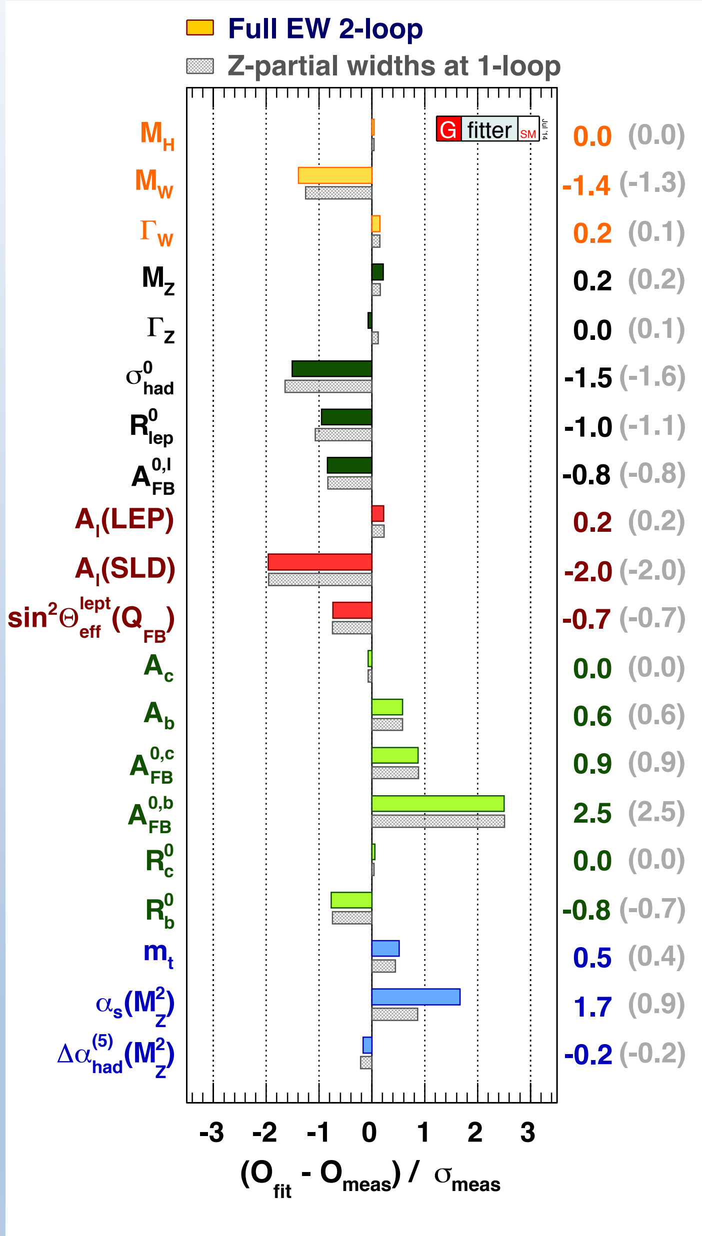


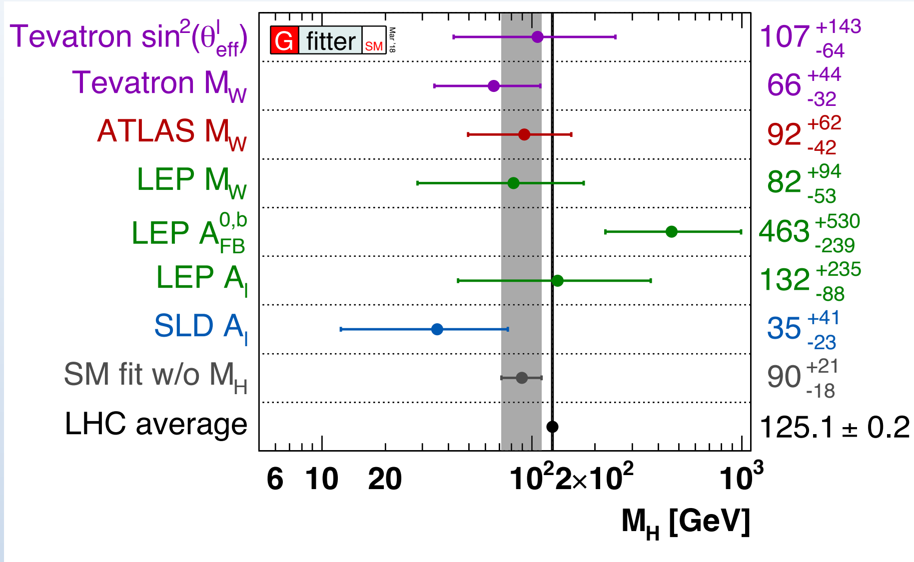
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 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

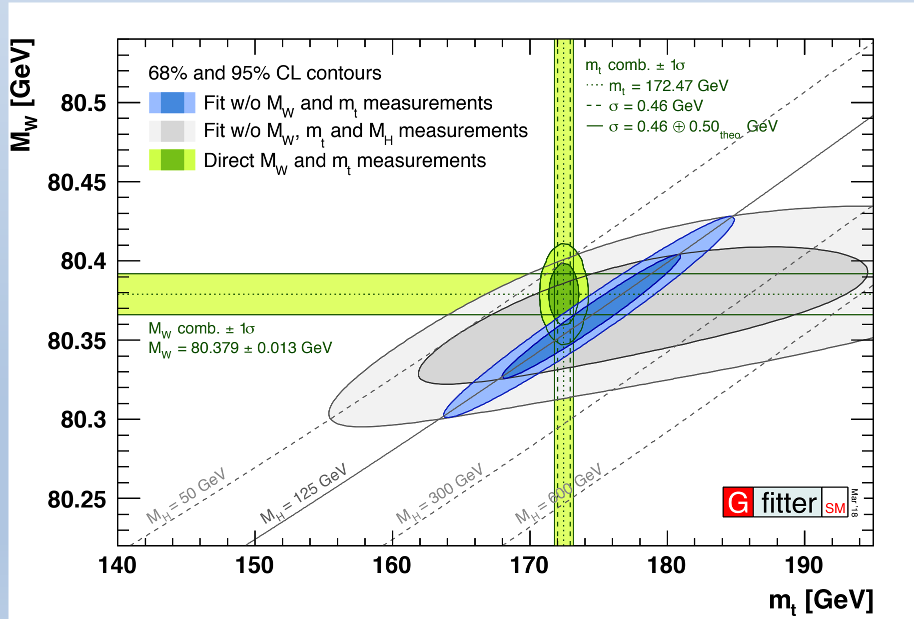
Where is the entry for Λ?!

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

Results for the Global Electroweak Standard Model Fit







Should we reject any possibility of deviations from the SM … because it all fits so well?

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 is likely an artefact of the local bulk flow … there is a strong dipole in q_0 aligned with the bulk flow, and the monopole drops in significance to be consistent with zero

Could all this be an indication of new horizon-scale physics?

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

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