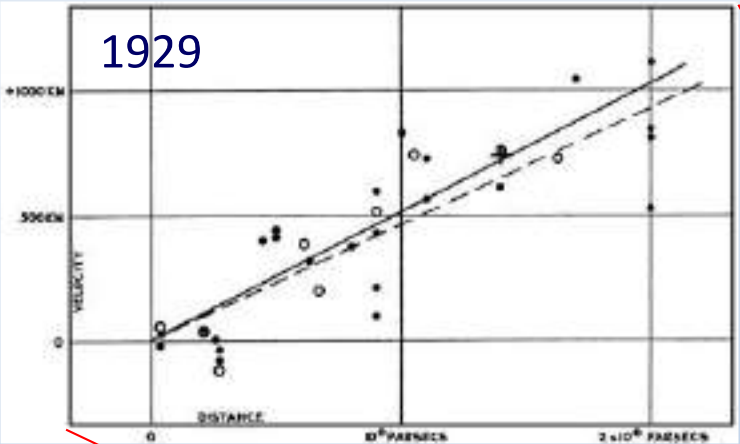
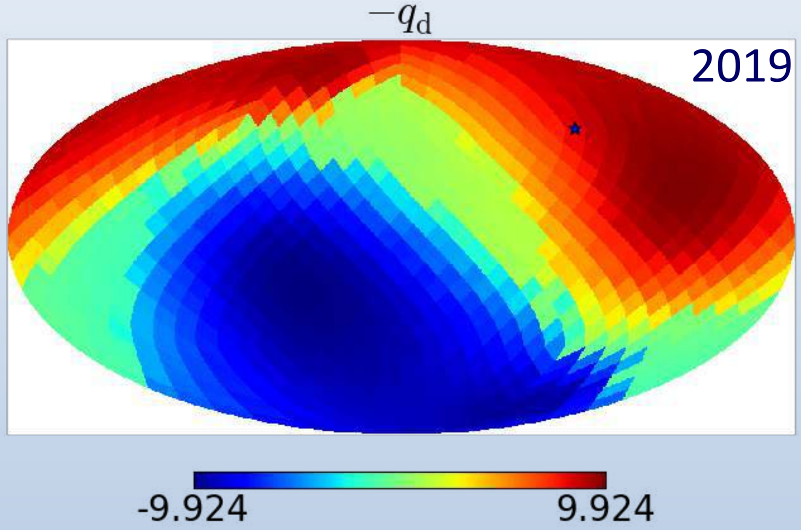
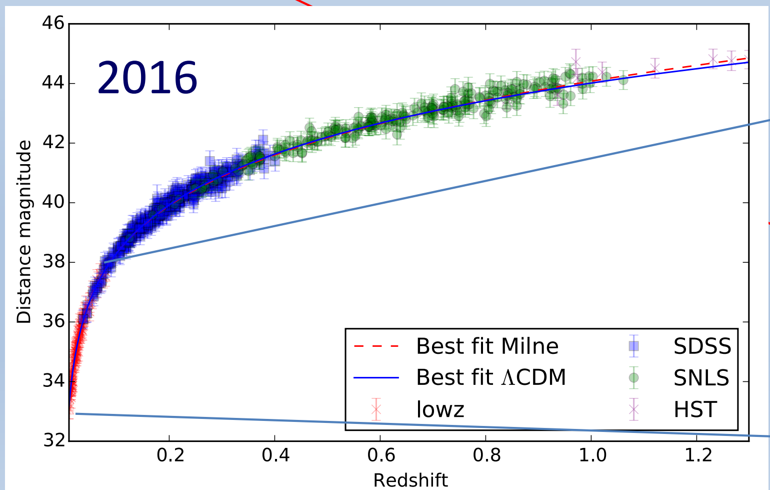
Evidence for anisotropy of cosmic acceleration

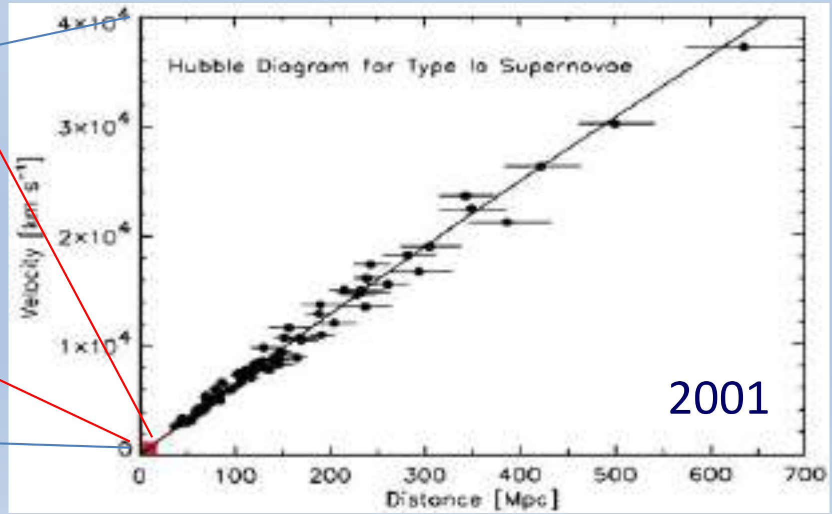
Subir Sarkar

Rudolf Peierls Centre for Theoretical Physics



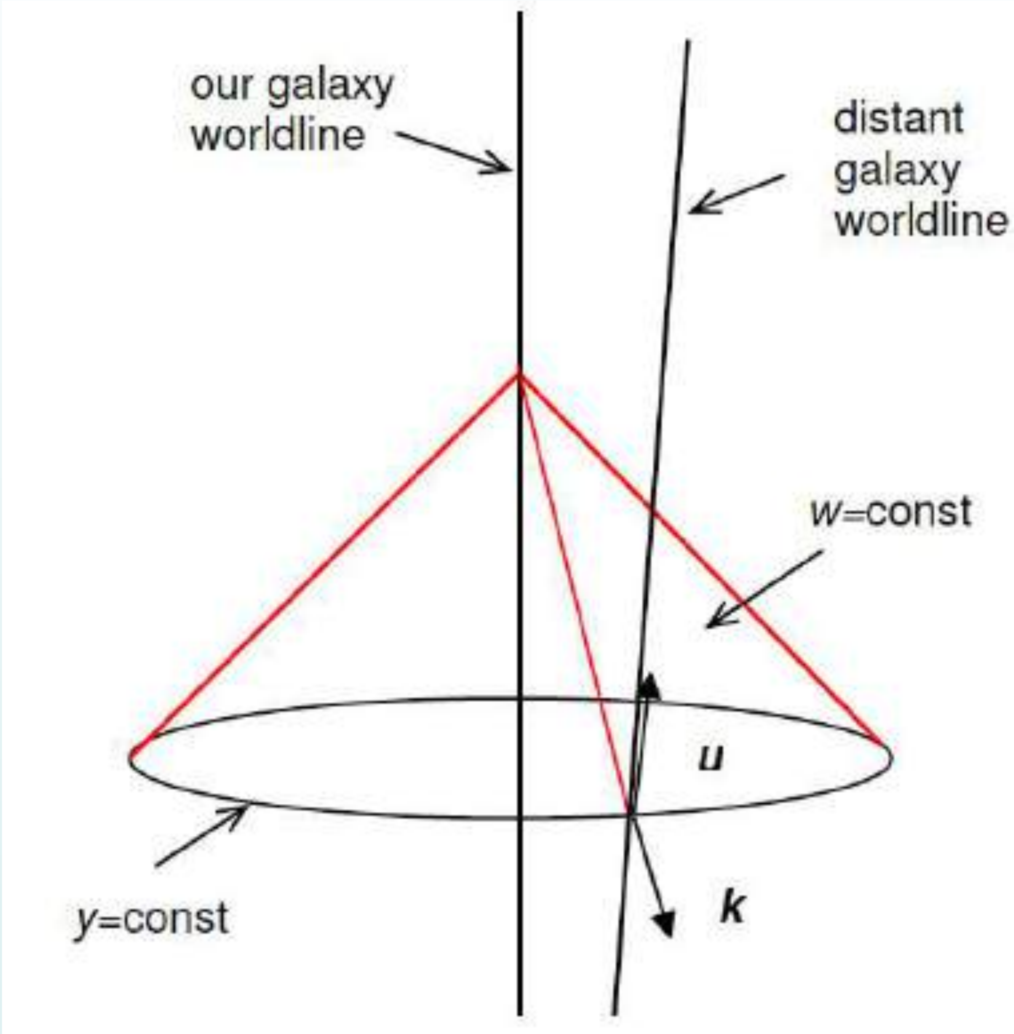






Colin, Mohavaee, Rameez & S.S., A&A **631:** L13, 2019

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

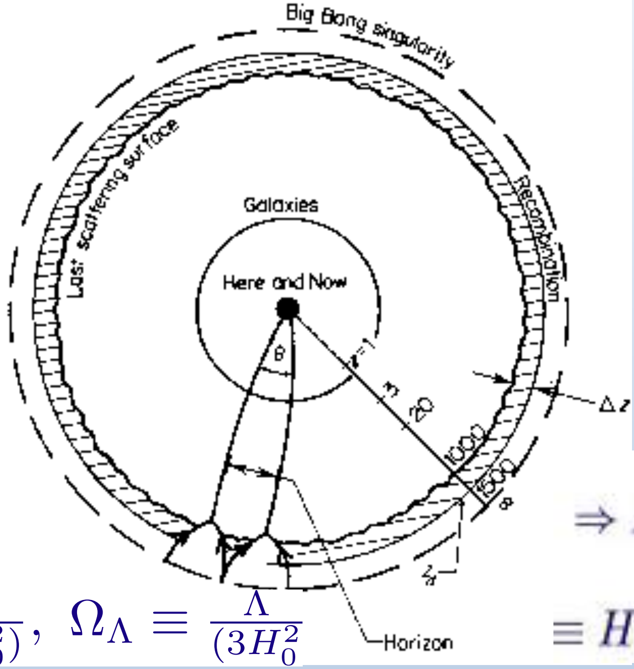
$$ds^2 \equiv g_{\mu\nu} dx^\mu dx^\nu$$

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

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

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

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

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

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

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

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

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

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)

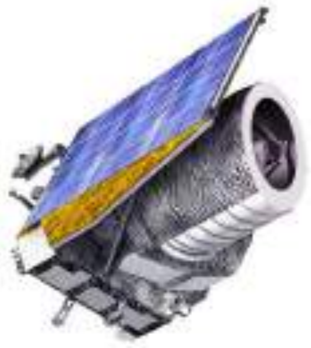
➞ infer universe is dominated by **dark energy**: $\Omega_\Lambda = 1 - \Omega_m - \Omega_k \sim 0.7 \Rightarrow \boldsymbol{\Lambda \sim 2H_0^2}$

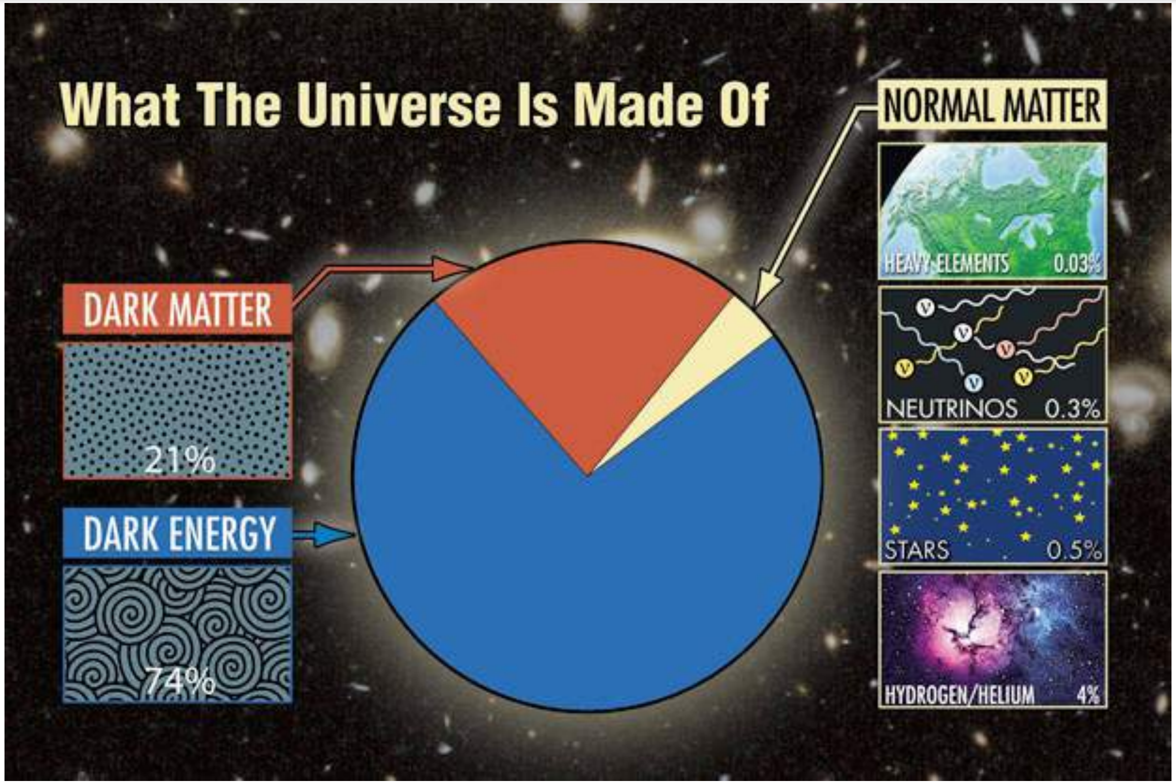
The scale is set by the *only* dimensionful parameter: $H_0 \sim 10^{-42}$ GeV

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!

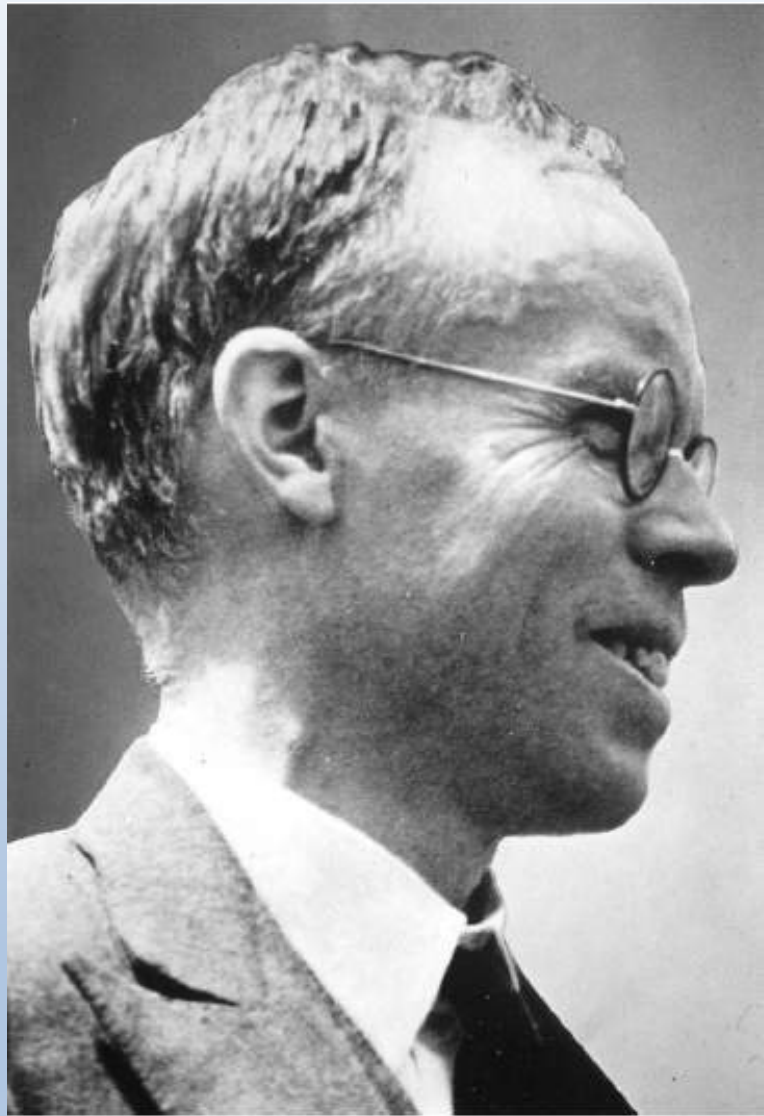
Since 1998 (Riess *et al.*[1], Perlmutter *et al.*[2]), surveys of cosmologically distant Type Ia supernovae (SNe Ia) have indicated an acceleration of the expansion of the Universe, distant SNe Ia being dimmer that expected in a decelerating Universe. With the assumption that the Universe can be described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

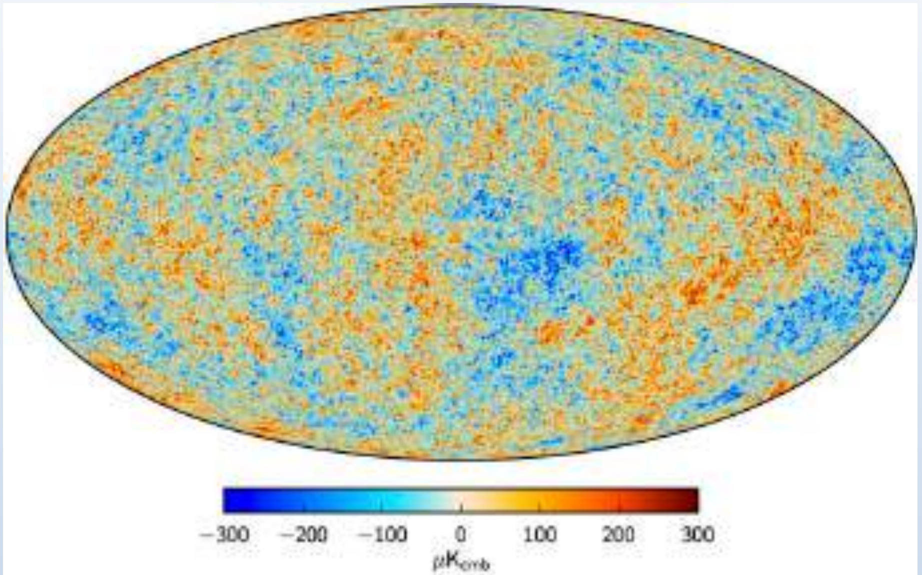
The Universe must appear to be the same to all observers wherever they are
*This '**cosmological principle**' …*

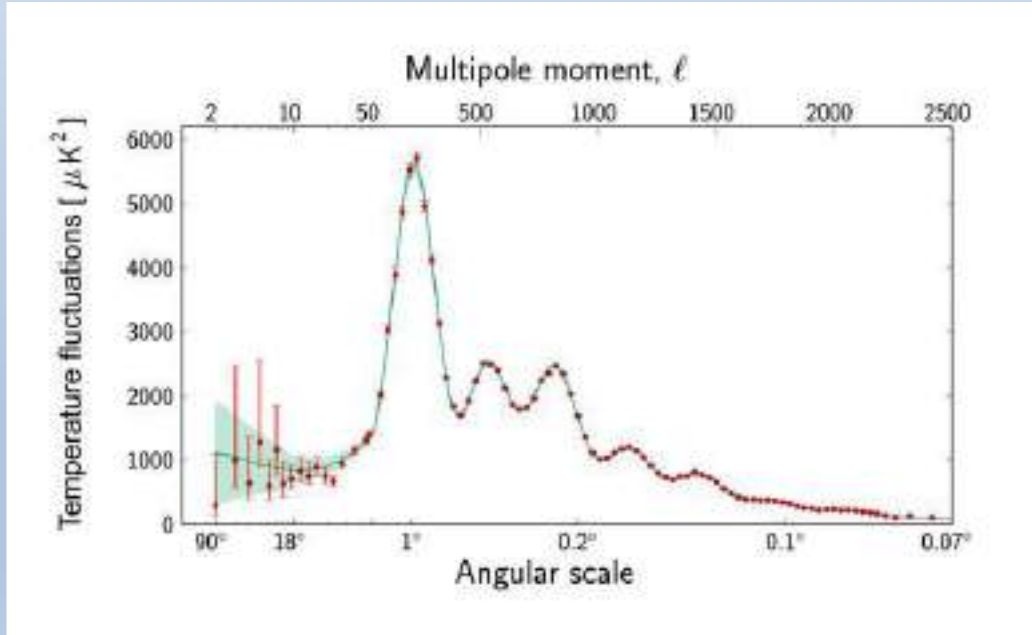


Edward Arthur Milne (1896-1950)

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

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

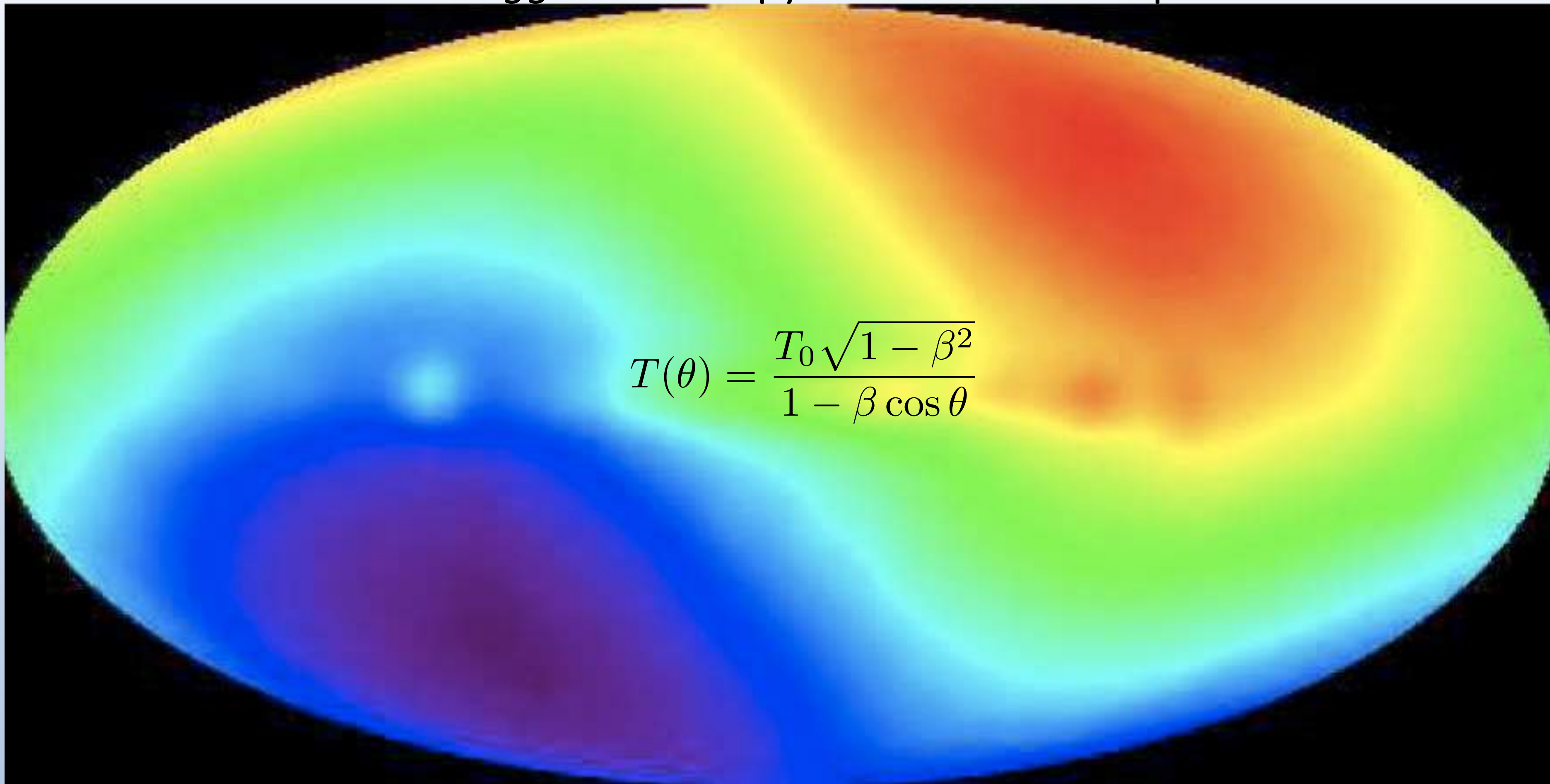




We observe a ~statistically isotropic ~Gaussian random field of small temperature fluctuations (quantified by the 2-point correlations ➛ angular power spectrum)

But the CMB sky is in fact *quite* anisotropic

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



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^o, b=29.6^o

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)

Count number of galaxies in a spheres of different radius, centred on each galaxy in survey.

$$D_q = \frac{\tau(q)}{q-1}$$

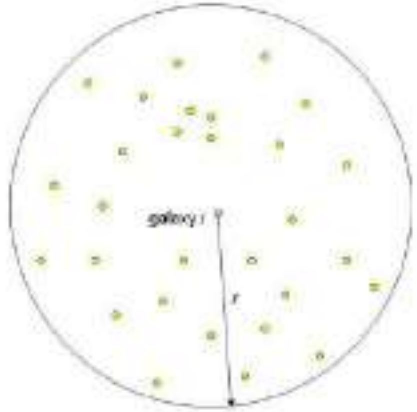
Scaling exponent

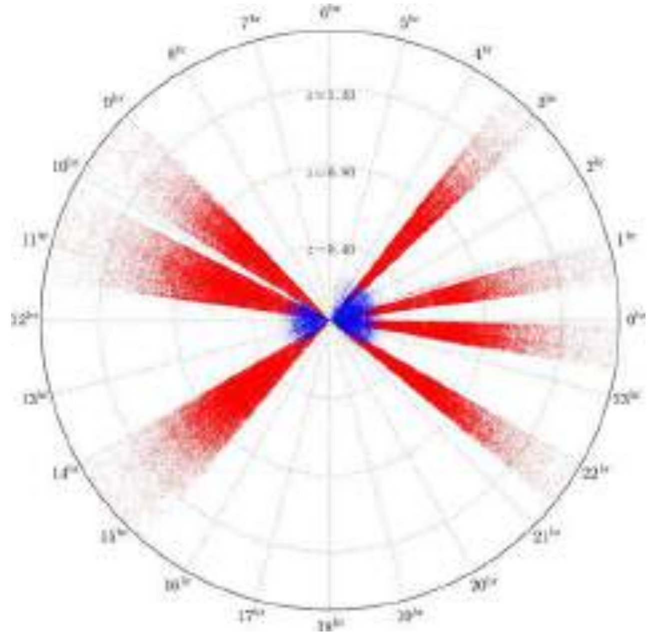
Set of generalised dimensions

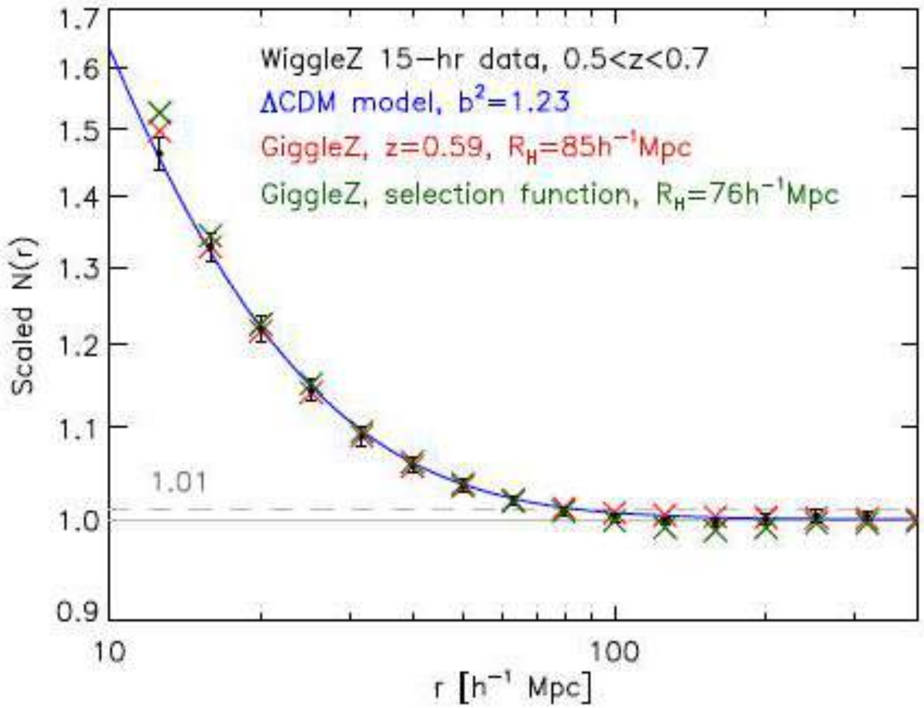
$$D_2 = 3 - \frac{d[\log \xi(r)]}{d[\log(r)]}$$

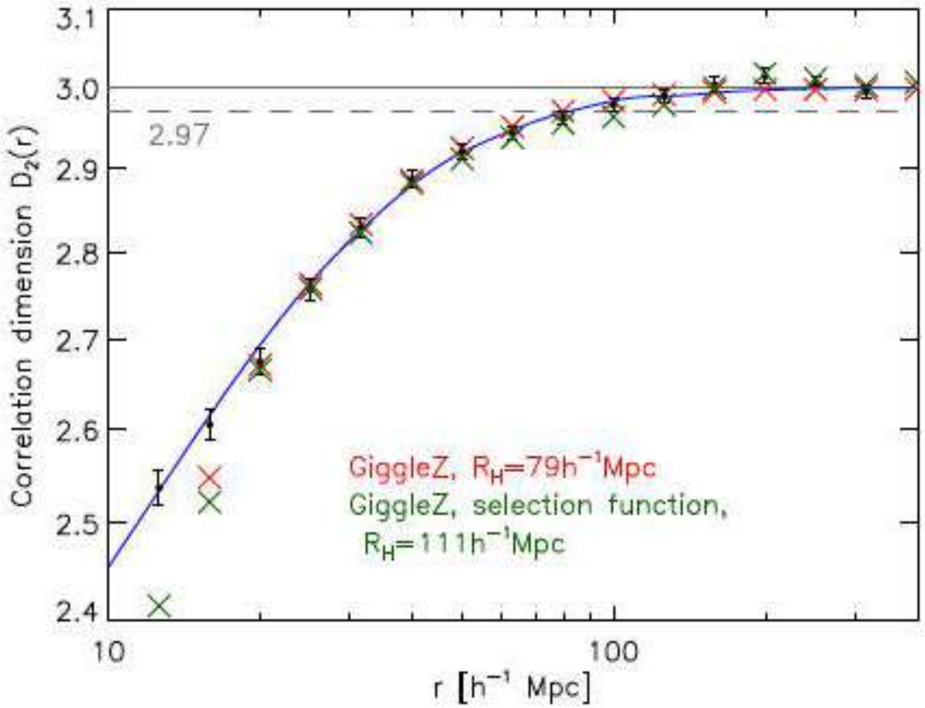
2PCF

Correlation dimension







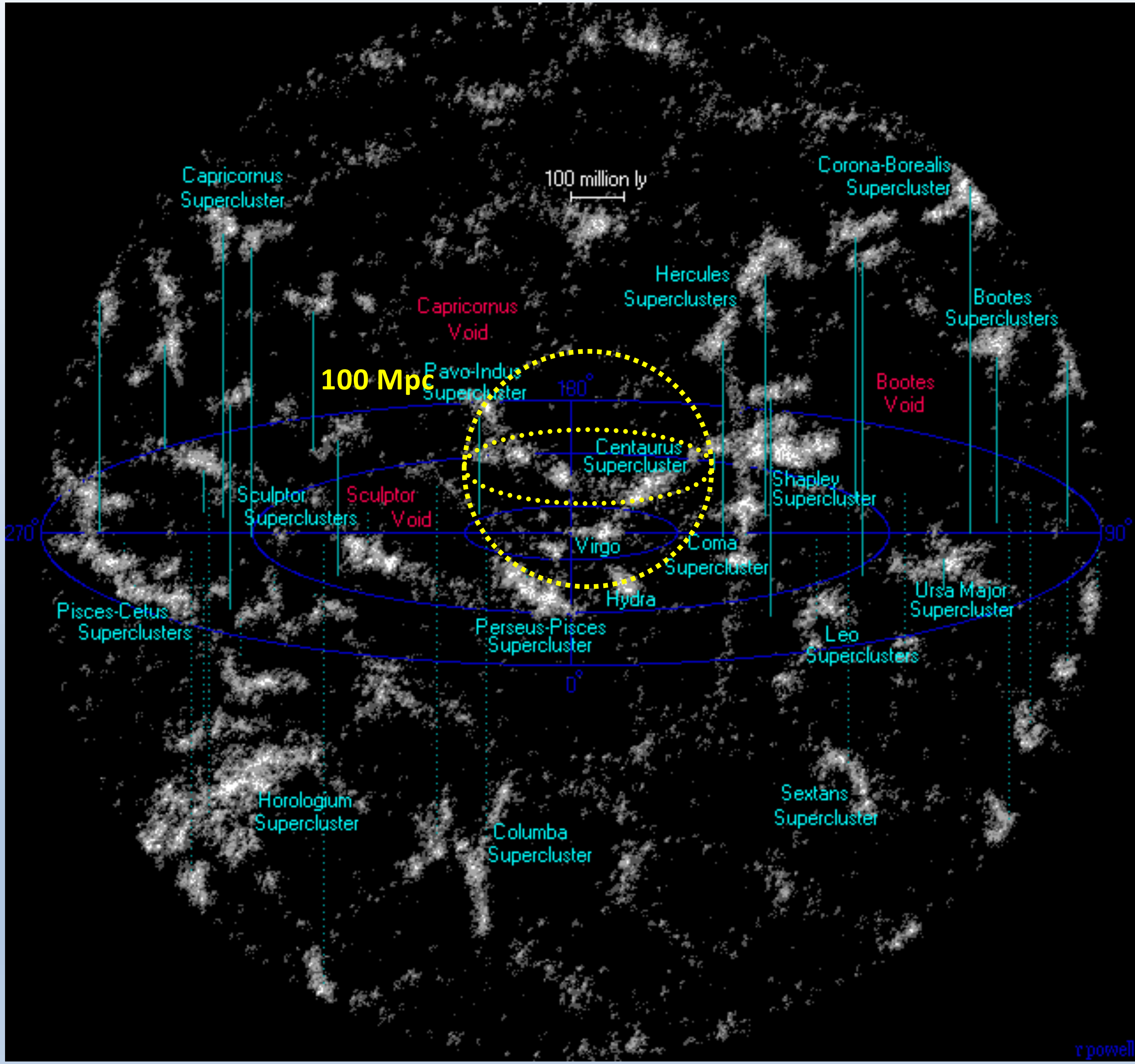


Scrimgeour *et al*, MNRAS **425**:116,2012

However the biggest spheres are *not* fully contained in the WiggleZ survey volume … so were filled with galaxies drawn from a ΛCDM model simulation!

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'



Courtesey: Richard Powell

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:

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

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

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

where $H_{\rm L}(\mathbf{x})$ 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 $\delta(\mathbf{k}) \equiv (2\pi)^{3/2} \int \mathrm{d}^3x\ \delta(\mathbf{x})\mathrm{e}^{i\mathbf{k}\cdot\mathbf{x}}$:

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

Window function

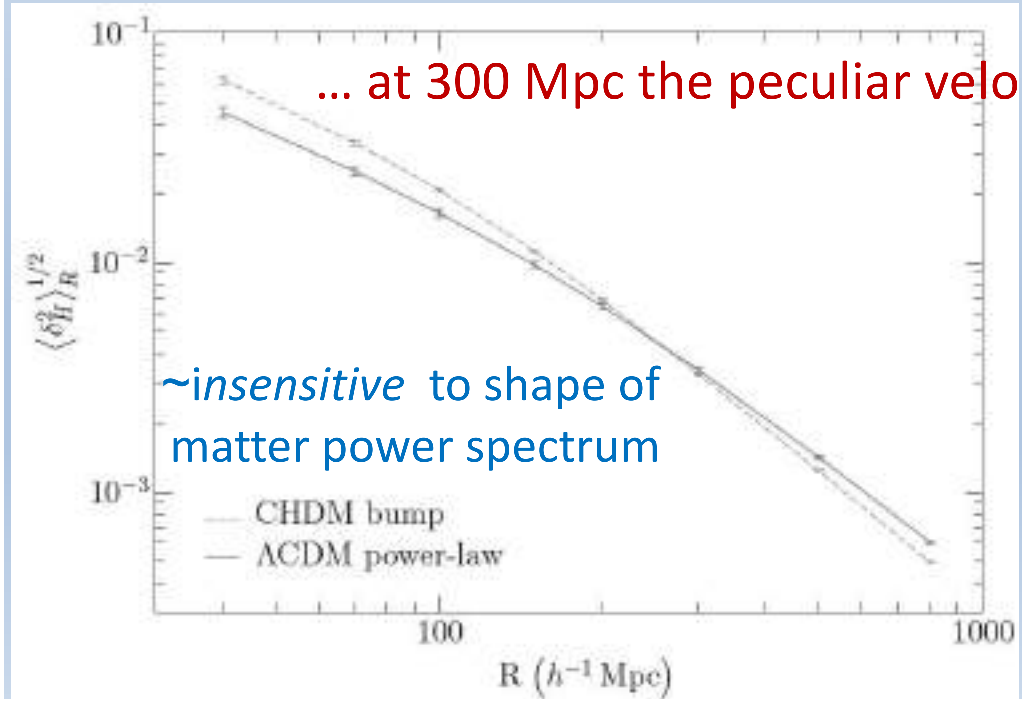
Then the RMS fluctuation in the local Hubble constant $\delta_H \equiv \langle(\delta H/H_0)^2\rangle^{1/2}$ is:

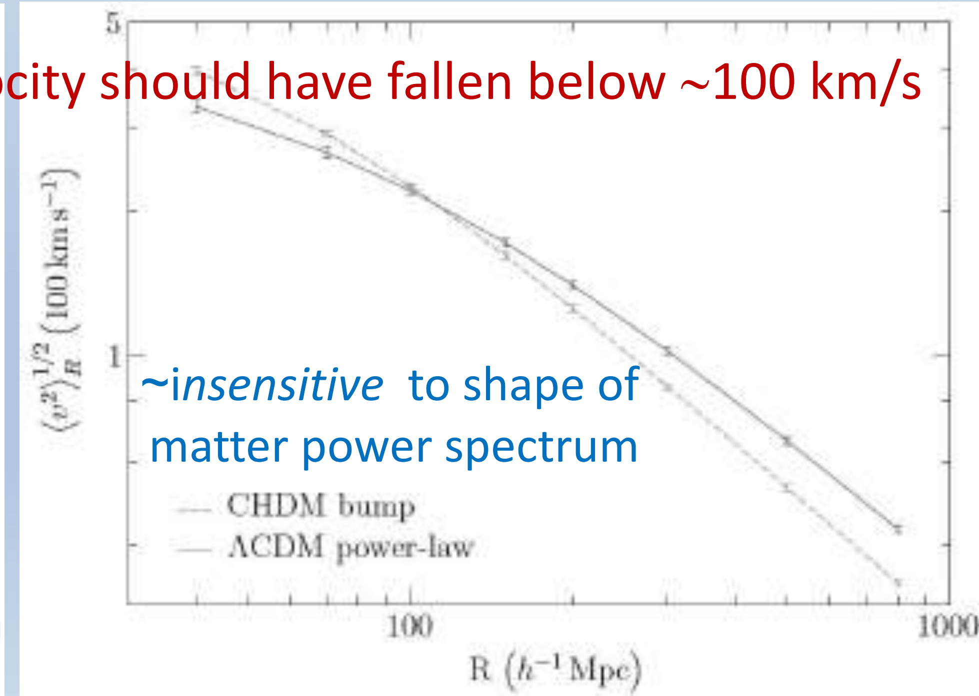
$$\delta_H^2 = \frac{f^2}{2\pi^2}\int_0^\infty k^2 \mathrm{d}k\ P(k)\mathcal{W}^2(kR),\ P(k) \equiv |\delta(k)^2|,\ f \simeq \Omega_{\mathrm{m}}^{4/7} + \frac{\Omega_\Lambda}{70}\left(1 + \frac{\Omega_{\mathrm{m}}}{2}\right)$$

Power spectrum of matter fluctuations — Growth rate

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

… at 300 Mpc the peculiar velocity should have fallen below ~100 km/s

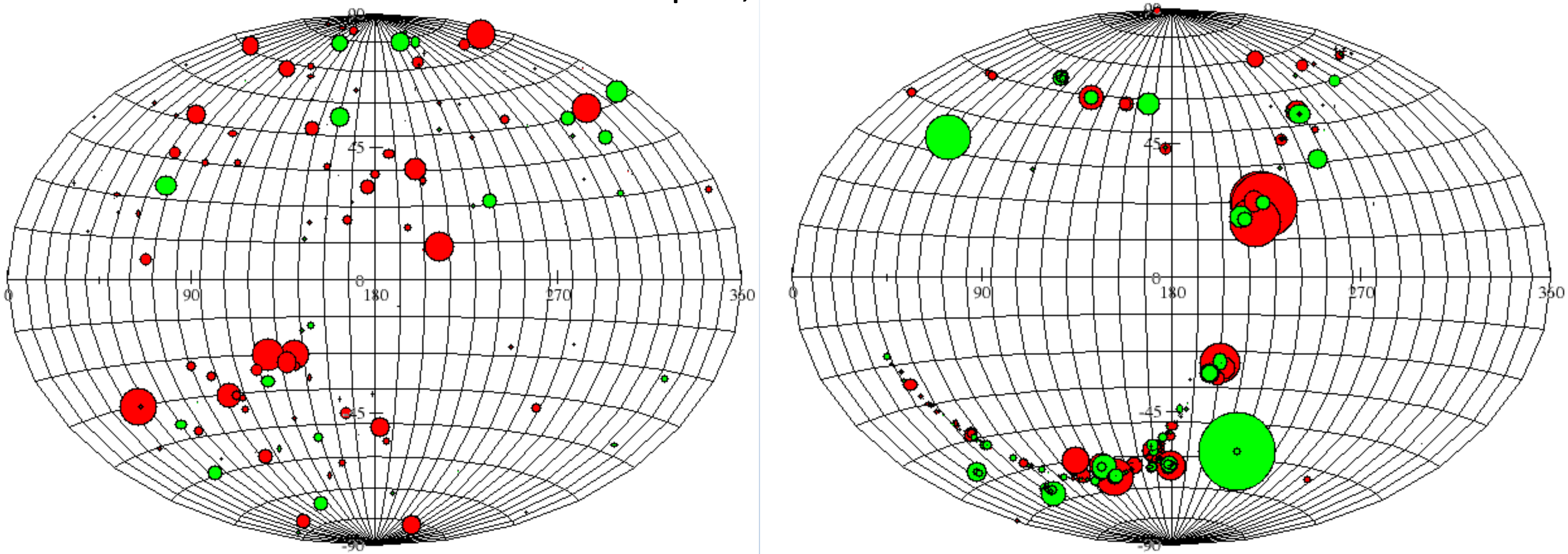




Hunt & S.S., MNRAS **401**:547,2010

Union 2 compilation of 557 SNe Ia

Aitoff-Hammer plot, Galactic coordinates

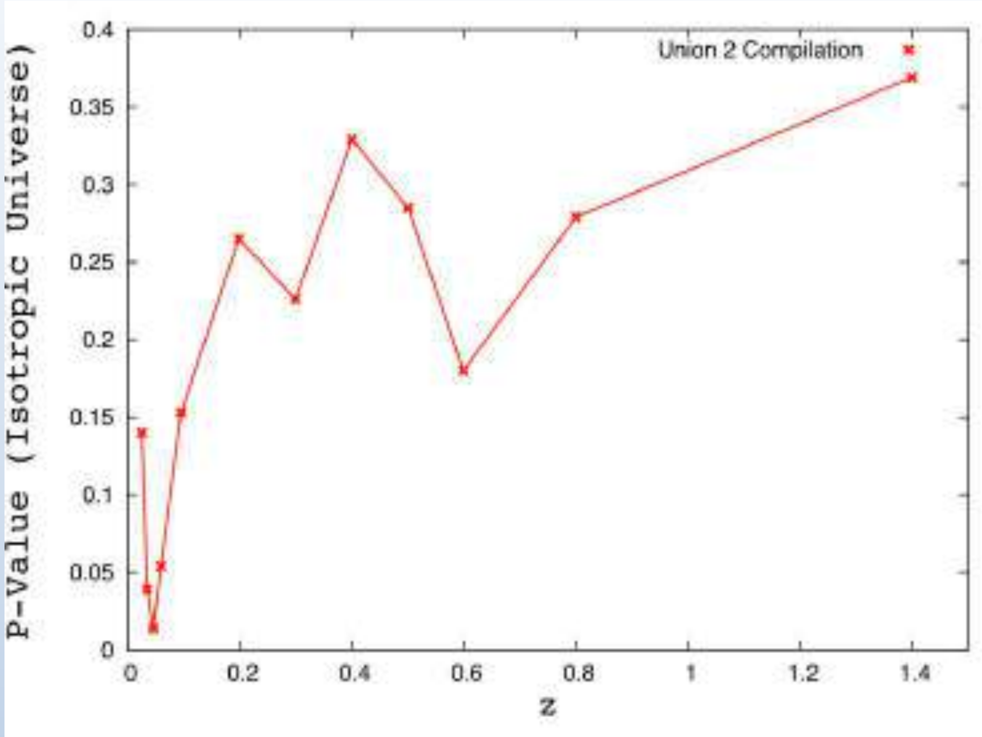


Colin, Mohayaee, S.S. & Shafieloo, MNRAS **414**:264,2011

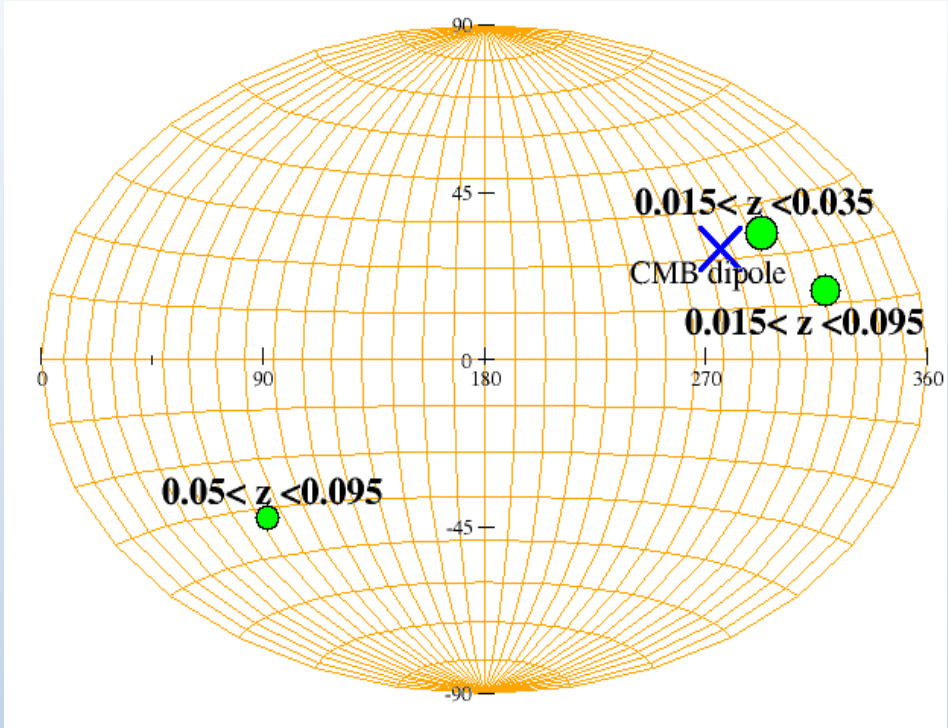
Left panel: The red spots represent the data points for $z < 0.06$ with distance moduli μ_{data} bigger than the values μ_{CDM} predicted by ΛCDM, and the green spots are those with μ_{data} less than μ_{CDM}; the spot size is a relative measure of the discrepancy. A dipole anisotropy is visible around 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 $z > 0.06$

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



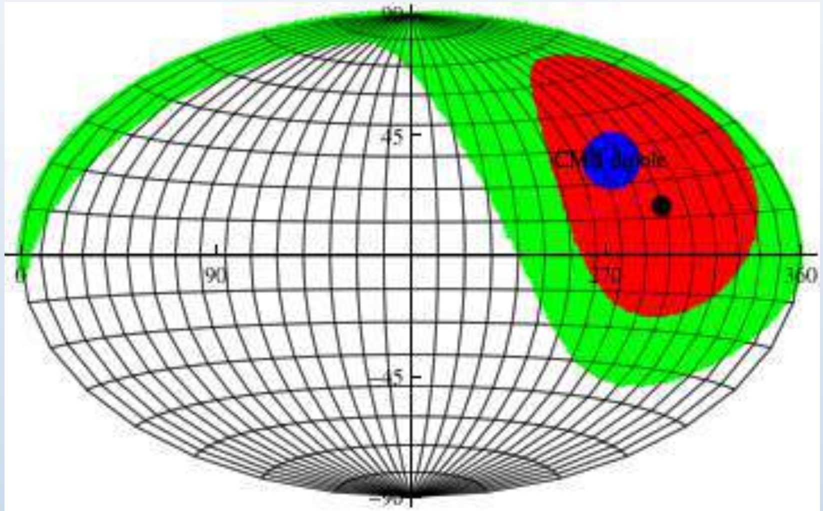
Left panel: P-value for the consistency of the isotropic universe with the data. At $z \approx 0.05$ (⇒200 Mpc) the P-value drops to 0.014 showing that isotropy is *excluded* at 3σ … i.e. we have *not* converged to the CMB rest frame even well beyond the scale where the universe supposedly becomes homogeneous.

Right panel: Cumulative analysis finds 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 runs out and there is consistency with isotropy within 1σ (P = 0.594).

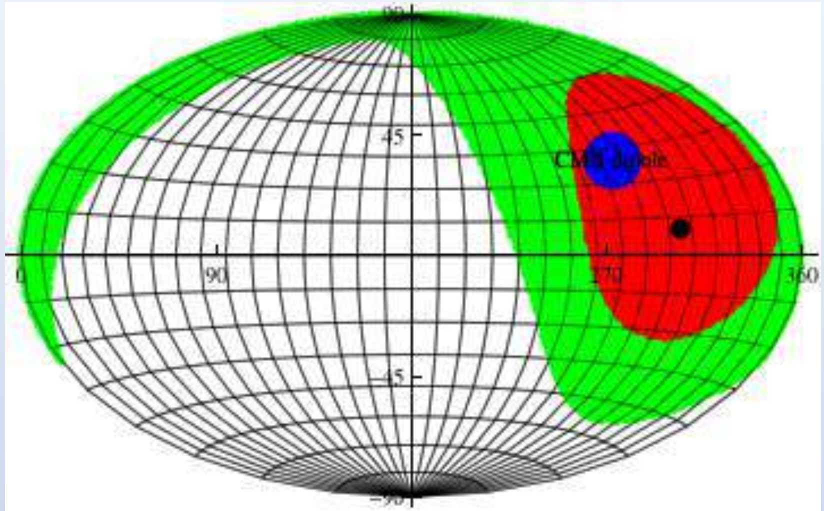
Maximum likelihood analysis can now be used to estimate the bulk flow at low redshifts where the velocities are not yet dominated by the cosmic expansion

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

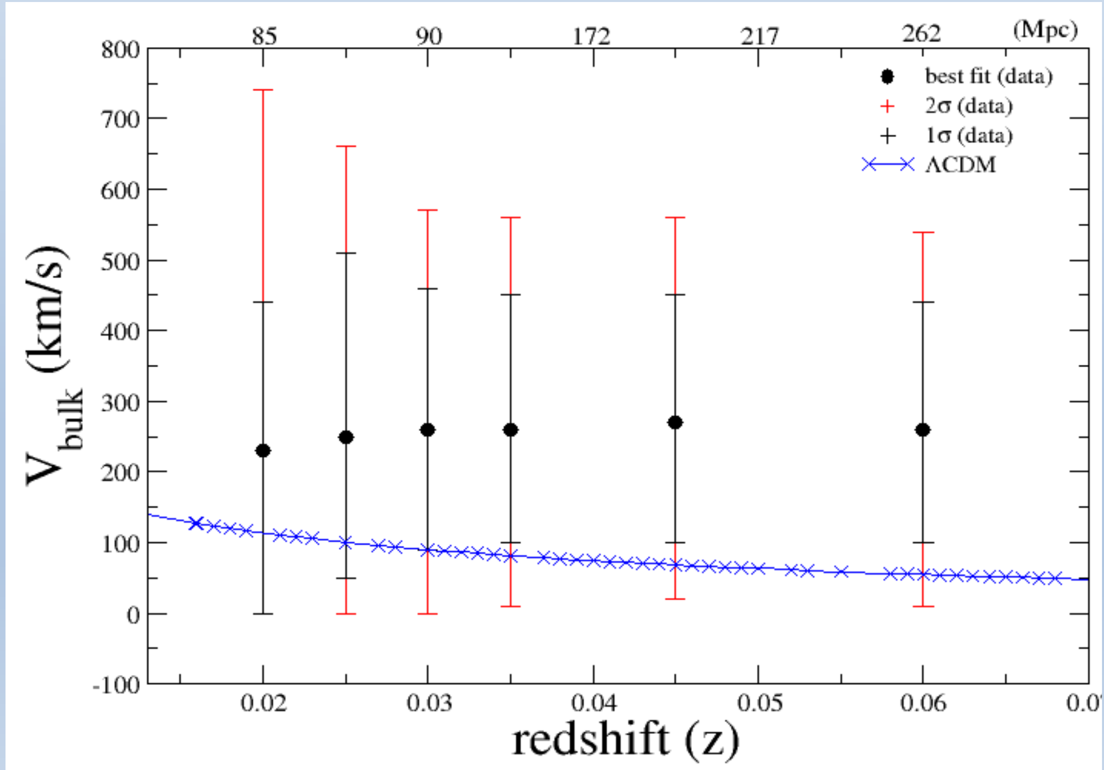
$0.015 < z < 0.045$, v = 270 km/s, l = 291, b = 15



$0.015 < z < 0.06$, 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

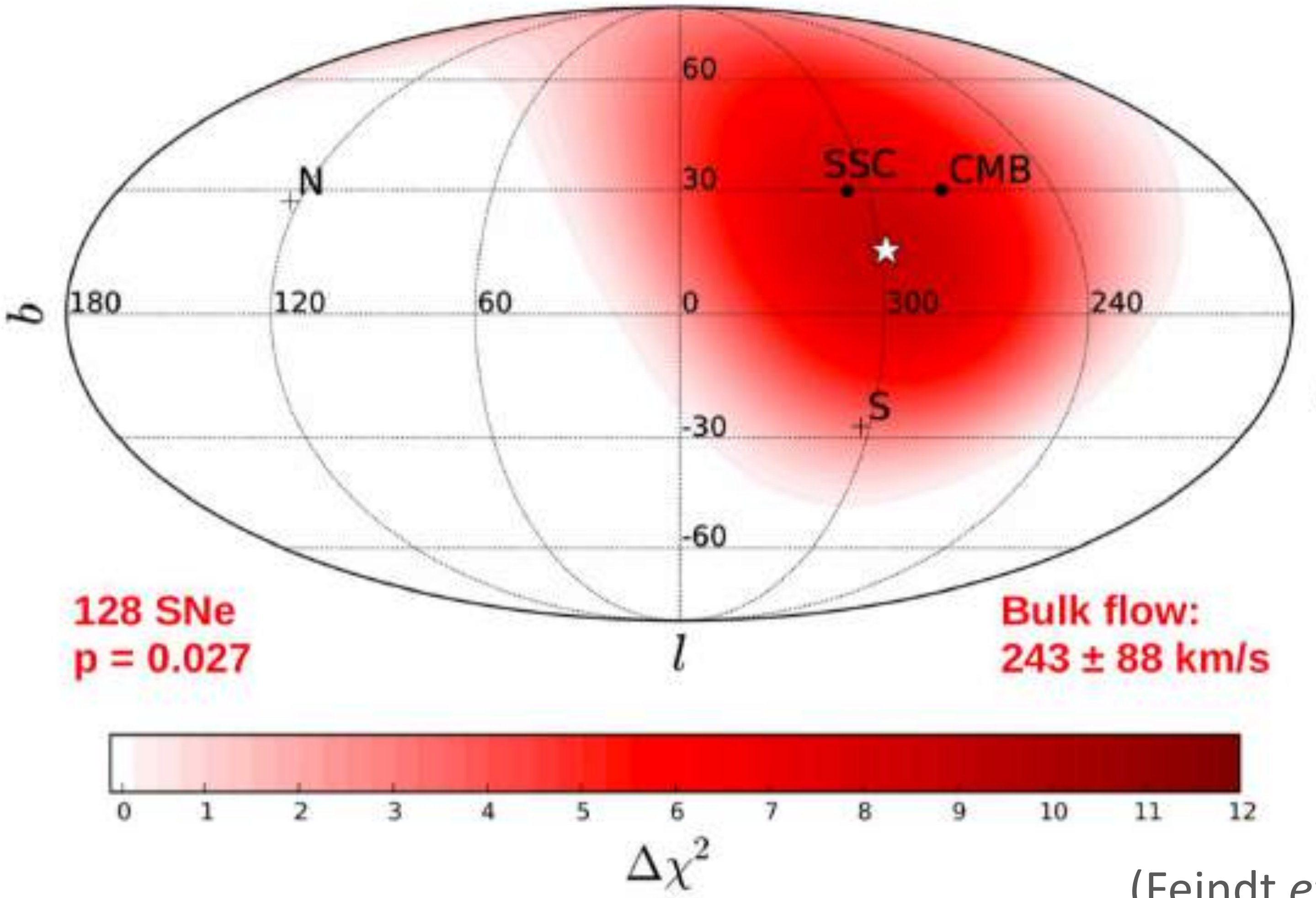
No convergence to CMB frame,even well beyond 'scale of homogeneity'

Bulk Flow Analysis

Courtesey: Ulrich Feindt

Dipole fit: $0.015 < z < 0.035$

Full dataset: 279 SNe ($z < 0.1$) from SNfactory & Union2 compilation



128 SNe
$p = 0.027$

Bulk flow:
243 ± 88 km/s

Bulk flow modeled as velocity dipole:

$$\tilde{d}_L(z) = d_L(z) + \frac{(1+z)^2}{H(z)} \vec{n} \cdot \vec{v}_d$$

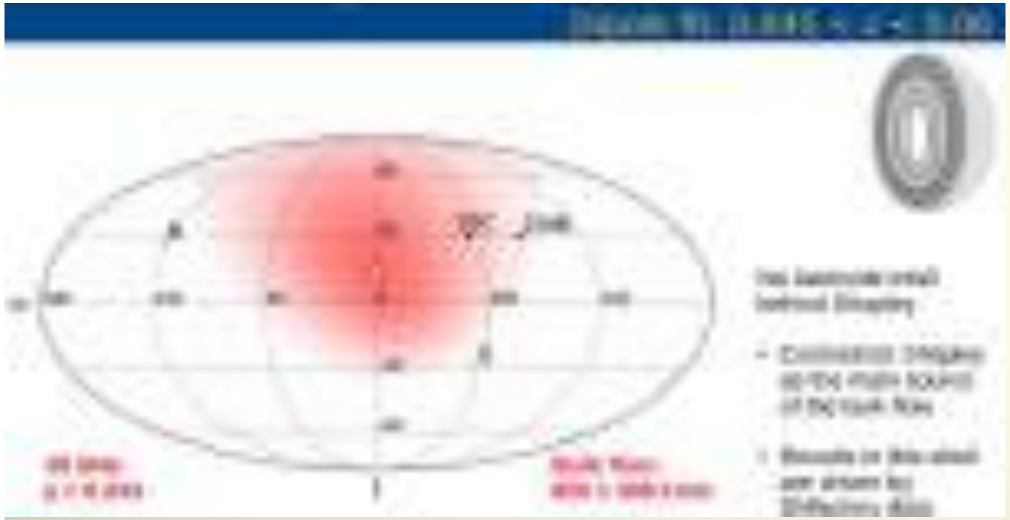
(Bonvin *et al* 2006)

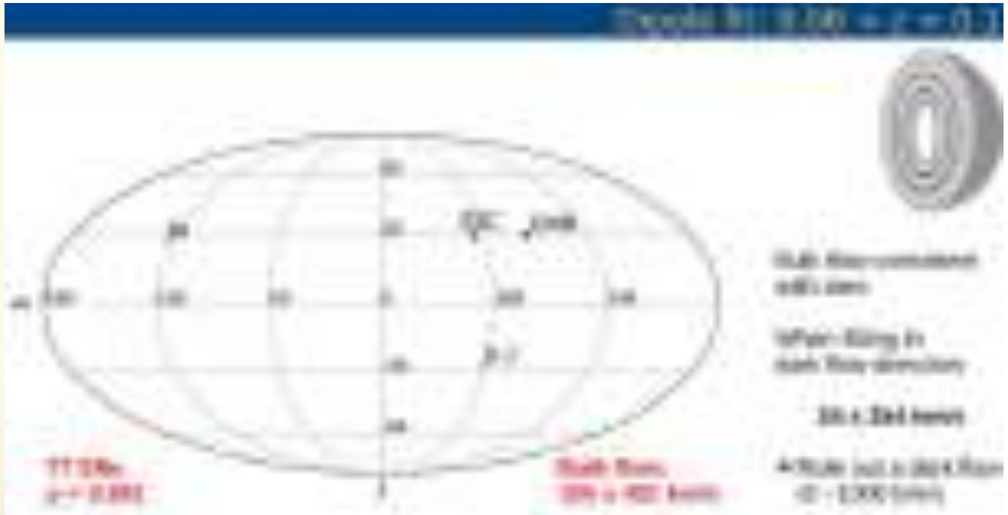
Best fit direction consistent with direction to Shapley

→ Amplitude matches previous studies

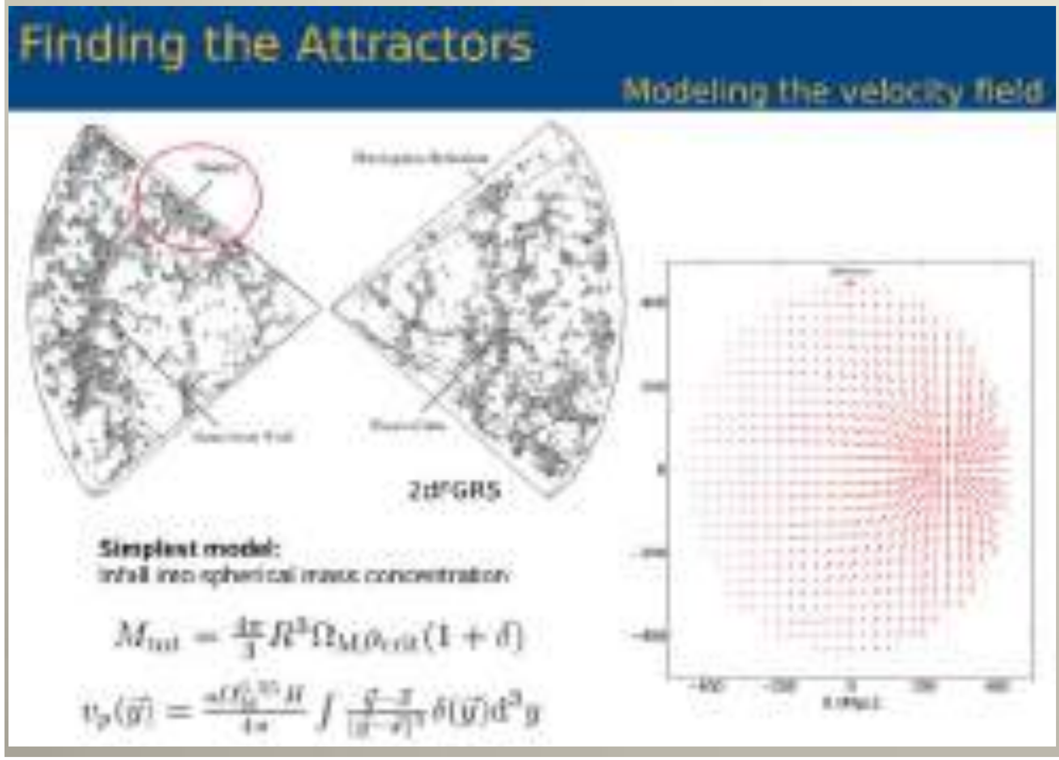
(Feindt *et al,* A&A **560**:A90,2013)

OUR RESULT WAS ***CONFIRMED*** BY THE NEARBY SUPERNOVA FACTORY SURVEY

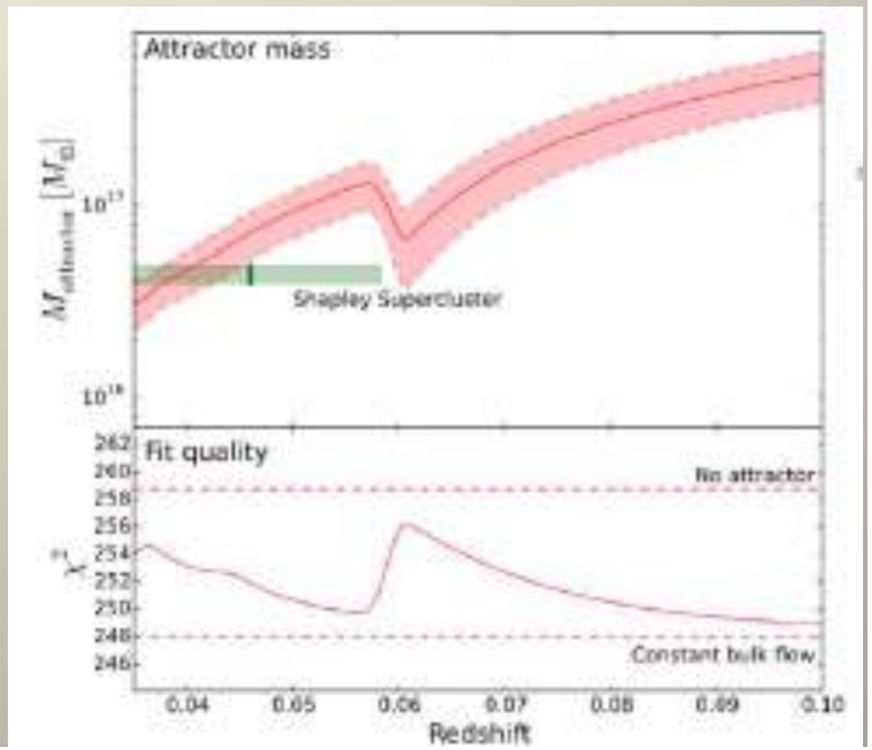




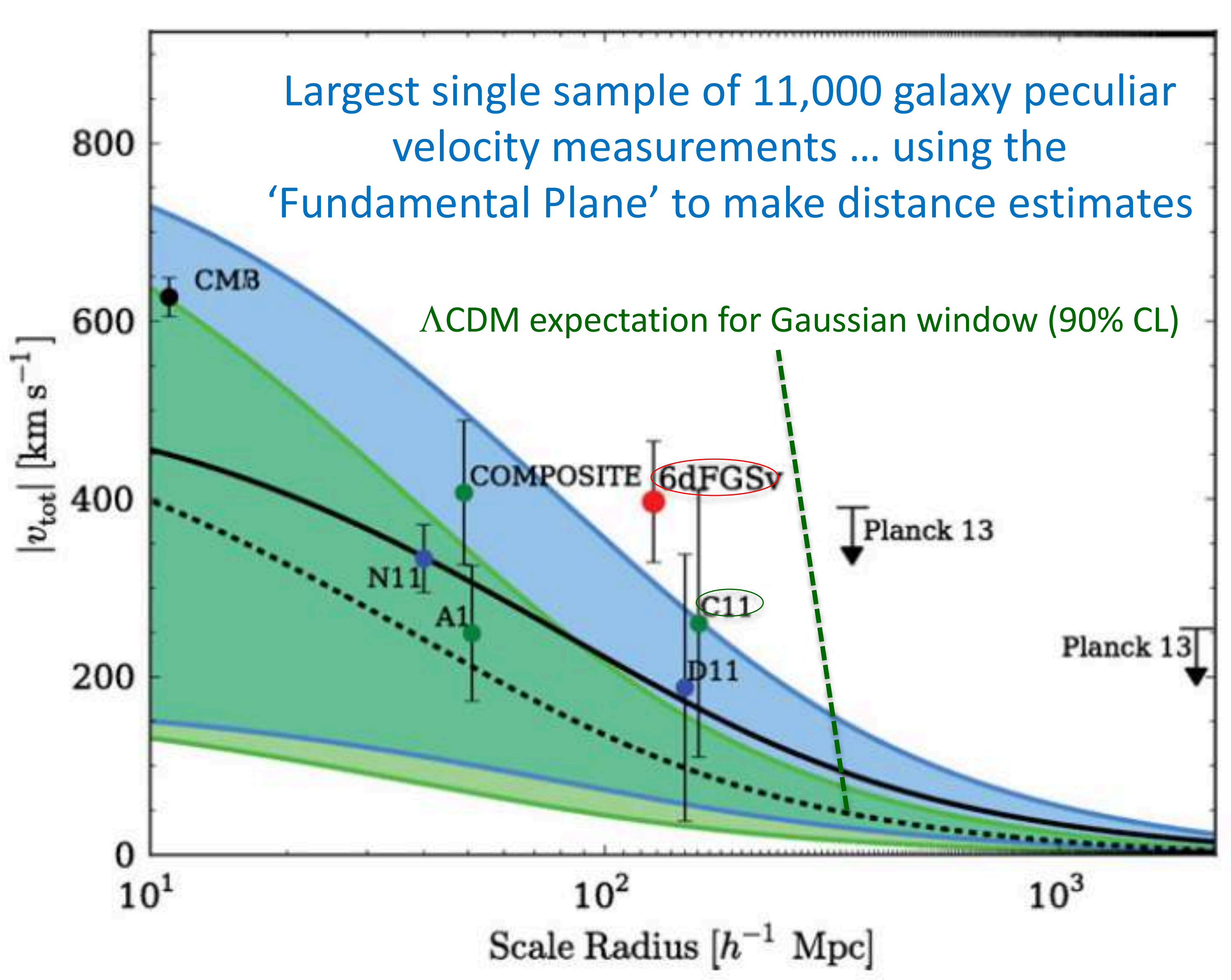
The data runs out at higher redshift but the bulk flow is established out to ~300 Mpc … implies a attractor mass of $>10^{17}$ M_{Sun} at that distance (Feindt *et al,* A&A 560:A90,2013)



Courtesey: Ulrich Feindt



FURTHER *CONFIRMATION* BY THE 6-DEGREE FIELD GALAXY SURVEY (6dFGSv)



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

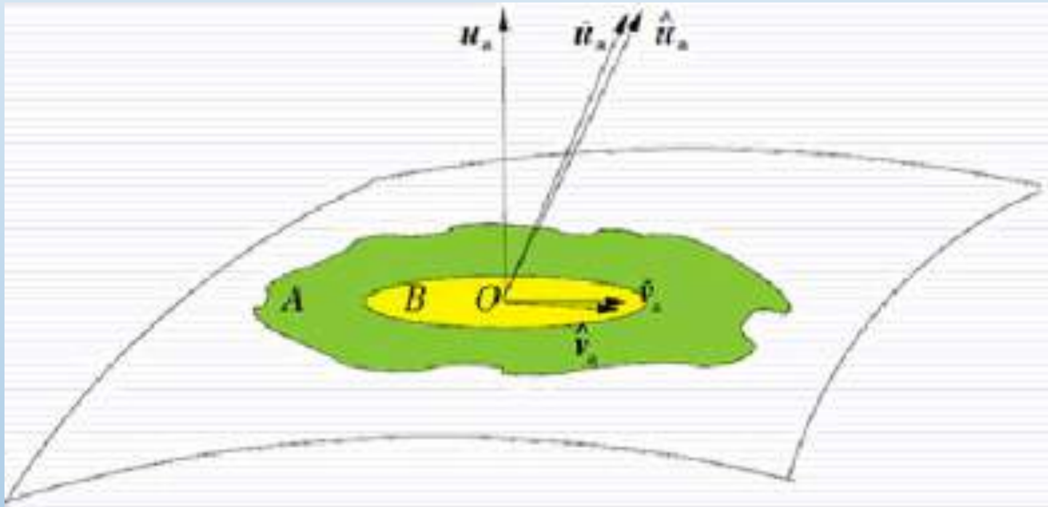
In the 'Dark Sky' ΛCDM simulations, *less than 1%* of Milky Way–like observers experience a bulk flow as large as is observed, extending out as far as is seen

Rameez, Mohayaee, S.S. & Colin, MNRAS **477**:1722,2018

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



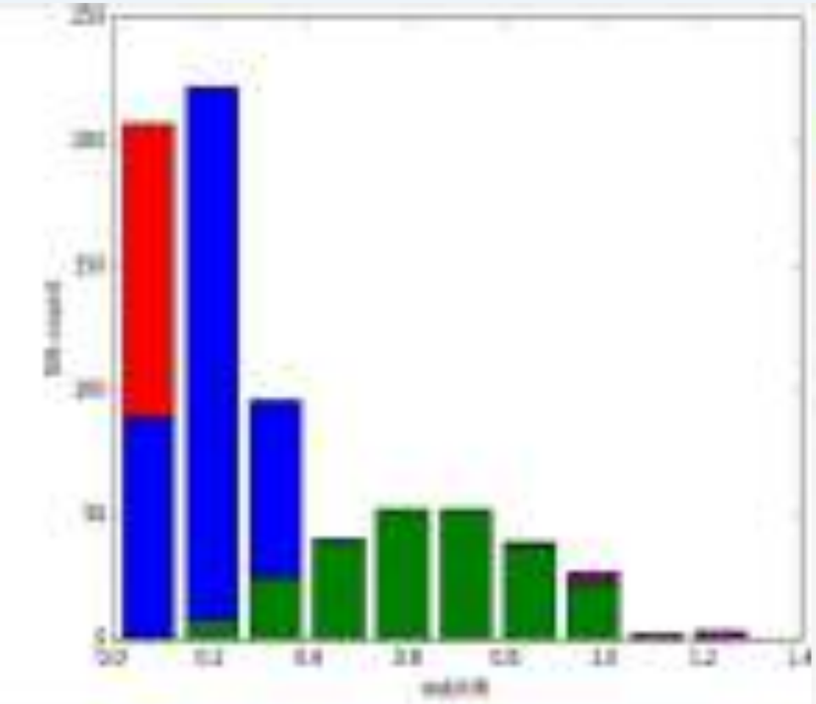
The patch A has mean peculiar velocity $\tilde{v}_a$ with $\vartheta = \tilde{\mathrm{D}}^a v_a \gtrless 0$ and $\dot{\vartheta} \gtrless 0$
(the sign depending on whether the bulk flow is faster or slower than the surroundings)

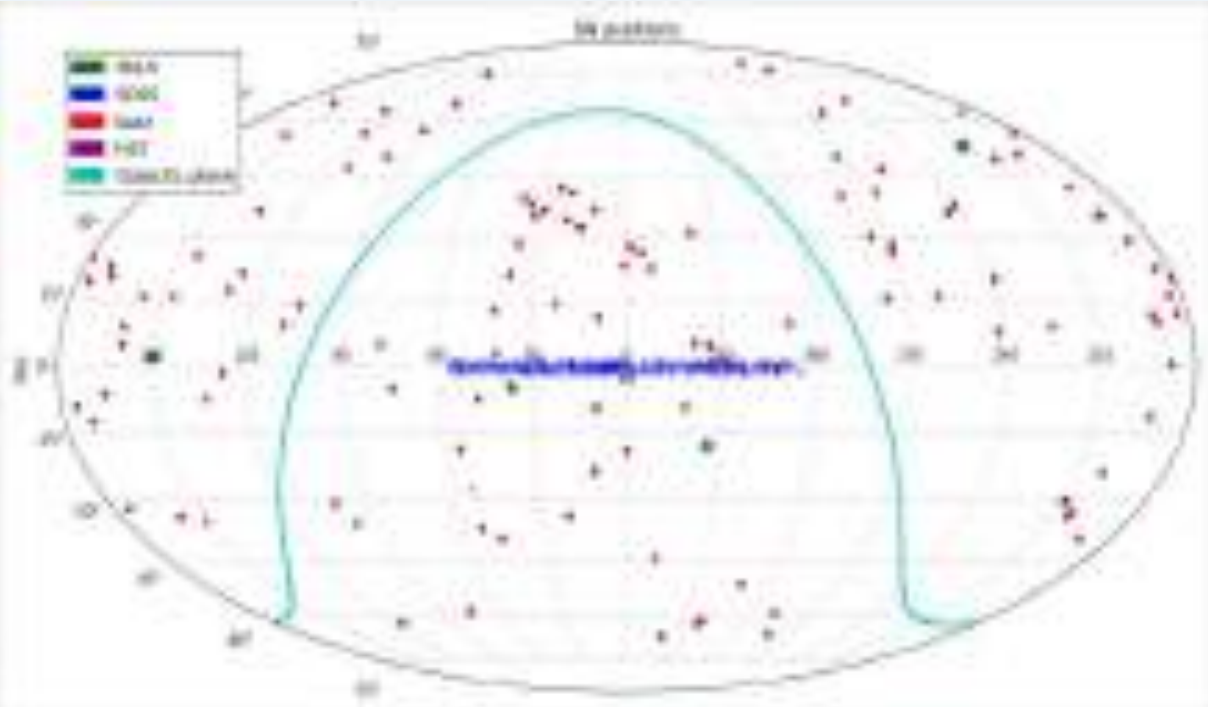
Inside region B, the r.h.s. of the expression

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

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

Joint Lightcurve Analysis data (740 SNe Ia)





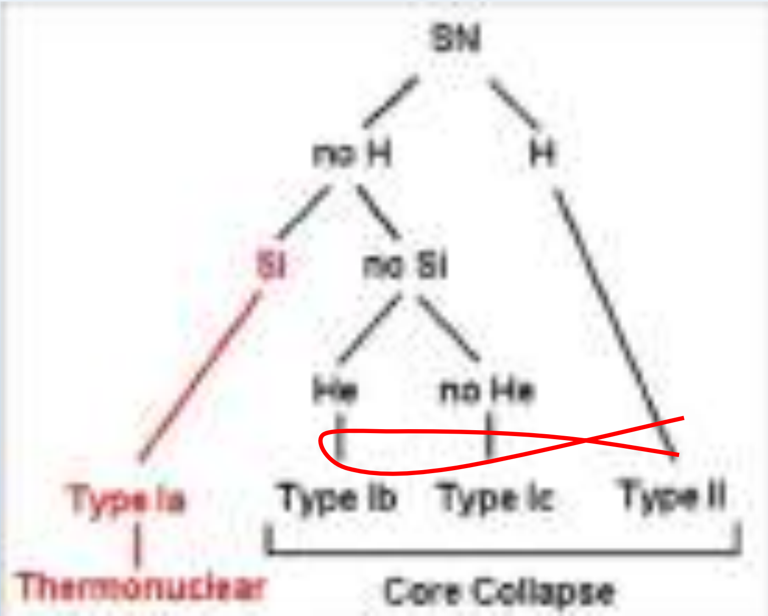
http://supernovae.in2p3.fr/sdss_snls_jla/

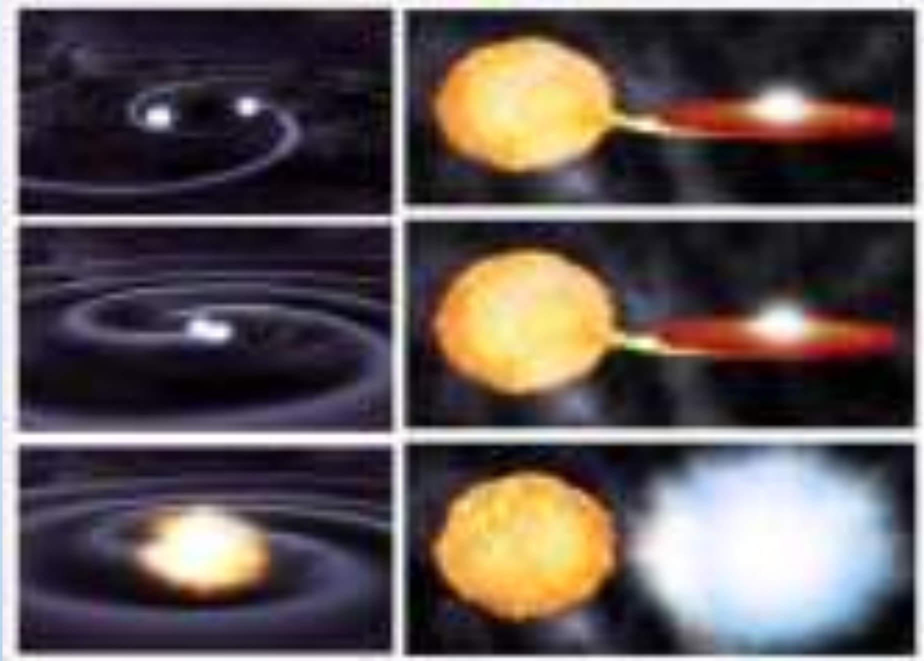
Betoule *et al*, A&A **568**:A22,2014 (included Conley, Filippenko, Frieman, Goobar, Guy, Hook, Jha, Kessler, Pain, Perlmutter, Riess, Sollerman, Sullivan …)

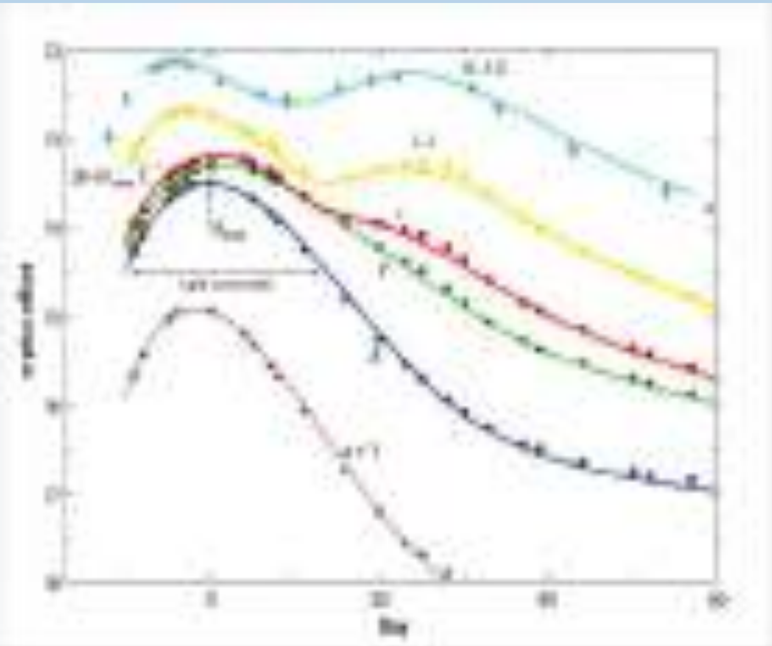
In contrast to previous analyses (which *assumed* ΛCDM and *adjusted* the errors to get a good fit) we apply a *principled* statistical analysis (Maximum Likelihood) … and obtain rather different results

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

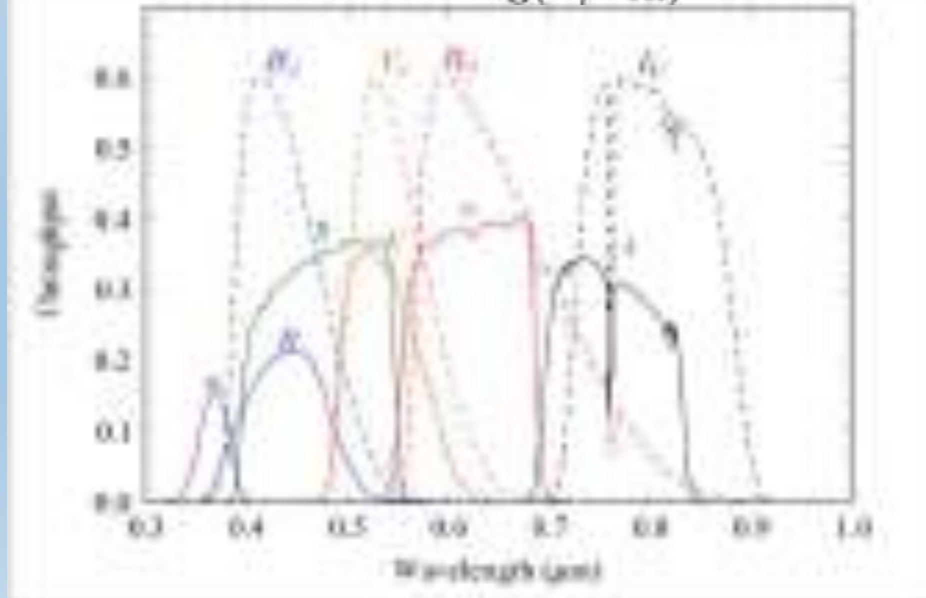
What are Type Ia supernovae?





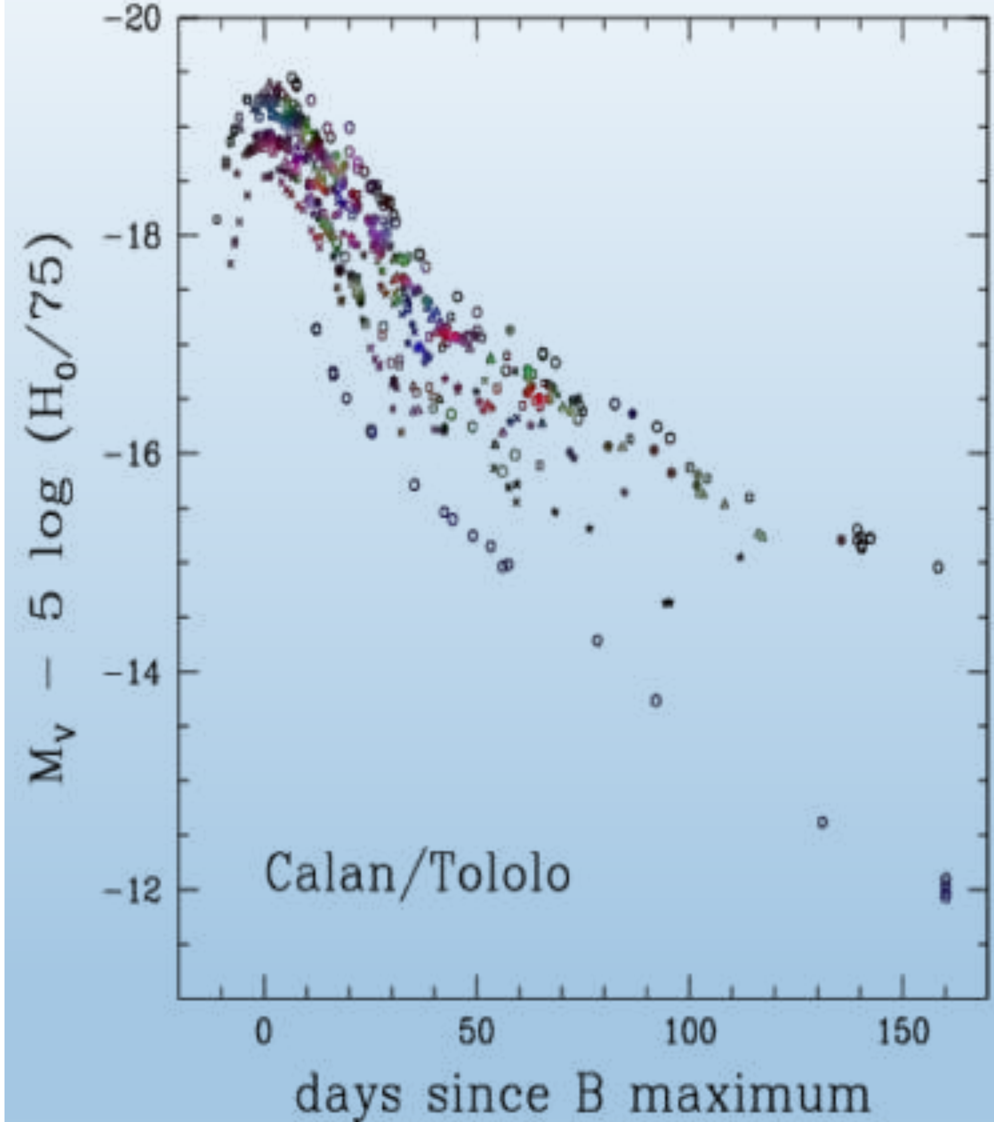


$$m = -2.5 \log(F/F_{\rm ref})$$

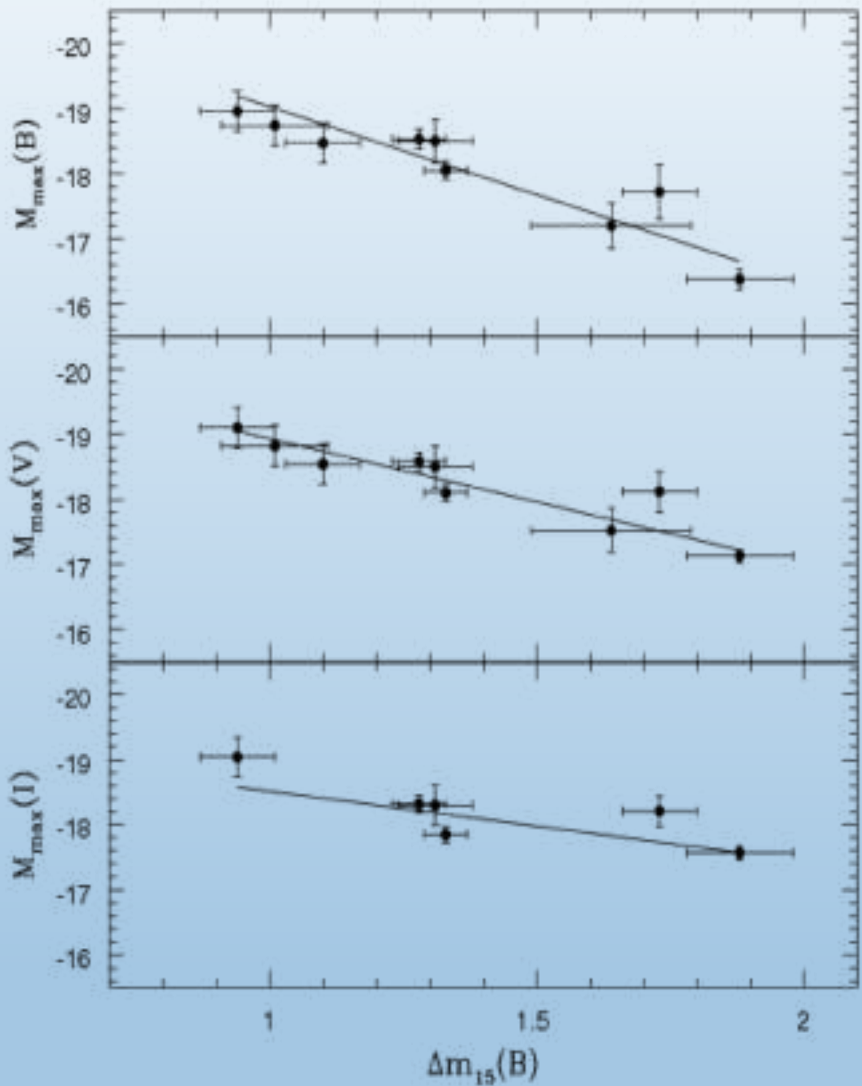


Goobar & Leibundgut, ARAA **61**:251,2011

THEY ARE CERTAINLY *NOT* ‘STANDARD CANDLES’



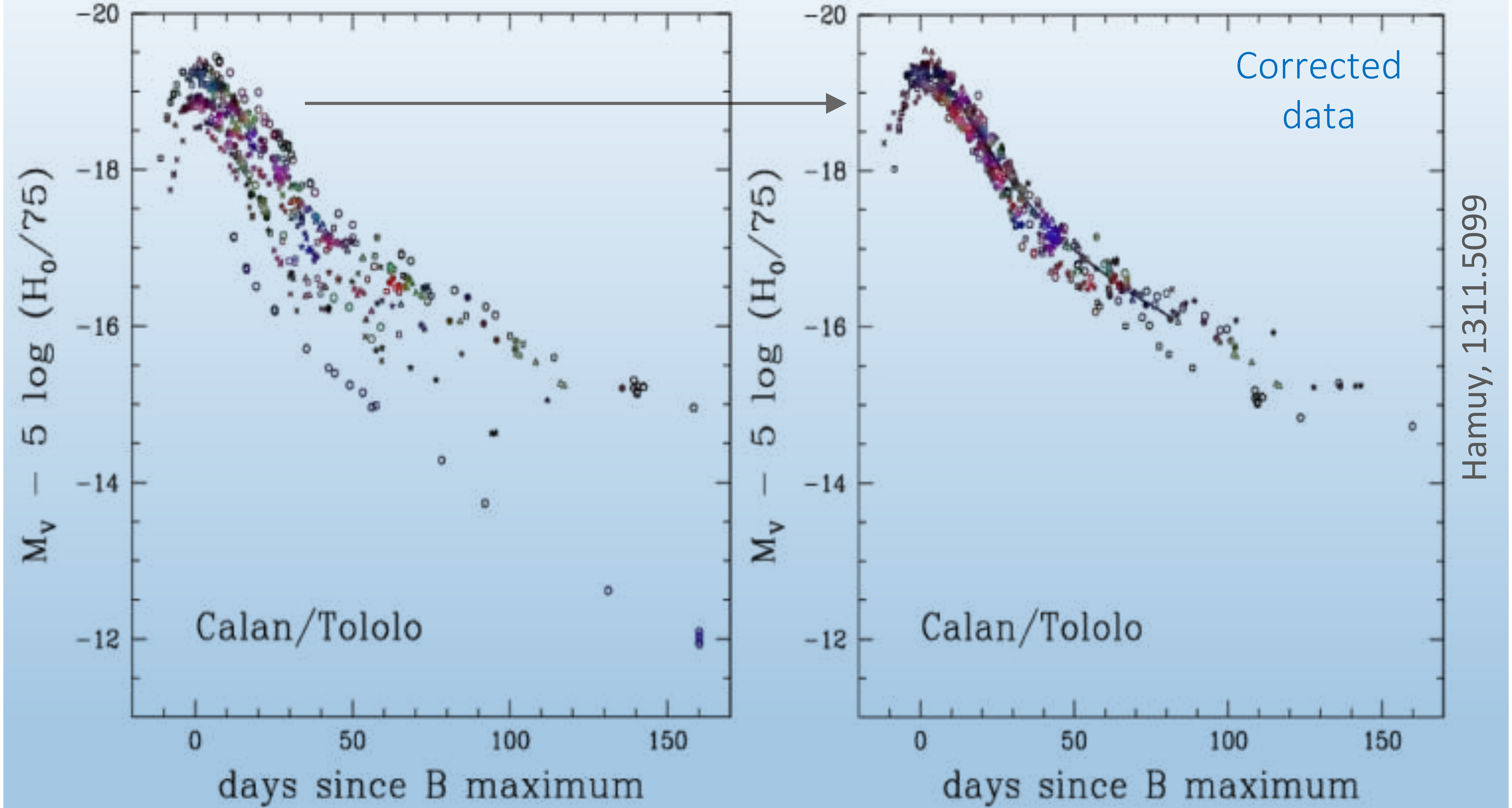
Hamuy, arXiv:311.5099



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'



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

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^*	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)

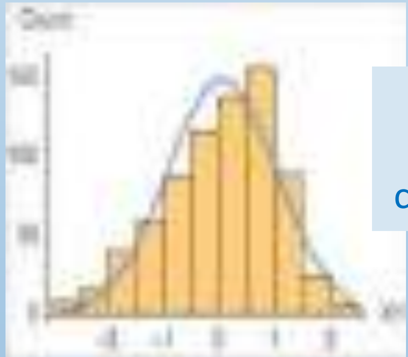
$$d_L(z) = \frac{c\,z}{H_0}\left\{1 + \frac{1}{2}\left[1 - q_0\right]z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 + \frac{kc^2}{H_0^2\,a_0^2}\right]z^2 + O(z^3)\right\}$$

Construct a Maximum Likelihood Estimator

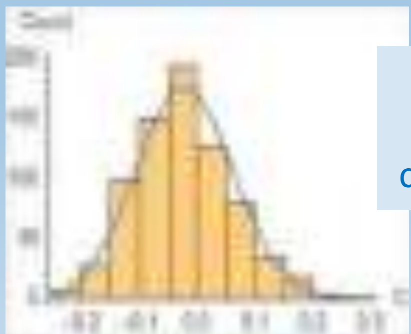
$$\mathcal{L} = \text{probability density(data|model)}$$

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

Well-approximated as Gaussian



JLA data 'Stretch' corrections



JLA data 'Colour' corrections

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

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

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

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

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

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

1,2,3-sigma

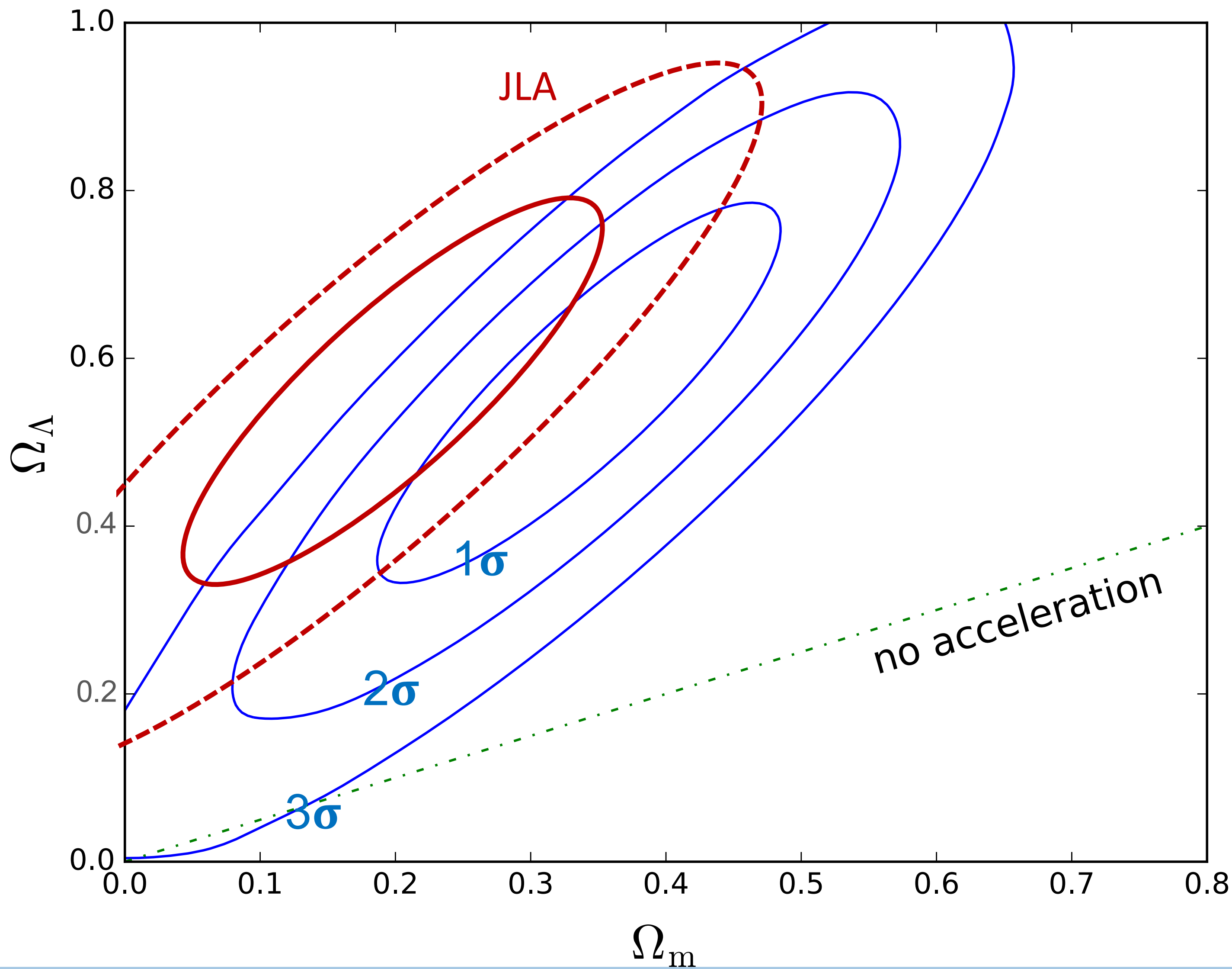
solve for Likelihood value

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

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

... 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** ($\Rightarrow \rho + 3p = 0$)



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

Profile Likelihood

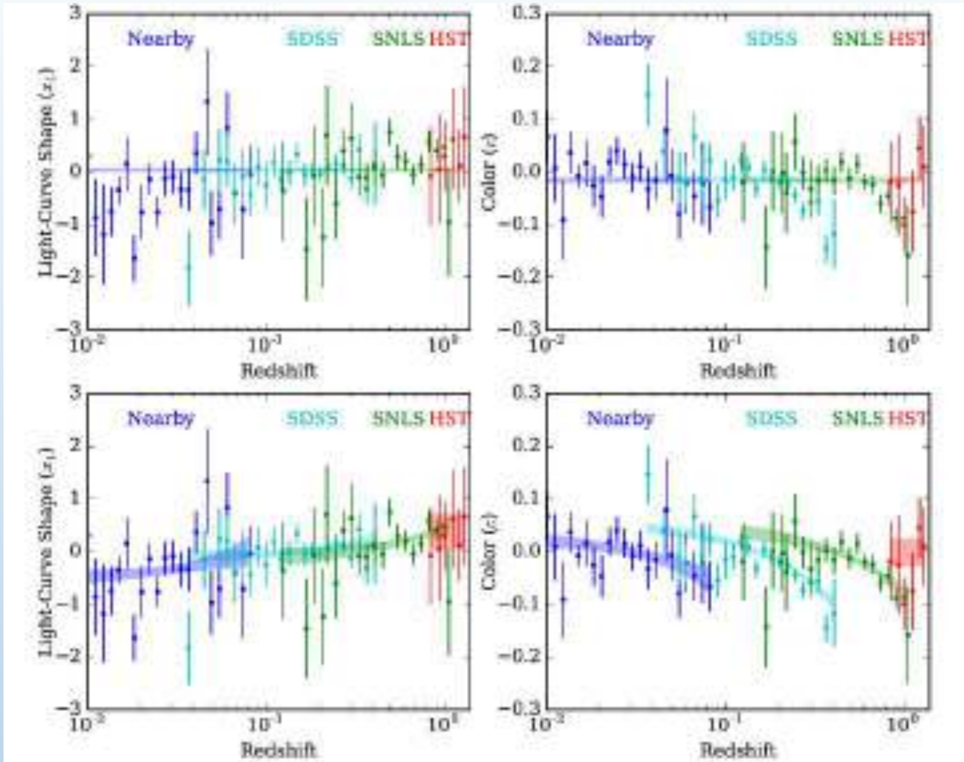
<u>MLE, *best fit*</u>

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

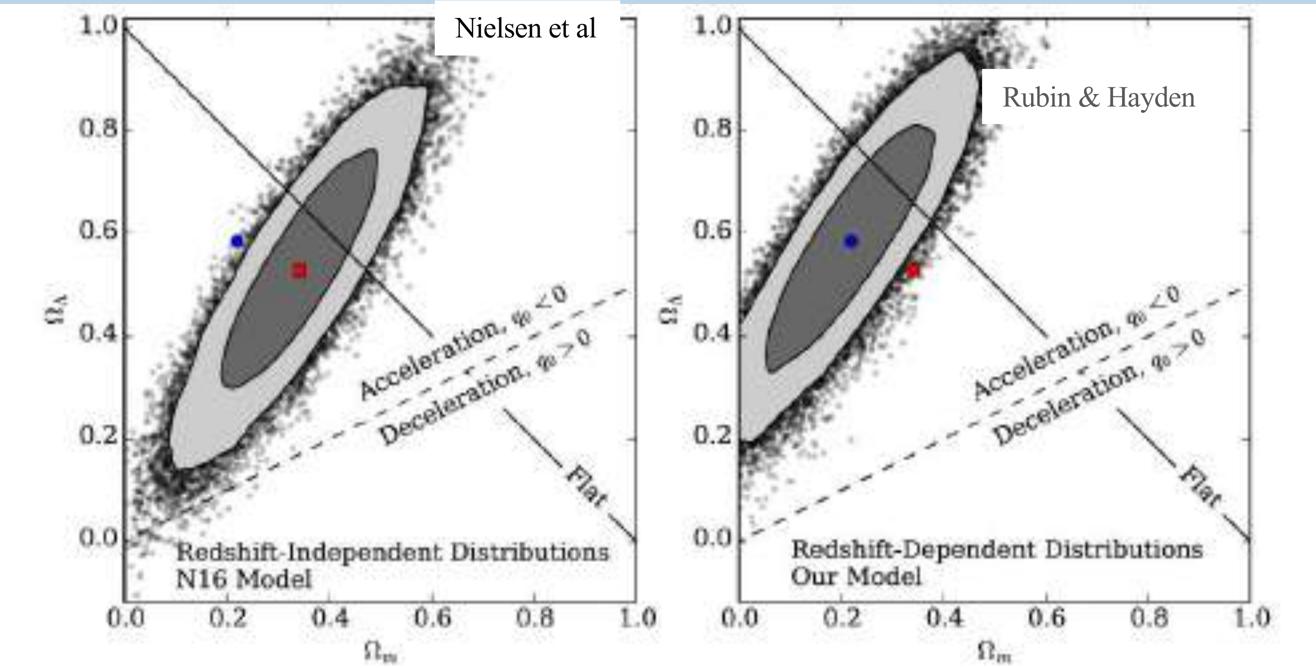
NB: We show the result in the Ω_m-Ω_Λ plane for comparison with previous results (JLA) simply to emphasise that the statistical analysis has *not* been done correctly earlier

(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

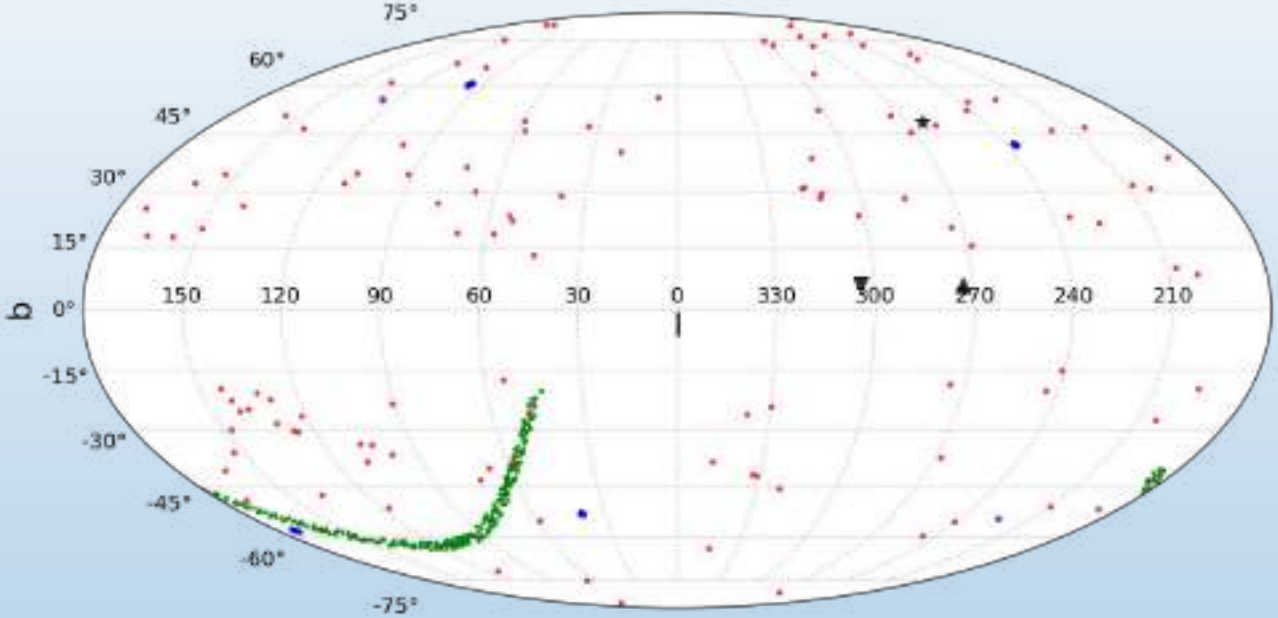


This *a posteriori* modification is not justified by the Bayesian Information criterion



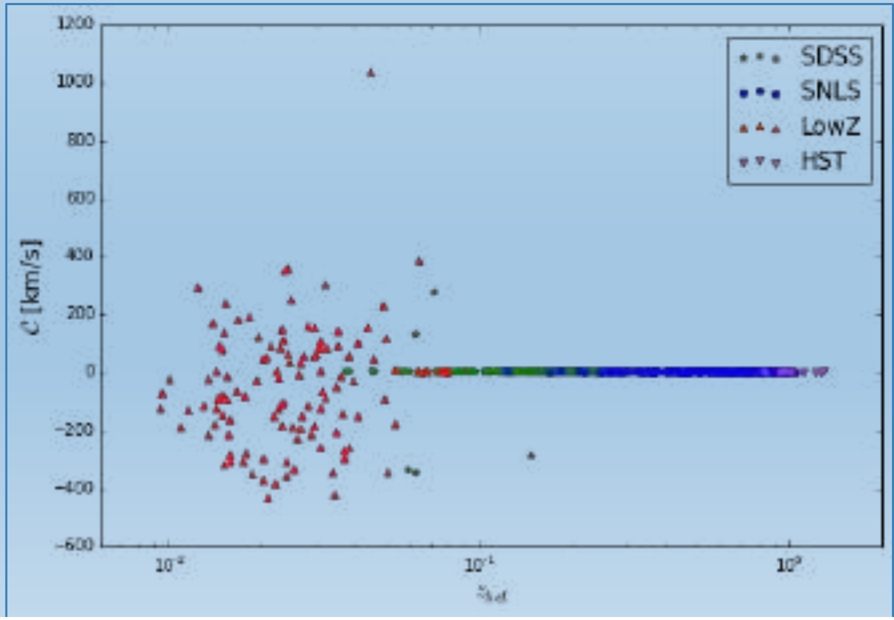
In any case this raises the significance with which a non-accelerating universe is rejected to only $\lesssim 4\sigma$ ... still inadequate to claim a 'discovery' (even though the dataset has increased from ~100 to 740 SNe Ia in 20 yrs)

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.



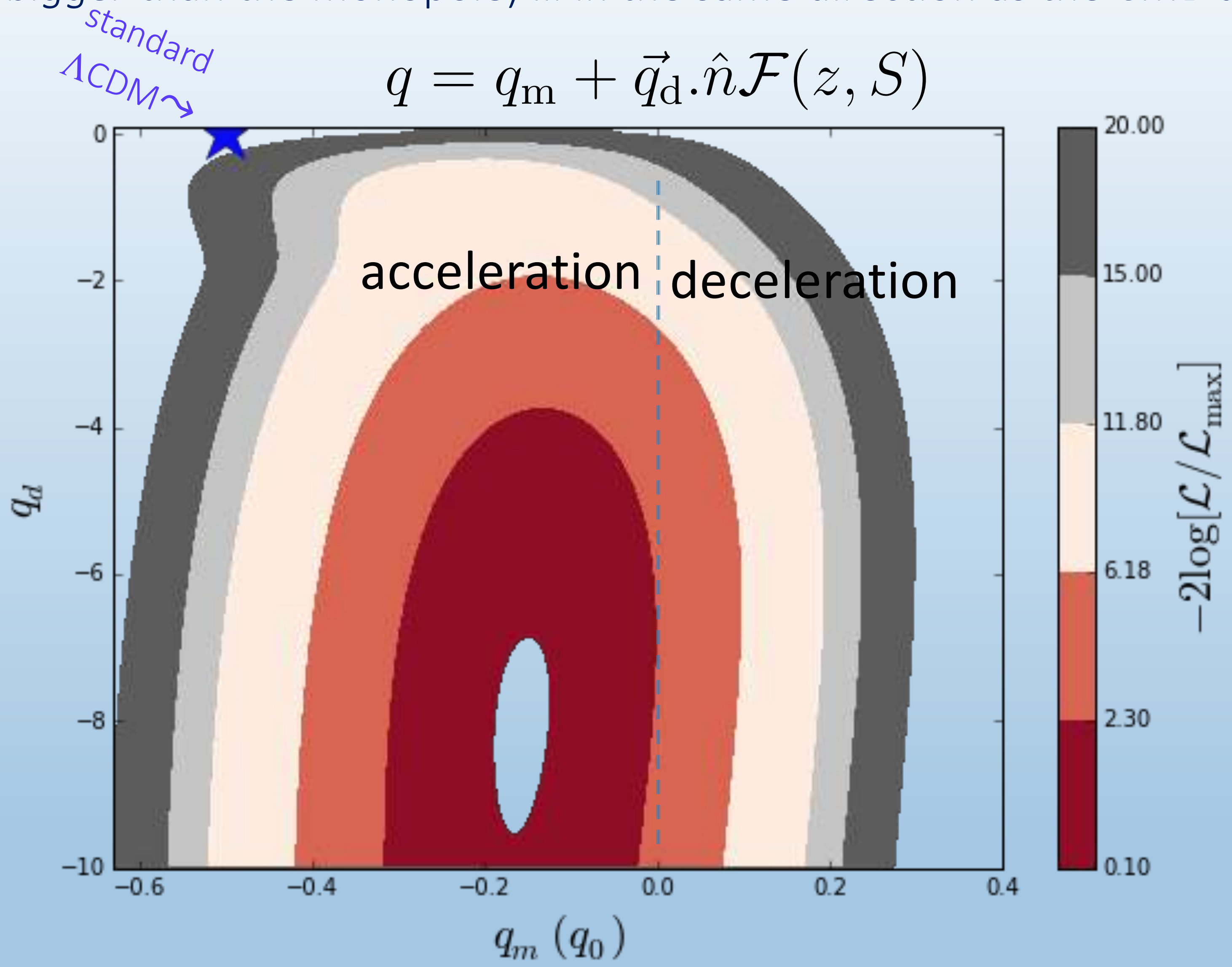
Subsequently we realised that the peculiar velocity `corrections' applied to the JLA catalogue assume that the bulk flow terminates suddenly at ~150 Mpc … so *undid* them

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



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

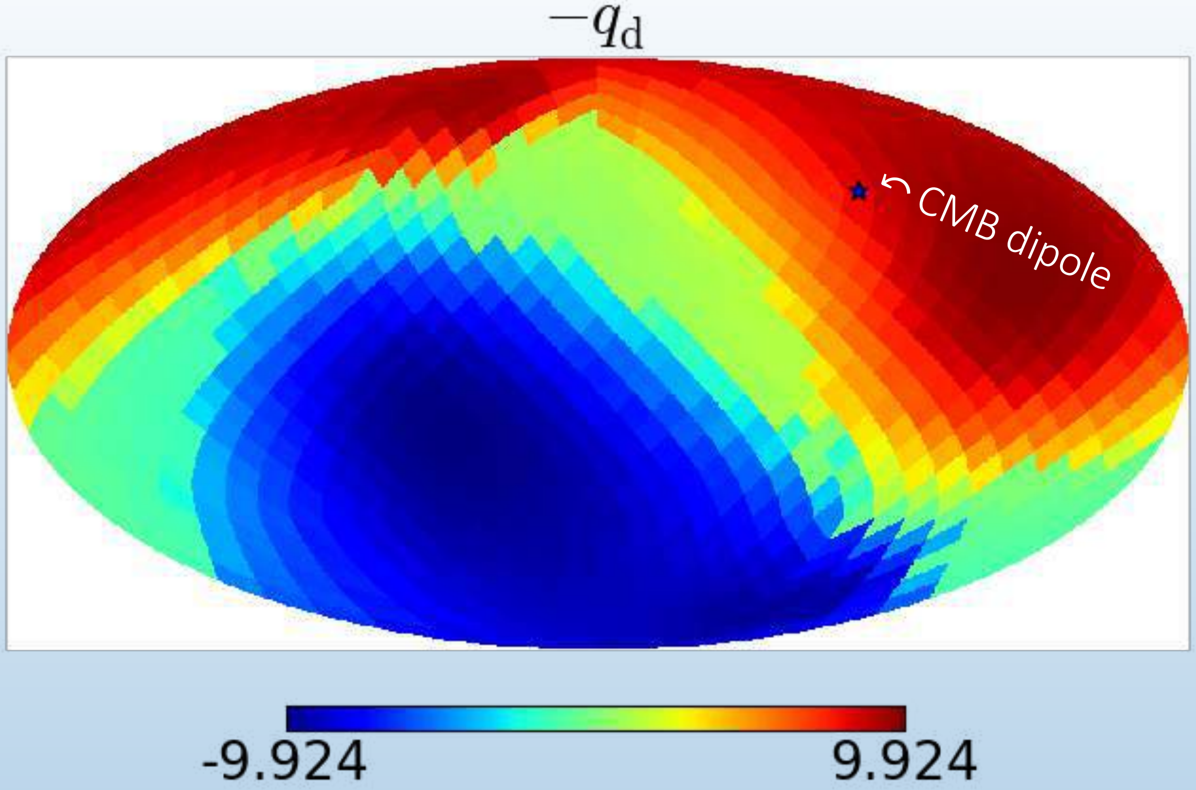
When the data is now analysed allowing for a dipole, we find the MLE *prefers* one (50 times *bigger* than the monopole) … in the same direction as the CMB dipole



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

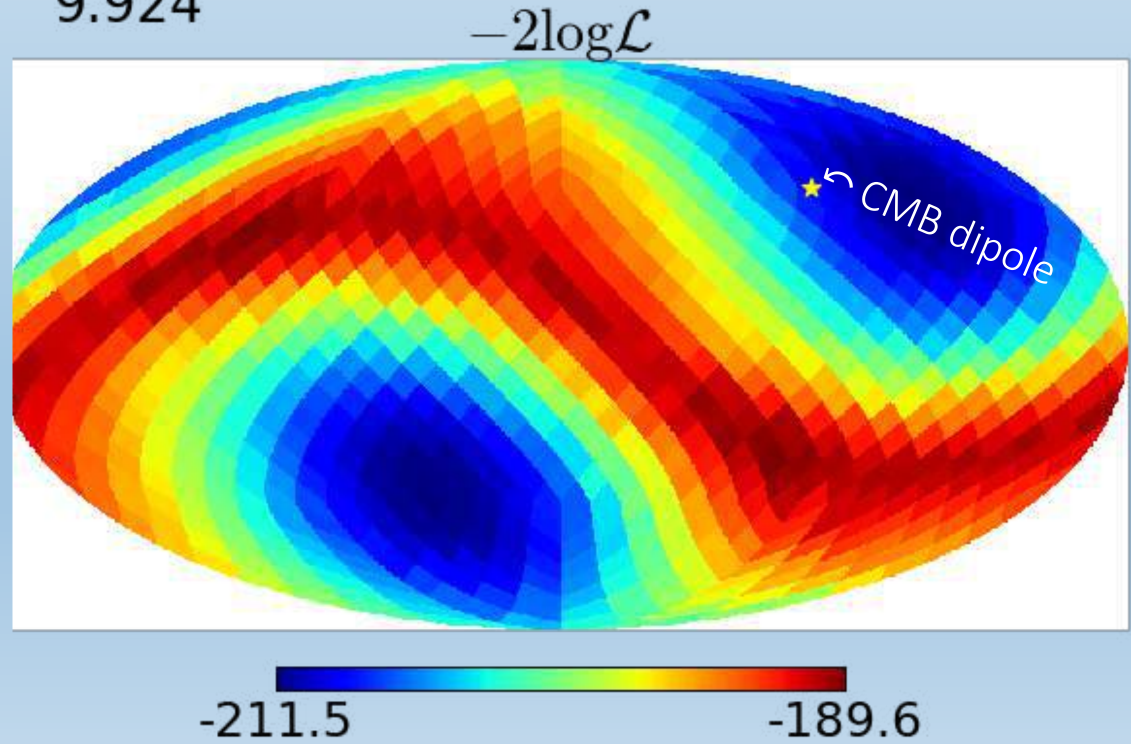
The significance of q_o being negative has now *decreased* to only 1.4σ

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)



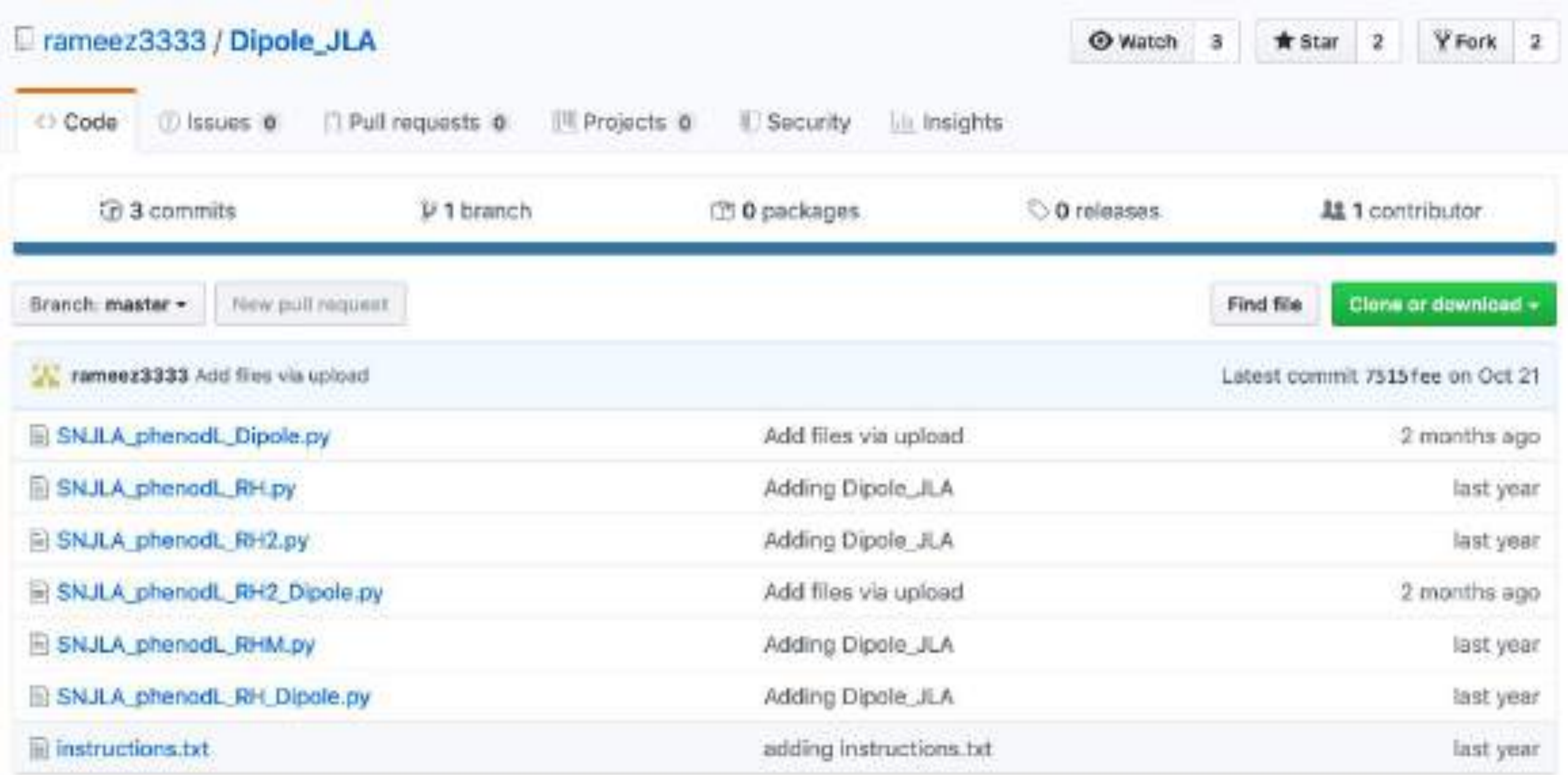
There is not enough data to do an *a priori* scan of the best-fit direction of $q_{\rm d}$ … but if done *a posteriori* it is found to be within 23^0 of the CMB dipole

The log-likelihood changes by just 3.2 between the two directions i.e. the direction of the acceleration is consistent with being due to the bulk flow



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 need to 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

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

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

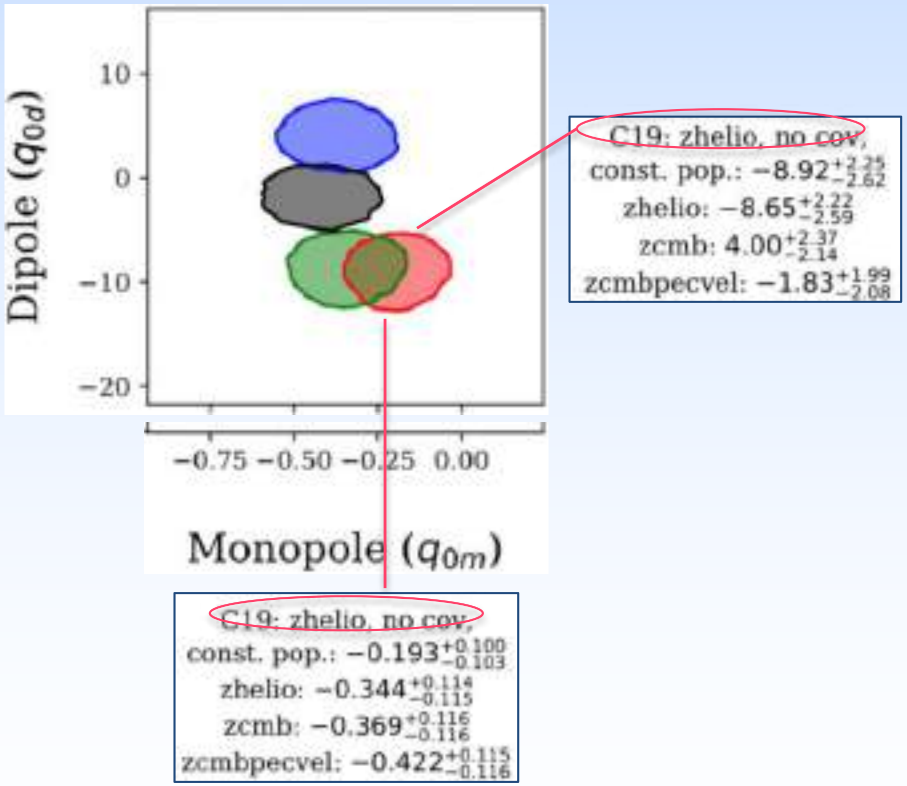
Target ID (sortable)	ZCMB (sortable)	ZHEL (sortable)	DZ (sortable)	MB (sortable)	DMB (sortable)
Type filter...	Type filter...	Type filter...	Type filter...	Type filter...	
03D1au	0.50309	0.50309	0.0	22.93445	0.12605
03D1aw	0.58073	0.58073	0.0	23.52355	0.1372
03D1ax	0.4948	0.4948	0.0	22.8802	0.11765
03D1bp	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

Data from he Carnegie Superova Project and the Dark Energy Survey are not publicly available

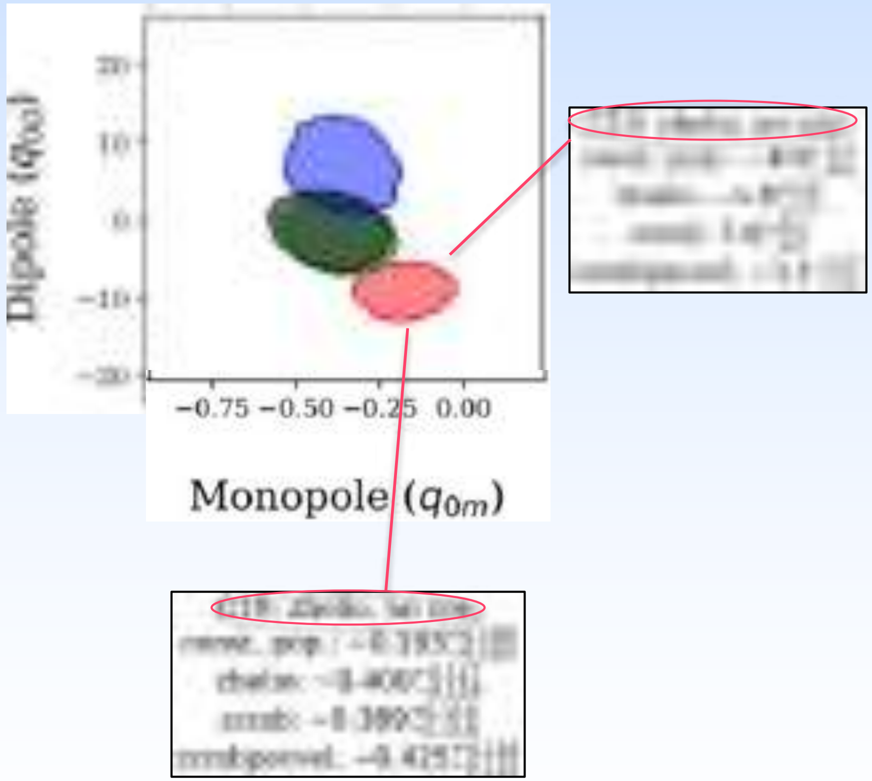
Runin & Heitlauf (arXiv:1912.02191) reproduce our result but criticise us:

1. For ‘incorrectly’ not allowing redshift-dependence of light-curve parameters (~~BIC~~)
2. For ‘shockingly’ using heliocentric redshifts (as was done by all SN analyses till 2011)
3. For not using data from southern sky surveys (which are in fact *not* public)
4. For using a ‘pathological’ model of the dipole anisotropy (it is in fact well behaved)

Without JLA peculiar velocity covariance



With JLA peculiar velocity covariance



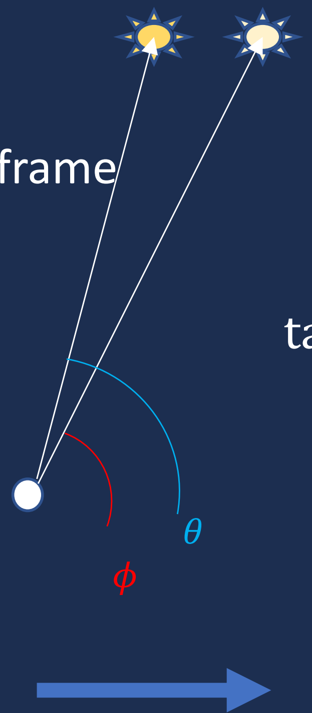
This shows the various “corrections” that must be made in order to extract significant evidence for *isotropic* acceleration (q_{0m}), rather than *anisotropic* acceleration (q_{0d})

… we believe these “corrections” are *not* justified (arXiv:1912:04257)

If the dipole in the CMB is due to our motion *wrt* the 'CMB frame' then we should see *same* dipole in the distribution of all distant sources

$$\sigma(\theta)_{obs} = \sigma_{rest}[1 + [2 + x(1+\alpha)]\frac{v}{c}\cos(\theta)]$$

Aberration



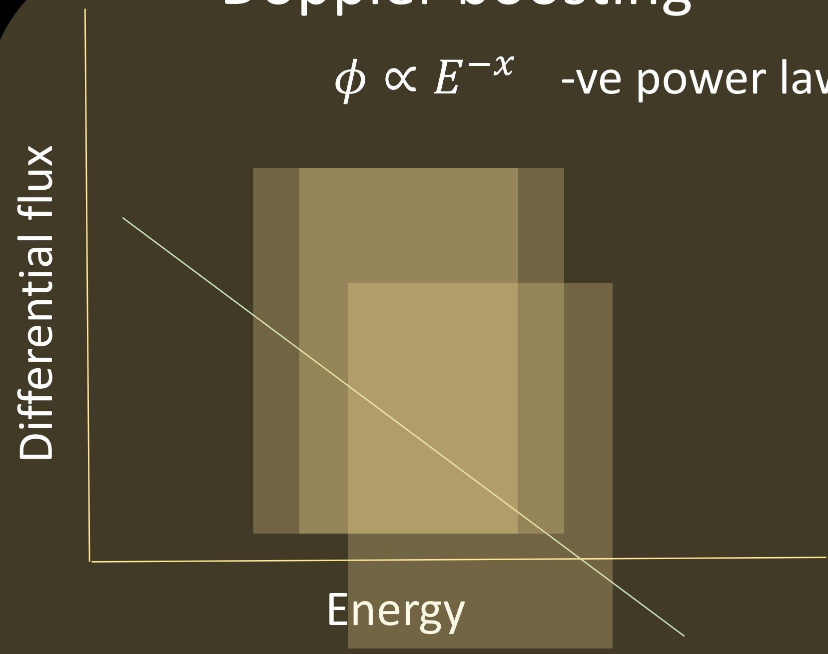
Moving frame

$$\tan\phi = \frac{\sin\theta}{\gamma * cos\theta \;- \frac{v}{c}}$$

+

Doppler boosting

$\phi \propto E^{-x}$ -ve power law

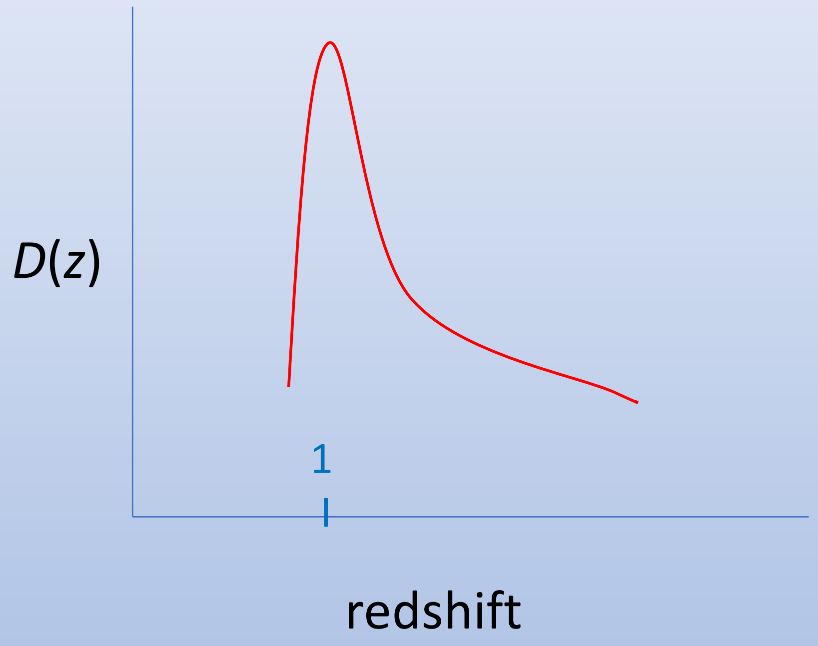


Flux limited catalog → more sources in direction of motion

Ellis & Baldwin (1984)

Dipoles in a catalogue of galaxies

All-sky catalogue with *N* sources with redshift distribution *D*(*z*) from a directionally unbiased survey



$$\vec{\delta} = \vec{\mathcal{K}}\,(\vec{v}_{obs}, x, \alpha) + \vec{\mathcal{R}}\,(N) + \vec{\mathcal{S}}\,(D(z))$$

$\vec{\mathcal{K}}$ → The kinematic dipole: *independent* of source distance, but depends on source spectrum, source flux function, observer velocity

$\vec{\mathcal{R}}$ → The random dipole: $\propto 1/\sqrt{N}$ isotropically distributed

$\vec{\mathcal{S}}$ → The dipole component of an actual anisotropy in the distribution of sources in the cosmic rest frame (significant for shallow surveys)

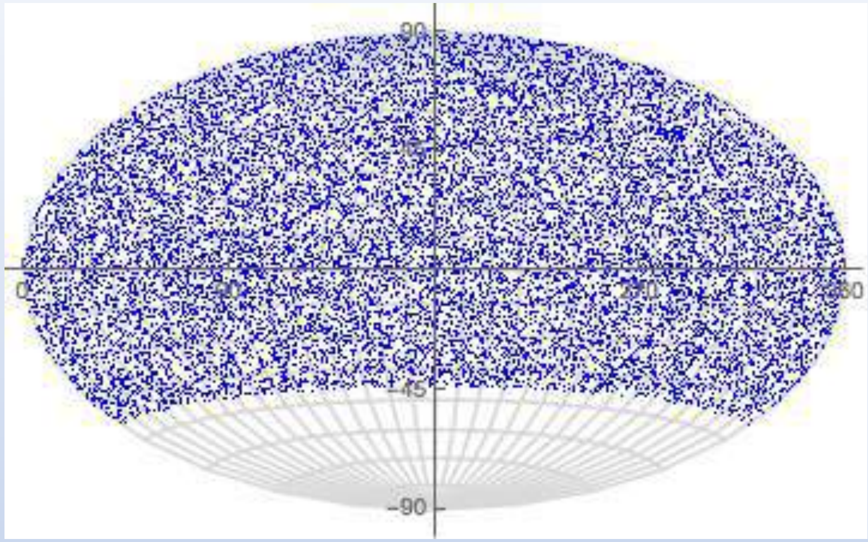
Radio sources: NVSS + SUMSS, 600,000 galaxies $z \sim 1$, $\vec{\mathcal{S}}\,(D(z)) \to 0$

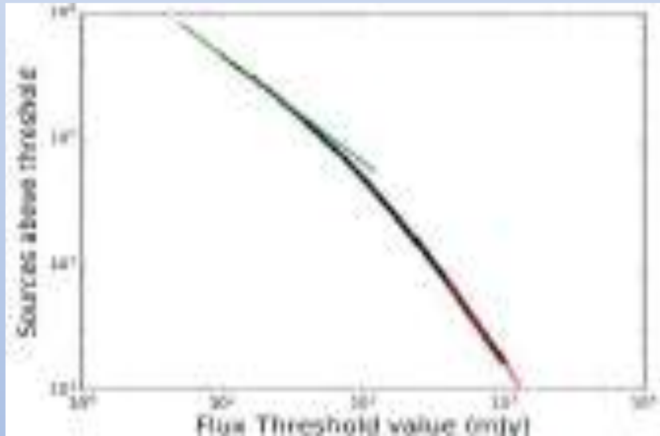
Colin, Mohayaee, Rameez & S.S., MNRAS **471**:1045,2017

Wide Field Infrared Survey Explorer, 2,400,000 galaxies, $z \sim 0.14$, $\vec{\mathcal{S}}\,(D(z))$ significant

Rameez, Mohayaee, S.S. & Colin MNRAS **477**:1722,2018

The NRAO VLA Sky Survey (NVSS)

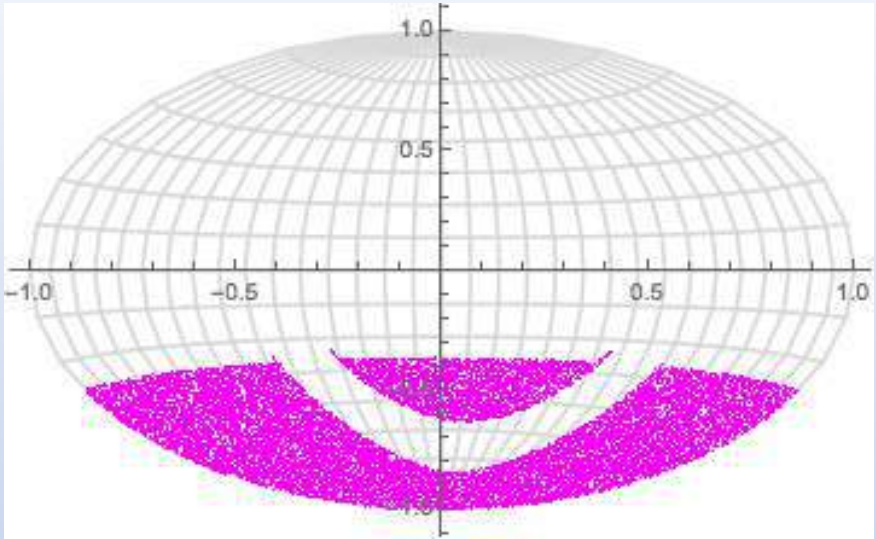


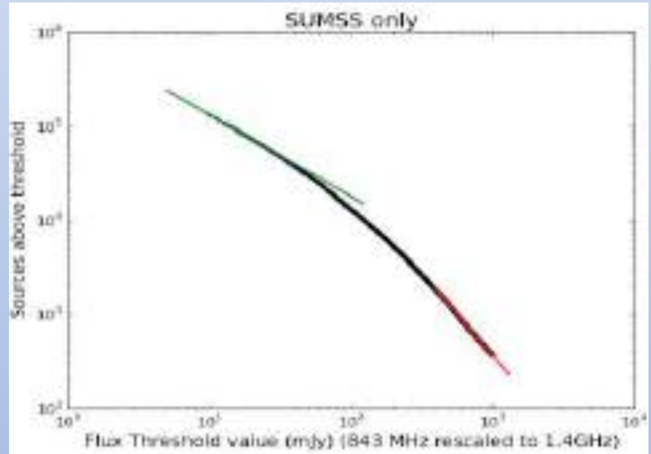


1.4 GHz survey (down to Dec = -40.4^{o})
National Radio Astronomy Observatory

1,773,488 sources >2.5 mJy
(complete above 10 mJy)
Most are believed to be at $z \gtrsim 1$

Sydney University Molonglo Sky Survey (SUMSS)



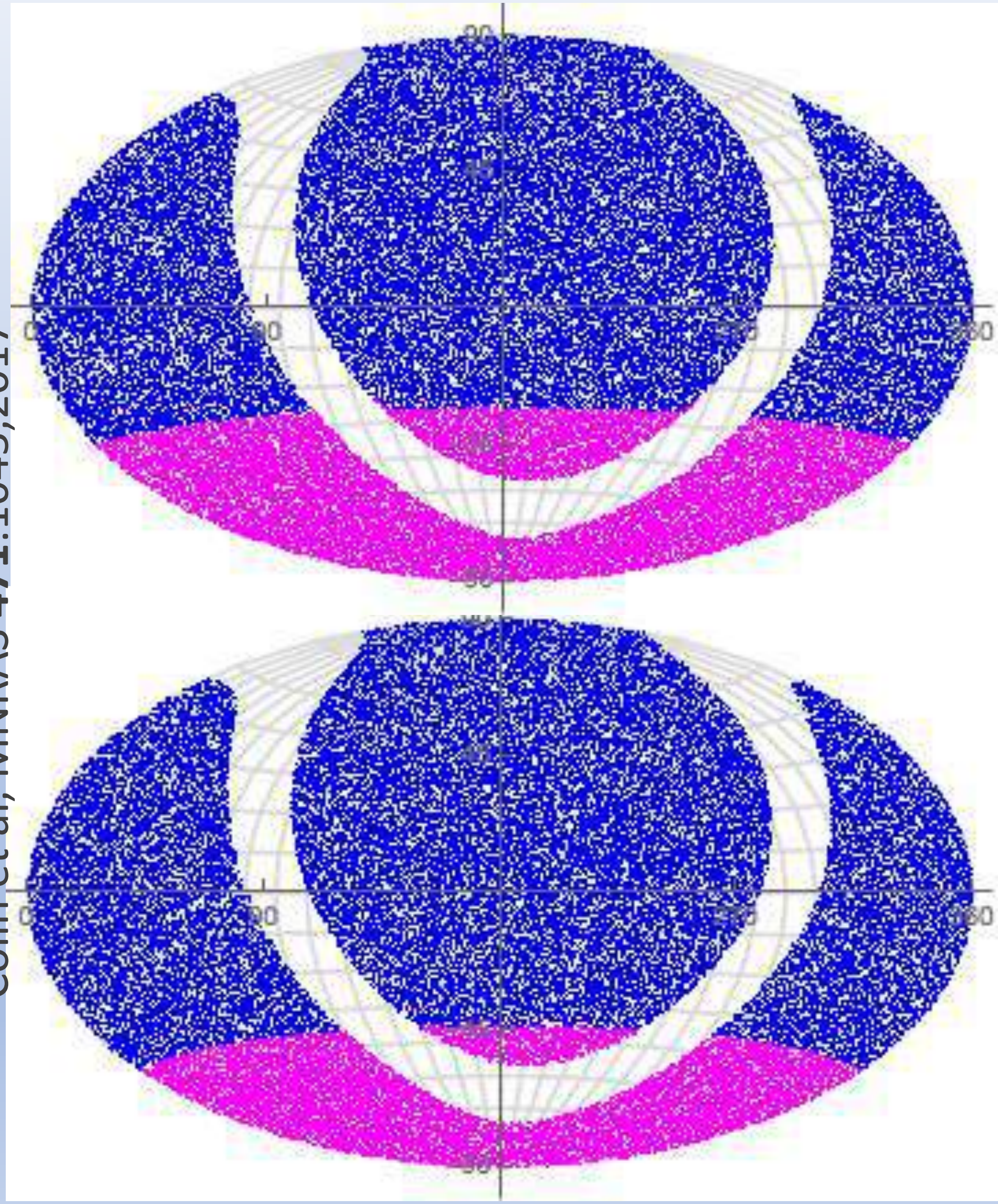


843 MHz survey (Dec < -30.0^{o})
Molonglo Observatory Synthesis telescope

211,050 sources (with similar sensitivity and resolution to NVSS catalogue)
… Similar expected redshift distribution

The NVSUMSS-Combined All Sky catalog

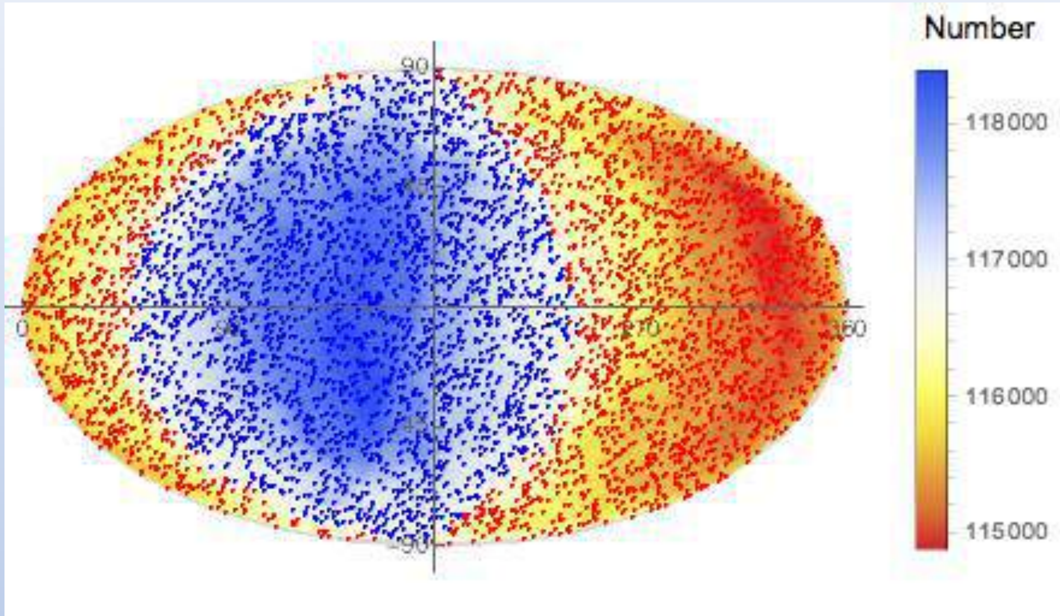
Colin et al, MNRAS **471**:1045,2017



- Rescale SUMSS fluxes by $(843/1400)^{-0.75} \sim 1.46$ to match with NVSS (works within ~1%)
- Remove Galactic Plane at $\pm 10^{o}$ (also Supergalactic plane)
- Remove NVSS sources below, and SUMSS sources above, Dec. -30)
- Apply common threshold flux cut to both samples
- Remove *any* nearby sources (common with 2MRS & LRS)

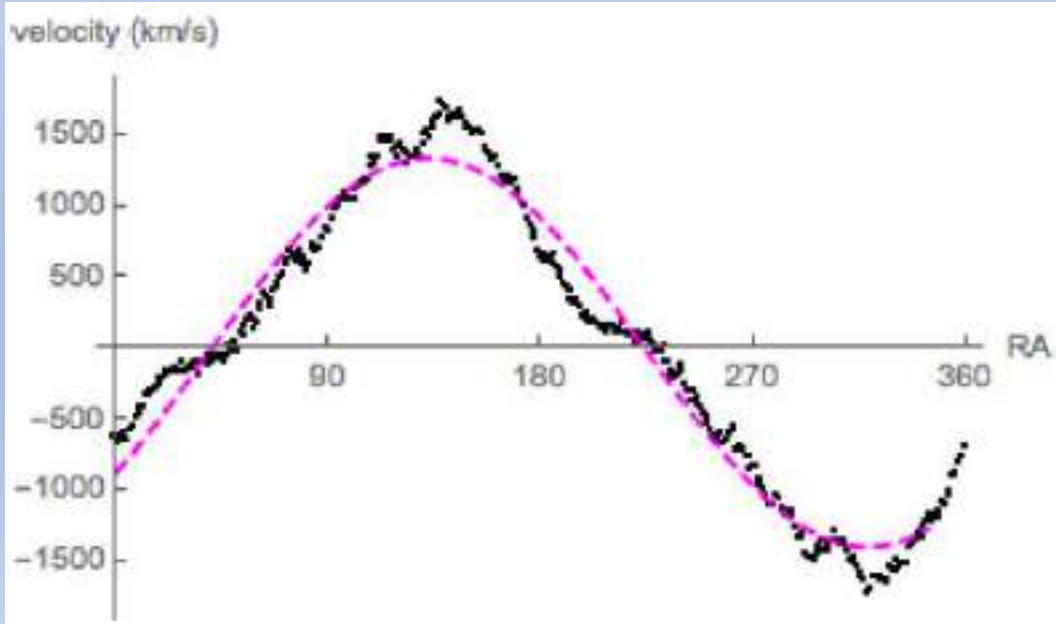
OUR PECULIAR VELOCITY WRT RADIO GALAXIES ≠ PECULIAR VELOCITY WRT THE CMB

Colin, Mohayaee, Rameez & S.S., MNRAS **471**:1045,2017



Velocity ~ 1355 ± 174 km/s
(with the linear estimator)

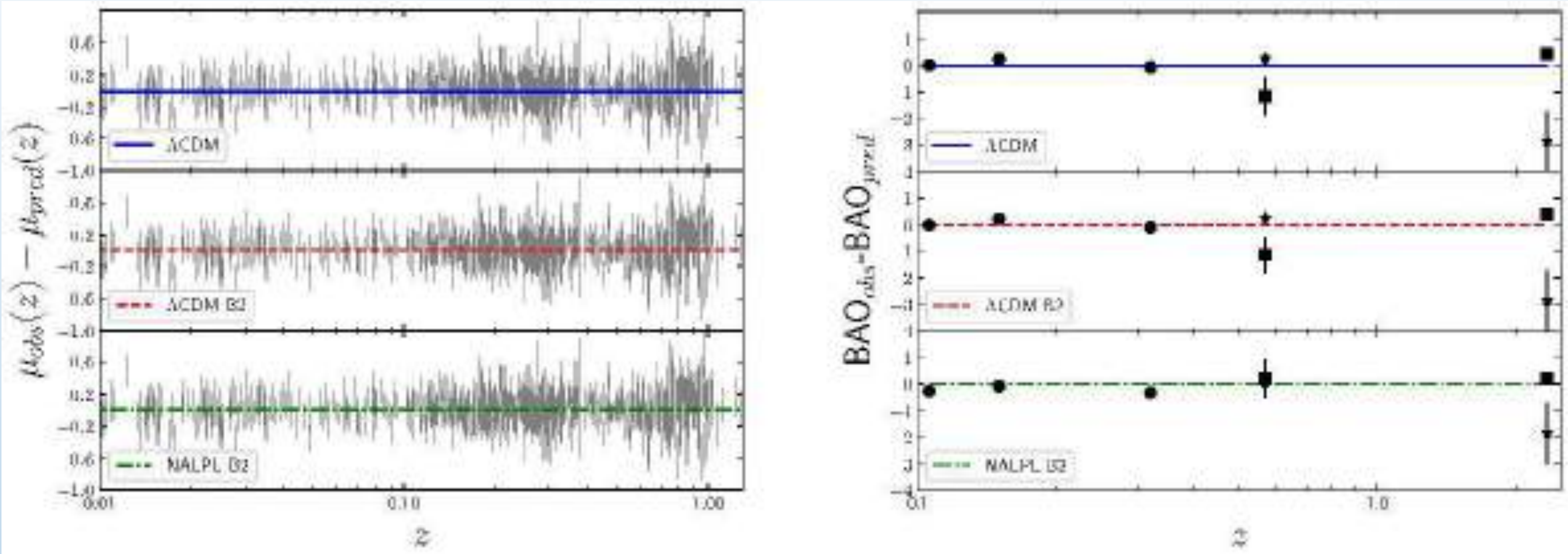
Direction within 10° of CMB dipole (but x**4 times *faster***)!



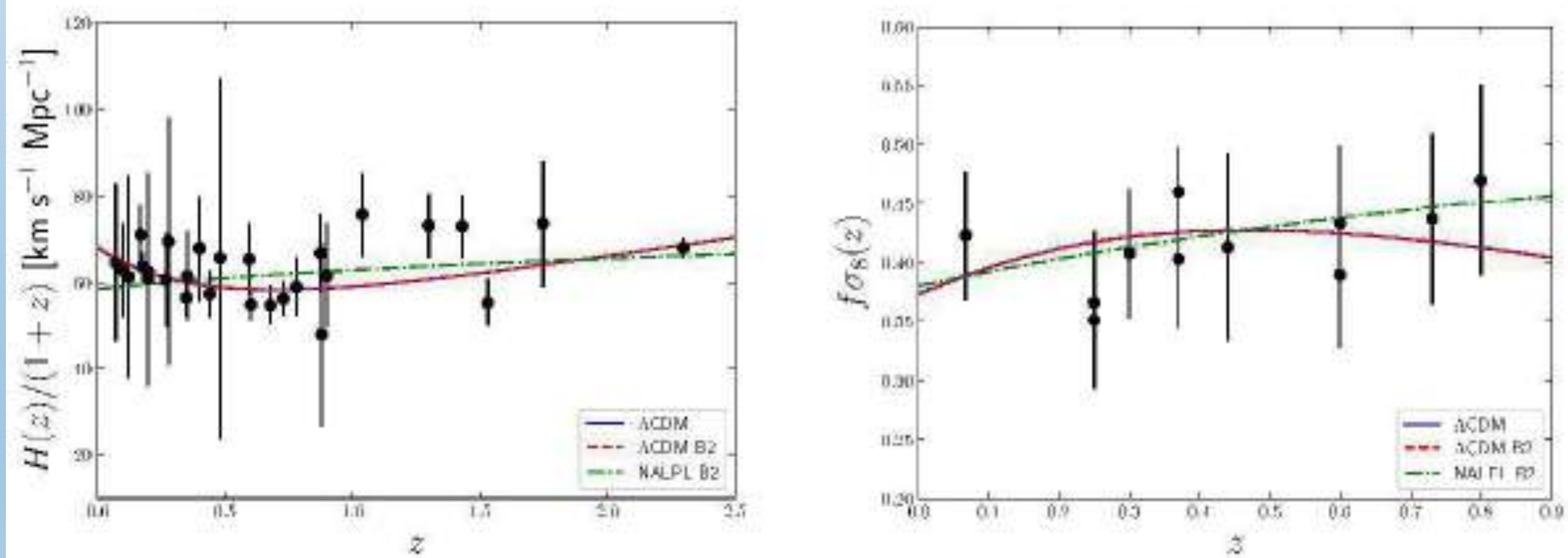
Confirms claim by Singal (2011) which was criticized subsequently
(Gibelyou & Huterer 2012, Rubart & Schwarz 2013, Nusser & Tiwari 2015)

We have addressed *all* the concerns but this strange anomaly remains … and casts doubt on the kinematic interpretation of the CMB dipole

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



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

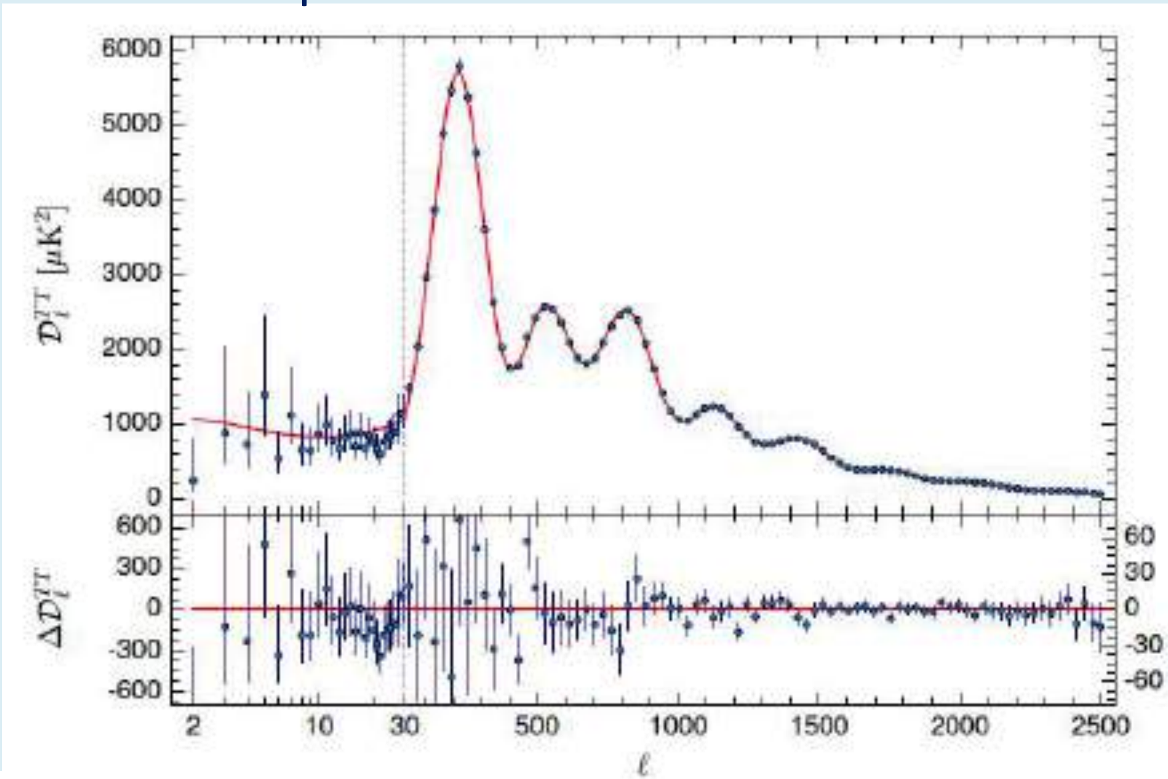


Tutusaus, Lamine, Dupays & Blanchard, A&A **602**:A73,2017

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)

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