Re-examining cosmic acceleration

Subir Sarkar

Rudolf Peierls Centre for Theoretical Physics

Type Ia supernovae are standard(isable) candles so observing them out to cosmological distances reveals the change of the Hubble parameter with redshift. Such observations have been interpreted to mean that the expansion rate of the universe is accelerating, as if driven by a Cosmological Constant. However reanalysis of the data shows that the inferred cosmic acceleration is anisotropic, so is likely to be an artefact due to our being untypical observers (embedded in a local non-Hubble `bulk flow'), rather than evidence for dark energy.

Colin *et al*, A&A 631: L13,2019; arXiv:1912.04257; 2003.10420 + Secrest *et al*, arXiv:2009.14826

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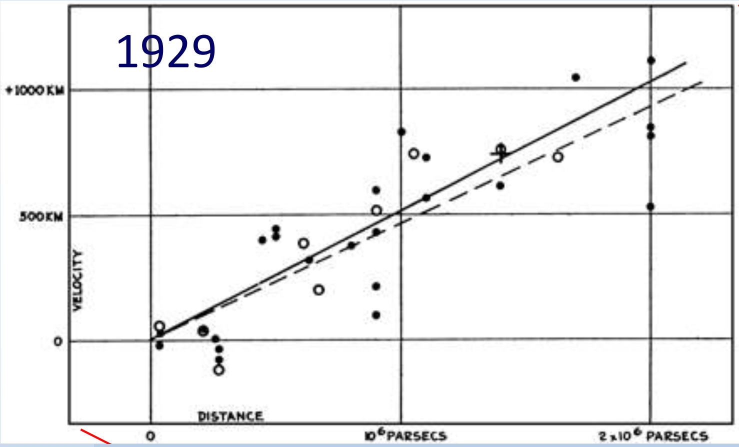
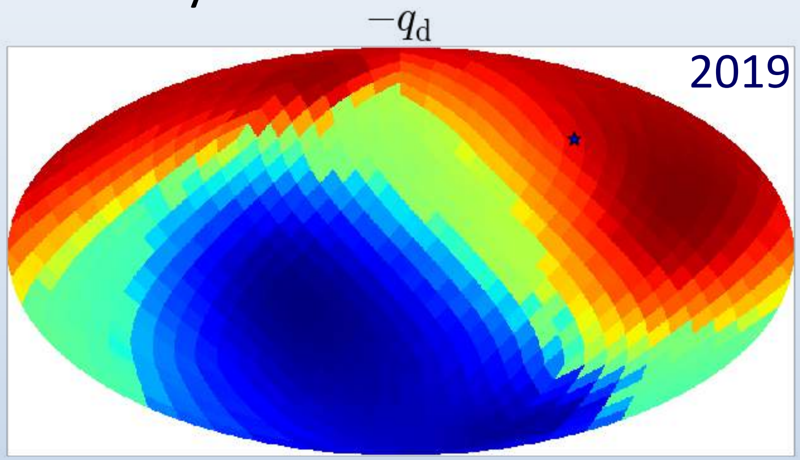
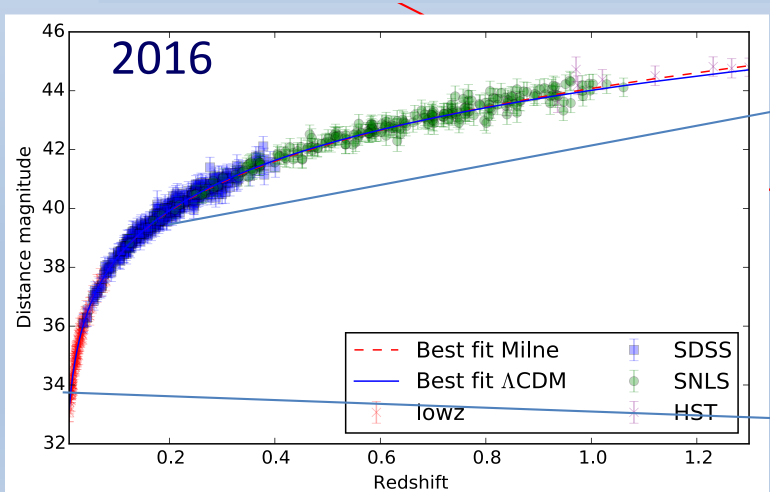
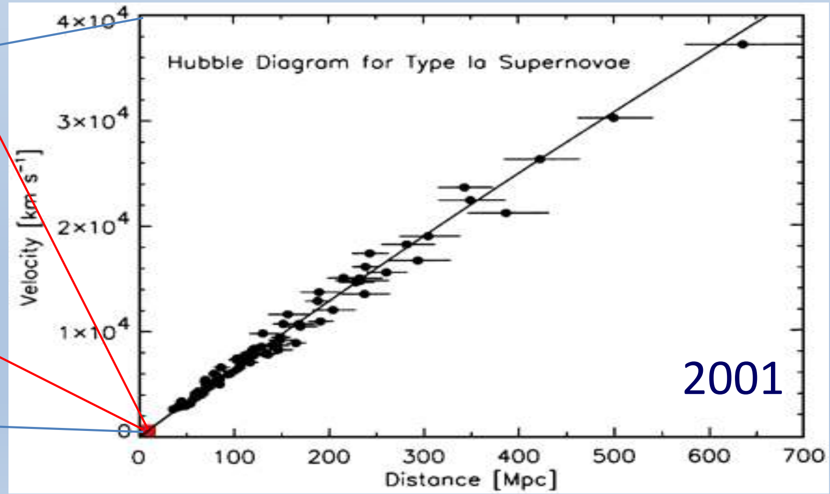




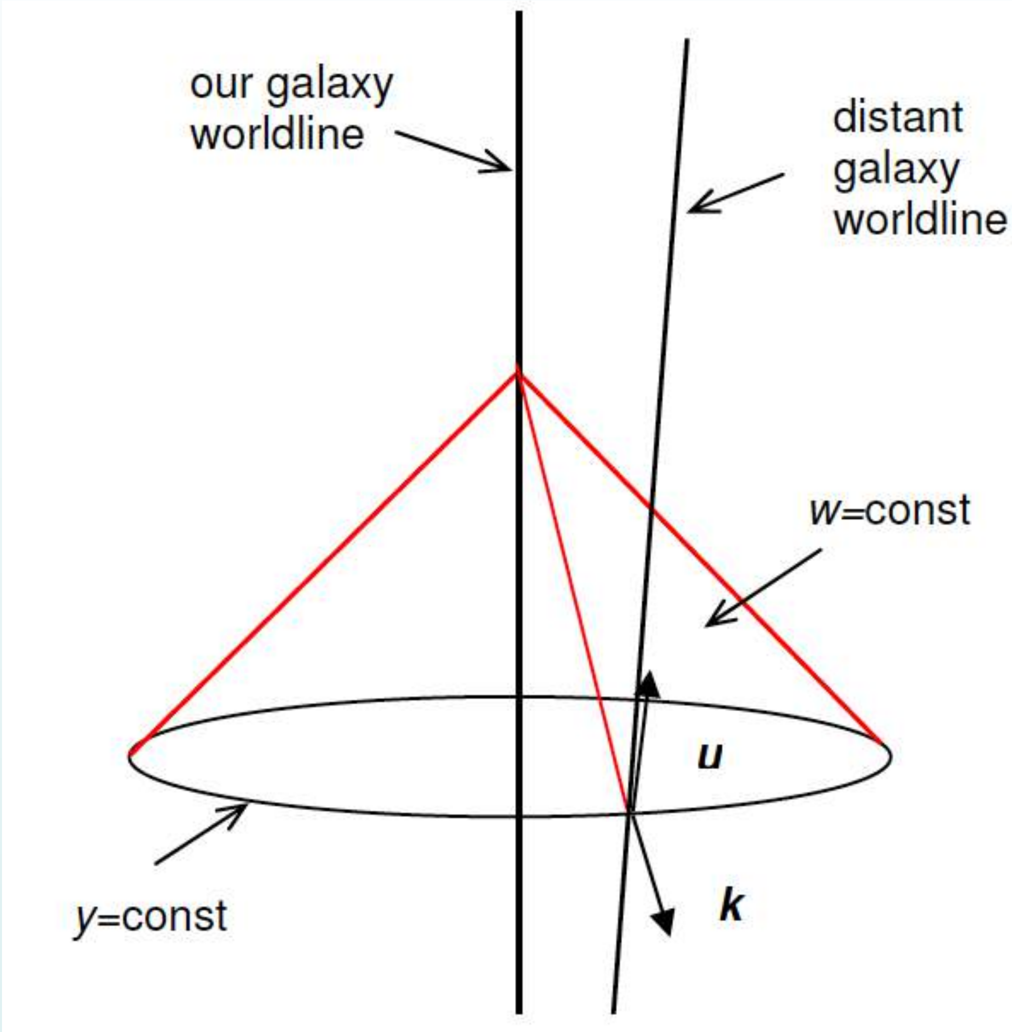
Hubble (1931) to De Sitter: “*The interpretation, we feel, should be left to you and the very few others who are competent to discuss the matter with authority*”





Colin et al, A&A 631: L13,2019; arXiv:1912.04257; 2003.10420 + Secrest et al, arXiv:2009.14826

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

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

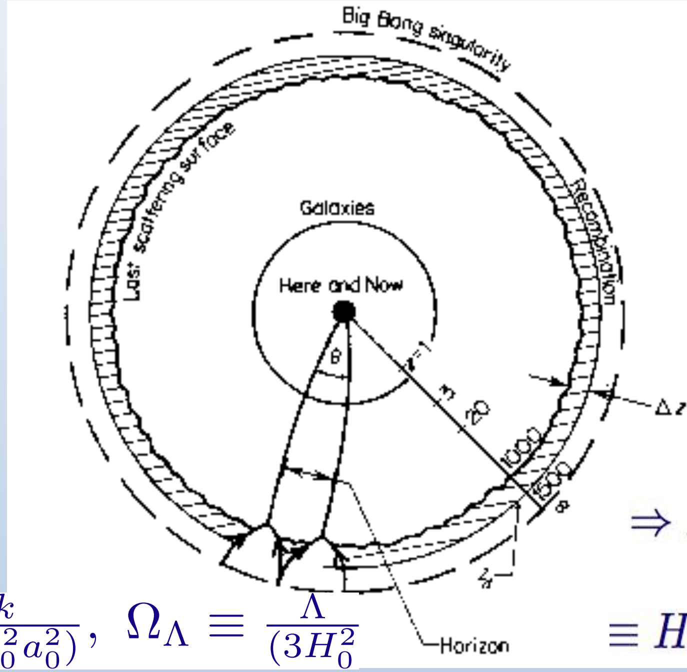
$$= a^2(\eta)\left[d\eta^2 - d\bar{x}^2\right]$$

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

Robertson-Walker

Friedmann-Lemaître

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



$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

Einstein

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

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

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

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

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

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

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 of $\mathbf{\Lambda}$ is set by the *only* dimensionful parameter in the model: $H_0 \sim 10^{-42}$ 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!

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

Interpreting Λ as vacuum energy also raises the 'coincidence problem':

Why is $\Omega_\Lambda \approx \Omega_{\text{m}}$ *today*?

An evolving ultralight scalar field ('quintessence') can display 'tracking' behaviour: this requires $V(\varphi)^{1/4} \sim 10^{-12}$ GeV but $\sqrt{d^2V/d\varphi^2} \sim H_0 \sim 10^{-42}$ GeV to ensure slow-roll ... i.e. *just as much fine-tuning as a bare cosmological constant*

A similar comment applies to models (e.g. 'DGP brane-world') wherein gravity is modified on the scale of the present Hubble radius $1/H_0$ so as to mimic vacuum energy ... this scale is absent in a fundamental theory and must be put in by hand

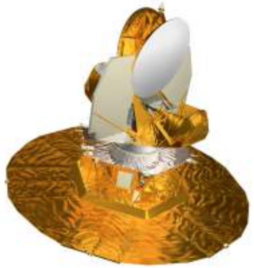
(There is similar fine-tuning in *every* proposal – massive gravity, chameleon fields, ...)

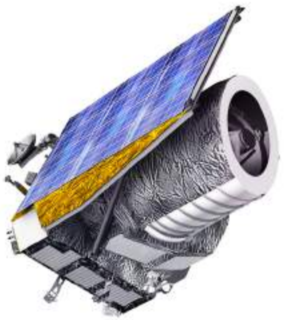
The only 'natural' option is if $\Lambda \sim H^2$ *always*, but this is just a renormalisation of G_N ! (recall: $H^2 = 8\pi G_N/3 + \Lambda/3$) → this is *ruled out* by Big Bang nucleosynthesis which requires G_N to be within 5% of its lab. value ... in any case this will *not* yield accelerated expansion

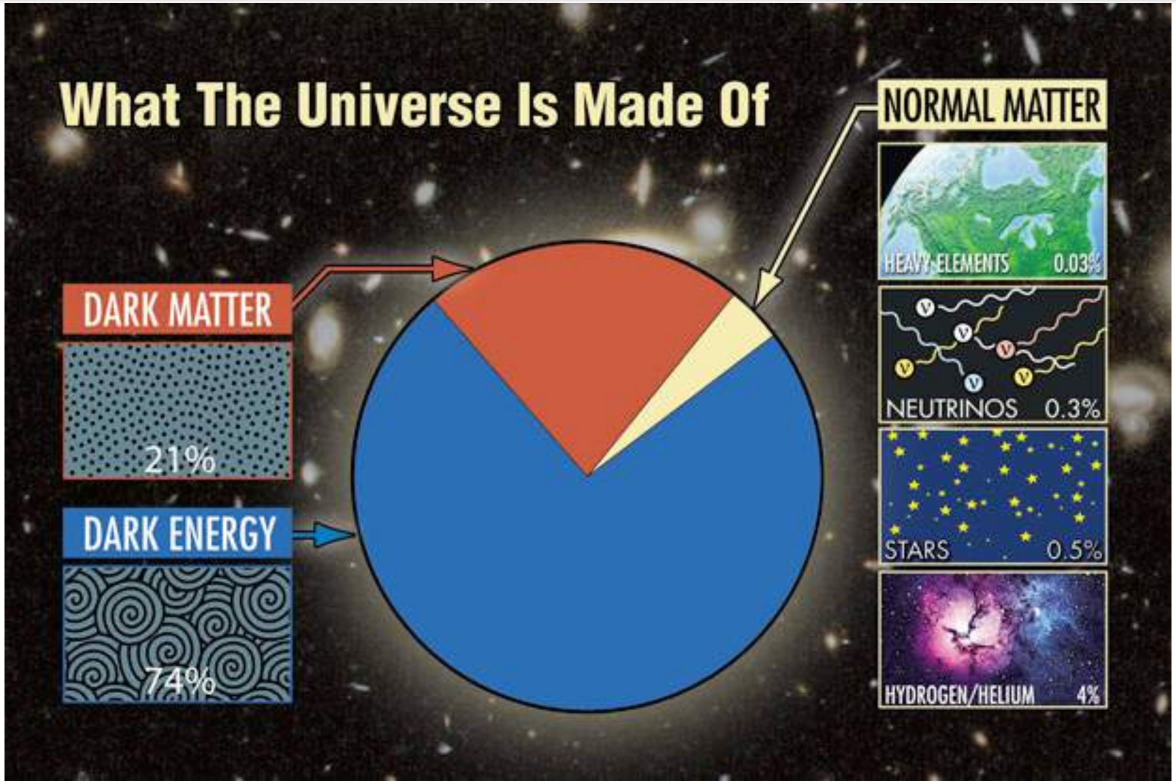
Every attempt to explain the coincidence problem is equally severely fine-tuned

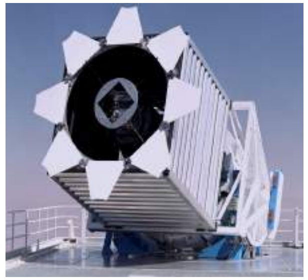
Do we infer $\Lambda \sim H_0^2$ from observations simply because H_0 ($\sim 10^{-42}$ GeV) is the *only* scale in the F-R-L-W model ... so this is the value imposed on Λ by **construction**?

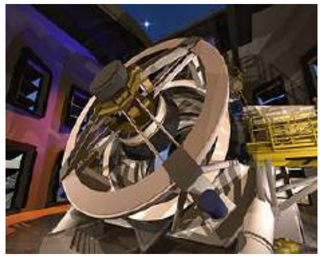
Since 1998 (Riess *et al.*[1], Perlmutter *et al.*[2]), surveys of cosmologically distant Type Ia supernovae (SNe Ia) have indicated an acceleration of the expansion of the Universe, distant SNe Ia being dimmer that expected in a decelerating Universe. With the assumption that the Universe can be described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







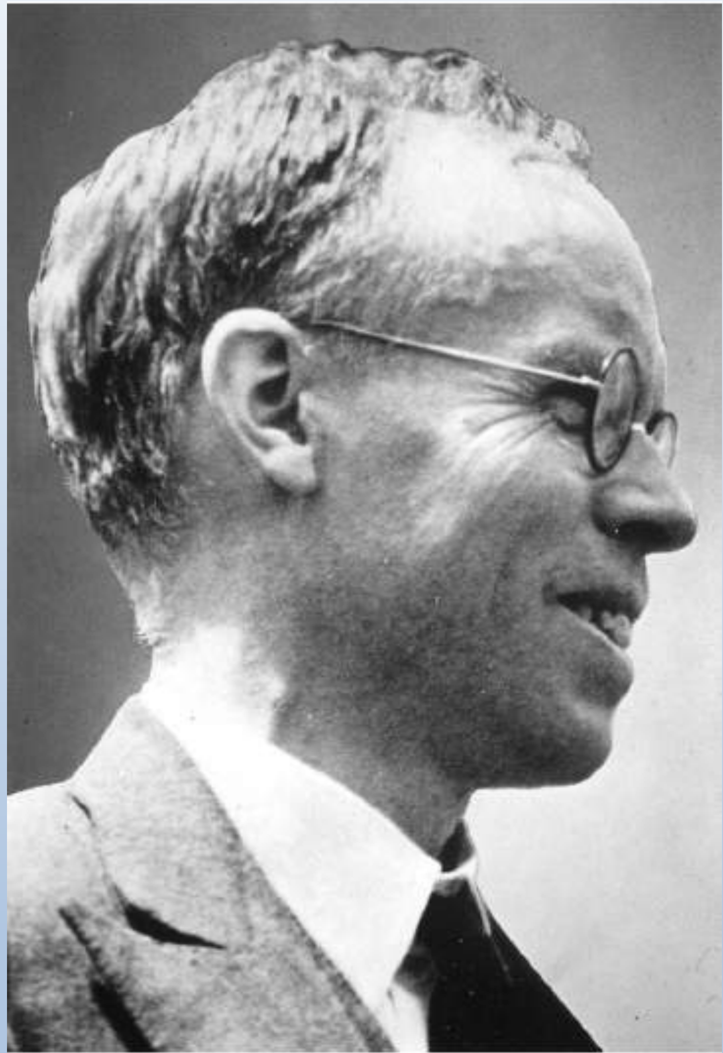




There has been substantial investment in major satellites & telescopes to precisely measure all the parameters of the 'standard cosmological model'… but not to test its **foundational assumptions**

The Universe must appear to be the same to all observers wherever they are

This ***'cosmological principle'*** *…*

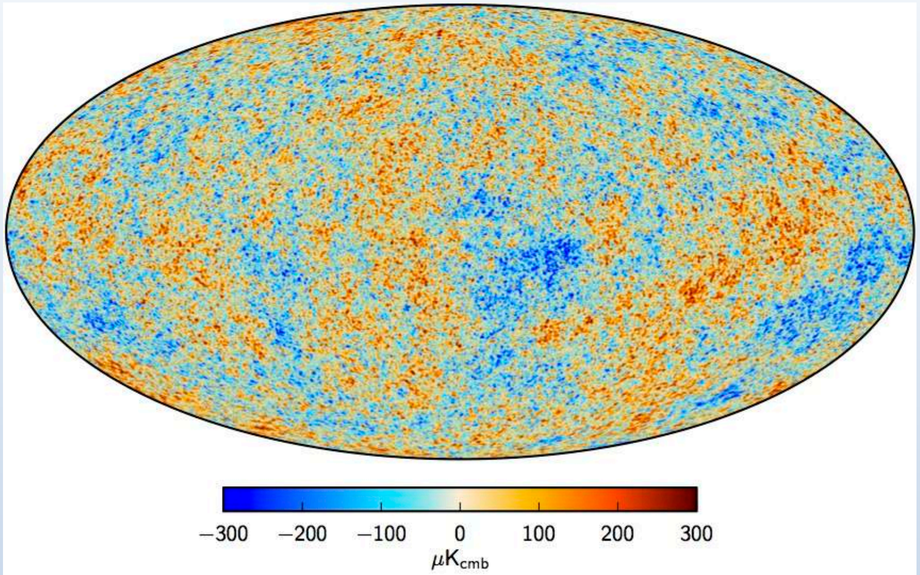


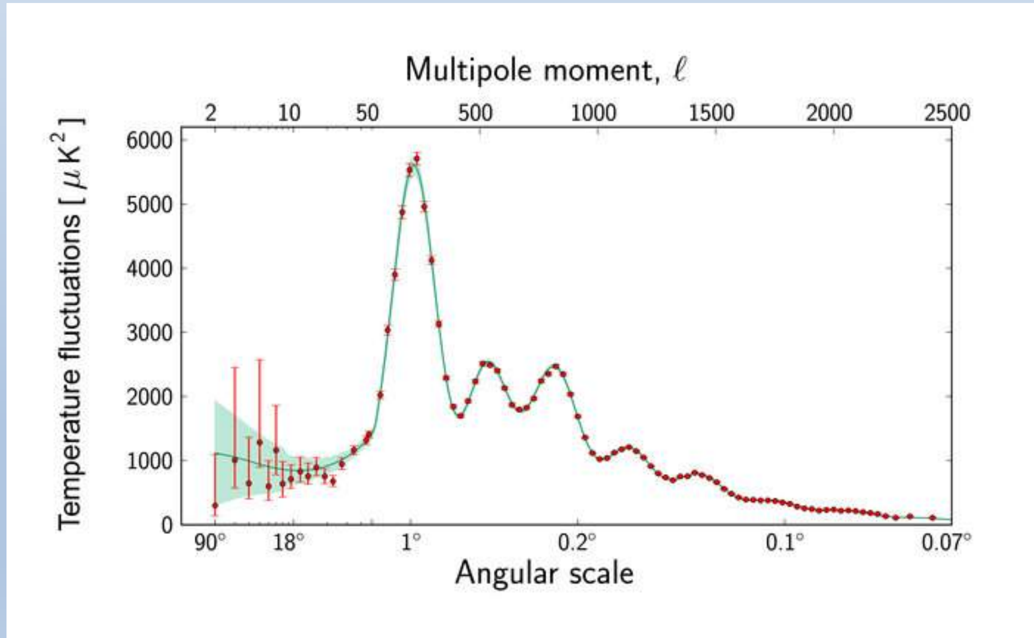
Kinematics, Dynamics, and the Scale of Time

By E. A. Milne, F.R.S.

(*Received* 28 *August*, 1936)

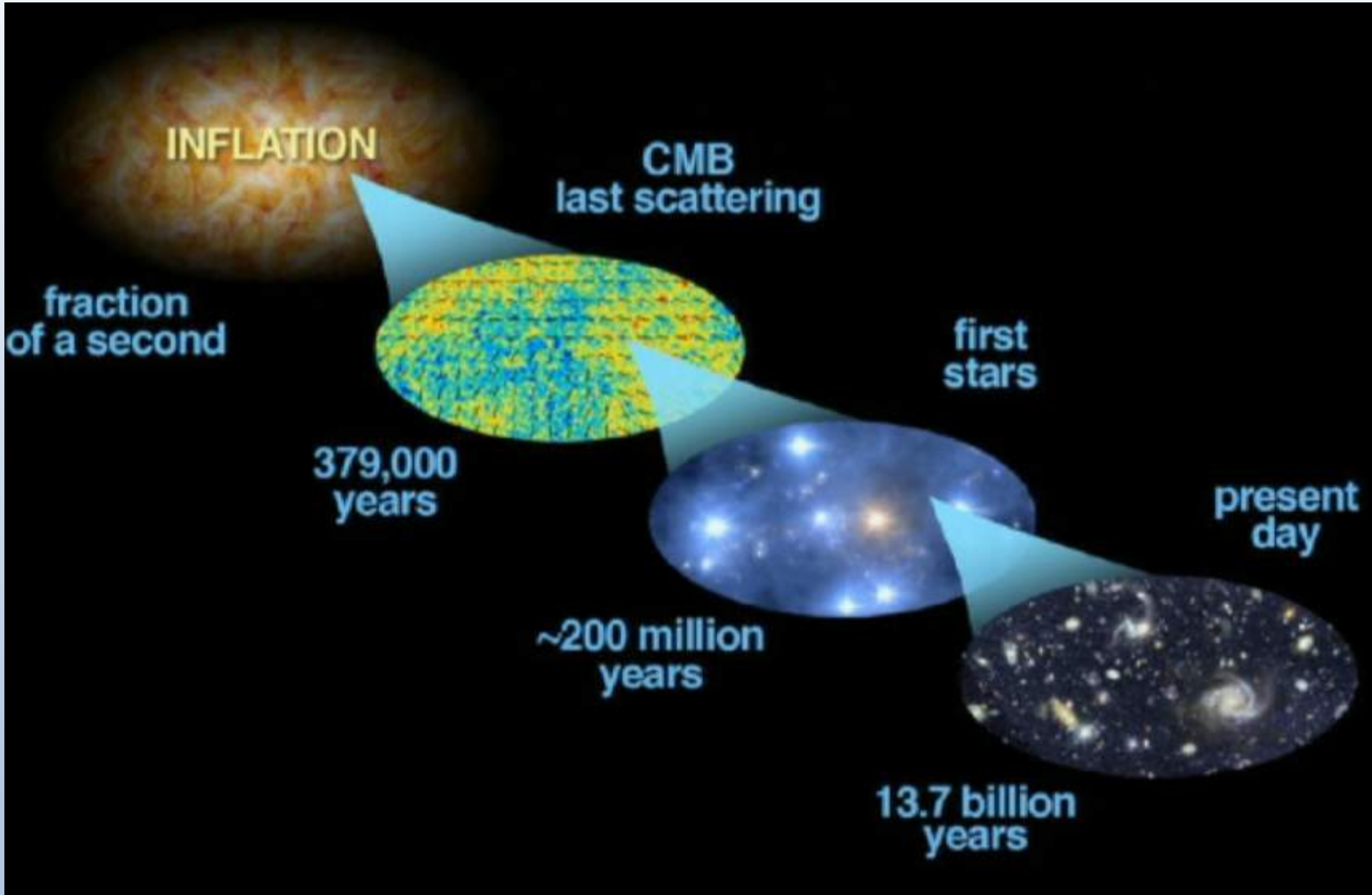
"Data from the Planck satellite show the universe to be highly isotropic" (Wikipedia)





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

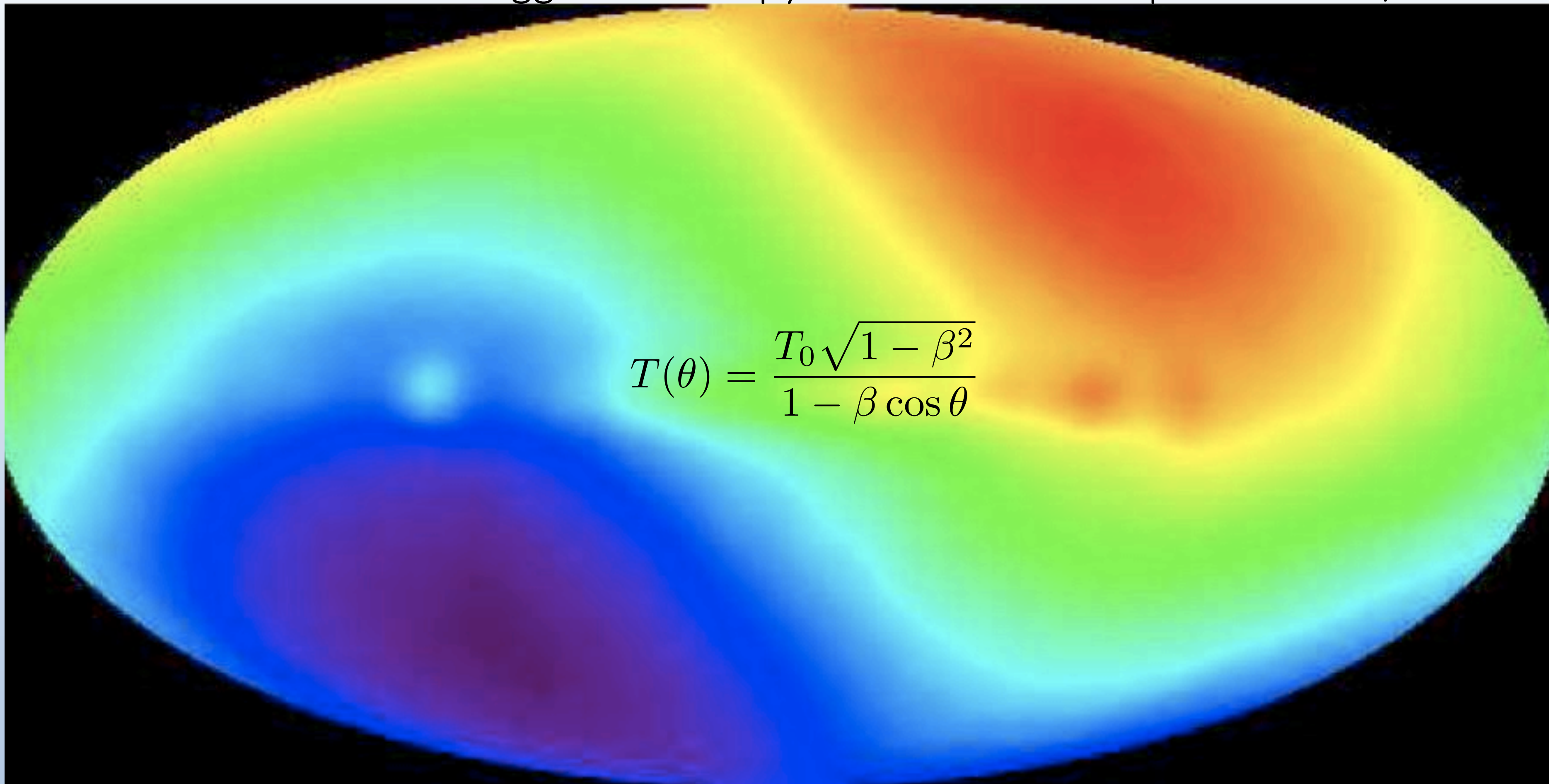
Standard model of structure formation



The ~10^{-5} **CMB temperature fluctuations** are understood as due to **scalar density perturbations** with a ~**scale-invariant spectrum** which were generated during an early **de Sitter phase of inflationary expansion** … these perturbations have subsequently grown into the **large-scale structure** of galaxies observed today through **gravitational instability** in a sea of **dark matter**

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

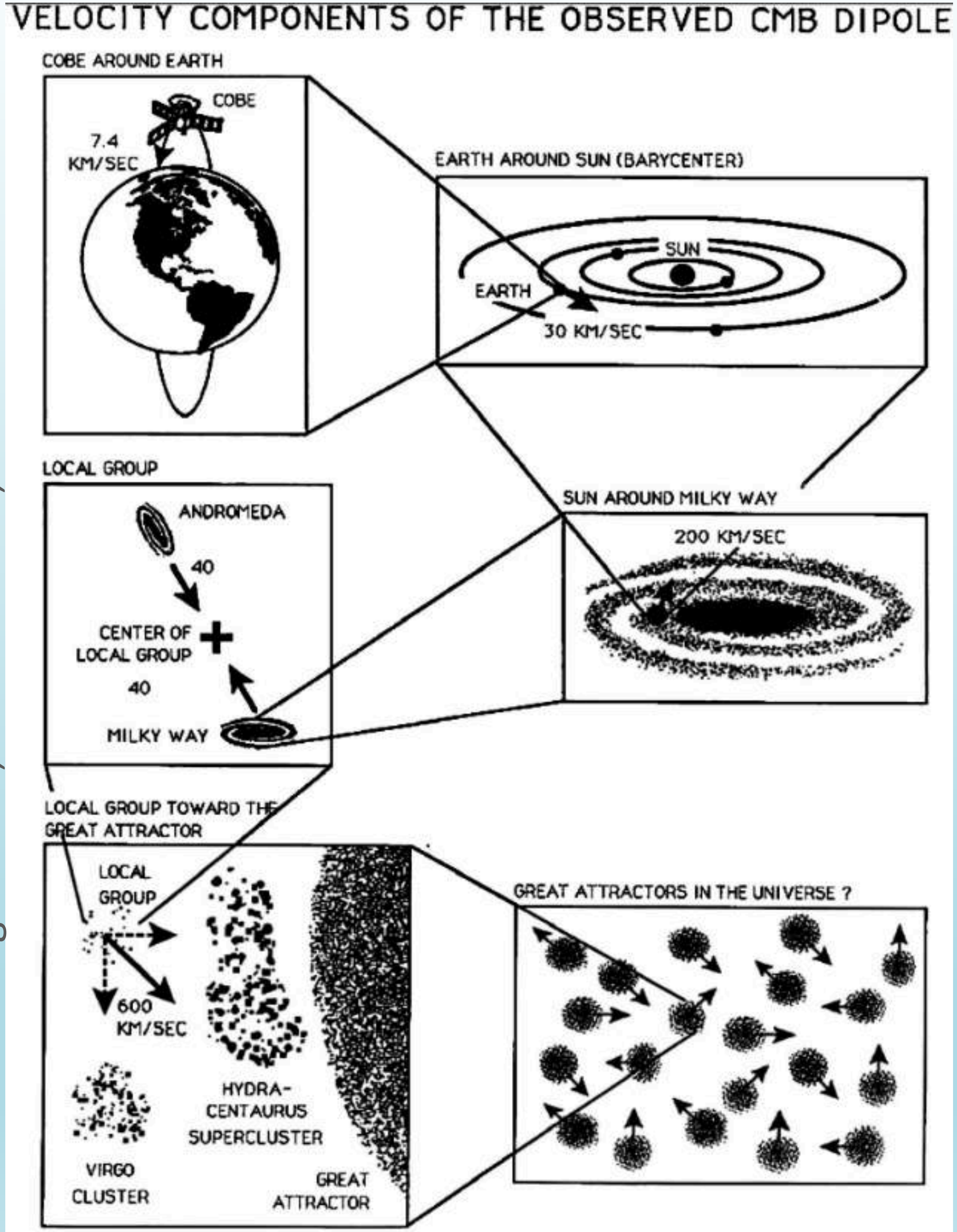
This is interpreted as due to our motion at 370 km/s wrt the frame in which the CMB is truly isotropic ⇒ motion of the Local Group at 620 km/s towards l=271.9°, b=29.6°

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)

George Smoot, Nobel Lecture, 8 Dec 2006



Peculiar Velocity of the Sun and its Relation to the Cosmic Microwave Background

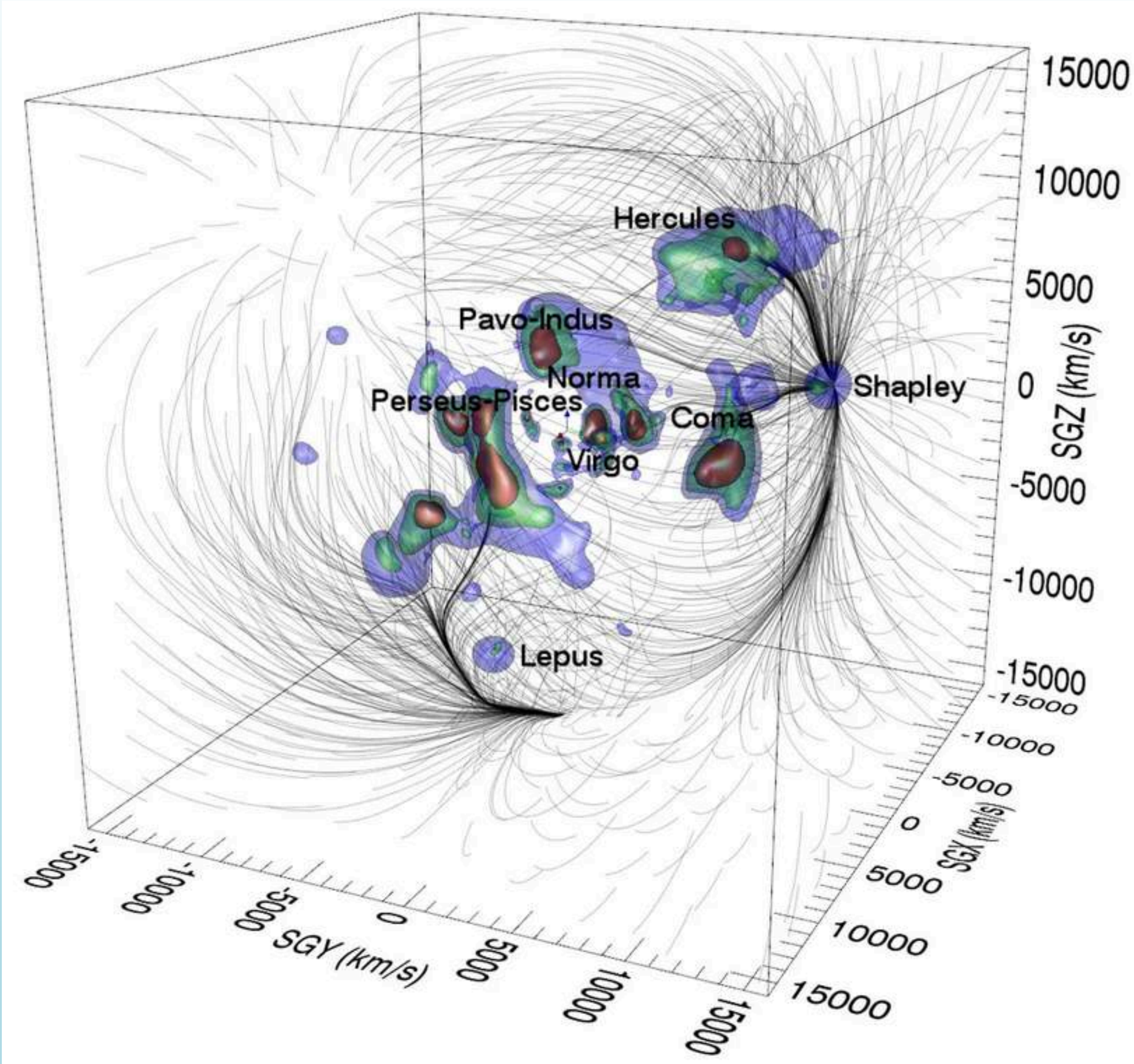
J. M. Stewart & D. W. Sciama

If the microwave blackbody radiation is both cosmological and isotropic, it will only be isotropic to an observer who is at rest in the rest frame of distant matter which last scattered the radiation. In this article an estimate is made of the velocity of the Sun relative to the distant matter, from which a prediction can be made of the anisotropy to be expected in the microwave radiation. It will soon be possible to compare this prediction with experimental results.

NATURE 216, 748 (1967)

"Cosmologists neglecting the motion of the Solar System are crackpots" - Lubos Motl

Structure within a cube extending ~200 Mpc from our position (Supergal. Coord.)



Tully, Courtois, Hoffman, Pomarede, Nature **513**:71,2014

We appear to be moving towards the Shapley supercluster due to a ‘Great Attractor’ …
if so, our local ‘peculiar velocity’ should fall off as ~1/*r* as we “converge to the CMB frame” in which the universe supposedly looks Friedmann-Lemaître-Robertson-Walker

THEORY OF PECULIAR VELOCITY FIELDS

In linear perturbation theory, the growth of the density contrast $\delta(x) = [\rho(x) - \bar{\rho}]/\bar{\rho}$ is governed by the continuity, Euler's & Poisson's equations … for pressureless 'dust':

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

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(x) = H_L(x) – H_0 (⇒ 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_L(x) is the local value of the Hubble parameter and *W* (x – y) is the 'window function' (e.g. $\theta(R - |x - y|)\,(4\pi R^3/3)^{-1}$ for a volume-limited survey out to distance R)

Theory of peculiar velocity fields (cont.)

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

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

Window function

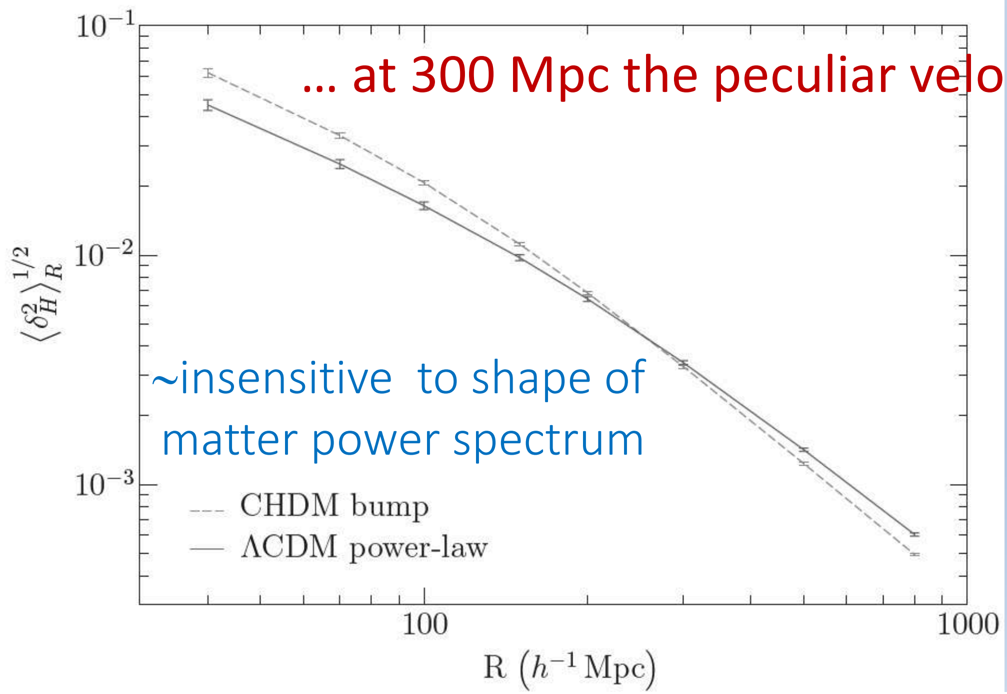
Then the RMS fluctuation in the local Hubble constant $\delta_H \equiv \langle (\delta H/H_0)^2 \rangle^{1/2}$ is:

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

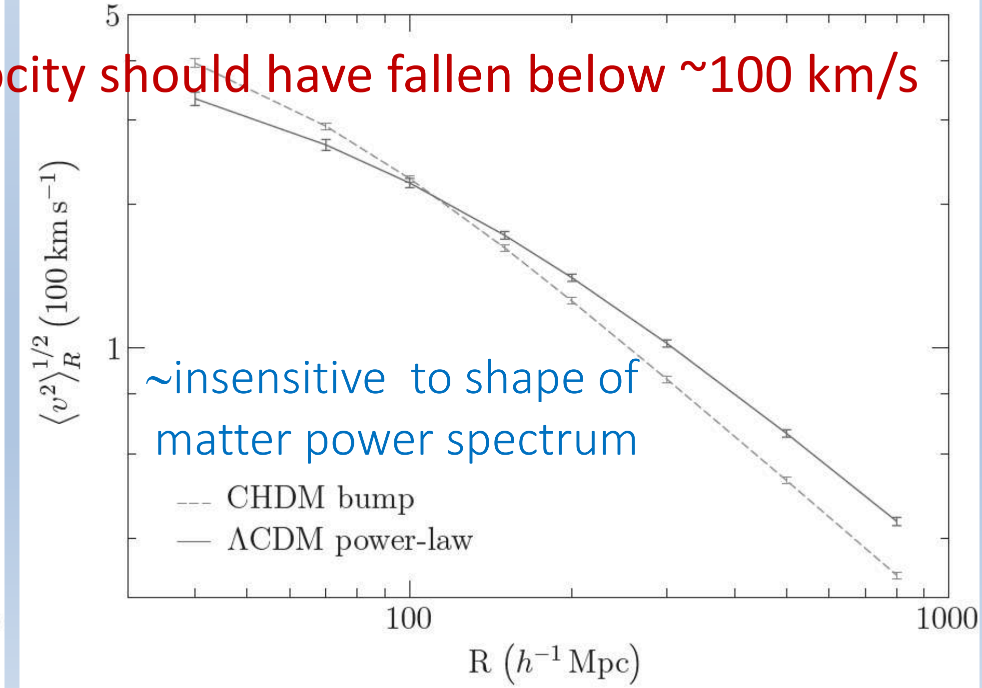
Power spectrum of matter fluctuations — Growth rate

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

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



~insensitive to shape of matter power spectrum

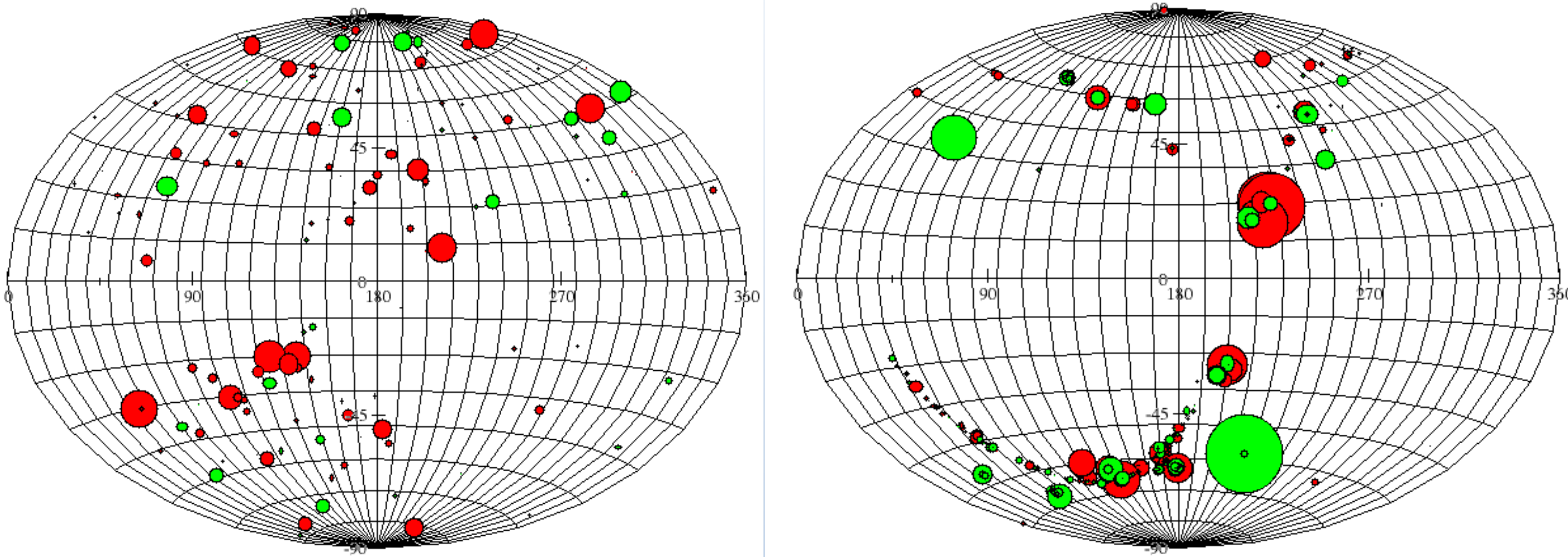


~insensitive to shape of matter power spectrum

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

Union 2 compilation of 557 Sne Ia

Aitoff-Hammer plot, Galactic coordinates

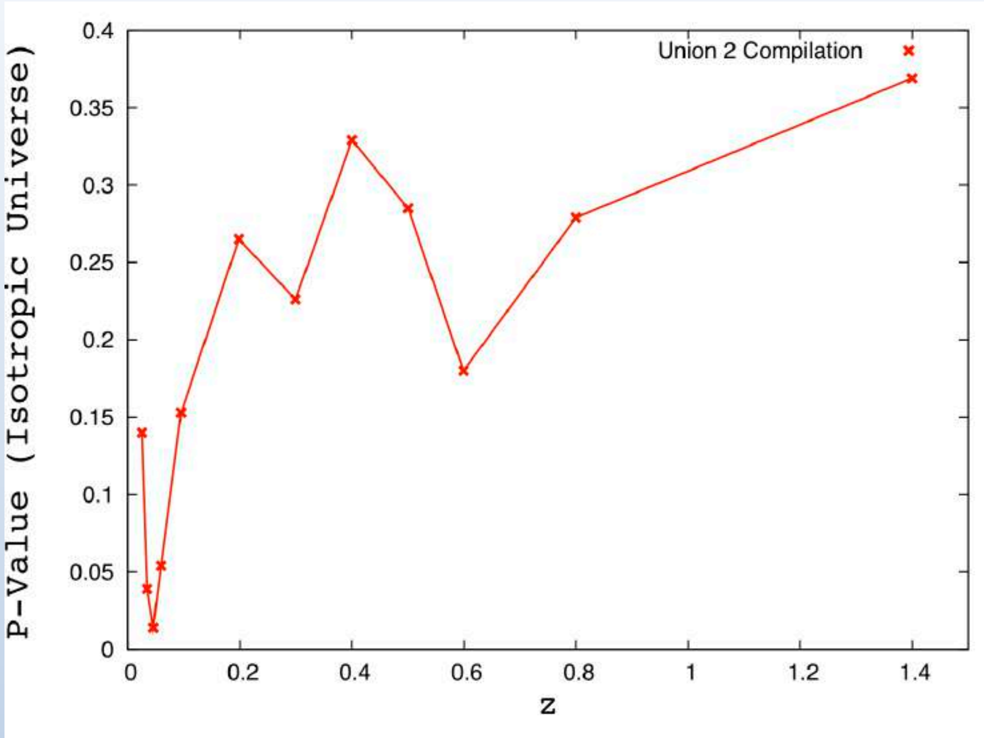


Colin, Mohayaee, S.S. & Shafieloo, MNRAS **414**:264,2011

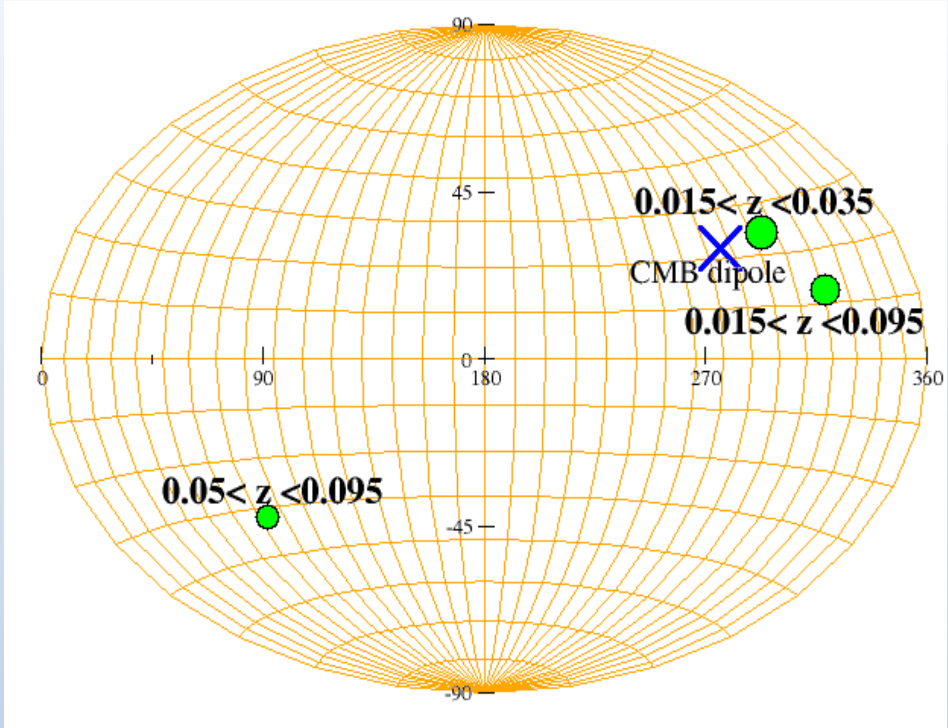
Left panel: The red spots represent the data points for $z < 0.06$ with distance moduli μ_{data} bigger than the values μ_{CDM} predicted by LCDM, and the green spots are those with μ_{data} less than μ_{CDM}; the spot size is a relative measure of the discrepancy. A dipole anisotropy is visible around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

IS THE UNIVERSE ISOTROPIC?



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



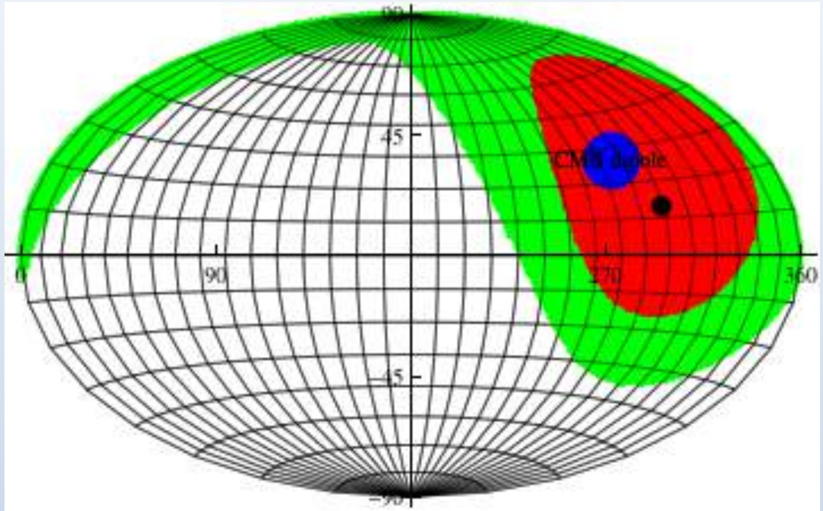
Left panel: P-value for the consistency of the isotropic universe with the data versus redshift. At $z \approx 0.05$ (~200 Mpc) the P-value drops to 0.014 showing that isotropy is excluded at ~3σ … i.e. we have *not* converged to the CMB rest frame.

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

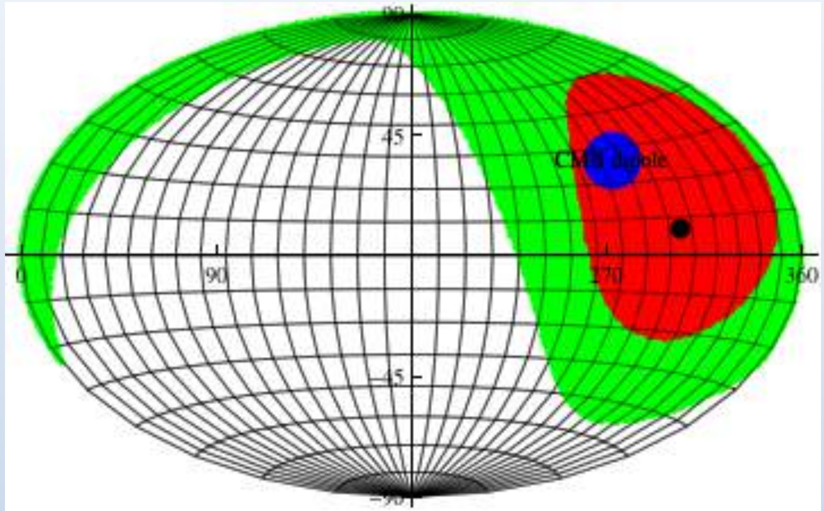
Maximum likelihood analysis can now be used to estimate the bulk flow at low redshifts where the velocities are not yet dominated by the cosmic expansion

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

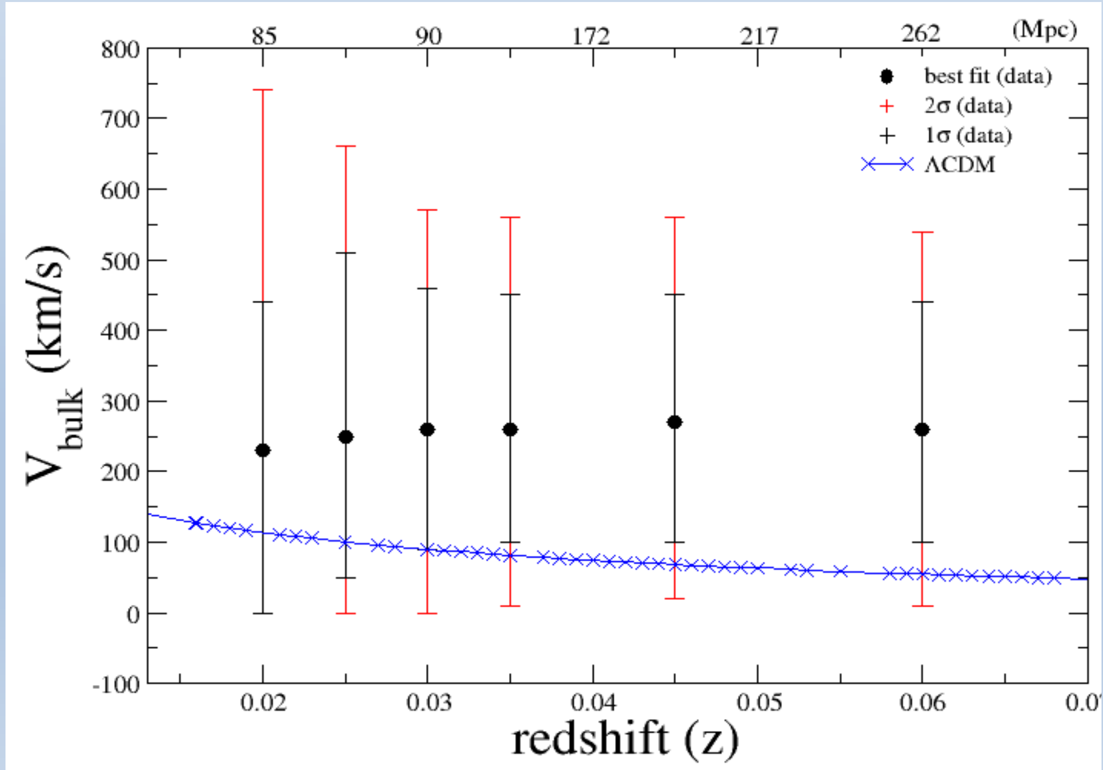
$0.015 < z < 0.045$, $v = 270$ km/s, $l = 291$, $b = 15$



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



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



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

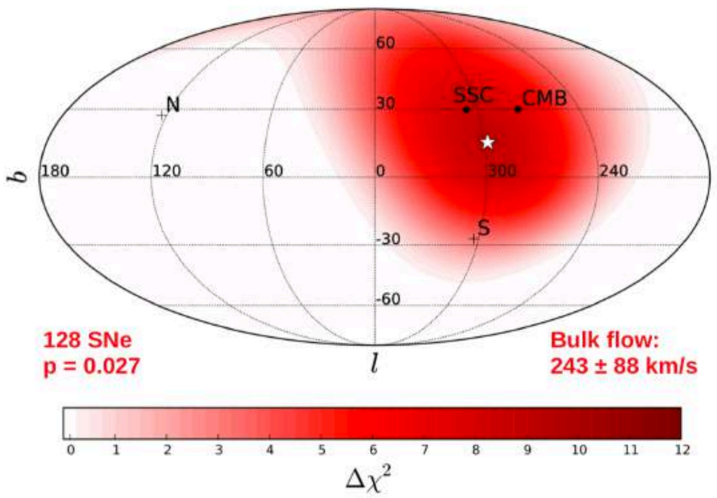
… consistent with Watkins et al (2009) who had earlier found a high bulk flow of 416±78 km/s towards $b = 60\pm6^0$, $l = 282\pm11^0$, going up to ~100 h^{-1} Mpc

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

Bulk Flow Analysis

Dipole fit: 0.015 < z < 0.035

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



Bulk flow modeled as velocity dipole:

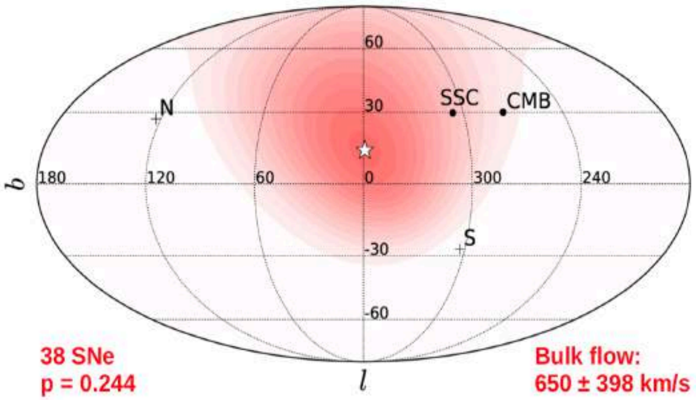
$$\tilde{d}_L(z) = d_L(z) + \frac{(1+z)^2}{H(z)} \vec{n} \cdot \vec{v}_d$$

Best fit direction consistent with direction to Shapley

➔ Amplitude matches previous studies

Nearby Supernova Factory survey

Dipole fit: 0.045 < z < 0.06



No backside infall behind Shapley

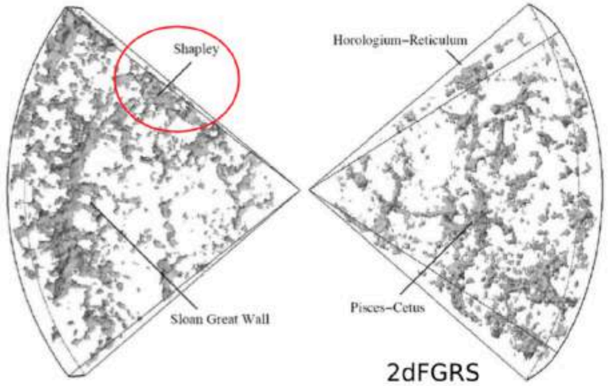
- Contradicts Shapley as the main source of the bulk flow
- Results in this shell are driven by SNfactory data

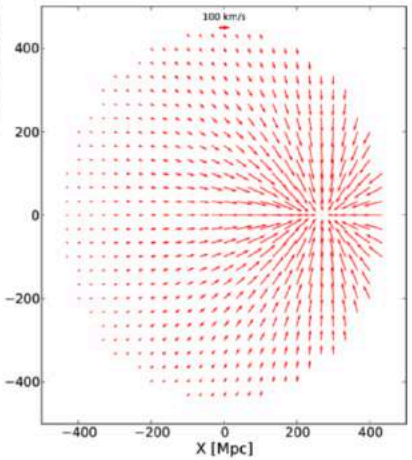
Feindt *et al,* A&A **560**:A90,2013

Need attractor mass of $>10^{17}$ M_{Sun} at ~300 Mpc to account for the flow

Finding the Attractors

Modeling the velocity field



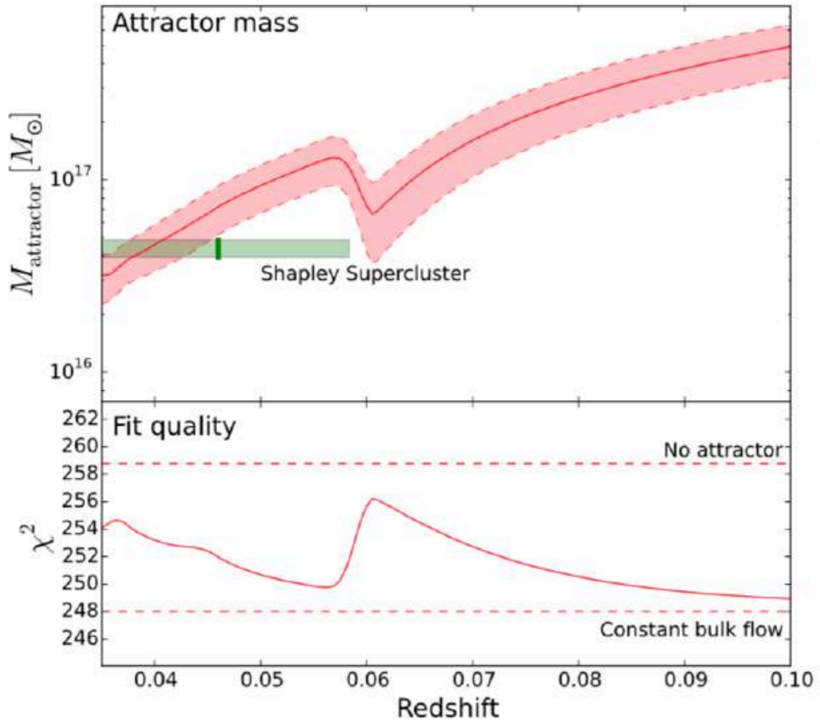


Simplest model:
Infall into spherical mass concentration

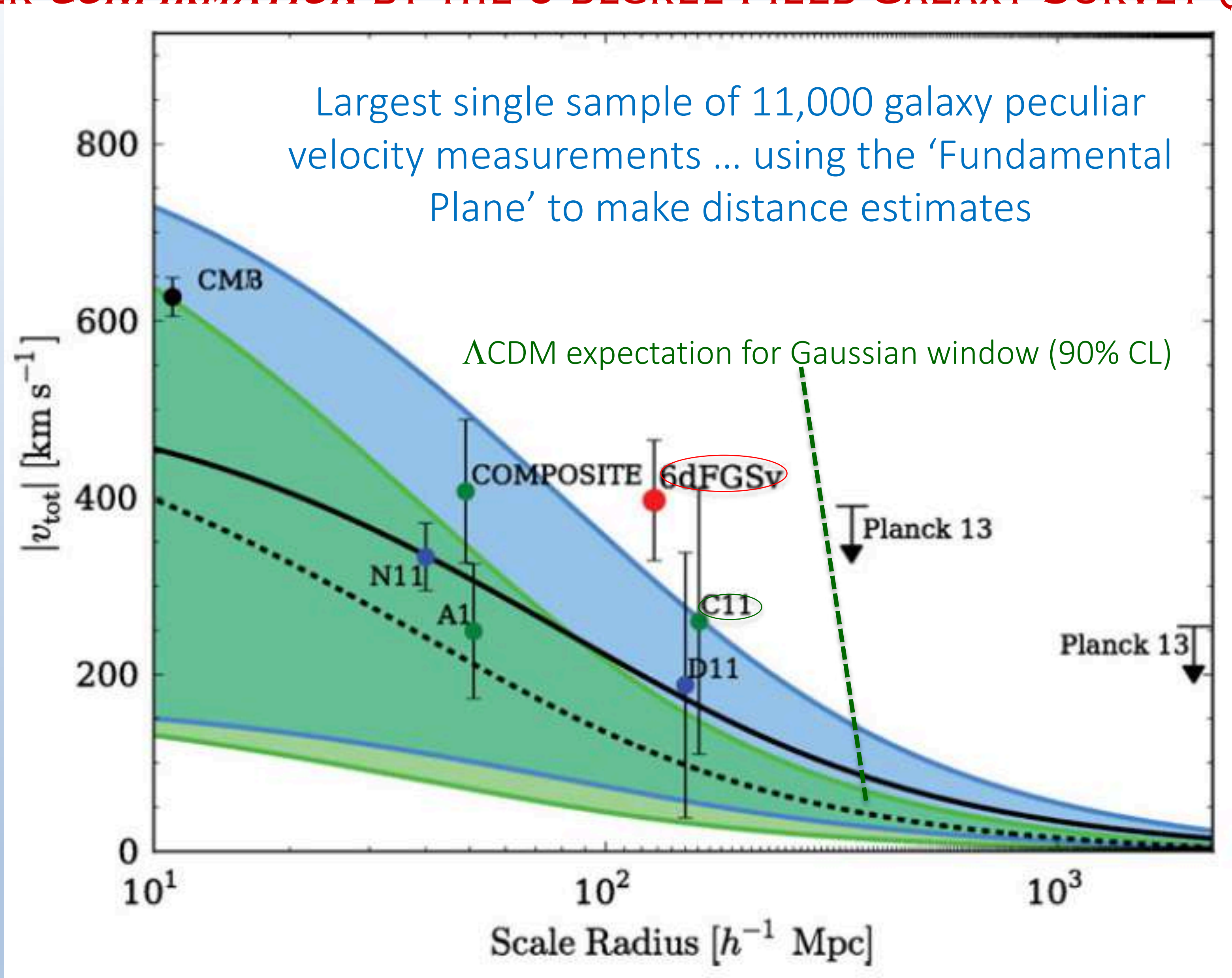
$$M_{\rm tot} = \frac{4\pi}{3} R^3 \Omega_{\rm M} \rho_{\rm crit} (1+\delta)$$

$$v_p(\vec{y}) = \frac{a\Omega_{\rm M}^{0.55} H}{4\pi} \int \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|^3} \delta(\vec{y}) \mathrm{d}^3 y$$

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, <1% of Milky Way–like observers experience a bulk flow as large as is observed and extending out as far as is seen …

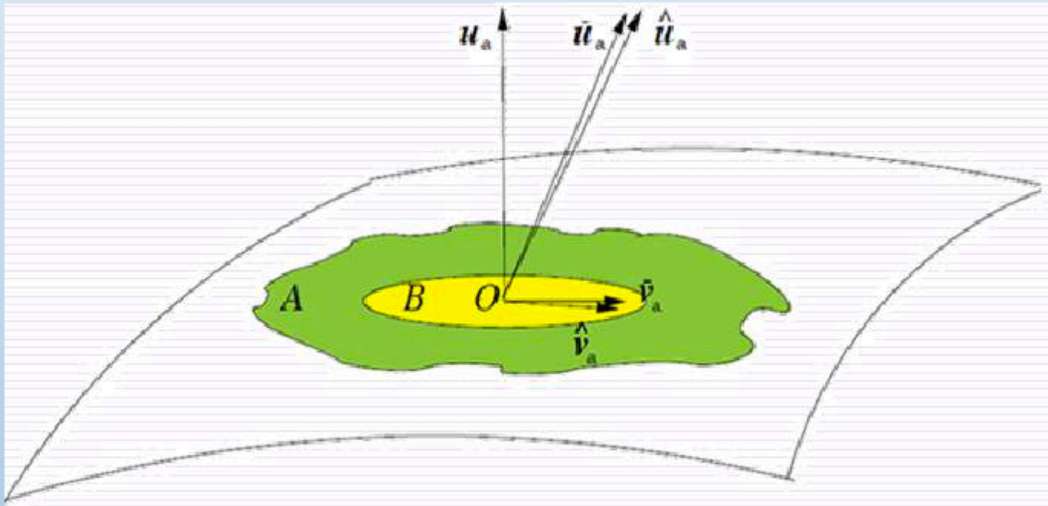
Rameez, Mohayaee, S.S. & Colin, MNRAS **477**:1722,2018

Do we infer acceleration although 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)

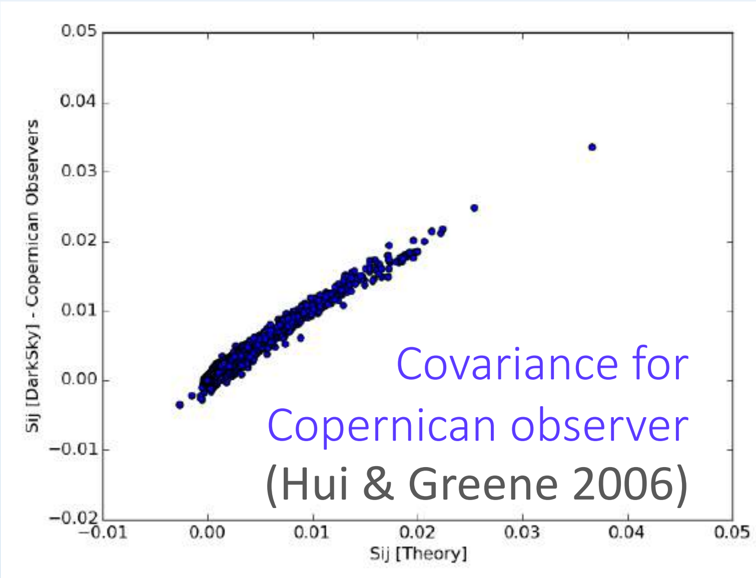
Inside region B, the r.h.s. of the expression

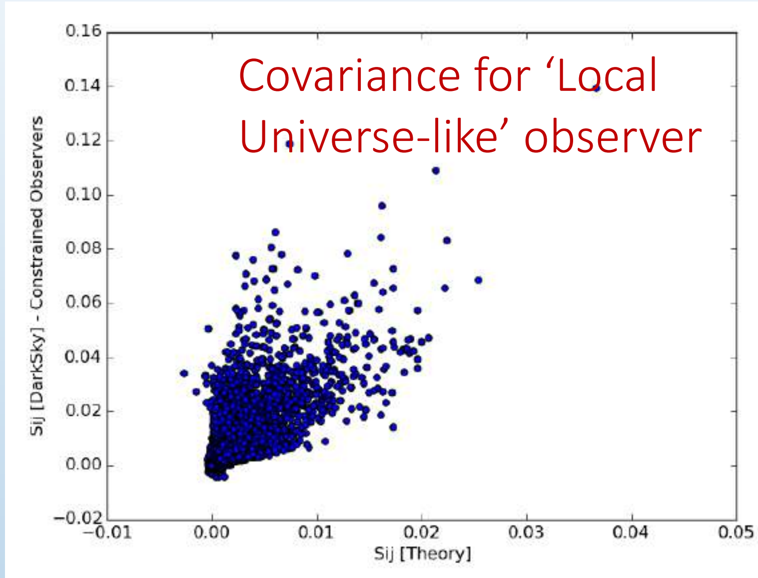
$$1 + \tilde{q} = (1+q)\left(1 + \frac{\vartheta}{\Theta}\right)^{-2} - \frac{3\dot{\vartheta}}{\Theta^2}\left(1 + \frac{\vartheta}{\Theta}\right)^{-2}, \qquad \tilde{\Theta} = \Theta + \vartheta,$$

drops below 1 and the comoving observer ‘measures’ negative deceleration parameter

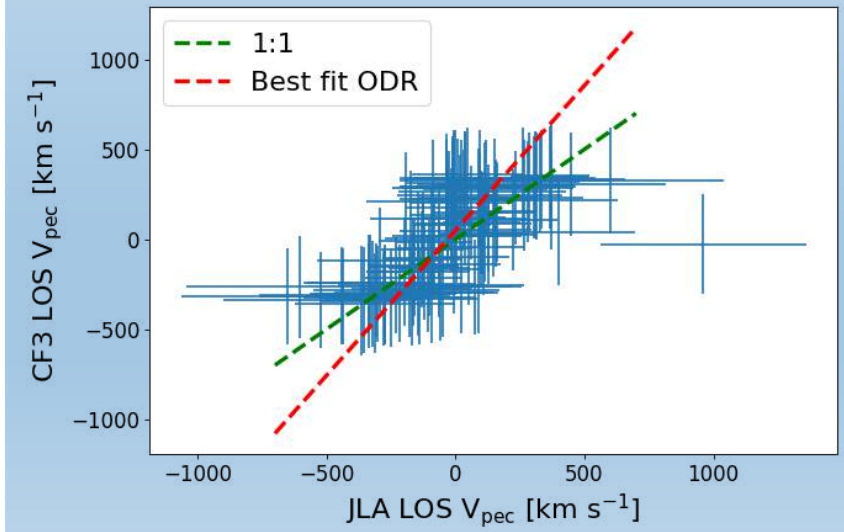
The impact of peculiar velocities on supernova cosmology

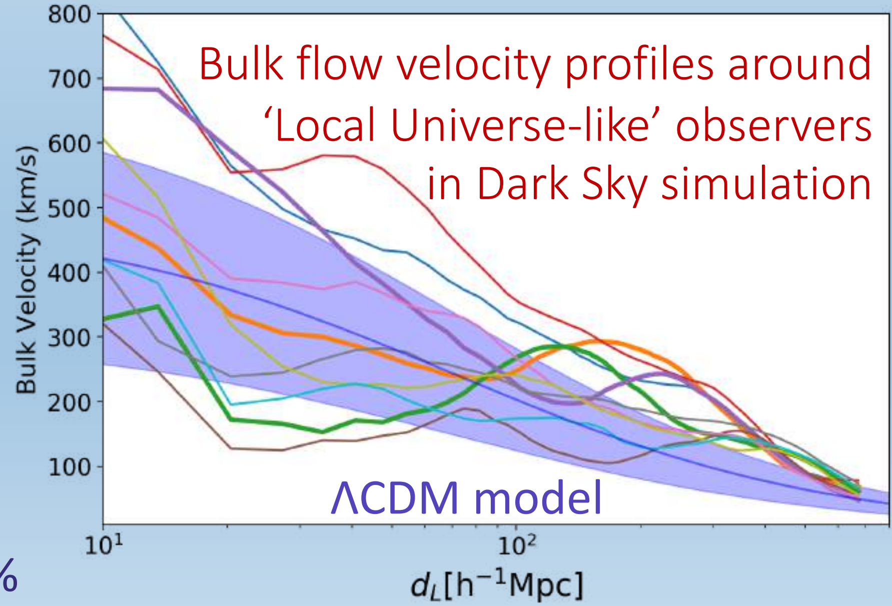
(Mohayaee, Rameez & S.S., arXiv:2003.10420)





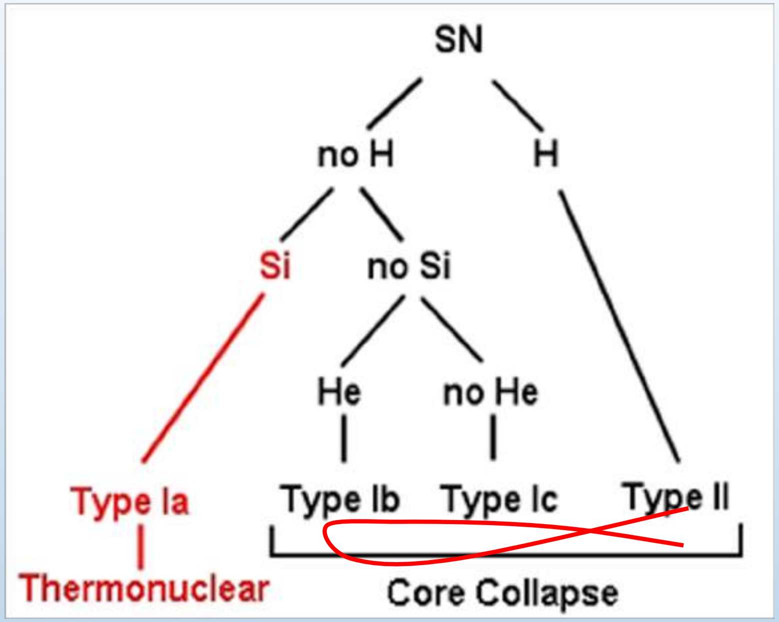
Correlated fluctuations of SNe Ia observables due to peculiar velocities of both the observer & the SNe Ia host galaxies can have considerable impact on cosmological parameter estimation

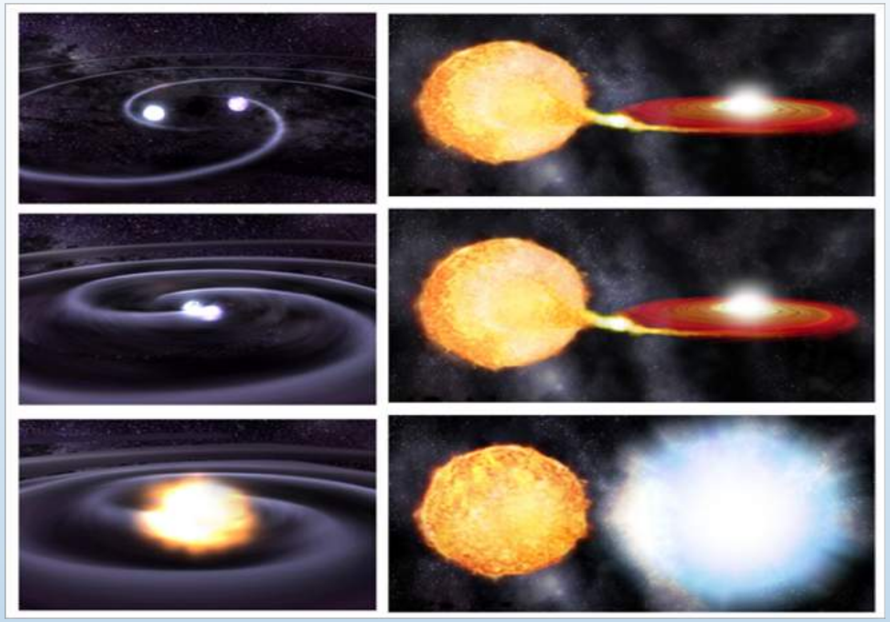




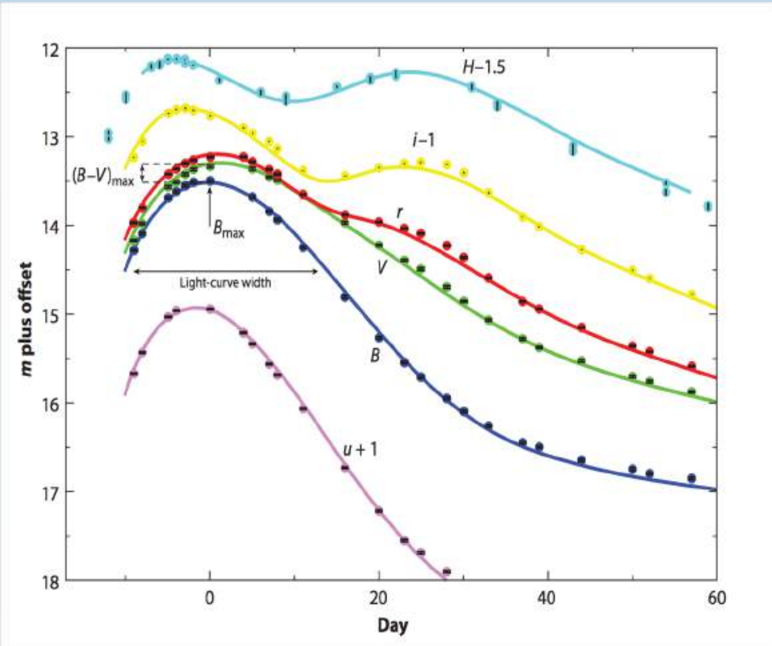
=> JLA velocities have been underestimated by ~48%

What are Type Ia supernovae?

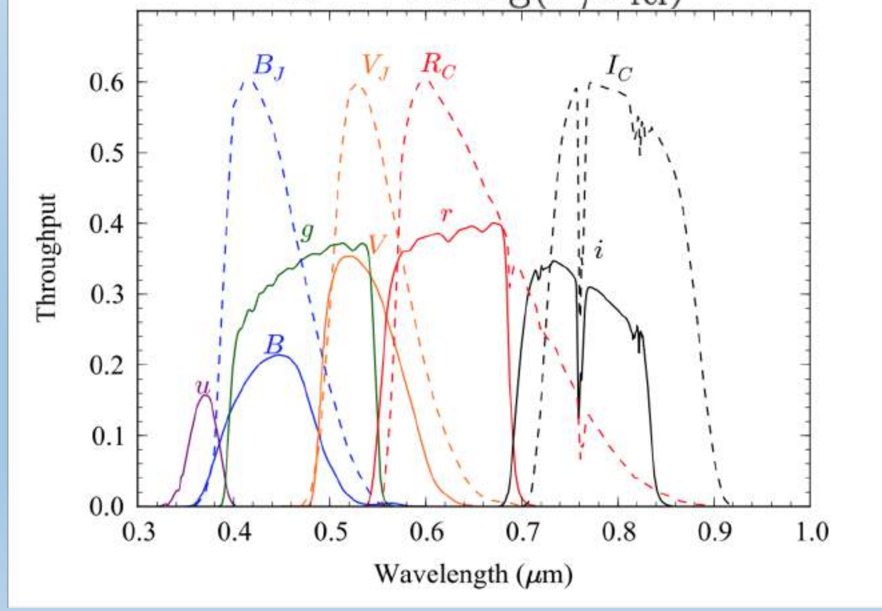




Goobar & Leibundgut, ARAA **61**:251,2011



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



Identify by multiple exposure of sky (+ spectroscopy) → measure peak magnitude and redshift

The magnitude-redshift data can be used to do cosmology

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

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

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

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

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

Distance modulus

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

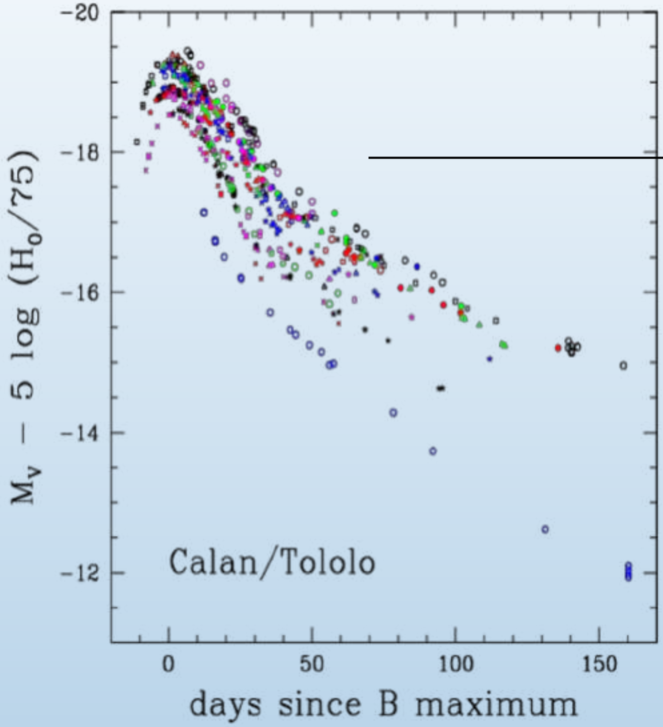
… Or for cosmography

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

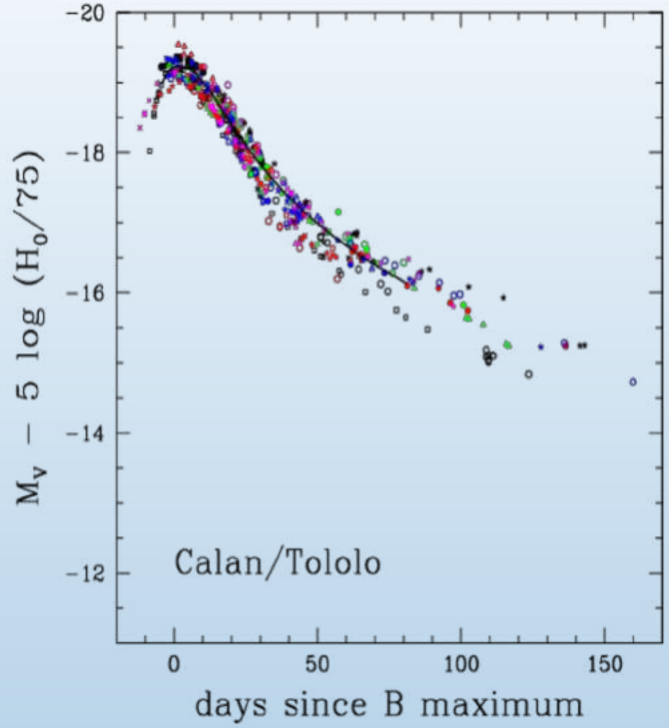
$q_0 \equiv -(\ddot{a}a)/\dot{a}^2$ $\quad$ $j_0 \equiv (\dddot{a}/a)(\dot{a}/a)^{-3}$ $\quad$ (e.g. Visser, CQG **21**:2603,2004)

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

SN IA ARE *NOT* 'STANDARD CANDLES'



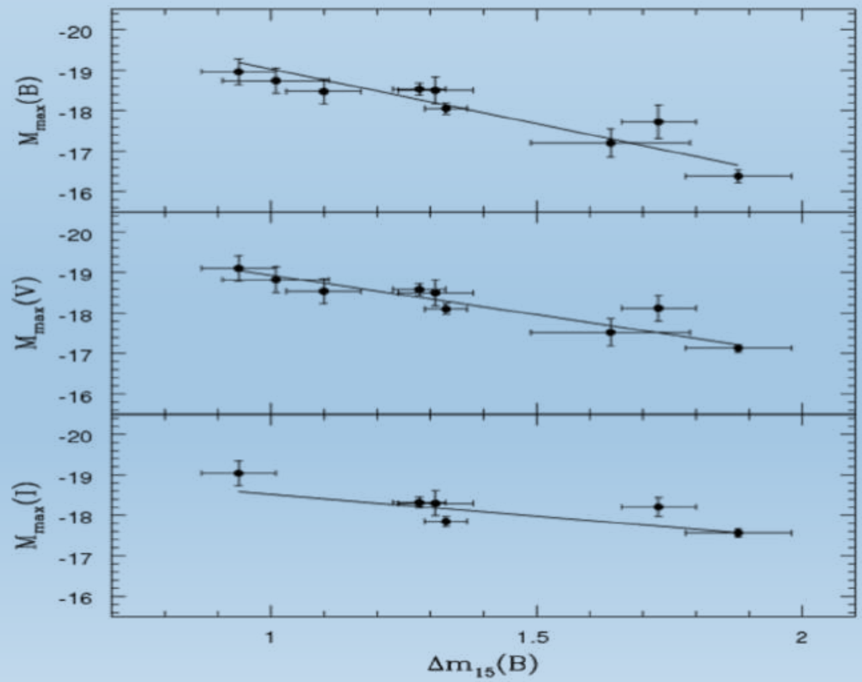
BUT THEY ARE 'STANDARDISABLE'



Hamuy, 1311.5099

… using the observed correlation between peak magnitude and light curve width

(NB: this is empirical and *not* understood theoretically)



Phillips, ApJ **413**:L105,1993

Spectral Adaptive Lightcurve Template

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

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

B-band

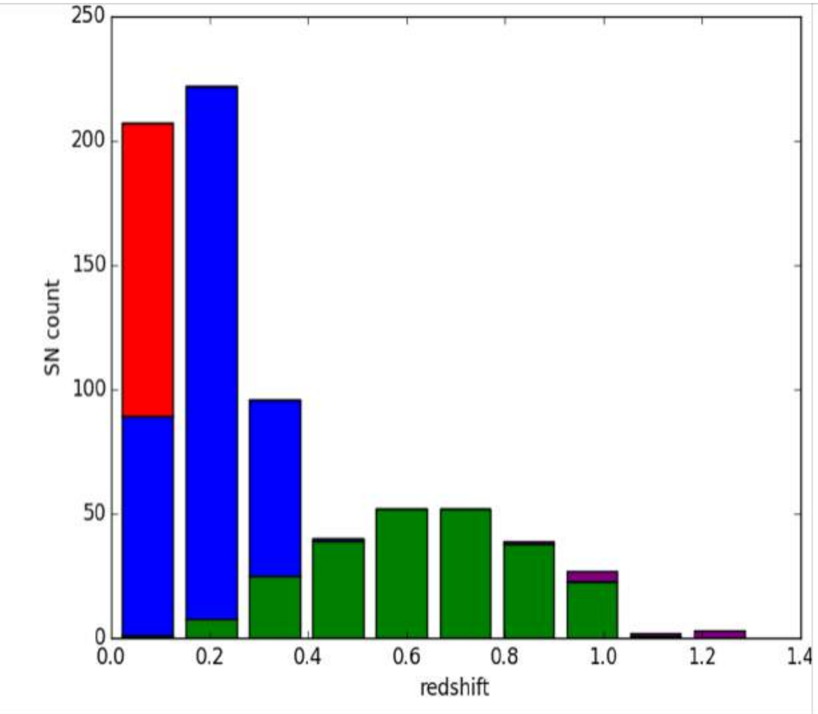
SALT 2 parameters

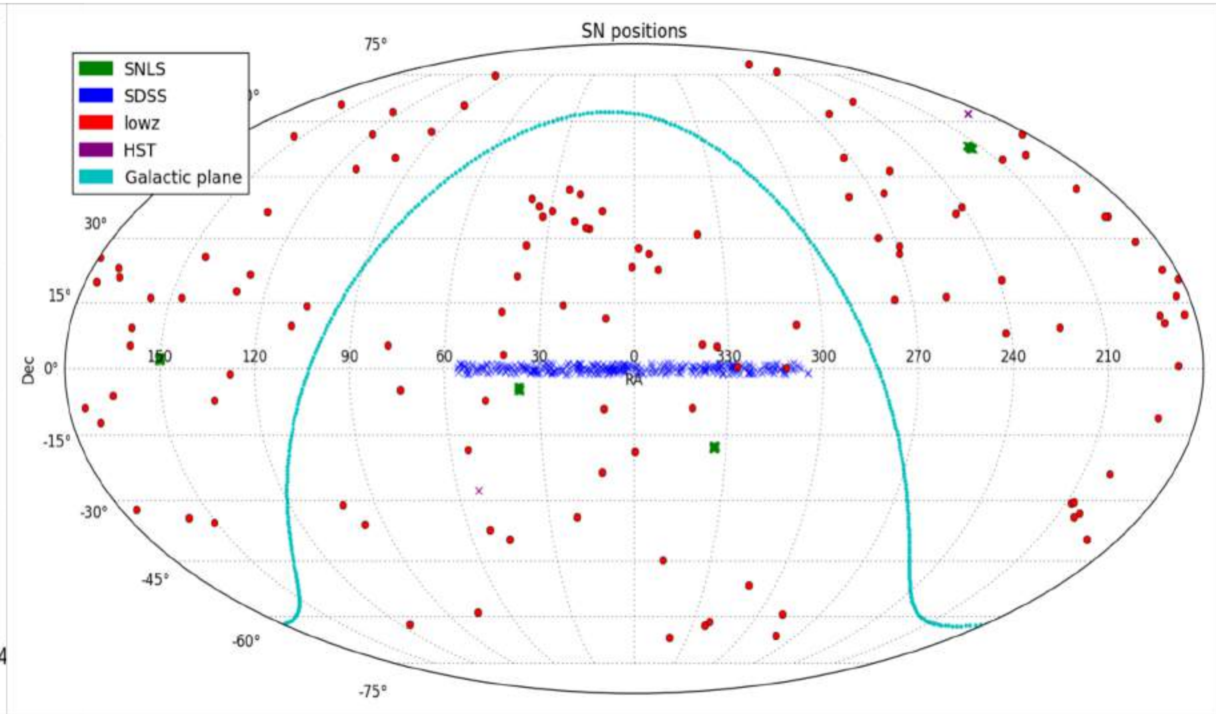
Betoule *et al.*, A&A **568**:A22,2014

Name	$z_{\rm cmb}$	$m_B^\star$	X_1	C	$M_{\rm stellar}$	?
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 …

Joint Lightcurve Analysis data (740 SNe Ia)





Betoule, Conley, Filippenko, Frieman, Goobar, Guy, Hook, Jha, Kessler, Pain, Perlmutter, Riess, Sollerman, Sullivan … A&A **568**:A22,2014) http://supernovae.in2p3.fr/sdss_snls_jla/

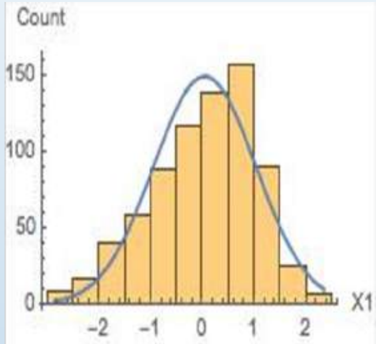
NB: Previous analyses used the 'constrained chi-squared' method … wherein $\sigma_{\rm int}$ is *adjusted* to get χ^2 of 1/d.o.f. for the fit to the assumed ΛCDM model

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

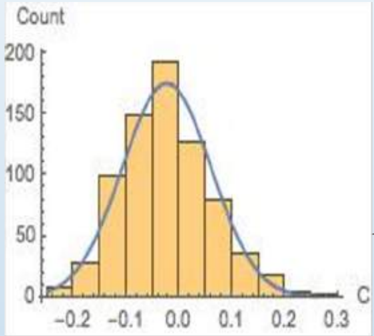
we employ a Maximal Likelihood Estimator … and get rather different results

Construct a Maximum Likelihood Estimator

Well-approximated as Gaussian



'Stretch' corrections



'Colour' corrections

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

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

$$p[(M, x_1, c)|\theta] = p(M|\theta)p(x_1|\theta)p(c|\theta), \quad \text{where:}$$
$$p(M|\theta) = (2\pi\sigma^2_{M_0})^{-1/2} \exp\left\{-\left[(M - M_0)/\sigma_{M_0}\right]^2/2\right\},$$
$$p(x_1|\theta) = (2\pi\sigma^2_{x_{1,0}})^{-1/2} \exp\left\{-\left[(x_1 - x_{1,0})/\sigma_{x_{1,0}}\right]^2/2\right\},$$
$$p(c|\theta) = (2\pi\sigma^2_{c_0})^{-1/2} \exp\left\{-\left[(c - c_0)/\sigma_{c_0}\right]^2/2\right\}.$$

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

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

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

intrinsic distributions

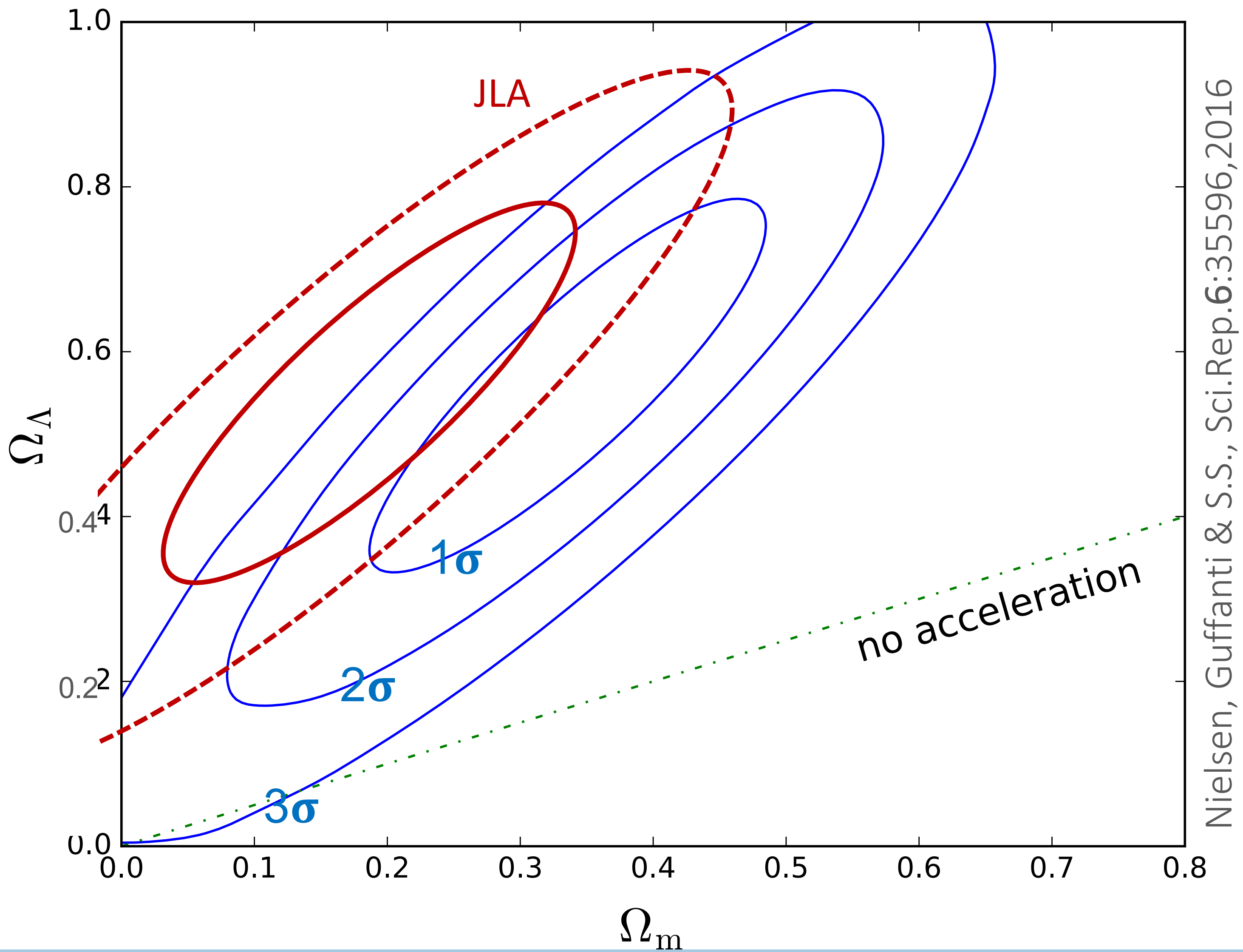
cosmology

SALT2

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

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

We find the data is consistent with an *uniform* rate of expansion ($\Rightarrow \rho + 3p = 0$) at **2.8σ**



Profile Likelihood

MLE, *best fit*

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

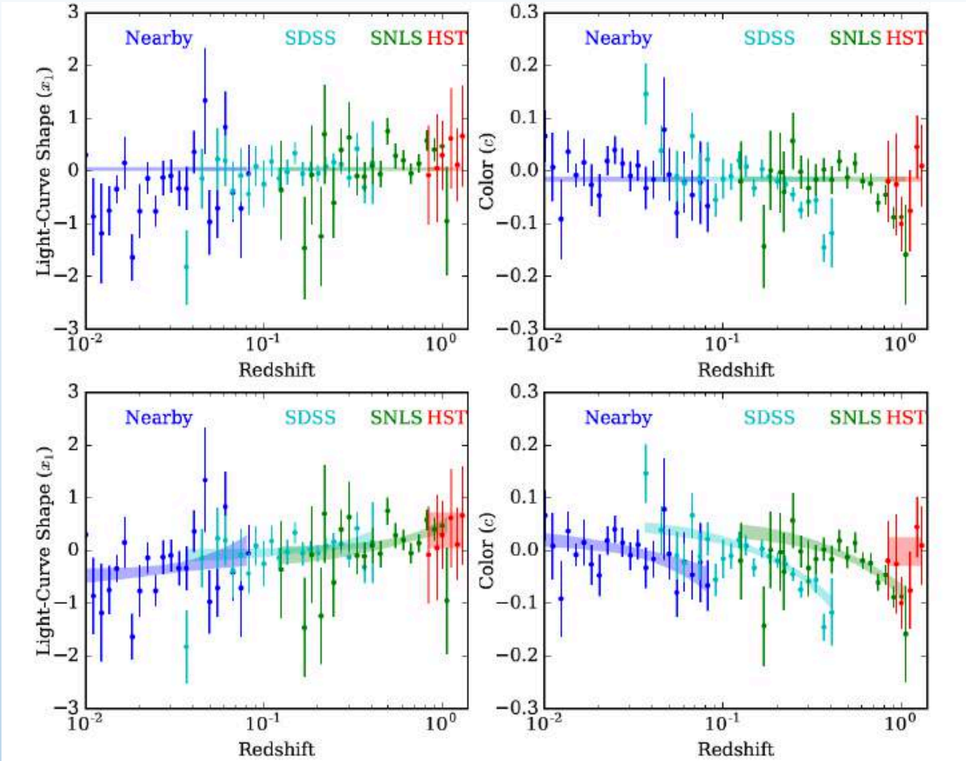
NB: We show the result in the Ω_m- Ω_Λ plane for comparison with previous results (JLA)

... simply to emphasise that the statistical analysis has not been done correctly earlier

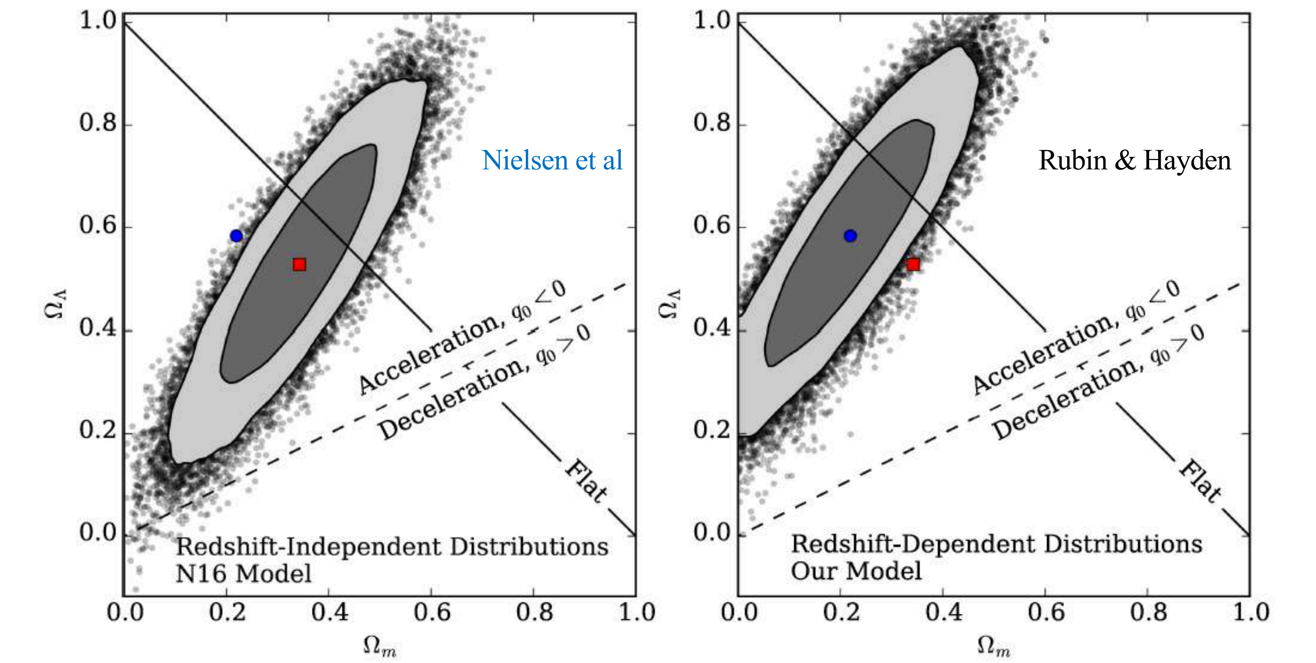
(Other constraints e.g. $\Omega_m \gtrsim 0.2$ or $\Omega_m + \Omega_\Lambda \simeq 1$ are relevant *only* to the ΛCDM model)

Rubin & Hayden (ApJ 833:L30,2016) say that our model for the distribution of the JLA light curve parameters should have included a dependence on redshift - which no previous analysis had allowed for

... they add 12 more parameters to our (10 parameter) model to describe this individually for each data sample

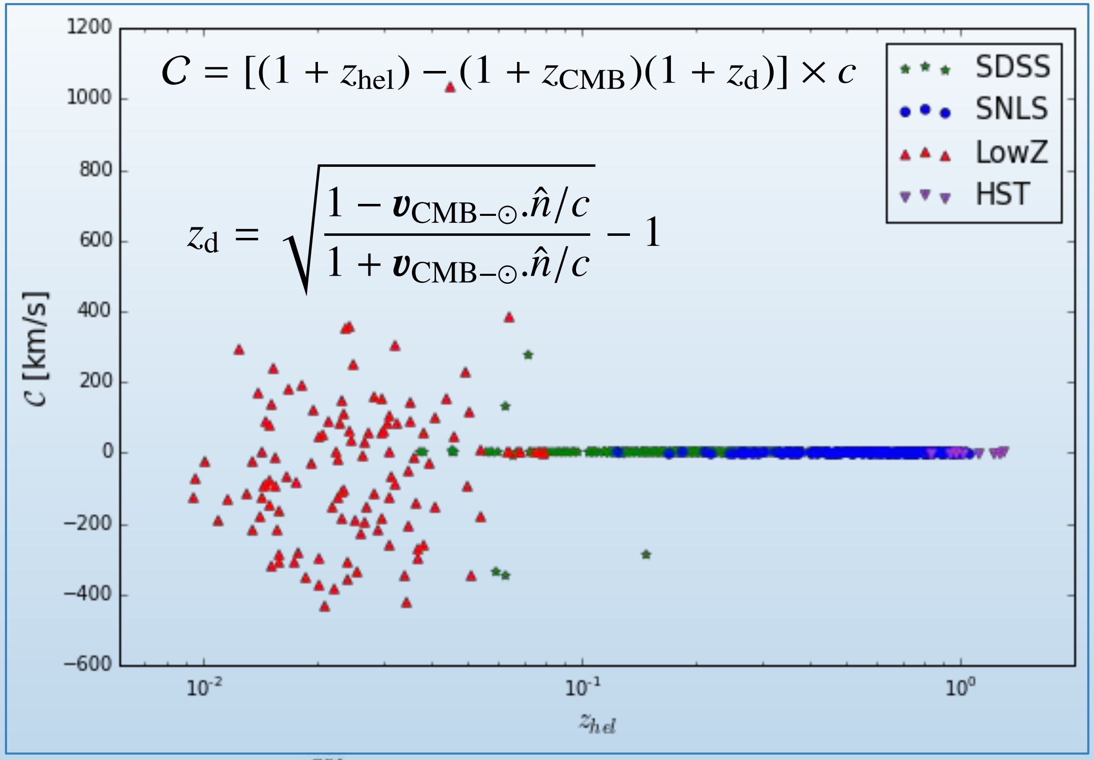


Such *a posteriori* modification is not justified by the Bayesian information criterion



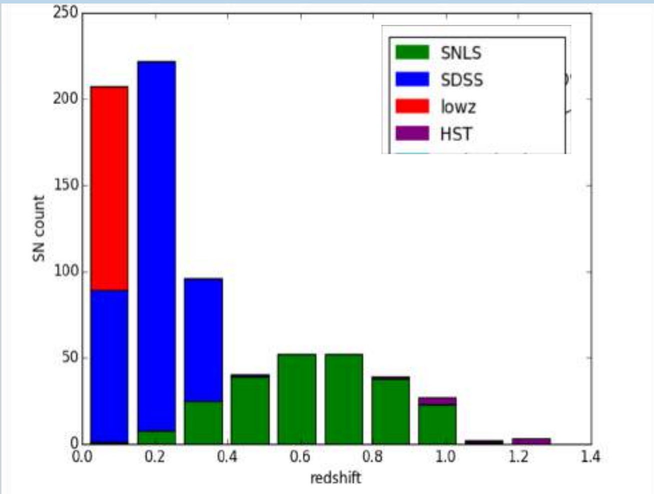
In any case this raises the significance with which a non-accelerating universe is rejected to only 3.7σ … still inadequate to claim a 'discovery' (even though the dataset has increased from ~100 to 740 SNe Ia in 20 yrs)

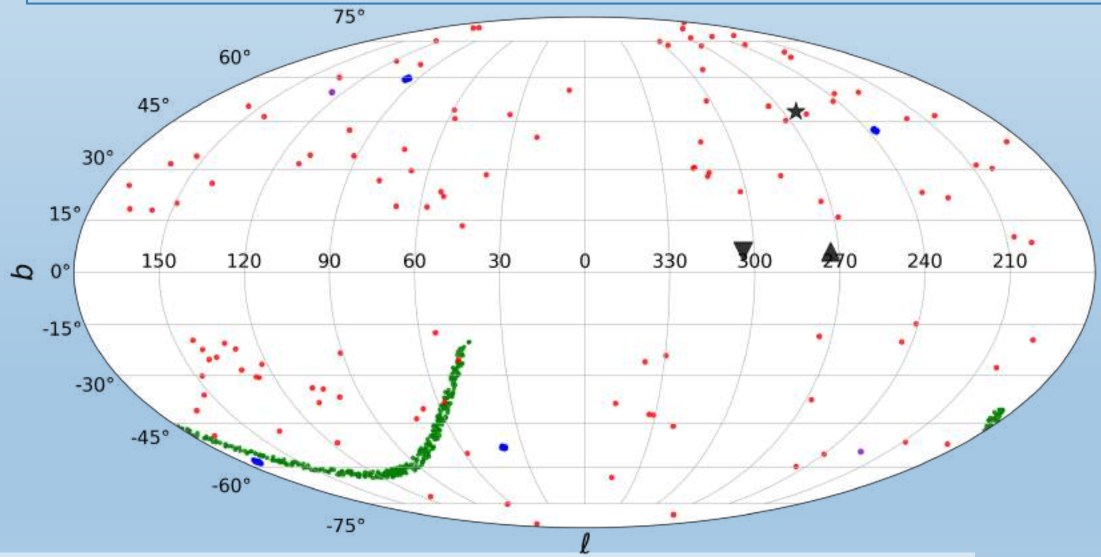
Subsequently we realised that the peculiar velocity `corrections' applied to the JLA catalogue are suspect … the bulk flow had been assumed to drop to zero at ~150 Mpc - even though it is *observed* to continue beyond 300 Mpc!



So we *undid* the corrections to recover the original data in the heliocentric frame … with some rather surprising findings

Colin *et al*, A&A **631**:L13,2019

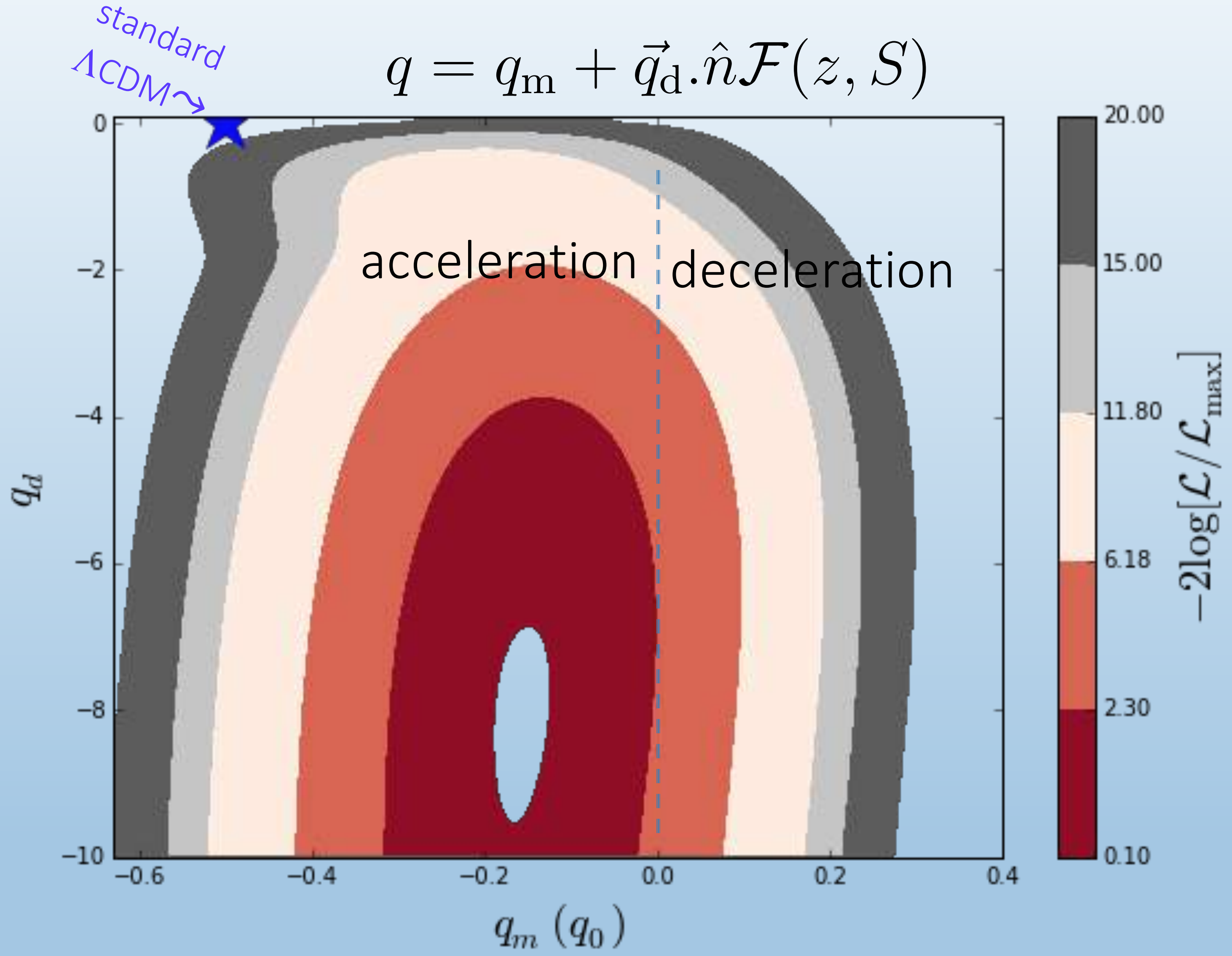




Sky distribution of the 4 sub-samples of the JLA catalogue in Galactic coordinates: SDSS (red dots), SNLS (blue dots), low redshift (green dots) and HST (black dots). CMB dipole (star), SMAC bulk flow (triangle), 2M++ bulk flow (inverted triangle)

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

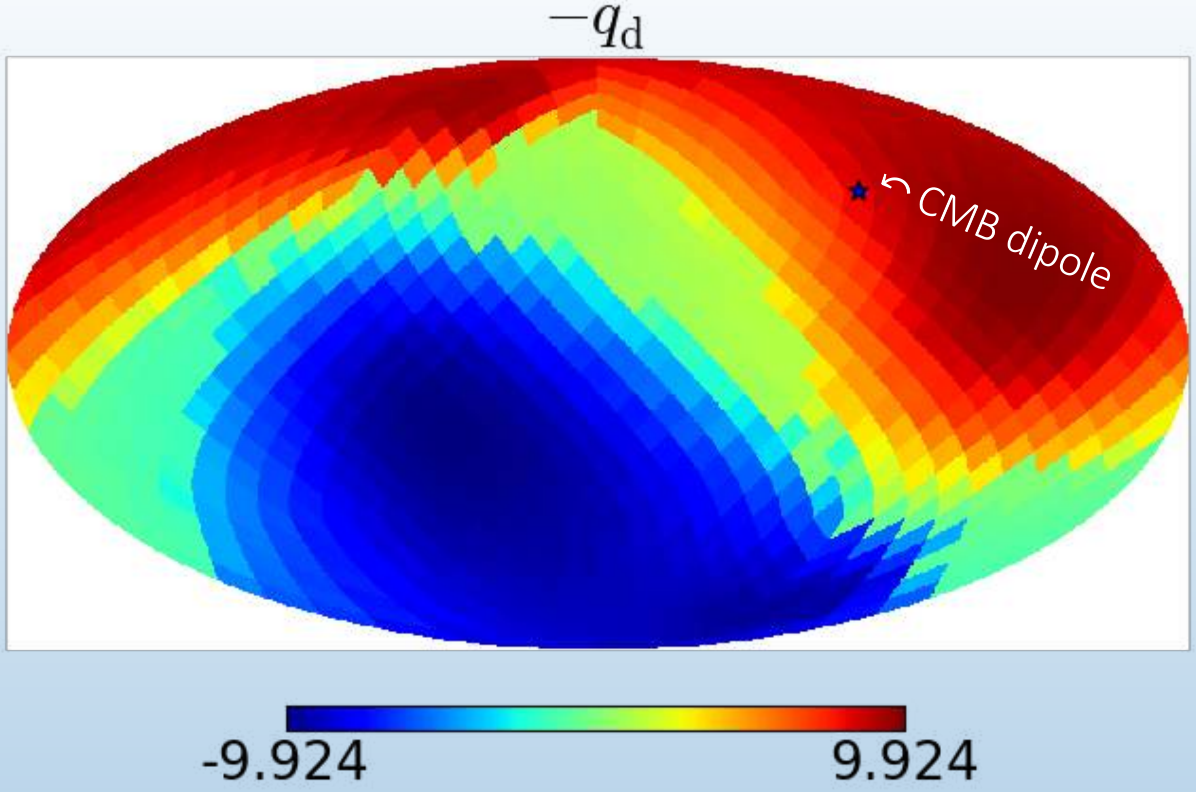
$$q = q_{\mathrm{m}} + \vec{q}_{\mathrm{d}}.\hat{n}\mathcal{F}(z, S)$$



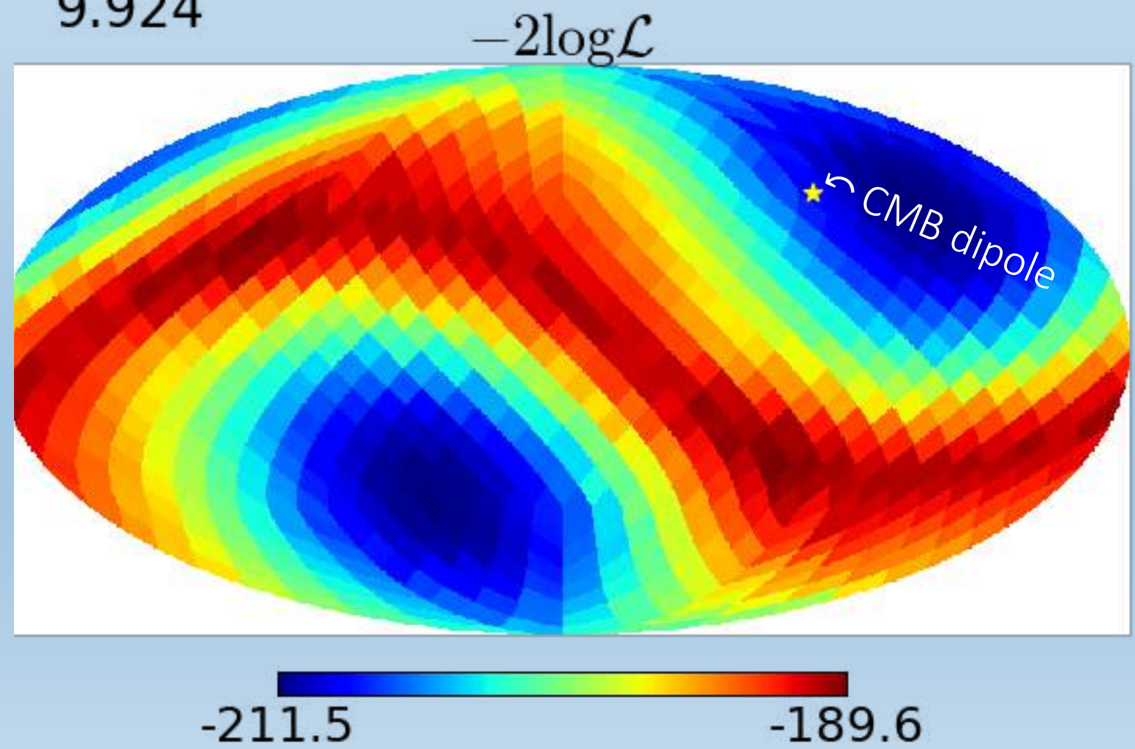
Colin, Mohayaee, Rameez & Sarkar, A&A **631**:L13,2019

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) and *not* due to Λ

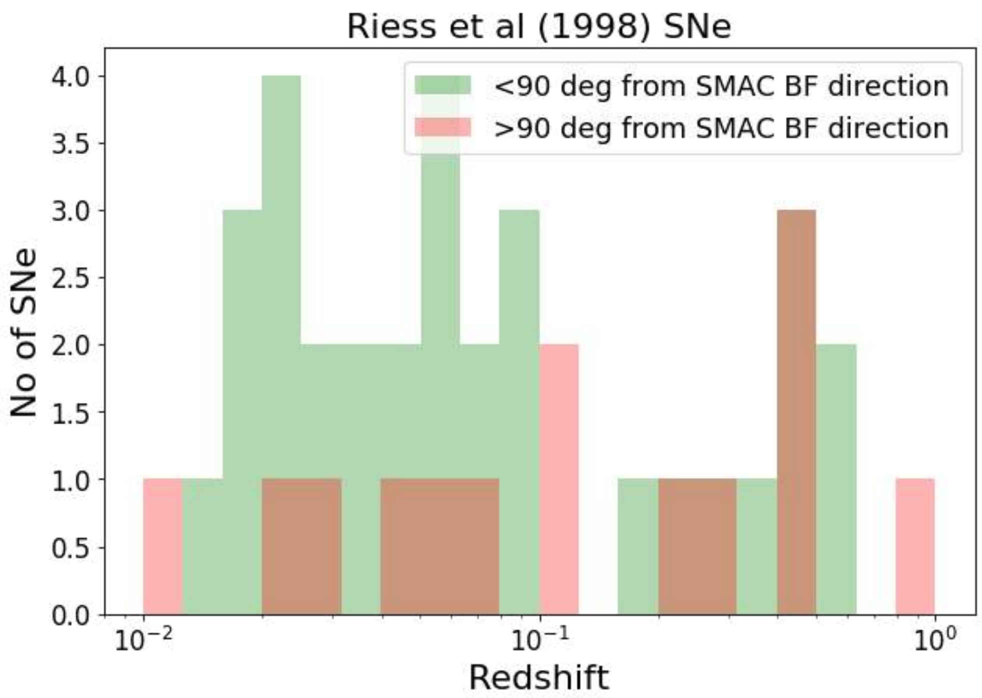


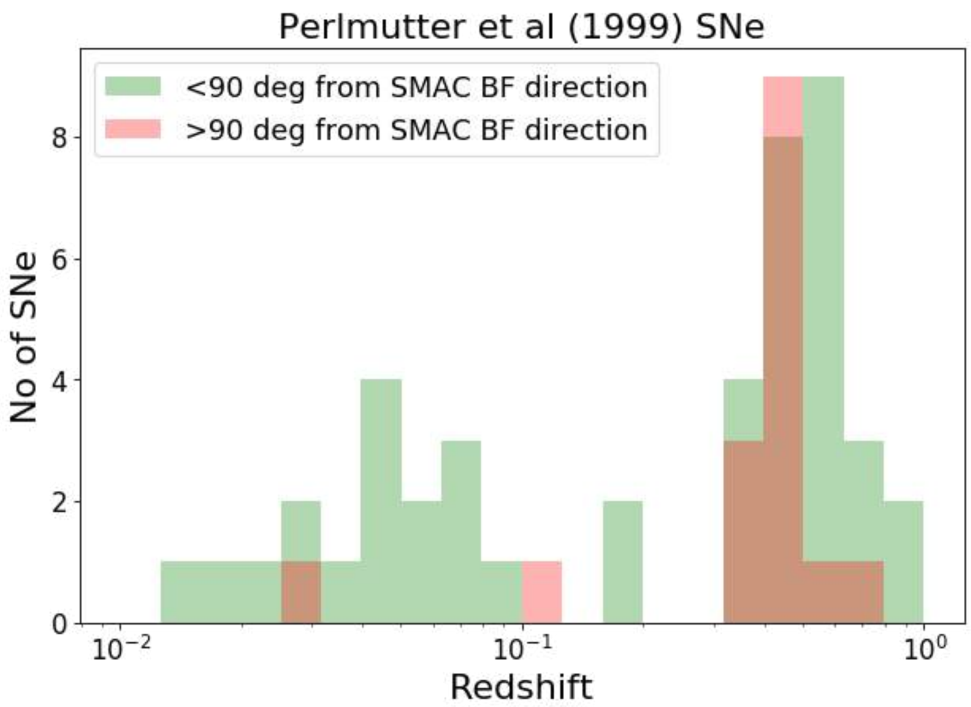
There is not enough data to do an *a priori* scan of the best-fit direction of $q_{\rm d}$ … but if done *a posteriori* it is found to be within 23^0 of the CMB dipole (ℓ = 254.4^0, b = 25.5^0)



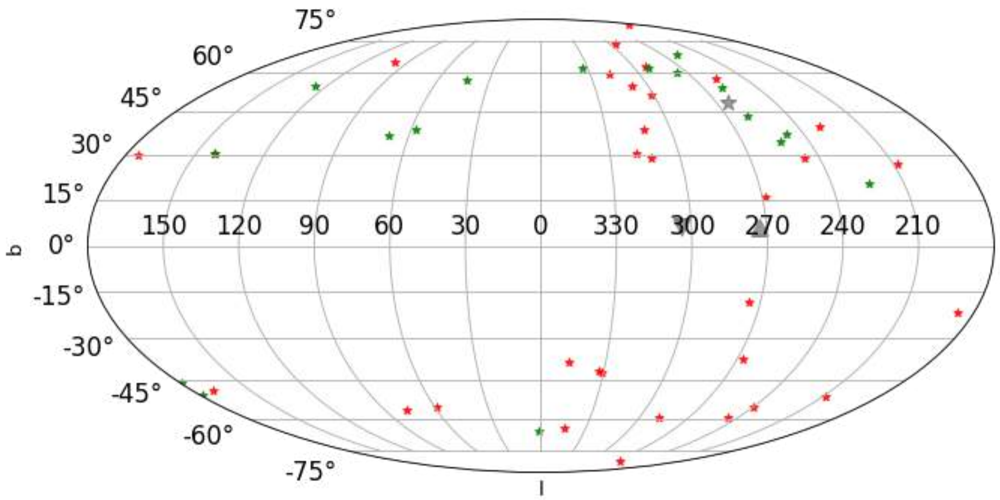
The log-likelihood changes by just 3.2 between the two directions i.e. the inferred acceleration is consistent with being due to the bulk flow (rather than due to Λ)

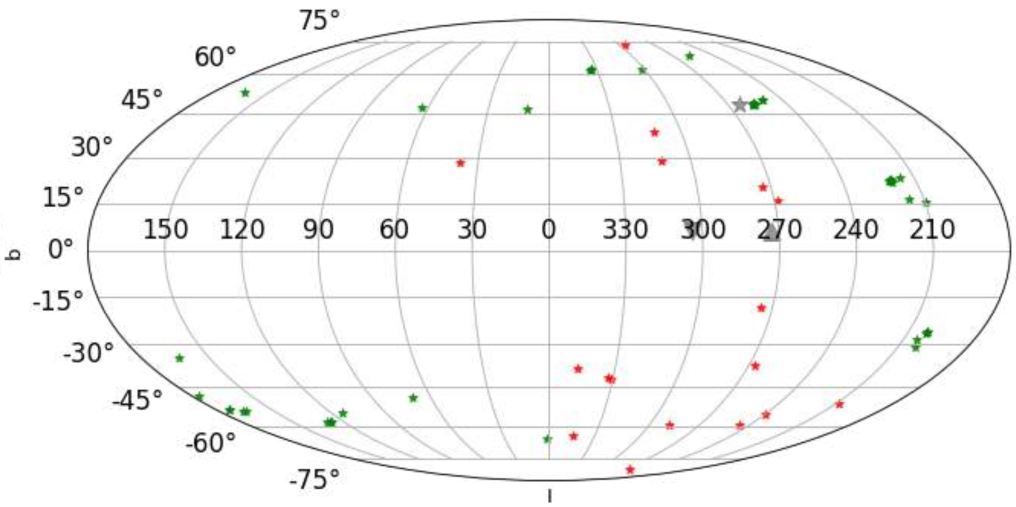
Colin, Mohayaee, Rameez & Sarkar, A&A **631**:L13,2019





Interestingly, most of the 60 SNe Ia studied by the High-*z* Team and the 45 SNe Ia studied by the Supernova Cosmology Project were in the direction of the bulk flow





We do not use the subsequent Pantheon catalogue because the z_{hel} values and individual contributions to the covariance are not public; also there are concerns about the accuracy of the data, e.g. >150 redshifts are *discrepant* with JLA (Rameez & S.S., arXiv:1911.06456)!

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 the Carnegie Supernova Project and the Dark Energy Survey are not publicly available in an usable form

Rubin & Heitlauf (ApJ **894**:68,2020) confirm our findings (C19), but criticise us for:

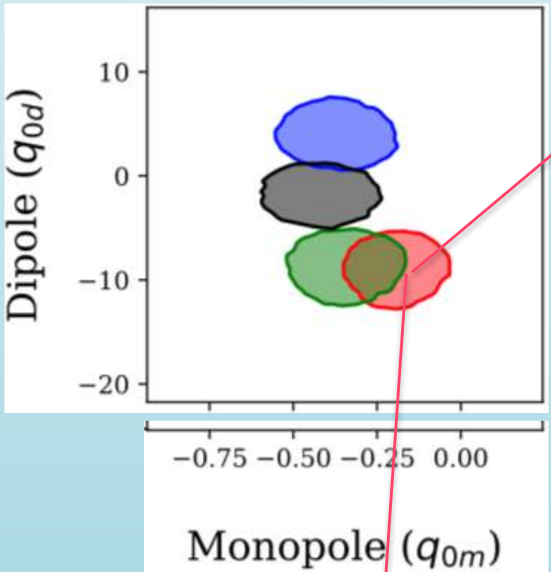
1. "Incorrectly" not allowing redshift-dependence of light-curve parameters (BIC?)
2. "Shockingly" using heliocentric redshifts (but is the CMB frame the correct frame?)

(3. Not using data from southern sky surveys … which are in fact *not* fully public)

(4. Using a "pathological" model of the dipole anisotropy … it is actually well behaved)

… we believe their criticism is not justified (arXiv:1912:04257)

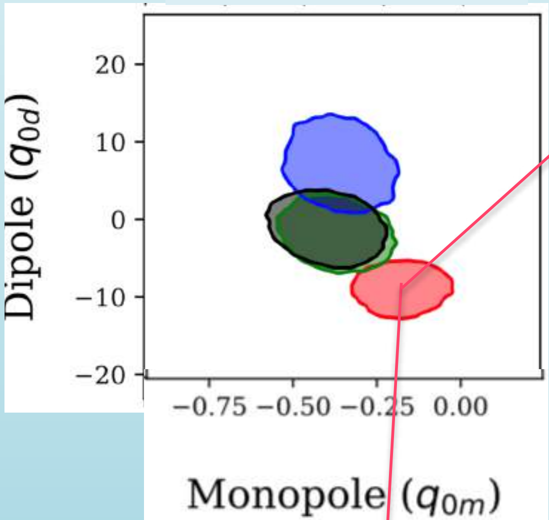
Without JLA peculiar velocity covariance



C19: zhelio, no cov,
const. pop.: $-8.92^{+2.25}_{-2.62}$
zhelio: $-8.65^{+2.22}_{-2.59}$
zcmb: $4.00^{+2.37}_{-2.14}$
zcmbpecvel: $-1.83^{+1.99}_{-2.08}$

C19: zhelio, no cov,
const. pop.: $-0.193^{+0.100}_{-0.103}$
zhelio: $-0.344^{+0.114}_{-0.115}$
zcmb: $-0.369^{+0.116}_{-0.116}$
zcmbpecvel: $-0.422^{+0.115}_{-0.116}$

With JLA peculiar velocity covariance



C19: zhelio, no cov,
const. pop.: $-8.9^{+2.2}_{-2.6}$
zhelio: $-1.8^{+3.3}_{-3.3}$
zcmb: $7.0^{+4.5}_{-3.8}$
zcmbpecvel: $-1.1^{+3.2}_{-3.4}$

C19: zhelio, no cov,
const. pop.: $-0.193^{+0.100}_{-0.103}$
zhelio: $-0.400^{+0.117}_{-0.119}$
zcmb: $-0.389^{+0.116}_{-0.118}$
zcmbpecvel: $-0.425^{+0.116}_{-0.122}$

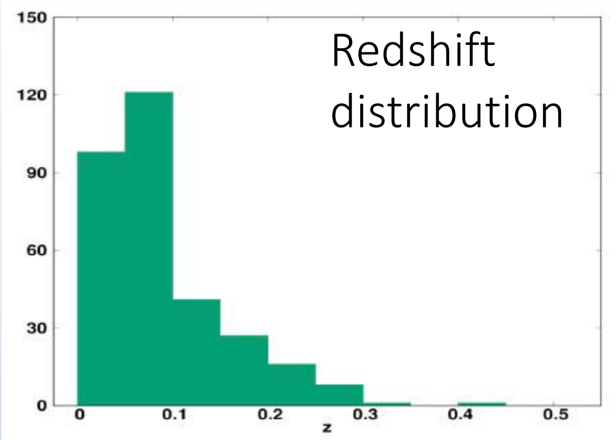
Correction: x_1 & c z-dep.

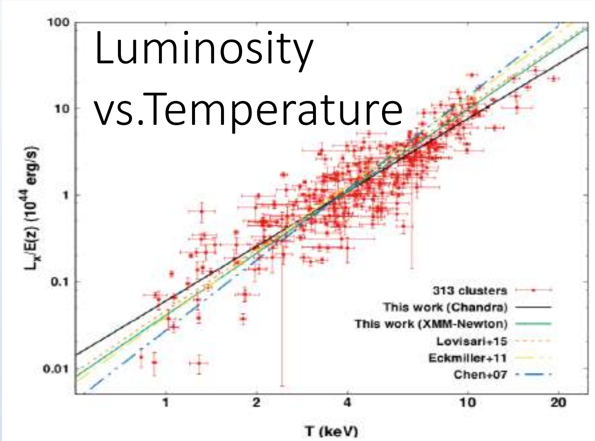
+ Correction: $z_{\mathrm{hel}} \rightarrow z_{\mathrm{CMB}}$

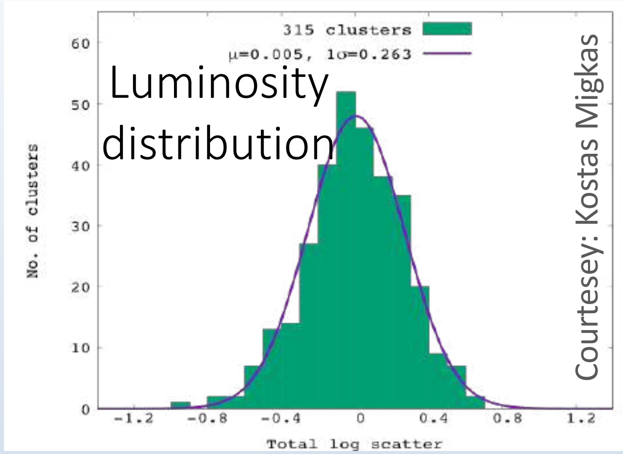
+ Correction: SNe pec. vel.

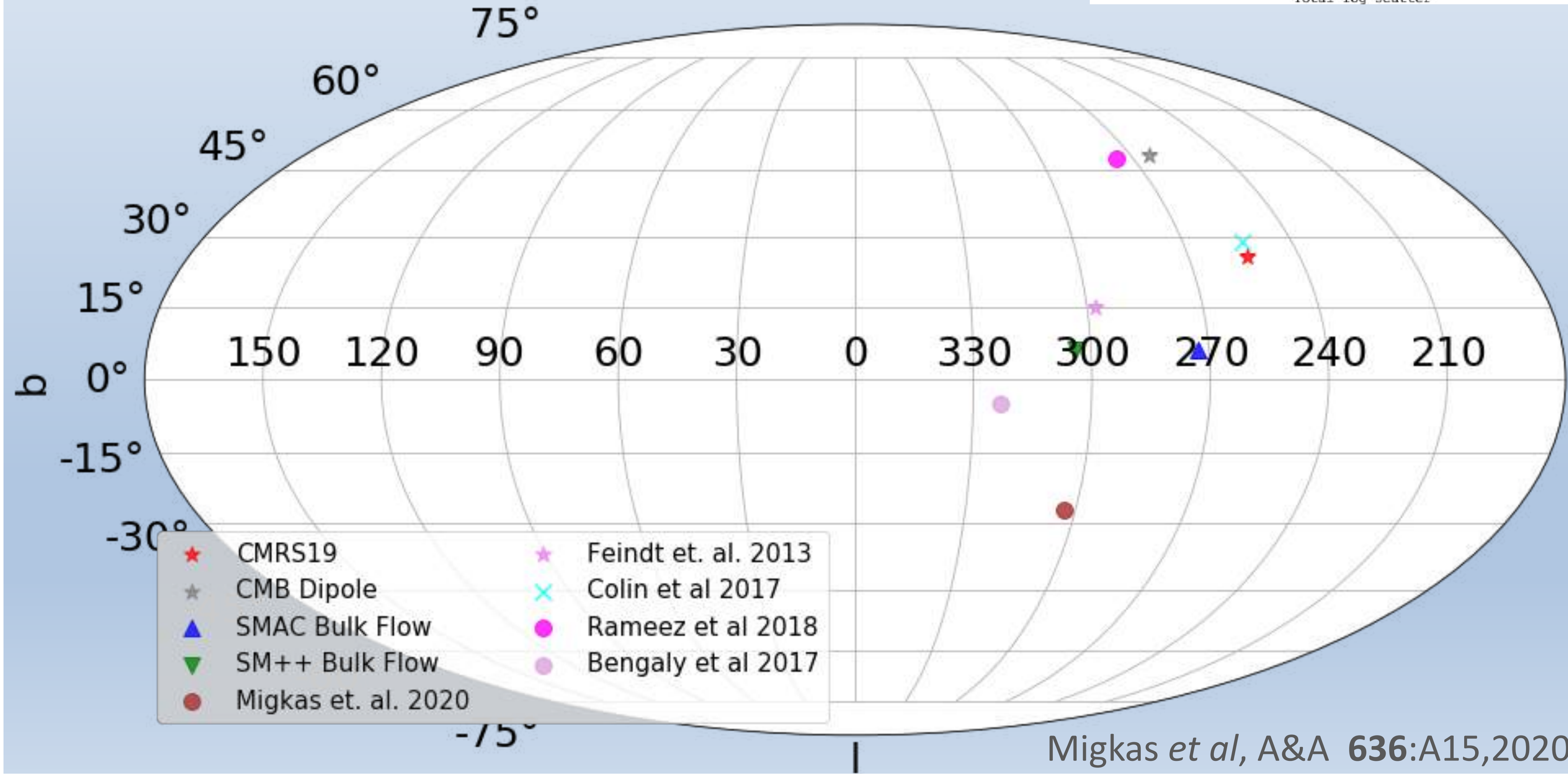
This illustrates just how many "corrections" need to be made to extract evidence for isotropic acceleration q_{0m}, when the data in fact indicate anisotropic acceleration q_{0d}!

Similar anisotropy found in a sample of 313 X-ray clusters









Migkas *et al*, A&A **636**:A15,2020

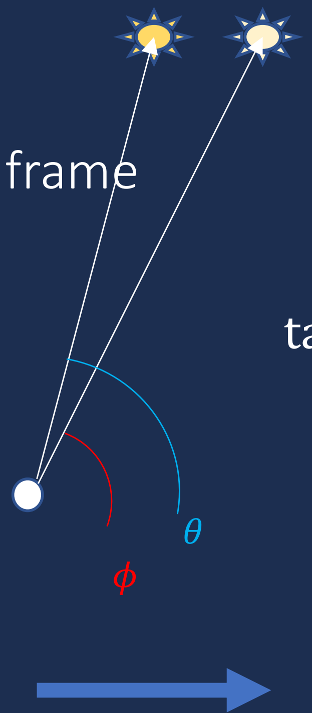
If the dipole in the CMB is due to our motion *wrt* the 'CMB frame' then we should see *similar* dipole in the distribution of distant sources

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

Aberration

Rest frame

Moving frame

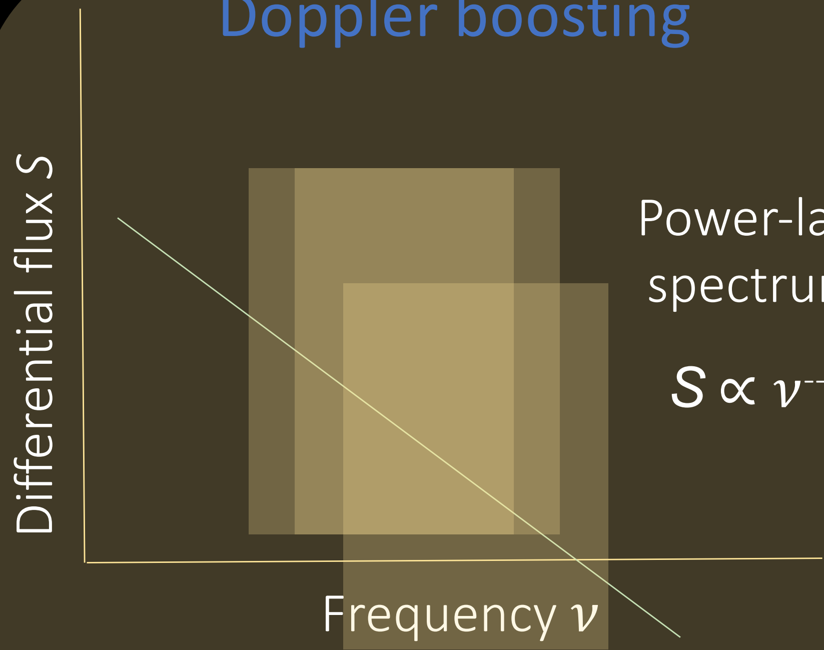


$$\tan\phi = \frac{\sin\theta}{\gamma * cos\theta \ - \frac{v}{c}}$$

Observer, velocity $\boldsymbol{v}$

+

Doppler boosting



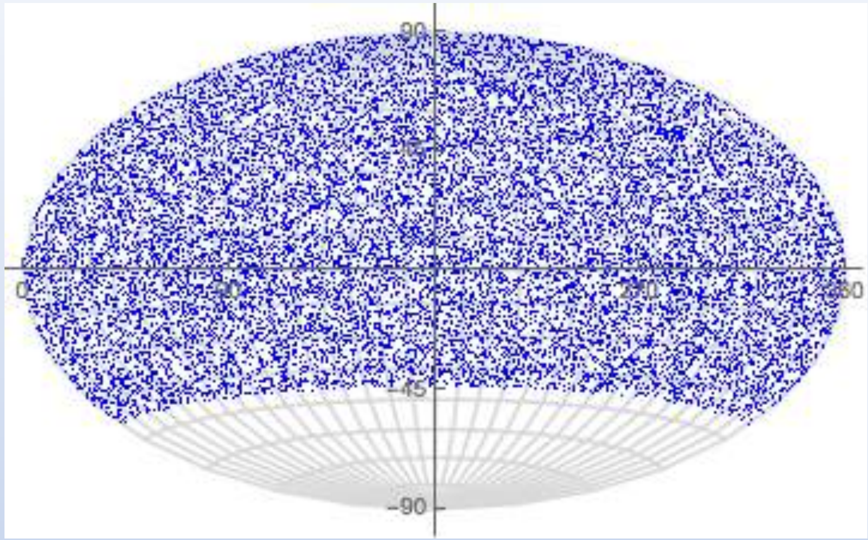
Power-law spectrum

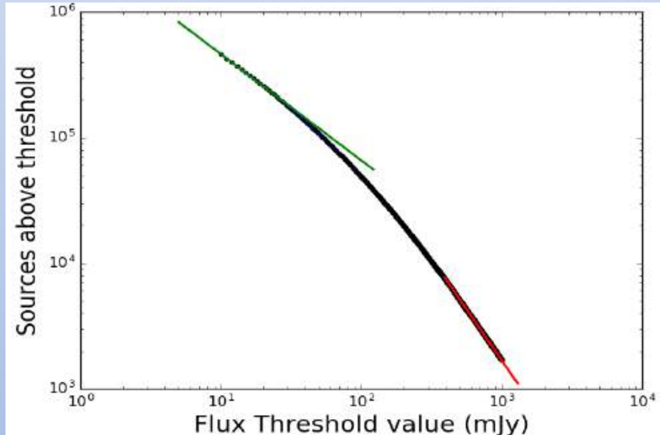
$S \propto \nu^{-\alpha}$

Integral flux distribution: $N\,(>S) \propto S^{-x}$

Flux-limited catalog ➞ *more* sources in direction of motion (Ellis & Baldwin 1984)

The NRAO VLA Sky Survey (NVSS)

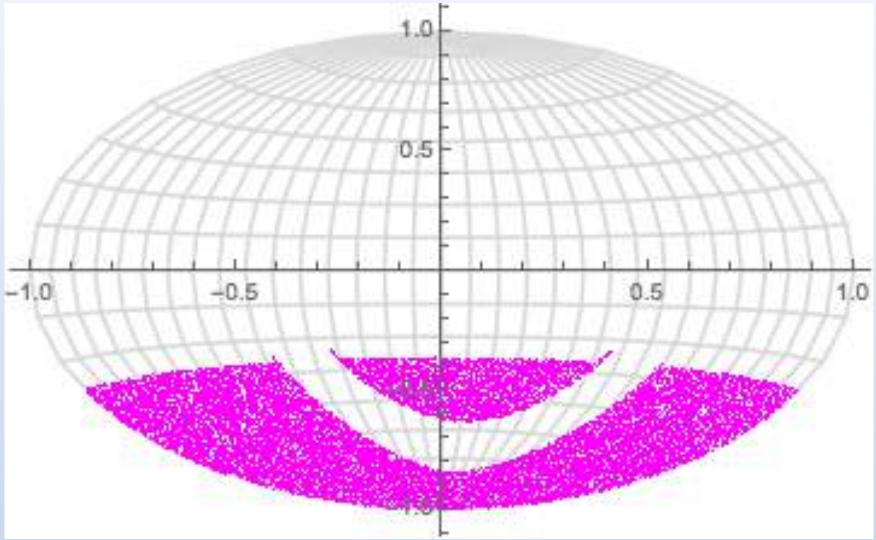


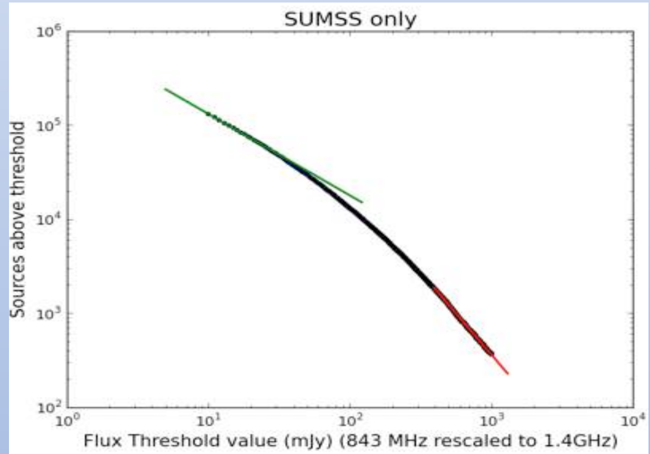


1.4 GHz survey (down to Dec = -40.4°)
National Radio Astronomy Observatory

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)

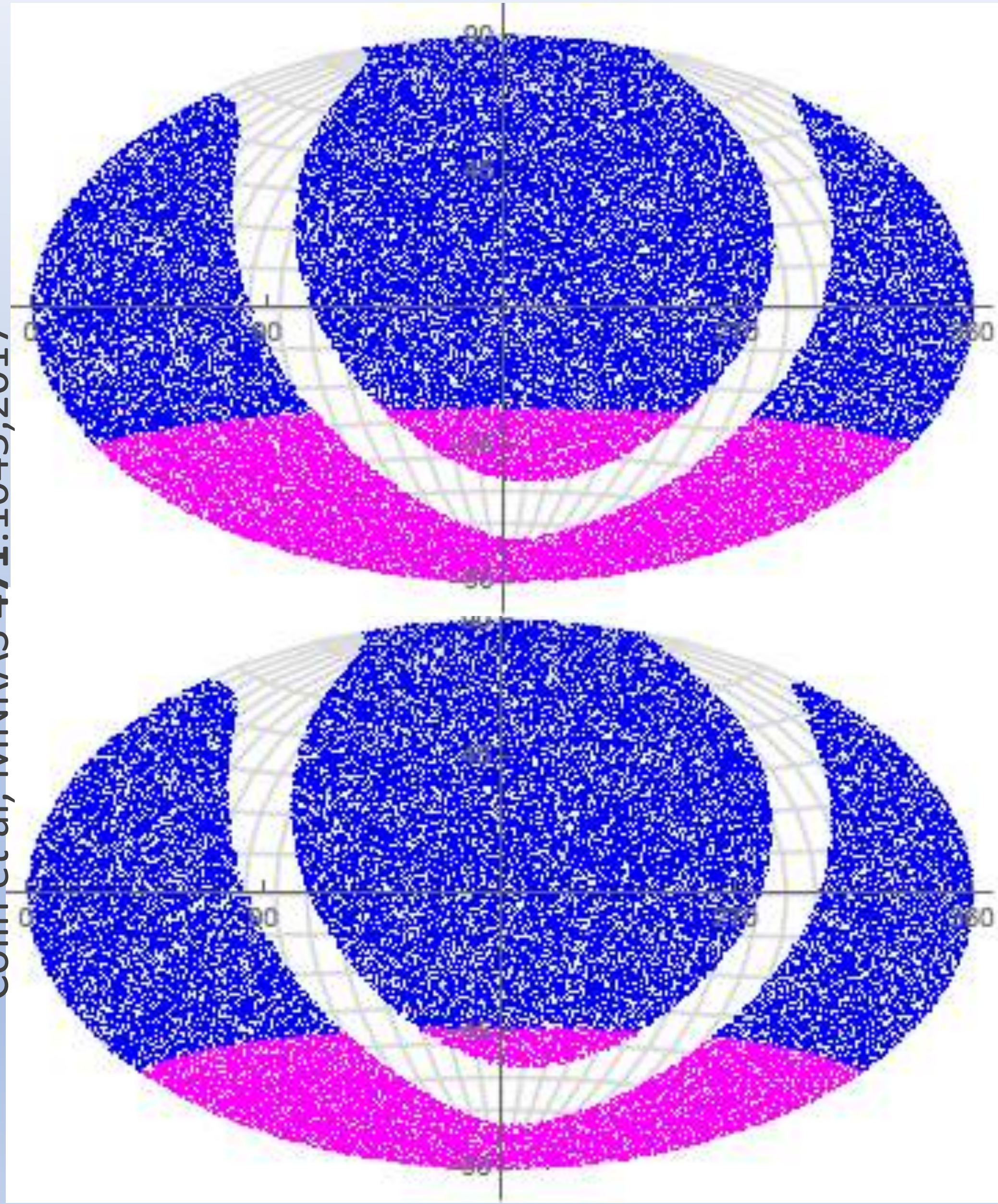




843 MHz survey (Dec < -30.0°)
Molonglo Observatory Synthesis telescope

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

The NVSUMSS-Combined All Sky catalog

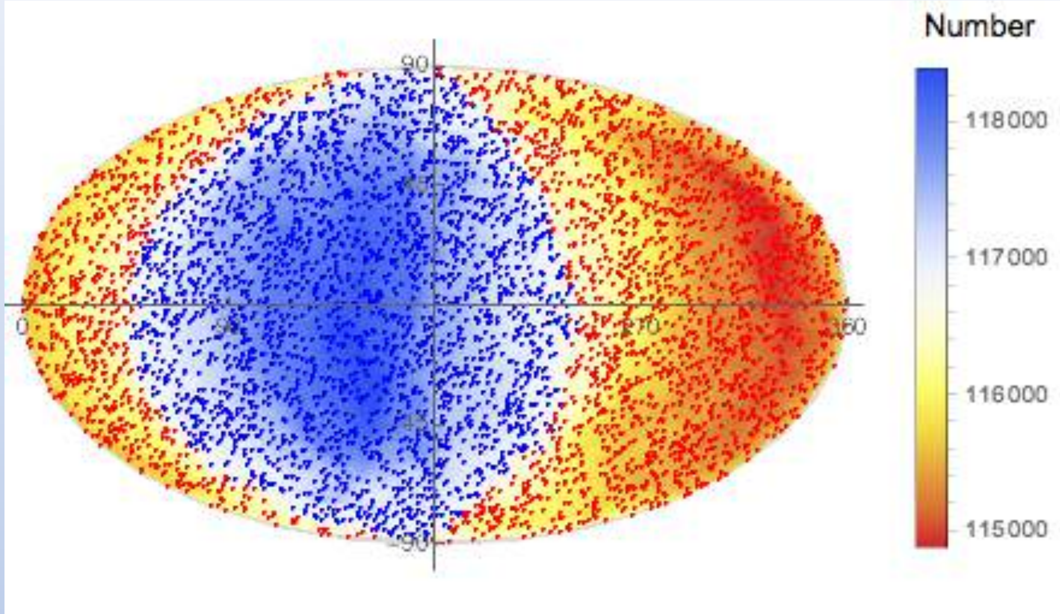


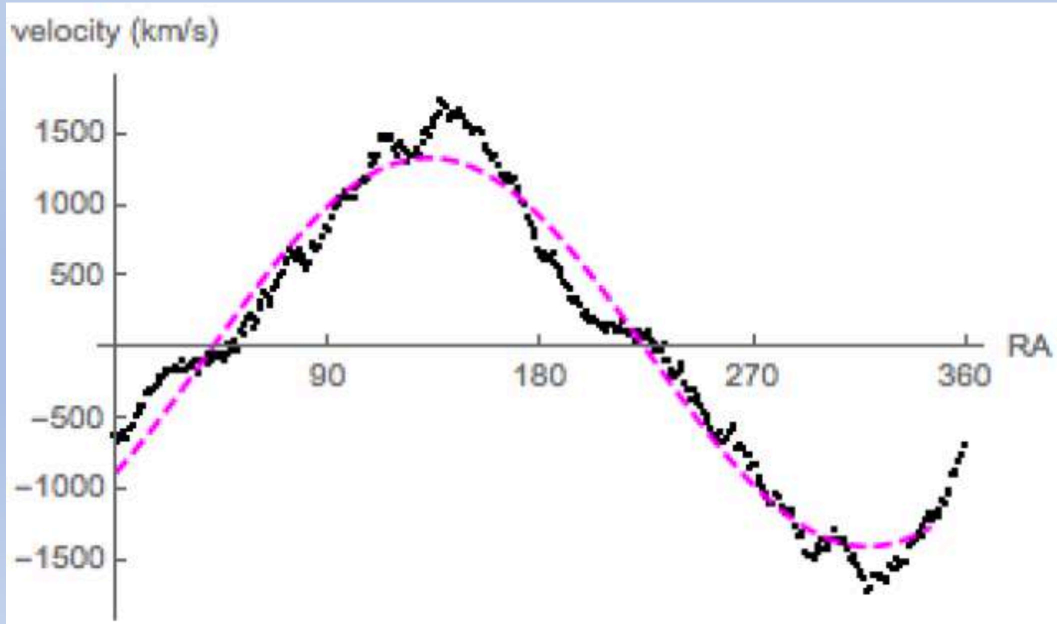
Colin et al, MNRAS **471**:1045,2017

- Rescale SUMSS fluxes by $(843/1400)^{-0.75} \sim 1.46$ to match with NVSS (works within ~1%)
- Remove Galactic Plane at ±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***)

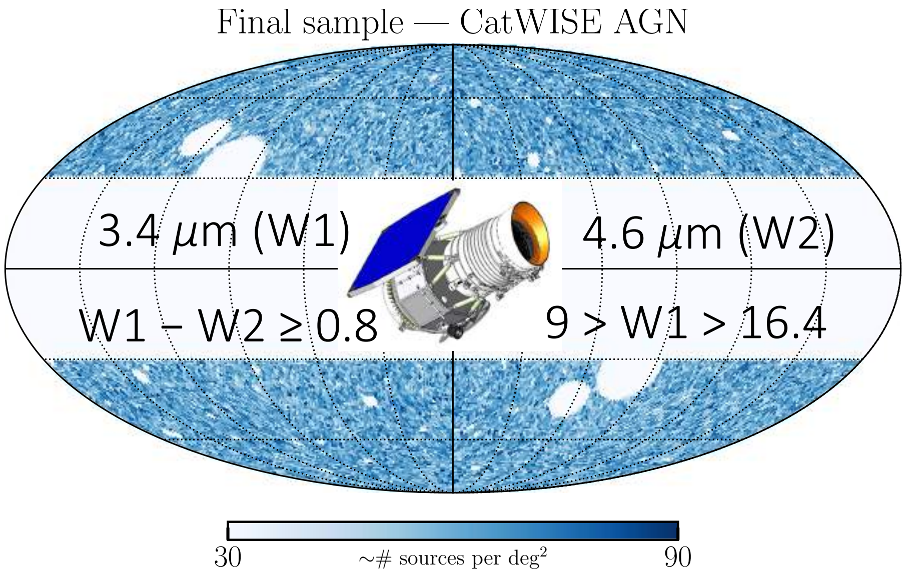
Confirms claim by Singal (2011) which was criticised subsequently (Gibelyou & Huterer 2012, Rubart & Schwarz 2013, Nusser & Tiwari 2015)

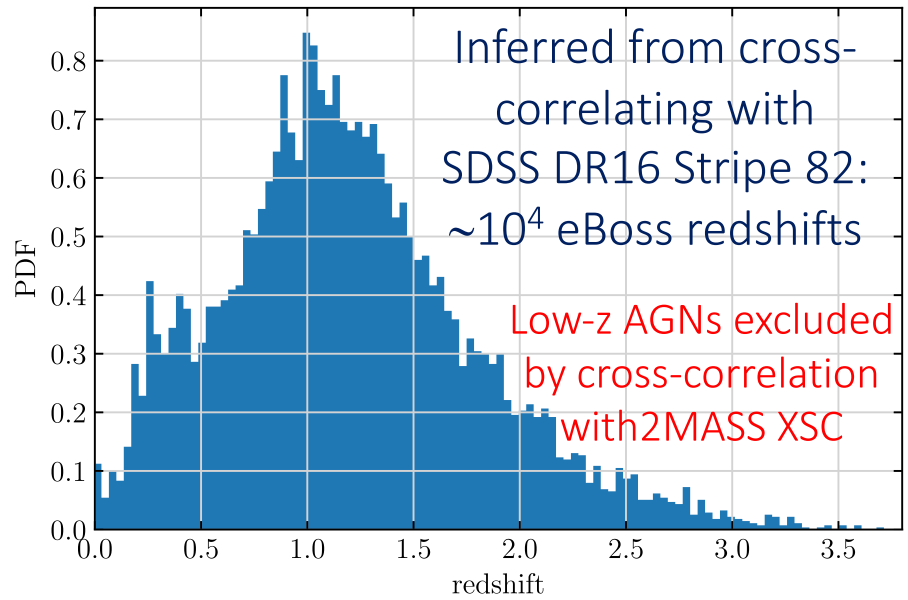
We have addressed *all* the concerns but this strange anomaly remains … and casts doubt on the kinematic interpretation of the CMB dipole

New confirmation with quasars from ALLWISE & unwise-Gaia catalogues
(Secrest *et al*, arXiv:2009.14826)

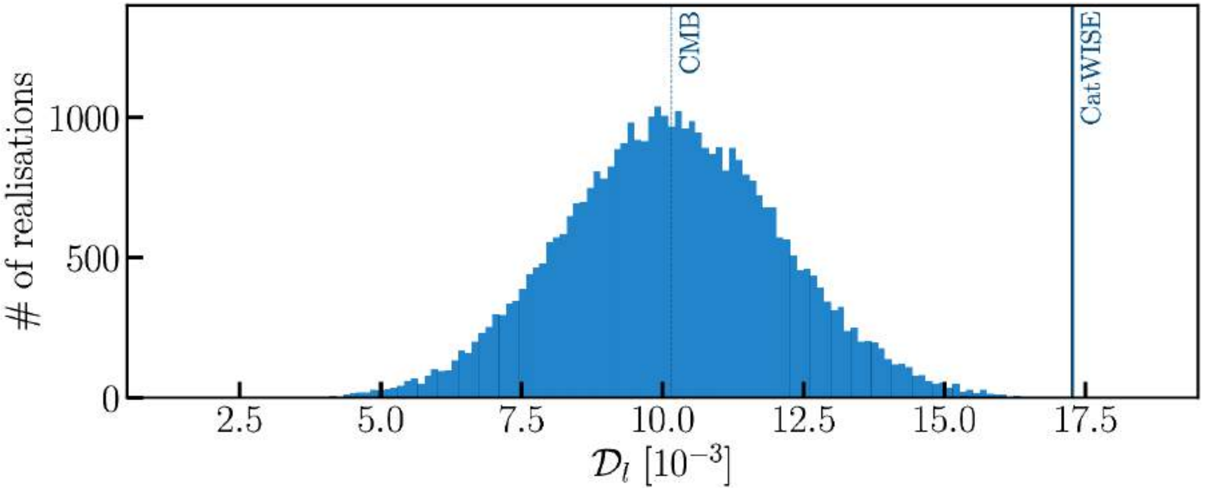
Our Peculiar velocity wrt quasars ≠ peculiar velocity wrt the CMB

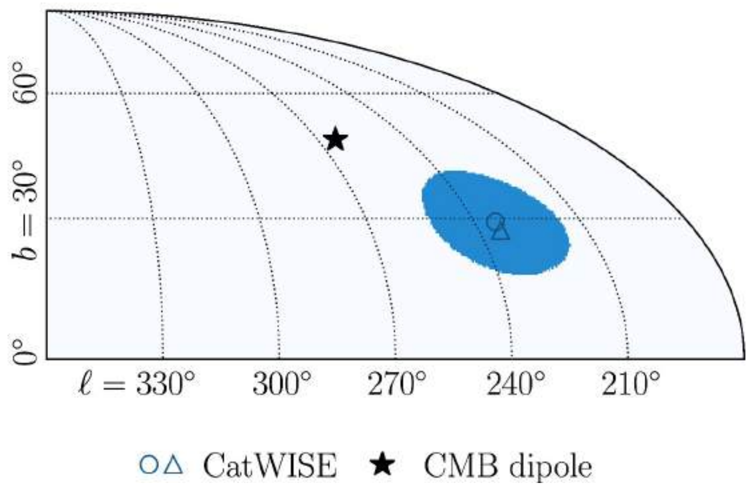
Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, arXiv:2009.14826





We now have a catalogue of ~1.3 million quasars, with 99% at redshift > 0.1





The kinematic interpretation of the CMB dipole is *rejected* with p=10^{-4} ⇒ 3.9**σ**

Beyond the F-L-R-W 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 … because the inferred q_0 is essentially a dipole (~aligned with CMB), and any monopole component is consistent with zero

- The rest frame in which distant quasars are isotropic ≠ rest frame of the CMB

The cause of the bulk flow is unknown - could it be new horizon-scale physics? (e.g. super-horizon isocurvature perturbation, Gunn 1988, Turner 1991)

How do we understand the CMB dipole if it is not kinematic in origin?

The ‘standard’ assumptions of isotropy and homogeneity are questionable – forthcoming surveys (DESI, Euclid, LSST, SKA …) can enable definitive tests

Meanwhile it is not established that the universe is dominated by ‘dark energy’