Re-examining cosmic acceleration

Subir Sarkar

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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 and aligned with the CMB dipole - so is likely an artefact due to our being untypical observers embedded in a local non-Hubble `bulk flow'. Moreover the usual kinematic interpretation of the CMB dipole is rejected at 4.9σ as the corresponding dipole in the distribution of distant quasars is much bigger than expected. The implications of these surprising findings will be discussed.

Colin *et al*, A&A 631: L13,2019; 1912.04257; 2003.10420 + Secrest *et al*, ApJ Lett (2009.14826)

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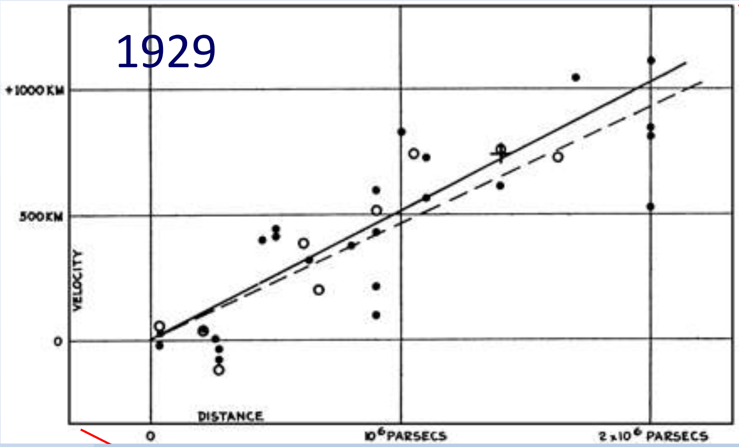
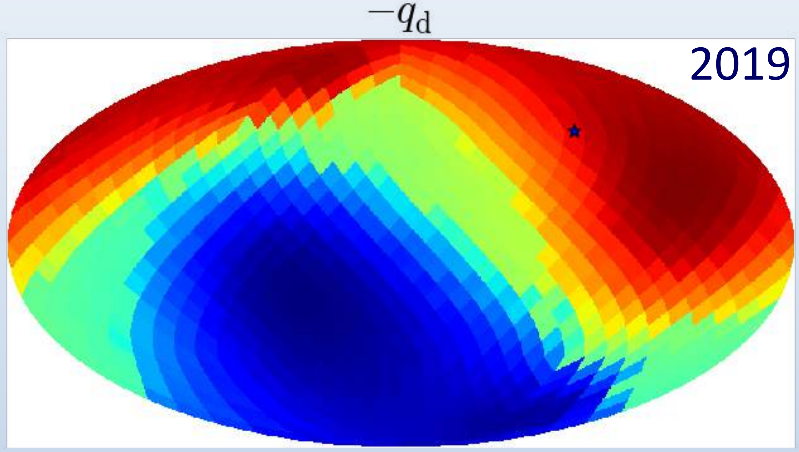
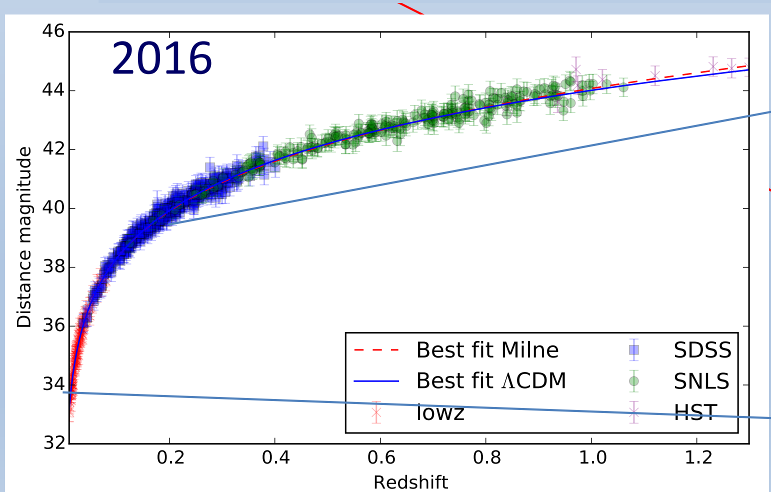
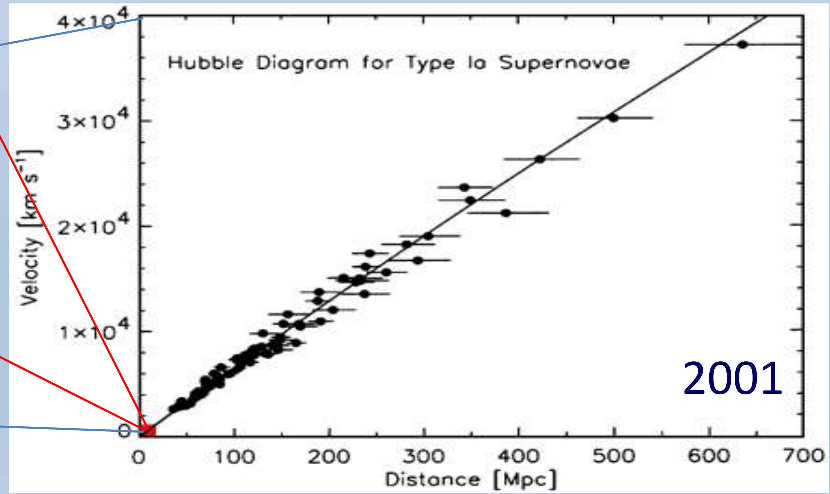




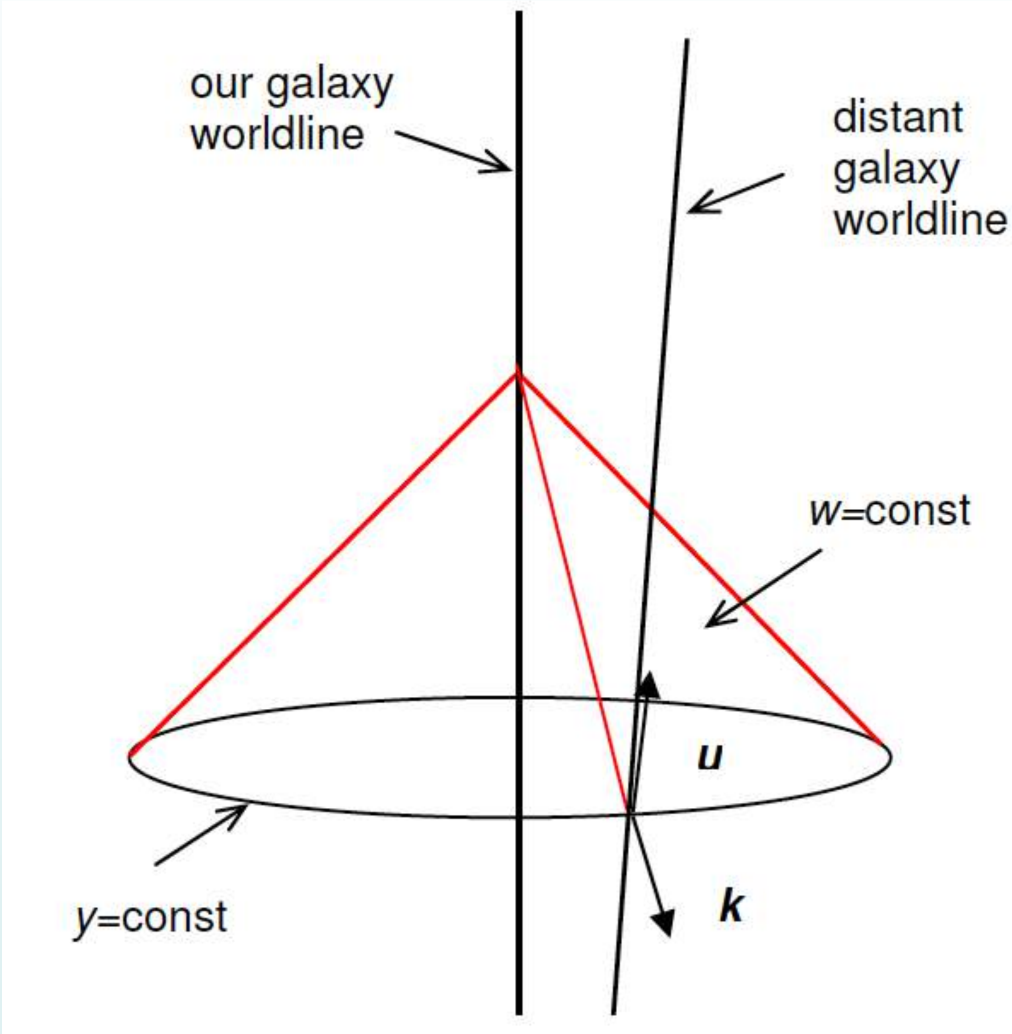
Hubble (1931) to De Sitter: "*The interpretation, we feel, should be left to you and the very few others who are competent to discuss the matter with authority*"





Colin *et al*, A&A 631: L13,2019; 1912.04257; 2003.10420 + Secrest *et al*, ApJ Lett (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

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

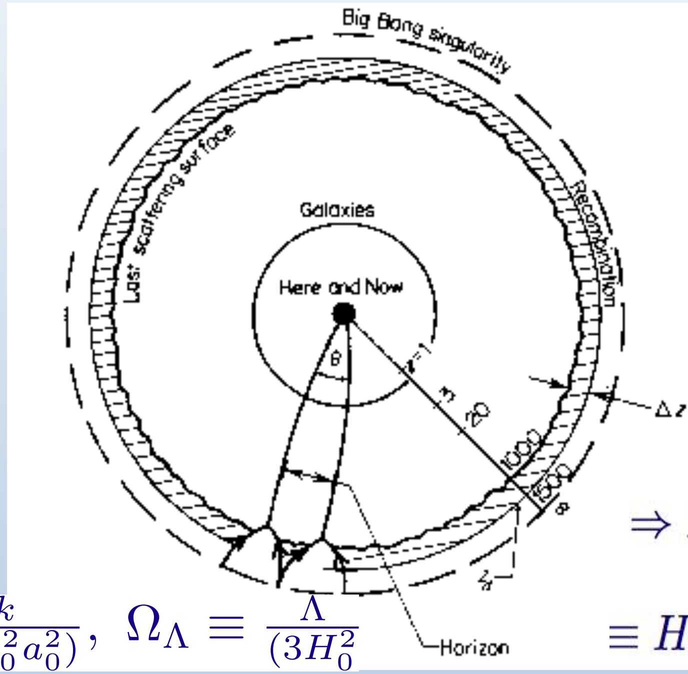
$$= a^2(\eta)\left[d\eta^2 - d\bar{x}^2\right]$$

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

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**': $\Omega_m + \Omega_k + \Omega_\Lambda = 1$

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**: $\Omega_\Lambda = 1 - \Omega_m - \Omega_k \sim 0.7 \Rightarrow \Lambda \sim 2H_0^2$

The scale of Λ 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!

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

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

$$+M^4 + M^2\Phi^2$$

Vacuum energy — Higgs mass correction

super-renormalisable

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

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

renormalisable

However there are two 'super-renormalisable' operators …
which become increasingly important as the cut-off *M* is raised

The second term gives rise to the notorious quadratic divergence of the Higgs mass
(attempted solutions: supersymmetry, compositeness …)

1st SR term couples to gravity so the *natural* expectation is

$$\rho_\Lambda \sim \mathcal{O}(\text{TeV})^4 \Rightarrow 10^{60} \text{ x } (\text{meV})^4$$

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

There must be a *good* reason why this did *not* happen!

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

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

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

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

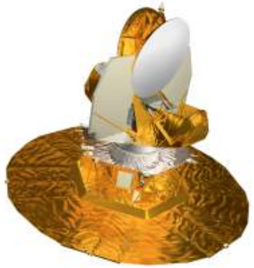
(There is similar fine-tuning in *every* proposal – massive gravity, chameleon fields, …)

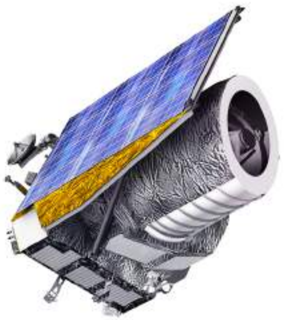
The only 'natural' option is if $\Lambda \sim H^2$ *always*, but this is just a renormalisation of G_N ! (recall: $H^2 = 8\pi G_N/3 + \Lambda/3$) → this is *ruled out* by Big Bang nucleosynthesis which requires G_N to be within 5% of its lab. value … in any case this will *not* yield accelerated expansion

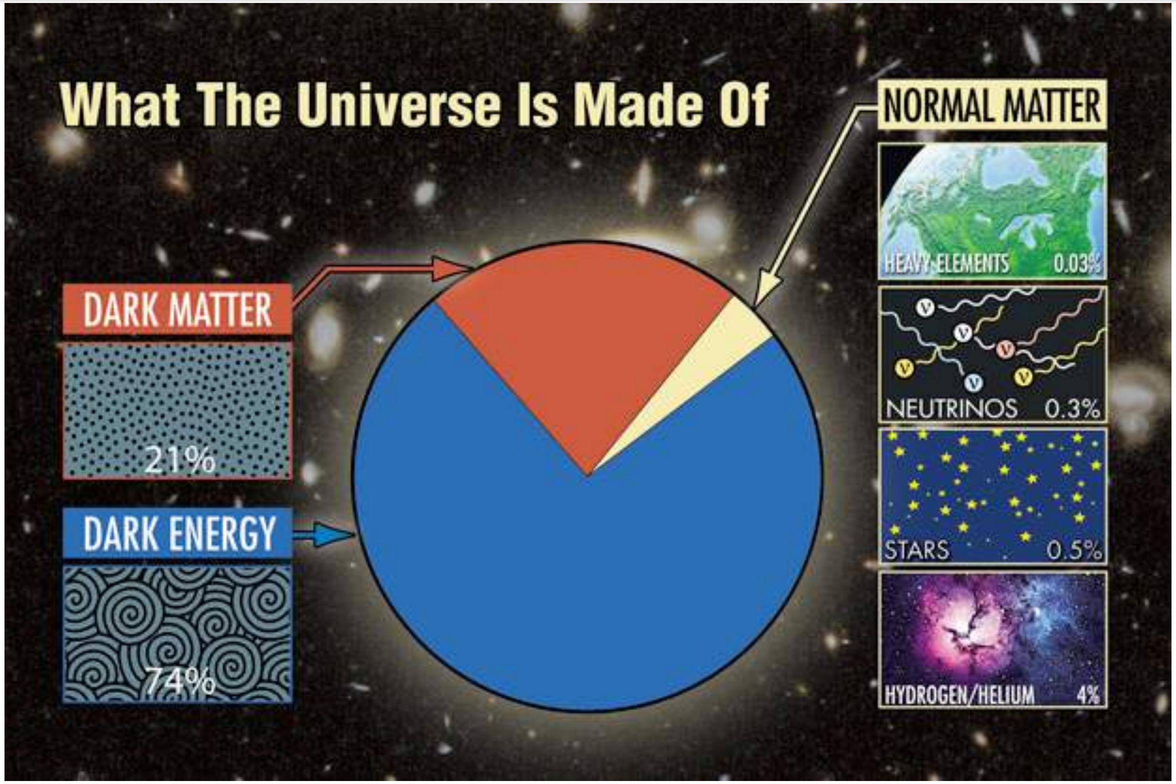
Every attempt to explain the coincidence problem is equally severely fine-tuned

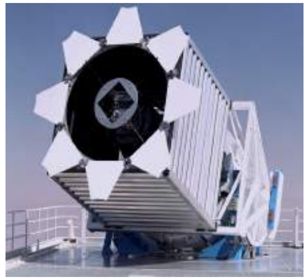
Do we infer $\Lambda \sim H_0^2$ from observations simply because H_0 ($\sim 10^{-42}$ GeV) is the *only* scale in the F-R-L-W model … so this is the value imposed on Λ by **construction**?

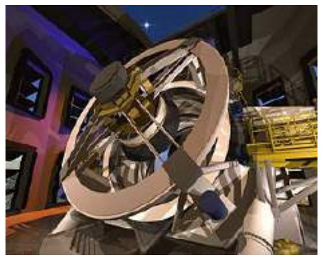
Since 1998 (Riess *et al.*[1], Perlmutter *et al.*[2]), surveys of cosmologically distant Type Ia supernovae (SNe Ia) have indicated an acceleration of the expansion of the Universe, distant SNe Ia being dimmer that expected in a decelerating Universe. With the assumption that the Universe can be described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







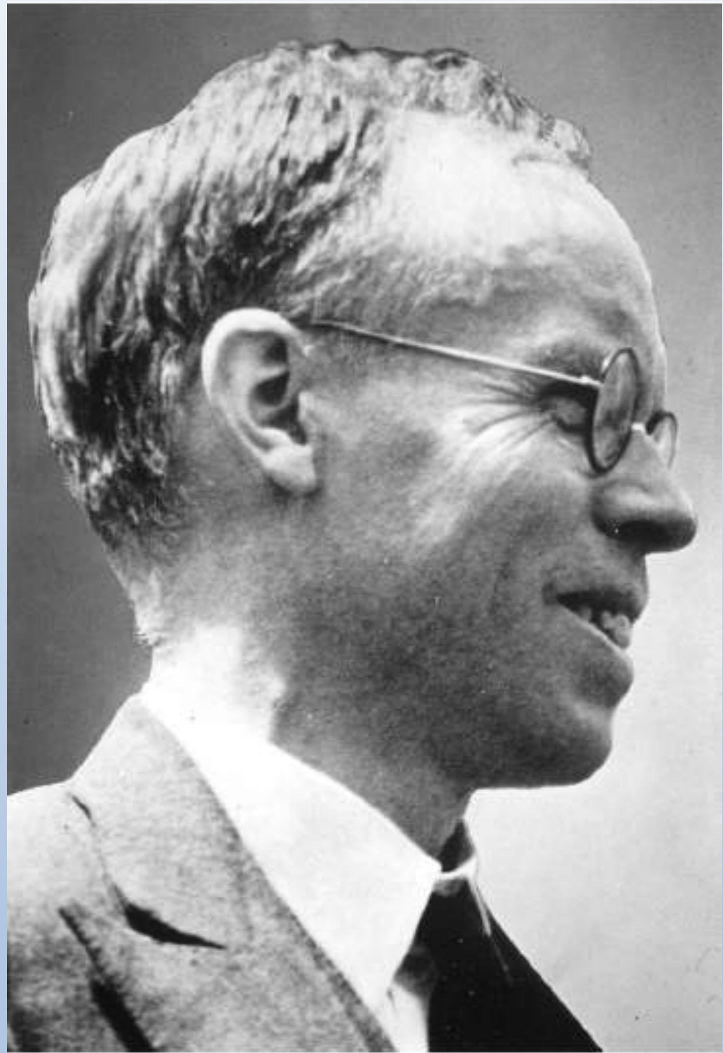




There has been substantial effort, using major satellites & telescopes, to precisely measure all the parameters of the 'standard cosmological model'… but far less on testing its **foundational assumptions**

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

*This '**cosmological principle**' …*

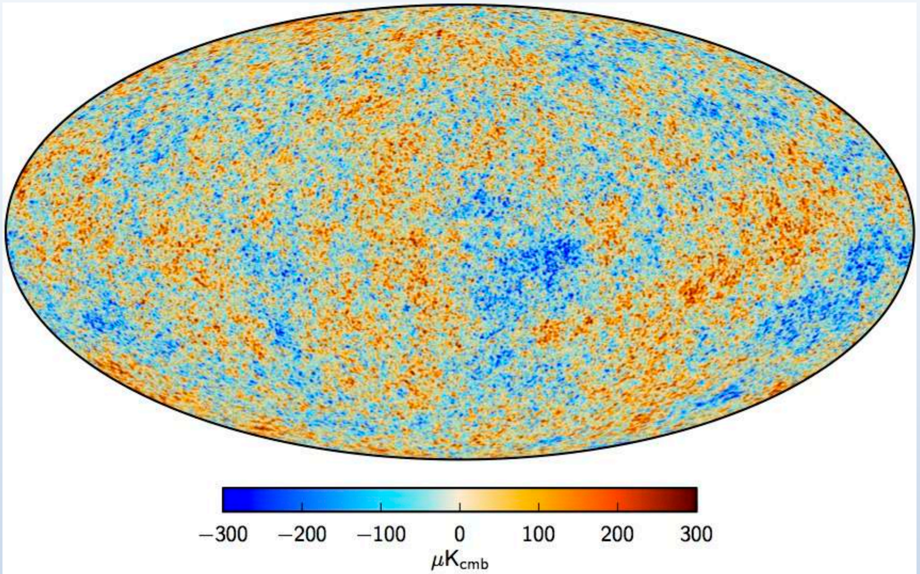


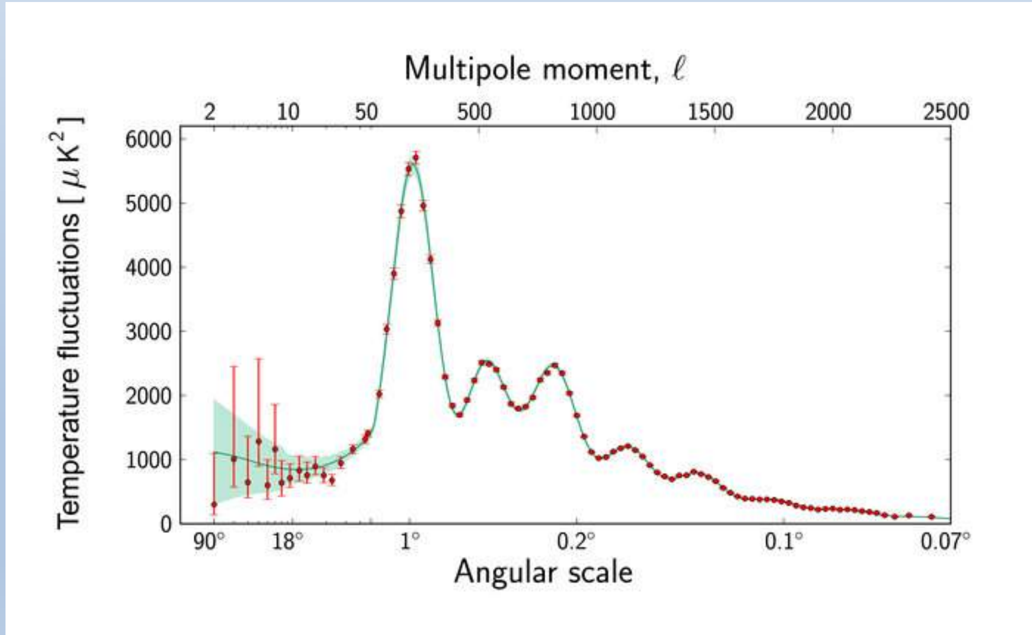
Kinematics, Dynamics, and the Scale of Time

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

(*Received* 28 *August*, 1936)

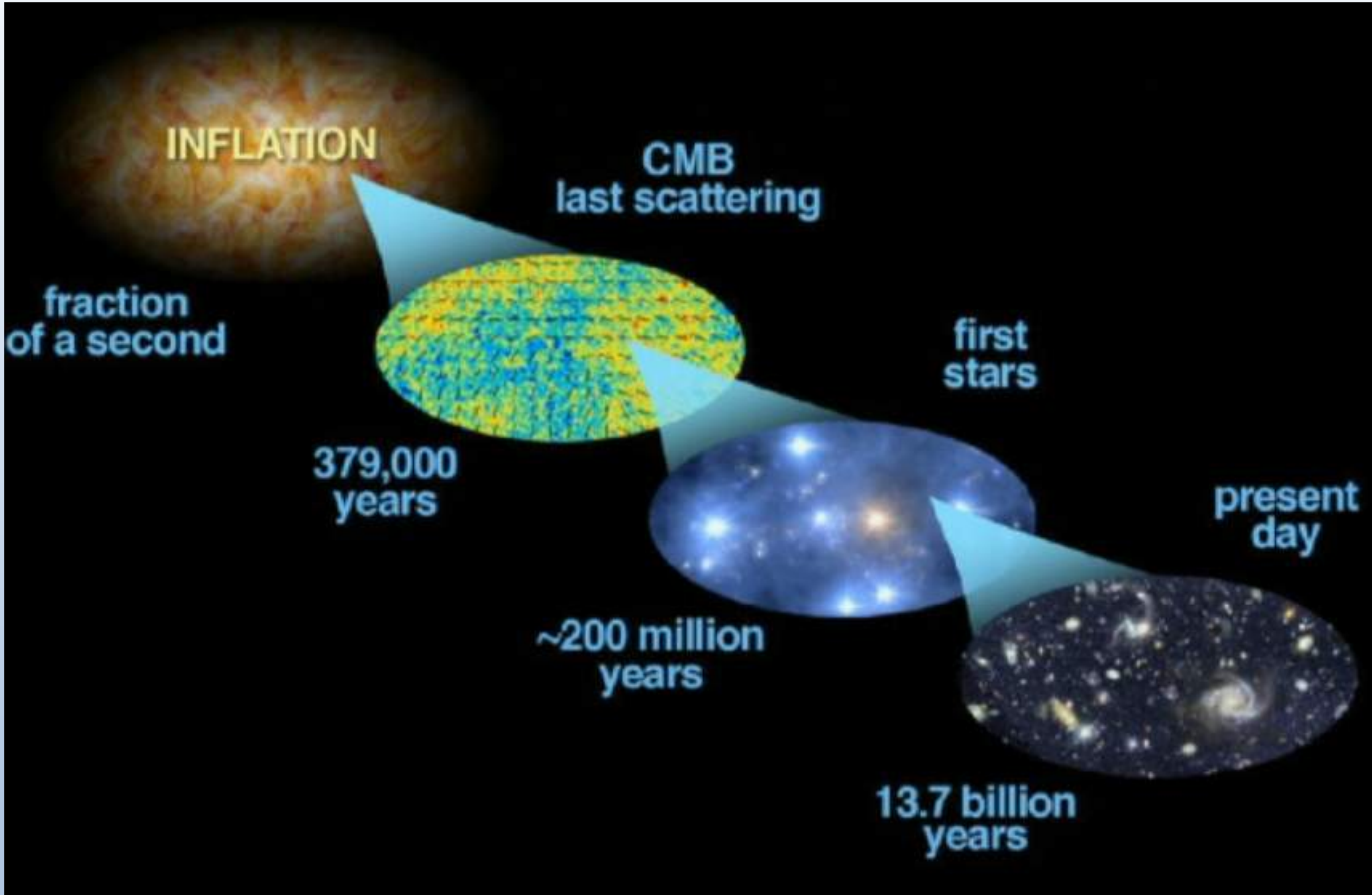
"Data from the Planck satellite show the universe to be highly isotropic" (Wikipedia)





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

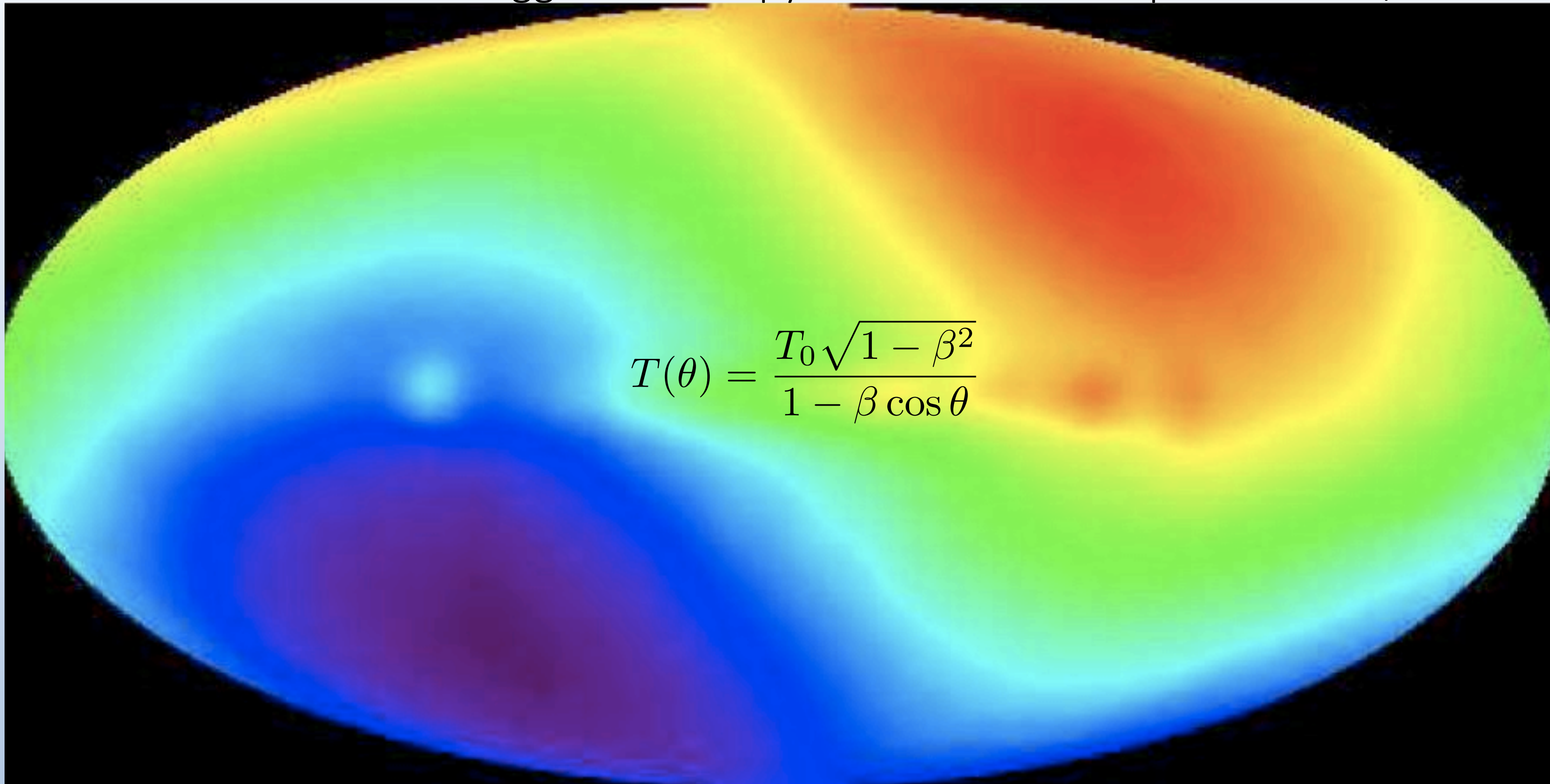
Standard model of structure formation



The $\sim 10^{-5}$ **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 $\Delta T/T \sim 10^{-3}$



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

Sciama 1967, Peebles & Wilkinson 1968

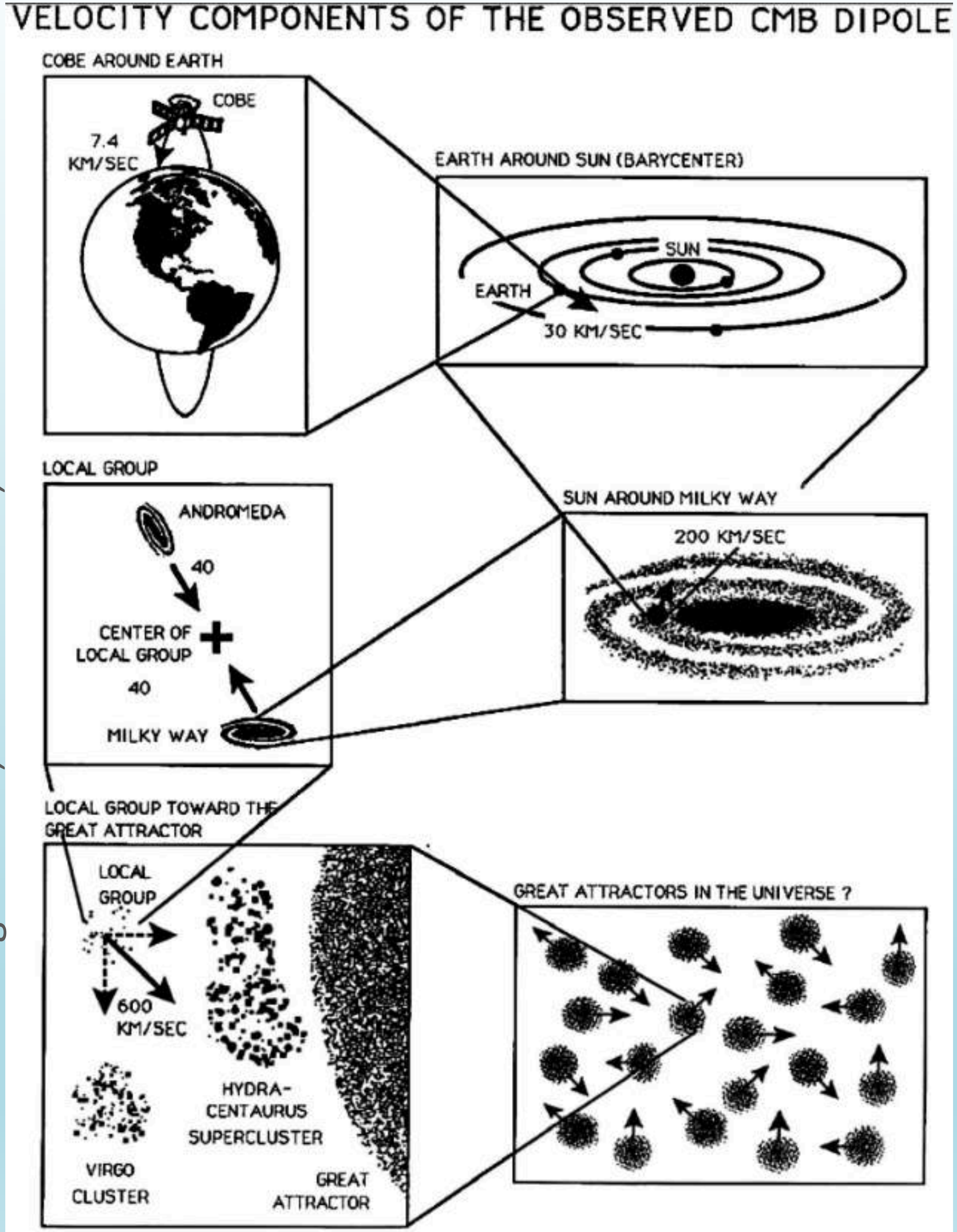
This is interpreted as due to our motion at 370 km/s wrt the frame in which the CMB is truly isotropic ⇒ motion of the Local Group at 620 km/s towards l=271.9°, b=29.6°

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 $\mathcal{O}$(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

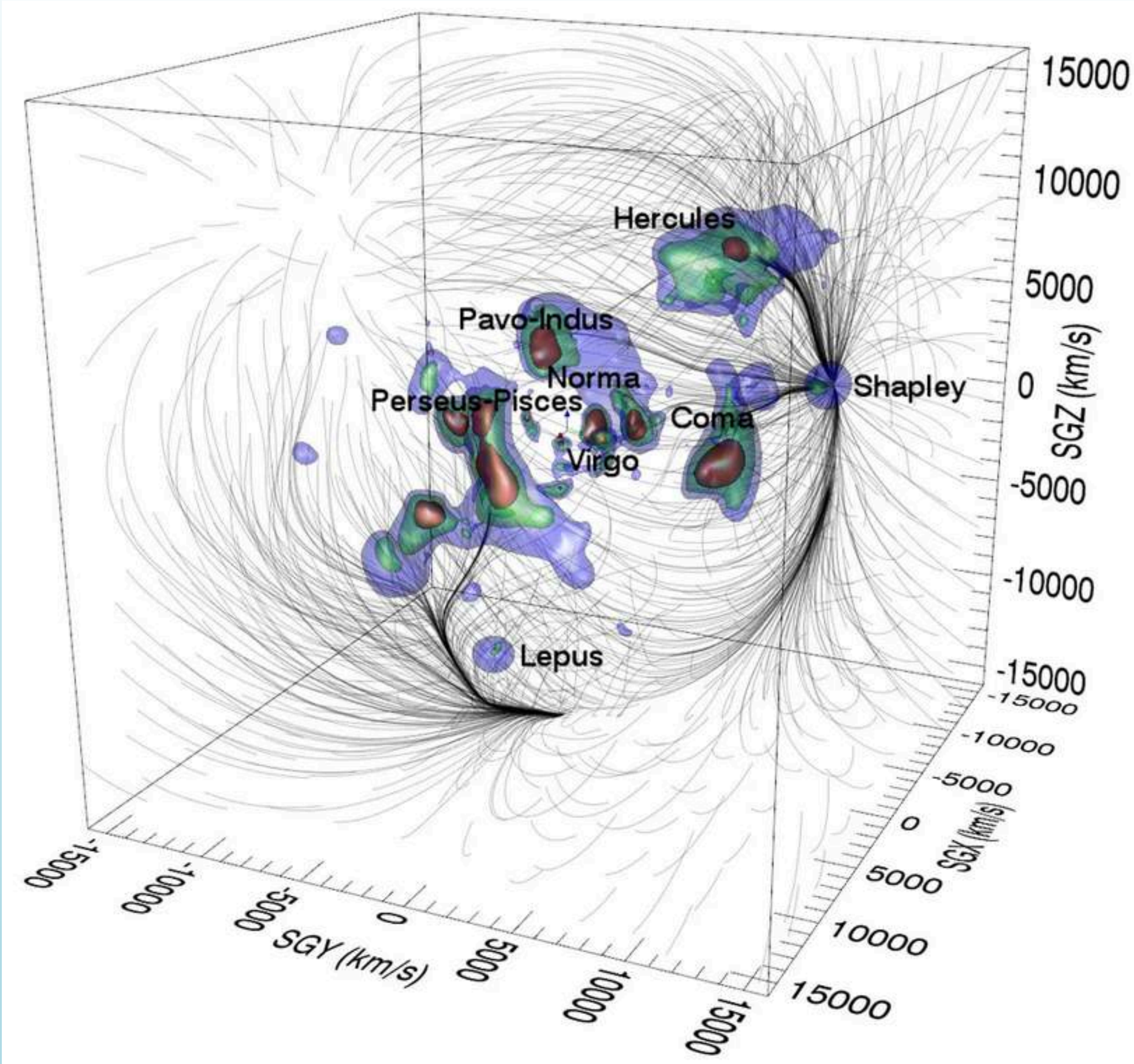
J. M. Stewart & D. W. Sciama

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)

The predicted CMB dipole was found soon afterwards … in broad *agreement* with expectations

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:

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

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

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

Window function

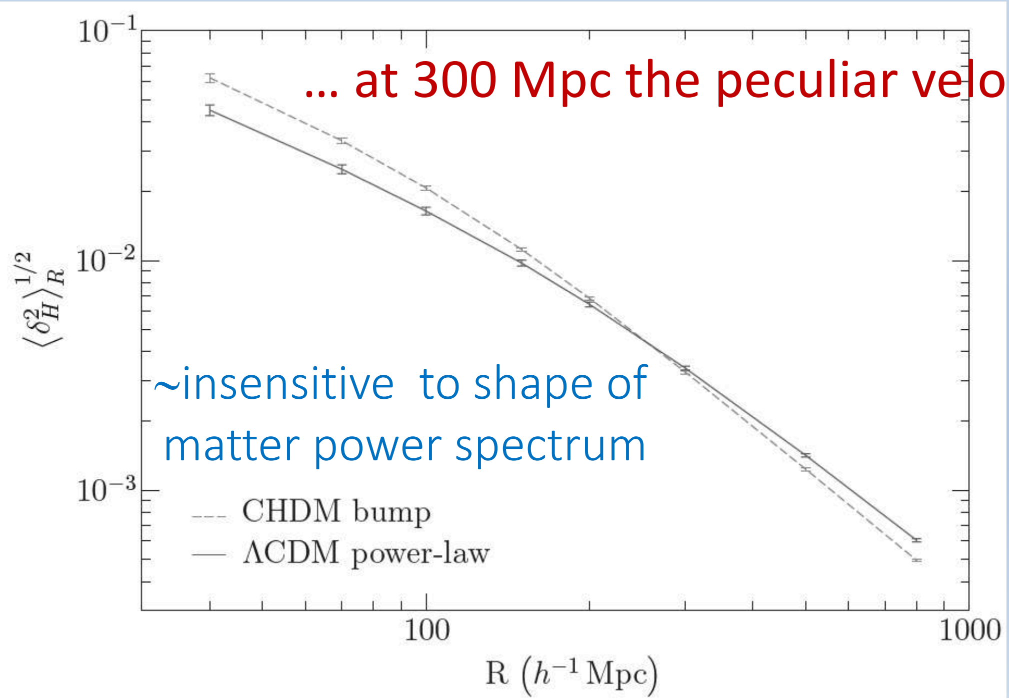
Then the RMS fluctuation in the local Hubble constant $\delta_H \equiv \langle (\delta H/H_0)^2 \rangle^{1/2}$ is:

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

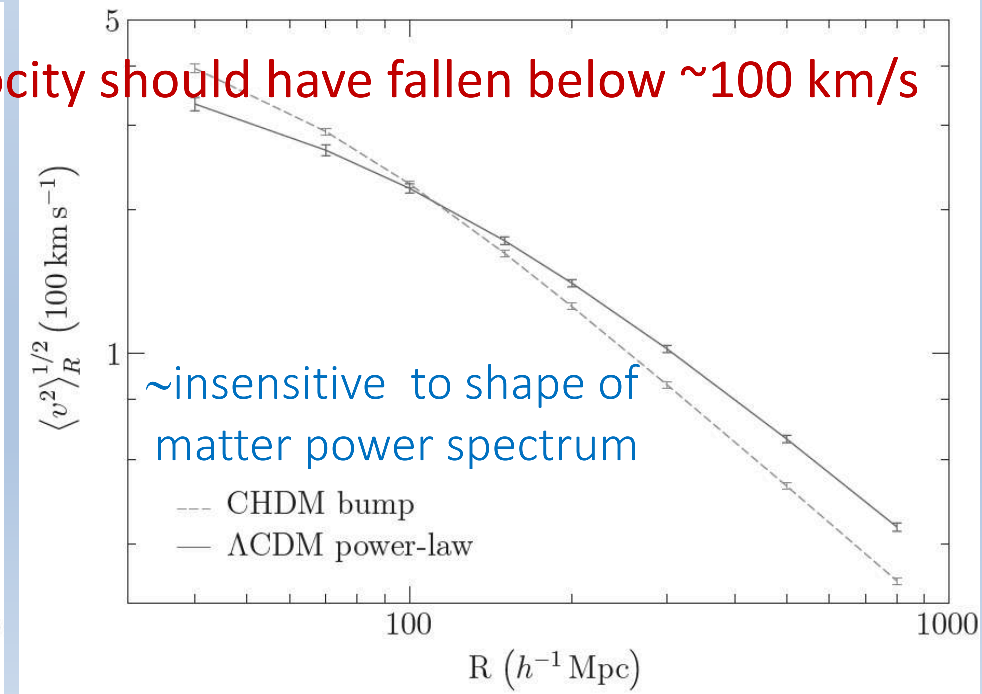
Power spectrum of matter fluctuations — Growth rate

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

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



~insensitive to shape of matter power spectrum

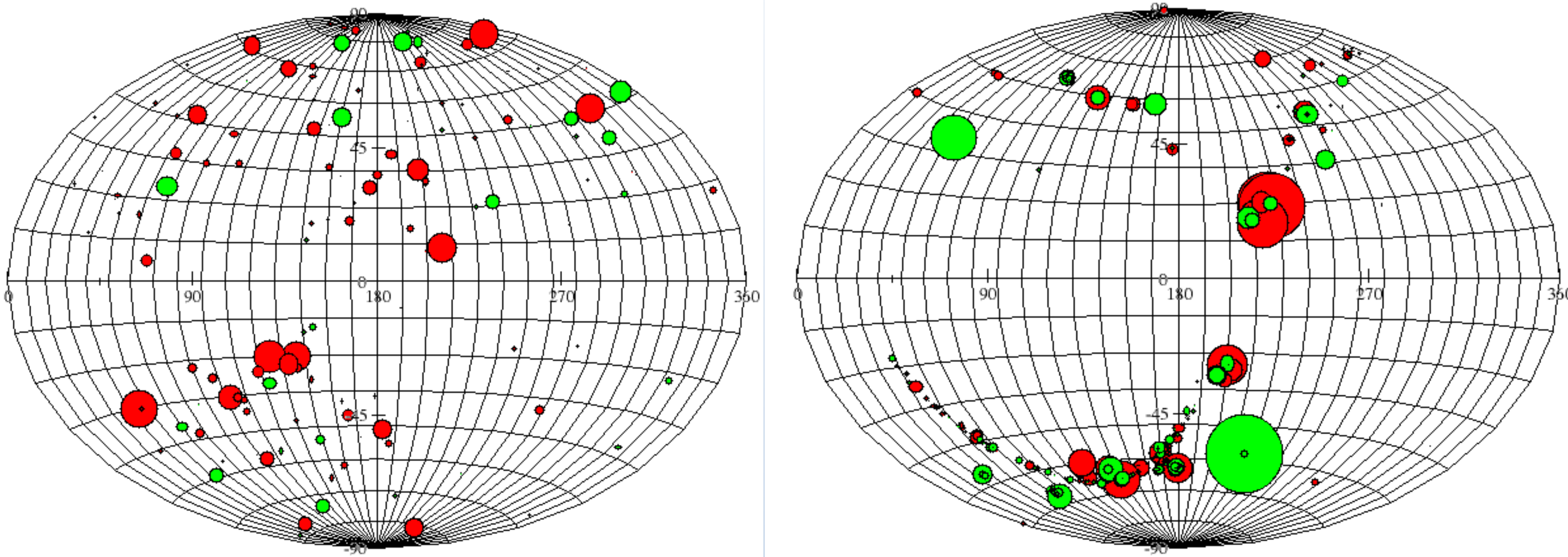


~insensitive to shape of matter power spectrum

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

Union 2 compilation of 557 SNe Ia

Aitoff-Hammer plot, Galactic coordinates

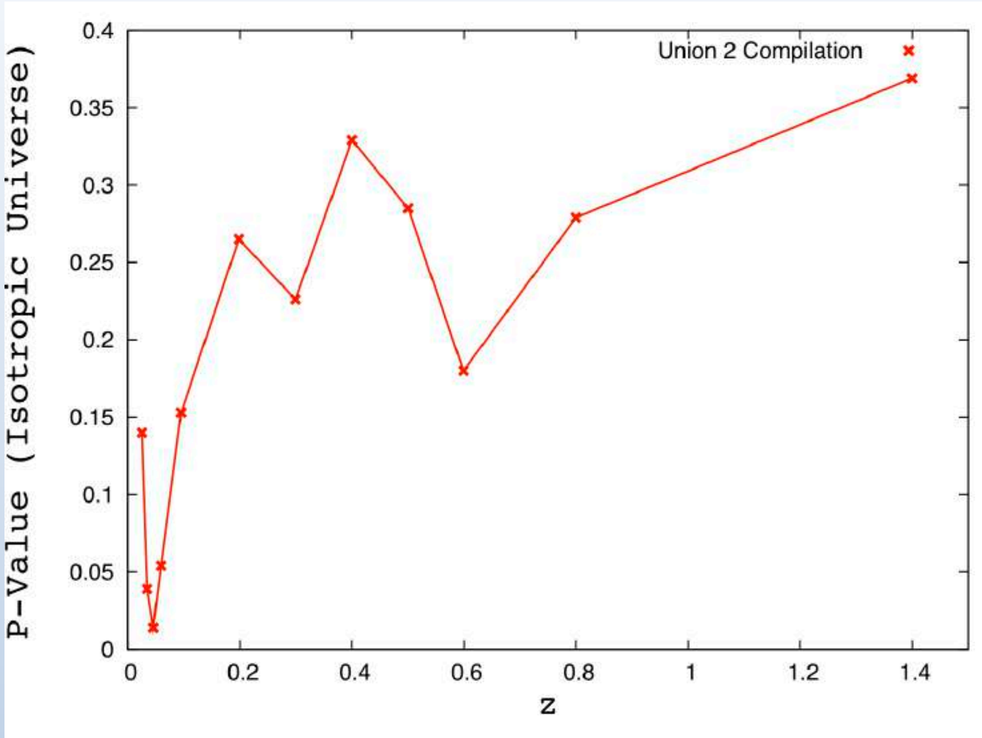


Colin, Mohayaee, S.S. & Shafieloo, MNRAS **414**:264,2011

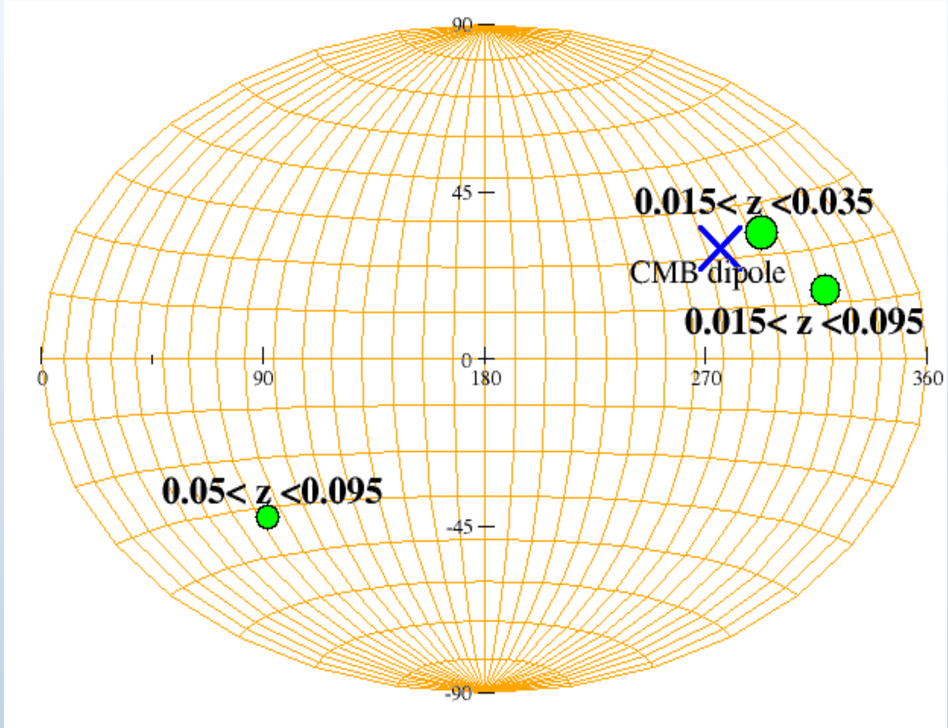
Left panel: The red spots represent the data points for $z < 0.06$ with distance moduli μ_{data} bigger than the values μ_{CDM} predicted by ΛCDM, and the green spots are those with μ_{data} less than μ_{CDM}; the spot size is a relative measure of the discrepancy. A dipole anisotropy is visible around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



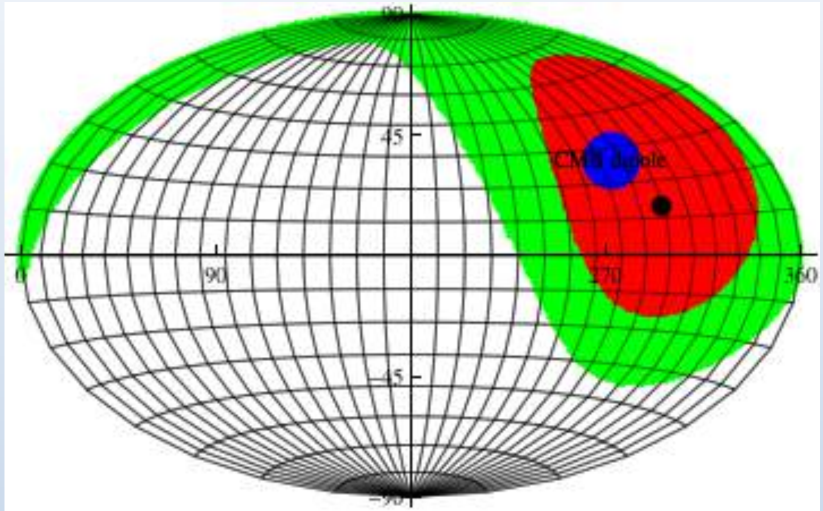
P-value for the consistency of the isotropic universe with the Union 2 supernova data. At $z \approx 0.05$ (~200 Mpc) the P-value drops to 0.014, i.e. isotropy is excluded at ~3σ … we have *not* converged to the CMB rest frame.

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

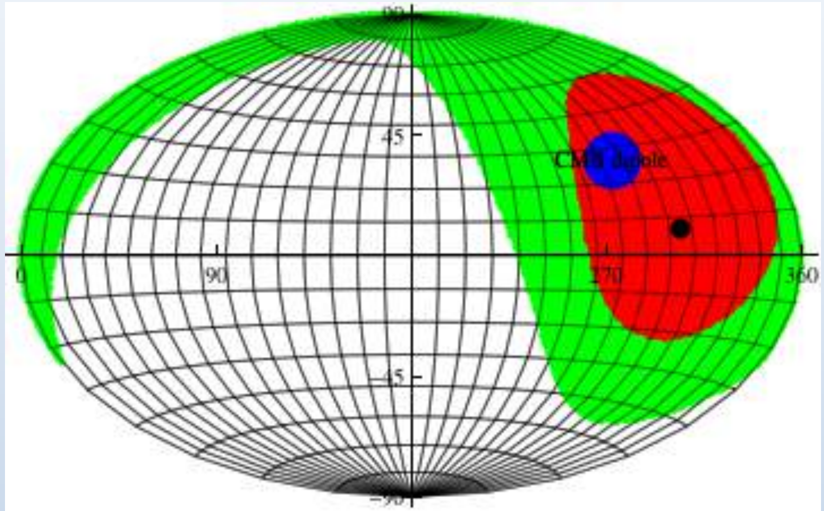
Maximum likelihood analysis can now be used to estimate the bulk flow at low redshifts where the velocities are not yet dominated by the cosmic expansion

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

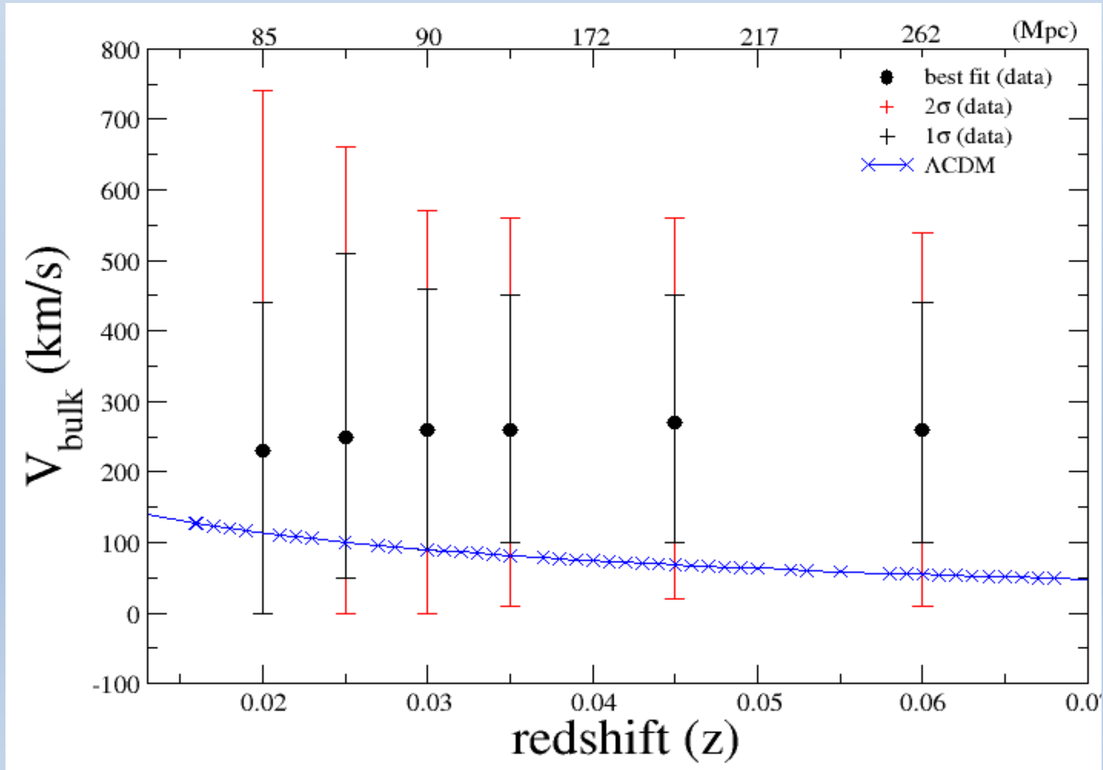
$0.015 < z < 0.045$, $v = 270$ km/s, $l = 291$, $b = 15$



$0.015 < z < 0.06$, $v = 260$ 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)

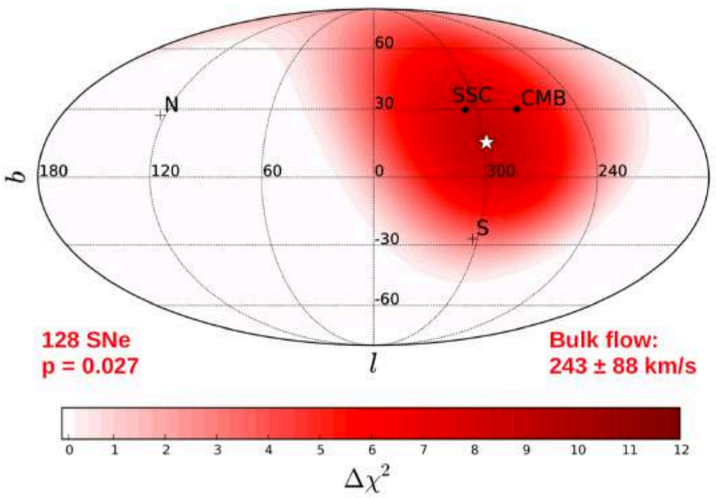
… consistent with Watkins et al (2009) who had earlier found a high bulk flow of 416±78 km/s towards $b = 60\pm6^0$, $l = 282\pm11^0$, going up to ~100 h^{-1} Mpc

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:

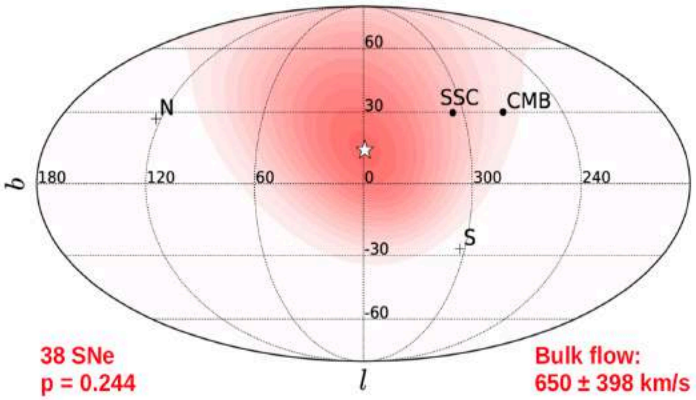
$$\tilde{d}_L(z) = d_L(z) + \frac{(1+z)^2}{H(z)} \vec{n} \cdot \vec{v}_d$$

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

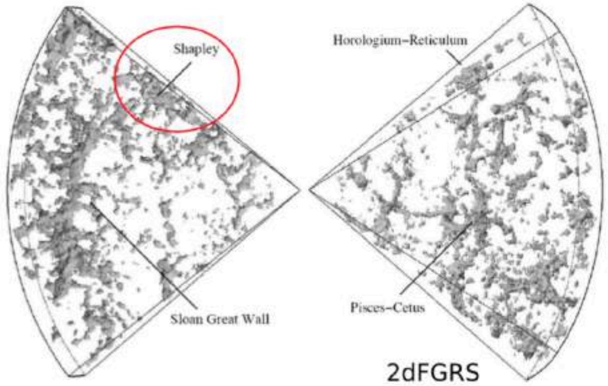
- Contradicts Shapley as the main source of the bulk flow
- Results in this shell are driven by SNfactory data

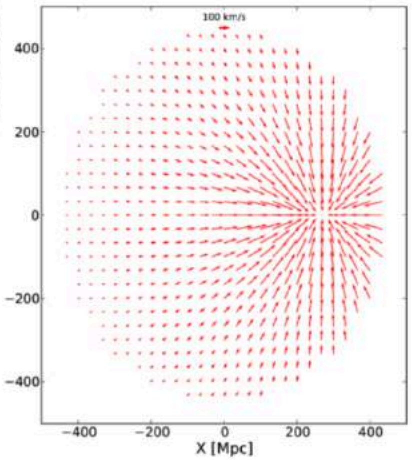
Feindt *et al,* A&A **560**:A90,2013

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

Finding the Attractors

Modeling the velocity field



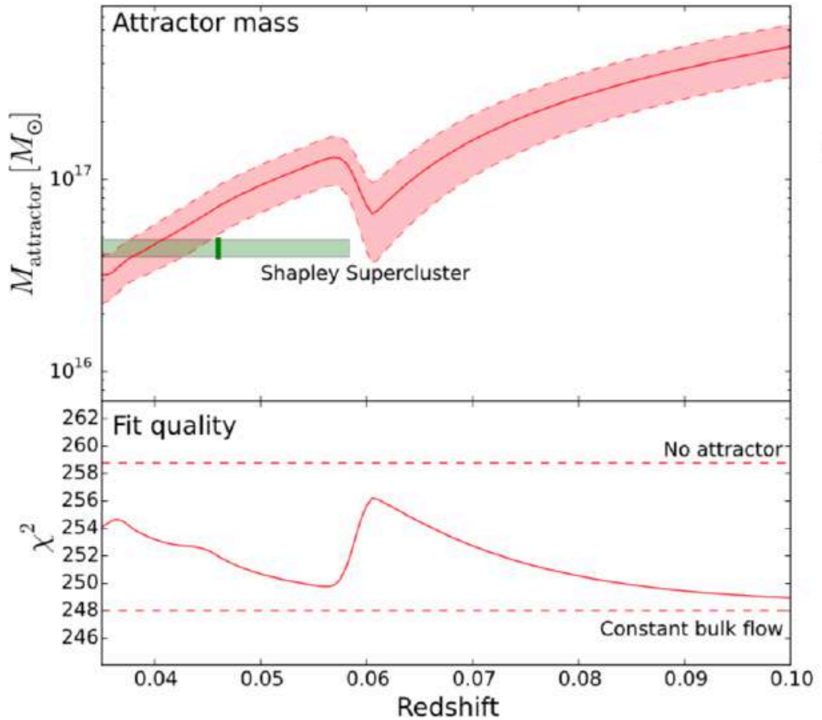


Simplest model:
Infall into spherical mass concentration

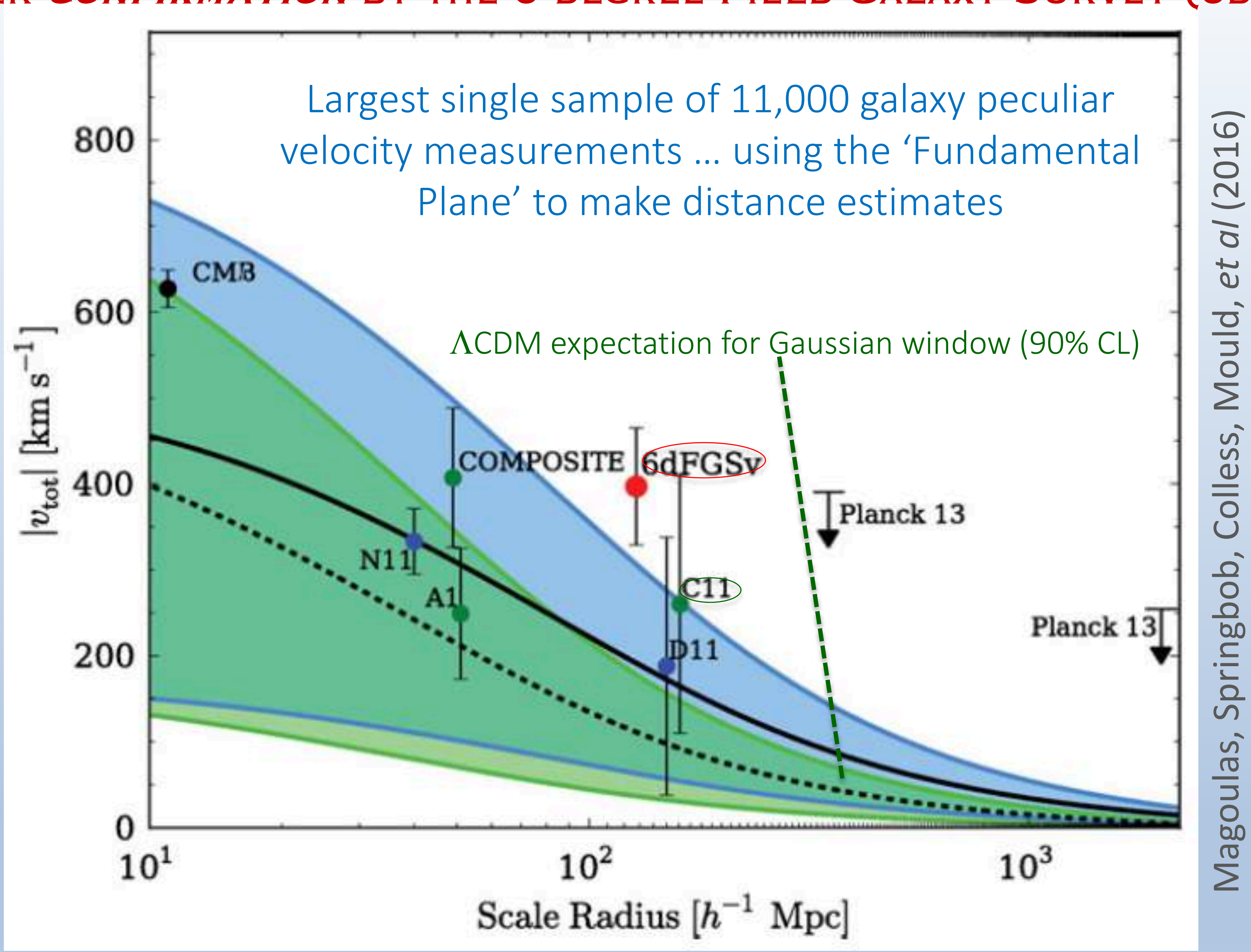
$$M_{tot} = \frac{4\pi}{3} R^3 \Omega_M \rho_{crit} (1 + \delta)$$

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

Courtesey: Ulrich Feindt



Further *confirmation* by the 6-degree Field Galaxy Survey (6dFGSv)



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 …

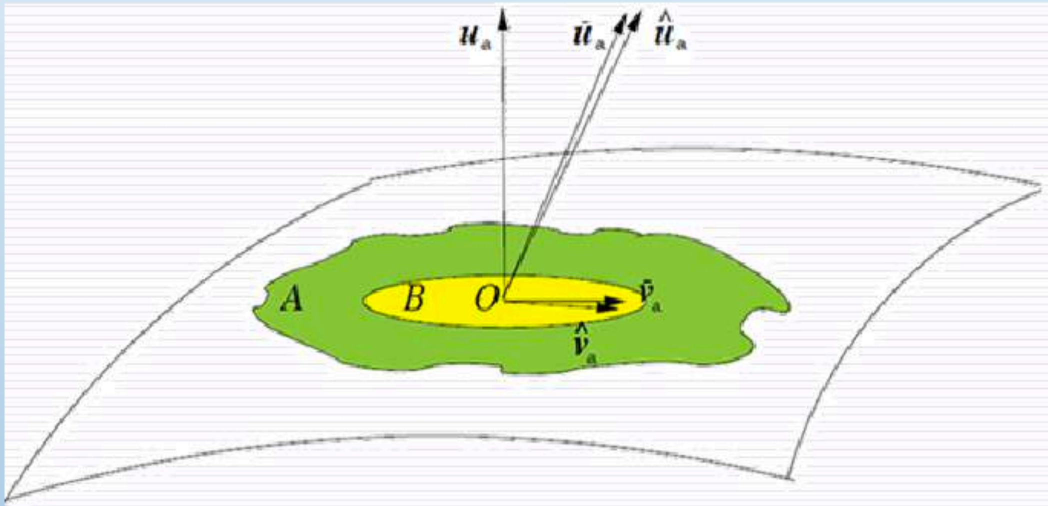
Rameez, Mohayaee, S.S. & Colin, MNRAS **477**:1722,2018

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



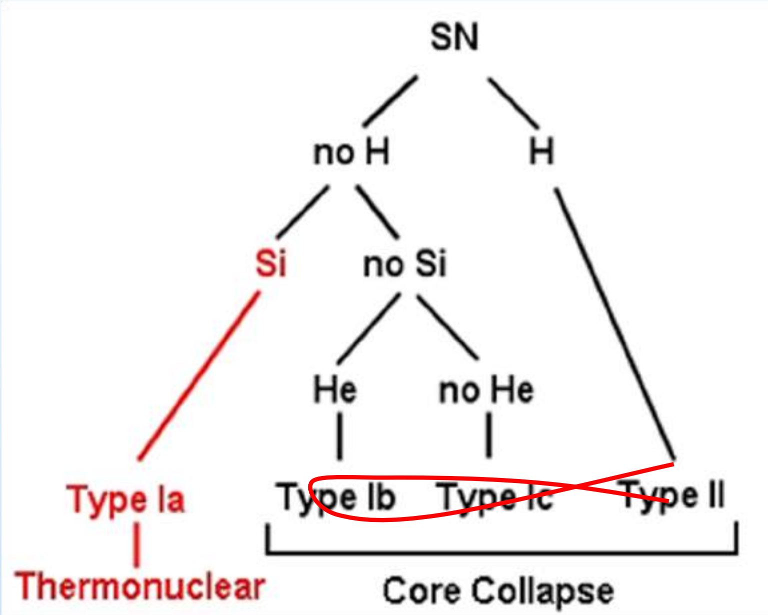
The patch A has mean peculiar velocity $\tilde{v}_a$ with $\vartheta = \tilde{\mathrm{D}}^a v_a \gtrless 0$ and $\dot{\vartheta} \gtrless 0$
(the sign depending on whether the bulk flow is faster or slower than the surroundings)

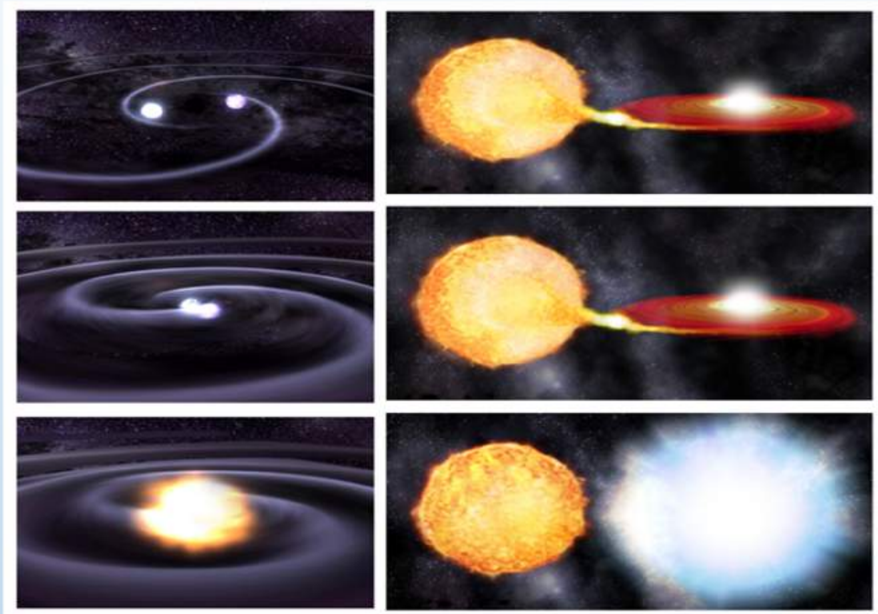
Inside region B, the r.h.s. of the expression

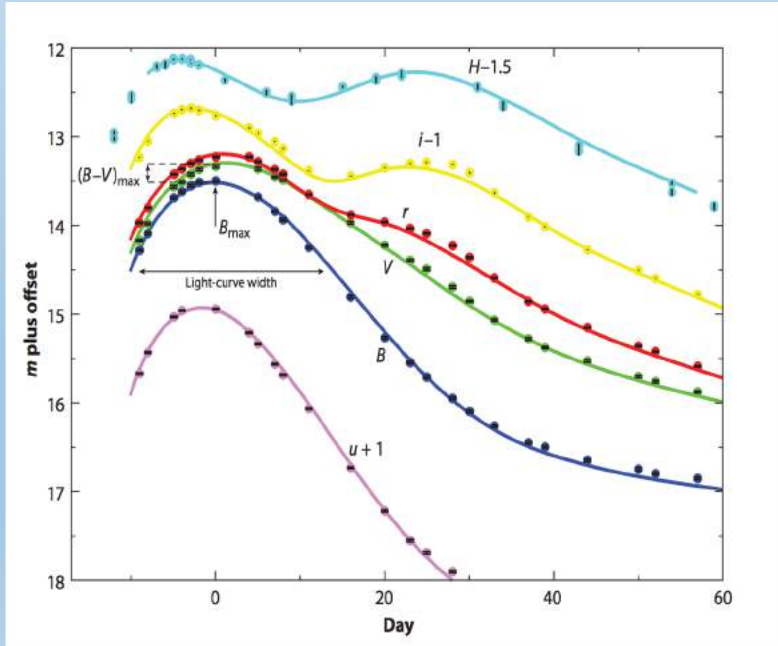
$$1 + \tilde{q} = (1+q)\left(1 + \frac{\vartheta}{\Theta}\right)^{-2} - \frac{3\dot{\vartheta}}{\Theta^2}\left(1 + \frac{\vartheta}{\Theta}\right)^{-2}, \qquad \tilde{\Theta} = \Theta + \vartheta,$$

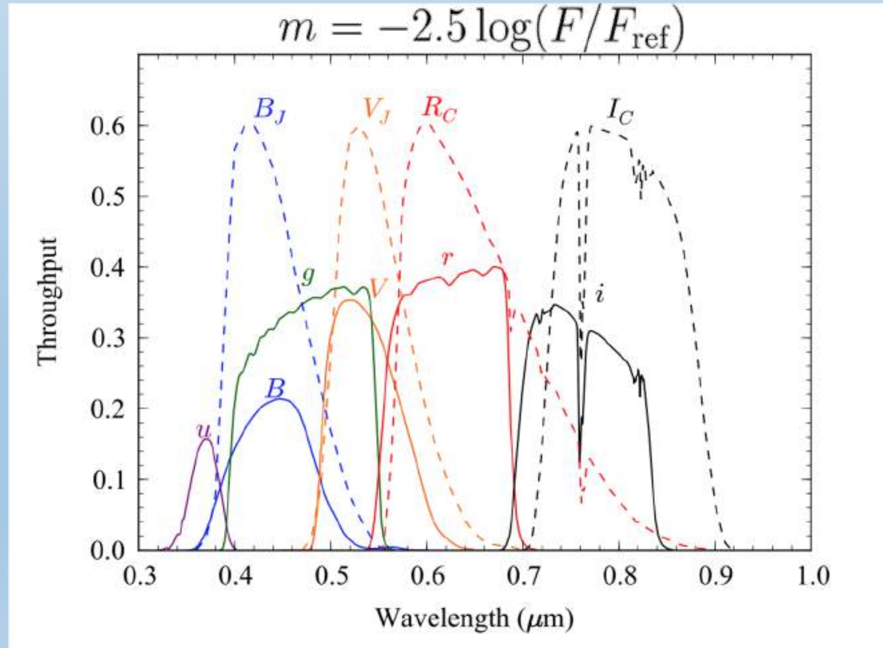
drops below 1 and the comoving observer 'measures' negative deceleration parameter

What are Type Ia supernovae?









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

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

Knowing the magnitudes and redshifts we can do cosmology

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

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

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

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

sinn $\rightarrow$ sinh for $\Omega_k > 0$ and sinn $\rightarrow$ sin for $\Omega_k < 0$

Distance modulus

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

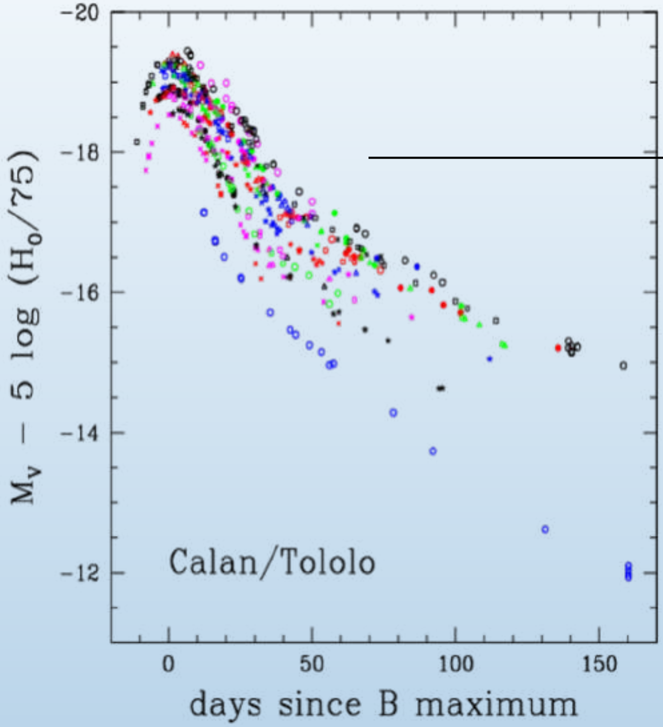
… Or (cosmological model-*independent*) cosmography

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

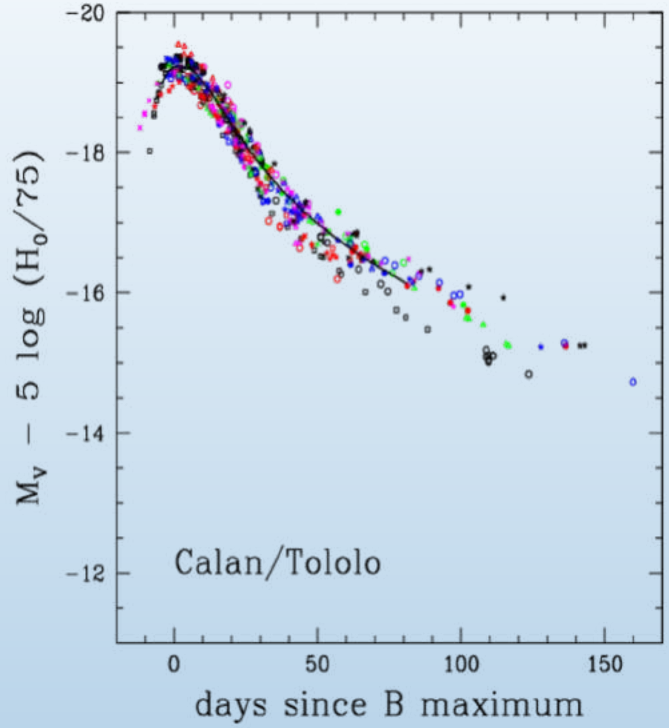
$q_0 \equiv -(\ddot{a}a)/\dot{a}^2$ $\quad$ $j_0 \equiv (\dddot{a}/a)(\dot{a}/a)^{-3}$ $\quad$ (e.g. Visser, CQG **21**:2603,2004)

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

SN Ia are *not* 'standard candles'



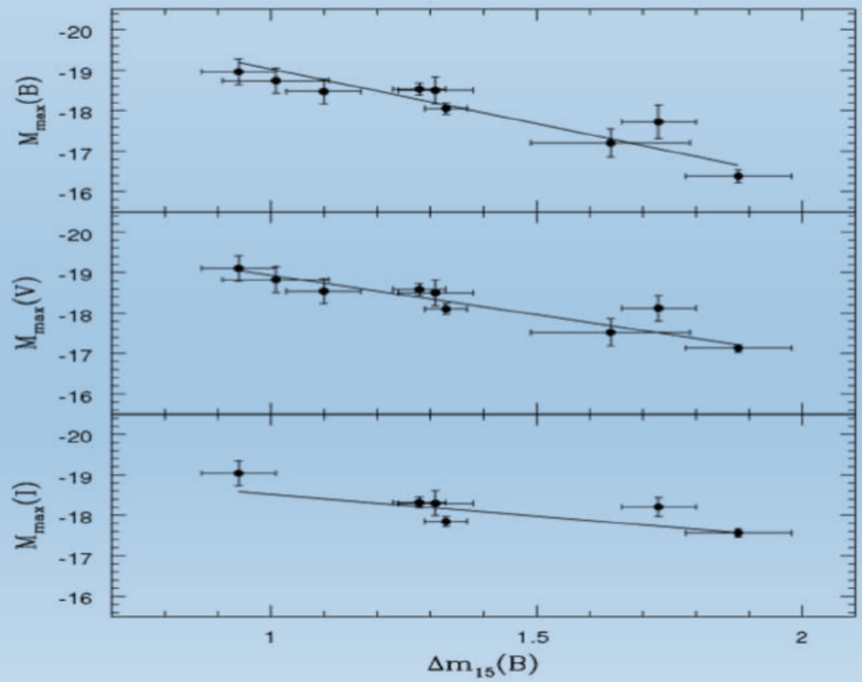
But they are 'standardisable'



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)

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

B-band

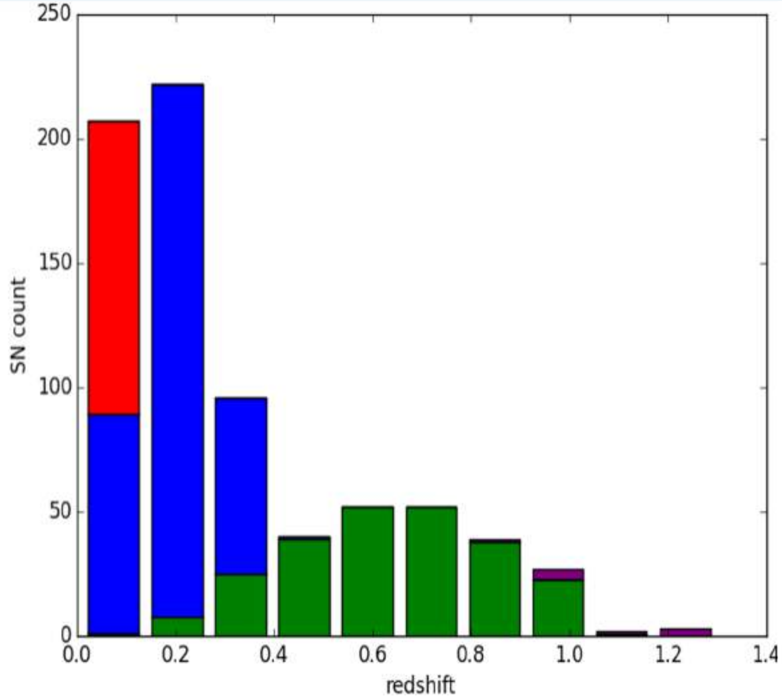
SALT 2 parameters

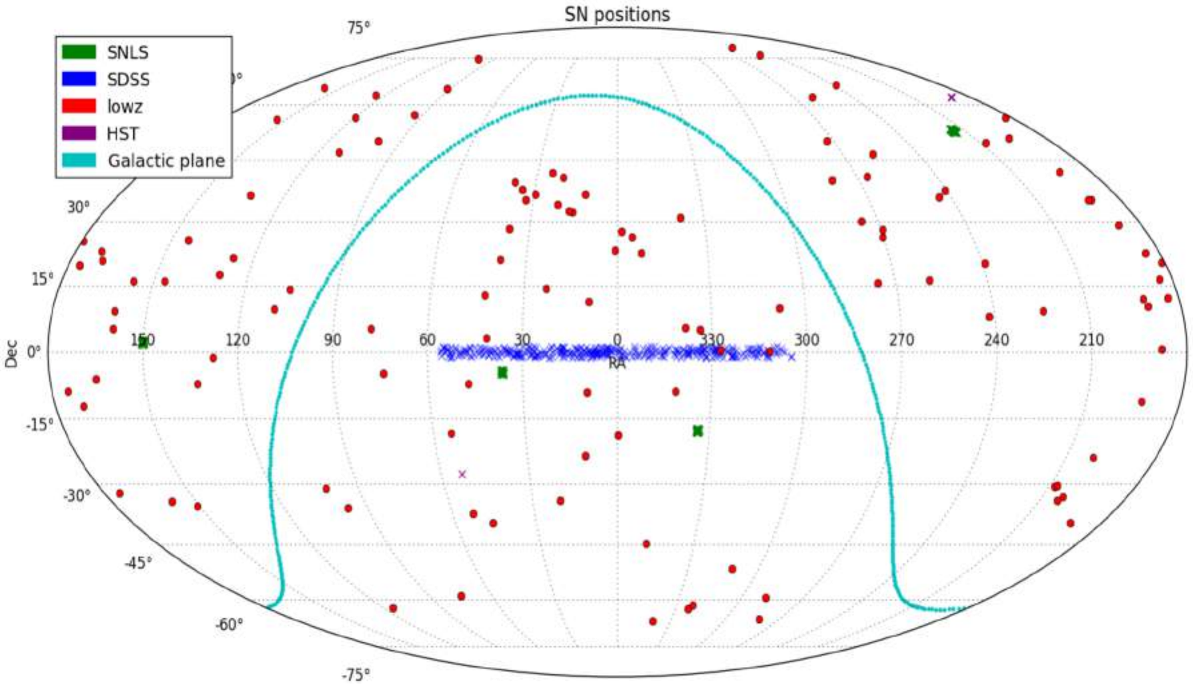
Betoule *et al.*, A&A **568**:A22,2014

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 …

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/

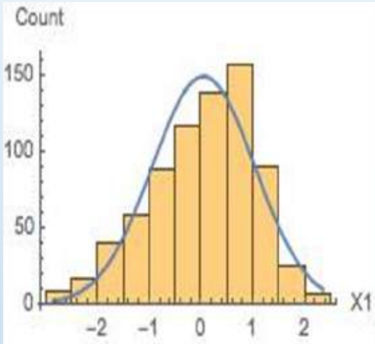
NB: Previous analyses used the 'constrained chi-squared' method … wherein σ_{int} is *adjusted* to get χ^2 of 1/d.o.f. for the fit to the assumed ΛCDM model

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

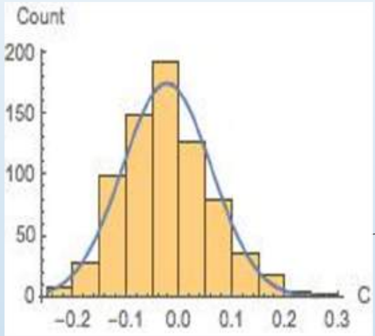
we employ a Maximal Likelihood Estimator … and get rather different results

Construct a Maximum Likelihood Estimator

Well-approximated as Gaussian



'Stretch' corrections



'Colour' corrections

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

$$\mathcal{L} = p[(\hat{m}_B^*, \hat{x}_1, \hat{c})|\theta]$$

$$= \int p[(\hat{m}_B^*, \hat{x}_1, \hat{c})|(M, x_1, c), \theta_{\text{cosmo}}]$$

$$\times p[(M, x_1, c)|\theta_{\text{SN}}]dM\,dx_1\,dc$$

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

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

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

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

$$p(x_1|\theta) = (2\pi\sigma_{x_{1,0}}^2)^{-1/2} \exp\left\{-\left[(x_1 - x_{1,0})/\sigma_{x_{1,0}}\right]^2/2\right\},$$

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

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

intrinsic distributions

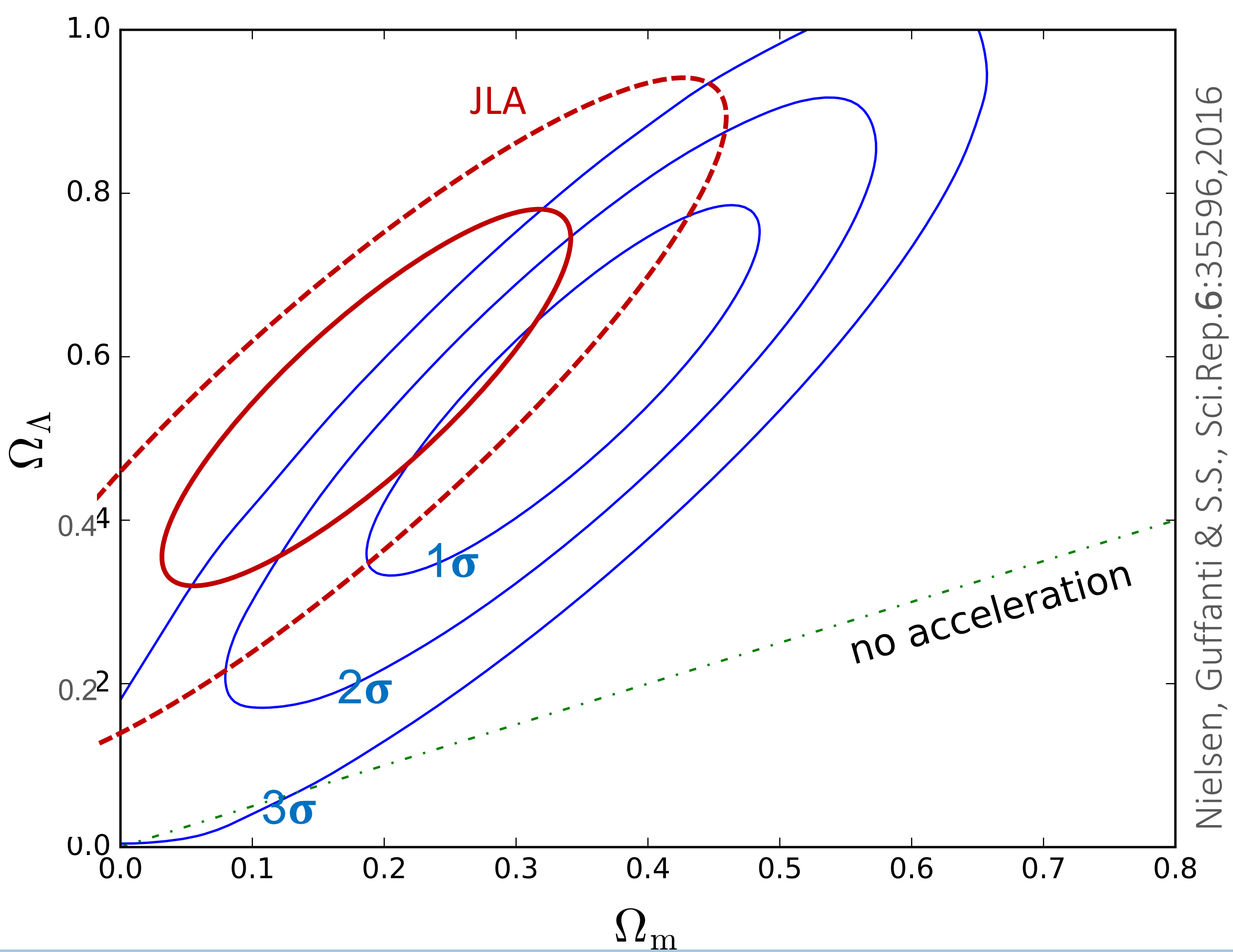
cosmology

SALT2

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

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

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



Profile Likelihood

MLE, *best fit*

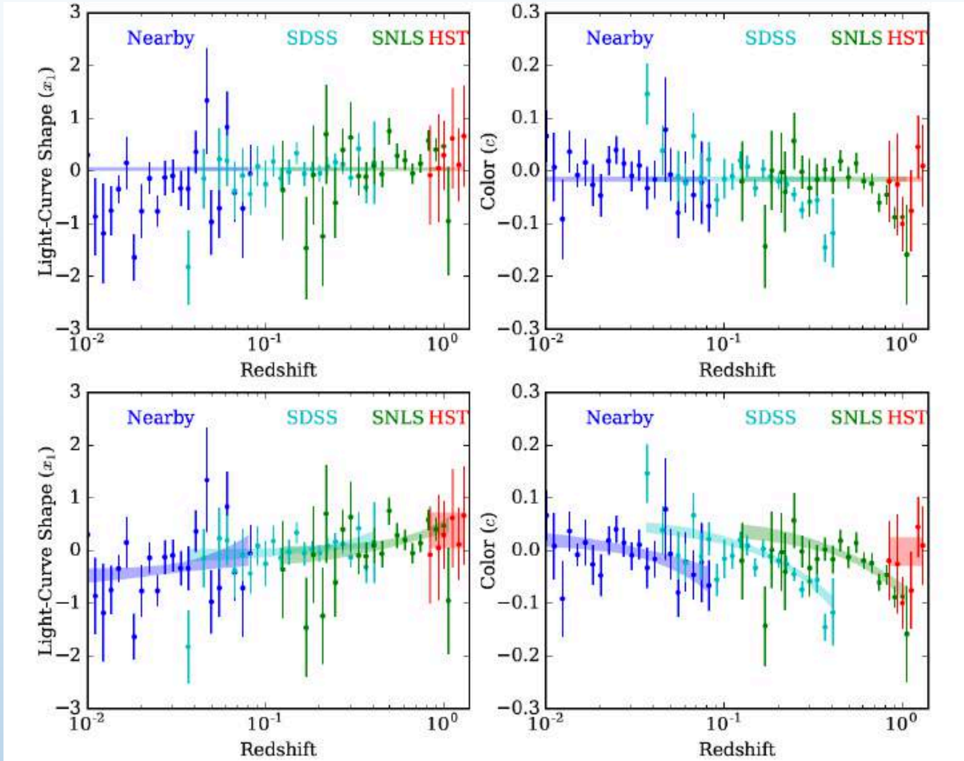
Ω_M	0.341
Ω_Λ	0.569
α	0.134
x_0	0.038
σ^2_{x0}	0.931
β	3.058
c_0	-0.016
σ^2_{c0}	0.071
M_0	-19.05
σ^2_{M0}	0.108

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

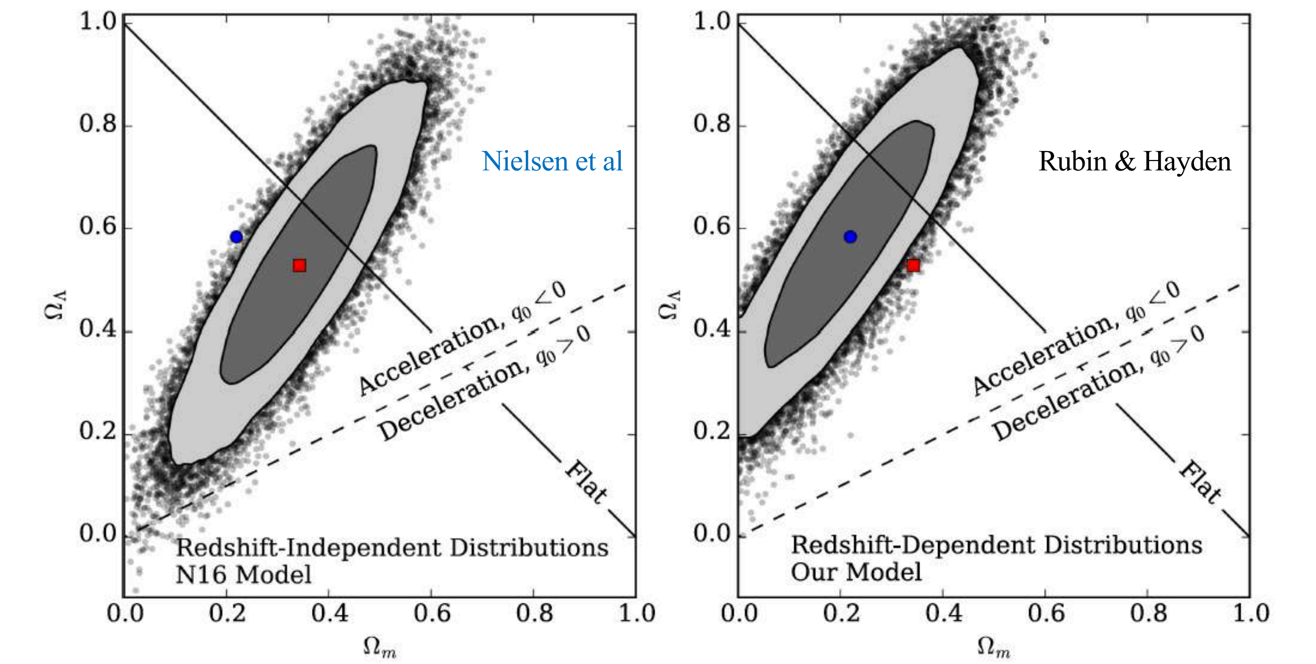
... simply to emphasise that the statistical analysis has not been done correctly earlier

(Other constraints e.g. $\Omega_m \gtrsim 0.2$ or $\Omega_m + \Omega_\Lambda \simeq 1$ are appropriate for 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 their possible dependence on redshift - which *no* previous analysis had allowed for - they add 12 more parameters to our 10 to model this individually for each sample ... although the absolute SNe magnitude is supposed *not* to evolve with redshift



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



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

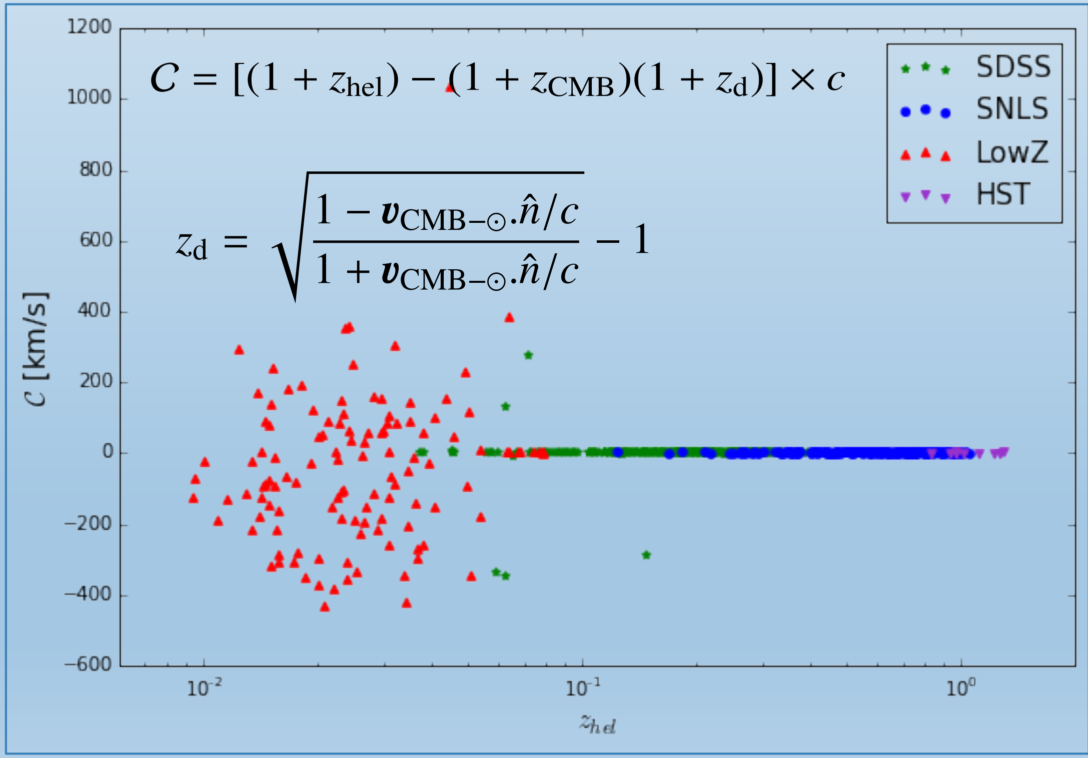
If the CMB dipole is due to our motion w.r.t. the CMB frame in which the universe supposedly looks F-L-R-W, then the *measured* redshift $z_{\rm hel}$ is related to $z_{\rm CMB}$ as:

$$1 + z_{\rm hel} = (1 + z_{\odot}) \times (1 + z_{\rm SN}) \times (1 + z)$$

where $z_{\odot}$ is the redshift induced by our motion w.r.t. the CMB and $z_{\rm SN}$ is the redshift due to the peculiar motion of supernova host galaxy in the CMB frame.

We find that the peculiar velocity 'corrections' applied to the JLA catalogue are suspect

… it is *assumed* that we converge to the CMB frame at ~150 Mpc (contrary to observations)



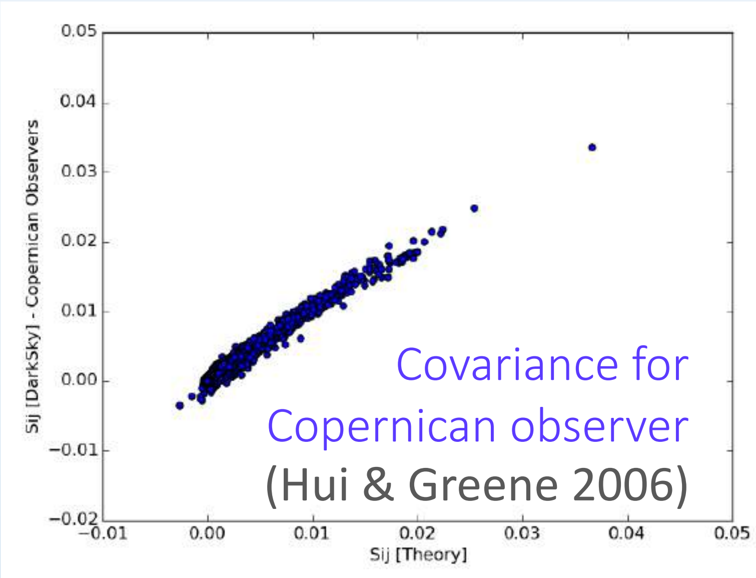
Colin *et al*, A&A **631**:L13,2019

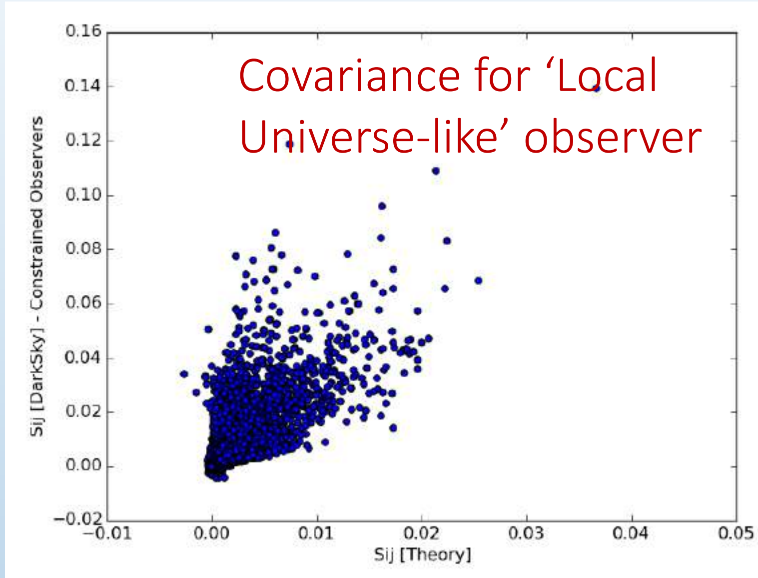
So we *undid* the corrections to recover the original data in the heliocentric frame

… to check if the inferred acceleration of the expansion rate is indeed isotropic

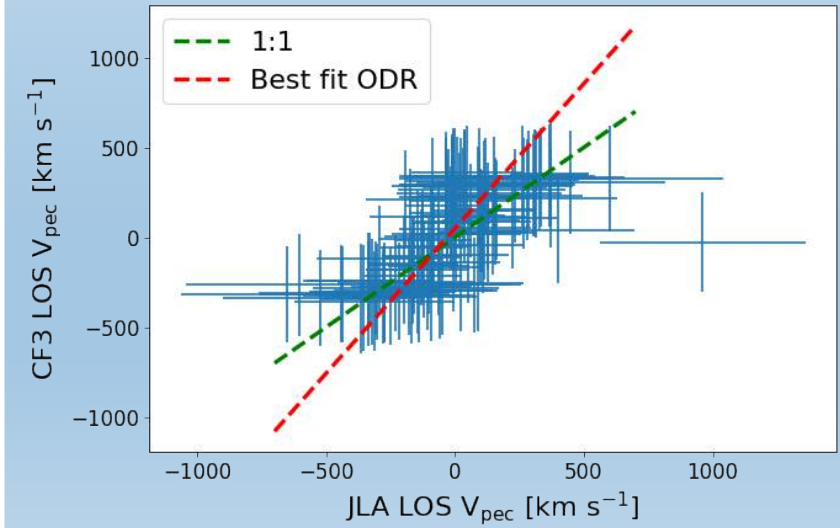
The impact of peculiar velocities on supernova cosmology

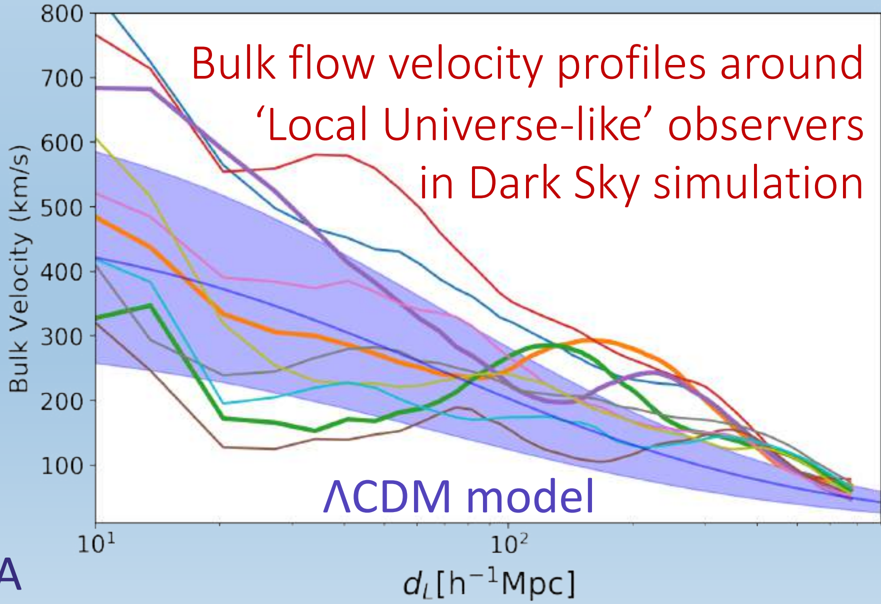
(Mohayaee, Rameez & S.S., arXiv:2003.10420)





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

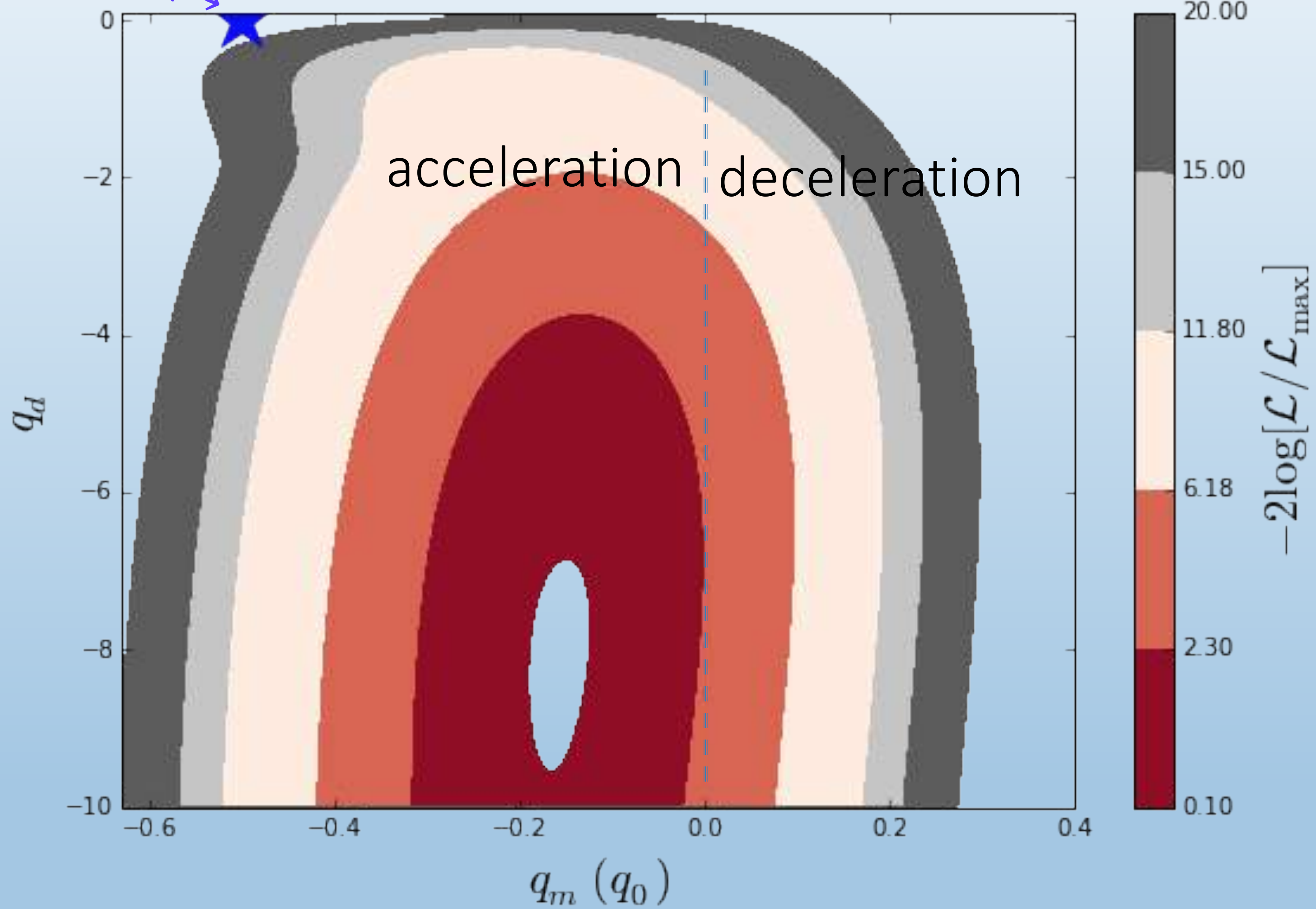




⇒ Velocities have been underestimated by 48% in JLA

When the data is now analysed allowing for a dipole, we find the MLE prefers one (~50 times *bigger* than the monopole) … close to the direction of the CMB dipole

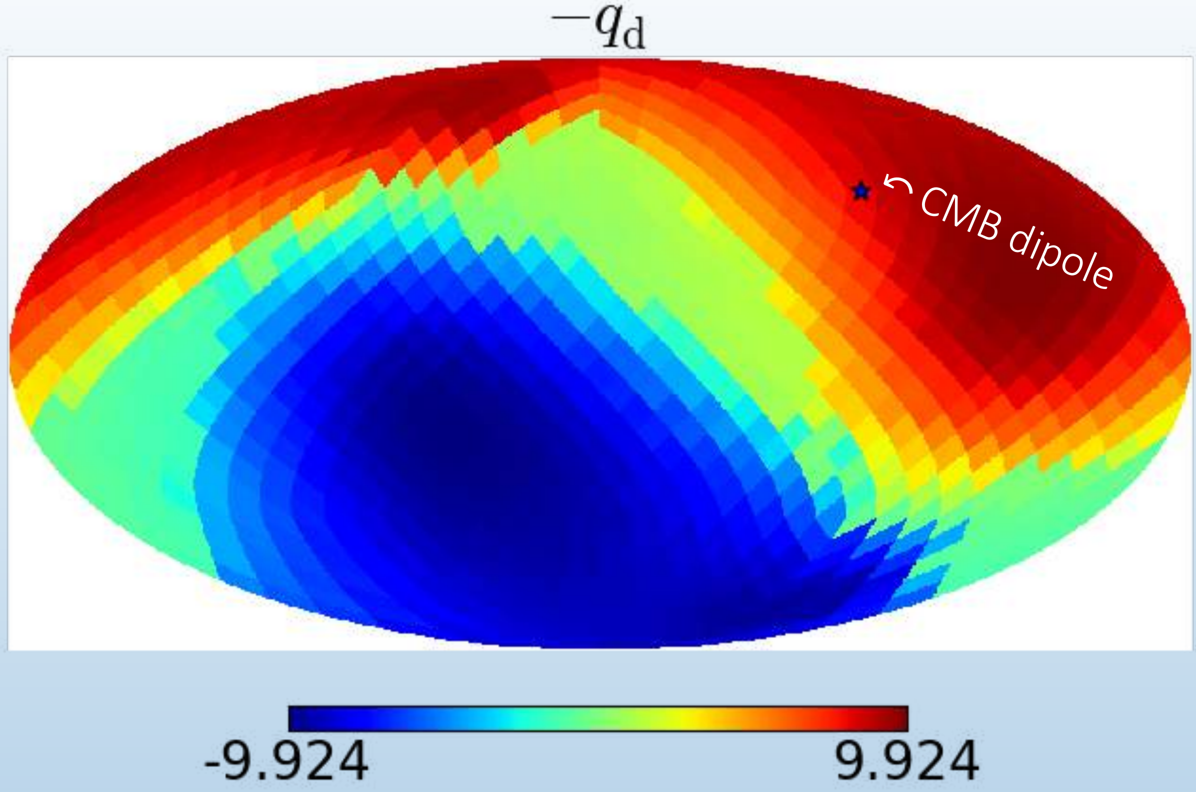
$$q = q_{\rm m} + \vec{q}_{\rm d}.\hat{n}\mathcal{F}(z, S)$$



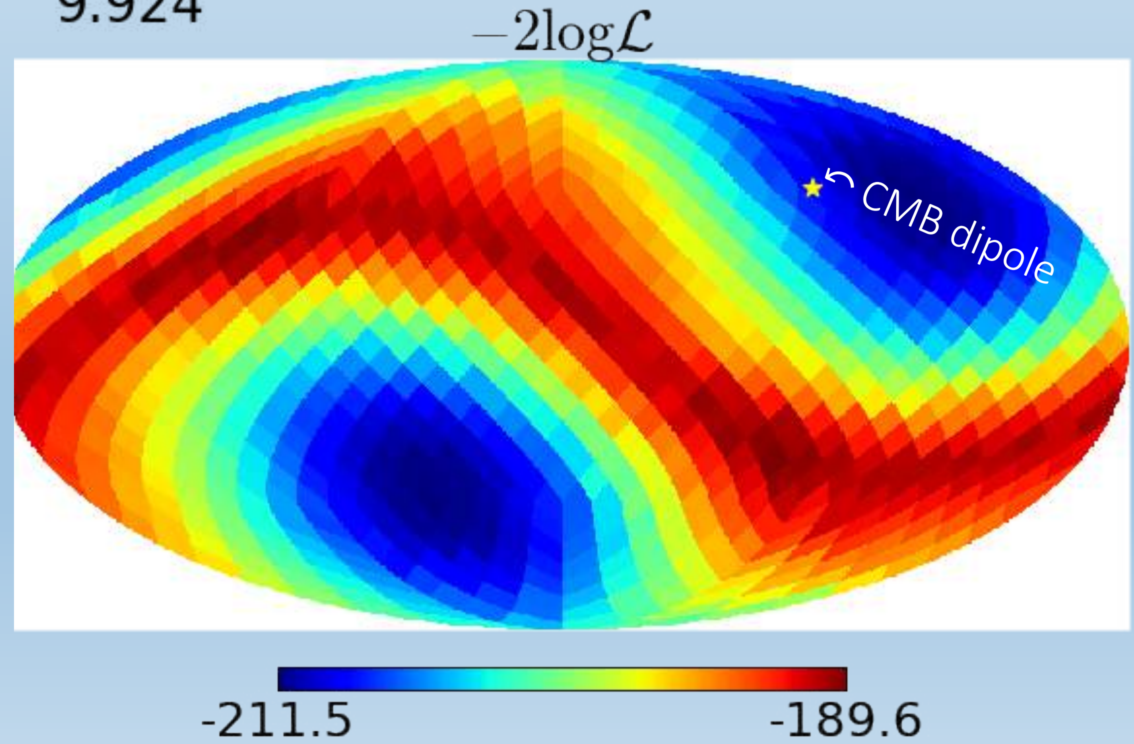
Colin, Mohayaee, Rameez & Sarkar, A&A **631**:L13,2019

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) and *not* due to Λ

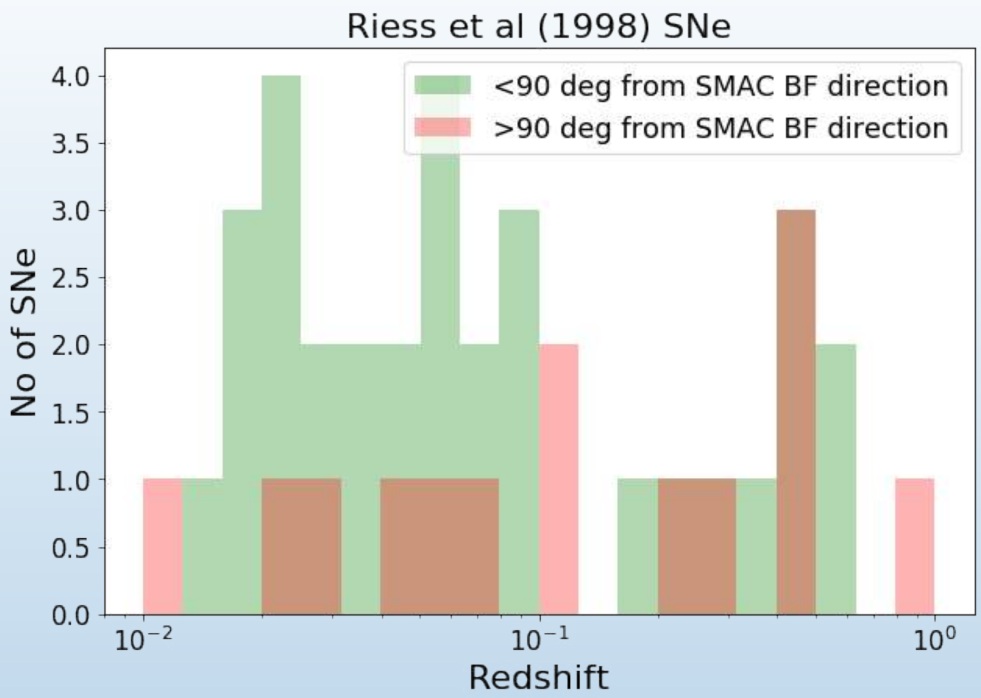


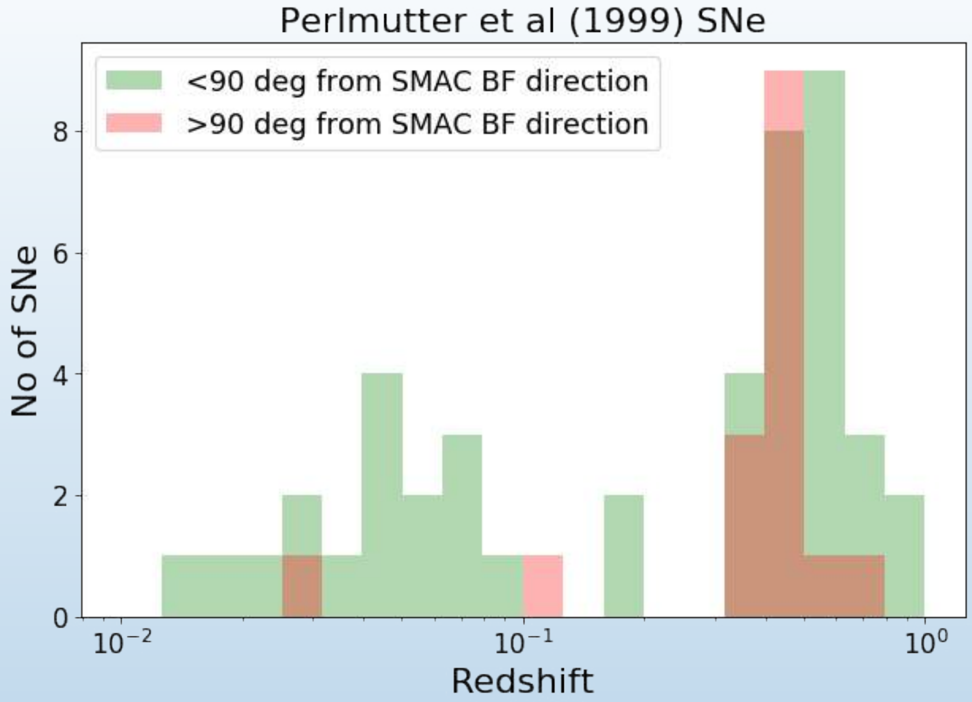
There is not enough data to do an *a priori* scan of the best-fit direction of q_{d} … but if done *a posteriori* it is found to be within 23^0 of the CMB dipole ($\ell = 254.4^0$, $b = 25.5^0$)



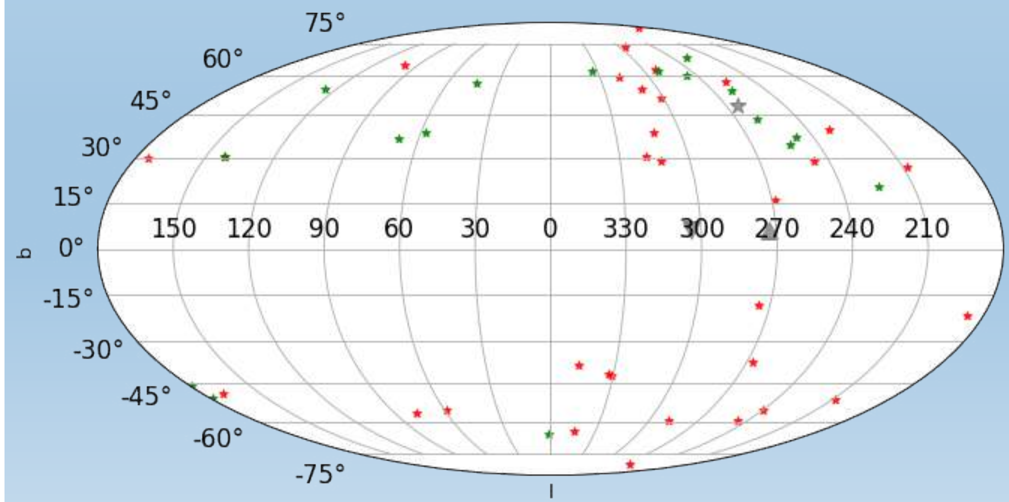
The log-likelihood changes by just 3.2 between the two directions i.e. the inferred acceleration is consistent with being due to the bulk flow (rather than due to Λ)

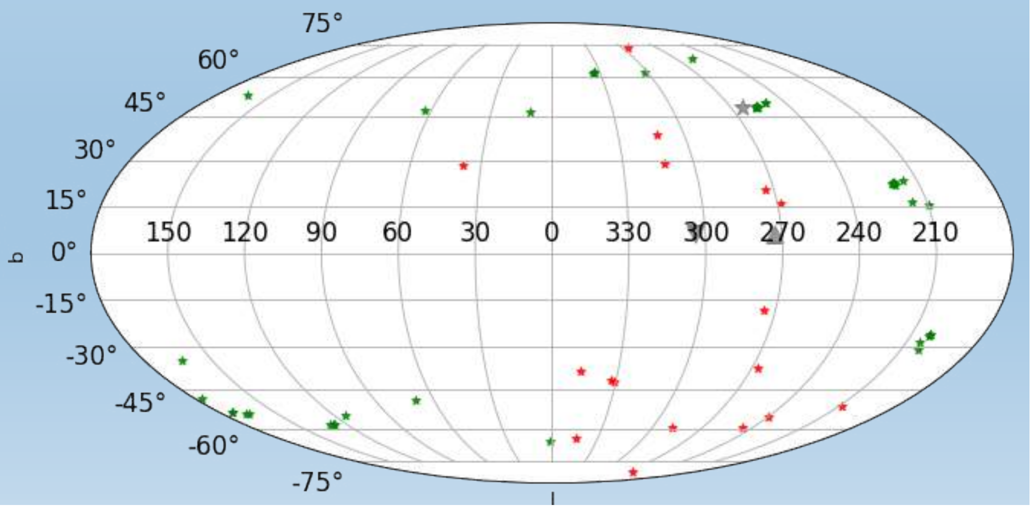
Colin, Mohayaee, Rameez & Sarkar, A&A **631**:L13,2019





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



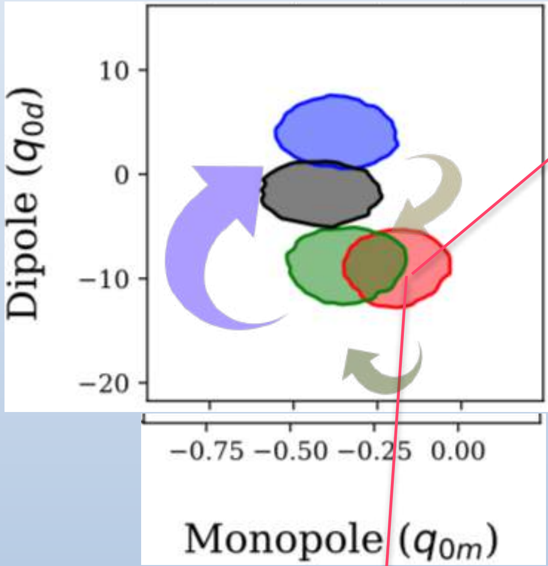


Rubin & Heitlauf (ApJ **894**:68,2020) *confirm* our findings (C19), but criticise us:

- For "incorrectly" not allowing redshift-dependence of light-curve parameters
- For "shockingly" using heliocentric redshifts

… then they make (questionable) peculiar velocity 'corrections' to get their final result

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: $-0.422^{+0.115}_{-0.116}$

Correction: x_1 & c are z-dependent

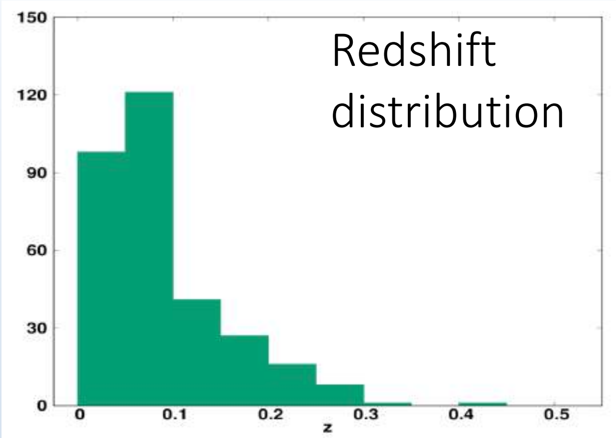
+ Correction: $z_{hel} \rightarrow z_{CMB}$

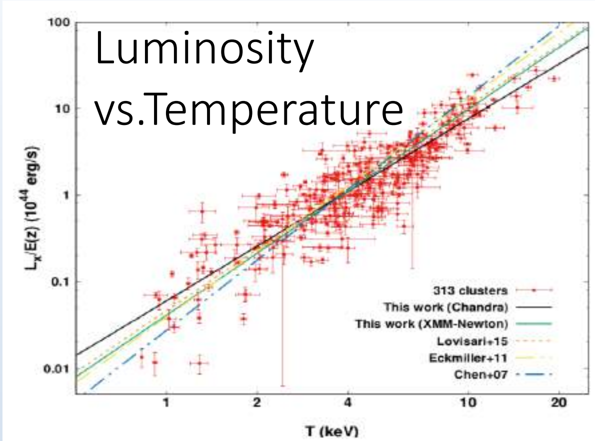
+ Correction: SNe peculiar velocities

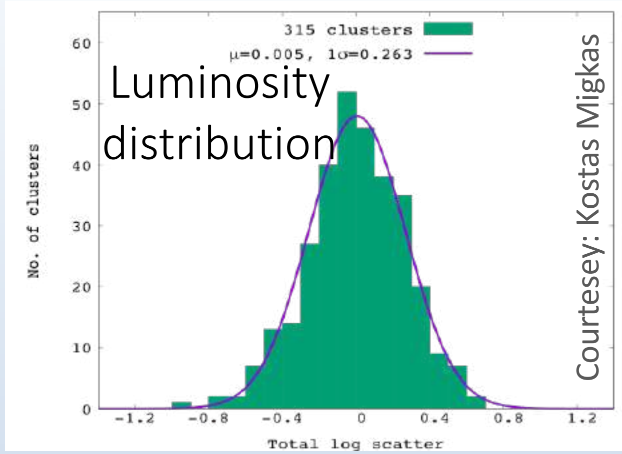
This vividly illustrates how many "corrections" need to be made to extract evidence for isotropic acceleration q_{0m}, when the data in fact indicate *anisotropic* acceleration q_{0d}!

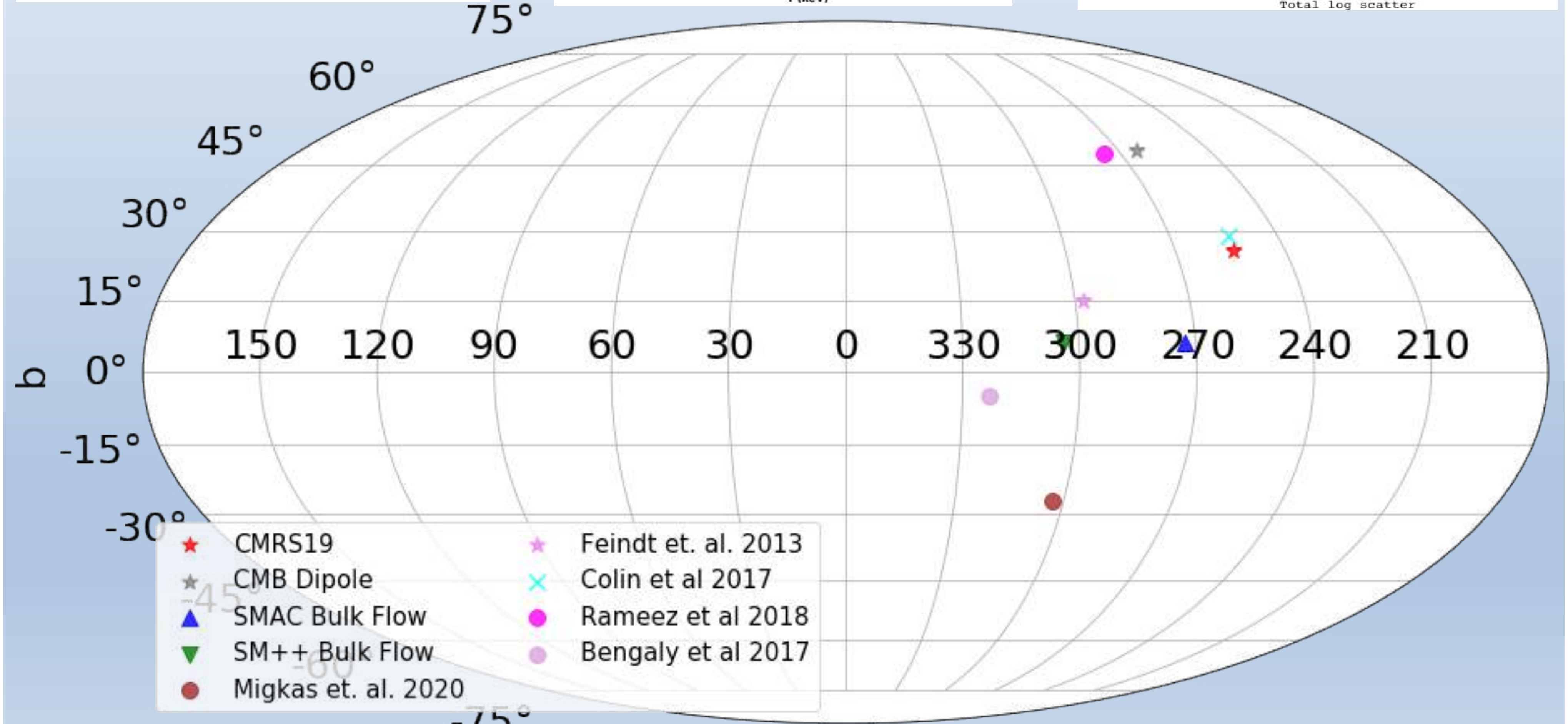
Most importantly, is the CMB frame the 'correct' frame? (Colin *et al*, arXiv:1912:04257)

ANISOTROPY (DUE TO BULK FLOW?) IN A SAMPLE OF 313 X-RAY CLUSTERS









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

Mon. Not. R. astr. Soc. (1984) **206**, 377–381

On the expected anisotropy of radio source counts

G. F. R. Ellis* and J. E. Baldwin† *Orthodox Academy of Crete, Kolymbari, Crete*

Received 1983 May 31; in original form 1983 March 31

Summary. If the standard interpretation of the dipole anisotropy in the microwave background radiation as being due to our peculiar velocity in a homogeneous isotropic universe is correct, then radio-source number counts must show a similar anisotropy. Conversely, determination of a dipole anisotropy in those counts determines our velocity relative to their rest frame; this velocity must agree with that determined from the microwave background radiation anisotropy. Present limits show reasonable agreement between these velocities.

4 Conclusion

Anisotropies in radio-source number counts can be used to determine a cosmological standard of rest. Current observations determine it to about $\pm 500\,\mathrm{km\,s^{-1}}$, but accurate counts of fainter sources will reduce the error to a level comparable to that set by observations of the microwave background radiation. If the standards of rest determined by the MBR and the number counts were to be in serious disagreement, one would have to abandon either

(a) the idea that the radio sources are at cosmological distances, or

(b) the interpretation of the cosmic microwave radiation as relic radiation from the big bang, or

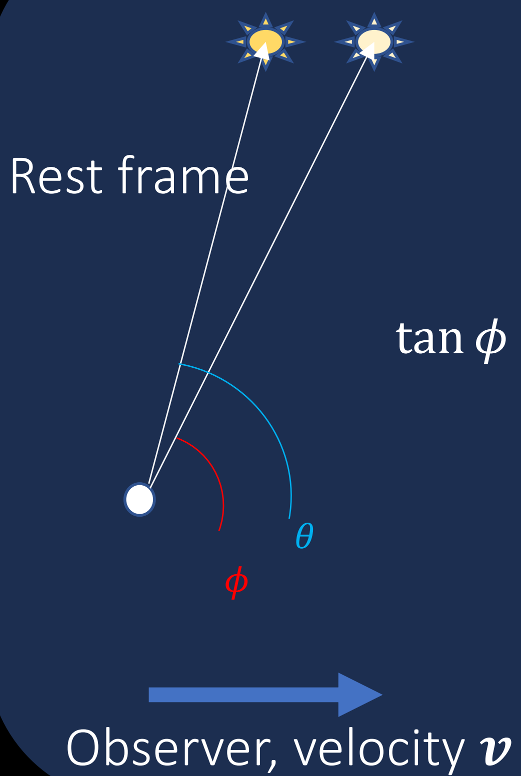
(c) the standard FRW Universe models.

Thus comparison of these standards of rest provides a powerful consistency test of our understanding of the Universe.

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

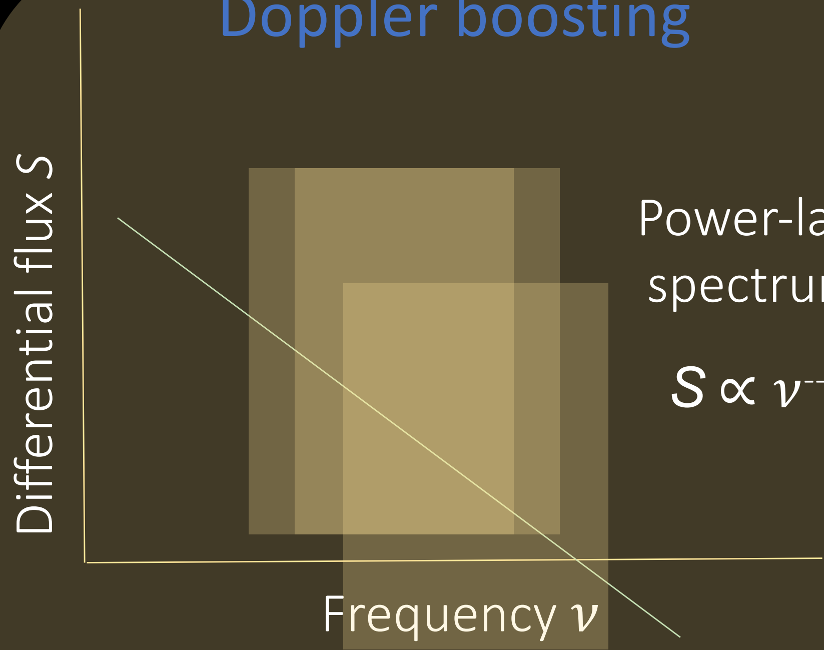


Moving frame

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

+

Doppler boosting



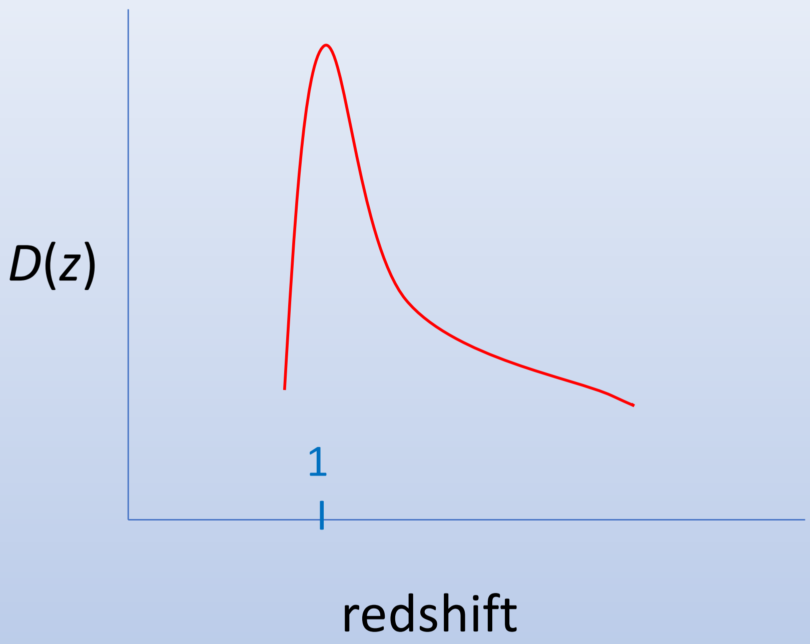
Power-law spectrum

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

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

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

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 'clustering dipole' ⇒ the actual anisotropy in the distribution of sources in the cosmic rest frame (significant for shallow surveys)

Radio sources: NVSS + SUMSS, 0.6 million sources $z \sim 1$, $\vec{\mathcal{S}} \rightarrow 0$
Colin, Mohayaee, Rameez & S.S., MNRAS **471**:1045,2017

Wide Field Infrared Survey Explorer, 1.2 million galaxies, $z \sim 0.14$, $\vec{\mathcal{S}}$ significant
Rameez, Mohayaee, S.S. & Colin, MNRAS **477**:1722,2018

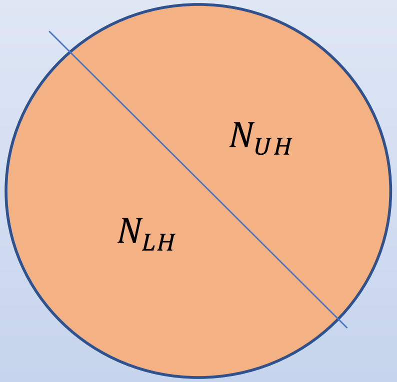
Wide Field Infrared Survey Explorer, 1.4 million quasars, $z \sim 1$, $\vec{\mathcal{S}} \lesssim 1\%$
Secrest, Rameez, von Hausegger, Mohayaee, S.S. & Colin, arXiv:2009.14826

Estimators for the Dipole

Rubart & Schwarz, A&A 555:A117,2013

Linear

$$\vec{D}_H = \hat{z} * \frac{N_{UH} - N_{LH}}{N_{UH} + N_{LH}}$$



Vary the direction of the hemispheres until maximum asymmetry is observed

High bias, statistical error $\sim 1/\sqrt{N}$

Quadratic

$$\vec{D}_C = \frac{1}{N}\sum_{i=1}^{N} \hat{r}_i$$

Add up unit vectors corresponding to directions in the sky for every source

Unbiased, Statistical error $1/\sqrt{N}$

$$\vec{D}_H = \frac{\hat{z}}{N}\int_{\phi=0}^{\phi=2\pi}\int_{\theta=0}^{\theta=\pi} \sigma(\theta)\frac{|\cos\theta|}{\cos\theta}\sin\theta \mathrm{d}\theta \mathrm{d}\phi$$

$$\vec{D}_C = \frac{\hat{z}}{N}\int_{\phi=0}^{\phi=2\pi}\int_{\theta=0}^{\theta=\pi} \sigma(\theta)\cos\theta\sin\theta \mathrm{d}\theta \mathrm{d}\phi$$

NEW: Unbiased least-squares estimator

$$\sum_p \left[n_p - \left(A_0 + \sum_{j=1}^{3} A_{1j} d_{j,p} \right) \right]^2$$

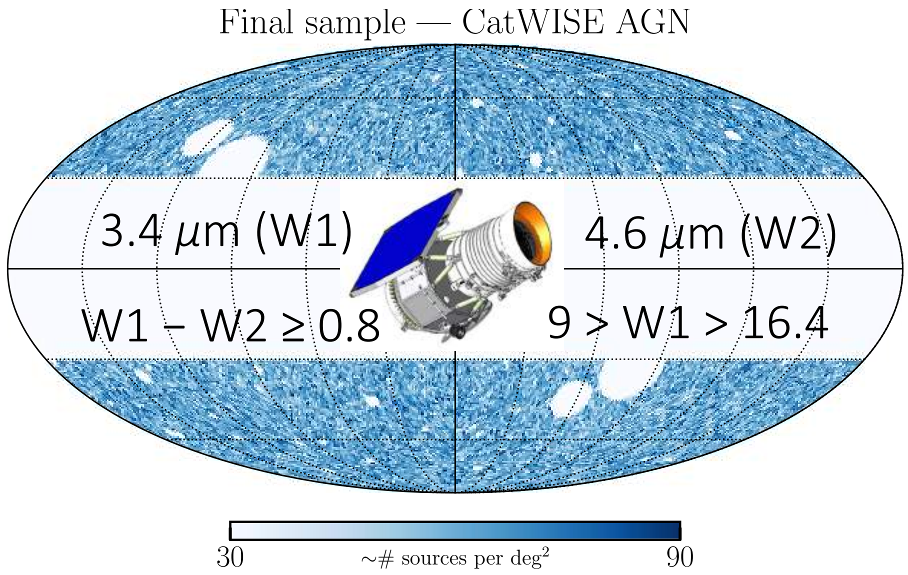
$$\vec{D} = (A_{1,p}/A_0, A_{2,p}/A_0, A_{3,p}/A_0)$$

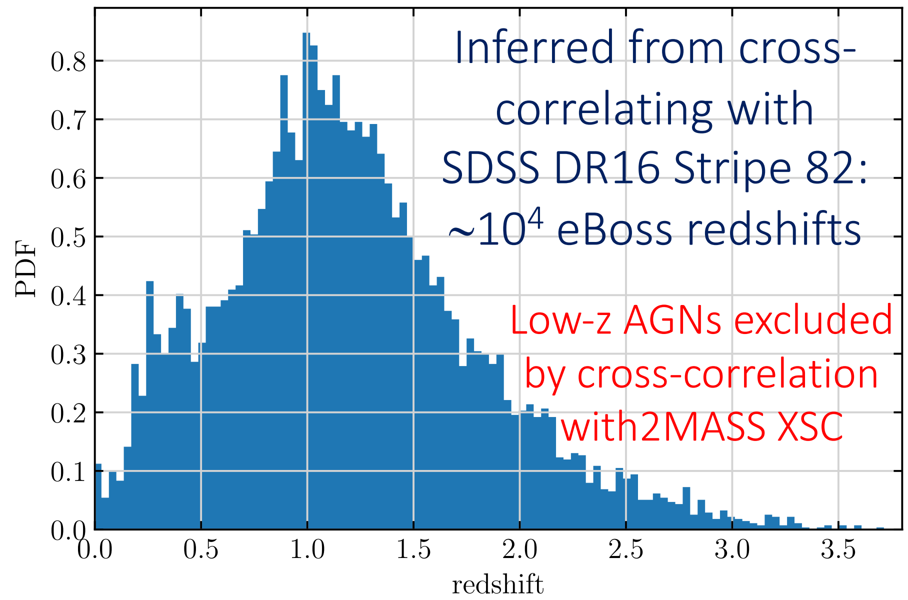
Secrest *et al*, arXiv:2009.14826

where n_p denotes the number density of sources in sky pixel p, A_0 is the mean density (monopole), A_{1j} are the amplitudes of the three orthogonal dipole templates $d_{j,p}$, and the sum is to be taken over all unmasked pixels

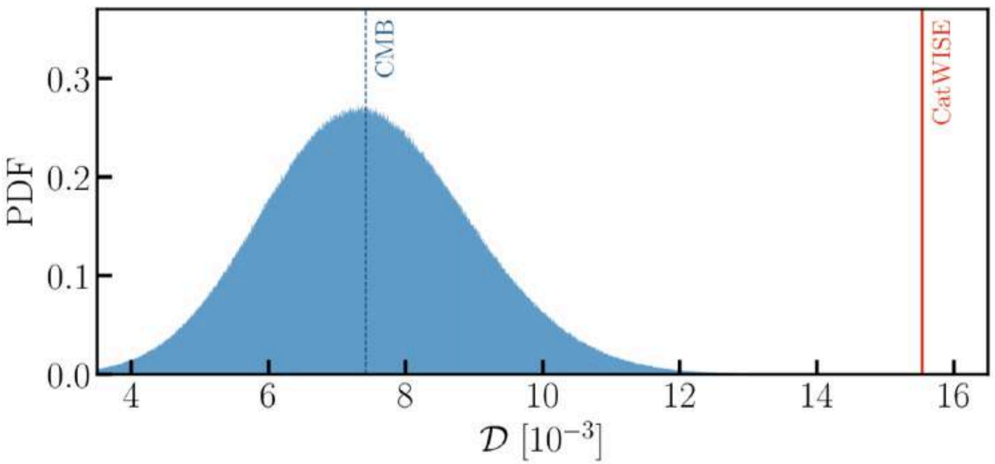
Our Peculiar velocity wrt quasars ≠ peculiar velocity wrt the CMB

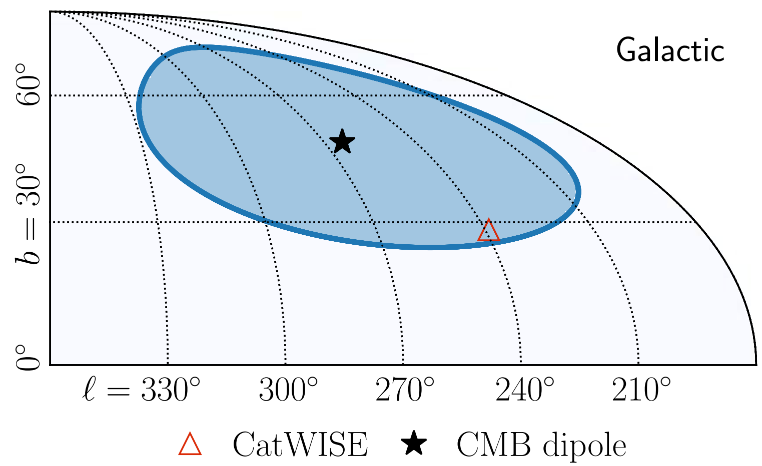
Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, ApJL in press, [2009.14826]





We now have a catalogue of ~1.36 million quasars, with 99% at redshift > 0.1





The kinematic interpretation of the CMB dipole is *rejected* with $p = 5 \times 10^{-7} \Rightarrow 4.9\sigma$

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

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

(Reconsider the 'cosmological fitting problem' (Ellis & Stoeger 1987) … use of heliocentric vs. CMB frame ⇒ different choices of corresponding 2-spheres in the 'null fitting' procedure)

The 'standard' assumptions of isotropy and homogeneity are questionable …

and it is *not* established that the universe is dominated by 'dark energy'