Testing the Cosmological Principle

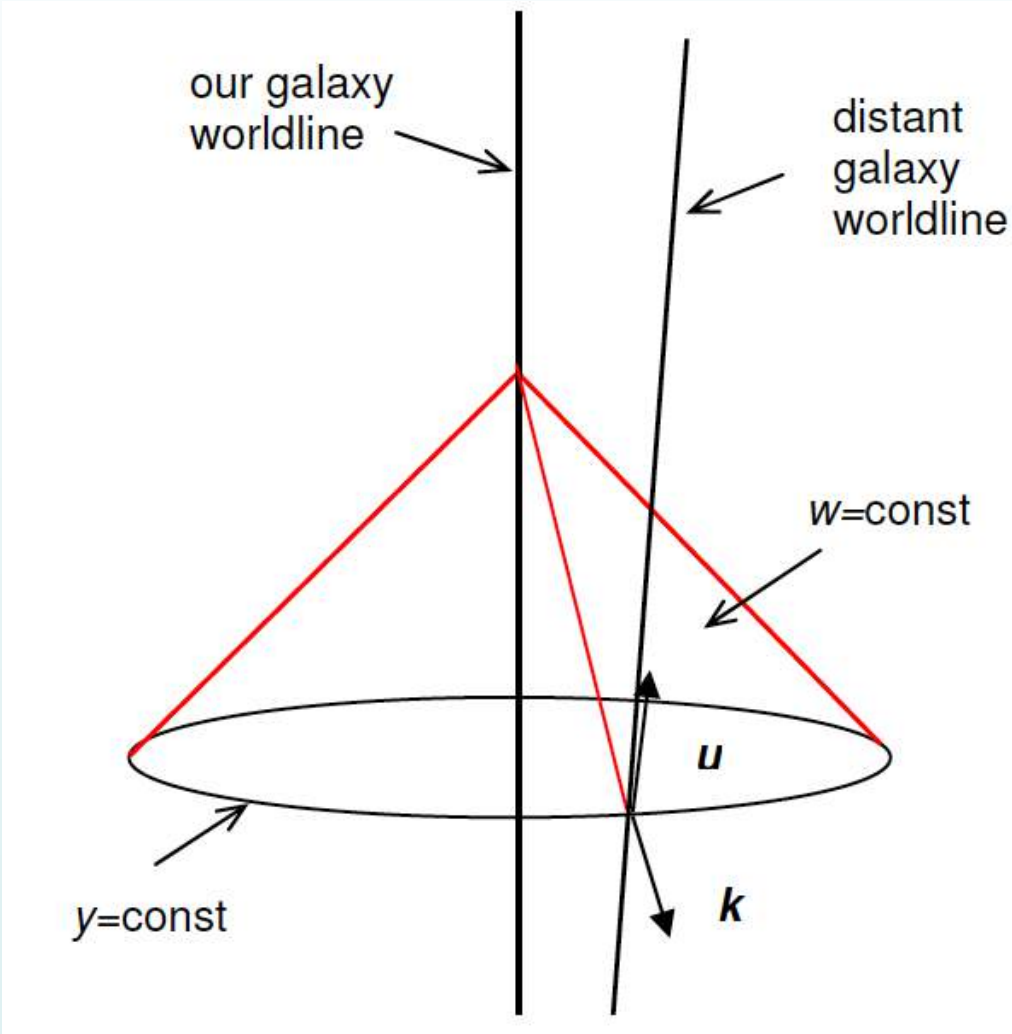
Subir Sarkar

None of us can understand why there is a Universe at all, why anything should exist; that's the ultimate question. But while we cannot answer this question, we can at least make progress with the next simpler one of what the Universe as a whole is like.

Dennis Sciama (1978)

Newton 1665 Seminar, 23 October 2019

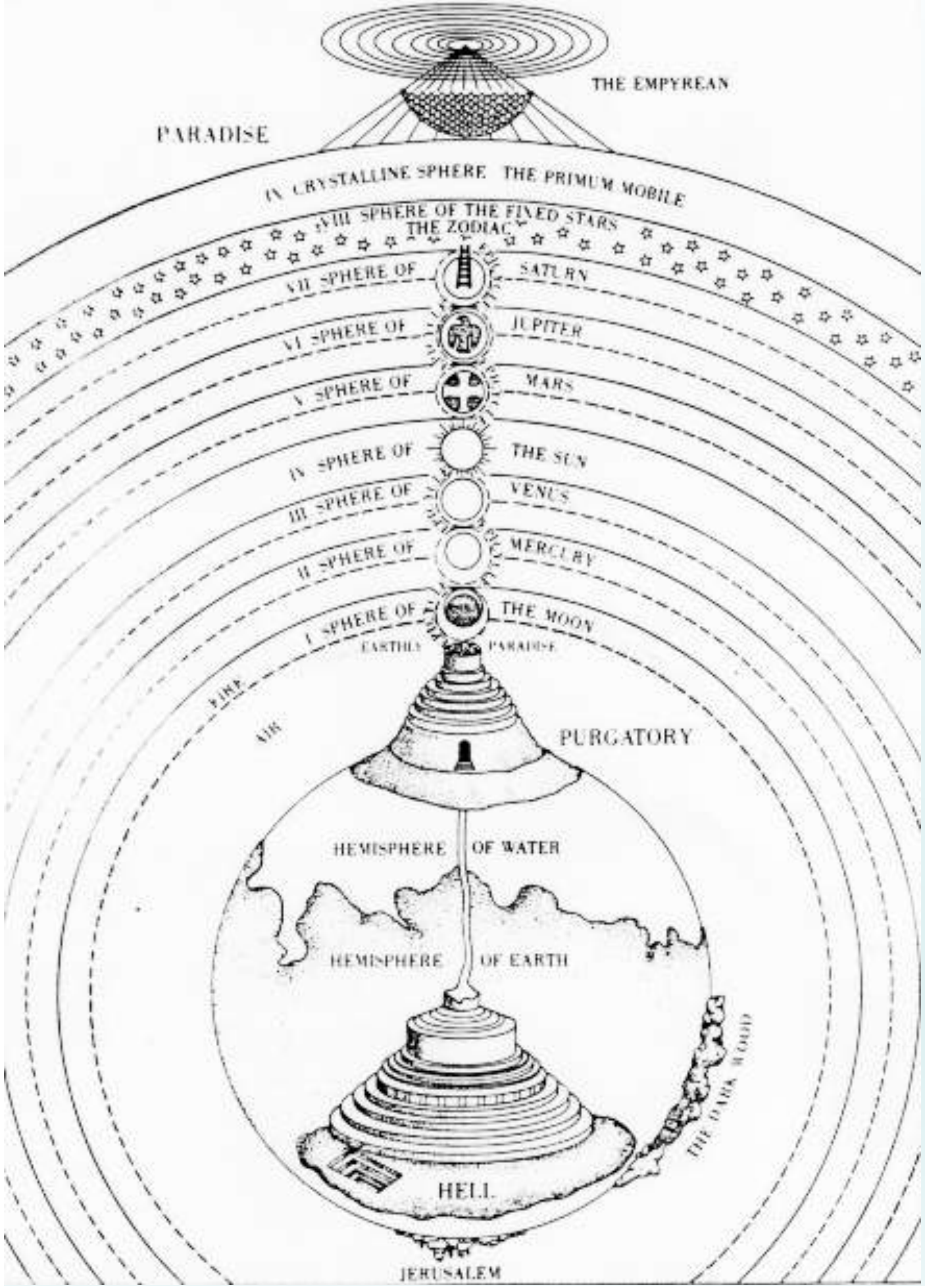
ALL WE CAN *EVER* LEARN ABOUT THE UNIVERSE IS CONTAINED WITHIN OUR PAST LIGHT CONE



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

The standard cosmology (in Europe)

~350 BC ⇨ ~1600 AD



The Divine Comedy, Dante Alighieri (1321)

Prescient discovery of the CMB

E' si distende in circular figura,
in tanto che la sua circunferenza
sarebbe al sol troppo larga cintura.

The shape which that light takes as it expands is circular, and its circumference would be too great a girdle for the sun.

O isplendor di Dio, per cu' io vidi
l'alto triunfo del regno verace,
dammi virtù a dir com'io il vidi!

O radiance of God, through which I saw the noble triumph of the true realm, give to me the power to speak of what I saw!

…

Standard cosmological model

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

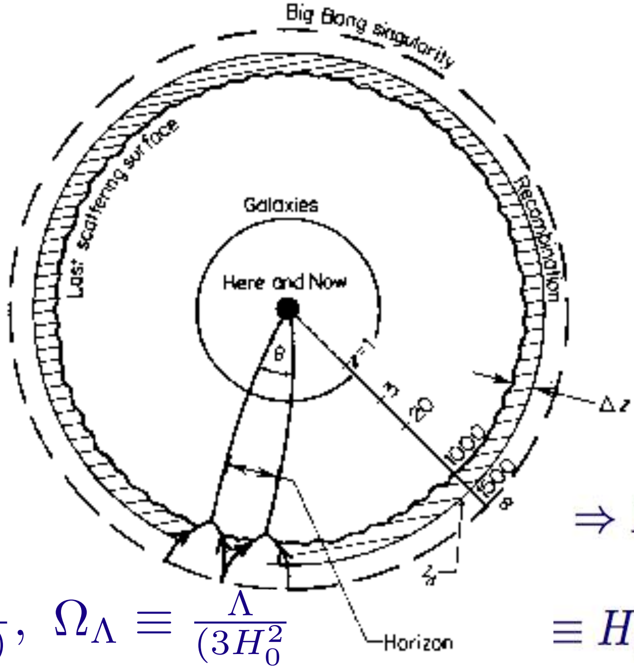
⇒ Maximally-symmetric space-time + **ideal fluid** energy-momentum tensor

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

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

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

Robertson-Walker
Friedmann-Lemaître



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

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

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

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

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

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

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

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

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

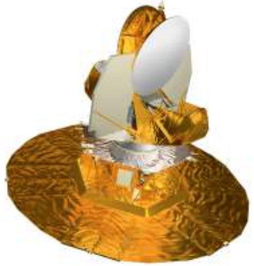
We observe: $0.8\Omega_m - 0.6\Omega_\Lambda \approx -0.2$ (**Supernovae**), $\Omega_k \approx 0.0$ (**CMB**), $\Omega_m \sim 0.3$ (**Clusters**)

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

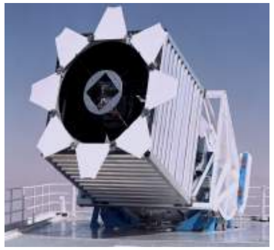
The scale of $\mathbf{\Lambda}$ is set by the *only* dimensionful parameter in the model: $H_0 \sim 10^{-42}$ GeV

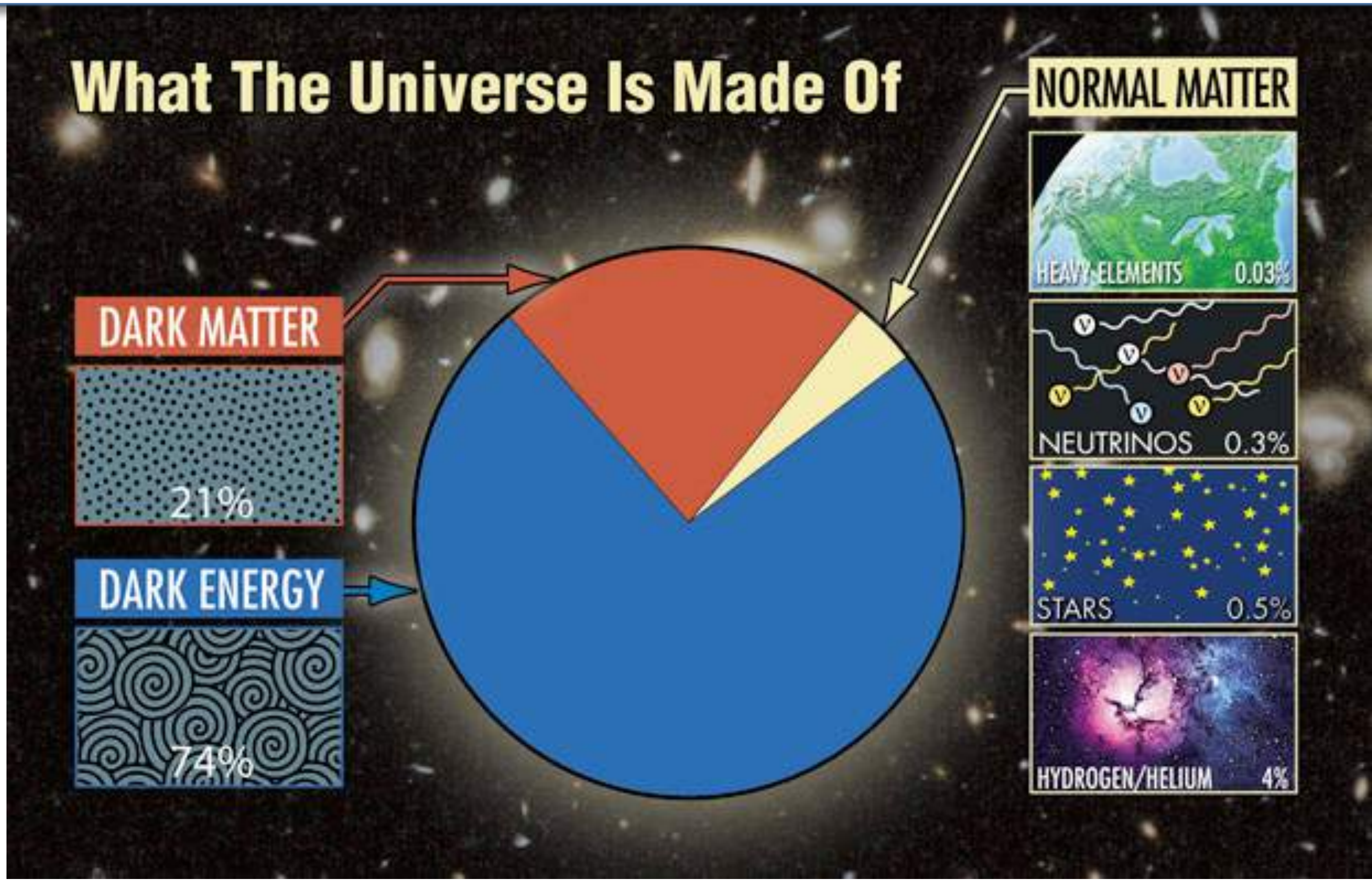
To drive **accelerated** expansion requires the pressure to be **negative** ($P < -\rho/3$) so this is *interpreted* as *vacuum* energy at the scale $(\rho_\Lambda)^{1/4} = (H_0^2/8\pi G_N)^{1/4} \sim 10^{-12}$ GeV << $G_F^{-1/2} \sim 10^2$ GeV

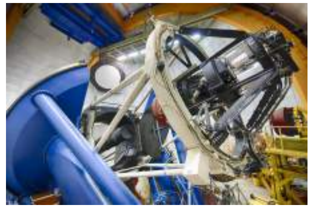
This makes *no* physical sense … but is nevertheless the 'standard model of cosmology'

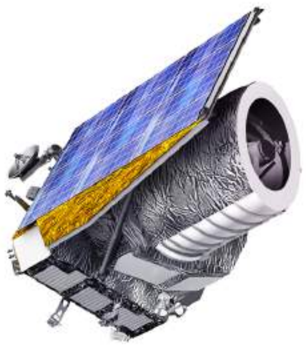


Since 1998 (Riess *et al.*[1], Perlmutter *et al.*[2]), surveys of cosmologically distant Type Ia supernovae (SNe Ia) have indicated an acceleration of the expansion of the Universe, distant SNe Ia being dimmer that expected in a decelerating Universe. With the assumption that the Universe can be described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

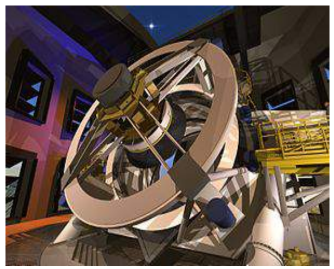








There has been substantial investment in major satellites and telescopes to *measure the parameters* of the 'standard cosmological model' with increasing 'precision'… but surprisingly little work on ***testing its foundational assumptions***

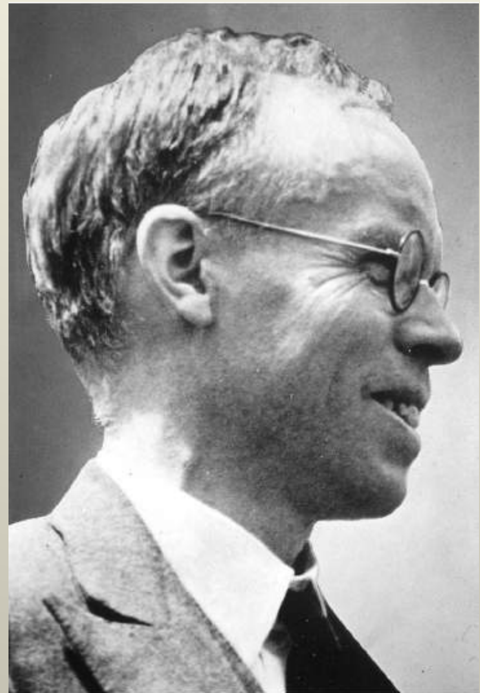


Kinematics, Dynamics, and the Scale of Time

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

(*Received* 28 *August*, 1936)

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



Edward Arthur Milne (1896-1950)

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

Mathematical Proceedings of the Cambridge Philosophical Society 51 (1955) 678 *The Cosmological Principle*, By D. E. Littlewood

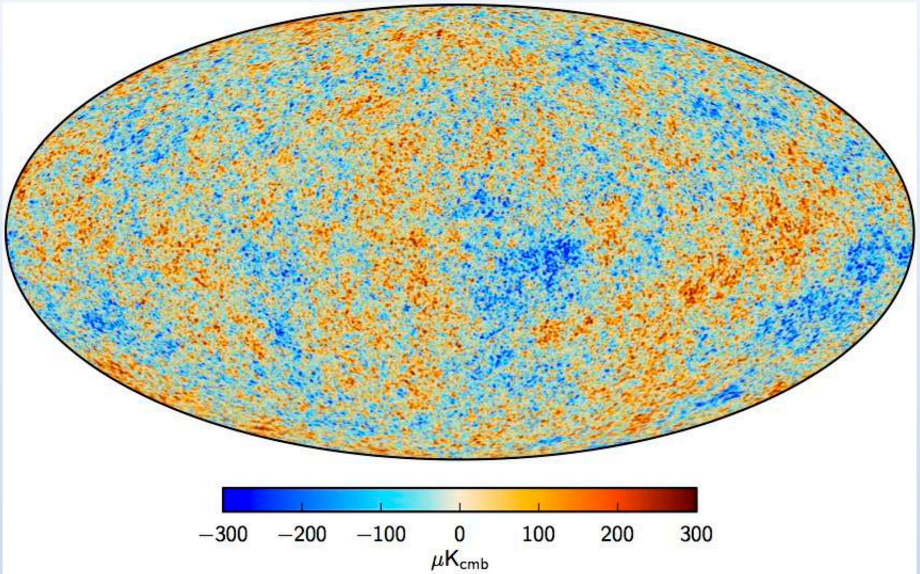
Many models of the universe have been proposed, by de Sitter, Milne, Bondi and Gold, Hoyle and others. The observed data being insufficient, the models are usually based on some simple hypothesis. The simplest is the cosmological principle, namely, that apart from local irregularities the universe presents the same general aspect at every point. Milne (5) has used a restricted form of the principle, namely, that the aspect is independent of spatial position but is dependent on the observed time from some fixed epoch in the past. Bondi and Gold (1) have proposed the 'perfect cosmological principle' that the aspect is completely independent of space and time.

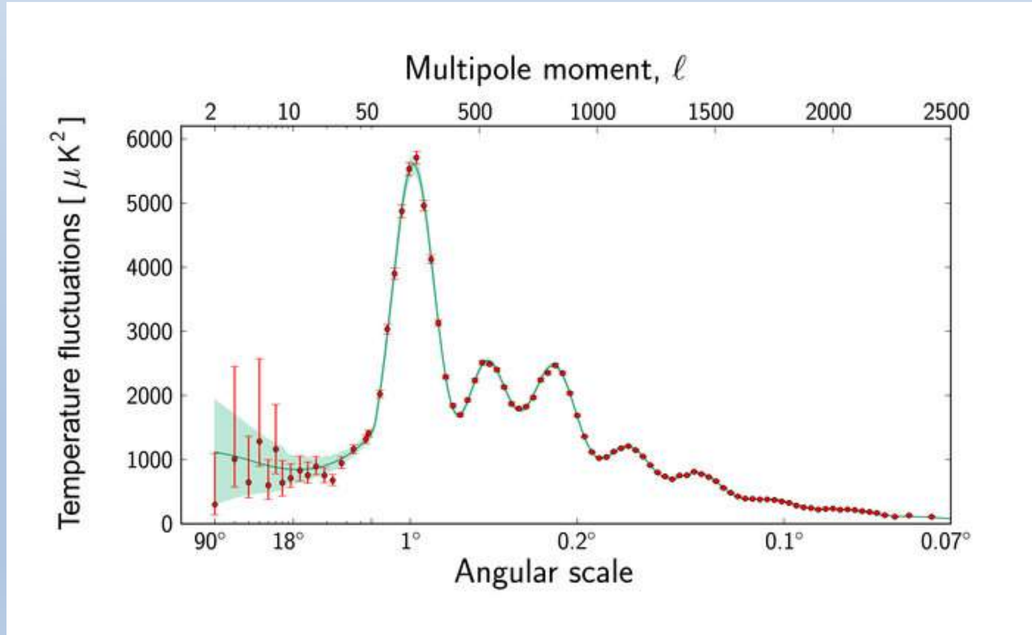
THE 'PERFECT' VERSION WAS ABANDONED FOLLOWING THE DISCOVERY OF THE CMB IN 1964 ... BUT THE COSMOLOGICAL PRINCIPLE LIVED ON

The real reason, though, for our adherence here to the Cosmological Principle is not that it is surely correct, but rather, that it allows us to make use of the extremely limited data provided to cosmology by observational astronomy. If we make any weaker assumptions, as in the anisotropic or hierarchical models, then the metric would contain so many undetermined functions (whether or not we use the field equations) that the data would be hopelessly inadequate to determine the metric. On the other hand, by adopting the rather restrictive mathematical framework described in this chapter, we have a real chance of confronting theory with observation. If the data will not fit into this framework, we shall be able to conclude that either the Cosmological Principle or the Principle of Equivalence is wrong. Nothing could be more interesting.

Steven Weinberg, *Gravitation and Cosmology* (1972)

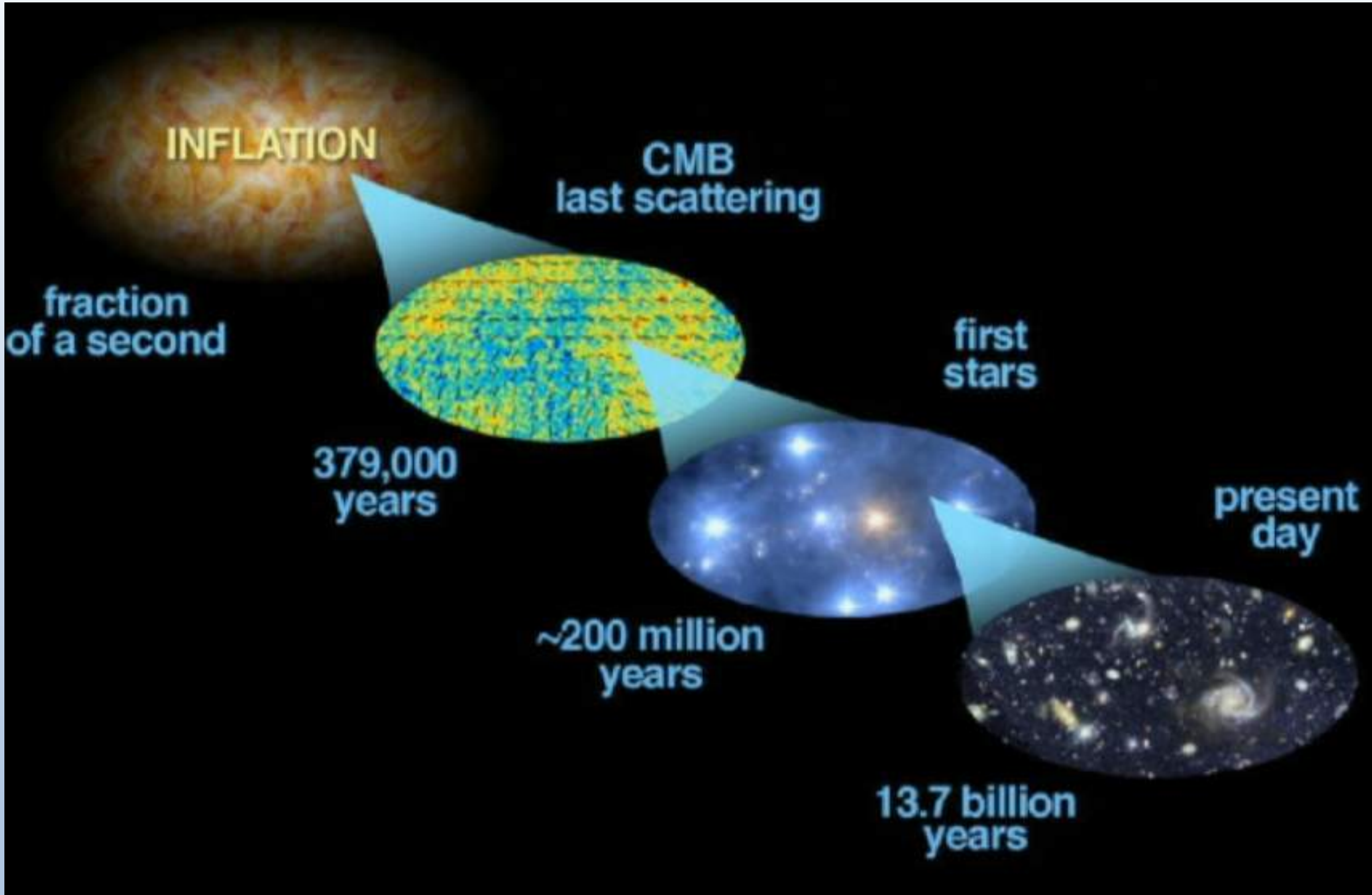
"Data from the Planck satellite show the universe to be highly isotropic" (Wikipedia)





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

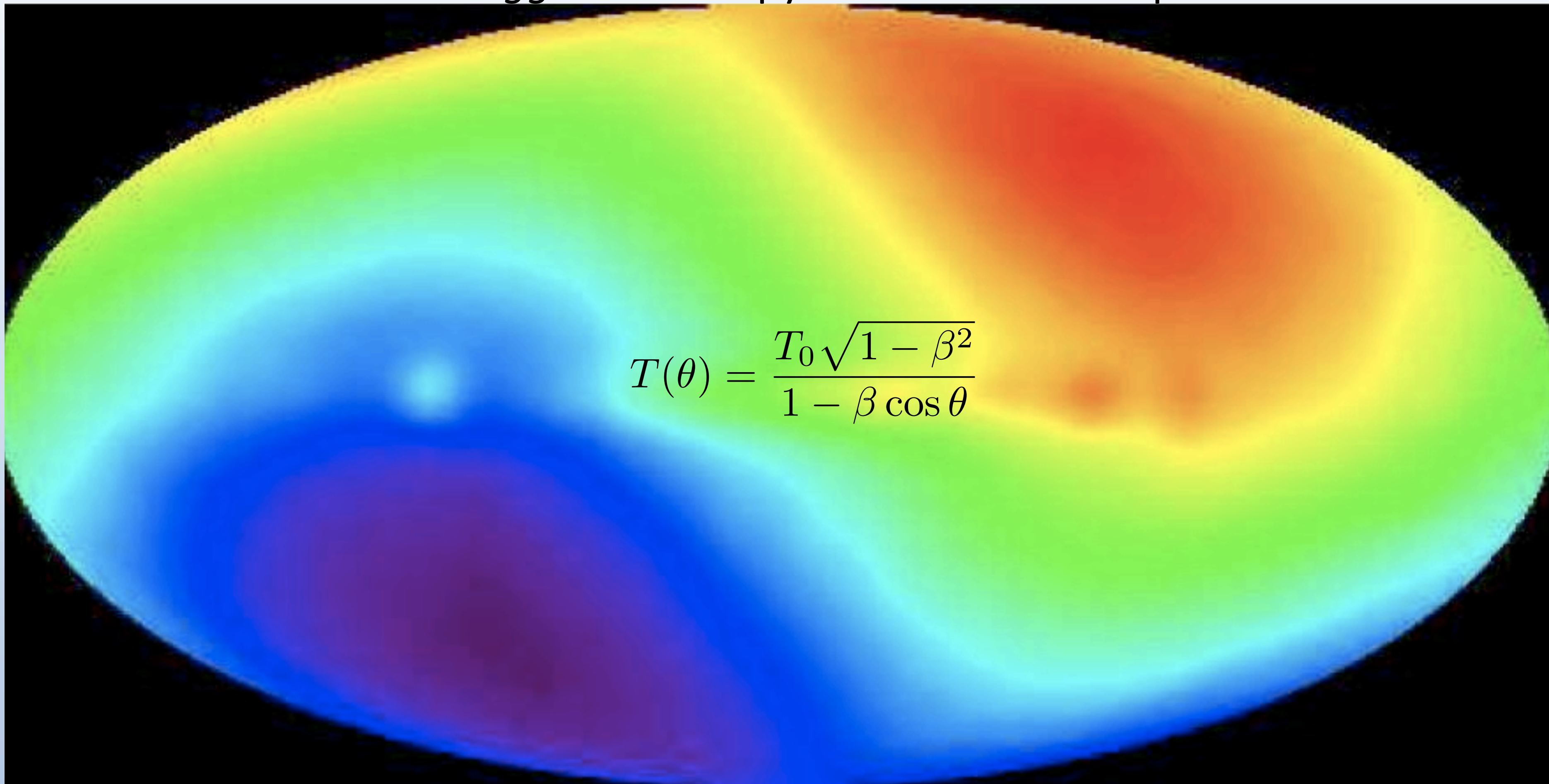
Standard model of structure formation



The ~10^{-5} **CMB temperature fluctuations** are understood as due to **scalar density perturbations** with an ~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 $\Delta T/T \sim 10^{-3}$



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)

VOLUME 18, NUMBER 24 PHYSICAL REVIEW LETTERS 12 JUNE 1967

PECULIAR VELOCITY OF THE SUN AND THE COSMIC MICROWAVE BACKGROUND

D. W. Sciama*†
Columbia University, New York, New York, and New York University, New York, New York
(Received 17 April 1967)

The sun's peculiar velocity with respect to distant galaxies is roughly estimated from the red-shift data for nearby galaxies to be ~400 km/sec toward $l_{\mathrm{II}} \sim 335°$, $b_{\mathrm{II}} \sim 7°$. Future observations on the angular distribution of the cosmic microwave background should be able to test this estimate, if the background has a cosmological origin. If the test is successful it would imply that a "local" inertial frame is nonrotating with respect to distant matter to an accuracy of 10^{-3} sec of arc per century, which would represent a 5000-fold increase of accuracy.

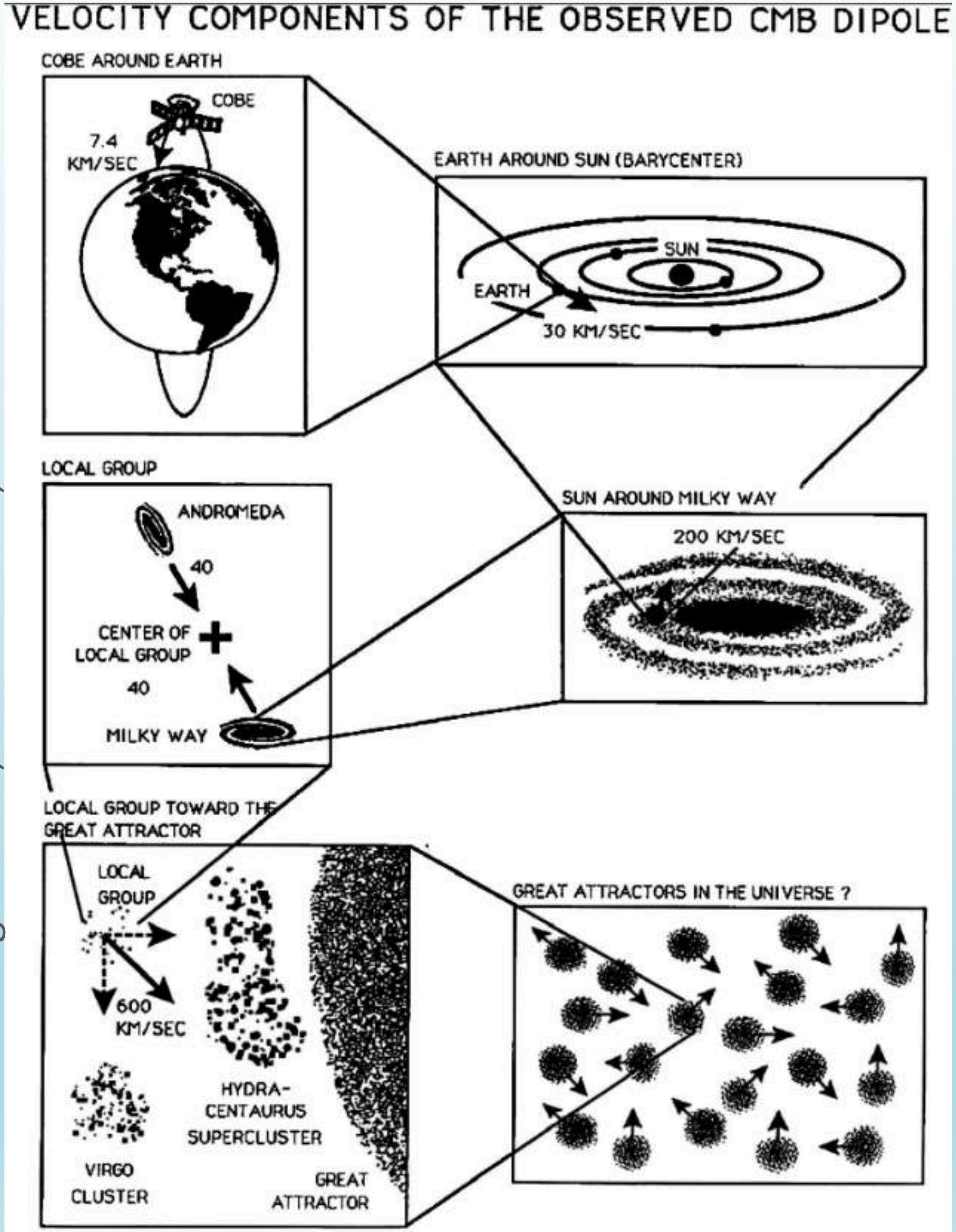
PHYSICAL REVIEW VOLUME 174, NUMBER 5 25 OCTOBER 1968

Comment on the Anisotropy of the Primeval Fireball*

P. J. E. PEEBLES† AND DAVID T. WILKINSON†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey 08540
(Received 17 June 1968)

This note presents an exact theory for the anisotropy of the primeval fireball as a function of our motion through the radiation.

$$\mathcal{T}'(\theta') = \mathcal{T}(1 - v^2/c^2)^{1/2}[1 - (v/c)\cos\theta']^{-1}$$



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 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” - L Motl

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.

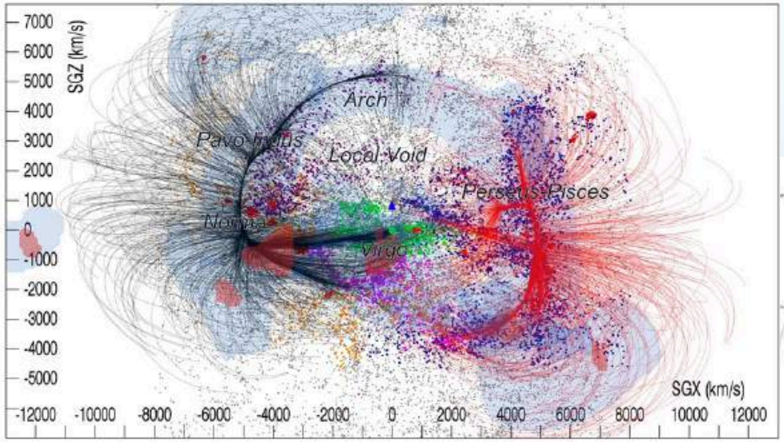
4 Conclusion

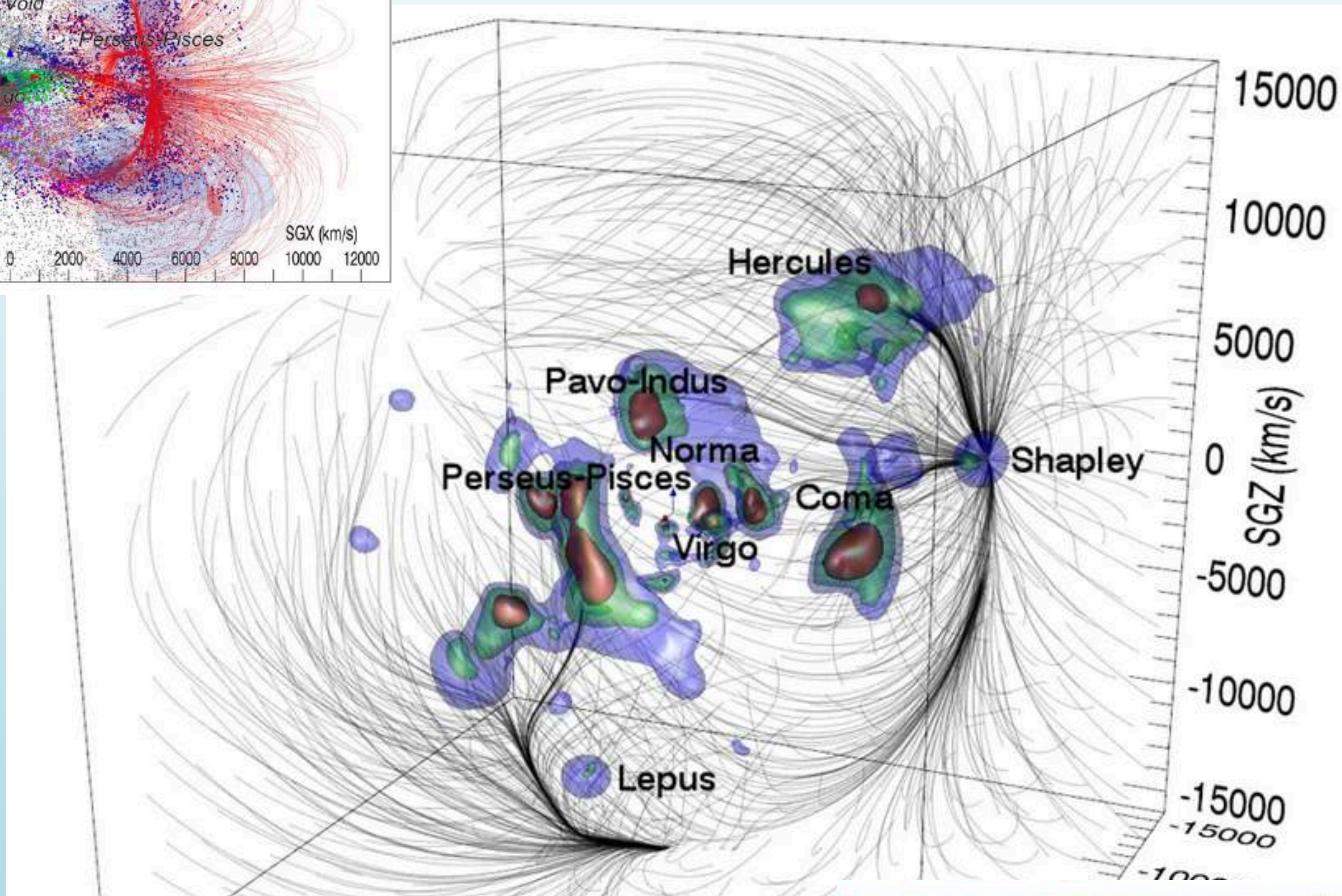
Anisotropies in radio-source number counts can be used to determine a cosmological standard of rest. Current observations determine it to about $\pm 500\ \mathrm{km\ s^{-1}}$, but accurate counts of fainter sources will reduce the error to a level comparable to that set by observations of the microwave 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

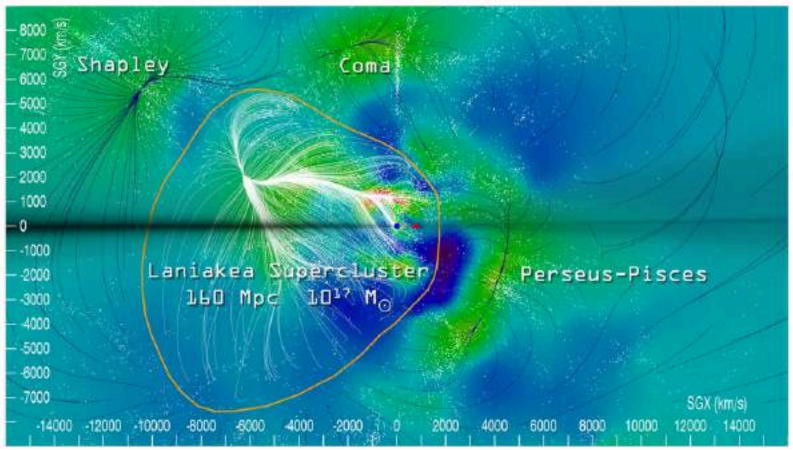
(a) the idea that the radio sources are at cosmological distances, or
(b) the interpretation of the cosmic microwave radiation as relic radiation from the big bang, or
(c) the standard FRW Universe models.

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

Structure within a cube extending ~200 Mpc from our position (at the origin - Supergal. coordinates)







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

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

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

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

Theory of peculiar velocity fields (cont.)

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

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

Window function

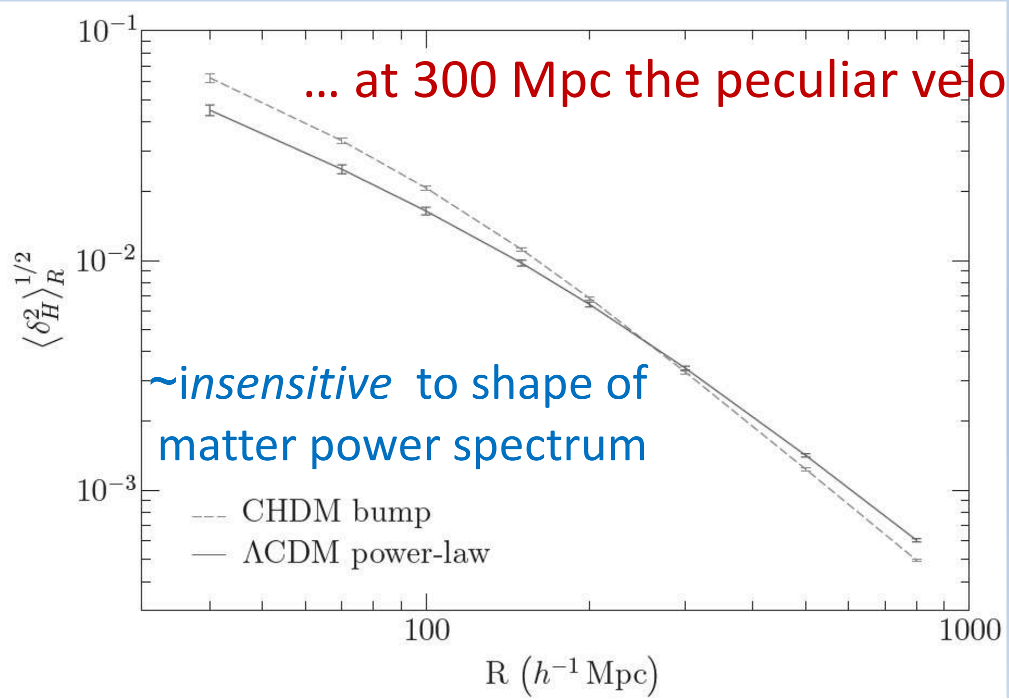
Then the RMS fluctuation in the local Hubble constant $\delta_H \equiv \langle (\delta H/H_0)^2 \rangle^{1/2}$ is:

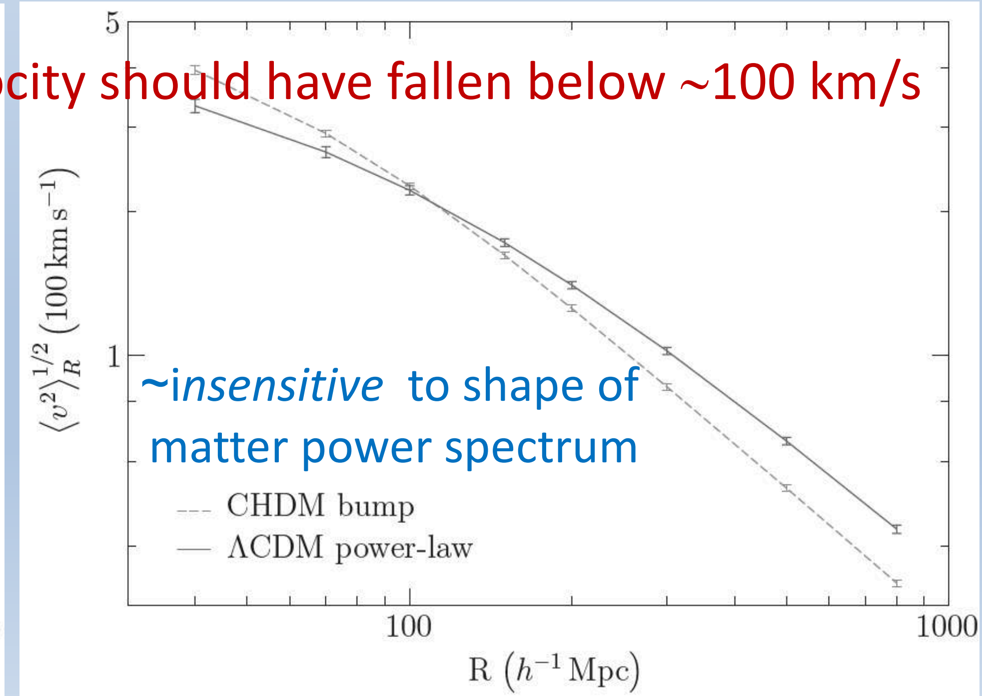
$$\delta_H^2 = \frac{f^2}{2\pi^2} \int_0^\infty k^2 \mathrm{d}k \; P(k) \mathcal{W}^2(kR), \; P(k) \equiv |\delta(k)^2|, \; f \simeq \Omega_{\mathrm{m}}^{4/7} + \frac{\Omega_\Lambda}{70}\left(1 + \frac{\Omega_{\mathrm{m}}}{2}\right)$$

Power spectrum of matter fluctuations — Growth rate

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

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

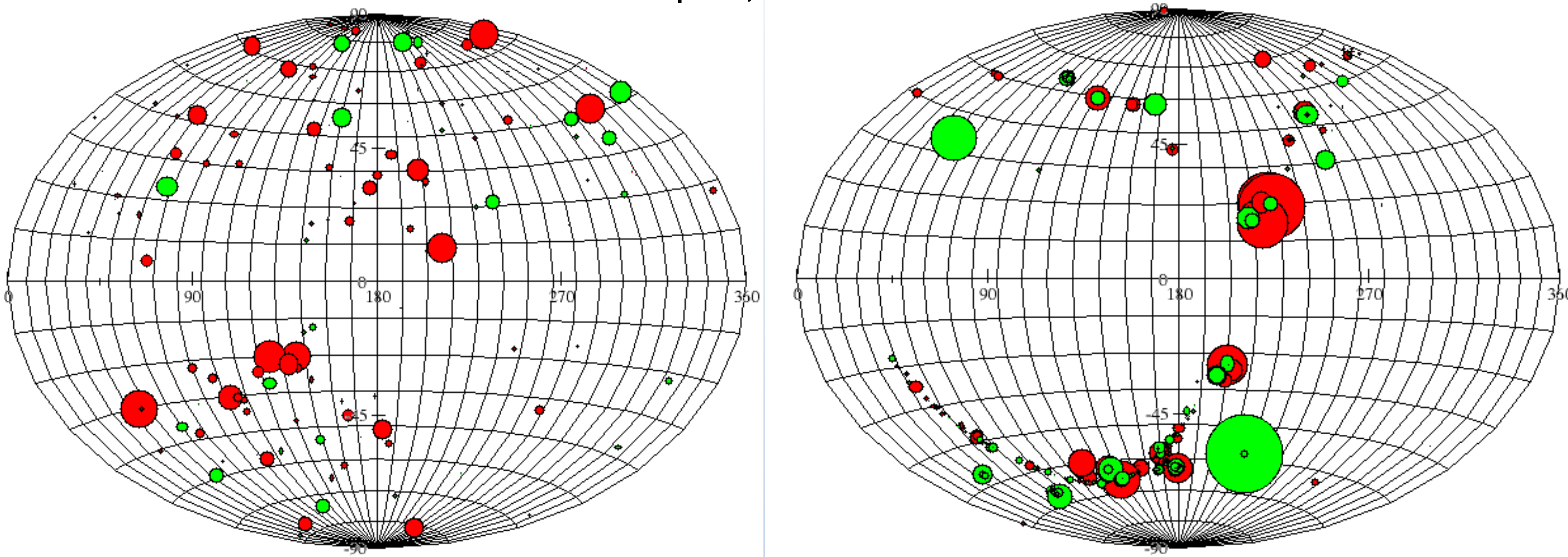




Hunt & S.S., MNRAS **401**:547,2010

Union 2 compilation of 557 SNe Ia

Aitoff-Hammer plot, Galactic coordinates

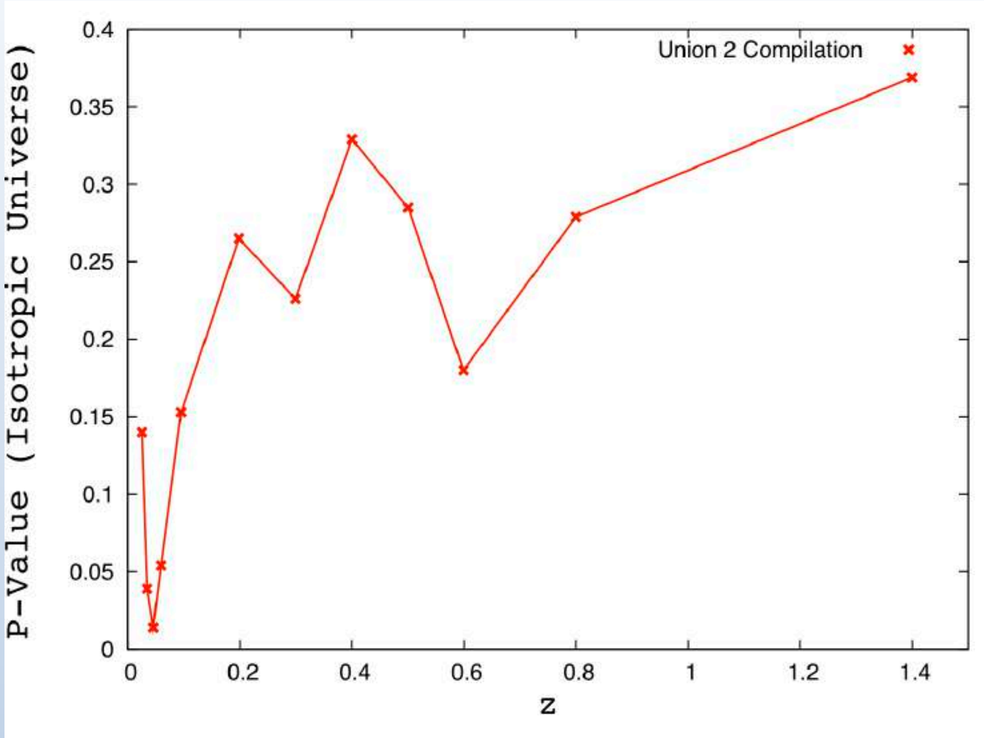


Left panel: The red spots represent the data points for $z < 0.06$ with distance moduli μ_{data} bigger than the values μ_{CDM} predicted by ΛCDM, and the green spots are those with μ_{data} less than μ_{CDM}; the spot size is a relative measure of the discrepancy. A dipole anisotropy is visible around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

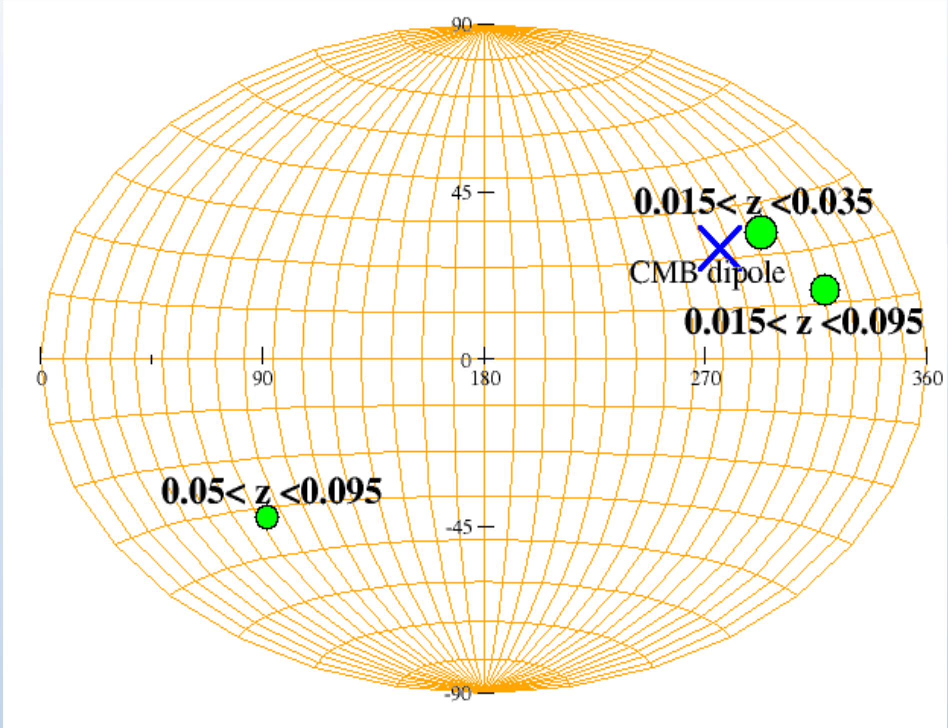
Colin, Mohayaee, S.S. & Shafieloo, MNRAS **414**:264,2011

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

IS THE UNIVERSE ISOTROPIC?



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



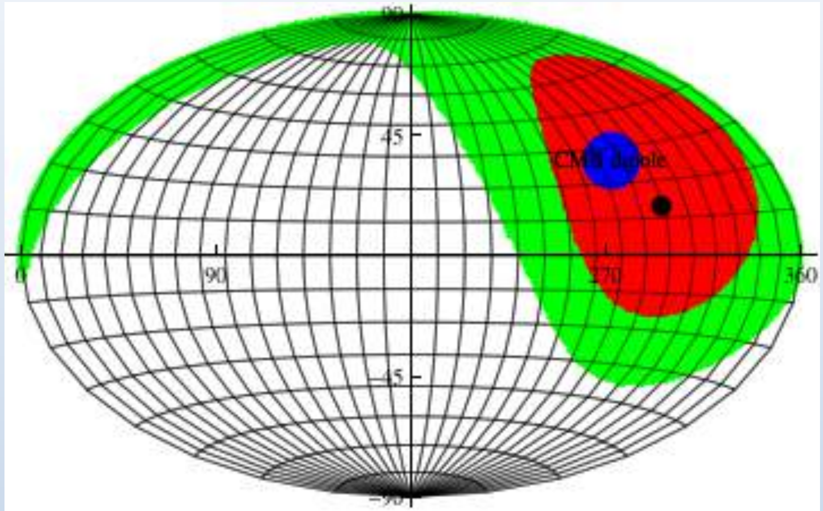
Left panel: P-value for the consistency of the isotropic universe with the data versus redshift. At $z \approx 0.05$ (~200 Mpc) the p-value drops to 0.014 showing that isotropy is *excluded* at ~3σ … i.e. we have *not* converged to the CMB rest frame.

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

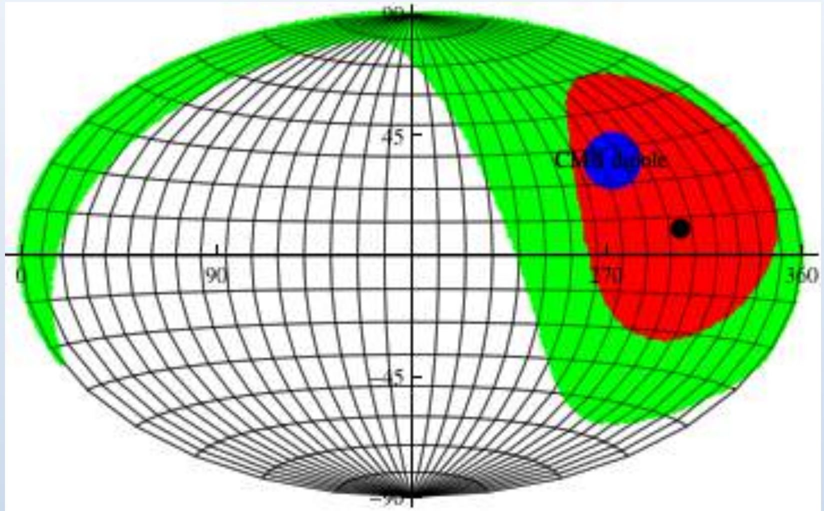
Maximum likelihood analysis can now be used to estimate the bulk flow at low redshifts where the velocities are not yet dominated by the cosmic expansion

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

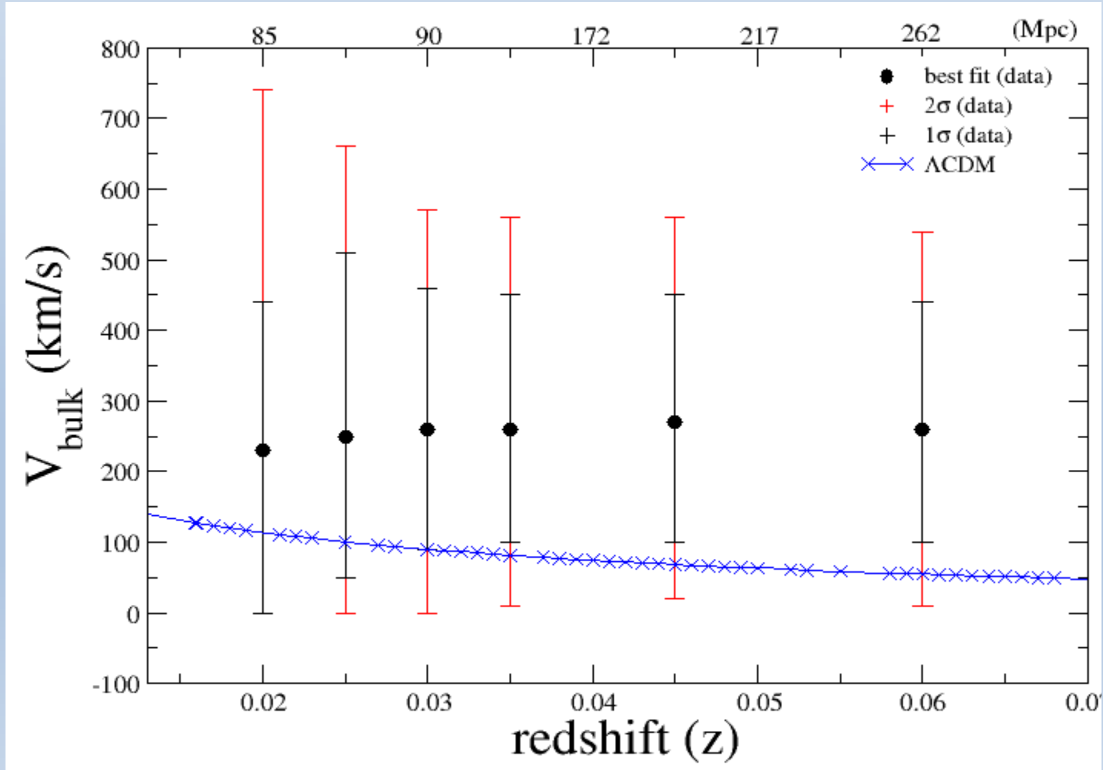
$0.015 < z < 0.045$, $v = 270$ km/s, $l = 291$, $b = 15$



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



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



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

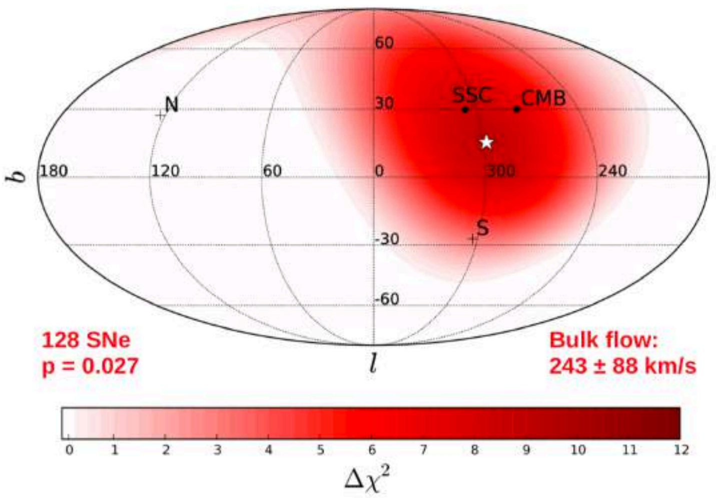
… consistent with Watkins *et al* (2009) who found a bulk flow of 416±78 km/s towards $b = 60 \pm 6^0$, $l = 282 \pm 11^0$ extending up to ~100 h^{-1} Mpc

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

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:

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

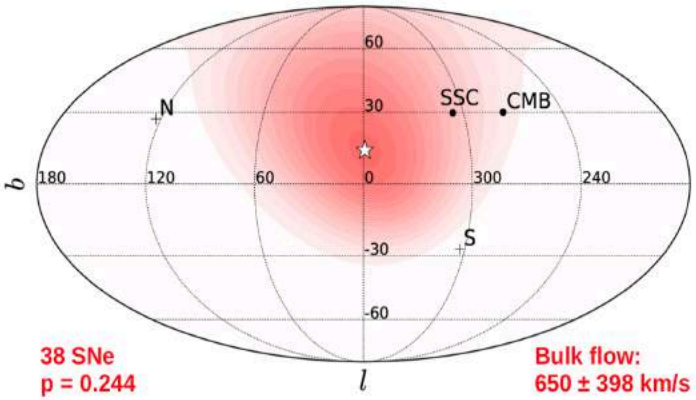
Best fit direction consistent with direction to Shapley

→ Amplitude matches previous studies

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

Nearby Supernova Factory survey

Dipole fit: $0.045 < z < 0.06$



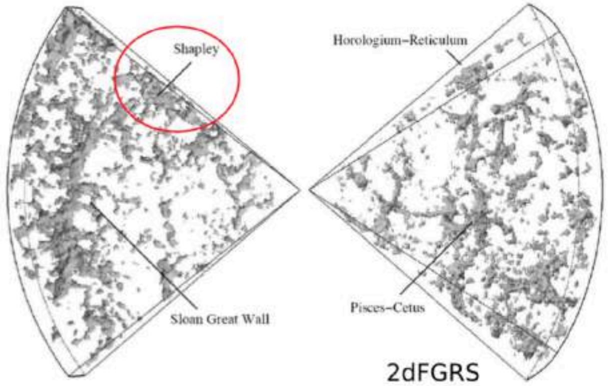
No backside infall behind Shapley

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

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

Finding the Attractors

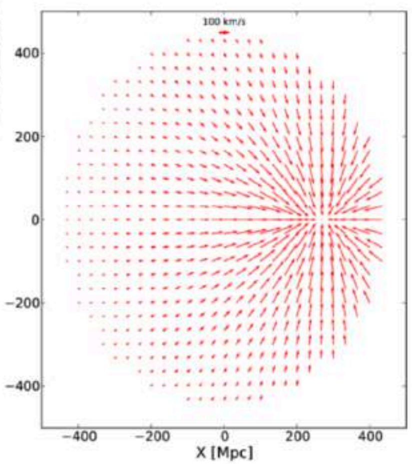
Modeling the velocity field



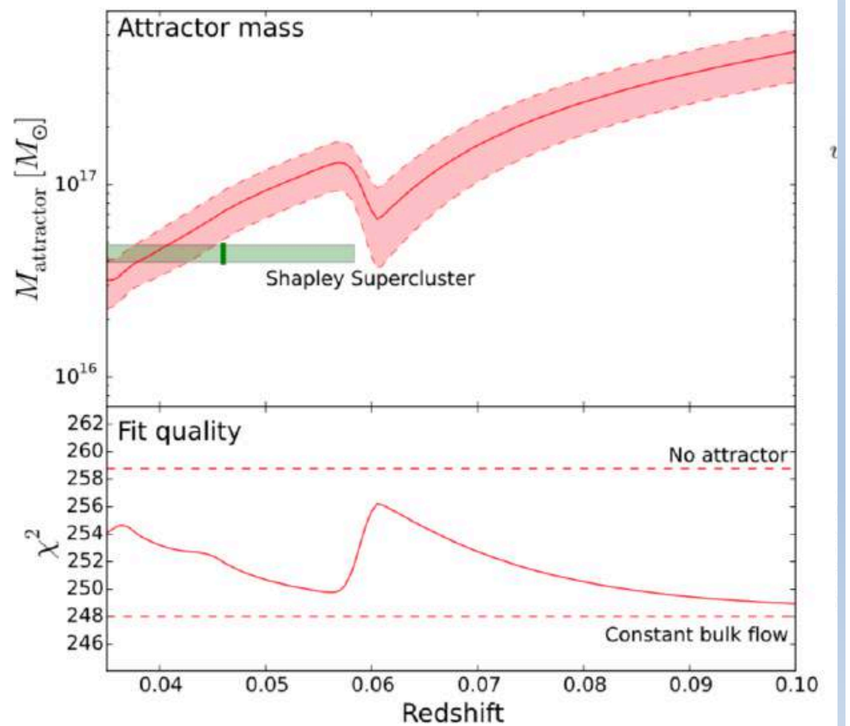
Simplest model:
Infall into spherical mass concentration

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

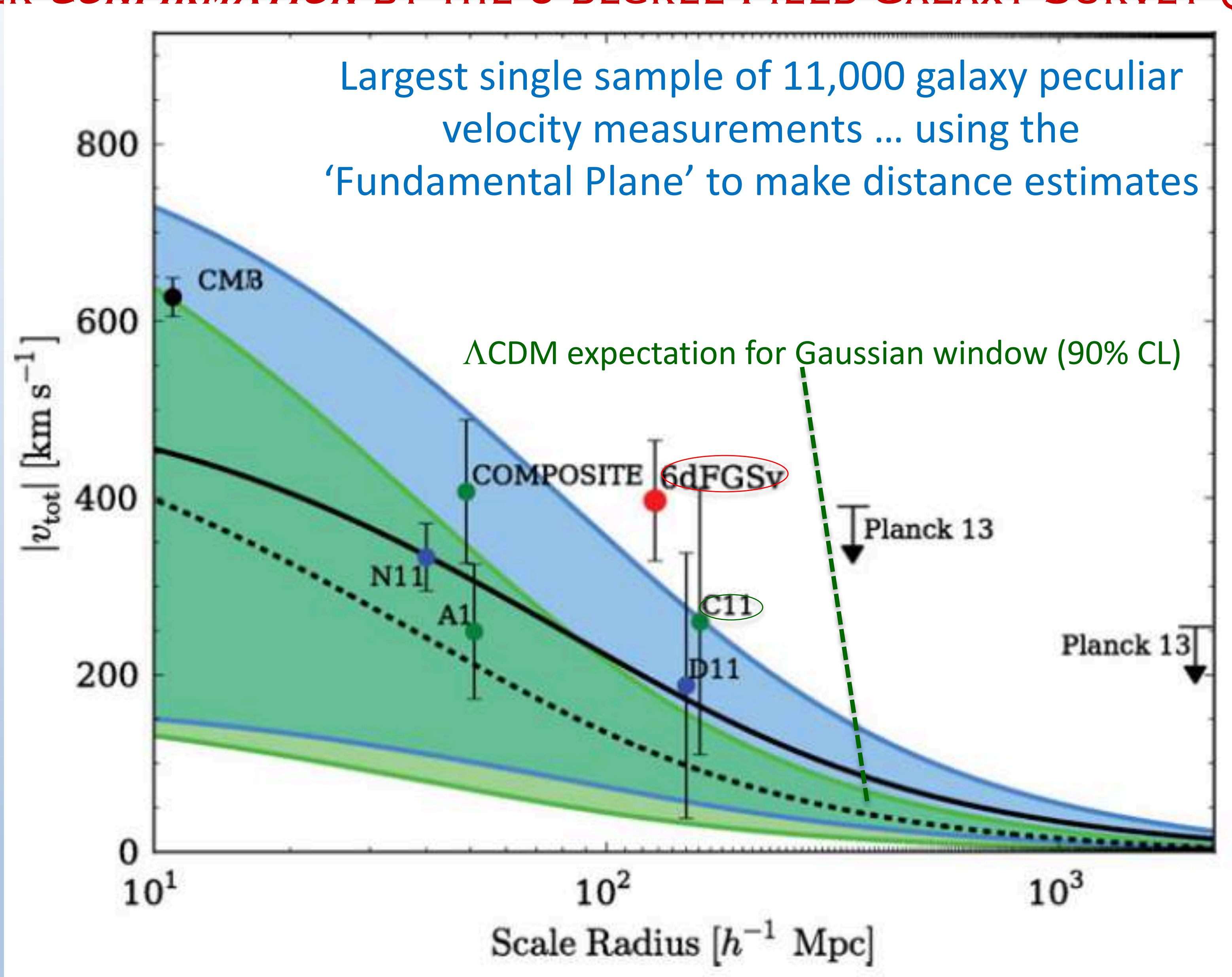
$$v_p(\vec{y}) = \frac{a\Omega_M^{0.55} H}{4\pi} \int \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|^3} \delta(\vec{y}) d^3y$$



Courtesey: Ulrich Feindt



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



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

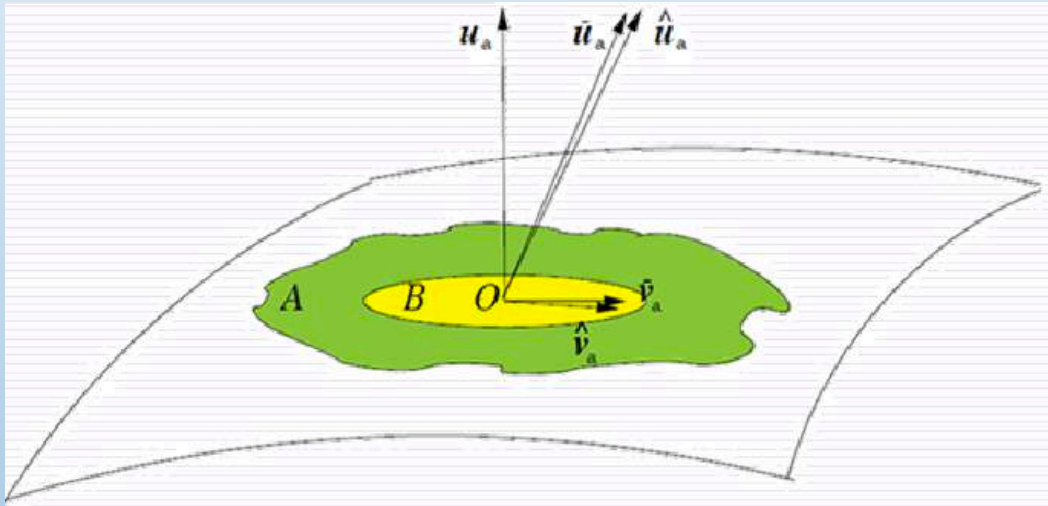
In the 'Dark Sky' ΛCDM simulations, *less than 1%* of Milky Way–like observers experience a bulk flow as large as is observed and extending out as far as is seen …

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

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

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

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



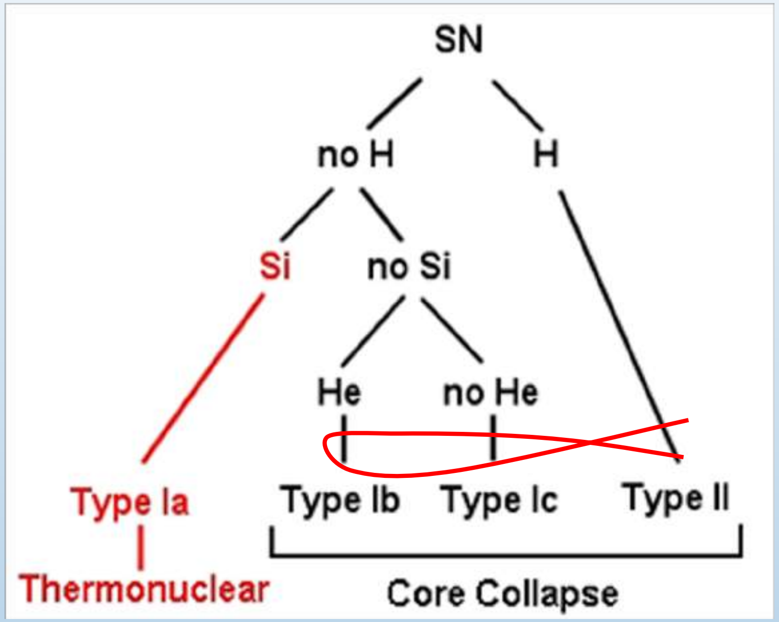
The patch A has mean peculiar velocity $\tilde{v}_a$ with $\vartheta = \tilde{\mathrm{D}}^a v_a \gtrless 0$ and $\dot{\vartheta} \gtrless 0$ (the sign depending on whether the bulk flow is faster or slower than the surroundings)

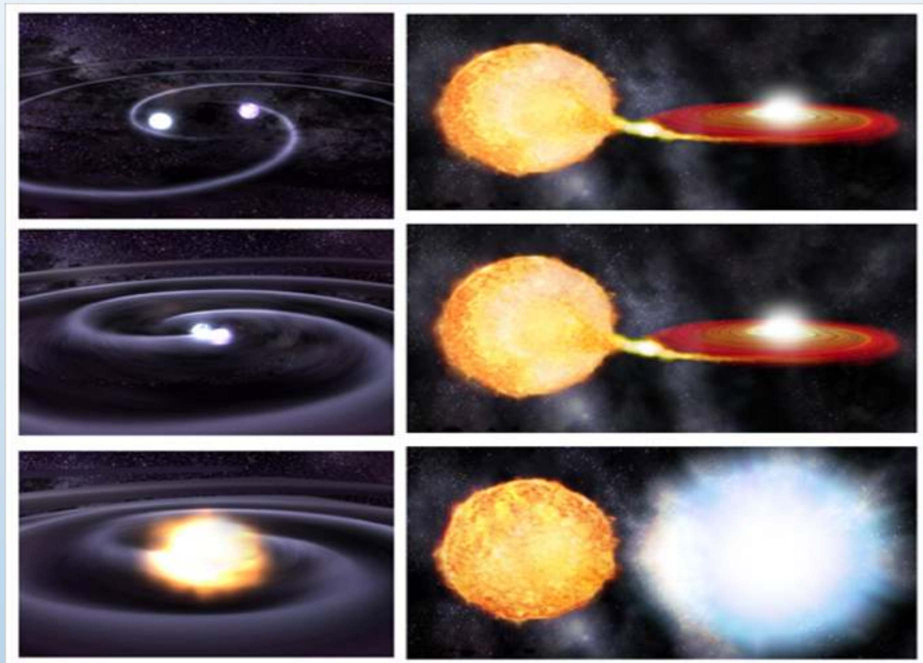
Inside region B, the r.h.s. of the expression

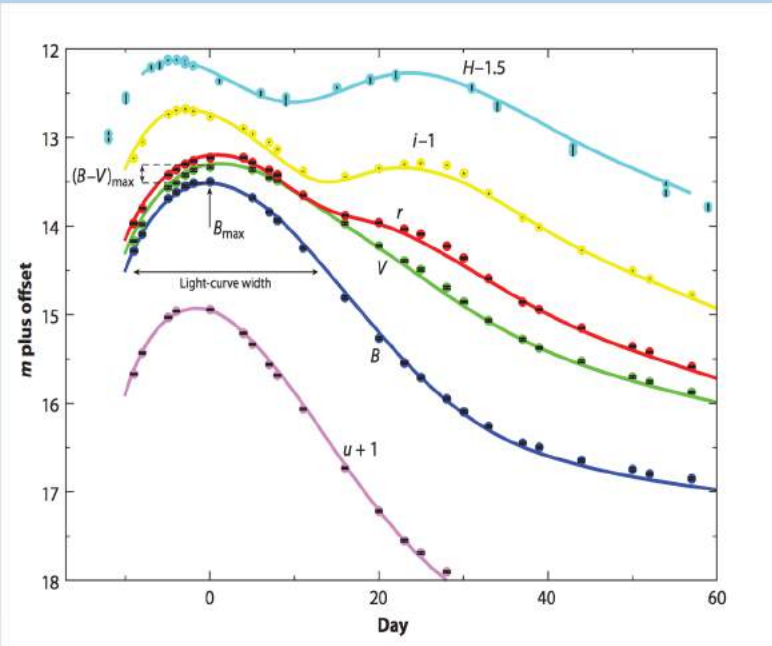
$$1 + \tilde{q} = (1+q)\left(1 + \frac{\vartheta}{\Theta}\right)^{-2} - \frac{3\dot{\vartheta}}{\Theta^2}\left(1 + \frac{\vartheta}{\Theta}\right)^{-2}, \qquad \tilde{\Theta} = \Theta + \vartheta,$$

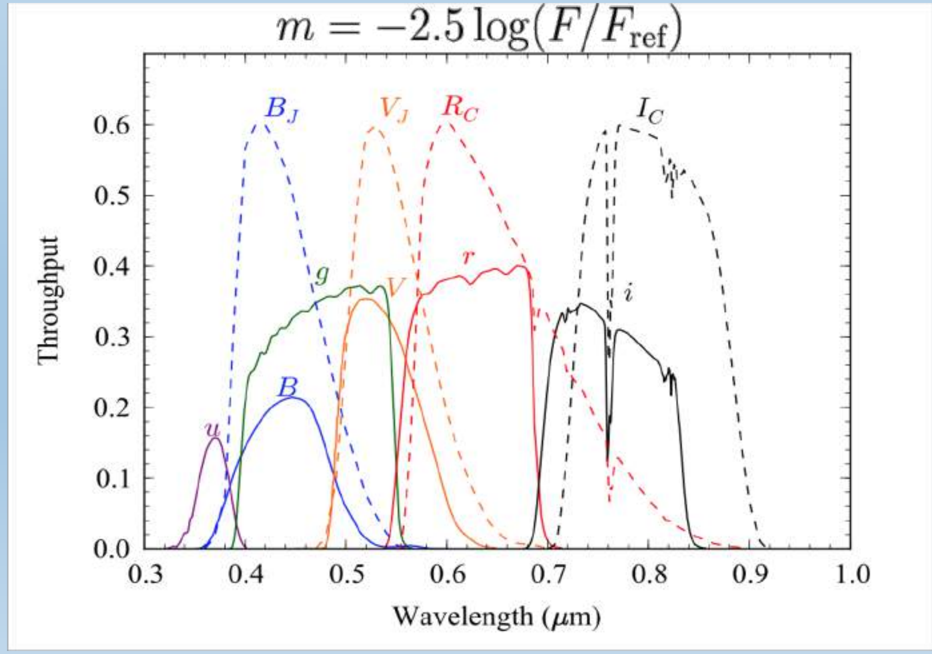
drops below 1 and the comoving observer 'measures' *negative* deceleration parameter

What are Type Ia supernovae?



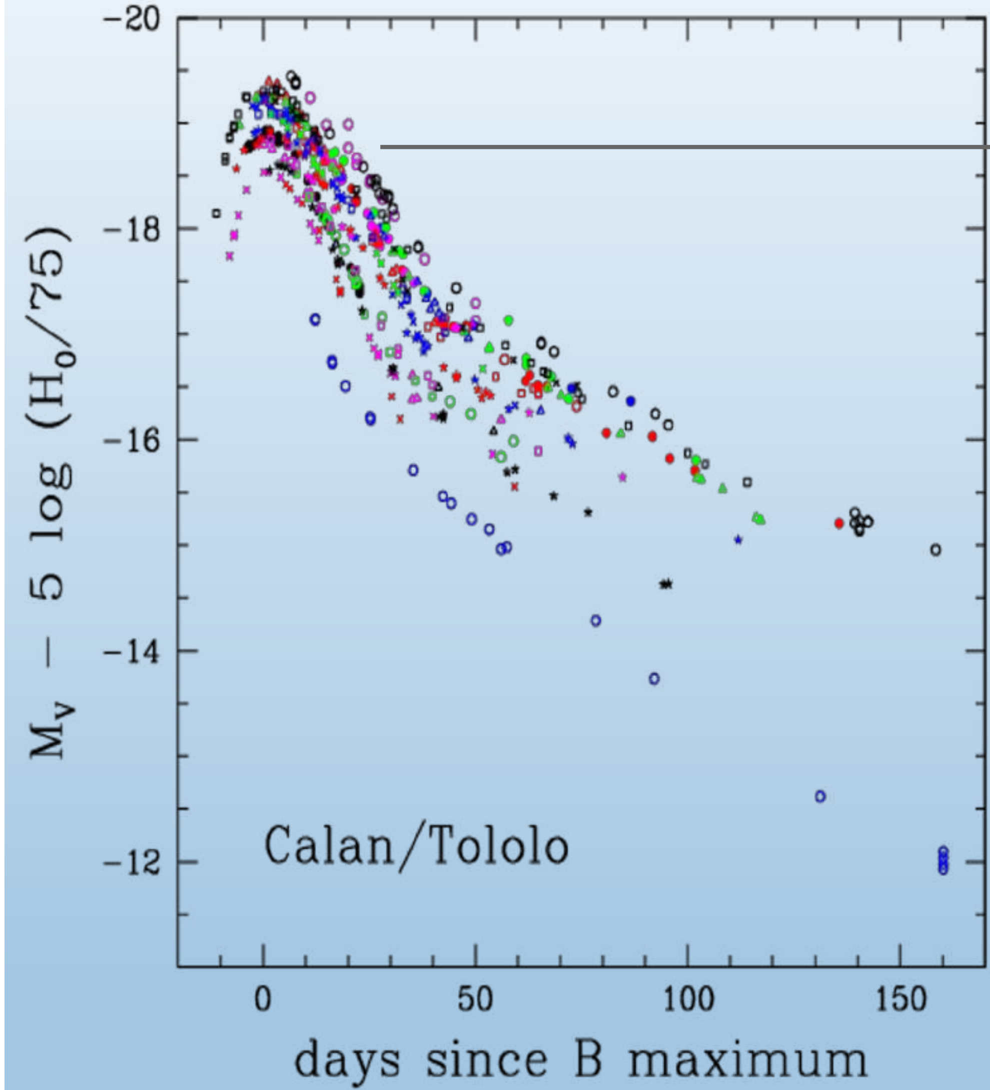


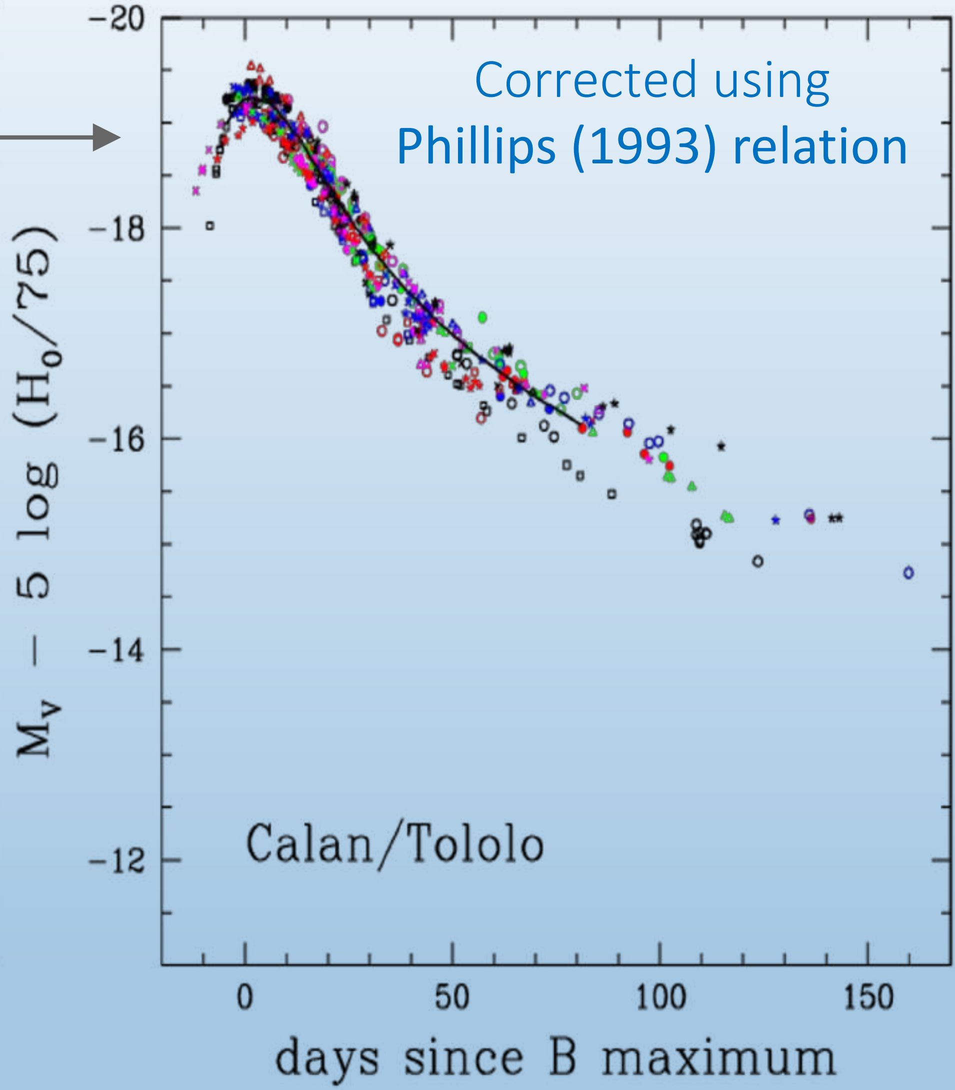




Goobar & Leibundgut, arXiv:1102.1431

Type Ia supernovae as 'standardisable candles'





Hamuy, 1311.5099

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

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

Cosmology

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

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

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

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

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

Distance modulus

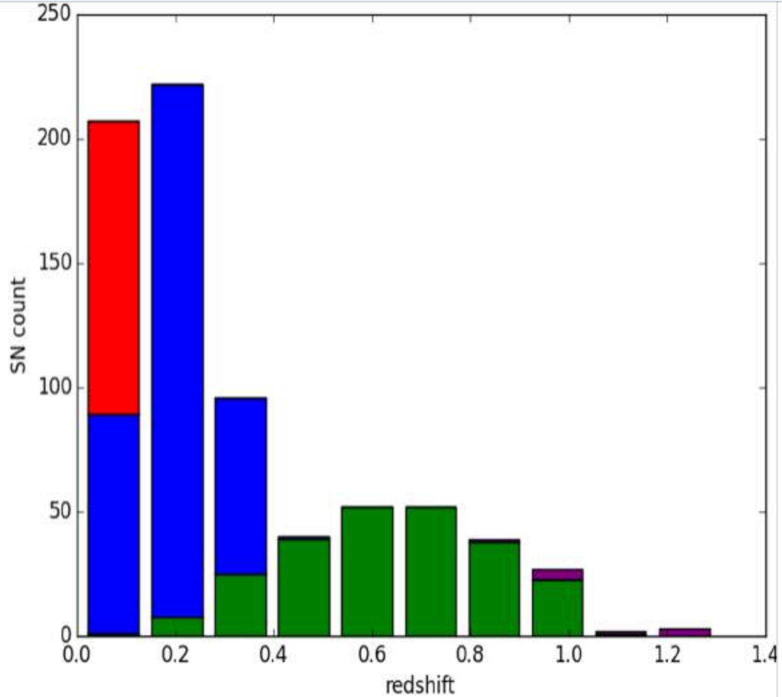
$$\mu_C = m - M = -2.5\log\frac{F/F_{\mathrm{ref}}}{L/L_{\mathrm{ref}}} = 5\log\frac{d_L}{10\mathrm{pc}}$$

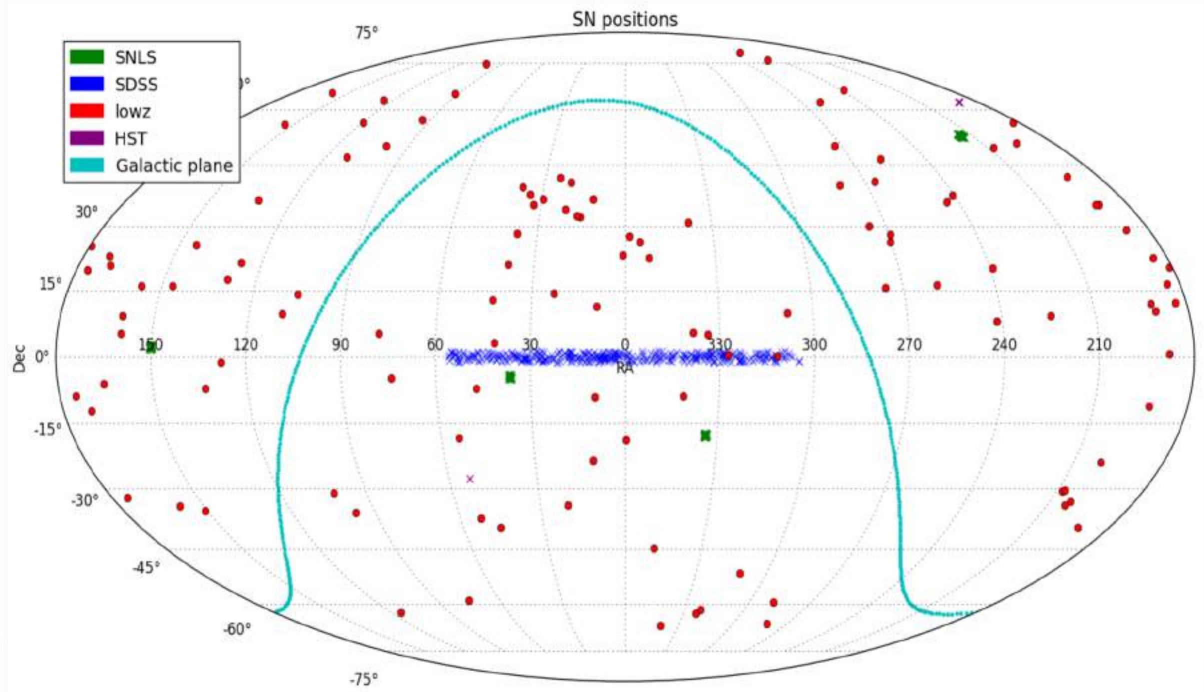
Acceleration is a *kinematic* quantity so the data can be analysed without assuming any dynamical model, by expanding the time variation of the scale factor in a Taylor series

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

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

Joint Lightcurve Analysis data (740 SNe Ia)





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

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

NB: Previous supernova 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!

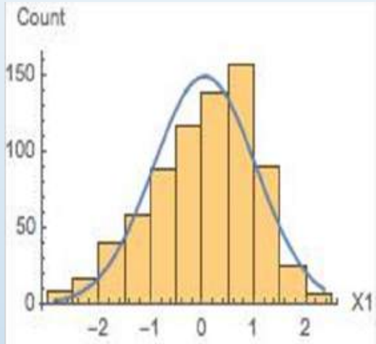
$$\chi^2 = \sum_{objects} \frac{(\mu_B - 5\log_{10}(d_L(\theta, z)/10pc))^2}{\sigma^2(\mu_B) + \sigma^2_{int}}$$

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

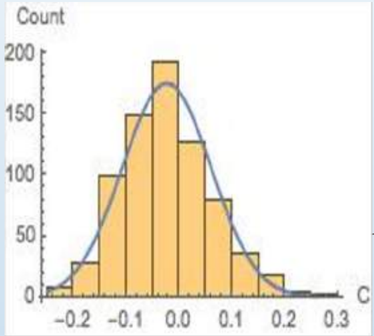
Nielsen, Guffanti & S.S., Sci.Rep. 6:35596,2016

Construct a Maximum Likelihood Estimator

Well-approximated as Gaussian



'Stretch' corrections



'Colour' corrections

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

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

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

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

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

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

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

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

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

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

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

intrinsic distributions

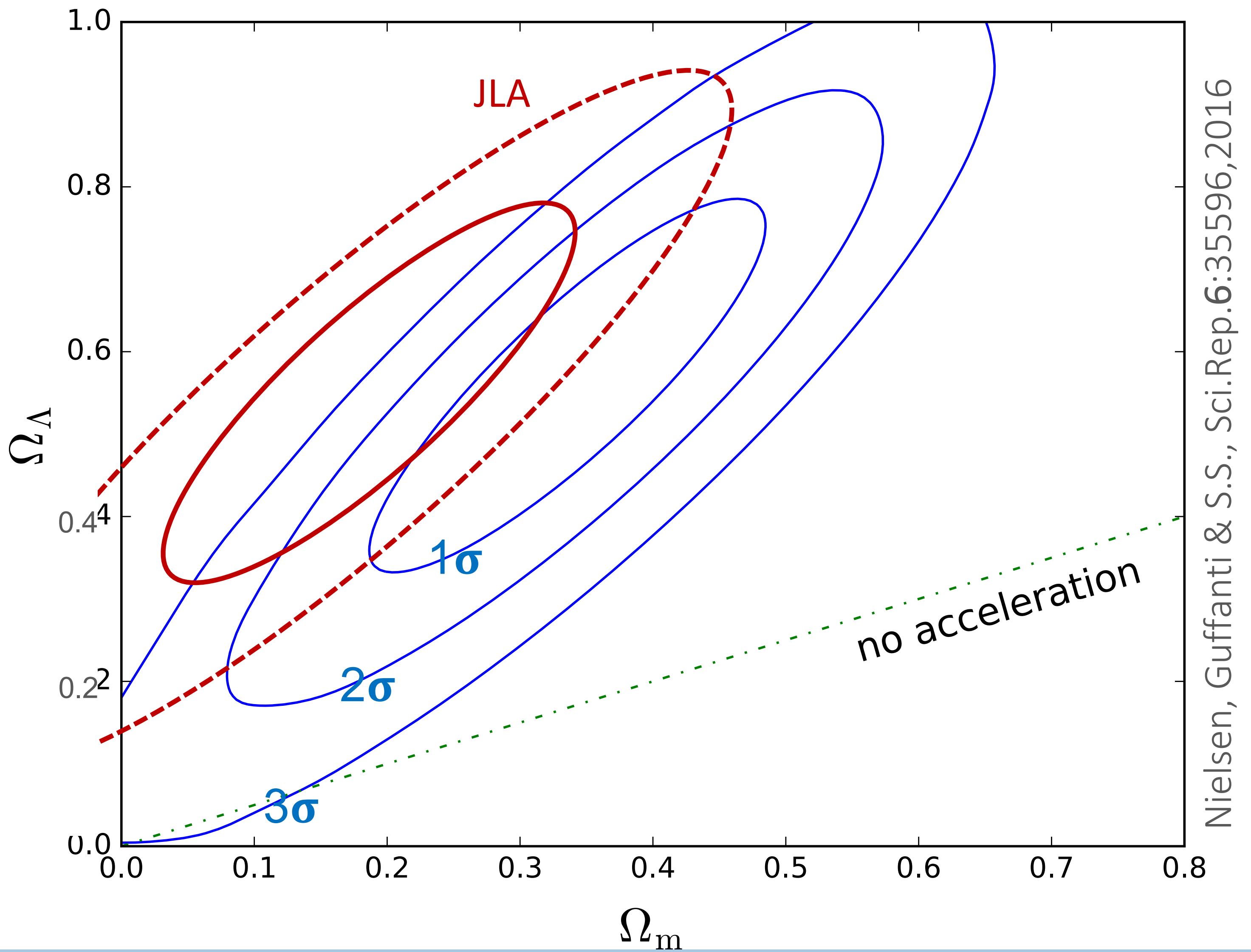
cosmology

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

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

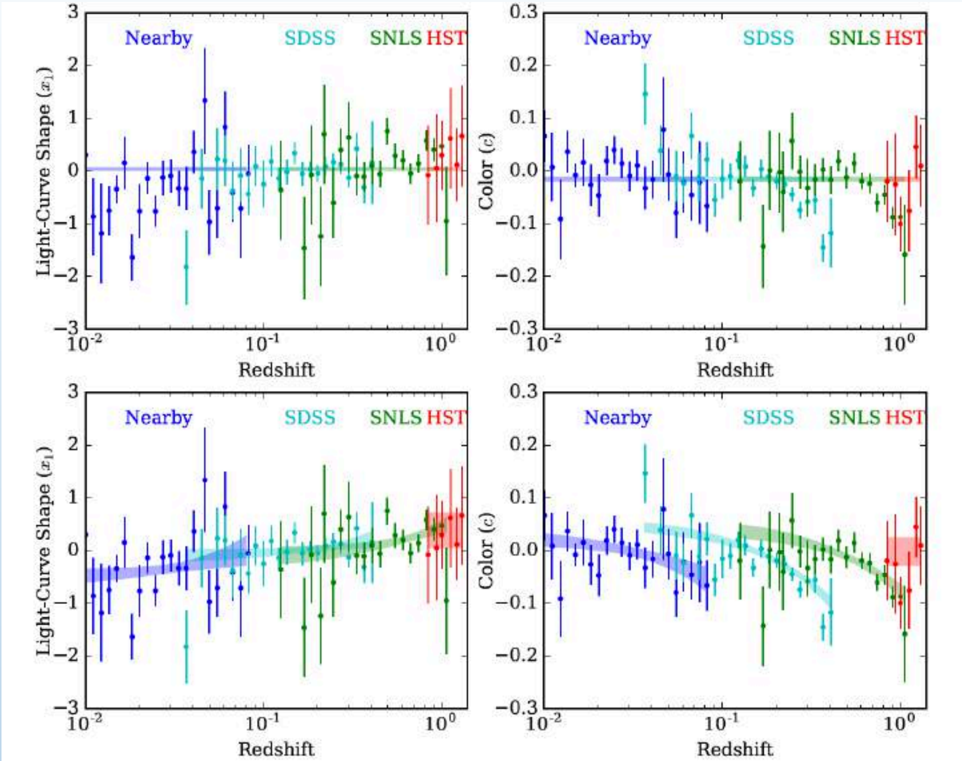
Ω_M	0.341
Ω_Λ	0.569
α	0.134
x_0	0.038
σ^2_{x0}	0.931
β	3.058
c_0	-0.016
σ^2_{c0}	0.071
M_0	-19.05
σ^2_{M0}	0.108

NB: We show the result in the $\Omega_{\rm m}$- Ω_Λ plane for comparison with previous results (JLA) simply to emphasise that the statistical analysis has *not* been done correctly earlier

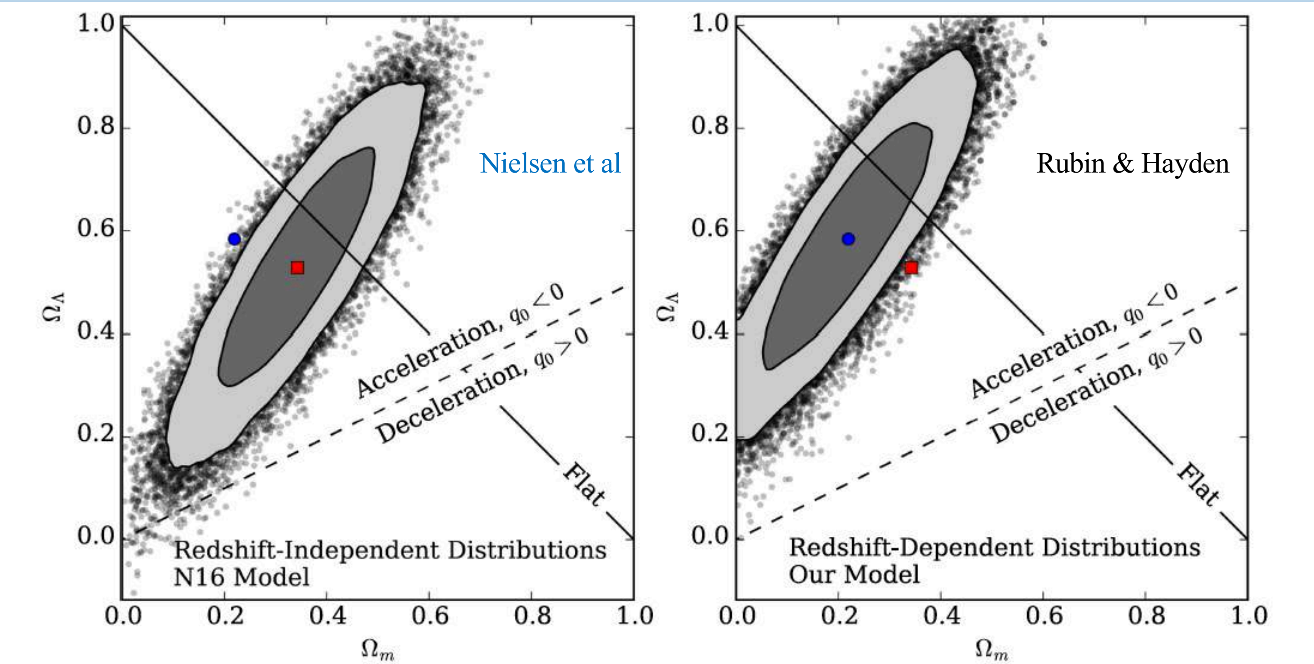
(Other constraints e.g. $\Omega_{\rm m} \gtrsim 0.2$ or $\Omega_m + \Omega_\Lambda \simeq 1$ are relevant *only* to the ΛCDM model)

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

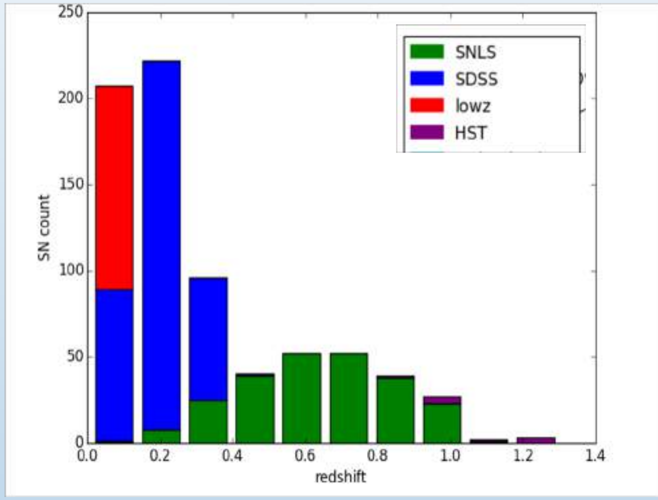


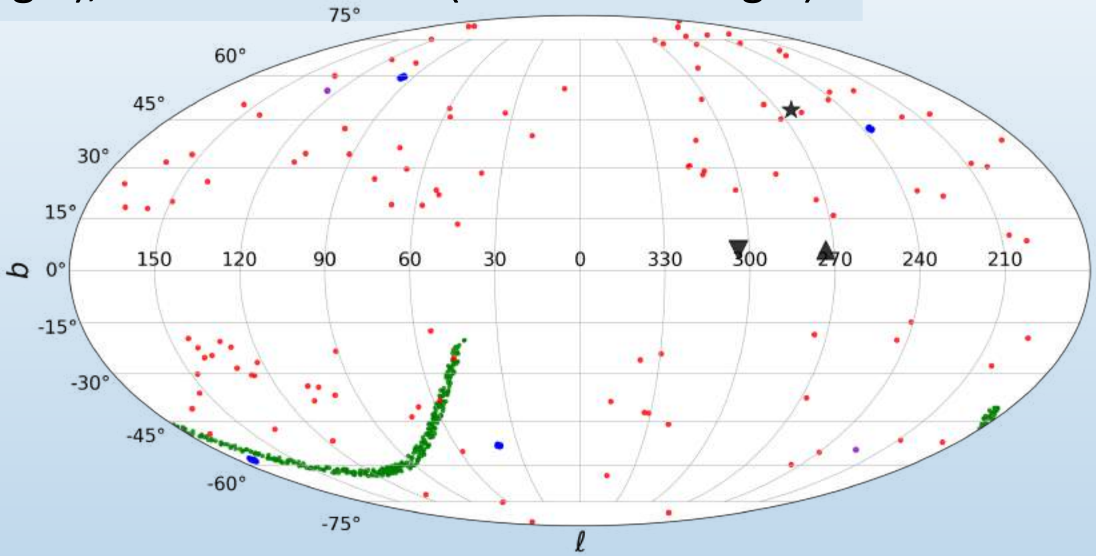
Such *a posteriori* modification is not justified by the Bayesian information criterion



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)

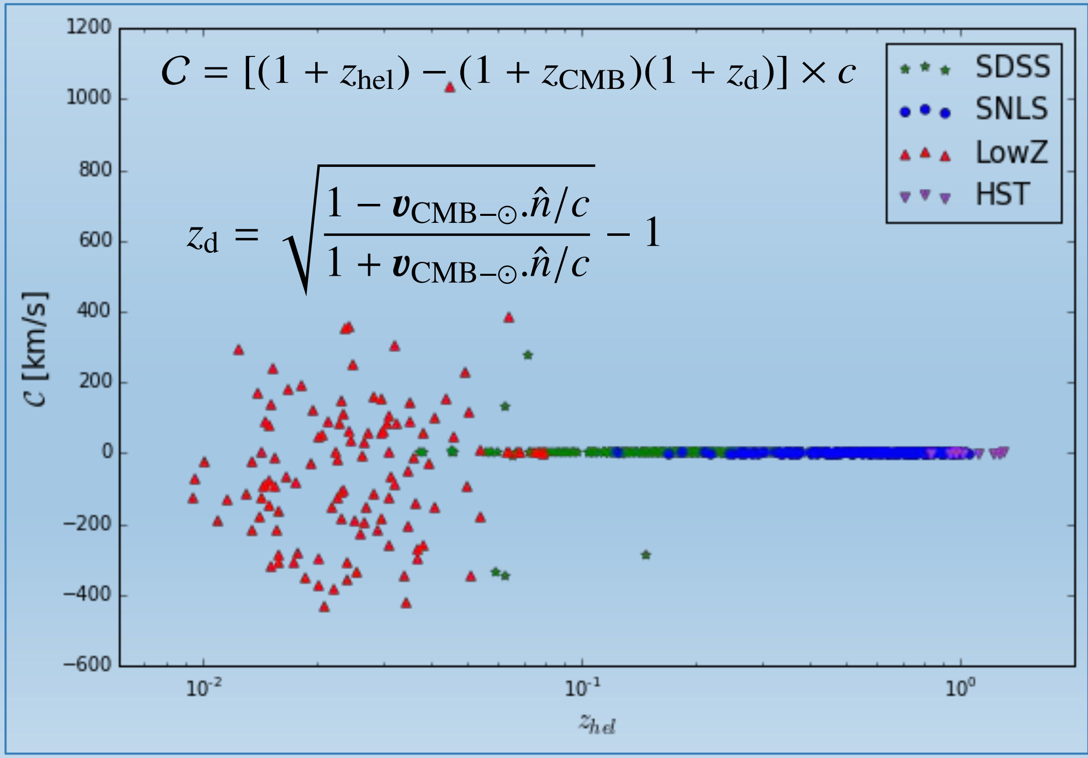
Sky distribution of the 4 sub-samples of the JLA catalogue in Galactic coordinates: SDSS (red dots), SNLS (blue dots), low redshift (green dots) and HST (black dots). CMB dipole (star), SMAC bulk flow (triangle), 2M++ bulk flow (inverted triangle)





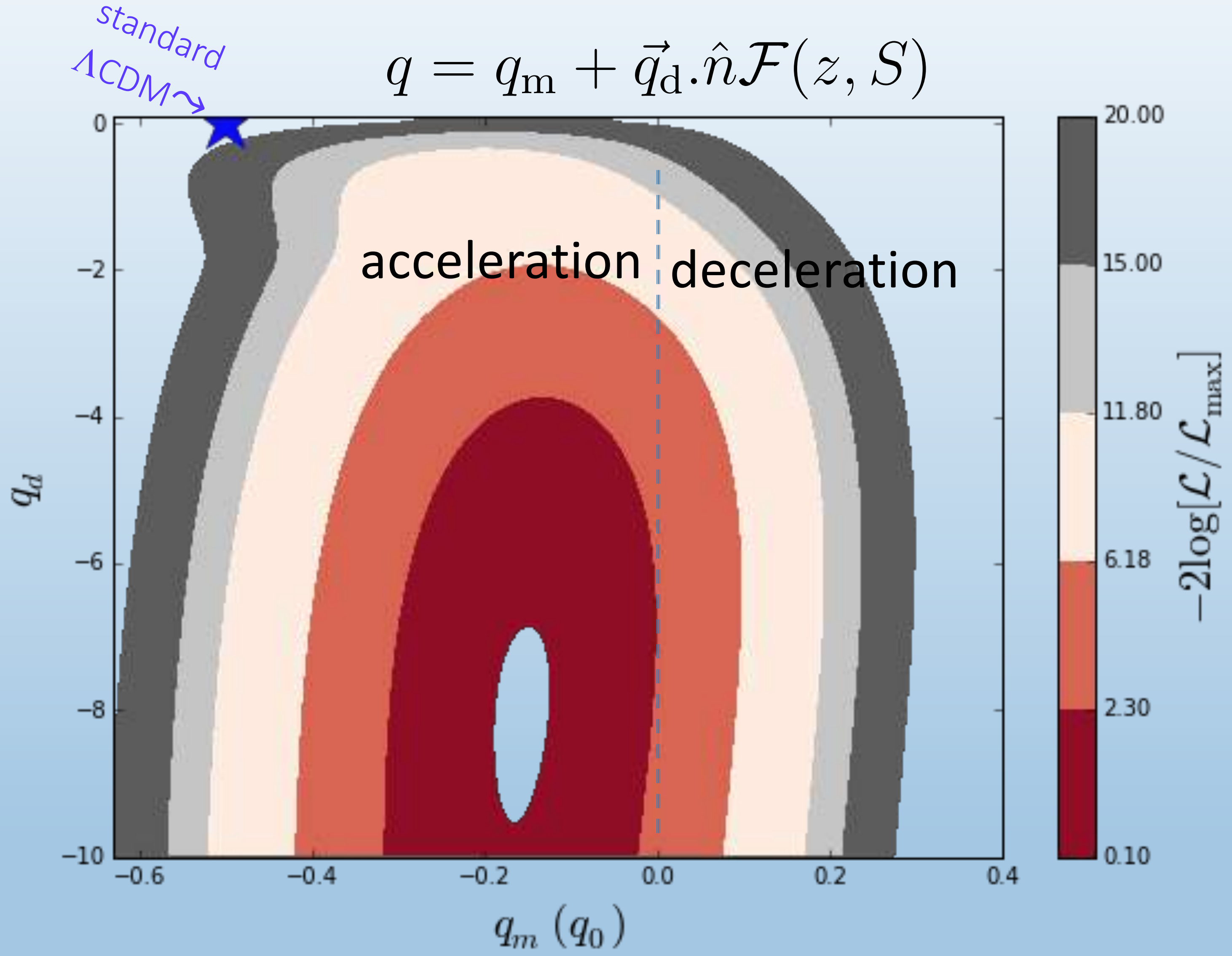
Subsequently we realised that the peculiar velocity `corrections' applied to the JLA catalogue are *suspect* … the bulk flow had been assumed to drop to zero at ~150 Mpc - although it is observed to continue to > 300 Mpc!

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



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

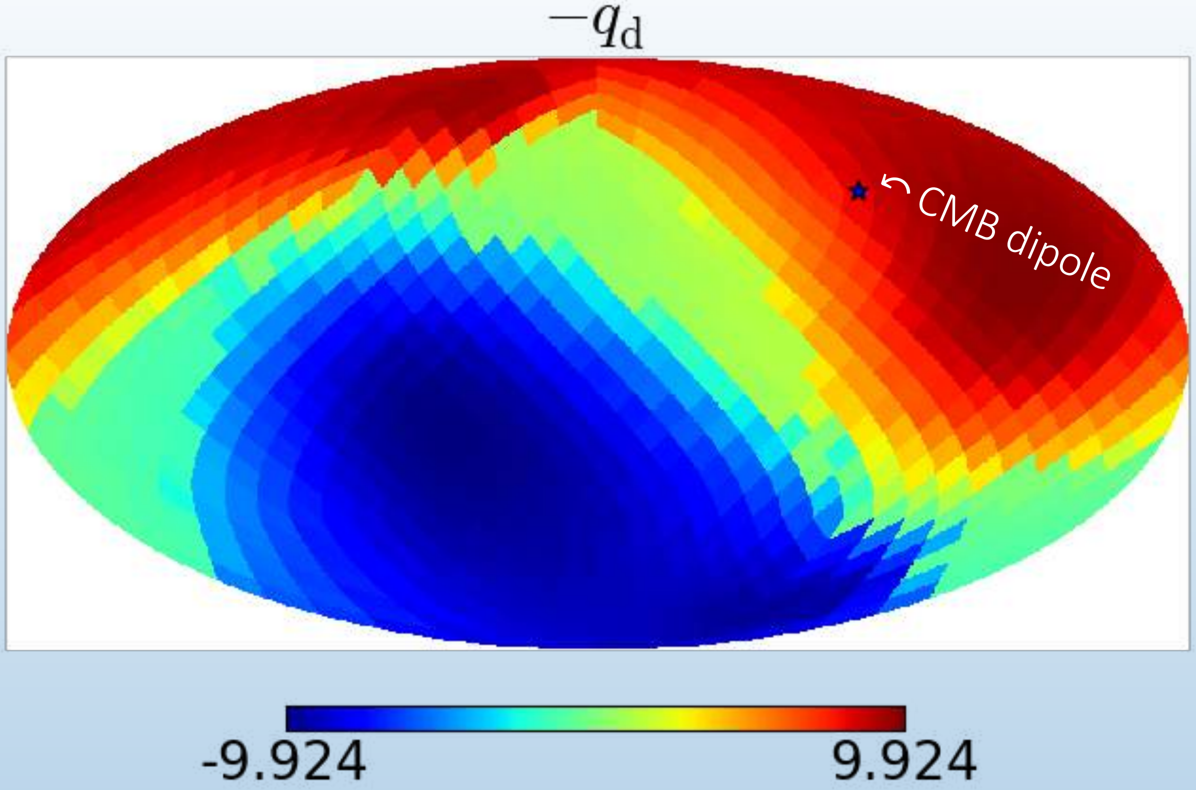
When the data is now analysed allowing for a dipole, we find the MLE *prefers* one (~50 times *bigger* than the monopole) … in ~the same direction as the CMB dipole



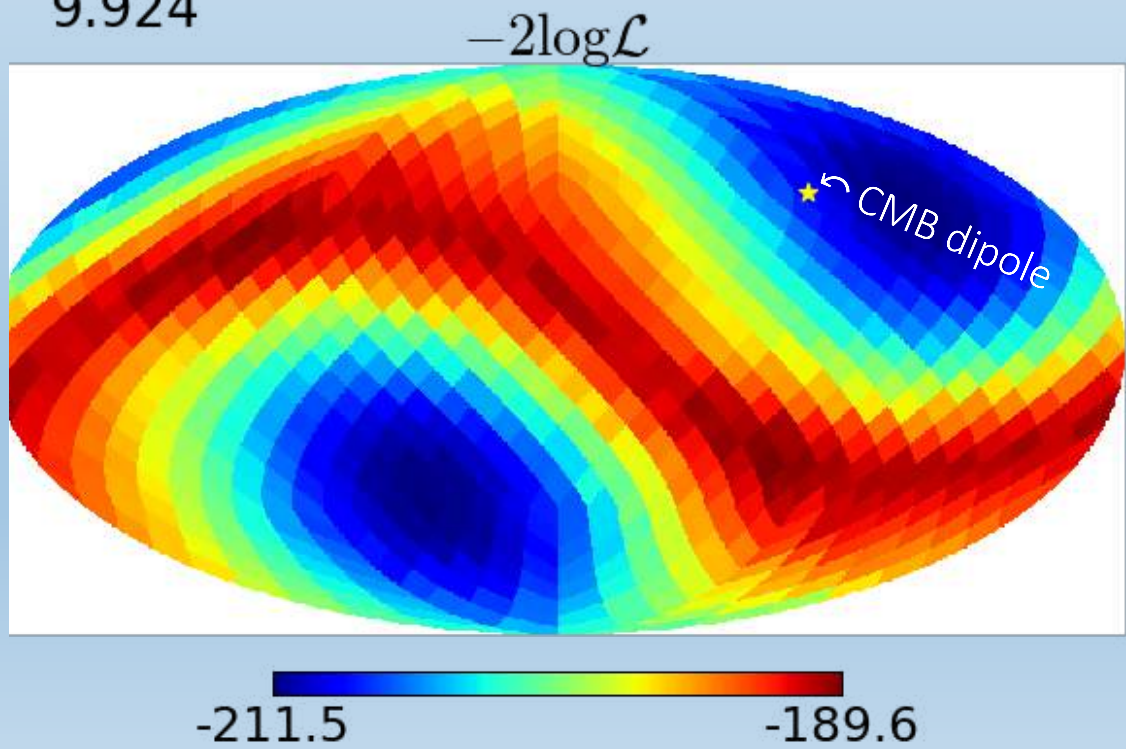
Colin, Mohayaee, Rameez & Sarkar, A&A **631**:L13,2019

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

This strongly suggests that cosmic acceleration is just an artefact of our being located inside a bulk flow (which includes ~3/4 of the observed SNe Ia) and *not* due to Λ



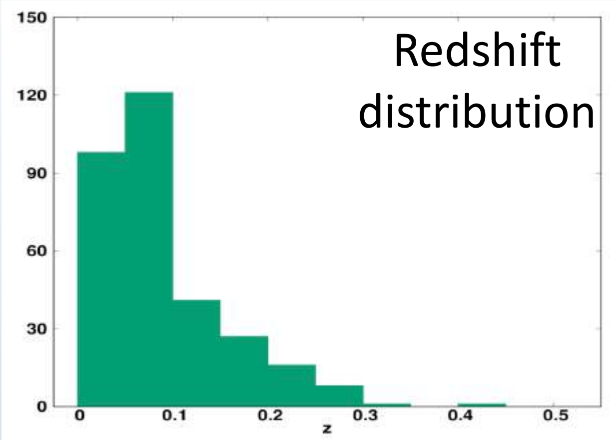
There is not enough data to do an *a priori* scan of the best-fit direction of $q_{\rm d}$ … but if done *a posteriori* it is found to be within 23^0 of the CMB dipole ($\ell = 254.4^0$, $b = 25.5^0$)

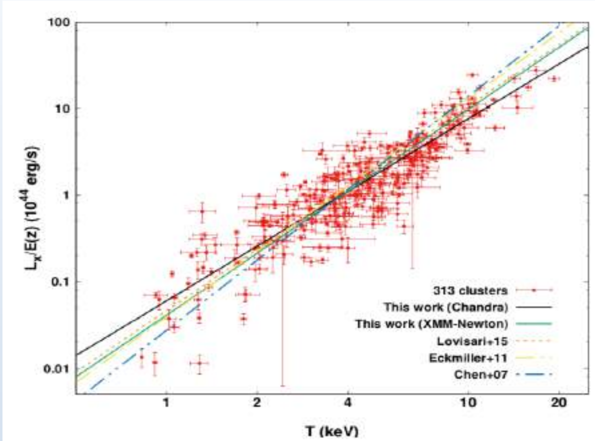


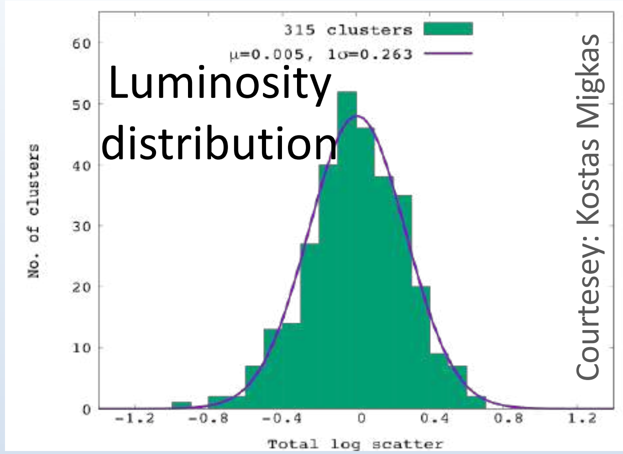
The log-likelihood changes by just 3.2 between the two directions i.e. the inferred acceleration is consistent with being due to the bulk flow (rather than due to Λ)

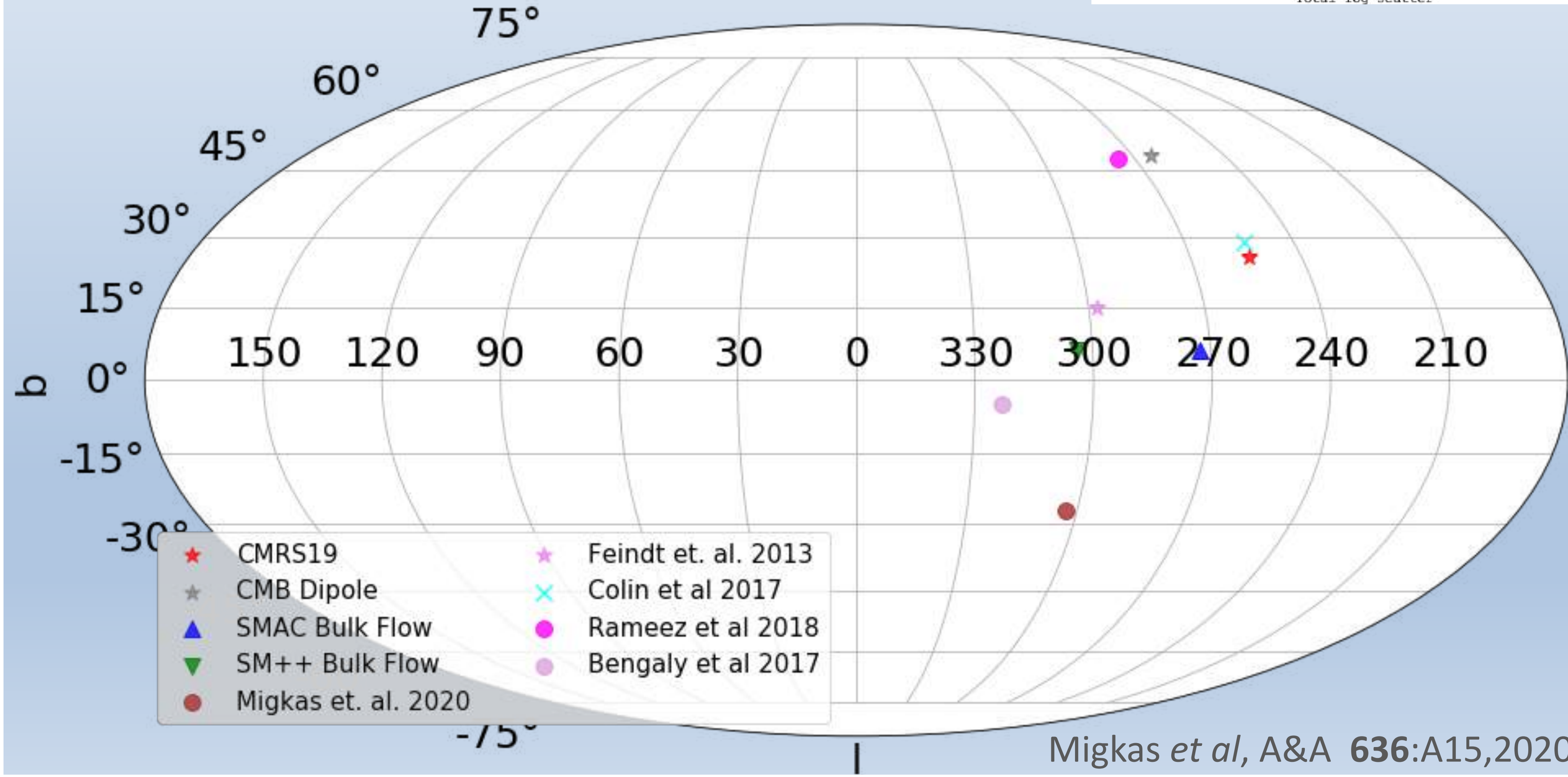
Colin, Mohayaee, Rameez & Sarkar, A&A **631**:L13,2019

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









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

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

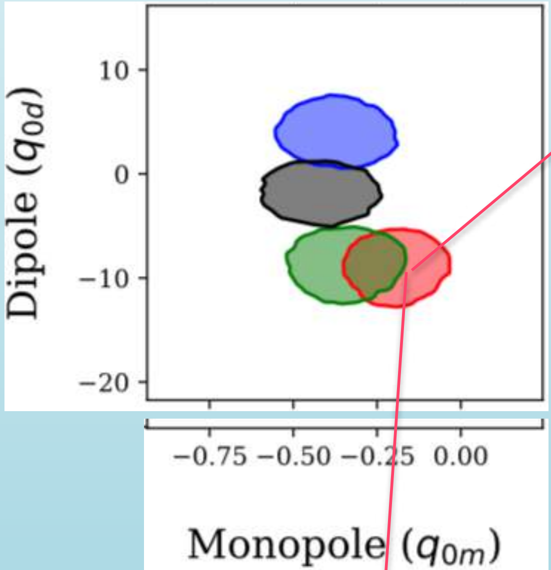
1. "Incorrectly" not allowing redshift-dependence of light-curve parameters (BIC?)
2. "Shockingly" using *heliocentric* redshifts (but is the CMB frame the *correct* frame?)

(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 therefore that their criticism is *not* justified (arXiv:1912:04257)

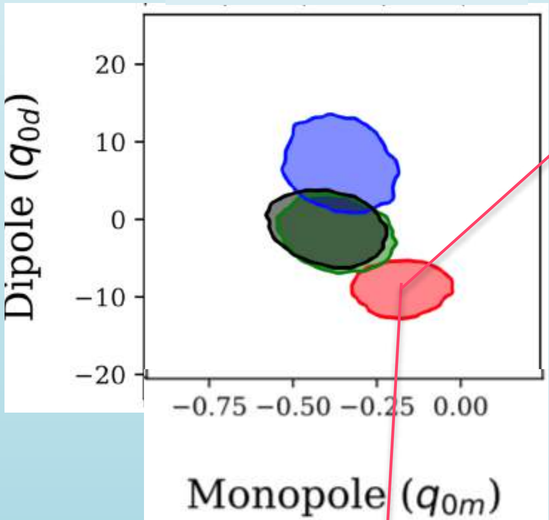
Without JLA peculiar velocity covariance



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

\+ 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}!

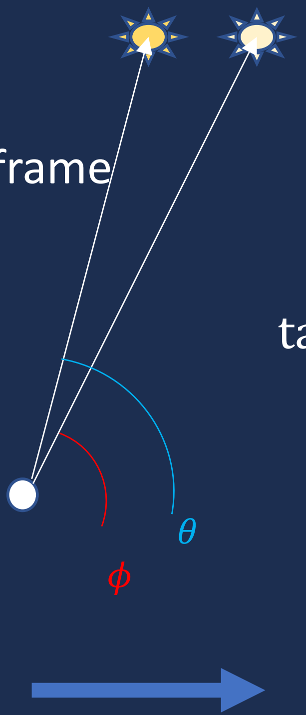
If the dipole in the CMB is due to our motion *wrt* the 'CMB frame' then we should see *same* dipole in the distribution of all distant sources

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

Aberration

Rest frame

Moving frame



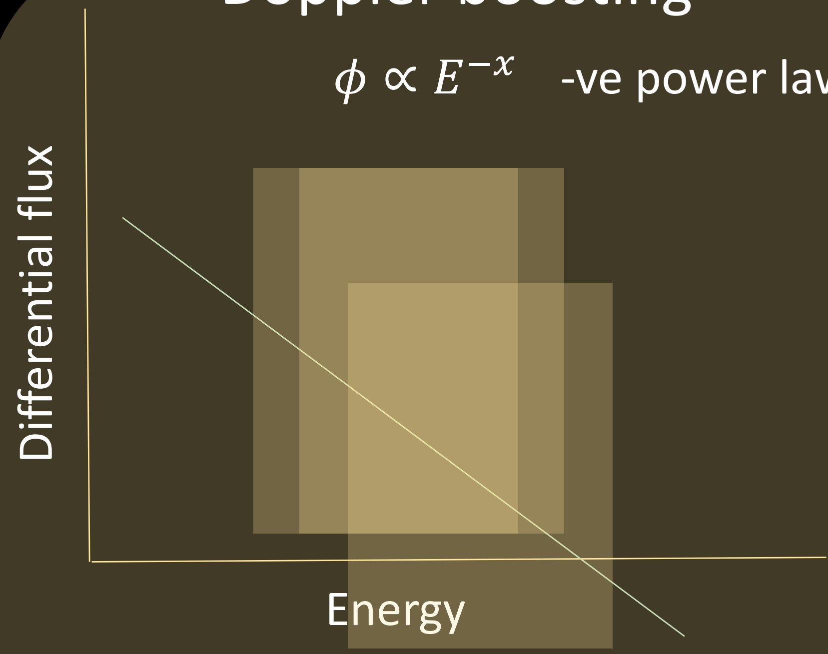
$$\tan\phi = \frac{\sin\theta}{\gamma * cos\theta - \frac{v}{c}}$$

Observer, velocity *v*

+

Doppler boosting

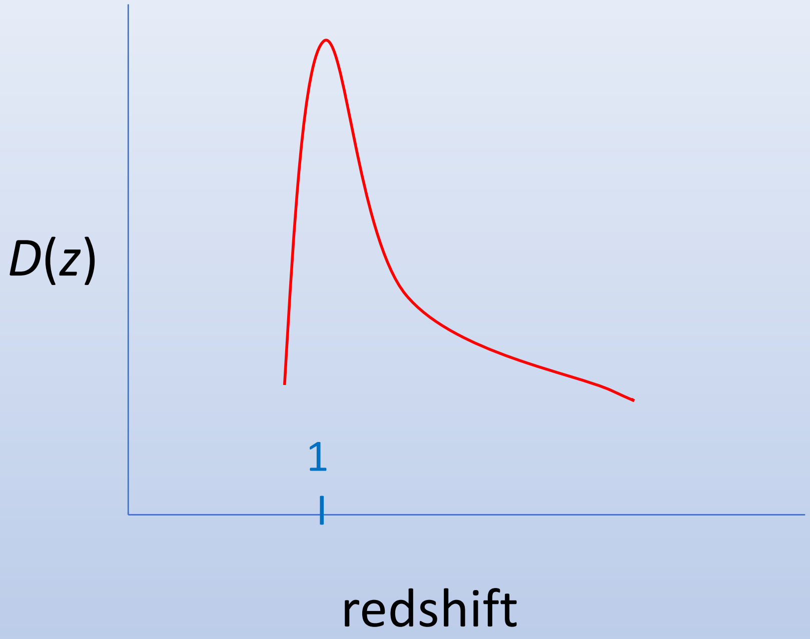
$\phi \propto E^{-x}$ -ve power law



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 dipole component of an actual anisotropy in the distribution of sources in the cosmic rest frame (significant for shallow surveys)

Radio sources: NVSS + SUMSS, 600,000 sources $z \sim 1$, $\vec{\mathcal{S}}\,(D(z)) \to 0$
Colin, Mohayaee, Rameez & S.S., MNRAS **471**:1045,2017

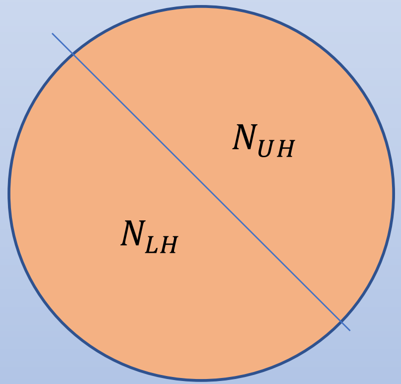
Wide Field Infrared Survey Explorer, 1,200,000 galaxies, $z \sim 0.14$, $\vec{\mathcal{S}}\,(D(z))$ significant
Rameez, Mohayaee, S.S. & Colin, MNRAS **477**:1722,2018

Wide Field Infrared Survey Explorer, 1,500,000 quasars, $z \sim 1$, $\vec{\mathcal{S}}\,(D(z)) \sim 1\%$
Secrest, Rameez, von Hausegger, Mohayaee, S.S. & Colin, arXiv:2009.14826

Estimators for the Dipole

<u>Linear</u>

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



Vary the direction of the hemispheres until maximum asymmetry is observed

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

<u>Quadratic</u>

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

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

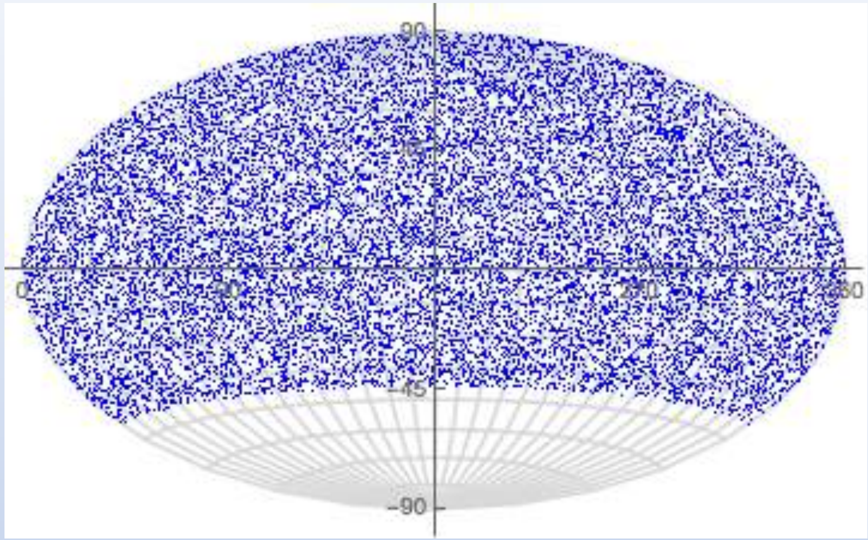
Unbiased
Statistical error $1/\sqrt{N}$

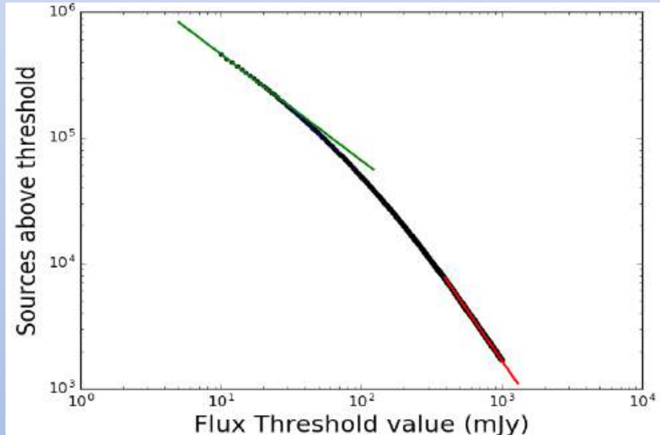
$$\vec{D}_C = \frac{\hat{z}}{N}\int_{\phi=0}^{\phi=2\pi}\int_{\theta=0}^{\theta=\pi}\sigma(\theta)\cos\theta\sin\theta \mathrm{d}\theta \mathrm{d}\phi$$

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

Rubart & Schwarz,
A&A 555 (2013) A117

The NRAO VLA Sky Survey (NVSS)

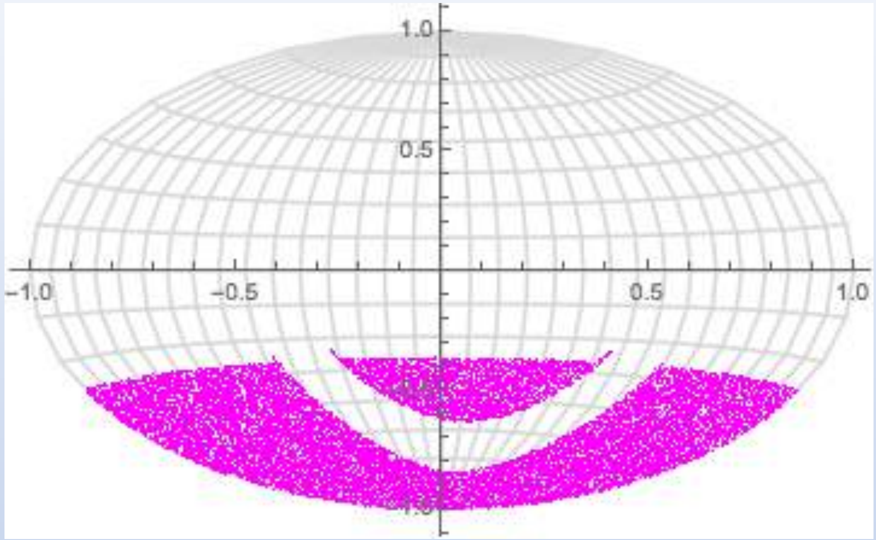


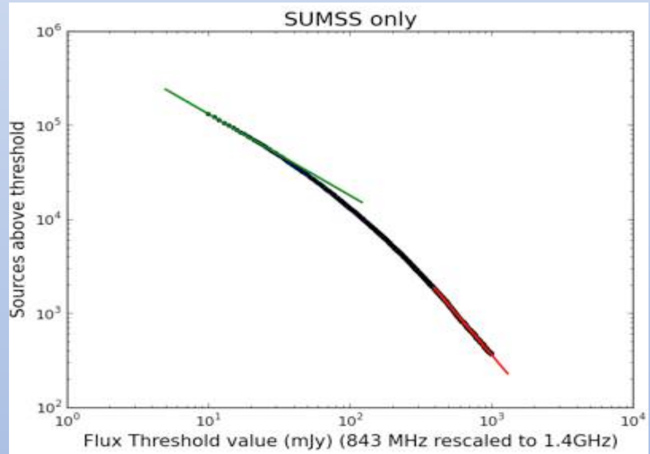


1.4 GHz survey (down to Dec = -40.4°)
National Radio Astronomy Observatory

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)

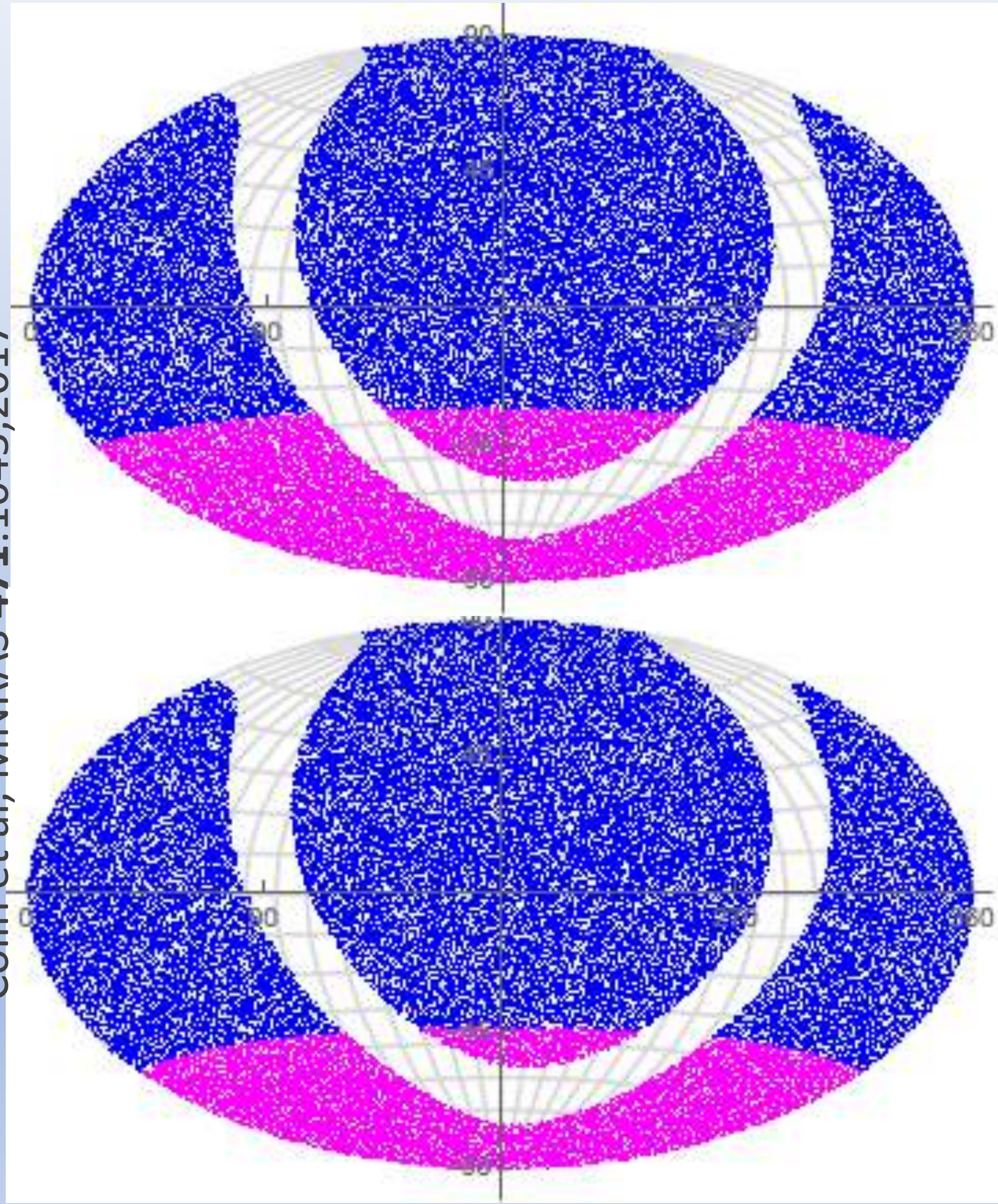




843 MHz survey (Dec < -30.0°)
Molonglo Observatory Synthesis telescope

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

The NVSUMSS-Combined All Sky catalog



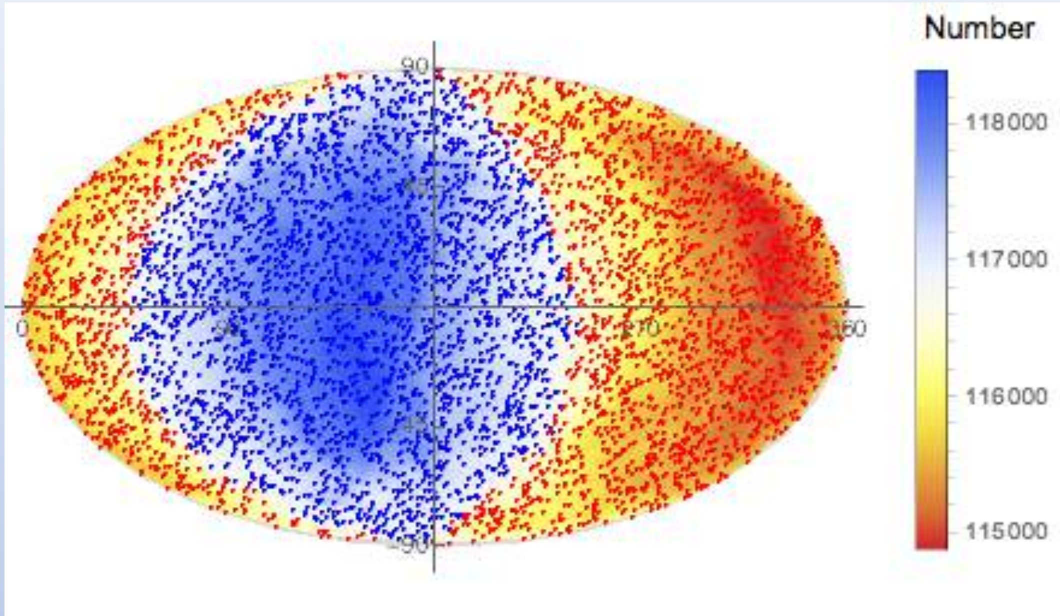
Colin et al, MNRAS **471**:1045,2017

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

None of the above makes a difference!

Our Peculiar velocity wrt radio galaxies ≠ peculiar velocity wrt the CMB

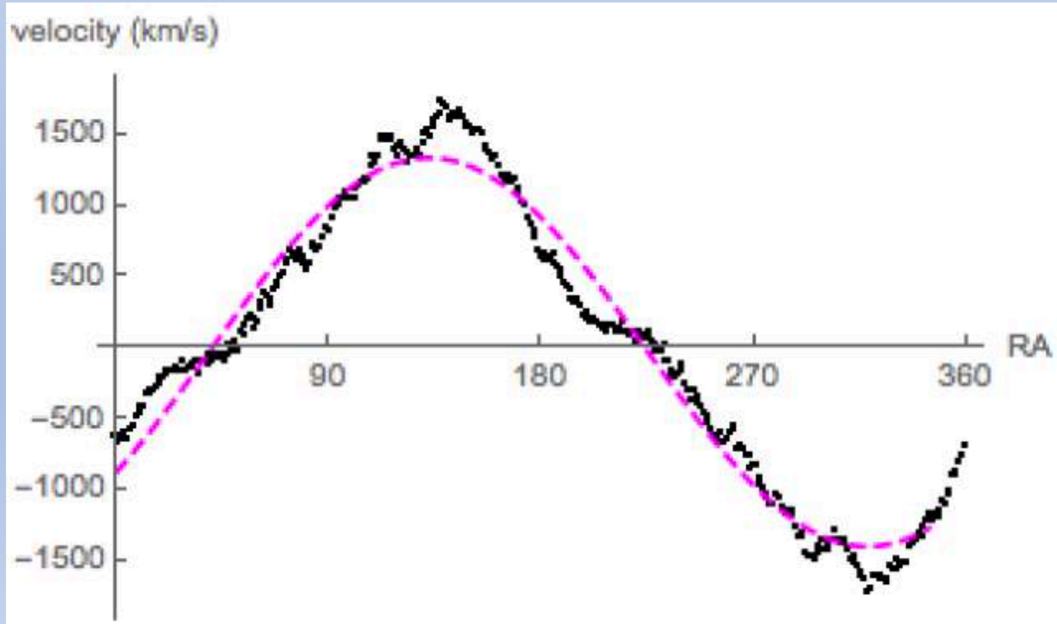
Colin, Mohayaee, Rameez & S.S., MNRAS **471**:1045,2017



Velocity ~ 1355 ± 174 km/s
(with 3D linear estimator)

Direction within 10° of CMB dipole (but **much *faster***)!

Statistical significance: 99.75%
⇒ 2.81**σ** (by Monte Carlo)

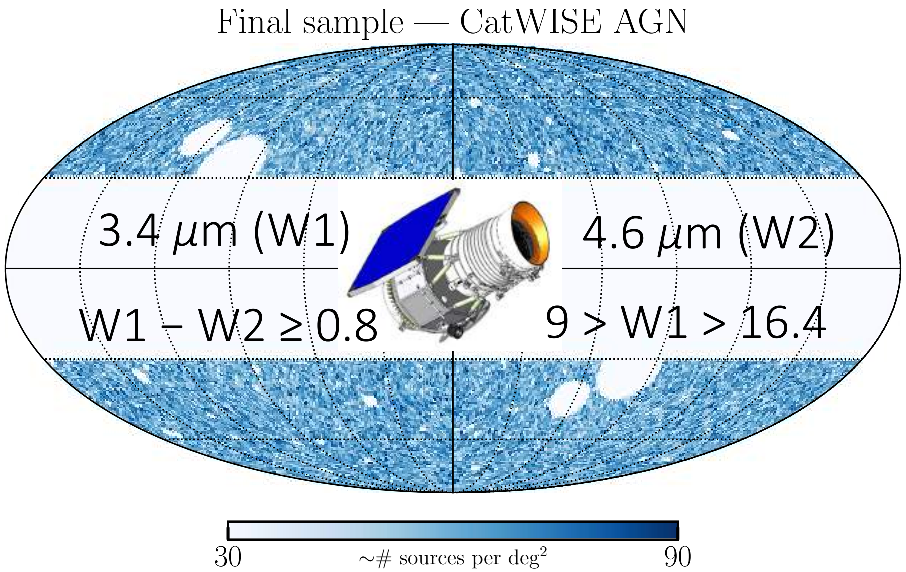


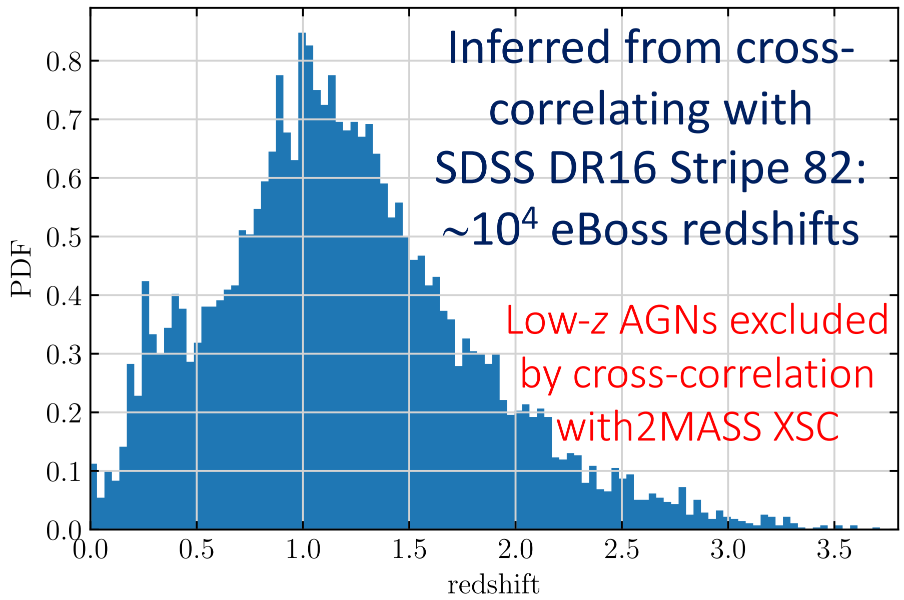
Confirms claim by Singal (2011) which was criticized subsequently
(Gibelyou & Huterer 2012, Rubart & Schwarz 2013, Nusser & Tiwari 2015)

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

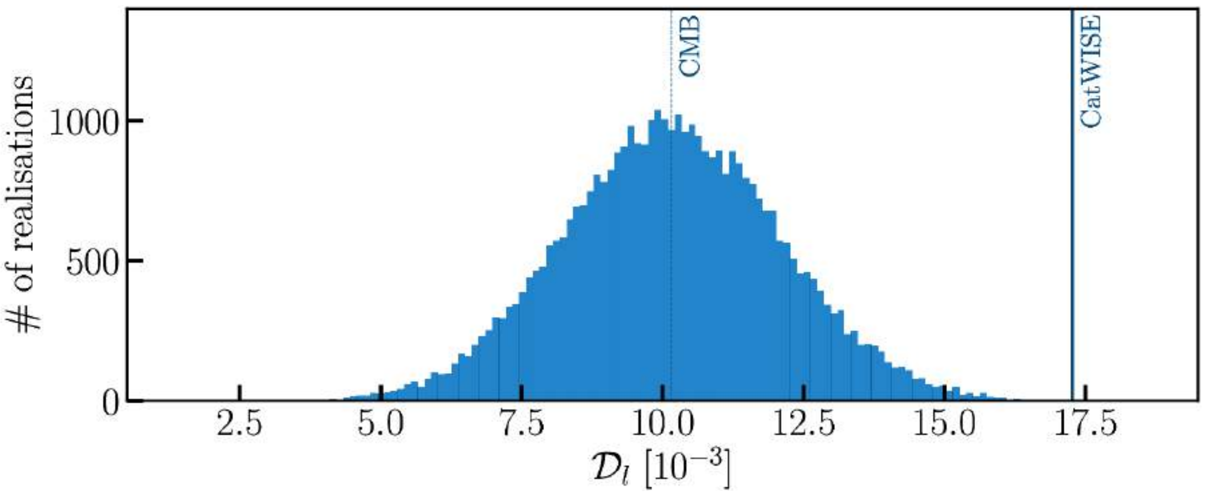
Our Peculiar velocity wrt quasars ≠ peculiar velocity wrt the CMB

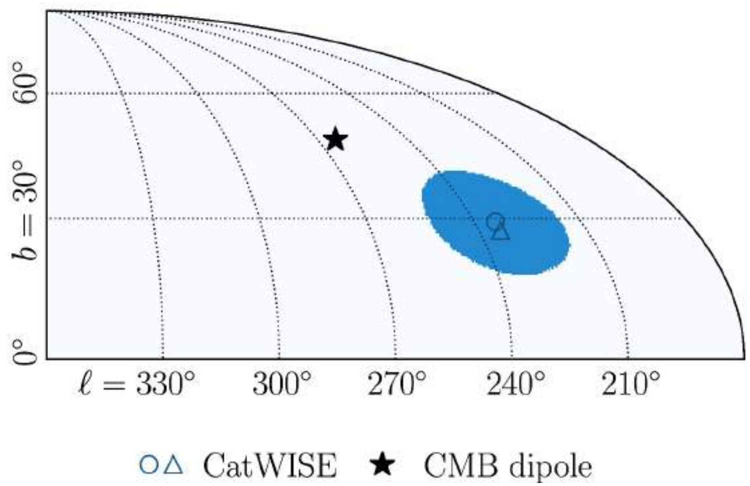
Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, arXiv:2009.14826





We now have a catalogue of ~1.5 million quasars, with 99% at redshift > 0.1





Update: The kinematic interpretation of the CMB dipole is rejected with $p=10^{-5} \Rightarrow 4.4\sigma$

A 'tilted' Universe?

- There is a dipole in the recession velocities of host galaxies of supernovae ⇒ we are in a 'bulk flow' stretching out well *beyond* the scale at which the universe supposedly becomes statistically homogeneous.

- The inference that the Hubble expansion rate is accelerating may be an artefact of the local bulk flow … there is a strong dipole in q_0 aligned with the bulk flow, and the monopole drops in significance to be consistent with zero

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

Could all this be an indication of new horizon-scale physics?
e.g. super-horizon *iso*curvature perturbation (Gunn 1988, Turner 1991)

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

… forthcoming surveys (Euclid, LSST, SKA …) will enable definitive tests

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