Testing the Cosmological Principle

Subir Sarkar

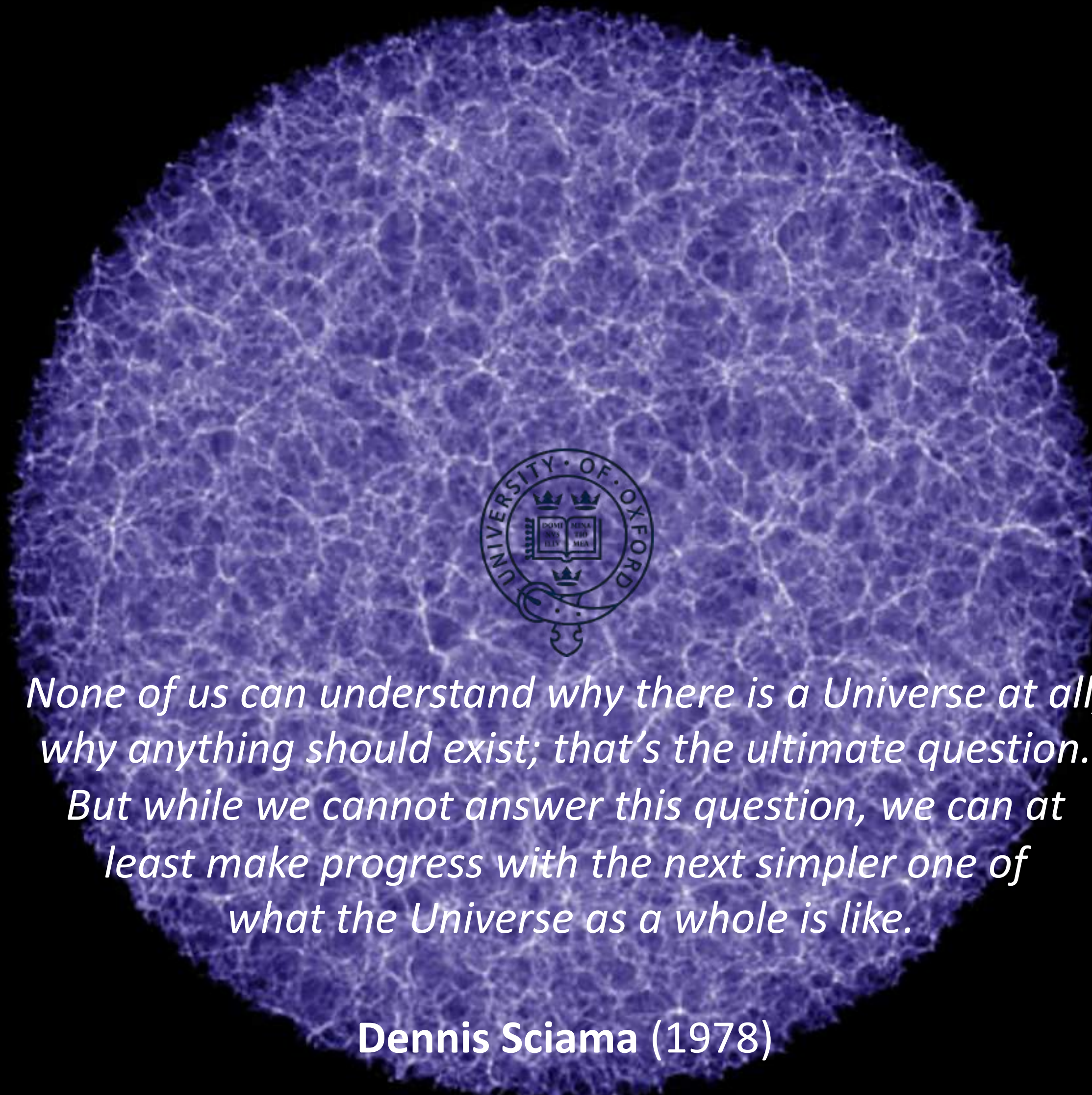
In the ΛCDM cosmological model it is assumed that the universe is statistically isotropic and homogeneous when averaged on scales $\gtrsim$100 Mpc. That the CMB has a large dipole anisotropy is explained as due to our 'peculiar motion' because of local inhomogeneity. There should then be a similar dipole in the sky distribution of high redshift sources. Using a catalogue of 1.4 million quasars we find this standard expectation is rejected at 4.9σ.

This calls into question the usual practice of boosting to the 'CMB frame' to analyse cosmological data. In the heliocentric frame the acceleration of the Hubble expansion rate is also found to be a dipole, aligned with the CMB, at 3.9σ confidence. It can no longer be argued that this acceleration can be made to look isotropic by boosting to the CMB frame … and interpreted as due to Λ.

Secrest *et al,* ApJL **908**:L51,2021, Colin *et al,* A&A **631**:L13,2019

Testing the Cosmological Principle

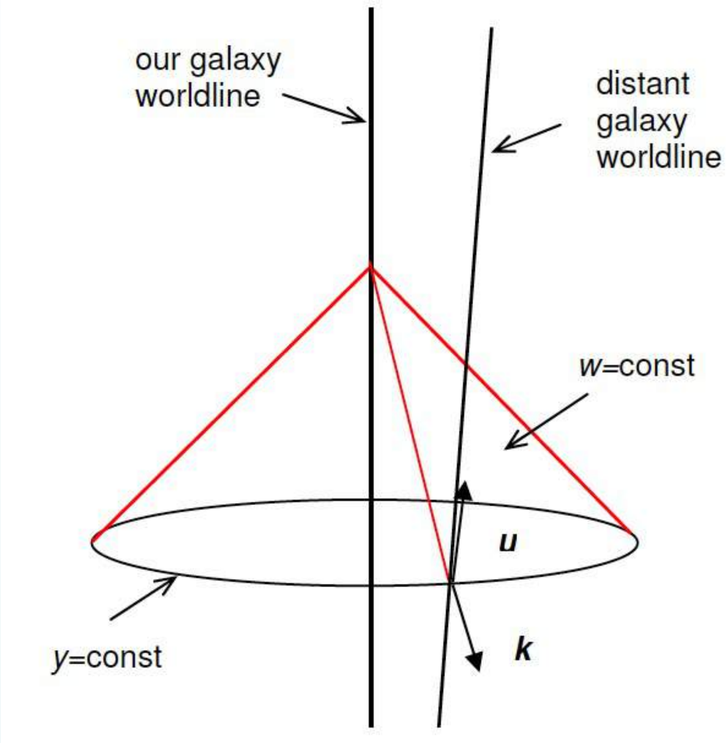
Subir Sarkar



*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)

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 … so must *assume* that our position is not special in any way

> *"The Universe must appear to be the same to all observers wherever they are. This 'cosmological principle' …"*
>
> Edward Arthur Milne, in 'Kinematics, Dynamics & the Scale of Time' (1936)

Mathematical Proceedings of the Cambridge Philosophical Society
Volume 51, Issue 4, October 1955 , pp. 678-683

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.

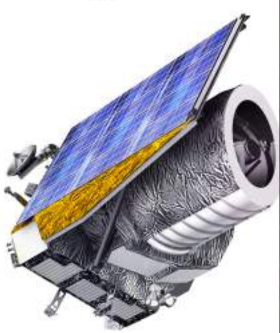
THE 'PERFECT' VERSION WAS ABANDONED FOLLOWING THE DISCOVERY IN 1964 OF THE CMB AND THE REALIZATION THAT THE UNIVERSE *DOES* HAVE A BEGINNING .... BUT THE COSMOLOGICAL PRINCIPLE LIVED ON

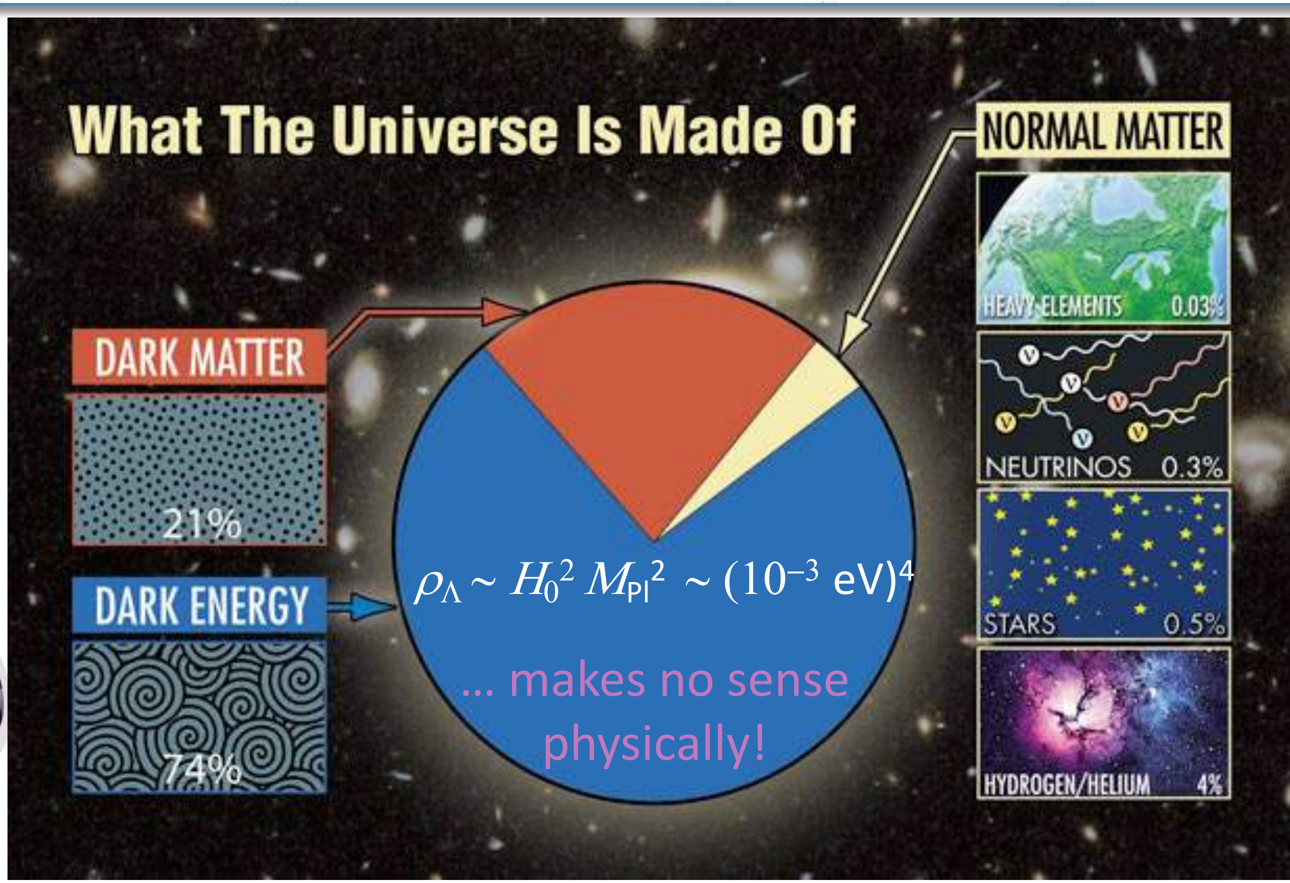
The real reason, though, for our adherence here to the Cosmological Principle is not that it is surely correct, but rather, that it allows us to make use of the extremely limited data provided to cosmology by observational astronomy. ...

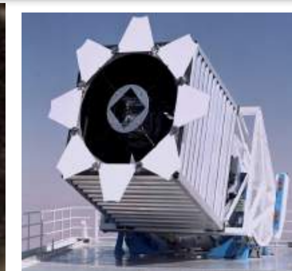
... If the data will not fit into this framework, we shall be able to conclude that either the Cosmological Principle or the Principle of Equivalence is wrong. Nothing could be more interesting.

Steven Weinberg, *Gravitation and Cosmology* (1972)

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.

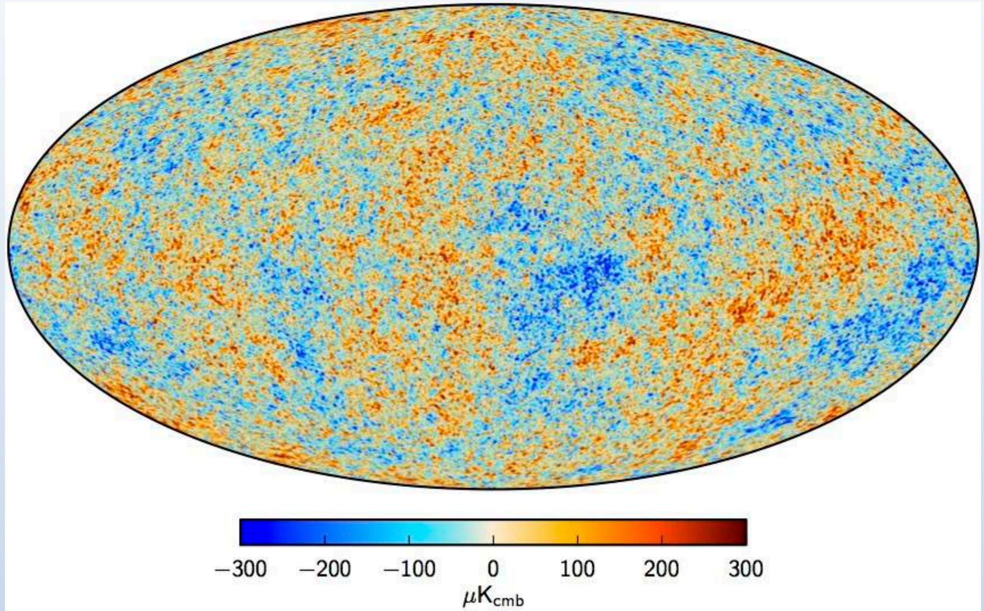


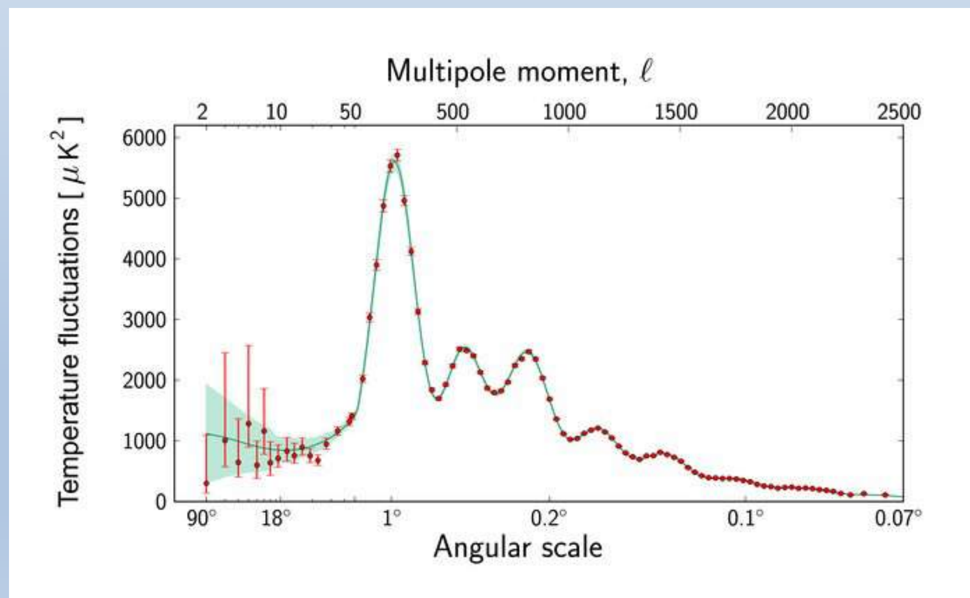




There has been substantial investment in major satellites and telescopes to *measure the parameters* of this 'standard cosmological model' with increasing precision … but surprisingly little work on ***testing its foundational assumptions***

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

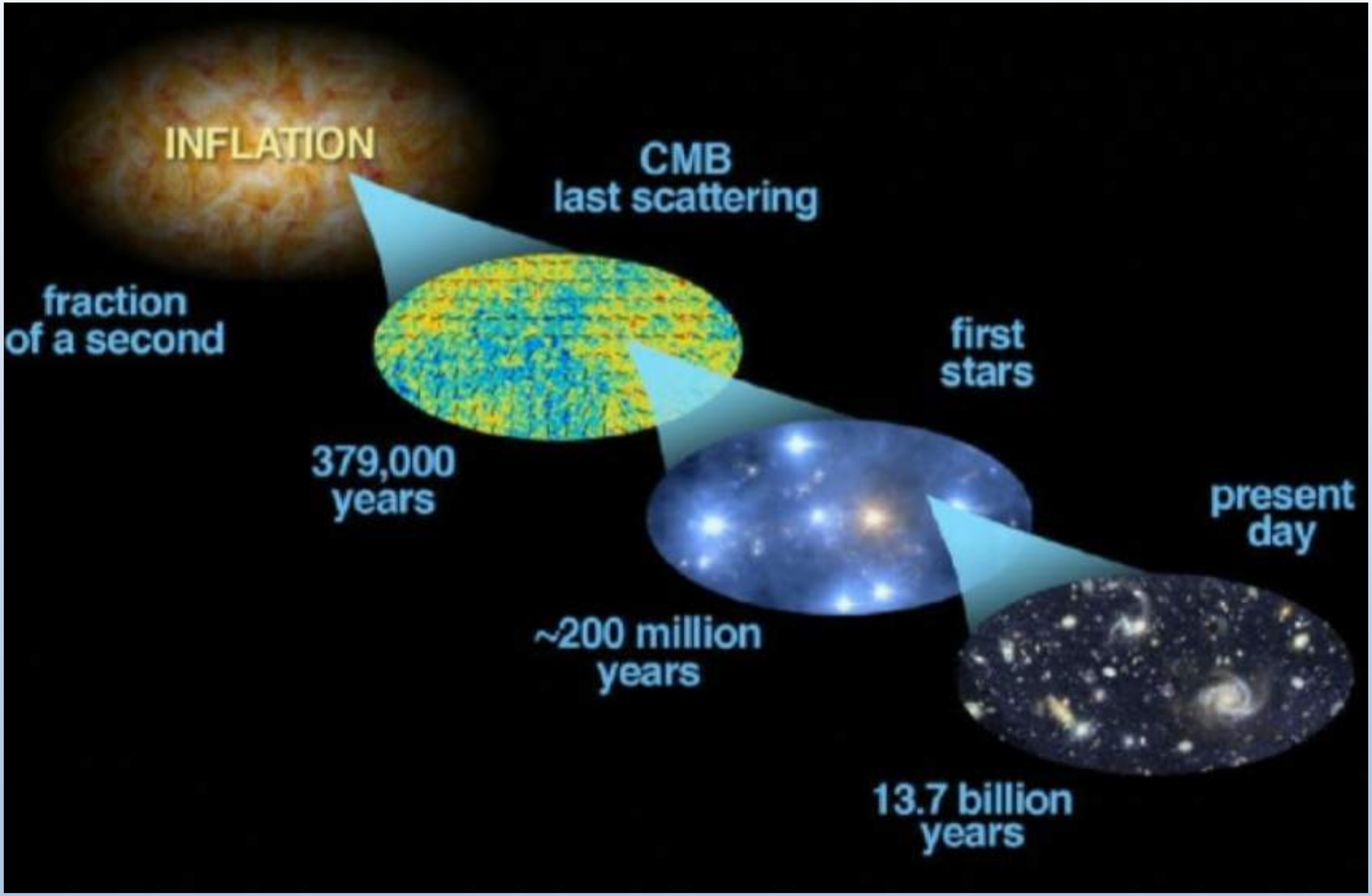




Planck collab., A&A **571**:A1,2014

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

Standard model of structure formation

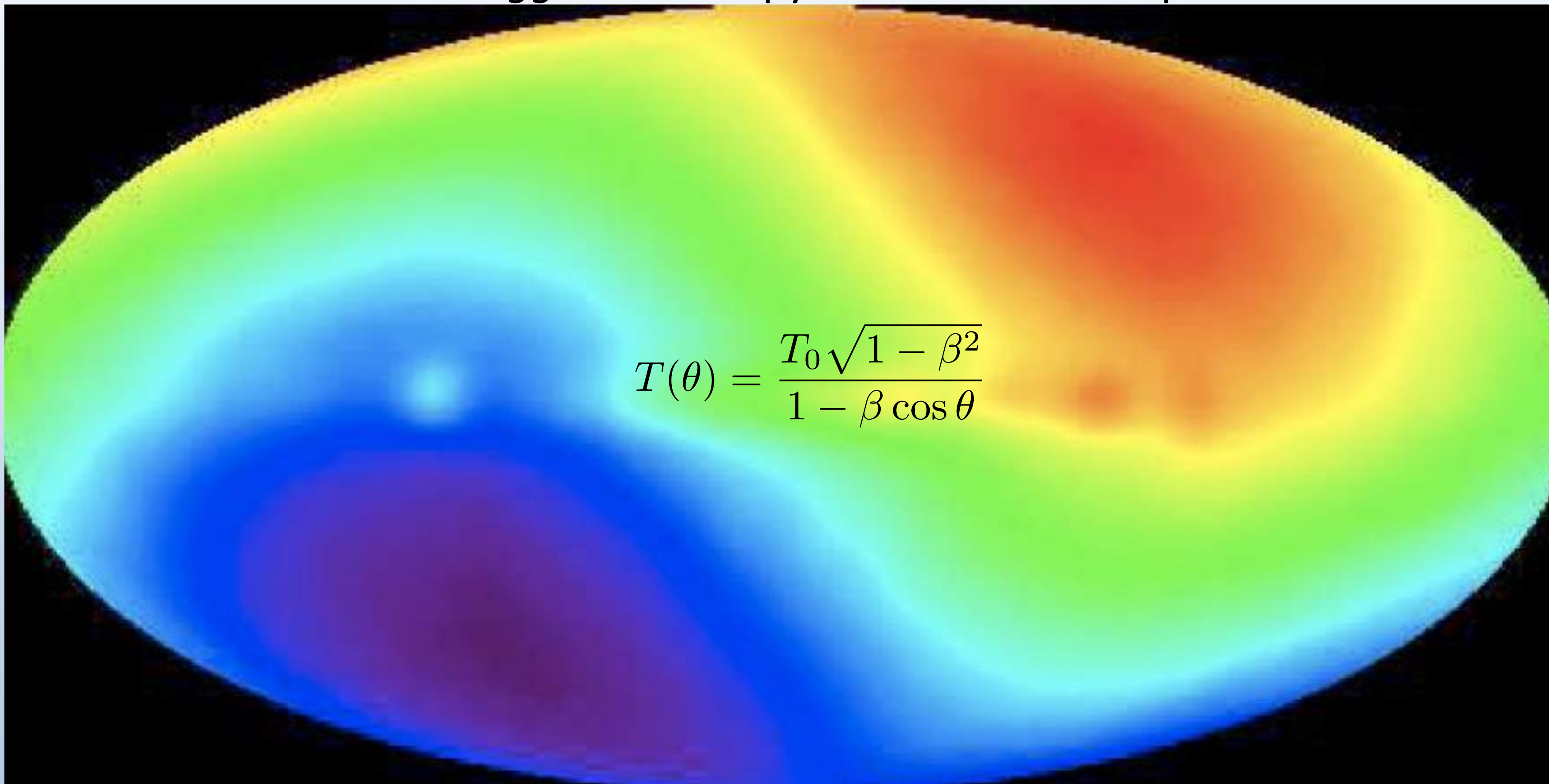


Courtesey: NASA

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



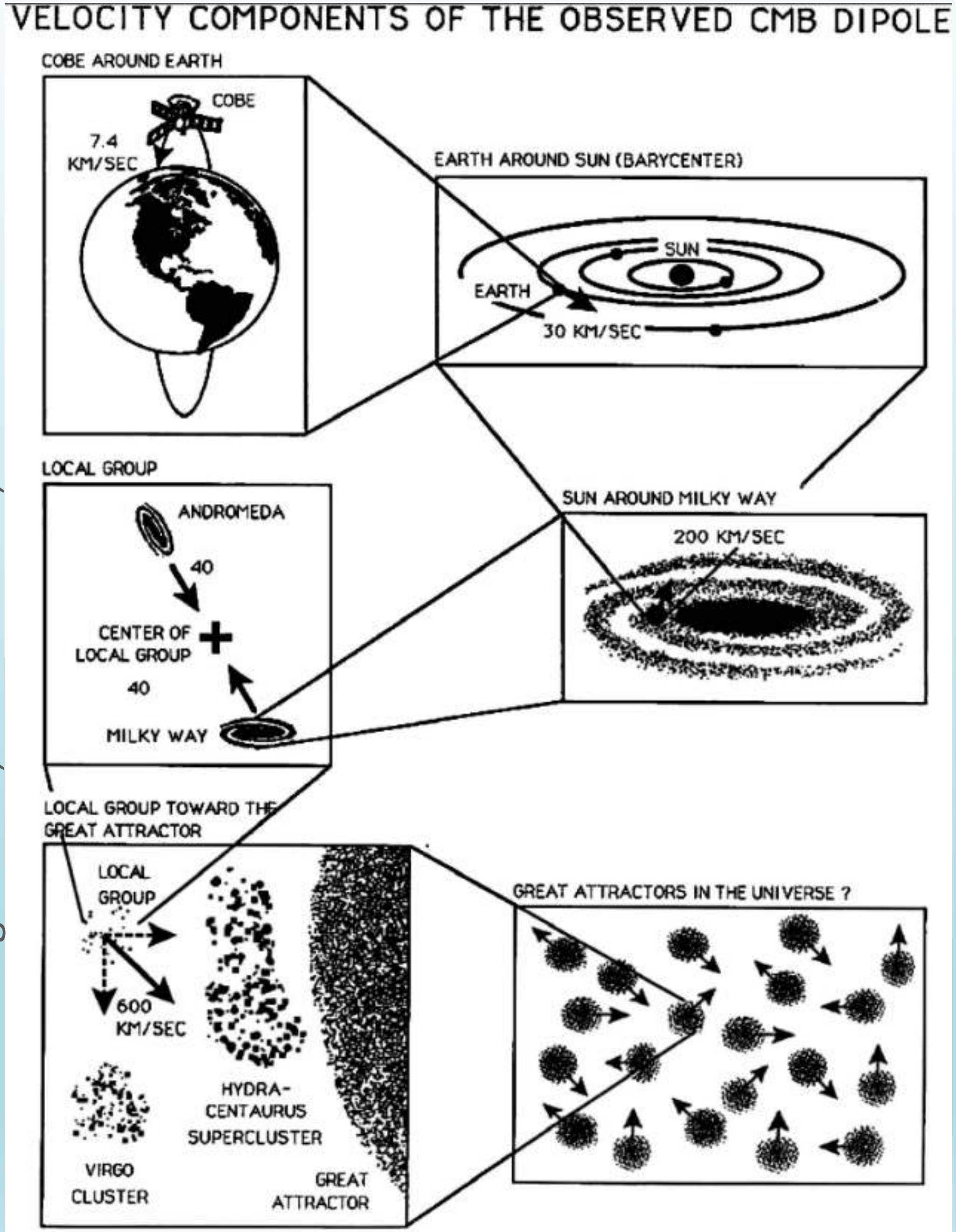
Sciama 1967, Peebles & Wilkinson 1968

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)



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

J. M. Stewart & D. W. Sciama

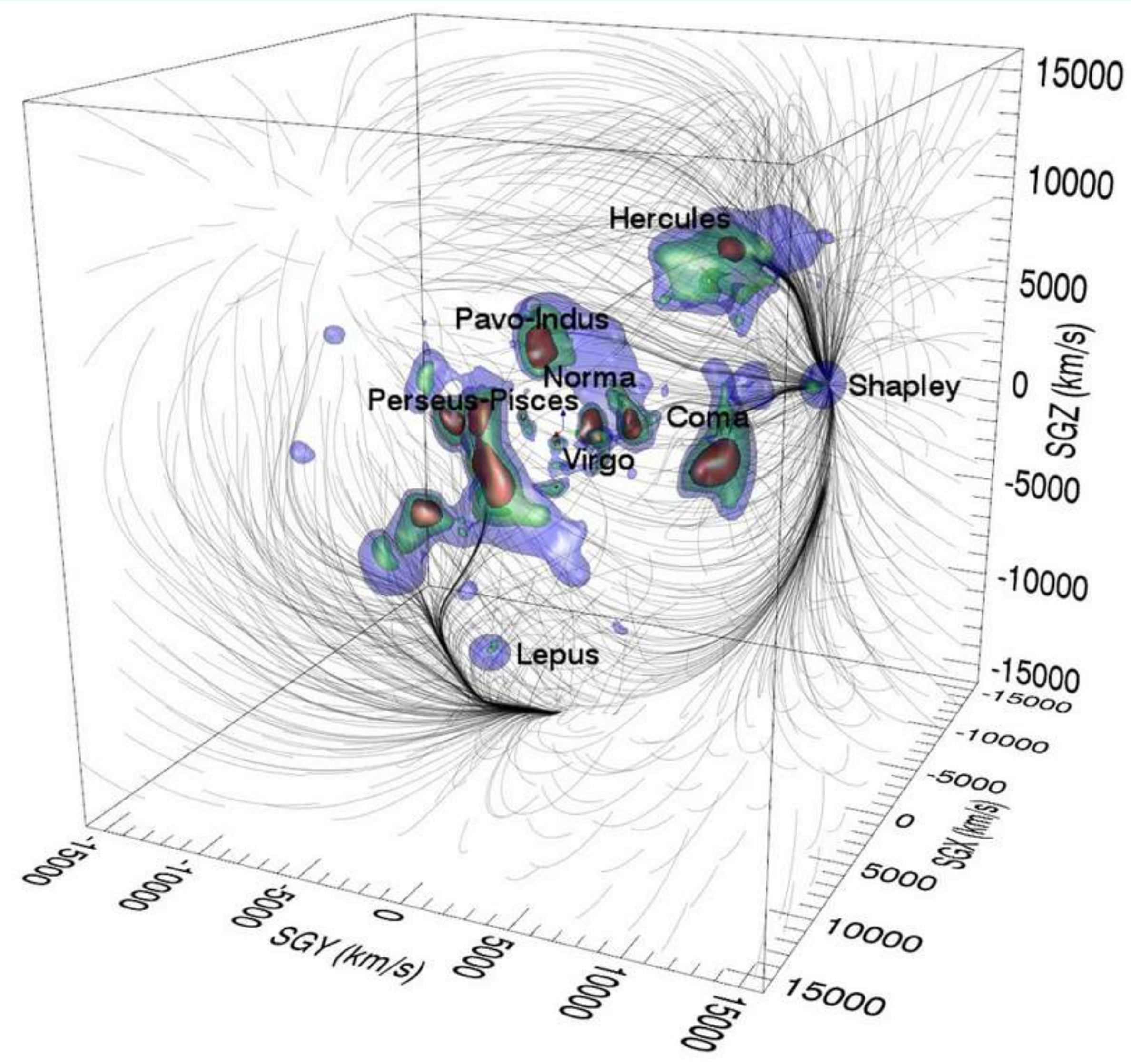
If the microwave blackbody radiation is both cosmological and isotropic, it will only be isotropic to an observer who is at rest in the rest frame of distant matter which last scattered the radiation. In this article an estimate is made of the velocity of the Sun relative to distant matter, from which 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

George Smoot, Nobel Lecture, 8 Dec 2006

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:

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

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

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

Window function

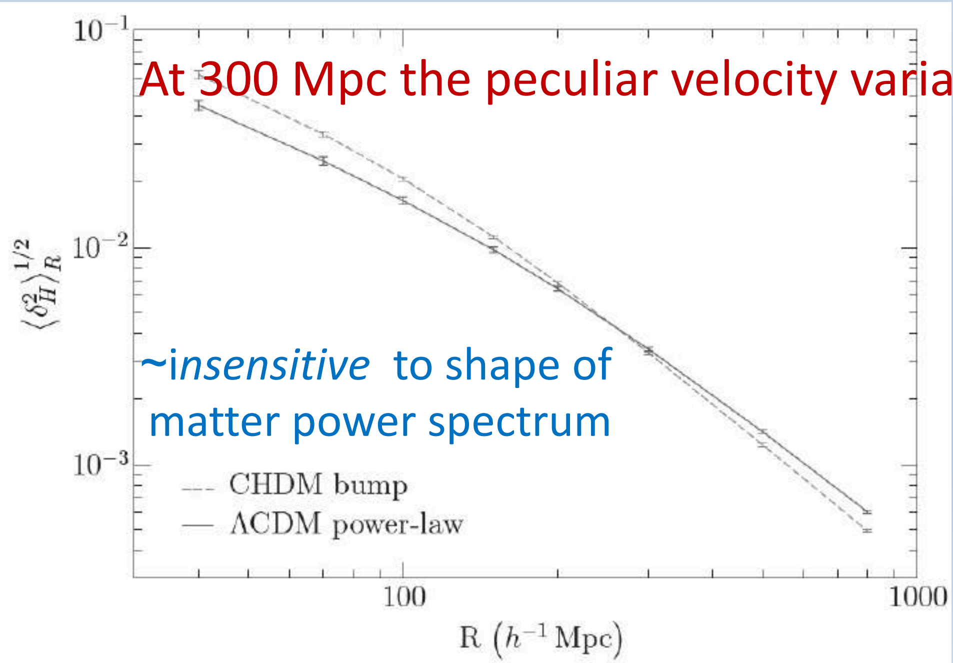
Then the RMS fluctuation in the local Hubble constant $\delta_H \equiv \langle (\delta H/H_0)^2 \rangle^{1/2}$ is:

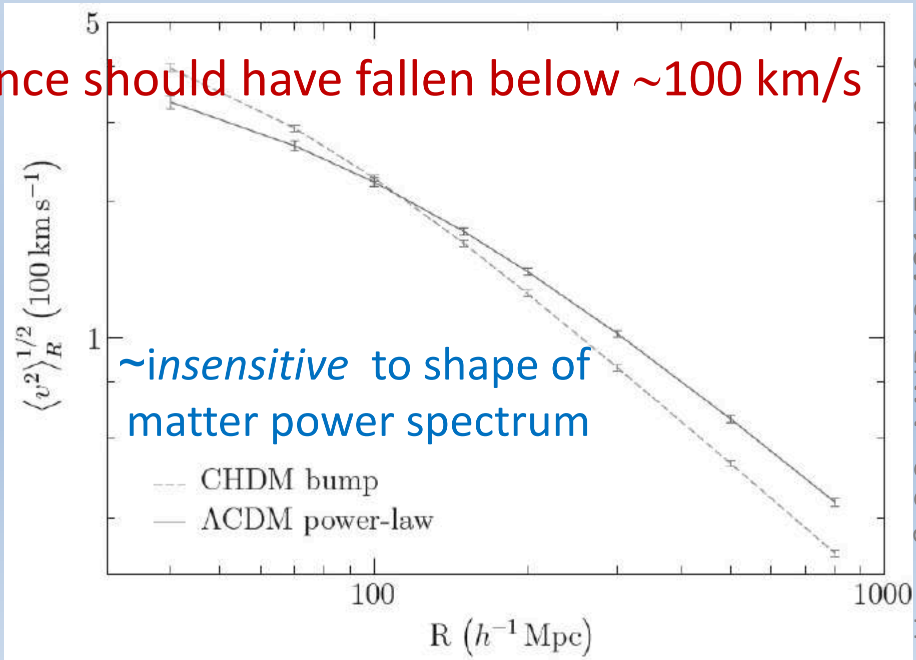
$$\delta_H^2 = \frac{f^2}{2\pi^2} \int_0^\infty k^2 dk\; P(k) \mathcal{W}^2(kR), P(k) \equiv |\delta(k)^2|, f \simeq \Omega_m^{4/7} + \frac{\Omega_\Lambda}{70}(1 + \frac{\Omega_m}{2})$$

Power spectrum of matter fluctuations — Growth rate

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

At 300 Mpc the peculiar velocity variance should have fallen below ~100 km/s



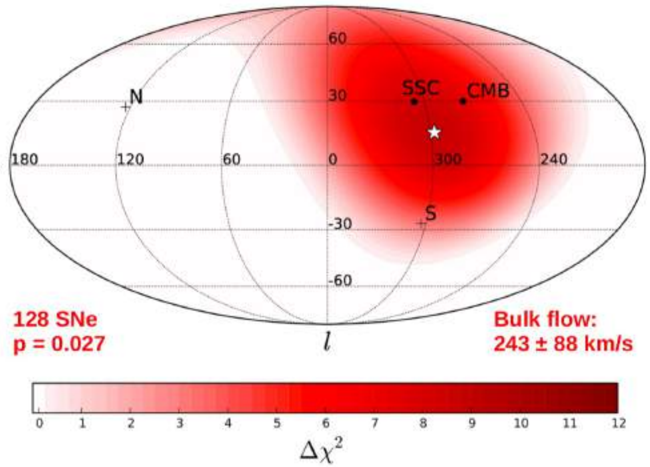


Hunt & S.S., MNRAS **401**:547,2010

Bulk Flow Analysis (Colin *et al*, MNRAS **414**:264,2011)

Dipole fit: 0.015 < z < 0.035

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



Bulk flow modeled as velocity dipole:

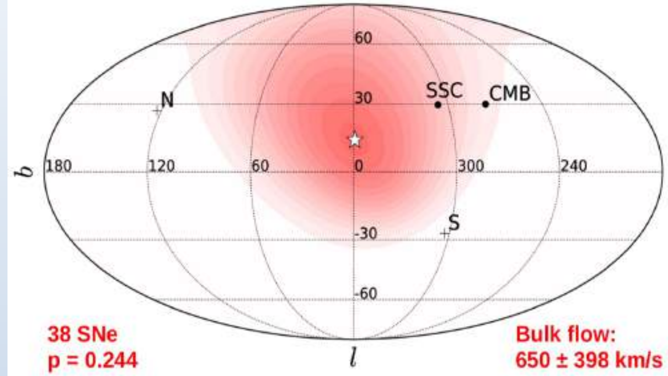
$$\tilde{d}_{\rm L}(z) = d_{\rm L}(z) + \frac{(1+z)^2}{H(z)}\vec{n}\cdot\vec{v}_{\rm d}$$

Best fit direction consistent with direction to Shapley

→ Amplitude matches previous studies

No convergence to the CMB frame out to ~260 Mpc

Dipole fit: 0.045 < z < 0.06



No backside infall behind Shapley

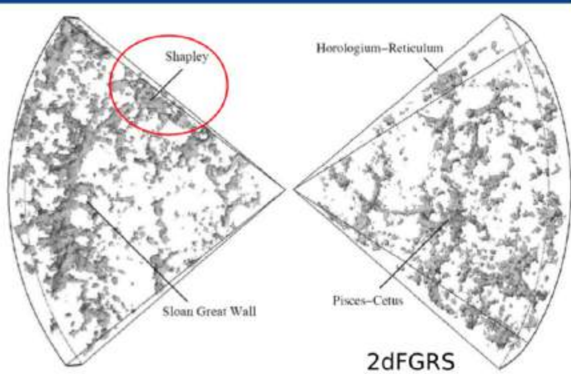
- Contradicts Shapley as the main source of the bulk flow
- Results in this shell are driven by SNfactory data

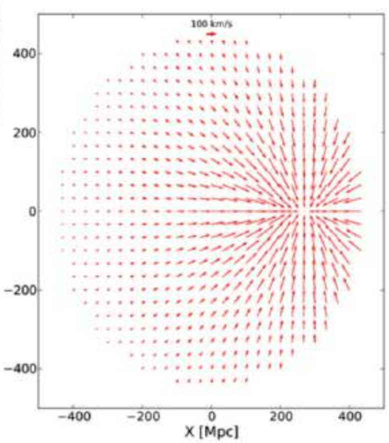
Need attractor mass of ~10^{17} M_{Sun} at ~300 Mpc to account for the flow

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

Finding the Attractors

Modeling the velocity field



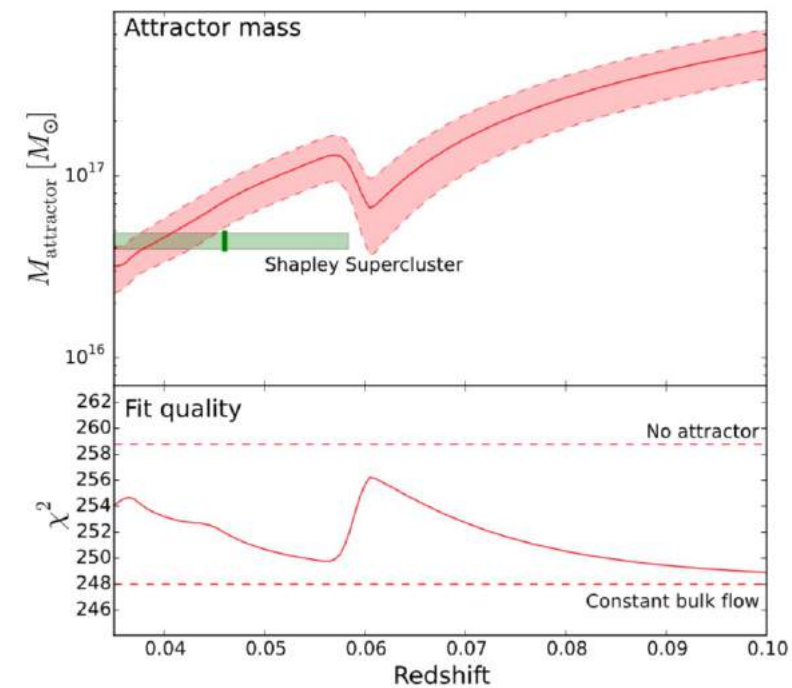


Simplest model:
Infall into spherical mass concentration

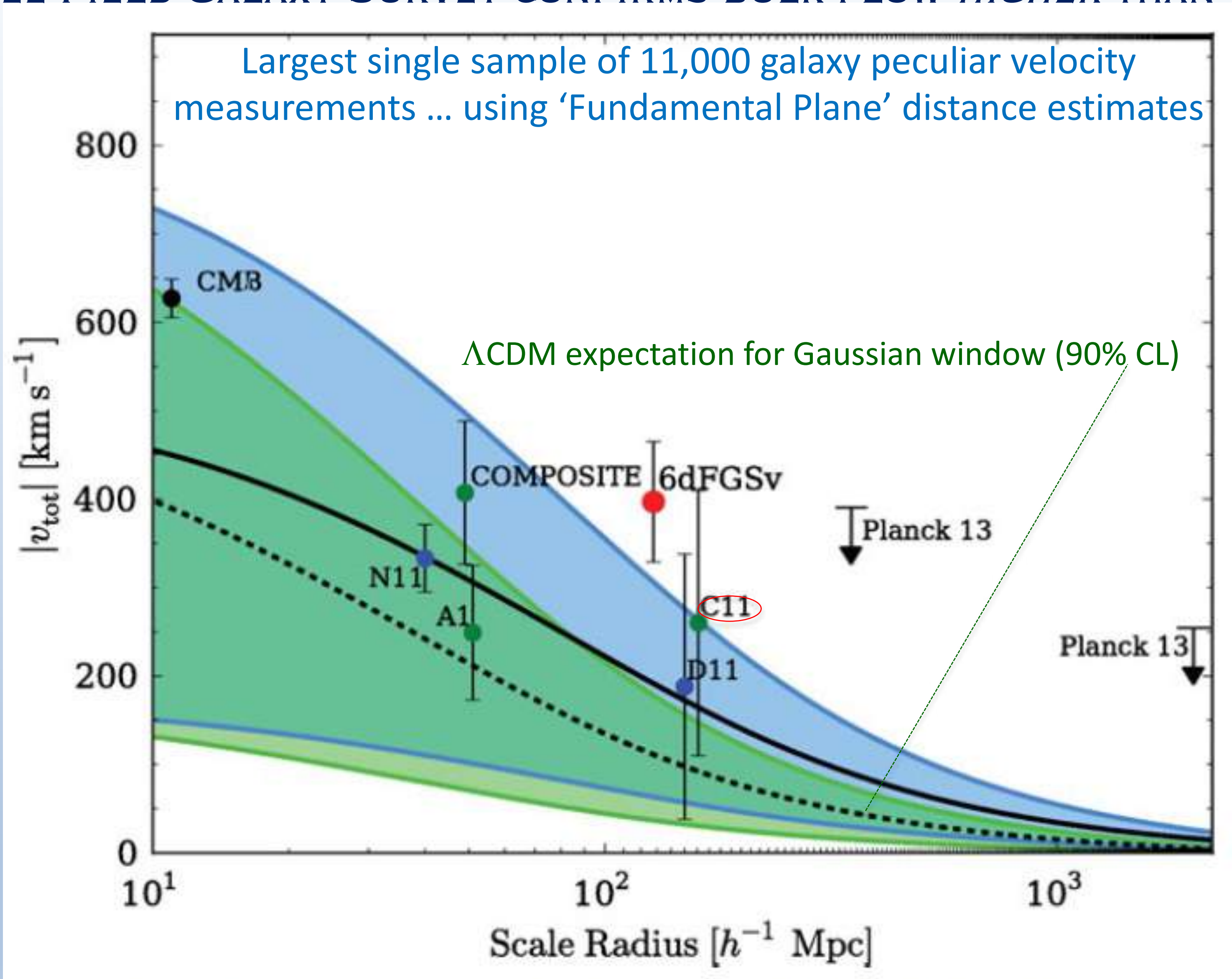
$$M_{\rm tot} = \frac{4\pi}{3}R^3\Omega_{\rm M}\rho_{\rm crit}(1+\delta)$$

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

Courtesey: Ulrich Feindt



6-degree Field Galaxy Survey confirms bulk flow *higher* than expected



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

In the 'Dark Sky' simulations, <1% of Milky Way–like observers experience a bulk flow as large as is observed and extending out as far as is seen … so the usually employed covariance (Hui & Greene 2006) is *not* applicable (Mohayaee *et al*, arXiv:2003.10420)

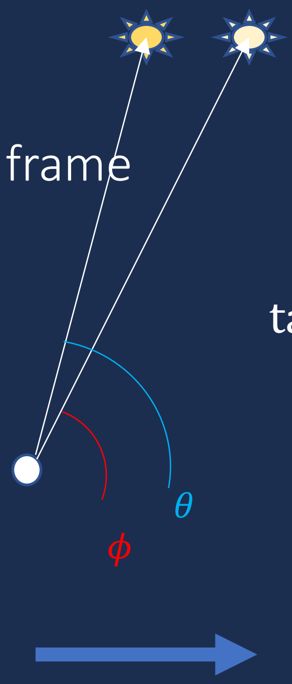
If the dipole in the CMB is due to our motion wrt the 'CMB frame' then we should see *similar* dipole in the distribution of distant sources

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

Aberration

Rest frame

Moving frame

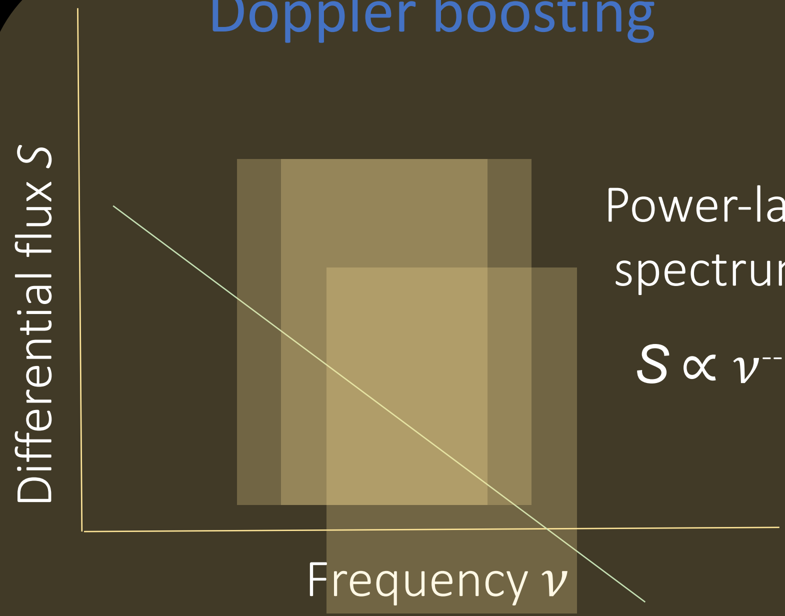


$$\tan\phi = \frac{\sin\theta}{\gamma * cos\theta - \frac{v}{c}}$$

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, MNRAS **206**:377,1984

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

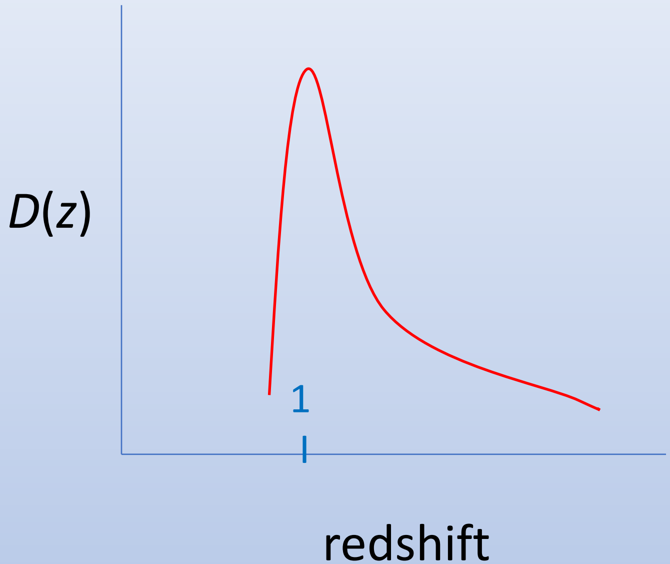
(a) the idea that the radio sources are at cosmological distances, or

(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.

Consider an all-sky catalogue of *N* sources with redshift distribution *D*(*z*) from a directionally unbiased survey



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

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

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

$\vec{\mathcal{S}} \rightarrow$ The 'clustering dipole' due to the anisotropy in the source distribution (significant for shallow surveys)

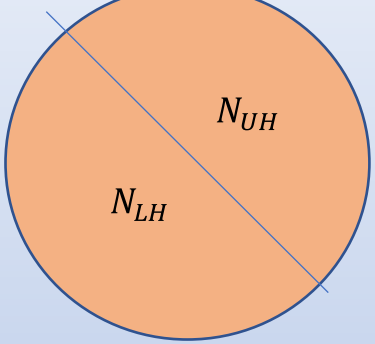
NVSS + SUMSS: 600,000 radio sources $\langle z \rangle \sim 1$ (est.), $\vec{\mathcal{S}}\,(D(z)) \rightarrow 0$ (est.)
Colin, Mohayaee, Rameez & S.S., MNRAS **471**:1045,2017

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

Wide Field Infrared Survey Explorer: 1,360,000 quasars, $\langle z \rangle \sim 1.2$, $\vec{\mathcal{S}}\,(D(z)) \sim 1\%$
Secrest, Rameez, von Hausegger, Mohayaee, S.S. & Colin, ApJ Lett.**908**:L51,2021

Estimators for the Dipole

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



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

Vary the direction of the hemispheres until maximum asymmetry is observed

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

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

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

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

However these estimators are biased (Rubart & Schwarz, A&A **555**:A117,2013)

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

New: *Unbiased* Least-Squares Estimator
Secrest *et al*, ApJL **908**:L51,2021

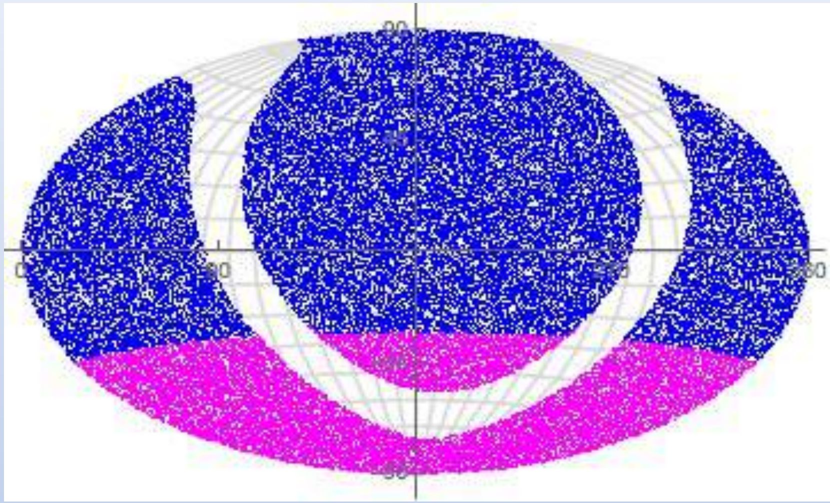
$$\vec{\mathcal{D}} = (A_{1,p}/A_0, A_{2,p}/A_0, A_{3,p}/A_0)$$

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

The NRAO VLA Sky Survey (NVSS) + Sydney University Molonglo Sky Survey (SUMSS)

(1.4 GHz survey down to Dec = -40.4°) (843 MHz survey at Dec < -30°)

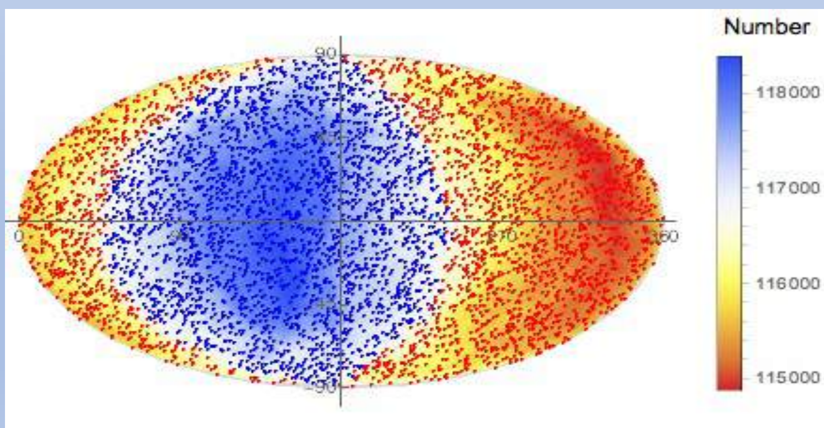
[Rescale the SUMSS fluxes by $(843\text{ MHz}/1.4\text{ GHz})^{-0.75} = 1.46$ to match with NVSS]

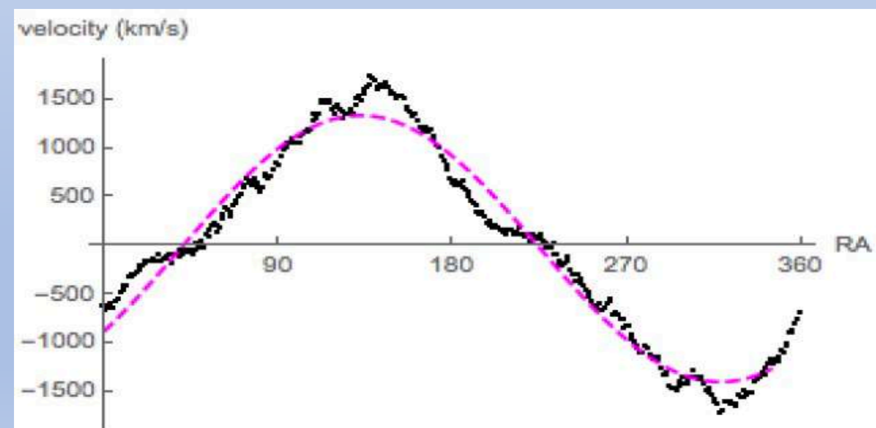


- Remove Galactic plane ±10° (also Supergalactic plane)
- Remove NVSS sources below (and SUMSS sources above) Dec = -30°
- Remove *any* nearby sources - in common with 2MRS & LRS surveys
- Adopt common flux threshold

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

The direction is within 10° of CMB dipole, but velocity is ~ 1355 ± 174 km/s

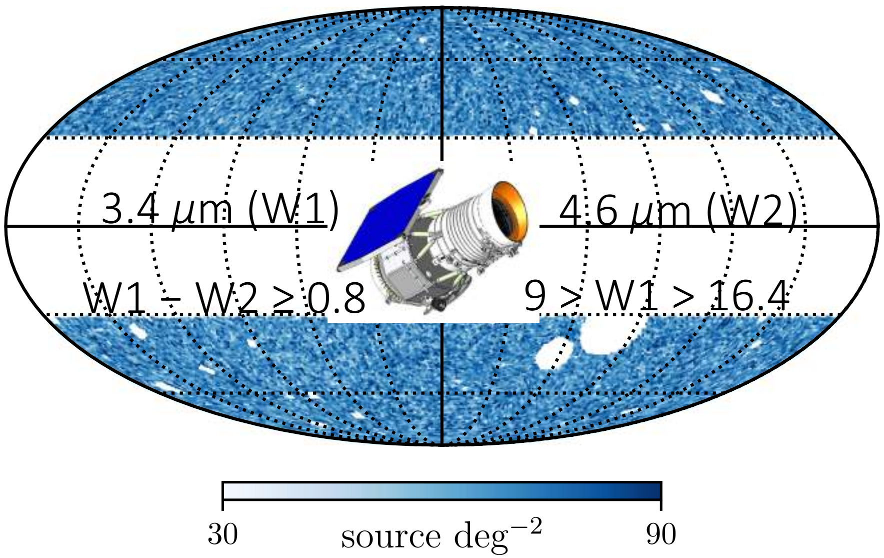


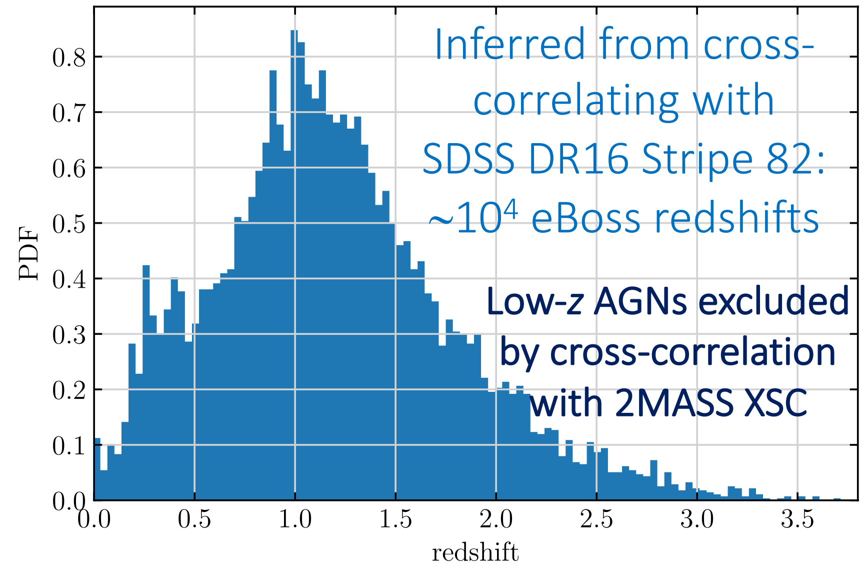


Confirms claim by Singal (ApJ **742**:L23,2011) … however source redshifts are not *directly* measured and the statistical significance is only 2.8**σ** (by Monte Carlo)

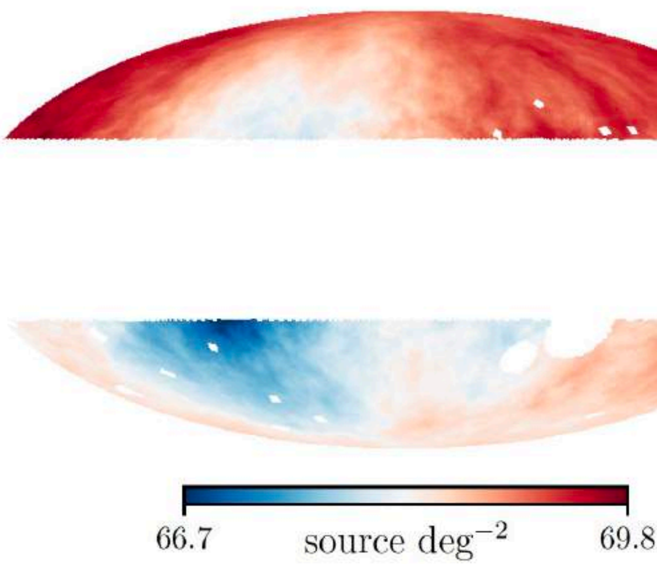
The CatWISE quasar catalogue (new)

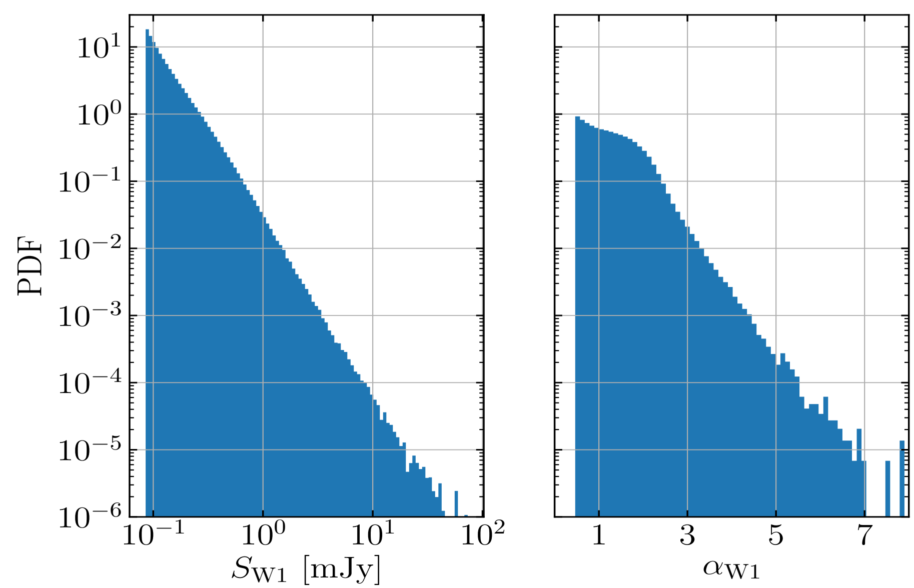
Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, ApJL **908**:L51,2021





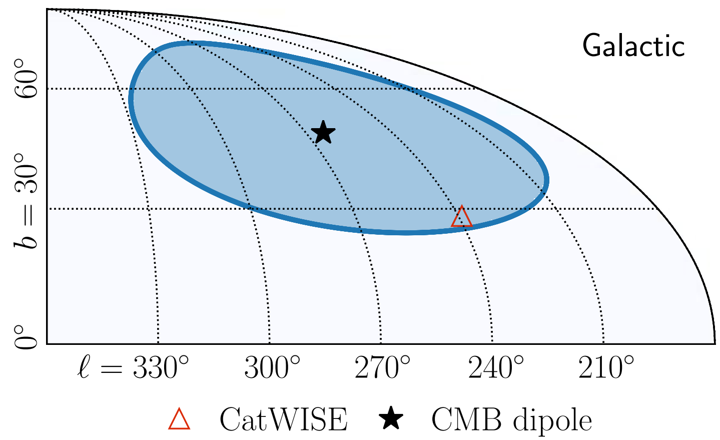
We now have a catalogue of ~1.36 million quasars, with 99% at redshift > 0.1



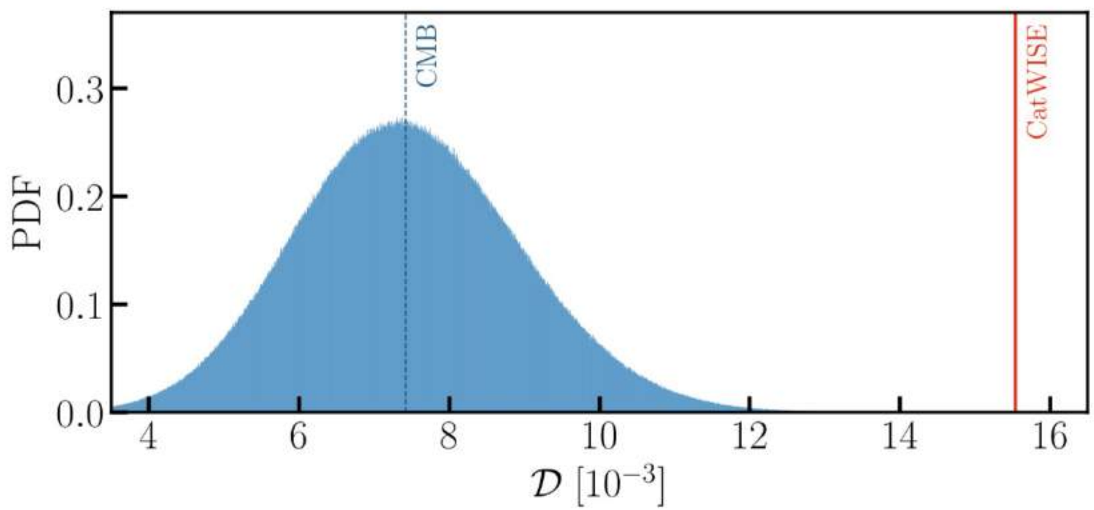


The dipole can be compared to that expected, knowing the spectrum & flux distribution

Our Peculiar velocity wrt quasars ≠ peculiar velocity wrt the CMB



The direction of the quasar dipole is consistent with the CMB dipole - but *not* the amplitude



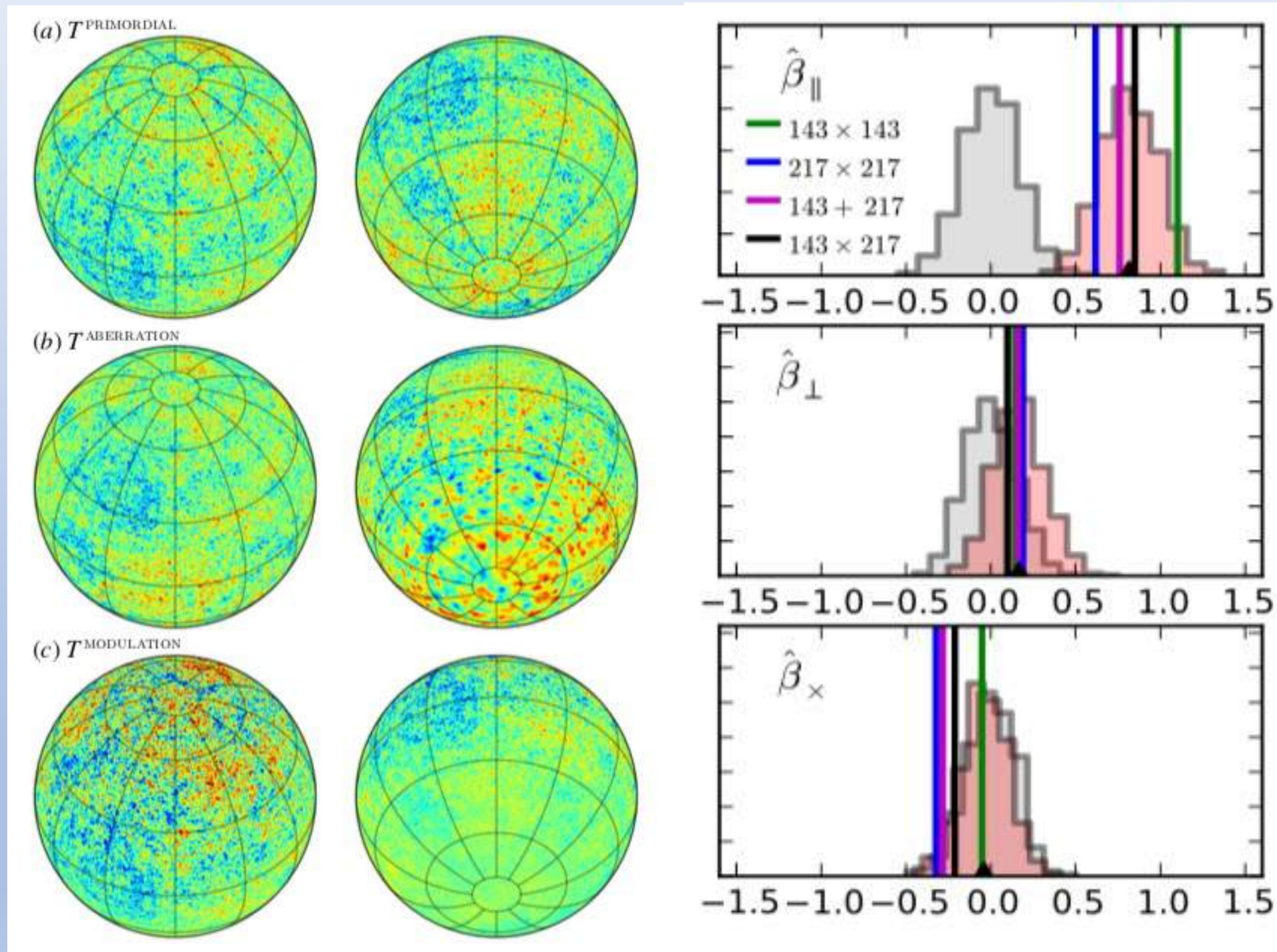
The kinematic interpretation of the CMB dipole is *rejected* with $p = 5 \times 10^{-7} \Rightarrow 4.9\sigma$

(All data and code available on: https://doi.org/10.5281/zenodo.4431089)

Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, ApJL **908**:L51,2021

Planck 2013 results. XXVII. Doppler boosting of the CMB: Eppur si muove★

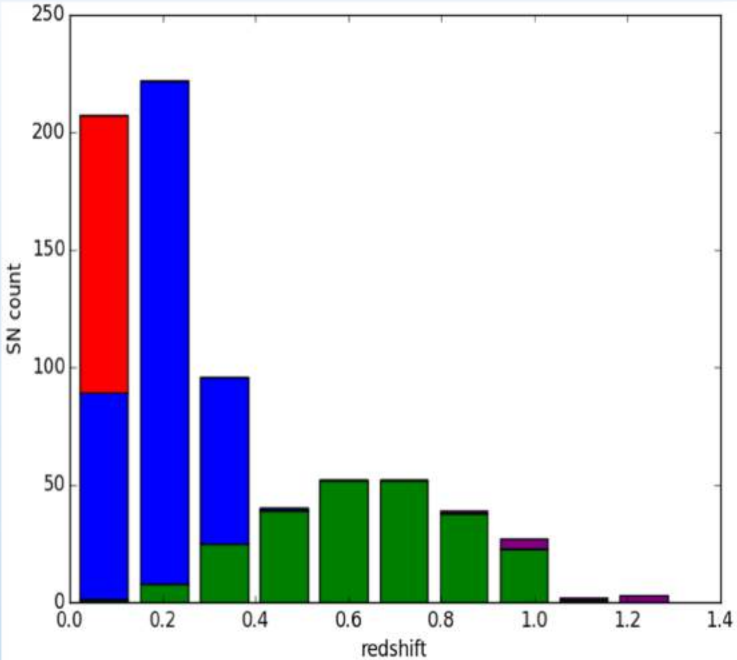
Planck attempted to measure the aberration effect on the CMB fluctuations, finding a velocity in the dipole direction of 384 ± 78 (stat) ± 115 (syst) km/s ⇒ <3σ detection

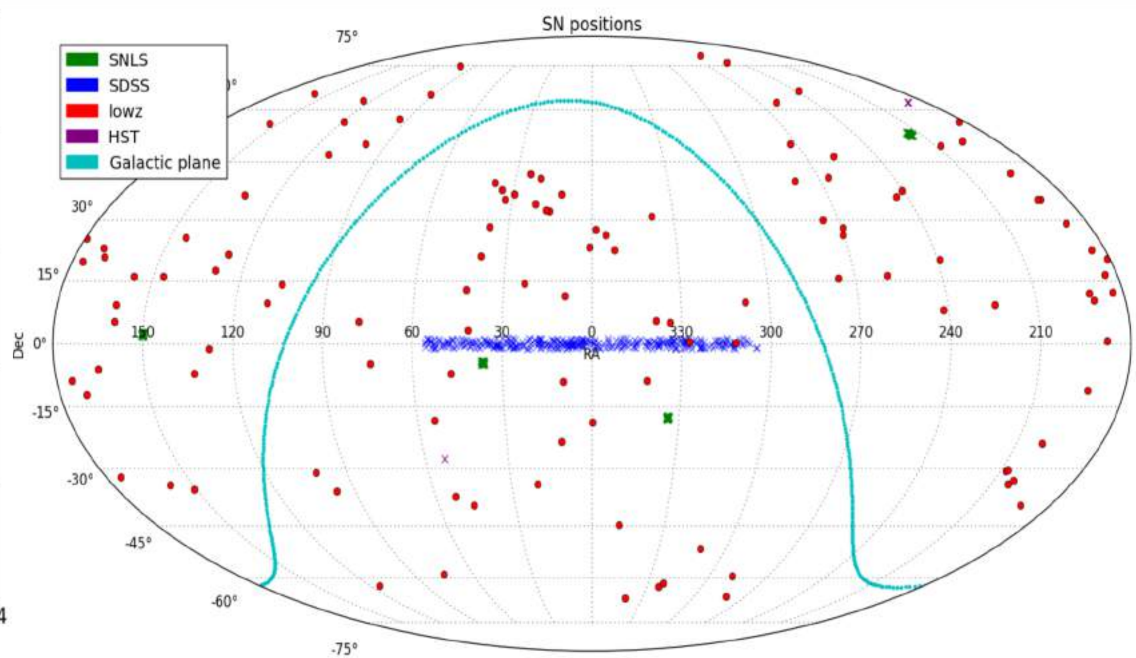


Planck collab., A&A **571**:A27,2014

Planck has also tried to measure the effect in tSZ (A&A **644**:A100,2020) … however this does not test the physical origin of the dipole (Notari & Quartin, PRD **94**:043006,2016)

Joint Lightcurve Analysis catalogue (740 Sne Ia)





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

Spectral Adaptive Lightcurve Template (SALT2) used to make ‘stretch’ and ’colour’ corrections to the observed peak magnitude)

B-band

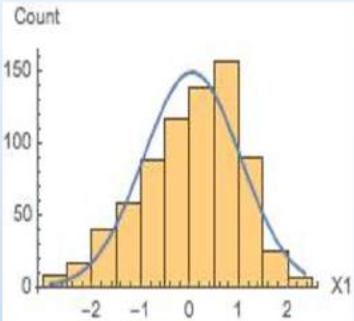
$$\mu_B = m_B^* - M + \alpha X_1 - \beta C$$

Name	$z_{\rm cmb}$	$m_B^\star$	X_1	C
03D1ar	0.002	23.941 ± 0.033	−0.945 ± 0.209	0.266 ± 0.035
03D1au	0.503	23.002 ± 0.088	1.273 ± 0.150	−0.012 ± 0.030

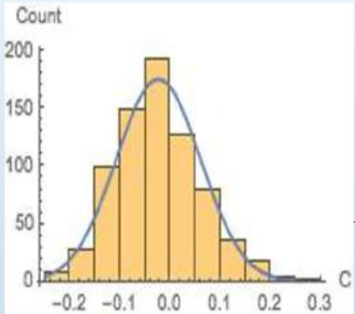
NB: The *measured* redshifts (in the heliocentric frame) have been ‘corrected’ to $z_{\rm CMB}$

Construct a Maximum Likelihood Estimator

Well-approximated as Gaussian



'Stretch' corrections



'Colour' corrections

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

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

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

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

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

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

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

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

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

intrinsic distributions

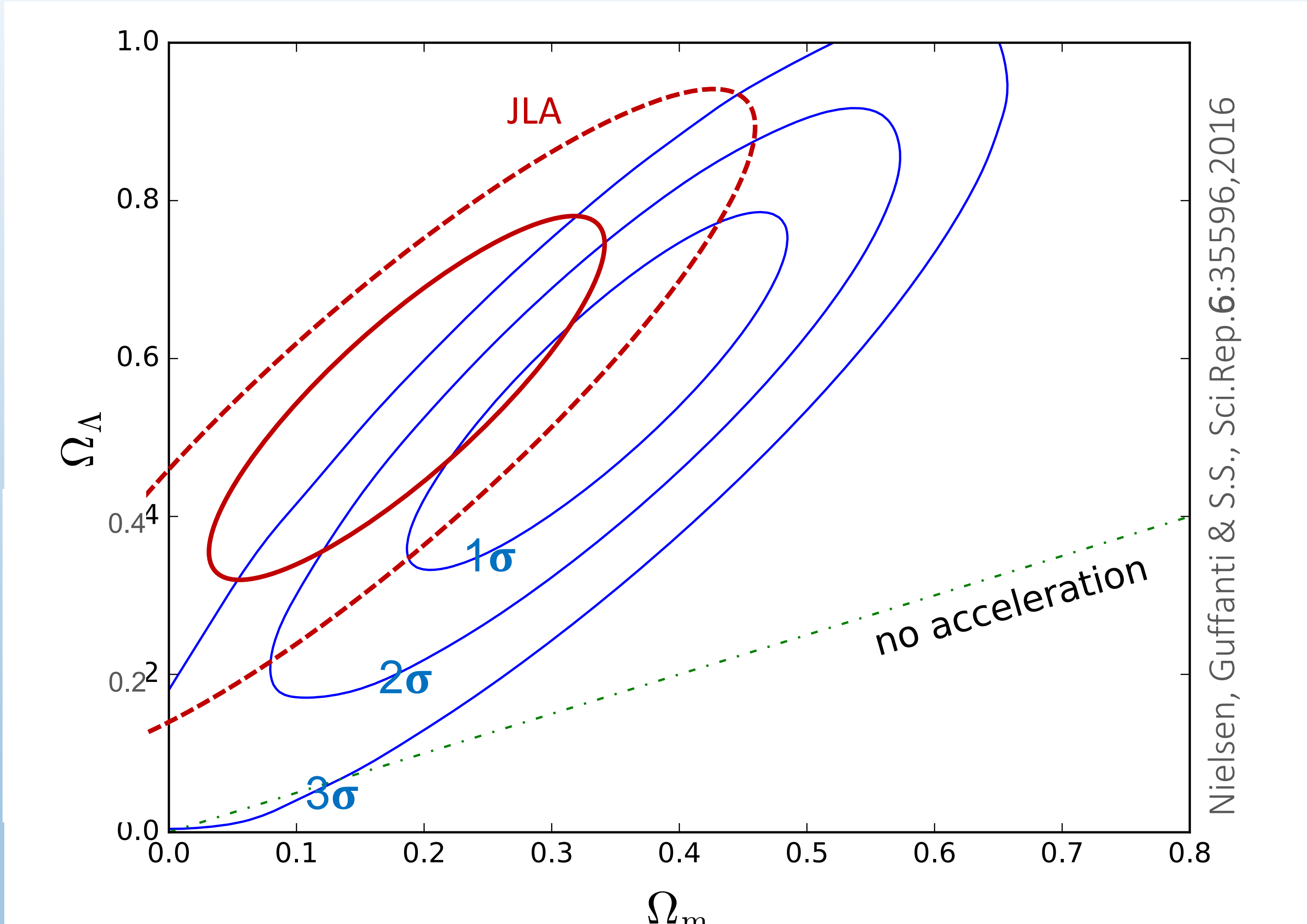
cosmology

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

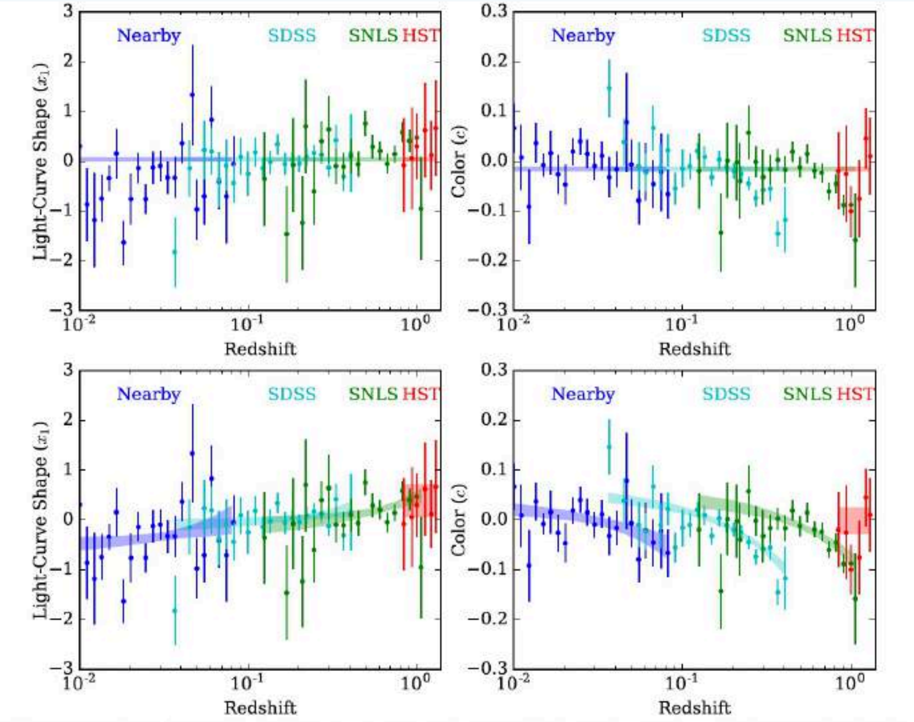
<u>MLE, *best fit*</u>

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

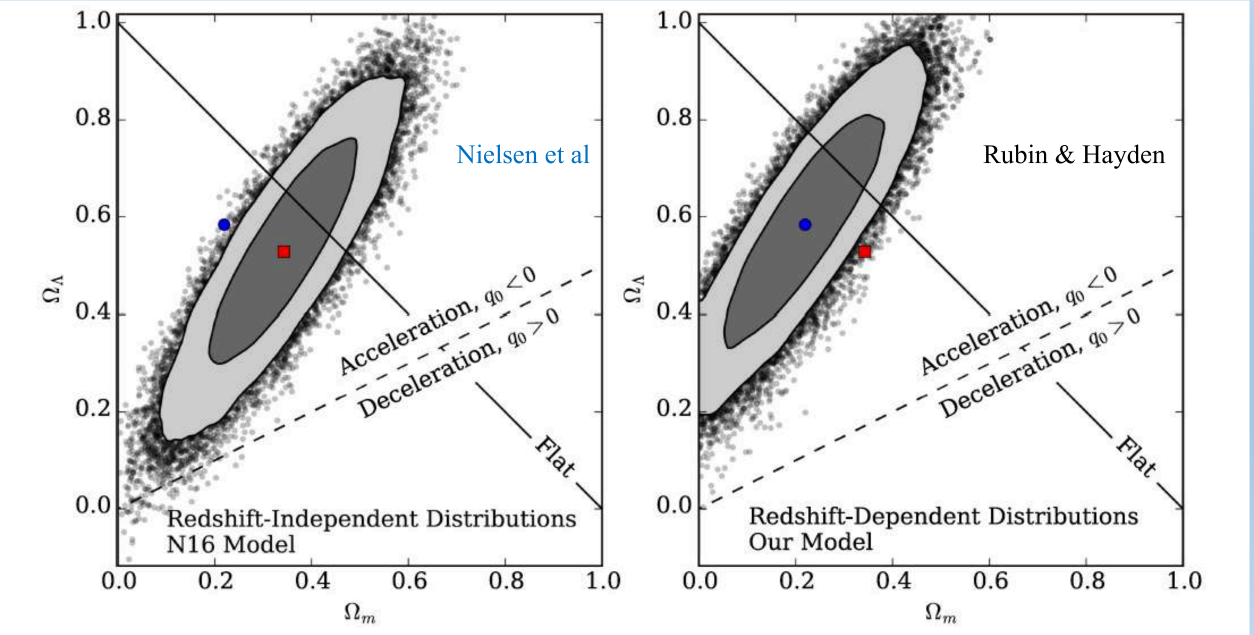
NB: We show the result in the Ω_m- Ω_Λ plane for comparison with previous results (JLA) simply to emphasise that the statistical analysis has *not* been done correctly earlier

(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



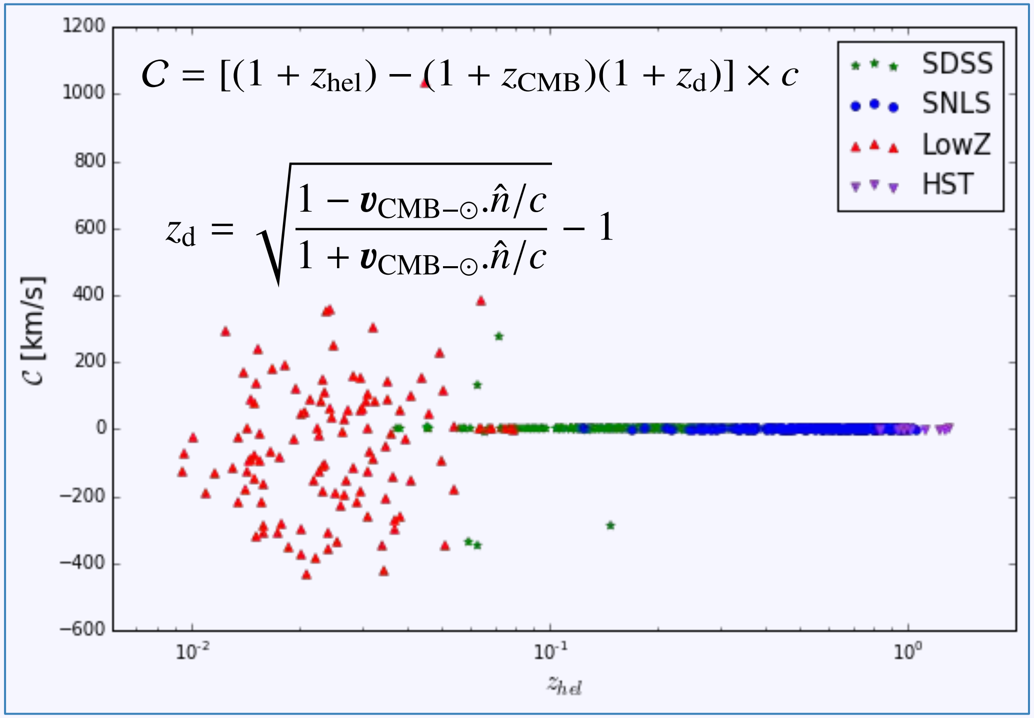
In any case this raises the significance with which a non-accelerating universe is rejected to only 3.7σ … still inadequate to claim a 'discovery' (even though the dataset has increased from ~100 to 740 SNe Ia in 20 yrs)

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_{hel} is related to $z_{CMB} \equiv z$ as:

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

where $z_{\odot}$ is the redshift induced by our motion w.r.t. the CMB and z_{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 have *assumed* that we converge to the CMB frame at ~150 Mpc (*contrary* to observations)



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

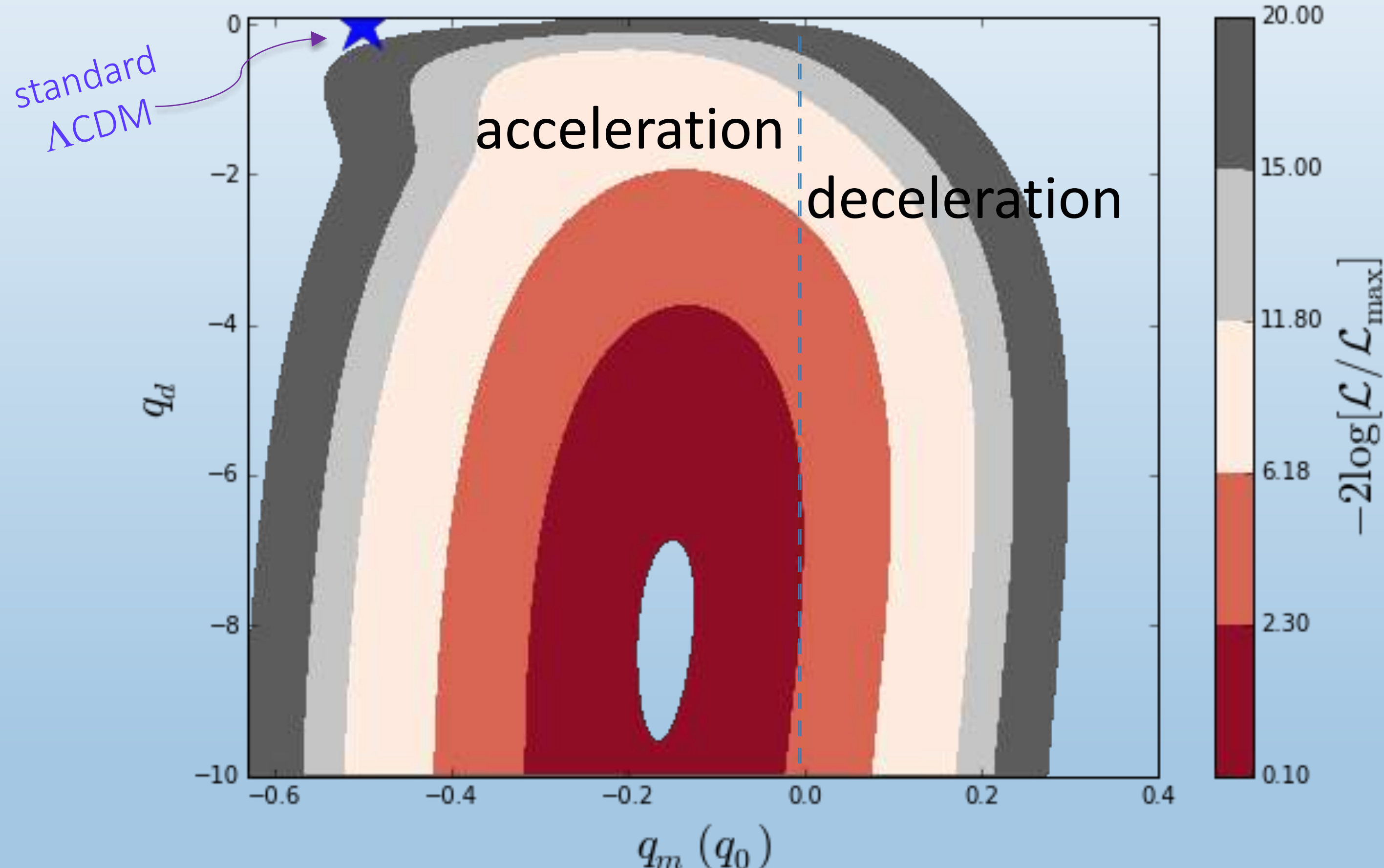
So we *undid* the corrections to recover the original data in the **heliocentric frame**

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

If we now do a cosmographic analysis allowing for a dipole in q_0, we find the MLE *prefers* one (x50 times the monopole!) … in the same direction as the CMB dipole

$$d_L(z) = \frac{cz}{H_0}\left[1 + \frac{1}{2}(1 - q_0)z + \ldots\right], \quad q_0 \equiv -(\ddot{a}a)/\dot{a}^2$$

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



Colin, Mohayaee, Rameez & S.S., A&A 631:L13,2019

The significance of q_0 being negative has now *decreased* to only 1.4σ

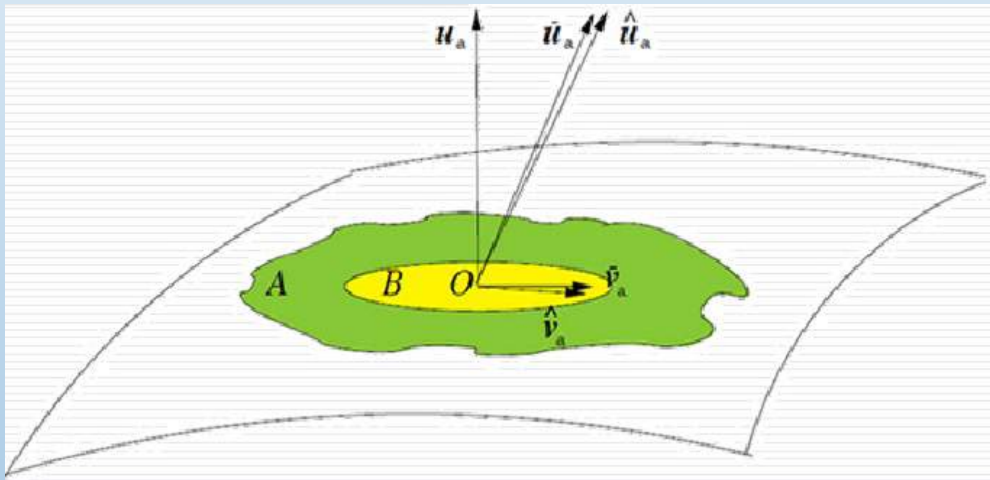
This strongly suggests that cosmic acceleration is an artefact of our being located in a deep bulk flow (which includes ~3/4 of the observed SNe Ia) … and *not* due to Λ

Do we infer acceleration although the expansion is actually decelerating

… because we are *embedded* in a local ‘bulk flow’?

(Tsagas 2010, 2011, 2012; Tsagas & Kadiltzoglou 2013, 2015)

… if so, there should be a dipole asymmetry in the inferred deceleration parameter in the *same* direction – i.e. ~aligned with the CMB dipole



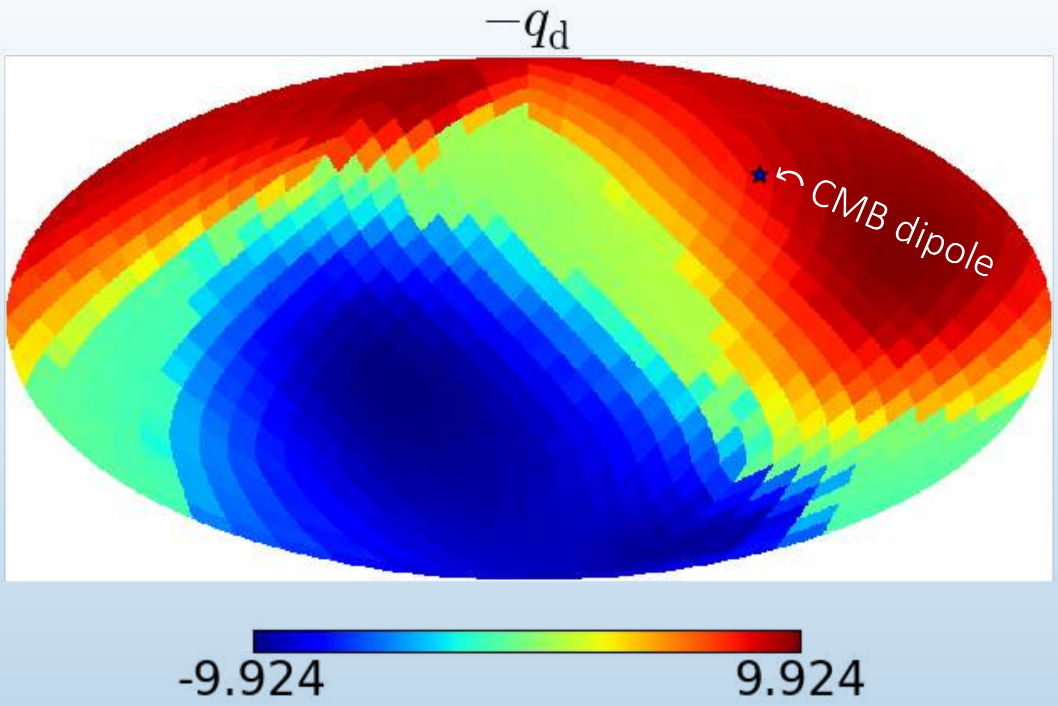
The patch A has mean peculiar velocity $\tilde{v}_a$ with $\vartheta = \tilde{\mathrm{D}}^a v_a \gtrless 0$ and $\dot{\vartheta} \gtrless 0$ (the sign depending on whether the bulk flow is faster or slower than the surroundings)

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

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

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

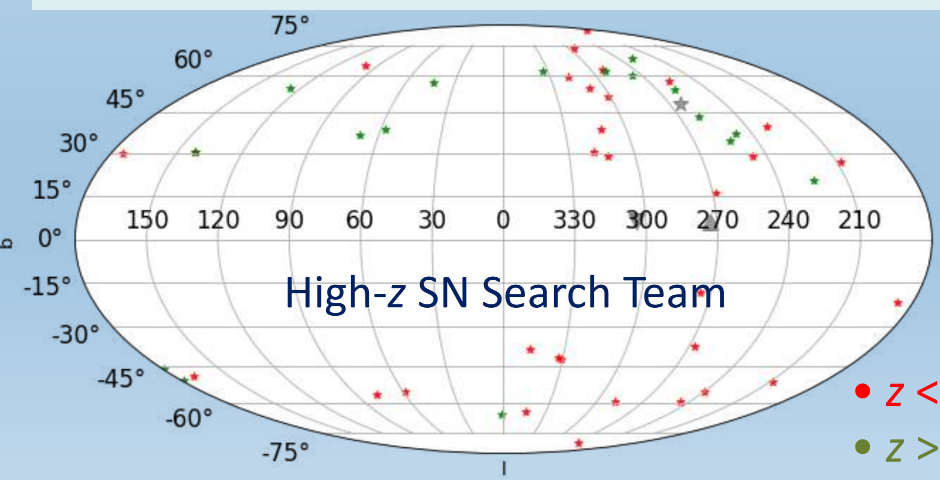
drops below 1 and the comoving observer ‘measures’ negative deceleration parameter

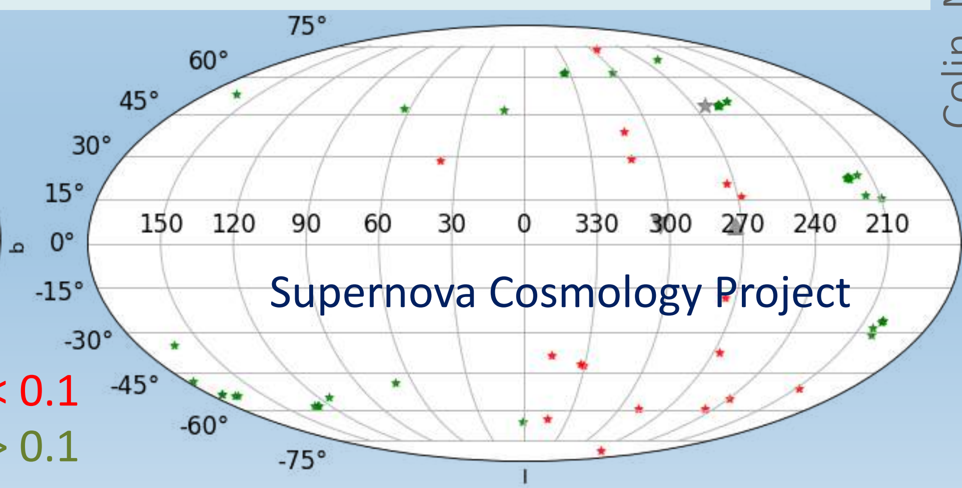


There is not enough data to do an *a priori* scan of the best-fit direction of q_d … but if done *a posteriori* it is within 23^0 of the CMB dipole. The log-likelihood changes very little between the two directions i.e. the inferred acceleration is consistent with being due to the bulk flow.

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

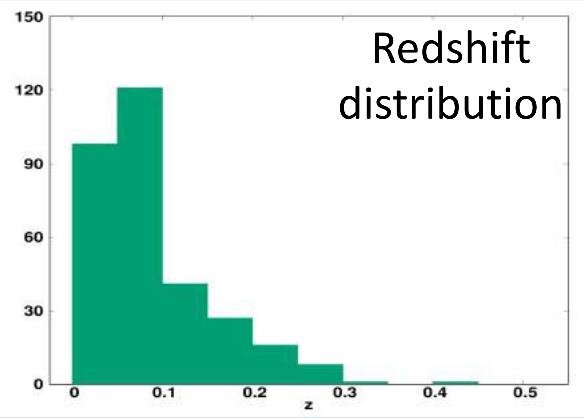
The 60 SNe Ia studied by Riess *et al.* (1998) and the 45 by Perlmutter *et al.* (1999) were mainly in the direction where the *apparent* acceleration peaks

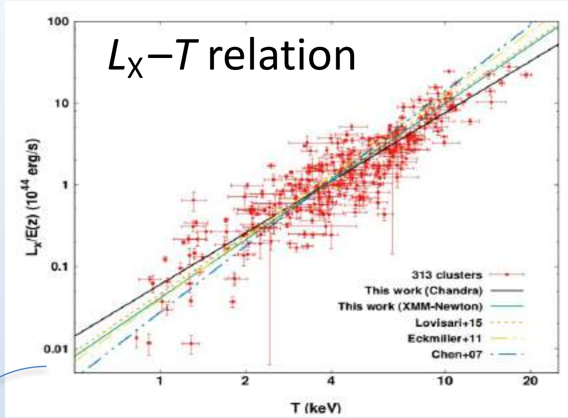


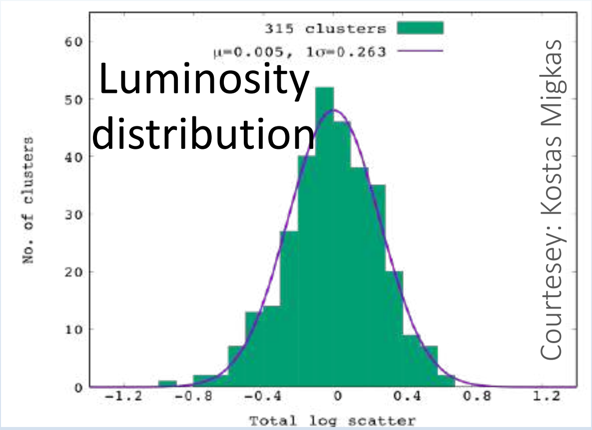


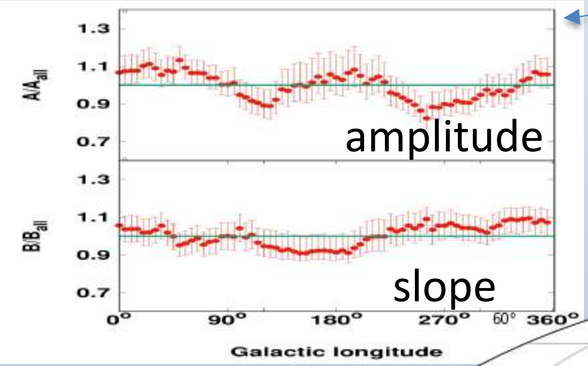
• $z < 0.1$
• $z > 0.1$

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

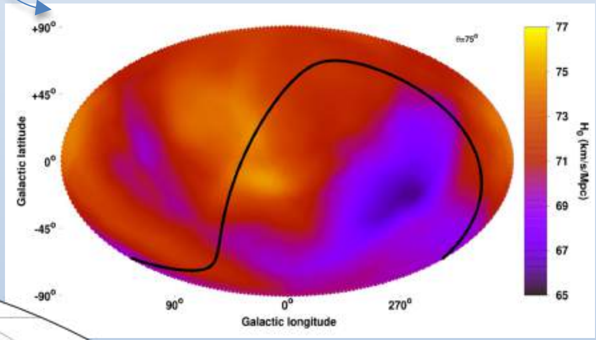


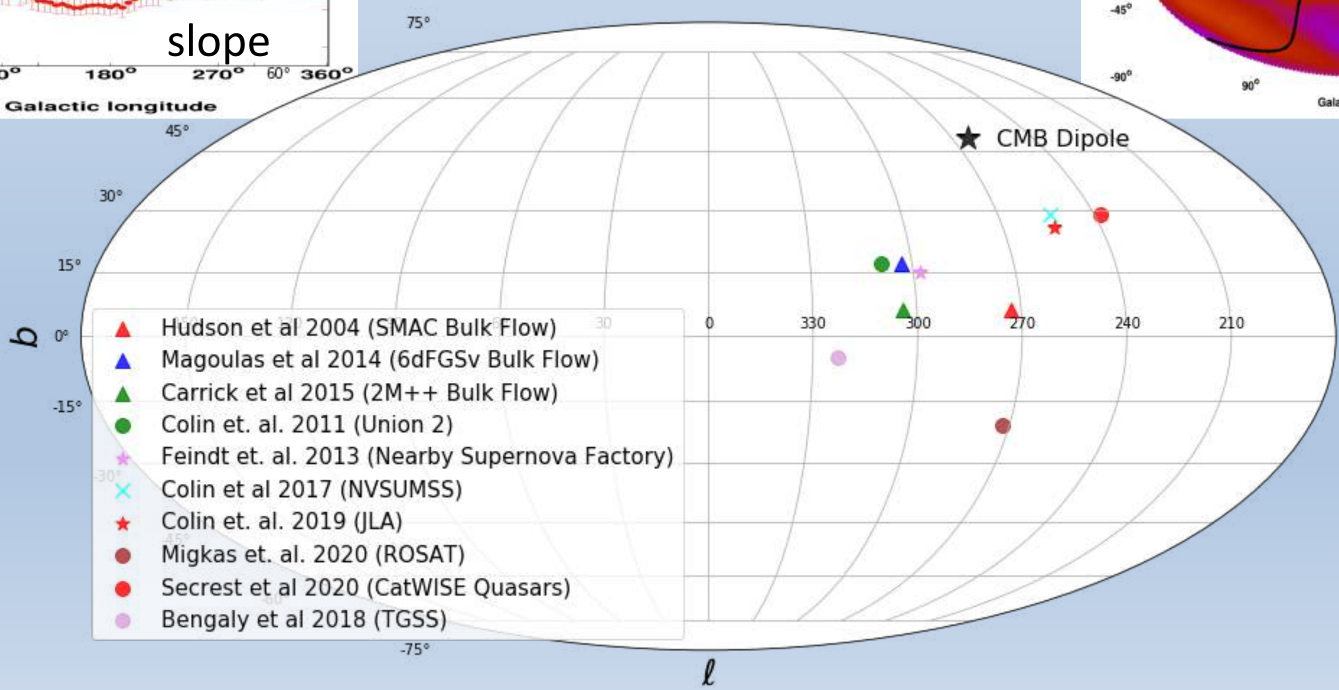






Migkas et al, A&A **636**:A15,2020, arXiv:2103.13904

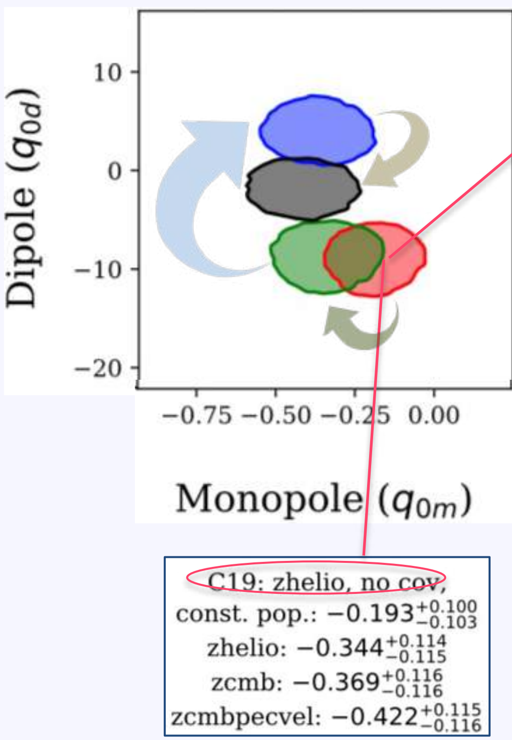




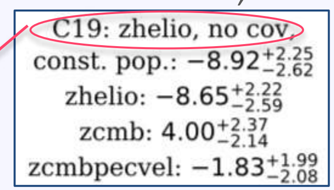
Our finding was *criticised* by Rubin & Heitlauf - who say that we should have:

- Allowed light-curve parameters to be *z*-dependent (doubles the # of parameters!)
- Used CMB frame rather than heliocentric redshifts
- R&H then reinstate the peculiar velocity 'corrections' (we have questioned earlier)

Without JLA peculiar velocity covariance



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



Correction: x_1 & *c* are *z*-dependent

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

\+ Correction: SNe peculiar velocities

Rubin & Heitlauf, ApJ **894**:68,2020 (rebuttal by Colin *et al*, 1912.04257)

All this assumes that the CMB frame is the 'correct' frame … which is now in question!

Prima facie the cosmic acceleration inferred from supernova data is *anisotropic* (q_{0d}) so cannot be interpreted as due to Λ - which would cause *isotropic* acceleration (q_{0m})

Standard cosmological model

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

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

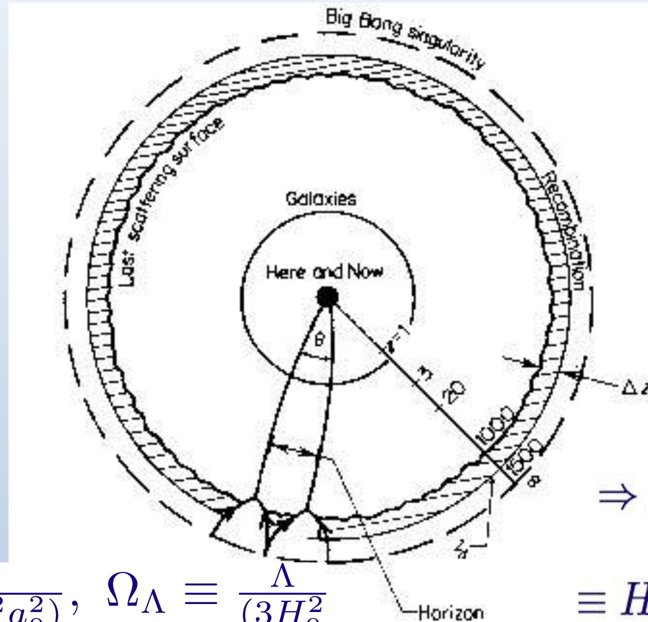
$$ds^2 \equiv g_{\mu\nu} dx^\mu dx^\nu$$

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

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

Robertson-Walker
Friedmann-Lemaître

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



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

Einstein

$$= 8\pi G_{\mathrm{N}} T_{\mu\nu}$$

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

$$\Lambda = \lambda + 8\pi G_{\mathrm{N}} \langle\rho\rangle_{\text{fields}}$$

$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\mathrm{N}} \rho_{\mathrm{m}}}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\Omega_{\mathrm{m}} \equiv \frac{\rho_{\mathrm{m}}}{(3H_0^2/8\pi G_{\mathrm{N}})},\ \Omega_k \equiv \frac{k}{(3H_0^2 a_0^2)},\ \Omega_\Lambda \equiv \frac{\Lambda}{(3H_0^2}$$

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

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

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

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

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 $(\rho_\Lambda)^{1/4} = (H_0^2/8\pi G_{\mathrm{N}})^{1/4} \sim 10^{-12}$ GeV << $G_F^{-1/2} \sim 10^2$ GeV

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

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

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: $H^2 = 8\pi G_{\text{N}}/3 + \Lambda/3$) → ruled out by Big Bang nucleosynthesis which requires G_{N} to be within 5% of lab value ... in any case this will *not* yield accelerated expansion

Therefore *every* attempt to explain the coincidence problem is severely fine-tuned

Recent suggestion that *S*-matrix formulation of quantum gravity *excludes* de Sitter vacua (Dvali, 2012.02133; Obied, Ooguri, Spodyneiko & Vafa, 1806.08362)

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*?

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 this bulk flow - the acceleration is mainly a dipole aligned with the 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 this be an indication of new horizon-scale physics (Gunn 1988, Turner 1991)?

['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 so is the inference that the universe is dominated by dark energy