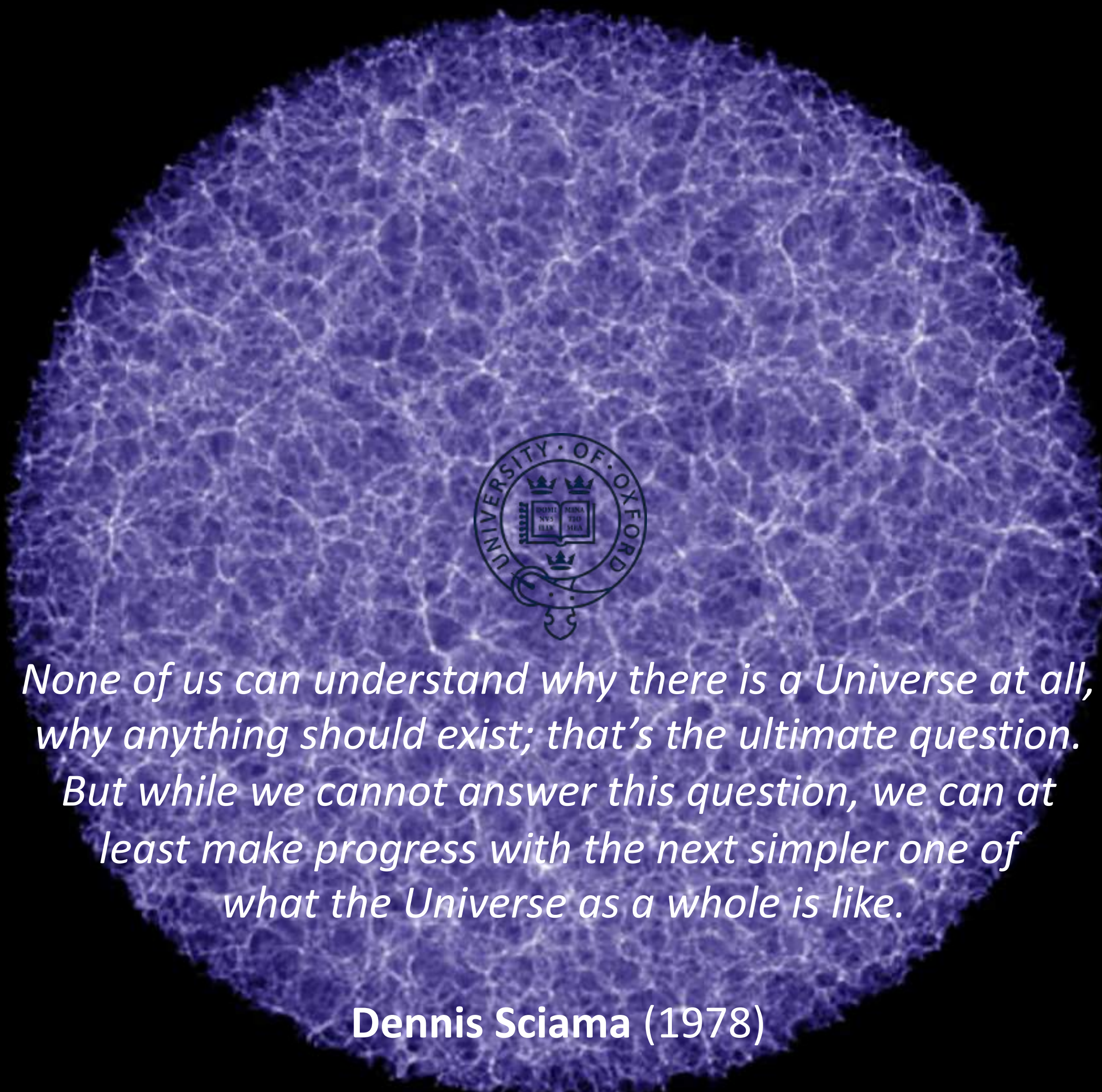
Reconstructing Cosmology

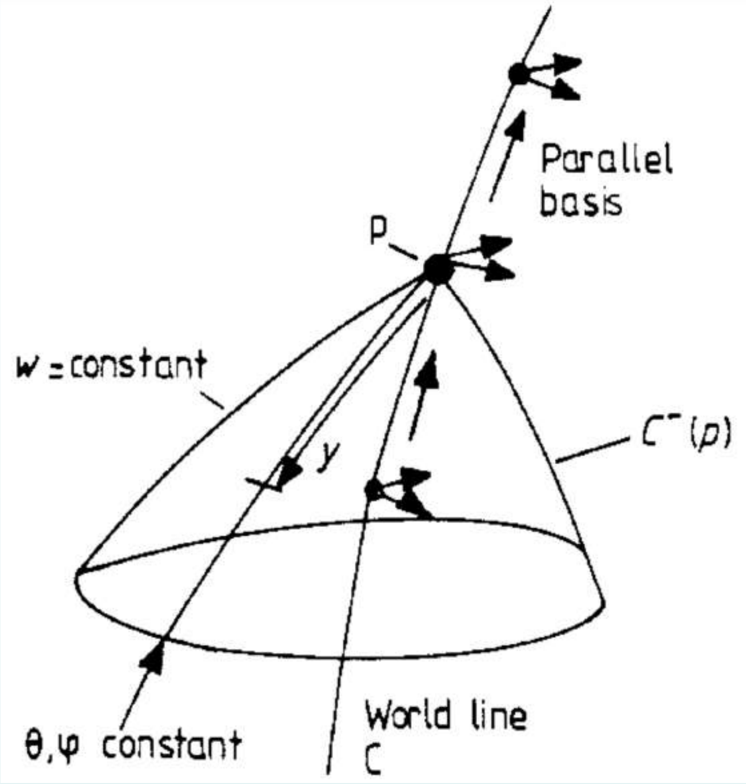
Subir Sarkar



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



Ellis & Stoeger, CQG 4:1697,1987

We cannot move over cosmological distances and check if the universe looks the same from 'over there' … so must *assume* that our position is not special

> *"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)

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)

An observational test was proposed after cosmologically distant radio sources were identified

On the expected anisotropy of radio source counts

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

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

If the standards of rest determined by the MBR and the number counts were to be in serious disagreement, one would have to abandon

...

c) The standard FRW universe models

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

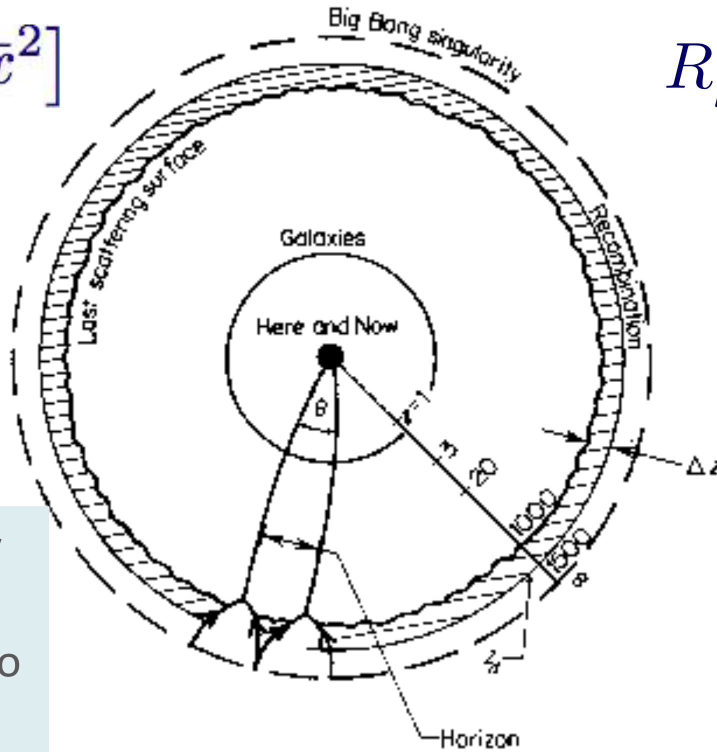
The standard cosmological model is based on three key assumptions:

Maximally symmetric space-time + General relativity + Ideal fluids

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

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

Space-time metric
Robertson-Walker



$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \lambda g_{\mu\nu} = 8\pi G_{\mathrm{N}} T_{\mu\nu}$$

Geometrodynamics
Einstein

It is the *assumed* homogeneity and isotropy that enables the Einstein eqn. to be simplified to the Friedmann-Lemaître eqns.

'Dust' → quantum fields

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

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

Eqn. of state of Λ: $P = -\rho \Rightarrow$ accn. at $z < 1$

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

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

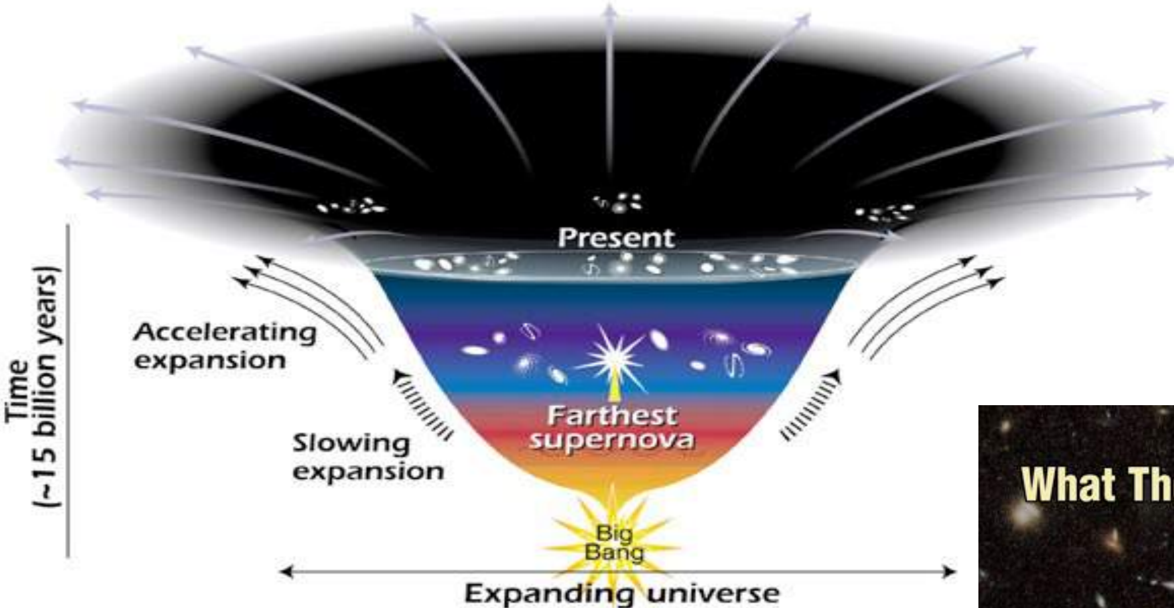
$$\equiv {H_0}^2\left[\Omega_{\mathrm{m}}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

$$z \equiv \frac{a_0}{a} - 1,\ \Omega_{\mathrm{m}} \equiv \frac{\rho_{\mathrm{m}}}{3H_0^2/8\pi G_{\mathrm{N}}},\ \Omega_k \equiv \frac{k}{a_0^2 H_0^2},\ \Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2}$$

This yields the 'cosmic sum rule': $1 \equiv \Omega_{\mathrm{m}} + \Omega_k + \Omega_\Lambda$

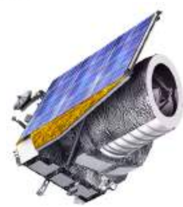
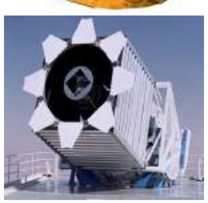
It is just this sum rule that is used to *infer* a non-zero Λ of order H_0^2 from observations of SNe Ia, CMB, BAO, lensing etc …

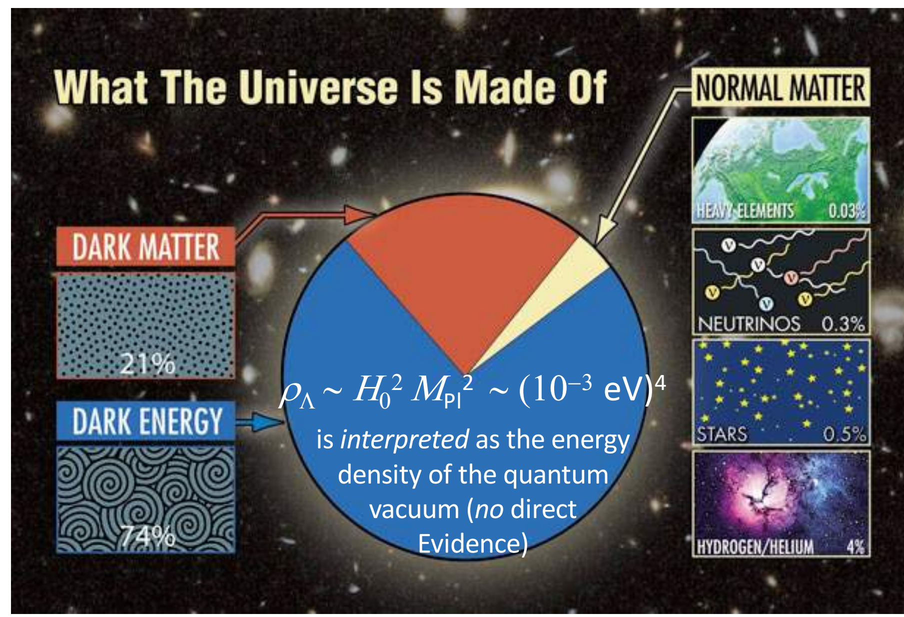
There is as yet no compelling *dynamical* evidence for Λ (e.g. the late-ISW effect)



The ΛCDM model is 'simple' (if we take Λ to be just another parameter!) and fits the data (with just a few anomalies) … but lacks a *physical* foundation`





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***

What do we know about Λ from 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 M)?

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

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

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 expectation (although strictly *not* calculable) is:

$\rho_\Lambda \sim (1\ \text{TeV})^4 \Rightarrow 10^{60}$ x $(1\ \text{meV})^4$

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

There must be a very 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

Is Λ in fact *forbidden* in S-matrix formulation of quantum gravity? (Dvali, *Symmetry* **13**:3,2021)

Interpreting $\Lambda \sim H_0^2$ as vacuum energy raises the 'coincidence problem':

why is $\Omega_\Lambda \sim \Omega_m$ 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 any fundamental theory and is just put in by hand!

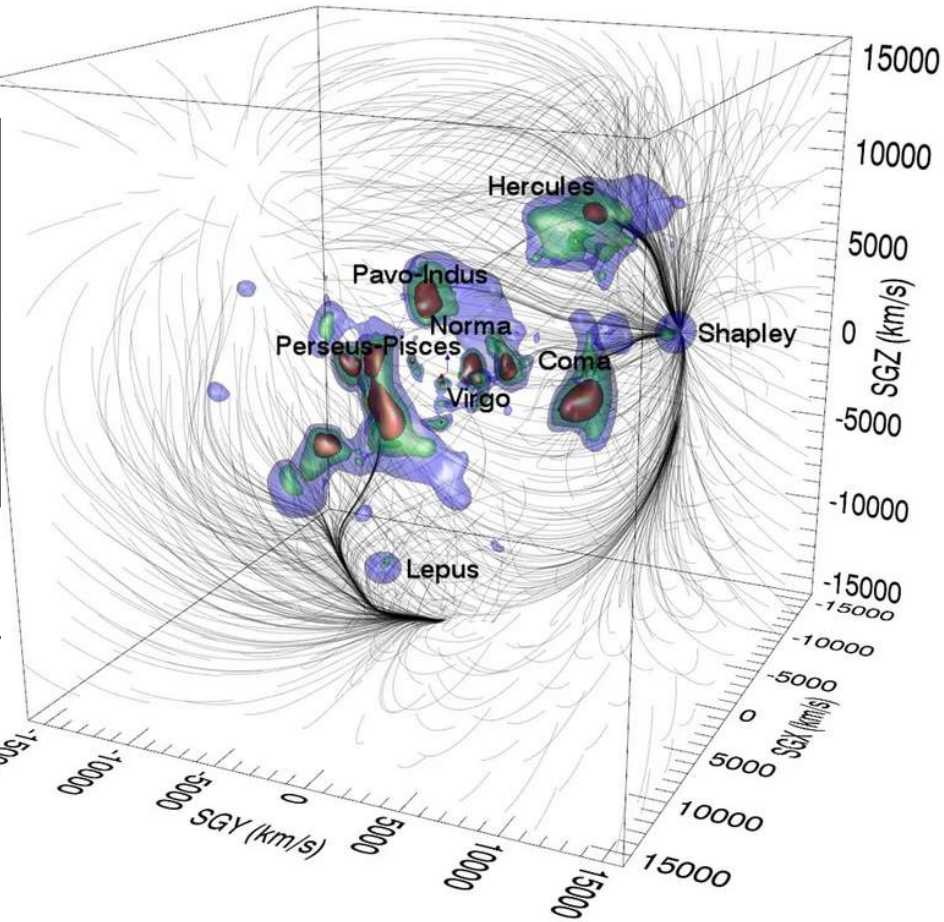
Similar fine-tuning in *every* proposal to explain DE, e.g. massive gravity, chameleon fields, ...

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

Thus there can be no *physical* explanation for the 'coincidence problem'

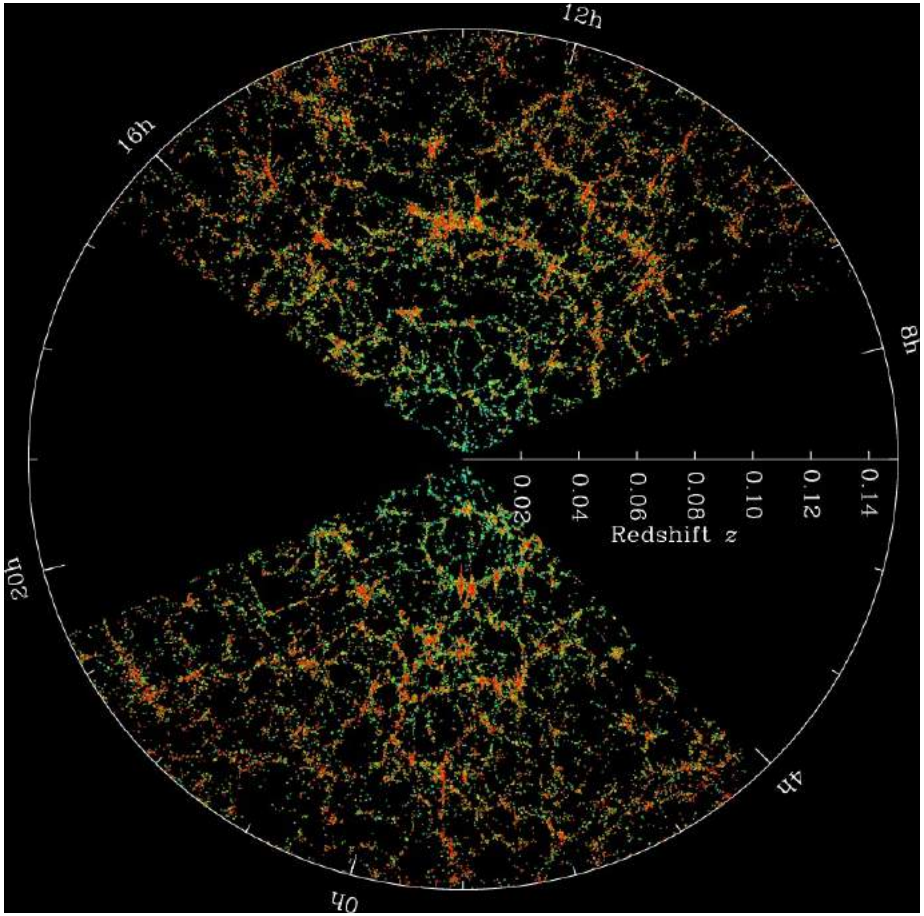
Do we infer $\Lambda \sim H_0^2$ because that is just the observational sensitivity (in the FLRW framework) to the arbitrary parameter Λ – in terms of H_0 the *only* dimensionful observable in the model ... which enters into *every* cosmological measurement?

Tully *et al*. *Nature* 513:71, 2014



This is what our Universe *actually* looks like locally (out to ~200 Mpc)

… and on the biggest scales (~ 600 Mpc) mapped



Is it justified to approximate it as *exactly* homogeneous?

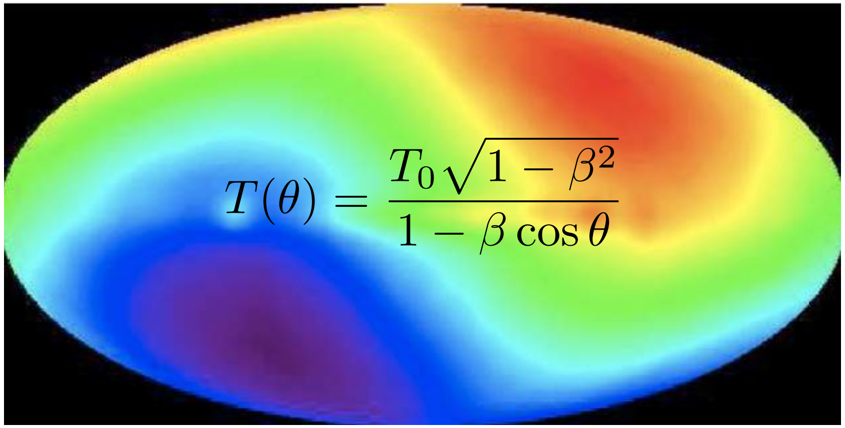
… To assume that we are a '*typical*' observer?

… To assume that all observed directions are *equivalent*?

THE UNIVERSE IS *NOT* ISOTROPIC AROUND US

Stewart & Sciama *Nature* **216**:748,1967
Peebles & Wilkinson, *PRL* **174**:2168,1968

The cosmic microwave background exhibits a dipole anisotropy with $\Delta T/T \sim 10^{-3}$

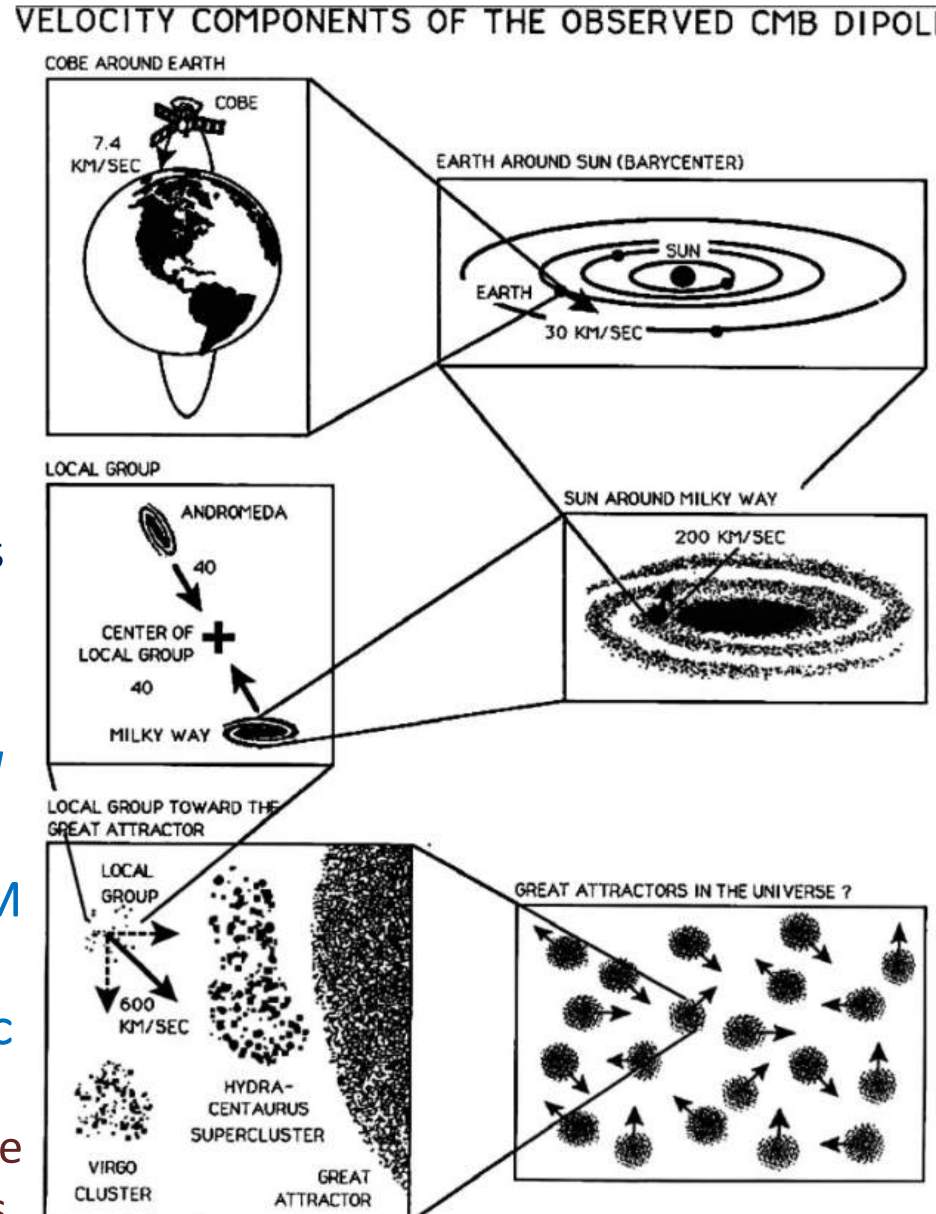


$$T(\theta) = \frac{T_0\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$

We interpret this 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 … according to structure formation in ΛCDM we should converge to the CMB frame by averaging on scales larger than ~100/*h* Mpc

So all data is ‘corrected’ by transforming to the CMB frame - in which FLRW *supposedly* holds



Smoot, Rev.Mod.Phys.**79**:349,2007

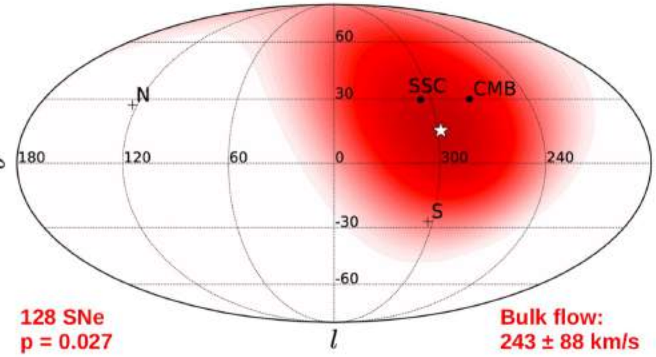
This motion is reflected in an anisotropy in the local SNe Ia *velocity* field

Bulk Flow Analysis

Tomography of Hubble flow

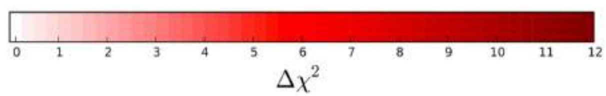
Dipole fit: 0.015 < z < 0.035

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



128 SNe
p = 0.027

Bulk flow:
243 ± 88 km/s



Bulk flow modeled as velocity dipole:

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

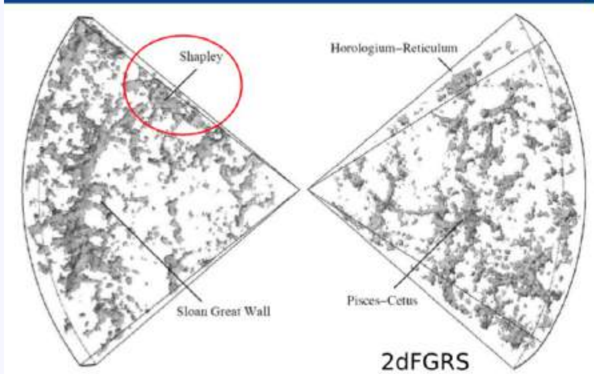
Best fit direction consistent with direction to Shapley

➔ Amplitude matches previous studies

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

Finding the Attractors

Modeling the velocity field

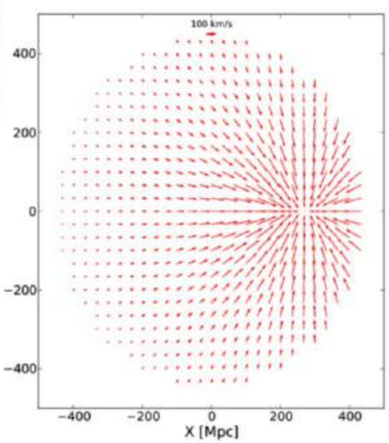


2dFGRS

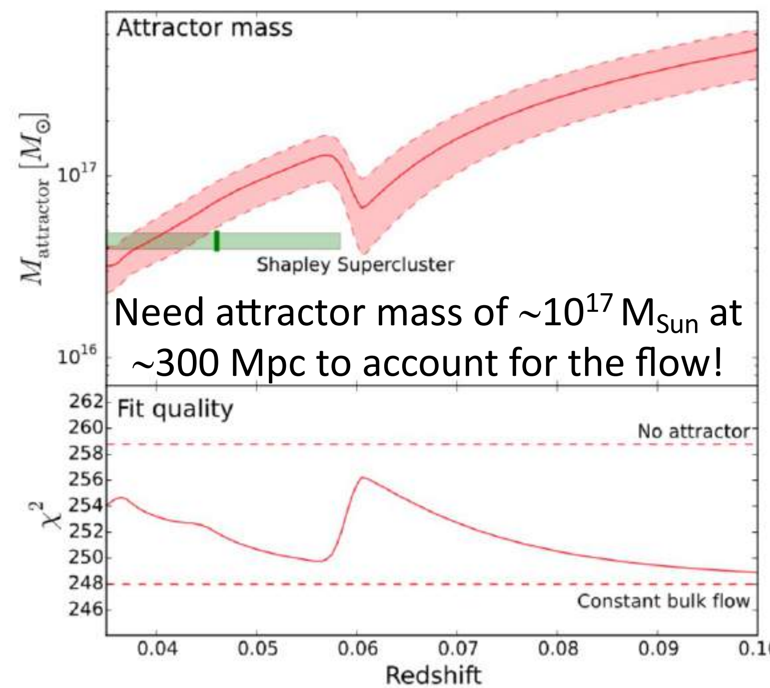
Simplest model:
Infall into spherical mass concentration

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

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

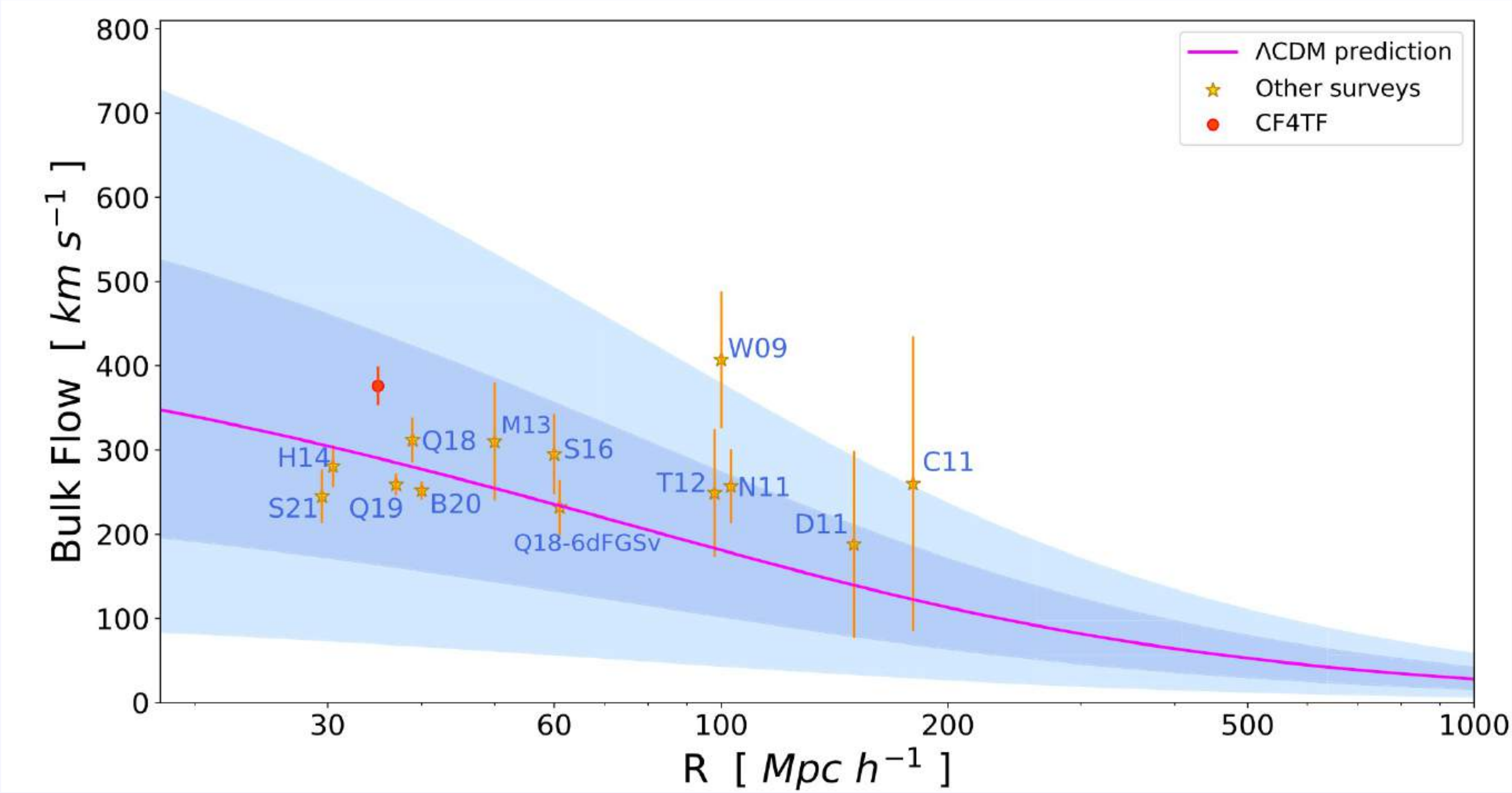


Courtesey: Ulrich Feindt



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

However convergence to the 'CMB frame' is not seen even out to ~200/h Mpc



Qin *et al*, Astrophys. J.922:59,2021

Bulk flow measurements from different surveys. The pink curve is the ΛCDM prediction for a spherical top-hat window function. The shaded areas indicate the 1σ and 2σ cosmic variance.

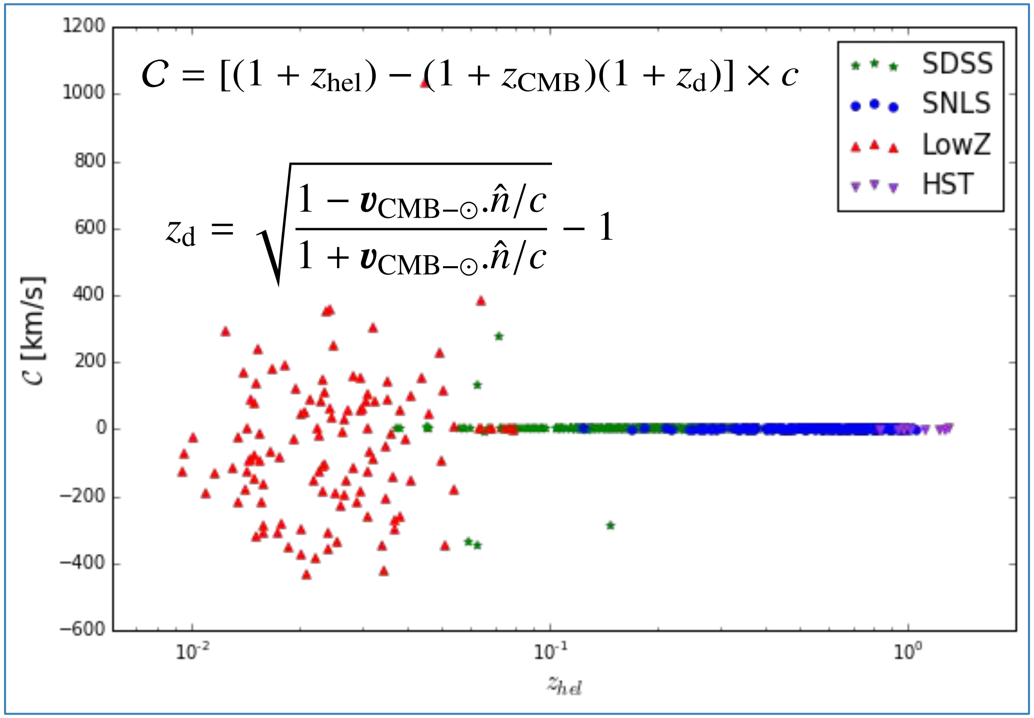
According to ΛCDM Hubble Volume simulations (e.g. 'Dark Sky'), *less than 1%* of Milky Way–like observers should experience a bulk flow as large as is observed, extending out as far as is seen.
So we are *not* typical 'Copernican' observers (Mohayaee, Rameez & S.S., arXiv: 2003.10420)

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 $z_{\rm CMB} \equiv z$ 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 SNe Ia catalogue have *assumed* that we converge to the CMB frame at 180/*h* Mpc (*contrary* to observations)



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

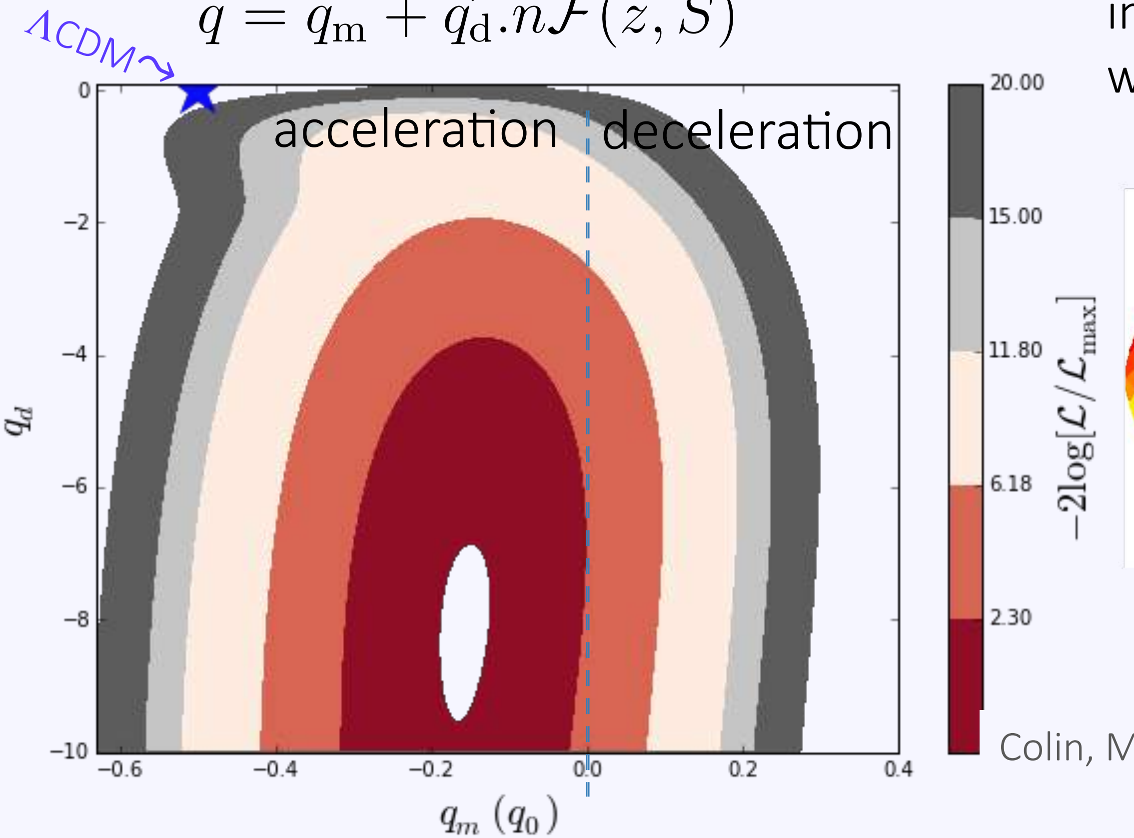
So we *undid* the corrections to recover the original data in the **heliocentric frame**

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

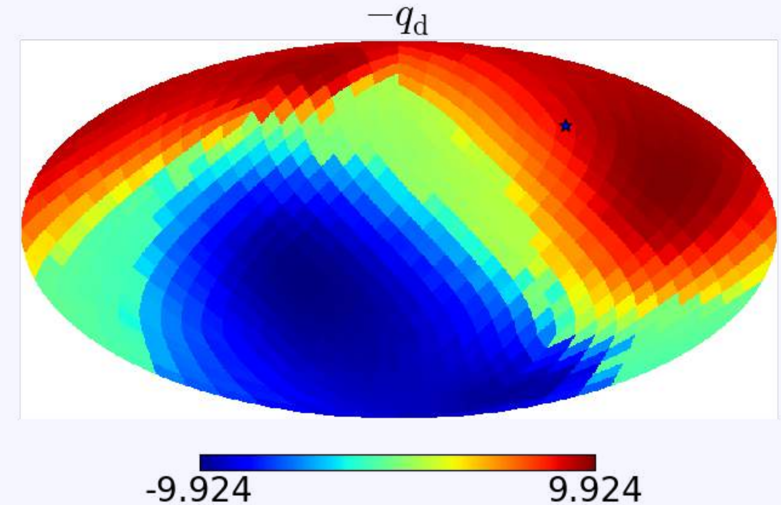
When cosmic acceleration is analysed allowing for a dipole, our MLE indeed *prefers* one (~50 times bigger than the monopole) … in the *same* direction as the CMB dipole

$$d_L(z) = \frac{cz}{H_0}\left[1 + \frac{1}{2}(1 - q_0)z + \ldots\right],$$

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



The best-fit direction of $q_{\rm d}$ is within 23^0 of the CMB dipole. i.e. the inferred acceleration is consistent with being due to the bulk flow.



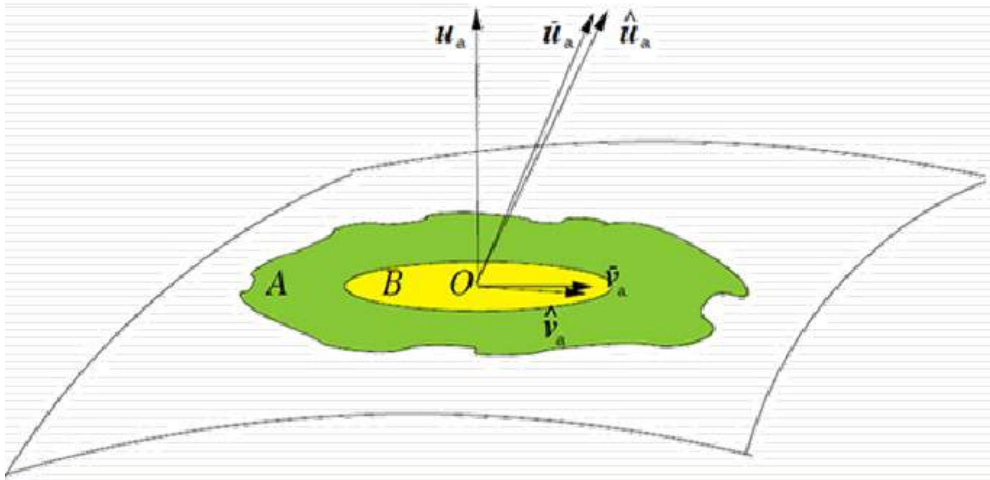
Colin, Mohayaee, Rameez & S.S., A&A **631**:L13,2019

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

This suggests that cosmic acceleration is an *artefact* of our being located within a bulk flow (which includes most of the observed SNe Ia) - and *not* due to Λ

A 'TILTED OBSERVER' EMBEDDED IN A BULK FLOW MAY INFER LOCAL ACCELERATION EVEN THOUGH THE EXPANSION IS ACTUALLY DECELERATING

(Tsagas, Phys.Rev.D**84**:063503,2011, Tsagas & Kadiltzoglou, PR D**92**:043515,2015)



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)

According to the Raychaudhury equation, inside region B, the r.h.s. of the expression

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

can drop below 1 so a comoving observer 'measures' negative deceleration parameter

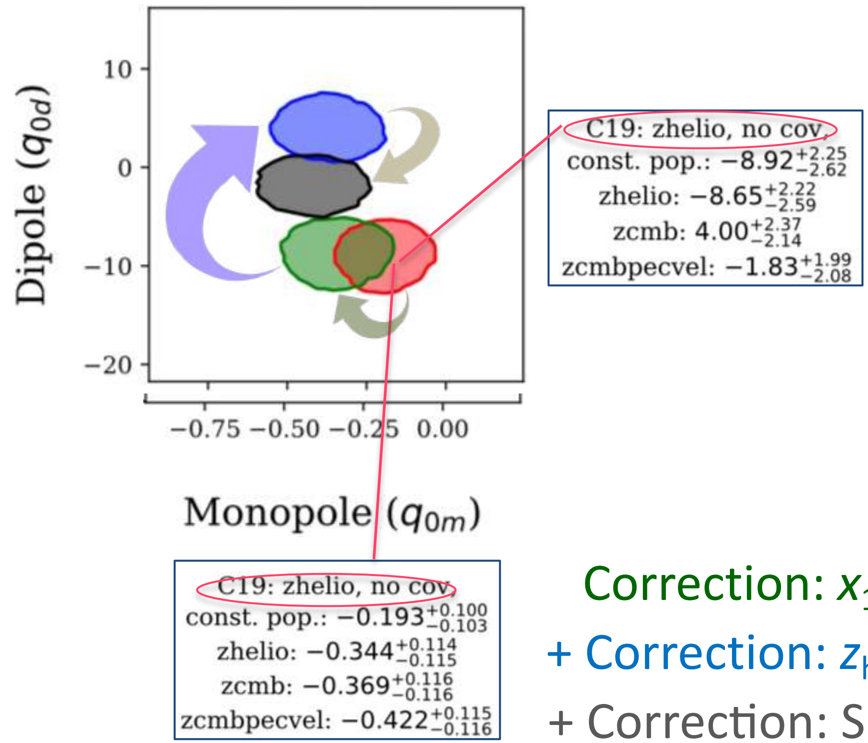
… if so, there should be a dipole asymmetry in the inferred deceleration parameter in the *same* direction – i.e. approximately aligned with the CMB dipole

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

Finally they make (questionable) peculiar velocity 'corrections' to get the *desired* result

Without JLA peculiar velocity covariance



Correction: x_1 & c are z-dependent

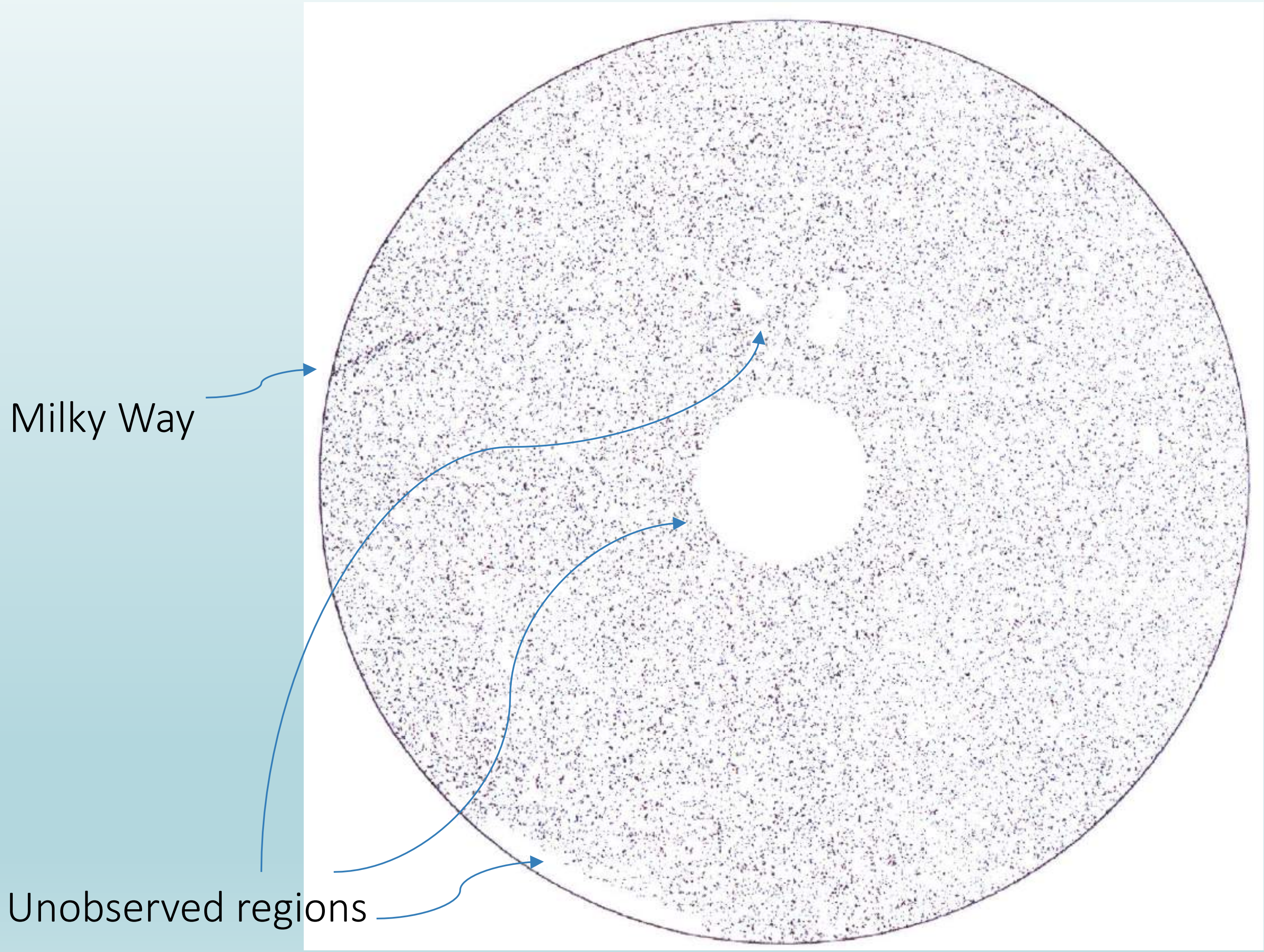
\+ Correction: $z_{\text{hel}} \rightarrow z_{\text{CMB}}$

\+ 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?

On very large scales ($z \sim 1$) the distribution of radio sources supposedly demonstrates the isotropy of the Universe



Peebles, <u>*Principles of Physical Cosmology*, 1993</u>

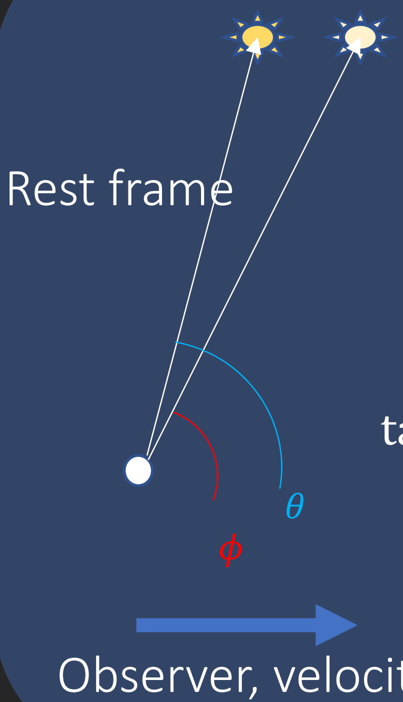
But if we are moving w.r.t. the cosmic rest frame, then distant sources *cannot* be isotropic!

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

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

Aberration

(Bradley 1727)



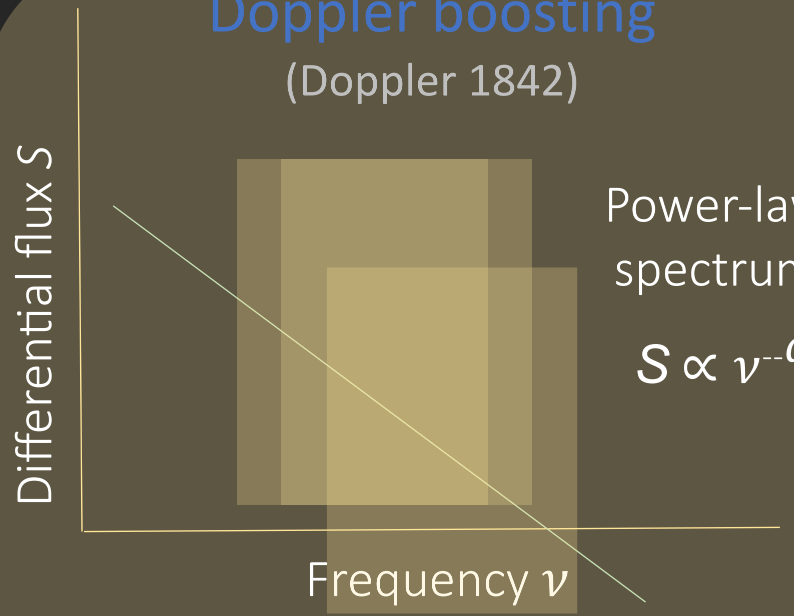
Moving frame

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

+

Doppler boosting

(Doppler 1842)



Power-law spectrum

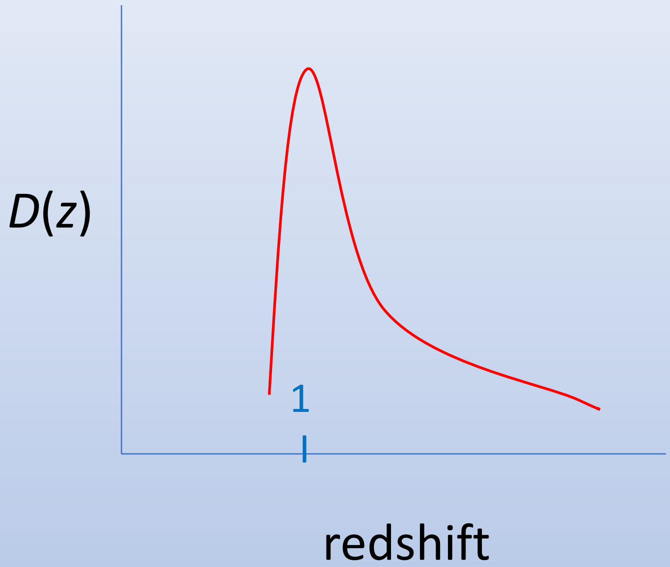
$S \propto \nu^{--\alpha}$

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

Flux-limited catalogue ➞ *more* sources in direction of motion

Ellis & Baldwin, MNRAS **206**:377,1984

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 only for shallow surveys)

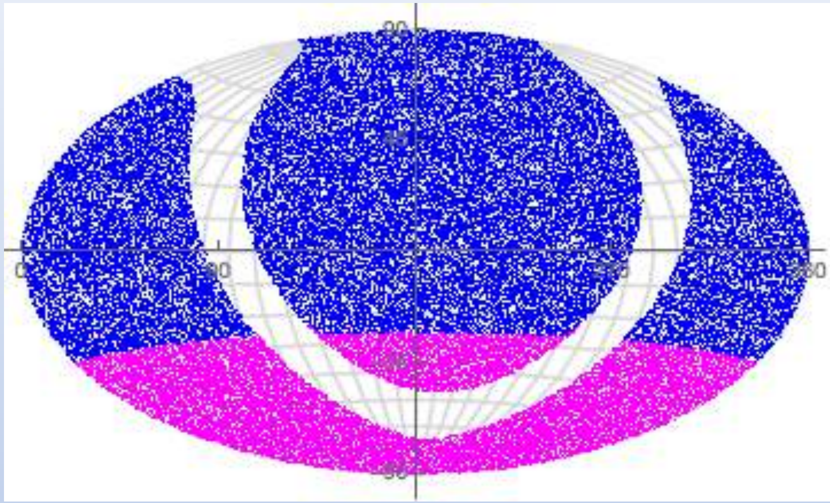
NVSS + SUMSS: 600,000 radio sources <*z*> ~ 1 (est.), $\vec{\mathcal{S}}$ (*D*(*z*)) → 0 (est.)
Colin, Mohayaee, Rameez & S.S., MNRAS **471**:1045,2017

Wide Field Infrared Survey Explorer: 1,200,000 galaxies, <*z*> ~ 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, <*z*> ~ 1.2, $\vec{\mathcal{S}}$ (*D*(*z*)) ~ 1%
Secrest, Rameez, von Hausegger, Mohayaee, S.S. & Colin, ApJ Lett.**908**:L51,2021

(1.4 GHz survey down to Dec = -40.4^{o}) (843 MHz survey at Dec < -30^{o})

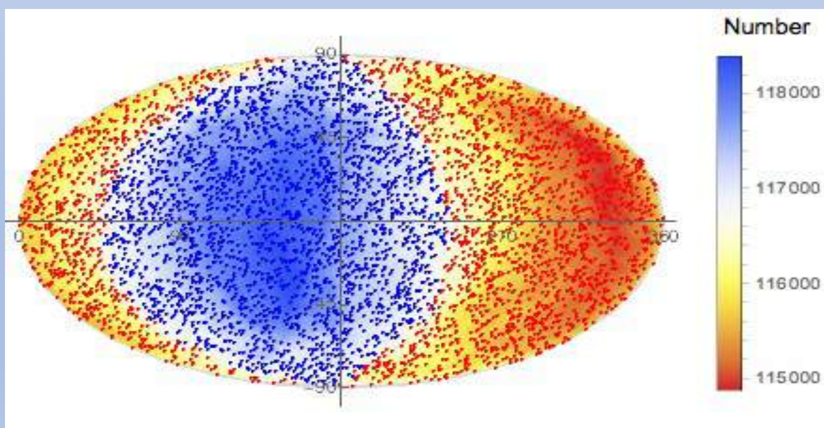
[Rescale the SUMSS fluxes by (843 MHz/1.4 GHz)$^{-0.75}$ = 1.46 to match with NVSS]

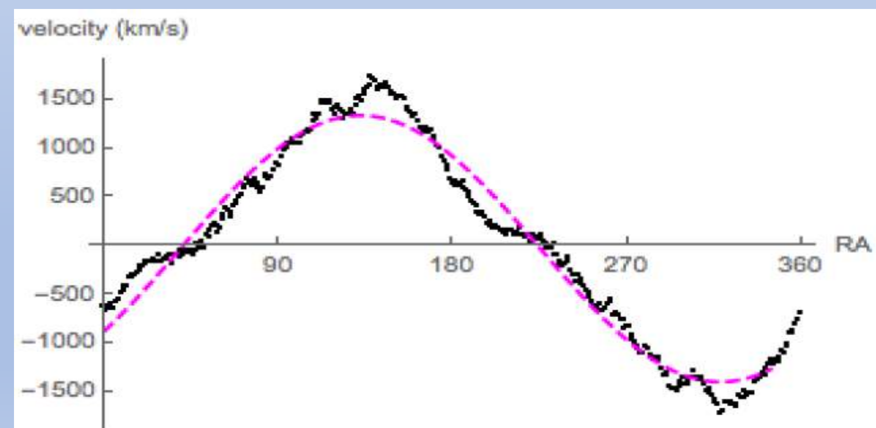


To get rid of any 'clustering dipole':

- Remove Galactic plane ±10^{o} (also Supergalactic plane)
- Remove nearby sources which are in common with 2MRS/LRS surveys

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



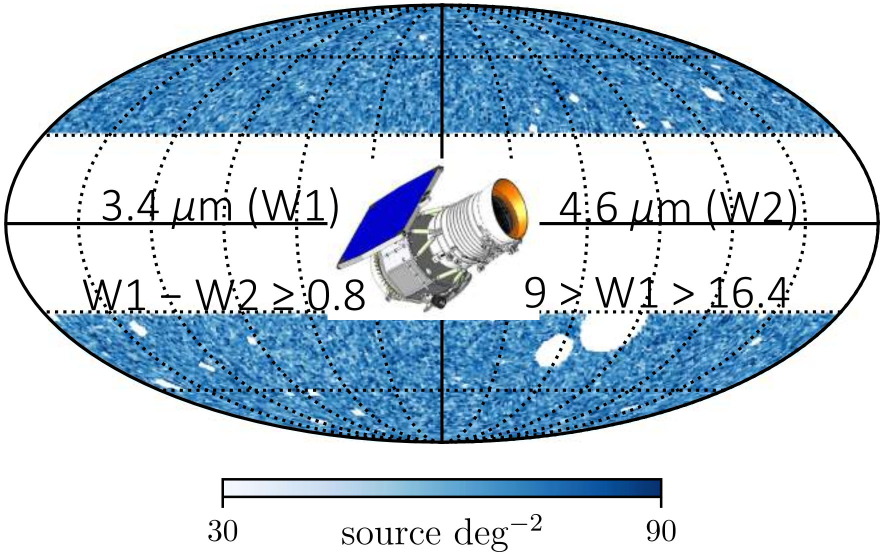


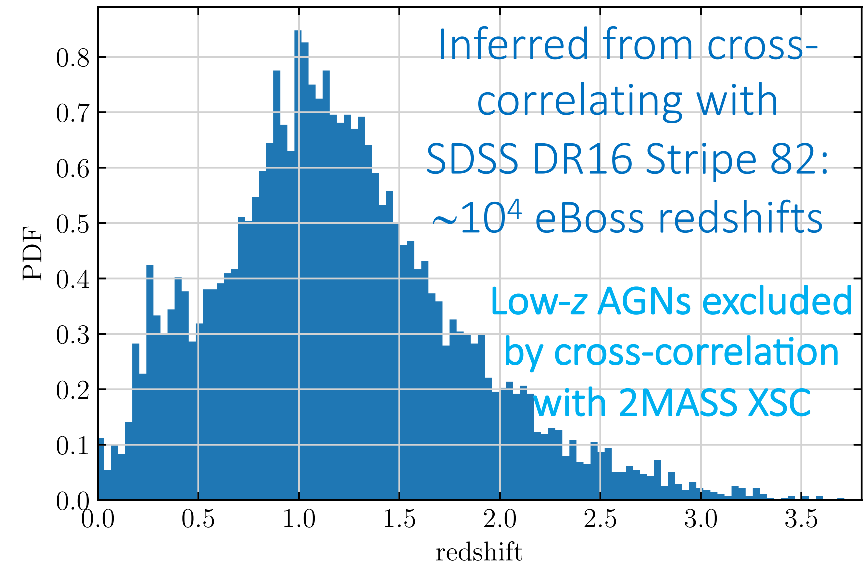
Confirms claim by Singal (ApJ **742**:L23,2011) … however source redshifts are not *directly* measured (and the statistical significance is only 2.8**σ** – by Monte Carlo)

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

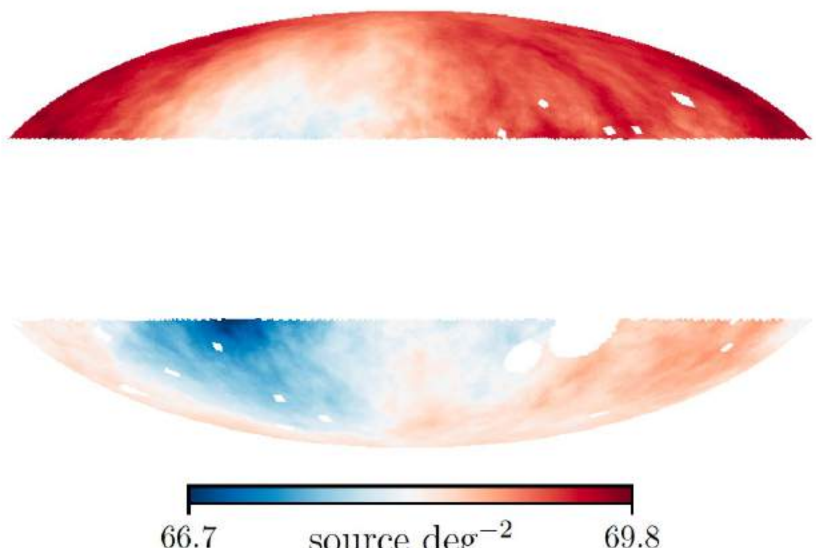
THE CATWISE QUASAR CATALOGUE

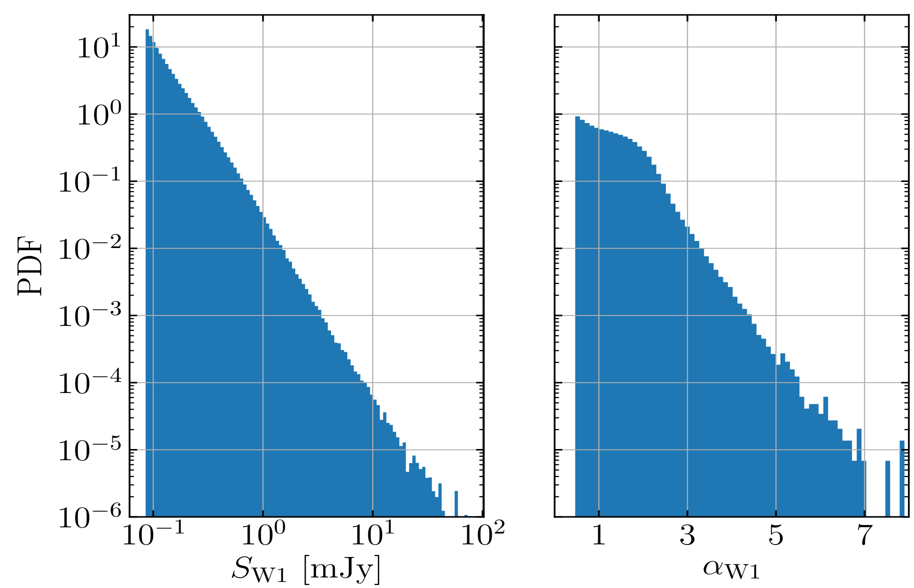
Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, ApJL 908:L51,2021





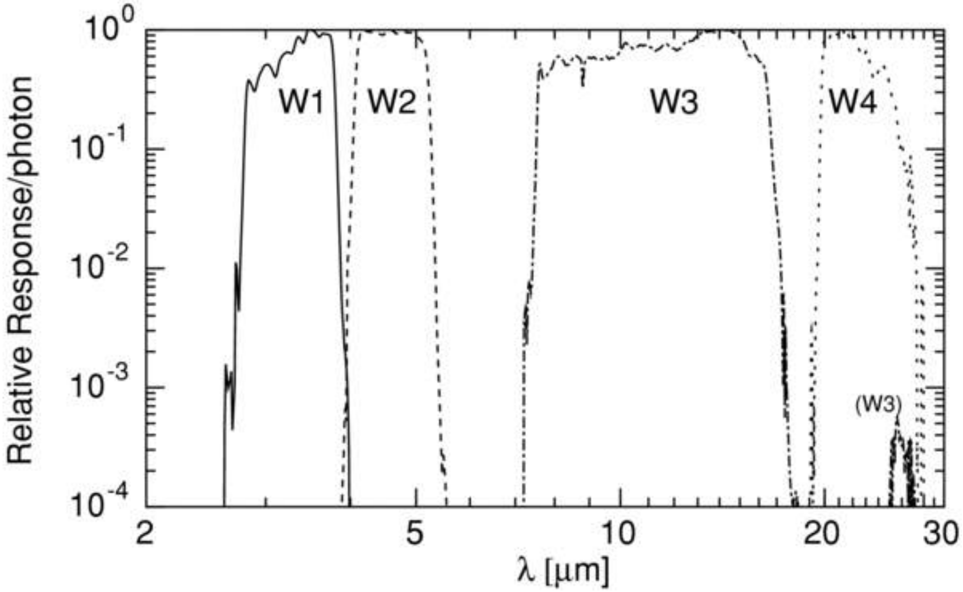
We now have a catalogue of 1.36 million quasars, with 99% at redshift > 0.1

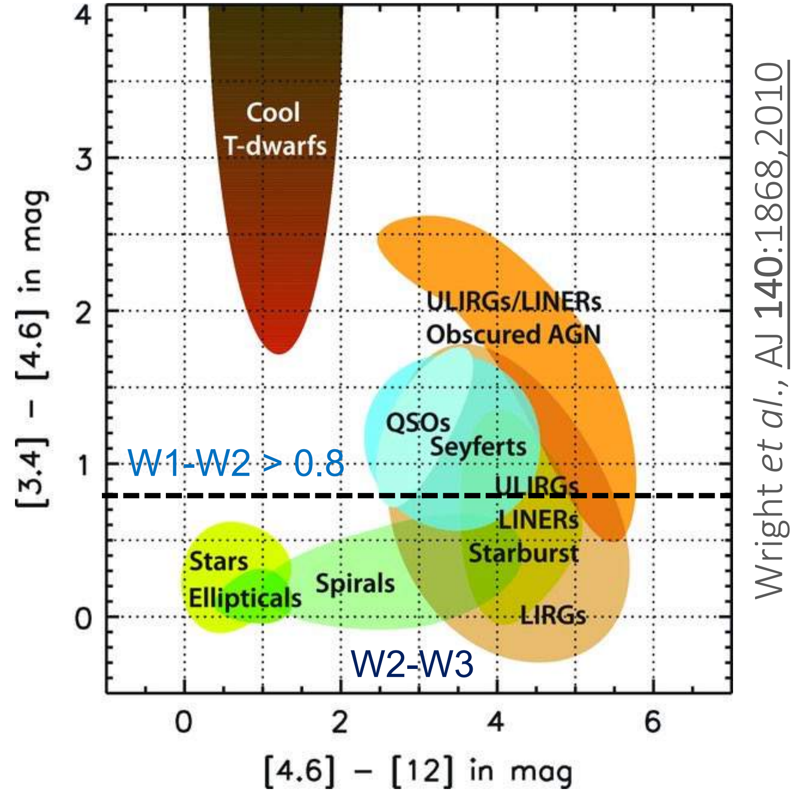


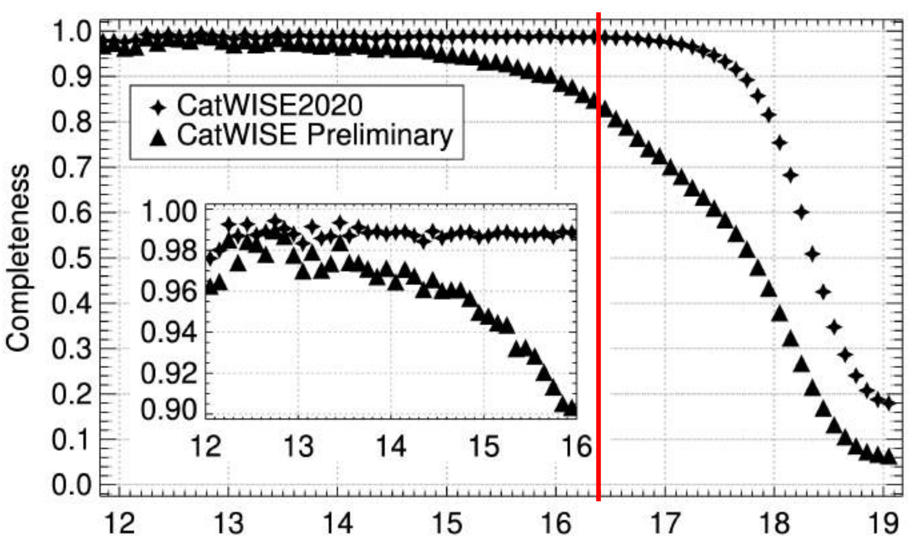


The dipole can be compared to that expected, knowing the spectrum & flux distribution

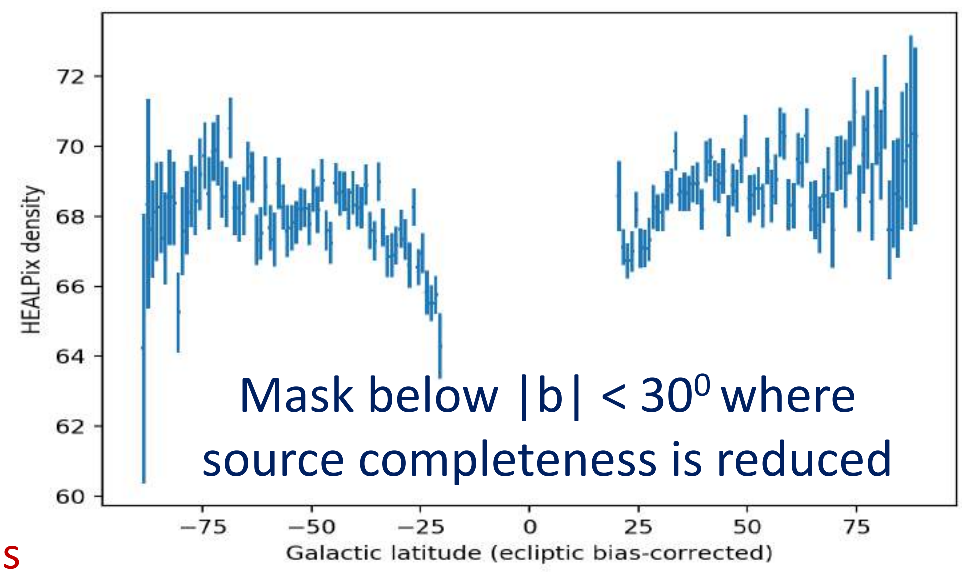
OUR COLOUR CUTS SELECTIVELY SELECT QUASARS … OUR SAMPLE PURITY IS 99% (CONFIRMED BY eBOSS SPECTRA OF SUB-SAMPLE)



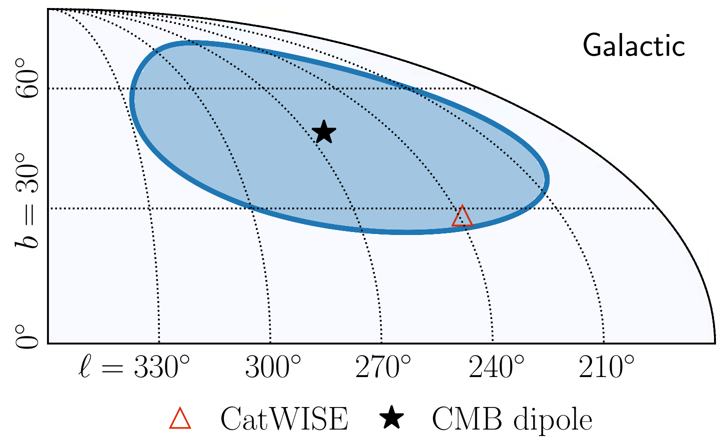




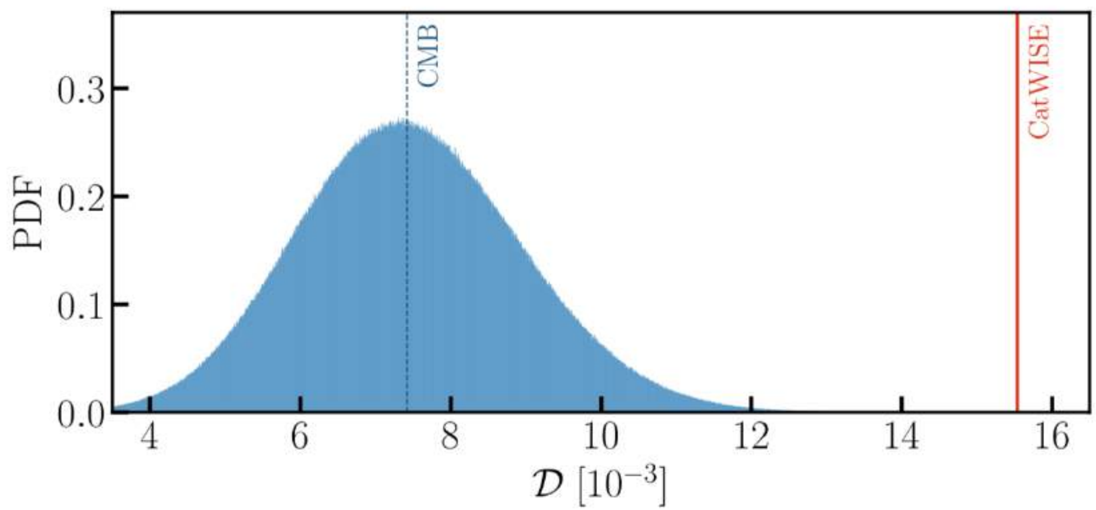
Magnitude cut W1 < 16.4 ensures completeness



Our peculiar velocity wrt quasars ≠ peculiar velocity wrt the CMB



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

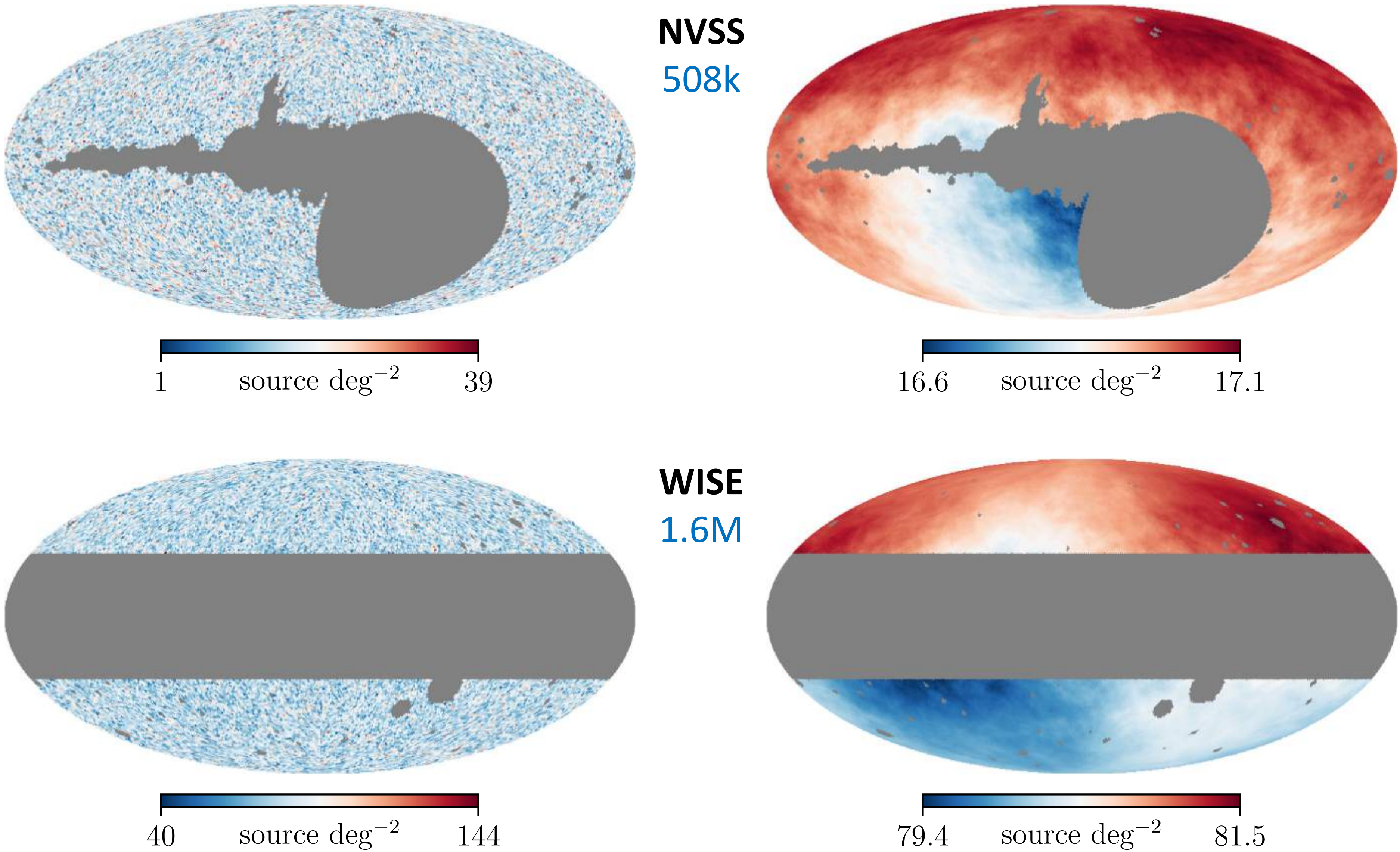


The kinematic interpretation of the CMB dipole is *rejected* with $p = 5 \times 10^{-7} \Rightarrow 4.9\sigma$

(Data & code available on: https://doi.org/10.5281/zenodo.4431089)

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

We have further cleaned the NVSS & WISE AGN catalogues of a variety of systematics

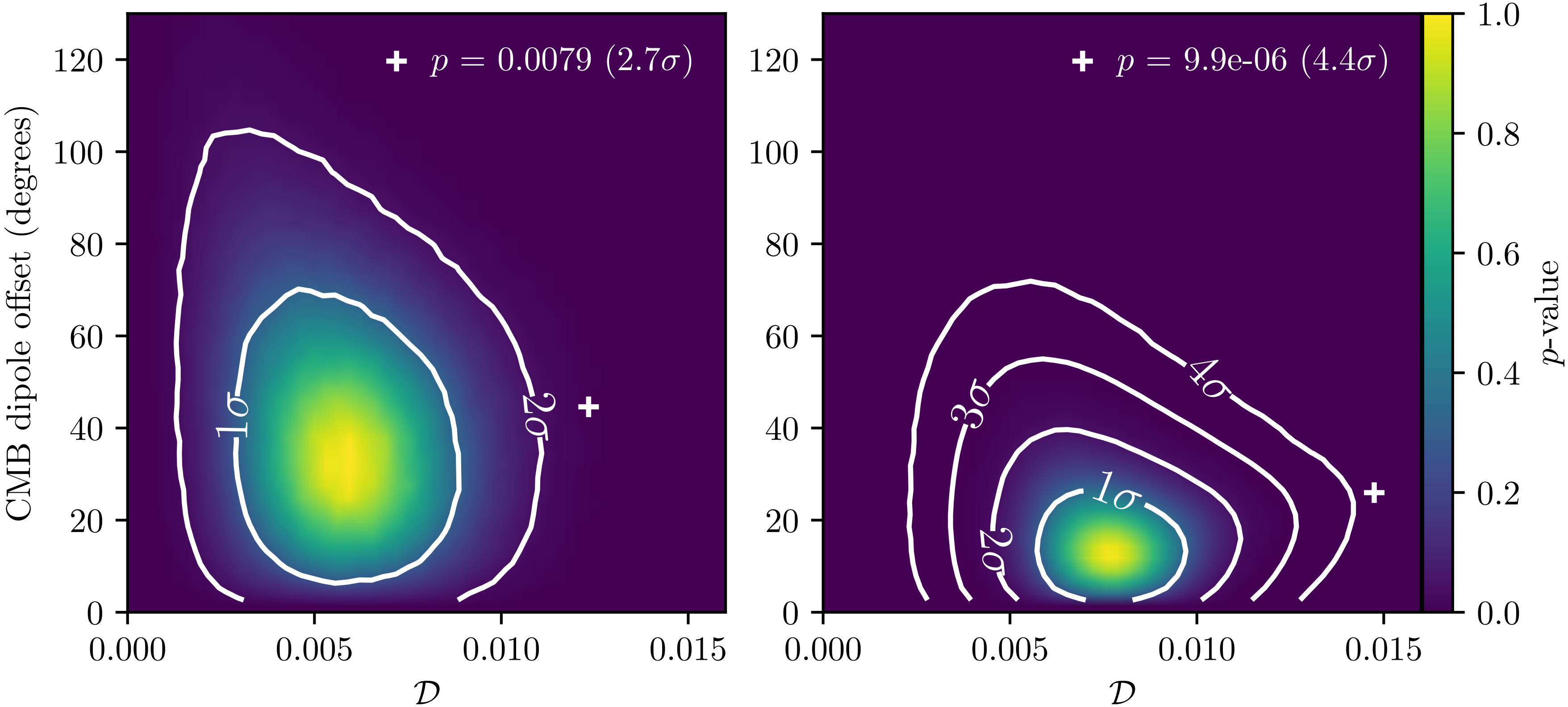


The two dipoles are *consistent* with each other; their vector mean is:

D = (1.40 ± 0.13)×10^{-3} towards (l, b) = (233.0,+34.4)

Secrest, Rameez, Von Hausegger, Mohayaee, S.S., arXiv:2206.05624

The NVSS & WISE AGN catalogues are *independent* so we can combine the p-values by which each rejects the null hypothesis



Distribution of CMB dipole offsets & kinematic dipole amplitudes of simulated null skies for NVSS (left) and WISE (right). Contours of equal *p*-value and equivalent σ are given (where the peak of the distribution corresponds to 0σ), with the found dipoles marked with + and their *p*-values are in the legends.

Combined significance ⇒ standard cosmology expectation is rejected at 5.2**σ**

Secrest, Rameez, Von Hausegger, Mohayaee, S.S., arXiv:2206.05624

Summary

- The 'standard model' of cosmology was established before there was any observational data and its empirical foundations have not been tested.

Now that we have data, we should test the *assumed* homogeneity and isotropy … not simply measure the model parameters with increasing `precision'

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

The inference that the Hubble expansion rate is *accelerating* may be just an artefact of the bulk flow (and *not* due to a Cosmological Constant)

- The rest frame of distant quasars ≠ the rest frame of the CMB

This is a serious challenge to the foundational FLRW metric assumption

We must begin again – to construct a new standard model of cosmology

(following Ellis & Stoeger's manifesto: *The 'fitting problem' in cosmology*, CQG **4**:1697,1987)

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ORAL HISTORIES

Interview date: Monday, 3 April 1989

Lightman**:**

Taking into account a large body of work besides the Geller, de Lapparent, Huchra work - your own work on the large-scale motions and the work of the Seven Samurai & all of that work which has shown that the universe is more inhomogeneous than might have been present in simple models - has that altered your view of the big bang model at all, or of the validity of model, the assumptions of the model, that kind of thing?

Rubin *et al*, *Motion of the Galaxy and the local group determined from the velocity anisotropy of distant SC I galaxies, I The data*, Astron.J.81:687,1976 *II The Analysis* Astron.J.81:719,1976

Dressler *et al*, *A Large-Scale Streaming Motion in the Local Universe* Astrophys.J.313:L37,1987

Rubin:

It certainly has convinced me that we're not living in a homogeneous, isotropic [universe]. I mean these things that I really suspected in the back of my mind, I can now say publicly. **I'm not sure the Robertson-Walker universe exists.** I can think of more questions to ask because of what they've done, which go more in the direction of making things more inhomogeneous, and I've at least asked some of my theorist friends some of them. No, it hasn't concerned me about the big bang - maybe because I just don't put my mind to it. **If someone came out with a different model that could incorporate such large-scale inhomogeneities, I would be delighted to see it**, but until then I will just live with the big bang model.